BSM searches at ATLAS

Run-1 Anomalies, Bumps and Deviations

Alex Martyniuk, UCL

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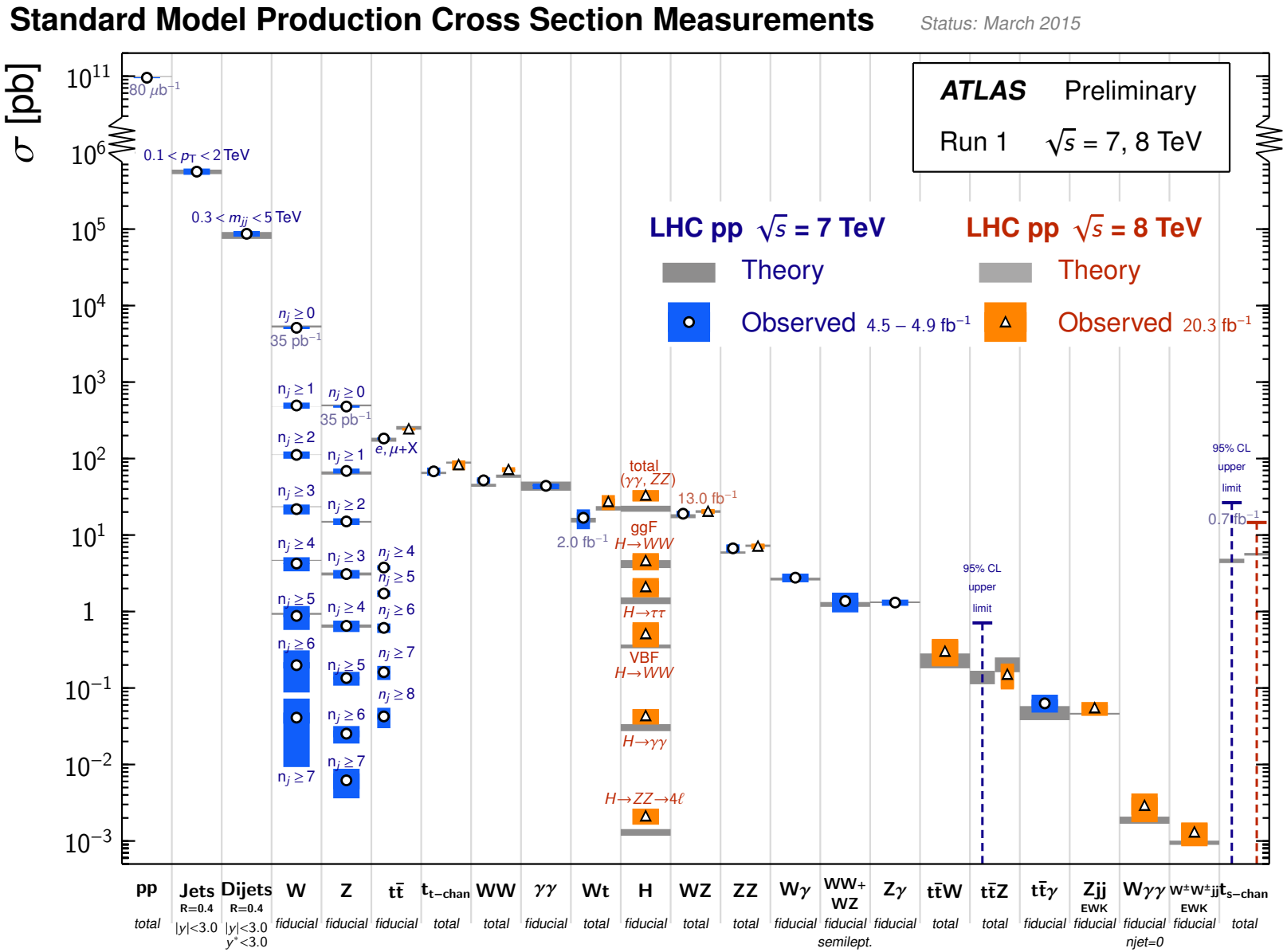
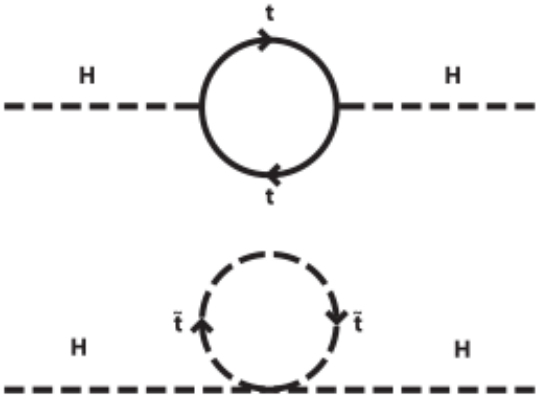
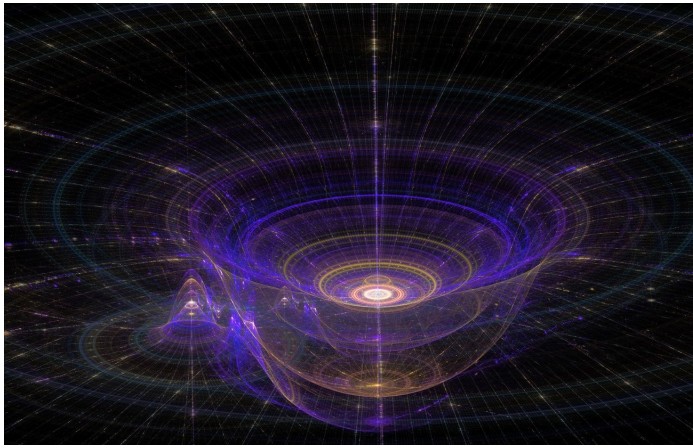

Standard Model Production Cross Section Measurements
Status: March 2015
ATLAS Preliminary
Run 1 √s = 7, 8 TeV
LHC pp √s = 7 TeV
Theory
Observed 4.5 – 4.9 fb⁻¹
LHC pp √s = 8 TeV
Theory
Observed 20.3 fb⁻¹
σ [pb]
80 μb⁻¹
0.1 < pT < 2 TeV
0.3 < mjj < 5 TeV
35 pb⁻¹
e, μ+X
2.0 fb⁻¹
13.0 fb⁻¹
total (γγ, ZZ)
ggF H→WW
H→ττ
VBF H→WW
H→γγ
H→ZZ→4ℓ
95% CL upper limit
0.7 fb⁻¹
pp total
Jets R=0.4 |y|<3.0
Dijets R=0.4 |y|<3.0 y*<3.0
W fiducial
Z fiducial
tt̄ fiducial
t t-chan total
WW total
γγ fiducial
Wt total
H fiducial
WZ total
ZZ total
Wγ fiducial
WW+WZ fiducial semilept.
Zγ fiducial
tt̄W total
tt̄Z total
tt̄γ fiducial
Zjj EWK fiducial
Wγγ fiducial njet=0
W±W±jj EWK fiducial
t s-chan total

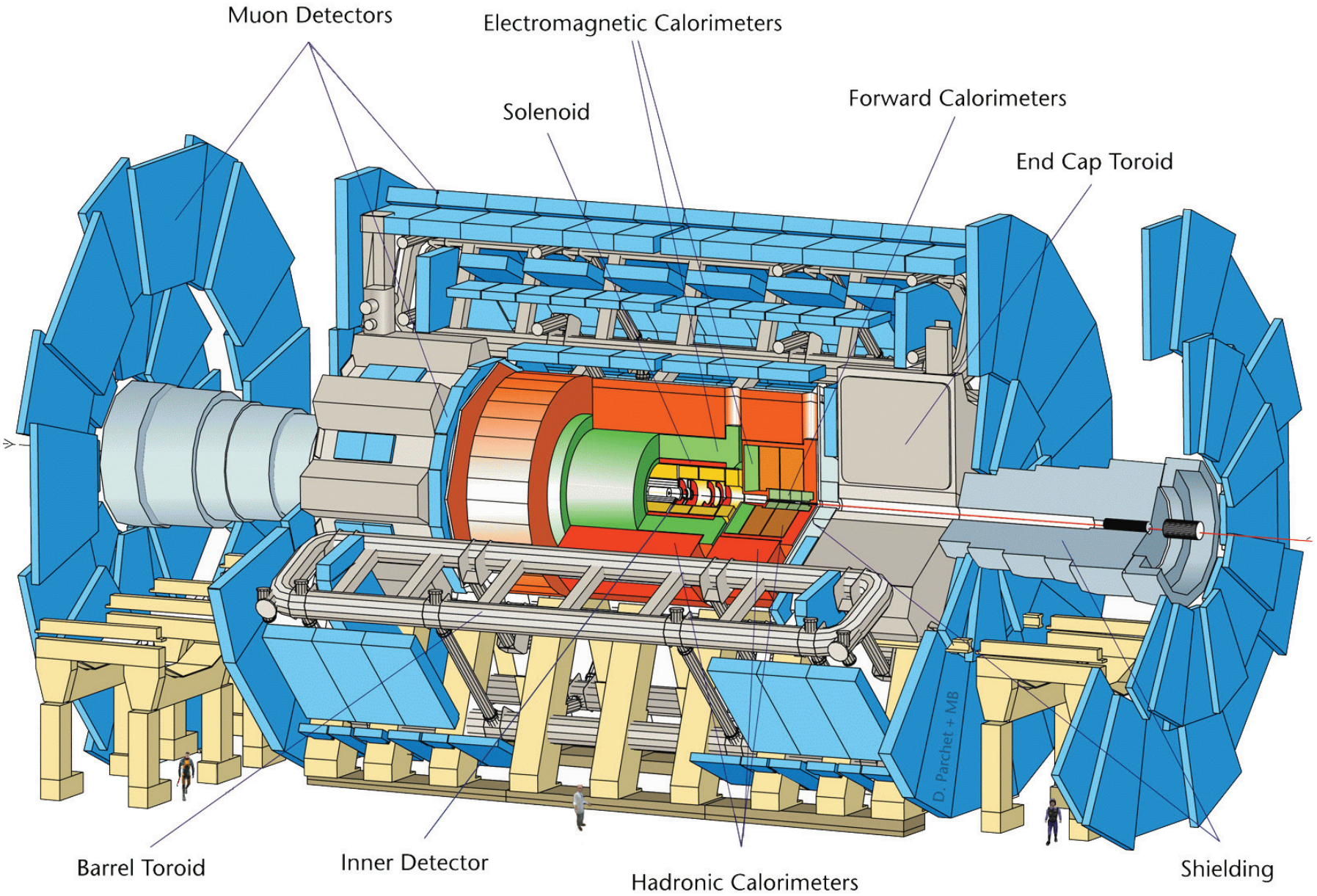
Introduction – The Problems





- Things are not as rosy as they seem for the Standard Model (SM)
- Problems lurk within.....
  - It contains no **dark matter candidate**
  - It requires immense **fine tuning** for the 125 GeV Higgs to make sense
  - It does not contain **gravity**
- **Beyond the SM** (BSM) theories try to solve these issues
- The ATLAS **SUSY**, **Exotics** and Higgs groups search for a wide range of BSM physics utilising the full ATLAS detector
  - Often at the limits or beyond the specification the detector
- We built a **general purpose detector** for a reason!

Introduction – Obligatory ATLAS Slide



Outline – What I will show

- I will cover a whirlwind tour of three searches from the ATLAS Exotics/SUSY groups that had some **'oddities'** in Run-1
- SUSY: **Pair produced cascade decays** search using same-flavour opposite-sign dilepton pair, jets, and large missing transverse momentum
  - [SUSY-2014-10]
- Exotics: Search for **anomalous production** of b-jets and a pair of leptons of the same charge
  - [EXOT-2013-16]
- Exotics: Search for **diboson resonances** decaying to boson-tagged jets
  - [EXOT-2013-08]
  - *Fair warning, I worked directly on this analysis and might well be biased to spend more time here...

SUSY Searches – needle in the haystack?

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: July 2015

ATLAS Preliminary

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

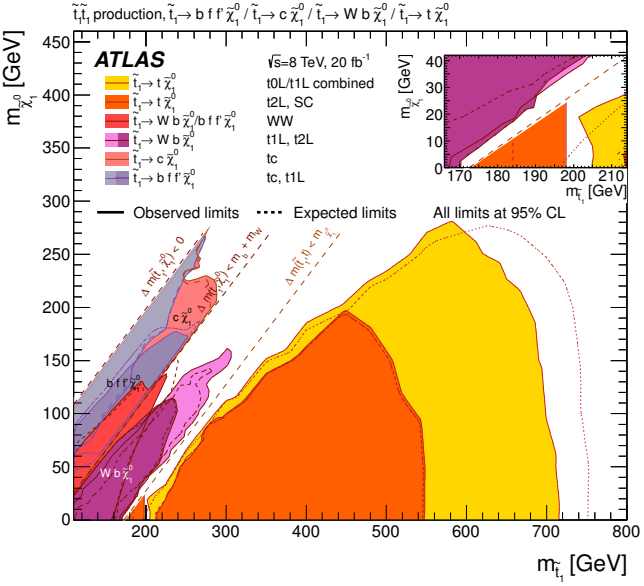
	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt [fb^{-1}]$	Mass limit ($\sqrt{s}$ = 7 TeV / $\sqrt{s}$ = 8 TeV)		Reference
Inclusive Searches	MSUGRA/CMSSM	0-3 e,μ/1-2 τ	2-10 jets/3 b	Yes	20.3	$\tilde{q}, \tilde{g}$ 1.8 TeV	$m(\tilde{q})=m(\tilde{g})$	1507.05525
	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$ 850 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, m(1st gen. $\tilde{q}$)=m(2nd gen. $\tilde{q}$)	1405.7875
	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$ (compressed)	mono-jet	1-3 jets	Yes	20.3	$\tilde{q}$ 100-440 GeV	$m(\tilde{q})-m(\tilde{\chi}_1^0)$<10 GeV	1507.05525
	$\tilde{q}\tilde{q}, \tilde{q}\to q(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e,μ (off-Z)	2 jets	Yes	20.3	$\tilde{q}$ 780 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	1503.03290
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$ 1.33 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	1405.7875
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}_1^\pm\to qqW^\pm\tilde{\chi}_1^0$	0-1 e,μ	2-6 jets	Yes	20	$\tilde{g}$ 1.26 TeV	$m(\tilde{\chi}_1^0)$<300 GeV, $m(\tilde{\chi}^\pm)=0.5(m(\tilde{\chi}_1^0)+m(\tilde{g}))$	1507.05525
	$\tilde{g}\tilde{g}, \tilde{g}\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e,μ	0-3 jets	-	20	$\tilde{g}$ 1.32 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	1501.03555
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	20.3	$\tilde{g}$ 1.6 TeV	$\tan\beta$ >20	1407.0603
	GGM (bino NLSP)	2 γ	-	Yes	20.3	$\tilde{g}$ 1.29 TeV	$c\tau$(NLSP)<0.1 mm	1507.05493
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	20.3	$\tilde{g}$ 1.3 TeV	$m(\tilde{\chi}_1^0)$<900 GeV, $c\tau$(NLSP)<0.1 mm, μ<0	1507.05493
	GGM (higgsino-bino NLSP)	γ	2 jets	Yes	20.3	$\tilde{g}$ 1.25 TeV	$m(\tilde{\chi}_1^0)$<850 GeV, $c\tau$(NLSP)<0.1 mm, μ>0	1507.05493
	GGM (higgsino NLSP)	2 e,μ (Z)	2 jets	Yes	20.3	$\tilde{g}$ 850 GeV	m(NLSP)>430 GeV	1503.03290
	Gravitino LSP	0	mono-jet	Yes	20.3	$F^{1/2}$ scale 865 GeV	$m(\tilde{G})>1.8\times10^{-4}$ eV, $m(\tilde{g})=m(\tilde{q})$=1.5 TeV	1502.01518
3rd gen. $\tilde{g}$ med.	$\tilde{g}\tilde{g}, \tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	20.1	$\tilde{g}$ 1.25 TeV	$m(\tilde{\chi}_1^0)$<400 GeV	1407.0600
	$\tilde{g}\tilde{g}, \tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.1 TeV	$m(\tilde{\chi}_1^0)$ <350 GeV	1308.1841
	$\tilde{g}\tilde{g}, \tilde{g}\to b\bar{t}\tilde{\chi}_1^+$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$ 1.34 TeV	$m(\tilde{\chi}_1^0)$<400 GeV	1407.0600
	$\tilde{g}\tilde{g}, \tilde{g}\to b\bar{t}\tilde{\chi}_1^+$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$ 1.3 TeV	$m(\tilde{\chi}_1^0)$<300 GeV	1407.0600
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to b\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$\tilde{b}_1$ 100-620 GeV	$m(\tilde{\chi}_1^0)$<90 GeV	1308.2631
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to t\tilde{\chi}_1^\pm$	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{b}_1$ 275-440 GeV	$m(\tilde{\chi}_1^\pm)$=2 $m(\tilde{\chi}_1^0)$	1404.2500
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to b\tilde{\chi}_1^\pm$	1-2 e,μ	1-2 b	Yes	4.7/20.3	$\tilde{t}_1$ 110-167 GeV, 230-460 GeV	$m(\tilde{\chi}_1^\pm)$ = 2$m(\tilde{\chi}_1^0)$, $m(\tilde{\chi}_1^0)$=55 GeV	1209.2102, 1407.0583
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$	0-2 e,μ	0-2 jets/1-2 b	Yes	20.3	$\tilde{t}_1$ 90-191 GeV, 210-700 GeV	$m(\tilde{\chi}_1^0)$=1 GeV	1506.08616
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to c\tilde{\chi}_1^0$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$ 90-240 GeV	$m(\tilde{t}_1)-m(\tilde{\chi}_1^0)$<85 GeV	1407.0608
	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_1$ 150-580 GeV	$m(\tilde{\chi}_1^0)$>150 GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1+Z$	3 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_2$ 290-600 GeV	$m(\tilde{\chi}_1^0)$<200 GeV	1403.5222
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e,μ	0	Yes	20.3	$\tilde{\ell}$ 90-325 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e,μ	0	Yes	20.3	$\tilde{\chi}_1^\pm$ 140-465 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_1^+)+m(\tilde{\chi}_1^0))$	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	20.3	$\tilde{\chi}_1^\pm$ 100-350 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\tau},\tilde{\nu})=0.5(m(\tilde{\chi}_1^+)+m(\tilde{\chi}_1^0))$	1407.0350
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu), \ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e,μ	0	Yes	20.3	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ 700 GeV	$m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_1^+)+m(\tilde{\chi}_1^0))$	1402.7029
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0Z\tilde{\chi}_1^0$	2-3 e,μ	0-2 jets	Yes	20.3	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ 420 GeV	$m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, sleptons decoupled	1403.5294, 1402.7029
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0h\tilde{\chi}_1^0, h\to b\bar{b}/WW/\tau\tau/\gamma\gamma$	e,μ,γ	0-2 b	Yes	20.3	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ 250 GeV	$m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, sleptons decoupled	1501.07110
	$\tilde{\chi}_2^0\tilde{\chi}_3^0, \tilde{\chi}_{2,3}^0\to\tilde{\ell}_R\ell$	4 e,μ	0	Yes	20.3	$\tilde{\chi}_{2,3}^0$ 620 GeV	$m(\tilde{\chi}_2^0)=m(\tilde{\chi}_3^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_2^0)+m(\tilde{\chi}_1^0))$	1405.5086
	GGM (wino NLSP) weak prod.	1 $e,\mu+\gamma$	-	Yes	20.3	$\tilde{W}$ 124-361 GeV	$c\tau$<1 mm	1507.05493
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}_1^\pm$ 270 GeV	$m(\tilde{\chi}_1^\pm)-m(\tilde{\chi}_1^0)$~160 MeV, $\tau(\tilde{\chi}_1^\pm)$=0.2 ns	1310.3675
	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	dE/dx trk	-	Yes	18.4	$\tilde{\chi}_1^\pm$ 482 GeV	$m(\tilde{\chi}_1^\pm)-m(\tilde{\chi}_1^0)$~160 MeV, $\tau(\tilde{\chi}_1^\pm)$<15 ns	1506.05332
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	$\tilde{g}$ 832 GeV	$m(\tilde{\chi}_1^0)$=100 GeV, 10 μs<$\tau(\tilde{g})$<1000 s	1310.6584
	Stable $\tilde{g}$ R-hadron	trk	-	-	19.1	$\tilde{g}$ 1.27 TeV		1411.6795
	GMSB, stable $\tilde{\tau}, \tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	-	-	19.1	$\tilde{\chi}_1^0$ 537 GeV	10<$\tan\beta$<50	1411.6795
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	20.3	$\tilde{\chi}_1^0$ 435 GeV	2<$\tau(\tilde{\chi}_1^0)$<3 ns, SPS8 model	1409.5542
	$\tilde{g}\tilde{g}, \tilde{\chi}_1^0\to ee\nu/e\mu\nu/\mu\mu\nu$	displ. $ee/e\mu/\mu\mu$	-	-	20.3	$\tilde{\chi}_1^0$ 1.0 TeV	7 <$c\tau(\tilde{\chi}_1^0)$< 740 mm, $m(\tilde{g})$=1.3 TeV	1504.05162
	GGM $\tilde{g}\tilde{g}, \tilde{\chi}_1^0\to Z\tilde{G}$	displ. vtx + jets	-	-	20.3	$\tilde{\chi}_1^0$ 1.0 TeV	6 <$c\tau(\tilde{\chi}_1^0)$< 480 mm, $m(\tilde{g})$=1.1 TeV	1504.05162
RPV	LFV $pp\to\tilde{\nu}_\tau+X, \tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$	$e\mu,e\tau,\mu\tau$	-	-	20.3	$\tilde{\nu}_\tau$ 1.7 TeV	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1503.04430
	Bilinear RPV CMSSM	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{q}, \tilde{g}$ 1.35 TeV	$m(\tilde{q})=m(\tilde{g})$, $c\tau_{LSP}$<1 mm	1404.2500
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$	4 e,μ	-	Yes	20.3	$\tilde{\chi}_1^\pm$ 750 GeV	$m(\tilde{\chi}_1^0)$>0.2×$m(\tilde{\chi}_1^\pm)$, $\lambda_{121}\neq0$	1405.5086
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to\tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$	3 $e,\mu+\tau$	-	Yes	20.3	$\tilde{\chi}_1^\pm$ 450 GeV	$m(\tilde{\chi}_1^0)$>0.2×$m(\tilde{\chi}_1^\pm)$, $\lambda_{133}\neq0$	1405.5086
	$\tilde{g}\tilde{g}, \tilde{g}\to qqq$	0	6-7 jets	-	20.3	$\tilde{g}$ 917 GeV	BR(t)=BR(b)=BR(c)=0%	1502.05686
	$\tilde{g}\tilde{g}, \tilde{g}\to q\tilde{\chi}_1^0, \tilde{\chi}_1^0\to qqq$	0	6-7 jets	-	20.3	$\tilde{g}$ 870 GeV	$m(\tilde{\chi}_1^0)$=600 GeV	1502.05686
	$\tilde{g}\tilde{g}, \tilde{g}\to\tilde{t}_1t, \tilde{t}_1\to bs$	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{g}$ 850 GeV		1404.250
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to bs$	0	2 jets + 2 b	-	20.3	$\tilde{t}_1$ 100-308 GeV		ATLAS-CONF-2015-026
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to b\ell$	2 e,μ	2 b	-	20.3	$\tilde{t}_1$ 0.4-1.0 TeV	BR($\tilde{t}_1\to be/\mu$)>20%	ATLAS-CONF-2015-015
Other	Scalar charm, $\tilde{c}\to c\tilde{\chi}_1^0$	0	2 c	Yes	20.3	$\tilde{c}$ 490 GeV	$m(\tilde{\chi}_1^0)$<200 GeV	1501.01325

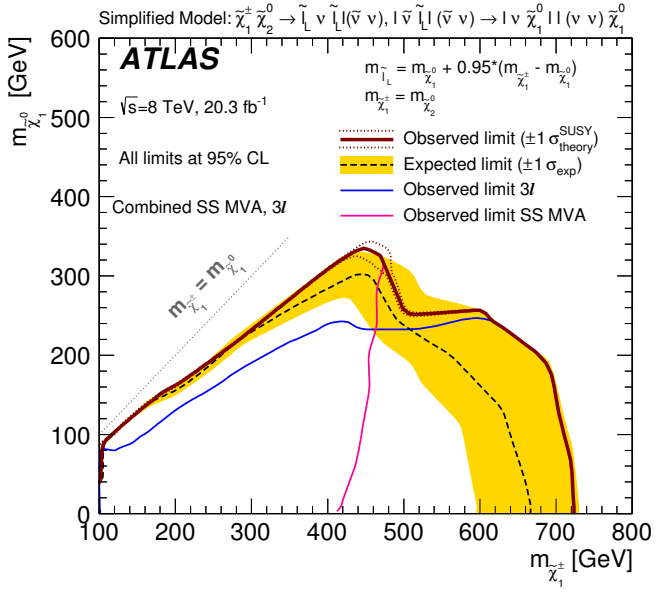
10^{-1} — 1 — Mass scale [TeV]

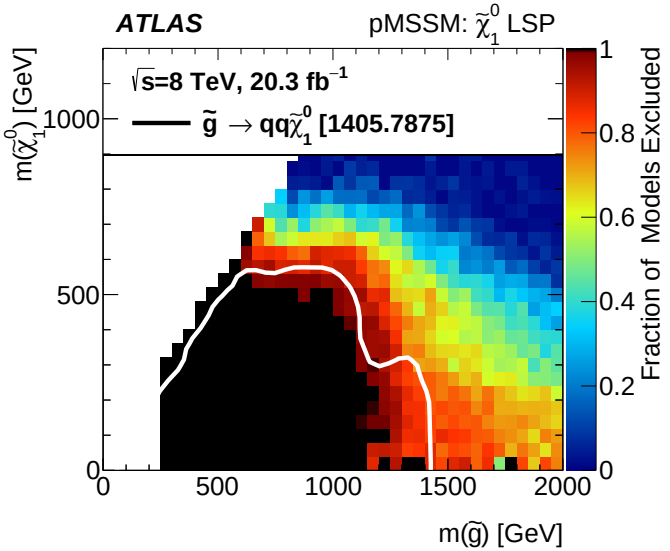
*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

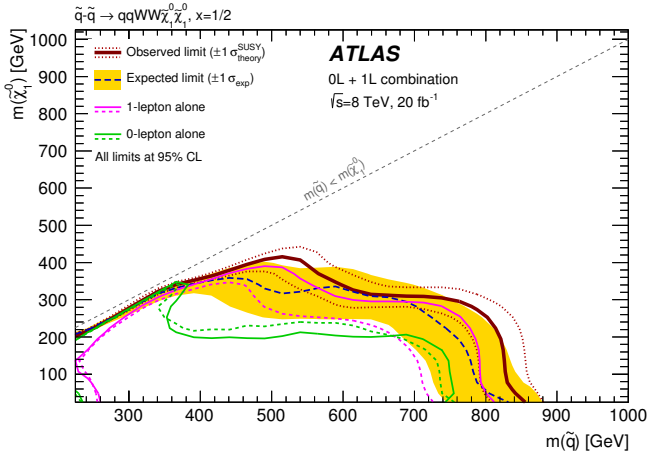
SUSY Searches – Exclusions

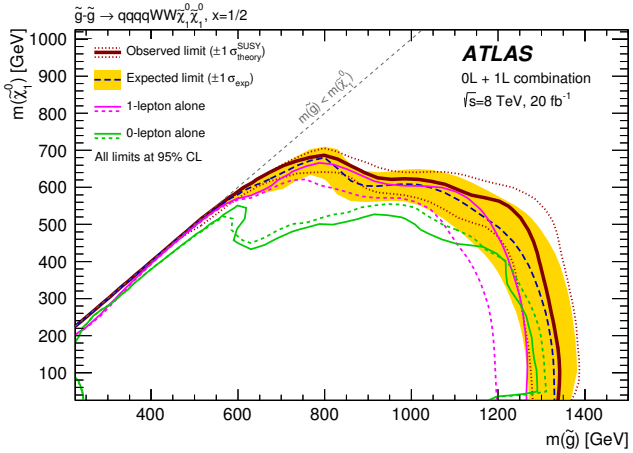
ATLAS SUSY summary papers **out now**,
[SUSY-2014-05], [SUSY-2014-06], [SUSY-2014-07], [SUSY-2014-08]

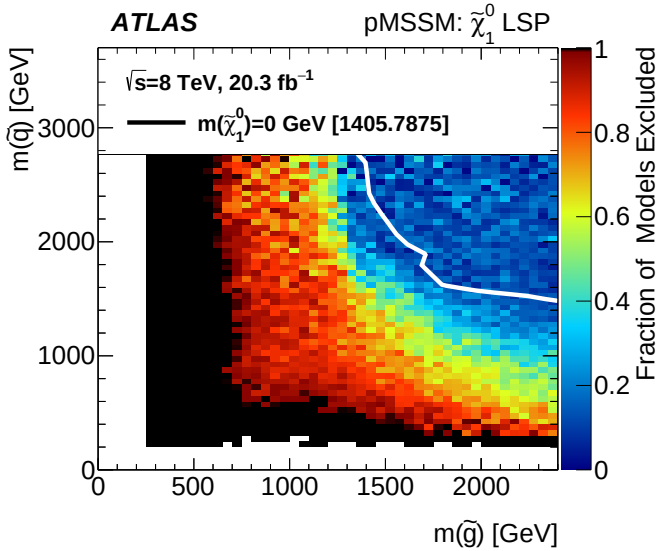






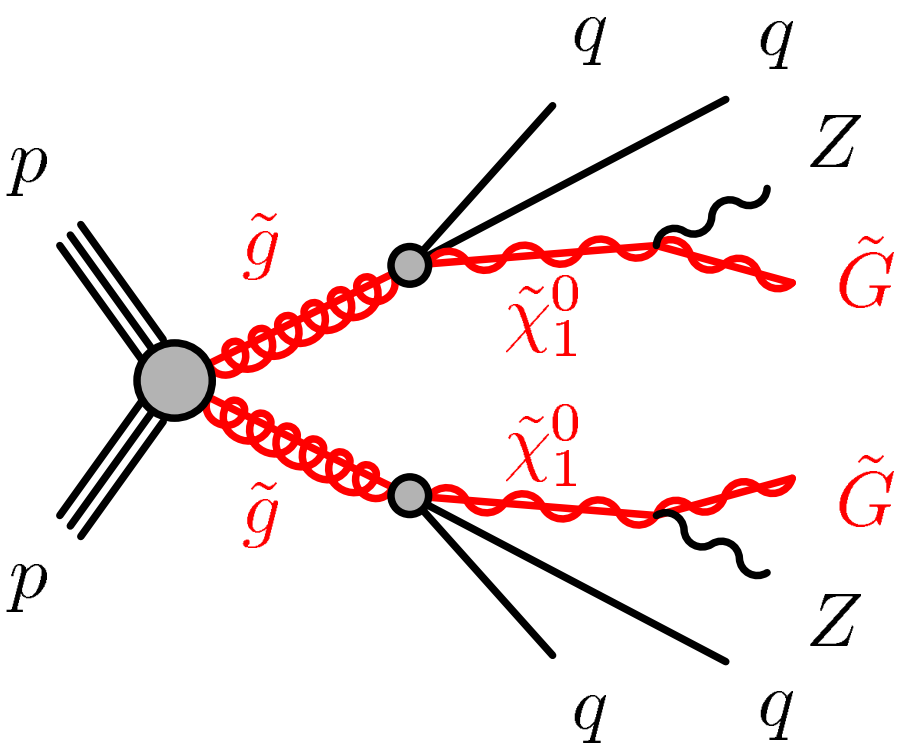


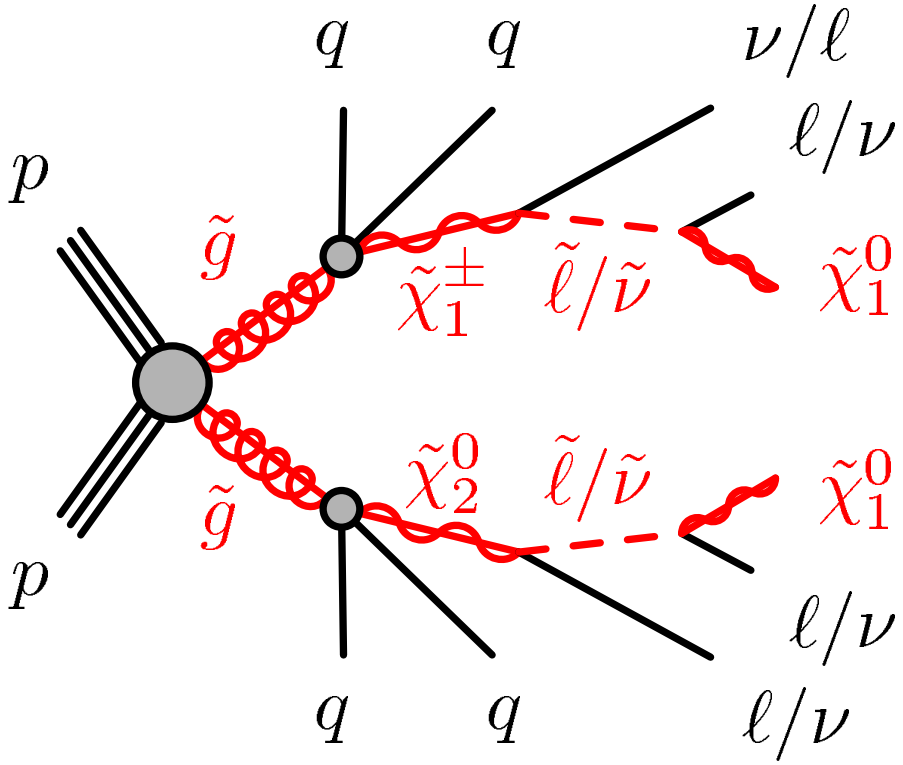




SUSY search using $ll + jets + E_T^{miss}$

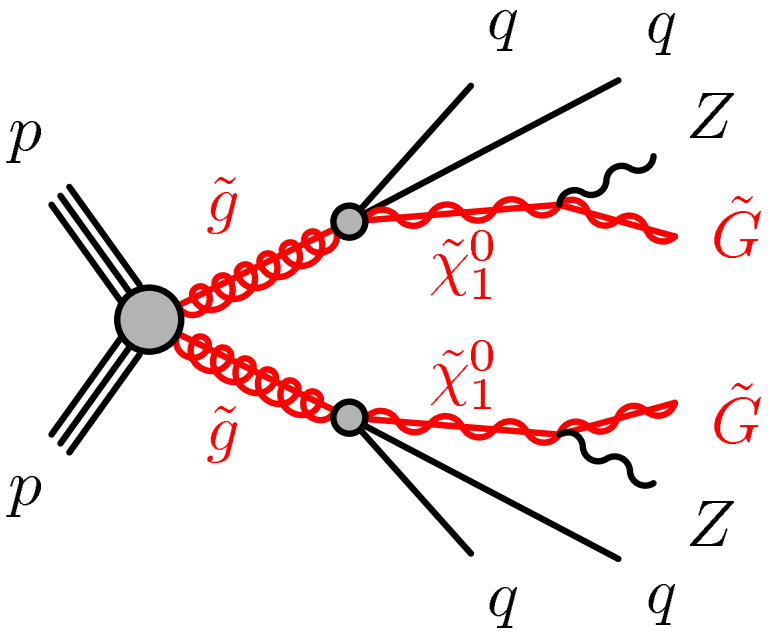
[SUSY-2014-10]





- **'Standard'** ATLAS SUSY search methodology
  - **Control regions** (CRs): Used to constrain SM backgrounds
  - **Validation regions** (VRs): CR background estimates extrapolated into VRs as cross-check
  - **Signal regions** (SRs): After VR check, extrapolate background into SR and look for excess of events over expected background
  - Search performed over a **grid** of signal masses

On shell Z channel regions

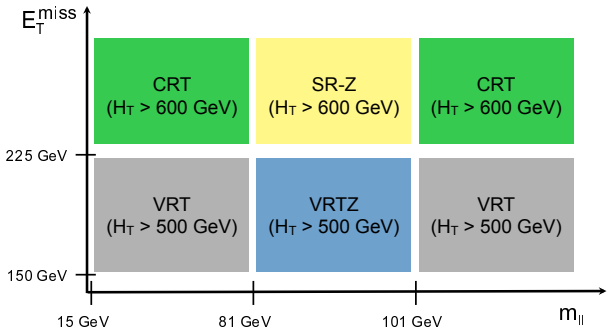


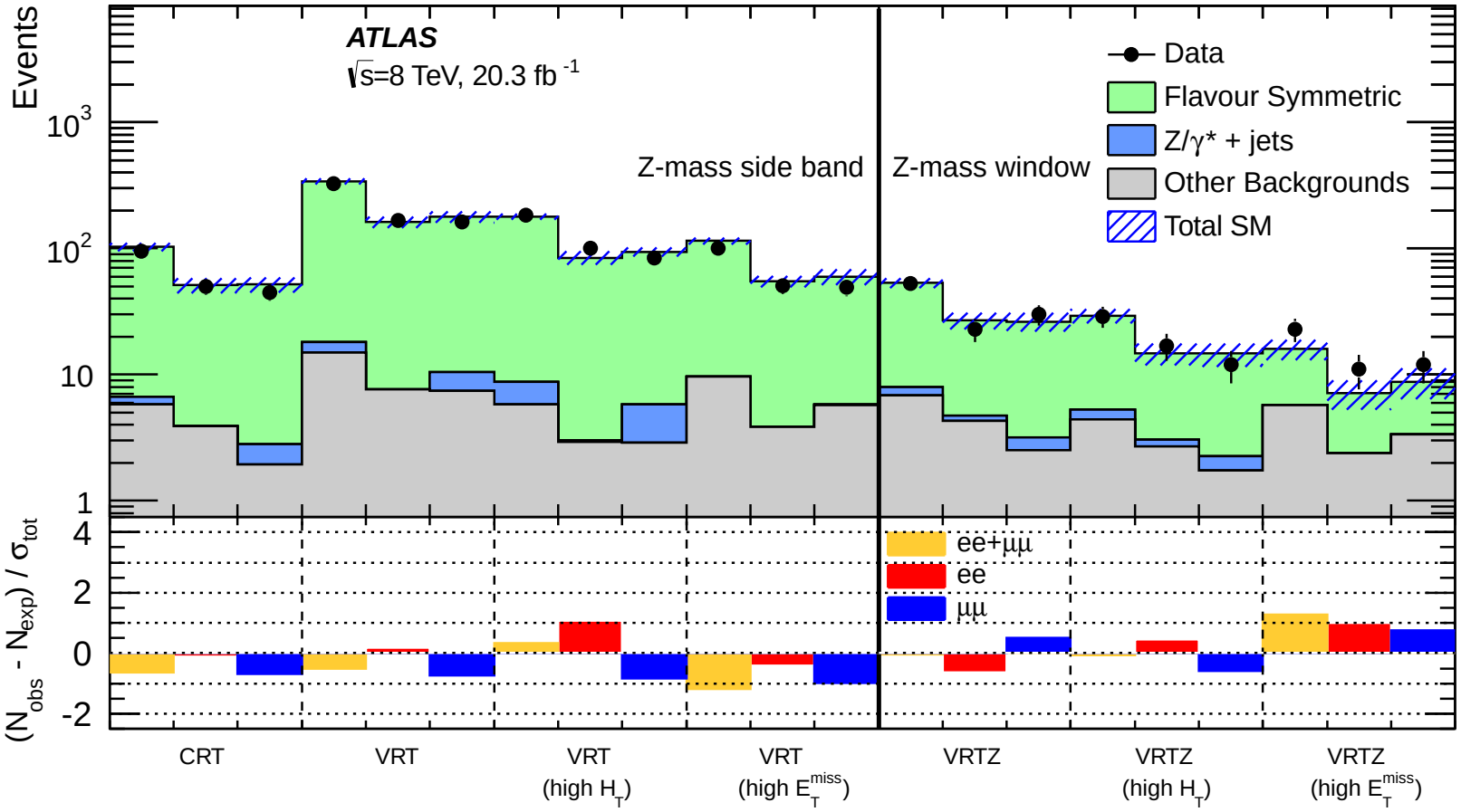
- Backgrounds studied
  - **Flavour symmetric** $t\bar{t}$, WW, Wt: Data-driven. CR$e\mu$ data (corrected for other backgrounds). Lepton selection eff. relations transfer to SR. Cross-checked with Z-mass sidebands. MC norm. in CRT, extrapolation checked in VRT/Z.
  - Z/γ**+ jets**: Data-driven. Seed CR jets smeared to mimic E_T^{miss} distribution. Tested in VRZ region.
  - **Fake leptons**: Data-driven. Derived from matrix method.
  - Other backgrounds. WZ, ZZ, Rare top. Modelled by MC.

On-Z region	$E_{\text{T}}^{\text{miss}}$ (GeV)	H_{T} (GeV)	n_{jets}	$m_{\ell\ell}$ (GeV)	SF/DF	$E_{\text{T}}^{\text{miss}}$ sig. ($\sqrt{\text{GeV}}$)	f_{ST}	$\Delta\phi(\text{jet}_{12}, E_{\text{T}}^{\text{miss}})$
Signal regions								
SR-Z	>225	>600	≥2	$81 < m_{\ell\ell} < 101$	SF	–	–	>0.4
Control regions								
Seed region	–	>600	≥2	$81 < m_{\ell\ell} < 101$	SF	<0.9	<0.6	–
CR$e\mu$	>225	>600	≥2	$81 < m_{\ell\ell} < 101$	DF	–	–	>0.4
CRT	>225	>600	≥2	$m_{\ell\ell} \notin [81, 101]$	SF	–	–	>0.4
Validation regions								
VRZ	<150	>600	≥2	$81 < m_{\ell\ell} < 101$	SF	–	–	–
VRT	150–225	>500	≥2	$m_{\ell\ell} \notin [81, 101]$	SF	–	–	>0.4
VRTZ	150–225	>500	≥2	$81 < m_{\ell\ell} < 101$	SF	–	–	>0.4

Flavour symmetric modelling

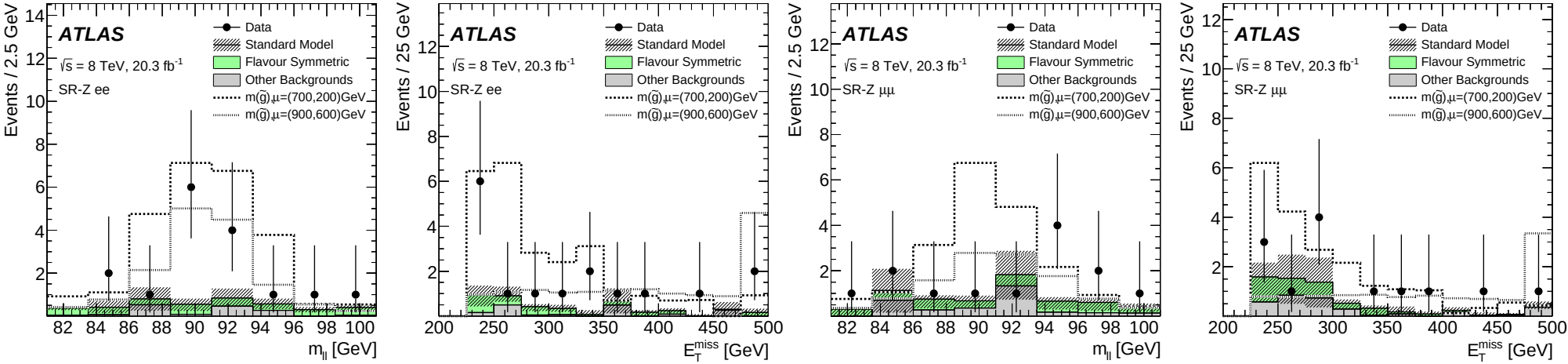
- Background normalisation modelling in **good agreement** with the data in the flavour symmetric cross-check CR/VRs (Z/γ+ jets in backup)
- High-H_T: $H_T > 600$ GeV
- High-E_T^{miss}: $E_T^{\text{miss}} > 225$ GeV, $400 > H_T > 600$ GeV





SR Results

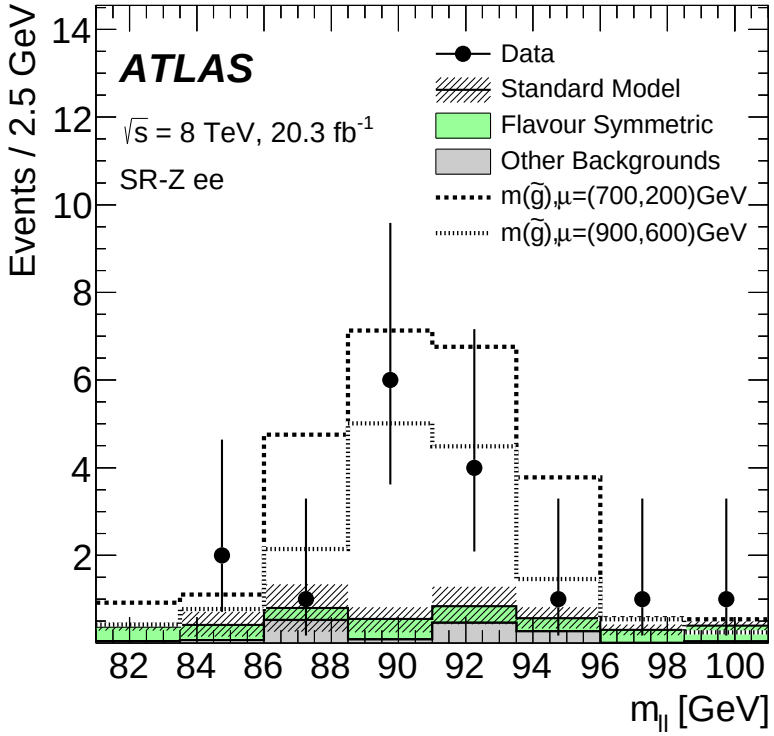
- **Excesses** seen in **both** channels (ee: 3.0σ, $\mu\mu$: 1.7σ)
- Combined significance 3.0σ
- CMS observes **no excess**

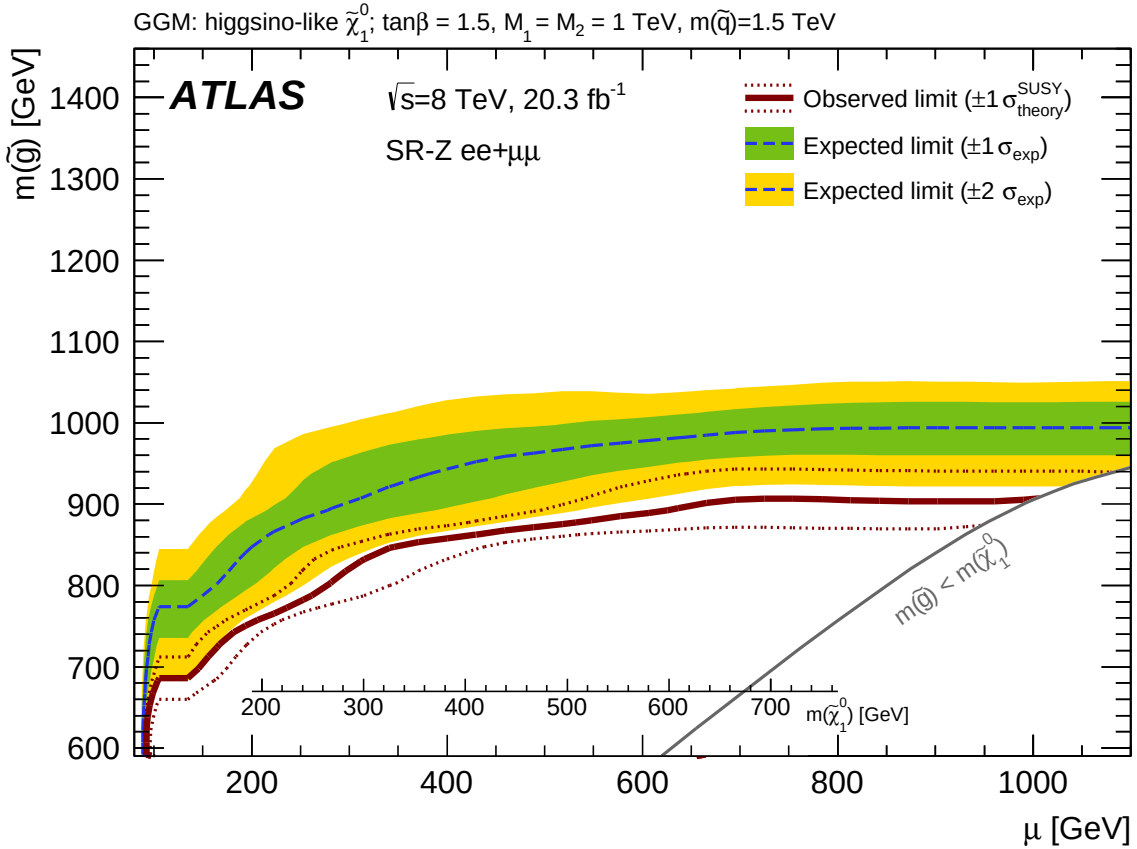


Channel	SR-Z ee	SR-Z $\mu\mu$	SR-Z same-flavour combined
Observed events	16	13	29
Expected background events	4.2 ± 1.6	6.4 ± 2.2	10.6 ± 3.2
Flavour-symmetric backgrounds	2.8 ± 1.4	3.3 ± 1.6	6.0 ± 2.6
$Z/\gamma^* +$ jets (jet-smearing)	0.05 ± 0.04	$0.02^{+0.03}_{-0.02}$	0.07 ± 0.05
Rare top	0.18 ± 0.06	0.17 ± 0.06	0.35 ± 0.12
WZ/ZZ diboson	1.2 ± 0.5	1.7 ± 0.6	2.9 ± 1.0
Fake leptons	$0.1^{+0.7}_{-0.1}$	$1.2^{+1.3}_{-1.2}$	$1.3^{+1.7}_{-1.3}$

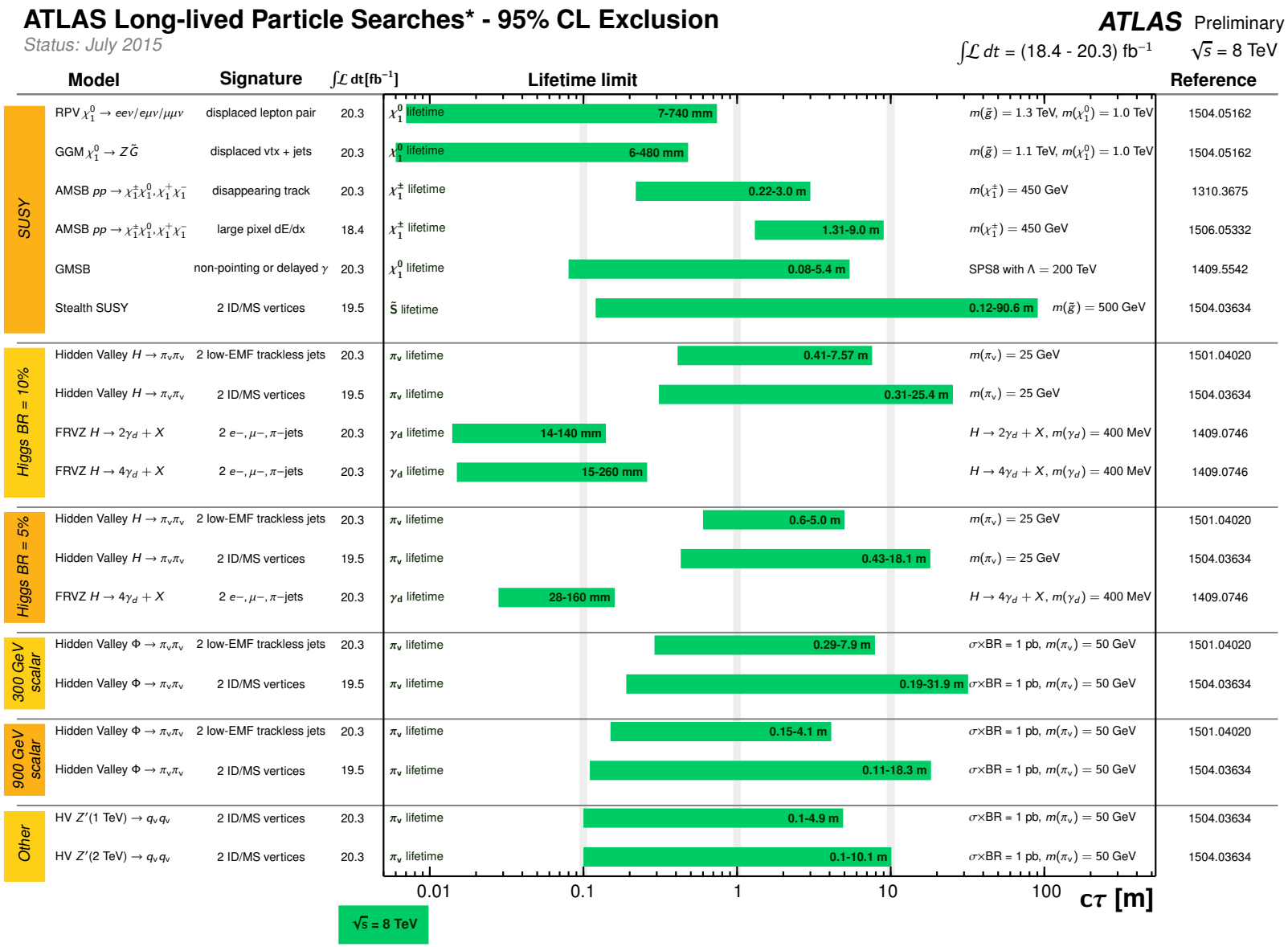
Summary – $ll + jets + E_T^{miss}$

- Channel searches for SUSY cascade decays with SF leptons, jets and E_T^{miss} both on and off Z mass shell
- Combined significance 3.0σ
- **Excesses** seen in **both** on shell channels, therefore weaker limits
- Devil's advocate/pessimist in me:
  - $\approx$ 180 SR in SUSY searches Run-1
  - Would naively expect $\approx 0.5 \times 3\sigma$ excesses and have seen one
  - Only Run-2 will tell



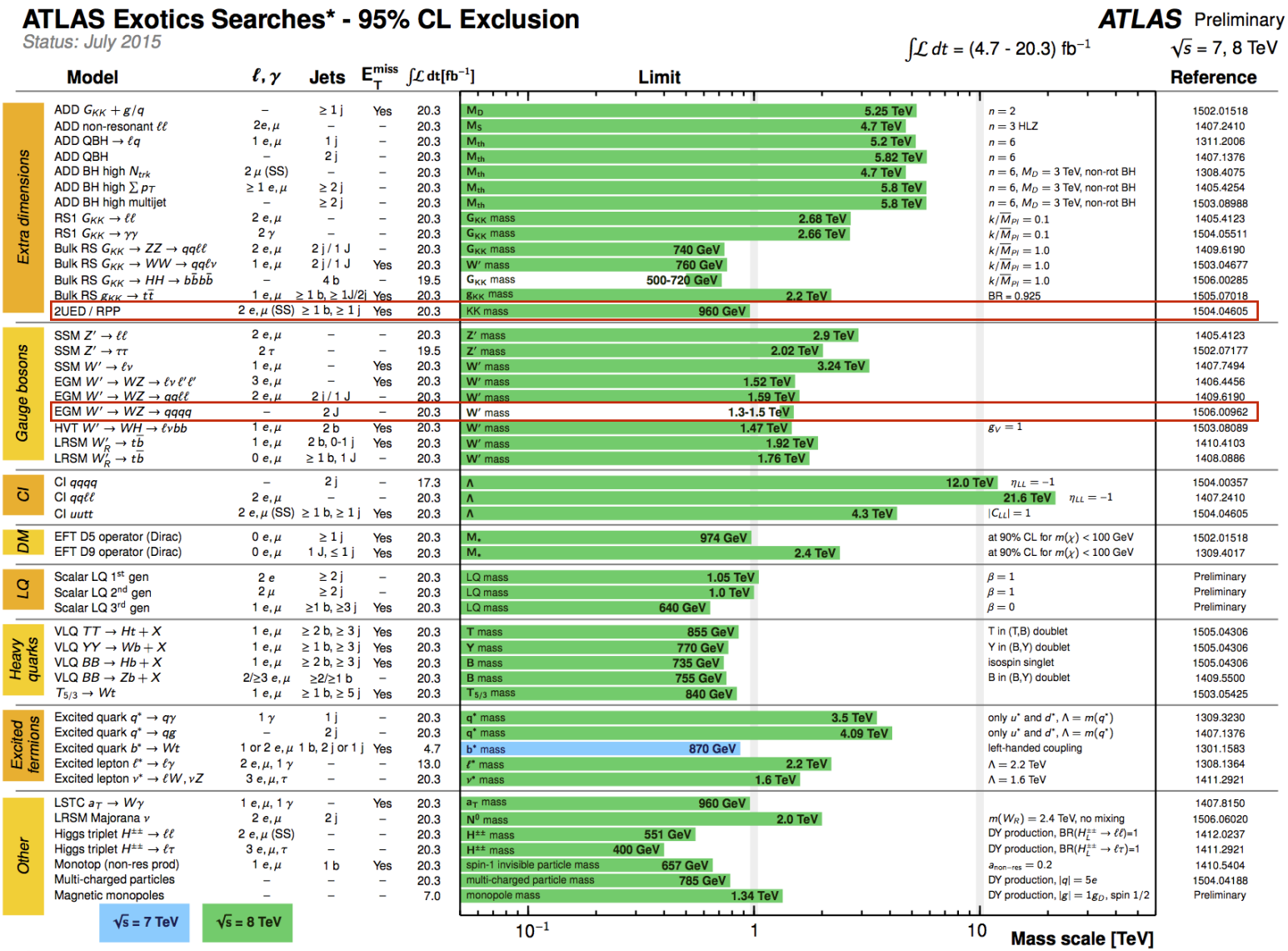


Exotic Searches – LLP



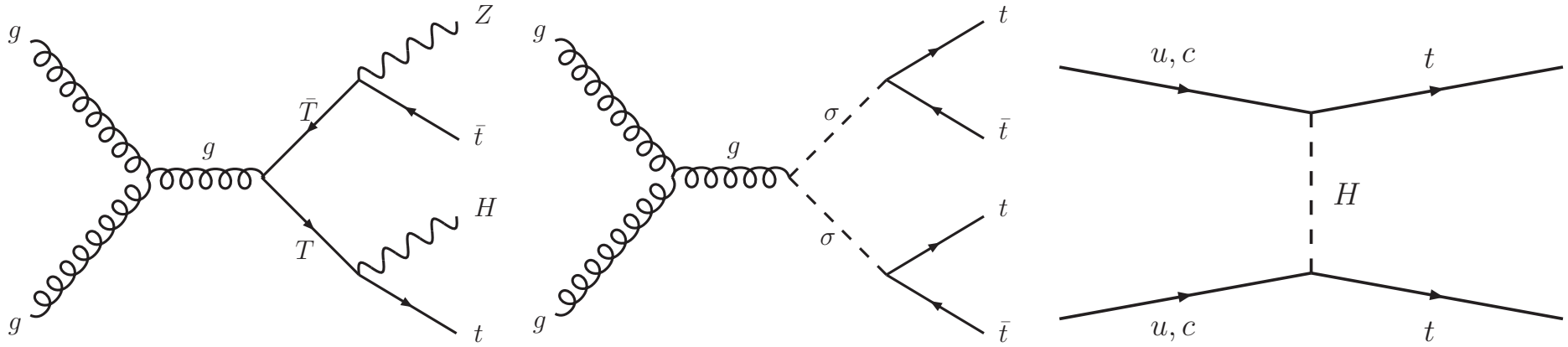
*Only a selection of the available lifetime limits on new states is shown.

Exotic Searches – needles in the haystack?



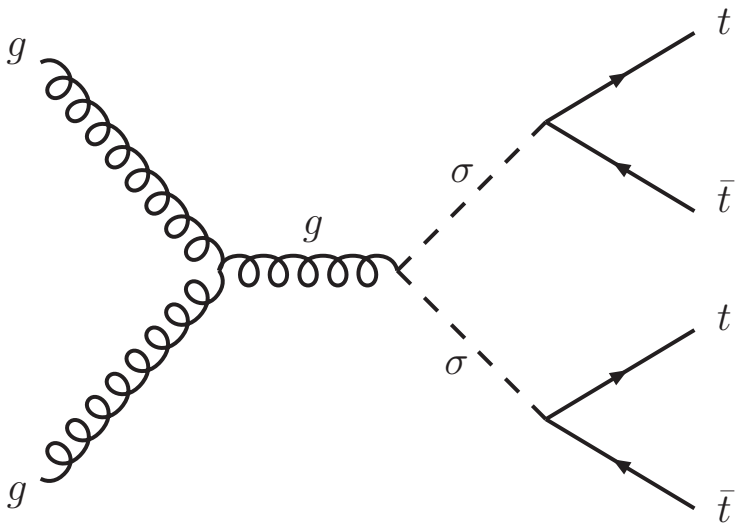
Exotics search in $ll + b - jets + E_T^{\text{miss}}$

[EXOT-2013-16]



- Look for excess of events with same-sign (SS) lepton pairs, b-jets and E_T^{miss}
- Using a simple 'cut and count' methodology
- As most Exotics analyses do, the channel is sensitive to a wide range of BSM theories
  - Vector-like quarks (VLQ)
  - Any enhancement of $t\bar{t}t\bar{t}$ production ($\tilde{g}$ pair production, 2UED/RPP)
  - Chiral quark production, $b' \to Wt$
  - Same-sign tt production via flavour changing neutral currents (FCNC)

Signal regions

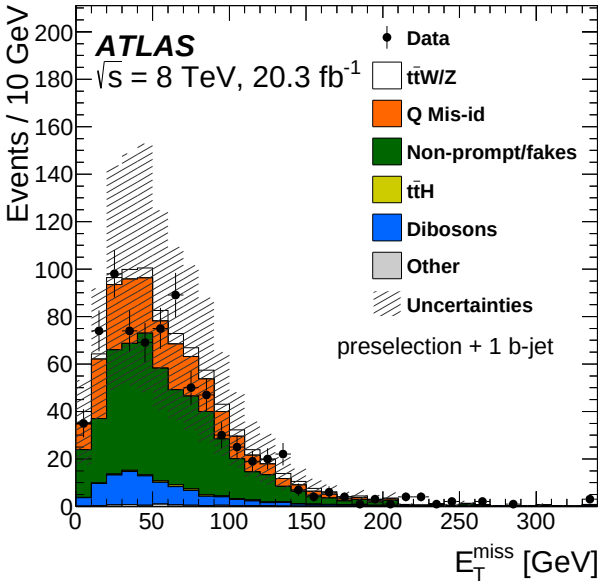


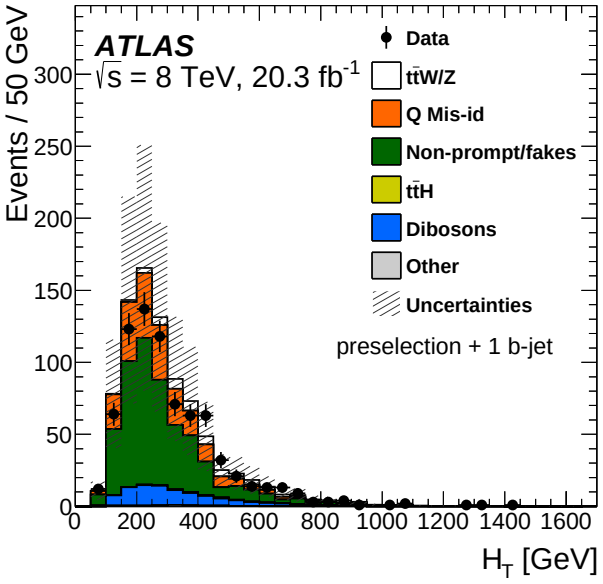
- Backgrounds studied
  - **Real SS lepton pairs** $W \pm W \pm jj$, $t\bar{t}W/Z$, $t\bar{t}W^+W^-$, $t\bar{t}H$, WH, ZH, tWZ, tH, WZ, ZZ and $t\bar{t}t\bar{t}$: MC modelled (low x-sections)
  - **Fake leptons**: Data-driven. Derived from matrix method.
  - **Charge misidentification**: Rate estimated in $Z \to ee$ events
- Estimates validated in low-H_T region, $100 > H_T > 400$ GeV

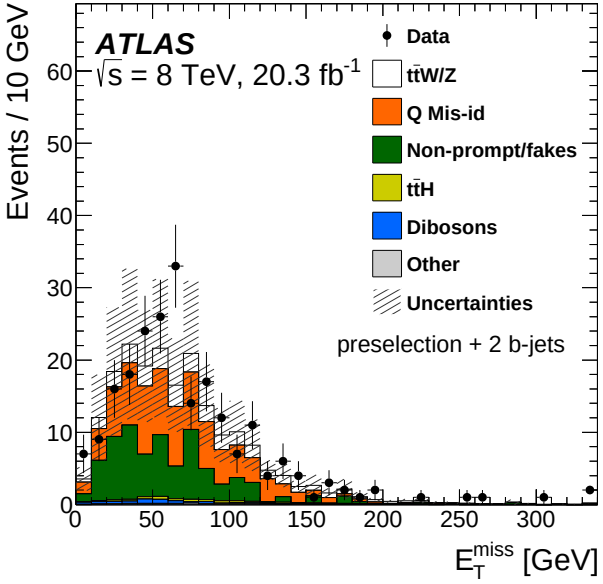
Definition			Name	
$e^\pm e^\pm + e^\pm\mu^\pm + \mu^\pm\mu^\pm + eee + ee\mu + e\mu\mu + \mu\mu\mu$, $N_j \geq 2$				
$400 < H_\mathrm{T} < 700 GeV$	$N_b = 1$	$E_\mathrm{T}^\mathrm{miss} > 40$ GeV	SRVLQ0	
	$N_b = 2$		SRVLQ1	SR4t0
	$N_b \geq 3$		SRVLQ2	SR4t1
$H_\mathrm{T} \geq 700\ GeV$	$N_b = 1$	$40 < E_\mathrm{T}^\mathrm{miss} < 100 GeV$	SRVLQ3	
		$E_\mathrm{T}^\mathrm{miss} \geq 100\ GeV$	SRVLQ4	
	$N_b = 2$	$40 < E_\mathrm{T}^\mathrm{miss} < 100 GeV$	SRVLQ5	SR4t2
		$E_\mathrm{T}^\mathrm{miss} \geq 100\ GeV$	SRVLQ6	SR4t3
	$N_b \geq 3$	$E_\mathrm{T}^\mathrm{miss} > 40$ GeV	SRVLQ7	SR4t4
e^+e^+, $e^+\mu^+$, $\mu^+\mu^+$, $N_j \in [2,4]$, $\Delta\phi_{\ell\ell} > 2.5$				
$H_\mathrm{T} > 450\ GeV$	$N_b \geq 1$	$E_\mathrm{T}^\mathrm{miss} > 40\ GeV$	SRttee, SRtt$e\mu$, SRtt$\mu\mu$	

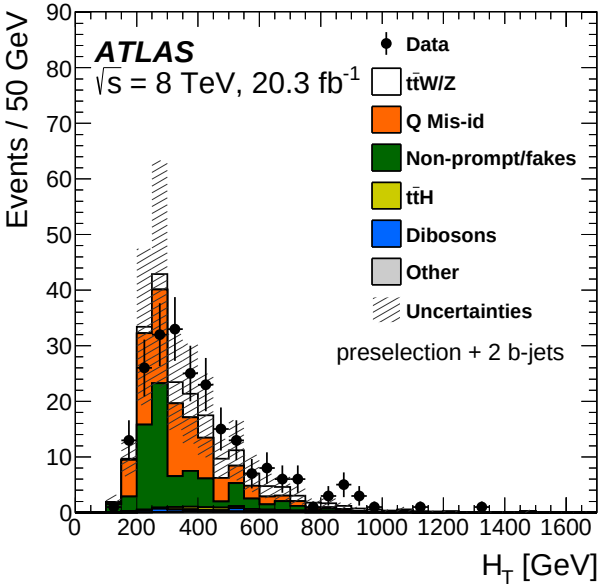
Preselection Results

- Preselection applied
  - Essentially SRLQ0/1/2 without the H_T or E_T^{miss} selections applied
- Good data/background agreement within uncertainties seen in preselection with one/two *b*-tagged jets
- Good agreement also seen in the validation regions



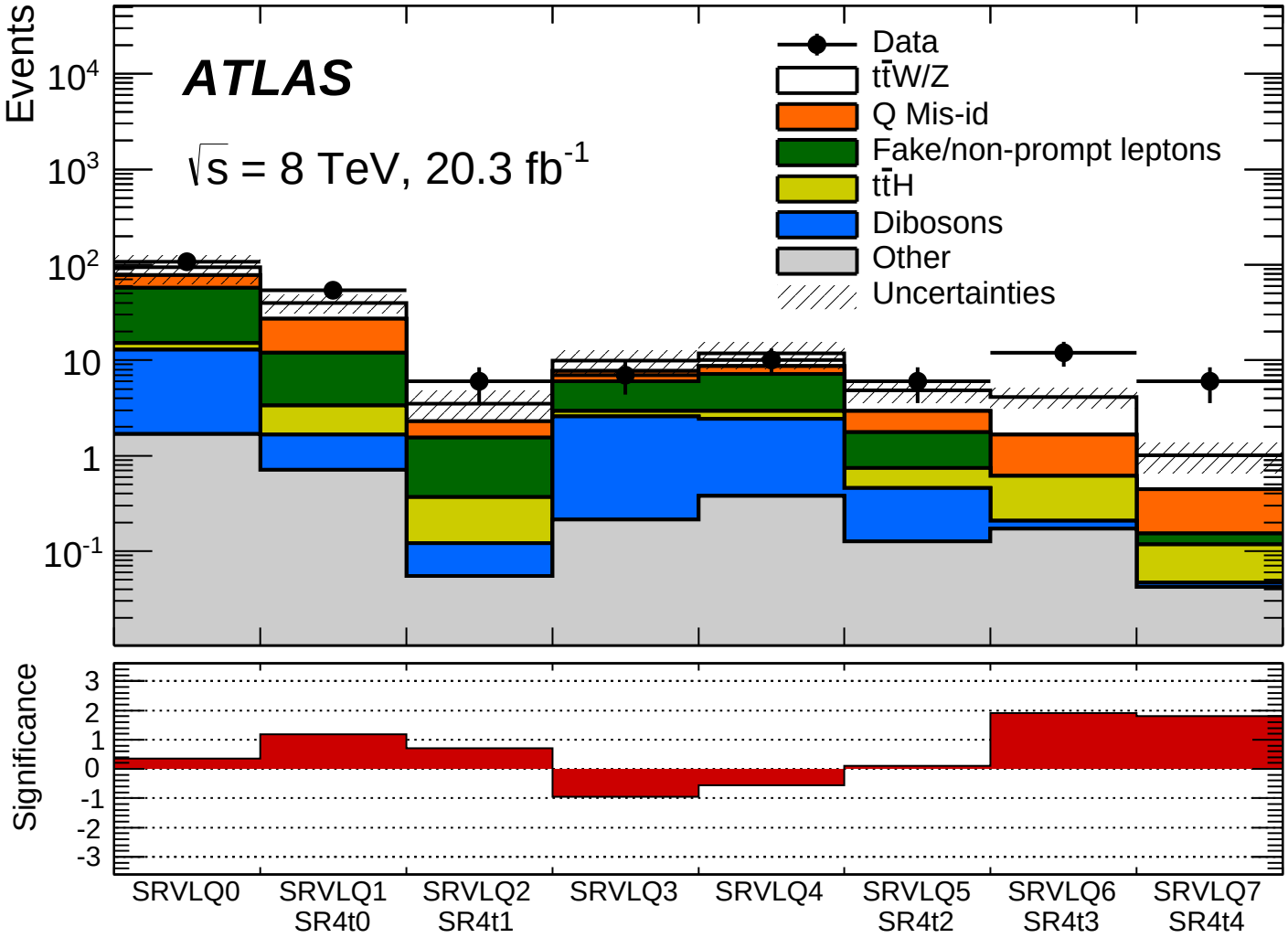






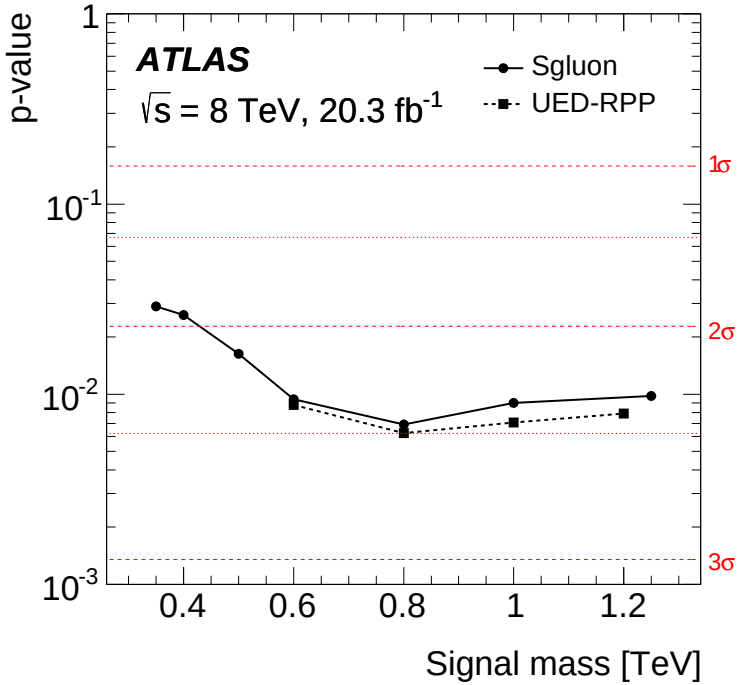
SR Results

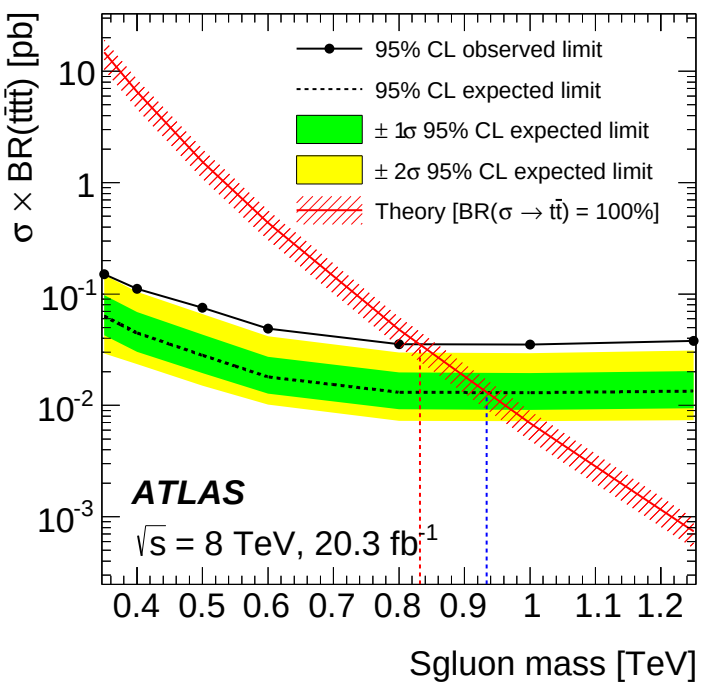
- **Excess** of 2.0σ seen taking **all SRVLQs** into account (*VLQ* and b' models)
- **Excess** of 2.5σ seen taking only **4-top SRs** into account
- SS+FCNC SRs are in good agreement with SM expectation



Summary – $ll + b - jets + E_T^{miss}$

- Cut/count analysis looking for events with **SS lepton pairs** and *b*-jets as a signal for many BSM signals
- **Excesses** of $2.5\sigma(2.0\sigma)$ seen taking **4-top SRs**(all SRs) into account
- Mass resolution of the analysis is **poor**
- Limits worse than expected due to presence of excess
- Again Run-2 is **needed** to to elucidate the origin of this excess

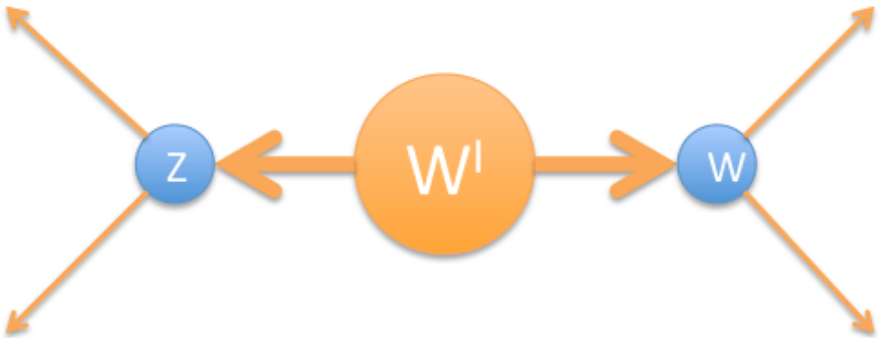




Exotics search in $X \rightarrow VV \rightarrow JJ$

[EXOT-2013-08] **Bias starts here**

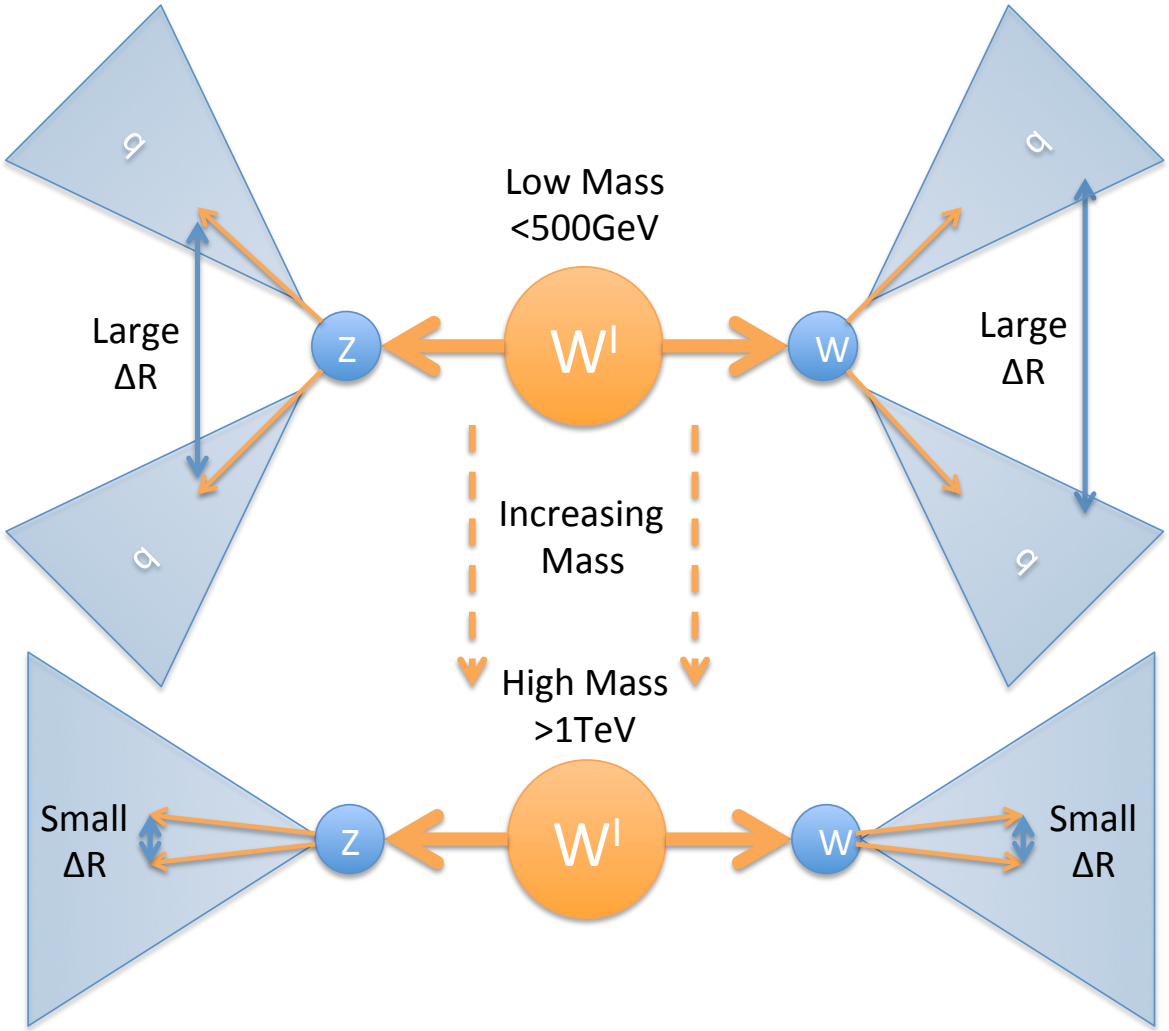
- Diboson resonances appear in many extensions to the standard model
- The following analysis concentrates on two **benchmark** models
  - Extended gauge sector models ($W' \rightarrow WZ$)
  - Extra dimensions models ($G_{RS} \rightarrow WW/ZZ$)
- **Low branching ratios** hinder the leptonic searches at the highest masses
- Obviously, a **fully hadronic** search has access to these lost events
- The problem, is controlling the **enormous QCD background** that the leptonic searches were avoiding



$W \Downarrow$	Diboson branching ratios		
$l\nu$ (33%)	23%	7%	3%
qq (67%)	47%	13%	7%
$Z \Rightarrow$	qq (70%)	$\nu\nu$ (20%)	ll (10%)

- Use **large-R** jets and jet **substructure** to select signal events from dominant QCD multi-jet backgrounds

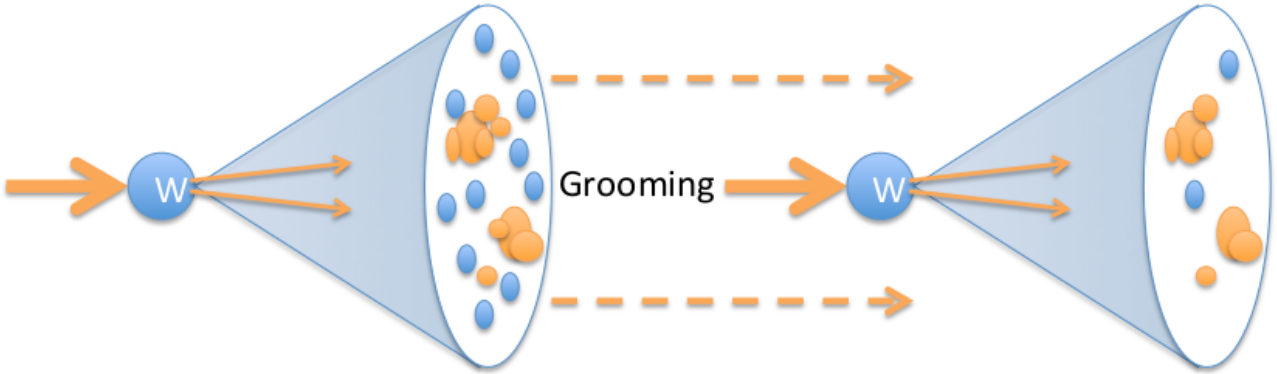
Boosted Bosons



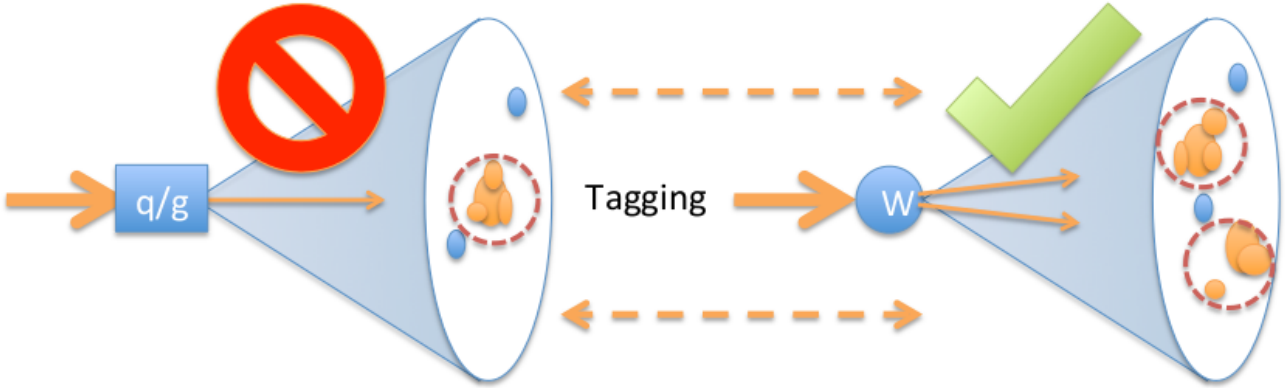
- Vector bosons have mass $\mathcal{O}(0.1\ \text{TeV})$
- We are interested in particles of mass $\geq \mathcal{O}(1\ \text{TeV})$
- Therefore the decays of the form, $X \to VV$ with large m_X, lead to vector bosons with **very high** p_{T}
- Therefore, boosted decay products become more **collimated**
- Rule of thumb for angular separation of decay products:
- $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2} \approx \frac{2m}{p_{\mathrm{T}}}$

Fat Jet→Grooming→Tagging

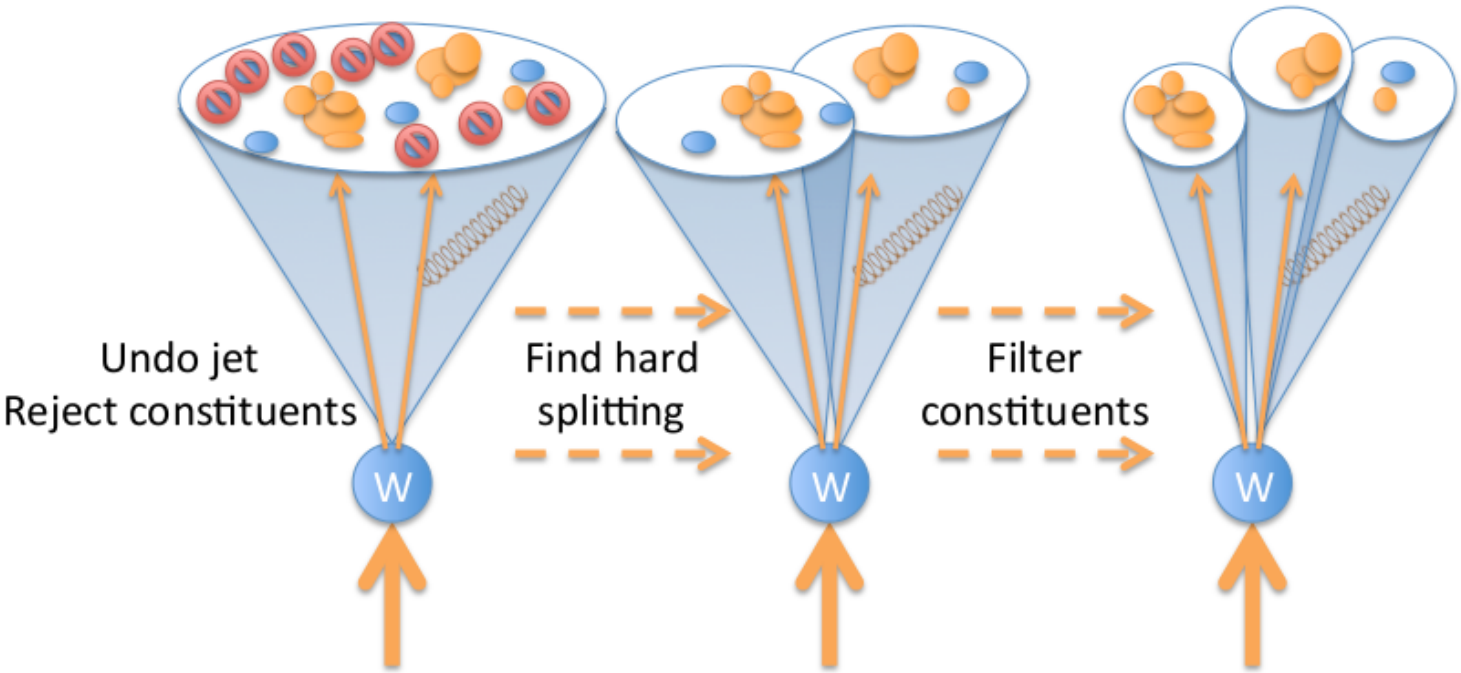
1. Reconstruct decay as fat-jet
   - Use large-R parameter jet to collect radiation from the original decay
2. Groom the jet
   - Signal: Remove unwanted jet constituents not from the signal, e.g. pile-up
   - Background: Preserve the background characteristics



3. Tag as boson jet
   - Use differences between signal and background jet characteristics to reject background jets



BDRS-A Split-Filter



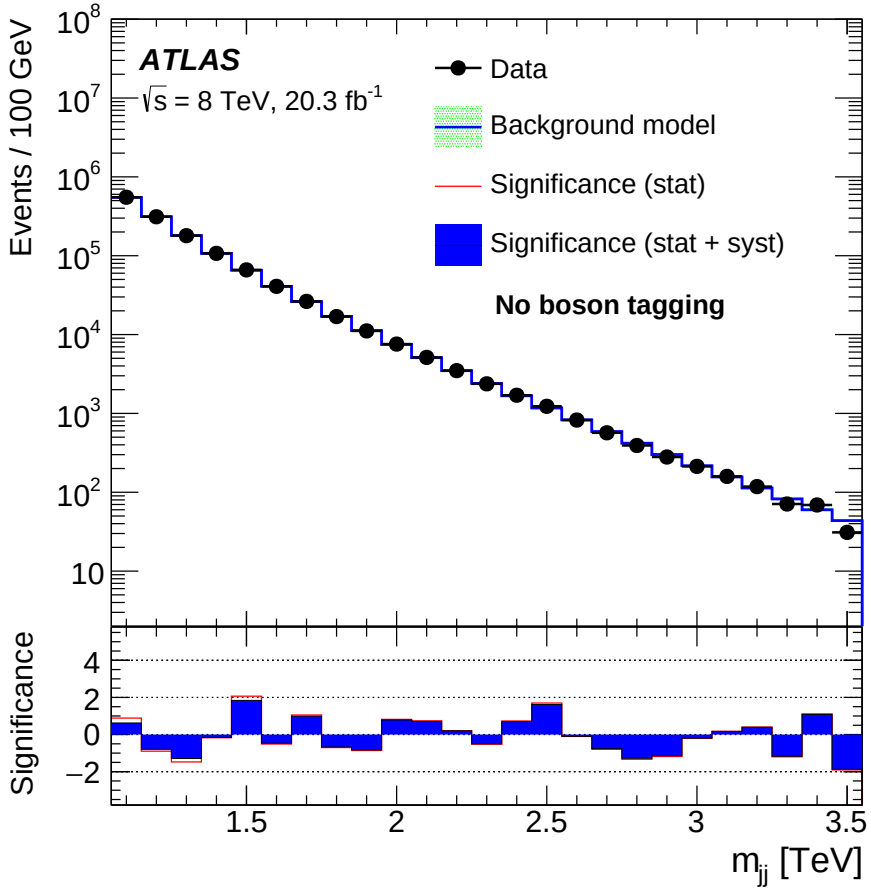
- In this analysis a **modified BDRS-A** split filtering algorithm is used
- Starts from $R = 1.2$ CA jets seeded from local cluster weighted (LCW) topological clusters
- Loose BDRS tagger, with **no mass drop** requirement

Iterative parameter	Value
$\sqrt{y_{\min}}$	0.20
$\mu_{\max}$	1.00
Filtering parameter	**Value**
n_{r}	3
R_{r}	0.3

Event selection

1. **Trigger:** $p_T > 360$ GeV anti-kt 1.0
2. Apply **BDRS-A** split-filter
3. Require $m_{JJ} > 1.05$ TeV
   - Ensures on **trigger plateau**
4. **Rapidity gap** between leading jets, $|\Delta y_{12}| < 1.2$
   - s-channel signal more **central** than t-channel QCD
5. Leading jets p_T **asymmetry** $A_{p_T} < 0.15$
   - Used as proxy for large-R **jet cleaning**
6. Leading jets $|\eta| < 2.0$
   - Ensures a good **overlap** with tracker
7. Correction for jets on **calorimetry holes**
8. **Boson tagging** cuts
   - Jet mass (WZ, WW, ZZ), momentum balance, n_{trk} ghost associated to jet

- Background efficiencies
  - **Topological** $\epsilon \approx 48\%$
  - **Tagger** $\epsilon \approx 1.2 - 0.6\%$ (per jet)



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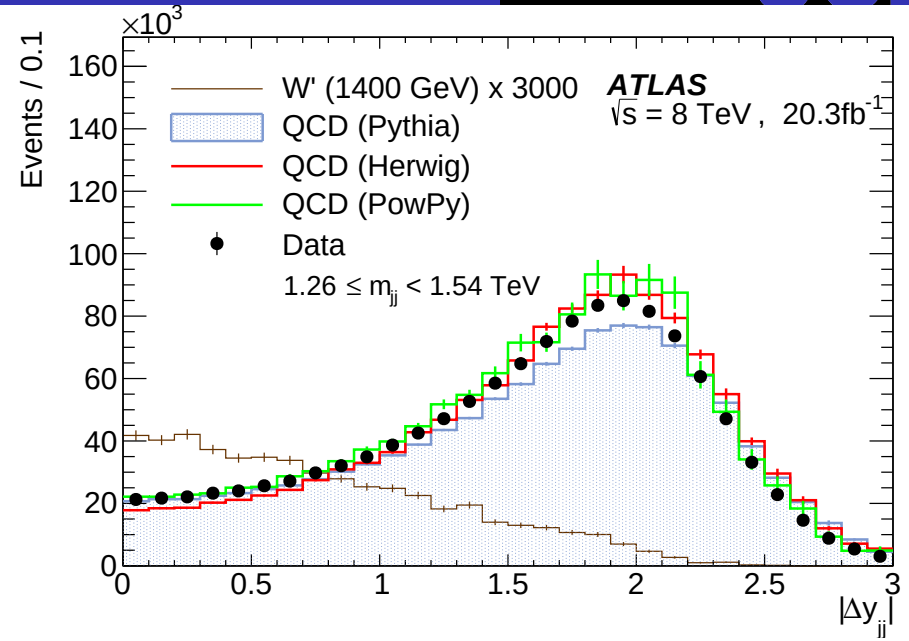

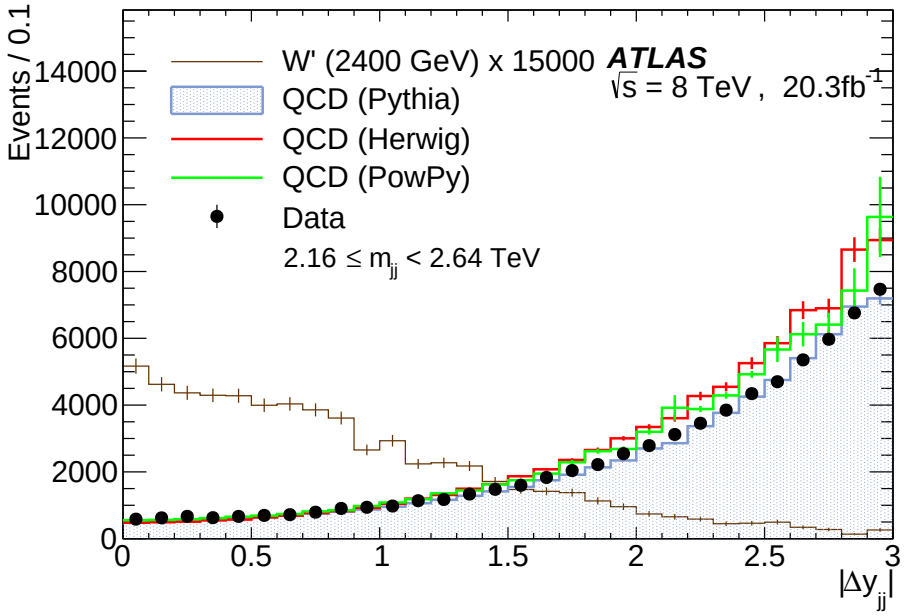

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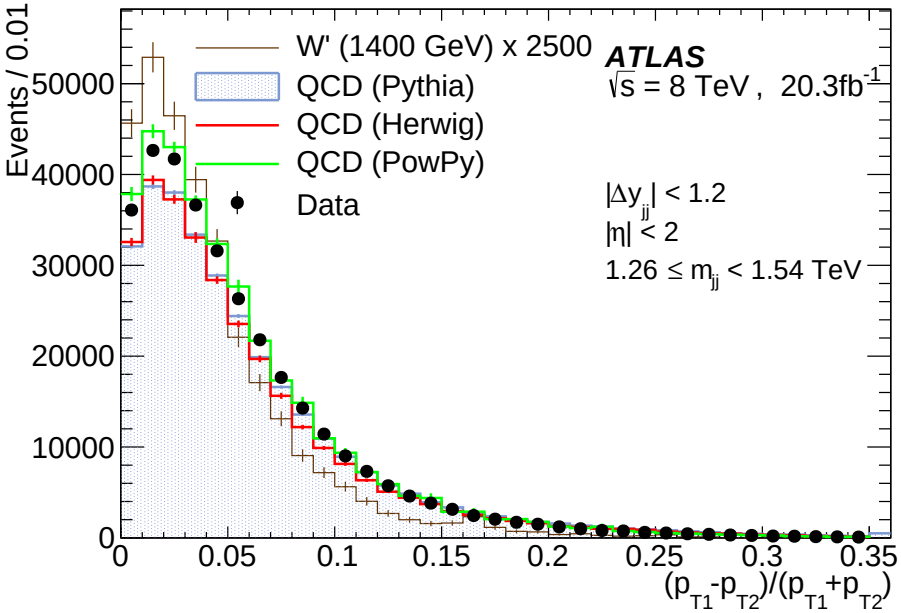

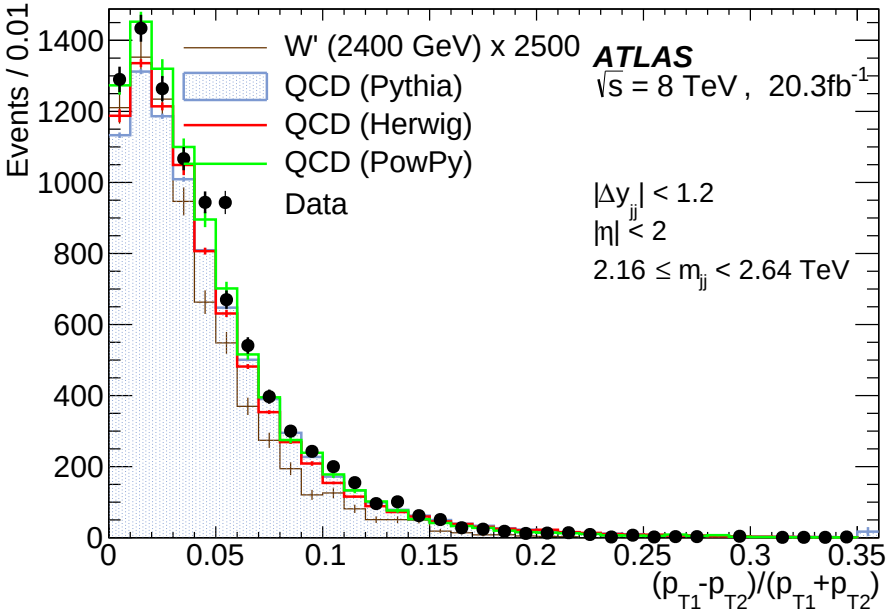

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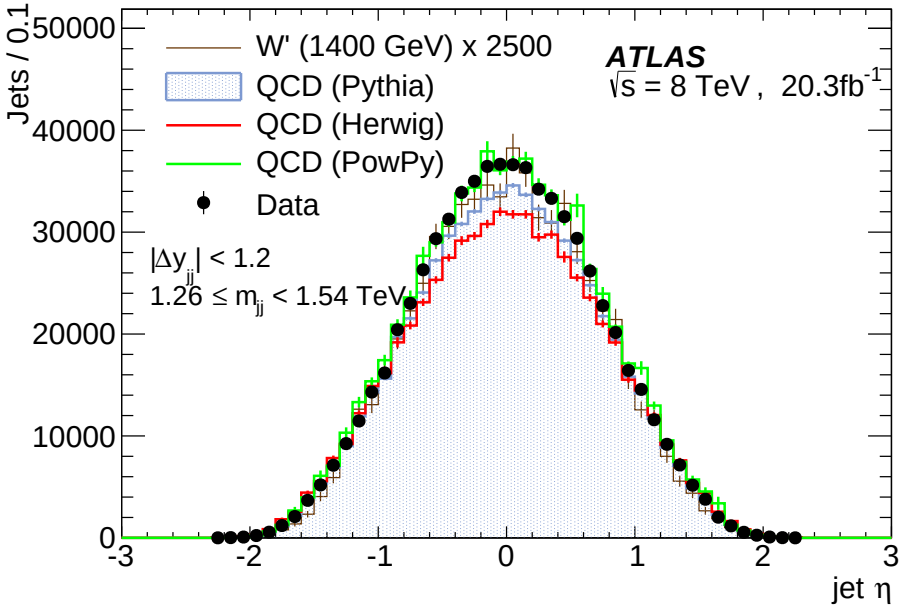

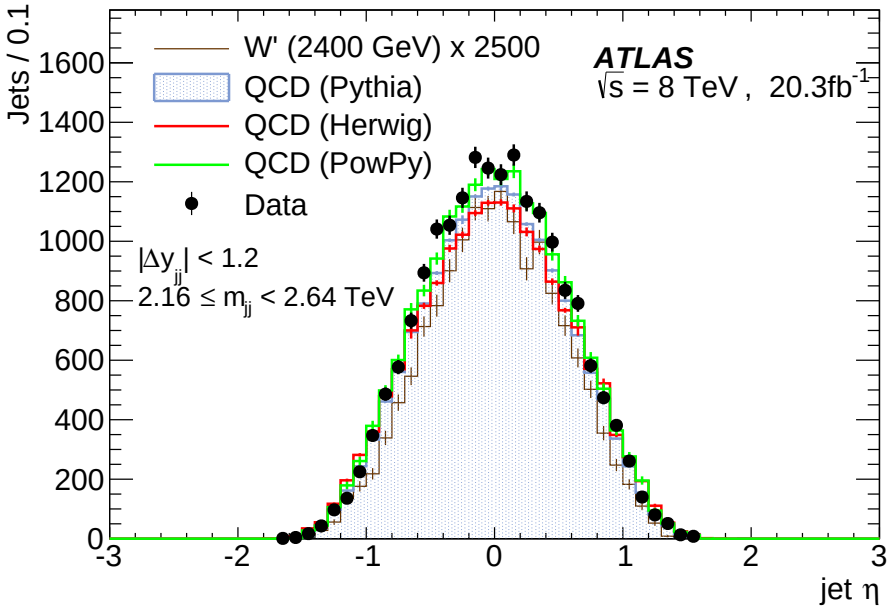

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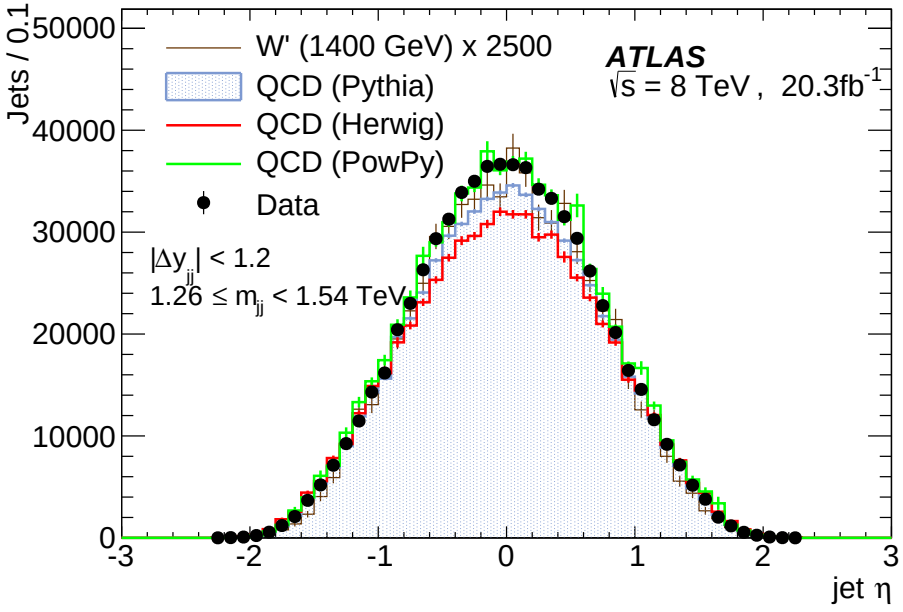

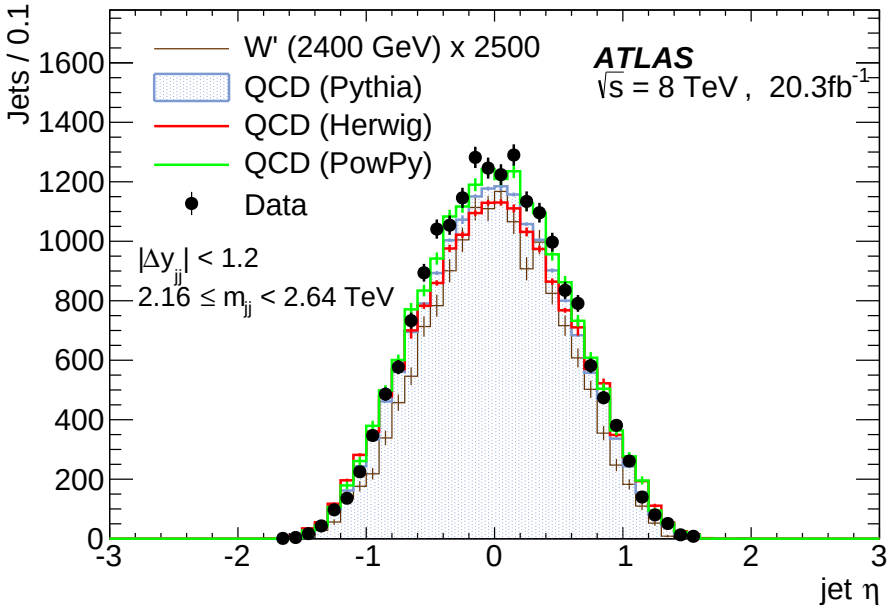

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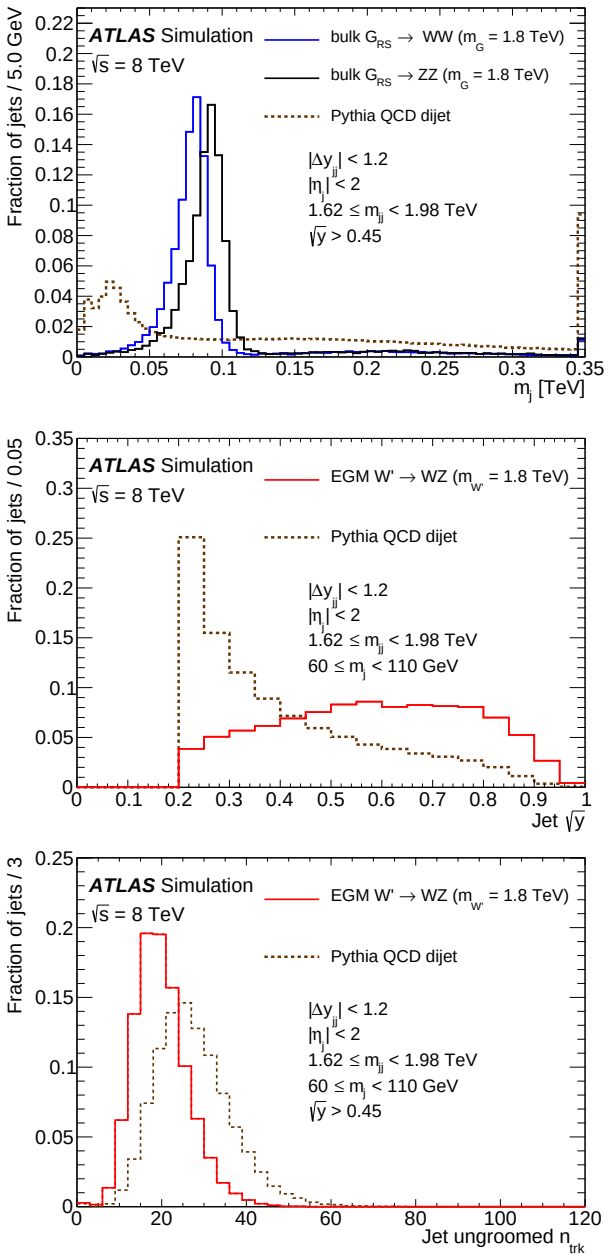
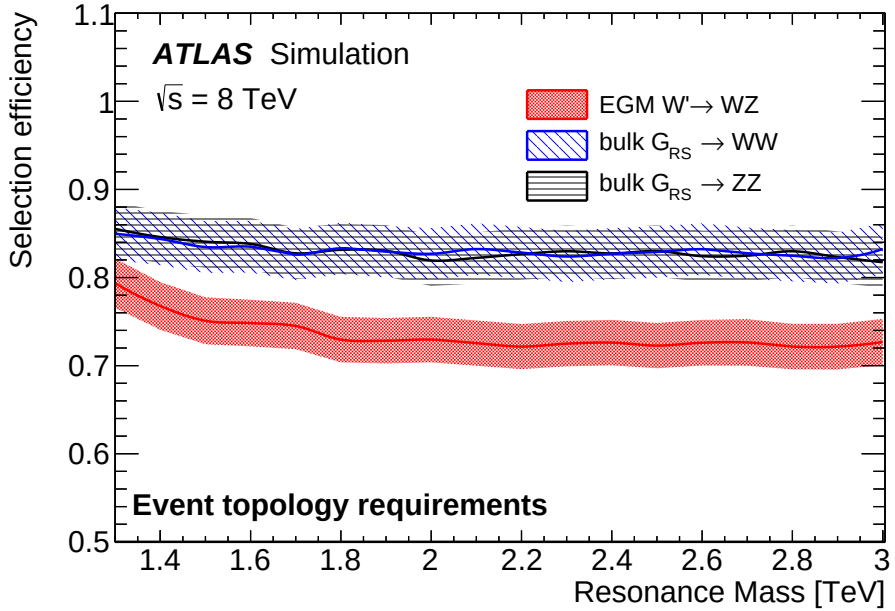
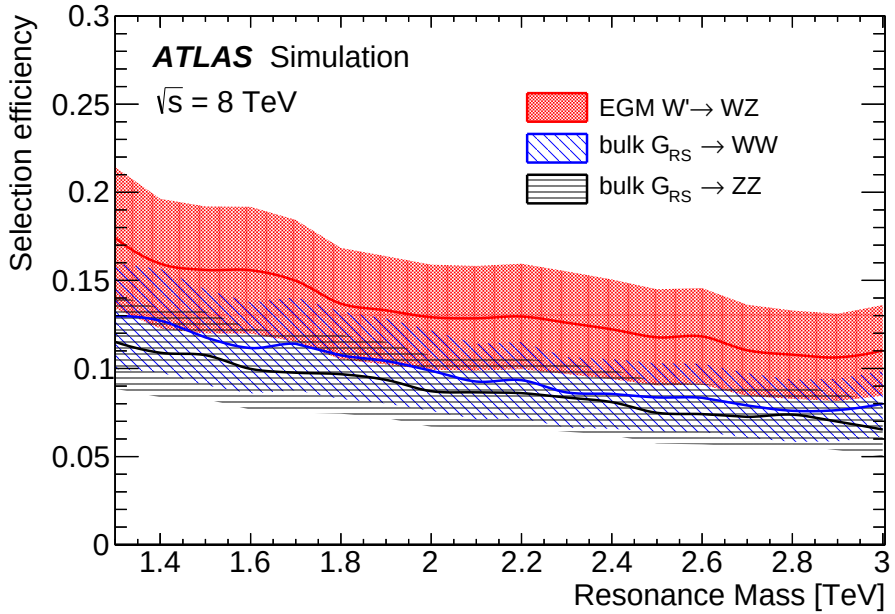


Event selection

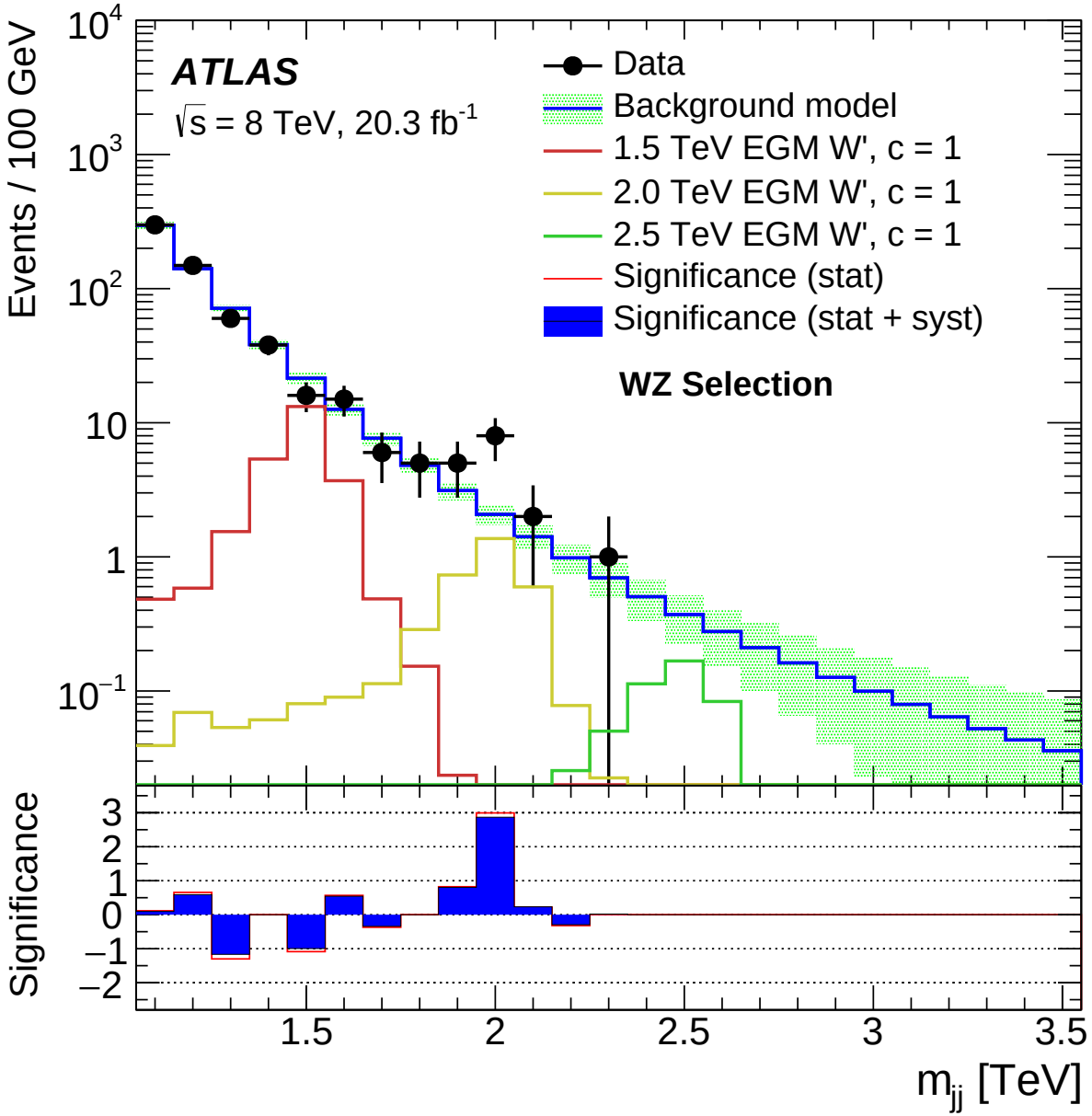
1. **Trigger:** $p_T > 360$ GeV anti-kt 1.0
2. Apply **BDRS-A** split-filter
3. Require $m_{JJ} > 1.05$ TeV
   - Ensures on **trigger plateau**
4. **Rapidity gap** between leading jets, $|\Delta y_{12}| < 1.2$
   - s-channel signal more **central** than t-channel QCD
5. Leading jets p_T **asymmetry** $A_{p_T} < 0.15$
   - Used as proxy for large-R **jet cleaning**
6. Leading jets $|\eta| < 2.0$
   - Ensures a good **overlap** with tracker
7. Correction for jets on **calorimetry holes**
8. **Boson tagging** cuts
   - Jet mass (WZ, WW, ZZ), momentum balance, n_{trk} ghost associated to jet

- Background efficiencies
  - **Topological** $\epsilon \approx 48\%$
  - **Tagger** $\epsilon \approx 1.2 - 0.6\%$ (per jet)





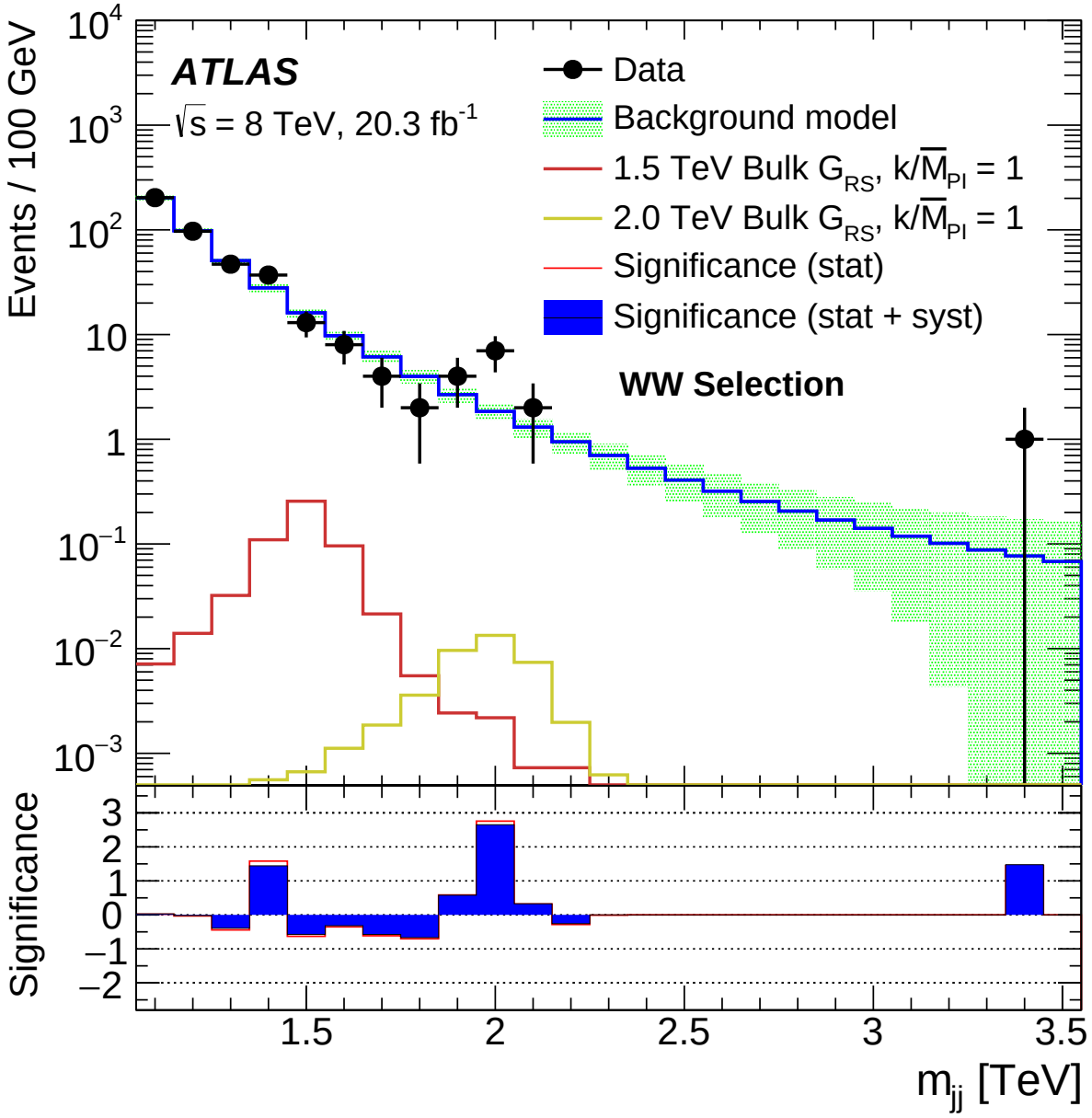
$X \rightarrow WZ$ selection



- Full **WZ** selection applied
  - Z mass window applied to **leading** mass jet
  - W mass window applied to **sub-leading** mass jet
- **Good agreement** seen with steeply, smoothly falling background model in the low/high mass regions
- **Deviation** from the background observed at around 2 TeV

M	WZ	WW	ZZ	Sum
1750-1850	5	2	1	6
1850-1950	5	4	5	6
1950-2050	8	7	3	8
2050-2150	2	2	1	3
2150-2250	0	0	0	0
2250-2350	1	0	0	1
3350-3450	0	1	0	1
Total	21	16	10	25

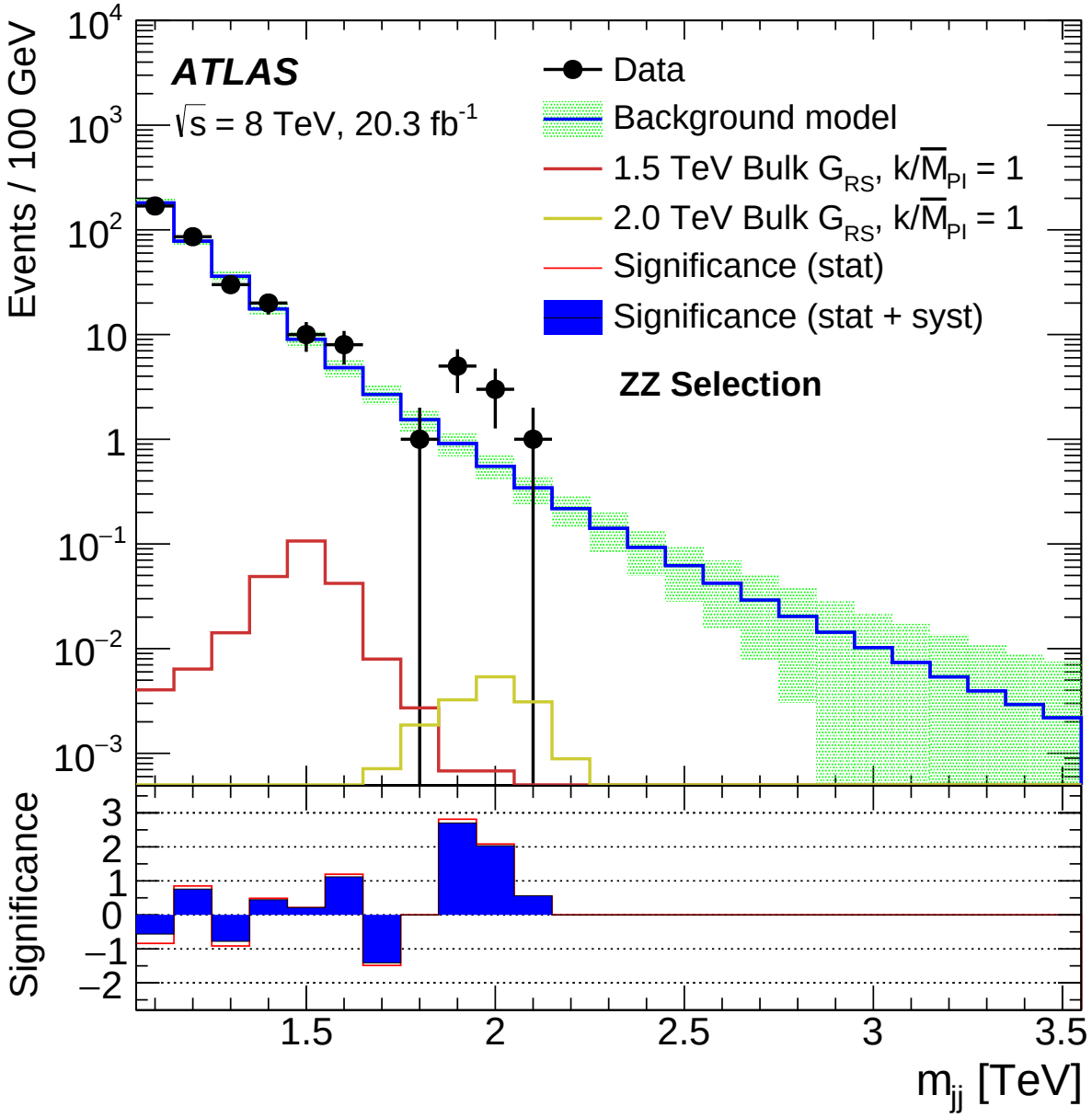
$X \to WW$ selection



- Full **WW** selection applied to the data
  - *W* mass window applied to **both** jets
- **Good agreement** again seen with steeply, smoothly falling background model
- **Deviation** from the background still observed at around 2 TeV
- **Remember:** There is an **overlap** between the *W*/*Z* mass windows

M	WZ	WW	ZZ	Sum
1750-1850	5	2	1	6
1850-1950	5	4	5	6
1950-2050	8	7	3	8
2050-2150	2	2	1	3
2150-2250	0	0	0	0
2250-2350	1	0	0	1
3350-3450	0	1	0	1
Total	21	16	10	25

$X \to ZZ$ selection



- Full **ZZ** selection applied to the data
  - Z mass window applied to **both** jets
- **Good agreement** again seen with steeply, smoothly falling background model
- **Deviation** from the background still observed at around 2 TeV
- **Remember:** There is an **overlap** between the W/Z mass windows

M	WZ	WW	ZZ	Sum
1750-1850	5	2	1	6
1850-1950	5	4	5	6
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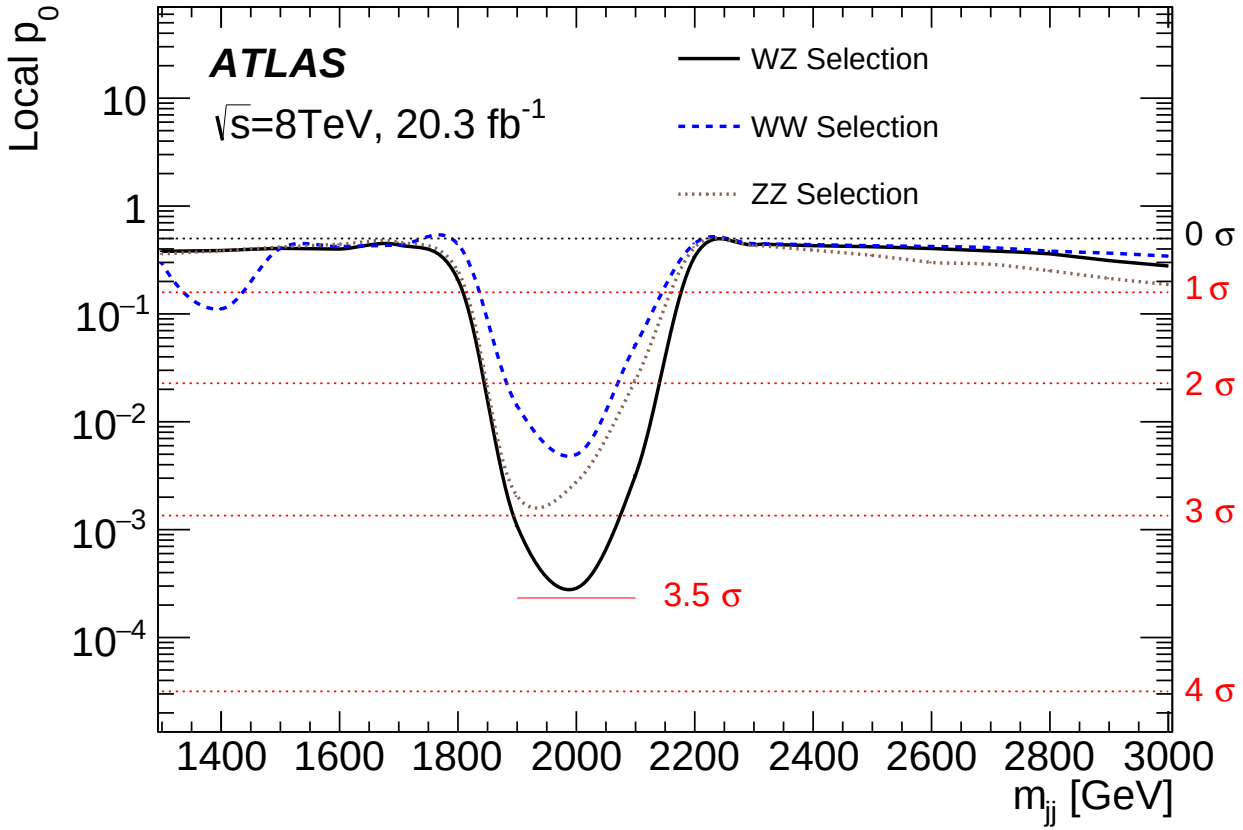
Total	21	16	10	25

Observed p_0 value

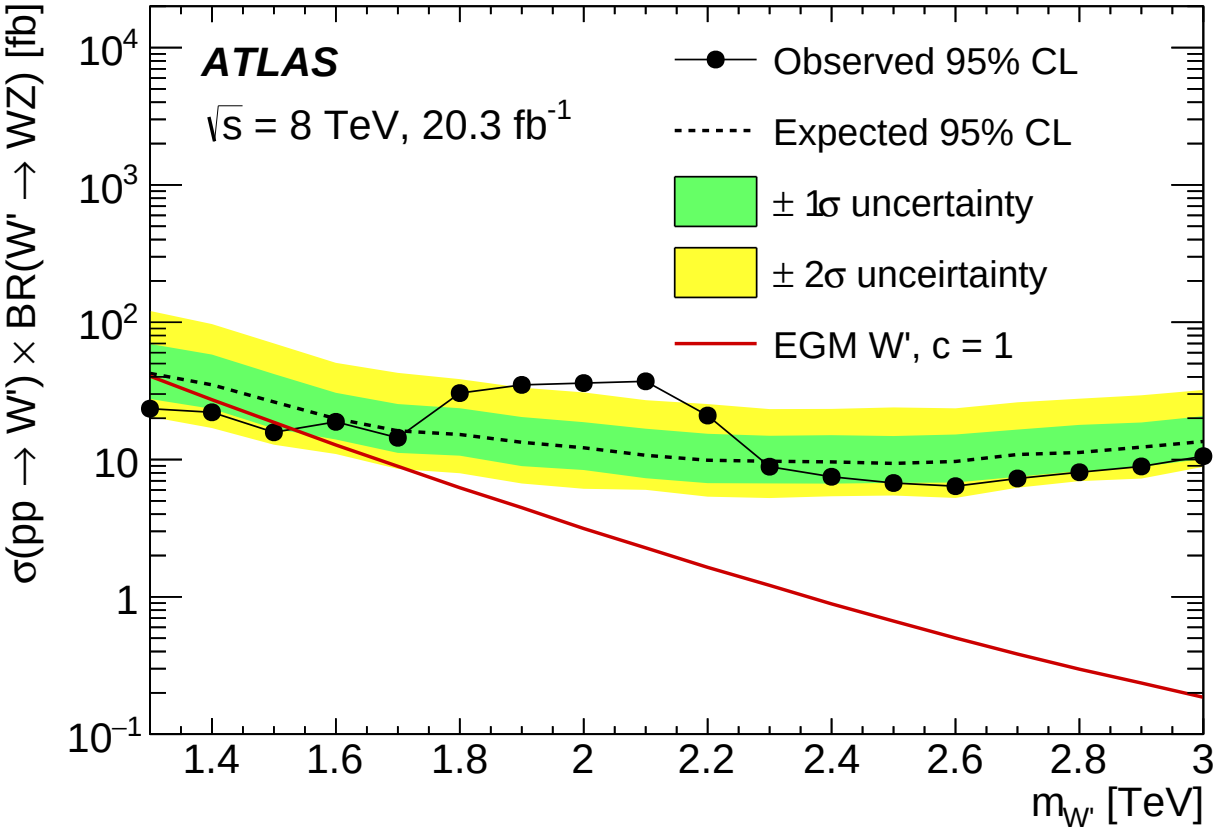


- A **discrepancy** was seen with respect to the expected background distribution
- Once suitably confident it is not an error, its significance should be **quantified**
- In the *WZ* channel:
- **Local** $p_0 = 3.4\sigma$
- **Global** $p_0 = 2.5\sigma$
  - Global σ takes into account the **look elsewhere effect**
  - LEE includes **weighted contribution** from *WW*/*ZZ* channels due to the overlap

- Therefore, no **statistically significant deviation** from the background has been observed

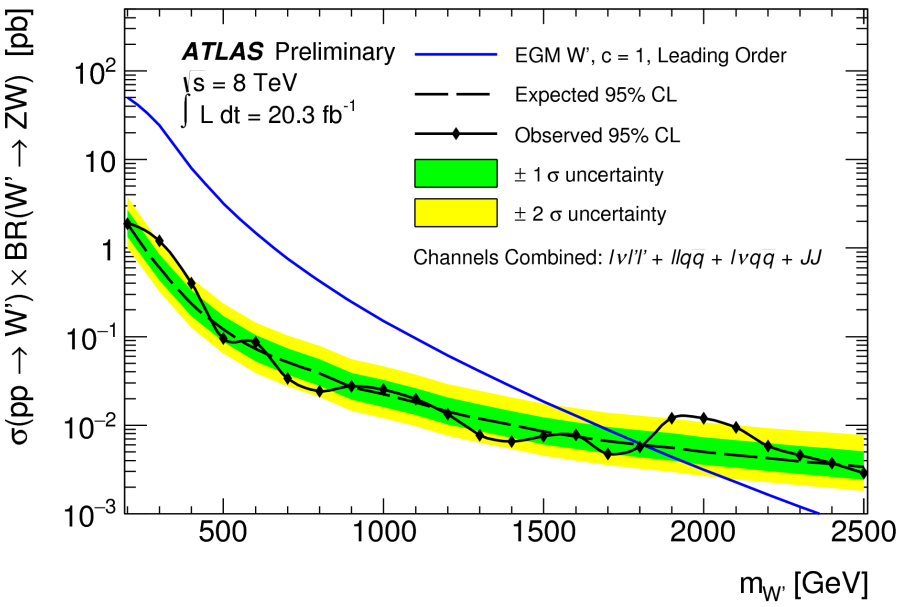
$X \to WZ$ limits

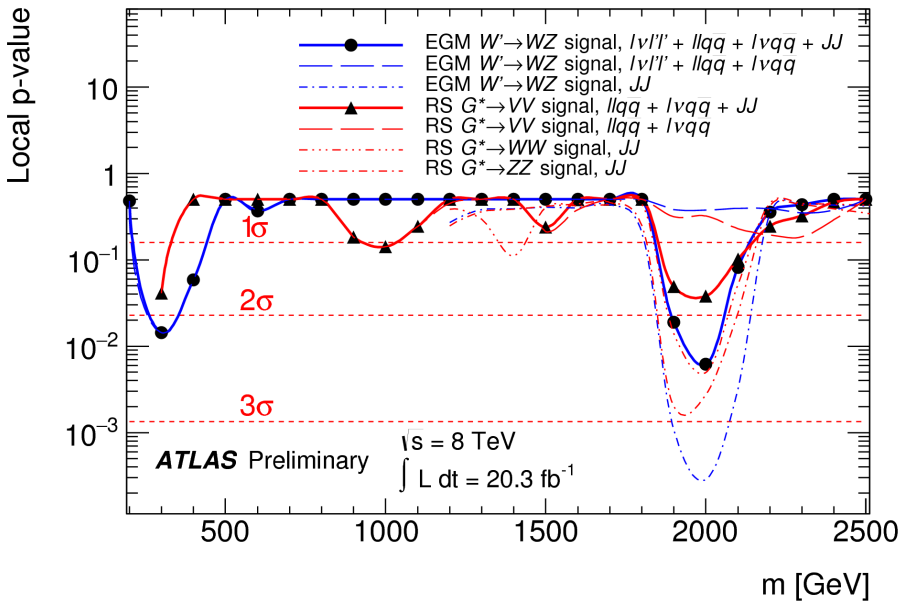
- As no **significant deviation** was observed, we continue to set limits on the observed distributions
- 95% confidence limits set on $\sigma \times \mathcal{B}$ using the $\mathrm{CL_S}$ prescription taking into account the **systematic uncertainties** and **background fit**



- **Expected** limits broadly agree with the observed limits
- **Exclusion** of EGM W' from $1.3 - 1.5$ TeV
- **Broad deviation** from the background observable at around 2 TeV
- **Benchmark** extended gauge model W' $\sigma \times \mathcal{B}$ shown for **comparison** purposes
- WW, ZZ in backup

Are we alone? ATLAS combination

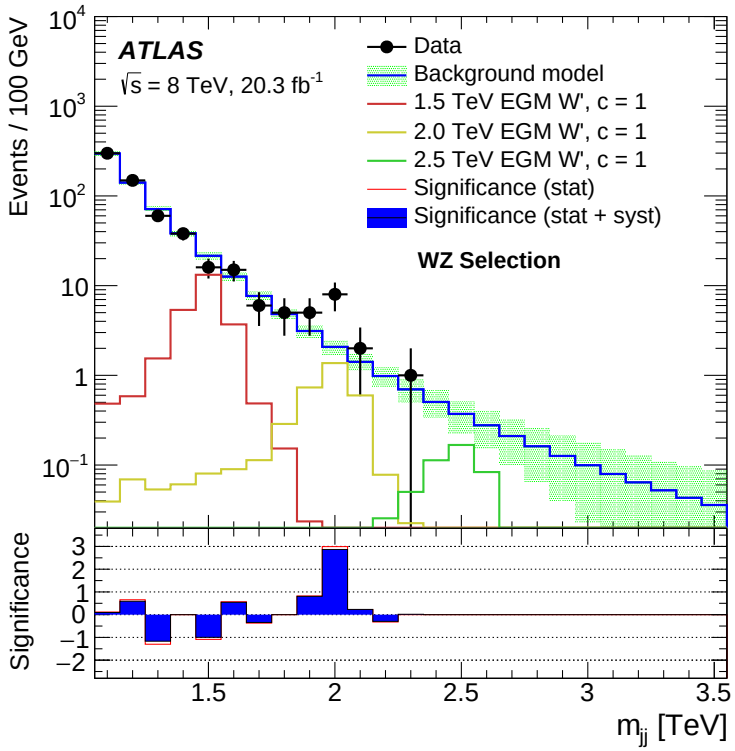


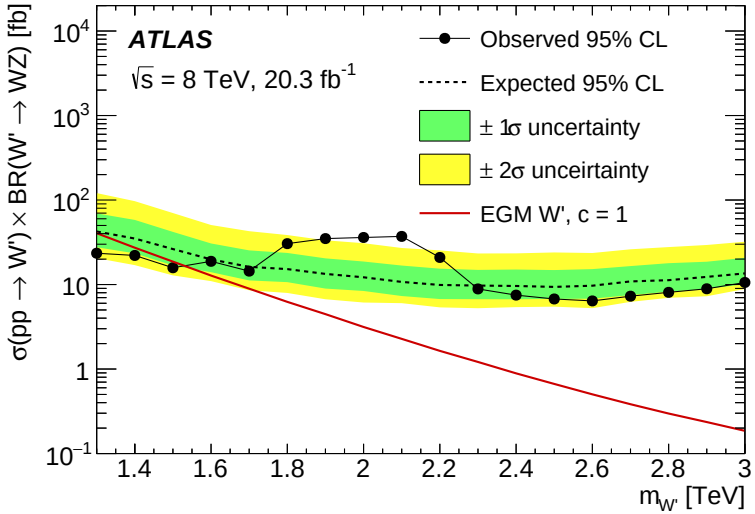


- ATLAS diboson combination ATLAS-CONF-2015-045
- In the full combination discrepancy is reduced to a 2.5σ local excess
- Limits increased to 1.81TeV in the W' search channels
- Fully hadronic channel in (significant) tension with the leptonic channels
  - Pointing to statistical fluctuation in fully hadronic channel?
  - Run-2 will sort this out!
- Full paper following up CONF note in the ATLAS pipeline

Summary – $X \to VV \to JJ$

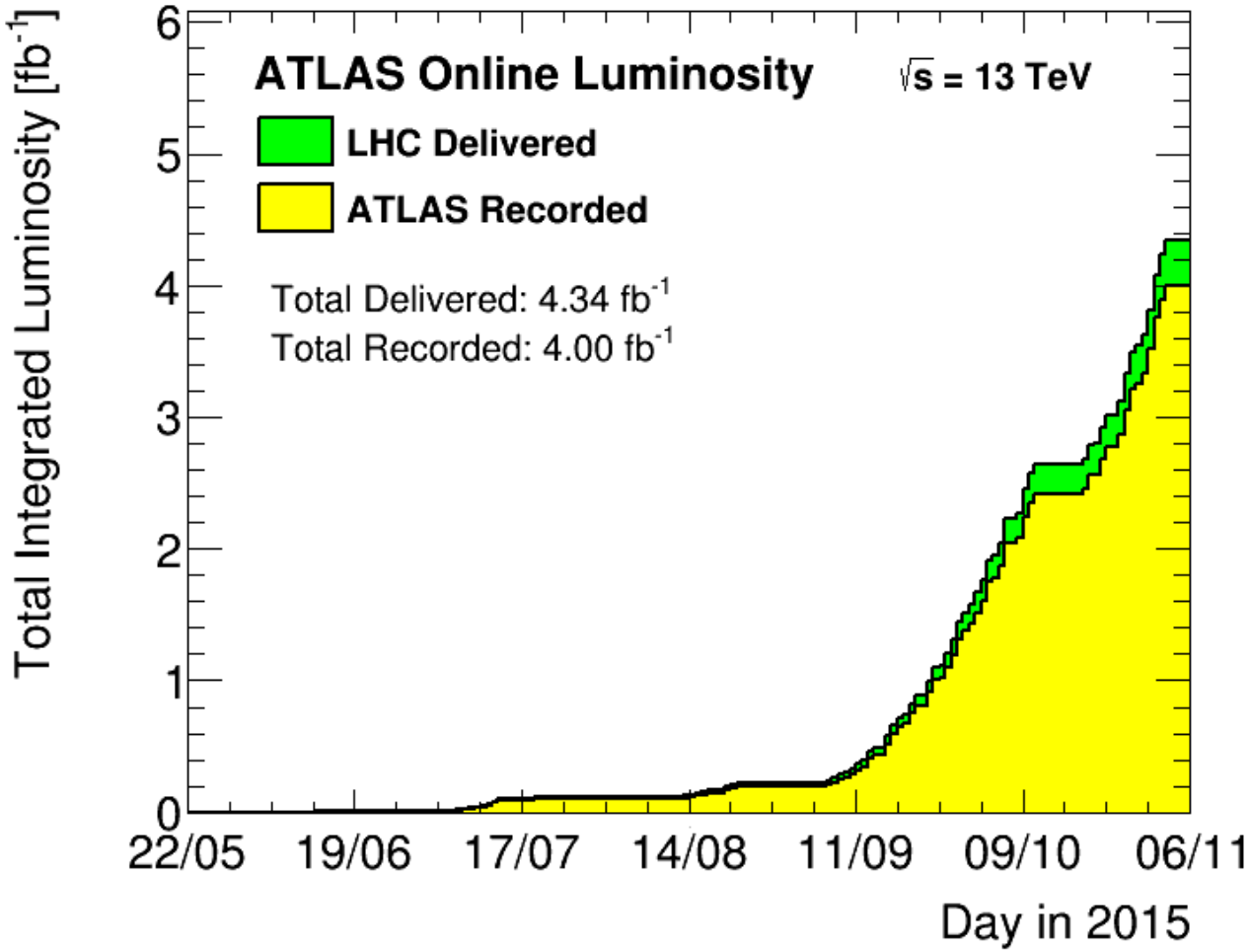
- Presented a search for a **high mass diboson resonance**, [arXiv:1506.00962]
  - Used 20.3fb^{-1} 8TeV ATLAS data
  - Jet substructure (BDRS-A CA 1.2 jets) used to separate signal from background
  - QCD dominated background modelled by parametric function
- **Deviation** from expected steeply, smoothly falling background seen at **2 TeV**
- Cross-checks performed, **no major issues** discovered
- **Excess** $p_0 = 3.4\sigma$ local, 2.5σ global
- **Limits** exclude EGM W' models with $1.3 < m_{W'} < 1.5$ TeV
- Combination with other diboson search channels **reduces excess** to 2.5σ local
- **Preparations** underway to repeat search in 13TeV data



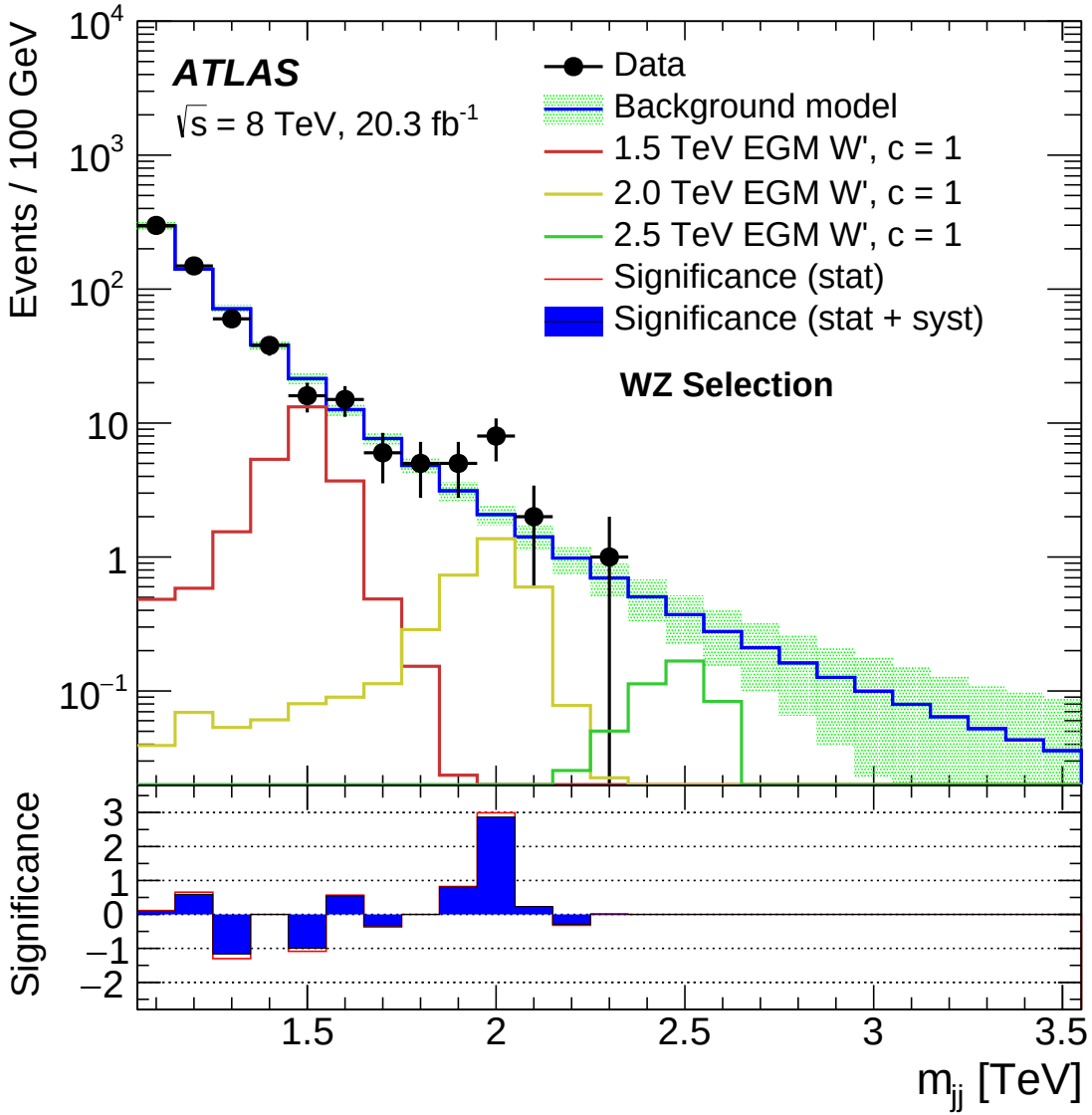


The Future: Run-2

~~The Future~~ How soon is now?

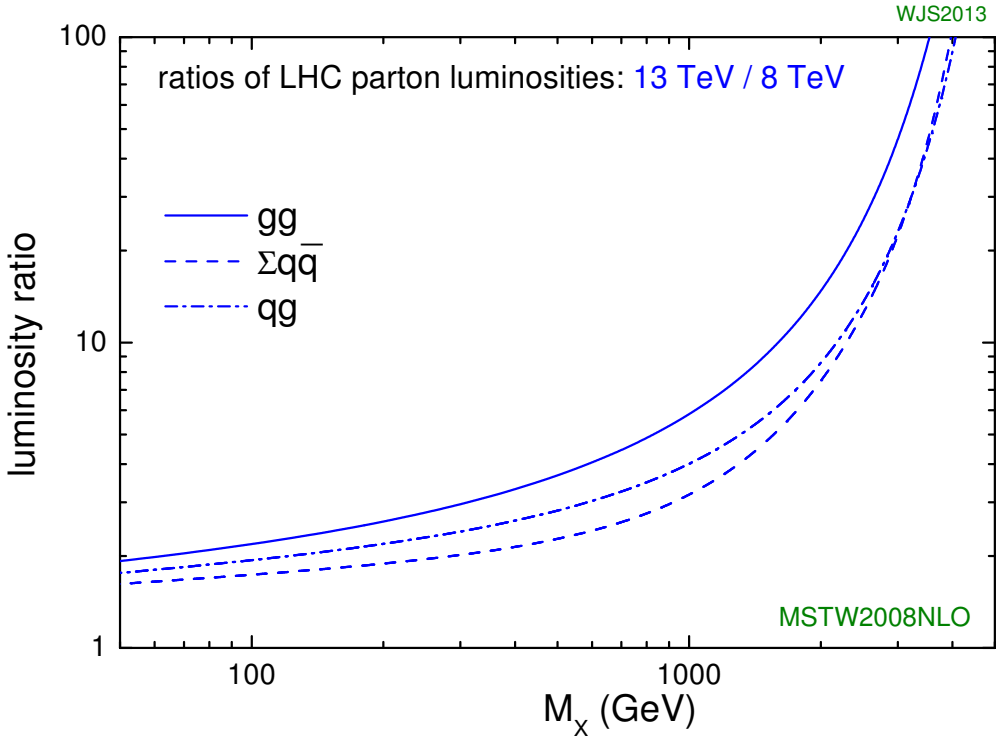


How much data is needed?



- So question one is **how much** Run-2 13 TeV data do we need to **surpass** for example the Run-1 $VV \rightarrow JJ$ result?
- At 2 TeV production cross-sections grow **considerably**
  - For gluon-gluon fusion $\times 15$, i.e. for G_{RS} production
  - For $q\bar{q}$ initiated $\times 8$, i.e. for W' production
  - Unfortunately QCD background also increases
- So a **smaller** amount of Run-2 data ($1 - 3 fb^{-1}$) should be roughly equivalent to the 8 TeV dataset

How much data is needed?



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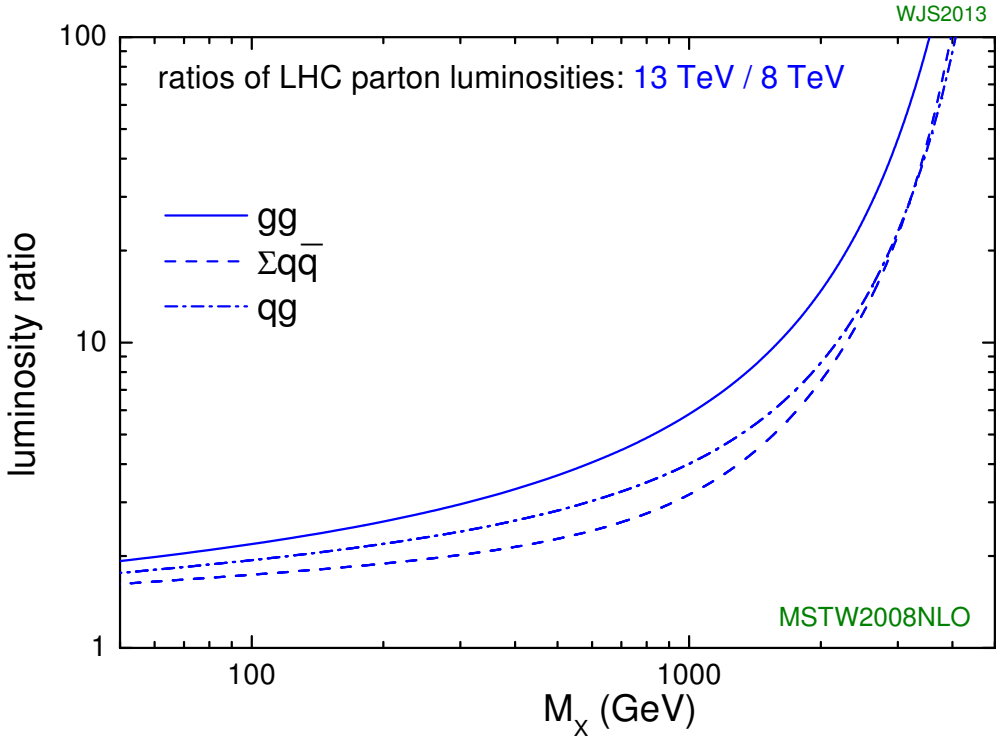

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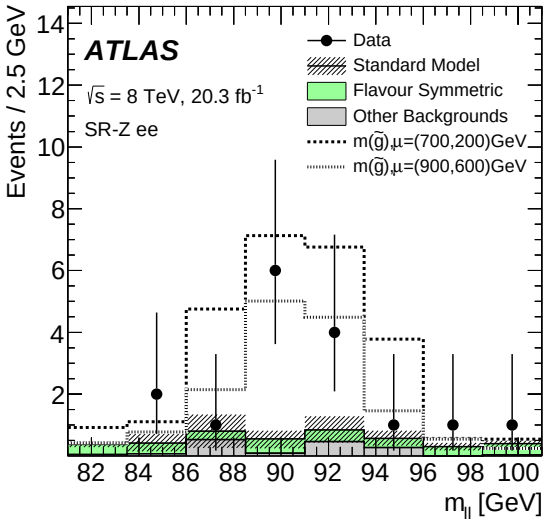
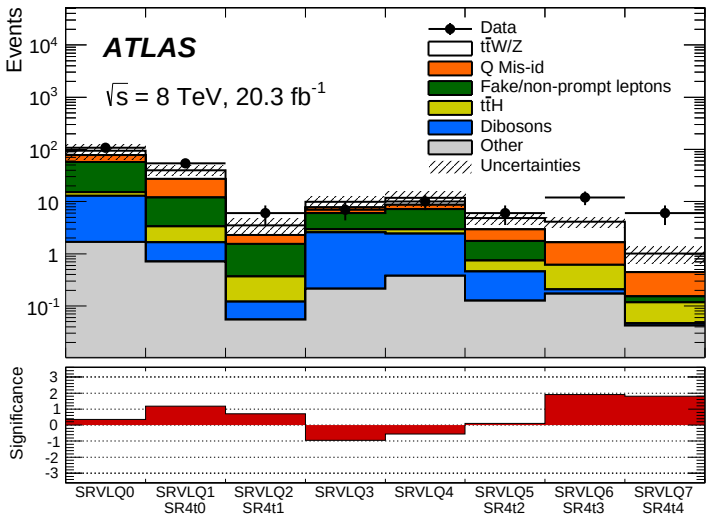
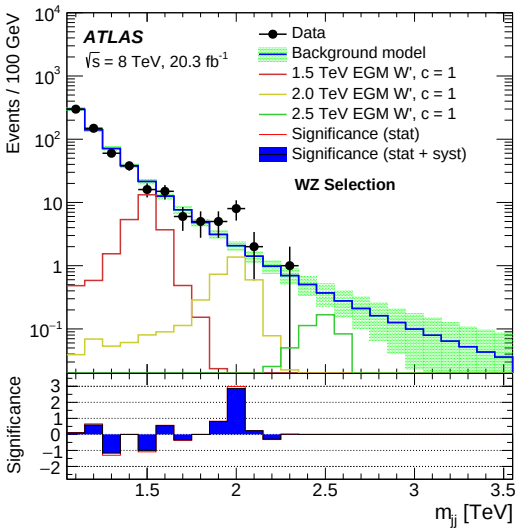
  - Unfortunately QCD background also increases
- So a **smaller** amount of Run-2 data ($1 - 3fb^{-1}$) should be roughly equivalent to the 8 TeV dataset

Conclusions

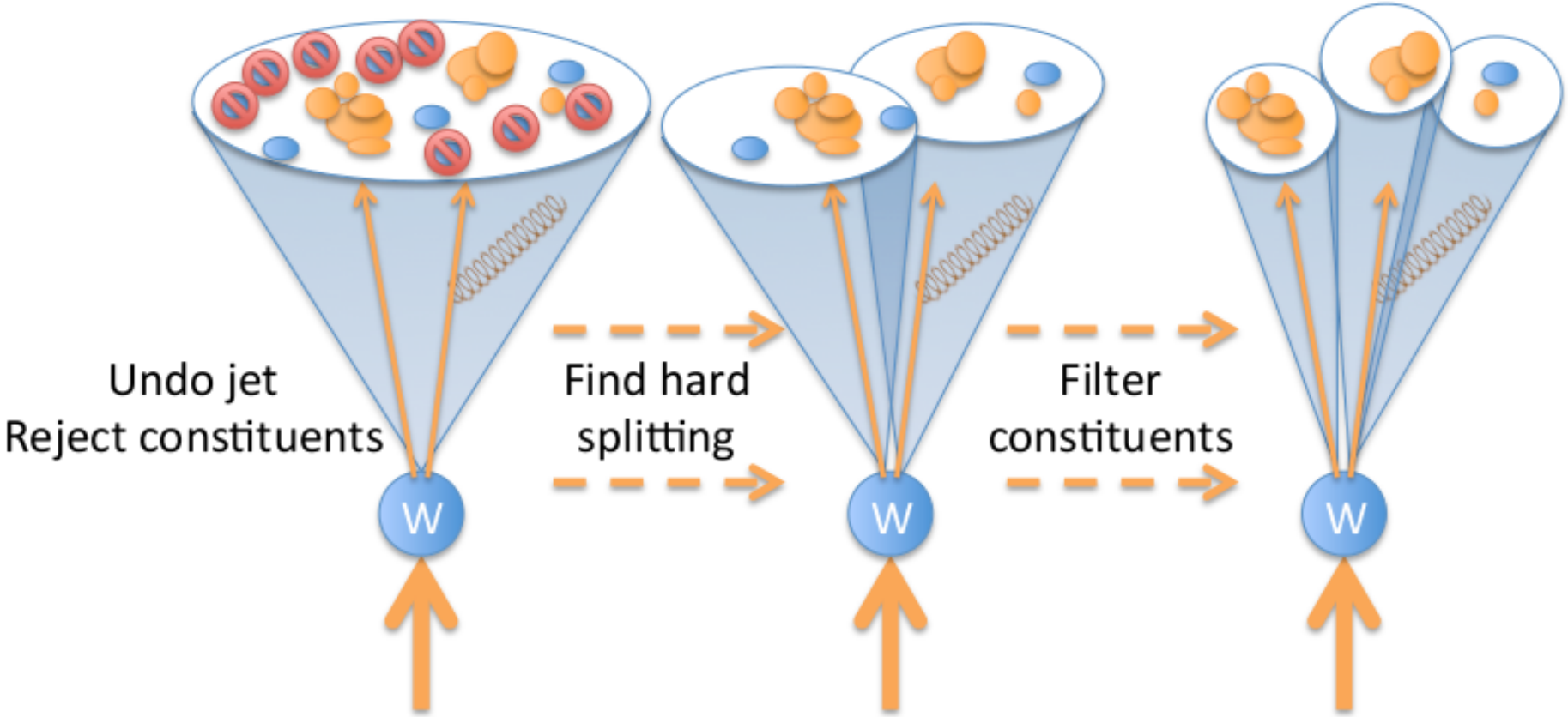
- Presented a series of searches for BSM physics by the ATLAS SUSY and Exotics groups in Run-1 of the LHC which showed anomalous features
- All used 20.3fb^{-1} 8TeV ATLAS data
- Deviations between $2 - 3.5\sigma$ local observed
- In the $VV \to JJ$ search a global significance of 2.5σ was observed, before combination with the leptonic channels



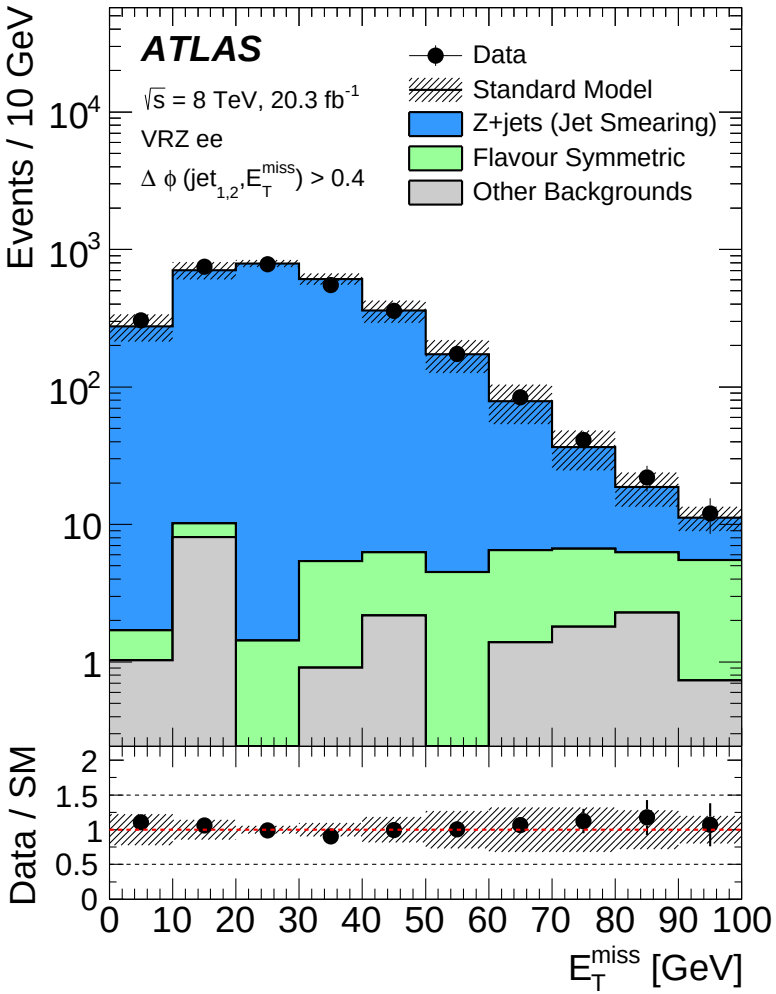


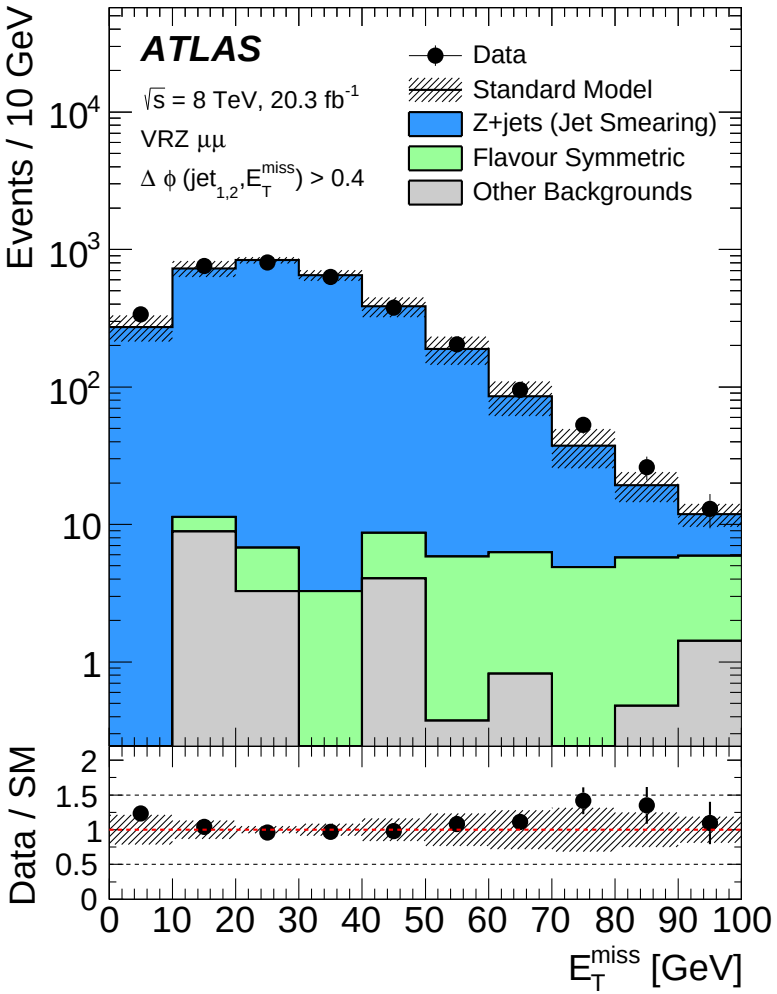


Backup


Undo jet
Reject constituents
Find hard
splitting
Filter
constituents
W
W
W

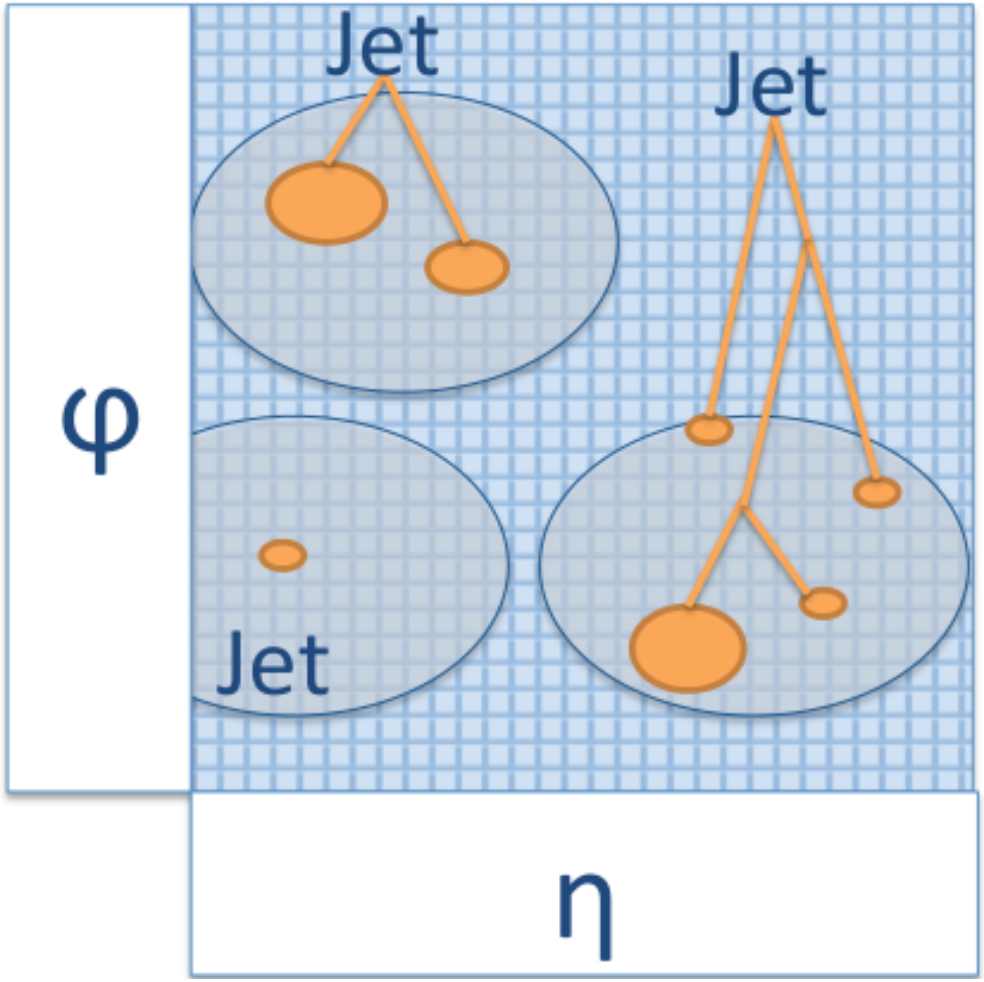
SUSY: Z/γ+jets modelling





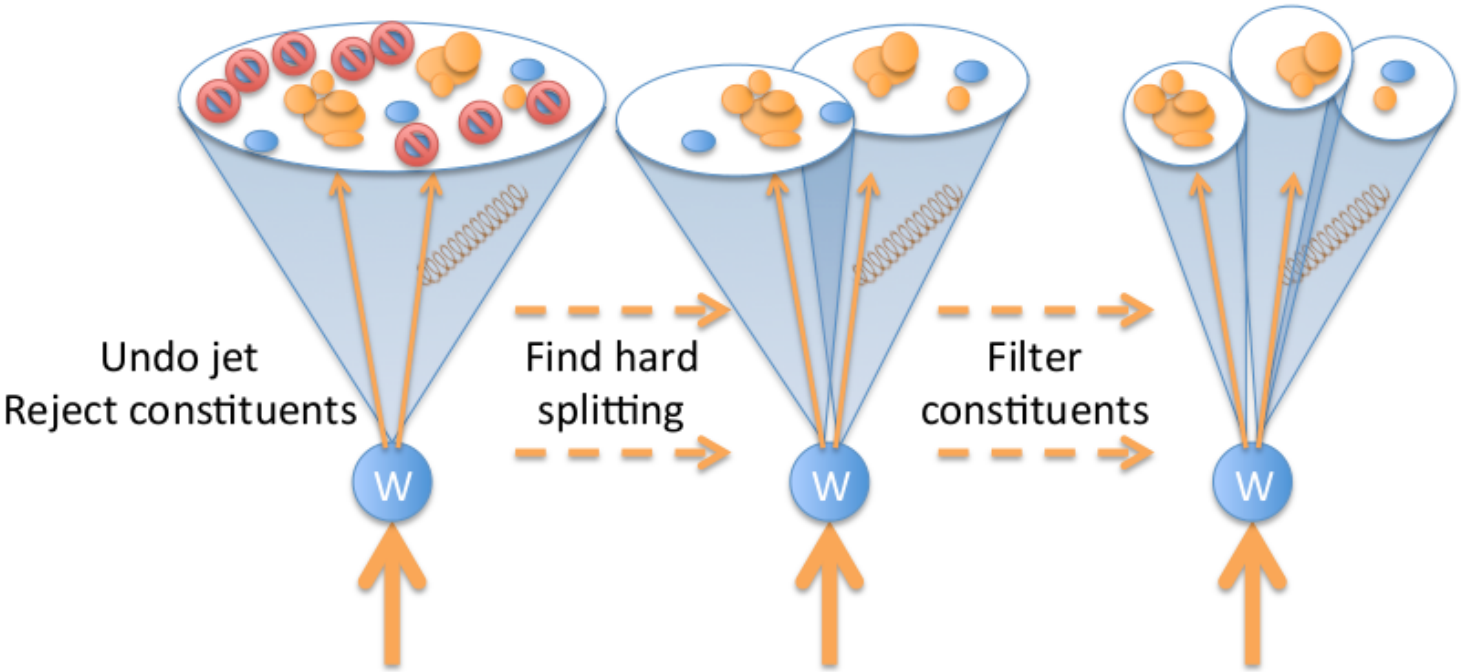
Cambridge-Aachen Jets

- **Cambridge-Aachen** jets (CA jets)
  - [arXiv:9707323] or [arXiv:0802.2470]
- Part of the **sequential recombination** family of jet reconstruction algorithms
  - Calculate the ΔR_{ij} between all jet constituents
  - Combine **closest constituents** first
  - Merge while $R \leq 1.2$ (in this analysis)
  - If there are no components within 1.2, **redefine as a jet** and remove from the collection of constituents
  - Merge until there are **no components** left
- **NO** p_{T} dependence!
- Therefore can look into the history and use the p_{T} splitting information



BDRS Split-Filter

- The **BDRS split filtering** algorithm, [arXiv:0802.2470], decomposes CA jets sequential clustering to find **hard substructure** within
- Originally defined to find **boosted** $H \to bb$ decays



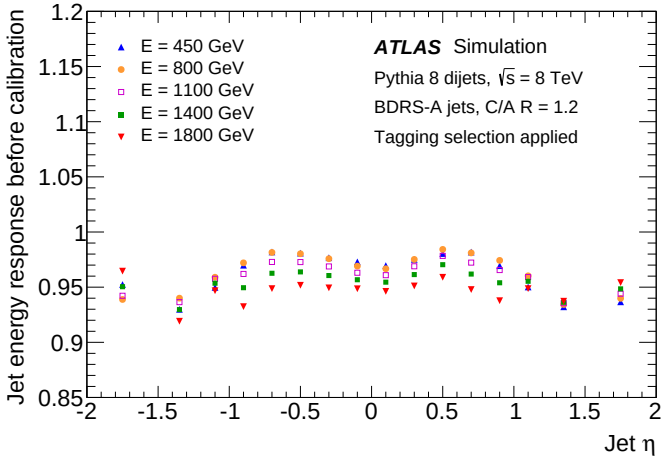
- The **decomposition** follows some simple steps
  - For jet j, undo the **last step** of clustering forming jets j_1 and j_2 ($m_{j_1} > m_{j_2}$)
  - If there was a **large mass drop**, $m_{j_1} < \mu_{\max} m_j$ and the p_{T} balance is not **too asymmetric**, $\frac{min(p^2_{T_{j_1}}, p^2_{T_{j_2}})}{m^2_{j_0}} \Delta R^2_{j_1,j_2} \geq y_{\min}$, define j as from a **hard** splitting and stop
  - Otherwise redefine j as j_1, discard j_2, and continue
- Filter the resulting jet by **re-clustering** as $n_{\mathrm{r}} \times R_{\mathrm{r}}$ sized subjets

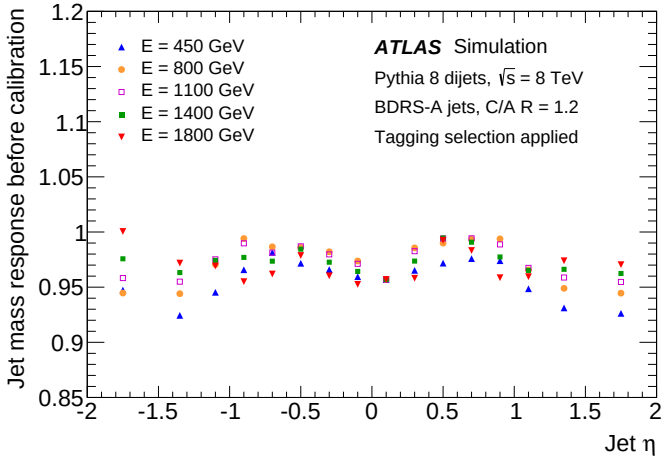
BDRS-A CA $R = 1.2$ Jet Calibration

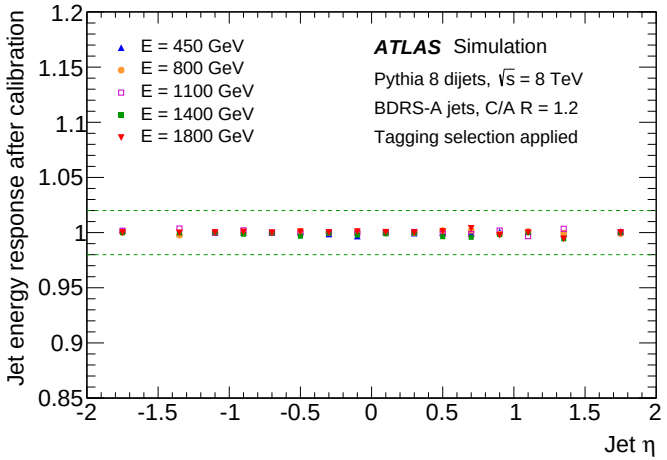
- Particle level jet **energy and mass calibrations** were derived and applied to the BDRS-A CA $R = 1.2$ jets used in the analysis
- Effectively **restores** jet energy/mass response over the **full** jet E and η range

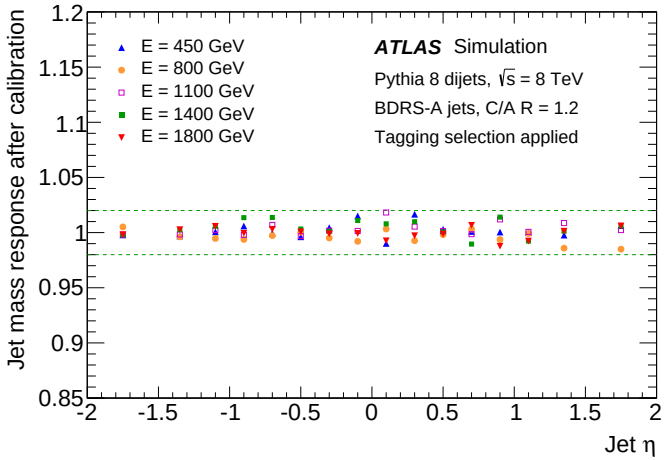
---

- Calculate the **jet energy response** in bins of η_{det} and E_{truth}
- Fit the responses with a Gaussian fit, to gain **mean response** in each bin, $< \mathrm{R}_{\mathrm{E}}^{\mathrm{jet}} >$
- Derive the mean reconstructed jet energy, $< \mathrm{E}_{\mathrm{reco}}^{\mathrm{jet}} >$
- Fit the $< \mathrm{R}_{\mathrm{E}}^{\mathrm{jet}} >$ vs $< \mathrm{E}_{\mathrm{reco}}^{\mathrm{jet}} >$ distribution to gain a **calibration function**
- Repeat process for **mass calibration** using the LCW+JES jets





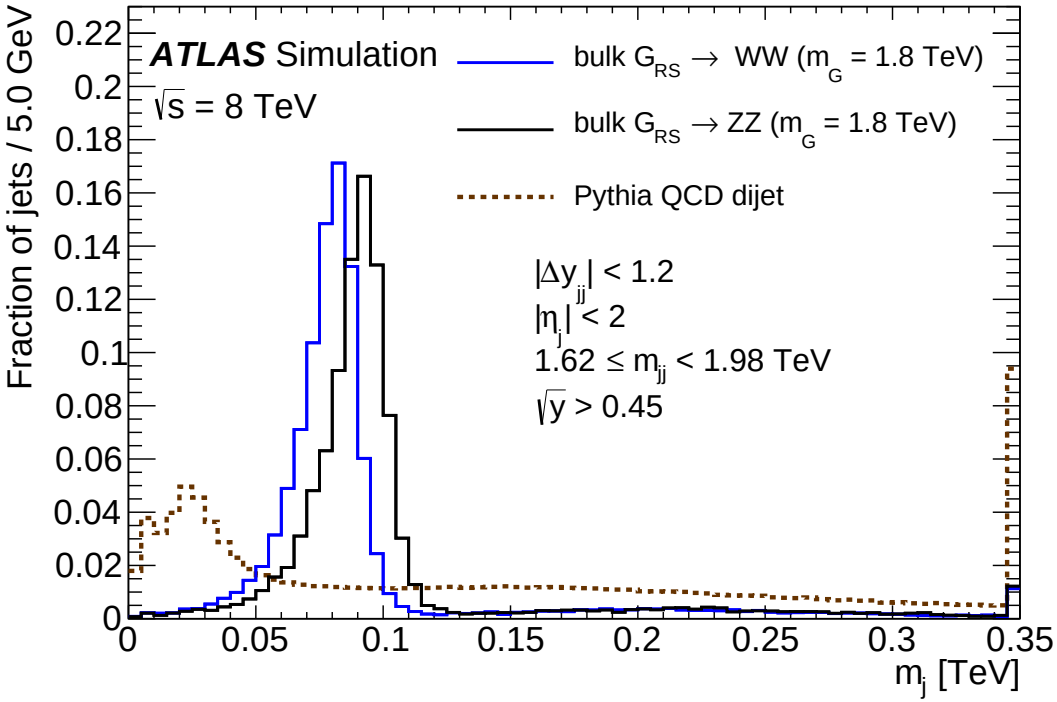




Tools: Jet mass

2. **Filtered jet mass**
   - Separates peaked boson mass from falling QCD spectrum

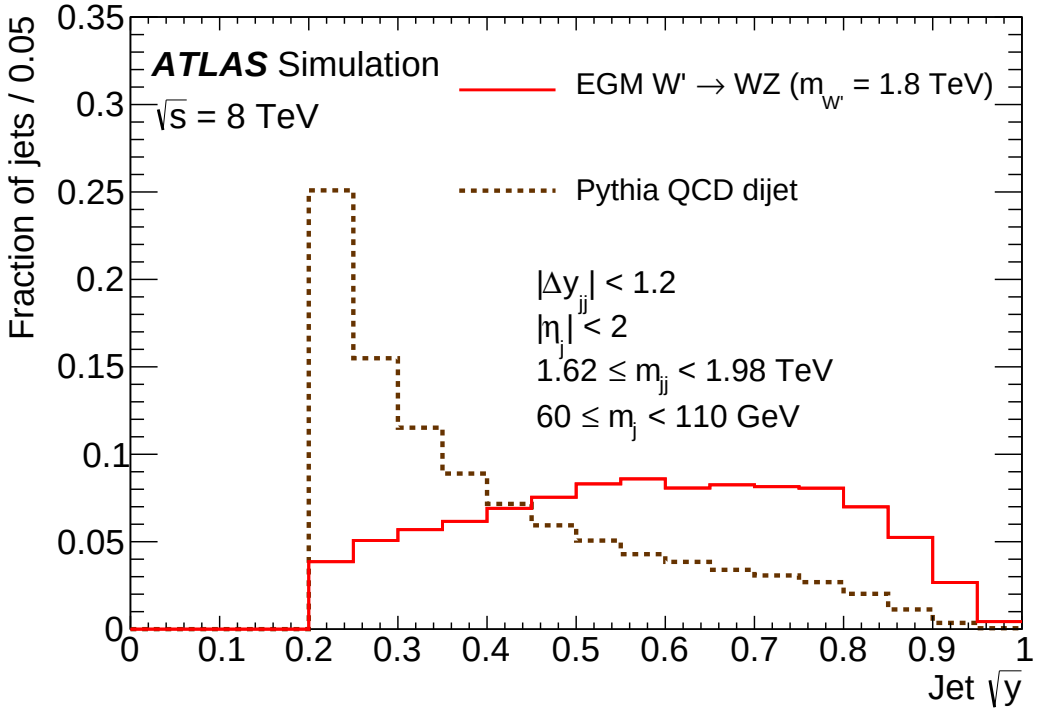
- Apply ± 13 GeV **window cuts** around boson mass from MC simulation peak ($m_W = 82.4$, $m_Z = 92.8$)
- For example, in the *WZ* cut;
  - Leading mass jet $79.8\text{ GeV} < m_{\text{jet}} < 105.8\text{ GeV}$
  - Subleading mass jet $69.4\text{ GeV} < m_{\text{jet}} < 95.4\text{ GeV}$
- Very **powerful** cut!
  - $\epsilon_{\text{signal}} \approx 80\%$
  - $\epsilon_{\text{background}} \approx 10 - 15\%$
- Cuts optimised using a **data CR**
  - Dijet formed from two tagged/un-tagged regions
- N.B. **Windows overlap!!!**



Tools: Subjet momentum balance

3. **Subjet momentum balance**
   - Boson jets **symmetric**, QCD **unbalanced**

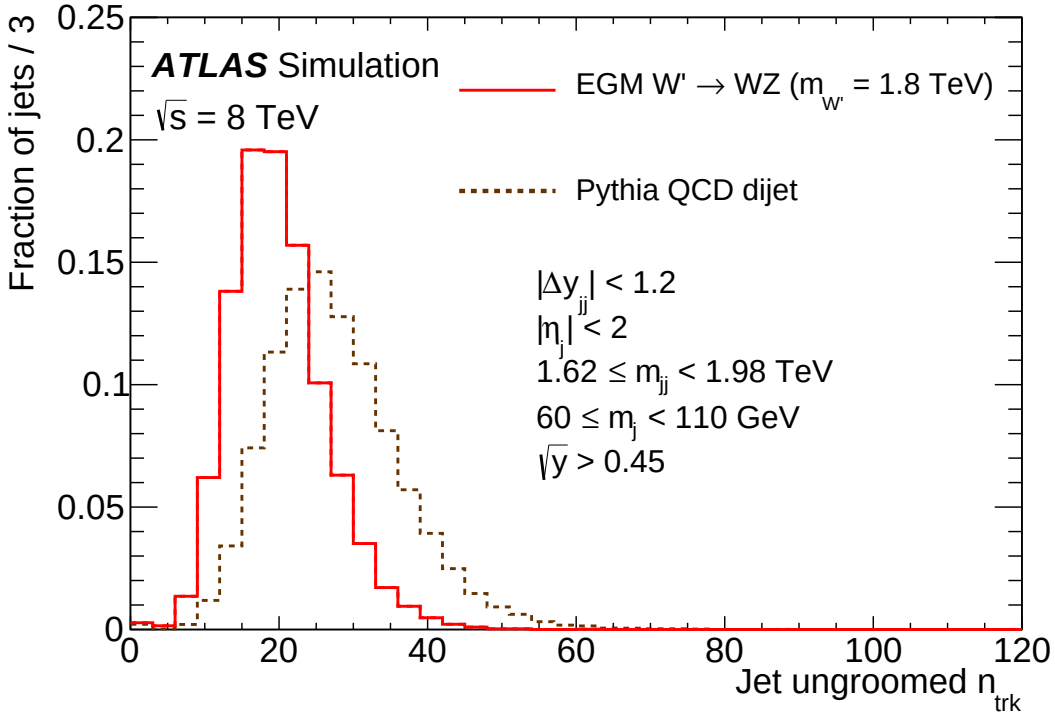
- **Soft gluon** radiation leads to asymmetric splittings
- $W/Z \to q\bar{q}$ decays tend to share momentum more **equally** between decay products
- Apply a more stringent $\sqrt{y} \geq 0.45$ cut on the subjet momentum balance
- Another **powerful** cut!
  - $\epsilon_{\text{signal}} \approx 70\%$
  - $\epsilon_{\text{background}} \approx 30\%$
- Cuts optimised using **MC**, using a wide mass window, $60\text{ GeV} < m_{\text{jet}} < 110\text{ GeV}$



Tools: Ghost matched jets

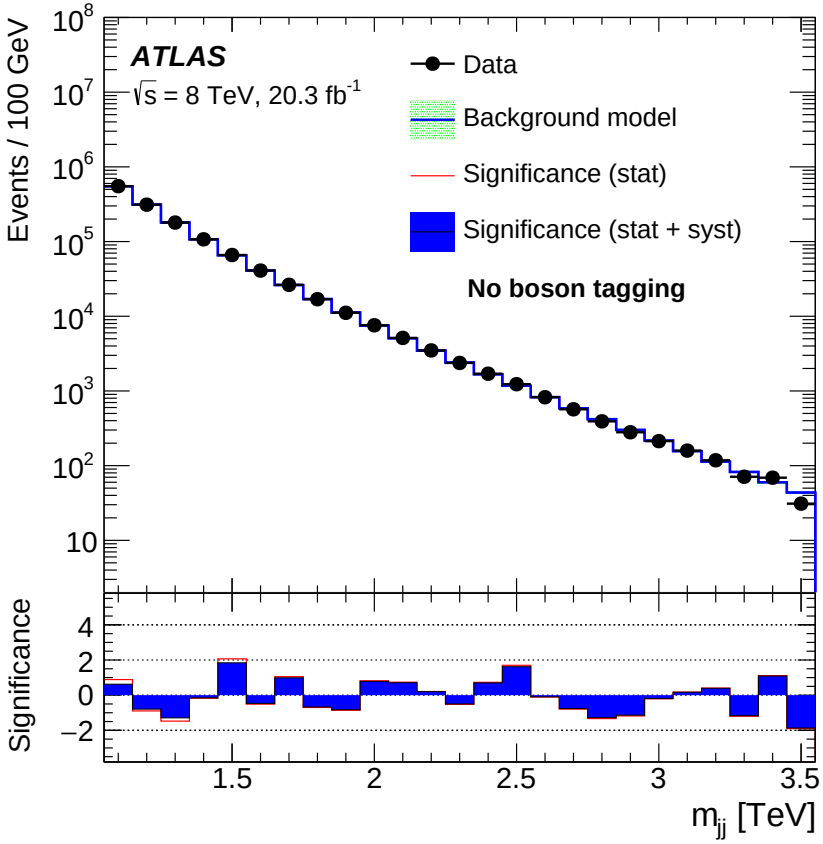
4. **Number of tracks** ghost matched to the unfiltered jet
   - More hadronic activity in QCD jets

- Emission of **hard gluon** dominates after mass/asymmetry cuts
- Expect increased **hadronic** activity from gluon
- Use the number of **ghost associated** ungroomed tracks, n_{trk}, as a proxy for hadronic activity, [arXiv:0802.1188]
- Apply $n_{\mathrm{trk}} \leq 30$ cut
- Efficiency after mass/asymmetry
  - $\epsilon_{\mathrm{signal}} = 83 \pm 7\%$
  - $\epsilon_{\mathrm{background}} \approx 65\%$
- Very **hard** to model in MC
- Cuts optimised using V+jets enriched **data CR**
- Efficiency **calibrated** in this CR



Modelling the Background

- After trying to **kill** the background we now arrive at the point of **modelling** it
- **MC statistics** needed to properly model the high m_{JJ} tail are **prohibitively** large



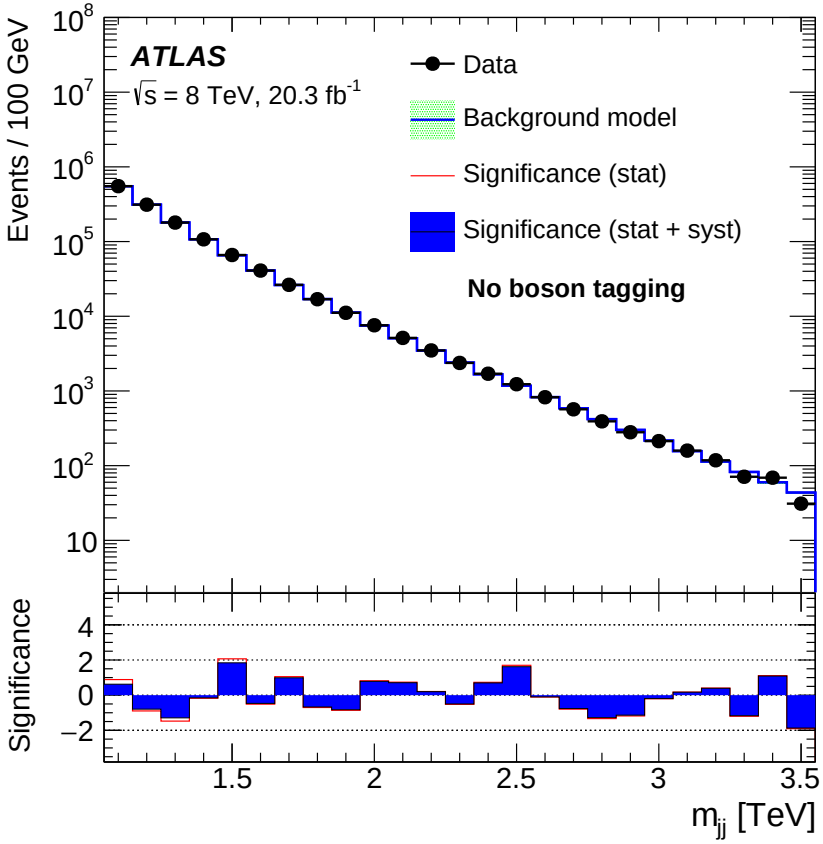
- Assume a **steeply** and **smoothly falling** distribution models the background
- Any resonance should be **narrow**, thus only affect a few bins
- Use a **parametric function** to model the background from the data

$$\frac{\mathrm{d}n}{\mathrm{d}x} = p_1(1-x)^{p_2-\xi p_3}x^{p_3}$$

- Where,
  - $x = m_{JJ}/\sqrt{s}$
  - m_{JJ} is the dijet invariant mass,
  - p_1 is a normalisation factor,
  - p_2 and p_3 are dimensionless shape parameters
  - ξ is a dimensionless constant chosen after fitting to minimise the correlations between p_2 and p_3

Modelling the Background

- After trying to **kill** the background we now arrive at the point of **modelling** it
- **MC statistics** needed to properly model the high m_{JJ} tail are **prohibitively** large



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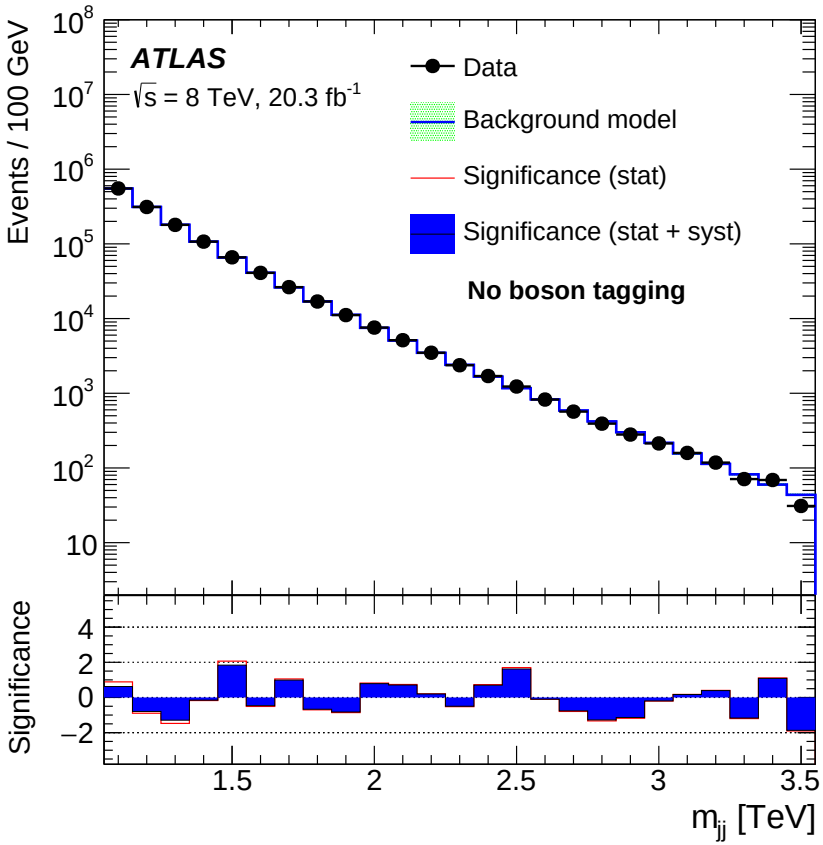

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PYTHIA dijet events	24.6/22	0.31
HERWIG++ dijet events	15.9/22	0.82
Data with $110 < m_{j1} \leq 140$ GeV and $40 < m_{j2} \leq 60$ GeV	12.1/11	0.79
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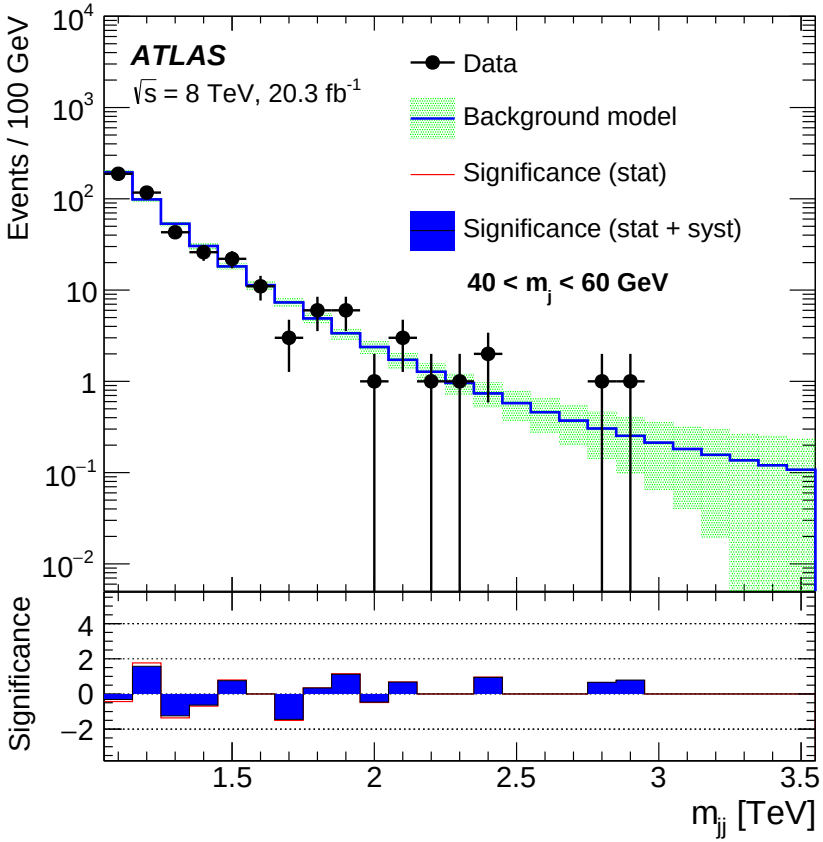

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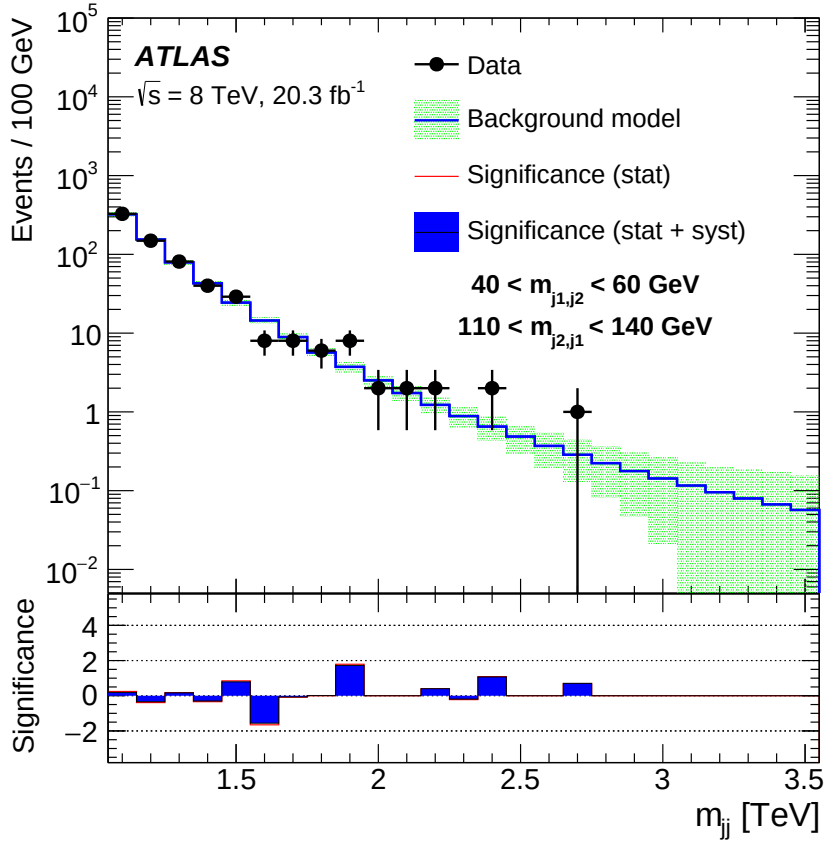

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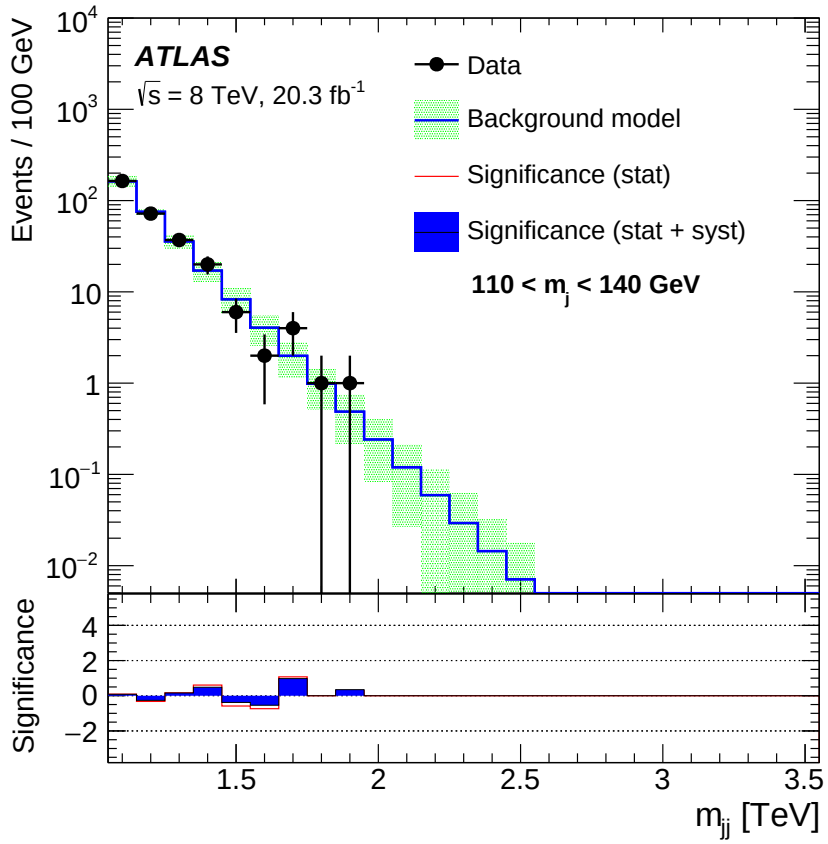

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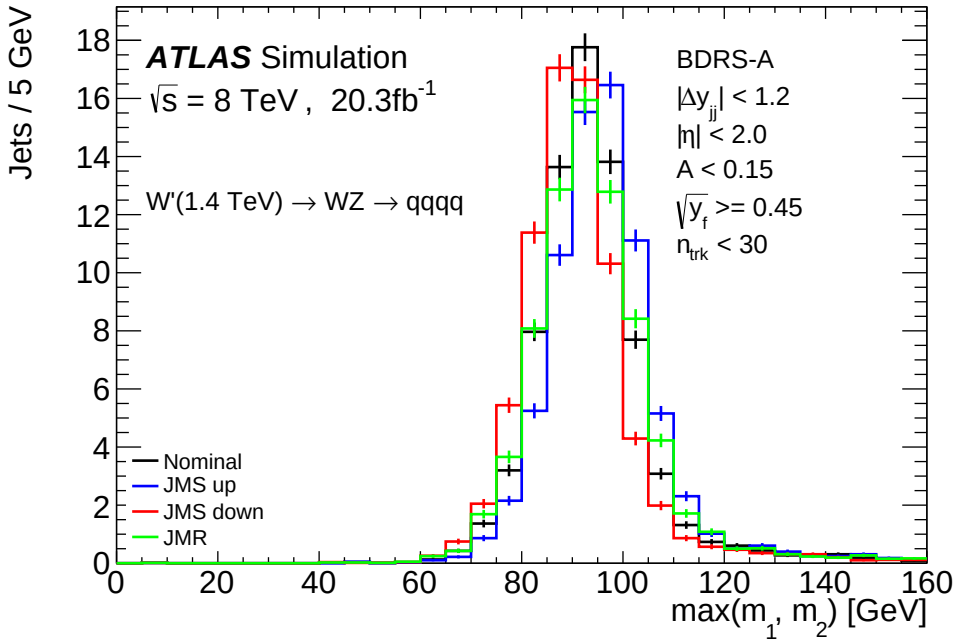
Systematic uncertainties: Shape

- **Background:** Taken from the uncertainties on the **fit parameters**
- **Signal:** Various systematics affect the signal **reconstruction** and **selection efficiency**

- **Shape systematics:**
- The jet p_{T} and jet mass scale uncertainties determined by the **track/calo double ratio** technique
- For example for a variable x,

$$\frac{x^{\mathrm{data}}_{\mathrm{track}} / x^{\mathrm{data}}_{\mathrm{calo}}}{x^{\mathrm{MC}}_{\mathrm{track}} / x^{\mathrm{MC}}_{\mathrm{calo}}}$$

- Applied as a Gaussian with $\mu = 1$ and σ equal to the **observed uncertainty**
  - jet p_{T} scale: 2%
  - jet mass scale: 3%
- An uncertainty on the jet p_{T} resolution of 20% is applied as an additional **smearing** on top of the nominal 5%

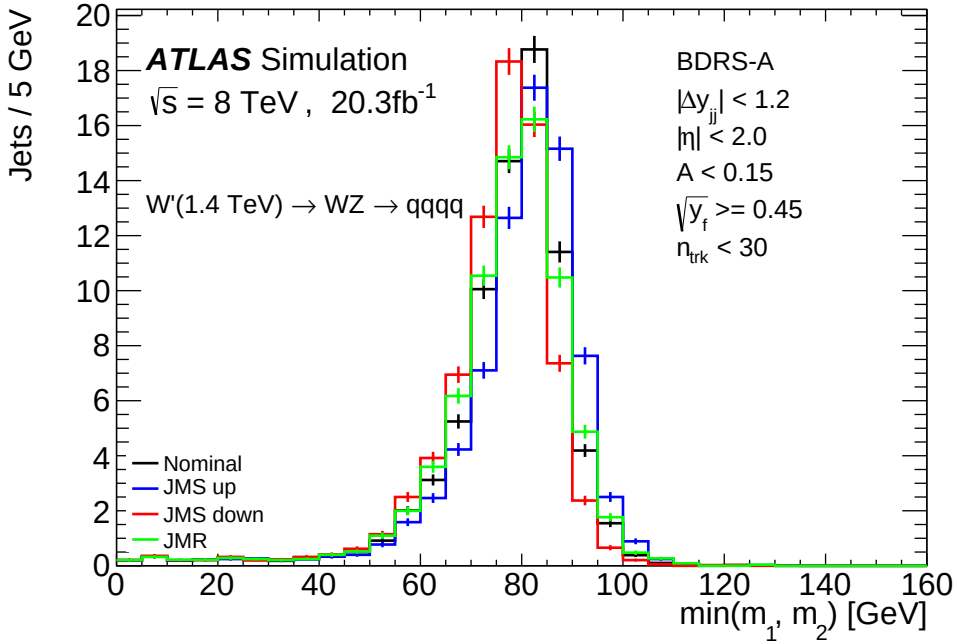


Source	Uncertainty	Constraining pdf
Jet p_{T} scale	2%	$G(\alpha_{\mathrm{PT}}\|1, 0.02)$
Jet p_{T} resolution	20%	$G(\sigma_{r_E}\|0, 0.05 \times \sqrt{1.2^2 - 1^2})$
Jet mass scale	3%	$G(\alpha_{\mathrm{m}}\|1, 0.03)$

Systematic uncertainties: Normalisation

- **Background:** Taken from the uncertainties on the **fit parameters**
- **Signal:** Various systematics affect the signal **reconstruction** and **selection efficiency**

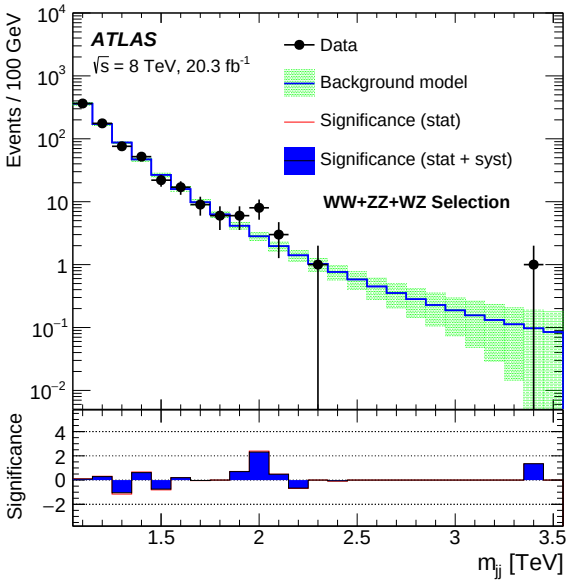
- **Normalisation systematics:**
- **Large uncertainty** on the n_{trk} cut evaluated in the data driven V+jets study used to define the efficiency of the cut
- Jet mass scale affects **both** shape and normalisation strongly
- $\sqrt{y}$ scale evaluated using the **double ratio** method
- Resolutions taken as 20% **smearings**
- **Shower model** evaluated by comparing MC showered by PYTHIA or HERWIG
- **PDF4LHC** method used to evaluate PDF uncertainties
- ATLAS **luminosity** uncertainty assumed

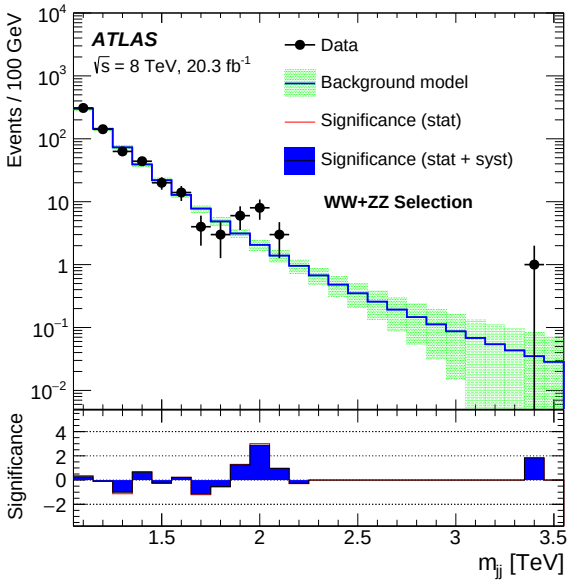


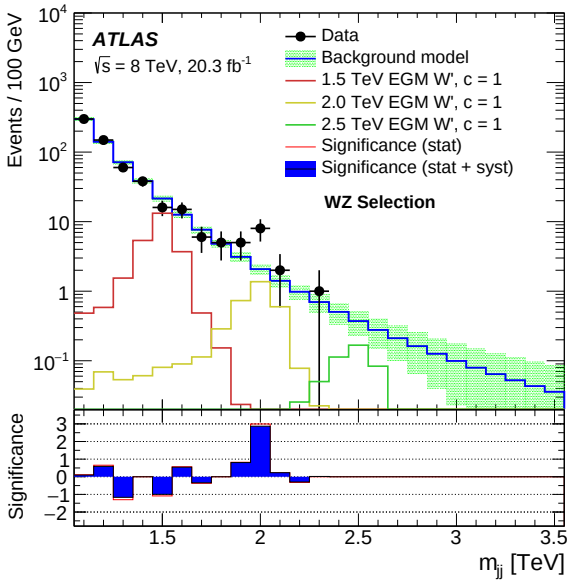
Source	Uncertainty
Efficiency of the track-multiplicity cut	20.0%
Jet mass scale	5.0%
Jet mass resolution	5.5%
Subjet momentum-balance scale	3.5%
Subjet momentum-balance resolution	2.0%
Parton shower model	5.0%
Parton distribution functions	3.5%
Luminosity	2.8%

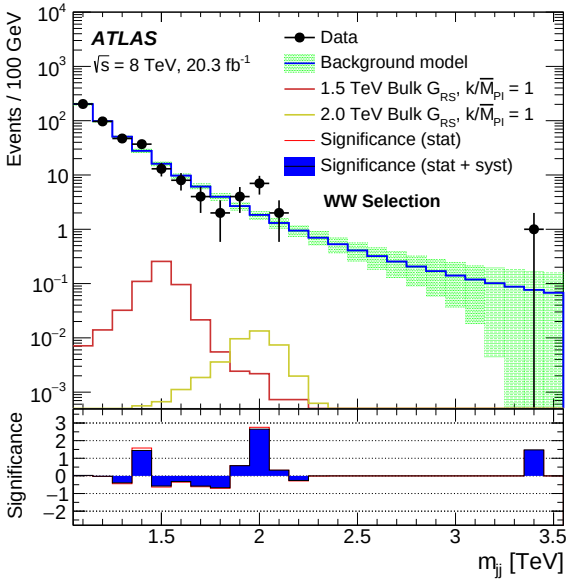
Selection overlaps

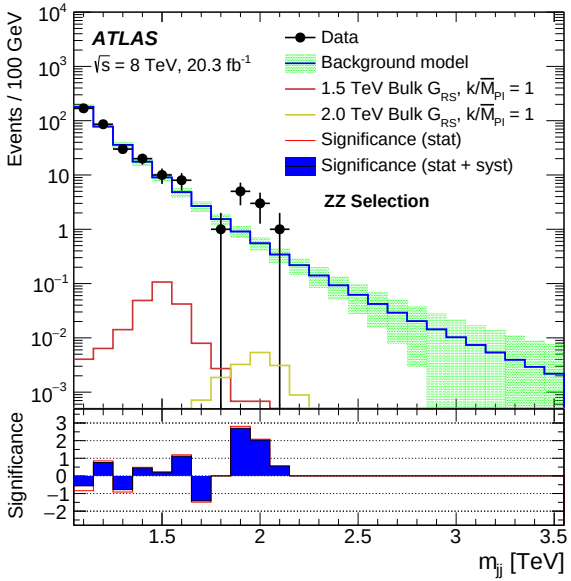
- Comparing the effect of applying all signal selections at once, and the same flavour selections at once



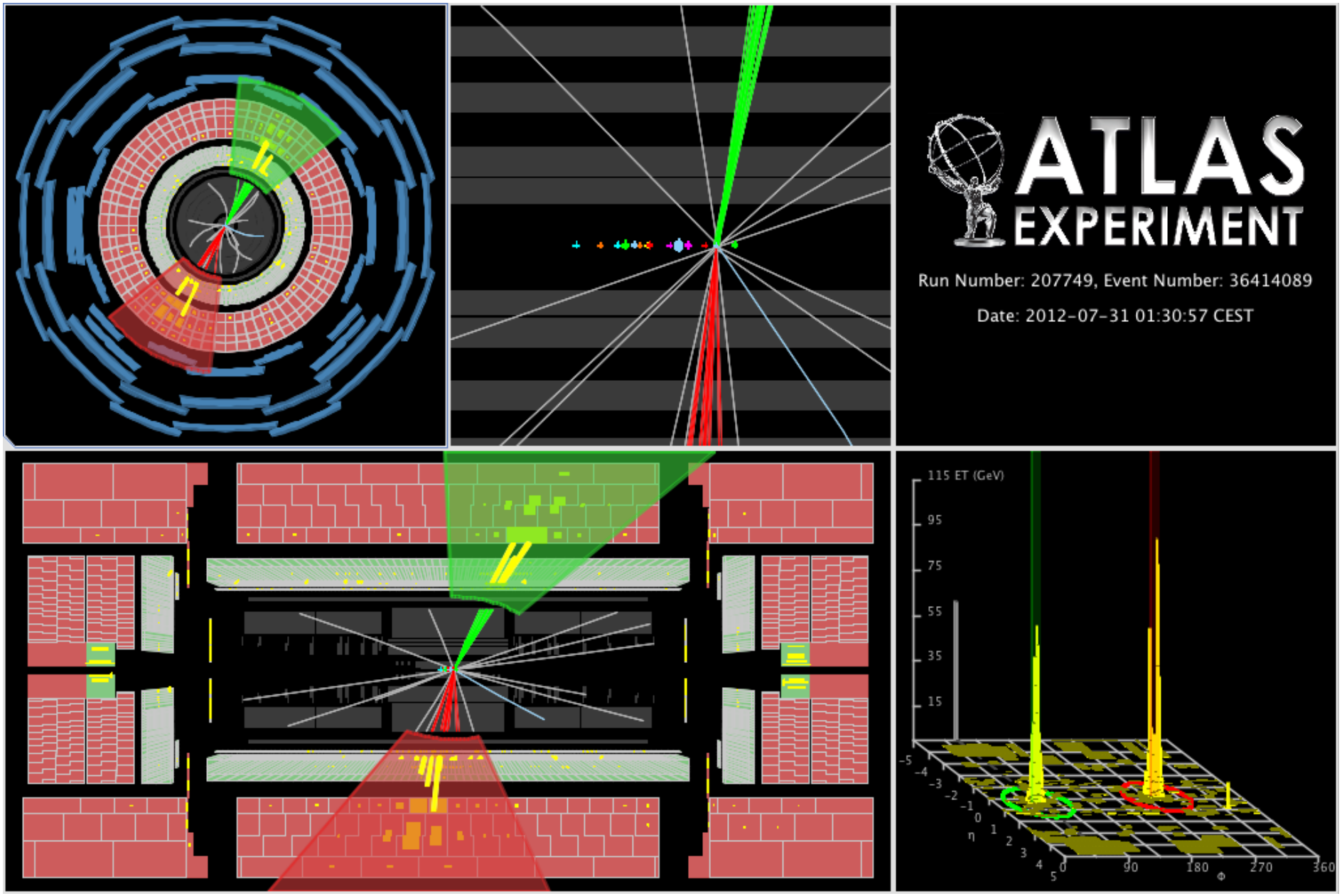




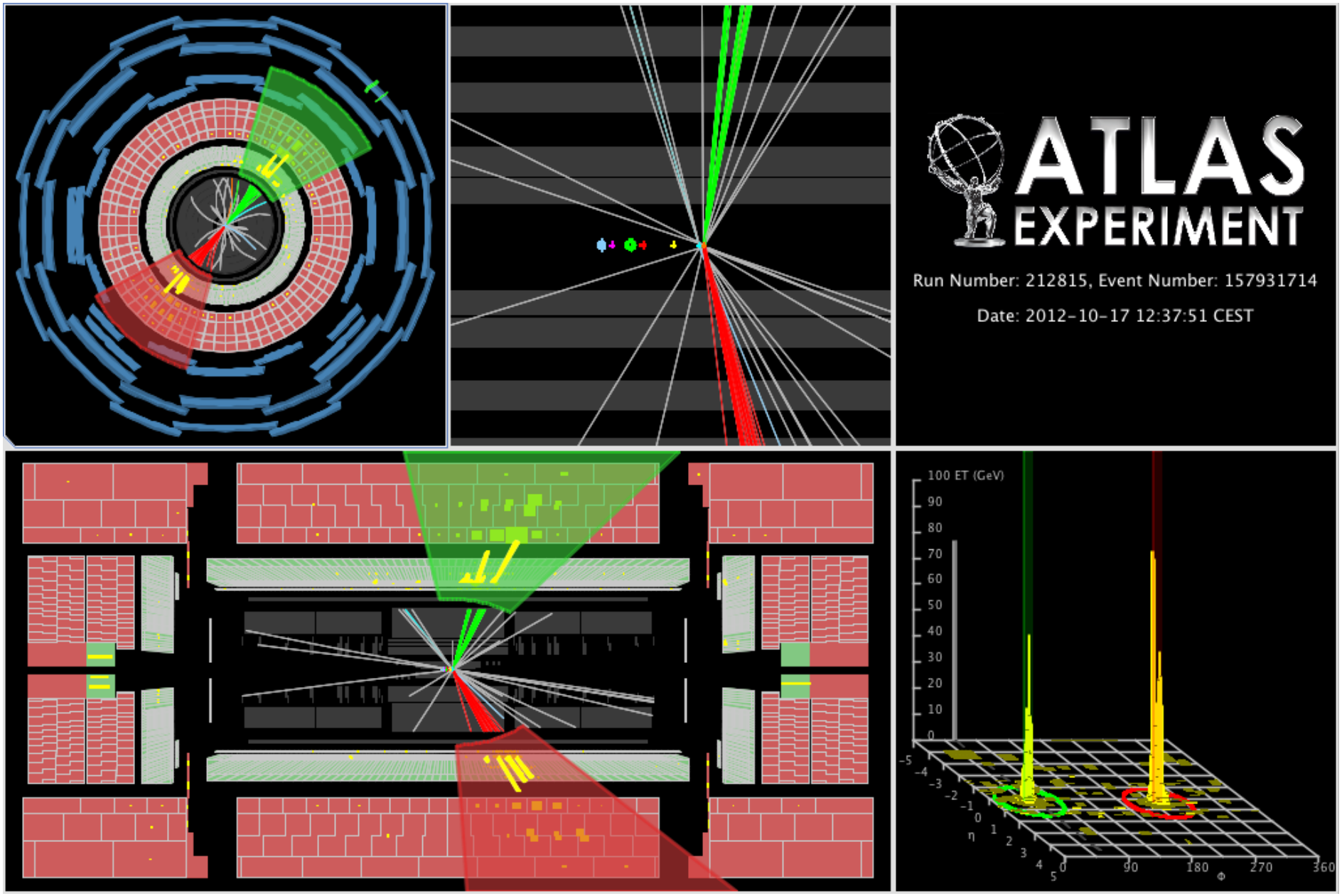




What do these events look like? Dramatic!



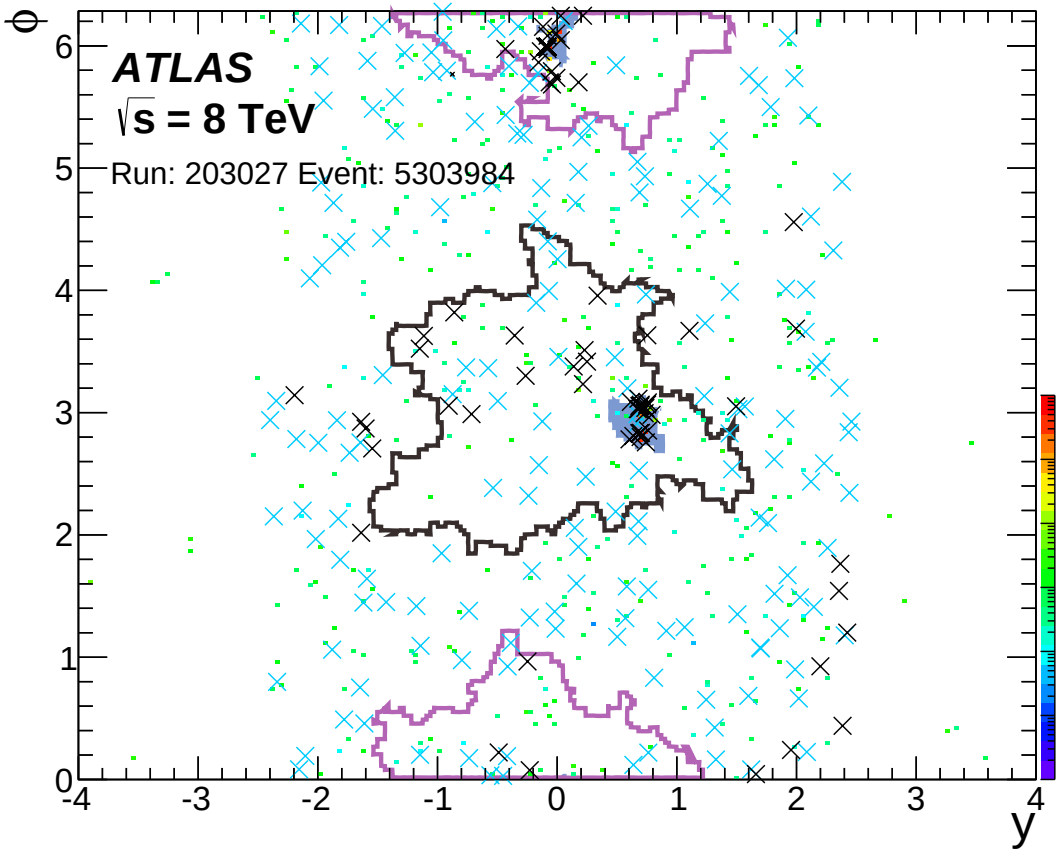
What do these events look like? Energetic!



Digging deeper into the jets....

These jet event displays take a bit more explanation, but offer a powerful insight into the analysis jets

- The ATLAS detector volume is shown unfolded in y and ϕ
- Inner detector track positions are shown as crosses
  - Black Tracks: From primary vertex
  - Blue Tracks: From secondary vertices
- Calorimeter deposits are displayed on the rainbow scale
- The outlines of the CA 1.2 jets are shown
  - Black: Leading p_T jet
  - Mauve: Sub-leading jet
- Grey area: Sub-jets after filtering



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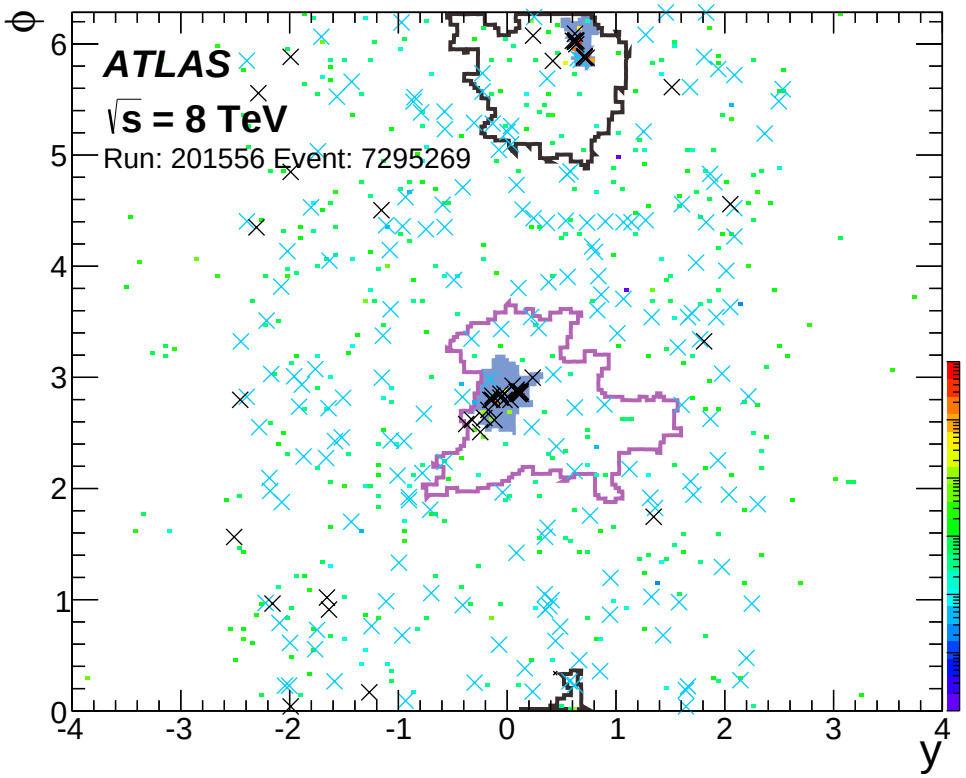
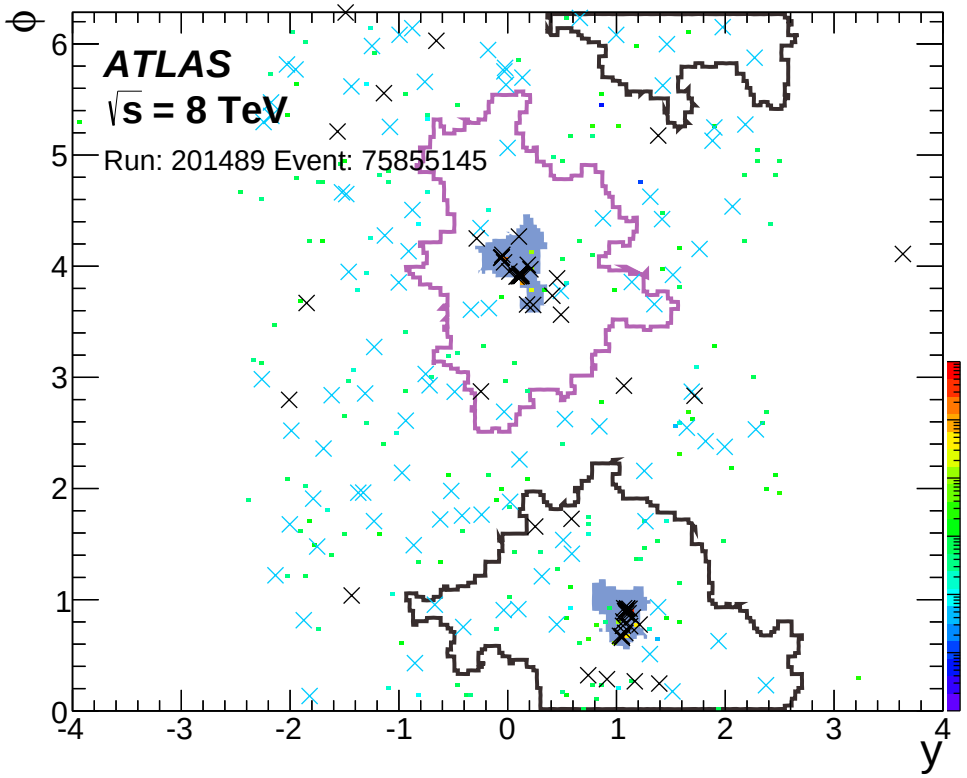


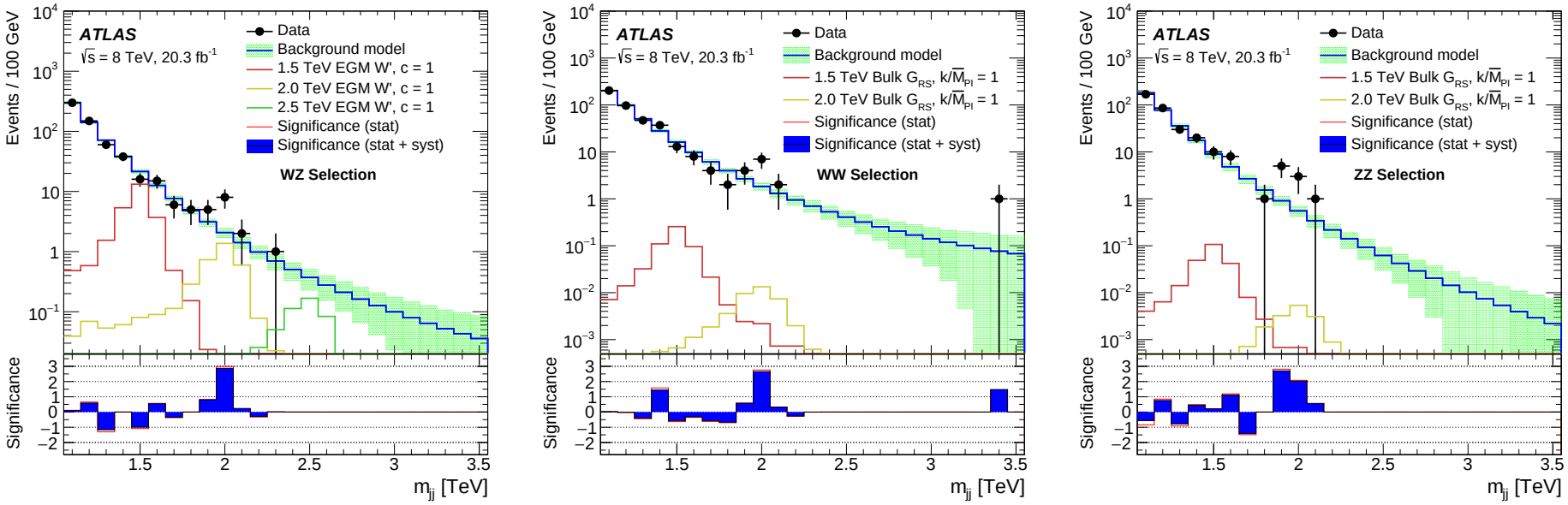


What do we see here?

- Subjets are highly collimated
- PV tracks are highly correlated with the selected sub-jets
- Energy deposits concentrated in the sub-jet
- Pile-up tracks/deposits sparsely distributed over the events
- Successfully picked the boson out of the pileup?

Time to cross-check.....

- Deviations from the expected background, especially ones at the tail of the data distribution, mean one thing for physicists....
  - What on Earth did we do wrong?
- Try to evaluate any possible issues with the analysis
- Operation Cross-check begins
- Look for mistakes, bugs or shaping effects in:
  - Detector/data taking effects
  - Jet reconstruction effects
  - Event selection effects

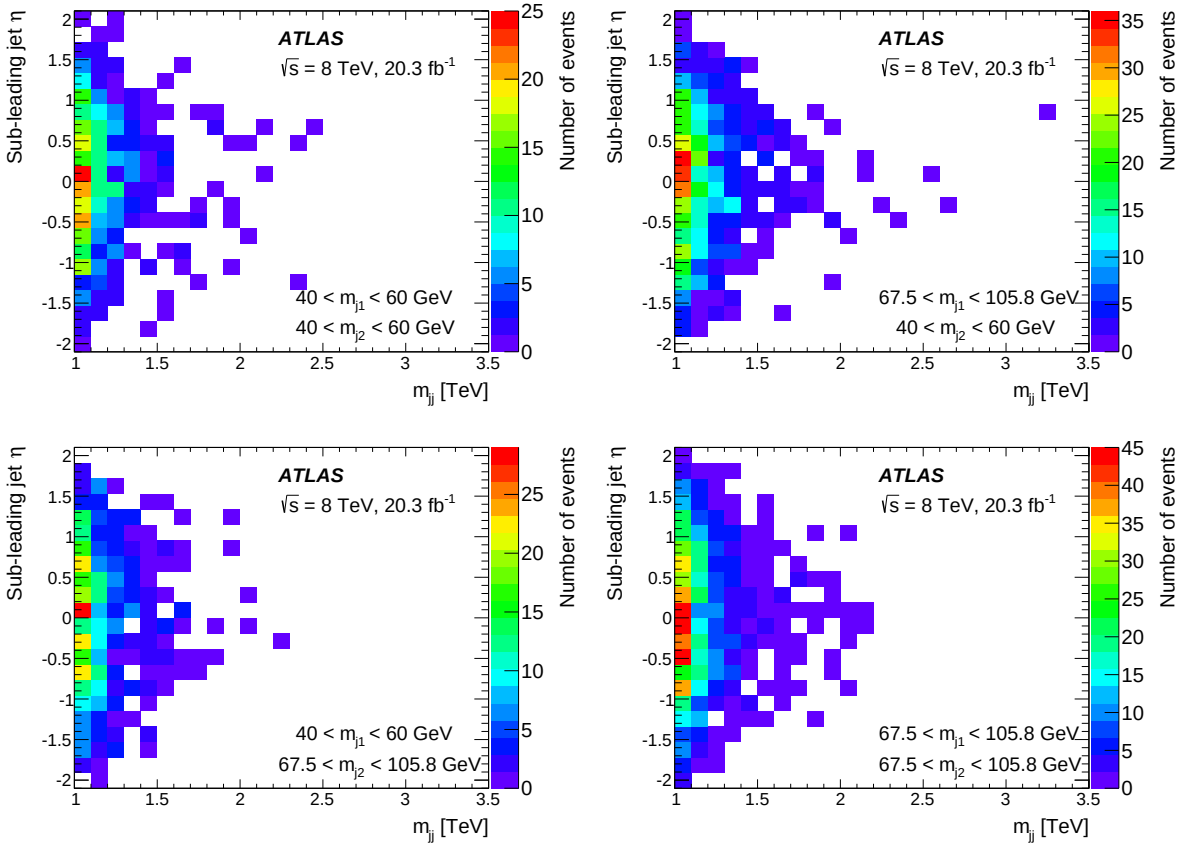


Time to cross-check.....

From E. Kajomovitz

Time to cross-check.....

- Started trawling through SR/CR kinematic distributions, looking for unusual features in the signal regions
- Look at the effect of single cuts on the distribution
- Look at the effect of $N-1$ cuts on the distribution
  - Is one cut driving all of the deviation?
- Many, many, many..... more, you can only get so much approved...



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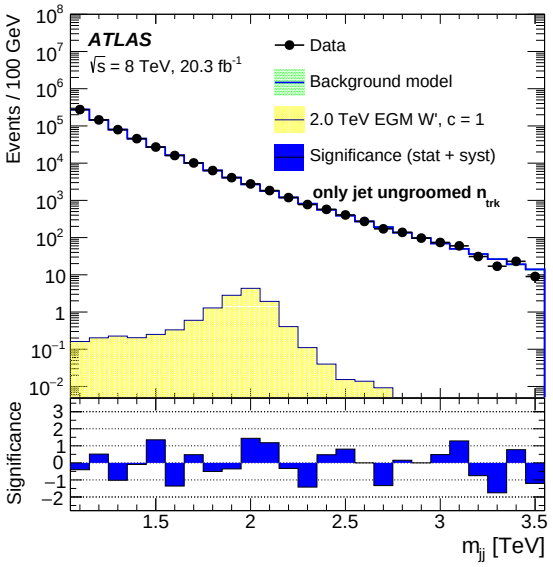

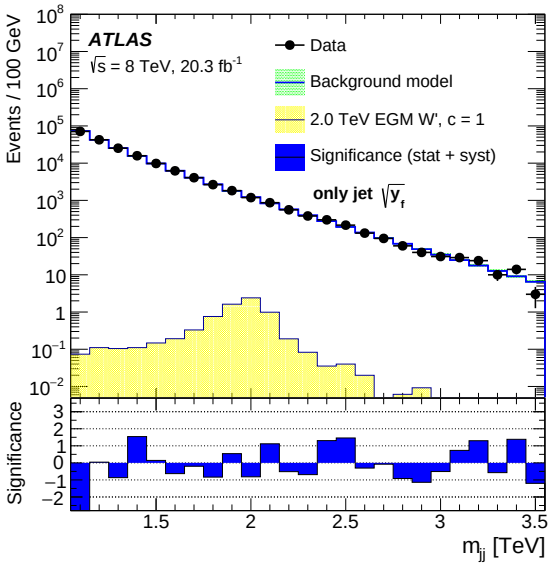

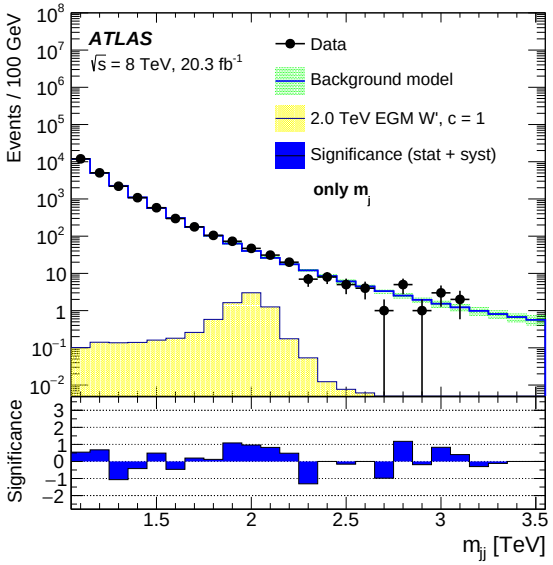

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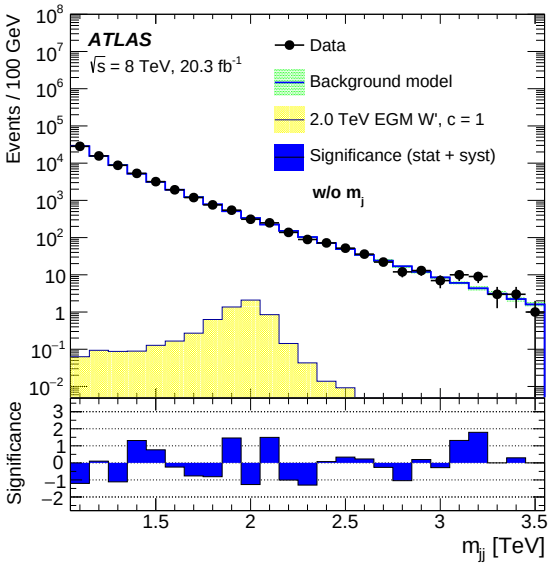
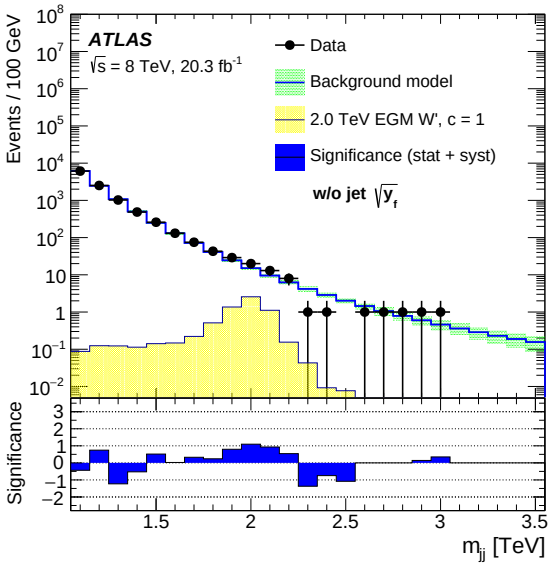
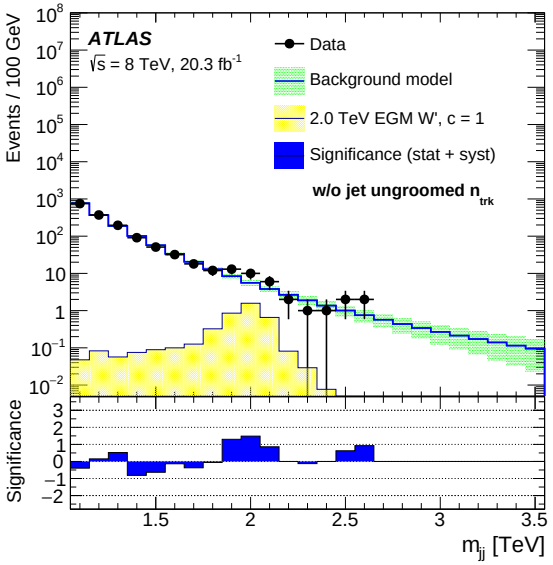
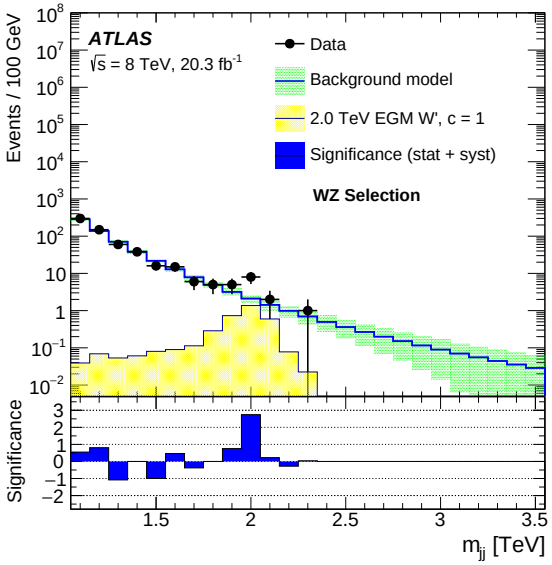






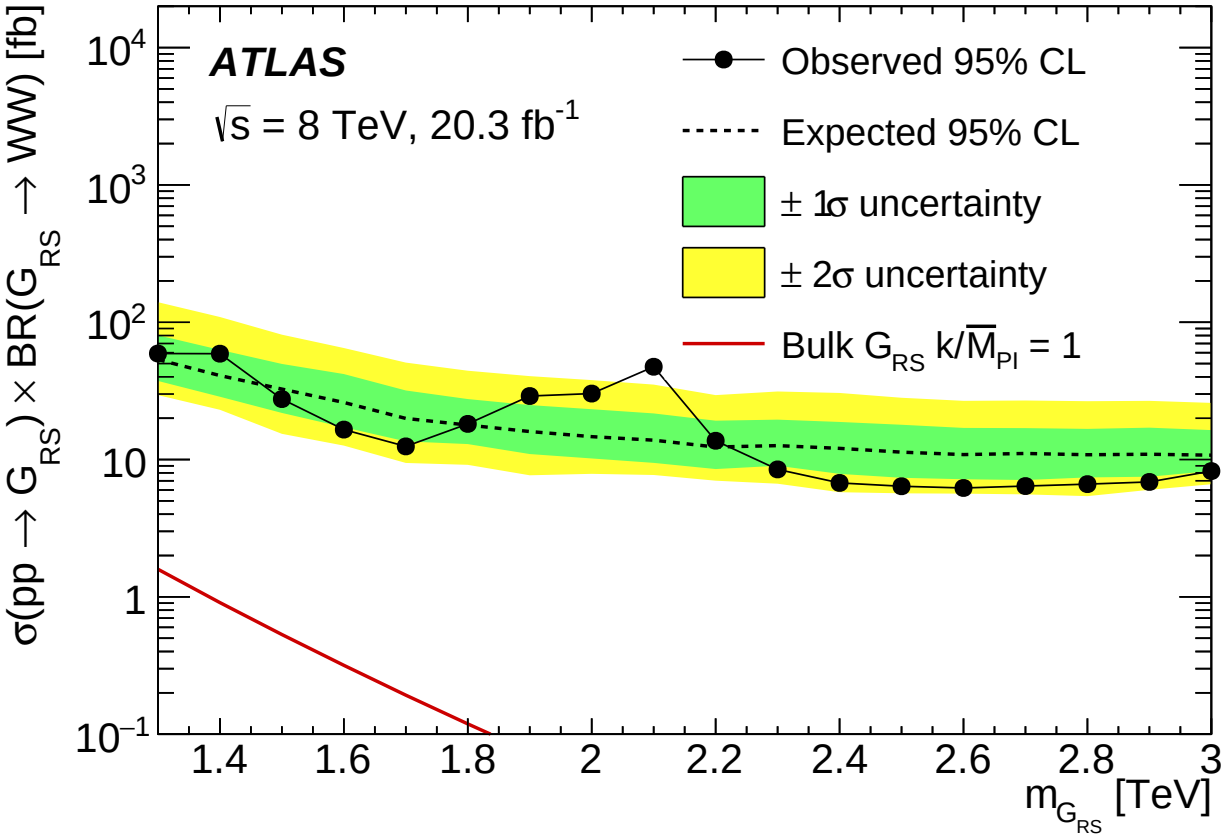


Did we find any errors?

- In so many cross-checks, yes, bugs were found and fixed
- Always attempted to shield the data from any possible biases by using control regions to test
- After almost a year and a half of scrutiny by the analysers/Exotics group/ATLAS we found no major issues
- Therefore we continue to publish the final results
- Run-2 was looming!

$X \to WW$ limits

- As no significant deviation was observed, we continue to set limits on the observed distributions
- 95% confidence limits set on $\sigma \times \mathcal{B}$ using the $\mathrm{CL_S}$ prescription taking into account the systematic uncertainties and background fit



- **Expected** limits broadly agree with the observed limits
- **Exclusion** of graviton production at no masses
- **Deviation** from the background observable at around 2.1 TeV
- **Benchmark** Bulk Randall-Sundrum graviton $\sigma \times \mathcal{B}$ shown for **comparison** purposes

$X \to ZZ$ limits

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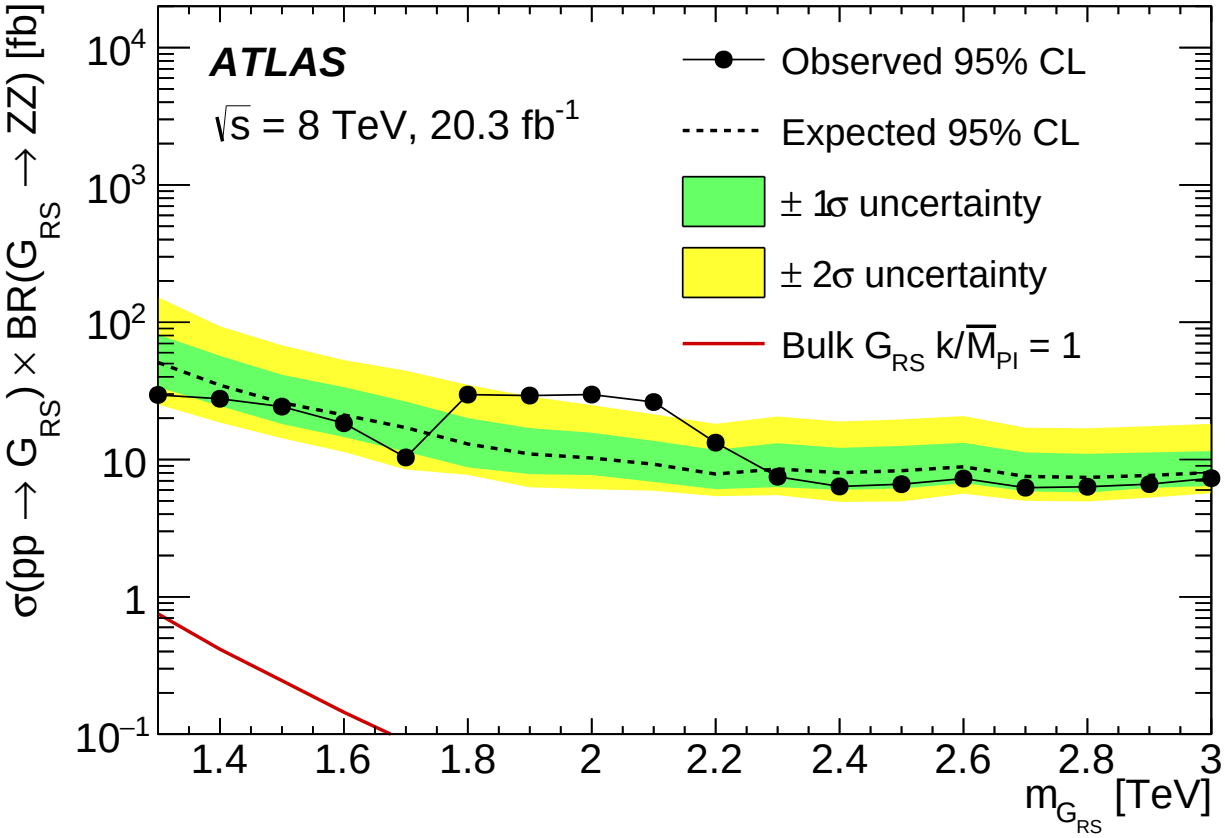

- **Expected** limits broadly agree with the observed limits
- **Exclusion** of graviton production at no masses
- **Broad deviation** from the background observable at around 2 TeV
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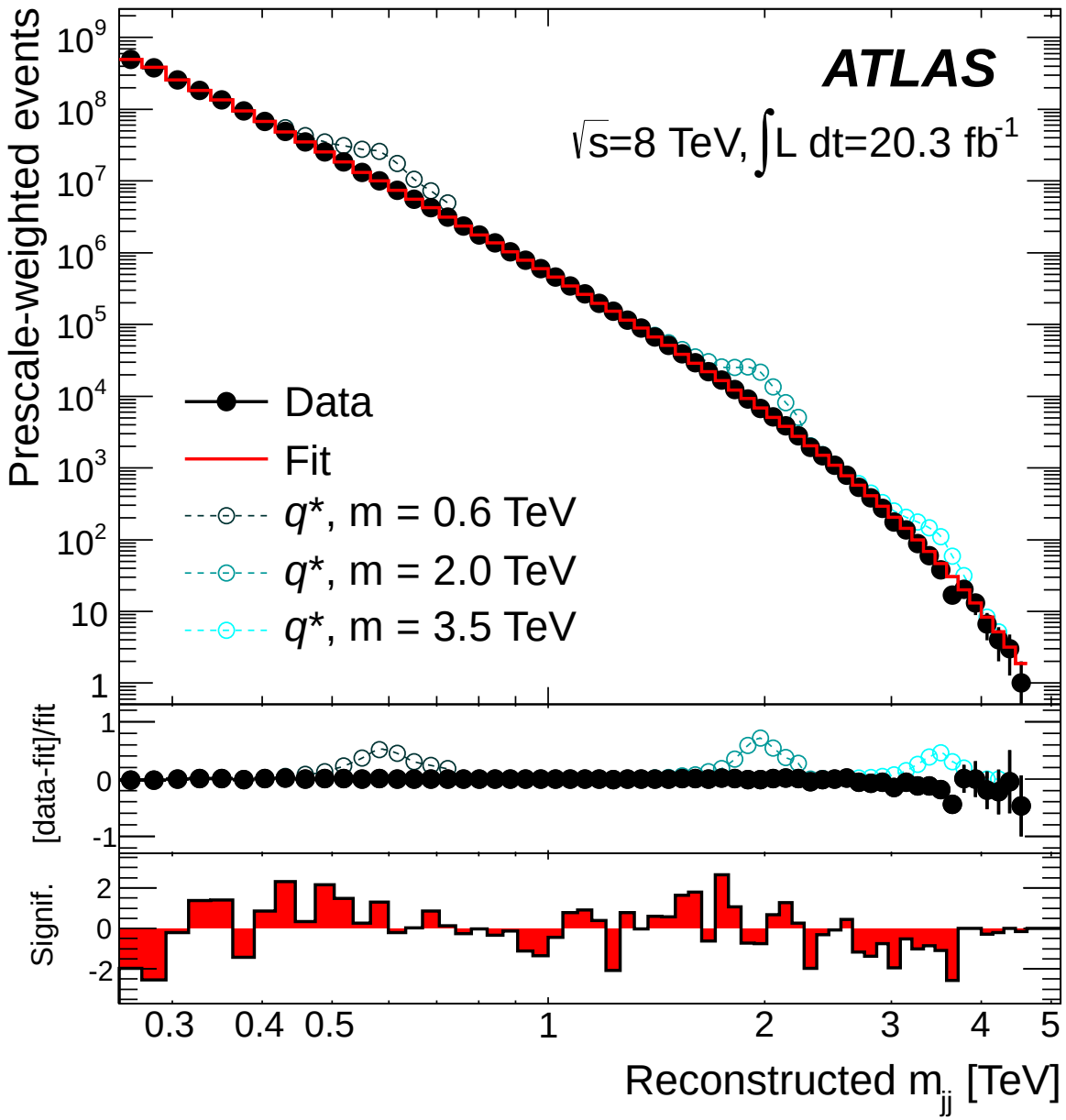
Are we alone? ATLAS searches



- ATLAS resolved dijet search [arXiv:1407.1376], nothing seen ⊠
- ATLAS resolved Run-2 dijet search ATLAS-CONF-2015-042, nothing seen ⊠
- ATLAS semi-leptonic search $W(l\nu)Z(jj)$ [arXiv:http://1503.04677], using similar BDRS-A CA 1.2 reconstruction, in tail/nothing seen ⊠
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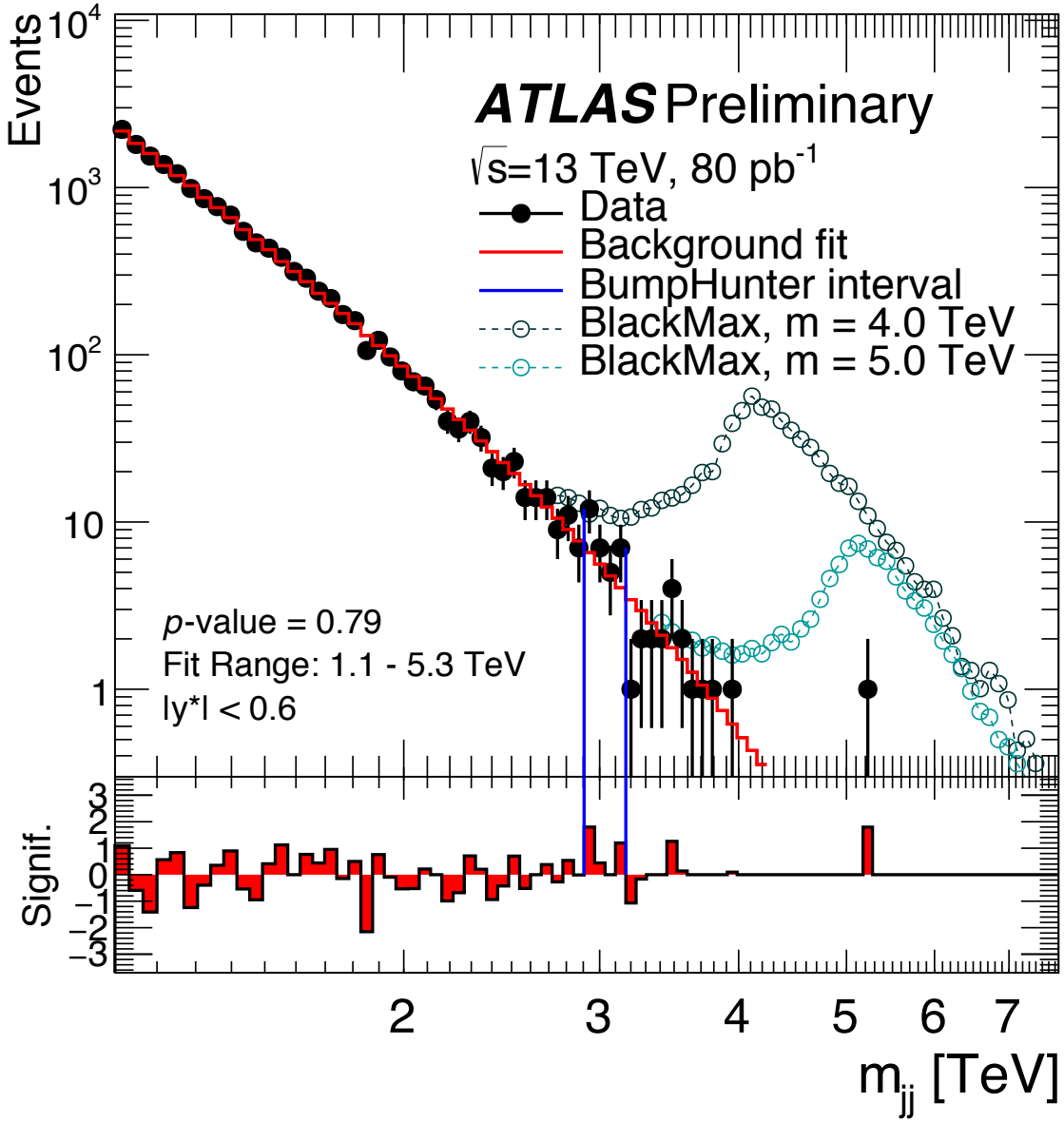

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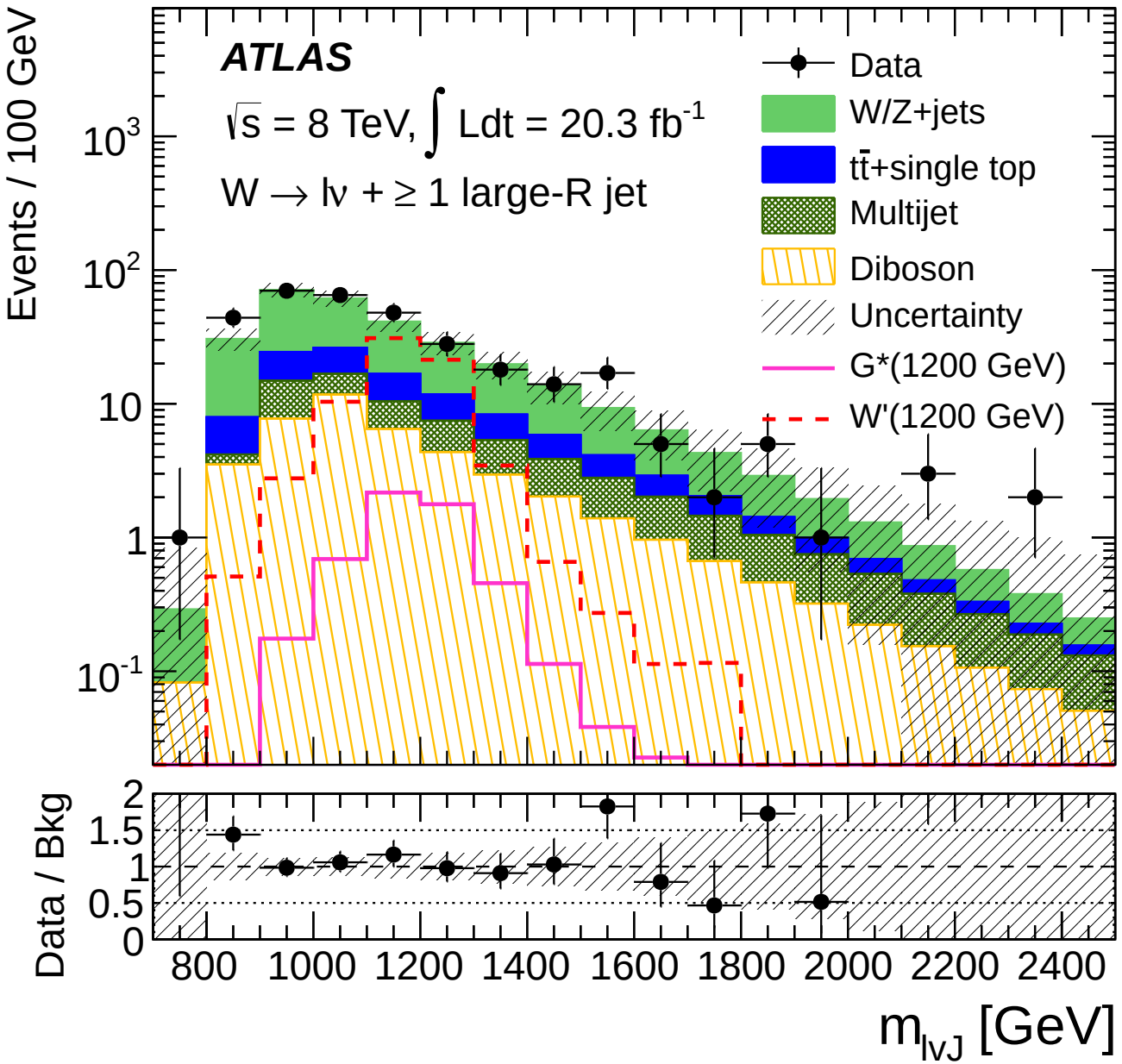
Are we alone? ATLAS searches



- ATLAS resolved dijet search [arXiv:1407.1376], nothing seen ⊠
- ATLAS resolved Run-2 dijet search ATLAS-CONF-2015-042, nothing seen ⊠
- ATLAS semi-leptonic search $W(l\nu)Z(jj)$ [arXiv:http://1503.04677], using similar BDRS-A CA 1.2 reconstruction, in tail/nothing seen ⊠
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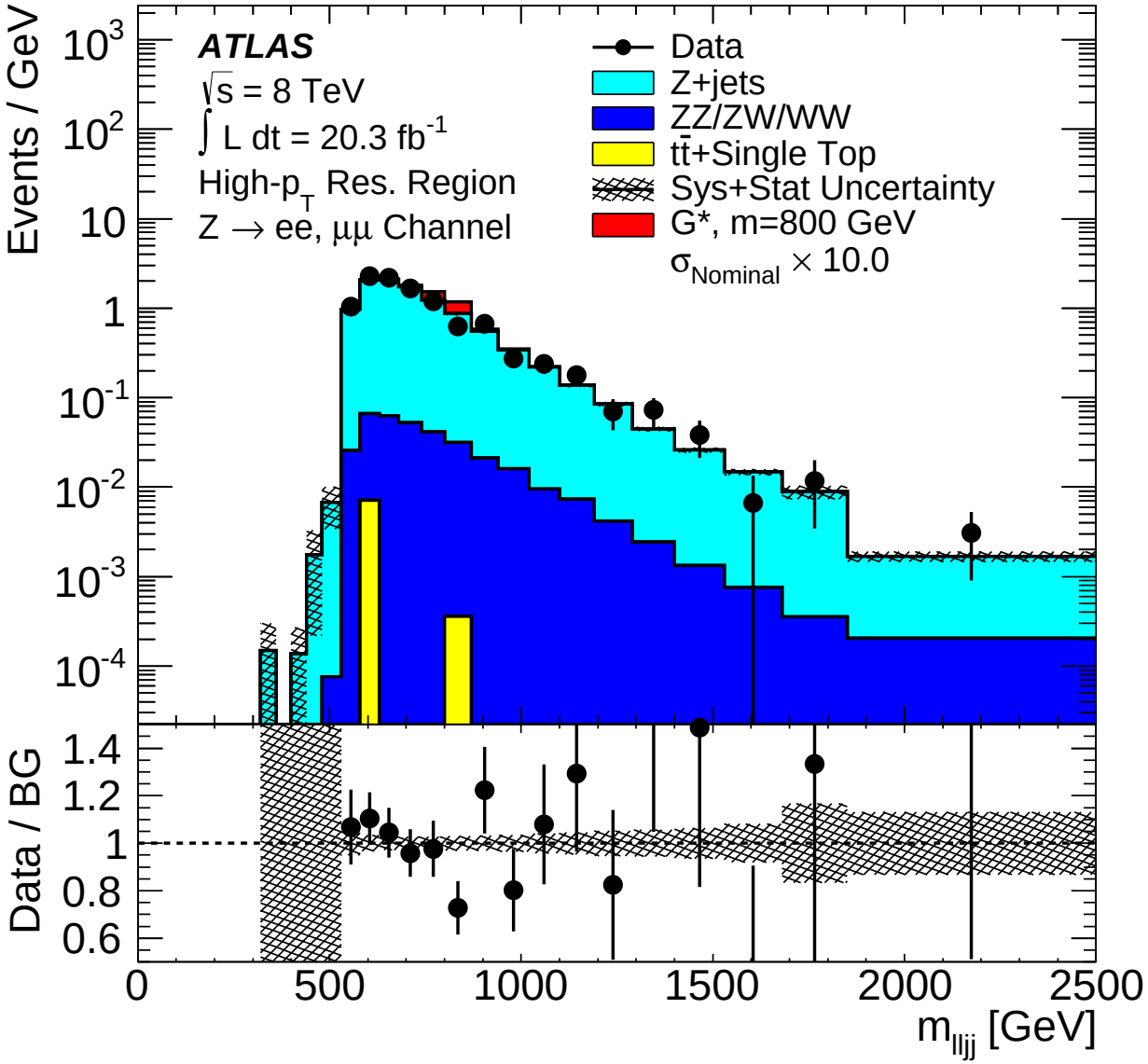
Are we alone? ATLAS searches



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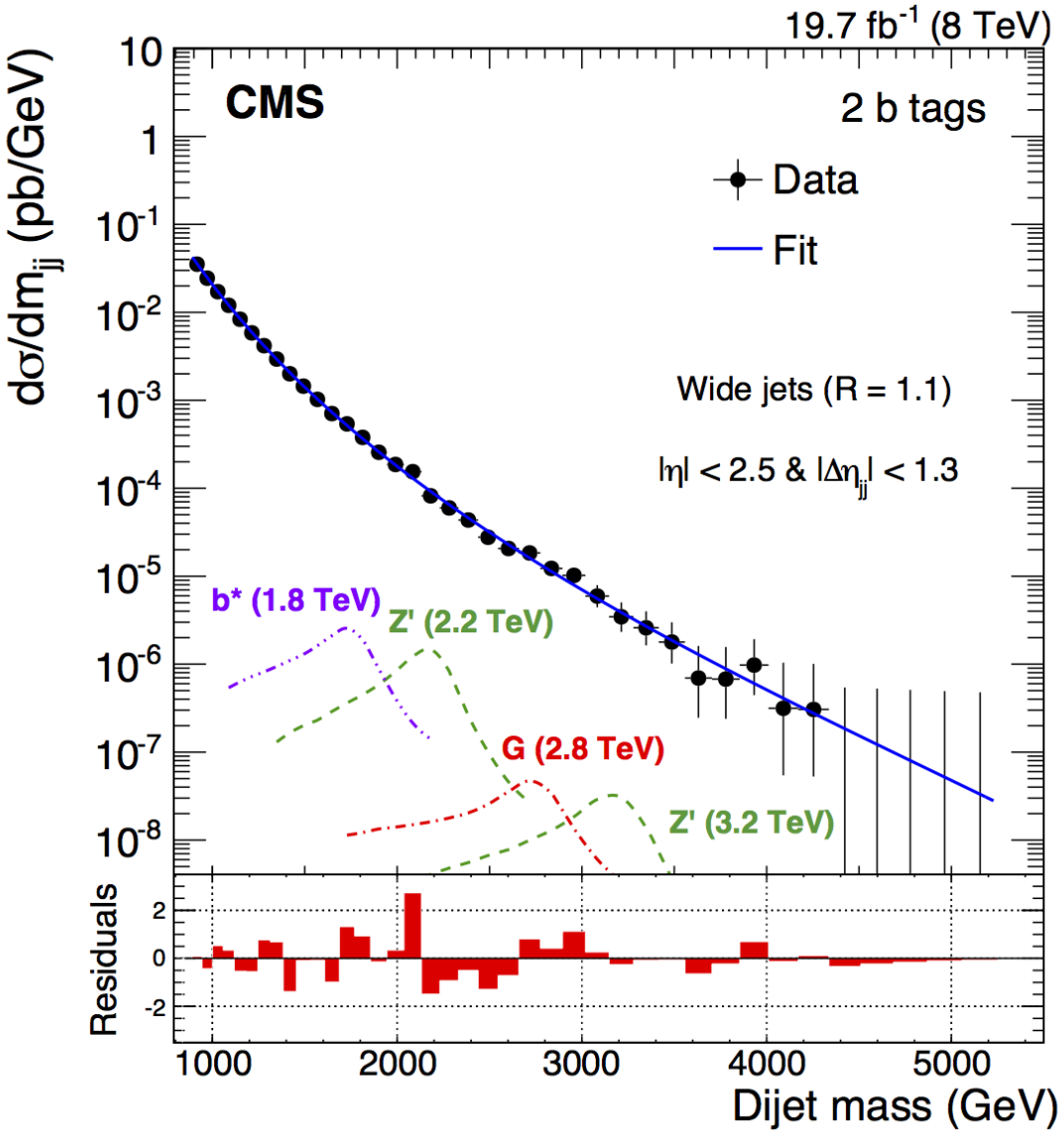
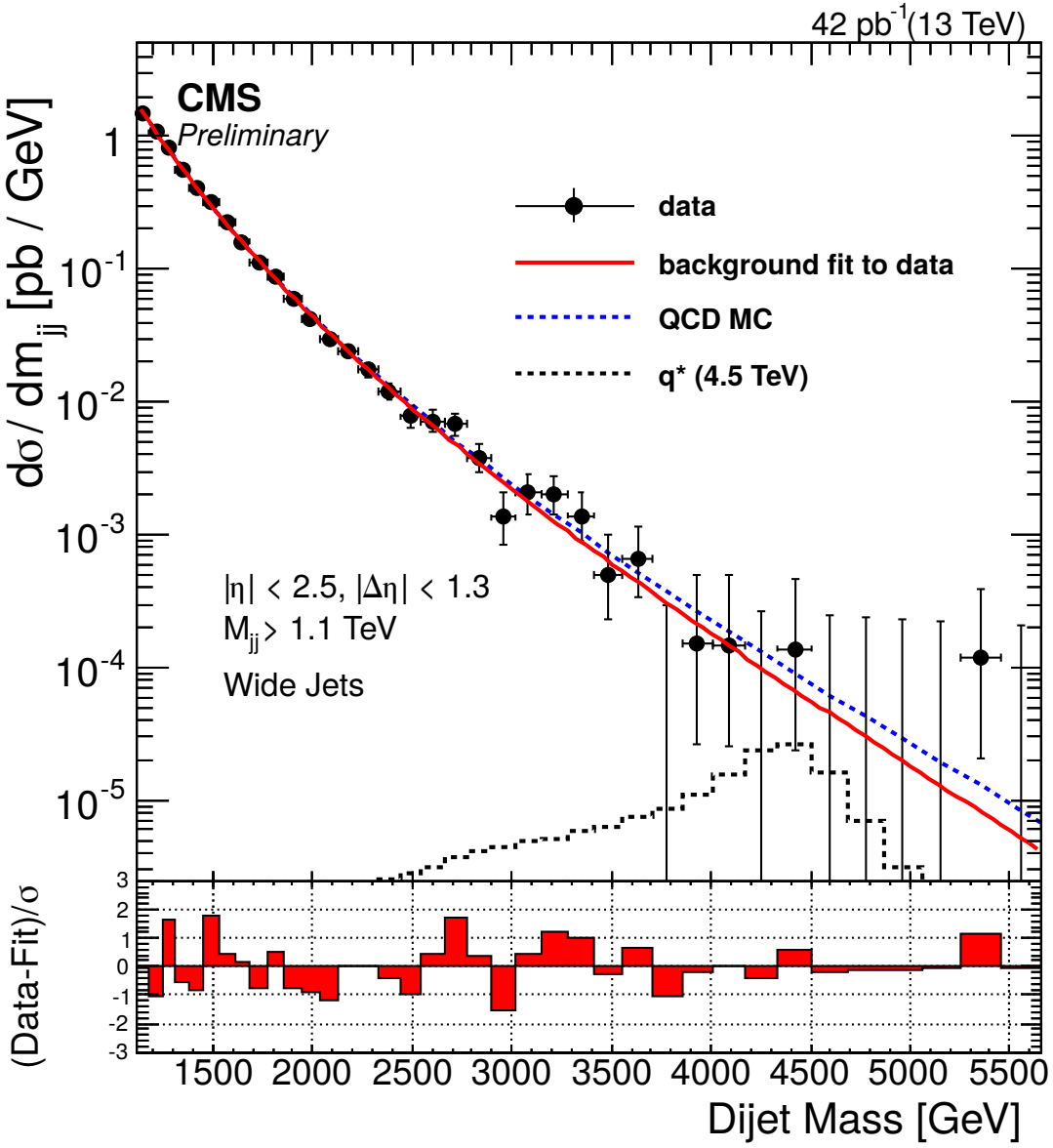
Are we alone? Across the ring....CMS



- CMS dijet search [arXiv:1501.04198], blip in 2-btag at 2 TeV? Trick of the eye? ☒
- CMS run-2 dijet search [CMS-PAS-EXO-15-001], nothing ☒
- CMS W_R search [arXiv:1407.3683], excess at 2 TeV in *eejj* channel only ☒☑
- CMS $WW/WZ/ZZ$ semi-leptonic search [arXiv:1405.3447], in tails/nothing seen ☒
- CMS $WW/WZ/ZZ$ fully hadronic search [arXiv:1405.3447], uses n-subjettiness, broad blip at $\approx$ 1.8TeV ☒☑

Are we alone? Across the ring....CMS



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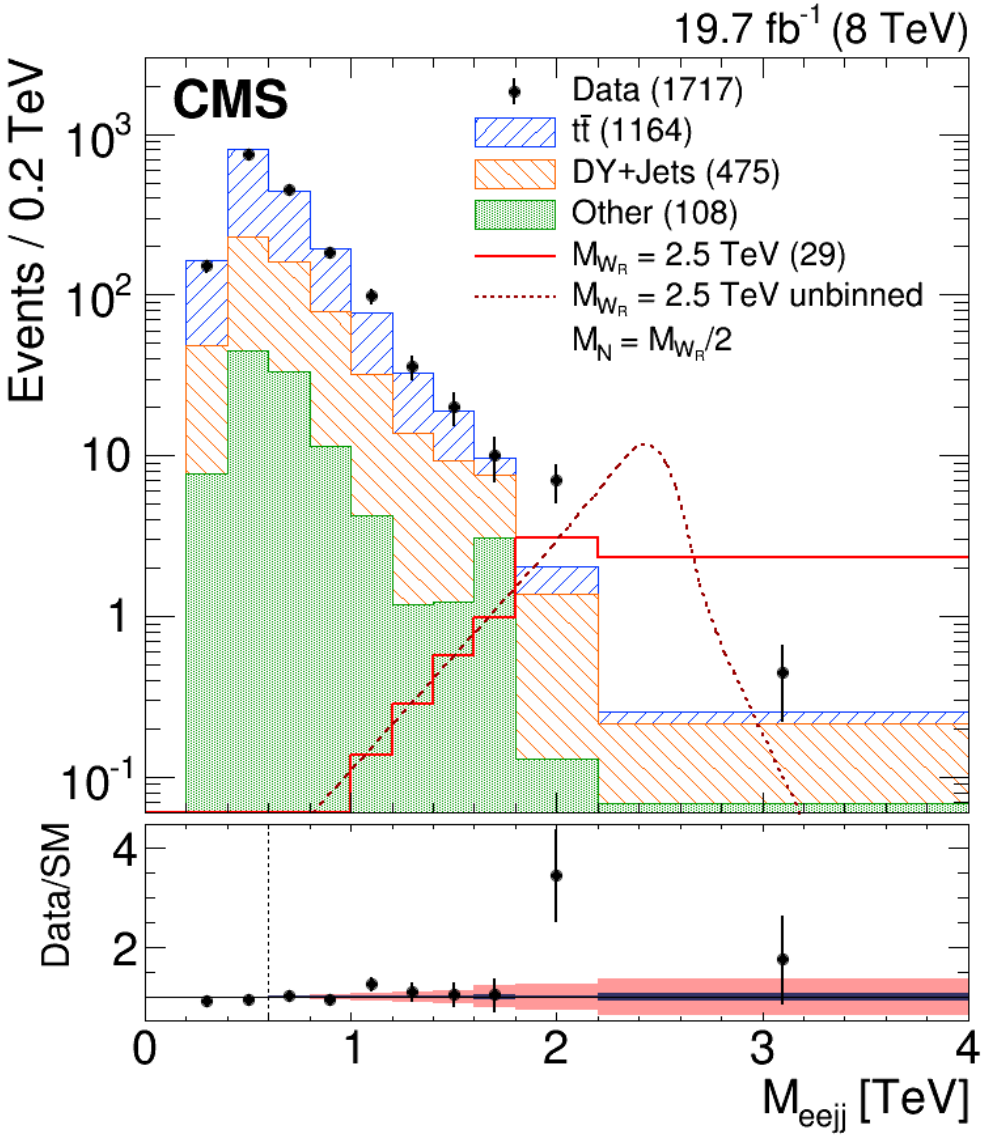

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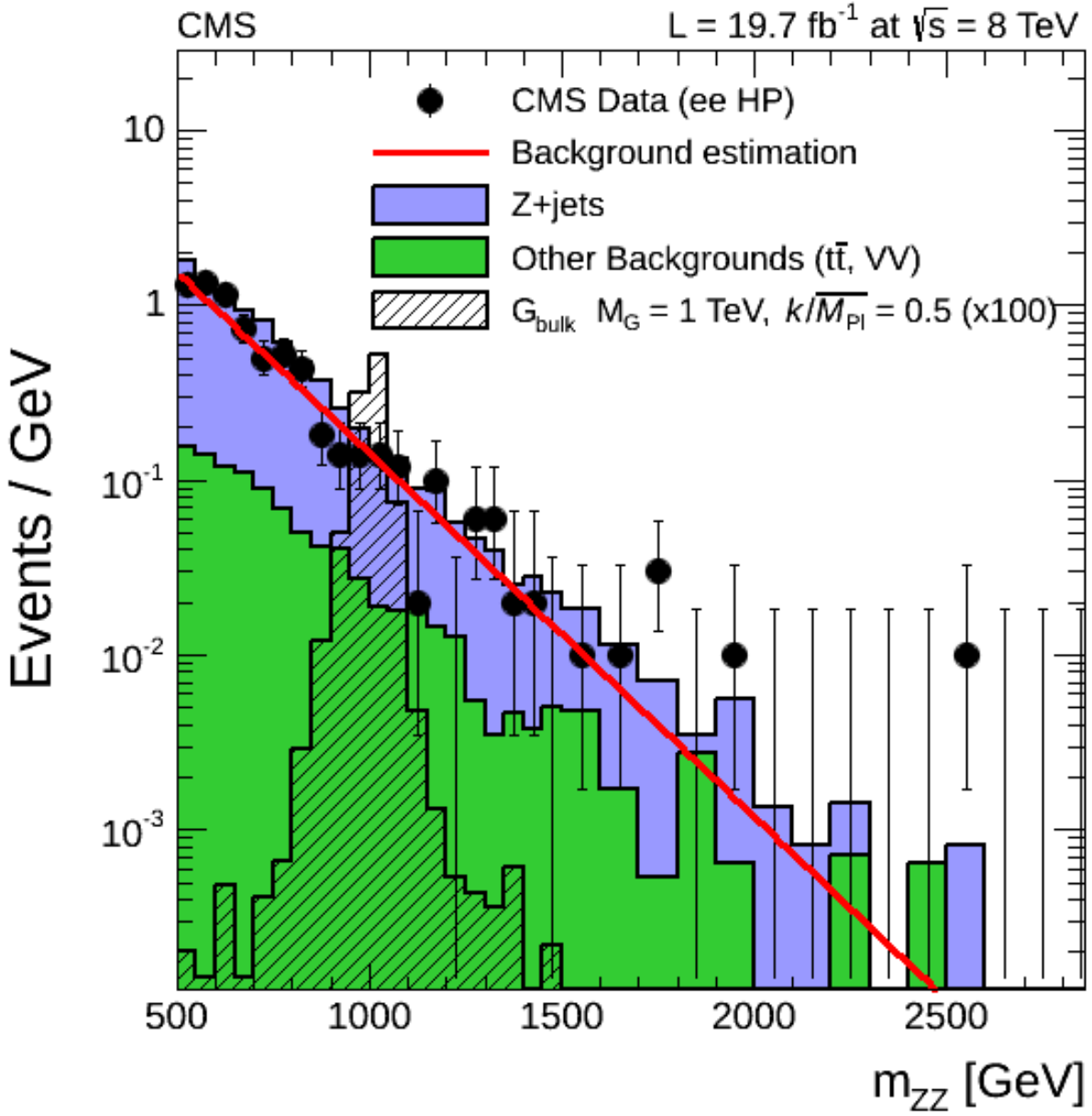
- CMS *WW*/*WZ*/*ZZ* fully hadronic search [arXiv:1405.3447], uses n-subjettiness, broad blip at ≈ 1.8TeV ☒☑

Are we alone? Across the ring....CMS



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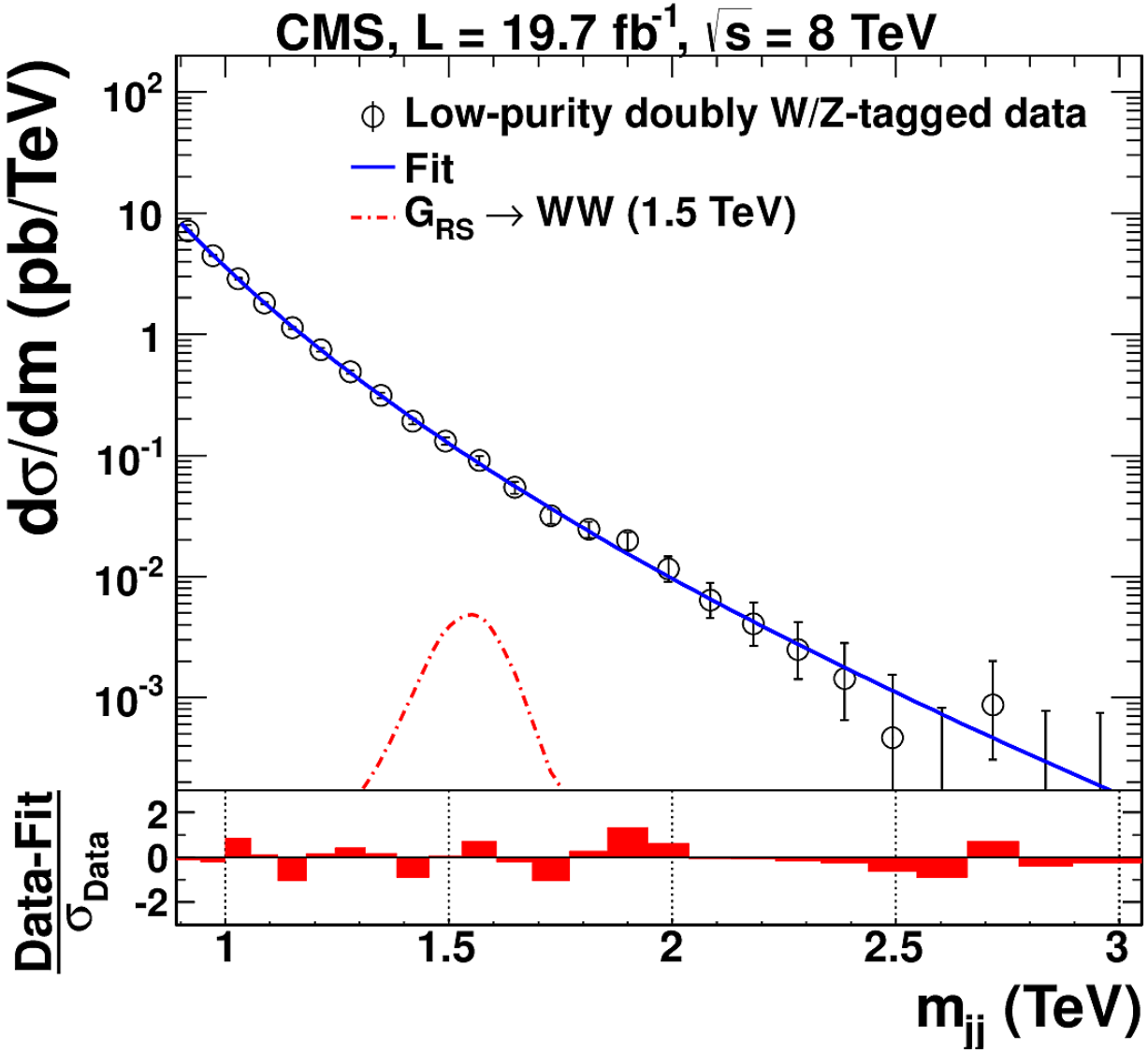

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