New physics - lecture 1

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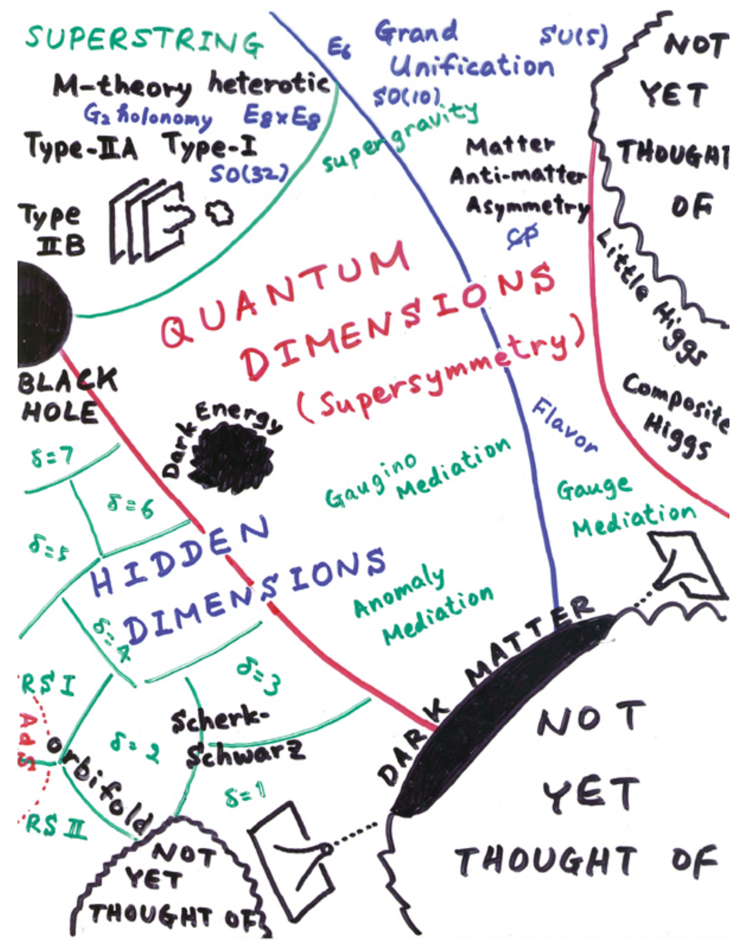
WHEPS 2019 - Weihai - 21st-28th August 2019

What is "new physics"?

- Potentially a **very broad topic** of course…
- In general: look for yet unknown phenomena, with guiding principles, or questions, in mind



- My aim:
  - Give **an overview of broad areas of New Physics searches**, mainly at colliders, but not only.
    - Such that you know the relevant bits to, e.g., listen to talks in conferences,
  - ….while, however, making a selection:
    - e.g., neutrino physics, although crucial, is neglected

Guiding principles/questions

- Ask **your favourite textbook** about open questions connected with particle physics. It will come up with **variations on the following:**
  - Dark matter (and dark energy)
  - Matter/anti-matter asymmetry
  - (Neutrino masses)
- Plus a bonus track on <u>theoretical</u> open issues of the SM:
  - Hierarchy problem
  - Strong CP
  - Landau pole
  - Gravity (quantum theory of)

What questions are more pressing?

- Difficult to know, we do not even know **whether these are the right questions** to ask….
- … and it probably depends **on the theorist** you ask…..
- Clearly, experimental results drive the answer

Pre-LHC	Post-LHC
- Higgs Boson has any mass (below ~200 GeV if SM assumed) - **Hierarchy problem** is key - Dark matter **may be accidental**	- Higgs Boson has a mass of **~125 GeV** - **Dark matter** is key - Solution to hierarchy problem **may be accidental**

Why is LHC a milestone?

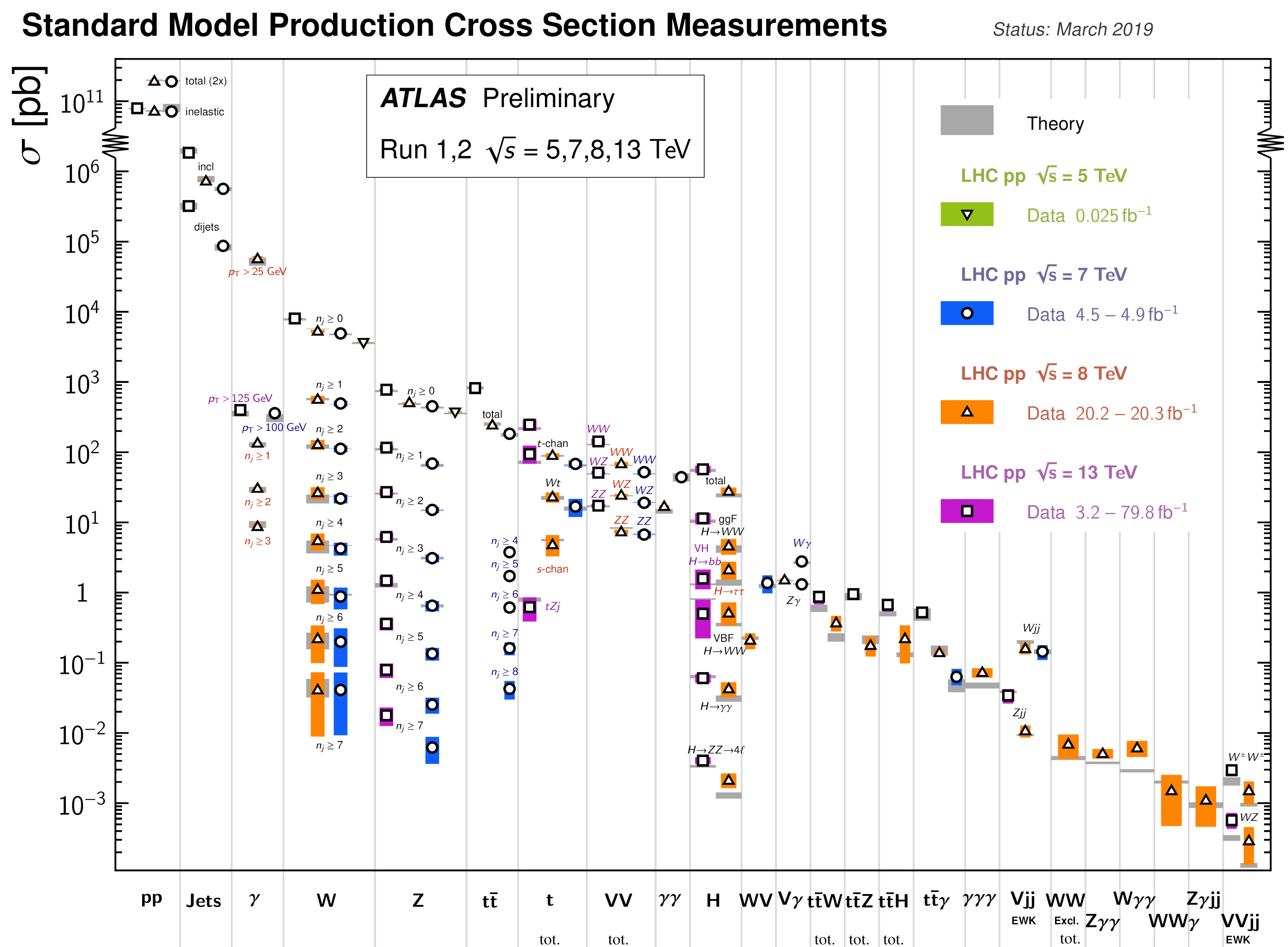
- From "ATLAS - A 25 years Insider Story of the LHC Experiment", talking about the Lausanne meeting in 1984

> In this context, it appeared for the first time that it was possible to quantitatively compare the potentials of vastly different accelerators, in terms of answering some of the fundamental questions at the time. These included questions on the existence (or not) of the following: (i) a Higgs boson responsible for the mechanism of the electroweak symmetry breaking, (ii) heavier quarks, including the missing third-generation top quark, and (iii) supersymmetry (see Chap. 9).
>
> So it is not a

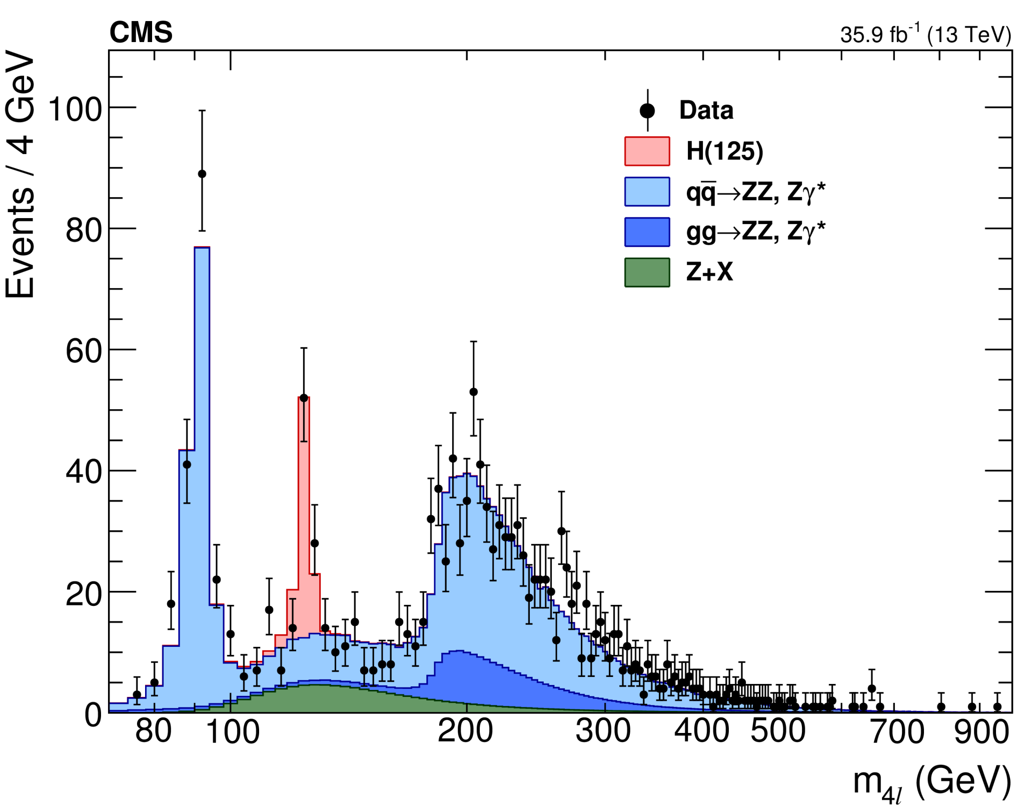
- To a large extent, points (i), (ii) and (iii) have all been completed successfully.

Full exploration of EW scale: known processes

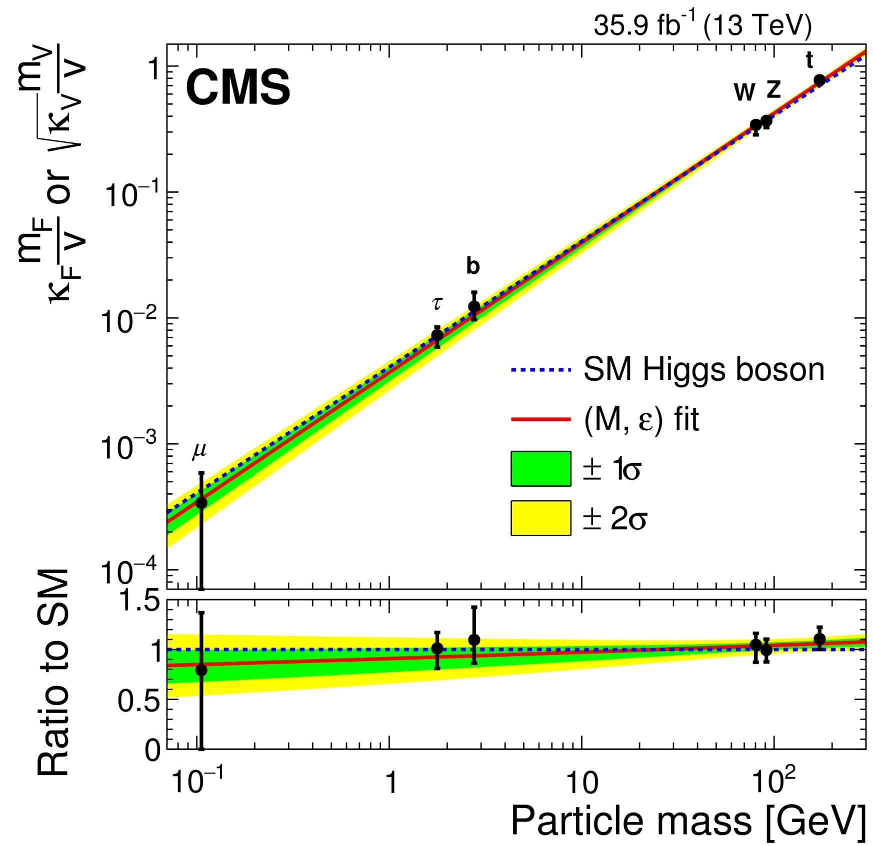
From ATL-PHYS-PUB-2019-010



Full exploration of the EW scale: BEH mechanism



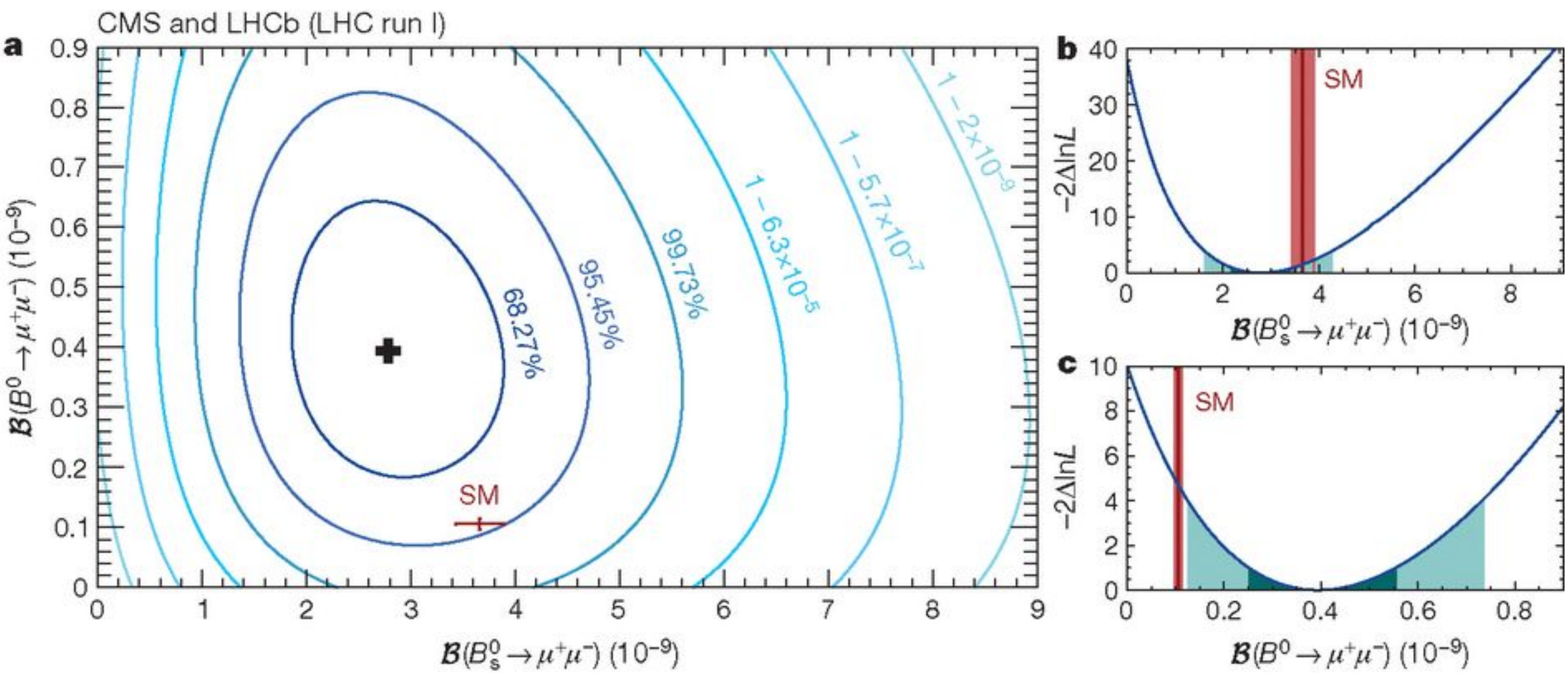
JHEP 11 (2017) 047



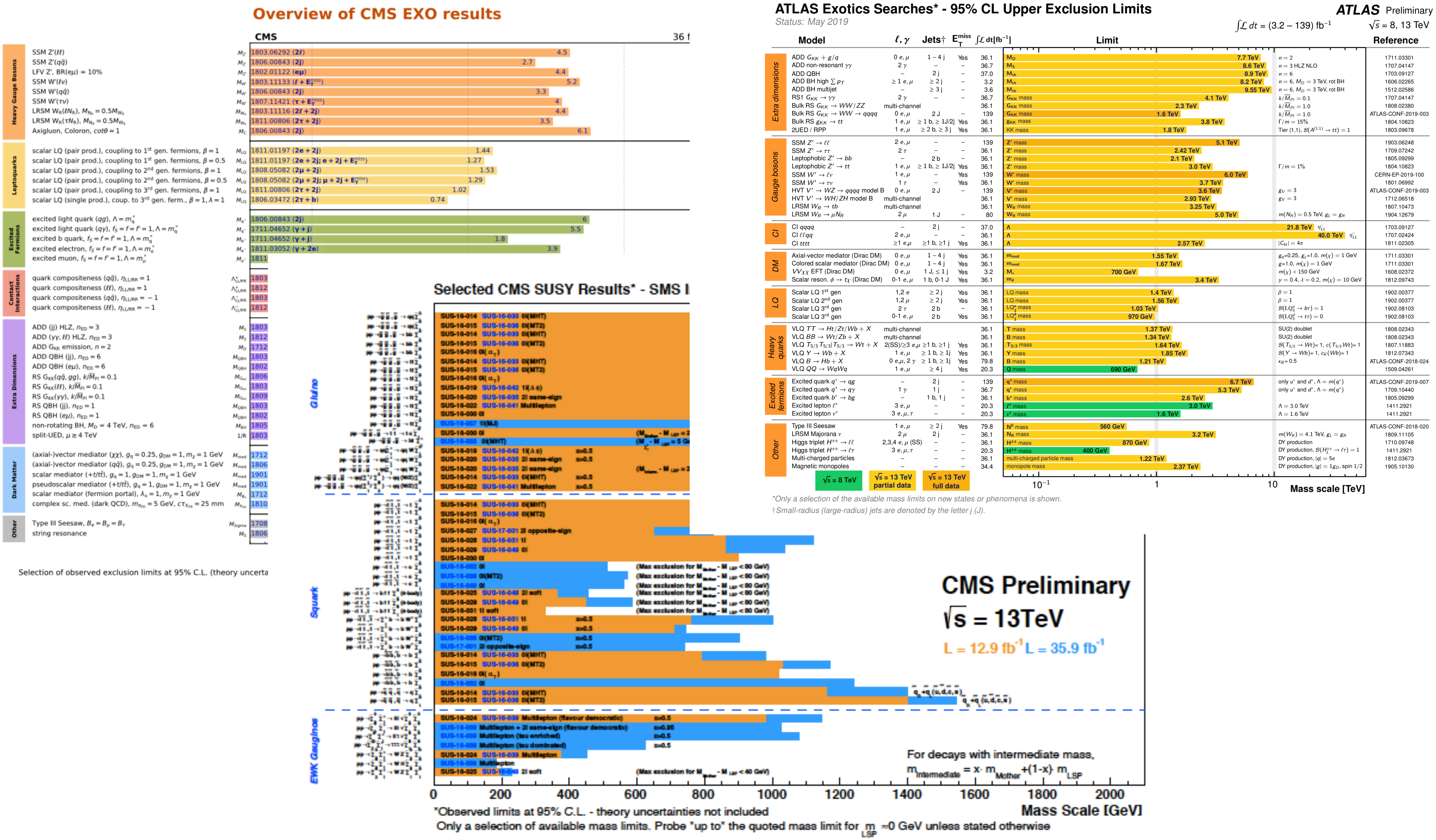
EPJC 79 (2019) 421

Precision physics - rare heavy flavour decays

Nature 522, 68-72 (2015)



New physics at the EW scale?



Structure

- Today:
  - EW scale supersymmetry (first part)
- Tomorrow:
  - Electroweak supersymmetry (second part)
  - Dark matter
- Last day:
  - Exotica

EW scale Supersymmetry

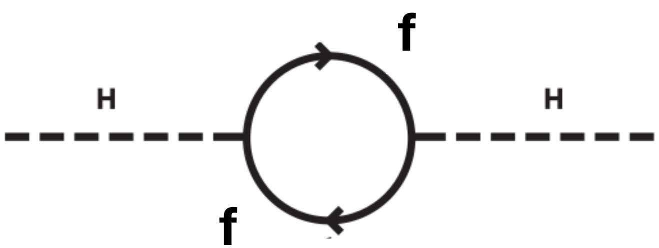
Outline

- A pragmatic introduction to (EW scale) SUSY
- Inclusive searches
  - Analysis walkthrough
- Exclusive searches
  - Third generation squarks
  - Electroweak production

A pragmatic introduction to (EW scale) SUSY

Supersymmetric solution to hierarchy

Take this argument away, and **there is no guarantee** of SUSY particles within the LHC reach



$$\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2}\Lambda_{\mathrm{UV}}^2 + \dots$$

$$\Delta m_H^2 = 2 \times \frac{|\lambda_f|^2}{16\pi^2}\Lambda_{\mathrm{UV}}^2 + \dots$$

With SUSY, **quadratic effects** (big hierarchy) are **cancelled exactly**, one is left with **only logs** (little hierarchy)

SUSY is a (broken) symmetry, not a model

For a given model, introduce an operator Q such that

$$Q\,|\,\text{fermionic state}\rangle = |\,\text{bosonic state}\rangle$$
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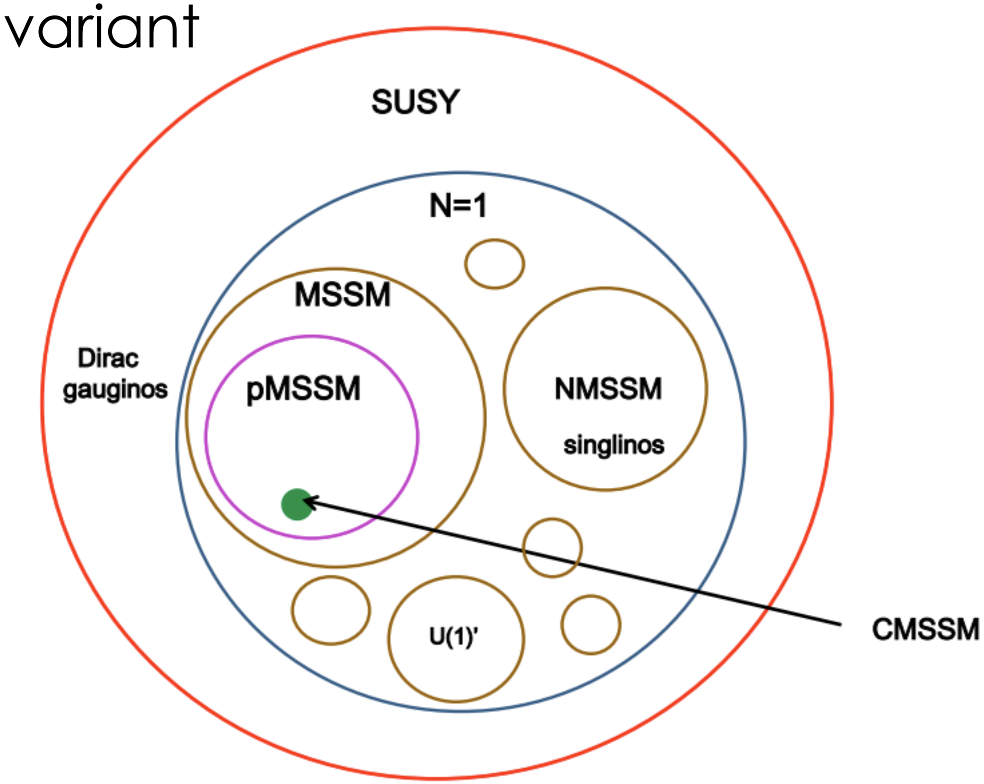
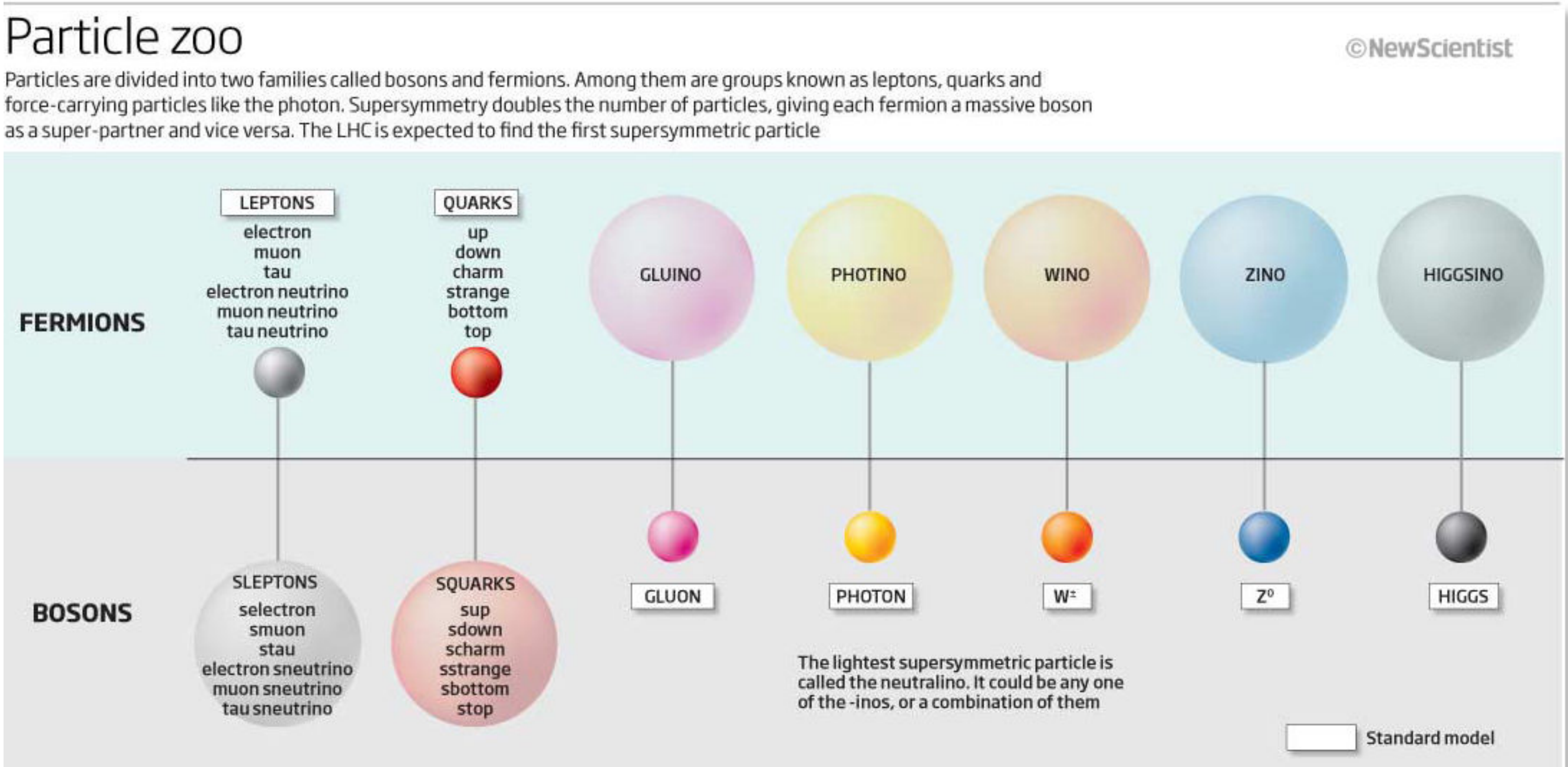
Then make sure the Lagrangian is invariant under Q



- If one super-symmetrises the Standard Model, one gets the MSSM
- "Excluding SUSY" is an ill-posed question
  - Excluding SUSY <u>models</u> is possible

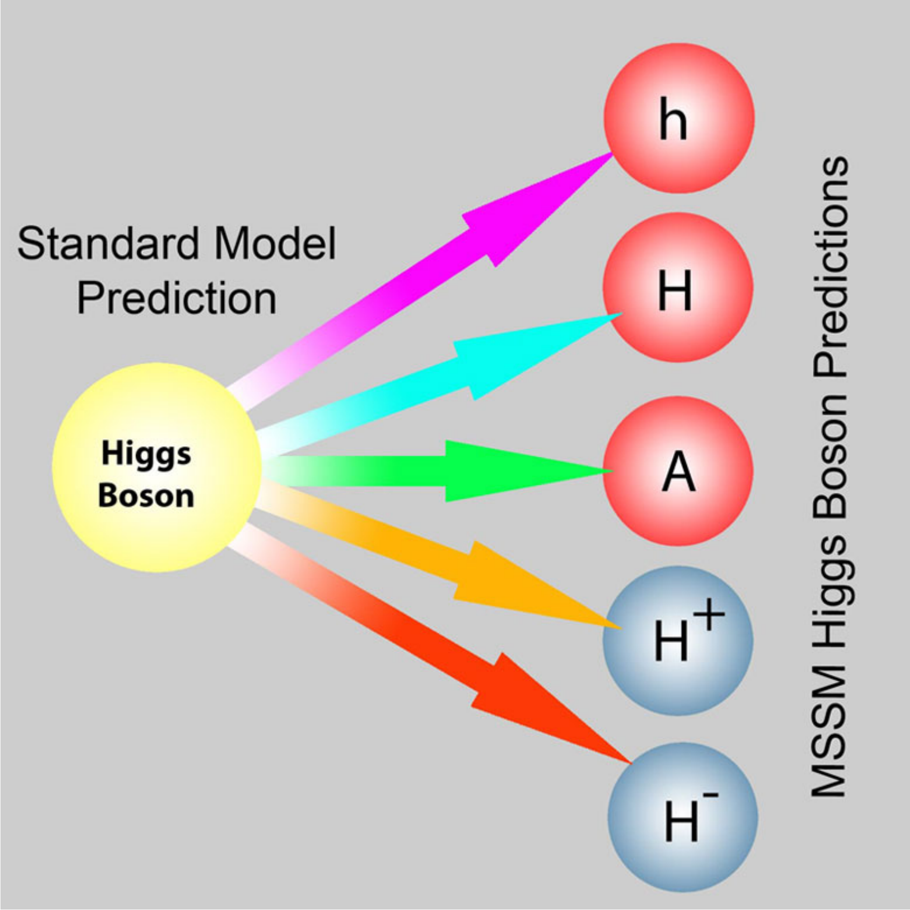
Double the particle family MSSM



SUSY particles masses different from SM partners. SUSY is a broken symmetry.

The Higgs sector

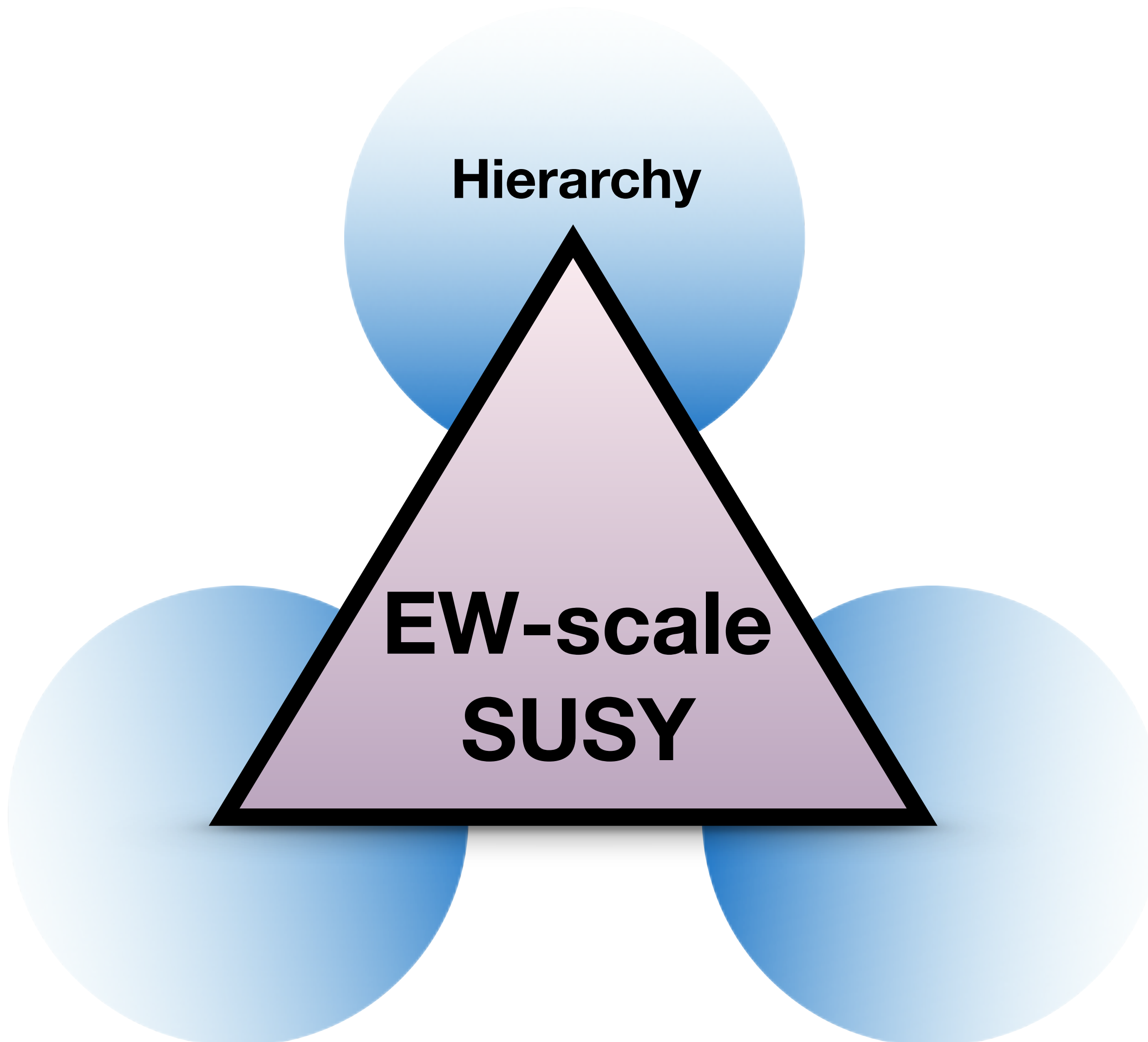
- The MSSM is a 2 Higgs Doublet Model (2HDM)
  - A single Higgs doublet would give rise to non-supersymmetric Yukawa terms in the Lagrangian.
  - Normally it is assumed that the discovered boson is the lightest scalar h.



The Minimal Supersymmetric Standard Model (MSSM)

Field Content of the MSSM					
Super-Multiplets	Boson Fields	Fermionic Partners	SU(3)	SU(2)	U(1)
gluon/gluino	g	$\widetilde{g}$	8	1	0
gauge/	$W^{\pm}, W^{0}$	$\widetilde{W}^{\pm}, \widetilde{W}^{0}$	1	3	0
gaugino	B	$\widetilde{B}$	1	1	0
slepton/	$(\widetilde{\nu}, \widetilde{e}^{-})_L$	$(\nu, e^{-})_L$	1	2	-1
lepton	$\tilde{e}^{-}_R$	e^{-}_R	1	1	-2
squark/	$(\widetilde{u}_L, \widetilde{d}_L)$	$(u, d)_L$	3	2	$1/3$
quark	$\widetilde{u}_R$	u_R	3	1	$4/3$
	$\widetilde{d}_R$	d_R	3	1	$-2/3$
Higgs/	(H^0_d, H^-_d)	$(\widetilde{H}^0_d, \widetilde{H}^-_d)$	1	2	-1
higgsino	(H^+_u, H^0_u)	$(\widetilde{H}^+_u, \widetilde{H}^0_u)$	1	2	1

The pre-LHC SUSY



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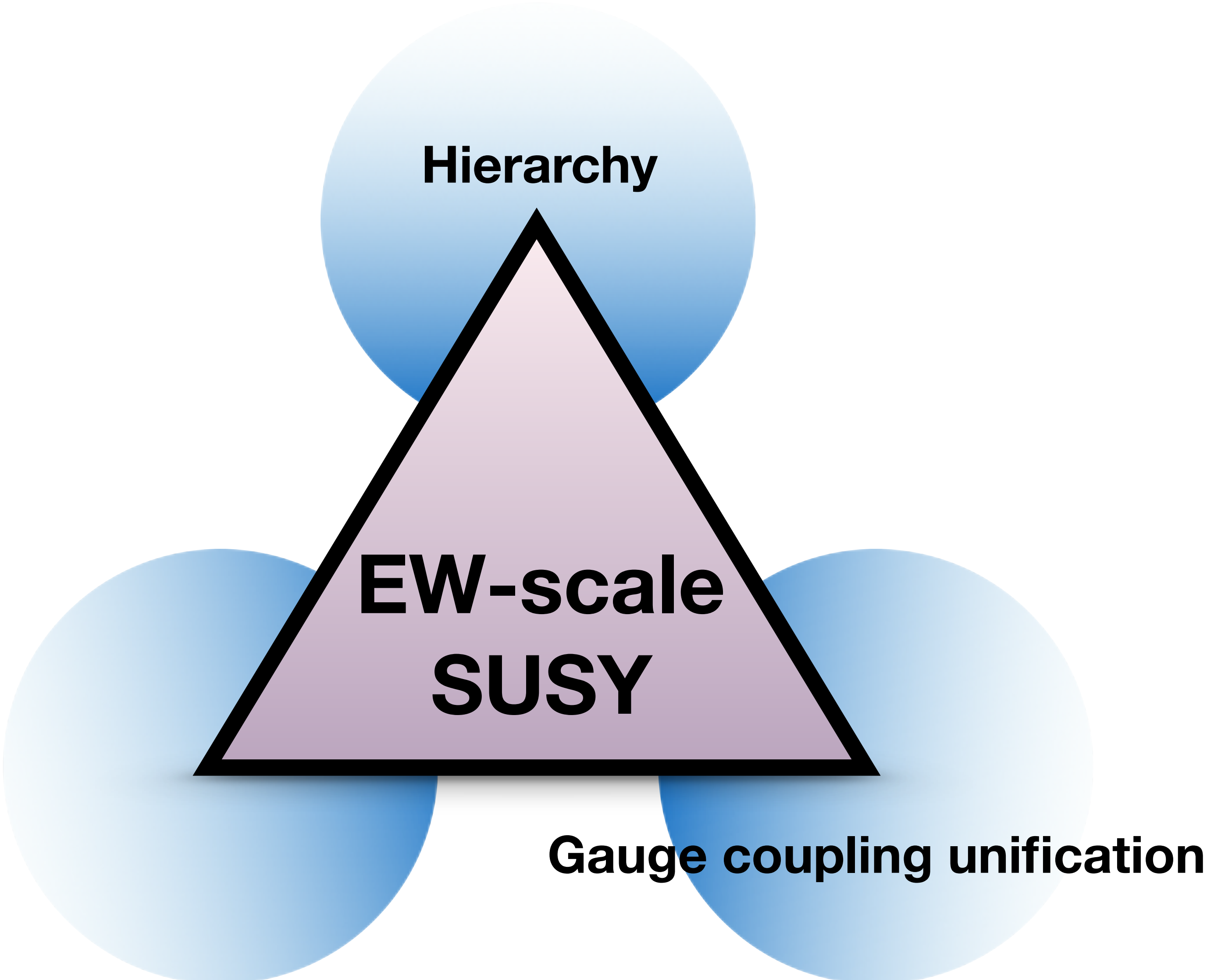


Gauge coupling unification

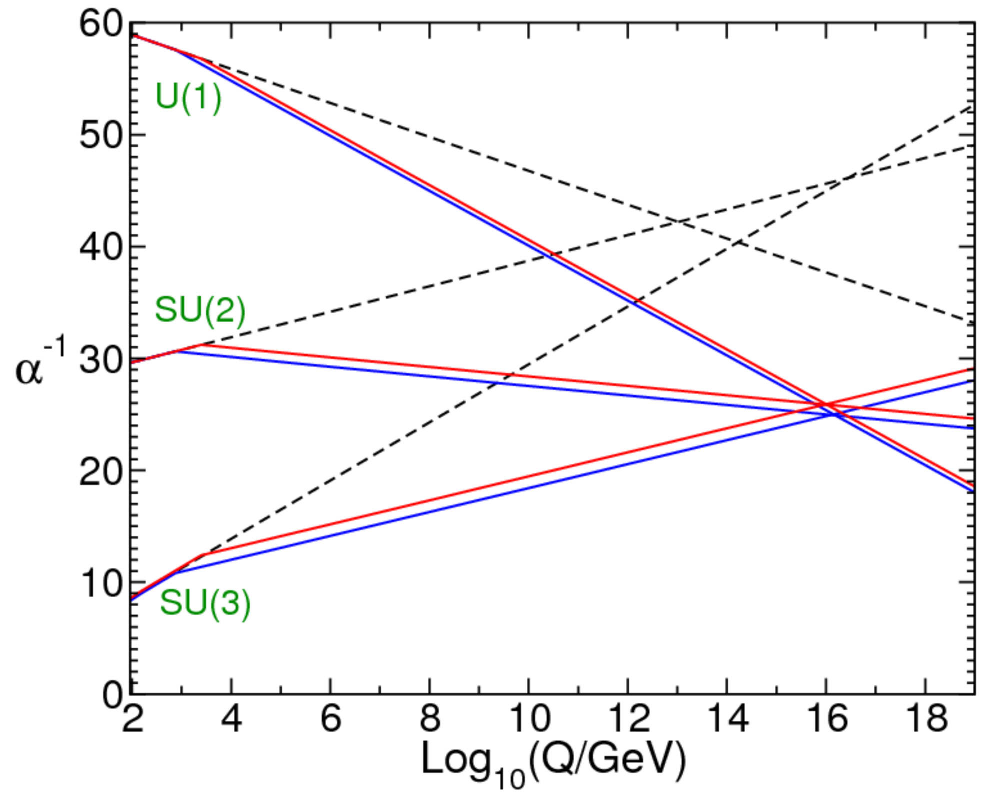
$$\beta_{g_a} \equiv \frac{d}{dt} g_a = \frac{1}{16\pi^2} b_a g_a^3, \qquad (b_1, b_2, b_3) = \begin{cases} (41/10,\ -19/6,\ -7) & \text{Standard Model} \\ (33/5,\ 1,\ -3) & \text{MSSM} \end{cases}$$

$$\frac{d}{dt}\alpha_a^{-1} = -\frac{b_a}{2\pi} \qquad (a = 1, 2, 3)$$

Evolution of RGE modified by additional particle content in MSSM

Couplings unify at ~ 10^{16} GeV

from arXiv:hep-ph/9709356



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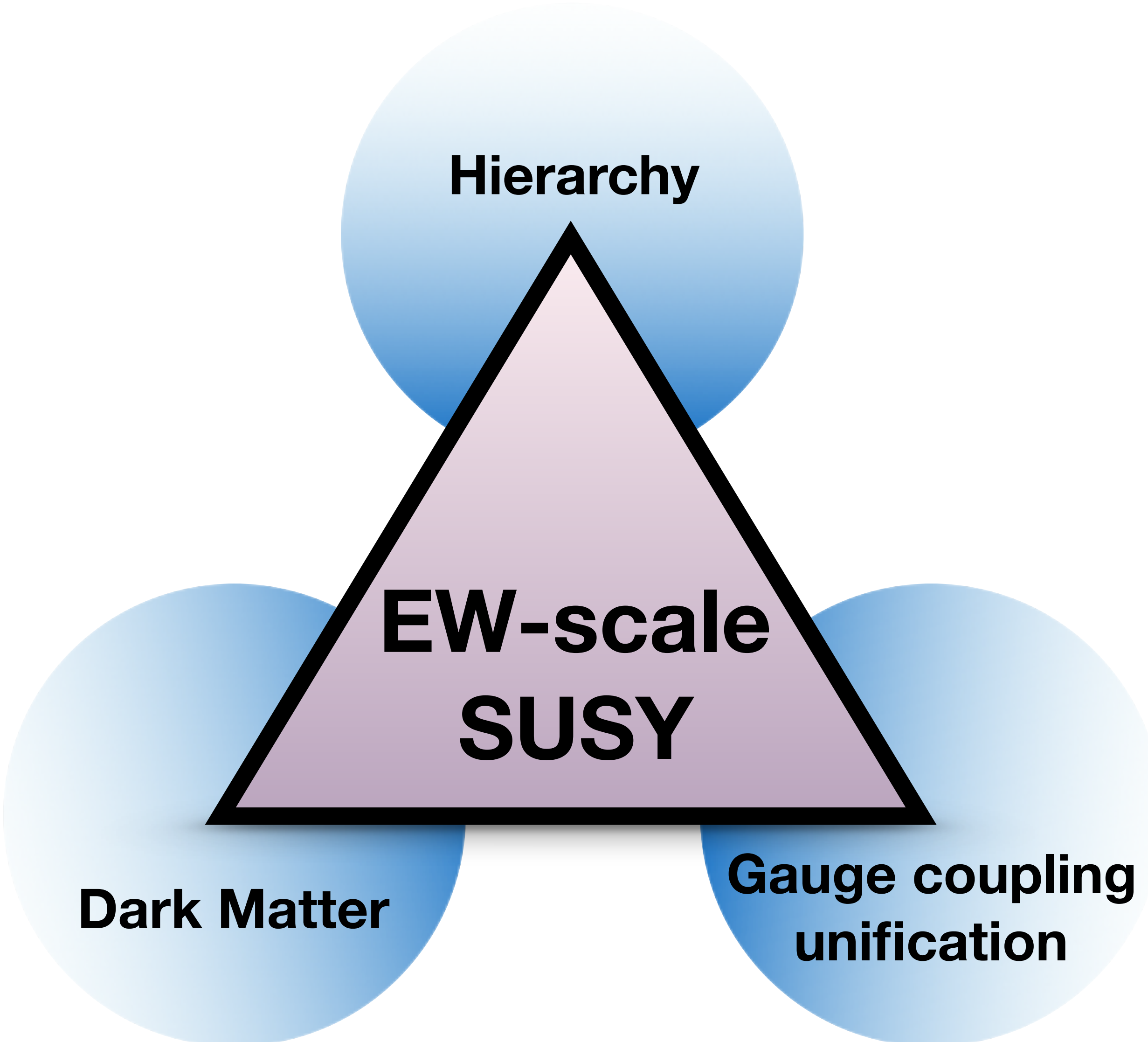


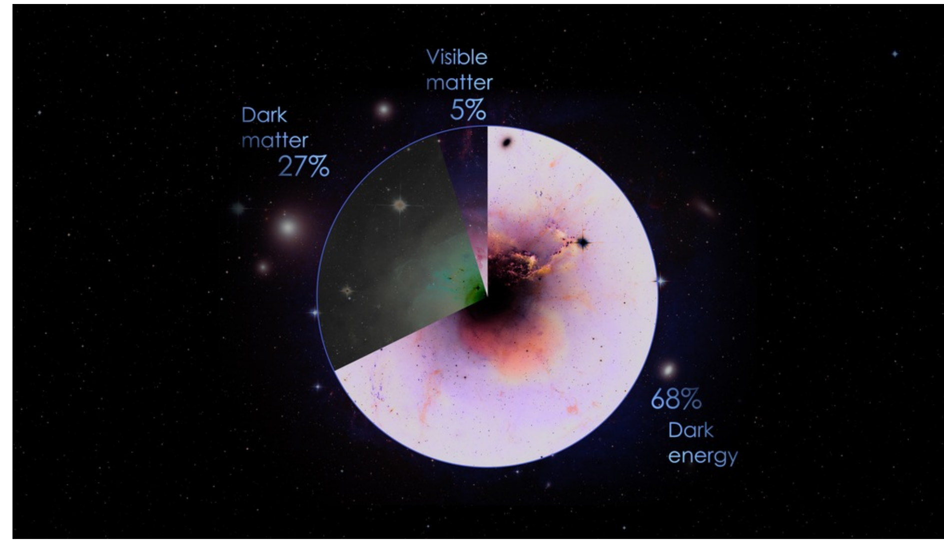
Dark matter

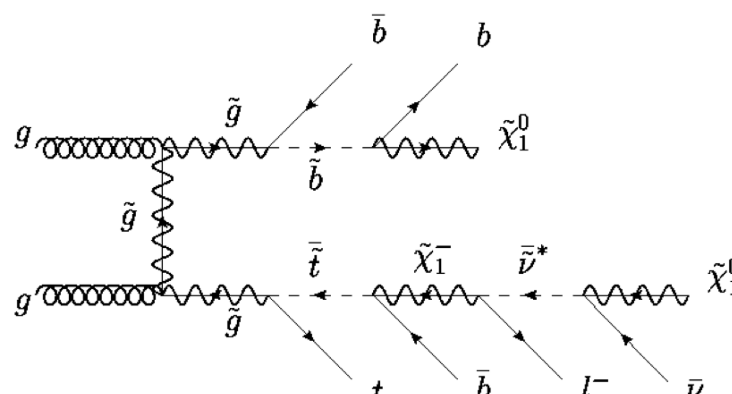
Much more on this tomorrow

Consensus on the **existence of Dark Matter,** but no good particle candidate in SM

In **R-parity conserving** SUSY, the lightest SUSY particle is stable. If it is weakly interacting, it is potentially a good DM candidate

R-parity = $(-1)^{3(B-L) + 2s}$
-1 for sparticles
1 for particles





Lightest SUSY Particle (LSP) is stable

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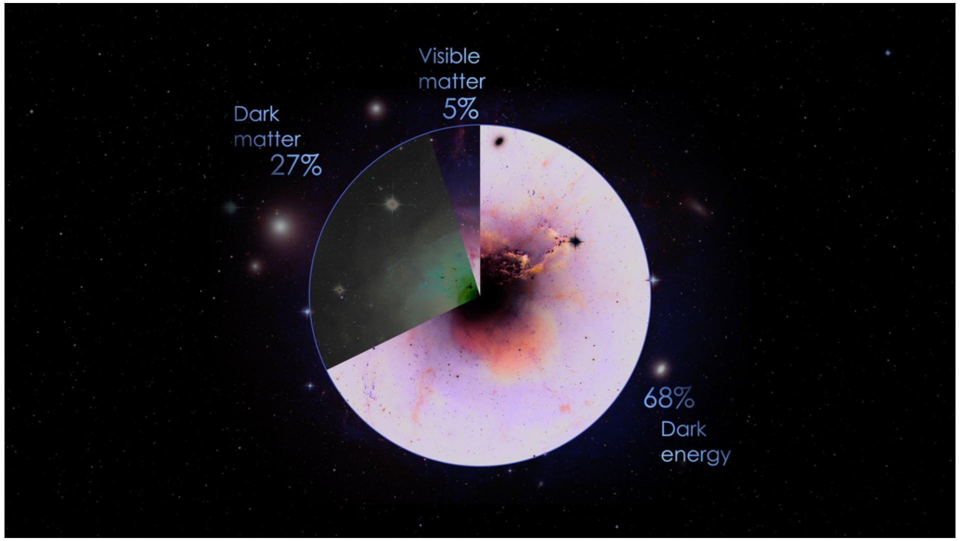
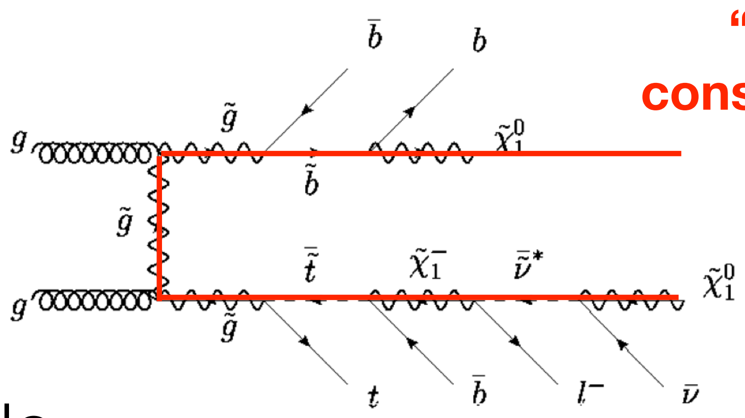




Lightest SUSY Particle (LSP) is stable

Fermion superpartners' mixing

- Supersymmetry dictates the existence of a **scalar partner** for every **fermionic degree of freedom**. In MSSM:

$$\begin{pmatrix} u_L \\ d_L \end{pmatrix}; u_R, d_R \rightarrow \begin{pmatrix} \tilde{u}_L \\ \tilde{d}_L \end{pmatrix}; \tilde{u}_R; \tilde{d}_R$$

- The **left and right chiral components** of the scalars have the **same couplings of the fermionic ones**
- And **they mix** to give mass eigenstates

SM quark mass

O(m$_Z$ terms)

$$\mathcal{M}^2 = \begin{pmatrix} M^2_{\tilde{Q}} + m_q^2 + L_q & m_q X_q^* \\ m_q X_q & M^2_{\tilde{R}} + m_q^2 + R_q \end{pmatrix}$$

SUSY breaking

fermion masses

$$(\tilde{u}_L, \tilde{u}_R) \rightarrow (\tilde{u}_1, \tilde{u}_2)$$

$\tilde{u}_1$ is the lightest by convention

Boson superpartners' mixing

- Neutralinos and charginos are **fermionic states**. In MSSM: they arise from the mixing of **Standard Model B and W fields**, and of the **two Higgs doublets.** The mixing matrices are

$$\mathbf{M}_{\widetilde{N}} = \begin{pmatrix} M_1 & 0 & -c_\beta\, s_W\, m_Z & s_\beta\, s_W\, m_Z \\ 0 & M_2 & c_\beta\, c_W\, m_Z & -s_\beta\, c_W\, m_Z \\ -c_\beta\, s_W\, m_Z & c_\beta\, c_W\, m_Z & 0 & -\mu \\ s_\beta\, s_W\, m_Z & -s_\beta\, c_W\, m_Z & -\mu & 0 \end{pmatrix}$$

$$\begin{pmatrix} \tilde{B} \\ \tilde{W}^0 \\ \tilde{H}_d^0 \\ \tilde{H}_u^0 \end{pmatrix} \rightarrow \begin{pmatrix} \tilde{\chi}_1^0 \\ \tilde{\chi}_2^0 \\ \tilde{\chi}_3^0 \\ \tilde{\chi}_4^0 \end{pmatrix}$$

$$\mathbf{M}_{\widetilde{C}} = \begin{pmatrix} \mathbf{0} & \mathbf{X}^T \\ \mathbf{X} & \mathbf{0} \end{pmatrix}$$

$$\mathbf{X} = \begin{pmatrix} M_2 & g v_u \\ g v_d & \mu \end{pmatrix} = \begin{pmatrix} M_2 & \sqrt{2} s_\beta\, m_W \\ \sqrt{2} c_\beta\, m_W & \mu \end{pmatrix}$$

$$\begin{pmatrix} \tilde{W}^+ \\ \tilde{H}_u^+ \end{pmatrix} \rightarrow \begin{pmatrix} \tilde{\chi}_1^+ \\ \tilde{\chi}_2^+ \end{pmatrix}$$

What do we expect to be produced?

- At a hadron collider:
  - **Gluinos and squarks** with **strong-like** production cross section
  - **Charginos, neutralinos and sleptons** with **EW-like** production cross section
  - So, for fixed sparticle mass, production **largely dominated by squarks and gluinos**

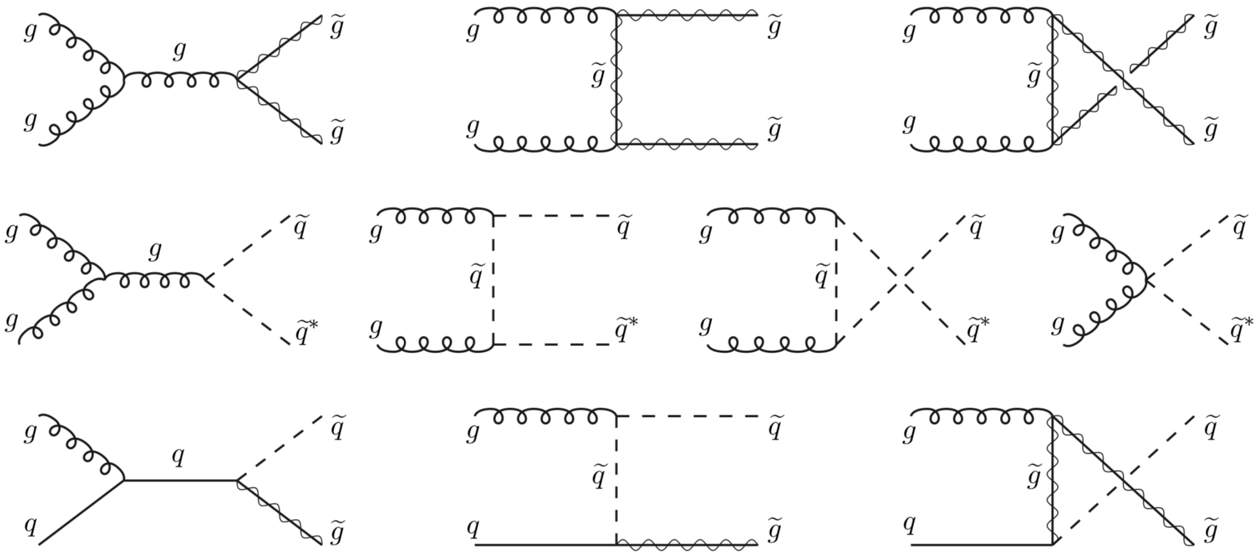
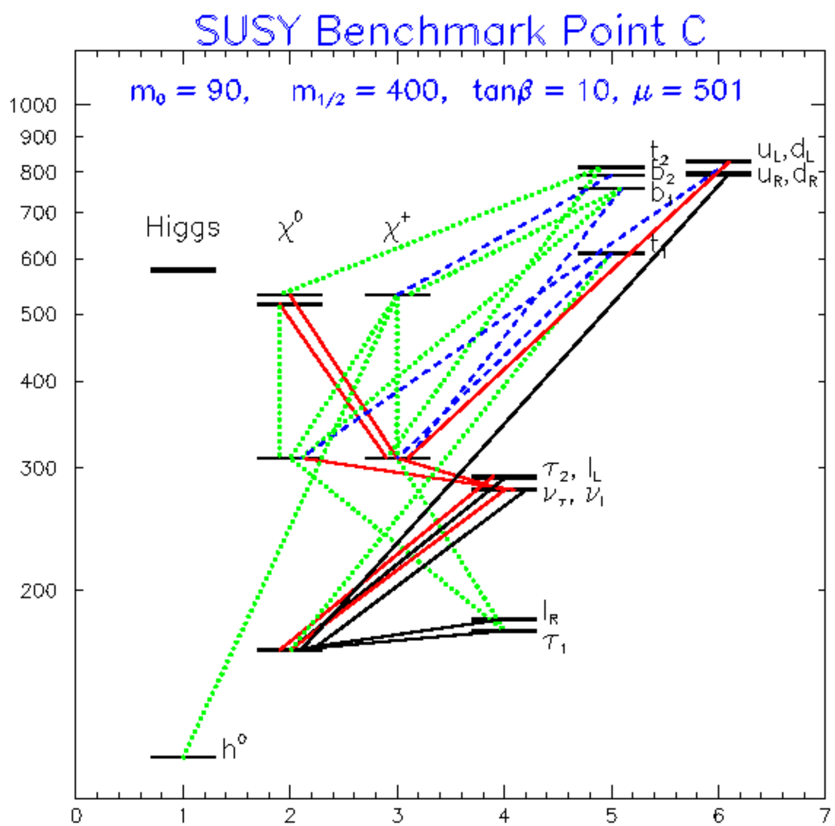


Figure 10.2: Feynman diagrams for gluino and squark production at hadron colliders from gluon-gluon and gluon-quark fusion.

Production cross section in general dependent on the full specific spectrum of the model

Decay processes

- Sparticles decay depend:
  - On the sparticle spectrum
  - On the (Standard Model like) couplings
  - On the mixing (right-left for sfermions, for example)



Example

Focus on the stop $\tilde{t}_1$

Possible decays

A. $\tilde{t}_1 \to t\tilde{\chi}^1_0$

B. $\tilde{t}_1 \to b\tilde{\chi}^{\pm}_1$

C. $\tilde{t}_1 \to t\chi^0_2$

Assuming $\tilde{\chi}^0_2$ and $\tilde{\chi}^{\pm}_1$ pure wino and mass degenerate, and $\tilde{t}_1 \sim \tilde{t}_L$ and m(stop) much bigger than the top mass, what is the ratio between the branching ratios of B. and C. ? And if $\tilde{t}_1 \sim \tilde{t}_R$, what can we say about the ratio of a), b) and c)?

Answer

$\tilde{t}_1 \sim \tilde{t}_L$ WEAK ISOSPIN $\left| |\vec{T}|, T_3 \right\rangle = \left| \frac{1}{2}, +\frac{1}{2} \right\rangle$

$\tilde{\chi}_2^0, \tilde{\chi}_1^\pm \sim$ WINO $\Rightarrow |\vec{T}| = 1$ $\quad \tilde{\chi}_2^0 : |1, 0\rangle \quad \tilde{\chi}_1^+ = |1, +1\rangle$

$\begin{pmatrix} t_L \\ b_L \end{pmatrix} \Rightarrow t_L = \left| \frac{1}{2}, +\frac{1}{2} \right\rangle \quad b_L = \left| \frac{1}{2}, -\frac{1}{2} \right\rangle$

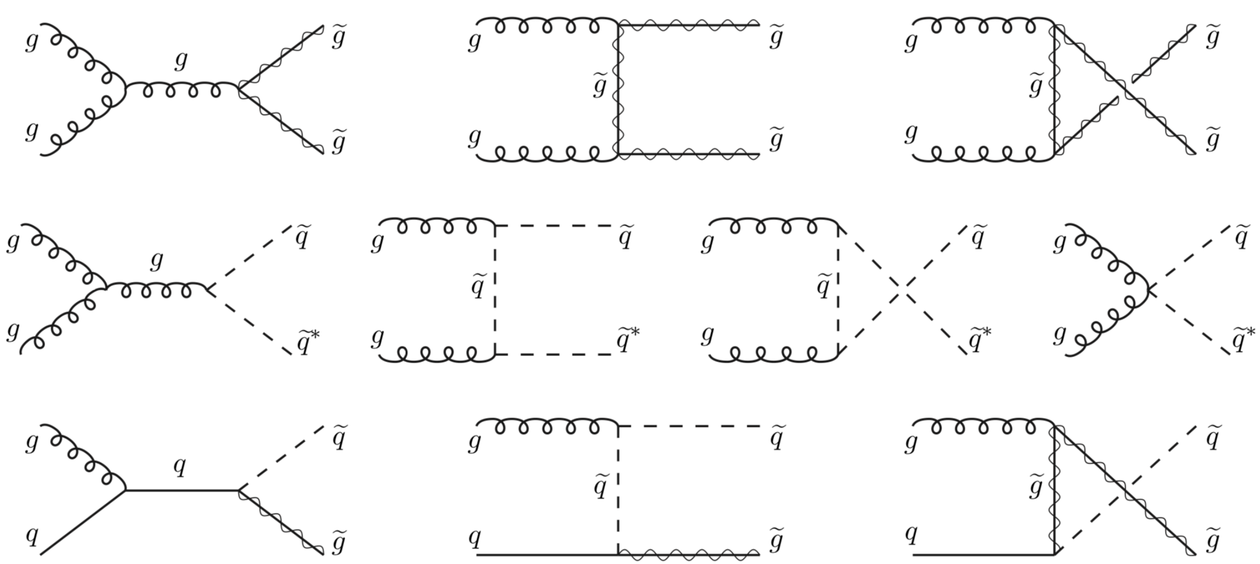
$$\frac{BR(\tilde{t}_1 \to \tilde{\chi}_2^0 t)}{BR(\tilde{t}_1 \to \tilde{\chi}_1^+ b)} \sim \frac{|A(\tilde{t}_1 \to \tilde{\chi}_2^0 t)|^2}{|A(\tilde{t}_1 \to \tilde{\chi}_1^\pm b)|^2} =$$

$$= \frac{|K|^2 \left| \left| \frac{1}{2}, +\frac{1}{2} \right\rangle \to |1, 0\rangle \left| \frac{1}{2}, +\frac{1}{2} \right\rangle \right|^2}{|K|^2 \left| \left| \frac{1}{2}, +\frac{1}{2} \right\rangle \to |1, +1\rangle \left| \frac{1}{2}, -\frac{1}{2} \right\rangle \right|^2}$$

FOR THE SECOND QUESTION: IF $\tilde{t}_1 \sim \tilde{t}_R$ THEN NO COUPLINGS TO WINOS

Simplified models

- Already used in the LHC **Run 1 (2009-2012)** and definitely in the LHC **Run 2 (2015-2018).**
- Assume **only a few** (typically a pair produced particle and the LSP) SUSY particles are relevant.
- For example, let's assume that **the gluinos and the lightest neutralino** are the only "light" particles



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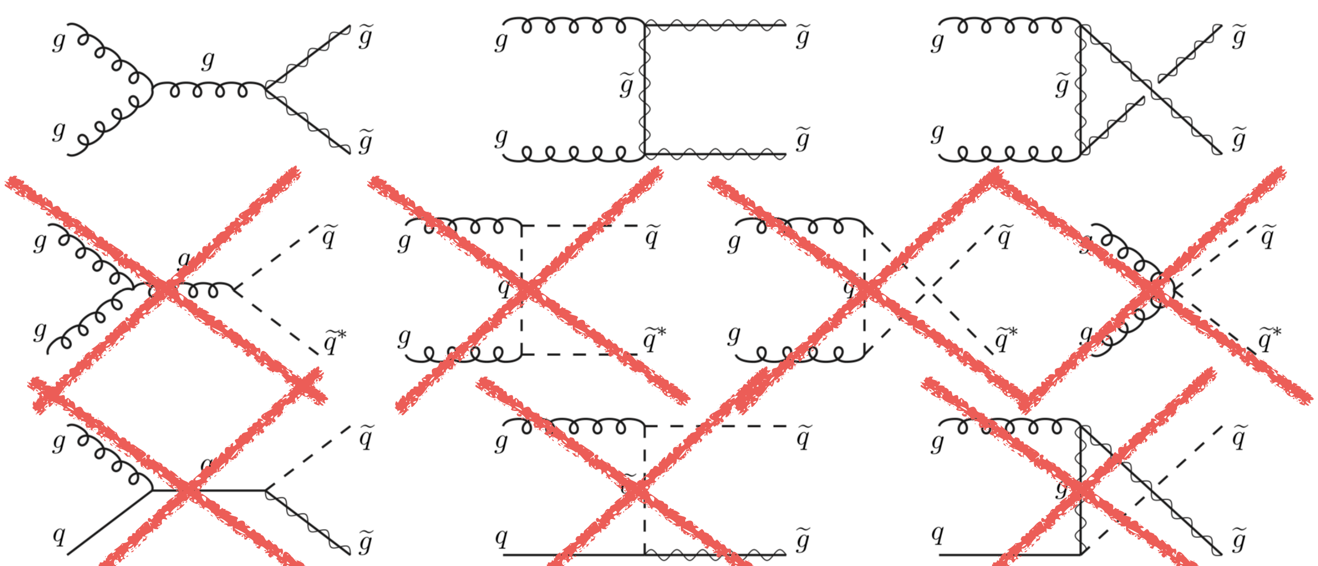

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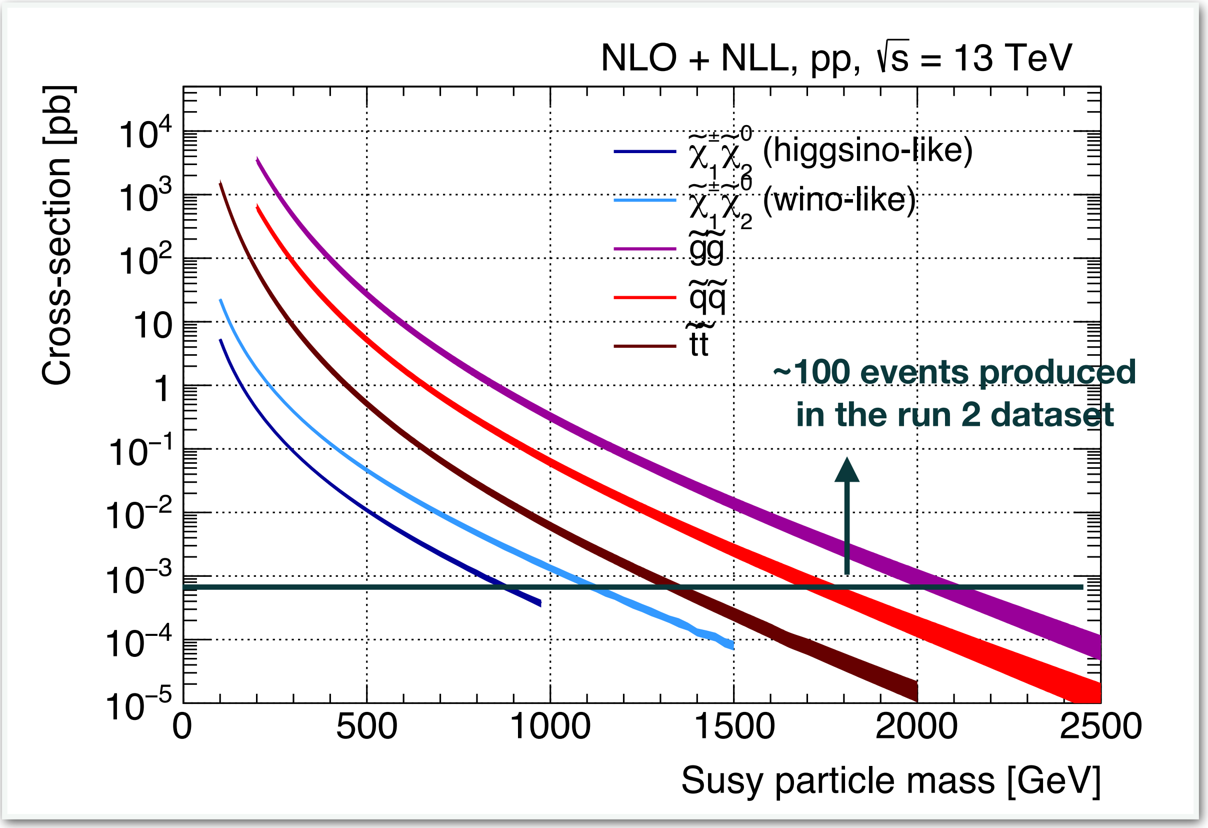
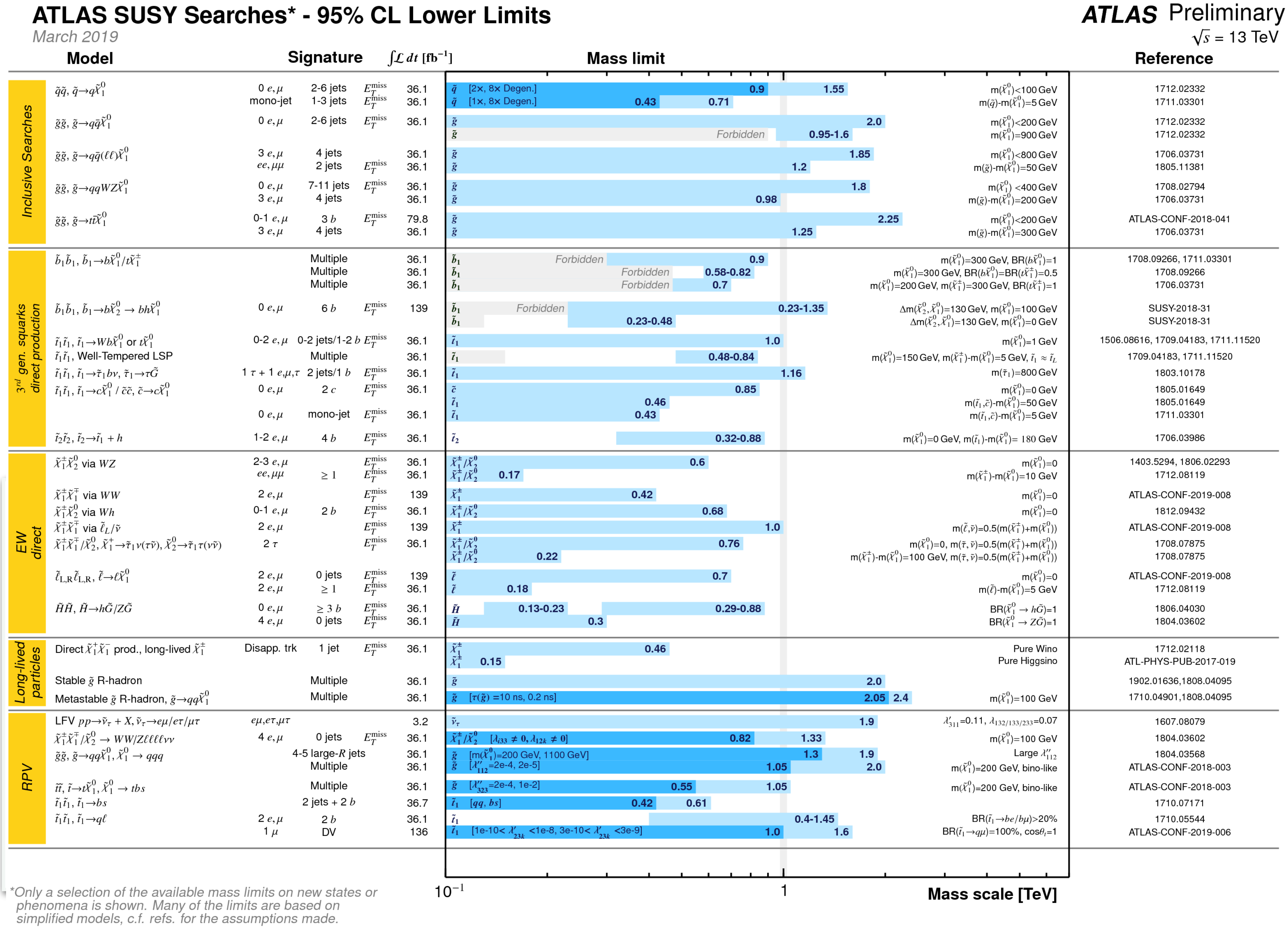
Production cross sections

- "Decoupled" production cross sections
- ...and immediately **an idea of the sensitivity** of the experiments.....



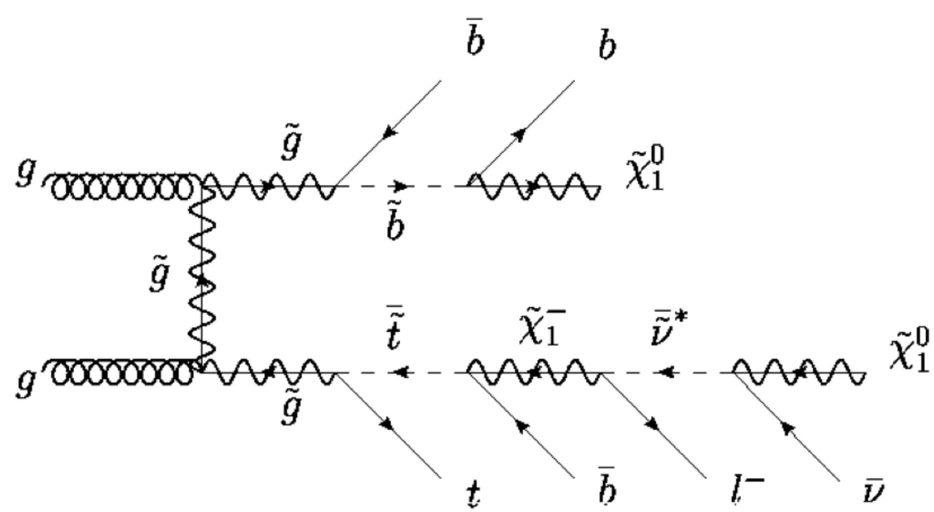


ATLAS SUSY Searches* - 95% CL Lower Limits
March 2019
ATLAS Preliminary
$\sqrt{s}$ = 13 TeV
Model
Signature
$\int \mathcal{L}\,dt$ [fb^{-1}]
Mass limit
Reference
Inclusive Searches
$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}^0_1$ | 0 e,μ 2-6 jets E_T^{miss} 36.1 | $\tilde{q}$ [2x, 8x Degen.] 0.9 1.55 | m($\tilde{\chi}^0_1$)<100 GeV | 1712.02332
mono-jet 1-3 jets E_T^{miss} 36.1 | $\tilde{q}$ [1x, 8x Degen.] 0.43 0.71 | m($\tilde{q}$)-m($\tilde{\chi}^0_1$)=5 GeV | 1711.03301
$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}^0_1$ | 0 e,μ 2-6 jets E_T^{miss} 36.1 | $\tilde{g}$ 2.0 | m($\tilde{\chi}^0_1$)<200 GeV | 1712.02332
$\tilde{g}$ Forbidden 0.95-1.6 | m($\tilde{\chi}^0_1$)=900 GeV | 1712.02332
$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}(\ell\ell)\tilde{\chi}^0_1$ | 3 e,μ 4 jets 36.1 | $\tilde{g}$ 1.85 | m($\tilde{\chi}^0_1$)<800 GeV | 1706.03731
$ee,\mu\mu$ 2 jets E_T^{miss} 36.1 | $\tilde{g}$ 1.2 | m($\tilde{g}$)-m($\tilde{\chi}^0_1$)=50 GeV | 1805.11381
$\tilde{g}\tilde{g}, \tilde{g}\to qqWZ\tilde{\chi}^0_1$ | 0 e,μ 7-11 jets E_T^{miss} 36.1 | $\tilde{g}$ 1.8 | m($\tilde{\chi}^0_1$) <400 GeV | 1708.02794
3 e,μ 4 jets 36.1 | $\tilde{g}$ 0.98 | m($\tilde{g}$)-m($\tilde{\chi}^0_1$)=200 GeV | 1706.03731
$\tilde{g}\tilde{g}, \tilde{g}\to t\bar{t}\tilde{\chi}^0_1$ | 0-1 e,μ 3 b E_T^{miss} 79.8 | $\tilde{g}$ 2.25 | m($\tilde{\chi}^0_1$)<200 GeV | ATLAS-CONF-2018-041
3 e,μ 4 jets 36.1 | $\tilde{g}$ 1.25 | m($\tilde{g}$)-m($\tilde{\chi}^0_1$)=300 GeV | 1706.03731
3rd gen. squarks direct production
$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to b\tilde{\chi}^0_1/t\tilde{\chi}^\pm_1$ | Multiple 36.1 | $\tilde{b}_1$ Forbidden 0.9 | m($\tilde{\chi}^0_1$)=300 GeV, BR($b\tilde{\chi}^0_1$)=1 | 1708.09266, 1711.03301
Multiple 36.1 | $\tilde{b}_1$ Forbidden 0.58-0.82 | m($\tilde{\chi}^0_1$)=300 GeV, BR($b\tilde{\chi}^0_1$)=BR($t\tilde{\chi}^\pm_1$)=0.5 | 1708.09266
Multiple 36.1 | $\tilde{b}_1$ Forbidden 0.7 | m($\tilde{\chi}^0_1$)=200 GeV, m($\tilde{\chi}^\pm_1$)=300 GeV, BR($t\tilde{\chi}^\pm_1$)=1 | 1706.03731
$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to b\tilde{\chi}^0_2\to bh\tilde{\chi}^0_1$ | 0 e,μ 6 b E_T^{miss} 139 | $\tilde{b}_1$ Forbidden 0.23-1.35 | Δm($\tilde{\chi}^0_2,\tilde{\chi}^0_1$)=130 GeV, m($\tilde{\chi}^0_1$)=100 GeV | SUSY-2018-31
$\tilde{b}_1$ 0.23-0.48 | Δm($\tilde{\chi}^0_2,\tilde{\chi}^0_1$)=130 GeV, m($\tilde{\chi}^0_1$)=0 GeV | SUSY-2018-31
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to Wb\tilde{\chi}^0_1$ or $t\tilde{\chi}^0_1$ | 0-2 e,μ 0-2 jets/1-2 b E_T^{miss} 36.1 | $\tilde{t}_1$ 1.0 | m($\tilde{\chi}^0_1$)=1 GeV | 1506.08616, 1709.04183, 1711.11520
$\tilde{t}_1\tilde{t}_1$, Well-Tempered LSP | Multiple 36.1 | $\tilde{t}_1$ 0.48-0.84 | m($\tilde{\chi}^0_1$)=150 GeV, m($\tilde{\chi}^\pm_1$)-m($\tilde{\chi}^0_1$)=5 GeV, $\tilde{t}_1\approx\tilde{t}_L$ | 1709.04183, 1711.11520
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to\tilde{\tau}_1 b\nu, \tilde{\tau}_1\to\tau\tilde{G}$ | 1 τ + 1 e,μ,τ 2 jets/1 b E_T^{miss} 36.1 | $\tilde{t}_1$ 1.16 | m($\tilde{\tau}_1$)=800 GeV | 1803.10178
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to c\tilde{\chi}^0_1$ / $\tilde{c}\tilde{c}, \tilde{c}\to c\tilde{\chi}^0_1$ | 0 e,μ 2 c E_T^{miss} 36.1 | $\tilde{c}$ 0.85 | m($\tilde{\chi}^0_1$)=0 GeV | 1805.01649
$\tilde{t}_1$ 0.46 | m($\tilde{t}_1,\tilde{c}$)-m($\tilde{\chi}^0_1$)=50 GeV | 1805.01649
0 e,μ mono-jet E_T^{miss} 36.1 | $\tilde{t}_1$ 0.43 | m($\tilde{t}_1,\tilde{c}$)-m($\tilde{\chi}^0_1$)=5 GeV | 1711.03301
$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1+h$ | 1-2 e,μ 4 b E_T^{miss} 36.1 | $\tilde{t}_2$ 0.32-0.88 | m($\tilde{\chi}^0_1$)=0 GeV, m($\tilde{t}_1$)-m($\tilde{\chi}^0_1$)= 180 GeV | 1706.03986
EW direct
$\tilde{\chi}^\pm_1\tilde{\chi}^0_2$ via WZ | 2-3 e,μ E_T^{miss} 36.1 | $\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$ 0.6 | m($\tilde{\chi}^0_1$)=0 | 1403.5294, 1806.02293
$ee,\mu\mu$ ≥ 1 E_T^{miss} 36.1 | $\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$ 0.17 | m($\tilde{\chi}^\pm_1$)-m($\tilde{\chi}^0_1$)=10 GeV | 1712.08119
$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1$ via WW | 2 e,μ E_T^{miss} 139 | $\tilde{\chi}^\pm_1$ 0.42 | m($\tilde{\chi}^0_1$)=0 | ATLAS-CONF-2019-008
$\tilde{\chi}^\pm_1\tilde{\chi}^0_2$ via Wh | 0-1 e,μ 2 b E_T^{miss} 36.1 | $\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$ 0.68 | m($\tilde{\chi}^0_1$)=0 | 1812.09432
$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1$ via $\tilde{\ell}_L/\tilde{\nu}$ | 2 e,μ E_T^{miss} 139 | $\tilde{\chi}^\pm_1$ 1.0 | m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}^\pm_1$)+m($\tilde{\chi}^0_1$)) | ATLAS-CONF-2019-008
$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1/\tilde{\chi}^0_2, \tilde{\chi}^+_1\to\tilde{\tau}_1\nu(\tau\tilde{\nu}), \tilde{\chi}^0_2\to\tilde{\tau}_1\tau(\nu\tilde{\nu})$ | 2 τ E_T^{miss} 36.1 | $\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$ 0.76 | m($\tilde{\chi}^0_1$)=0, m($\tilde{\tau},\tilde{\nu}$)=0.5(m($\tilde{\chi}^\pm_1$)+m($\tilde{\chi}^0_1$)) | 1708.07875
$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$ 0.22 | m($\tilde{\chi}^\pm_1$)-m($\tilde{\chi}^0_1$)=100 GeV, m($\tilde{\tau},\tilde{\nu}$)=0.5(m($\tilde{\chi}^\pm_1$)+m($\tilde{\chi}^0_1$)) | 1708.07875
$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell}\to\ell\tilde{\chi}^0_1$ | 2 e,μ 0 jets E_T^{miss} 139 | $\tilde{\ell}$ 0.7 | m($\tilde{\chi}^0_1$)=0 | ATLAS-CONF-2019-008
2 e,μ ≥ 1 E_T^{miss} 36.1 | $\tilde{\ell}$ 0.18 | m($\tilde{\ell}$)-m($\tilde{\chi}^0_1$)=5 GeV | 1712.08119
$\tilde{H}\tilde{H}, \tilde{H}\to h\tilde{G}/Z\tilde{G}$ | 0 e,μ ≥ 3 b E_T^{miss} 36.1 | $\tilde{H}$ 0.13-0.23 0.29-0.88 | BR($\tilde{\chi}^0_1\to h\tilde{G}$)=1 | 1806.04030
4 e,μ 0 jets E_T^{miss} 36.1 | $\tilde{H}$ 0.3 | BR($\tilde{\chi}^0_1\to Z\tilde{G}$)=1 | 1804.03602
Long-lived particles
Direct $\tilde{\chi}^+_1\tilde{\chi}^-_1$ prod., long-lived $\tilde{\chi}^\pm_1$ | Disapp. trk 1 jet E_T^{miss} 36.1 | $\tilde{\chi}^\pm_1$ 0.46 | Pure Wino | 1712.02118
$\tilde{\chi}^\pm_1$ 0.15 | Pure Higgsino | ATL-PHYS-PUB-2017-019
Stable $\tilde{g}$ R-hadron | Multiple 36.1 | $\tilde{g}$ 2.0 | 1902.01636,1808.04095
Metastable $\tilde{g}$ R-hadron, $\tilde{g}\to qq\tilde{\chi}^0_1$ | Multiple 36.1 | $\tilde{g}$ [$\tau(\tilde{g})$ =10 ns, 0.2 ns] 2.05 2.4 | m($\tilde{\chi}^0_1$)=100 GeV | 1710.04901,1808.04095
RPV
LFV $pp\to\tilde{\nu}_\tau+X, \tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$ | $e\mu,e\tau,\mu\tau$ 3.2 | $\tilde{\nu}_\tau$ 1.9 | λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07 | 1607.08079
$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1/\tilde{\chi}^0_2\to WW/Z\ell\ell\ell\ell\nu\nu$ | 4 e,μ 0 jets E_T^{miss} 36.1 | $\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$ [$\lambda_{i33}\neq 0, \lambda_{12k}\neq 0$] 0.82 1.33 | m($\tilde{\chi}^0_1$)=100 GeV | 1804.03602
$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}^0_1, \tilde{\chi}^0_1\to qqq$ | 4-5 large-R jets 36.1 | $\tilde{g}$ [m($\tilde{\chi}^0_1$)=200 GeV, 1100 GeV] 1.3 1.9 | Large λ''_{112} | 1804.03568
Multiple 36.1 | $\tilde{g}$ [λ''_{112}=2e-4, 2e-5] 1.05 2.0 | m($\tilde{\chi}^0_1$)=200 GeV, bino-like | ATLAS-CONF-2018-003
$\tilde{t}\tilde{t}, \tilde{t}\to t\tilde{\chi}^0_1, \tilde{\chi}^0_1\to tbs$ | Multiple 36.1 | $\tilde{g}$ [λ''_{323}=2e-4, 1e-2] 0.55 1.05 | m($\tilde{\chi}^0_1$)=200 GeV, bino-like | ATLAS-CONF-2018-003
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to bs$ | 2 jets + 2 b 36.7 | $\tilde{t}_1$ [qq, bs] 0.42 0.61 | 1710.07171
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to q\ell$ | 2 e,μ 2 b 36.1 | $\tilde{t}_1$ 0.4-1.45 | BR($\tilde{t}_1\to be/b\mu$)>20% | 1710.05544
1 μ DV 136 | $\tilde{t}_1$ [1e-10< λ'_{23k} <1e-8, 3e-10< λ'_{23k} <3e-9] 1.0 1.6 | BR($\tilde{t}_1\to q\mu$)=100%, cosθ_t=1 | ATLAS-CONF-2019-006
10^{-1}
1
Mass scale [TeV]
*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

Inclusive searches

Inclusive searches

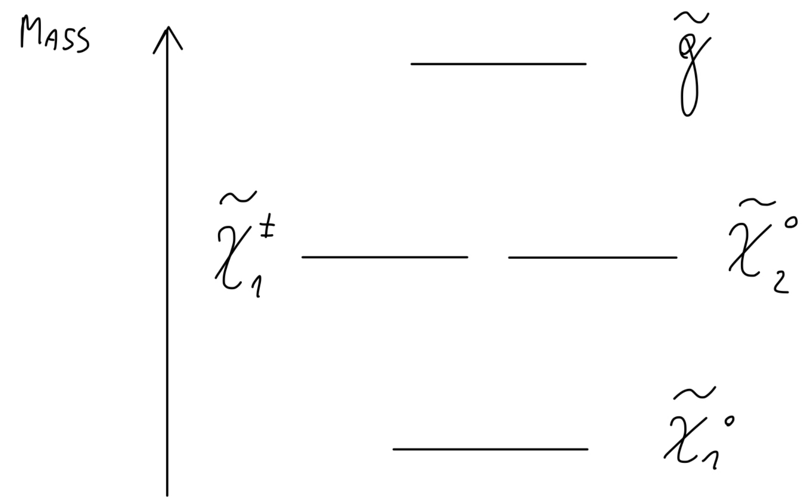
- Generic searches that look for the "bread and butter" signature of jets + E_T^{miss} with or without additional features (leptons, b-jets, etc.)
- Optimised for squark and gluino production, but wide sensitivity

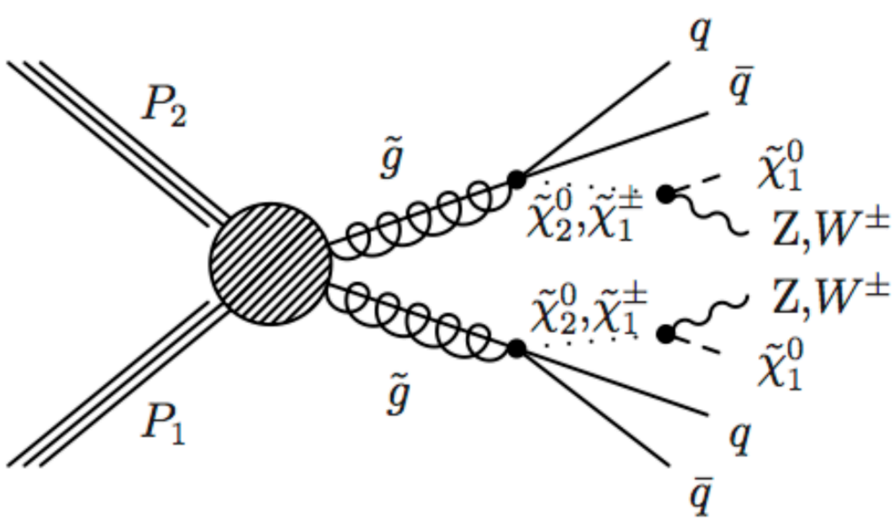


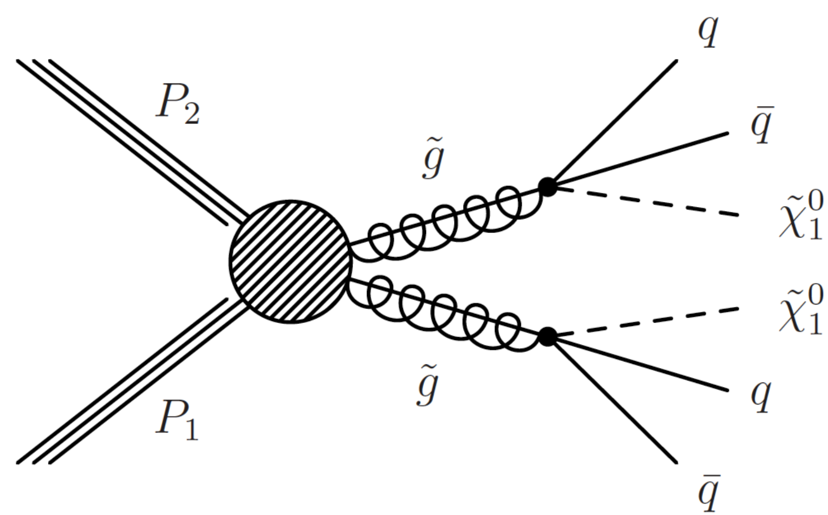
Take CMS-PAS-SUS-19-006 as an example

Search strategy

1. Define your signal

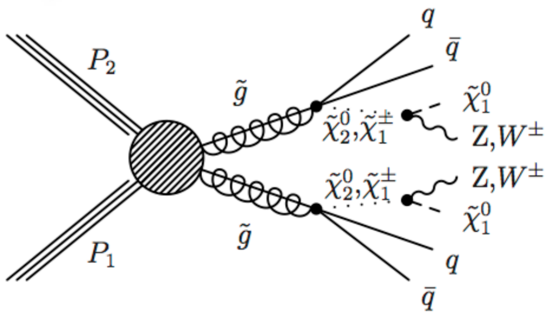


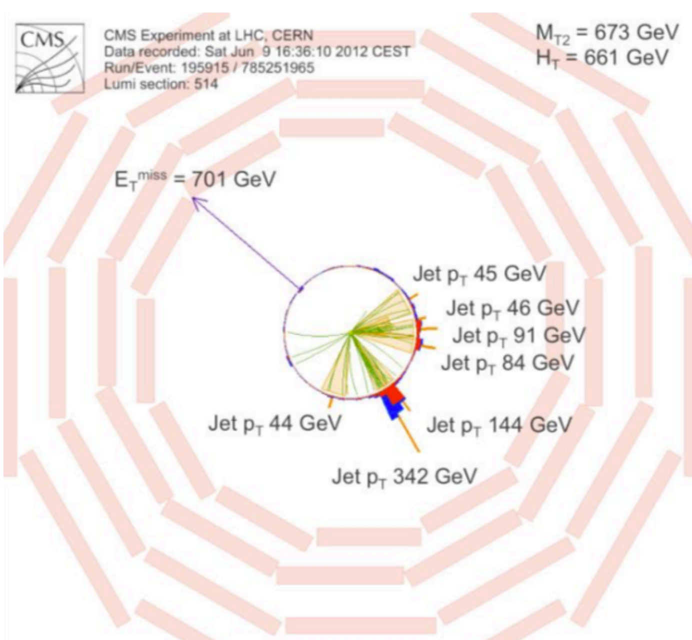




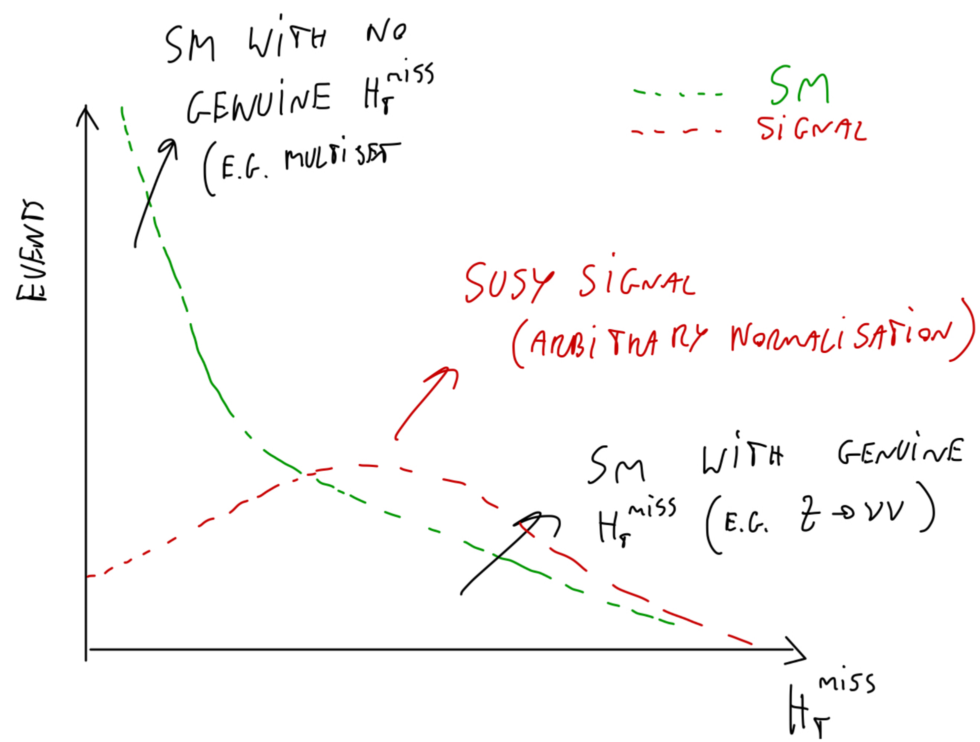
Search strategy

1. Define your signal
2. Define your selection



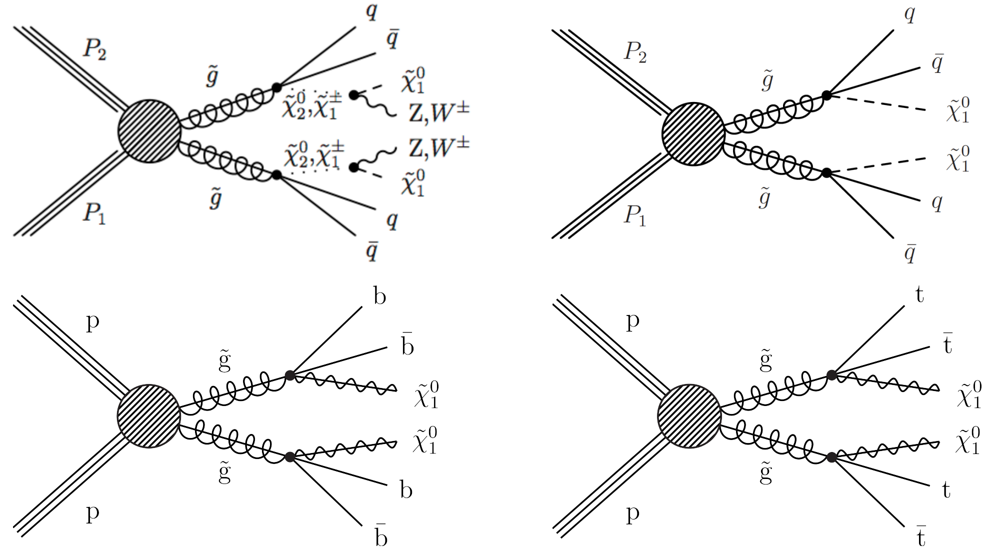


- E_T^{miss} from **undetected** $\tilde{\chi}_1^0$
- Jets
- Possibly **boosted bosons** that could end up in a large-R jet with mass ~ boson.
- Possibly leptons
- Possibly endpoints
  - In this example from massive vector boson mass constraints



Search strategy

1. Define your signal
2. Define your selection



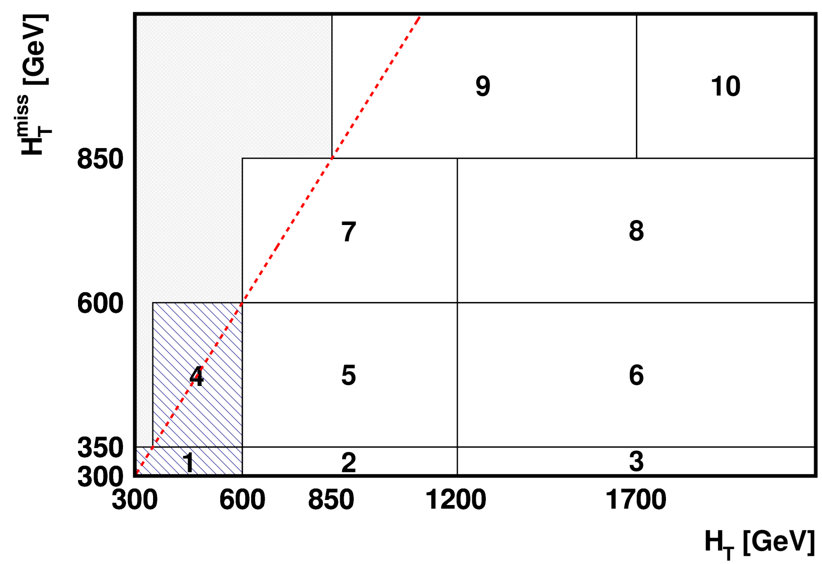
Reduce the background (while taking into account its uncertainty)

From CMS-PAS-SUS-19-006 (just an example):

- No leptons, no isolated tracks compatible with leptons
- $N_{jets} > 2$
- $\Delta\phi_{H_T^{miss},j} > 0.5$

$$H_T = \sum p_T^{jet}$$

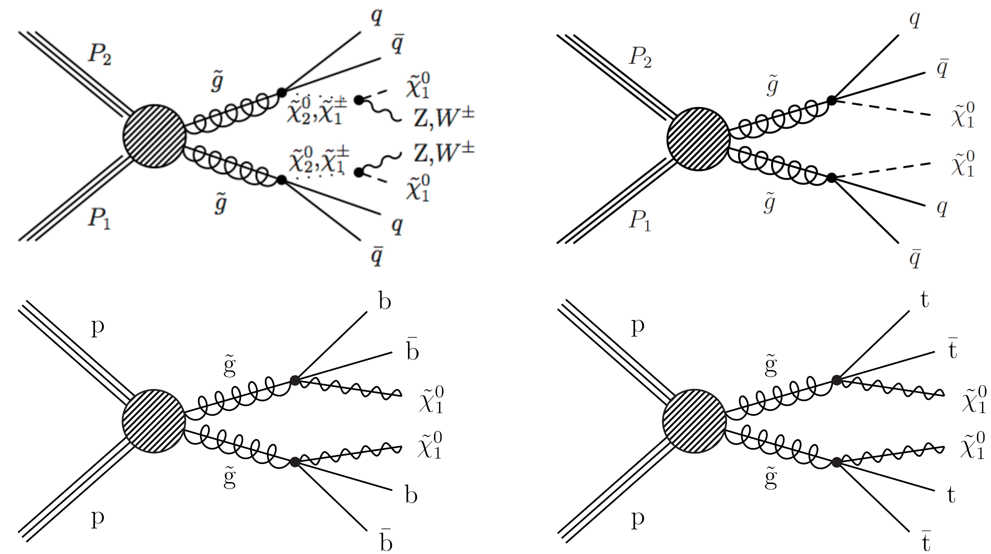
$$H_T^{miss} = -\sum \mathbf{p}_T^{jet}$$



Bin phase space in $N_{jet}, N_{b-jet}, H_T, H_T^{miss}$

Search strategy

1. Define your signal
2. Define your selection
3. Estimate your background



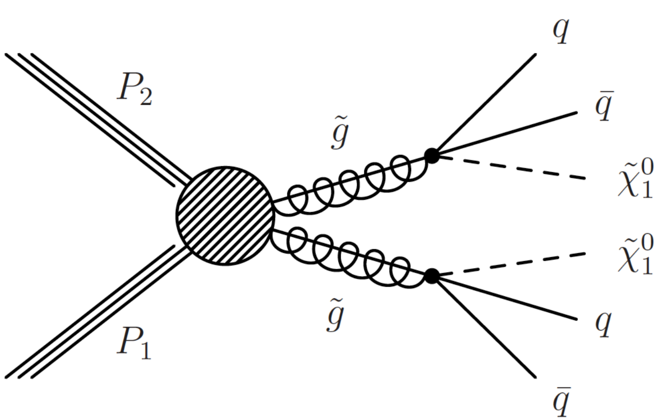
A big chapter:

Strategy driven by **answers to the following questions**:

- How **easy** it is to determine the background **directly from the data**?
- How **accurate** and **precise** is the MC estimation for a given process?
- Can the data **improve** the MC prediction?

Reducible and irreducible background

- Irreducible background:
  - Topology and final state object content **similar, or identical to signal**
- Reducible background:
  - Topology and/or final state object content **different from the signal**
    - Dangerous when its cross section is large



$W + jets \rightarrow l\nu + jets$ is

$Z \rightarrow \nu\nu$ is

Multijet

Reducible and irreducible background

- Irreducible background:
  - Topology and final state object content **similar, or identical to signal**
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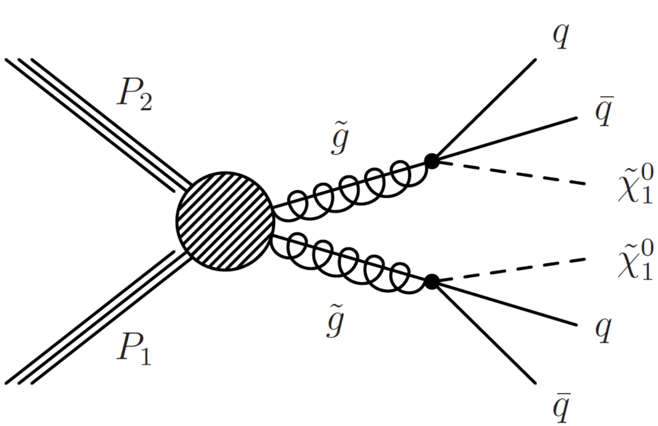

$W + jets \to l\nu + jets$ is **reducible**, so long as the lepton can be identified

$Z \to \nu\nu$ is

Multijet

Reducible and irreducible background

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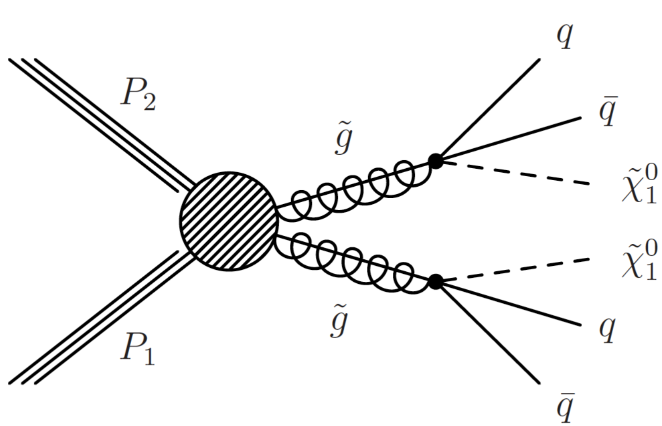

$W + jets \rightarrow l\nu + jets$ is **reducible**, so long as the lepton can be identified

$Z \rightarrow \nu\nu$ is **irreducible** (although it can be suppressed with topological cuts)

Multijet

Reducible and irreducible background

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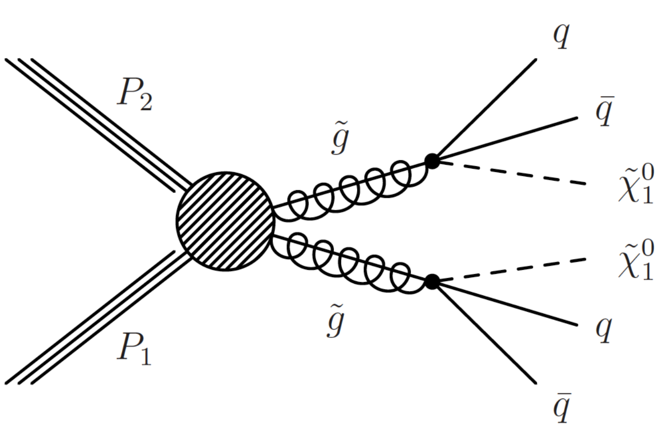


$W + jets \to l\nu + jets$ is **reducible**, so long as the lepton can be identified

$Z \to \nu\nu$ is **irreducible** (although it can be suppressed with topological cuts)

Multijet production is **reducible** (no genuine H_T^{miss} expected)

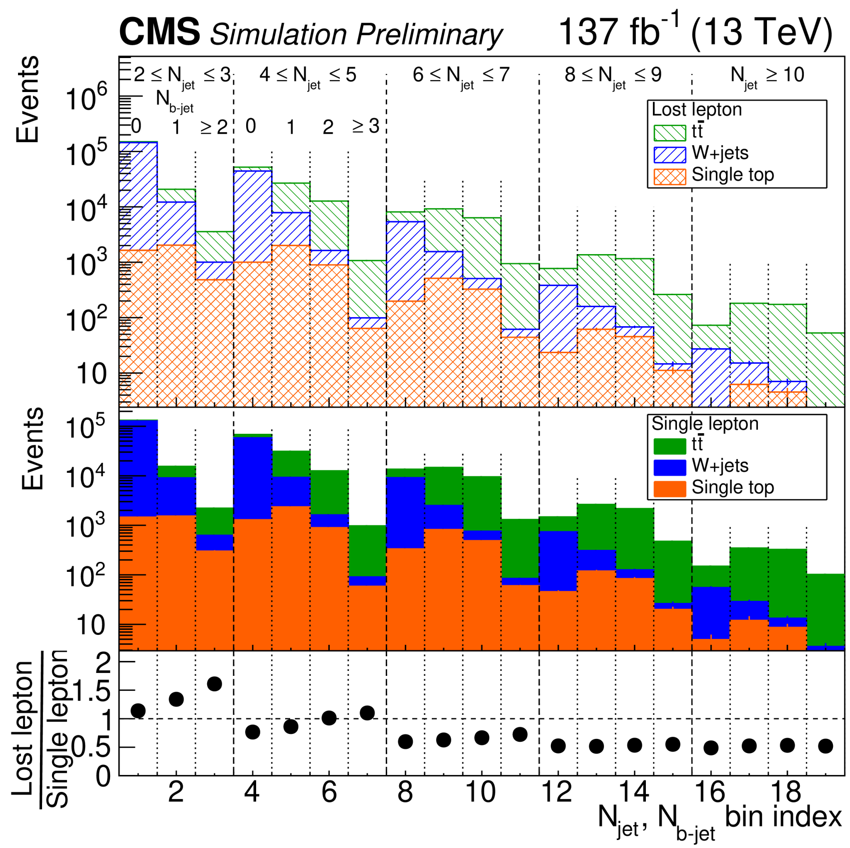
Reducible background estimation

- $t\bar{t}, W + jets$, single top all potentially enter the 0-lepton selection if $W \rightarrow l\nu$ and lepton lost or is a $\tau \rightarrow h\nu$

CR bins: same as search bins, but with one e or μ

$$b_{i,j} = o_i^{CR} m_{i,j}^{CR} \Gamma_i$$

where o_i^{CR} is the data yield in bin i, $m_{i,j}^{CR}$ is the MC prediction for fraction of process j in bin i of the 1-lepton control region, Γ_i is the ratio of the SR and CR yields

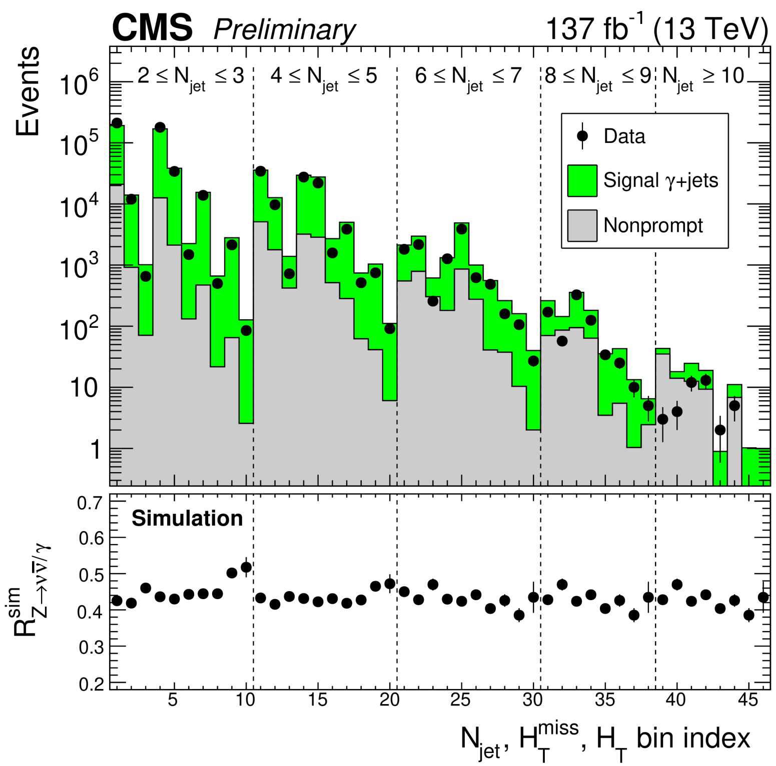


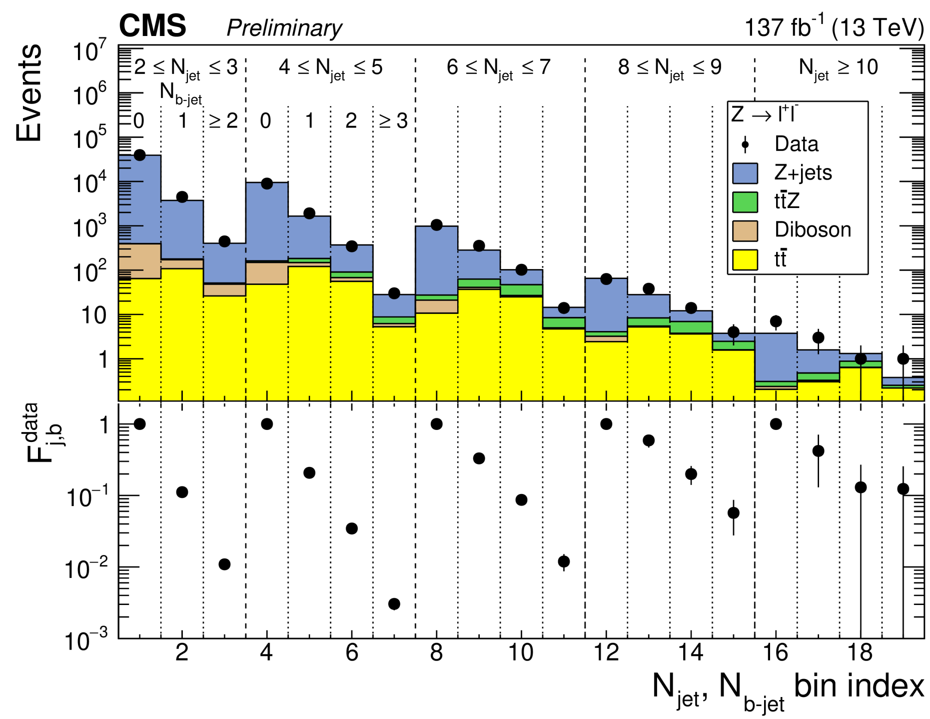
$Z \to \nu\nu$ estimate

- $Z \to \nu\nu$ events are irreducible. Estimated with a combination of $\gamma + jets$ and $Z \to \ell\ell$ events

$$N^{\text{pred}}_{Z\to\nu\bar{\nu}}\Big|_{N_{\text{b-jet}}=0} = \langle\rho\rangle \mathcal{R}^{\text{sim}}_{Z\to\nu\bar{\nu}/\gamma} \mathcal{F}_{\text{dir}} \beta_\gamma N^{\text{data}}_\gamma \,/\, \mathcal{C}^\gamma_{\text{data/sim}},$$

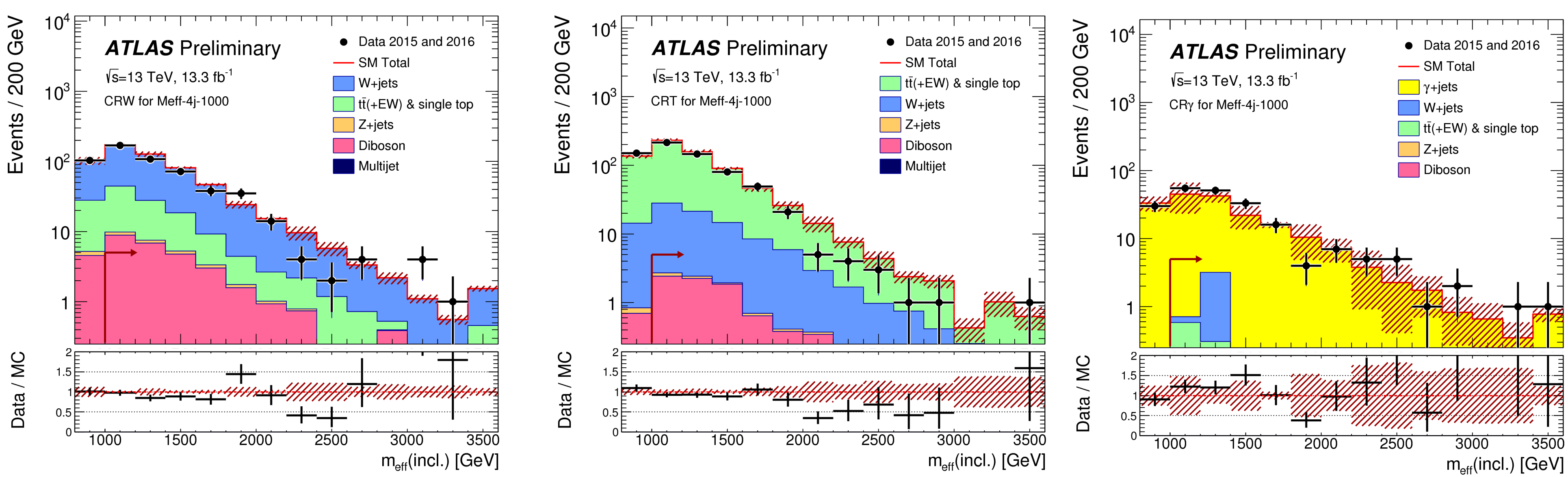
$$\left(N^{\text{pred}}_{Z\to\nu\bar{\nu}}\right)_{j,b,k} = \left(N^{\text{pred}}_{Z\to\nu\bar{\nu}}\right)_{j,0,k} \mathcal{F}^{\text{data}}_{\text{j,b}} \equiv \left(N^{\text{pred}}_{Z\to\nu\bar{\nu}}\right)_{j,0,k} \frac{\left(N^{\text{data}}_{Z\to\ell^+\ell^-}\beta^{\text{data}}_{\ell\ell}\right)_{j,b}}{\left(N^{\text{data}}_{Z\to\ell^+\ell^-}\beta^{\text{data}}_{\ell\ell}\right)_{j,0}},$$





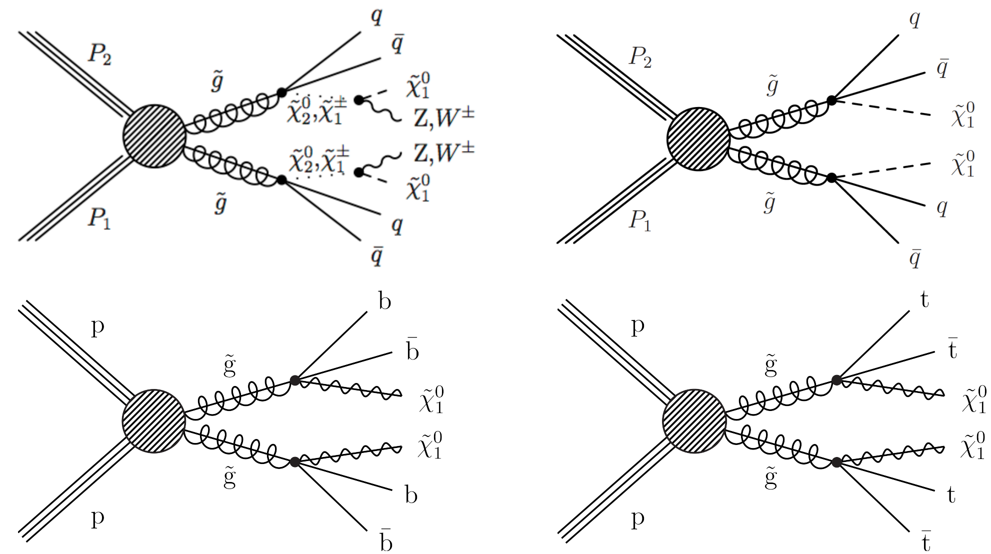
In other searches: Background from MC corrected with data

- The contribution of process j in the search bin i is $b_{i,j}(\mu_j, \vec{\theta}_j)$, where μ_j normally is an unconstrained normalisation factor, and $\vec{\theta}_j$ are the (constrained) nuisance parameters
- Depending on the analysis, μ_j maybe be fixed to 1, or additional **control regions** may be added to improve the accuracy and precision of μ_j, $\vec{\theta}_j$ determination.



Search strategy

1. Define your signal
2. Define your selection
3. Estimate your background
4. Systematic uncertainties



Search strategy

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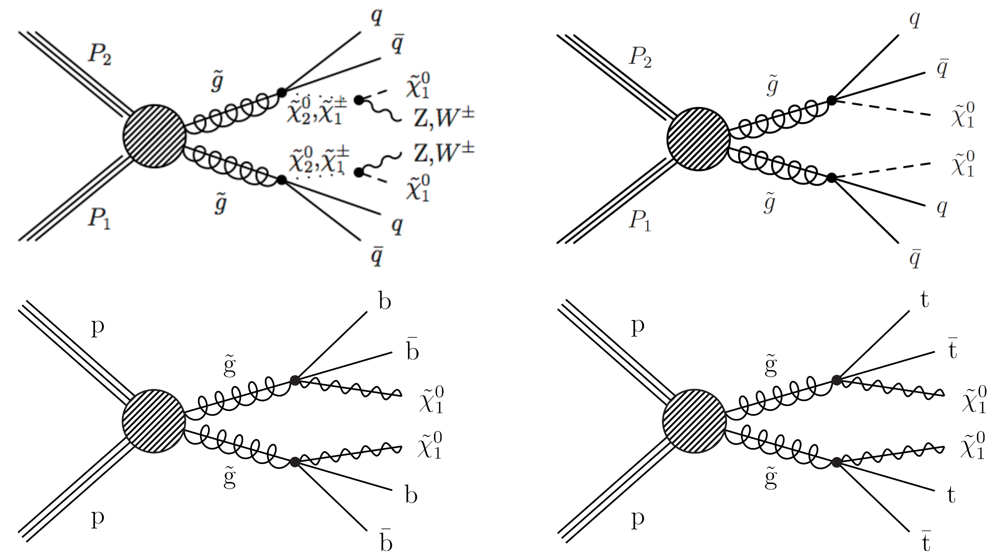


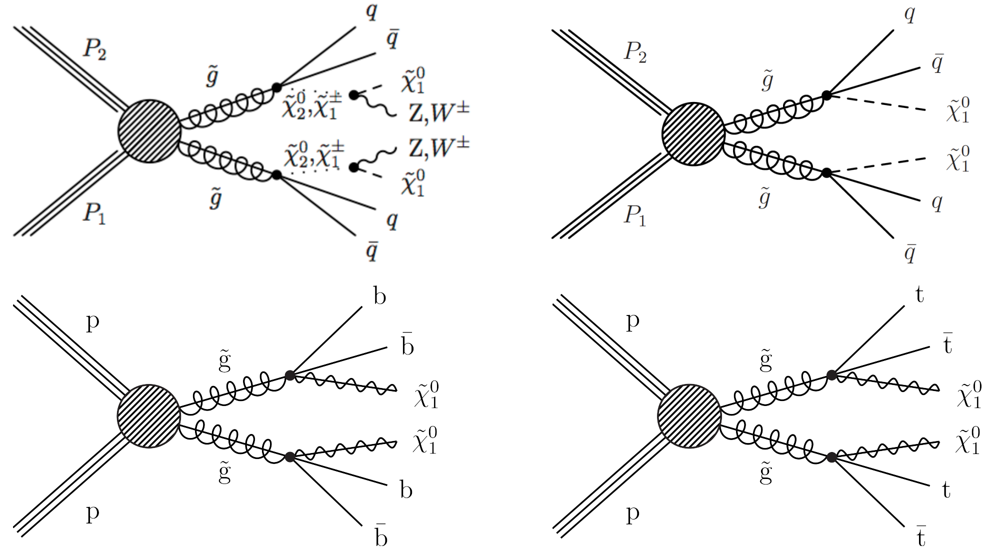
Theory/modelling uncertainties:
-Generator modelling (μ_F,μ_R, ME/PS matching, α_s scale choice when possible - otherwise compare generators)
- PS uncertainties
- PDF choice

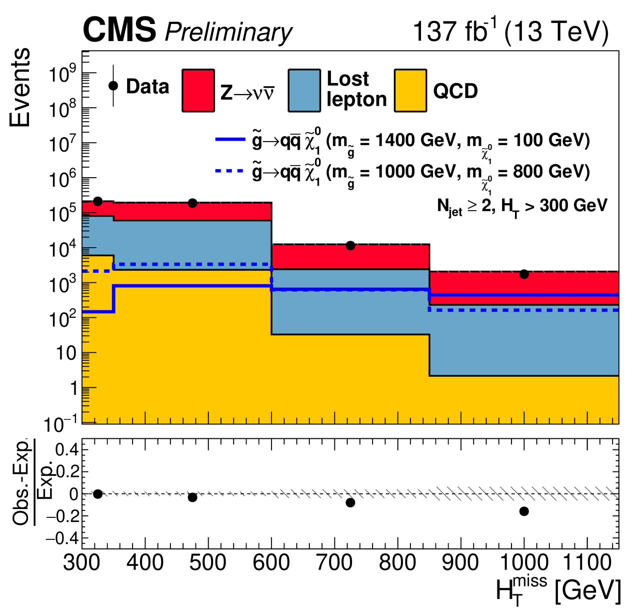
Typical Experimental uncertainties:
-Trigger efficiency
-Jet energy scale and resolution
-Lepton energy scale and efficiency
-b-tagging
-Luminosity
-pileup modelling

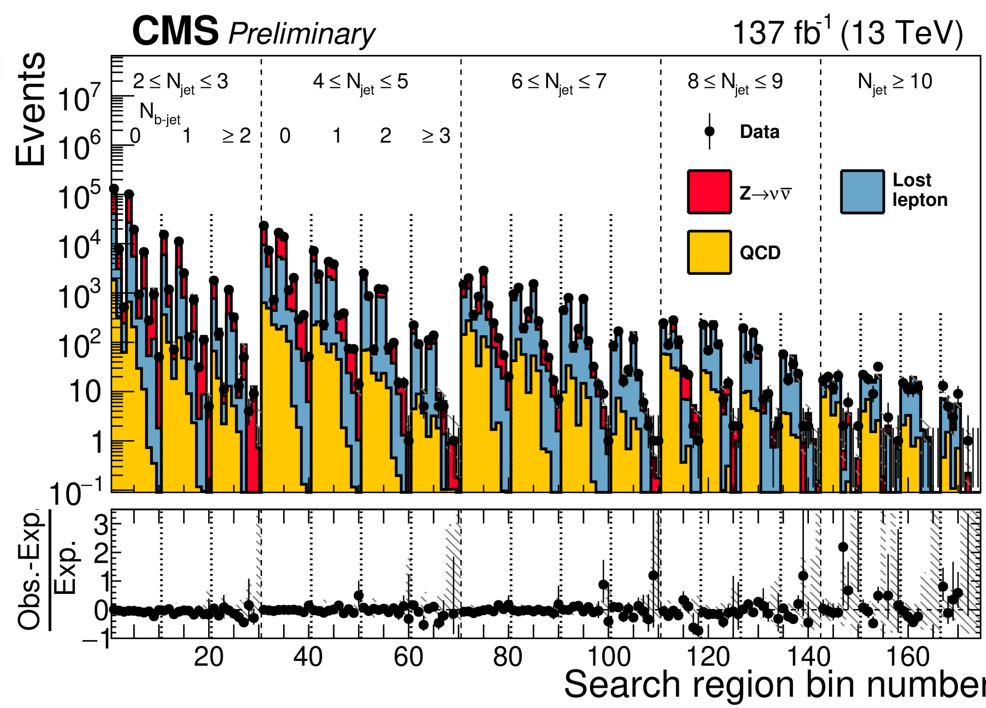
Analysis specific uncertainties
-Background estimation non-closure
- ??

Search strategy

1. Define your signal
2. Define your selection
3. Estimate your background
4. Systematic uncertainties
5. Compare predictions to data







Search strategy

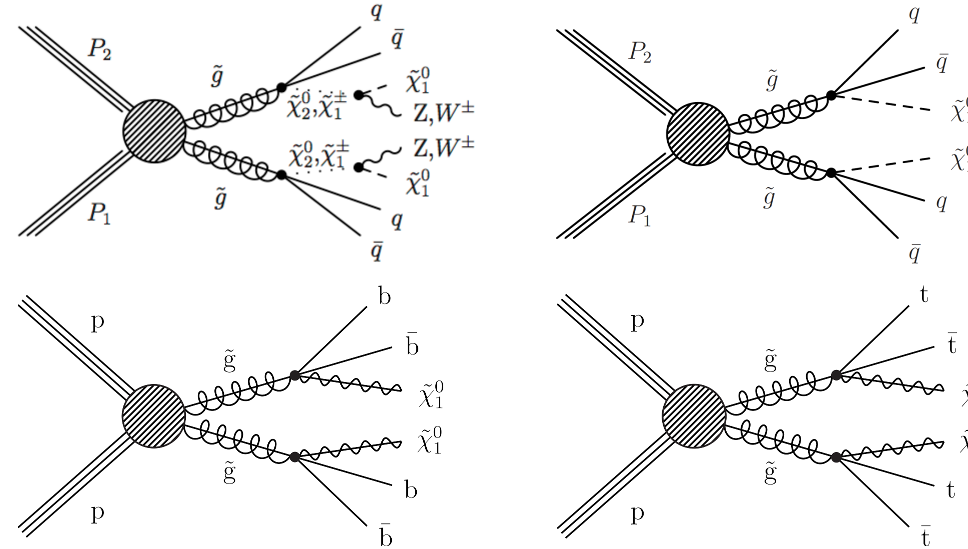
1. Define your signal
2. Define your selection
3. Estimate your background
4. Systematic uncertainties
5. Compare predictions to data
6. Result interpretation

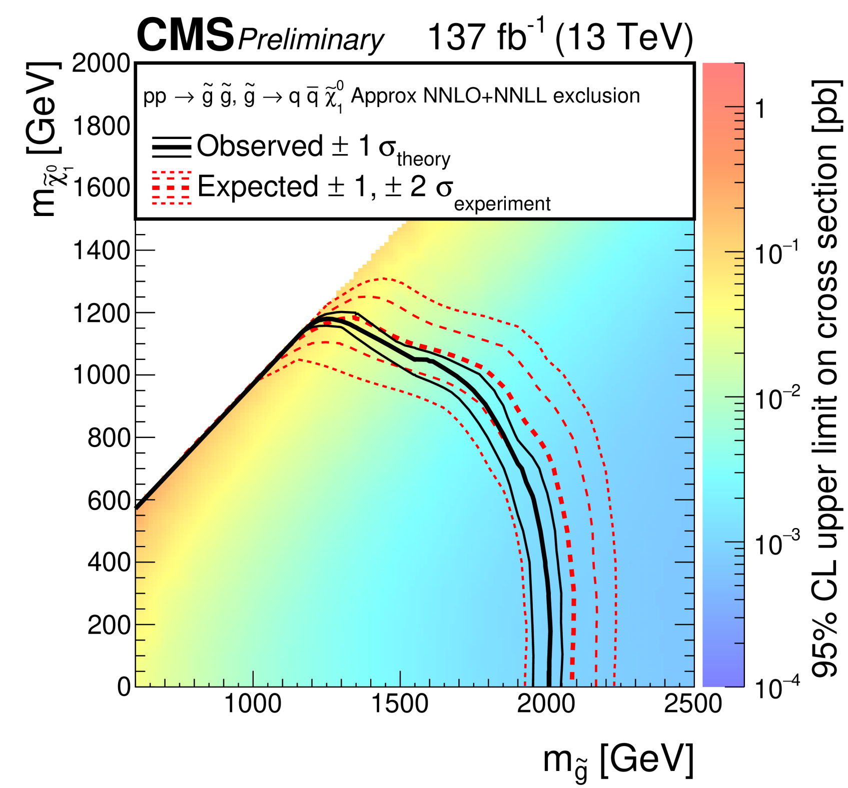
   Have I discovered SUSY?

   If not, then extract limits

Test statistics $q(\mu) = -2\ln\frac{\mathfrak{L}(\mu,\hat{\hat{\theta}})}{\mathfrak{L}(\hat{\mu},\hat{\theta})}$

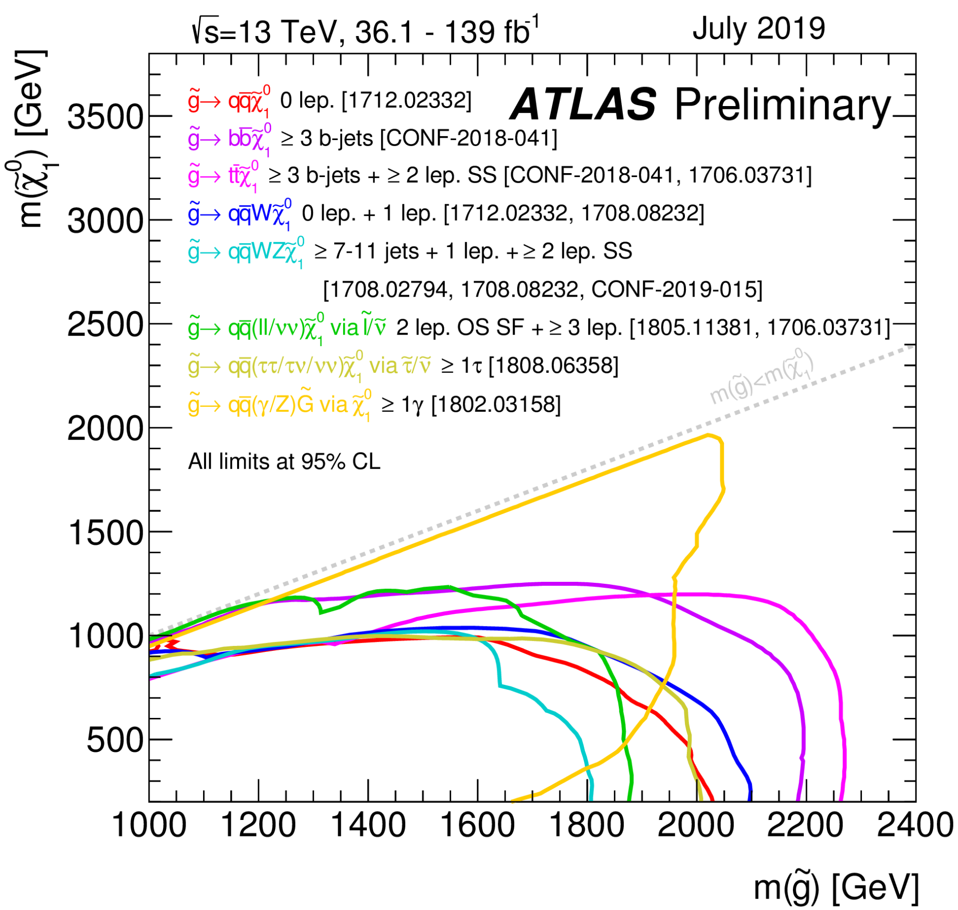
And using the CLs prescription

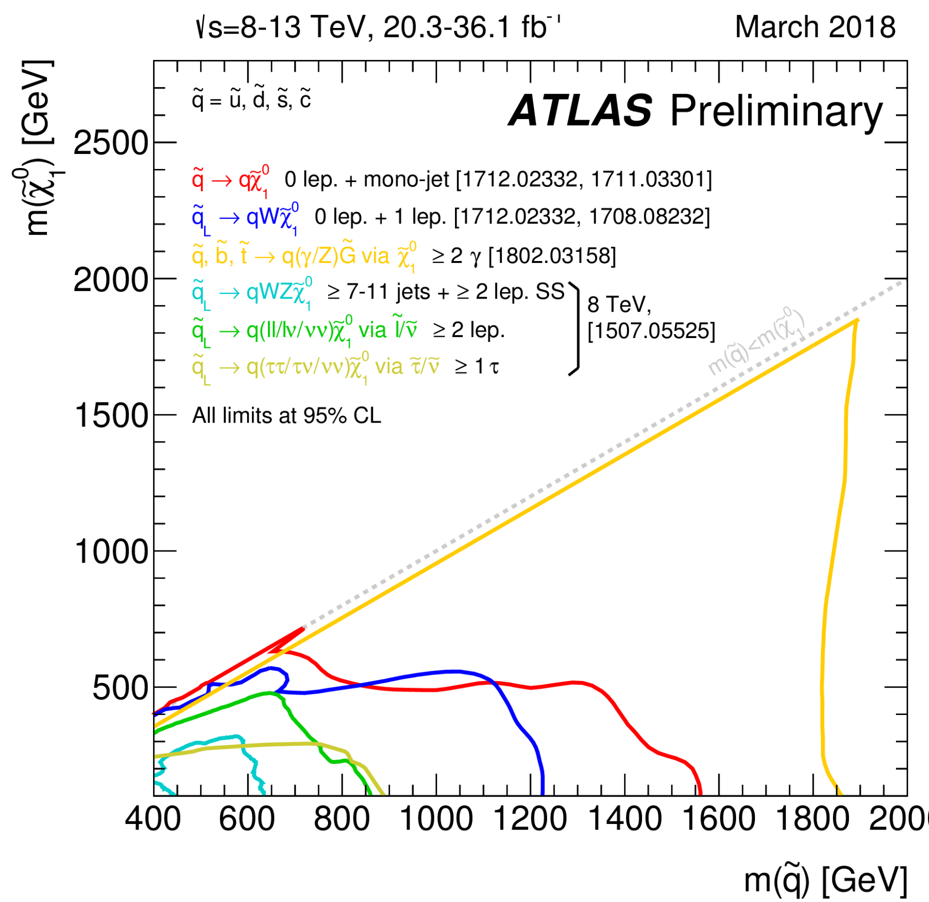




Limits on squarks and gluinos

- Bear in mind these are simplified models



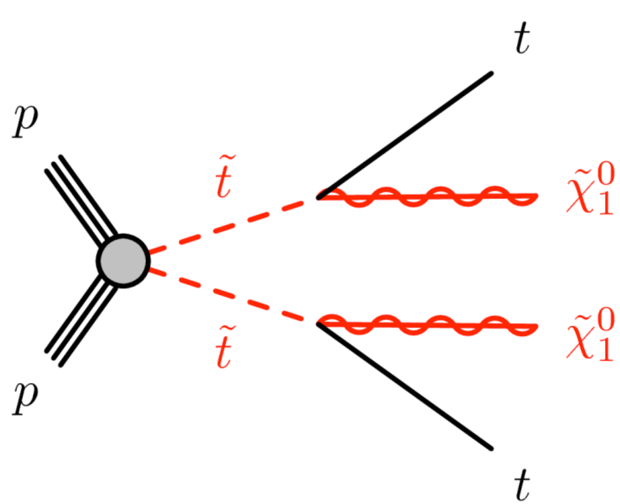


Exclusive SUSY searches

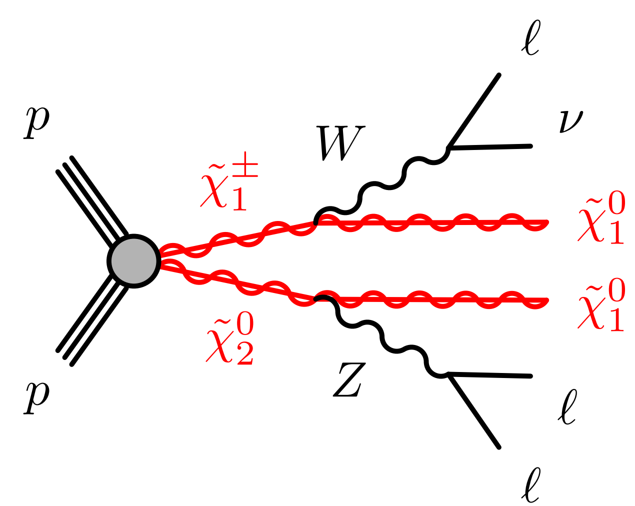
Exclusive searches

- Targeted searches that focus on a specific scenario.
- Profit from specific signatures associated with that scenario.

Third generation squark direct pair production



Electroweak production



The Higgs boson connection

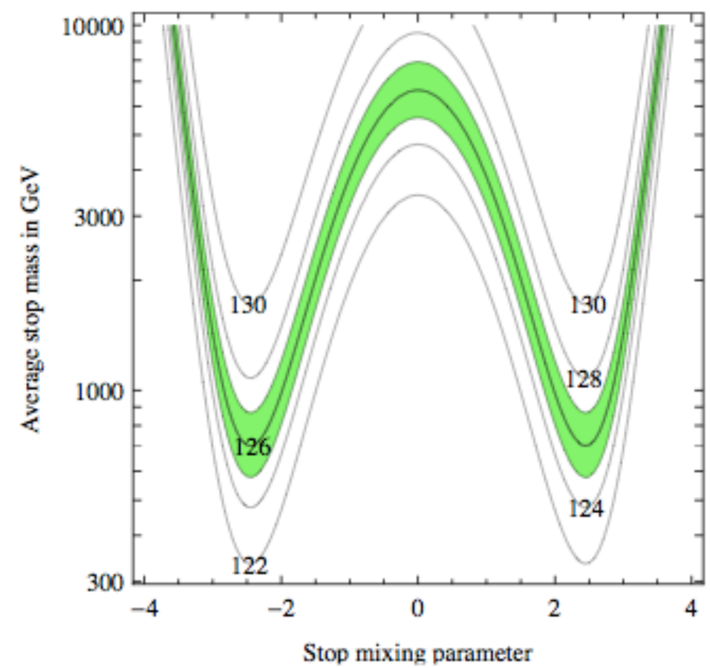
- The **Higgs boson mass** in the MSSM is determined (at 1-loop) by **EW parameters** and by the **stop masses and mixing**

$$m_h^2 = m_Z^2 \cos^2 2\beta + \frac{3y_t^2 m_t^2}{4\pi^2}\left[\log\left(\frac{m_S^2}{m_t^2}\right) + X_t^2\left(1 - \frac{X_t^2}{12}\right)\right] + \cdots$$

$$M_{\tilde{t}}^2 = \begin{pmatrix} m_{\tilde{t}_L}^2 + m_t^2 + D_L^t & m_t X_t \\ m_t X_t & m_{\tilde{t}_R}^2 + m_t^2 + D_R^t \end{pmatrix}$$

- Critical connection of stops and electroweakinos (actually higgsinos) **to the heart of the crucial argument in favour of EW-scale SUSY**
- Expect stops with mass **0.5-1 TeV max**, Higgsinos with mass **few hundreds GeV**

Exercise: derive the curve to the right



Stop/sbottom

- Supersymmetry dictates the existence of a **scalar partner** for every **fermionic degree of freedom**. In MSSM:

$$\begin{pmatrix} t_L \\ b_L \end{pmatrix}; t_R; b_R \rightarrow \begin{pmatrix} \tilde{t}_L \\ \tilde{b}_L \end{pmatrix}; \tilde{t}_R; \tilde{b}_R$$

- The **left and right chiral components** of the scalars have the **same couplings of the fermionic ones**

- And **they mix** to give mass eigenstates

$$M^2_{\tilde{t}} = \begin{pmatrix} m^2_{\tilde{t}_L} + m^2_t + D^t_L & m_t X_t \\ m_t X_t & m^2_{\tilde{t}_R} + m^2_t + D^t_R \end{pmatrix}$$

$$M^2_{\tilde{b}} = \begin{pmatrix} m^2_{\tilde{t}_L} + m^2_b + D^b_L & m_b X_b \\ m_b X_b & m^2_{\tilde{b}_R} + m^2_b + D^b_R \end{pmatrix}$$

Stop/sbottom

- Supersymmetry dictates the existence of a **scalar partner** for every **fermionic degree of freedom**. In MSSM:

$$\begin{pmatrix} t_L \\ b_L \end{pmatrix}; t_R; b_R \rightarrow \begin{pmatrix} \tilde{t}_L \\ \tilde{b}_L \end{pmatrix}; \tilde{t}_R; \tilde{b}_R$$

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$$M_{\tilde{b}}^2 = \begin{pmatrix} m_{\tilde{t}_L}^2 + m_b^2 + D_L^b & m_b X_b \\ m_b X_b & m_{\tilde{b}_R}^2 + m_b^2 + D_R^b \end{pmatrix}$$

- Same mass parameter for **stop and sbottom "left"**

Stop/sbottom

- Supersymmetry dictates the existence of a **scalar partner** for every **fermionic degree of freedom**. In MSSM:

$$\begin{pmatrix} t_L \\ b_L \end{pmatrix}; t_R; b_R \rightarrow \begin{pmatrix} \tilde{t}_L \\ \tilde{b}_L \end{pmatrix}; \tilde{t}_R; \tilde{b}_R$$

- The **left and right chiral components** of the scalars have the **same couplings of the fermionic ones**

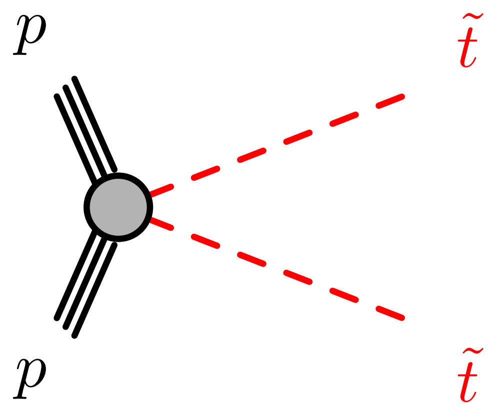
- And **they mix** to give mass eigenstates

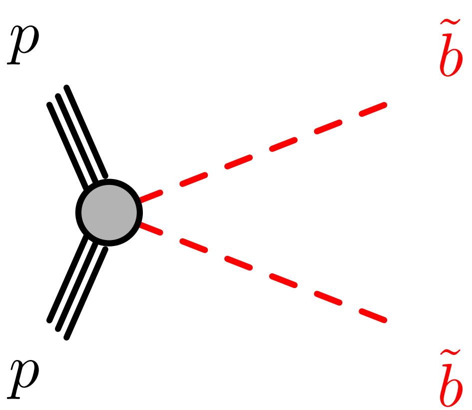
$$M_{\tilde{t}}^2 = \begin{pmatrix} m_{\tilde{t}_L}^2 + m_t^2 + D_L^t & m_t X_t \\ m_t X_t & m_{\tilde{t}_R}^2 + m_t^2 + D_R^t \end{pmatrix}$$

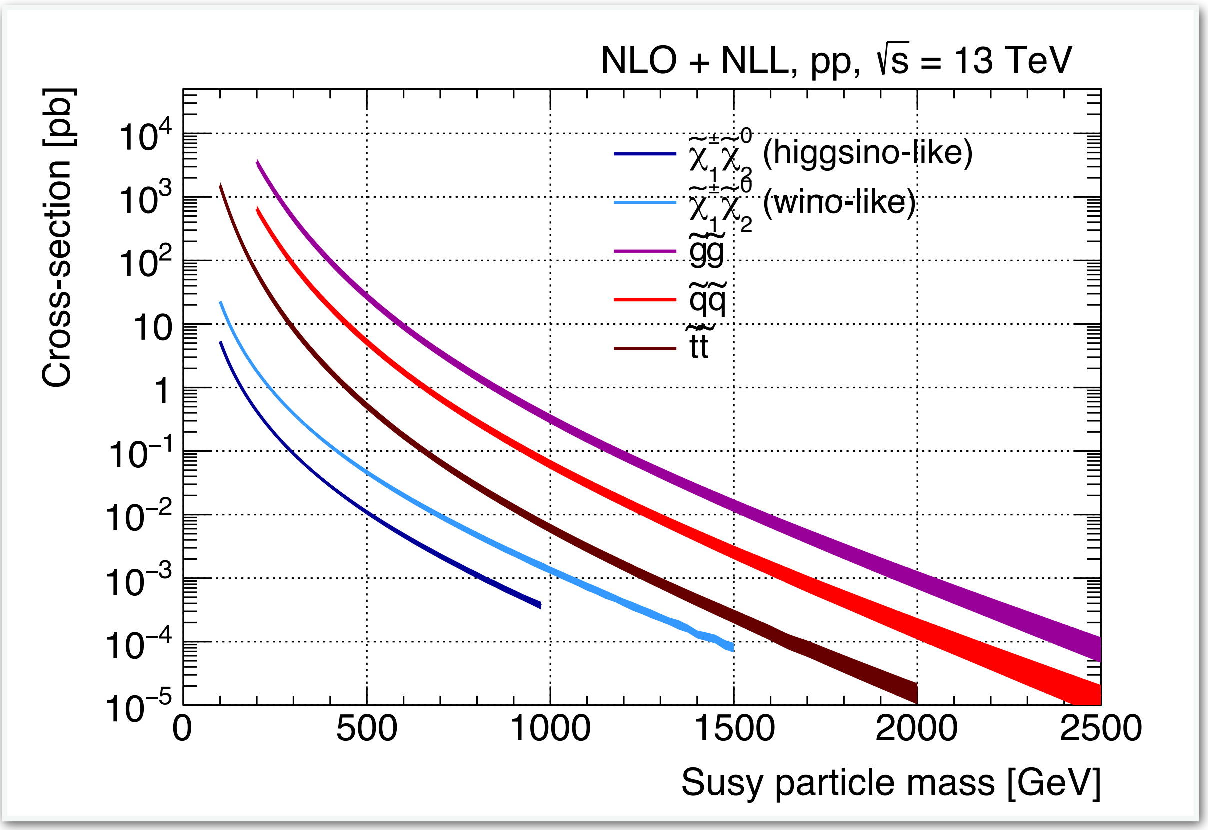
$$M_{\tilde{b}}^2 = \begin{pmatrix} m_{\tilde{t}_L}^2 + m_b^2 + D_L^b & m_b X_b \\ m_b X_b & m_{\tilde{b}_R}^2 + m_b^2 + D_R^b \end{pmatrix}$$

- Same mass parameter for **stop and sbottom "left"**
- Possibly **large mixing** between **left and right component** for stop

Direct stop (and/or bottom) pair production

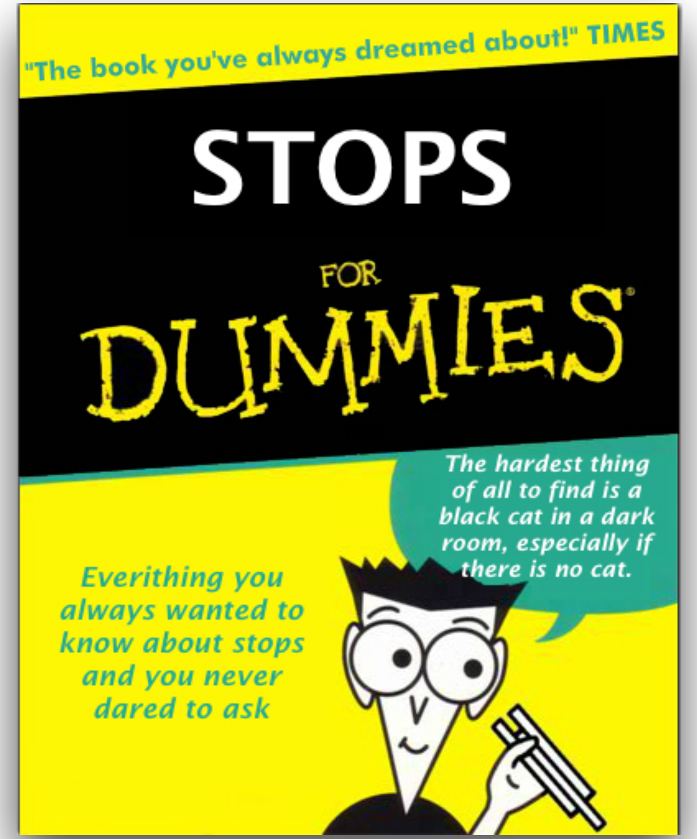






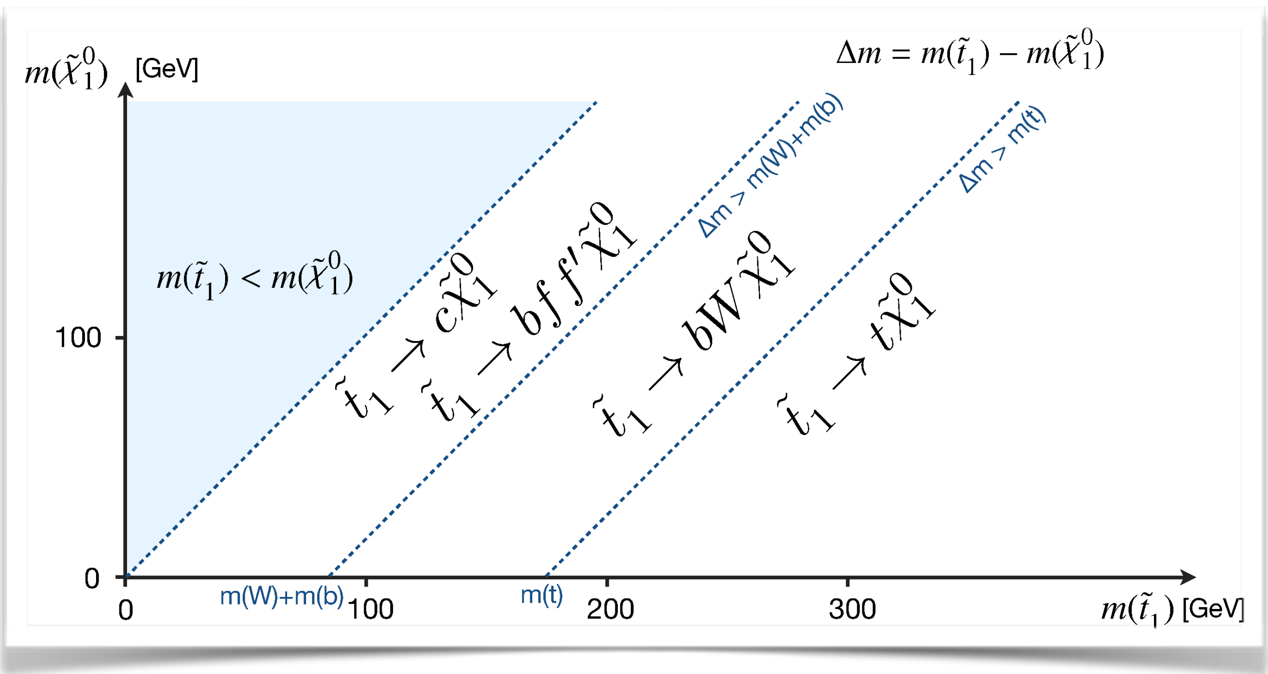
A one-page guide to stops

- Naturalness/hierarchy problem requires **relatively light stop(s)**
- A **light stop left** implies a **light sbottom left** (but a light stop right does not)
- Unless there is some conspiracy of SUSY parameters, **b-jets will be present in stop decay**
- For the stop, the phenomenology depends a lot on whether an **on-shell top quark** can be produced in the decay.
- Higgs mass constraints have (model dependent) implications on stop sector



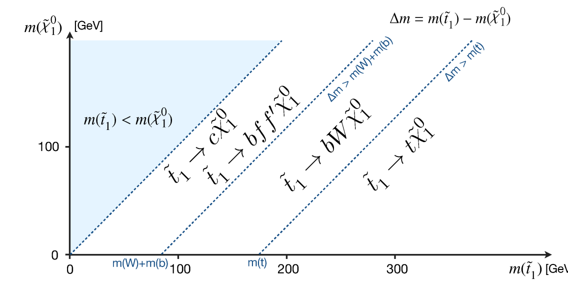
A well-motivated simplified model

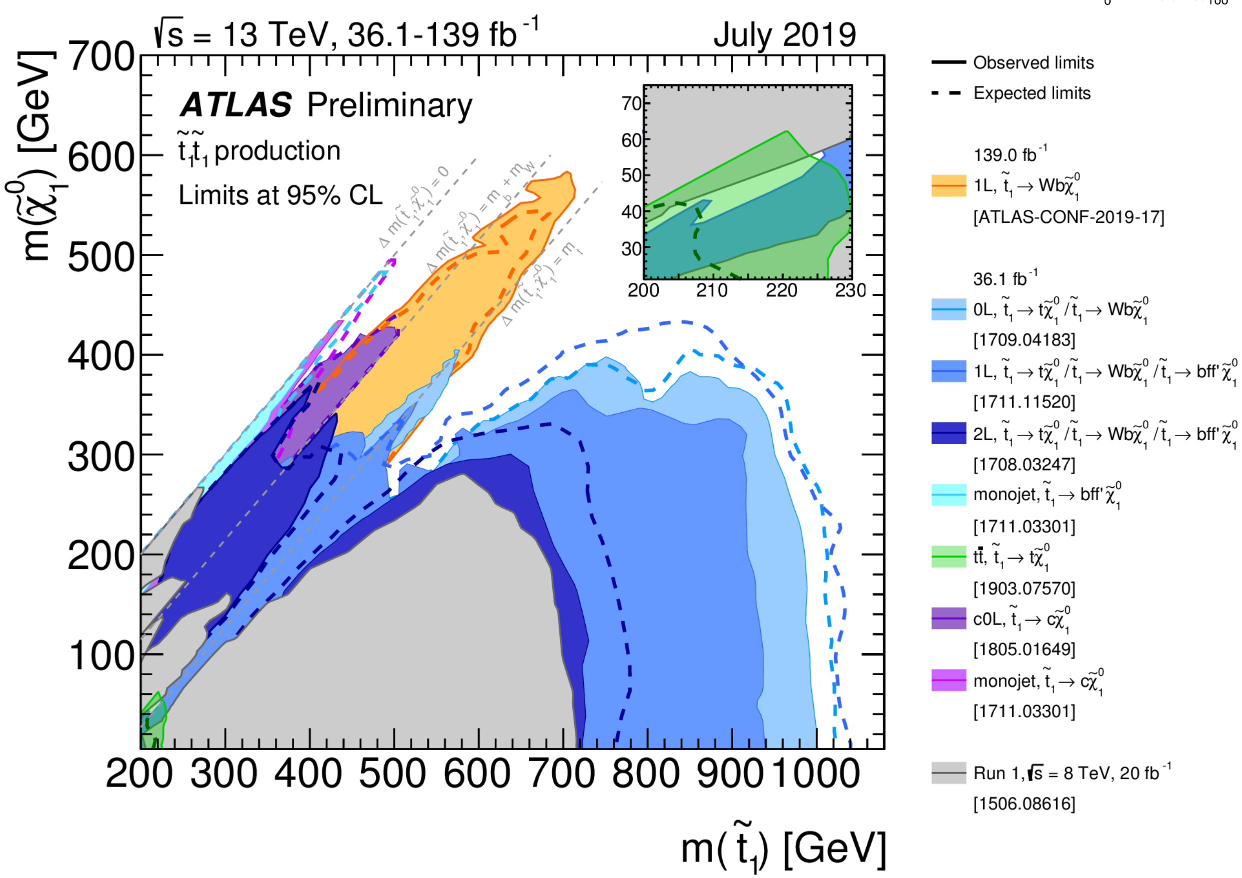
- Assuming **R-parity conservation**:
  - If **stop and neutralino** are the only light SUSY particles*
  - then the decay is $\tilde{t}_1 \rightarrow t^{(*)}\tilde{\chi}_1^0$ with 100% BR



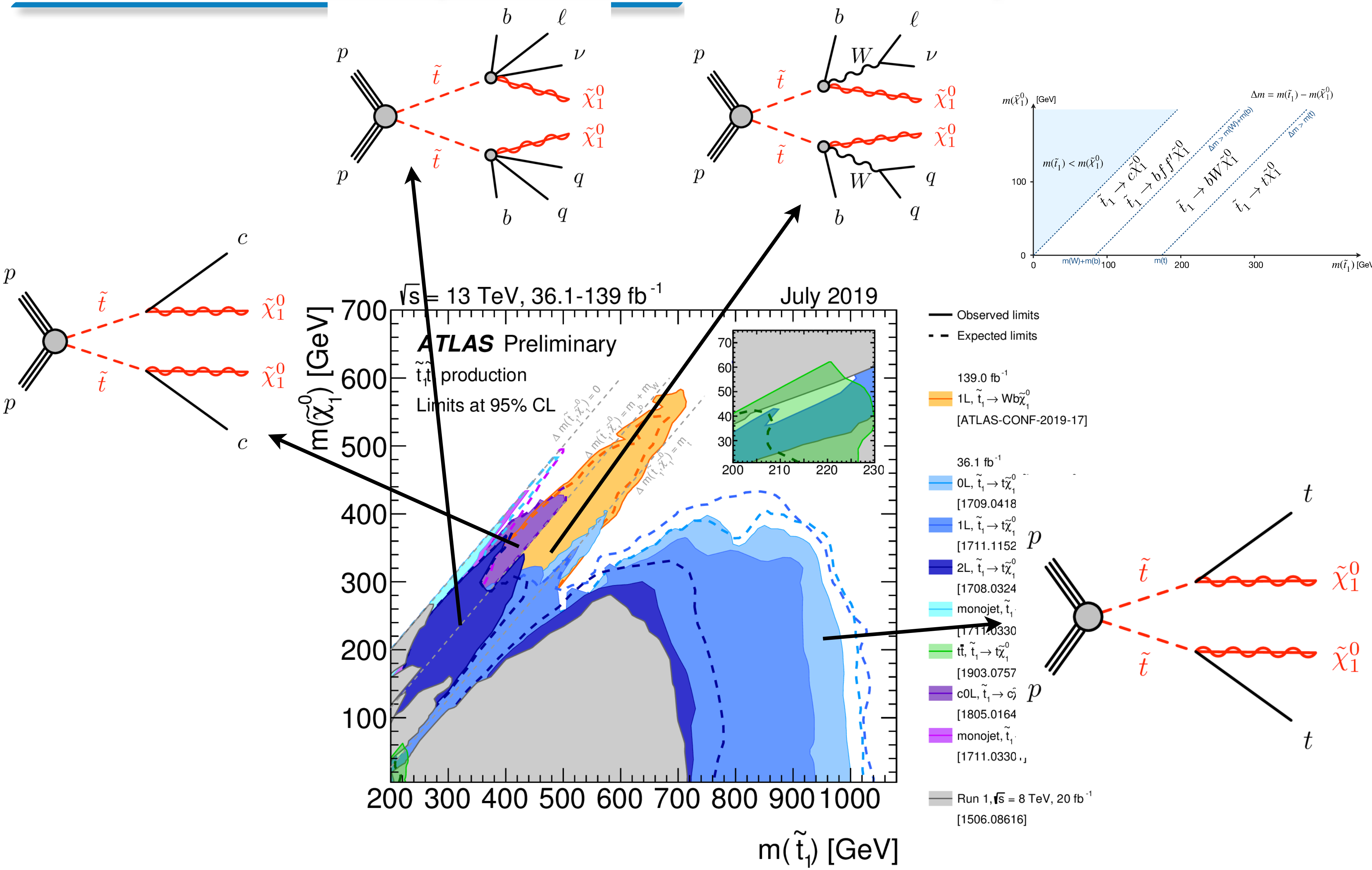
*OR **light stop** mostly **stop right** and **wino-like chargino** and the **LSP is a Bino**

A wealth of experimental techniques





A wealth of experimental techniques

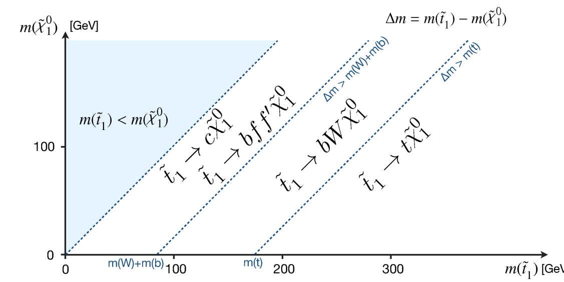


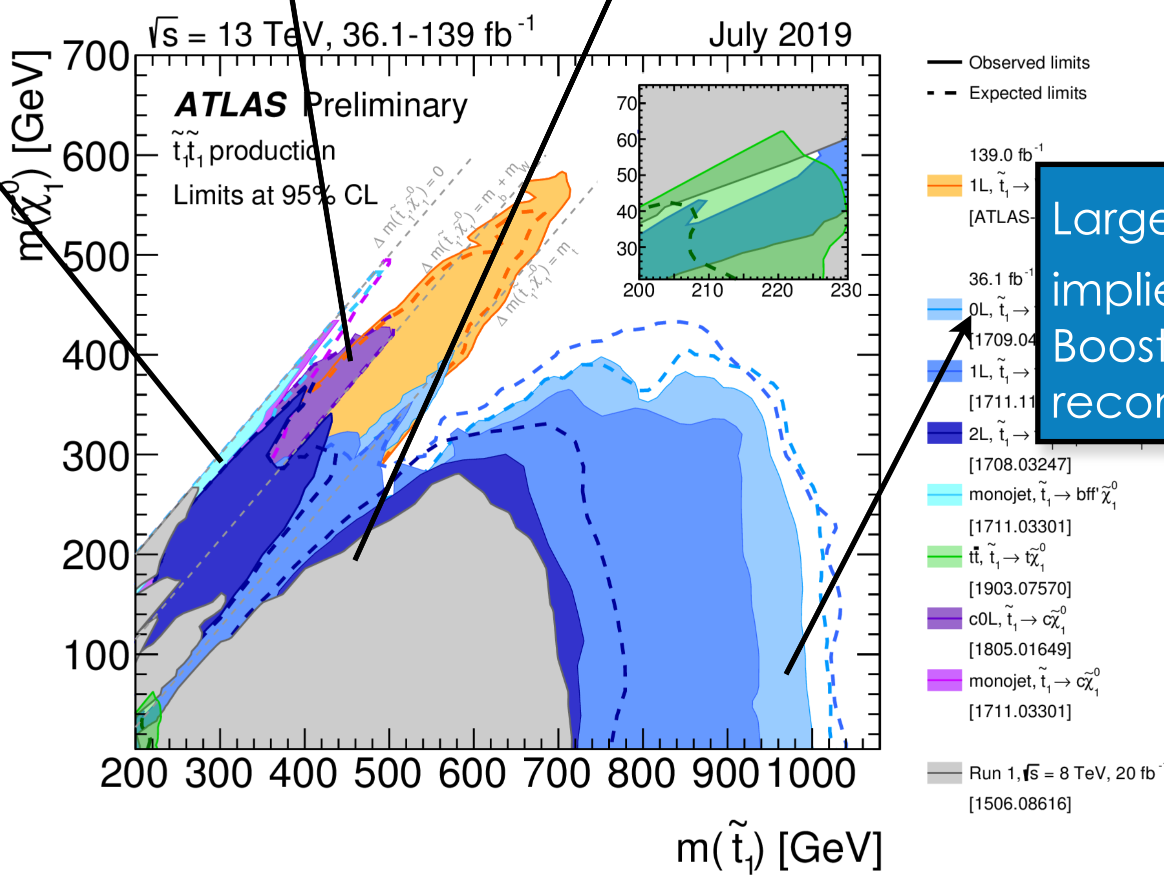
A wealth of experimental techniques

c-tagging

$$\frac{E_T^{miss}}{p_T^{ISR}} \sim \frac{m_{\tilde{\chi}_0^1}}{m_{\tilde{t}_1}}$$

Mono-jet





Large $\Delta m = m_{\tilde{t}_1} - m_{\tilde{\chi}_0^1}$ implies large top boost. Boosted top reconstruction

plus transverse mass variables, plus all techniques for the bX decay...

The electroweak sector - reminder

- Neutralinos and charginos are **fermionic states**. In MSSM: they arise from the mixing of **Standard Model B and W fields**, and of the **two Higgs doublets**. The mixing matrices are

$$\mathbf{M}_{\tilde{N}} = \begin{pmatrix} M_1 & 0 & -c_\beta\, s_W\, m_Z & s_\beta\, s_W\, m_Z \\ 0 & M_2 & c_\beta\, c_W\, m_Z & -s_\beta\, c_W\, m_Z \\ -c_\beta\, s_W\, m_Z & c_\beta\, c_W\, m_Z & 0 & -\mu \\ s_\beta\, s_W\, m_Z & -s_\beta\, c_W\, m_Z & -\mu & 0 \end{pmatrix}$$

$$\mathbf{M}_{\tilde{C}} = \begin{pmatrix} \mathbf{0} & \mathbf{X}^T \\ \mathbf{X} & \mathbf{0} \end{pmatrix}$$

$$\mathbf{X} = \begin{pmatrix} M_2 & g v_u \\ g v_d & \mu \end{pmatrix} = \begin{pmatrix} M_2 & \sqrt{2} s_\beta\, m_W \\ \sqrt{2} c_\beta\, m_W & \mu \end{pmatrix}$$

The electroweak sector - reminder

- Neutralinos and charginos are **fermionic states**. In MSSM: they arise from the mixing of **Standard Model B and W fields**, and of the **two Higgs doublets**. The mixing matrices are

Bino mass parameter

Wino mass parameter

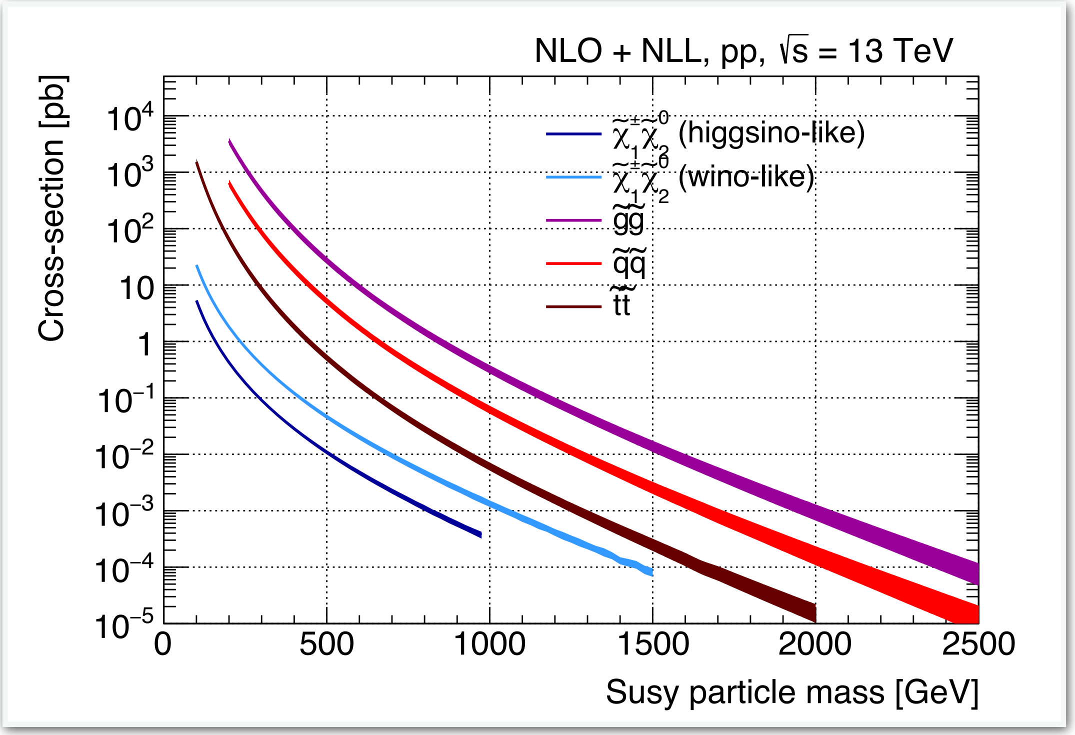
$$\mathbf{M}_{\tilde{N}} = \begin{pmatrix} M_1 & 0 & -c_\beta\, s_W\, m_Z & s_\beta\, s_W\, m_Z \\ 0 & M_2 & c_\beta\, c_W\, m_Z & -s_\beta\, c_W\, m_Z \\ -c_\beta\, s_W\, m_Z & c_\beta\, c_W\, m_Z & 0 & -\mu \\ s_\beta\, s_W\, m_Z & -s_\beta\, c_W\, m_Z & -\mu & 0 \end{pmatrix}$$

Higgsino mass parameter

$$\mathbf{M}_{\tilde{C}} = \begin{pmatrix} \mathbf{0} & \mathbf{X}^T \\ \mathbf{X} & \mathbf{0} \end{pmatrix}$$

$$\mathbf{X} = \begin{pmatrix} M_2 & g v_u \\ g v_d & \mu \end{pmatrix} = \begin{pmatrix} M_2 & \sqrt{2} s_\beta\, m_W \\ \sqrt{2} c_\beta\, m_W & \mu \end{pmatrix}$$

Lower cross sections for the same mass



Production cross sections small (because of EW couplings)

…and dependent on electroweakino's actual composition

The electroweak sector

“Standard Model”
(scalars and vectors,
before EW simmetry breaking)

$$B$$
$$\vec{W}$$
$$H_u, H_d$$

The electroweak sector

"Standard Model"
(scalars and vectors,
before EW simmetry breaking)

SUSY partners (fermions)

"Standard Model"		SUSY partners	
B	$\Rightarrow$	$\tilde{B}$	b-ino, 1 neutral state
$\vec{W}$		$\tilde{W}$	w-ino, 1 neutral, 2 charged states
H_u, H_d		$\tilde{h}$	higgs-ino, 2 neutral, 2 charged states

The electroweak sector

"Standard Model"
(scalars and vectors,
before EW simmetry breaking)

$$B$$
$$\vec{W}$$
$$H_u, H_d$$

SUSY partners (fermions)

$\tilde{B}$ b-ino, 1 neutral state

$\tilde{W}$ w-ino, 1 neutral, 2 charged states

$\tilde{h}$ higgs-ino, 2 neutral, 2 charged states

$$\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$$
$$\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$$

The electroweak sector

“Standard Model”
(scalars and vectors,
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B
$\vec{W}$
H_u, H_d

$\Rightarrow$

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$\tilde{B}$ b-ino, 1 neutral state

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$\tilde{h}$ higgs-ino, 2 neutral, 2 charged states

$\Rightarrow$

$\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$
$\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$

Let’s neglect the mixing

The electroweak sector

“Standard Model”
(scalars and vectors,
before EW simmetry breaking)

SUSY partners (fermions)

B, $\vec{W}$, H_u, H_d ⇒

$\tilde{B}$ b-ino, 1 neutral state

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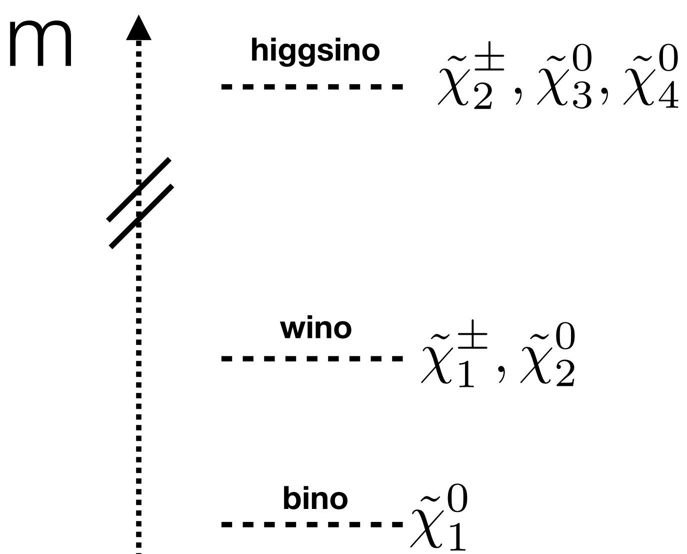
⇒ $\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$
$\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$

Let’s neglect the mixing

wino-bino ($\mu \gg M_2 > M_1$)



The electroweak sector

"Standard Model"
(scalars and vectors,
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B
$\vec{W}$
H_u, H_d

⇒

SUSY partners (fermions)

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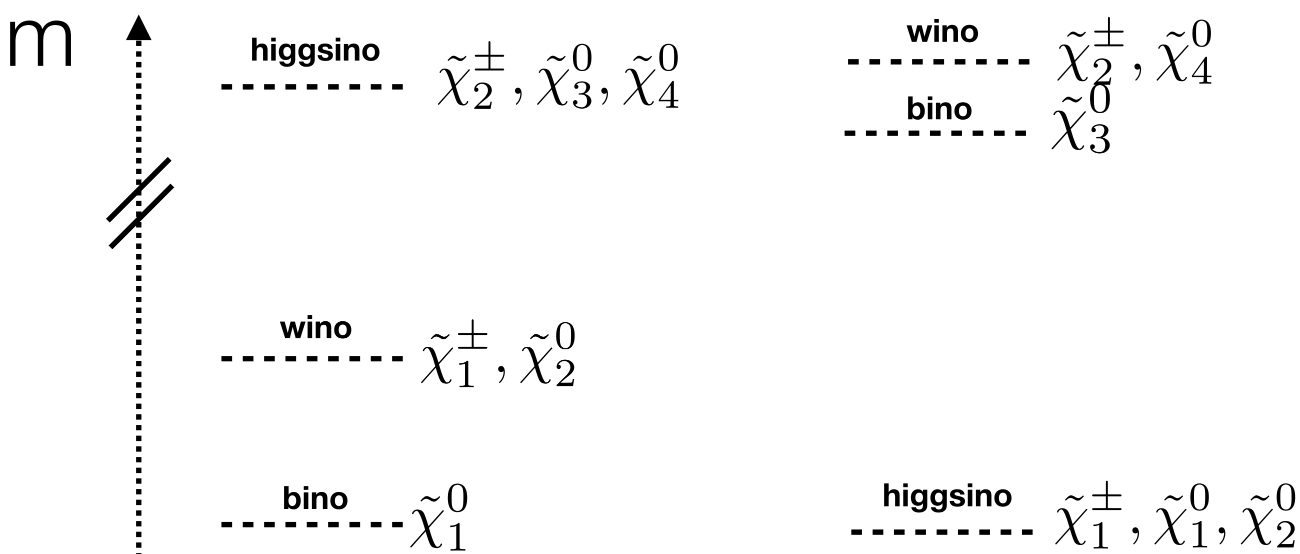
⇒

$\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$
$\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$

Let's neglect the mixing

wino-bino ($\mu \gg M_2 > M_1$)

higgsino LSP ($M_2, M_1 \gg \mu$)



The electroweak sector

"Standard Model"
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B
$\vec{W}$
H_u, H_d

$\Rightarrow$

SUSY partners (fermions)

$\tilde{B}$ b-ino, 1 neutral state

$\tilde{W}$ w-ino, 1 neutral, 2 charged states

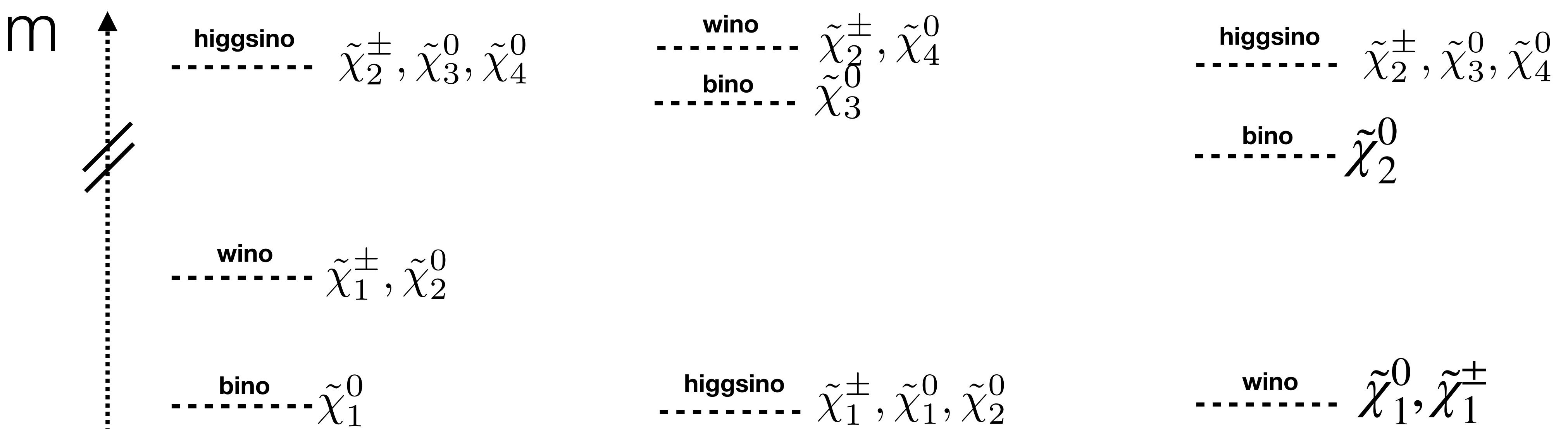
$\tilde{h}$ higgs-ino, 2 neutral, 2 charged states

$\Rightarrow$

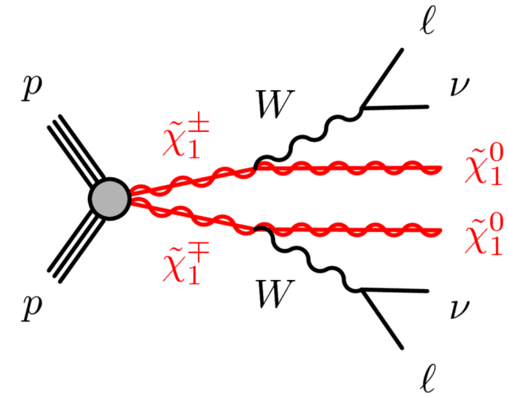
$\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$
$\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$

Let's neglect the mixing

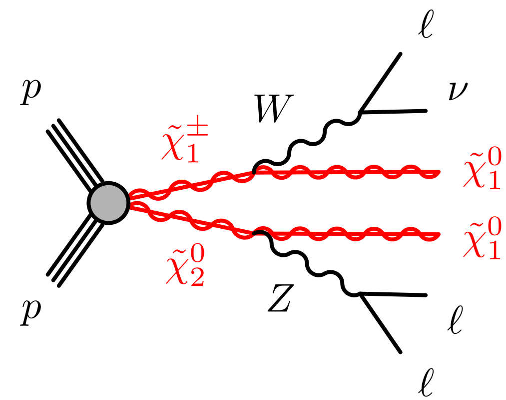
wino-bino ($\mu \gg M_2 > M_1$) | higgsino LSP ($M_2, M_1 \gg \mu$) | Wino LSP ($\mu, M_1 \gg M_2$)



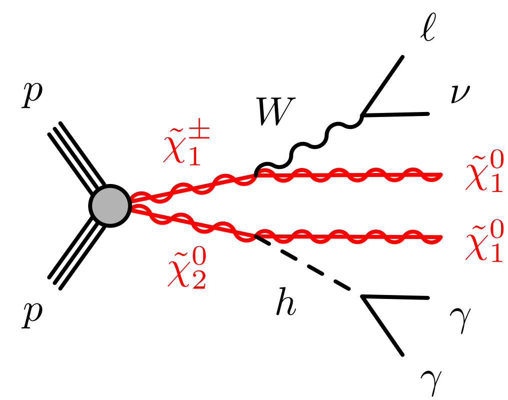
Wino-bino



- One of the **most studied scenarios**
- WW final state studied mostly in **di-lepton final state**
- WZ mostly three-lepton and di-lepton final states



- Wh offers many different channels depending on Higgs boson decay



Wino-bino

- One of the **most studied scenarios**
- WW final state studied mostly in **di-lepton final state**
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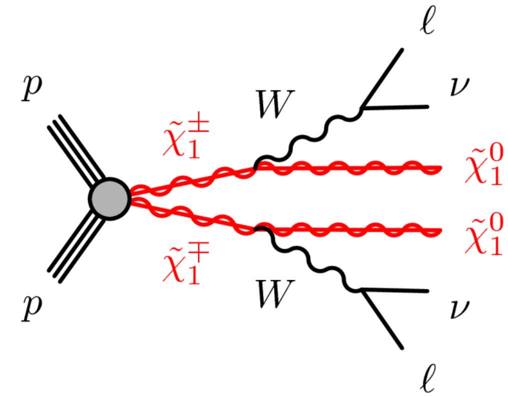
wino-bino

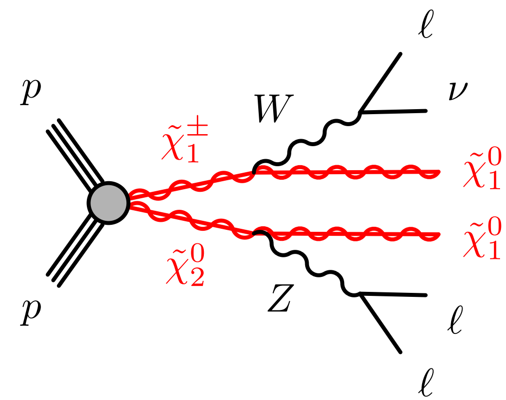
higgsino $\tilde{\chi}_2^{\pm}, \tilde{\chi}_3^0, \tilde{\chi}_4^0$

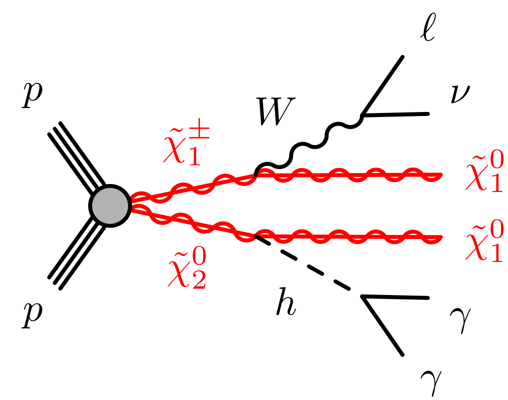
wino $\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$

bino $\tilde{\chi}_1^0$

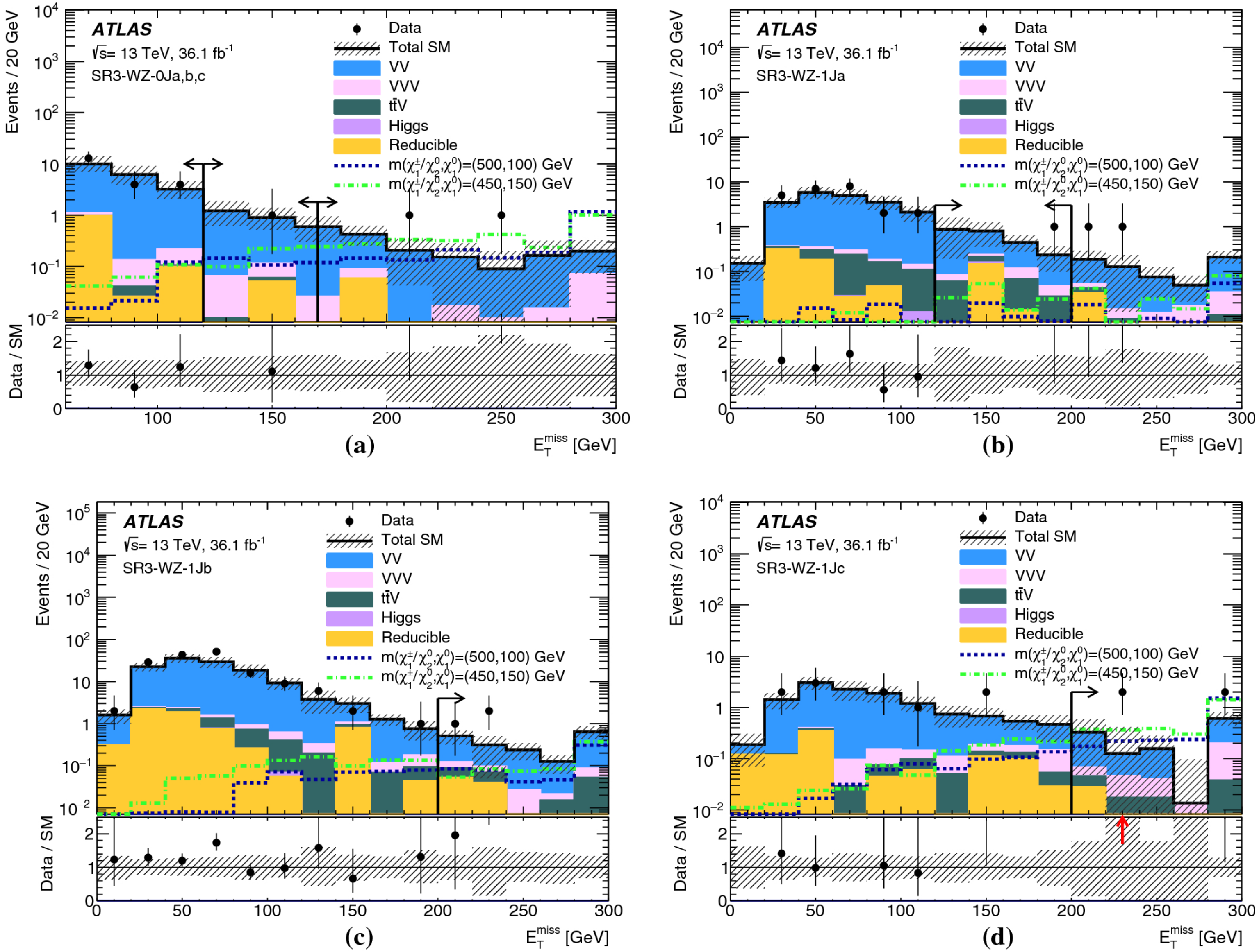
- Wh offers many different channels depending on Higgs boson decay





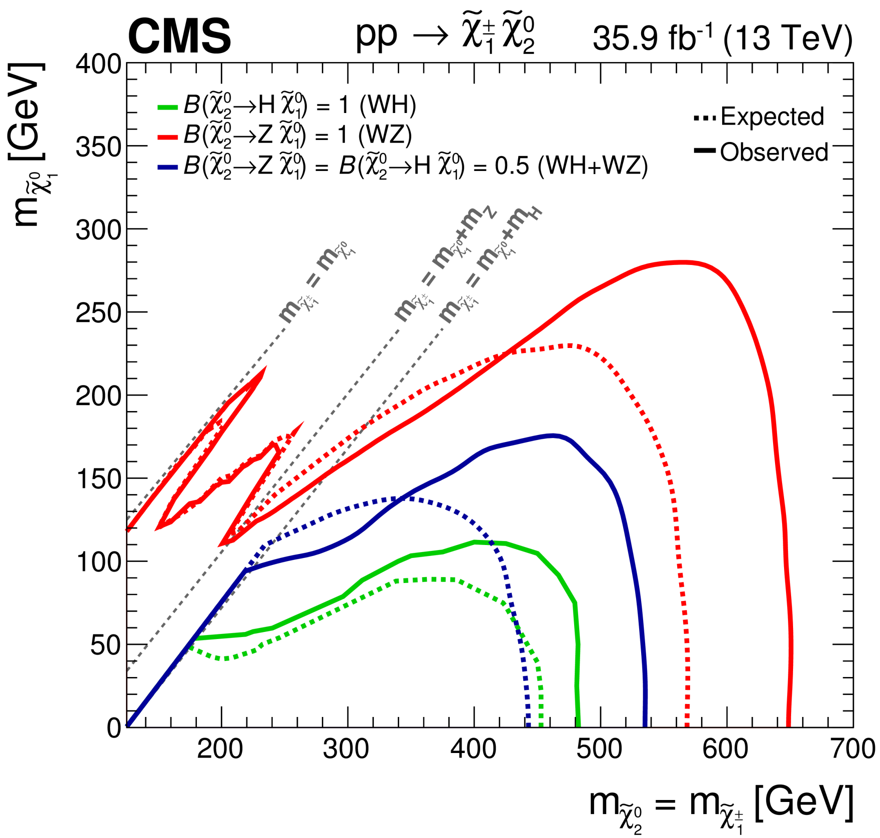


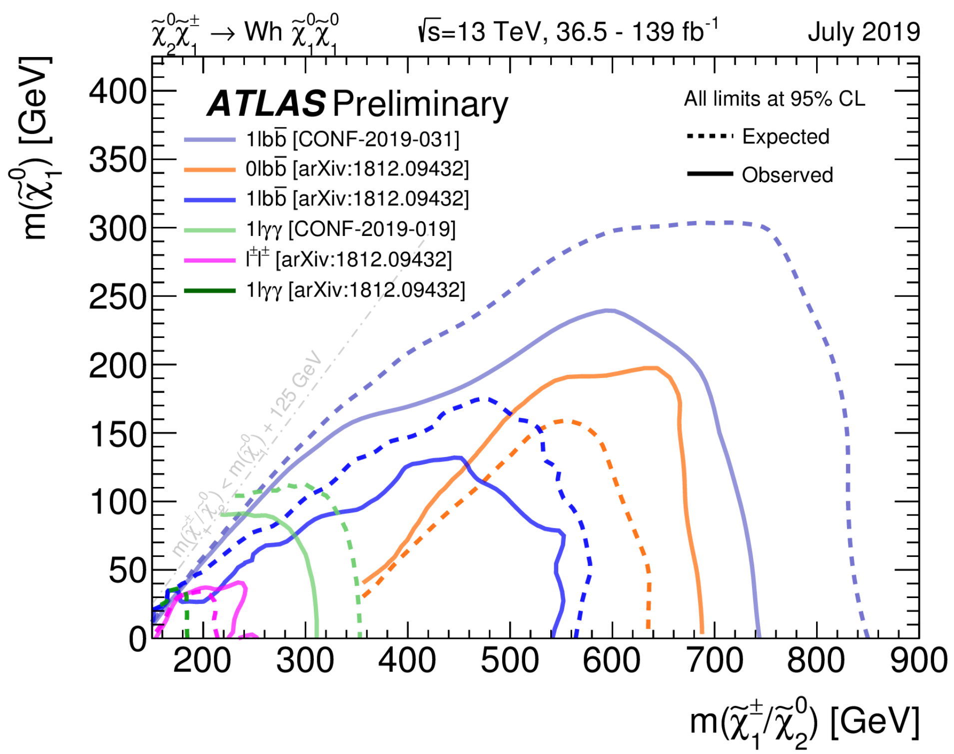
Wino-Bino- typical background composition



Wino-Bino - results

- Many more results and interpretations available





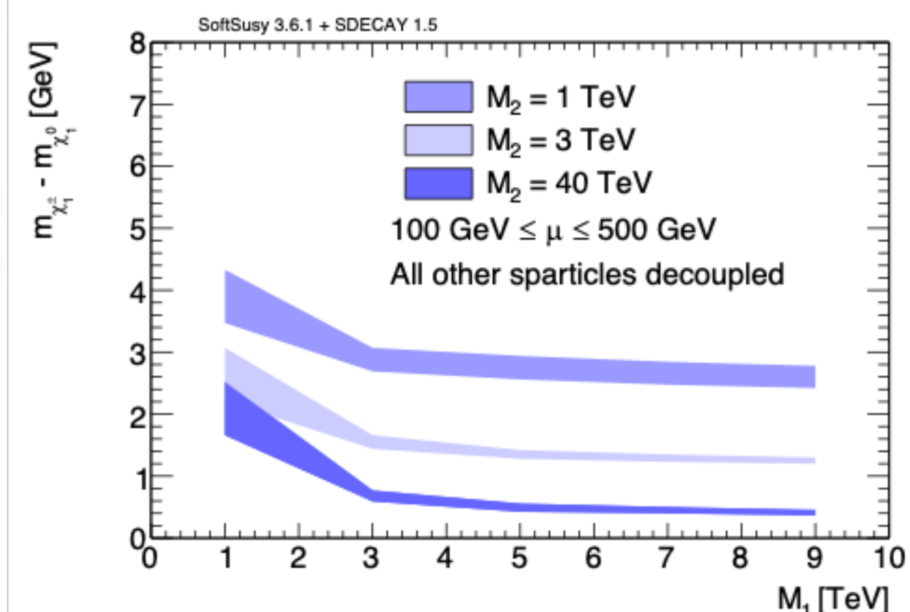
Higgsino LSP

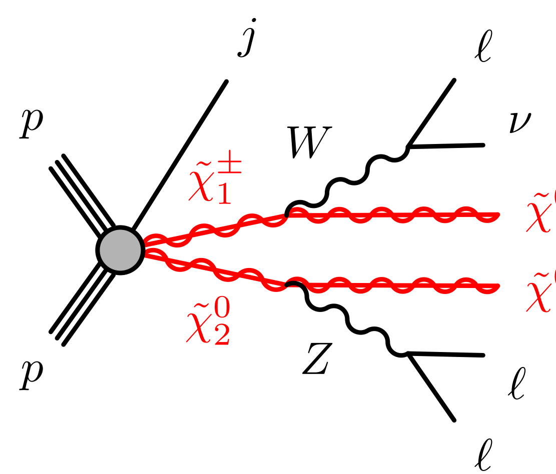
$$\mathbf{M}_{\tilde{N}} = \begin{pmatrix} M_1 & 0 & -c_\beta\, s_W\, m_Z & s_\beta\, s_W\, m_Z \\ 0 & M_2 & c_\beta\, c_W\, m_Z & -s_\beta\, c_W\, m_Z \\ -c_\beta\, s_W\, m_Z & c_\beta\, c_W\, m_Z & 0 & -\mu \\ s_\beta\, s_W\, m_Z & -s_\beta\, c_W\, m_Z & -\mu & 0 \end{pmatrix}$$

- Going at the heart of the hierarchy problem…
- Nearly degenerate (mass splitting $\Delta m = o(10\text{ GeV})$ or less) triplet of states
- Production of $\tilde{\chi}_2^0\tilde{\chi}_1^\pm$, $\tilde{\chi}_2^0\tilde{\chi}_1^0$, $\tilde{\chi}_2^\pm\tilde{\chi}_1^\pm$, $\tilde{\chi}_2^\pm\tilde{\chi}_1^0$ followed by

$$\tilde{\chi}_2^0 \to W^{(*)}\tilde{\chi}_1^\pm \quad \tilde{\chi}_2^0 \to Z^{(*)}\tilde{\chi}_1^0 \quad \tilde{\chi}_1^\pm \to W^{(*)}\tilde{\chi}_1^0$$

- Low p_T objects and small E_T^{miss}…..
- …. unless one aims for boosted charginos and neutralinos!

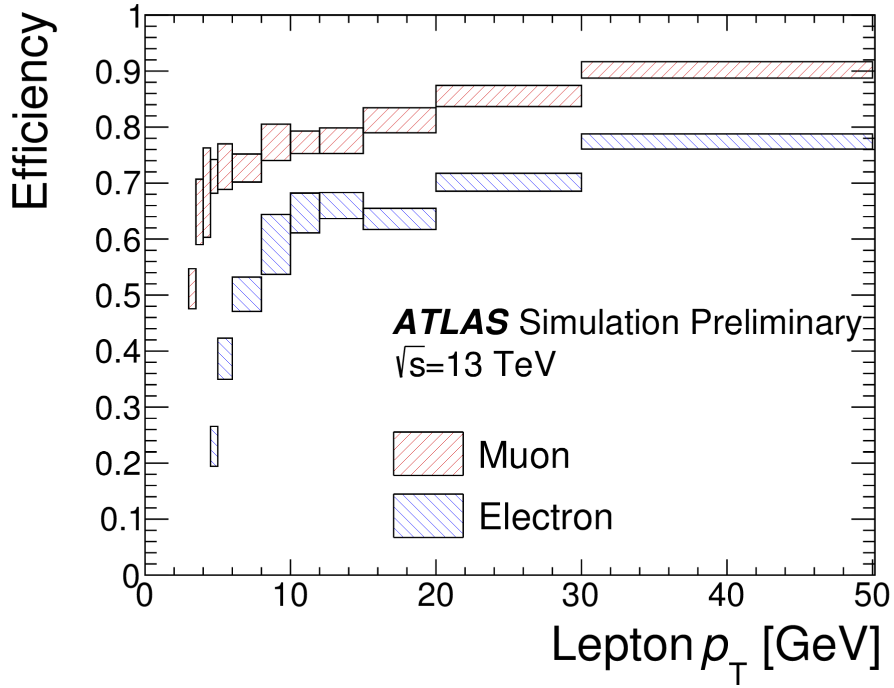


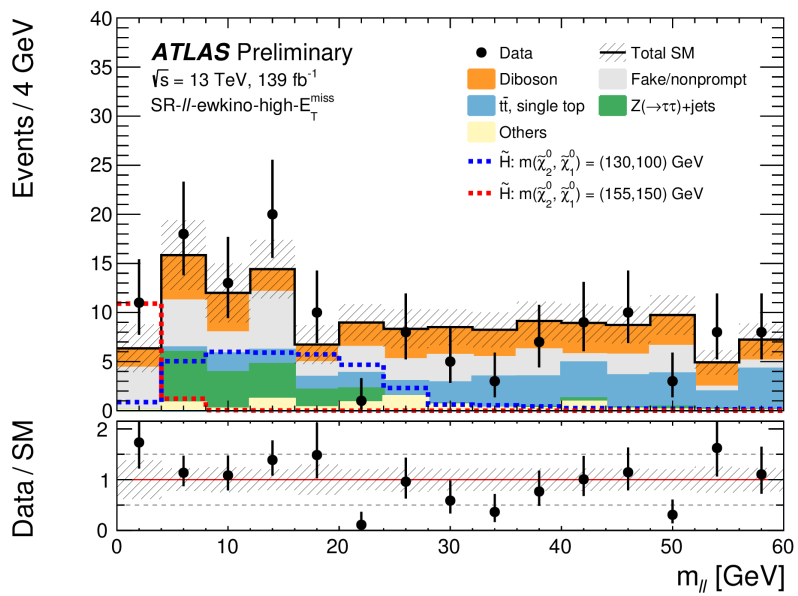


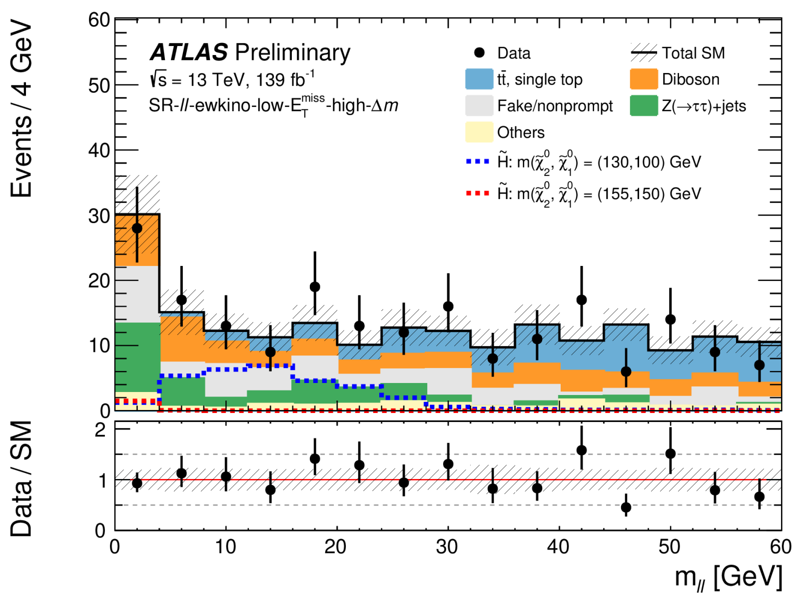
Exercise: assume $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 10\text{ GeV}$, $p_T^{ISR} = 200\text{ GeV}$, $m(\tilde{\chi}_2^0) = 100\text{ GeV}$. What is p_T^{miss} on average? And p_T^{lep}?

Higgsino LSP - strategy

- Search the m_{ll} spectrum in **di-lepton events** with an Initial State Radiation (ISR) jet and E_T^{miss}
- Sensitivity to low p_T leptons crucial
  - Use also single track plus identified lepton

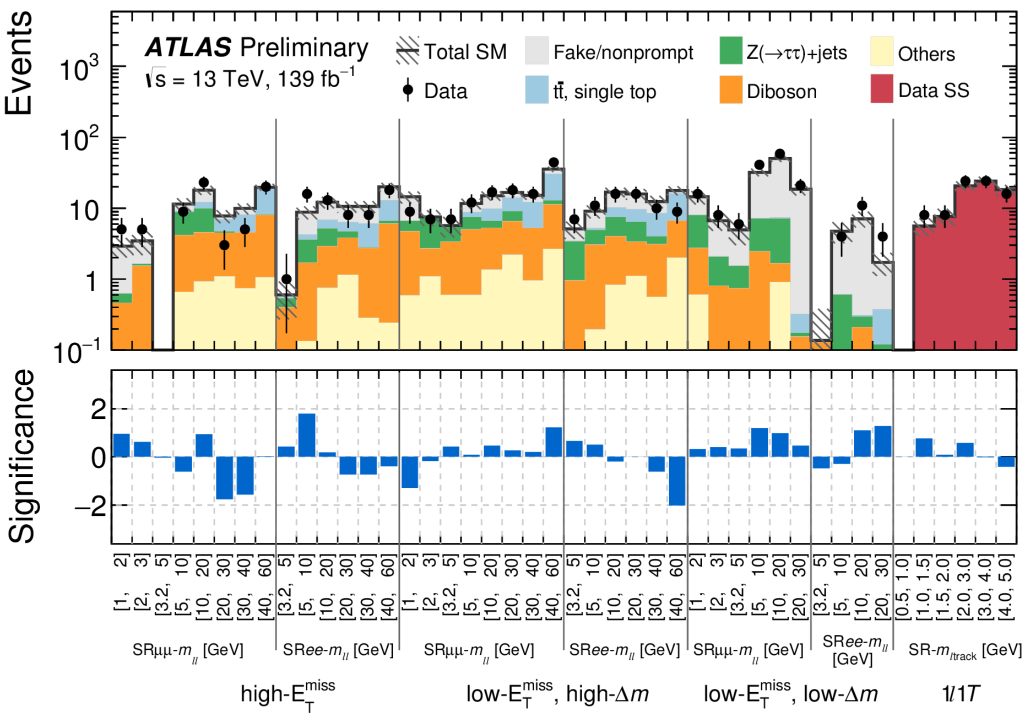


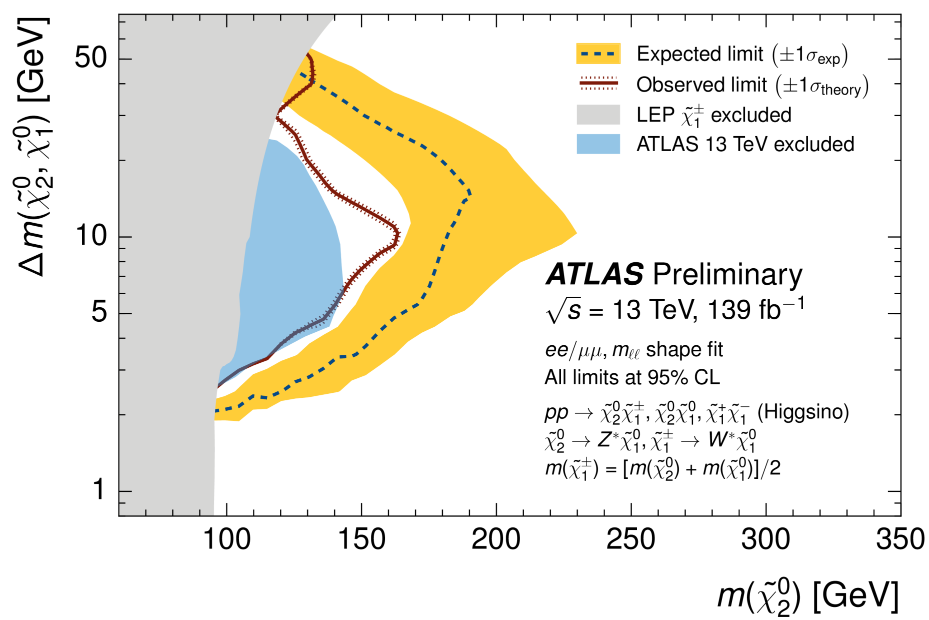




Higgsino LSP

- LHC sensitivity slowly overcoming that of LEP
- Large progress on this front expected with Run 3 and later with HL-LHC





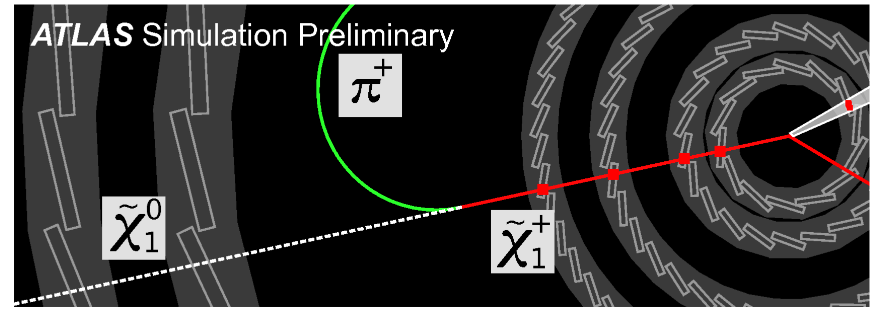
Long lived Higgsinos

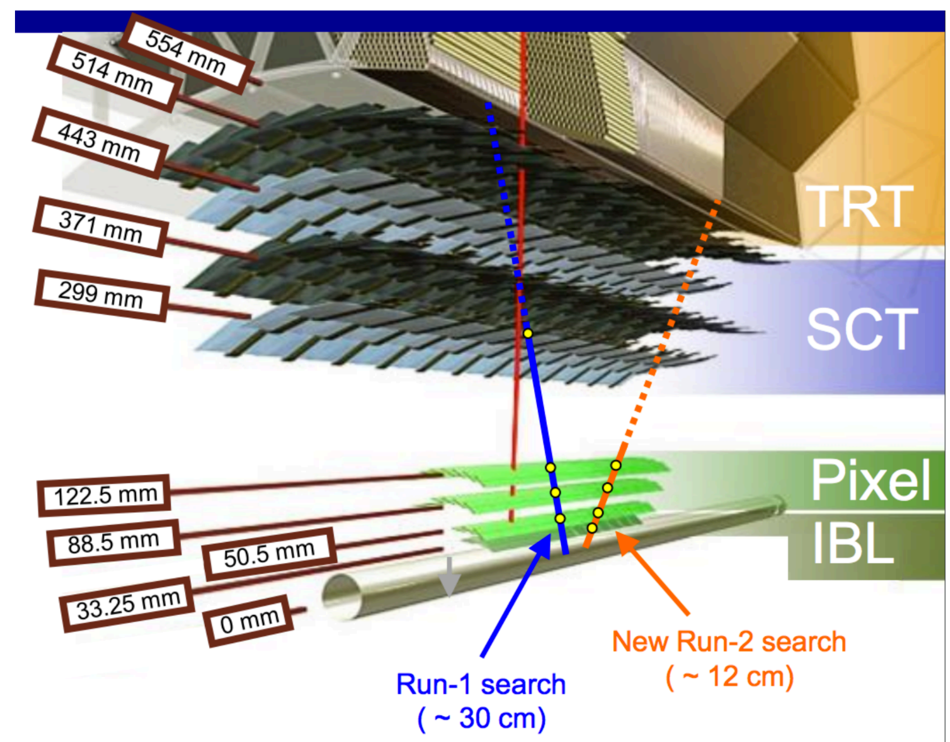
JHEP 06 (2018) 022

JHEP 08 (2018) 016

- In the extreme case (large M_1,M_2), the mass separation between Higgsinos is ~ 350 MeV,
- Similarly, Wino LSP has mass separation of ~150 MeV
- The mother particle **becomes long-lived** (typical cτ~ 0.8 cm for higgsinos, 6 cm for winos).

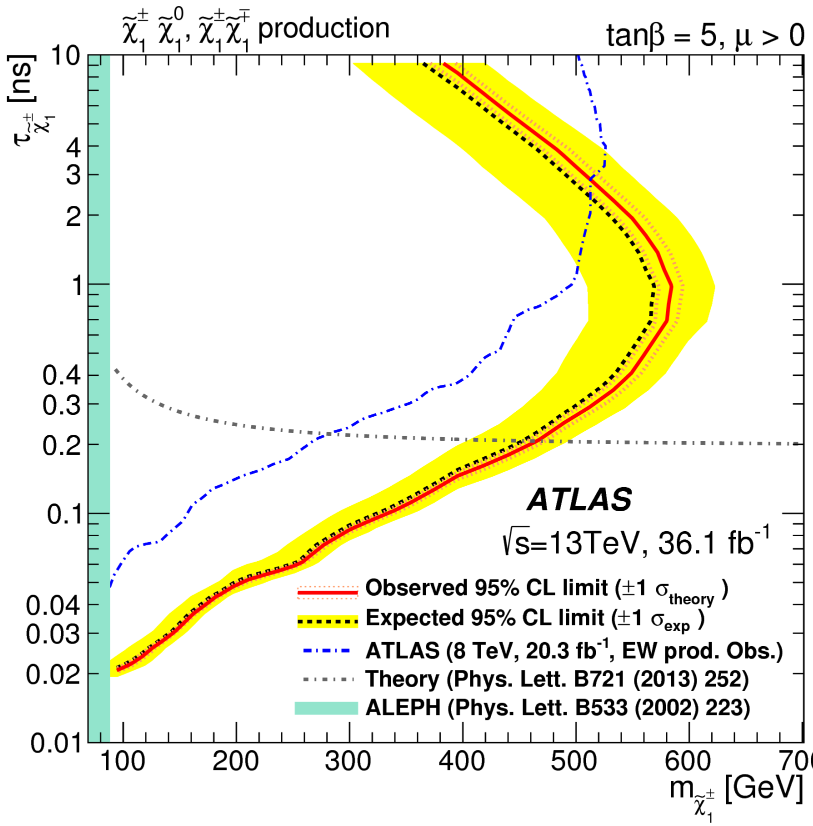
$$\Gamma(\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 \pi^\pm) = \frac{G_F^2}{\pi} \cos^2\vartheta_c \, f_\pi^2 \delta m^3 \sqrt{1 - \frac{m_\pi^2}{\delta m^2}}$$



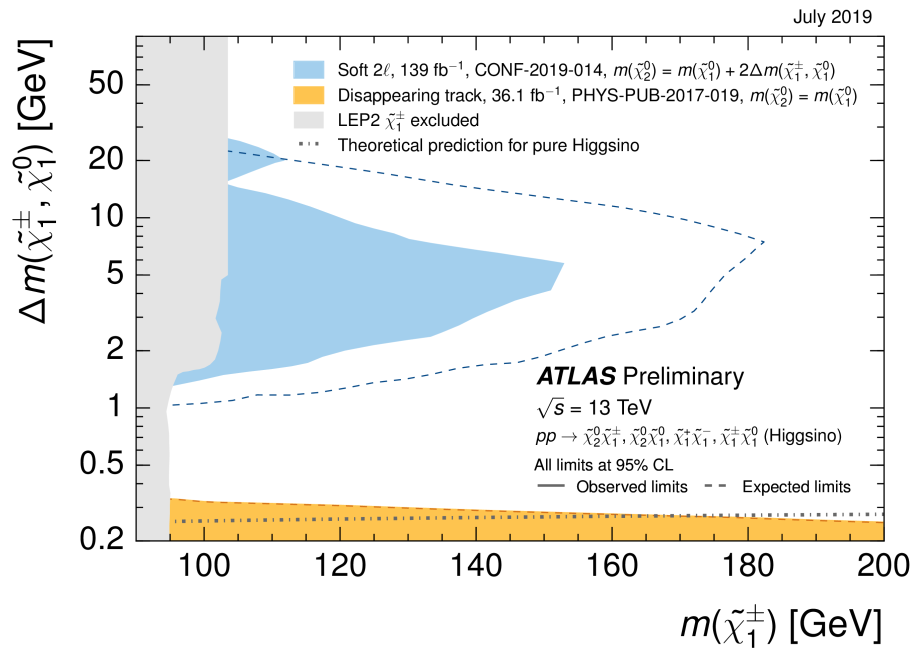


Results

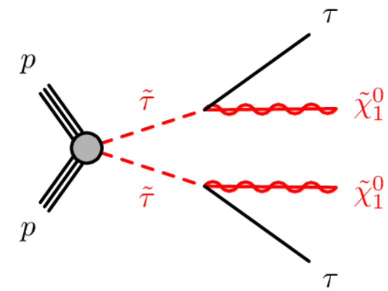
Wino



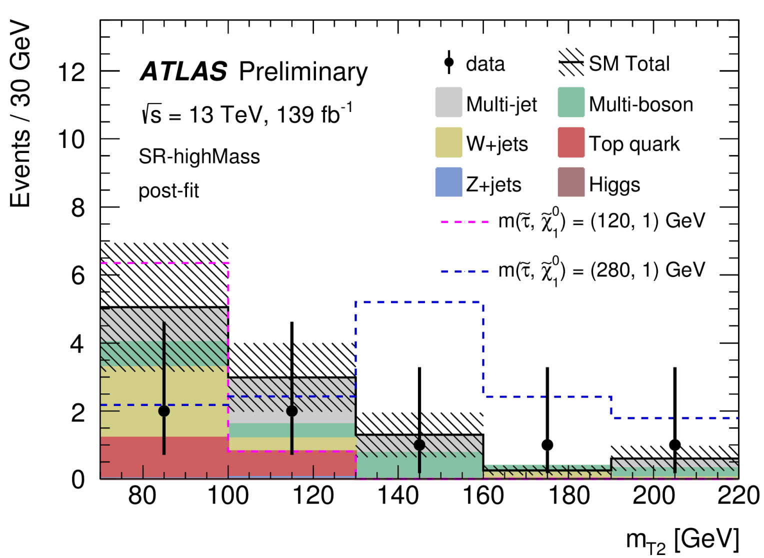
Higgsino

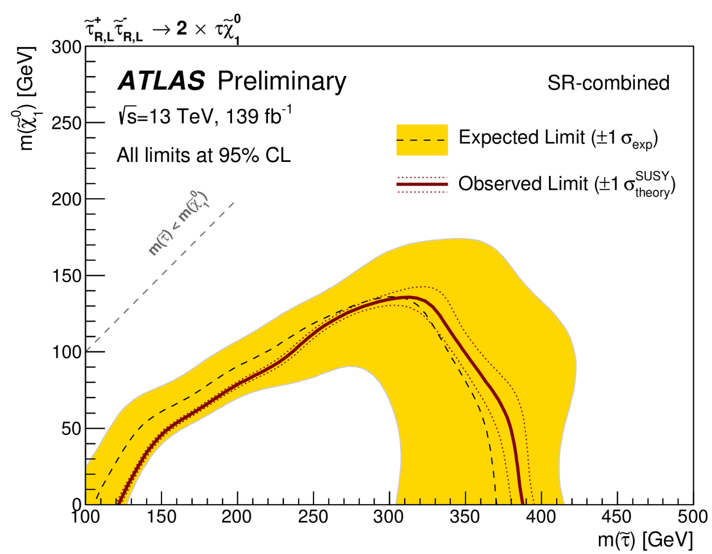


Sleptons



- Pair production of 1st and 2nd generation sleptons would lead to Opposite Sign Same Flavour lepton pairs
  - Relatively well constrained experimentally
- Recent exciting results on direct stau production are a highlight for full Run 2
  - Also because of connection with Dark Matter.





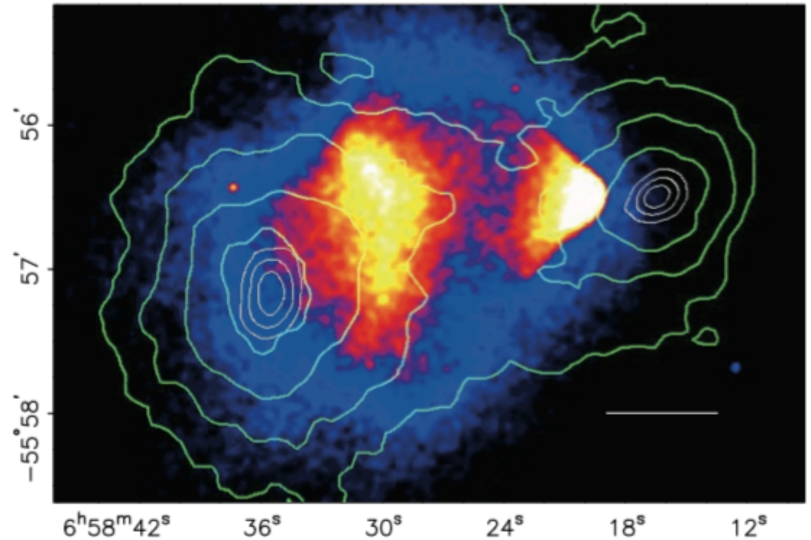
Summary (EW scale supersymmetry)

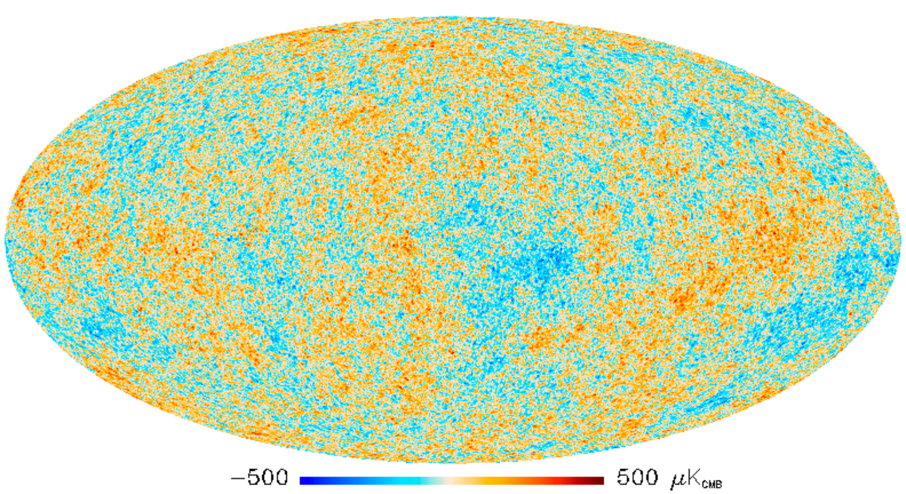
- **No evidence for SUSY processes** at the LHC (or elsewhere)
- Limits are **always model dependent** to some extent. Limits on specific simplified models **uncomfortably tight**
  - Especially those on gluinos and stops…
  - But limits **a lot more relaxed** in less simplified models (more true for stops than for gluinos)
- Crucial targets like **direct higgsinos** and **staus** are getting enough sensitivity only ~ now.
- General disbelief in the community, mainly lead by **clash of current LHC exclusion limits and future discovery prospects**
  - … but a solid excess may still appear

Dark matter

Dark matter evidence

- We inferred the existence of dark matter from its **gravitational interaction** with ordinary matter and radiation
  - "Anomalous" galaxy's rotational speed, gravitational lensing point, evolution of large-scale structure point to the existence of more "stuff" than we see. Modifications to gravity on large scale do not seem able to account for all observations (see D. Clowe et al., Astrophysics J. 648 (2006) L109)



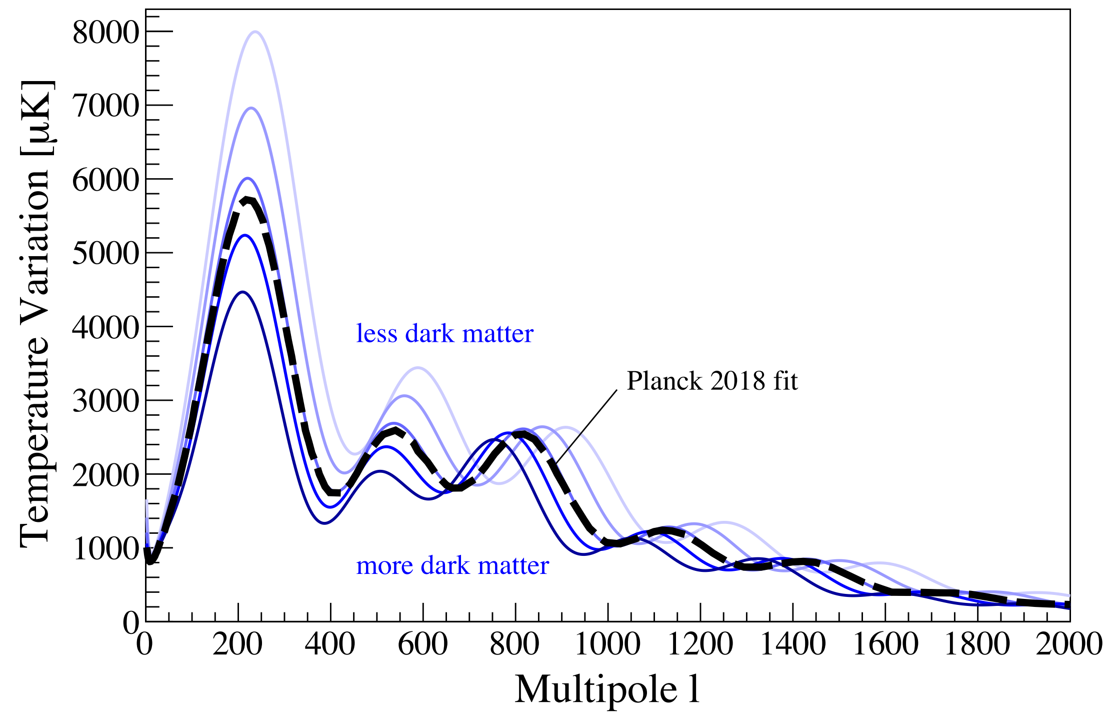


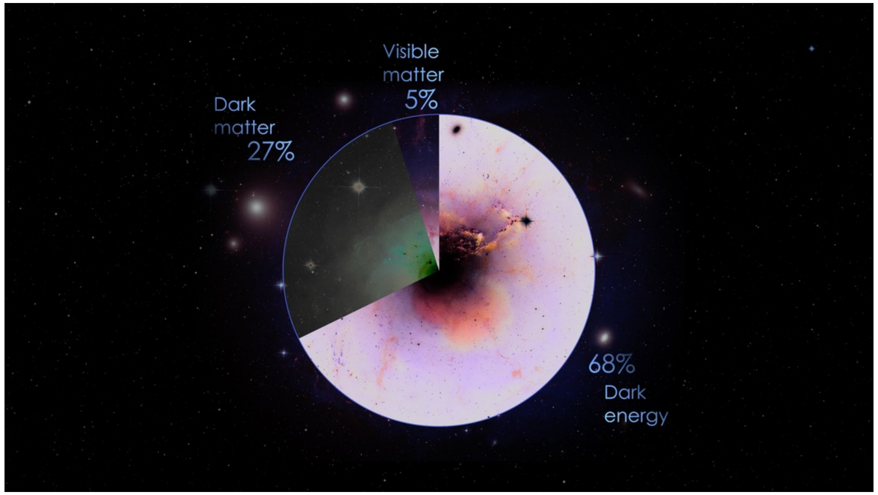
- **Quantitative estimate** about dark matter density coming (mainly) from **fits to Cosmic Microwave Background** (CMB) temperature anisotropies.

CMB fits and dark matter

- Multipole fit to two point temperature anisotropies:
  - Well described by ΛCDM model (which includes cosmological constant and a cold dark matter component)
  - See for example, the Planck Collaboration results.

Taken from arXiv:1903.03026





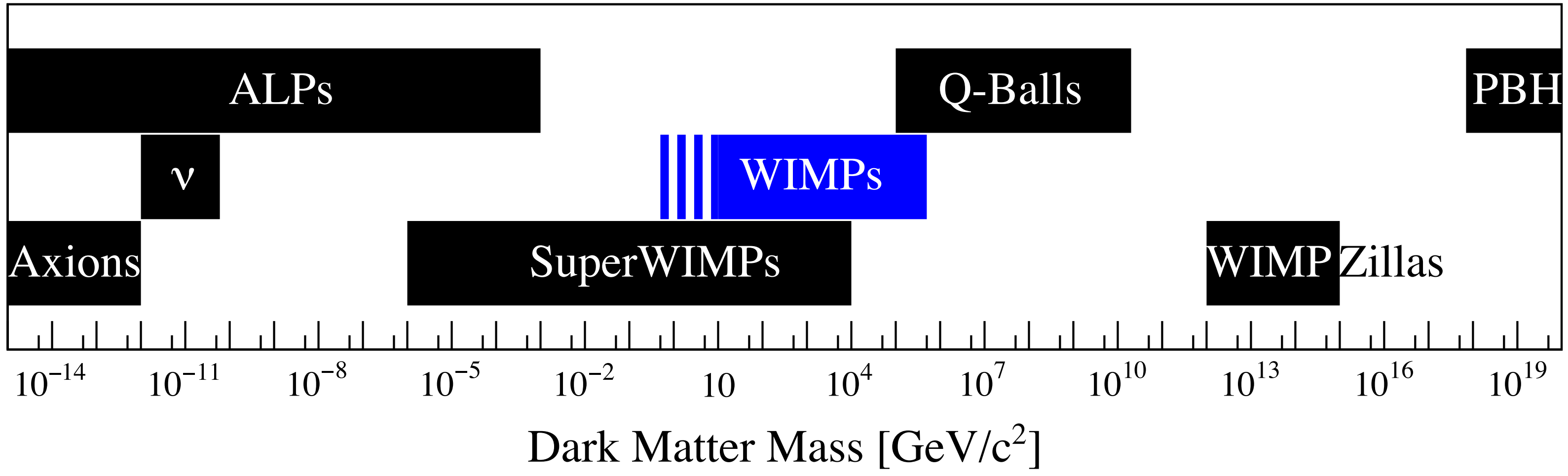
Picture not fully up to date with values

- Matter in universe largely dominated by cold dark matter.
- Energy/matter content of the universe dominated by dark energy.

$$\Omega_c h^2 = 0.120 \pm 0.001$$

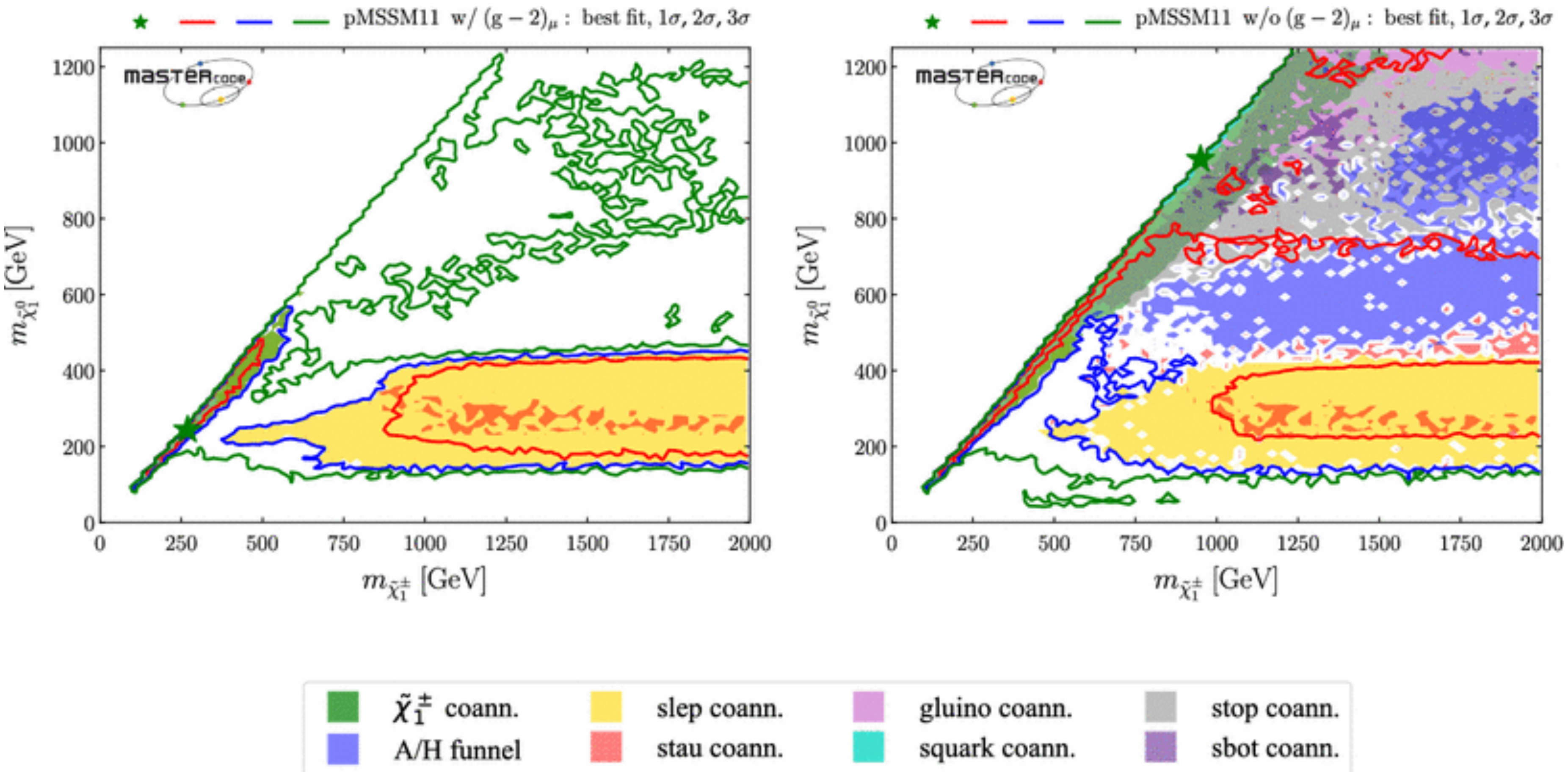
What is dark matter?

- Dark matter from **astrophysical objects** (MACHOS, Primordial Black Holes) disfavoured (see ref [1], [2], [3])
- Weakly Interacting Massive Particles (WIMPS) have been **often assumed as a paradigm**:
  - WIMP miracle (EW size cross section yielding ~ correct relic density for masses of 1-10^5 GeV)
  - Arising in **many theories** (R-parity conserving SUSY, lightest KK particle in KK extra dimensions, lightest particle in Little Higgs models, etc.)
- But **other candidates** also **very attractive** (Axions and Axion-Like Particles in particular)



EW SUSY sector and Dark Matter

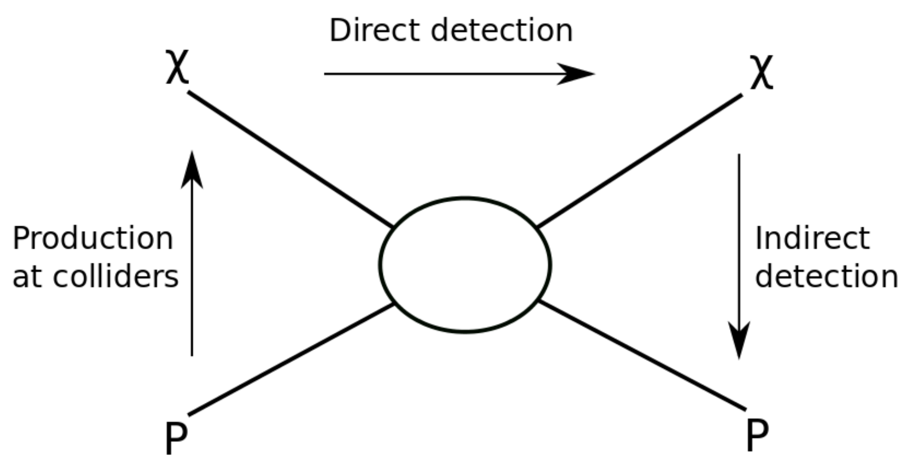
- Lightest neutralino: a good dark matter candidate



From EPJC 78 (2018) 3, 256

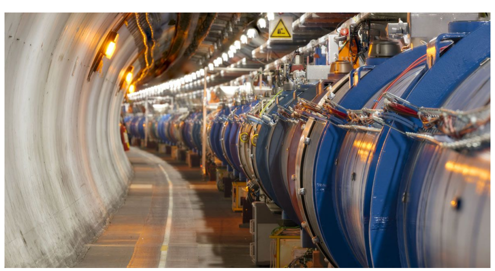
Where do we look for Dark matter?

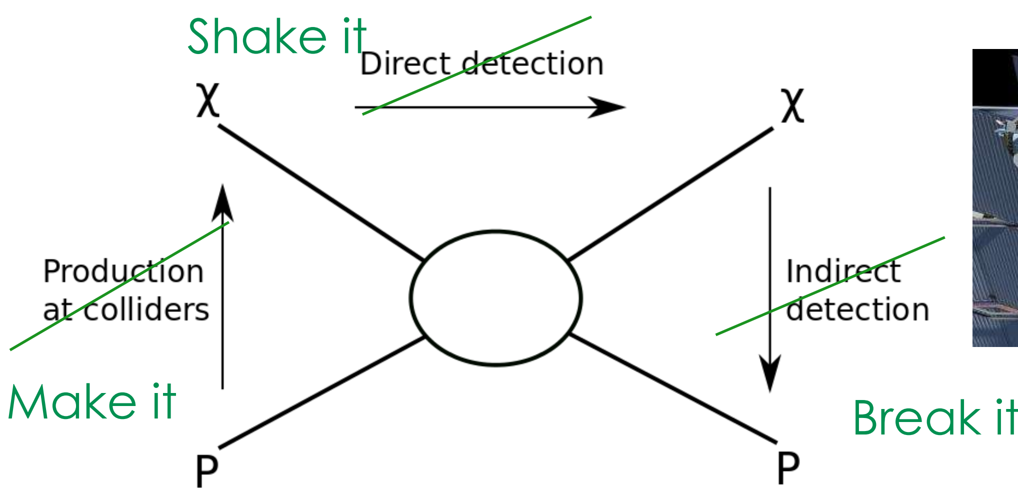
- Shake it, make it, break it approach

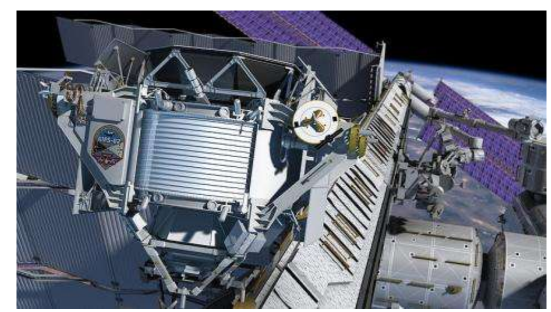


Where do we look for Dark matter?

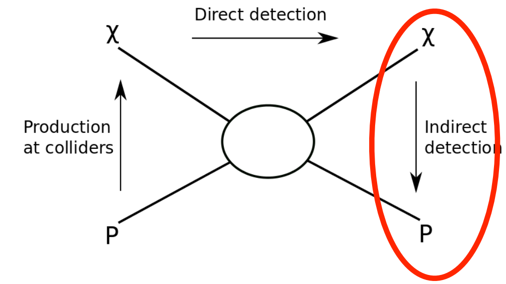
- Shake it, make it, break it approach





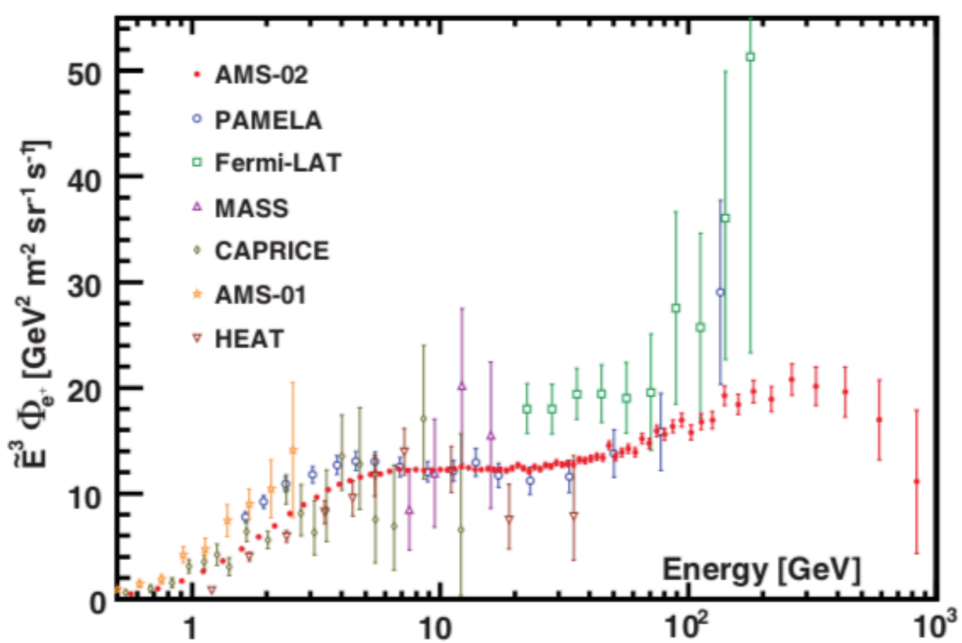


Indirect detection

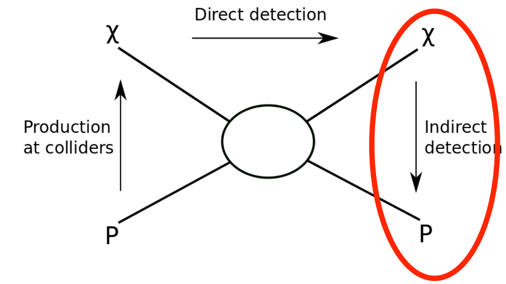


- Only to mention that I will not cover it in any detail. Excellent (and reasonably recent) review here.
- Basic idea: detect **signal from DM annihilation** at ~ rest
- Actual signature depends on the **exact annihilation reaction** taking place. Possible signatures:
  - Gamma rays (either from direct production in 2-body process or from charge particle bremsstrahlung).
  - Excesses in **positrons/electron** and **anti-proton/proton** ratios in cosmic rays.
  - Neutrinos.

- For example: positron spectrum compatible with **diffuse signal** from secondary production of **cosmic rays collisions** plus **a "source" term** causing the structure at higher energy.
- The source could be **dark matter** or of **astrophysical origin**.
- See Phys. Rev. Lett. 122, 041102 and Phys. Rev. Lett. 122, 101101 and references therein.

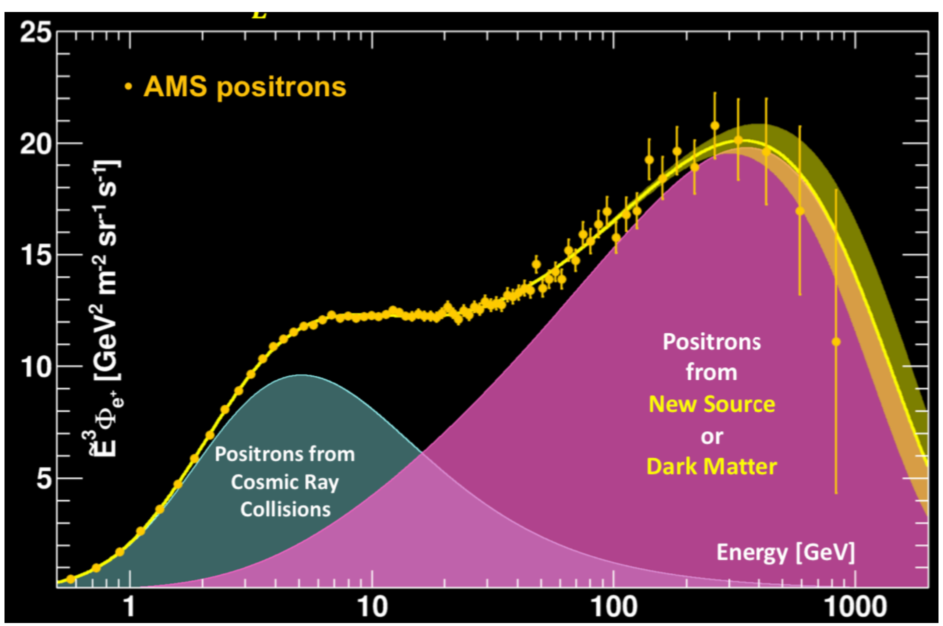


Indirect detection



In a nutshell:

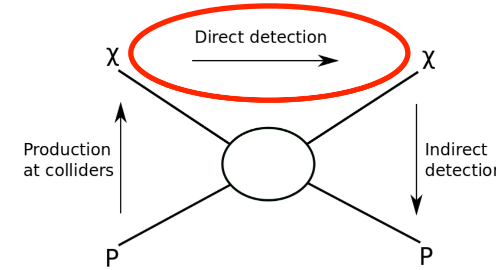
- DM annihilation happening nearly at rest. Available CM energy $E_{CM} = 2M_\chi$, where M_χ is the DM candidate's mass
- The reaction products will have $E = E_{CM}/2 = M_\chi$ when produced
- When detected they will have a cutoff energy at M_χ



Taken from A. Kounine's talk at EPS/HEP

Dark matter direct detection

Direct detection



- Basic idea: detect the **nuclear recoil** of a DM particle interaction with matter.
- Dark matter "wind" in our position in the galaxy is non relativistic ($v \sim 10^{-3}c$). Therefore:

Recoil nuclear energy E_R

$$E_R = \frac{1}{2} m_\chi v^2 \frac{4\mu_N}{m_N + m_\chi} \frac{1 + \cos\theta}{2}$$

with $\mu_N = \dfrac{m_N m_\chi}{m_N + m_\chi}$

Maximum energy transfer E_R^{max}

$$E_R^{max} = \frac{1}{2} m_\chi v^2 \sim \frac{1}{2} \left(\frac{m_\chi}{1 \text{ GeV}} \right) \text{keV}$$

Exercise: derive the relation for E_R^{max}

We need to detect signals of o(10-10[4]) keV

Direct detection

- For particles with speed v, the number of interactions in the detector will be

$$\frac{dN}{dE_R} = tnvN_T \frac{d\sigma}{dE_R}$$

t :observation time
n :number density of DM particles
v :speed of DM particles
N_T :number of target nuclei
σ :interaction cross section

Remember in general
$$N = \phi\sigma t$$

- If DM particles have a distribution of speeds $f(\vec{v})$, then

$$\frac{dN}{dE_R} = tnvN_T \int_{v_{\min}} vf(\vec{v})\frac{d\sigma}{dE_R} d\vec{v}$$

with $v_{\min} = \sqrt{m_N \frac{E_R}{2\mu_N^2}}$

Minimum speed to achieve E_R

- This can be re-written using $n = \rho/m_\chi$, $N_T = M_T/m_N$ and $\epsilon = tM_T$.
  - ρ is the local DM density, M_T the detector mass and ϵ the exposure.

Direct detection

$$\frac{dN}{dE_R} = \epsilon \frac{\rho}{m_\chi m_N} \int_{v_{\min}} v f(\vec{v}) \frac{d\sigma}{dE_R} d\vec{v}$$

- Cross section $\frac{d\sigma}{dE_R}$:
  - This can be rewritten as

$$\frac{d\sigma}{dE_R} = \frac{m_N}{2v^2\mu_N^2}\left(\sigma_{\rm SI}F^2_{\rm SI}(E_R) + \sigma_{\rm SD}F^2_{\rm SD}(E_R)\right)$$

- $\sigma_{\rm SI}, \sigma_{\rm SD}$ depend **on the details of the physical interaction between the DM particle and the nucleus**. They are the Spin Independent and Spin Dependent contributions to the cross section. Typically computed using an Effective Field Theory.
- The former is caused by **scalar or vector effective operators** in the Lagrangian, the latter by **axial operators**.
- The E_R dependency of the form factors is relevant only for heavy nuclei

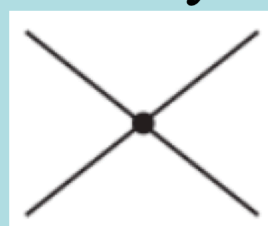
Effective Field Theory

John Ellis, here, two days ago

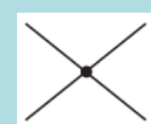
Effective Field Theories (EFTs)

a long and glorious History

- 1930's: "Standard Model" of QED had d=4
- Fermi's four-fermion theory of the weak force d=6



- Dimension-6 operators: form = S, P, V, A, T?
- Due to exchanges of massive particles?
- V-A ➔ massive vector bosons ➔ gauge theory
- Yukawa's meson theory of the strong N-N force



- Due to exchanges of mesons? ➔ pions
- Chiral dynamics of pions (dπdπ)ππ clue ➔ QCD

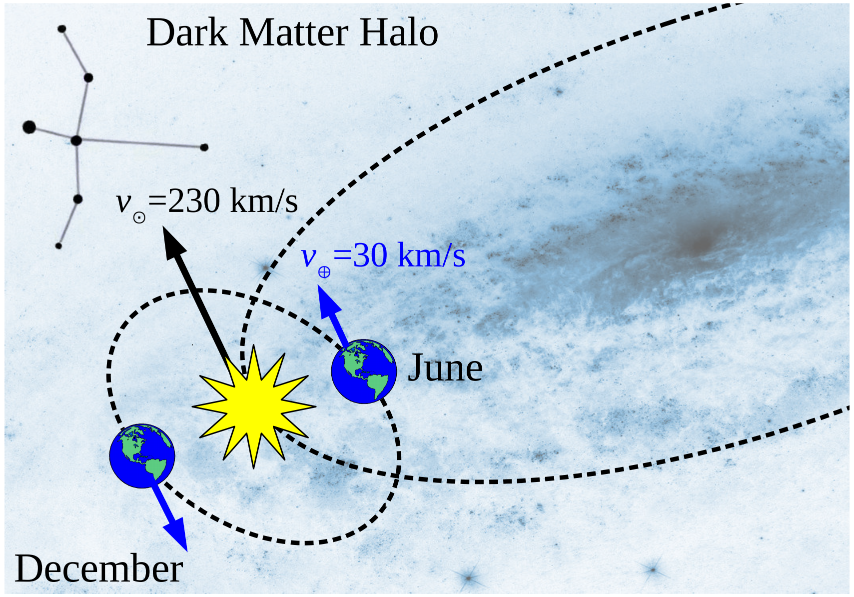
Direct detection

$$\frac{dN}{dE_R} = \epsilon \frac{\rho}{m_\chi m_N} \int_{v_{\min}} v f(\vec{v}) \frac{d\sigma}{dE_R} d\vec{v}$$

- Let's now focus on the velocity distribution.
- Standard Halo Model (SHM) is often assumed: **in the rest frame of the galactic centre**, DM particles distributed in an isotropic isothermal sphere, therefore $f(\vec{v})$ is a Maxwellian distribution.
- However, the detector motion is complex with respect to the galactic centre

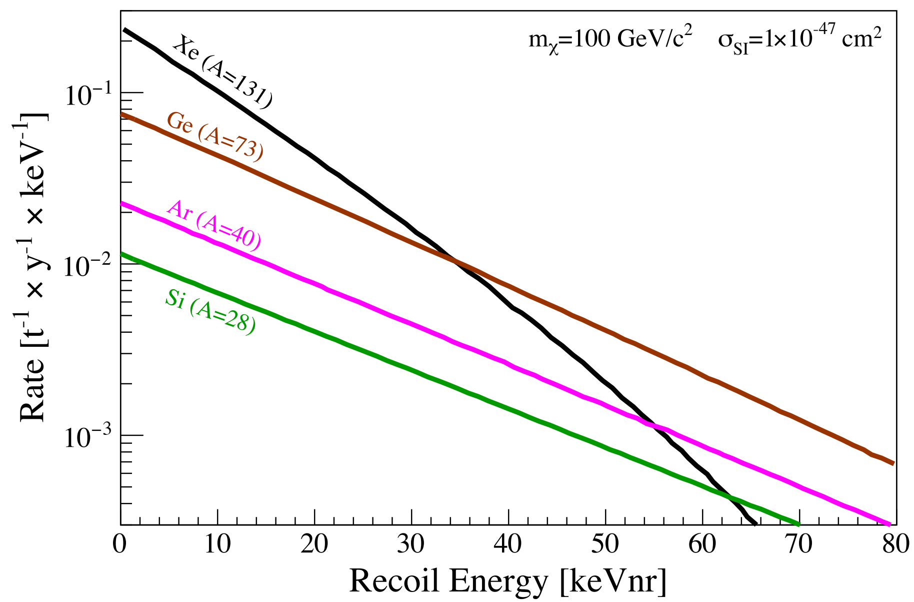
$$v_E = v_\odot + v_\oplus \cos\theta \cos\omega(t - t_0)$$

Potential annual modulation in the signal

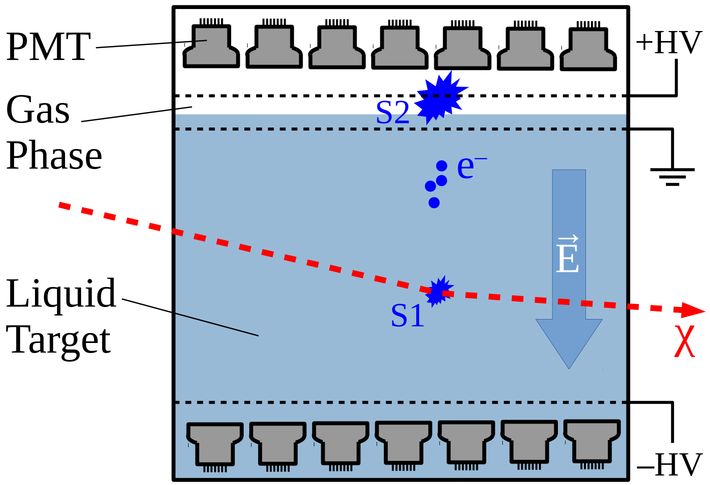


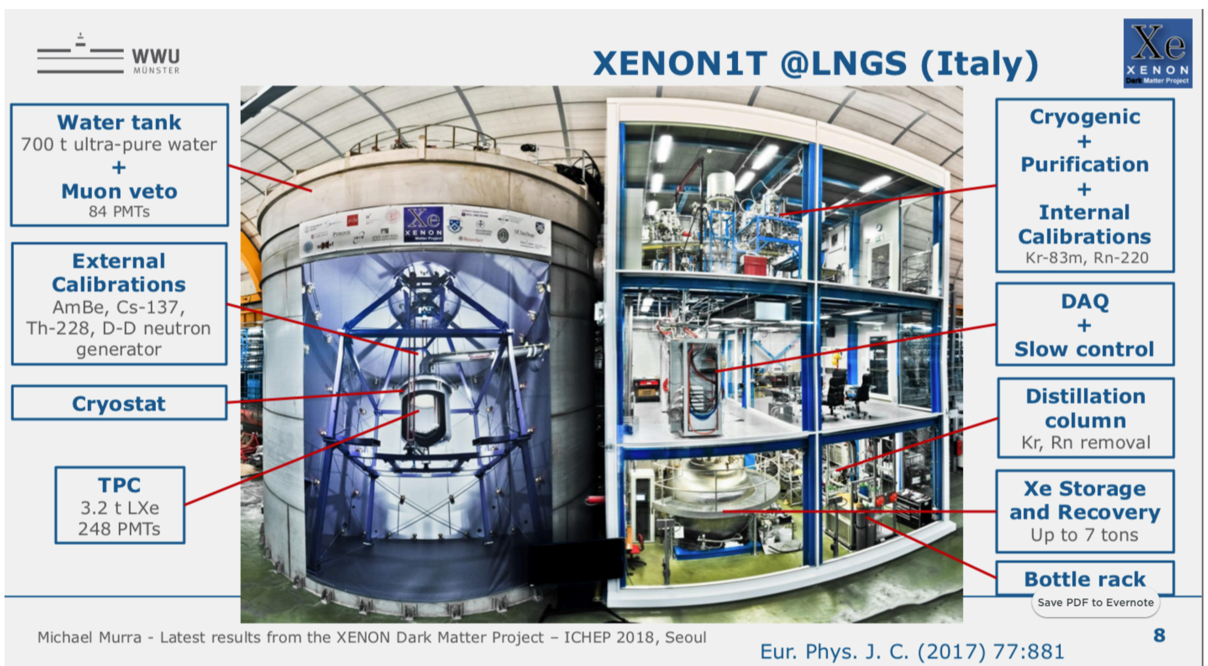
Direct detection

- Expected rates for **several targets**
- Dark matter direct detection experiments exploit:
  - **Phonons** from nuclear excitations (cryogenic detectors)
  - **Scintillation** signal from excited nuclei
  - **Ionisation** signal
- Often a **combination** of these.



An example: Dual Phase TPC



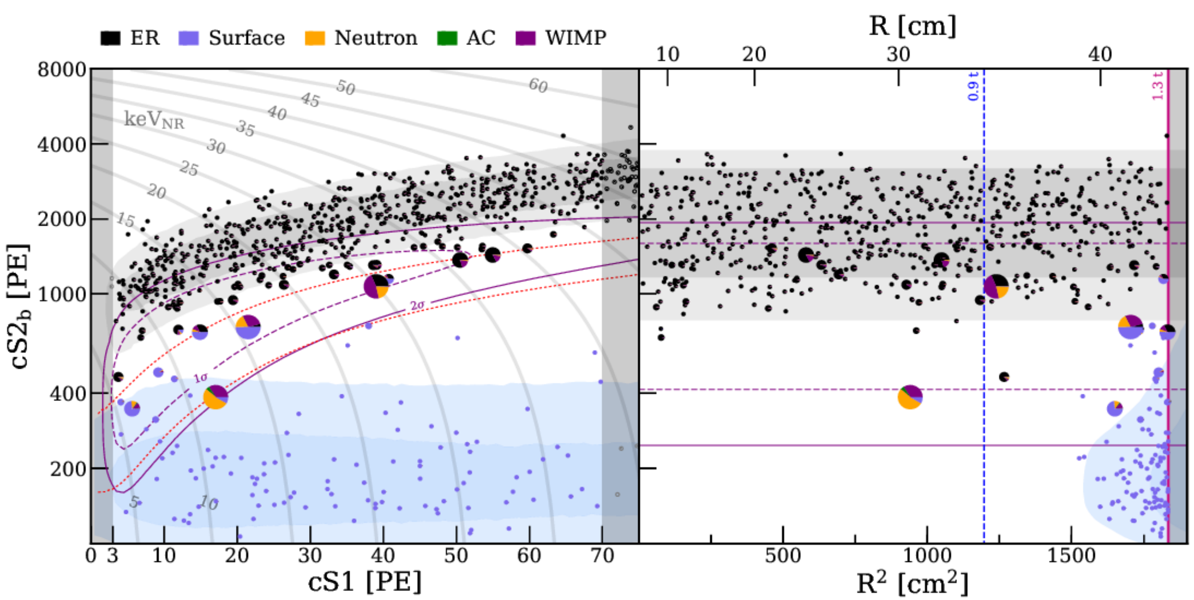


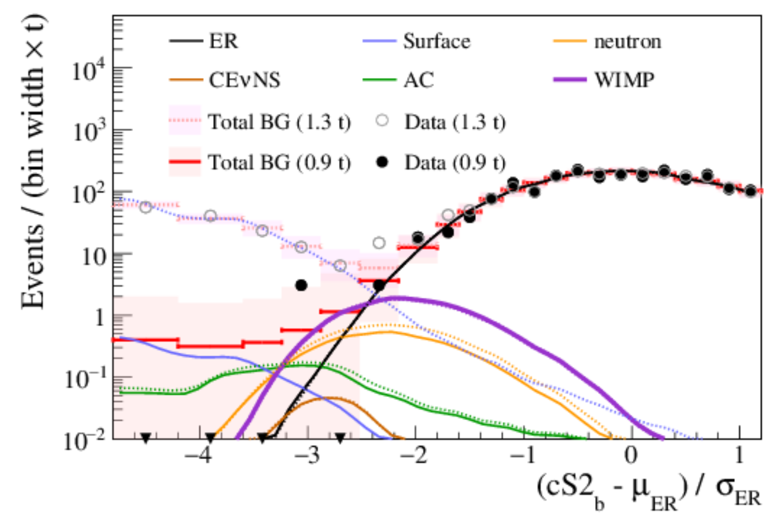
- Noble gas in dual phase
- Scintillation signal S1 from **primary interaction DM-nucleon**
- Electric field for drifting ionisation electrons:
  - Delayed S2 signal from **ionisation electrons**
- Keeping background low is key
  - Underground experiments, high-purity material, shielding outside sensitive region + self-shielding with fiducial region

Background and results

Phys. Rev. Lett. 121, 111302

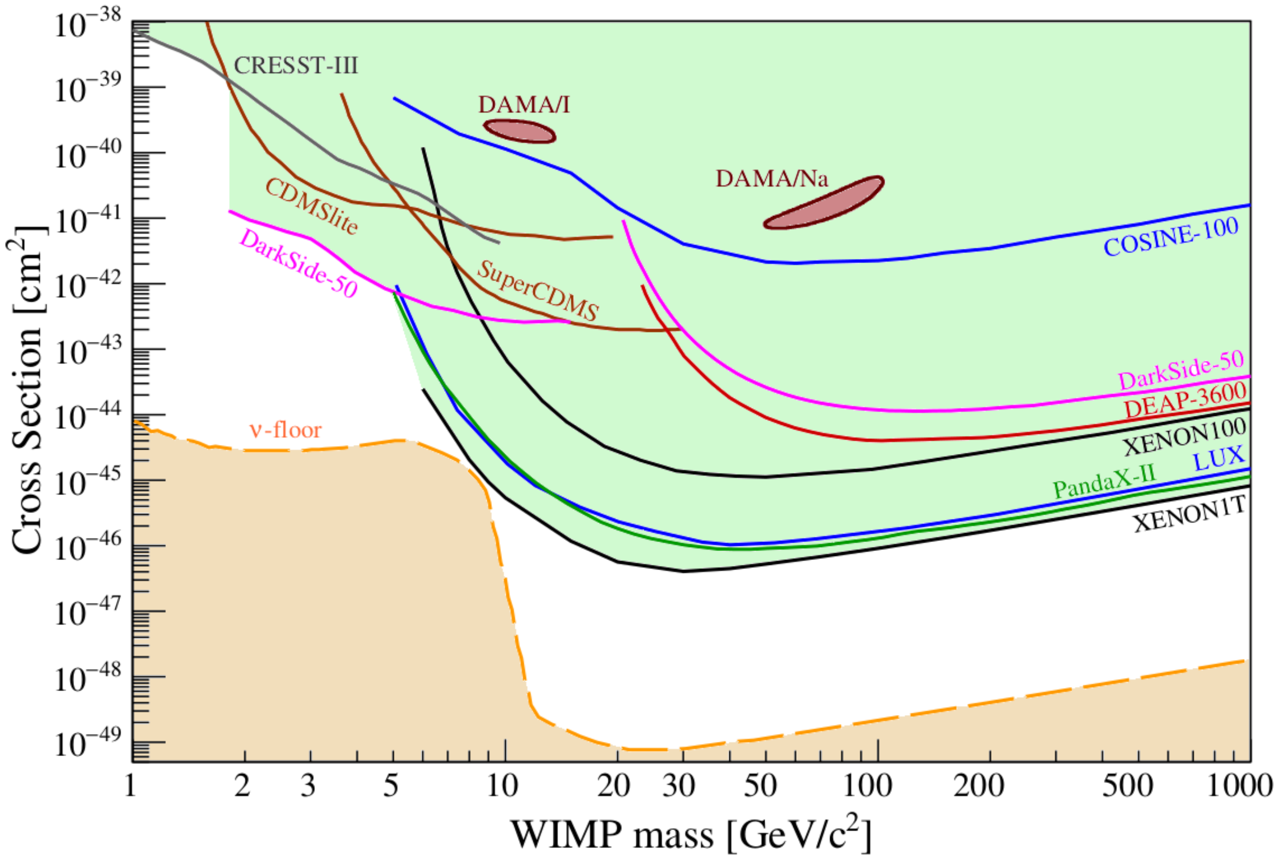
- Main backgrounds:
  - **Electron recoil** from γ and β particles in detector, producing electrons
  - **Nuclear recoil** from α or n (either radiogenic or cosmogenic)
  - For Dual Phase TPCs these are suppressed looking at **pulse shape discrimination** and 2D **S1/S2 information**.





Direct detection limits

Spin-independent WIMP limits

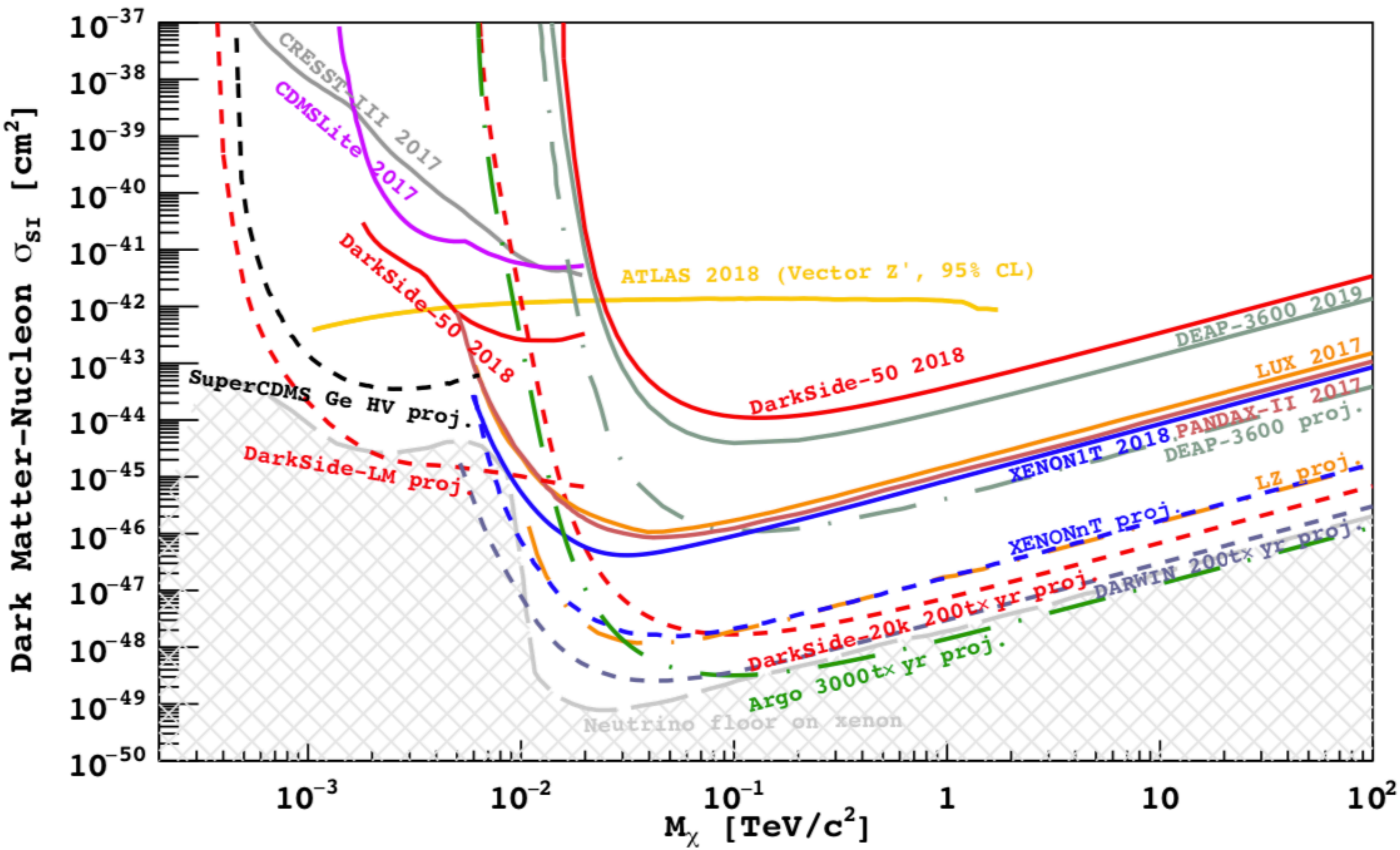


- Low-mass region dominated by cryogenic experiments (smaller thresholds but smaller detectors)
- High-mass region dominated by noble gas dual phase TPC

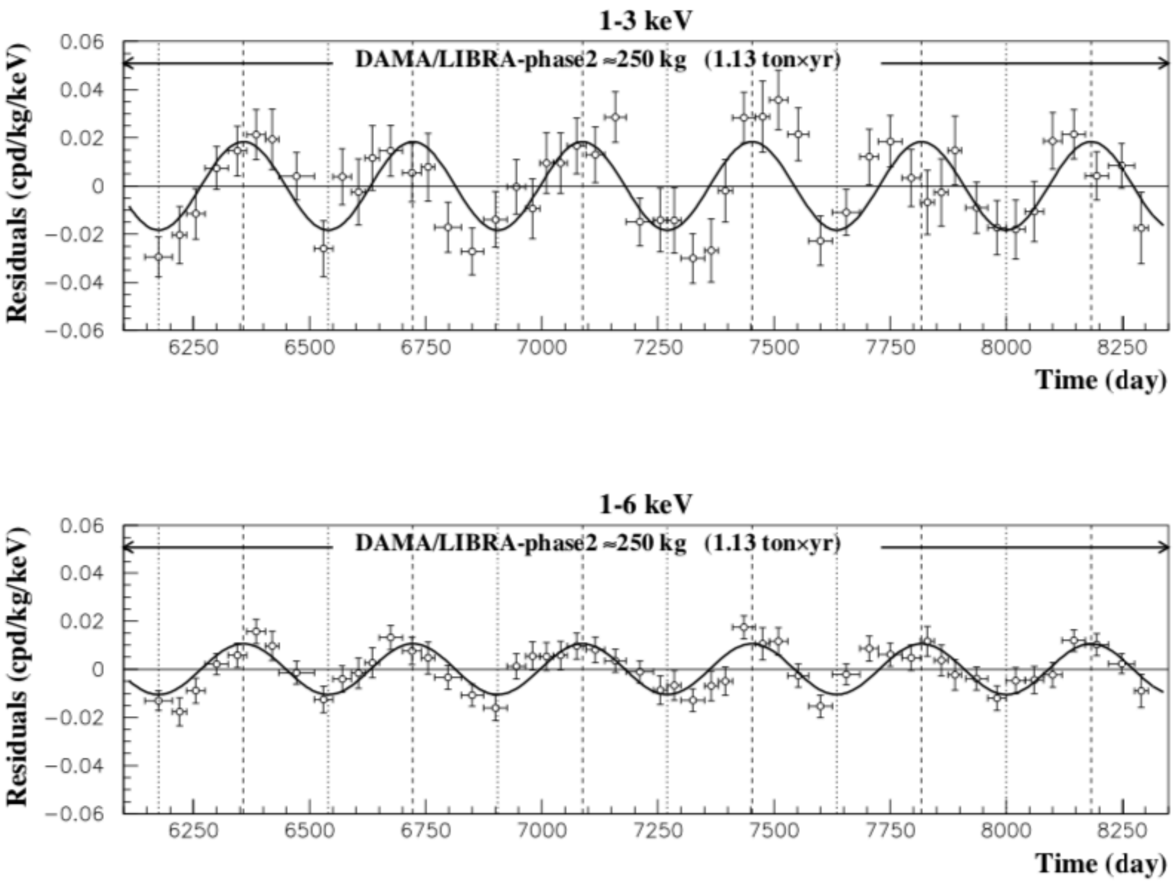
Exercise: take the E_R formula here, consider Ge and Xe and a threshold on E_R, and a maximum speed of 550 km s^{-1} (galaxy escape velocity). Find the minimum mass that can be detected (taken from here)

A glance to the future

Taken from here



DAMA/Libra (controversial) signal

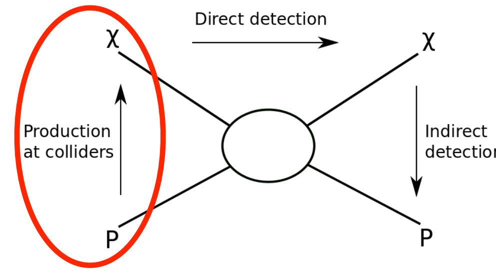


- Looking for a **yearly modulation** of rates from DM interactions on NaI crystals (250 kg).
- Signal visible with **high statistical significance**
  - Under WIMP hypothesis, signal excluded by other experiments.
  - Work underway to check result with new experiments.

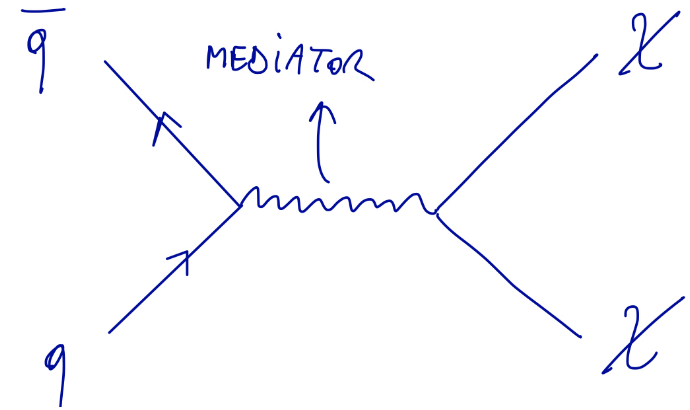
See arXiv:1805.10486

Dark matter (WIMPS) - production

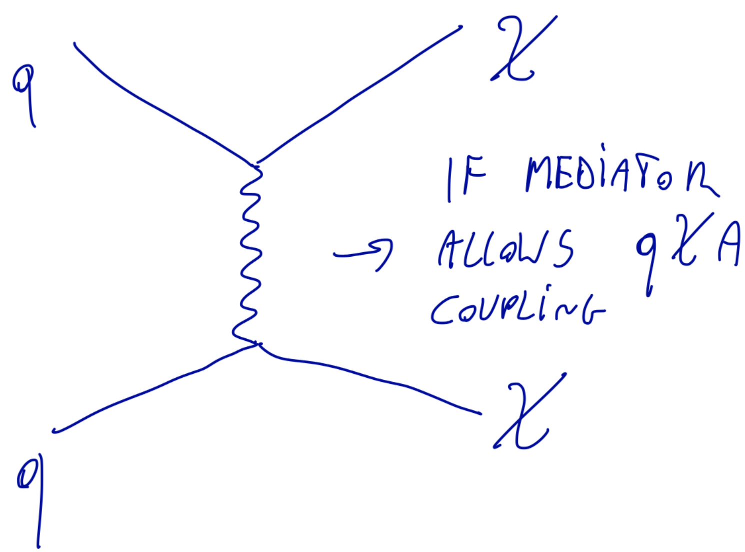
Dark matter production

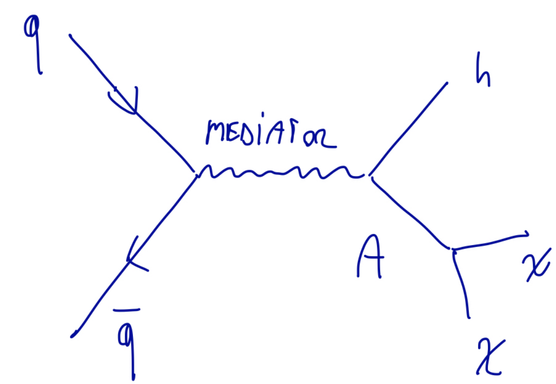


- Direct detection relies on the **existence of interaction** between **hadrons and DM**
- That implies DM **could be produced in pp collisions**
- The interaction with hadrons will be mediated by some (SM or BSM) particle



BUT ALSO SOMETHING MORE COMPLEX AND NON MINIMAL IS POSSIBLE





Dark matter production

Number of signatures, complexity (and reliability) of interpretation ↓

Simplified models (one mediator + DM particles)

↓

Less simple models (few extra states + DM particles. For example - 2HDM plus stuff)

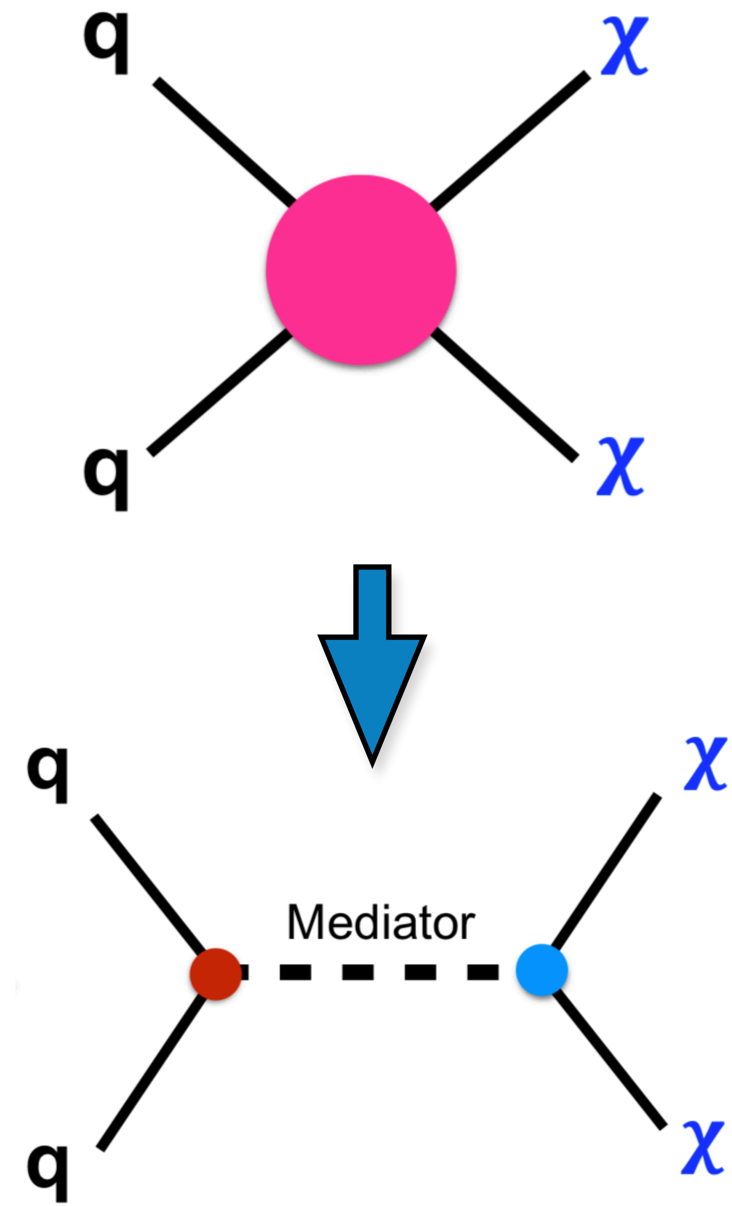
↓

Complete models (e.g. SUSY models)

Generality, model dependence ↑

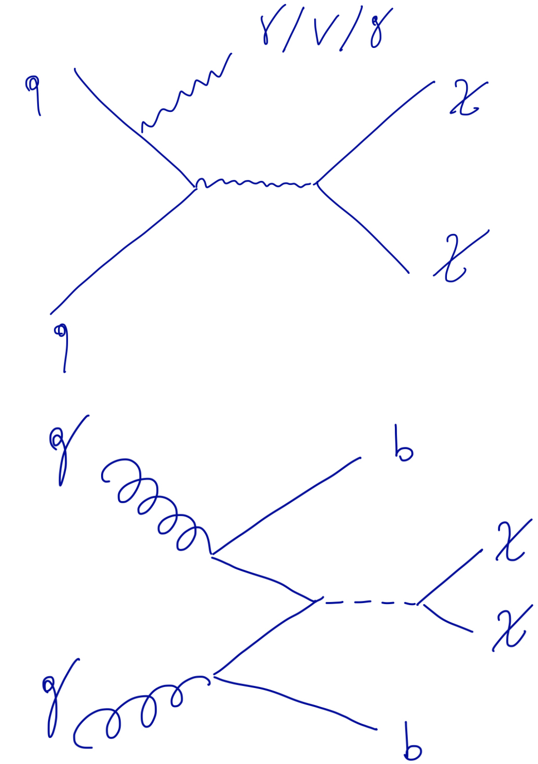
Simplified models

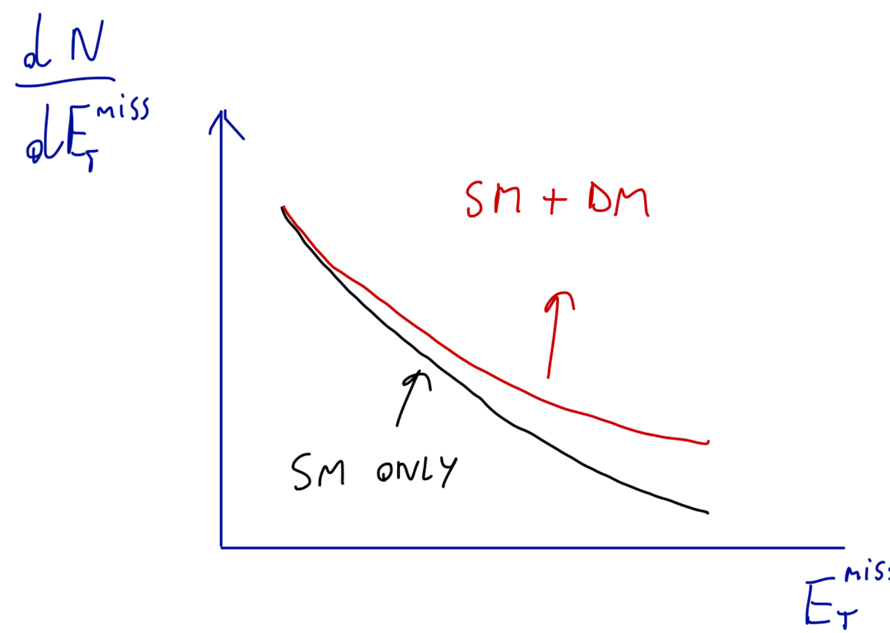
- EFT approach **not suitable** whenever mediator mass not infinitely large w.r.t. scale probed.
  - … which is **not necessarily the case at the LHC.**
- Evolution from **EFT approach to simplified model approach**
- All discussed within the LHC dark matter forum
- See, e.g.,
  - arXiv:1507.00966
  - arXiv:1603.04156
  - arXiv:1703.05703
  - arXiv:1705.04664



Strategy

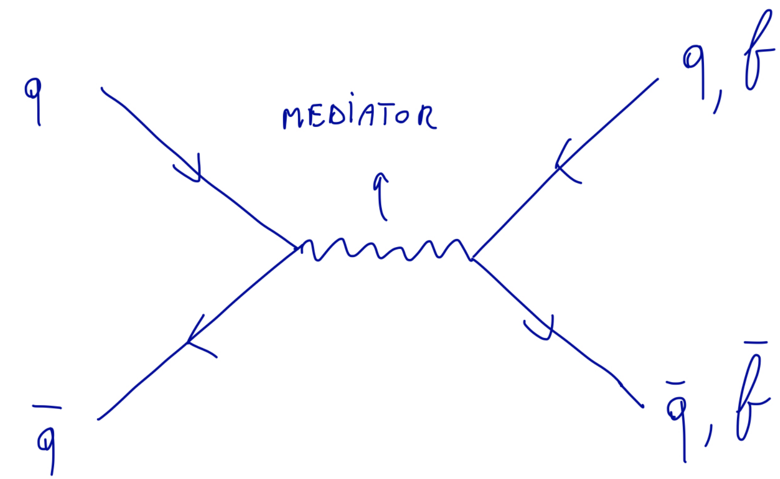
- Two **complementary** approaches:
  - Dark matter particles **directly produced** interacting **weakly with detector**, leading to E_T^{miss}
    - E_T^{miss} + X paradigm: look for **associated production of DM** with other objects

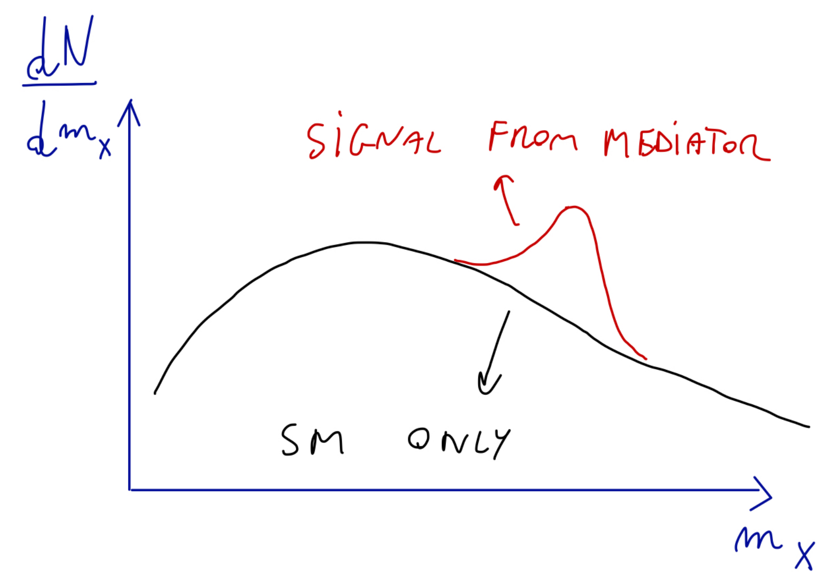




Strategy

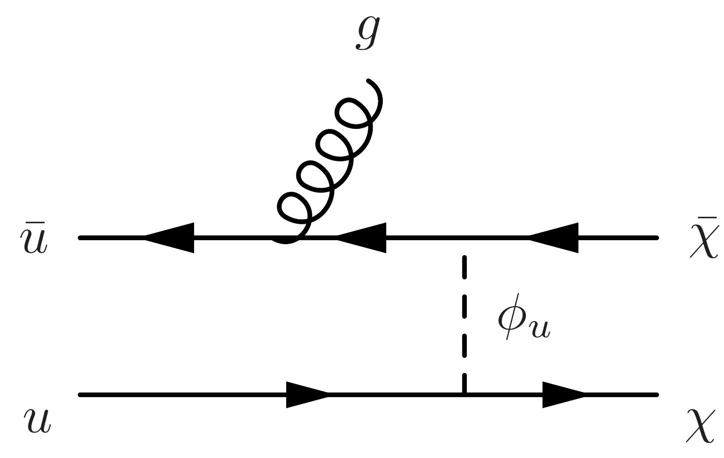
- Two complementary approaches:
  - Dark matter particles **directly produced** interacting **weakly with detector**, leading to E_T^{miss}
  - The mediator certainly **couples to hadrons** (or no production happens): further decay into SM particles:
    - Searches for resonances

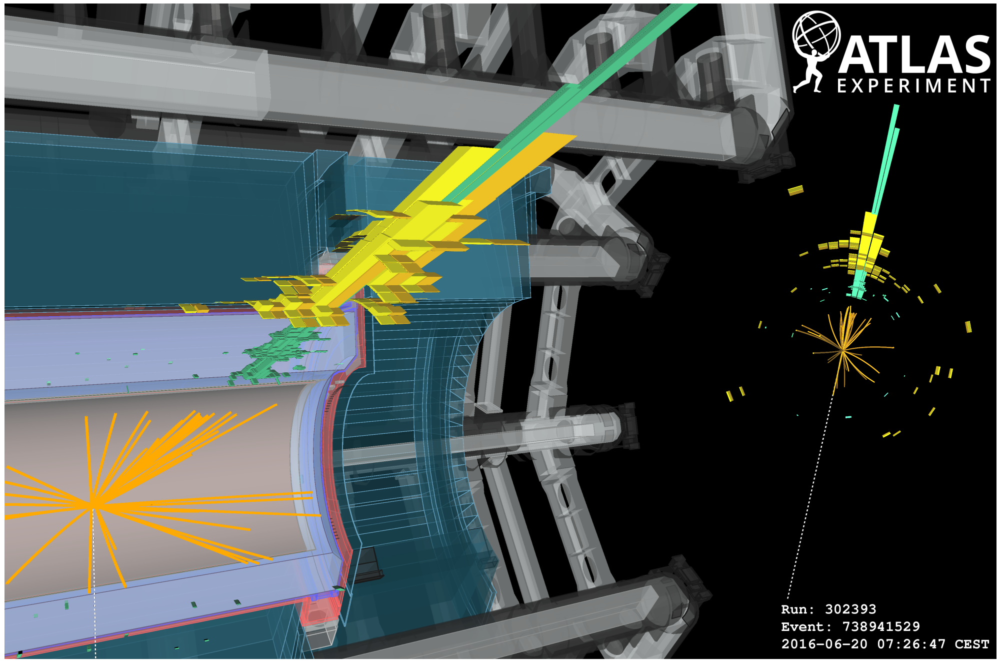




E_T^{miss} + X

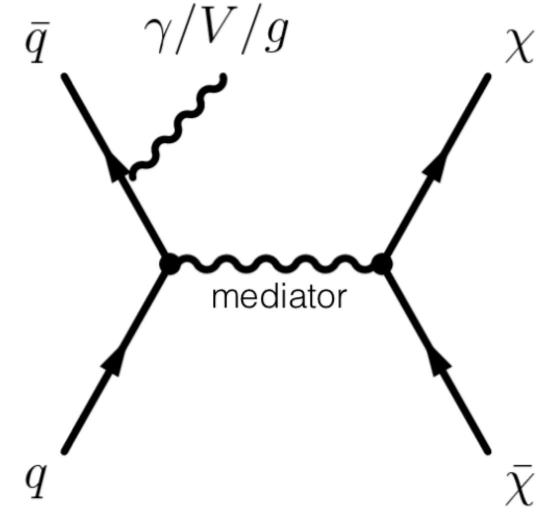
- Simple and versatile signature: **monojet**
  - The invisible final state **is boosted**
  - Sensitivity to a number of **potential new physics processes** yielding only invisible objects in the final state:
    - Extra-dimensions (see lecture tomorrow)
    - $X \to \bar{\nu}\nu$ (with X a new state)
    - Compressed SUSY scenarios
    - etc.

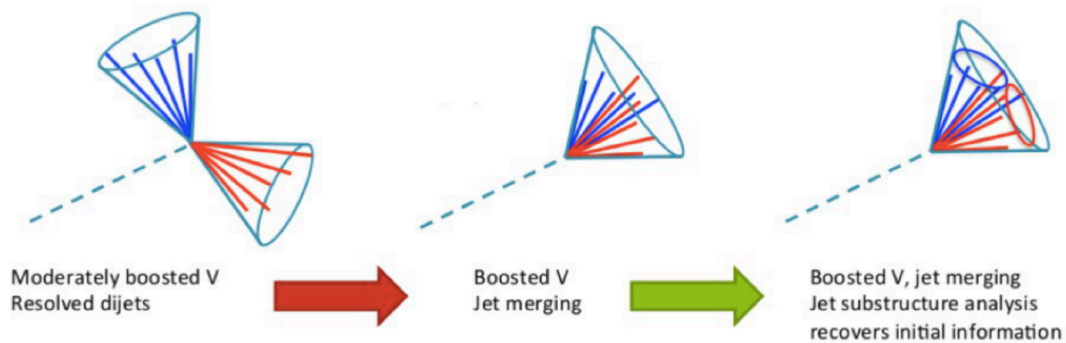




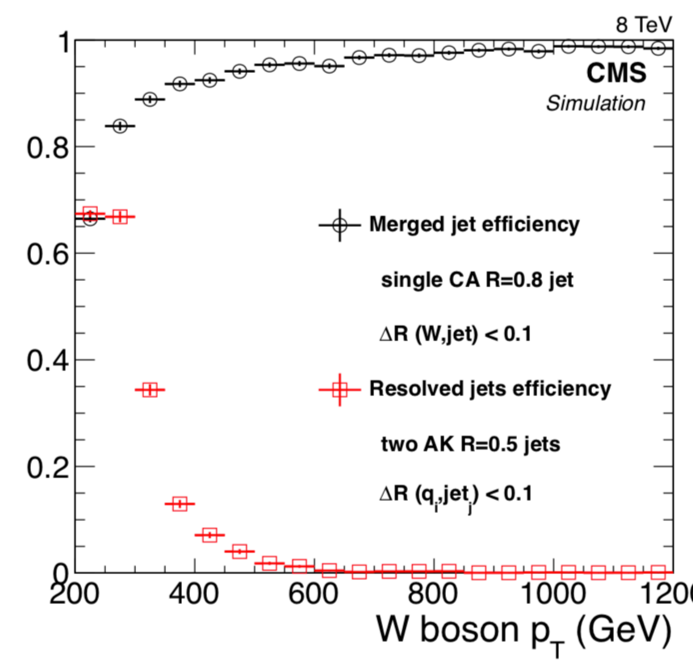
X does not need to be a jet

- See, e.g., Phys. Rev. D 97 (2018) 092005
- Combined search for **mono-jet** and **mono-vector boson** events.
- Mono-vector boson events selected by **tagging anti-k$_t$ R = 0.8 jets** compatible with coming from W or Z decay.



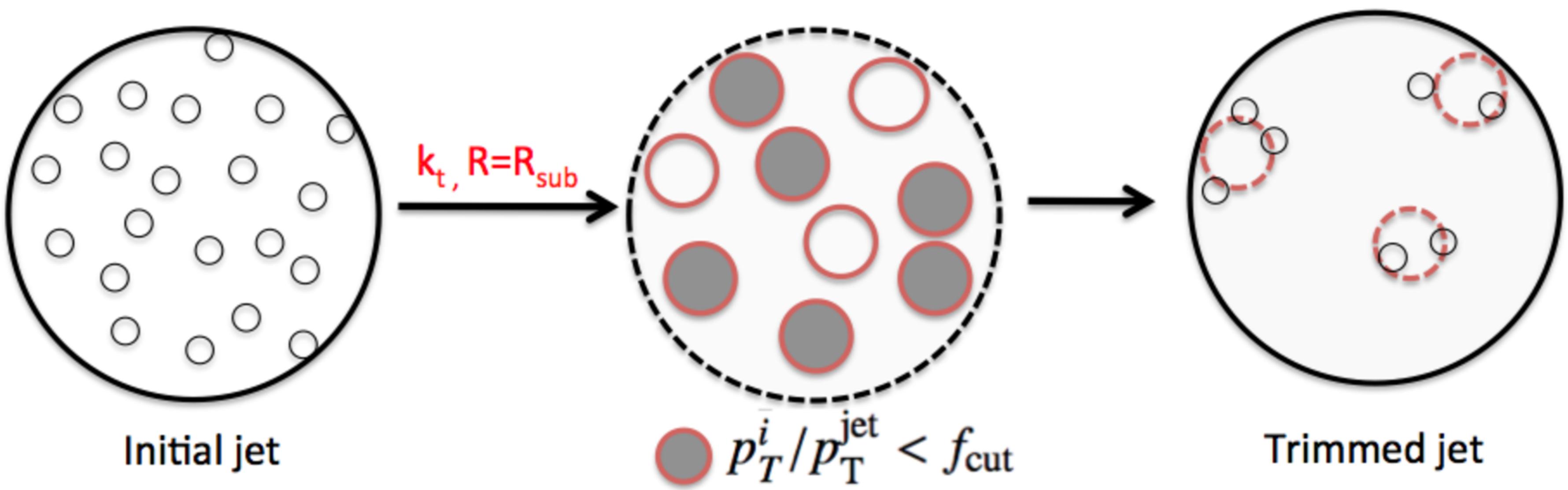


Opening cone: $\Delta R_{\min} \sim \dfrac{2m_B}{p_B}$



Intermezzo - jet substructure

- Possibly one of the most **innovative techniques** of the last few years
- Widely used whenever **boosted object** (top, W, Z, H, BSM) expected in final state.
- Large cone jet reconstruction normally **sensitive to soft QCD/pileup.**
- "Cleaning" procedure required - in the picture: trimming procedure.
- Soft-Drop procedure yielding calculable, Sudakov-safe observable.



See arXiv:1011.2268

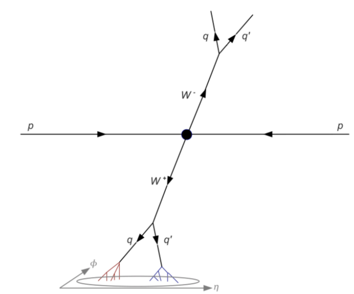
One slide about jet substructure

- N-subjettiness: how "compatible" is a jet to a N-prong structure:
  - Reconstruct N subjets with exclusive k_T. Then:

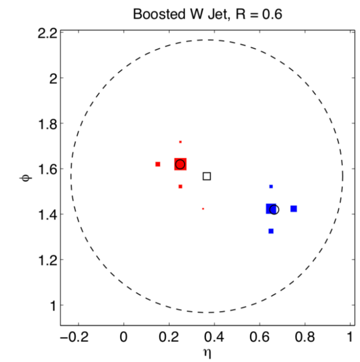
$$\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \min\left\{\Delta R_{1,k}, \Delta R_{2,k}, \cdots, \Delta R_{N,k}\right\}$$

with $\Delta R_{i,k}$ the angular distance between the jet constituent k and the subject i.

- Often ratios between different N-subjettiness used as discriminator



(a)



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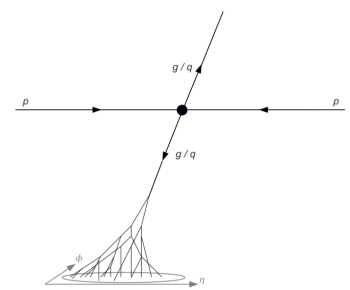
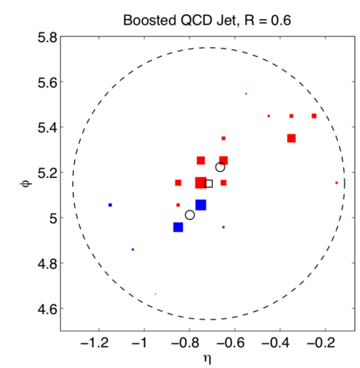
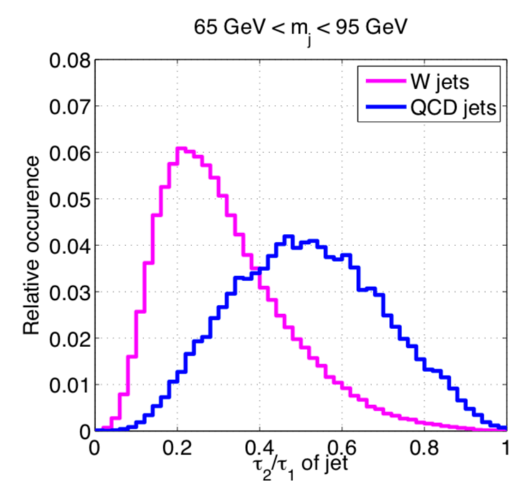
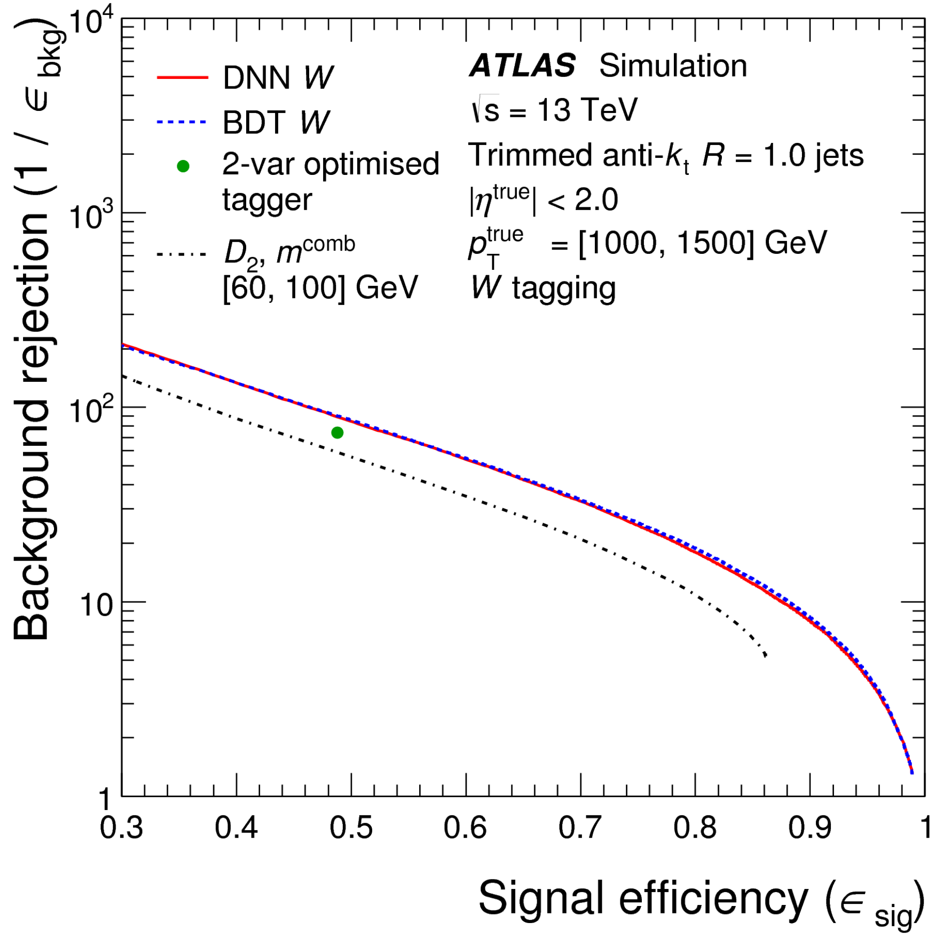


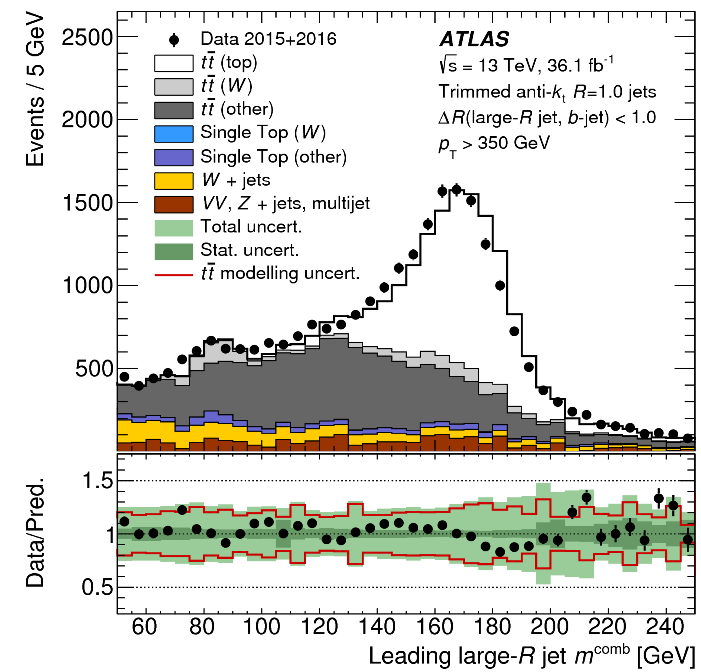


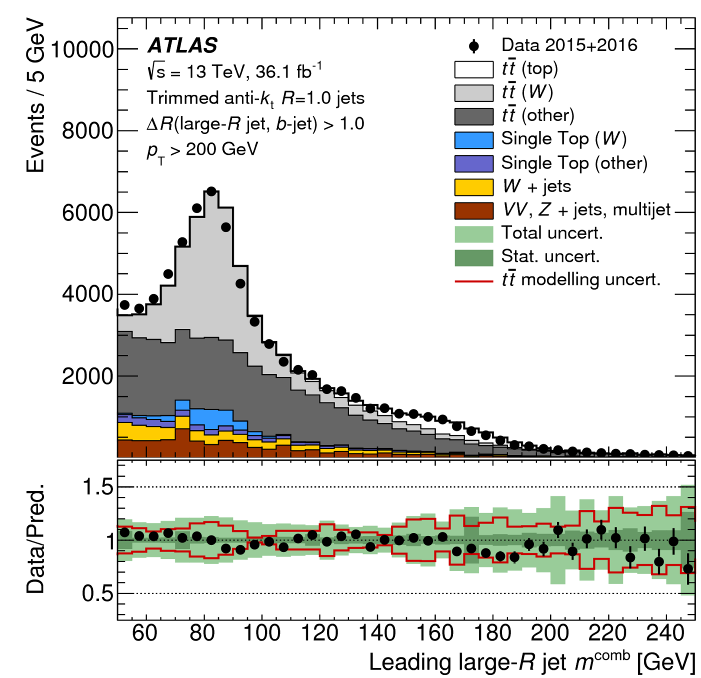


Intermezzo - jet substructure

- A well developed tool in use in many analyses (see Eur. Phys. J. C 79 (2019) 375)

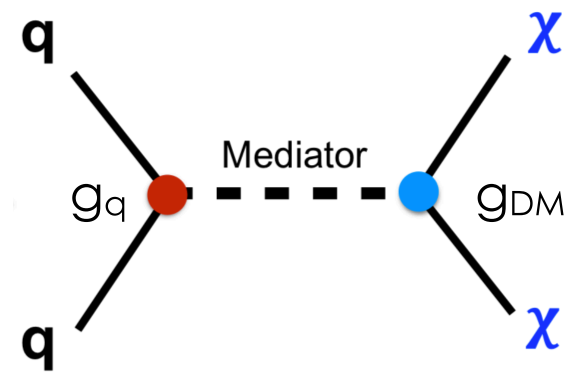


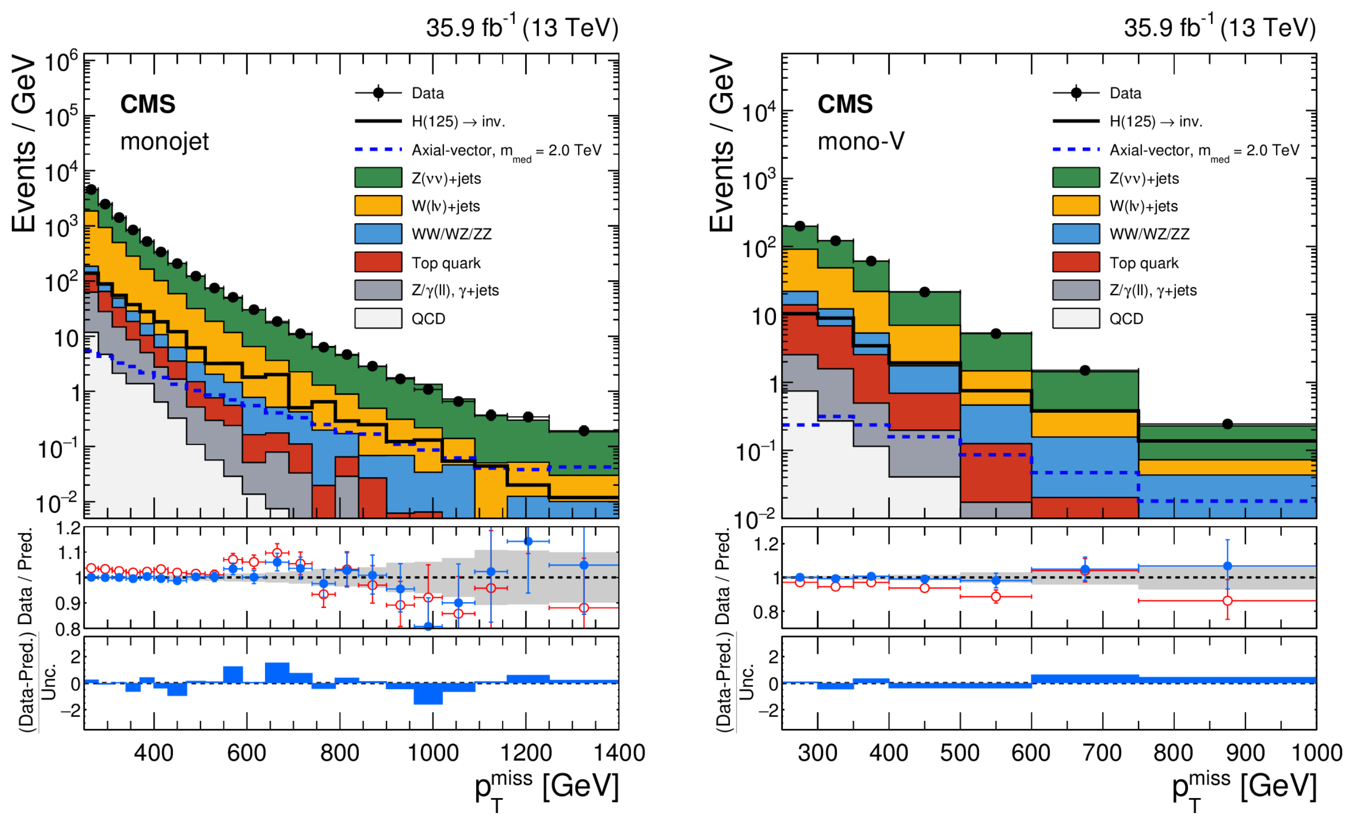




Monojet/Mono-V results

- Main background from W/Z estimated from $\gamma + jets, W \to l\nu, Z \to ll$ control regions.
- Careful work of the **theory community** to bring the theoretical uncertainties on, e.g., p_T^{γ}/p_T^{Z} under control (see for example here).

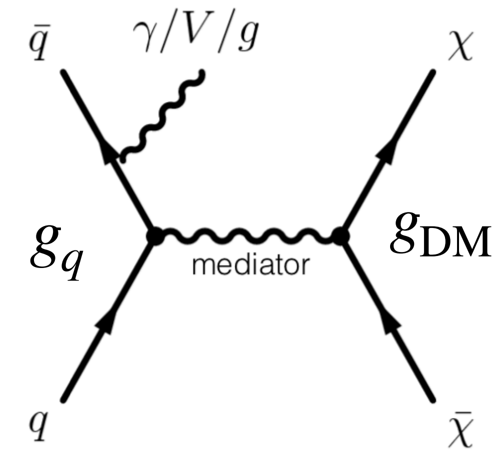


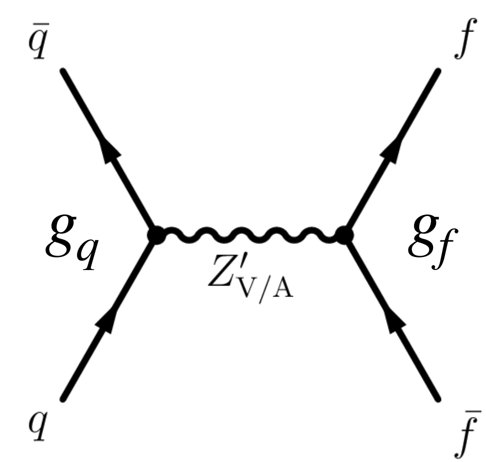


Monojet/Mono-V results

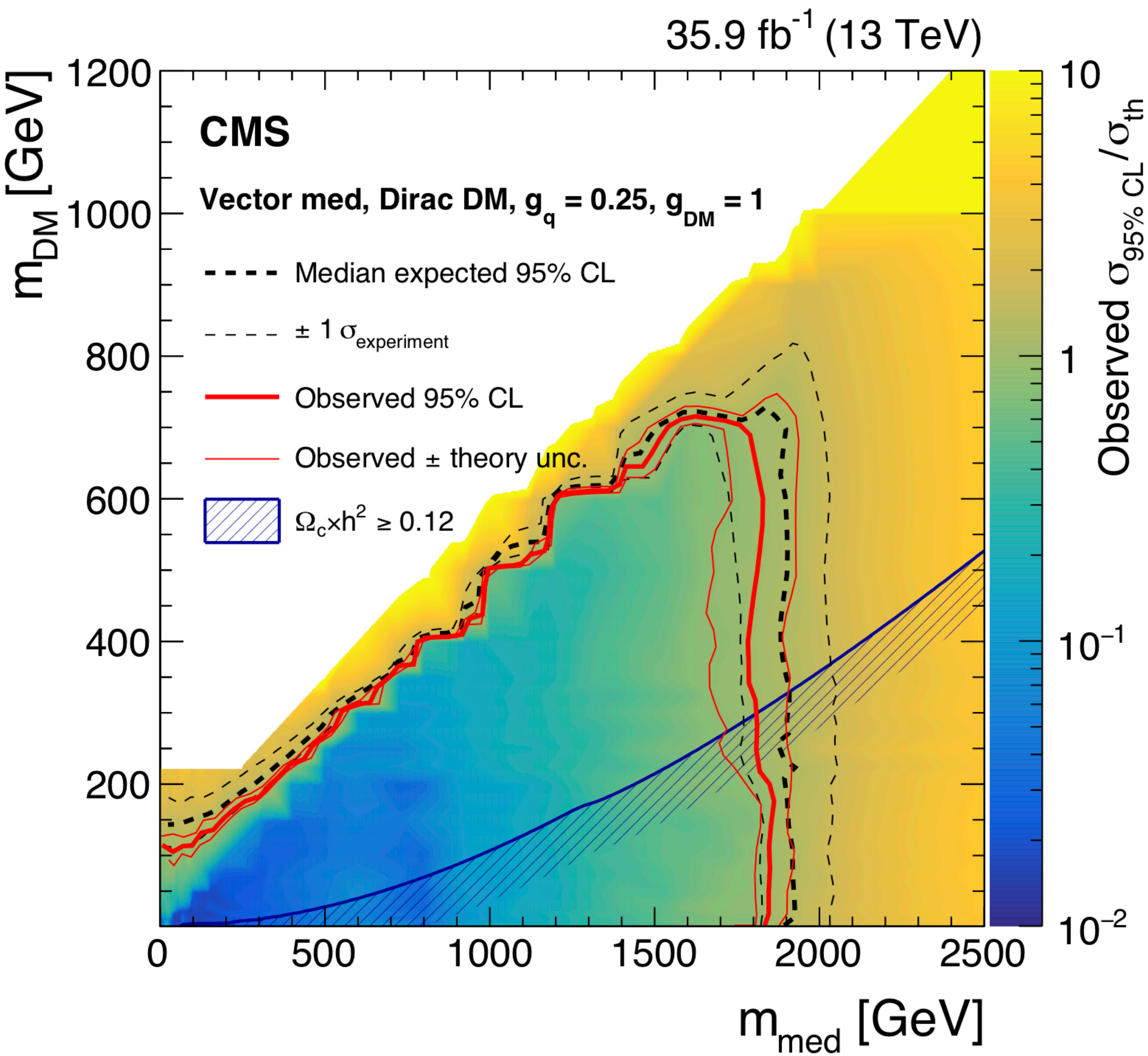
- **Simplest simplified model**: a vector or axial mediator with **5 free parameters**:
  - g_q : universal mediator coupling to quarks.
  - g_l : universal mediator coupling to leptons.
  - g_{DM} : mediator/DM coupling
  - m_{med} : mediator mass.
  - m_{DM} : dark matter particle mass
- For example, mono-jet signal proportional to

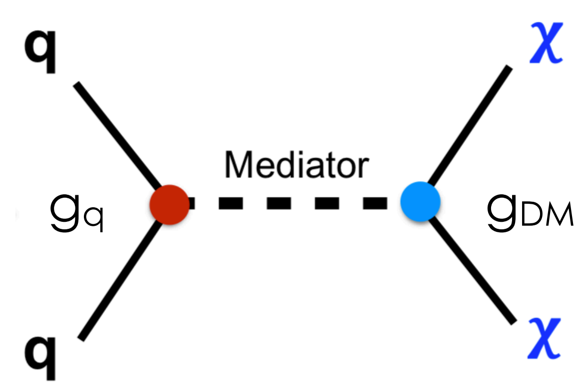
$$N_S \propto g_q^2 g_{\mathrm{DM}}^2$$





Monojet/Mono-V results





More E_T^{miss} + X

	ATLAS	CMS
jet + MET	JHEP 01 (2018) 126	PRD 97 (2018) 092005
γ + MET	EPJC 77 (2017) 393	JHEP 02 (2019) 074
Z($\ell\ell$) + MET	PLB 776 (2017) 318	EPJC 78 (2018) 291
V(had) + MET	JHEP 10 (2018) 180	PRD 97 (2018) 092005

	ATLAS	CMS
t + MET	JHEP 05 (2019) 41	JHEP 03 (2019) 141
tt + MET	EPJC 78 (2018) 18	
b + MET		
bb + MET		

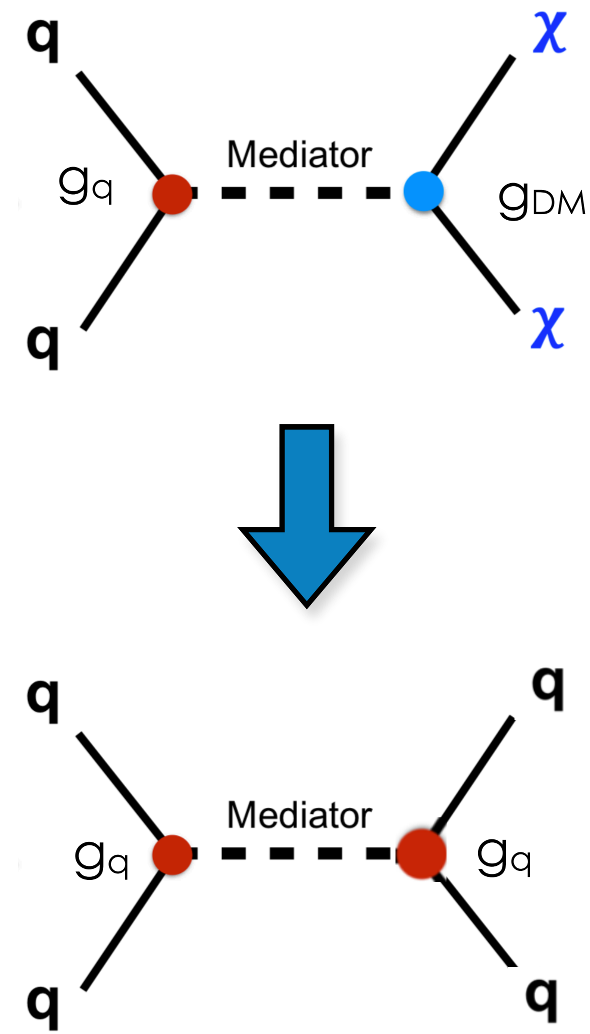
	ATLAS	CMS
H→bb	PRL 119 (2017) 181804	JHEP 11 (2018) 172 EPJC 79 (2019) 280
H→$\gamma\gamma$	PRD 96 (2017) 112004	JHEP 09 (2018) 046
H→$\tau\tau$		
H→WW		CMS PAS EXO-18-011 (new)
H→ZZ		
Combination		

Resonant mediator search

- If the mediator **couples to quarks** in production, then it must couple to quarks **for its decay** with intensity

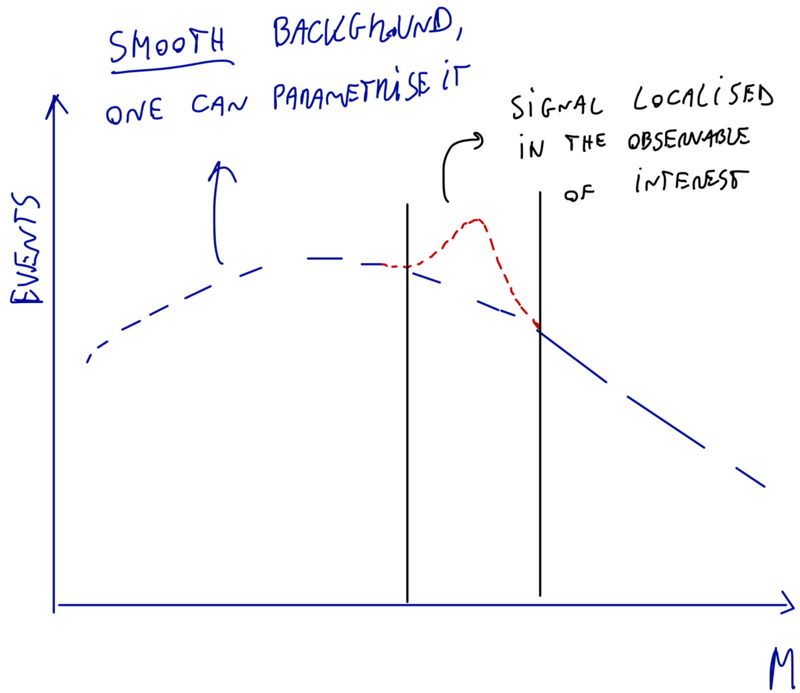
$$N_S \propto g_q^4$$

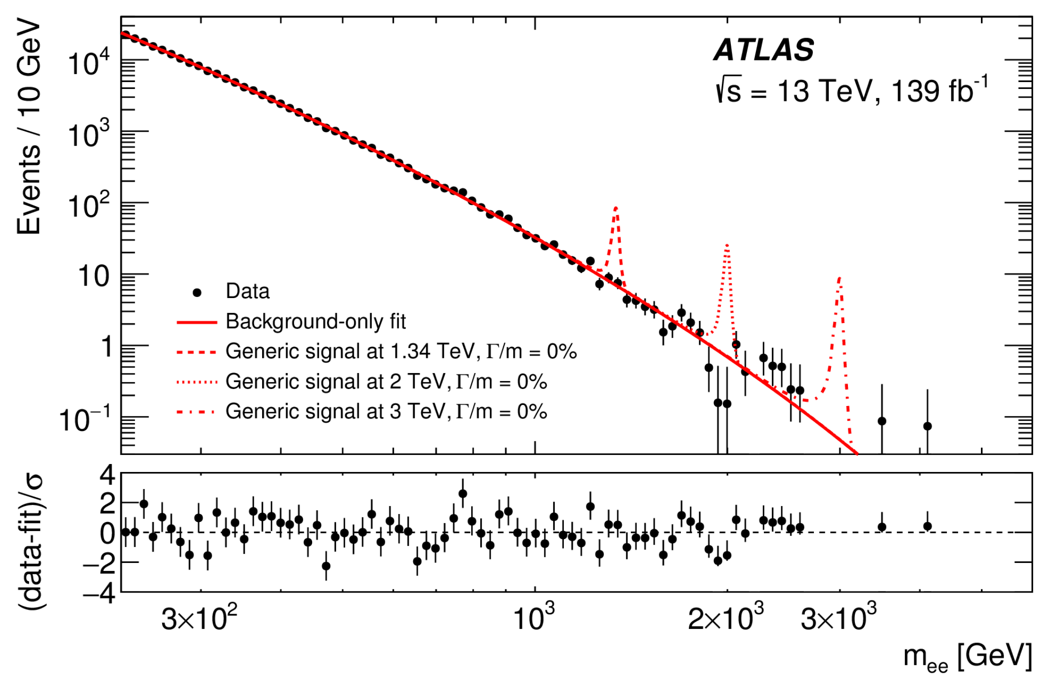
- Di-jet resonance analyses give a lot of sensitivity to mediator
    - But for different values of g_q, g_l, also **di-lepton resonances**
    - And for more complex DM models, other resonant analyses (diboson, di-higgs, HV, etc.) would become relevant.



Background directly from the data

- Main example: resonant searches
  - Background is normally fit with a smooth function (sometimes a simple polynomial)

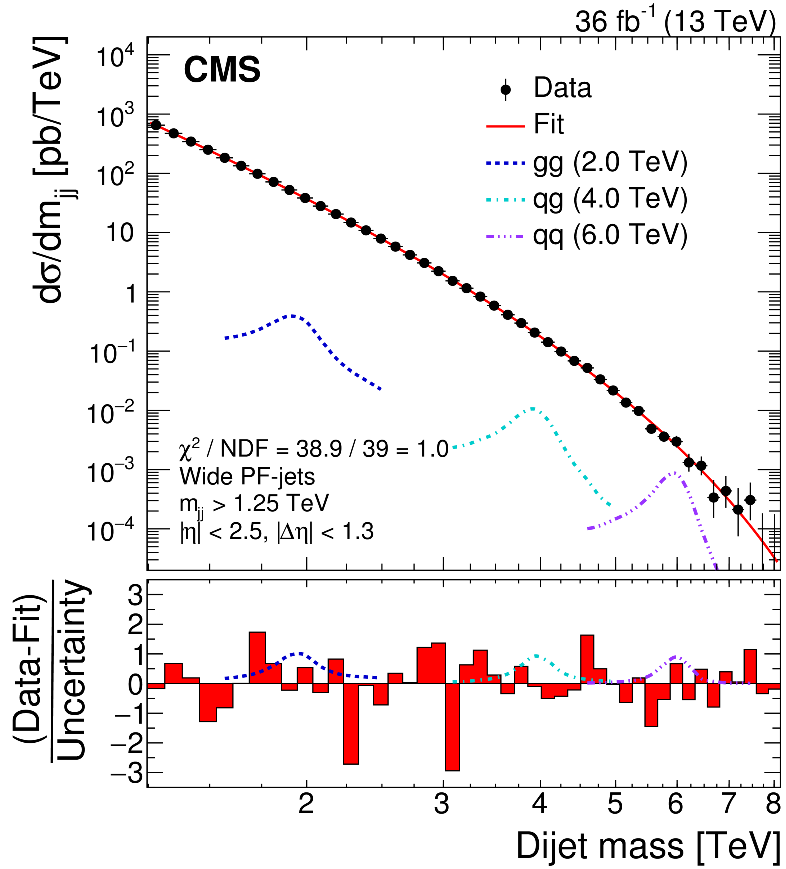


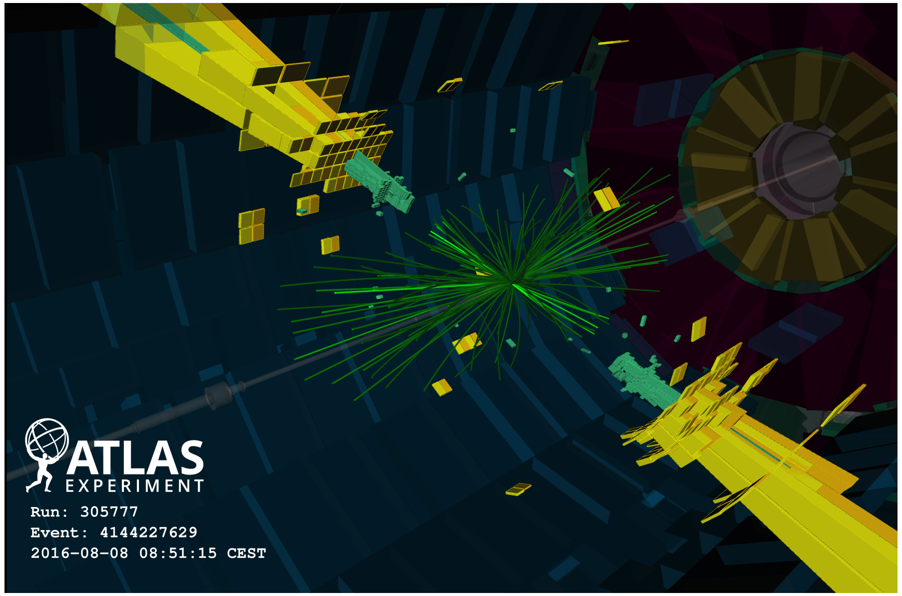


Di-jet analysis

- Look for a bump on a smooth parametrised background

$$\frac{d\sigma}{dm_{jj}} = \frac{P_0(1-x)^{P_1}}{x^{P_2+P_3\ln(x)}},$$





- Low mass acceptance **limited essentially by trigger threshold**
  - Huge rate from QCD di-jet events
- Two strategies to overcome this:
  - Trigger level analysis/data scouting.
  - ISR + di-jet

See arXiv:1806.00843, ATLAS-CONF-2019-007

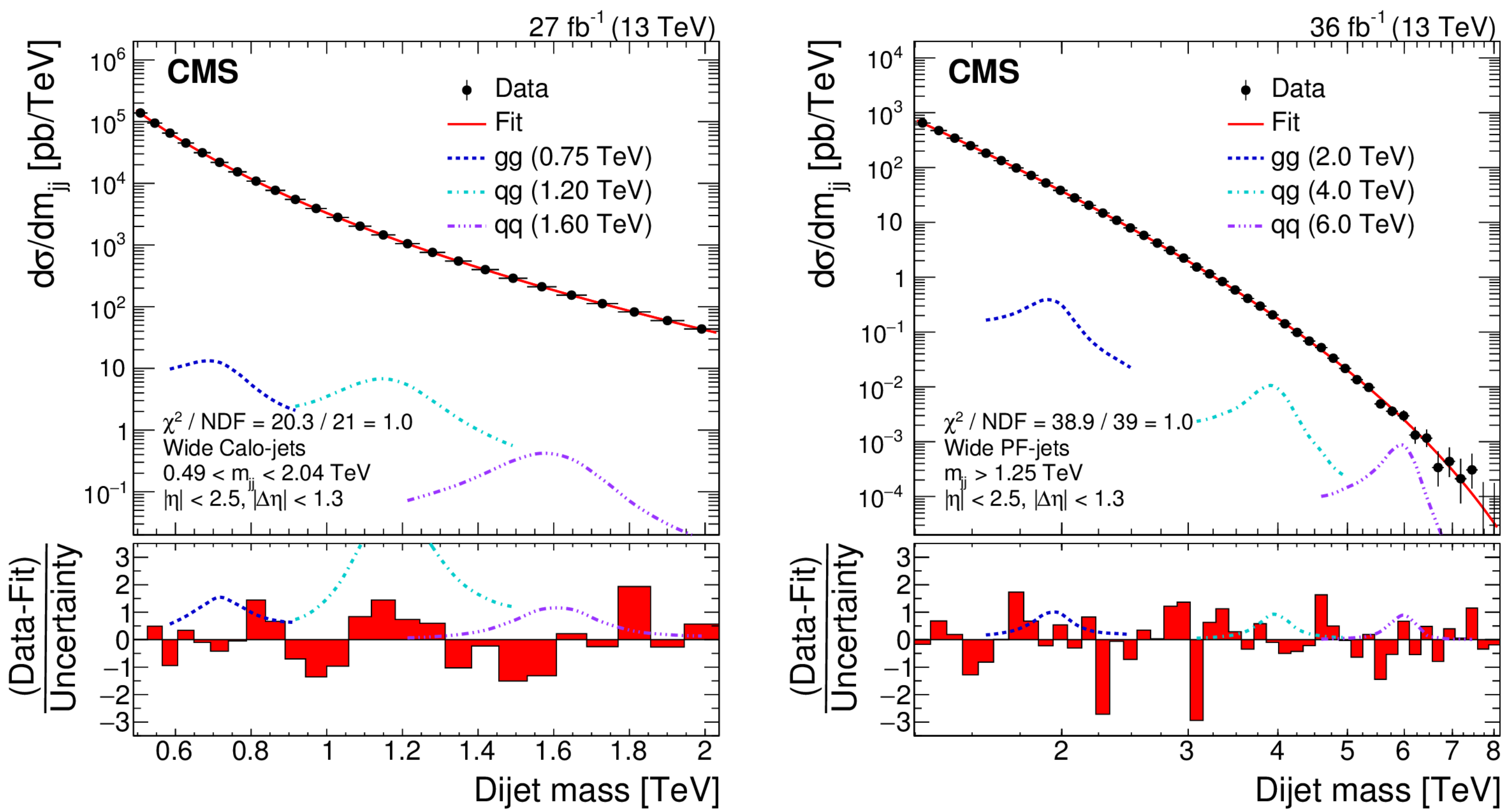
Overcoming QCD dijet rate

See arXiv:1806.00843, Phys. Rev. Lett. 121 (2018) 081801

- Data scouting/Trigger Level Analysis

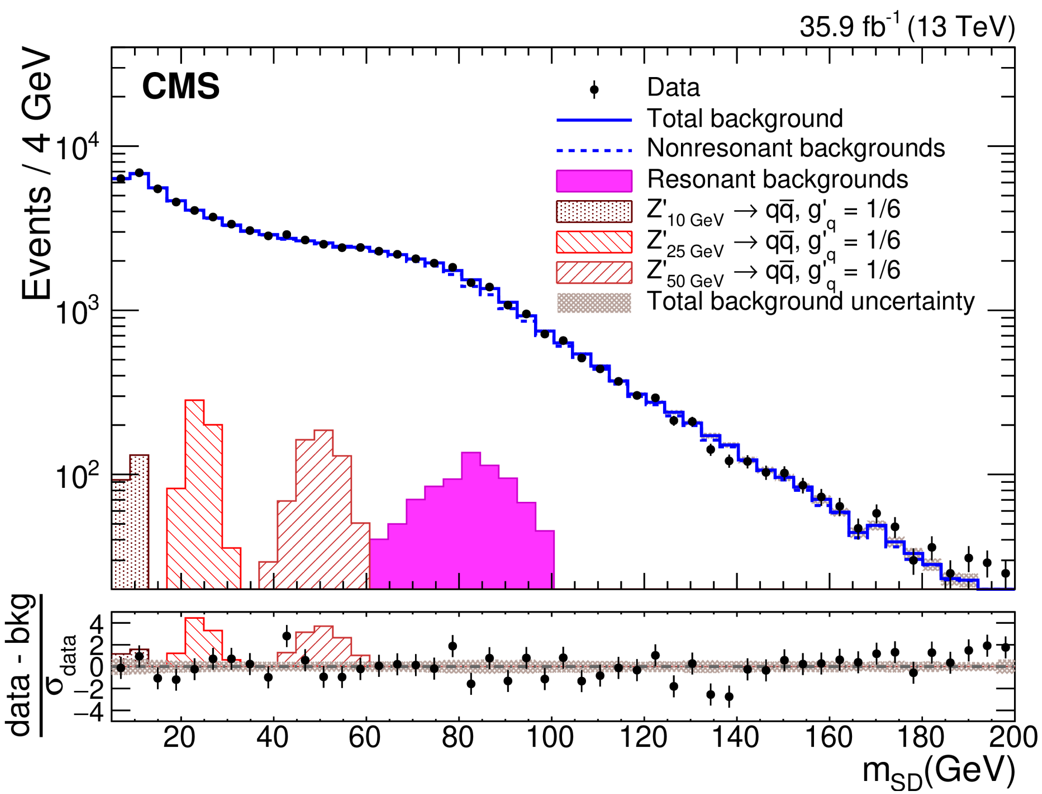
$$\text{Size on tape} \propto \text{Event size} \times \text{rate}$$

- If information saved kept to a minimum, event rate can be high



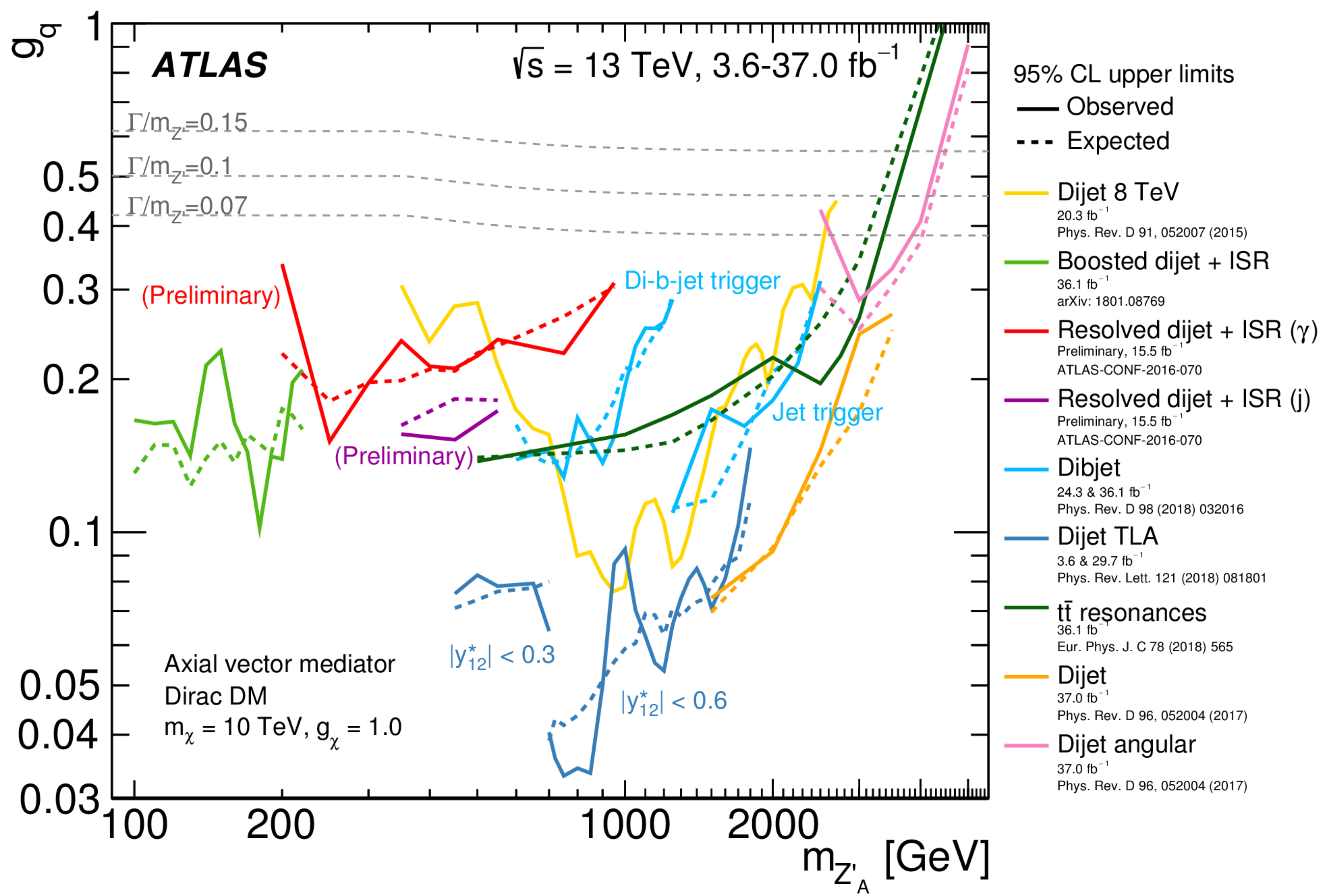
Overcoming QCD dijet rate

- To go even lower in m_{jj}: look at ISR + di-jet.
- See for example arXiv:1905.10331



- Look at an Anti-k_T R = 0.8 jet with a **two-prong substructure**
  - Grooming done with soft drop
- The modelling of the jet mass distribution done through a parametrisation developed in dedicated control regions.

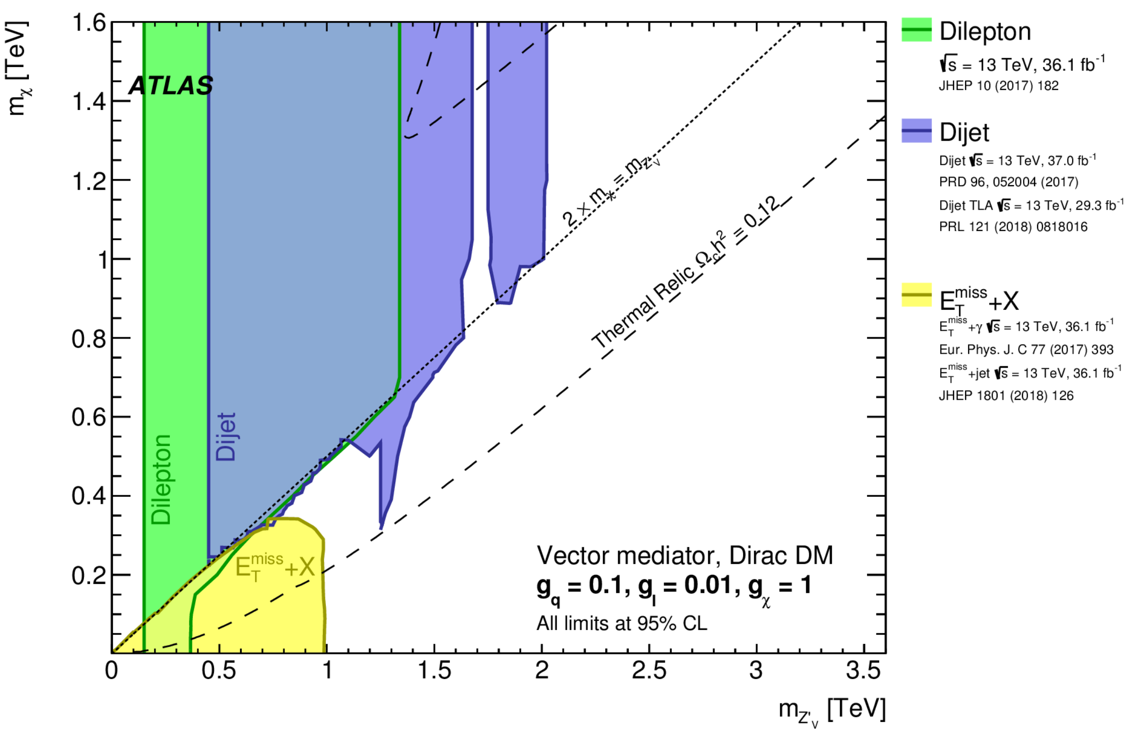
Putting everything together

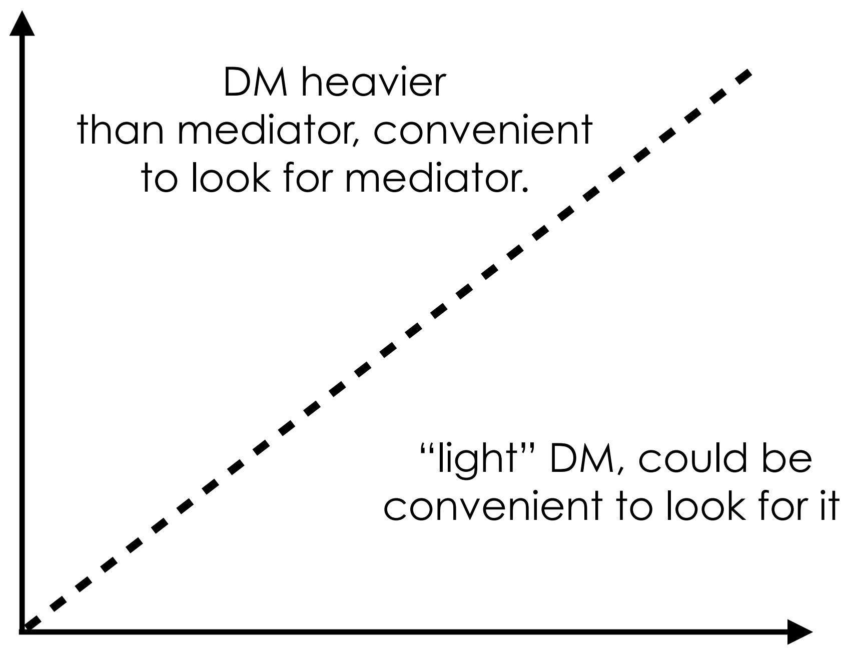


Vector-like couplings

- Note the choice of the couplings

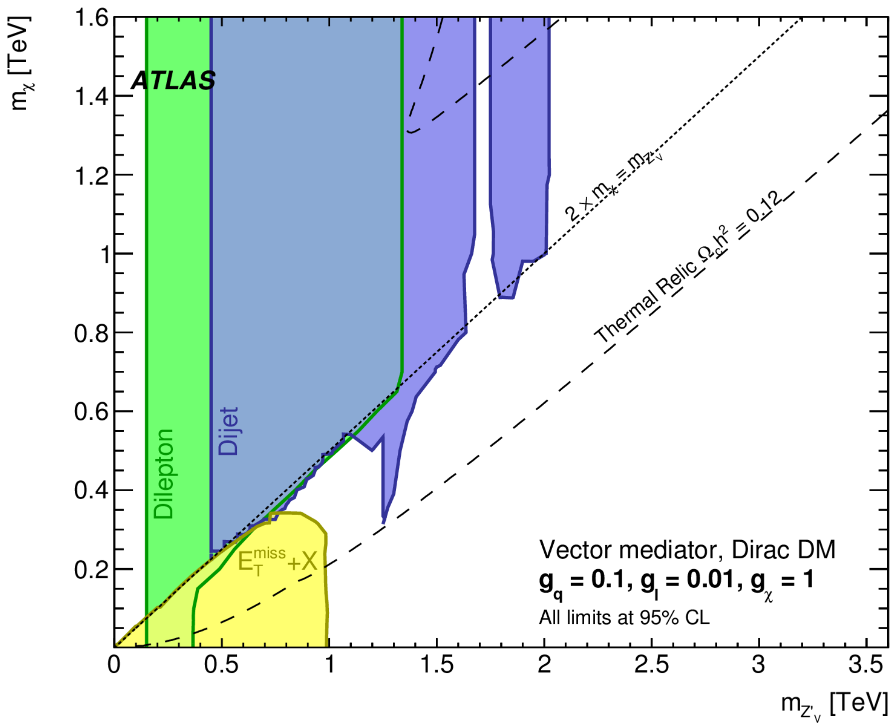
How to understand the plot

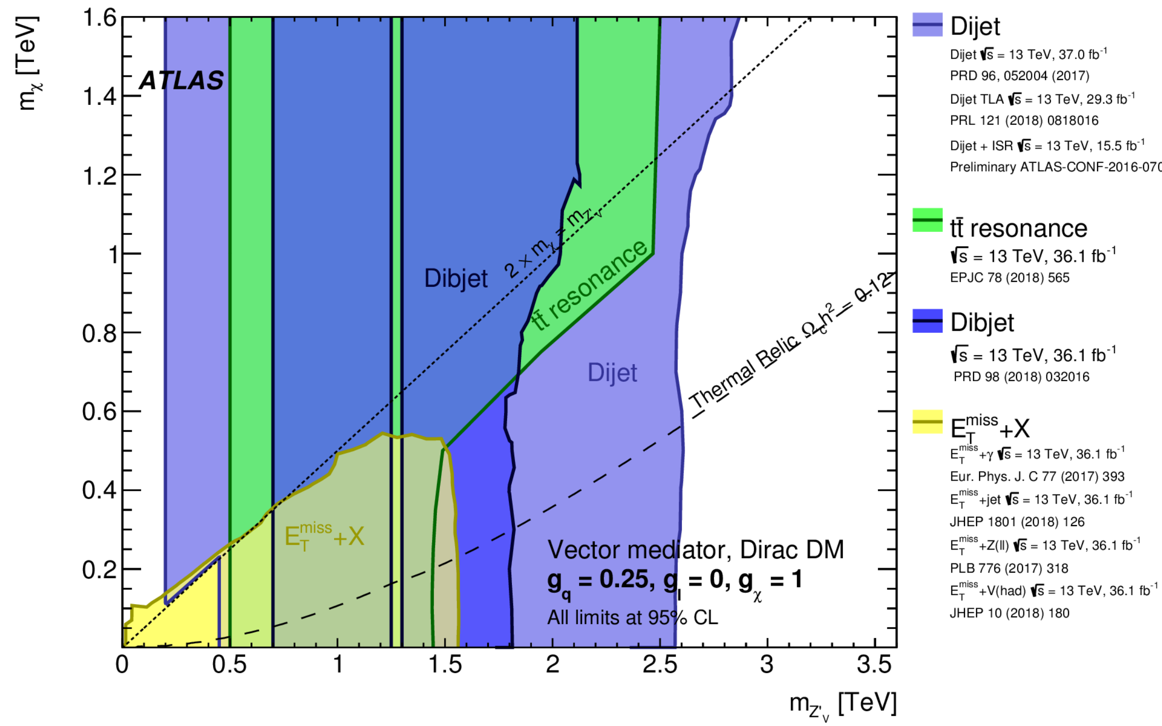




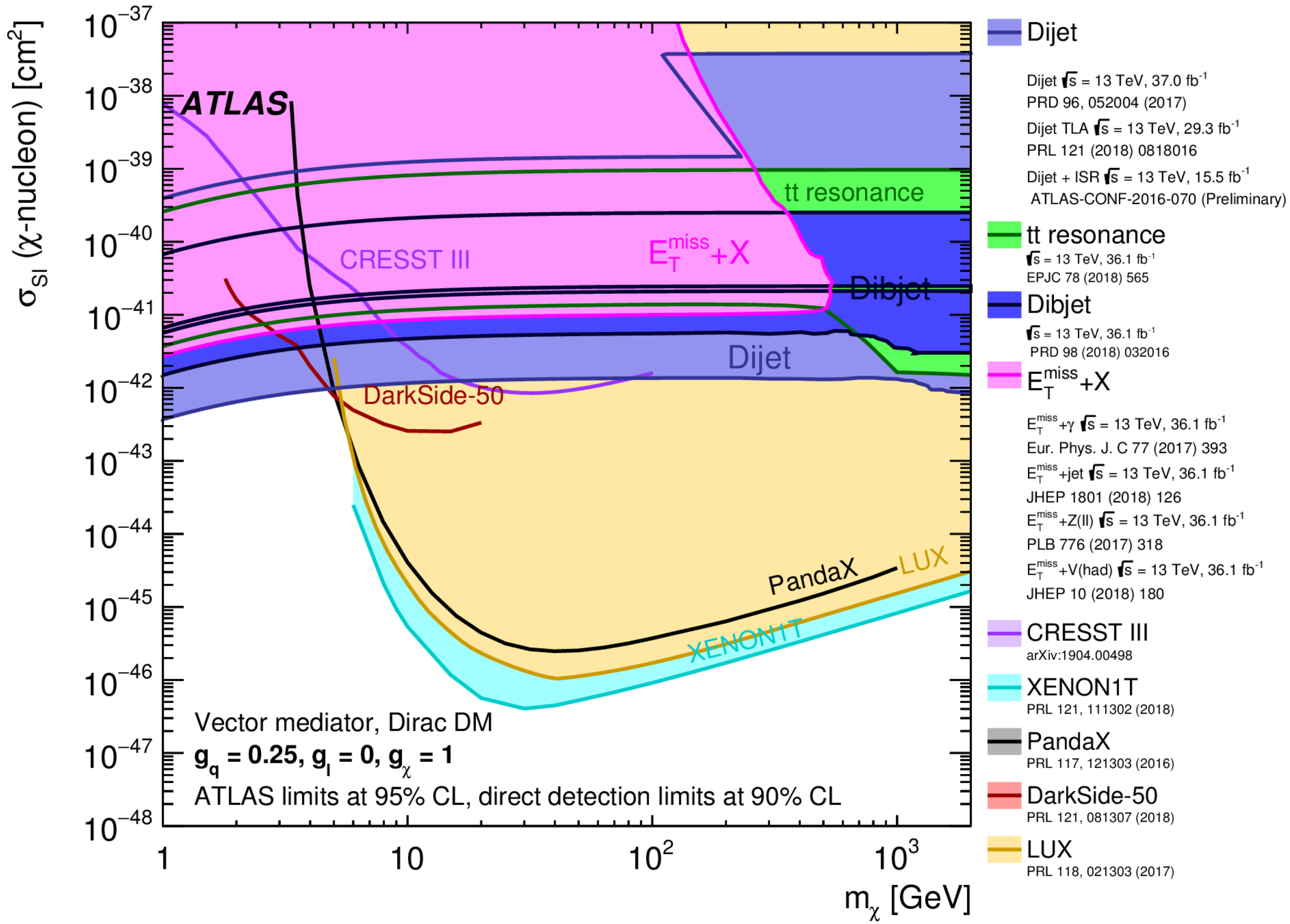
Vector-like couplings

- Note the choice of the couplings

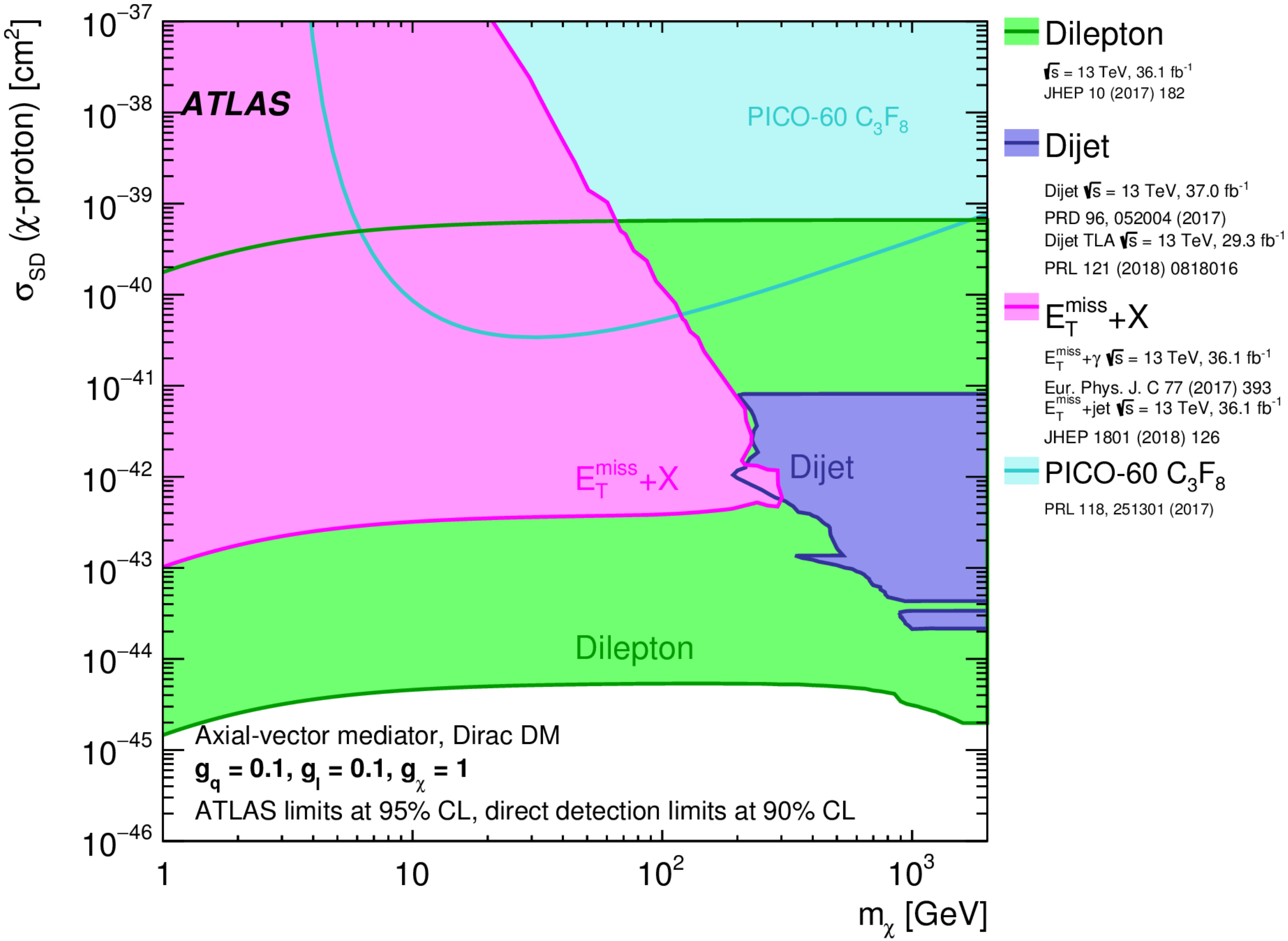




Spin-independent DM limits



Spin-dependent SM limits



Other DM candidates: axions

- Among the other DM candidates, **axions** are appealing.
- Axions are **pseudo-goldstone bosons** of the (spontaneously broken) Peccei-Quinn symmetry.
- Let's start from the beginning. The QCD Lagrangian contains a CP violating term.

$$L_{CP} = \frac{\alpha_s}{8\pi}\theta\tilde{G}^{\mu\nu}_a G_{\mu\nu a}$$

This would predict for the neutron EDM d_n

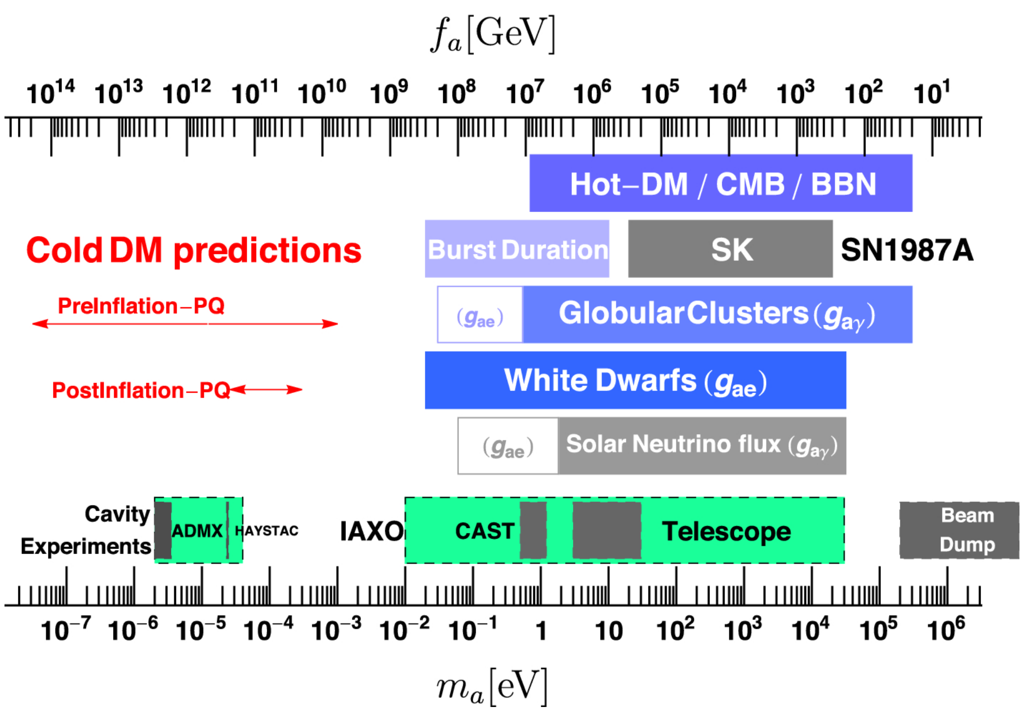
$$d_n = 2.4 \cdot 10^{-16}\theta e \text{ cm}$$

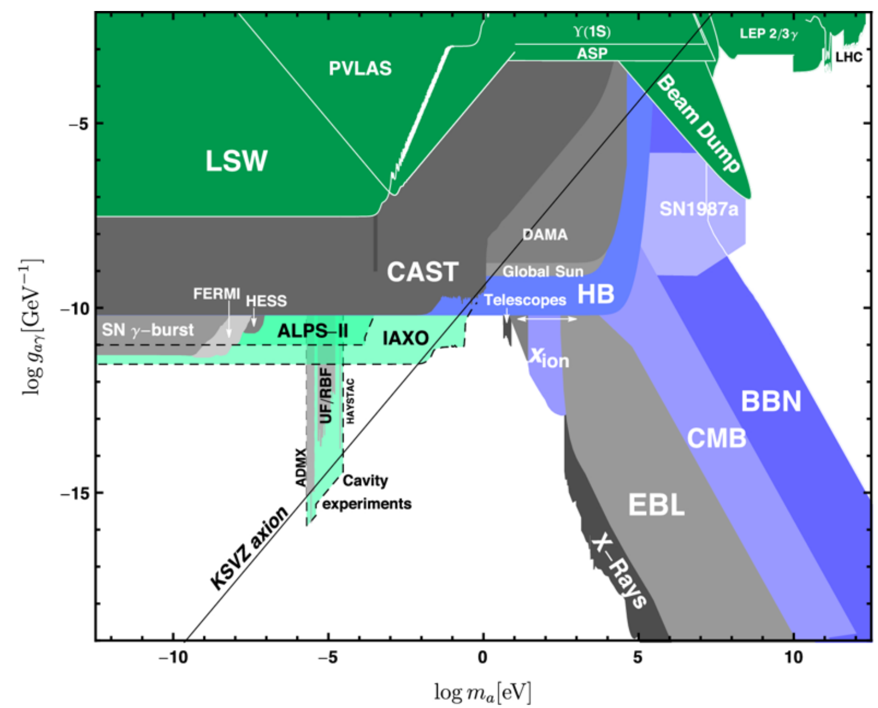
Experimentally $|d_n| < 2.9 \cdot 10^{-26} e \text{ cm}$, which implies $\theta < 1.3 \cdot 10^{-10}$ for no good reason…. Peccei-Quinn symmetry explains this as a result of a spontaneously broken symmetry. This introduces a relation between **the axion mass** m_a and the **PQ scale** f_a

$$m_a = 5.70 \ \mu\text{eV} \left(\frac{10^{12} \text{ GeV}}{f_a} \right)$$

Axions and ALPs

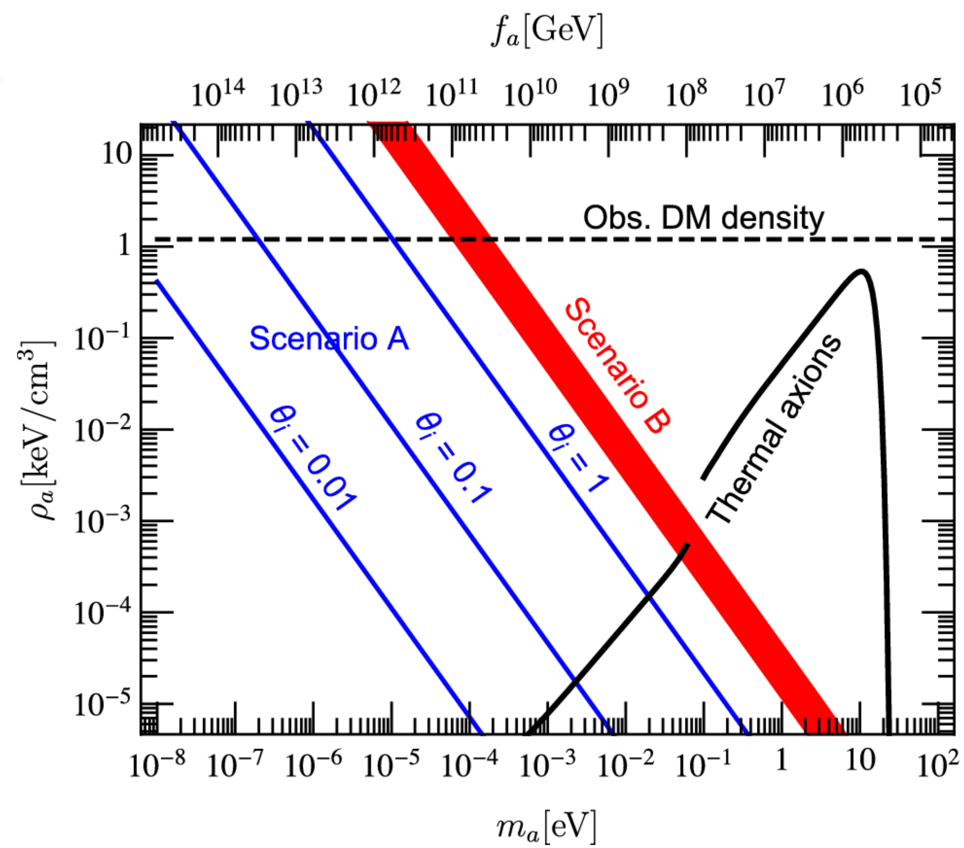
- Axions interactions with SM are $\sim \frac{1}{f_a}$ (therefore small)
- Axions interact with photons (EM field) with strength fixed by m_a and f_a
- A set of astrophysical limits indicate $f_a > 10^8$ GeV
- Axion Like Particles (ALP) do not have a fix constrain between f_a and m_a





Dark matter axions

- Different cosmological scenarios point to different ranges of allowed m_a to match DM relic density
- Scenario A and B refer to whether the PQ symmetry is broken **before or after inflation**
- The bottom line is that DM axions have mass of **meV or lower.**



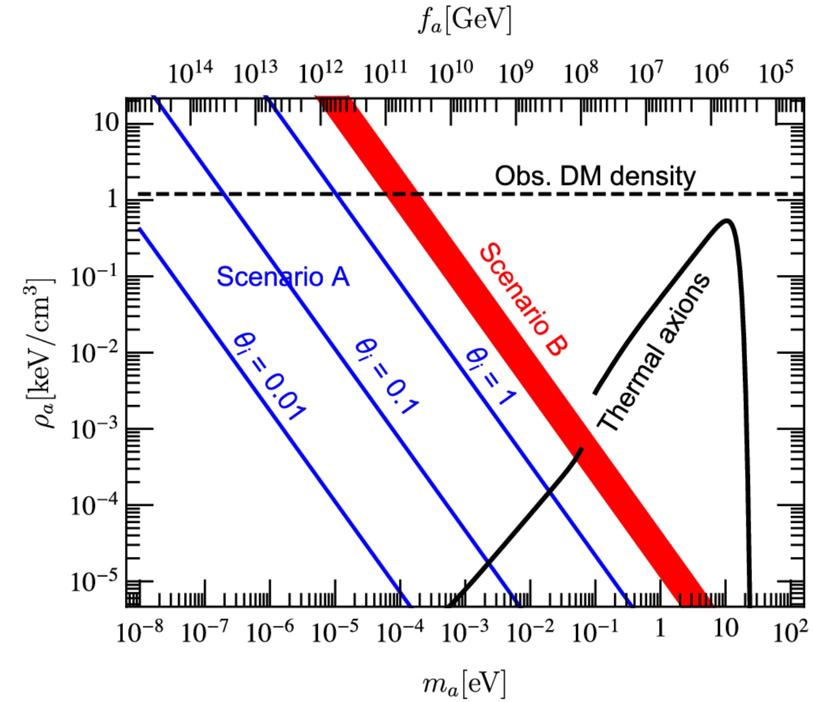
Note that the De Broglie length for, e.g., $m_a = 40\ \mu\text{eV}$ and DM speed $v \sim 10^{-3}\ c$ is

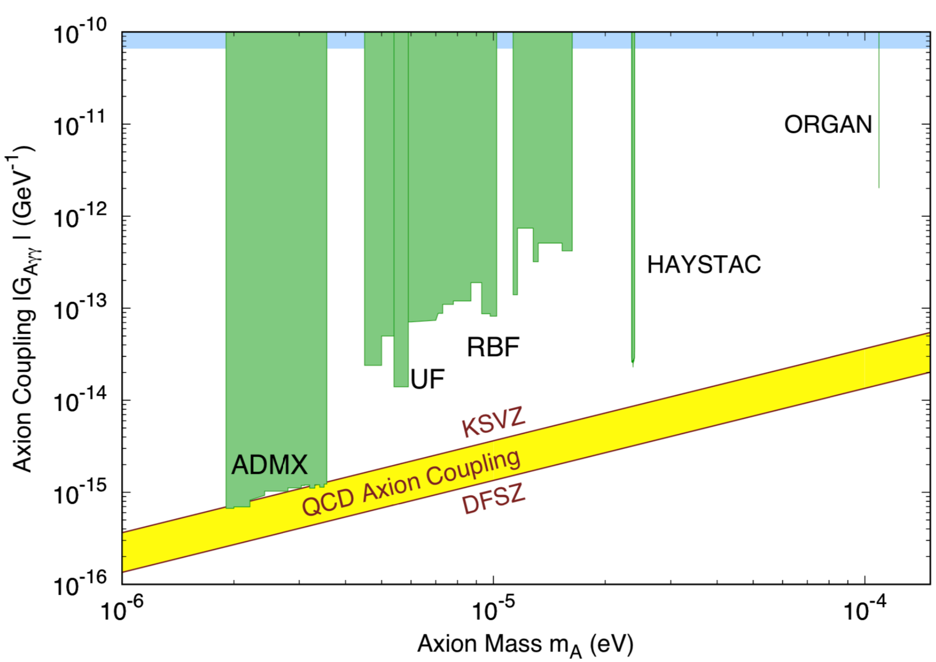
$$\lambda = \frac{2\pi}{m_a v} \sim 10^{10}\ \text{eV}^{-1}$$

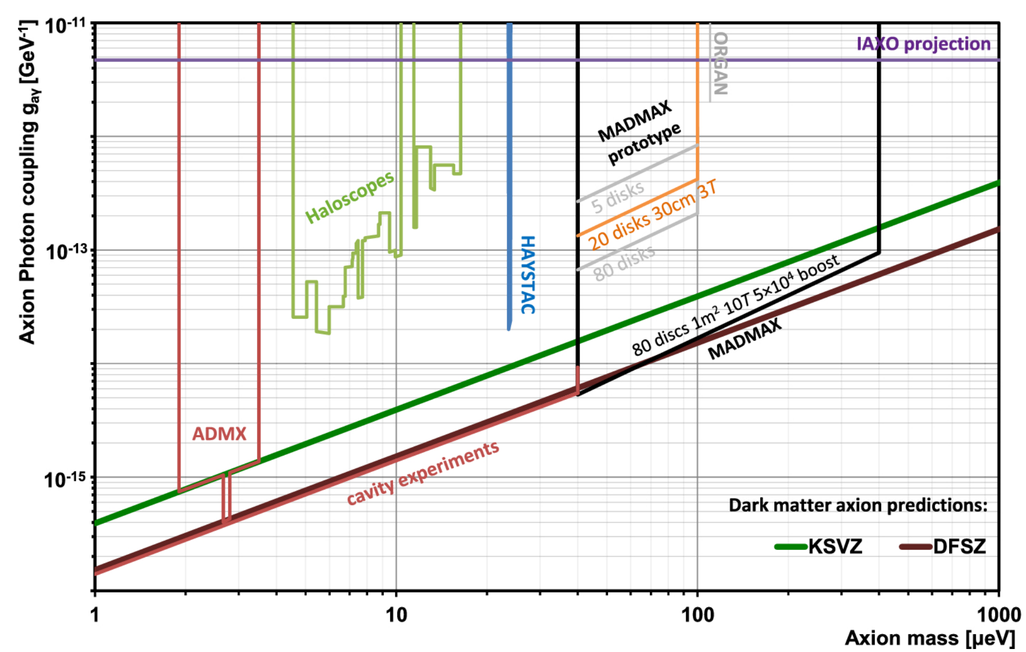
Remember $\hbar c = 197\ \text{MeV} \cdot \text{fm}$, then λ is macroscopic

DM axions detection

- Detect a microwave monochromatic signal
  - Historically done with EM cavity with strong B
  - New technique: use of Fabry-Perot resonator MADMAX and others

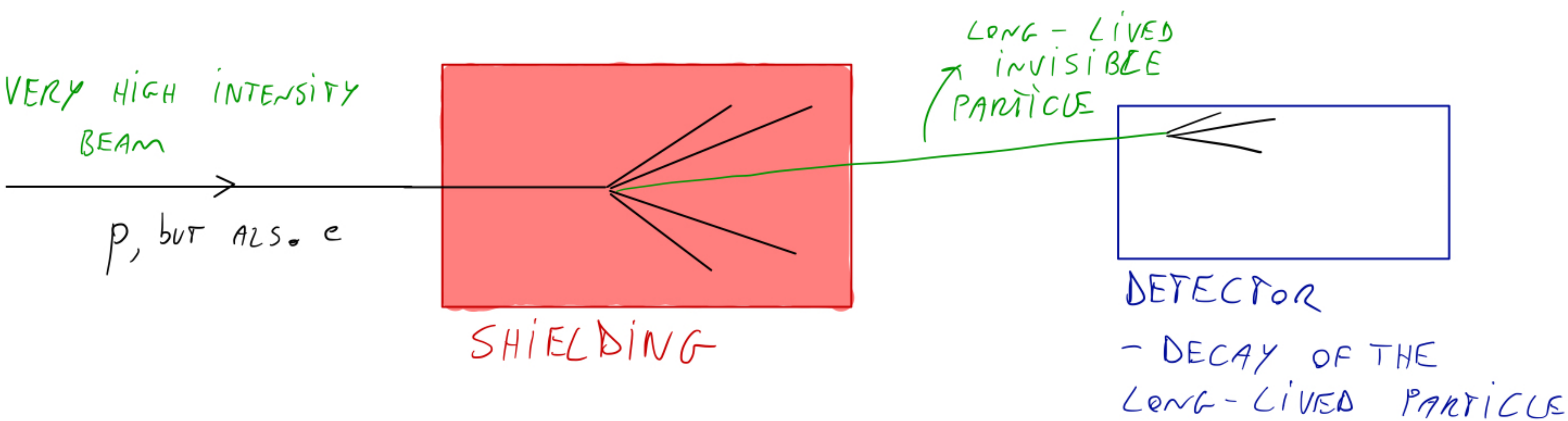






Beam dump experiments

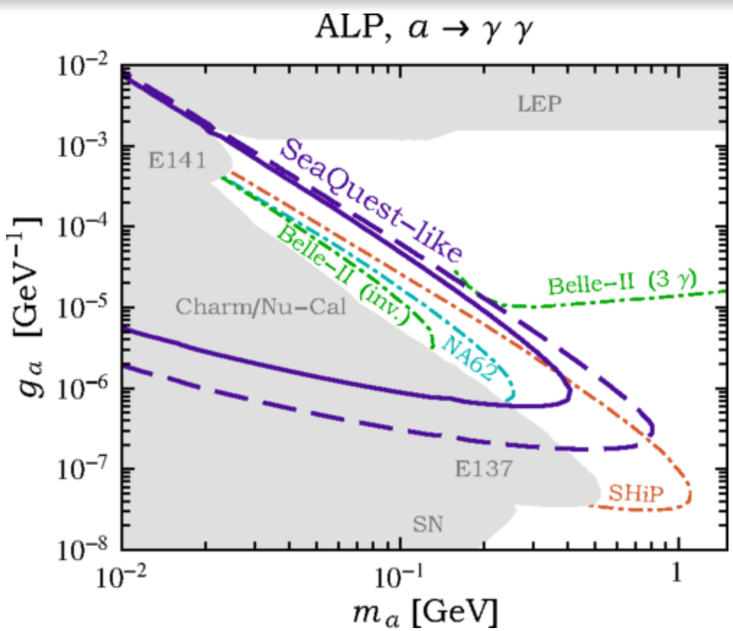
- **Large beam intensities on fixed targets** can probe limited mass scales, but **very small couplings**.

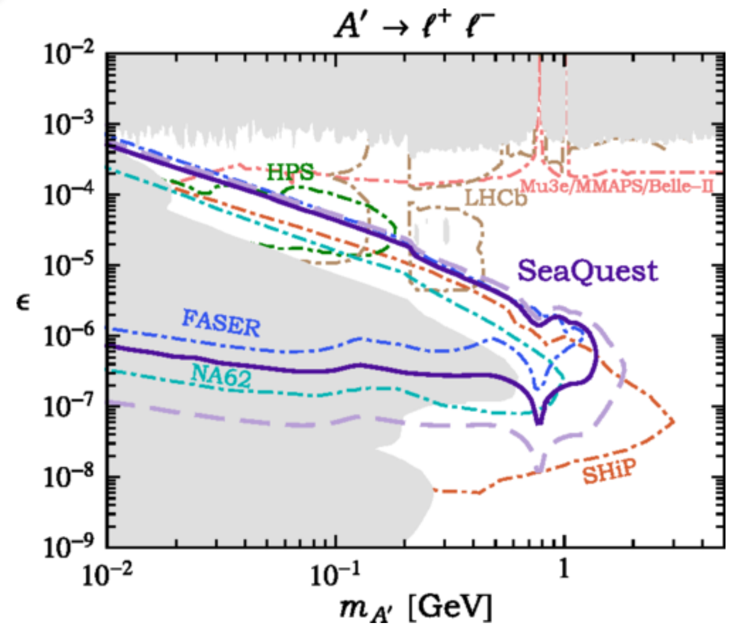


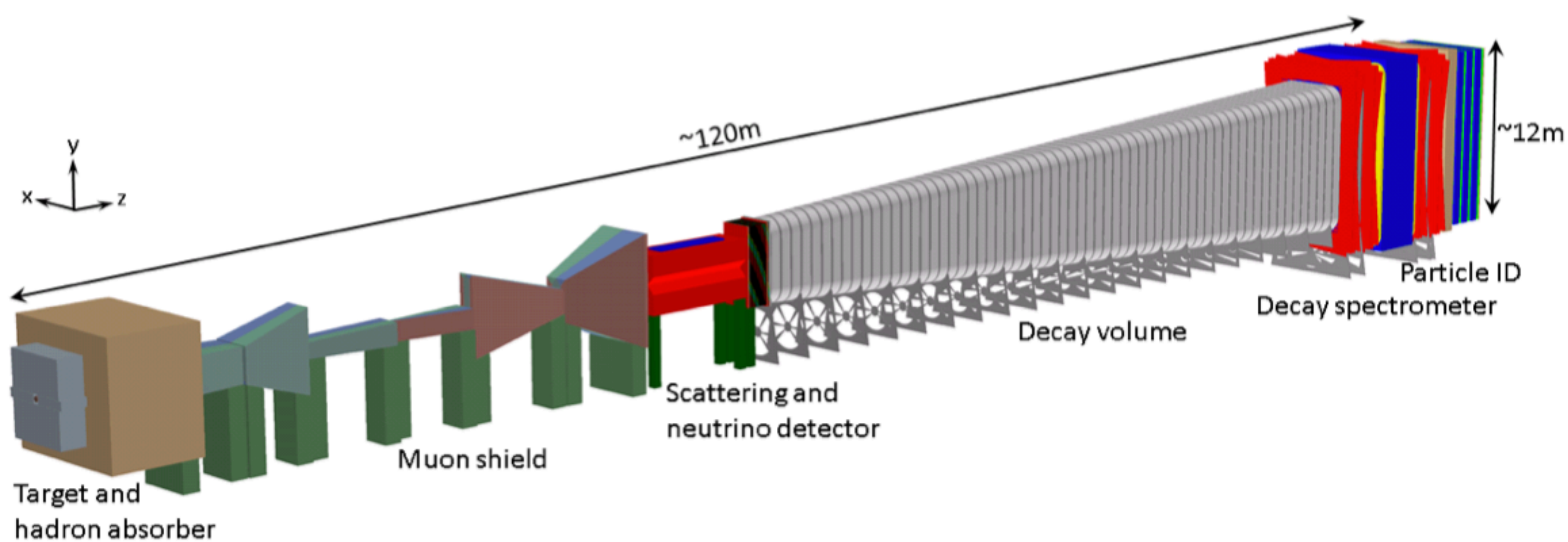
- A paradigm that applies to few different scenarios, among which ALPs and, for example, dark photons.

Beam dump experiments

Plots taken from Phys. Rev. D 98, 035011







Summary (dark matter)

- **No (uncontroversial) DM detection** (either at LHC or direct detection experiments) beside through gravitational interactions.
- **Complementarity** between the **different approaches** in the search for DM.
- Direct detection experiments will **soon reach** the neutrino floor:
  - Directional detection is the only idea on the market for the moment.
- At the same time LHC is kind of starting to **saturate its sensitivity** (at least to "large" cross sections).
  - But hard to say how and when the next generation of colliders will take part to the quest.

Exotica

What is "exotic physics"?

- It is a **very broad category** of models, which can basically be defined as "anything which is not R-parity conserving SUSY"
- Many experiments attacking "exotic physics":
  - LHC (certainly ATLAS and CMS, but also LHCb)
  - B-factories (BaBar, Bell, soon Bell II)
  - Fixed target experiments (beam dump - electron and hadron, neutrino accelerator experiments, NA62, SHiP and SeaQuest soon?)
  - Lower energy experiments (g-2,$\mu \to e\gamma$, etc.)

Where to find additional resources

- ATLAS Exotics Public Results
- ATLAS SUSY Public Results
- ATLAS Higgs And Diboson Searches
- CMS SUSY Public Results
- CMS Exotica Public Results
- CMS Beyond 2 Generations
- LHCB QCD, Electroweak and Exotica

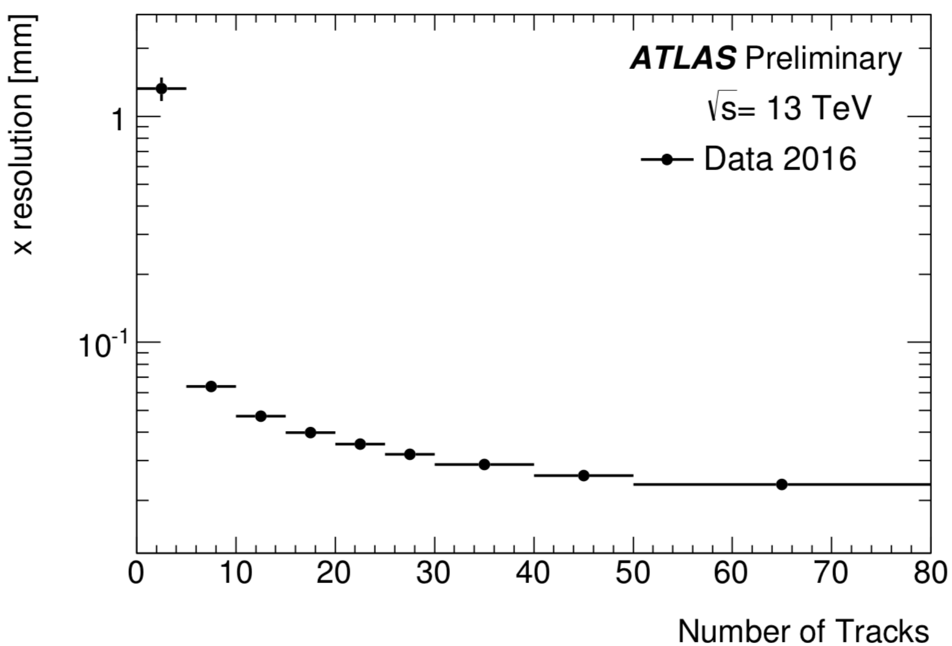
Outline

- Long-Lived particles
- Prompt signals
  - Extra-Dimensions
  - Resonances
  - Lepto-quarks
  - Vector-Like quarks
- Reinterpreting searches

Long-Lived particles

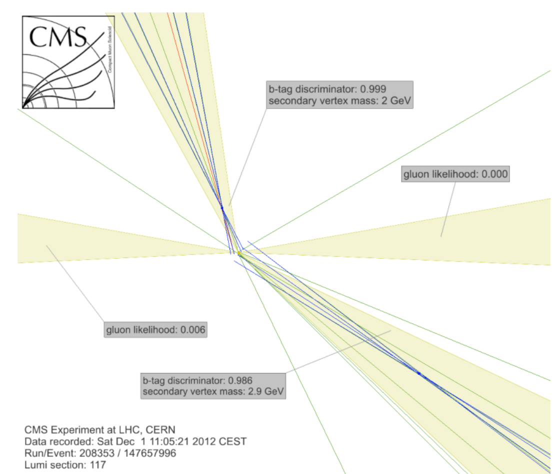
Long lived (LL) particles

- One of the **most active fields** of research for BSM in the last few years.
- What "long-lived" means depends on the context:
  - At LHC the scale is set by the resolution on the transverse position of the primary vertex. If L > 100 μm - 1 mm the particle is LL



$$c\tau \sim 1 \text{ mm} \implies \tau \sim 3 \text{ ps}$$

$$\tau(B^0) \sim 1.5 \text{ ps}$$
$$\tau(\tau) \sim 0.3 \text{ ps}$$
$$\tau(\pi^0) \sim 8 \times 10^{-3} \text{ ps}$$



Long lived particles

- Why is a particle long lived?

$$\frac{\hbar}{\tau} = \frac{f_\pi^2}{256\pi m_\pi}\left(\frac{g^2}{m_W^2}\frac{m_\mu}{m_\pi}(m_\pi^2 - m_\mu^2)\right)^2$$

Small coupling constant

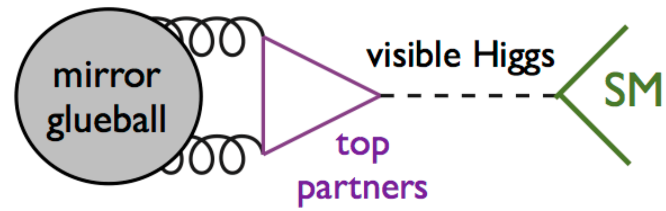
Small mass splitting to decay product

Large mediator mass

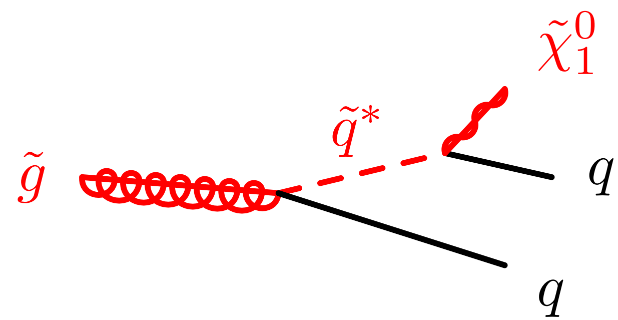
Helicity suppression

Few examples

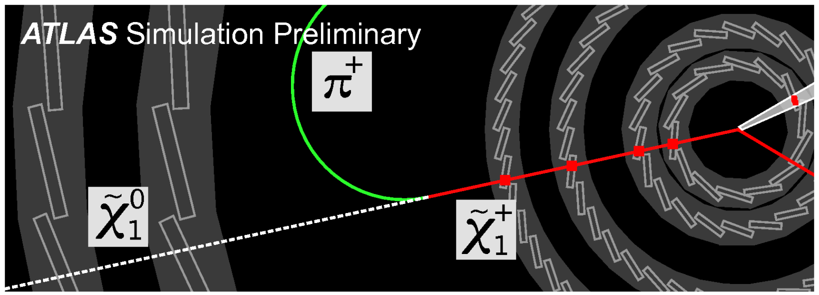
- Small coupling:
  - **Neutral naturalness:** twin, color neutral sector, for example coupling to the Higgs boson through twin top partners.



- Heavy mediator:
  - **Split SUSY:** gluinos relatively light but squarks heavy.

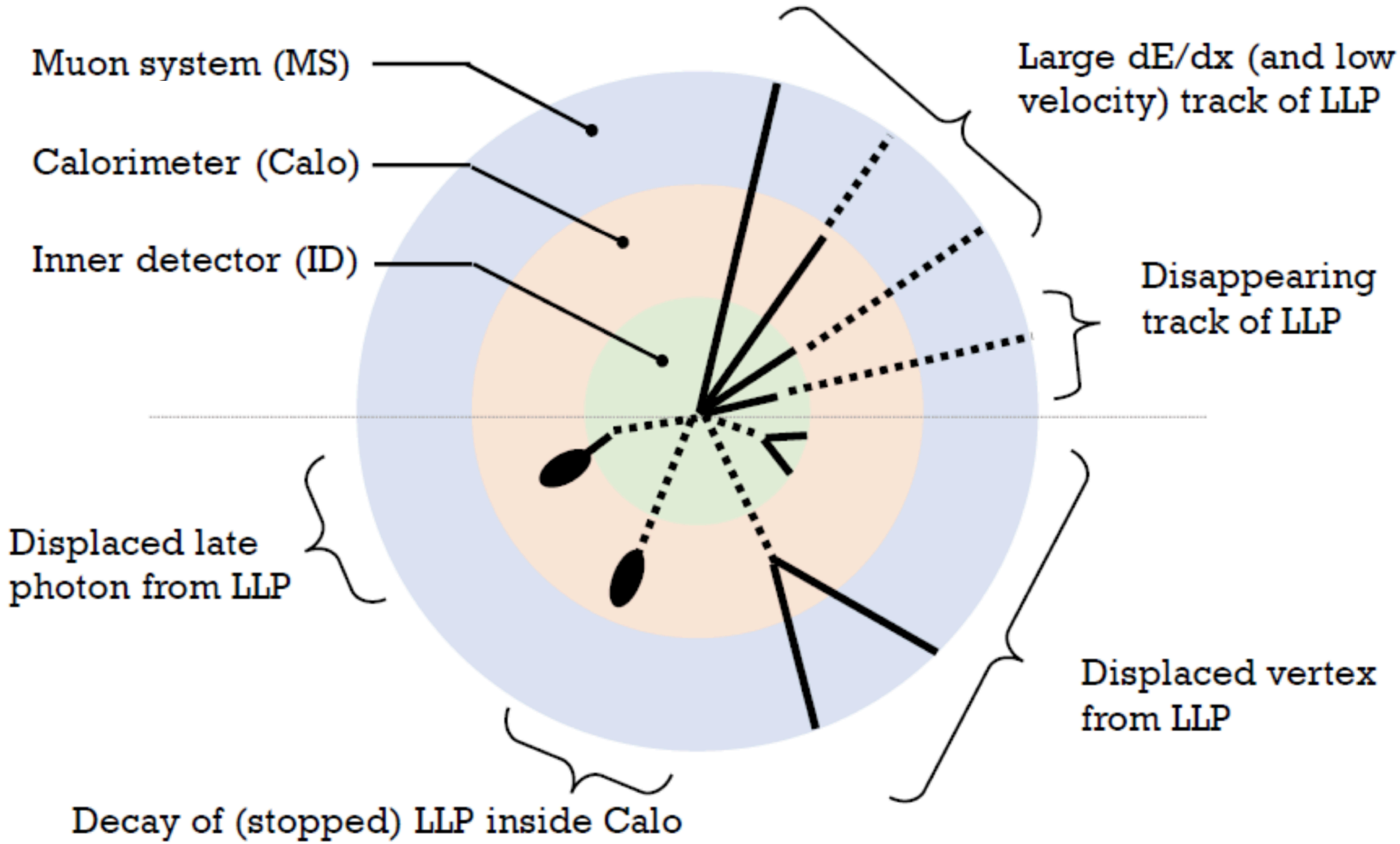


- Small mass splitting:
  - Already discussed **Wino-like SUSY LSP doublet.**



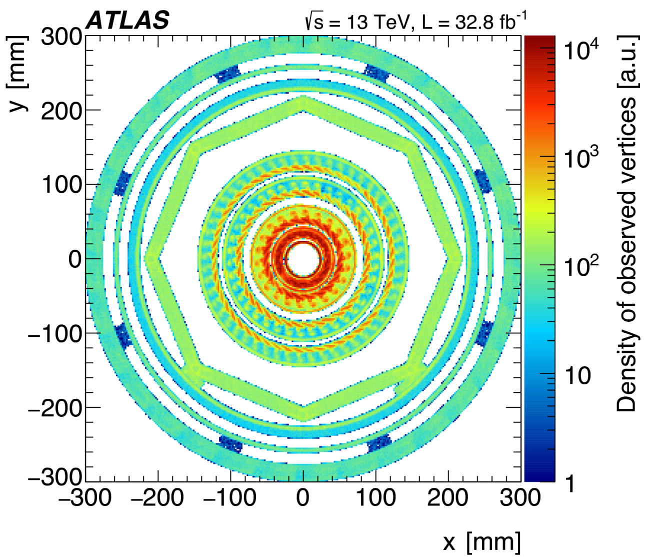
Signatures of LL particles

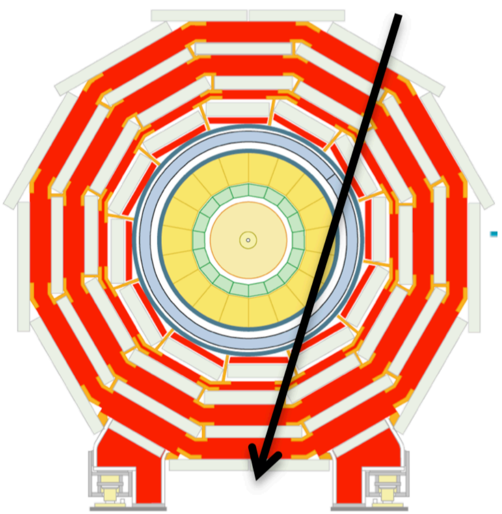
It depends on lifetime, charge and LL particle decay products

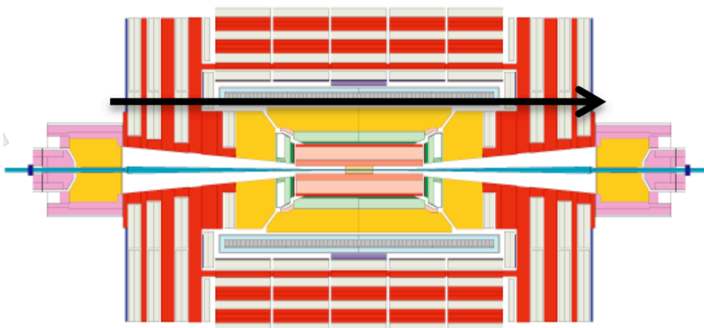


Common items in LL signature detection

- Normally **low background**, but hard to rely on any simulation





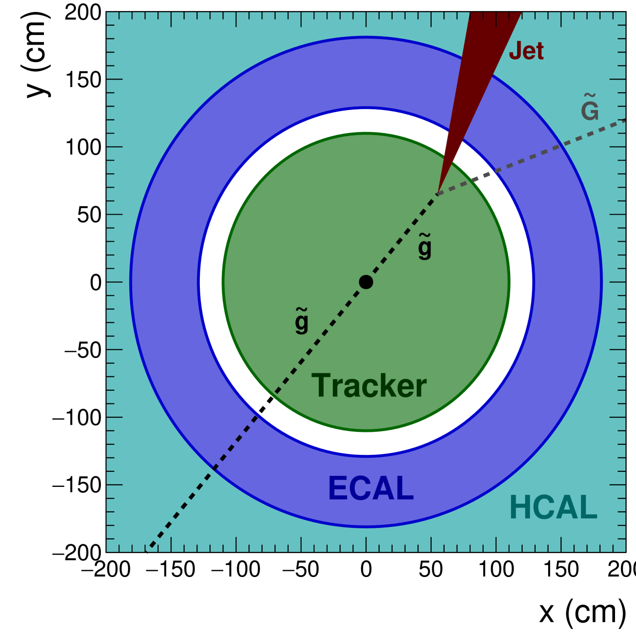


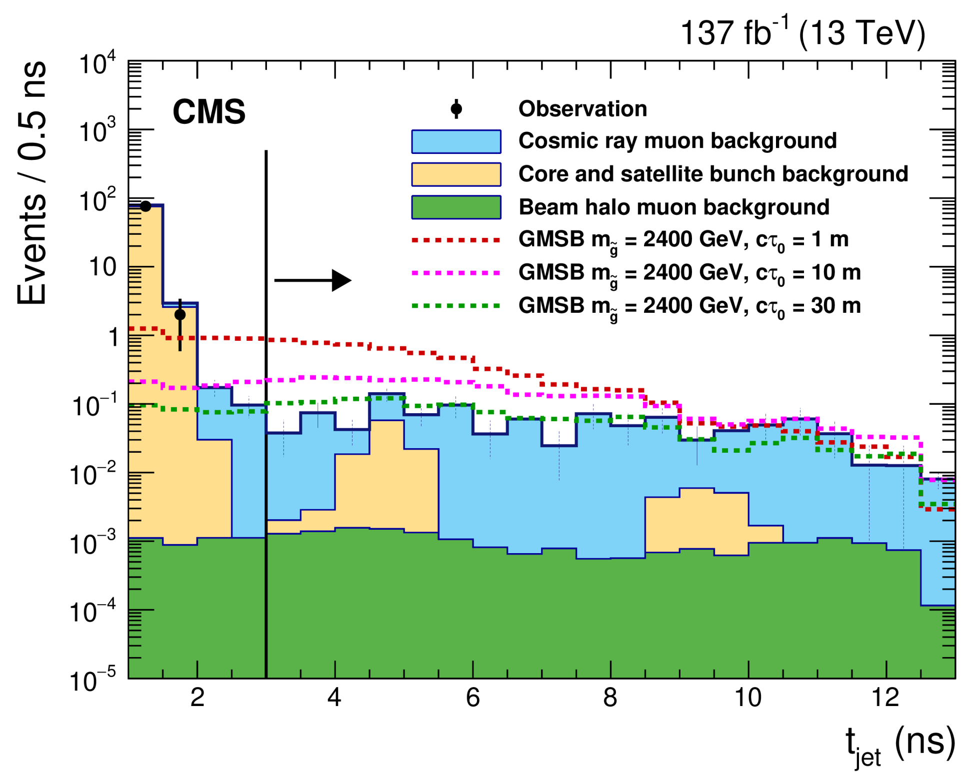
- Trigger: **low-level trigger** not always LL particle **compliant**
  - For example displaced vertices and disappearing track analyses **trigger on MET** rather than the LL particle itself.

See arXiv:1906.06441

A few examples

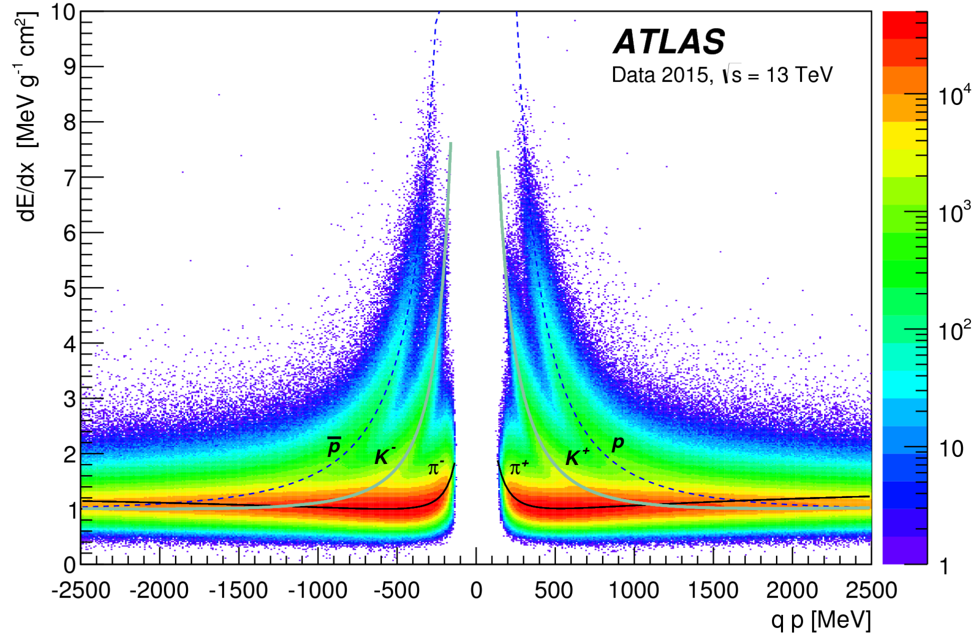
- Look for **displaced jets** based on the **timing in the EM calorimeter.** Highlight of the selection:
  - Topological selections based on jet shower shape (e.g. E_{em}/E_{had})
  - Small RMS of **timing of associated cells.**
  - Small fraction of **jet energy** attached to PV.
  - Background estimated with **a series of control regions** obtained by inverting the analysis requirements.

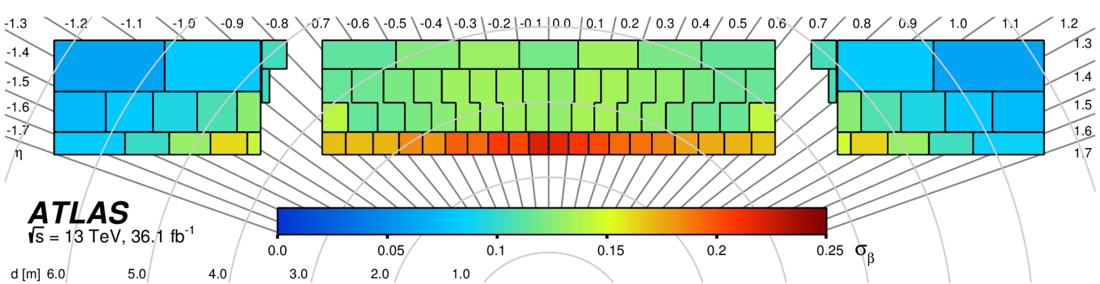


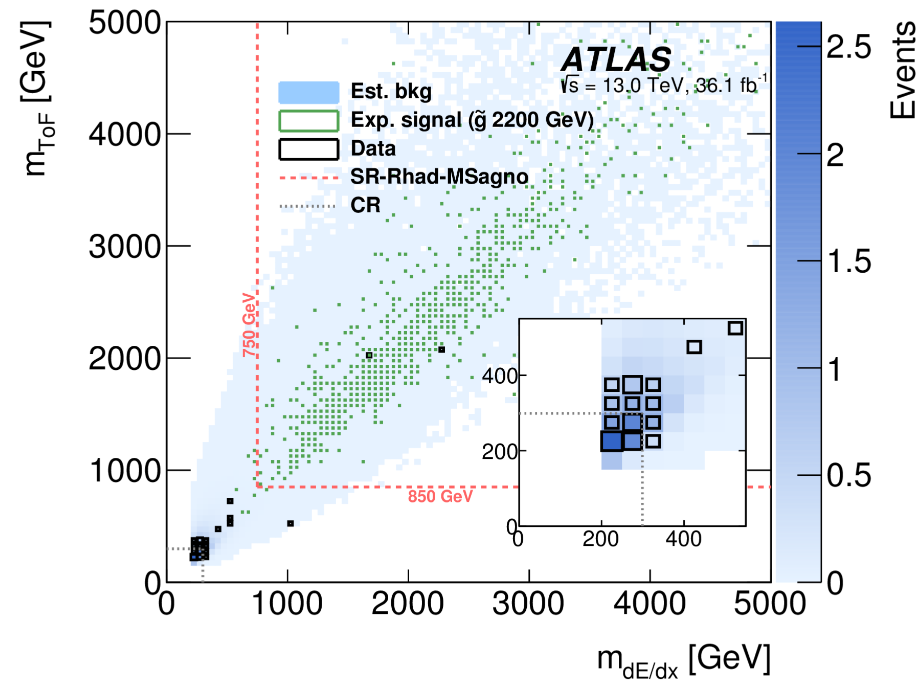


A few examples

- Heavy BSM particles **will be slow** and **ionise** a lot:
  - Use dE/dx information combined with timing of calorimeter and muon spectrometer.
- Background estimated exploiting **independence of timing and ionisation information.**

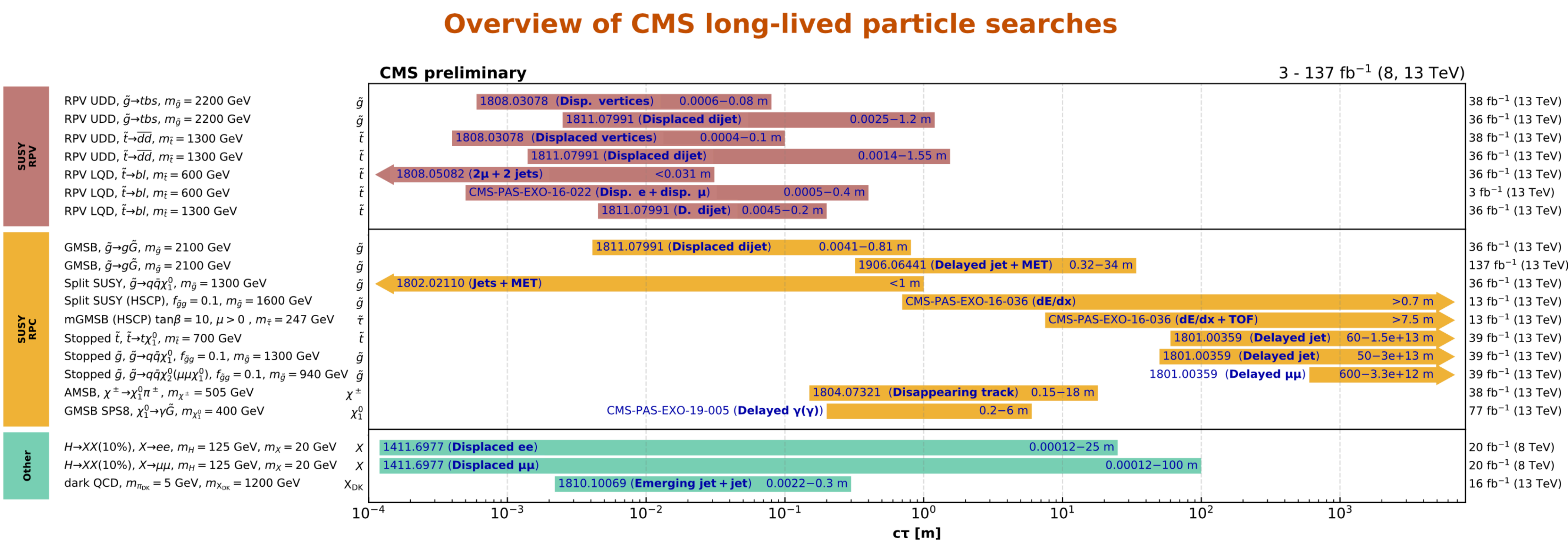






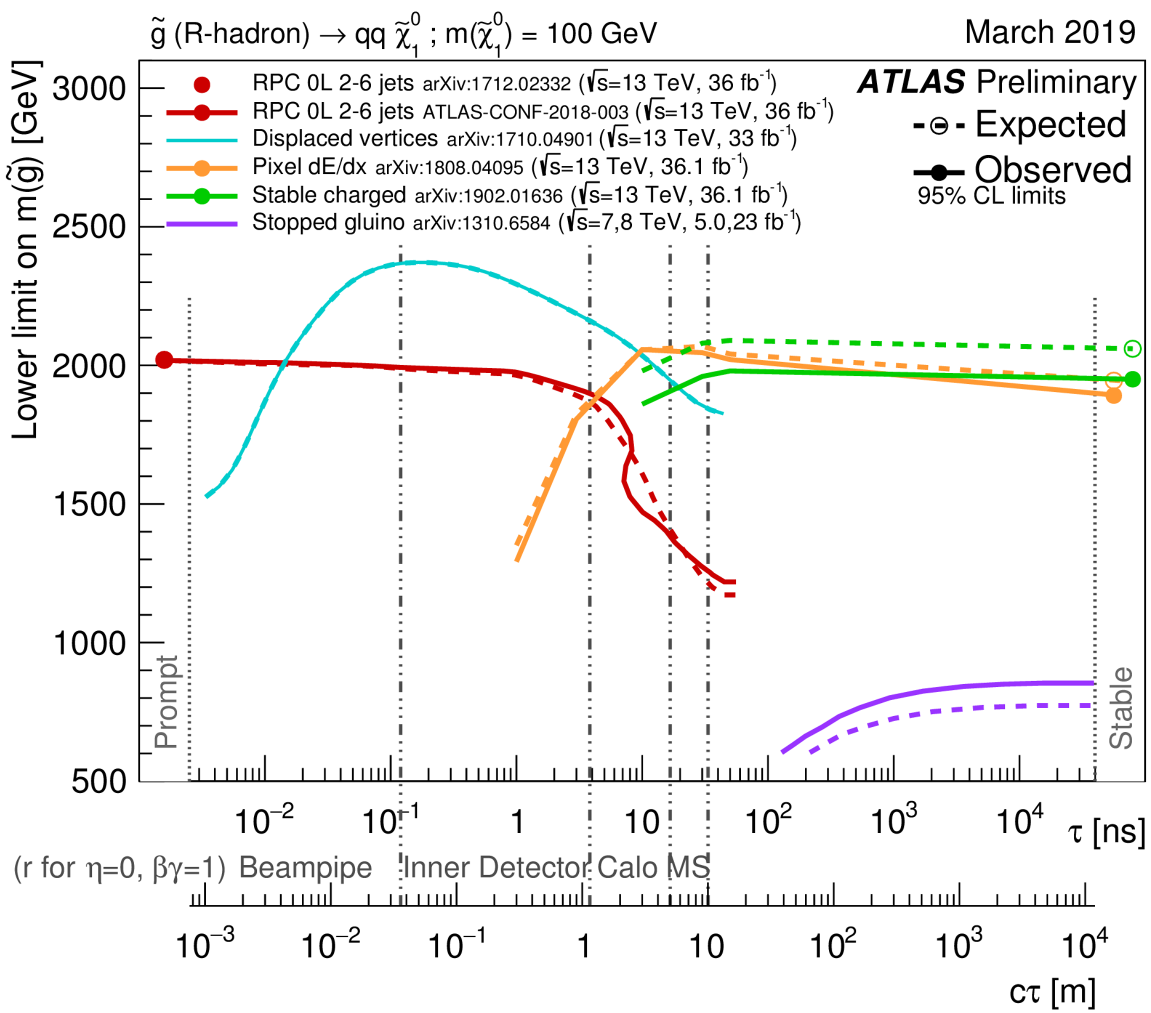
See Phys. Rev. D 99 (2019) 092007

Summary on LL particles



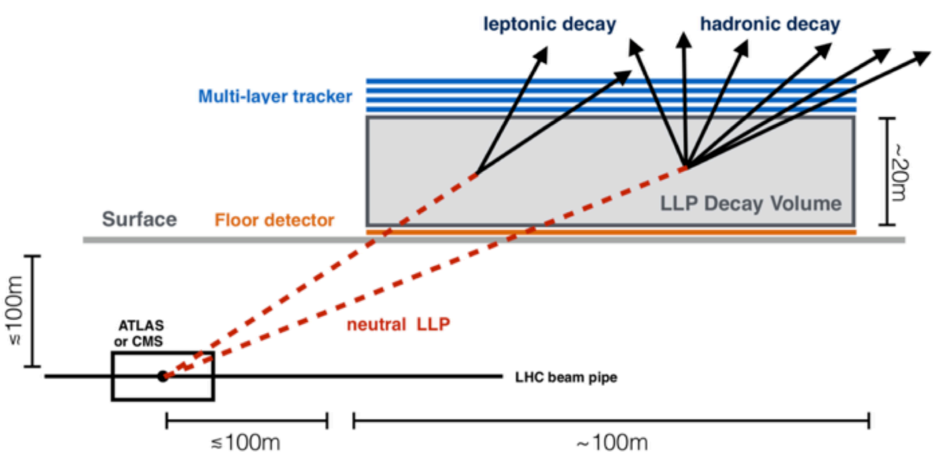
Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included). The y-axis tick labels indicate the studied long-lived particle.

Complementarity (depending on the signature)

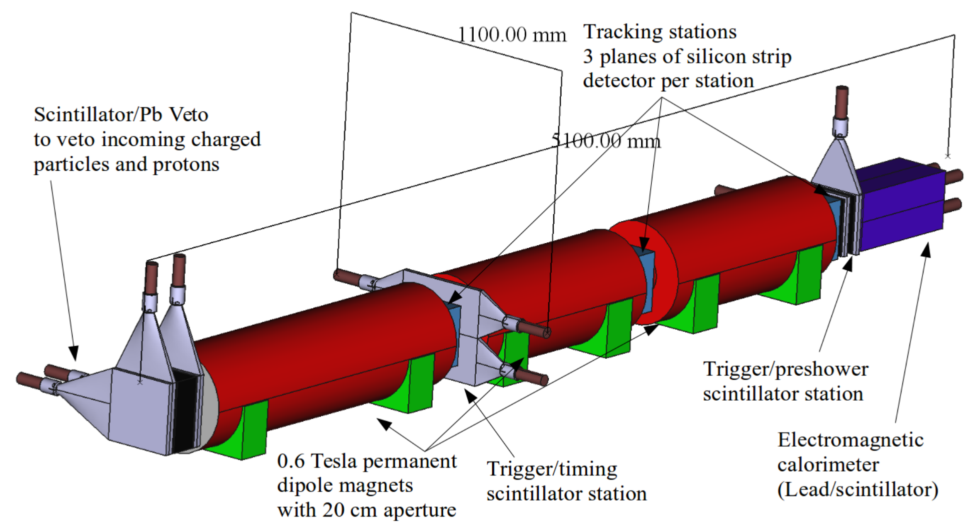


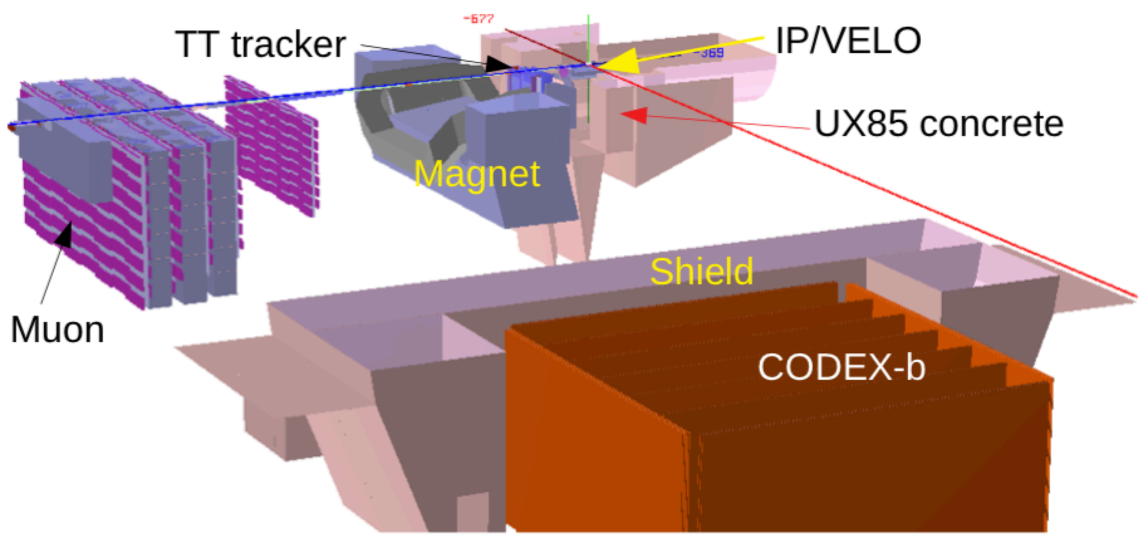
LL particles: looking ahead

FASER



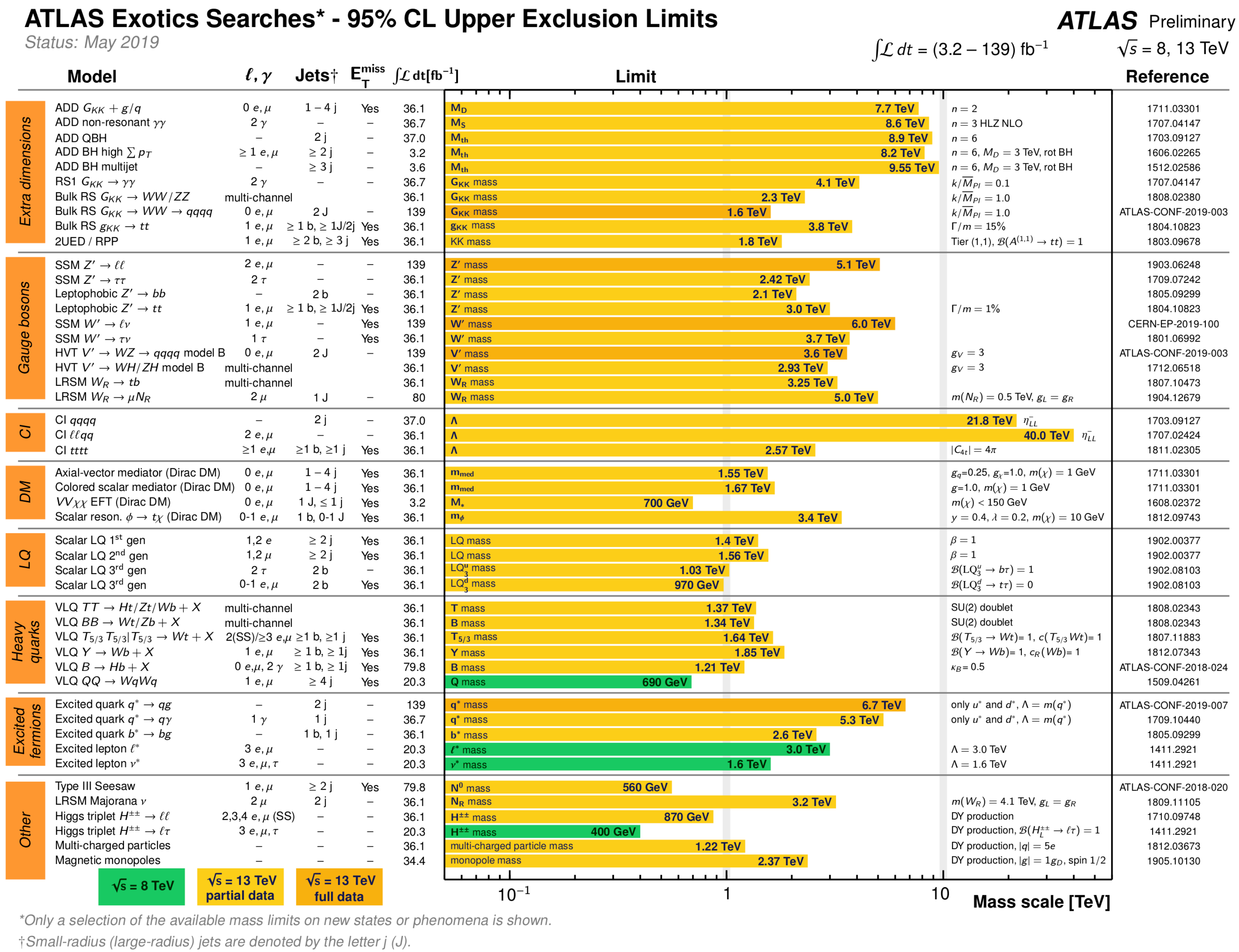
Mathusala



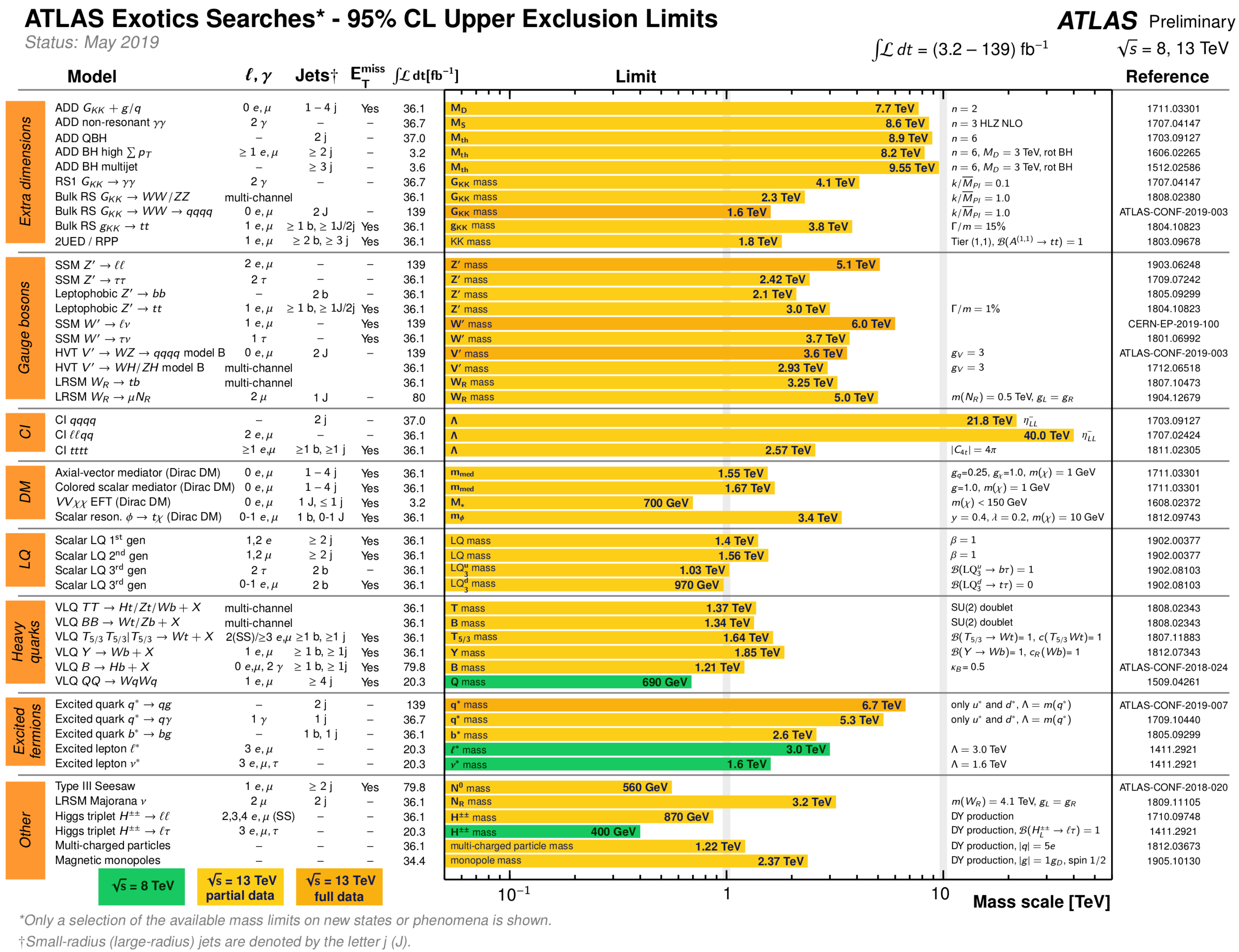


Prompt searches

Where to start from? Maybe from the end



Where to start from? Maybe from the end



Extra-Dimensions

- First introduced **in 1920s by Kaluza and Klein** to unify gravity with other forces:
  - Additional dimensions w.r.t. ordinary 3+1 (space + time).
  - Additional dimensions **compactified** $\Longrightarrow$ boundary conditions on the fields $\Longrightarrow$ KK excitations.
- Idea developed further **during 1970s, 1980s and 1990s** in the context of superstring theory.
- 1998 Arkani-Hamed, Dimopoulos, Dvali develop the **ADD extra-dimensions**
- Soon after that, development of **Randall-Sundrum (RS)** warped extra-dimensions

KK theories (in a nutshell)

- A an illustrative example: assume we have a complex scalar field living on a 5D spacetime. The action would be

$$S_5 = -\int d^4x\, dy\, M_5 \left[|\partial_\mu \phi|^2 + |\partial_y \phi|^2 + \lambda_5 |\phi|^4 \right]$$

- If the 5th dimension is compactified with the topology of a circle ($\phi(x, y) = \phi(x, y + 2\pi nR)$), I can rewrite the field with a Fourier expansion

$$\phi(x, y) = \frac{1}{\sqrt{2\pi R M_5}} \sum_{n=-\infty}^{\infty} e^{iny/R} \phi^{(n)}(x)$$

- The action becomes $S_5 = S_4^{(0)} + S_4^{(n)}$

$$S_4^{(0)} = -\int d^4x \left[|\partial_\mu \phi^{(0)}|^2 + \lambda_4 |\phi^{(0)}|^4 \right]$$

$$S_4^{(n)} = -\int d^4x \sum_{n \neq 0} \left[|\partial_\mu \phi^{(n)}|^2 + \left(\frac{n}{R}\right)^2 |\phi^{(n)}|^2 \right]$$

- That is, a 4D theory with a set of KK modes with

$$m_n \sim \frac{n}{R}$$

ADD extra-dimensions - the idea

See also hep-ph/9803315.pdf

- Potential solution to the **hierarchy problem**: in a higher dimensional world, gravity is as strong as the EW interaction. It **looks** small because we see its 4D projection.

- Let's assume that the only scale is $m_{EW} \sim 1\ \mathrm{TeV}$ and that there are n additional dimensions with a scale R. The Planck scale in $n+4$ dimensions is $M_{pl(n+4)} \sim m_{EW}$

- In natural units, G in n+ 4 dimensions is $G_{n+4} = \left(\frac{1}{M_{pl(n+4)}}\right)^{n+2}$

- The Gauss law on a mass m at a distance $r \ll R$ is

$$\int \frac{m}{M_{pl(n+4)}^{n+2} r^{n+2}} dS^{n+2} = \frac{m}{M_{pl(n+4)}^{n+2}}$$

ADD extra-dimensions - the idea

See also hep-ph/9803315.pdf

- If $r \gg R$ however

$$\int \frac{m}{M_{pl(n+4)}^{n+2} r^{n+2}} dS^{(n+2)} \sim \int \frac{m}{M_{pl(4)}^{2} r^{2}} dS^{(2)} R^n = \frac{m}{M_{pl(n+4)}^{n+2}} \implies M_{pl}^2 \sim M_{pl(n+4)}^{2+n} R^n$$

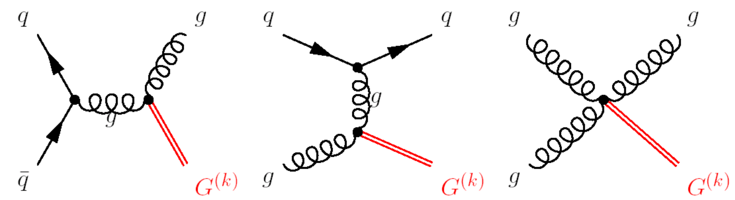
- If $M_{pl(n+4)}^{2+n} \sim m_{EW}$, $\quad R \sim 10^{\frac{30}{n}-17} \mathrm{cm} \times \left(\frac{1\mathrm{TeV}}{m_{EW}}\right)^{1+\frac{2}{n}}$

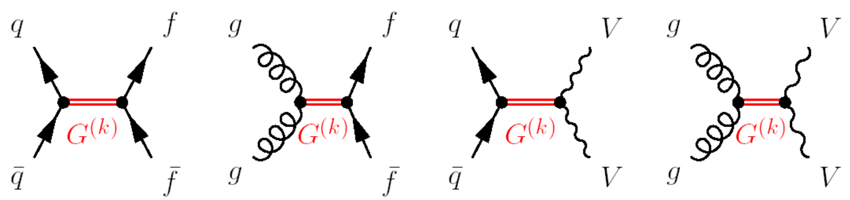
- For n = 2, $R \sim 0.1 - 1\ \mathrm{mm}$ (hence the name “large” extra-dimensions)

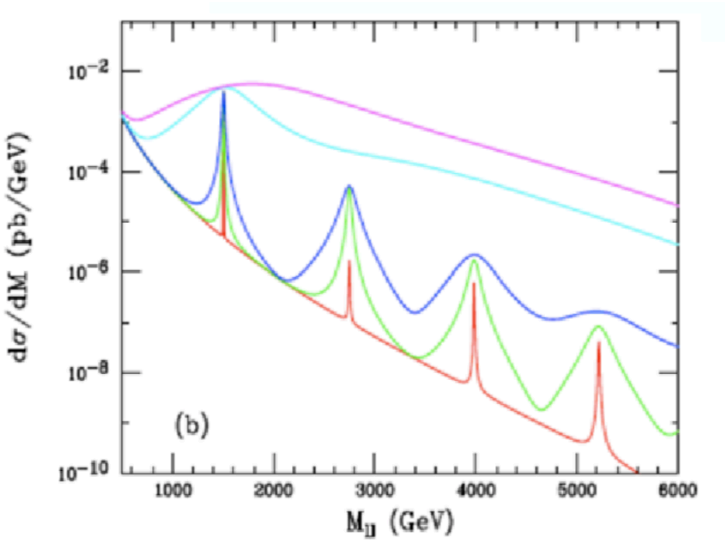
Extra-dimensions signatures

ADD:
- **Real production** of (invisible) graviton ⇒ mono-X analyses sensitive
  - Already discussed in the context of DM
- Exchange of **virtual graviton** leads to a **continuum of KK states** ⇒ Excess of di-fermion, di-photon high mass states
- **Black hole production** from modified Schwarzshield radius.

RS: additional **resonances from discrete KK excitations**

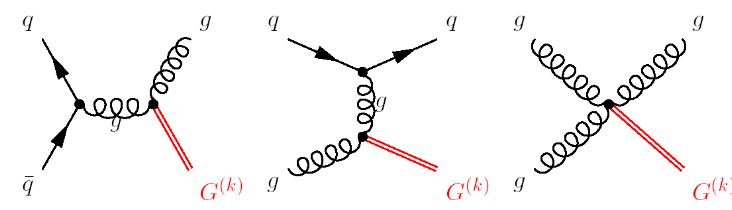


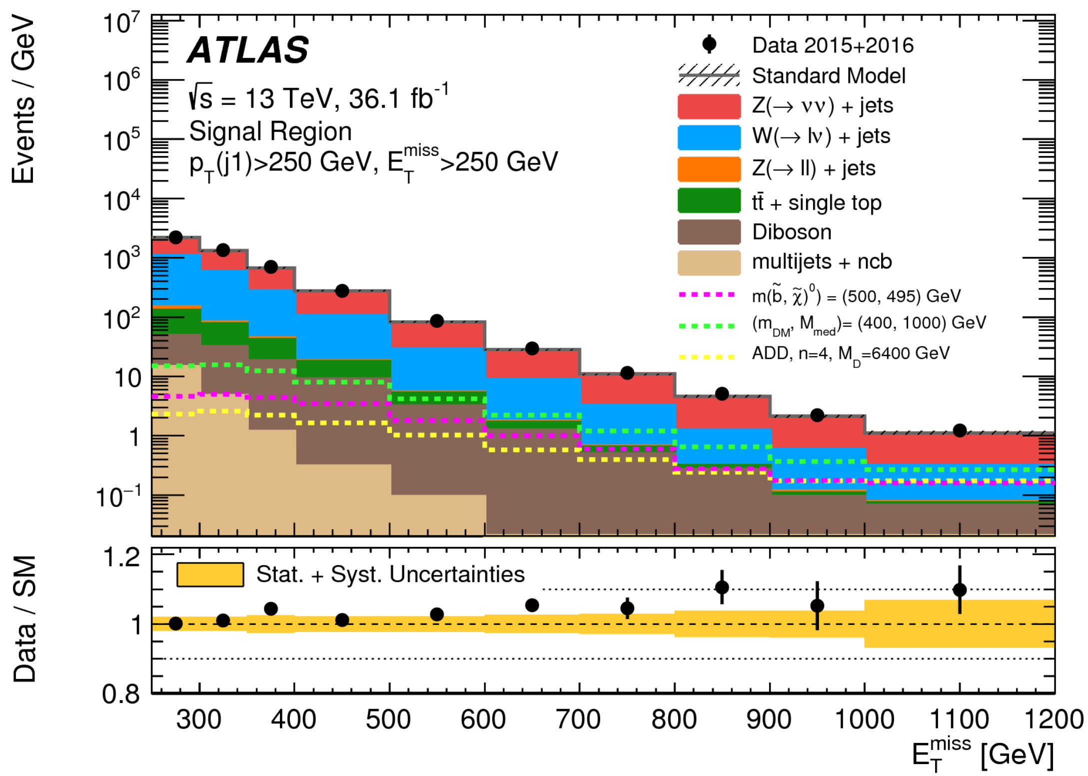




Mono-jet limits on ADD extra-dimensions

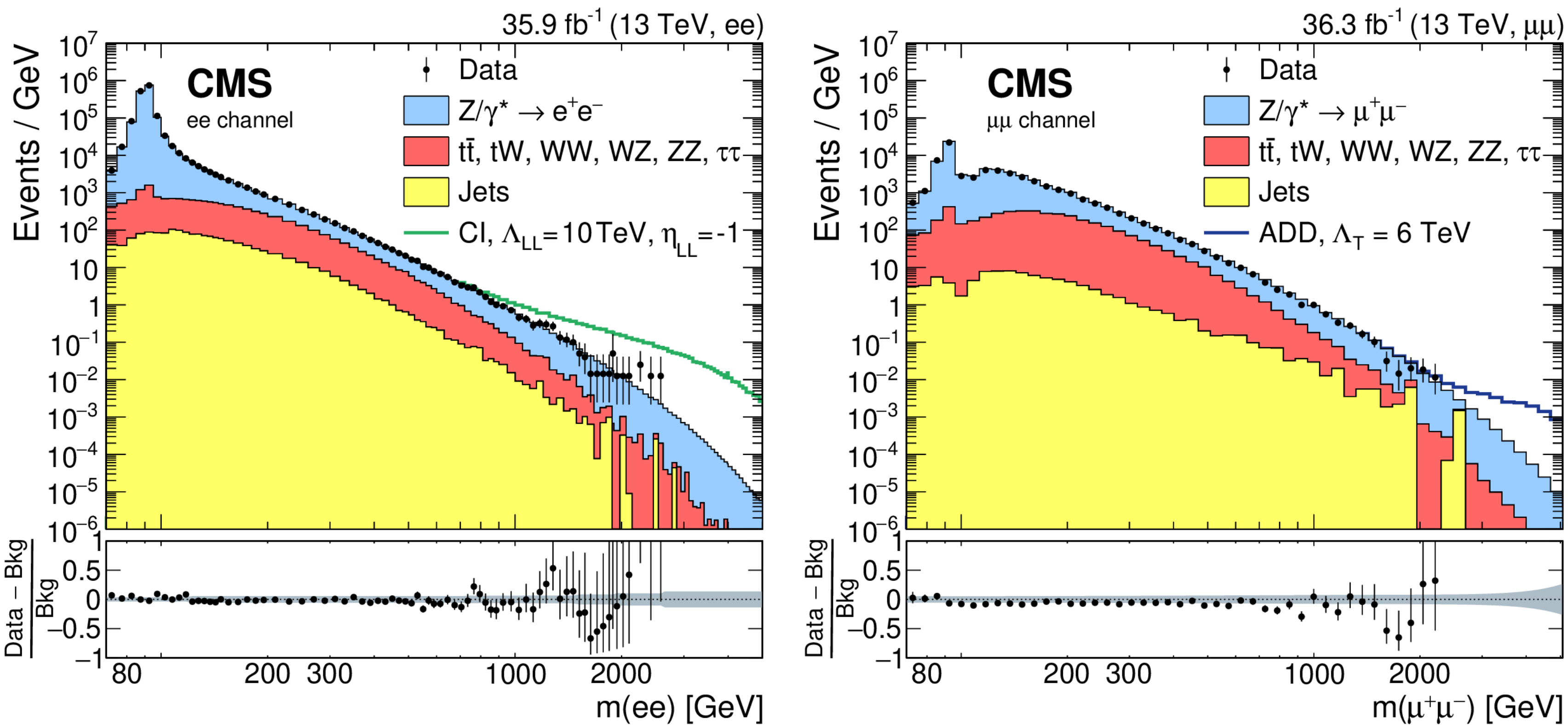
- Graviton produced in the collision would show up as **missing transverse momentum** in the detector.
- Mono-X analyses are **sensitive to these scenarios.**

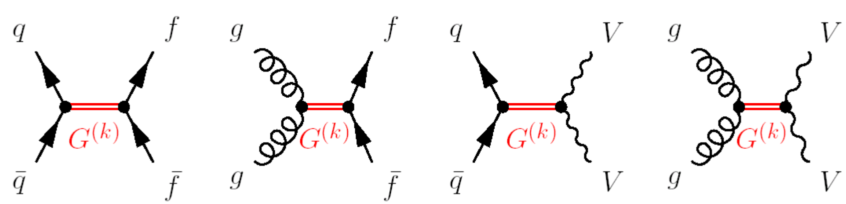




Non-resonant di-lepton searches

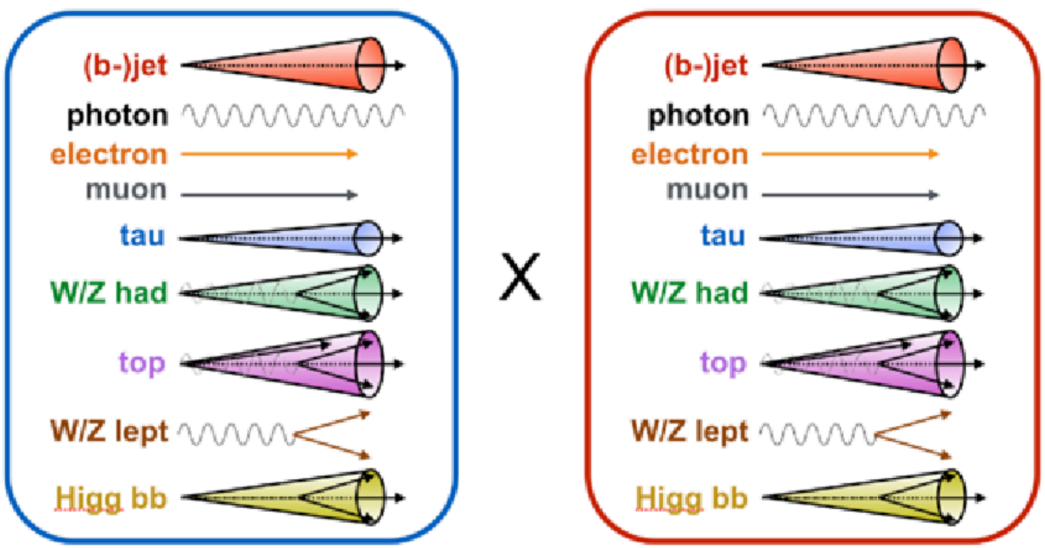
See arXiv:1812.10443





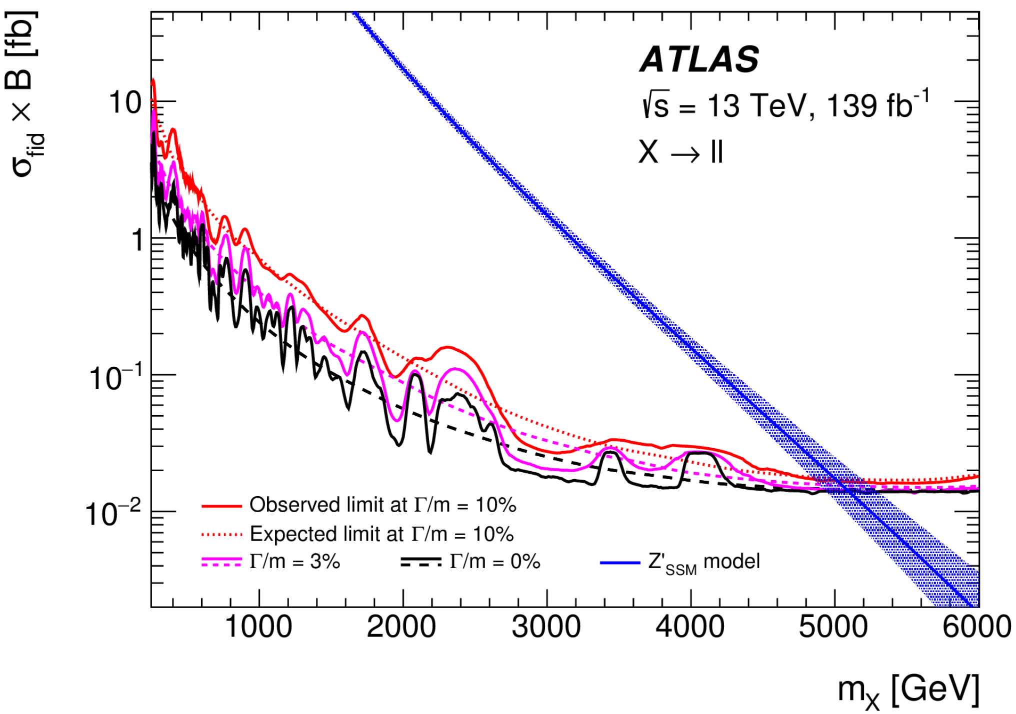
Additional heavy resonances

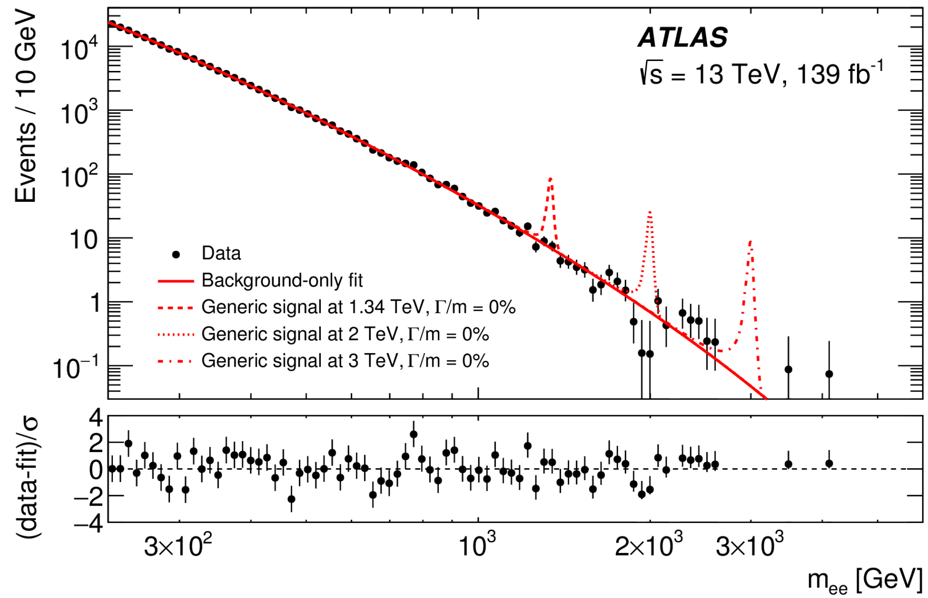
- Additional **vector bosons** arise in many BSM models (extra-dimensions, left-right symmetric SU(2) models, extra symmetry groups, grand-unification models (SU(5), E(6)), etc).
  - Phenomenology driven by **assumed couplings to SM and BSM particles.**
  - In general expect **resonances in di-lepton, di-jet, di-bosons**, etc.
- Many other models predict all sort of **possible resonant combinations** (RPV SUSY, vector like quarks, etc.)
- LHC experiments do all permutations below

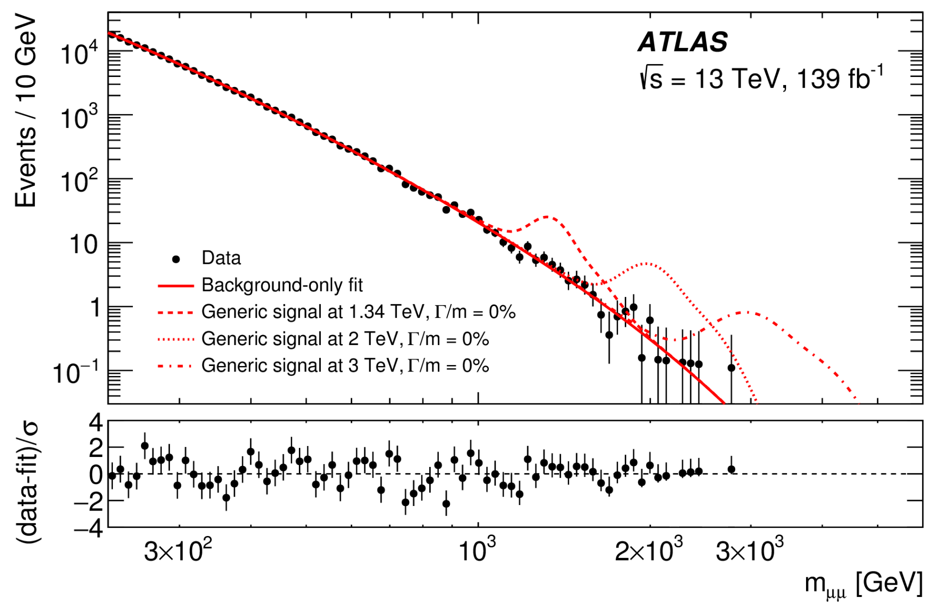


Starting from the easiest final states….

- Di-jet covered extensively in the context of DM
- Di-lepton resonances are among the cleanest signatures possible

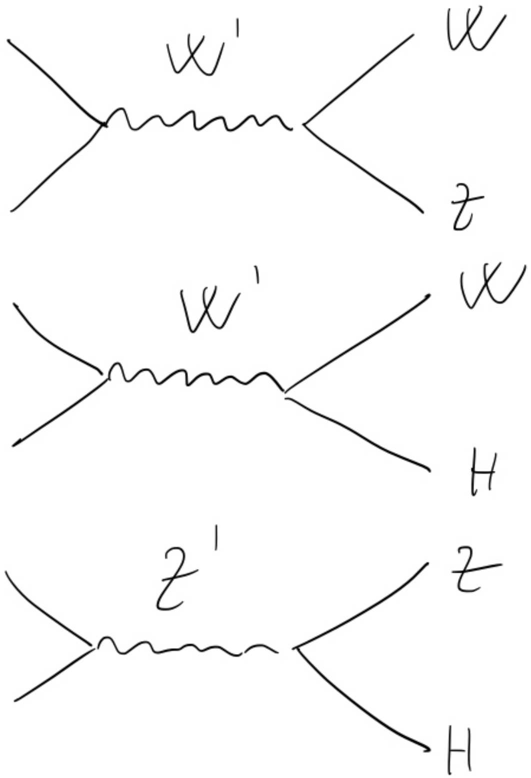






… into more complex final states

- Diboson resonances **at the heart** of LHC investigation in these last few years
- It is, in fact, an **ensemble of analyses**.



$W \to \ell\nu$ BOOSTED

$\otimes$ $W/Z/H \to qq$ $\otimes$ RESOLVED

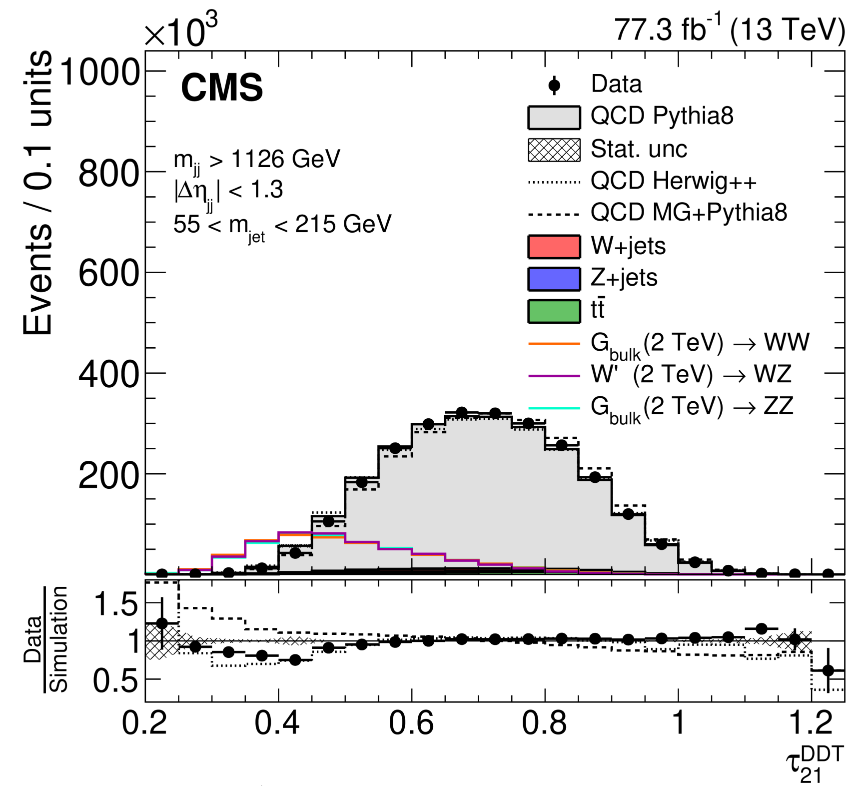
$Z \to \ell\ell$

$H \to bb, \gamma\gamma, \tau\tau, VV^{(*)}$

Example: full-hadronic diboson

See arXiv:1906.05977

- Select events with anti-k_T R=0.8 jets (soft drop grooming), whose substructure is **compatible with that of V/H→ jj.**
- Do a **combined fit** to m_{jet1}, m_{jet2}, m_{jj}.
    - All three variables should show a resonant behaviour for the signal.
- **Jet calibration and background modelling** are the **challenges** of the analysis.

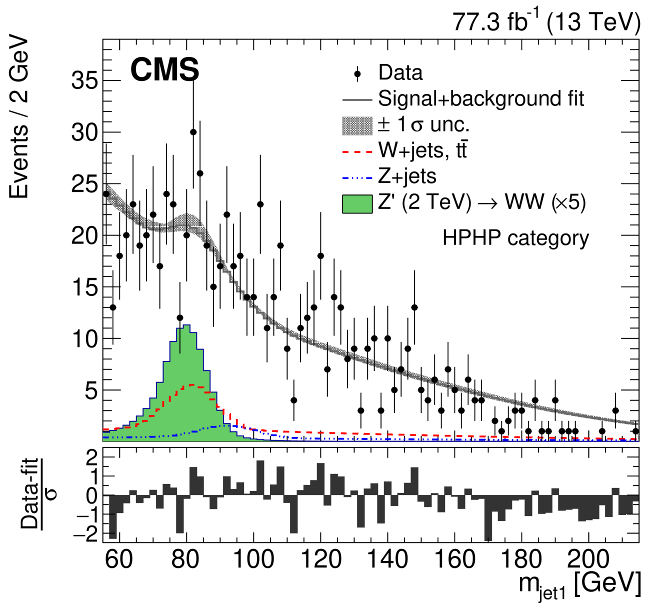


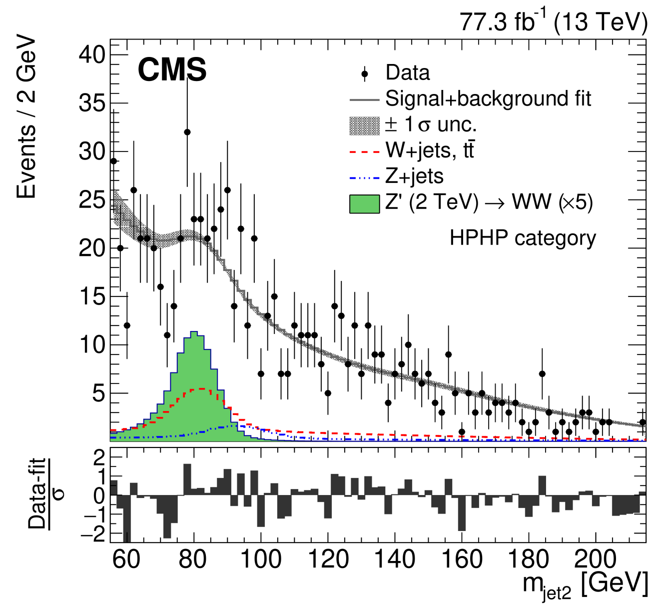
$$\tau_i = \frac{1}{R \sum_k p_{Tk}} \sum_k \min(\Delta R_{1,k}, \ldots, \Delta R_{N,k})$$

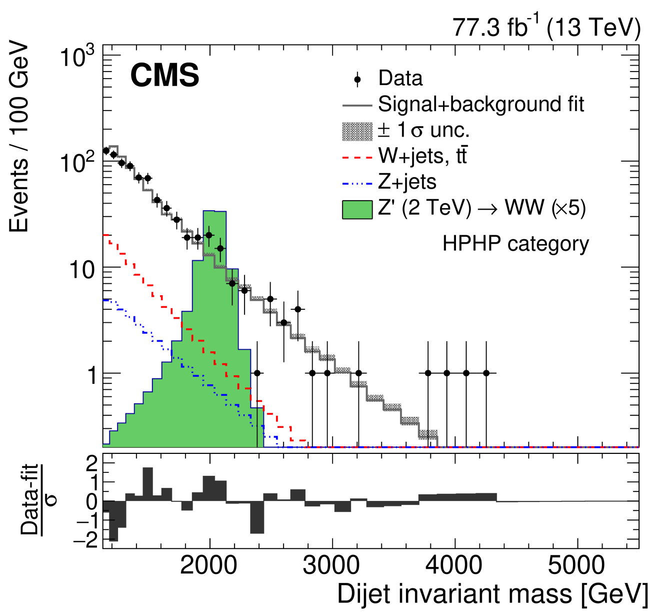
$$\tau_{21} = \frac{\tau_2}{\tau_1}$$

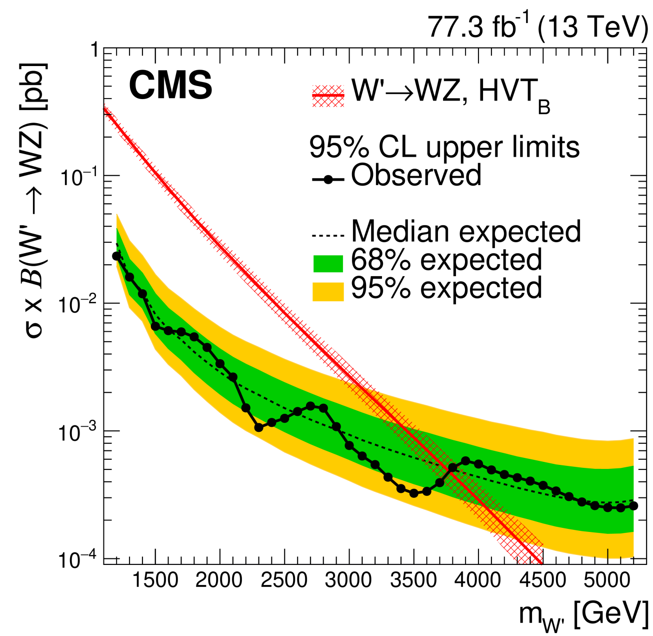
k runs over the jet constituents

Example: full-hadronic diboson









HVT model (in a nutshell)

- Heavy Vector Triplett (HVT) model commonly used in interpretation of diboson searches
  - Introduce a SU(2) triplett $\mathscr{W}$ of colourless vector bosons with zero U(1) hypercharge yielding a nearly degenerate $W'^{\pm}, Z'$
  - The interaction Lagrangian is assumed to be

$$\mathcal{L}_{\mathcal{W}}^{\text{int}} = -g_q \mathcal{W}_\mu^a \bar{q}_k \gamma^\mu \frac{\sigma_a}{2} q_k - g_\ell \mathcal{W}_\mu^a \bar{\ell}_k \gamma^\mu \frac{\sigma_a}{2} \ell_k - g_H \left(\mathcal{W}_\mu^a H^\dagger \frac{\sigma_a}{2} i D^\mu H + \text{h.c.} \right)$$

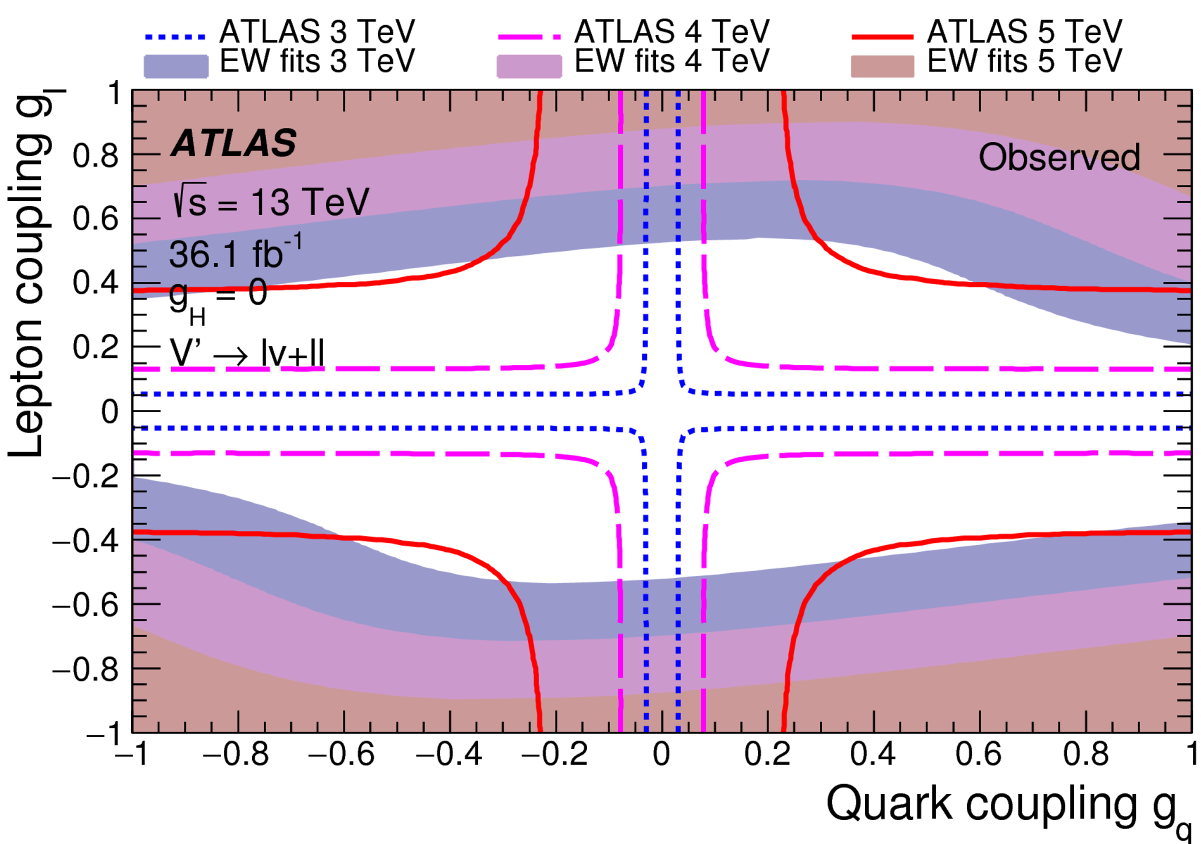
- Normally g_ℓ, g_q are assumed to be universal w.r.t. generation.
- Branching fractions for $W' \to WZ$, $W' \to WH$, $Z' \to WW$, $Z' \to ZH$ all similar for high V' mass.
- Two models often used:
  - Model A: $g_H = -0.56,\ g_f = -0.55$
  - Model B: $g_H = -2.9,\ g_f = 0.14$

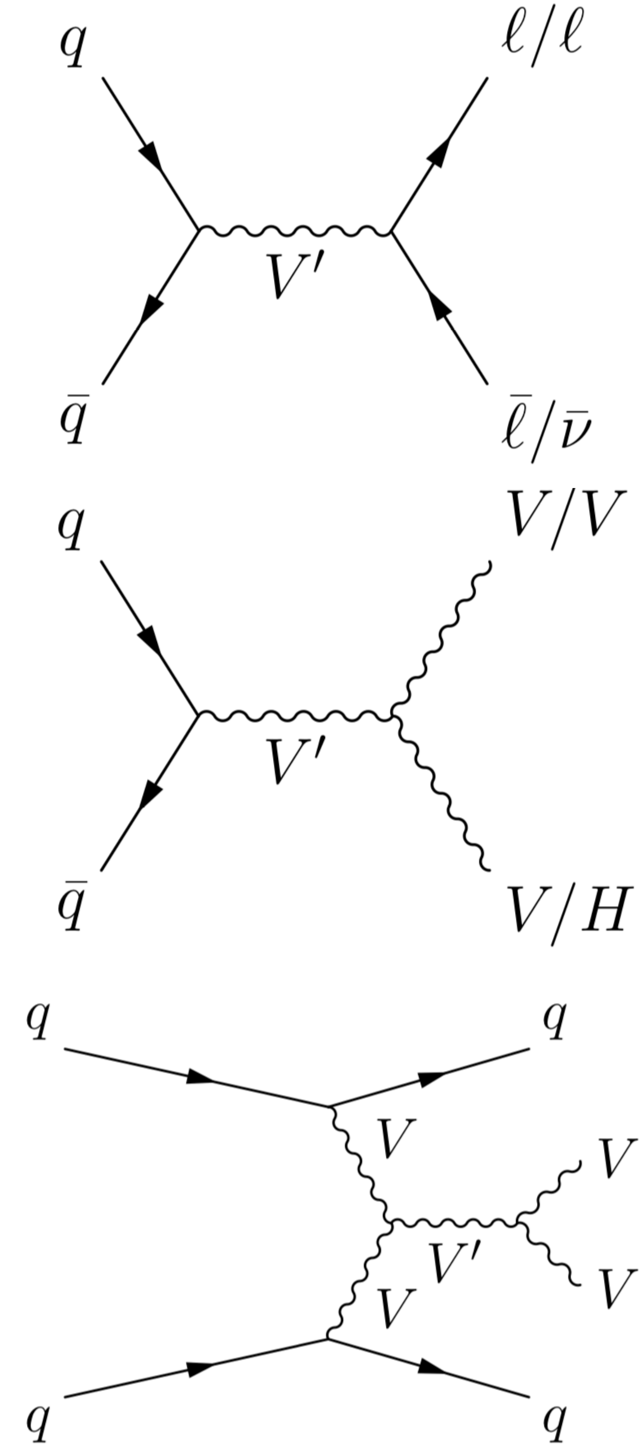
$$g_f = g_q = g_l$$

HVT interpretations

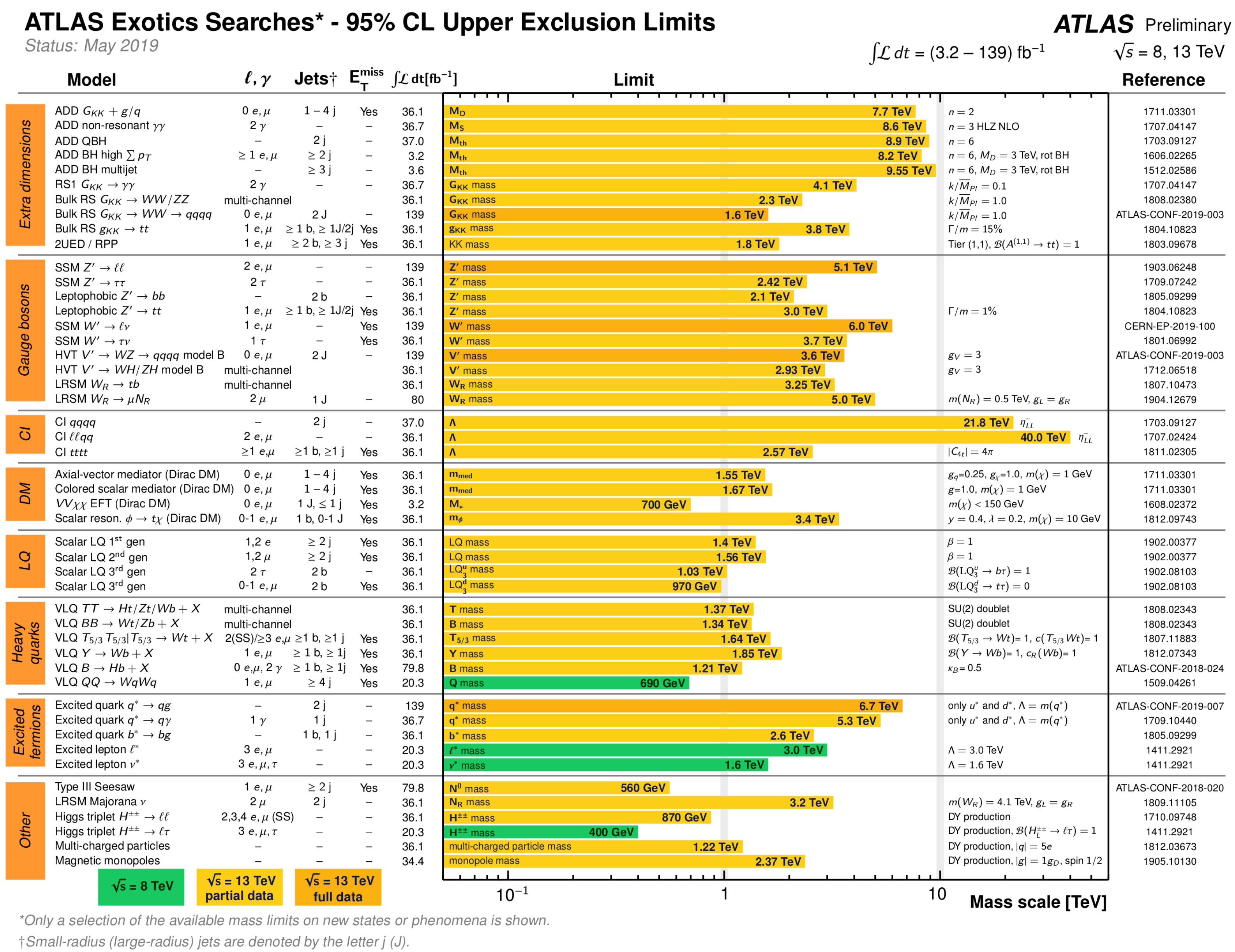
- Combination of analyses yields direct sensitivity to limits on couplings in HVT models

See Phys. Rev. D 98 (2018) 052008





Moving on



ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits
Status: May 2019
ATLAS Preliminary
∫L dt = (3.2 – 139) fb⁻¹
√s = 8, 13 TeV
Model | ℓ, γ | Jets† | E_T^miss | ∫L dt[fb⁻¹] | Limit | Reference
Extra dimensions
ADD G_KK + g/q | 0 e, μ | 1 – 4 j | Yes | 36.1 | M_D 7.7 TeV | n = 2 | 1711.03301
ADD non-resonant γγ | 2 γ | – | – | 36.7 | M_S 8.6 TeV | n = 3 HLZ NLO | 1707.04147
ADD QBH | – | 2 j | – | 37.0 | M_th 8.9 TeV | n = 6 | 1703.09127
ADD BH high ∑p_T | ≥ 1 e, μ | ≥ 2 j | – | 3.2 | M_th 8.2 TeV | n = 6, M_D = 3 TeV, rot BH | 1606.02265
ADD BH multijet | – | ≥ 3 j | – | 3.6 | M_th 9.55 TeV | n = 6, M_D = 3 TeV, rot BH | 1512.02586
RS1 G_KK → γγ | 2 γ | – | – | 36.7 | G_KK mass 4.1 TeV | k/M̄_Pl = 0.1 | 1707.04147
Bulk RS G_KK → WW/ZZ | multi-channel | 36.1 | G_KK mass 2.3 TeV | k/M̄_Pl = 1.0 | 1808.02380
Bulk RS G_KK → WW → qqqq | 0 e, μ | 2 J | – | 139 | G_KK mass 1.6 TeV | k/M̄_Pl = 1.0 | ATLAS-CONF-2019-003
Bulk RS g_KK → tt | 1 e, μ | ≥ 1 b, ≥ 1J/2j | Yes | 36.1 | g_KK mass 3.8 TeV | Γ/m = 15% | 1804.10823
2UED / RPP | 1 e, μ | ≥ 2 b, ≥ 3 j | Yes | 36.1 | KK mass 1.8 TeV | Tier (1,1), B(A^(1,1) → tt) = 1 | 1803.09678
Gauge bosons
SSM Z′ → ℓℓ | 2 e, μ | – | – | 139 | Z′ mass 5.1 TeV | 1903.06248
SSM Z′ → ττ | 2 τ | – | – | 36.1 | Z′ mass 2.42 TeV | 1709.07242
Leptophobic Z′ → bb | – | 2 b | – | 36.1 | Z′ mass 2.1 TeV | 1805.09299
Leptophobic Z′ → tt | 1 e, μ | ≥ 1 b, ≥ 1J/2j | Yes | 36.1 | Z′ mass 3.0 TeV | Γ/m = 1% | 1804.10823
SSM W′ → ℓν | 1 e, μ | – | Yes | 139 | W′ mass 6.0 TeV | CERN-EP-2019-100
SSM W′ → τν | 1 τ | – | Yes | 36.1 | W′ mass 3.7 TeV | 1801.06992
HVT V′ → WZ → qqqq model B | 0 e, μ | 2 J | – | 139 | V′ mass 3.6 TeV | g_V = 3 | ATLAS-CONF-2019-003
HVT V′ → WH/ZH model B | multi-channel | 36.1 | V′ mass 2.93 TeV | g_V = 3 | 1712.06518
LRSM W_R → tb | multi-channel | 36.1 | W_R mass 3.25 TeV | 1807.10473
LRSM W_R → μN_R | 2 μ | 1 J | – | 80 | W_R mass 5.0 TeV | m(N_R) = 0.5 TeV, g_L = g_R | 1904.12679
CI
CI qqqq | – | 2 j | – | 37.0 | Λ 21.8 TeV η⁻_LL | 1703.09127
CI ℓℓqq | 2 e, μ | – | – | 36.1 | Λ 40.0 TeV η⁻_LL | 1707.02424
CI tttt | ≥1 e,μ | ≥1 b, ≥1 j | Yes | 36.1 | Λ 2.57 TeV | |C_4t| = 4π | 1811.02305
DM
Axial-vector mediator (Dirac DM) | 0 e, μ | 1 – 4 j | Yes | 36.1 | m_med 1.55 TeV | g_q=0.25, g_χ=1.0, m(χ) = 1 GeV | 1711.03301
Colored scalar mediator (Dirac DM) | 0 e, μ | 1 – 4 j | Yes | 36.1 | m_med 1.67 TeV | g=1.0, m(χ) = 1 GeV | 1711.03301
VVχχ EFT (Dirac DM) | 0 e, μ | 1 J, ≤ 1 j | Yes | 3.2 | M_* 700 GeV | m(χ) < 150 GeV | 1608.02372
Scalar reson. φ → tχ (Dirac DM) | 0-1 e, μ | 1 b, 0-1 J | Yes | 36.1 | m_φ 3.4 TeV | y = 0.4, λ = 0.2, m(χ) = 10 GeV | 1812.09743
LQ
Scalar LQ 1st gen | 1,2 e | ≥ 2 j | Yes | 36.1 | LQ mass 1.4 TeV | β = 1 | 1902.00377
Scalar LQ 2nd gen | 1,2 μ | ≥ 2 j | Yes | 36.1 | LQ mass 1.56 TeV | β = 1 | 1902.00377
Scalar LQ 3rd gen | 2 τ | 2 b | – | 36.1 | LQ^u_3 mass 1.03 TeV | B(LQ^u_3 → bτ) = 1 | 1902.08103
Scalar LQ 3rd gen | 0-1 e, μ | 2 b | Yes | 36.1 | LQ^d_3 mass 970 GeV | B(LQ^d_3 → tτ) = 0 | 1902.08103
Heavy quarks
VLQ TT → Ht/Zt/Wb + X | multi-channel | 36.1 | T mass 1.37 TeV | SU(2) doublet | 1808.02343
VLQ BB → Wt/Zb + X | multi-channel | 36.1 | B mass 1.34 TeV | SU(2) doublet | 1808.02343
VLQ T5/3 T5/3|T5/3 → Wt + X | 2(SS)/≥3 e,μ | ≥1 b, ≥1 j | Yes | 36.1 | T5/3 mass 1.64 TeV | B(T5/3 → Wt)= 1, c(T5/3 Wt)= 1 | 1807.11883
VLQ Y → Wb + X | 1 e, μ | ≥ 1 b, ≥ 1j | Yes | 36.1 | Y mass 1.85 TeV | B(Y → Wb)= 1, c_R(Wb)= 1 | 1812.07343
VLQ B → Hb + X | 0 e,μ, 2 γ | ≥ 1 b, ≥ 1j | Yes | 79.8 | B mass 1.21 TeV | κ_B= 0.5 | ATLAS-CONF-2018-024
VLQ QQ → WqWq | 1 e, μ | ≥ 4 j | Yes | 20.3 | Q mass 690 GeV | 1509.04261
Excited fermions
Excited quark q* → qg | – | 2 j | – | 139 | q* mass 6.7 TeV | only u* and d*, Λ = m(q*) | ATLAS-CONF-2019-007
Excited quark q* → qγ | 1 γ | 1 j | – | 36.7 | q* mass 5.3 TeV | only u* and d*, Λ = m(q*) | 1709.10440
Excited quark b* → bg | – | 1 b, 1 j | – | 36.1 | b* mass 2.6 TeV | 1805.09299
Excited lepton ℓ* | 3 e, μ | – | – | 20.3 | ℓ* mass 3.0 TeV | Λ = 3.0 TeV | 1411.2921
Excited lepton ν* | 3 e, μ, τ | – | – | 20.3 | ν* mass 1.6 TeV | Λ = 1.6 TeV | 1411.2921
Other
Type III Seesaw | 1 e, μ | ≥ 2 j | Yes | 79.8 | N⁰ mass 560 GeV | ATLAS-CONF-2018-020
LRSM Majorana ν | 2 μ | 2 j | – | 36.1 | N_R mass 3.2 TeV | m(W_R) = 4.1 TeV, g_L = g_R | 1809.11105
Higgs triplet H±± → ℓℓ | 2,3,4 e, μ (SS) | – | – | 36.1 | H±± mass 870 GeV | DY production | 1710.09748
Higgs triplet H±± → ℓτ | 3 e, μ, τ | – | – | 20.3 | H±± mass 400 GeV | DY production, B(H±±_L → ℓτ) = 1 | 1411.2921
Multi-charged particles | – | – | – | 36.1 | multi-charged particle mass 1.22 TeV | DY production, |q| = 5e | 1812.03673
Magnetic monopoles | – | – | – | 34.4 | monopole mass 2.37 TeV | DY production, |g| = 1g_D, spin 1/2 | 1905.10130
√s = 8 TeV
√s = 13 TeV partial data
√s = 13 TeV full data
10⁻¹
1
10
Mass scale [TeV]
*Only a selection of the available mass limits on new states or phenomena is shown.
†Small-radius (large-radius) jets are denoted by the letter j (J).

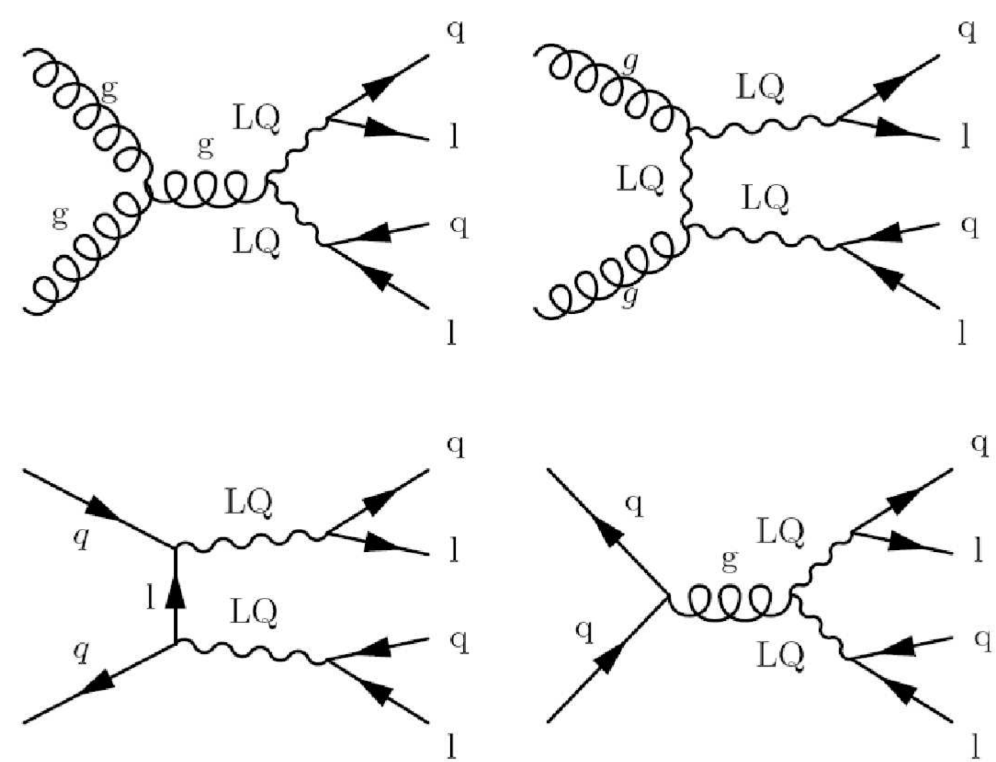
Leptoquarks

- Models with **baryon and lepton number violation** sometimes foresee the presence of **resonance decaying in quarks and leptons.**

- Leptoquarks carry both lepton and baryon number

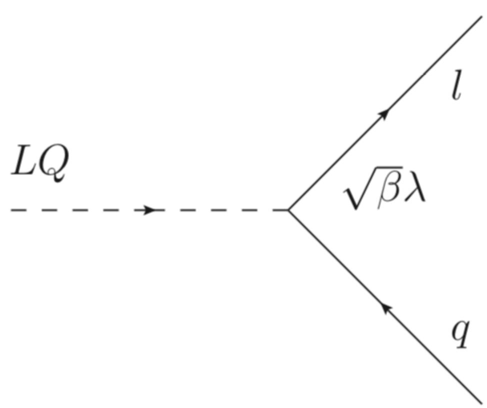
- Main model used Buchmüller-Rückl-Wyler model

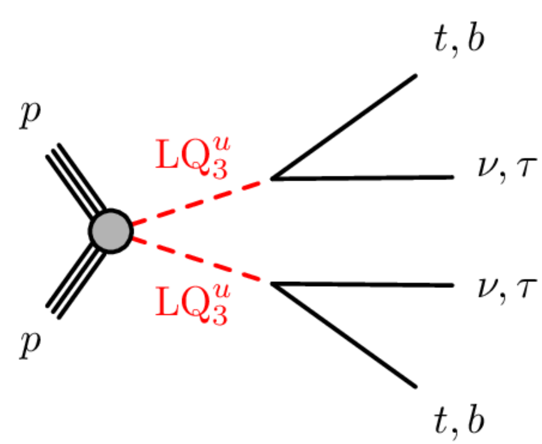
Spin	$3B+L$	$SU(3)_c$	$SU(2)_W$	$U(1)_Y$	Allowed coupling
0	-2	$\bar{3}$	1	1/3	$\bar{q}_L^c \ell_L$ or $\bar{u}_R^c e_R$
0	-2	$\bar{3}$	1	4/3	$\bar{d}_R^c e_R$
0	-2	$\bar{3}$	3	1/3	$\bar{q}_L^c \ell_L$
1	-2	$\bar{3}$	2	5/6	$\bar{q}_L^c \gamma^\mu e_R$ or $\bar{d}_R^c \gamma^\mu \ell_L$
1	-2	$\bar{3}$	2	$-1/6$	$\bar{u}_R^c \gamma^\mu \ell_L$
0	0	3	2	7/6	$\bar{q}_L e_R$ or $\bar{u}_R \ell_L$
0	0	3	2	1/6	$\bar{d}_R \ell_L$
1	0	3	1	2/3	$\bar{q}_L \gamma^\mu \ell_L$ or $\bar{d}_R \gamma^\mu e_R$
1	0	3	1	5/3	$\bar{u}_R \gamma^\mu e_R$
1	0	3	3	2/3	$\bar{q}_L \gamma^\mu \ell_L$



Leptoquarks in a nutshell

- They can be **pair-produced** or **singly produced**.
    - Single LQ production **subdominant**, but relevant for **very high LQ masses.**
- Scalar LQ production cross section normally **much larger** than vector LQ:
    - Focus on scalar.
- Pair-production cross section depends only on **LQ mass.**
- BR into charged leptons parametrised as a function of a parameter β. $\beta = 1 \implies BR(\ell^{\pm}q) = 100\,\%$
    - Therefore $BR(\nu q) \propto (1-\beta)$
- Normally study 1st, 2nd, and 3rd generation LQ (depending on the fermion generation they couple to).



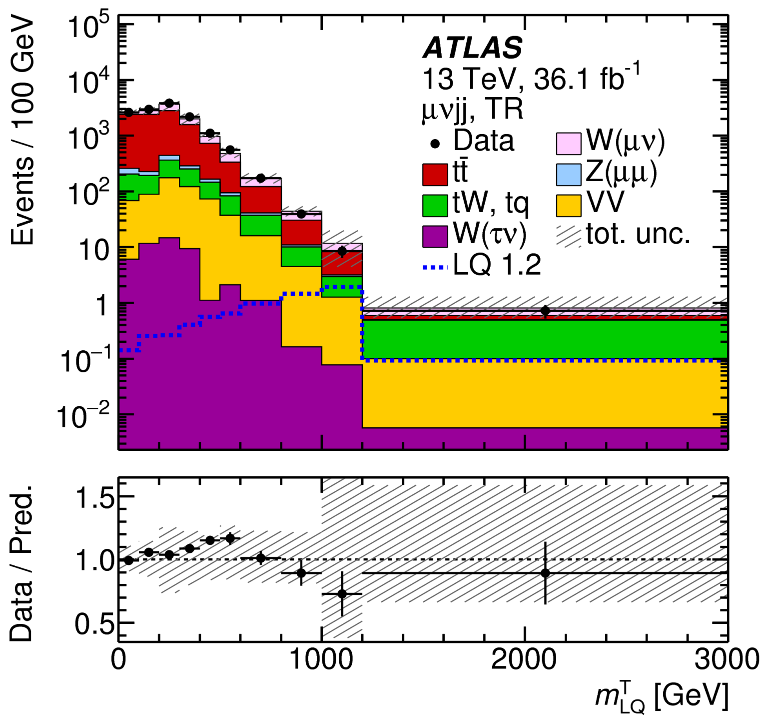


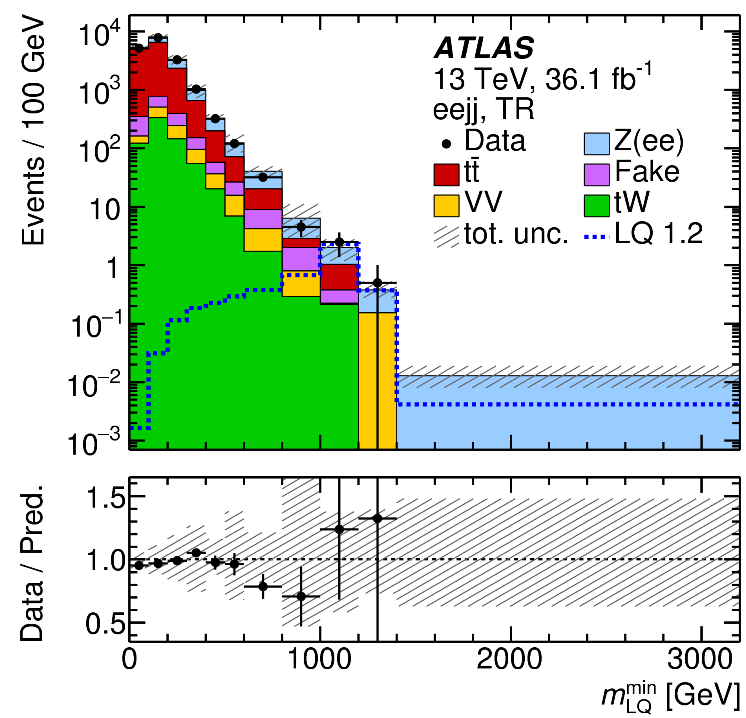
Leptoquark resonances

See arXiv:1902.00377, Phys. Rev. D 99 (2019) 032014

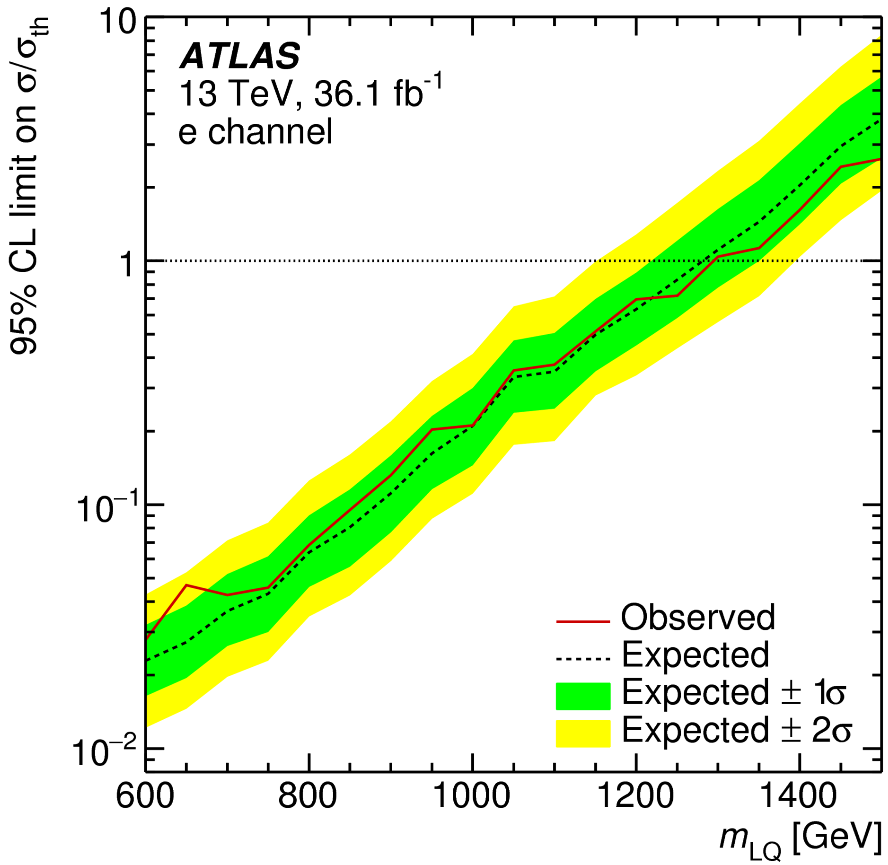
- 1st and 2nd LQ search example: analysis based on the presence of two lj resonances (or lvjj resonance), exploited with a BDT in the following variables

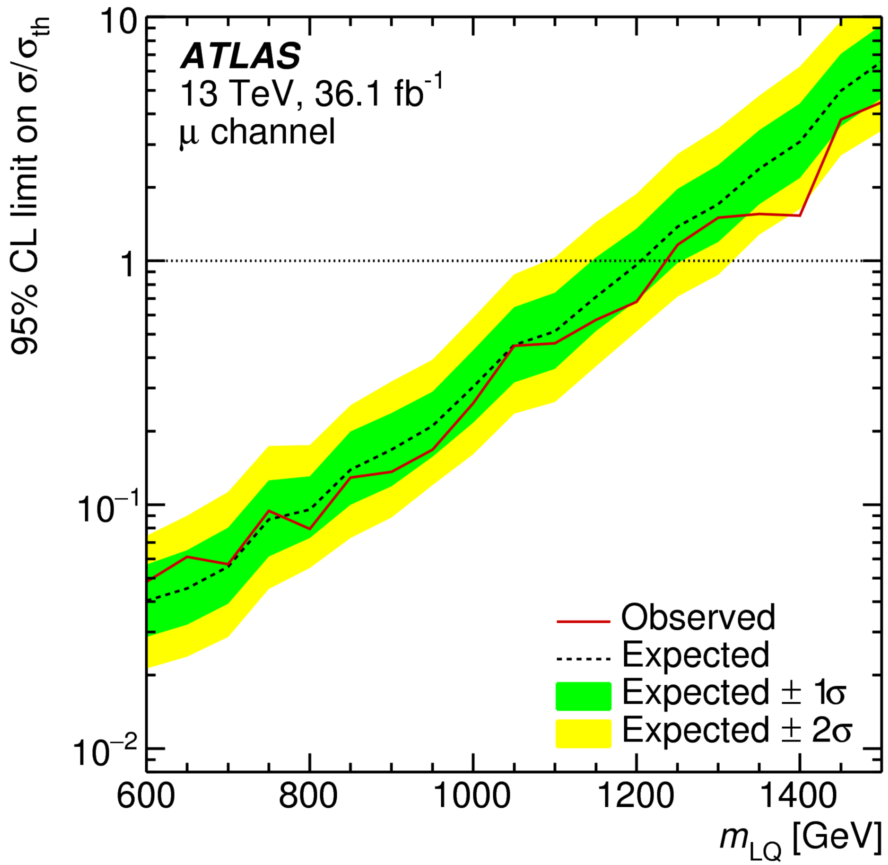
Channel	Input variables
$\ell\ell jj$	m_{LQ}^{min}, $m_{\ell\ell}$, p_T^{j2}, $p_T^{\ell 2}$, m_{LQ}^{max}
$\ell\nu jj$	m_{LQ}, m_{LQ}^{T}, m_T, E_T^{miss}, p_T^{j2}, p_T^{ℓ}



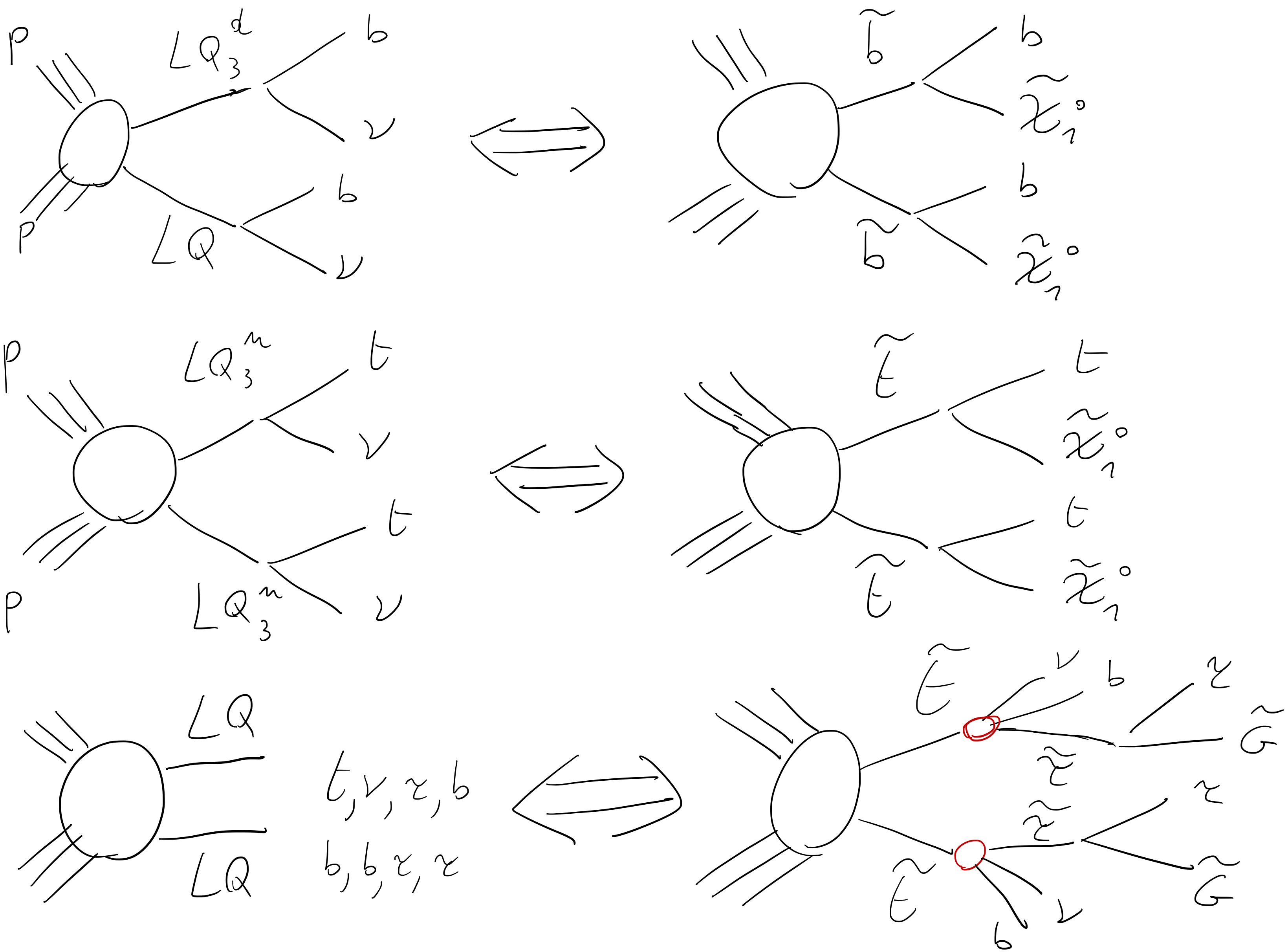


(1st and 2nd generation) LQ limits





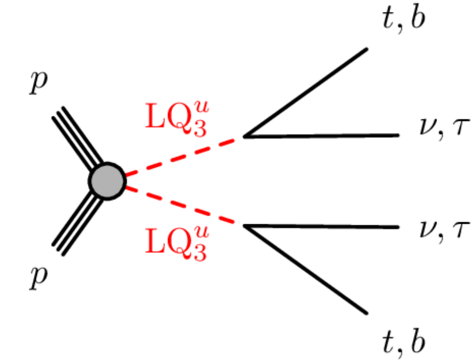
LQ signatures and similarities



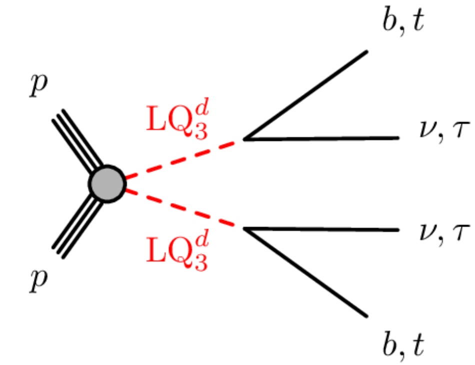
Third generation LQ

- Combination of dedicated searches with SUSY 3rd generation searches to yield limits on 3rd generation LQ

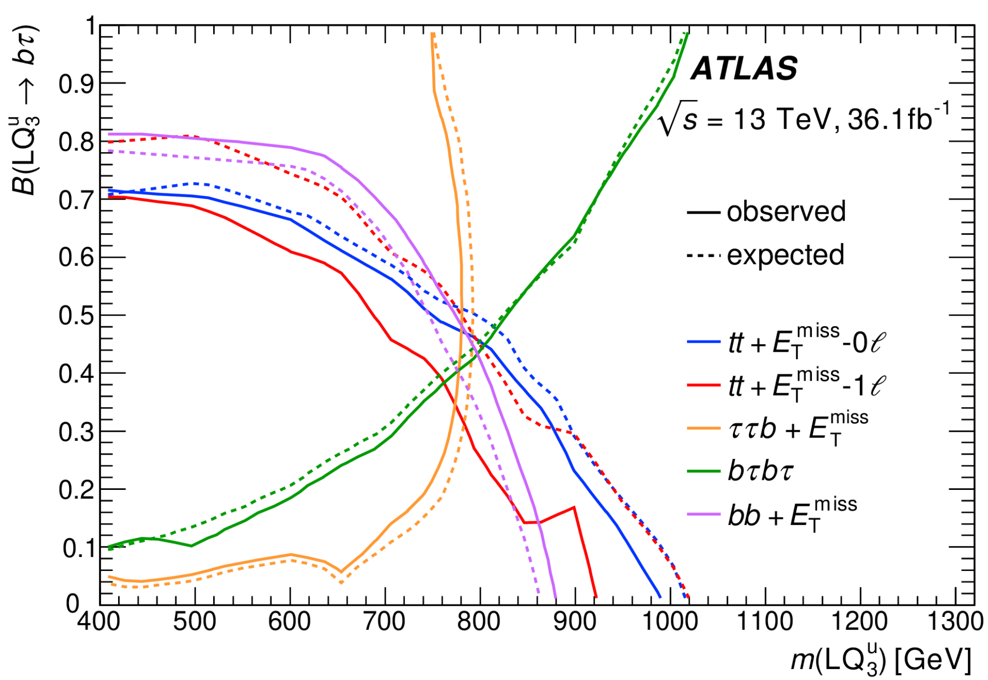
Up-type

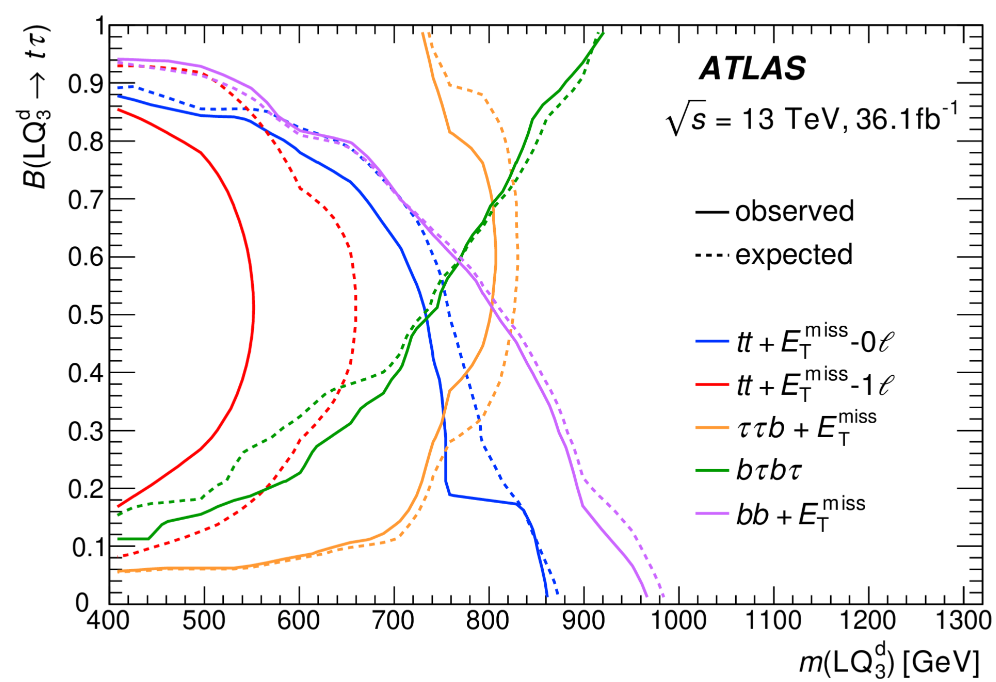


Down-type



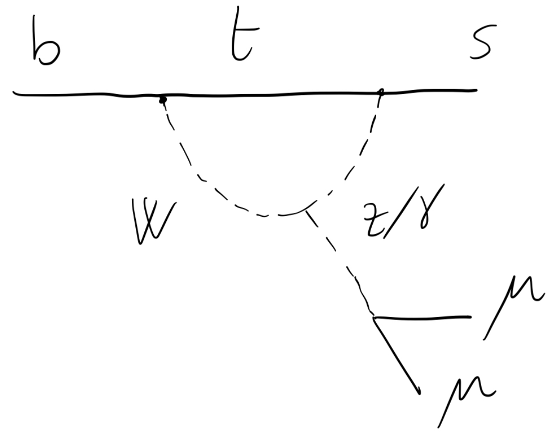
See JHEP 06 (2019) 144

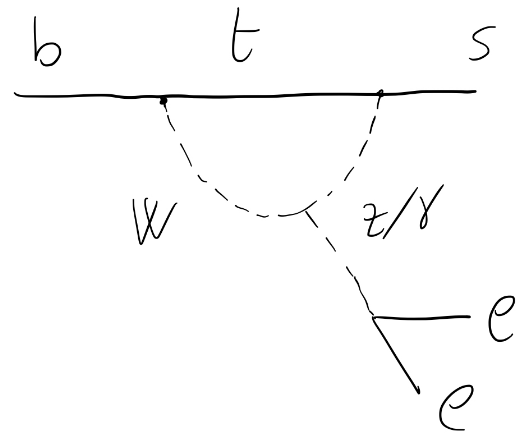


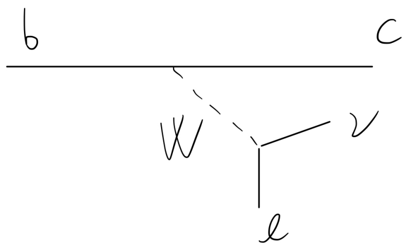


Recent revamp of attention on leptoquarks

- A number of flavour anomalies reported in the past years
- A (probably non-exhaustive) list from a non-expert:
  - Semi-rare $b \to s\mu\mu$ transitions (angles and BR) (see PLB 781 (2018) 517 and references therein)
  - Lepton Flavour Universality in (loop suppressed) $b \to s\ell\ell$ transitions.
  - Lepton Flavour Universality in (tree level) $b \to c\ell\nu$ transitions.







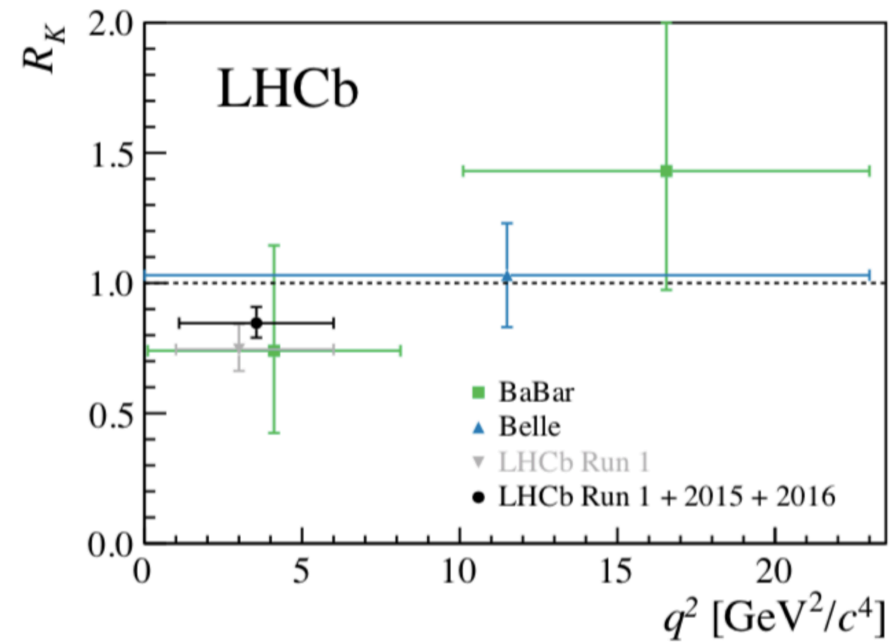
Recent revamp of attention on leptoquarks

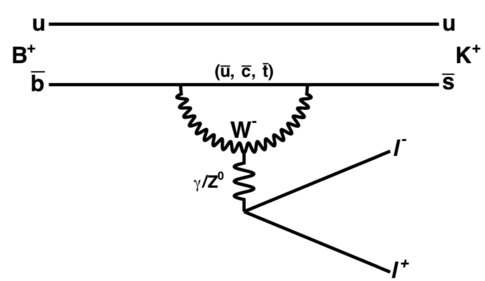
Rare decays (BR ~ 10^{-6}-10^{-7})

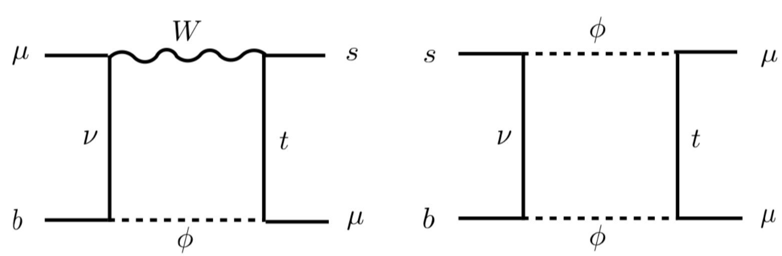
$$R_{K^{(*)}} = \frac{\Gamma\left(\bar{B}_0 \to K^{*0}\mu^+\mu^-\right)/\Gamma\left(\bar{B}_0 \to K^{*0}J/\psi_{\mu\mu}\right)}{\Gamma\left(\bar{B}_0 \to K^{*0}e^+e^-\right)/\Gamma\left(\bar{B}_0 \to K^{*0}J/\psi_{ee}\right)}$$

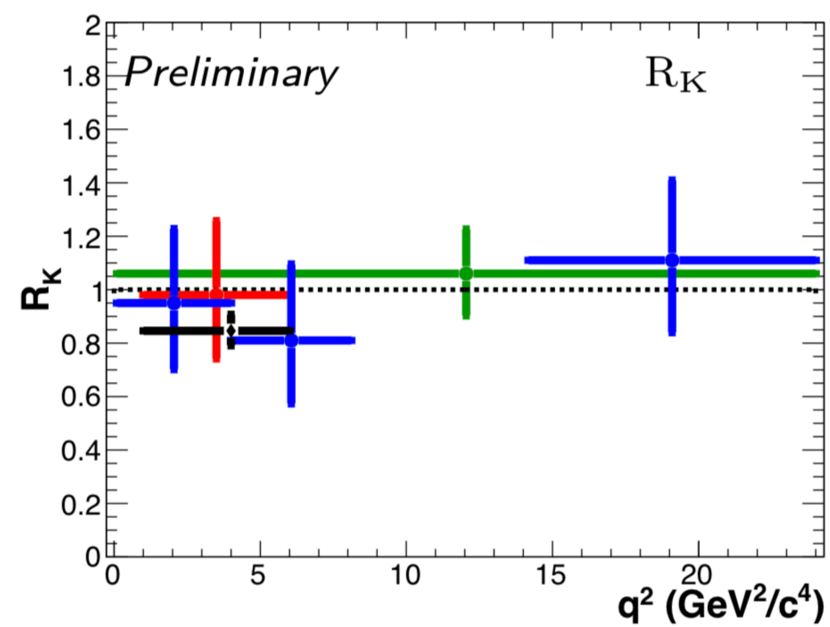
LHCb results by year

$$R_K^{7\,\mathrm{and}\,8\,\mathrm{TeV}} = 0.717\,^{+0.083}_{-0.071}\,^{+0.017}_{-0.016}$$
$$R_K^{13\,\mathrm{TeV}} = 0.928\,^{+0.089}_{-0.076}\,^{+0.020}_{-0.017}$$

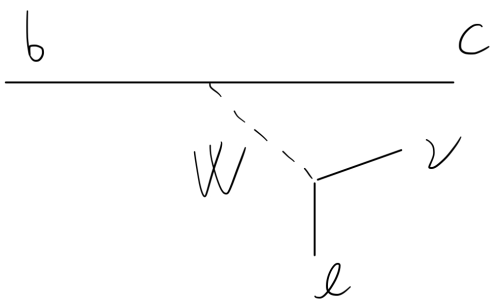


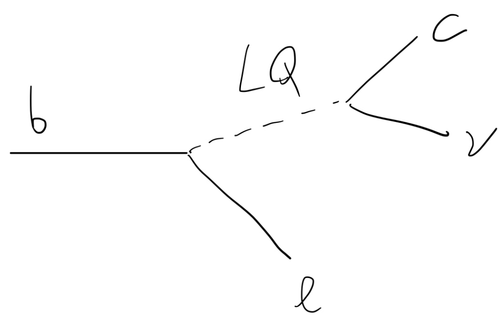




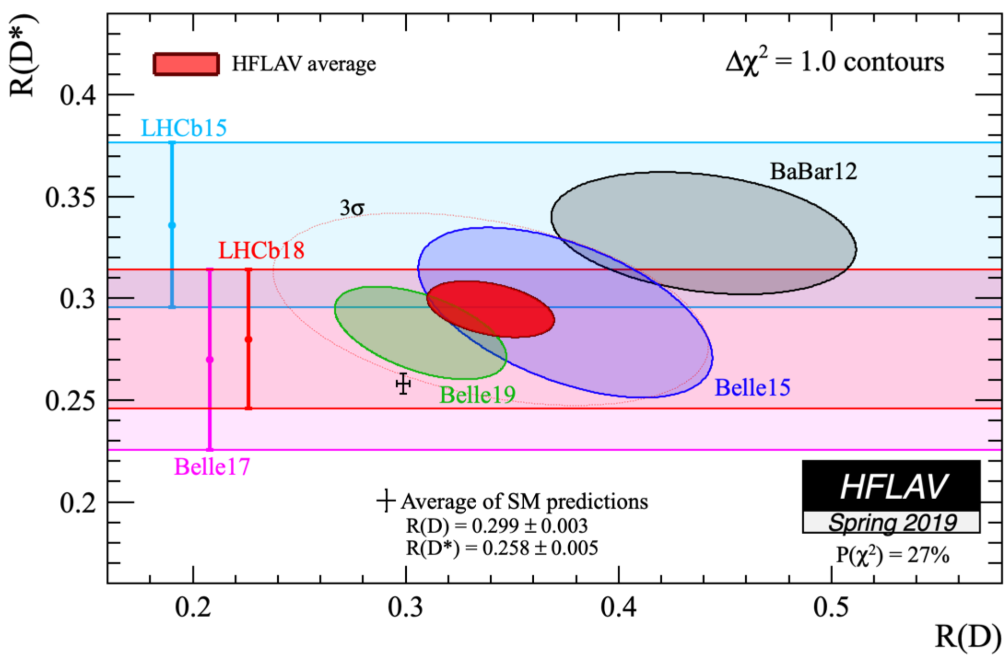


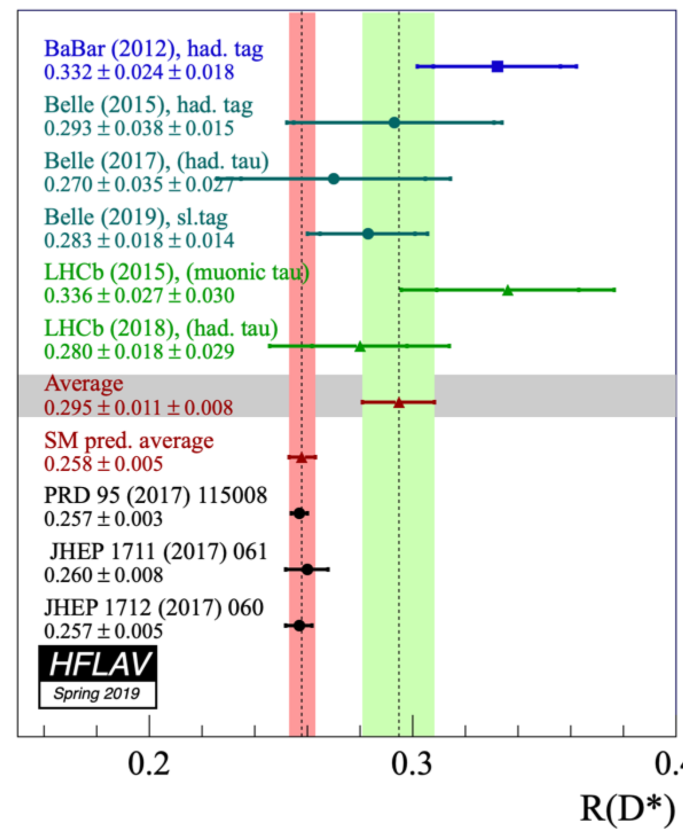
Recent revamp of attention on leptoquarks





$$R_{D^{(*)}} = \frac{\Gamma(\bar{B} \to D^{(*)}\tau\nu)}{\Gamma(\bar{B} \to D^{(*)}\ell\nu)}$$





Potential explanations for flavour anomalies

- arXiv:1906.01222 and references therein
- A step by step EFT discussion here
- A solution in terms of an additional Z' boson here

Moving on

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: May 2019

ATLAS Preliminary

$\int \mathcal{L}\, dt = (3.2 - 139)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 8, 13$ TeV

	Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L}\, dt [\mathrm{fb}^{-1}]$	Limit			Reference
Extra dimensions	ADD $G_{KK} + g/q$	$0\ e, \mu$	$1-4$ j	Yes	36.1	M_D	7.7 TeV	$n = 2$	1711.03301
	ADD non-resonant $\gamma\gamma$	$2\ \gamma$	–	–	36.7	M_S	8.6 TeV	$n = 3$ HLZ NLO	1707.04147
	ADD QBH	–	2 j	–	37.0	M_{th}	8.9 TeV	$n = 6$	1703.09127
	ADD BH high $\sum p_T$	$\geq 1\ e, \mu$	≥ 2 j	–	3.2	M_{th}	8.2 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1606.02265
	ADD BH multijet	–	≥ 3 j	–	3.6	M_{th}	9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \to \gamma\gamma$	$2\ \gamma$	–	–	36.7	G_{KK} mass	4.1 TeV	$k/\overline{M}_{Pl} = 0.1$	1707.04147
	Bulk RS $G_{KK} \to WW/ZZ$	multi-channel			36.1	G_{KK} mass	2.3 TeV	$k/\overline{M}_{Pl} = 1.0$	1808.02380
	Bulk RS $G_{KK} \to WW \to qqqq$	$0\ e, \mu$	2 J	–	139	G_{KK} mass	1.6 TeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2019-003
	Bulk RS $g_{KK} \to tt$	$1\ e, \mu$	≥ 1 b, ≥ 1J/2j	Yes	36.1	g_{KK} mass	3.8 TeV	$\Gamma/m = 15\%$	1804.10823
	2UED / RPP	$1\ e, \mu$	≥ 2 b, ≥ 3 j	Yes	36.1	KK mass	1.8 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt) = 1$	1803.09678
Gauge bosons	SSM $Z' \to \ell\ell$	$2\ e, \mu$	–	–	139	Z' mass	5.1 TeV		1903.06248
	SSM $Z' \to \tau\tau$	$2\ \tau$	–	–	36.1	Z' mass	2.42 TeV		1709.07242
	Leptophobic $Z' \to bb$	–	2 b	–	36.1	Z' mass	2.1 TeV		1805.09299
	Leptophobic $Z' \to tt$	$1\ e, \mu$	≥ 1 b, ≥ 1J/2j	Yes	36.1	Z' mass	3.0 TeV	$\Gamma/m = 1\%$	1804.10823
	SSM $W' \to \ell\nu$	$1\ e, \mu$	–	Yes	139	W' mass	6.0 TeV		CERN-EP-2019-100
	SSM $W' \to \tau\nu$	$1\ \tau$	–	Yes	36.1	W' mass	3.7 TeV		1801.06992
	HVT $V' \to WZ \to qqqq$ model B	$0\ e, \mu$	2 J	–	139	V' mass	3.6 TeV	$g_V = 3$	ATLAS-CONF-2019-003
	HVT $V' \to WH/ZH$ model B	multi-channel			36.1	V' mass	2.93 TeV	$g_V = 3$	1712.06518
	LRSM $W_R \to tb$	multi-channel			36.1	W_R mass	3.25 TeV		1807.10473
	LRSM $W_R \to \mu N_R$	$2\ \mu$	1 J	–	80	W_R mass	5.0 TeV	$m(N_R) = 0.5$ TeV, $g_L = g_R$	1904.12679
CI	CI $qqqq$	–	2 j	–	37.0	Λ	21.8 TeV	η_{LL}^{-}	1703.09127
	CI $\ell\ell qq$	$2\ e, \mu$	–	–	36.1	Λ	40.0 TeV	η_{LL}^{-}	1707.02424
	CI $tttt$	$\geq 1\ e,\mu$	≥ 1 b, ≥ 1 j	Yes	36.1	Λ	2.57 TeV	$\lvert C_{4t} \rvert = 4\pi$	1811.02305
DM	Axial-vector mediator (Dirac DM)	$0\ e, \mu$	$1-4$ j	Yes	36.1	m_{med}	1.55 TeV	g_q=0.25, g_χ=1.0, $m(\chi) = 1$ GeV	1711.03301
	Colored scalar mediator (Dirac DM)	$0\ e, \mu$	$1-4$ j	Yes	36.1	m_{med}	1.67 TeV	g=1.0, $m(\chi) = 1$ GeV	1711.03301
	$VV\chi\chi$ EFT (Dirac DM)	$0\ e, \mu$	1 J, ≤ 1 j	Yes	3.2	M_*	700 GeV	$m(\chi) < 150$ GeV	1608.02372
	Scalar reson. $\phi \to t\chi$ (Dirac DM)	0-1 e, μ	1 b, 0-1 J	Yes	36.1	m_ϕ	3.4 TeV	$y = 0.4$, $\lambda = 0.2$, $m(\chi) = 10$ GeV	1812.09743
LQ	Scalar LQ 1st gen	1,2 e	≥ 2 j	Yes	36.1	LQ mass	1.4 TeV	$\beta = 1$	1902.00377
	Scalar LQ 2nd gen	1,2 μ	≥ 2 j	Yes	36.1	LQ mass	1.56 TeV	$\beta = 1$	1902.00377
	Scalar LQ 3rd gen	$2\ \tau$	2 b	–	36.1	LQ_3^u mass	1.03 TeV	$\mathcal{B}(LQ_3^u \to b\tau) = 1$	1902.08103
	Scalar LQ 3rd gen	0-1 e, μ	2 b	Yes	36.1	LQ_3^d mass	970 GeV	$\mathcal{B}(LQ_3^d \to t\tau) = 0$	1902.08103
Heavy quarks	VLQ $TT \to Ht/Zt/Wb + X$	multi-channel			36.1	T mass	1.37 TeV	SU(2) doublet	1808.02343
	VLQ $BB \to Wt/Zb + X$	multi-channel			36.1	B mass	1.34 TeV	SU(2) doublet	1808.02343
	VLQ $T_{5/3}T_{5/3} \vert T_{5/3} \to Wt + X$	2(SS)/$\geq$3 e,μ	≥ 1 b, ≥ 1 j	Yes	36.1	$T_{5/3}$ mass	1.64 TeV	$\mathcal{B}(T_{5/3} \to Wt)$= 1, $c(T_{5/3}Wt)$= 1	1807.11883
	VLQ $Y \to Wb + X$	$1\ e, \mu$	≥ 1 b, ≥ 1j	Yes	36.1	Y mass	1.85 TeV	$\mathcal{B}(Y \to Wb)$= 1, $c_R(Wb)$= 1	1812.07343
	VLQ $B \to Hb + X$	0 e,μ, 2 γ	≥ 1 b, ≥ 1j	Yes	79.8	B mass	1.21 TeV	κ_B= 0.5	ATLAS-CONF-2018-024
	VLQ $QQ \to WqWq$	$1\ e, \mu$	≥ 4 j	Yes	20.3	Q mass	690 GeV		1509.04261
Excited fermions	Excited quark $q^* \to qg$	–	2 j	–	139	q^* mass	6.7 TeV	only u^* and d^*, $\Lambda = m(q^*)$	ATLAS-CONF-2019-007
	Excited quark $q^* \to q\gamma$	$1\ \gamma$	1 j	–	36.7	q^* mass	5.3 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1709.10440
	Excited quark $b^* \to bg$	–	1 b, 1 j	–	36.1	b^* mass	2.6 TeV		1805.09299
	Excited lepton ℓ^*	$3\ e, \mu$	–	–	20.3	ℓ^* mass	3.0 TeV	$\Lambda = 3.0$ TeV	1411.2921
	Excited lepton ν^*	$3\ e, \mu, \tau$	–	–	20.3	ν^* mass	1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	Type III Seesaw	$1\ e, \mu$	≥ 2 j	Yes	79.8	N^0 mass	560 GeV		ATLAS-CONF-2018-020
	LRSM Majorana ν	$2\ \mu$	2 j	–	36.1	N_R mass	3.2 TeV	$m(W_R) = 4.1$ TeV, $g_L = g_R$	1809.11105
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	2,3,4 e, μ (SS)	–	–	36.1	$H^{\pm\pm}$ mass	870 GeV	DY production	1710.09748
	Higgs triplet $H^{\pm\pm} \to \ell\tau$	$3\ e, \mu, \tau$	–	–	20.3	$H^{\pm\pm}$ mass	400 GeV	DY production, $\mathcal{B}(H_L^{\pm\pm} \to \ell\tau) = 1$	1411.2921
	Multi-charged particles	–	–	–	36.1	multi-charged particle mass	1.22 TeV	DY production, $\lvert q \rvert = 5e$	1812.03673
	Magnetic monopoles	–	–	–	34.4	monopole mass	2.37 TeV	DY production, $\lvert g \rvert = 1g_D$, spin 1/2	1905.10130

$\sqrt{s}$ = 8 TeV | $\sqrt{s}$ = 13 TeV partial data | $\sqrt{s}$ = 13 TeV full data

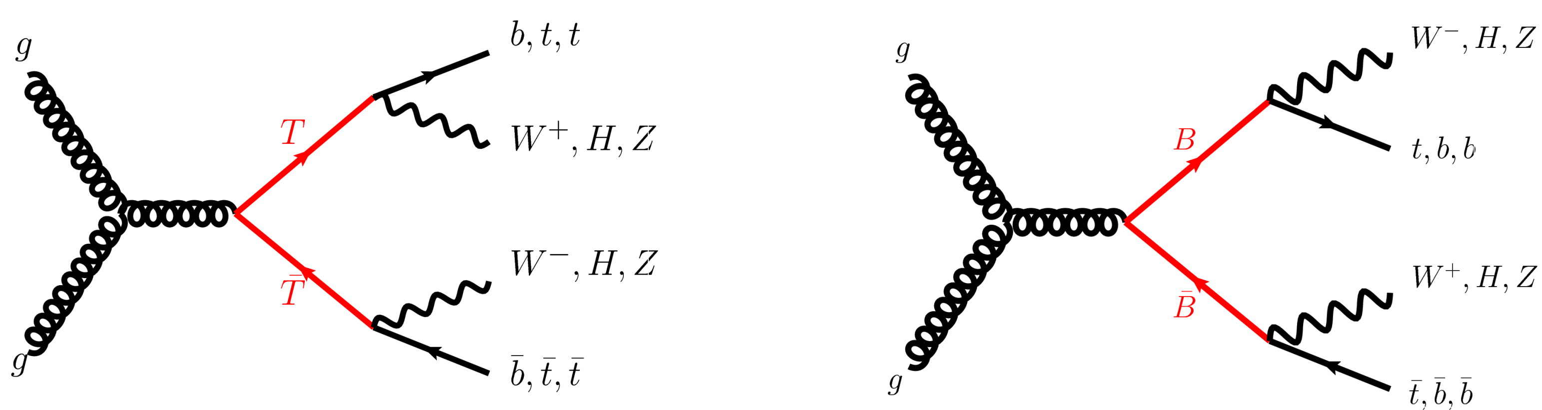
10^{-1} 1 10 **Mass scale [TeV]**

*Only a selection of the available mass limits on new states or phenomena is shown.

†Small-radius (large-radius) jets are denoted by the letter j (J).

Vector-Like Quarks

- VLQ for dummies (to learn more see, for example, arXiv:1306.0572) :
  - These are **color-triplet**, spin 1/2 fermions whose **left and right chiralities** transform **the same** way under weak isospin.
    - Mass terms not **explicitly forbidden** by SU(2) symmetry → They do not get mass through coupling with the Higgs field.
  - In their simplest realisation, they manifest as singlets $T^0_{L,R}$, $B^0_{L,R}$, of charge 2/3, -1/3 Doublets and triplets can also be considered.
  - They normally couple preferentially to 3rd generation quarks, due to large mixing.



Vector-Like Quarks

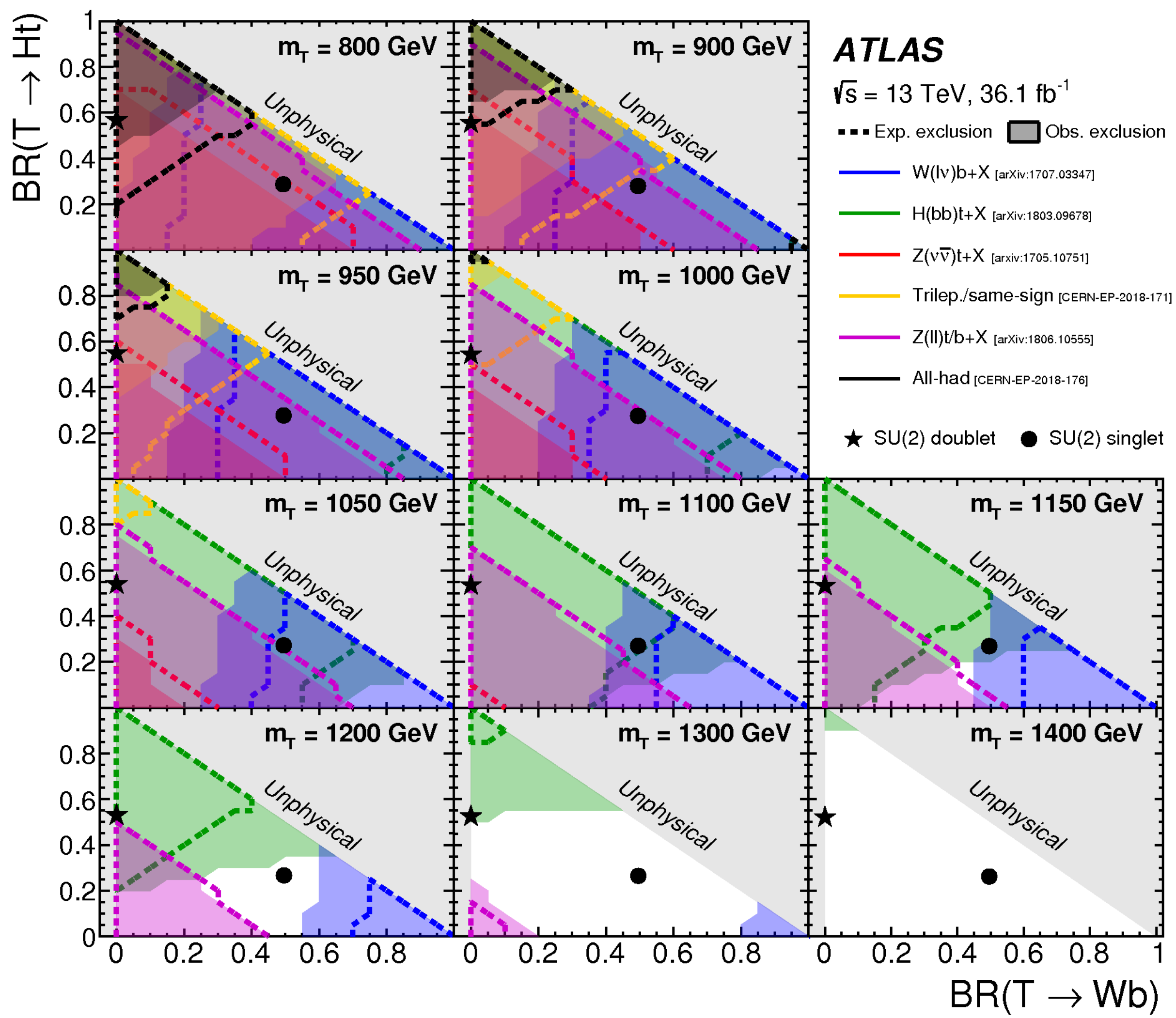
See Phys. Rev. Lett. 121 (2018) 211801

- A plethora of **possible final states** possible depending on the BR of $T \to bW, tH, tZ$ and $B \to tW, bH, bZ$.
- Targeted with an **ensemble of analyses** (either dedicated or targeting similar final states)
  - For example, final states of tt inv, bb inv **equivalent to LQ or stop, sbottom production**.

Analysis	$T\bar{T}$ decay	$B\bar{B}$ decay
$H(bb)t + X$ [16]	$HtH\bar{t}$	-
$W(\ell\nu)b + X$ [30]	$WbW\bar{b}$	-
$W(\ell\nu)t + X$ [32]	-	$WtW\bar{t}$
$Z(\nu\nu)t + X$ [33]	$ZtZ\bar{t}$	-
$Z(\ell\ell)t/b + X$ [35]	$ZtZ\bar{t}$	$ZbZ\bar{b}$
Tril./s.s. dilepton [36]	$HtH\bar{t}$	$WtW\bar{t}$
Fully hadronic [37]	$HtH\bar{t}$	$HbH\bar{b}$

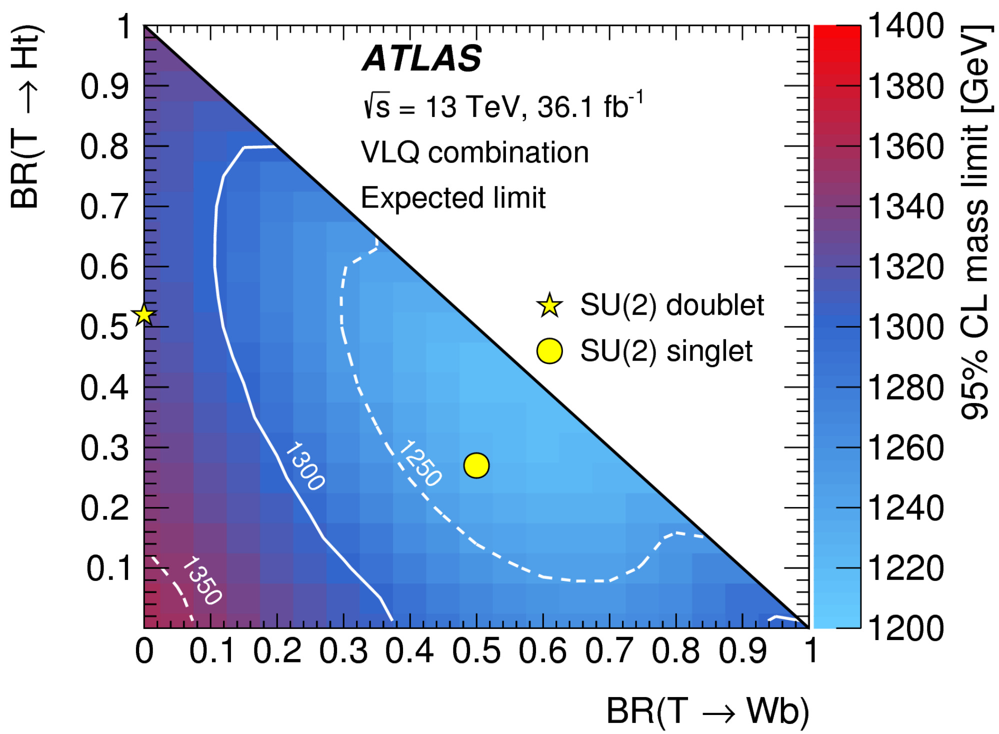
Vector-like quarks

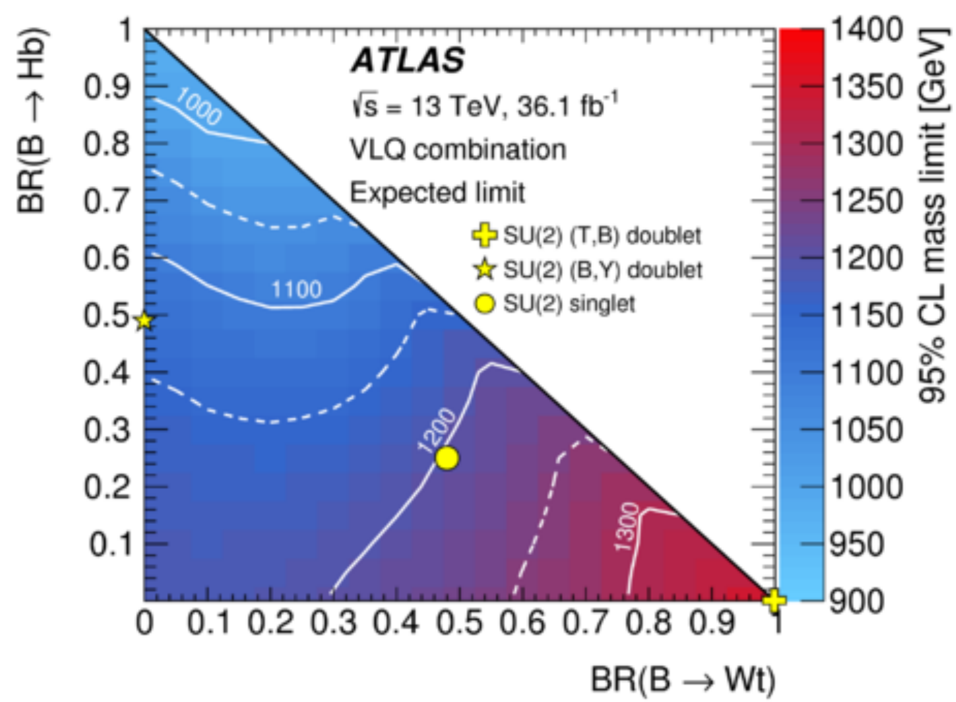
Assuming $BR(T \to Wb) + BR(T \to Ht) + BR(T \to Zt) = 1$



Vector-like quarks

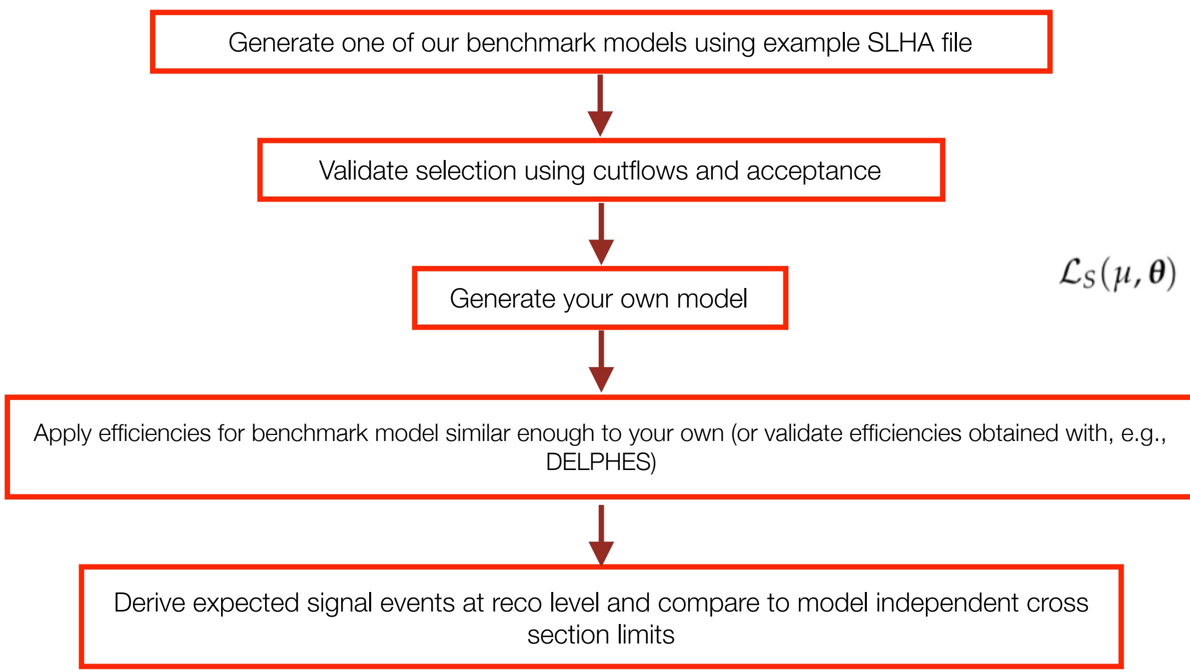
Assuming $BR(T \to Wb) + BR(T \to Ht) + BR(T \to Zt) = 1,$
$BR(B \to Wt) + BR(B \to Hb) + BR(B \to Zb) = 1$





Reinterpreting/Recasting LHC analyses

- A crucial aspect of searches: they are nice if they can be applied to models not used in the original publication
- The experiments provide a wealth of material to the community to be able to reinterpret searches, usually through HepData



- Sometimes using simplified likelihoods, as detailed here

$$\mathcal{L}_S(\mu, \boldsymbol{\theta}) = \prod_{i=1}^{N} \frac{(\mu \cdot s_i + b_i + \theta_i)^{n_i} e^{-(\mu \cdot s_i + b_i + \theta_i)}}{n_i!} \cdot \exp\left(-\frac{1}{2}\boldsymbol{\theta}^T \mathbf{V}^{-1} \boldsymbol{\theta}\right)$$

Tools for recasting LHC searches

- A full list available here

CHECKMATE

GAMBIT

Constraints On New Theories Using Rivet

Exploring the sensitivity of unfolded collider measurements to BSM models

Fastlim

Summary - exotica

- Plenty of searches **trying to turn every stone**, but no positive result.
- Searches for **long-lived particles** and **small couplings** are where a lot of the effort and the innovation is going.
- A **long programme ahead** still (although we would have enjoyed some solid excess at this point in the LHC life).

Grand-Summary

- I believe that high-energy physics (and in particular collider physics) is **at a turning point**.
  - Plenty of evidence for "unexplained things", but no **reference energy scale** to target.
  - Is this **a stalemate** (no actual winner, but no winning move left)?
- Hierarchy and Dark Matter are not solved:
  - Searches + precision + direct detection is **still the way to go.**
  - The LHC has **a 15 years programme ahead**. Any other collider joining the fun? e^+e^- precision is the obviously next step
  - Big improvements at the horizon for DM direct detection (e.g. DarkSide).
    - A positive detection would still need a collider to understand what physics this is…
- Keep an eye on PAMELA/AMS02 positron excesses, flavour anomalies. New physics might actually be in plain sight.

Backup

AMS02 antiproton results

- Taken from A. Kounine's talk at EPS/HEP