Three lectures on Beyond the Standard Model (BSM)

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UC Santa Cruz

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TRIUMF

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Overview

Chapter 1: **Introduction:**
The Standard Model and its open problems

Chapter 2: **Heavy New Physics**

- The hierarchy problem (SUSY and EFTs)
- The SM and the NP flavor puzzle, EFT
- NP flavor puzzle, UV models
- The origin of neutrino masses

Chapter 3: **Light New Physics**

- Dark Matter and the dark sectors in the MeV-GeV range
- Axions and axion-like-particles

TODAY

TOMORROW

Goal: Some basics + overview of what I find exciting about BSM theories + pheno
Disclaimer: not comprehensive!
Please interrupt to ask questions! We do not have to go through all slides! :)

List of references for BSM

Obviously, this is a very vast topic…

One can start with these TASI, TRISEP, ESHEP lectures:

A. Wulzer, https://arxiv.org/pdf/1901.01017
ESHEP 2015 (hierarchy problem and SUSY)

M. McCullough, https://inspirehep.net/files/dbd74aa24943e72752778f0bb7e5656d
TRISEP 2018 (hierarchy problem and strong CP problem/axions)

A. Hook, https://arxiv.org/pdf/1812.02669
TASI 2018 (strong CP problem and axions)

T. Lin, https://arxiv.org/pdf/1904.07915
TASI 2018 (light Dark Matter)

W. Altmannshofer, https://inspirehep.net/files/4522a7c318aaec7fffb5de3321b62501
TASI 2022 (flavor physics)

Please send me a message,
if you have questions!
sgori@ucsc.edu

Let us start!

Chapter 1: Introduction:
The Standard Model and its open problems

see lectures by N. Blinov

S.Gori

First: what is the Standard Model (SM)?

The SM is

- a remarkably successful description of nature
- a Quantum Field Theory
- based on symmetry principles
- ~minimal
- a model with an enormous predictive power

But we do not understand why it works so well. . .

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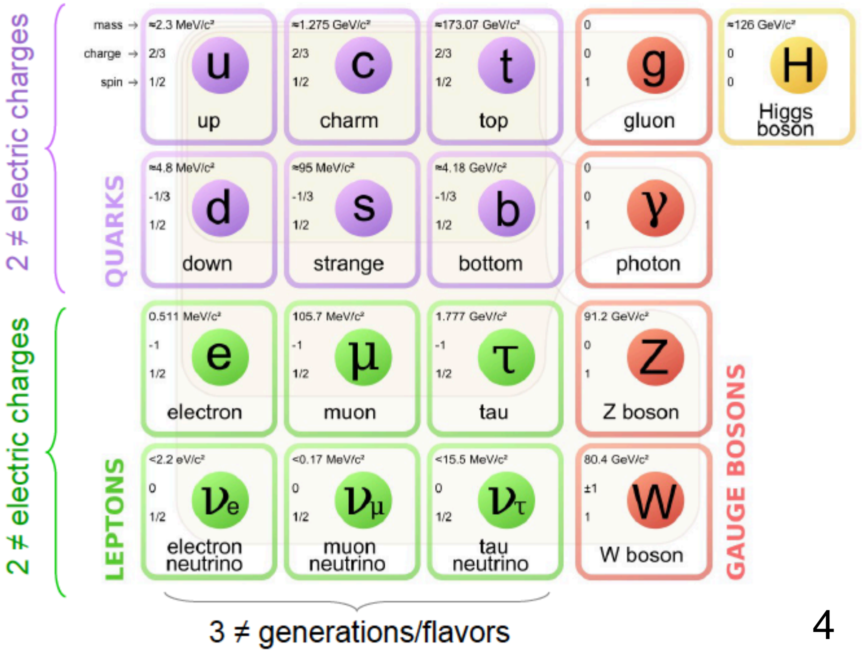
Particle content:



mass → charge → spin →	≈2.3 MeV/c^2 2/3 1/2 u up	≈1.275 GeV/c^2 2/3 1/2 c charm	≈173.07 GeV/c^2 2/3 1/2 t top	0 0 1 g gluon	≈126 GeV/c^2 0 0 H Higgs boson
	≈4.8 MeV/c^2 -1/3 1/2 d down	≈95 MeV/c^2 -1/3 1/2 s strange	≈4.18 GeV/c^2 -1/3 1/2 b bottom	0 0 1 γ photon	
	0.511 MeV/c^2 -1 1/2 e electron	105.7 MeV/c^2 -1 1/2 μ muon	1.777 GeV/c^2 -1 1/2 τ tau	91.2 GeV/c^2 0 1 Z Z boson	
	<2.2 eV/c^2 0 1/2 ν_e electron neutrino	<0.17 MeV/c^2 0 1/2 ν_μ muon neutrino	<15.5 MeV/c^2 0 1/2 ν_τ tau neutrino	80.4 GeV/c^2 ±1 1 W W boson	

Fundamental principles of the SM

We write down a Lagrangian based on

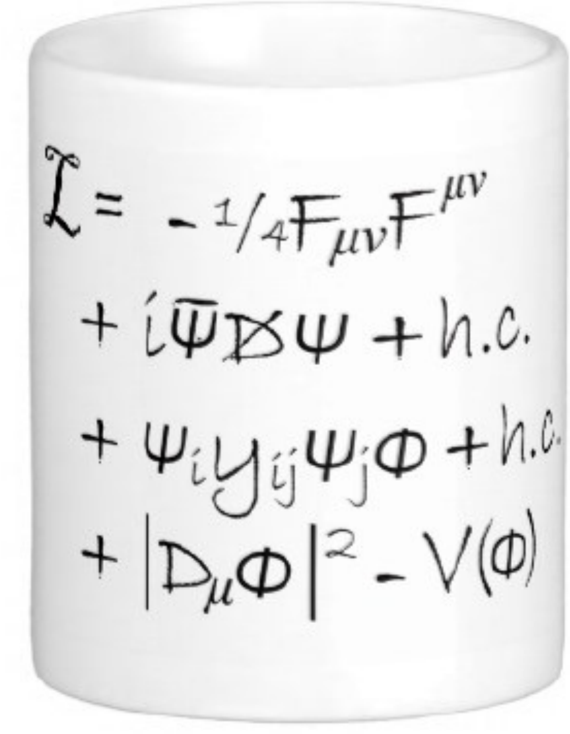
- minimality: only observed and/or unavoidable objects
- unitarity
- renormalizability: finite predictions for the physical observables
- symmetries

Symmetries:

- Lorentz symmetry
- Gauge symmetries: $SU(3)_C \times SU(2)_L \times U(1)_Y$
- we do not impose global symmetries. They are "accidental": e.g.
  - ✔ $SU(3)^5$ flavor symmetry broken by the Higgs interactions with fermions
  - ✔ Lepton and baryon number
  - ✔ ...

We will introduce this in the context of the New Physics (NP) flavor puzzle

Free parameters of the SM Lagrangian



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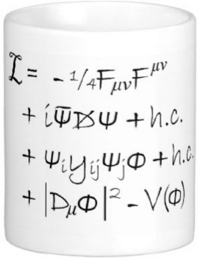


$$-\frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

$$i\bar{\Psi}\not{D}\psi + h.c.$$

- Describes the gauge interactions of quarks and leptons

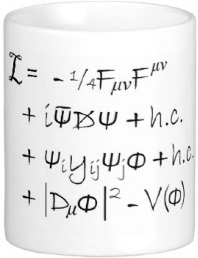
- Parametrized by 3 gauge couplings g_1, g_2, g_3

- Stable with respect to quantum corrections

- Highly symmetric

Gauge sector

Free parameters of the SM Lagrangian



$$\mathcal{L} = -\tfrac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\Psi}\not{D}\psi + h.c. + \psi_i y_{ij}\psi_j\Phi + h.c. + |D_\mu\Phi|^2 - V(\Phi)$$

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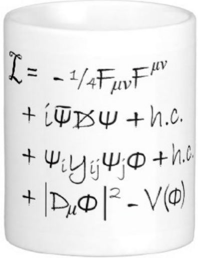
Gauge sector

$$+|D_\mu\Phi|^2 - V(\Phi)$$

- Breaks electro-weak symmetry and gives mass to the *W* and *Z* bosons
- 2 free parameters: Higgs mass Higgs vev
- Not stable with respect to quantum corrections **(hierarchy problem)** ⊗

Higgs sector

Free parameters of the SM Lagrangian



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(hierarchy problem) ✗

Higgs sector

$$+\psi_i y_{ij}\psi_j\Phi + h.c.$$

- Leads to masses and mixings of the quarks and leptons
- 10+10 free parameters in the quark+lepton sector (12 in the lepton sector in case of Majorana masses)

✓ ✗ **(flavor puzzle)**

- Stable with respect to quantum corrections

Flavor sector

Open problems/questions for the SM

Let us re-write the SM Lagrangian allowing also for operators up to dimension 6 in the SM fields

$$\begin{aligned}
\mathcal{L}_{\mathrm{SM}} \sim\ & \Lambda^4 - \Lambda_H^2 H^2 + \lambda H^4 \\
+\ & \bar{\psi} \not{D} \psi + (D_\mu H)^2 + (F_{\mu\nu})^2 \\
+\ & F_{\mu\nu} \tilde{F}_{\mu\nu} + Y H \bar{\psi} \psi \\
+\ & \frac{1}{\Lambda}(LH)^2 + \frac{1}{\Lambda^2} \sum_i O_i(\mathrm{dim6})
\end{aligned}$$

Open problems/questions for the SM

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1. Cosmological constant problem

$$\left(\frac{\Lambda}{M_{\rm Planck}}\right)^4 \sim 10^{-120}$$

2. Hierarchy problem

$$\left(\frac{m_h}{M_{\rm Planck}}\right)^2 \sim 10^{-36}$$

3. Vacuum stability problem

4. Strong CP problem

$$\frac{\Theta}{16\pi^2} F_{\mu\nu}\tilde{F}_{\mu\nu}, \quad \Theta \leq 10^{-10}$$

5. SM Flavor puzzle

$$\frac{y_t}{y_u} \sim 10^{-5}$$

6. Origin of neutrino masses

7. New Physics flavor puzzle

→ **Beyond the Standard Model (BSM) physics?**

Open problems/questions for the SM

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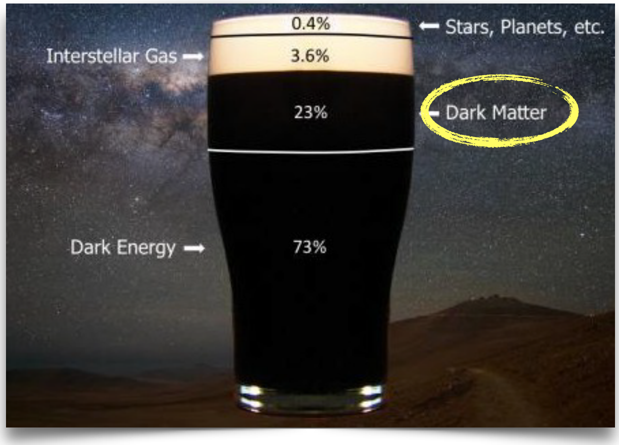
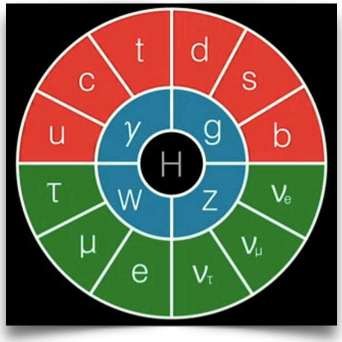
→ **Beyond the Standard Model (BSM) physics?**

More open problems for the SM

Nature of Dark Matter





+ ?

We do not know (if and) how it interacts with the Standard Model

See lectures by C.Wagner

Baryon-antibaryon asymmetry

The observable universe contains **matter**, but almost no **antimatter**.

From CMB + BBN measurements: $\eta_B \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} \simeq 6 \cdot 10^{-10}$

Early universe: baryon + antibaryon in equal amounts → they should completely annihilate

Today: ~Only matter survives → requires a mechanism to generate the asymmetry

Principles to build a “good” BSM theory

- Take a local, lorentz invariant, unitary field theory;
- Preserve gauge invariance ($SU(3)_c \times SU(2)_L \times U(1)_Y$), anomaly free;
- (Typically) do not introduce too large sources of breaking of the accidental / approximate symmetries of the SM classical Lagrangian

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  - baryon and lepton number
  B_{quark} = 1/3, $B_{anti\text{-}quark}$ = -1/3, B_{lepton} = 0 (L_{lepton} = 1, $L_{anti\text{-}lepton}$ = -1, L_{quark} = 0)
  - Individual lepton families
  L_e, L_μ, L_τ (these are broken by neutrino masses in the SM (tiny))
  - Custodial symmetry: $SU(2)_L$ x $SU(2)_R$ → $SU(2)_V$ (diagonal)
  (this is broken by hypercharge and Yukawas in the SM)
  - $SU(3)^5$ flavor symmetry (this is broken by the Yukawas in the SM)

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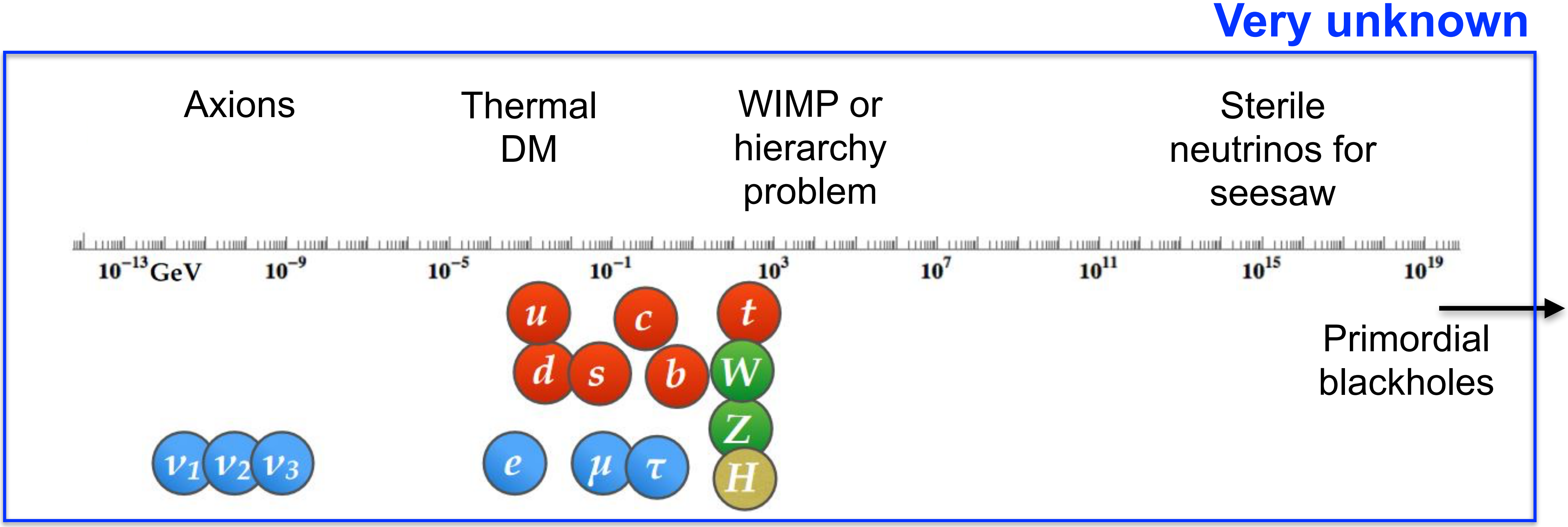
    (this is broken by hypercharge and Yukawas in the SM)
  - $SU(3)^5$ flavor symmetry (this is broken by the Yukawas in the SM)
- Not be ruled out by experiments!

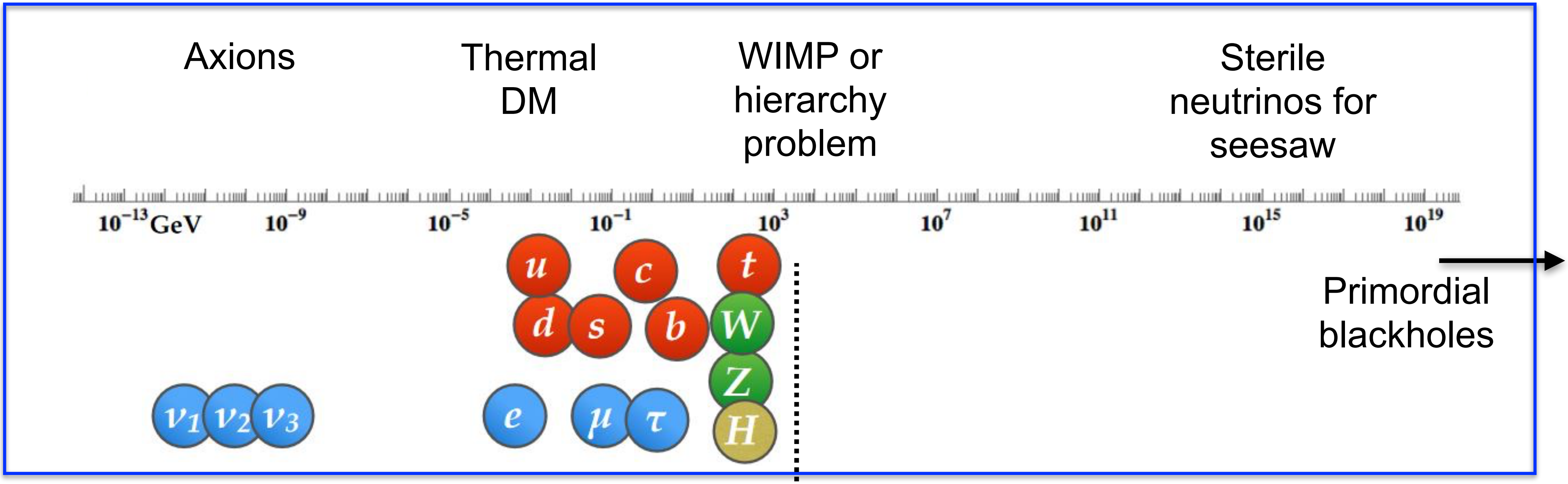
The scale of New Physics



We need to keep searching as broadly as possible!

The scale of New Physics

Very unknown



Axions

Thermal DM

WIMP or hierarchy problem

Sterile neutrinos for seesaw

Primordial blackholes

We need to keep searching as broadly as possible!

We will include here NP at the ~electro-weak (EW) scale

Light New Physics

Chapter 3

Heavy New Physics

⇨ SM effective theory (SMEFT)

Chapter 2

Chapter 1: Introduction:
The Standard Model and its open problems ✓

Chapter 2: Heavy New Physics

- The hierarchy problem (SUSY and EFTs)
- The SM and the NP flavor puzzle, EFT
- NP flavor puzzle, UV models
- The origin of neutrino masses

Heavy New Physics

The hierarchy problem

Let us take a generic theory of scalars, φ, and fermions, ψ:

$$\mathcal{L} = |\partial_\mu \phi|^2 + \bar{\psi} i \not{\partial} \psi - m_f^0 \bar{\psi}\psi - y\phi\bar{\psi}\psi + \mu_0^2 |\phi|^2 - \lambda |\phi|^4$$

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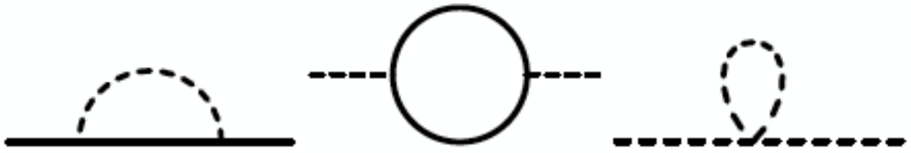

etc.

$$\Delta m_f \sim -\frac{y^2}{16\pi^2} m_f \log\left(\frac{\Lambda}{m_f}\right)$$

$$\Delta\mu^2 \sim \frac{y^2-\lambda}{16\pi^2}\Lambda^2 + \cdots \qquad \mu^2 = \mu_0^2 + \Delta\mu^2 = \mathcal{O}((100\ \mathrm{GeV})^2)$$

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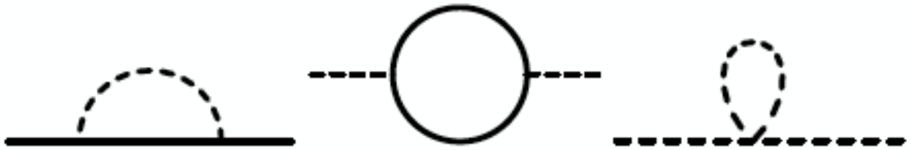

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Scalars are very sensitive to the highest scale of the theory

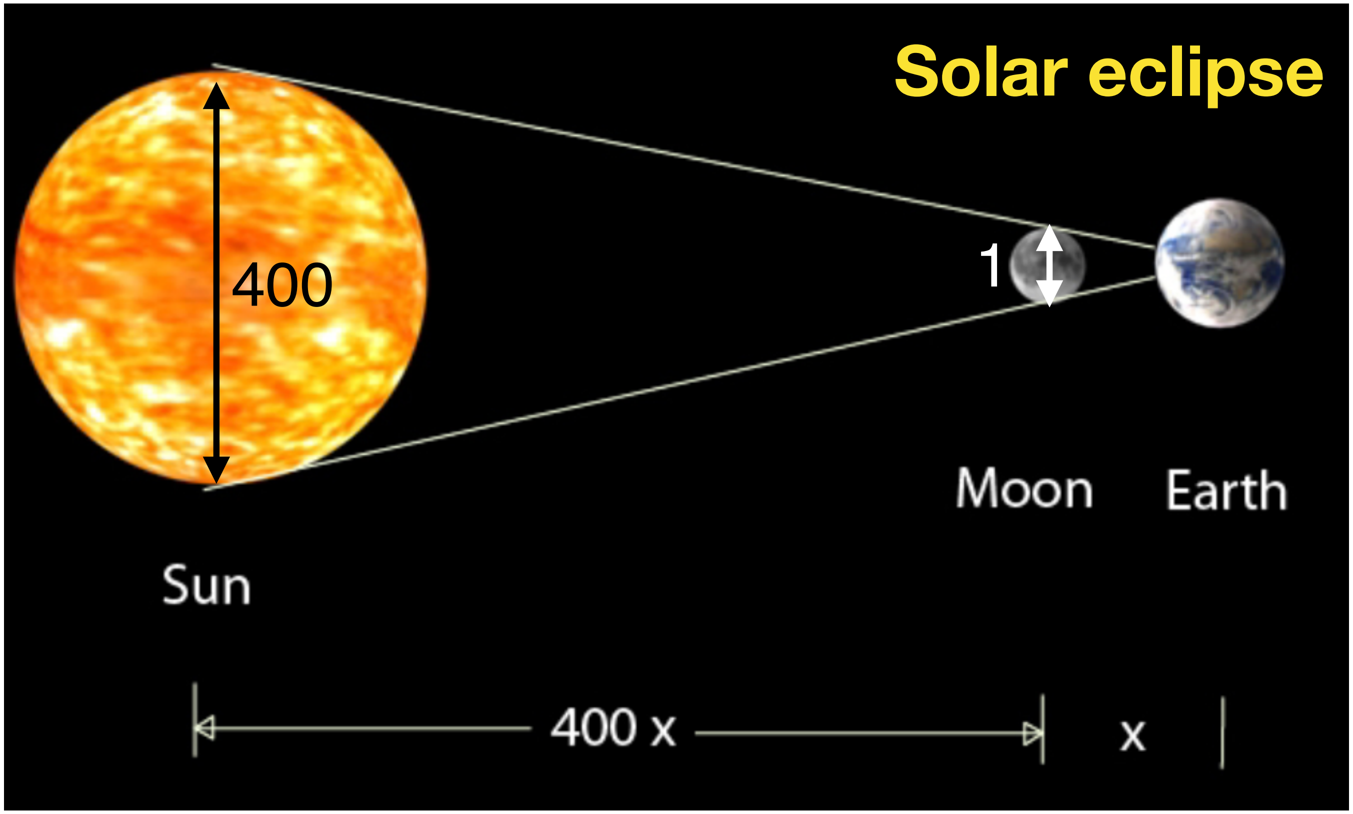
Generically, we would expect some New Physics at the scale $\Lambda = \mathcal{O}\left(\frac{4\pi}{g} m_h\right)$

$m_h \sim 125$ GeV
$M_{Planck} \sim 10^{19}$ GeV

~TeV scale New Physics?

This argument has been motivating NP searches at the LHC

Putting it in perspective…



The distance 1 : 400 should be precise at the **~ 0.05** level

to compare → The precision needed to predict the measured Higgs mass: **0.0000000000000000000000000000000001**

Addressing the hierarchy problem

Most studied

Supersymmetry

Composite Higgs models or, equivalently, extra-dimensional models

A bit more recently:

Neutral naturalness models (twin Higgs, Chacko et al, 0506256**)**,

Relaxation models (Graham et al, 1504.07551),

Nnaturalness (Arkani-Hamed et al, 1607.06821), ...

Signals at the LHC

Addressing the hierarchy problem

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Signals at the LHC

SUSY (basic principle)

Introduce **new scalar degrees of freedom** that are related to the fermions of the SM

$$\Delta\mu^2 \sim \frac{y^2-\lambda}{16\pi^2}\Lambda^2+\cdots$$

Cancel the quadratic sensitivity of the Higgs mass to the New Physics scale

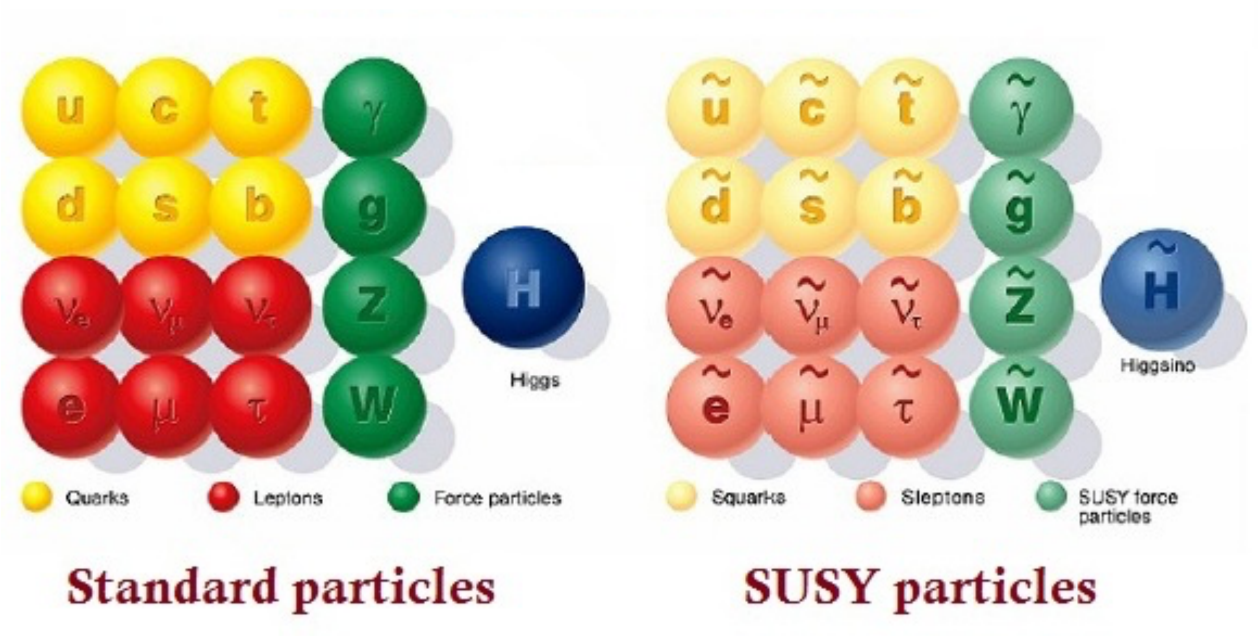
Neutral naturalness (basic principle)

Introduce **new fermionic degrees of freedom** that are related to the fermions of the SM but **not charged under the SM gauge symmetries**

Cancellation of the quadratic sensitivity is ensured by a **global symmetry** (e.g. SU(4) x Z_2).

Supersymmetry

Minimal Supersymmetric Standard Model (MSSM)



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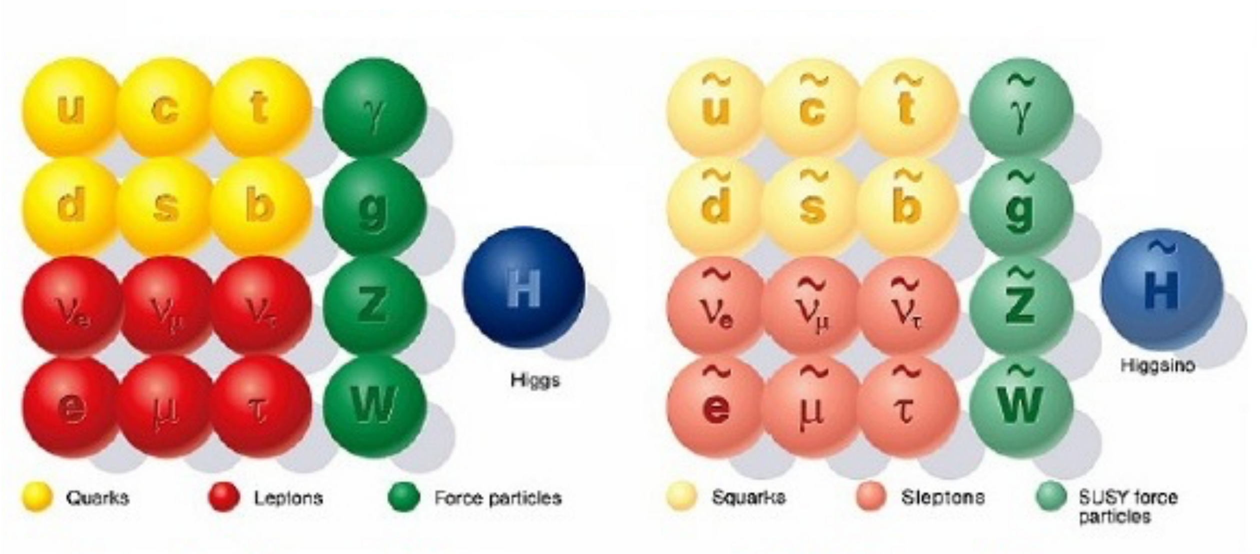


Standard particles SUSY particles

SUSY is broken

(in fact, we know that e.g. the sbottom cannot have the same mass as the bottom quark)

Log sensitivity of the Higgs mass to the New Physics scale:

$$\Delta\mu_h^2 \sim \frac{C^2}{4\pi^2} m_{\rm SUSY}^2 \log\left(\frac{\Lambda}{m_t}\right)$$

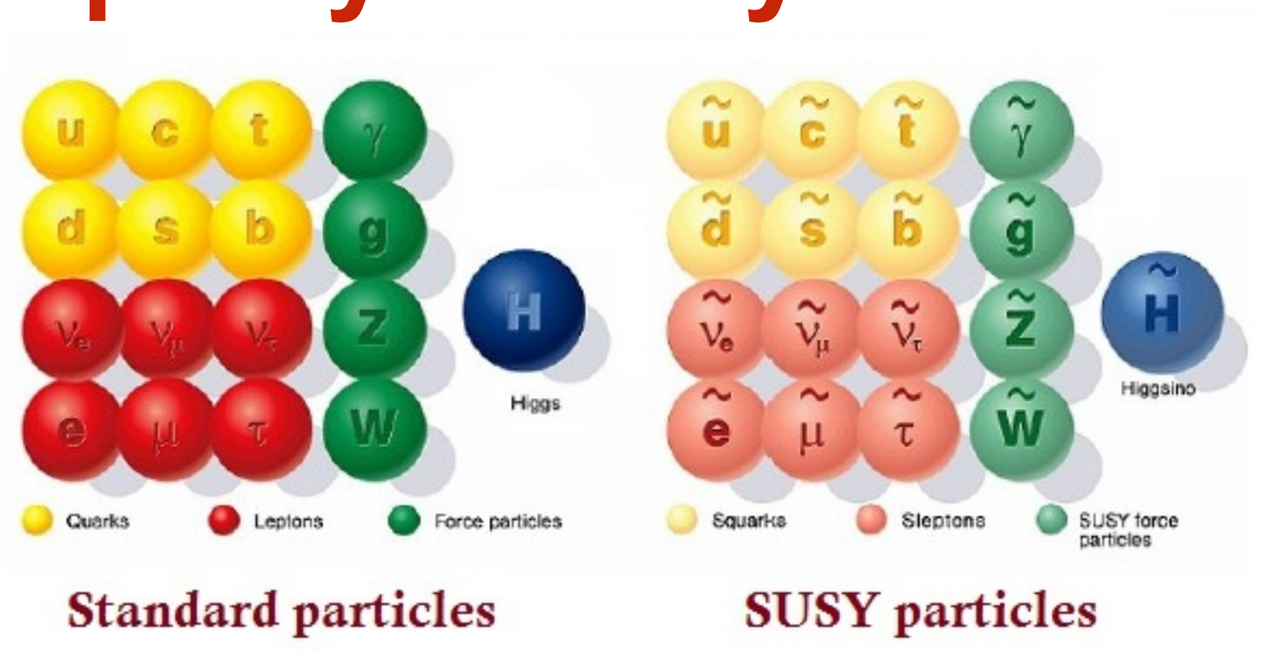
TeV-scale SUSY?

$$\Delta\mu^2 \sim \frac{y^2-\lambda}{16\pi^2}\Lambda^2 + \cdots$$

cancel because of SUSY

Supersymmetry

Minimal Supersymmetric
Standard Model
(MSSM)



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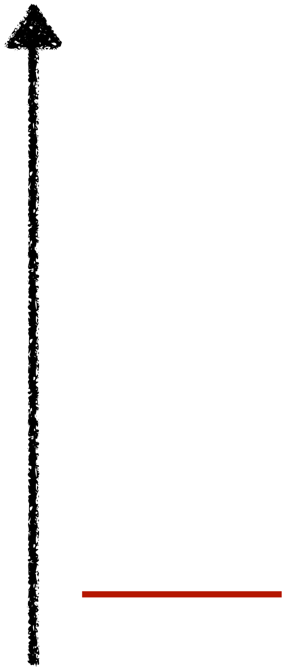
TeV-scale SUSY?

Additional remarkable properties:

- Gauge coupling unification: if SUSY particles are not too heavy, $g_3 \sim g_2 \sim g_1$ at M_{GUT}
- If we impose R-parity (sparticles with R-parity = -1, SM particles with R-parity = +1), the lightest SUSY particle can be WIMP Dark Matter (see lectures by C. Wagner)

The SUSY mass scale

The “natural spectrum”:



Higgsinos

$$-\frac{m_Z^2}{2} = \mu^2 + m_{H_u}^2 + \cdots$$

(tree level)

The SUSY mass scale

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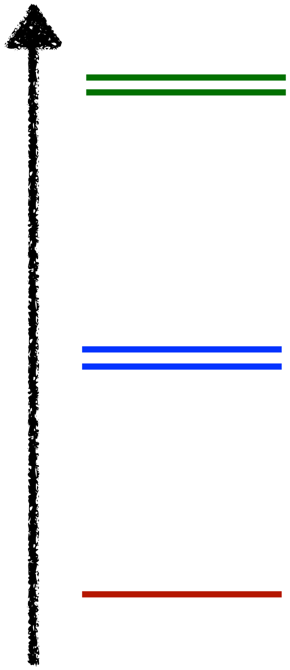

Gluinos

$$\Delta\mu_h^2 \sim -2\frac{\alpha_s}{\pi^2}\frac{y_t^2}{\pi}|M_3|^2\log^2\left(\frac{\Lambda}{m_t}\right)$$

(2 loops)

Stops
(left handed sbottom)

$$\Delta\mu_h^2 \sim -3\frac{y_t^2}{8\pi^2}\left(m_{Q3}^2 + m_{u3}^2 + |A_t|^2\right)\log\left(\frac{\Lambda}{m_t}\right)$$

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The SUSY mass scale

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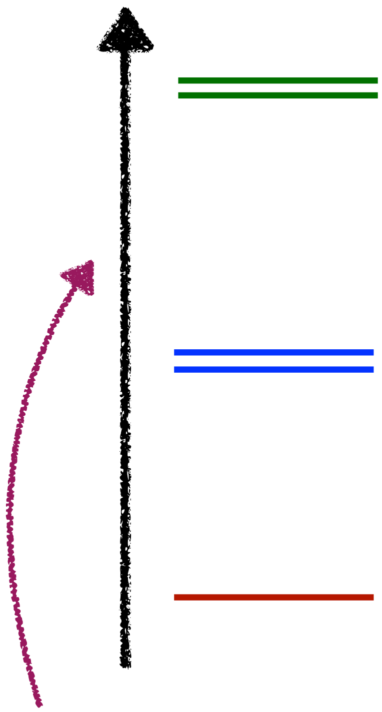

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(1 loop)

Higgsinos

$$-\frac{m_Z^2}{2}=\mu^2+m_{H_u}^2+\cdots$$

(tree level)

What is the exact scale?

Said in other words: what is the level of “fine tuning” we are comfortable allowing?

No guaranteed discovery. Exploration of the SUSY paradigm!

(TeV-scale stops imply ~O(1%) fine tuning)

(Some) pheno of SUSY particles

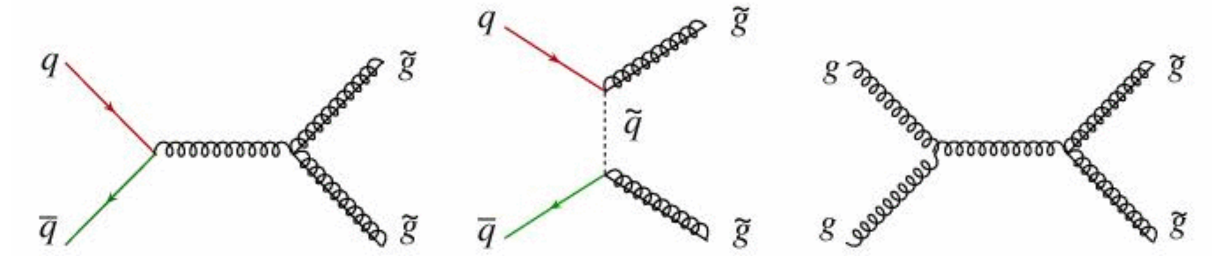
SUSY provides a remarkably rich set of signatures for the LHC

(Some) pheno of SUSY particles

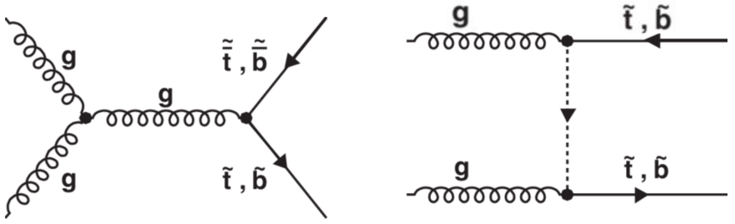
SUSY provides a remarkably rich set of signatures for the LHC

All SUSY particles are charged under the SM gauge symmetries.
That means that SUSY particles will be copiously produced at the LHC

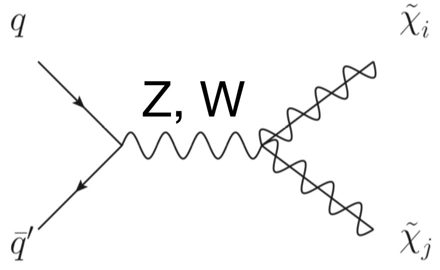
In the case of R-parity conservation:



gluino production (SU(3) interactions)



squark production
(SU(3) interactions)



Chargino and neutralino production
(SU(2) and U(1) interactions)

(Some) pheno of SUSY particles

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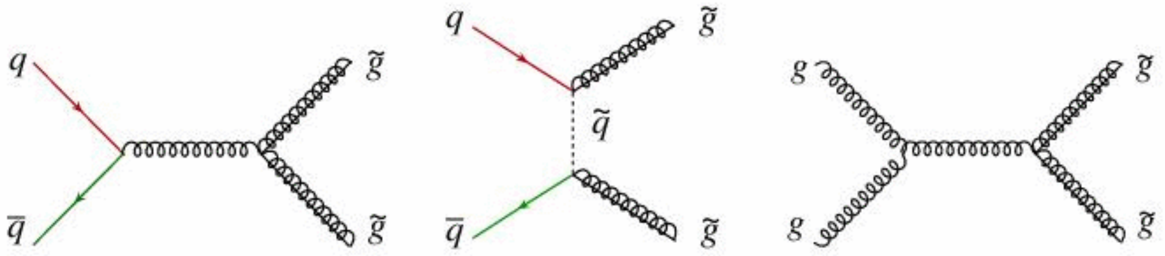
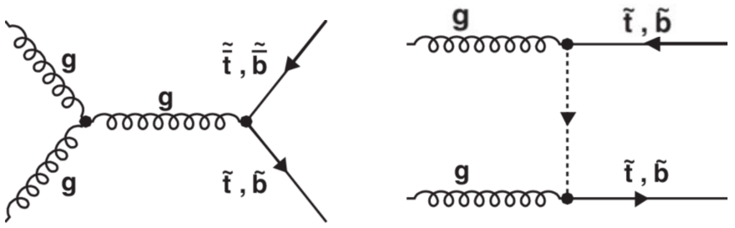
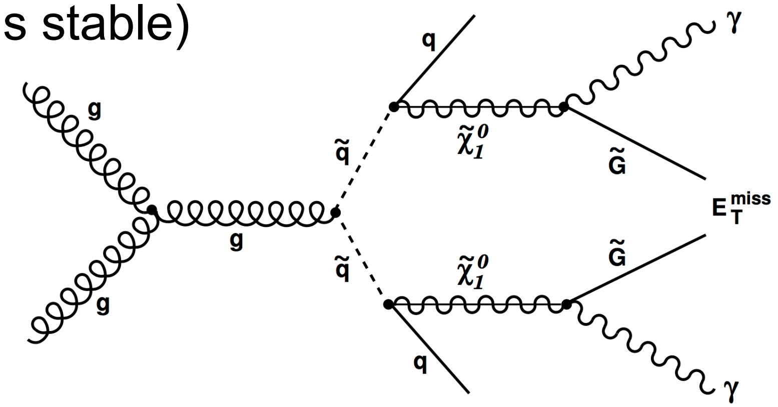


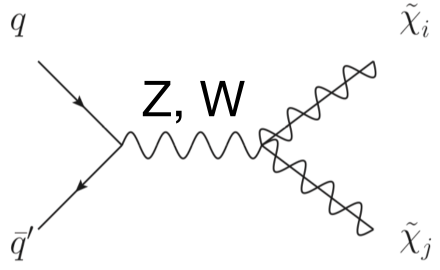
gluino production (SU(3) interactions)



squark production
(SU(3) interactions)

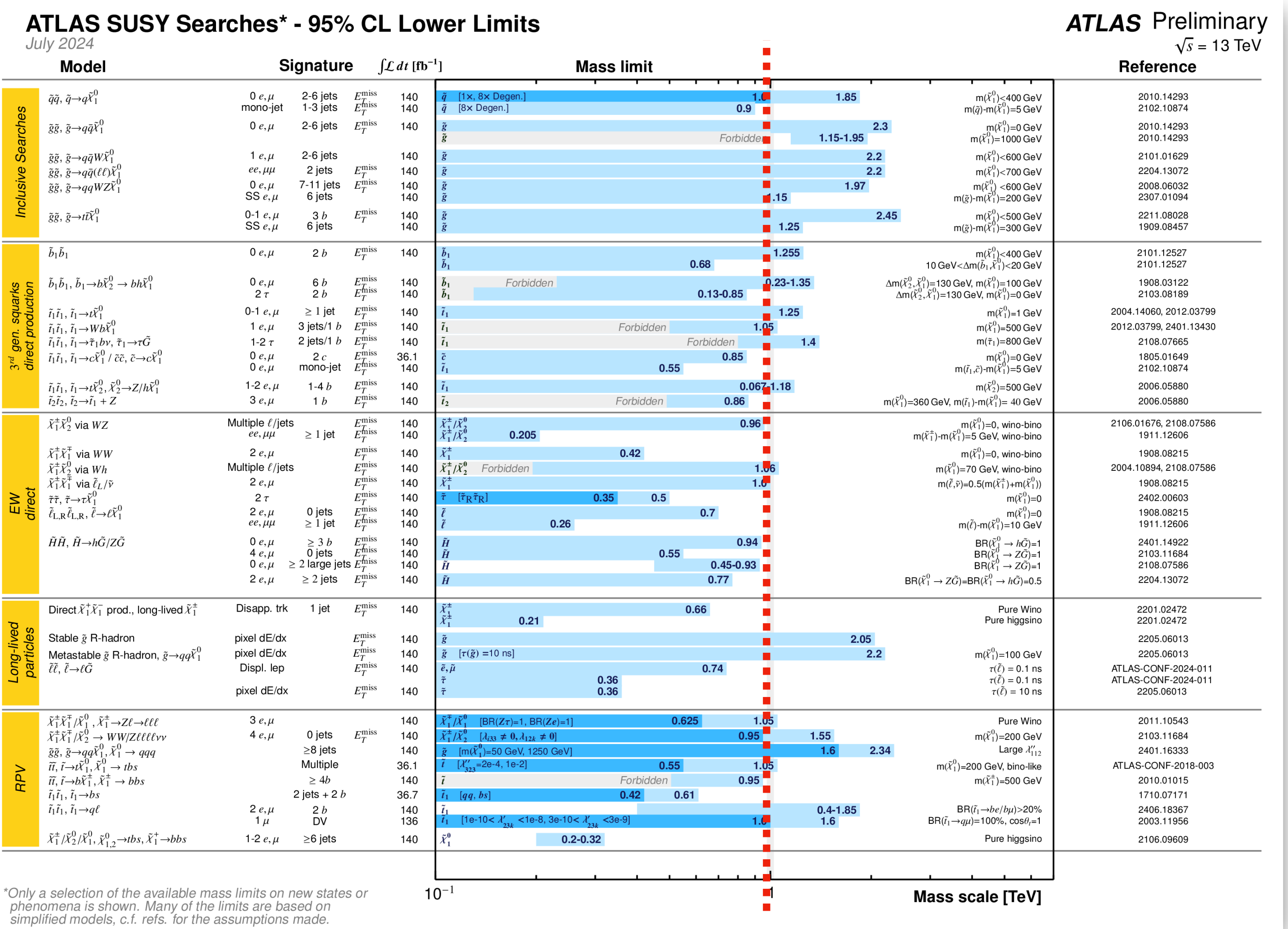
Missing energy-enriched signatures
(MET arises from the lightest SUSY particle that is stable)





Chargino and neutralino production
(SU(2) and U(1) interactions)

Stringent bounds on SUSY from the LHC



ATLAS SUSY Searches* - 95% CL Lower Limits
July 2024

ATLAS Preliminary
$\sqrt{s}$ = 13 TeV

	Model	Signature			$\int\mathcal{L}\,dt$ [fb^{-1}]	Mass limit			Reference
Inclusive Searches	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}^0_1$	0 e,μ	2-6 jets	$E_T^{\rm miss}$	140	$\tilde{q}$ [1×, 8× Degen.]	1.0 1.85	m($\tilde{\chi}^0_1$)<400 GeV	2010.14293
		mono-jet	1-3 jets	$E_T^{\rm miss}$	140	$\tilde{q}$ [8× Degen.]	0.9	m($\tilde{q}$)-m($\tilde{\chi}^0_1$)=5 GeV	2102.10874
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}^0_1$	0 e,μ	2-6 jets	$E_T^{\rm miss}$	140	$\tilde{g}$	2.3	m($\tilde{\chi}^0_1$)=0 GeV	2010.14293
						$\tilde{g}$ Forbidden	1.15-1.95	m($\tilde{\chi}^0_1$)=1000 GeV	2010.14293
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}W\tilde{\chi}^0_1$	1 e,μ	2-6 jets		140	$\tilde{g}$	2.2	m($\tilde{\chi}^0_1$)<600 GeV	2101.01629
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}(\ell\ell)\tilde{\chi}^0_1$	$ee,\mu\mu$	2 jets	$E_T^{\rm miss}$	140	$\tilde{g}$	2.2	m($\tilde{\chi}^0_1$)<700 GeV	2204.13072
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qqWZ\tilde{\chi}^0_1$	0 e,μ	7-11 jets	$E_T^{\rm miss}$	140	$\tilde{g}$	1.97	m($\tilde{\chi}^0_1$) <600 GeV	2008.06032
		SS e,μ	6 jets		140	$\tilde{g}$	1.15	m($\tilde{g}$)-m($\tilde{\chi}^0_1$)=200 GeV	2307.01094
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}^0_1$	0-1 e,μ	3 b	$E_T^{\rm miss}$	140	$\tilde{g}$	2.45	m($\tilde{\chi}^0_1$)<500 GeV	2211.08028
		SS e,μ	6 jets		140	$\tilde{g}$	1.25	m($\tilde{g}$)-m($\tilde{\chi}^0_1$)=300 GeV	1909.08457
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$	0 e,μ	2 b	$E_T^{\rm miss}$	140	$\tilde{b}_1$	1.255	m($\tilde{\chi}^0_1$)<400 GeV	2101.12527
						$\tilde{b}_1$	0.68	10 GeV<Δm($\tilde{b}_1$,$\tilde{\chi}^0_1$)<20 GeV	2101.12527
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}^0_2\to bh\tilde{\chi}^0_1$	0 e,μ	6 b	$E_T^{\rm miss}$	140	$\tilde{b}_1$ Forbidden	0.23-1.35	Δm($\tilde{\chi}^0_2$,$\tilde{\chi}^0_1$)=130 GeV, m($\tilde{\chi}^0_1$)=100 GeV	1908.03122
		2 τ	2 b	$E_T^{\rm miss}$	140	$\tilde{b}_1$	0.13-0.85	Δm($\tilde{\chi}^0_2$,$\tilde{\chi}^0_1$)=130 GeV, m($\tilde{\chi}^0_1$)=0 GeV	2103.08189
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to t\tilde{\chi}^0_1$	0-1 e,μ	$\geq$ 1 jet	$E_T^{\rm miss}$	140	$\tilde{t}_1$	1.25	m($\tilde{\chi}^0_1$)=1 GeV	2004.14060, 2012.03799
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to Wb\tilde{\chi}^0_1$	1 e,μ	3 jets/1 b	$E_T^{\rm miss}$	140	$\tilde{t}_1$ Forbidden	1.05	m($\tilde{\chi}^0_1$)=500 GeV	2012.03799, 2401.13430
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to\tilde{\tau}_1 b\nu$, $\tilde{\tau}_1\to\tau\tilde{G}$	1-2 τ	2 jets/1 b	$E_T^{\rm miss}$	140	$\tilde{t}_1$ Forbidden	1.4	m($\tilde{\tau}_1$)=800 GeV	2108.07665
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}^0_1$ / $\tilde{c}\tilde{c}$, $\tilde{c}\to c\tilde{\chi}^0_1$	0 e,μ	2 c	$E_T^{\rm miss}$	36.1	$\tilde{c}$	0.85	m($\tilde{\chi}^0_1$)=0 GeV	1805.01649
		0 e,μ	mono-jet	$E_T^{\rm miss}$	140	$\tilde{t}_1$	0.55	m($\tilde{t}_1$,$\tilde{c}$)-m($\tilde{\chi}^0_1$)=5 GeV	2102.10874
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to t\tilde{\chi}^0_2$, $\tilde{\chi}^0_2\to Z/h\tilde{\chi}^0_1$	1-2 e,μ	1-4 b	$E_T^{\rm miss}$	140	$\tilde{t}_1$	0.067-1.18	m($\tilde{\chi}^0_2$)=500 GeV	2006.05880
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+Z$	3 e,μ	1 b	$E_T^{\rm miss}$	140	$\tilde{t}_2$ Forbidden	0.86	m($\tilde{\chi}^0_1$)=360 GeV, m($\tilde{t}_1$)-m($\tilde{\chi}^0_1$)= 40 GeV	2006.05880
EW direct	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2$ via WZ	Multiple ℓ/jets		$E_T^{\rm miss}$	140	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$	0.96	m($\tilde{\chi}^0_1$)=0, wino-bino	2106.01676, 2108.07586
		$ee,\mu\mu$	$\geq$ 1 jet	$E_T^{\rm miss}$	140	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$	0.205	m($\tilde{\chi}^\pm_1$)-m($\tilde{\chi}^0_1$)=5 GeV, wino-bino	1911.12606
	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1$ via WW	2 e,μ		$E_T^{\rm miss}$	140	$\tilde{\chi}^\pm_1$	0.42	m($\tilde{\chi}^0_1$)=0, wino-bino	1908.08215
	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2$ via Wh	Multiple ℓ/jets		$E_T^{\rm miss}$	140	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$ Forbidden	1.06	m($\tilde{\chi}^0_1$)=70 GeV, wino-bino	2004.10894, 2108.07586
	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1$ via $\tilde{\ell}_L/\tilde{\nu}$	2 e,μ		$E_T^{\rm miss}$	140	$\tilde{\chi}^\pm_1$	1.0	m($\tilde{\ell}$,$\tilde{\nu}$)=0.5(m($\tilde{\chi}^\pm_1$)+m($\tilde{\chi}^0_1$))	1908.08215
	$\tilde{\tau}\tilde{\tau}$, $\tilde{\tau}\to\tau\tilde{\chi}^0_1$	2 τ		$E_T^{\rm miss}$	140	$\tilde{\tau}$ [$\tilde{\tau}_R\tilde{\tau}_R$]	0.35 0.5	m($\tilde{\chi}^0_1$)=0	2402.00603
	$\tilde{\ell}_{\rm L,R}\tilde{\ell}_{\rm L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}^0_1$	2 e,μ	0 jets	$E_T^{\rm miss}$	140	$\tilde{\ell}$	0.7	m($\tilde{\chi}^0_1$)=0	1908.08215
		$ee,\mu\mu$	$\geq$ 1 jet	$E_T^{\rm miss}$	140	$\tilde{\ell}$	0.26	m($\tilde{\ell}$)-m($\tilde{\chi}^0_1$)=10 GeV	1911.12606
	$\tilde{H}\tilde{H}$, $\tilde{H}\to h\tilde{G}/Z\tilde{G}$	0 e,μ	$\geq$ 3 b	$E_T^{\rm miss}$	140	$\tilde{H}$	0.94	BR($\tilde{\chi}^0_1\to h\tilde{G}$)=1	2401.14922
		4 e,μ	0 jets	$E_T^{\rm miss}$	140	$\tilde{H}$	0.55	BR($\tilde{\chi}^0_1\to Z\tilde{G}$)=1	2103.11684
		0 e,μ	$\geq$ 2 large jets	$E_T^{\rm miss}$	140	$\tilde{H}$	0.45-0.93	BR($\tilde{\chi}^0_1\to Z\tilde{G}$)=1	2108.07586
		2 e,μ	$\geq$ 2 jets	$E_T^{\rm miss}$	140	$\tilde{H}$	0.77	BR($\tilde{\chi}^0_1\to Z\tilde{G}$)=BR($\tilde{\chi}^0_1\to h\tilde{G}$)=0.5	2204.13072
Long-lived particles	Direct $\tilde{\chi}^+_1\tilde{\chi}^-_1$ prod., long-lived $\tilde{\chi}^\pm_1$	Disapp. trk	1 jet	$E_T^{\rm miss}$	140	$\tilde{\chi}^\pm_1$	0.66	Pure Wino	2201.02472
						$\tilde{\chi}^\pm_1$	0.21	Pure higgsino	2201.02472
	Stable $\tilde{g}$ R-hadron	pixel dE/dx		$E_T^{\rm miss}$	140	$\tilde{g}$	2.05		2205.06013
	Metastable $\tilde{g}$ R-hadron, $\tilde{g}\to qq\tilde{\chi}^0_1$	pixel dE/dx		$E_T^{\rm miss}$	140	$\tilde{g}$ [$\tau(\tilde{g})$ =10 ns]	2.2	m($\tilde{\chi}^0_1$)=100 GeV	2205.06013
	$\tilde{\ell}\tilde{\ell}$, $\tilde{\ell}\to\ell\tilde{G}$	Displ. lep		$E_T^{\rm miss}$	140	$\tilde{e},\tilde{\mu}$	0.74	$\tau(\tilde{\ell})$ = 0.1 ns	ATLAS-CONF-2024-011
						$\tilde{\tau}$	0.36	$\tau(\tilde{\ell})$ = 0.1 ns	ATLAS-CONF-2024-011
		pixel dE/dx		$E_T^{\rm miss}$	140	$\tilde{\tau}$	0.36	$\tau(\tilde{\ell})$ = 10 ns	2205.06013
RPV	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1/\tilde{\chi}^0_1$, $\tilde{\chi}^\pm_1\to Z\ell\to\ell\ell\ell$	3 e,μ			140	$\tilde{\chi}^\mp_1/\tilde{\chi}^0_1$ [BR($Z\tau$)=1, BR(Ze)=1]	0.625 1.05	Pure Wino	2011.10543
	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1/\tilde{\chi}^0_2\to WW/Z\ell\ell\ell\ell\nu\nu$	4 e,μ	0 jets	$E_T^{\rm miss}$	140	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$ [$\lambda_{i33}\neq 0,\lambda_{12k}\neq 0$]	0.95 1.55	m($\tilde{\chi}^0_1$)=200 GeV	2103.11684
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\to qqq$		$\geq$8 jets		140	$\tilde{g}$ [m($\tilde{\chi}^0_1$)=50 GeV, 1250 GeV]	1.6 2.34	Large λ''_{112}	2401.16333
	$\tilde{t}\tilde{t}$, $\tilde{t}\to t\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\to tbs$		Multiple		36.1	$\tilde{t}$ [λ''_{323}=2e-4, 1e-2]	0.55 1.05	m($\tilde{\chi}^0_1$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}\tilde{t}$, $\tilde{t}\to b\tilde{\chi}^\pm_1$, $\tilde{\chi}^\pm_1\to bbs$		$\geq$ 4b		140	$\tilde{t}$ Forbidden	0.95	m($\tilde{\chi}^\pm_1$)=500 GeV	2010.01015
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to bs$		2 jets + 2 b		36.7	$\tilde{t}_1$ [qq, bs]	0.42 0.61		1710.07171
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to q\ell$	2 e,μ	2 b		140	$\tilde{t}_1$	0.4-1.85	BR($\tilde{t}_1\to be/b\mu$)>20%	2406.18367
		1 μ	DV		136	$\tilde{t}_1$ [1e-10< λ'_{23k} <1e-8, 3e-10< λ'_{23k} <3e-9]	1.0 1.6	BR($\tilde{t}_1\to q\mu$)=100%, cosθ_t=1	2003.11956
	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2/\tilde{\chi}^0_1$, $\tilde{\chi}^0_{1,2}\to tbs$, $\tilde{\chi}^+_1\to bbs$	1-2 e,μ	$\geq$6 jets		140	$\tilde{\chi}^0_1$	0.2-0.32	Pure higgsino	2106.09609

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

Perhaps SUSY is hidden because of a compressed spectrum?

Perhaps the SUSY mass scale is a (little) bit higher than the TeV scale?

Effective field theories

The SM Lagrangian can be only the low-energy limit of a more complete theory with new particles with a mass (well) above the electroweak scale.
Effective field theory (EFT)

New degrees of freedom are expected at a scale Λ above the electroweak scale. These new degrees of freedom can be too heavy for being directly produced and detected at the LHC, with s = (14 TeV)^2

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Wilson coefficients

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum_{d\geq 5} \frac{c_n}{\Lambda^{d-4}} O_n^{(d)}(\rm SM)$$

Renormalizable

Operators of dimension d ≥ 5 containing SM fields only, and compatible with the SM gauge symmetry

see e.g.,
Grzadkowski et al., 1008.4884;
Alonso et al., 1312.2014

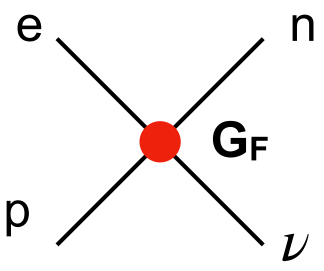
This is the most general parameterization of the new degrees of freedom, (assuming Λ above the electroweak scale), as long as we perform low-energy ($s << \Lambda^2$) experiments

Following Fermi: The birth of an effective field theory

Fermi's Theory (1934) describes beta decays of nuclei (four-fermion interaction)

$$\mathcal{L}_F = -\frac{G_F}{\sqrt{2}}(\bar{p}\gamma^\mu n)(\bar{e}\gamma_\mu \nu_e)$$

Dimension-6 operator



Parity violation ⇒ only **left-handed fermions** couple to weak force

$$\gamma_\mu \Rightarrow \gamma_\mu \gamma_5$$

Now interpreted as a **low-energy effective field theory**

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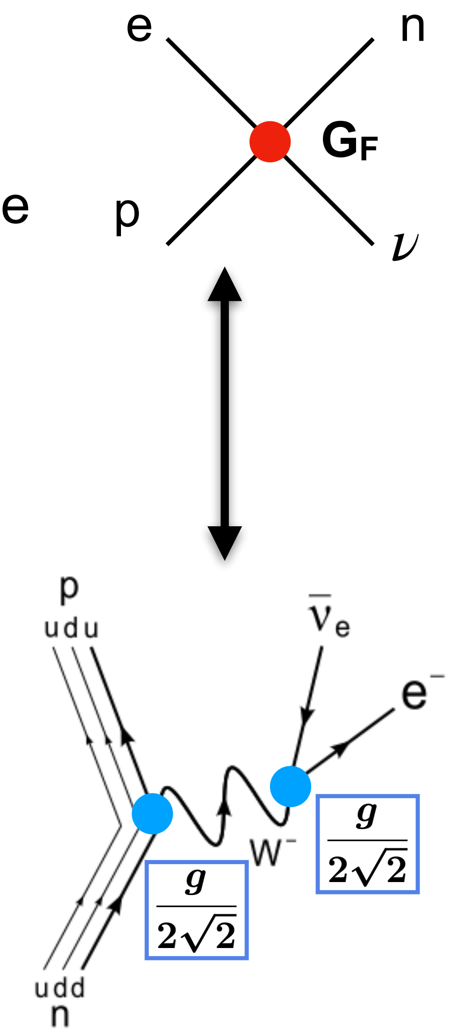

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Discovery of the W Boson (CERN, 1983),
Direct production at UA1/UA2 experiments

Fermi interaction arises from **integrating out** the W boson

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8m_W^2} \Rightarrow m_W = \Lambda$$

(NP scale)

EFTs at the LHC, the Higgs

These higher dimensional operators have an effect on SM processes that are accurately measured at the LHC ⇨ constraints on the Wilson coefficients

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For example, the rate and distributions of **pp** $\rightarrow$ **H** $\rightarrow \gamma\gamma$ are affected by the presence of higher dimensional operators

$$\frac{c_{HW}}{\Lambda^2}(H^\dagger H)W^i_{\mu\nu}W^{\mu\nu,i}$$

$$\frac{c_{HB}}{\Lambda^2}(H^\dagger H)B_{\mu\nu}B^{\mu\nu}$$

$$\frac{c_{HWB}}{\Lambda^2}(H^\dagger\sigma^i H)W^i_{\mu\nu}B^{\mu\nu}$$

$$\frac{c_{HG}}{\Lambda^2}(H^\dagger H)G^a_{\mu\nu}G^{\mu\nu,a}$$

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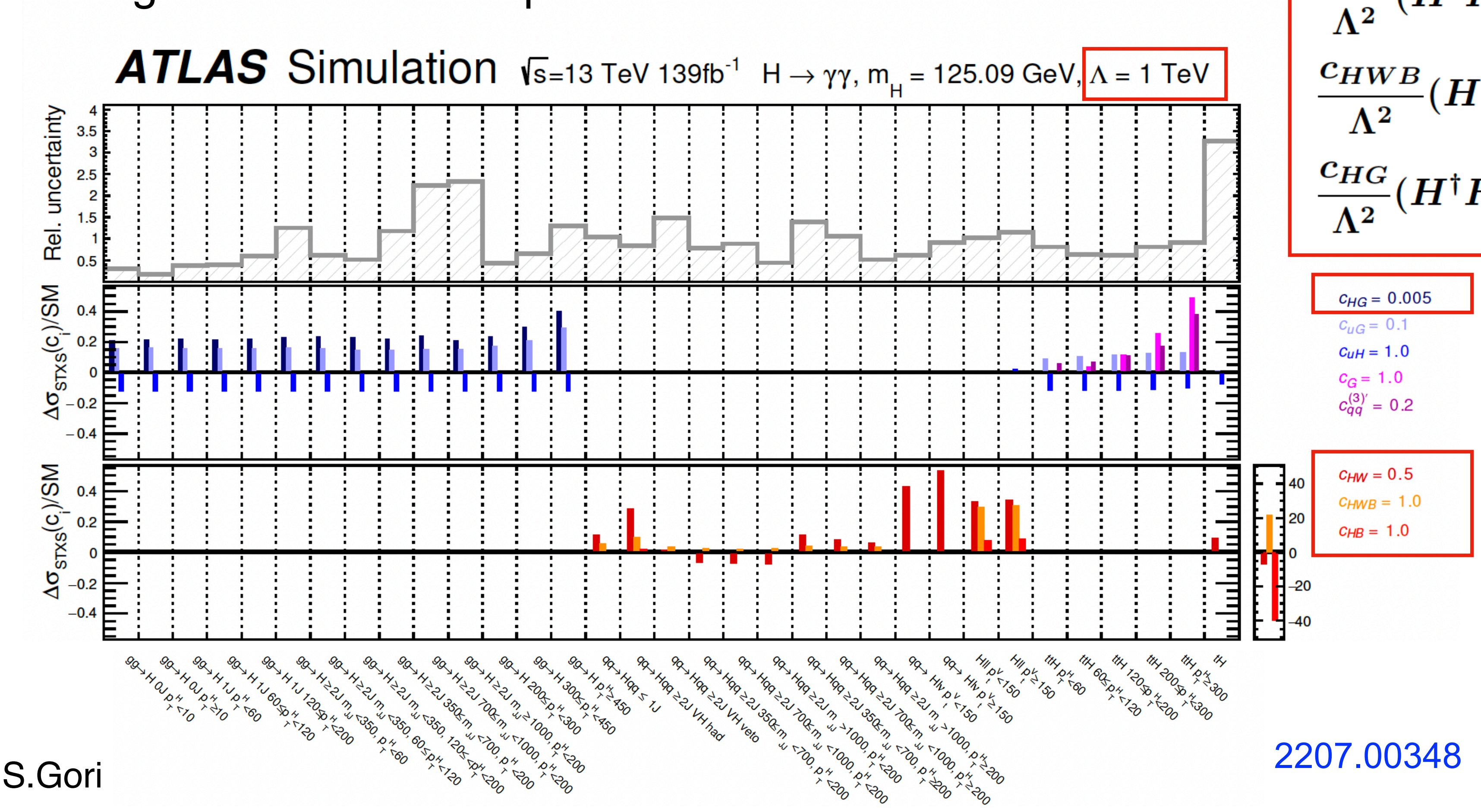

2207.00348

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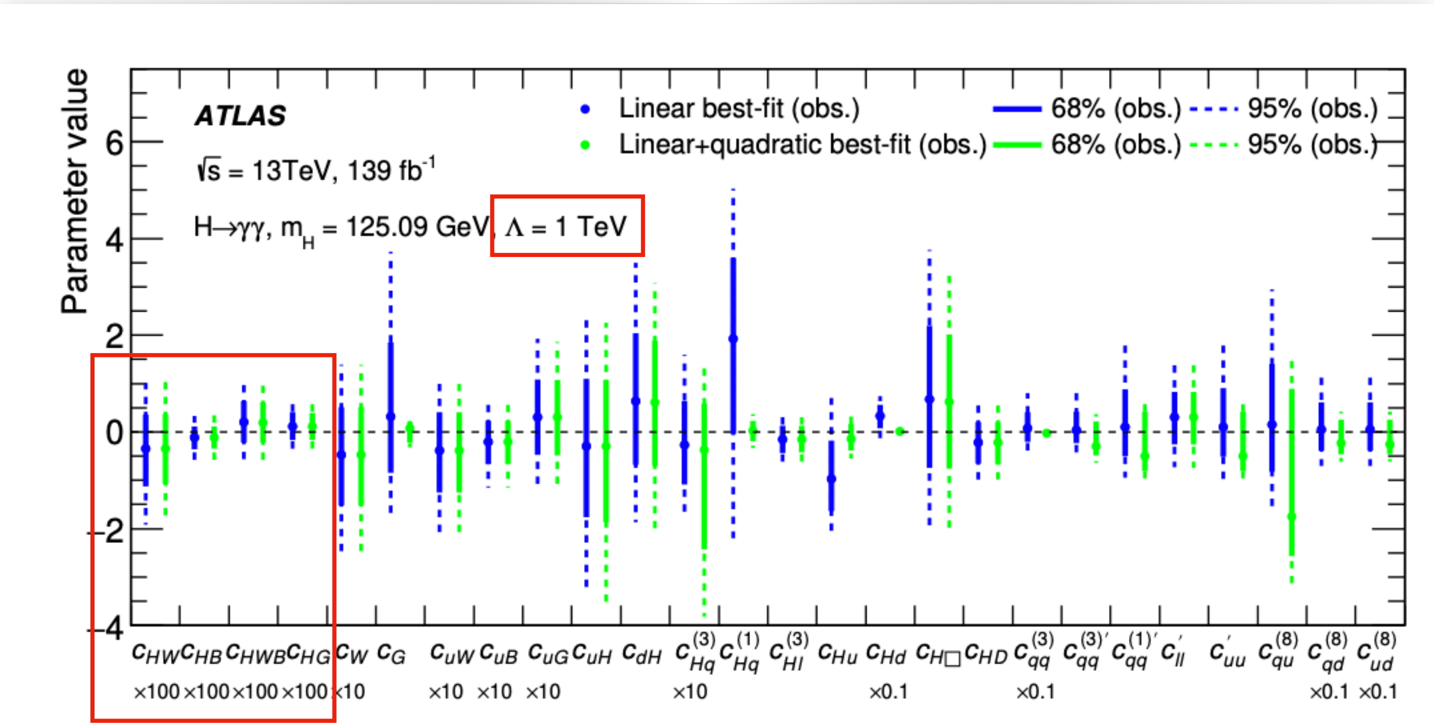

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EFTs at the LHC, other SM measurements

It’s not just the Higgs. Fits of SMEFT coefficients include

- Higgs data,
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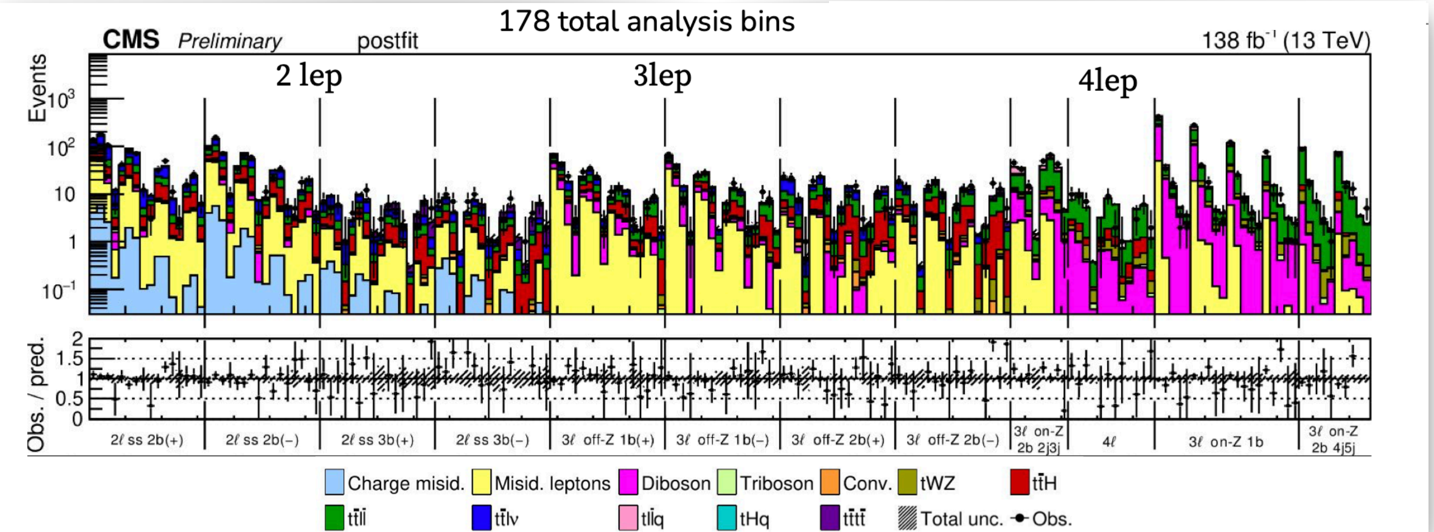
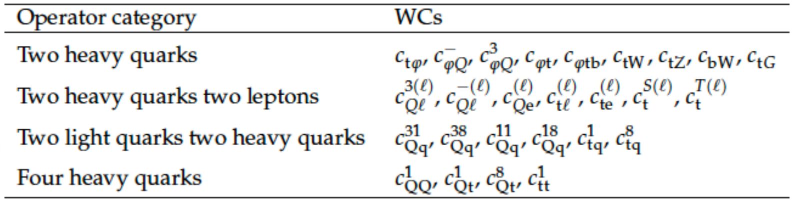
For example:



CMS PAS TOP-22-006



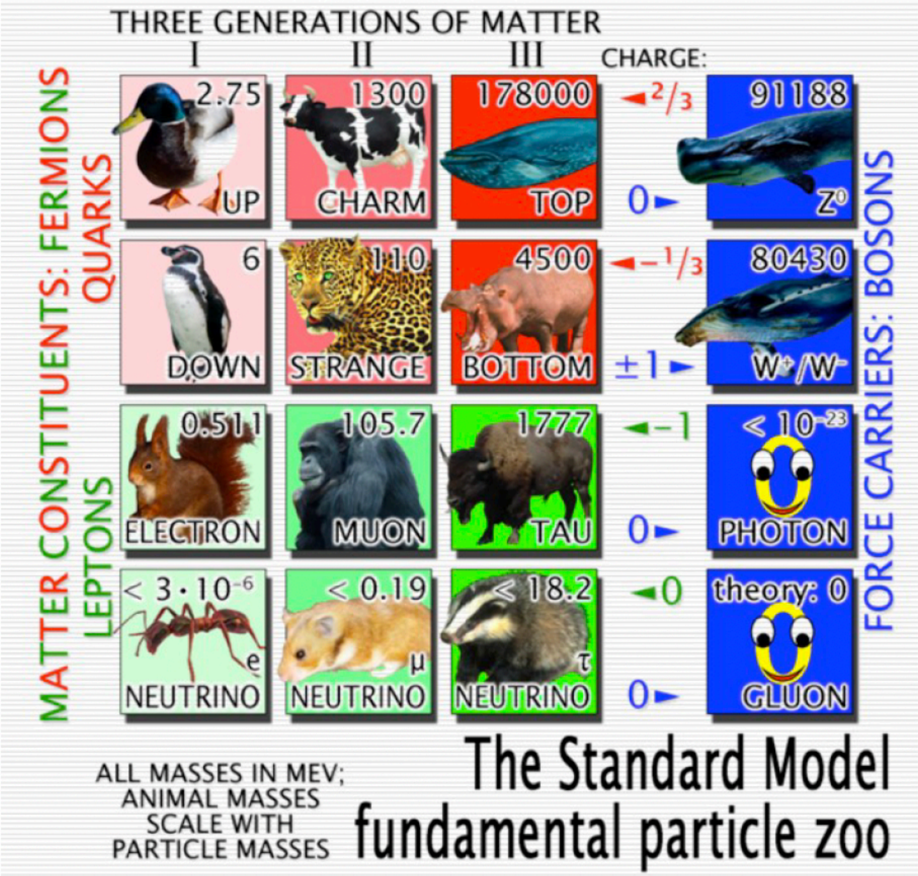
Operator category	WCs
Two heavy quarks	$c_{t\varphi}$, $c^{-}_{\varphi Q}$, $c^{3}_{\varphi Q}$, $c_{\varphi t}$, $c_{\varphi tb}$, c_{tW}, c_{tZ}, c_{bW}, c_{tG}
Two heavy quarks two leptons	$c^{3(\ell)}_{Q\ell}$, $c^{-(\ell)}_{Q\ell}$, $c^{(\ell)}_{Qe}$, $c^{(\ell)}_{t\ell}$, $c^{(\ell)}_{te}$, $c^{S(\ell)}_{t}$, $c^{T(\ell)}_{t}$
Two light quarks two heavy quarks	c^{31}_{Qq}, c^{38}_{Qq}, c^{11}_{Qq}, c^{18}_{Qq}, c^{1}_{tq}, c^{8}_{tq}
Four heavy quarks	c^{1}_{QQ}, c^{1}_{Qt}, c^{8}_{Qt}, c^{1}_{tt}

Future indirect discovery of a New Physics scale, Λ?

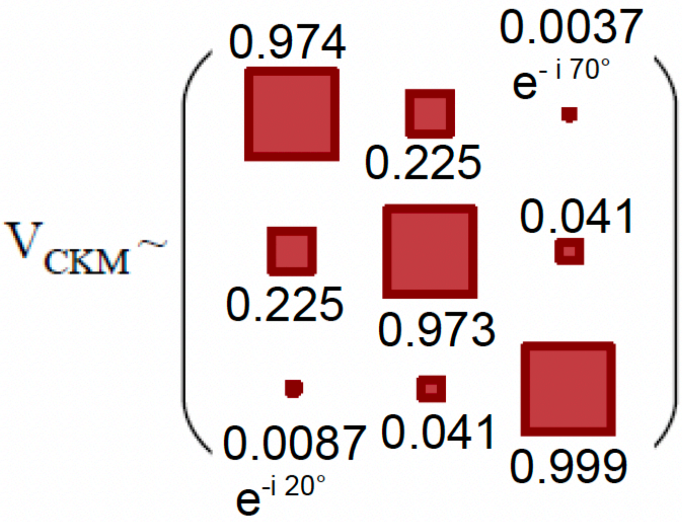
see lectures by N. Blinov

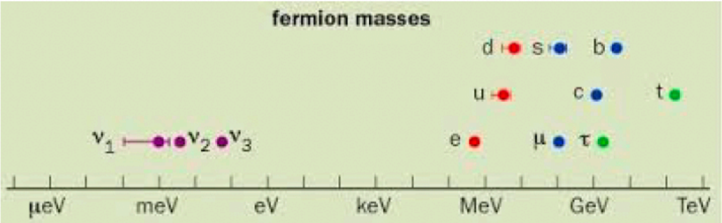
The SM flavor puzzle

Measurements tell us that:



E.Lunghi





Reminder for the gauge couplings: g_1~ 0.35; g_2~ 0.65; g_3~ 1.2

This structure does not seem accidental. New dynamics?

Is there a New Physics scale associated to it?

Froggatt-Nielsen mechanism

Nucl.Phys.B 147 (1979) 277-298

Basic idea: fermion masses are forbidden by flavor symmetries and arise only after spontaneous breaking of the symmetry

Simple $U(1)_{FN}$ model:

$Q(t_L) = Q(t_R) = 0$; $Q(u_L) = - Q(u_R) = 3$

$Q(h) = 0$; $Q(\phi) = -1$

Flavon = scalar field with a potential such that $<\phi>\neq 0$

(it breaks the $U(1)_{FN}$ symmetry)

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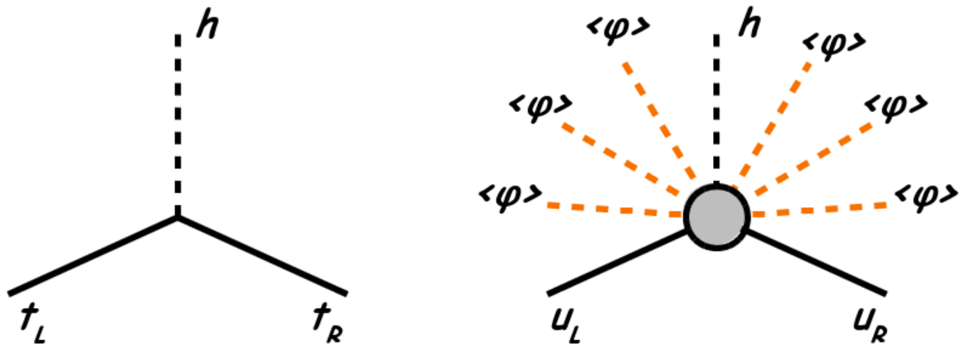


Quark and lepton mass and mixing hierarchies are given by powers of the “spurion”, $<\phi>/M$

In this specific case:

$$\frac{m_u}{m_t} \sim \left(\frac{\langle\phi\rangle}{M}\right)^6$$

M = heavy mass scale of the system

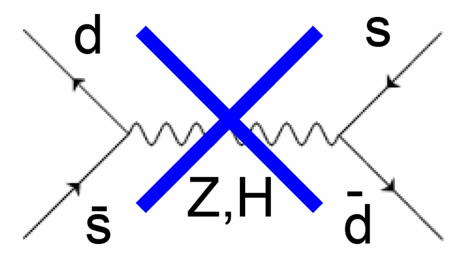
(typically vector like fermions charged under $U(1)_{FN}$)

S.Gori

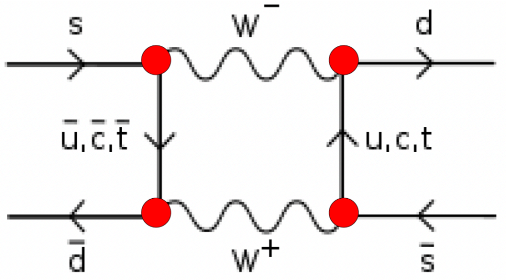
Flavor transitions in the SM and in SMEFT

In the SM, there are no FCNCs at the tree level

Only loop mediated processes with charged interactions



(example for Kaon mixing)

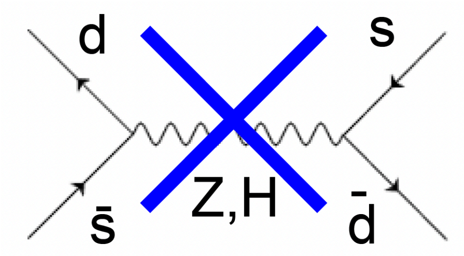


(example for Kaon mixing)

A lot of flavor transitions (including observables in Kaon mixing) have been precisely measured and they agree with the SM predictions

Flavor transitions in the SM and in SMEFT

In the SM, there are no FCNCs at the tree level



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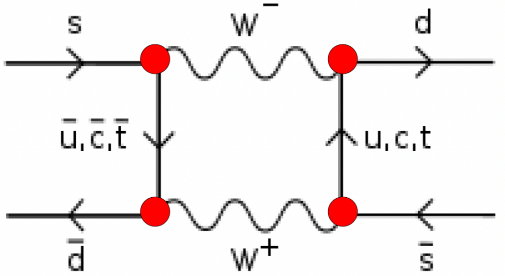

(example for Kaon mixing)

A lot of flavor transitions (including observables in Kaon mixing) have been precisely measured and they agree with the SM predictions

In the context of the SMEFT, we can write dimension-6 operators that contribute to flavor transitions. For example, for Kaon mixing:

$$\mathcal{L} = \sum_i \frac{c_i}{\Lambda^2} Q_i$$

$$Q_1^{\mathrm{VLL}} = (\bar{s}\gamma_\mu P_L d)(\bar{s}\gamma^\mu P_L d)$$ (SM operator)

$$\begin{aligned} Q_1^{\mathrm{LR}} &= (\bar{s}\gamma_\mu P_L d)(\bar{s}\gamma^\mu P_R d) \\ Q_2^{\mathrm{LR}} &= (\bar{s} P_L d)(\bar{s} P_R d) \end{aligned}$$

$$\begin{aligned} Q_1^{\mathrm{SLL}} &= (\bar{s} P_L d)(\bar{s} P_L d) \\ Q_2^{\mathrm{SLL}} &= (\bar{s}\sigma_{\mu\nu} P_L d)(\bar{s}\sigma^{\mu\nu} P_L d) \end{aligned}$$

The NP flavor puzzle

Updated from Isidori, Nir, Perez,1002.0900

Operator	Kaon, $c_i = 1$, Λ[TeV] Re	Im	B_d, $c_i = 1$, Λ[TeV] Re	Im	B_s, $c_i = 1$, Λ[TeV] Re	Im	D, $c_i = 1$, Λ[TeV] Re	Im
$Q_1^{\rm VLL}$	1000	$2 \cdot 10^4$	700	1000	100	200	1300	3200
$Q_2^{\rm LR}$	10^4	$2 \cdot 10^5$	1600	2300	300	600	4200	10^4

Note: generically, the LHC probes NP particles with ~ TeV mass

Remember: $\mathcal{L} = \sum_i \frac{c_i}{\Lambda^2} Q_i$

Precision flavor measurements impose **very stringent bounds on the NP scale**, much beyond the LHC reach

New Physics flavor puzzle

The NP flavor puzzle

Updated from Isidori, Nir, Perez,1002.0900

	Kaon, $c_i = 1$, Λ[TeV]		B_d, $c_i = 1$, Λ[TeV]		B_s, $c_i = 1$, Λ[TeV]		D, $c_i = 1$, Λ[TeV]	
Operator	Re	Im	Re	Im	Re	Im	Re	Im
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New Physics flavor puzzle

OR

The **NP flavor structure** is **highly non generic** ⇨ **Minimal Flavor Violation?**

End of the first class

What did we learn yesterday?

Reasons to go beyond the Standard Model

The hierarchy problem and SUSY.
Perhaps SUSY is a bit heavier than the TeV? → Effective field theories (EFTs)

The SM flavor puzzle and Froggatt Nielsen
The NP flavor puzzle. Very high energy scales are probed by flavor

For today…

We will conclude the discussion about flavor: Minimal flavor violating theories

The origin of neutrino masses and sterile neutrinos

Light (< GeV) New Physics: Dark Matter/dark sectors and axions

Breaking the SM flavor symmetry

Flavor symmetry: $U(3)^5 = SU(3)_Q \times SU(3)_U \times SU(3)_D \times \cdots$

(global symmetry of the SM gauge sector)

Symmetry-breaking terms: $\bar{Q}_L^i Y_D^{ij} d_R^j \Phi + \bar{Q}_L^i Y_U^{ij} u_R^j \tilde{\Phi}$

(quark Yukawa couplings)

This specific symmetry + symmetry-breaking pattern is responsible for all the successful SM predictions in the quark flavor sector

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This specific symmetry + symmetry-breaking pattern is responsible for all the successful SM predictions in the quark flavor sector

However, we can (formally) promote this symmetry to be an exact symmetry, assuming the Yukawa matrices are the vacuum expectation values of appropriate auxiliary fields: **spurions**

$Y_D \sim (3, 1, \bar{3})$, $Y_U \sim (3, \bar{3}, 1)$ (transformation under SU(3)$_Q$ × SU(3)$_U$ × SU(3)$_D$)

$$\underset{(\bar{3},1,1)}{\bar{Q}_L}\,\underset{(3,1,\bar{3})}{Y_D}\,\underset{(1,1,3)}{D_R}\,\Phi + \underset{(\bar{3},1,1)}{\bar{Q}_L}\,\underset{(3,\bar{3},1)}{Y_U}\,\underset{(1,3,1)}{U_R}\,\tilde{\Phi} \Longrightarrow (1,1,1)$$

The Minimal Flavor Violation ansatz

In all generality, New Physics theories with additional degrees of freedom can further break this flavor symmetry

A natural mechanism to reproduce the SM successes in flavor physics is the MFV hypothesis: **The SM Yukawa couplings are the only sources of flavor violation in and beyond the Standard Model**

Chivukula, Georgi '87

Going back to EFTs…

A low-energy EFT satisfies the criterion of MFV if all higher-dimensional operators, constructed from SM and Y fields, are (formally) invariant under the flavor group

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For example, for processes with external down-type quarks, the relevant FCNC vertices:

$$\bar{Q}_L Y_U Y_U^\dagger Q_L,\ \bar{D}_R Y_D^\dagger Y_U Y_U^\dagger Q_L,\ \bar{D}_R Y_D^\dagger Y_U Y_U^\dagger Y_D D_R$$

Where, for convenience, we have chosen the basis for which

$$Y_D = \mathrm{diag}(y_d, y_s, y_b),\ Y_U = V^\dagger \mathrm{diag}(y_u, y_c, y_t)$$

CKM matrix introduced by N. Blinov

If we expand, at the leading order in the quark masses and CKM elements:

$$y_t^4 \left(\bar{Q}_L^i V_{3i}^* V_{3j} \gamma_\mu Q_L^j\right)^2$$

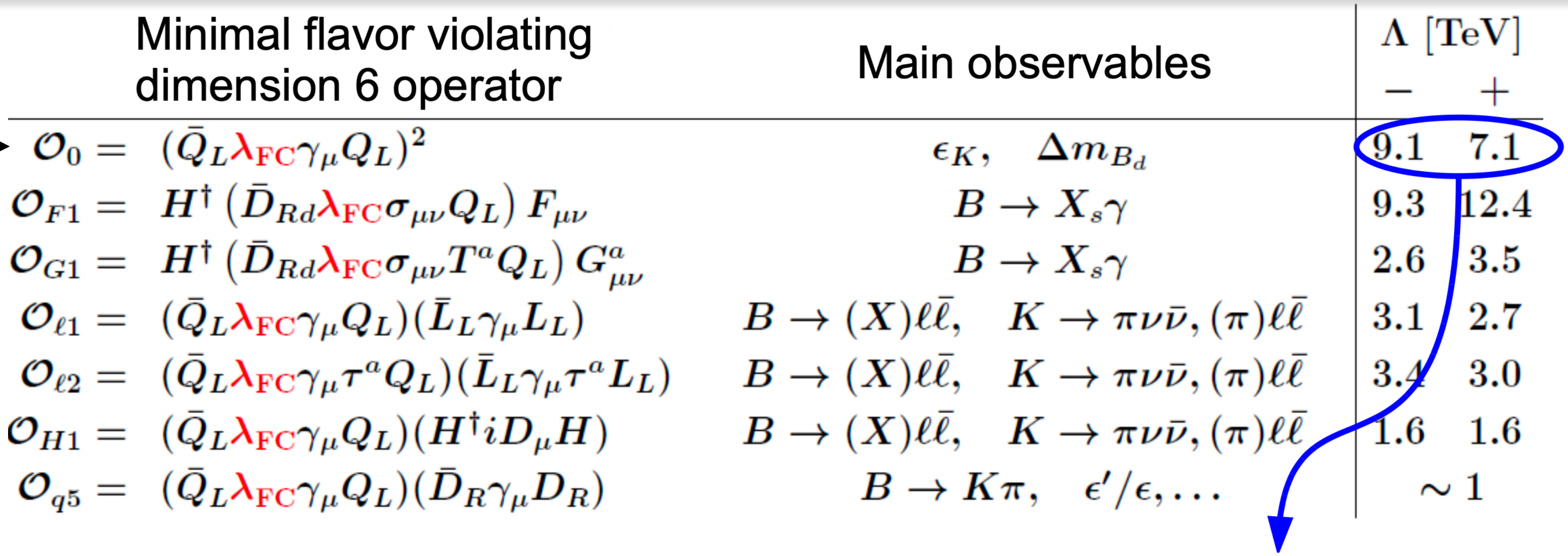
The Wilson coefficient, C, is not anymore O(1)!

TeV scale New Physics is now allowed by flavor!

D´Ambrosio, Giudice, Isidori, Strumia, 0207036

One of the operators seen before

Other flavor transitions



Minimal flavor violating dimension 6 operator	Main observables	Λ [TeV]	
		$-$	$+$
$\mathcal{O}_0 = (\bar{Q}_L \lambda_{FC} \gamma_\mu Q_L)^2$	$\epsilon_K, \quad \Delta m_{B_d}$	9.1	7.1
$\mathcal{O}_{F1} = H^\dagger \left(\bar{D}_R \lambda_{FC} \sigma_{\mu\nu} Q_L\right) F_{\mu\nu}$	$B \to X_s \gamma$	9.3	12.4
$\mathcal{O}_{G1} = H^\dagger \left(\bar{D}_R \lambda_{FC} \sigma_{\mu\nu} T^a Q_L\right) G^a_{\mu\nu}$	$B \to X_s \gamma$	2.6	3.5
$\mathcal{O}_{\ell 1} = (\bar{Q}_L \lambda_{FC} \gamma_\mu Q_L)(\bar{L}_L \gamma_\mu L_L)$	$B \to (X)\ell\bar{\ell}, \quad K \to \pi\nu\bar{\nu}, (\pi)\ell\bar{\ell}$	3.1	2.7
$\mathcal{O}_{\ell 2} = (\bar{Q}_L \lambda_{FC} \gamma_\mu \tau^a Q_L)(\bar{L}_L \gamma_\mu \tau^a L_L)$	$B \to (X)\ell\bar{\ell}, \quad K \to \pi\nu\bar{\nu}, (\pi)\ell\bar{\ell}$	3.4	3.0
$\mathcal{O}_{H1} = (\bar{Q}_L \lambda_{FC} \gamma_\mu Q_L)(H^\dagger i D_\mu H)$	$B \to (X)\ell\bar{\ell}, \quad K \to \pi\nu\bar{\nu}, (\pi)\ell\bar{\ell}$	1.6	1.6
$\mathcal{O}_{q5} = (\bar{Q}_L \lambda_{FC} \gamma_\mu Q_L)(\bar{D}_R \gamma_\mu D_R)$	$B \to K\pi, \quad \epsilon'/\epsilon, \ldots$	~ 1	

$$\lambda_{FC})_{ij} = y_t^2 V_{3i}^* V_{3j}$$

Without MFV, this would be ~10^3 - 10^4 TeV!

The MFV ansatz leads to a very predictive framework…

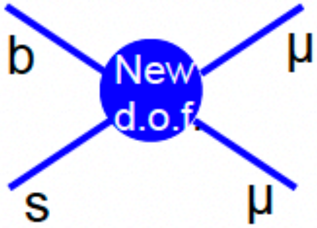
- ✱ TeV scale NP with interesting flavor effects
- ✱ Opportunities for discoveries at the LHC

Effective Lagrangians for B meson decays

$$\mathcal{H}_{\rm eff} = \frac{G_F}{\sqrt{2}} \sum_i C_i Q_i$$

Semileptonic operators

A new flavor structure can appear in this Wilson coefficient (if no MFV)



d.o.f = degree of freedom

$$\mathcal{O}_{10} = (\bar{b}\gamma_\mu P_L s)(\bar{\mu}\gamma_\mu\gamma_5\mu)$$ (the one of the SM)

$$\mathcal{O}'_{10} = (\bar{b}\gamma_\mu P_R s)(\bar{\mu}\gamma_\mu\gamma_5\mu)$$

$$\mathcal{O}_S = (\bar{b}P_L s)(\bar{\mu}\mu)$$

$$\mathcal{O}'_S = (\bar{b}P_R s)(\bar{\mu}\mu) \qquad \left(P_{L,R} = \frac{1 \mp \gamma_5}{2}\right)$$

$$\mathcal{O}_P = (\bar{b}P_L s)(\bar{\mu}\gamma_5\mu)$$

$$\mathcal{O}'_P = (\bar{b}P_R s)(\bar{\mu}\gamma_5\mu)$$

$$\mathrm{BR}(B_s \to \mu^+\mu^-) \propto m_\mu^2 \left(\left| (C_{10}^{\rm SM} + C_{10}^{\rm NP} - C'_{10}) + \frac{m_{B_s}}{2m_\mu}(C_P - C'_P) \right|^2 + \left| \frac{m_{B_s}}{2m_\mu}(C_S - C'_S) \right|^2 \right)$$

The helicity suppression can be eliminated thanks to the scalar/pseudoscalar operators

The prediction of MFV models

- To satisfy the MFV condition:

$$C_i \sim V_{tb}^* V_{ts} \qquad \text{(B}_s\text{ decay)}$$

$$C_i \sim V_{tb}^* V_{td} \qquad \text{(B}_d\text{ decay)}$$

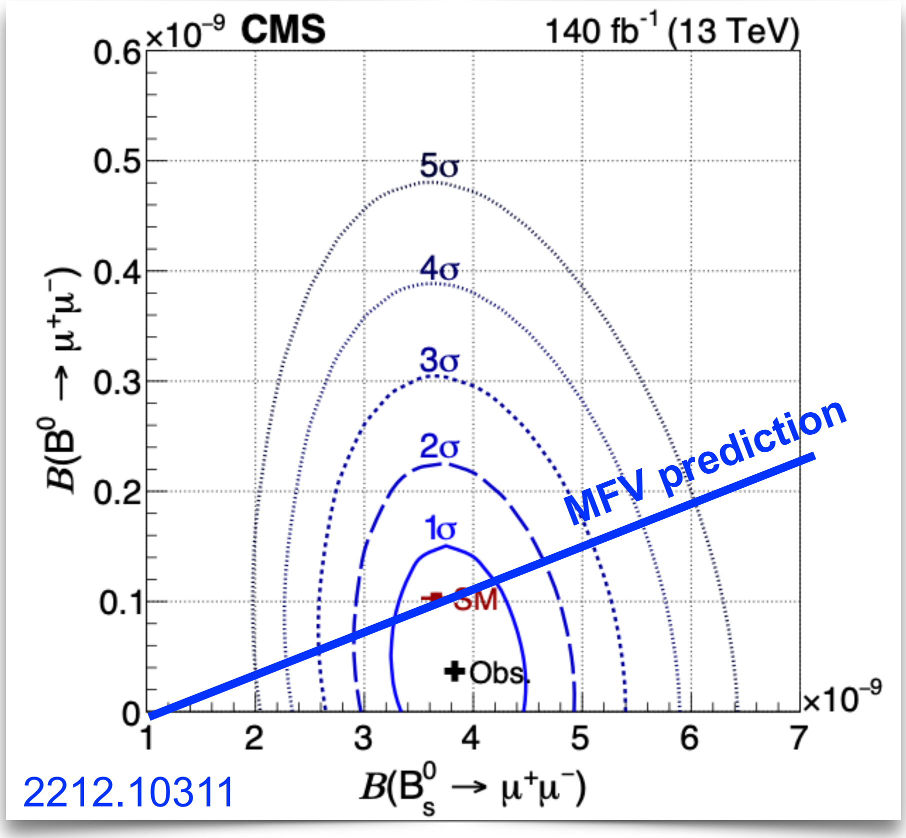
- Therefore, in MFV theories we always get

$$\boxed{\frac{\mathrm{BR}(B_s \to \mu^+\mu^-)}{\mathrm{BR}(B_d \to \mu^+\mu^-)} \sim \left|\frac{V_{ts}}{V_{td}}\right|^2}$$

Large part of the theory uncertainty (top mass, decay constant, …) is canceled in the ratio

We can extract info on BR($B_d \to \mu\mu$) using info on BR($B_s \to \mu\mu$) that is better measured

Theory uncertainty ~ few %



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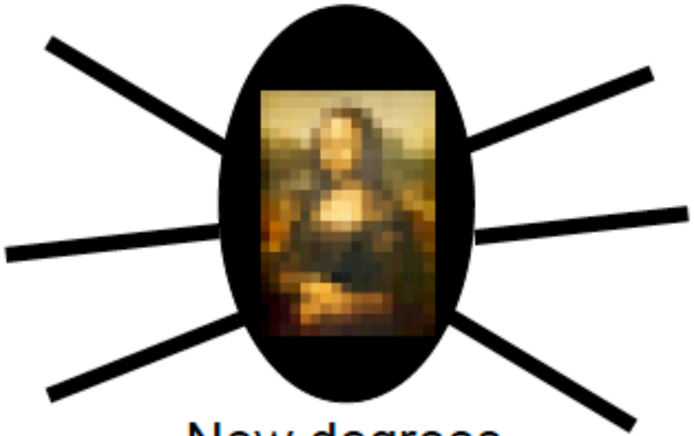
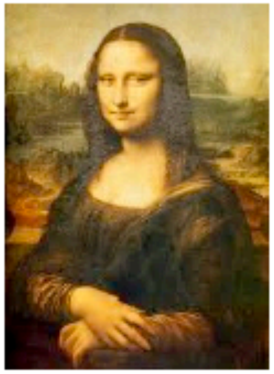
Beyond EFTs

- Up to now, we have considered effective theories arising from more complete theories beyond the SM, with new heavy degrees of freedom that they can be integrated out



- What is the complete BSM theory?
  What are the new degrees of freedom?



Next: models with additional Higgs bosons…

A Two-Higgs-Doublet-Model (2HDM)

- Several extensions of the SM involve an extended Higgs sector, with more than one Higgs doublet.
  Most studied example: SUSY

SM doublet

- A two Higgs dublet: $H_1 = (1,2,-1/2)$, $H_2 = (1,2,1/2)$ ⇒ Physical fields: h, H, A, $H^\pm$

- Most general Lagrangian

$$V(H_1,H_2) = \mu_1^2|H_1|^2 + \mu_2^2|H_2|^2 + (bH_1H_2 + \mathrm{h.c}) + \frac{\lambda_1}{2}|H_1|^4 + \frac{\lambda_2}{2}|H_2|^4 + \lambda_3|H_1|^2|H_2|^2$$

$$+\lambda_4|H_1H_2|^2 + \left[\frac{\lambda_5}{2}(H_1H_2)^2 + \lambda_6|H_1|^2H_1H_2 + \lambda_7|H_2|^2H_1H_2 + \mathrm{h.c}\right]$$

These coefficients are generically complex.
Possible new sources of CP violation

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$$\mathcal{H}_Y^{\rm gen} = \bar{Q}_L X_{d1} D_R H_1 + \bar{Q}_L X_{u1} U_R H_1^c + \bar{Q}_L X_{d2} D_R H_2^c + \bar{Q}_L X_{u2} U_R H_2$$

Each Higgs doublet can generically couple to up and down quarks.

Flavor Changing Neutral Currents in a 2HDM

$$\mathcal{H}_Y^{\rm gen} = \bar{Q}_L X_{d1} D_R H_1 + \bar{Q}_L X_{u1} U_R H_1^c + \bar{Q}_L X_{d2} D_R H_2^c + \bar{Q}_L X_{u2} U_R H_2$$

We can rotate to the basis in which only one Higgs has a VEV

$$\begin{pmatrix} \Phi_v \\ \Phi_H \end{pmatrix} = \begin{pmatrix} c_\beta & s_\beta \\ -s_\beta & c_\beta \end{pmatrix} \begin{pmatrix} H_1 \\ H_2^c \end{pmatrix}$$

$$\langle \Phi_v^\dagger \Phi_v \rangle = v^2/2,$$
$$\langle \Phi_H^\dagger \Phi_H \rangle = 0$$

$$\tan\beta \equiv \frac{\langle H_2 \rangle}{\langle H_1 \rangle}$$

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$$\mathcal{H}_Y^{\rm gen} = \bar{Q}_L \left[\frac{\sqrt{2}}{v} M_d \Phi_v + Z_d \Phi_H \right] D_R \, .$$

3x3 matrices

$$\begin{cases} Z_d = \cos\beta X_{d2} - \sin\beta X_{d1} \\ M_d = \frac{v}{\sqrt{2}} (\cos\beta X_{d1} + \sin\beta X_{d2}) \end{cases}$$

(analogous in the up sector)

Generically not proportional to each other! ⇒ It is not possible to diagonalize them simultaneously

Flavor Changing Neutral Currents in a 2HDM

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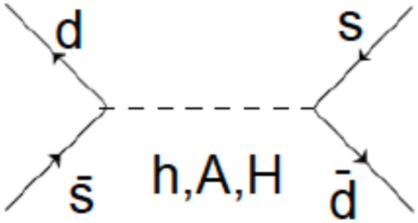


No loop suppression of the four fermion operators!

BAD!

A MFV 2HDM

$$\mathcal{H}_Y^{\mathrm{gen}} = \bar{Q}_L X_{d1} D_R H_1 + \bar{Q}_L X_{u1} U_R H_1^c + \bar{Q}_L X_{d2} D_R H_2^c + \bar{Q}_L X_{u2} U_R H_2$$

$$\begin{cases} X_{d1} &= Y_d \\ X_{u1} &= \epsilon_u Y_u + \epsilon_1' Y_u^\dagger Y_u Y_u + \epsilon_2' Y_d^\dagger Y_d Y_u + \cdots \\ X_{d2} &= \epsilon_b Y_d + \epsilon_1 Y_d^\dagger Y_d Y_d + \epsilon_2 Y_u^\dagger Y_u Y_d + \cdots \\ X_{u2} &= Y_u \end{cases}$$

higher orders in the small Yukawa couplings

The ε_i are in general complex coefficients

- The most studied 2HDMs are the so called Type I, II, III, IV: these are models where up and down quarks only couple to one Higgs type.

  Example: Type II: U_R only couple to H_2 and D_R only coupled to H_1 ($X_{u1} = X_{d2} = 0$)

- All these models are a particular limit of a MFV 2HDM

Flavor phenomenology of a MFV 2HDM

- Constraints from meson mixing observables

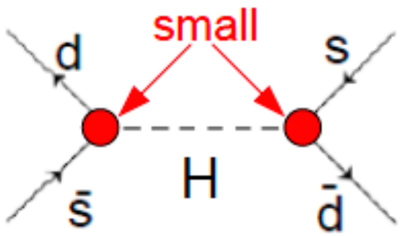
Kaon $\sim \dfrac{A_0}{M_H^2} \tan^4\beta\, m_s m_d [V_{ts}^* V_{td}]^2$

$B_d \sim \dfrac{A_1}{M_H^2} \tan^4\beta\, m_b m_d [V_{tb}^* V_{td}]^2$

$B_s \sim \dfrac{A_2}{M_H^2} \tan^4\beta\, m_b m_s [V_{tb}^* V_{ts}]^2$

Larger NP effect

A_i are combinations of the ε_i of the previous slide



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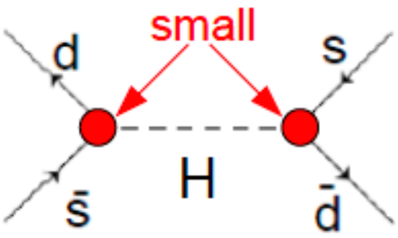
$\downarrow$ Larger NP effect

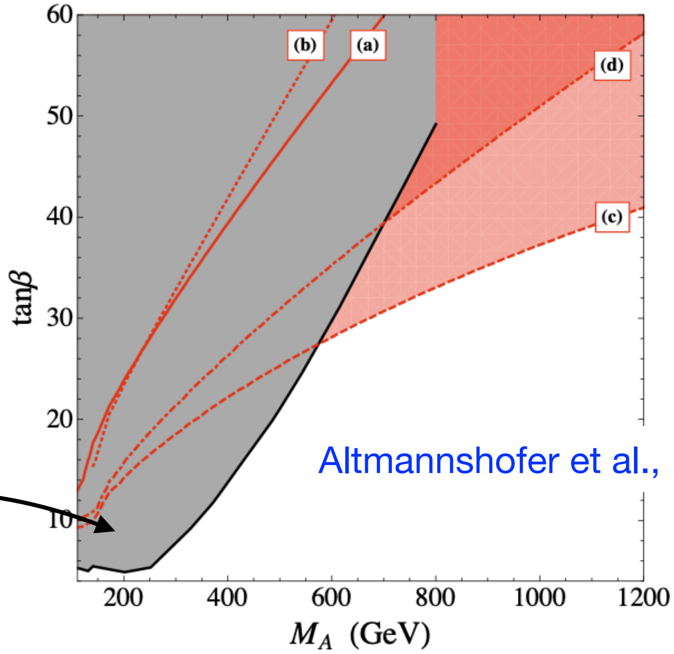


A_i are combinations of the ε_i of the previous slide

- Some possible NP in rare B-decays

$$\frac{\mathrm{Br}(B_q \to \mu^+\mu^-)}{\mathrm{Br}(B_q \to \mu^+\mu^-)_{\mathrm{SM}}} = (|1 + R_q|^2 + |R_q|^2)$$

$$R_q \propto \frac{M_{B_q}^2 t_\beta^3}{M_H^2}$$



Altmannshofer et al., 1211.1976

Interplay with direct searches, H/A → $\tau\tau$

The origin of fermion masses

In 2012, the LHC ATLAS and CMS collaborations announced the discovery of the Higgs boson.

Is the Higgs field indeed responsible of giving mass to the elementary fermions?

It definitely gives mass (or at least part of the mass) to the most massive fermions:

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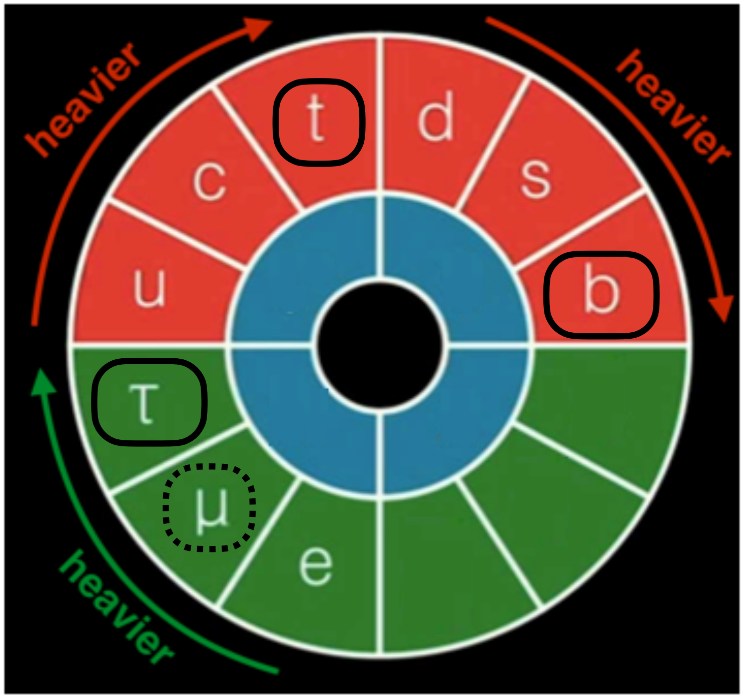

The Standard Model of particle physics predicts

$$Y_f = m_f / v$$

vacuum expectation value of the Higgs

Higgs-fermion interaction strength

▢ These interactions are already discovered
⇨ the Higgs gives mass to the top, bottom, tau

⬚ First evidence of the muon-Higgs coupling
~2, 3σ (through the search for H → μμ)

CMS: JHEP 01 (2021) 148
ATLAS: Phys.Lett.B 812 (2021) 135980

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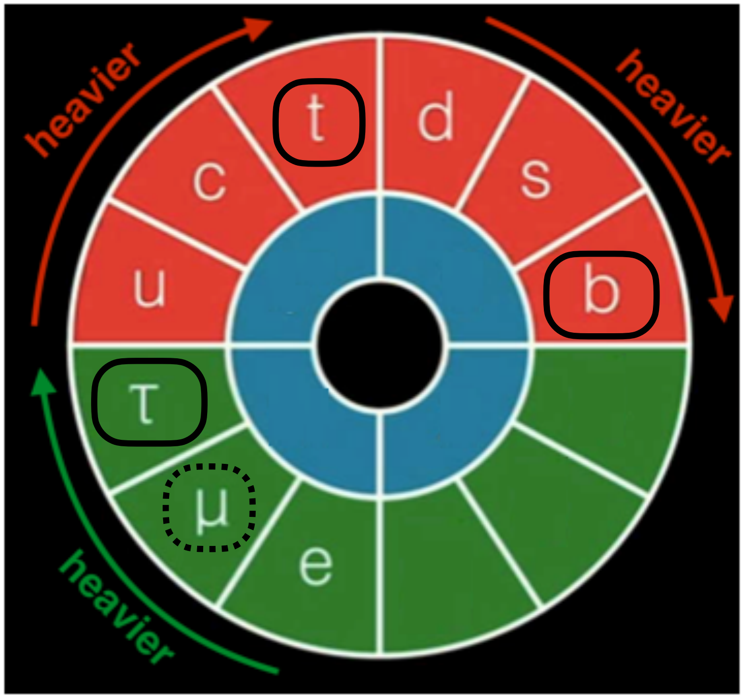

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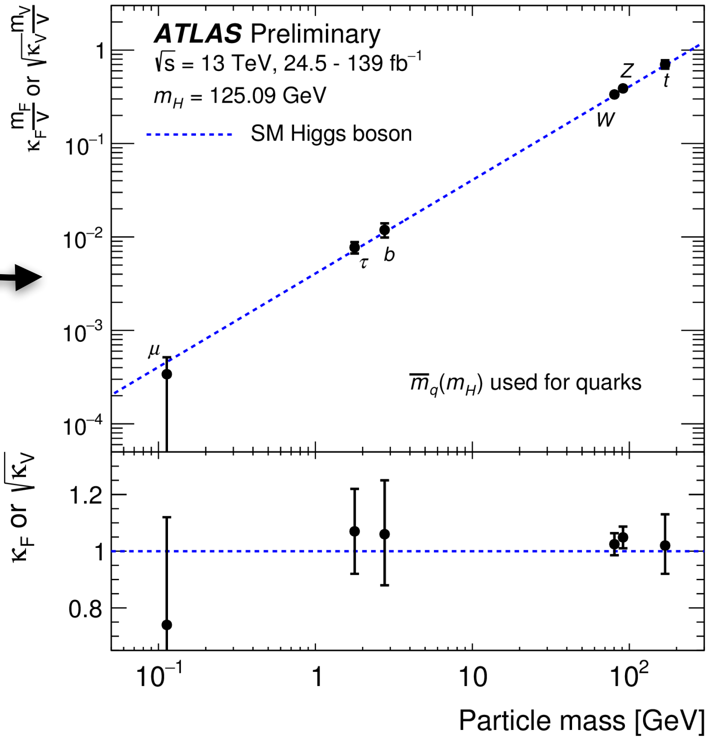
$$Y_f = m_f / v$$

Accurate test of this proportionality



Future tests of fermion mass generation

We will most probably discover the Higgs interaction with **muons** ✓
⇨ Higgs responsible for the muon mass

Testing the mass generation of electrons and light quarks is very challenging ⚠

✱ Electrons: BR(H →ee)~10^{-9} but the LHC will only produce ~O(10^8) Higgs bosons
Future e^+e^- collider running at the Higgs peak? ($\sqrt{s} \simeq m_h$)

see e.g., JHEP 05 (2015) 125;
Eur.Phys.J.Plus 137 (2022) 2, 201;
Phys.Rev.D 110 (2024) 7, 075026

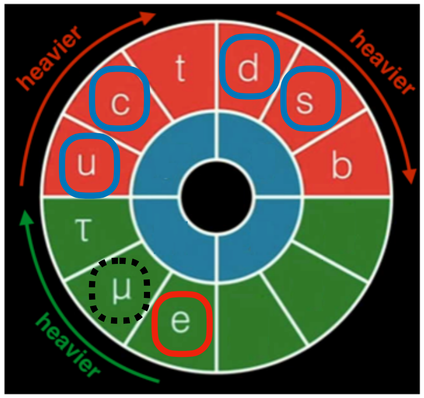
✱ Charm: several ways to test this coupling:

for a review, see e.g., Phys.Lett.B 832 (2022) 137255

H →cc, Higgs kinematical distributions, VH associated production, …

$y_c \lesssim (1-2) y_c^{\rm SM}$ at the High-luminosity stage of the LHC
(a factor of ~10 more data if compared to now)

✱ Lighter quarks: even more challenging



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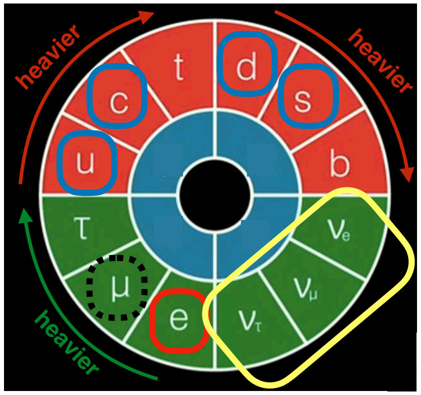
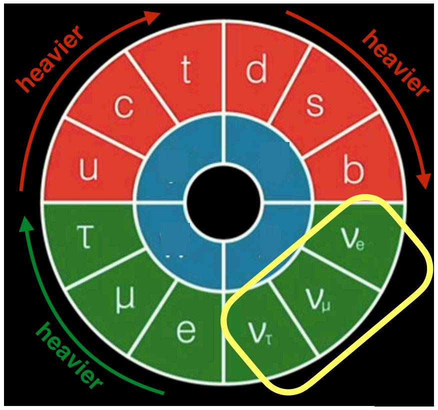


And what about neutrino masses?

Do neutrino have a mass?

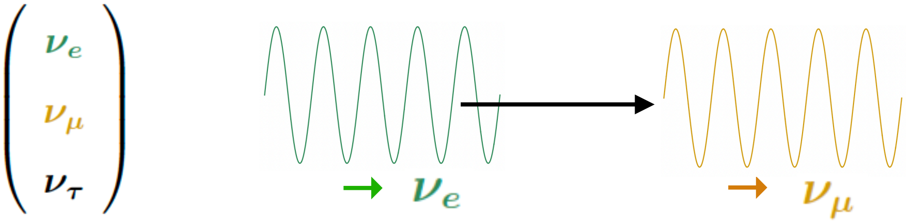
YES! At least 2 neutrinos have a non-zero mass

See lectures by S. Li



How do we know about it?

We have observed **“neutrino oscillations”**



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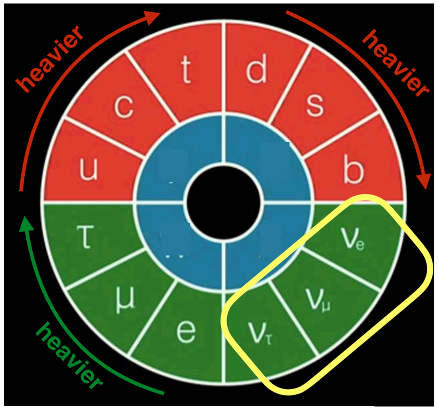

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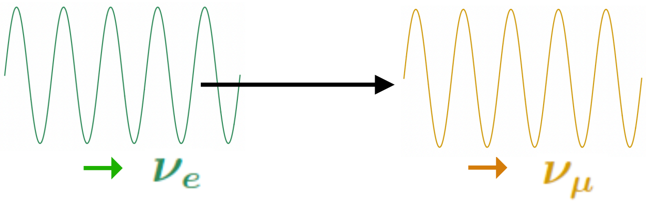
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$



What is the origin of these masses?

Brief historical note on neutrinos and neutrino oscillations:

1930: “Neutrino" hypothesis by Pauli to explain missing energy in beta decay (later called neutrinos by Fermi).

1956: Neutrino Discovery by C. Cowan and F. Reines.

1958: Neutrino oscillation hypothesis by Pontecorvo.

1962: Discovery of the Muon Neutrino by Lederman, Schwartz, and Steinberger at BNL

1968: Solar Neutrino Problem: deficit of electron neutrinos from the sun

1986: Atmospheric Neutrino Anomaly: deficit of muon neutrinos from cosmic rays

1998: Discovery of Atmospheric Neutrino Oscillations by Super-Kamiokande in Japan.

2001: Confirmation of solar neutrino oscillations by Sudbury Neutrino Observatory.

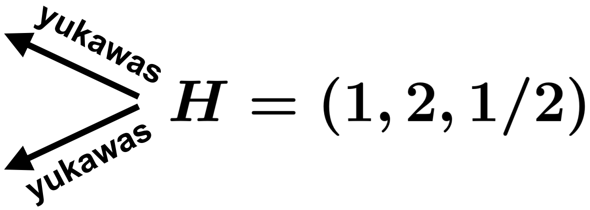
The problem with neutrino masses

The SM is based on a SU(3)$_c$ x SU(2)$_L$ x U(1)$_Y$ gauge symmetry

The building blocks of the SM are the fermion representations:

$$Q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix} = (3, 2, 1/6), \quad u_R = (3, 1, 2/3), \quad d_R = (3, 1, -1/3)$$

$$L_L = \begin{pmatrix} \nu_L \\ \ell_L \end{pmatrix} = (1, 2, -1/2), \quad e_R = (1, 1, -1)$$



$$H = (1, 2, 1/2)$$

SM neutrinos.
Need to have a mass

There is no Yukawa interaction that we can write down that involves the ν_L fields $\Rightarrow$ In the SM, the neutrinos would be massless!

We need to go **beyond the SM** to explain neutrino masses.
What's the mechanism that gives mass to neutrinos?

Let's start with a little background…

Dirac or Majorana neutrinos

There are two different types of spinors under Lorentz transformations

- Left handed (LH) Weyl spinors: $\psi_L \rightarrow \exp\left((-i\bar{\theta} - \bar{\eta})\frac{\bar{\sigma}}{2}\right)\psi_L$
- Right handed (RH) Weyl spinors: $\psi_R \rightarrow \exp\left((-i\bar{\theta} + \bar{\eta})\frac{\bar{\sigma}}{2}\right)\psi_R$

rotation angle

boost

Pauli matrices

Different chirality

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Pauli matrices

Different chirality

From here, we can build a Dirac fermion

$$\psi_D = \begin{pmatrix} \psi_L \\ \psi_R \end{pmatrix}$$

4-degrees of freedom
(2 complex Weyl spinors)

A Majorana fermion is a **particle that is equal to its anti-particle**:

$$\psi_M = \begin{pmatrix} \psi_L \\ i\sigma_2\psi_L^* \end{pmatrix}$$

2-degrees of freedom

We do not know if neutrinos are Dirac or Majorana fermions

(all the other Standard Model fermions are Dirac fermions since particle ≠ anti-particle)

Dirac and Majorana masses

In all generality, spinors can have two different types of masses:
Dirac masses & Majorana masses

$$-\mathcal{L}_M = \frac{1}{2}\left(m_D\bar{\psi}_L\psi_R + m_D\bar{\psi}^c_R\psi^c_L + \frac{M_R}{2}\bar{\psi}^c_R\psi_R + \frac{M_L}{2}\bar{\psi}^c_L\psi_L\right) + \mathbf{h.c.}$$

conjugate fermion

Both terms are allowed by Lorentz invariance

$$\Rightarrow -\frac{1}{2}\begin{pmatrix}\bar{\psi}_L & \bar{\psi}^c_R\end{pmatrix}\begin{pmatrix}M_L & m_D \\ m_D & M_R\end{pmatrix}\begin{pmatrix}\psi^c_L \\ \psi_R\end{pmatrix} + \mathbf{h.c.}$$

If M_L, $M_R = 0$ $\Rightarrow$ Dirac fermion
If M_L, $M_R \neq 0$ $\Rightarrow$ Majorana fermion

One possible realization of Majorana neutrinos

So far, we know of the existence of three LH neutrinos that interact through the SU(2)$_L$ weak interactions, ν_L

If we add three RH neutrinos, N_R, that are not charged under SU(3)$_c$ x SU(2)$_L$ x U(1)$_Y$, then we can write the following Lagrangian terms (invariant under both the SM gauge symmetries and the Lorentz symmetry)

$$L_L = \begin{pmatrix} \boxed{\nu_L} \\ \ell_L \end{pmatrix}$$

$$-\mathcal{L}_\nu = (Y_\nu \bar{L}_L H N_R + \text{h.c.}) + M \bar{N}_R^c N_R$$

we do not know if RH neutrinos exist

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Dirac neutrinos, **M = 0**

$$Y_\nu \simeq 10^{-12}$$

a really tiny Yukawa interaction would be needed. **Why so small?**

For comparison, the electron Yukawa: $Y_e \simeq 10^{-6}$

Neutrinos behave exactly as all the other SM fermions

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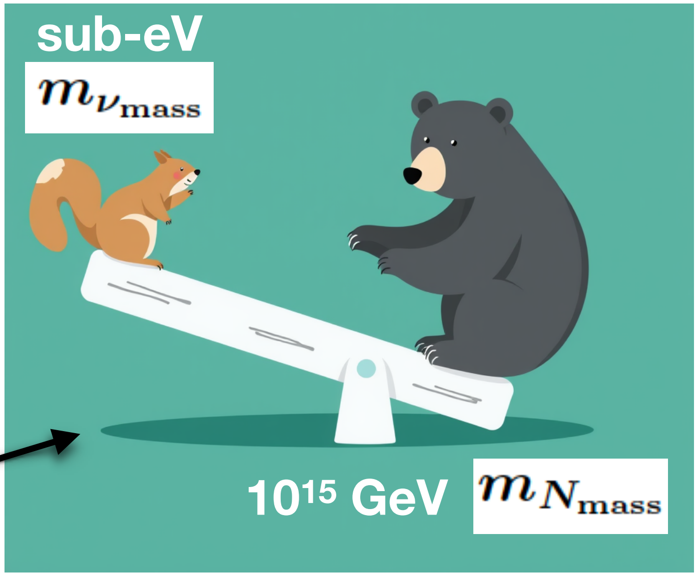
if Y$_\nu$ v << M, $m_{\nu_{\rm mass}} = \mathcal{O}\left(\frac{Y_\nu^2 v^2}{M}\right), \quad m_{N_{\rm mass}} \sim M$

$$Y_\nu \simeq 1 \quad \text{and} \quad M \simeq 10^{15}\ \text{GeV}$$

RH neutrinos can be lighter if smaller Yukawa

(Type-I) seesaw mechanism



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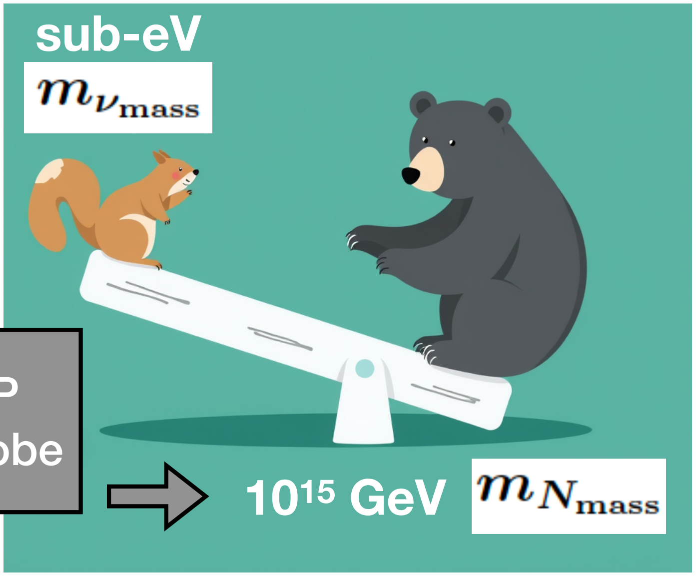
$Y_\nu \simeq 1$ and $M \simeq 10^{15}$ GeV ⇦

RH neutrinos can be lighter if smaller Y

This is a very heavy NP scale. Challenging to probe

(Type-I) seesaw mechanism



A “mixed” solution: lighter sterile neutrinos

$$m_{\nu_{\rm mass}} = \mathcal{O}\left(\frac{Y_\nu^2 v^2}{M}\right), \quad m_{N_{\rm mass}} \sim M$$

Sterile neutrinos can be **lighter** than 10^{15} GeV.

For example, if $Y_\nu \sim Y_e$, M ~ TeV

How to detect this type of neutrinos?

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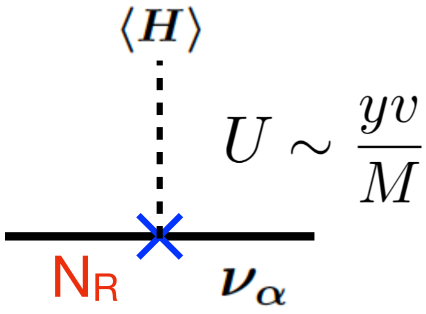
This operator will generically induce some mixing of N with the three active SM neutrinos, $\alpha = 1{,}2{,}3$



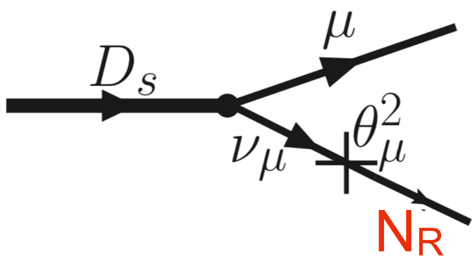
Whenever we produce SM neutrinos, we can also produce sterile neutrinos

Sterile neutrinos @ colliders

Production

- From meson decays:

example:

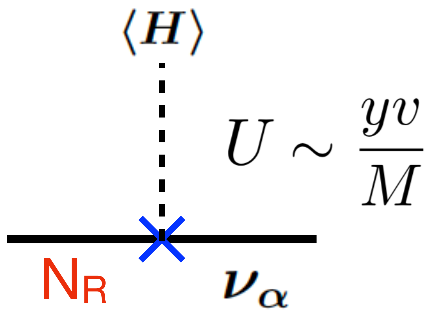


- At higher energies, decays of W, Z, H

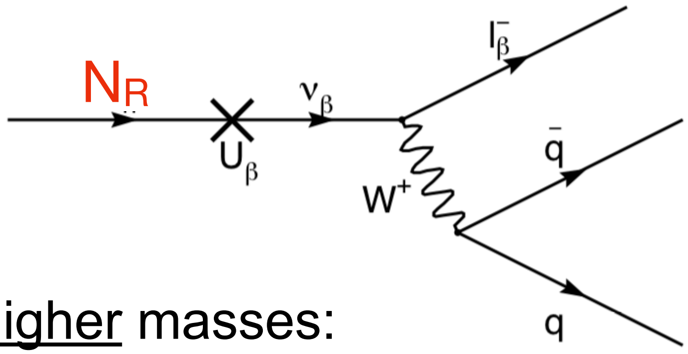
W → l N, Z/H → NN, Z/H → Nv

(mass eigenstate)

see Atre et al., 0901.3589
Gorbunov, Shaposhnikov, 0705.1729



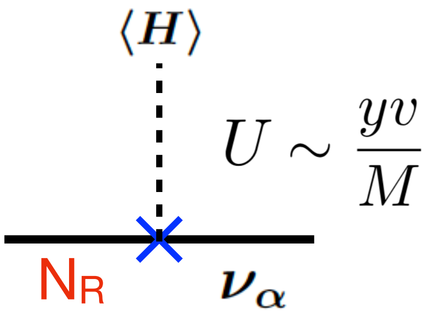
Decay



At higher masses:
N → $Z^{(*)}$v, N → $W^{(*)}$ l, N → $H^{(*)}$v

At lower masses: vector meson dominance technique:
N → l meson(s), N → v meson(s), …

Sterile neutrinos @ colliders



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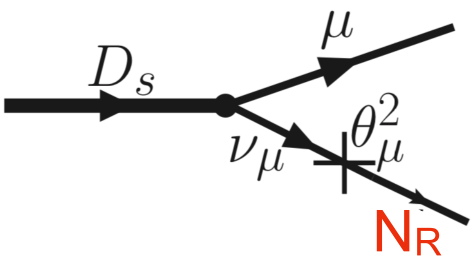

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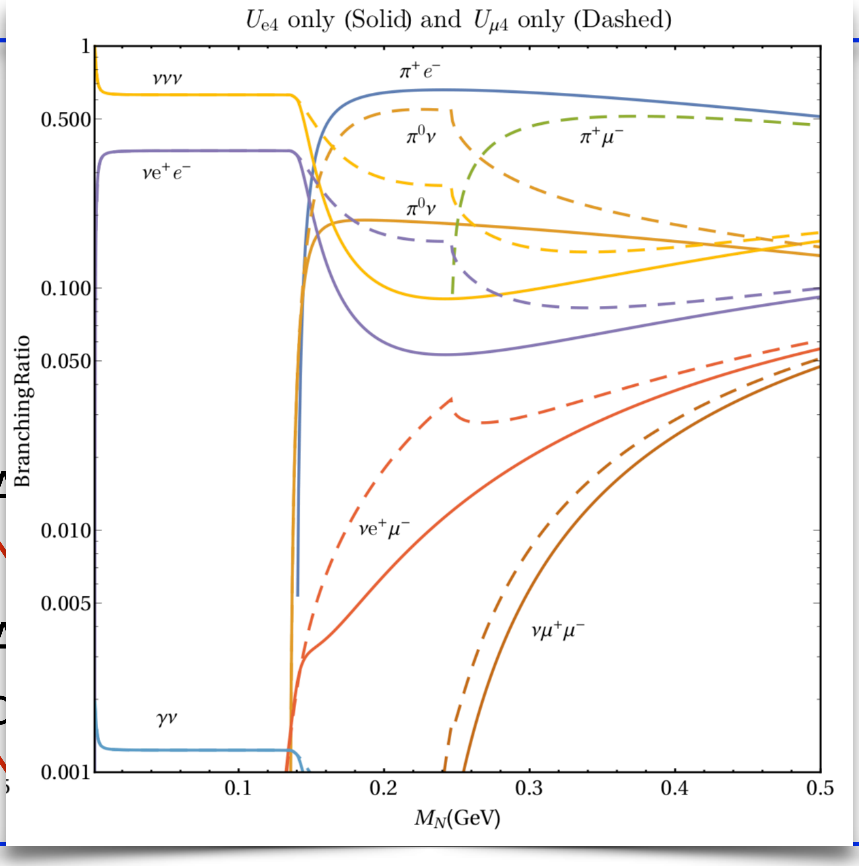
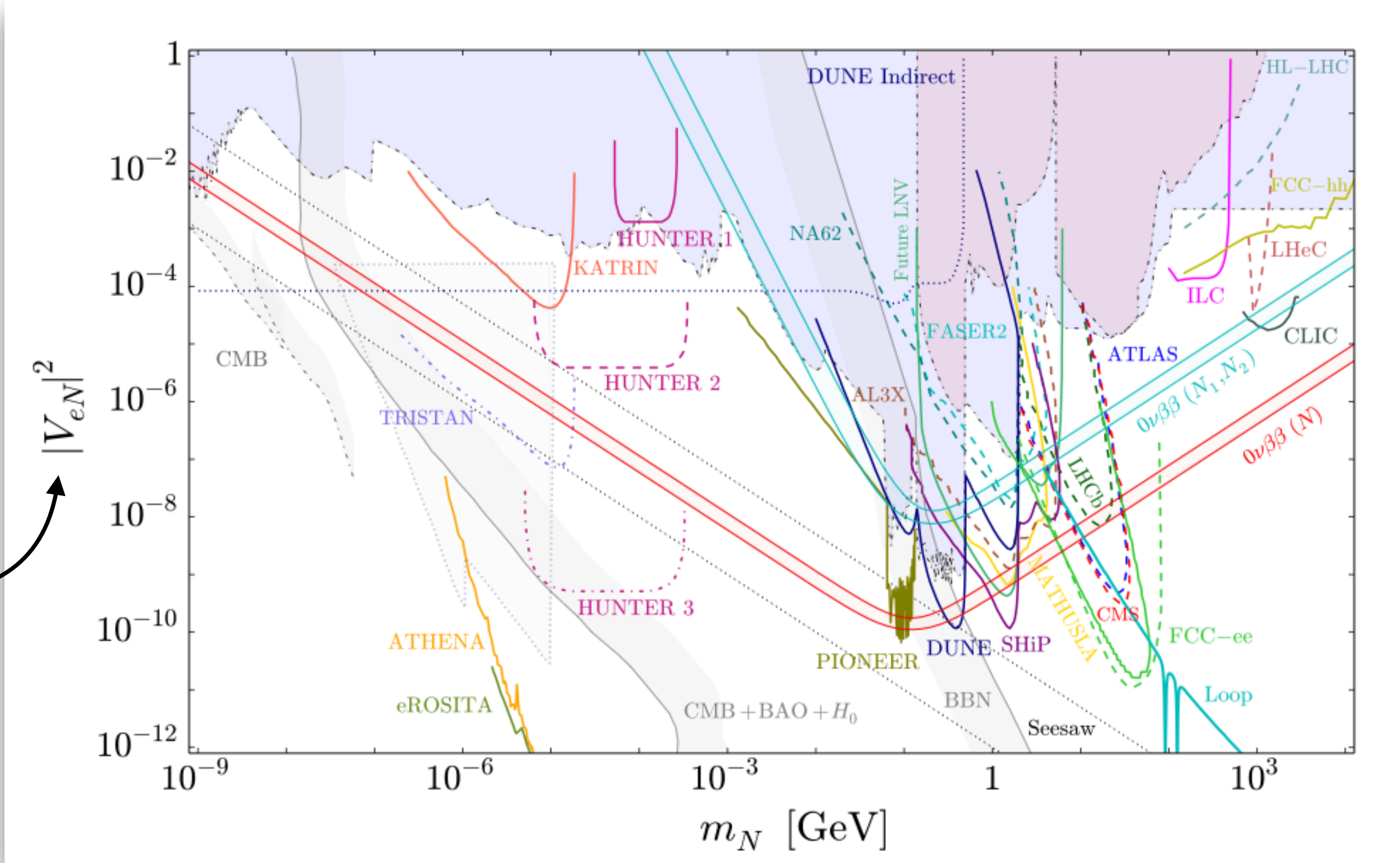


Ballett et al., 1610.08512

Bounds on sterile neutrinos

Bolton et al., 2206.01140

sterile neutrino
that mixes with the
SM electron neutrino



Cosmology

X ray
observatory

nuclear
beta
decays

meson
factories:
NA62: K
PIONEER: π

beam dump
experiments

high energy
colliders

More on
these experiments
later…

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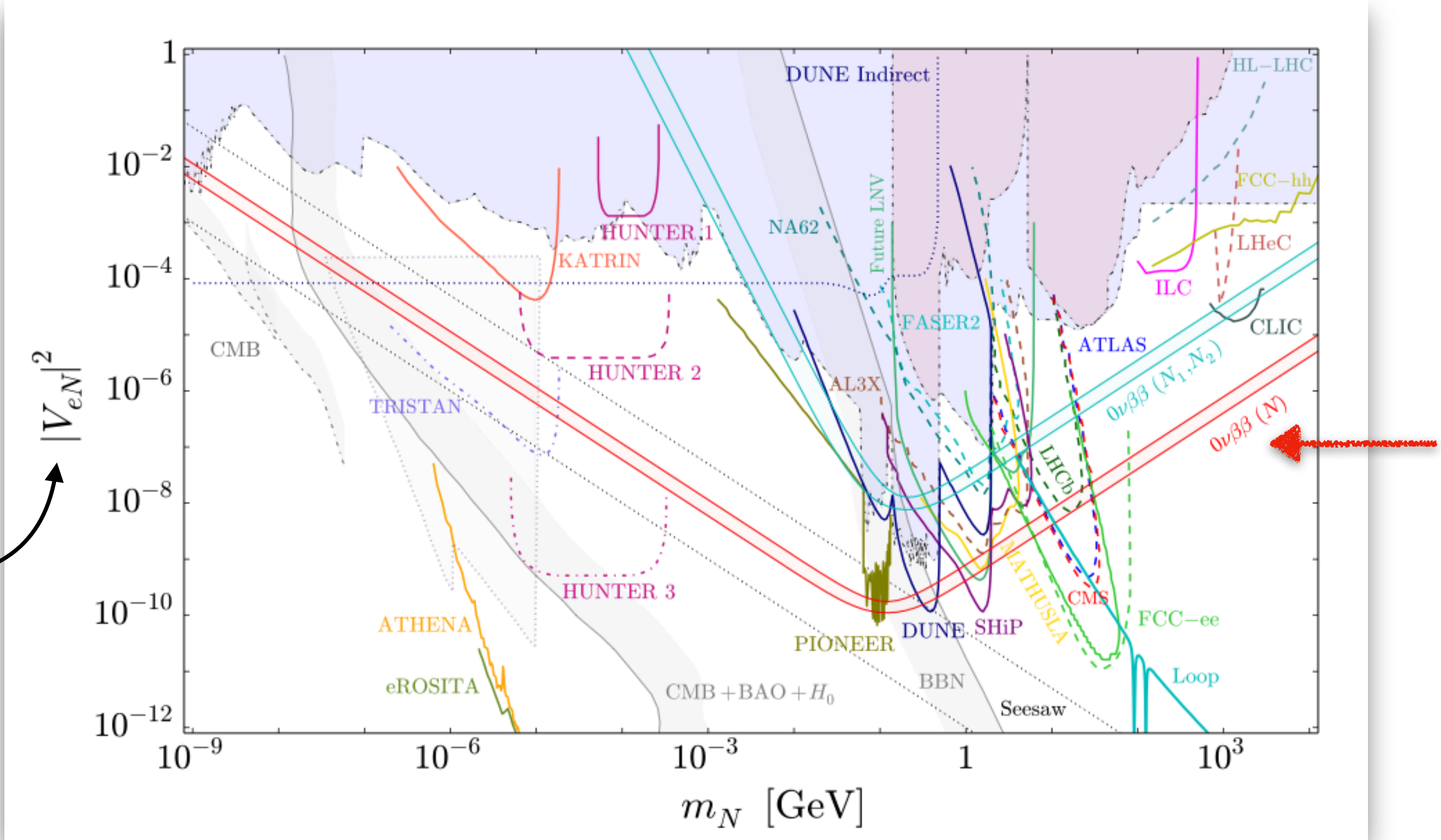

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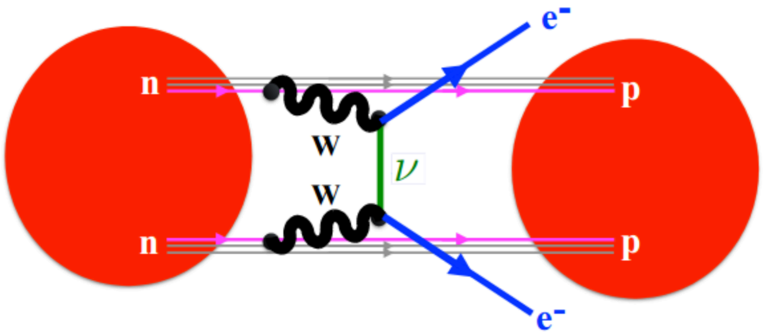
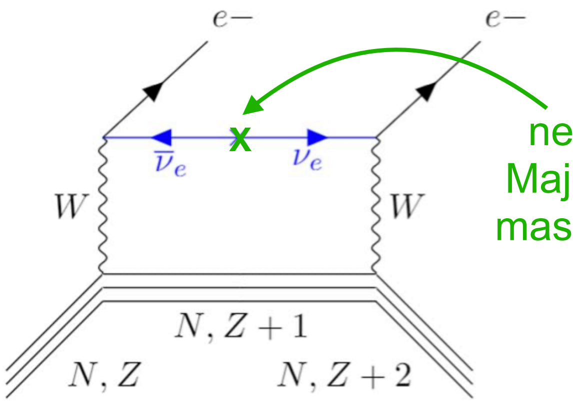
S.Gori

Neutrino-less-double-beta decay



nucleus with N nucleons
and Z atomic number

nucleus with N nucleons
and Z+2 atomic number



need a
Majorana
mass term

violation of the lepton number

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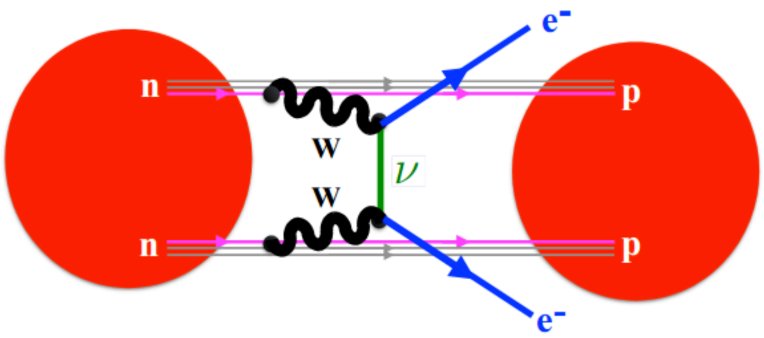
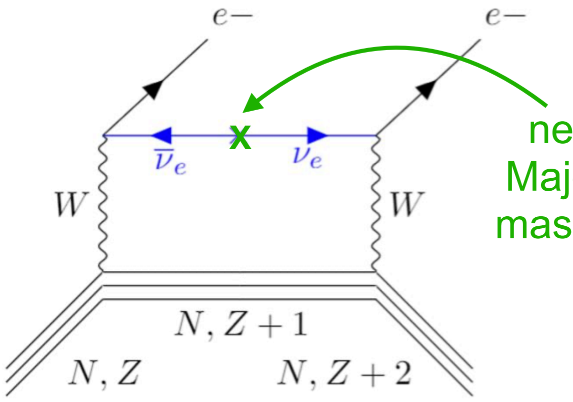


nucleus with N nucleons and Z atomic number

nucleus with N nucleons and Z+2 atomic number



need a Majorana mass term

violation of the lepton number

$$1/T_{1/2} = G_{0\nu}|M_{0\nu}|^2 m_{ee}^2$$

Nuclear Matrix Element. Difficult calculation with large uncertainties

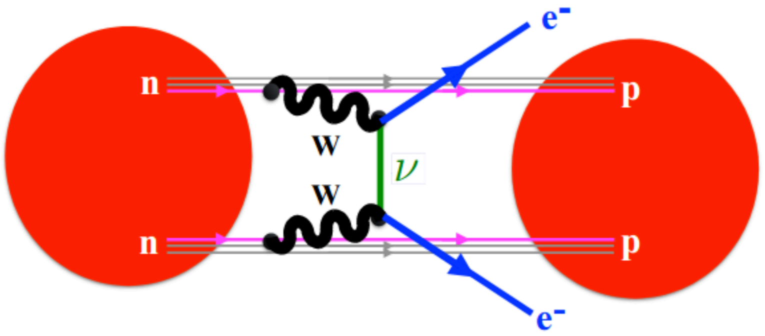
Phase space factor

$$m_{ee} = \left|\sum_{i=1}^{3} m_i U_{ei}^2\right| = \left|\cos^2\theta_{13}\,(m_1 e^{2i\eta_1}\cos^2\theta_{12} + m_2\sin^2\theta_{12}e^{2i\eta_2}) + m_3 e^{2i\delta}\sin^2\theta_{13}\right|$$

with the PMNS matrix:
(introduced in the lectures by N.Blinov)

$$U = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & & s_{13}\,e^{-i\delta} \\ & 1 & \\ -s_{13}\,e^{i\delta} & & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \times \begin{pmatrix} e^{i\eta_1} & & \\ & e^{i\eta_2} & \\ & & 1 \end{pmatrix}$$

Neutrino-less-double-beta decay



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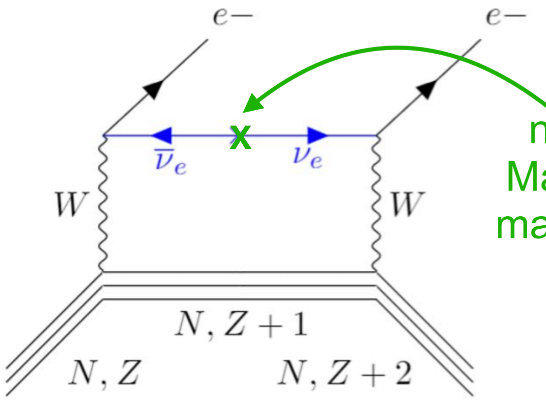

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In the presence of sterile neutrinos:

$$\begin{cases} \dfrac{10^{28}\text{yr}}{T_{1/2}} = \left(\dfrac{|V_{eN}|^2}{10^{-9}}\dfrac{1\text{ GeV}}{m_N}\right)^2, & m_N \gtrsim 100\text{ MeV} \\ \dfrac{10^{28}\text{yr}}{T_{1/2}} = \left(\dfrac{|V_{eN}|^2}{10^{-9}}\dfrac{m_N}{10\text{ MeV}}\right)^2, & m_N \lesssim 100\text{ MeV} \end{cases}$$

Experimental searches for 0νββ

Current experimental bound: $m_{ee} < (28 - 122)\ \mathrm{meV}$

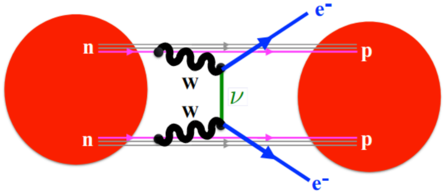
(range due to nuclear matrix element uncertainties)

This correspond to a half-time, $T_{1/2}$: **3.8 x 10^{26} years!**

KamLAND-Zen, 2406.11438

Five decays per Year per Ton of Isotope!

Is this a larger number? YES



Key of these searches:
we have **Avogadro numbers** of nuclei!

for comparison

- **age of the universe ~10^{10} years**
- neutrino double beta decay ~ 10^{20} years
- proton decay > 10^{30} years

Future goal:
probing half-time
of **~10^{28} years**
(LEGEND-1000, nEXO)

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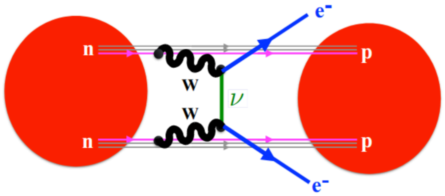

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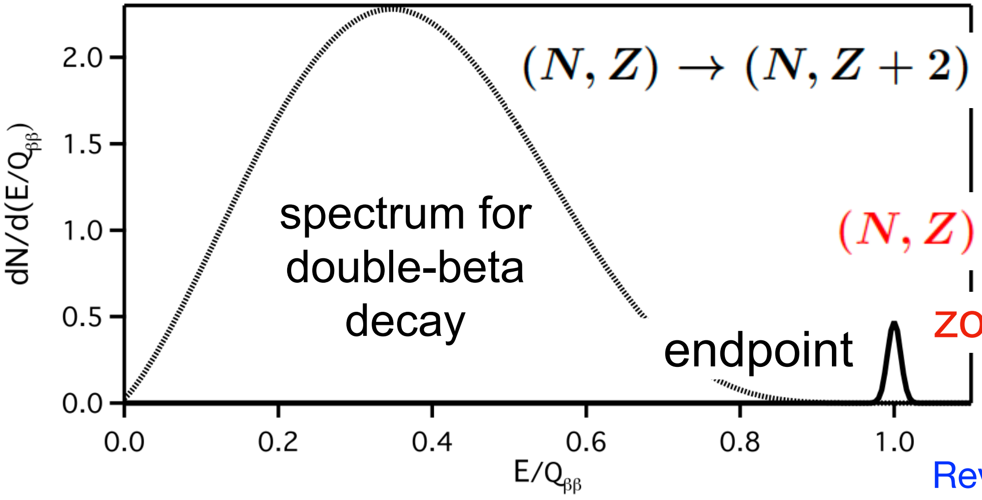
measurement of the electron energy spectrum:



$(N, Z) \to (N, Z+2)\ e^- \bar{\nu}\ e^- \bar{\nu}$

$(N, Z) \to (N, Z+2)\ e^- e^-$

**More in
S.Li's lectures**

Rev.Mod.Phys., 481-516 (2008)

Chapter 3: Light New Physics

- Dark Matter and the dark sectors in the MeV-GeV range
- Axions and axion-like-particles

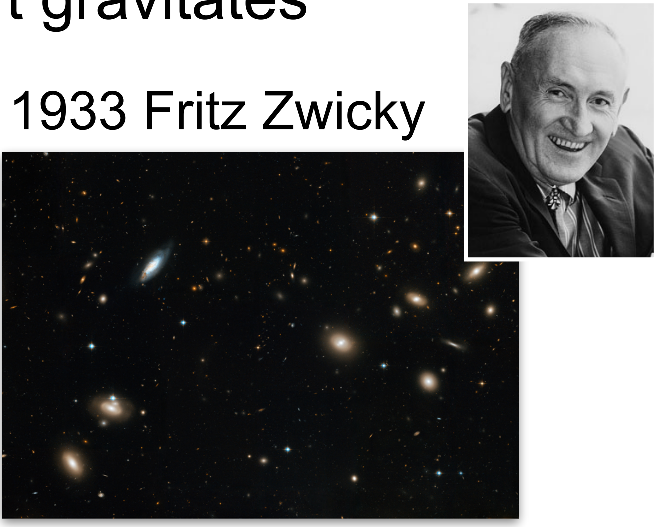
See lectures by C.E.M. Wagner

Dark Matter (DM) is there!

What do we know about it? Not much

1. It gravitates

1933 Fritz Zwicky



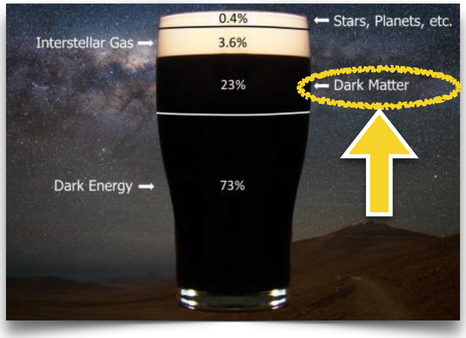
Coma cluster (of galaxies)

1970, Vera Rubin

Andromeda Galaxy

2. It is dark (i.e. it does not interact with photons)

3. It is stable on cosmological scales



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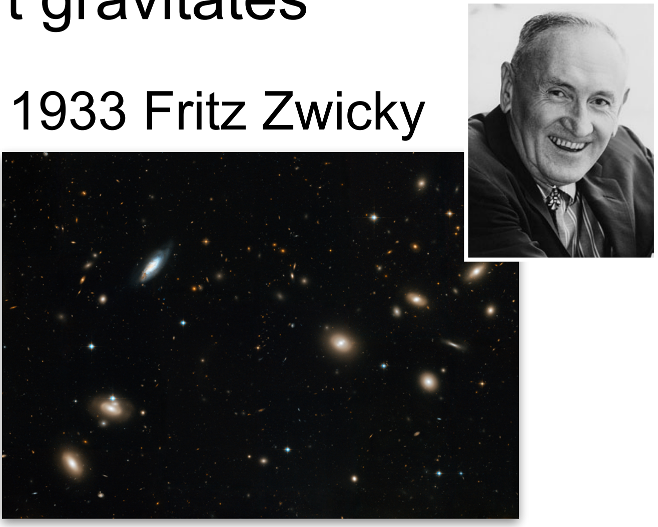

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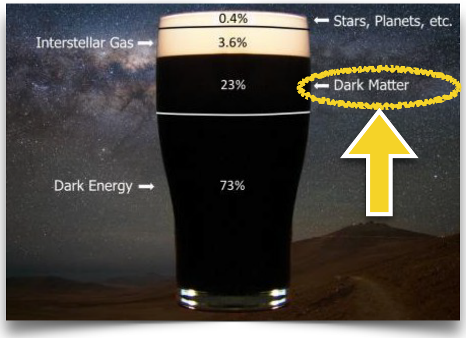

Fun fact: There is lots of DM in the Universe, but for DM particles weighing several hundred times the mass of the proton, there should be about one DM particle per coffee-cup-sized volume of space.

“Weakly” interacting or collision less DM

Optical, X-ray gas (ordinary matter), dark matter

The “WIMP” paradigm

Weakly **Interacting Massive Particles** (WIMP) models:
One of the dominant models for more than 3 decades

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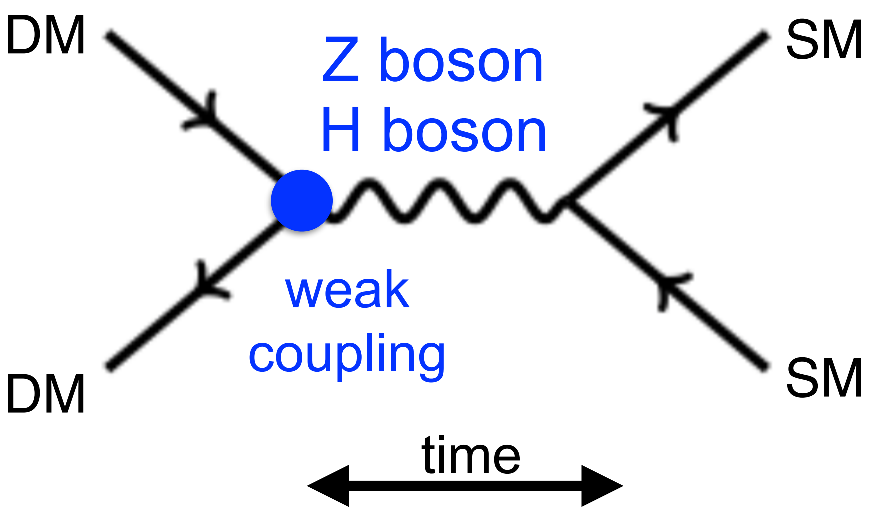
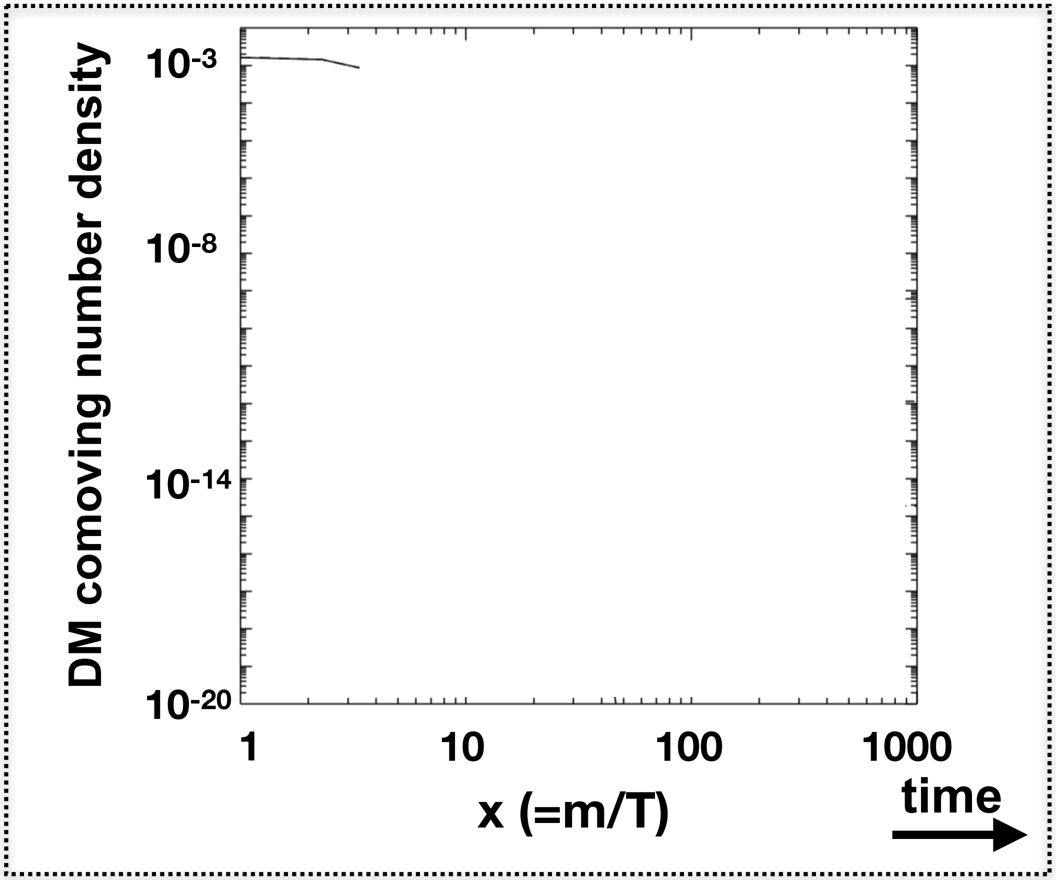
Thermal Dark Matter





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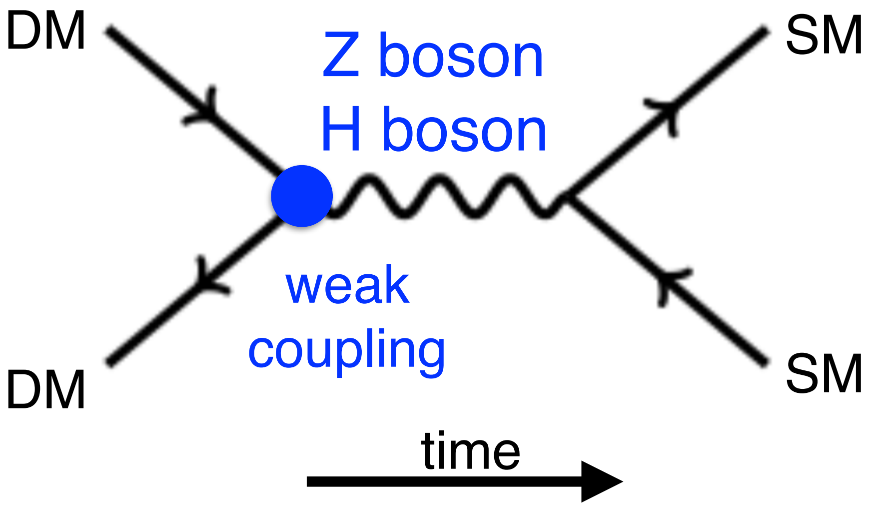

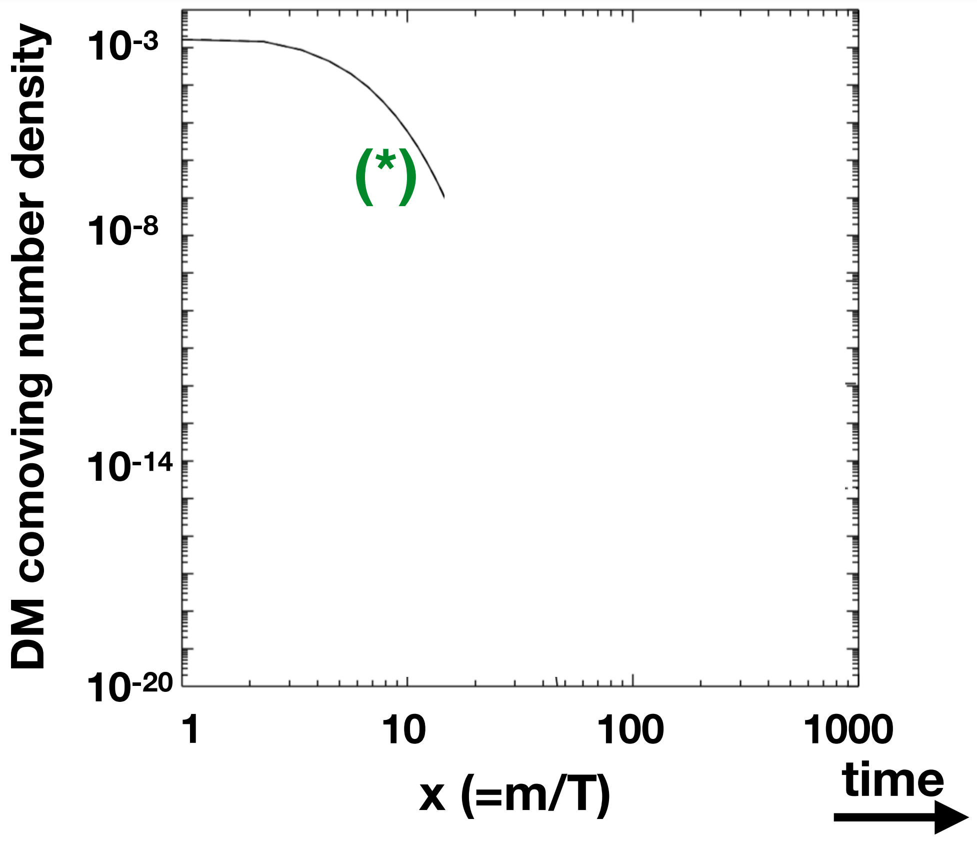

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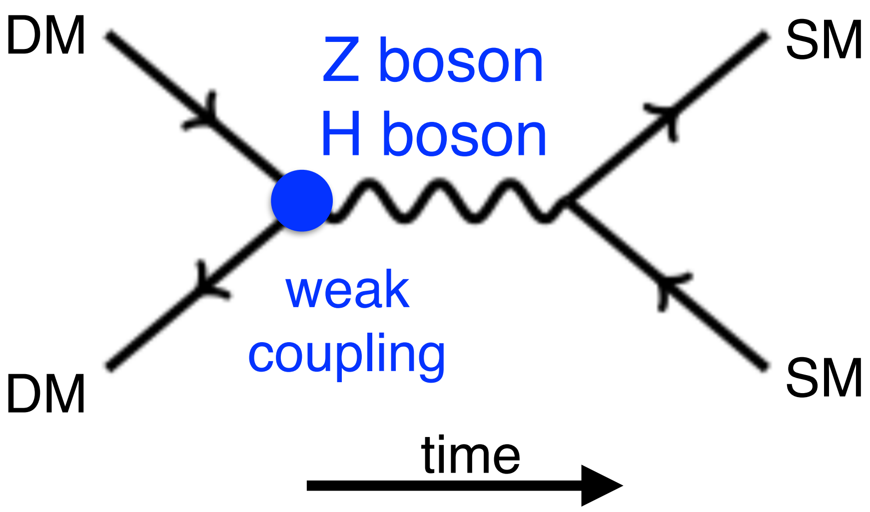
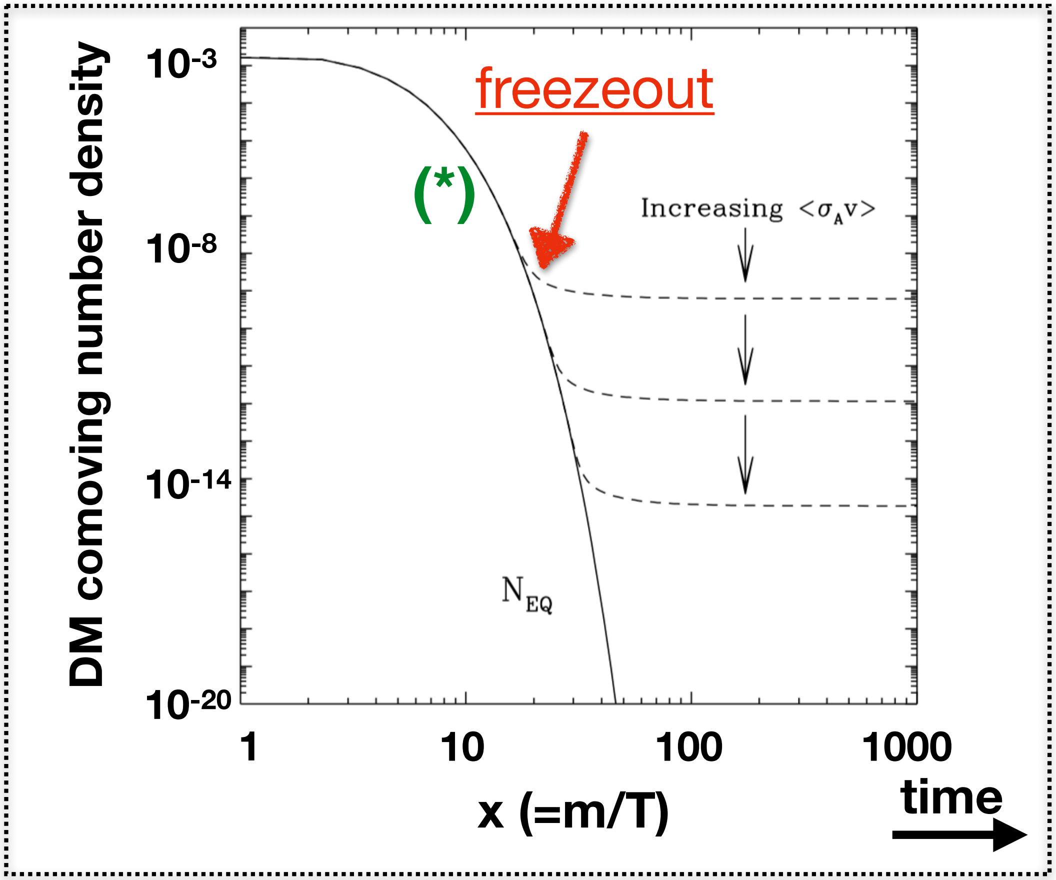


At certain point, annihilation rate becomes smaller than the Hubble rate: DM freezeout



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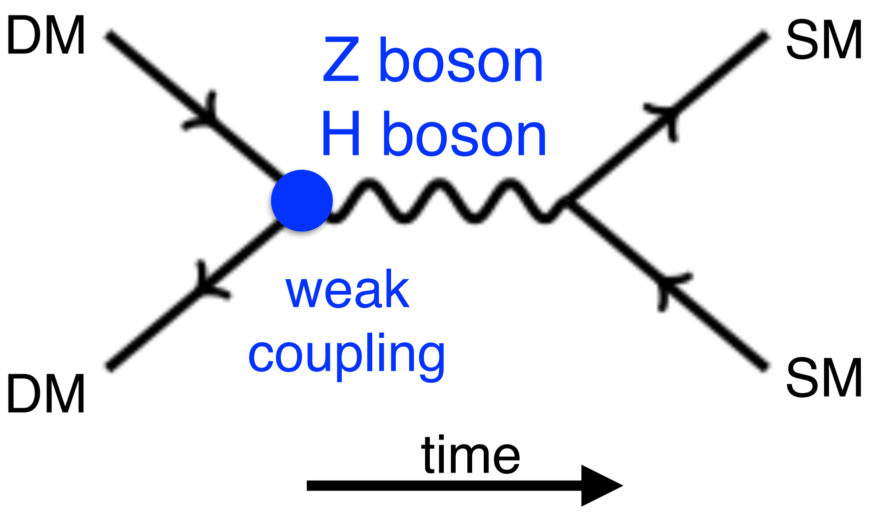

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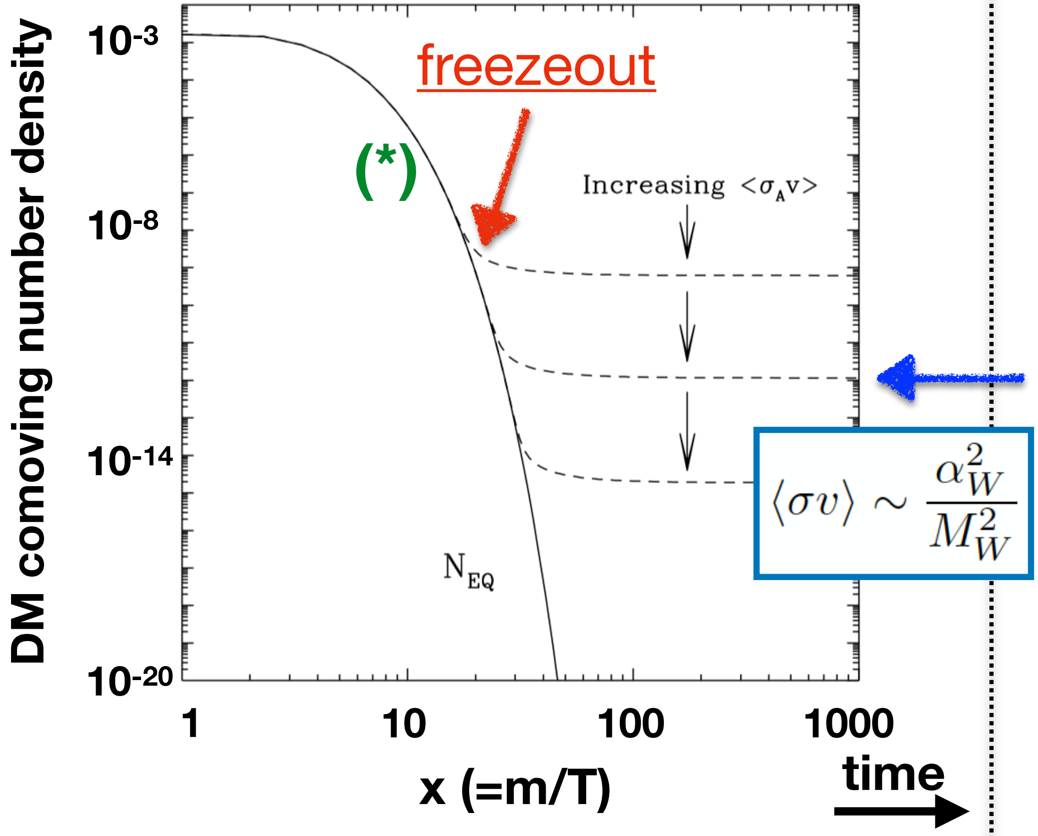
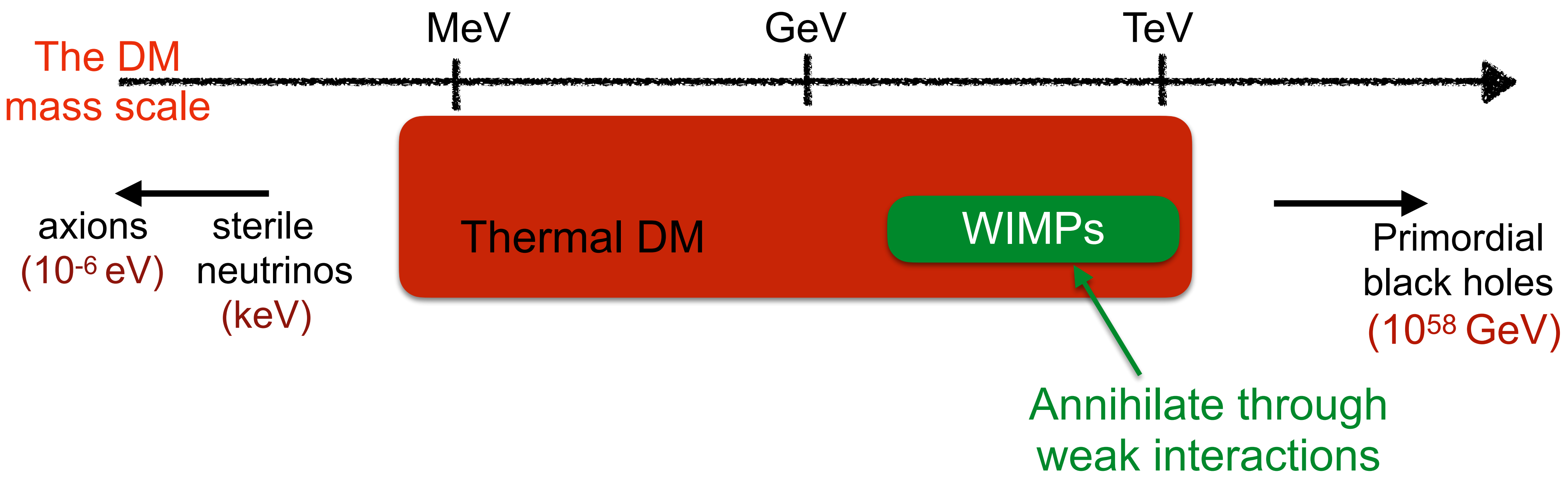


$$\langle \sigma v \rangle \sim \frac{\alpha_W^2}{M_W^2}$$

Thanks to these interactions, DM with a mass O(100 GeV) can freeze-out and obtain the measured relic abundance

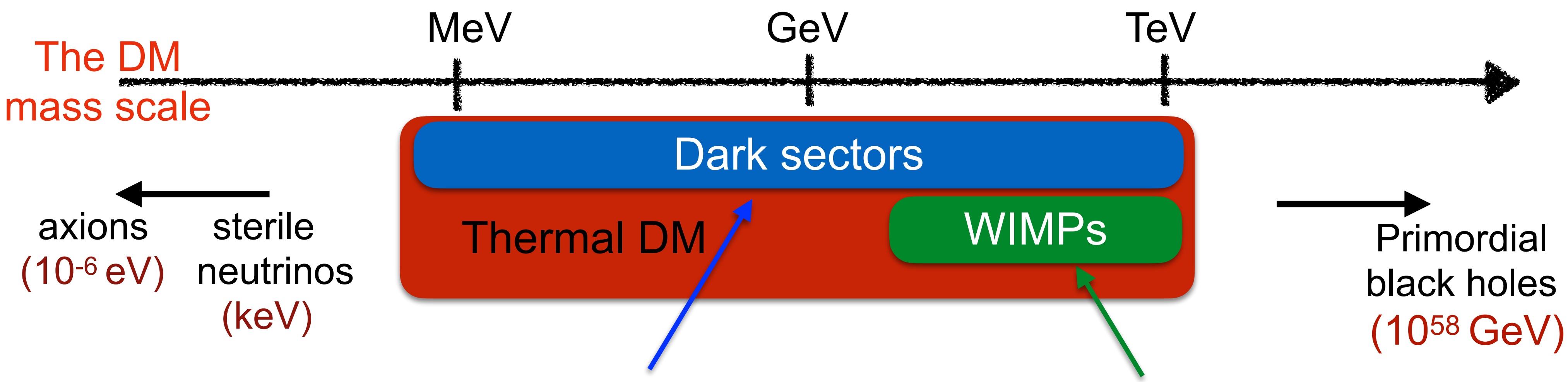
WIMP “miracle”?
… or “coincidence”

Dark Matter & dark sectors



The dark matter scale is **unknown**.
Completely different search strategies depending on the mass of dark matter

Dark Matter & dark sectors



The DM mass scale

MeV

GeV

TeV

Dark sectors

Thermal DM

WIMPs

axions
(10^{-6} eV)

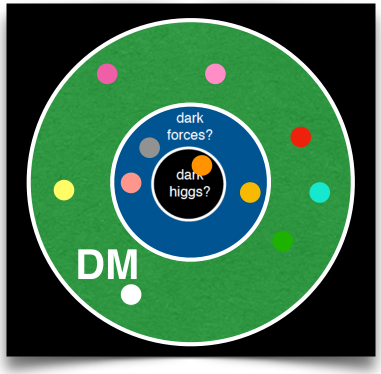
sterile
neutrinos
(keV)

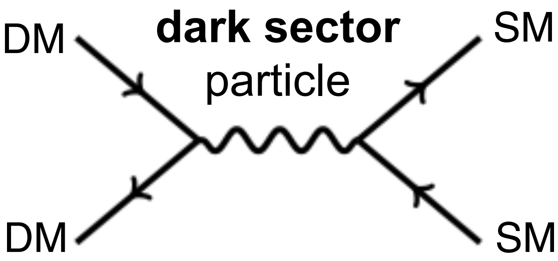
Primordial
black holes
(10^{58} GeV)

Neutral under the SM interactions.
If thermal, Dark Matter **generically** **<u>needs</u> additional particles** to annihilate with

Annihilate through
weak interactions

**dark sector particle =
particle not charged under
the SM gauge symmetries**





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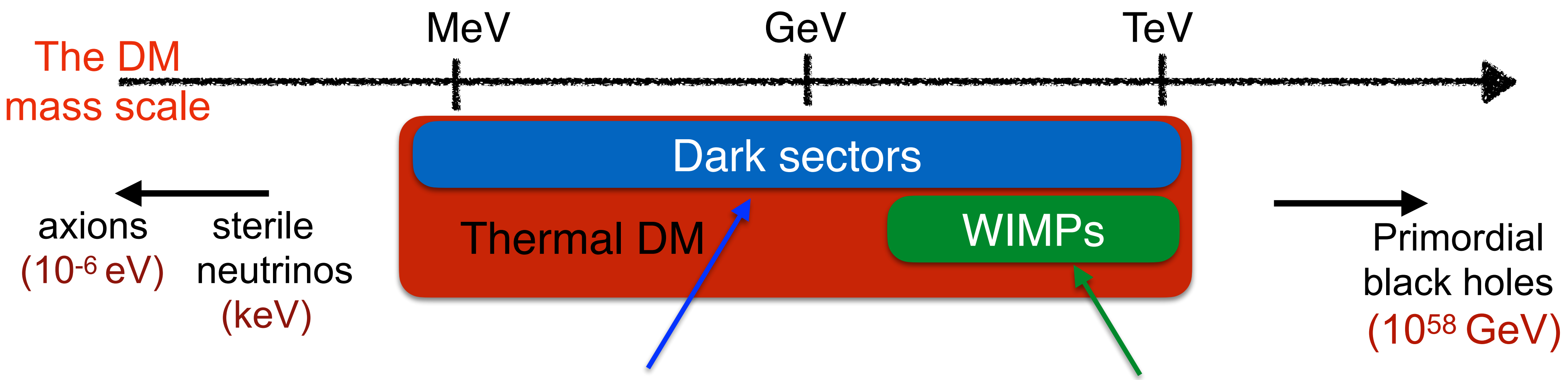

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Lee-Weinberg bound →

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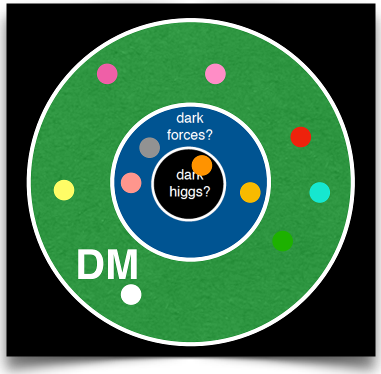

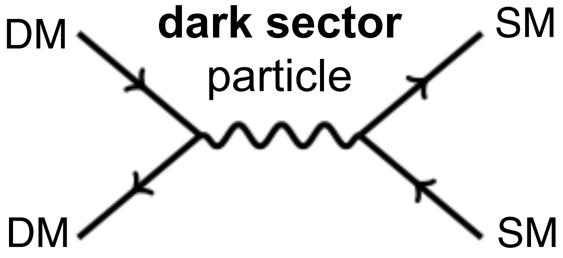

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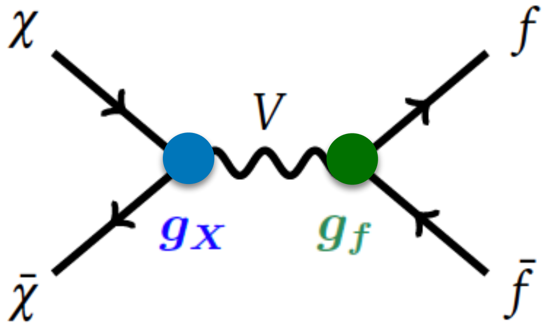
S.Gori

Computation of the Lee-Weinberg bound

Thermal freezeout calculation for a (light) DM particle annihilating to light fermions



Minimum annihilation cross section needed for a thermal relic DM candidate (to avoid overabundance):

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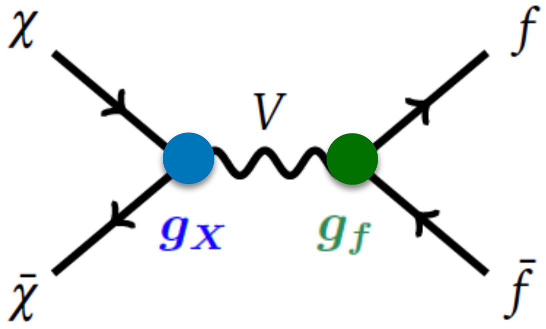

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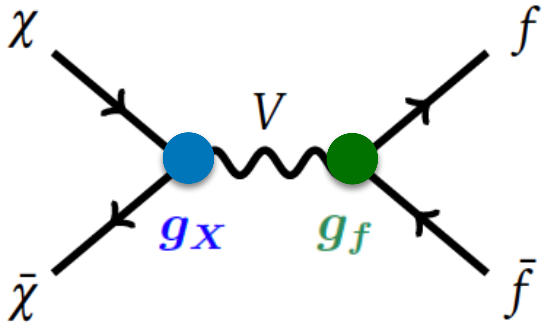

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$m_V \sim m_Z$,
$\alpha_f \sim \alpha_W$

→

$$\langle\sigma v\rangle < \langle\sigma v\rangle^{\min}$$
$$\text{for} \quad m_X \lesssim 1\mathrm{GeV}$$

Need an additional (light) mediator that is not the Z (or Higgs) boson

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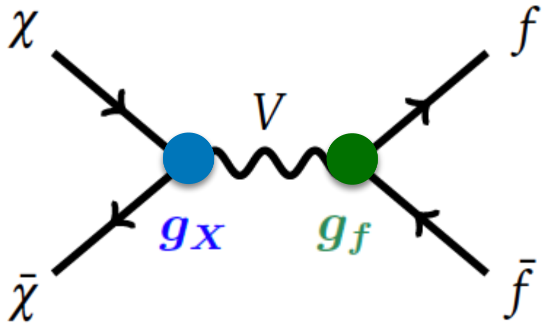

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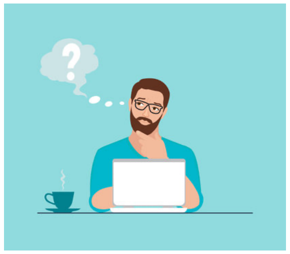
Thermal origin is a simple and compelling idea for the origin of dark matter.
How does it work at low mass?



End of the second class

Dark sector portals to the Standard Model

Since we live in the Standard Model sector, how can we access
(and test) the dark sector?
What are the interactions responsible of Dark Matter-SM thermalization?

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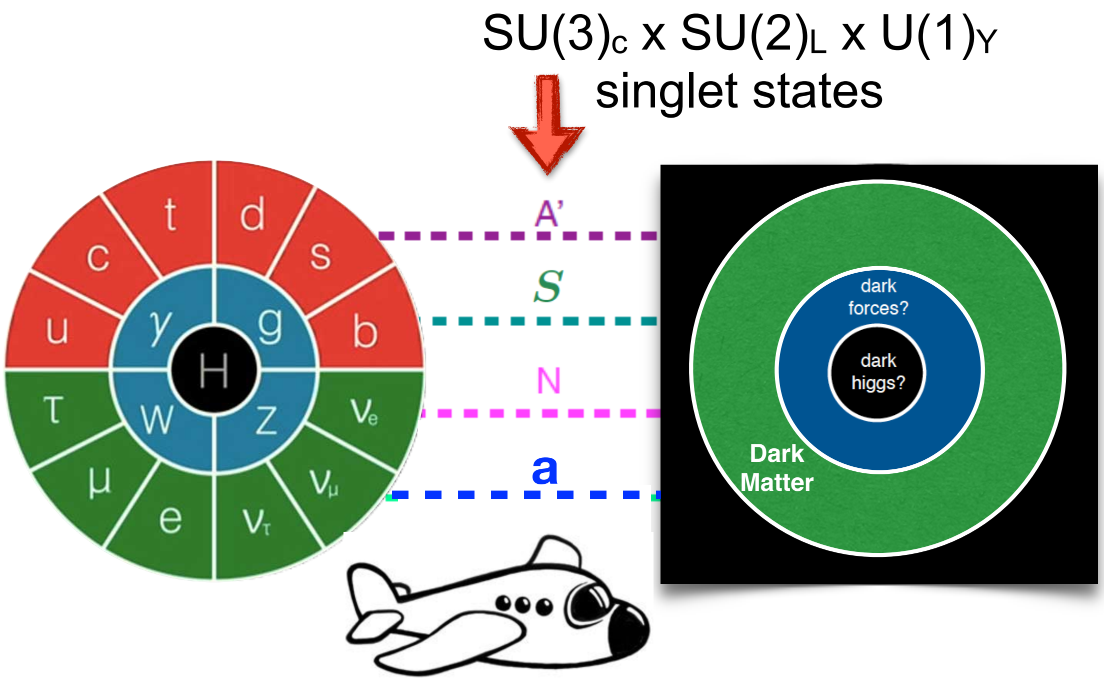

$SU(3)_c \times SU(2)_L \times U(1)_Y$ singlet states

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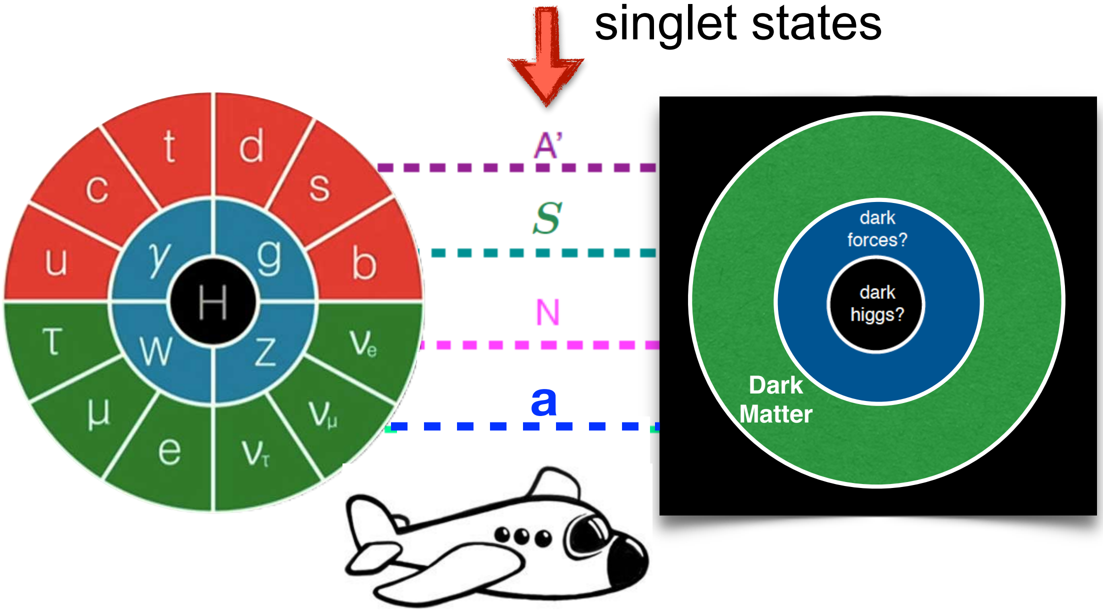

“Portals”:

Dark photon	$\epsilon Z^{\mu\nu} A'_{\mu\nu}$
Higgs	$\kappa \lvert H \rvert^2 \lvert S \rvert^2$
Neutrino	$y H L N$
Axion	$\frac{1}{f_s} F_{\mu\nu} \tilde{F}_{\mu\nu} a$

Only possible couplings at dimension < 6, consistent with SM symmetries

We can also gauge an anomaly-free approximate symmetry of the SM, $U(1)_{B-L}$, $U(1)_{L\mu - L\tau}$: $(\bar{f} \gamma^\mu f) Z'_\mu$

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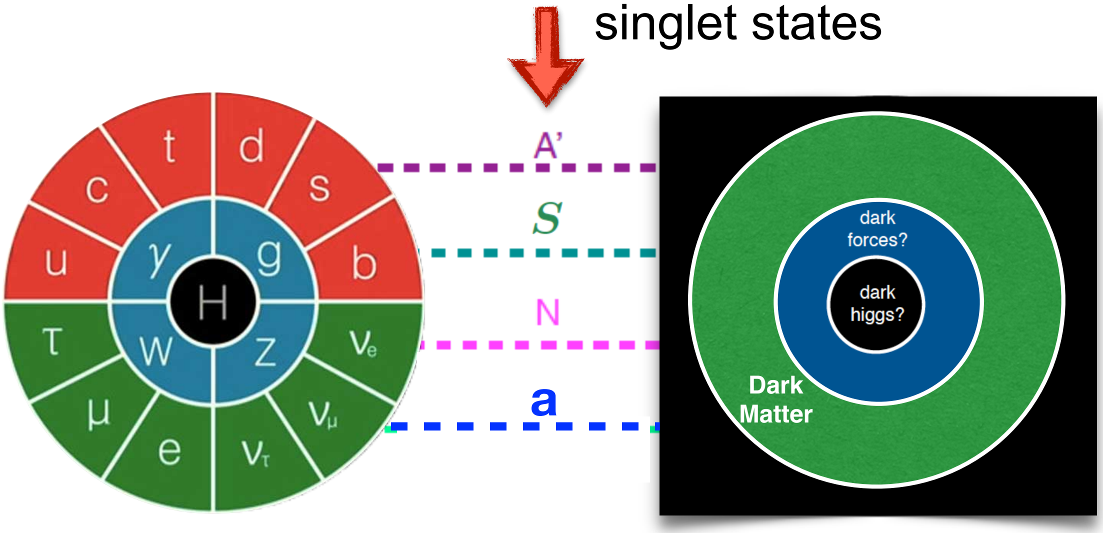

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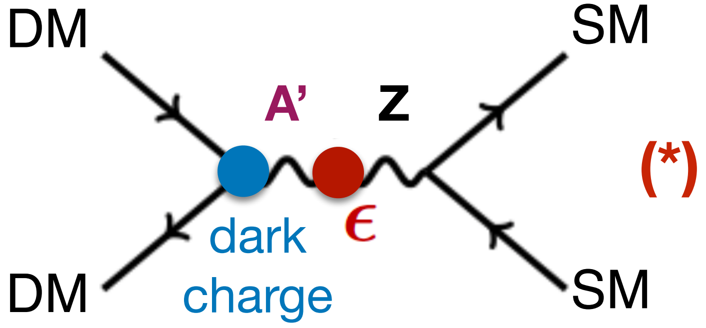
Example:



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“Thermal goal” for Dark Matter models

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The portal coupling cannot be too small if we want to have a thermal Dark Matter freeze-out scenario

The Standard Model needs to be at least a little coupled to the dark sector

Experimental thermal target

Many opportunities for collider experiments!

high energy

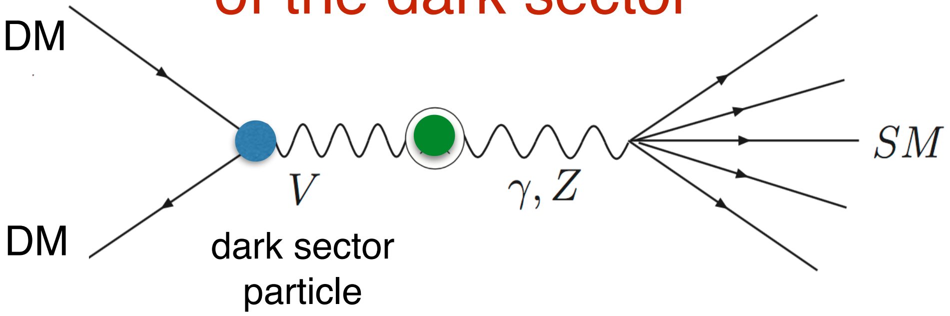
high intensity

Thermal targets

Two general classes of thermal DM:

1.

DM is the lightest state
of the dark sector



Relic abundance regulated by ●, ●

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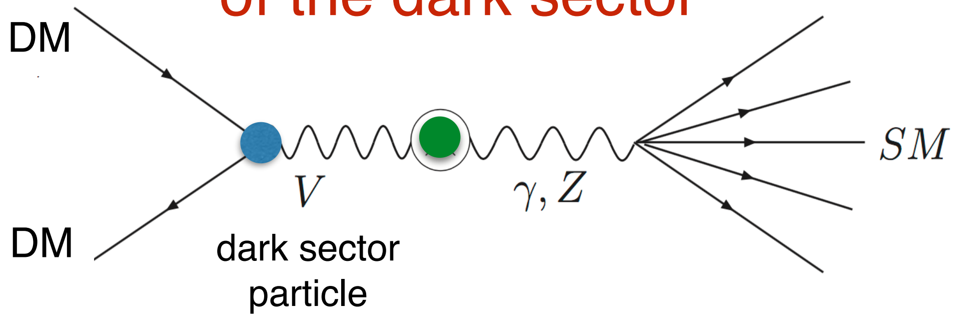

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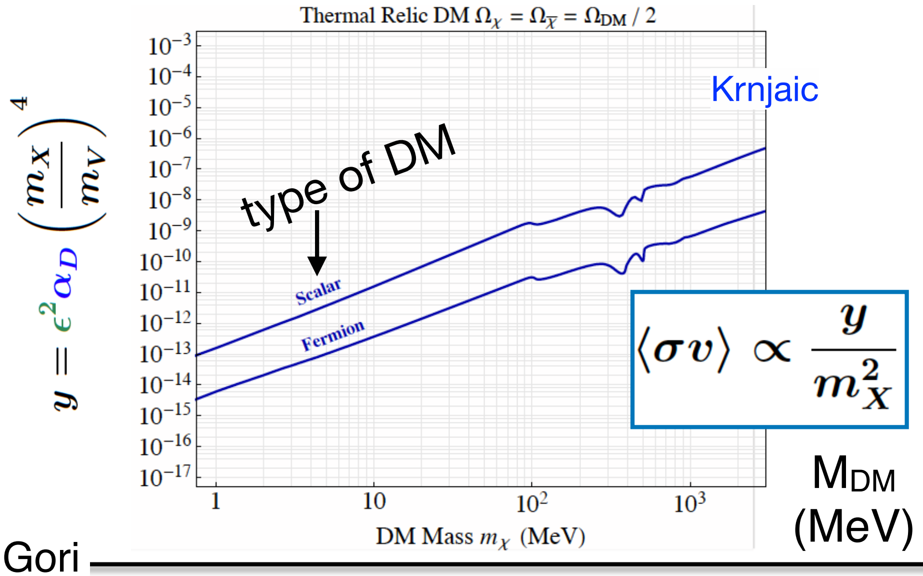

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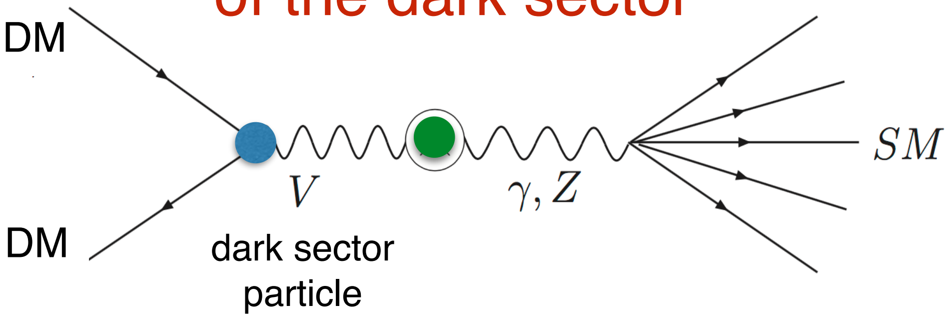

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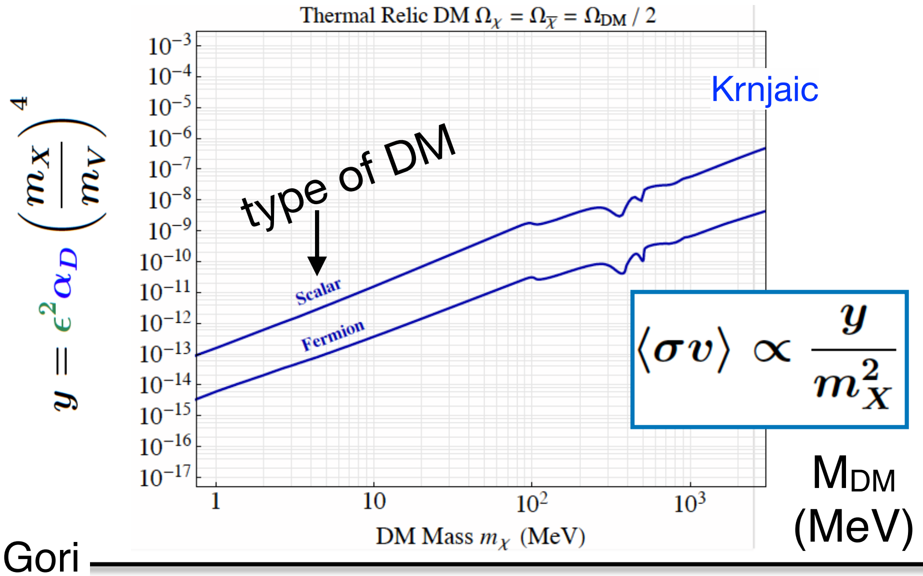
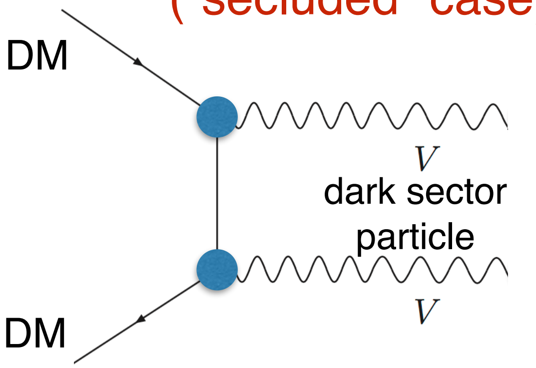


$$\langle \sigma v \rangle \propto \frac{y}{m_X^2}$$

2. **One (or more) particles** of the dark sector **are lighter than DM**

(“secluded” case)

Pospelov, Ritz, Voloshin, 0711.4866



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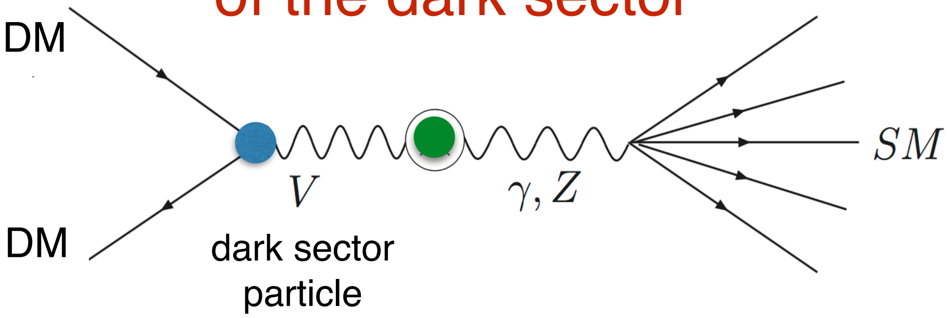
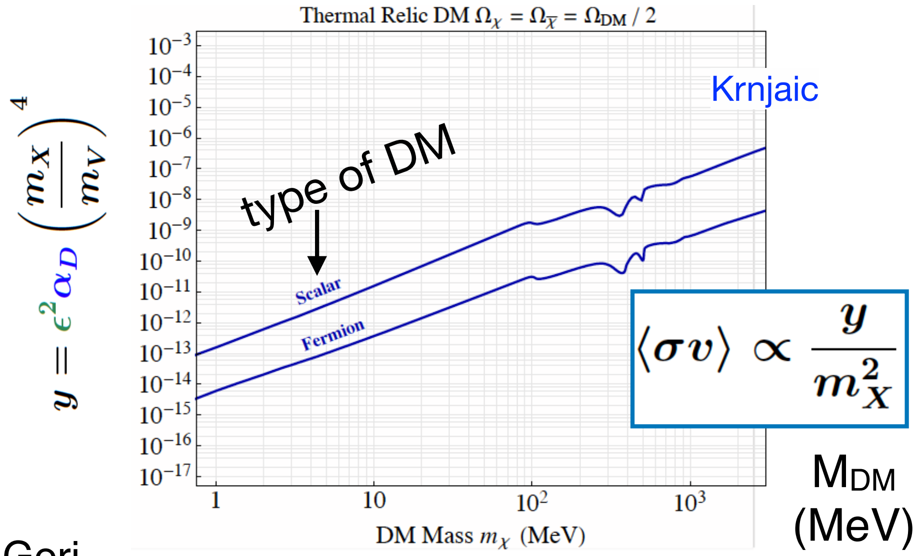


Relic abundance regulated by 🔵, 🟢



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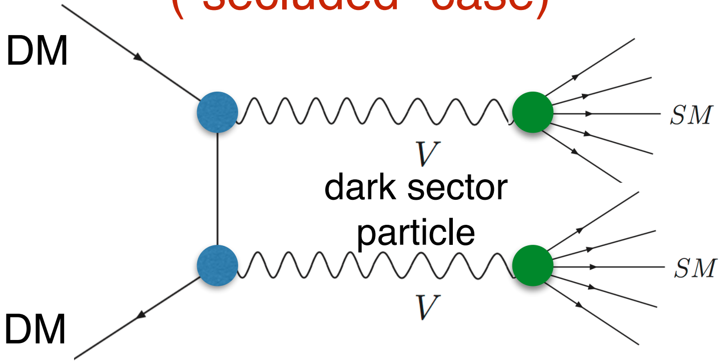

thermalization

Thermal targets

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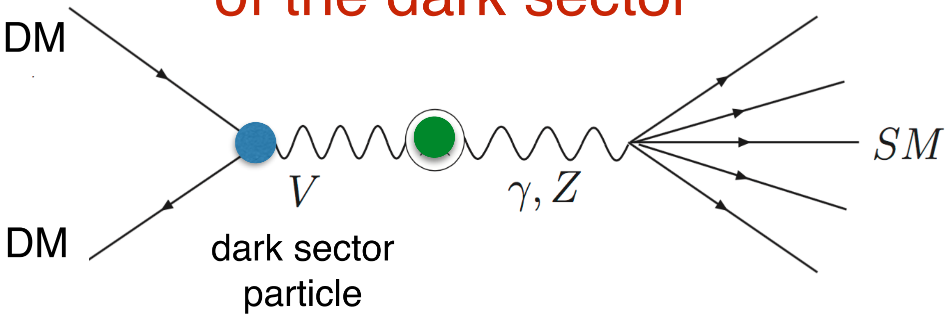

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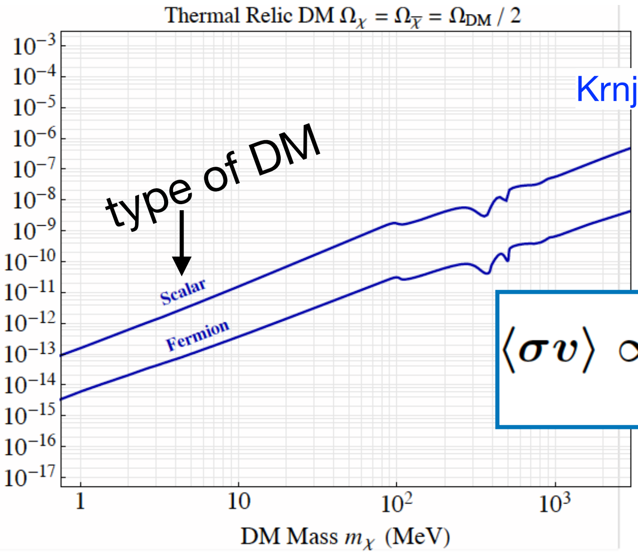

$$y = \epsilon^2 \alpha_D \left(\frac{m_\chi}{m_V}\right)^4$$

Krnjaic

$$\boxed{\langle \sigma v \rangle \propto \frac{y}{m_\chi^2}}$$

M_{DM} (MeV)

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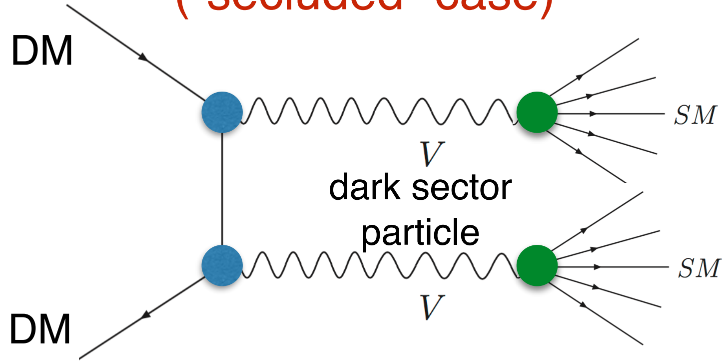
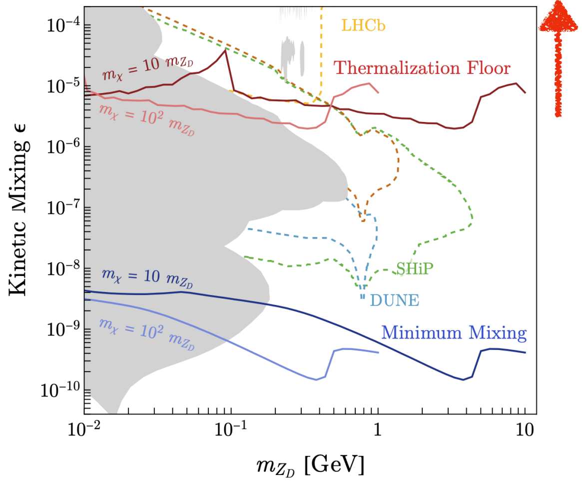
("secluded" case)



Thermalization regulated by ●



Lower bound

Alenezi, Cesarotti, SG, Shelton, 2504.00077

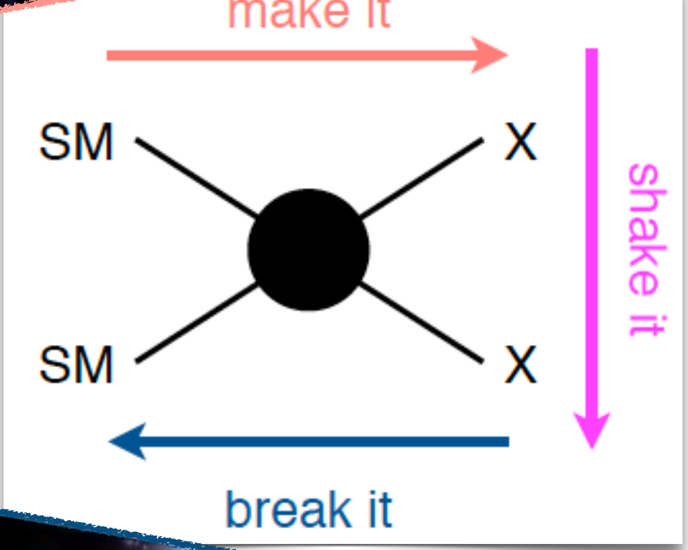
Complementary probes of thermal DM

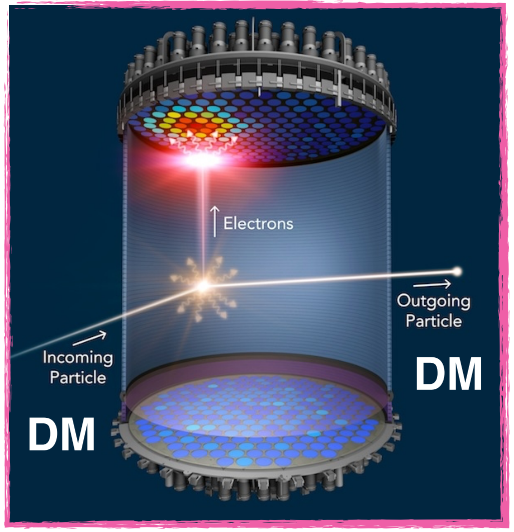
Accelerator searches

3.

2.

Direct detection



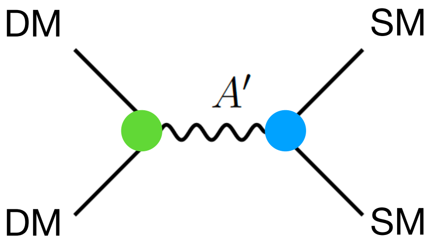


Astrophysical probes

1.

Accelerators / DM direct detection complementarity

annihilation



if $m_{A'} > 2m_{DM}$

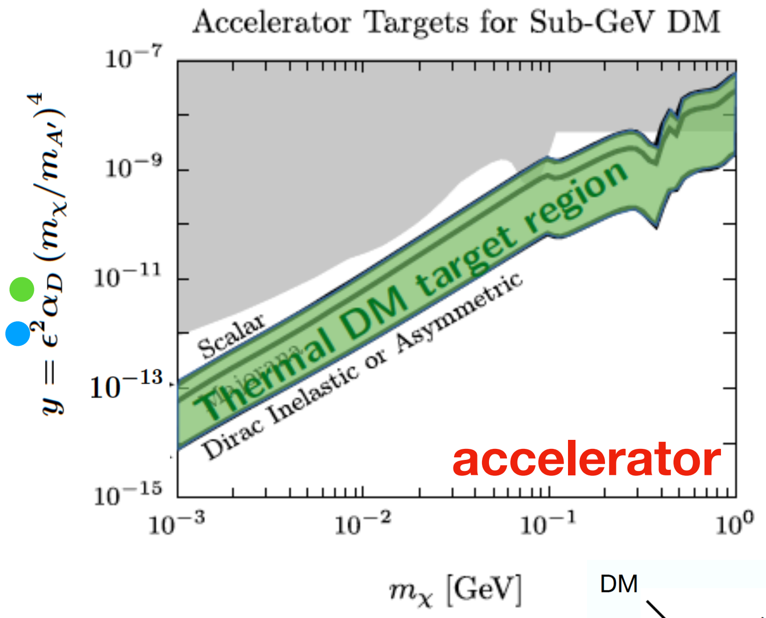
$$\sigma \propto \frac{y}{m_{\rm DM}^2},$$

$$y \equiv \epsilon^2 \alpha_D \left(\frac{m_{\rm DM}}{m_{A'}}\right)^4$$

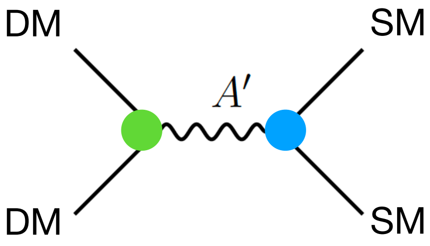
● ●

1.

Accelerators / DM direct detection complementarity



annihilation

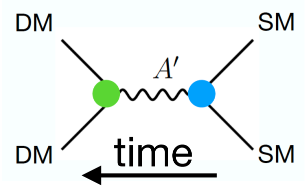


if $m_{A'} > 2m_{DM}$

$$\sigma \propto \frac{y}{m_{\rm DM}^2},$$

$$y \equiv \epsilon^2 \alpha_D \left(\frac{m_{\rm DM}}{m_{A'}}\right)^4$$

1.



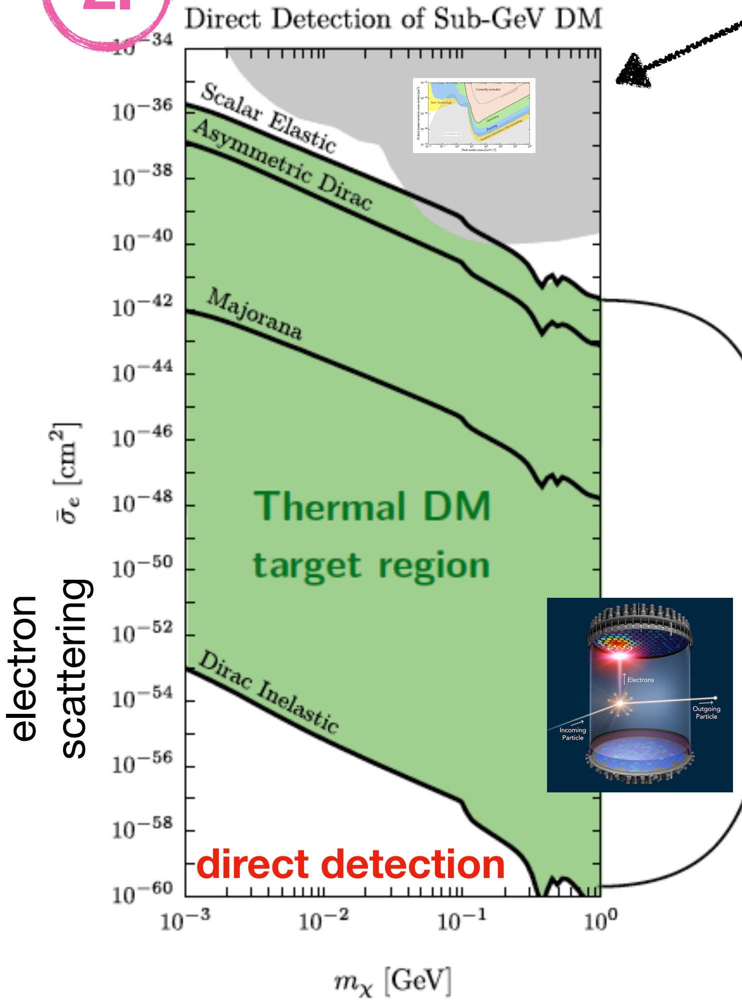
Accelerator production recreates the kinematic conditions of the early universe.

It is ~ unaffected by the nature of DM

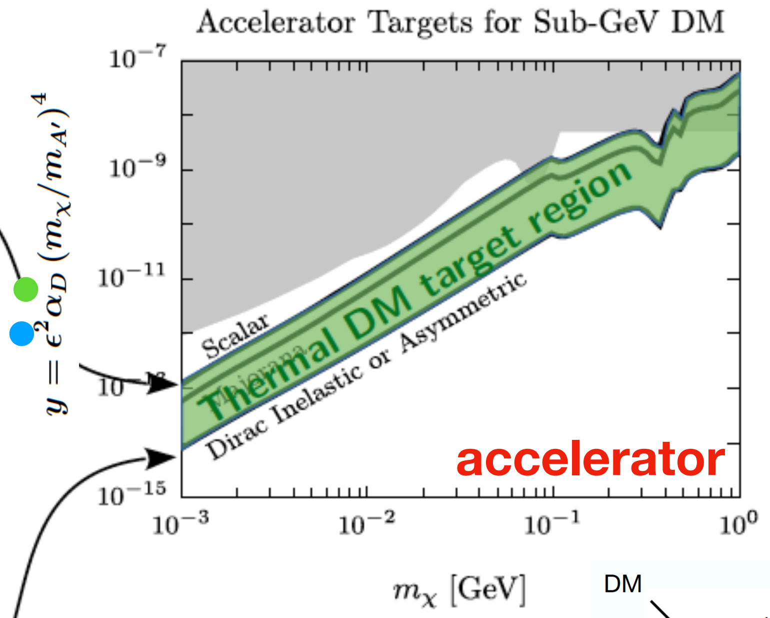
3.

Accelerators / DM direct detection complementarity

2.



To connect these two probes, one needs to make model assumptions



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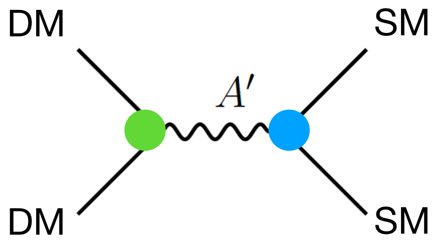

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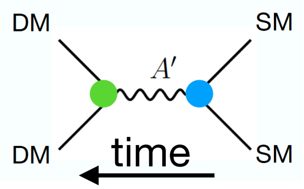

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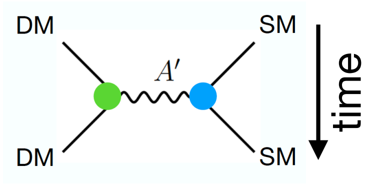

Accelerators / DM direct detection complementarity

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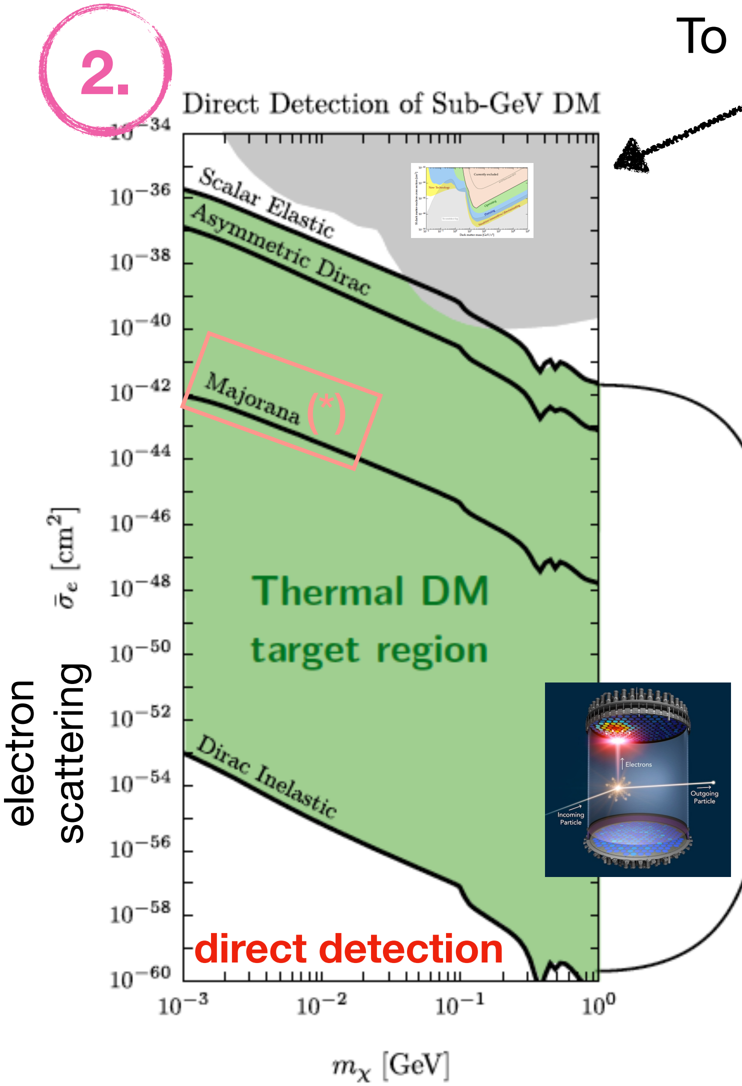
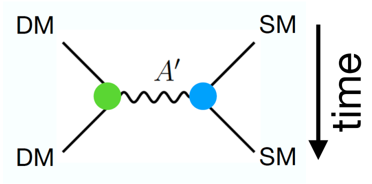
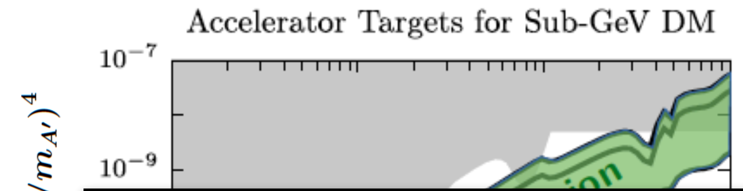
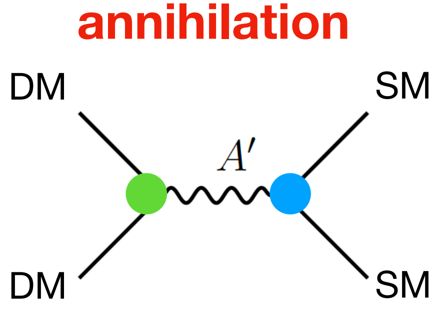








Why such a spread in cross sections at direct detection experiments?

The cross section can be suppressed by different factors, e.g. DM velocity or small mass splittings.

For example, in the case of Majorana DM (*),

$$\bar{\sigma}_e \propto v_{\rm DM}^2$$

⇨ ~6 orders of magnitude suppression, if compared to the Dirac DM case

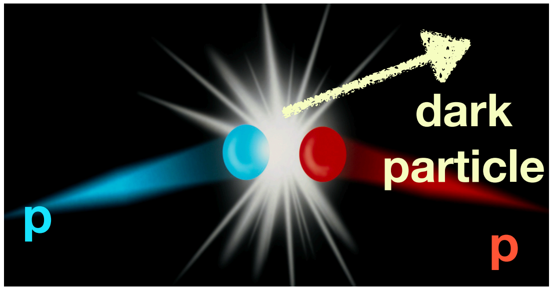
1.

3.

A broad program at accelerator experiments

… of light (< few GeV) DM and dark-sector particles

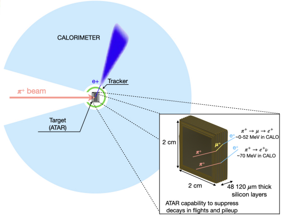
The LHC



Meson factories

NA62

Belle II



Fixed target experiments

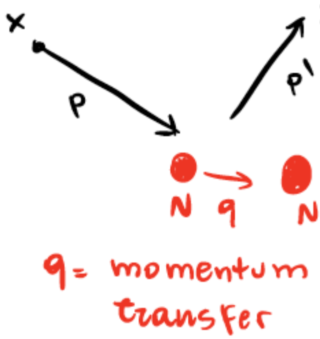
Beam
(high intensity)

Dump/shield/
thin target

Decay volume

Detector

Beyond accelerator experiments: DM direct detection



$$E_R^{\max} = \frac{q^2_{\max}}{2m_N} = \frac{2\mu^2_{\chi N} v^2}{m_N}$$

DM velocity

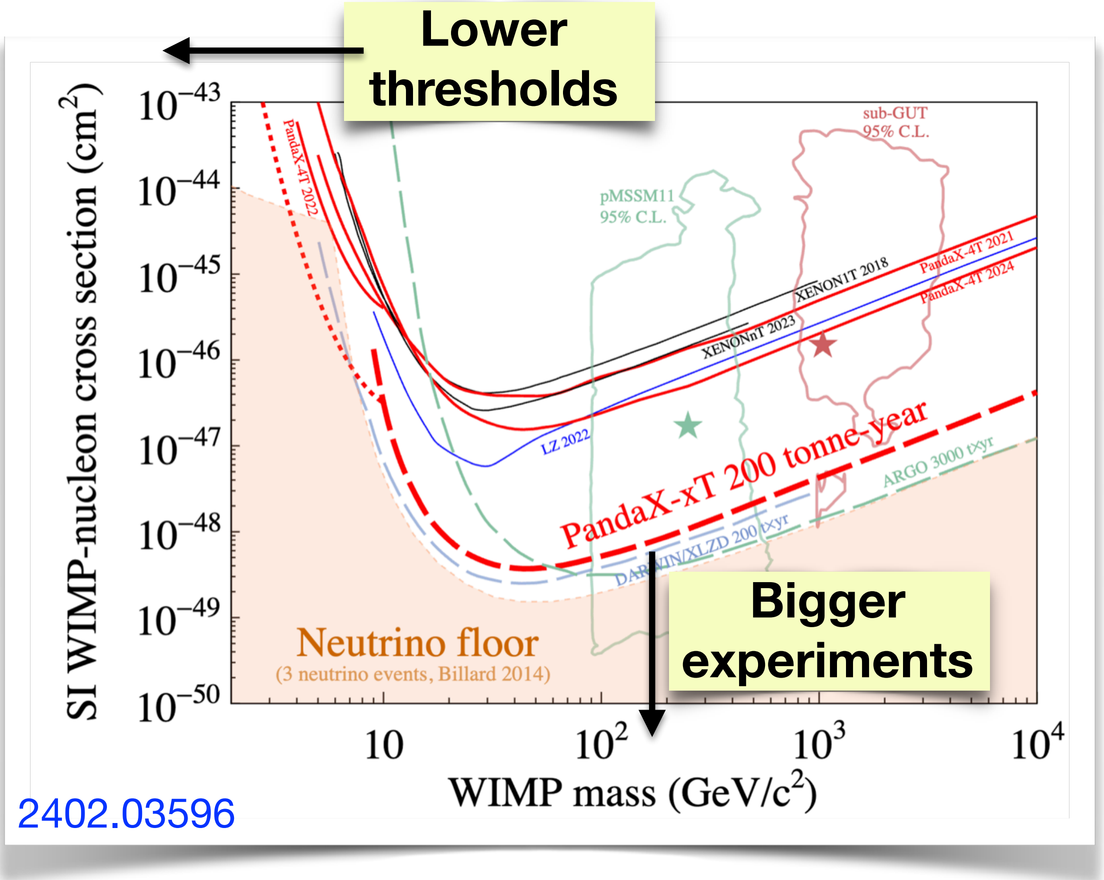
Reduced mass of the DM-nucleus system: $\mu_{\chi N} = \frac{m_\chi m_N}{m_\chi + m_N} \simeq m_\chi$

E.g., m_χ= 1GeV → E_R^{max} ~ **0.2 keV**

$E_R \geq$ O(keV) in most experiments

This gives a ~lower bound on the DM masses we can probe.

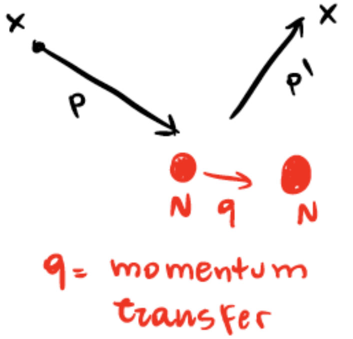
Beyond accelerator experiments: DM direct detection



Lower thresholds

Bigger experiments

2402.03596



q= momentum transfer

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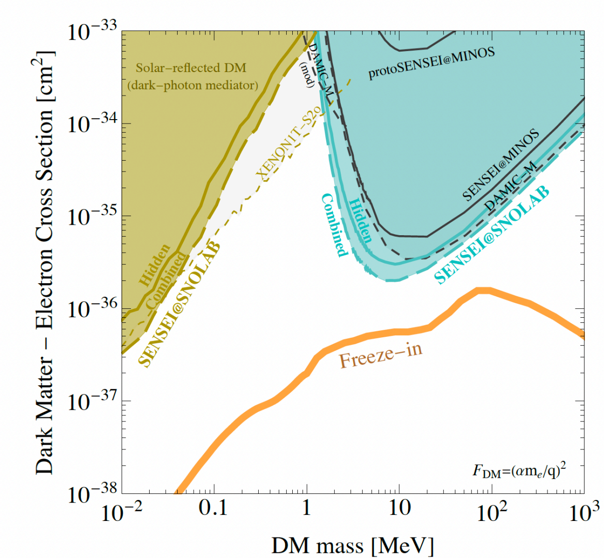
Light (≲ GeV) DM at direct detection

Many new ideas in the past ~10 years:

DM-electron scattering

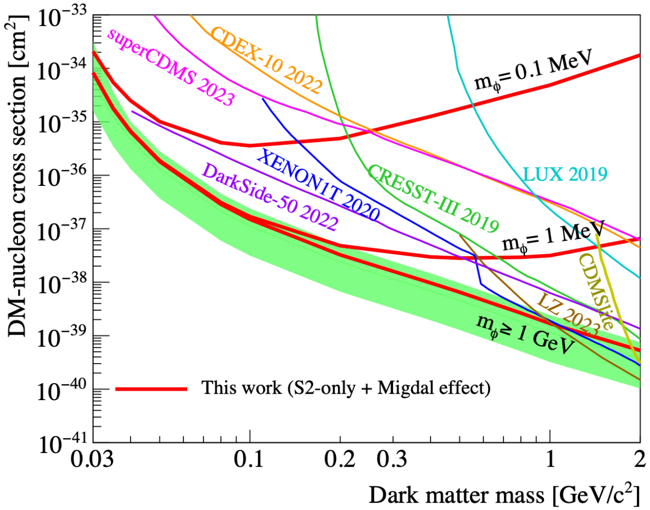


2312.13342

Very low energy thresholds.

It allows to transfer O(1) amount of DM kinetic energy

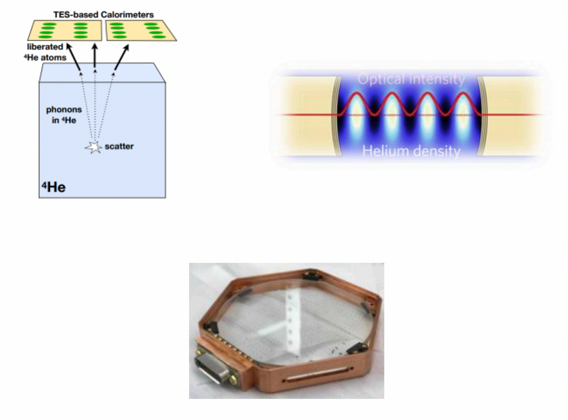
Migdal effect



2308.01540

Nuclear recoil + delayed electron signal (excitation / ionization of the atom)

Low-threshold detectors



R&D,
several experiments ongoing or planned for the coming years.

TESSERACT,
HeRALD, DELight

for a review: Fabbrichesi, Gabrielli, Lanfranchi, 2005.01515

Let’s study one example in more details:

DM models mediated by the dark photon, A’
(focus on accelerator experiments and visible A’)
in backup, you can find the invisible A’

Apologies…sometimes the dark photon will be called A’, sometimes Z’ or Z_D…

The dark photon / Z boson

Nature seems well described by a SU(3)c x $SU(2)_L$ x $U(1)_Y$ gauge theory. We need to check this assumption!

Additional gauge symmetries in nature? **U(1)’?**

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Additional gauge symmetries in nature? **U(1)'?**

Holdom, '86

$$\mathcal{L} \supset -\frac{1}{4}\hat{B}_{\mu\nu}\hat{B}^{\mu\nu} - \frac{1}{4}\hat{Z}_{D\mu\nu}\hat{Z}_D^{\mu\nu} + \frac{\epsilon}{2\cos\theta}\hat{Z}_{D\mu\nu}\hat{B}_{\mu\nu} + \frac{1}{2}m_{D,0}^2\hat{Z}_D^{\mu}\hat{Z}_{D\mu} - g_D\hat{Z}_D^{\mu}(\bar{X}\gamma_\mu X)$$

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Mixing with the SM hyper-charge gauge boson

coupling to DM

$$\mathcal{L} \supset -\frac{1}{4}\hat{B}_{\mu\nu}\hat{B}^{\mu\nu} - \frac{1}{4}\hat{Z}_{D\mu\nu}\hat{Z}_D^{\mu\nu} + \frac{\epsilon}{2\cos\theta}\hat{Z}_{D\mu\nu}\hat{B}_{\mu\nu} + \frac{1}{2}m_{D,0}^2\hat{Z}_D^{\mu}\hat{Z}_{D\mu} - g_D\hat{Z}_D^{\mu}(\bar{X}\gamma_\mu X)$$

arising from

* dark Higgs mechanism or

* Stueckelberg mechanism

⇒ **Massive photon**

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After electroweak symmetry breaking, the mass terms are given by:

~SM photon

$$(A^\mu, Z_0^\mu, Z_{D,0}^\mu)\; m_{Z,0}^2 \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & \boxed{-\epsilon\tan\theta} \\ 0 & -\epsilon\tan\theta & \epsilon^2\tan^2\theta + \frac{m_{D,0}^2}{m_{Z,0}^2} \end{pmatrix} \begin{pmatrix} A^\mu \\ Z_0^\mu \\ Z_{D,0}^\mu \end{pmatrix}$$

~dark photon/Z

mixing

having defined

$$\begin{pmatrix} Z_{D,0} \\ B \end{pmatrix} = \begin{pmatrix} \sqrt{1-\frac{\epsilon^2}{\cos^2\theta}} & 0 \\ -\frac{\epsilon}{\cos\theta} & 1 \end{pmatrix} \begin{pmatrix} \hat{Z}_D \\ \hat{B} \end{pmatrix}$$

after diagonalization: A, Z, **Z'** (mass eigenstates)

How large is ε?

- This is a dimensionless parameter ⇨ it can be O(1)

$$\boxed{\frac{\epsilon}{2\cos\theta}\widehat{Z}_{D\mu\nu}\widehat{B}_{\mu\nu}}$$

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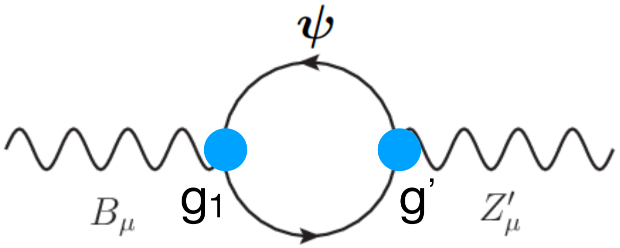
$$\boxed{\frac{\epsilon}{2\cos\theta}\widehat{Z}_{D\mu\nu}\widehat{B}_{\mu\nu}}$$

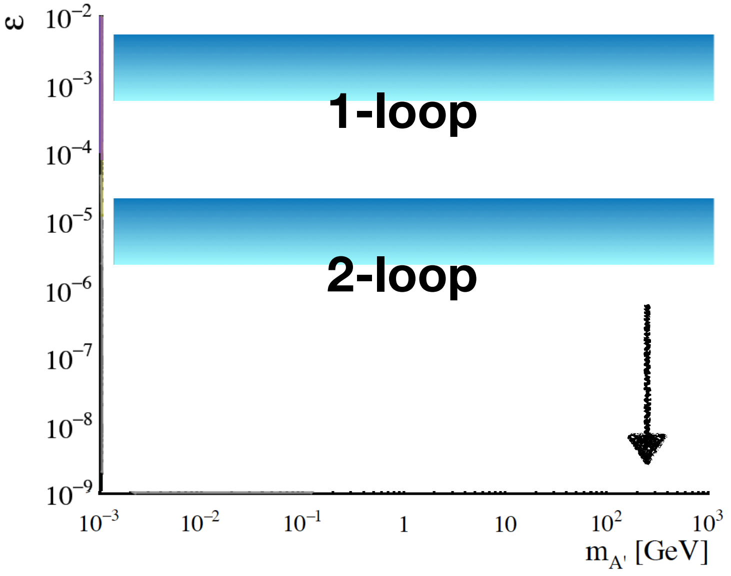
- If it is absent at the tree level, it can be generated by the loop of heavy New Physics particles charged under both U(1)’ and U(1)$_Y$



→ $$\epsilon = \frac{g' g_1}{16\pi^2}\log\left(\frac{M_\psi}{\Lambda}\right) \simeq 10^{-3}\,\mathcal{O}(1-10)$$

- Some theories predict a even smaller kinetic mixing parameter: New Physics particles in doublets of opposite dark charges

  → 2-loop contributions, O(10^{-5})



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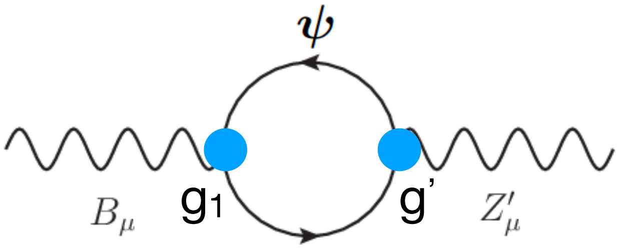

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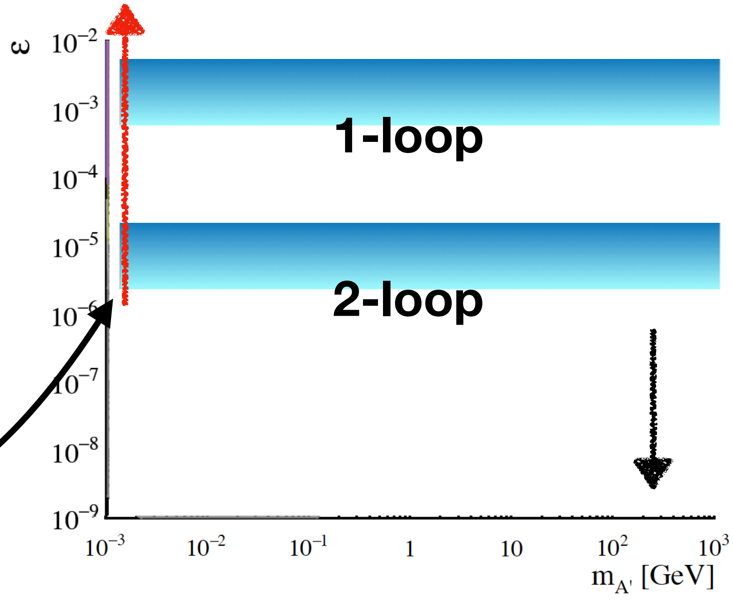

We have seen that to have SM-dark sector **thermalization**, we need $\epsilon \gtrsim \text{few} \times 10^{-6}$

Couplings of the dark photon

Couplings to SM fermions

$$\mathcal{L}_{Z'\bar{f}f} = g_{Z'f\bar{f}}\, Z'_\mu (\bar{f}\gamma^\mu f)$$

$$g_{Z'f\bar{f}} \equiv \frac{g}{\cos\theta}\left(-\sin\alpha\,(t^3\ \cos^2\theta - Y\ \sin^2\theta) + \epsilon\cos\alpha\ \tan\theta\, Y\right)$$

$g_{Z'f\bar{f}} \simeq eQ\epsilon$ for a light Z’ (photon-like couplings)

$\sin\alpha \propto \epsilon$

Coupling to DM

$$\mathcal{L}_{Z'\bar{X}X} = g_{Z'X\bar{X}}\, Z'_\mu (\bar{X}\gamma^\mu X)$$

$$g_{Z'X\bar{X}} \equiv g_D\cos\alpha$$

Coupling to the Higgs

$$\mathcal{L}_{hZZ'} = \left[\frac{2i\epsilon\tan\theta}{v} m^2_{Z_0}\left(2\frac{\epsilon^2\tan^2\theta - 1}{\epsilon\tan\theta}\sin 2\alpha - \cos 2\alpha\right)\right] hZ^\mu Z'_\mu$$

$$\simeq \frac{2i\epsilon\tan\theta}{v}\frac{m^2_{Z'}m^2_Z}{m^2_Z - m^2_{Z'}} hZ^\mu Z'_\mu$$

Does the dark photon decay?

1.

For **$m_{Z'} > 2m_X$**, Z' mainly decays to DM particles

(in fact, experimental bounds constrain ε to be small ⇒ larger g_D to obtain a DM thermal relic with the measured relic abundance, $\langle \sigma v \rangle \simeq \epsilon^2 \alpha_D \frac{m_X^2}{m_{Z'}^4}$)

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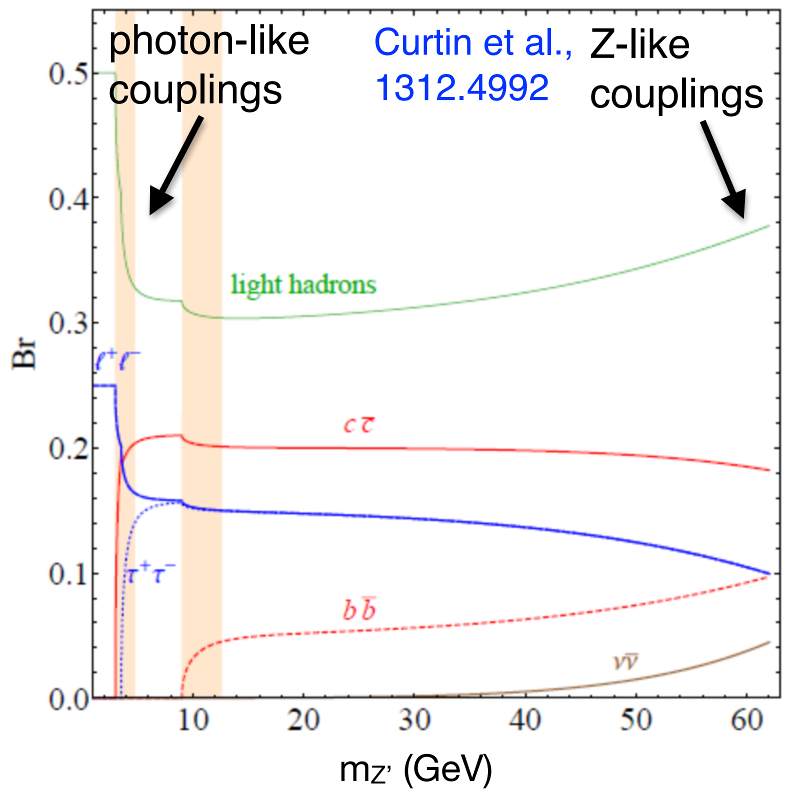
For **$m_{Z'}$ < 2m_X**, Z’ only decays to SM particles **2.**

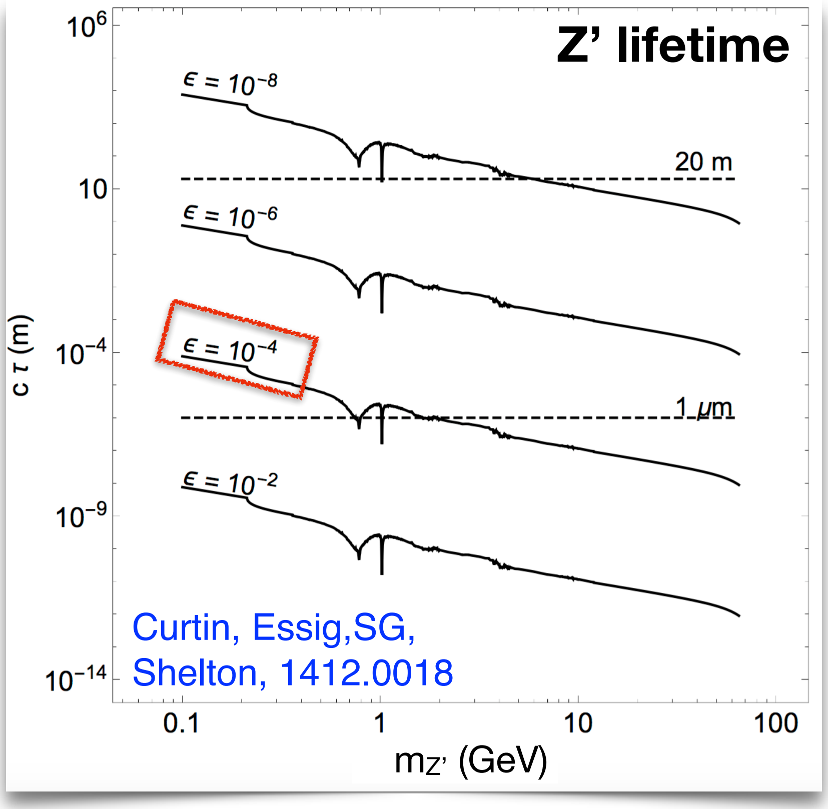


photon-like couplings

Curtin et al., 1312.4992

Z-like couplings

No ϵ dependence



Z’ lifetime

Curtin, Essig,SG, Shelton, 1412.0018

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(in fact, experimental bounds constrain ε to be small ⇨ larger g_D to obtain a DM thermal relic with the measured relic abundance, $\langle \sigma v \rangle \simeq \epsilon^2 \alpha_D \frac{m_X^2}{m_{Z'}^4}$)

For $\mathbf{m_{Z'} < 2m_X}$, Z’ only decays to SM particles **2.**

Some detail on the calculation:

Define the ratio: $$R_{Z'} \equiv \frac{\Gamma(Z' \to \text{hadrons})}{\Gamma(Z' \to \mu^+\mu^-)} = R_{Z'}(m_{Z'})$$

then the total width: $$\Gamma_{Z'} = R_{Z'}\Gamma(Z' \to \mu^+\mu^-) + \sum_{f=\ell,\nu} \Gamma(Z' \to \bar{f}f)$$

$$R(s) \equiv \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$ is measured accurately and is highly dominated by off-shell γ* → ff in the s-channel.

⇨ We can use experimental data to determine $R_{Z'}(m_{Z'}) = R(m_{Z'}^2)$

In this way, we can determine all branching ratios of the dark photon at low mass (where the dark photon has photon-like couplings)

How to produce a dark photon? ("direct")

(At low mass) Z' couples proportionally to the electric charge

⇨ Whenever there is a γ, there is a Z'

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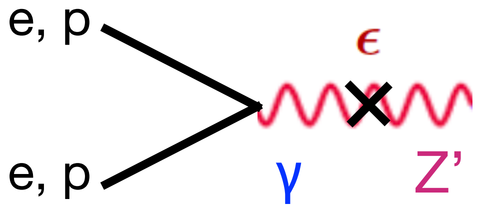
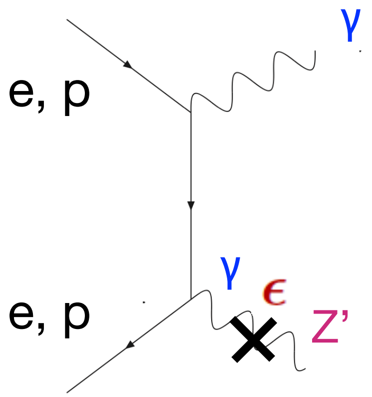
Collider experiments

Drell-Yan production:





$$\sigma \propto \frac{\varepsilon^2 \alpha_{\rm em}^2}{E^2}$$

1/fb at 1GeV (KLOE)
competes with
1/ab at 10 GeV
(B-factories)

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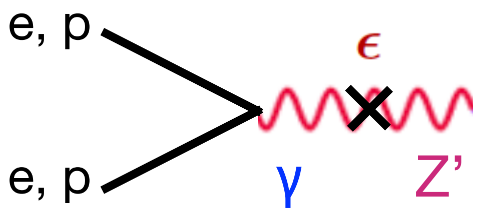

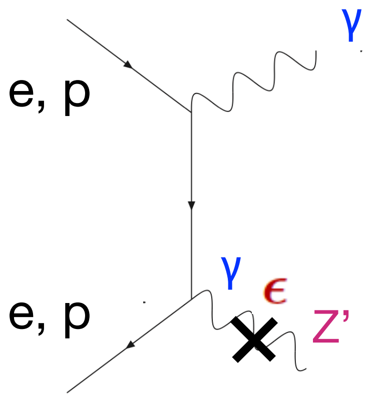

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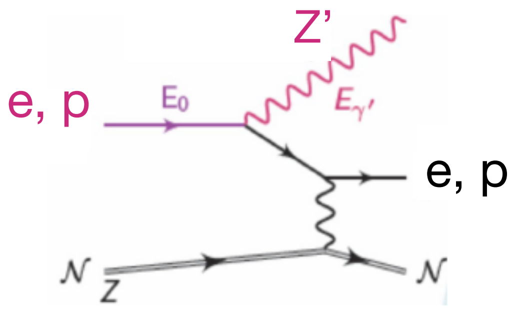
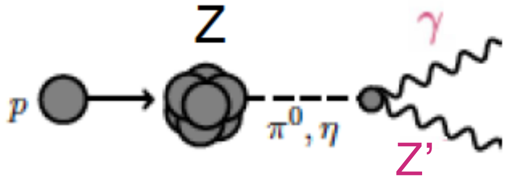
1/fb at 1GeV (KLOE) competes with 1/ab at 10 GeV (B-factories)

Fixed target experiments



brems-strahlung



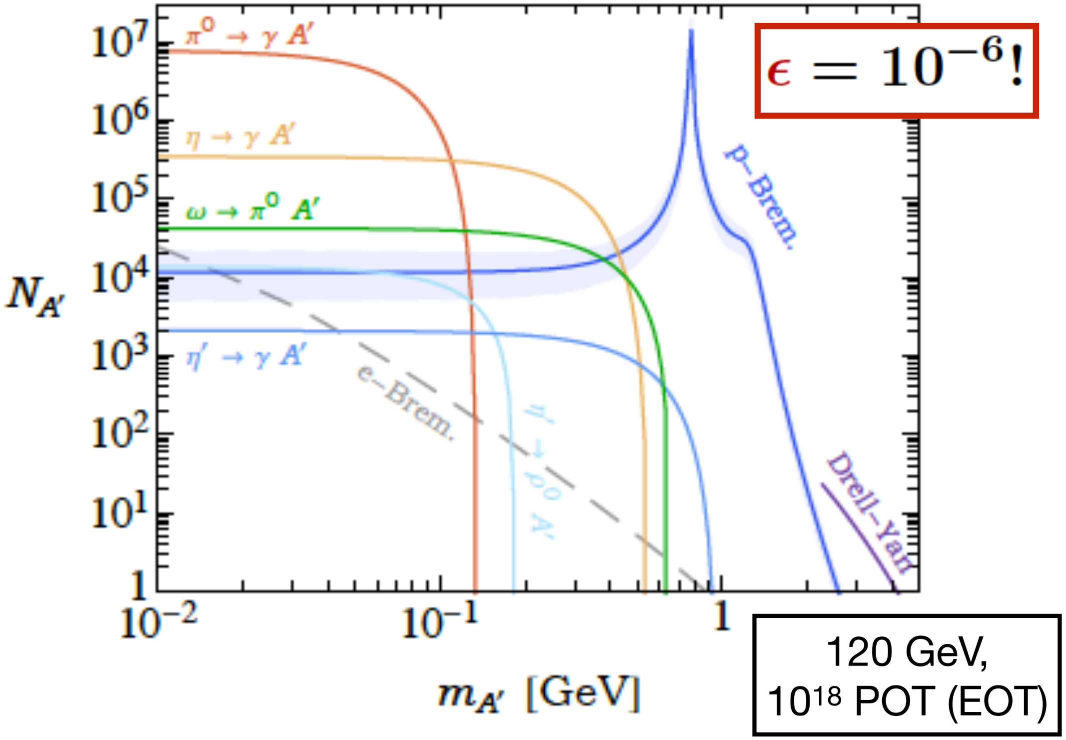
meson decay

$$\sigma \sim \alpha_{\rm em}\epsilon^2 \times \sigma_{pp}$$ proton

$$\sigma \sim \frac{\alpha_{\rm em}^3 \epsilon^2}{m_{Z'}^2} Z^2$$ electron

Many dark photons can be produced

Berlin, SG, Schuster, Toro, 1804.00661



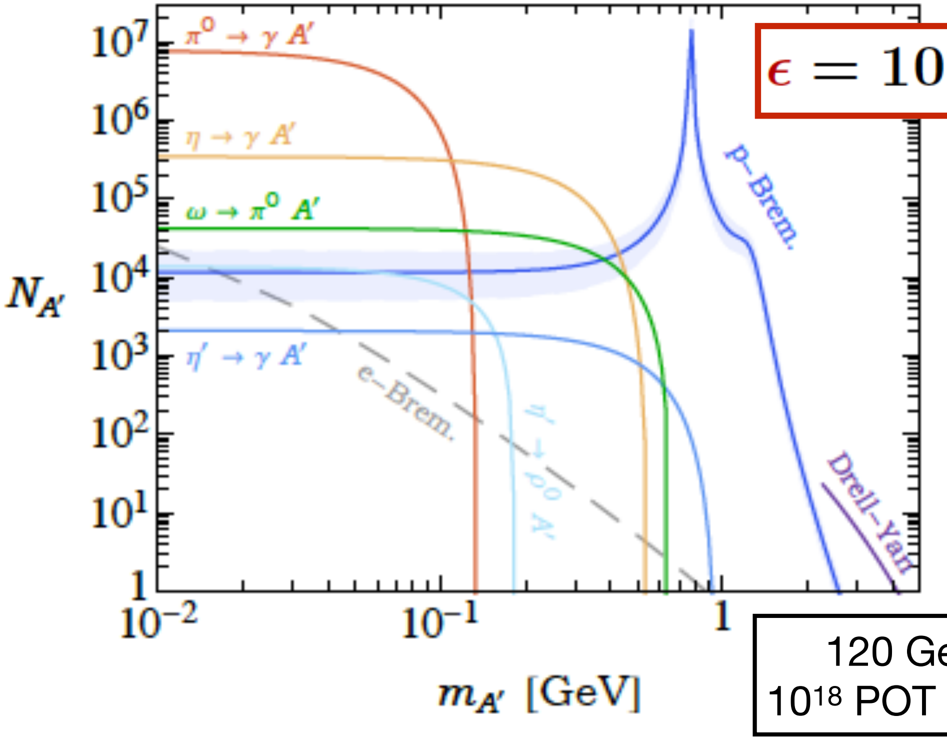
$\epsilon = 10^{-6}$!

120 GeV,
10^{18} POT (EOT)

Number of dark photon @ proton fixed target

Many dark photons can be produced

Berlin, SG, Schuster, Toro, 1804.00661

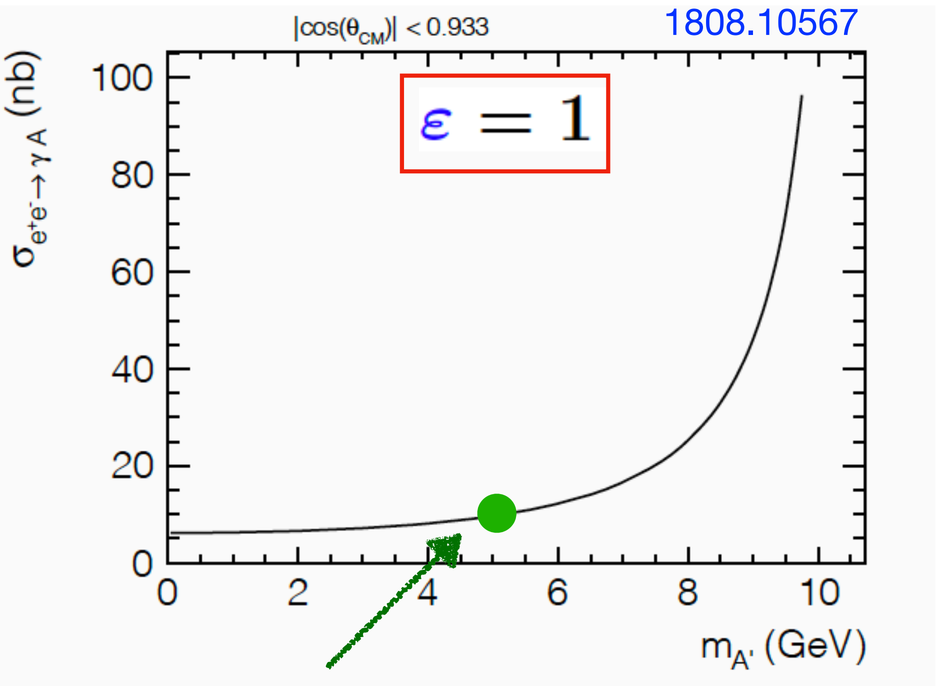


$\epsilon = 10^{-6}!$

120 GeV,
10^{18} POT (EOT)

Number of dark photon @ proton fixed target

production cross section @ Belle II

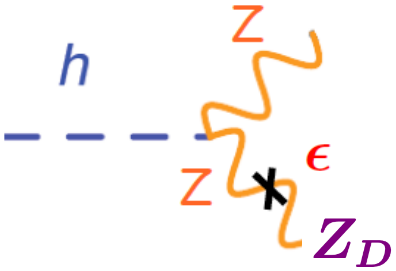


1808.10567

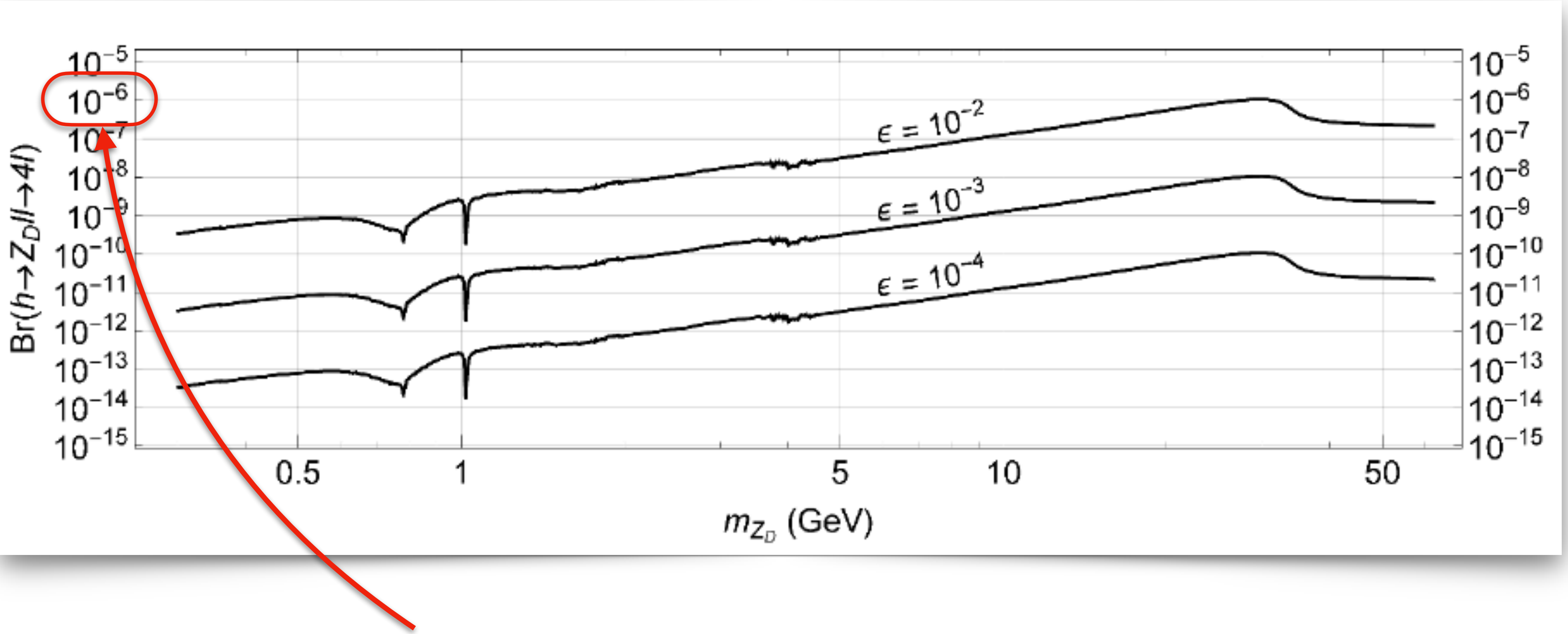
$\varepsilon = 1$

$N_{A'} \sim 10^{10}$ for 50/ab luminosity

How to produce a dark photon? (Higgs decays)

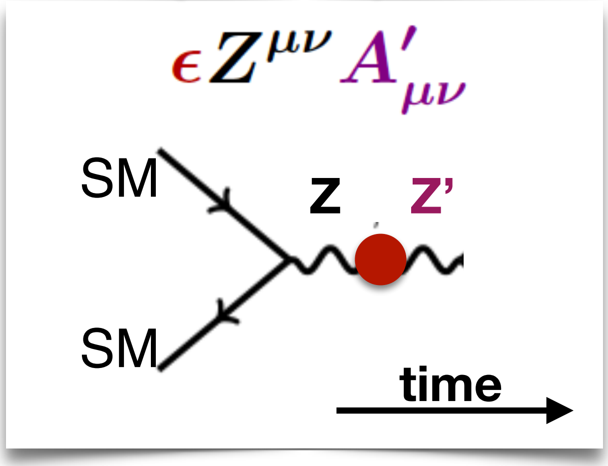


Curtin, Essig,SG, Shelton, 1412.0018



Roughly 100 event at the HL-LHC

What to look for at accelerator experiments?


$\epsilon Z^{\mu\nu} A'_{\mu\nu}$

(Typically) high energy

Colliding beam experiments

- B-factories (Belle-II)
  e^+e^- collider
- The LHC (pp collider)

(Typically) high intensity

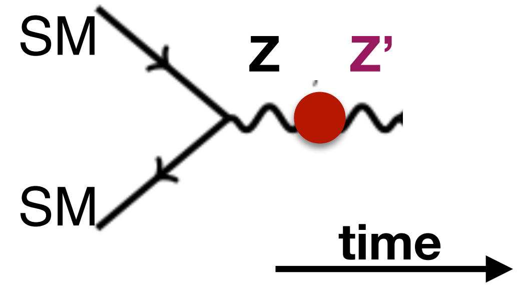
Fixed target experiments

- Kaon exp.
- proton beam dump exp.
- electron beam dump exp.
- electron fixed target exp.
- neutrino exp.
- light meson (e.g. pion) exp.

Two different types of accelerator experiments

What to look for at accelerator experiments?

$\epsilon Z^{\mu\nu} A'_{\mu\nu}$



(Typically) high energy

Colliding beam experiments

- B-factories (Belle-II)
  e+e- collider
- The LHC (pp collider)

1.

(Typically) high intensity

Fixed target experiments

- Kaon exp.
- proton beam dump exp.
- electron beam dump exp.
- electron fixed target exp.
- neutrino exp.
- light meson (e.g. pion) exp.

2.

Two different types of accelerator experiments

We will focus on the dark photon, but (broadly speaking) similar studies hold for the other portals

$\epsilon Z^{\mu\nu} A'_{\mu\nu}$ $\kappa |H|^2 |S|^2$

$y H L N$ $\frac{1}{f_s} F_{\mu\nu} \tilde{F}_{\mu\nu} a$

Last topic of these lectures

1. Dark photons at the LHC

Higgs exotic decays are one of the primary mechanisms to produce dark photons at the LHC

It is challenging to constrain the Higgs width at the LHC.
Few % branching ratio into exotic particles is a reasonable target for the duration of the LHC program.

Reason: At the LHC, we measure rates:

$$\sigma = \sigma(pp \to H) \times \mathrm{BR}(H \to \mathrm{SM})$$
$$= \sigma(pp \to H) \times \frac{\Gamma(H \to \mathrm{SM})}{\Gamma_{\mathrm{tot}}}$$

1% of Higgs bosons decaying to dark photons would mean O(10^6) dark photons produced!

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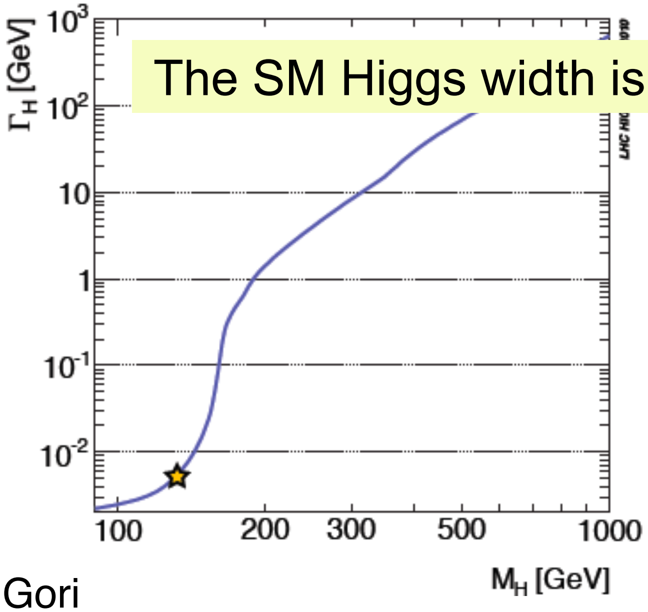

The SM Higgs width is small

Even a small coupling to light NP particles can lead to a sizable branching ratio

(all these conclusions would be completely different if m_H > 200GeV)

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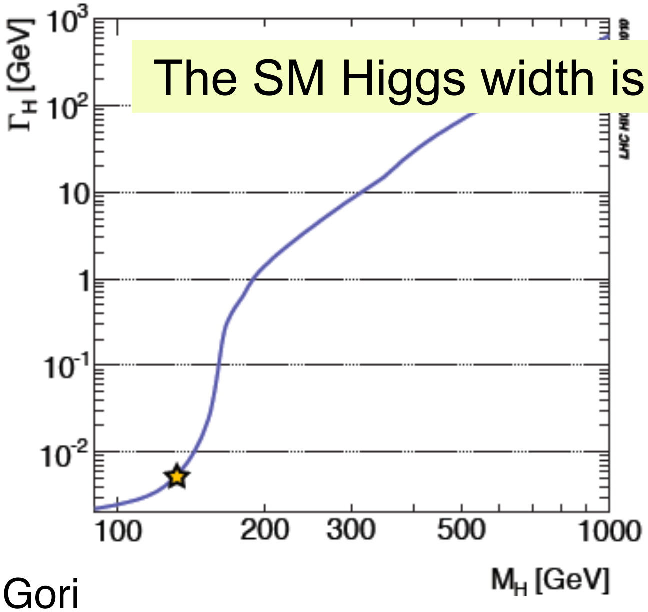

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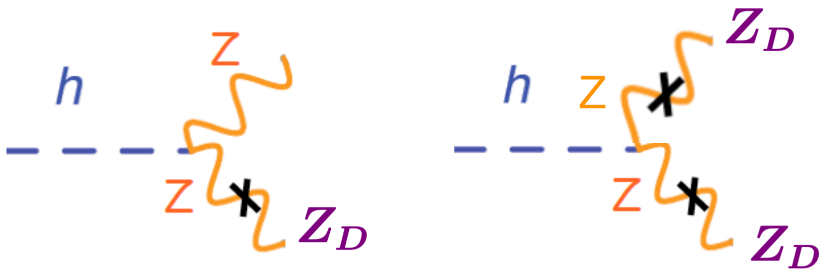
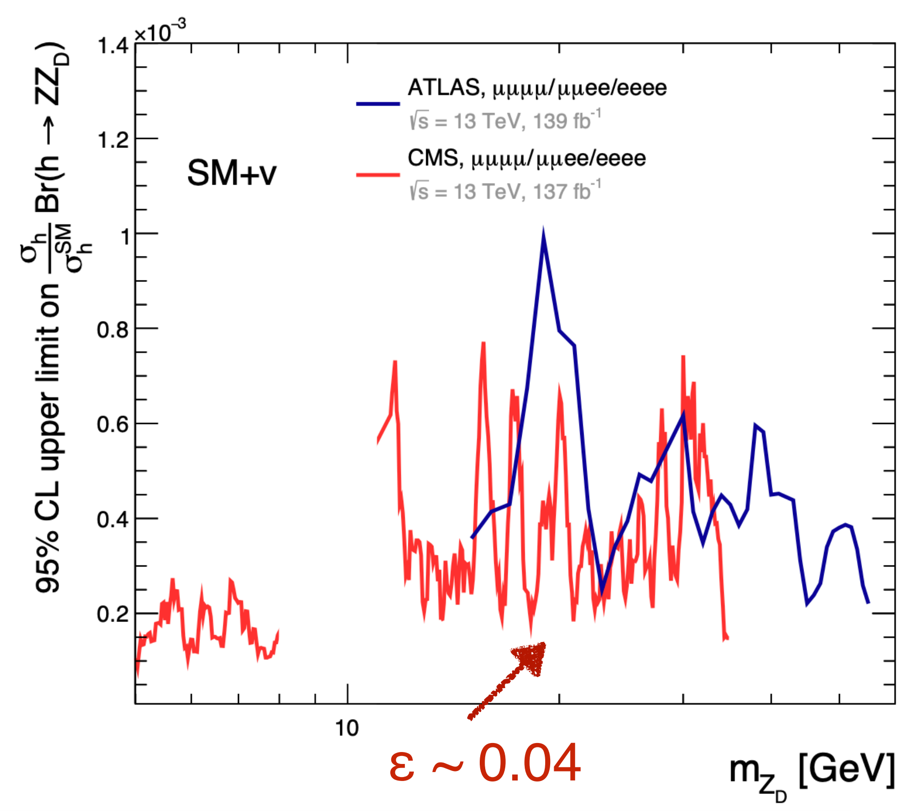


prompt or displaced

Visible dark photons from Higgs exotic decays (prompt)

$$h \to Z Z_D \to 2\ell\ 2\ell'$$



ε ~ 0.04

Cepeda, SG, Martínez Outschoorn, Shelton, 2111.12751

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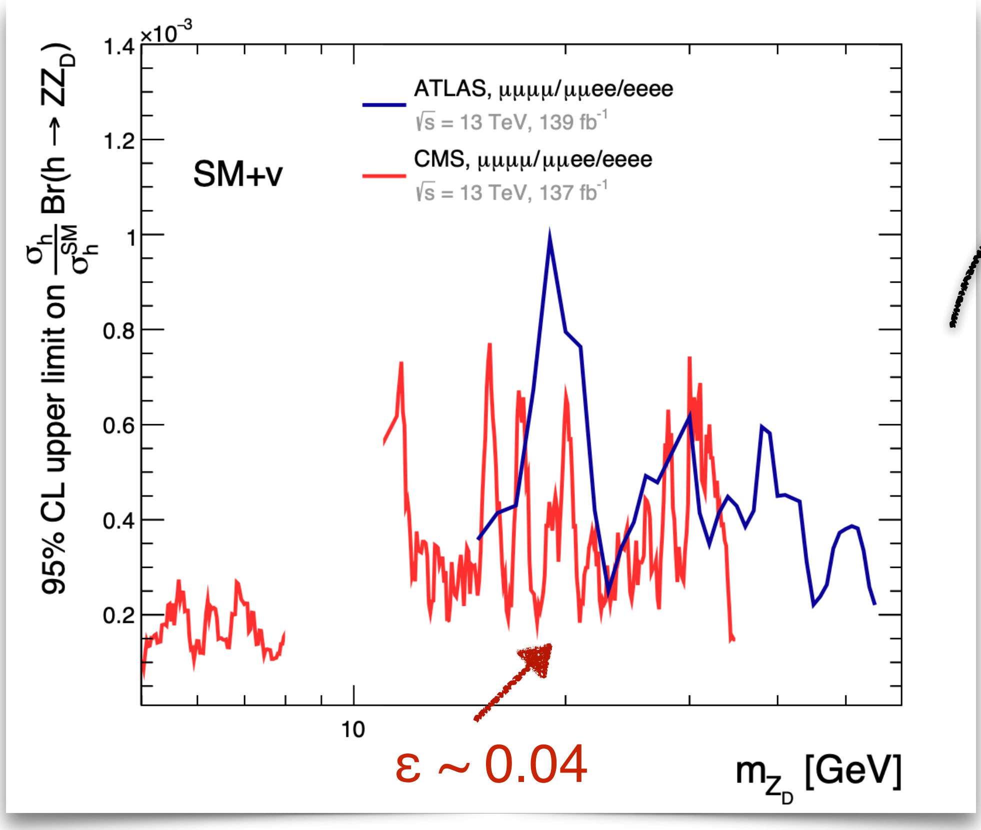

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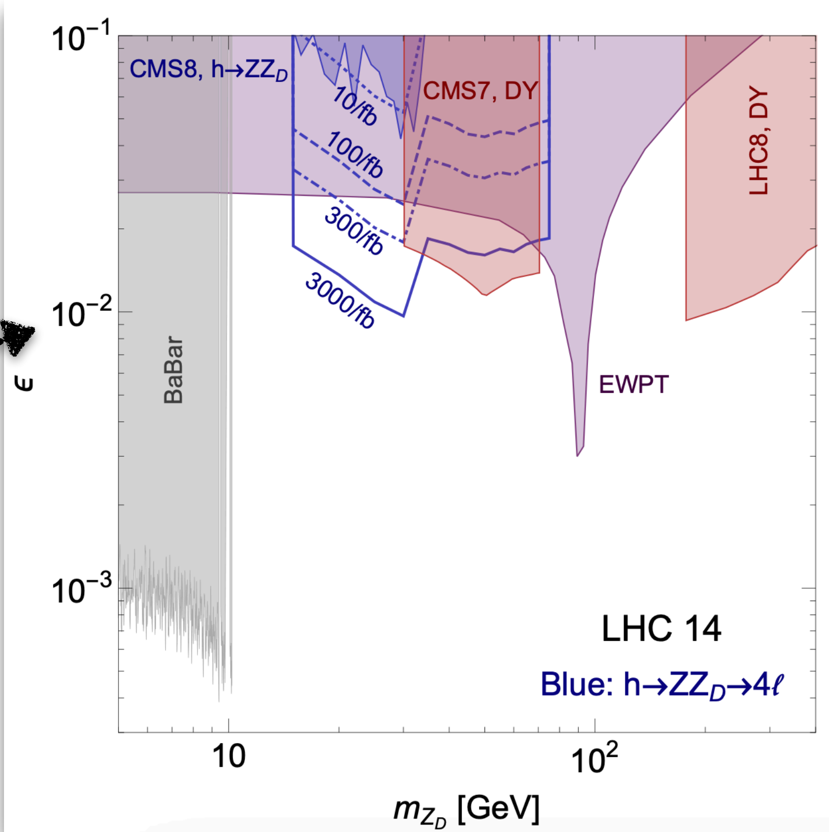
Cepeda, SG, Martínez Outschoorn, Shelton, 2111.12751

Curtin, Essig, SG, Shelton, 1412.0018

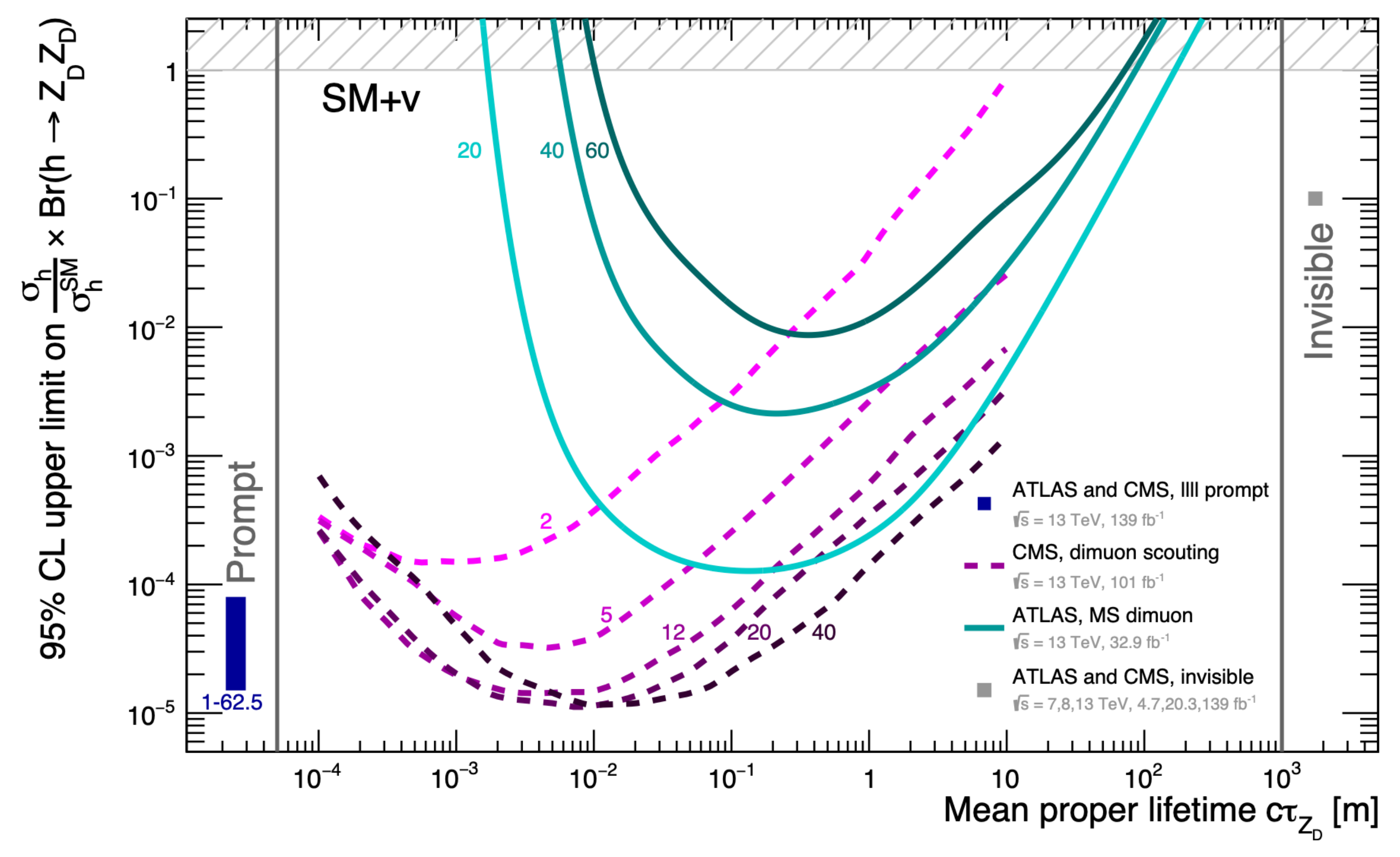


interplay with direct searches for

$$pp \to Z_D \to 2\ell$$

Visible dark photons from Higgs exotic decays (displaced)

Cepeda, SG, Martínez Outschoorn, Shelton, 2111.12751



$$h \to Z_D Z_D \to 2\ell\ 2\ell'$$

long-lived dark photons (small values of ε)

The challenge of Higgs exotic decays: soft objects

To be sensitive to Higgs exotic decays, dedicated studies of trigger strategies are needed

The challenge of Higgs exotic decays: soft objects

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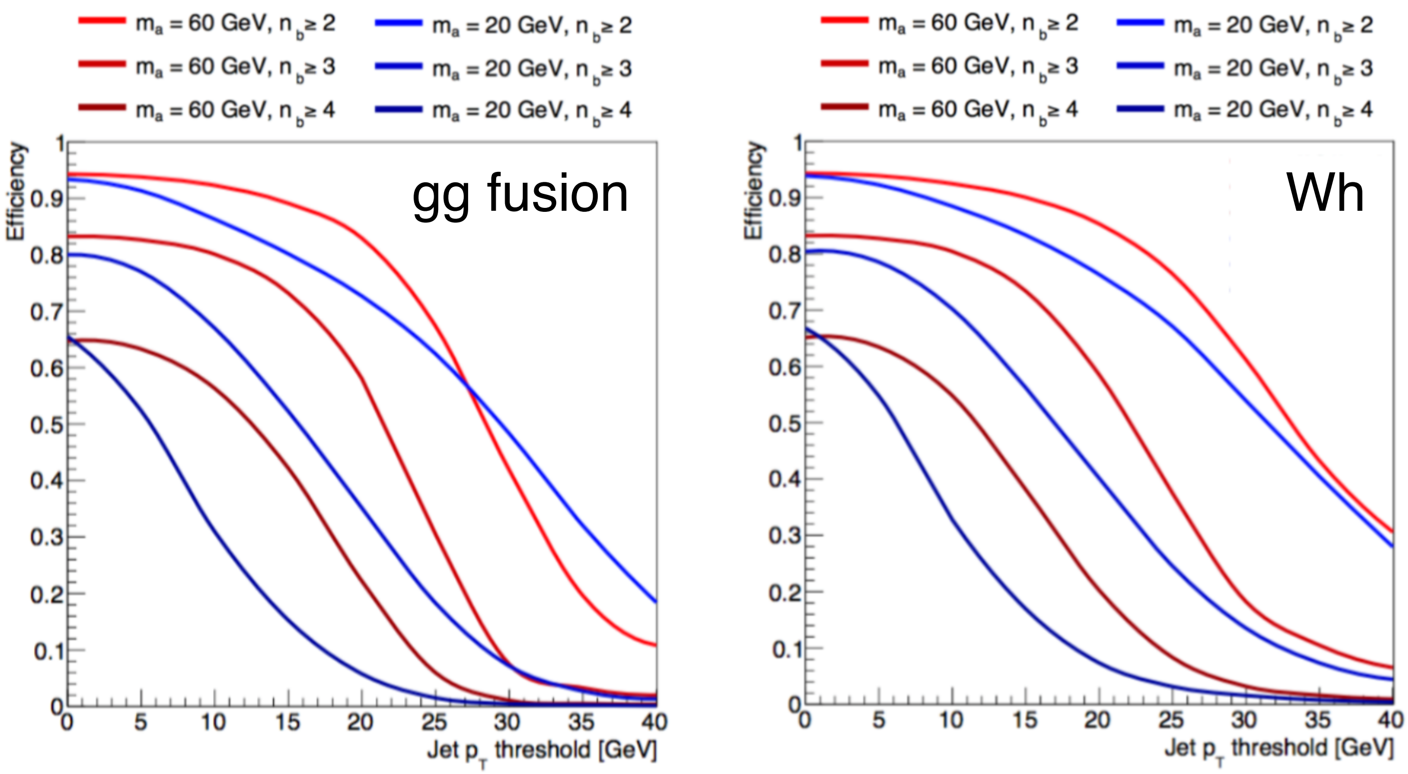
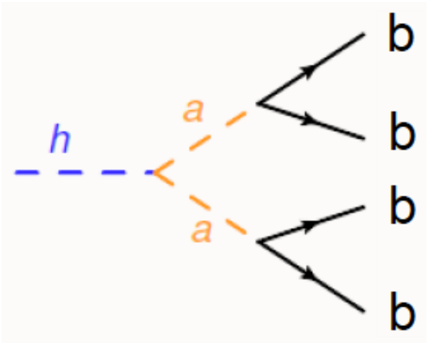
Let us take, for example, the challenging decay mode h → a a → 4b

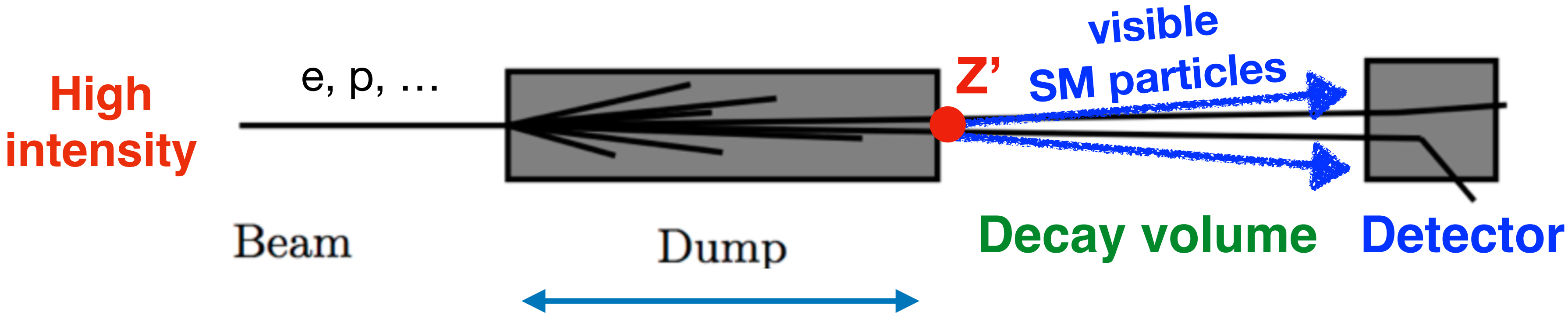




Risk of loosing the signal already at the trigger level

From the LHC Higgs cross section working group, Yellow report 4, 1610.07922

2. Visible dark photons at beam dump experiments



this length sets the typical lifetime of the dark particle that we can probe

Low background experiments
(depending on the size of the dump)

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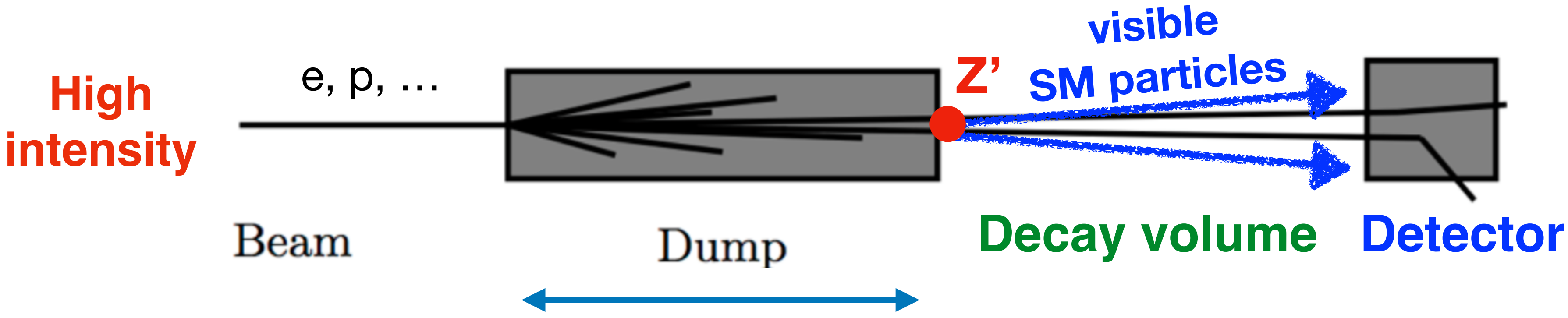

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Low background experiments
(depending on the size of the dump)

p beam for the SeaQuest/DarkQuest experiment at Fermilab

p beam for the NA62 experiment at CERN

e- beam for the HPS experiment at JLAB

e- beam for the DarkLight experiment here at TRIUMF

…

Running experiments

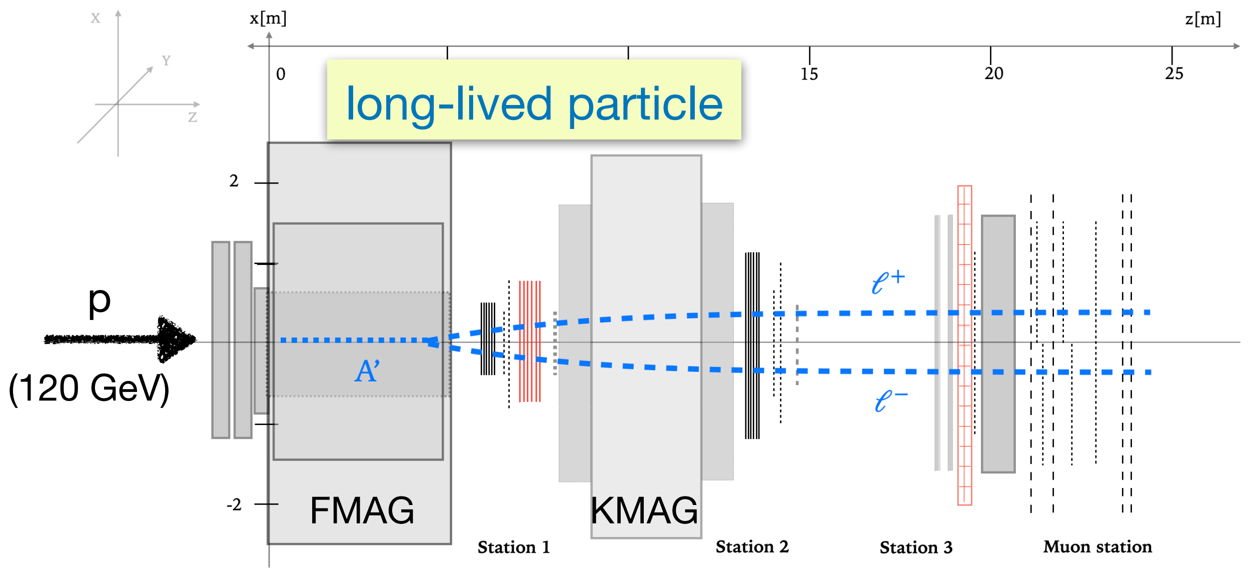
Future experiments

Proton (beam dump) vs. electron fixed target experiments:

Protons: typically higher energies (→ reach towards larger dark sector masses)

but larger backgrounds (needs shielding!)

The DarkQuest experiment @ Fermilab



SeaQuest → SpinQuest → DarkQuest

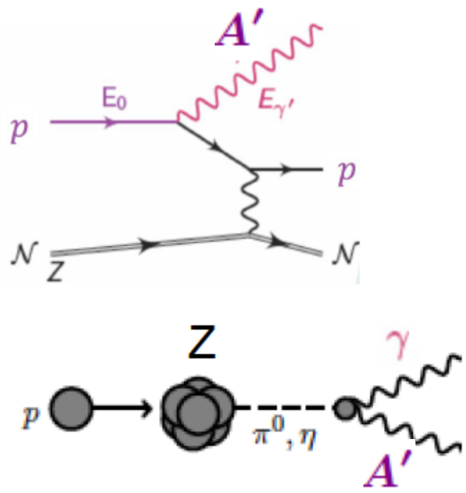
SeaQuest
1706.09990

SpinQuest
polarized target
+ displaced trigger
NOW

DarkQuest
upgrade
(calorimeter +
more tracking layers +
hodoscope for triggering)
FUTURE

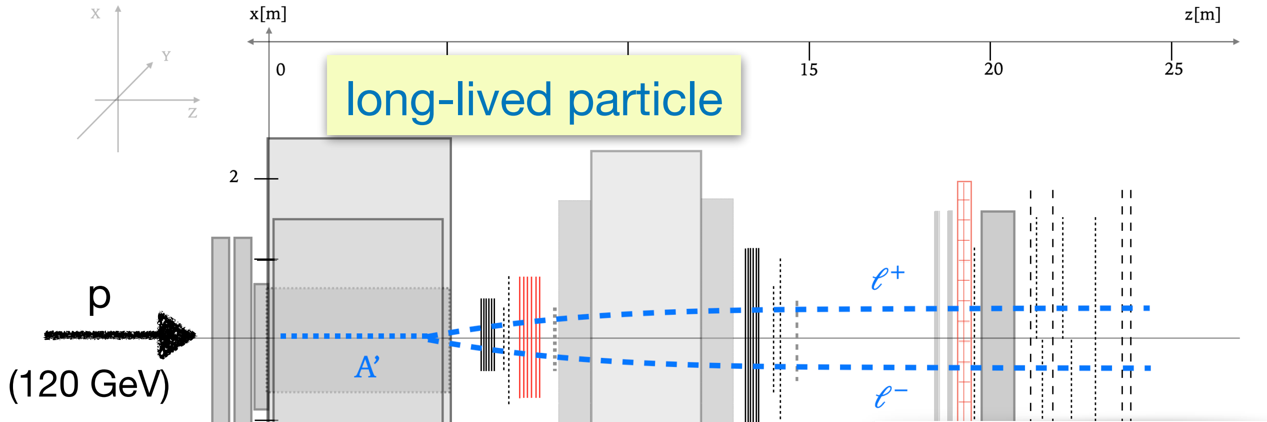
Initial proposal:
Gardner, Holt, Tadepalli, 1509.00050
Berlin, SG, Schuster, Toro, 1804.00661

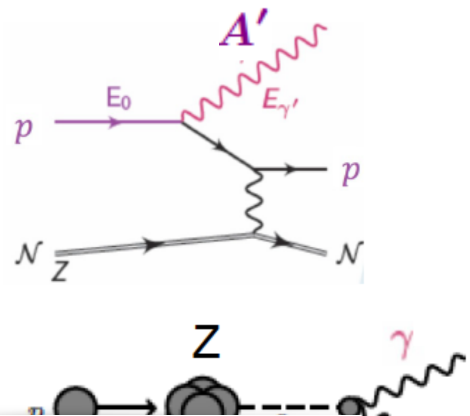
Snowmass white paper: 2203.08322
Test beam studies: 2502.20590



Low backgrounds if the dark photon decays to electrons

The DarkQuest experiment @ Fermilab





SeaQuest → SpinQuest → D

1706.09990

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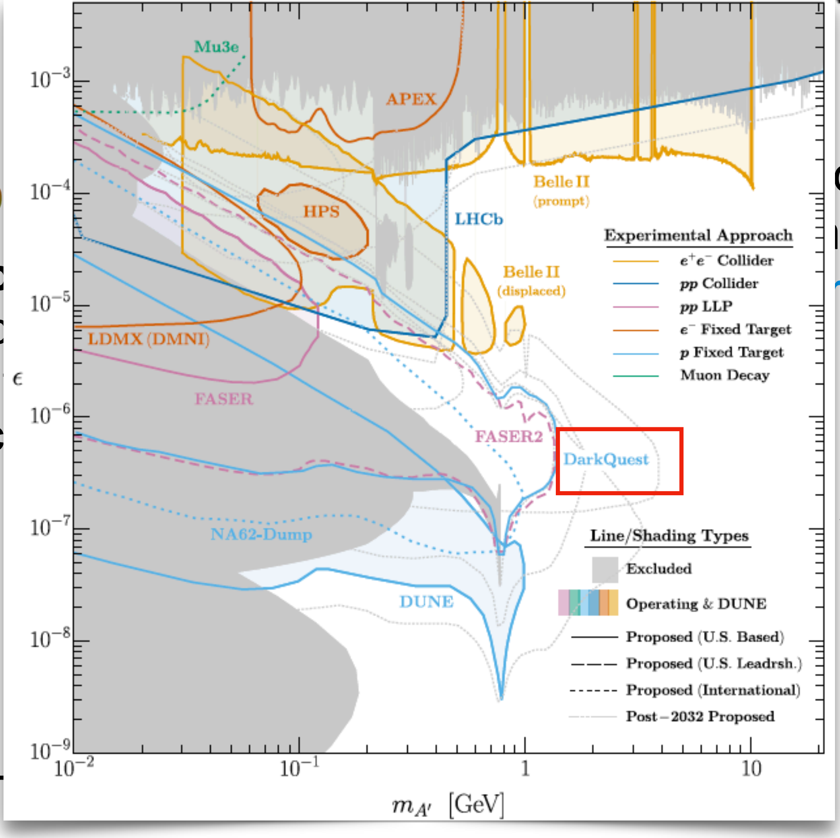

Longer lifetimes

Initial proposal:
Gardner, Holt, Tadepalli, 1509.00050
Berlin, SG, Schuster, Toro, 1804.00661

Snowmass white paper: 2203.08322
Test beam studies: 2502.20590

✱ Axions and axion-like-particles

The strong CP problem and axions

Strong CP problem:

why is the QCD $\bar{\theta}$ parameter so small? $\mathcal{L}_{\text{QCD}} \supset \bar{\theta}\frac{g^2}{32\pi^2}G_{\mu\nu}\tilde{G}^{\mu\nu}$ (CP violating term)

$$\bar{\theta} \equiv \theta + \arg(\det(Y_u Y_d))$$

We need this parameter to be $<10^{-10}$ since, otherwise, it would lead to too large contributions to the neutron EDM and it would be experimentally excluded

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Let's introduce a global $U(1)_{PQ}$ symmetry that is broken spontaneously by a complex scalar field

Peccei-Quinn symmetry breaking scale

$$V(\Phi) = \lambda(|\Phi|^2 - f_a^2/2)^2$$

This spontaneous breaking will lead to a massless goldstone boson, the axion, a.

$$\Phi(x) = \frac{f_a}{\sqrt{2}}e^{ia(x)/f_a}$$

When QCD enters the confining phase, it generates an axion potential that is minimized at $a = -\bar{\theta} f_a$ and this cancel the Lagrangian term that contributes to the neutron EDM.
It also generates a non-zero mass for the axion: $m_a\, f_a \sim f_\pi\, m_\pi$

The generic expectation is that the axion couples ~$1/f_a$

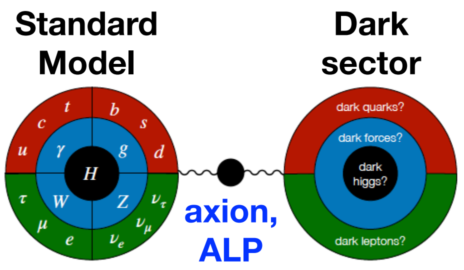
Additional motivations for sub-GeV axions (or ALPs)

Beyond the strong CP problem…

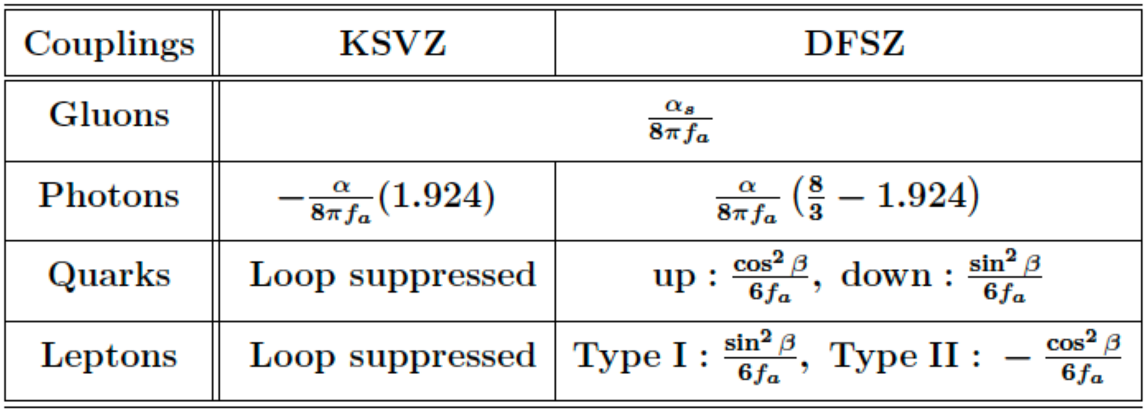
Axions or axion-like-particles (ALPs) are pretty generic new physics particles
Pseudo Nambu Goldstone boson in models with a spontaneously broken global symmetry

Couplings with the Standard Model (SM) particles determined by the particular UV theory

- Models to address the gauge hierarchy problem (relaxion)
- SUSY extended models (NMSSM with an approximate PQ symmetry)
- Generic feature of string compactification
- Models addressing anomalies in data ($(g-2)_\mu$, galactic center excess for DM, …)
- General (low dimensional) portal to the dark sector



The minimal canonical axion models



Couplings	KSVZ	DFSZ
Gluons	$\frac{\alpha_s}{8\pi f_a}$	
Photons	$-\frac{\alpha}{8\pi f_a}(1.924)$	$\frac{\alpha}{8\pi f_a}\left(\frac{8}{3}-1.924\right)$
Quarks	Loop suppressed	up : $\frac{\cos^2\beta}{6f_a}$, down : $\frac{\sin^2\beta}{6f_a}$
Leptons	Loop suppressed	Type I : $\frac{\sin^2\beta}{6f_a}$, Type II : $-\frac{\cos^2\beta}{6f_a}$

Kim-Shifman-Vainshtein-Zakharov (KSVZ) model, Phys. Rev. Lett. 43 (1979) 103, Nucl. Phys. B 166 (1980) 493.
UV model with a vector-like color-triplet fermion and a complex scalar

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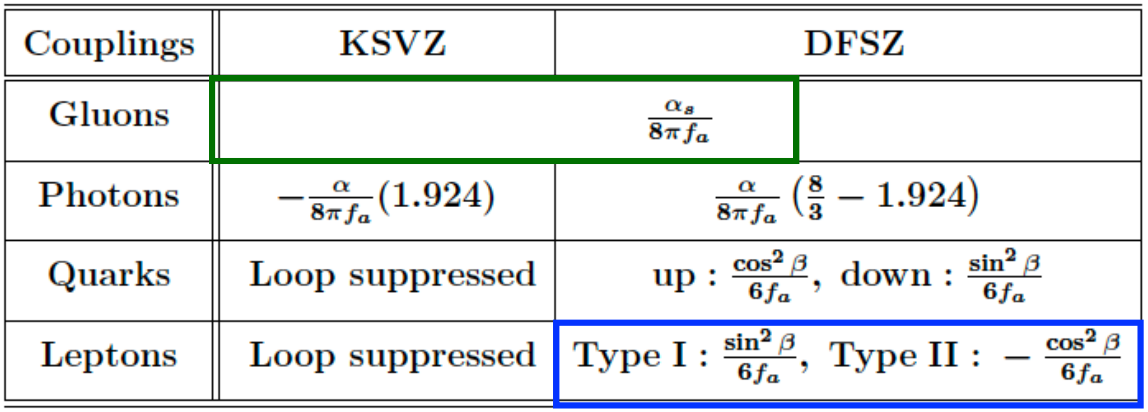

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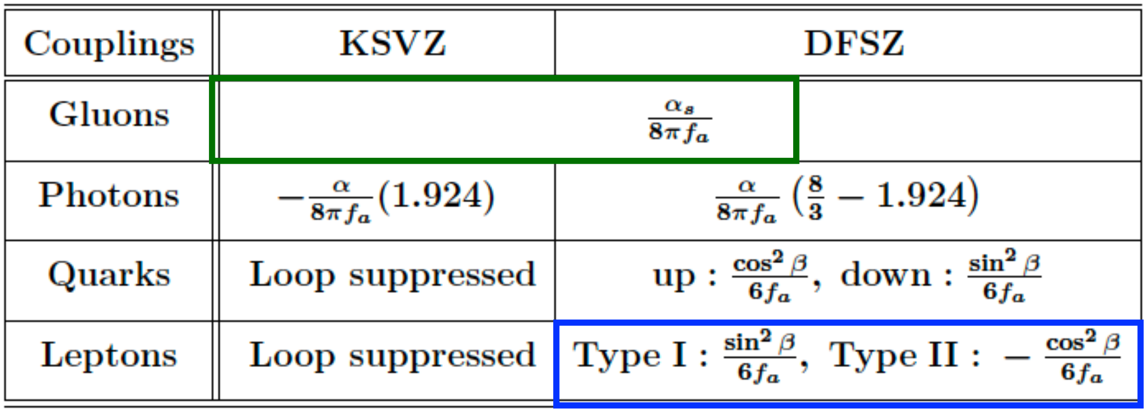
supernova cooling bounds (axion-nucleon interaction)

cooling bounds on red giant (axion-electron interaction)

The minimal canonical axion models



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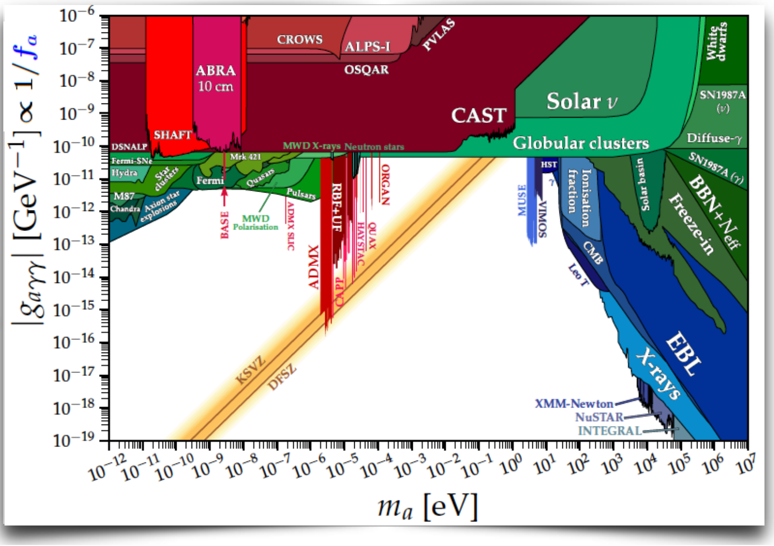
Common plot that we can find in the literature:

coupling to photons



Present probes

Adams at al., 2203.14923

S.Gori

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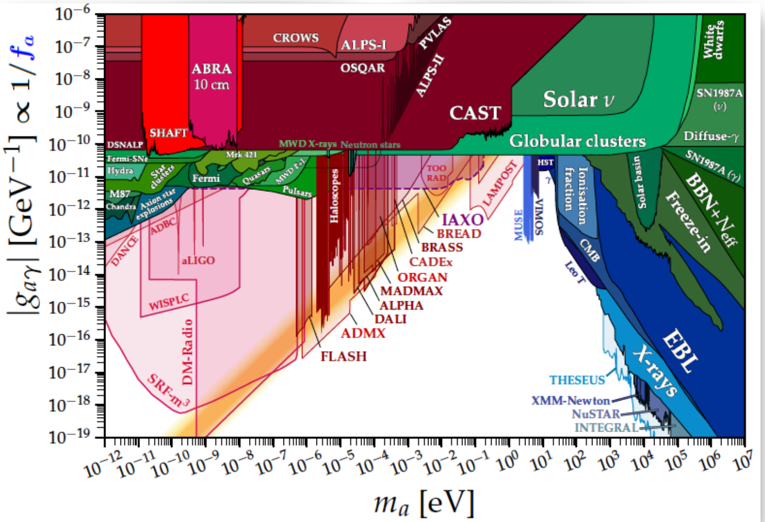

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Future probes

Adams at al., 2203.14923

Let’s go back to the EFT for axions

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Georgi, Kaplan, Randall 1986

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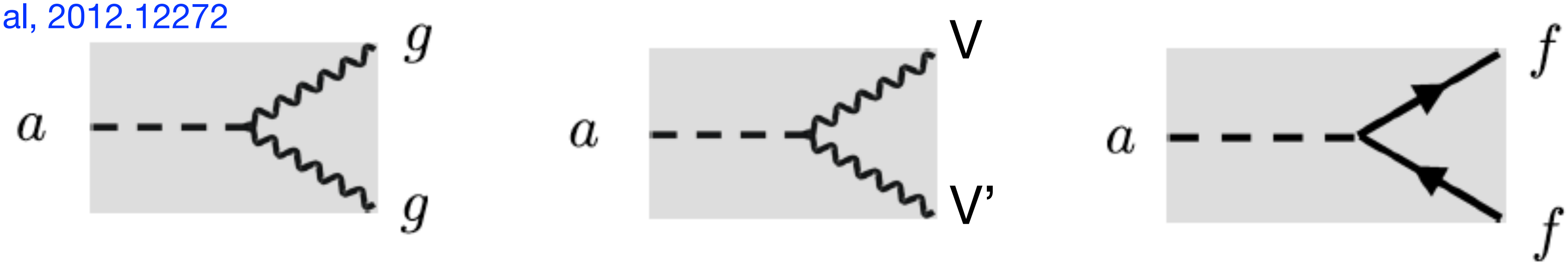
For the complete one-loop analysis, see
Bonilla et al, 2107.11392
Bauer et al, 2012.12272



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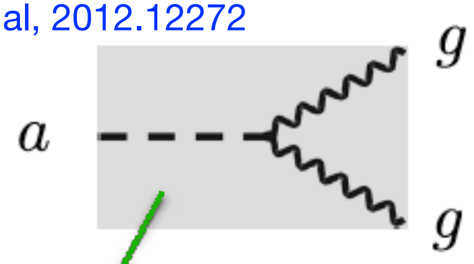

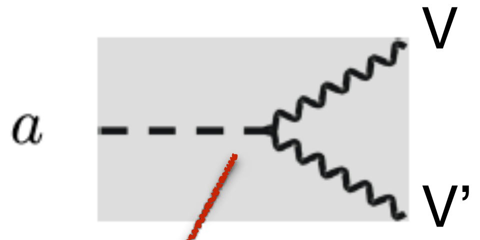

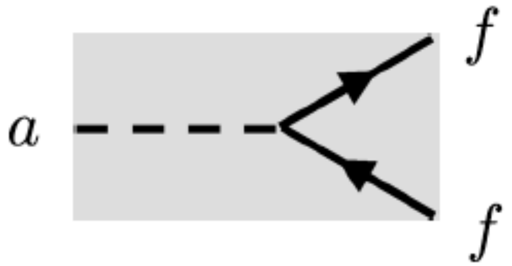

Minimal coupling expected if connection to the strong CP problem.

A axion-photon coupling is generated in the broken phase

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This is the **main coupling** that has been considered for phenomenological studies of axions in the sub-GeV scale.

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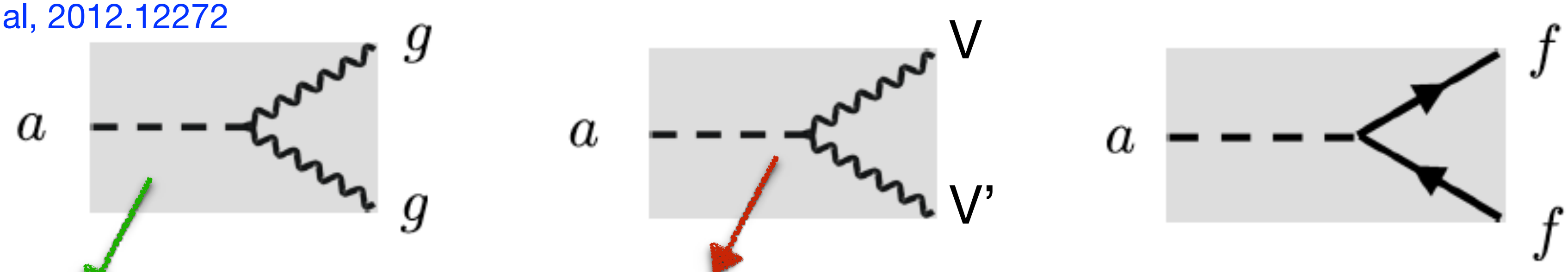

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These are **the least studied couplings**. Nevertheless they are present and sizable even in the minimal DFSZ QCD axion model.

Fast progressing number of theory studies + experimental searches

Many signatures still to explore!

Axions at pion experiments

Axions can be produced from pion decays

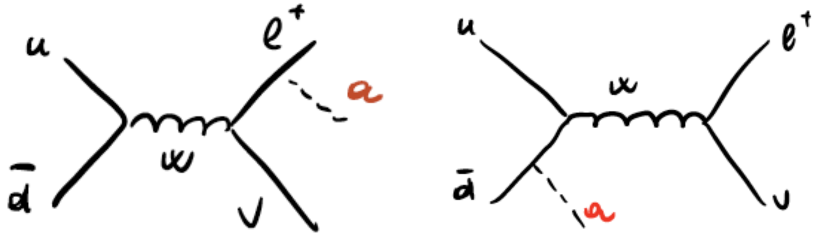
$\boxed{\pi^+ \to e^+ \nu a}$

not helicity suppressed (as $\pi^+ \to e^+\nu$),
nor phase-space suppressed (as $\pi^+ \to \pi^0 e^+\nu$)

These decays are very generic and they happen in any UV theory where

- the axion mixes with the SM π^0
- the axion couples to quarks
- the axion couples to leptons

Altmannshofer, SG, Robinson, 1909.00005
Altmannshofer, Dror, SG, 2209.00665



Axions at pion experiments

Axions can be produced from pion decays

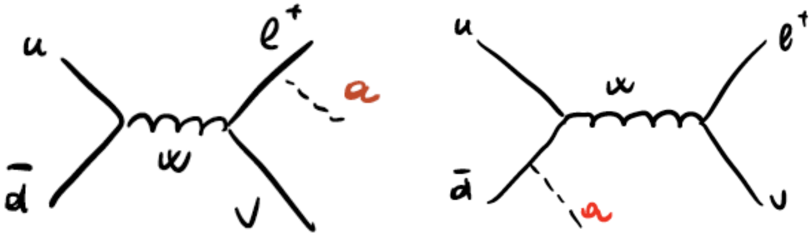
$\boxed{\pi^+ \to e^+\nu a}$

not helicity suppressed (as $\pi^+ \to e^+\nu$),
nor phase-space suppressed (as $\pi^+ \to \pi^0 e^+\nu$)

These decays are very generic and they happen in any UV theory where

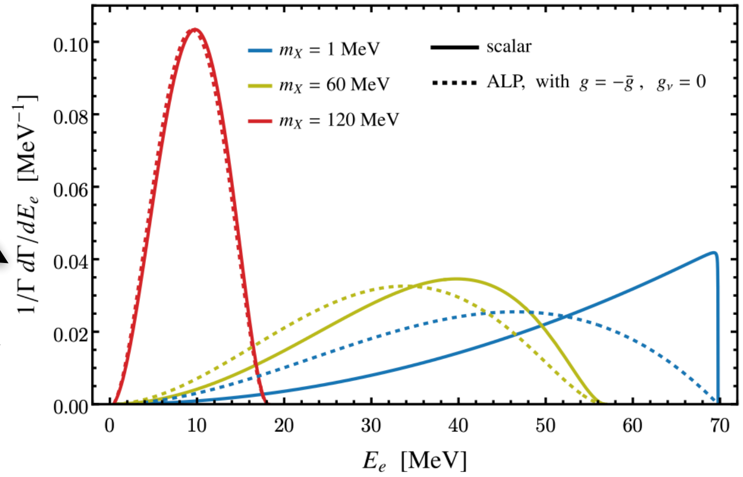
- the axion mixes with the SM π^0
- the axion couples to quarks
- the axion couples to leptons

Altmannshofer, SG, Robinson, 1909.00005
Altmannshofer, Dror, SG, 2209.00665



Altmannshofer, Giffin, SG, Jackson, Luong, in progress

- ✱ If the axion is **invisible**, it will affect the measurement of the e⁺ spectrum in $\pi^+ \to e^+\nu$ (PIENU experiment here at TRIUMF + future PIONEER experiment)



- ✱ If the axion **decays back to the SM**, we can search for exotic pion signatures. E.g. $\pi^+ \to a e^+\nu \to (\gamma\gamma)e^+\nu$ (possibly searched for in the future by PIONEER)

Take home message on BSM

Many motivations to consider physics beyond the Standard Model (BSM)

Some motivations are more “theory driven” (hierarchy problem, flavor puzzle, …); some are observational (origin of neutrino masses, DM, …)

The range of phenomena that are predicted by BSM theories is vast. In fact, we don’t know where the next NP scale is going to be

It is important to look as broadly as possible for NP at many different experiments and to explore a variety of theories!

Backup

Precision pion experiments

Several (past and present) small-scale experiments built to measure π^+ rare decays

$$\boxed{\pi^+ \to e^+\nu}$$

$$\mathrm{BR} \sim \frac{m_e^2}{m_\mu^2}\frac{(m_\pi^2 - m_e^2)^2}{(m_\pi^2 - m_\mu^2)^2}$$

Helicity suppressed decay

- ✱ Most precise measurement: PIENU experiment @ TRIUMF

$$\mathrm{BR}^{\mathrm{exp}} = (1.234 \pm 0.004) \times 10^{-4}$$

Mainly stat. uncertainty

- ✱ Theoretical uncertainty ~1 order of magnitude smaller!
- ✱ PIONEER future measurement: ~20 times more accurate

$$\boxed{\pi^+ \to \pi^0 e^+\nu}$$

$$\mathrm{BR} \sim \frac{(m_{\pi^\pm} - m_{\pi^0})^5\, m_{\pi^\pm}^3}{f_\pi^2 m_\mu^2 (m_{\pi^\pm}^2 - m_\mu^2)^2}$$

Phase space suppressed decay

- ✱ Most precise measurement: PIBETA experiment @ PSI

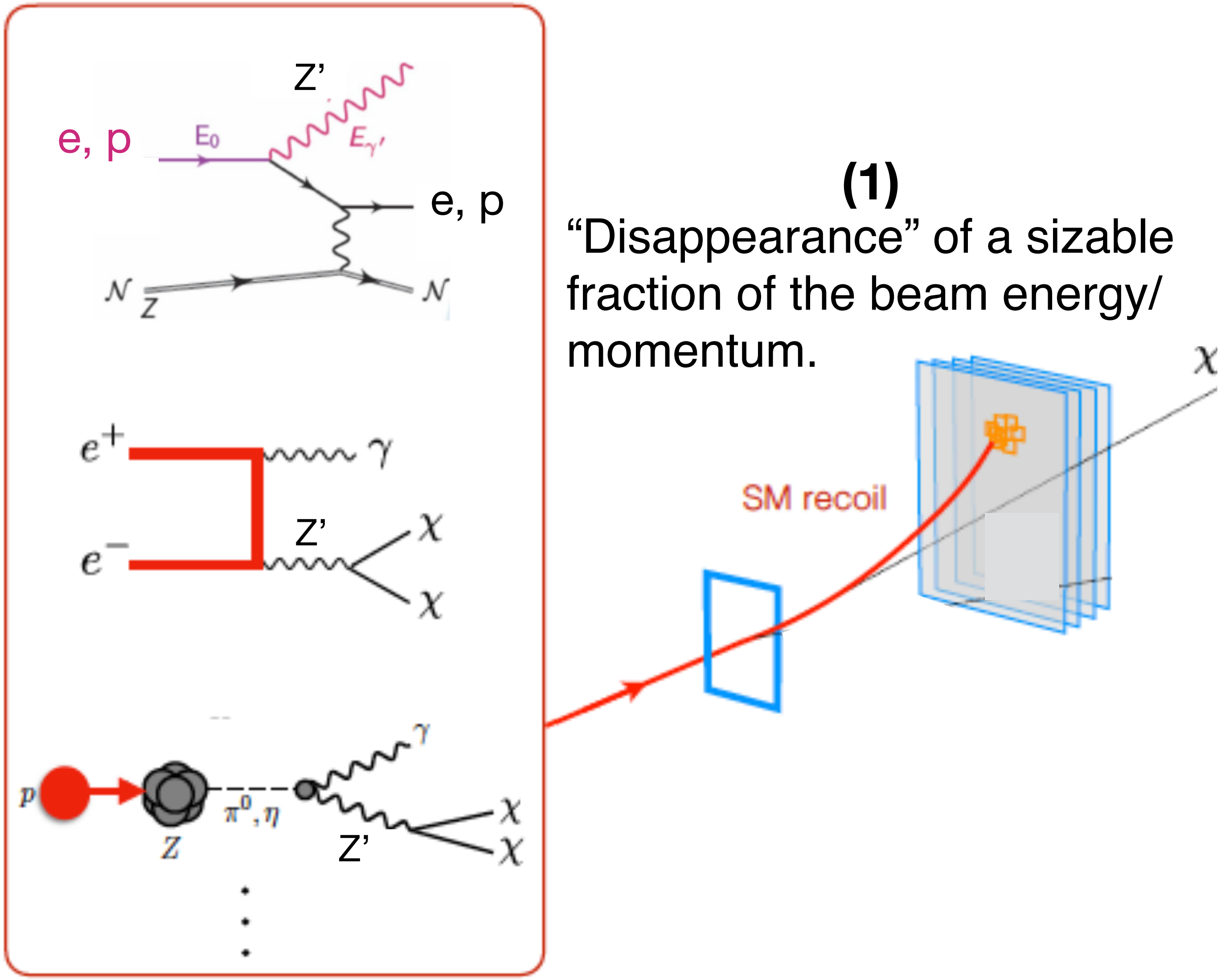
$$\mathrm{BR}^{\mathrm{exp}} = (1.036 \pm 0.006) \times 10^{-8}$$

Comparable stat. and sys. uncertainties

- ✱ Theoretical uncertainty a factor of ~2 smaller
- ✱ PIONEER future measurement: ~10 times more accurate

Invisible dark photons. DM production

$m_{Z'} > 2m_X$



(1)

“Disappearance” of a sizable fraction of the beam energy/ momentum.

https://arxiv.org/abs/2207.00597

Invisible dark photons. DM production

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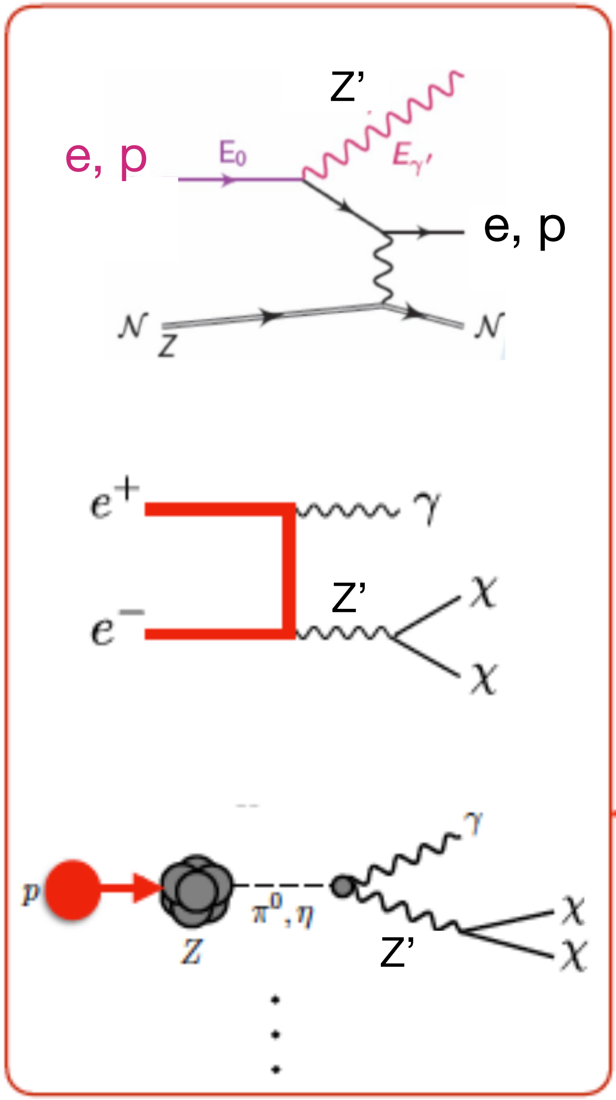
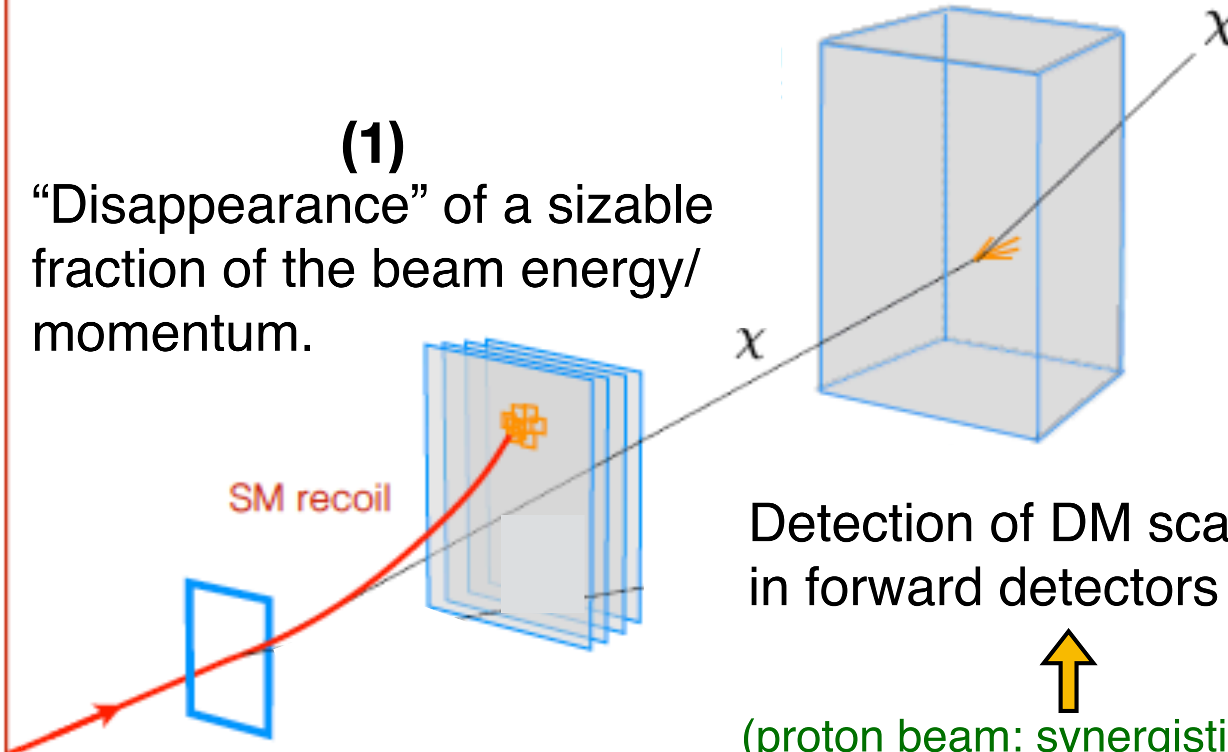




(1)

“Disappearance” of a sizable fraction of the beam energy/ momentum.

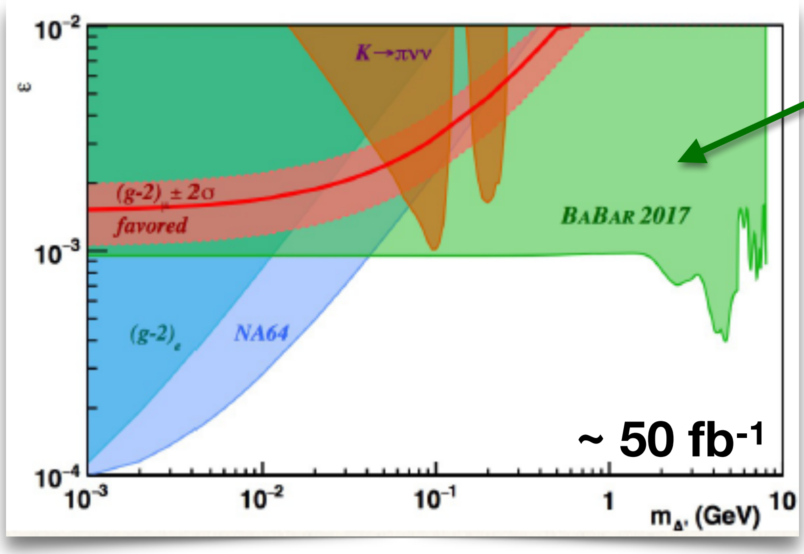
Detection of DM scattering in forward detectors **(2)**

(proton beam: synergistic with the accelerator-based **neutrino physics program**)

https://arxiv.org/abs/2207.00597

Invisible dark photon at Belle II

1702.03327

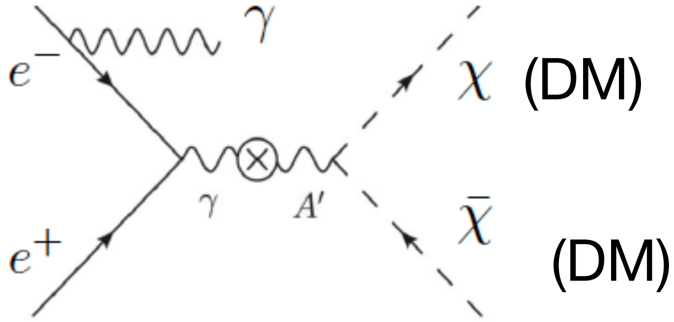


Babar search

single-photon trigger

This analysis excludes the entire region favored by $(g\text{-}2)_\mu$!

mono-photon + invisible



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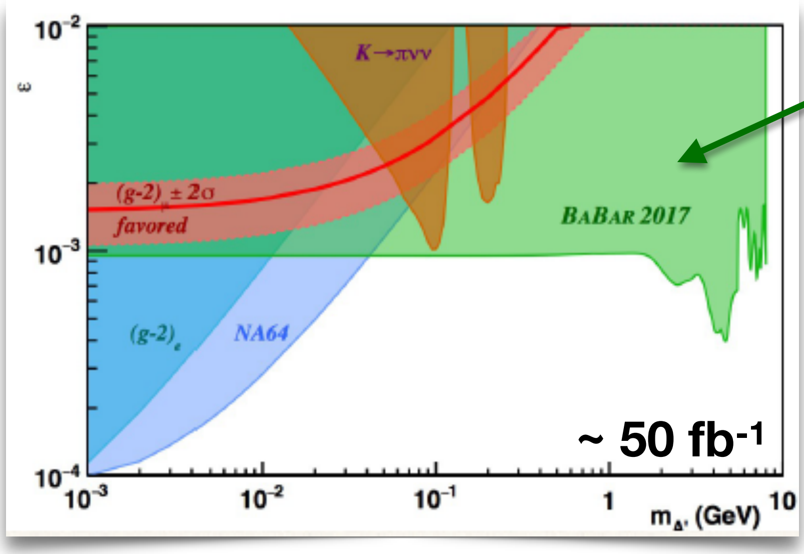

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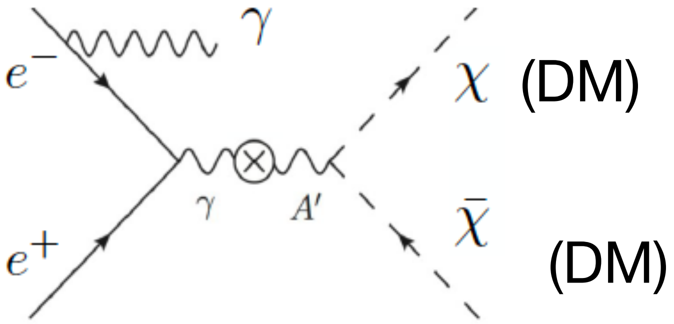

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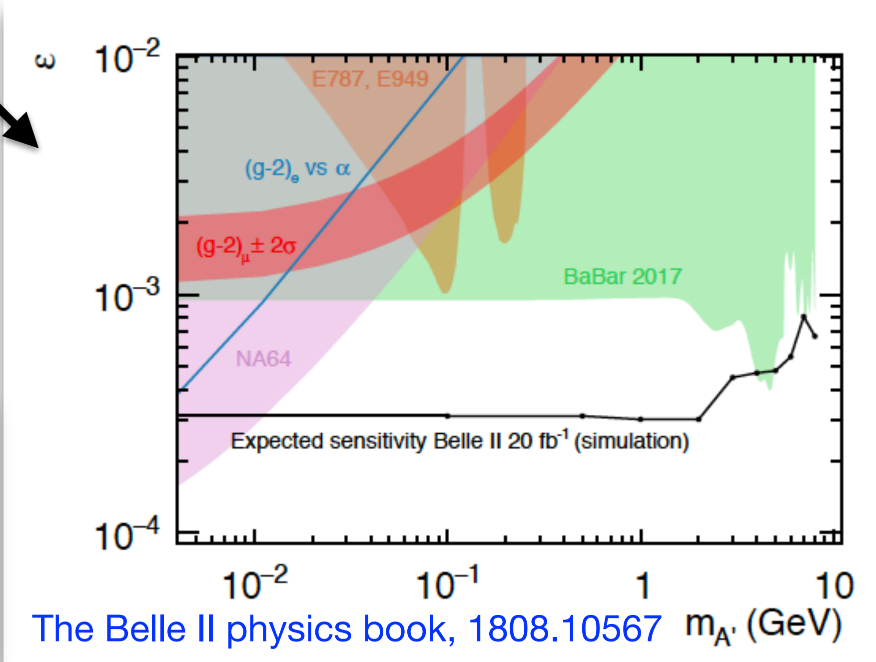
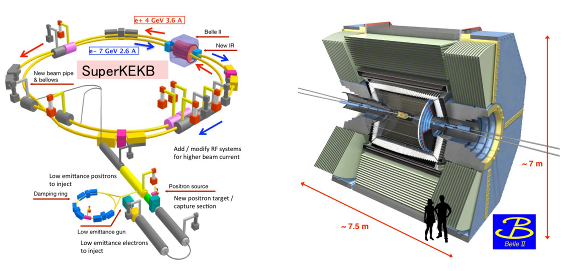


The Belle II physics book, 1808.10567

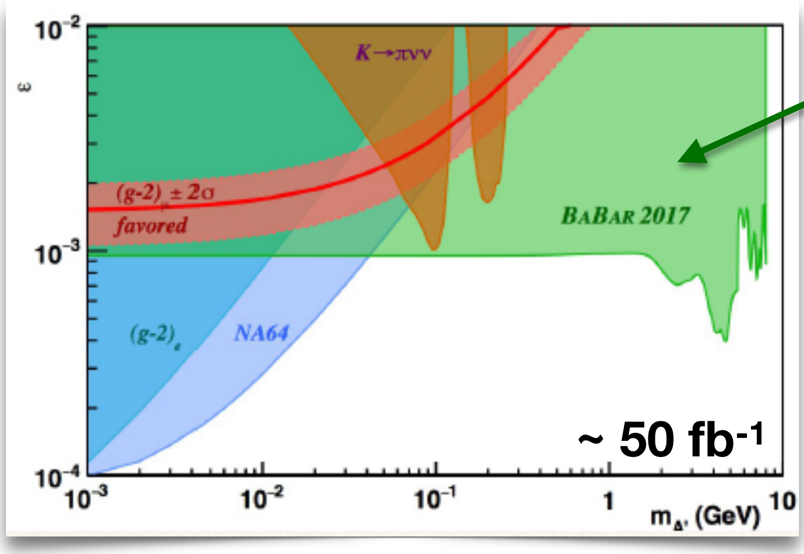


S.Gori

backup

Invisible dark photon at Belle II

1702.03327



~ 50 fb^{-1}

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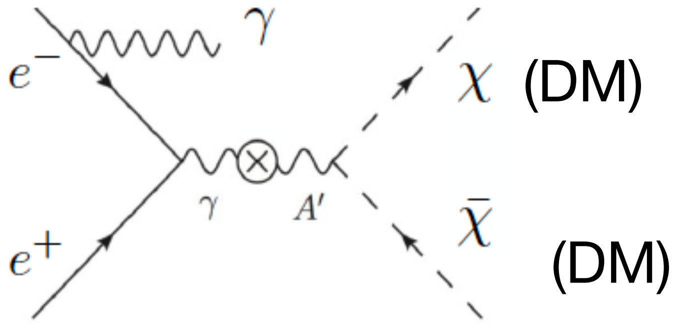
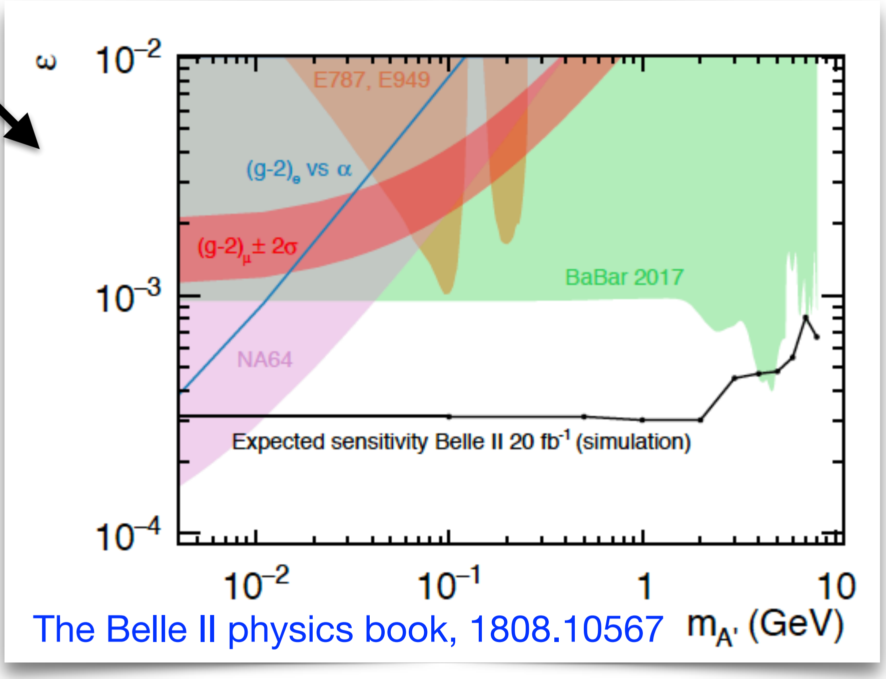




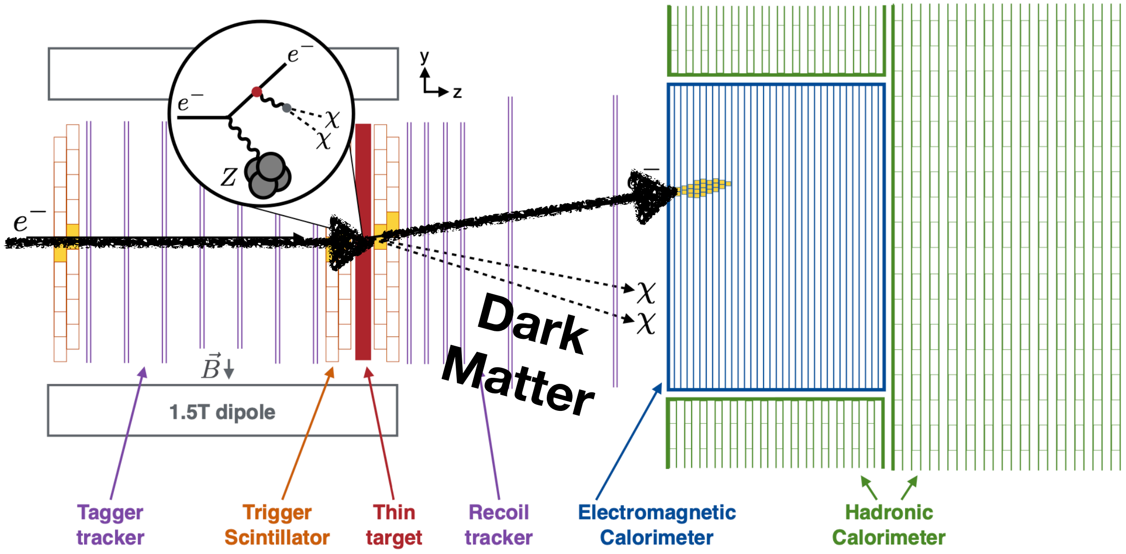
The Belle II physics book, 1808.10567

Belle II is supposed to collect 50 ab^{-1}!

Invisible dark photon at LDMX

Akesson et al., 2203.08192

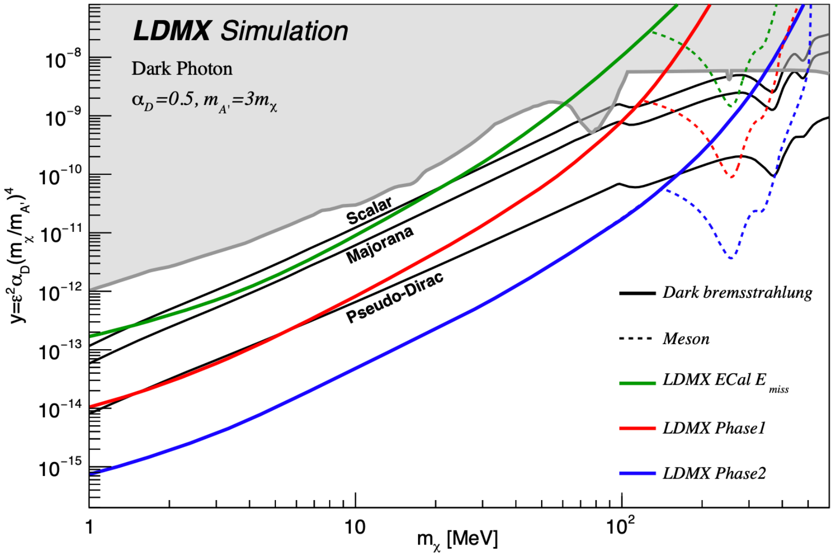
High intensity electron beam (4 and 8 GeV)



See Izaguirre, Krnjaic, Schuster, Toro, 1411.1404 for the initial proposal

Missing momentum experiment

(accurate measurement of the momentum of the deflected electron beam)



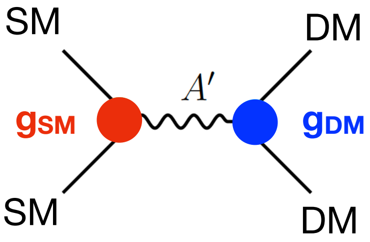
S.Gori

backup

Summary: the invisible dark photon

$\epsilon B^{\mu\nu} A'_{\mu\nu}$

A'→DM DM



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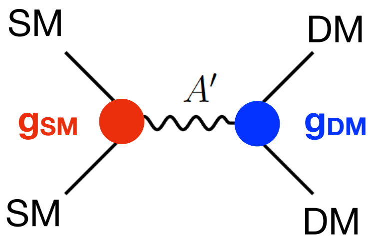

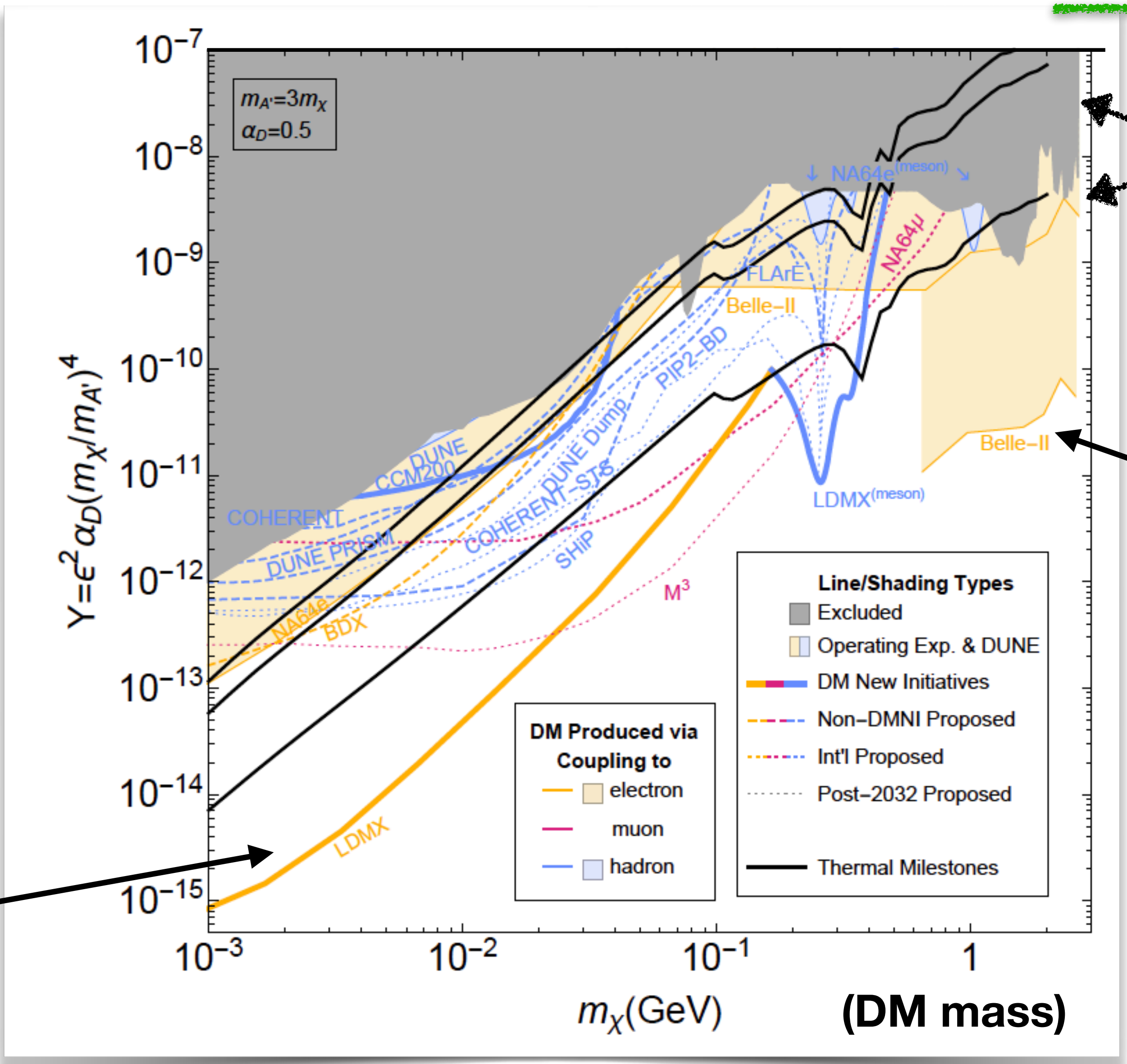

LHC

benchmarks for thermal DM

Belle II

LDMX

(DM mass)

Krnjaic, Toro et al, 2207.00597

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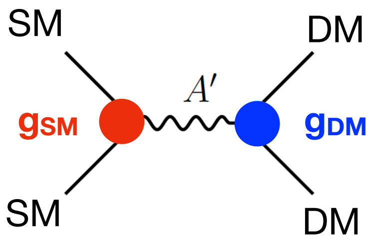

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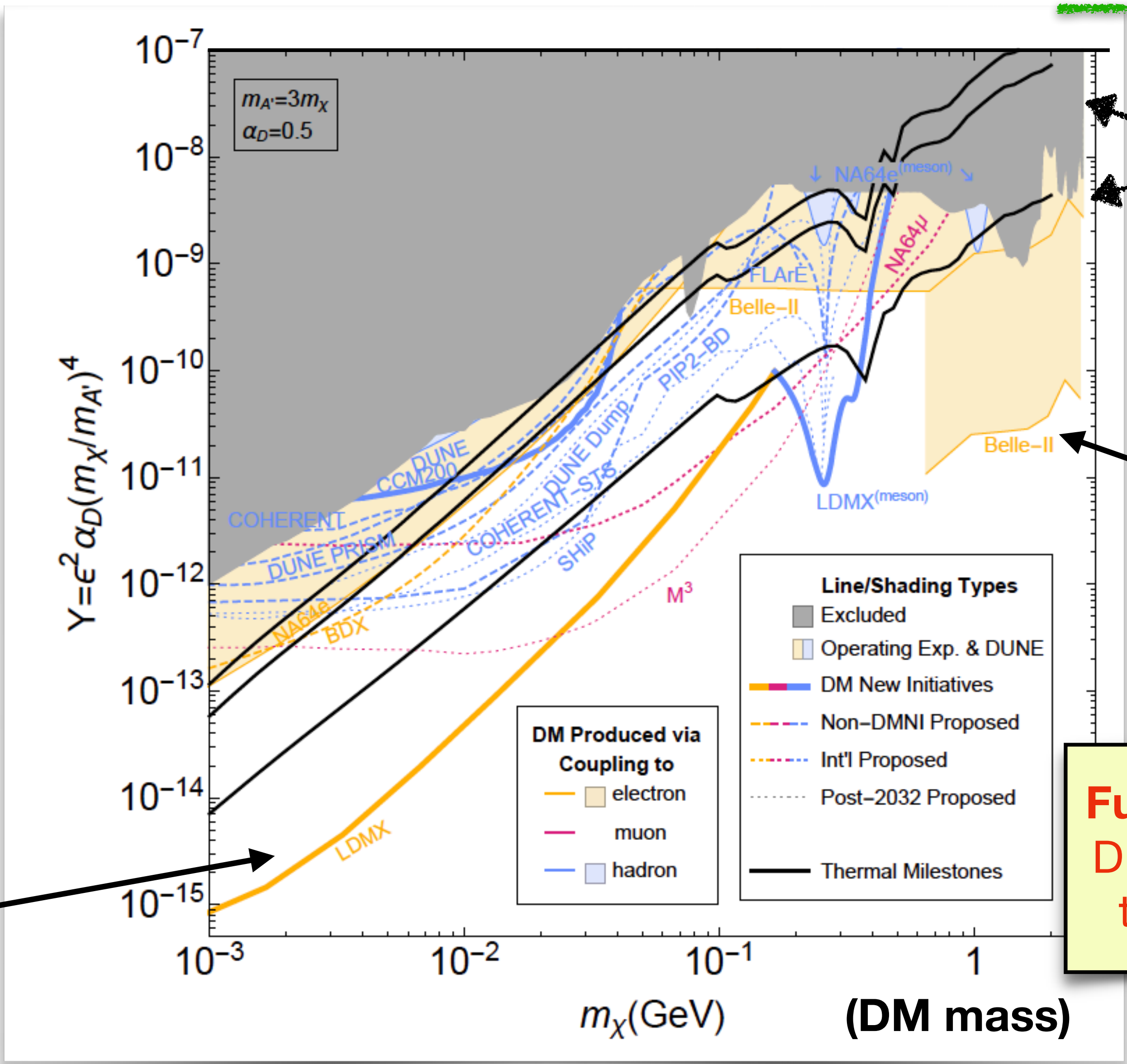

Belle II

LDMX

(DM mass)

Full coverage of this DM thermal target in the coming years!

Krnjaic, Toro et al, 2207.00597