SUSY/BSM IV

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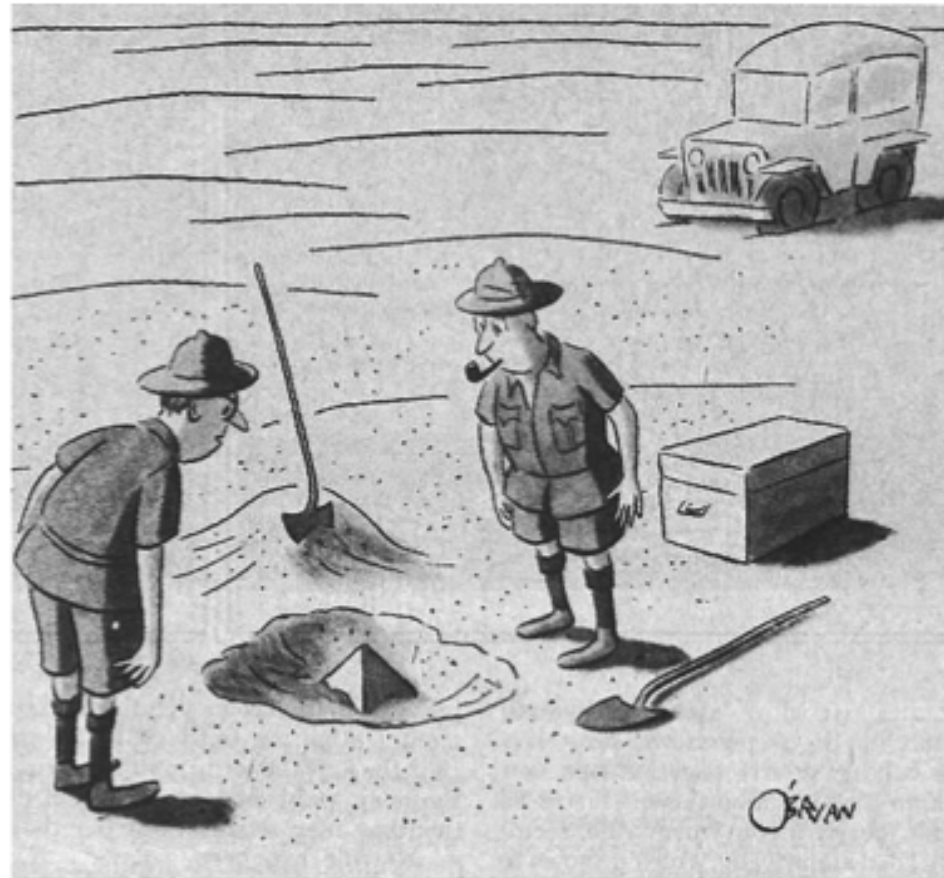
HASCO SUMMER SCHOOL 2016

Outline for Part IV

- **New bosons**
- **Excited leptons**
- **Extra dimensions**
- **New resonances**
- **Vector-like quarks**
- **Leptoquarks**
- **Other Exotica**
- **……**

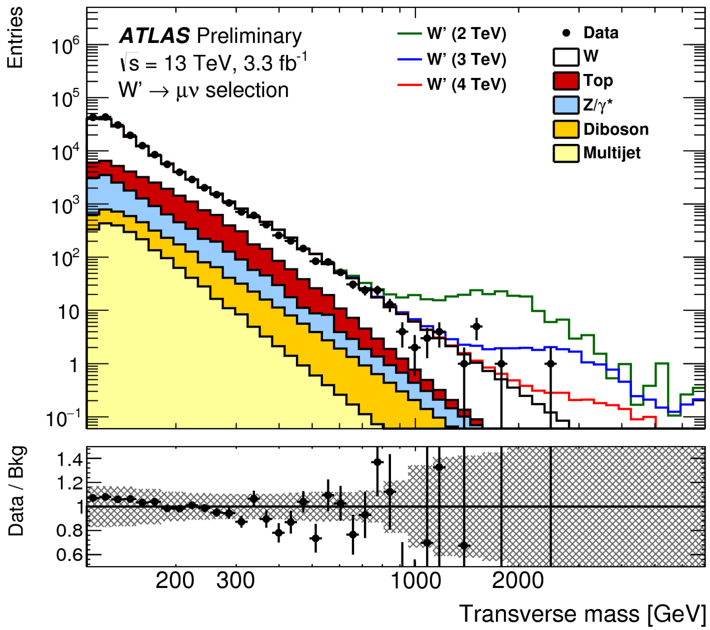


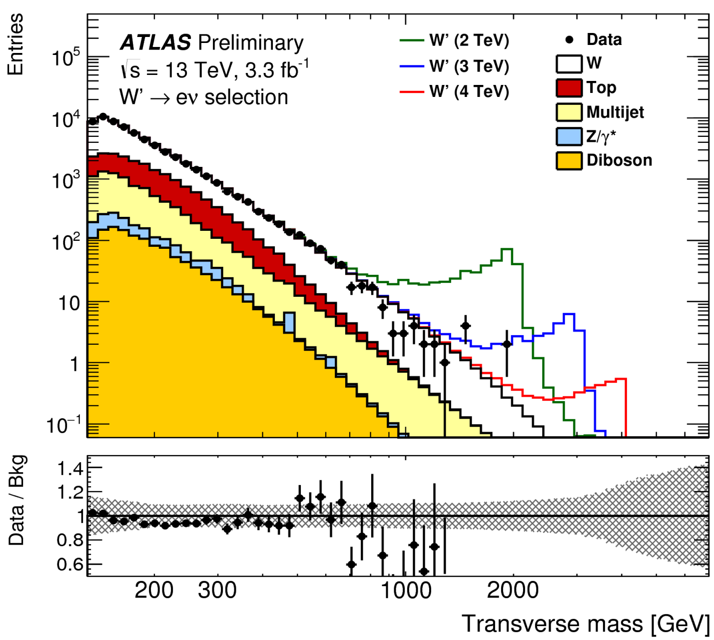
"This could be the discovery of the century. Depending, of course, on how far down it goes."

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

ATLAS-CONF-2015-063

W' → lν

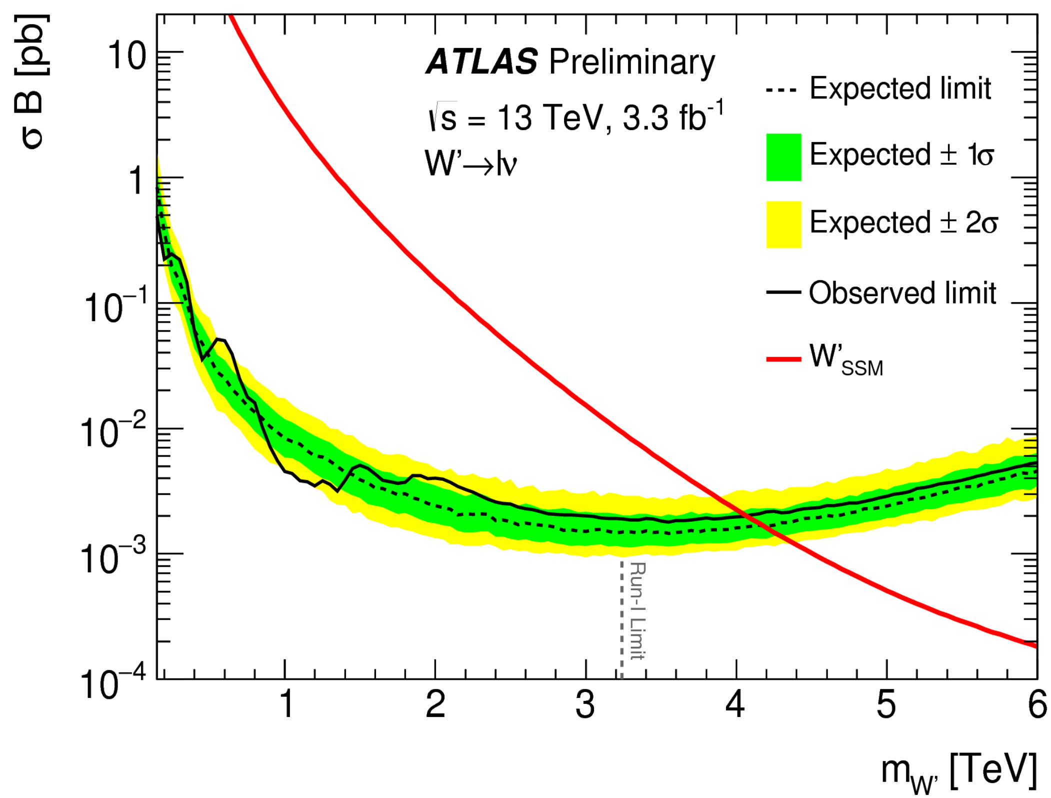




Theories with larger groups than those of the SM might predict to the presence of new bosons

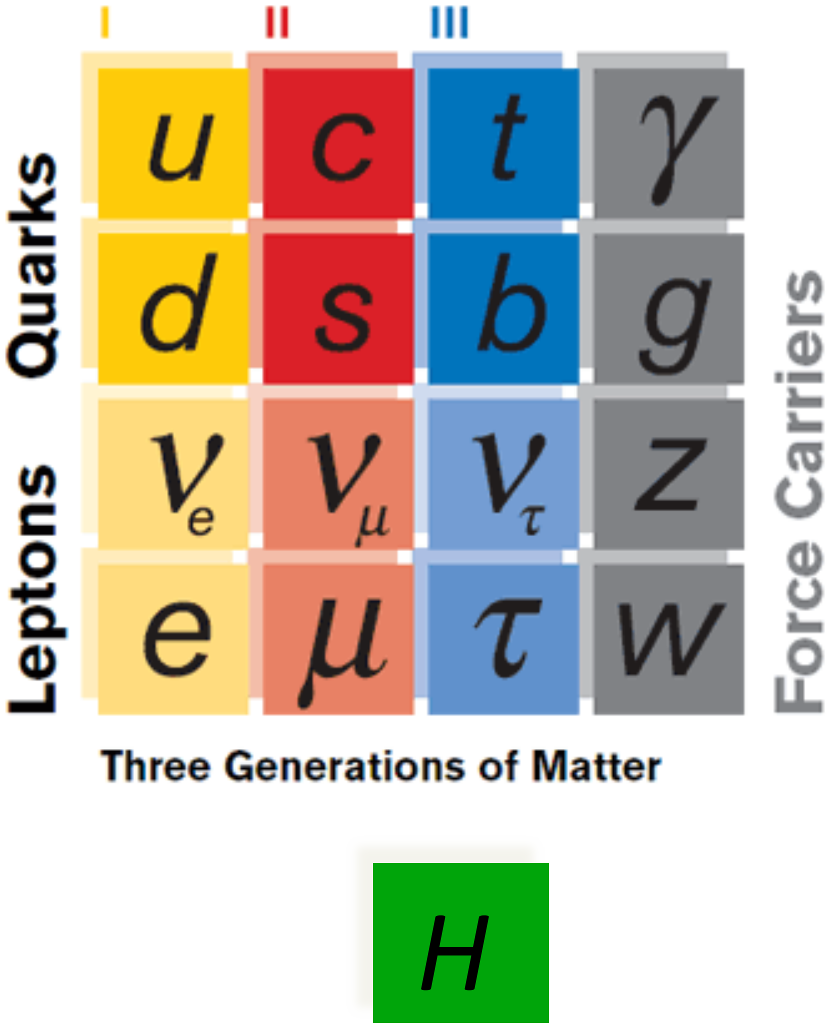
→ One typically assumes SM-like couplings

$$m_T = \sqrt{2 p_T E_T^{miss}(1 - \cos\phi_{\ell\nu})},$$



Some of the open questions

(i.e., the need for new physics)

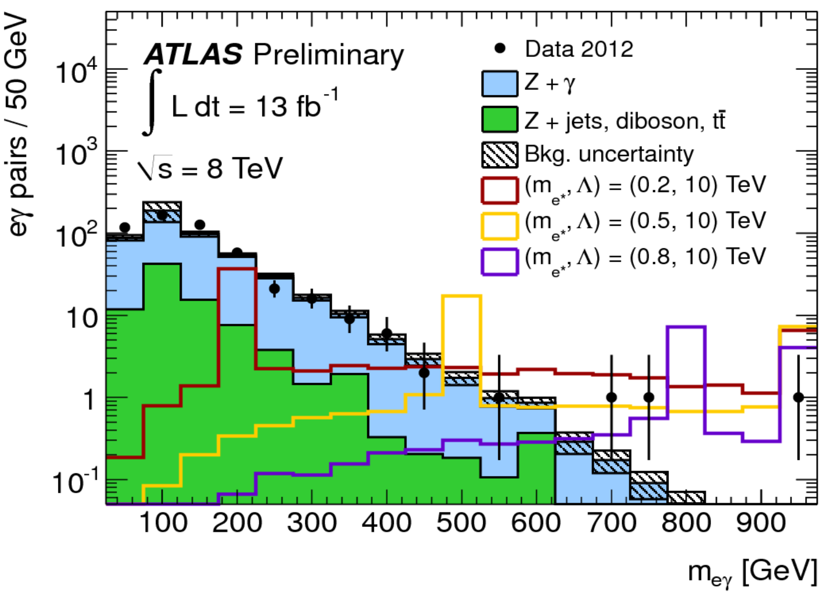


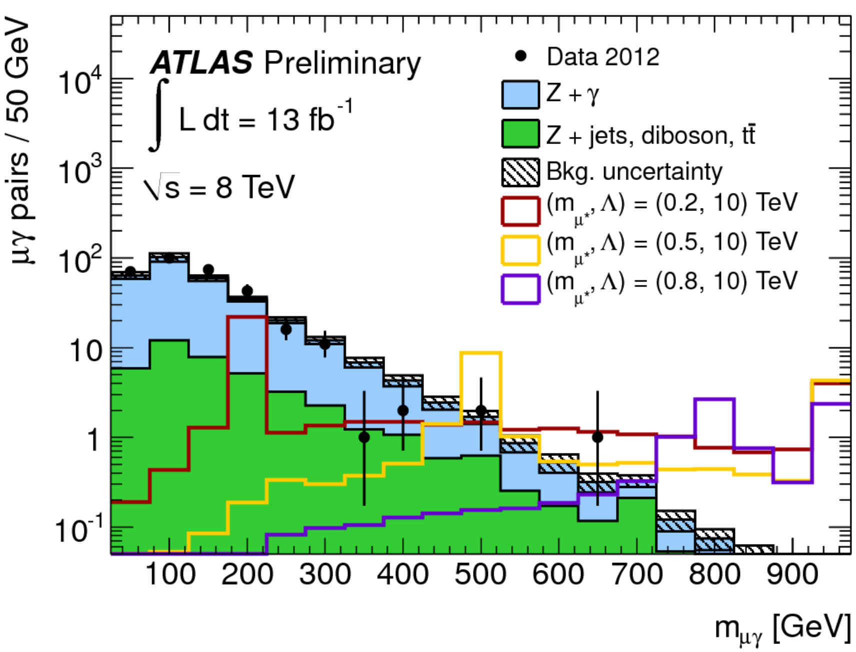
- **Who ordered 3 generations?**
- **Matter/Anti-Matter ?**
- **……..**

- **Hierarchy Problem …**
- **Unification at Large Scale?**
- **Dark Matter in the Cosmos?**
- **………**
- **What about Gravity ?**
- **………**

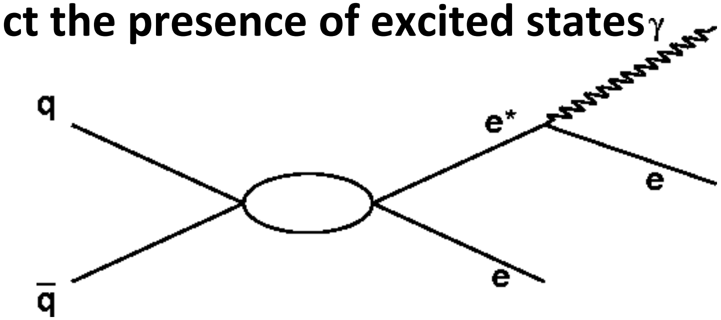
ATLAS-CONF-2012-146

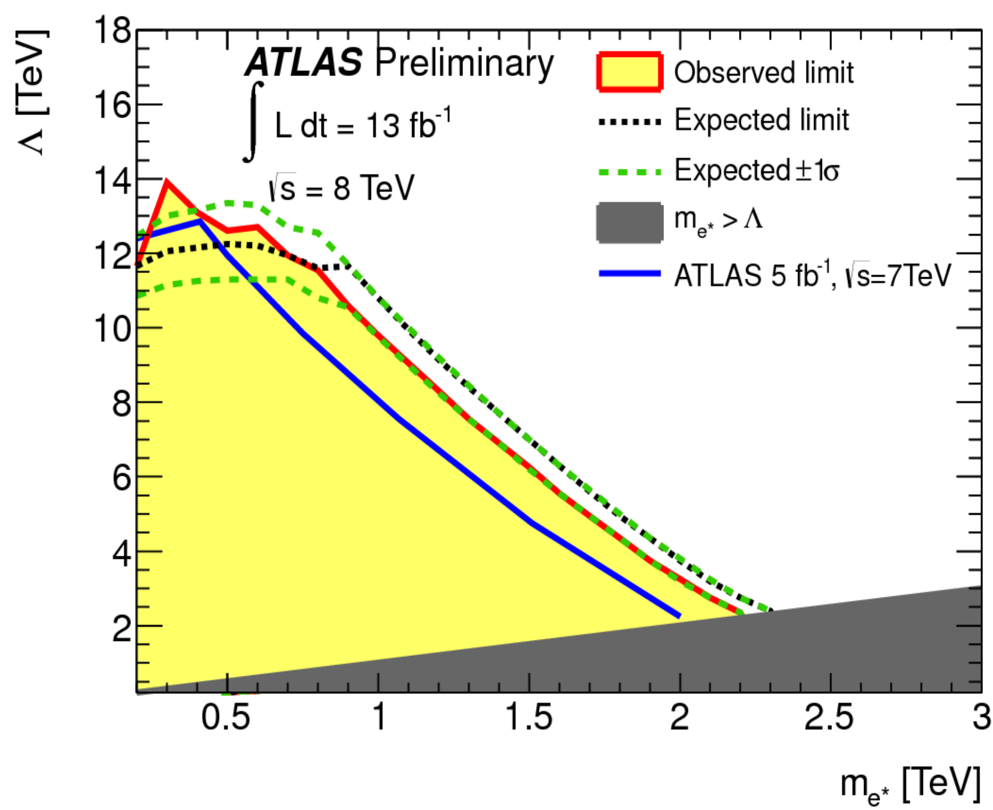
Excited Leptons





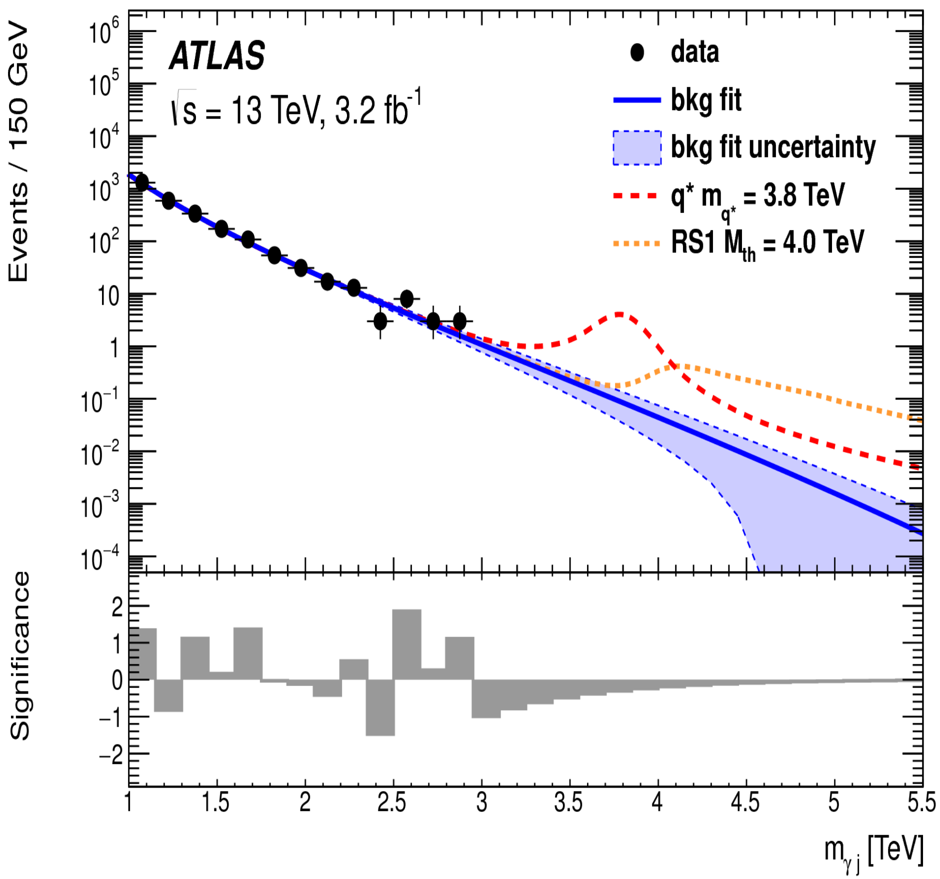
Composite models try to understand the Lepton/quark degeneracy and usually predict the presence of excited states

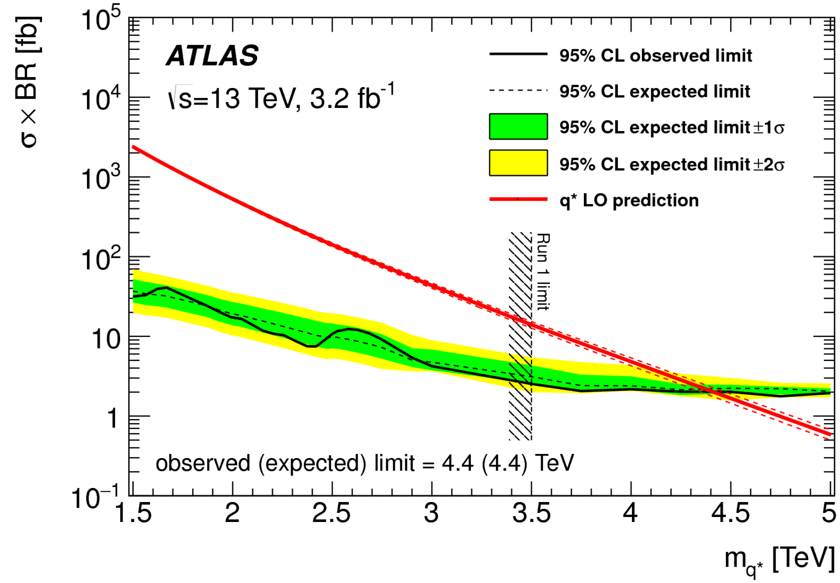


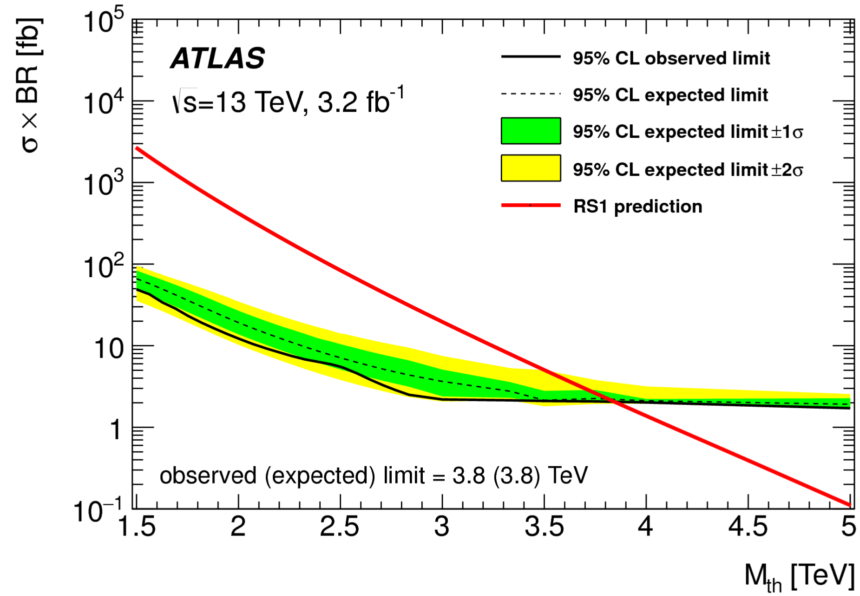


Excited quarks q* → qγ

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

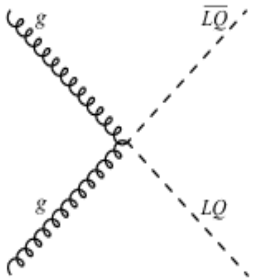


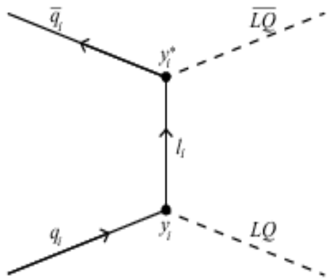




arXiv:1508.04735

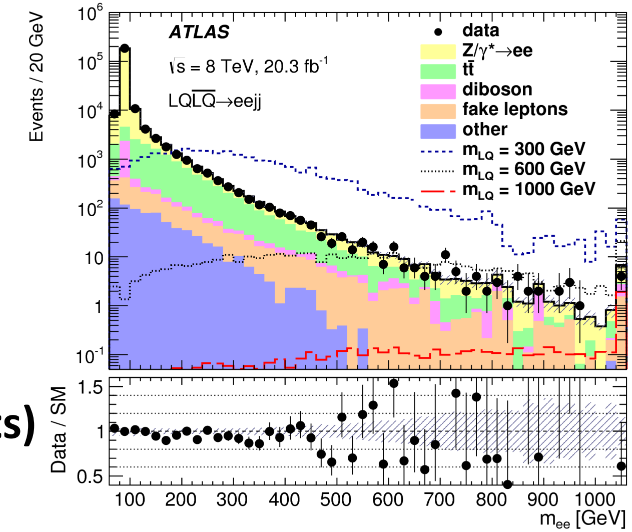
Lepto-quarks

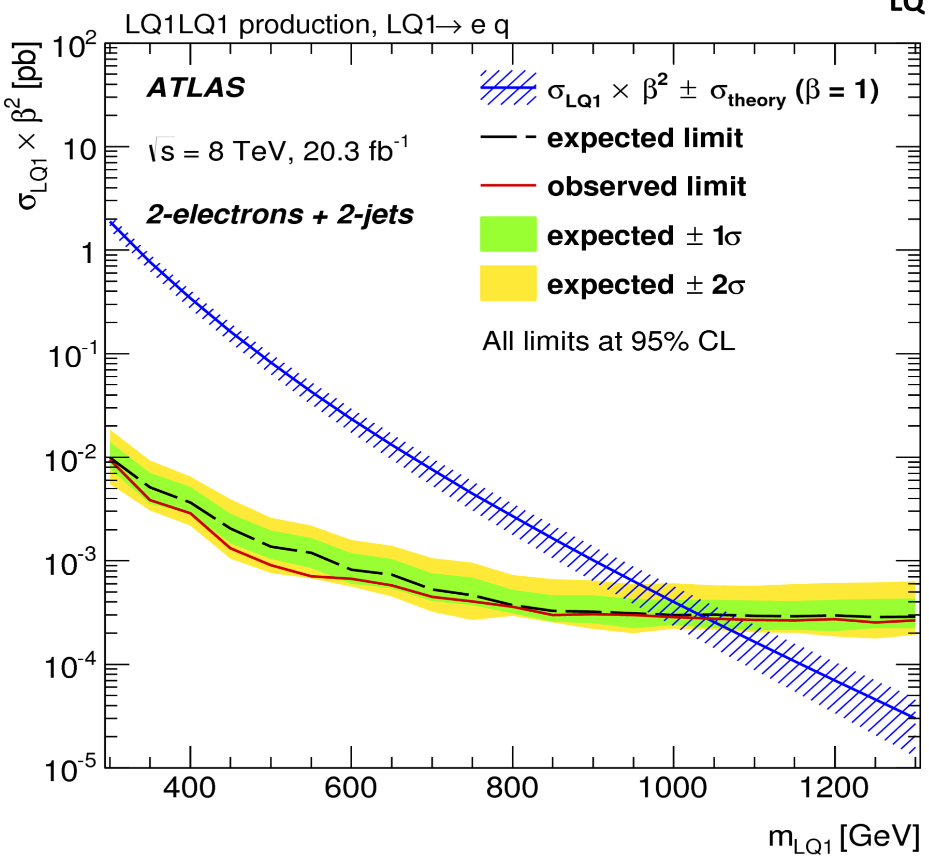


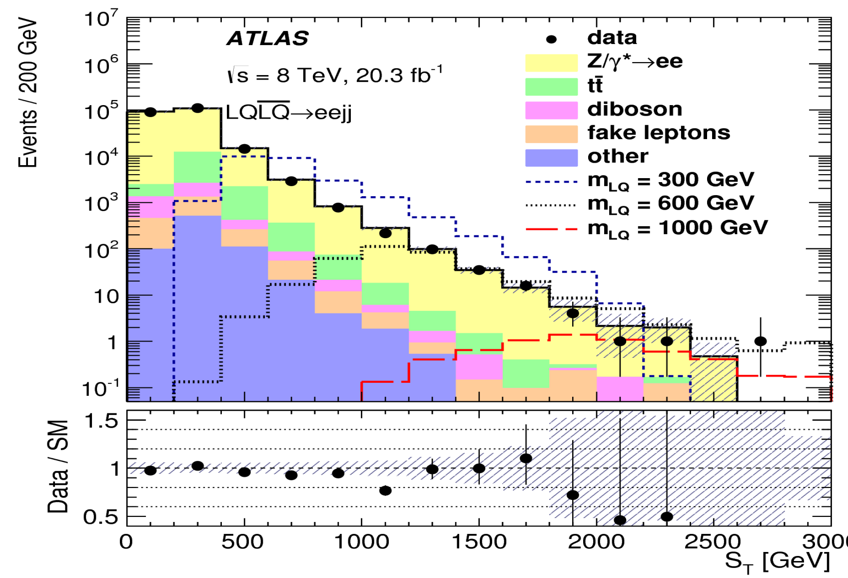


2leptons + 2 jets
Selection based on

- **Dilepton mass**
- **S_T (leptons and jets)**
- **M_{LQ}^{Min}**



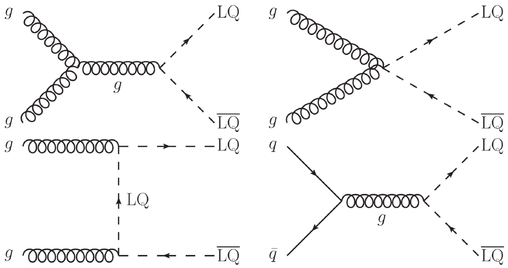


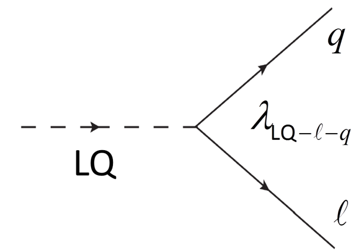


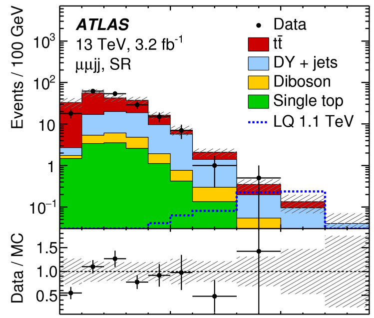
Lepto-quark (1st -2nd gene.)
masses below 1 TeV excluded

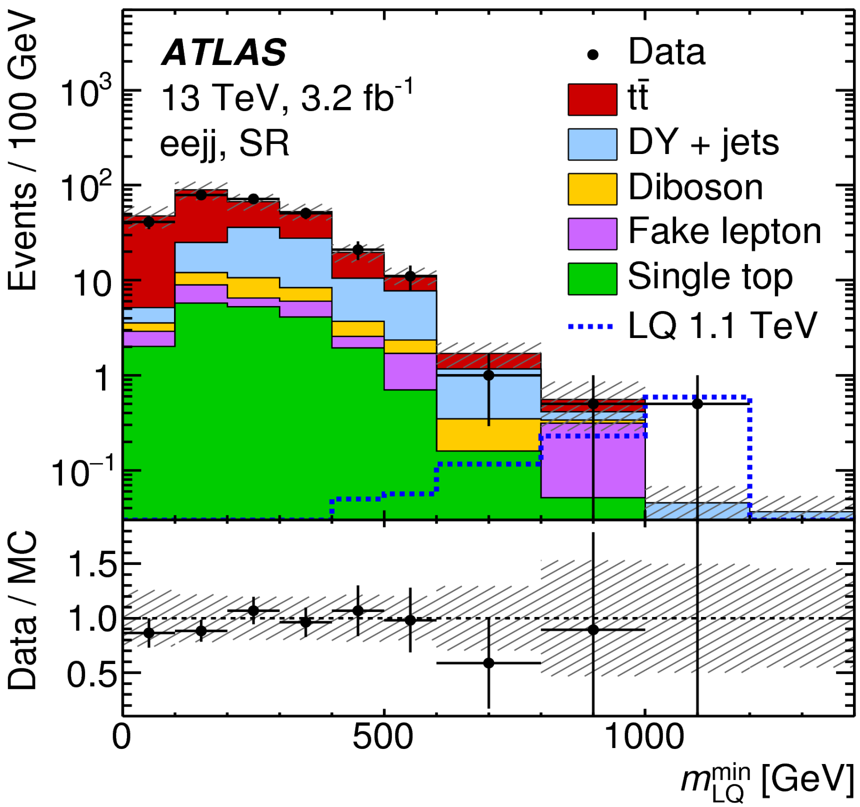
arXiv:1605.06035

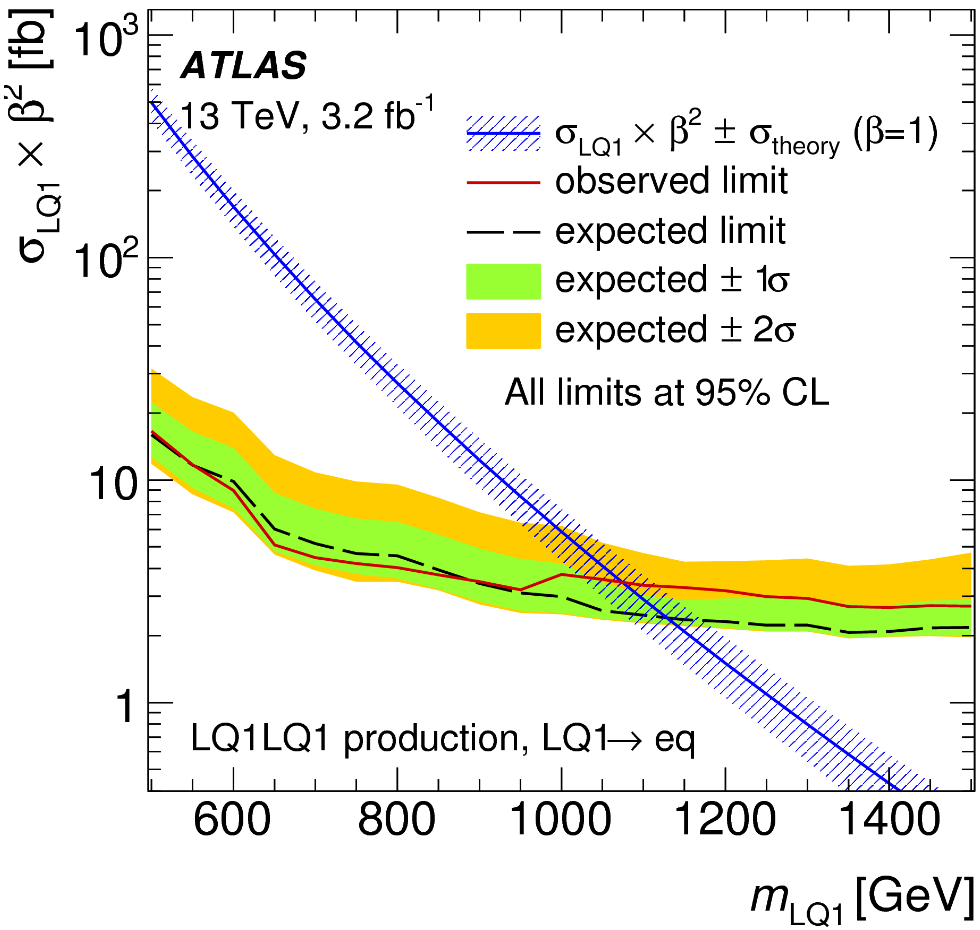
LQ @ 13 TeV





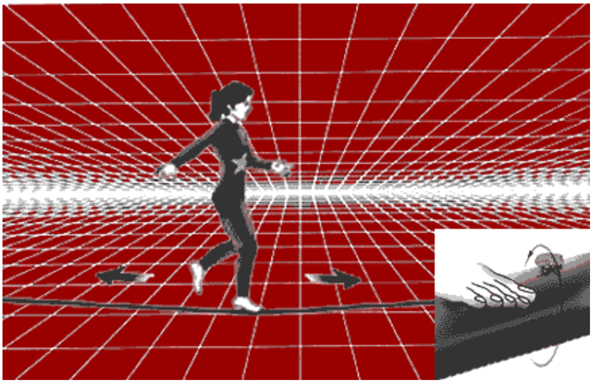




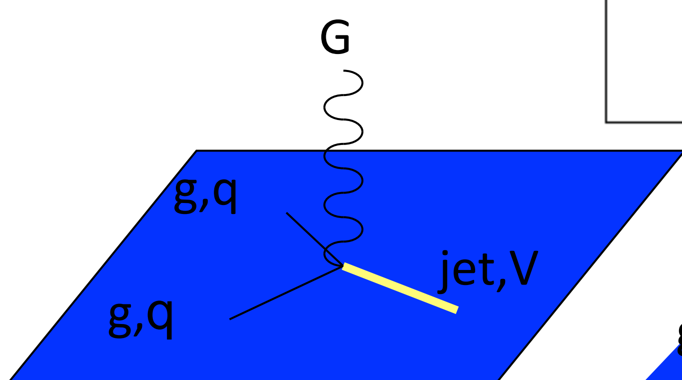


Extra Dimensions

Alternative to solve Hierarchy Problem



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

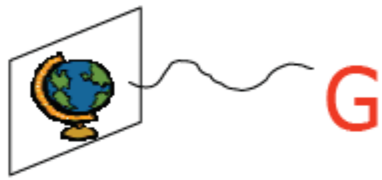


mono-jet

ADD

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

Many large compactified EDs
In which G can propagate



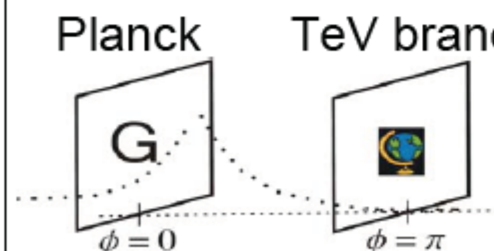
$$M_{Pl}^2 \sim R^n M_{Pl(4+n)}^{(2+n)}$$

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

RS

Randall, Sundrum,
Phys Rev Lett 83 (99)

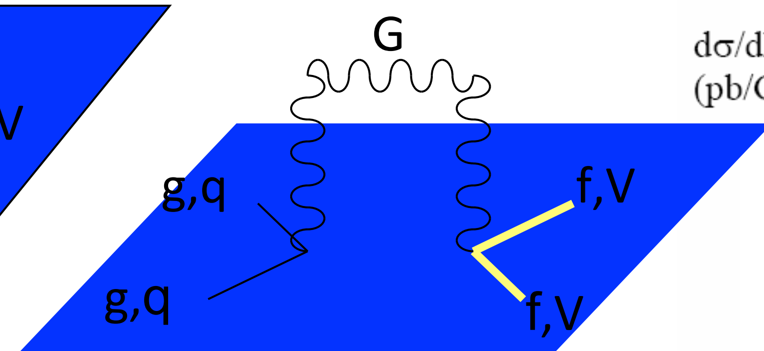
1 highly curved ED
Gravity localised in the ED

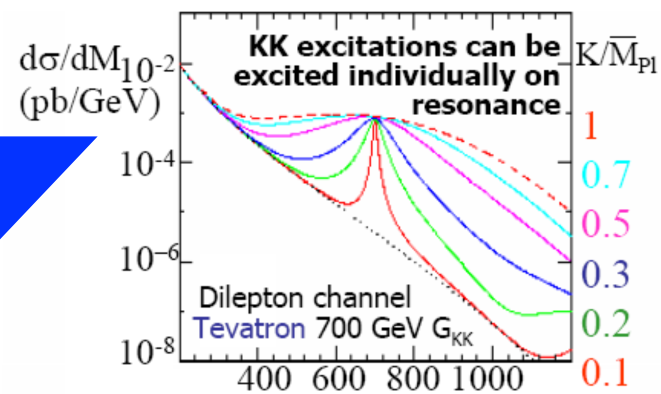


$$\Lambda_\pi = \overline{M}_{pl} e^{-kR_c\pi}$$

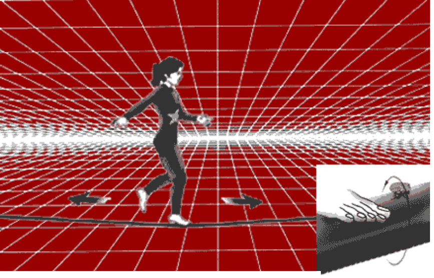
Λ_π ~ TeV

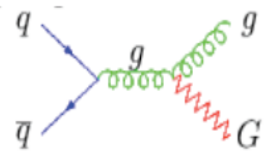
if warp factor kR_c ~11-12
k/M_{Pl}, k: curvature scale



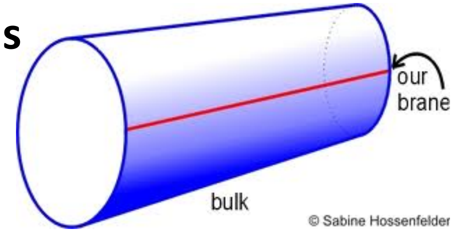


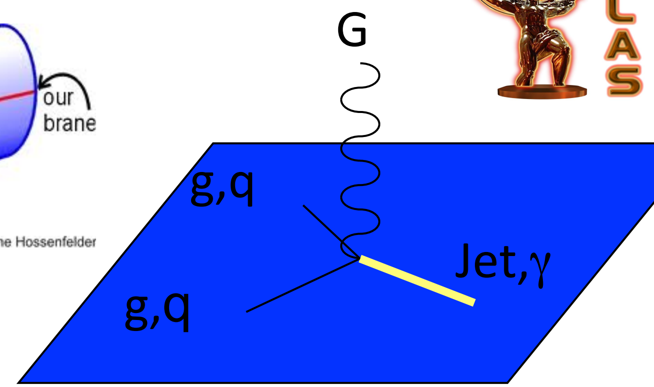
Large Extra Dimensions



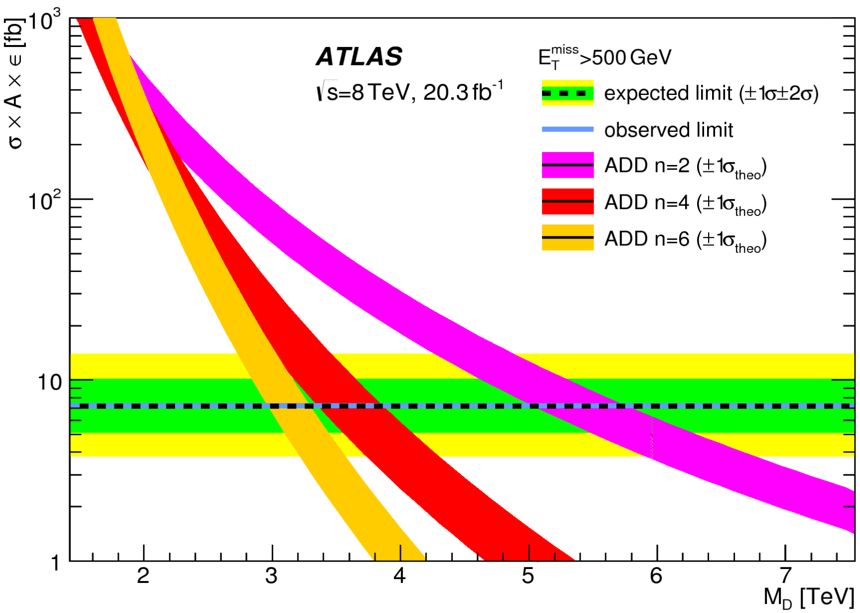


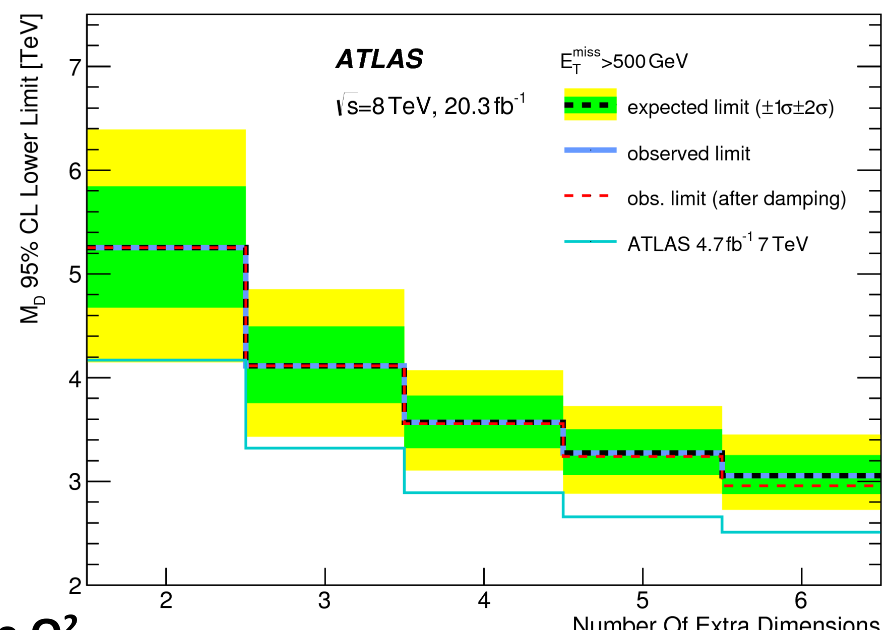
Extra spatial dimensions explain the apparent weakness of Gravity (relevant scale ~TeV)





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



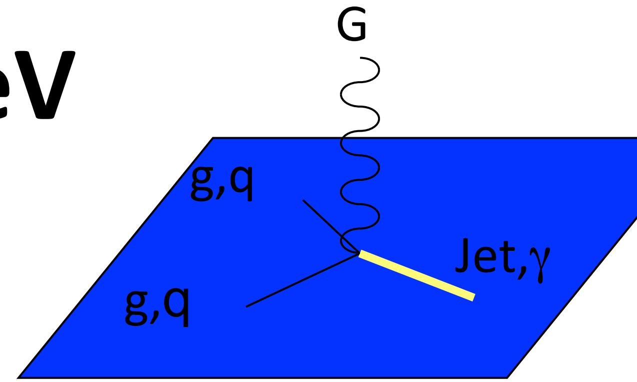


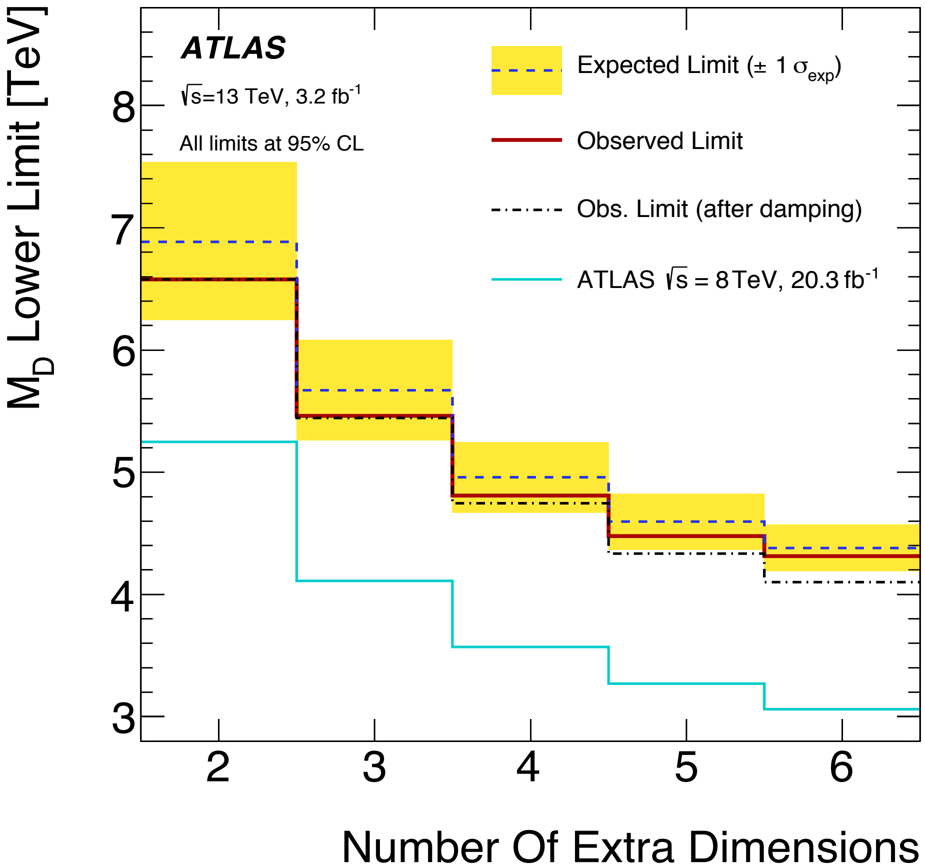
Limits on M_D beyond 5 TeV
(a real challenge of the model validity)

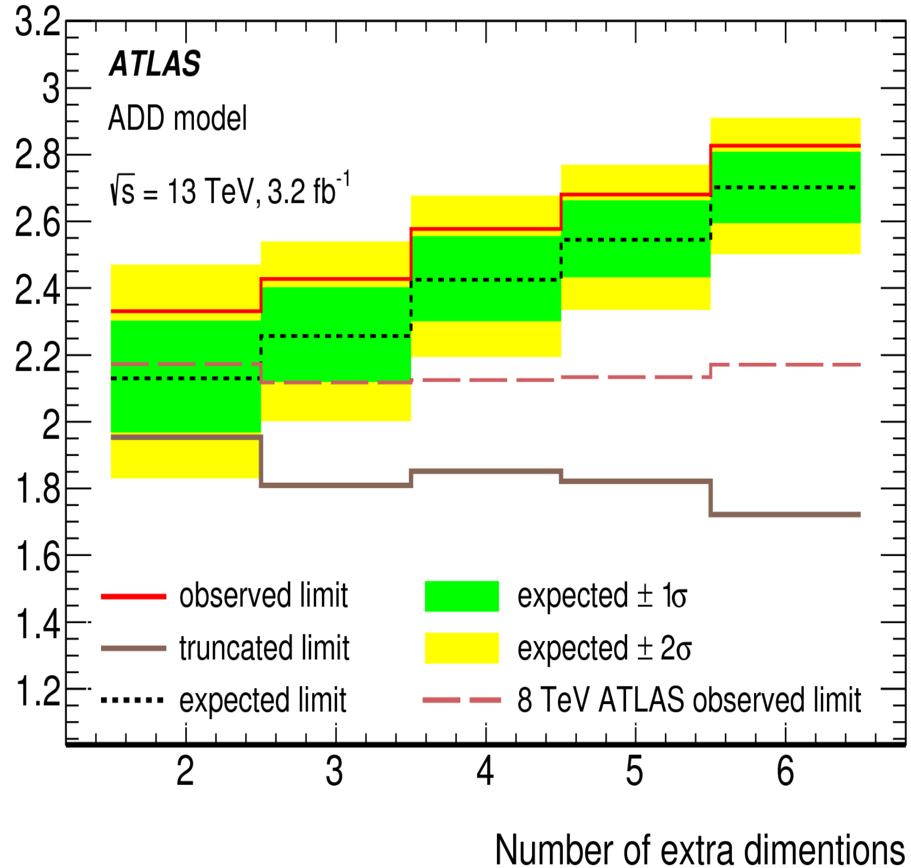
Note: Limits sensitive to the truncation strategy for s-hat > M_D^2, LHC probing phase space at large Q^2

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

Results @ 13 TeV







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

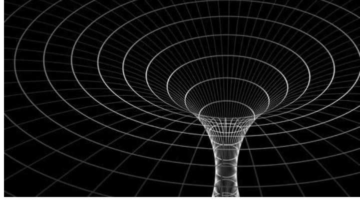
→ Note the model is implemented in a EFT manner

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

JHEP08(2014)103

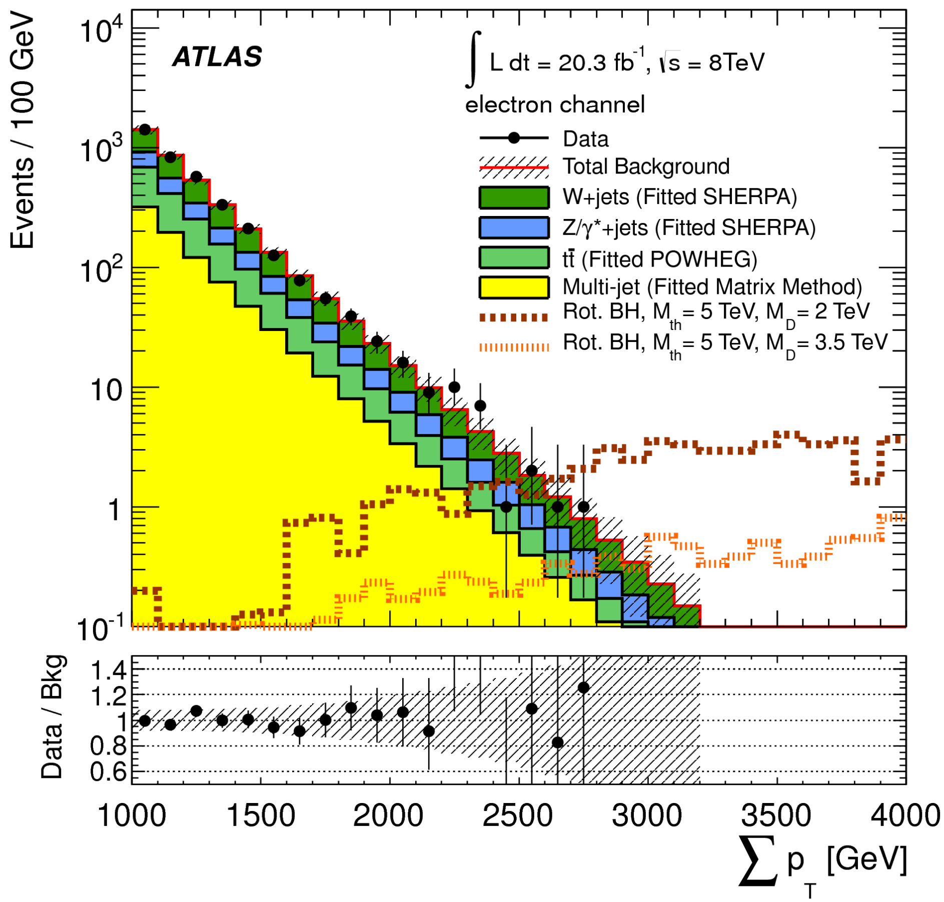
[JHEP 07 (2015) 032]

QBH

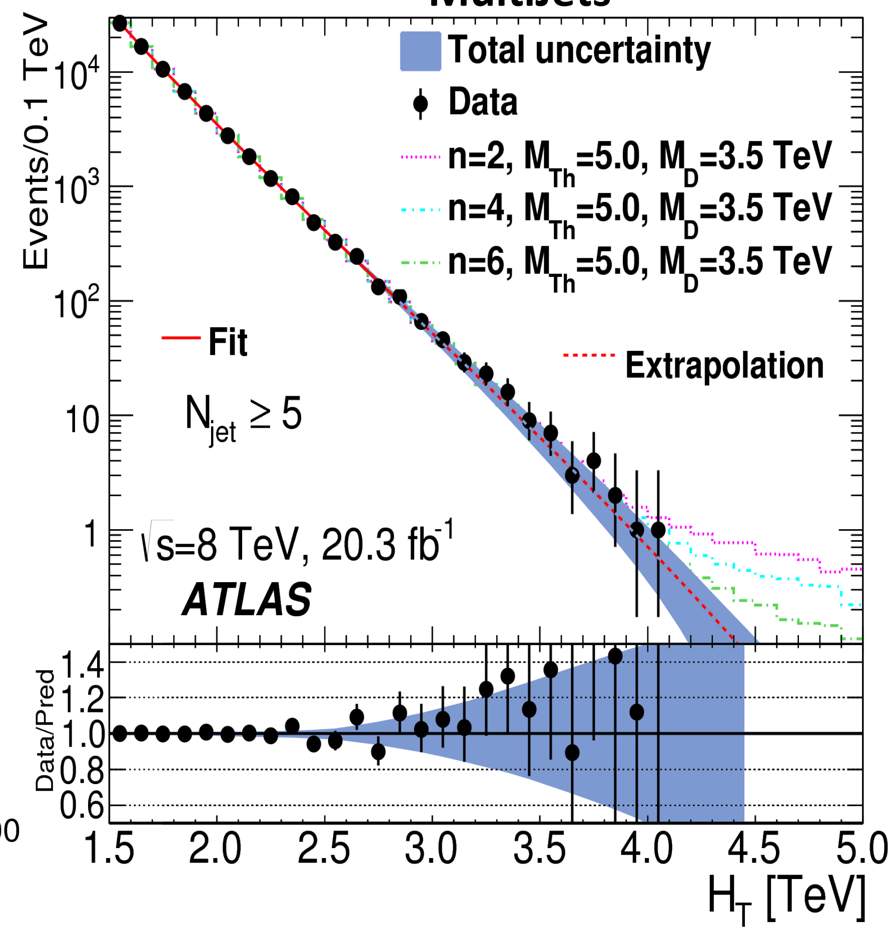


(production of Black Holes in models with extra spatial dimensions)

Lepton + Jets



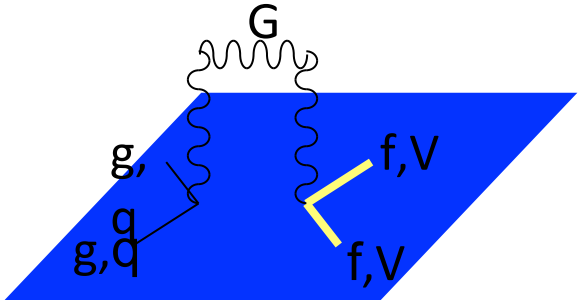
MultiJets

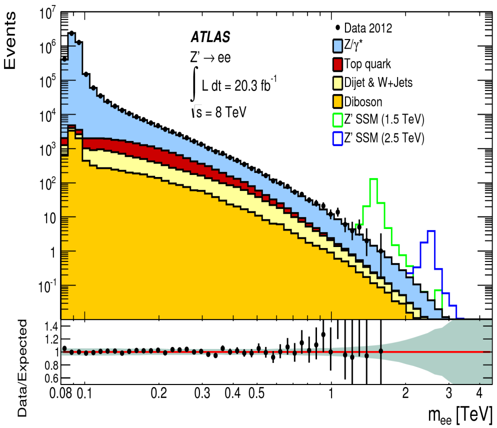


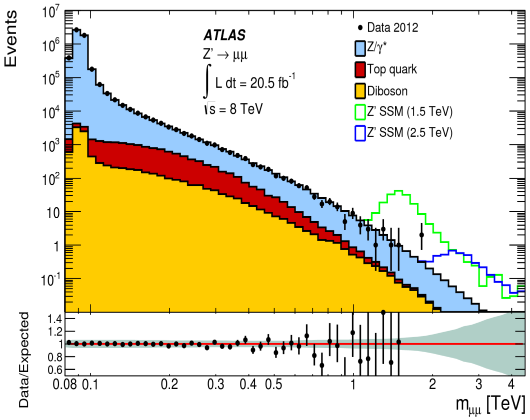
Spectacular Events.. Large Multiplicities of Jets and Leptons…. No surprises yet

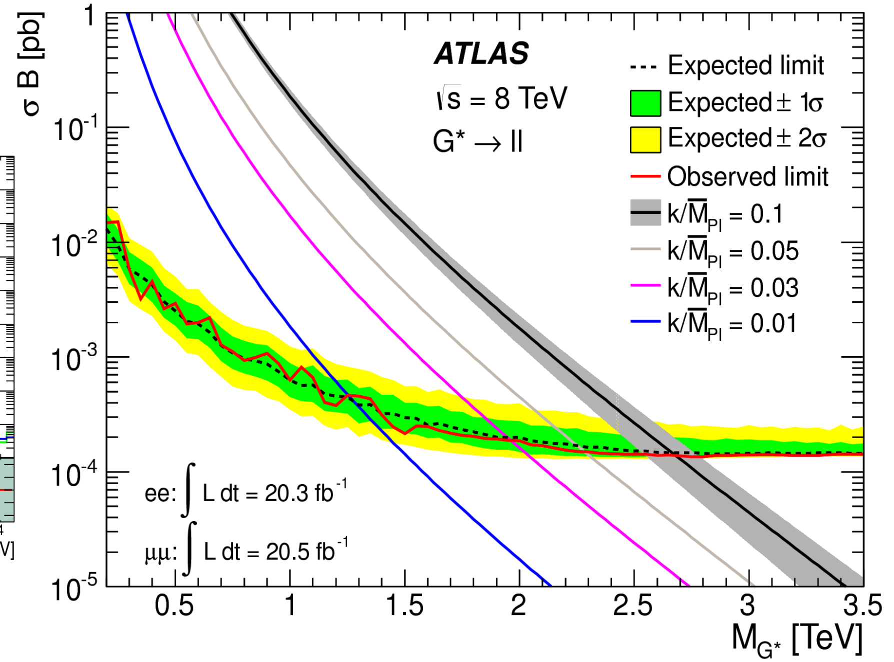
Dileptons

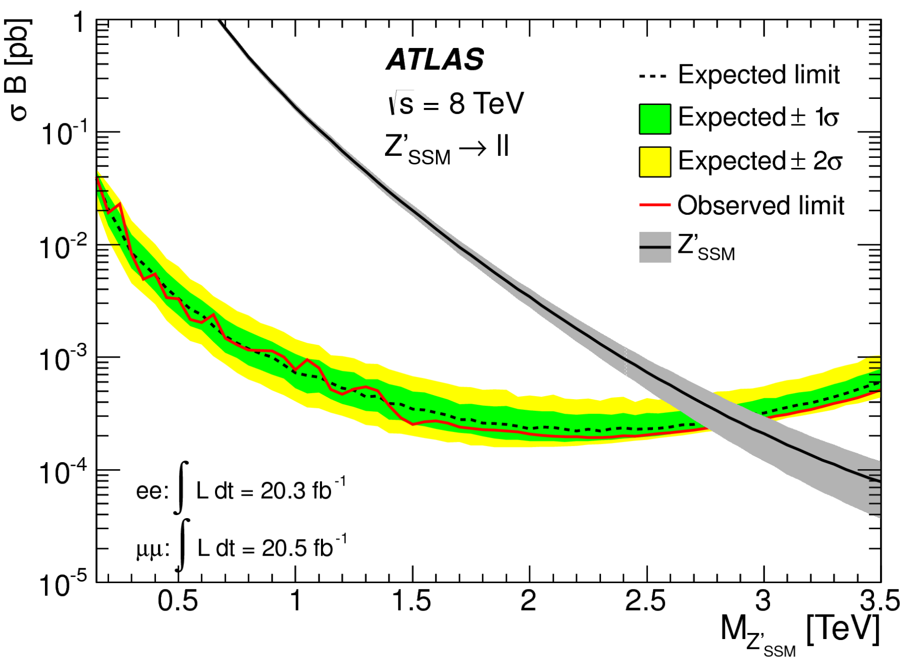
Phys. Rev. D. 90, 052005 (2014)









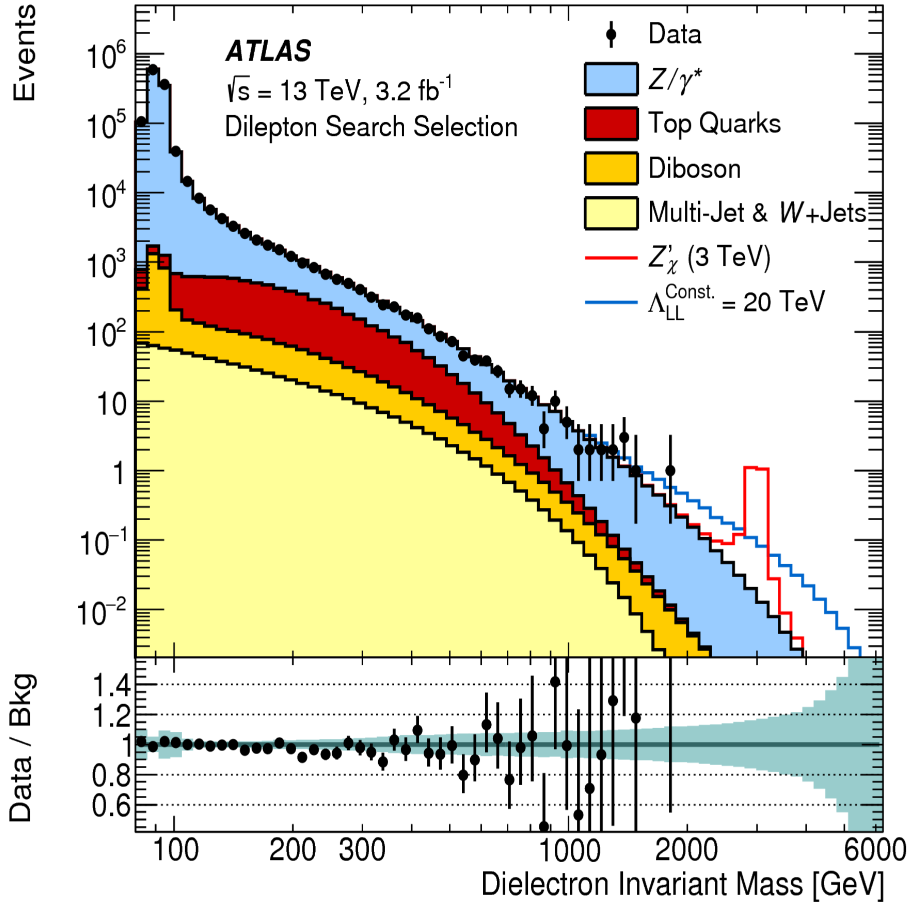


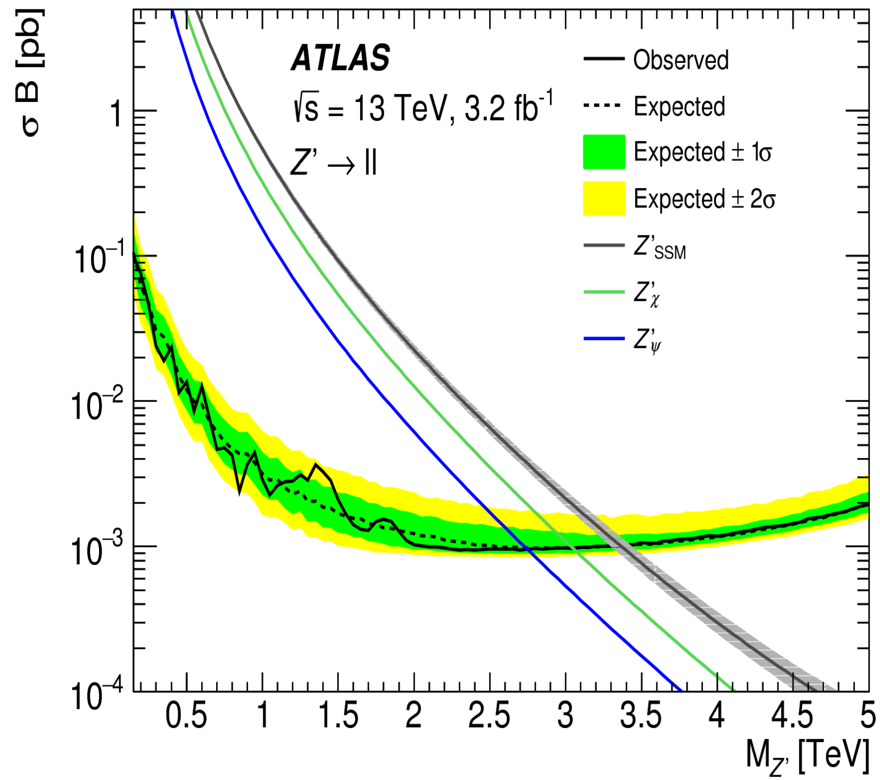
Limits on RS (ED) Graviton mass vs coupling
→95% CL exclusion in the mass range
M_G = 1.2 TeV – 2.7 TeV

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





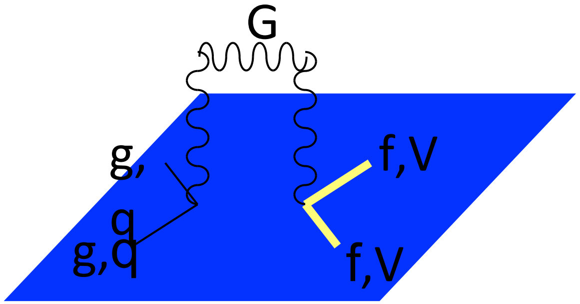
→ No real surprises at the edge of the phase space yet

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

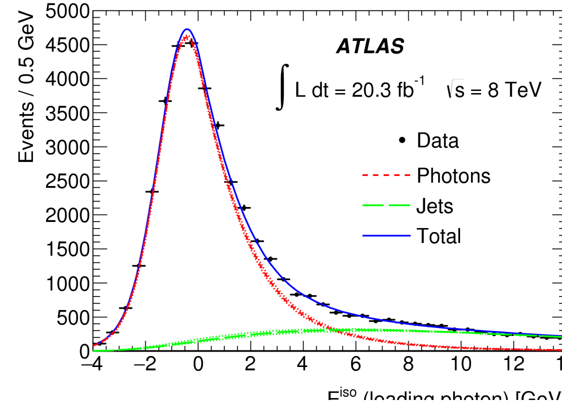
→ Also considering a model with a 20 TeV Z' (implemented as a contact interaction)

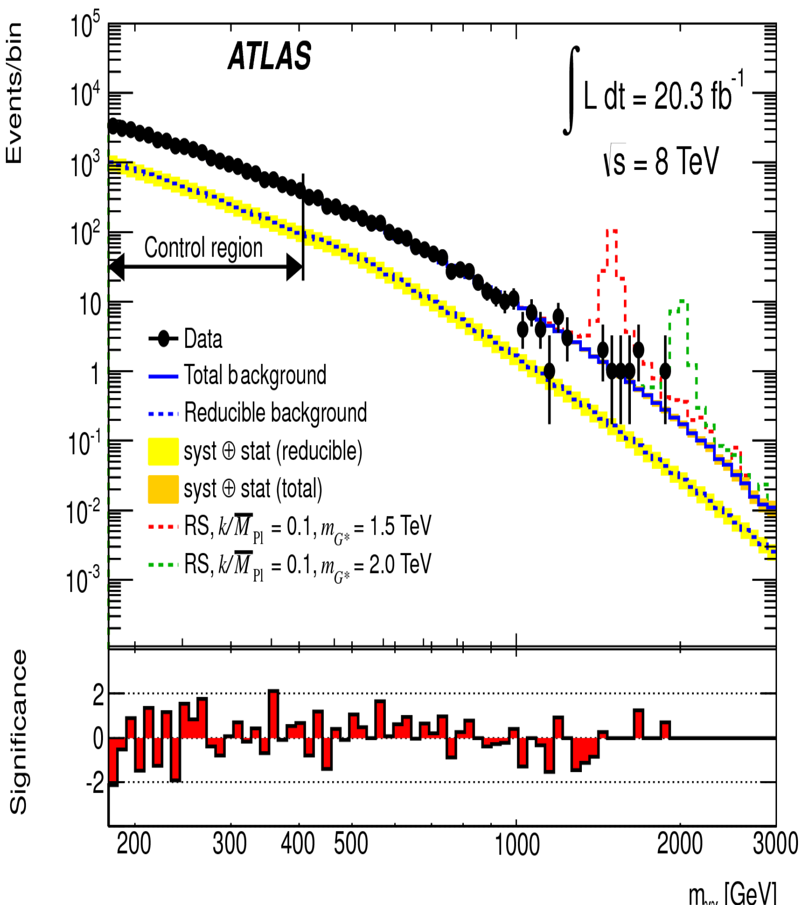
Phys. Rev. D 92, 032004 (2015)

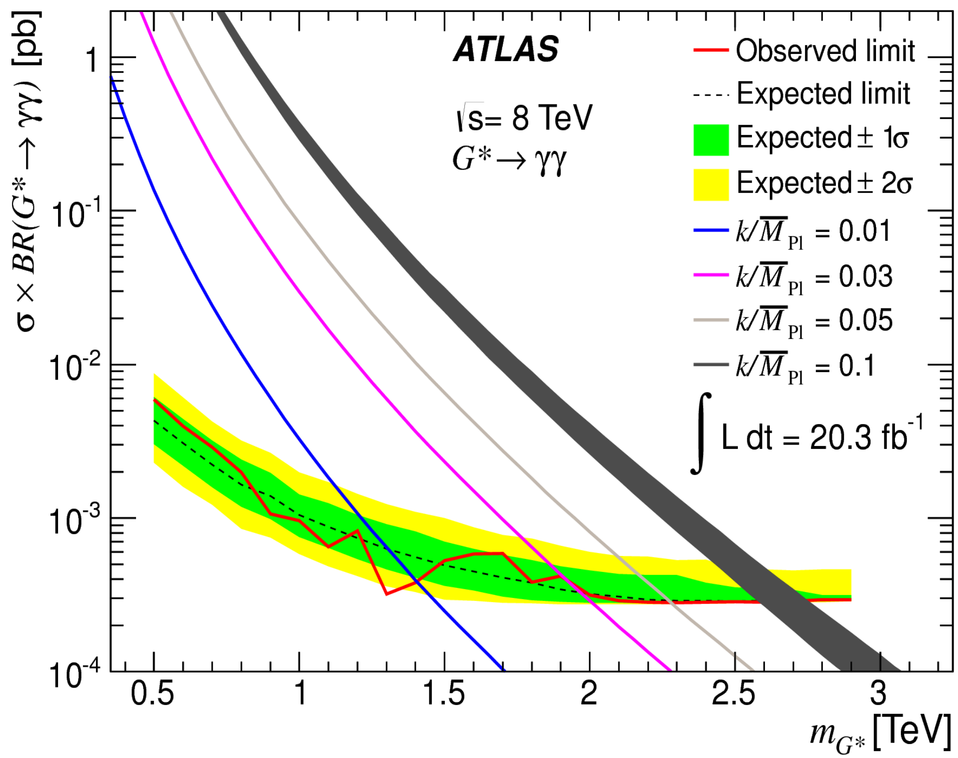
Di-photons



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





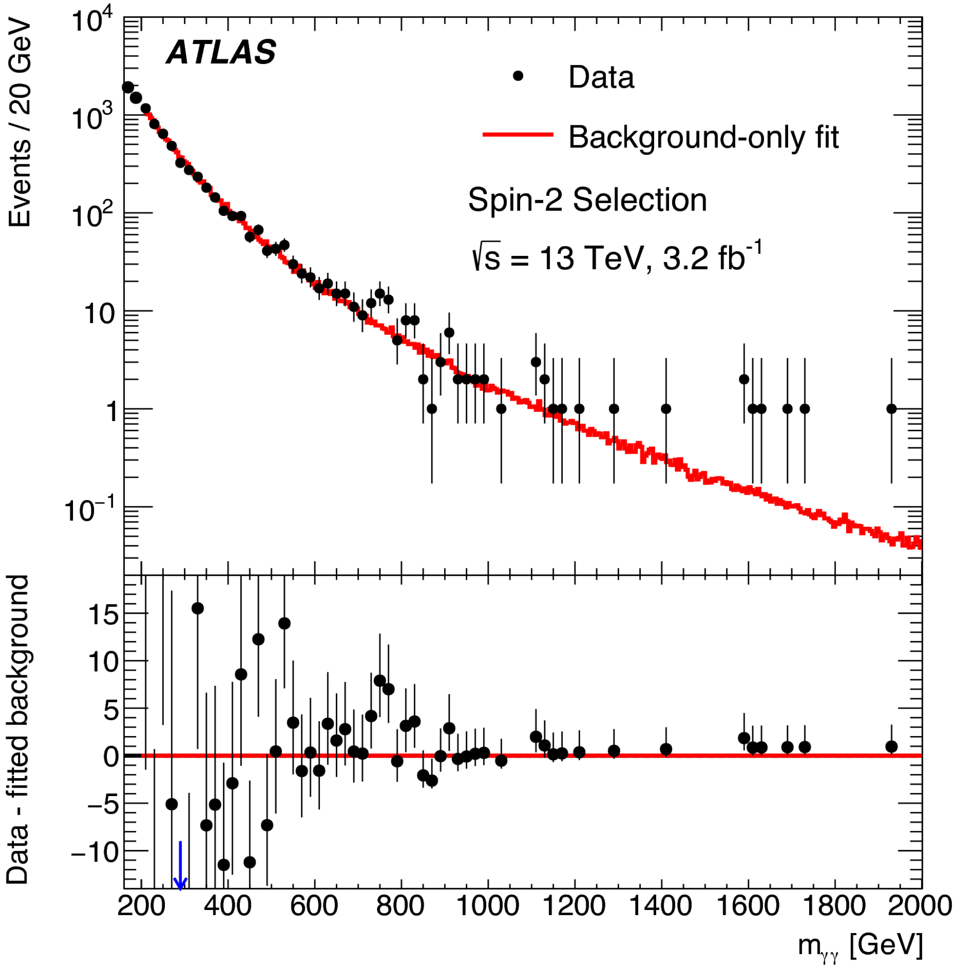


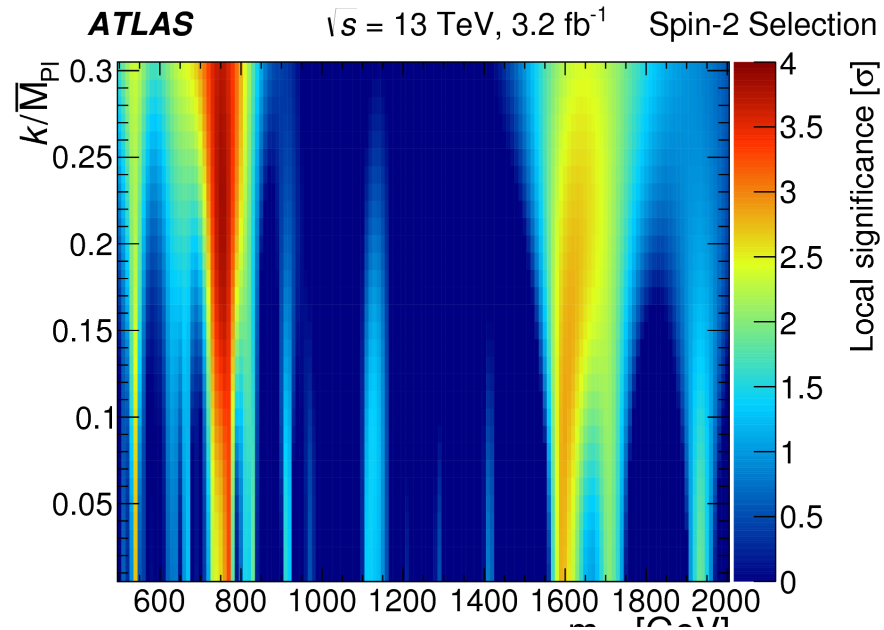
Limits on RS (ED) Graviton mass vs coupling
→95% CL exclusion in the mass range
M_G = 1.4 TeV – 2.5 TeV

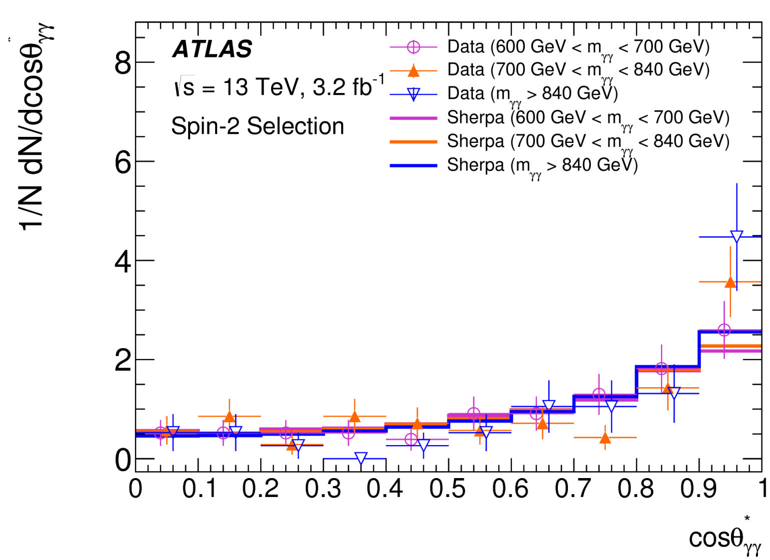

BUMP

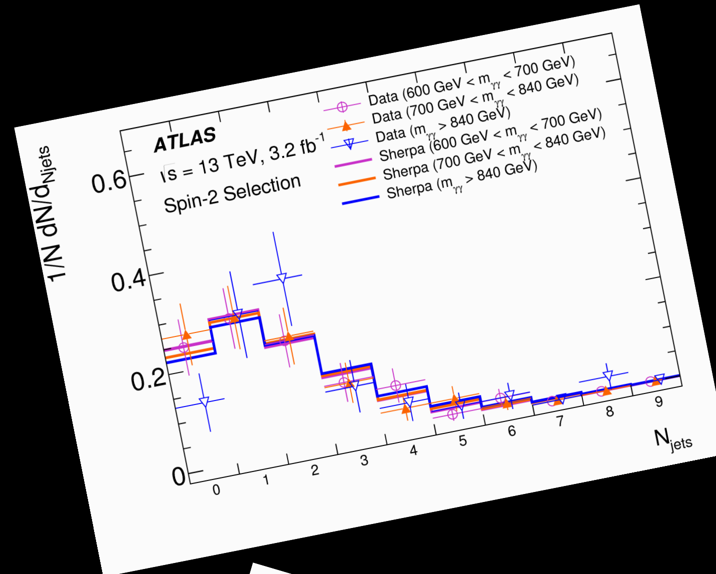
arXiv:1606.03833

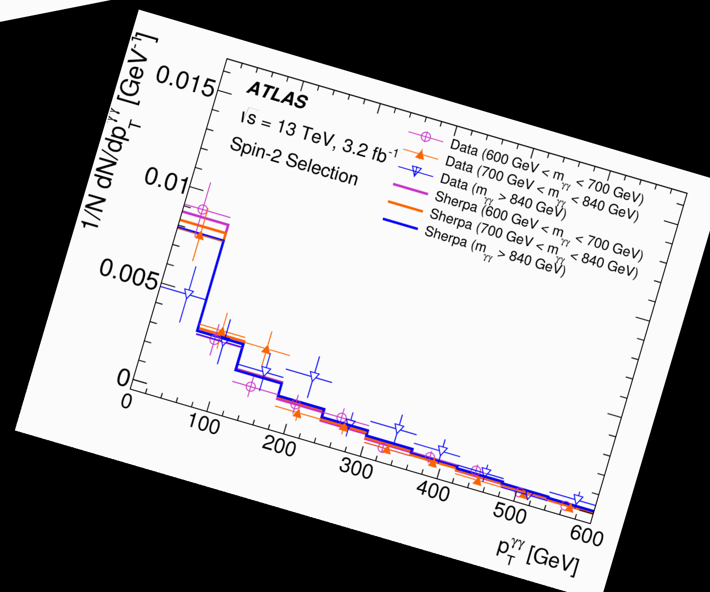
Diphotons @ 13 TeV



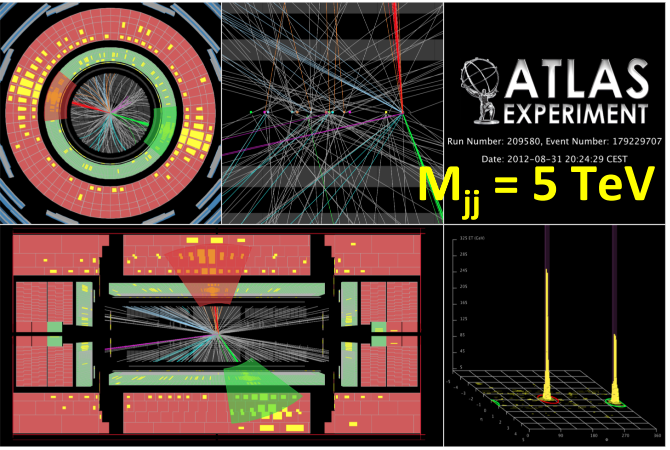








Only more data will tell

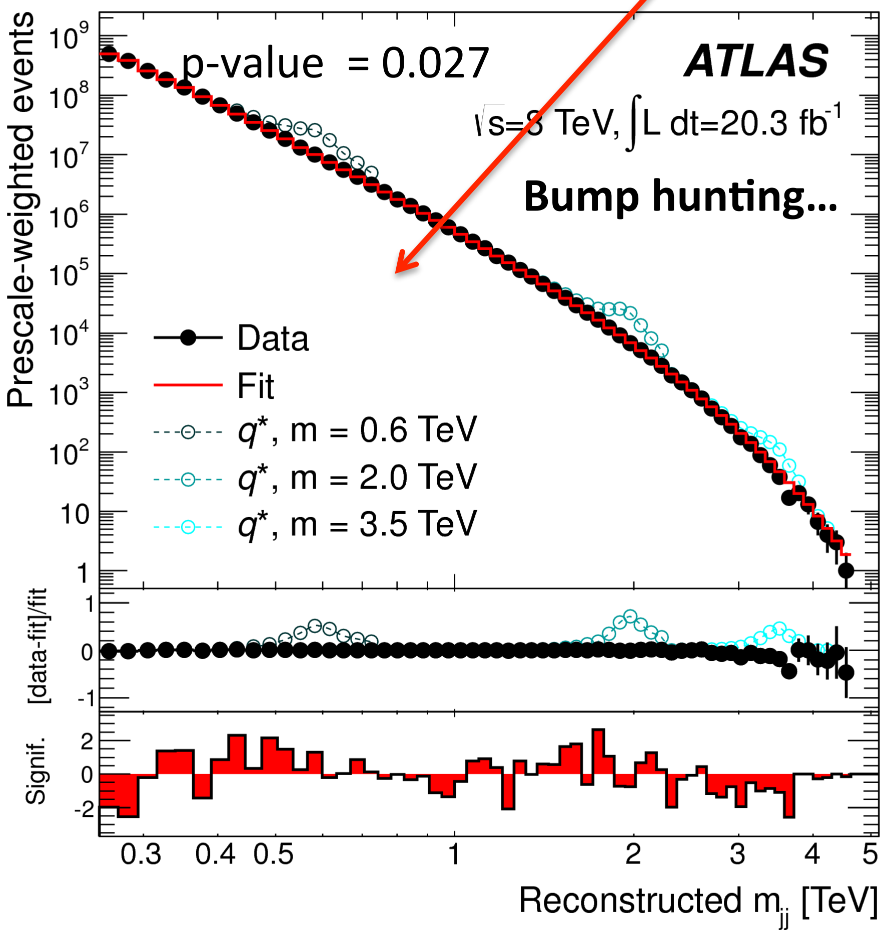


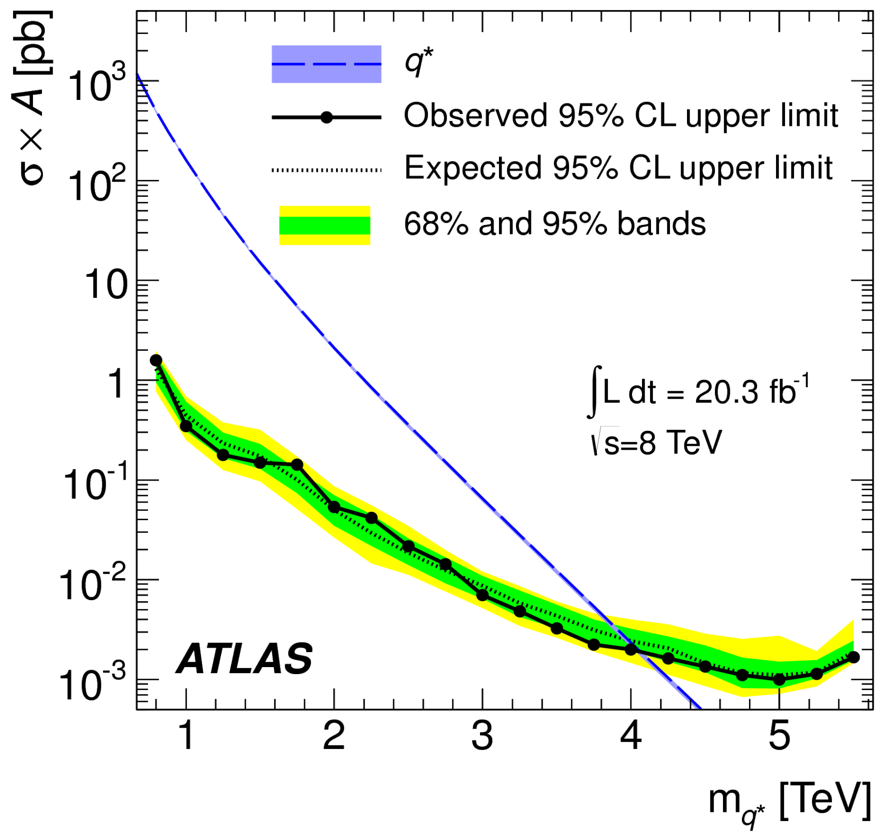
[Phys. Rev. D. 91, 052007 (2015)](#)

Dijets

Dijet mass spectrum fitted to the functional form

$$f(x) = p_1(1-x)^{p_2} x^{p_3 + p_4 \ln x} \qquad x \equiv m_{jj}/\sqrt{s}$$



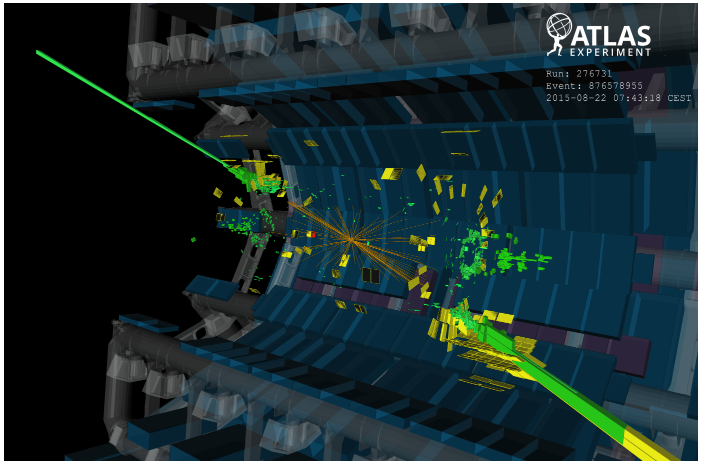


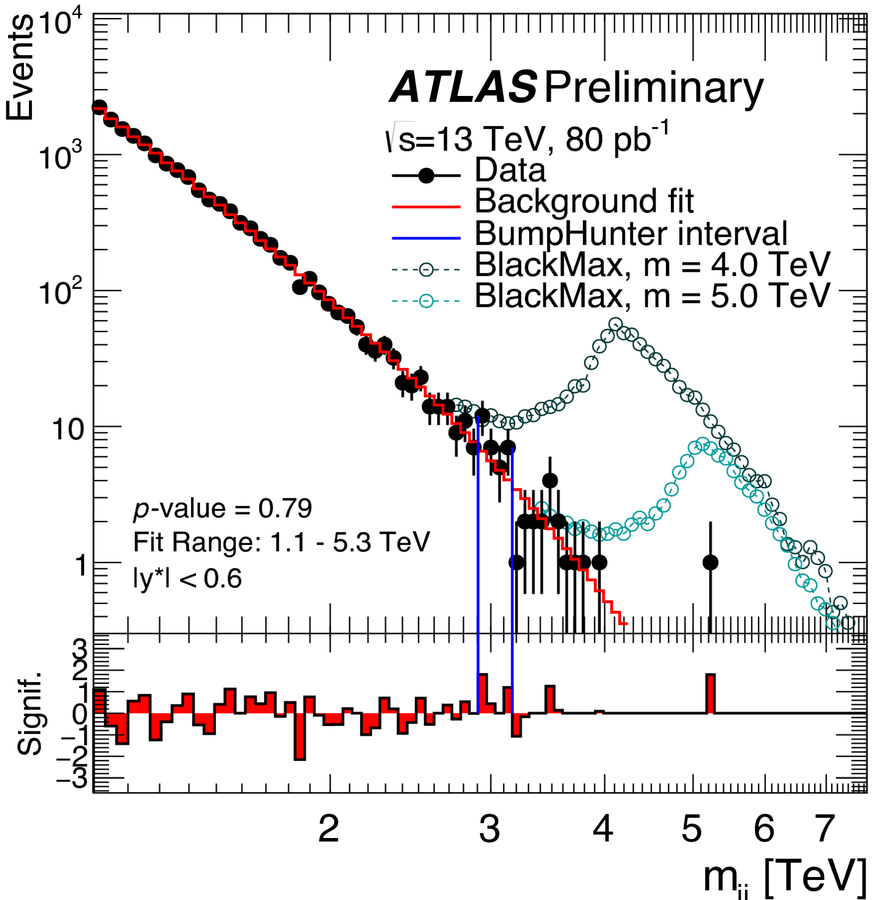
Excited quarks with mass < 4 TeV excluded at 95% CL

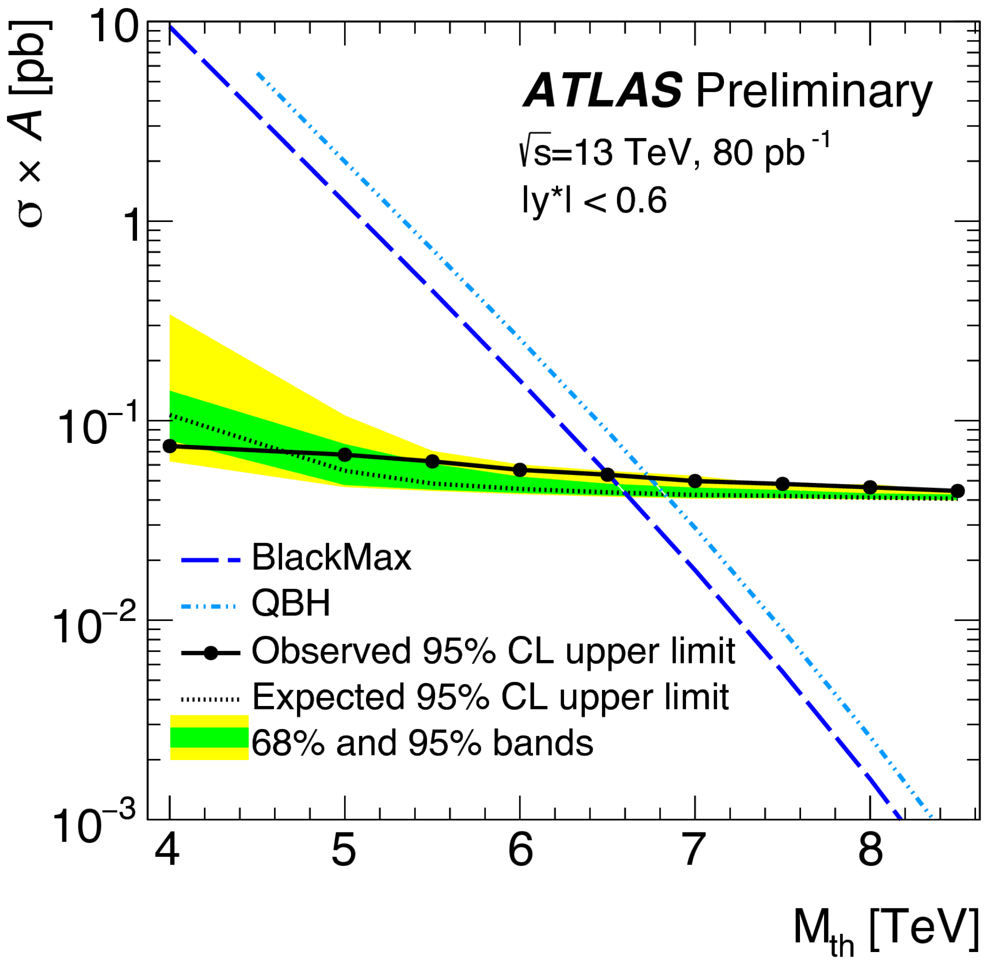
Early 13 TeV Results

80 pb^{-1}

ATLAS-CONF-2015-04



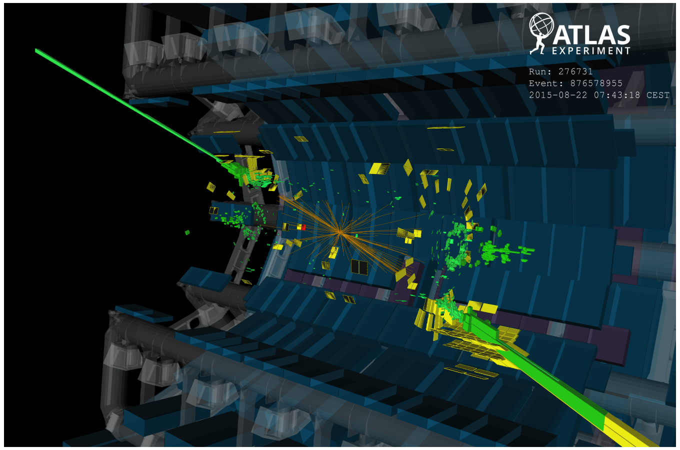


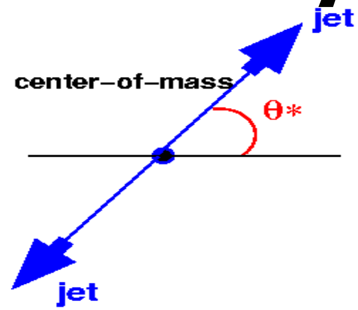


Going beyond Run I sensitivity

ATLAS-CONF-2015-042

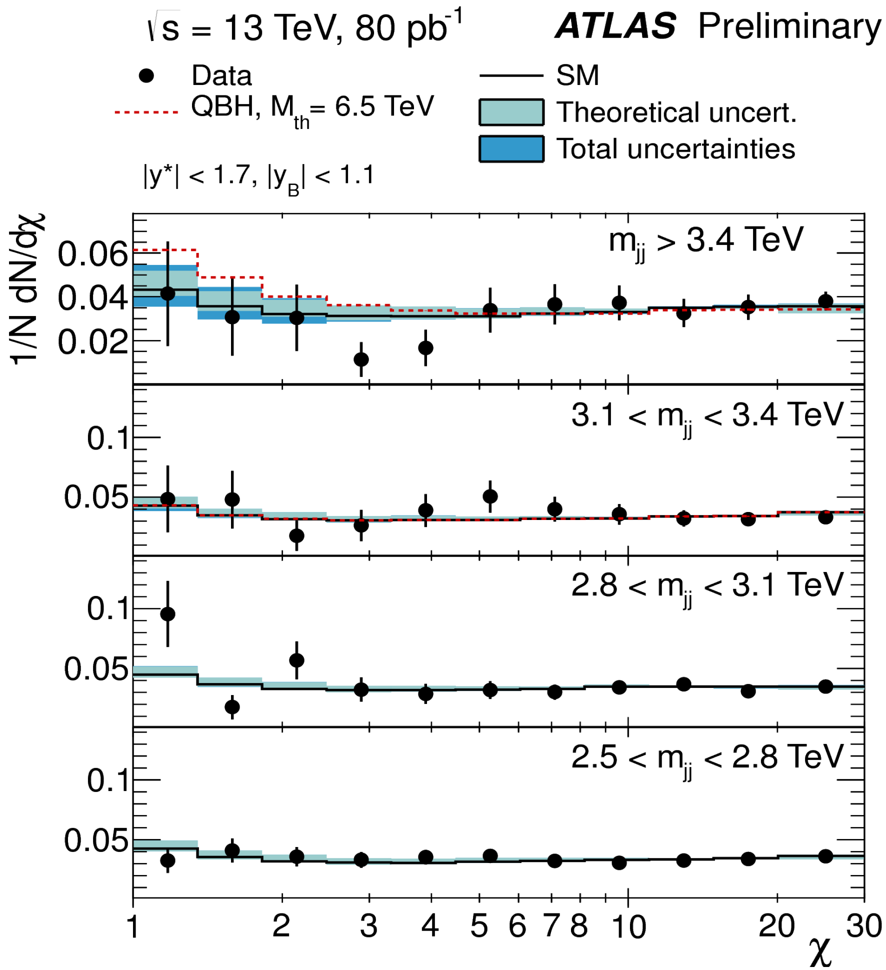
Early 13 TeV Results

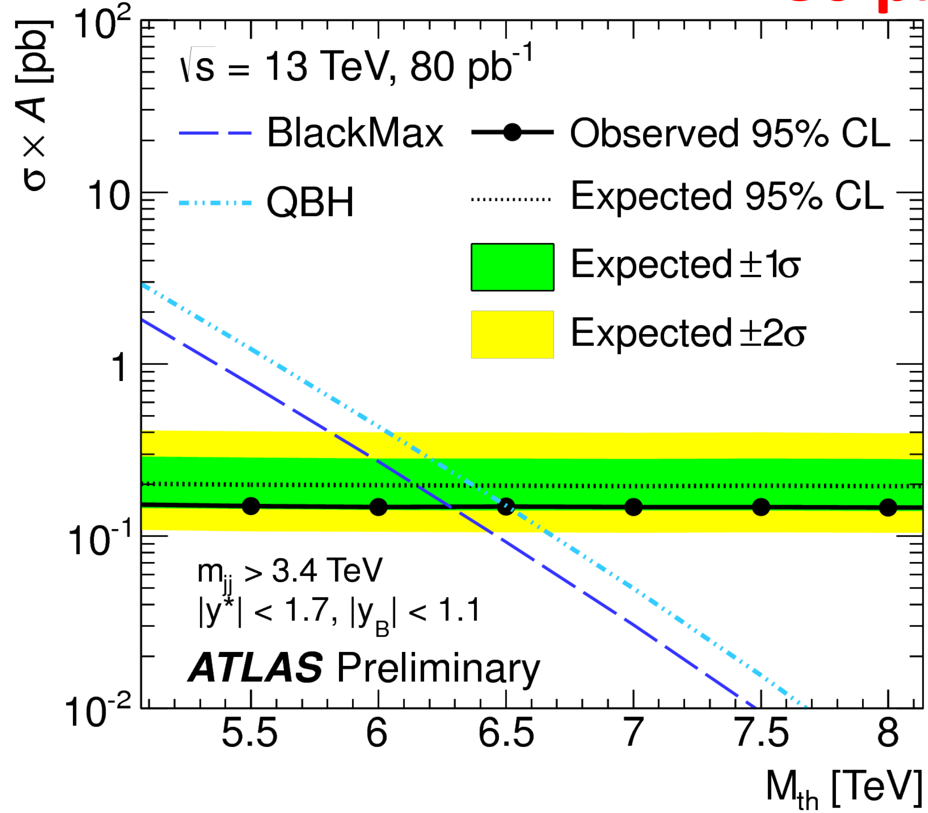




$$\chi = \frac{1 + \cos\theta^*}{1 - \cos\theta^*}$$

80 pb^{-1}





Going beyond Run I sensitivity

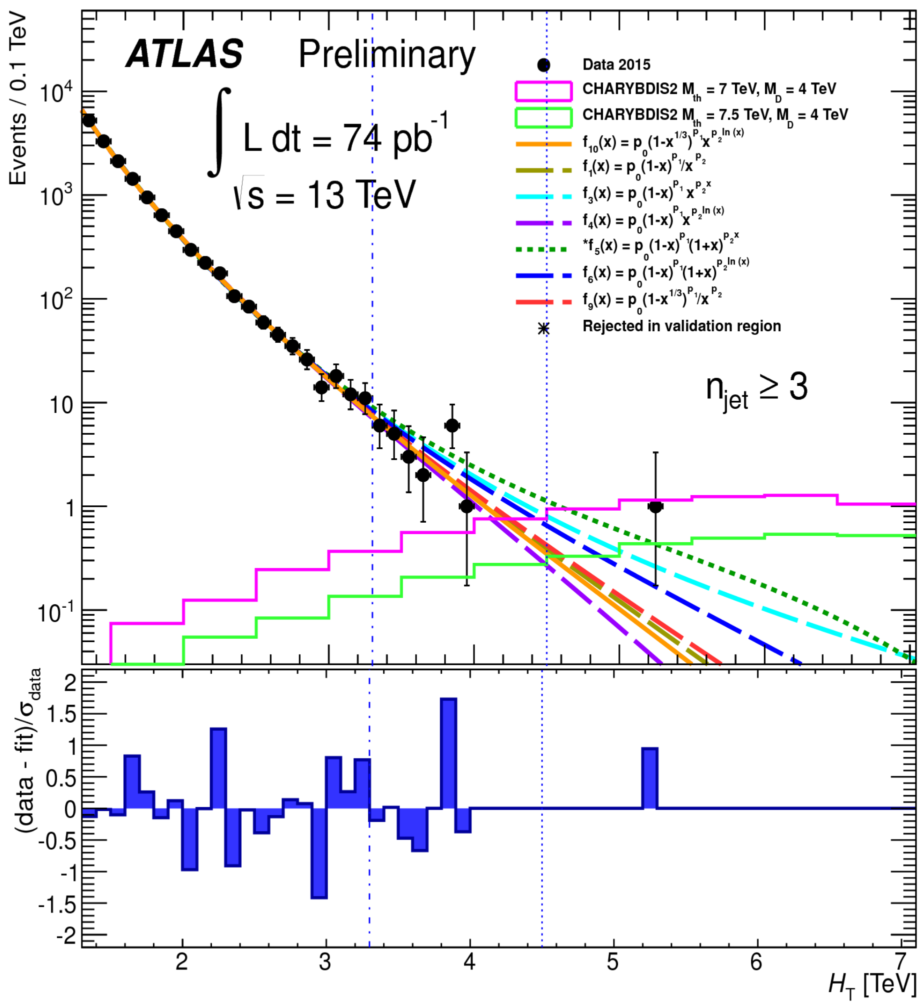
ATLAS-CONF-2015-043

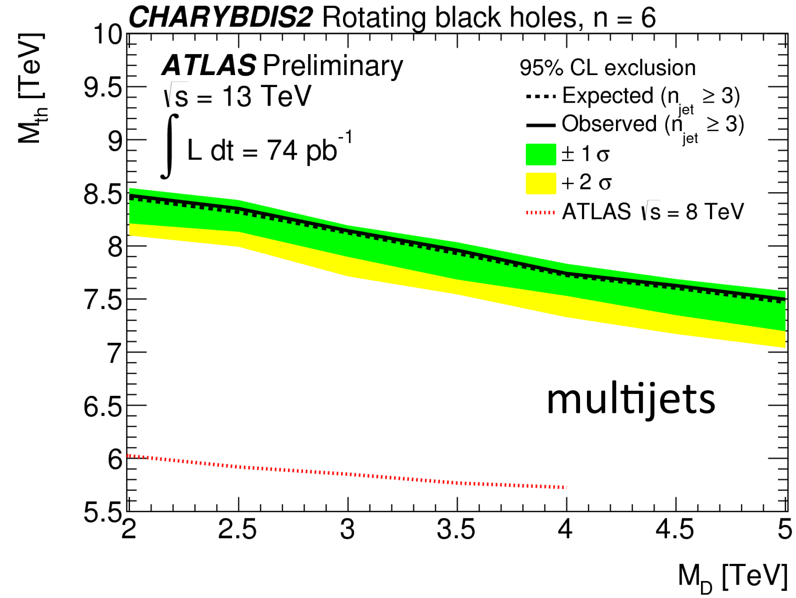
ATLAS-CONF-2015-046

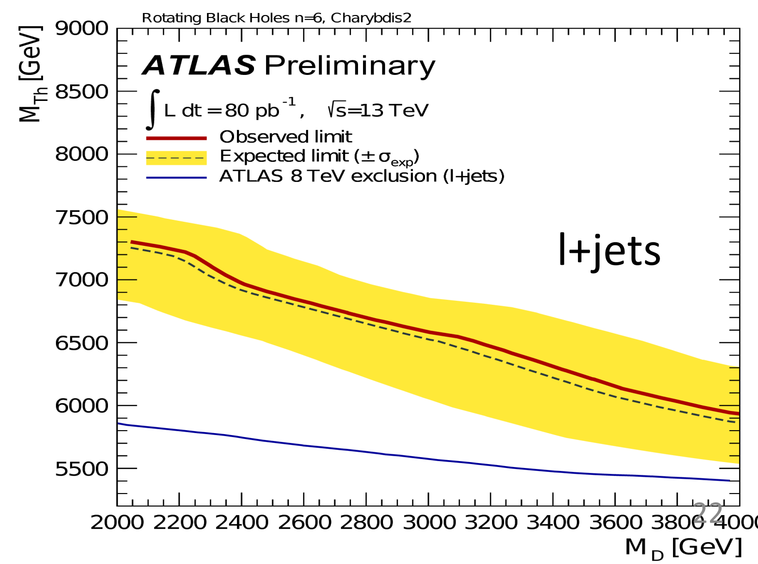
QBH Search at 13 TeV

(multijets & lepton + jets)

80 pb^{-1}



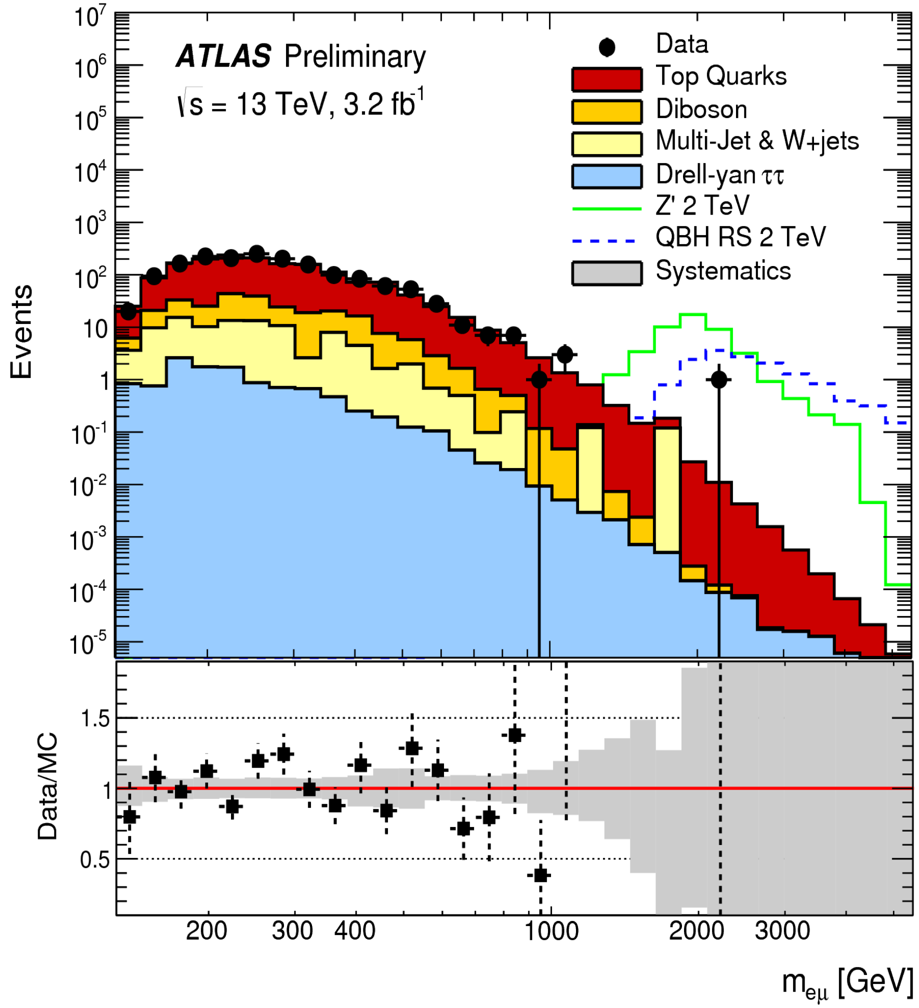


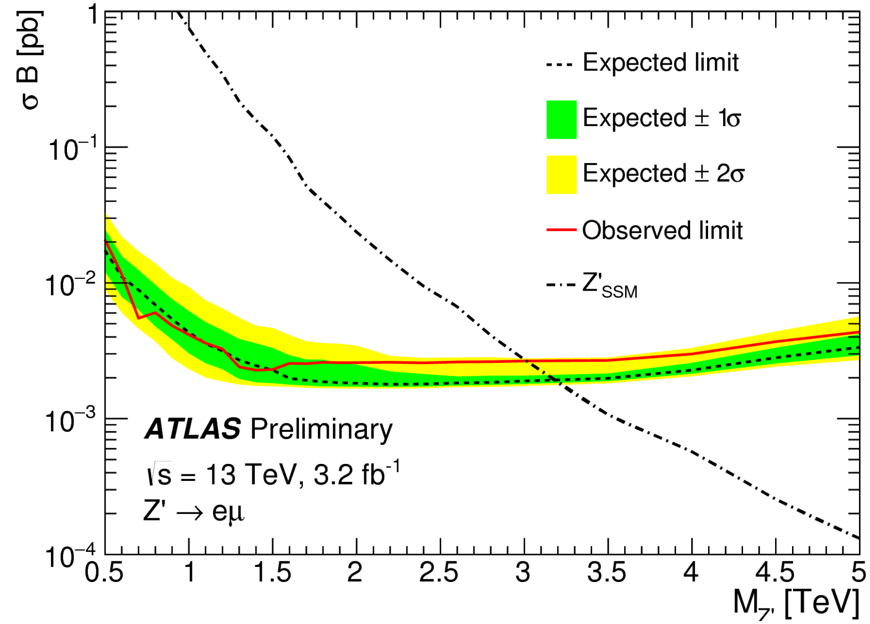


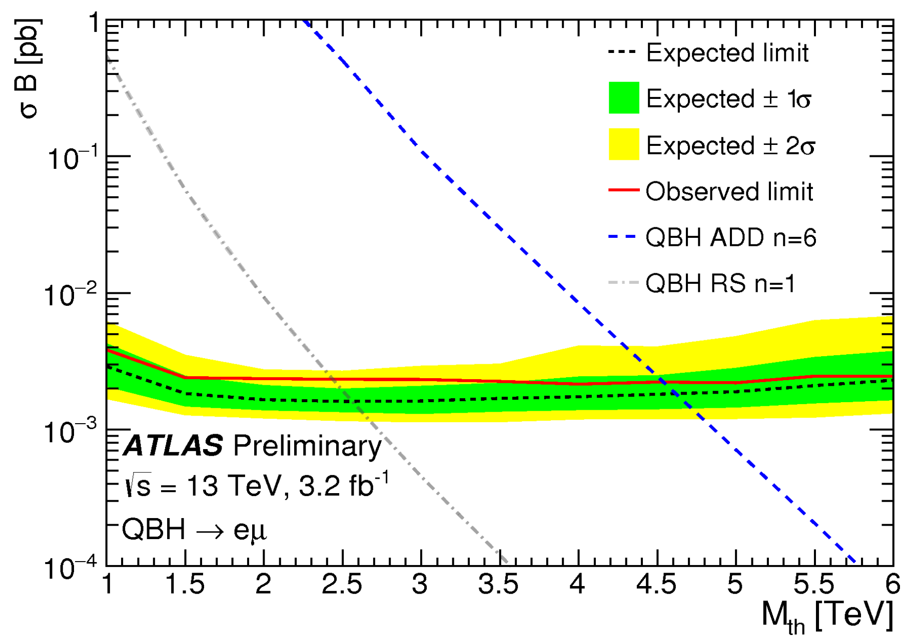
Going beyond Run I sensitivity

ATLAS-CONF-2015-072

Z' → eμ , QBH → eμ



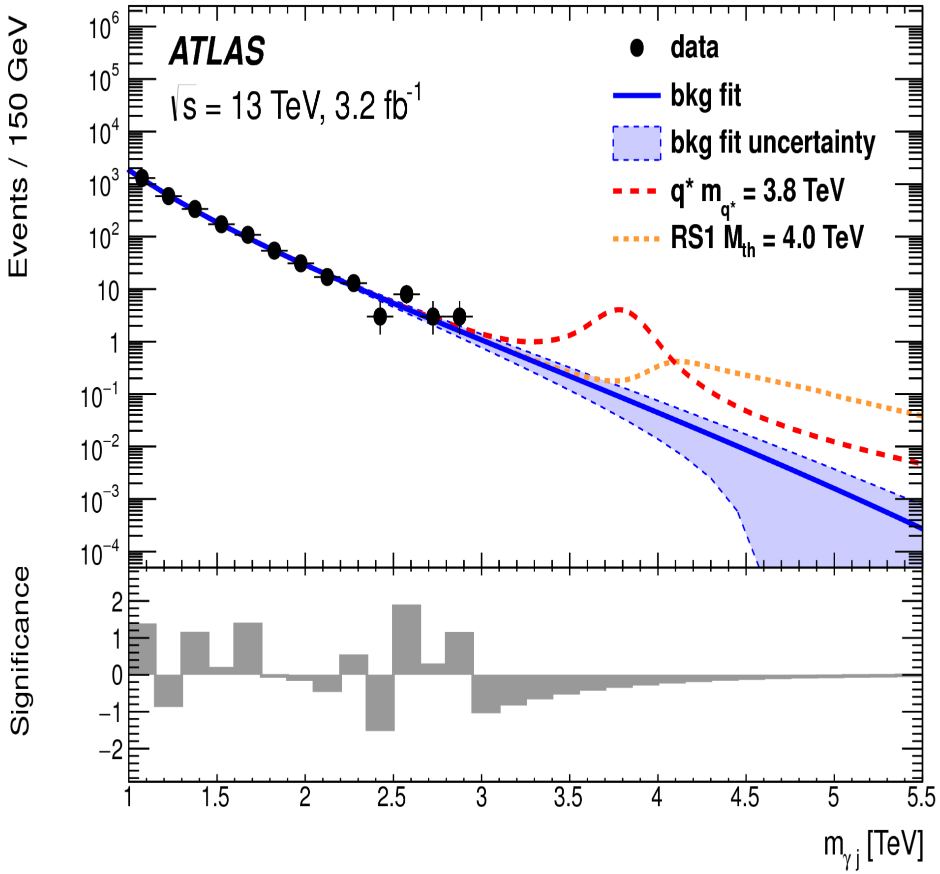


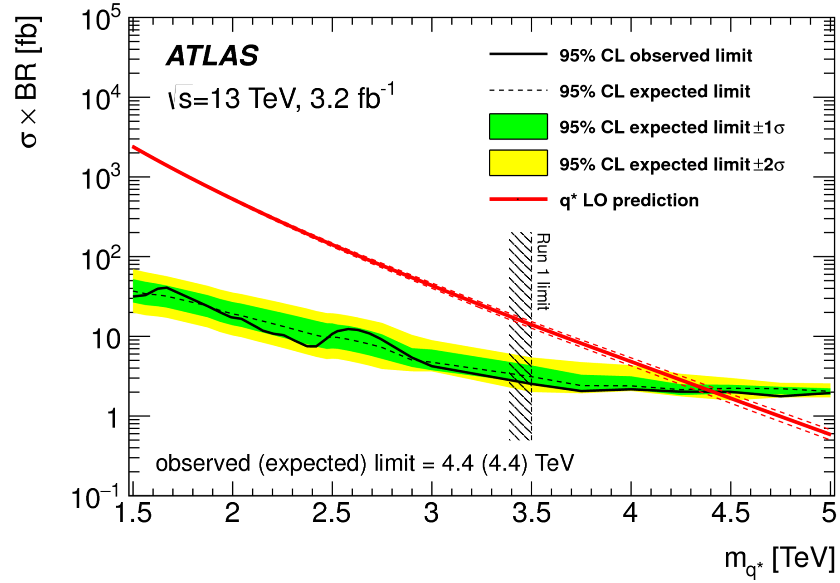


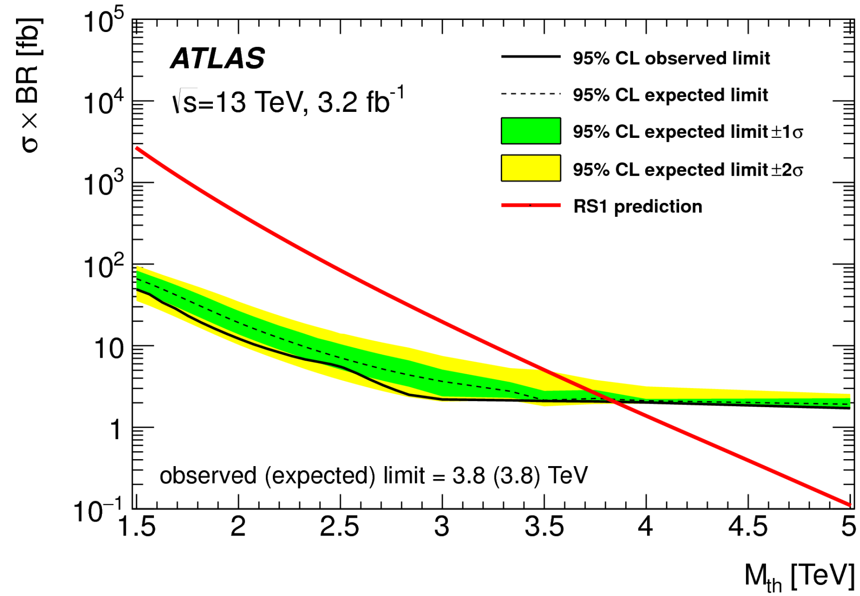
Excited quarks q* → qγ

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

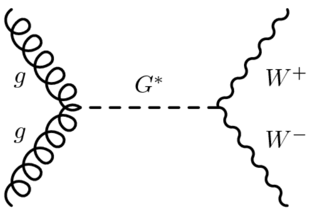
→ Now interpreted as a QBH search…





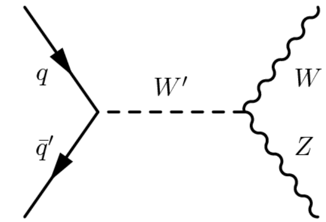


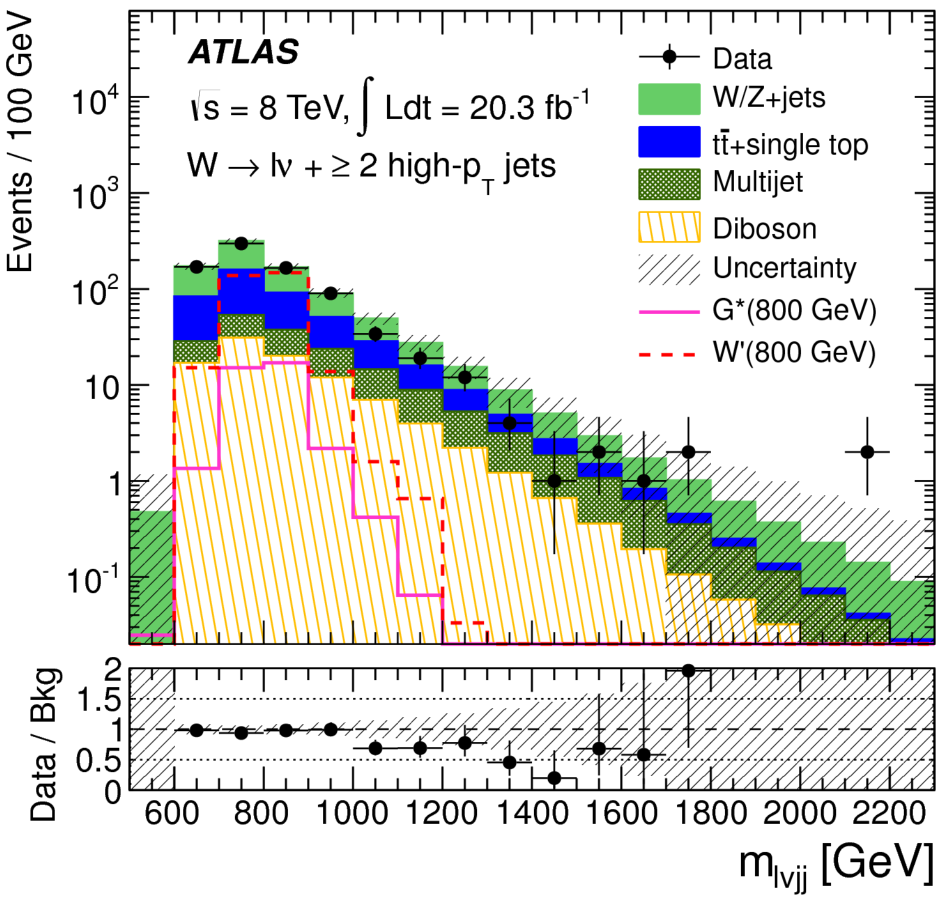
Eur. Phys. J. C (2015) 75:209

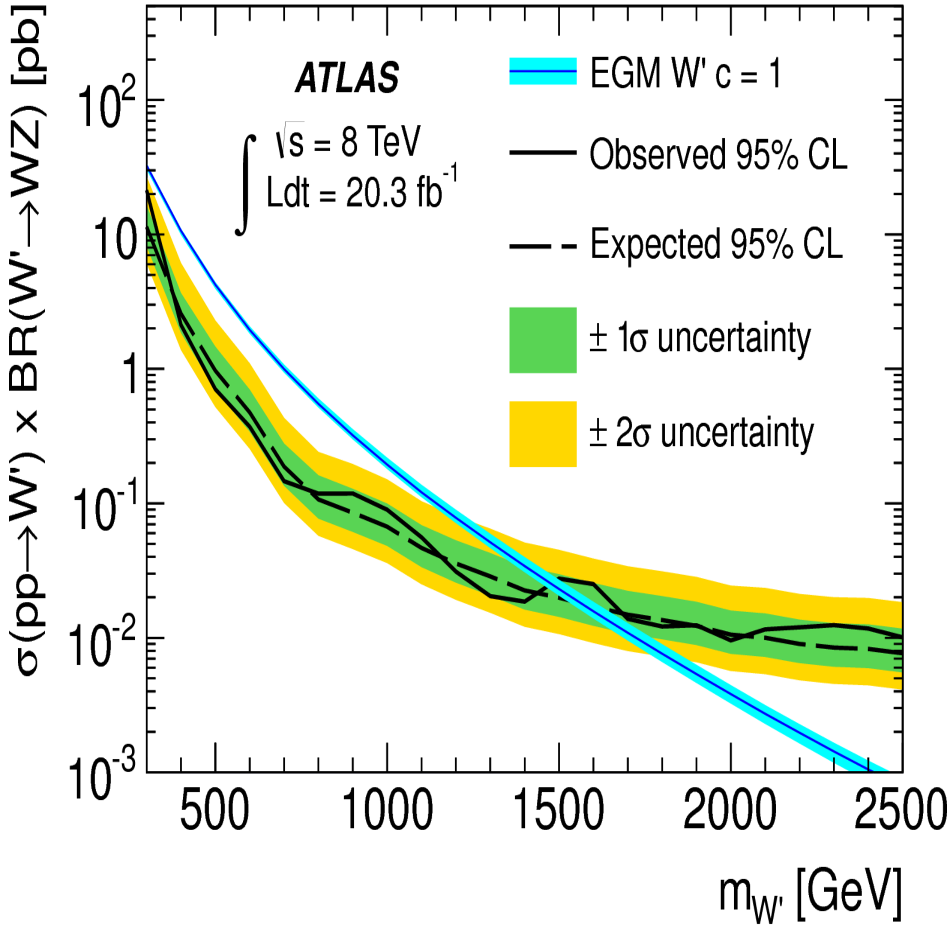


WW/WZ Resonances

(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

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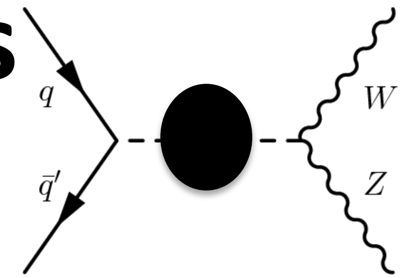
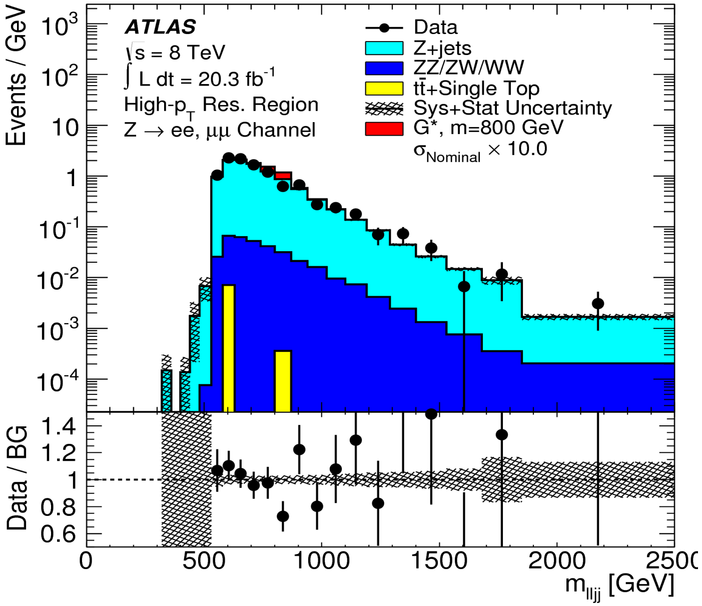
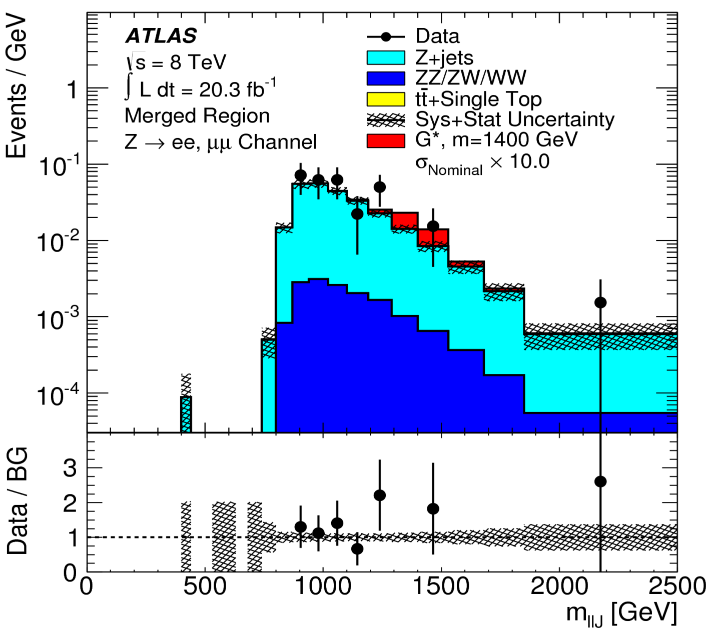
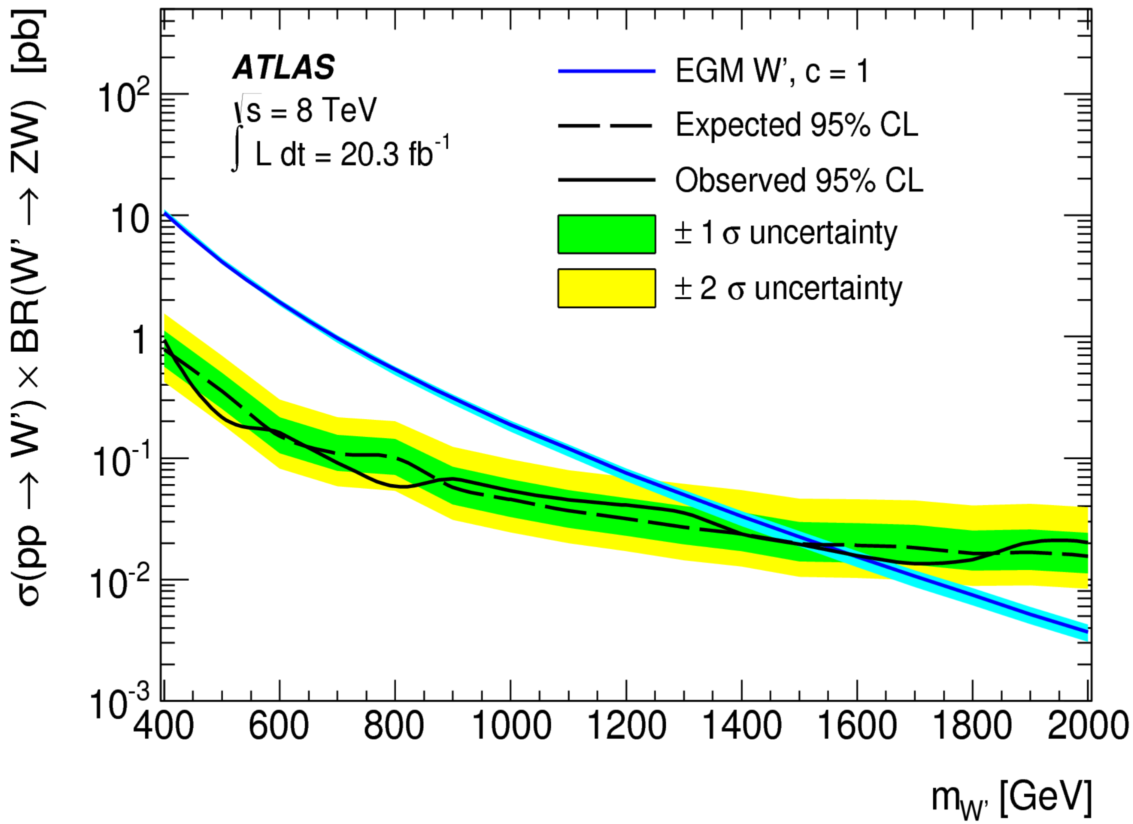
Diboson Resonances

lepton+lepton + qq)





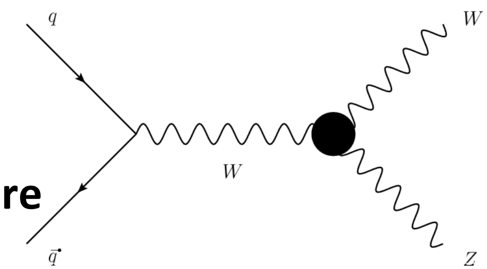




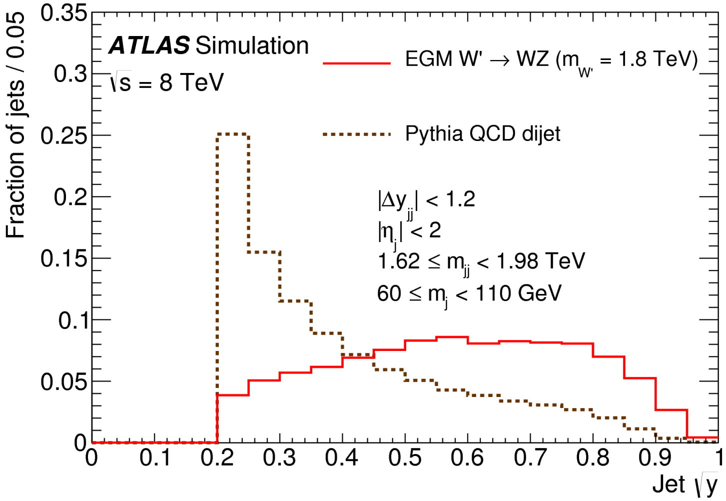
Using both resolved W → qq' and boosted W
A W' is excluded up to 1.5 TeV at 95% CL

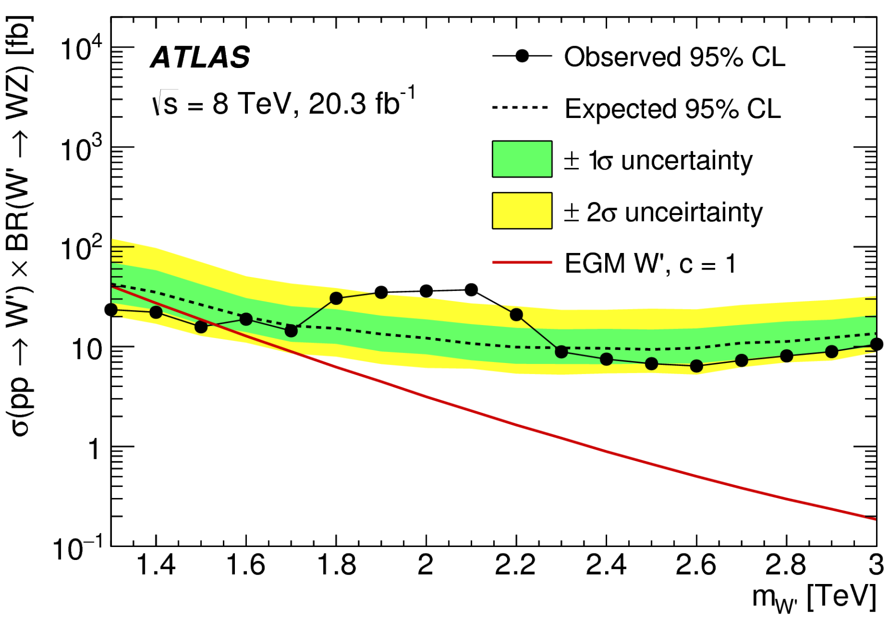
High-mass diboson resonances with boson-tagged jets

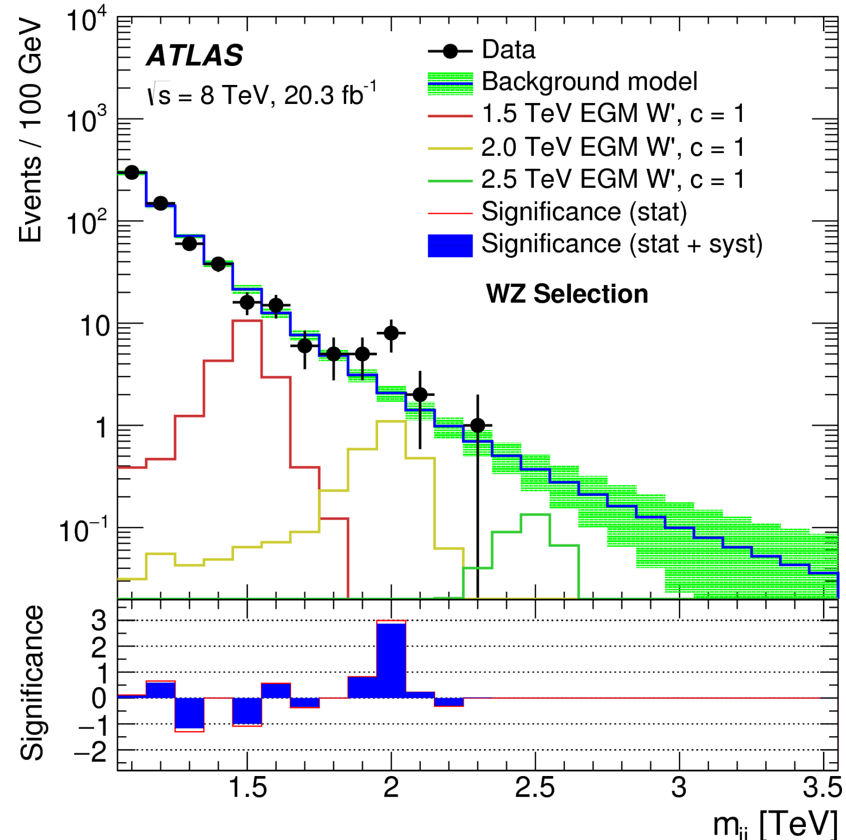
arXiv:1506.00962



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

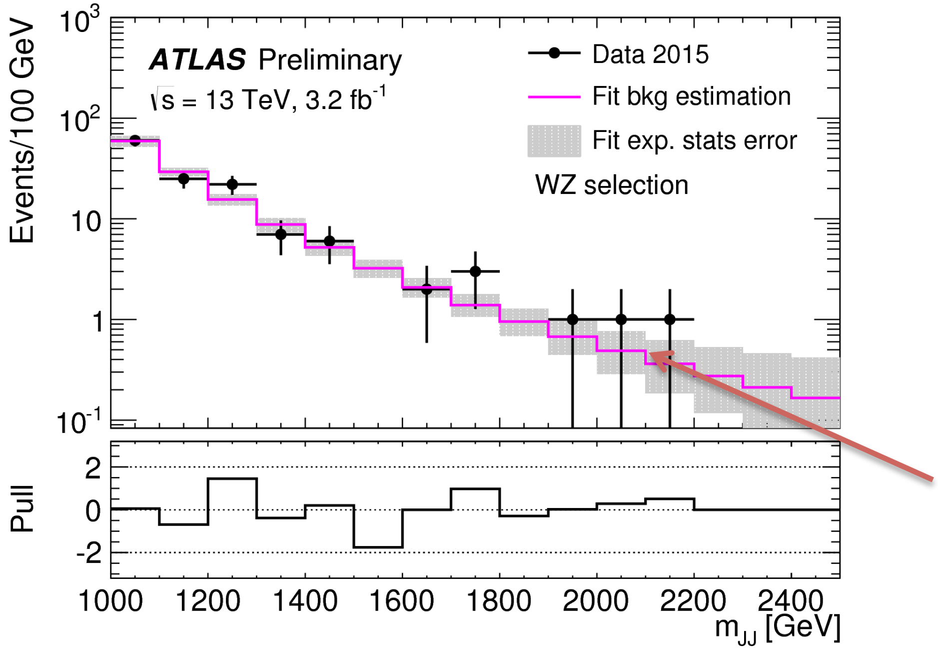




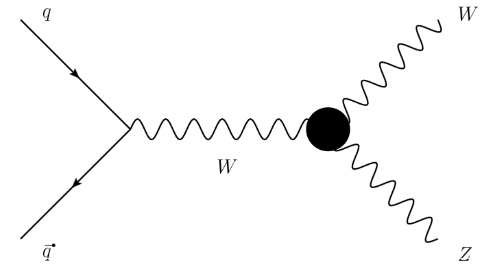


2.5 sigma effect

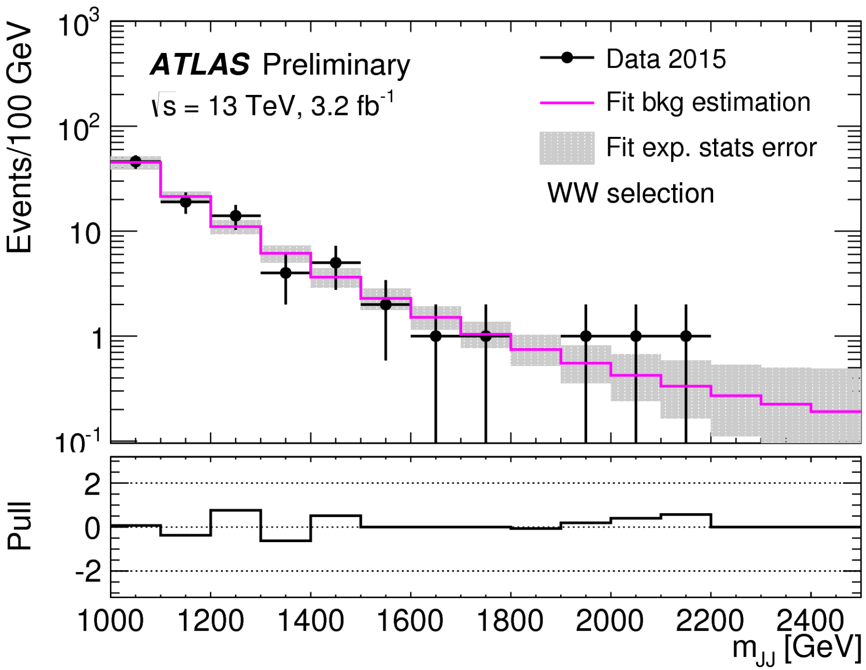
New look @ 13 TeV data

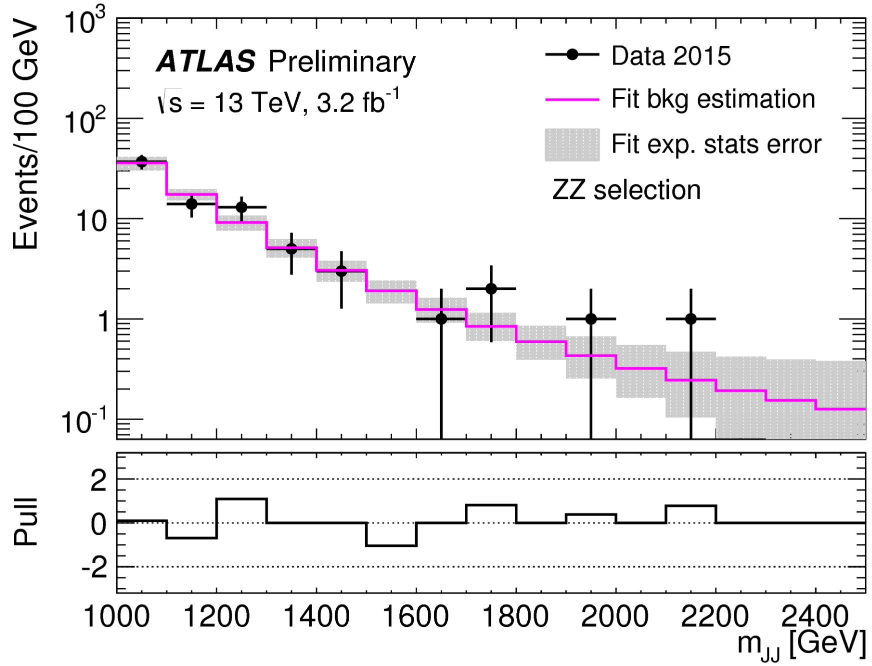


ATLAS-CONF-2015-073



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

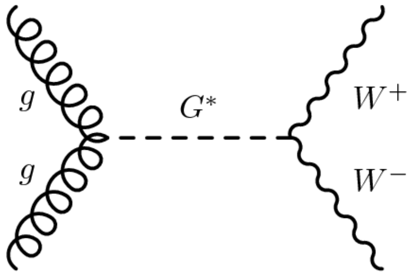


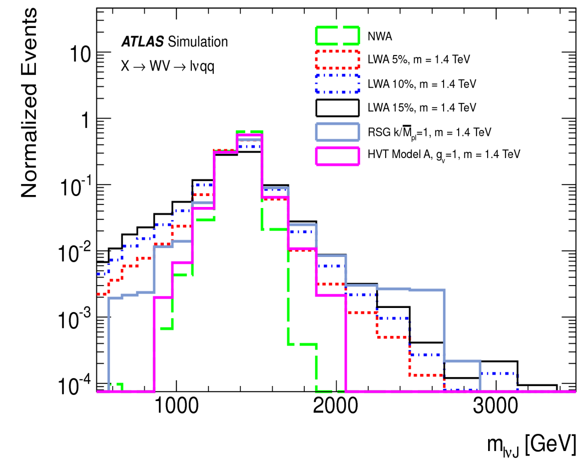


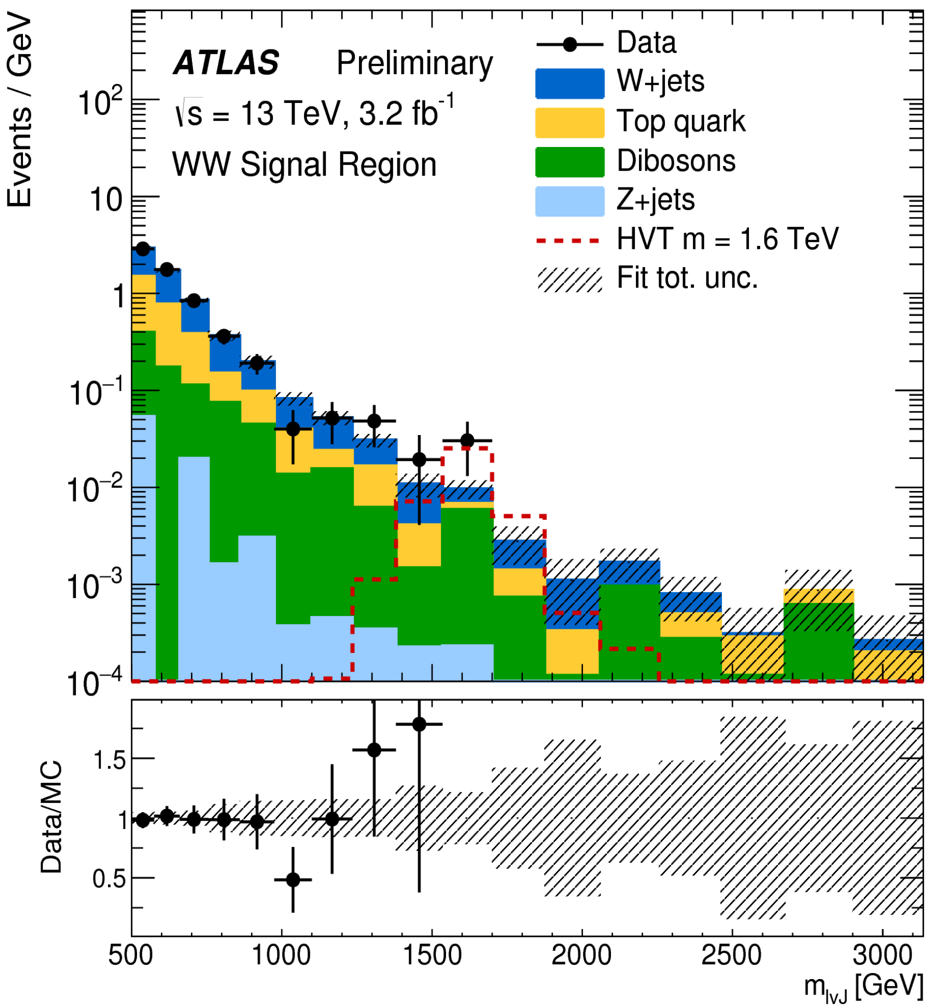
ATLAS-CONF-2015-075

WW/WZ @ 13 TeV

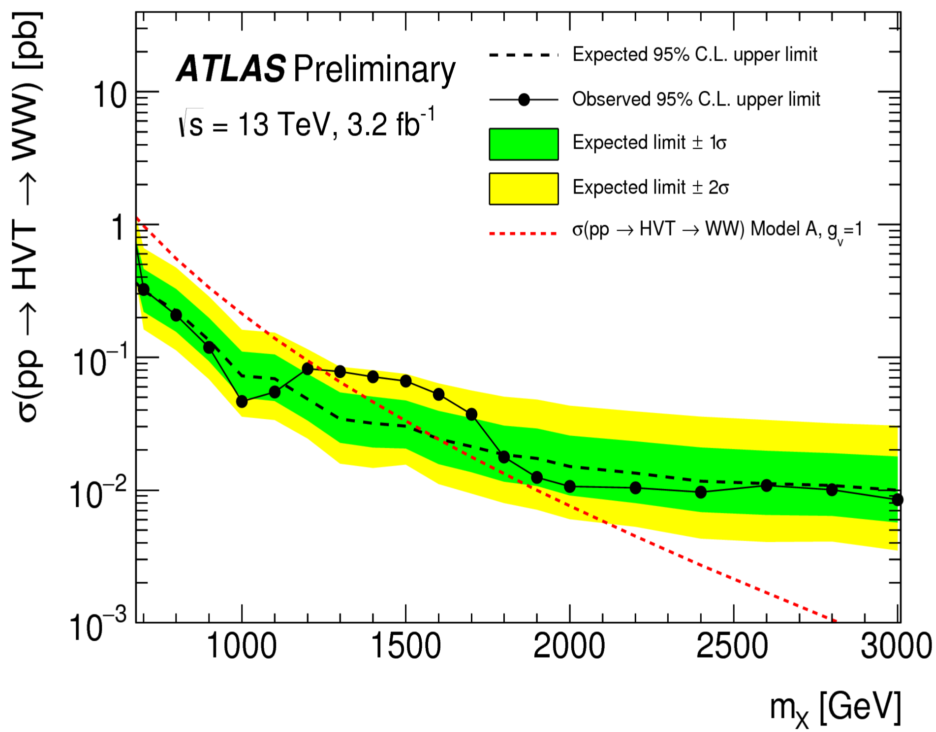
(lepton+jets channel)





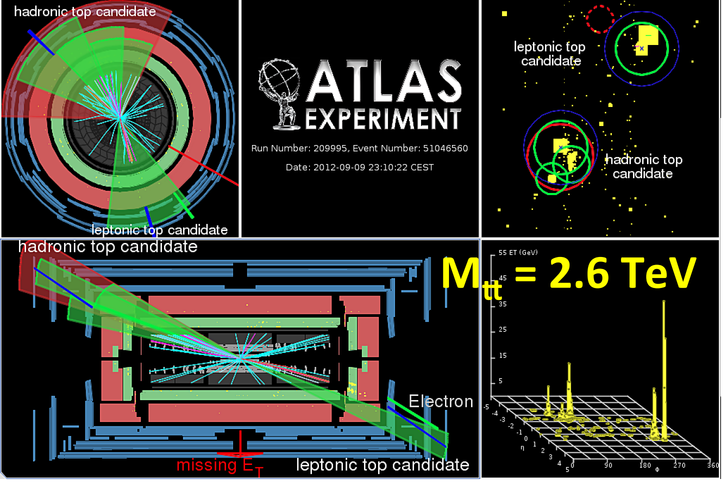


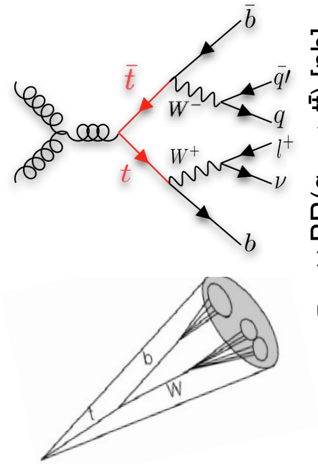
Interpreted in terms of Heavy Higgs-like

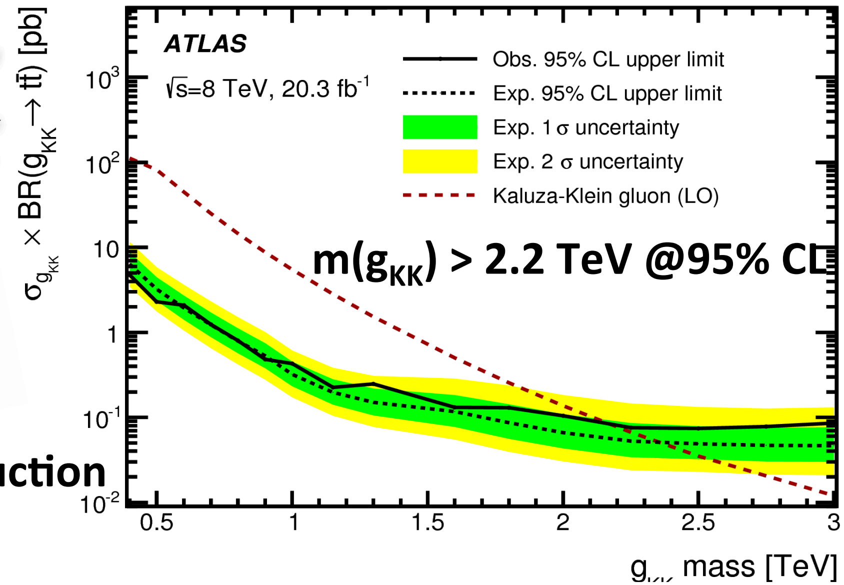


tt Resonances

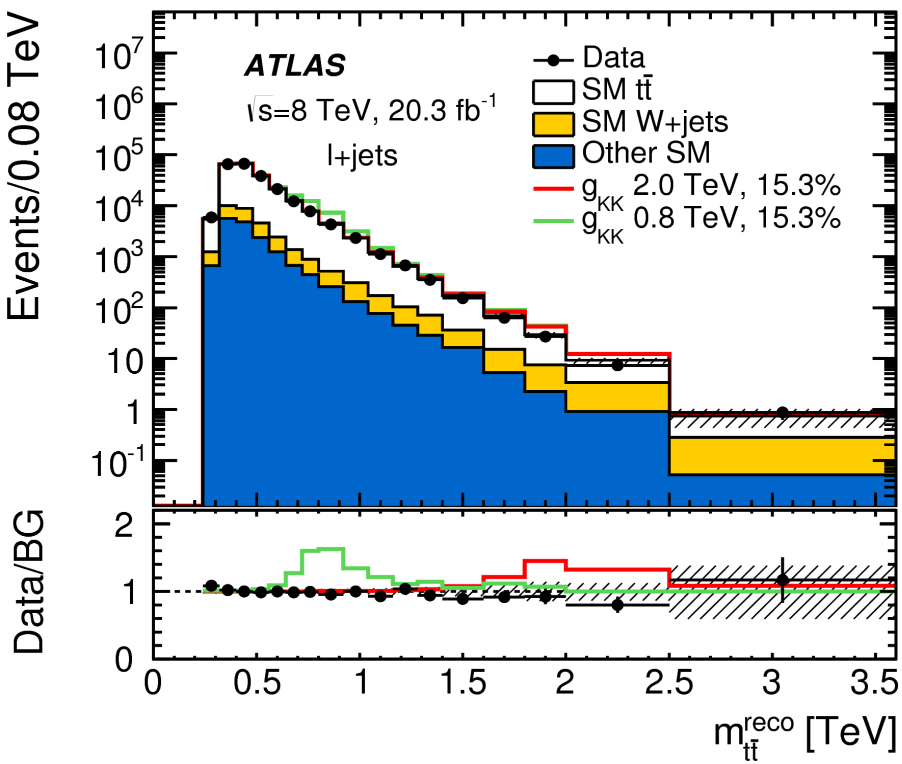
arXiv:1505.07018

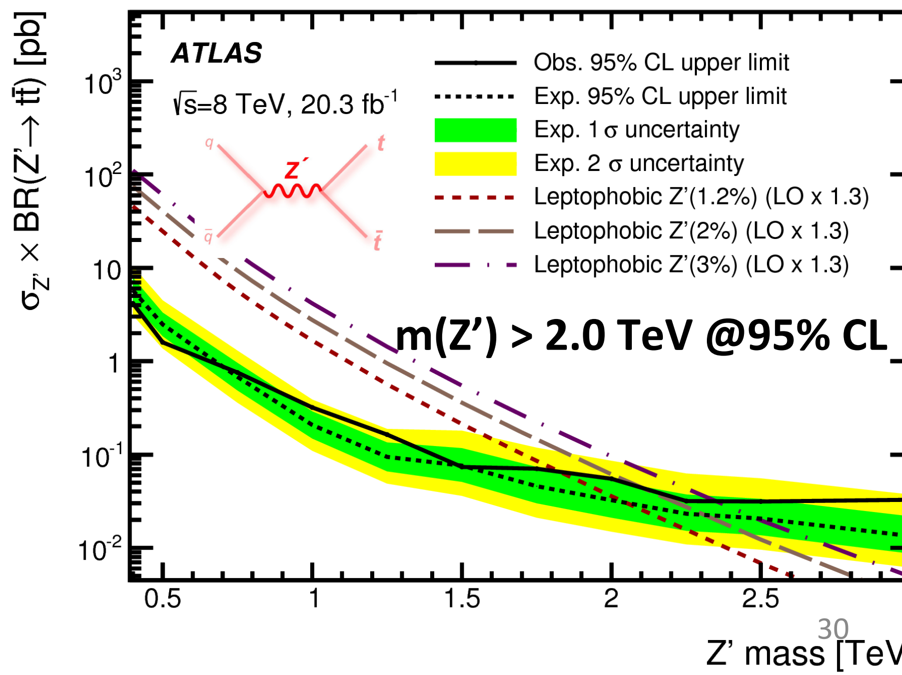






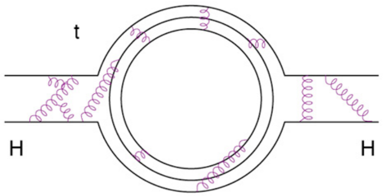
Using both resolved and boosted t→ Wb reconstruction

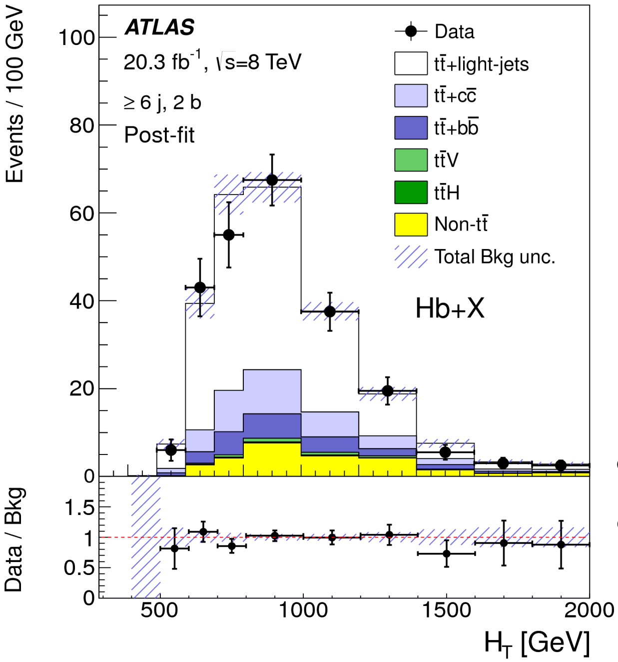




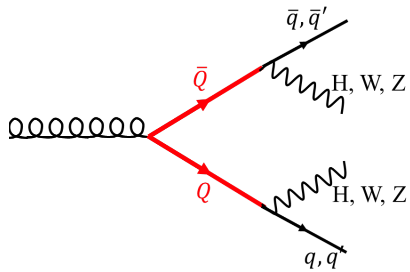
Vector-like quarks

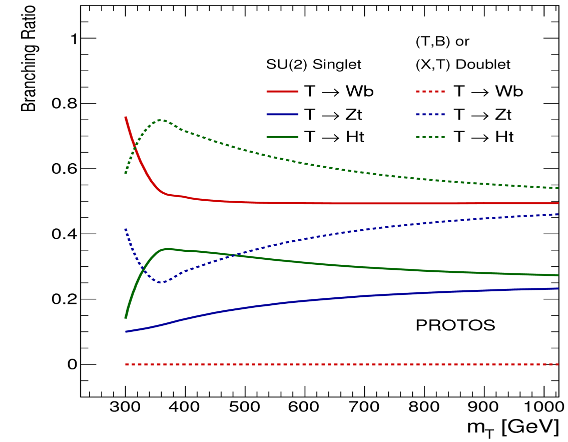
[JHEP 08 (2015) 105](#)



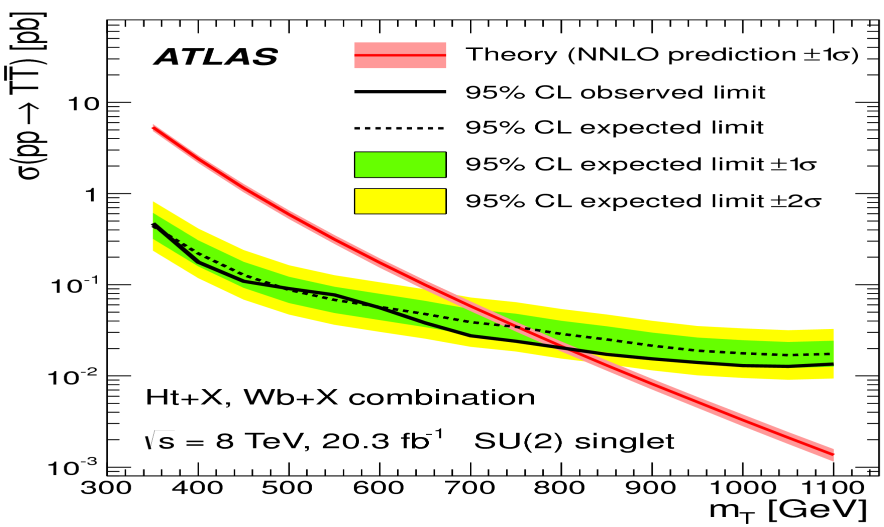


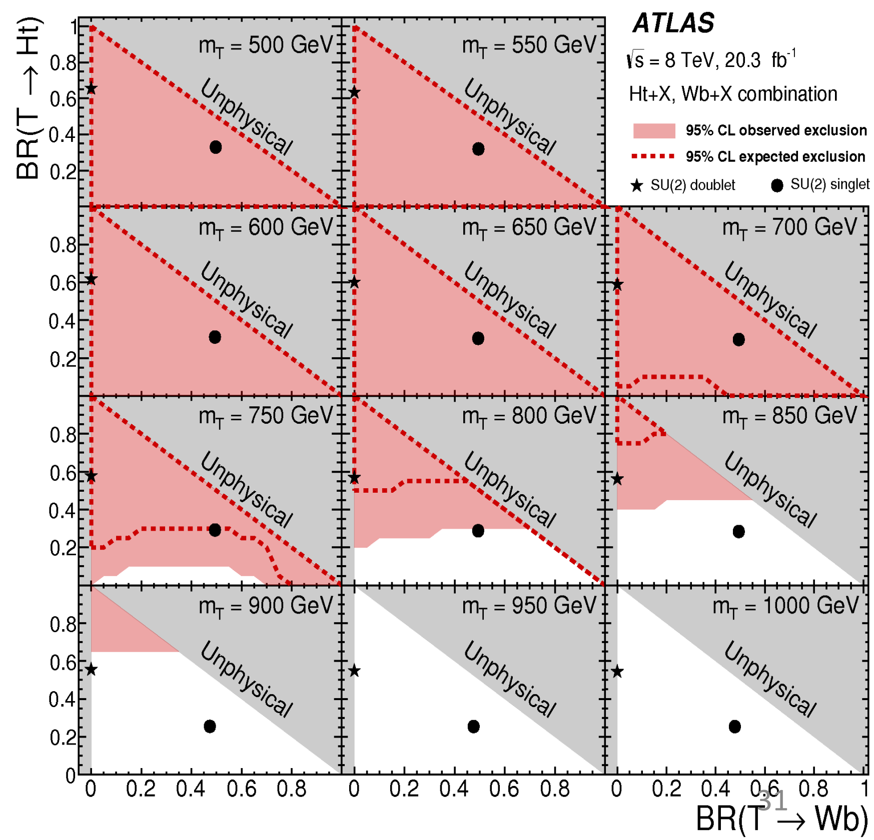
Explores the decay
t' → Ht (H → bb)

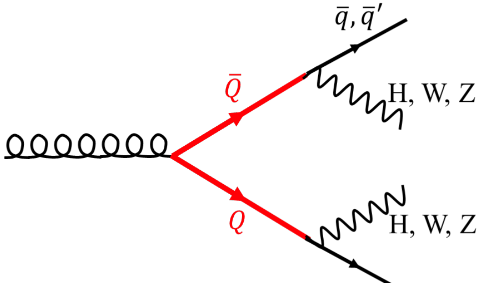




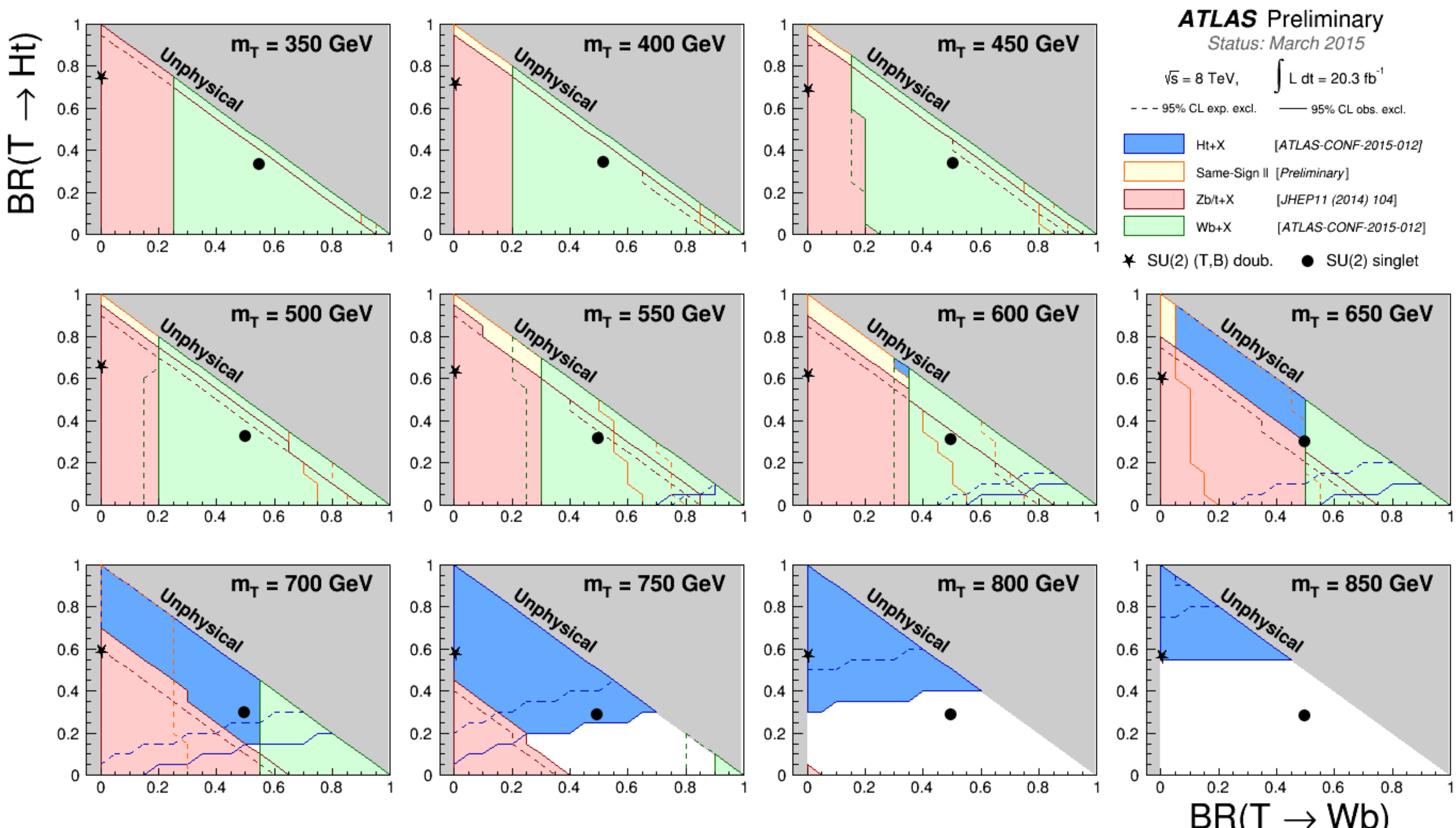
Masses below 800 GeV excluded at 95% CL





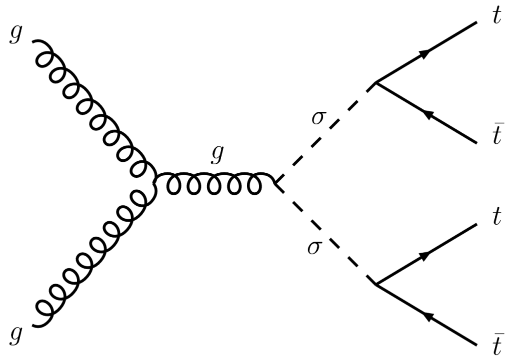


Summary VLQ (T)

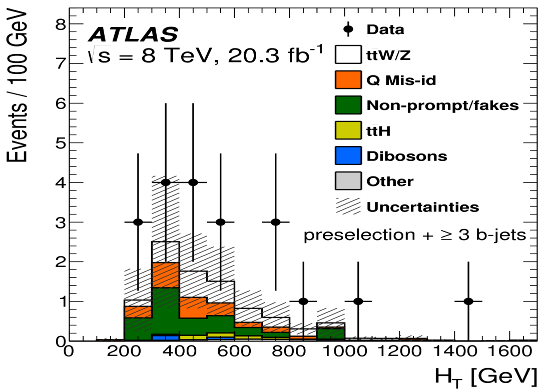


Events with b-jets and a pair of leptons of the same charge

arXiv:1504.04605

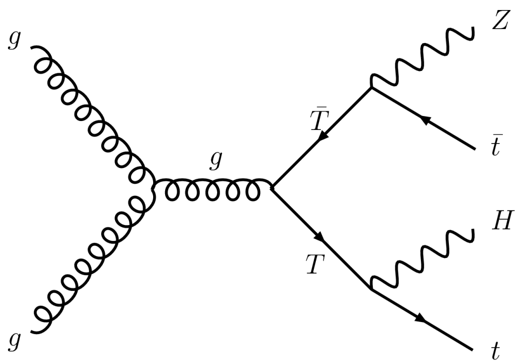


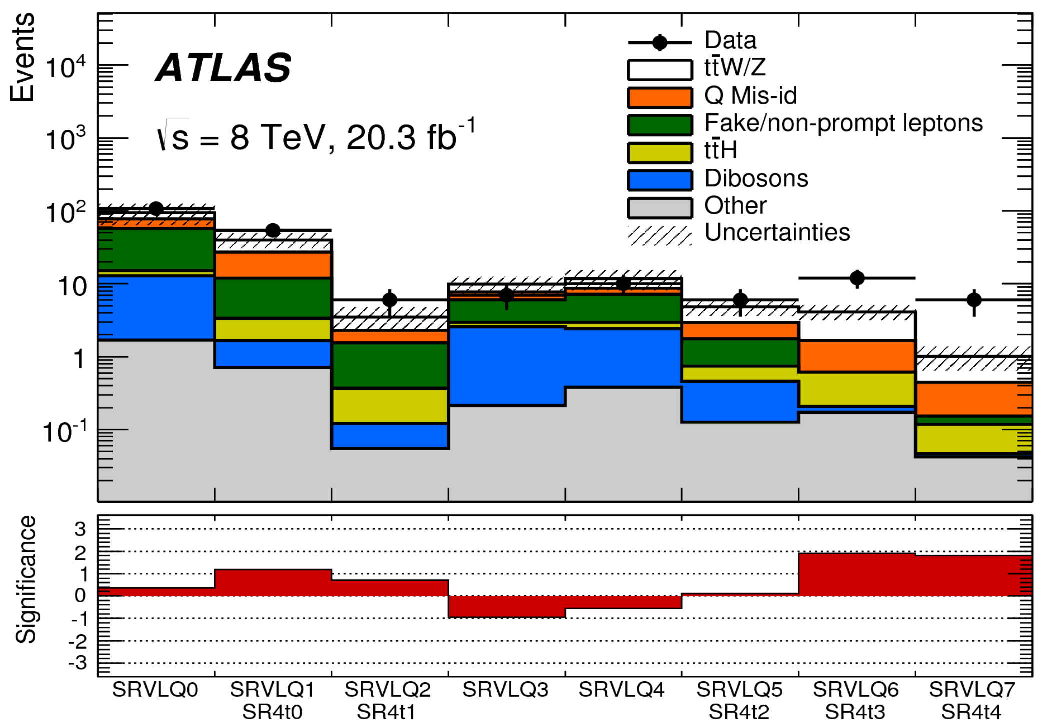
Two same-sign leptons, E_T^{miss} and 1-3 b-jets (SRs in H_T and E_t^{miss})



2.5 sigma effect

production of chiral *b'*-quarks





production of vector-like quarks

FCNC

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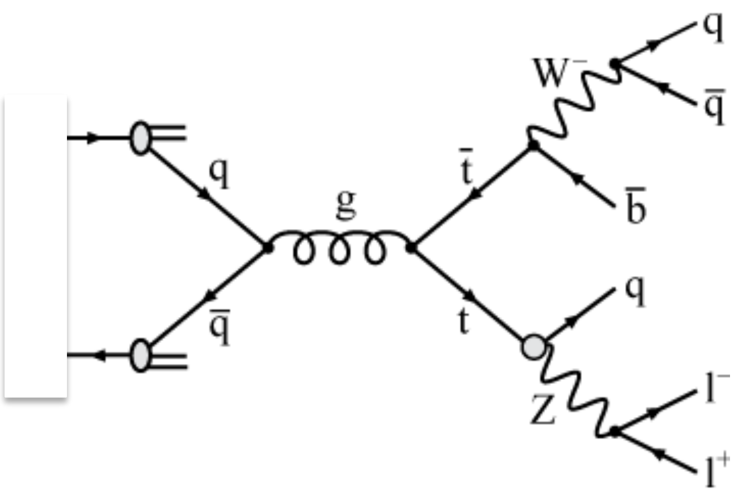
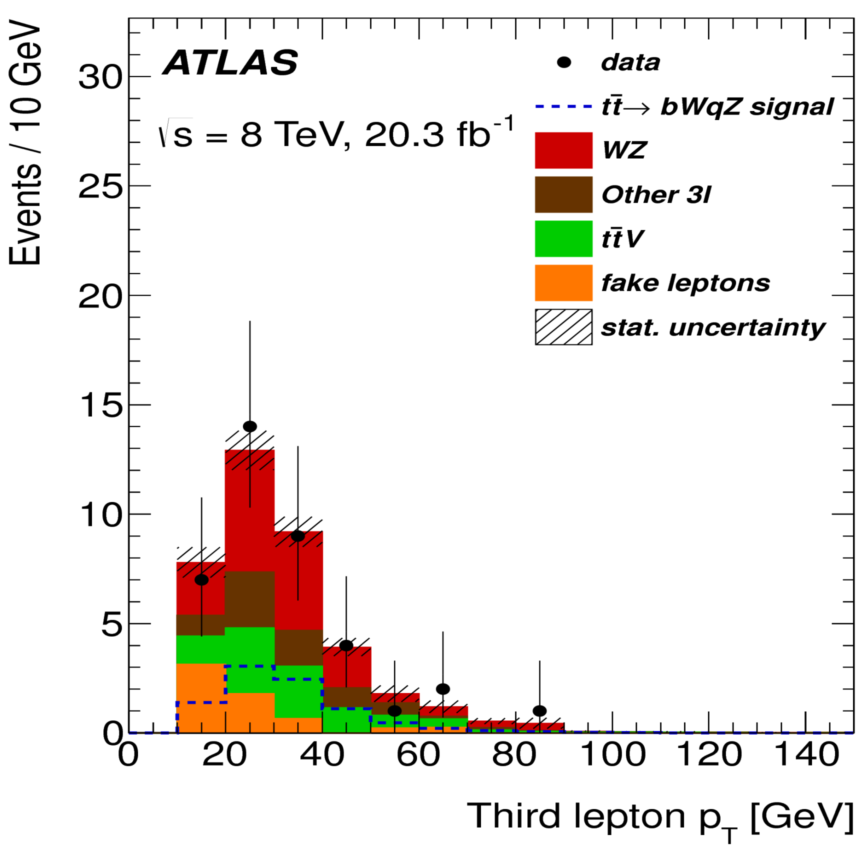
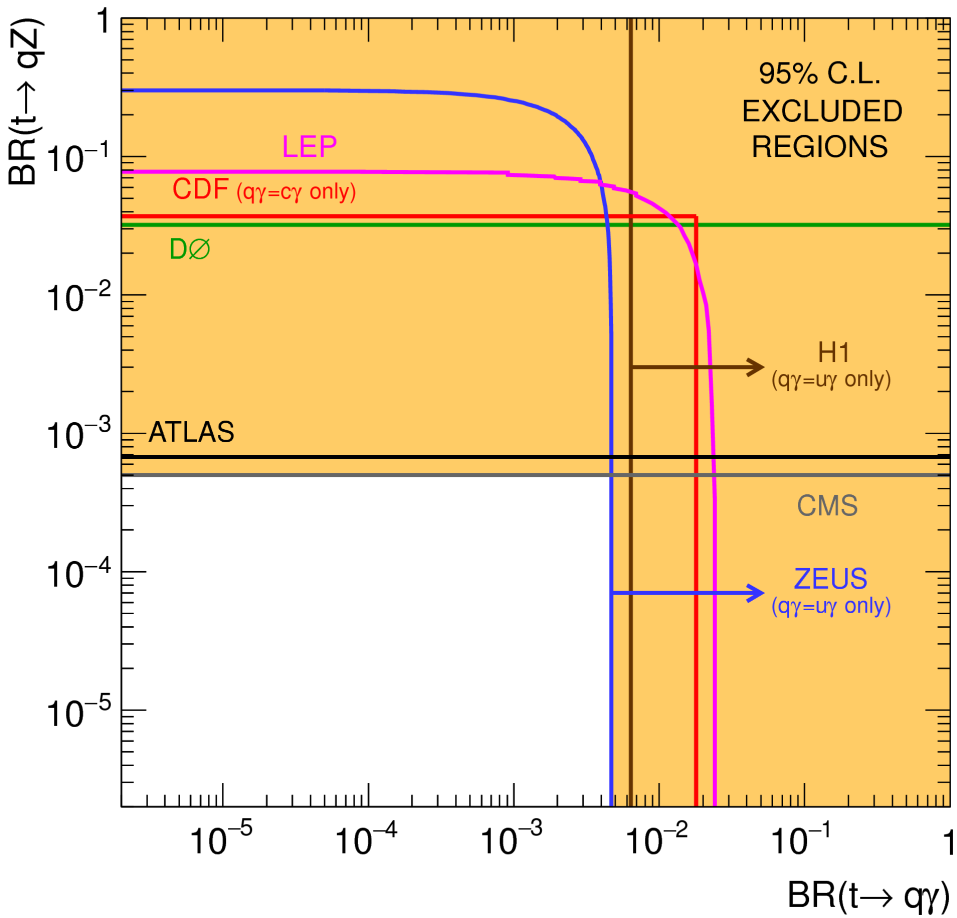






ATLAS Exotics Searches* - 95% CL Exclusion

Status: March 2016

ATLAS Preliminary

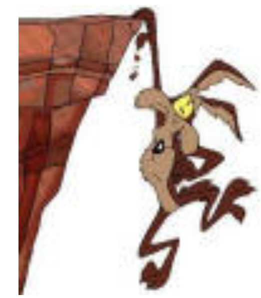
$\int \mathcal{L}\, dt = (3.2 - 20.3)\ \text{fb}^{-1}$ $\sqrt{s} = 8, 13$ TeV

No hint for BSM ?

	Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	–	≥ 1 j	Yes	3.2	M_D 6.58 TeV	$n = 2$	1604.07773
	ADD non-resonant $\ell\ell$	2 e, μ	–	–	20.3	M_S 4.7 TeV	$n = 3$ HLZ	1407.2410
	ADD QBH $\to \ell q$	1 e, μ	1 j	–	20.3	M_{th} 5.2 TeV	$n = 6$	1311.2006
	ADD QBH	–	2 j	–	3.6	M_{th} 8.3 TeV	$n = 6$	1512.01530
	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 $G_{KK} \to \ell\ell$	2 e, μ	–	–	20.3	G_{KK} mass 2.68 TeV	$k/\overline{M}_{Pl} =$	
	RS1 $G_{KK} \to \gamma\gamma$	2 γ	–	–	20.3	G_{KK} mass 2.66 TeV	$k/\overline{M}_{Pl} =$	
	Bulk RS $G_{KK} \to WW \to qq\ell\nu$	1 e, μ	1 J	Yes	3.2	G_{KK} mass 1.06 TeV	$k/\overline{M}_{Pl} =$	
	Bulk RS $G_{KK} \to HH \to bbbb$	–	4 b	–	3.2	G_{KK} mass 480-770 GeV	$k/\overline{M}_{Pl} =$	
	Bulk RS $g_{KK} \to tt$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	20.3	g_{KK} mass 2.2 TeV	BR = 0.92	
	2UED / RPP	1 e, μ	≥ 2 b, ≥ 4 j	Yes	3.2	KK mass 1.46 TeV	Tier (1,1),	
Gauge bosons	SSM $Z' \to \ell\ell$	2 e, μ	–	–	3.2	Z' mass 3.4 TeV		ATLAS-CONF-2015-070
	SSM $Z' \to \tau\tau$	2 τ	–	–	19.5	Z' mass 2.02 TeV		1502.07177
	Leptophobic $Z' \to bb$	–	2 b	–	3.2	Z' mass 1.5 TeV		1603.08791
	SSM $W' \to \ell\nu$	1 e, μ	–	Yes	3.2	W' mass 4.07 TeV		1606.03977
	HVT $W' \to WZ \to qq\nu\nu$ model A	0 e, μ	1 J	Yes	3.2	W' mass 1.6 TeV	$g_V = 1$	ATLAS-CONF-2015-068
	HVT $W' \to WZ \to qqqq$ model A	–	2 J	–	3.2	W' mass 1.38-1.6 TeV	$g_V = 1$	ATLAS-CONF-2015-073
	HVT $W' \to WH \to \ell\nu bb$ model B	1 e, μ	1-2 b, 1-0 j	Yes	3.2	W' mass 1.62 TeV	$g_V = 3$	ATLAS-CONF-2015-074
	HVT $Z' \to ZH \to \nu\nu bb$ model B	0 e, μ	1-2 b, 1-0 j	Yes	3.2	Z' mass 1.76 TeV	$g_V = 3$	ATLAS-CONF-2015-074
	LRSM $W'_R \to tb$	1 e, μ	2 b, 0-1 j	Yes	20.3	W' mass 1.92 TeV		1410.4103
	LRSM $W'_R \to tb$	0 e, μ	≥ 1 b, 1 J	–	20.3	W' mass 1.76 TeV		1408.0886
CI	CI $qqqq$	–	2 j	–	3.6	Λ 17.5 TeV	$\eta_{LL} = -1$	1512.01530
	CI $qq\ell\ell$	2 e, μ	–	–	3.2	Λ 23.1 TeV	$\eta_{LL} = -1$	ATLAS-CONF-2015-070
	CI $uutt$	2 e, μ (SS)	≥ 1 b, 1-4 j	Yes	20.3	Λ 4.3 TeV	$\lvert C_{LL} \rvert = 1$	1504.04605
DM	Axial-vector mediator (Dirac DM)	0 e, μ	≥ 1 j	Yes	3.2	m_A 1.0 TeV	g_q=0.25, g_χ=1.0, $m(\chi)$ < 250 GeV	1604.07773
	Axial-vector mediator (Dirac DM)	0 e, μ, 1 γ	1 j	Yes	3.2	m_A 710 GeV	g_q=0.25, g_χ=1.0, $m(\chi)$ < 150 GeV	1604.01306
	$ZZ\chi\chi$ EFT (Dirac DM)	0 e, μ	1 J, ≤ 1 j	Yes	3.2	M_* 550 GeV	$m(\chi)$ < 150 GeV	ATLAS-CONF-2015-080
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 $TT \to Ht + X$	1 e, μ	≥ 2 b, ≥ 3 j	Yes	20.3	T mass 855 GeV	T in (T,B) doublet	1505.04306
	VLQ $YY \to Wb + X$	1 e, μ	≥ 1 b, ≥ 3 j	Yes	20.3	Y mass 770 GeV	Y in (B,Y) doublet	1505.04306
	VLQ $BB \to Hb + X$	1 e, μ	≥ 2 b, ≥ 3 j	Yes	20.3	B mass 735 GeV	isospin singlet	1505.04306
	VLQ $BB \to Zb + X$	2/≥3 e, μ	≥2/≥1 b	–	20.3	B mass 755 GeV	B in (B,Y) doublet	1409.5500
	VLQ $QQ \to WqWq$	1 e, μ	≥ 4 j	Yes	20.3	Q mass 690 GeV		1509.04261
	$T_{5/3} \to Wt$	1 e, μ	≥ 1 b, ≥ 5 j	Yes	20.3	$T_{5/3}$ mass 840 GeV		1503.05425
Excited fermions	Excited quark $q^* \to q\gamma$	1 γ	1 j	–	3.2	q^* mass 4.4 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1512.05910
	Excited quark $q^* \to qg$	–	2 j	–	3.6	q^* mass 5.2 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1512.01530
	Excited quark $b^* \to bg$	–	1 b, 1 j	–	3.2	b^* mass 2.1 TeV		1603.08791
	Excited quark $b^* \to Wt$	1 or 2 e, μ	1 b, 2-0 j	Yes	20.3	b^* mass 1.5 TeV	$f_g = f_L = f_R = 1$	1510.02664
	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	LSTC $a_T \to W\gamma$	1 e, μ, 1 γ	–	Yes	20.3	a_T mass 960 GeV		1407.8150
	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 e, μ (SS)	–	–	20.3	$H^{\pm\pm}$ mass 551 GeV	DY production, BR($H_L^{\pm\pm} \to \ell\ell$)=1	1412.0237
	Higgs triplet $H^{\pm\pm} \to \ell\tau$	3 e, μ, τ	–	–	20.3	$H^{\pm\pm}$ mass 400 GeV	DY production, BR($H_L^{\pm\pm} \to \ell\tau$)=1	1411.2921
	Monotop (non-res prod)	1 e, μ	1 b	Yes	20.3	spin-1 invisible particle mass 657 GeV	$a_{\text{non-res}} = 0.2$	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, $\lvert g \rvert = 1 g_D$, spin 1/2	1509.08059

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

Mass scale [TeV] (10^{-1}, 1, 10)



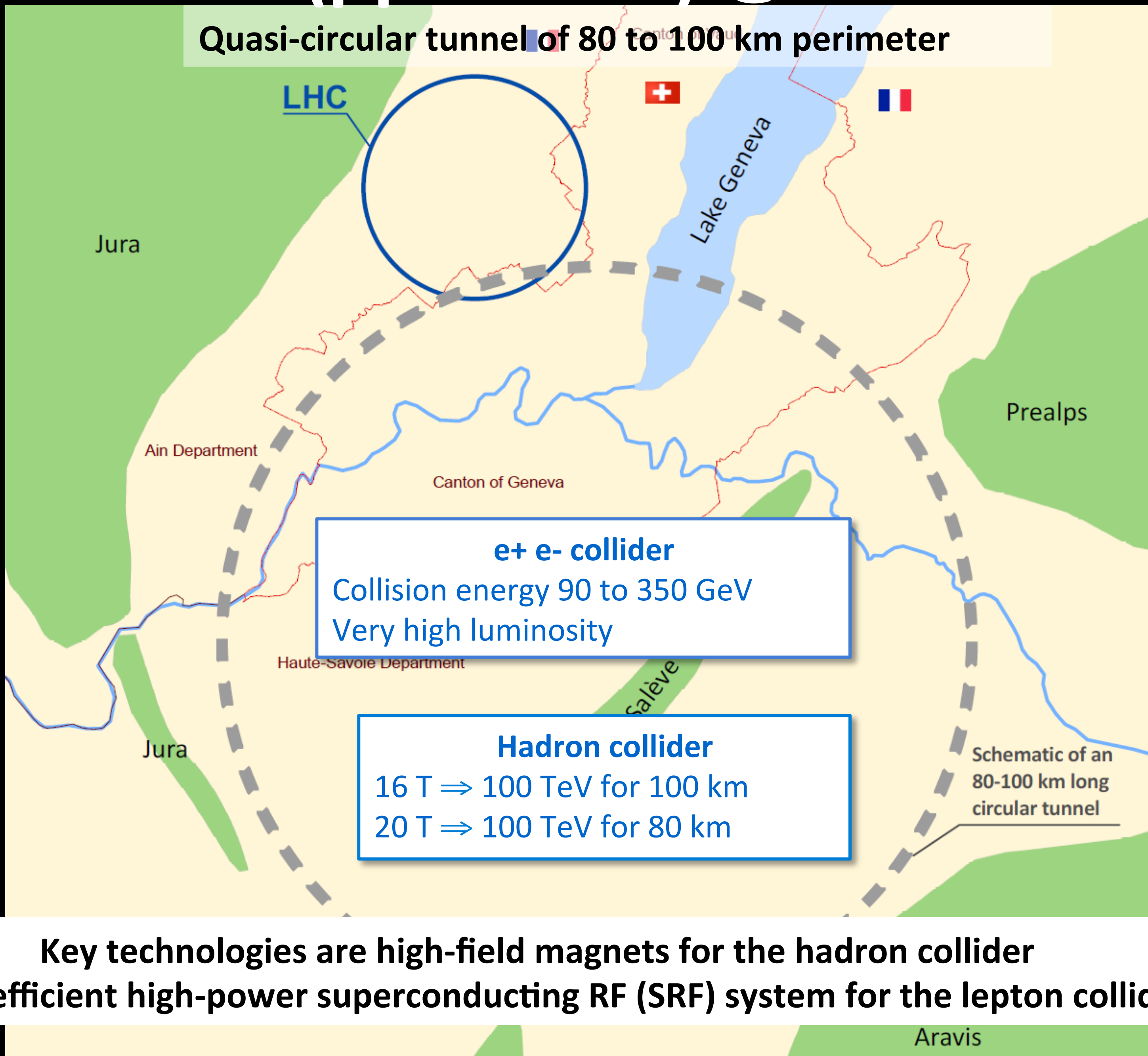
*Only a selection of the available mass limits on new states or phenomena is shown. Lower bounds are specified only when explicitly not excluded.

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

Only time will tell…..

FCC (pp and ee) @ CERN

Quasi-circular tunnel of 80 to 100 km perimeter



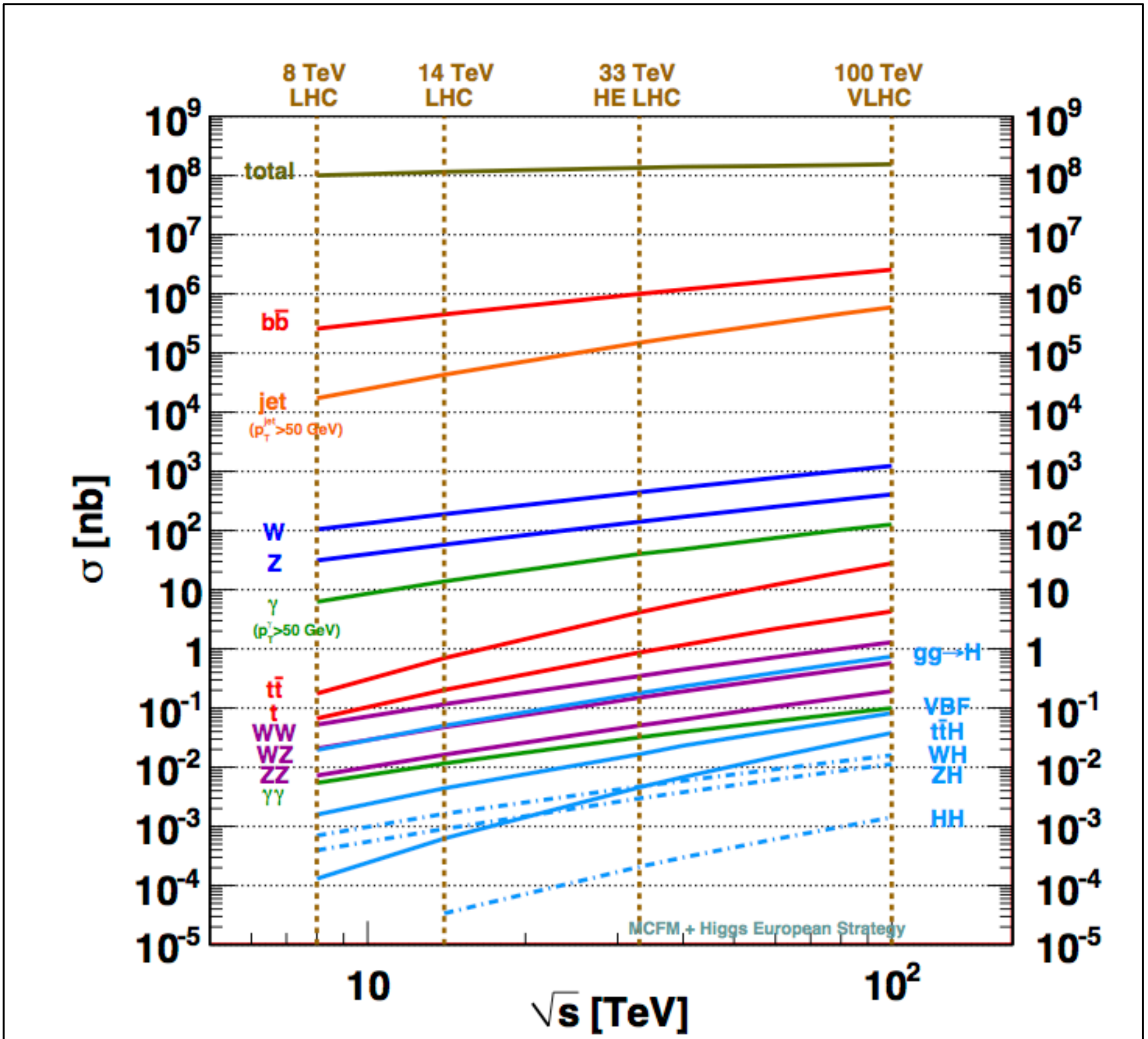
e+ e- collider
Collision energy 90 to 350 GeV
Very high luminosity

Hadron collider
16 T ⇒ 100 TeV for 100 km
20 T ⇒ 100 TeV for 80 km

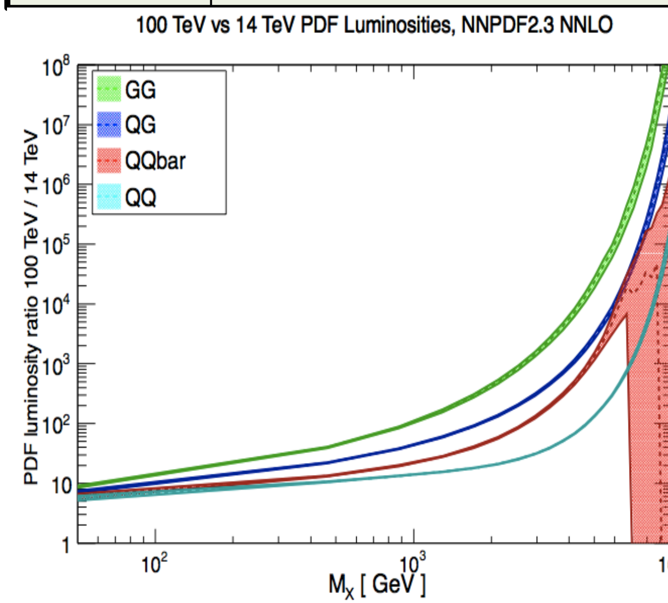
Key technologies are high-field magnets for the hadron collider and an efficient high-power superconducting RF (SRF) system for the lepton collider.

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)	$\sim 10^3$

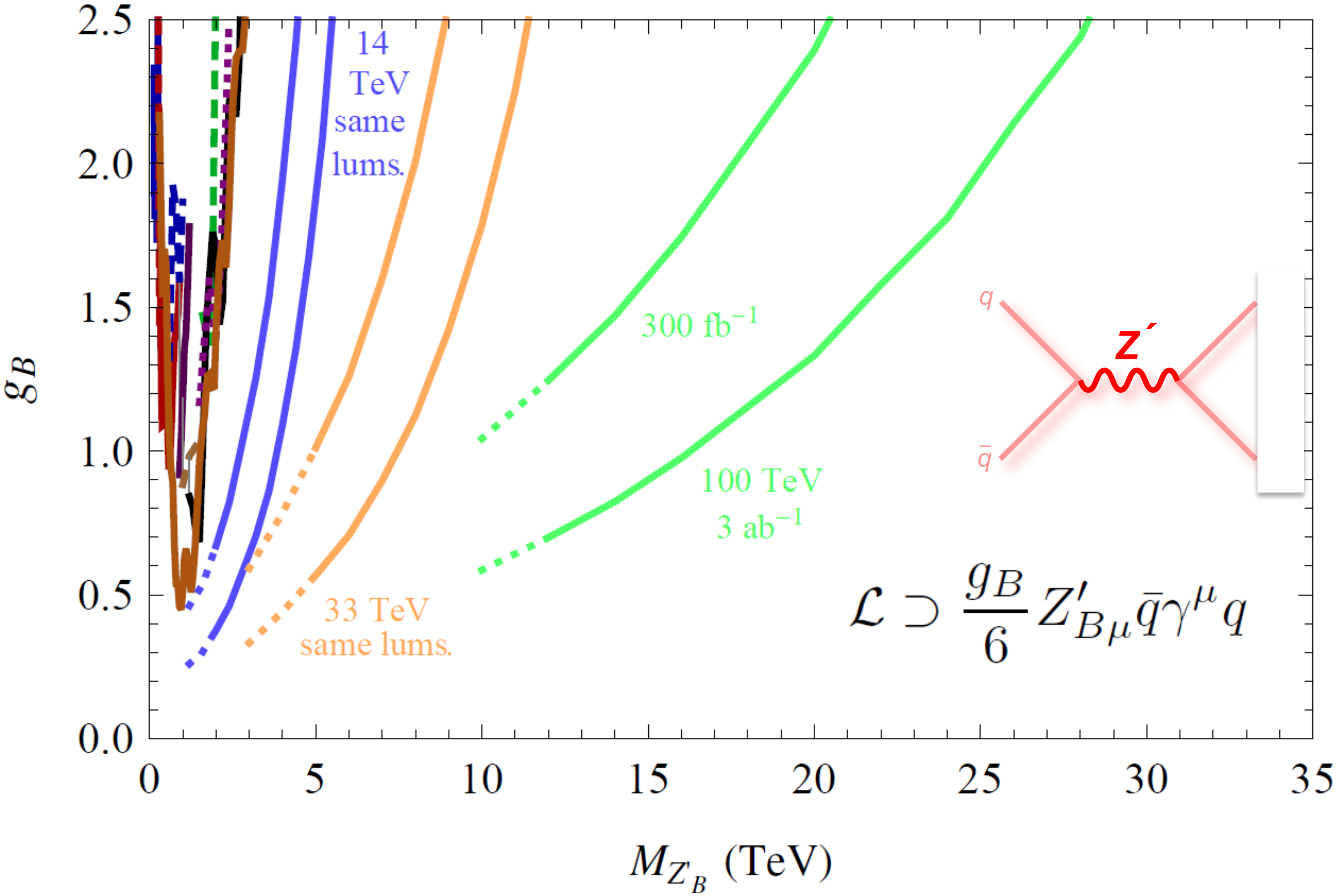


It really opens a new energy frontier---

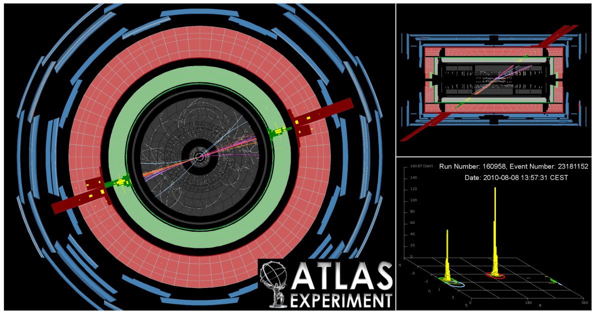
FCC-pp at 100 TeV and considering a total integrated luminosity of 3 ab-1

Drell-Yan

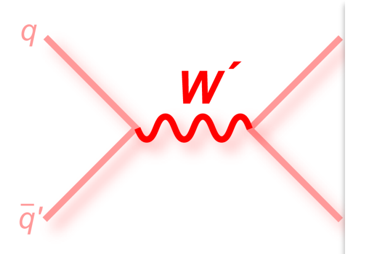
Discovery reach
4.5 TeV @ 14 TeV LHC, 300 fb-1
5.5 TeV @ 14 TeV LHC, 3 ab-1
28 TeV @ 100 TeV, 3 ab-1

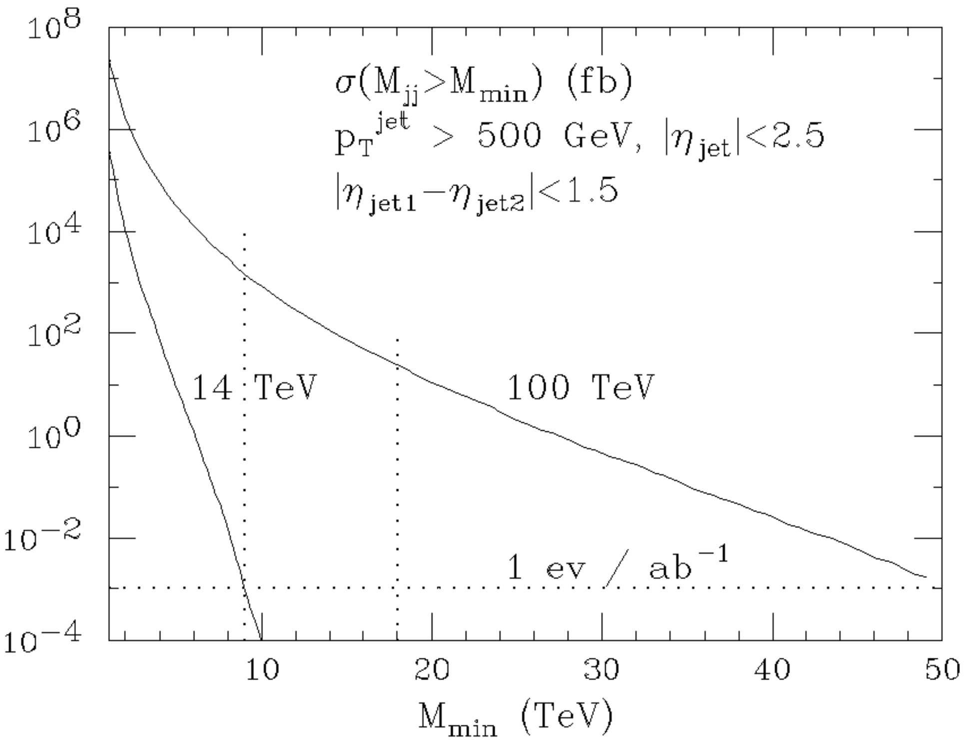


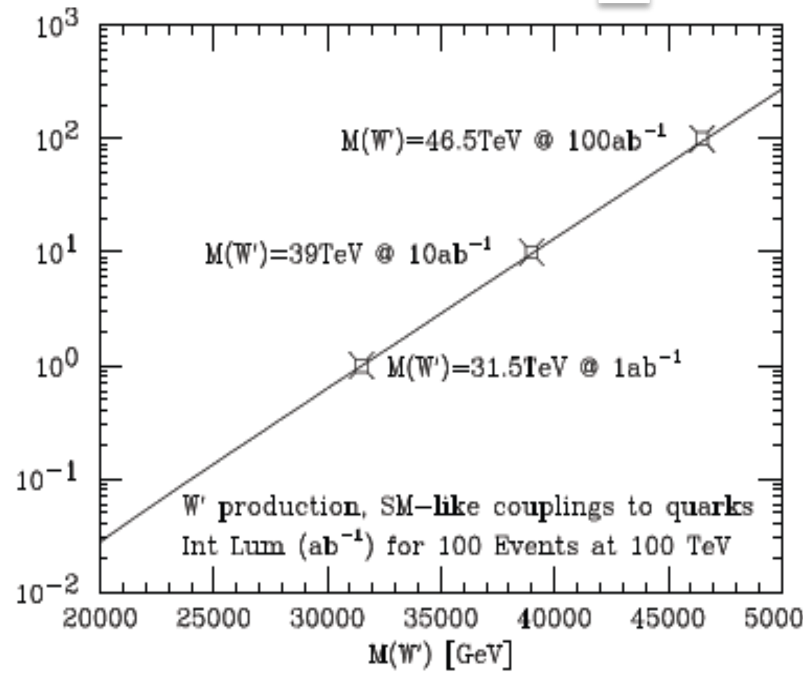
FCC-pp at 100 TeV and considering a total integrated luminosity of 3 ab-1



Dijets and W’



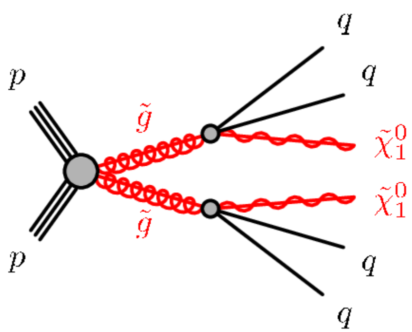


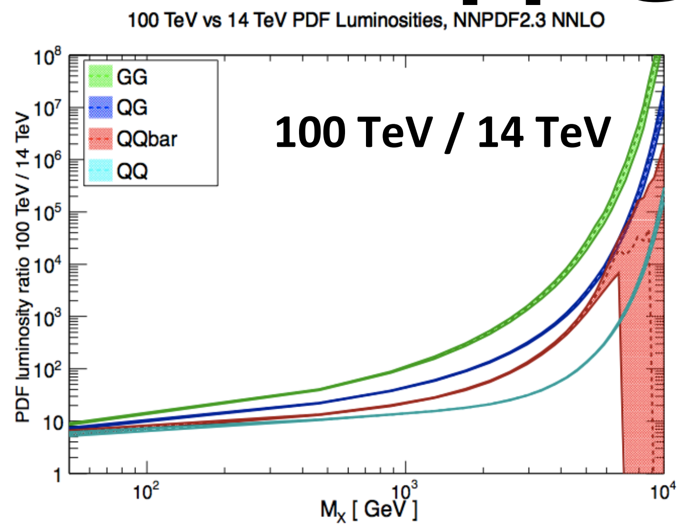


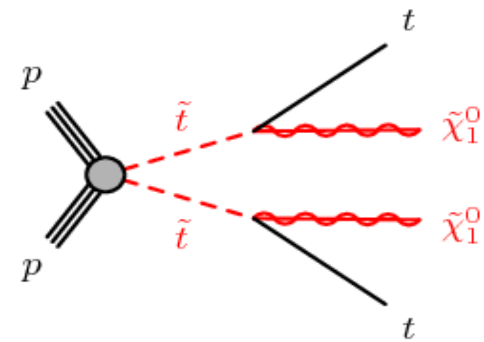
To recover LHC-HL sensitivity would take 1 pb-1 (1 day operations)

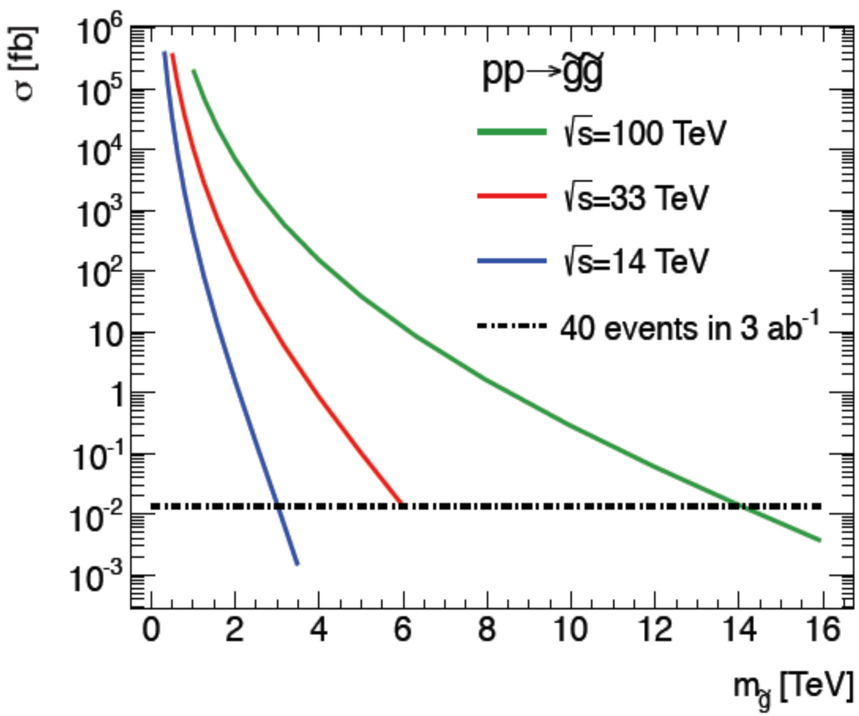
Assuming SM couplings… FCC-pp could exclude a W’ of 32 TeV

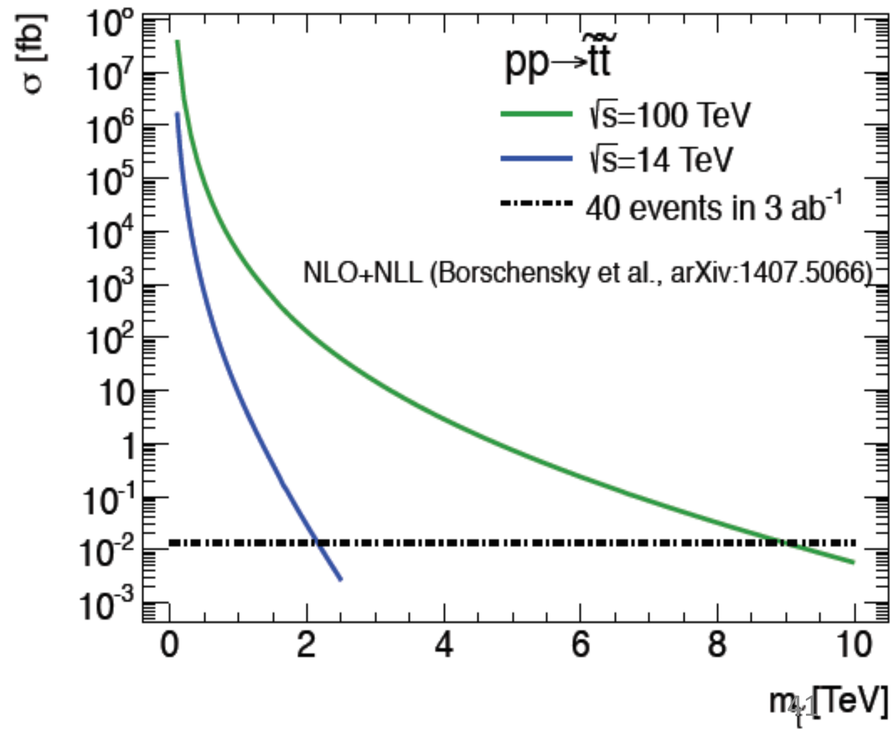
SUSY Reach for pp @ 100 TeV



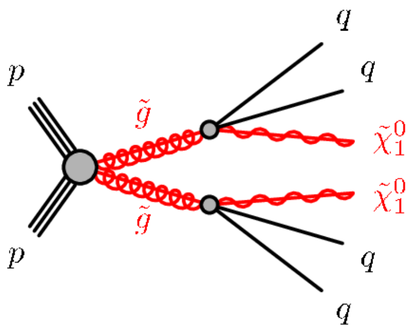






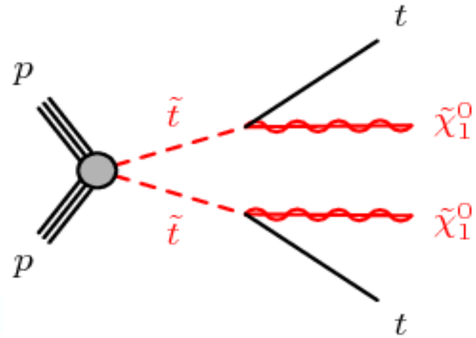


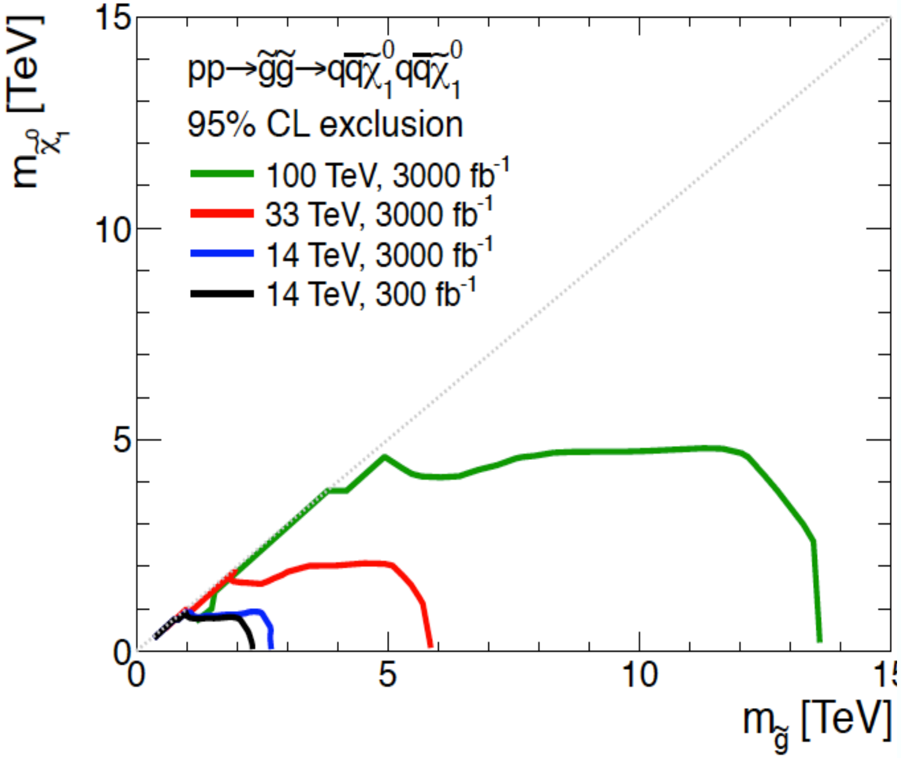
SUSY Reach for pp @ 100 TeV

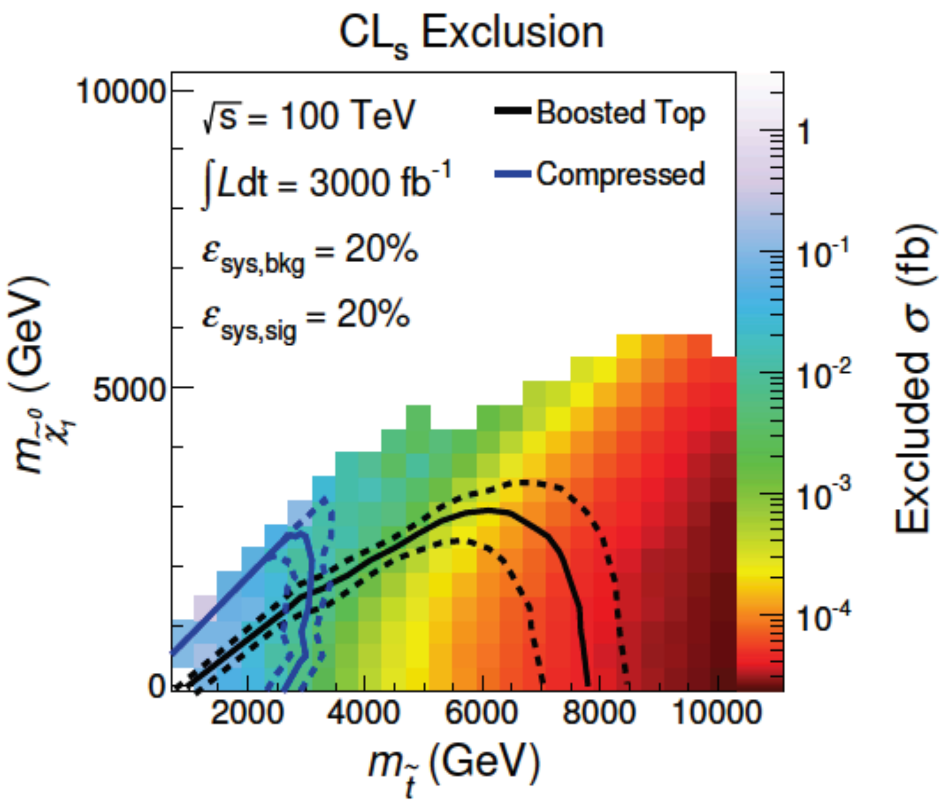


In terms of Higgs/EWK hierarchy problem

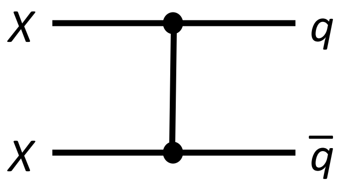
This scenario implies a tuning of the level of 0.05%



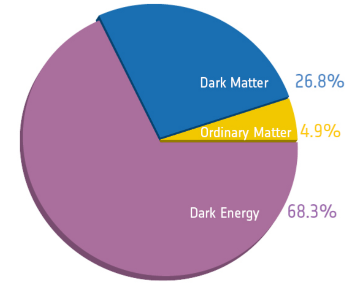




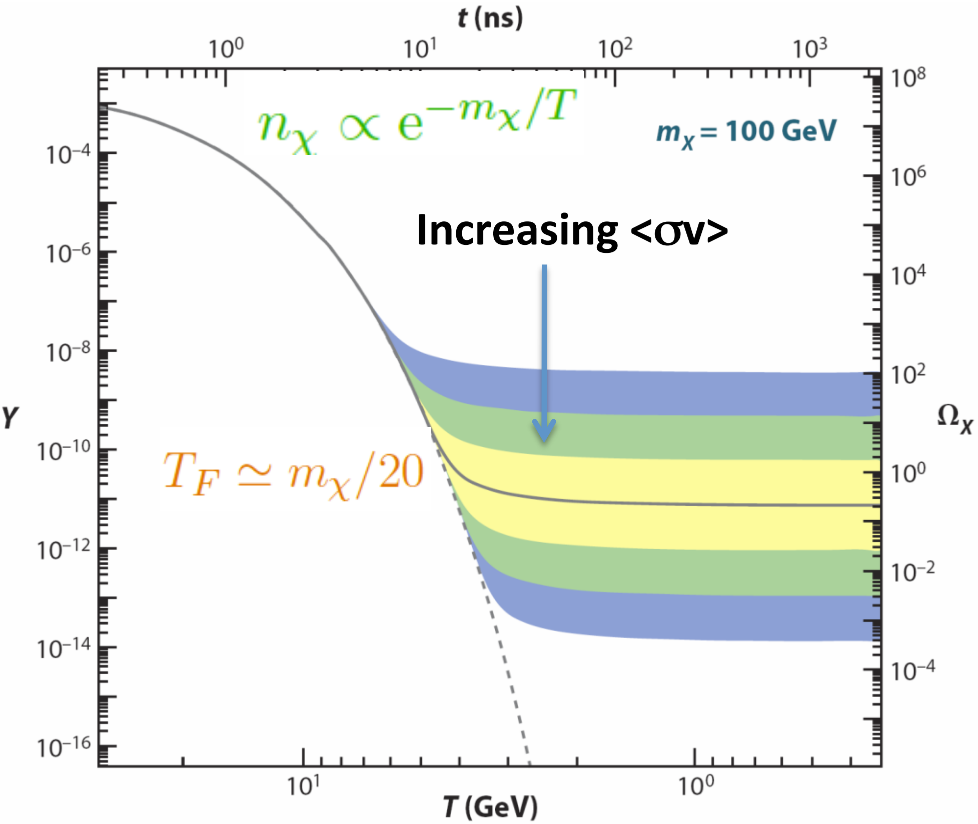
Dark Matter

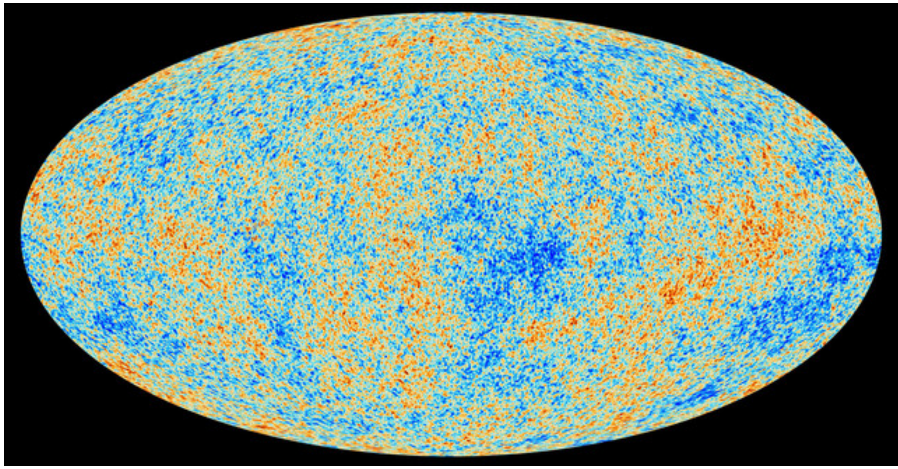


$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$



After Planck





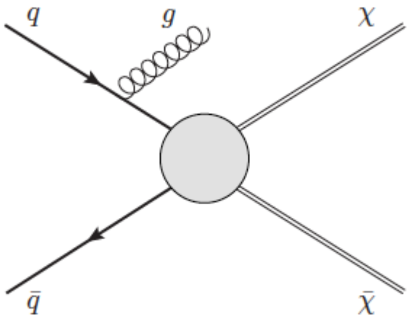
$$\Omega_\chi h^2 \simeq \frac{0.1\ \mathrm{pb}\cdot c}{\langle \sigma(\chi\chi \to \mathrm{SM}) v \rangle}$$

$$M_{\mathrm{WIMP}} \leq 1.8\ \mathrm{TeV}\ \left(\frac{g^2}{0.3}\right)$$

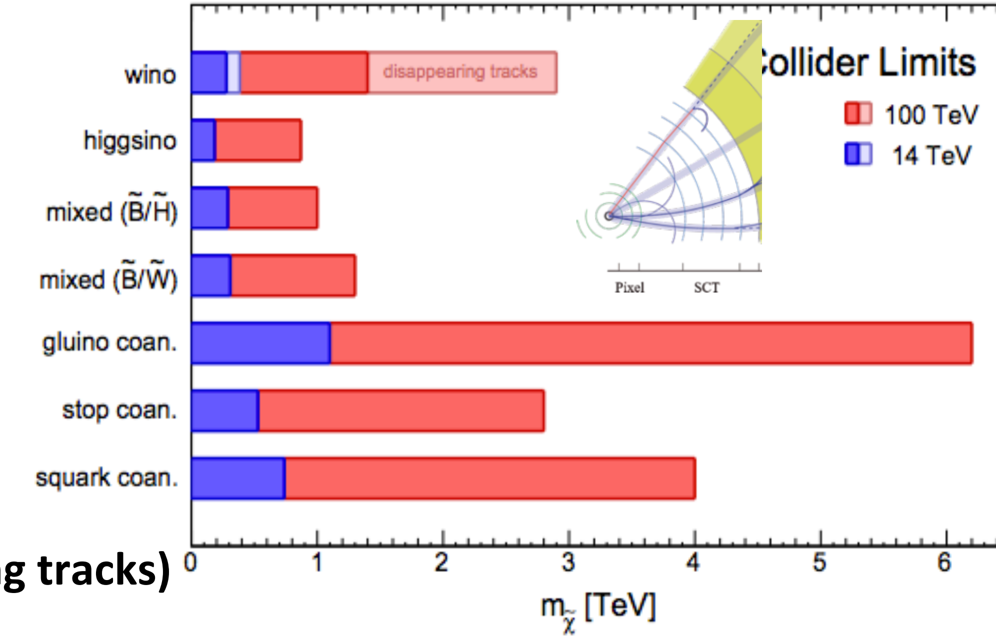
$$\langle \sigma(\chi\chi \to \mathrm{any}) v \rangle \simeq 3 \cdot 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}$$

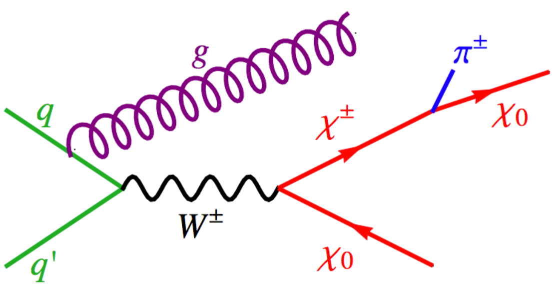
Weak scale for χχ annihilation cross section

Dark Matter @ 100 TeV

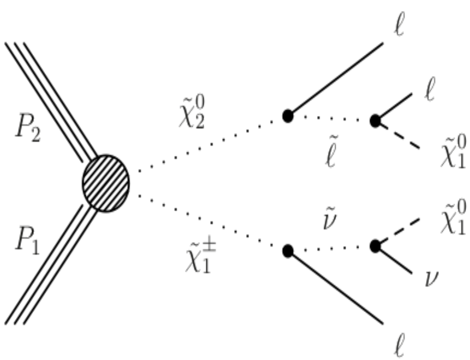


Monojets

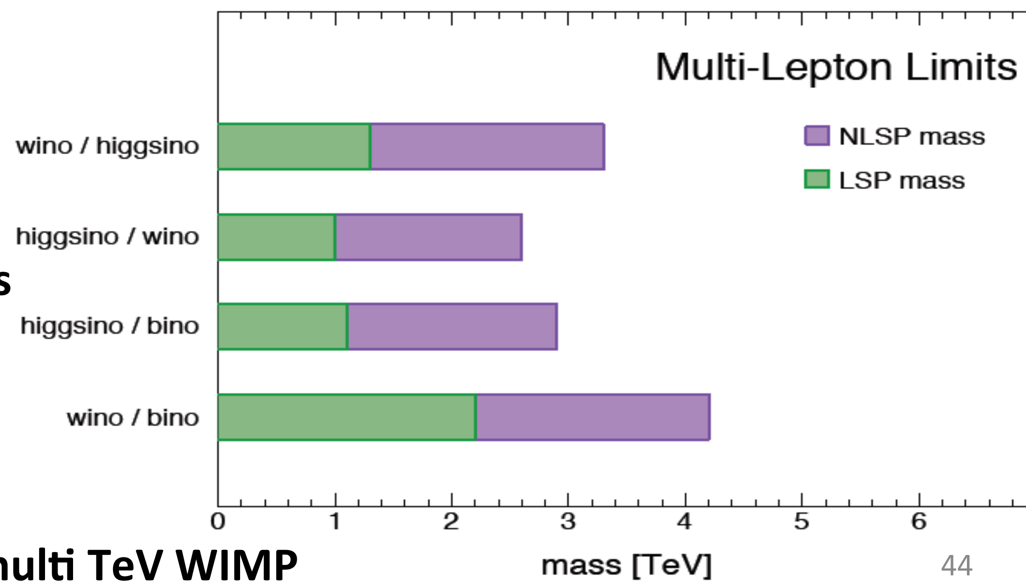




Long-lived (disappearing tracks)



Multileptons



A 100 TeV pp collider would probe the multi TeV WIMP

End Part IV

Thanks for your attention