Searching for exotic physics with the ATLAS detector

Les Rencontres de Physique de la Vallée d'Aoste

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Exotic ?

- Many open questions on Physics Beyond the Standard Model
  - Hierarchy/naturalness/fine-tuning ?
  - number of flavor ?
  - dark matter ?
  - matter/anti-matter asymmetry
  - GUT , quantum gravity ?
  - ...

Possible solutions :

- **Supersymmetry**
- Extra-dimensions
- Compositeness
- GUT/New Gauge Bosons
- Top partners
- Additional Higgs Bosons
- ...

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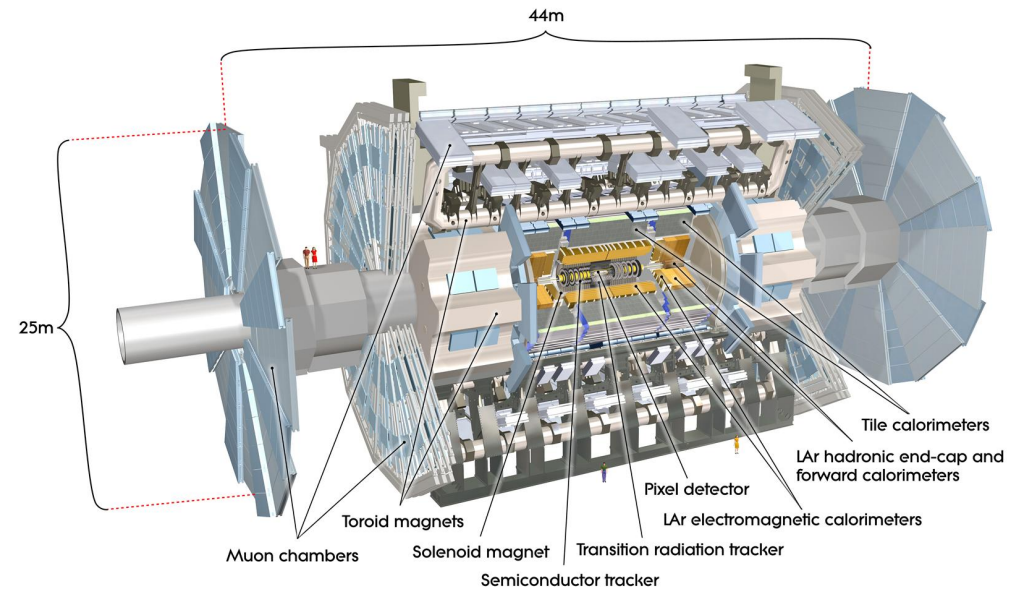
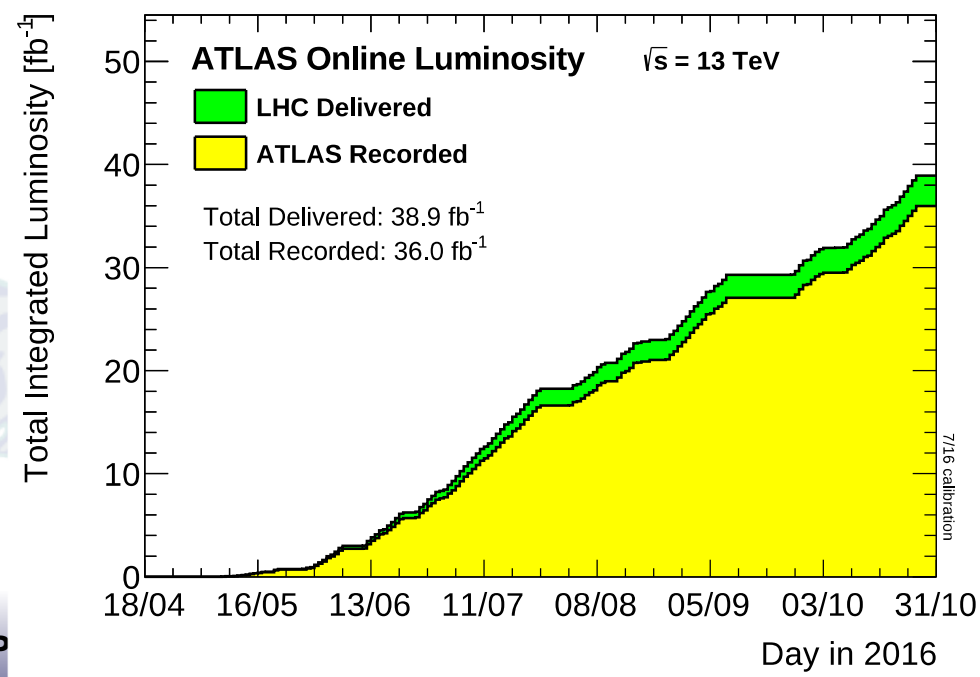
- Additional Higgs Bosons
- ...

Exotic

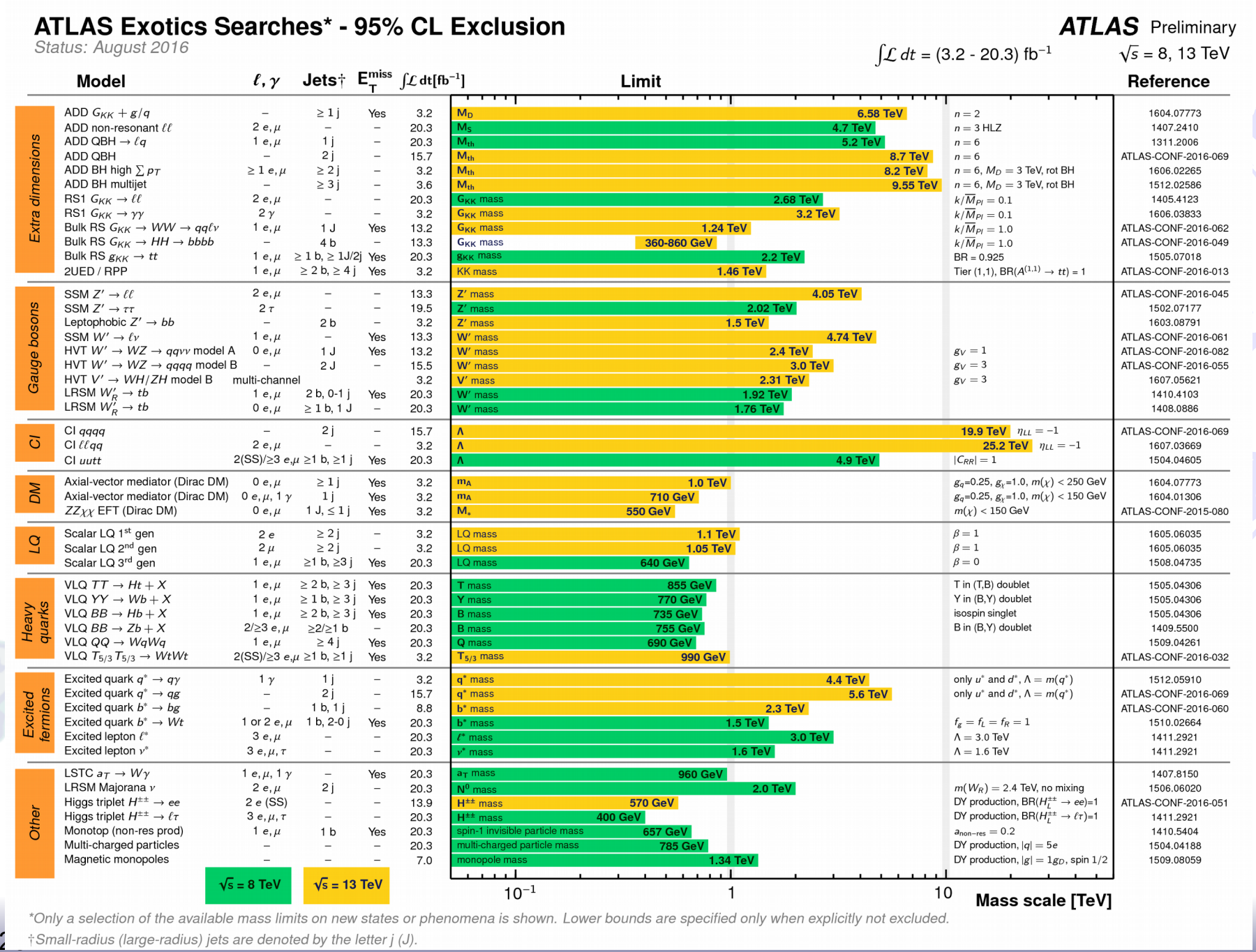
ATLAS and the LHC

- ATLAS: multi-purpose detector at the LHC
- recorded **36.0 fb^{-1}** of pp collisions at **√s=13TeV** in 2016
- Analyses with full dataset not yet ready
  - presenting results with limited luminosity
  - using ~13 fb^{-1} of 2016+2015 data





Exotic in ATLAS



Exotic in ATLAS

All ATLAS exotic results

ATLAS Exotics Searches* - 95% CL Exclusion

Status: August 2016

ATLAS Preliminary

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

	Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$	Limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	–	≥ 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	–	15.7	M_{th} 8.7 TeV	$n = 6$	ATLAS-CONF-2016-069
	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	$k/\overline{M}_{Pl} = 0.1$	1405.4123
	RS1 $G_{KK} \to \gamma\gamma$	2 γ	–	–	3.2	G_{KK} mass 3.2 TeV	$k/\overline{M}_{Pl} = 0.1$	1606.03833
	Bulk RS $G_{KK} \to WW \to qq\ell\nu$	1 e, μ	1 J	Yes	13.2	G_{KK} mass 1.24 TeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2016-062
	Bulk RS $G_{KK} \to HH \to bbbb$	–	4 b	–	13.3	G_{KK} mass 360-860 GeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2016-049
	Bulk RS $g_{KK} \to tt$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	20.3	g_{KK} mass 2.2 TeV	BR = 0.925	1505.07018
	2UED / RPP	1 e, μ	≥ 2 b, ≥ 4 j	Yes	3.2	KK mass 1.46 TeV	Tier (1,1), BR($A^{(1,1)} \to tt$) = 1	ATLAS-CONF-2016-013
Gauge bosons	SSM $Z' \to \ell\ell$	2 e, μ	–	–	13.3	Z' mass 4.05 TeV		ATLAS-CONF-2016-045
	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	13.3	W' mass 4.74 TeV		ATLAS-CONF-2016-061
	HVT $W' \to WZ \to qq\nu\nu$ model A	0 e, μ	1 J	Yes	13.2	W' mass 2.4 TeV	$g_V = 1$	ATLAS-CONF-2016-082
	HVT $W' \to WZ \to qqqq$ model B	–	2 J	–	15.5	W' mass 3.0 TeV	$g_V = 3$	ATLAS-CONF-2016-055
	HVT $V' \to WH/ZH$ model B	multi-channel			3.2	V' mass 2.31 TeV	$g_V = 3$	1607.05621
	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	–	15.7	Λ 19.9 TeV	$\eta_{LL} = -1$	ATLAS-CONF-2016-069
	CI $\ell\ell qq$	2 e, μ	–	–	3.2	Λ 25.2 TeV	$\eta_{LL} = -1$	1607.03669
	CI $uutt$	2(SS)/≥3 e, μ	≥1 b, ≥1 j	Yes	20.3	Λ 4.9 TeV	$\lvert C_{RR}\rvert = 1$	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
	VLQ $T_{5/3}T_{5/3} \to WtWt$	2(SS)/≥3 e, μ	≥1 b, ≥1 j	Yes	3.2	$T_{5/3}$ mass 990 GeV		ATLAS-CONF-2016-032
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	–	15.7	q^* mass 5.6 TeV	only u^* and d^*, $\Lambda = m(q^*)$	ATLAS-CONF-2016-069
	Excited quark $b^* \to bg$	–	1 b, 1 j	–	8.8	b^* mass 2.3 TeV		ATLAS-CONF-2016-060
	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 $H^{\pm\pm} \to ee$	2 e (SS)	–	–	13.9	$H^{\pm\pm}$ mass 570 GeV	DY production, BR($H_L^{\pm\pm} \to ee$)=1	ATLAS-CONF-2016-051
	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	$a_{non-res} = 0.2$	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 | $\int \mathcal{L}\, dt$ = 13 TeV | [TeV]

*Only a selection of the available mass limits on new states or p

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

Many different experimental final states
This talk will present a few selected ones

Mono- lepton/photon/jet

- Mono-X final states imply high Missing E_T
- Mono-X final states involved in **Dark Matter** models

Several Dark Matter searches in ATLAS

- Covered in Frederik Ruehr's presentation

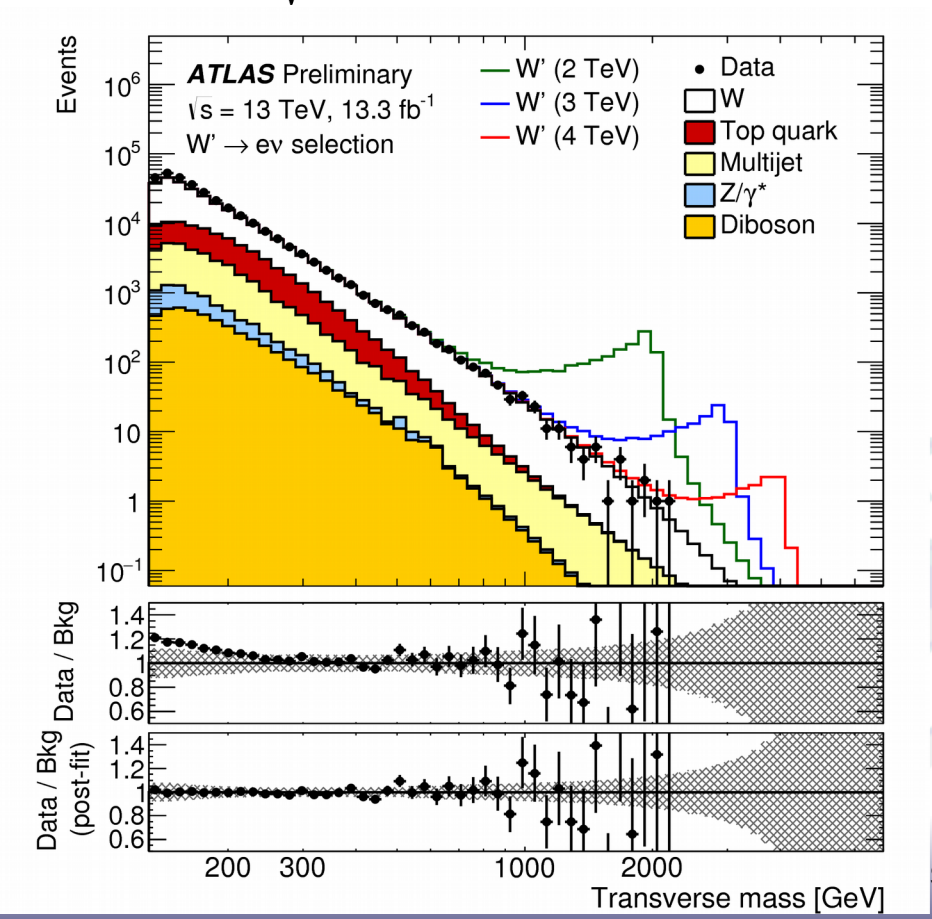
1 lepton & Missing Et

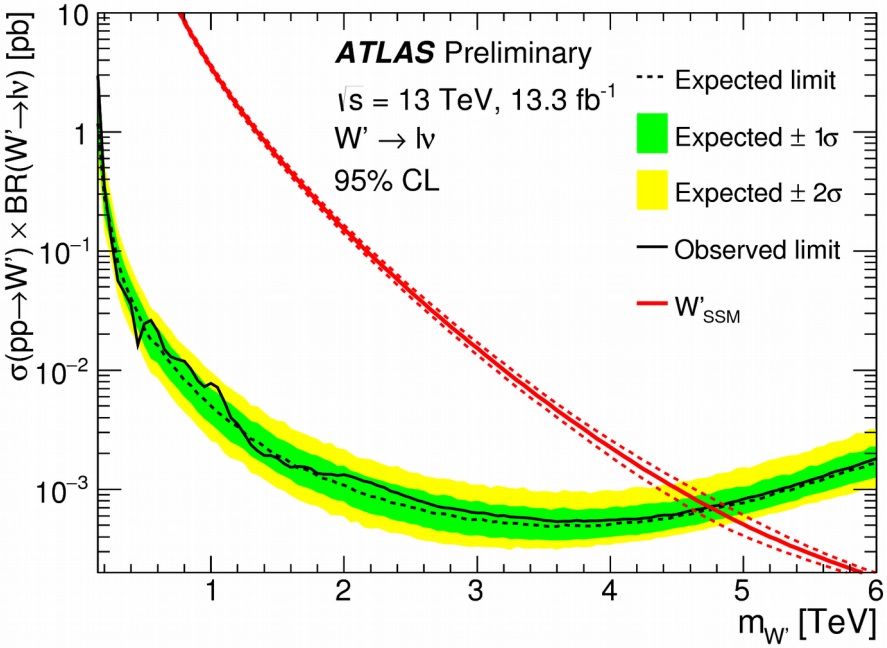
W' → ℓν (ℓ=e,μ) tested in Sequential Standard Model (SSM)

- Observable : transverse mass

ATLAS-CONF-2016-061

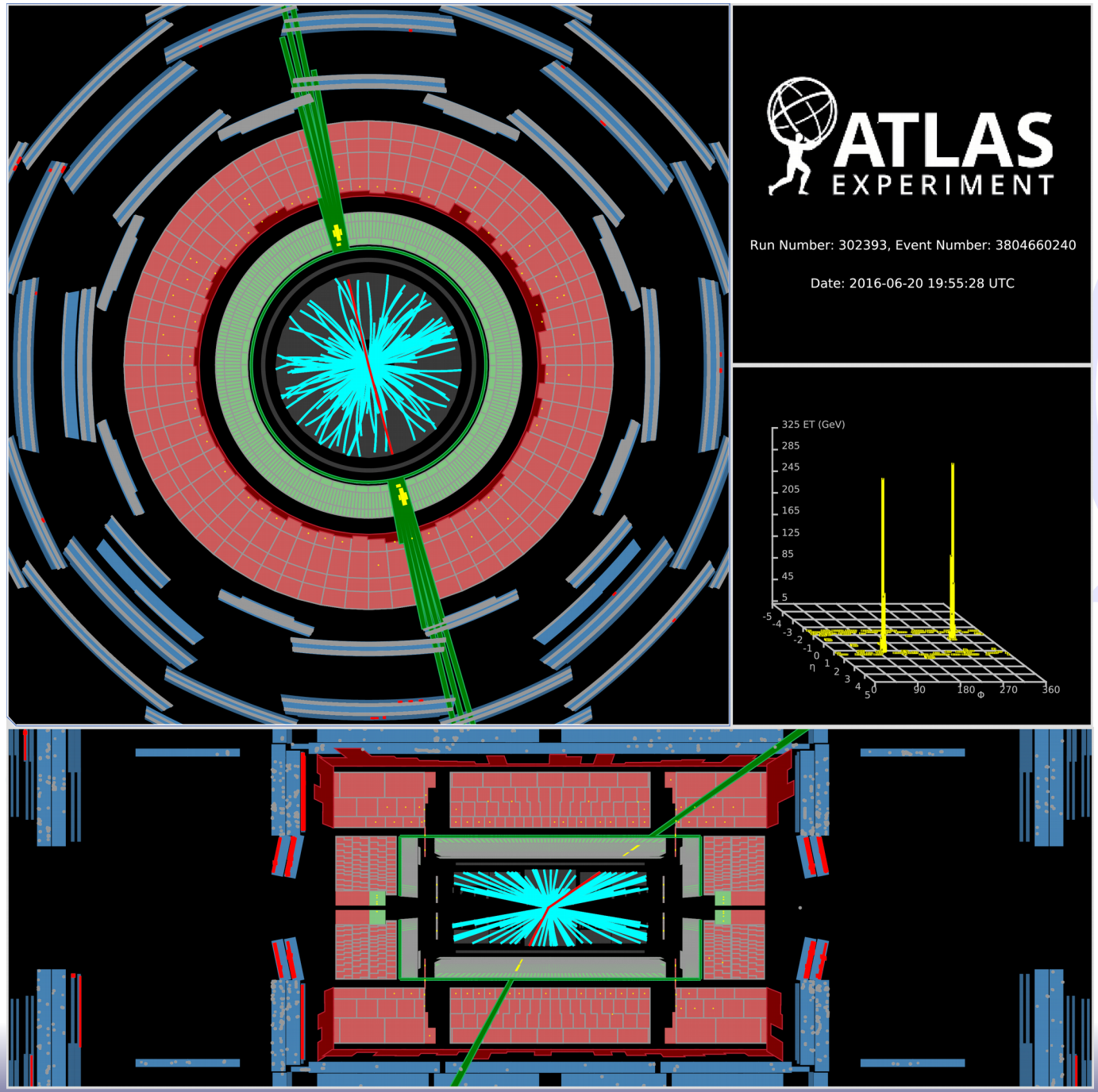
$$m_T = \sqrt{2 p_T E_T^{miss} (1 - \cos \Phi_{l\nu})}$$





No excess found → **$M_{W'}$ > 4.4 TeV**

Di-lepton final states



Highest di-electron invariant mass selected by di-lepton searches

m_{ee} = 2.38 TeV

Di-lepton final states

Events with 2e or 2mu

Backgrounds with

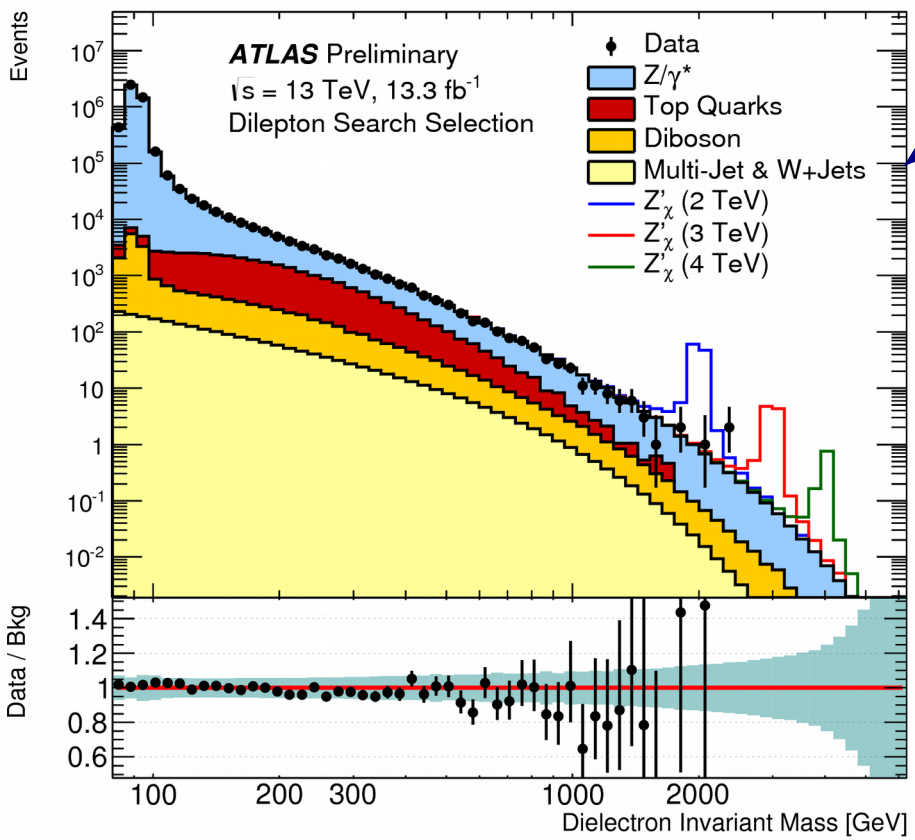
- **real leptons** (Drell-Yann, top, di-boson) : MC predictions (with (N)NLO corrections)
- **fake electrons** (multijets, W+jets) : data-driven estimations or corrections

- Reconstruct invariant mass $m_{\ell\ell}$ of the 2 leptons
- Search $m_{\ell\ell}$ distributions for
  - Resonance peaks
  - deviation from bkg continuum

Di-lepton final states

Several models are constrained by 2e or 2μ final states

- Z' in **SSM, GUT-inspired E_6** models, extra-dimensions, technicolor, ...



Search for resonances in invariant mass → no excess found.

ATLAS-CONF-2016-045

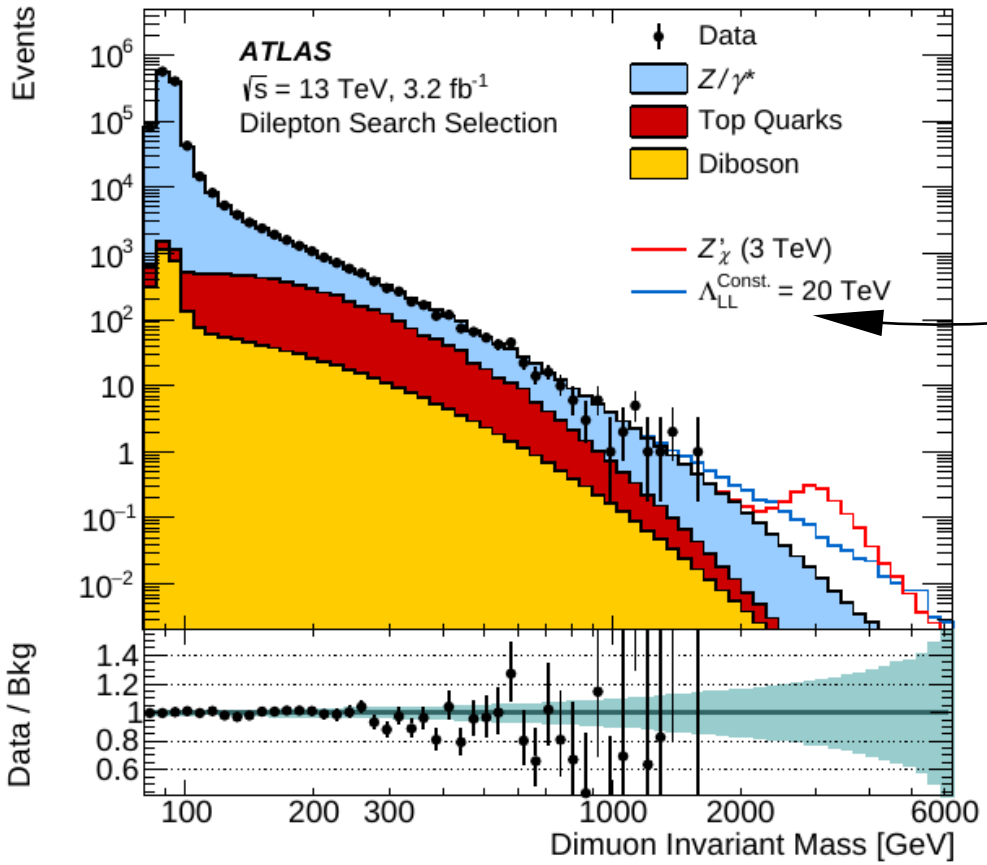
Model	Width [%]	θ_{E_6} [Rad]	Lower limits on $m_{Z'}$ [TeV]					
			ee		$\mu\mu$		$\ell\ell$	
			Obs	Exp	Obs	Exp	Obs	Exp
Z'_{SSM}	3.0	-	3.85	3.86	3.49	3.53	4.05	4.06
Z'_{χ}	1.2	0.50	3.48	3.49	3.18	3.19	3.66	3.67
Z'_{S}	1.2	0.63 π	3.43	3.44	3.14	3.14	3.62	3.61
Z'_{I}	1.1	0.71 π	3.37	3.37	3.08	3.08	3.55	3.55
Z'_{η}	0.6	0.21 π	3.25	3.25	2.96	2.94	3.43	3.42
Z'_{N}	0.6	-0.08 π	3.23	3.23	2.95	2.94	3.41	3.41
Z'_{ψ}	0.5	0 π	3.18	3.18	2.90	2.88	3.36	3.35

Z' Mass excluded below 3.36 – 4.0 TeV

Di-lepton final states

Several models are constrained by 2e or 2μ final states

- Contact Interaction (CI): use an effective Lagrangian with 4-lepton couplings depending on a scale **Λ**



Search for excess in high invariant masses → no excess found.

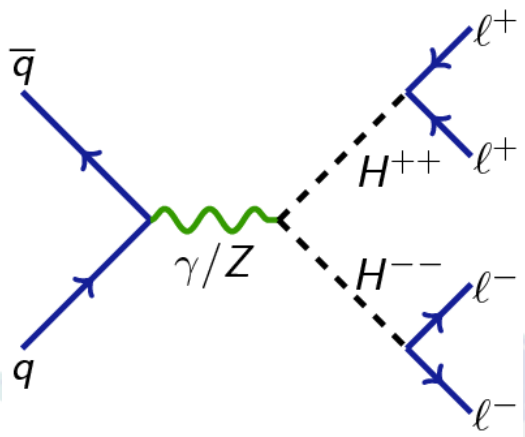
Λ > 15 – 25 TeV
depending on the scenario

Phys. Lett. B 761 / 1607.03669

Di-lepton final states

Several models are constrained by 2e or 2μ final states

- Doubly charged Higgs occur in many BSM models
  - Left-Right symmetric models, Higgs Triplet, little Higgs, ...



Select **pairs of same** sign electrons

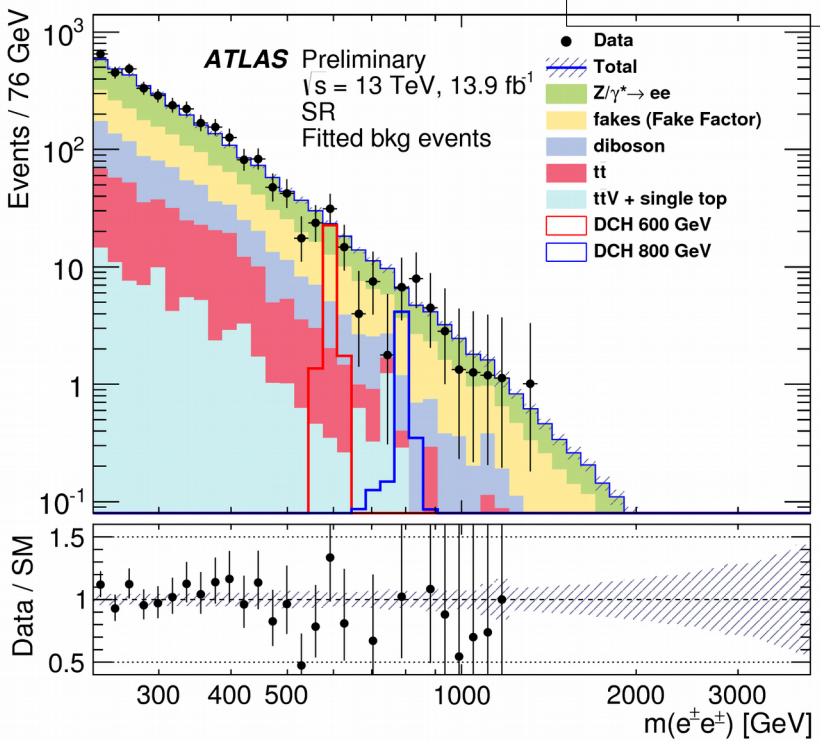
- Lower irreducible bkg
- But charge mis-identification bkg
  - mis-id probabilities estimated with data-driven methods

Di-lepton final states

Several models are constrained by 2e or 2μ final states

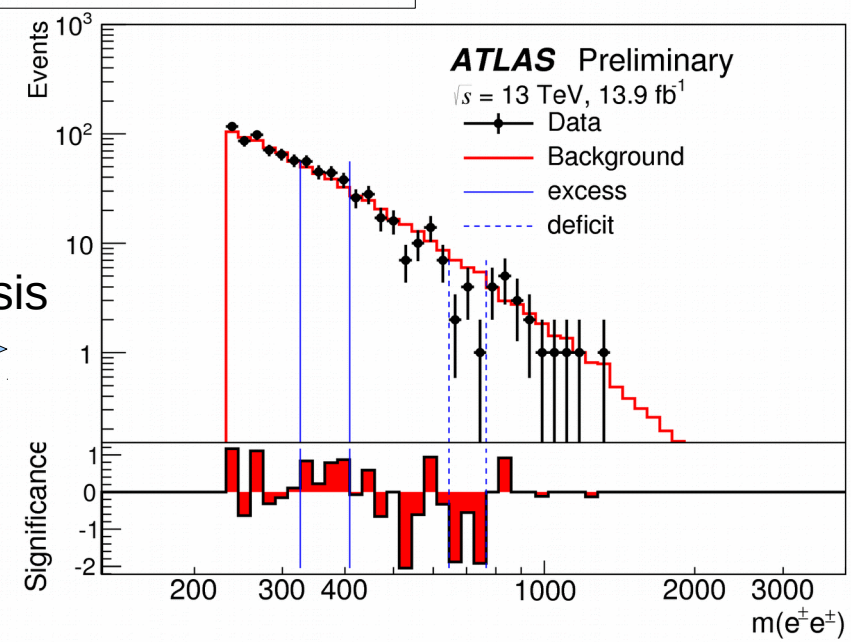
- Doubly charged Higgs occur in many BSM models

Search for resonances in invariant mass of **same sign electrons**
→ no excess found.



Statistical analysis

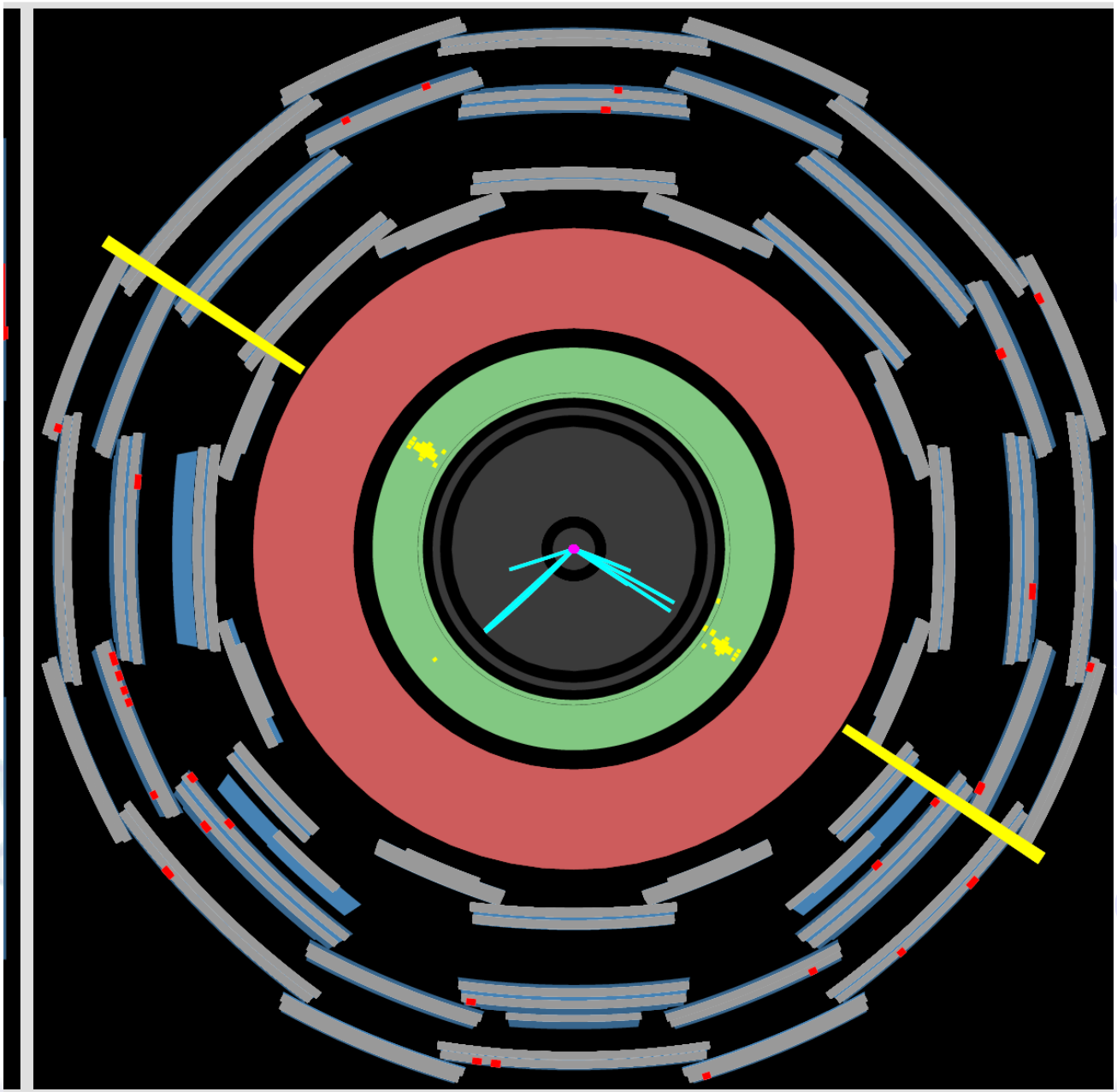
"bump hunt"



Right-handed mass > 420 GeV
Left-handed mass > 570 GeV

ATLAS-CONF-2016-051

Di-photon final state



Highest di-photon invariant mass

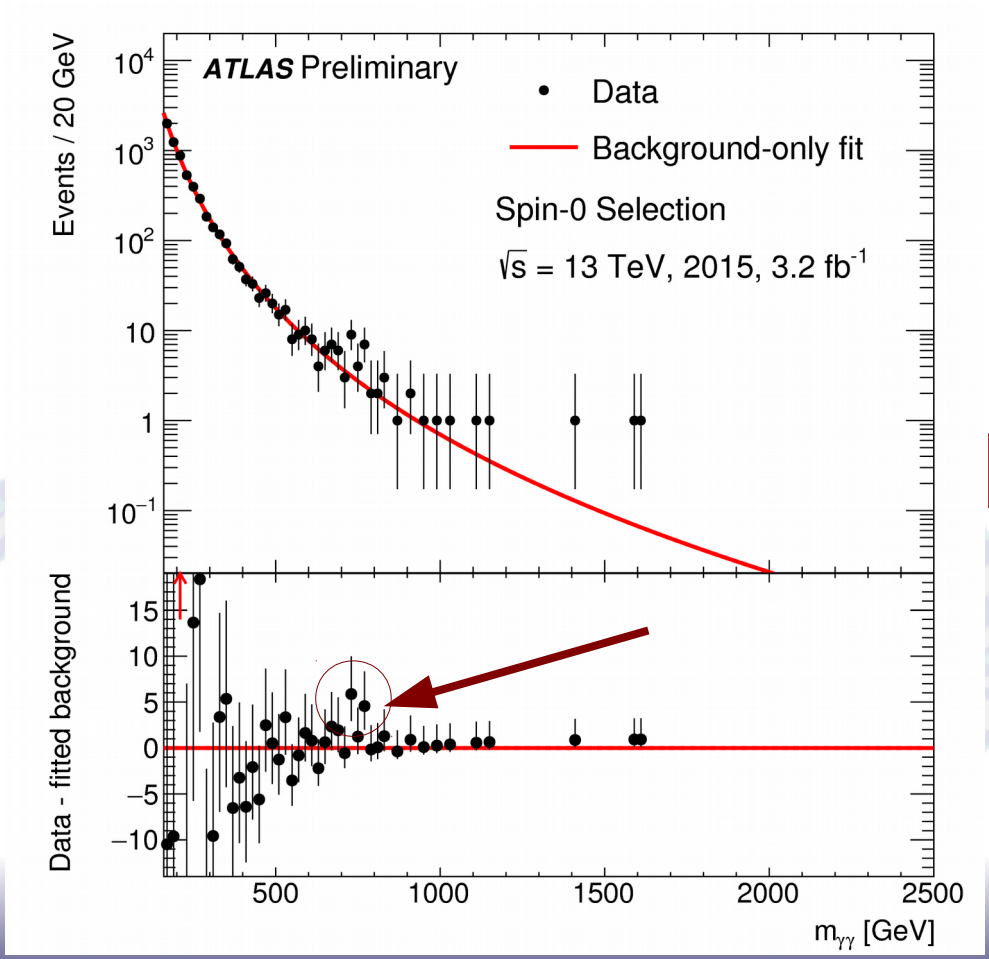
$m_{\gamma\gamma}$ = 2.2 TeV

ATLAS-CONF-2016-059

Di-photon final state

New scalar decaying in 2 photons predicted by several models (extra-dim, additional Higgs fields,...)

- Great excitation in 2015 : excess at 750GeV !



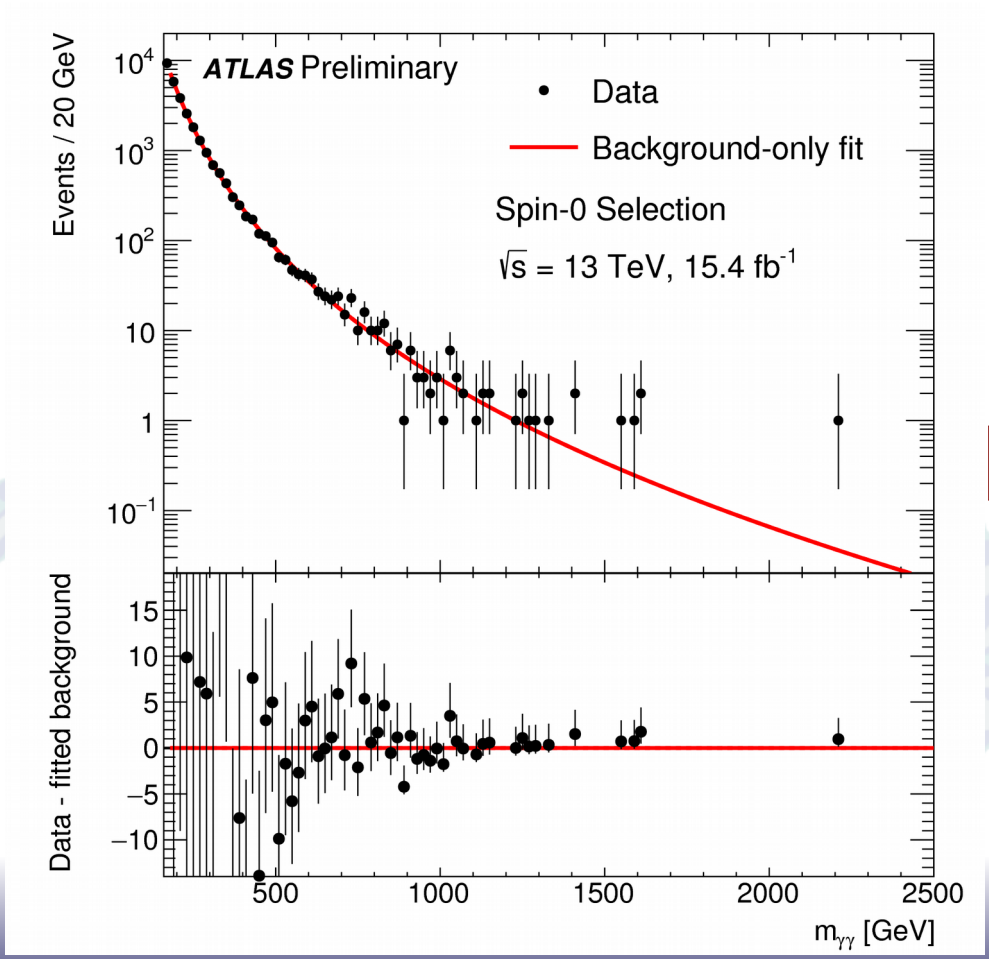
Search for resonances in γγ invariant mass

$m_{\gamma\gamma}$ ~ 750 GeV, 3.9σ (local)/2.1σ (global)

Di-photon final state

New scalar decaying in 2 photons predicted by several models (extra-dim, additional Higgs fields,...)

- 2016+2015 data (lumi x3) show no significant excess

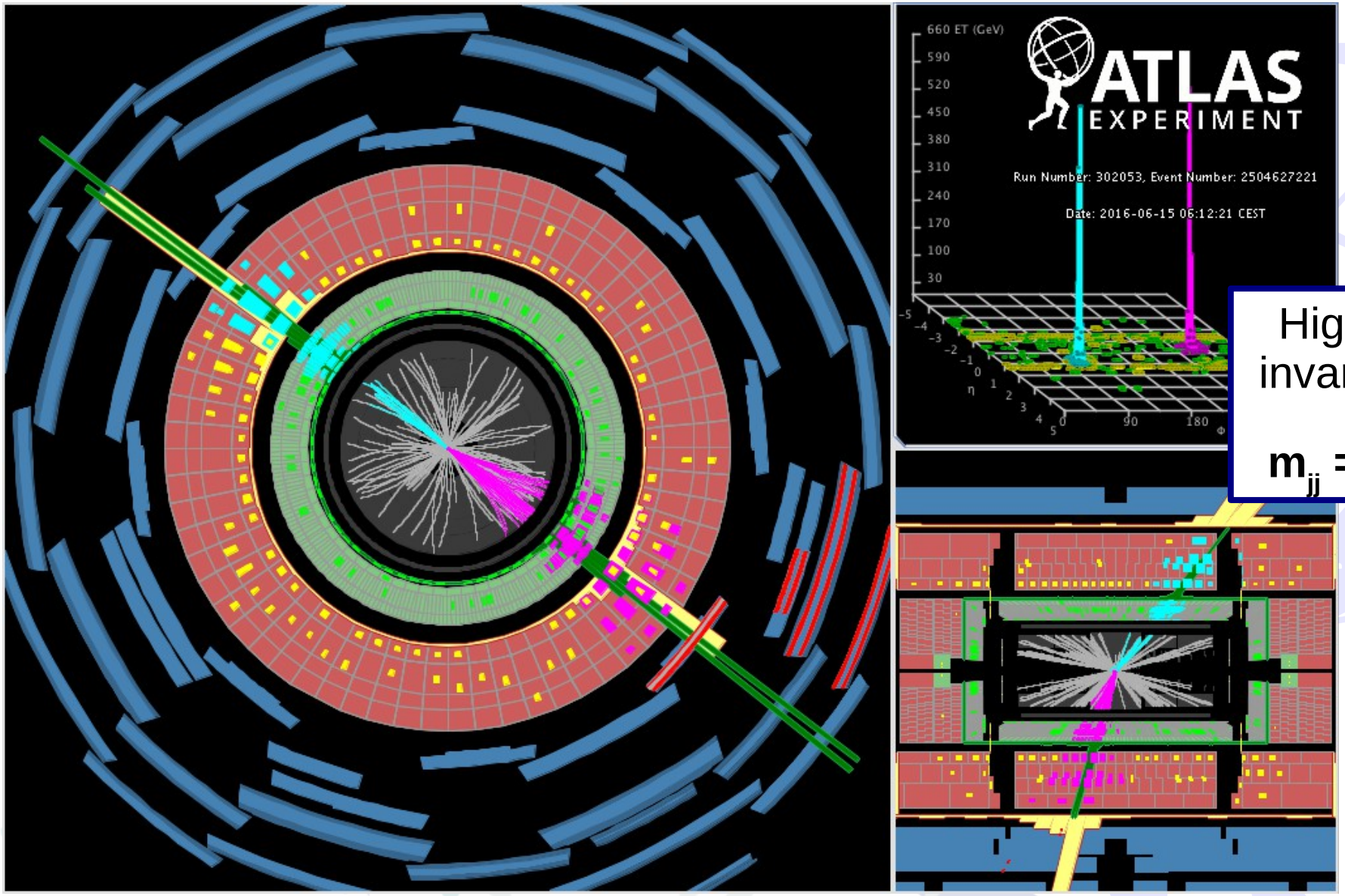


Search for resonances in γγ invariant mass

$m_{\gamma\gamma}$ ~ 710 GeV, 2.3σ (local)/ <1σ (global)

ATLAS-CONF-2016-059

Di-jet final state



Highest di-jet invariant mass

m_{jj} = 6.46 TeV

Di-jet final state

Intrinsic experimental issue : high background & trigger limitation

- Search at **high di-jet mass**
  - excited quarks, W', Z', W*
  - Quantum black hole, CI

ATLAS-CONF-2016-069

Resonance search in the di-jet **invariant mass**

Fully data-driven background modelling by fitting

$$f(z) = p_1(1-z)^{p_2} z^{p_3},$$

+

Statistical bump hunt

OR

Angular distribution of the di-jet system

Compare MC (+NLO correction) **shape** predictions to data

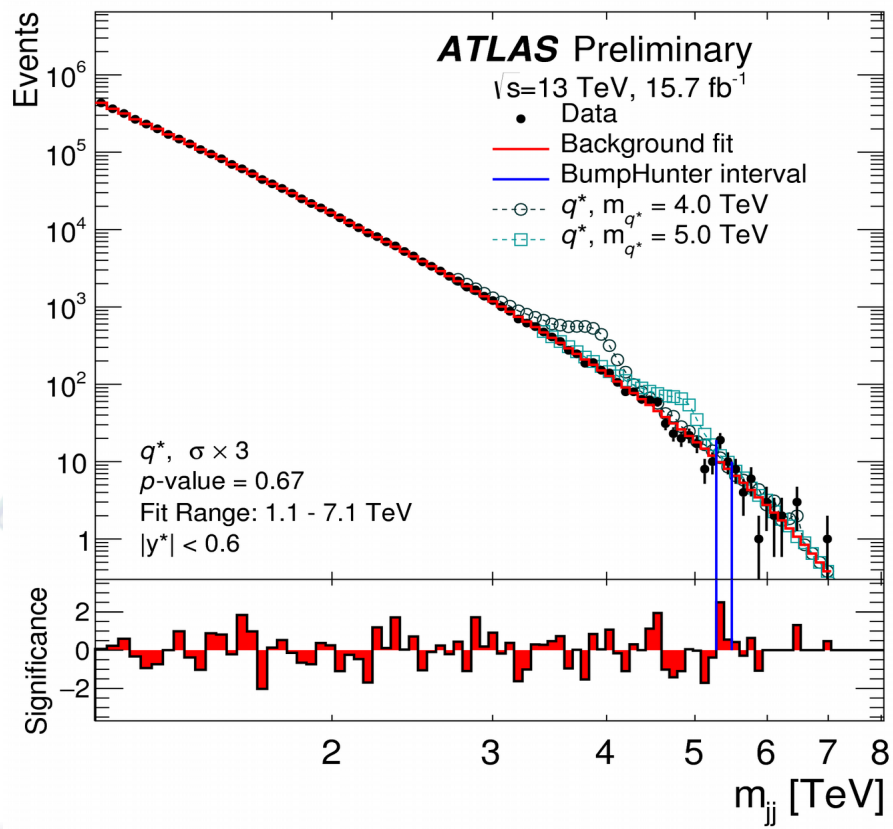
Di-jet final state

Intrinsic experimental issue : high background & trigger limitation

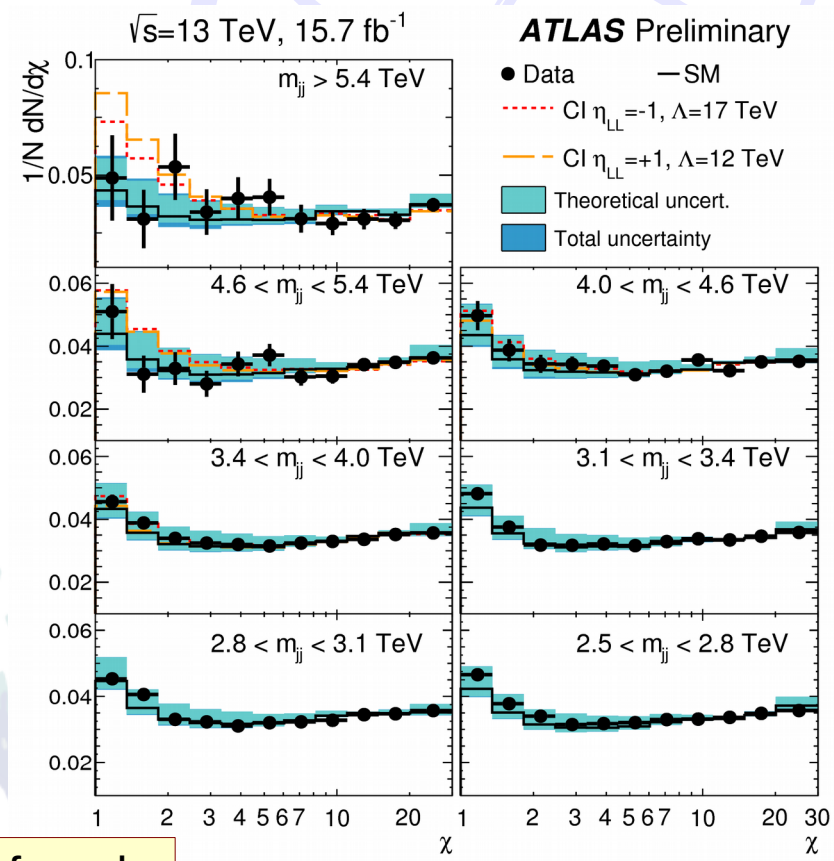
- Search at **high di-jet mass**
  - excited quarks, W', Z', W*
  - Quantum black hole, CI

ATLAS-CONF-2016-069

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



OR



No excess found

Di-jet final state

Intrinsic experimental issue : high background & trigger limitation

- Search at **high di-jet mass**
  - excited quarks, W', Z', W*
  - Quantum black hole, CI

ATLAS-CONF-2016-069

Model	95% CL exclusion limit Observed	Expected
Quantum black holes, ADD (BlackMax generator)	8.7 TeV	8.7 TeV
Excited quark	5.6 TeV	5.5 TeV
W'	2.9 TeV	3.3 TeV
W^*	3.3 TeV	3.3 TeV
Contact interactions (η_{LL} =+1)	12.6 TeV	13.7 TeV
Contact interactions (η_{LL} =-1)	19.9 TeV	23.7 TeV

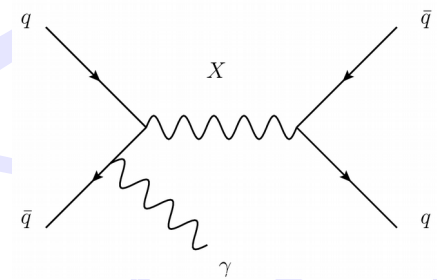
Limits from resonance search

Limits from angular search

Di-jet final state

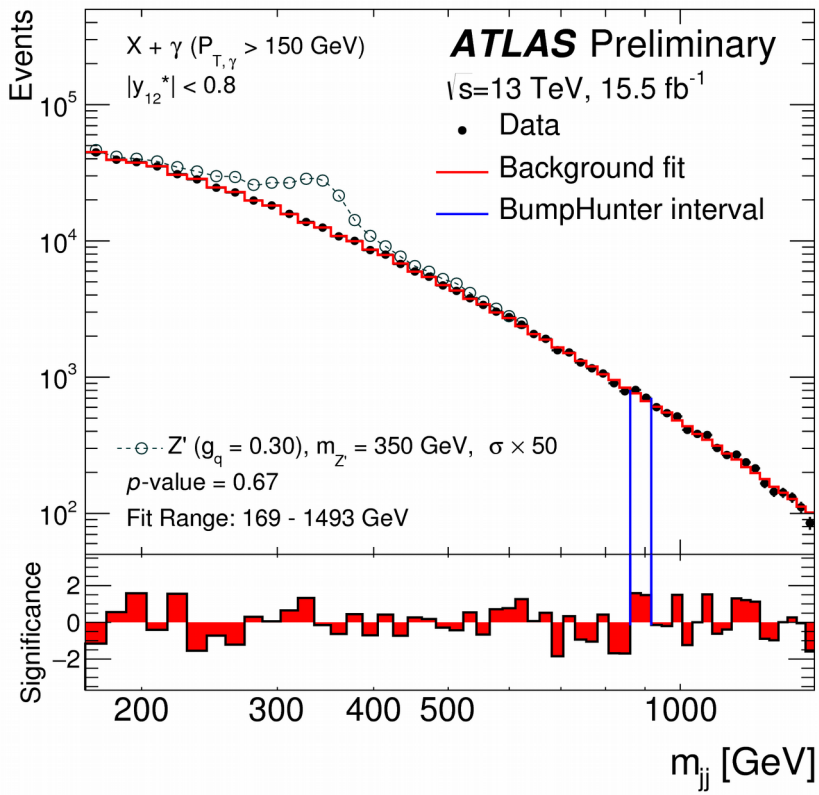
Intrinsic experimental issue : high background & trigger limitation

- Search at **low di-jet mass** with ISR jet or γ
  - fermiophobic Z' models

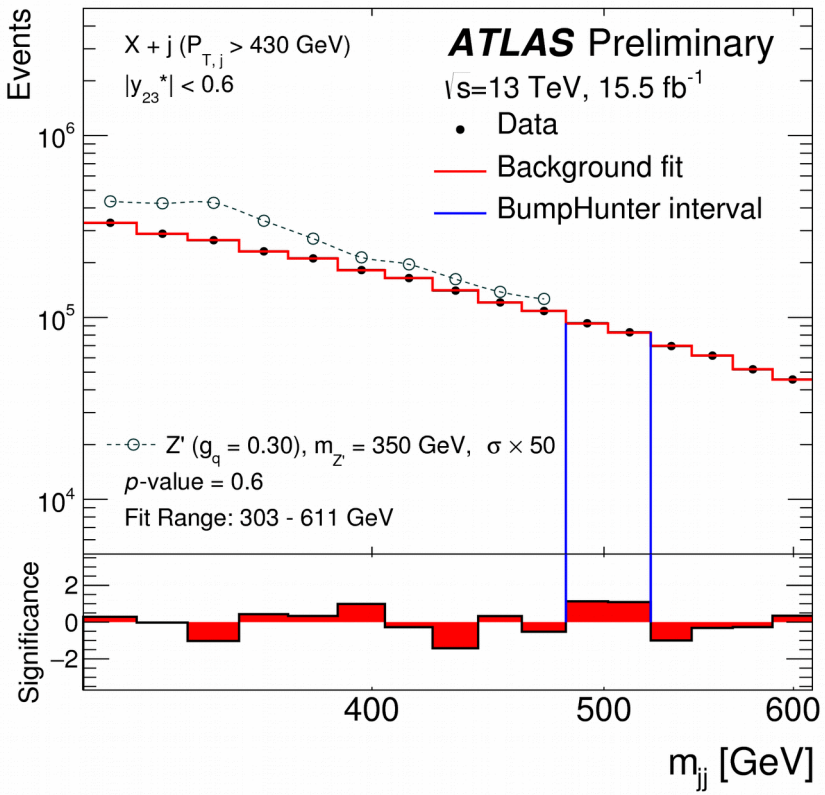


ATLAS-CONF-2016-070

ISR γ



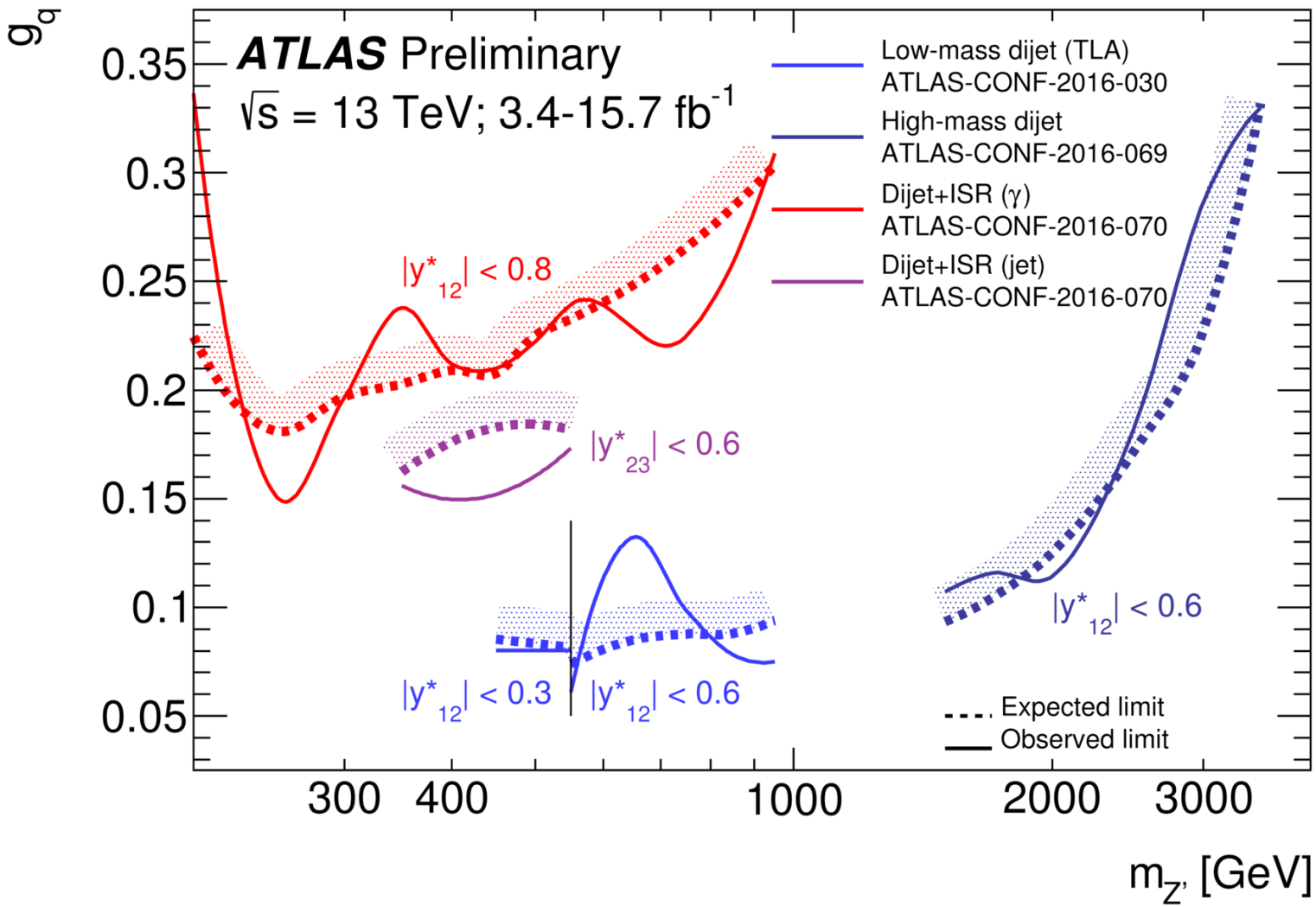
ISR jet



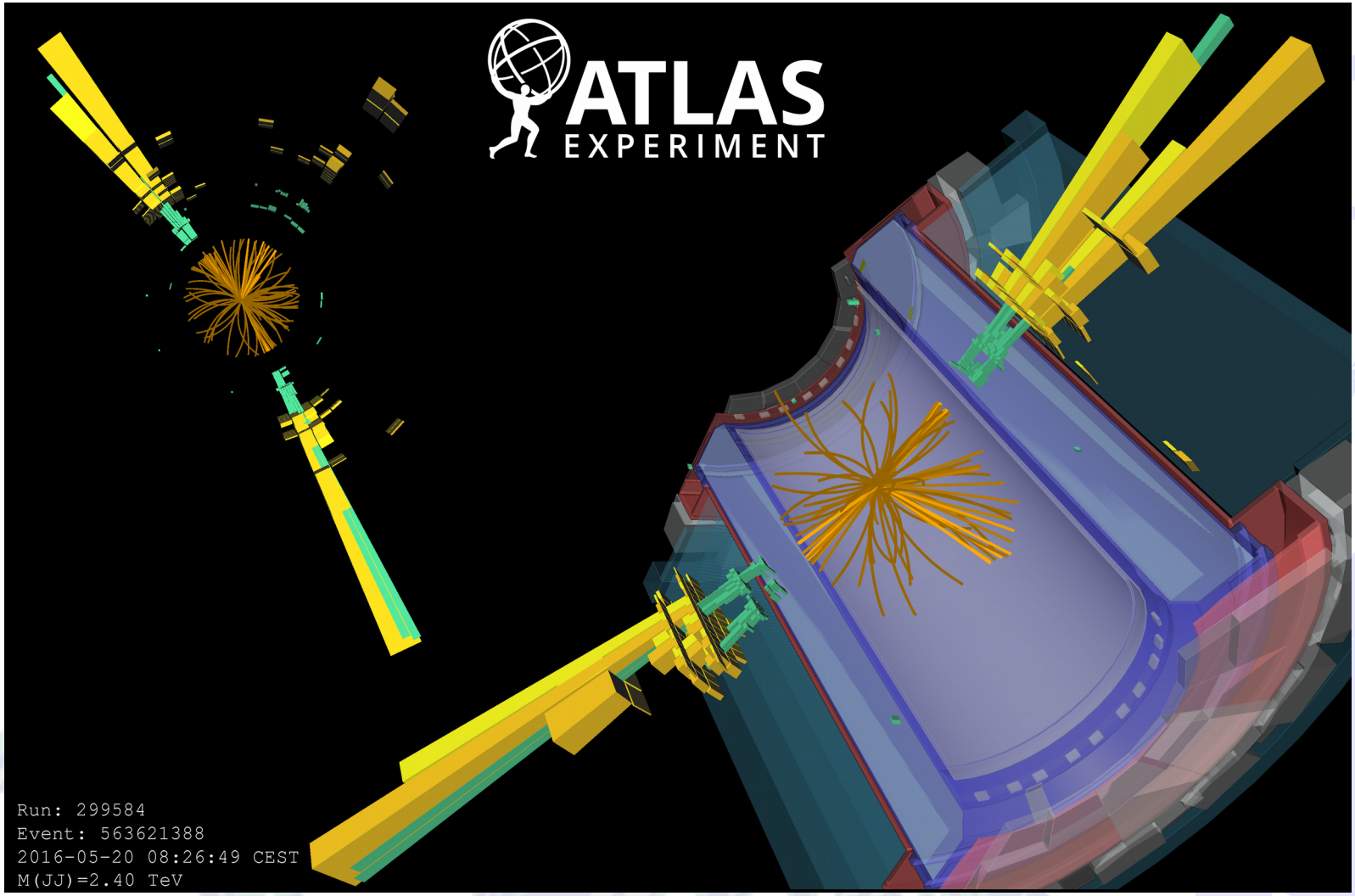
No excess, limits set on σ x BR x A

Di-jet final state summary

- ATLAS studies summarized on the leptophobic Z' model
  - Also showing the Trigger Level Analysis (TLA) result



Di-Boson final state



Di-boson final states

WW, WZ or ZZ final states are searched

- Benchmark models used
  - Spin 0 : Heavy Higgs with narrow width
  - Spin 1 : Heavy weakly coupled Vector Triple (HVT)
  - Spin 2 : Randall-Sundrum Graviton (RSG)
- Hadronic decays can be boosted
  - due to high mass resonances
  - use of substructure techniques to reject QCD background

Di-boson all hadronic

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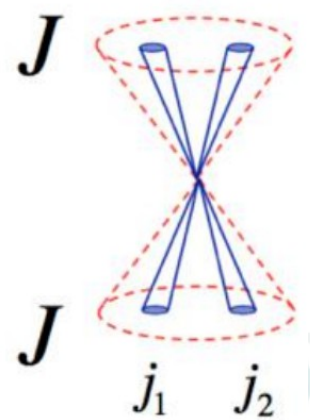
- Testing 2 models
  - RSG (WW and ZZ)
  - HVT W' → WZ and Z' → WW



Identify large jets containing W/Z hadronic decay (**W/Z-tagging**) → (using mass, "D_2", num tracks)

Resonance search in the large jet **invariant mass**

Fully data-driven background modelling
+
Statistical bump hunt

Di-boson all hadronic

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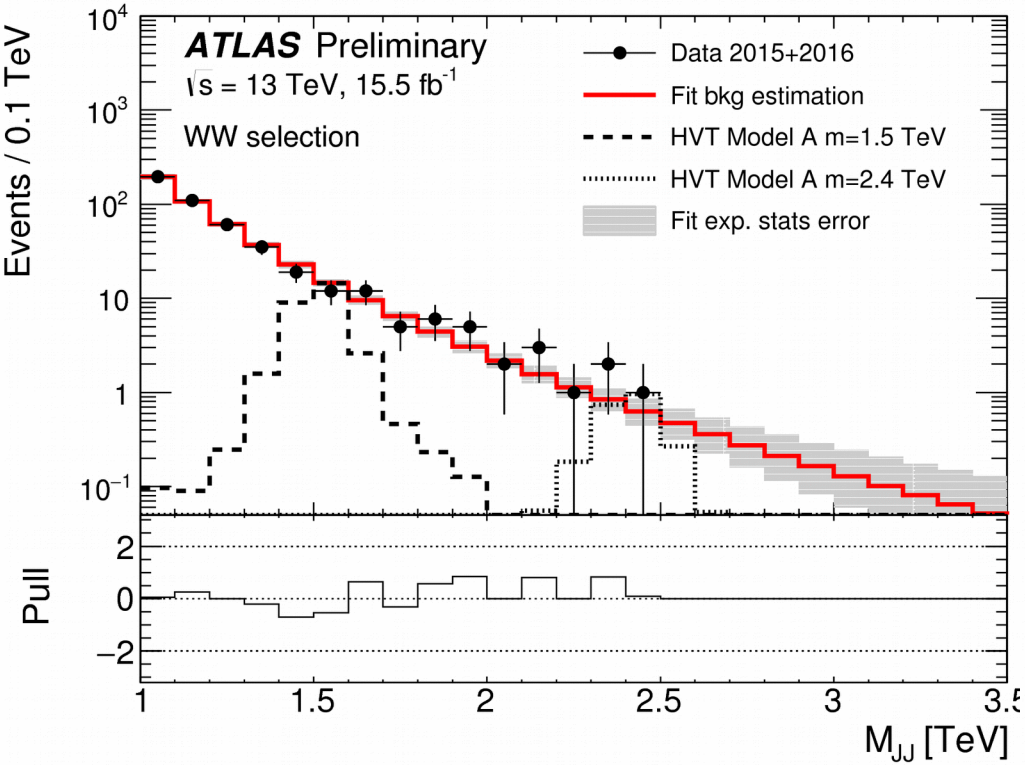
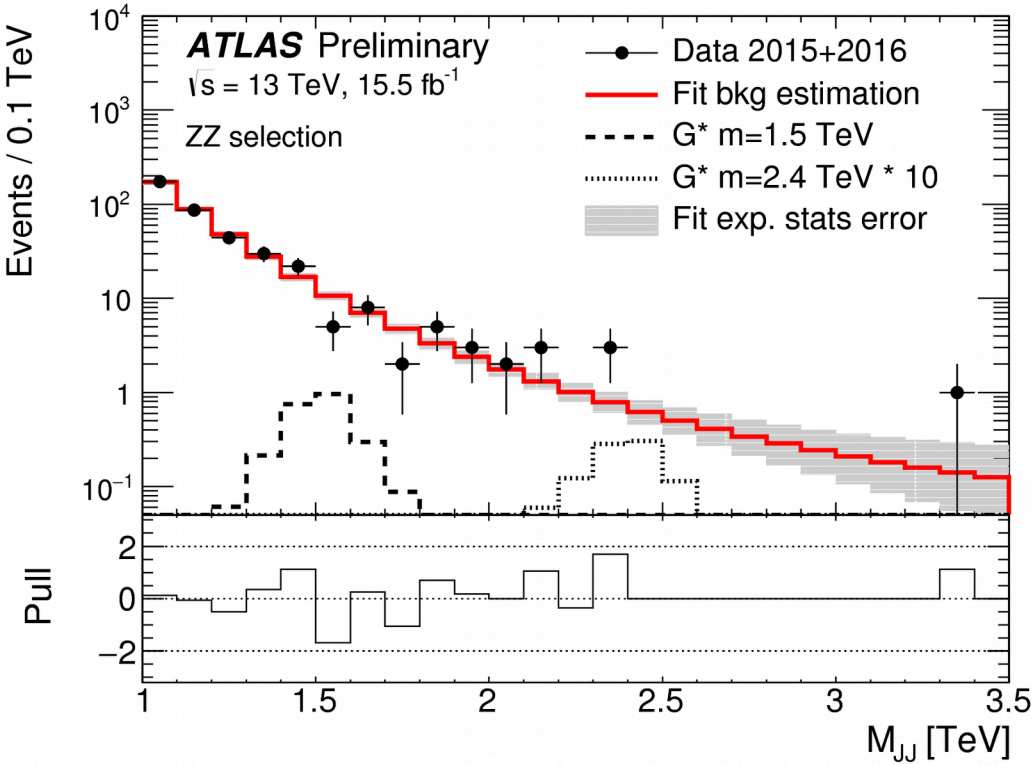
- Testing 2 models
  - RSG (WW and ZZ)
  - HVT W' → WZ and Z' → WW





No excess found

Di-boson summary

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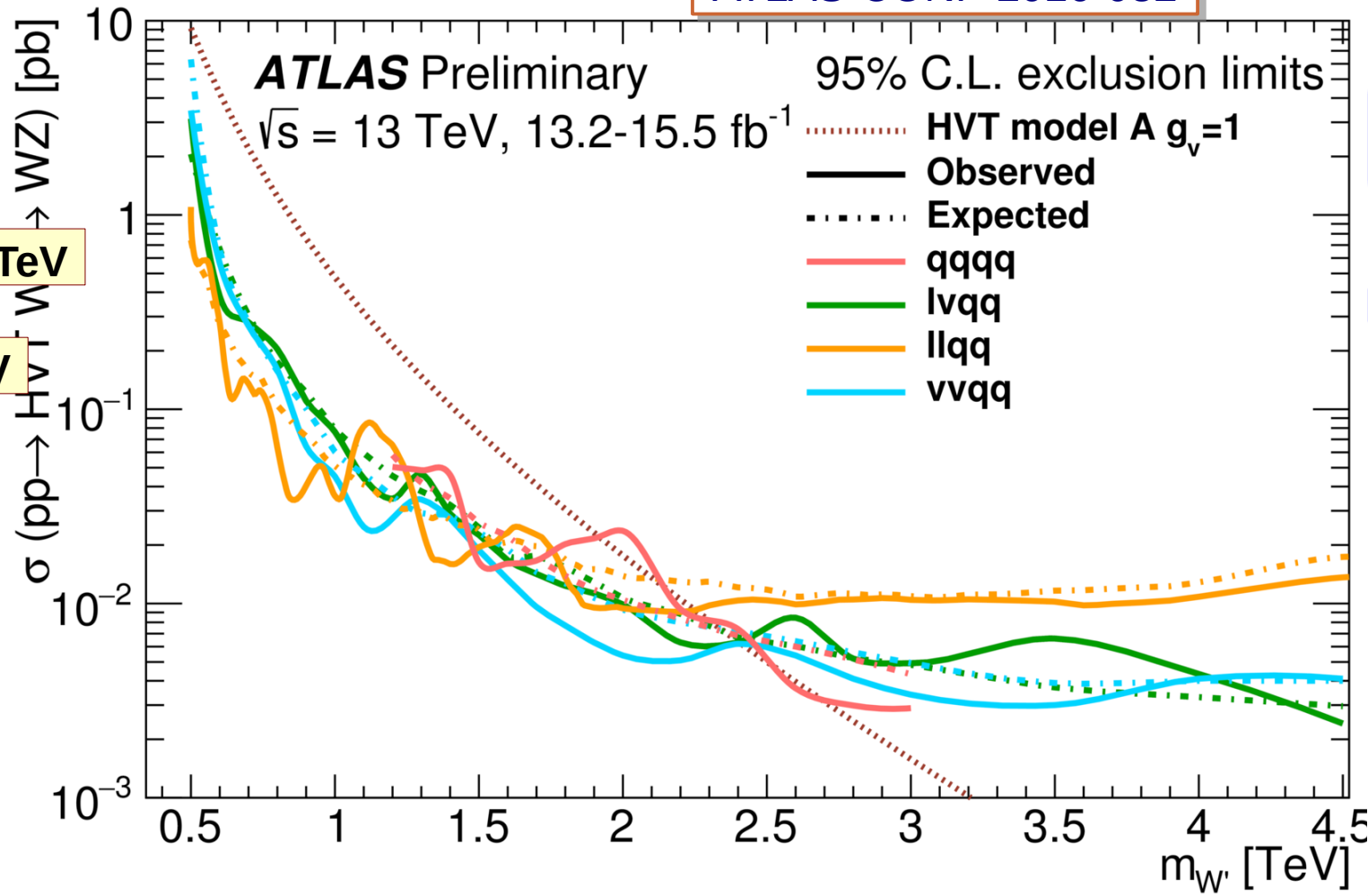
Limit on W' cross-section x BR(WZ) from various decay modes

HVT (model A) **mass>2.4 TeV**

Bulk RSG **mass >1.24 TeV**

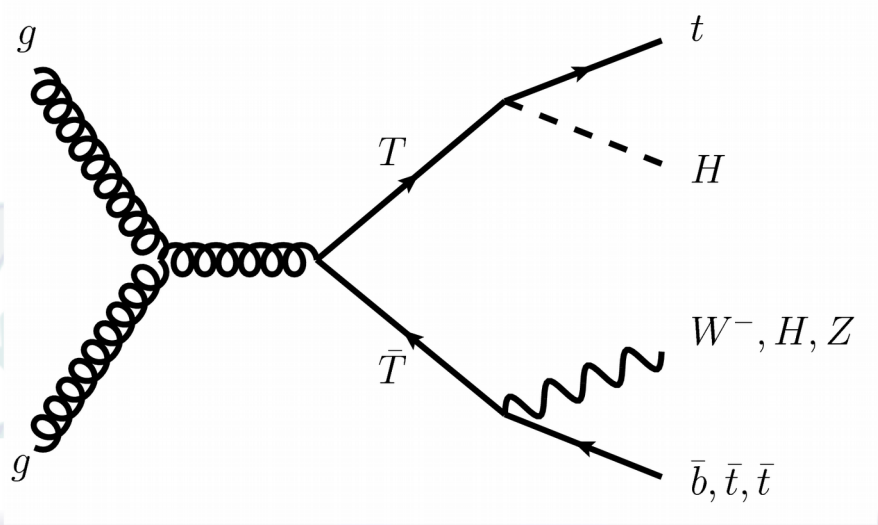


Complex final states

Searches involving multiple tops, Higgs, vector bosons are conducted in ATLAS

Example : Vector Like Quark (**VLQ**) searches

- Predicted in Little Higgs or composite Higgs models
- top-partners searched in
  - **T → Ht**
  - T → Zt
  - T → Wb



Complex final states : VLQ

ttbar+b-jets search sensitive to
TT production

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Complex analysis

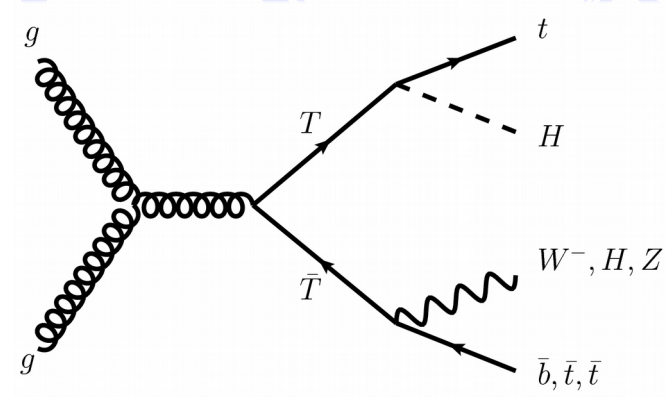
20 signal regions depending on
- 0 or 1 lepton
- num jets & b-tagged jets
- kinematic variables based on mass

15 validation regions

Main observable :
m_{eff} = Sum(jets, lepton, Etmiss)

Combined fit of signal+bkg on signal & validation regions

example final decay :
TT → HtHt → bblνb bbjjb



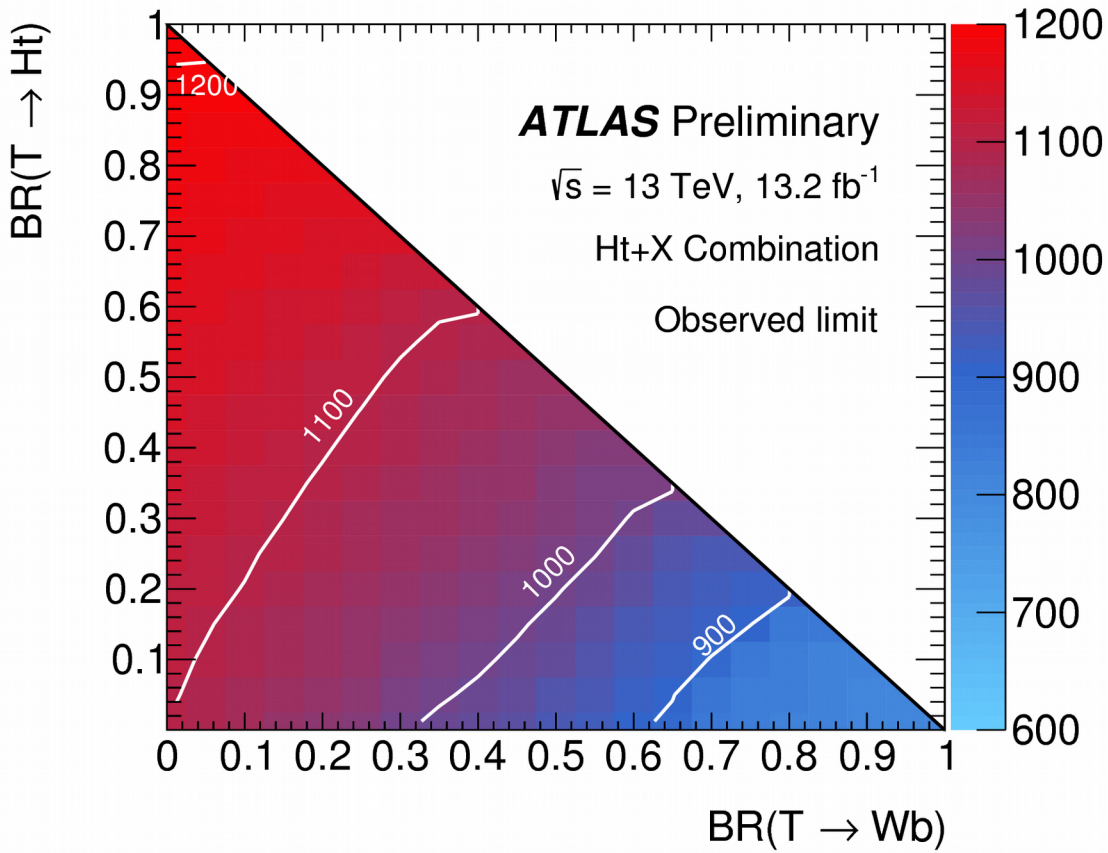
Note : analysis also sensitive to
- tttt final states (ex : KK excitations in extra dim)
- Heavy Higgs +b/t (2HDM models)

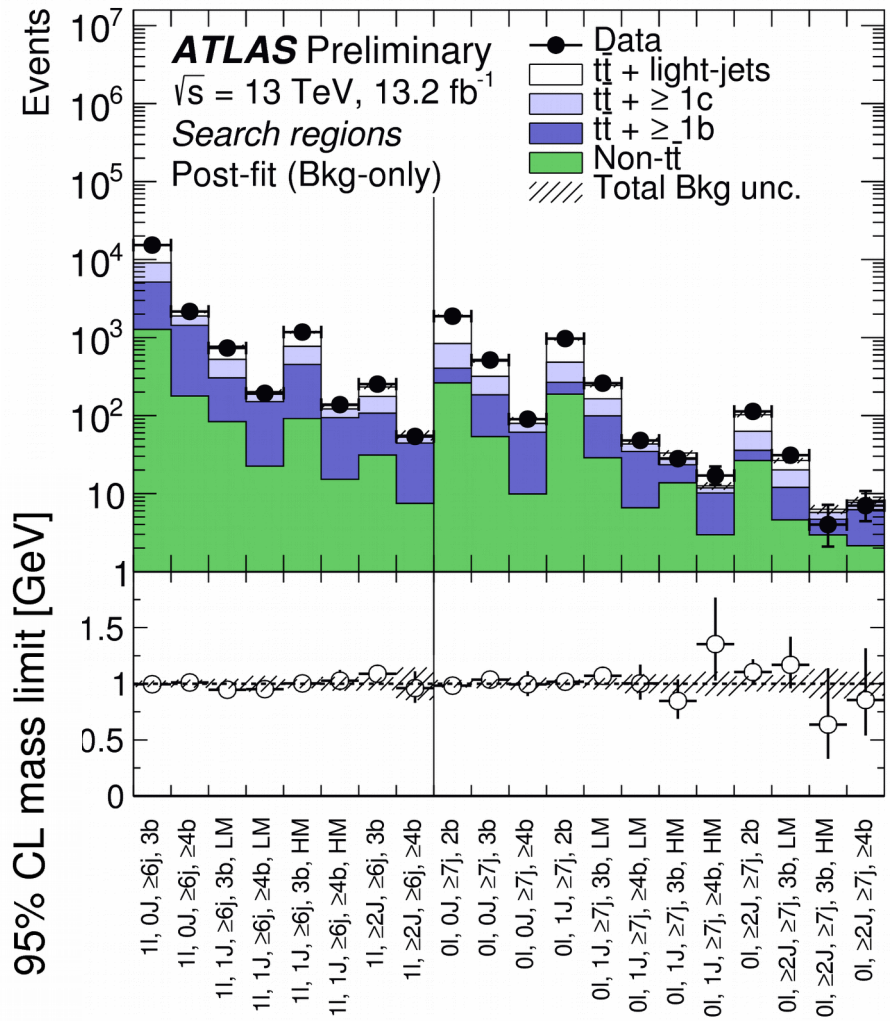
Complex final states : VLQ

ttbar+b-jets search sensitive to **TT** production

No excess found

Limits set in the VLQ BR plan :





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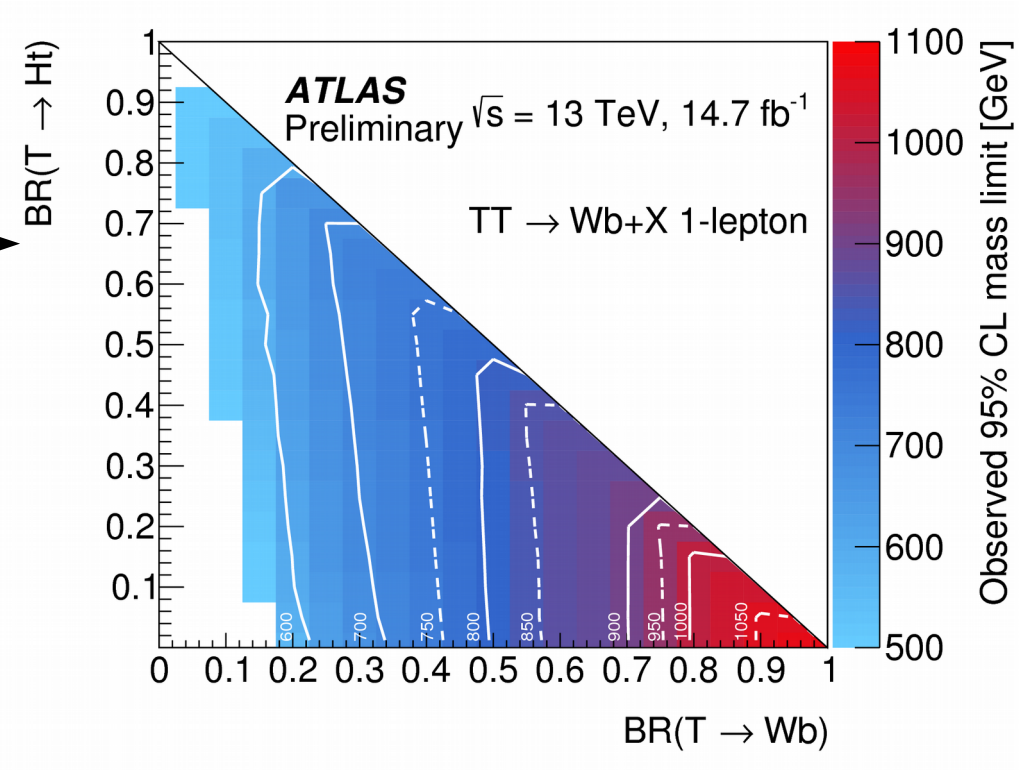
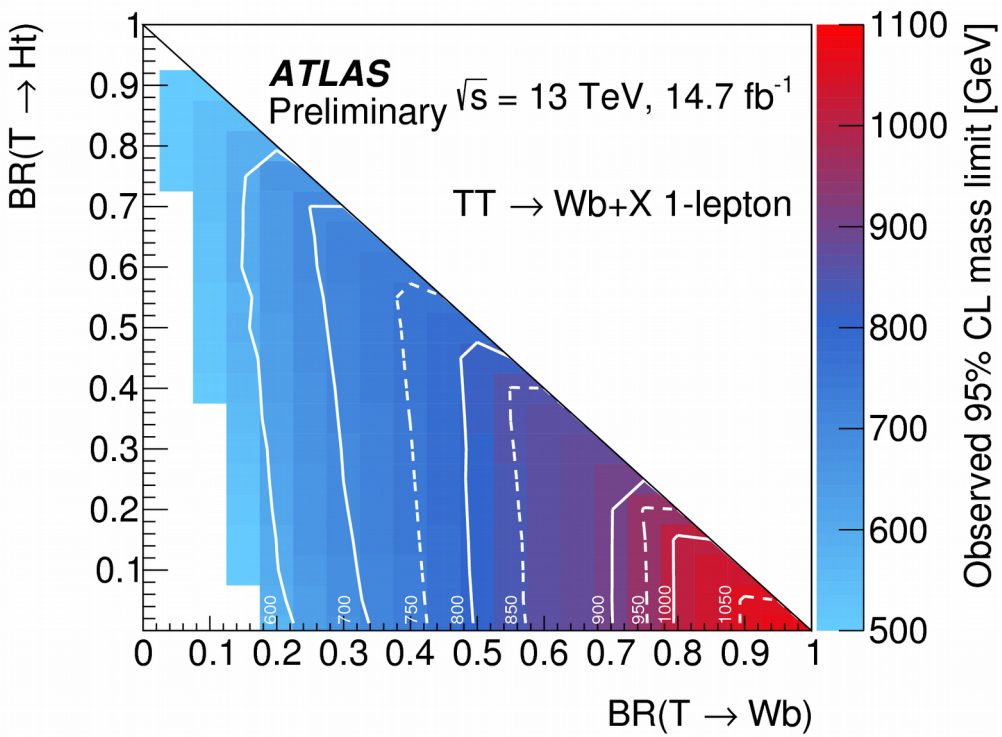
Complex final states : VLQ

Also 2 others VLQ analysis

T → Zt → νν+qqb

T → Wb → νl+b





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Conclusions

- LHC delivered excellent data in 2016
- ATLAS performed a broad variety of EXOTIC (non-SUSY BSM) search
- No hint of new physics found...
- 2016 data not yet fully analyzed
- Several new/updated results imminent

More data and analysis to come...

the Quest for exotic physics is continuing !