LHC Physics (SUSY/BSM II)

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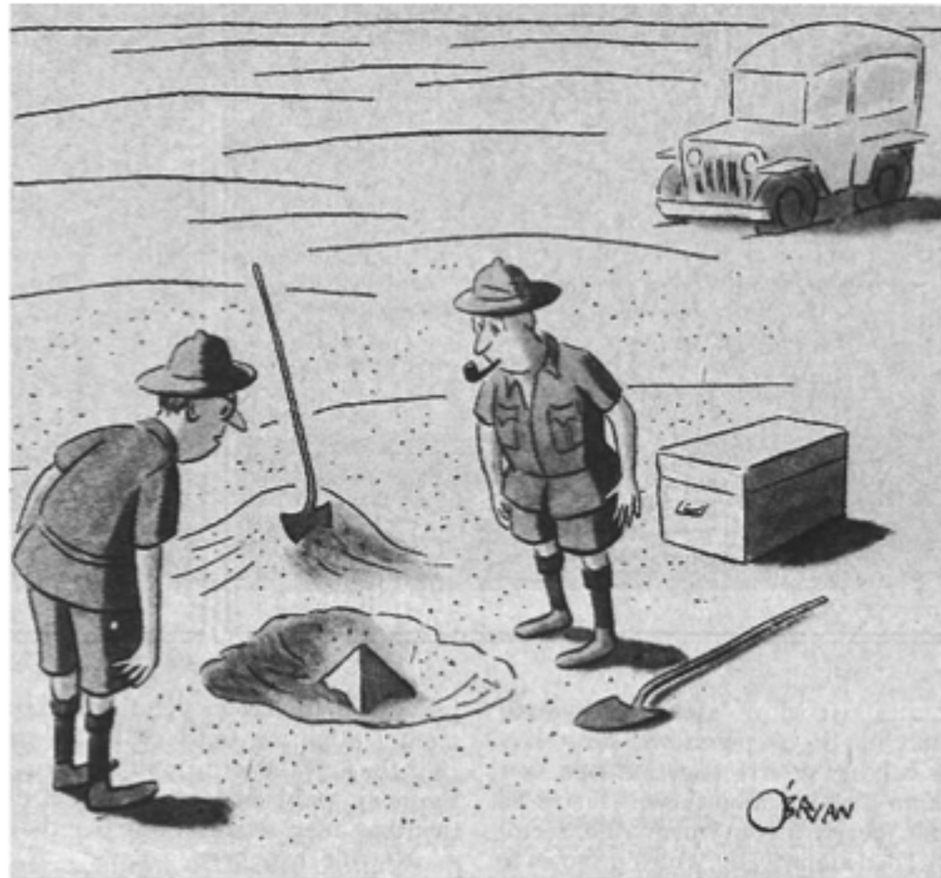
TAE, Benasque, September 2018

Outline for Part IV

- **SUSY/DM Searches**
- **Exotics**
  - **New bosons**
  - **Excited leptons**
  - **Extra dimensions**
  - **New resonances**
  - **Vector-like quarks**
  - **Leptoquarks**
  - **Other Exotica**
  - **……**
- **Future Prospects**



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

Disclaimer: completely unbalanced set of results from CMS and ATLAS
No attempt to have latest results

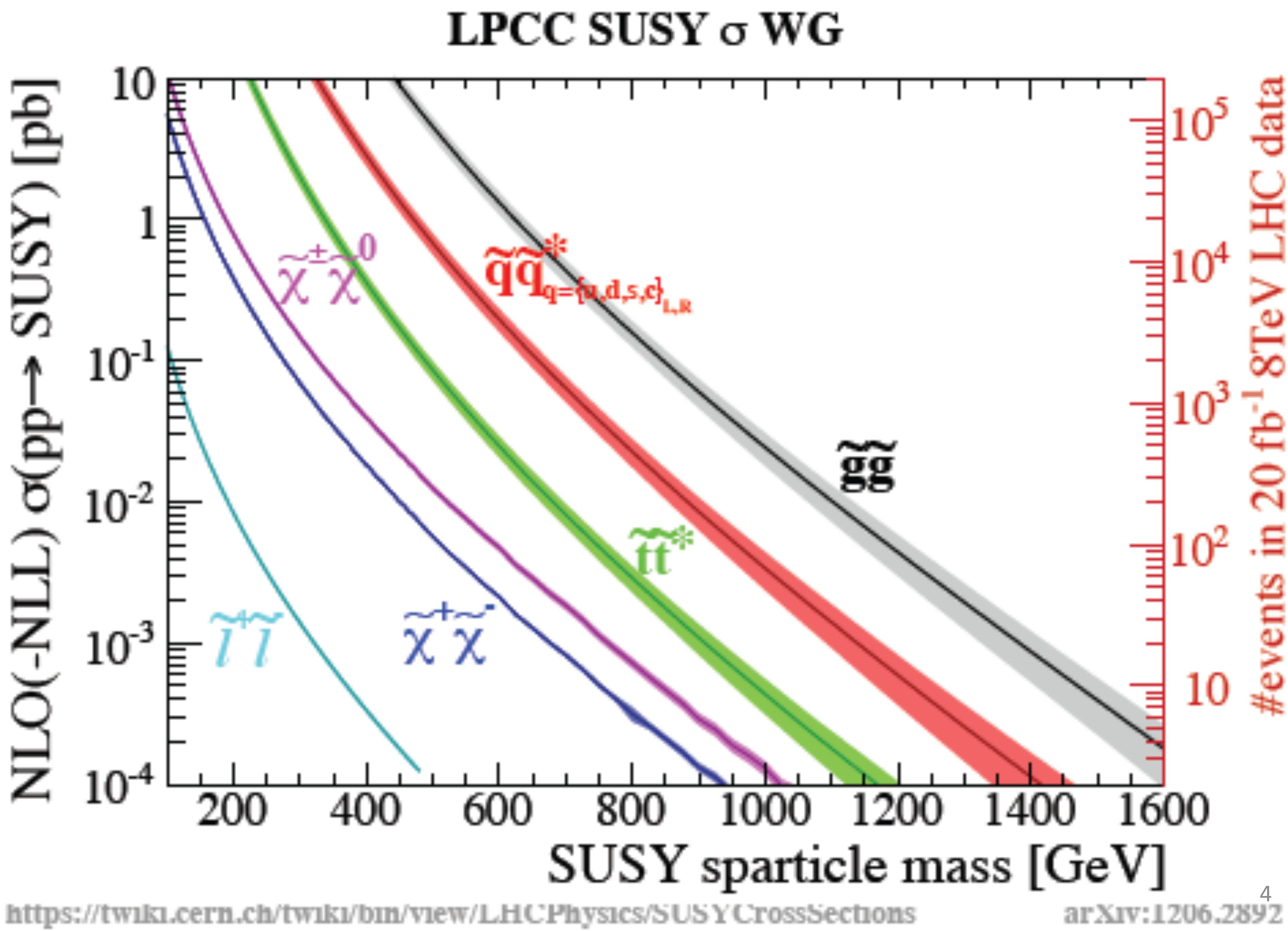
SUSY Searches

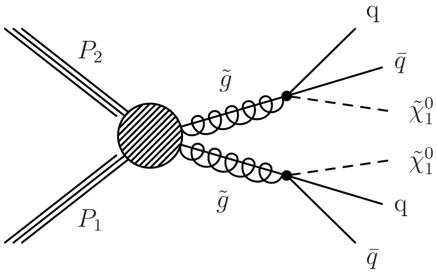
Inclusive searches

3rd generation squarks

EWK searches

SUSY Cross Sections @ LHC (8 TeV)

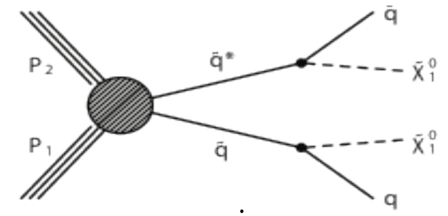




Inclusive Searches

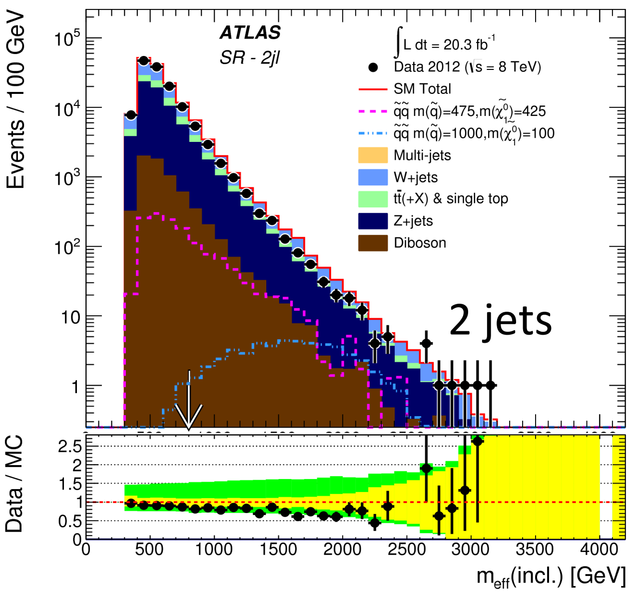
Multiple-jets and large E_T^{miss}

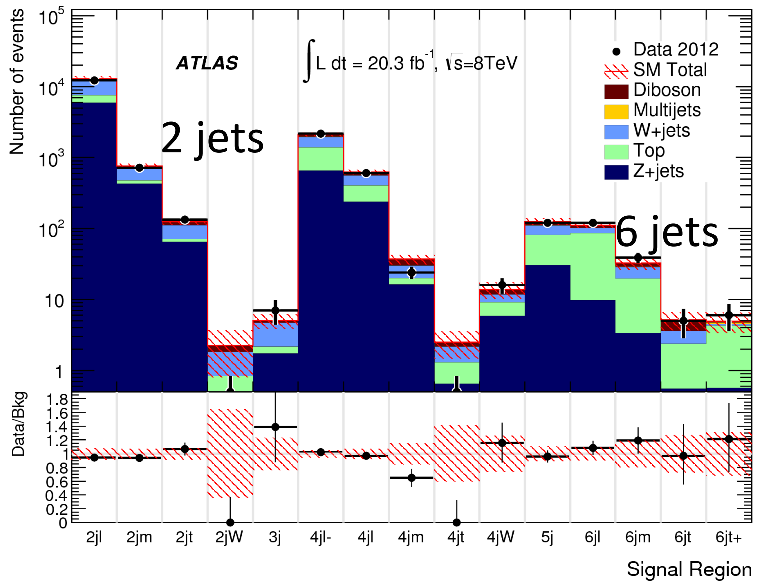
[JHEP09(2014)176]



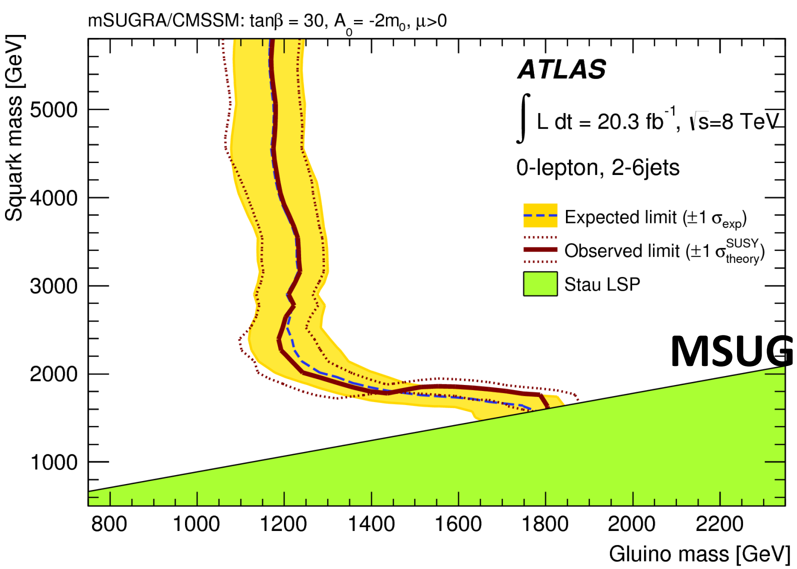
$$m_{eff} = E_T^{miss} + H_T$$

$$H_T = \sum_{jets} p_T$$



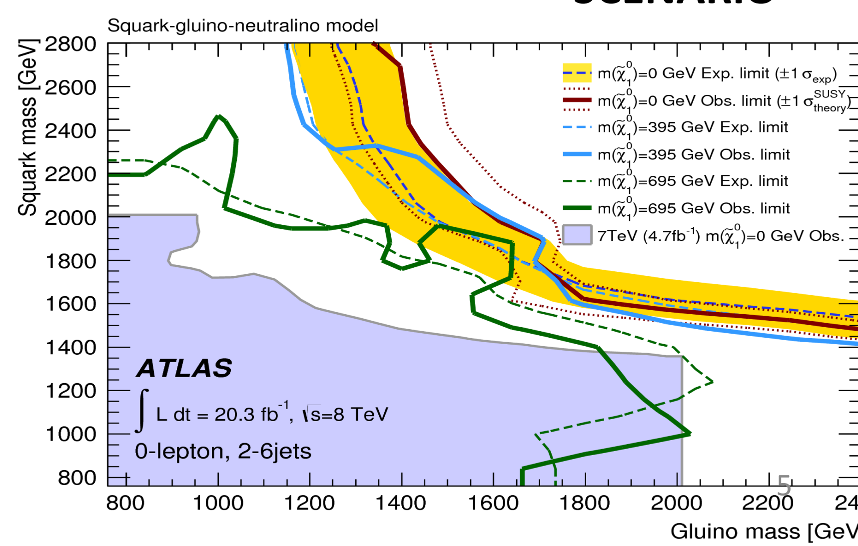


Background from 1 lepton b-tag/veto & photon CRs with similar jet and kinematic selections as in SRs

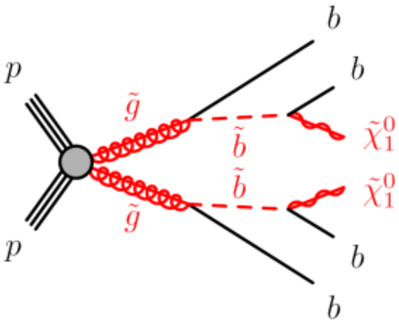


MSUGRA

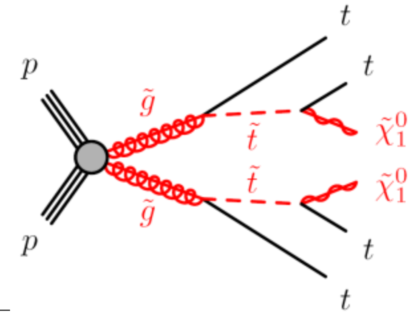
SIMPLIFIED SCENARIO



JHEP 10 (2014) 024



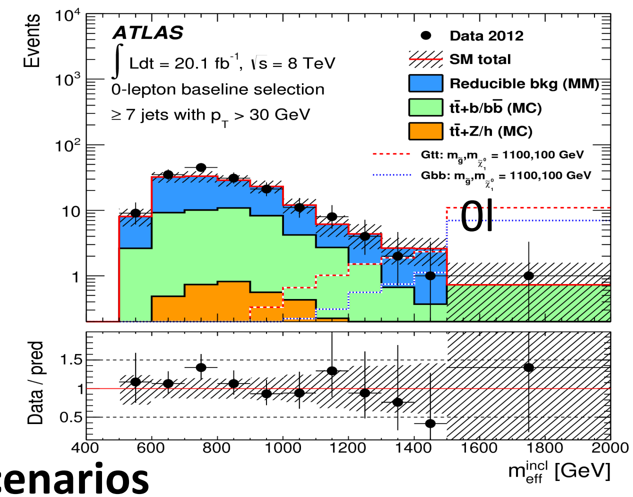
Gluino-mediated
Stop/Sbottom Production

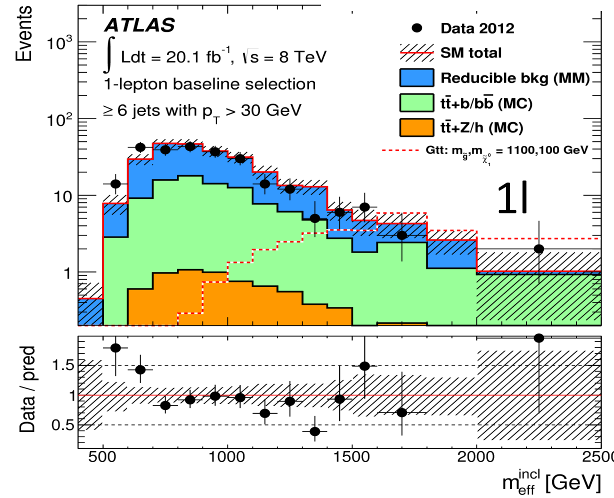


0/1 lepton + 3b-jets + E_t^{miss}

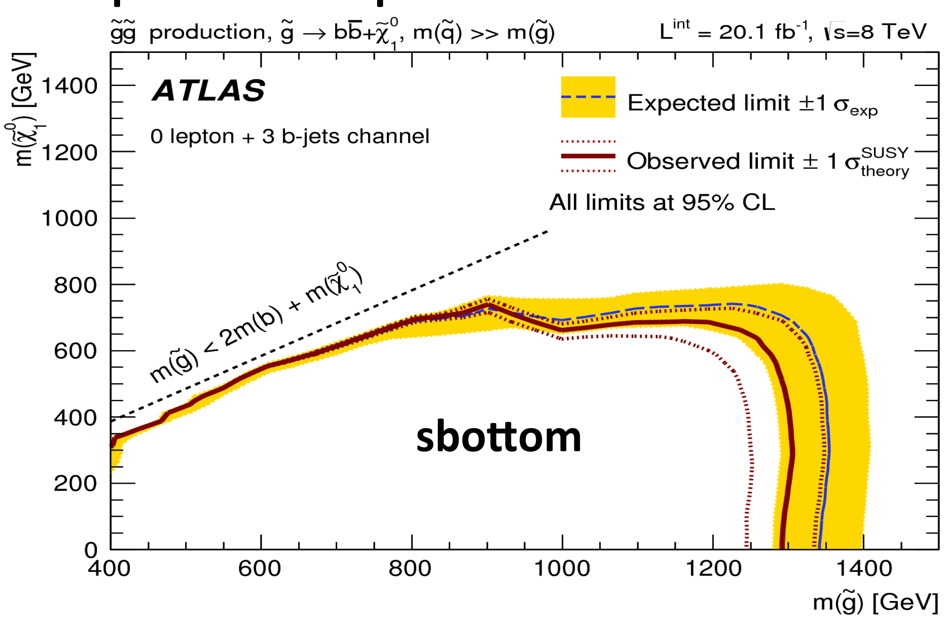
Background dominated by tt+bb, tt+V and tt+fakes

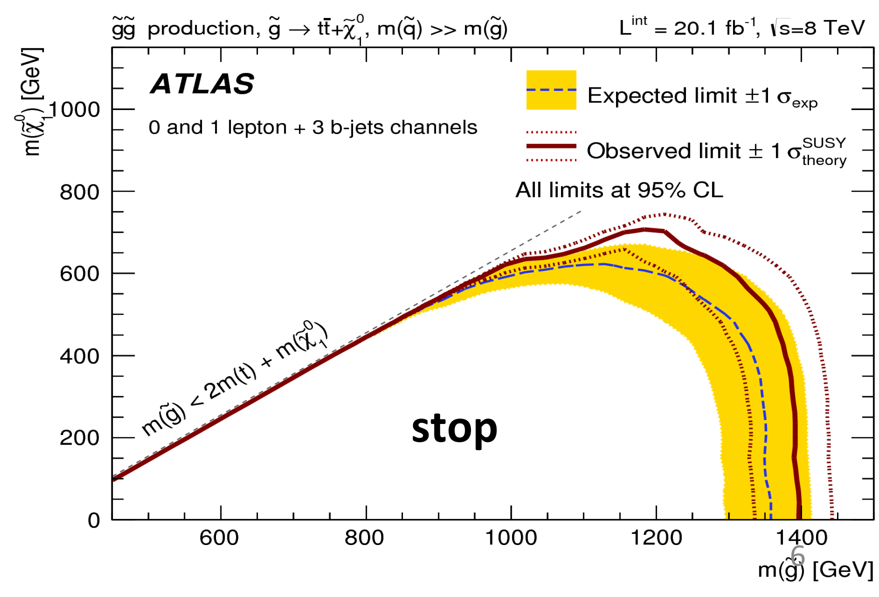
most powerful for very heavy gluinos





Interpreted in simplified scenarios

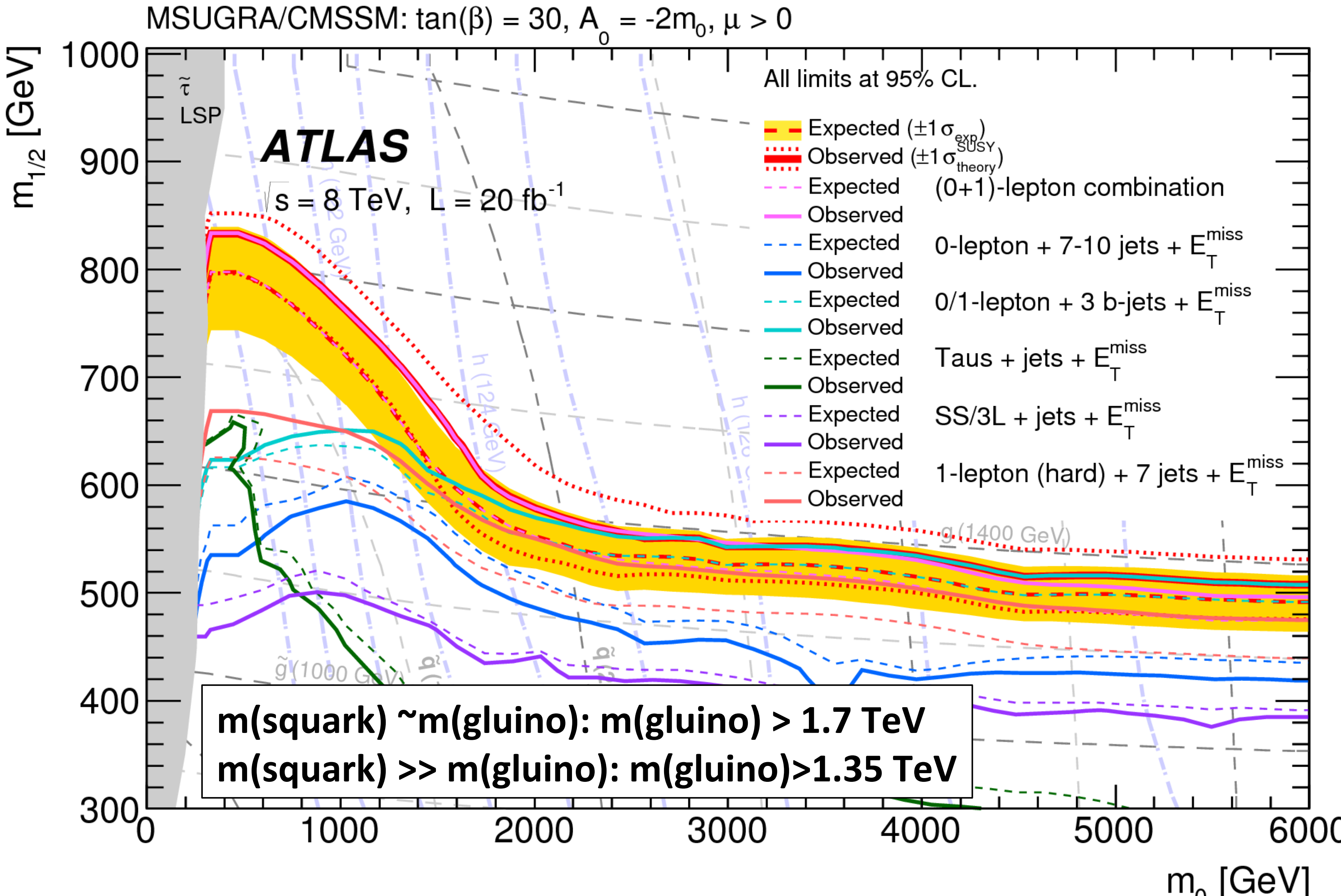




MSUGRA Scenario

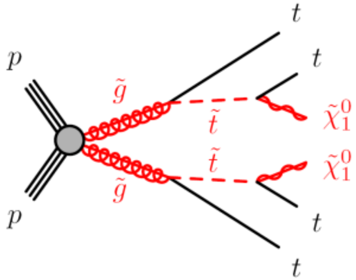
arXiv:1507.05525

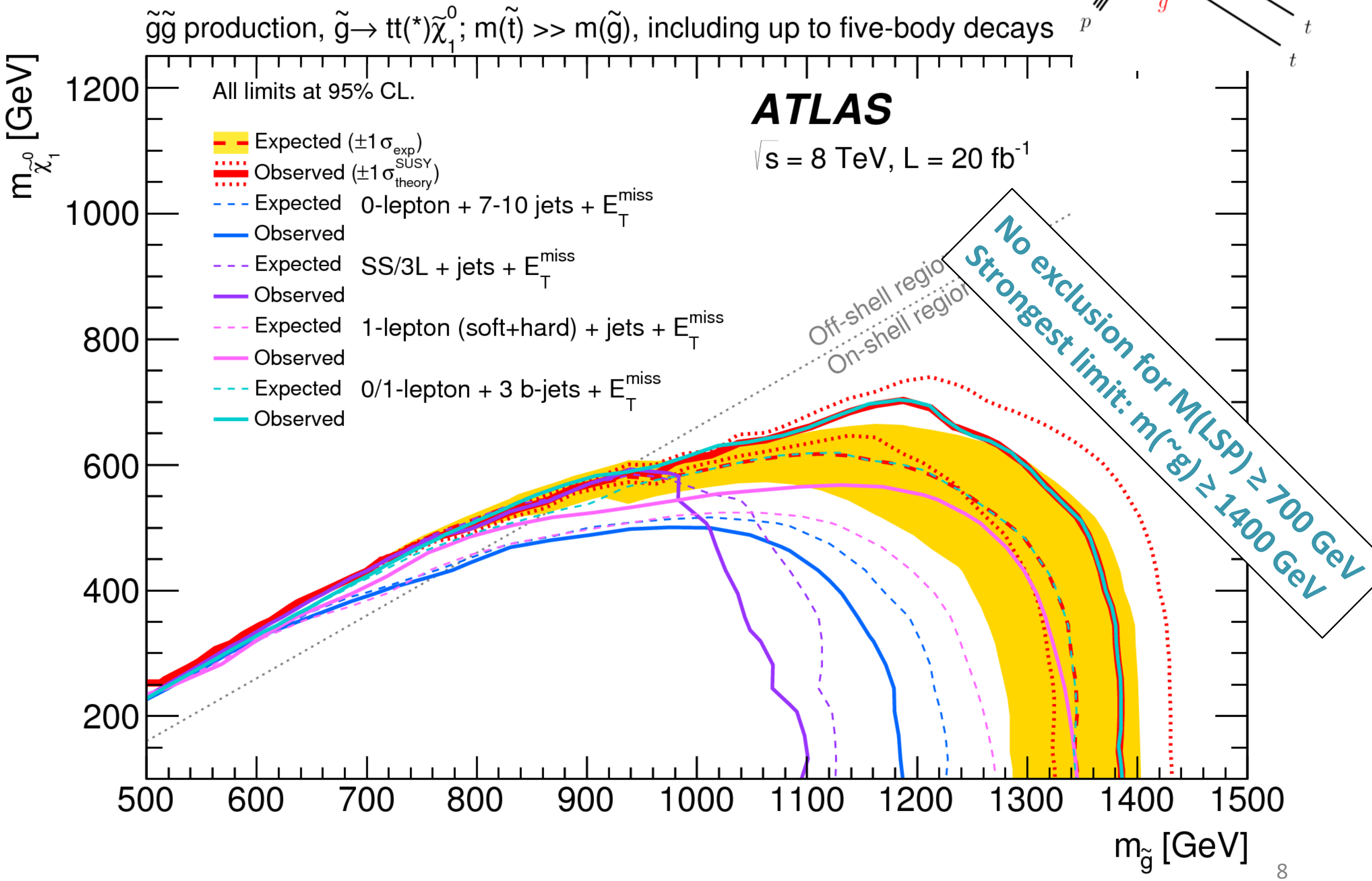
Run-1 summary on inclusive squark and gluino searches



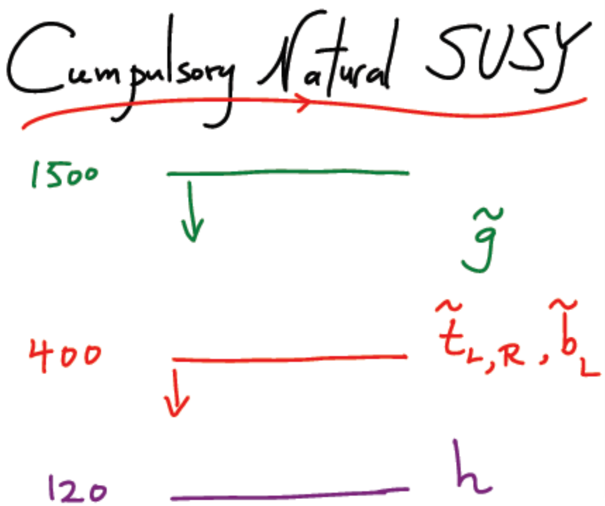
Part of the model plane accommodates a lightest neutral scalar Higgs boson mass of 125 GeV [arXiv:1507.05525](https://arxiv.org/abs/1507.05525)

Simplified model



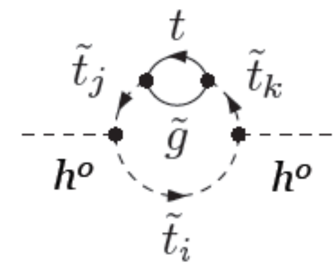


"Natural SUSY 2012"



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

N. Arkani-Hamed talk at CERN Oct. 2012



$$\frac{m_H^2}{2} = -|\mu|^2 + \ldots + \delta m_H^2$$

$$\delta m_H^2\Big|_{stop} \cong -\frac{3y_t^2}{8\pi^2}\left(m_{Q_3}^2 + m_{U_3}^2 + |A_t|^2\right)\ln\left(\frac{\Lambda}{TeV}\right)$$

$$\delta m_H^2\Big|_{gluino} \cong -\frac{2y_t^2}{\pi^2}\left(\frac{\alpha_s}{\pi}\right)|M_3|^2 \ln^2\left(\frac{\Lambda}{TeV}\right)$$

$$\begin{pmatrix} \tilde{t}_1 \\ \tilde{t}_2 \end{pmatrix} = \begin{pmatrix} \cos\theta_t & \sin\theta_t \\ -\sin\theta_t & \cos\theta_t \end{pmatrix} \begin{pmatrix} \tilde{t}_L \\ \tilde{t}_R \end{pmatrix}$$

→ Light higgsinos

→ Light stop (t_1 < 1 TeV)

→ Light gluinos (< 1-2 TeV)

One light stop and sbotton ….rest of sparticles can be decoupled….

$$\begin{pmatrix} \tilde{t}_L \\ \tilde{b}_L \end{pmatrix} \quad \tilde{t}_R \quad \tilde{b}_R$$

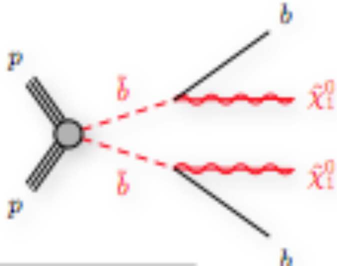
(same weak isospin multiplet)

Direct Stop/Sbottom

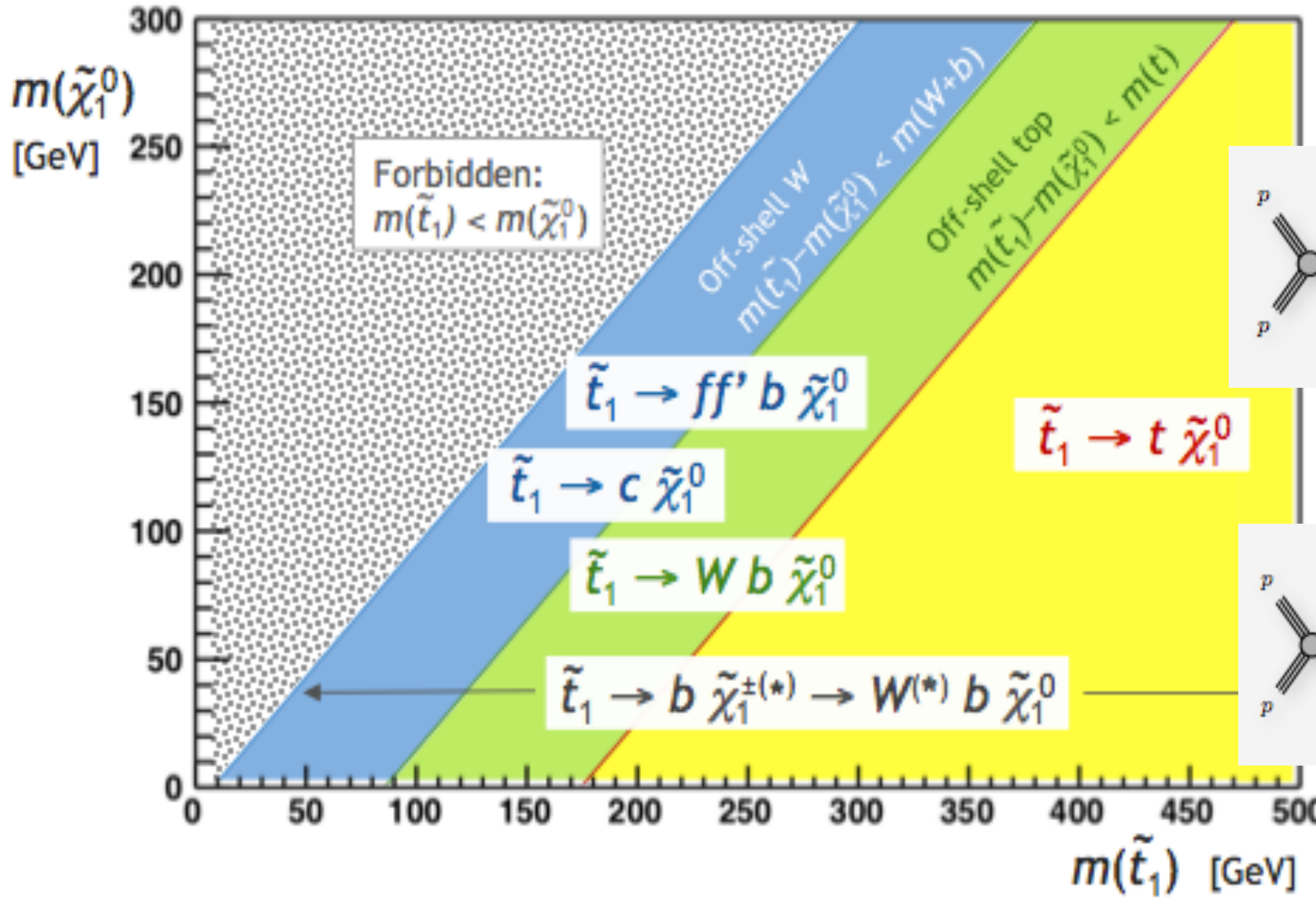
$\tilde{b}_1 \rightarrow b\,\tilde{\chi}_1^0$

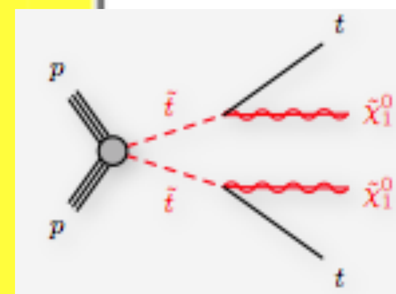
$\tilde{b}_1 \rightarrow t\,\tilde{\chi}_1^\pm$

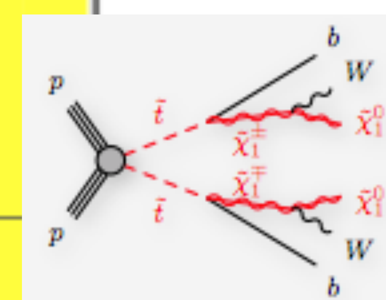
$\tilde{b}_1 \rightarrow b\,\tilde{\chi}_2^0 \rightarrow b\,h(Z)\,\tilde{\chi}_1^0$



In the scenario with TeV gluinos / squarks (1st/2nd generations)
All the attention is put now in searches for stop/sbottom
Multiple channels according to the decays



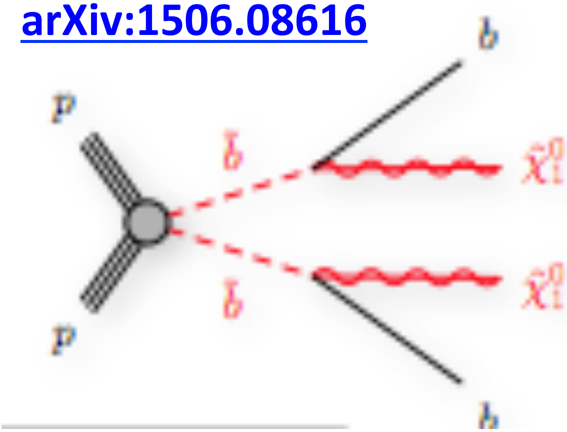




JHEP 10 (2013) 189

arXiv:1506.08616

Sbottom Direct Production

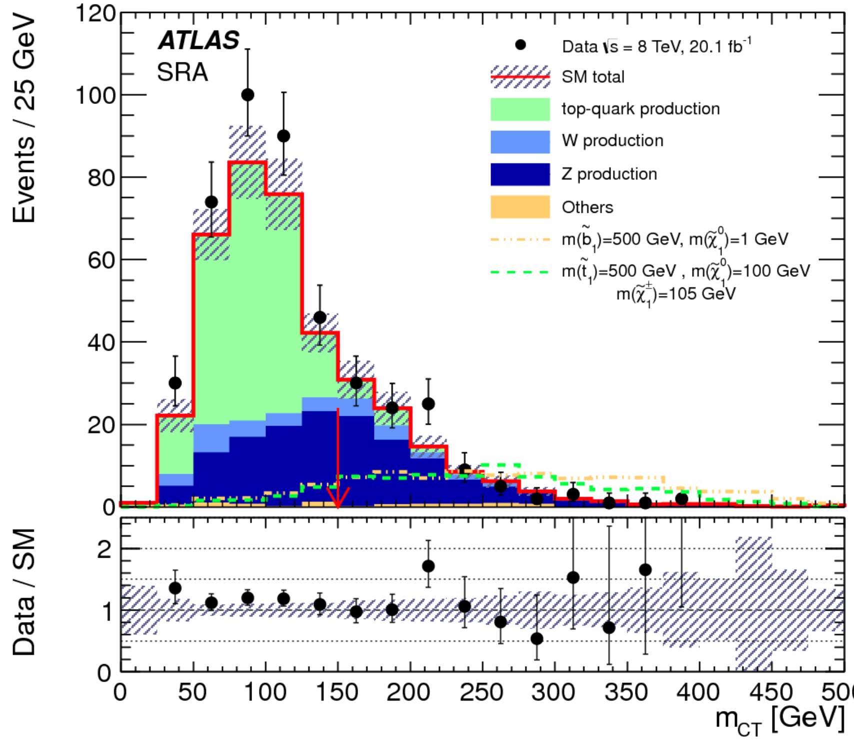


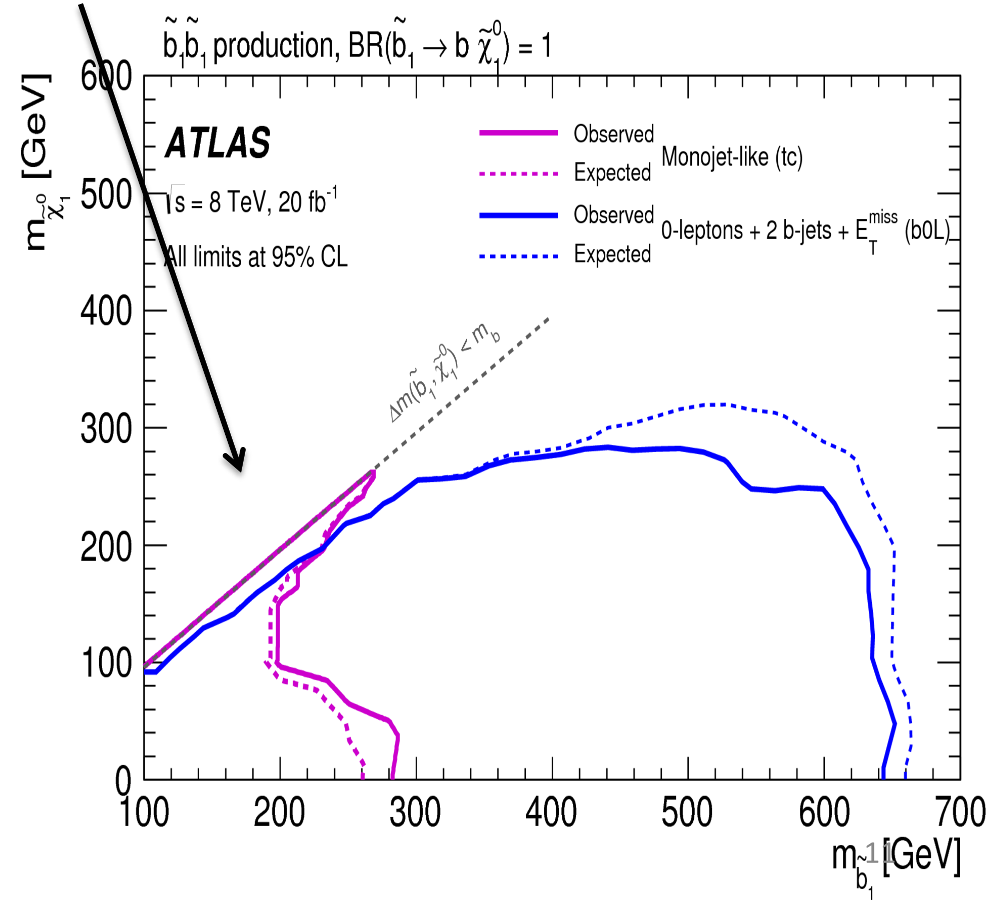
Large E_T^{miss} and 2 b-jets

Discriminating variable MCT

Additional selections to target also compressed scenarios (assisted with ISR jets)

$$m_{\mathrm{CT}}^2(v_1, v_2) = [E_{\mathrm{T}}(v_1) + E_{\mathrm{T}}(v_2)]^2 - [\boldsymbol{p}_{\mathrm{T}}(v_1) - \boldsymbol{p}_{\mathrm{T}}(v_2)]^2$$

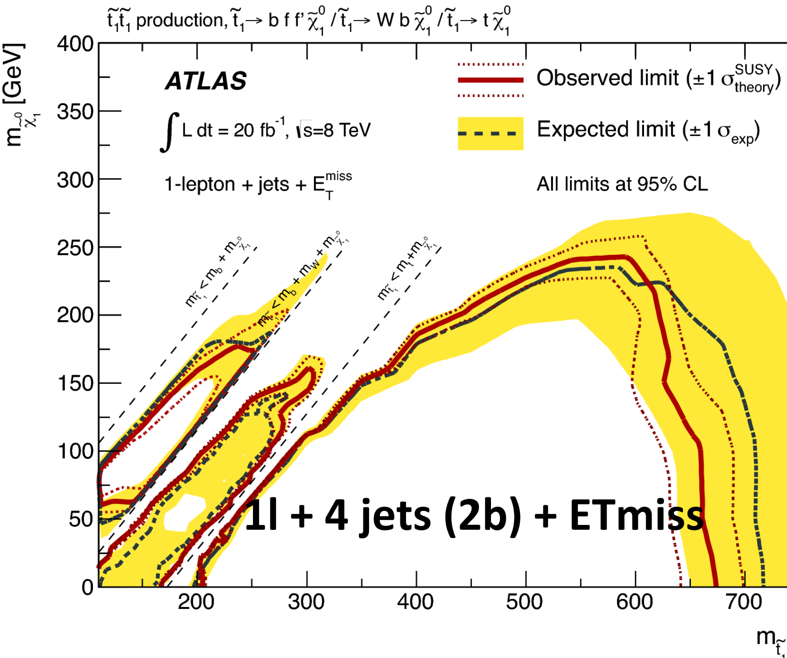


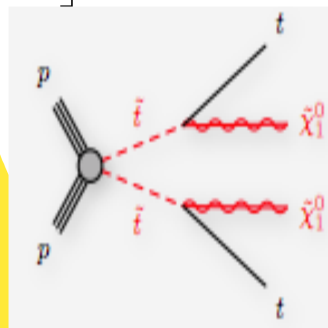


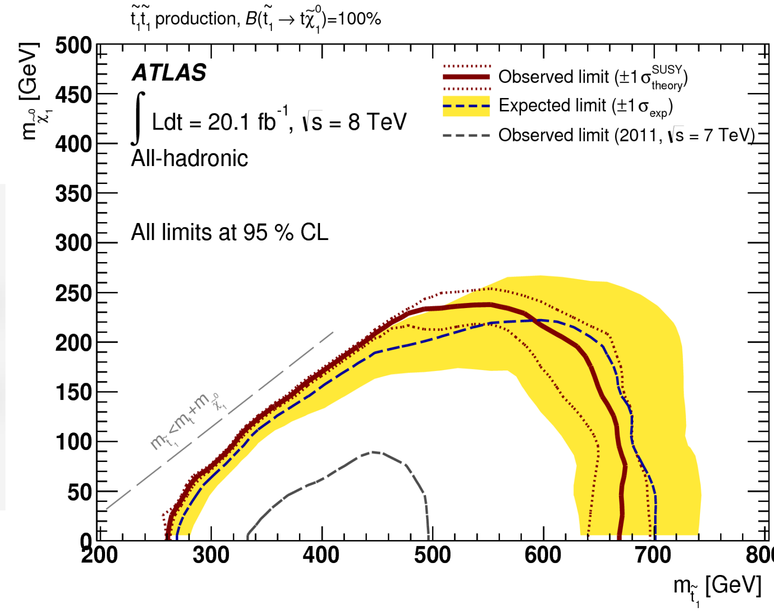
JHEP11(2014)118

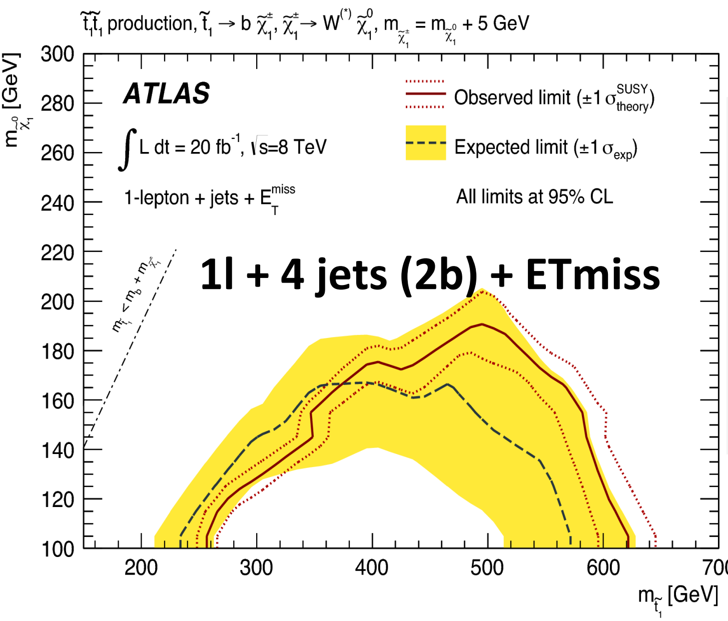
Direct Stop

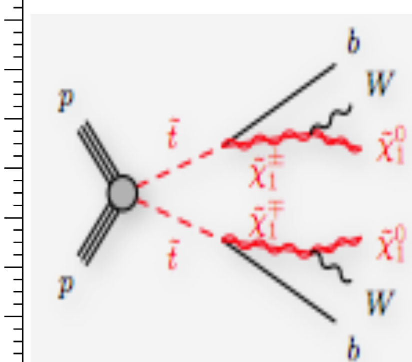
JHEP 09 (2014) 015

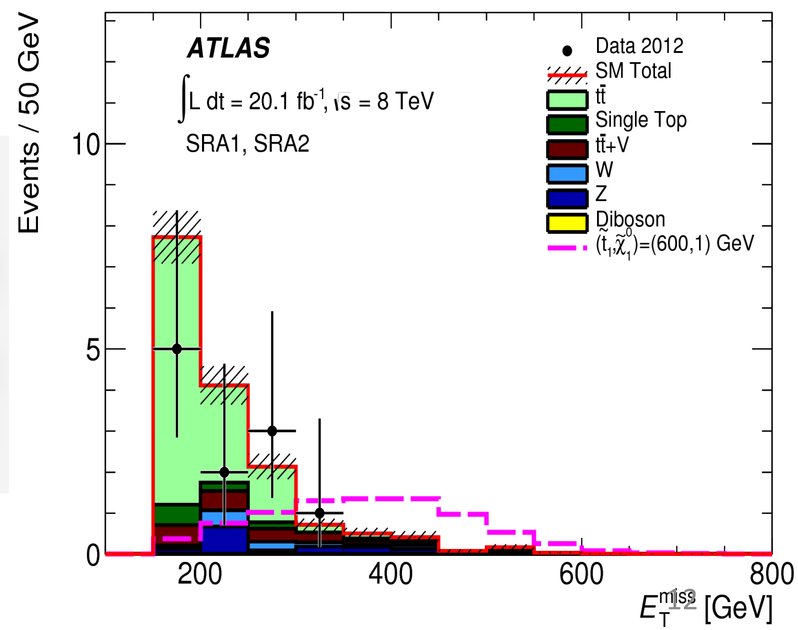












[Phys. Rev. D. 90, 052008 (2014)](#)

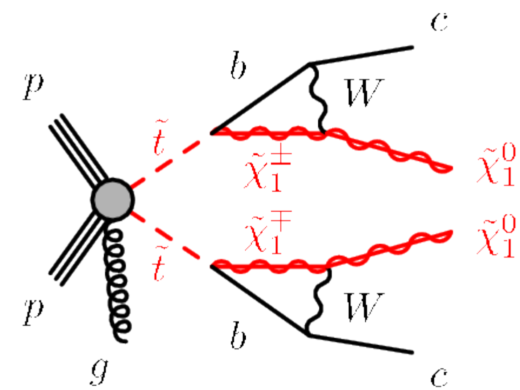
Direct Stop

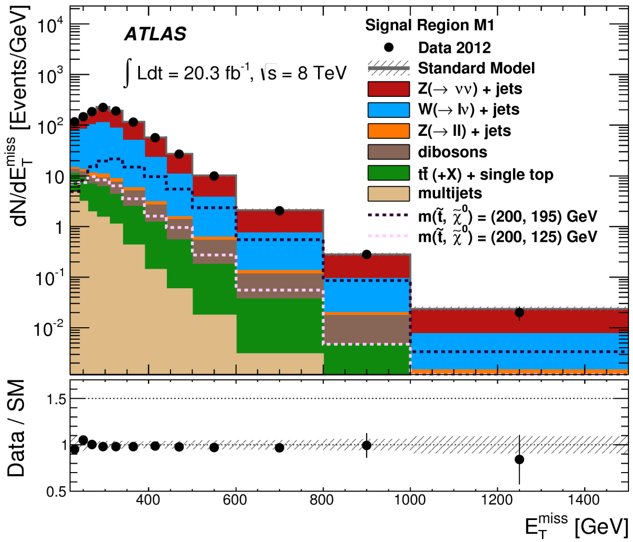
Two selections:

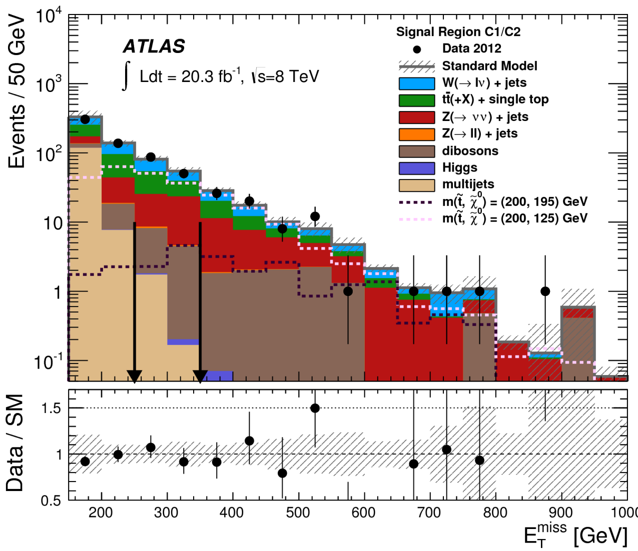
Monojet for compressed scenario

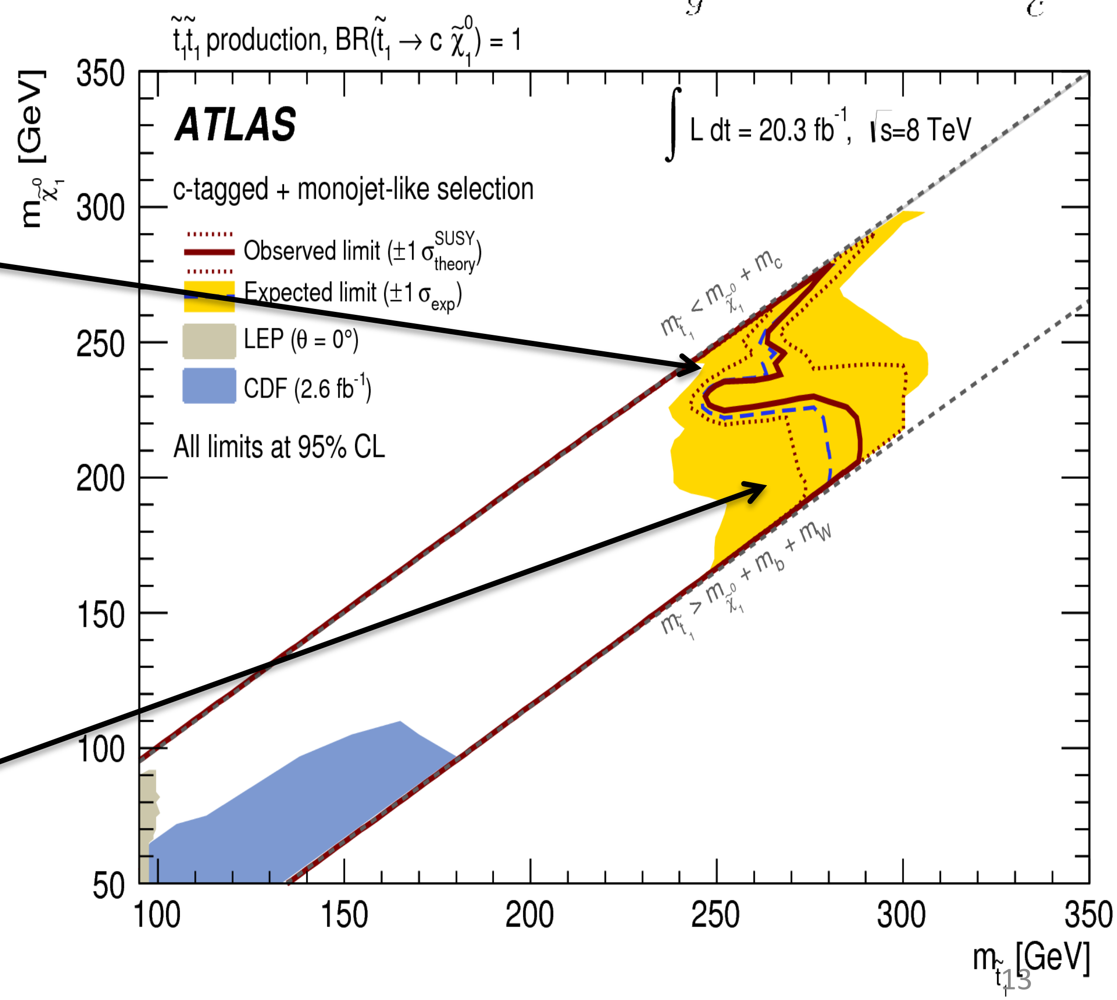
Large E_T^{miss} and c-jets

Very light stop

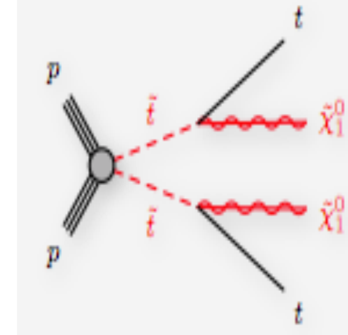






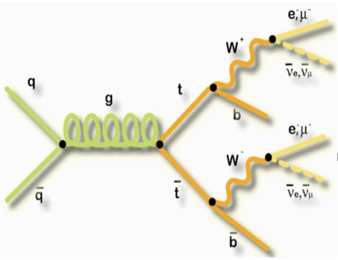


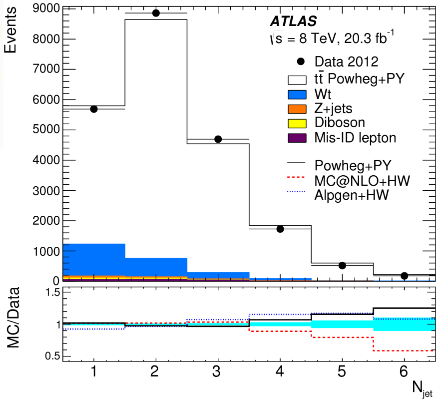
Eur. Phys. J. C74 (2014) 3109



Further stop constrains

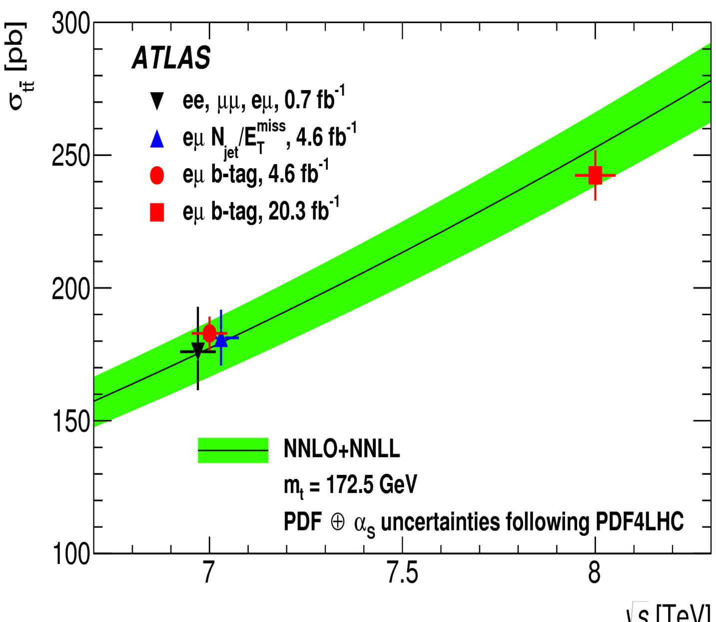
(using the top cross section measurements)

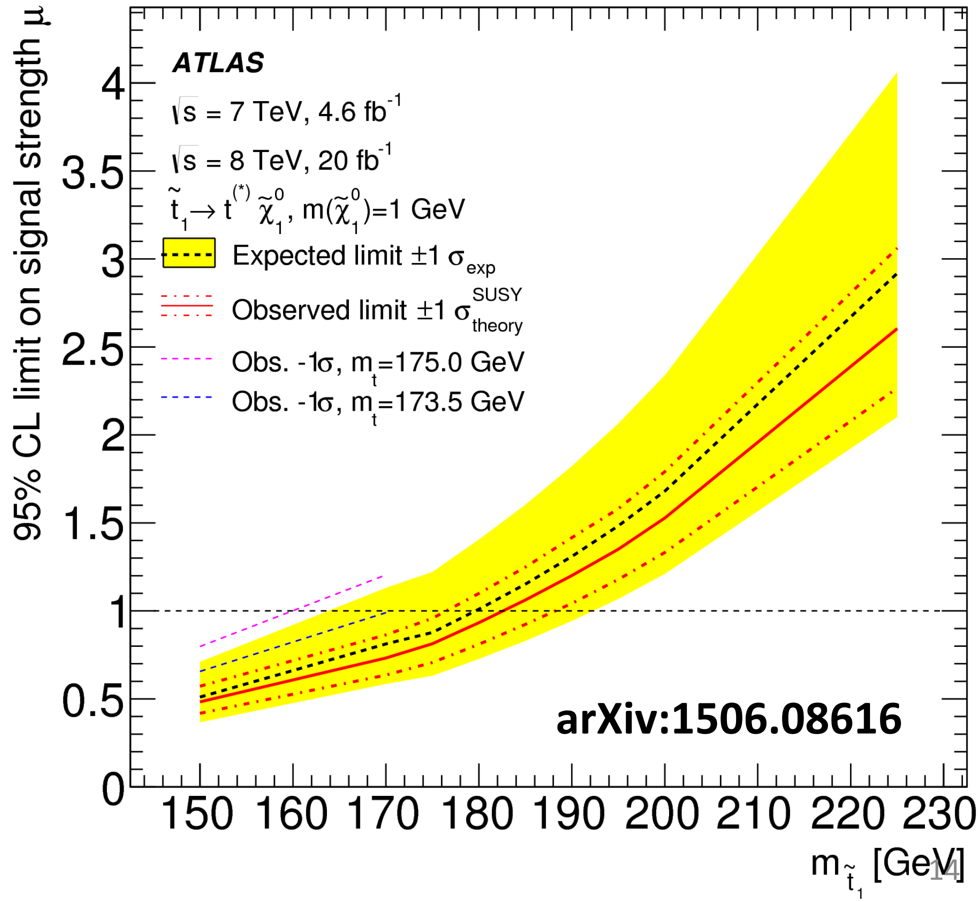




For stop masses close to the top mass the separation of SUSY signal and background is very challenging → use top cross section

Dilepton (e-μ) channel with exactly one and two b-jets



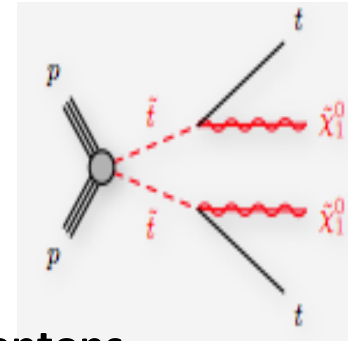


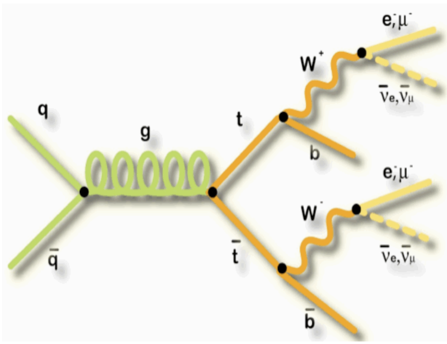
arXiv:1506.08616

Phys. Rev. Lett. 114. 142001 (2015)

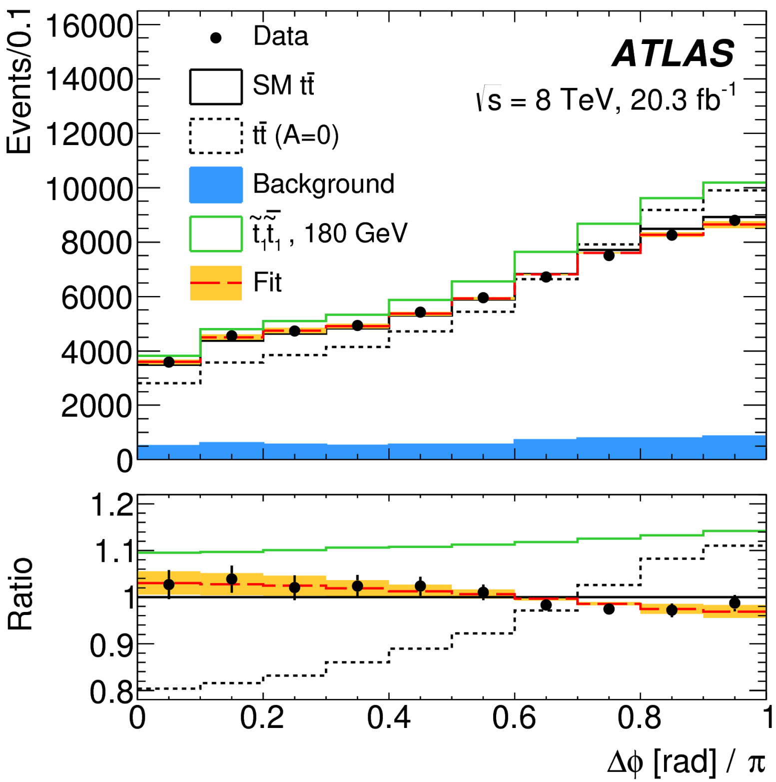
Further stop constrains

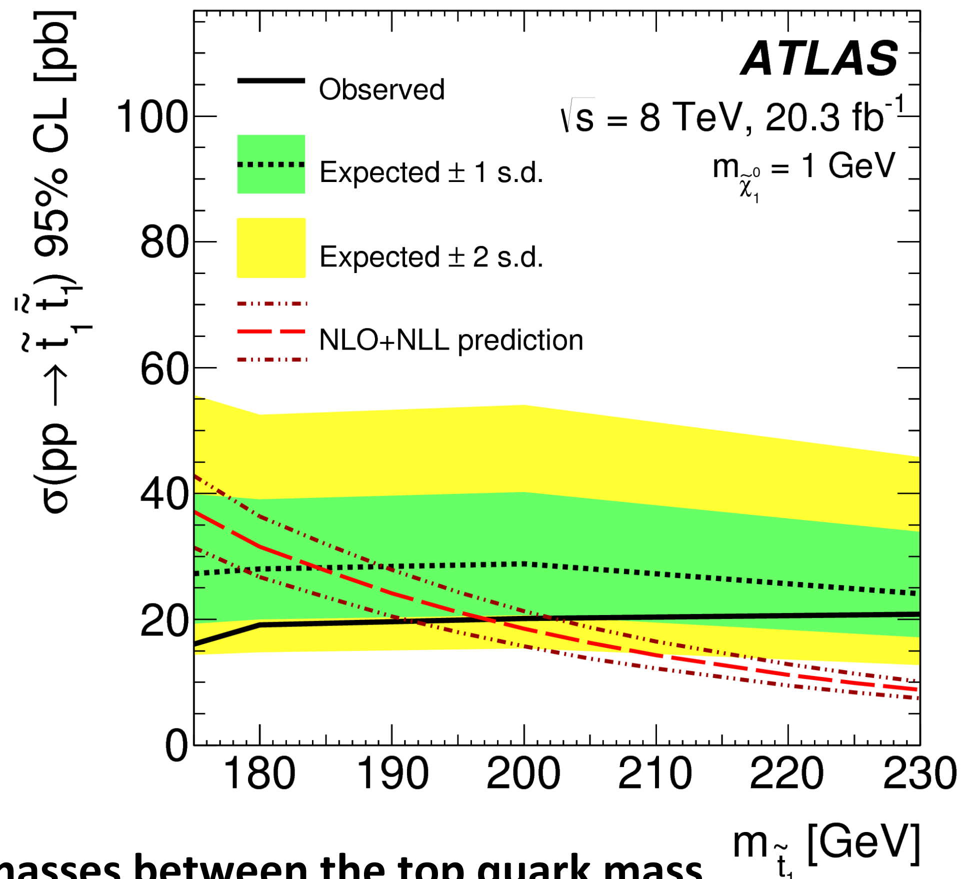
(using the top-(anti)top spin correlations)





using azimuthal separation of leptons from top-(anti)top decays in the final state



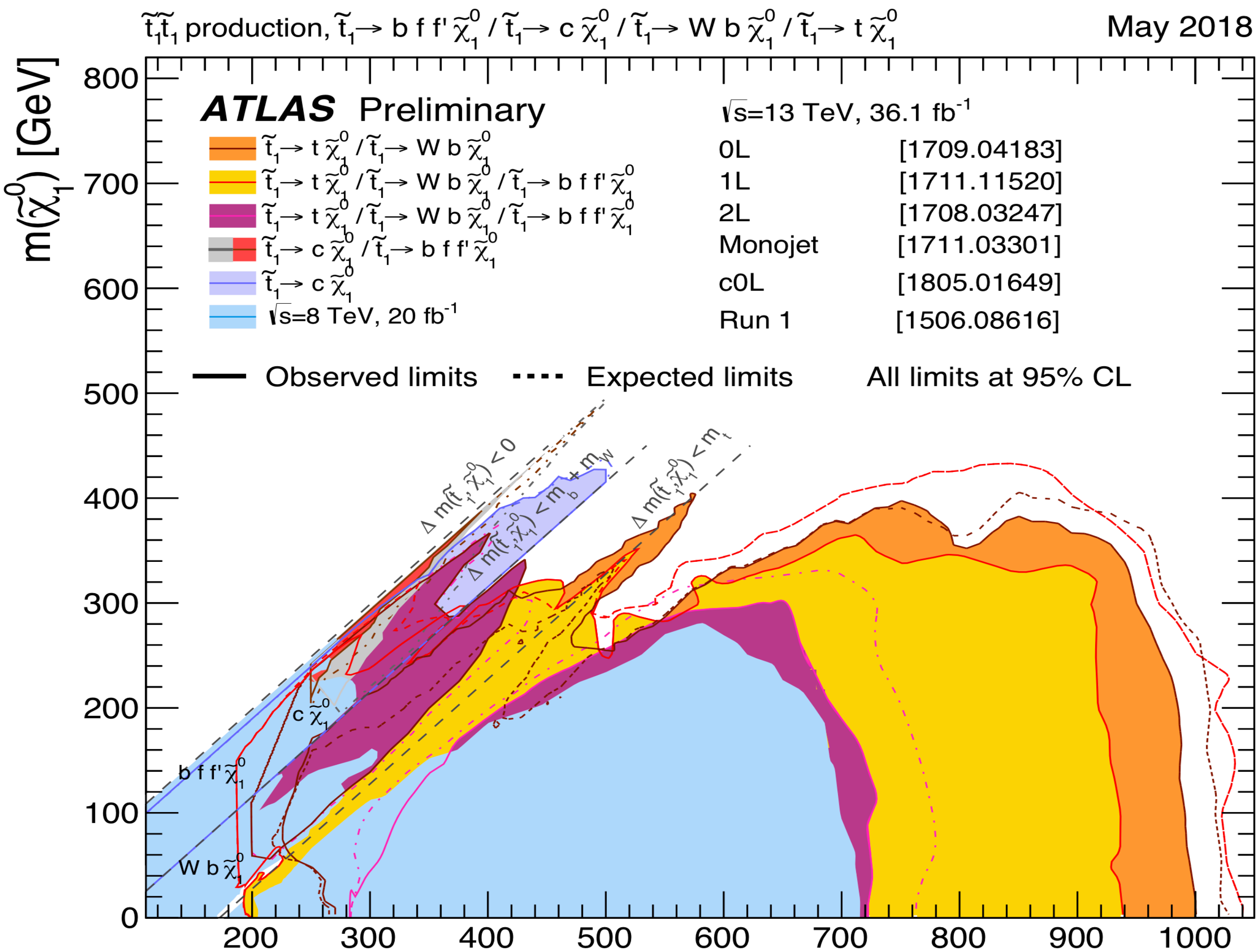


masses between the top quark mass and 191 GeV are excluded

Summary Searches for Stop

(different mass hierarchies, simplified models)

May 2018



Exclusion for $m(\tilde{t}_1) < 1$ TeV for massless LSP

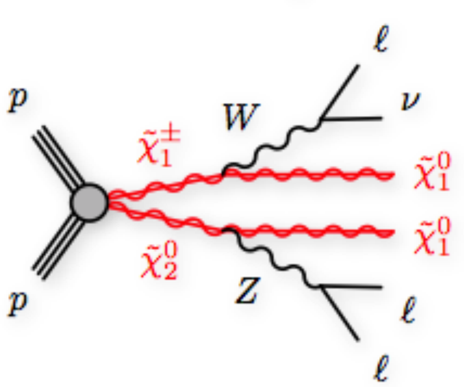
Exclusion up to m(LSP) ~400 GeV

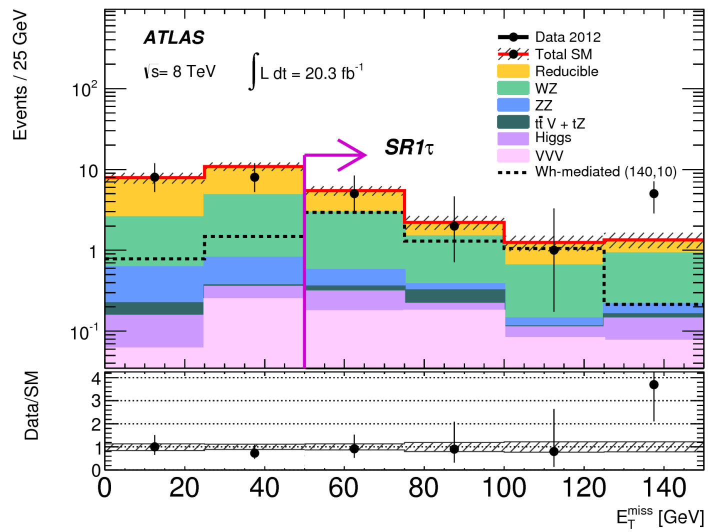
JHEP04(2014)169

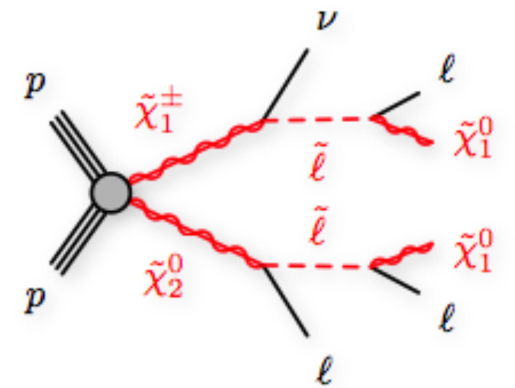
Chargino/Neutralino

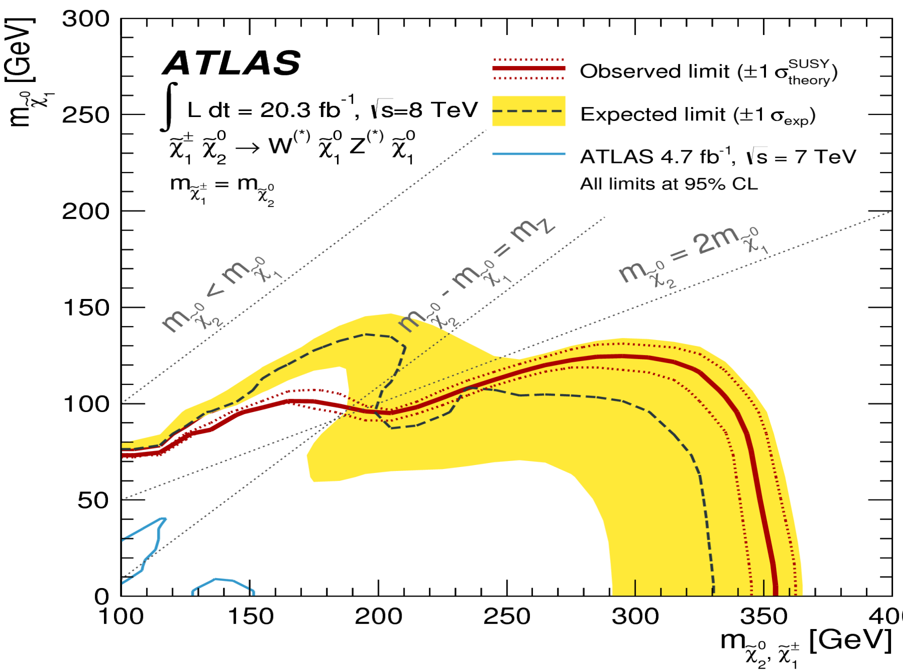
3 leptons + E_T^{miss}

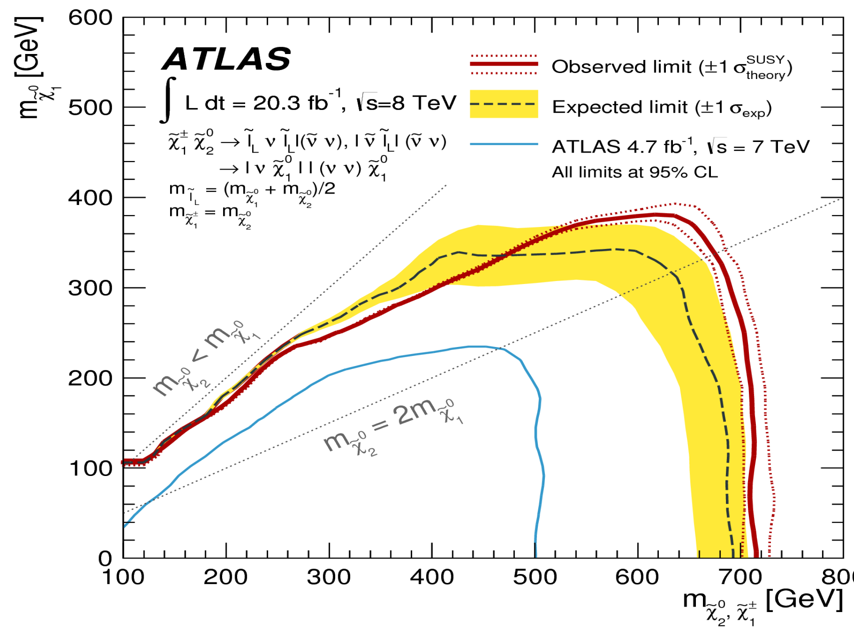
Background mostly WZ, ZZ followed by ttV and tribosons





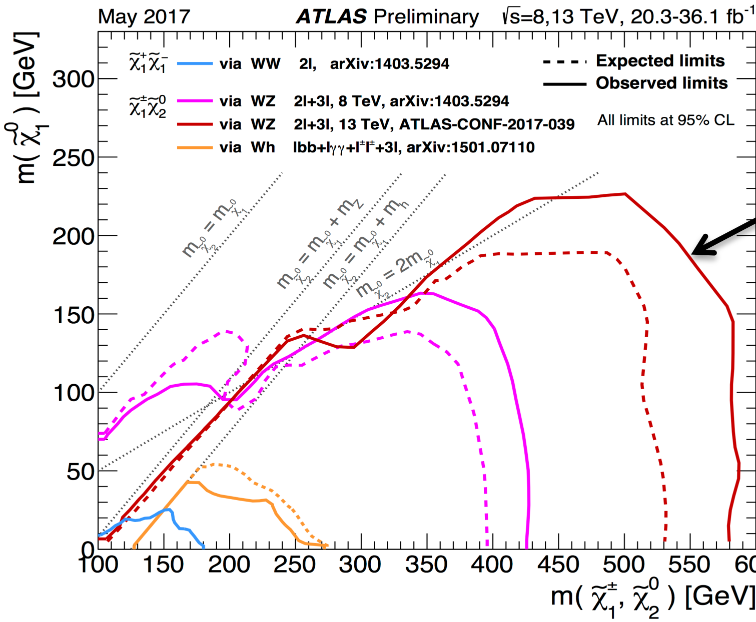


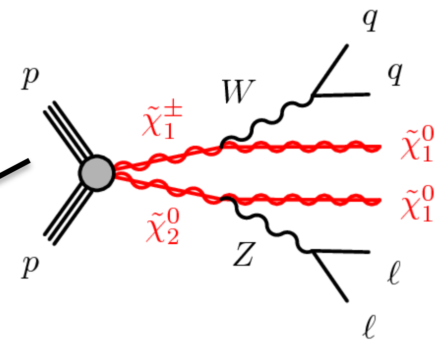




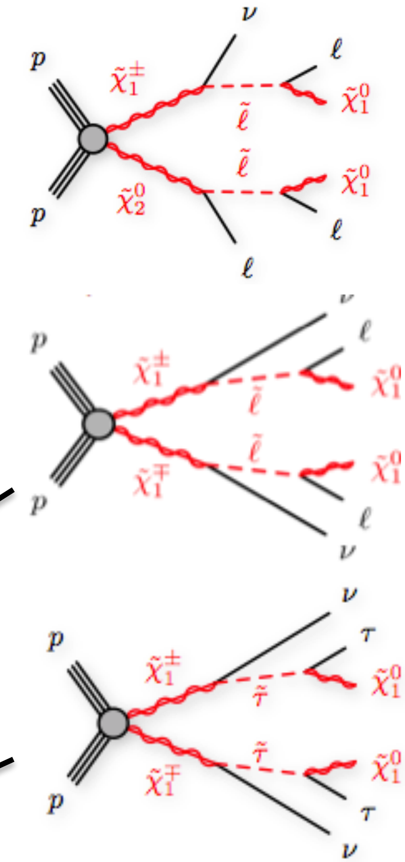
EWK production

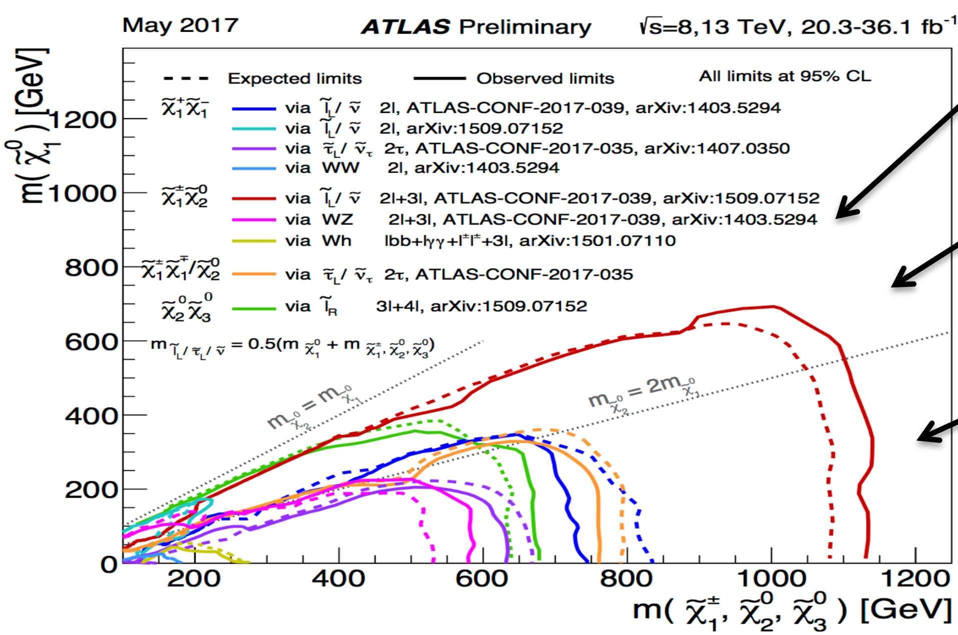
MAY 2017





2 or 3 leptons + E_T^{miss}





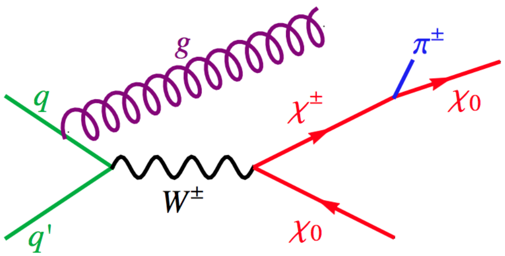
Chargino mass > ~1100 GeV
Neutralino mass > 600 GeV

Very sensitive to the details of the scenario considered

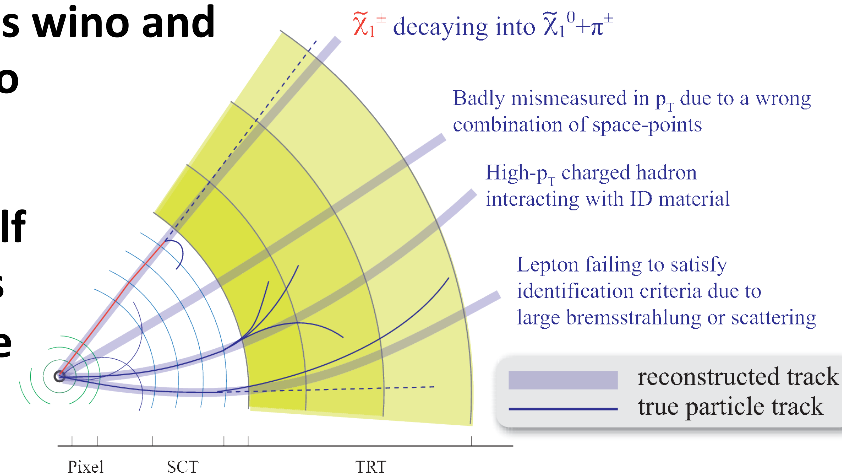
Phys. Rev. D 88 112006 (2013)

Disappearing track

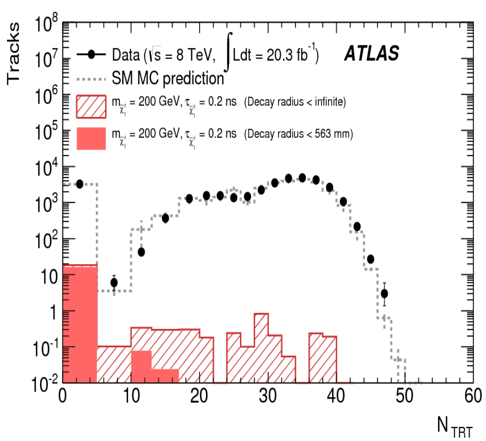
In AMSB model where the lightest chargino (N)LSP is wino and nearly mass-degenerate with the lightest neutralino

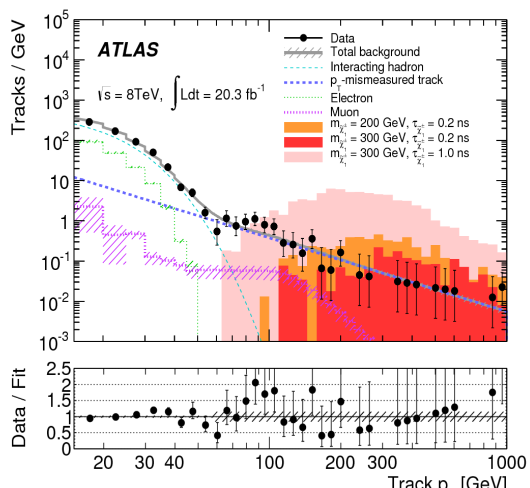


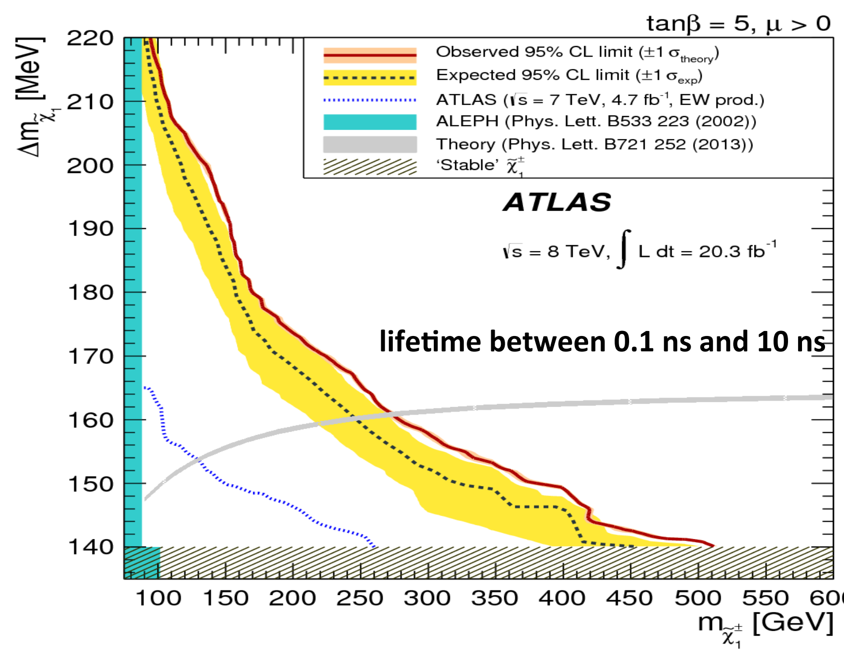
The signal reveals itself as disappearing tracks in the outer ID volume



At least one jet with PT > 90 GeV, Etmiss > 90 GeV
Lepton (electron and muon) vetoes
One good isolated track with pT > 15 GeV
and less than 5 hits in the TRT







A chargino mass below 270 GeV is excluded at 95% CL

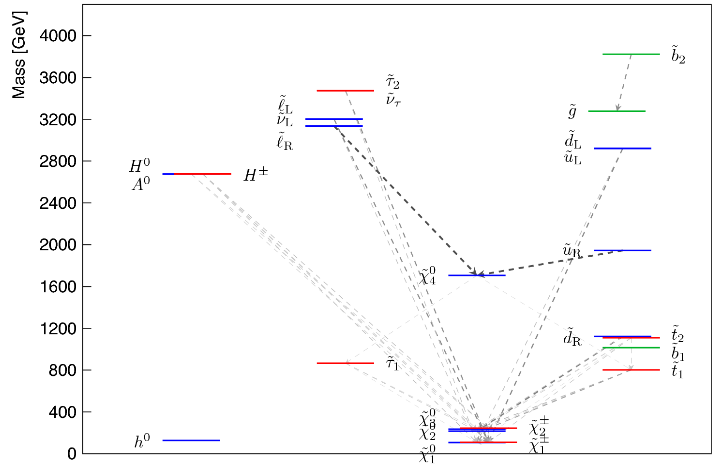
pMSSM

arXiv:1508.06608

Up to 22 different ATLAS searches considered

Analysis	Ref.	Category
0-lepton + 2–6 jets + E_T^{miss}	[57]	Inclusive
0-lepton + 7–10 jets + E_T^{miss}	[58]	
1-lepton + jets + E_T^{miss}	[59]	
$\tau(\tau/\ell)$ + jets + E_T^{miss}	[60]	
SS/3-leptons + jets + E_T^{miss}	[61]	
0/1-lepton + 3b-jets + E_T^{miss}	[62]	
Monojet	[63]	
0-lepton stop	[64]	Third generation
1-lepton stop	[55]	
2-leptons stop	[65]	
Monojet stop	[66]	
Stop with Z boson	[67]	
2b-jets + E_T^{miss}	[68]	
$tb+E_T^{miss}$, stop	[56]	
ℓh	[69]	Electroweak
2-leptons	[53]	
2-τ	[54]	
3-leptons	[52]	
4-leptons	[70]	
Disappearing Track	[71]	
Long-lived particle	[72,73]	Other
$H/A \to \tau^+\tau^-$	[74]	

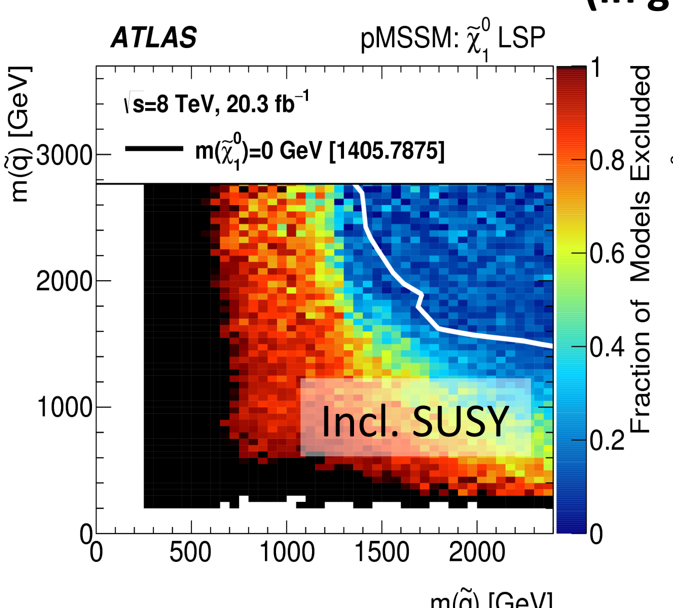
One example of particle spectra

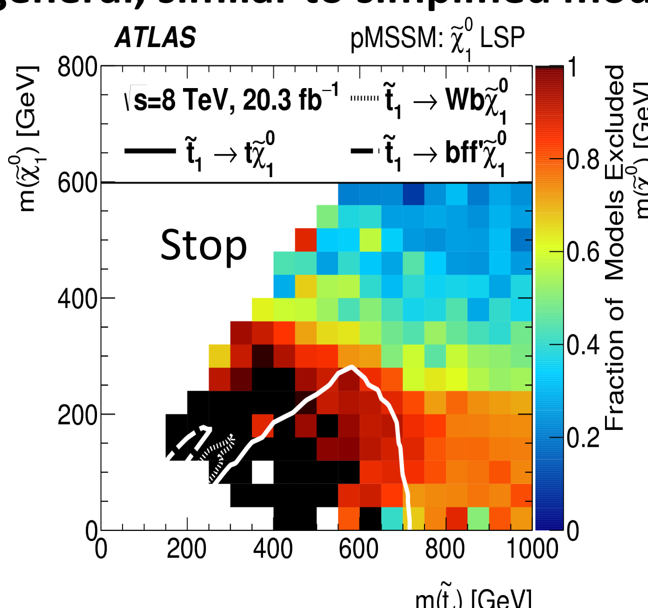


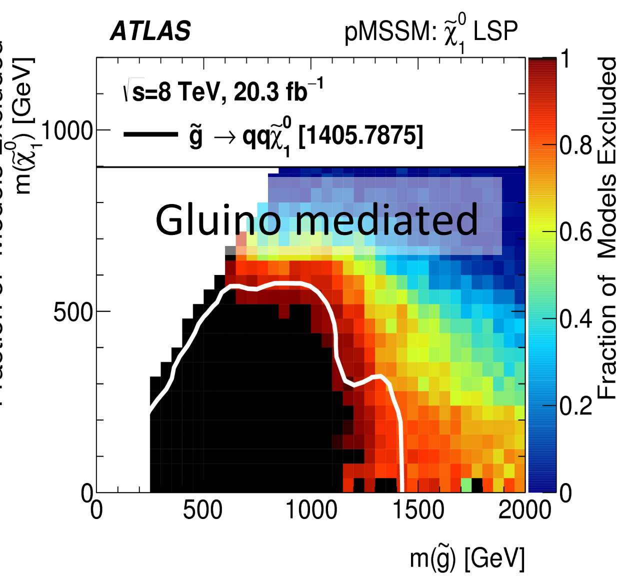
The results are interpreted in the context of 19-parameter

Parameter	Min value	Max value	Note
$m_{\tilde L_1}(=m_{\tilde L_2})$	90 GeV	4 TeV	Left-handed slepton (first two gens.) mass
$m_{\tilde e_1}(=m_{\tilde e_2})$	90 GeV	4 TeV	Right-handed slepton (first two gens.) mass
$m_{\tilde L_3}$	90 GeV	4 TeV	Left-handed stau doublet mass
$m_{\tilde e_3}$	90 GeV	4 TeV	Right-handed stau mass
$m_{\tilde Q_1}(=m_{\tilde Q_2})$	200 GeV	4 TeV	Left-handed squark (first two gens.) mass
$m_{\tilde u_1}(=m_{\tilde u_2})$	200 GeV	4 TeV	Right-handed up-type squark (first two gens.) mass
$m_{\tilde d_1}(=m_{\tilde d_2})$	200 GeV	4 TeV	Right-handed down-type squark (first two gens.) mass
$m_{\tilde Q_3}$	100 GeV	4 TeV	Left-handed squark (third gen.) mass
$m_{\tilde u_3}$	100 GeV	4 TeV	Right-handed top squark mass
$m_{\tilde d_3}$	100 GeV	4 TeV	Right-handed bottom squark mass
$\vert M_1\vert$	0 GeV	4 TeV	Bino mass parameter
$\vert M_2\vert$	70 GeV	4 TeV	Wino mass parameter
$\vert\mu\vert$	80 GeV	4 TeV	Bilinear Higgs mass parameter
M_3	200 GeV	4 TeV	Gluino mass parameter
$\vert A_t\vert$	0 GeV	8 TeV	Trilinear top coupling
$\vert A_b\vert$	0 GeV	4 TeV	Trilinear bottom coupling
$\vert A_\tau\vert$	0 GeV	4 TeV	Trilinear τ lepton coupling
M_A	100 GeV	4 TeV	Pseudoscalar Higgs boson mass
$\tan\beta$	1	60	Ratio of the Higgs vacuum expectation values

Fraction of pMSSM models excluded (in general, similar to simplified models)







ATLAS SUSY Searches* - 95% CL Lower Limits

July 2018

July 2018

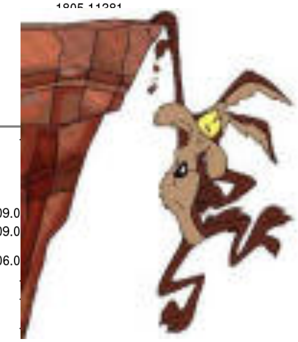
ATLAS **Preliminary**

$\sqrt{s}$ = 7, 8, 13 TeV

$\sqrt{s}$ = 7, 8 TeV | $\sqrt{s}$ = 13 TeV

	Model	e,μ,τ,γ	Jets	E_T^{miss}	$\int\mathcal{L}\,dt[\mathrm{fb}^{-1}]$	Mass limit		Reference
Inclusive Searches	$\tilde q\tilde q$, $\tilde q\to q\tilde\chi^0_1$	0	2-6 jets	Yes	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	Yes	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	2-6 jets	Yes	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	Yes	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	7-11 jets	Yes	36.1	$\tilde g$ 1.8	m($\tilde\chi^0_1$) <400 GeV	
		3 e,μ	4 jets	-	36.1	$\tilde g$ 0.98	m($\tilde g$)-m($\tilde\chi^0_1$)=200 GeV	
	$\tilde g\tilde g$, $\tilde g\to t\bar t\tilde\chi^0_1$	0-1 e,μ	3 b	Yes	36.1	$\tilde g$ 2.0	m($\tilde\chi^0_1$)<200 GeV	
		3 e,μ	4 jets	-	36.1	$\tilde g$ 1.25	m($\tilde g$)-m($\tilde\chi^0_1$)=300 GeV	
3^{rd} 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	
			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	
			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	
	$\tilde b_1\tilde b_1$, $\tilde t_1\tilde t_1$, $M_2=2\times M_1$		Multiple		36.1	$\tilde t_1$ 0.7	m($\tilde\chi^0_1$)=60 GeV	1709.0
			Multiple		36.1	$\tilde t_1$ Forbidden 0.9	m($\tilde\chi^0_1$)=200 GeV	1709.0
	$\tilde t_1\tilde t_1$, $\tilde t_1\to Wb\tilde\chi^0_1$ or $t\tilde\chi^0_1$	0-2 e,μ	0-2 jets/1-2 b	Yes	36.1	$\tilde t_1$ 1.0	m($\tilde\chi^0_1$)=1 GeV	1506.0
	$\tilde t_1\tilde t_1$, $\tilde H$ LSP		Multiple		36.1	$\tilde t_1$ 0.4-0.9	m($\tilde\chi^0_1$)=150 GeV, m($\tilde\chi^\pm_1$)-m($\tilde\chi^0_1$)=5 GeV, $\tilde t_1\approx\tilde t_L$	
			Multiple		36.1	$\tilde t_1$ Forbidden 0.6-0.8	m($\tilde\chi^0_1$)=300 GeV, m($\tilde\chi^\pm_1$)-m($\tilde\chi^0_1$)=5 GeV, $\tilde t_1\approx\tilde t_L$	
	$\tilde t_1\tilde t_1$, 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, $\tilde t_1\approx\tilde t_L$	
	$\tilde t_1\tilde t_1$, $\tilde t_1\to c\tilde\chi^0_1$ / $\tilde c\tilde c$, $\tilde c\to c\tilde\chi^0_1$	0	$2c$	Yes	36.1	$\tilde t_1$ 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	mono-jet	Yes	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	Yes	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	-	Yes	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	Yes	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
	$\tilde\chi^\pm_1\tilde\chi^0_2$ via Wh	$\ell\ell/\ell\gamma\gamma/\ell bb$	-	Yes	20.3	$\tilde\chi^\pm_1/\tilde\chi^0_2$ 0.26	m($\tilde\chi^0_1$)=0	1501.07110
	$\tilde\chi^\pm_1\tilde\chi^\mp_1/\tilde\chi^0_2$, $\tilde\chi^+_1\to\tilde\tau\nu(\tau\tilde\nu)$, $\tilde\chi^0_2\to\tilde\tau\tau(\nu\tilde\nu)$	2 τ	-	Yes	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	Yes	36.1	$\tilde\ell$ 0.5	m($\tilde\chi^0_1$)=0	1803.02762
		2 e,μ	≥ 1	Yes	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	$\geq 3b$	Yes	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	Yes	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	Yes	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	SMP	-	-	3.2	$\tilde g$ 1.6		1606.05129
	Metastable $\tilde g$ R-hadron, $\tilde g\to qq\tilde\chi^0_1$		Multiple		32.8	$\tilde g$ [$\tau(\tilde g)$ =100 ns, 0.2 ns] 1.6 2.4	m($\tilde\chi^0_1$)=100 GeV	1710.04901, 1604.04520
	GMSB, $\tilde\chi^0_1\to\gamma\tilde G$, long-lived $\tilde\chi^0_1$	2 γ	-	Yes	20.3	$\tilde\chi^0_1$ 0.44	1<$\tau(\tilde\chi^0_1)$<3 ns, SPS8 model	1409.5542
	$\tilde g\tilde g$, $\tilde\chi^0_1\to eev/e\mu v/\mu\mu v$	displ. $ee/e\mu/\mu\mu$	-	-	20.3	$\tilde g$ 1.3	6 <$c\tau(\tilde\chi^0_1)$< 1000 mm, m($\tilde\chi^0_1$)=1 TeV	1504.05162
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	Yes	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
	$\tilde g\tilde g$, $\tilde g\to qq\tilde\chi^0_1$, $\tilde\chi^0_1\to qqq$	0	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
	$\tilde g\tilde g$, $\tilde g\to tbs$ / $\tilde g\to t\bar t\tilde\chi^0_1$, $\tilde\chi^0_1\to tbs$		Multiple		36.1	$\tilde g$ [λ''_{323}=1, 1e-2] 1.8 2.1	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
	$\tilde t_1\tilde t_1$, $\tilde t_1\to bs$	0	2 jets + 2 b	-	36.7	$\tilde t_1$ [qq, bs] 0.42 0.61		1710.07171
	$\tilde t_1\tilde t_1$, $\tilde t_1\to b\ell$	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

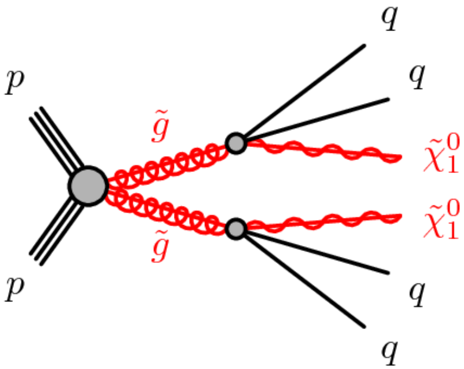
10^{-1} 1 **Mass scale [TeV]**



*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.

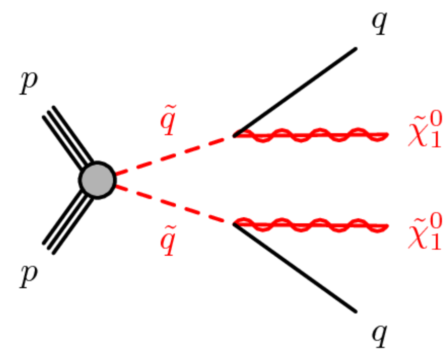
ATL-PHYS-PUB-2013-011
ATL-PHYS-PUB-2014-010

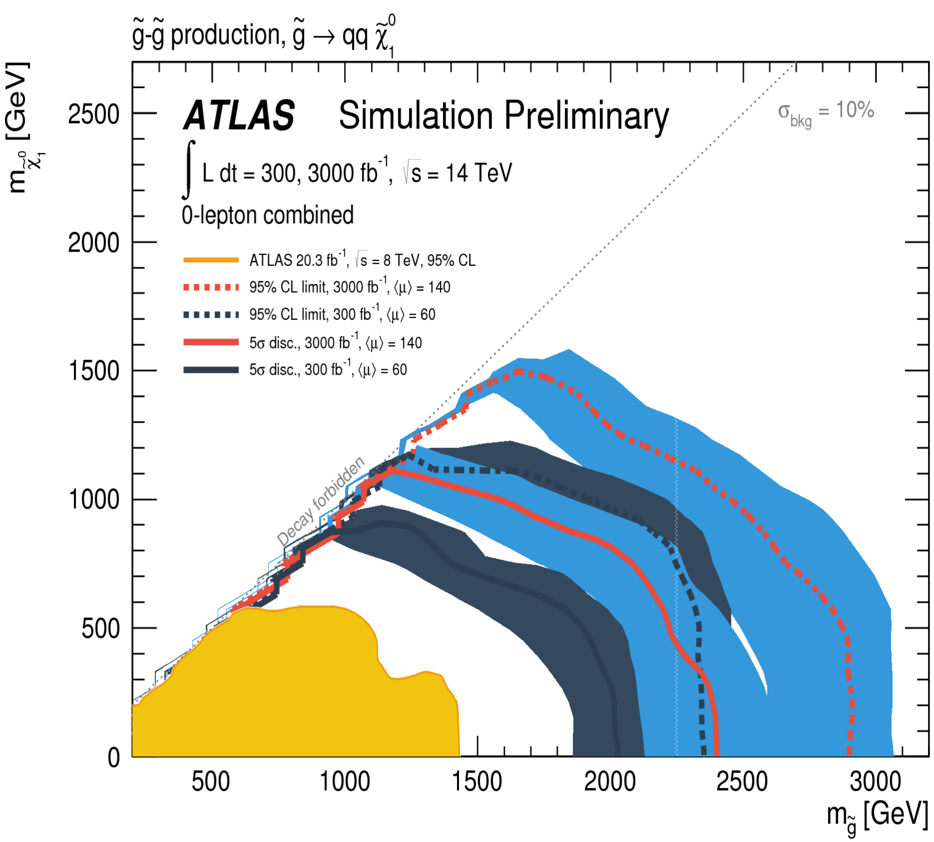
HL-LHC prospects

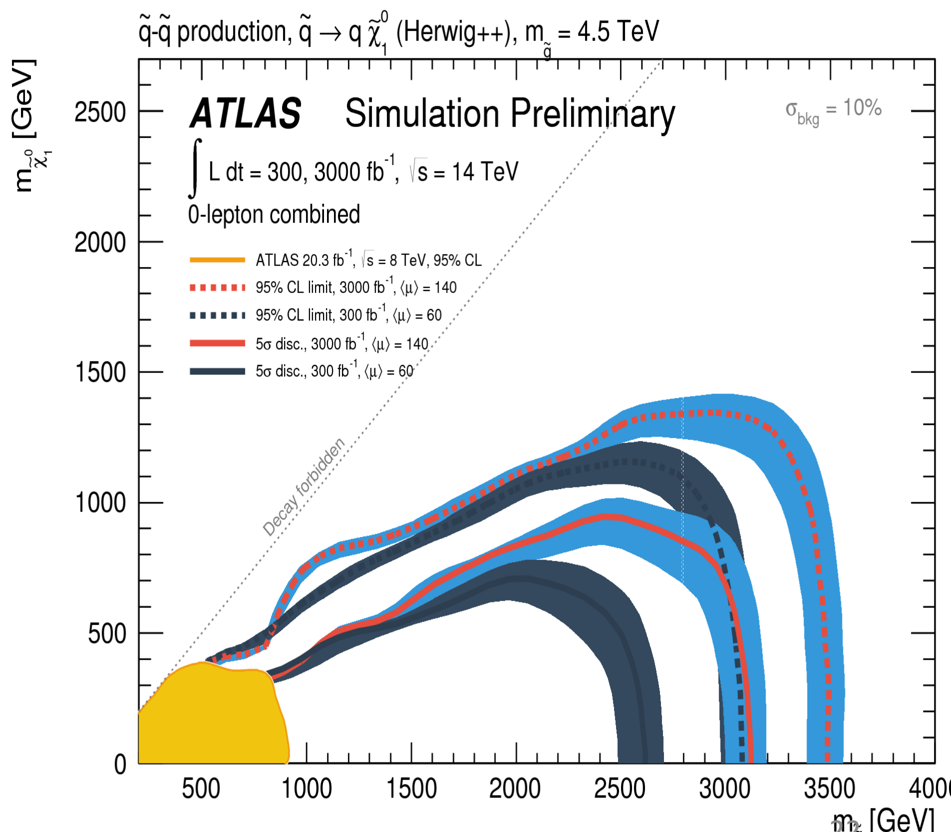


Will be in the position to "kill natural SUSY"

Sensitivity up to 3 – 3.5 TeV

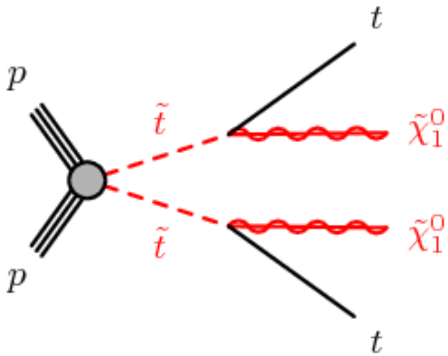






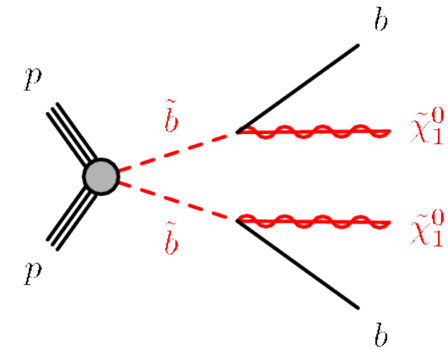
ATL-PHYS-PUB-2013-011
ATL-PHYS-PUB-2014-010

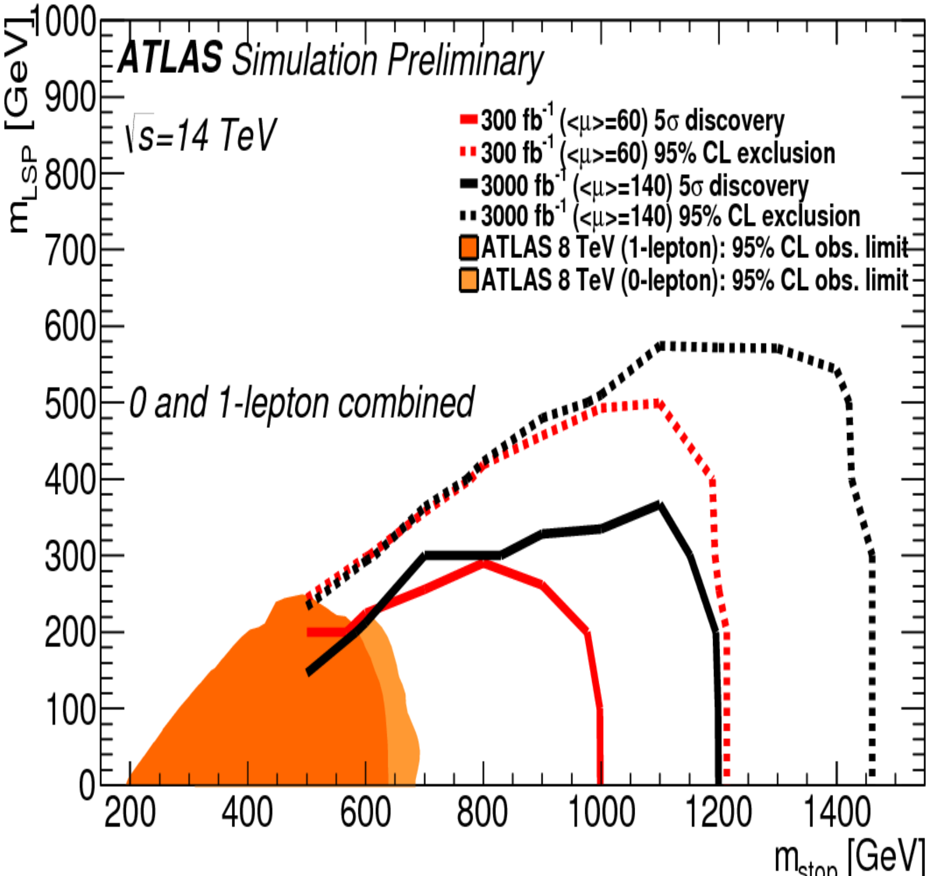
HL-LHC prospects

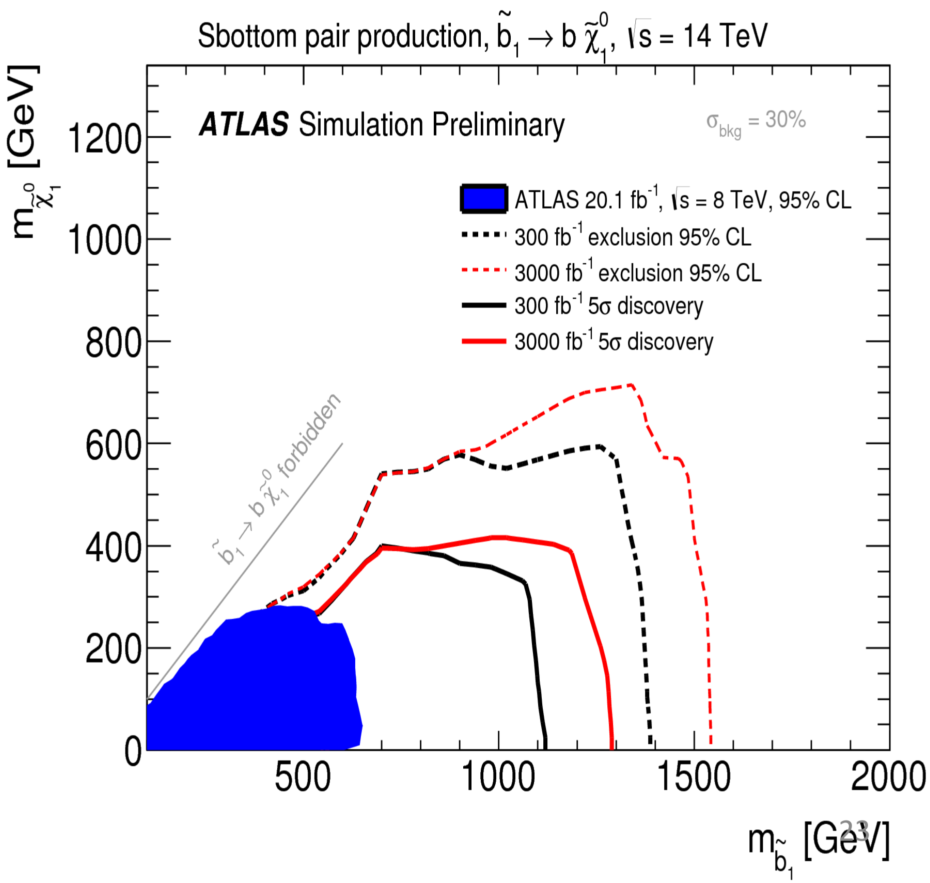


Will be in the position to "kill natural SUSY"

Sensitivity up to 1 – 1.5 TeV

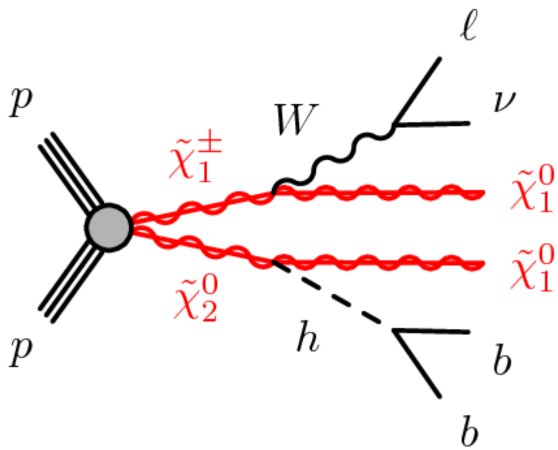






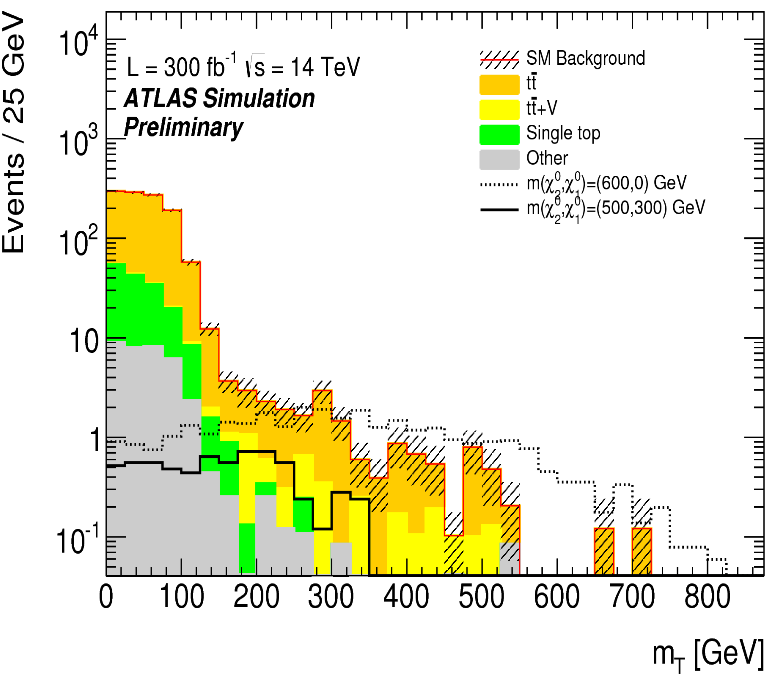
ATL-PHYS-PUB-2015-032

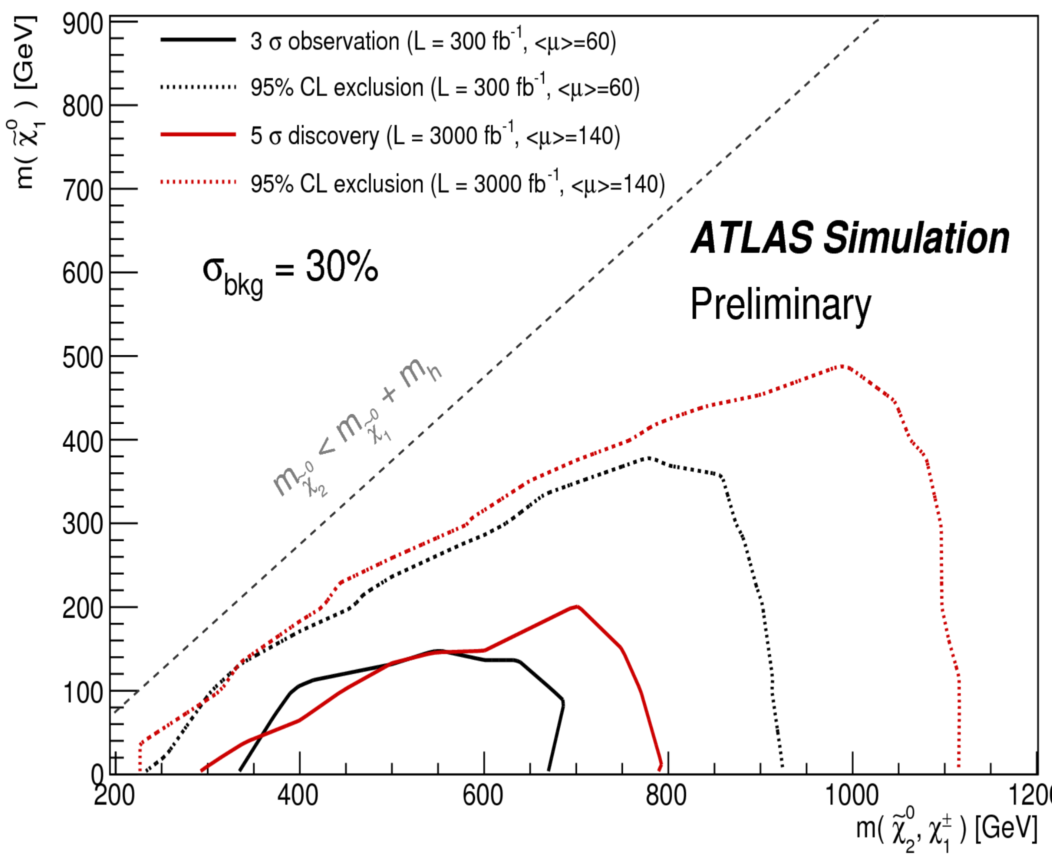
HL-LHC prospects



SUSY Weakly interacting

Sensitivity up to 1.1 TeV

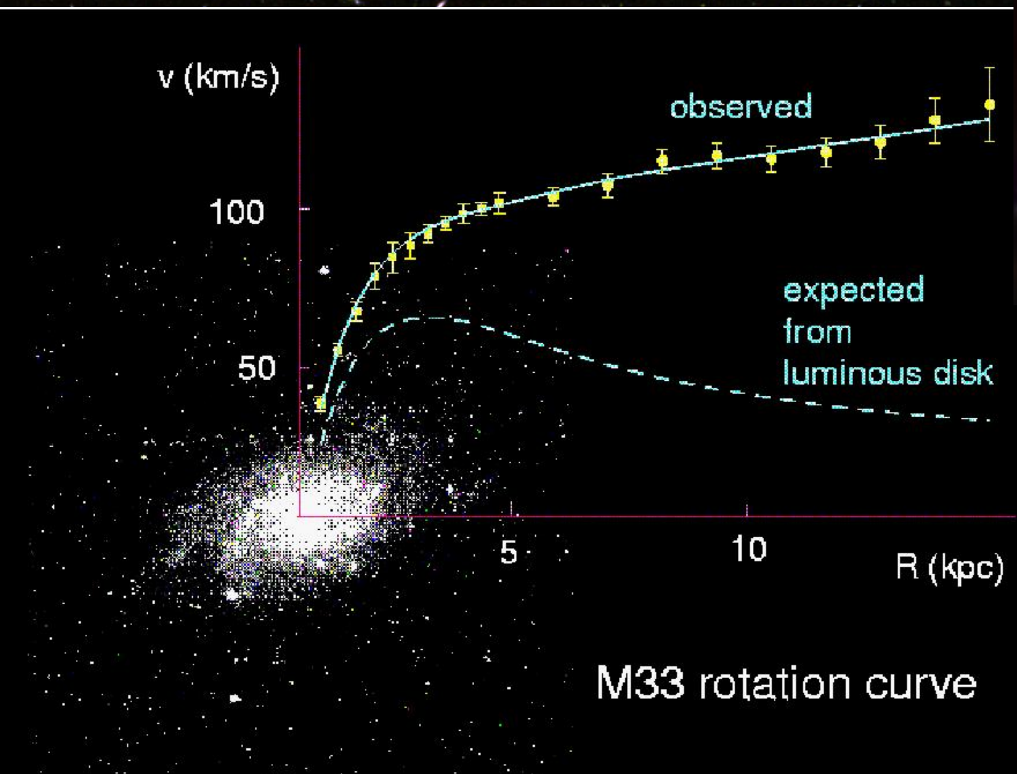




Evidence for Dark Matter

The rotation of the stars around the center of the galaxies is not consistent with the amount of mass observed $(L/M\ ratio)_{SUN}$

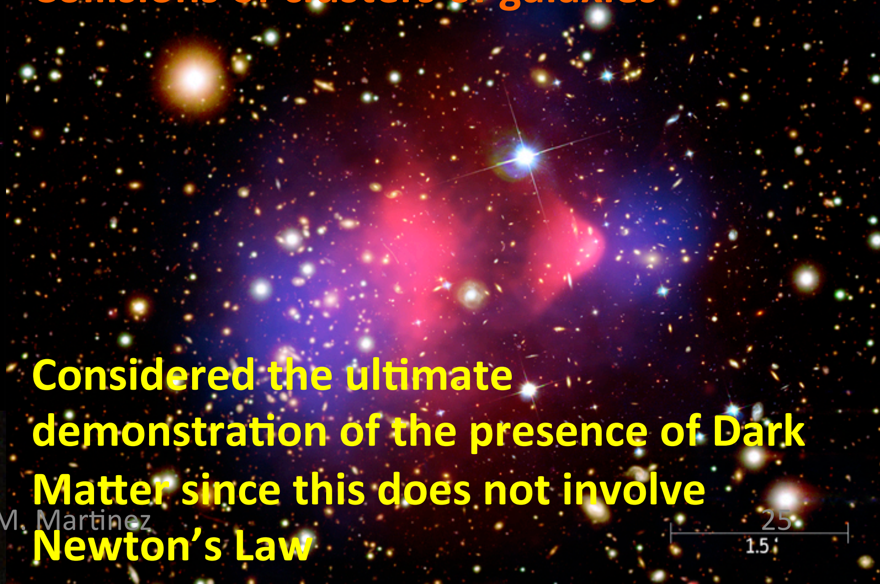
Spherical dark matter halo



Gravitational Lensing

Large distortion of the images of distant galaxies due to gravitation lensing

→ indication of DM in galaxy clusters

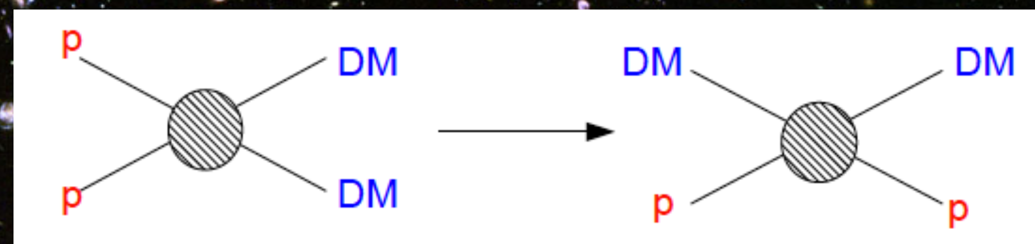


Collisions of clusters of galaxies

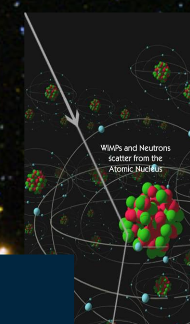
Considered the ultimate demonstration of the presence of Dark Matter since this does not involve Newton's Law

Introductory notes

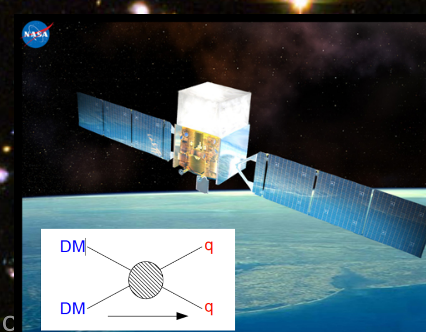
If Dark Matter turns to be WIMP like (weakly interacting) there is a chance to produce it directly at colliders (Golden channel → Mono-jet final state)

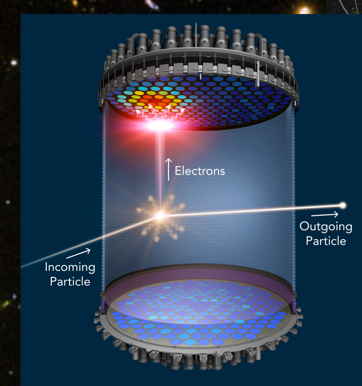


This makes the LHC complementary to direct-detection dedicated experiments underground

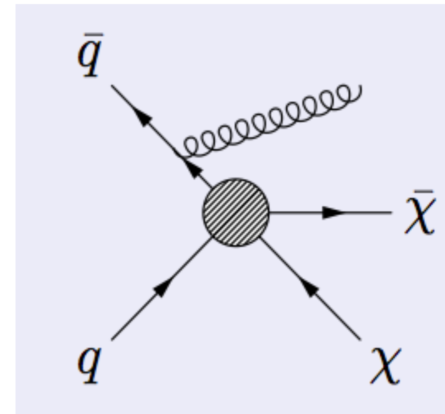


Some of the models explored at the LHC are also inspired by the Higgs boson and /or indirect searches at satellites → heavy flavors involved





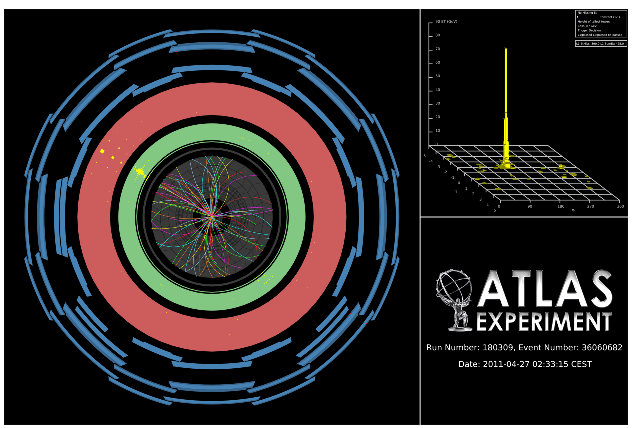
WIMP Pair Production at Hadron Colliders

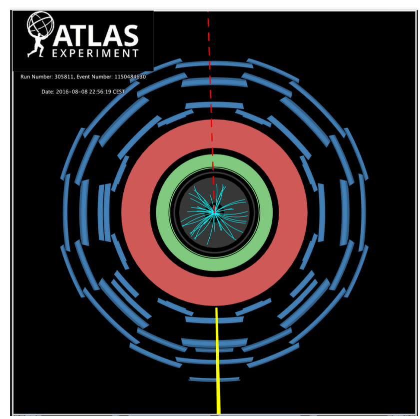


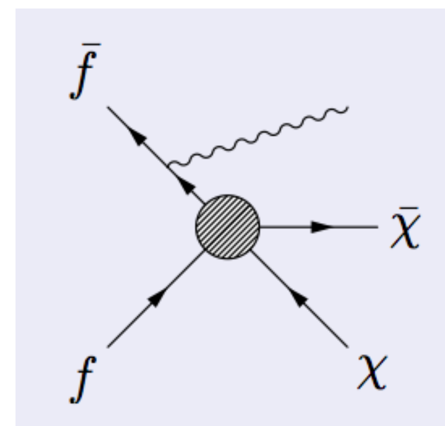
At colliders (LHC) WIMPs are produced in pairs leading to "nothing to detect" in the final state

Such events are tagged via the presence of an energetic jet or a photon (or a W/Z) from initial state radiation

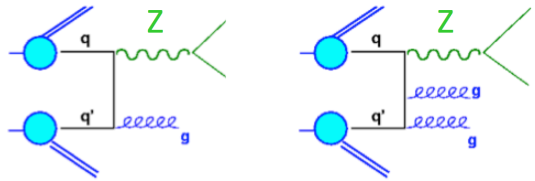
→Mono-jet, Mono-photon, Mono-W/Z







Rather spectacular and distinctive signature to search for new physics



Jet+X

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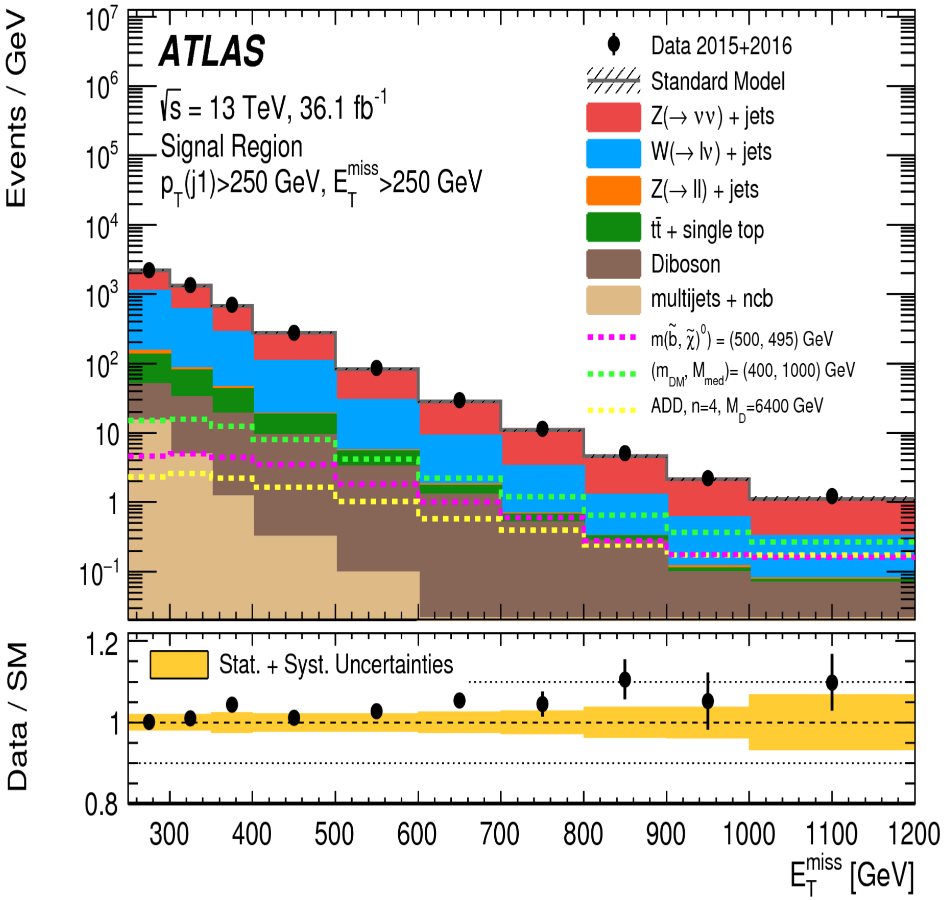
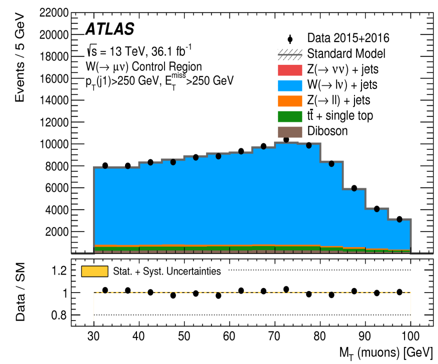
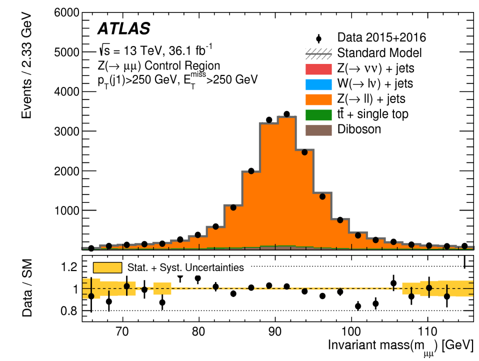
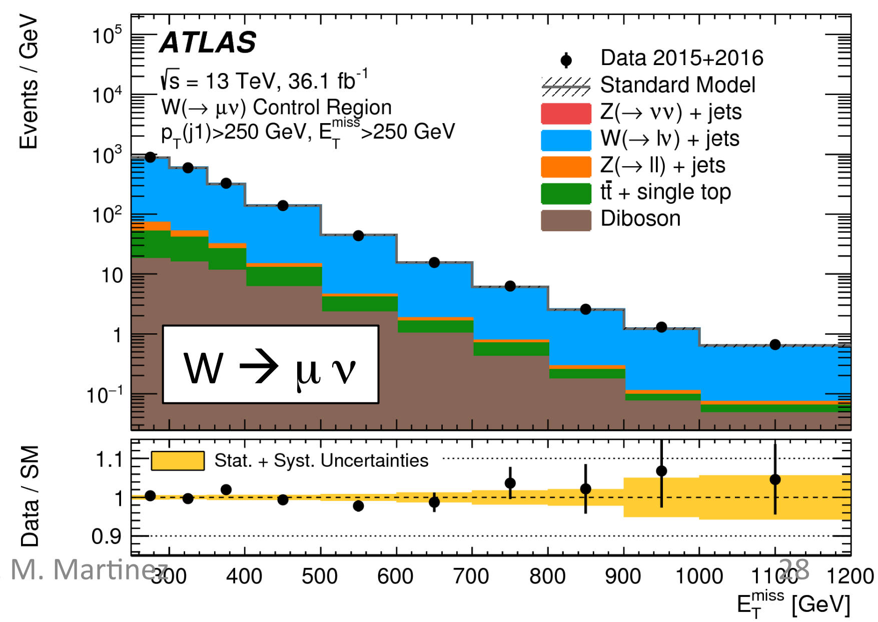
36.2 fb^{-1}

Data driven estimation of the dominant Z+jets and W+jets background using control regions in order to constrain MC predictions as determined @ NLO (QCD+EWK) accuracy

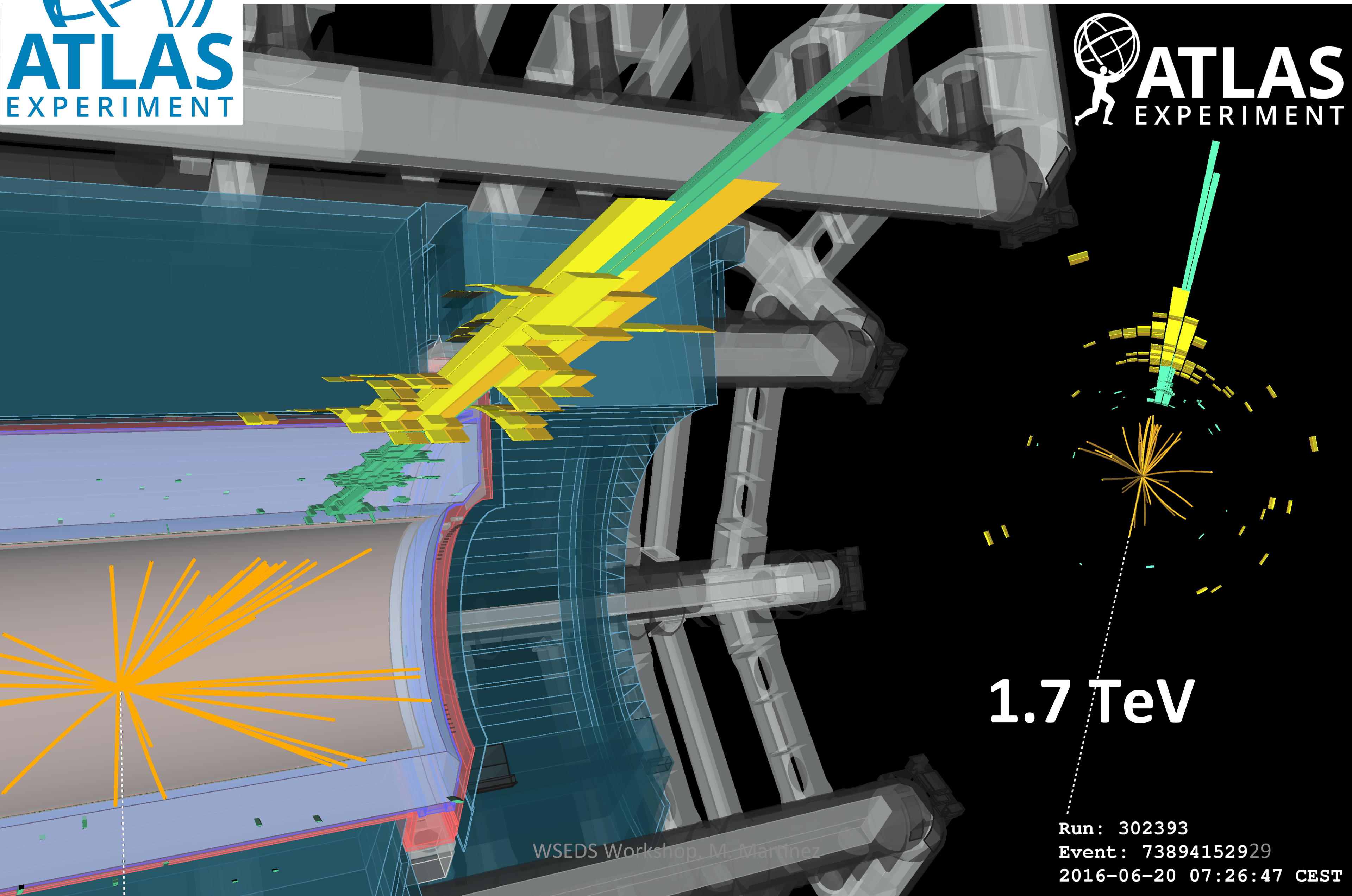




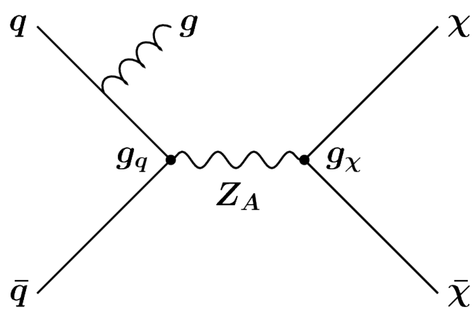


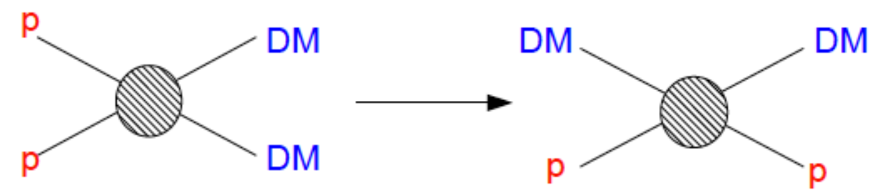


E_T^{miss} > , 250, 300 GeV, …, 1 TeV
p_T (j_1) > 250 GeV
N_{jet}(p_T > 30 GeV) < 4
$\Delta\phi$ (E_T^{miss}, jets) > 0.4
Lepton vetoes

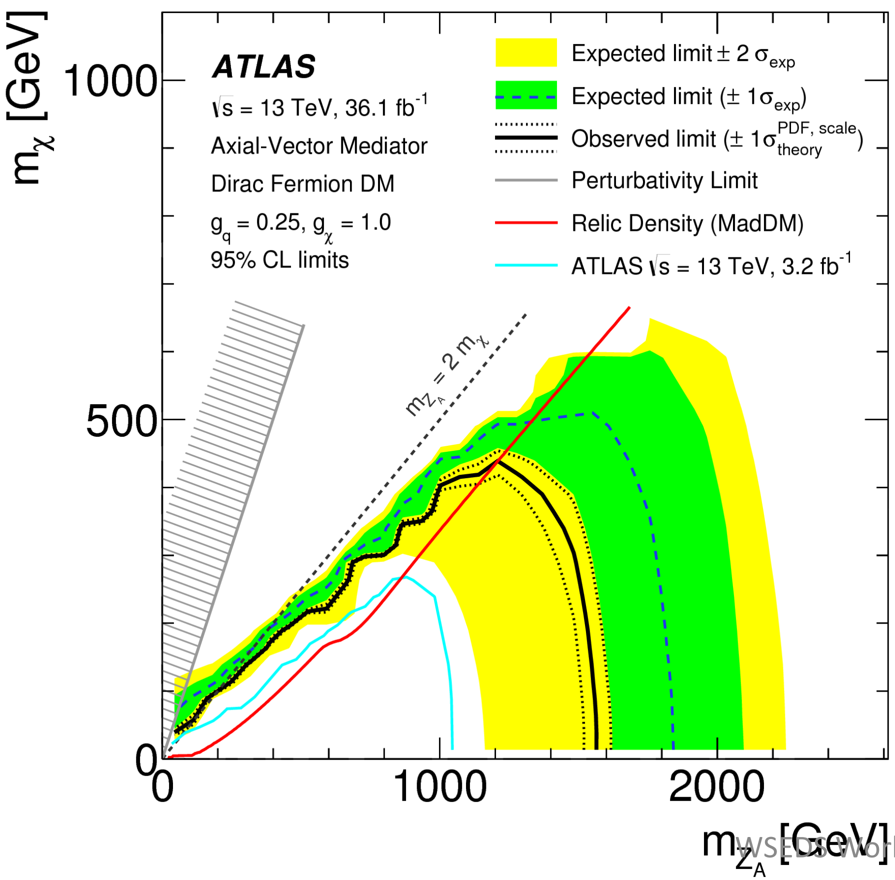

ATLAS
EXPERIMENT
1.7 TeV
Run: 302393
Event: 738941529
2016-06-20 07:26:47 CEST

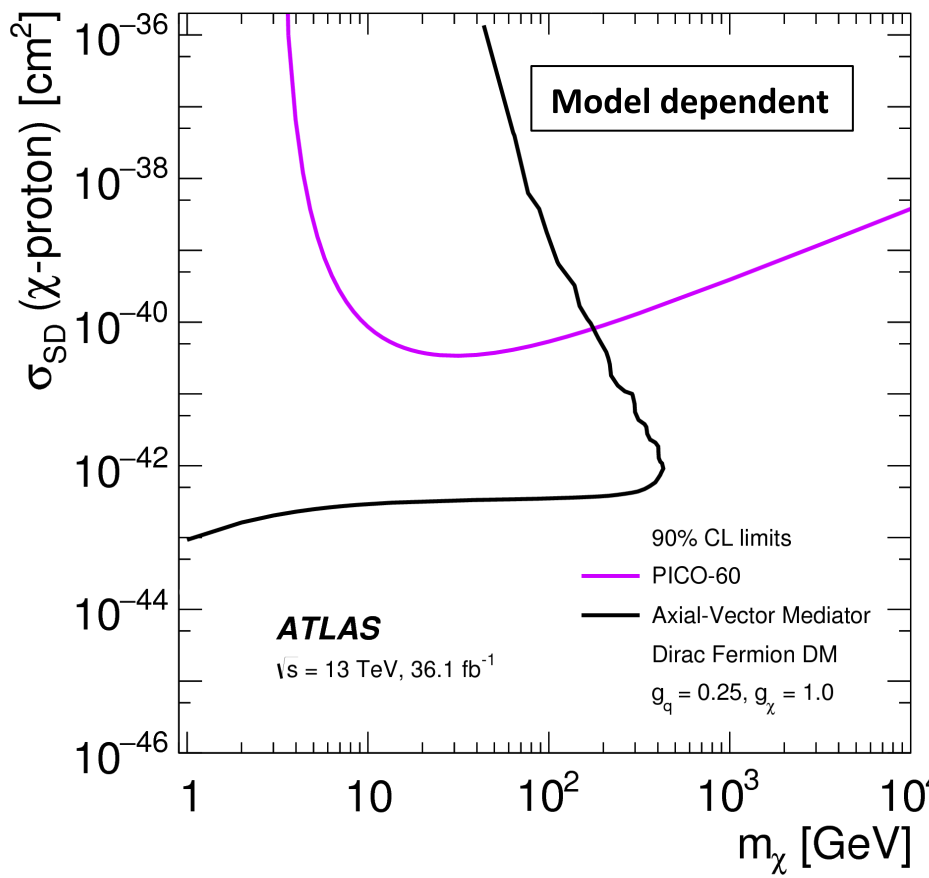
Jet+X





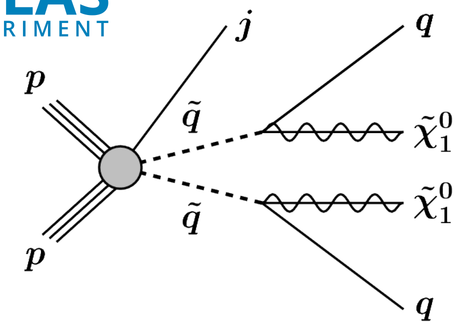
95% CL limits on axial-vector mediator model with couplings fixed to g_q = ¼ and g_{DM}= 1



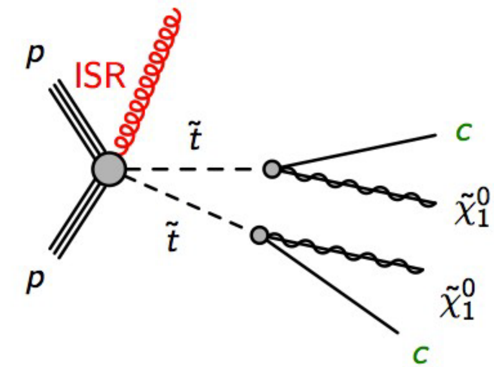


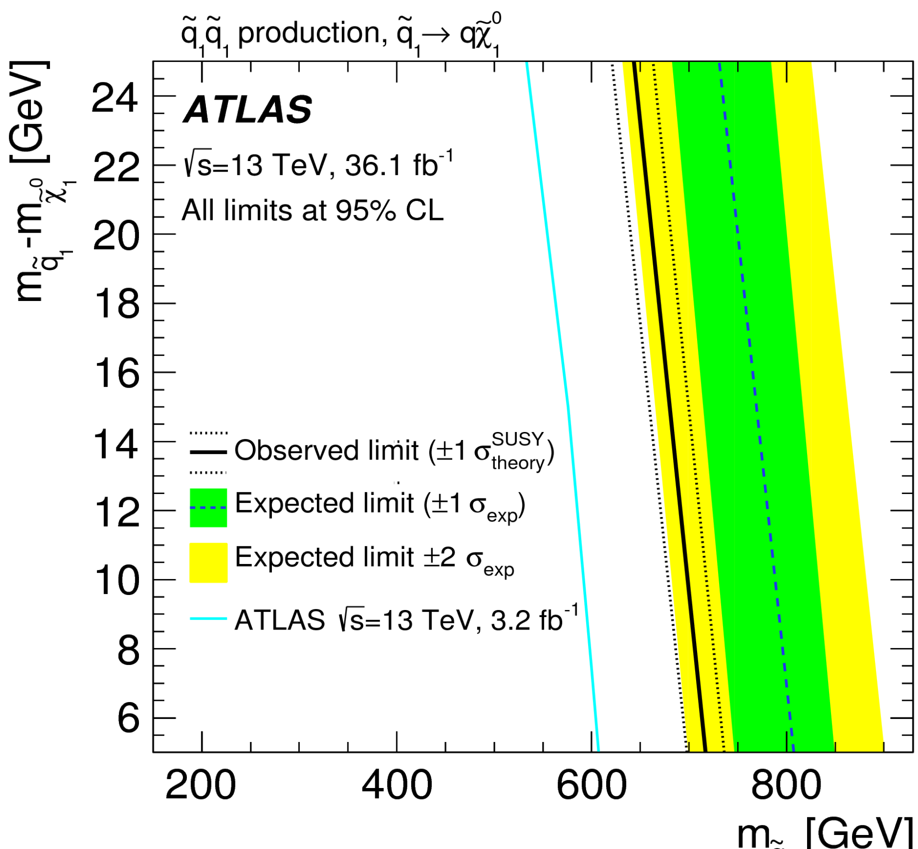
LHC results complement Direct DM experiments at low DM mass.

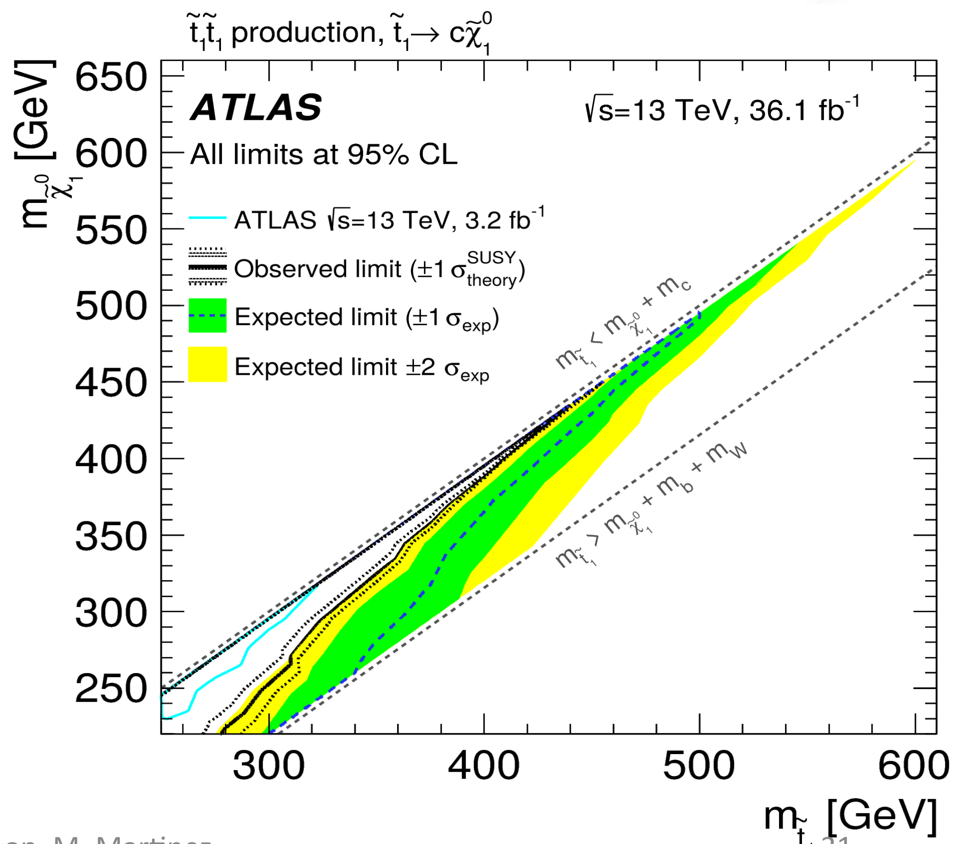
SUSY Compressed



Mono-Jet final state opens access to compressed spectra and neutralinos in the range 450 GeV – 800 GeV



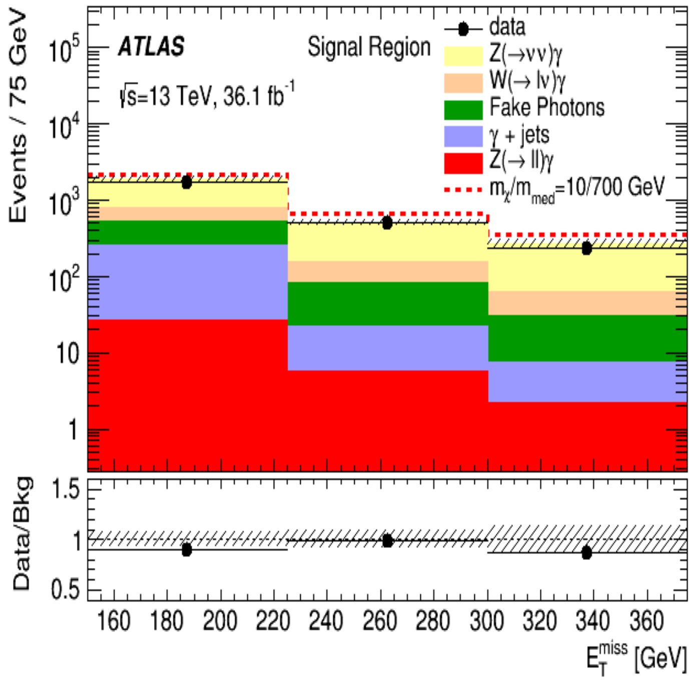




Eur. Phys. J. C 77 (2017) 393

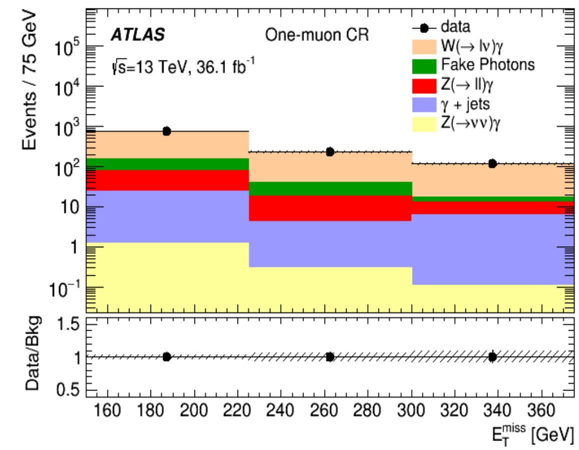
γ+X

36.1 fb^{-1}



Background dominated by Z/W+γ followed by contributions with jets faking photons plus other small contributions (γ+jets) **(γ+ μ + E_t^{miss} CR)**

- **Z/W+γ from MC normalized in CRs**
- **γ+jets CR at low E_T^{miss}**
- **Jet and electron fakes also fully data driven**

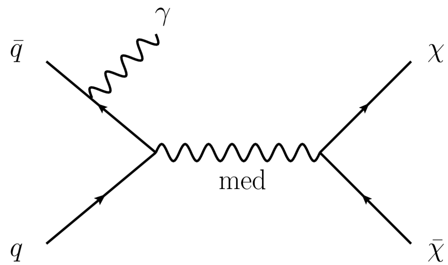


P_T^{γ} >150 GeV, $|\eta^{\gamma}|$ < 2.37, isolated
E_T^{miss} > 150, 225, 300 GeV
E_T^{miss} / SQRT(H_T) > 8.5 GeV$^{1/2}$

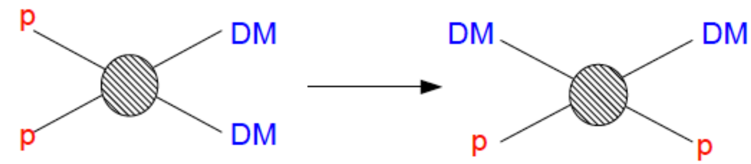
N^{jet} < 2 (p_T > 30 GeV)
$\Delta\phi$ (γ, E_T^{miss}) >0.4, $\Delta\phi$ (jet, E_T^{miss}) >0.4
Veto on leptons

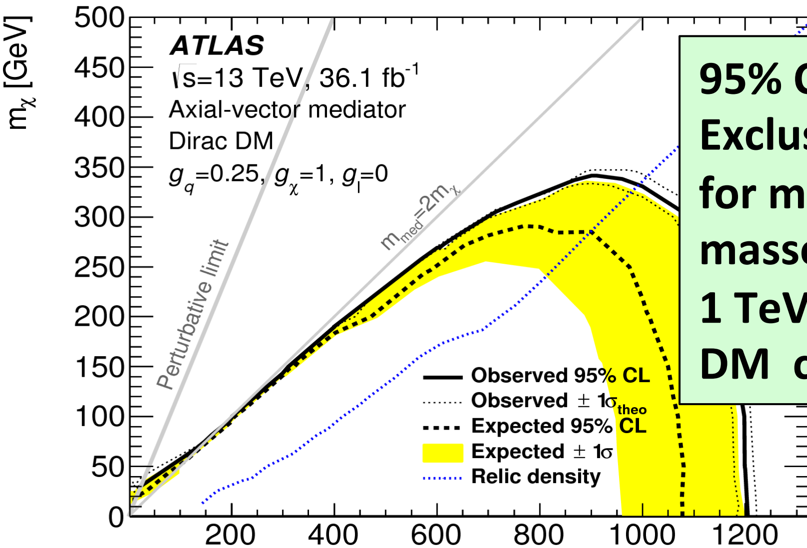
σxA < 7 – 2 fb @ 95% CL	SRI1	SRI2	SRI3
Observed events	2400	729	236
Fitted Background	2600±160	765±59	273±37
$Z(\to \nu\nu)\gamma$	1600±110	543±54	210±35
$W(\to \ell\nu)\gamma$	390±24	109±9	33±4
$Z(\to \ell\ell)\gamma$	35±3	7.8±0.8	2.2±0.4
γ + jets	248±80	22±7	5.2±1.0
Fake photons from electrons	199±40	47±11	13±3
Fake photons from jets	152±22	37±15	$9.7^{+10}_{-9.7}$

Good agreement with SM

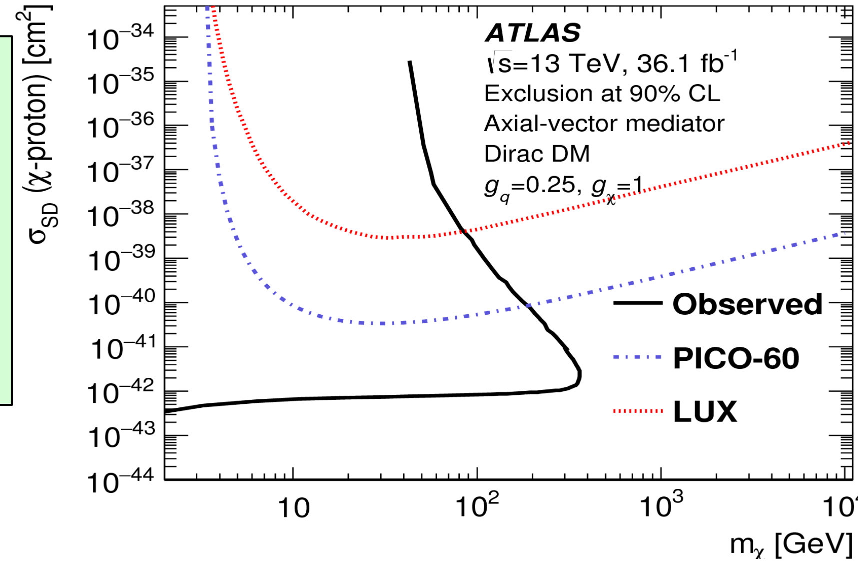


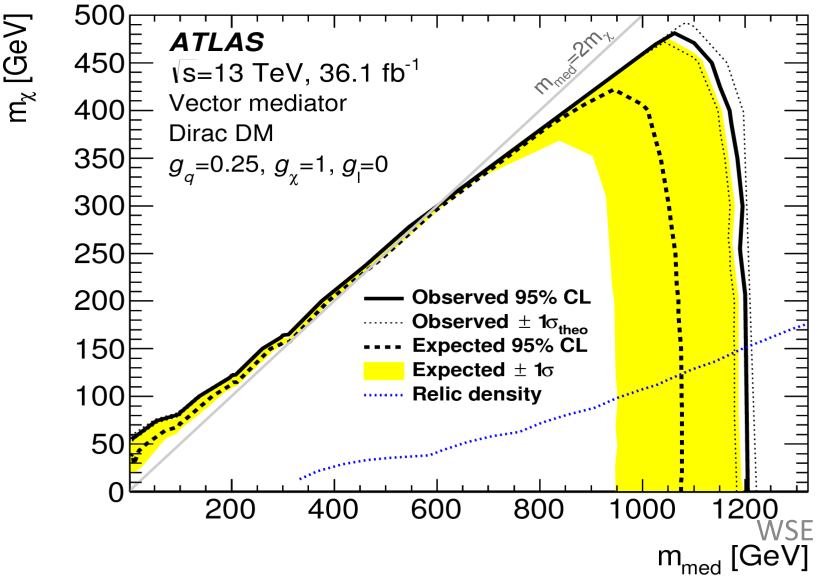
γ+X

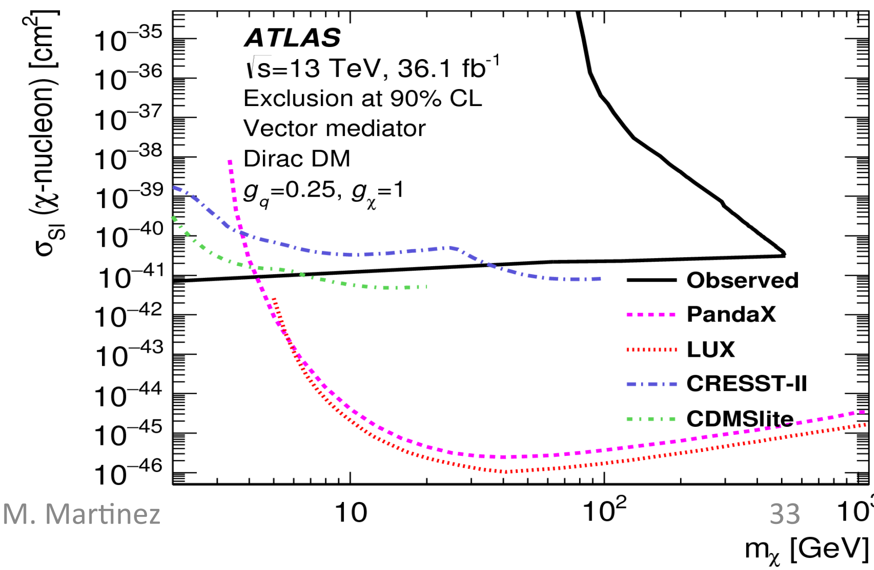




95% CL Exclusions for mediator masses below 1 TeV and light DM candidates



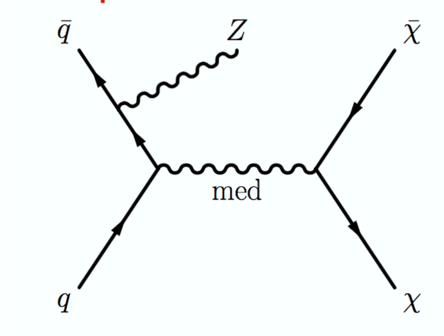


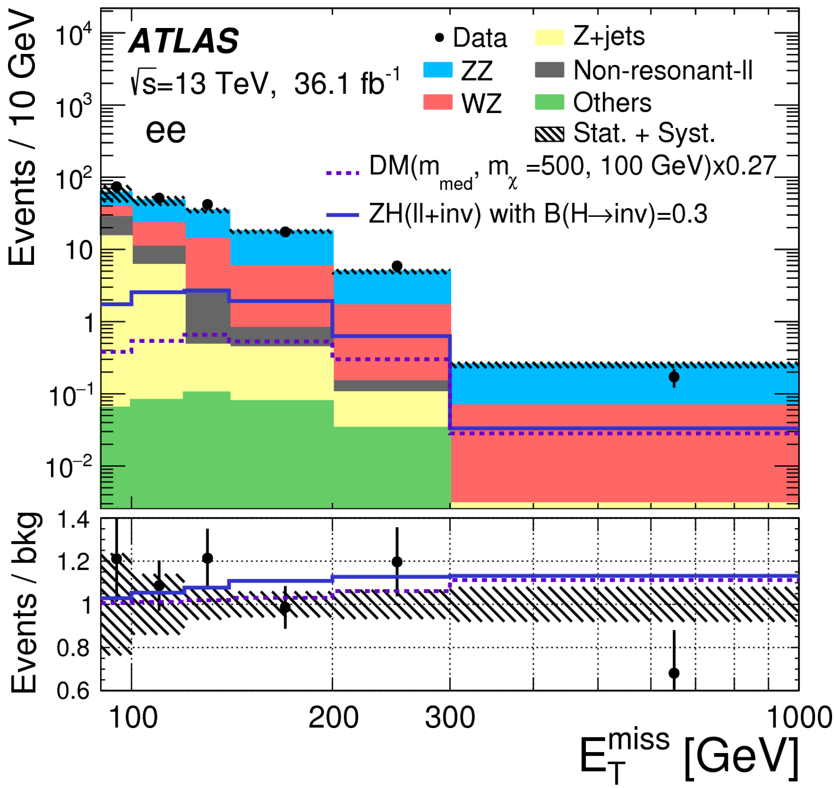


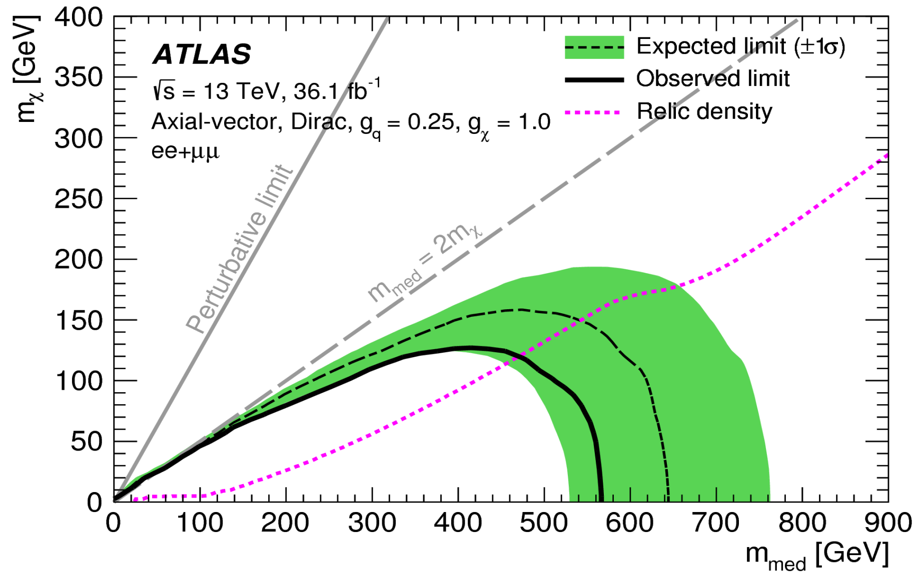
Mono-Z(→ll)

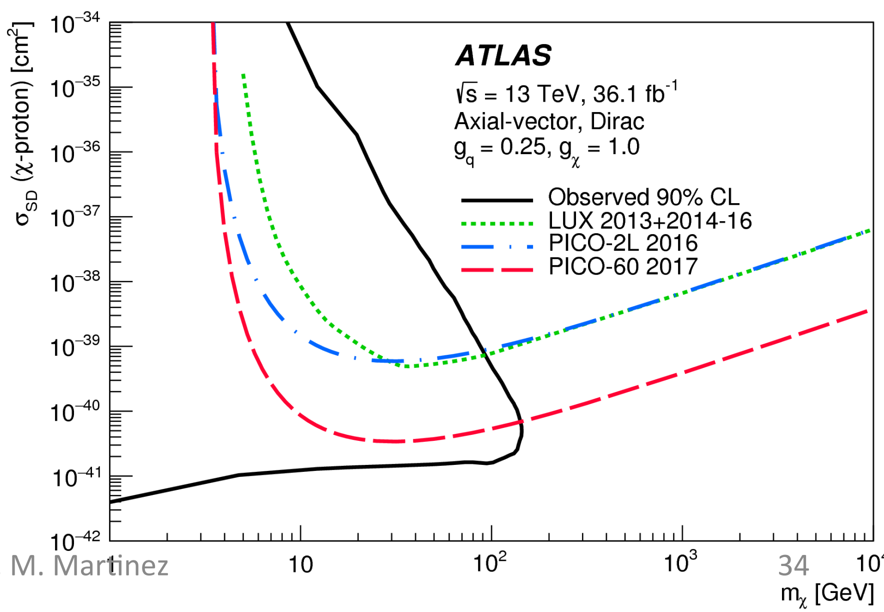
PLB 776 (2017) 318

36.1 fb^{-1}





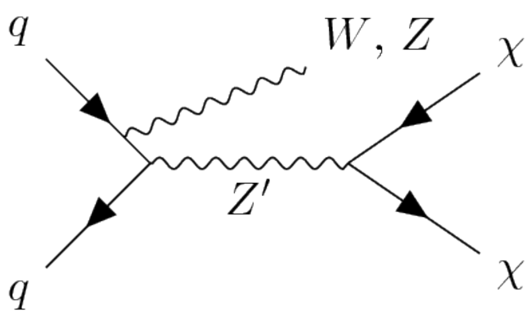




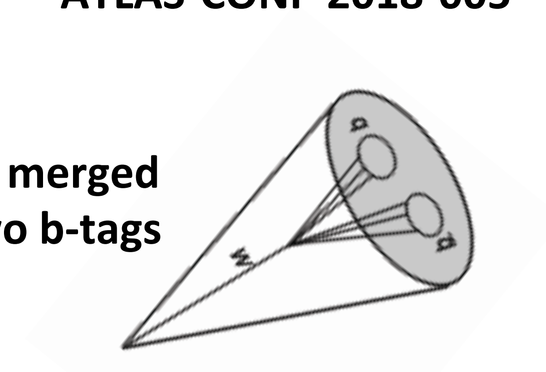
Mono-W/Z

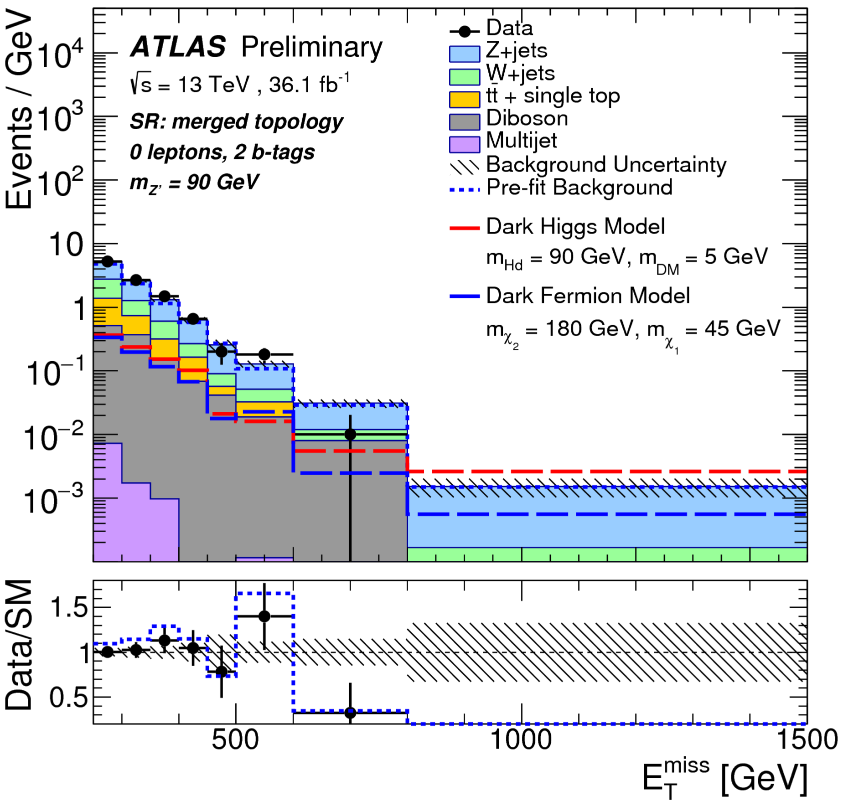
(hadronic channel)

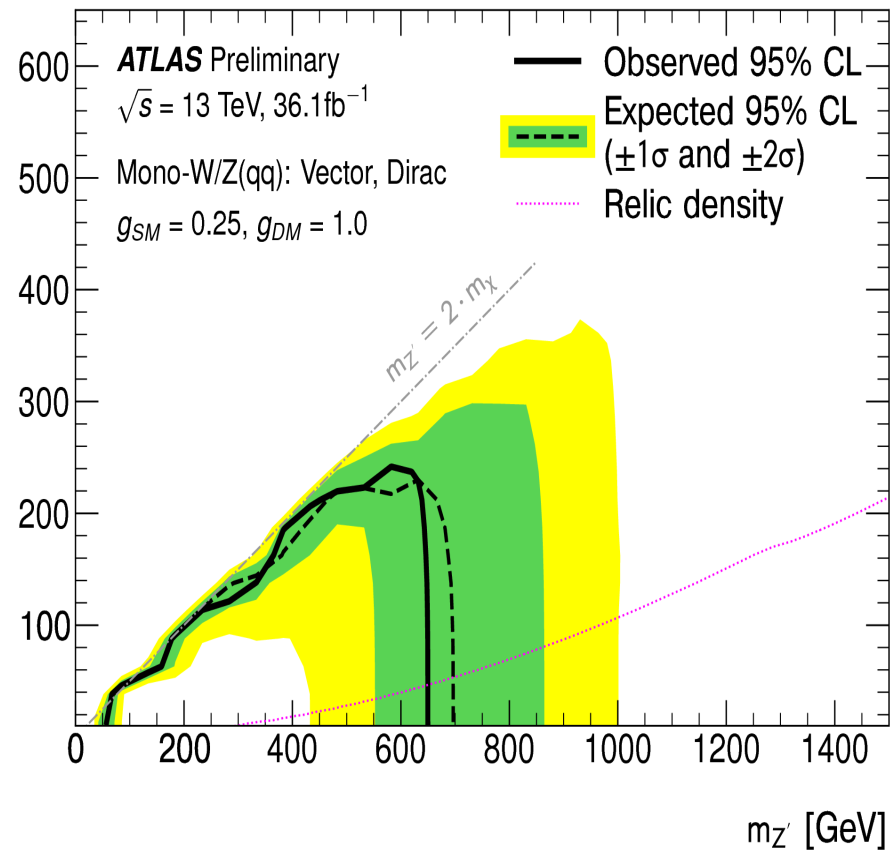
ATLAS-CONF-2018-005



Including resolved and merged configuration and w/wo b-tags







Dijets

37 fb^{-1}

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

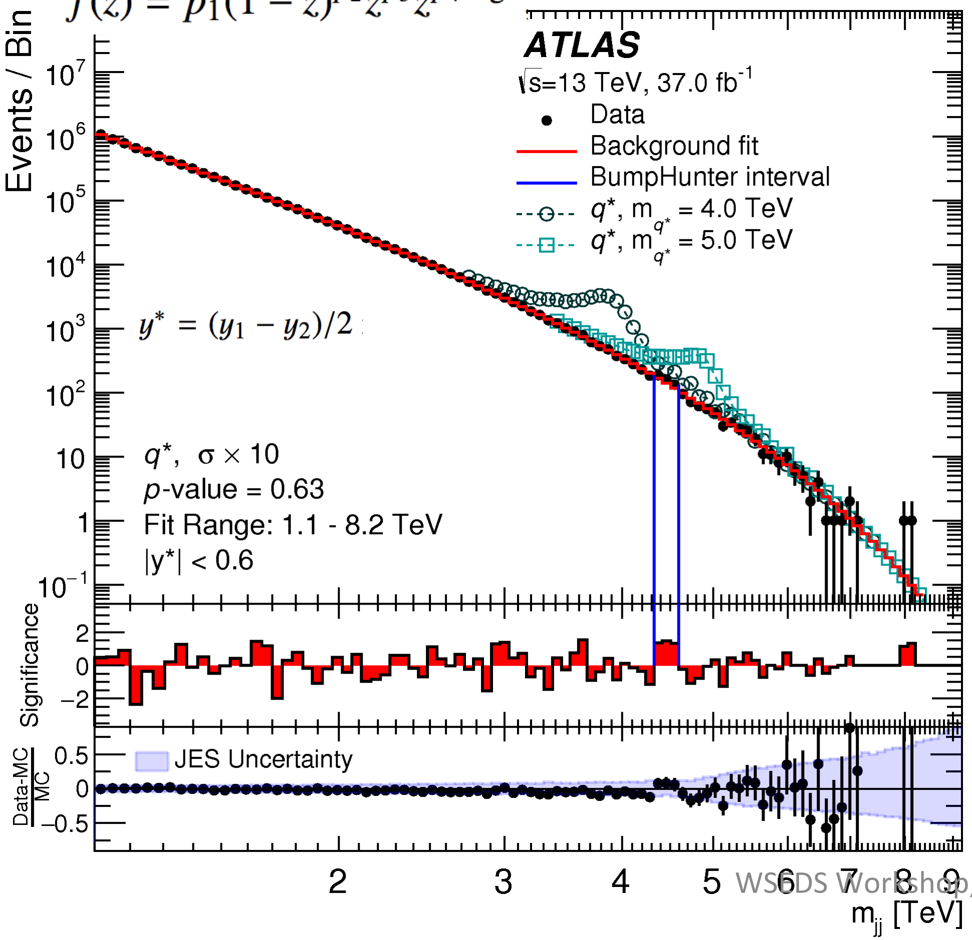
Phys. Rev. D 96 (2017) 052004

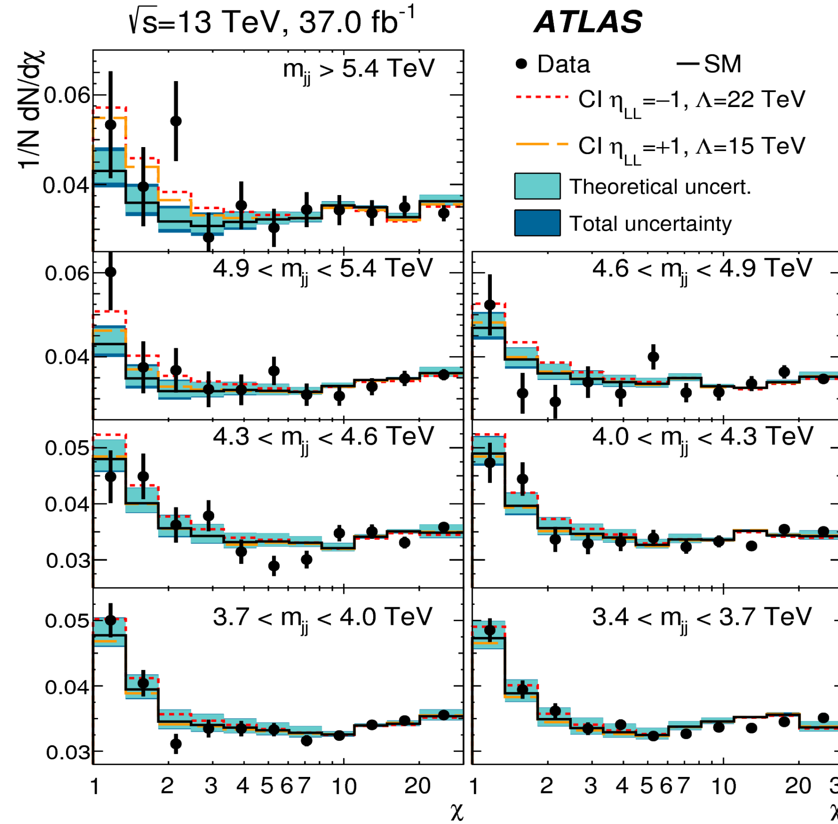
Search for resonances in dijets

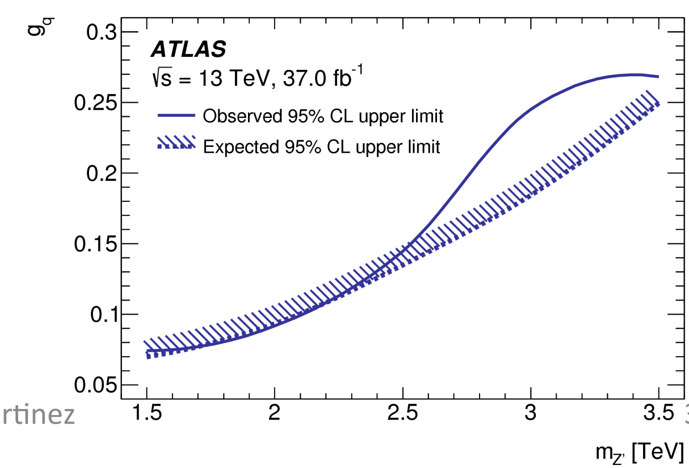
→ New physics should be central

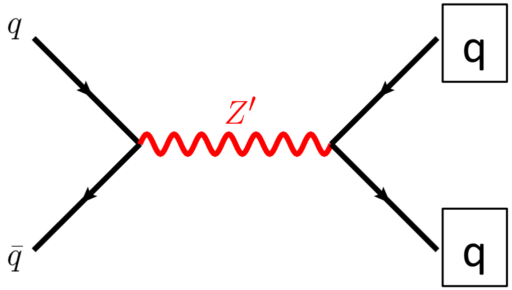
→ 95% CL on Z' → qq model (linked with DM)

$$f(z) = p_1(1-z)^{p_2} z^{p_3} z^{p_4 \log z}$$





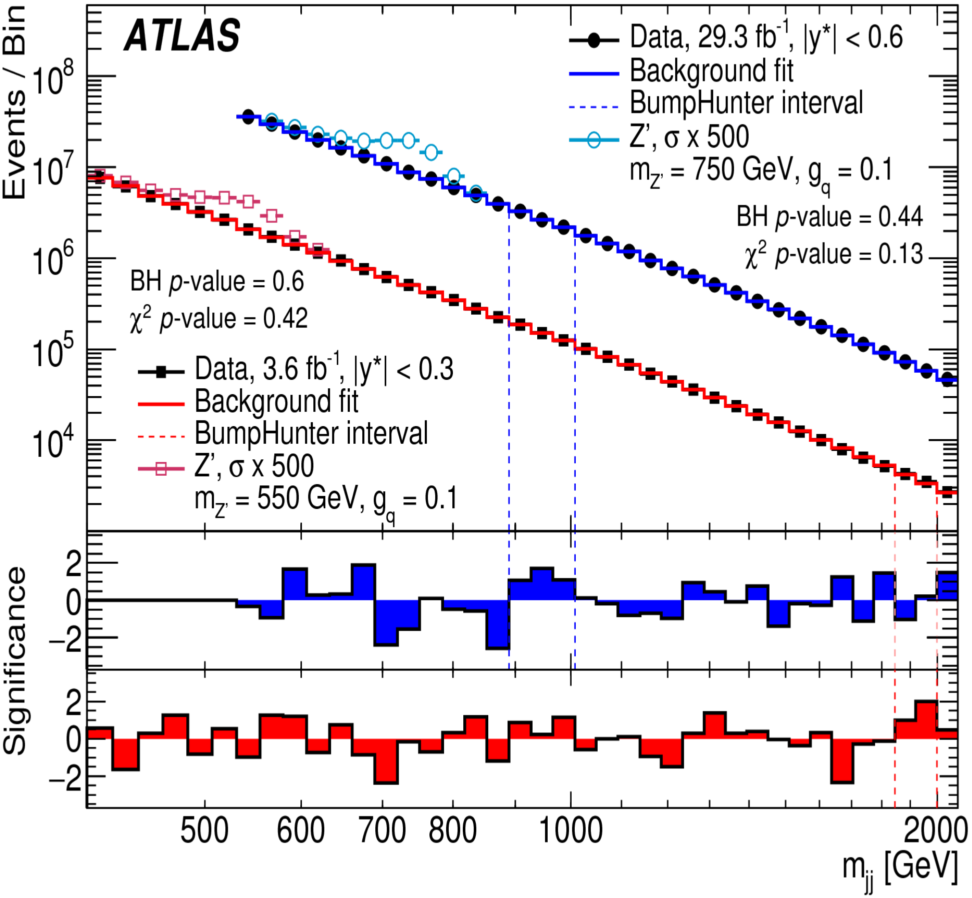


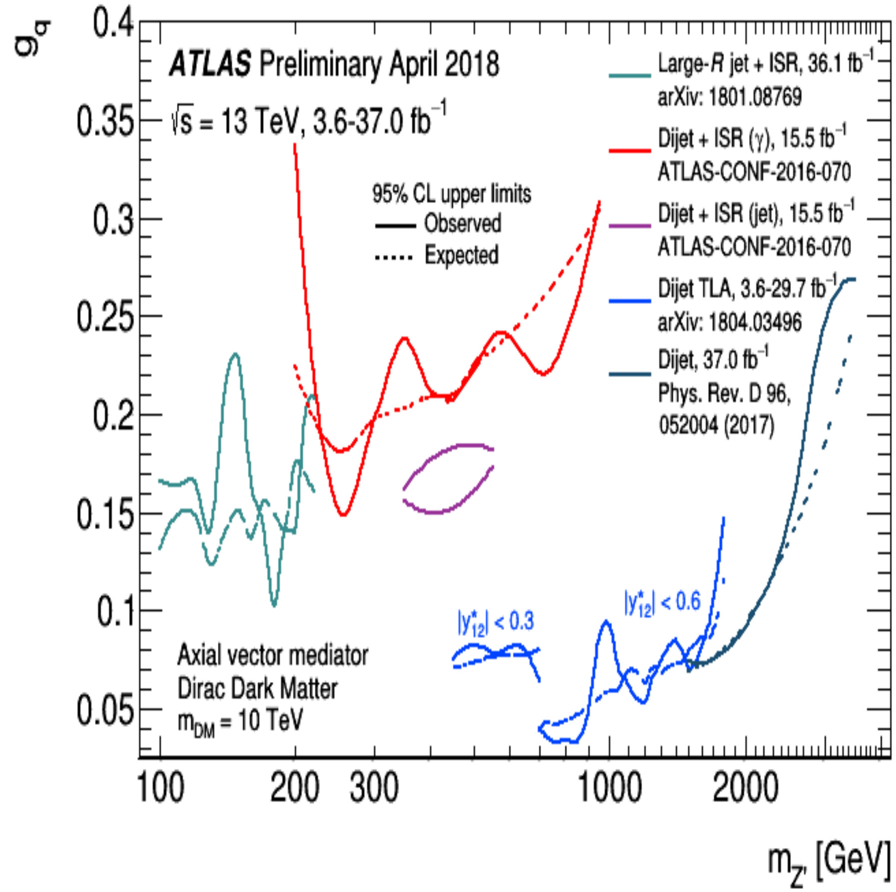


Dijet low mass

29.3 fb^{-1}

ATLAS: arXiv:1804.03496





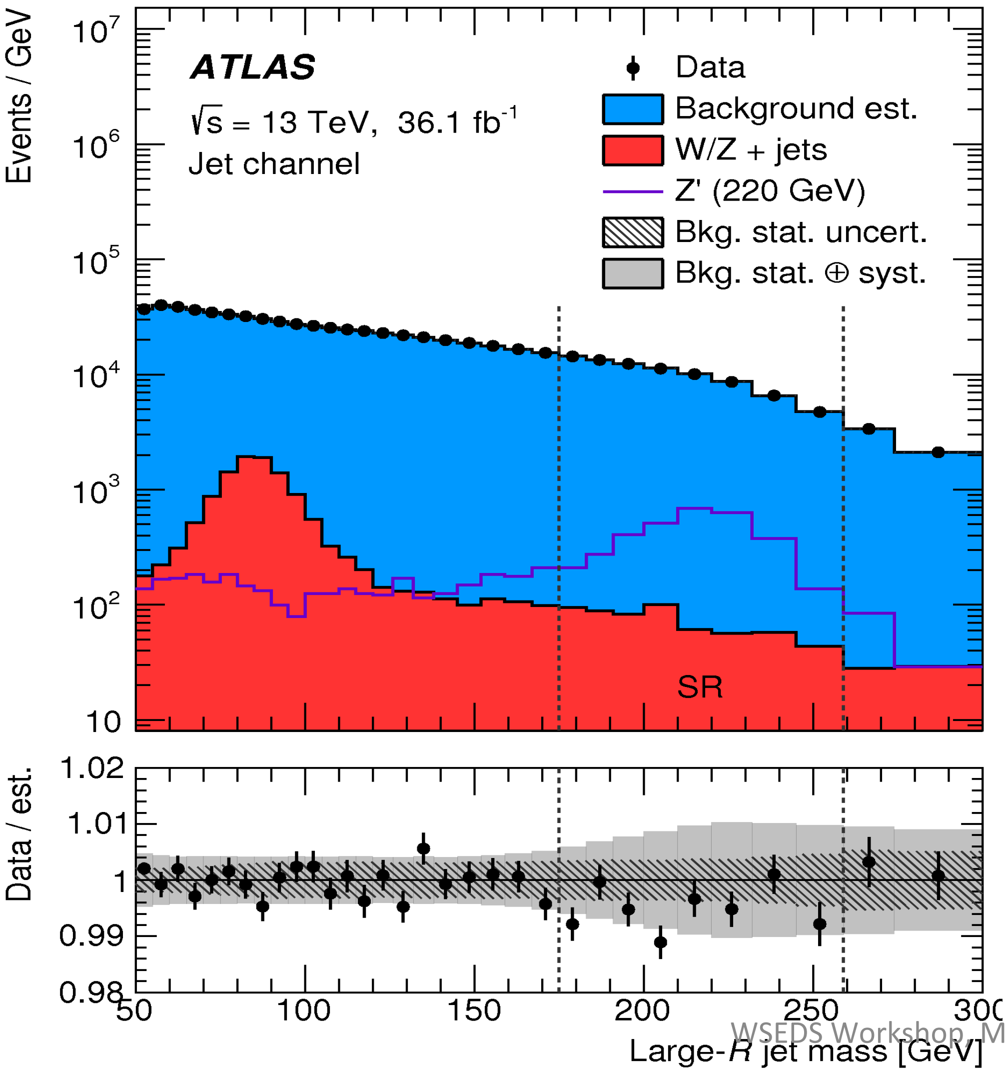
New ways at the trigger level to re-explore low mass dijets without paying bandwidth price
This opened the way to explore Z' low mass (0.5 – 1 TeV) at the LHC with coupling to quarks
→ **and can be reinterpreted in terms of the Z' mediator in DM models**

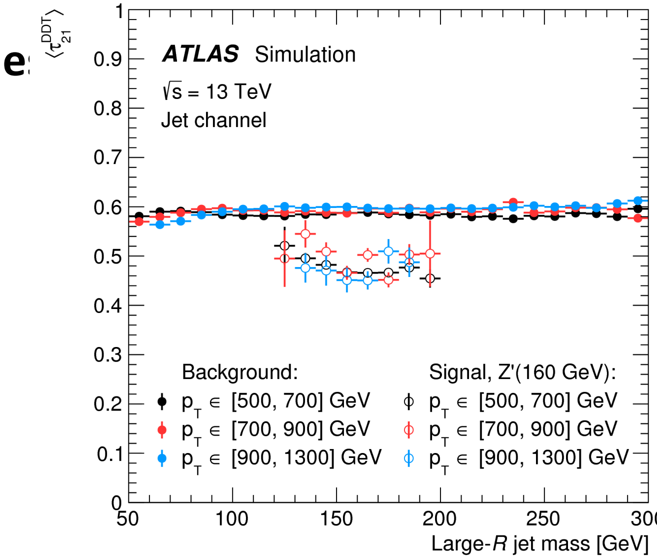
dijets + ISR

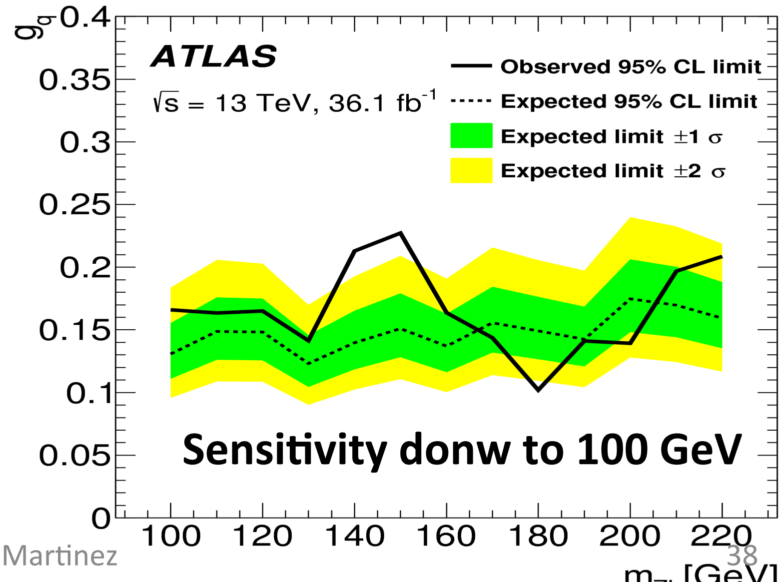
36.1 fb^{-1}

ATLAS: arXiv:1801.08769
Jesse Thaler, Ken Van Tilburg, JHEP 1103:015,2011

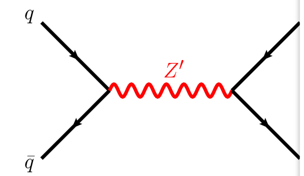
Search for low mass Z' (→ qq) + jet reconstructing the qq system (boosted) with refined subjet variables

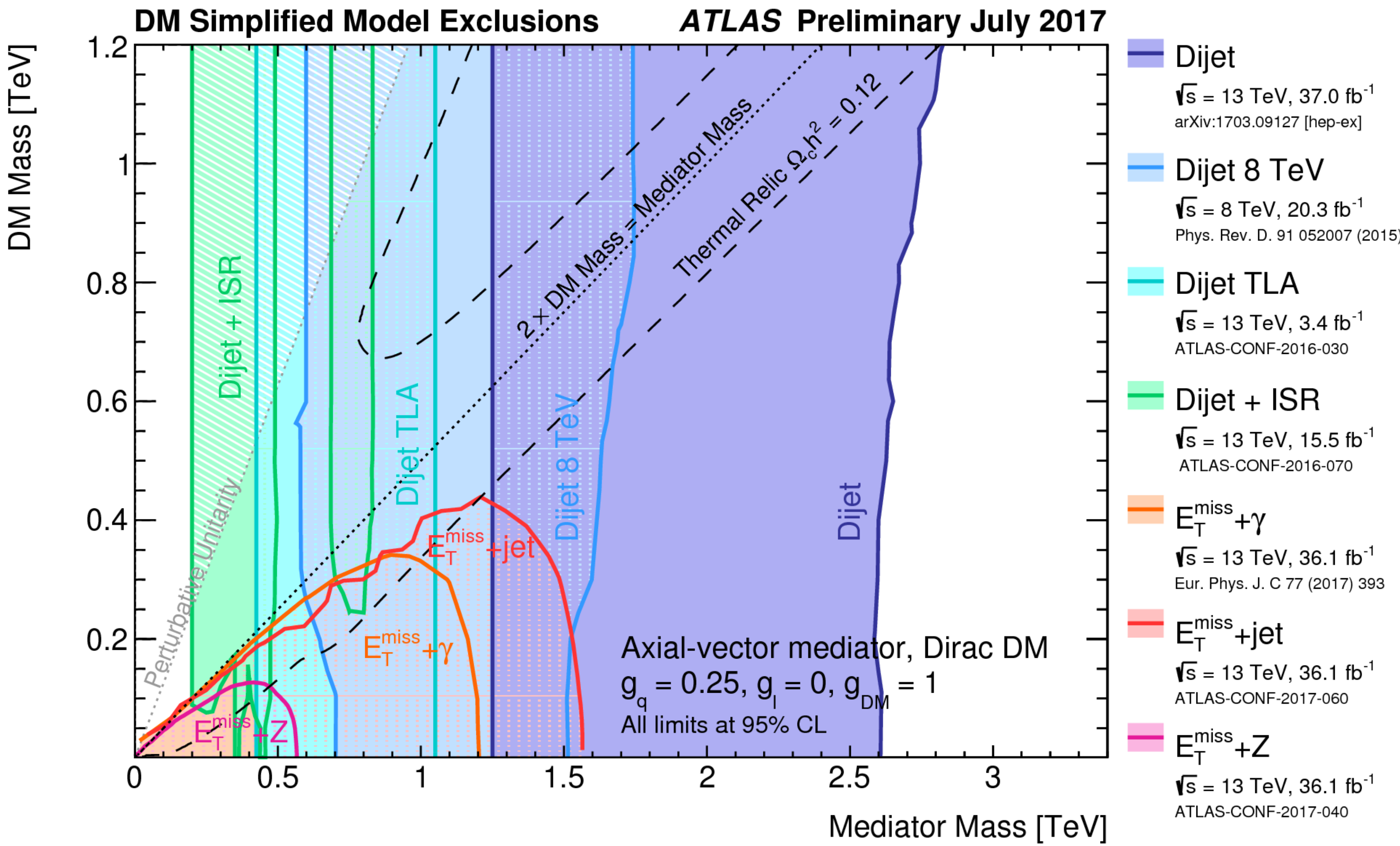






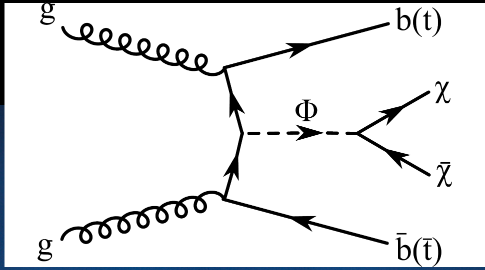
Summary Mono-X + Dijets





Benchmark Models

A set of well-defined simplified diagrams with heavy mediators is now considered motivated by a number of different considerations (DM Forum: arXiv:1507.00966)



- **Simple extensions of SM symmetries**
- **Minimal Flavor Violation**
- **Assuming Yukawa couplings → favor 3rd generation**
- **Some models inspired by satellite "hints"**

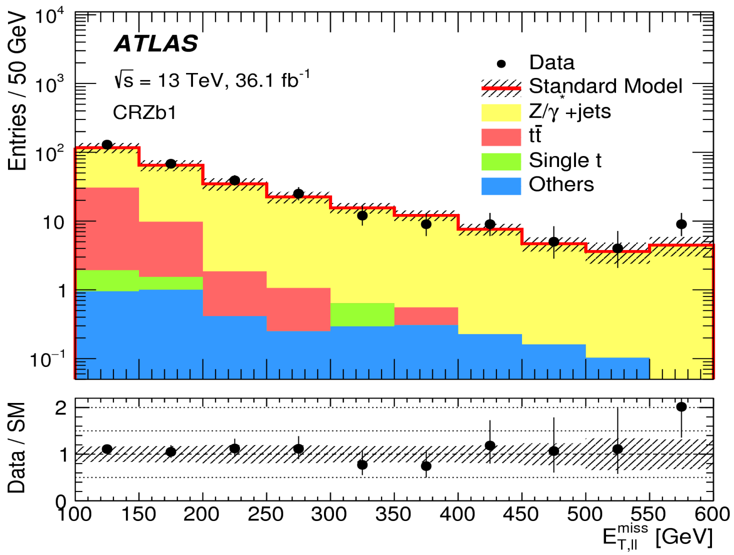
In some cases a clear overlap with SUSY-inspired simplified models for direct production of 3rd generation squarks

This part focused on DM+HF

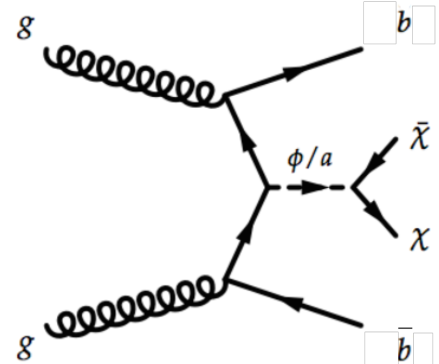
[Eur. Phys. J. C 78 (2018) 18]

DM+bb

√s=13 TeV, 36.1 fb^{-1}



Parameters:
Mediator and DM masses
(minimal mediator width)
couplings: g_q,g_{DM} = g=1



The analysis is optimized for a spin-0 mediator
Final state characterized by

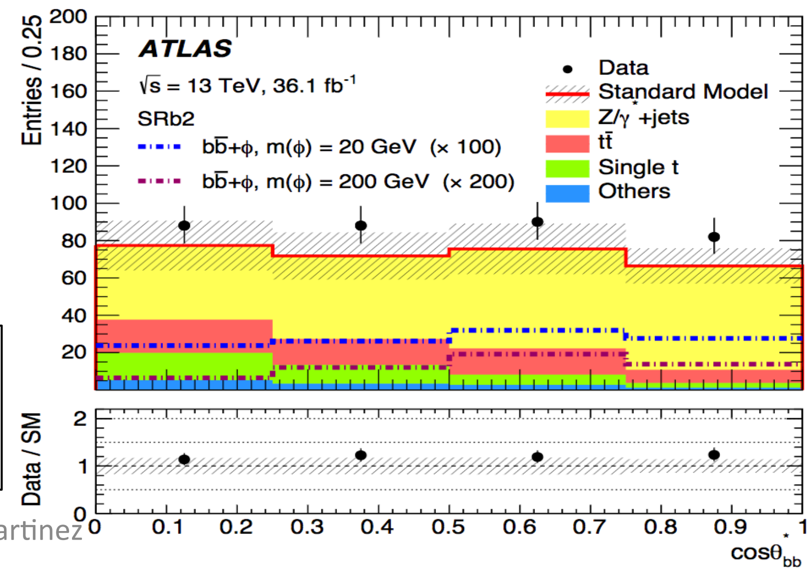
- Two b-jets, no more than 3-jets,
- Large missing transverse energy
- No leptons
- Azimuthal E_T^{miss}-Jet separation against QCD

As expected SM backgrounds driven by
Z(→νν)+bb, W(→lν)+bb and top quark production

Observable	SRb1	SRb2
Trigger	E_T^{miss}	
$\mathcal{N}_j$	≥ 2	2 or 3
$\mathcal{N}_b^T$	≥ 1	≥ 2
$\mathcal{N}_\ell^B$	0	
E_T^{miss} [GeV]	> 650	> 180
$p_T(bj_1)$ [GeV]	> 160	> 150
$p_T(j_1)$ [GeV]	> 160	> 150
$p_T(j_2)$ [GeV]	> 160	> 20
$p_T(j_3)$ [GeV]	-	< 60
H_{T3} [GeV]	< 100	-
H_T^{ratio}	-	> 0.75
δ^- [rad]	-	< 0
δ^+ [rad]	-	< 0.5
Multi-jet rejection specific		
$\Delta\phi(j, \vec{p}_T^{miss})$ [rad]	> 0.6	> 0.4

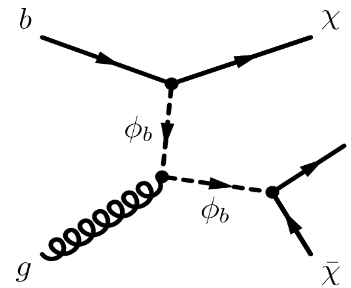
$$\delta^- = \Delta\phi(j, \vec{p}_T^{miss}) - \Delta\phi_{bb},$$
$$\delta^+ = |\Delta\phi(j, \vec{p}_T^{miss}) + \Delta\phi_{bb} - \pi|.$$

$$\boxed{\cos\theta^*_{bb} = \left|\tanh\left(\frac{\Delta\eta_{bb}}{2}\right)\right|}$$

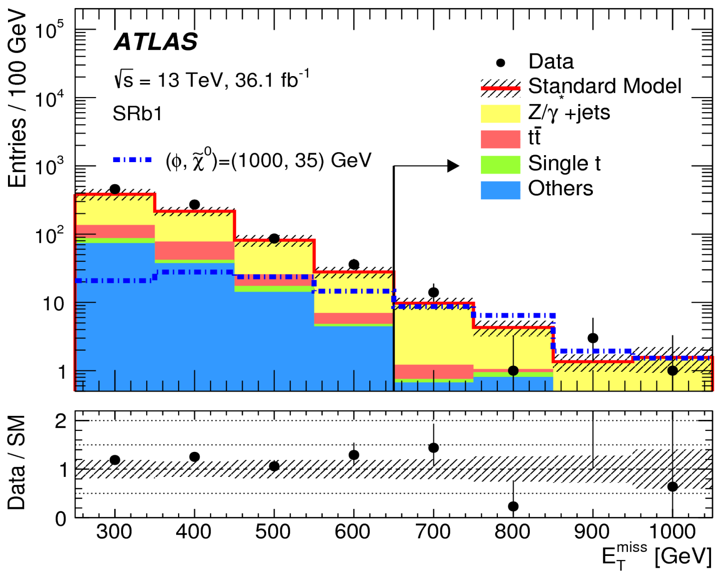


Eur. Phys. J. C 78 (2018) 18

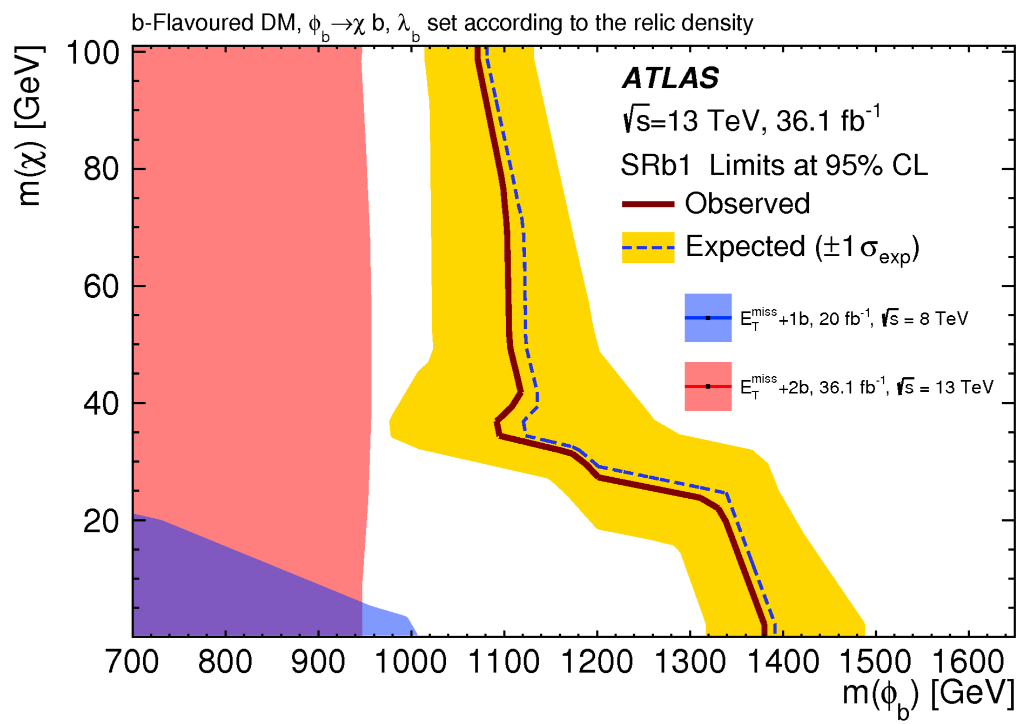
DM+b



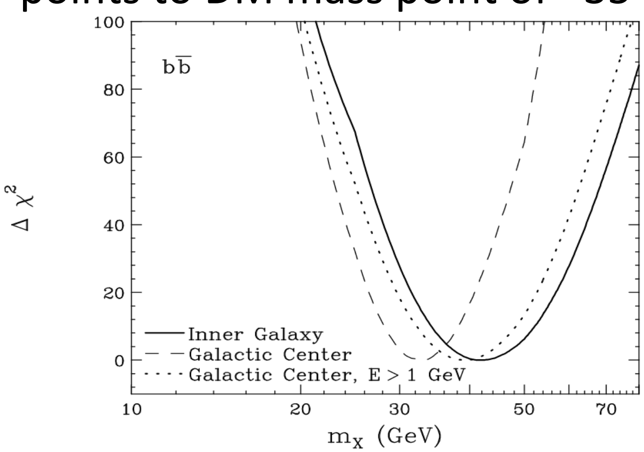
√s=13 TeV, 36.1 fb^{-1}



Bottom Flavored DM model
(motivated to accommodate Fermi-LAT hints)
P. Agrawal et al., Phys. Rev. D 90, 063512 (2014)



Analysis of Fermi-LAT data
points to DM mass point of ~35 GeV



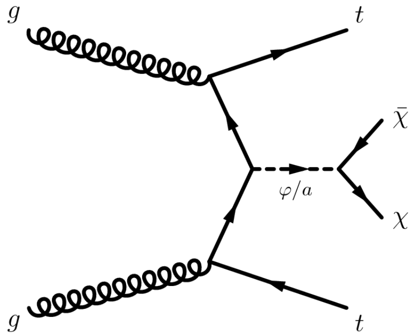
For a DM mass of 35 GeV, mediator masses in the range of 1.1 TeV are excluded at 95% CL

Taken from: T. Daylan et al.,
Physics of the Dark Universe Volume 12, P1, 2016

DM+tt

(hadronic channel)

$\sqrt{s}$=13 TeV, 36.1 fb^{-1}
Eur. Phys. J. C 78 (2018) 18



Large E_T^{miss} and E_T^{miss} significance
At least four jets, and 2 b-jets, lepton veto

Reconstruction of two large jets R=1.2
with masses above 140 and 80 GeV

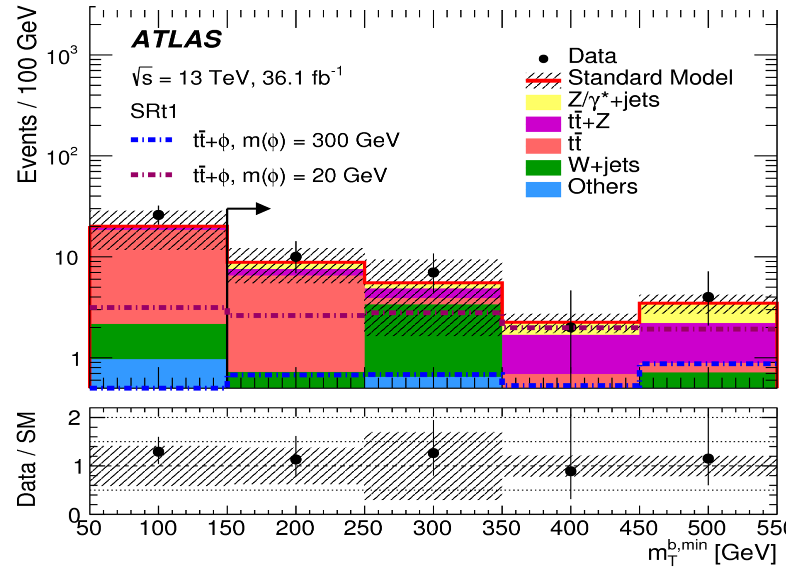
Some topological requirements optimized for a
DM signal with M_{MED} = 100-300 GeV and M_{DM} = 1 GeV

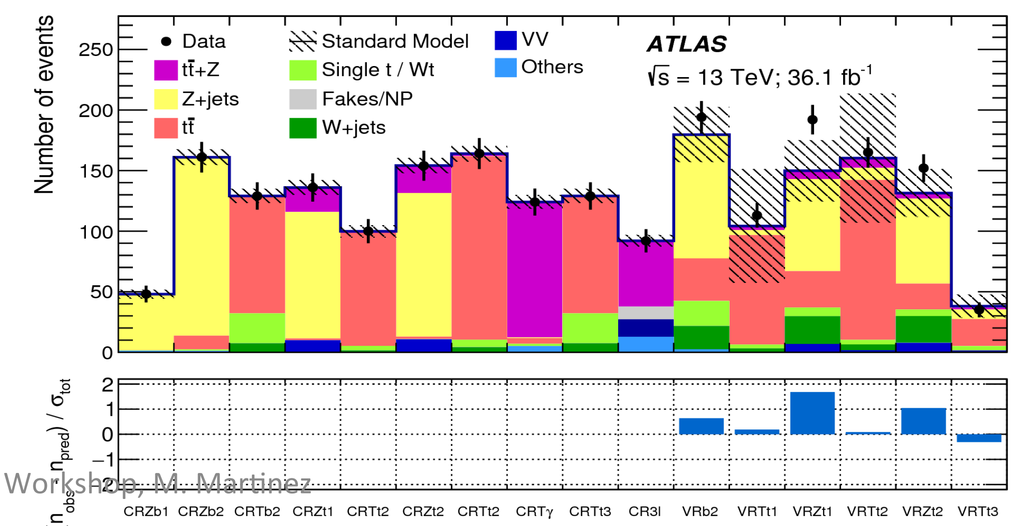
$\Delta R(bb) > 1.5$, $M_T{}^{b,min} > 200$ GeV

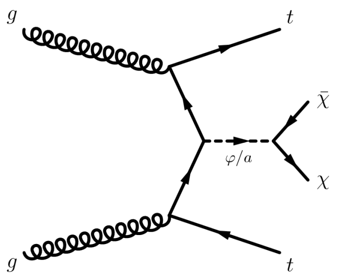
→ Dominated by top production
(tt & Z(→ νν)+jets)

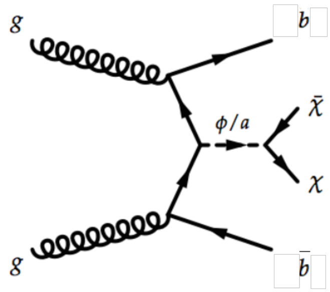
Background normalizations constrained
in dedicated control regions.

$$m_T^{b,\min} = \sqrt{2\, p_T^b\, E_T^{\text{miss}} \left[1 - \cos\Delta\phi\left(\mathbf{p}_T^b, \mathbf{p}_T^{\text{miss}}\right)\right]}$$







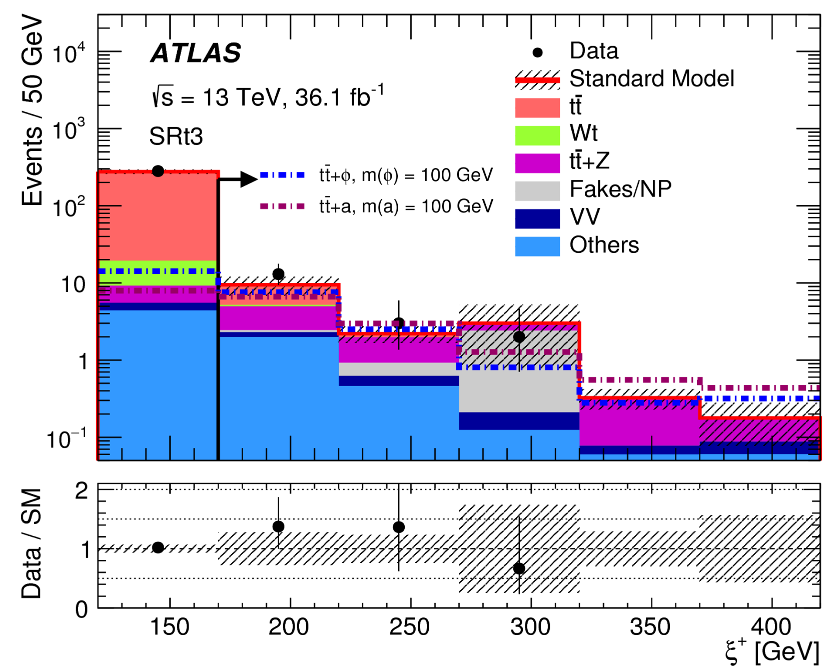


Results

√s=13 TeV, 36.1 fb^{-1}
[Eur. Phys. J. C 78 (2018) 18]

	SRt1	SRt2	SRt3
Observed	23	24	18
Total background (fit)	20.5 ± 5.8	20.4 ± 2.9	15.2 ± 4.3
$t\bar{t}$	7.0 ± 3.9	3.1 ± 1.3	4.5 ± 2.5
$t\bar{t}$+Z	4.3 ± 1.1	6.9 ± 1.4	4.4 ± 1.9
W+jets	3.3 ± 2.6	1.28 ± 0.50	incl. in Fakes/NP
Wt	incl. in Others	incl. in Others	$0.33^{+0.53}_{-0.33}$
Z/γ^*+ jets	3.7 ± 1.4	6.2 ± 1.1	incl. in Others
VV	incl. in Others	incl. in Others	0.61 ± 0.25
Fakes/NP	-	-	2.7 ± 1.3
Others	2.2 ± 1.2	3.00 ± 1.6	2.69 ± 0.93
$t\bar{t}$ (pre-fit)	6.1	2.8	4.0
$t\bar{t}$+Z (pre-fit)	3.53	5.6	5.6
Z/γ^*+ jets (pre-fit)	3.2	5.72	-

$$\xi^+ = m_{\mathrm{T2}}^{\ell\ell} + 0.2 \cdot E_{\mathrm{T}}^{\mathrm{miss}}$$



Good agreement with SM predictions in all SRs

Analyses with a sensitivity to Exclude new physics processes at the 1 fb level

$$\cos\theta^*_{bb} = \left|\tanh\left(\frac{\Delta\eta_{bb}}{2}\right)\right|$$

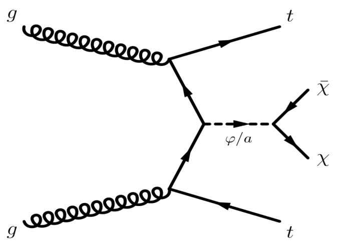
Signal channel	$\langle\epsilon\mathcal{A}\sigma\rangle_{95}^{\mathrm{obs}}$[fb]	S_{95}^{obs}	S_{95}^{exp}	$p(s=0)$ (Z)
SRb1	0.37	13.4	12^{+5}_{-1}	0.33 (0.43)
SRb2 bin-1	1.10	39.6	33^{+12}_{-8}	0.22 (0.76)
SRb2 bin-2	1.17	42.1	31^{+10}_{-8}	0.11 (1.21)
SRb2 bin-3	1.21	43.7	33^{+11}_{-8}	0.16 (1.00)
SRb2 bin-4	1.10	39.8	26^{+11}_{-7}	0.10 (1.26)
SRt1	0.51	18.4	16^{+5}_{-4}	0.33 (0.44)
SRt2	0.44	15.7	12^{+5}_{-3}	0.24 (0.70)
SRt3	0.44	15.9	13^{+5}_{-2}	0.33 (0.45)

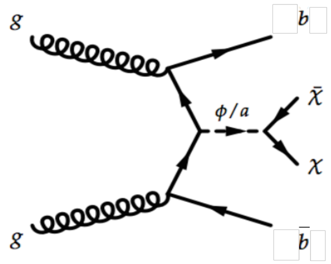
Results

√s=13 TeV, 36.1 fb^{-1}

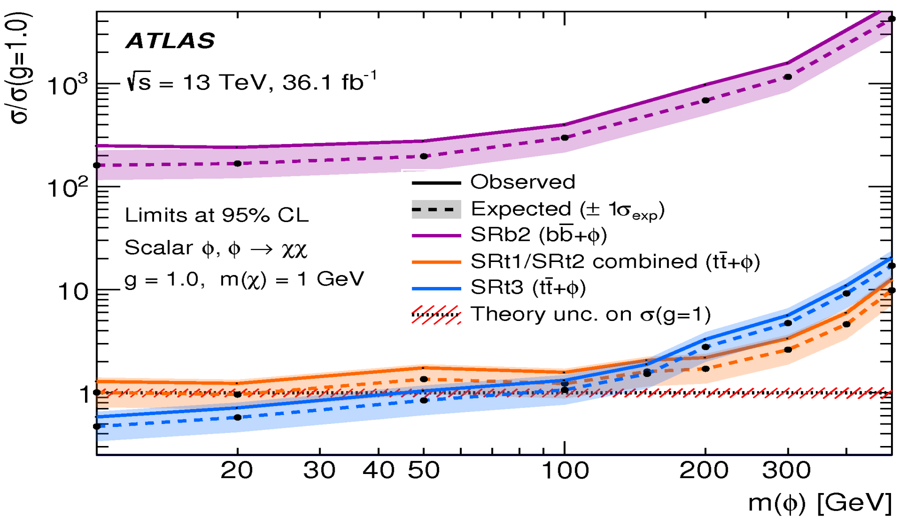
Eur. Phys. J. C 78 (2018) 18

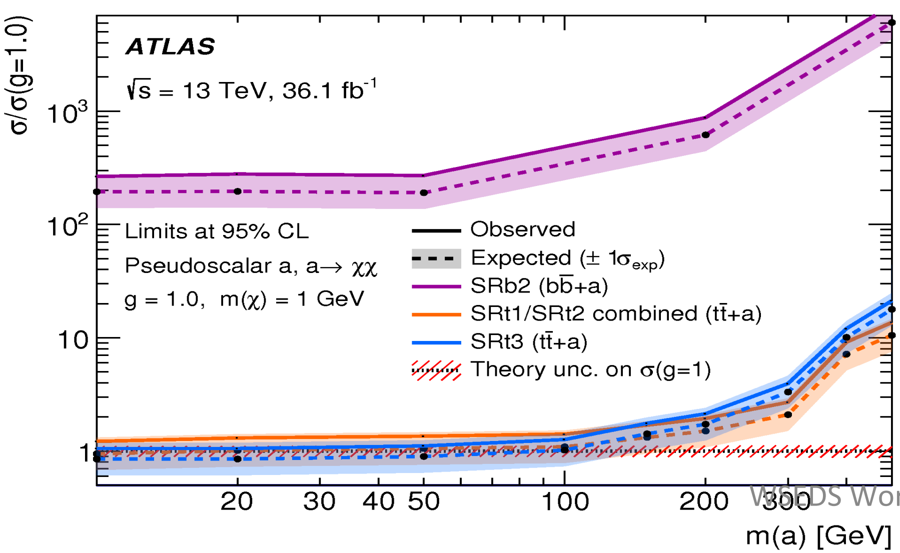
ATLAS EXPERIMENT

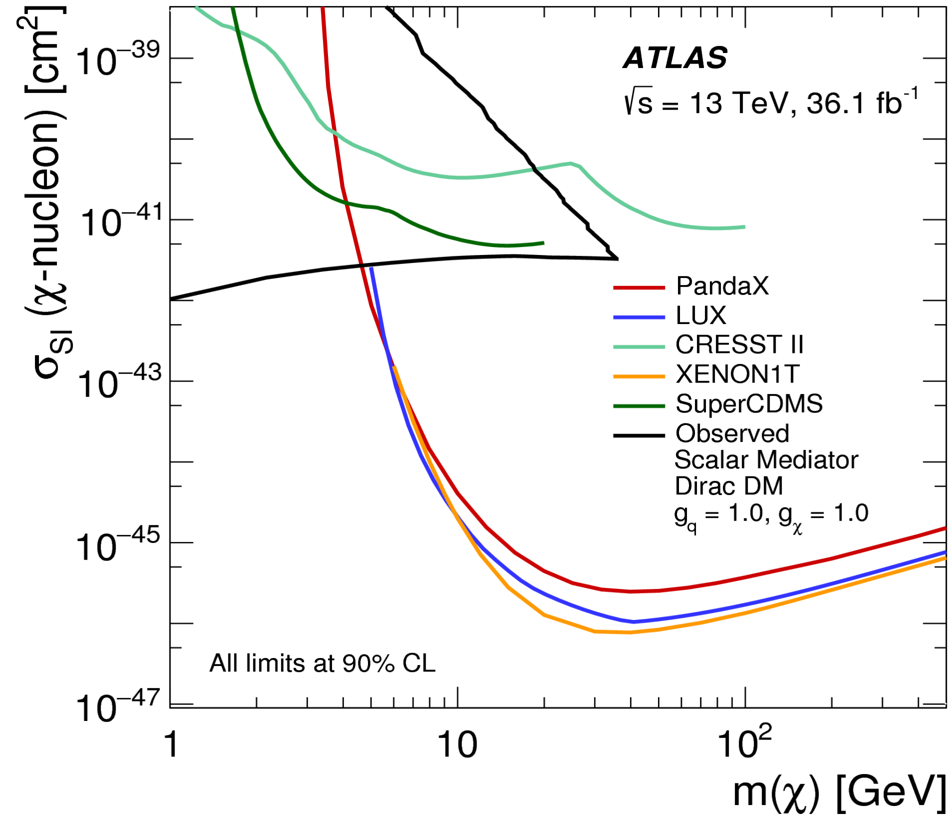




95%CL upper limits w.r.t σ_{signal} @ g=1







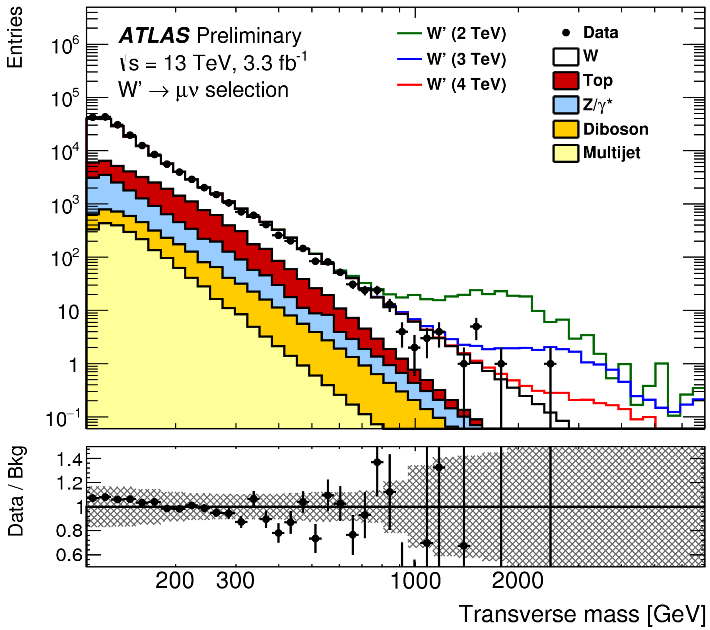
The tt+X analysis shows the sensitivity of the benchmark model with g= 1 for 1GeV DM for both scalar and pseudo-scalar mediators
→ Limits depend strongly on the DM mass.

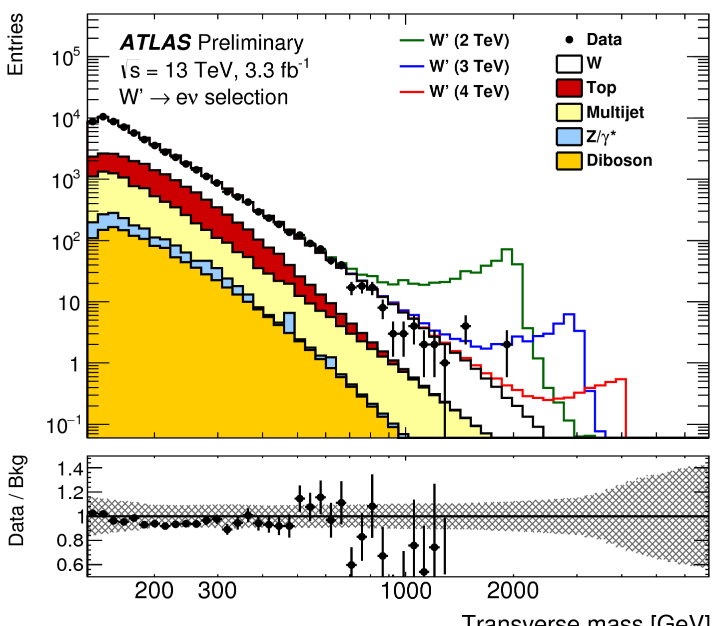
Exotic Searches

Not complete sampling of different searches

ATLAS-CONF-2015-063

W' → lν

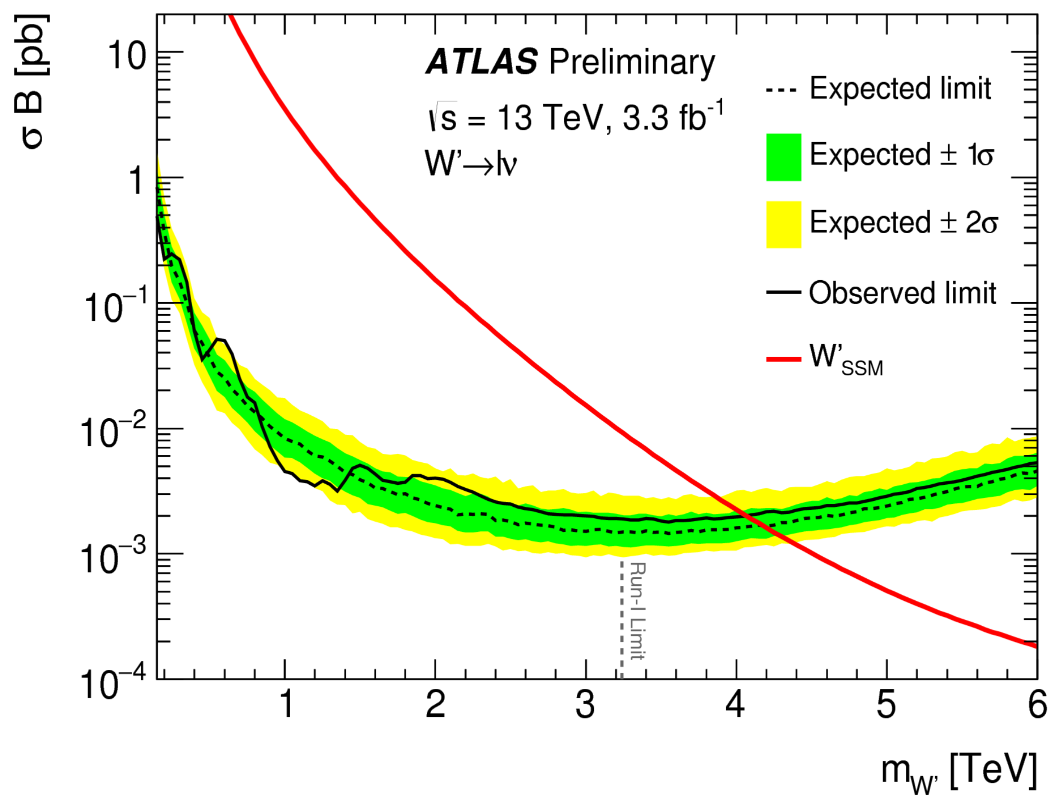




Theories with larger groups than those of the SM might predict to the presence of new bosons

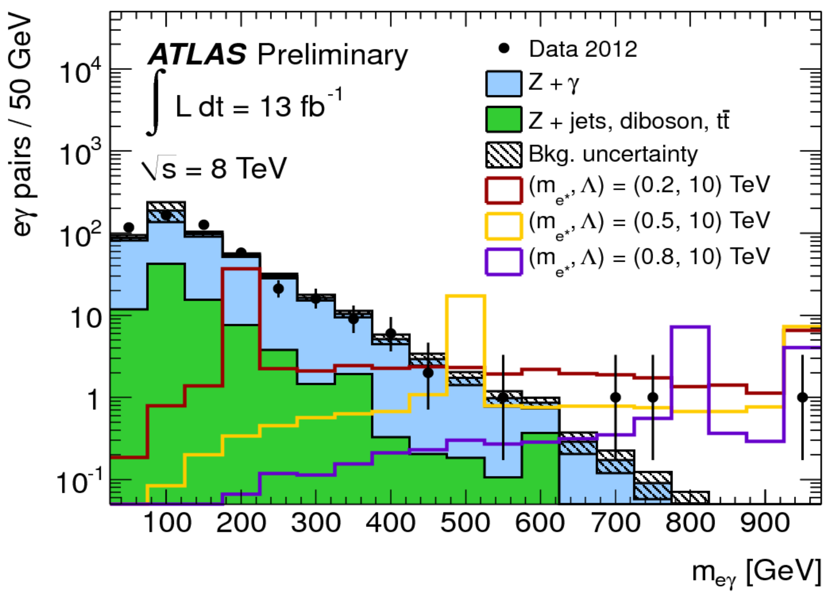
→ One typically assumes SM-like couplings

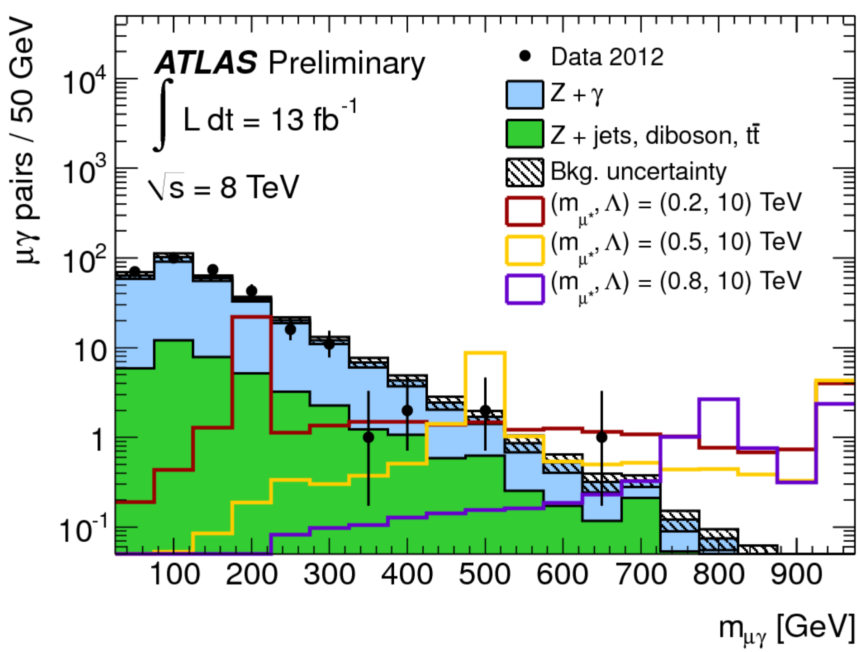
$$m_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}} E_{\mathrm{T}}^{\mathrm{miss}} (1 - \cos \phi_{\ell\nu})},$$



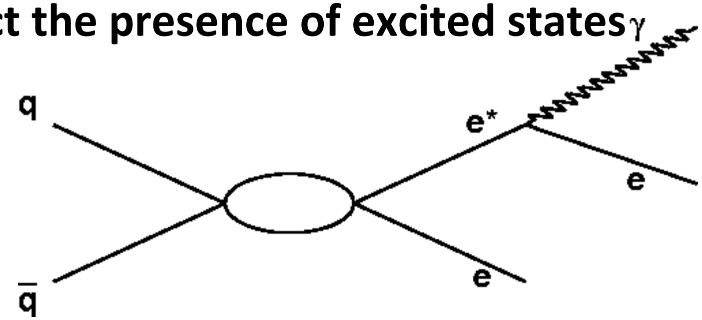
ATLAS-CONF-2012-146

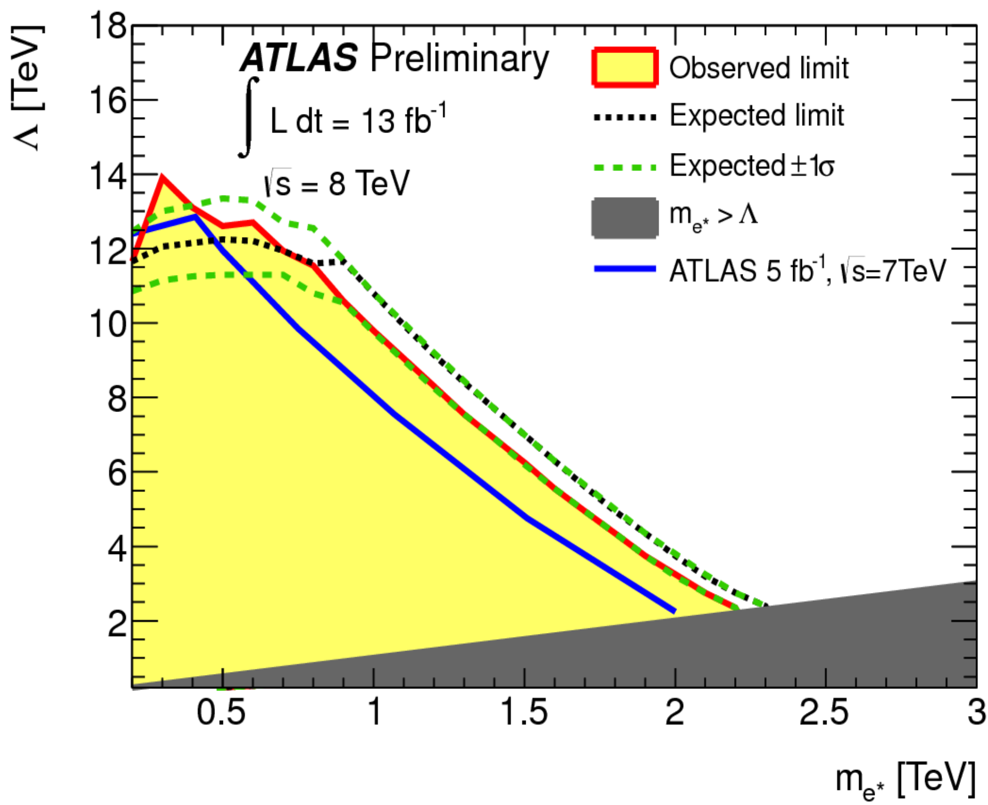
Excited Leptons





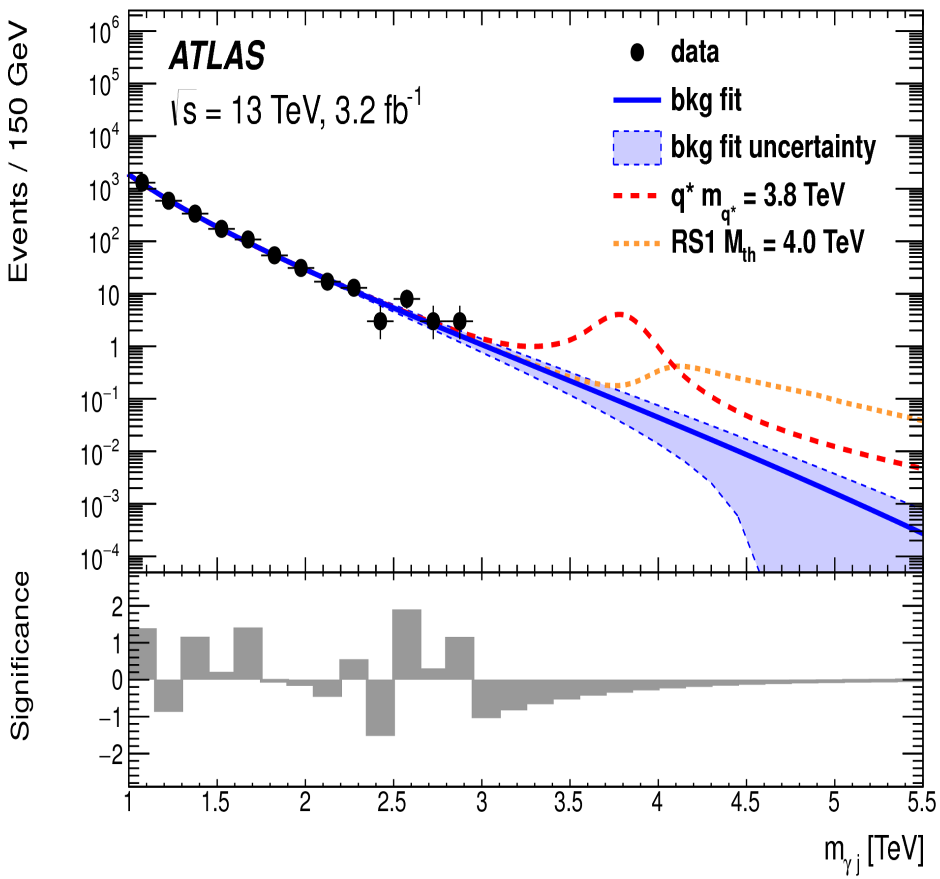
Composite models try to understand the Lepton/quark degeneracy and usually predict the presence of excited states

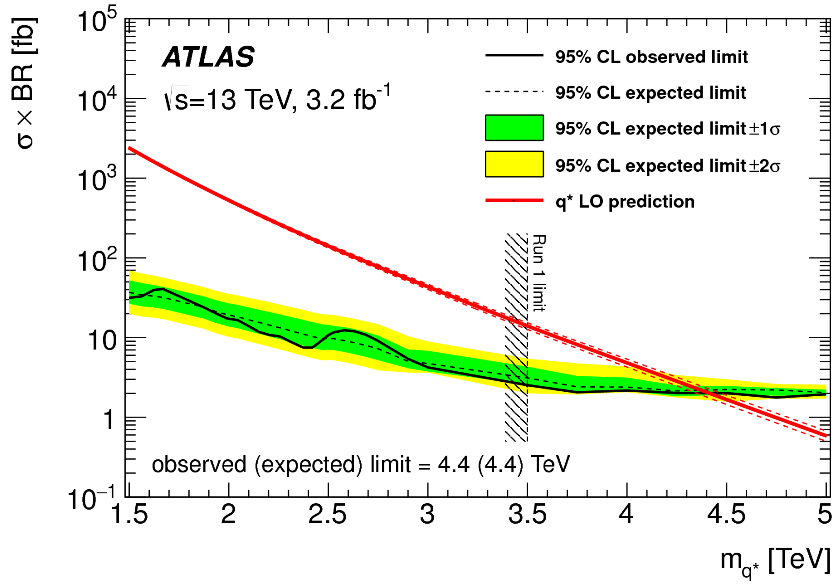


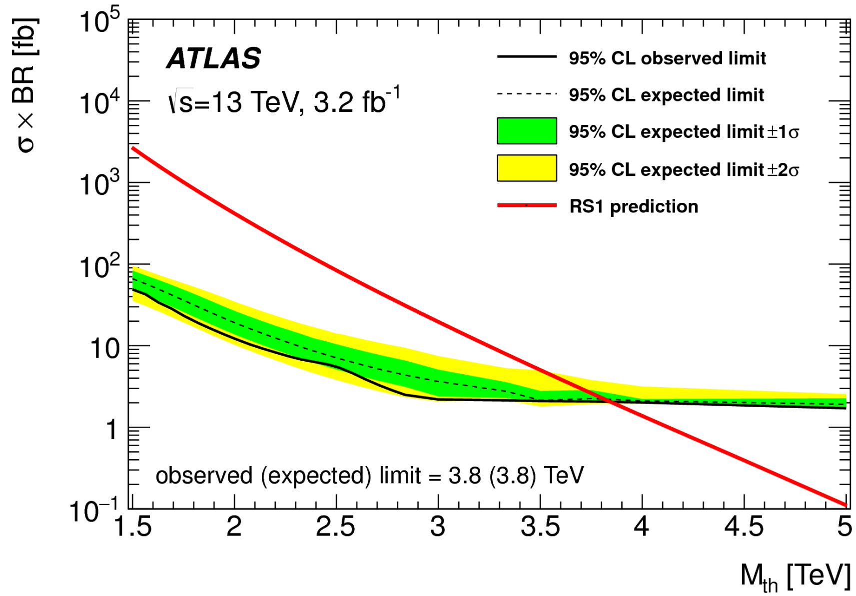


Excited quarks q* → qγ

Composite models try to understand the Lepton/quark degeneracy and usually predict the presence of excited states

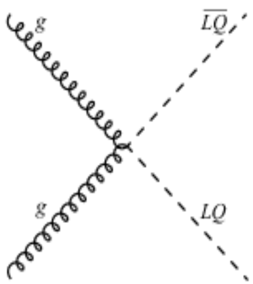


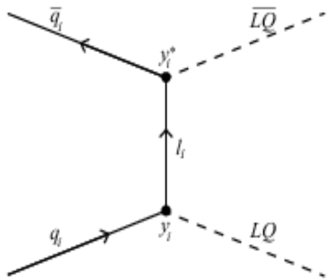




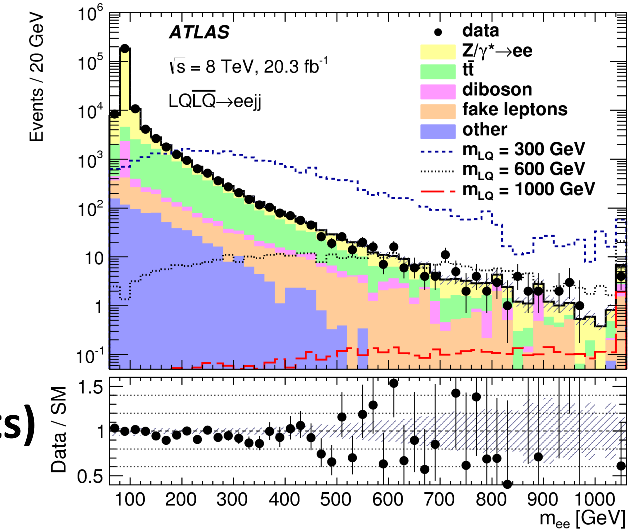
arXiv:1508.04735

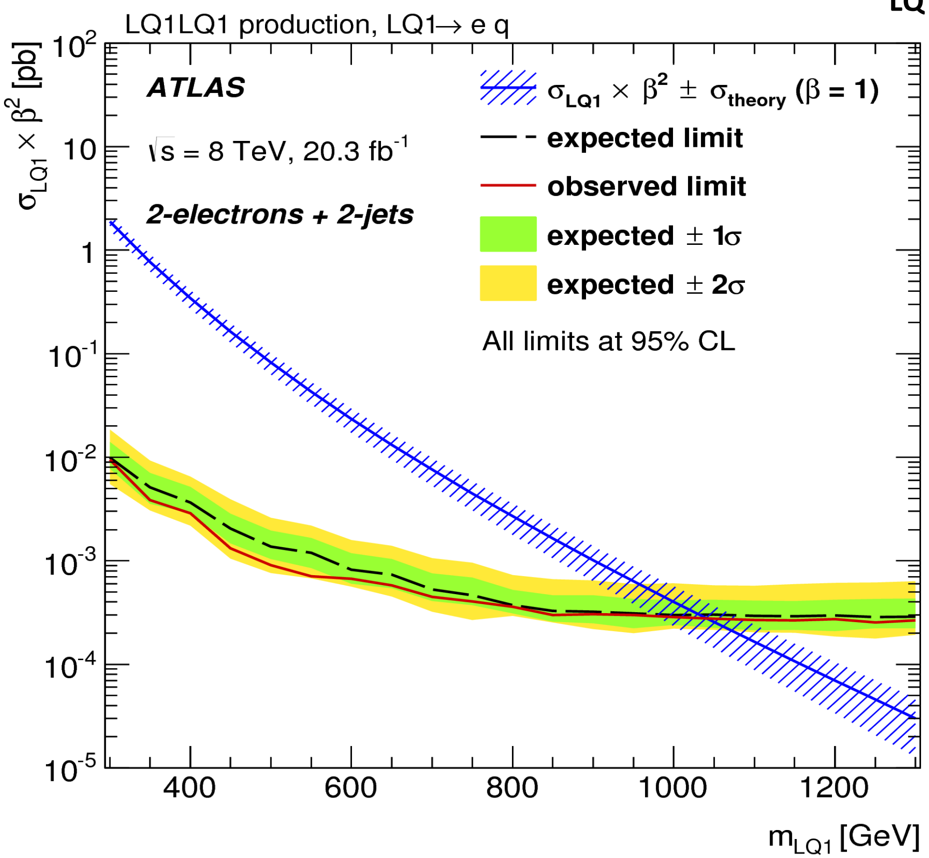
Lepto-quarks

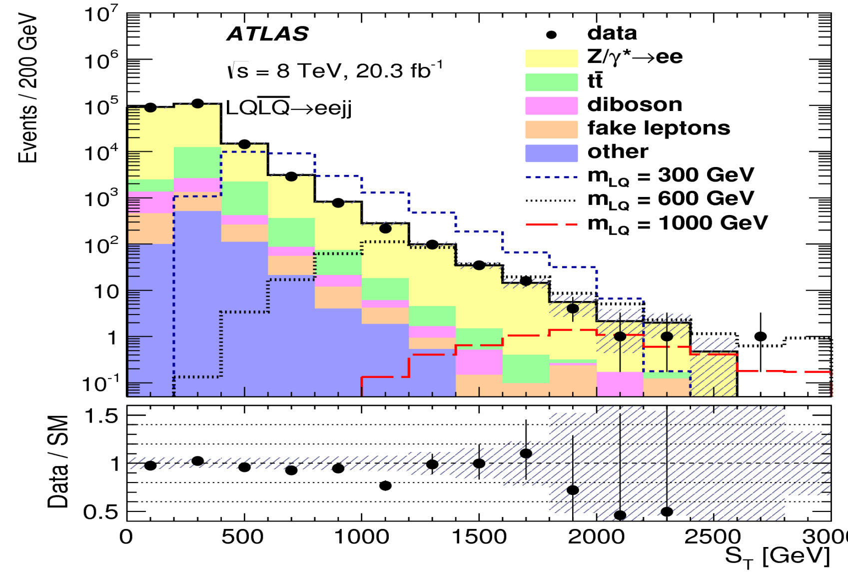




2leptons + 2 jets
Selection based on
- **Dilepton mass**
- **S_T (leptons and jets)**
- **M_{LQ}^{Min}**



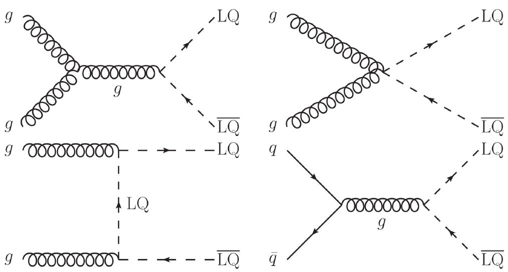


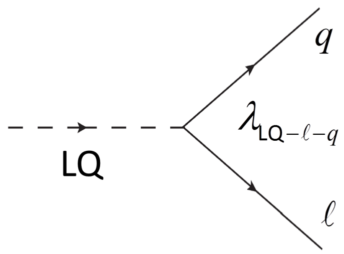


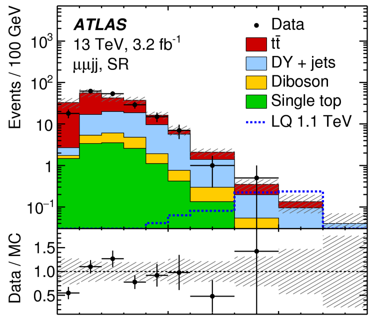
Lepto-quark (1^{st} -2^{nd} gene.)
masses below 1 TeV excluded

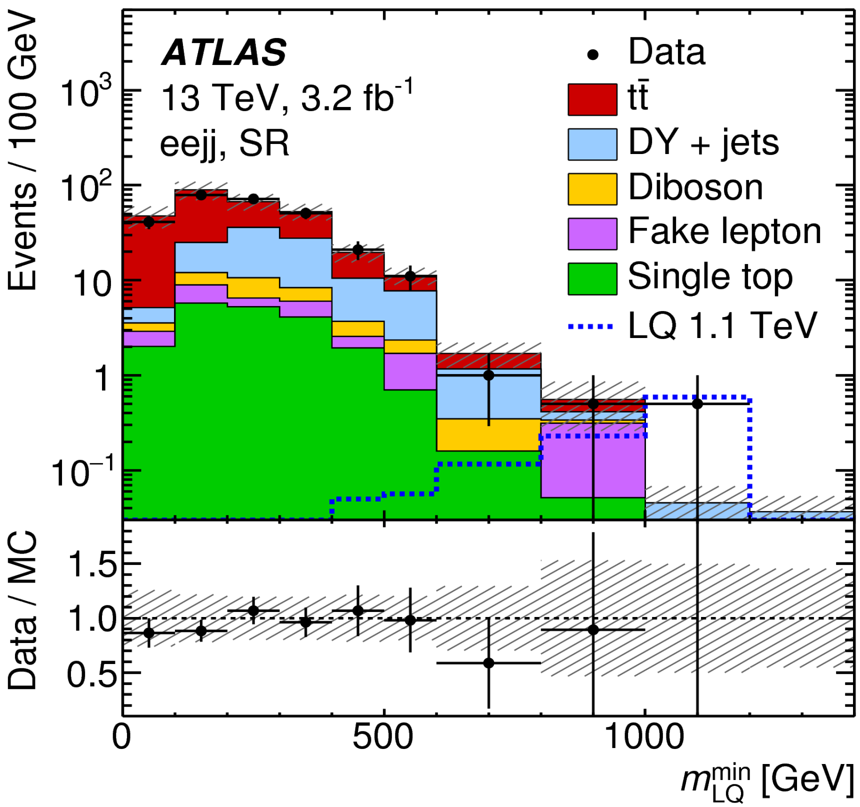
arXiv:1605.06035

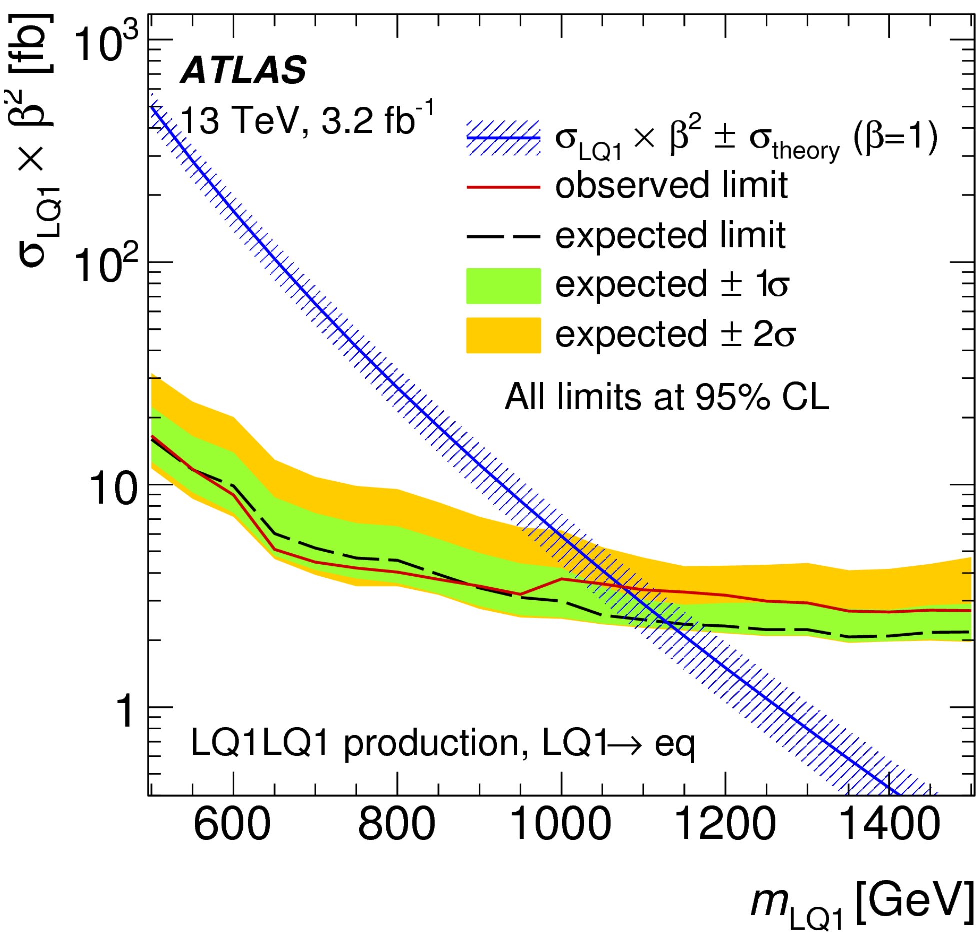
LQ @ 13 TeV





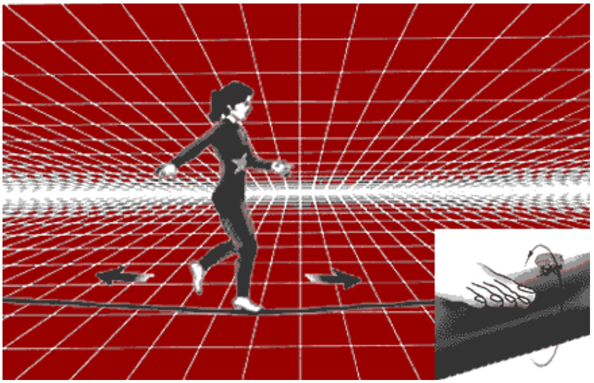






Extra Dimensions

Alternative to solve Hierarchy Problem

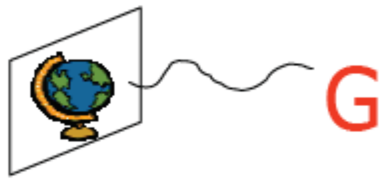


Extra spatial dimensions explain the apparent weakness of Gravity (relevant scale ~ 1 TeV)

ADD

Arkani-Hamed, Dimopoulos, Dvali,
Phys Lett B429 (98)

Many large compactified EDs
In which G can propagate



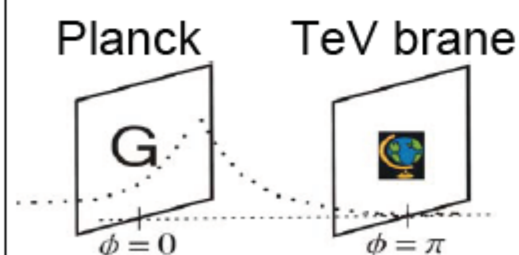
$$\boxed{M_{Pl}^2 \sim R^n M_{Pl(4+n)}^{(2+n)}}$$

Effective M_{Pl} ~ 1TeV → if compact space (R^n) is large

RS

Randall, Sundrum,
Phys Rev Lett 83 (99)

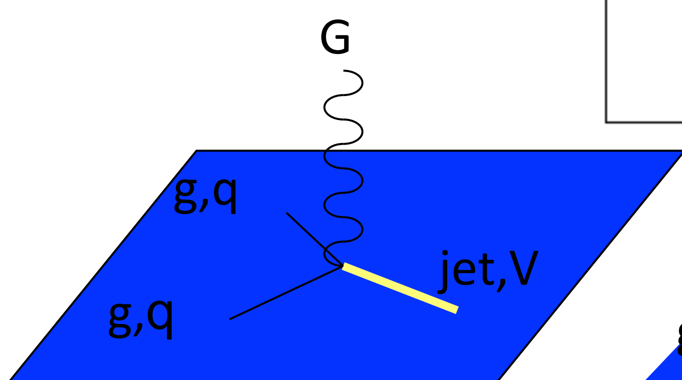
1 highly curved ED
Gravity localised in the ED



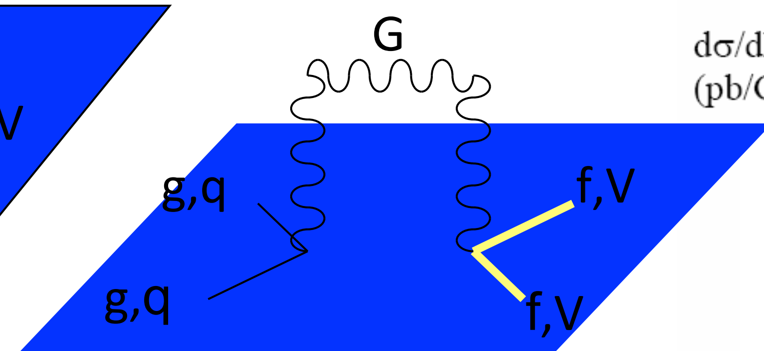
$$\boxed{\Lambda_\pi = \overline{M}_{pl} e^{-kR_c\pi}}$$

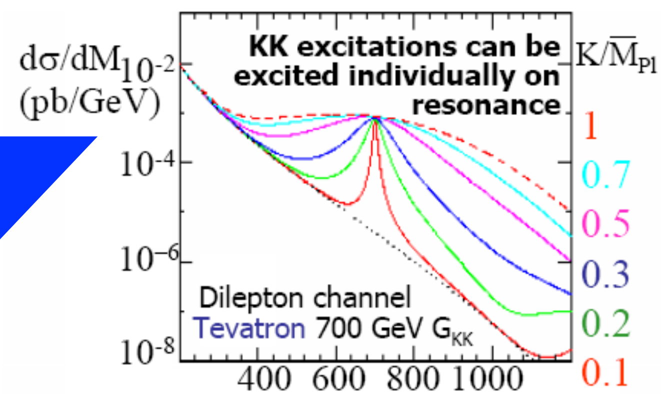
Λ_π ~ TeV

if warp factor kR_c ~11-12
k/M_{Pl}, k: curvature scale

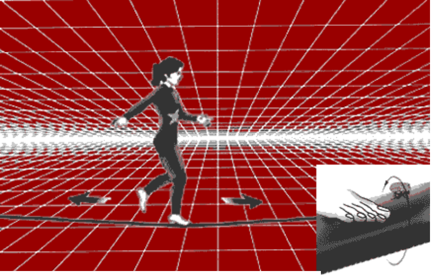


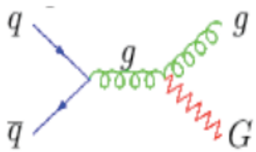
mono-jet



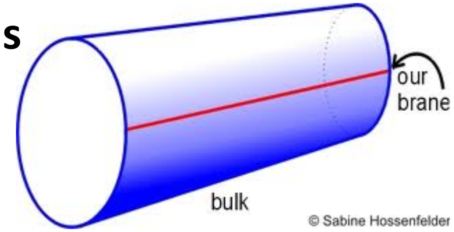


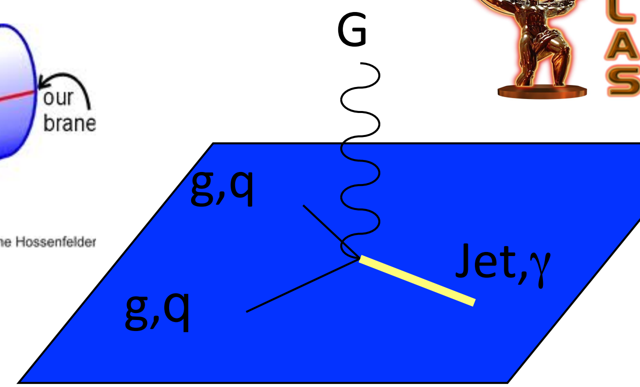
Large Extra Dimensions



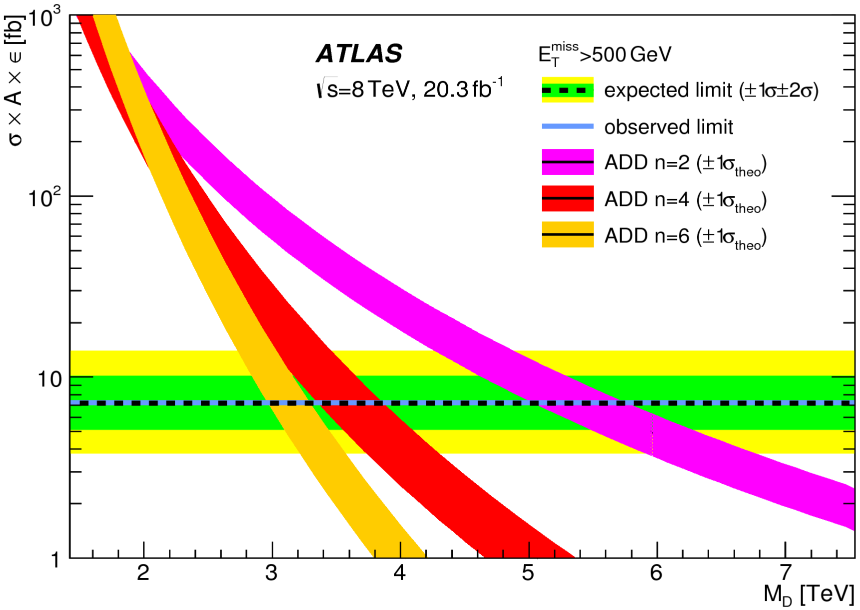


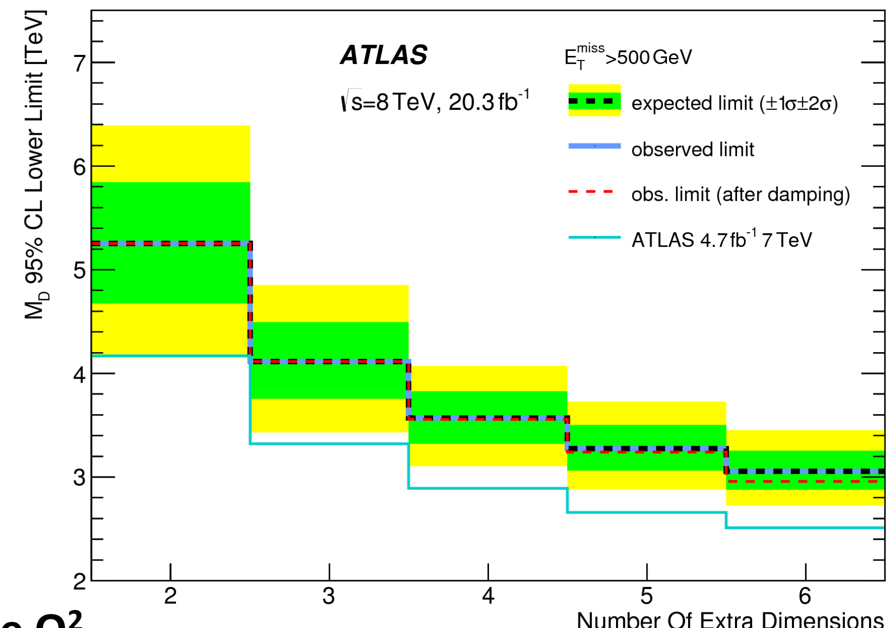
Extra spatial dimensions explain the apparent weakness of Gravity (relevant scale ~TeV)





$$(M_{PL})^2 \sim R^n (M_D)^{2+n}$$



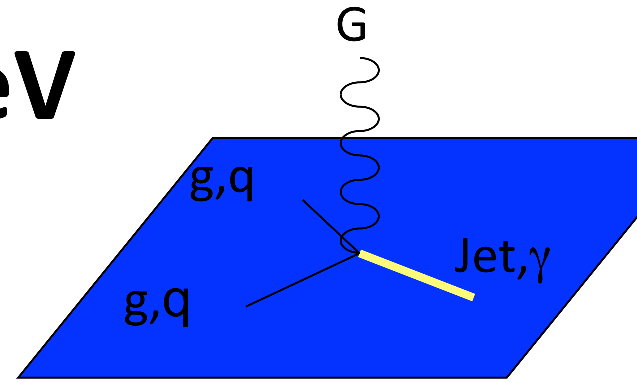


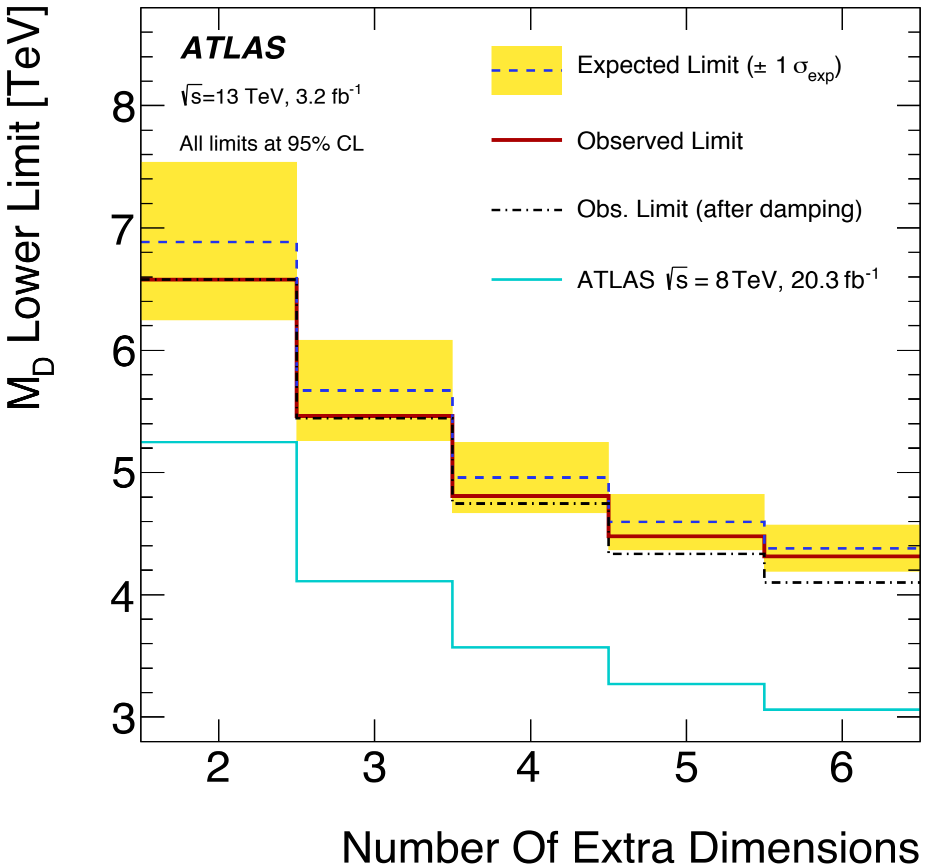
Limits on M_D beyond 5 TeV
(a real challenge of the model validity)

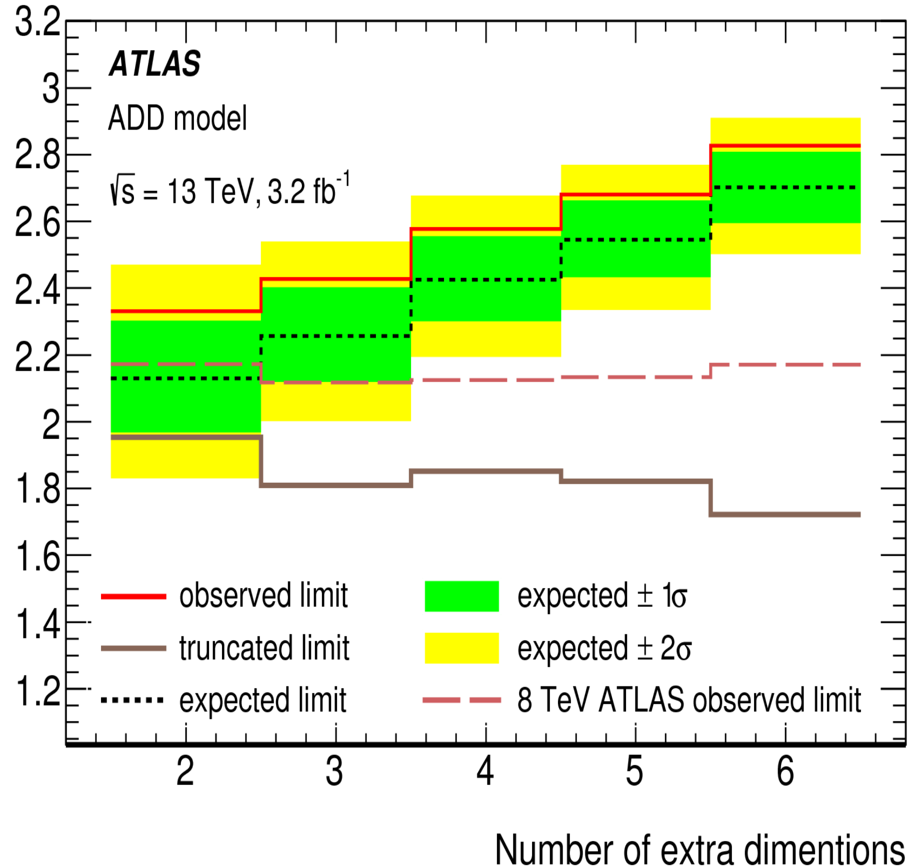
Note: Limits sensitive to the truncation strategy for s-hat > M_D^2, LHC probing phase space at large Q^2

$(M_{PL})^2 \sim R^n (M_D)^{2+n}$

Results @ 13 TeV







Values for M_D beyond multiple TeV are already excluded @ 95% CL vs n-dimensions

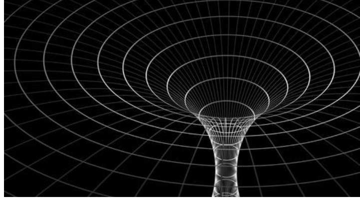
→ Note the model is implemented in a EFT manner

→ For high $s > M_D^2$ the model is not valid (damp/truncate the x-section to estimate the impact)

JHEP08(2014)103

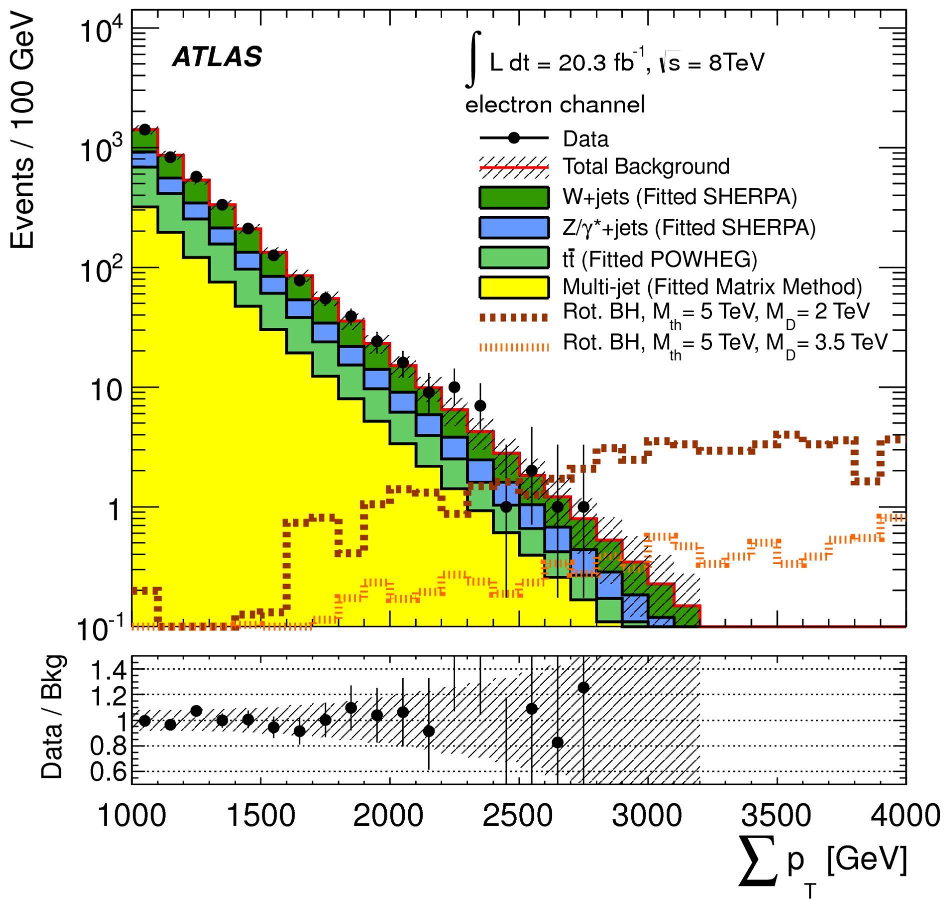
[JHEP 07 (2015) 032]

QBH

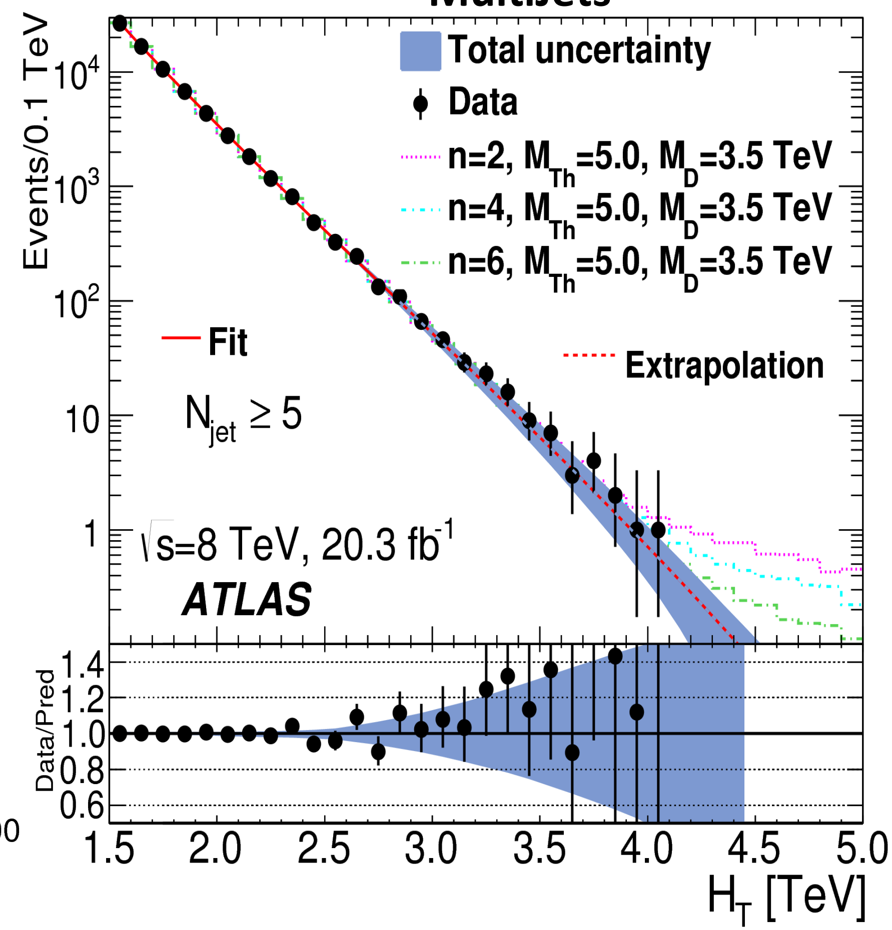


(production of Black Holes in models with extra spatial dimensions)

Lepton + Jets



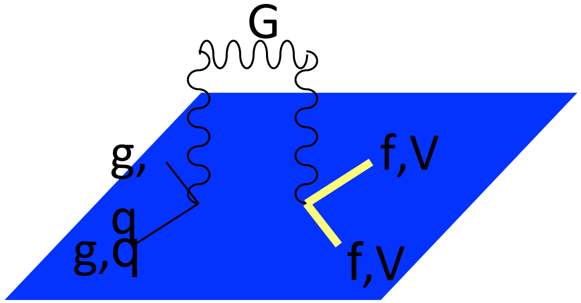
MultiJets

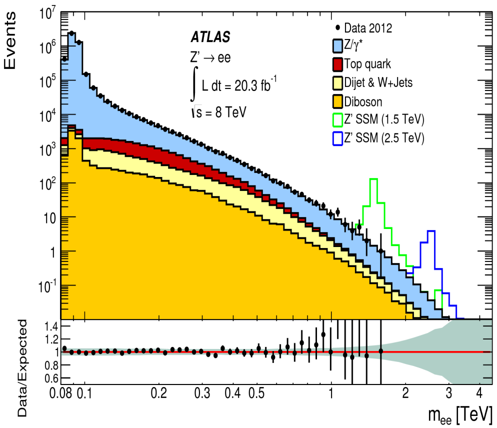


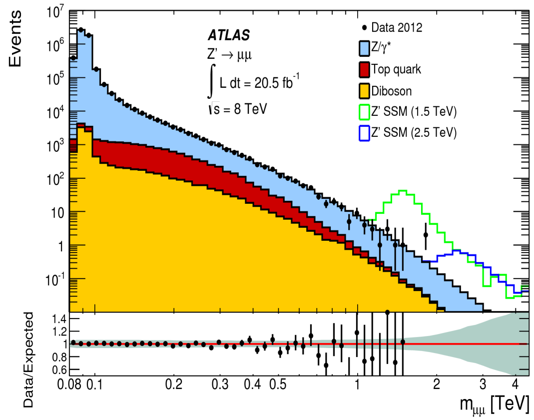
Spectacular Events.. Large Multiplicities of Jets and Leptons…. No surprises yet

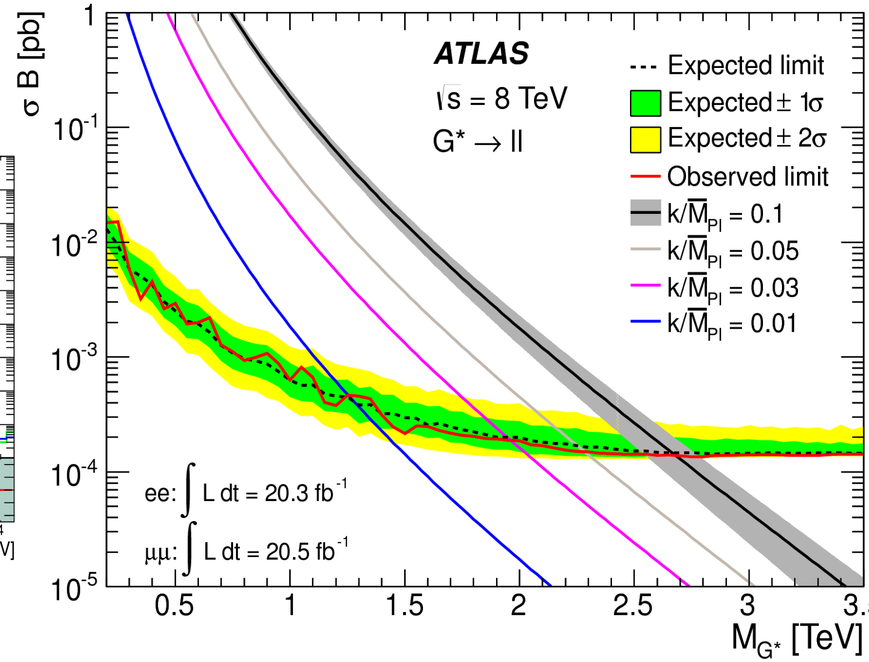
Dileptons

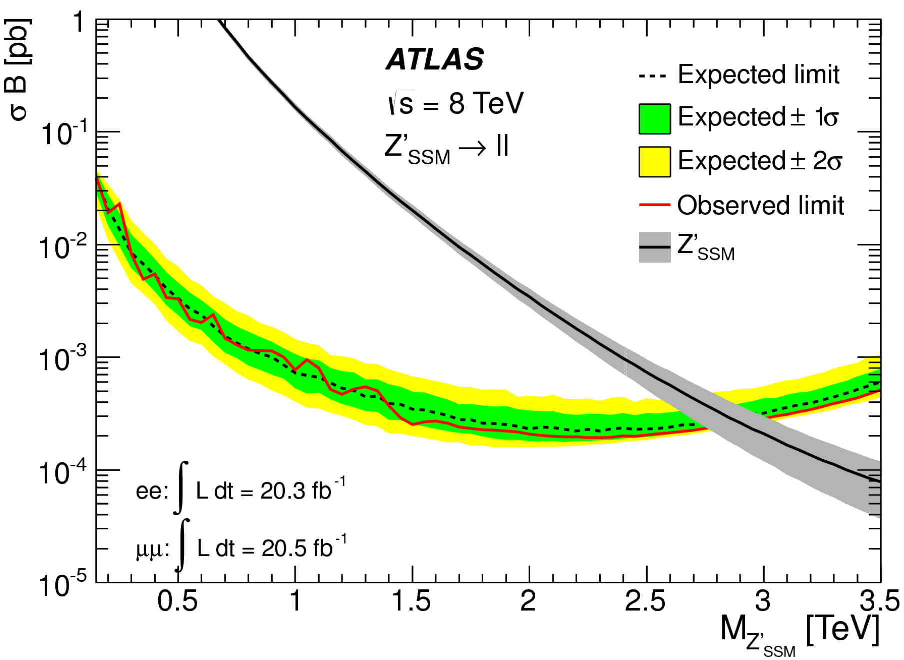
Phys. Rev. D. 90, 052005 (2014)









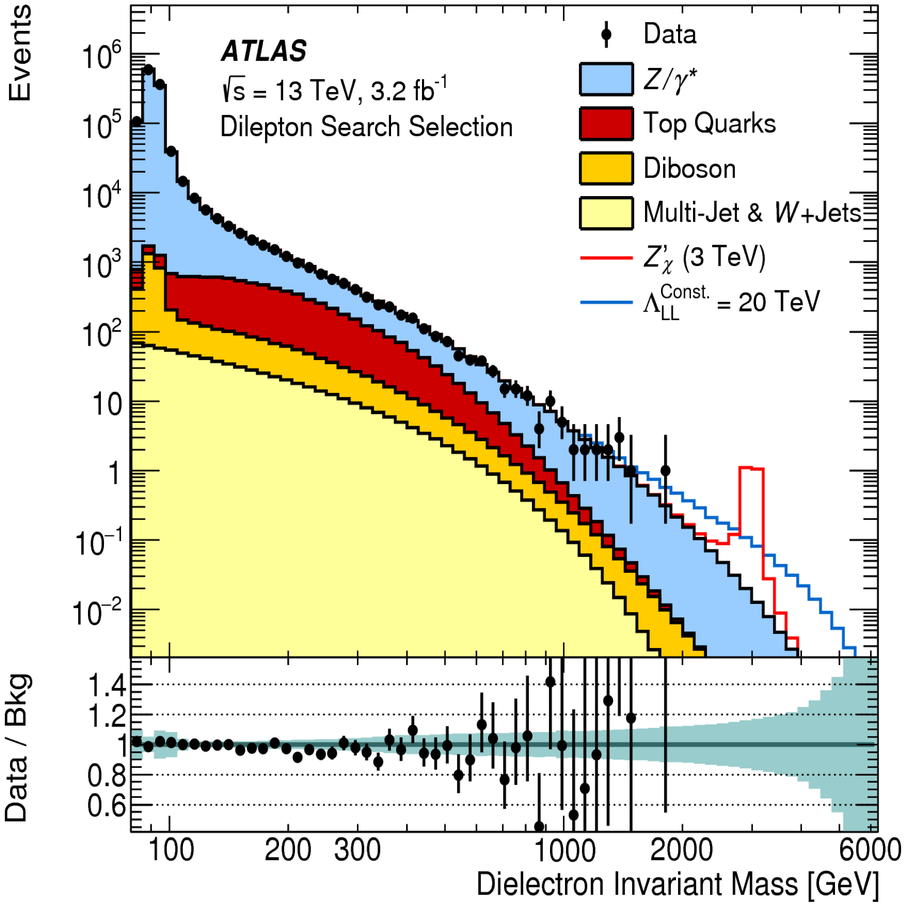


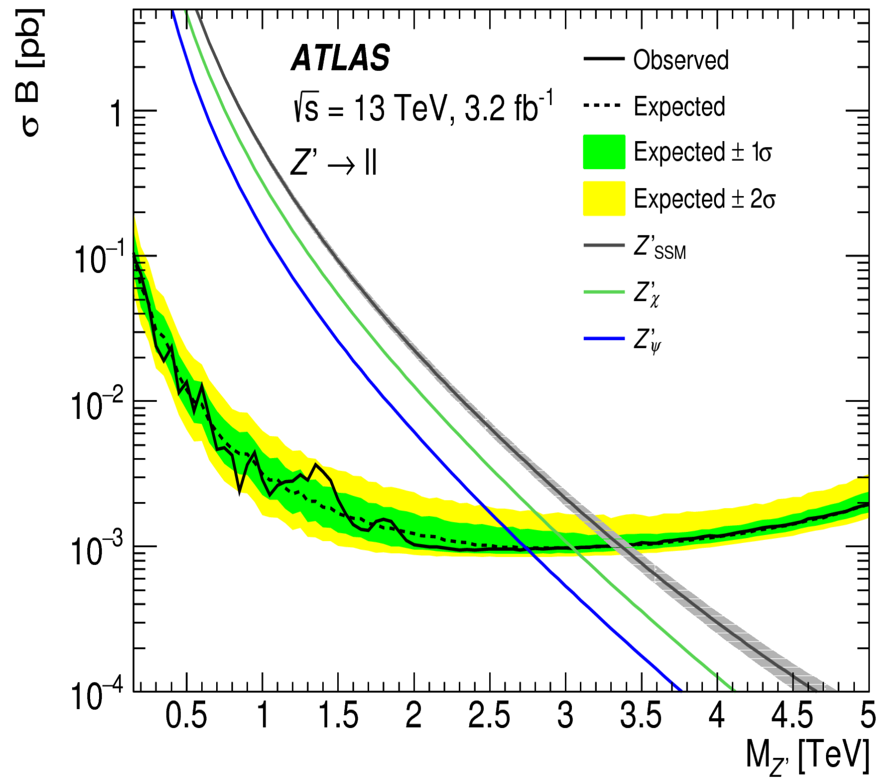
Limits on RS (ED) Graviton mass vs coupling
→95% CL exclusion in the mass range
M_G = 1.2 TeV – 2.7 TeV

Limits on SSM and E_6 GUT inspired models
→$M_{Z'}$ (SSM) < 2.86 TeV excluded
→$M_{Z'}$ (E_6) < 2.4 TeV – 2.6 TeV excluded

arXiv:1607.03669

Dileptons @ 13 TeV





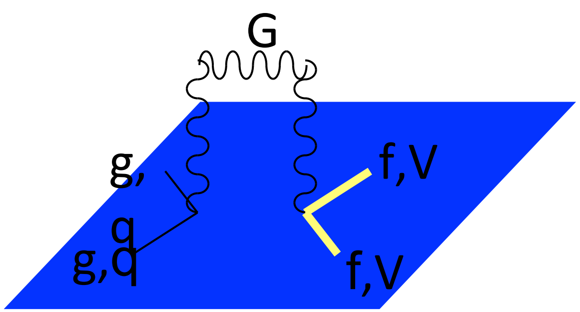
→ **No real surprises at the edge of the phase space yet**

→ **Limits on Z' for different models (leading to different couplings)**

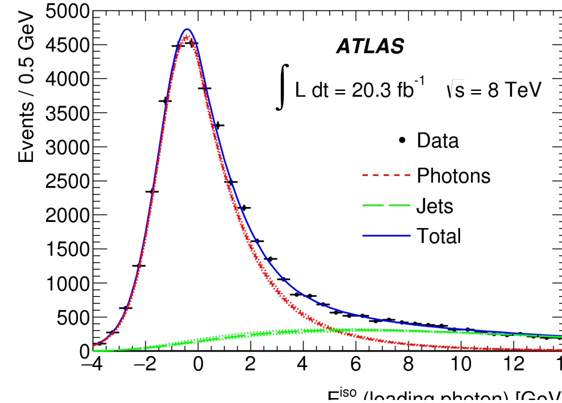
→ **Also considering a model with a 20 TeV Z' (implemented as a contact interaction)**

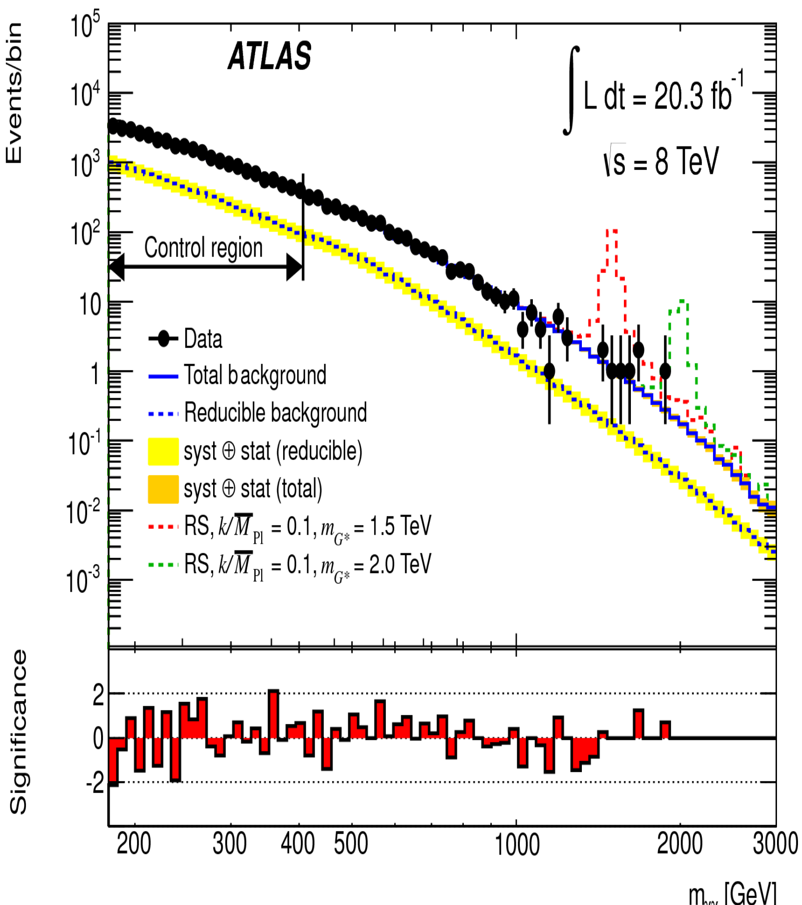
Phys. Rev. D 92, 032004 (2015)

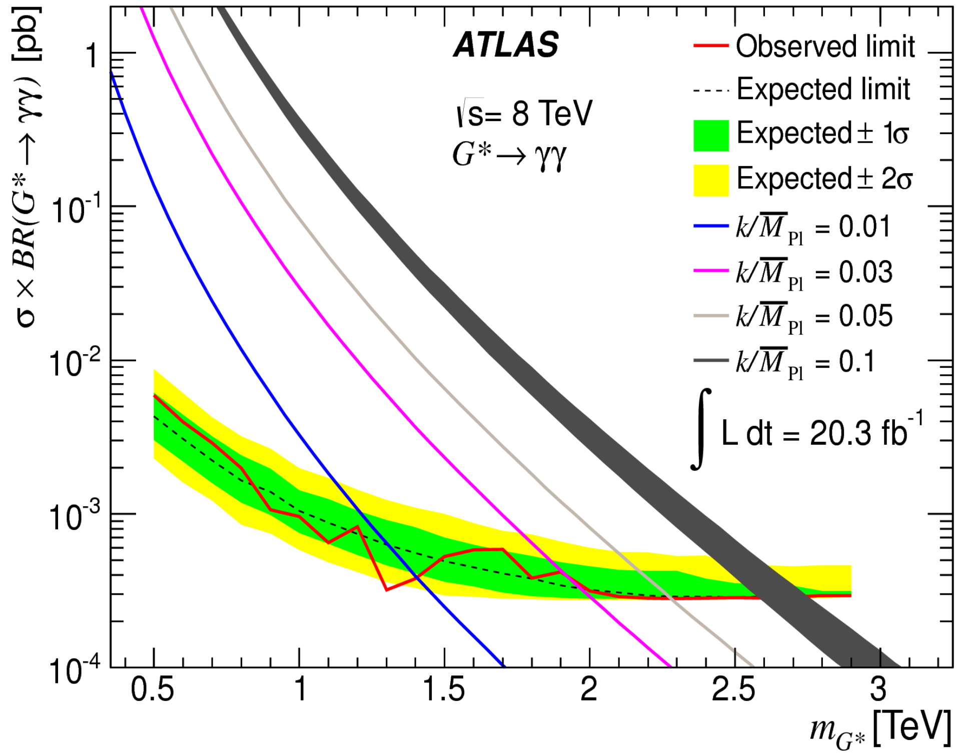
Di-photons



Data Driven BG estimation
Fakes taken from the ISO
Distribution and fit to data







Limits on RS (ED) Graviton mass vs coupling
→95% CL exclusion in the mass range
M_G = 1.4 TeV – 2.5 TeV

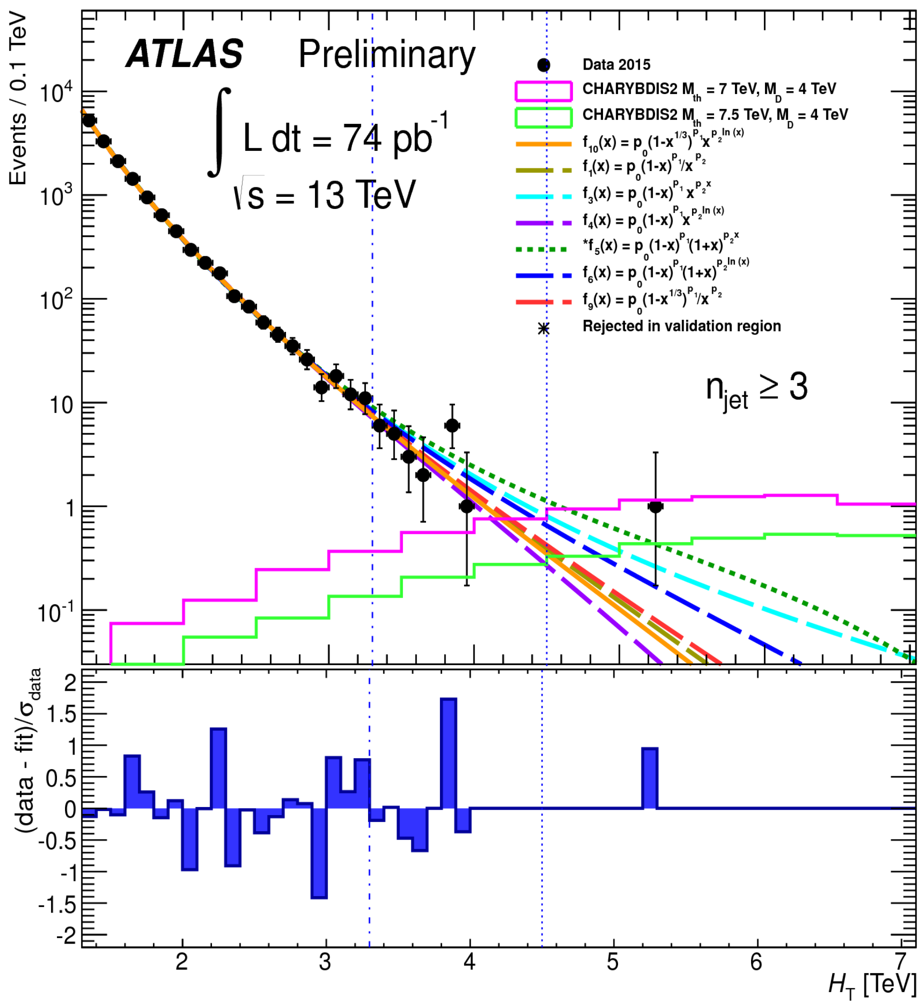
ATLAS-CONF-2015-043

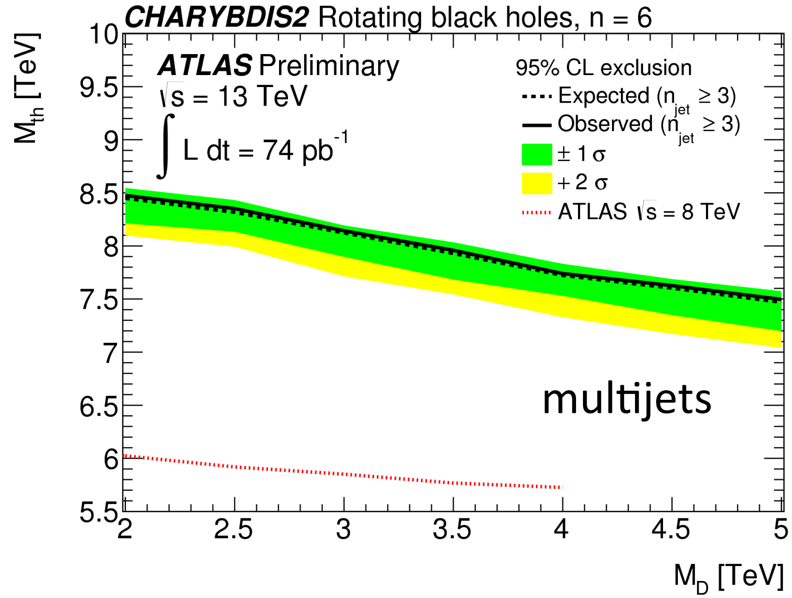
ATLAS-CONF-2015-046

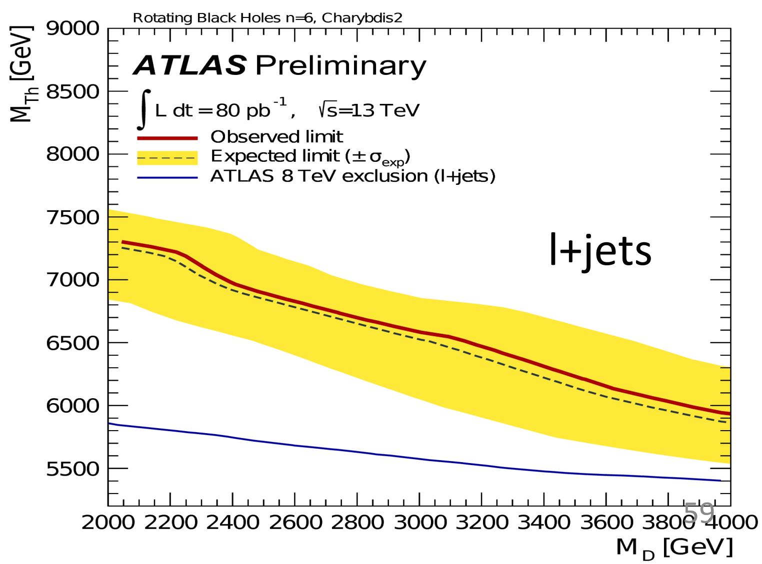
QBH Search at 13 TeV

(multijets & lepton + jets)

80 pb^{-1}



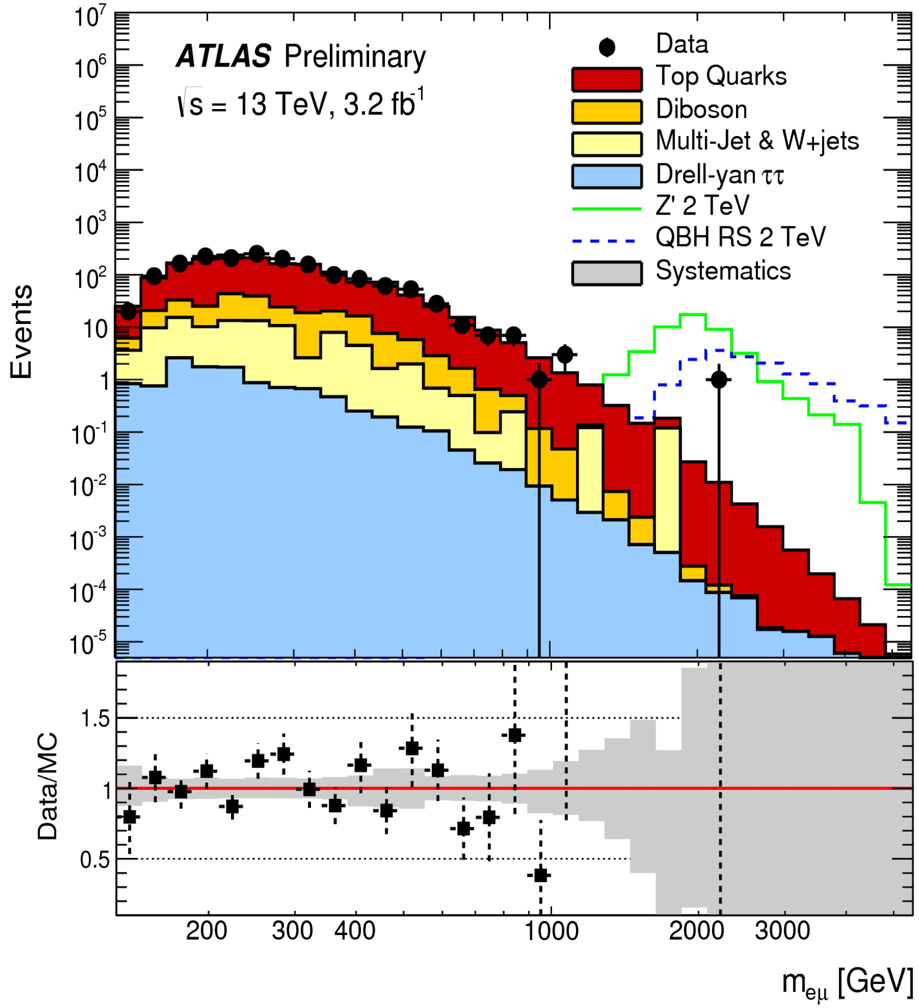


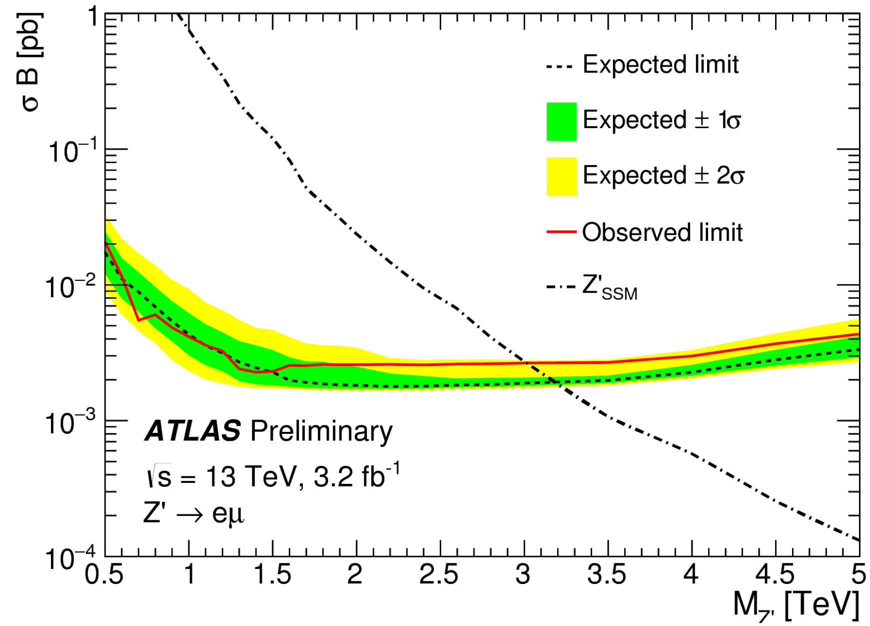


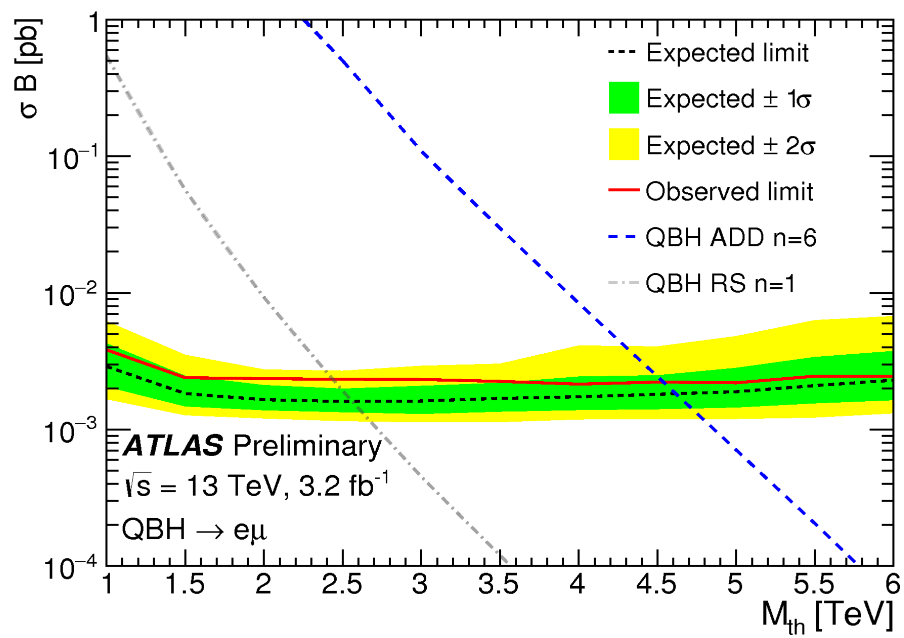
Going beyond Run I sensitivity

ATLAS-CONF-2015-072

Z’ → eμ , QBH → eμ



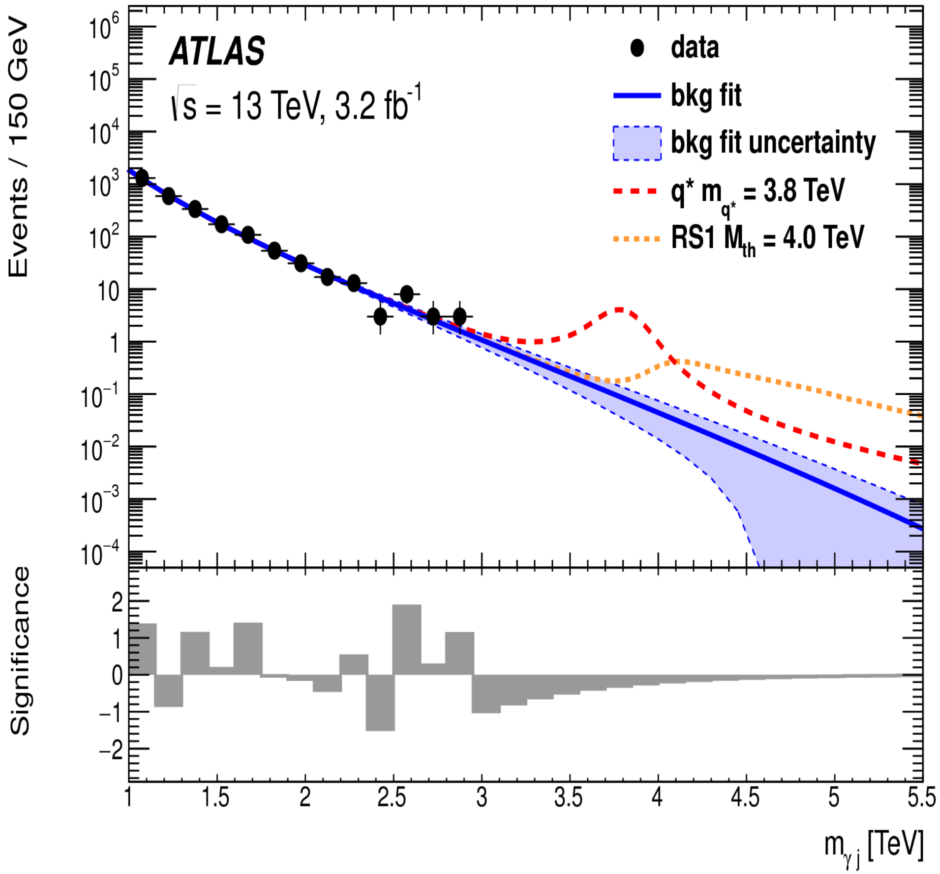


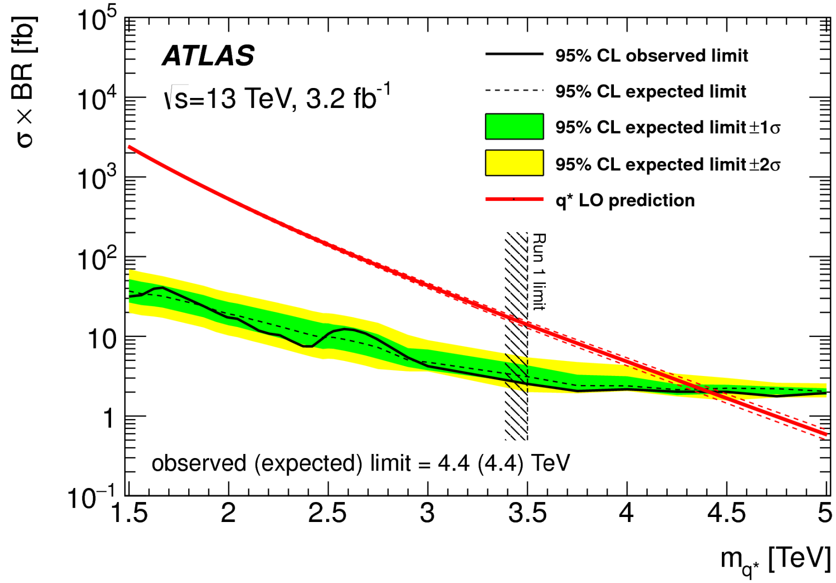


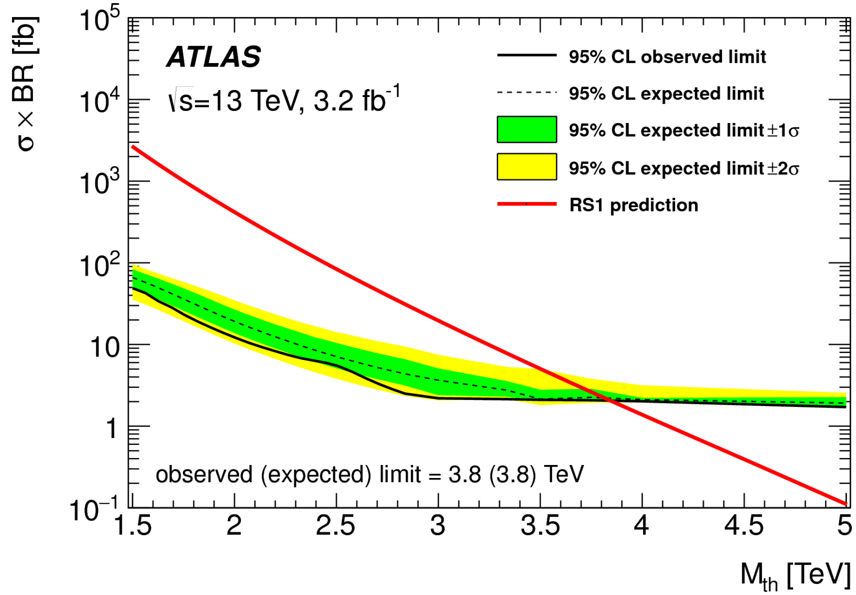
Excited quarks q* → qγ

Composite models try to understand the Lepton/quark degeneracy and usually predict the presence of excited states

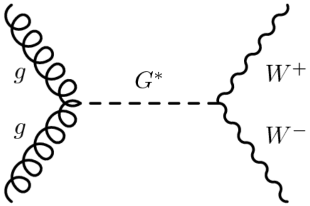
→ Now interpreted as a QBH search…





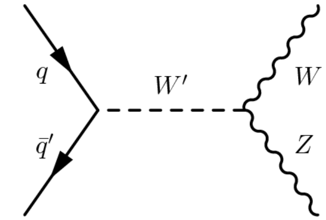


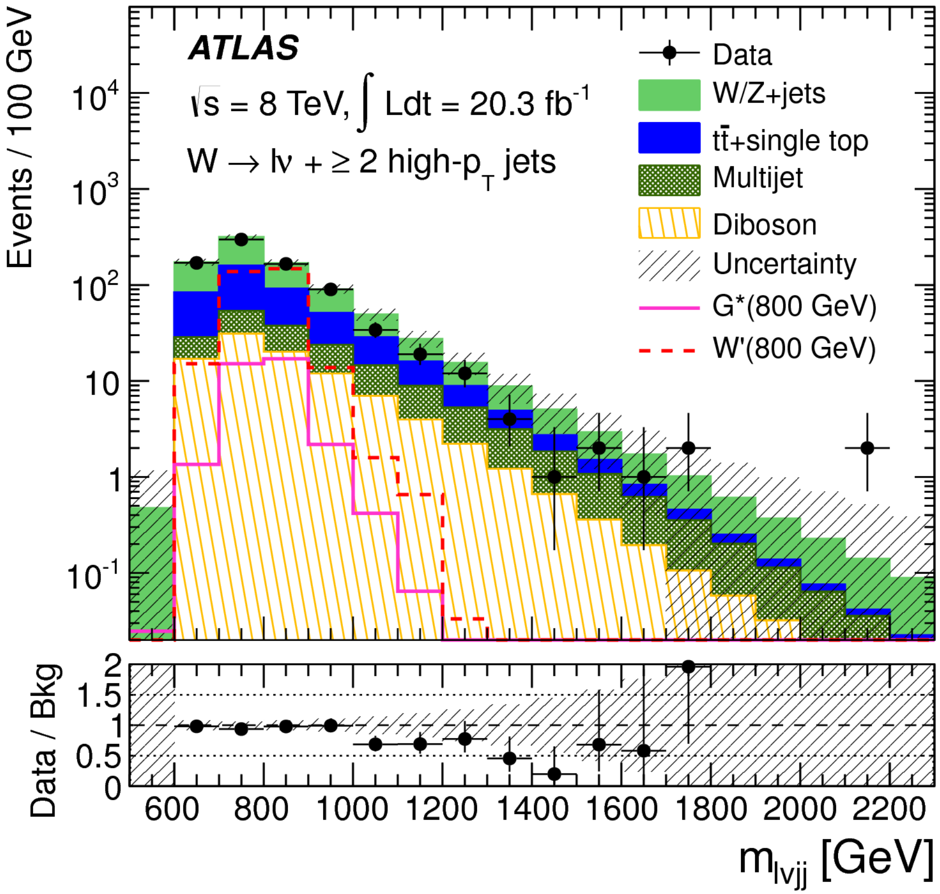
Eur. Phys. J. C (2015) 75:209

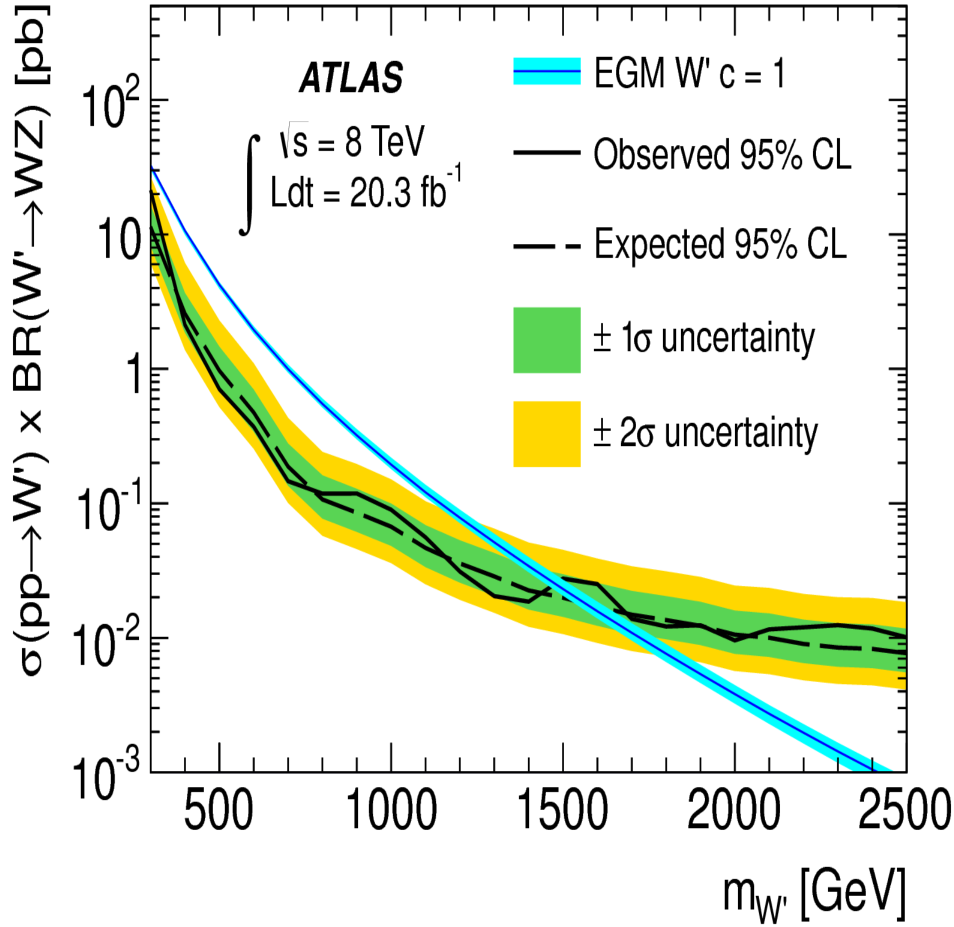


WW/WZ Resonances

(lepton+jets channels)





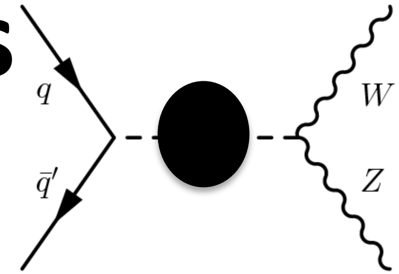


Using both resolved W → qq' and large R-jets in boosted W → qq

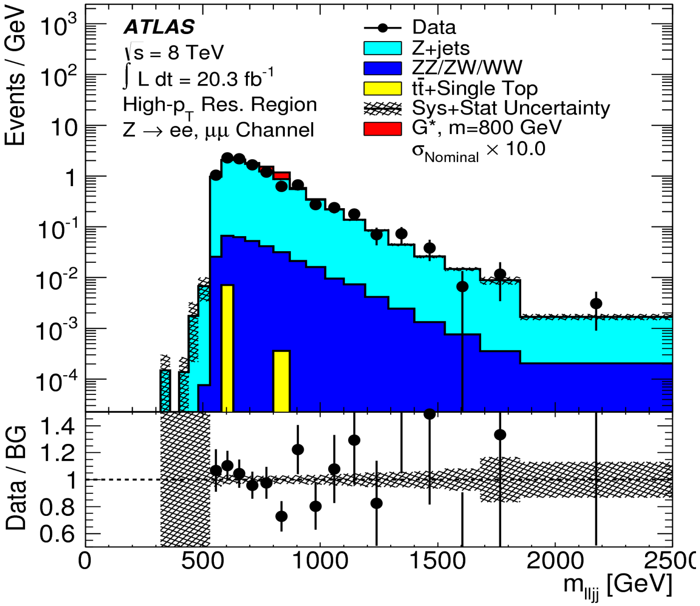
A W' is excluded up to 1.5 TeV at 95% CL

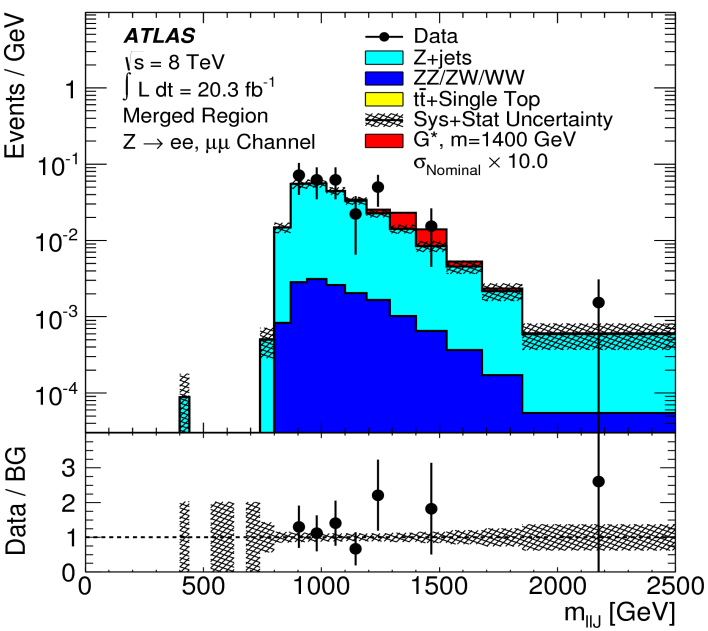
Eur. Phys. J. C (2015) 75:69

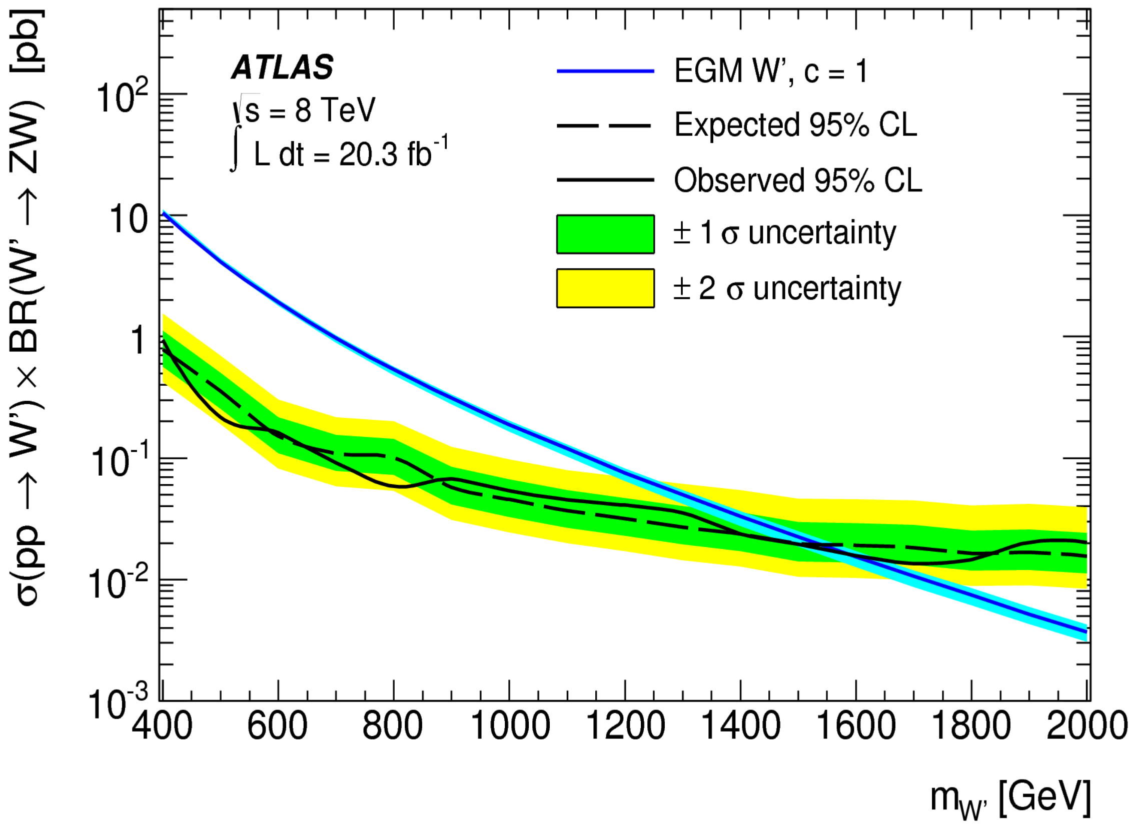
Diboson Resonances



lepton+lepton + qq)



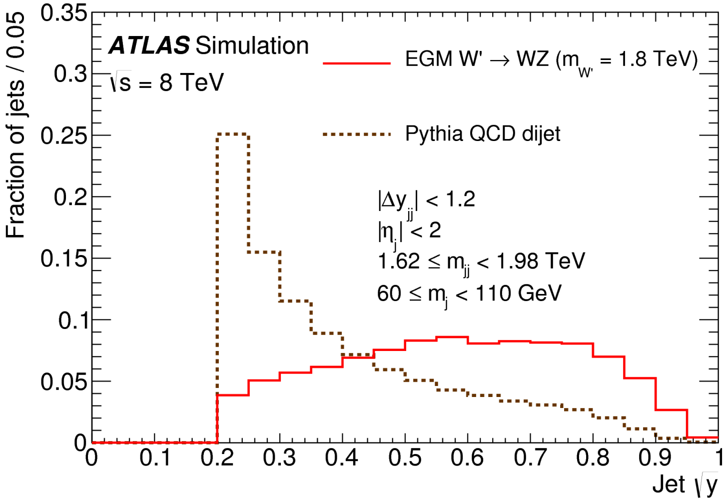




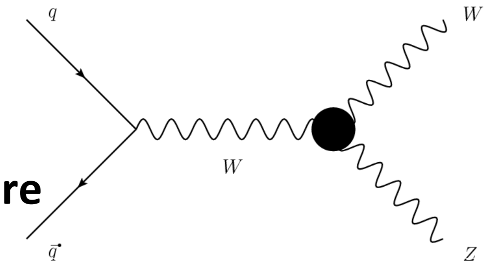
Using both resolved W → qq' and boosted W
A W' is excluded up to 1.5 TeV at 95% CL

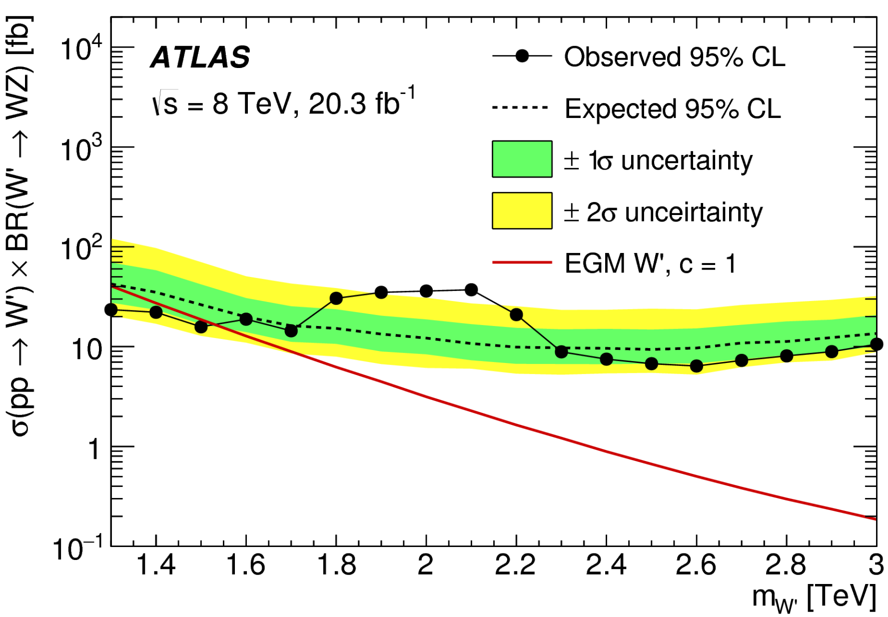
High-mass diboson resonances with boson-tagged jets

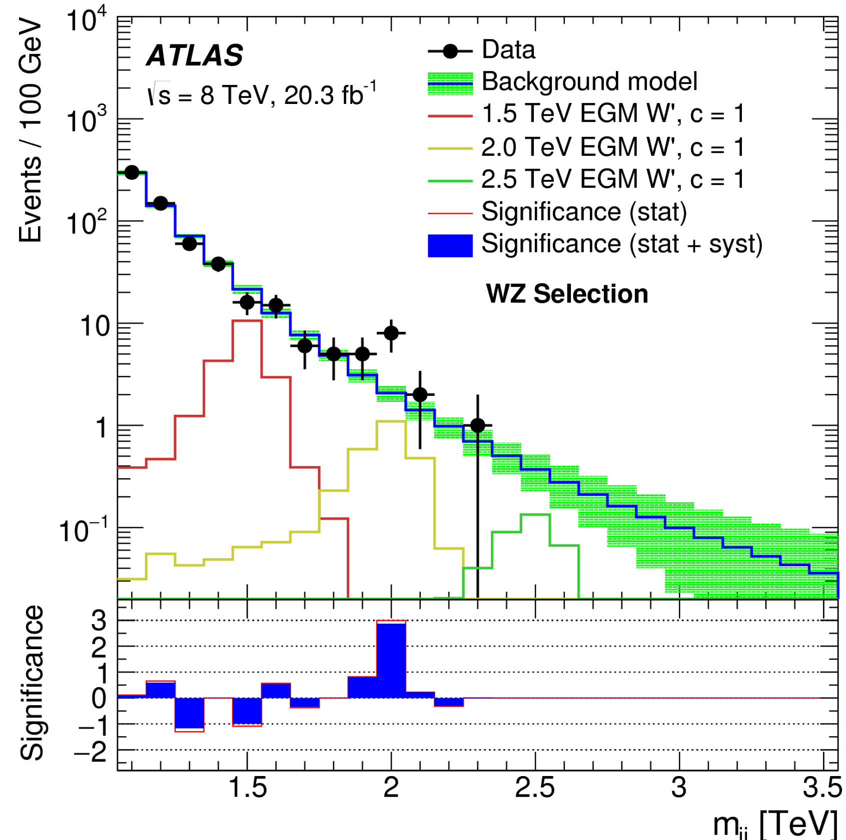
arXiv:1506.00962



Hadronic decays of W and Z using jet mass and substructure properties

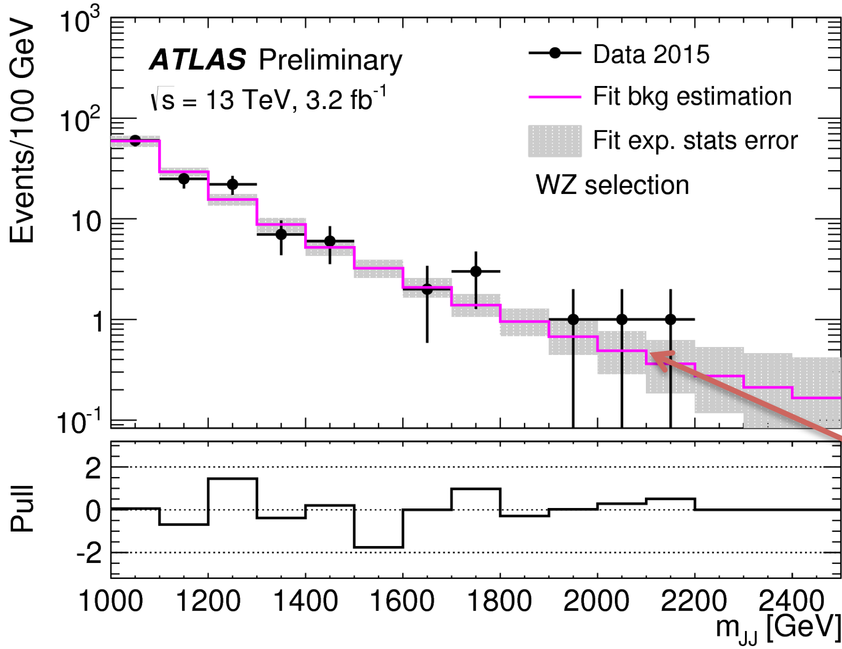




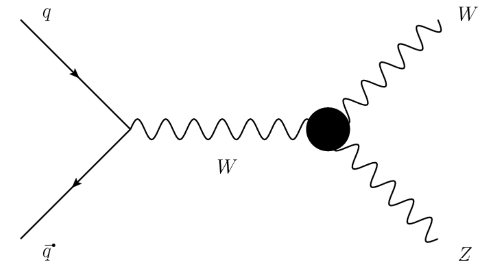


2.5 sigma effect

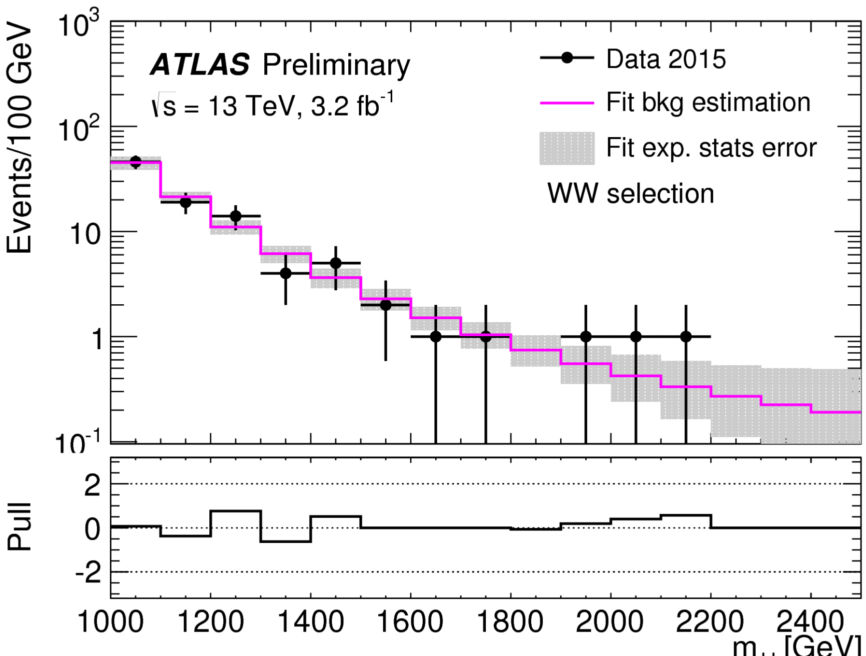
New look @ 13 TeV data

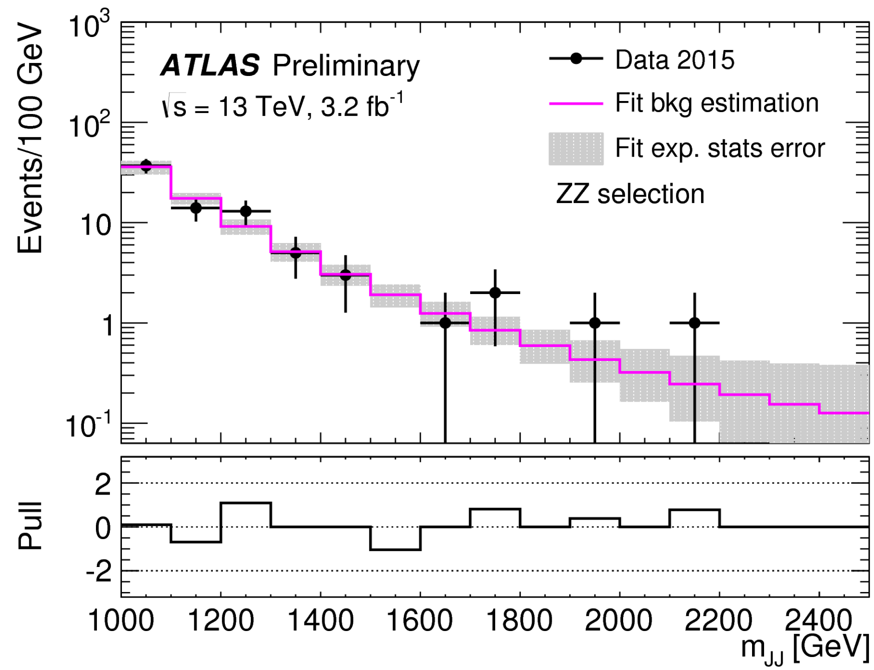


ATLAS-CONF-2015-073

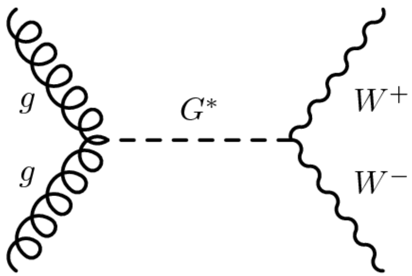


The new data at 13 TeV did not confirm the 8 TeV result: bad luck…



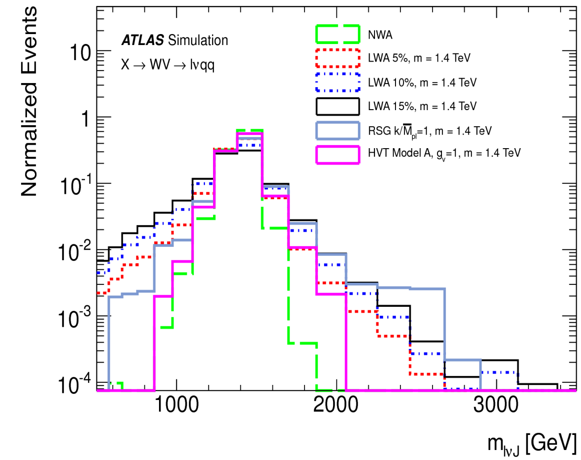


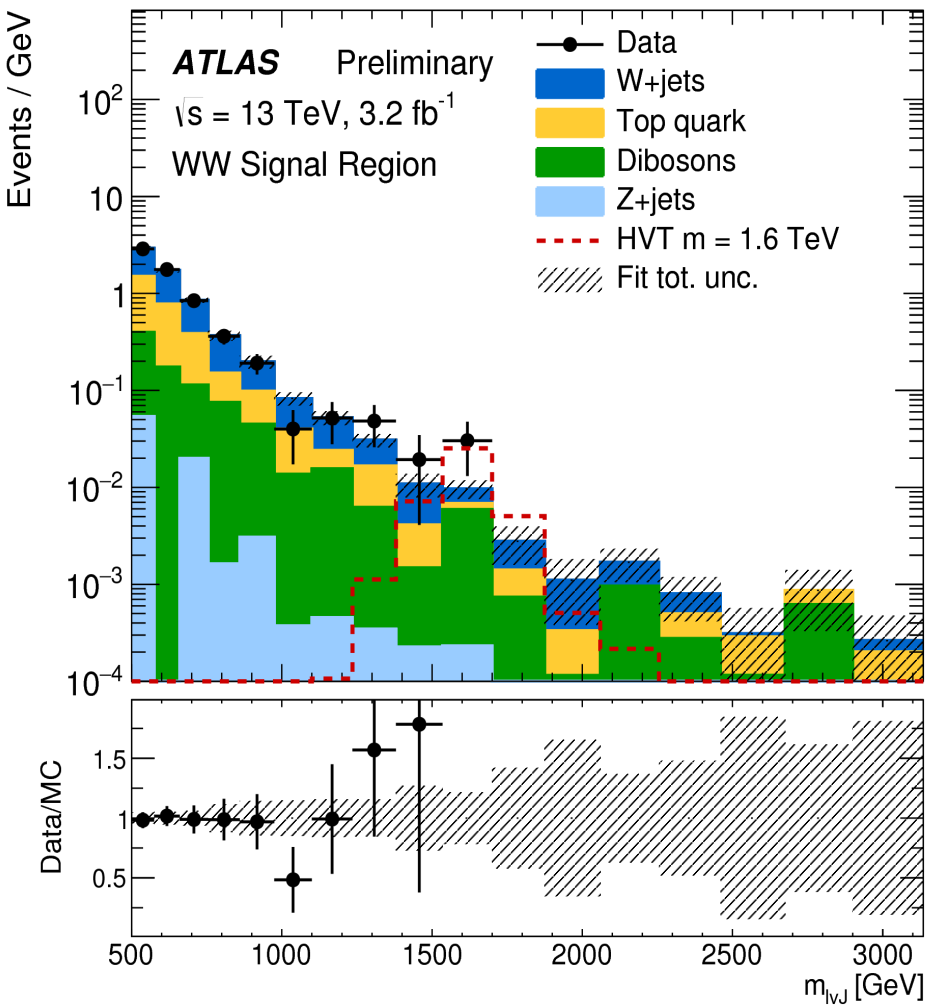
ATLAS-CONF-2015-075



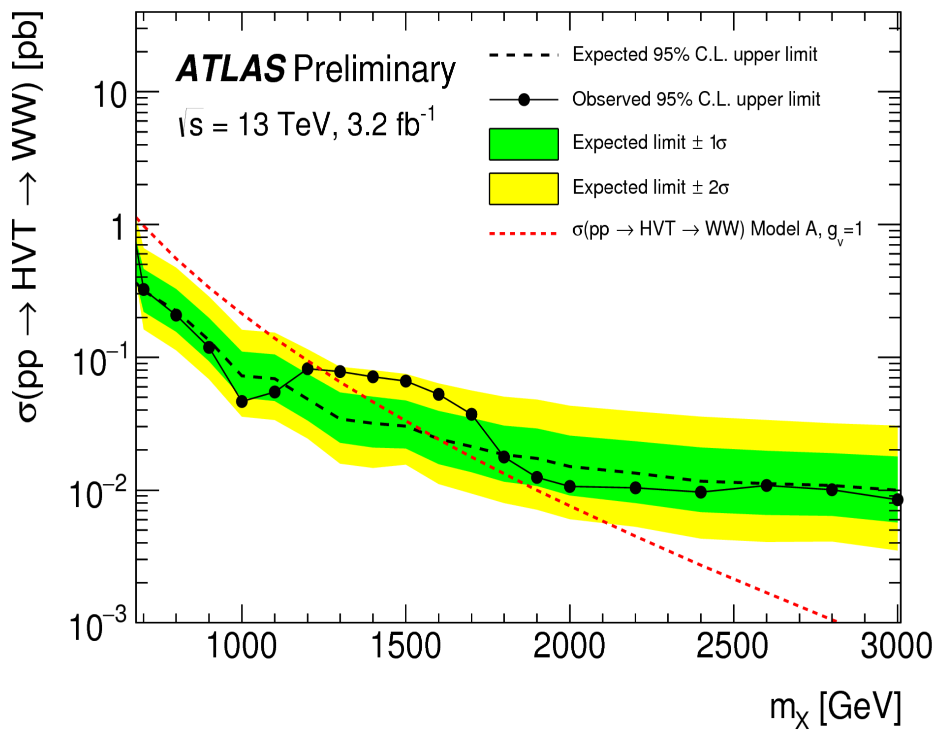
WW/WZ @ 13 TeV

(lepton+jets channel)



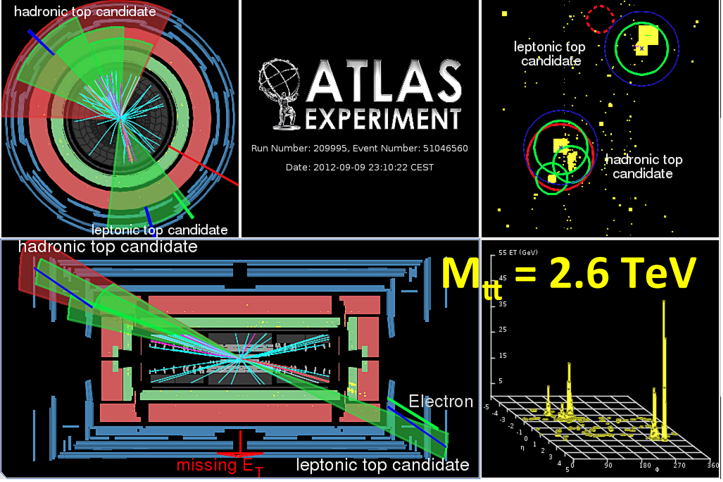


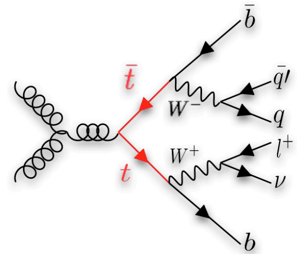
Interpreted in terms of Heavy Higgs-like

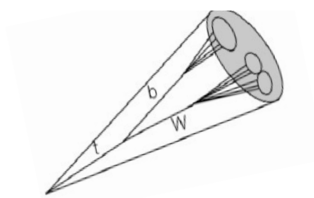


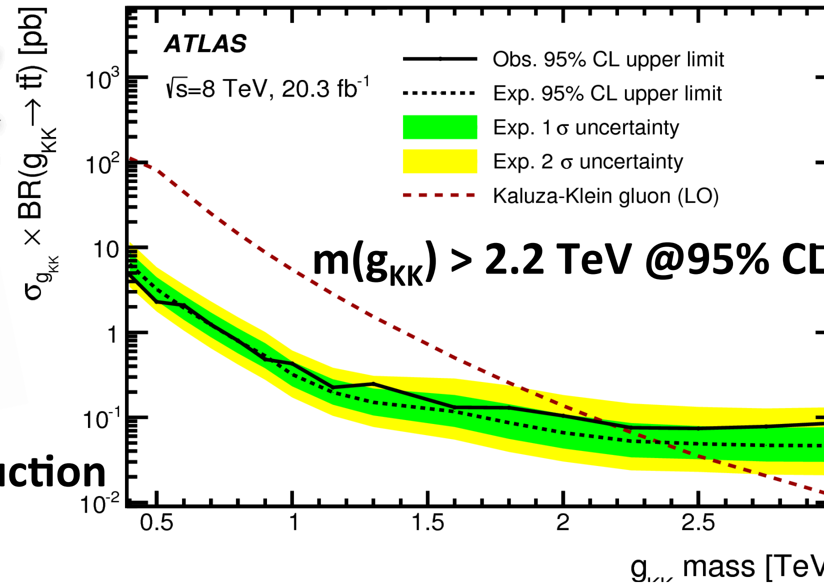
tt Resonances

arXiv:1505.07018

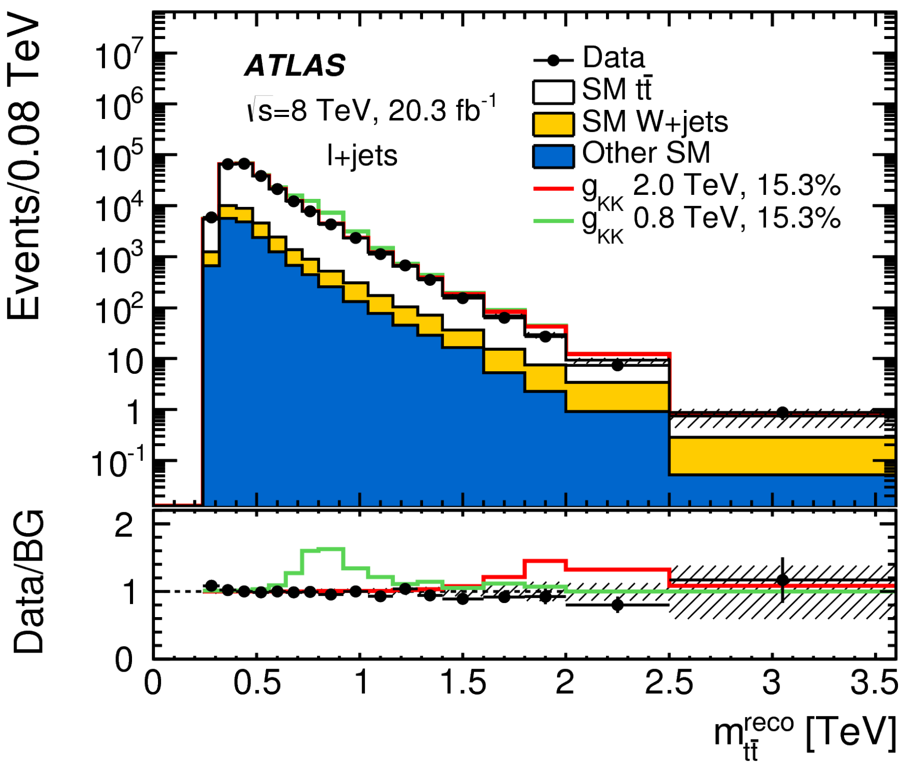


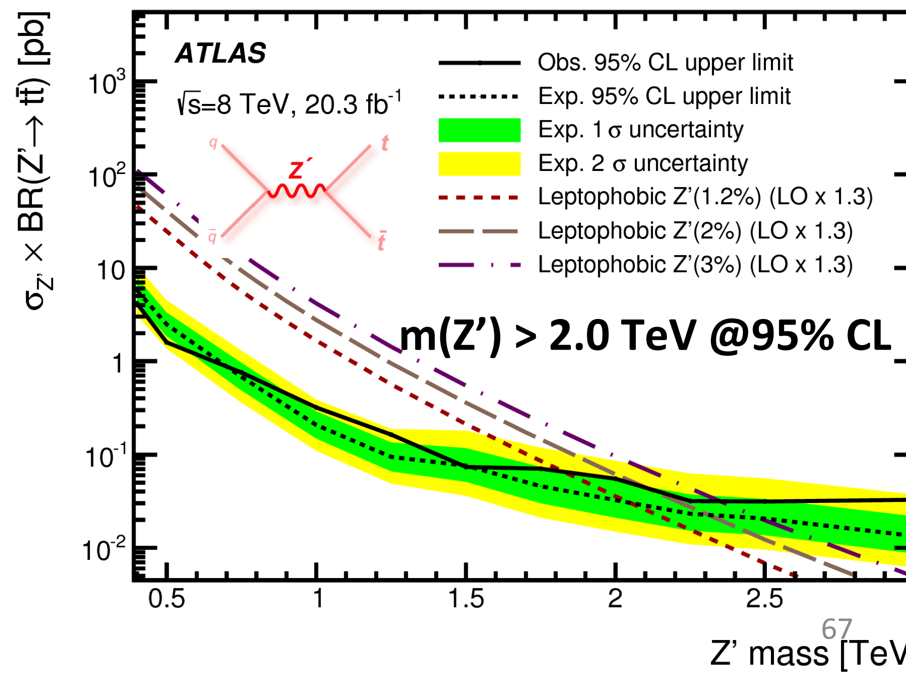






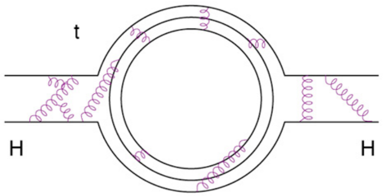
Using both resolved and boosted t→ Wb reconstruction



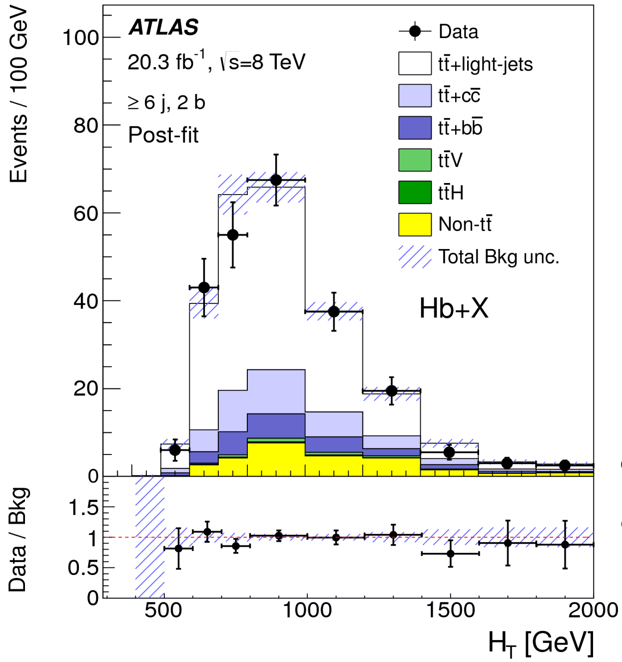


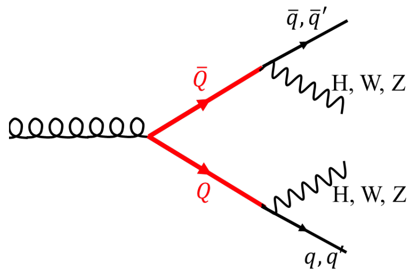
Vector-like quarks

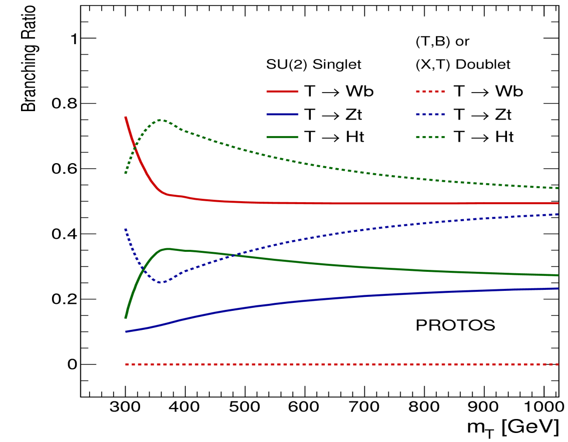
[JHEP 08 (2015) 105]



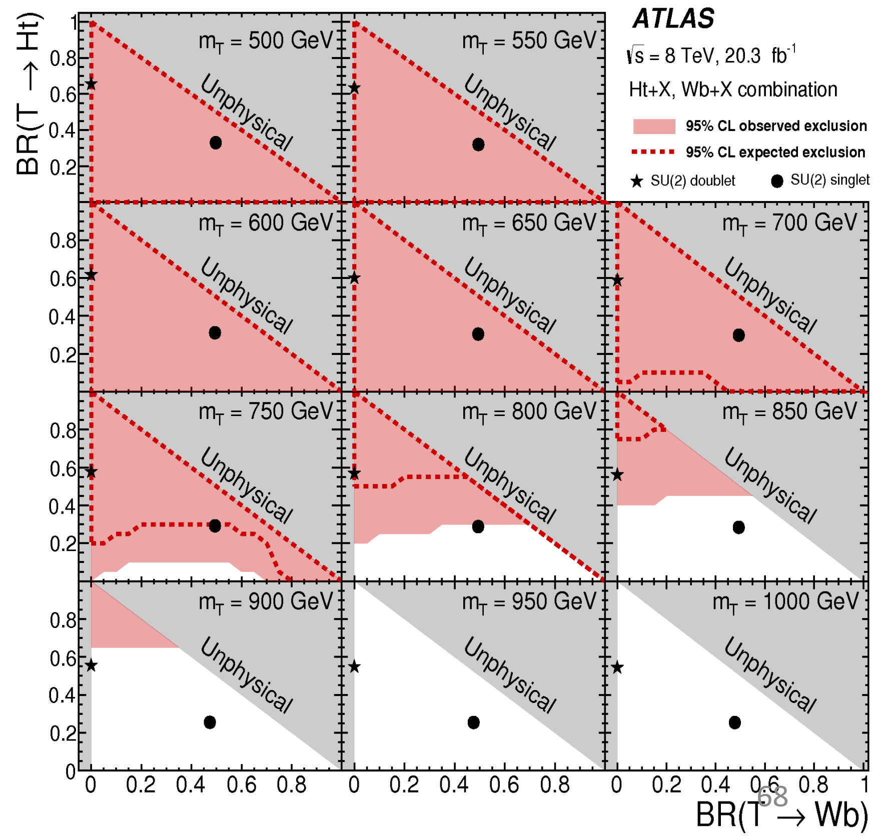
Explores the decay
t' → Ht (H → bb)

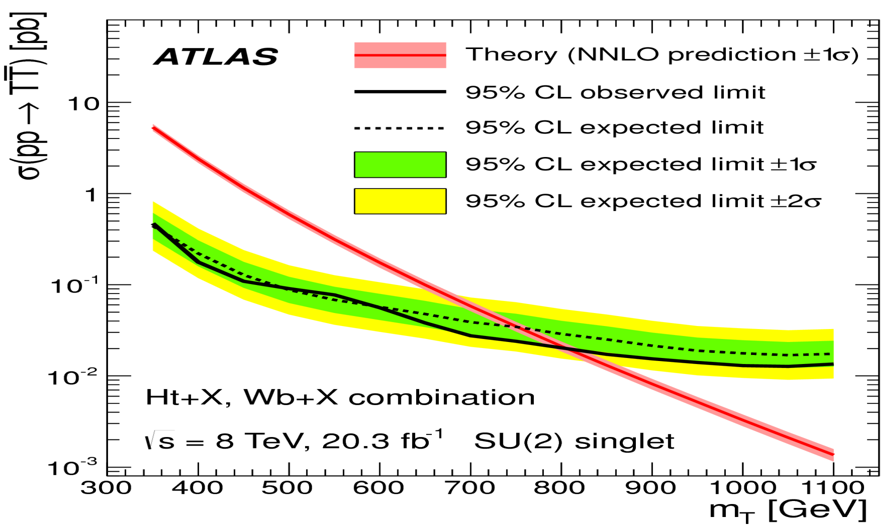


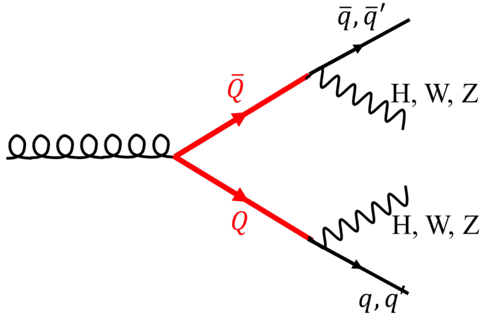




Masses below 800 GeV excluded at 95% CL

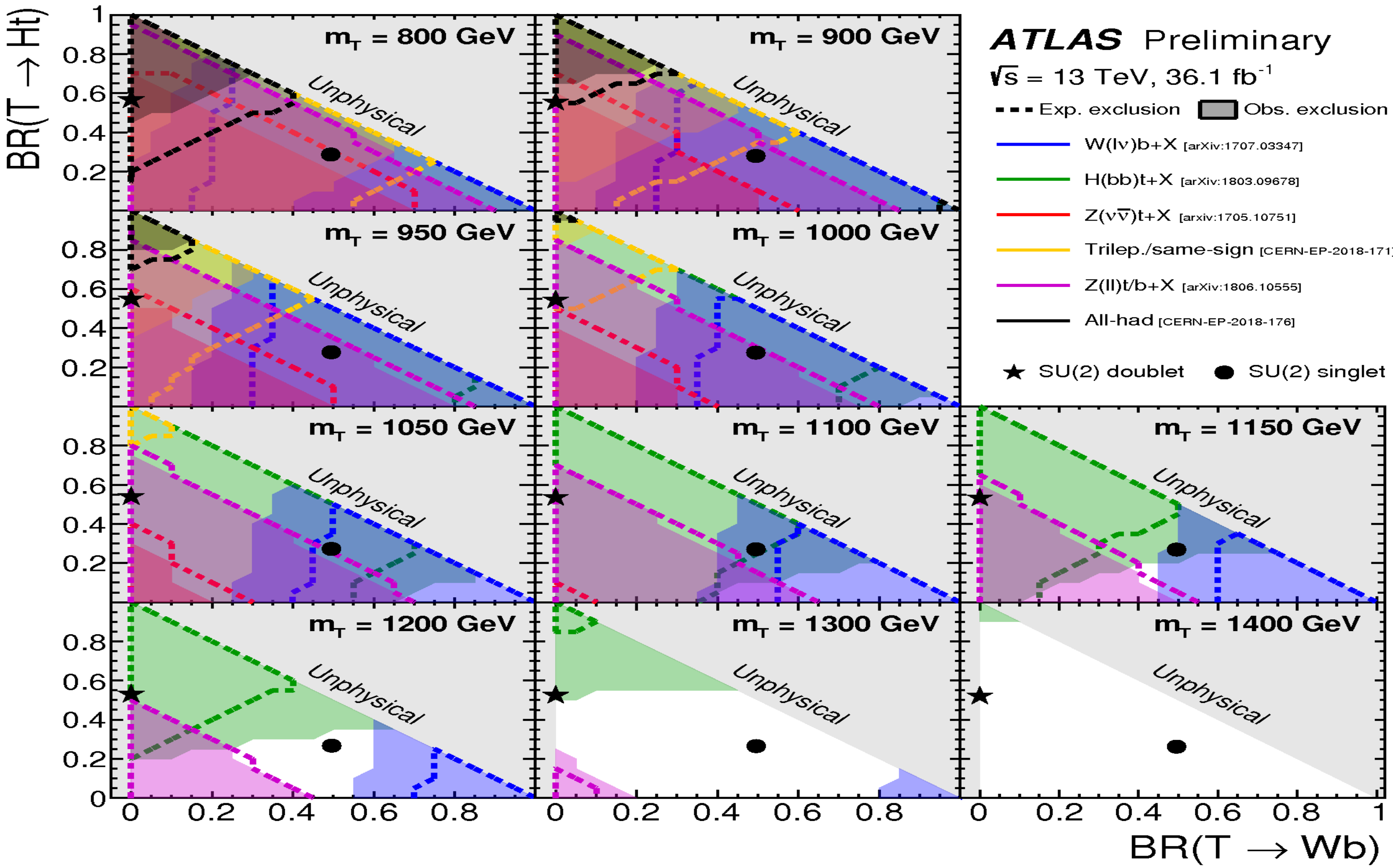






Summary VLQ (T)

July 2018



ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

July 2018

Status: July 2018

ATLAS Preliminary

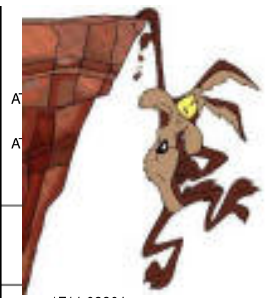
$\int \mathcal{L}\,dt = (3.2 - 79.8)\ \text{fb}^{-1}$ $\sqrt{s} = 8, 13$ TeV

	Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L}\,dt[\text{fb}^{-1}]$	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 $\gamma\gamma$	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 $\sum p_T$	≥ 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 $G_{KK} \to \gamma\gamma$	2 γ	–	–	36.7	G_{KK} mass 4.1 TeV		
	Bulk RS $G_{KK} \to WW/ZZ$	multi-channel			36.1	G_{KK} mass 2.3 TeV		
	Bulk RS $g_{KK} \to tt$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	g_{KK} mass 3.8 TeV		
	2UED / RPP	1 e, μ	≥ 2 b, ≥ 3 j	Yes	36.1	KK mass 1.8 TeV		
Gauge bosons	SSM $Z' \to \ell\ell$	2 e, μ	–	–	36.1	Z' mass 4.5 TeV		
	SSM $Z' \to \tau\tau$	2 τ	–	–	36.1	Z' mass 2.42 TeV		
	Leptophobic $Z' \to bb$	–	2 b	–	36.1	Z' mass 2.1 TeV		
	Leptophobic $Z' \to tt$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	Z' mass 3.0 TeV	$\Gamma/m = 1\%$	
	SSM $W' \to \ell\nu$	1 e, μ	–	Yes	79.8	W' mass 5.6 TeV		A
	SSM $W' \to \tau\nu$	1 τ	–	Yes	36.1	W' mass 3.7 TeV		
	HVT $V' \to WV \to qqqq$ model B	0 e, μ	2 J	–	79.8	V' mass 4.15 TeV	$g_V = 3$	A
	HVT $V' \to WH/ZH$ model B	multi-channel			36.1	V' mass 2.93 TeV	$g_V = 3$	
	LRSM $W'_R \to tb$	multi-channel			36.1	W' mass 3.25 TeV		
CI	CI $qqqq$	–	2 j	–	37.0	Λ 21.8 TeV	η^-_{LL}	
	CI $\ell\ell qq$	2 e, μ	–	–	36.1	Λ 40.0 TeV	η^-_{LL}	
	CI $tttt$	≥1 e,μ	≥1 b, ≥1 j	Yes	36.1	Λ 2.57 TeV	$\lvert C_{4t}\rvert = 4\pi$	
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, $m(\chi) = 1$ 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, $m(\chi) = 1$ GeV	1711.03301
	$VV\chi\chi$ EFT (Dirac DM)	0 e, μ	1 J, ≤ 1 j	Yes	3.2	M_* 700 GeV	$m(\chi) < 150$ GeV	1608.02372
LQ	Scalar LQ 1st gen	2 e	≥ 2 j	–	3.2	LQ mass 1.1 TeV	$\beta = 1$	1605.06035
	Scalar LQ 2nd gen	2 μ	≥ 2 j	–	3.2	LQ mass 1.05 TeV	$\beta = 1$	1605.06035
	Scalar LQ 3rd gen	1 e, μ	≥1 b, ≥3 j	Yes	20.3	LQ mass 640 GeV	$\beta = 0$	1508.04735
Heavy quarks	VLQ $TT \to Ht/Zt/Wb + X$	multi-channel			36.1	T mass 1.37 TeV	SU(2) doublet	ATLAS-CONF-2018-032
	VLQ $BB \to Wt/Zb + X$	multi-channel			36.1	B mass 1.34 TeV	SU(2) doublet	ATLAS-CONF-2018-032
	VLQ $T_{5/3}T_{5/3}\lvert T_{5/3} \to Wt + X$	2(SS)/≥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	CERN-EP-2018-171
	VLQ $Y \to Wb + X$	1 e, μ	≥ 1 b, ≥ 1j	Yes	3.2	Y mass 1.44 TeV	$\mathcal{B}(Y \to Wb)$= 1, $c(YWb)$= $1/\sqrt{2}$	ATLAS-CONF-2016-072
	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, μ	≥ 4 j	Yes	20.3	Q mass 690 GeV		1509.04261
Excited fermions	Excited quark $q^* \to qg$	–	2 j	–	37.0	q^* mass 6.0 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1703.09127
	Excited quark $q^* \to q\gamma$	1 γ	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, μ	–	–	20.3	ℓ^* mass 3.0 TeV	$\Lambda = 3.0$ TeV	1411.2921
	Excited lepton ν^*	3 e, μ, τ	–	–	20.3	ν^* mass 1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	Type III Seesaw	1 e, μ	≥ 2 j	Yes	79.8	N^0 mass 560 GeV		ATLAS-CONF-2018-020
	LRSM Majorana ν	2 e, μ	2 j	–	20.3	N^0 mass 2.0 TeV	$m(W_R) = 2.4$ TeV, no mixing	1506.06020
	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, μ, τ	–	–	20.3	$H^{\pm\pm}$ mass 400 GeV	DY production, $\mathcal{B}(H^{\pm\pm}_L \to \ell\tau) = 1$	1411.2921
	Monotop (non-res prod)	1 e, μ	1 b	Yes	20.3	spin-1 invisible particle mass 657 GeV	$a_{non-res} = 0.2$	1410.5404
	Multi-charged particles	–	–	–	20.3	multi-charged particle mass 785 GeV	DY production, $\lvert q\rvert = 5e$	1504.04188
	Magnetic monopoles	–	–	–	7.0	monopole mass 1.34 TeV	DY production, $\lvert g\rvert = 1g_D$, spin 1/2	1509.08059

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

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

No hint for BSM ?

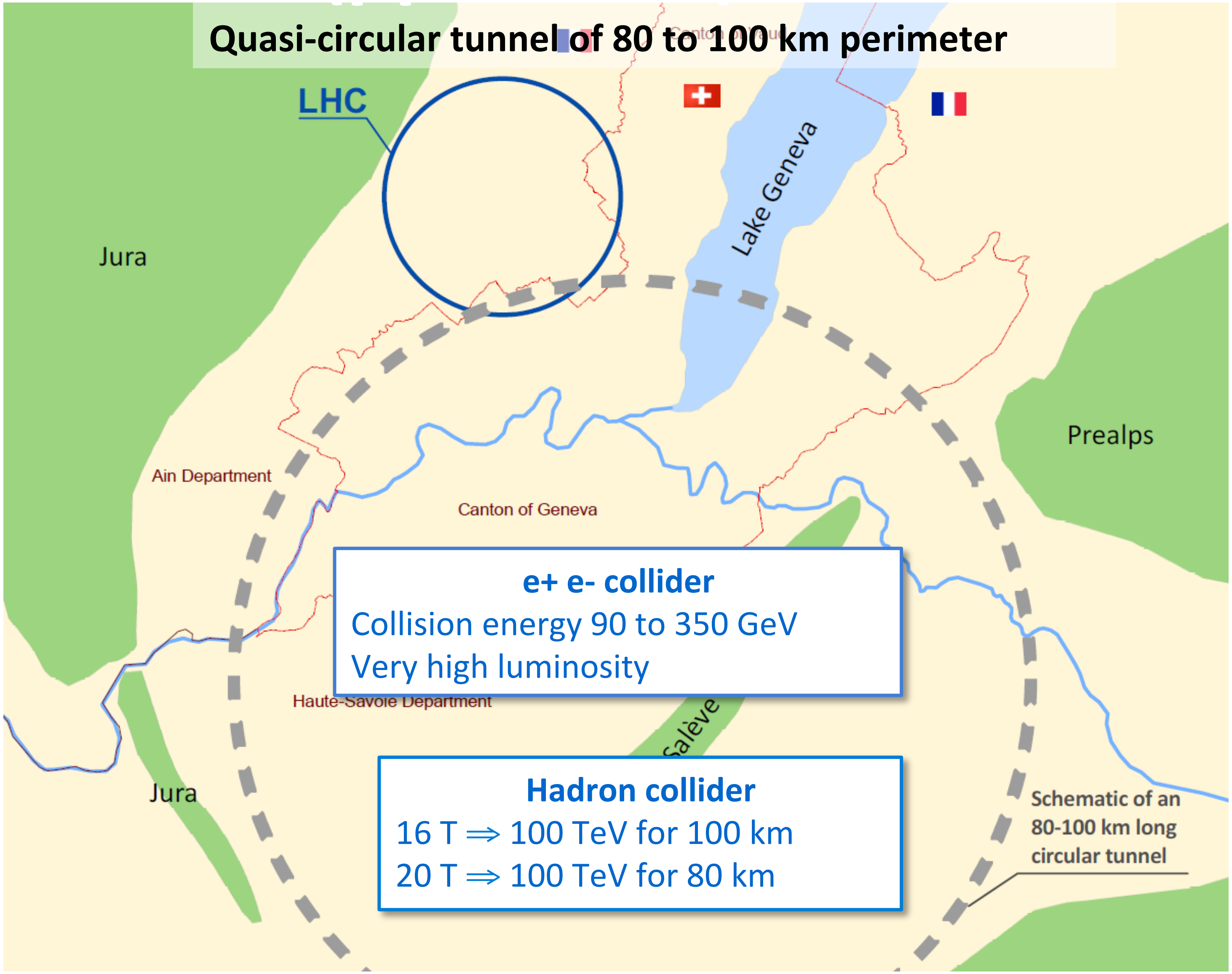


*Only a selection of the available mass limits on new states or phenomena is shown.

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


Only time will tell…..
SUSY/BSM
LHC Luminosity

Quasi-circular tunnel of 80 to 100 km perimeter



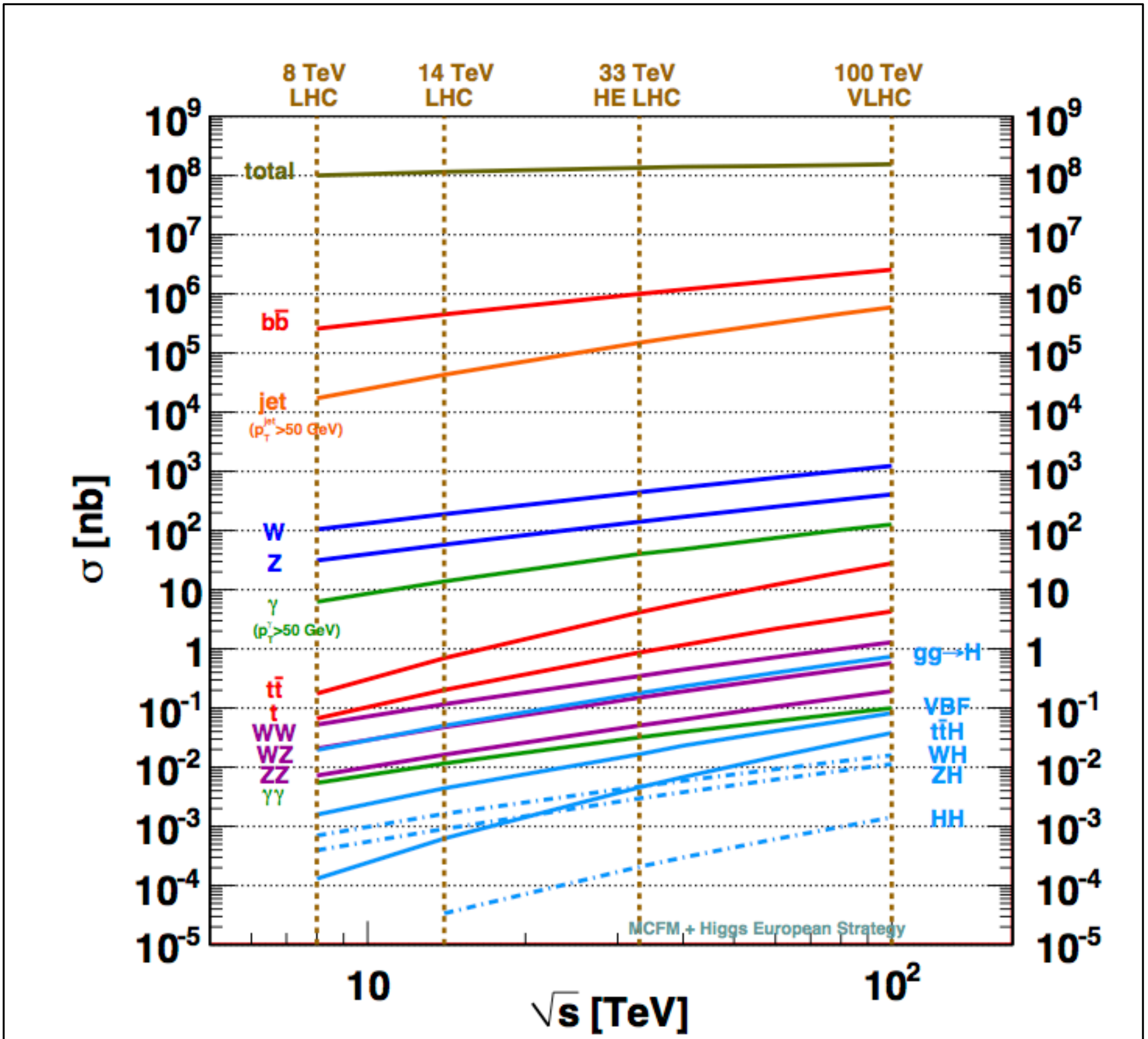
e+ e- collider
Collision energy 90 to 350 GeV
Very high luminosity

Hadron collider
16 T $\Rightarrow$ 100 TeV for 100 km
20 T $\Rightarrow$ 100 TeV for 80 km

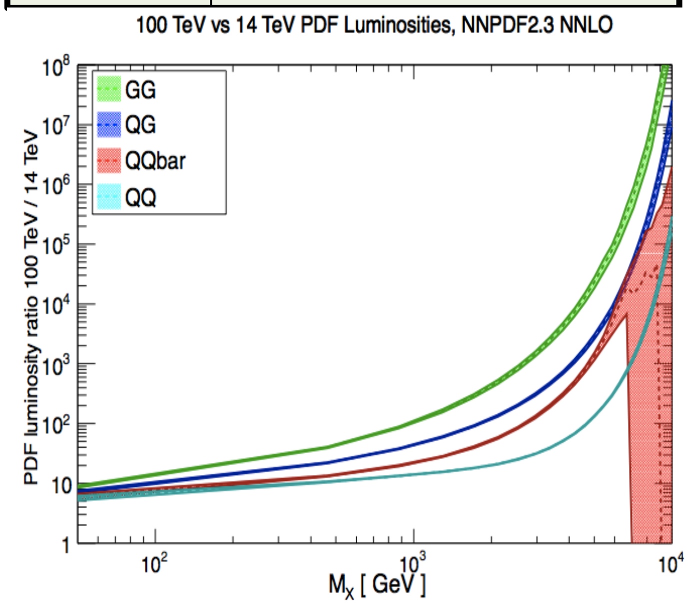
Key technologies are high-field magnets for the hadron collider and an efficient high-power superconducting RF (SRF) system for the lepton collider.

Snowmass report: arXiv:1310.5189

100 TeV pp collisions

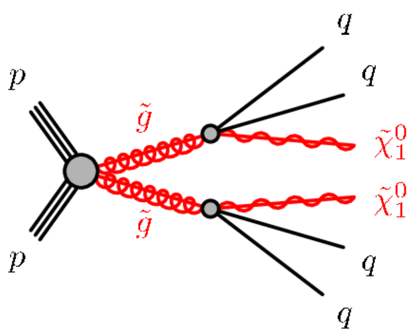


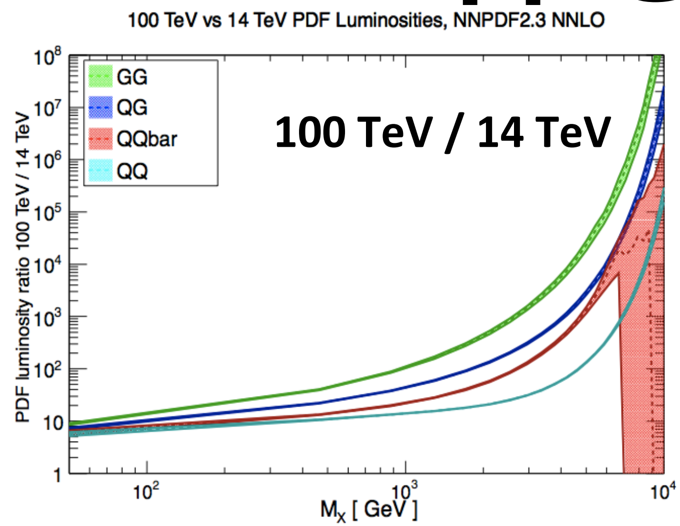
Process	σ (100 TeV)/σ (14 TeV)
WW	~10
ZZ	~10
tt	~30
H	~15 (ttH ~60)
HH	~40
stop (m=1 TeV)	~10^3

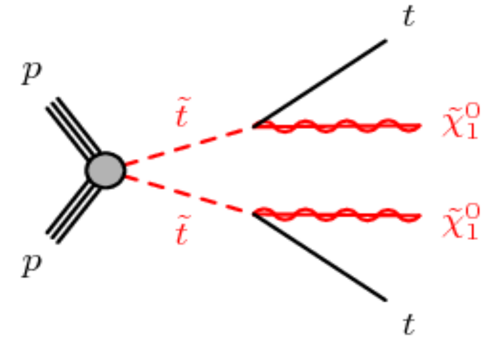


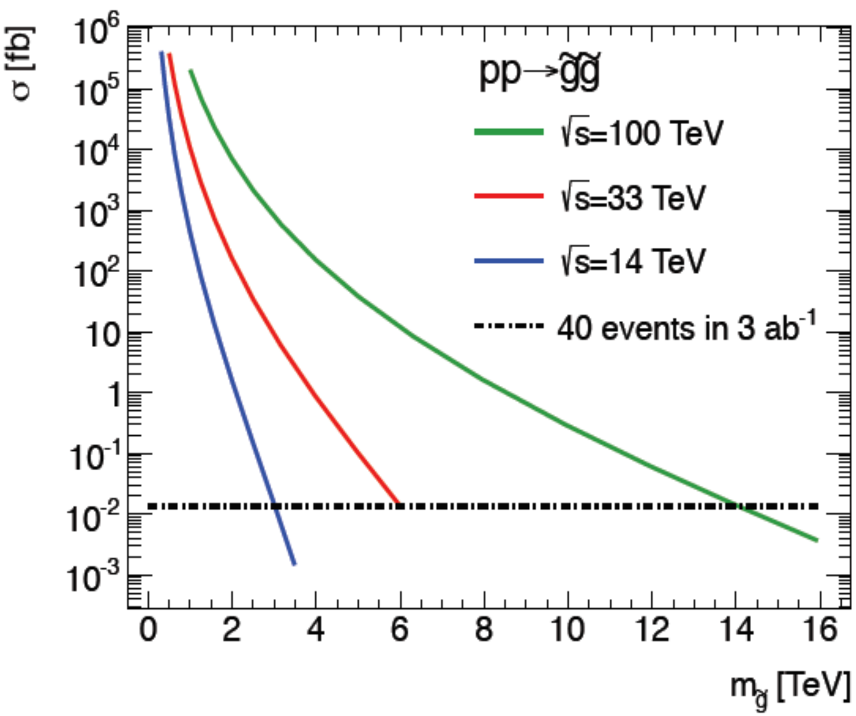
It really opens a new energy frontier---

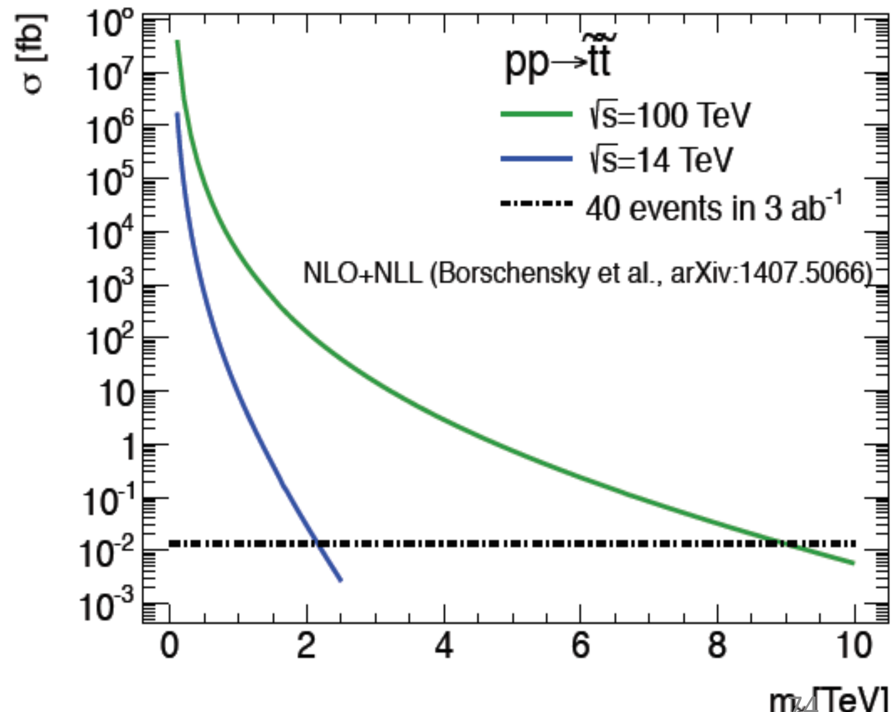
SUSY Reach for pp @ 100 TeV



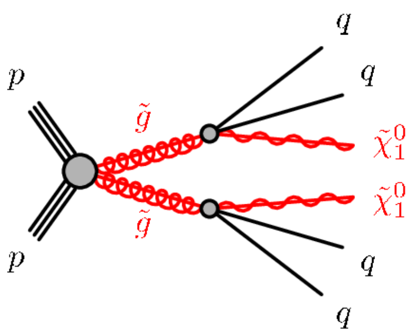






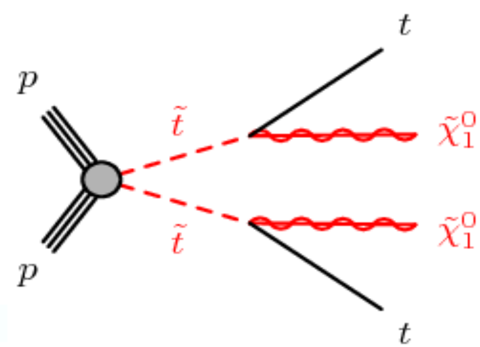


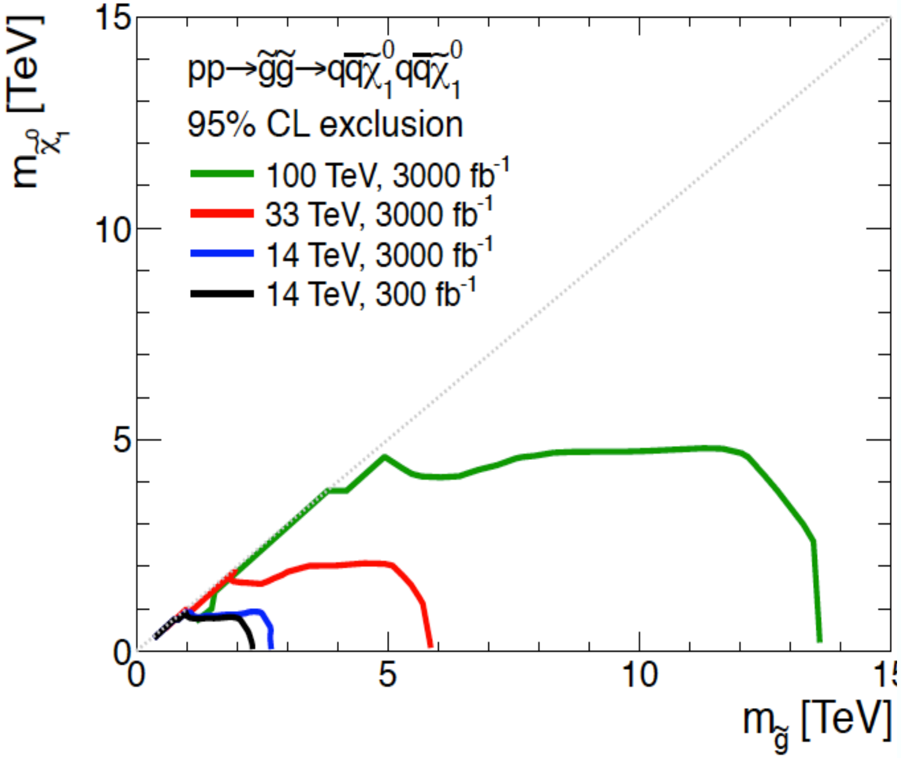
SUSY Reach for pp @ 100 TeV

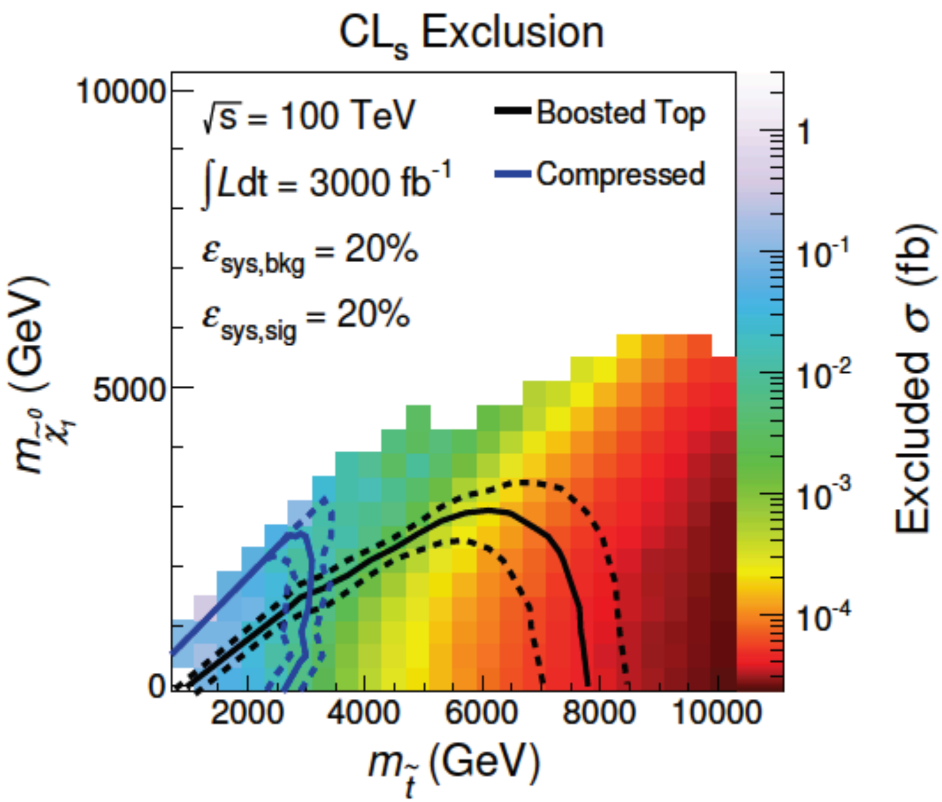


In terms of Higgs/EWK hierarchy problem

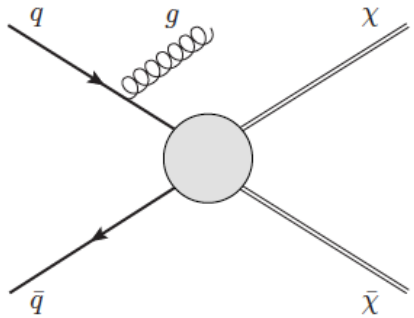
This scenario implies a tuning of the level of 0.05%



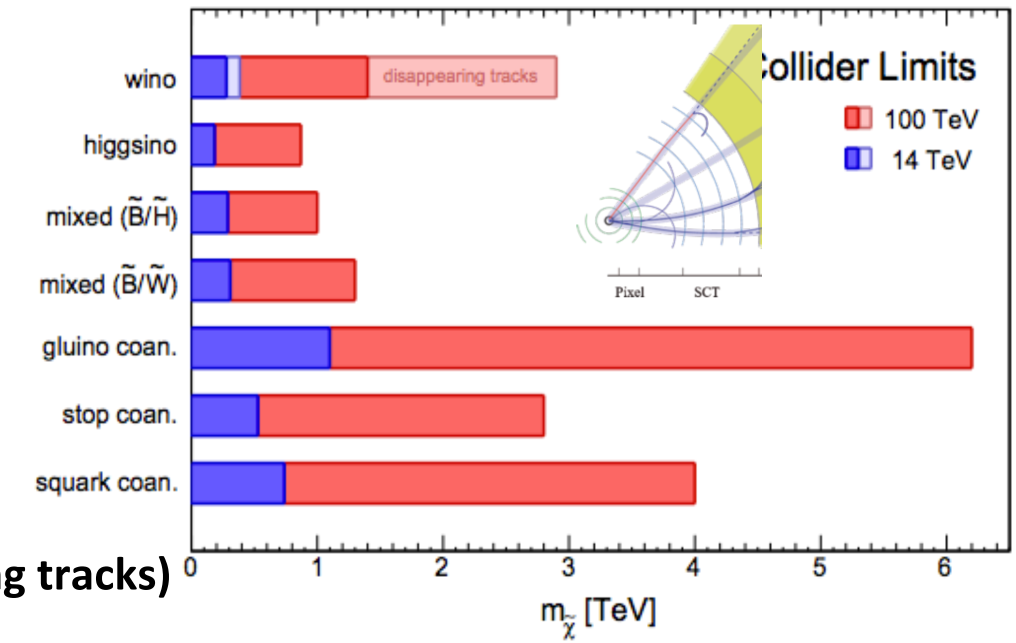


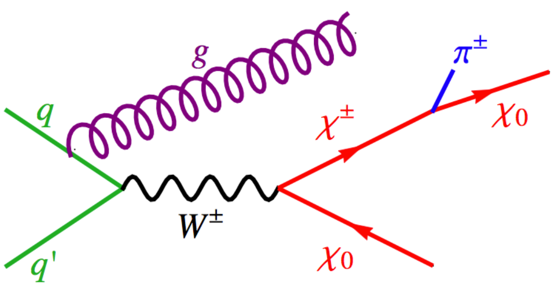


SUSY EWK @ 100 TeV

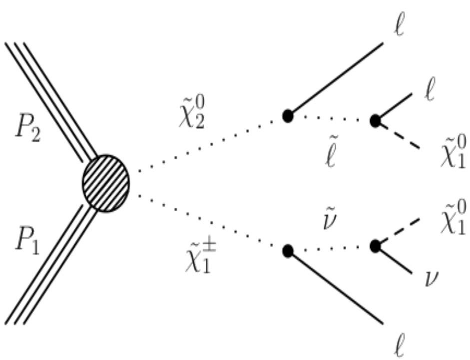


Monojets

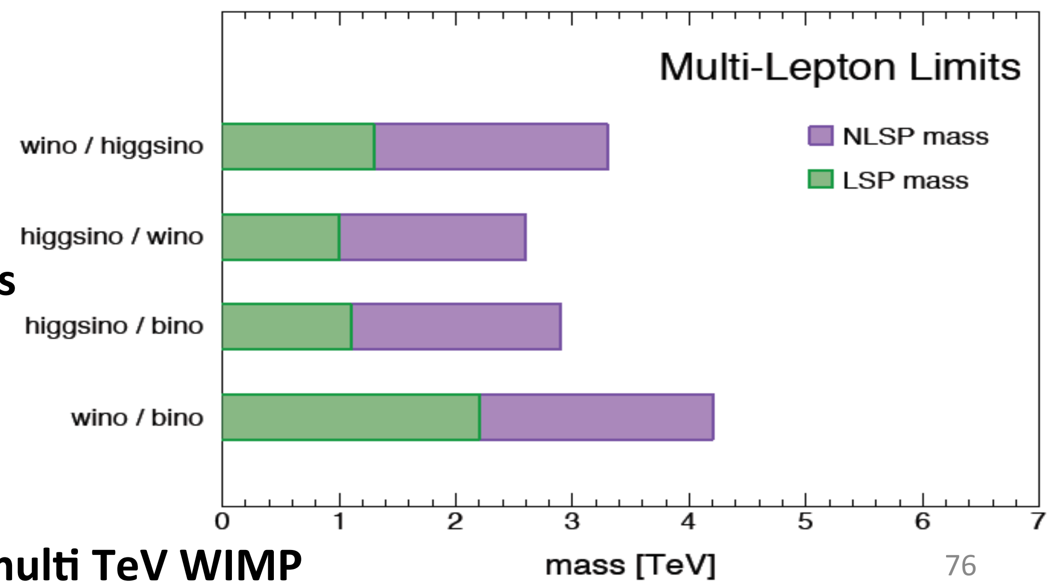




Long-lived (disappearing tracks)



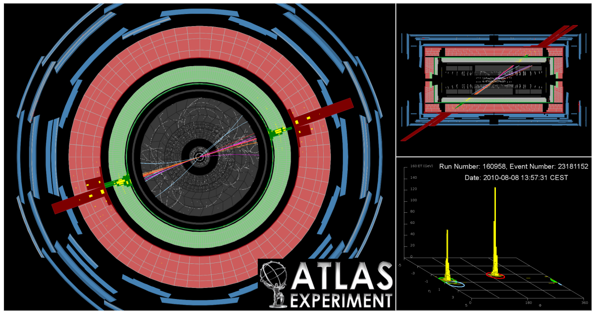
Multileptons

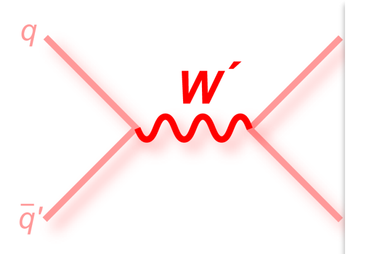


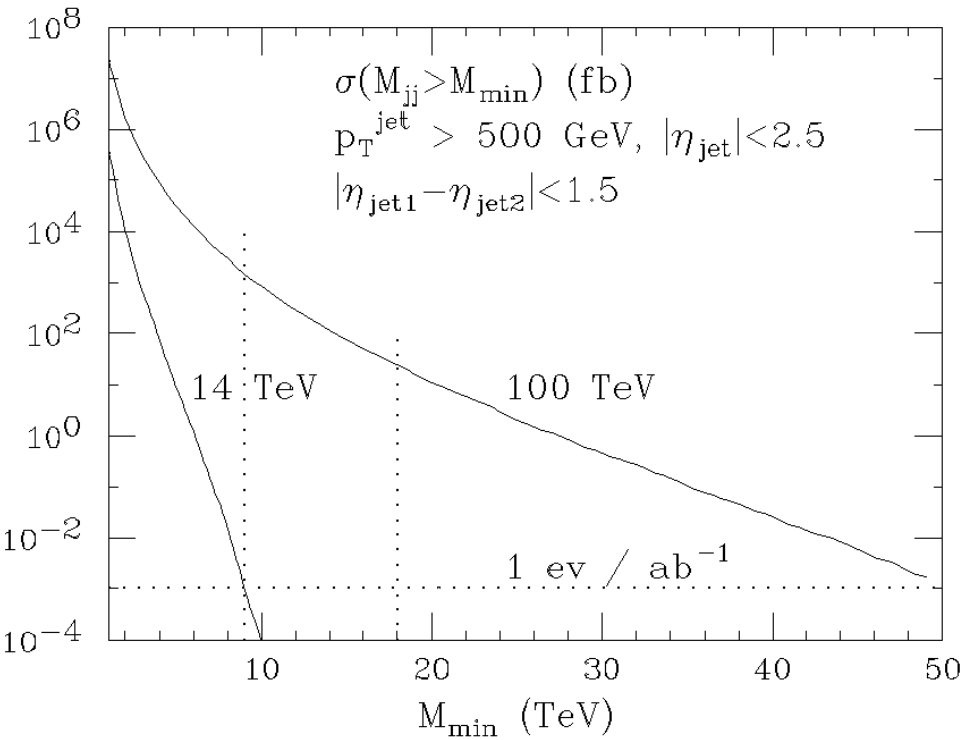
A 100 TeV pp collider would probe the multi TeV WIMP

FCC-pp at 100 TeV and considering a total integrated luminosity of 3 ab-1

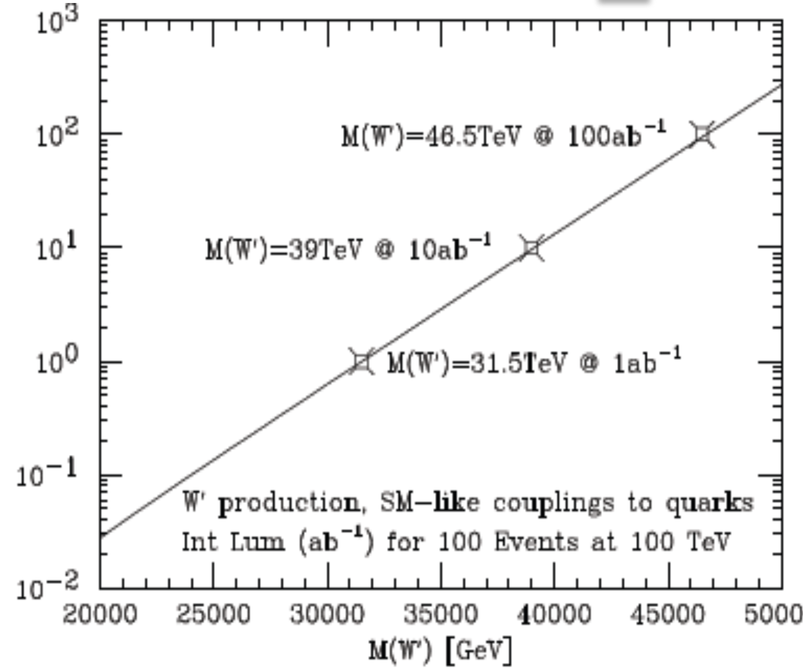
Dijets and W’







To recover LHC-HL sensitivity would take 1 pb-1 (1 day operations)

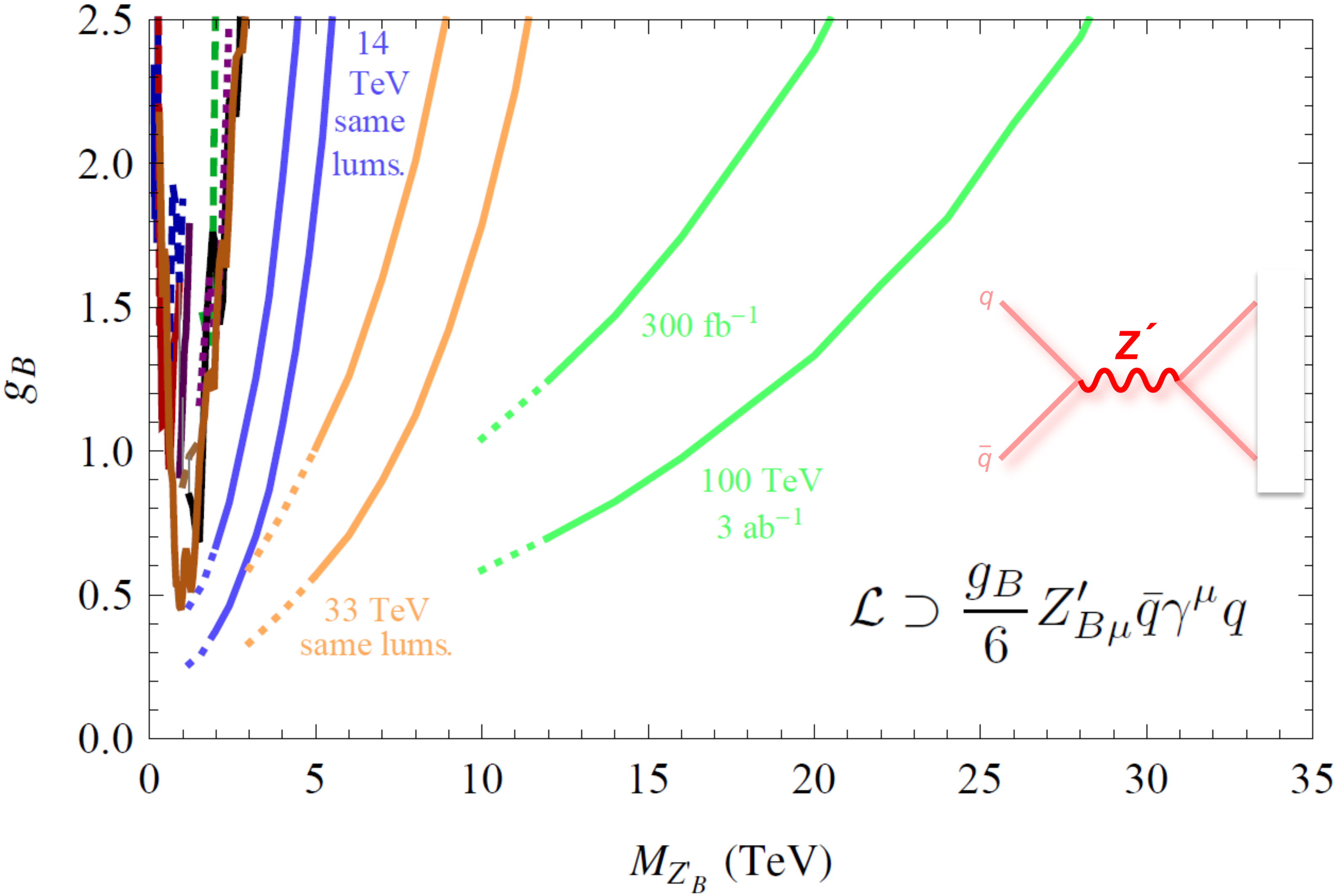


Assuming SM couplings… FCC-pp could exclude a W’ of 32 TeV

FCC-pp at 100 TeV and considering a total integrated luminosity of 3 ab-1

Drell-Yan

Discovery reach
4.5 TeV @ 14 TeV LHC, 300 fb-1
5.5 TeV @ 14 TeV LHC, 3 ab-1
28 TeV @ 100 TeV, 3 ab-1



End Part IV

Thanks for your attention