Physics at Colliders II

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DESY and University of Freiburg

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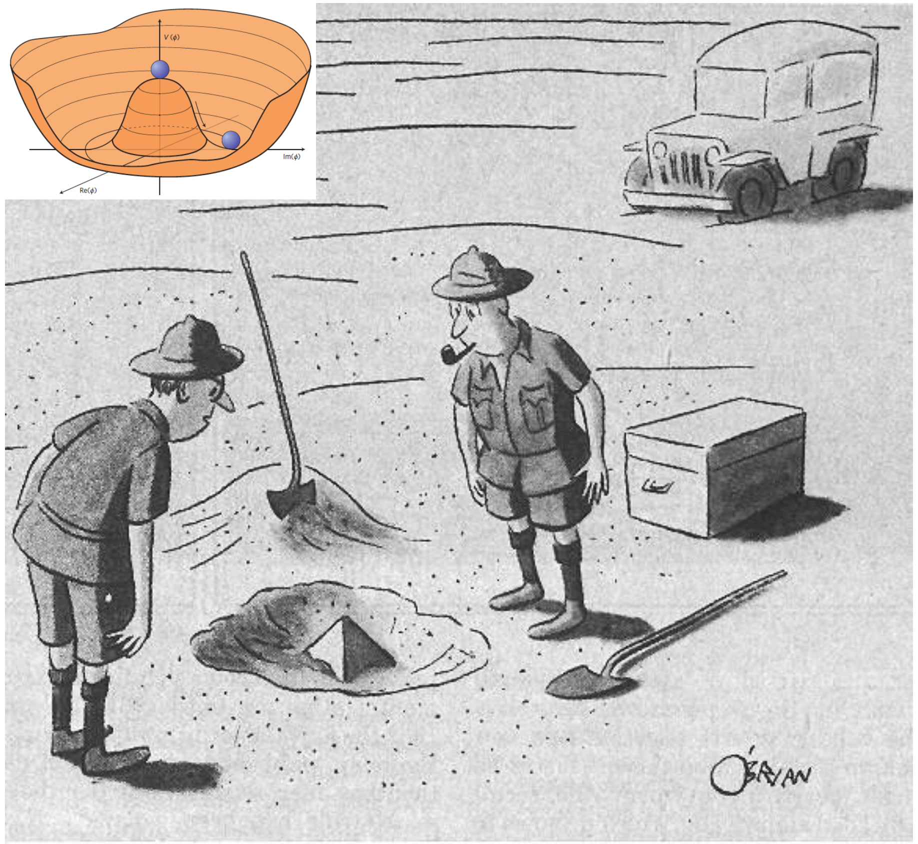
Outline

- **Lecture I: Introduction and Standard Model Measurements**
    - Current and Future colliders
    - Tests of QCD
    - Precision measurements in electroweak sector
- **Lecture II: Higgs Boson and New Physics Searches**
    - The Standard Model Higgs Boson
    - Problems with the Standard Model
    - Supersymmetry
    - Dark Matter at Colliders
    - Flavour measurements and anomalies

Higgs Boson

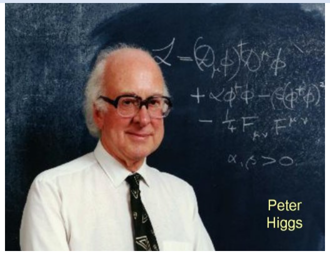


"This could be the discovery of the century. Depending, of course, on how far down it goes."

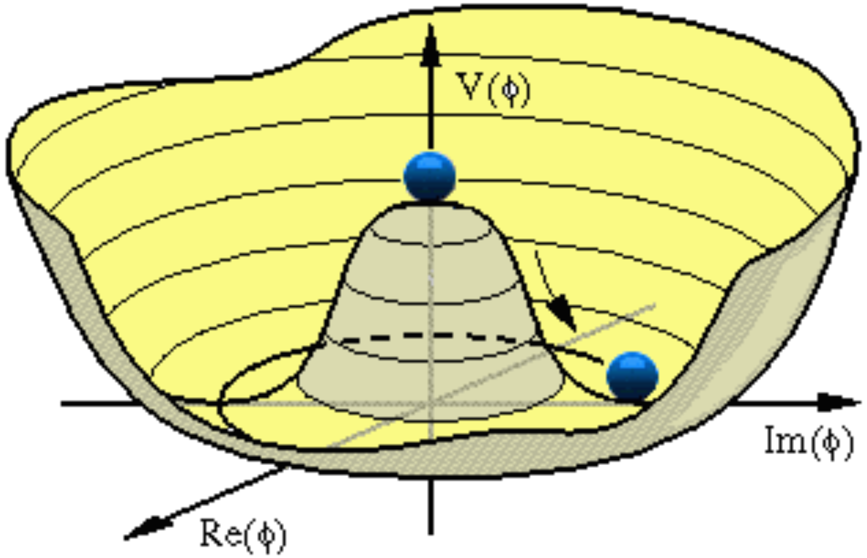
M. Lancaster, 2019

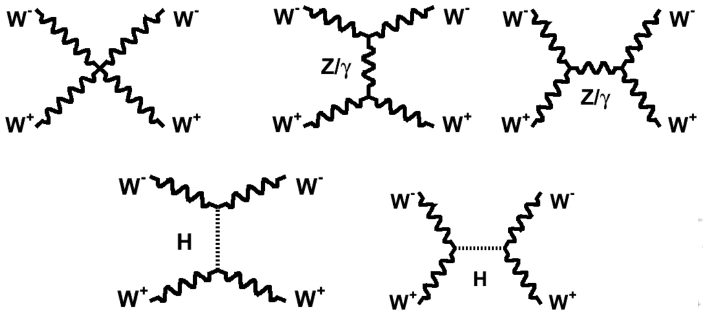
The Higgs Boson

Peter Higgs



- Electroweak Symmetry breaking
  - caused by scalar Higgs field
- vacuum expectation value of the Higgs field $<\Phi>$ =246 GeV/c^2
  - gives mass to the W and Z gauge bosons,
    - $M_W \propto g_W<\Phi>$
  - fermions gain a mass by Yukawa interactions with the Higgs field,
    - $m_f \propto g_f<\Phi>$
  - Higgs boson couplings are proportional to mass
- Higgs boson prevents unitarity violation of WW cross section
  - $\sigma(pp \to WW) > \sigma(pp \to \text{anything})$
    - => illegal!
    - At $\sqrt{s}$=1.4 TeV!



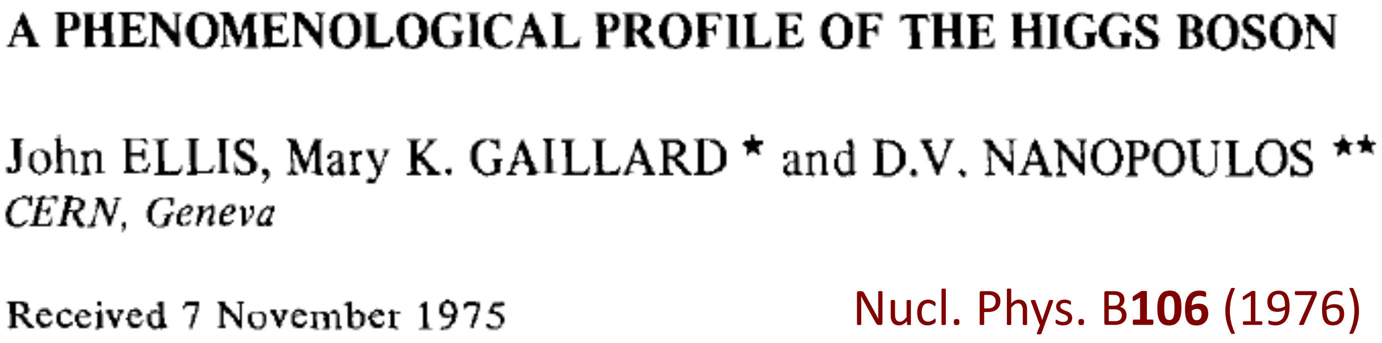


$$A \approx g^2 \frac{E^2}{M_W^2}$$

$$A \approx -g^2 \frac{E^2}{M_W^2}$$

Terms which grow with energy cancel for E >> M_H

This cancellation requires $M_H < 800$ GeV

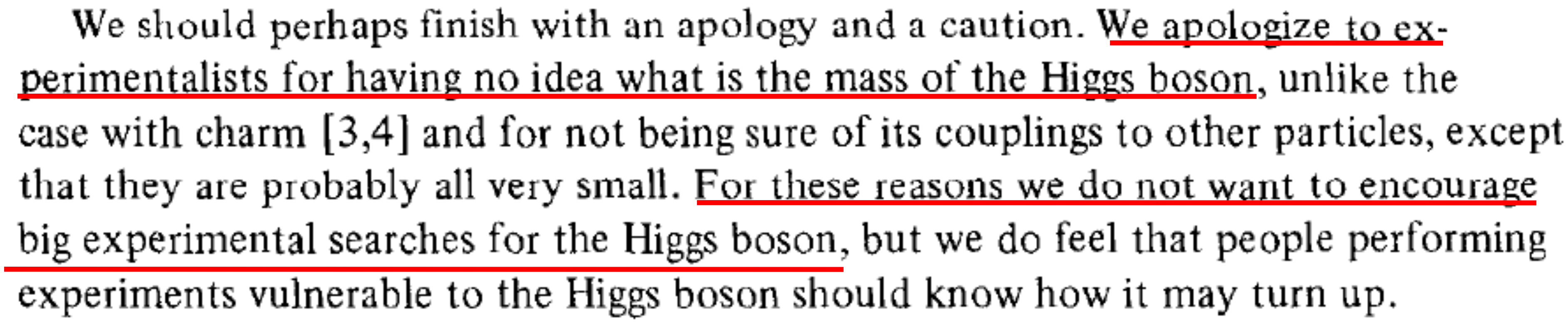


A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

Received 7 November 1975

Nucl. Phys. B**106** (1976)



We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

Nucl. Phys. B**106** (1976)

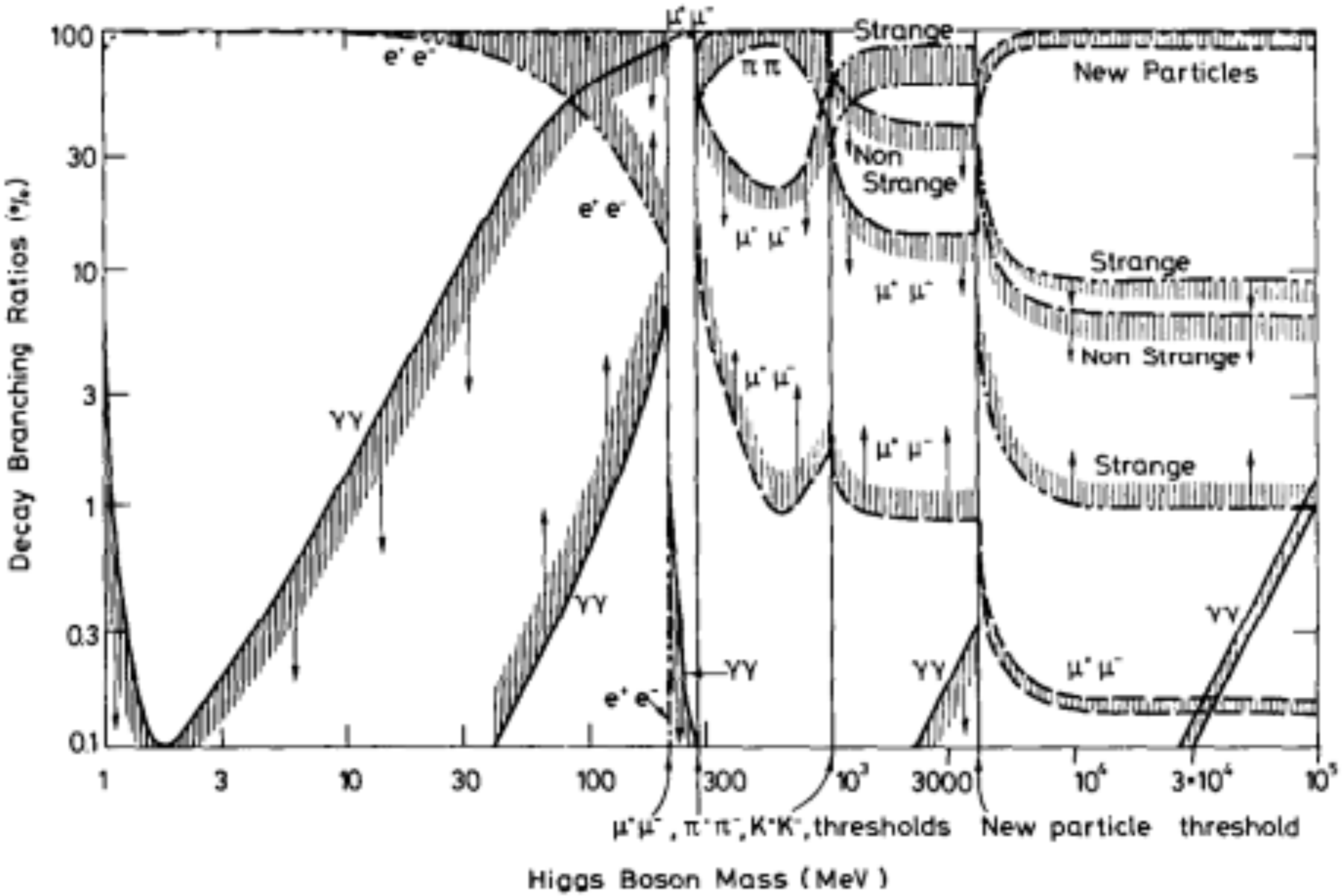
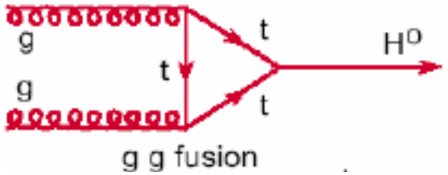
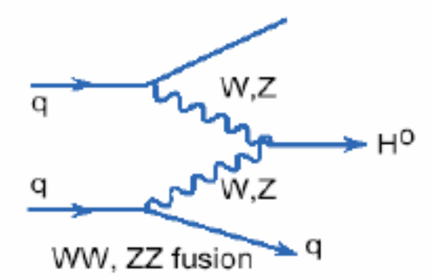
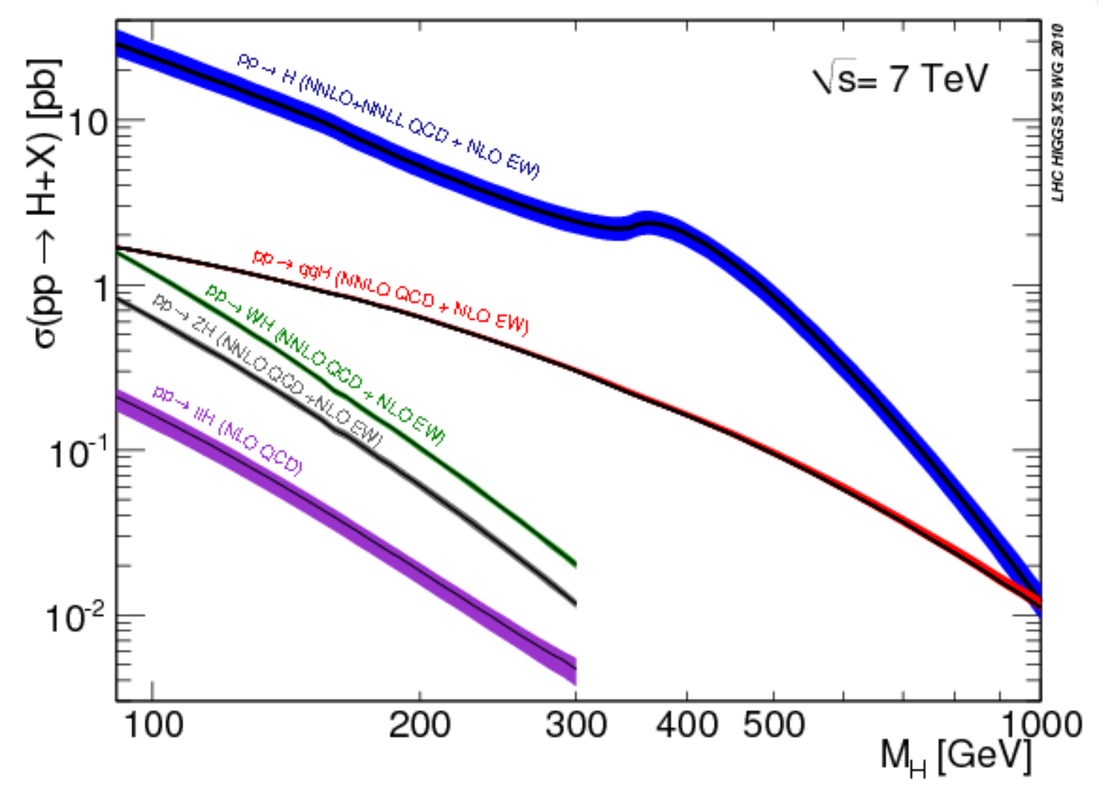


Fig. 1. Branching ratios of the Higgs boson for different values of its mass. The curves are calculated from the decay rates of sect. 4.

Higgs Boson Production

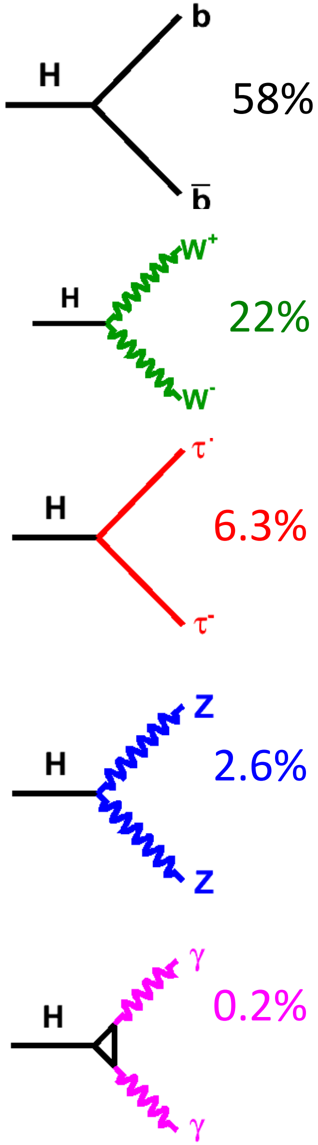


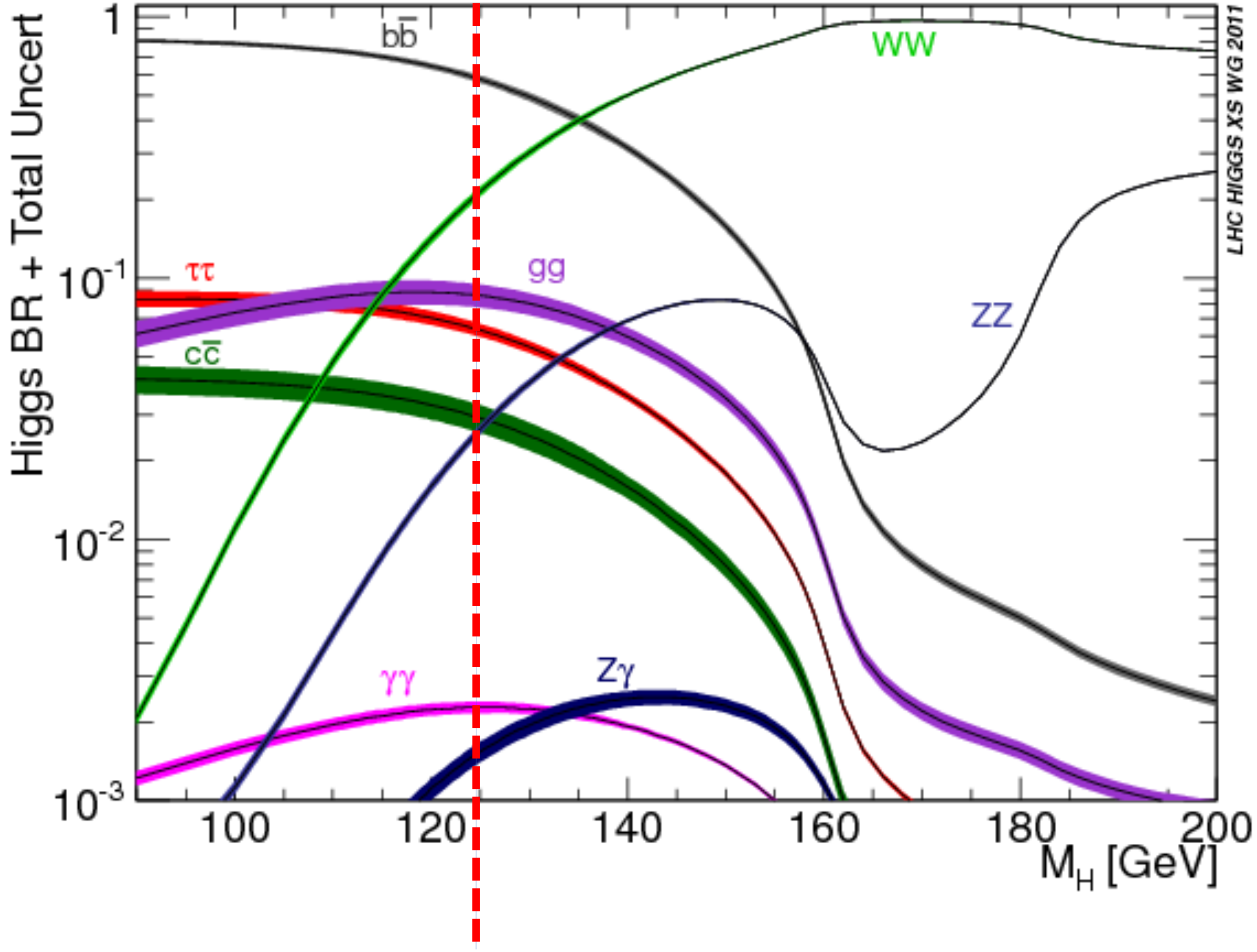




- Production via various processes sensitive to different couplings of Higgs boson
  - ggF and ttH processes known in QCD to 5-10%
  - VBF, WH and ZH processes known in QCD to 2-4%

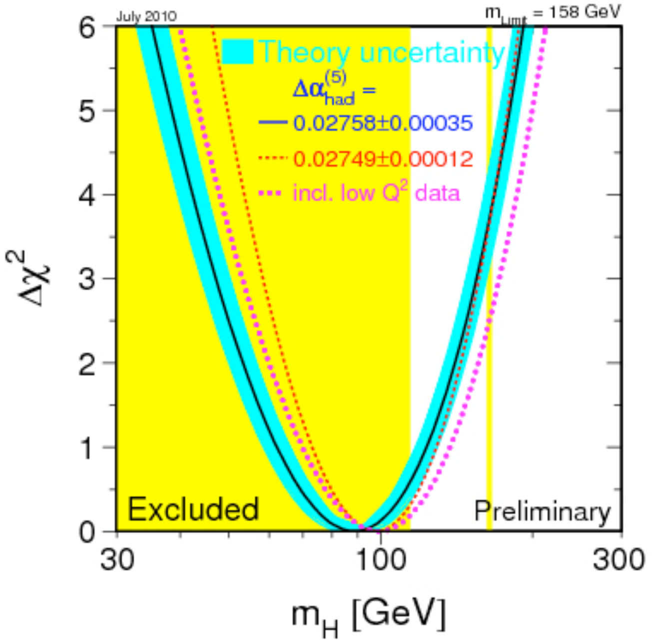
Higgs Boson Decay

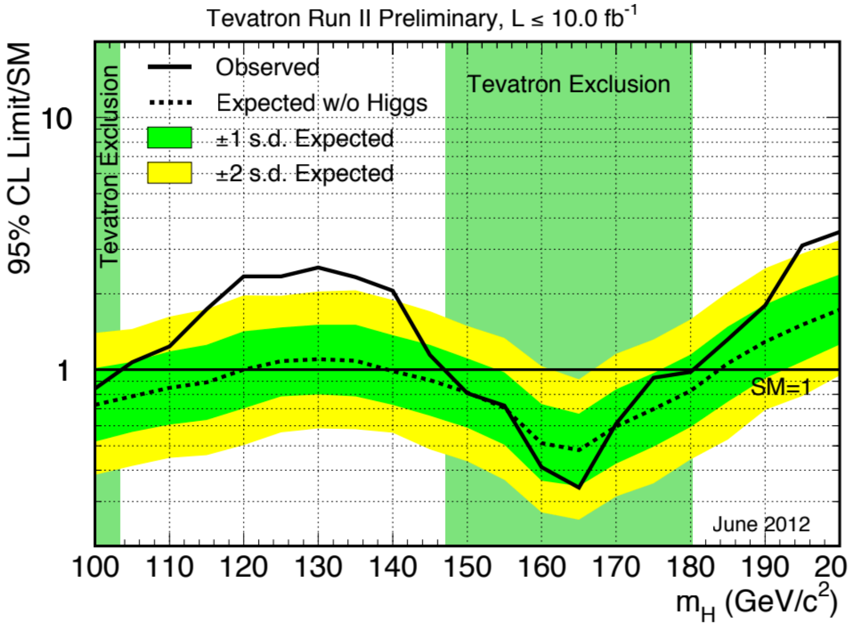


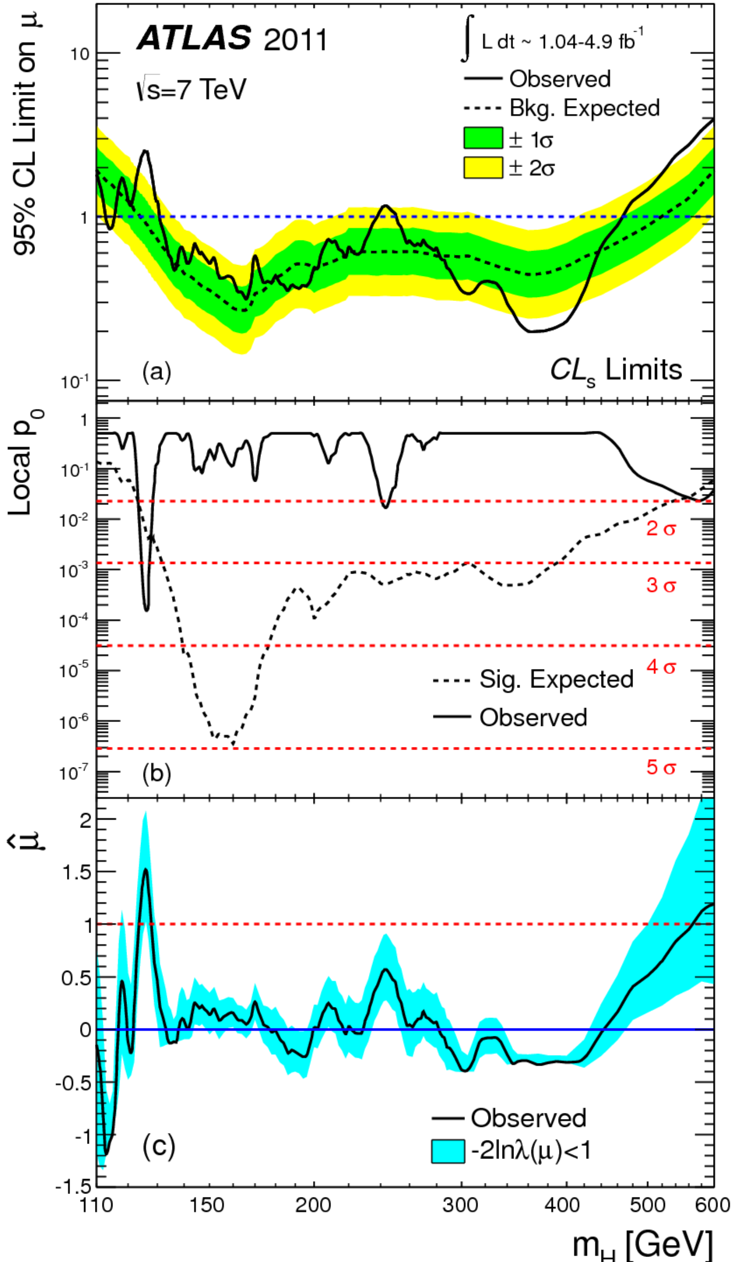


Status end of 2011

$m_H = 89^{+35}_{-26}$ GeV

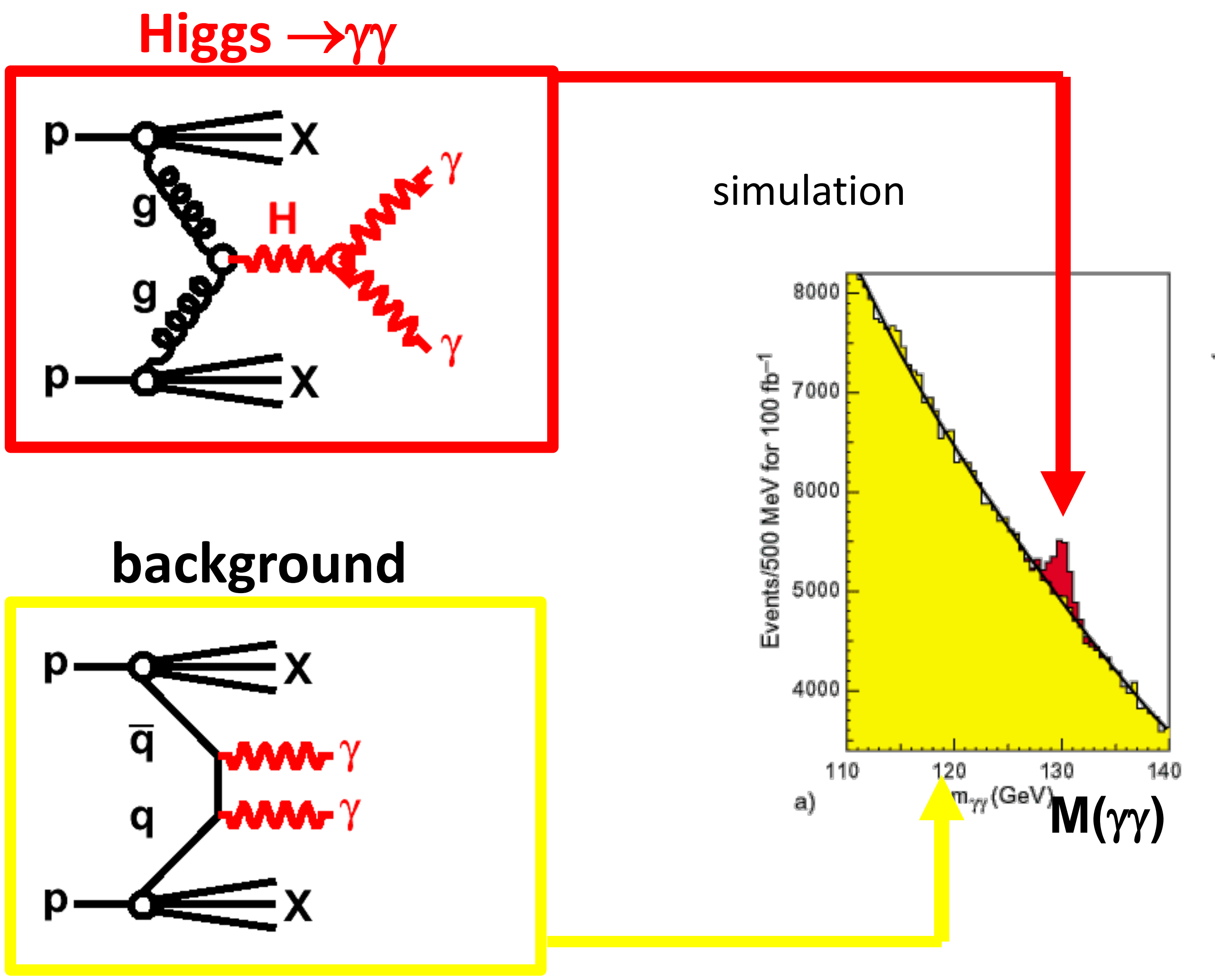






- Indirect constraints point towards low-mass Higgs
- Slight excess at low mass in Tevatron data
- 2011 LHC data rule out mass range of ~130-500 GeV

Finding the Higgs Boson (with photons)



Higgs →γγ

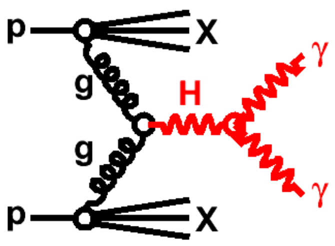
background

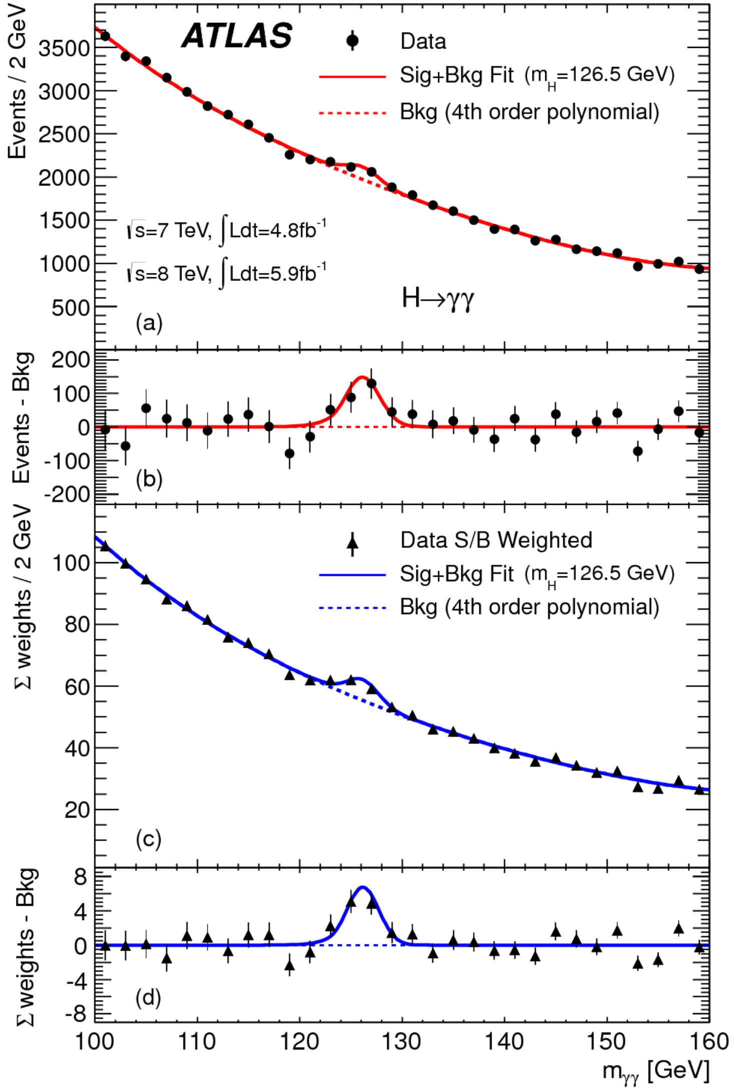
simulation

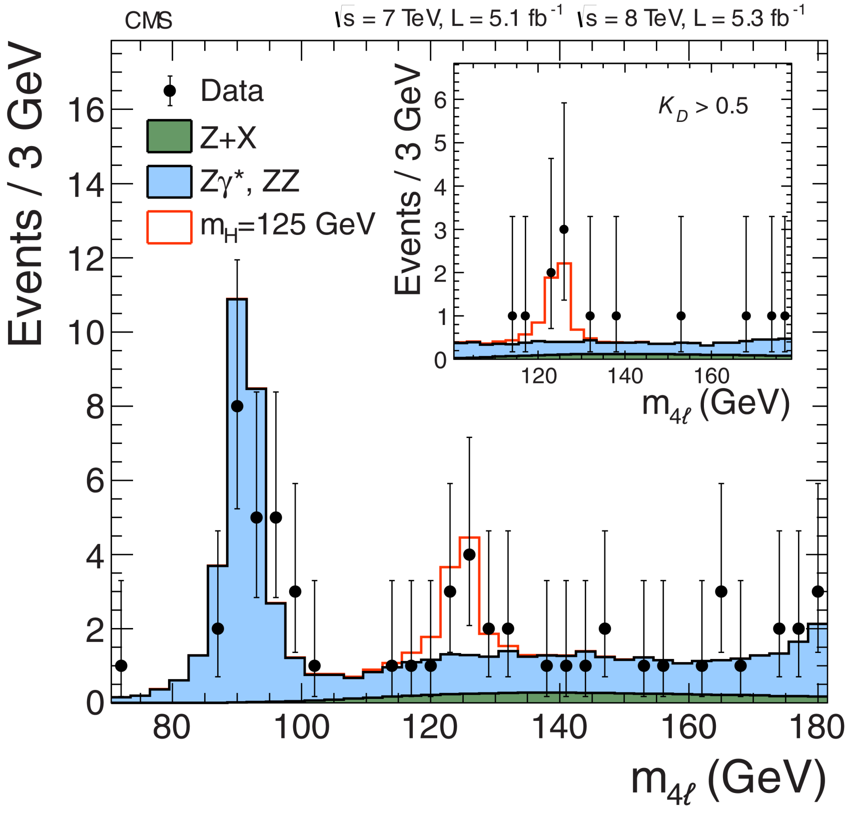
M(γγ)

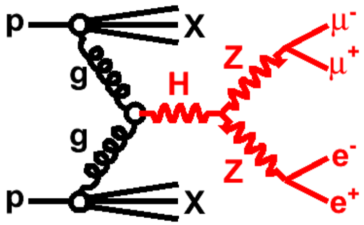
$$M_{Higgs} \approx M(\gamma\gamma) = 2\, E_1\, E_2\, (1-\cos\alpha)$$

Higgs Boson Discovery 2012









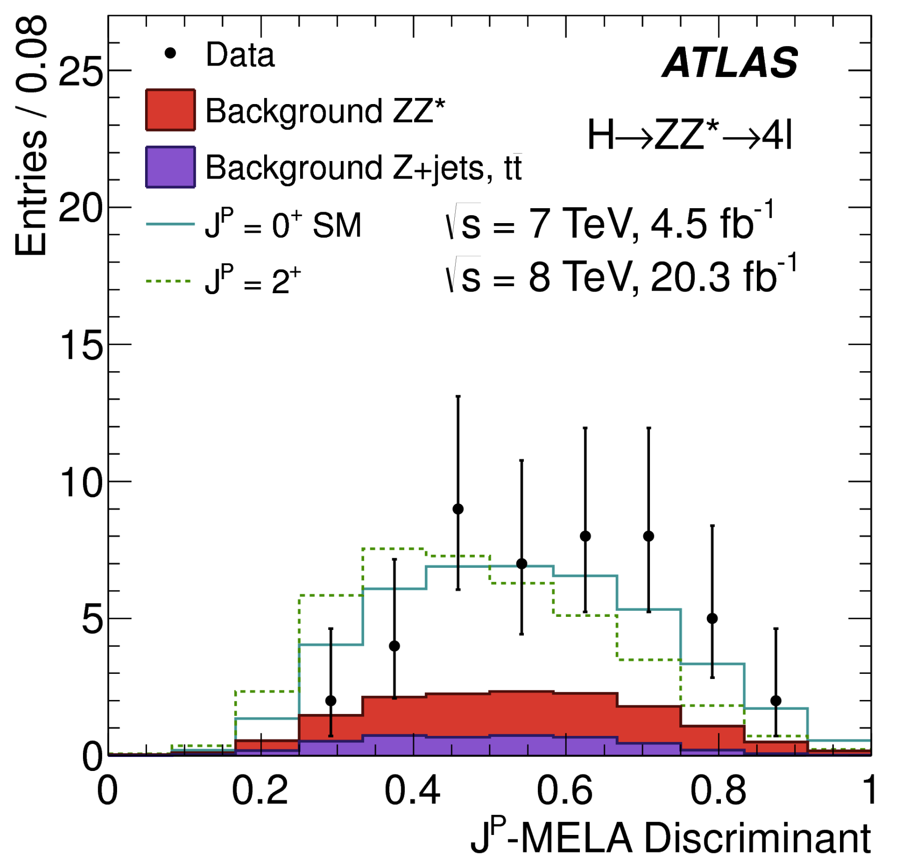
Both experiments saw narrow peak at ~125 GeV in two different decay channels

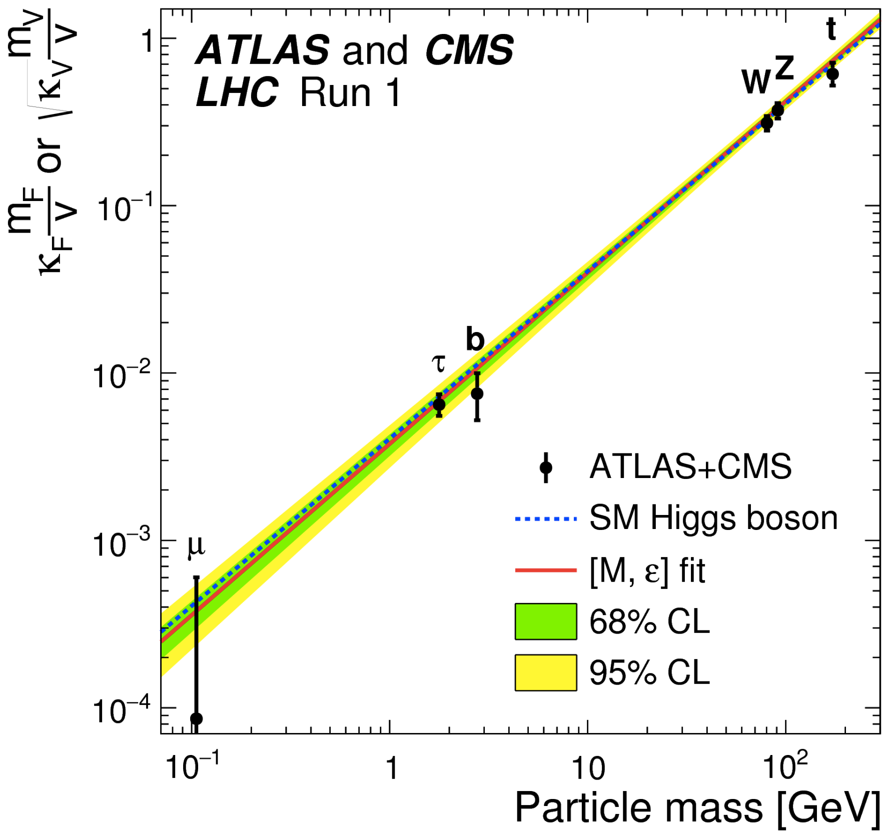
Nobel Prize 2013

Francois Englert and Peter Higgs:

for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

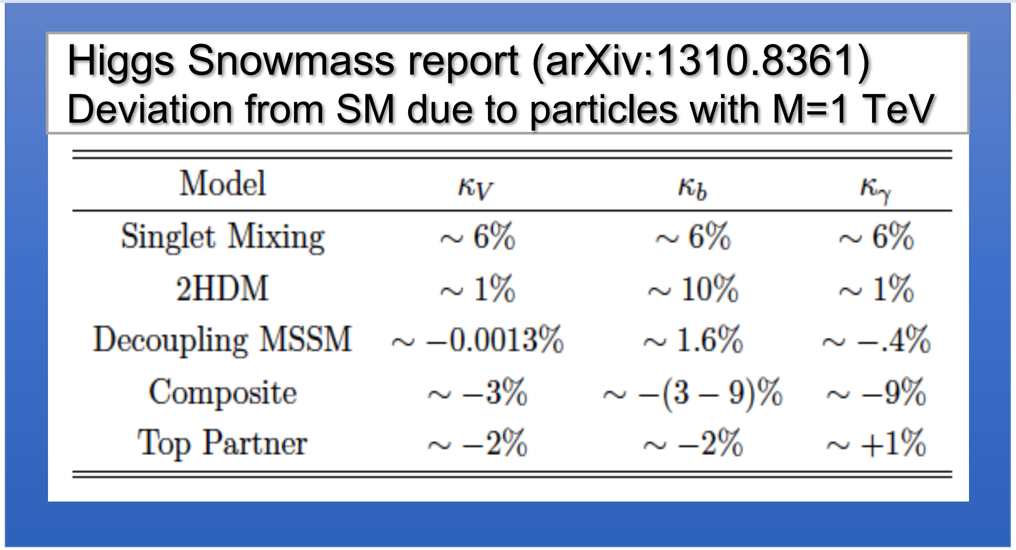
Is it a Higgs boson actually?





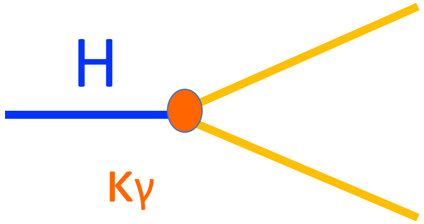
- Spin and parity consistent with Higgs: 0^+
- Coupling strength to SM particles proportional to mass
  - Within uncertainties of 20-50%

Understanding the Higgs boson



Higgs Snowmass report (arXiv:1310.8361)
Deviation from SM due to particles with M=1 TeV

Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$\sim -.4\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$



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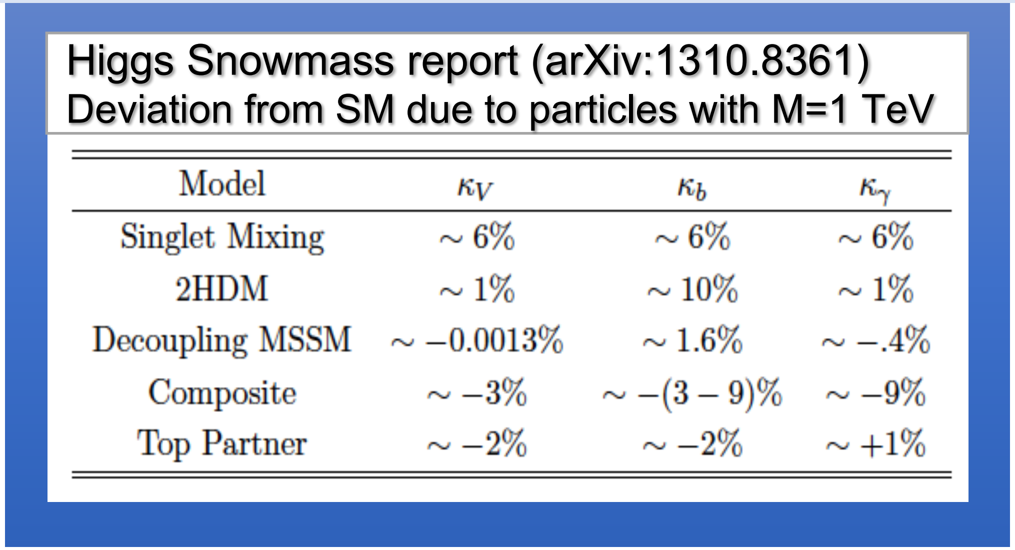

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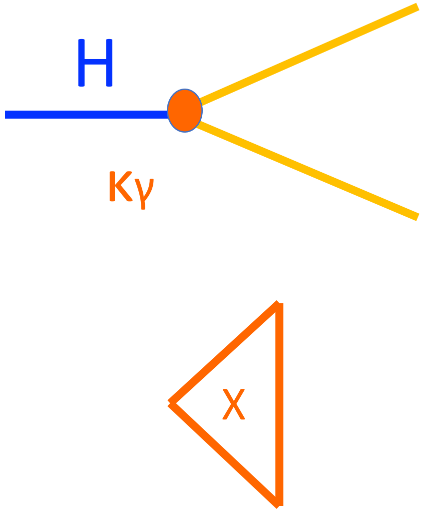

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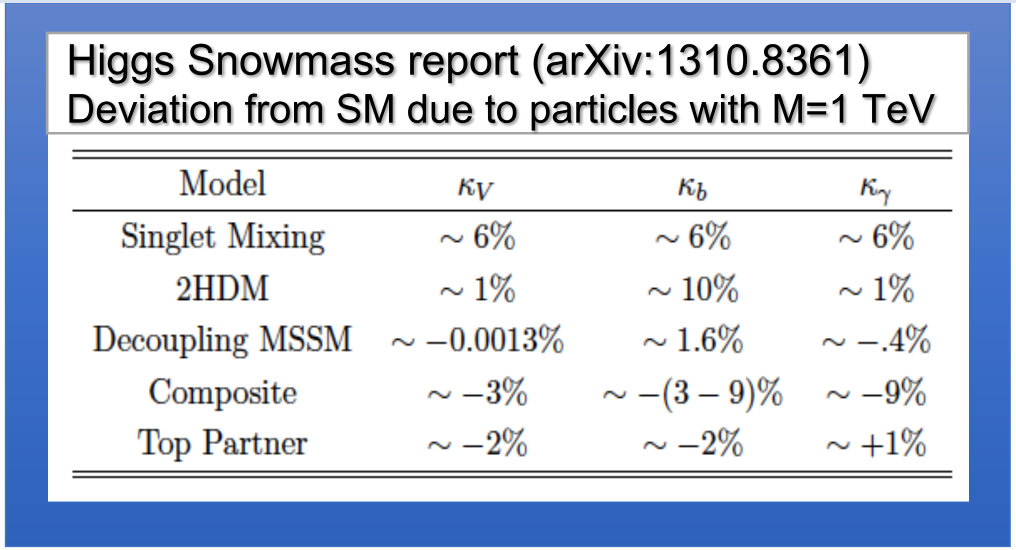

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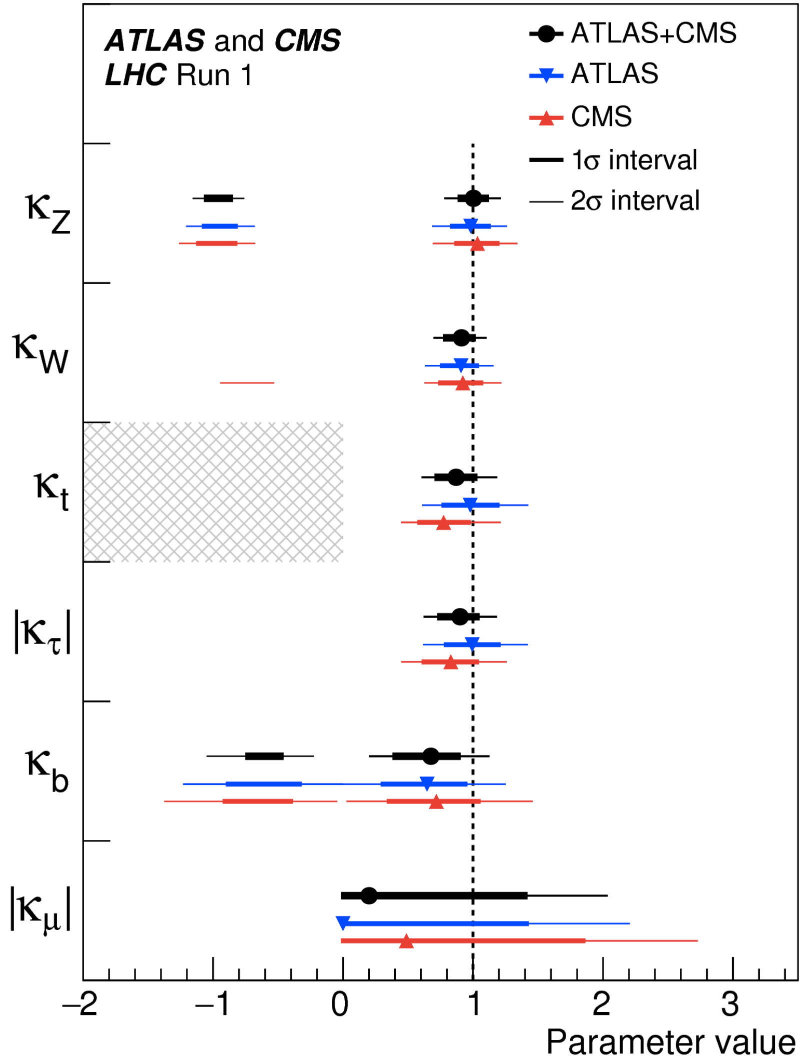
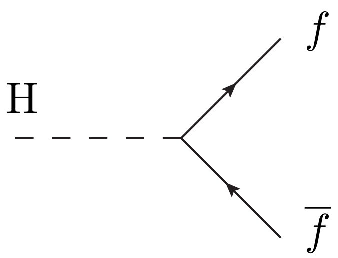
Run 1 Results on couplings κ



Higgs studies have only just begun:

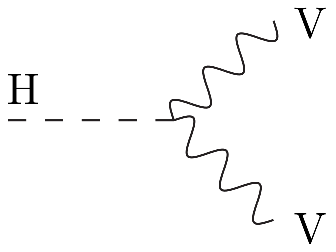
- **Run-1** precision on about 20-50%
- Need ~3% precision on couplings to probe TeV scale particles
- Need much more data (run-2 and beyond) to e.g.
  - Observe and measure H->bb, H->μμ, H->Zγ decays
  - Observe and measure ttH and VH production

The Higgs boson



$\frac{m_f}{v}$ $+ \bar{\psi}_i y_{ij} \psi_j \phi + h.c.$

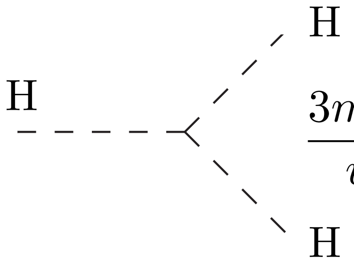
<= Coupling to fermions



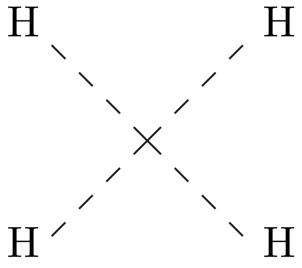
$\frac{2m_V^2}{v}$ $+ |D_\mu \phi|^2$

This term could not exist without a vev

<= Coupling to gauge bosons



$\frac{3m_H^2}{v}$



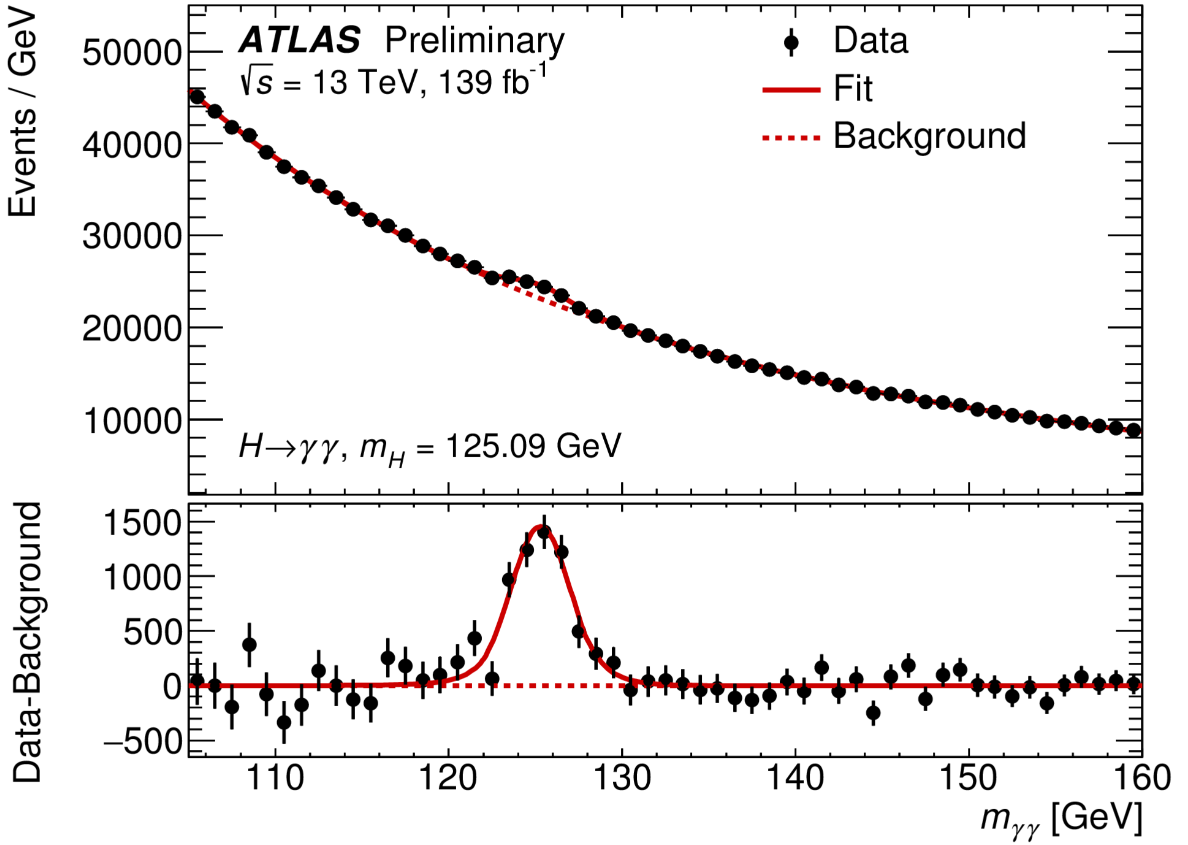
$\frac{3m_H^2}{v^2}$ $V(\phi)$

<= Coupling to itself

Higgs in Run 2

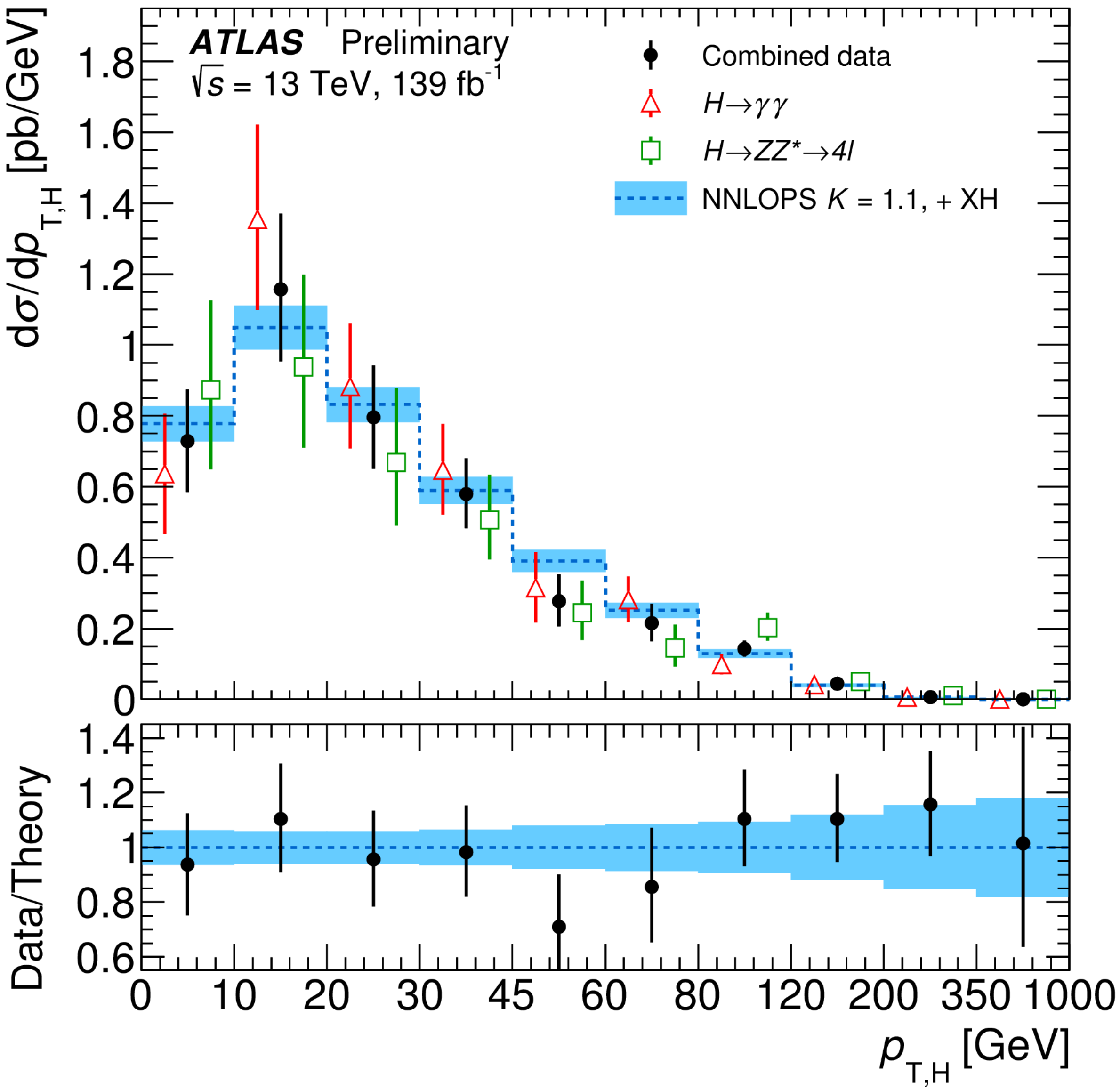
Diphoton channel

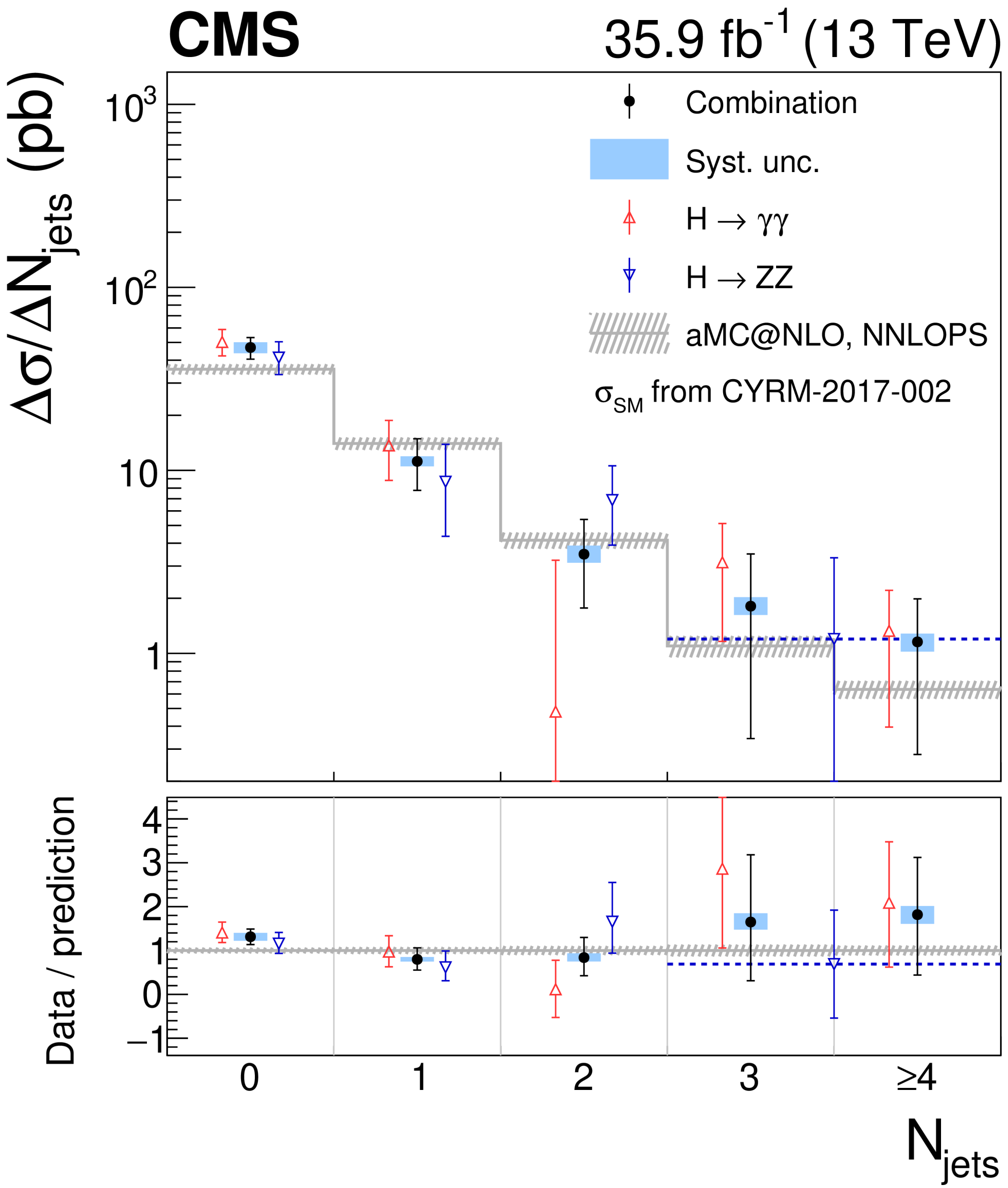
- More than 10x higher statistics than during discovery
  - Precision measurement of cross section
  - Measurement of differential distribution



	ATLAS
σ (data) [fb]	65.2±7.1
σ(theory) [fb]	63.6±3.3

Differential Cross Section Measurements

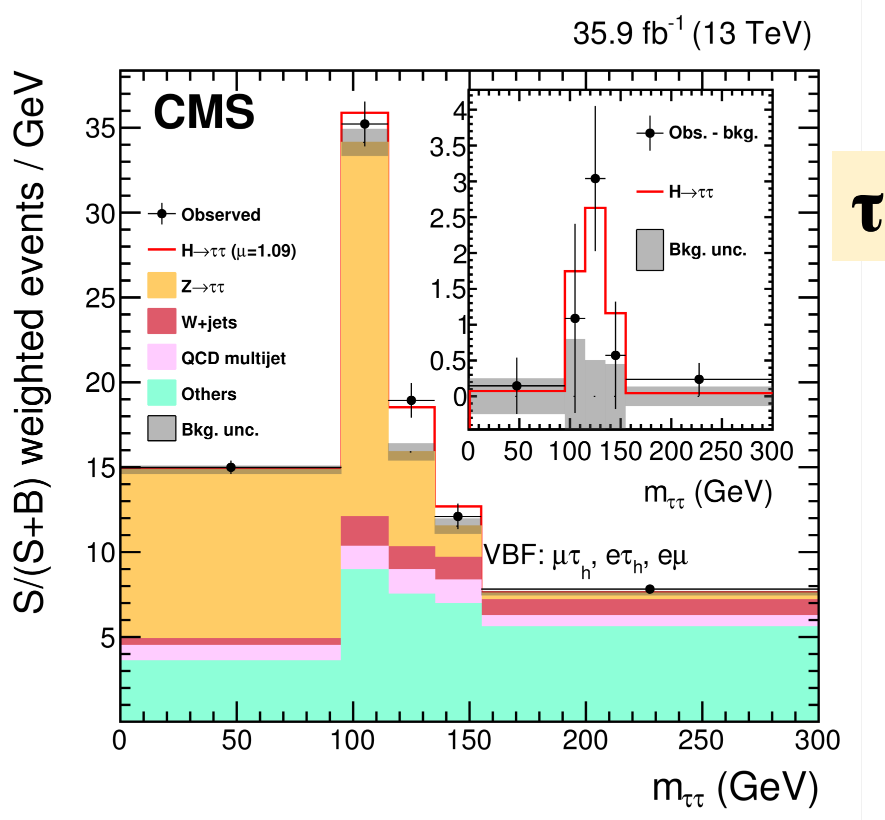




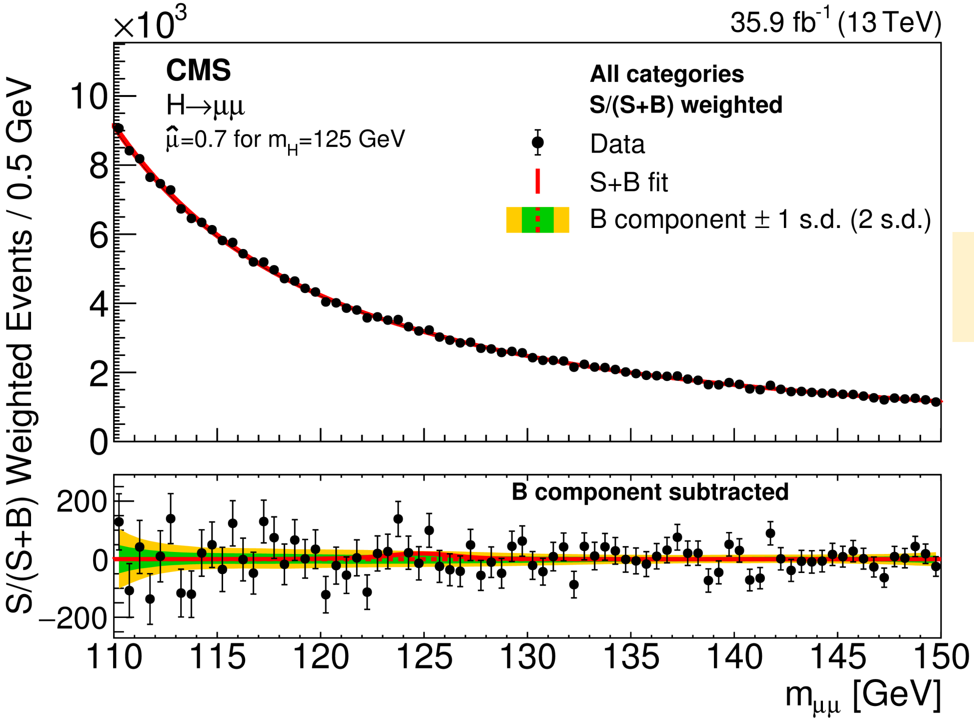
Higgs Couplings to Fermions

- SM predicts $m_f = g_f \frac{v}{\sqrt{2}}$ =>

$$\frac{\mathrm{BR_{SM}}(\mathrm{H} \rightarrow \tau\tau)}{\mathrm{BR_{SM}}(\mathrm{H} \rightarrow \mu\mu)} = \frac{m_\tau^2}{m_\mu^2} = 288$$



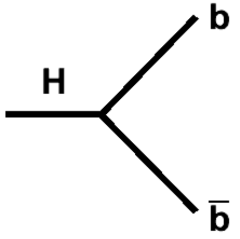
ττ



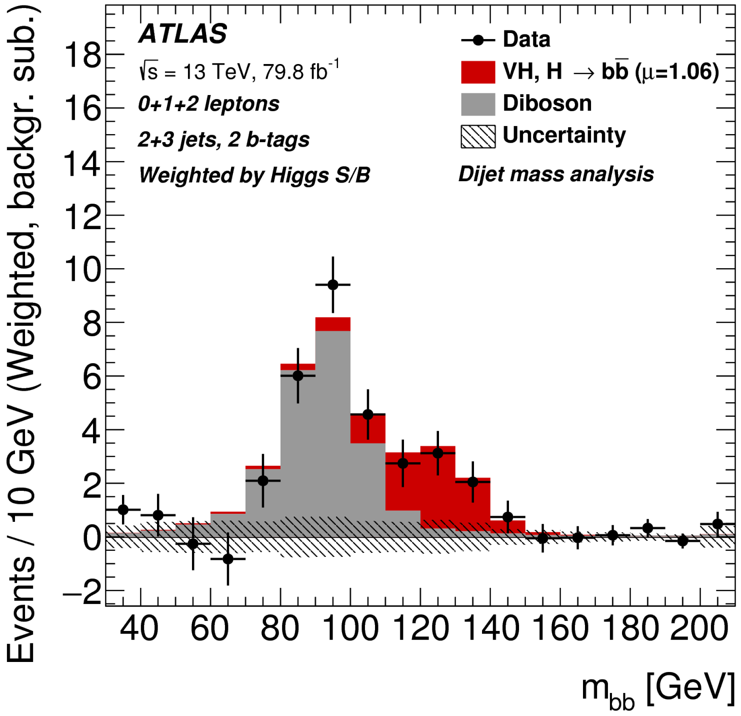
μμ

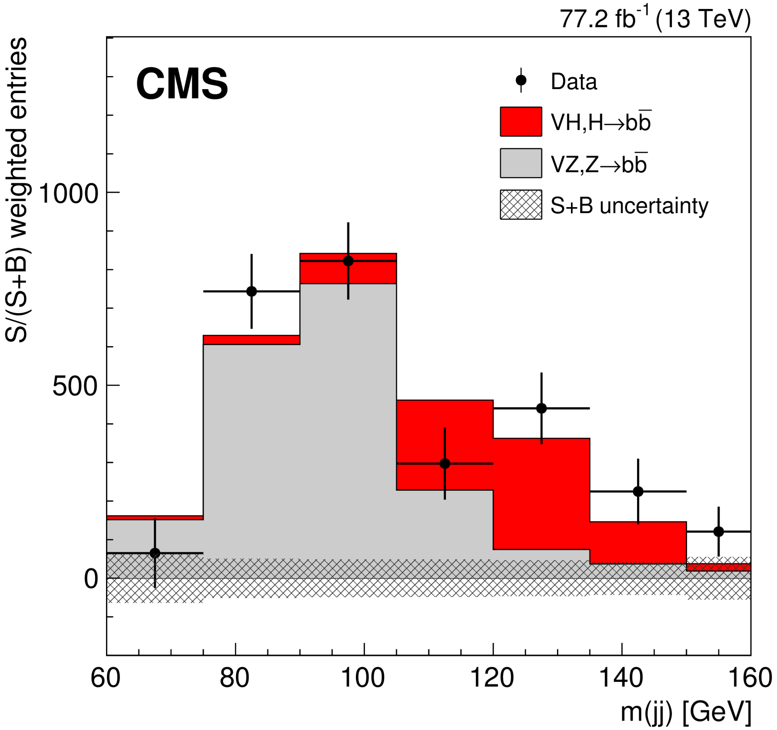
- tau-tau channel observed at 5σ end of Run-1
- $\mathrm{BR_{exp}}(H \rightarrow \tau\tau)/\mathrm{BR_{exp}}(H \rightarrow \mu\mu)$>100 at 95% CL
- Observation of dimuon decay with full run-2 data?

Higgs Coupling to b-quarks



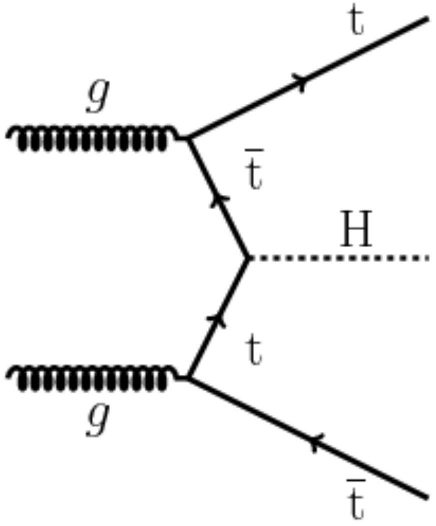
- Most Higgs bosons decay to b-quarks in SM: 57%
  - Very large backgrounds from W+jets
- Search for W/Z+H production
  - Use complex event selection (multi-variate analysis)

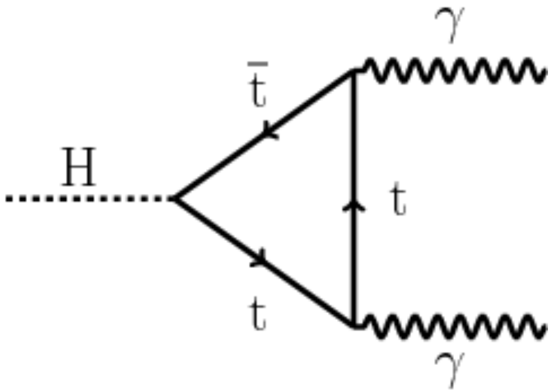


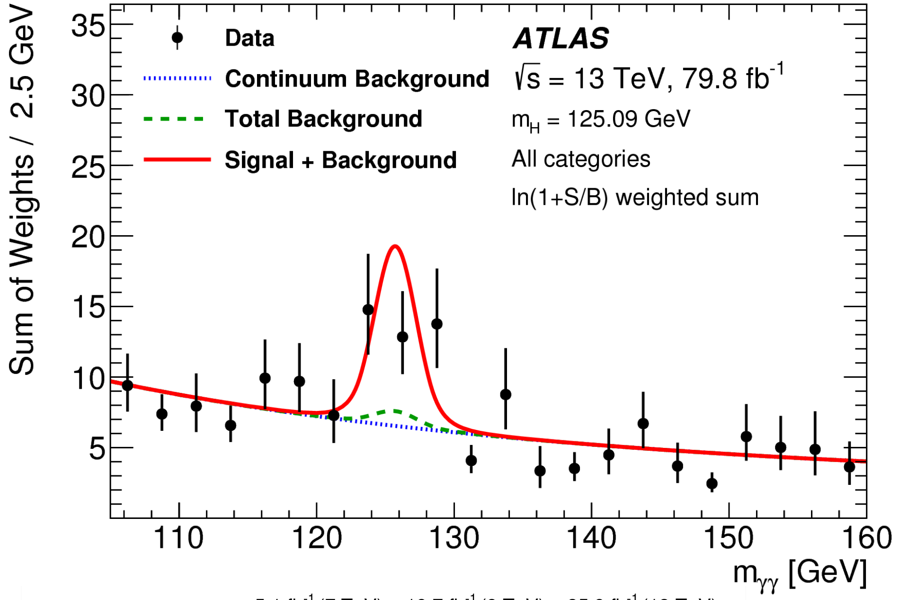


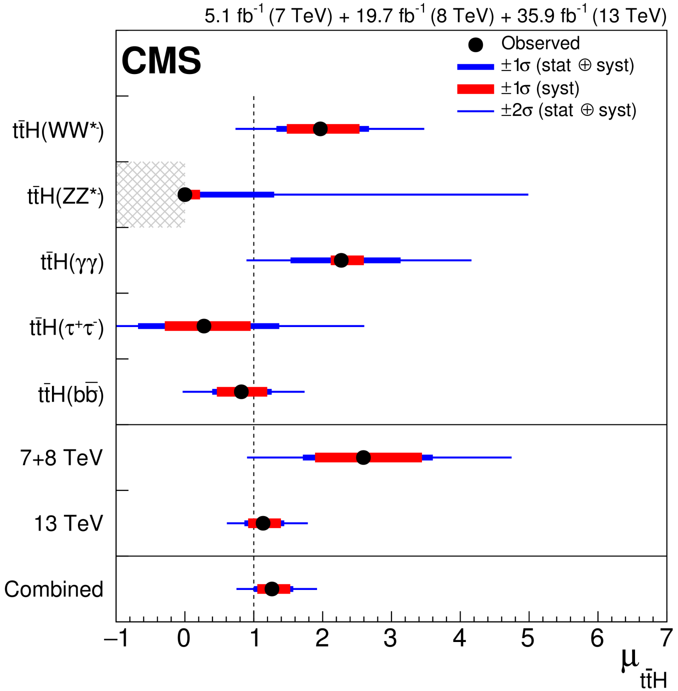
Observation in 2018!

ttH production





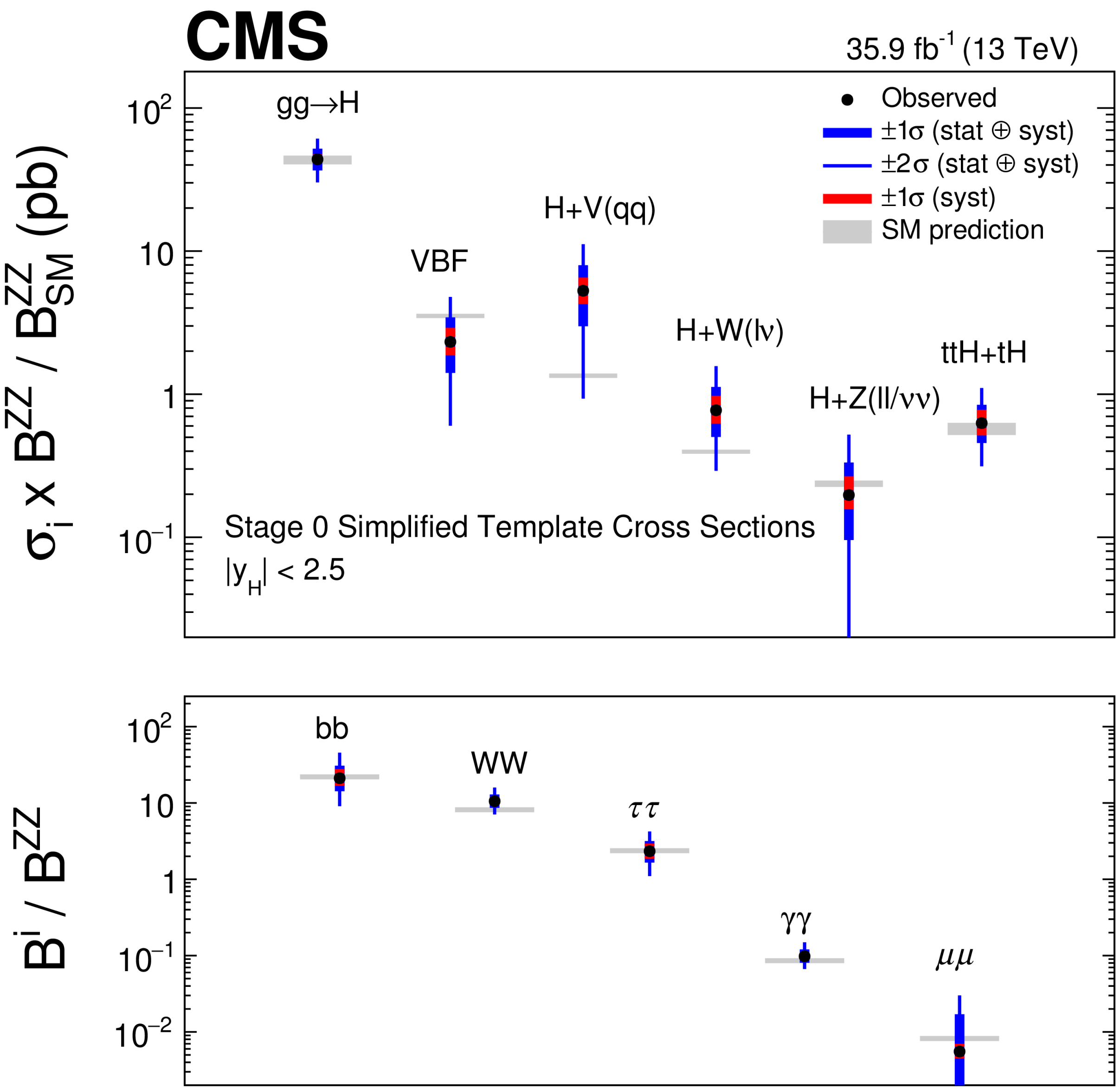




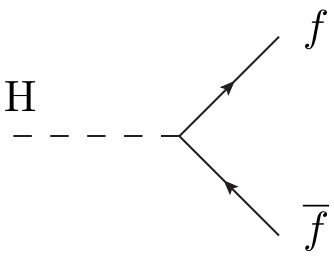
- Directly probes Higgs-Yukawa coupling of top quark
  - Diphoton probes same coupling indirectly
- 5σ observation in 2018
- Agrees with SM value

What do we know about H now?

- Production and decay consistent with SM expectation
    - All production modes observed
    - Decays to gauge bosons and 3rd generation fermions observed
- Deviations possible but for now all agrees with SM
    - Higher precision with more data



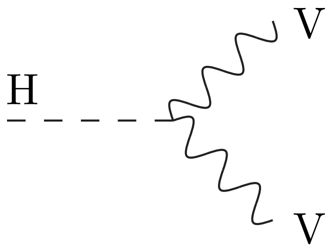
The Higgs boson



$\frac{m_f}{v}$ $+ \bar{\psi}_i y_{ij} \psi_j \phi + h.c.$

<= Coupling to fermions ✓

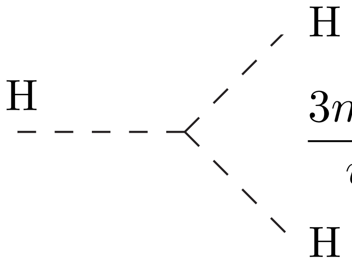
(for 3rd generation)



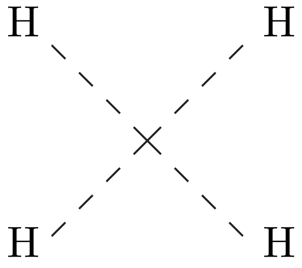
$\frac{2m_V^2}{v}$ $+ |D_\mu \phi|^2$

This term could not exist without a vev

<= Coupling to gauge bosons ✓



$\frac{3m_H^2}{v}$

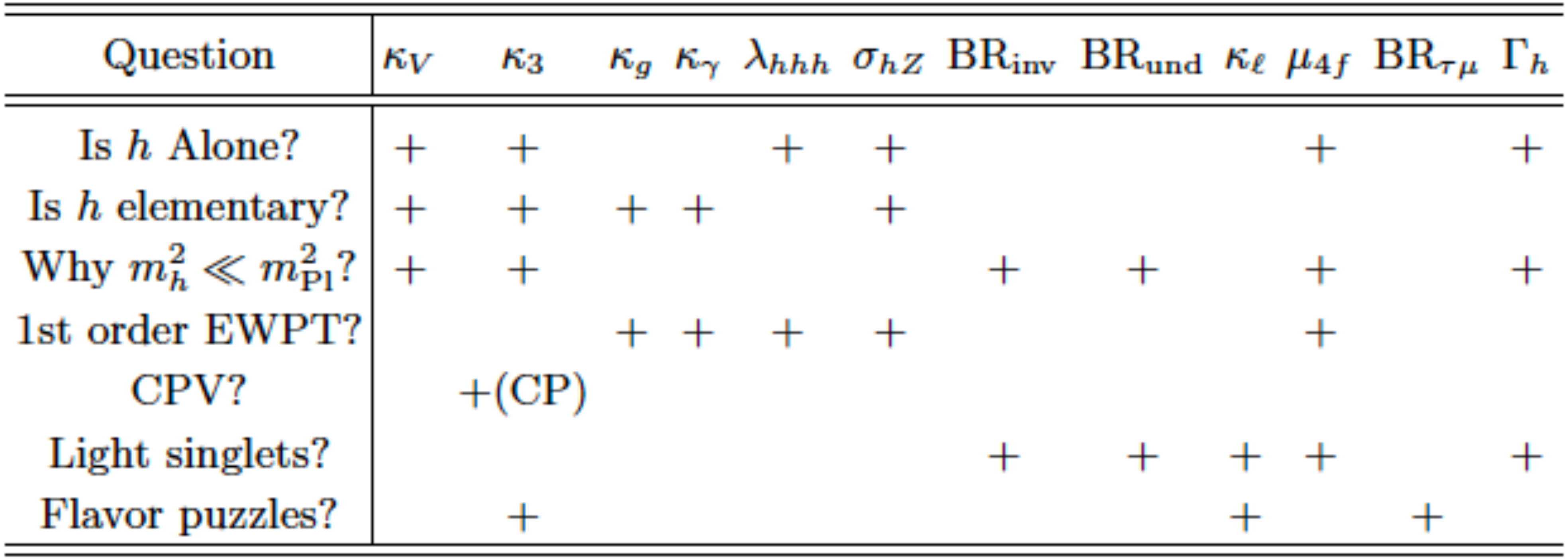


$\frac{3m_H^2}{v^2}$ $V(\phi)$

<= Coupling to itself ?

=> HL-LHC

What else do we learn from Higgs?

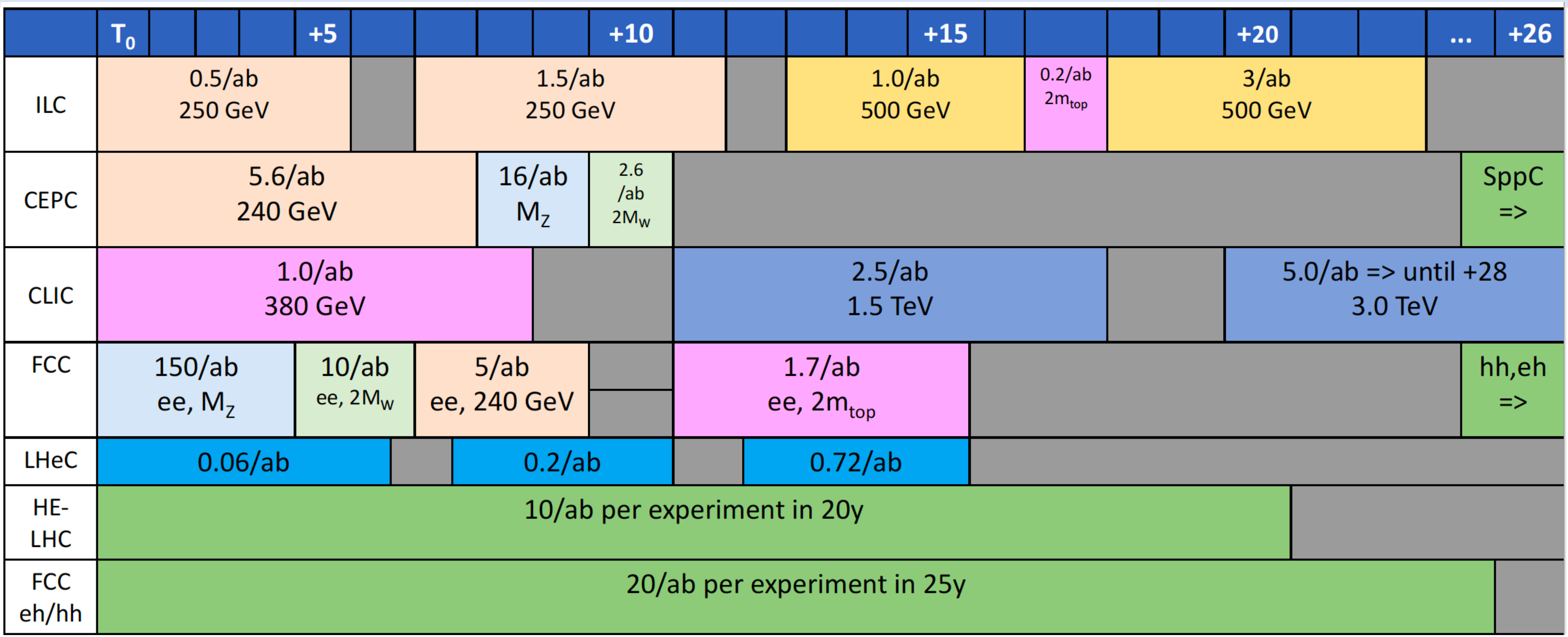


Question	κ_V	κ_3	κ_g	κ_γ	λ_{hhh}	σ_{hZ}	$\mathrm{BR}_{\mathrm{inv}}$	$\mathrm{BR}_{\mathrm{und}}$	κ_ℓ	μ_{4f}	$\mathrm{BR}_{\tau\mu}$	Γ_h
Is h Alone?	+	+			+	+				+		+
Is h elementary?	+	+	+	+		+						
Why $m_h^2 \ll m_{\mathrm{Pl}}^2$?	+	+					+	+		+		+
1st order EWPT?			+	+	+	+				+		
CPV?		+(CP)										
Light singlets?							+	+	+	+		+
Flavor puzzles?		+							+		+	

BH, Y. Nir,
arXiv:1905.00382

- Many problems of particle physics today relate to Higgs observables

Collider Schedules: starting from T_0



<table>
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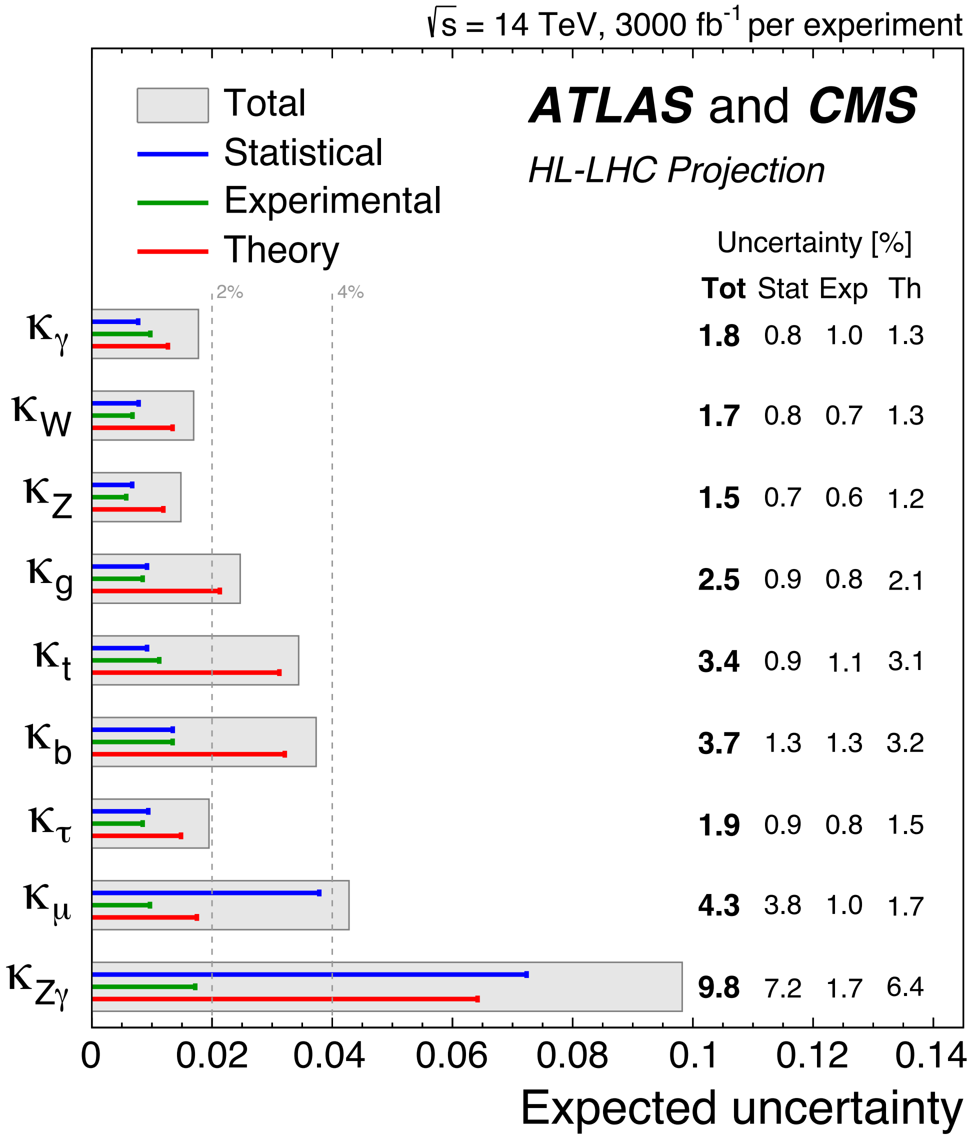
<tr><td>ILC</td><td colspan="5">0.5/ab
250 GeV</td><td></td><td colspan="5">1.5/ab
250 GeV</td><td></td><td colspan="4">1.0/ab
500 GeV</td><td>0.2/ab
$2m_{top}$</td><td colspan="5">3/ab
500 GeV</td><td colspan="2"></td></tr>
<tr><td>CEPC</td><td colspan="7">5.6/ab
240 GeV</td><td colspan="2">16/ab
M_Z</td><td>2.6
/ab
$2M_W$</td><td colspan="13"></td><td>SppC
=></td></tr>
<tr><td>CLIC</td><td colspan="8">1.0/ab
380 GeV</td><td colspan="2"></td><td colspan="7">2.5/ab
1.5 TeV</td><td colspan="2"></td><td colspan="5">5.0/ab => until +28
3.0 TeV</td></tr>
<tr><td>FCC</td><td colspan="4">150/ab
ee, M_Z</td><td colspan="2">10/ab
ee, $2M_W$</td><td colspan="3">5/ab
ee, 240 GeV</td><td></td><td colspan="5">1.7/ab
ee, $2m_{top}$</td><td colspan="8"></td><td>hh,eh
=></td></tr>
<tr><td>LHeC</td><td colspan="6">0.06/ab</td><td></td><td colspan="3">0.2/ab</td><td></td><td colspan="4">0.72/ab</td><td colspan="9"></td></tr>
<tr><td>HE-LHC</td><td colspan="20">10/ab per experiment in 20y</td><td colspan="4"></td></tr>
<tr><td>FCC eh/hh</td><td colspan="23">20/ab per experiment in 25y</td><td></td></tr>
</table>

NB: number of seconds/year differs: ILC 1.6×10^7, FCC-ee & CLIC: 1.2×10^7, CEPC: 1.3×10^7

HL-LHC Higgs measurement projections



Uncertainty [%]

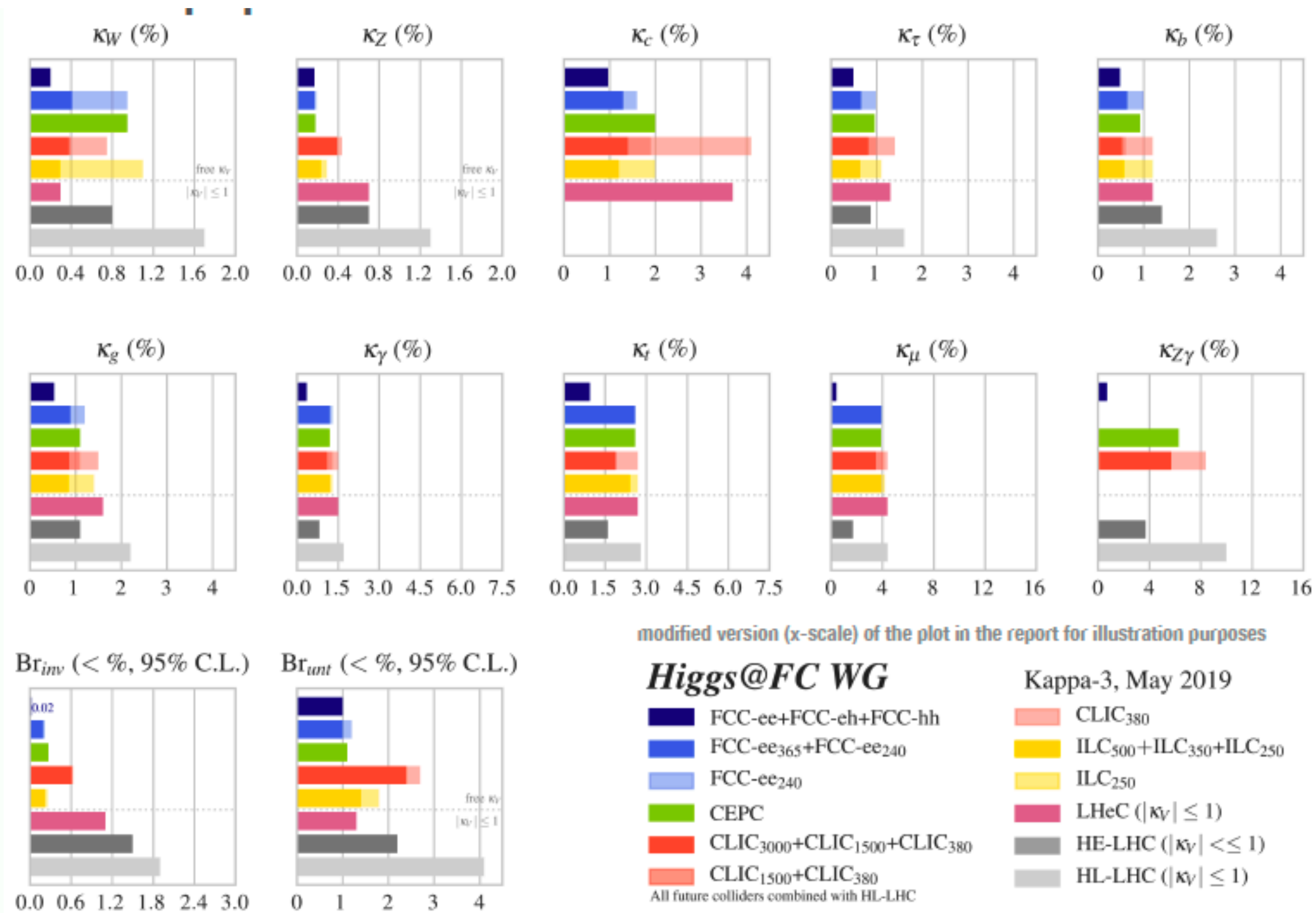
	Tot	Stat	Exp	Th
κ_γ	**1.8**	0.8	1.0	1.3
κ_W	**1.7**	0.8	0.7	1.3
κ_Z	**1.5**	0.7	0.6	1.2
κ_g	**2.5**	0.9	0.8	2.1
κ_t	**3.4**	0.9	1.1	3.1
κ_b	**3.7**	1.3	1.3	3.2
κ_τ	**1.9**	0.9	0.8	1.5
κ_μ	**4.3**	3.8	1.0	1.7
$\kappa_{Z\gamma}$	**9.8**	7.2	1.7	6.4

- Precision:1.5-4.3% (except Zγ)
  - dominated by theoretical uncertainties for most decay modes
  - Scaled by factor 2 compared to present uncertainties
- Measurement of absolute couplings model-dependent
  - Here: assumes no decays to non-SM particles

Comparison of Colliders

- HL-LHC achieves precision of ~1-3% in most cases
  - In some cases model-dependent
- Proposed e^+e^- and ep colliders improve w.r.t. HL-LHC by factors of ~2 to 10
- Initial stages of e^+e^- colliders have comparable sensitivities (within factors of 2)
- ee colliders constrain $BR \to untagged$ w/o assumptions
- Access to κ_c at ee and eh

arXiv:1905.03764



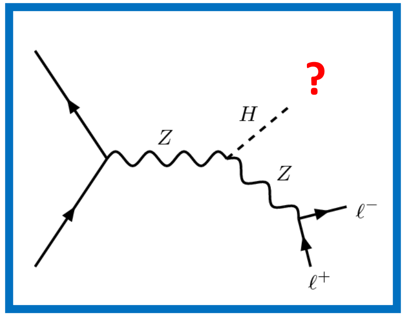
Higgs width and/or untagged decays

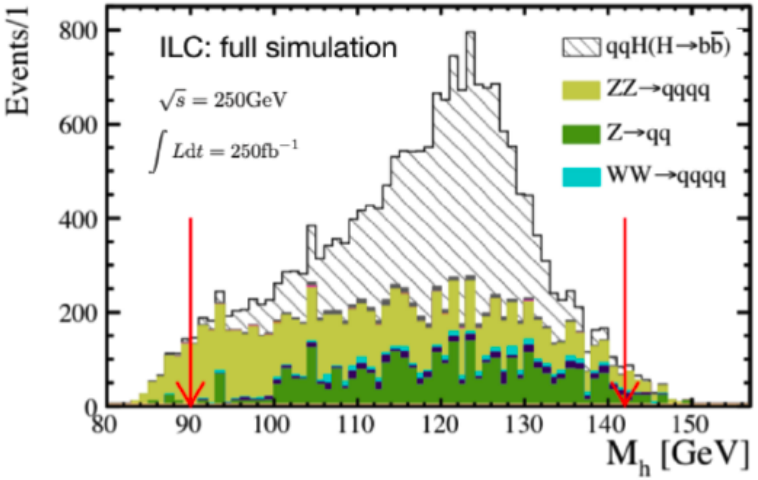
- Unique feature of lepton-lepton colliders:
  - Detecting the Higgs boson without seeing decay: “recoil method”
  - Measure ZH cross section with high precision without assumptions on measurement of width

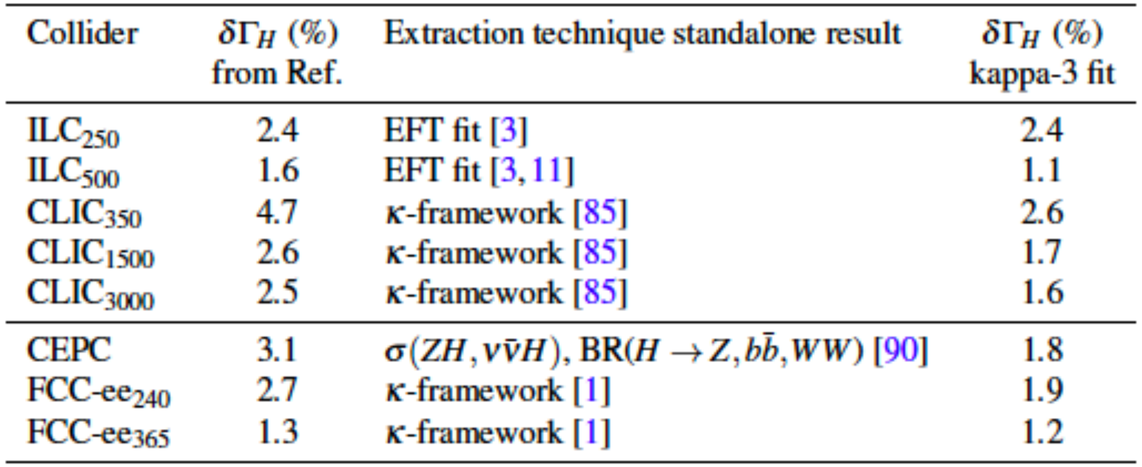
$$\frac{\sigma(e^+e^-\to ZH)}{\mathrm{BR}(H\to ZZ^*)} = \frac{\sigma(e^+e^-\to ZH)}{\Gamma(H\to ZZ^*)/\Gamma_H} \simeq \left[\frac{\sigma(e^+e^-\to ZH)}{\Gamma(H\to ZZ^*)}\right]_{\mathrm{SM}} \times \Gamma_H$$

In kappa-framework: $$\Gamma_H = \frac{\Gamma_H^{\mathrm{SM}}\cdot\kappa_H^2}{1-(BR_{inv}+BR_{unt})}$$

=> Will probe width with 1-2% precision



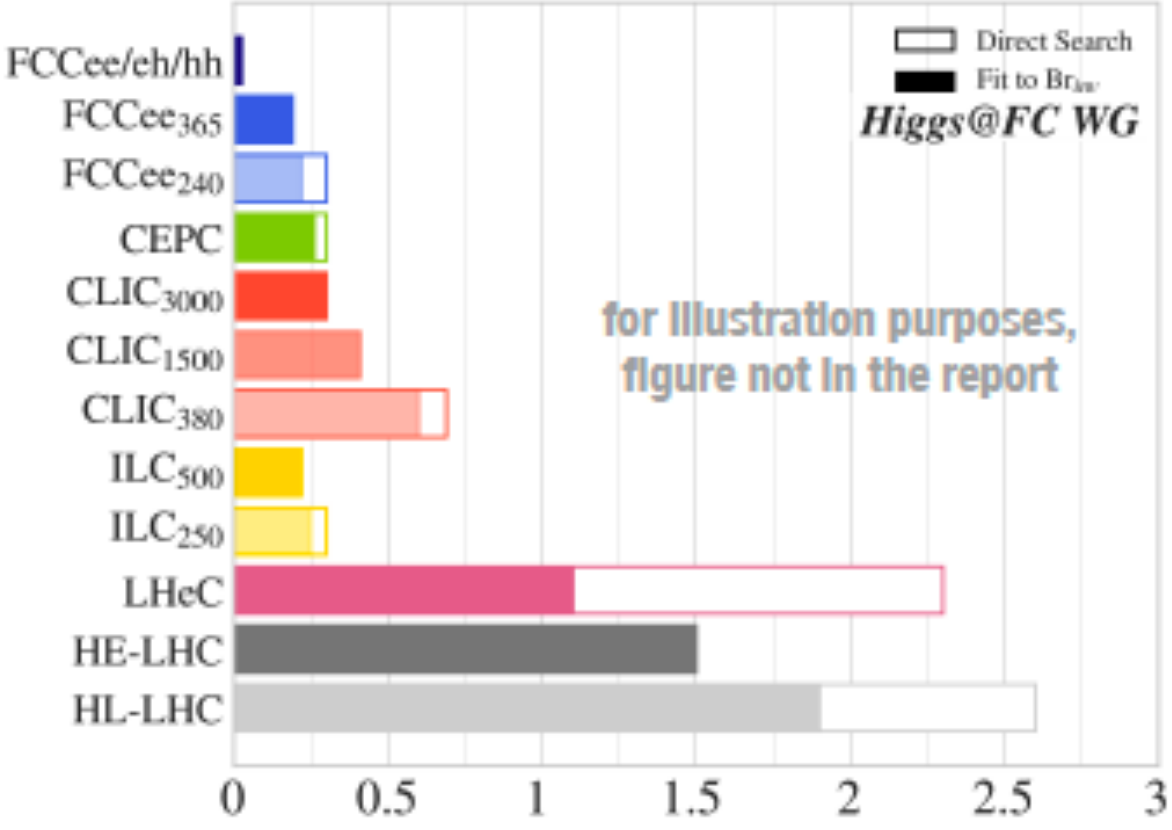


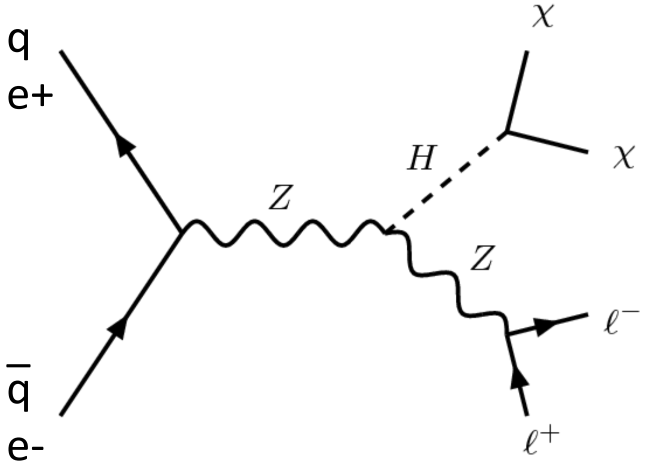


Collider	$\delta\Gamma_H$ (%) from Ref.	Extraction technique standalone result	$\delta\Gamma_H$ (%) kappa-3 fit
ILC_{250}	2.4	EFT fit [3]	2.4
ILC_{500}	1.6	EFT fit [3, 11]	1.1
CLIC_{350}	4.7	κ-framework [85]	2.6
CLIC_{1500}	2.6	κ-framework [85]	1.7
CLIC_{3000}	2.5	κ-framework [85]	1.6
CEPC	3.1	$\sigma(ZH,\nu\bar{\nu}H)$, BR$(H\to Z,b\bar{b},WW)$ [90]	1.8
$\mathrm{FCC\text{-}ee}_{240}$	2.7	κ-framework [1]	1.9
$\mathrm{FCC\text{-}ee}_{365}$	1.3	κ-framework [1]	1.2

arXiv:1905.03764

Invisible H decays: $H \rightarrow E_T^{miss}$



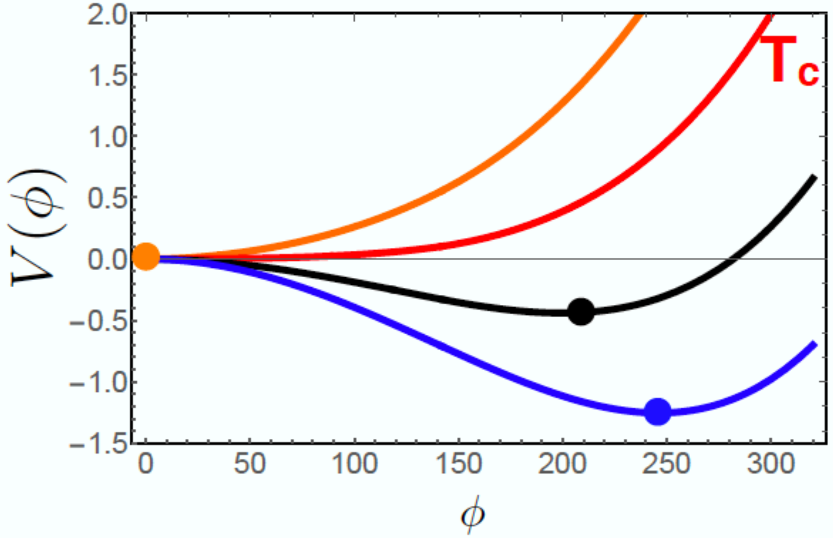


- Direct searches dominate sensitivity
  - HL-LHC will have sensitivity to ~2.6%
  - e+e- colliders improve to ~0.3%
  - FCC-hh probes below SM value: ~0.025%

Electroweak potential

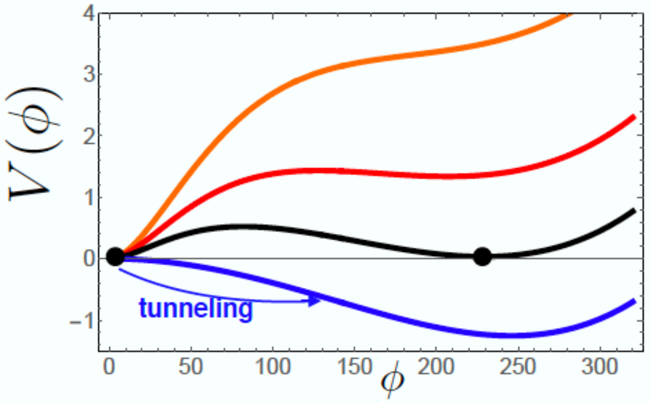
HEATING UP THE STANDARD MODEL .

EW sym. restored at T≳130 GeV through a smooth crossover



No departure from thermal equilibrium

First-order EW phase transition .



Barrier separates 2 degenerate minima

2 phases can coexist

Nucleation, expansion and collision of Higgs bubbles

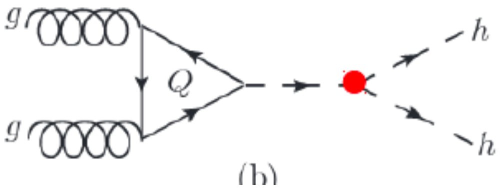
> Framework for EW baryogenesis !

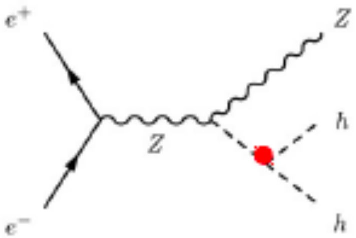
> Stochastic bgd of gravitational waves detectable at LISA !

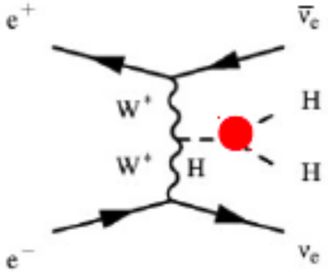
G. Servant

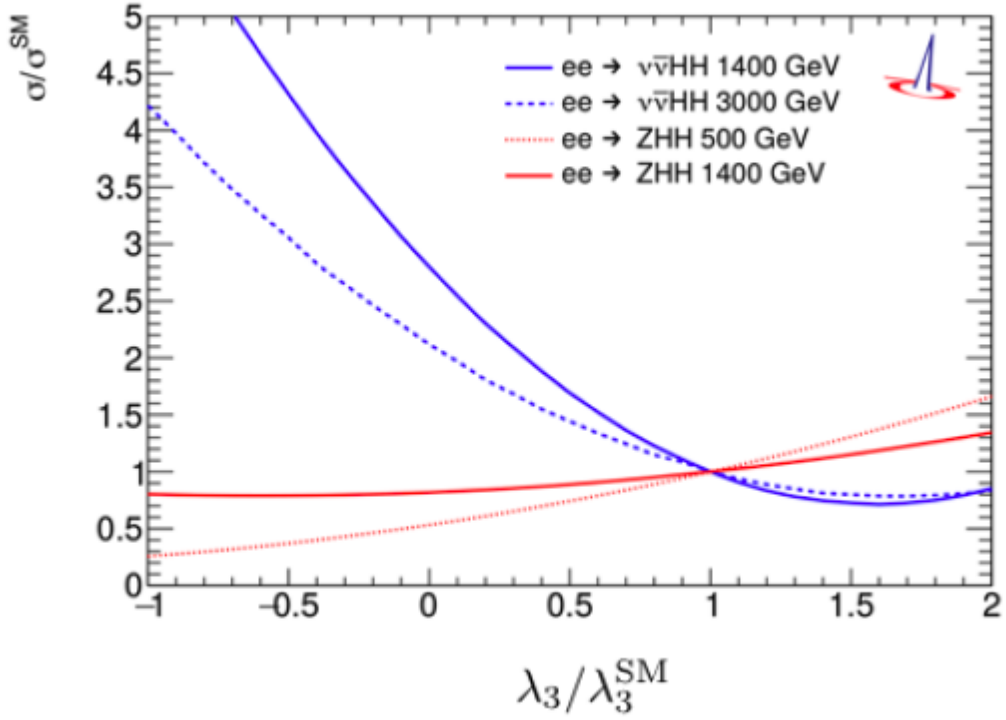
Measurement of Higgs Self-Coupling

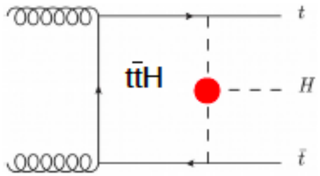
- Di-Higgs processes at hadron colliders:
  - $\boldsymbol{\sigma(HH) \approx 0.01\times\sigma(H)}$
  - Important to use differential measurements
- Di-Higgs processes at lepton colliders
  - ZHH or VBF production complementary
- Single-Higgs production sensitive through loop effects, e.g. for $\boldsymbol{\kappa_\lambda = 2}$:
  - Hadron colliders: ~3%
  - Lepton colliders: ~1%

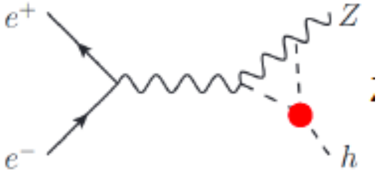






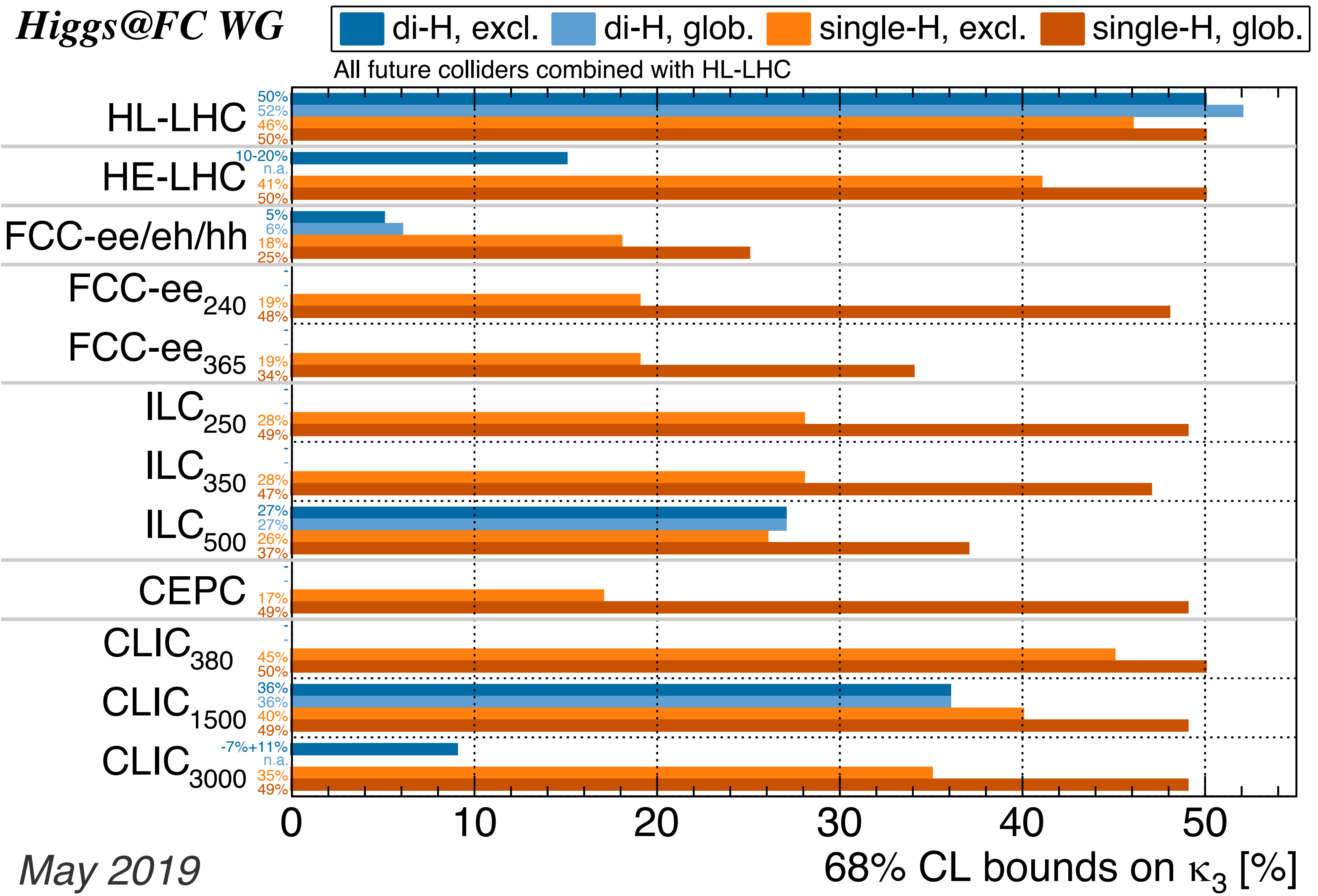






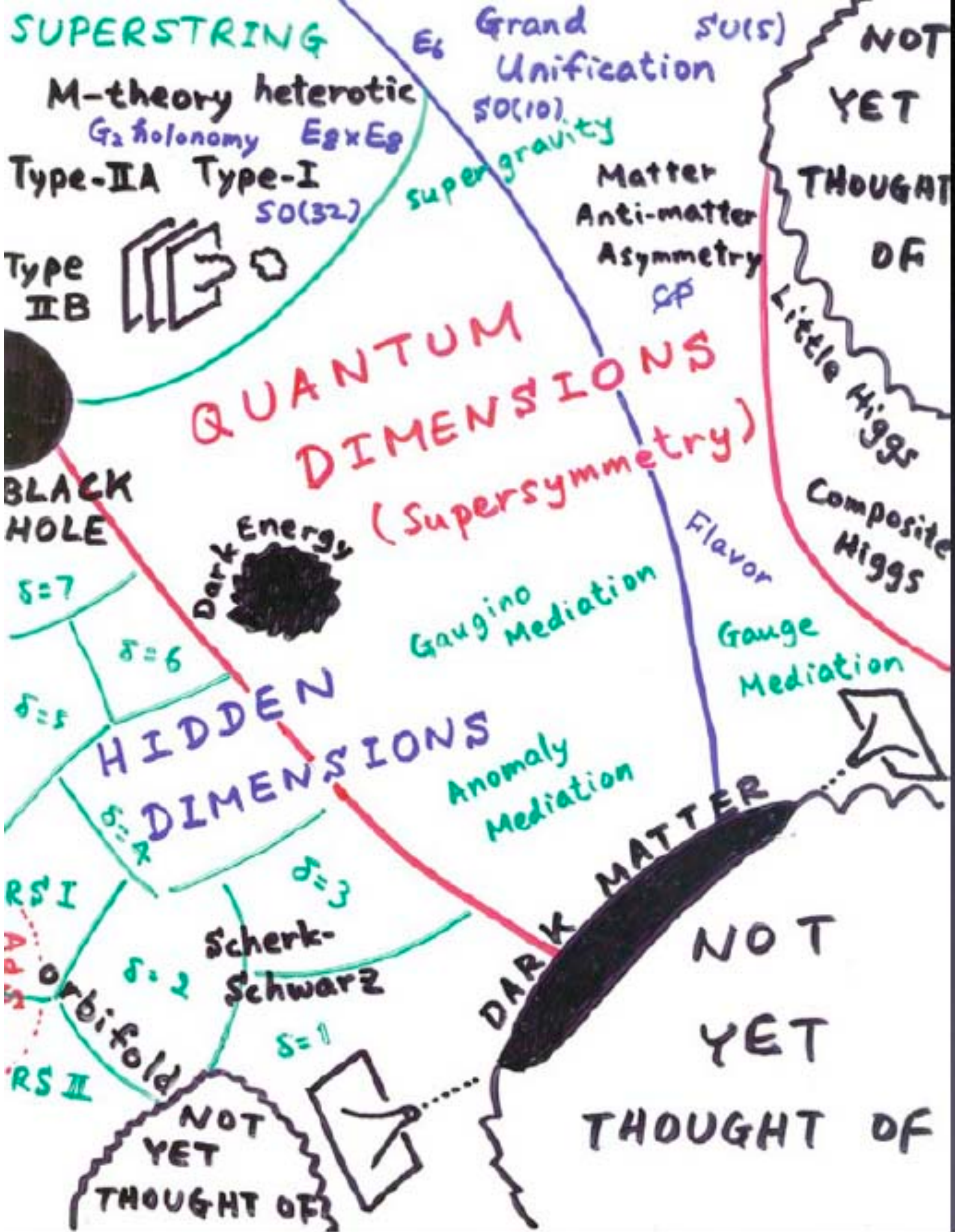
Sensitivity to λ: via single-H and di-H production

- **Di-Higgs:**
  - HL-LHC: ~50% or better?
  - Improved by HE-LHC (~15%), ILC_{500} (~27%), CLIC_{1500} (~36%)
  - Precisely by CLIC_{3000} (~9%), FCC-hh (~5%),
  - Robust w.r.t other operators
- **Single-Higgs:**
  - Global analysis: FCC-ee365 and ILC500 sensitive to ~35% when combined with HL-LHC
    - ~21% if FCC-ee has 4 detectors
  - Exclusive analysis: too sensitive to other new physics to draw conclusion



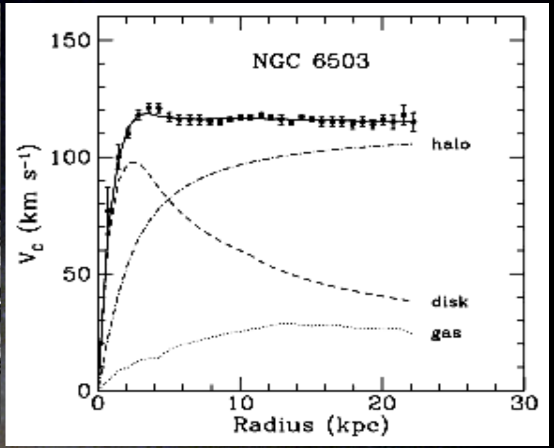
Sensitive enough to probe if there is a strong first order EWK phase transition in early Universe!

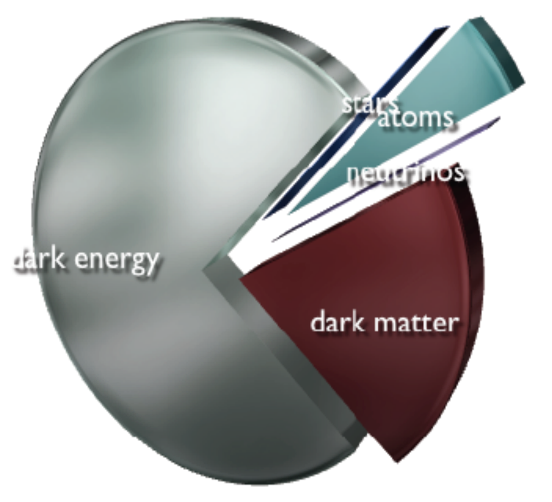
Beyond the SM Searches



- We really don't know what is going on at TeV
- stupid theorists!
- Can we zoom in onto a point on this map?
- Expect the unexpected

What is the Dark Matter?

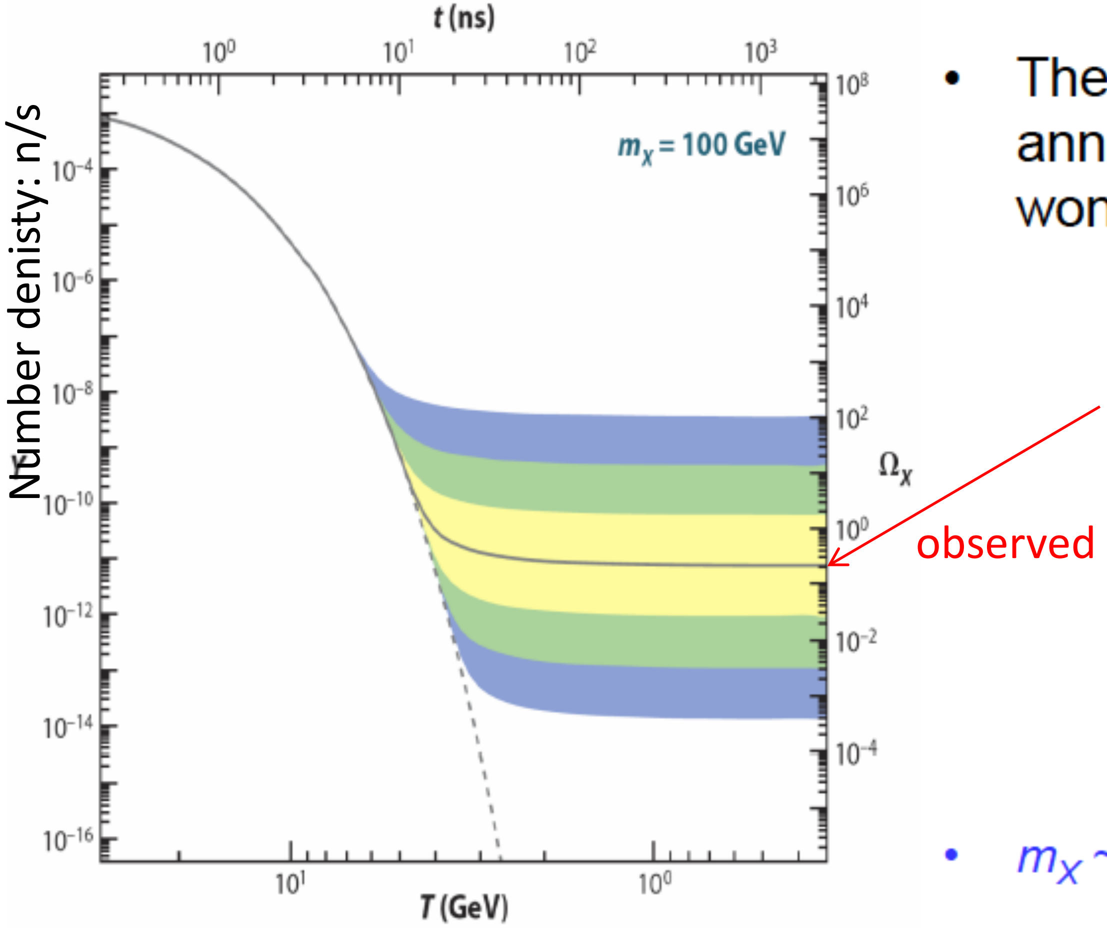




Standard Model only accounts for 20% of the matter of the Universe

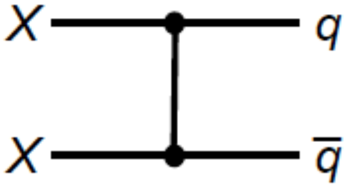
$$\frac{\text{matter}}{\text{all atoms}} = 5.70^{+0.39}_{-0.61}$$

Dark Matter: the WIMP miracle



- The relation between Ω_X and annihilation strength is wonderfully simple:

$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$

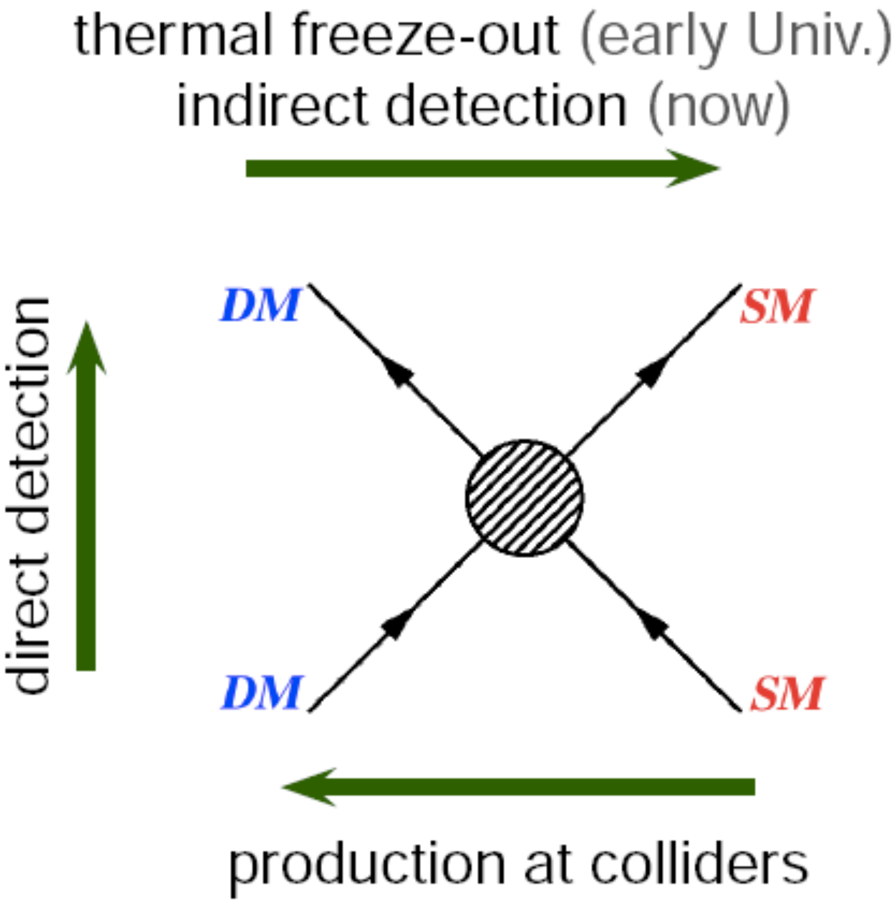


- $m_X \sim 100$ GeV, $g_X \sim 0.6 \rightarrow \Omega_X \sim 0.1$

Remarkable coincidence that particle required has approximately the mass of weak scale particles

How to search for WIMPs?

XENON1T in Gran Sasso

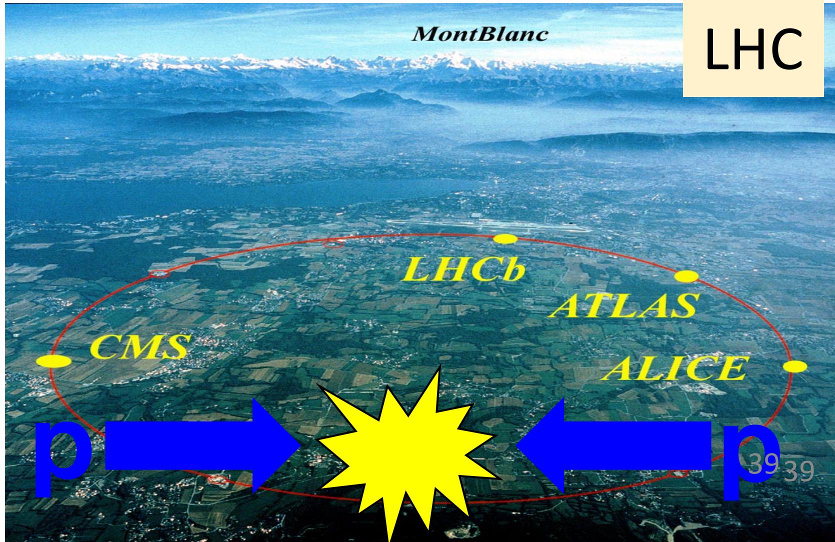


thermal freeze-out (early Univ.)
indirect detection (now)

direct detection

production at colliders

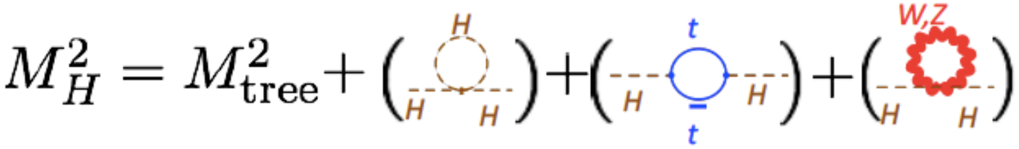
AMS satellite



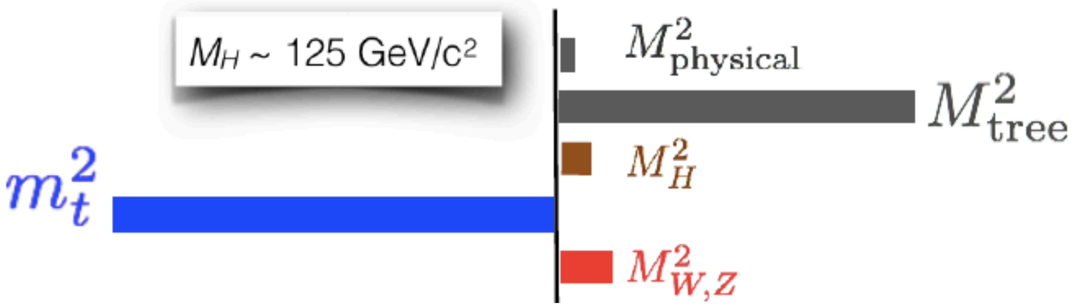
LHC

Problem: why is m_{Higgs} so small?

Higgs mass unstable



$M_H^2 = M_{\mathrm{tree}}^2 + (\ ) + (\ ) + (\ )$



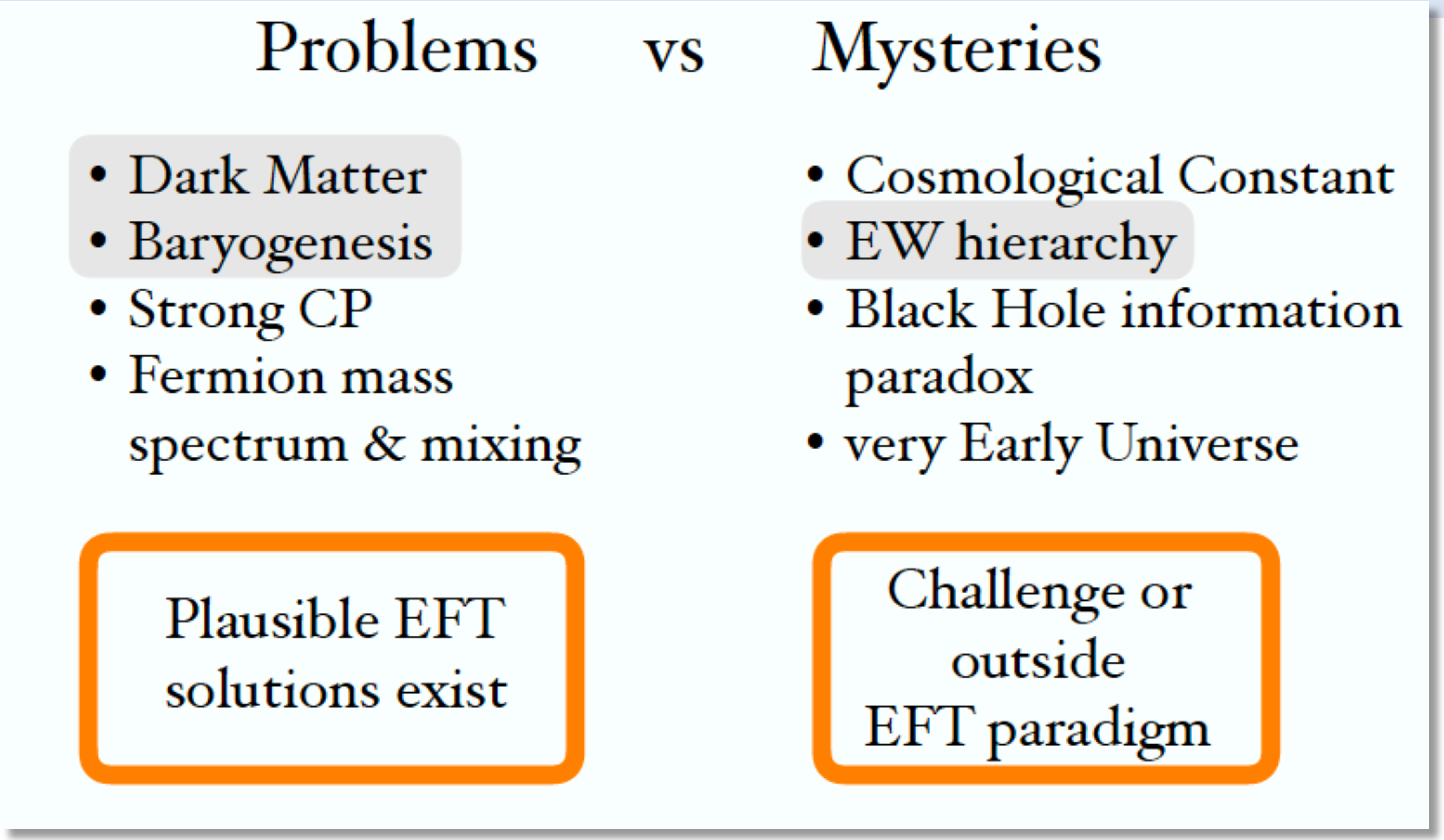
M_{tree} needs to be tuned precisely =>seems very unnatural!

$$\begin{aligned} M_H^2 \quad = \quad & 3.273, 459, 429, 634, 290, 543, 867, 496, 473, 159, 645 \\ & -3.273, 459, 429, 634, 290, 543, 867, 496, 473, 159, 643\ \mathrm{GeV}^2 \end{aligned}$$

“Naturalness” or “Finetuning” Problem

from H. Murayama

What and Why?



Problems vs Mysteries

- Dark Matter
- Baryogenesis
- Strong CP
- Fermion mass spectrum & mixing

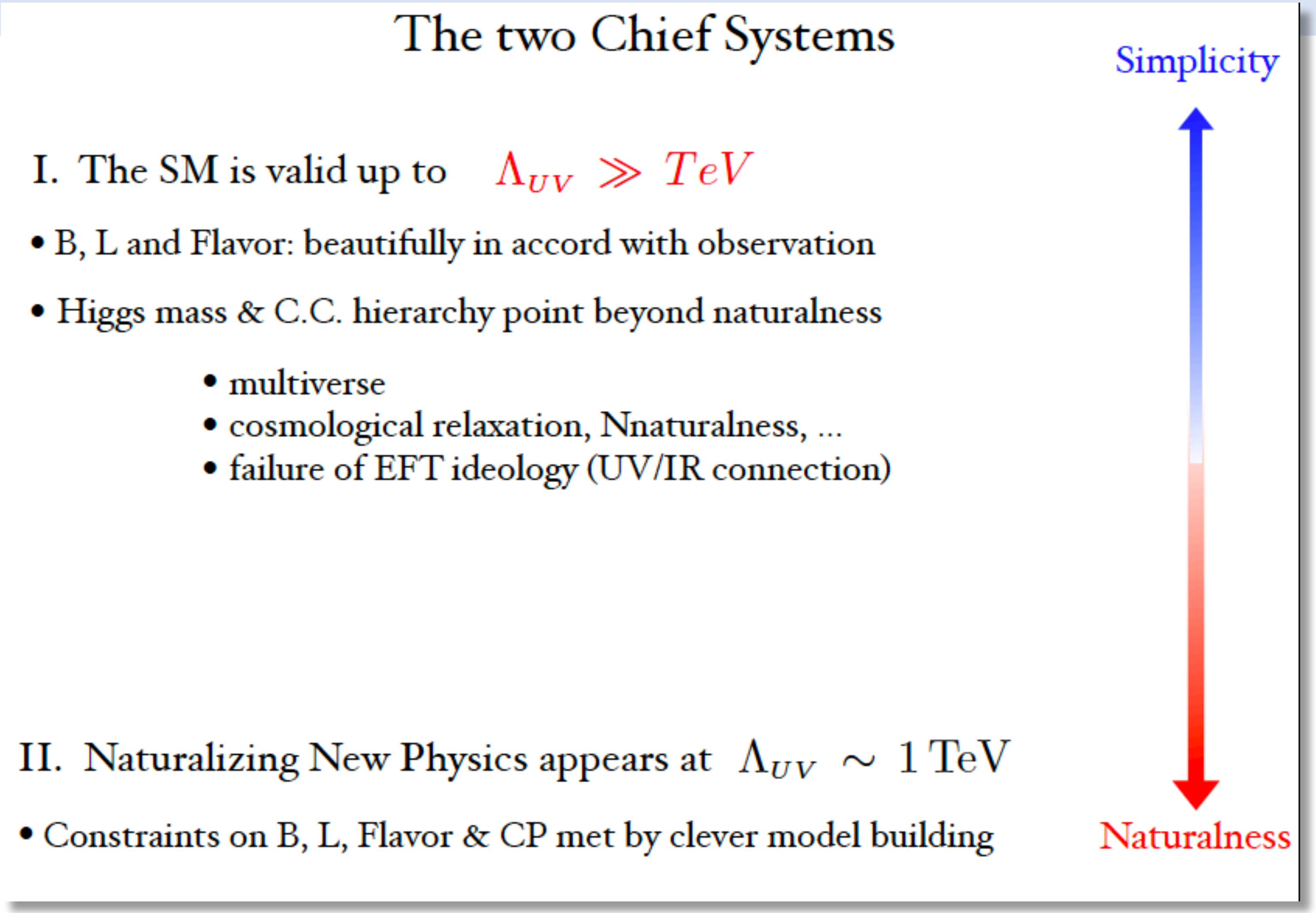
Plausible EFT solutions exist

- Cosmological Constant
- EW hierarchy
- Black Hole information paradox
- very Early Universe

Challenge or outside EFT paradigm

R. Rattazzi

Simplicity vs Naturalness



The two Chief Systems

Simplicity

I. The SM is valid up to $\Lambda_{UV} \gg TeV$

- B, L and Flavor: beautifully in accord with observation
- Higgs mass & C.C. hierarchy point beyond naturalness
    - multiverse
    - cosmological relaxation, Nnaturalness, ...
    - failure of EFT ideology (UV/IR connection)

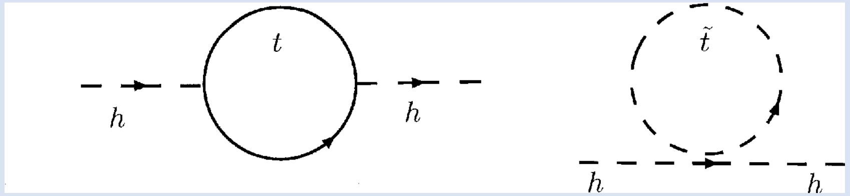
II. Naturalizing New Physics appears at $\Lambda_{UV} \sim 1\,\text{TeV}$

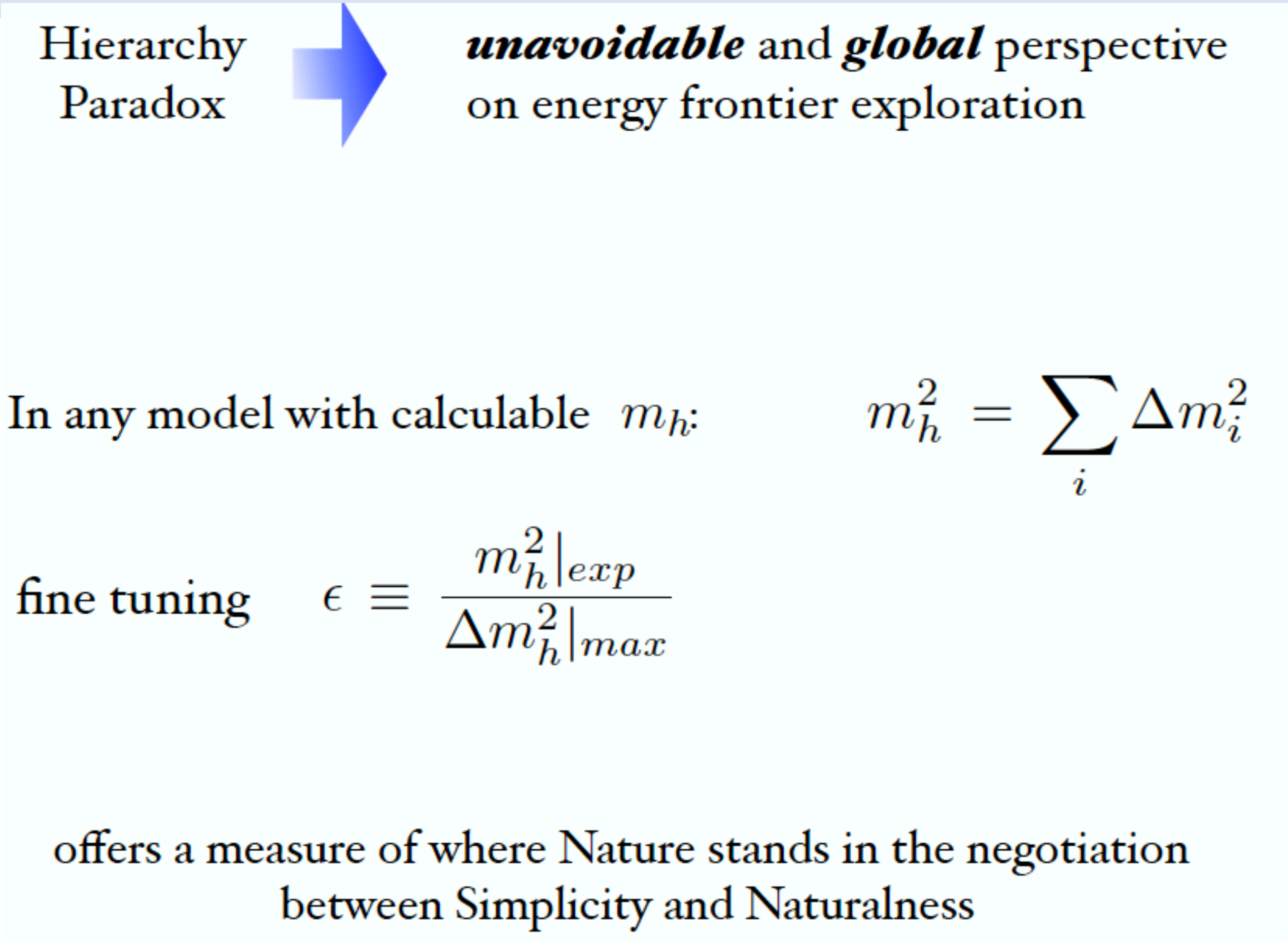
- Constraints on B, L, Flavor & CP met by clever model building

Naturalness

R. Rattazzi

Measuring Naturalness





Hierarchy Paradox → ***unavoidable*** and ***global*** perspective on energy frontier exploration

In any model with calculable m_h: $$m_h^2 = \sum_i \Delta m_i^2$$

fine tuning $$\epsilon \equiv \frac{m_h^2|_{exp}}{\Delta m_h^2|_{max}}$$

offers a measure of where Nature stands in the negotiation between Simplicity and Naturalness

R. Rattazzi

- Measures of fine tuning
  - Direct searches: depends on top partner constraints in model (e.g. SUSY varieties, composite H, twin H)
    - LHC now: $\epsilon \lesssim 10^{-2} - 1$
    - FCC-hh: $\epsilon \lesssim 10^{-4} - 10^{-2}$ (if nothing)
  - Higgs observables: $\boldsymbol{\epsilon \sim \delta g/g}$
  - Electroweak precision: $\boldsymbol{\epsilon \sim 10^2 \times \delta S/S}$

Higgs and EWK precision observables can test naturalness beyond direct searches

Comparison of Colliders

- HL-LHC achieves precision of ~1-3% in most cases
  - In some cases model-dependent
- Proposed $\boldsymbol{e^+e^-}$ and ep colliders improve w.r.t. HL-LHC by factors of ~2 to 10
- Initial stages of $\boldsymbol{e^+e^-}$ colliders have comparable sensitivities (within factors of 2)
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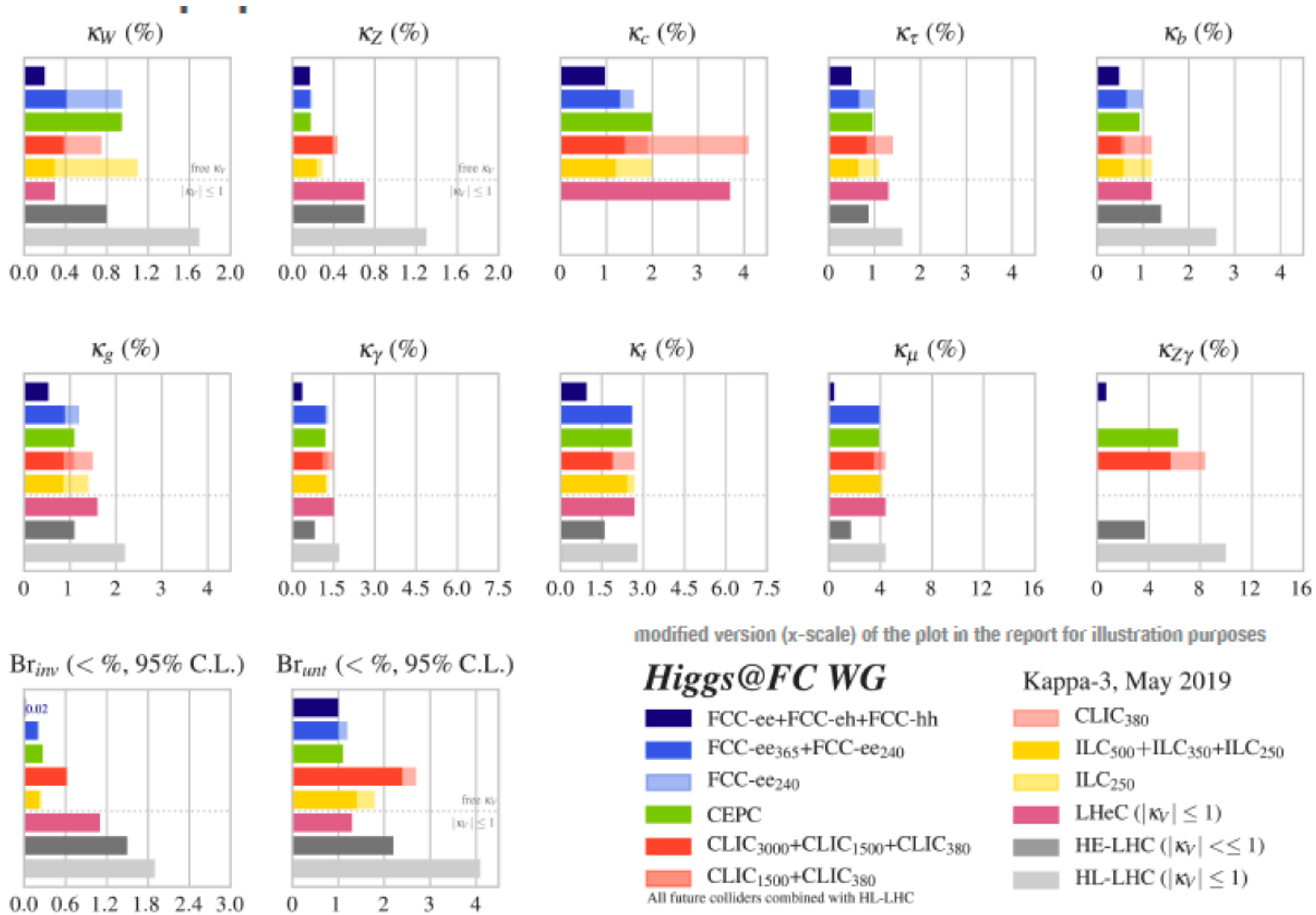
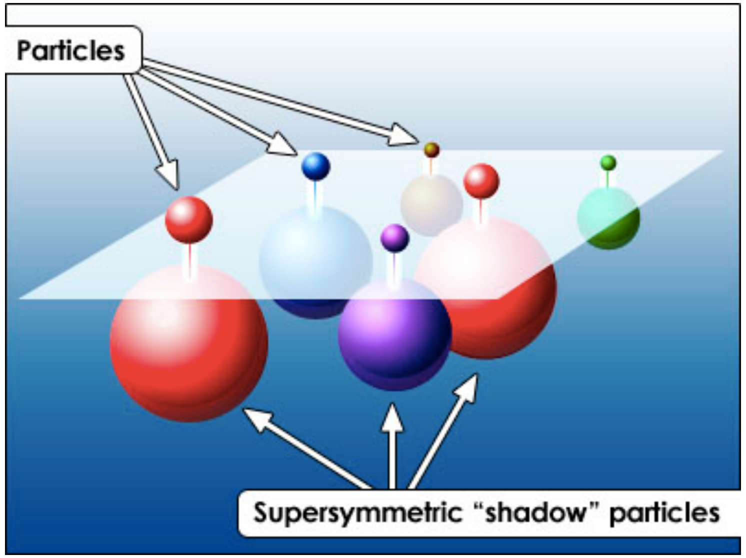


modified version (x-scale) of the plot in the report for illustration purposes

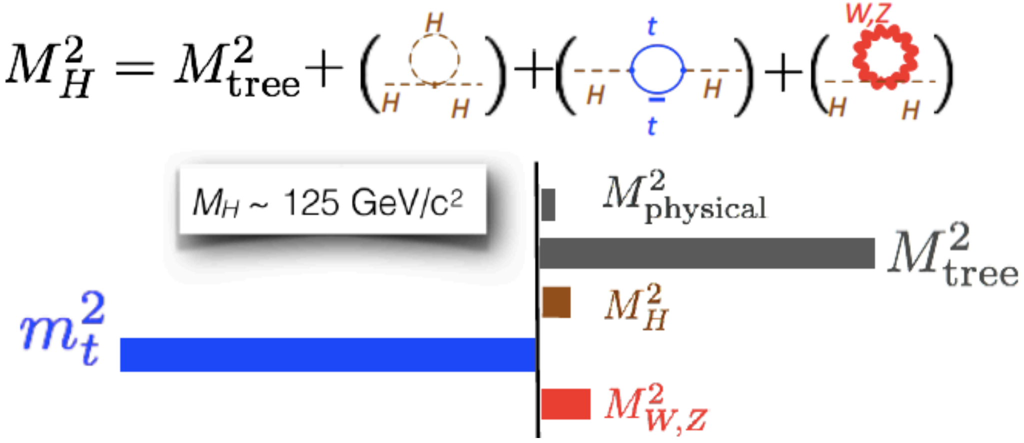
arXiv:1905.03764

Supersymmetry (SUSY)

- Standard Model particles have supersymmetric “partners”
  - Similar to matter vs anti-matter particles
- Has candidate for Dark Matter:
  - called “WIMP” (weekly interacting massive particle)
- Can solve finetuning problem
  - Requires stop to be light(ish)



Without SUSY:



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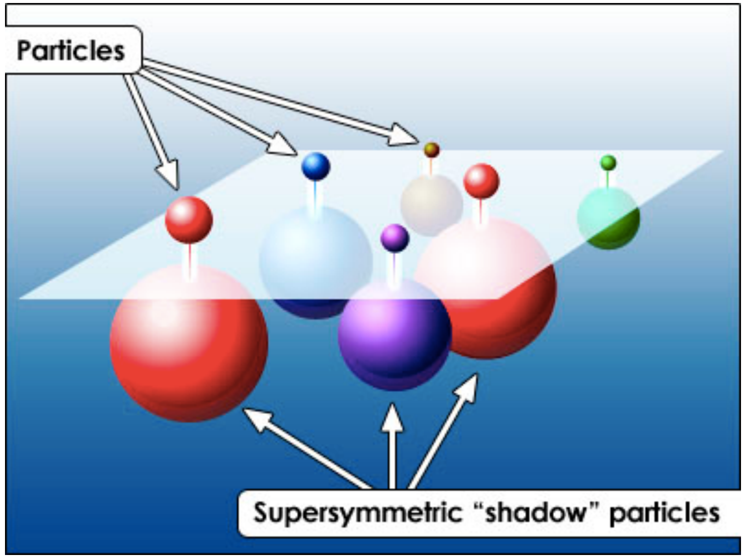
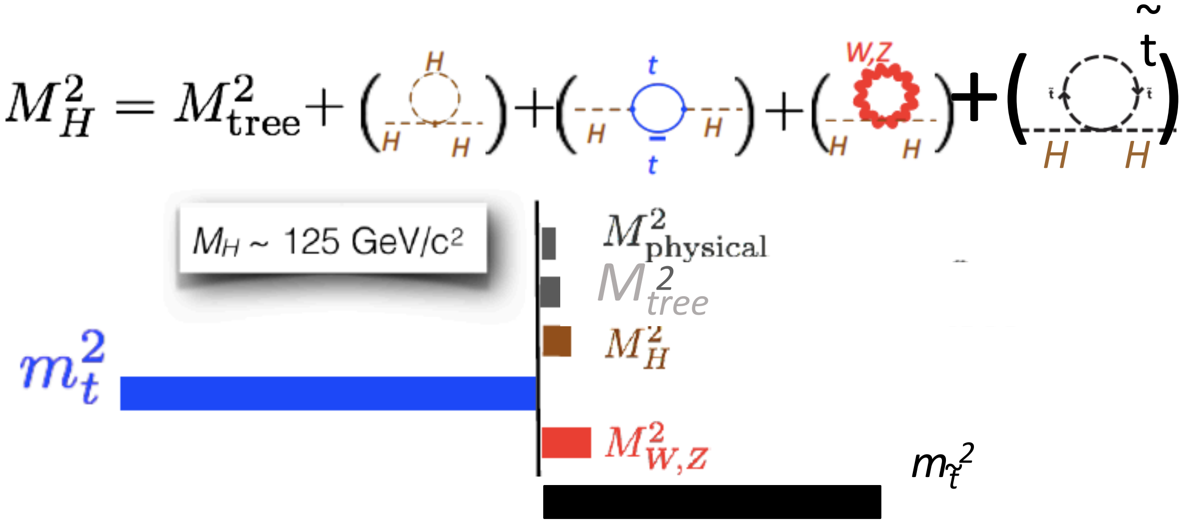
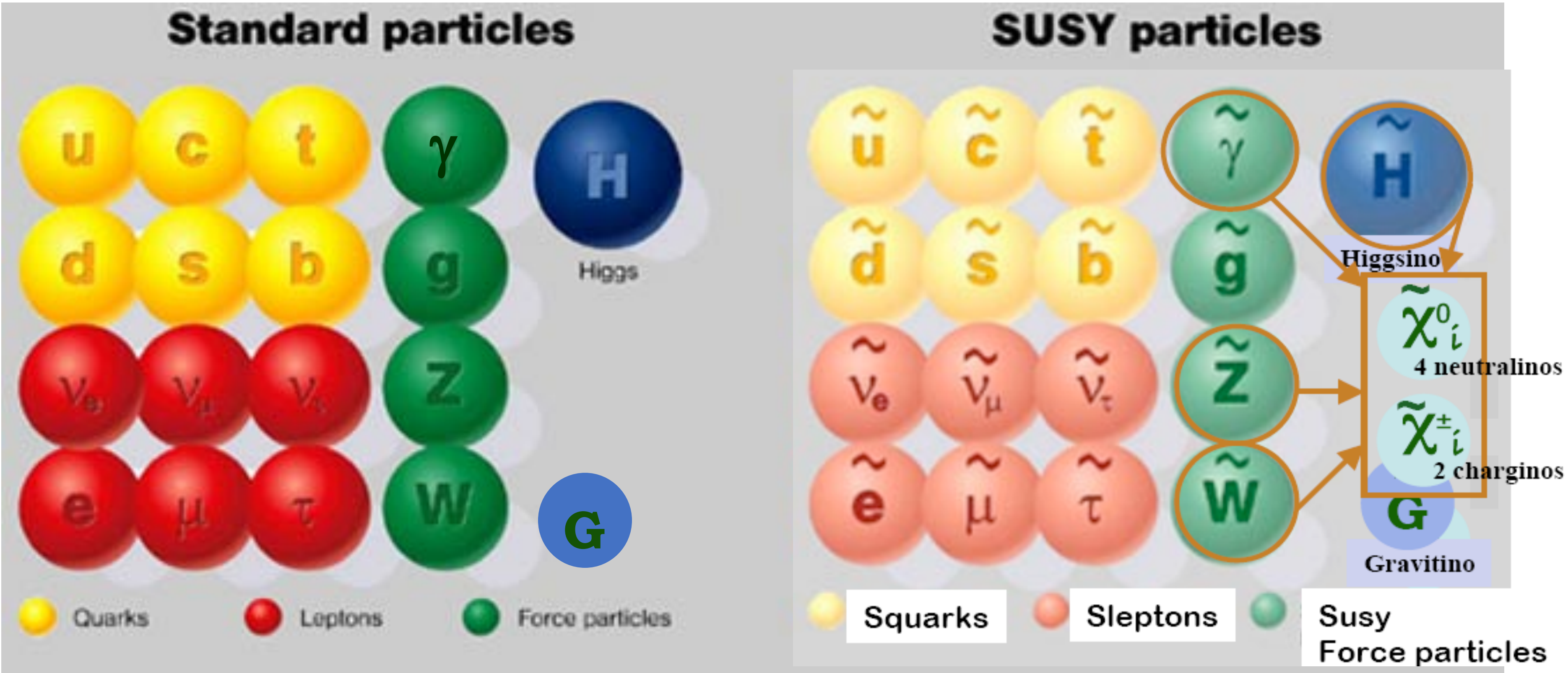


With SUSY:

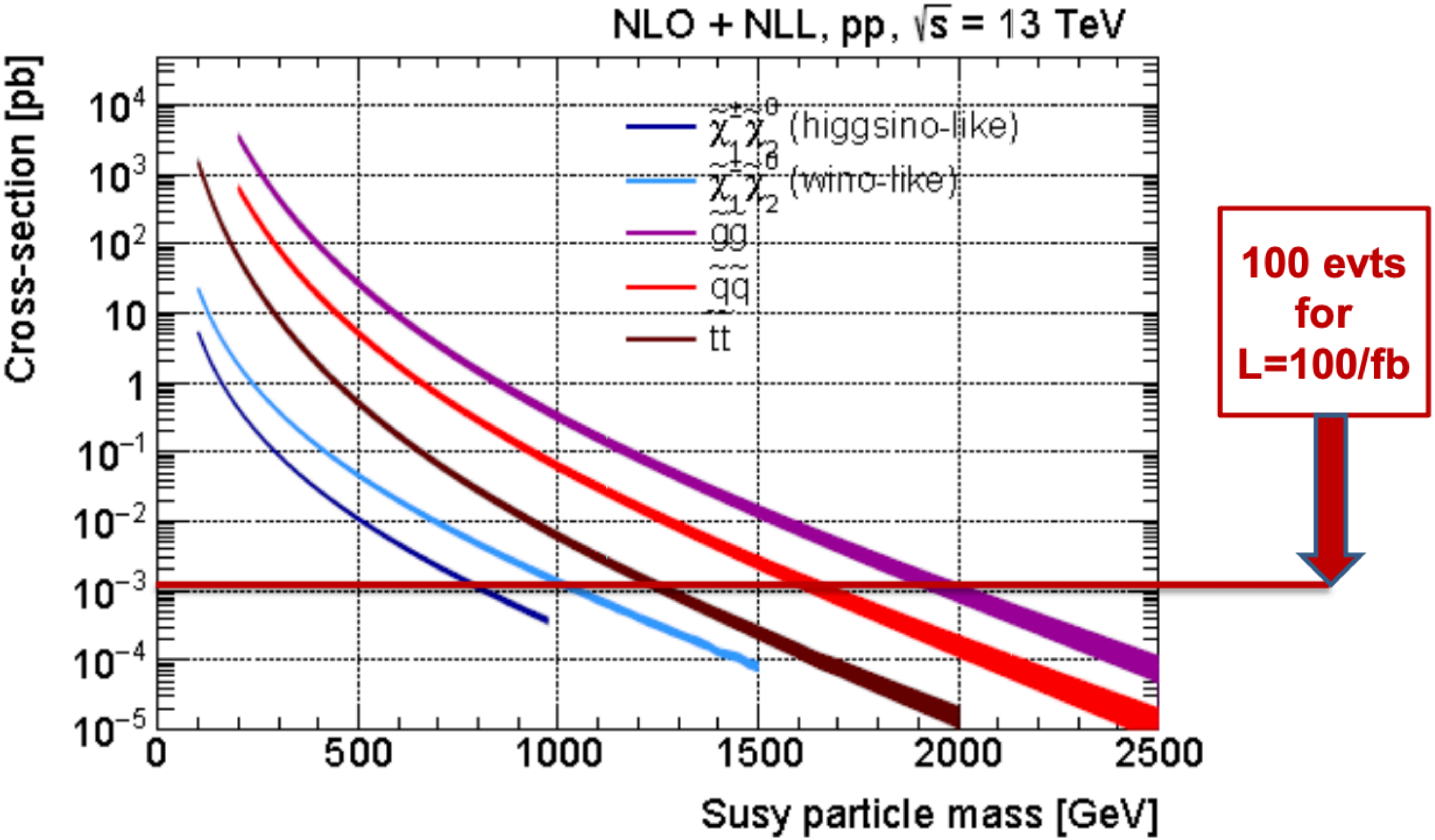


Supersymmetry (SUSY)



- SM particles have supersymmetric partners:
  - Differ by 1/2 unit in spin
    - **Sfermions** (squark, selectron, smuon, ...): spin 0
    - **gauginos** (chargino, neutralino, gluino,…): spin 1/2
- No SUSY particles found as yet:
  - SUSY must be broken: breaking mechanism determines phenomenology
  - More than 100 parameters even in “minimal” models!

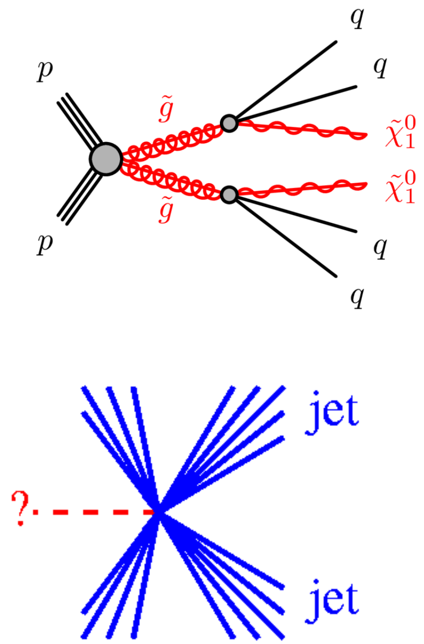
Sparticle Cross Sections



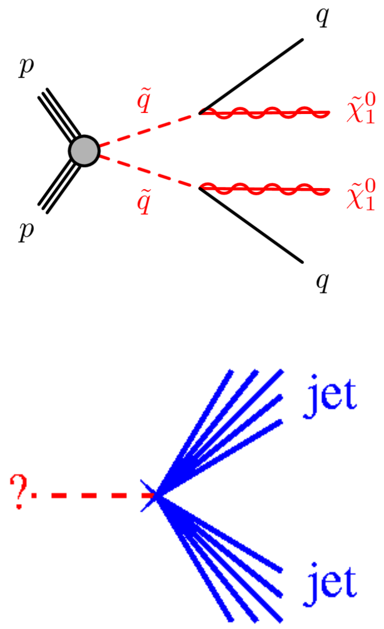
100 evts for L=100/fb

Signature depends many parameters

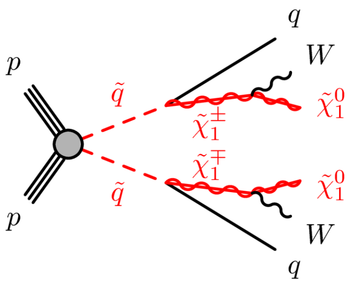
4 jets + E_T^{miss}



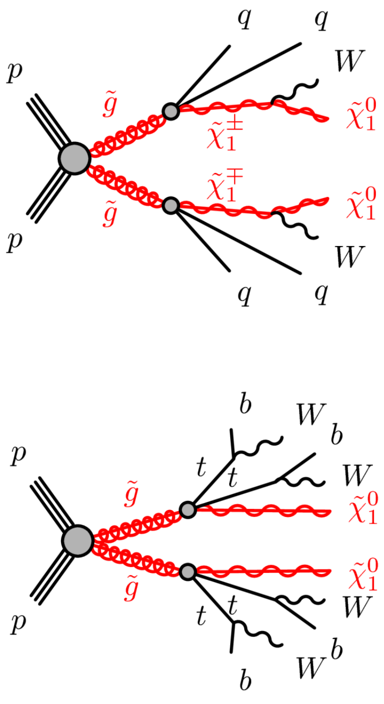
2 jets + E_T^{miss}



6 jets + E_T^{miss}



8 jets + E_T^{miss}



- In any *real* model many signatures may appear at the same time
  - But which exactly and with what strength very unclear
- Strategy is to look for many signatures and to interpret both in simplified models and in more complete models (e.g. pMSSM)

Selection and Procedure

- Selection:
  - Large missing E_T
    - Due to neutralinos
  - Large H_T
    - $H_T = \sum E_T^{jet}$
  - Large $\Delta\phi$
    - Between missing E_T and jets and between jets
    - Suppress QCD dijet background due to jet mismeasurements
  - Veto leptons:
    - Reject W/Z+jets, top

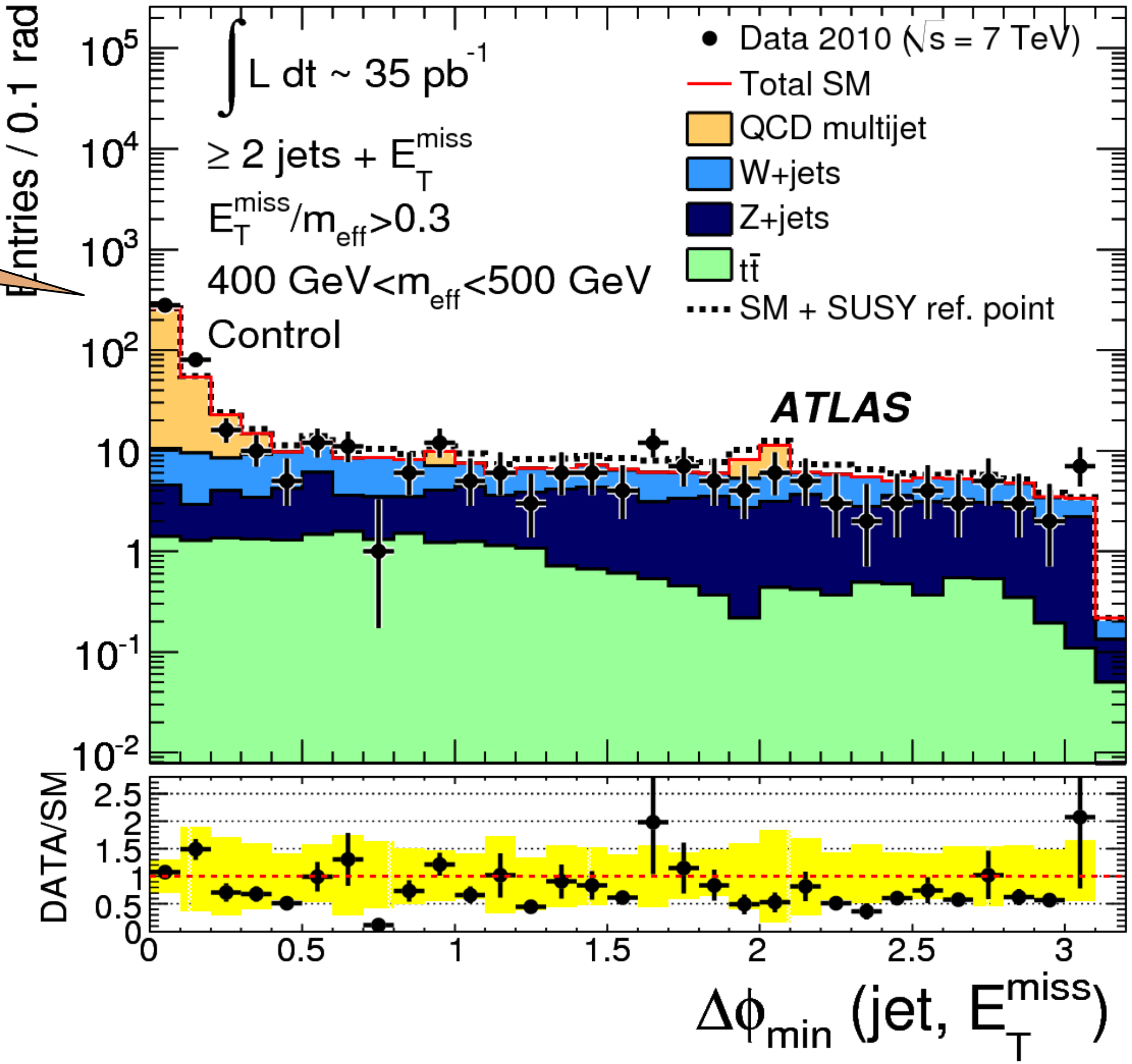
- Procedure:

1. Define signal cuts based on background and signal MC studies
2. Select control regions that are sensitive to individual backgrounds
3. Keep data “blind” in signal region until data in control regions are understood
4. Open the blind box!

QCD Dijet Rejection Cut

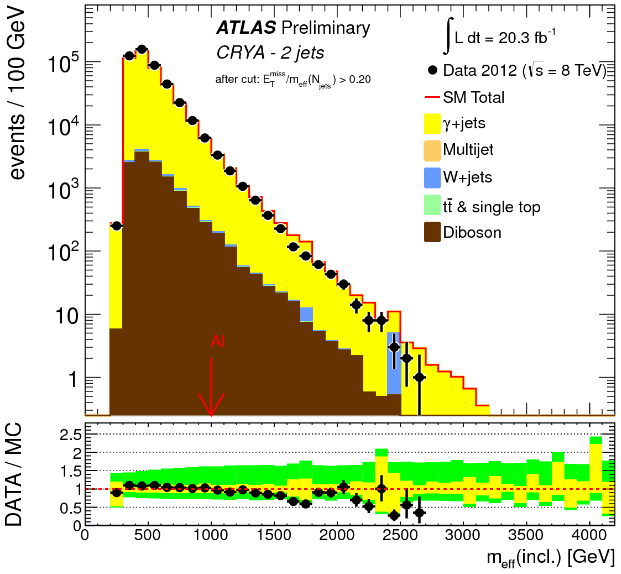
QCD multijet background

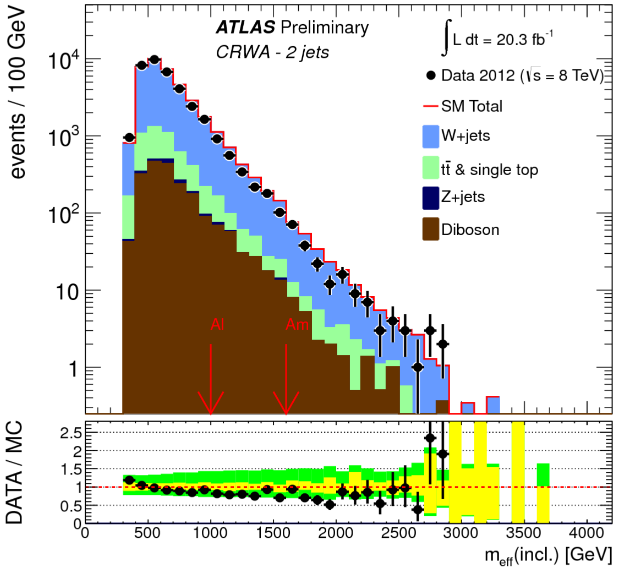
- Cut on $\Delta\phi(\text{jet}, E_T^{\text{miss}})$
- Used to suppress and to understand and reject QCD multi-jet background

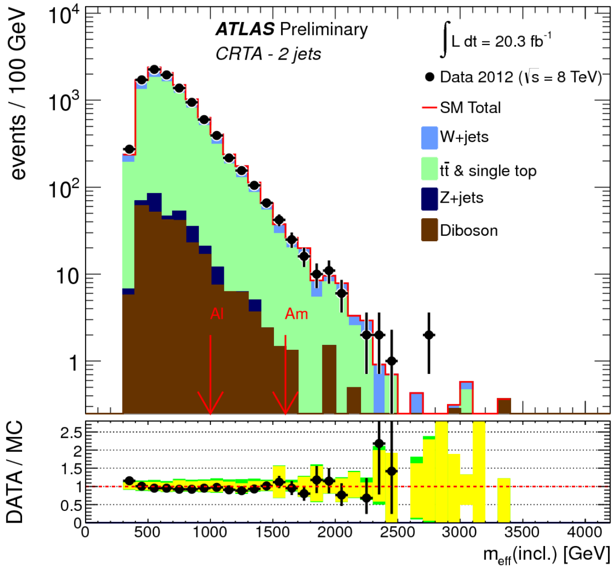


Control Regions to check backgrounds

CR	SR background	CR process	CR selection
CRY	$Z(\to \nu\nu)$+jets	γ+jets	Isolated photon
CRQ	multi-jets	multi-jets	Reversed $\Delta\phi(\text{jet}, \mathrm{E}_\mathrm{T}^{\mathrm{miss}})_{\mathrm{min}}$ and $E_\mathrm{T}^{\mathrm{miss}}/m_{\mathrm{eff}}(Nj)$ requirements[a]
CRW	$W(\to \ell\nu)$+jets	$W(\to \ell\nu)$+jets	30 GeV $< m_T(\ell, E_\mathrm{T}^{\mathrm{miss}}) <$ 100 GeV, b-veto
CRT	$t\bar{t}$ and single-t	$t\bar{t} \to bbqq'\ell\nu$	30 GeV $< m_T(\ell, E_\mathrm{T}^{\mathrm{miss}}) <$ 100 GeV, b-tag


γ+jets


W+jets


top

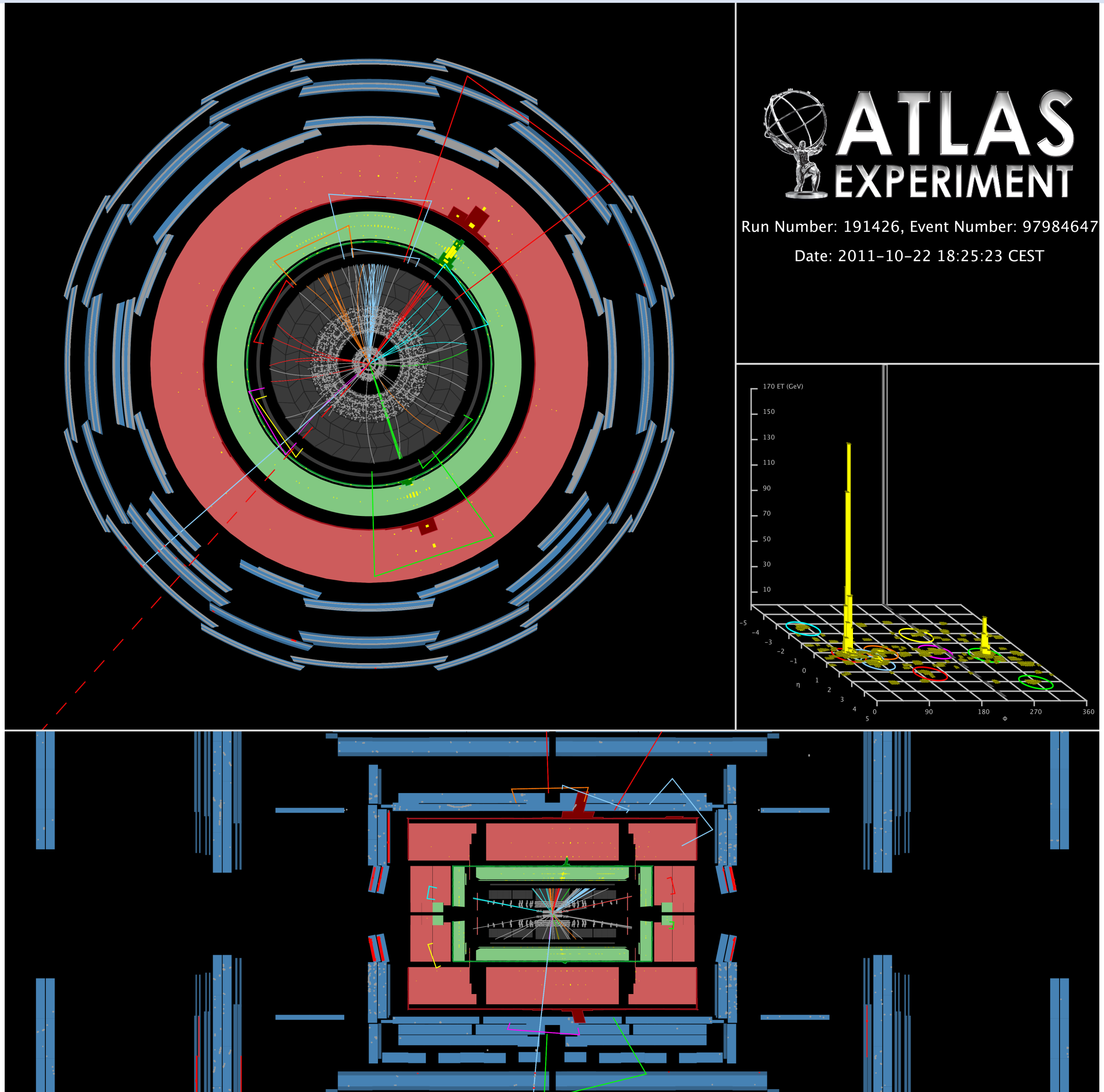
- Adjust background normalization if disagreement observed
- Next: look at the signal region!

A Nice Candidate Event!

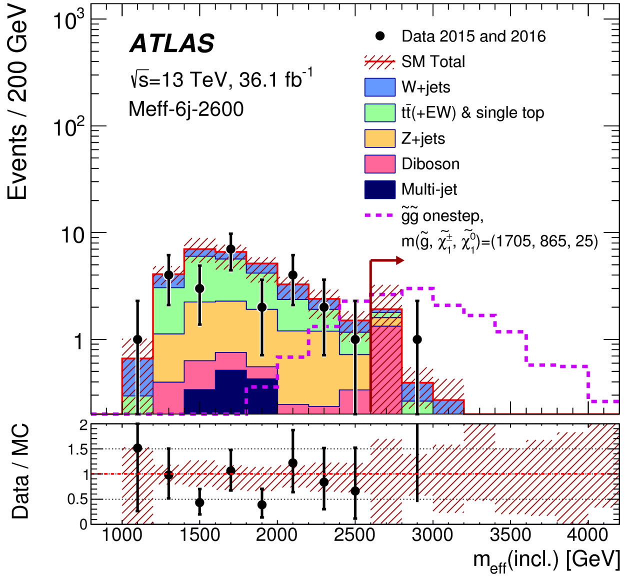
4 jets: p_T=974, 276, 146 and 61 GeV

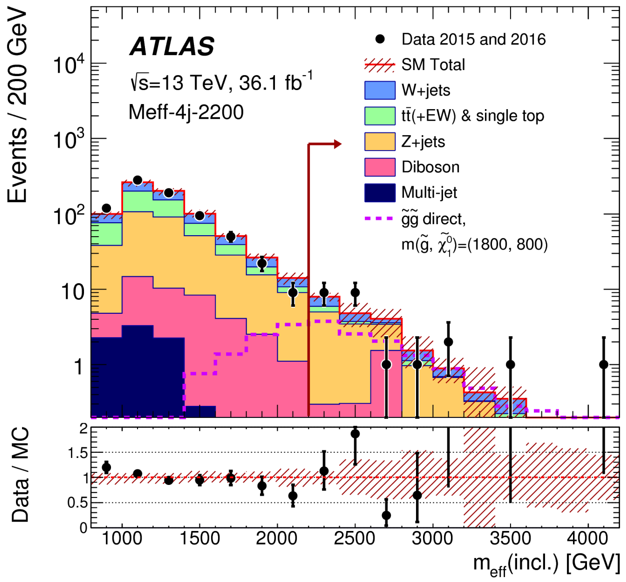
E_T^{miss}=984 GeV

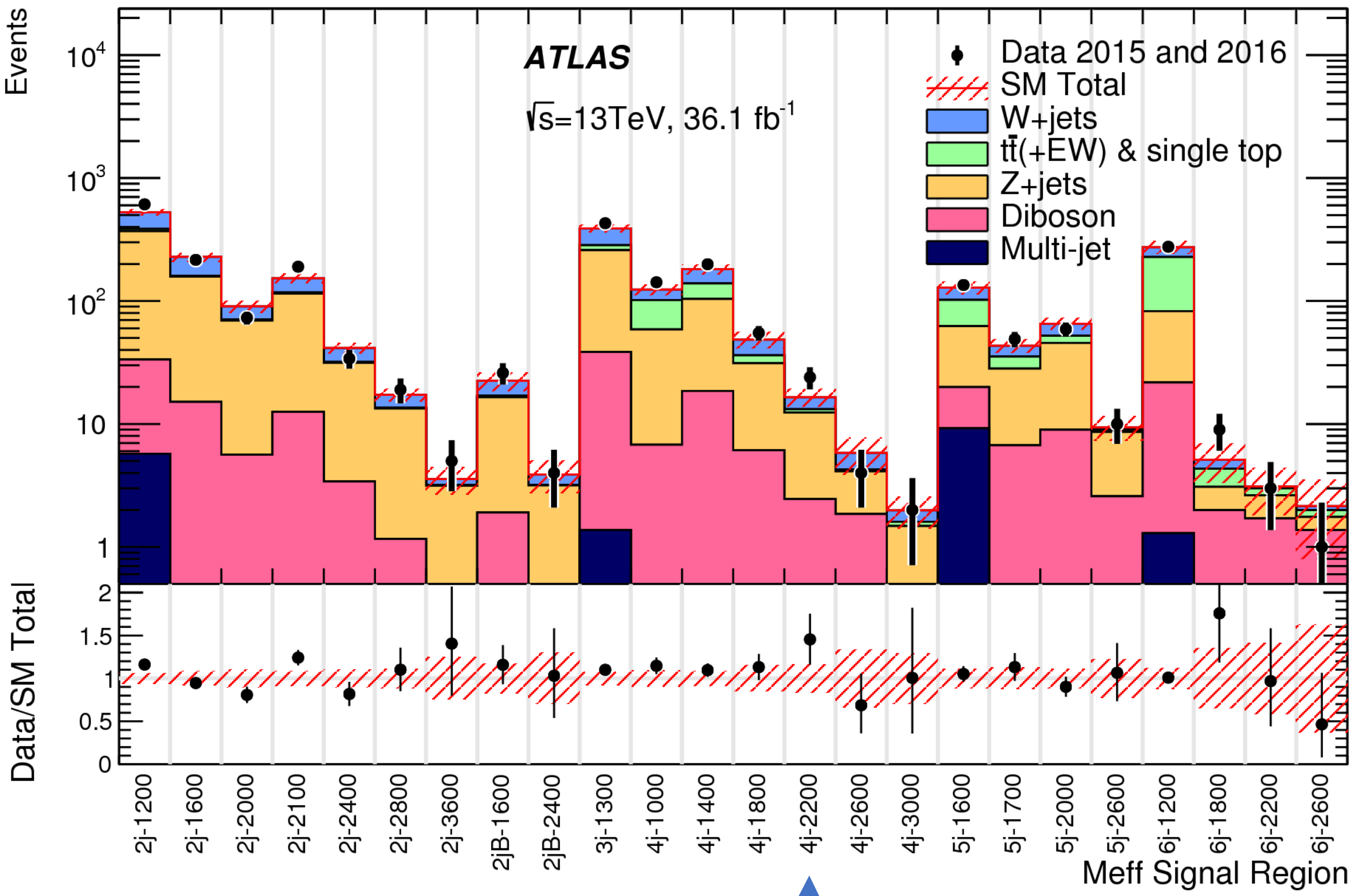
M_{eff}=2441 GeV



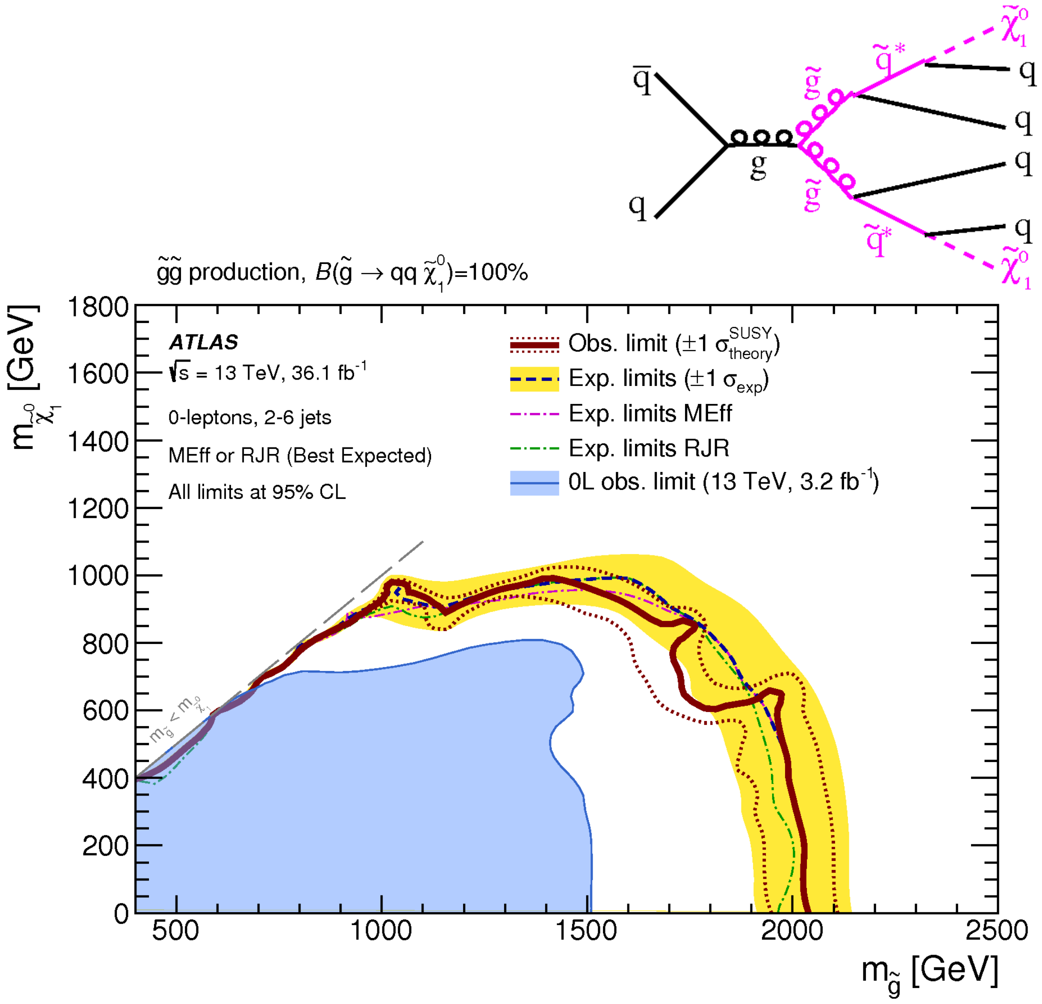
Signal Region: Data vs Background

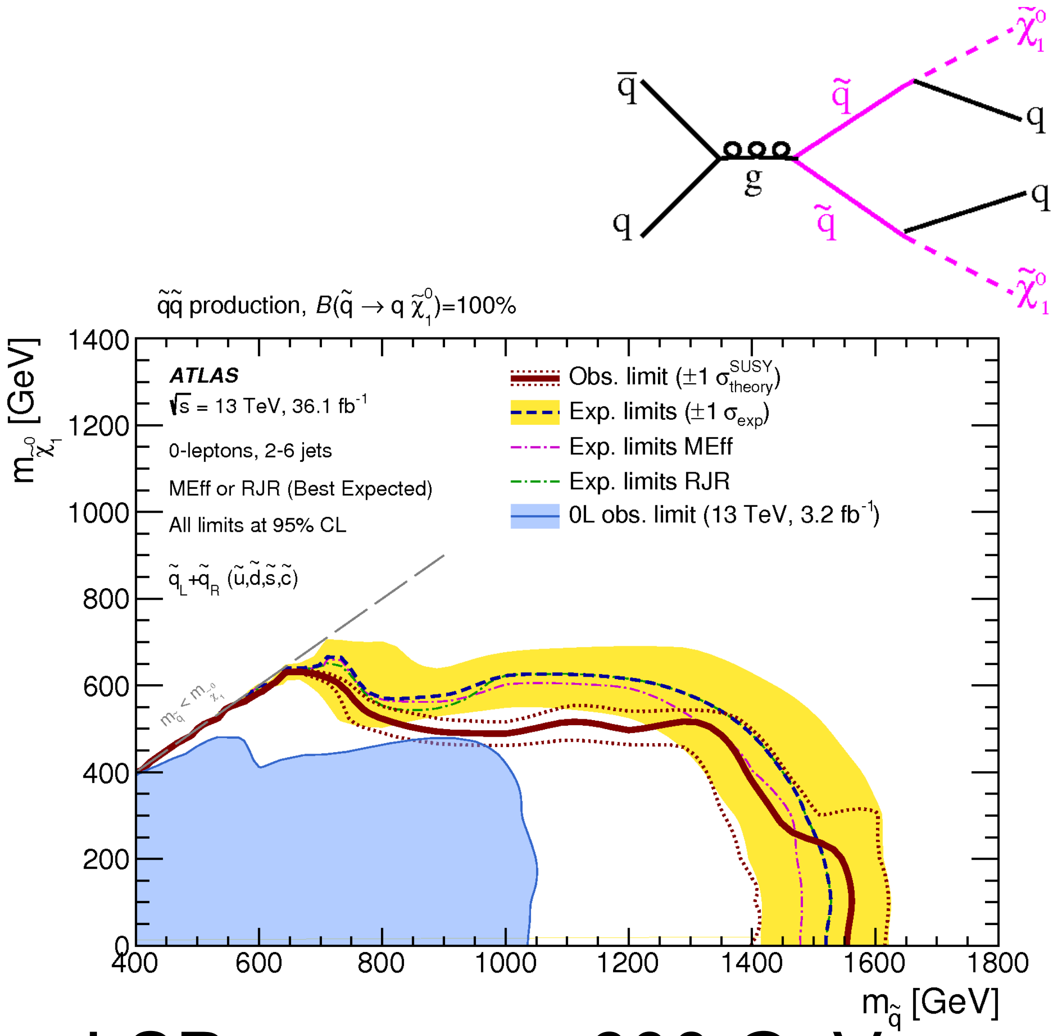






Constraints on Simplified Model



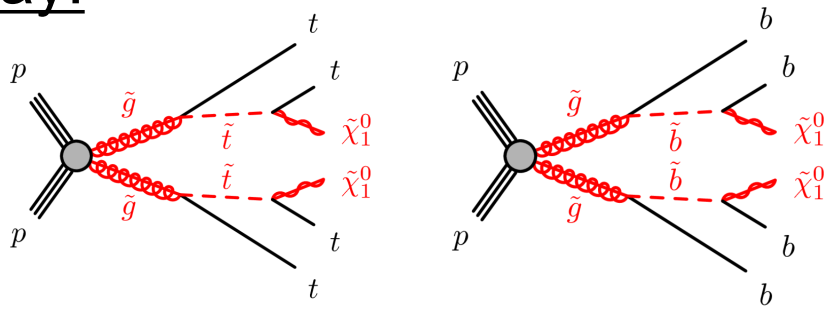


- Limits exclude gluinos up to 2 TeV for LSP masses < 600 GeV
- Limits exclude squarks up to 1.5 TeV for LSP masses < 300 GeV

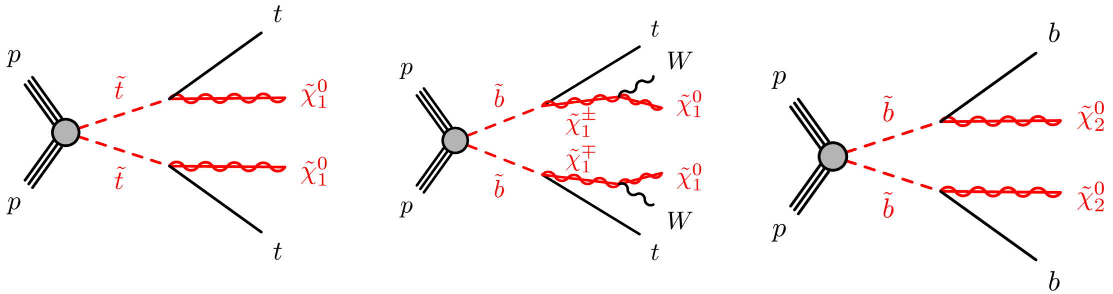
Searches with b-jets

- Strong theoretical motivation for searches with b-jets from naturalness arguments
  - Sbottom and stop should be “light”
  - Both decay via b-jets!

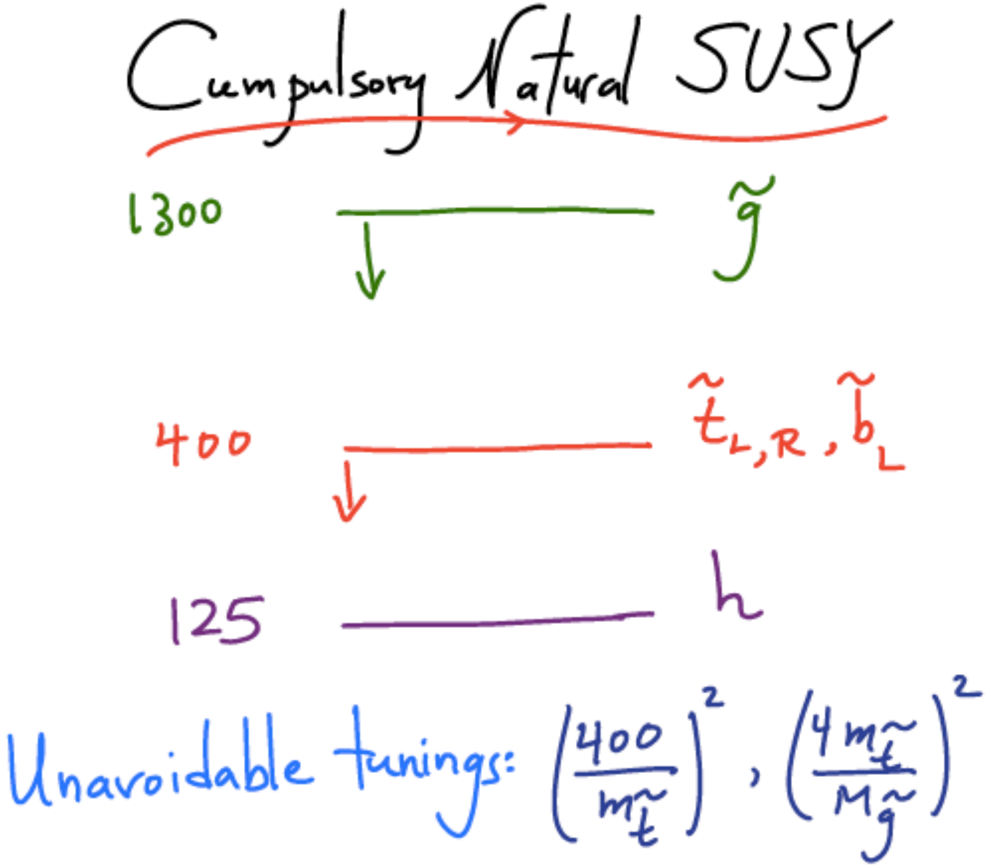
Gluino decay:



Direct pair production:



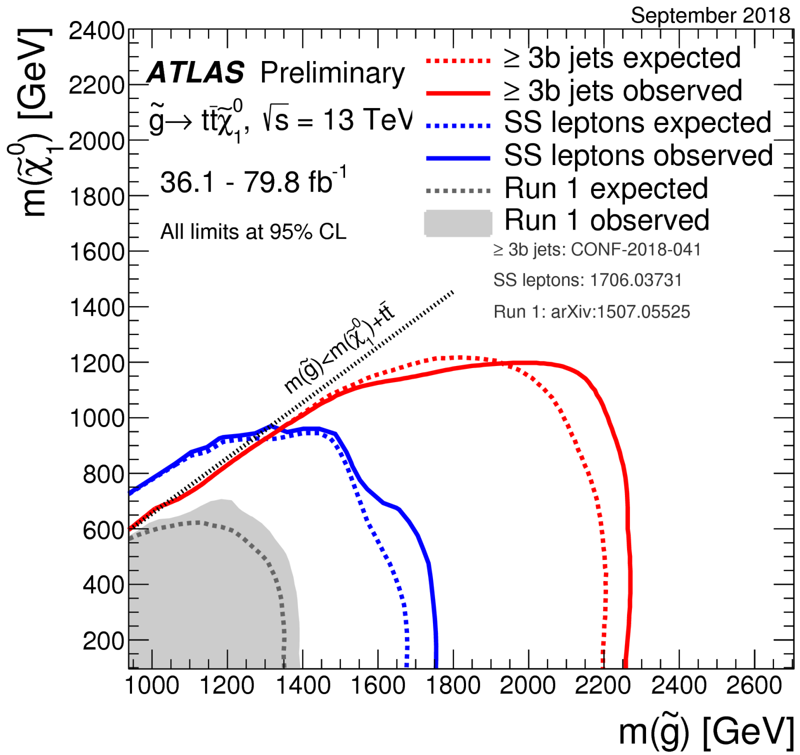
N. Arkani-Hamed

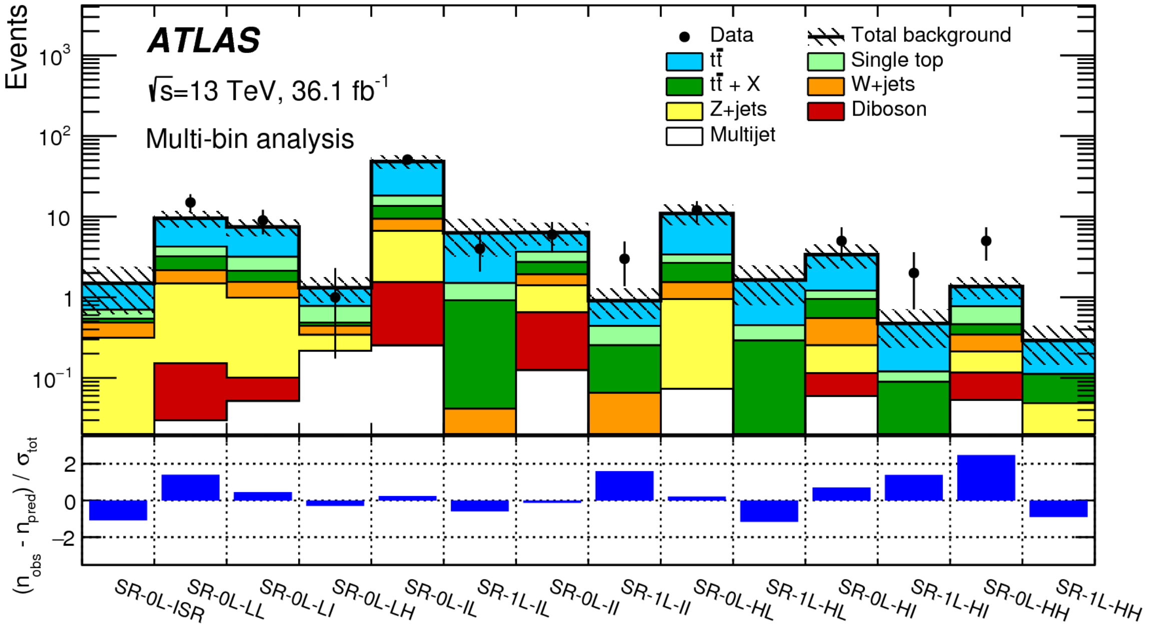


Unavoidable tunings: $\left(\frac{400}{m_{\tilde{t}}}\right)^2, \left(\frac{4 m_{\tilde{t}}}{M_{\tilde{g}}}\right)^2$

Multiple b-jets + missing E_T

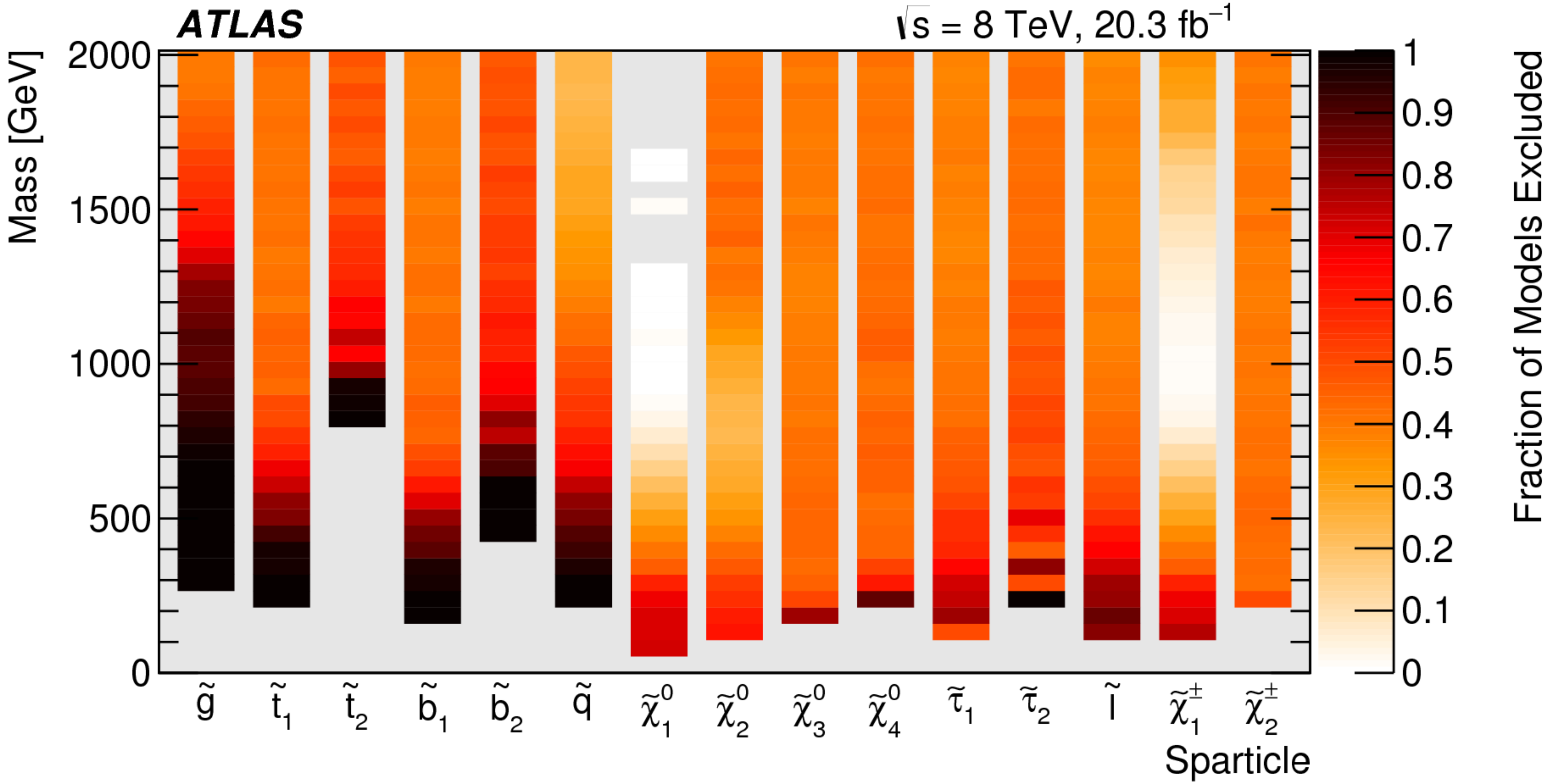
- Several signal regions with varying number of jets and 0 or 1 lepton
- Main background: top
- Sensitive to gluinos decaying via top or b quarks



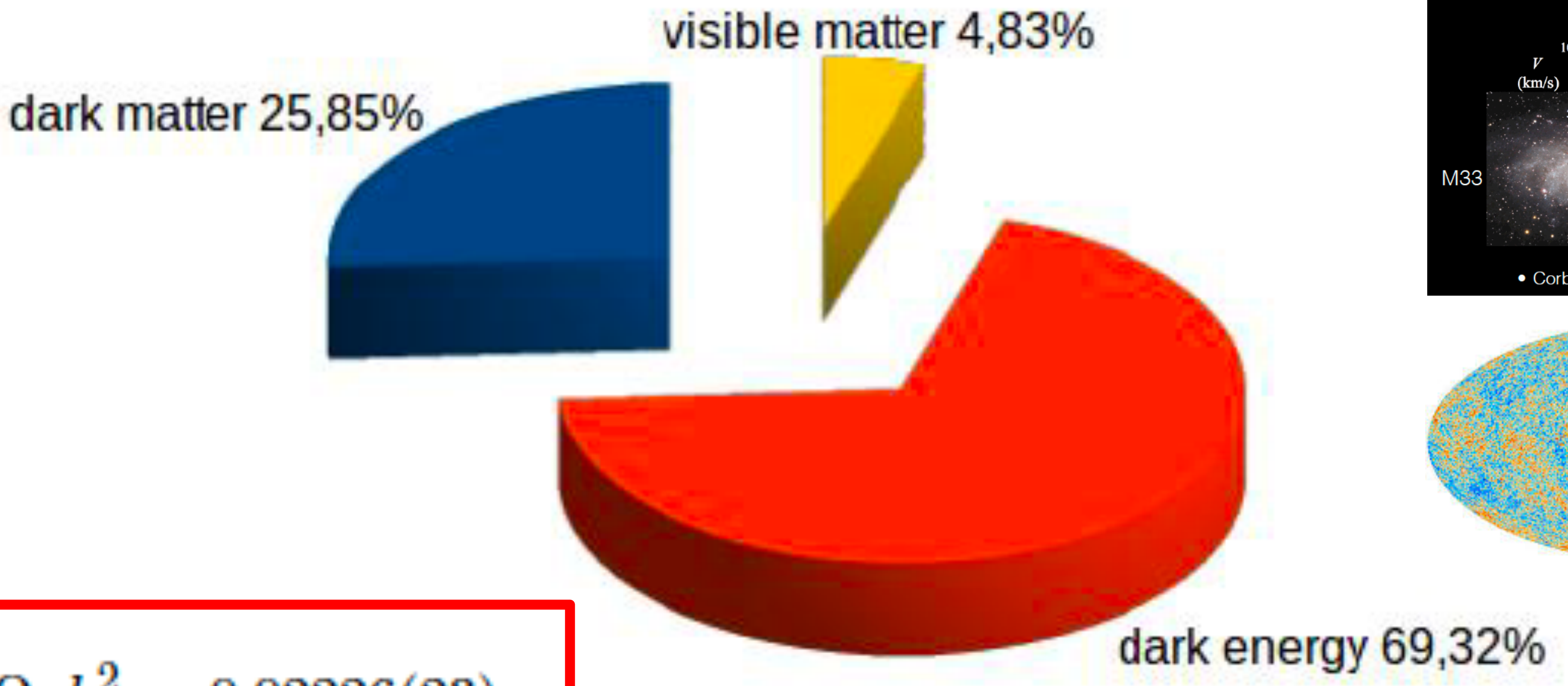


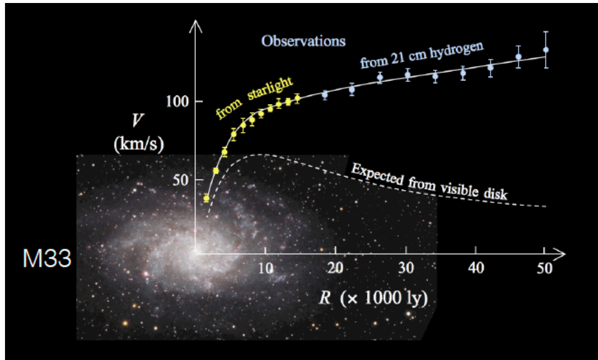
Excludes gluino mass <2.2 TeV for LSP mass < 1 TeV

Summary of Supersymmetry searches

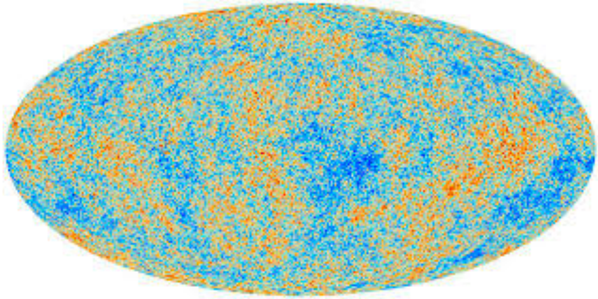


Universe Content





- Corbelli, Salucci, MNRAS **311**, 411 (2000).



$$\Omega_b h^2 = 0.02226(23),$$
$$\Omega_{\rm DM} h^2 = 0.1186(20),$$

Planck, 2013-2015

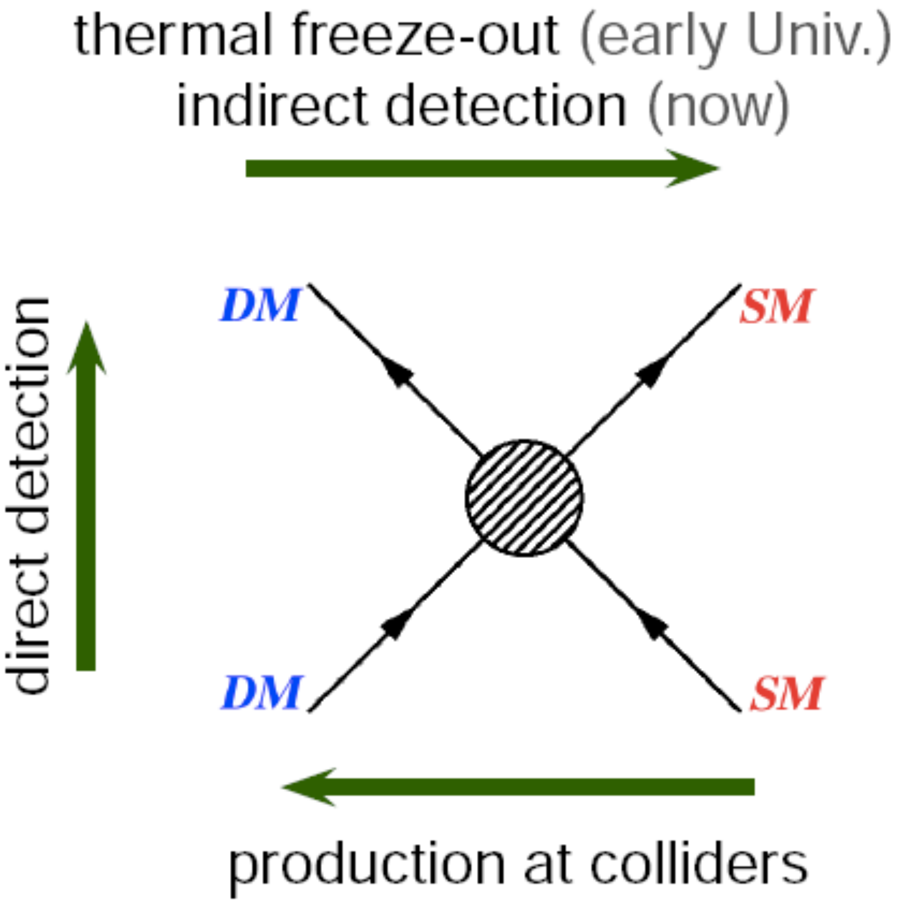
What type of particle can Dark Matter be?

- Dark Matter particle properties
  - Electrically neutral
  - Stable (cosmologically)
  - Non-relativistic when galaxies form

- Not a Standard Model particle

How to search for WIMPs?

XENON1T in Gran Sasso



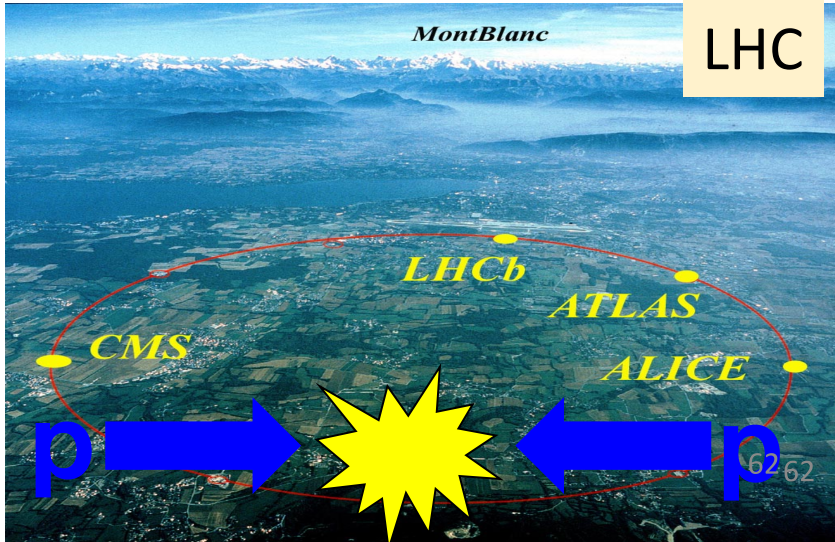
thermal freeze-out (early Univ.)
indirect detection (now)

direct detection

production at colliders

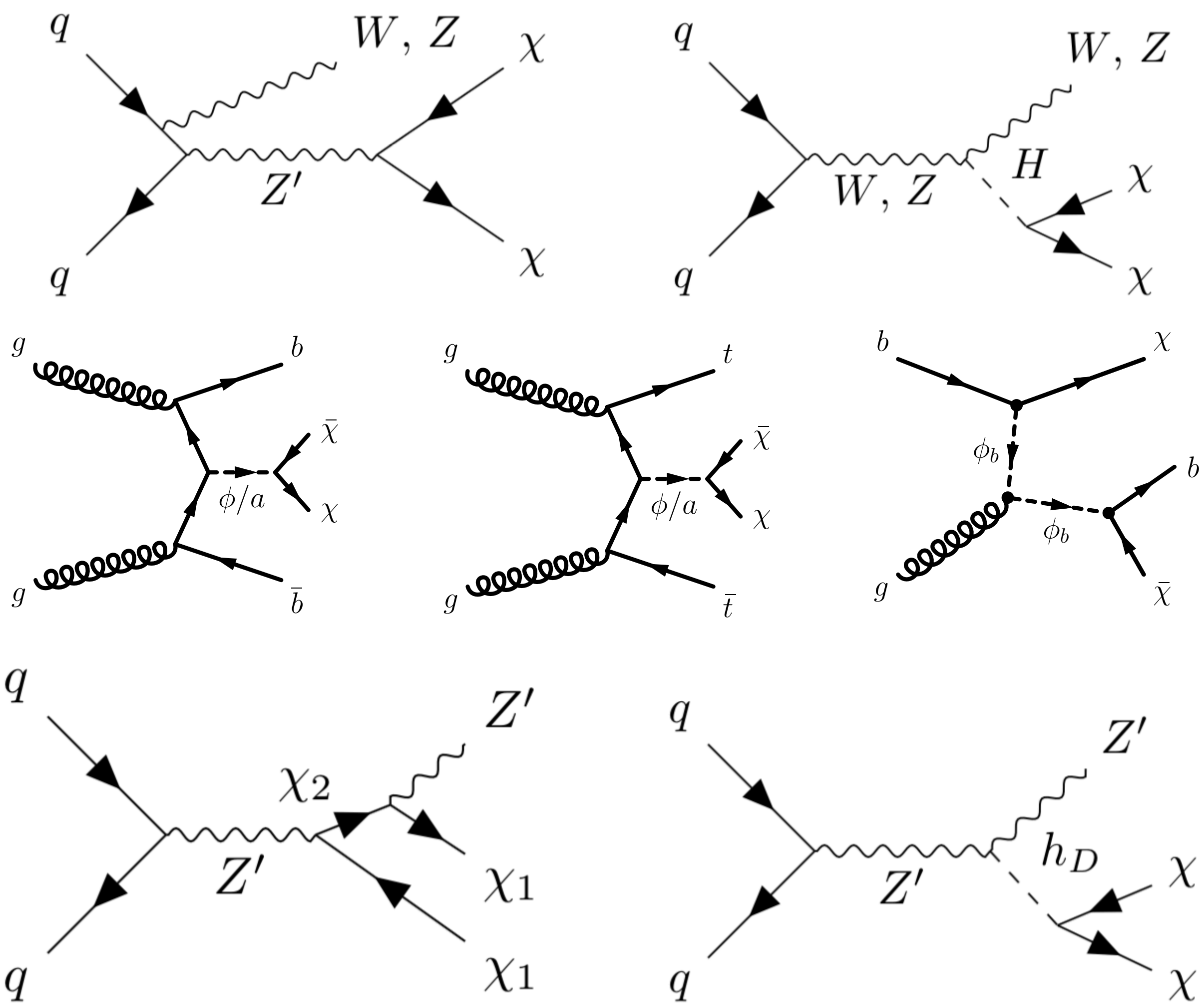
AMS satellite

LHC



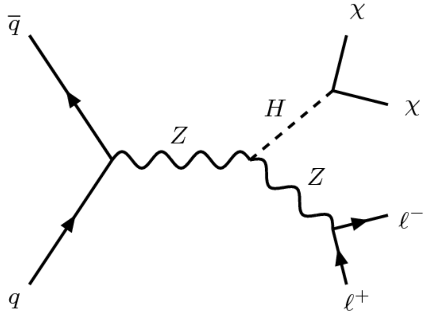
Signatures for Dark Matter χ

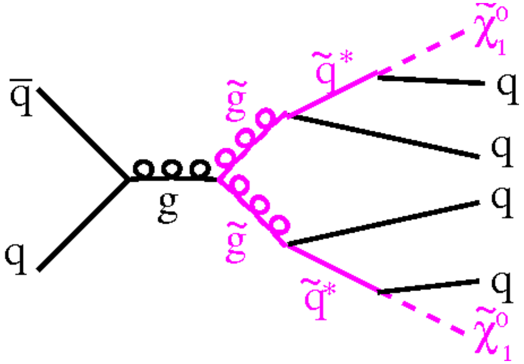
- Many signatures possible depending on properties of particle that couples to DM
    - Could be the H boson
        - Only unknown: coupling to DM g_χ
    - Could be new particle, e.g. Z’
        - Many unknowns: mass, g_χ, g_q, g_l, spin
    - Could be several new particle (“dark sector”)
        - Even more unknowns…

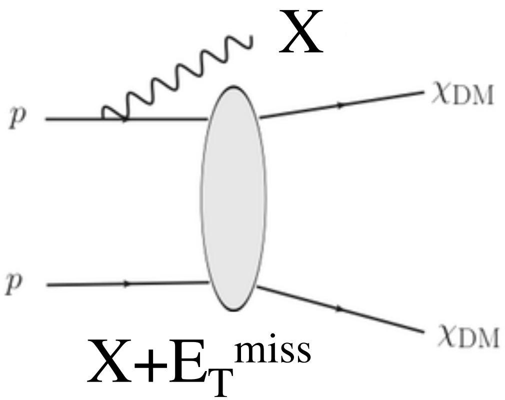


Three ways to search for WIMPs at LHC

1. Invisible Higgs-boson decays
   - If Dark Matter acquires mass through Higgs mechanism and is light enough
2. Supersymmetry
   - Decay from other particles, e.g. supersymmetric partner of gluon (gluino)
3. pp->$\chi\chi$ + X
   - Inverse of freeze-out process
   - Mono-X signature: E_T^{miss}+X
     - X=jet, photon, W, Z…

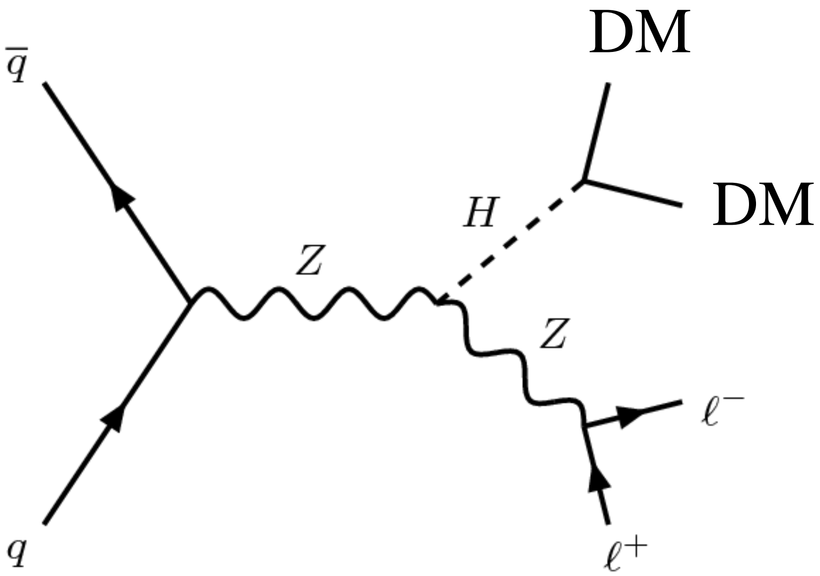




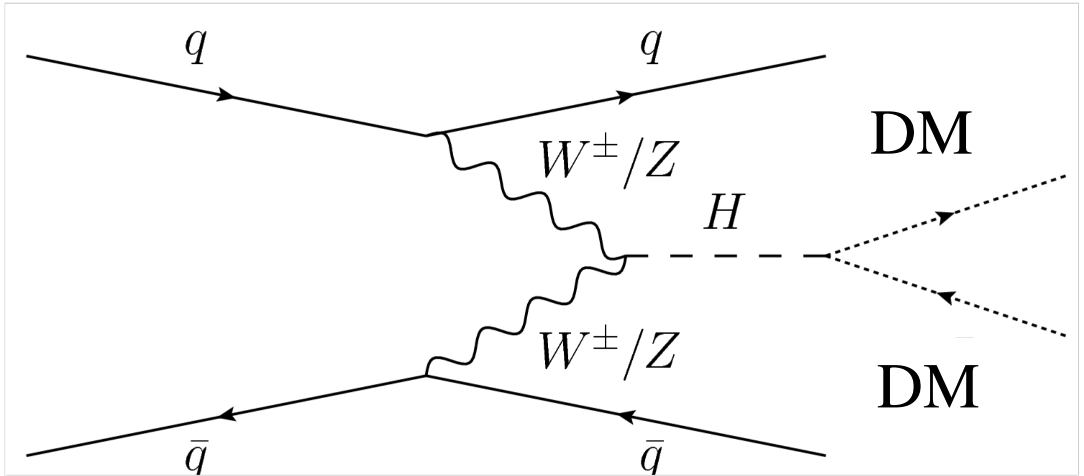


“Invisible” Higgs decays?

- Does dark matter (χ) interact with the Higgs?
  - Higgs can decay to dark matter candidates if $m_H > 2\ m_\chi$

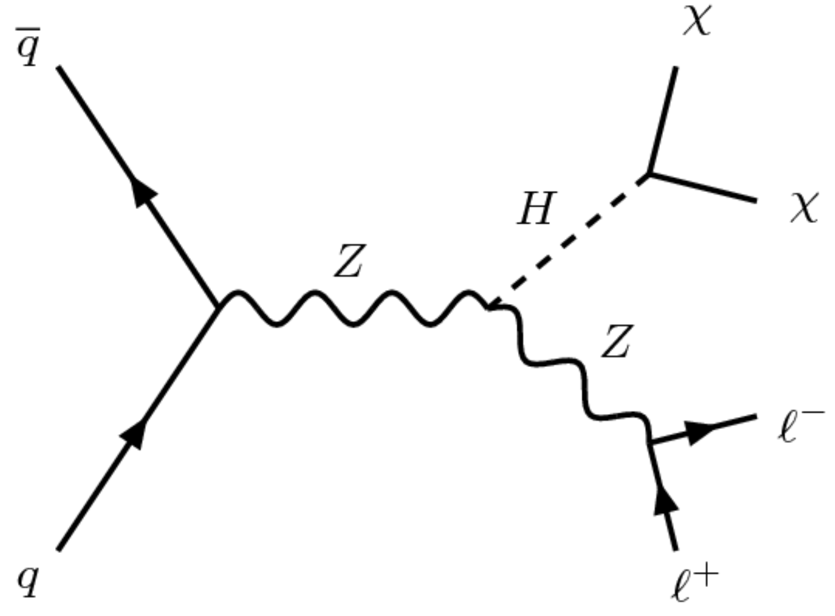


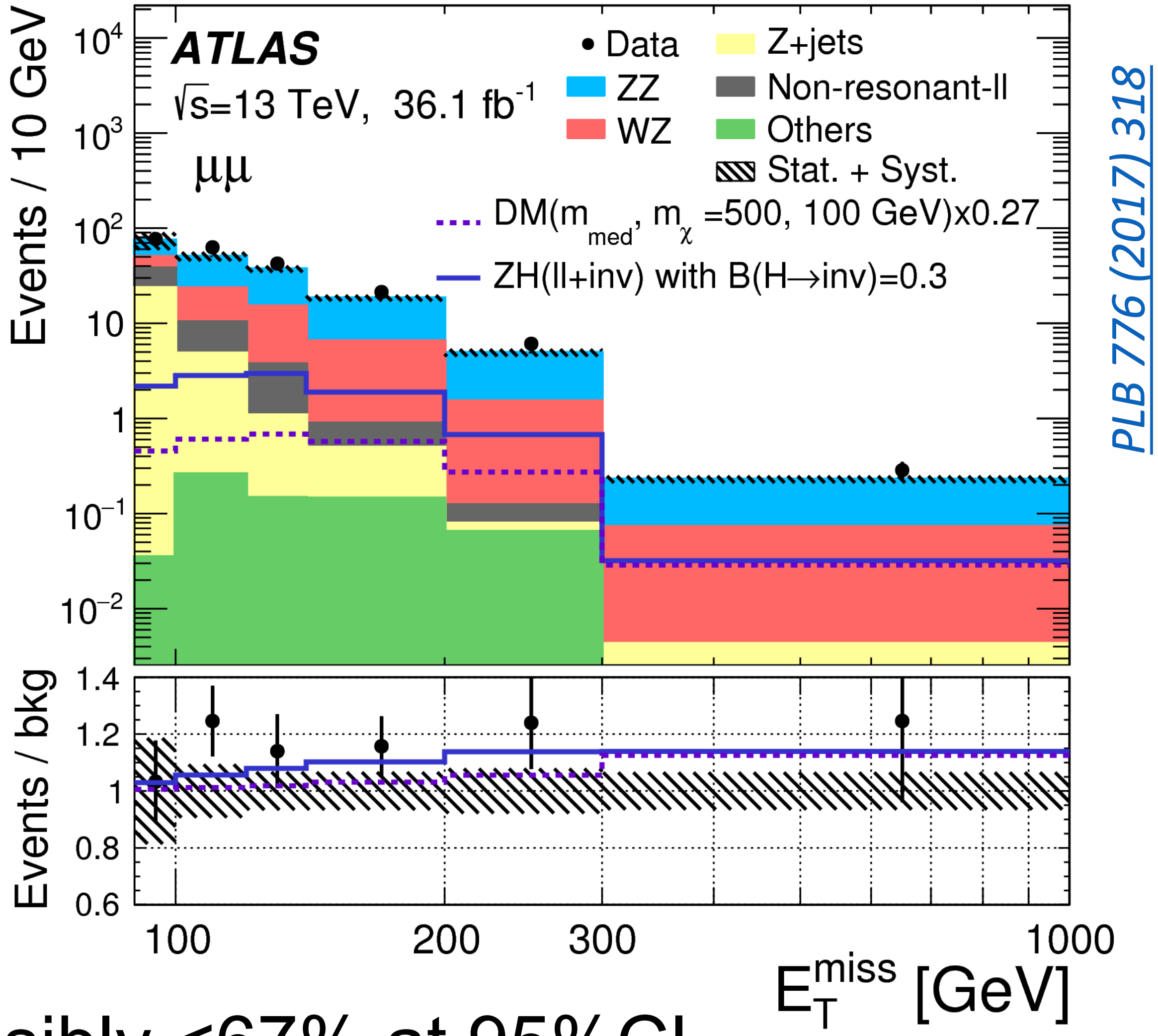
Z+Dark Matter



2 jets+Dark Matter

Search for invisible Higgs decays



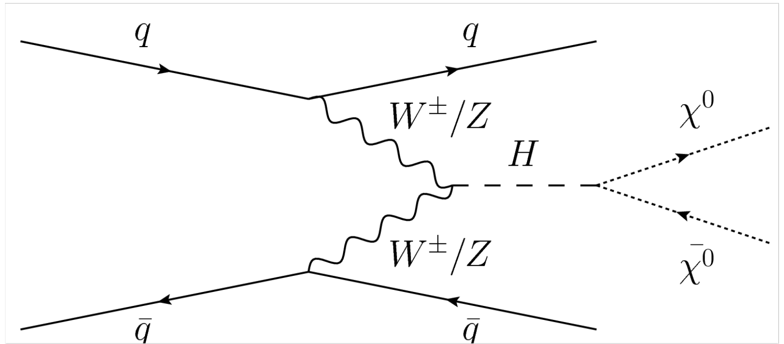


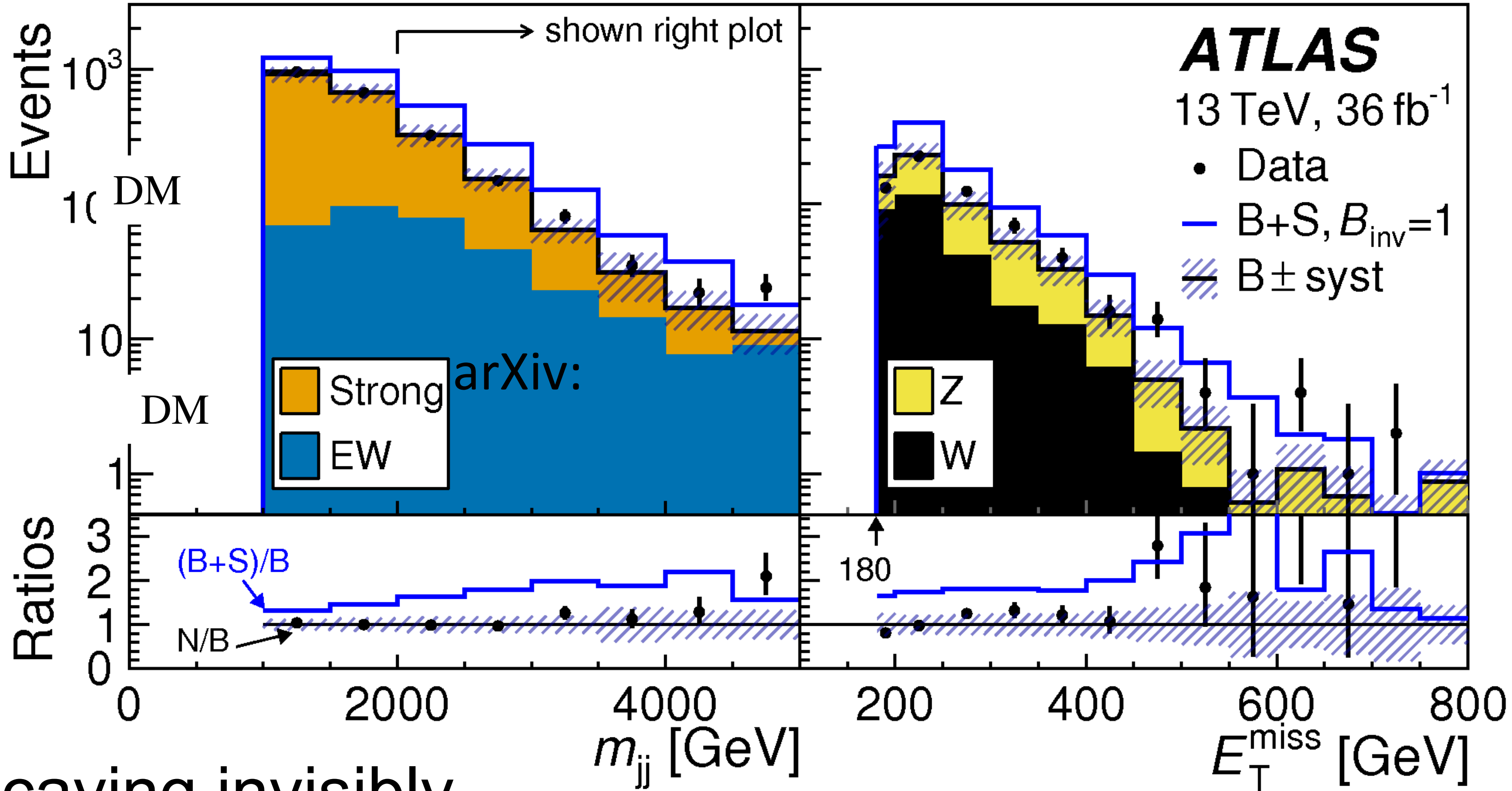
PLB 776 (2017) 318

Main Backgrounds:
- $ZZ \rightarrow \nu\nu ll$
- $WZ \rightarrow lll\nu$

- Fraction of H bosons decaying invisibly <67% at 95%CL
  - Expected limit BR(H->invisible)<39% at 95% CL

Invisible Higgs decays: VBF jets +E_T^{miss}





Main Backgrounds:

- VBF jets + Z ($\rightarrow \nu\nu$)
- VBF jets + W($\rightarrow l\nu$)

Fraction of H bosons decaying invisibly

- Using only direct searches: <26% at 95% CL (exp. <20%) arXiv:1809.06682
- Direct and indirect measurements: <23% at 95% CL

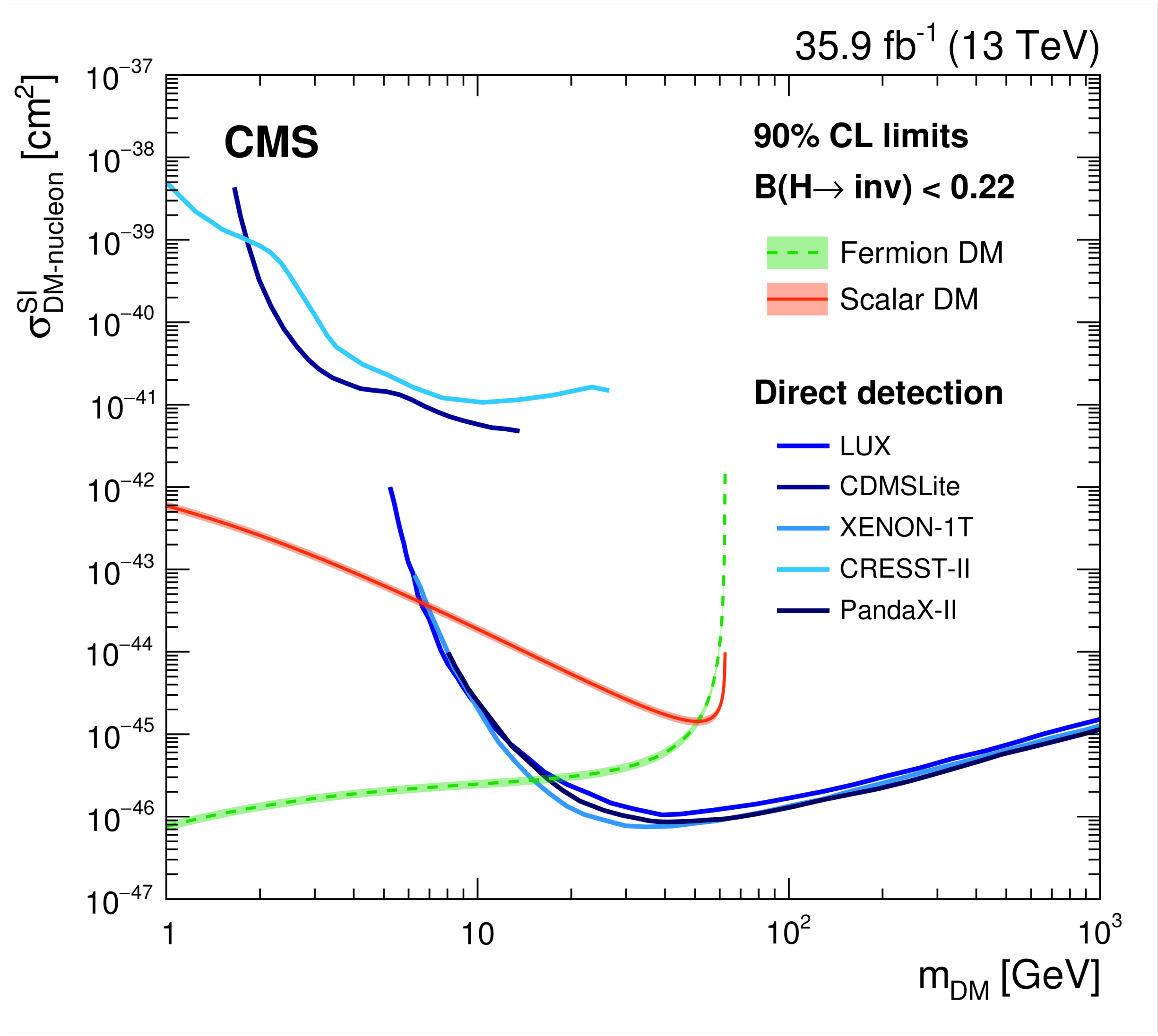
Comparing direct detection and Higgs constraints

arXiv:1809.05937

Assume Higgs is sole mediator for interactions between nucleons and dark matter

$$\boxed{\mathrm{BR}_{\chi}^{\mathrm{inv}} \equiv \frac{\Gamma(H \to \chi\chi)}{\Gamma_H^{\mathrm{SM}} + \Gamma(H \to \chi\chi)} = \frac{\sigma_{\chi p}^{\mathrm{SI}}}{\Gamma_H^{\mathrm{SM}}/r_\chi + \sigma_{\chi p}^{\mathrm{SI}}}}$$

With $r_\chi = \Gamma(H \to \chi\chi)/\sigma_{\chi p}^{\mathrm{SI}}$



Comparing direct detection and Higgs constraints

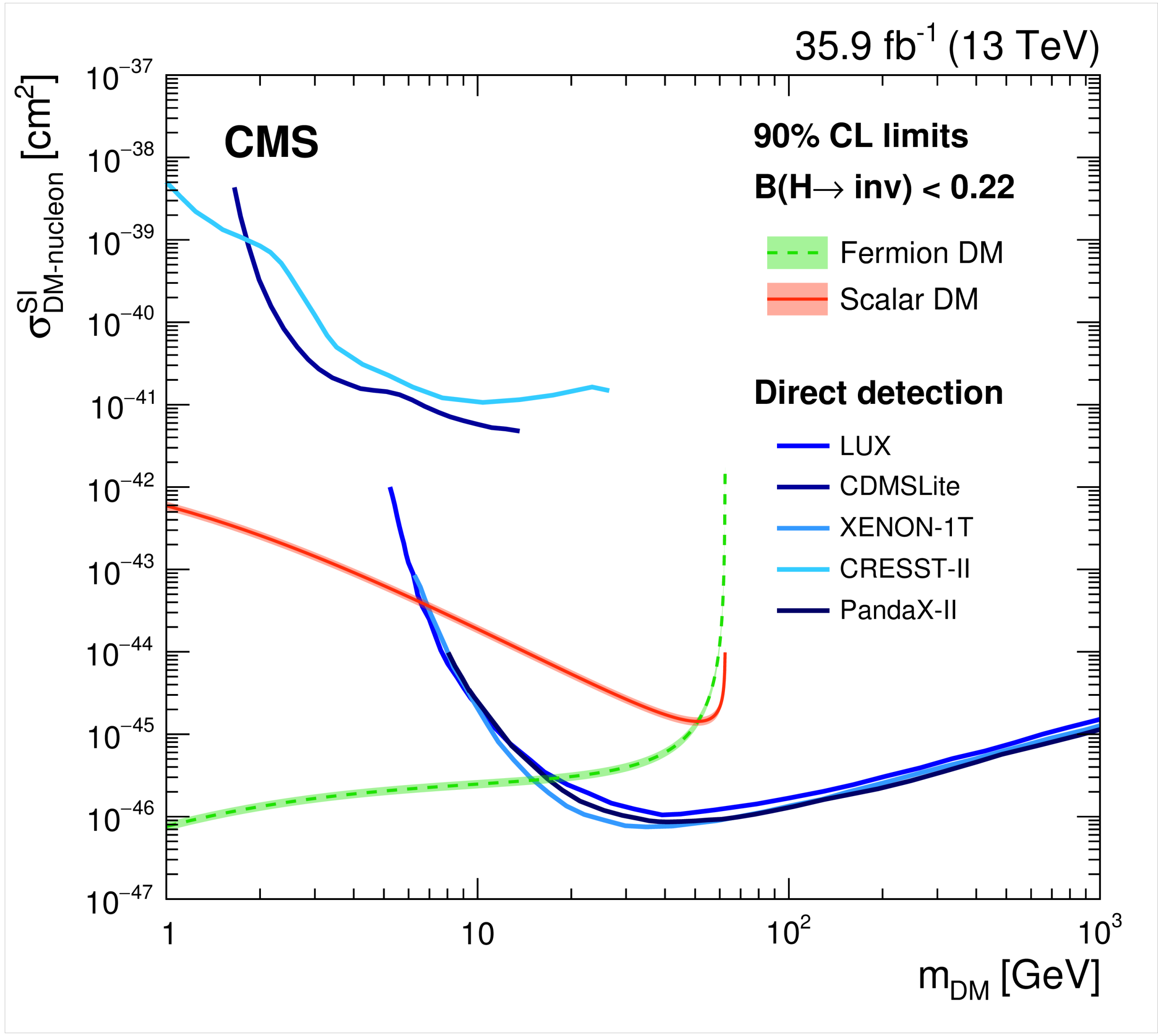
arXiv:1809.05937

Assume Higgs is sole mediator for interactions between nucleons and dark matter

$$\boxed{\mathrm{BR}_{\chi}^{\mathrm{inv}} \equiv \frac{\Gamma(H \to \chi\chi)}{\Gamma_H^{\mathrm{SM}} + \Gamma(H \to \chi\chi)} = \frac{\sigma_{\chi p}^{\mathrm{SI}}}{\Gamma_H^{\mathrm{SM}}/r_\chi + \sigma_{\chi p}^{\mathrm{SI}}}}$$

With $r_\chi = \Gamma(H \to \chi\chi)/\sigma_{\chi p}^{\mathrm{SI}}$

- Approaches are complementary
  - Invisible Higgs searches more sensitive at low mass (in this model!)
  - Direct detection experiments more sensitive at high mass (>$m_H/2$)
- If we see anything in the future the other will be needed for truly understanding it
- Future: probe BR to ~1% or better



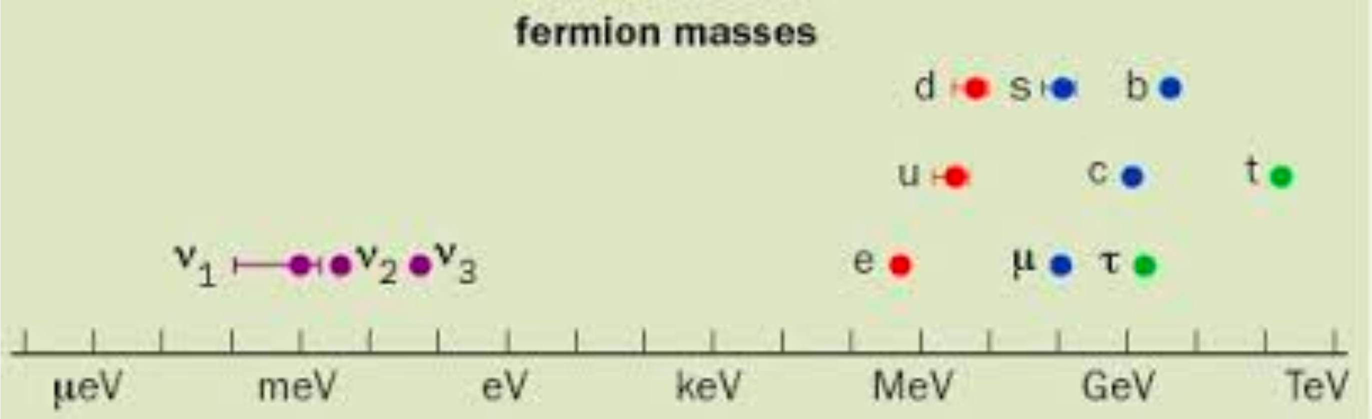
Flavour

The flavour puzzles

- *Why is there structure in charged fermion masses and mixing angles?*
- *Why is there no structure in the neutrino fermion masses and mixing?*
- *If there is new physics at the TeV scale, why are there not flavor-changing neutral currents?*

Y. Nir, 2018

From http://ctp.berkeley.edu



Quark mixing matrix:

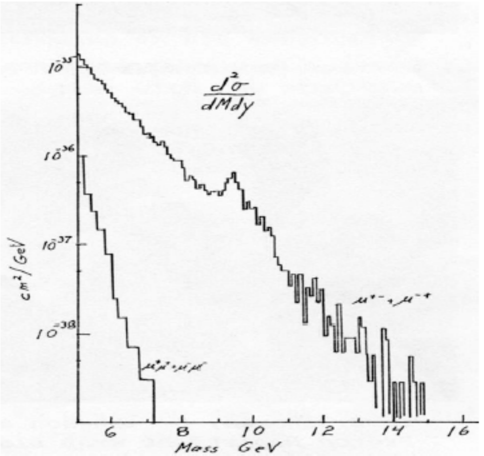
$$V_{\mathrm{CKM}} = \begin{pmatrix} 0.97446 \pm 0.00010 & 0.22452 \pm 0.00044 & 0.00365 \pm 0.00012 \\ 0.22438 \pm 0.00044 & 0.97359^{+0.00010}_{-0.00011} & 0.04214 \pm 0.00076 \\ 0.00896^{+0.00024}_{-0.00023} & 0.04133 \pm 0.00074 & 0.999105 \pm 0.000032 \end{pmatrix}$$

Neutrino mixing matrix:

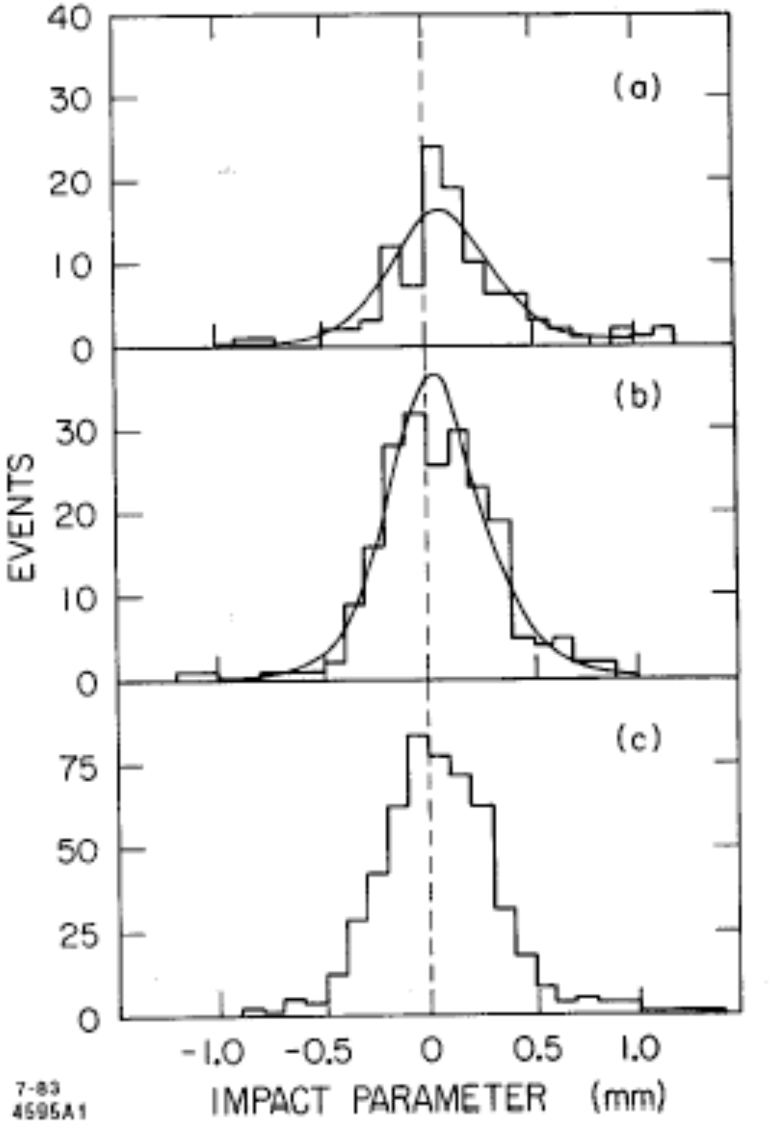
$$V_{MNS} = \begin{bmatrix} 0.799 \ldots 0.844 & 0.516 \ldots 0.582 & 0.141 \ldots 0.156 \\ 0.242 \ldots 0.494 & 0.467 \ldots 0.678 & 0.639 \ldots 0.774 \\ 0.284 \ldots 0.521 & 0.490 \ldots 0.695 & 0.615 \ldots 0.754 \end{bmatrix}$$

History: B Mass and Lifetime

- Upsilon observation 1978
  - 3rd generation exists
  - Mass about 5 GeV

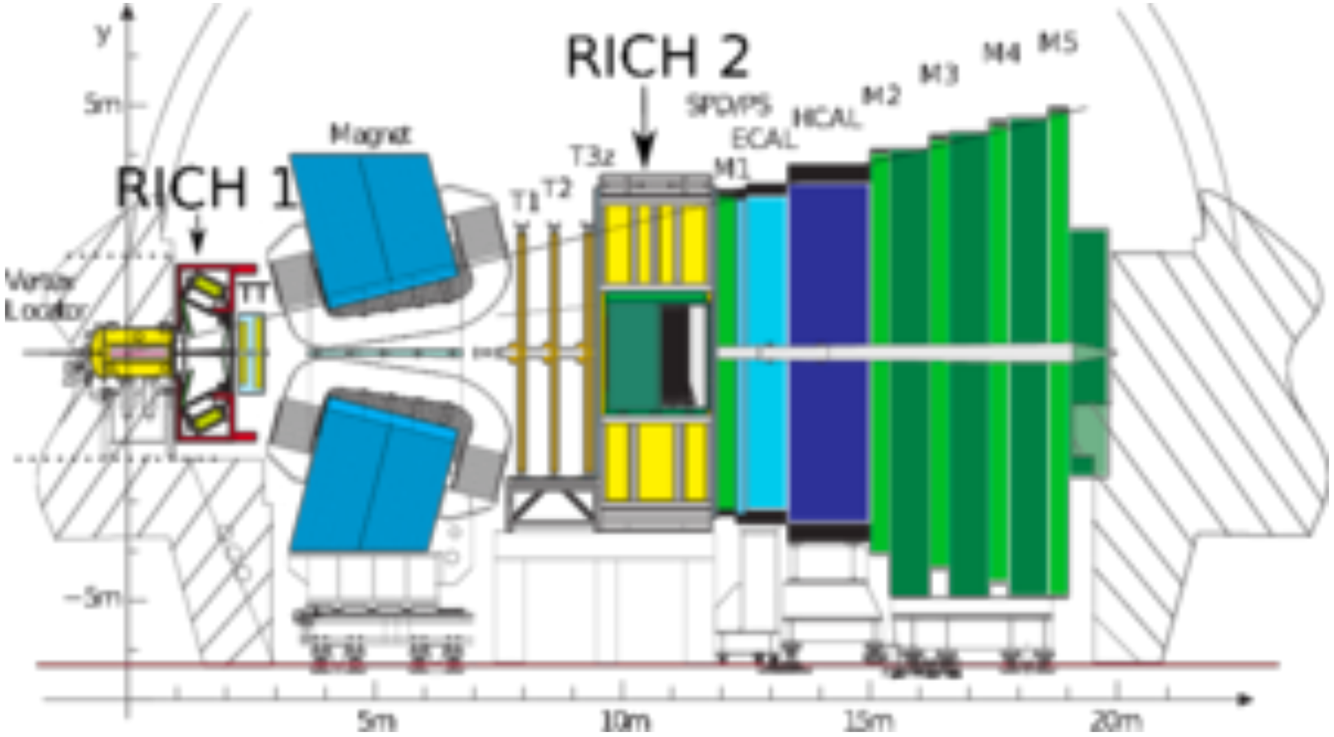


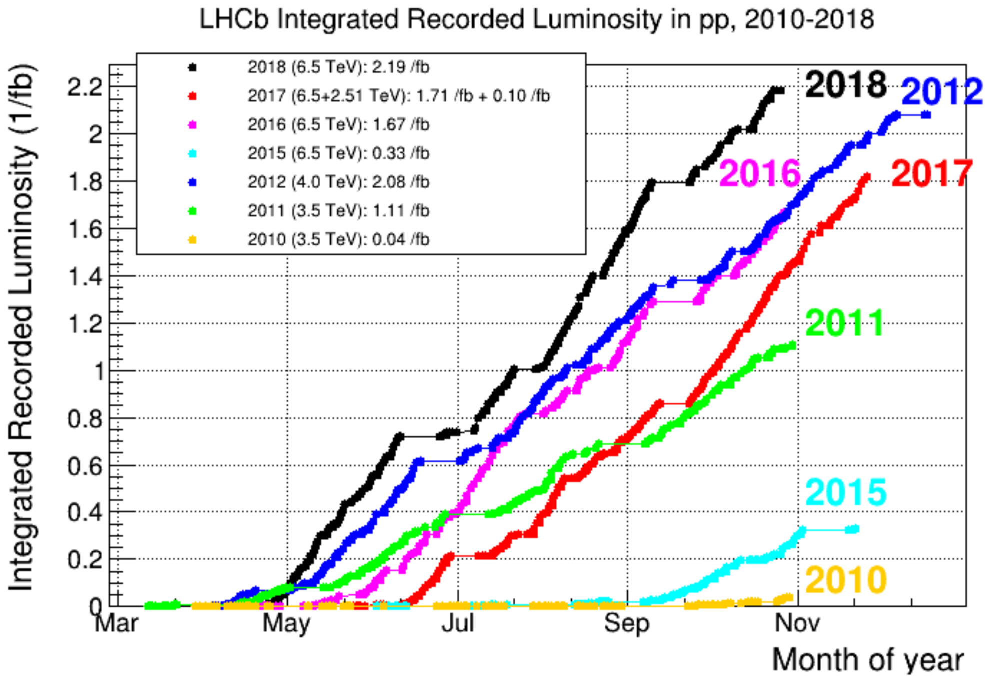
- Lifetime observation 1983:
  - Lifetime = 1.5 ps^{-1}
  - Enables experimental techniques to identify B's



Phys.Rev.Lett.51:1316,1983

LHCb at the LHC





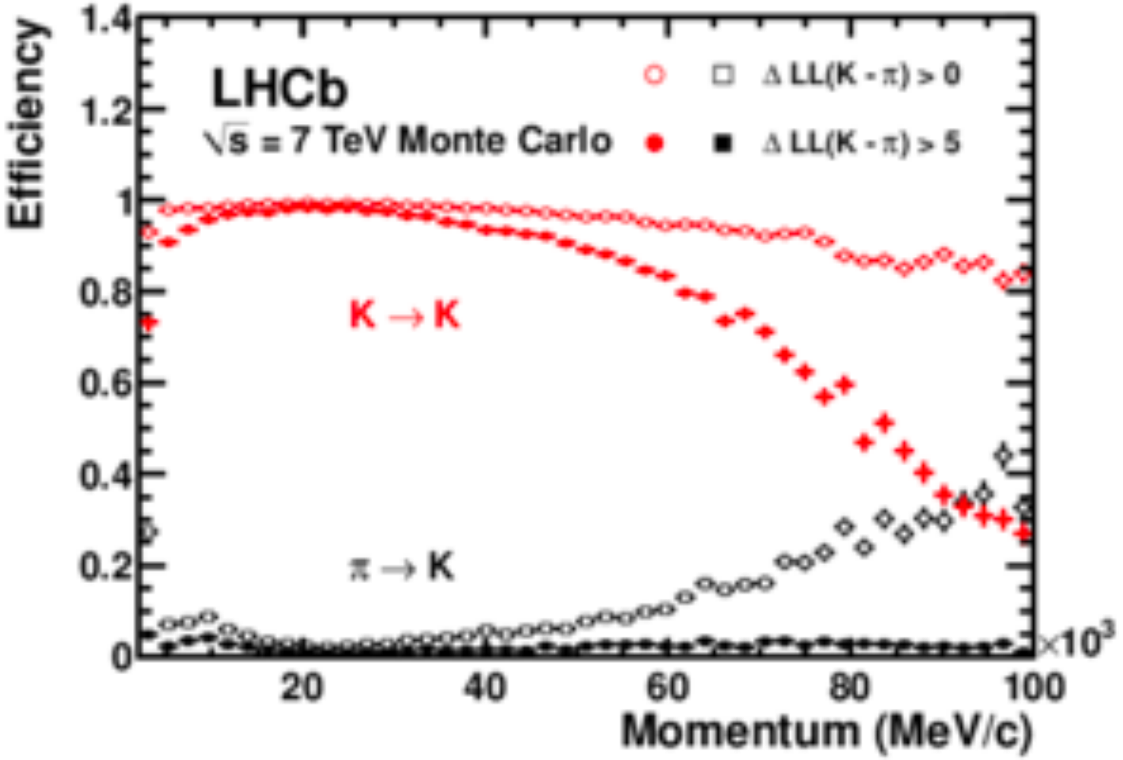
- Spectrometer layout: instrumented at |η|>2.1
- Optimized for B-physics: strong tracking and particle ID
- Luminosity lower than ATLAS and CMS

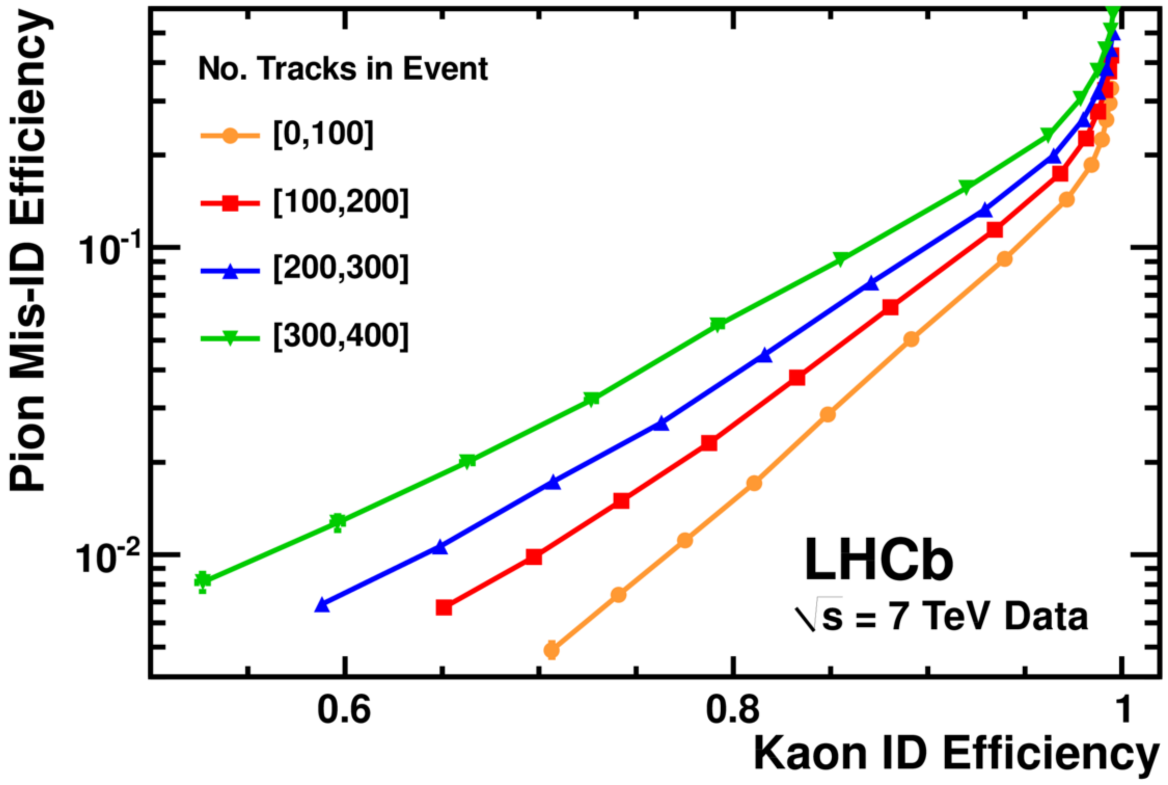
Particle Identification LHCb

Important to distinguish hadron species, e.g. pion and kaon

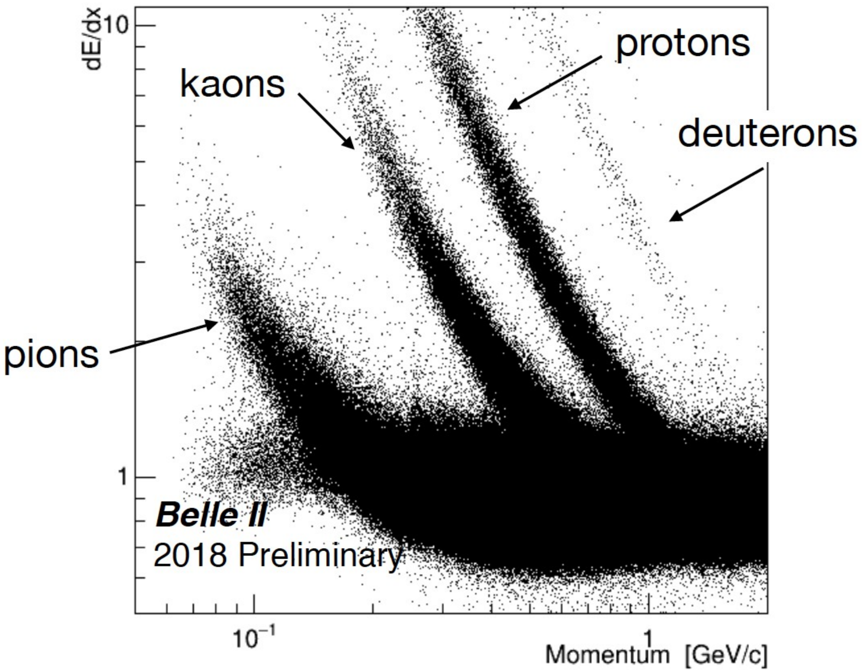
- e.g. B->DK much more common than B->Dπ

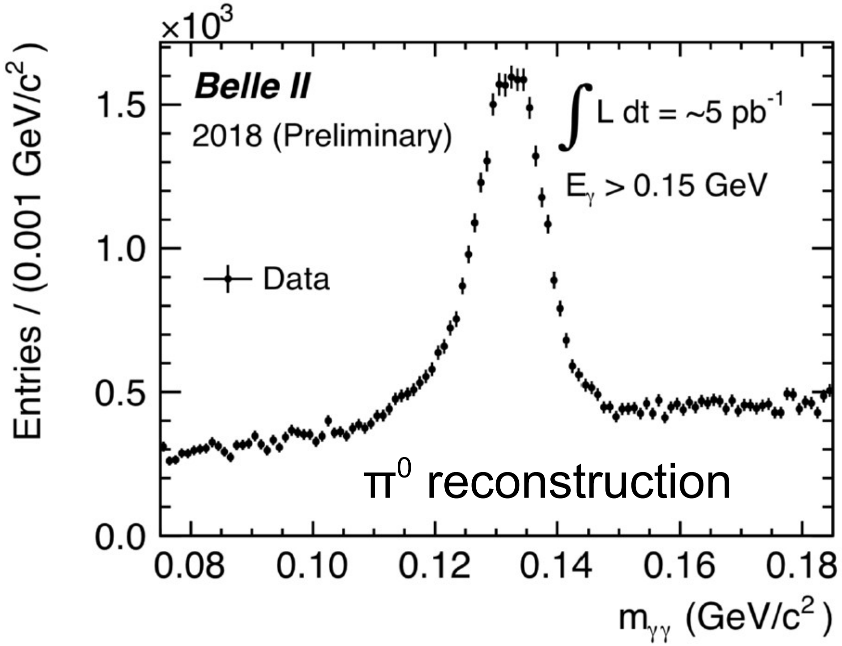
Use RICH detector to separate K and π

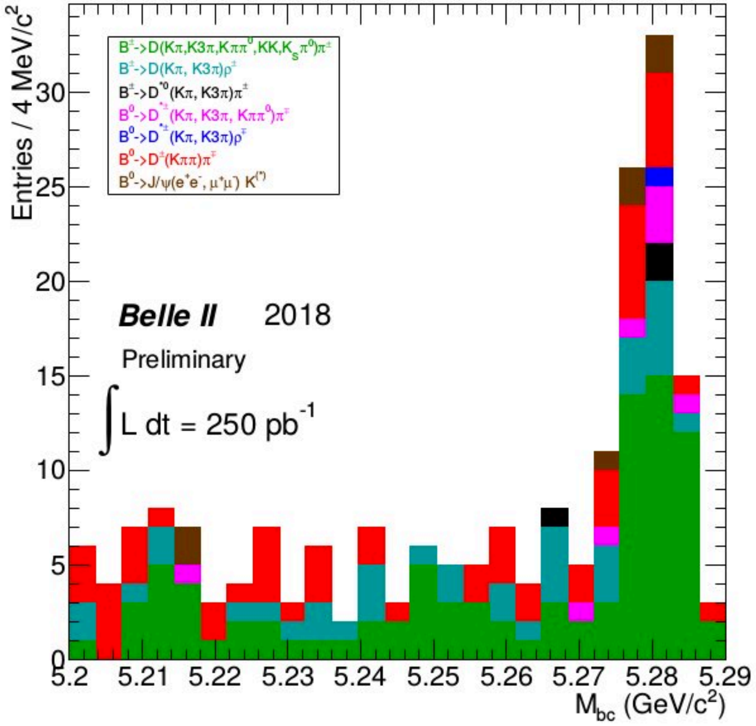




Performance Belle II (2018 data)


Drift chamber (CDC)

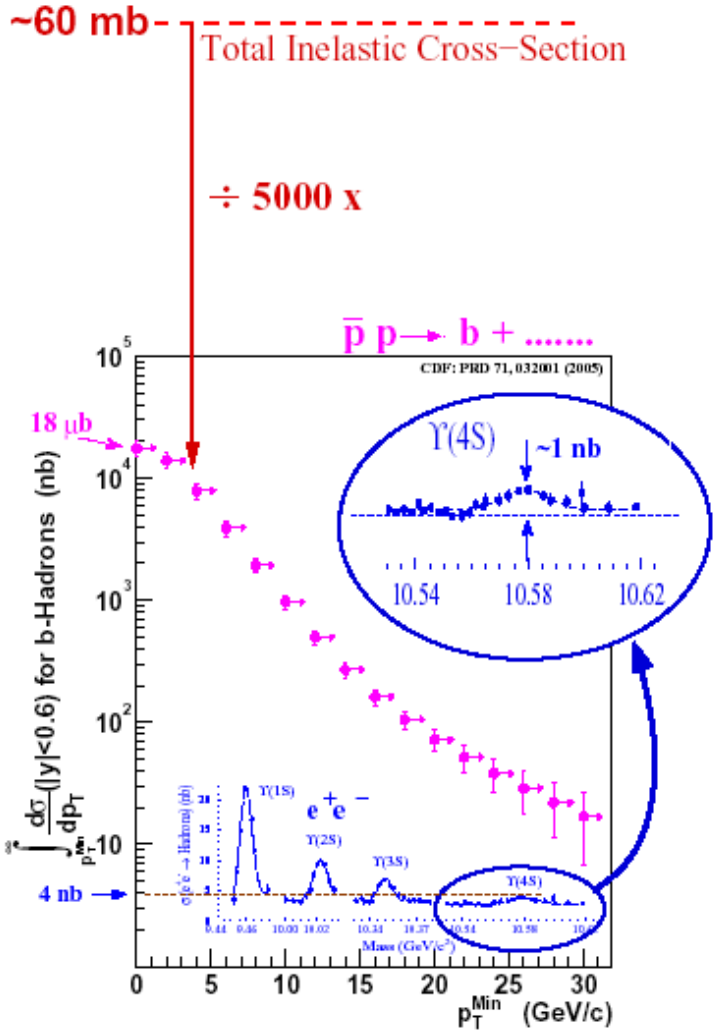




- Commissioning of experiment successful based on ~0.5 fb^{-1} of data
- Expect to exceed current Belle+Babar dataset in 2021
- Ultimarte goal: 50 fb^{-1} by 2025

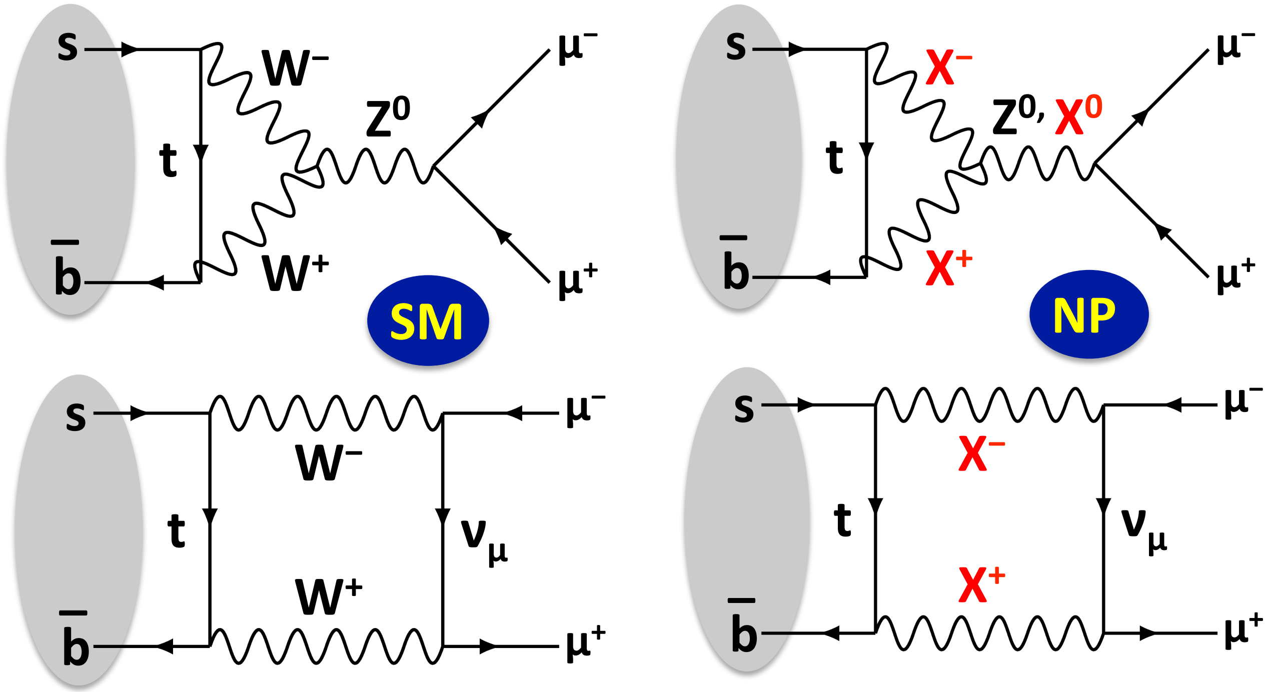
B Physics: Lepton vs Hadron Colliders

	B Factories *Belle (1999-2010)* *BaBar (1999-2008)*	**Hadron colliders** *Tevatron (<2 TeV, 1983–2011)* *LHC (<14 TeV, 2008–)*
Collision environment	Asymmetric $e^+e^- \to \Upsilon(4S)$ Clean! Pure $B\bar{B}$ event ✔	pp or $p\bar{p}$ (also ions…) Messy! Proton remnants give background particles
Flavour tagging (initial B^0 or $\bar{B}^0$)	Excellent ✔ (30% ‘tagging power’)	Challenging (~5%)
Production σ(B)	1 nb	~100–500 μb ✔
B hadron boost	Small ($\beta\gamma \approx 0.5$)	Large ($\beta\gamma \approx 100$) ✔
B hadrons created	B^+B^- (50%), $B^0\bar{B}^0$ (50%)	$B^\pm$ (40%), B^0 (40%), B_s^0 (10%) ✔ b baryons (10%)



New physics contributions to B decays

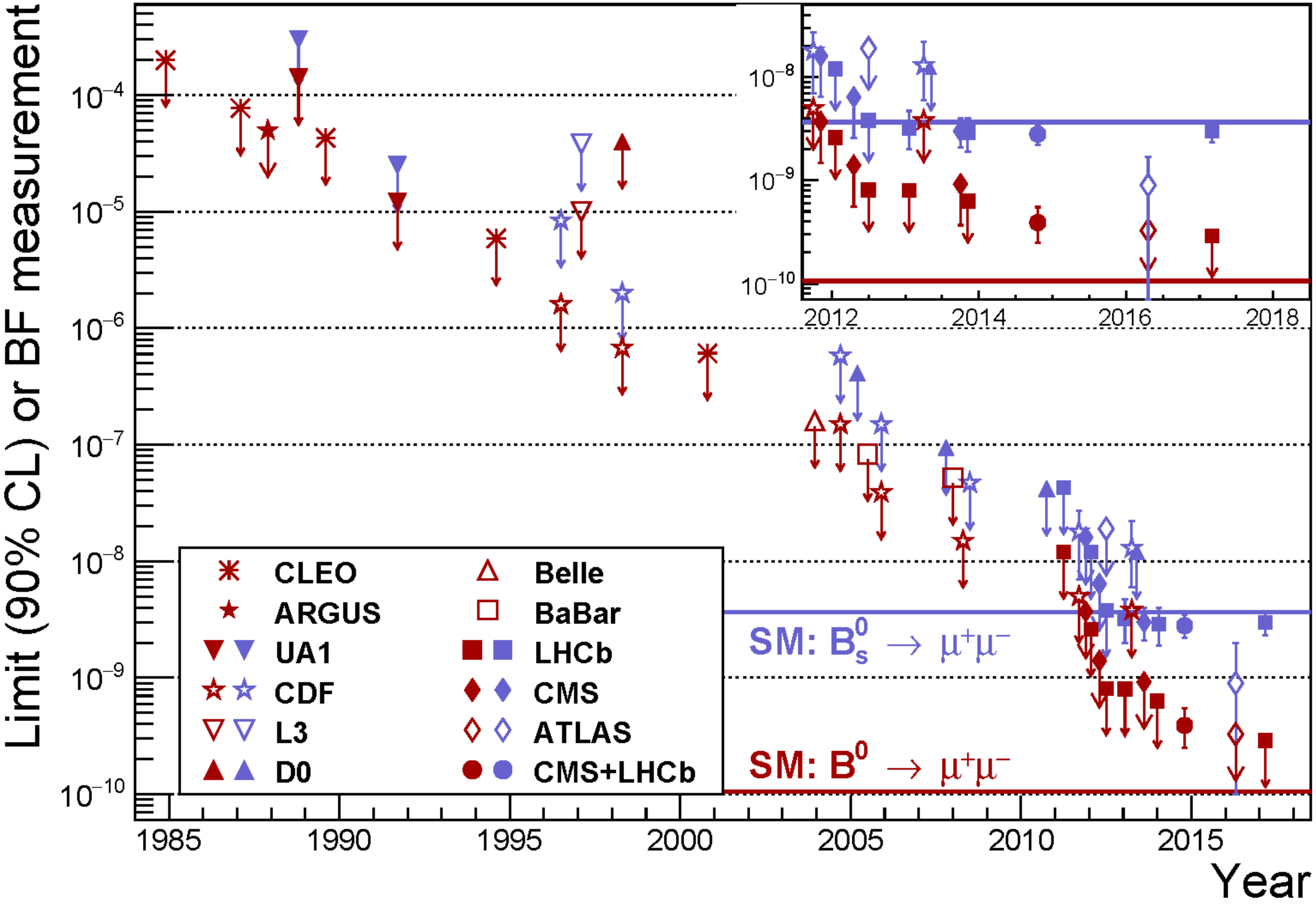
- New physics could contribute to B-decays
    - SUSY particles can contribute in addition to SM particles
    - Z' bosons could also alter the effective couplings
- Complementary to direct searches



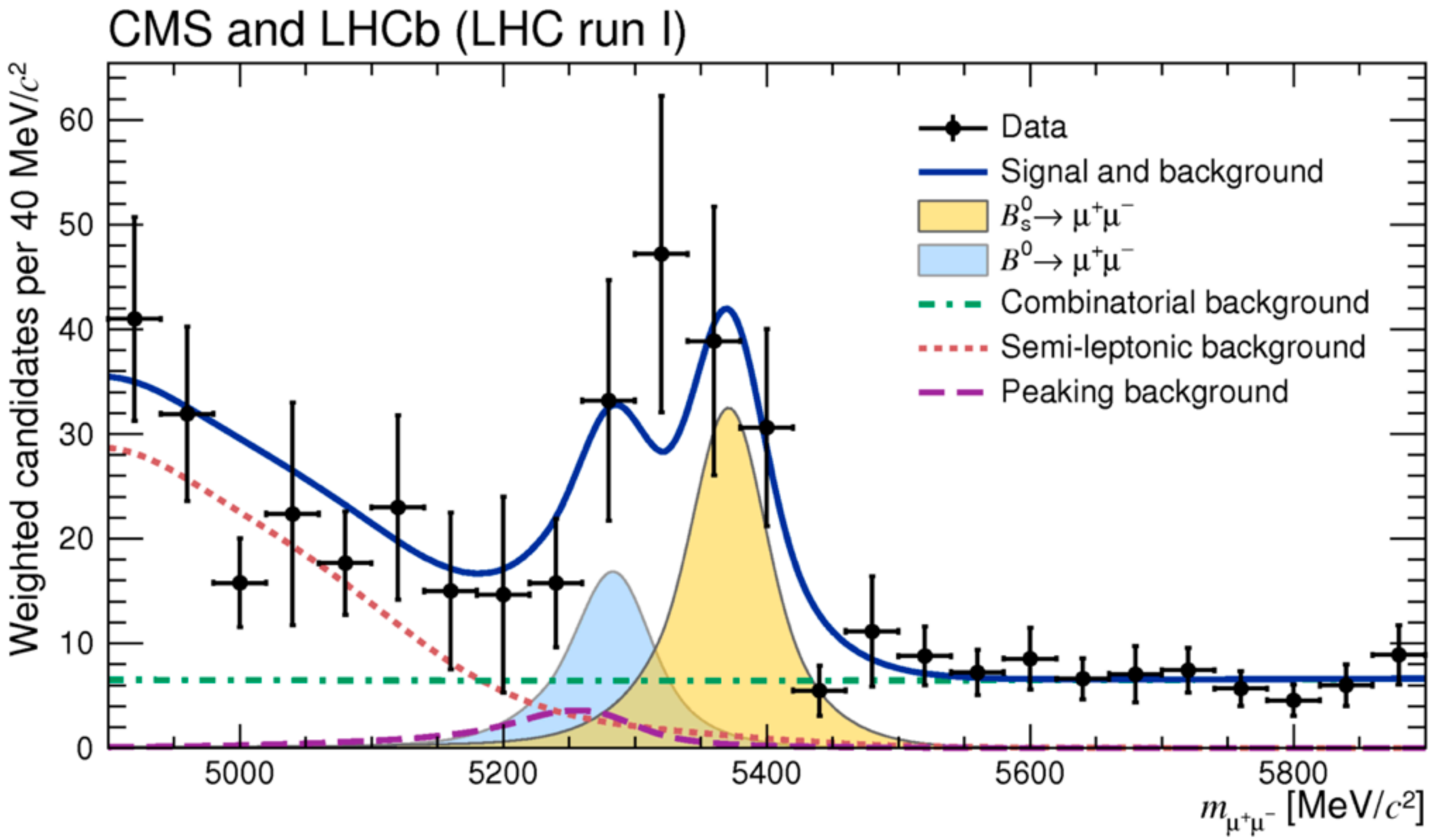
$Br(B_s^0 \rightarrow \mu^+\mu^-) = 3.3 \times 10^{-9}$

$Br(B_s^0 \rightarrow \mu^+\mu^-) \propto \tan^6\beta$

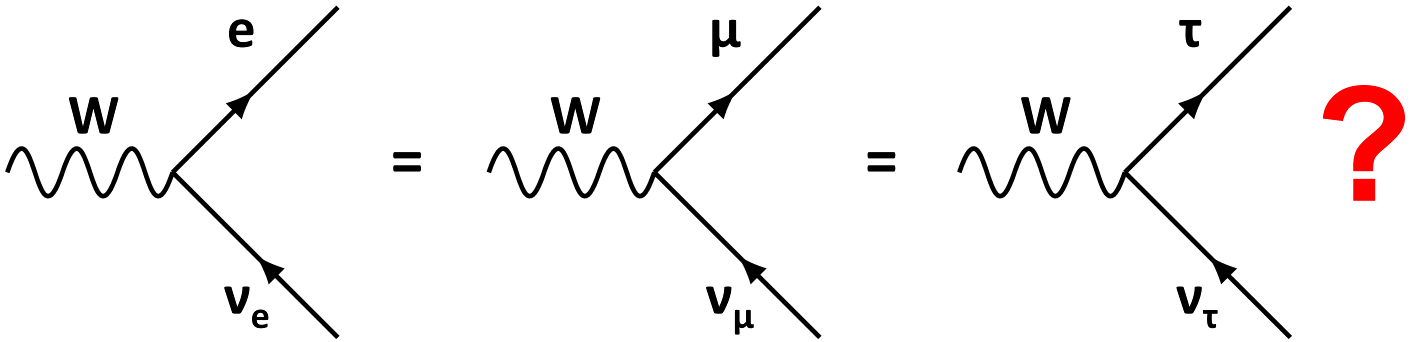
Observation of $B_s \to \mu^+\mu^-$



Observation of $B_s \to \mu^+\mu^-$



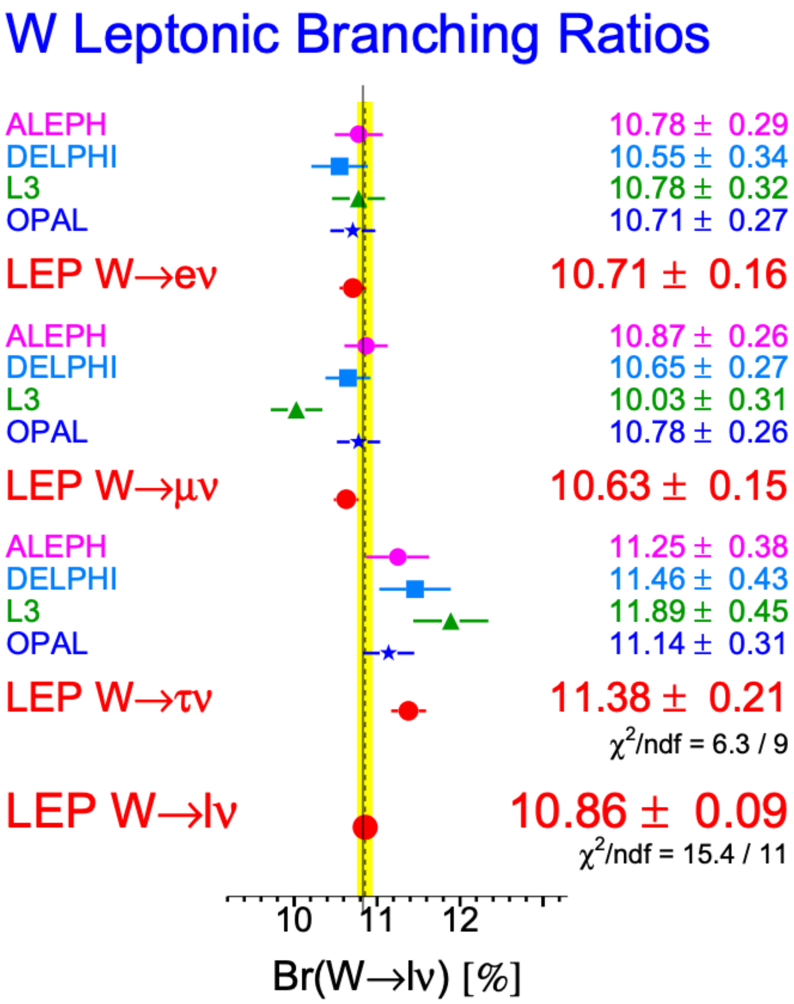
Lepton Flavor Violation (LFV)?



- LEP measured leptonic BR of Ws:
  - 2.6σ lower for tau decays

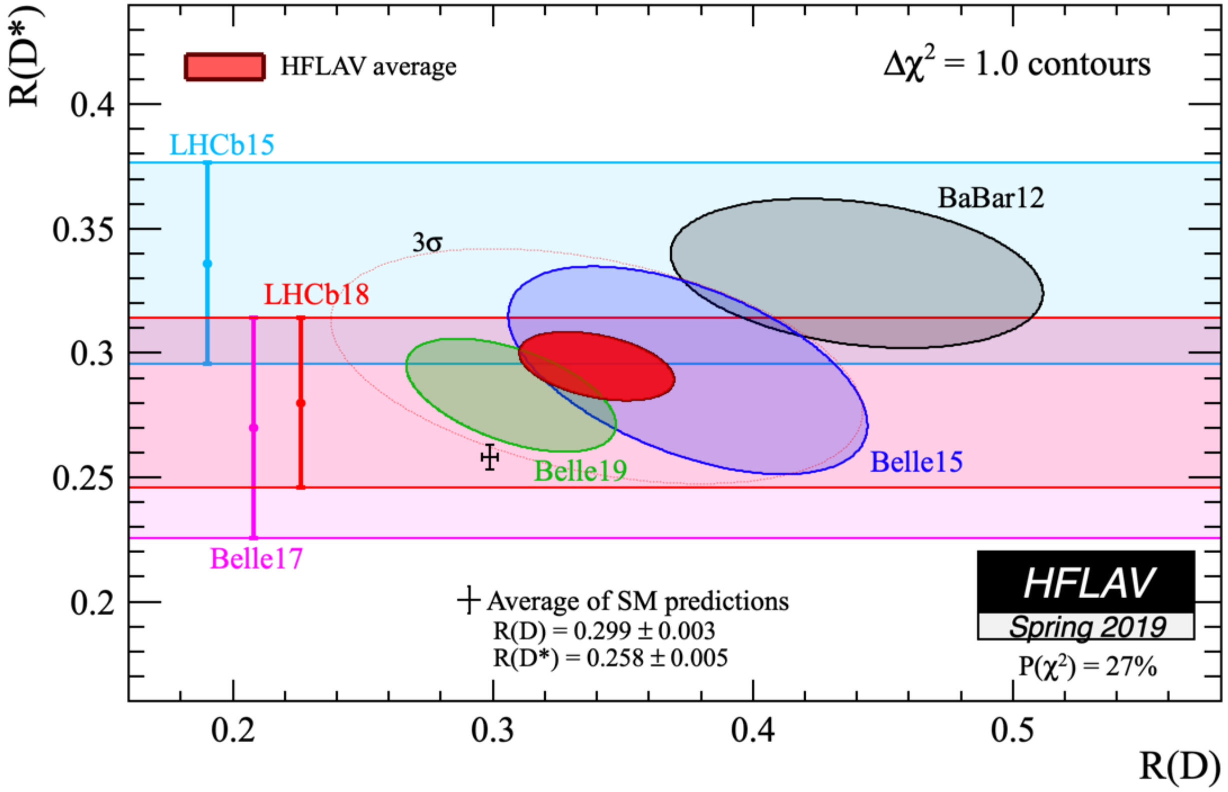
$$2\mathcal{B}(\mathrm{W} \to \tau\overline{\nu}_\tau) \,/\, (\mathcal{B}(\mathrm{W} \to \mathrm{e}\overline{\nu}_\mathrm{e}) + \mathcal{B}(\mathrm{W} \to \mu\overline{\nu}_\mu)) \quad = \quad 1.066 \pm 0.025$$

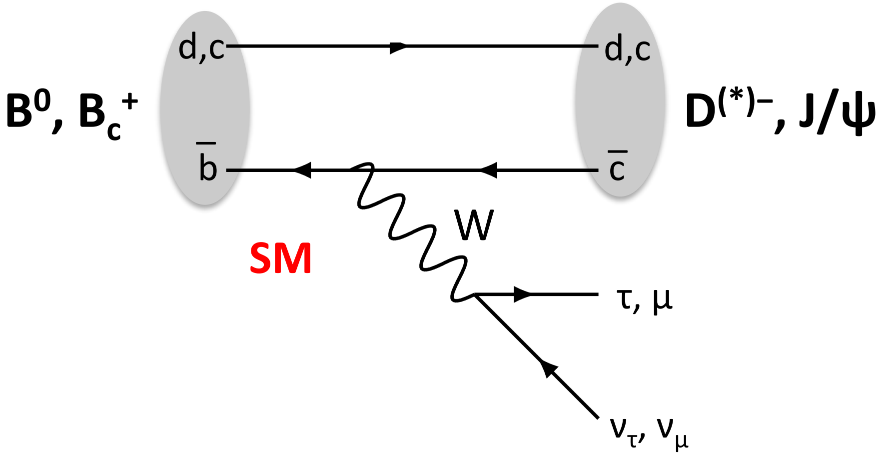
- Precision tests in B decays interesting!

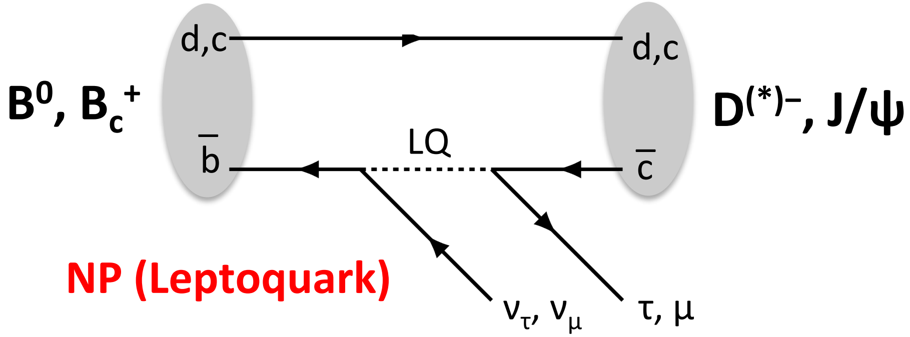


Search for LFV in $B \to D^{(*)} l \nu_l$ decays

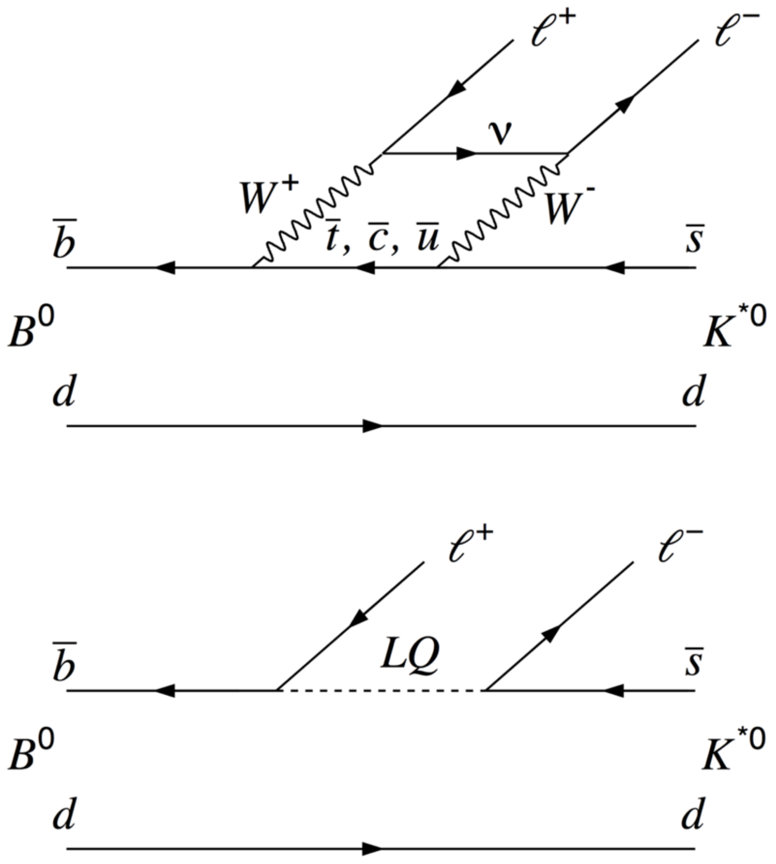
- Measure $$R_{D^{(*)}} = \frac{BR(B \to D^{(*)} \tau \nu_\tau)}{BR(B \to D^{(*)} \mu \nu_\mu)}$$

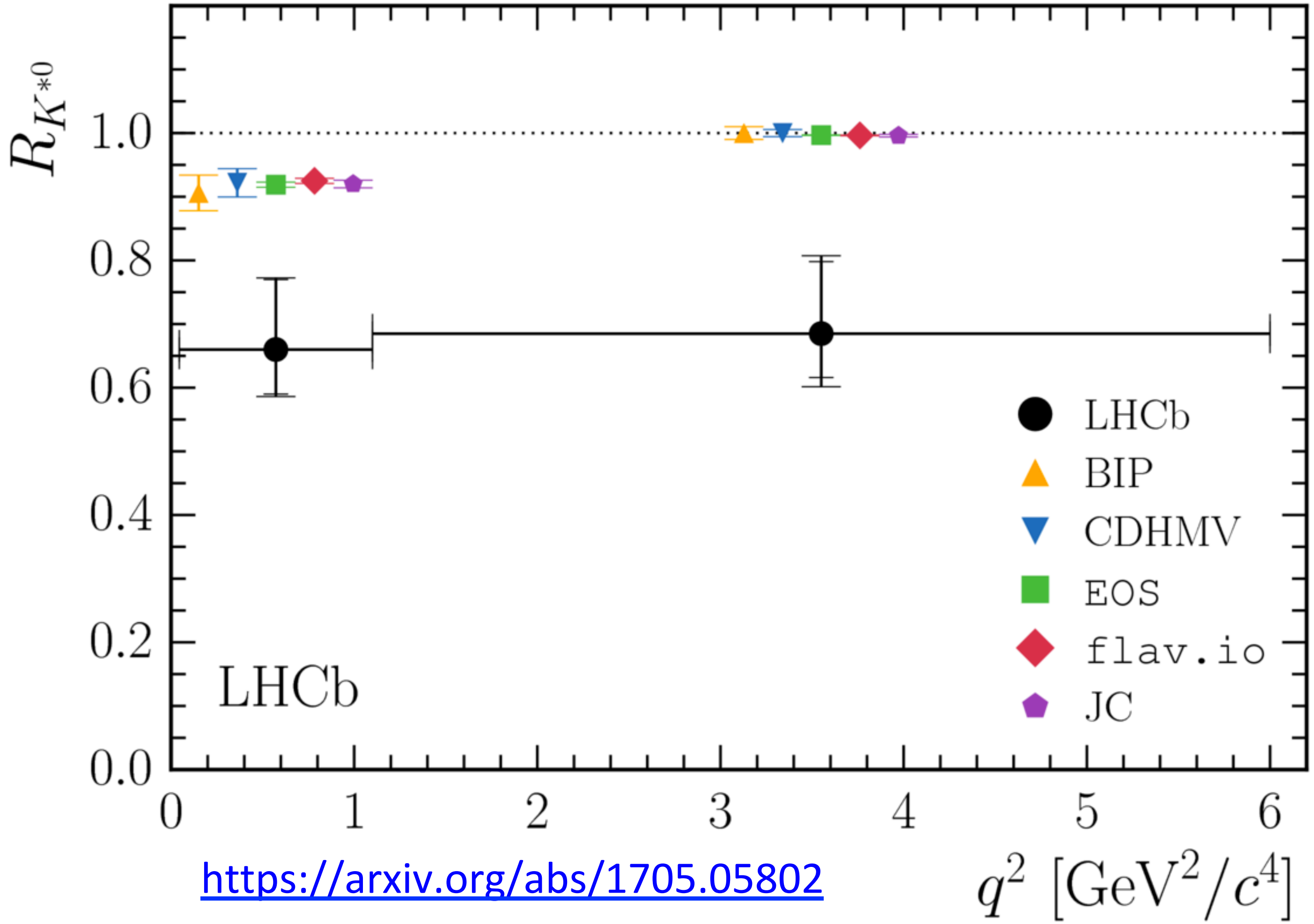






Search for LFV in $B^0 \rightarrow K^{*0} l^+ l^-$



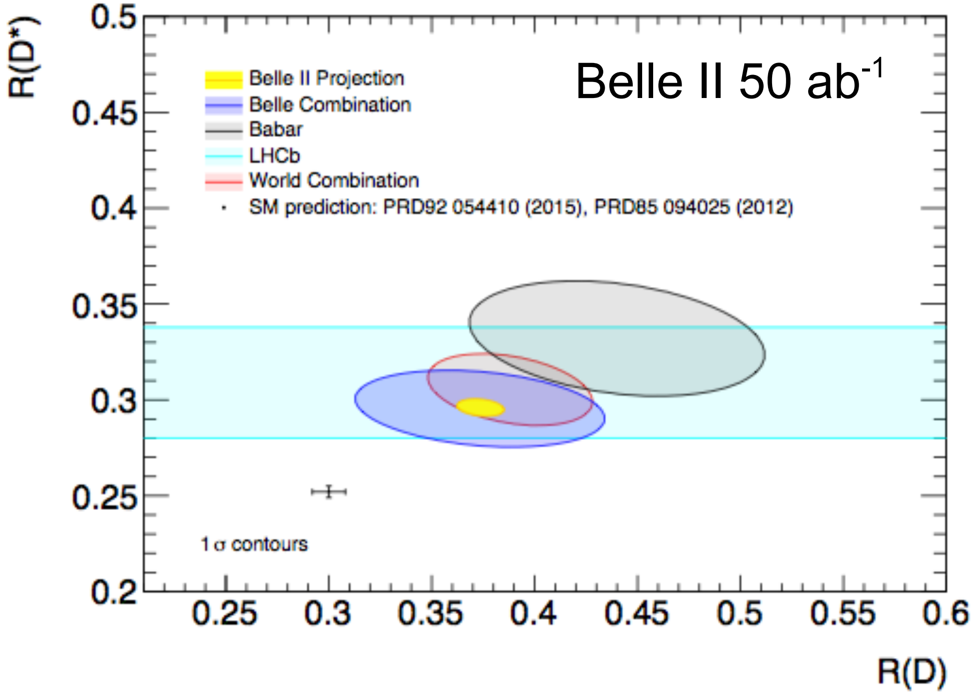


https://arxiv.org/abs/1705.05802

Discrepancies are >2.1σ and 2.4σ in the two regions

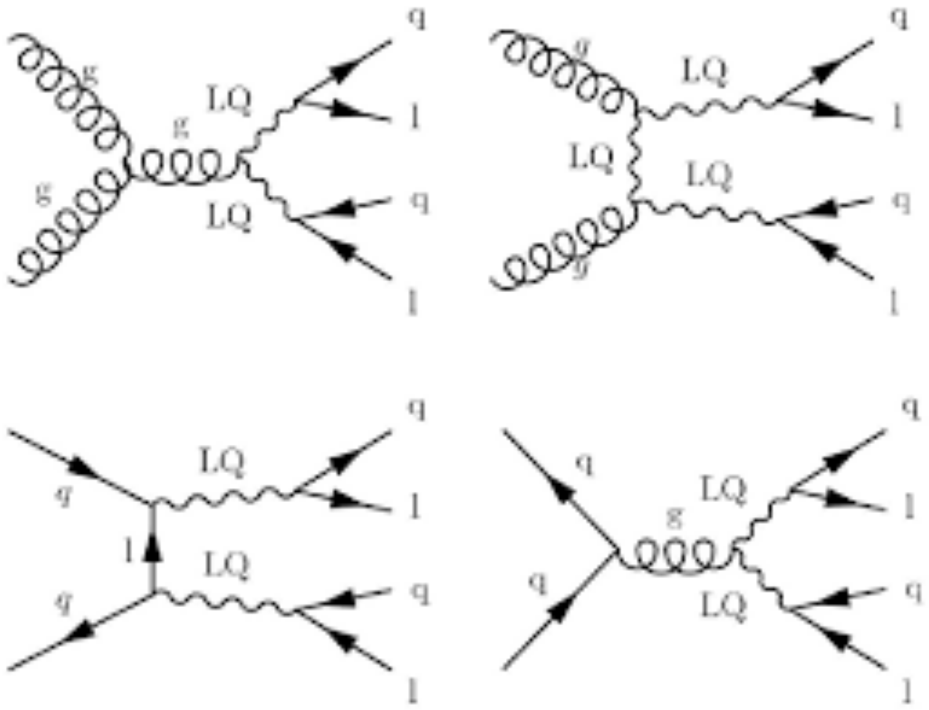
Follow-ups on “Flavour Anomalies”

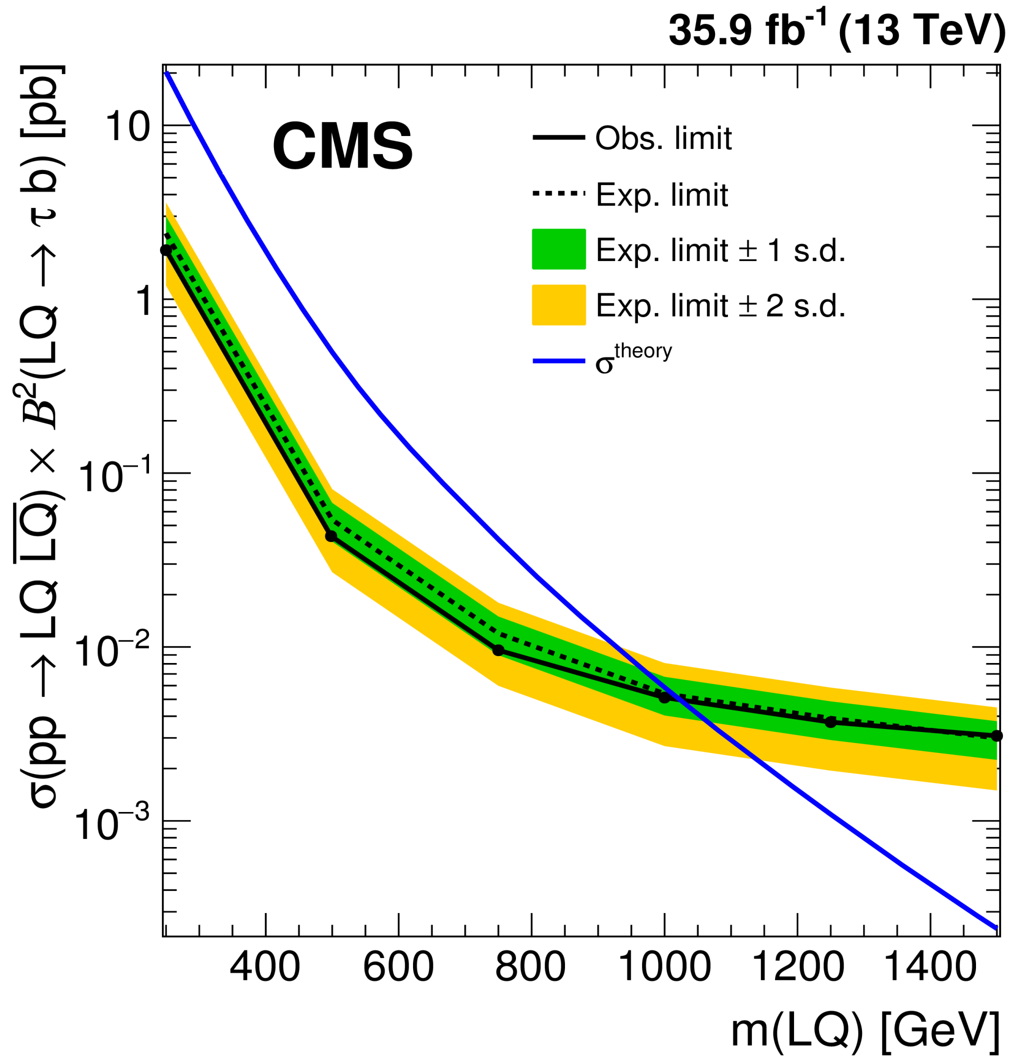
- More data from LHCb: Run-2 data about 2x more than Run-1
  - Eagerly awaiting update
- Completely independent analysis by Belle-II
  - Expect Belle result on RK soon but unclear if statistically sufficient
  - Belle-II expected to pass Belle+BaBar by ~2021
- Searches for related phenomena in ATLAS and CMS
  - E.g. leptoquarks => tomorrow



Leptoquarks

- New bosons that carry lepton and baryon.
- Became interesting recently due to flavor anomalies in B-physics experiments (=> yesterday)

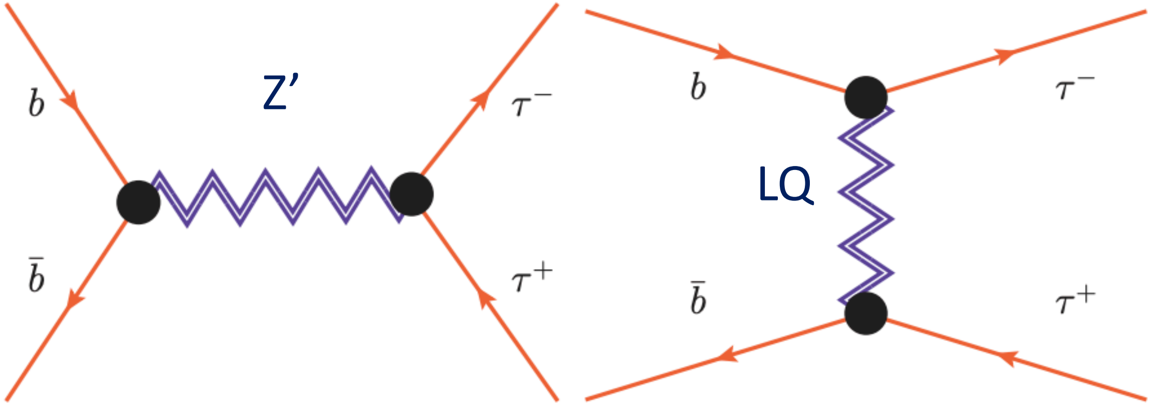




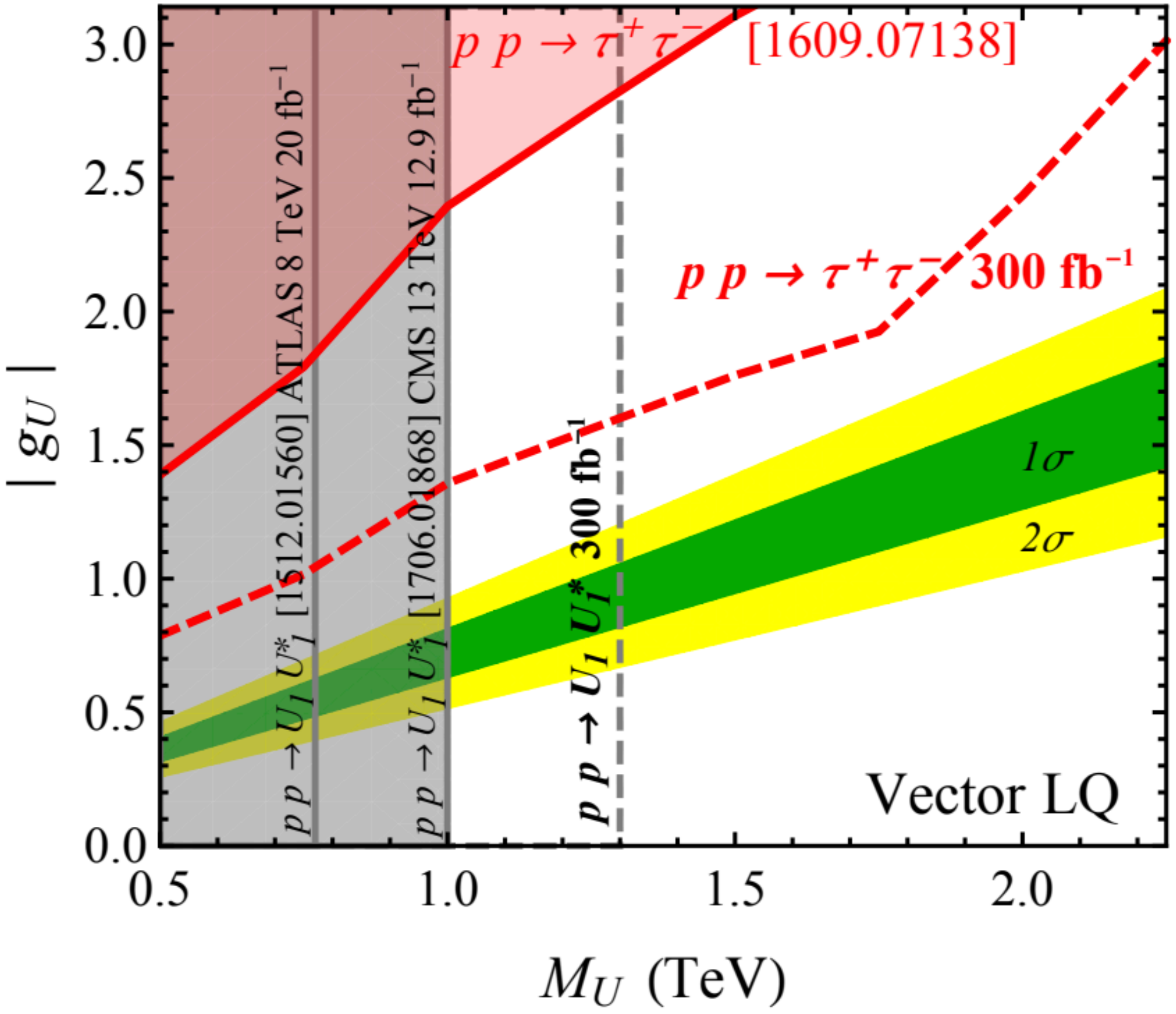
arXiv:1811.0080

Explanations of Flavor Anomalies

1706.07808



- High mass di-tau events also sensitive to models explaining anomaly, e.g. LQ or Z’ exchange
- Will probe region needed to explain anomaly with run-2 data.



Summary

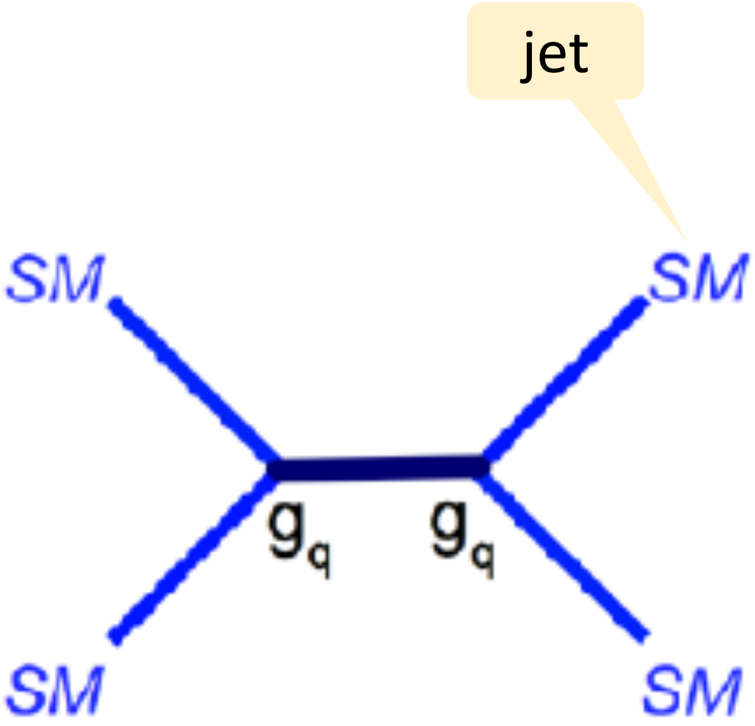
- Higgs boson scientific programme grown a lot since discovery
  - Properties and cross sections agree with SM prediction
  - Much higher precision expected in the next years
- Many puzzles continue to exist which might be related to the electroweak scale
  - Huge programme of searches for new particles
  - No significant hints so far
  - Much of interesting parameter space excluded in e.g. SUSY

Many LHC searches are ongoing!

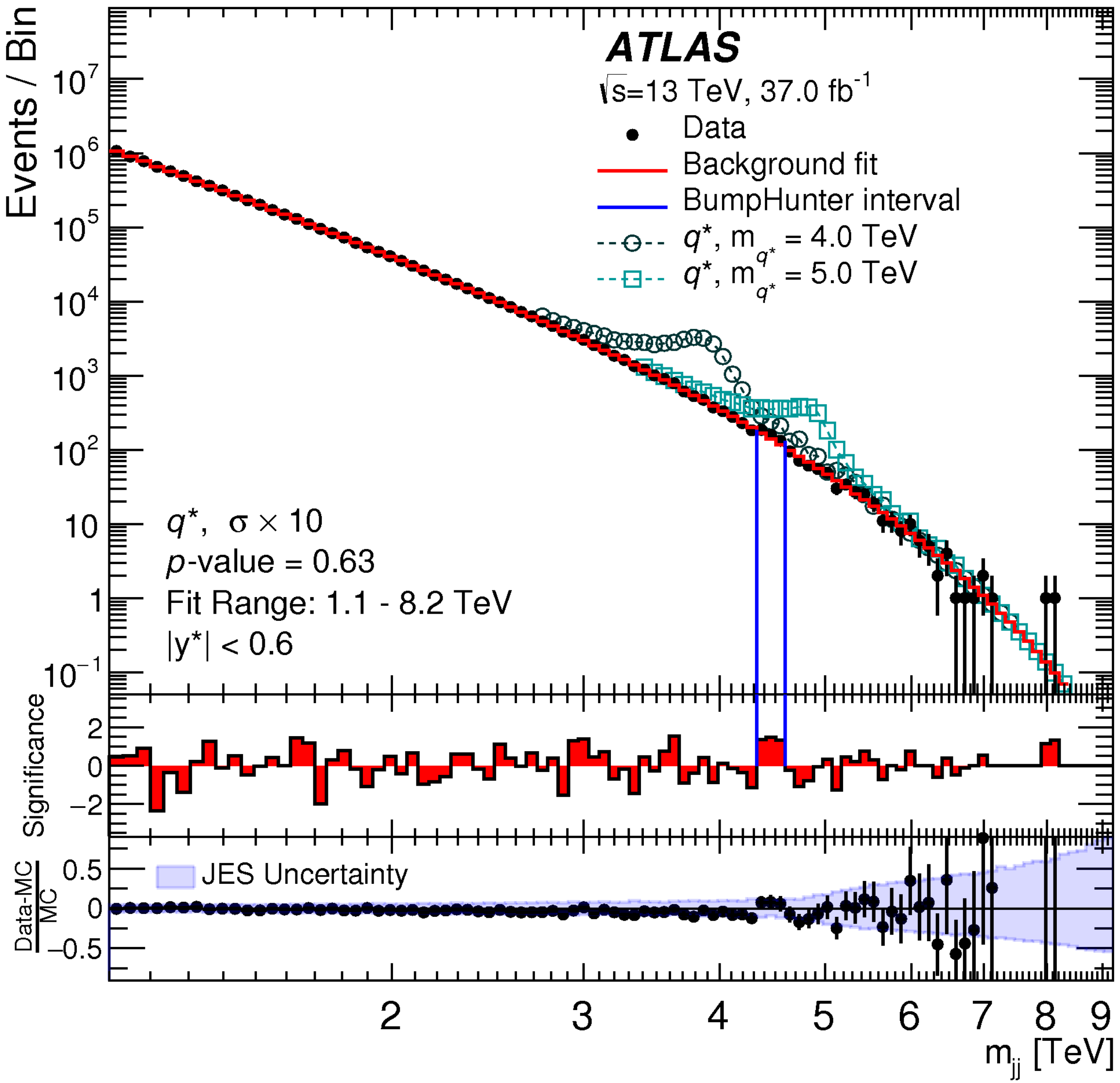
Hopefully some/one will find something interesting!!

Backup Slides

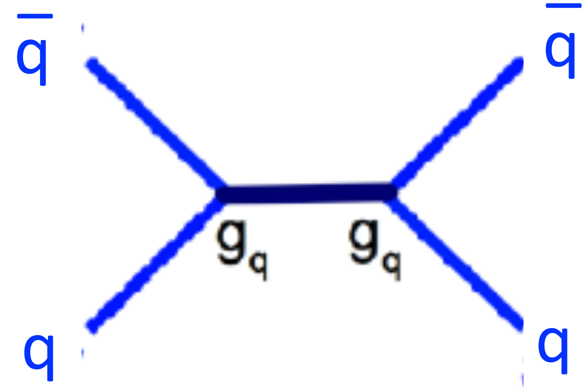
Dijet search

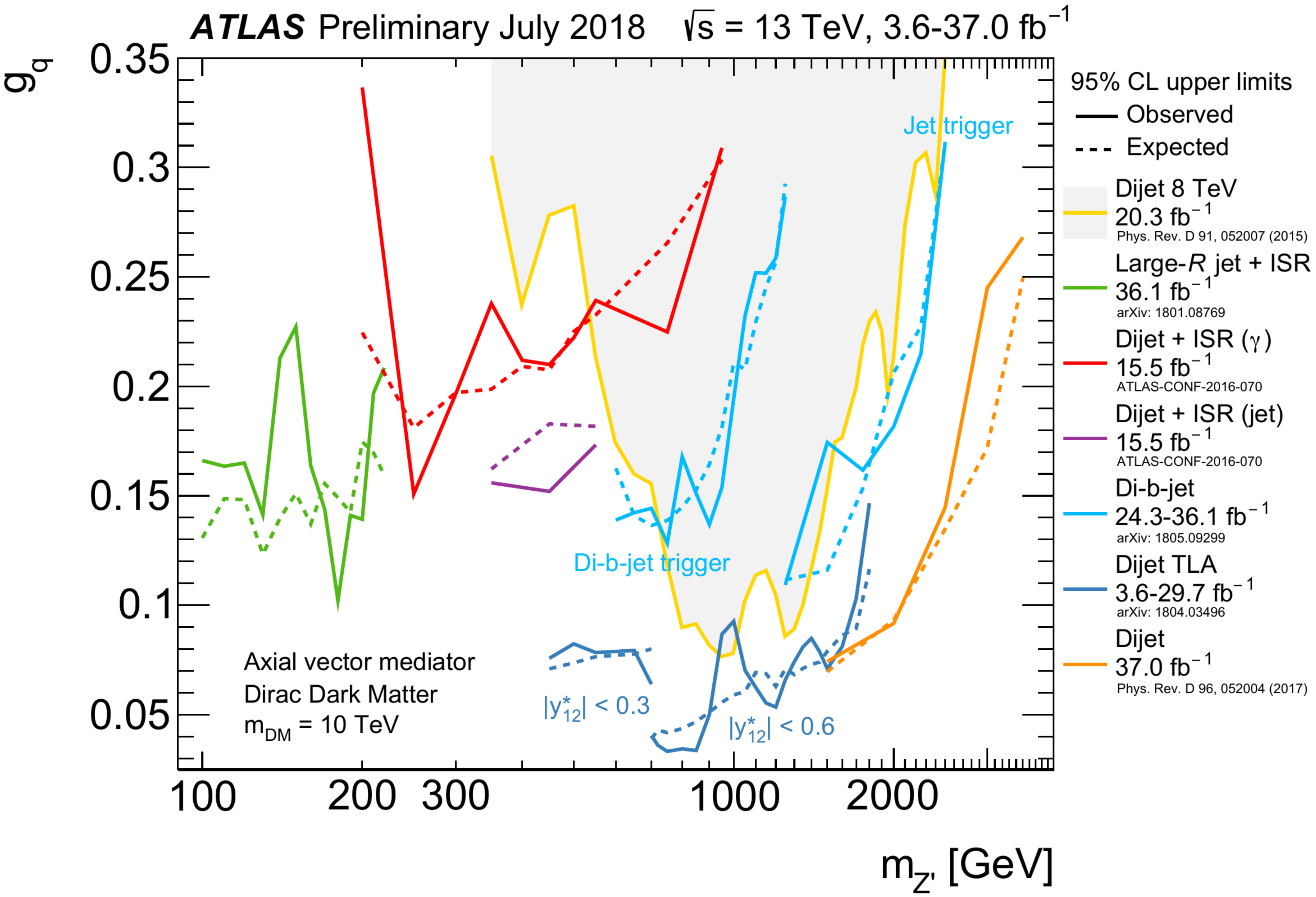


Phys. Rev. D 96 (2017) 052004

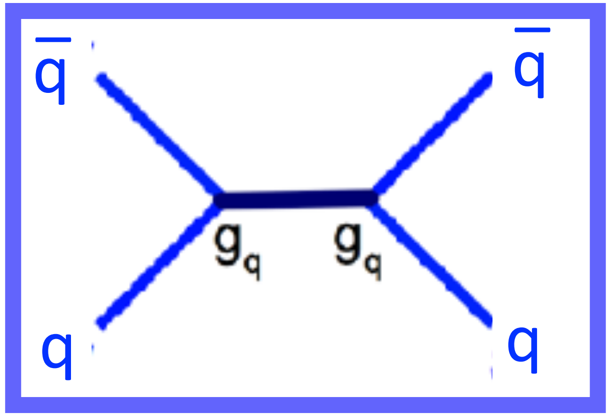


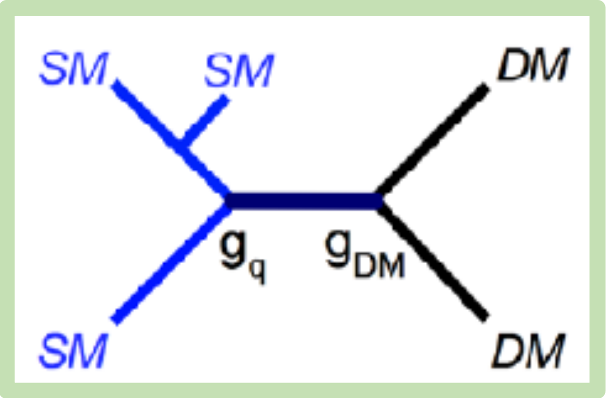
Dijet Searches: Summary of Constraints on g_q and M

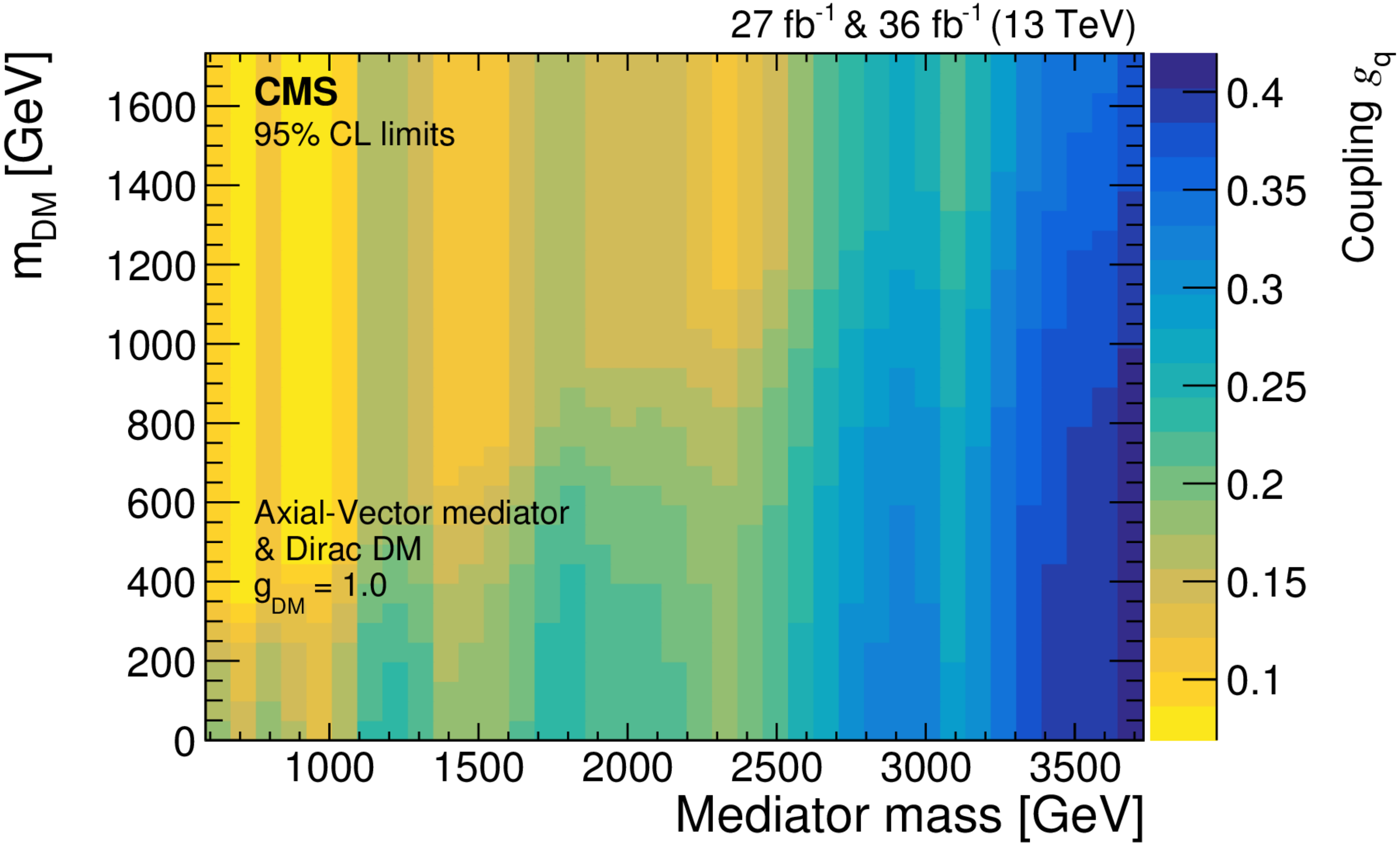




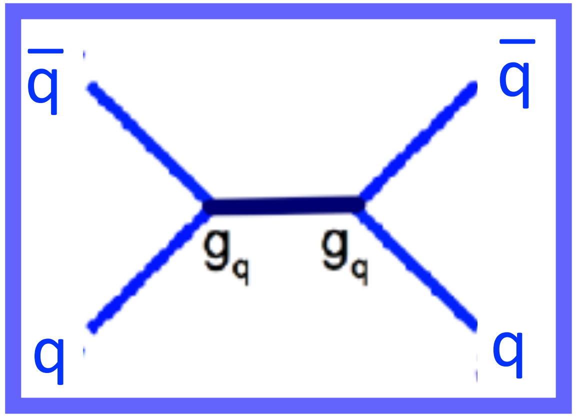
Constraints on DM and Mediator masses: g_{DM}=1

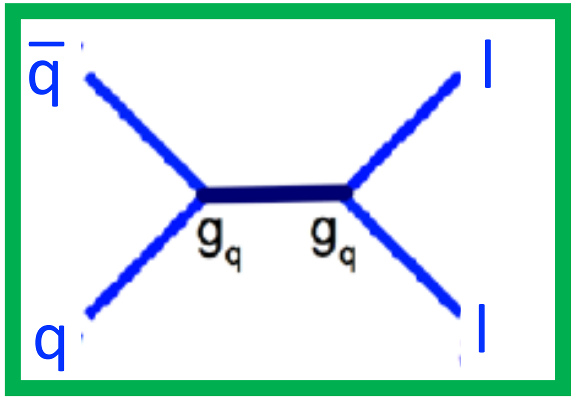


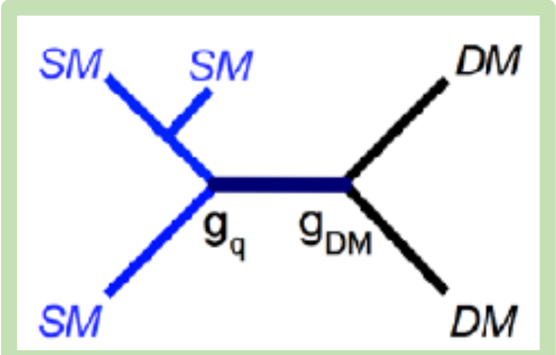


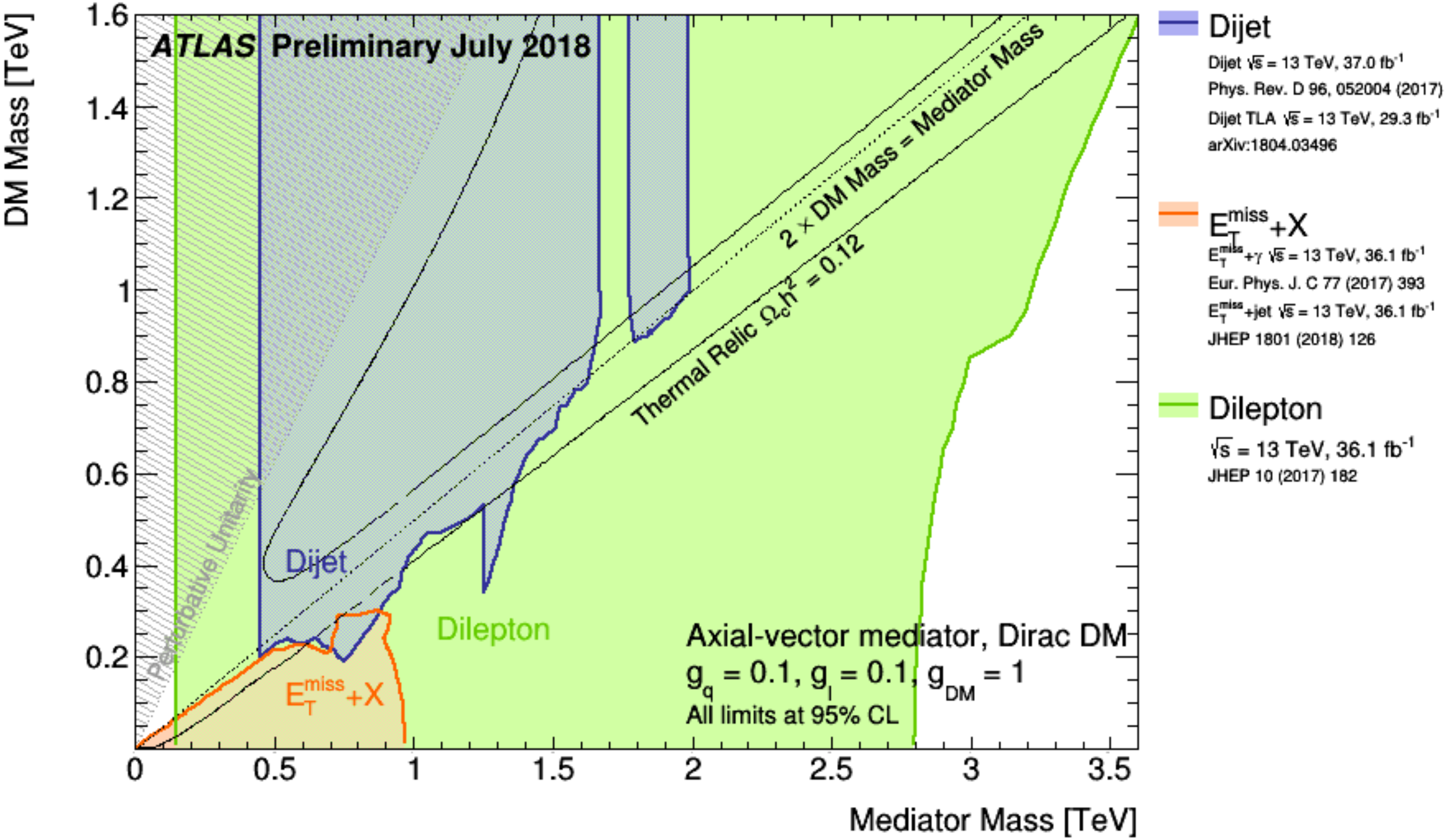


Constraints on DM and Mediator masses: g_q=0.1, g_l=0.1

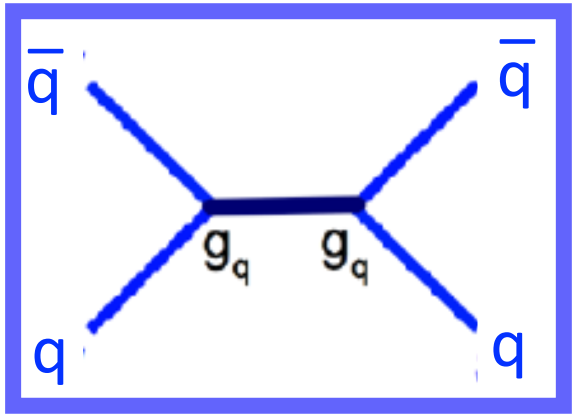


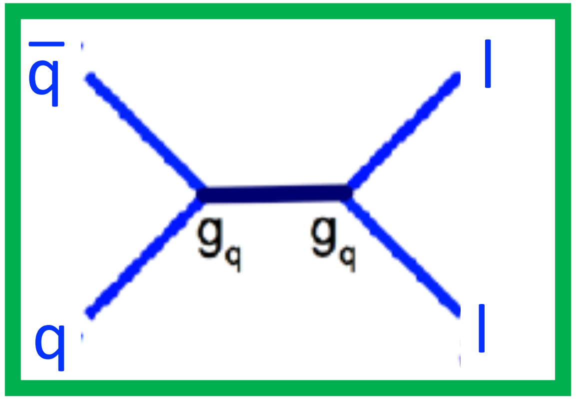


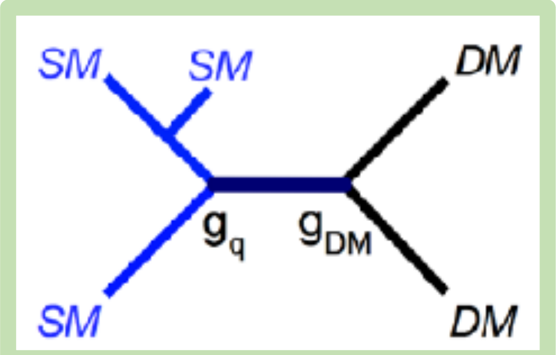


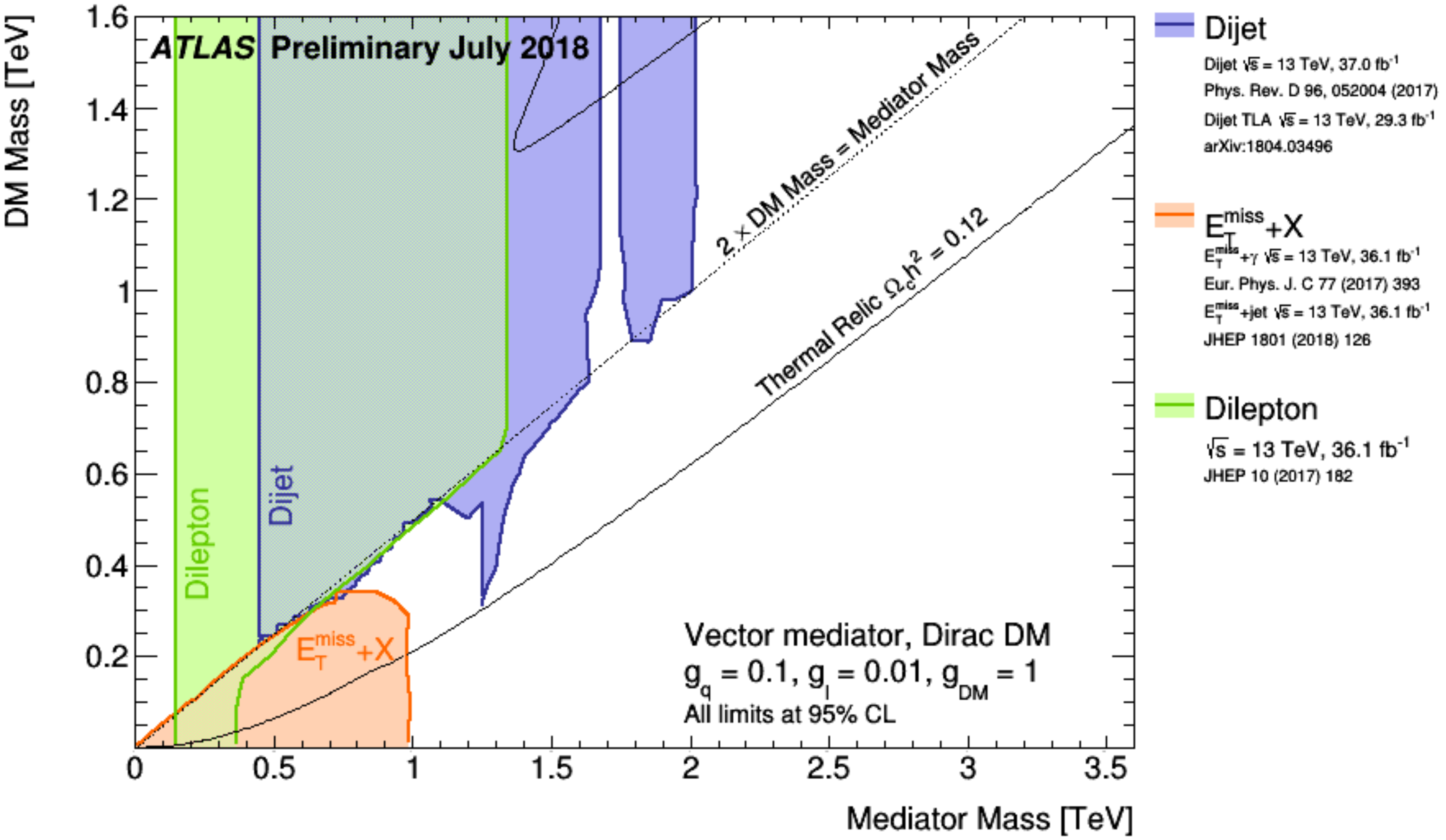


Constraints on DM and Mediator masses: g_q=0.1, g_l=0.01

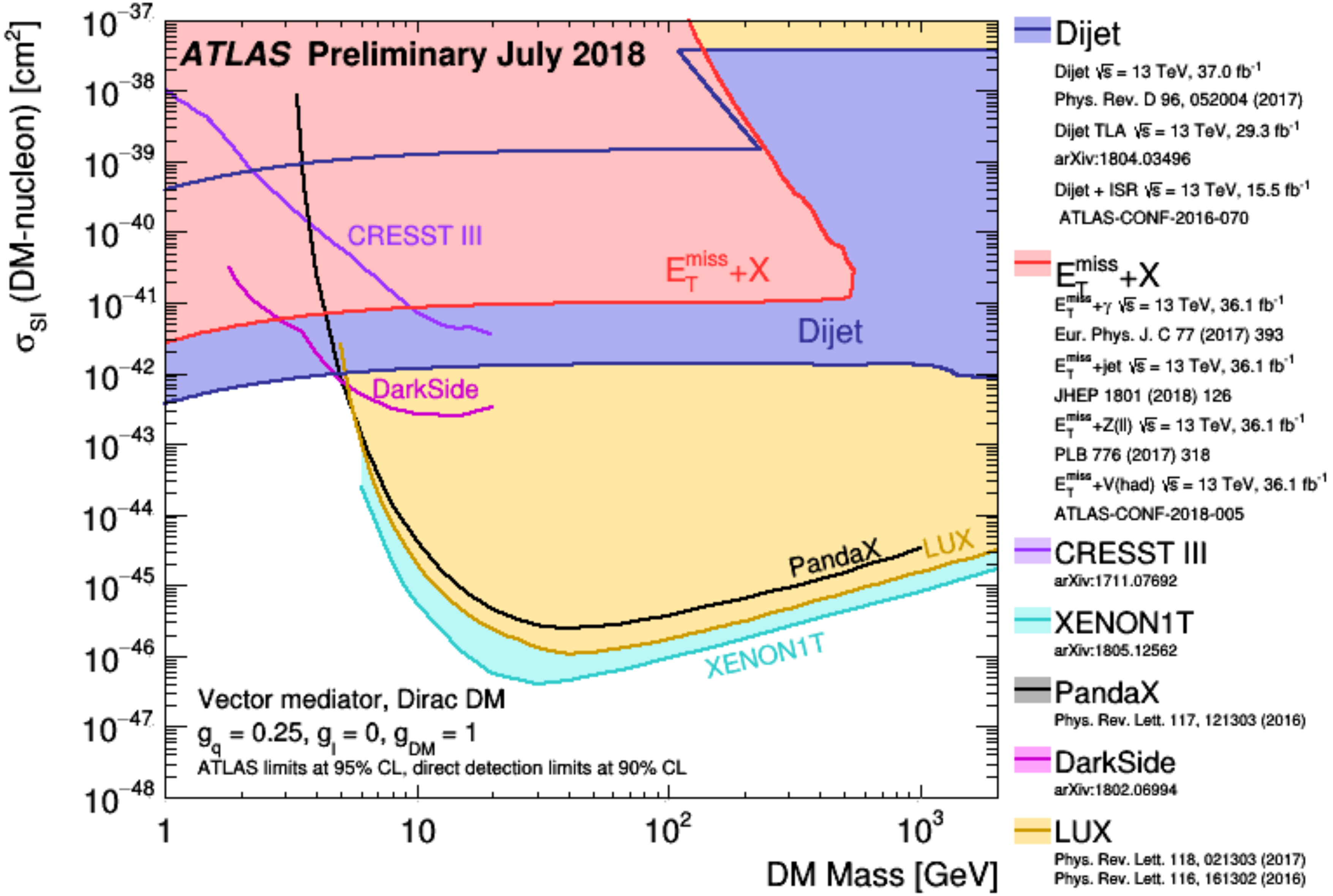








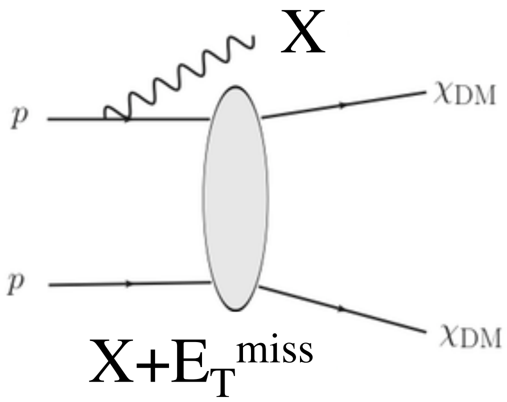
Constraints on DM-nuclean cross section



g_q=0.25, g_l=0, g_{DM}=1

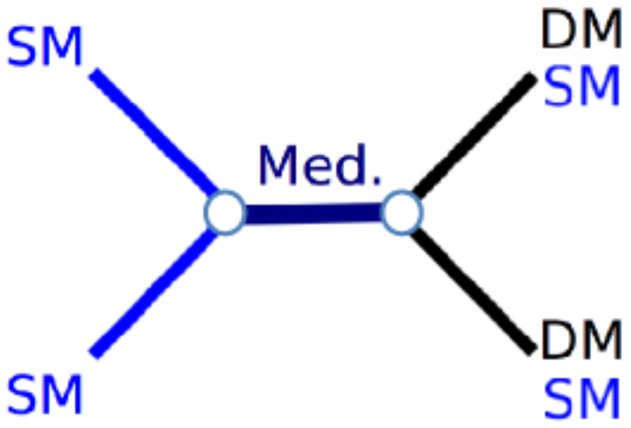
Three ways to search for WIMPs at LHC

3. pp->$\chi\chi$ + X
    - Inverse of freeze-out process
    - Mono-X signature: E_T^{miss}+X
        - X=jet, photon, W, Z…

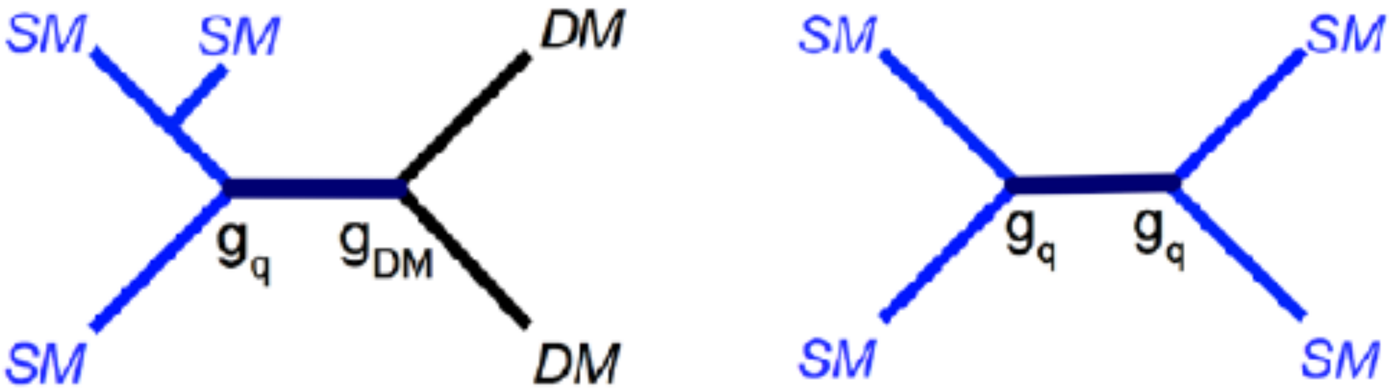


Simplified Models for Dark Matter

- Assume there is some “mediator” which couples to both SM and DM particles

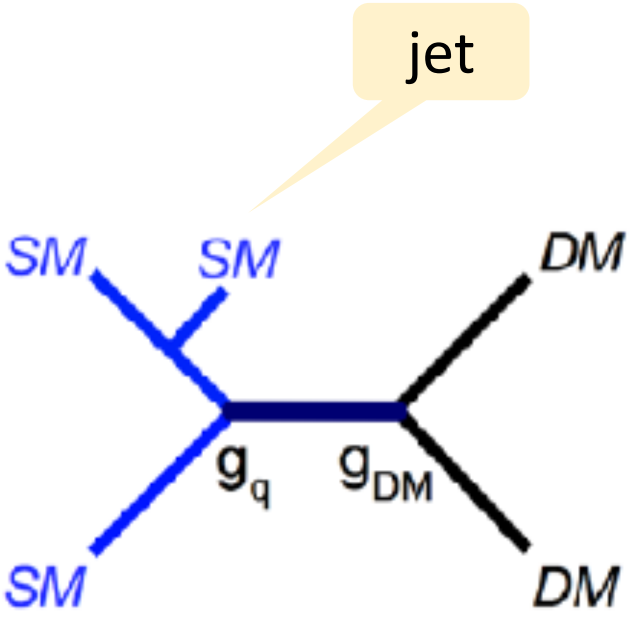


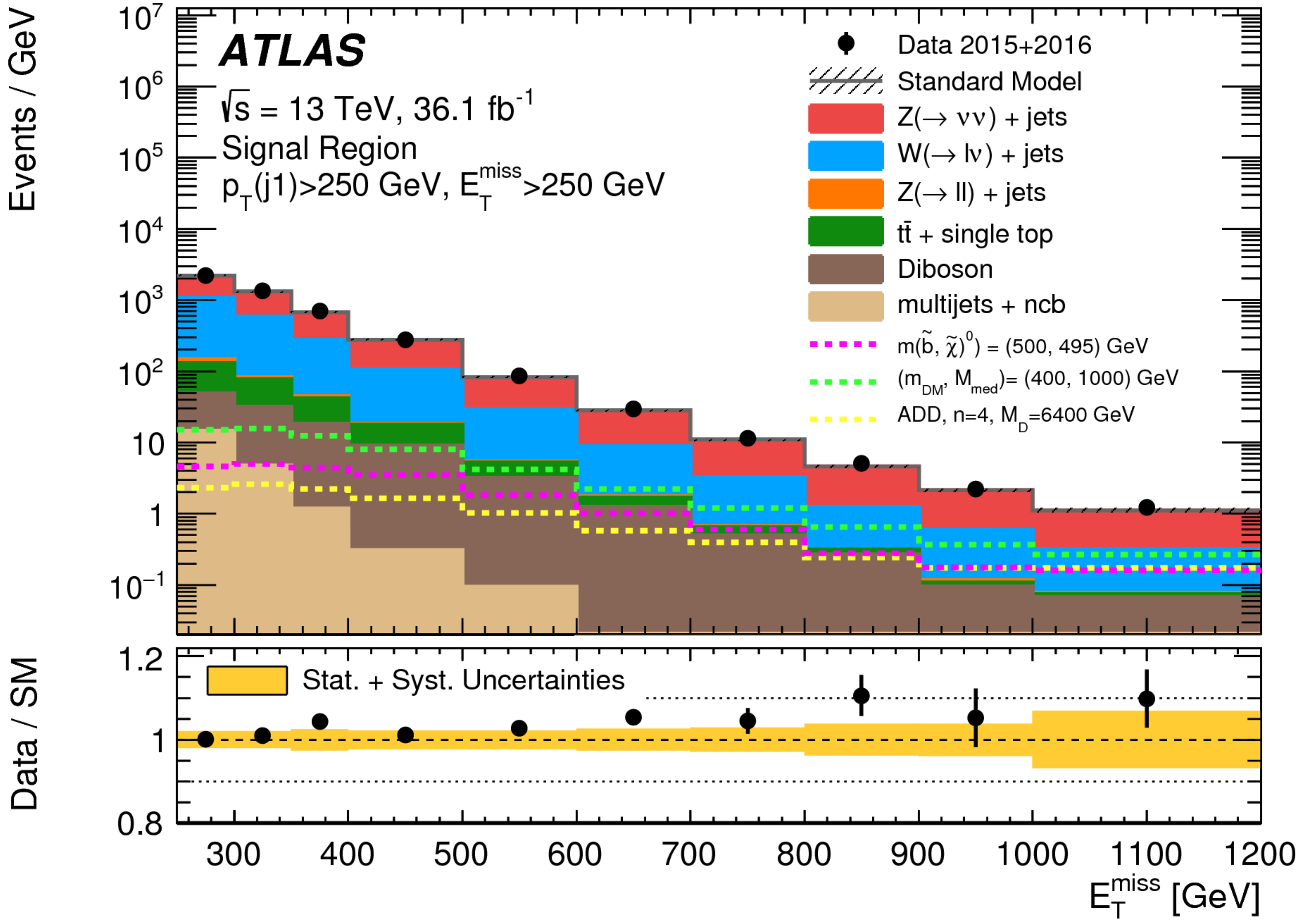
- LHC produces mediator, and then looks for its decay into either DM or SM

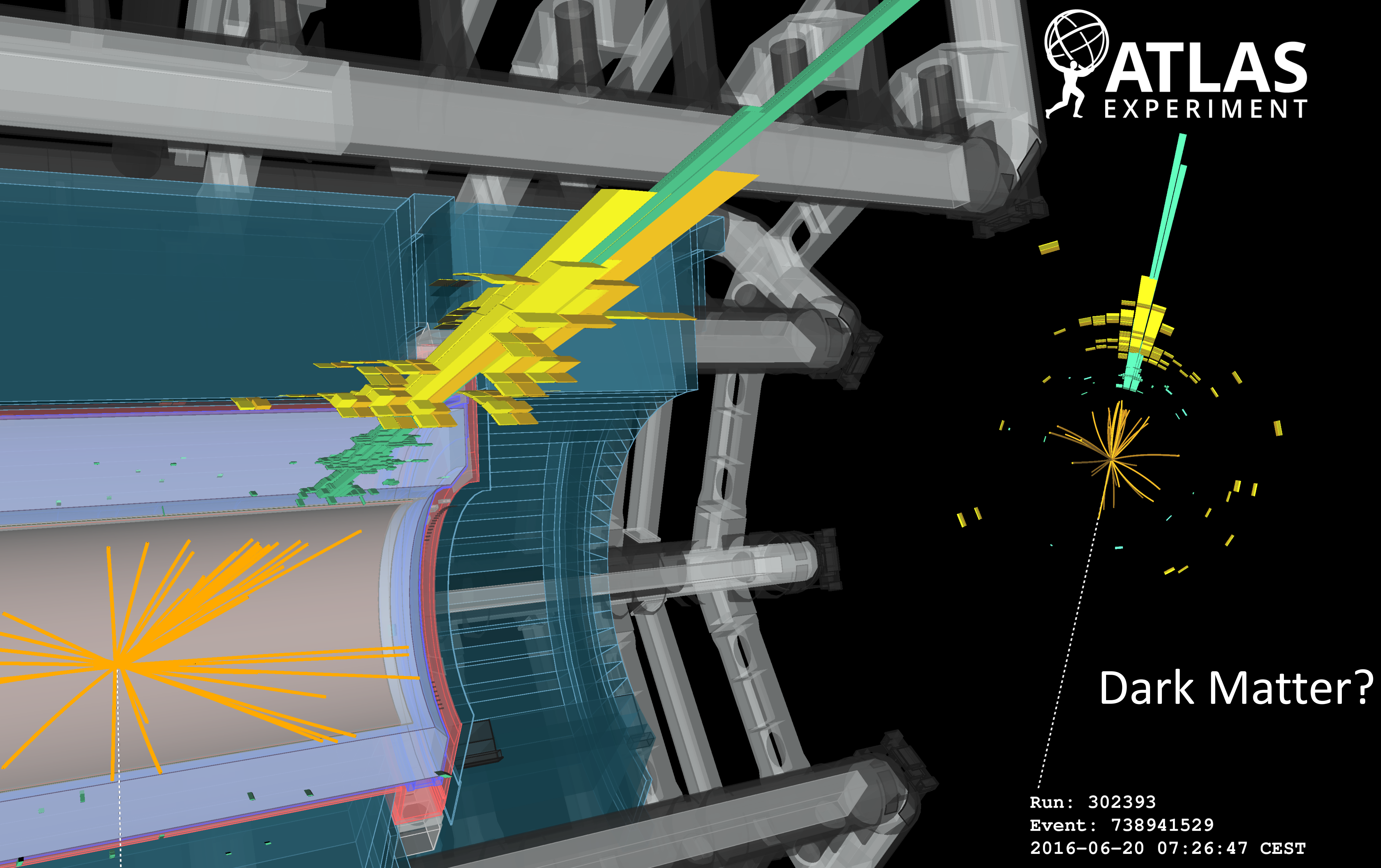


Mono-jet search

JHEP 01 (2018) 126



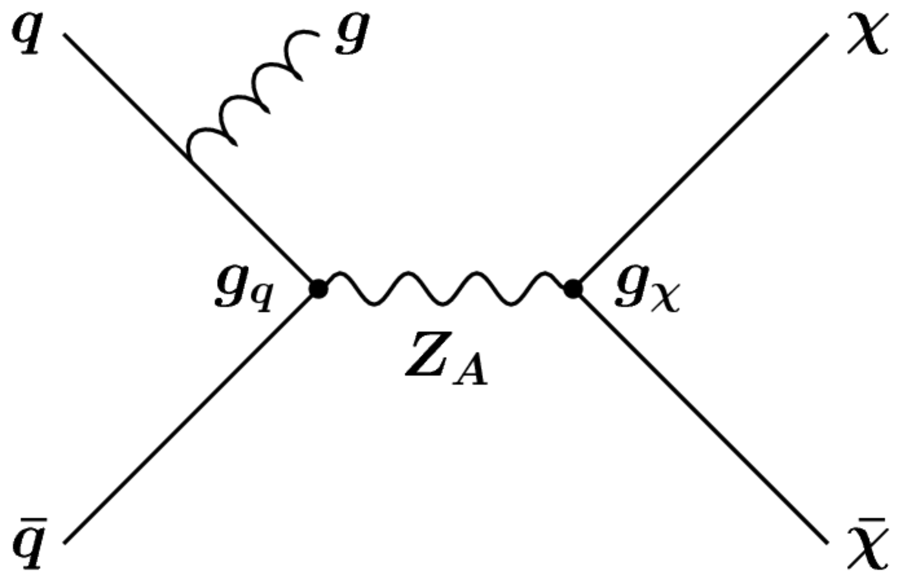




Dark Matter?

Run: 302393
Event: 738941529
2016-06-20 07:26:47 CEST

Monojet search interpretation



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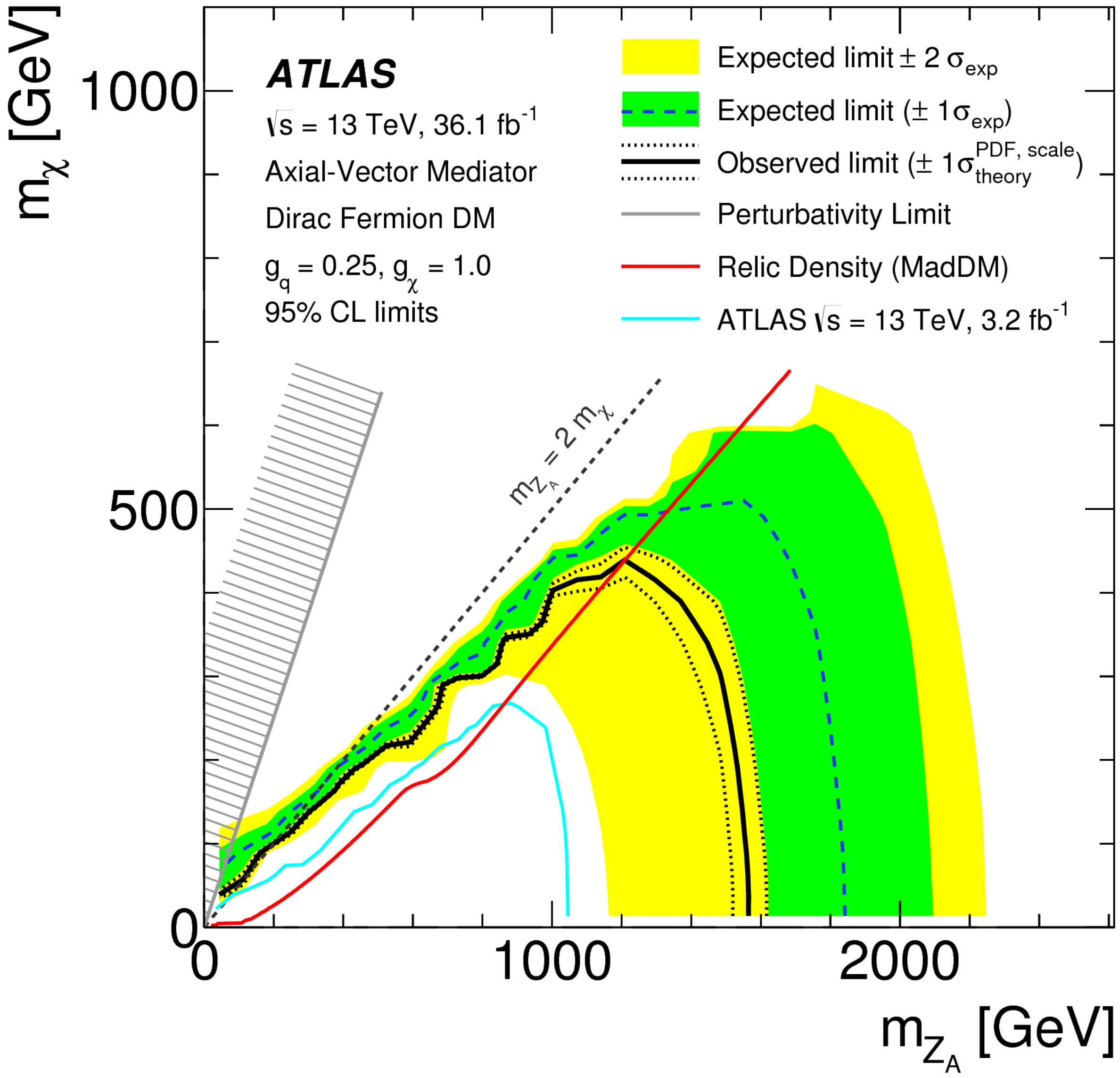
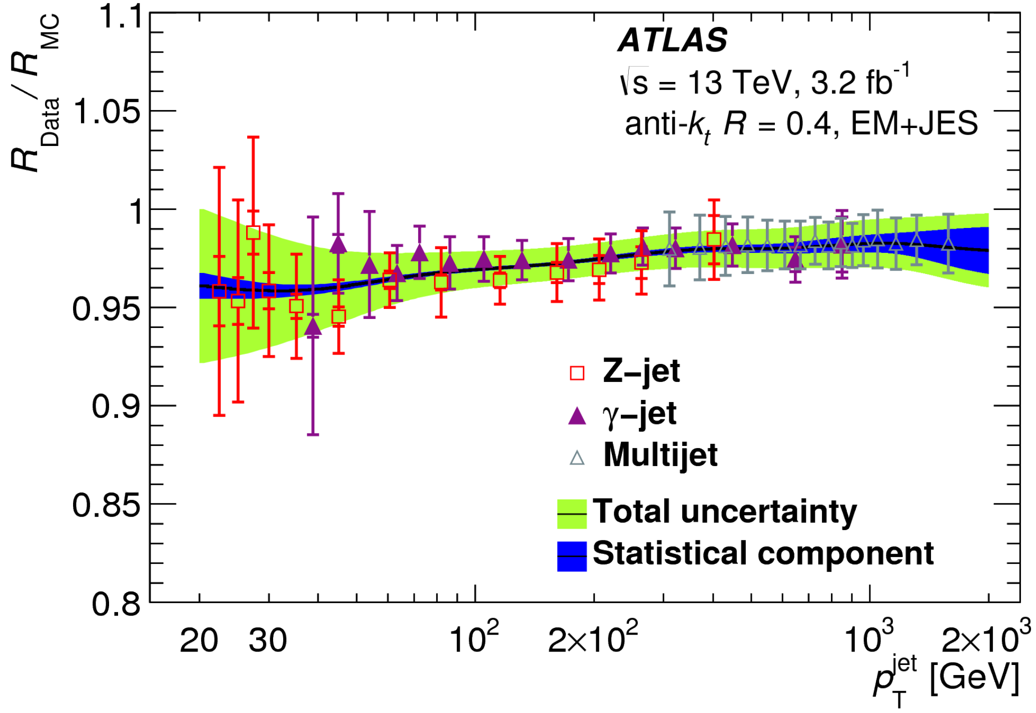
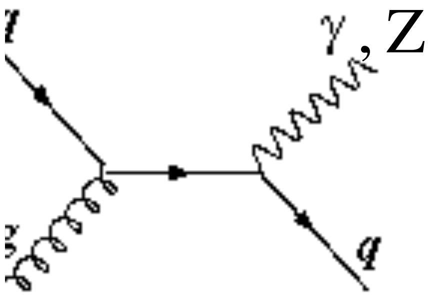
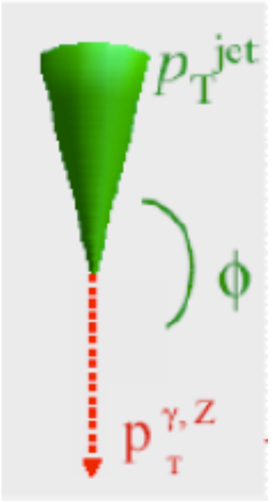
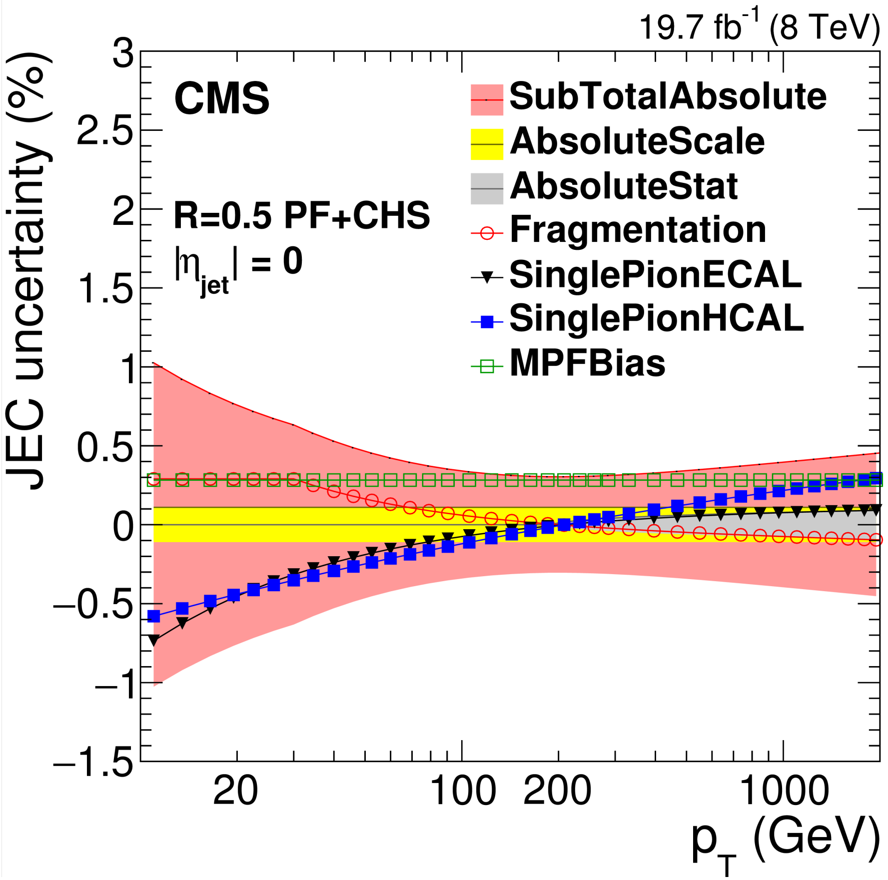


Jet Energy Scale



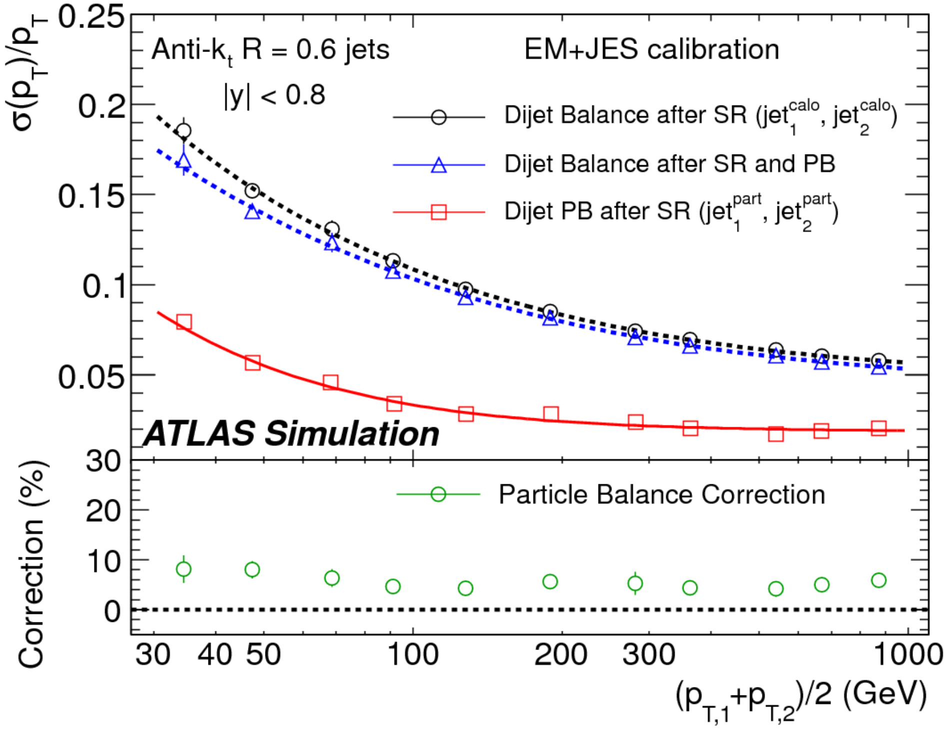


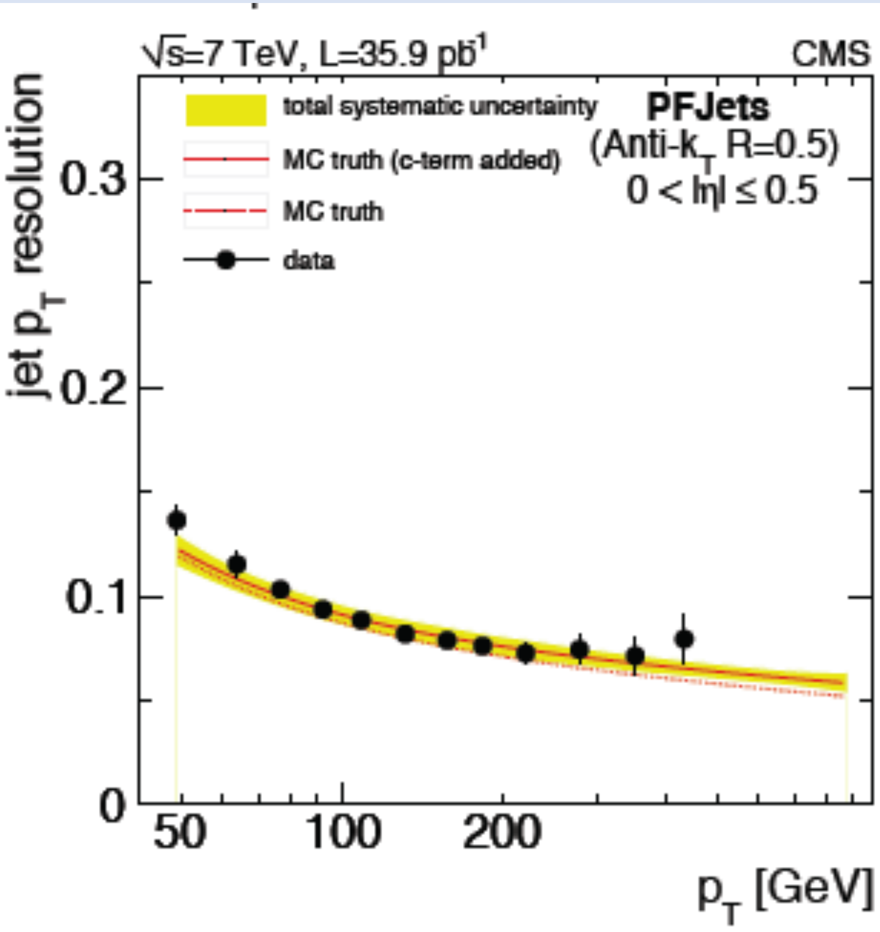




- Jets are calibrated *in situ* with calibration processed:
  - photon+jet, Z+jet, multijet
- Systematic uncertainty due to understanding of
  - calibration procedure, jet flavor composition/response, pileup

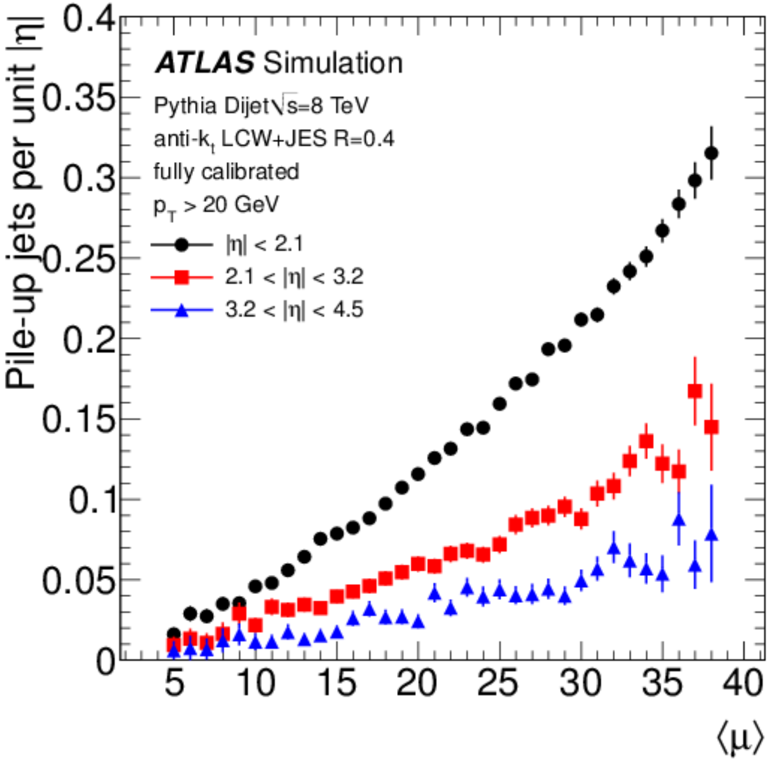
Jet Energy Resolution

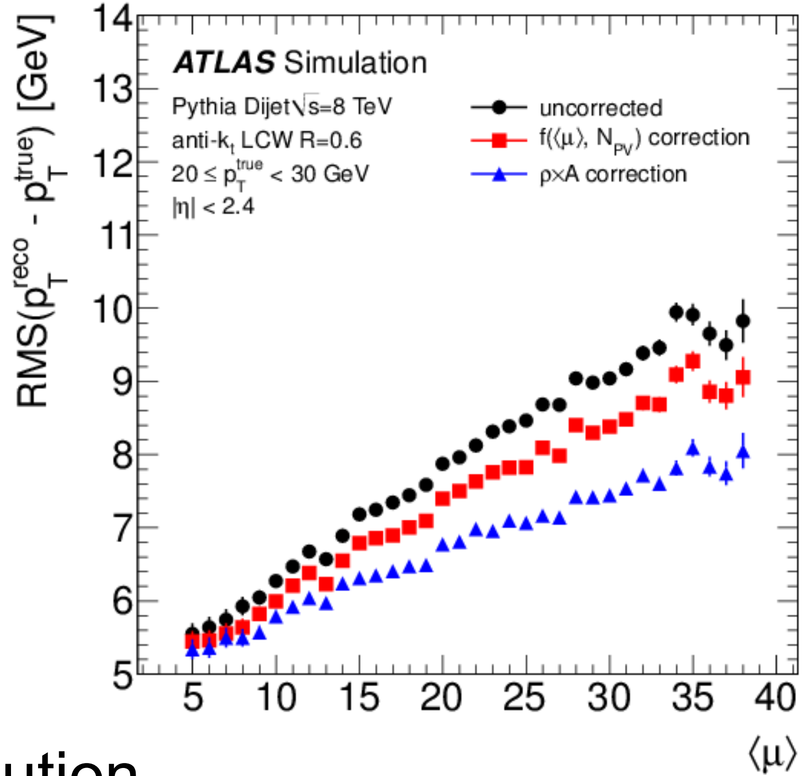




- Jet energy resolution
  - p_T=50 GeV: σ~12-15%
  - p_T=200 GeV: σ~8%
- Deteriorates with pileup (see tomorrow's lecture)

Impact of Pileup



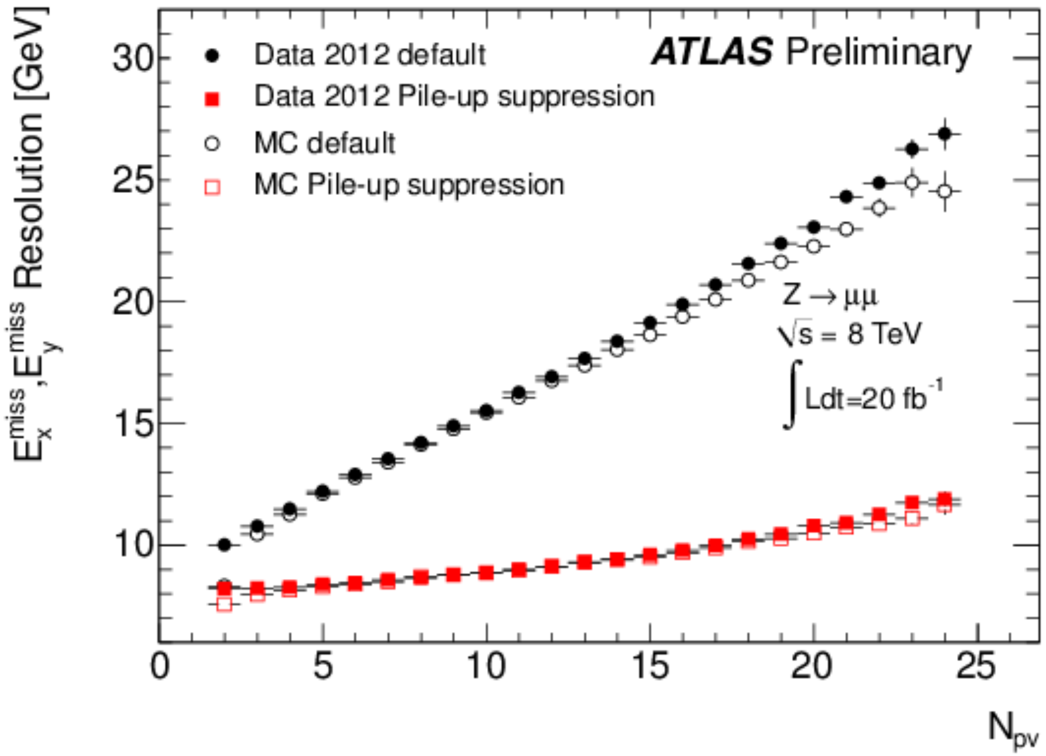


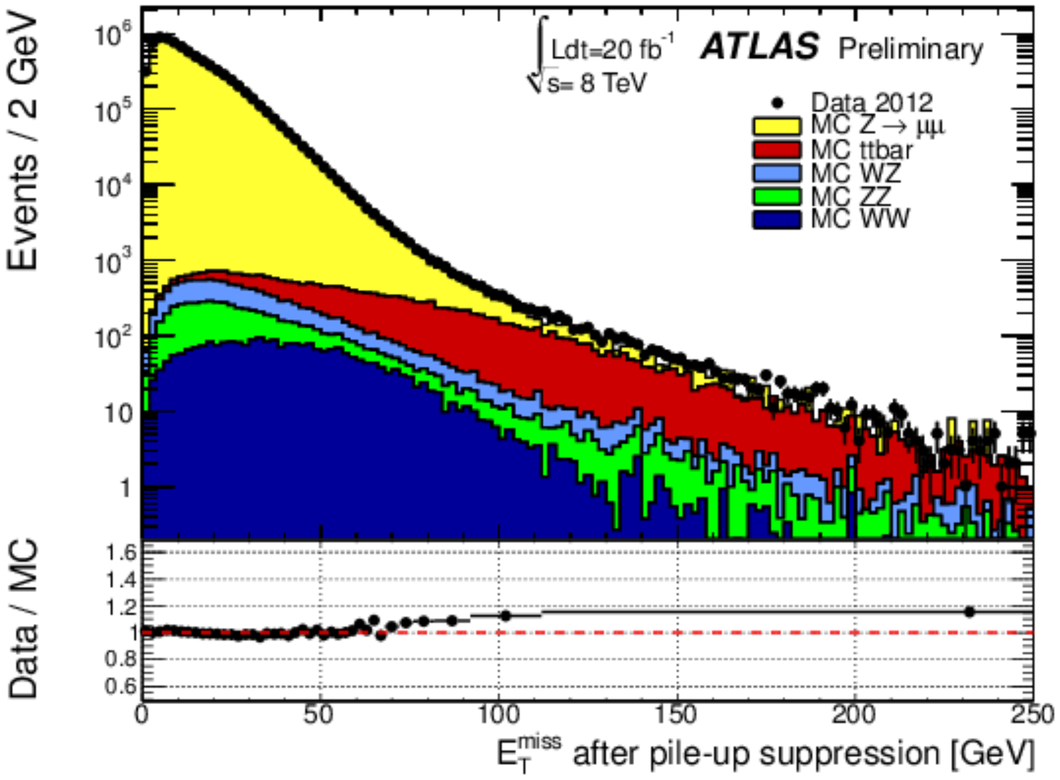
- Pileup can create jets and degrades resolution
- Several correction methods exist
  - All work on average but fluctuations are large
- "Jet Area Correction" by M. Cacciari and G. Salam works best

$$p_T^{jet,corr} = p_T^{jet} - \rho \times A_T^{jet}$$

arXiv:0707.1378

Missing E_T

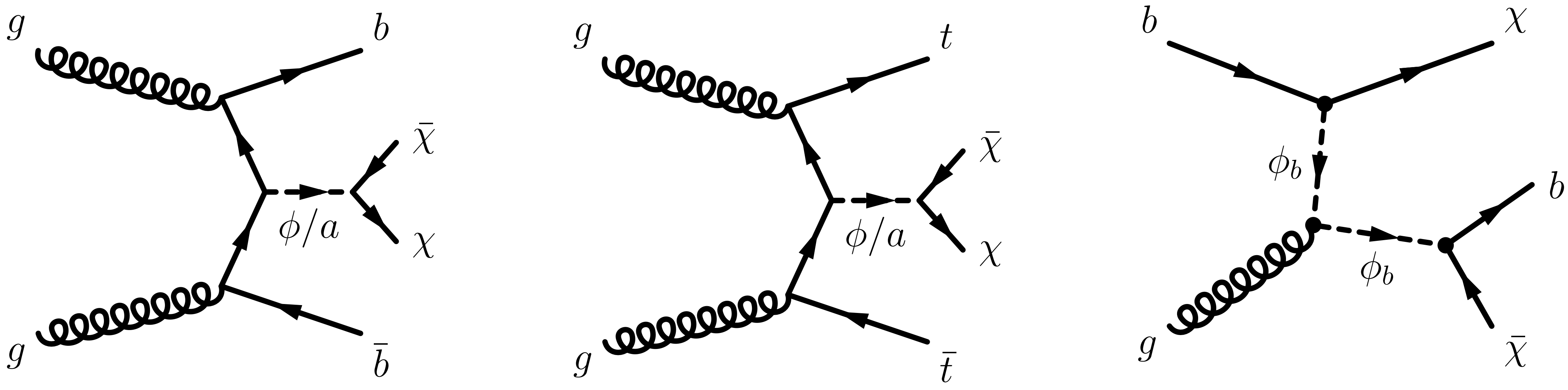




- Pileup suppression important to retain missing ET resolution
  - Resolution typically 5-10 GeV (for events with no E_T^{miss})
- Long tails can cause up to ~100 GeV of E_T^{miss}

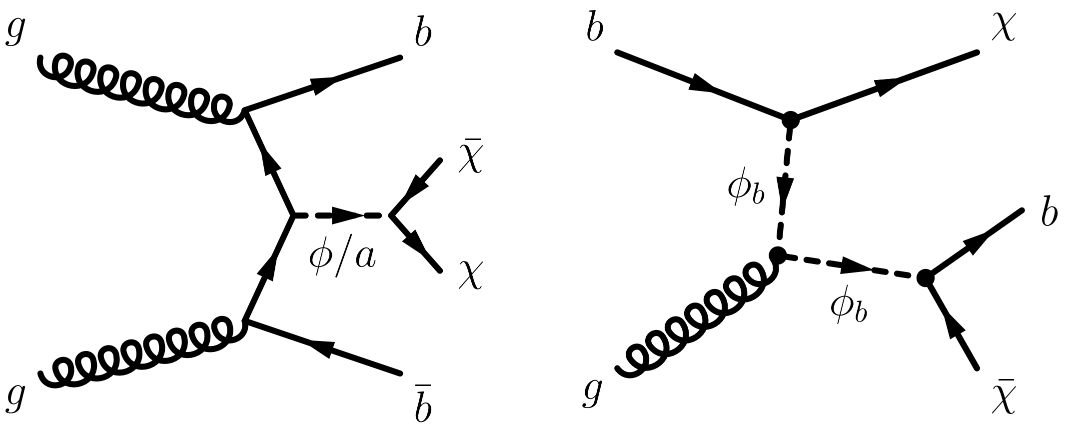
What if mediators mostly couple to 3rd generation?

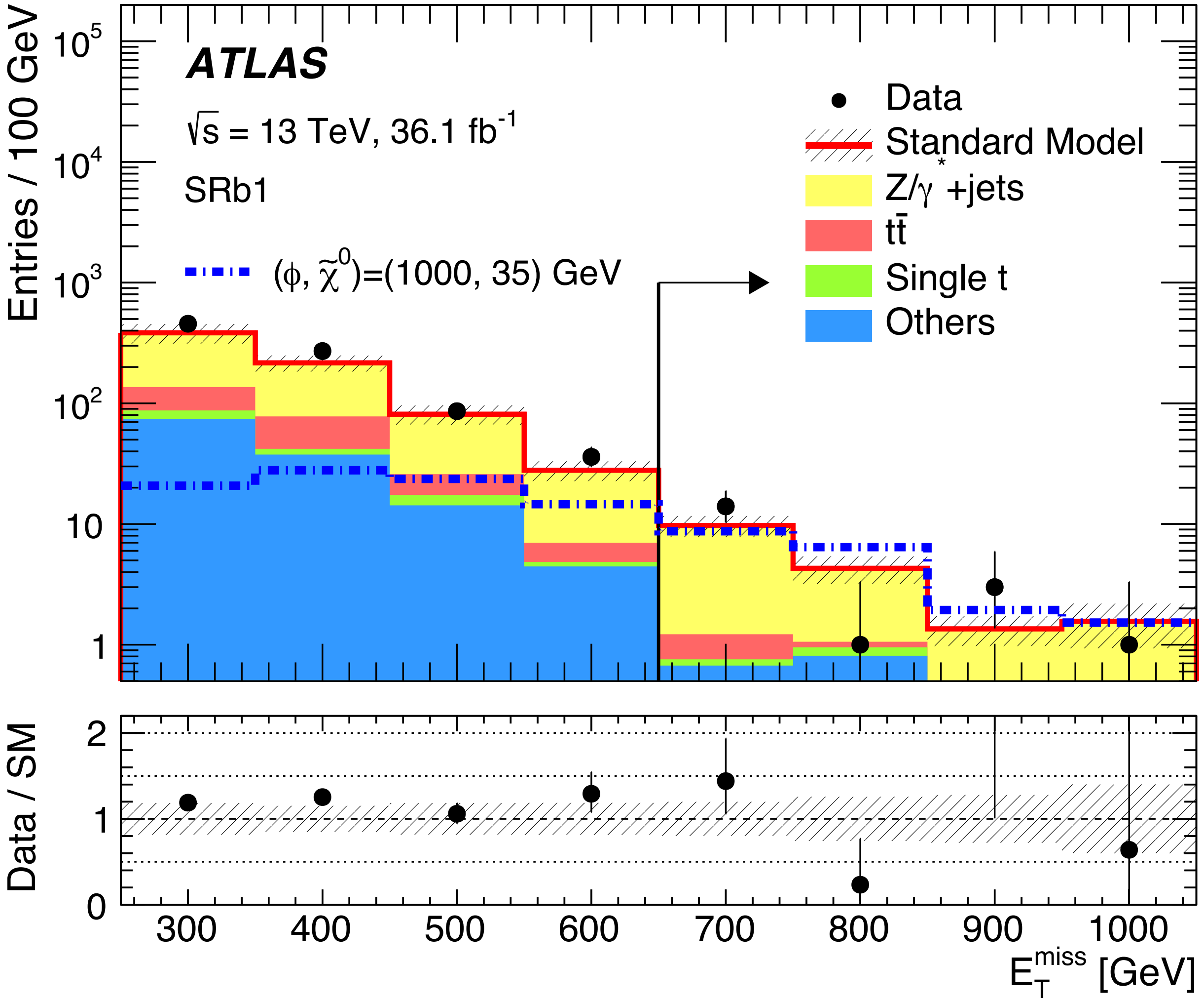
- Direct detection and dijet constraints can largely be evaded if mediators couple primarily to 3rd generation, e.g.



=> Searches for b- or t-jets + E_T^{miss} , b-jet resonances, …

Searches for E_T^{miss} + b-jets

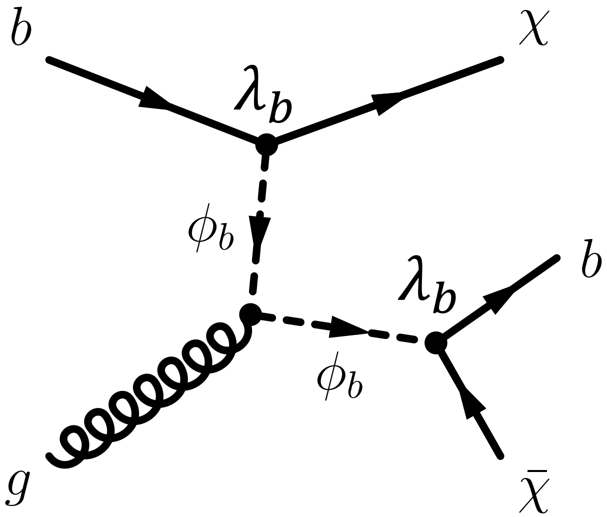




- Jets from b-quarks experimentally identified due to long lifetime of b-hadrons
- Main Background:
  - $Z \rightarrow \nu\nu$ + b-jets

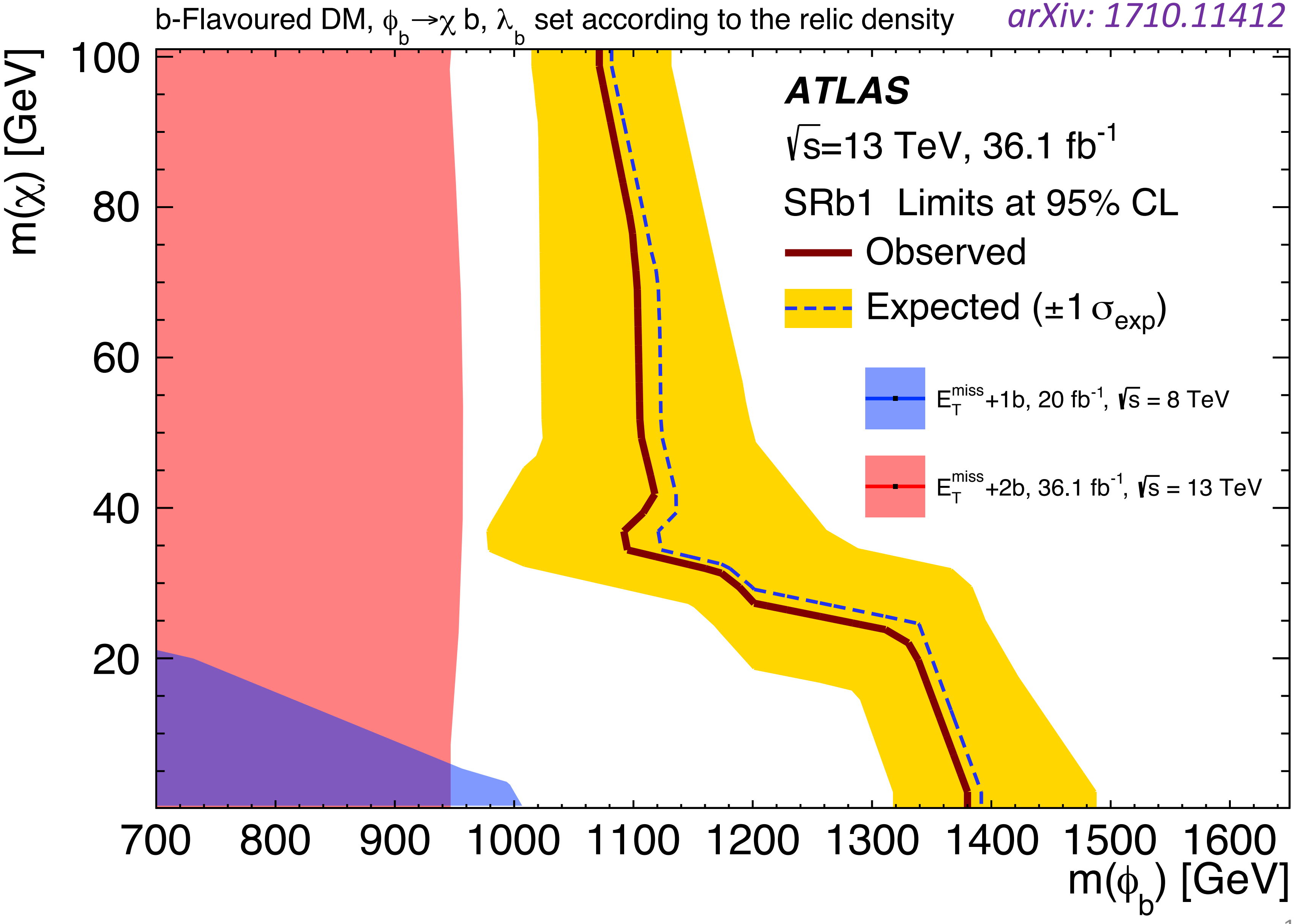
Interpretation of E_T^{miss}+b-jet search

E.g. colour-charged fermionic mediator



P. Agrawal et al., PRD 90 (2014) 063512

arXiv: 1710.11412



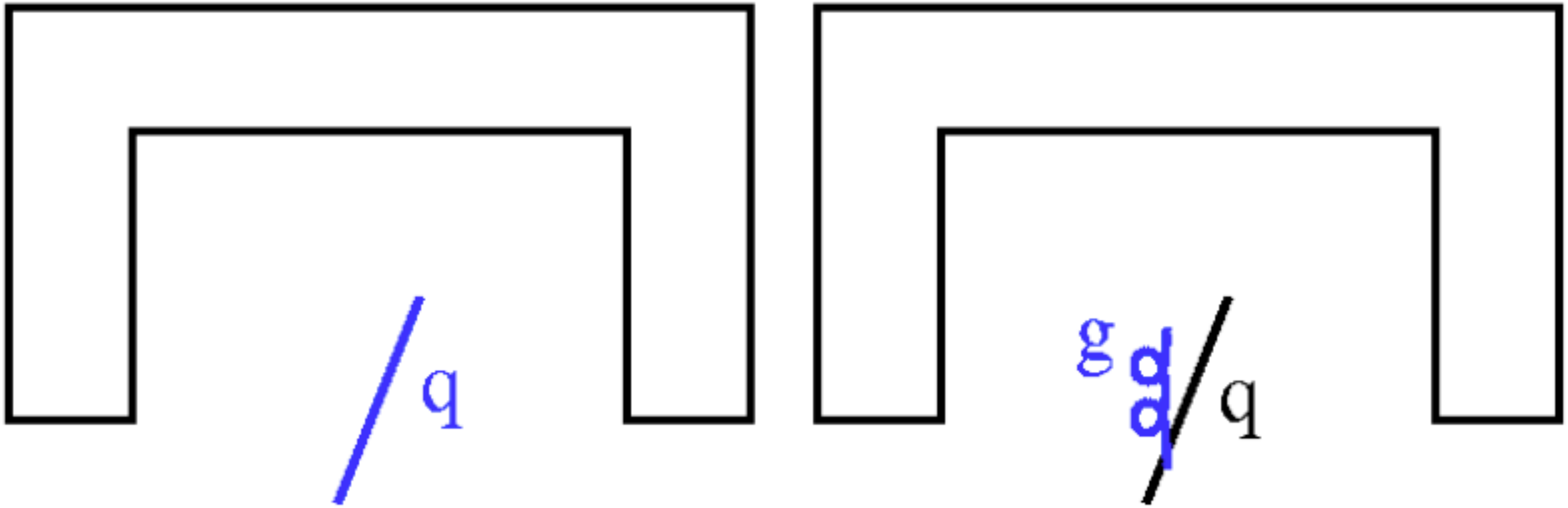
Interlude: Measuring Jets and Missing E_T

- Jets and E_T^{miss} are experimentally among the most challenging quantities to measure
  - Jets are primarily measured by calorimeter but significantly aided by tracker
    - E.g. CMS has so-called “particle flow” algorithm which attempts to use tracker for charged hadrons and calorimeter for neutral hadrons only
  - E_T^{miss} is a derived quantity:

$$\begin{aligned} E^{\mathrm{miss}}_{\mathrm{x(y)}} &= E^{\mathrm{miss},e}_{\mathrm{x(y)}} + E^{\mathrm{miss},\gamma}_{\mathrm{x(y)}} + E^{\mathrm{miss},\tau}_{\mathrm{x(y)}} + E^{\mathrm{miss,jets}}_{\mathrm{x(y)}} \\ &+ E^{\mathrm{miss,softjets}}_{\mathrm{x(y)}} + (E^{\mathrm{miss,calo},\mu}_{\mathrm{x(y)}}) + E^{\mathrm{miss,CellOut}}_{\mathrm{x(y)}} + E^{\mathrm{miss},\mu}_{\mathrm{x(y)}}, \end{aligned}$$

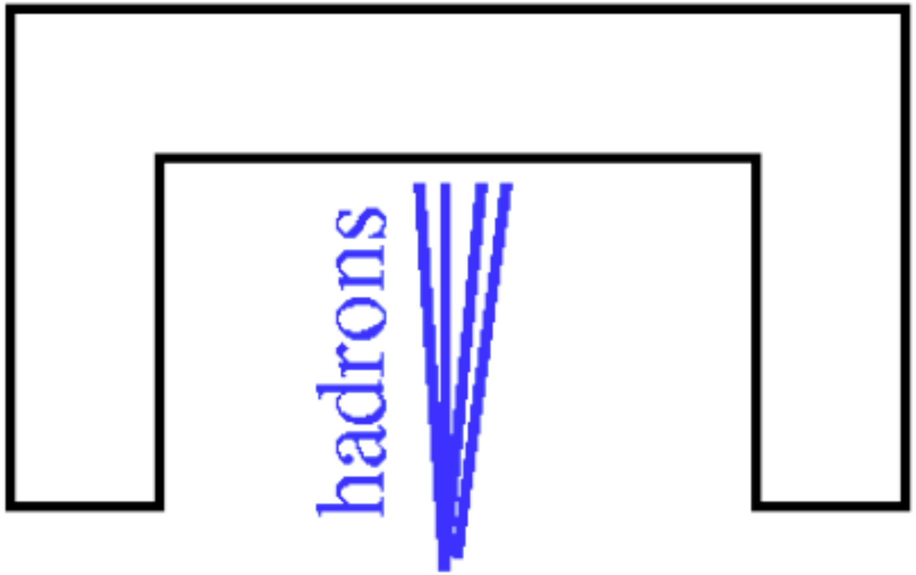
$$\begin{aligned} E^{\mathrm{miss}}_{\mathrm{T}} &= \sqrt{(E^{\mathrm{miss}}_{\mathrm{x}})^2 + \left(E^{\mathrm{miss}}_{\mathrm{y}}\right)^2}, \\ \phi^{\mathrm{miss}} &= \arctan(E^{\mathrm{miss}}_{\mathrm{y}} / E^{\mathrm{miss}}_{\mathrm{x}}). \end{aligned}$$

Partons are Produced in the hard scatter



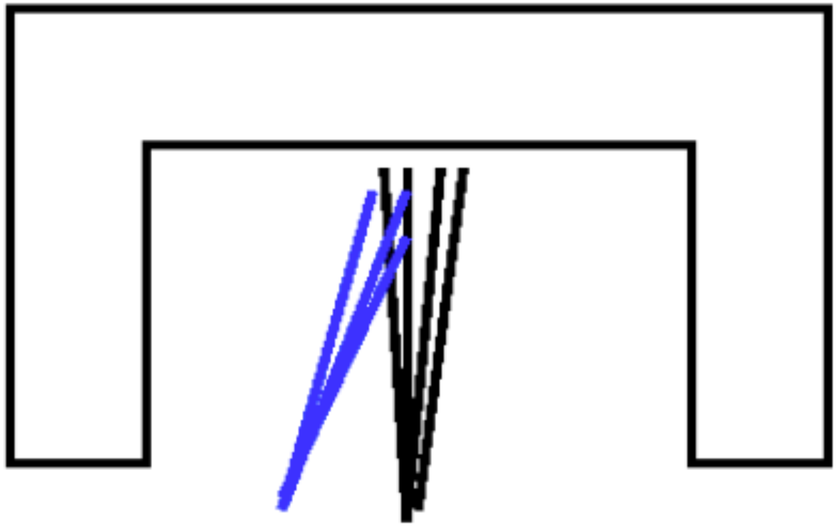
- Would like to know the 4-vector of these partons

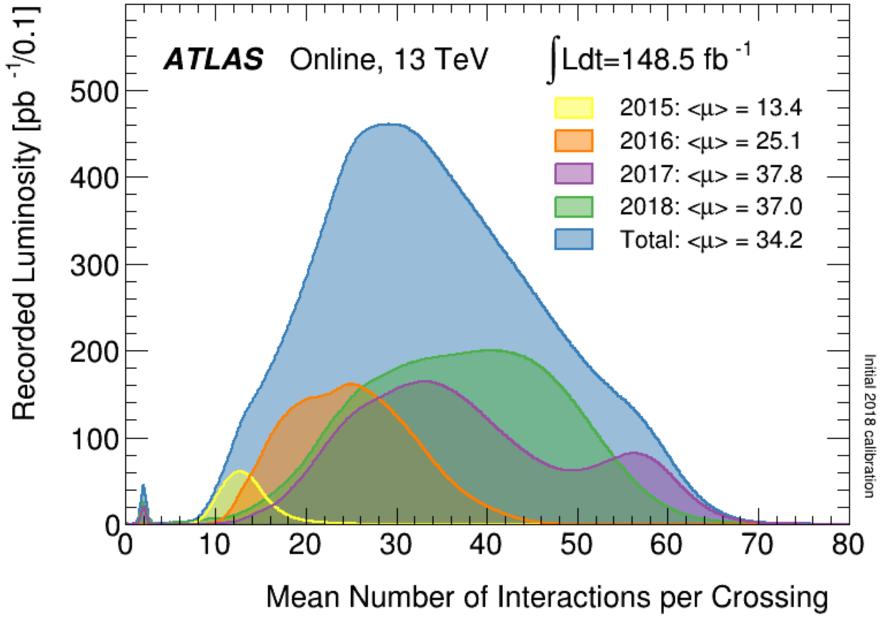
Partons hadronize



- Hadronization is non-perturbative QCD phenomenon
  - Phenomenological models implemented in Monte Carlo generators
    - Lund String Model: PYTHIA, SHERPA
    - Cluster fragmentation: HERWIG
- Semileptonic decays of heavy quarks cannot be recovered by experimental technique event by event

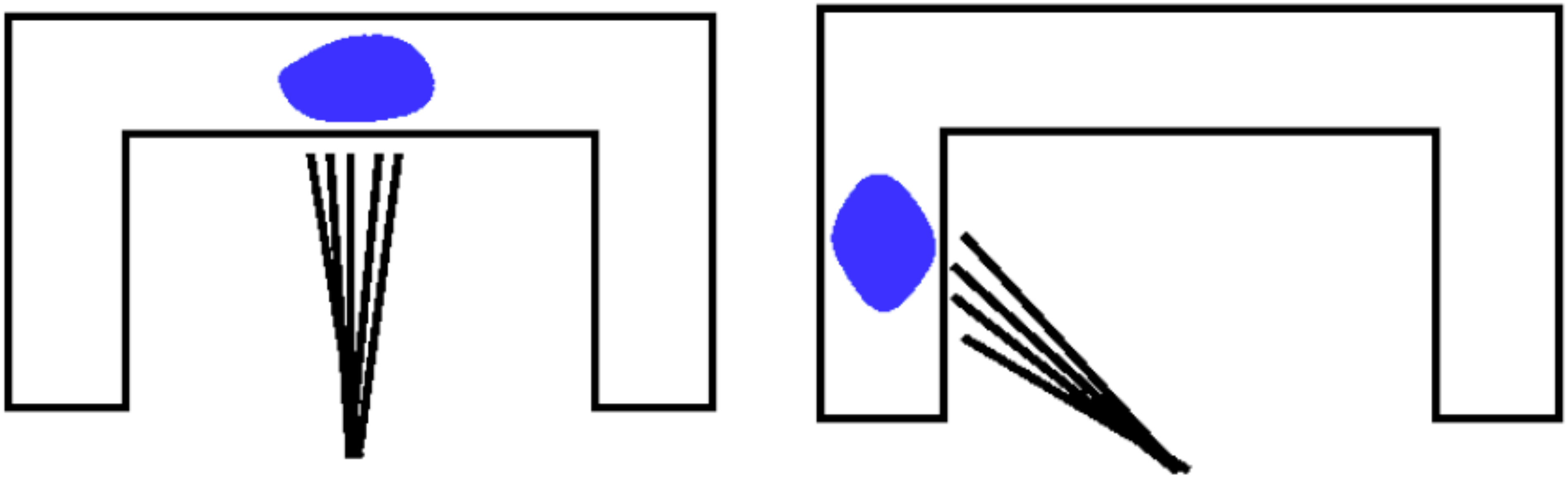
Multiple pp interactions (Pileup)





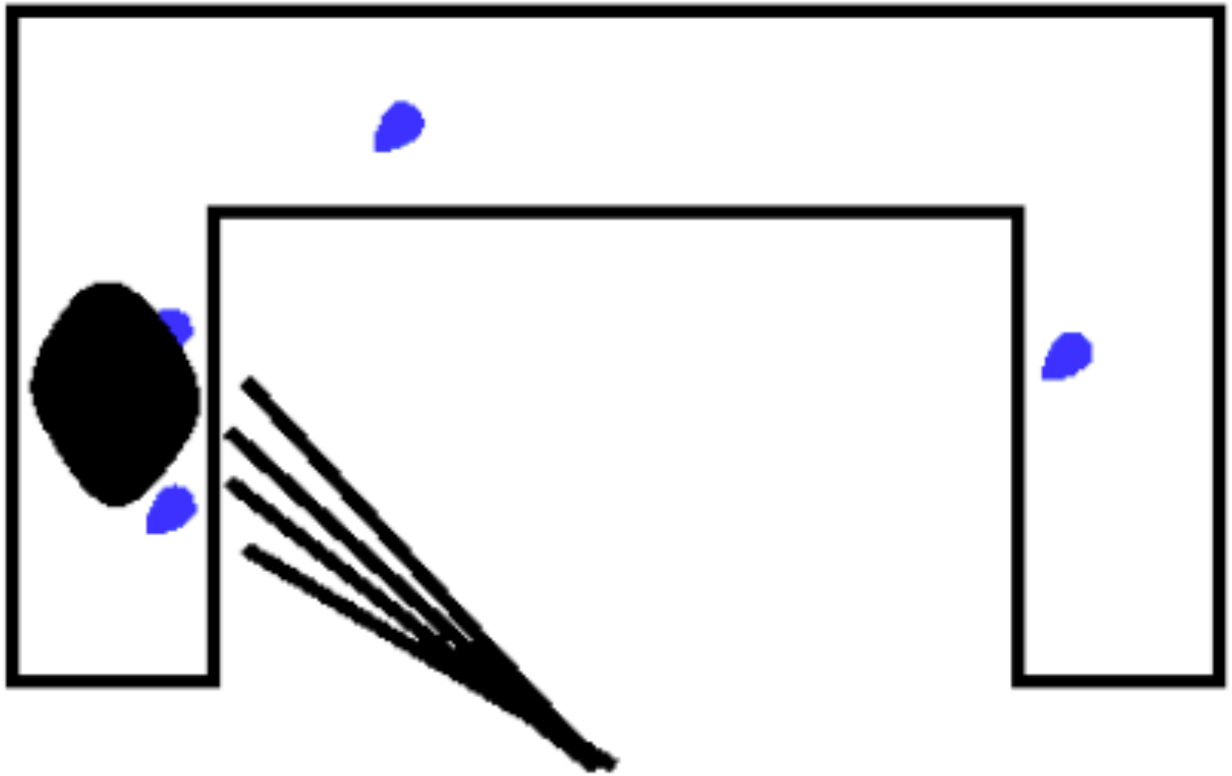
- Particles from additional pp interactions can overlap jet from hard scatter
  - LHC run 2: <μ>=10-70
  - HL-LHC: up to ~200
- There is also so-called “out-of-time pileup”
  - ATLAS calorimeter integrates signal from several bunch crossings

Hadrons enter Calorimeter



- Calorimeter response to hadrons determines what we measure: typical resolution
  - ~1% for pi0’s (as they decay to photons)
  - ~10% for charged hadrons (+ significant tail)
- Hadrons can also get stuck before entering calorimeter
- Response may be non-uniform as function of angle
  - There are often “crack” regions with poorer instrumentation

Noise

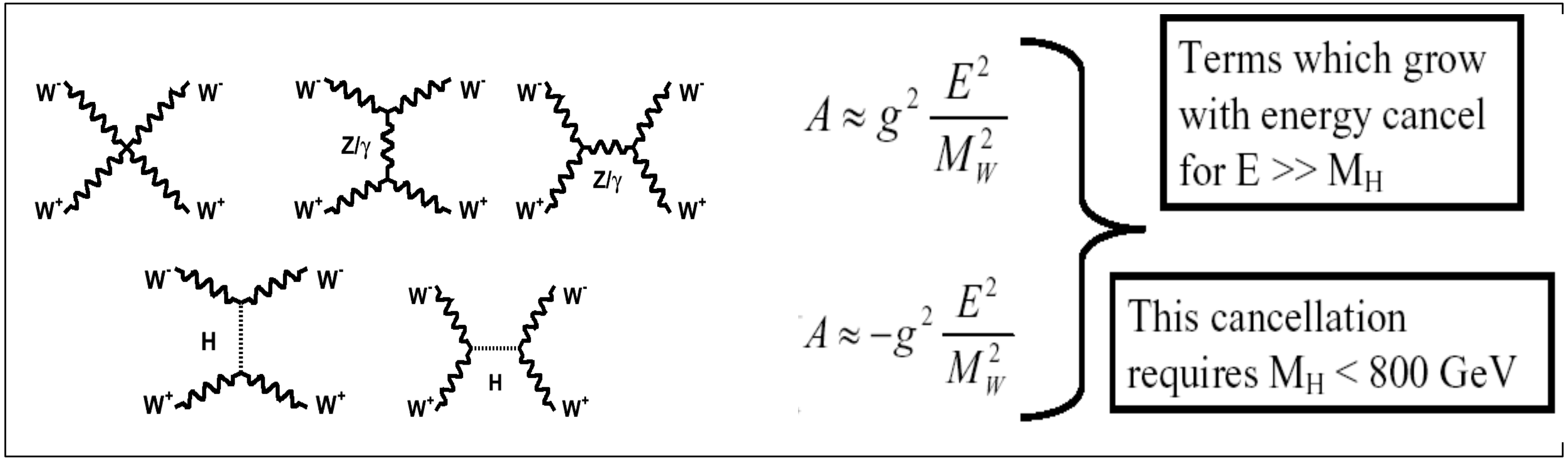


- Noise can overlap the jet in the calorimeter
  - May depend on e.g. instantaneous luminosity
  - Must be subtracted from jet on average

End of Interlude => Back to Searches with Jets

WW scattering

- Higgs prevents unitarity violation of $W_L W_L$ cross section
  - $\sigma(pp \rightarrow WW) > \sigma(pp \rightarrow \text{anything})$
    - => illegal!
    - at $\sqrt{s}=\sqrt{(8\pi\langle\Phi\rangle^2)}=1.2$ TeV



$$A \approx g^2 \frac{E^2}{M_W^2}$$

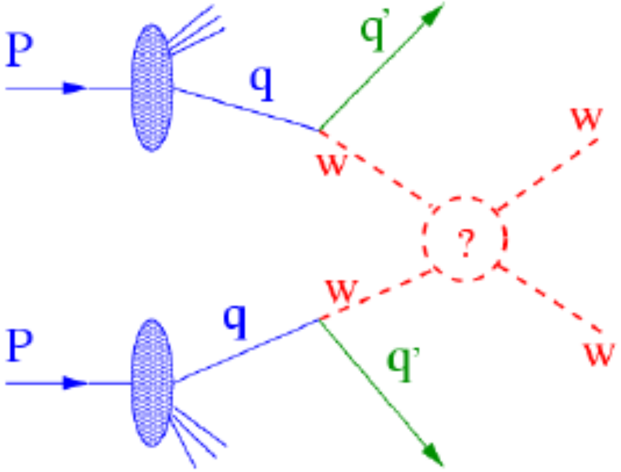
$$A \approx -g^2 \frac{E^2}{M_W^2}$$

Terms which grow with energy cancel for E >> M_H

This cancellation requires $M_H < 800$ GeV

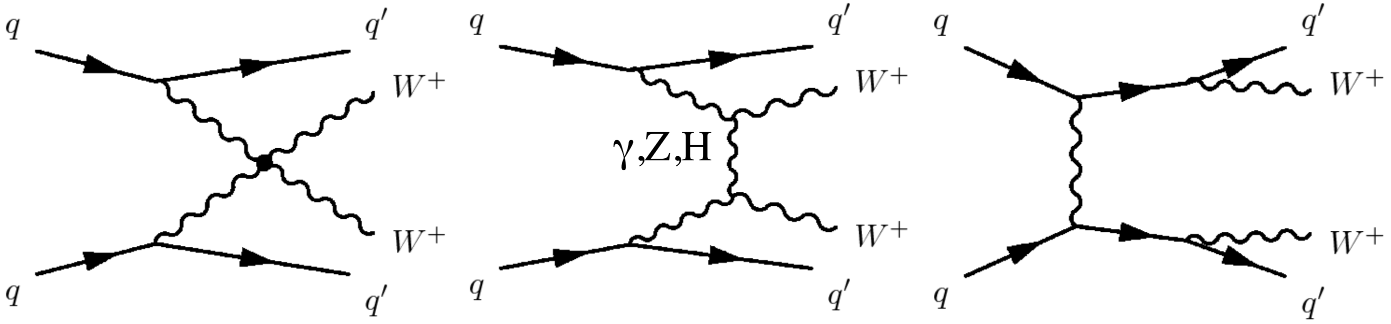
- Before finding the Higgs boson we knew that something had to be found at LHC to prevent unitarity violation
  - check if energy dependence as expected from SM Higgs
    - will not be the case if new particles contribute to vertex

Vector boson fusion and scattering

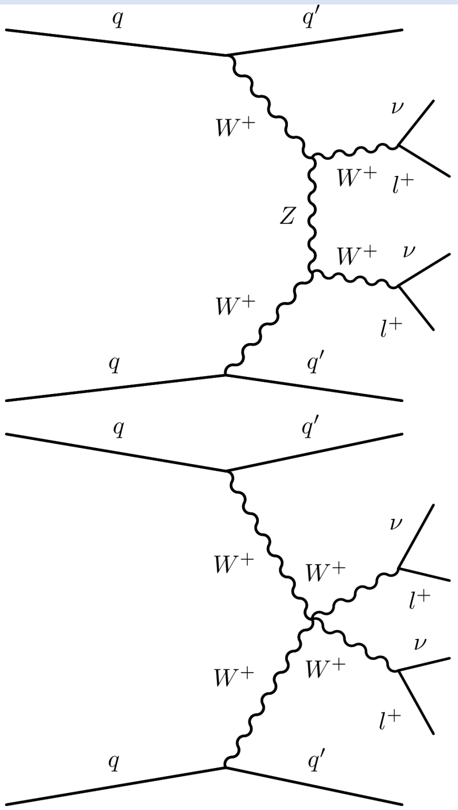


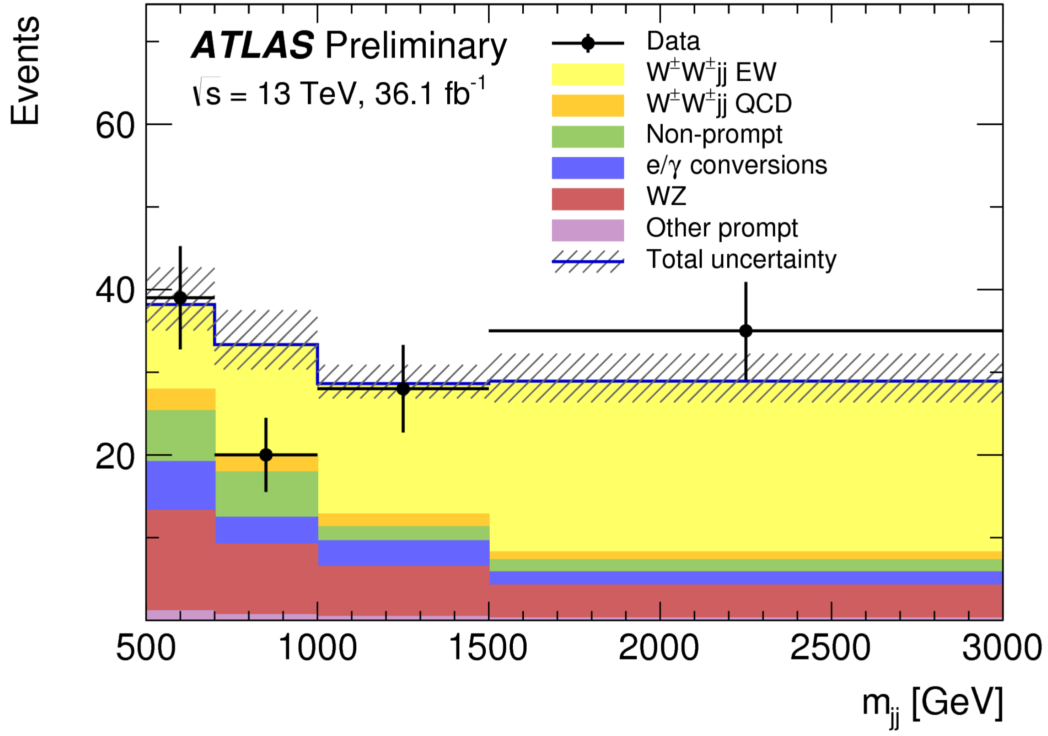
- Process characterized by
  - 2 high p_T jets at high $|\eta|$
  - Large separation between these two jets $|\Delta\eta|$
    - No hard jets between them
- Typical analysis signature
  - High invariant dijet mass mjj
  - Large $\Delta\eta$

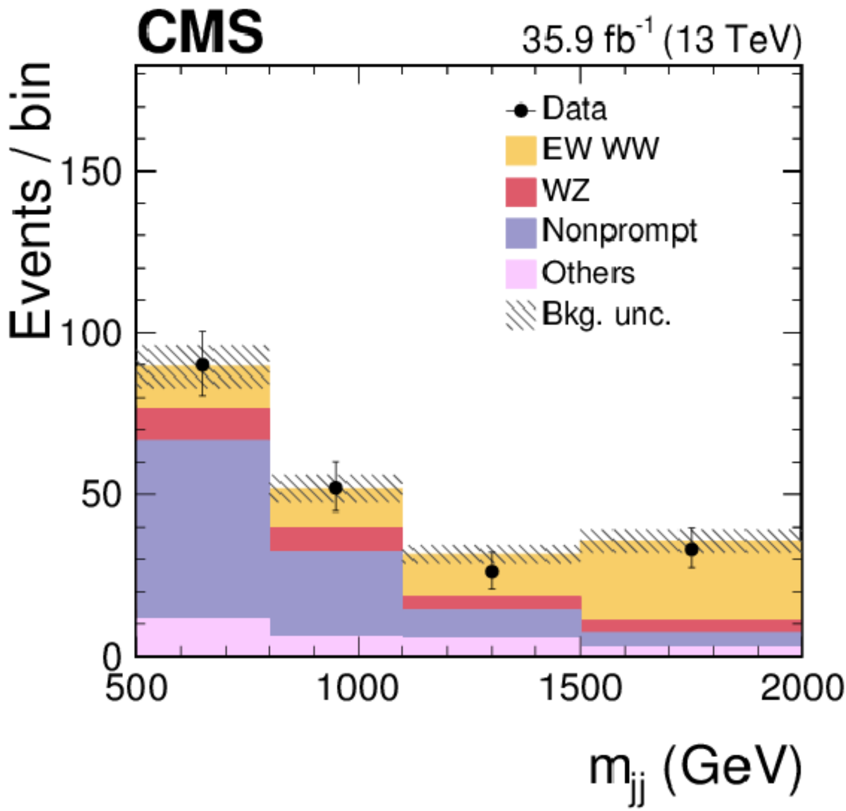
- Recent analysis:
  - Observation for electroweak production of $W^\pm W^\pm$ pairs



Vector Boson Scattering



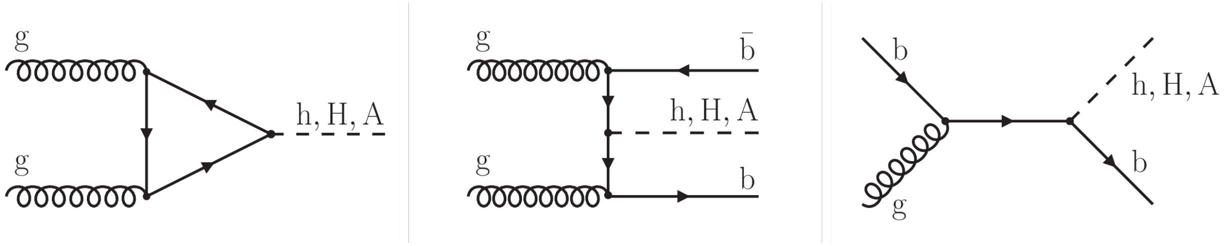




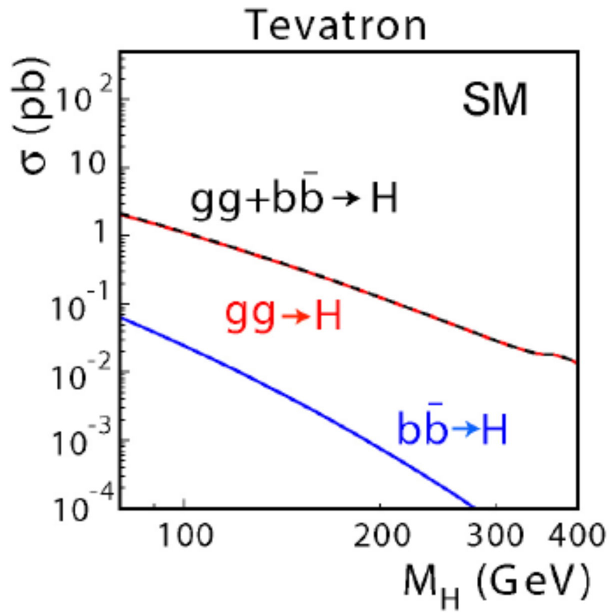
- Cross sections measured in fiducial regions corresponding to measurement phase space
  - in agreement with SM expectation
- Significance of signal for electroweak production of $W^\pm W^\pm$: >5σ

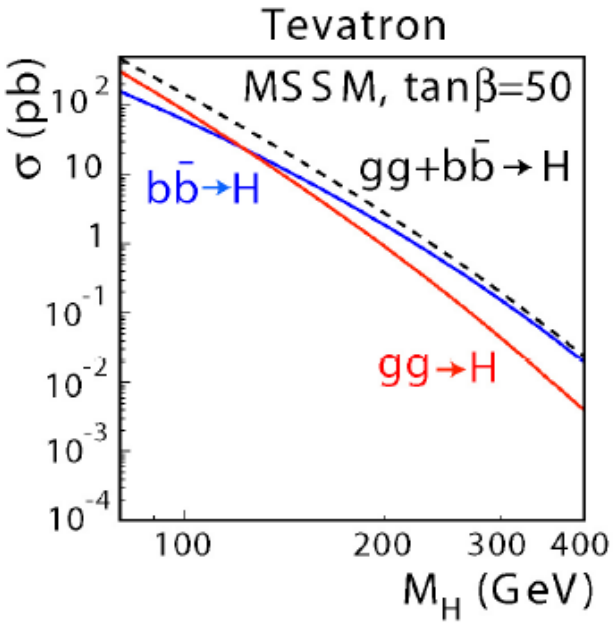
Higgs in Supersymmetry (MSSM)

- Minimal Supersymmetric Standard Model:
  - 2 Higgs-Fields: Parameter tanβ=<H_u>/<H_d>
  - 5 Higgs bosons: h, H, A, $H^{\pm}$
- Neutral Higgs Boson:
  - Pseudoscalar A
  - Scalar H, h
    - Lightest Higgs (h) very similar to SM

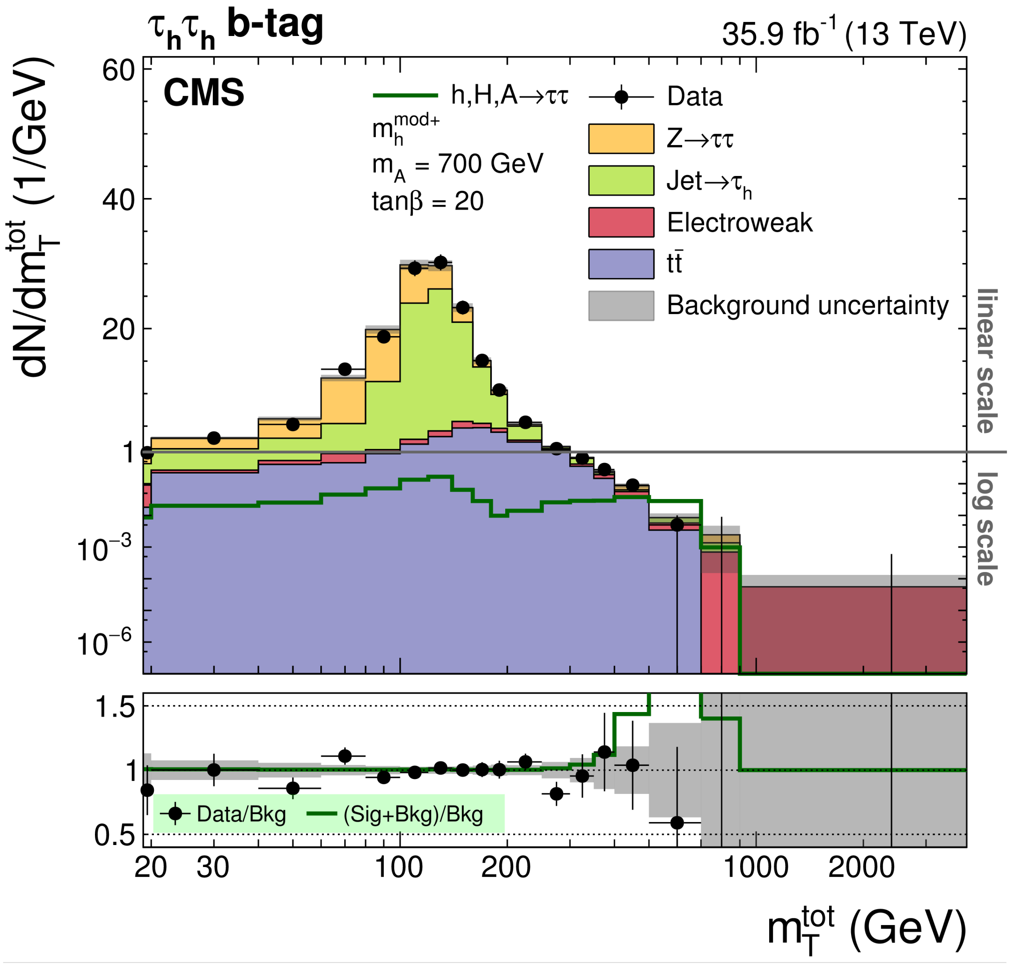


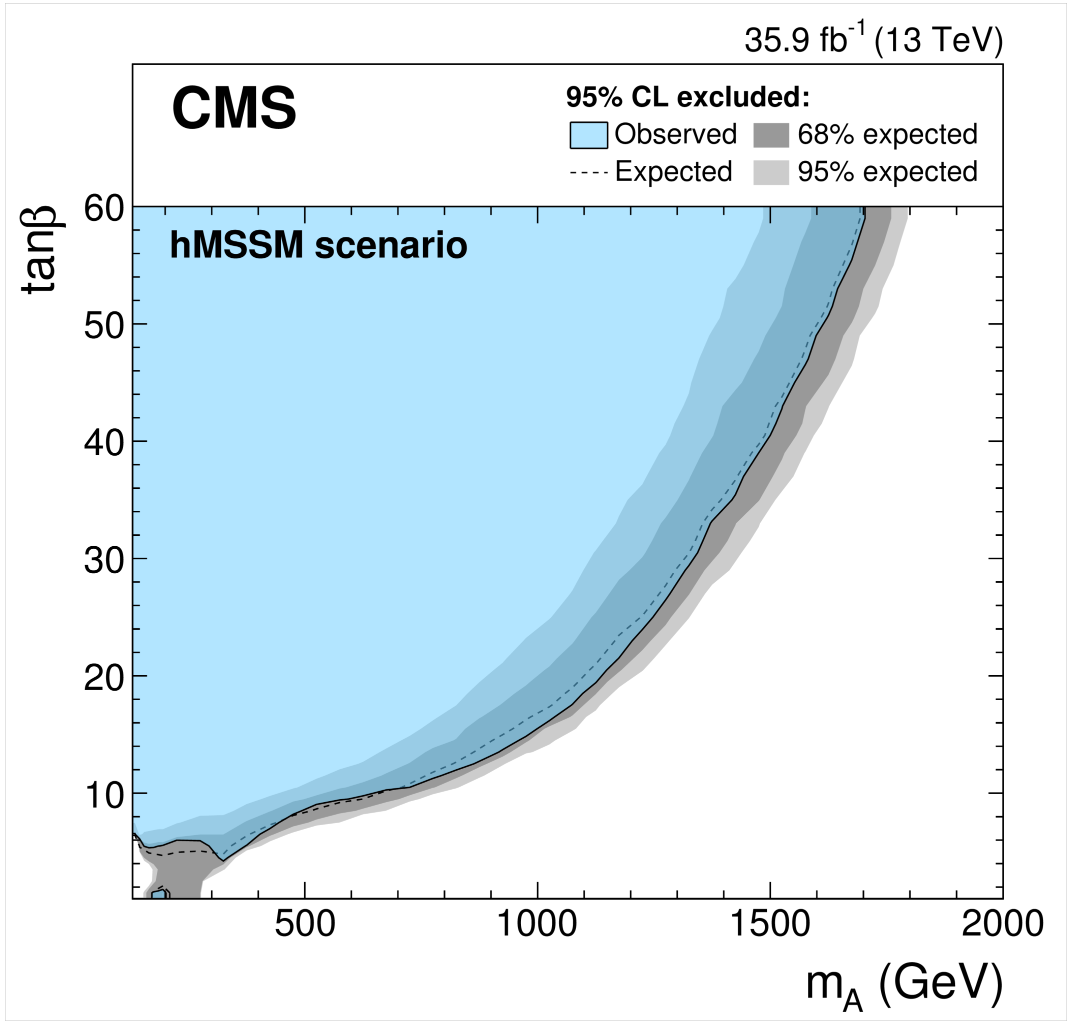
$$\sigma \times BR_{SUSY} = 2\times\sigma_{SM}\times\frac{\tan\beta^{2}}{(1+\Delta_b)^2}\times\frac{9}{[9+(1+\Delta_b)^2]}$$





Supersymmetric Higgs boson





- Constraints on mass of A vs tanβ