science week /23
Jul 31 - Aug 4

The Status & Future of Particle Physics

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WAYNE STATE UNIVERSITY

TRIUMF Science Week 2023

Tuesday, August 1st

Mystery of

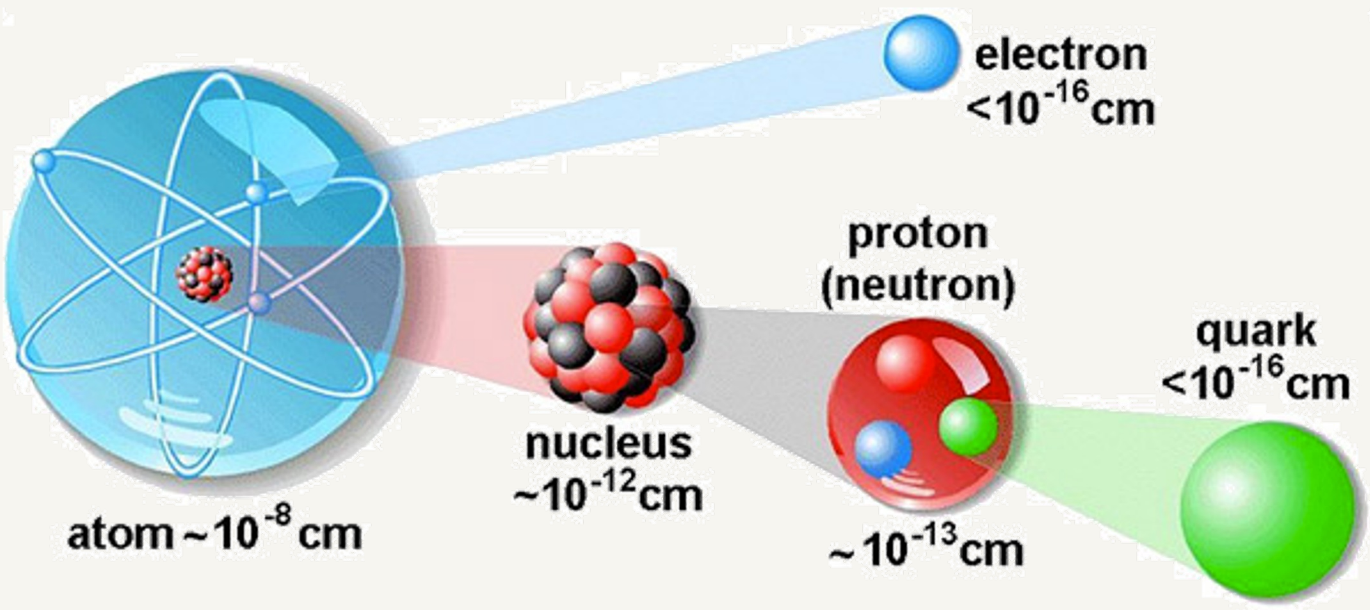
The Naturally

UNNATURAL

Standard Model of

Particle Physics

Particle physicists study the smallest pieces of matter…
… and their interactions.



	Big	Small
Slow	Classical Physics	Quantum Mechanics
Fast	Relativistic Physics	Quantum Field Theory

https://en.wikipedia.org/wiki/Capillary_wave#/media/File:2006-01-14_Surface_waves.jpg

Natural Units:

m_p ~ 1 GeV ~ 2 x 10^{-27} kg

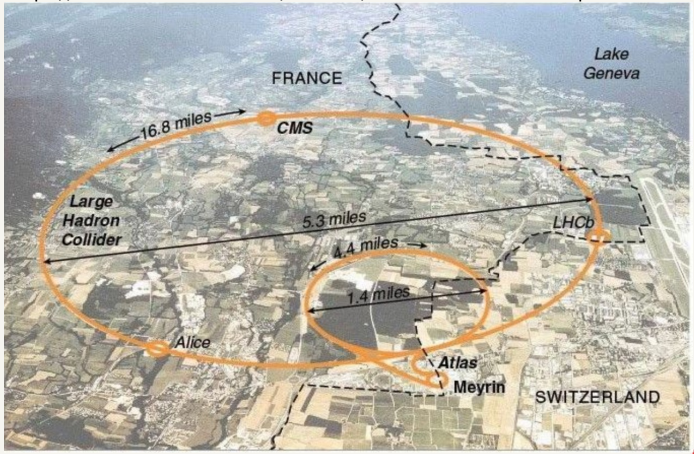
Energy = 1 GeV ~ 2 x 10^{-10} J

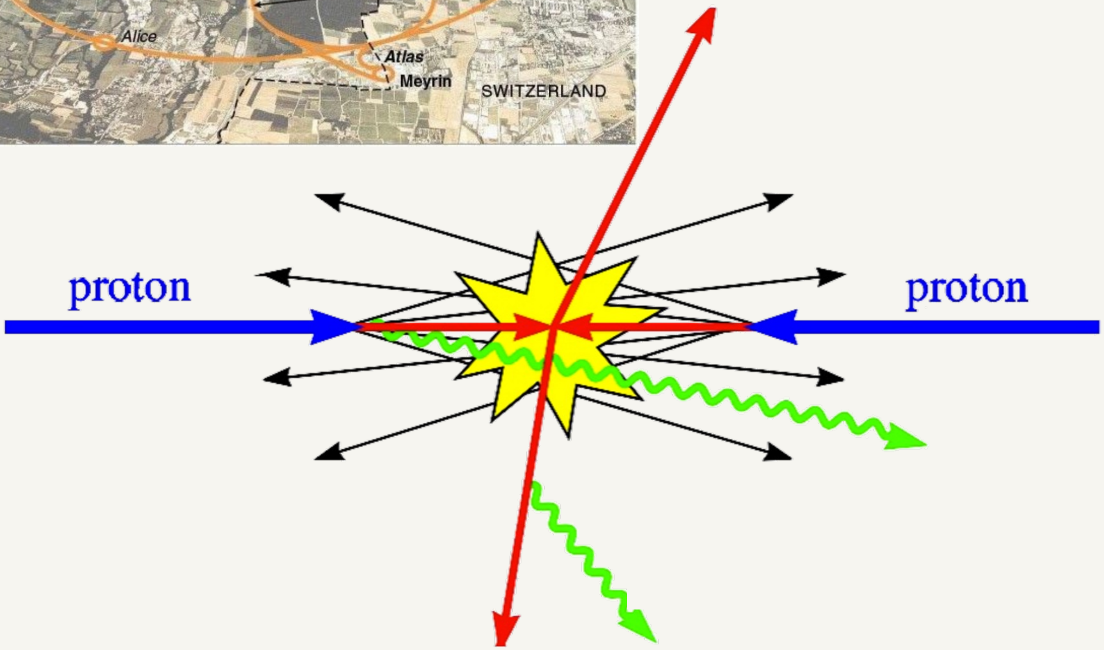
Length = GeV^{-1} ~ 0.2 x 10^{-15} m

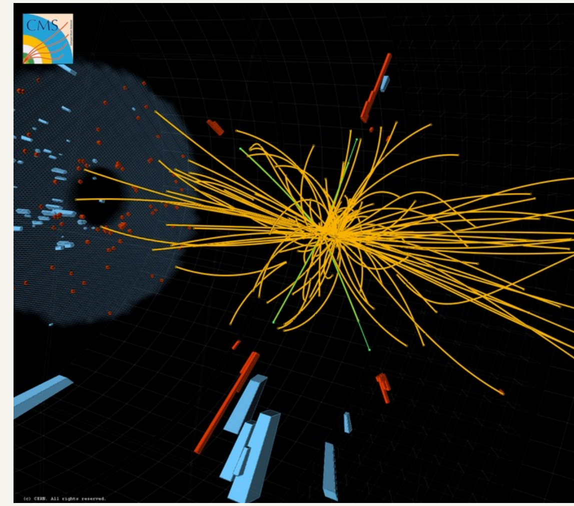
Time = GeV^{-1} ~ 10^{-25} s

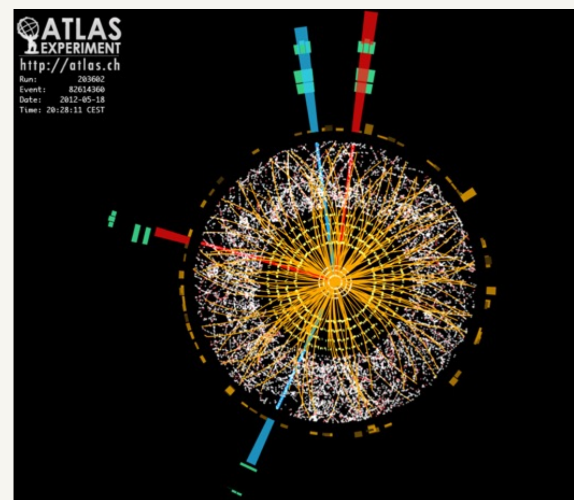
https://www.extremetech.com/extreme/210215-extremetech-explains-what-is-the-large-hadron-collider

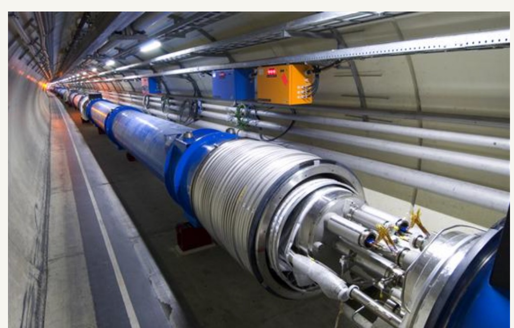
The Large Hadron Collider.



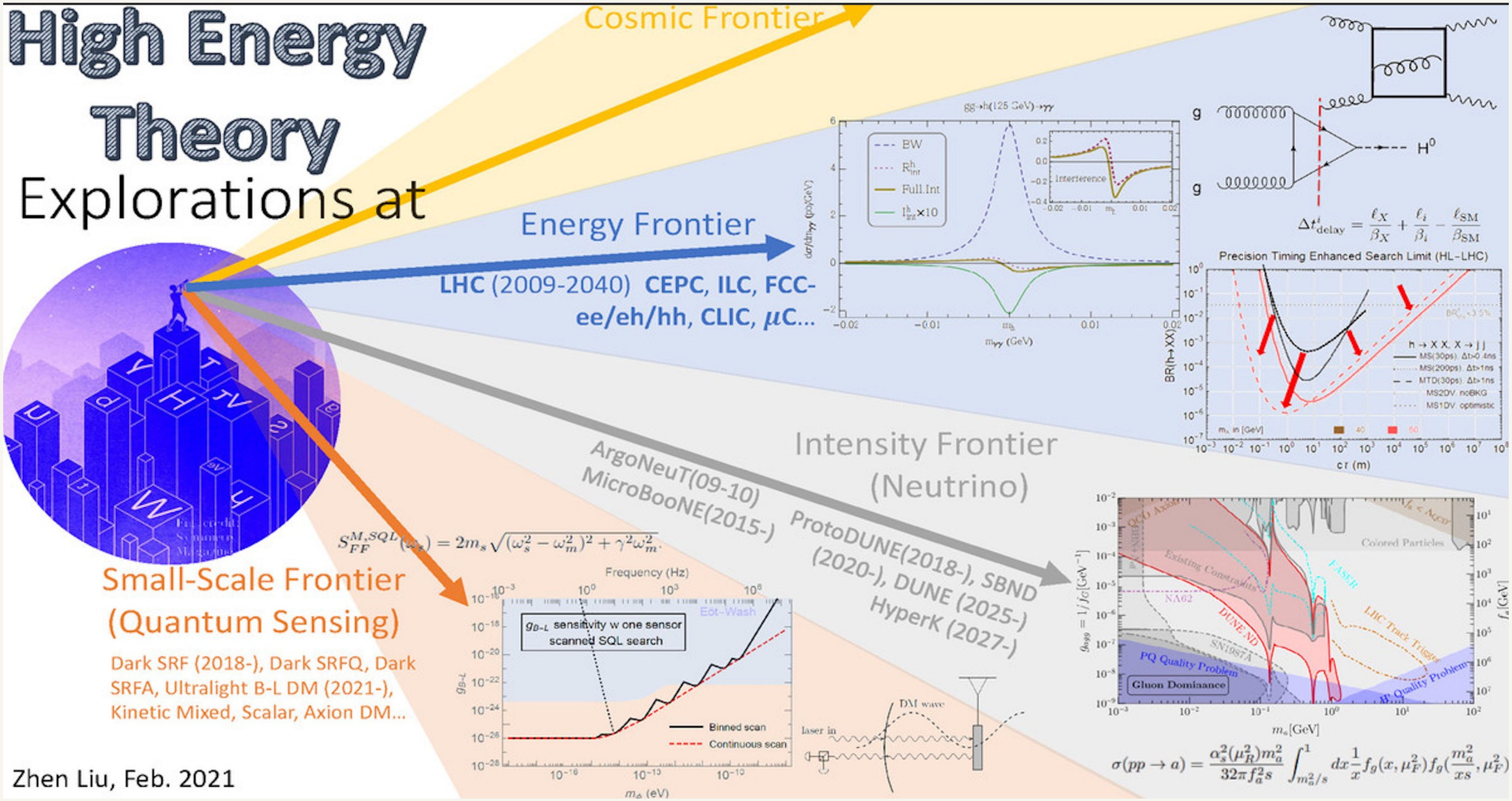


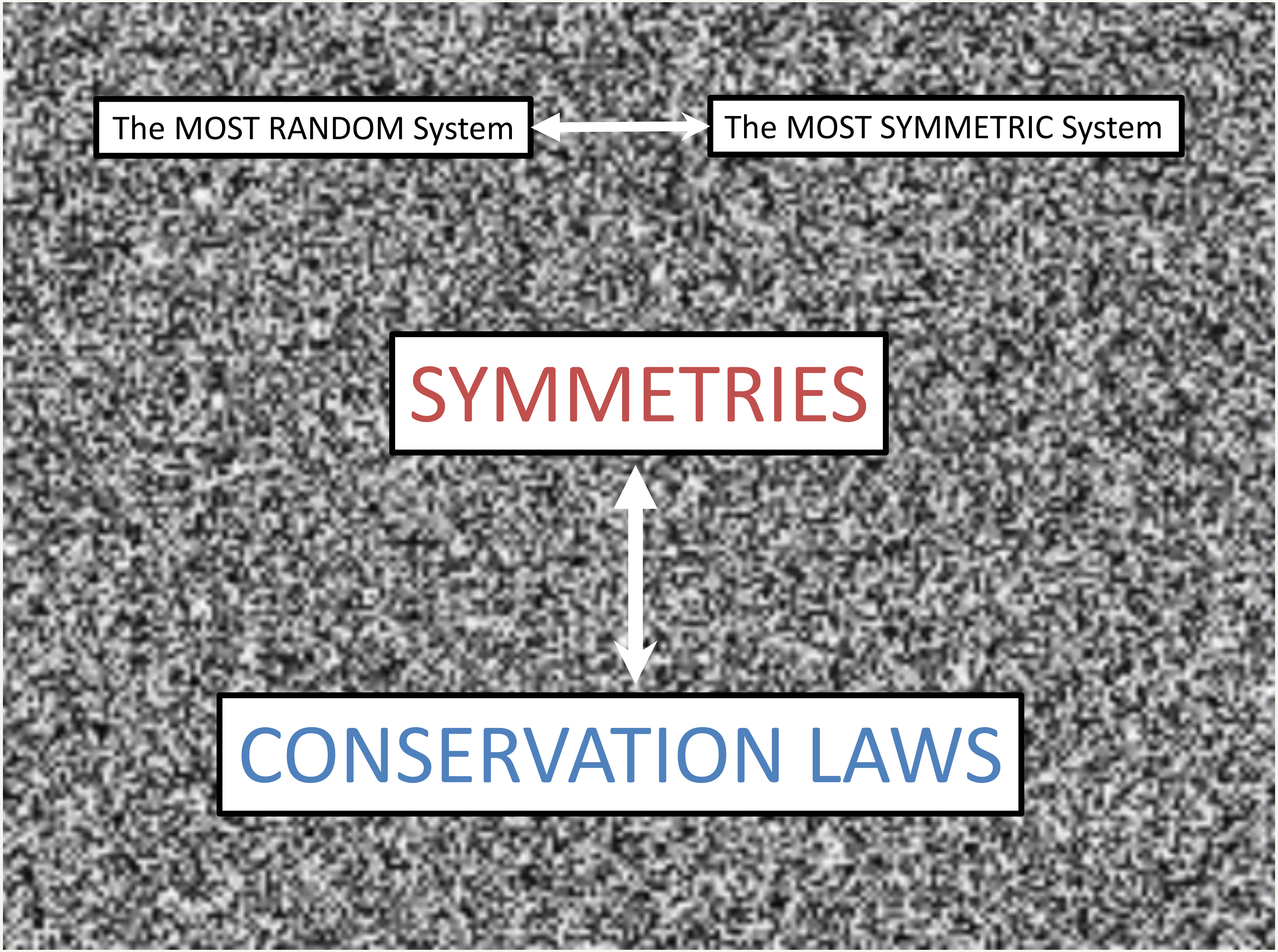




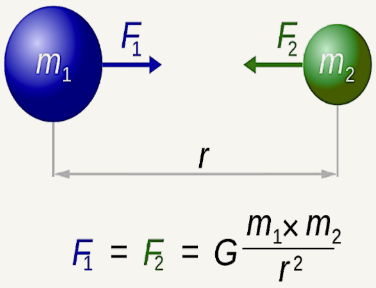


https://home.cern/resources/faqs/facts-and-figures-about-lhc


High Energy
Theory
Explorations at
Cosmic Frontier
Energy Frontier
LHC (2009-2040) CEPC, ILC, FCC-ee/eh/hh, CLIC, μC...
Intensity Frontier
(Neutrino)
ArgoNeuT(09-10)
MicroBooNE(2015-)
ProtoDUNE(2018-), SBND (2020-), DUNE (2025-)
HyperK (2027-)
Small-Scale Frontier
(Quantum Sensing)
Dark SRF (2018-), Dark SRFQ, Dark SRFA, Ultralight B-L DM (2021-), Kinetic Mixed, Scalar, Axion DM...
Zhen Liu, Feb. 2021
Precision Timing Enhanced Search Limit (HL-LHC)
Binned scan
Continuous scan
PQ Quality Problem
Gluon Dominance
Colored Particles
Existing Constraints
FASER
LHC Track Trigger
DUNE ND
NA62
Frequency (Hz)
Interference
laser in
DM wave

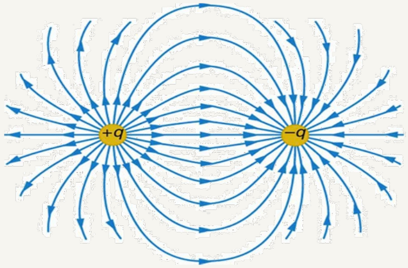

The MOST RANDOM System
The MOST SYMMETRIC System
SYMMETRIES
CONSERVATION LAWS

Forces in Nature.



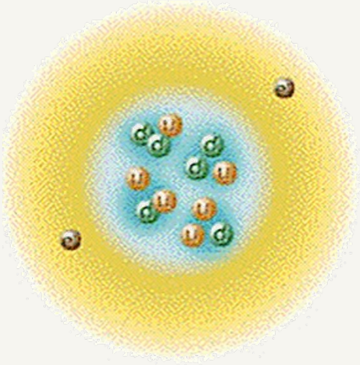
Gravity

Attractive force between two massive objects.



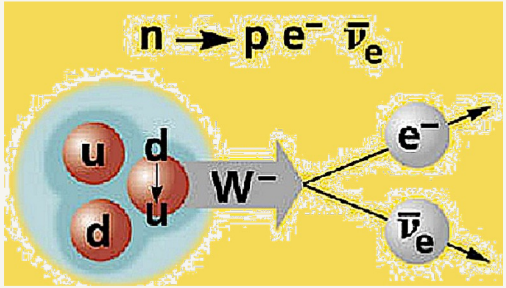
Electromagnetism

- Attracts particles of opposite charge, between and within atoms.
- Is mediated by photons.



Strong Force

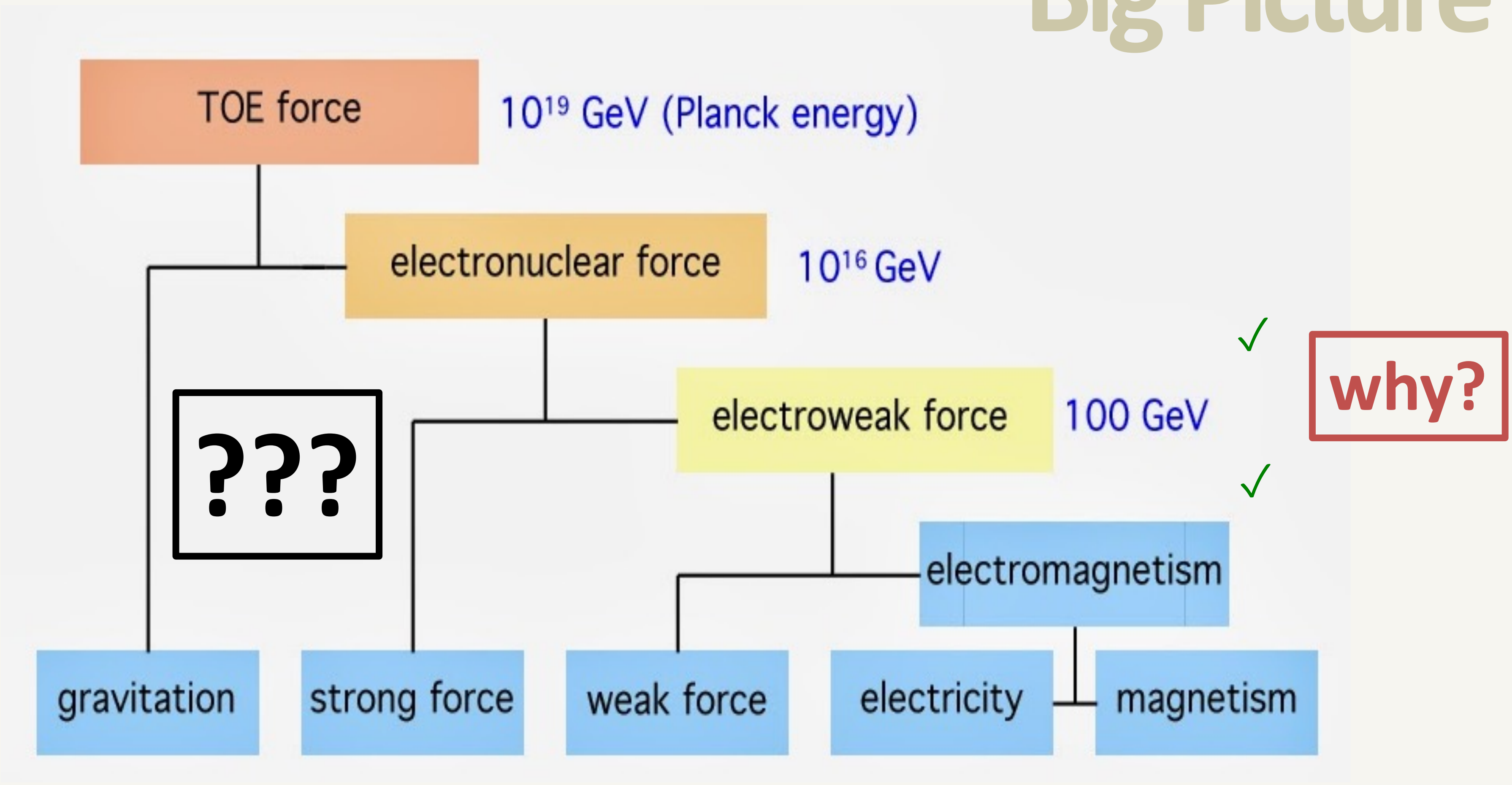
- Binds protons and neutrons to form atomic nuclei.
- proton: **uud**
- neutron: **udd**
- Formed by 3 quarks bound together by gluons of the strong interactions.



Weak Force

- Mediates particle transformations
- e.g., **β-Decay**
- Is mediated by massive W/Z bosons.

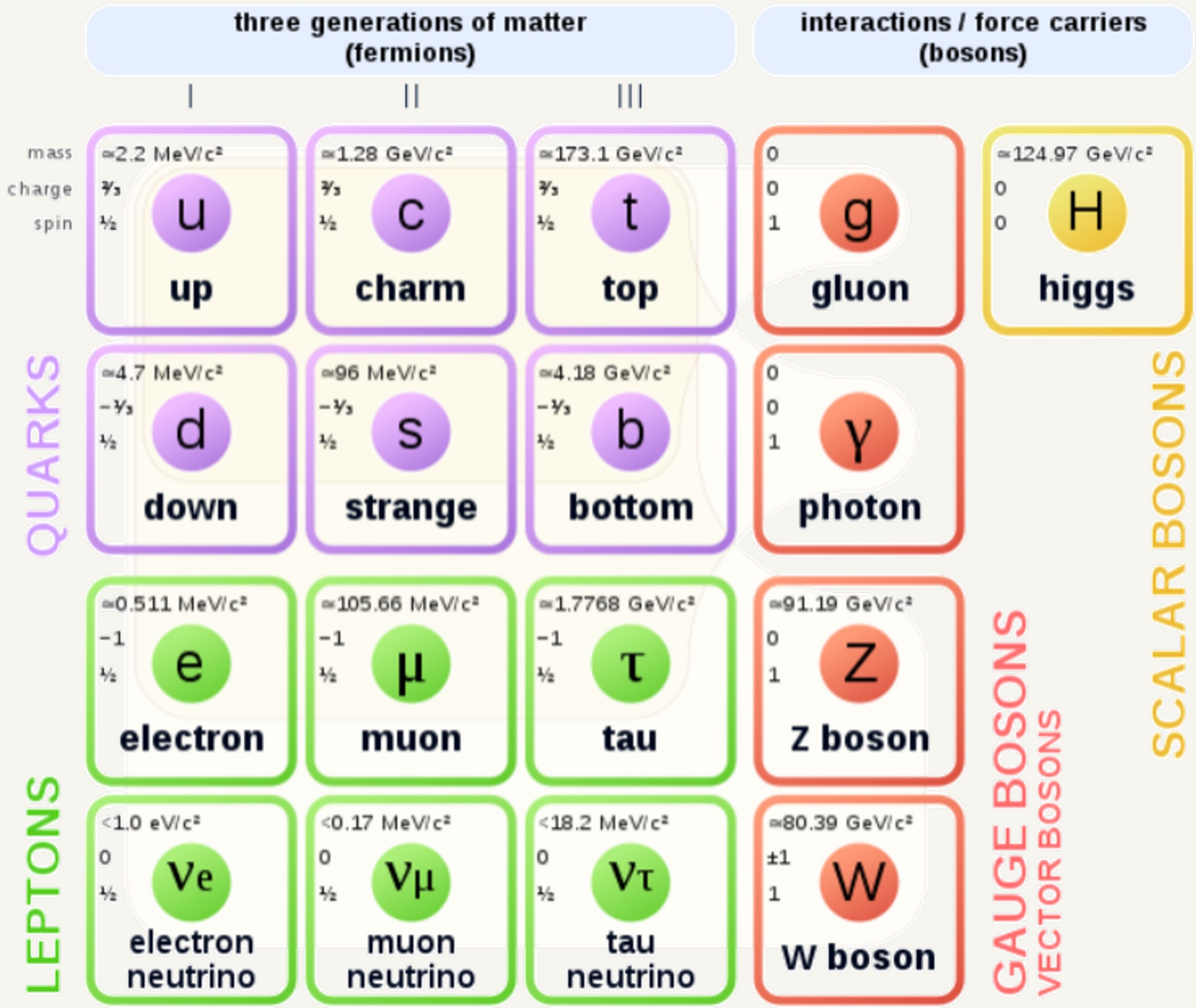
Big Picture



What is Dark Matter?

The Beloved *Beautiful* (& Unnatural)

Standard Model



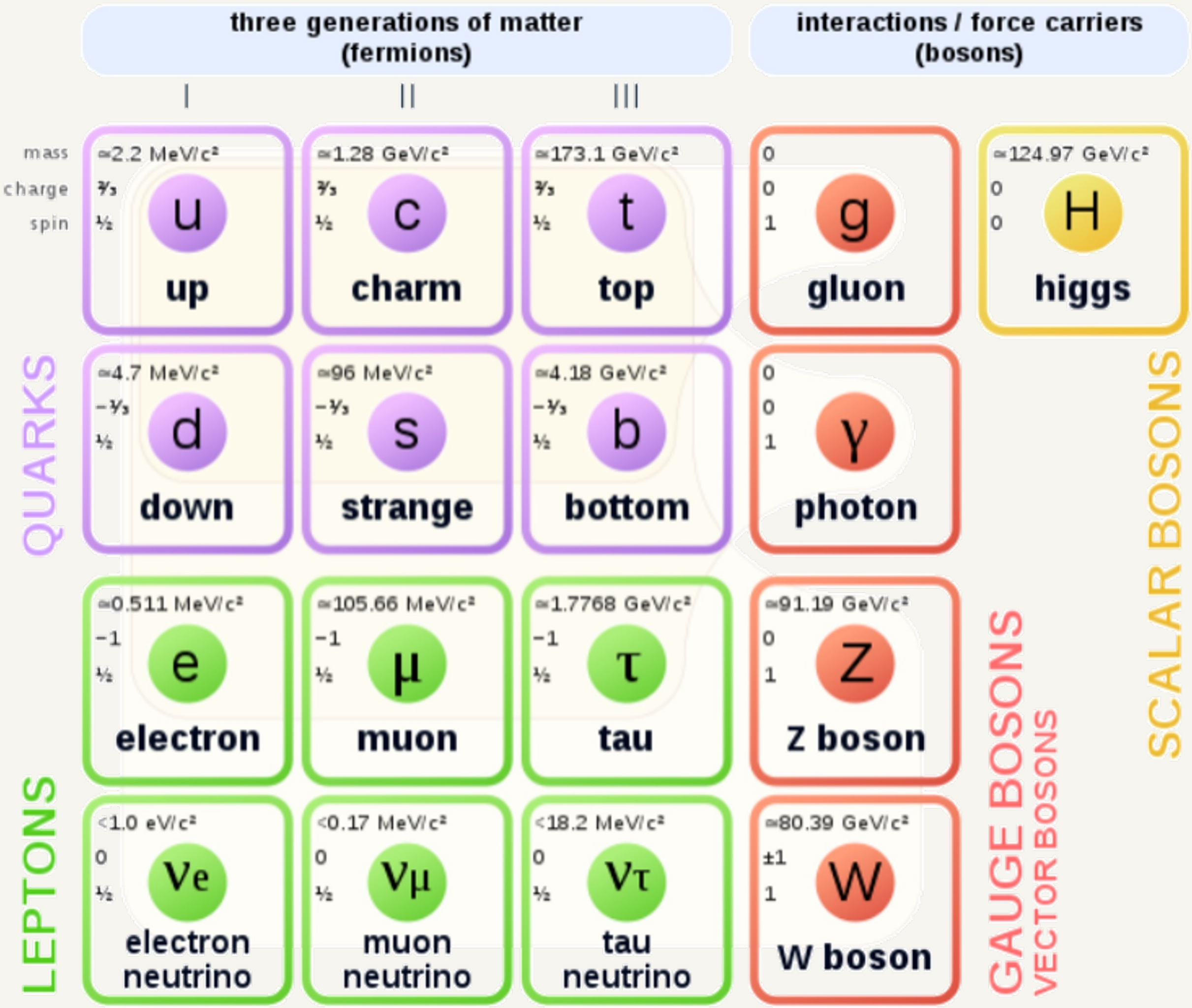
https://en.wikipedia.org/wiki/Elementary_particle

3 generations of matter
$SU(3)_C \times SU(2)_L \times U(1)_Y$

WHY????

The Beloved *Beautiful* (& Unnatural)

Standard Model



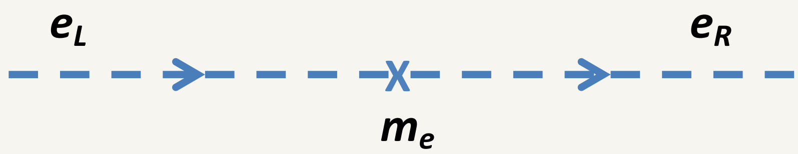
https://en.wikipedia.org/wiki/Elementary_particle

Non-Minimal
Unnatural

Arbitrary Content
Arbitrary Masses
Arbitrary Mixings

Arbitrary Higgs Mechanism

The Beloved *Beautiful* (& Unnatural) Standard Model



Only ***Left*** handed fermions charged under the weak SM gauge group.

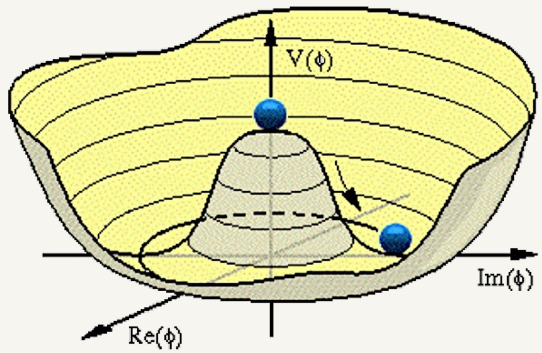
Fermion and gauge boson masses **FORBIDDEN** by symmetry.

Whatever gives rise to fundamental particle masses has to break electroweak symmetry (EWSB).

The Higgs Mechanism.

Spontaneous Breakdown of the symmetry:
$SU(2)_L \times U(1)_Y \rightarrow U(1)_{EM}$

A scalar (Higgs) field is introduced. The Higgs field acquires a nonzero value to minimize its energy.



$$V(\phi) = -m^2|\phi|^2 + \lambda|\phi|^4$$

Vacuum becomes source of energy
= a source of mass
$< H^0 > = v$

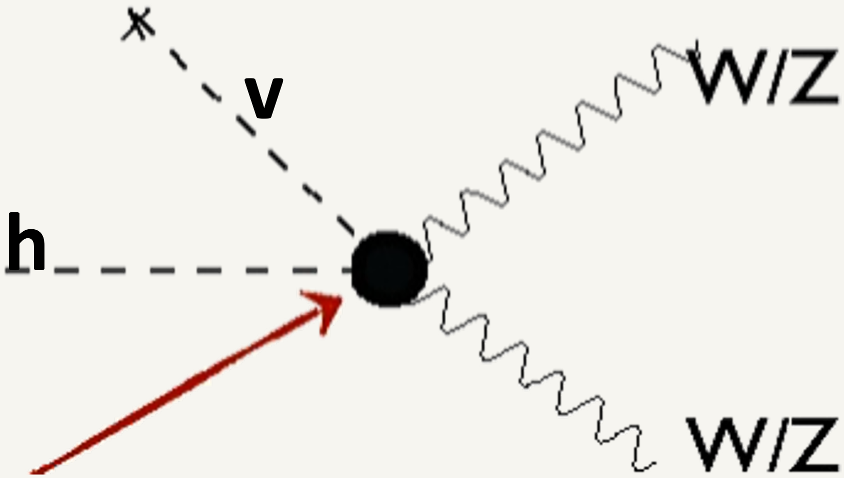
Masses of fermions and gauge bosons proportional to their couplings to the Higgs field:

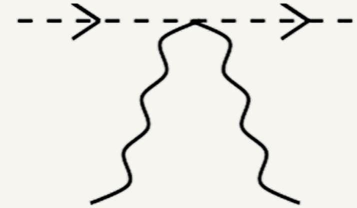
$M_{Z,W} = g_{Z,W}\, v$ $m_t = h_t\, v$ $m_h^2 = \lambda\, v^2$

v = 246 GeV

How do scalars interact with gauge bosons?

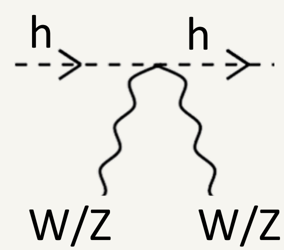
$$|D_\mu \phi|^2 = (\partial_\mu \phi + ieA_\mu \phi)(\partial^\mu \phi^* - ieA^\mu \phi^*)$$

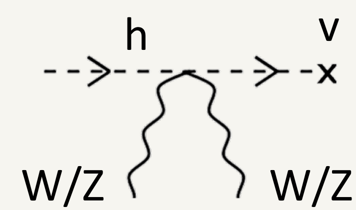


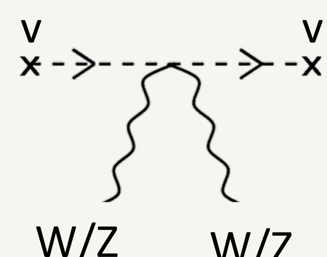


$$e^2 A^2 |\phi|^2$$

$$\phi \rightarrow h + v$$







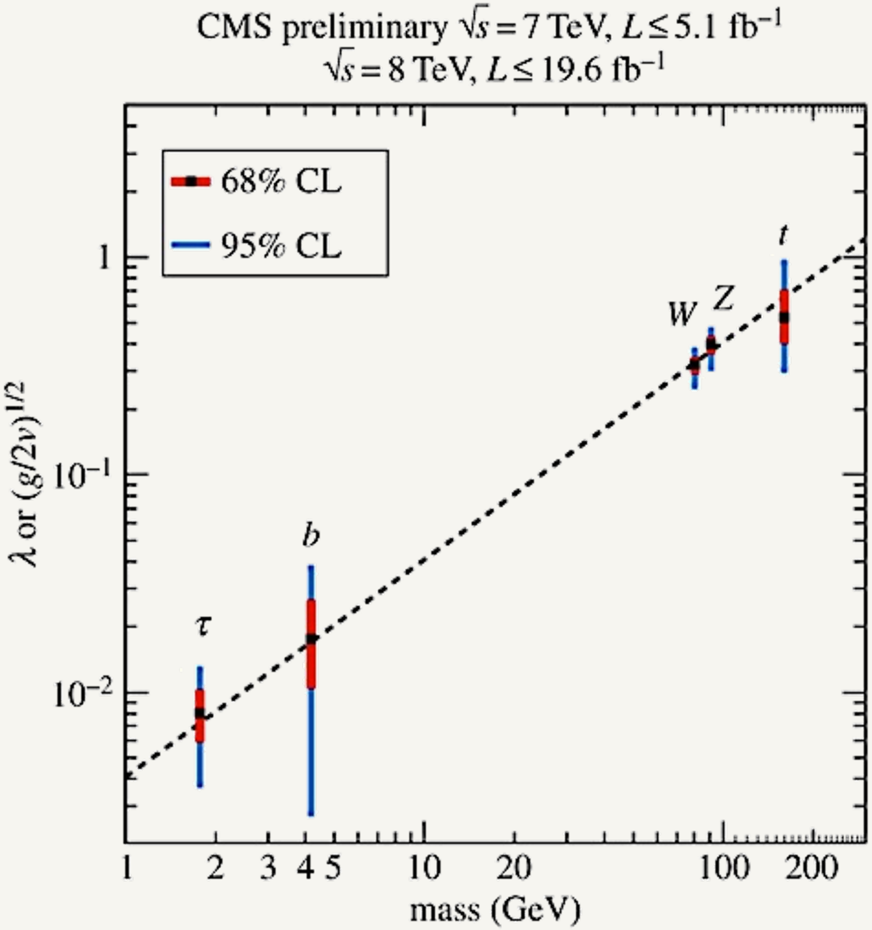
We have seen that the Higgs couples to W/Z, with approximately the right strength!!

SM-Like Higgs!

Higgs generates masses of the SM particles!

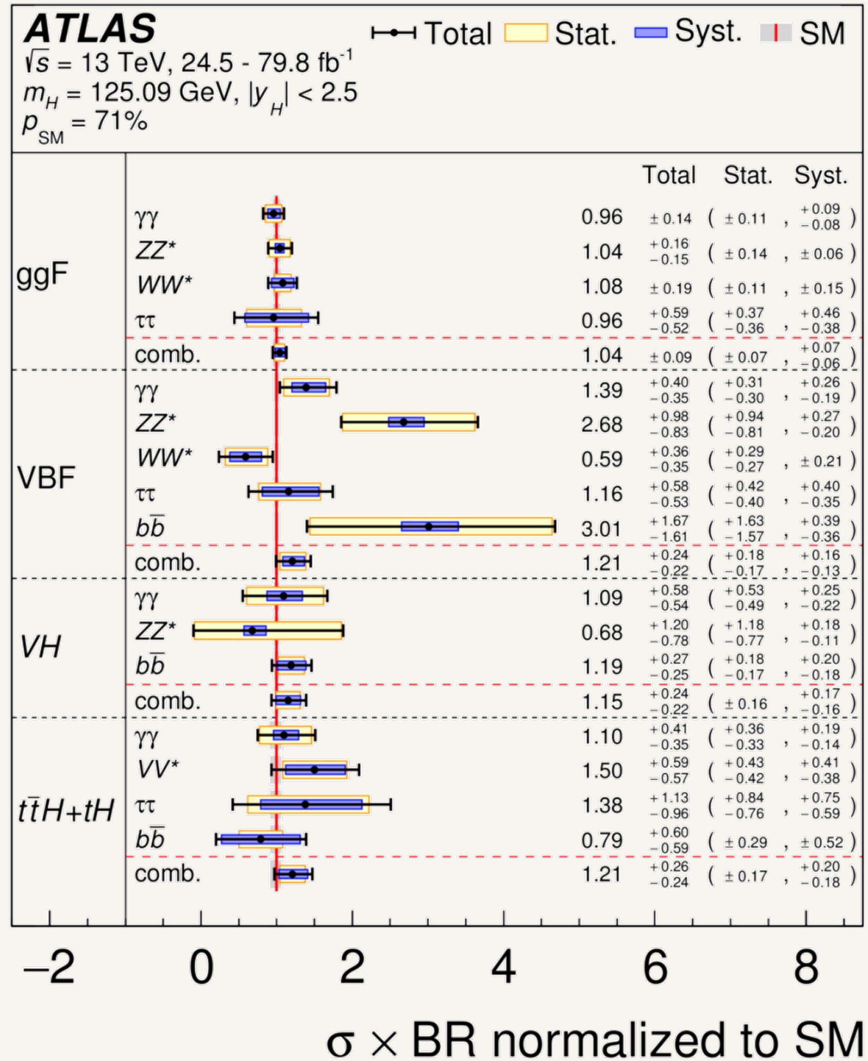
P. Higgs:

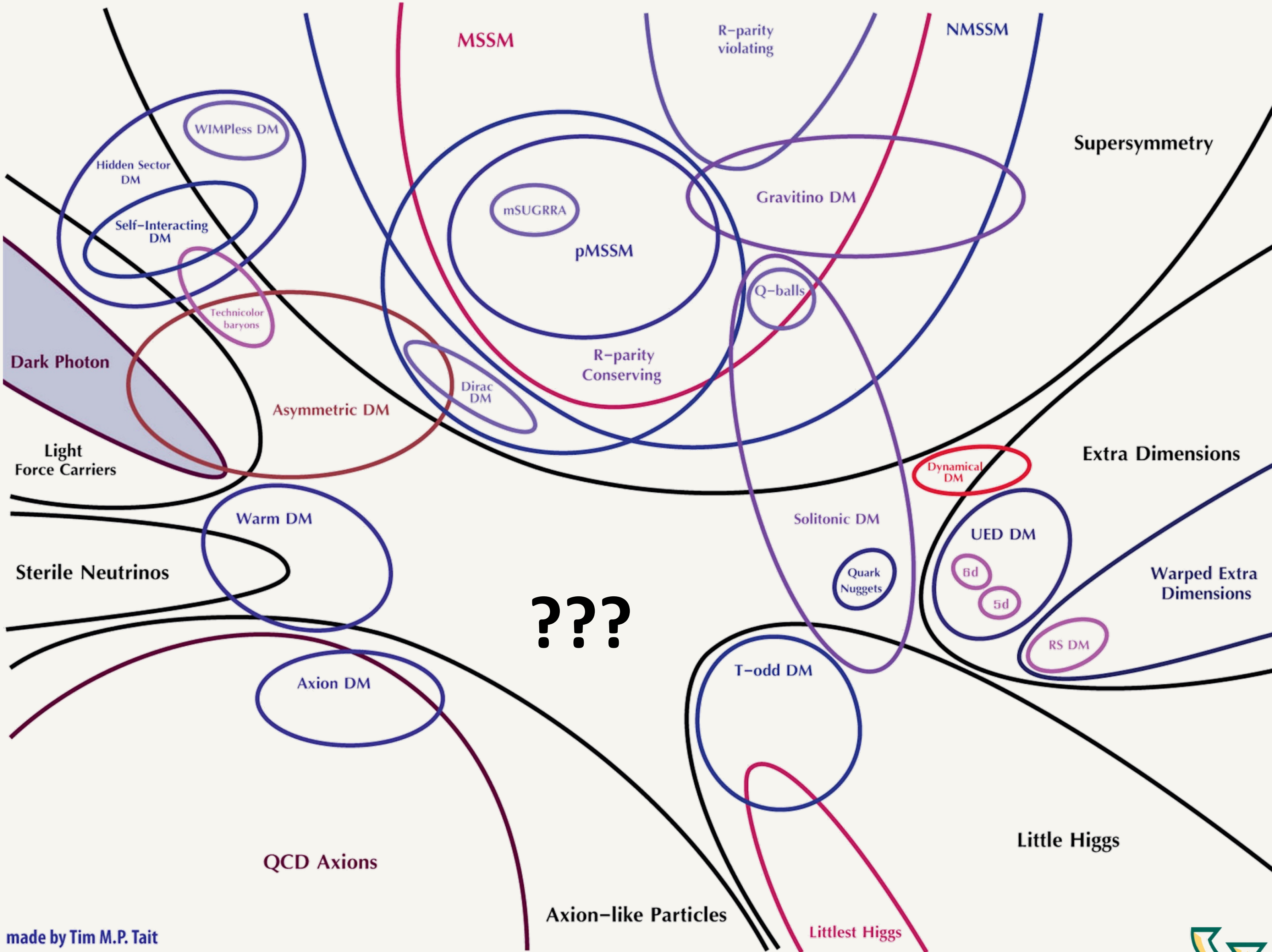
“My first paper was rejected because it was not relevant for phenomenology”



Still large uncertainties in couplings… but compatible with SM expectations.

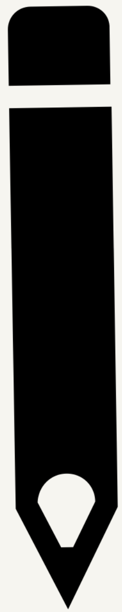
Observed Higgs Production x Branching Ratios as a ratio to SM expectation



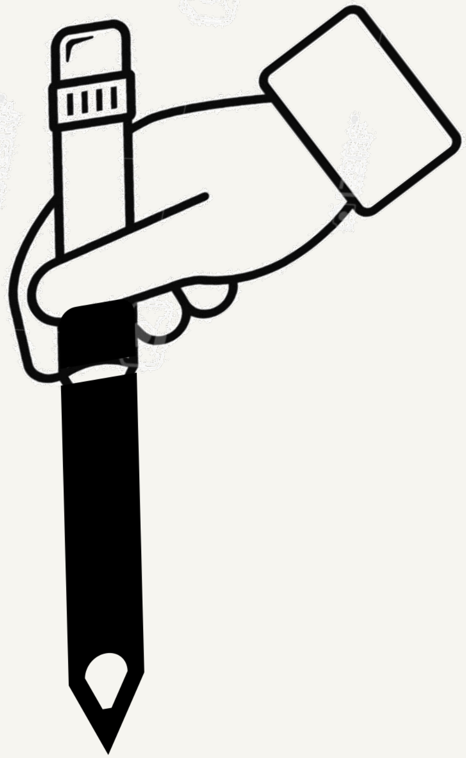

MSSM
R-parity violating
NMSSM
WIMPless DM
Hidden Sector DM
Self-Interacting DM
Technicolor baryons
mSUGRRA
pMSSM
Gravitino DM
Supersymmetry
Q-balls
Dark Photon
R-parity Conserving
Dirac DM
Asymmetric DM
Light Force Carriers
Dynamical DM
Extra Dimensions
Warm DM
Solitonic DM
UED DM
Sterile Neutrinos
Quark Nuggets
6d
5d
Warped Extra Dimensions
???
RS DM
T-odd DM
Axion DM
Little Higgs
QCD Axions
Axion-like Particles
Littlest Higgs
made by Tim M.P. Tait

UV Symmetries?

UV Structure?



Fine-Tuning ?



Prediction?

Accidental?

https://www.pinterest.com/pin/304978206018018128/

https://www.pinterest.com/pin/334744184798019537/?d=t&mt=login

Beyond the Standard Model with the Higgs.

SM Higgs is a Doublet

- The Higgs *FIELD* is a two component weakly charged doublet.
- *h* is the neutral particle we think we have observed at the LHC: h_{125}
- *v* is the SM vev: 246 GeV.
- $G^{+/-}$ and G^0 are "eaten" by the W and Z gauge bosons to give them mass.

$$H_{SM} = \frac{1}{\sqrt{2}} \begin{pmatrix} G^{\pm} \\ h + v + iG^0 \end{pmatrix}$$

Why do we want more???

More Doublets??

The Higgs vev generates the SM fermion masses

Large Hierarchy!!

Maybe because different Higgs vevs generate different masses?

This is what happens in Supersymmetric (SUSY) Models

SUSY requires AT LEAST TWO Higgs Doublets!

Maybe there are multiple extra dimensions?

Different Higgs Doublets get different vevs due to different warping in ED

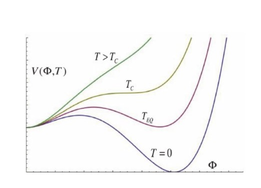
Consider a model of two Higgs doublets as a case study: 2HDM

Dark Higgs??

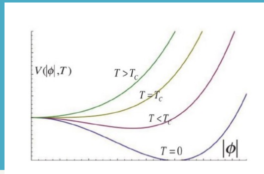
Scalar with no electric, weak or strong charge = SM Singlet S

Dark Matter has no electric or strong charge.
Singlets as Portal to Dark Matter?
Singlets as Dark Matter Candidates?

Matter-Antimatter asymmetry? Baryogenesis!
As the Universe cools down, Higgs field develops a vev.
For successful Baryogenesis, need first-order phase transition.



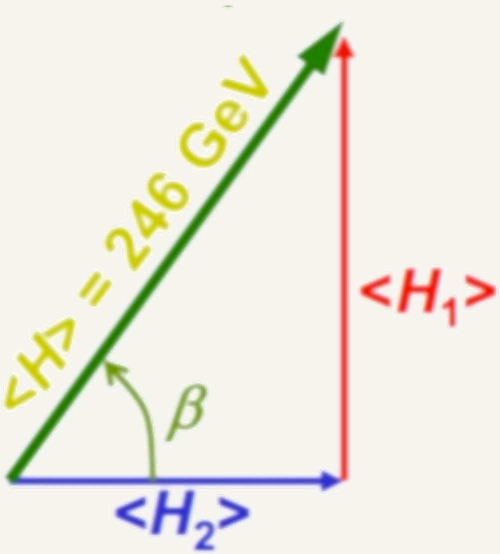
SM: Roll over
Singlets can make it happen!



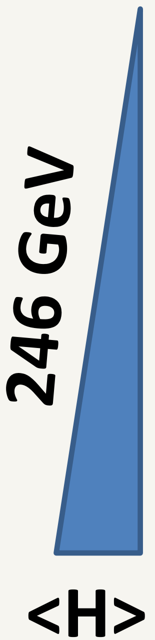
Consider 2HDM + S Higgs sector

But we SEE a SM-like Higgs!

2 Higgs Doublet Model (2HDM).



$\langle H_1 \rangle , \langle H_2 \rangle \to \langle H \rangle , \tan\beta$



$\langle h \rangle \sim \langle H_{SM} \rangle$

5 Physical Higgs bosons:

CP-Even: **h, H**

CP-Odd: **A**

Charged Higgs: $\mathbf{H^{+,-}}$

SM: Only 1 Higgs which then acquires a vev and leads to EWSB.

This is what we want!

ALIGNMENT

Recipe: SM-Like Higgs.

246 GeV

<H>

<h> ~ $\langle H_{SM} \rangle$

$v \sin^2 \beta$

$$H_{SM} = \sin\beta H_u + \cos\beta H_d$$

$v \cos^2 \beta$

$$H_{NSM} = -\cos\beta H_u + \sin\beta H_d$$

SM: Only 1 Higgs which then acquires a vev and leads to EWSB.

This is what we want!

Lighter (*h*) is 125 GeV SM-like Higgs.

Additional states can exist!

Additional States can be light!

Haber and Gunion, '03, M. Carena, I. Low, N.R.S. & C. Wagner, '13, A. Delgado, G. Nardini & M. Quiros, '13, N. Craig, J. Galloway & S. Thomas,'13, P. Dev, A. Pilaftsis '14, M. Carena, H. Haber, I. Low, N.R.S. & C. Wagner '14 & '15 etc....

$\langle H_d \rangle = v \cos\beta$

$\langle H_u \rangle = v \sin\beta$

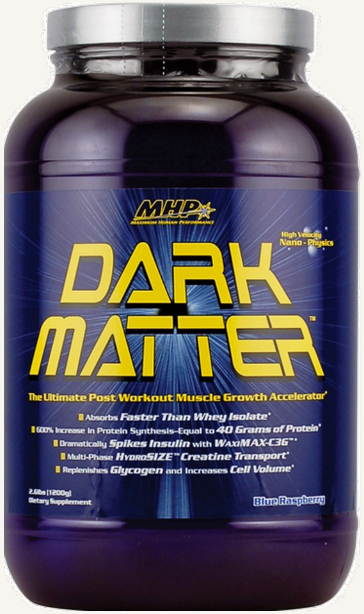
$\Rightarrow \langle H_{SM} \rangle = v$

$\langle H_{NSM} \rangle = 0$

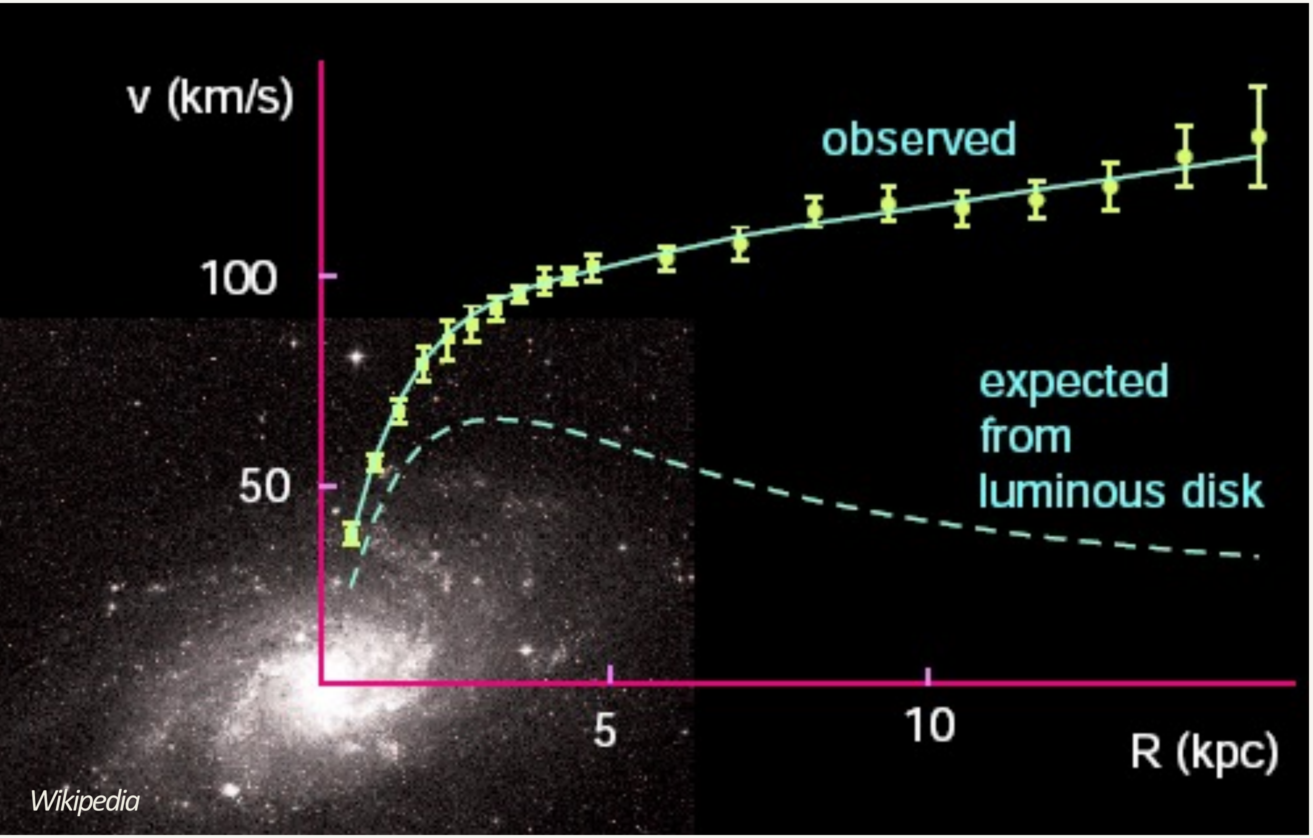
SM-like HIGGS

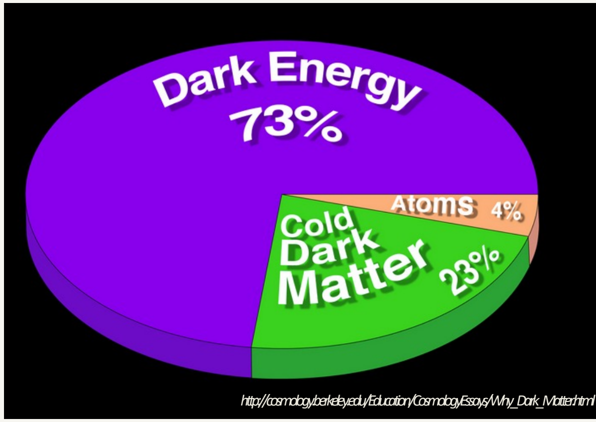
ALIGNMENT

What's the matter with Dark Matter: $35.99 online!



Welcome to the Dark Side!



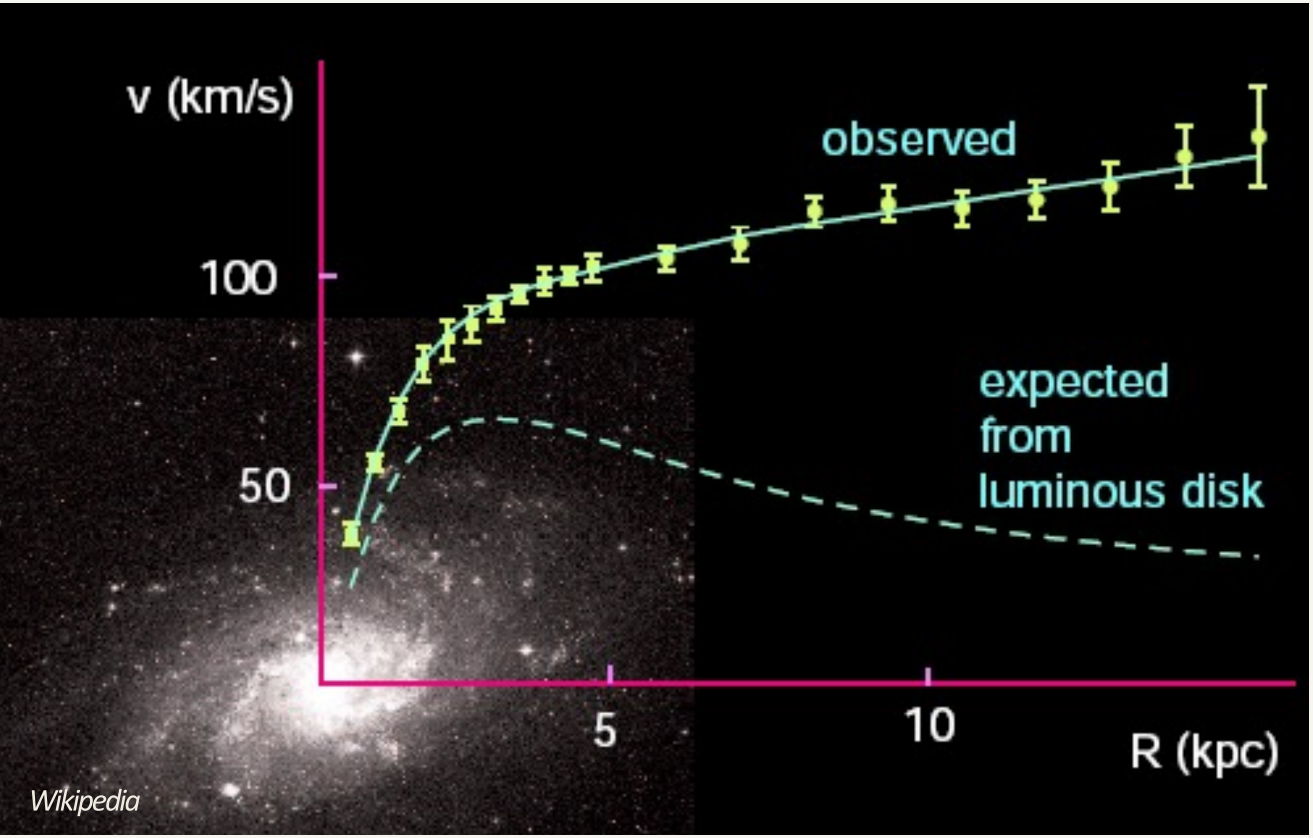


We know both A LOT and VERY LITTLE about Dark Matter

Experimental Observation: $\Omega h^2 = 0.1188 \pm 0.0011$

Planck 2015

Welcome to the Dark Side!



What is Dark Matter?

- No strong or EM interactions
- Interacts gravitationally
- Could interact weakly
- Stable on Universe lifetime scales

More than one DM species?

Higgs Interactions?

☹ Neutrinos?? Too Hot: No Structure formation

We know both A LOT and VERY little about Dark Matter

Experimental Observation: $\Omega h^2 = 0.1188 \pm 0.0011$

Thermal Relic?

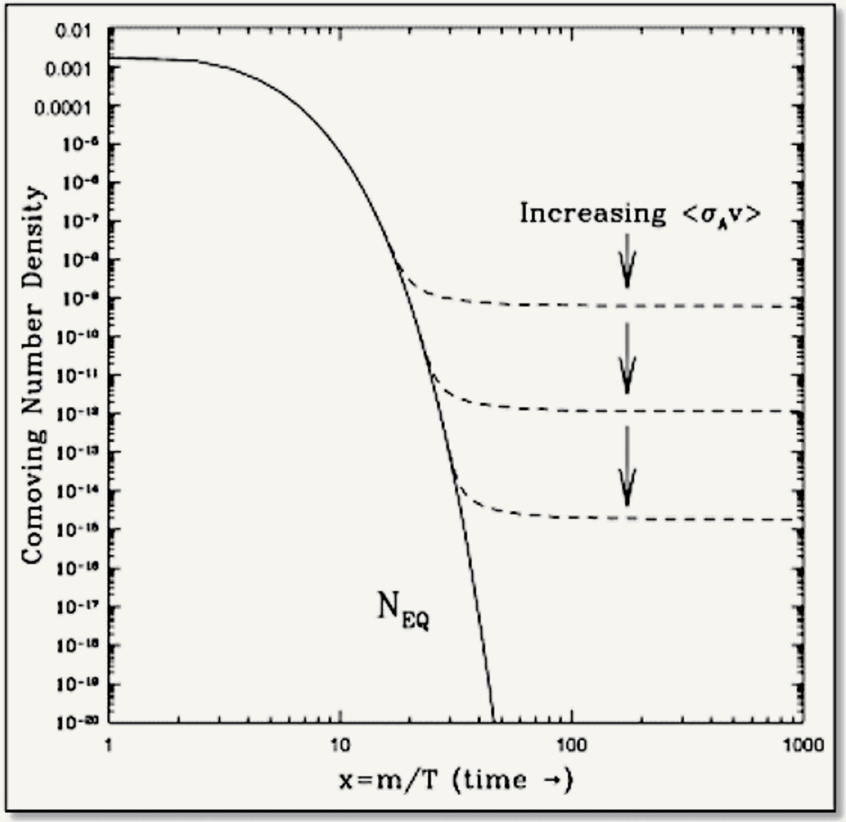
What sets the abundance of the Dark Matter observed?

Annihilations try to maintain thermal equilibrium.

Universe is Expanding!

At some point a DM particle can't "find" another DM particle to annihilate with: FREEZE-OUT.

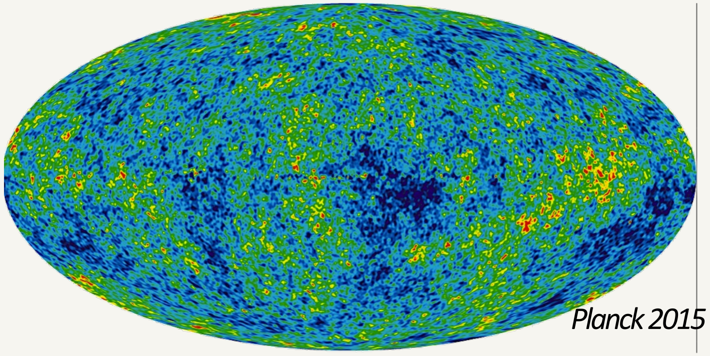
LARGER annihilation rate means LOWER number density.



Hooper, 09

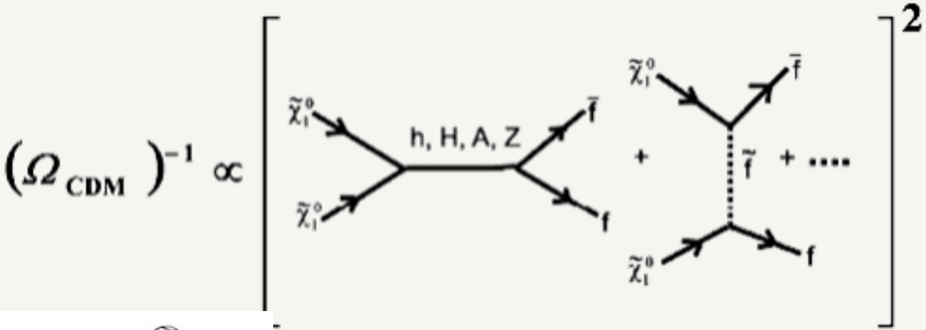
The WIMP Miracle.

$$\sigma = \frac{``\alpha"^2}{m^2}$$

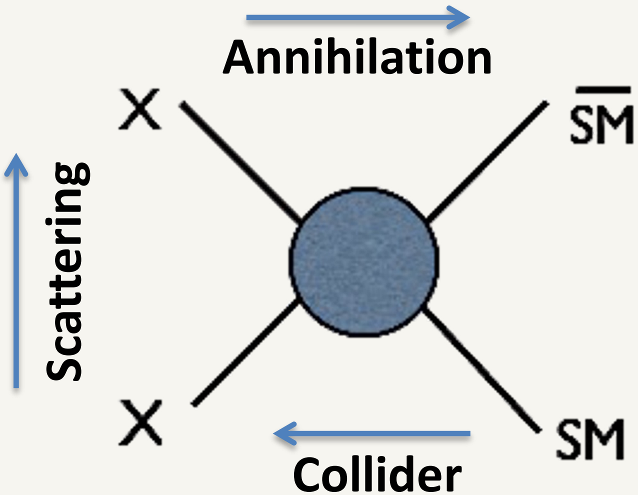


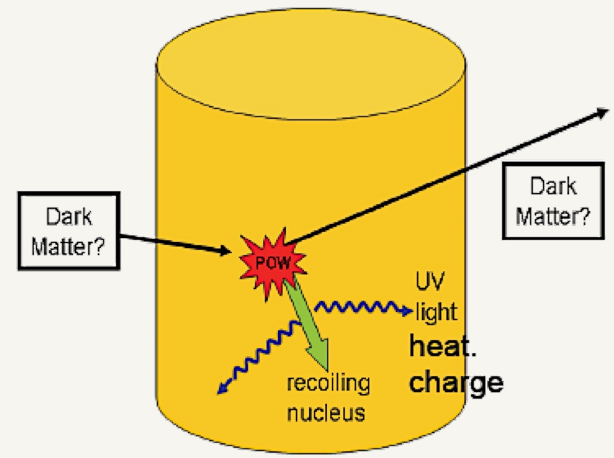
Planck 2015

Interestingly, the annihilation cross-section required to give rise to an observationally consistent relic density is naturally of the right order given weak scale couplings and masses (100 GeV) !



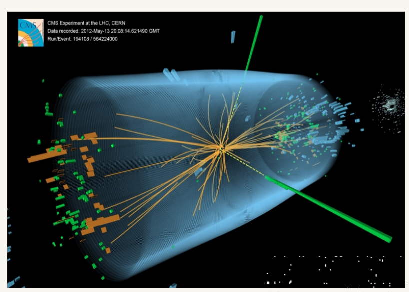
Break it!

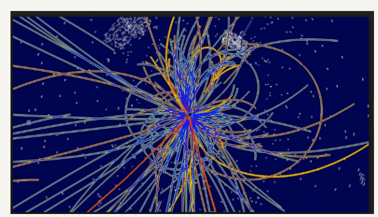




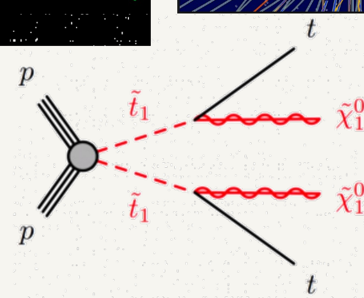
Underground detector

Shake it!

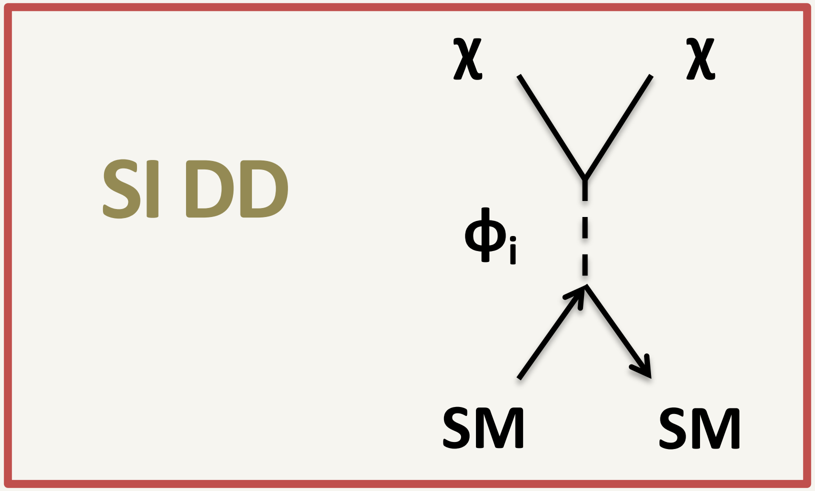


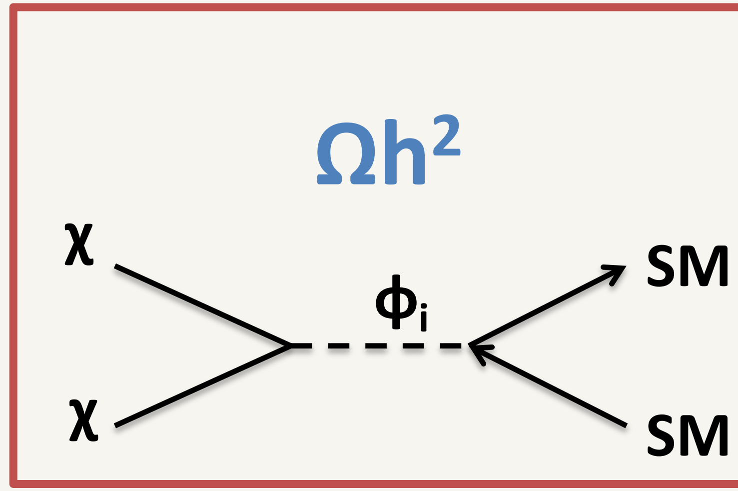


Make it!

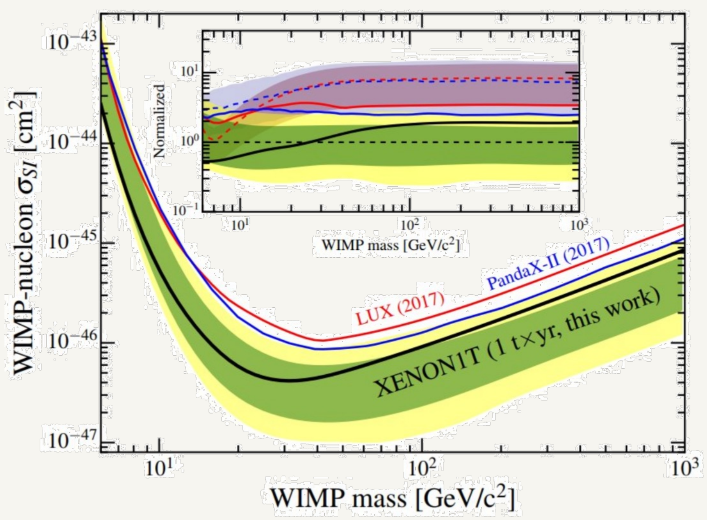


SI DD + Ωh^2 ??





XENON1T arXiv:1805.12562



m_χ ~ few 100 GeV

Break the Connection!

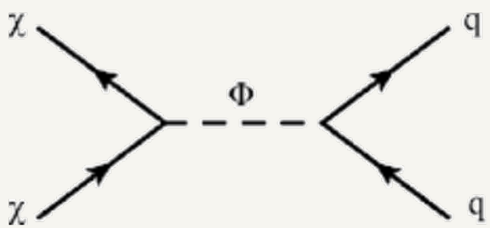
Co-annihilation/resonance

Multiple mediators for destructive interference

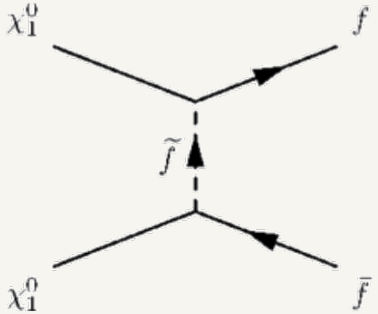
Relic Density: Annihilations

Stable "singlet" non-SM particle as Dark Matter candidate.

s-channel Resonance:
When the Dark Matter mass is close to a half of the mediating particle mass (eg: Higgs particle).
Highly constrained for the light Higgs..



LHC search bounds on Heavy Higgs seriously limit resonant annihilation of light Dark Matter.



*A*nnihilation via other new light weakly interacting particles.

NRS, Pierce, Freese'13

Relic Density: Co - Annihilations

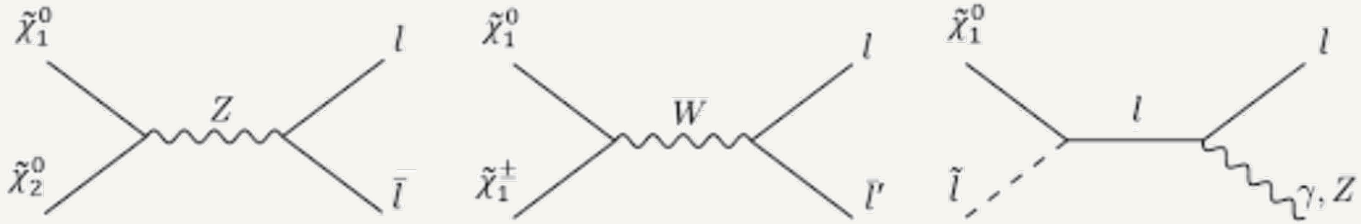
When Dark Matter can annihilate against other rapidly annihilating particles.

Mass difference of Dark Matter with the other weak scale weakly interacting particles must be of the order of a few tens of GeV.

Naturally leads to compressed spectrum

–> Reduced sensitivity at the LHC in the missing energy channel.

Some relevant channels:



Direct Detection

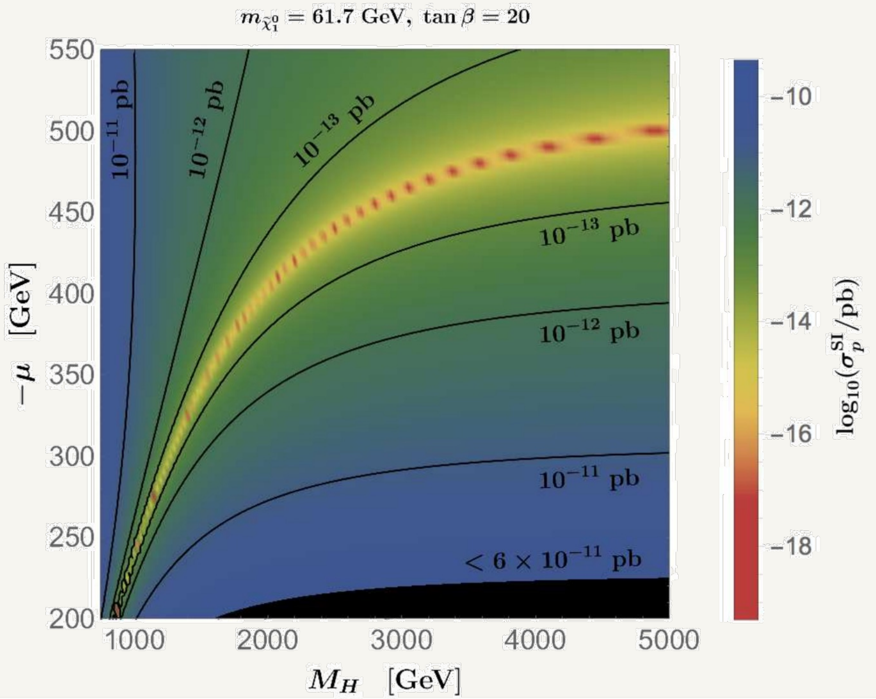
$$\sigma_p^{\rm SI} \propto \frac{m_Z^4}{\mu^4}\left[2(m_{\tilde{\chi}_1^0}+2\mu/\tan\beta)\frac{1}{m_h^2}+\mu\tan\beta\frac{1}{m_H^2}+(m_{\tilde{\chi}_1^0}+\mu\tan\beta/2)\frac{1}{m_{\tilde{Q}}^2}\right]^2$$

$$2\left(m_{\tilde{\chi}_1^0}+2\frac{\mu}{\tan\beta}\right)\frac{1}{m_h^2} \simeq -\mu\tan\beta\left(\frac{1}{m_H^2}+\frac{1}{2m_{\tilde{Q}}^2}\right)$$

$\mu \times m_{\tilde{\chi}^0} < 0$

$m_{\tilde{\chi}^0} \simeq M_1$

Cheung, Hall, Ruderman ‘12,
Huang, Wagner ‘14,
Cheung, Papucci, NRS, Stanford, Zurek ‘14,
Han, Liu, Makhapadhyay, Wang ‘18.



Carena, Osborne, NRS, Wagner, ‘18

Destructive interference between different Higgs exchanges.

Small spin independent DD can easily be obtained via such **blind spots**.

Spin Dependent DD mediated only by *Z!*
May be probed in the near future.

$$\sigma^{\rm SD} \propto \frac{m_Z^4}{\mu^4}\cos^2(2\beta)$$

The Beloved *Beautiful* (& Unnatural)

Standar… …del

Non-Minimal
Unnatural

Arbitrary Content
Arbitrary Masses
Arbitrary Mixings

Arbitrary Higgs Mechanism

https://en.wikipedia.org/wiki/Elementary_particle

$$\Delta a_\mu \equiv (a_\mu^{\text{exp}} - a_\mu^{\text{SM}}) = (251 \pm 59) \times 10^{-11}$$

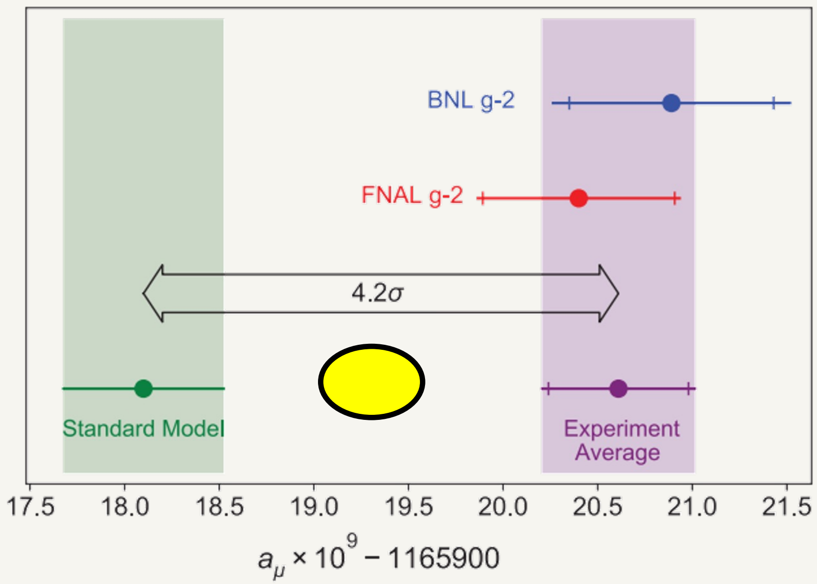
Flavor Anomalies!!

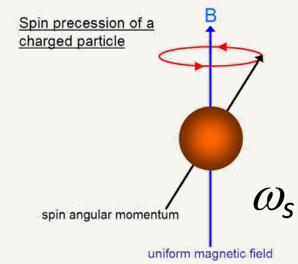
Fermilab Muon g-2

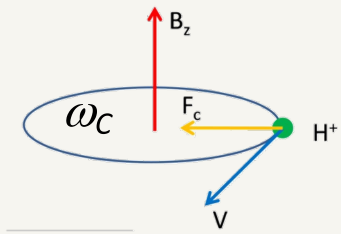
$(g_\mu - 2)/2 = 0.00116592061(41)$

FNAL Muon g-2, PRL Apr 2021.

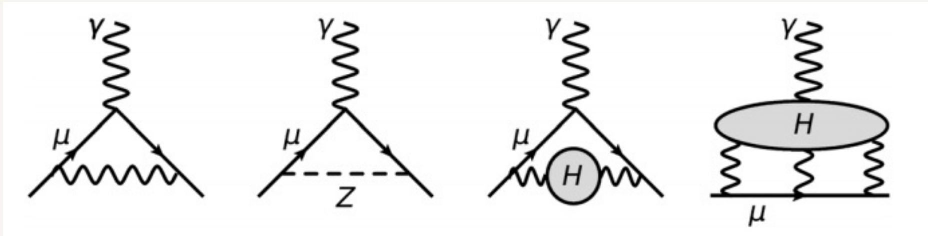
(New results to be announced Aug 10!)





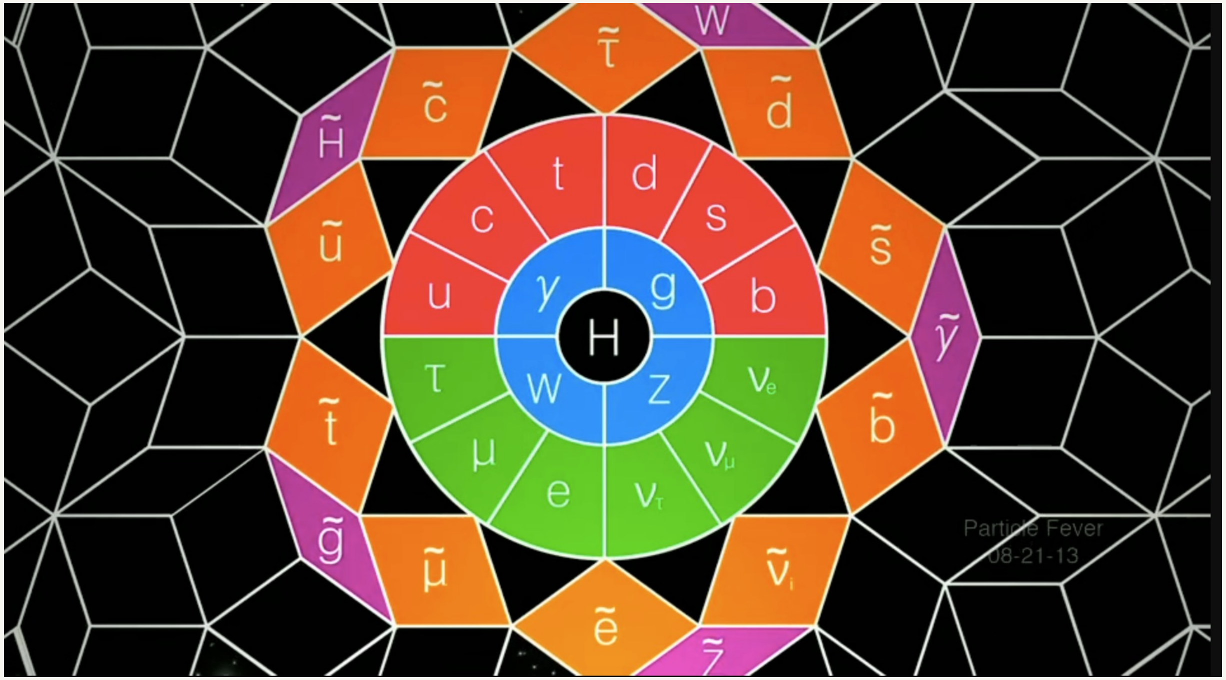


$$\omega_a = \omega_C - \omega_s = \left(\frac{g-2}{2}\right)\frac{qB}{m}$$



Anomalous magnetic moment of the Muon

“Particle Fever” – The movie



NOTORIOUS

SUPERSYMMETRY

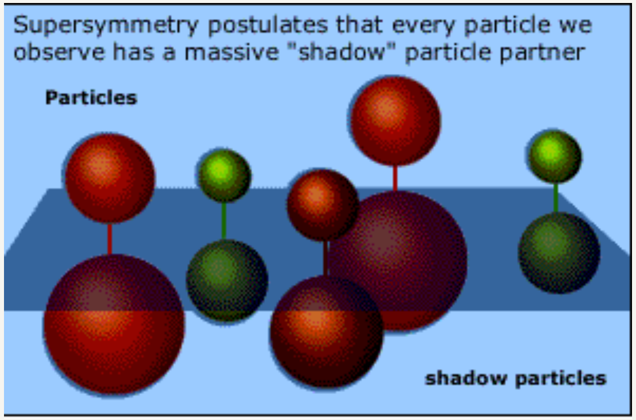
Supersymmetry:

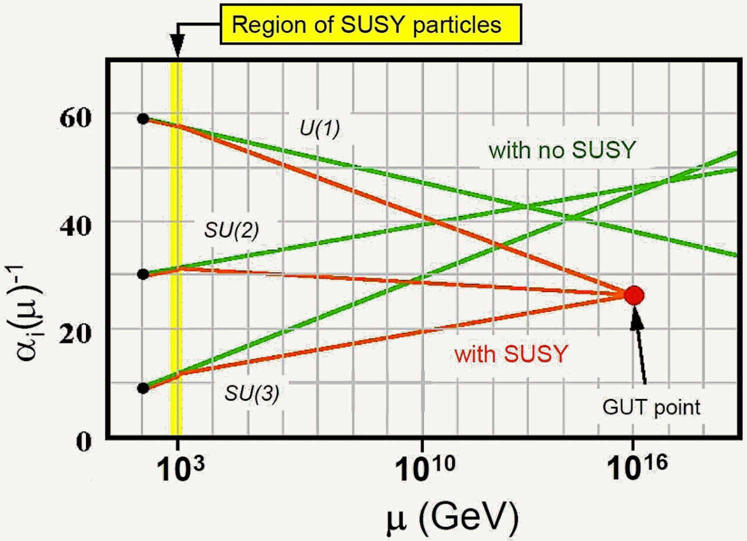
Explains hierarchy between the EW scale and the Planck/unification scales.

Generates electroweak symmetry breaking (EWSB).

Allows unification of electroweak and strong forces at energies ~10^{16} GeV.

Provides a good dark matter candidate: The Lightest SUSY Particle (LSP)





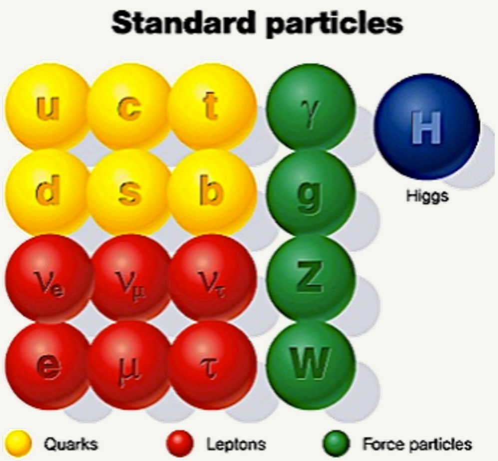
Minimal Supersymmetric SM (MSSM).

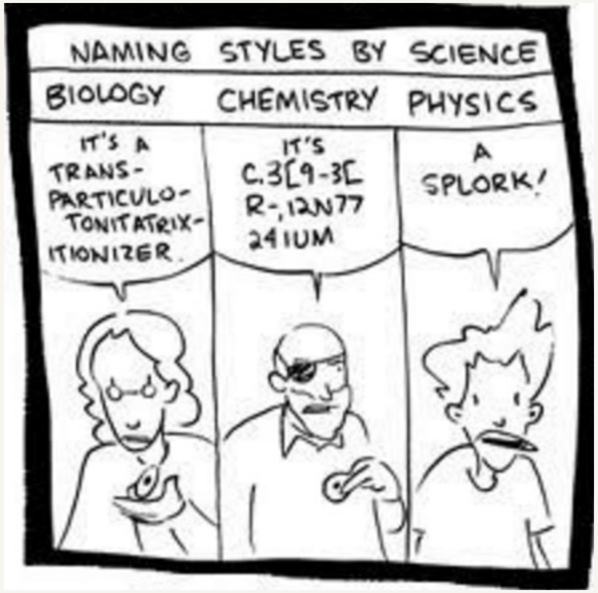
For every fermion there is a boson of equal mass and couplings and visa versa.

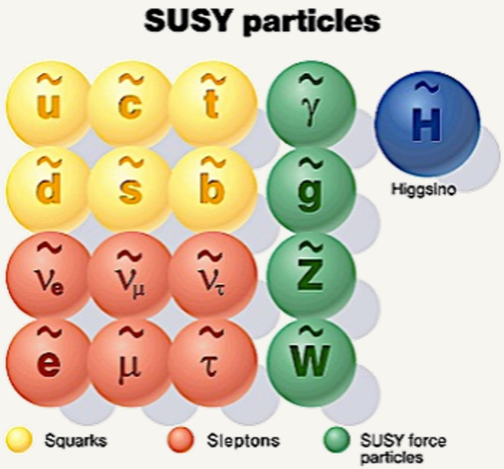
's'particles and 'inos ☺

No new couplings.

SUSY has to be broken.



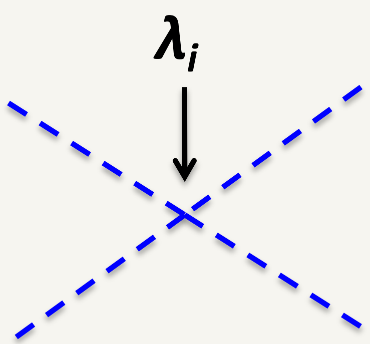




SUSY: 2HDM, Higgs Mass = 125 GeV.

$$V = m_{ij}^2 \Phi_i^\dagger \Phi_j + \lambda_i \Phi_j^\dagger \Phi_k \Phi_l^\dagger \Phi_m$$

H. Haber and J. Gunion, '03



Quartics without quantum corrections related only to SM couplings.

Higgs mass bounded by m_Z at tree-level.

91 ≠ 125

Need large radiative corrections.
…Or something else?
BOTH possible!
STOPS & SINGLETS

Charginos/Neutralinos & Sleptons...

SM Gauge Bosons, Higgs (2HDM in SUSY) and leptons Superpartners	→	Bunch of weakly coupled scalars, neutral Majorana fermions, lightest stable due to R-parity: **WIMP!**
B: SU(2) singlet		Bino M_1 g_1
$\{W^0, W^1, W^2\}$: SU(2) triplet		Winos M_2 g_2 1 neutral, 2 charged
$\{H_u\ H_d\}$: SU(2) doublets		Higgsinos μ Yukawas etc 2 neutral, 2 charged
$\{e, \mu, \tau\}$		Selectron, smuon, staus $M_{\mu L,R}$ etc SM couplings

MSSM: 4 neutral "Neutralinos", mixtures of interaction states (Also 2 charged "Charginos" mixtures of wino and Higgsinos).

$$\chi = N_{11}\tilde{B} + N_{12}\tilde{W} + N_{13}\tilde{H}_d + N_{14}\tilde{H}_u$$

(g$_\mu$ -2) has two contributions:

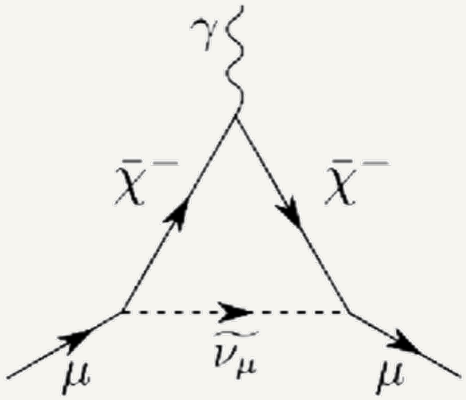
the Bino one, proportional to **(μ x M$_1$)**

the chargino proportional to (**μ x M$_2$**)

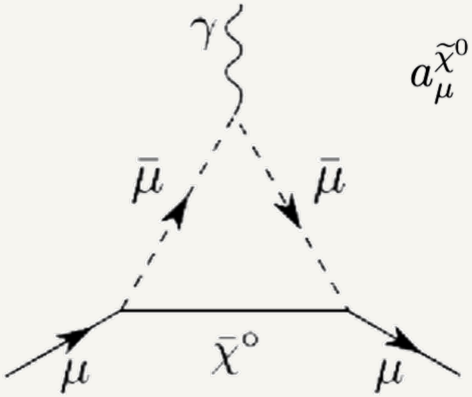
$(g_\mu - 2)$?

Dominant Contributions:

Barbieri, Maiani,'82; Ellis et al,'82; Grifols and Mendez,'82; Moroi,'95; Carena, Giudice, Wagner, '95; Martin and Wells, '00 …



$$a_\mu^{\tilde{\chi}^\pm - \tilde{\upsilon}_\mu} \simeq \frac{\alpha m_\mu^2 \mu M_2 \tan\beta}{4\pi \sin^2\theta_W m_{\tilde{\upsilon}_\mu}^2} \left[\frac{f_{\chi^\pm}\left(M_2^2/m_{\tilde{\upsilon}_\mu}^2\right) - f_{\chi^\pm}\left(\mu^2/m_{\tilde{\upsilon}_\mu}^2\right)}{M_2^2 - \mu^2} \right]$$

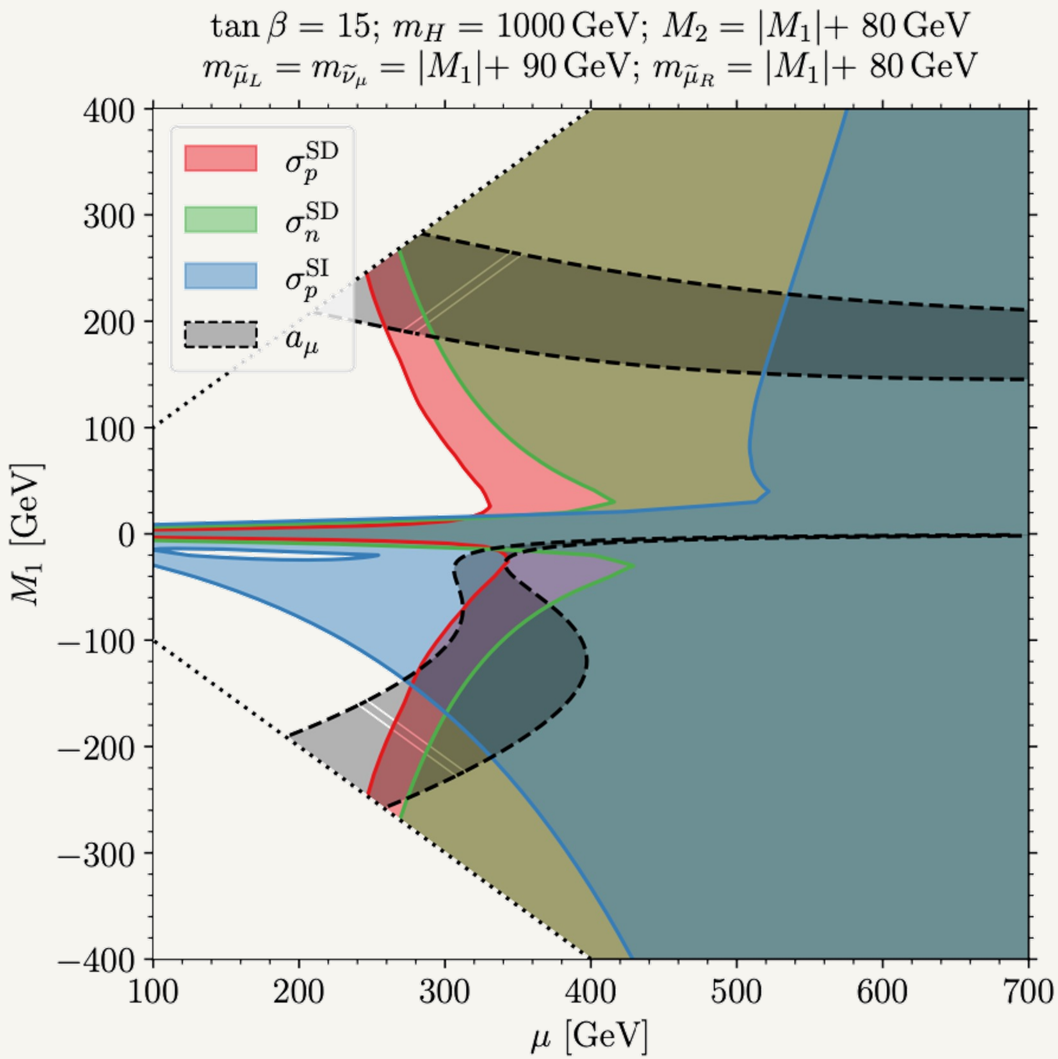


$$a_\mu^{\tilde{\chi}^0 - \tilde{\mu}} \simeq \frac{\alpha m_\mu^2 M_1 \left(\mu \tan\beta - A_\mu\right)}{4\pi \cos^2\theta_W \left(m_{\tilde{\mu}_R}^2 - m_{\tilde{\mu}_L}^2\right)} \left[\frac{f_{\chi^0}\left(M_1^2/m_{\tilde{\mu}_R}^2\right)}{m_{\tilde{\mu}_R}^2} - \frac{f_{\chi^0}\left(M_1^2/m_{\tilde{\mu}_L}^2\right)}{m_{\tilde{\mu}_L}^2} \right]$$

Interplay between contributions

Baum, Carena, NRS, Wagner, arXiv:2104.03302

A Qualitative Picture



Shaded regions are **allowed**.

μ: Higgsino
M_1: Bino

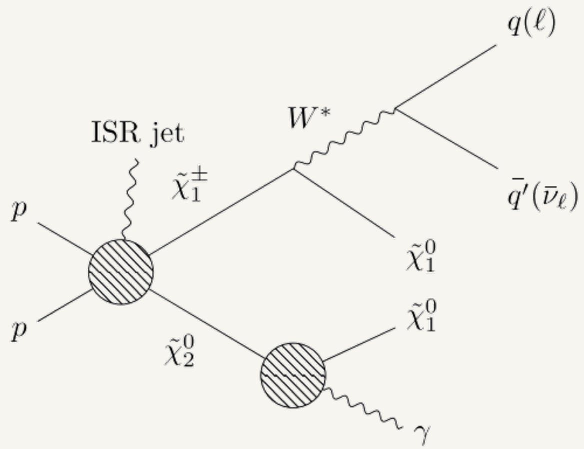
$\mu < 500$ GeV for $M_1 < 0$

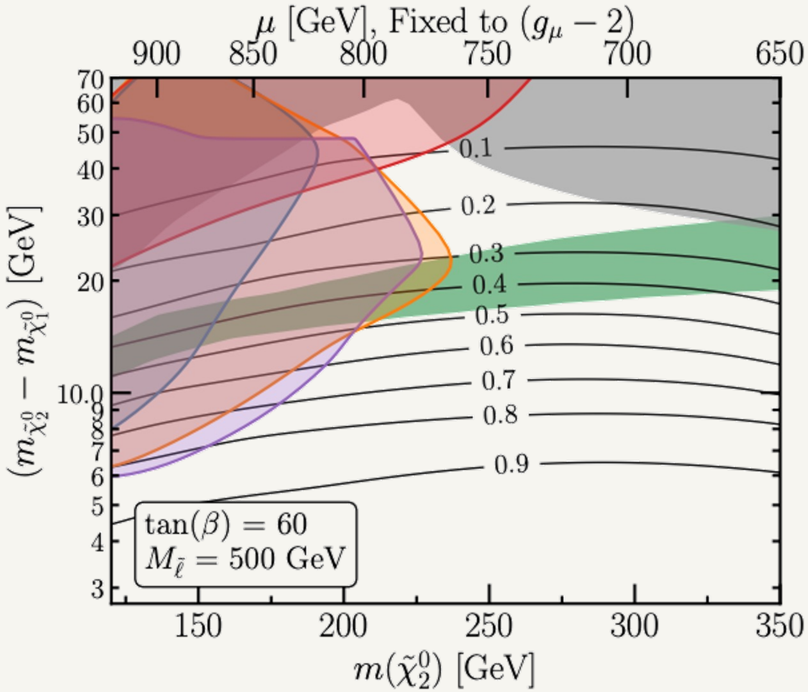
Compatibility of Direct Detection and (g_μ - 2) Constraints for a representative example of a compressed spectrum. Stau co-annihilation is assumed

Lighting up the LHC with Dark Matter

Baum, Carena, Ou, Rocha, NRS, Wagner, arXiv:2303.01523

Compressed region leads to new possible signatures at the LHC with photon and missing energy!





Green: Correct relic density

Other shaded regions excluded by experiment

Large branching fractions into photons (labeled contours) !!

Many Avenues to Explore

Rich BSM phenomenology:

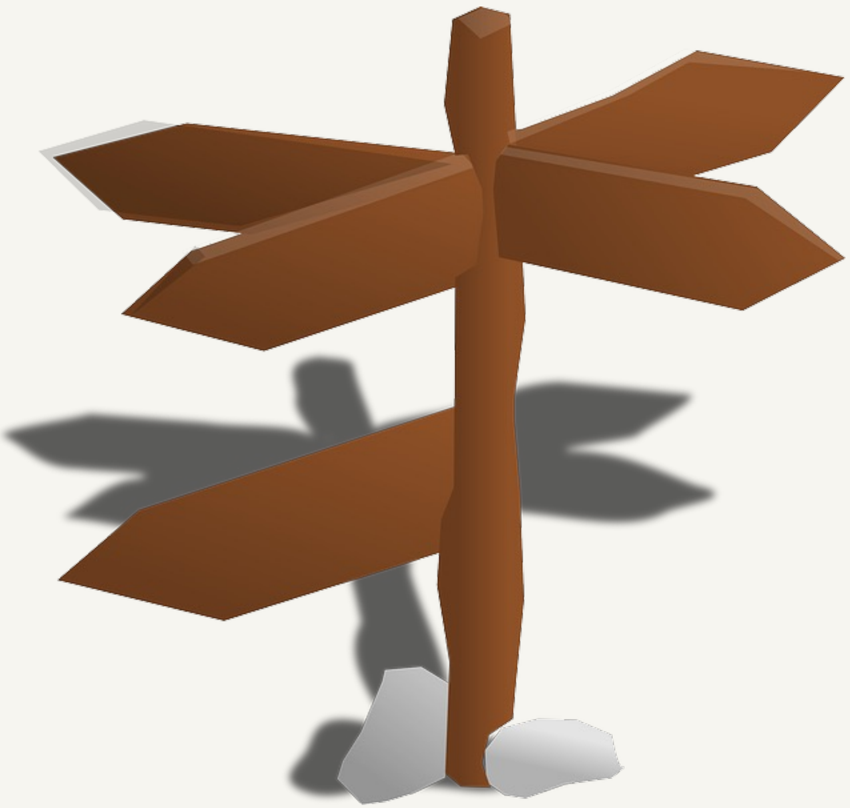
Many new particles expected

Collider signatures?

Precision SM physics?

Dark Matter connections?

Cosmology + …



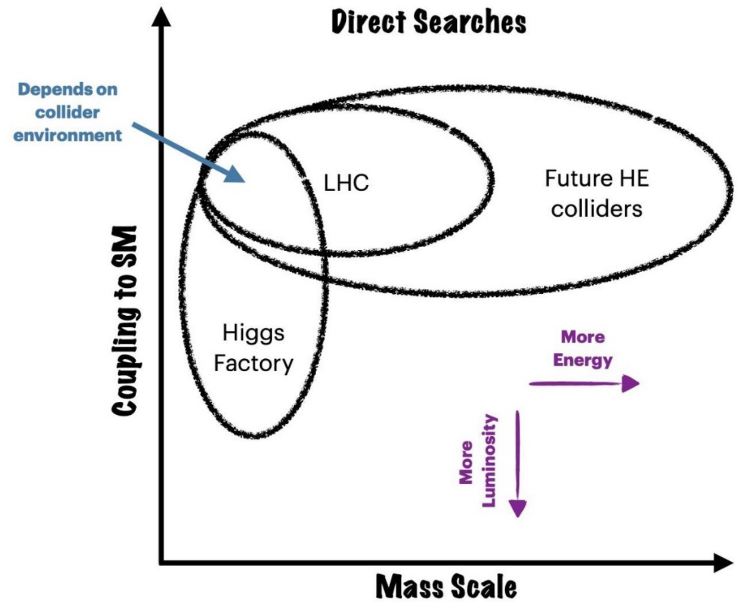
Energy Frontier Machines: energy and precision

M. Narain

New physics can be at low and at high mass scales: Naturalness would prefer mass scale close to the EW scale, but direct searches of specific models have placed stronger bounds around 1-2 TeV.

Depending on the mass scale of new physics and the type of collider, the primary method for discovery new physics can vary.

We need to use both energy and precision.



CCC Session@CSS, Seattle, July 22, 2022

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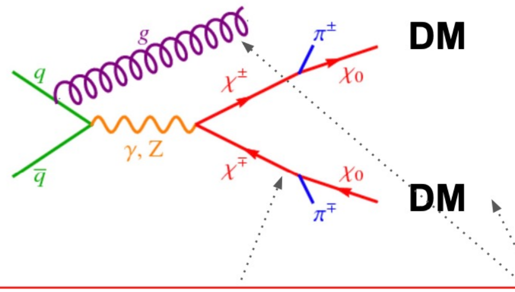
How can we best test the minimal WIMP paradigm?

Zhen Liu, EF Snowmass 2021

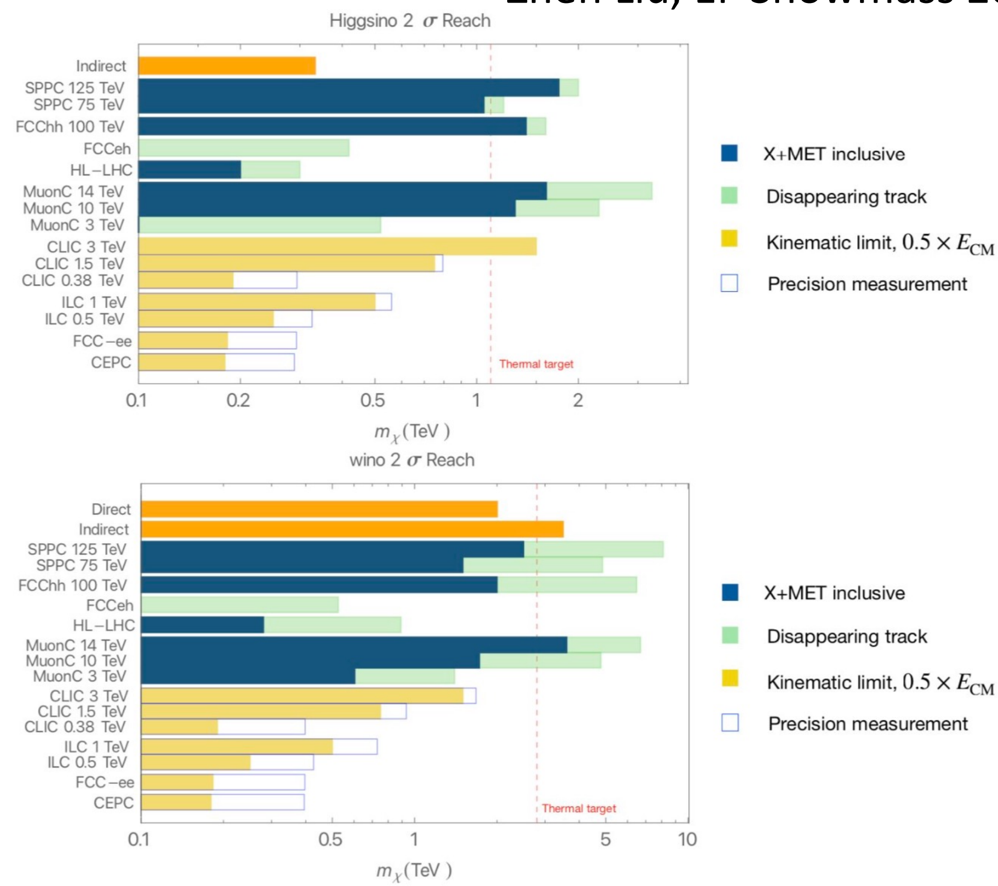


Signatures: **disappearing track, X+MET**

Model (color, n, Y)		Therm. target
(1,2,1/2)	Dirac	1.1 TeV
(1,3,0)	Majorana	2.8 TeV

Higgsino
Wino

Reaching the **thermal target** (where model produces correct relic abundance): **complete coverage** for minimal WIMP candidate for **FCC complex and muon collider**



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Thank You!

SM works beautifully…

But **MANY** puzzles remain.

UV physics -> ? Cancellations and degeneracies.
What appears to be structure may be an accidental artifact.

What are the right questions?

???

Data + Theory: Where to look next!

Absence of Evidence != Evidence of Absence
Data driven age: Collider + Precision + Astrophysical Probes

“May we live in interesting times.”