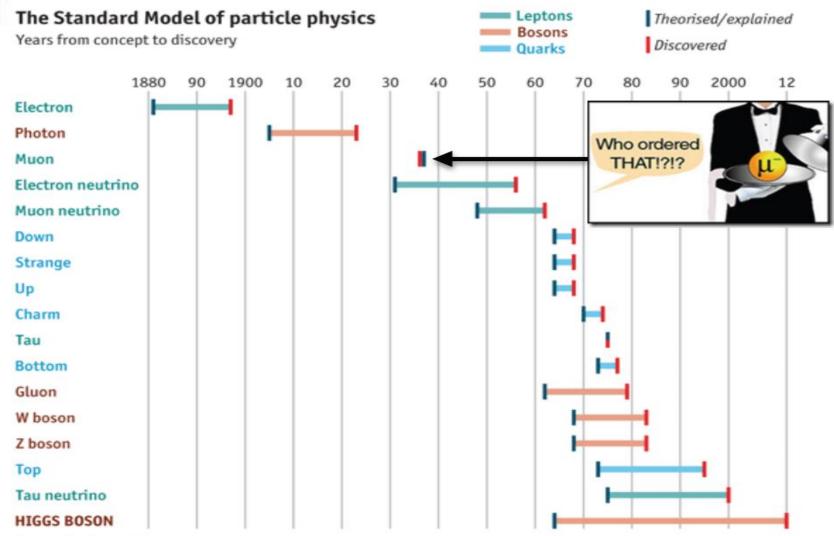
Introduction to particle physics: experimental part

Searches for New Physics

- **Supersymmetry**
- **Exotic models**
- **Dark Matter**
- **Unconventional signatures**

Uncharted discoveries?



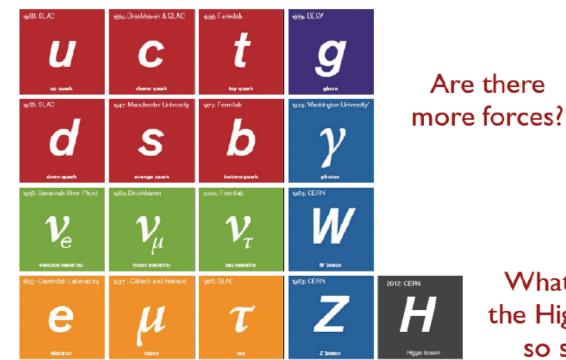
Source: The Economist

Many unanswered questions ...

Why there are 3 families of particles? Are there more? Why is the top quark so heavy?

Why there's more matter then antimatter?

How do neutrinos get mass?



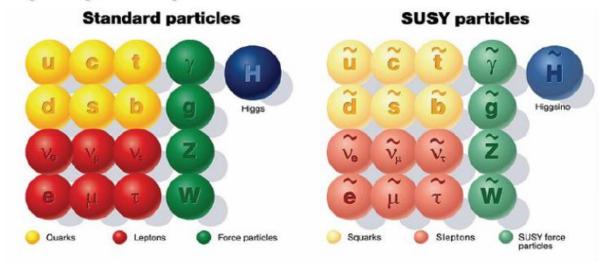
What keeps the Higgs mass so small?

How do we incorporate gravity?

What is Dark Matter?

... and as many possible answers to probe!

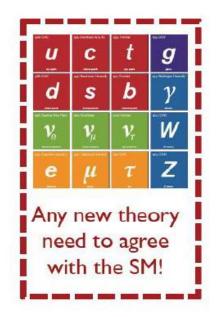
Super-symmetry?



- Composite quark and/or leptons?
- New Heavy bosons?
- Gravitons?

...

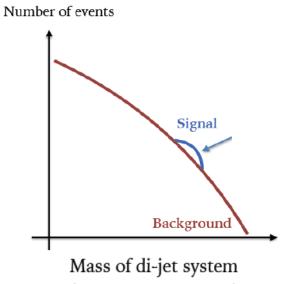
Dark Matter particles?



How would new phenomena manifest?

New particles:

resonant excess (bump) over Standard Model background



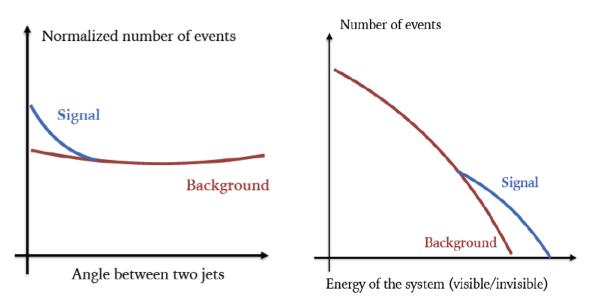
(~new particle mass)

New interactions:

more central production (~Rutherford experiment)

New particles and states:

larger multiplicity of objects at high masses



Long list of models and signatures

- Many extensions of the SM have been developed over the past decades:
- Supersymmetry
- Extra-Dimensions
- Technicolor(s)
- Little Higgs
- No Higgs
- GUT
- Hidden Valley
- Leptoquarks
- Compositeness
- 4th generation (t', b')
- LRSM, heavy neutrino
- etc...

(for illustration only)

- 1 jet + MET
- jets + MET
- 1 lepton + MET
- Same-sign di-lepton
- Dilepton resonance
- Diphoton resonance
- Diphoton + MET
- Multileptons
- Lepton-jet resonance
- Lepton-photon resonance
- Gamma-jet resonance
- Diboson resonance
- Z+MET
- W/Z+Gamma resonance
- Top-antitop resonance
- Slow-moving particles
- Long-lived particles
- Top-antitop production
- Lepton-Jets
- Microscopic blackholes
- Dijet resonance

Long list of models and signatures

- Many extensions of the SM have been developed over the past decades;
- Supersymmetry^{*}
- Extra-Dimensions
- Technicolor(s)
- Little Higgs
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- Hidden Valley
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- Compositeness
- 4th generation (t', b')⁴
- LRSM, heavy neutrino
- etc...

(for illustration only)

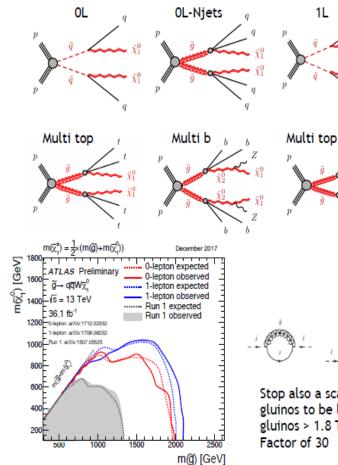
- 1 jet + MET jets + MET 1 lepton + MET Same-sign di-lepton Dilepton resonance Diphoton resonance Diphoton + MET Multileptons Lepton-jet resonance Lepton-photon resonance Gamma-jet resonance Diboson resonance Z+MET W/Z+Gamma resonance Top-antitop resonance Slow-moving particles Long-lived particles Top-antitop production Lepton-Jets Microscopic blackholes Dijet resonance
- etc...

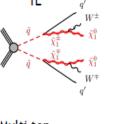
A complex 2D problem

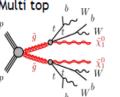
- Experimentally, a **signature standpoint** makes a lot of sense:
 - → Practical
 - → Less modeldependent
 - → Important to cover every possible signature

Strongly produced SUSY searches

Squarks and gluinos

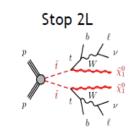


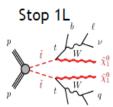






Stop also a scalar requires light gluinos to be light enough: for gluinos > 1.8 TeV ~tuning of Factor of 30





ATLAS Preliminary

[+12²/[+Wb2²

——E→cg /E→bfFs

/L+Wbx /L+bffi

 $\tilde{t}, \tilde{t}, production, \tilde{t}, \rightarrow b \uparrow f \chi^2 / \tilde{t}, \rightarrow c \chi^2 / \tilde{t}, \rightarrow W b \chi^2 / \tilde{t}, \rightarrow t \chi^2$

/L→Wby /L→bir

<u>արուրուրուիուրորուրուրուրո</u>

Fe-13 TeV 38 1 9V

Monoje c0L

Run

Expected limits

ا بينايينا بينا

600

700 800

500

400

300

1709.04183

1711.11520

1708.03247

[1711.03301]

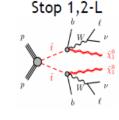
[1805.01849]

[1508.08816]

All limits at 95% CL

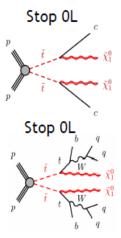
900 1000

m(f) [GeV]

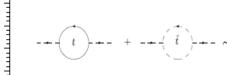


Stop 1,2-L

May 2018



Stop



Not so natural SUSY: Stops > 800 GeV ~Tuning of factor 20, but these exclusions are under specific conditions, and there are unexcluded corridors.

8

Strongly produced SUSY searches

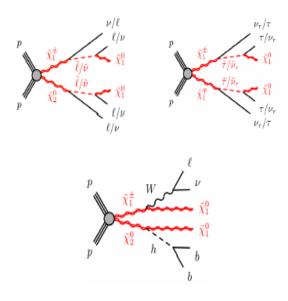
Squarks and gluinos Stop 0L Stop 2L Stop 1.2-**OL-Njets** 0L 1L Large number of topologies which can cover different SUSY or other new physics Stop 0 scenarios Multi top Multi b All signatures feature missing transverse energy! $m(\overline{\chi}_{\cdot}^{\pm}) = \frac{1}{2} \times (m(\overline{g}) + m(\overline{\chi}_{\cdot}^{0}))$ December 201 Ĩ,Ĩ, production, Ĩ,→ b f f 🛫 / Ĩ,→ c 🛫 / Ĩ,→ W b 🛫 / Ĩ,→ t 🛫 May 2018 mແູ່) [GeV] 0-lepton expected 0-lepton observed ATLAS Preliminar -13 TeV, 38 1 fb 1600 T→wby 1709.04183 -lepton expected +Why (I + htt 1711.11520 -lepton observed 1708.03247 /s = 13 TeV 1400 1711.03301 Run 1 expected L→cg /L→birg -01 [1805.01840] 36 1 fb Run 1 observed Run 1 [1508.08816] 1200 lepton: arXiv:1712.02832 lepton: arXiv:1708.08232 Bup 1: arXiv:1507.05526 1000 800 Not so natural SUSY: Stops > 600 Stop also a scalar requires light 800 GeV ~Tuning of factor 20. gluinos to be light enough: for 400 but these exclusions are under gluinos > 1.8 TeV ~tuning of specific conditions, and there Factor of 30 are unexcluded corridors. 300 400 500 600 700 800 900 m@)[GeV] m(ť.) [GeV]

9

Stop

More intricate scenarios

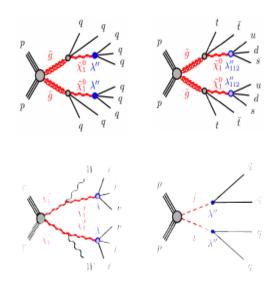
Weak production of chagrinos, neutralinos and sleptons



Weak production in compressed scenarios

Scenarios where the charginos, neutralinos with the lightest SUSY particle (LSP).

R-Parity violating SUSY



Resulting in topologies without LSP in the final state and therefore no MET.

$$\frac{1}{2}\lambda_{ijk}L_iL_j\bar{E}_k + \lambda'_{ijk}L_iQ_j\bar{D}_k + \frac{1}{2}\lambda''_{ijk}\bar{U}_i\bar{D}_j\bar{D}_k + \kappa_iL_iH_2$$



1 to 4 leptons (including taus) in the final state. Including decays to electroweak bosons.

or sleptons are close to mass degenerate

SUSY Searches Overview

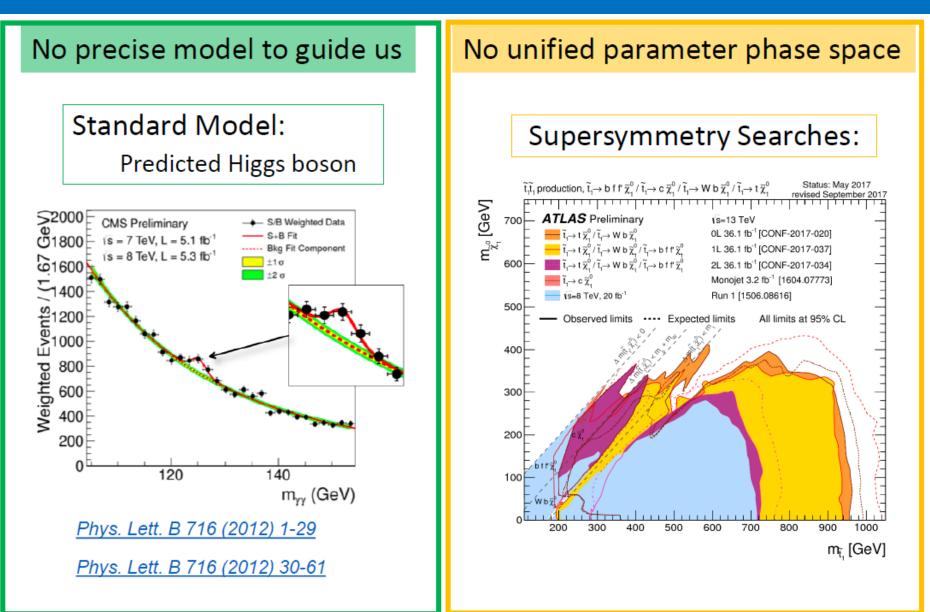
ATLAS SUSY Searches* - 95% CL Lower Limits

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

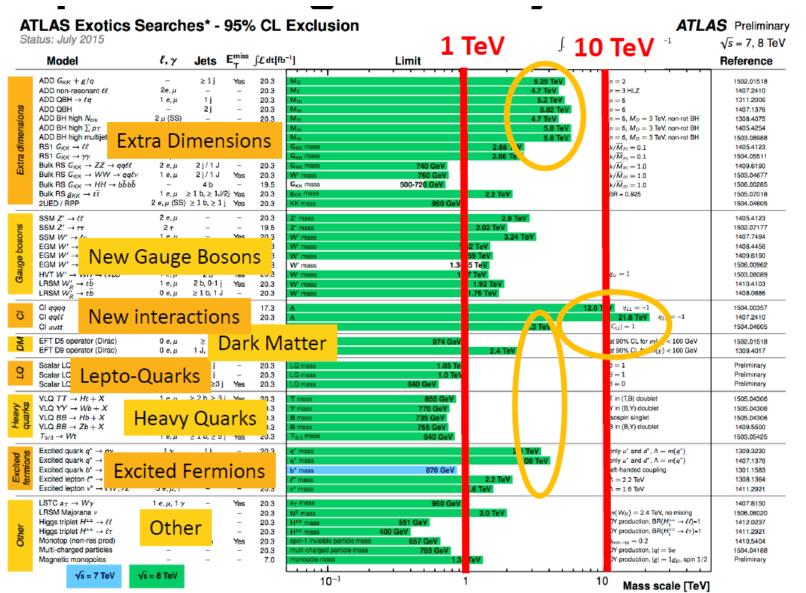
March 2019								$\sqrt{s} = 13 \text{ TeV}$					
Model		S	Signature ∫£ dt [fi				M	ass limit					Reference
Inclusive Searches	$\tilde{q}\tilde{q}, \tilde{q} \! ightarrow \! q \tilde{\ell}_1^0$	0 <i>e</i> ,μ mono-jet	2-6 jets 1-3 jets	E_T^{miss} E_T^{miss}	36.1 36.1	q [2x,8 q [1x,8	Bx Degen.] Bx Degen.]	0.43	0.9 0.71	1.5	55	m(x̃ ⁰ ₁)<100 GeV m(q̃)-m(x̃ ⁰ ₁)=5 GeV	1712.02332 1711.03301
	$\tilde{g}\tilde{g}, \; \tilde{g} \rightarrow q \bar{q} \tilde{\chi}_1^0$	0 <i>e</i> , <i>µ</i>	2-6 jets	E_T^{miss}	36.1	ř ř			Forbidden	0.95-	2.0 1.6	$m(\bar{\chi}_{1}^{0}) < 200 \text{ GeV}$ $m(\bar{\chi}_{1}^{0}) = 900 \text{ GeV}$	1712.02332 1712.02332
	$\tilde{g}\tilde{g}, \; \tilde{g} \rightarrow q \tilde{q}(\ell \ell) \tilde{\chi}_1^0$	3 е, µ ее, µµ	4 jets 2 jets	E_T^{miss}	36.1 36.1	18 18				1.2	1.85	m(x̄ ⁰ ₁)<800 GeV m(ȳ)-m(x̄ ⁰ ₁)=50 GeV	1706.03731 1805.11381
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qqWZ\tilde{\chi}_1^0$	0 e, μ 3 e, μ	7-11 jets 4 jets	E_T^{miss}	36.1 36.1	ğ ğ			0.98		1.8	$m(\bar{x}_{1}^{0}) < 400 \text{ GeV}$ $m(\bar{g})-m(\bar{x}_{1}^{0})=200 \text{ GeV}$	1708.02794 1706.03731
	$\bar{g}\bar{g}, \ \bar{g} \rightarrow t\bar{t}\bar{\chi}_1^0$	0-1 e,μ 3 e,μ	3 b 4 jets	E_T^{miss}	79.8 36.1	ê ê				1.25	2.25	m($\bar{\chi}_{1}^{0}$)<200 GeV m(\tilde{g})-m($\bar{\chi}_{1}^{0}$)=300 GeV	ATLAS-CONF-2018-041 1706.03731
3 ^{,4} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1,\tilde{b}_1{\rightarrow}b\tilde{\chi}_1^0/t\tilde{\chi}_1^\pm$		Multiple Multiple Multiple		36.1 36.1 36.1	$egin{array}{c} & & & & \ & & \ & & & \ & \ & \ & $	Forbidder	r Forbidden Forbidden	0.9 0.58-0.82 0.7			$m(\bar{\chi}_{1}^{0})=300 \text{ GeV}, BR(b\bar{\chi}_{1}^{0})=1$ $1^{0}=300 \text{ GeV}, BR(b\bar{\chi}_{1}^{0})=BR(b\bar{\chi}_{1}^{+})=0.5$ $0 \text{ GeV}, m(\bar{\chi}_{1}^{+})=300 \text{ GeV}, BR(b\bar{\chi}_{1}^{+})=1$	1708.09266, 1711.03301 1708.09266 1706.03731
	$\tilde{b}_1 \tilde{b}_1, \tilde{b}_1 \rightarrow b \tilde{\chi}^0_2 \rightarrow b h \tilde{\chi}^0_1$	0 e, µ	6 <i>b</i>	E_T^{miss}	139		Forbidden	0.23-0.48	().23-1.35	Δπ	$n(\tilde{\chi}_{2}^{0}, \tilde{\chi}_{1}^{0}) = 130 \text{ GeV}, m(\tilde{\chi}_{1}^{0}) = 100 \text{ GeV}$ $\Delta m(\tilde{\chi}_{2}^{0}, \tilde{\chi}_{1}^{0}) = 130 \text{ GeV}, m(\tilde{\chi}_{1}^{0}) = 0 \text{ GeV}$	SUSY-2018-31 SUSY-2018-31
	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow W b \tilde{t}_1^0 \text{ or } t \tilde{t}_1^0$ $\tilde{t}_1 \tilde{t}_1, \text{ Well-Tempered LSP}$)-2 jets/1-2 Multiple	'	36.1 36.1	\tilde{l}_1 \tilde{l}_1			1.0 0.48-0.84		$m(\bar{x}_{1}^{0})=15$	$m(\bar{\chi}_{1}^{0})=1 \text{ GeV}$ 50 GeV, $m(\bar{\chi}_{1}^{\pm})-m(\bar{\chi}_{1}^{0})=5 \text{ GeV}$, $\bar{\imath}_{1} \approx \bar{\imath}_{L}$	1506.08616, 1709.04183, 1711.11520 1709.04183, 1711.11520
	$ \begin{split} & \tilde{\iota}_1 \tilde{\iota}_1, \tilde{\iota}_1 \! \rightarrow \! \tilde{\tau}_1 b \nu, \tilde{\tau}_1 \! \rightarrow \! \tau G \\ & \tilde{\iota}_1 \tilde{\iota}_1, \tilde{\iota}_1 \! \rightarrow \! c \! \tilde{\chi}_1^0 / \tilde{c} \tilde{c}, \tilde{c} \! \rightarrow \! c \! \tilde{\chi}_1^0 \end{split} $	1 τ + 1 e,μ,τ 0 e,μ	2 jets/1 b 2 c	E_T^{miss} E_T^{miss}	36.1 36.1	<i>ι</i> ₁ <i>č</i> <i>ι</i> ₁		0.46	0.85	1.16		m(īt_1)=800 GeV m(tt_1^0)=0 GeV m(tt_1,z)-m(tt_1^0)=50 GeV	1803.10178 1805.01649 1805.01649
	$\tilde{i}_2 \tilde{i}_2, \tilde{i}_2 \rightarrow \tilde{i}_1 + h$	0 e, μ 1-2 e, μ	mono-jet 4 b	E_T^{miss} E_T^{miss}	36.1 36.1	ĩ ₁ ĩ ₂		0.43	0.32-0.88			$m(\tilde{t}_1, \epsilon) - m(\tilde{t}_1^0) = 5 \text{ GeV}$ $(\tilde{t}_1^0) = 0 \text{ GeV}, m(\tilde{t}_1) - m(\tilde{t}_1^0) = 180 \text{ GeV}$	1711.03301 1706.03986
	$\bar{\chi}_1^{\pm} \bar{\chi}_2^0$ via WZ	2-3 e, μ ee, μμ	≥1	ETT ETT ETT	36.1 36.1	$\tilde{\chi}_{1}^{\pm}/\tilde{\chi}_{2}^{0}$ $\tilde{\chi}_{1}^{\pm}/\tilde{\chi}_{2}^{0}$	0.17		0.6	-		$m(\tilde{\chi}_1^0)=0$ $m(\tilde{\chi}_1^0)=0$ $m(\tilde{\chi}_1^0)=10$ GeV	1403.5294, 1806.02293 1712.08119
	$\bar{\chi}_1^{\pm} \bar{\chi}_1^{\pm}$ via WW	2 e, µ		E_T^{miss} E_T^{miss} E_T^{miss}	139	$\tilde{\chi}_{1}^{\pm}$	0.17	0.42				$m(\bar{\chi}_1^0)=0$	ATLAS-CONF-2019-008
	$\bar{\chi}_{1}^{\pm} \bar{\chi}_{2}^{0}$ via Wh $\bar{\chi}_{1}^{\pm} \bar{\chi}_{1}^{\mp}$ via $\tilde{\ell}_{I} / \bar{\nu}$	0-1 e,μ 2 e,μ	2 b	E_T^{miss} E_T^{miss}	36.1 139	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$ $\tilde{\chi}_1^{\pm}$			0.68			$m(\bar{\chi}_{1}^{0})=0$ $m(\bar{\chi}_{2}^{\bar{\nu}})=0.5(m(\bar{\chi}_{1}^{\pm})+m(\bar{\chi}_{1}^{0}))$	1812.09432 ATLAS-CONF-2019-008
EW direct	$\begin{split} &\tilde{\chi}_1 \chi_1 \forall \mathbf{a} t_L $	2τ		E_T^{miss}	36.1	$\tilde{\chi}_{1}^{\pm} / \tilde{\chi}_{2}^{0}$ $\tilde{\chi}_{1}^{\pm} / \tilde{\chi}_{2}^{0}$	0.22		0.76			$m(\tilde{\epsilon}, \tilde{\nu}) = 0.5(m(\tilde{\epsilon}_1^-) + m(\tilde{\epsilon}_1^-))$ $m(\tilde{\epsilon}_1^0) = 0, m(\tilde{\tau}, \tilde{\nu}) = 0.5(m(\tilde{\epsilon}_1^+) + m(\tilde{\epsilon}_1^0))$ 100 GeV, $m(\tilde{\tau}, \tilde{\nu}) = 0.5(m(\tilde{\epsilon}_1^+) + m(\tilde{\epsilon}_1^0))$	1708.07875 1708.07875
	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R},\tilde{\ell}{\rightarrow}\ell\tilde{\chi}^0_1$	2 e, μ 2 e, μ	0 jets ≥ 1	E_T^{miss} E_T^{miss}	139 36.1	2	0.18		0.7			$m(\bar{x}_1^0)=0$ $m(\bar{\ell})-m(\bar{x}_1^0)=5 \text{ GeV}$	ATLAS-CONF-2019-008 1712.08119
	$\tilde{H}\tilde{H}, \tilde{H} \rightarrow h\tilde{G}/Z\tilde{G}$	0 e, μ 4 e, μ	≥ 3 b 0 jets	E_T^{miss} E_T^{miss}	36.1 36.1	Ĥ Ĥ	0.13-0.23 0.3	3	0.29-0.88			$\begin{array}{c} BR(\bar{k}_1^0 \to hG) 1\\ BR(\bar{k}_1^0 \to ZG) 1\end{array}$	1806.04030 1804.03602
lived cles	$\mathrm{Direct} \tilde{x}_1^* \! \tilde{x}_1^-$ prod., long-lived \tilde{x}_1^*	Disapp. trk	1 jet	E_T^{miss}	36.1	$ \tilde{\chi}_{1}^{\pm} \\ \tilde{\chi}_{1}^{\pm} = 0. $	15	0.46				Pure Wino Pure Higgsino	1712.02118 ATL-PHYS-PUB-2017-019
Long-lived particles	Stable \tilde{g} R-hadron Metastable \tilde{g} R-hadron, $\tilde{g} \rightarrow qq \tilde{\chi}_1^0$		Multiple Multiple		36.1 36.1	ğ ğ [τ(ğ)	=10 ns, 0.2 ns]				2.0 2.05 2.4	$m(\tilde{\chi}_1^0)$ =100 GeV	1902.01636,1808.04095 1710.04901,1808.04095
	LFV $pp \rightarrow \tilde{v}_{\tau} + X$, $\tilde{v}_{\tau} \rightarrow e\mu/e\tau/\mu\tau$	еµ,ет,µт			3.2	Ϋ́ _τ					1.9	$\lambda'_{311}=0.11, \lambda_{132/133/233}=0.07$	1607.08079
	$\tilde{\chi}_1^{\pm} \tilde{\chi}_1^{\mp} / \tilde{\chi}_2^0 \rightarrow WW / Z\ell\ell\ell\ell\nu\nu$	4 e, µ	0 jets	E_T^{miss}	36.1	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$	$[\lambda_{i33} \neq 0, \lambda_{12k} \neq 0]$		0.82	1.33		m($\bar{\chi}_{1}^{0}$)=100 GeV	1804.03602
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qq\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow qqq$	4	5 large- <i>R</i> je Multiple	its	36.1 36.1	₹ m(X))-200 GeV, 1100 GeV] -2e-4, 2e-5]		1.0	1.3	1.9 2.0	Large $\mathcal{X}_{112}^{\prime\prime}$ m($\bar{\chi}_{1}^{0}$)=200 GeV, bino-like	1804.03568 ATLAS-CONF-2018-003
RPV	$t\bar{t}, t \rightarrow t \bar{\chi}_1^0, \bar{\chi}_1^0 \rightarrow tbs$		Multiple		36.1		=2e-4, 1e-2]	0.5			2.0	m(x ₁)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow bs$		2 jets + 2 b		36.7	$\tilde{t}_1 = [qq, t]$	bs]	0.42	0.61				1710.07171
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1{\rightarrow}q\ell$	2 e, μ 1 μ	2 <i>b</i> DV		36.1 136	\tilde{t}_1 \tilde{t}_1 [1e-1	10< X' <1e-8, 3e-10< X	, 23k <3e-9]	1.0	0.4-1.45	1.6	$\begin{array}{l} BR(\bar{t}_1 \rightarrow b \varepsilon / b \mu) > 20\% \\ BR(\bar{t}_1 \rightarrow q \mu) = 100\%, \ \cos \theta = 1 \end{array}$	1710.05544 ATLAS-CONF-2019-006
*Only a selection of the available mass limits on new states or 10^{-1} 1 Mass scale [TeV]													

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

What characterizes Exotics Searches



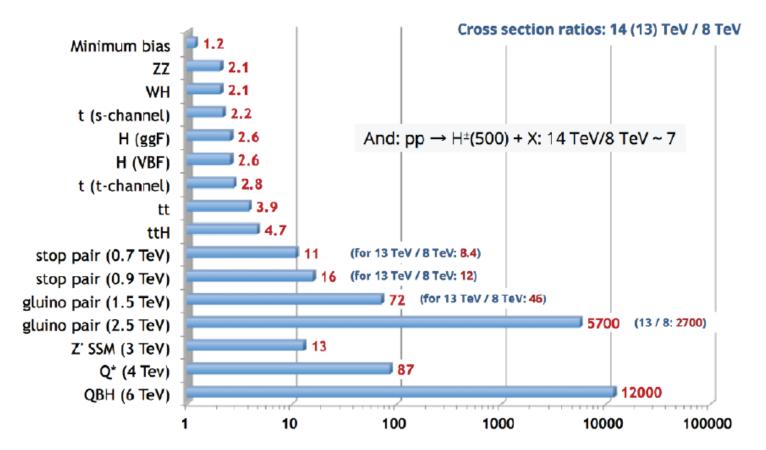
Exploration range of LHC by mid 2015



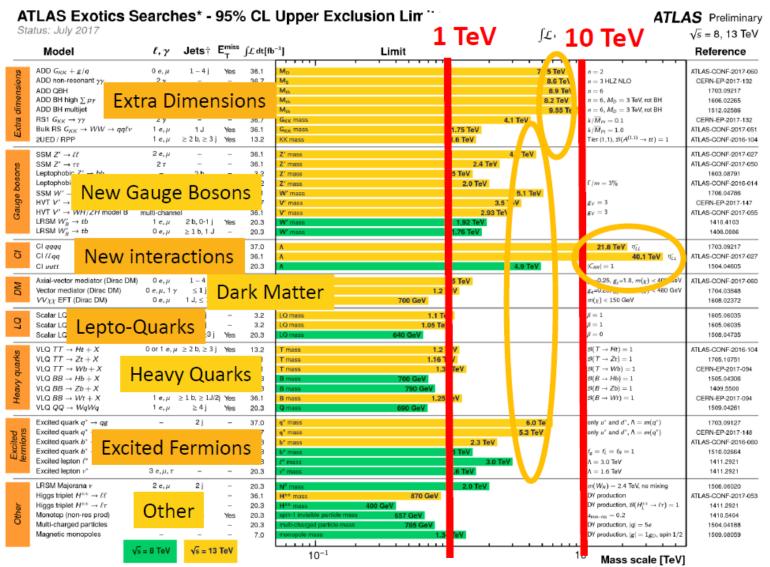
*Only a selection of the available mass limits on new states or phenomena is shown.

LHC Run II

Hugely increased potential for discovery of heavy particles at 13 TeV Perfect occasion for young motivated physicists: join the search!



Exploration range of LHC by mid 2017



*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).

Exploration range of LHC by mid 2019

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

ATLAS Preliminary

Status: March 2019

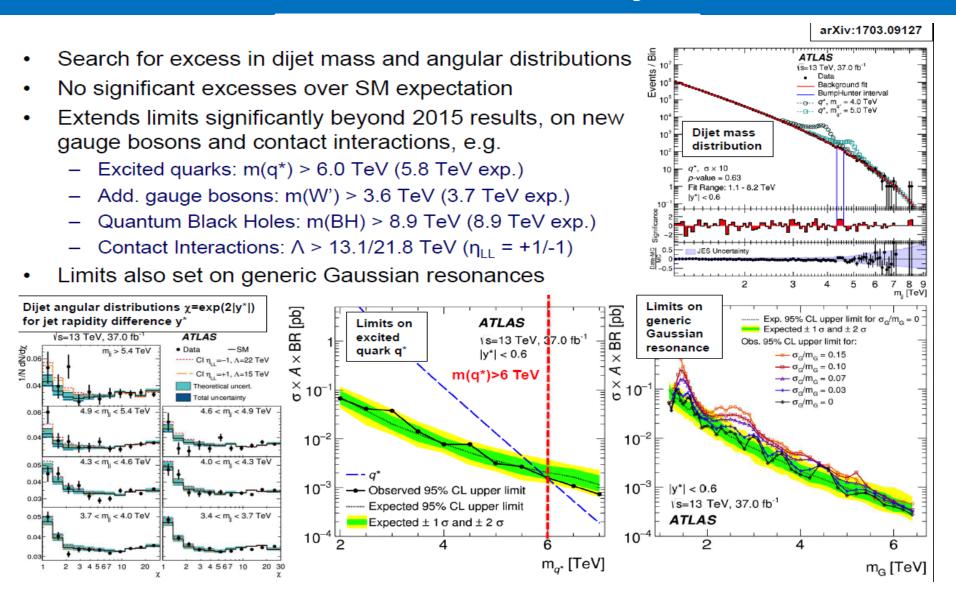
 $\int \mathcal{L} dt = (3.2 - 139) \, \text{fb}^{-1}$

 $\sqrt{s} = 8, 13 \text{ TeV}$

	Model ℓ, γ Jets† E	miss ∫£ dt[fb		5.2 - 139/10	Reference
Extra dimensions	$\begin{array}{c c c c c c c c c c c c c c c c c c c $		Mp 7.7 TeV Ms 8.6 TeV Min 8.9 TeV Min 8.2 TeV Min 9.55 TeV GKK mass 2.3 TeV GKK mass 2.8 TeV KK mass 3.8 TeV KK mass 1.8 TeV	$\begin{array}{l} n=2 \\ n=3 \; \text{HLZ NLO} \\ n=6 \\ n=6, \; M_D=3 \; \text{TeV, rot BH} \\ n=6, \; M_D=3 \; \text{TeV, rot BH} \\ k/\overline{M}_{Pl}=0.1 \\ k/\overline{M}_{Pl}=1.0 \\ k/\overline{M}_{Pl}=1.0 \\ F/m=15\% \\ \hline \text{Tier}\; (1,1), \; \mathcal{B}(A^{(1,1)} \to \text{tt})=1 \end{array}$	1711.03301 1707.04147 1703.09127 1606.02265 1512.02586 1707.04147 1806.02380 ATLAS-CONF-2019-003 1804.10823 1803.09678
Gauge bosons		- 139 - 36.1 - 36.1 Yes 36.1 Yes 79.8 Yes 36.1 - 139 36.1 36.1	Z' mass 5.1 TeV Z' mass 2.42 TeV Z' mass 2.1 TeV Z' mass 3.0 TeV W' mass 5.6 TeV W' mass 5.6 TeV V' mass 3.7 TeV V' mass 4.4 TeV V' mass 2.93 TeV W' mass 3.25 TeV	$\Gamma/m = 1\%$ $g_V = 3$ $g_V = 3$	1903.06248 1709.07242 1805.09299 1804.10823 ATLAS-CONF-2018-017 1801.06992 ATLAS-CONF-2019-003 1712.06518 1807.10473
CI	Cl qqqq - 2 j Cl ℓℓqq 2 e, μ - Cl tttt ≥1 e,μ ≥1 b, ≥1 j	- 37.0 - 36.1 Yes 36.1	Λ Λ Λ 2.57 TeV	21.8 TeV η_{LL}^- 40.0 TeV η_{LL}^- $ C_{4c} = 4\pi$	1703.09127 1707.02424 1811.02305
WD	$ \begin{array}{llllllllllllllllllllllllllllllllllll$	Yes 36.1 Yes 36.1 Yes 3.2 Yes 36.1	Immed 1.55 TeV Immed 1.67 TeV M, 700 GeV M _# 3.4 TeV	$\begin{array}{l} g_{q} = 0.25, \ g_{\chi} = 1.0, \ m(\chi) = 1 \ {\rm GeV} \\ g = 1.0, \ m(\chi) = 1 \ {\rm GeV} \\ m(\chi) < 150 \ {\rm GeV} \\ y = 0.4, \ \lambda = 0.2, \ m(\chi) = 10 \ {\rm GeV} \end{array}$	1711.03301 1711.03301 1608.02372 1812.09743
ΓO	Scalar LQ 2^{nd} gen $1, 2 \mu \ge 2 j$ Scalar LQ 3^{rd} gen $2 \tau = 2 b$	Yes 36.1 Yes 36.1 - 36.1 Yes 36.1	LC mass 1.4 TeV LC mass 1.56 TeV LC ^a mass 1.03 TeV LC ^a mass 970 GeV	$\begin{split} \beta &= 1 \\ \beta &= 1 \\ \mathcal{B}(\mathrm{LQ}_3^u \to b\tau) &= 1 \\ \mathcal{B}(\mathrm{LQ}_3^d \to t\tau) &= 0 \end{split}$	1902.00377 1902.00377 1902.08103 1902.08103
Heavy quarks	$VLQ B \rightarrow Hb + X$ $0 e, \mu, 2 \gamma \ge 1 b, \ge 1 J$	36.1 36.1 Yes 36.1 Yes 36.1 Yes 79.8 Yes 20.3	T mass 1.37 TeV B mass 1.34 TeV T _{5/3} mass 1.64 TeV Y mass 1.85 TeV B mass 1.21 TeV Q mass 690 GeV	$\begin{array}{l} & \mathrm{SU(2)\ doublet} \\ & \mathrm{SU(2)\ doublet} \\ & \mathcal{B}(T_{5/3} \rightarrow Wt) - 1,\ c(T_{5/3}Wt) - 1 \\ & \mathcal{B}(Y \rightarrow Wb) - 1,\ c_R(Wb) - 1 \\ & \kappa_B - 0.5 \end{array}$	1808.02343 1808.02343 1807.11883 1812.07343 ATLAS-CONF-2018-024 1509.04261
Excited fermions	$\begin{array}{llllllllllllllllllllllllllllllllllll$	- 139 - 36.7 - 36.1 - 20.3 - 20.3	q* mass 6,7 TeV q* mass 5.3 TeV b* mass 2.6 TeV /* mass 3.0 TeV V* mass 1.6 TeV	only u^* and $d^*, \Lambda = m(q^*)$ only u^* and $d^*, \Lambda = m(q^*)$ $\Lambda = 3.0 \text{ TeV}$ $\Lambda = 1.6 \text{ TeV}$	ATLAS-CONF-2019-007 1709.10440 1805.09299 1411.2921 1411.2921
Other	$\begin{array}{c c c c c c c c c c c c c c c c c c c $		Nº mass 560 GeV N _R mass 3.2 TeV H ^{±±} mass 870 GeV H ^{±±} mass 400 GeV multi-charged particle mass 1.22 TeV monopole mass 1.34 TeV 1.0 ⁻¹ 1	$\begin{split} m(W_R) &= 4.1 \text{ TeV}, g_L = g_R \\ \text{DY production} \\ \text{DY production}, \mathcal{B}(H_L^{\pm\pm} \to \ell\tau) = 1 \\ \text{DY production}, q &= 5e \\ \text{DY production}, g &= 1g_D, \text{ spin } 1/2 \\ \end{split}$	ATLAS-CONF-2018-020 1809.11105 1710.09748 1411.2921 1812.03673 1509.08059

*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).

Searches with Dijets



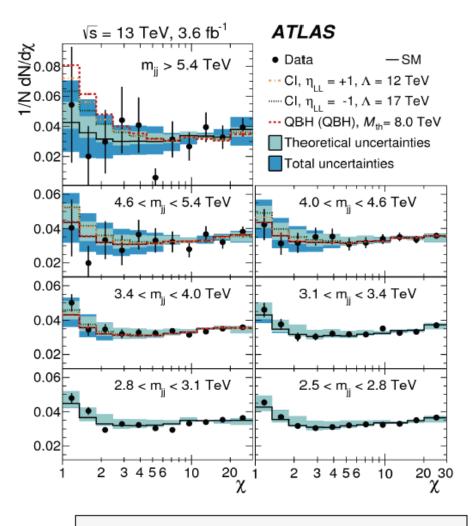
Dijet Angular Searches

Search in dijet mass bins using angular distribution

 $\chi = e^{2|y^*|} \sim \frac{1 + \cos\theta *}{1 - \cos\theta *}$

<u>1512.01530</u>

Search for distortions of the dijet angular distribution from Contact Interactions of particles at much higher masses $O(\Lambda)$ with color-singlet lefthanded chiral couplings (in 4-fermion effective field theory)

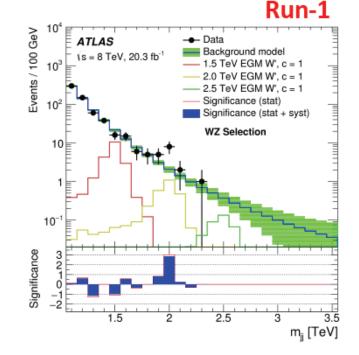


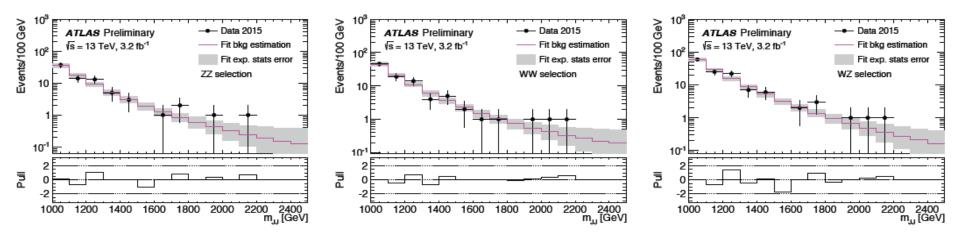
No deviations observed, limits set at 12 TeV on Λ (for η_{LL} = 1)

Fully hadronic JJ Diboson Searches

ATLAS-CONF-2015-073

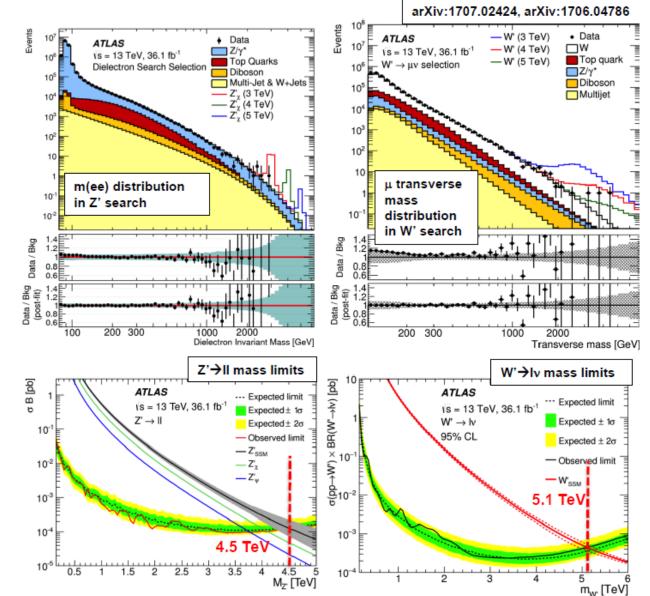
- Modest excess at Run-1: 3.40 local / 2.50 global
- Analysis very similar to Run 1, with functional fit of the background
- No significant excess is observed however sensitivity not high enough for conclusive probe of the Run 1 excess





Resonance Searches (Dilepton, Lepton+ETmiss)

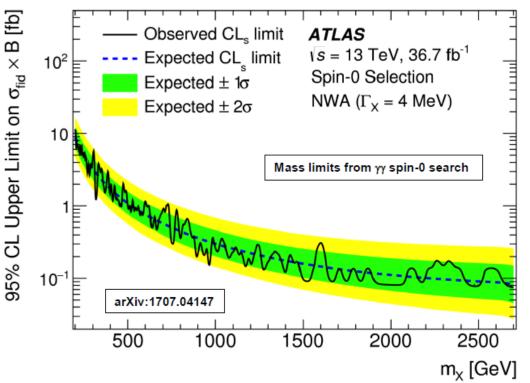
- Searches for new resonances decaying to lepton pairs (e.g. Z') or lepton+E_T^{miss} (e.g. W')
- Signature is peak in invariant mass distribution (dilepton) or tranverse mass distributions (lepton+E_T^{miss})
- No significant excess over SM expectation
- 95% CL exclusion limits extracted in various new physics Z' and W' scenarios, e.g. the Sequential Standard Model (SSM)

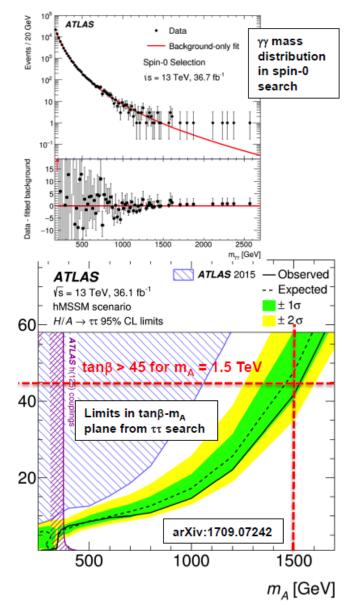


Resonance Searches ($\gamma\gamma$, $\tau\tau$)

tanβ

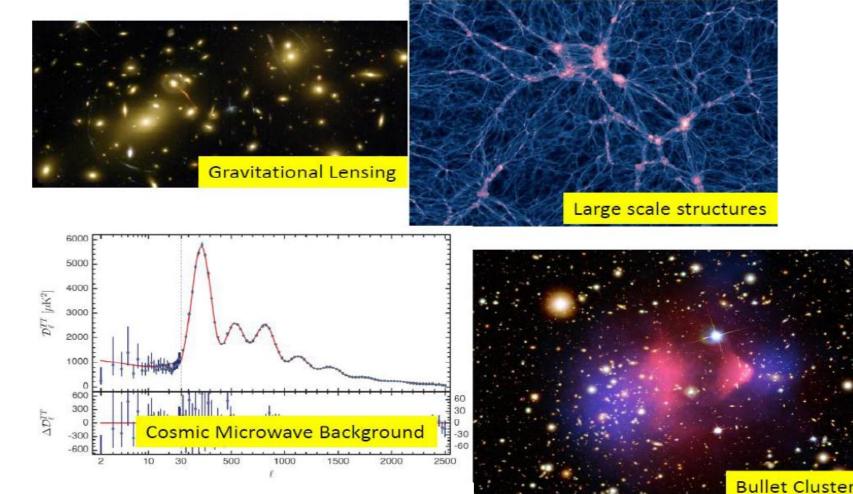
- Diboson resonance searches also sensitive to new heavy scalars, e.g. Higgs bosons.
- Searches also conducted with $\gamma\gamma$ and $\tau\tau$ final states
- γγ search also targets spin-2 (graviton) production with a dedicated selection
- ττ searches sensitive to SUSY Higgs (H/A) models
- No significant excesses over SM expectation



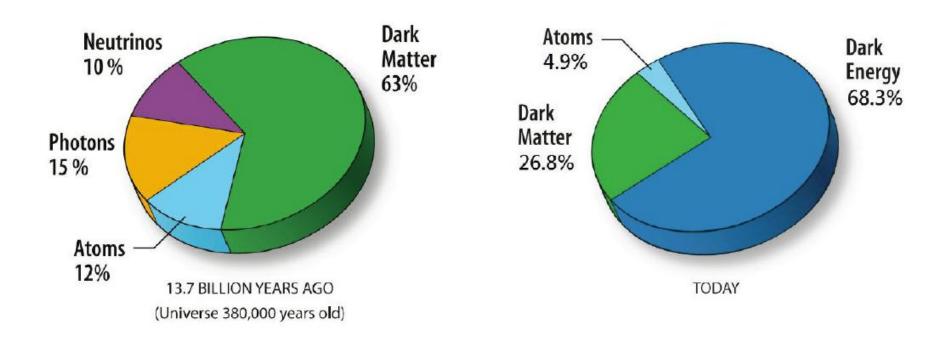


Why Dark Matter?

Evidence piling up...



What do we know about Dark Matter



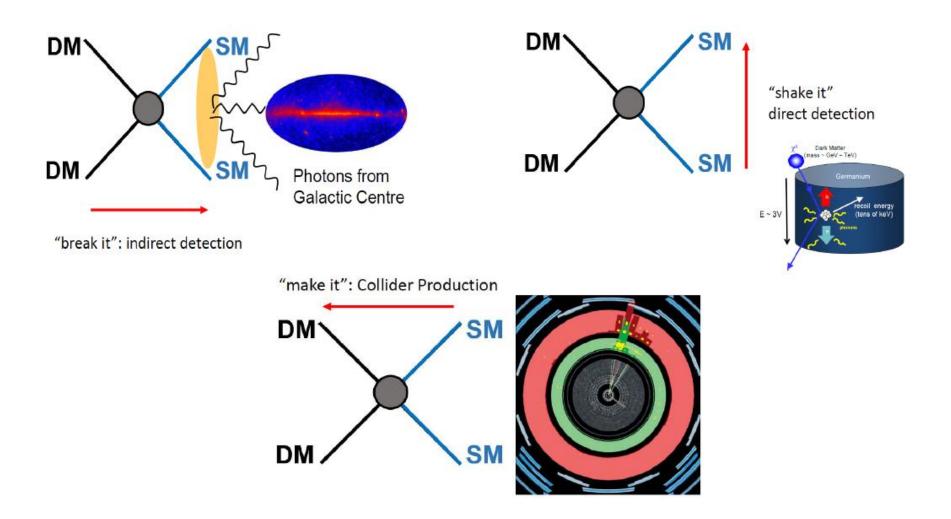
Strong astrophysical evidence for the existence of dark matter

What do we know about Dark Matter

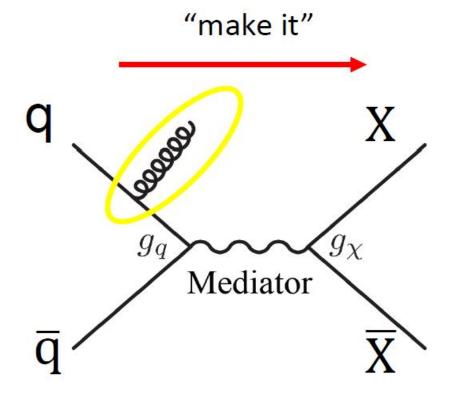
Massive

- Non-relativistic (slow)
- Long lived (old)
- No electric or colour charge
- Very weakly interacting with ordinary matter
- Subject to gravity interactions

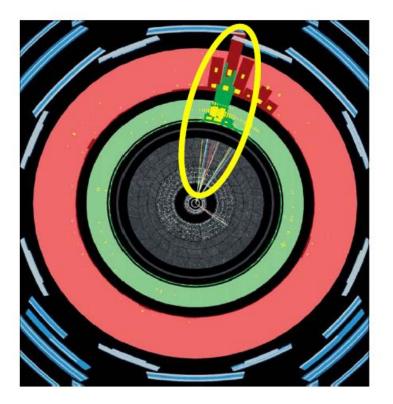
Experimental detection of Dark Matter



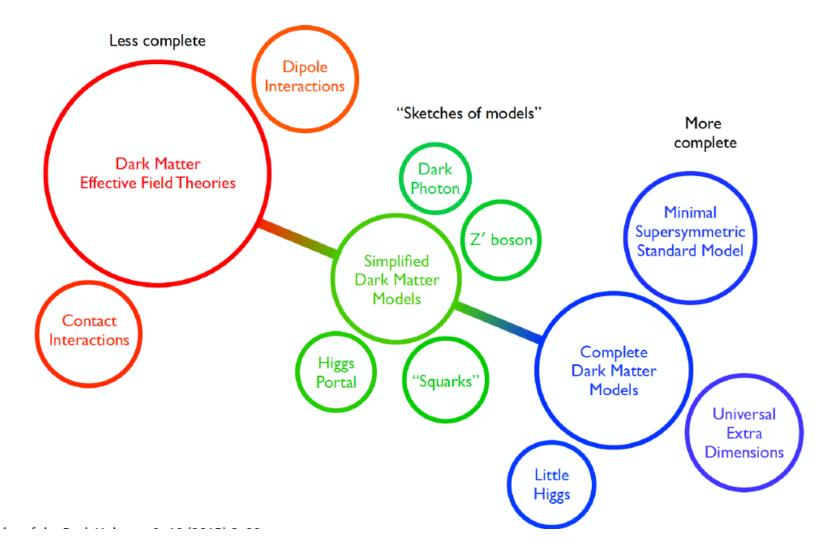
Dark Matter serches at Colliders

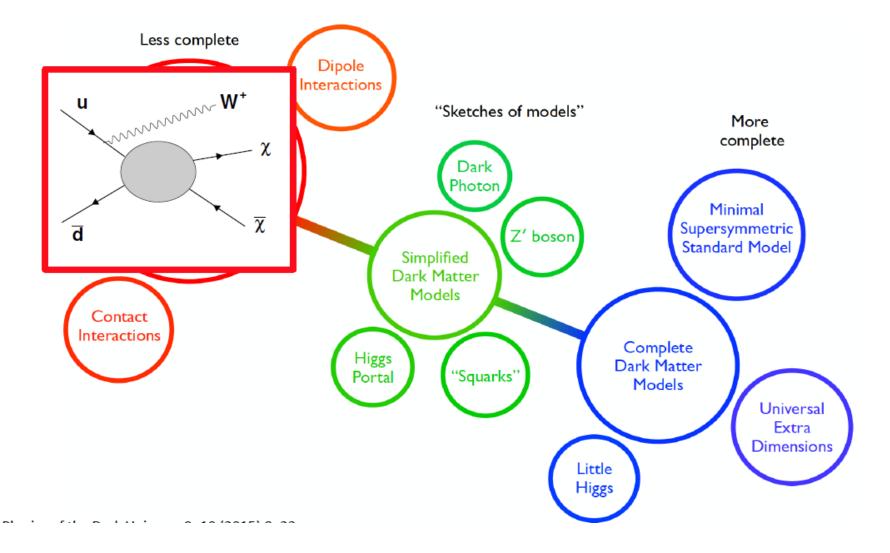


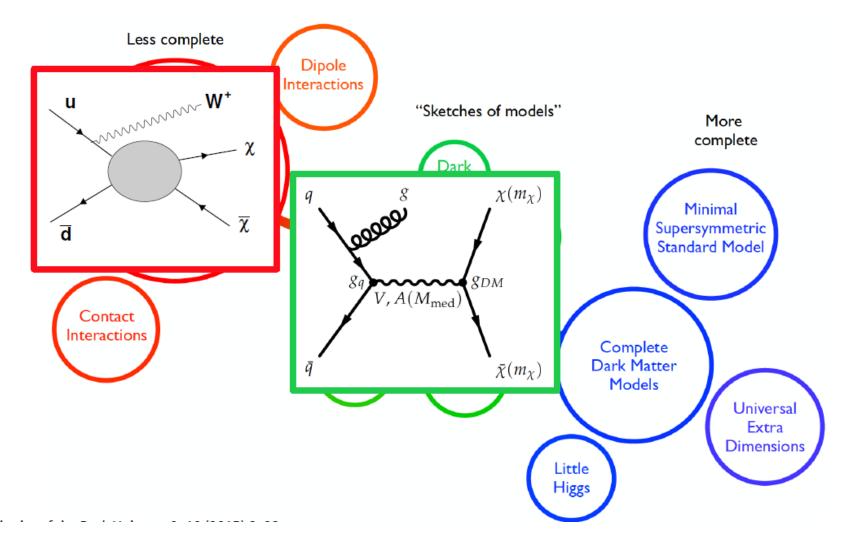
 g_q and g_χ coupling strengths

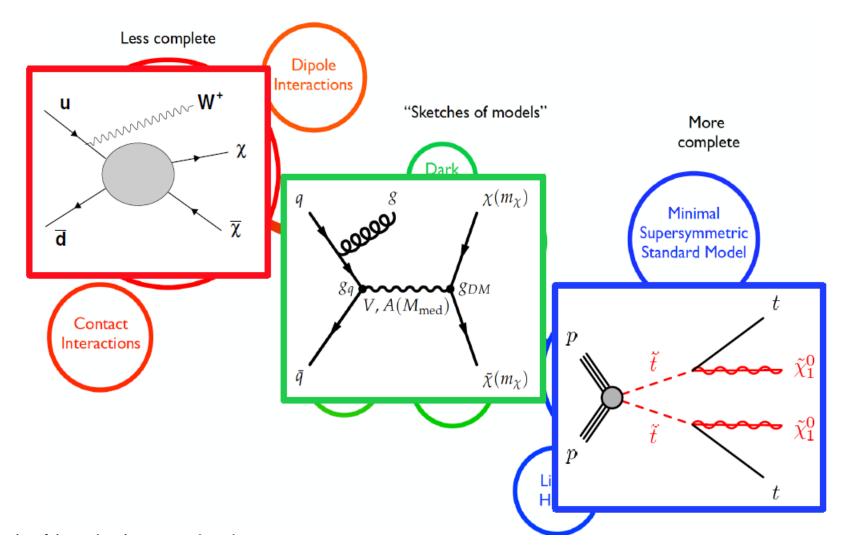


Empty detector + something

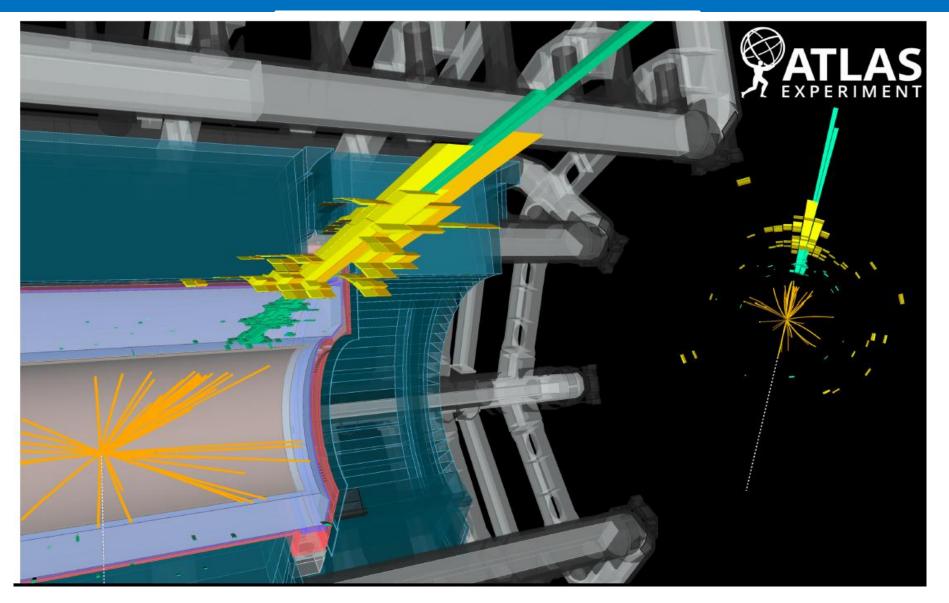






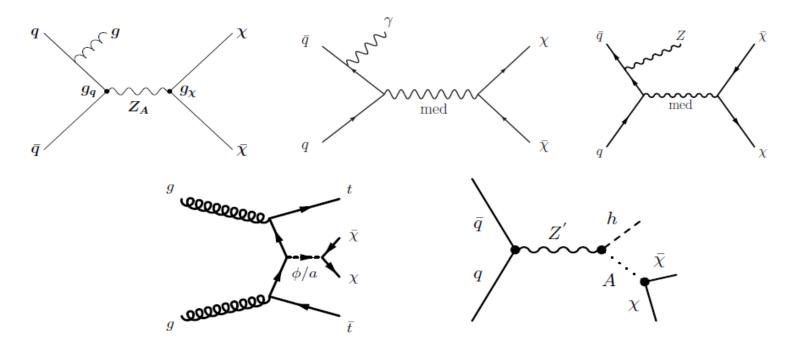


Searches for DM with (E_T^{miss} +X) Signatures



(E_T^{miss} +X) or Mono-X Signatures

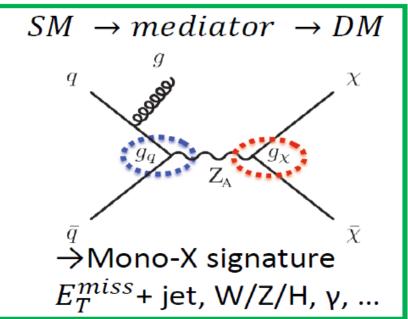
SM-DM mediator decays to DM pairs $\chi \bar{\chi}$ when $M_{\text{med}}/2 > m_{\chi}$. DM escapes detection $\Rightarrow E_T^{\text{miss}} + X$ signature where X = SM particles that tag the event, $X = \text{jet}, \gamma, V, t, b, h \dots$

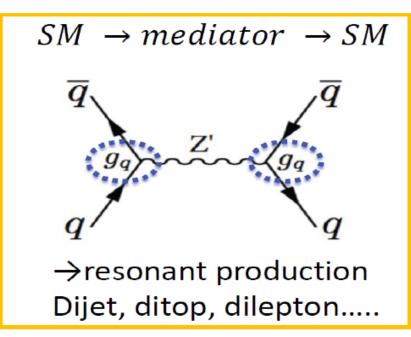


Mediators: vector, axial-vector, scalar, pseudoscalar Parameters: $m_{med}, m_{\chi}, g_q, g_{\chi}$

Simplified Model

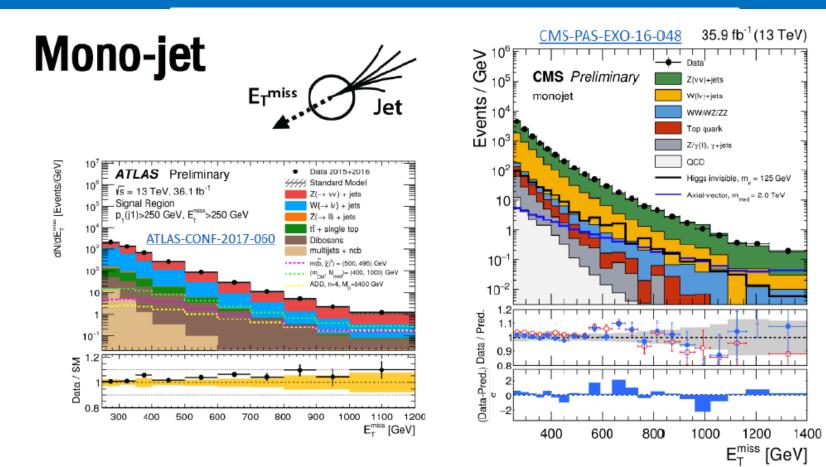
Simplified Model





	spin 0	spin 1					
Charge	Q=0 for s-channel						
Lorentz structure	Scalar $g_q \frac{\phi}{\sqrt{2}} \sum_f y_f \bar{f} f$ Pseudoscalar $g_q \frac{iA}{\sqrt{2}} \sum_f y_f \bar{f} \gamma^5 f$	Vector $g_q \sum_q V_\mu \bar{q} \gamma^\mu q$ Axial-vector $g_q \sum_q A_\mu \bar{q} \gamma^\mu \gamma^5 q$					
Coupling	∝ mass	∝ charge					

Mono-X searches



ATLAS

- $E_T^{miss} > 250 \text{ GeV}, \Delta \phi(\text{jet}, p_T^{miss}) > 0.4$
- * Jet $p_T > 250$ GeV, $|\eta| < 2.4$
- $N_{jets} \le 4$

CMS

- $E_T^{miss} > 250 \text{ GeV}$
- Jet $p_T > 100$ GeV, $|\eta| < 2.5$

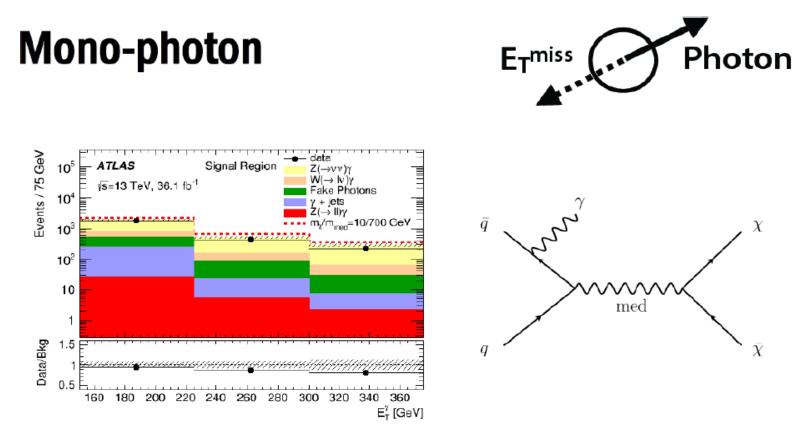
Mono-X searches

Axial-Vector Mediator Vector Mediator 35.9 fb⁻¹ (13 TeV) [/ab] ¹²⁰⁰ [Ge/] ^{MO} m m_{χ} [GeV] 10 Expected limit ± 2 σ_{exp} Observed $\sigma_{95\%} _{\text{CL}} / \sigma_{ ext{th}}$ CMS ATLAS 1000 Expected limit (± 1 σ_{exp}) Vs = 13 TeV, 36.1 fb⁻¹ Vector med, Dirac DM, $g_a = 0.25$, $g_{DM} = 1$ Observed limit (± 1 σ_{theory} Axial-Vector Mediator Dirac Fermion DM Perturbativity Limit ---- Median expected 95% CL g_n = 0.25, g_y = 1.0 Relic Density (MadDM) - ± 1 σ_{experiment} 800 95% CL limits ATLAS VS = 13 TeV, 3.2 fb⁻¹ Observed 95% CL Observed ± theory un 600 $\Omega_c \times h^2 \ge 0.12$ 500 400 10⁻¹ 200 10^{-2} 500 1500 2000 2500 1000 0 1000 2000 m_{med} [GeV] m_{Z₄} [GeV]

For couplings $g_q = 0.25$, $g_{\chi} = 1.0$, axial-vector and vector mediators excluded up to 1.8 TeV (1.55 TeV) by CMS (ATLAS) for $m_{\chi} \sim 1$ GeV.

JHEP 01 (2018) 126 arXiv:1712.02345

Mono-X searches

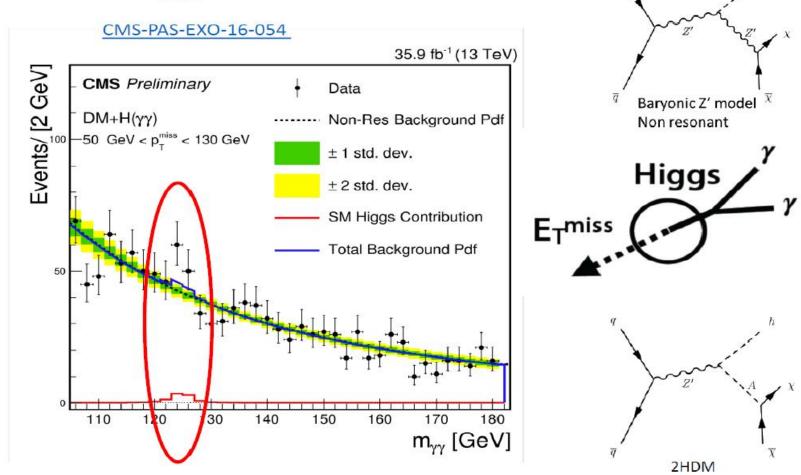


- Photon $E_T > 150$ GeV, $|\eta| < 2.37$
- $E_{\rm T}^{\rm miss} / \sqrt{\sum E_{\rm T}} > 8.5 \ {\rm GeV}^{1/2}$
- $\Delta \varphi$ (photon, E_T^{miss}) > 0.4
- $N_{jets}(p_T > 30 \text{ GeV}, |\eta| < 4.5) \le 1$

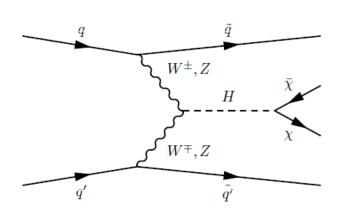
Mono-X searches

9

Mono-Higgs

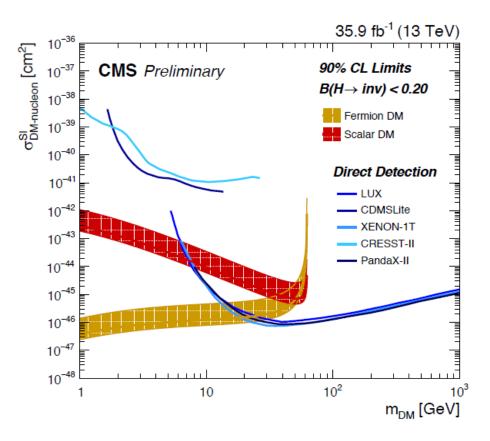


H-> invisible: Comparison with DD



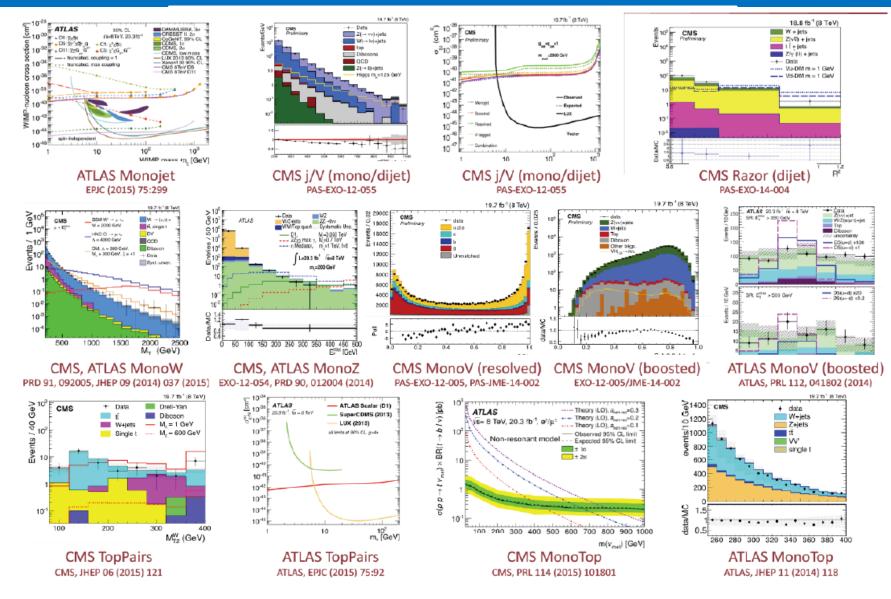
 $\mathcal{B}(H\rightarrow inv) < 0.2 \text{ at } 90\% \text{ CL}$ interpreted in context of Higgs-portal DM model.

Strongest limits for fermion (scalar) χ for $m_{\chi} < 20$ (7) GeV.

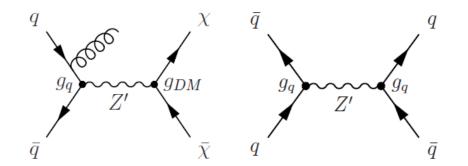


CMS-PAS-HIG-17-023 (14 March 2018)

Plenty of mono-signatures



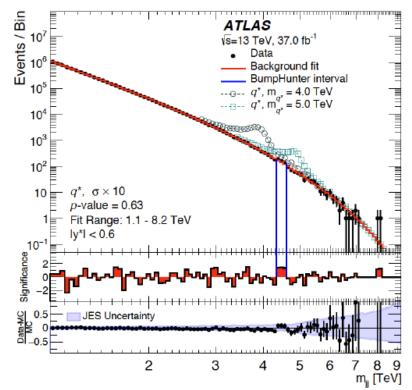
LHC is a mediator machine



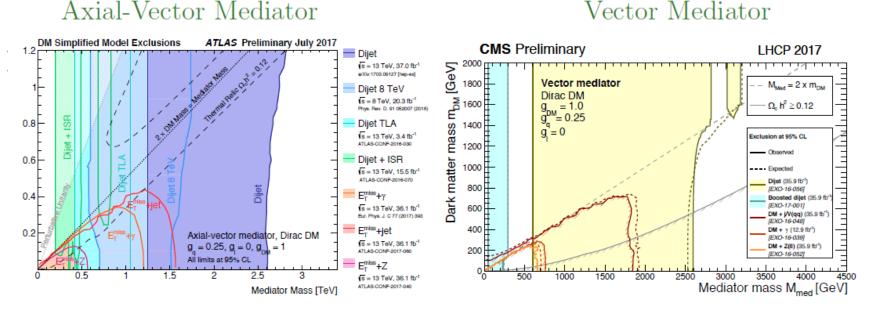
Signature: 2 high $p_{\rm T}$ jets, same as search for leptophobic Z'.

 m_{jj} is the discriminant, search for bump on a smooth, falling background.

Background modeled by a parameterized function.



Limits on DM mass vs Mediator mass



Couplings: $g_{\text{DM}} = 1$, $g_q = 0.25$, $g_l = 0$ (leptophobic)

Dijet searches significantly extend DM reach, particularly for $m_{\rm DM} > M_{\rm med}/2$. Limits are same as leptophobic Z' search.

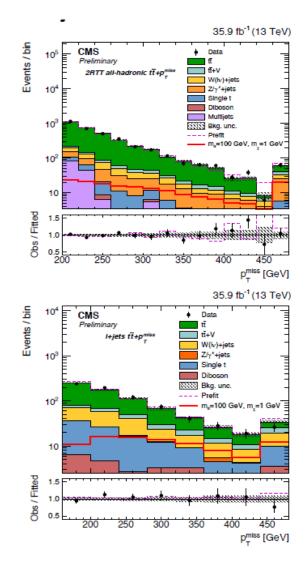
Mediator masses excluded up to about 2.6 TeV for low m_{χ} .

Search for DM + Heavy Flavor

 $(t\bar{t} + \chi\bar{\chi})$ discriminant is $p_{\rm T}^{\rm miss}$.

SRs based on $t\bar{t}$ decays: all-hadronic, ℓ + jets, dileptonic provide complementary sensitivity.

 $t\bar{t}, W + jets, Z + jets$ backgrounds constrained by CRs.

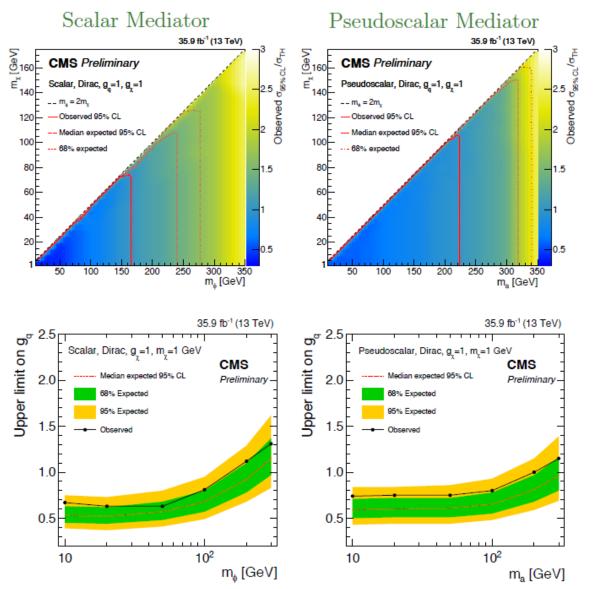


Search for DM + Heavy Flavor

For $g_q = 1$, $g_{\text{DM}} = 1$, $m_{\chi} = 1$ GeV: exclusion for $m_{\phi} < 165$ GeV and $m_a < 223$ GeV.

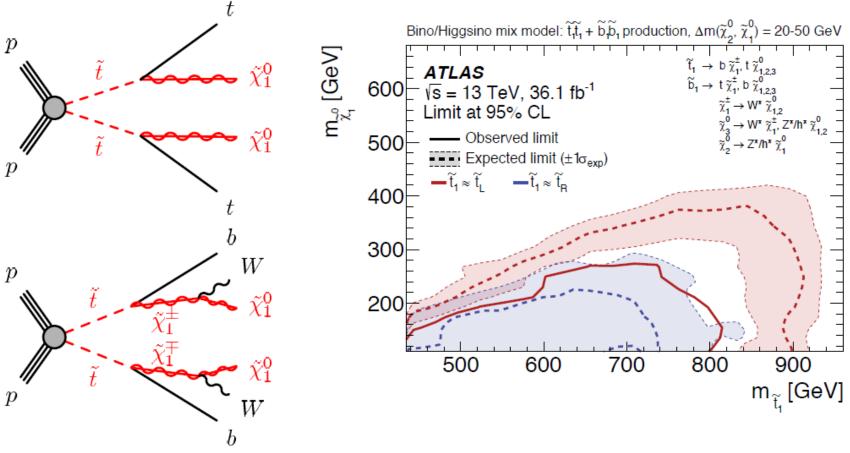
CMS-PAS-EXO-16-049 (3 April 2018)

For $g_{\text{DM}} = 1$, $m_{\chi} = 1$ GeV: limits on coupling of ϕ or ato SM quarks.

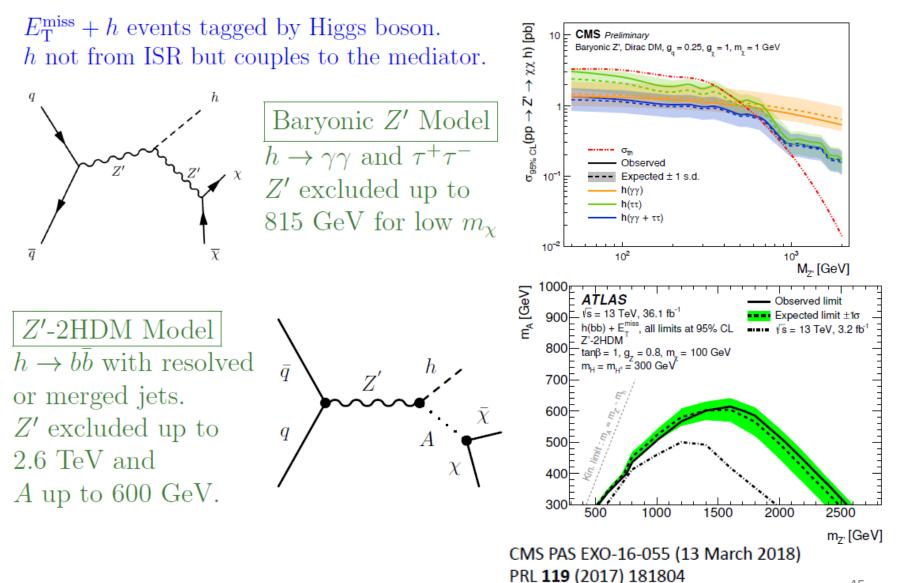


SUSY DM candidates

In many SUSY models the LSP is stable and weakly interacting \Rightarrow a DM candidate. Some models are tuned to reproduce the DM relic density, e.g. the "well tempered neutralino" scenario.



Search for DM + Higgs

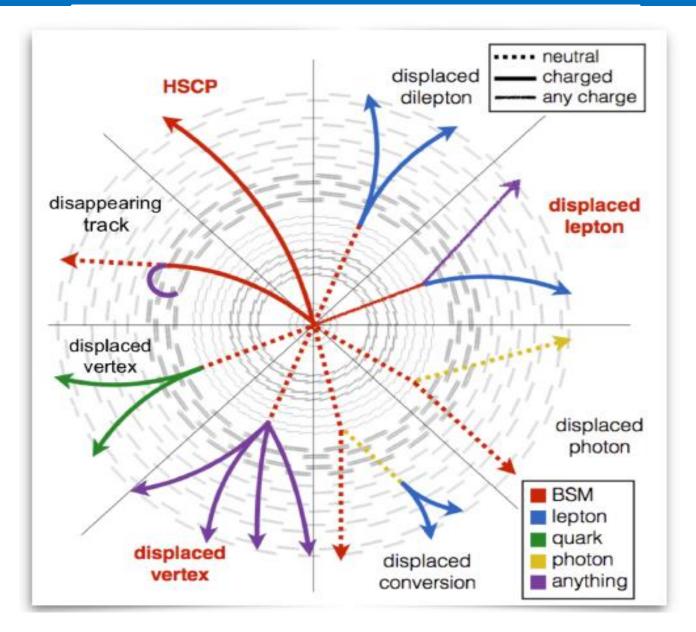


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Outlook for DM searches

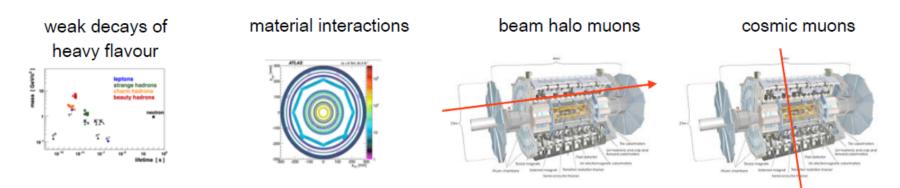
- Experiments at the LHC are actively searching for DM
 - Sensitivity to DM under many model assumptions for the interaction and mediator
- No evidence for DM so far but there is much more phase space to be explored
- Outlook for DM Searches
 - Small fraction of total LHC data set in hand to date
 - New analysis techniques continuously being developed
 - New directions: models and signatures
- LHC is just getting started with DM searches

Unconventional signatures



Unconventional signatures: challenges

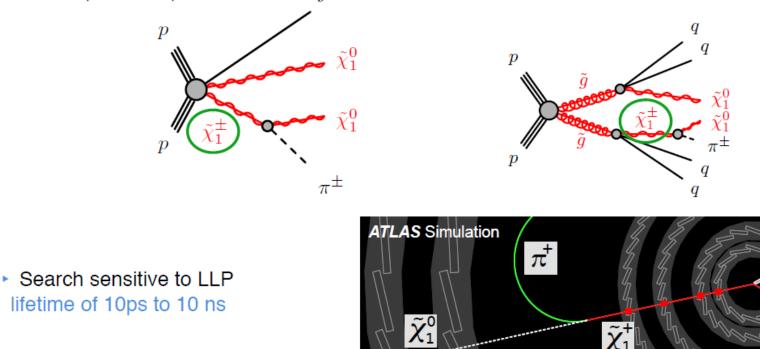
- Trigger: combination of hardware + software that must decide very quickly whether to save an event or lose it forever
 - First step in every search for LLPs: make sure that interesting events are saved!
 - 1. In associated production, trigger on prompt particle (Eg. WH prod. trigger on mu; ISR trigger on MET)
 - 2. Design and develop a new trigger. Need to keep trigger rates under control and within budget
- Object identification algorithms assume prompt particles. Need to adapt them
- Backgrounds: usually instrumental background such as miss-identified leptons ("fakes") and non-collision backgrounds (NCB) have to be taken into account



> Systematic uncertainties: can't use standard recommendations for object reconstruction nor trigger

Unconventional signatures: disapearing tracks

- Search for disappearing track + MET + jets
- Signature: Chargino track "disappears" when it decays, into MET
 - Low momentum pion track (~0.1 GeV) is hard to reconstruct
 - Challenge to identify the legitimate real tracklets (non-fake) using only a few measurement tracks
- Benchmark model: AMSB model with almost degenerate neutralino and chargino Δm ~ O(100 MeV)



LLP

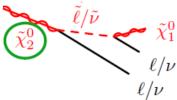
Unconventional signatures: stopped particles

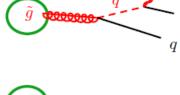
- Search for stopped LLPs decaying during non-collision bunch crossings (BX)
- Signature: LLPs come to rest in the detector and decays after the current BX
 - most likely to stop in the densest detector materials:
 - Calorimeters (ECAL, HCAL):
 - a) Split SUSY: two-body and three-body decays of a gluino
 - b) top squark decay

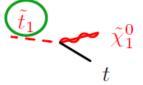
- Steel yoke in the muon system:
 - a) three-body decay of the gluino (g \rightarrow qq $\chi_2,\,\chi_2$ \rightarrow μ μ χ_1)
 - b) MCHAMPs, with charge IQI = 2e decays into two same-sign muons (MCHAMP → μ±μ±)

 ^(μ/i)

Search sensitive to wide range of LLP lifetime: 10-5 to 106 s







Summary (Exotic Searches)

Searches for Exotic searches

- All major search channels reached 1 TeV scales
- Quite a few at 10 TeV
- New probe: Higgs boson → emerging field
- Dark Matter Searches are thriving at the LHC
- For vector and axial vector interactions
 - Dark Matter masses up 400 GeV 700 GeV (mono-jet) excluded
 - Mediator mass up to 1.6 1.8 TeV (mono-jet) excluded
 - Mediator mass up to 1.2 TeV (mono-photon) excluded
 - Mediator mass up to 0.7 TeV (mono-Z) excluded
- LHC searches complement DD experiments
 - m_{DM} < O(10 GeV)

Glimpse at Future Hadron Collider

The candidate machines in a tiny nutshell

Project	HL-LHC	HE-LHC	FCC-hh	SppC
Location	CERN	CERN	CERN	China TBD
Circ.	27 km	27 km	100 km	55 - 100 km
COM energy	14 (15?) TeV	27 TeV	100 TeV	70 -140 TeV
Luminosity	3 ab-1	15 ab-1	20-30 ab-1	TBD
PU	up to 200	up to 800	up to 1000	TBS
Bunch sp.	25 ns	25 ns	25 ns	25 ns
Field	8T	16T	16T	20T
When?	Until 2037	After 2037?	After 2037	TBS

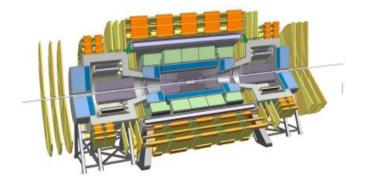


Much much more in Lecture by R. Corsini

- Detector, Trigger DAQ, Reconstruction challenges Two challenges: higher PU (1000) higher pT
 - Answer: granularity and resolution

Decay products of a Z at 10 TeV are separated by $\,\Delta R=0.01\,$

A b at 5 TeV can travel 50cm and a tau 10 cm



Glimpse at Future Hadron Collider

Numbers given here for FCC-hh and HL-LHC physics potential of HE-LHC is under study, however rule of thumbs scaling can give a fair estimate.

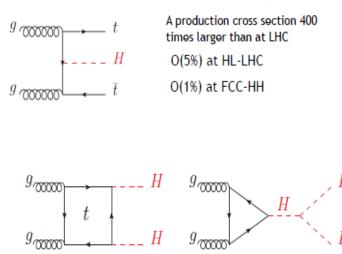
Direct searches

The reach in searches will range typically between a few TeV for weakly produced particles and reach 20 TeV for strongly interacting new particles as gluinos.

Precision SM and Higgs

- Precision EW measurements could reach unprecedented levels of accuracy with very high luminosity programs at the Z peak, the WW threshold and the tt threshold (MeV precision on the W mass, and tens of MeV on the top mass).

- Precision Higgs measurements will rely on a very complementary electron-positron collider which should reach sub percent level precision on most couplings (as well as measuring the total width of the Higgs boson) - Complementarity with the ee collider program



Precision reach at HL-LHC O(100%) O(3%) at FCC-HH

Precision SM and Higgs

High energy FCC is a natural environment for measurements of SM processes, which will have first been measured at the HL-LHC.