Searching for Exotic Diboson Resonances at the Large Hadron Collider

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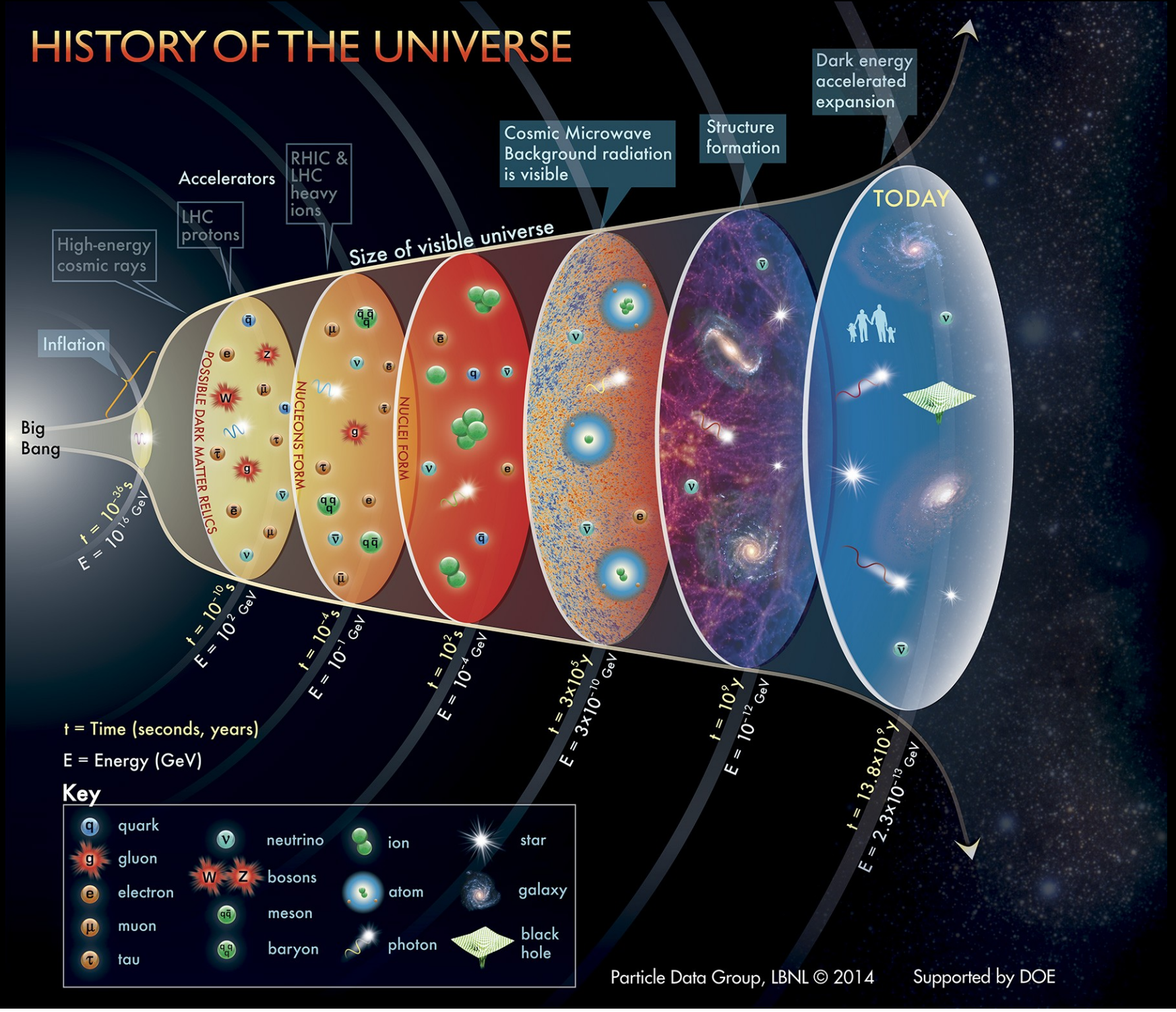
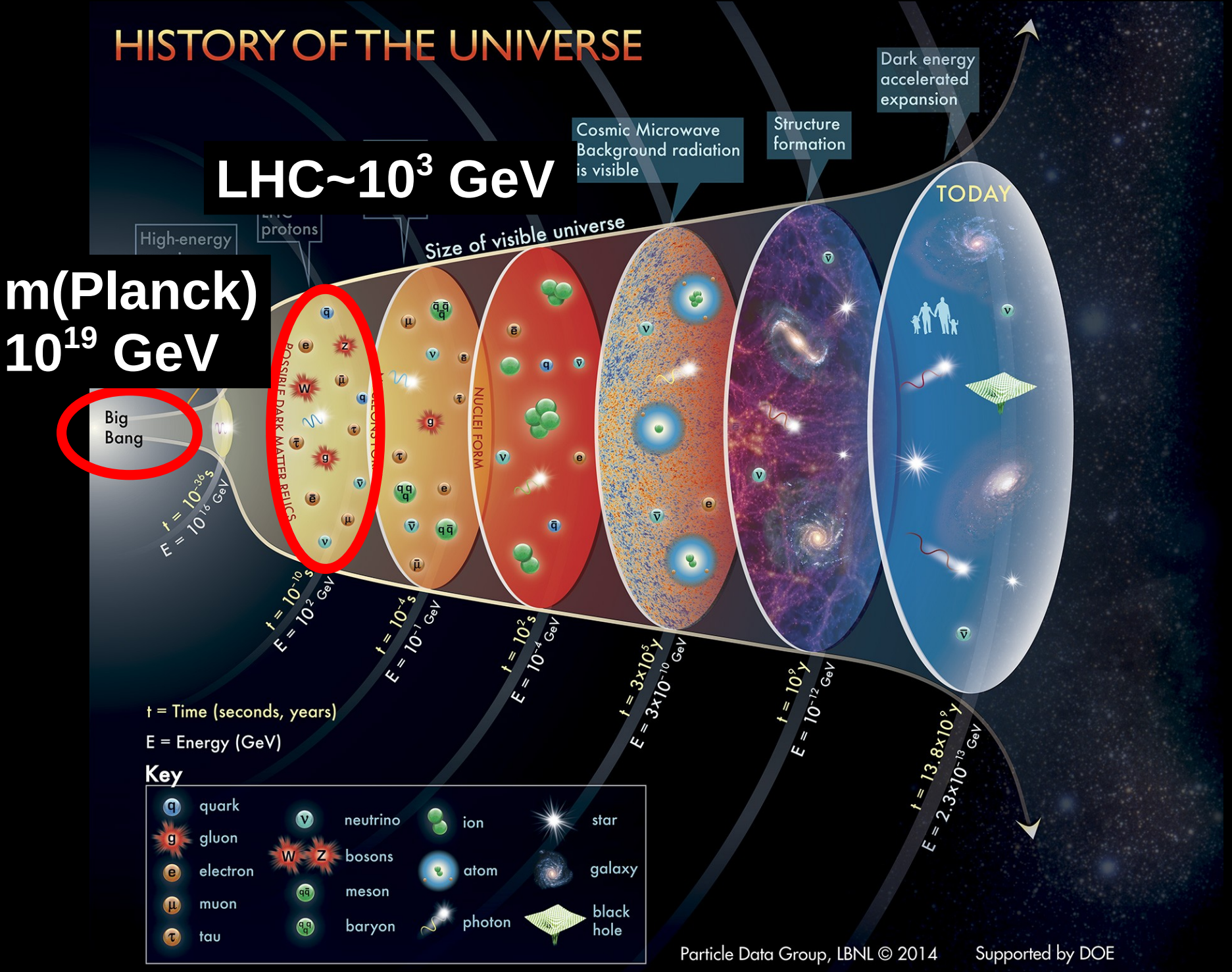
Introduction

mass →	≈2.3 MeV/c²	≈1.275 GeV/c²	≈173.07 GeV/c²	0	≈126 GeV/c²
charge →	2/3	2/3	2/3	0	0
spin →	1/2	1/2	1/2	1	0
	u	c	t	g	H
	up	charm	top	gluon	Higgs boson
QUARKS	≈4.8 MeV/c²	≈95 MeV/c²	≈4.18 GeV/c²	0	
	-1/3	-1/3	-1/3	0	
	1/2	1/2	1/2	1	
	d	s	b	γ	
	down	strange	bottom	photon	
	0.511 MeV/c²	105.7 MeV/c²	1.777 GeV/c²	91.2 GeV/c²	
	-1	-1	-1	0	
	1/2	1/2	1/2	1	
	e	μ	τ	Z	
	electron	muon	tau	Z boson	
LEPTONS	<2.2 eV/c²	<0.17 MeV/c²	<15.5 MeV/c²	80.4 GeV/c²	
	0	0	0	±1	
	1/2	1/2	1/2	1	
	ν_e	ν_μ	ν_τ	W	
	electron neutrino	muon neutrino	tau neutrino	W boson	

GAUGE BOSONS


HISTORY OF THE UNIVERSE
Dark energy accelerated expansion
Cosmic Microwave Background radiation is visible
Structure formation
Accelerators
RHIC & LHC heavy ions
LHC protons
High-energy cosmic rays
Inflation
Size of visible universe
TODAY
Big Bang
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
t = 10^-36 s
E = 10^16 GeV
t = 10^-10 s
E = 10^2 GeV
t = 10^-4 s
E = 10^-1 GeV
t = 10^2 s
E = 10^-4 GeV
t = 3x10^5 y
E = 3x10^-10 GeV
t = 10^9 y
E = 10^-12 GeV
t = 13.8x10^9 y
E = 2.3x10^-13 GeV
t = Time (seconds, years)
E = Energy (GeV)
Key
quark
gluon
electron
muon
tau
neutrino
bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL © 2014
Supported by DOE


HISTORY OF THE UNIVERSE
LHC~10^3 GeV
m(Planck)
10^19 GeV
High-energy
protons
Size of visible universe
Cosmic Microwave Background radiation is visible
Structure formation
Dark energy accelerated expansion
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POSSIBLE DARK MATTER RELICS
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t = 10^-36 s
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Particle Data Group, LBNL © 2014
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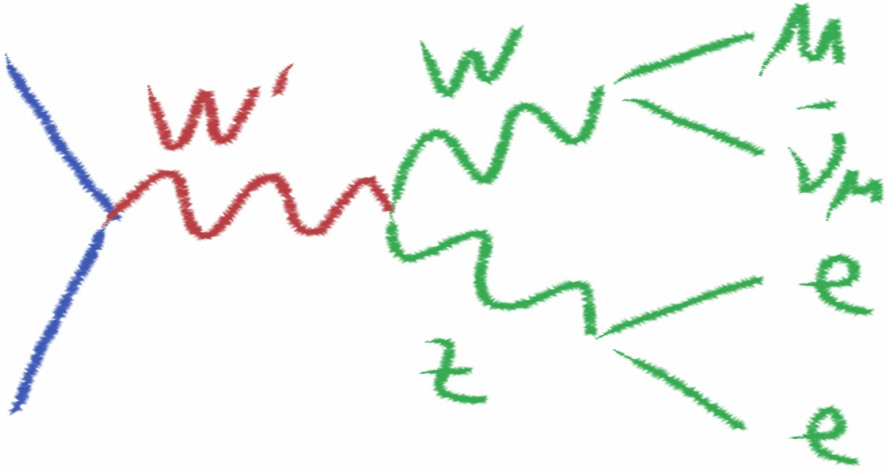
Room for Improvement

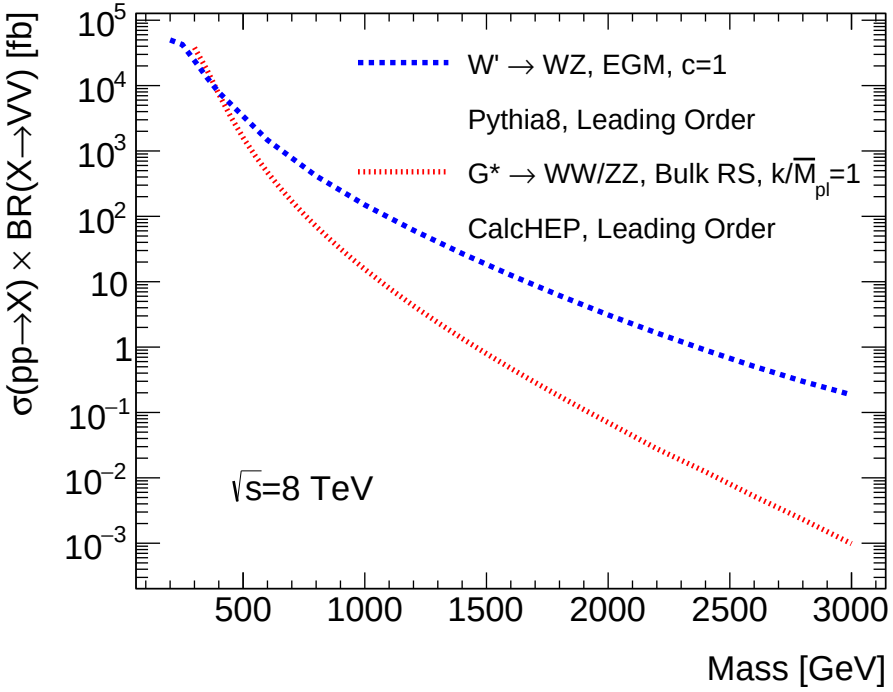
Lingering questions....

- SM does not accommodate quantum gravity (gravitons)
- If the SM is valid to 10^{19} GeV, why are masses < 1 TeV?
  - "Hierarchy problem"
- $\sim$85% of matter is *not* contained in the SM
  - Dark matter
- (non) unification of gauge couplings
- No room for Dark Energy
- Many others....
  - no explanation for mass structure of fermions
  - baryon/antibaryon asymmetry
  - neutrino masses and mixing

...motivates some "new physics" at or above the weak scale

Extended Gauge Sectors





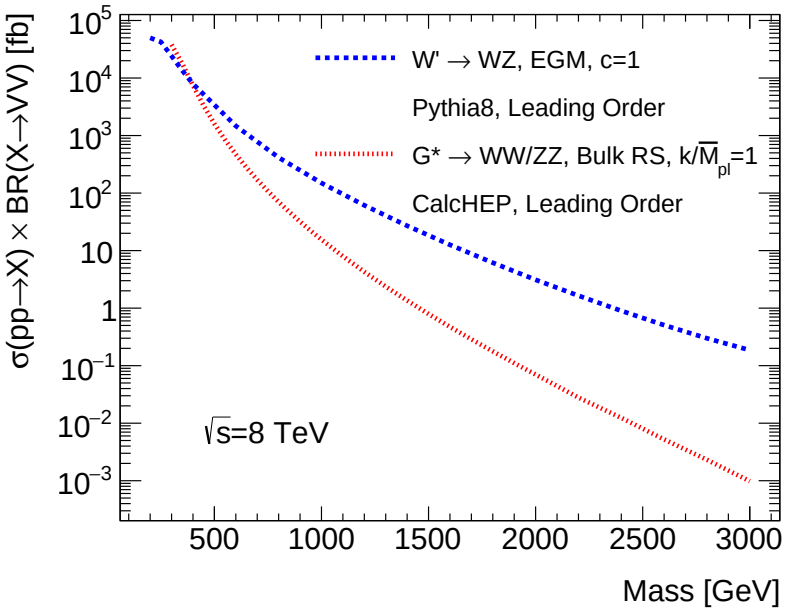
Generic search for extended gauge sectors

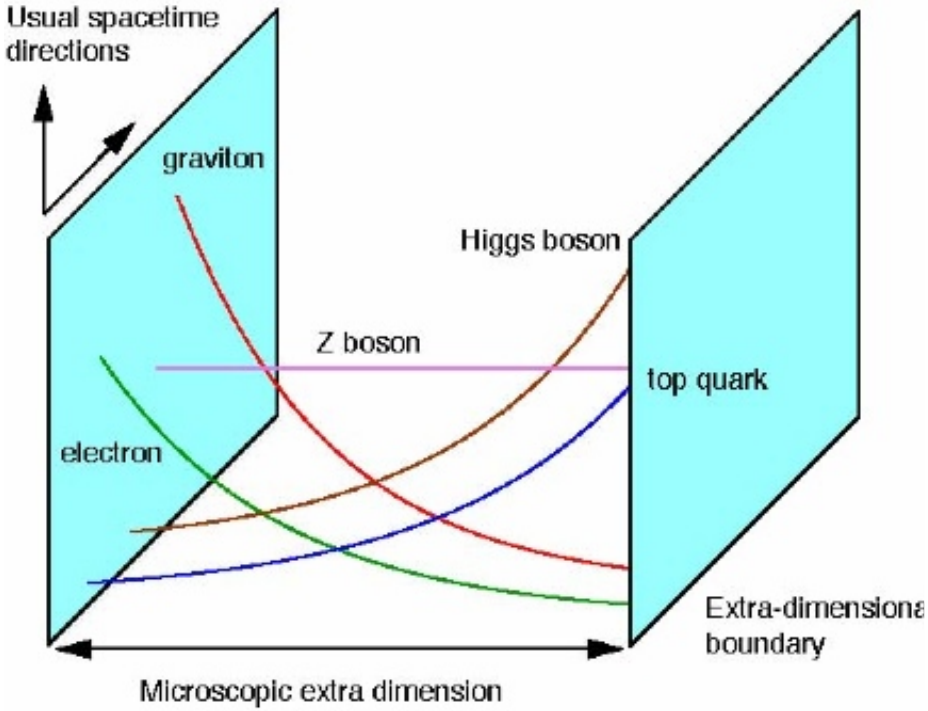
- Weakly coupled: Extended gauge model (EGM) W'
- Strongly coupled: Technicolor, Composite Higgs, etc.
- Simplified models, e.g. Heavy Vector Triplet

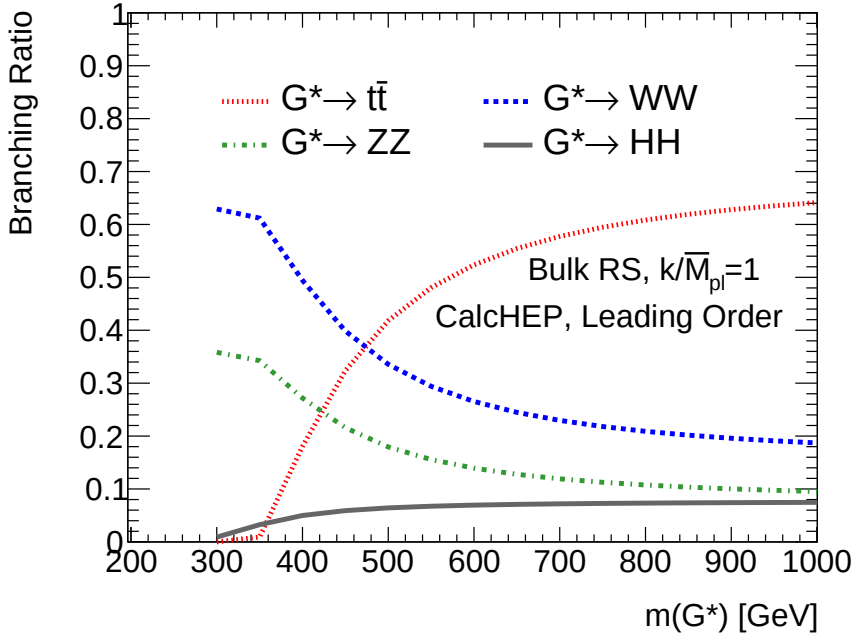
$$\mathcal{L}_V = -\frac{1}{4} D_\mu V_\nu^a D^\mu V^{\nu a} + \frac{m_V^2}{2} V_\mu^a V^{\mu a} + i g_V c_H V_\mu^a H^\dagger \tau^a D^\mu H + \frac{g^2}{g_V} c_F V_\mu^a J_F^{\mu a} + \frac{g_V}{2} c_{VVV} \epsilon_{abc} V_\mu^a V_\nu^b D^\mu V^{\nu c} + g_V^2 c_{VVHH} V_\mu^a V^{\mu a} H^\dagger H - \frac{g}{2} c_{VVW} \epsilon_{abc} W^{\mu\nu a} V_\mu^b V_\nu^c$$

Extra spacetime dimensions

- Gravity is weak because it is diluted in $(4+n)$ dimensions
- **Randall-Sundrum** extension: predicts heavy partners of the graviton, G^*
  - Free parameters: mass of G^*, coupling constant k/M_{pl}







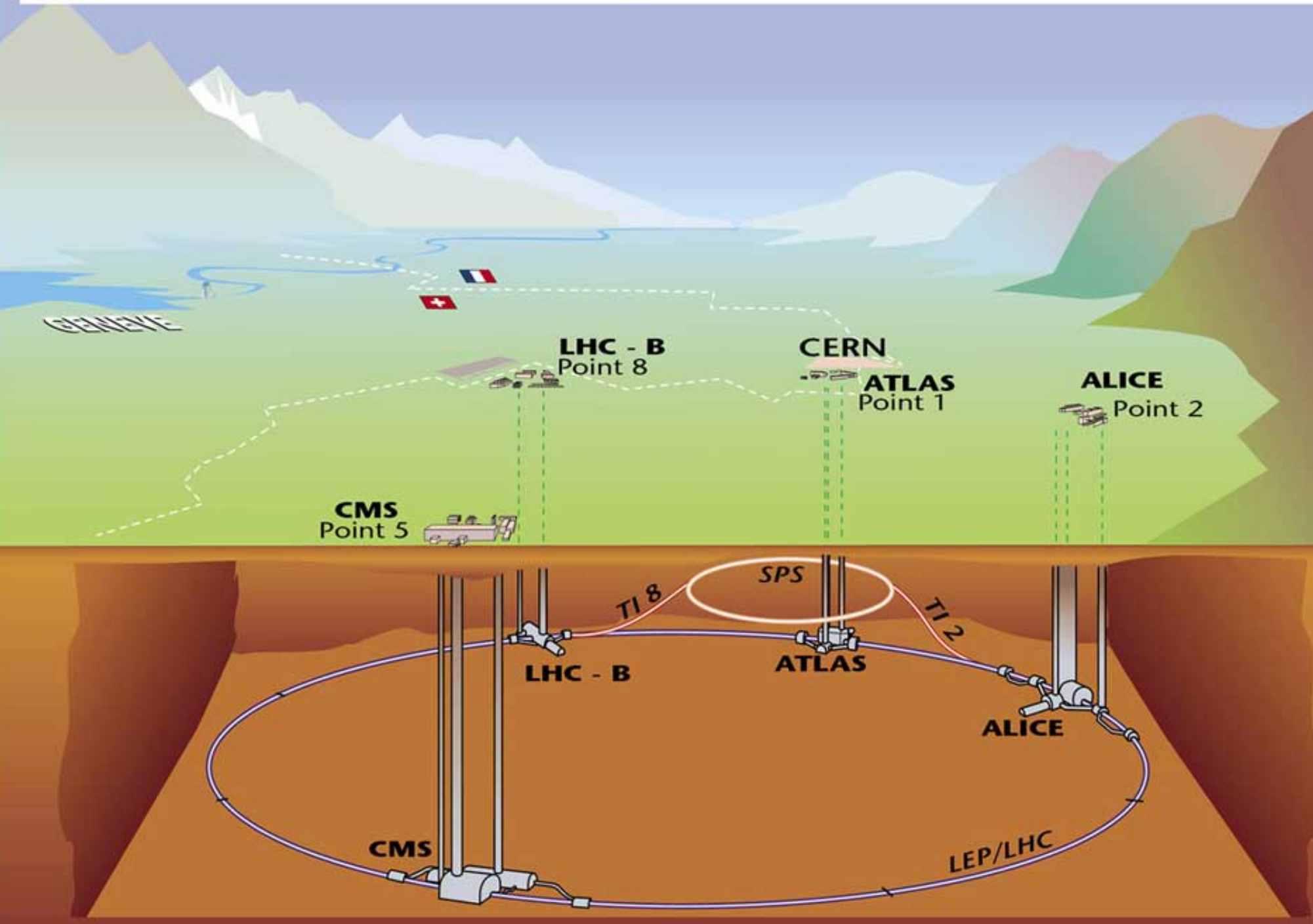
Outline

✓ Introduction

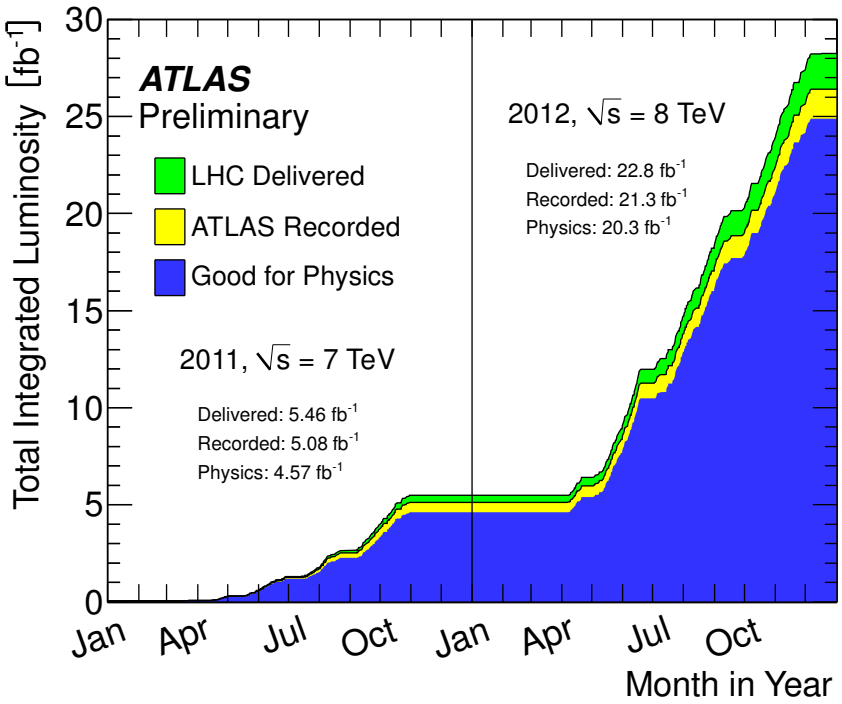
1. ATLAS and the LHC
   - Accelerator and detector
   - Detector performance
   - Standard Model physics results
2. Searching for exotic diboson resonances
   - $W' \to \ell\nu\ell\ell$
   - $V' \to \ell\ell qq$
   - $V' \to \ell\nu qq$
   - $V' \to JJ$
   - Combined Search
3. Looking ahead to Run 2 (and beyond)

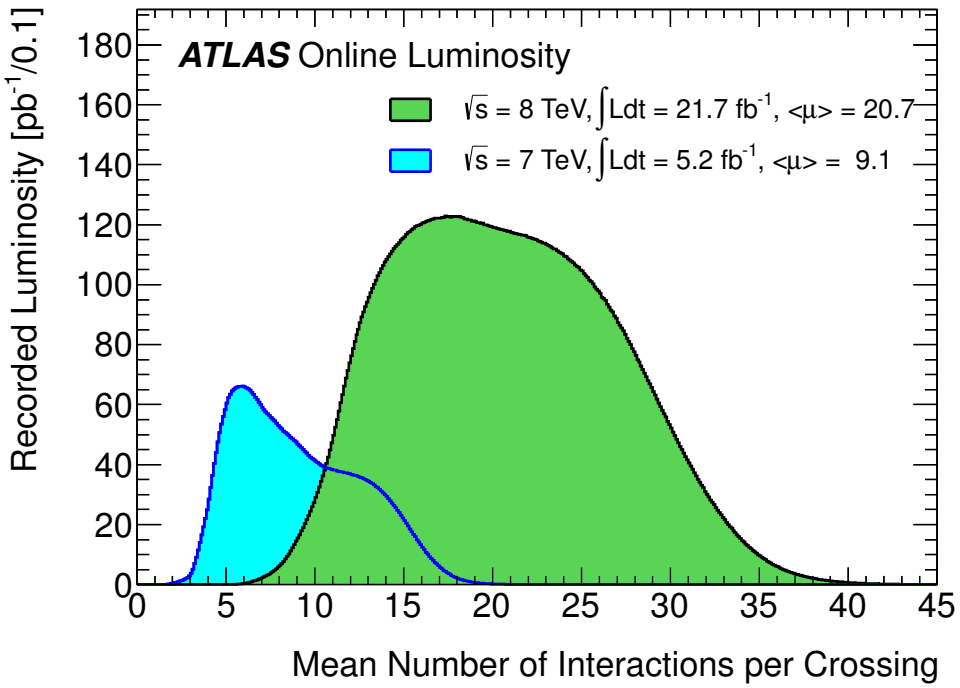
Run 1 Highlights

Overall view of the LHC experiments.

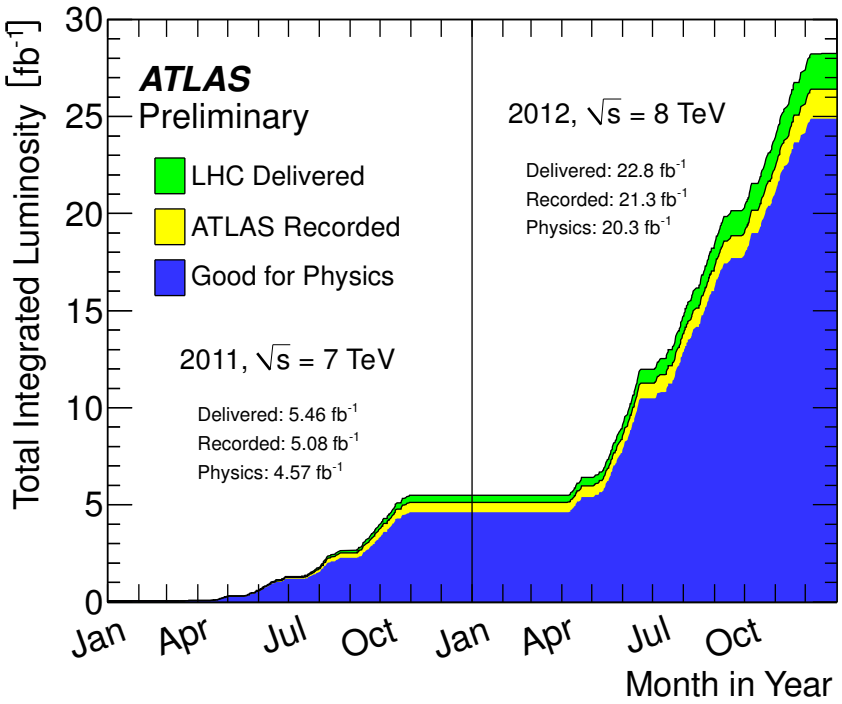


Data Taking


ATLAS
Preliminary
LHC Delivered
ATLAS Recorded
Good for Physics
2011, √s = 7 TeV
Delivered: 5.46 fb-1
Recorded: 5.08 fb-1
Physics: 4.57 fb-1
2012, √s = 8 TeV
Delivered: 22.8 fb-1
Recorded: 21.3 fb-1
Physics: 20.3 fb-1
Total Integrated Luminosity [fb-1]
Jan
Apr
Jul
Oct
Jan
Apr
Jul
Oct
Month in Year


ATLAS Online Luminosity
√s = 8 TeV, ∫Ldt = 21.7 fb-1, <μ> = 20.7
√s = 7 TeV, ∫Ldt = 5.2 fb-1, <μ> = 9.1
Recorded Luminosity [pb-1/0.1]
Mean Number of Interactions per Crossing

Data Taking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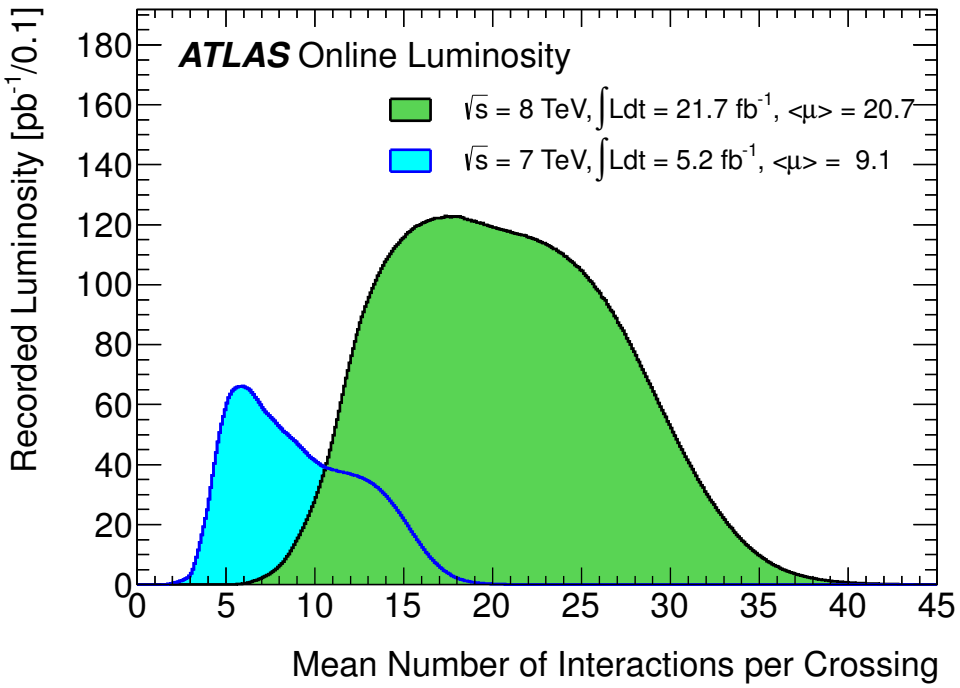
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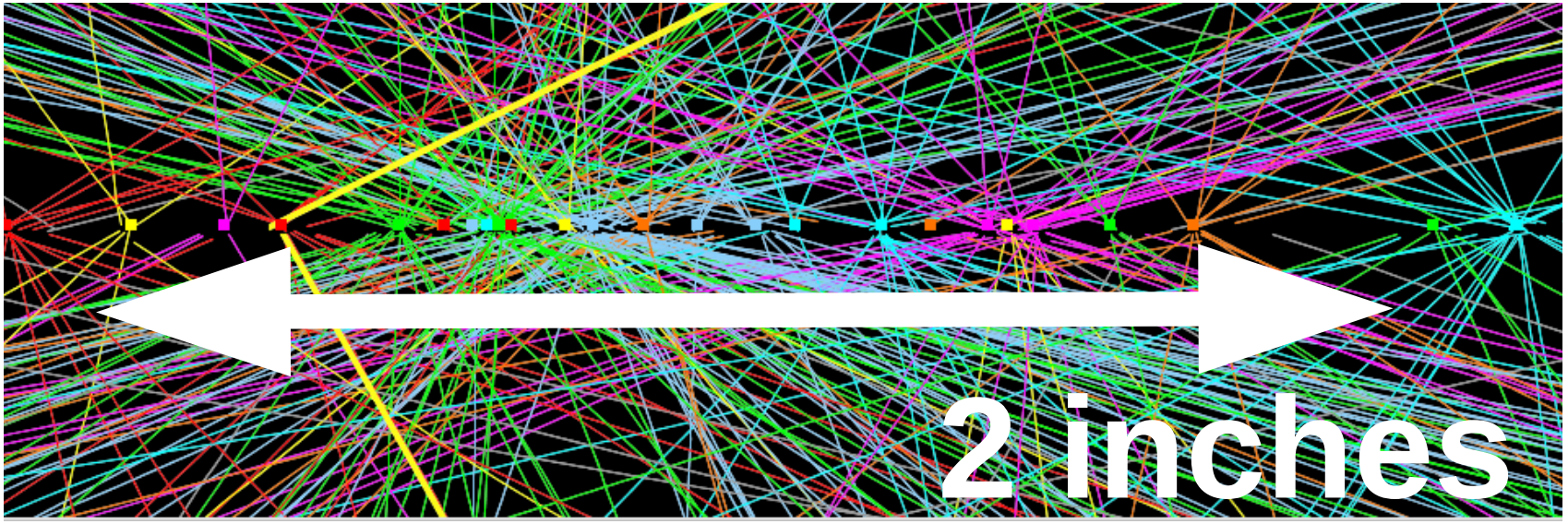
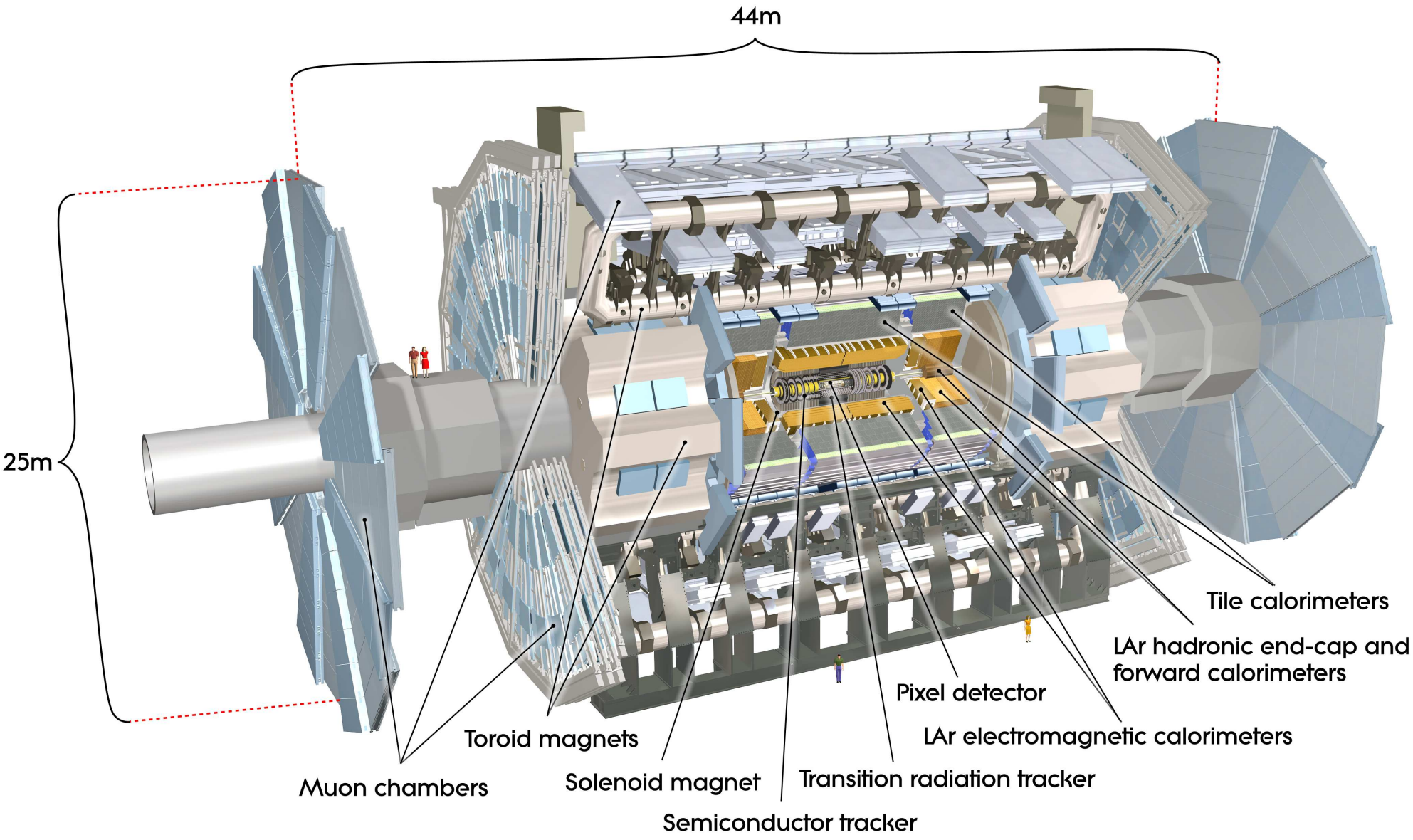
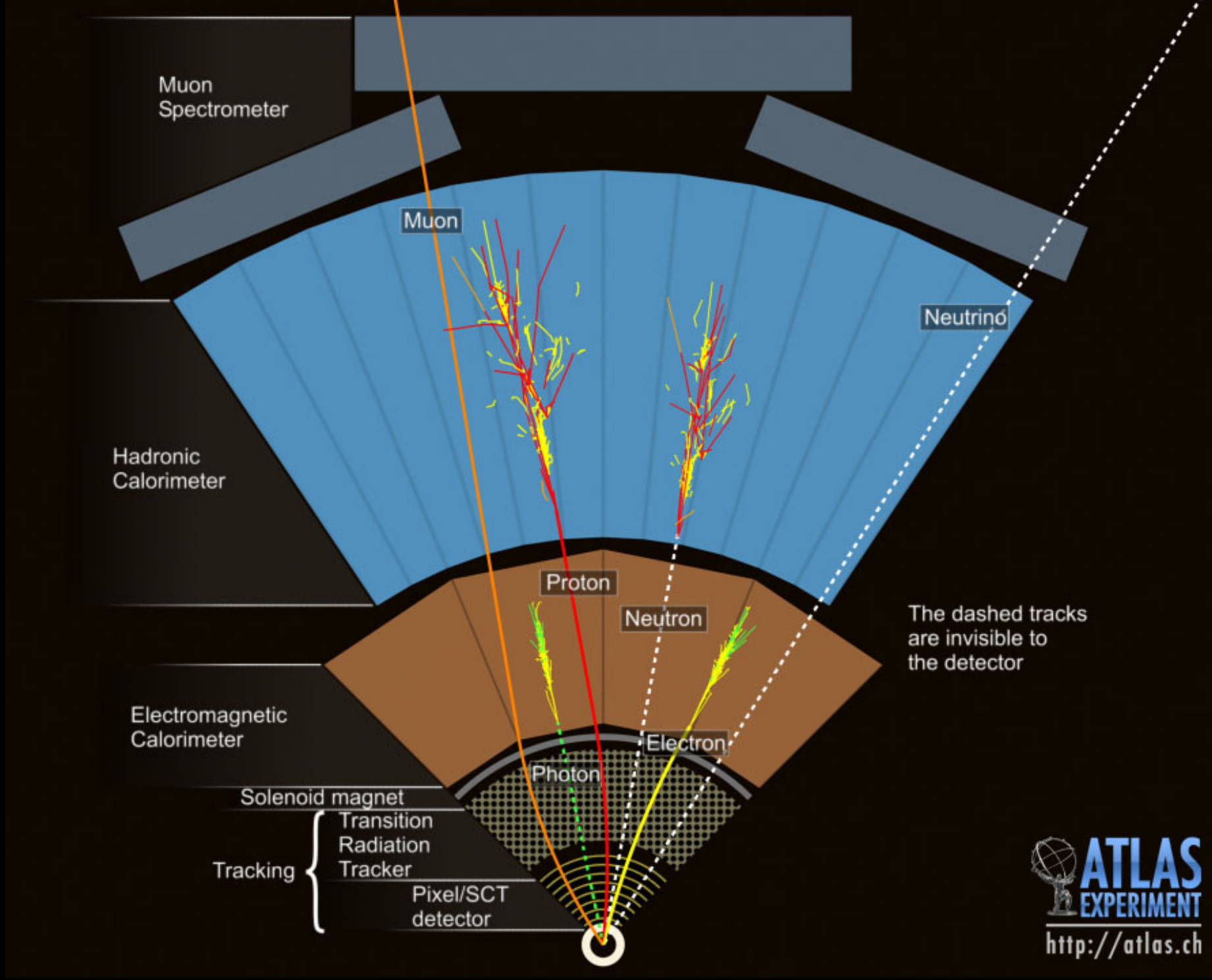
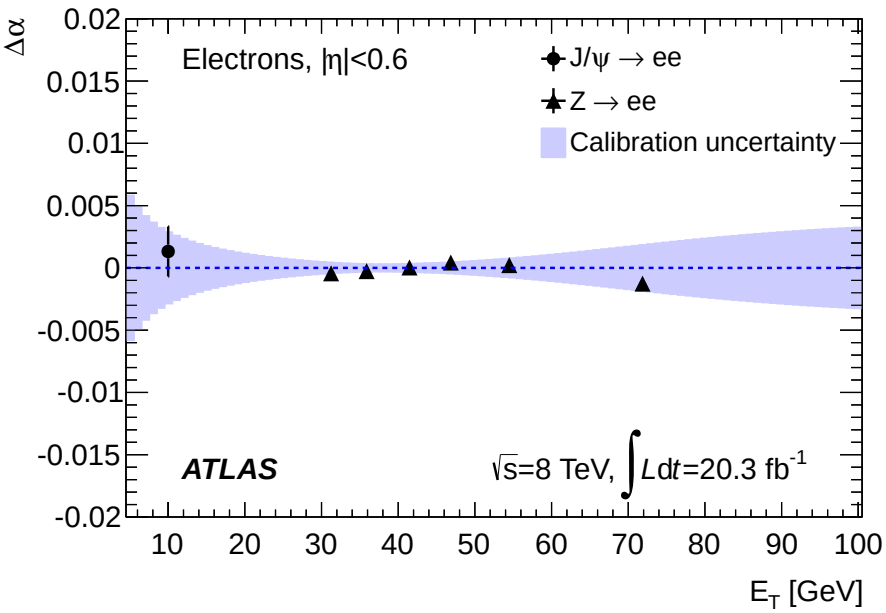

2 inches

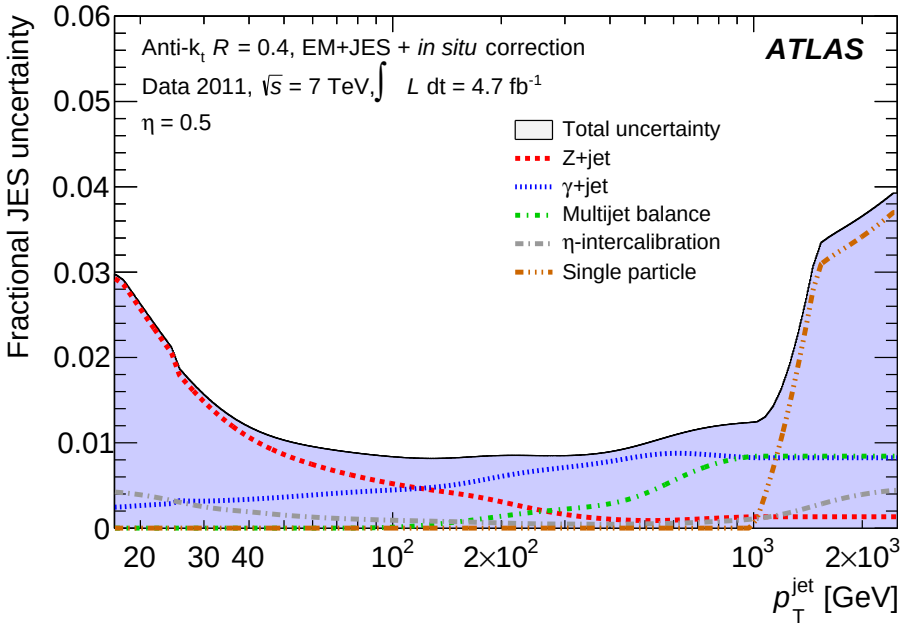
A Toroidal LHC ApparatuS

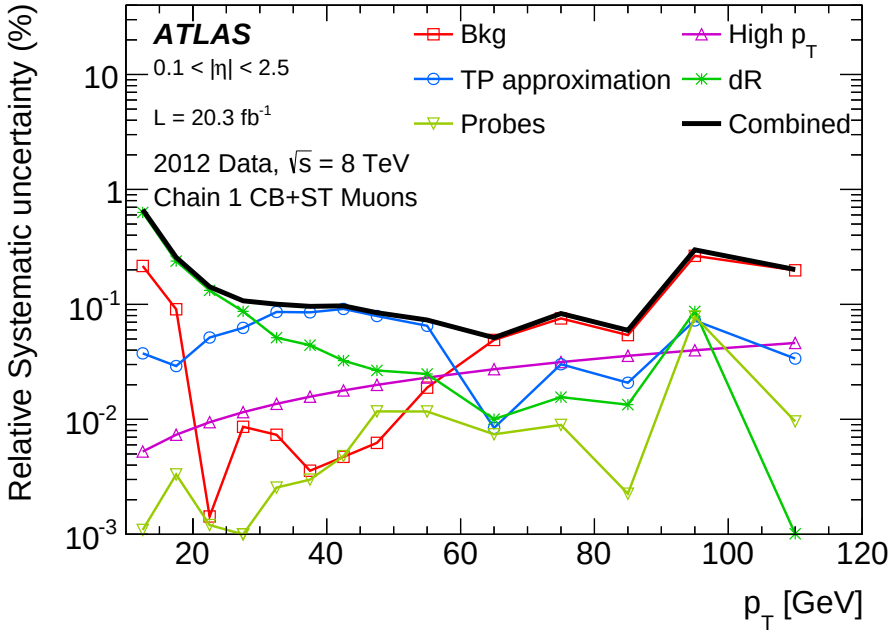


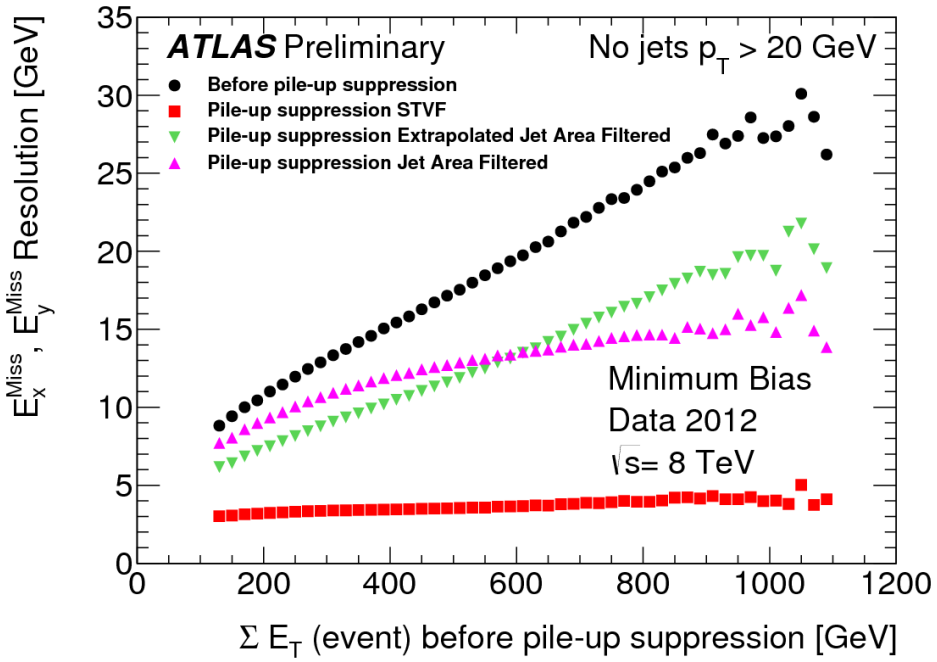

Muon Spectrometer
Muon
Neutrino
Hadronic Calorimeter
Proton
Neutron
The dashed tracks are invisible to the detector
Electromagnetic Calorimeter
Electron
Photon
Solenoid magnet
Tracking
Transition Radiation Tracker
Pixel/SCT detector
ATLAS EXPERIMENT
http://atlas.ch

ATLAS Performance





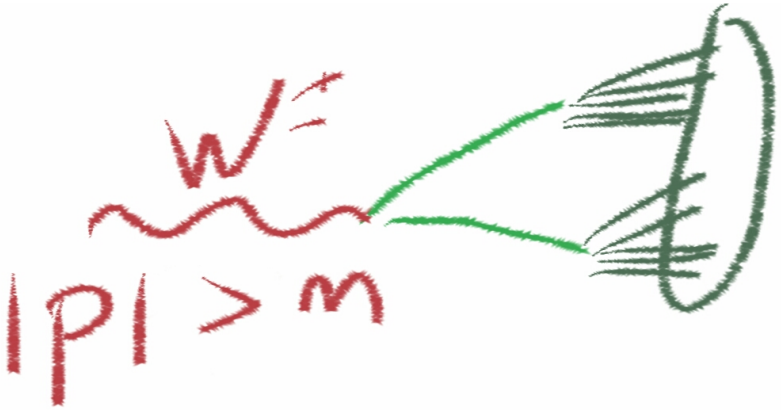




Jet Substructure for Hadronic W/Z

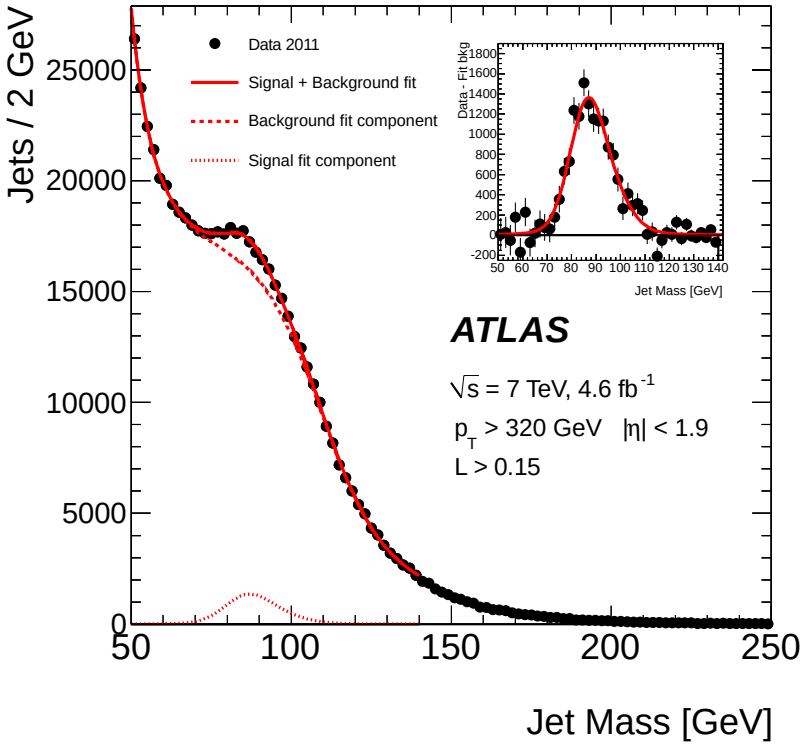
Bosons at rest

Bosons with boost!

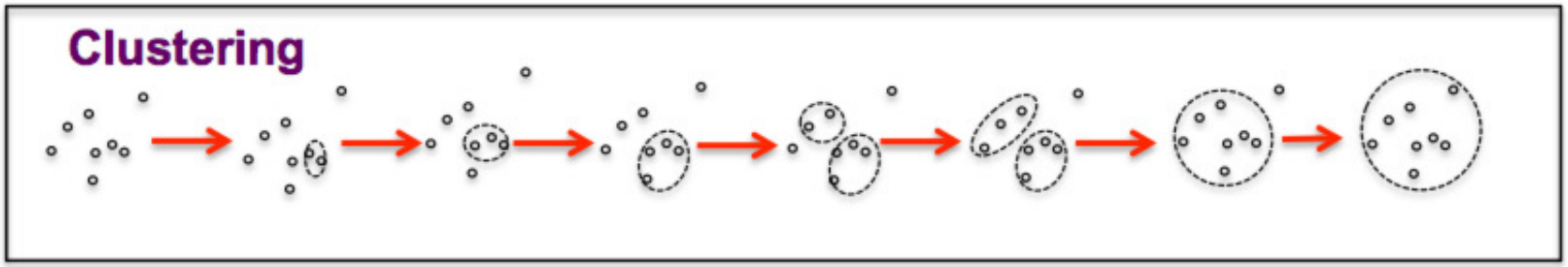


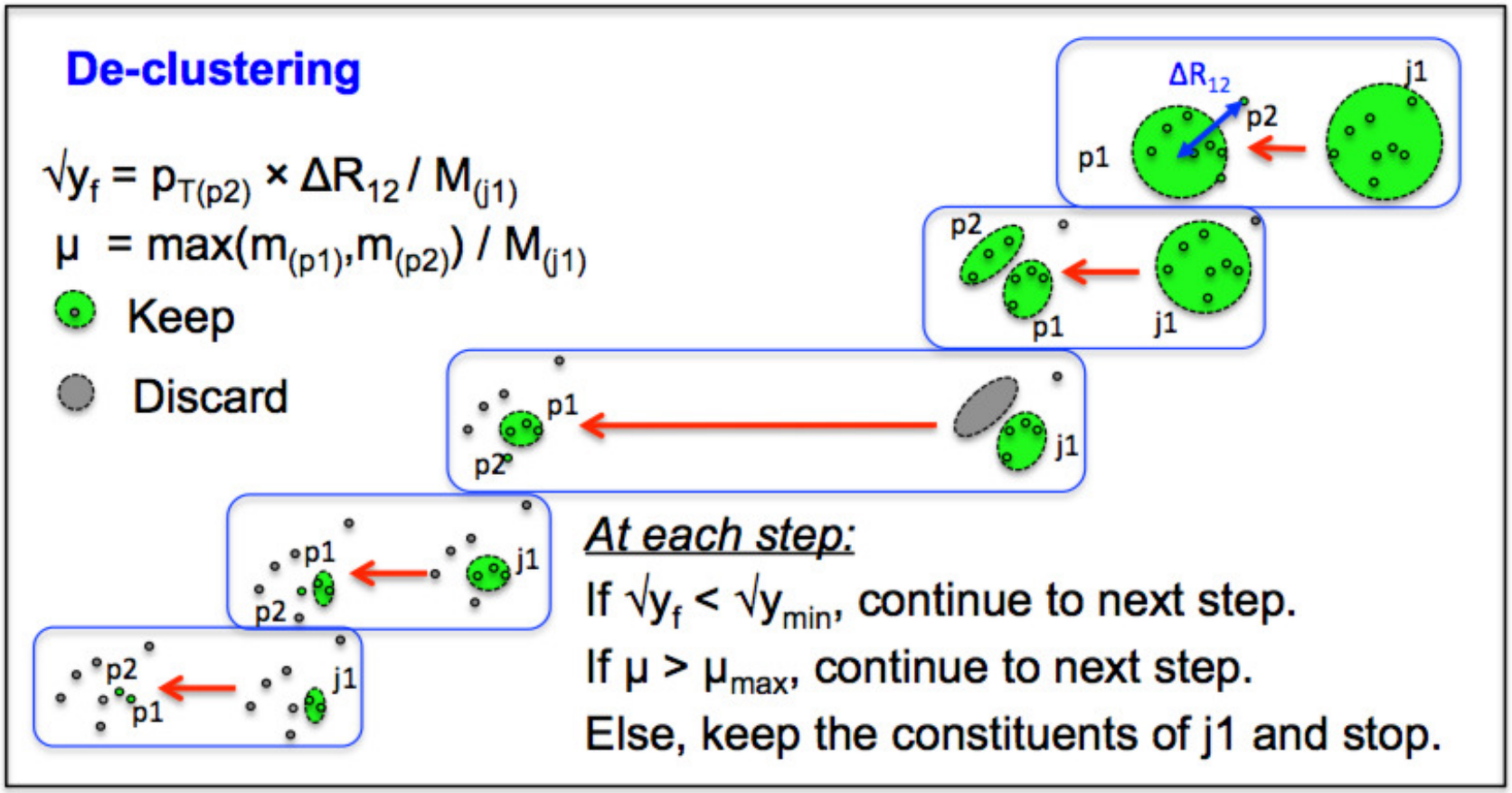
"Jet Substructure" allows us to discriminate signal from background

- Boosted bosons have a 2-prong shape
- Different from QCD evolution of gluon or quark
- Validation via SM measurement
- New J. Phys. 16 113013



Boosted Bosons

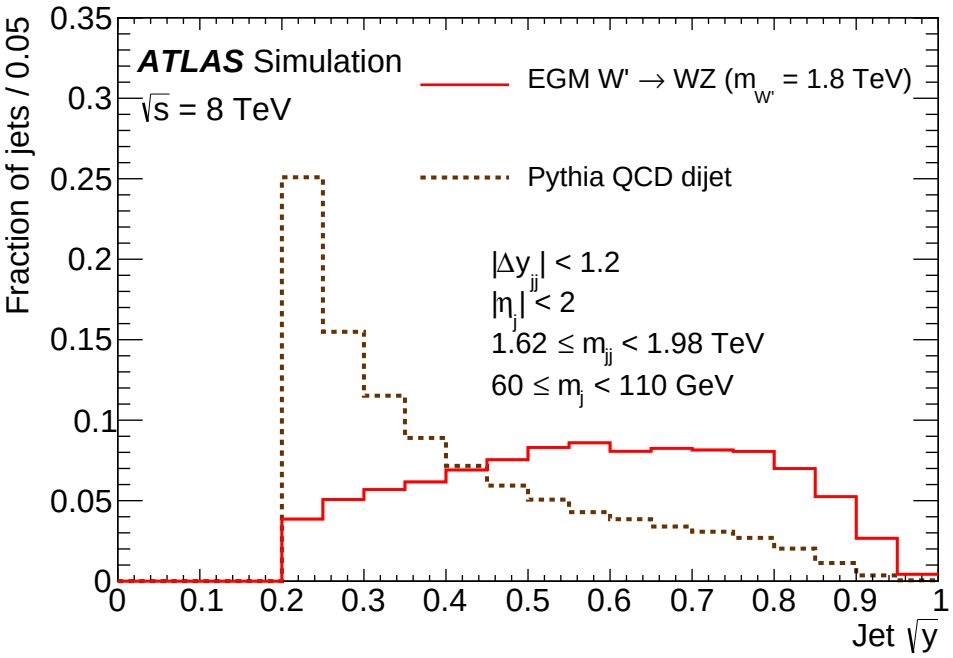


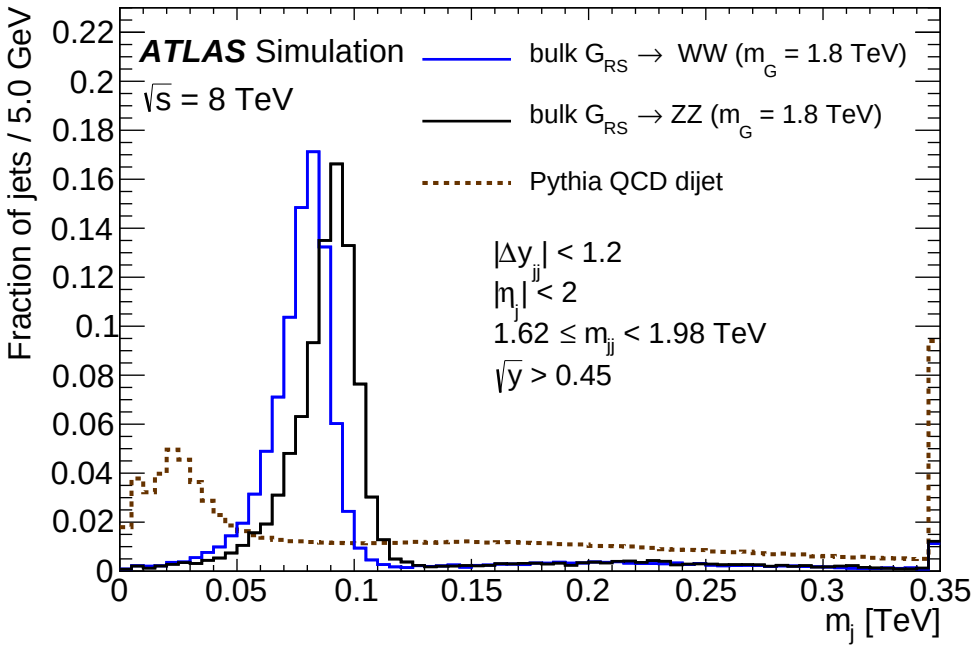


Boosted Bosons

Common large-R/merged jet (J) selection:

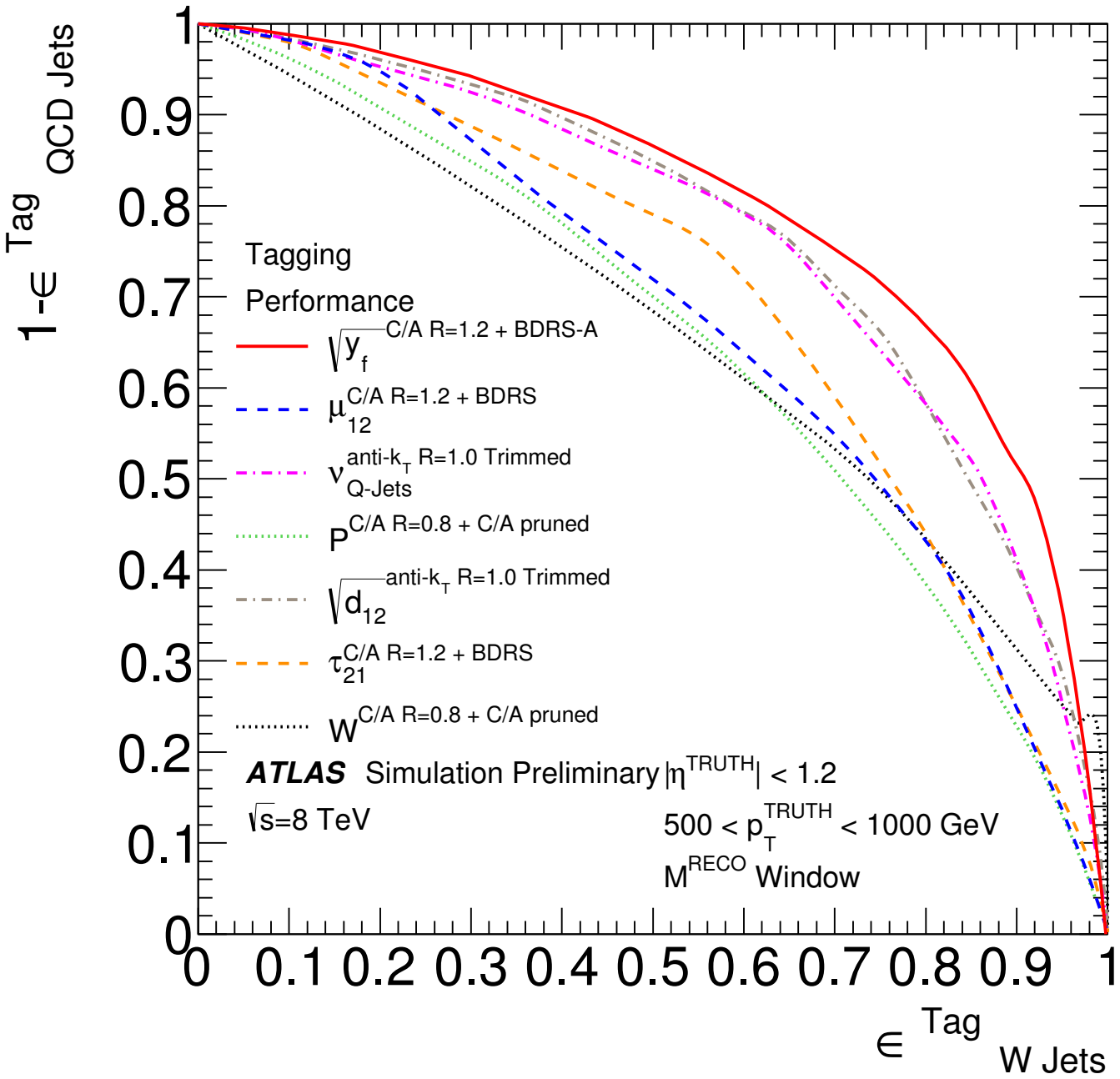
- Cambridge-Aachen jets, $R = 1.2$
- Reclustering mass-drop split-filter algorithm (BDRS-A)
- Use subjets to require $\sqrt{y_F} = \min(p_{\mathrm{T}}^{j1}, p_{\mathrm{T}}^{j2})\Delta R_{12}/m_{12} > 0.45$
- Require mass to be in window around W or Z mass (window size varies)





Boosted Bosons

ATL-PHYS-PUB-2014-004



Searches for Exotic Diboson Resonances

Outline

- ✓ Introduction
- ✓ ATLAS and the LHC
  - ✓ Accelerator and detector
  - ✓ Detector performance
  - ✓ Standard Model physics results
- 1 Searching for exotic diboson resonances
  - $W' \to \ell\nu\ell\ell$
  - $V' \to \ell\ell qq$
  - $V' \to \ell\nu qq$
  - $V' \to JJ$
  - Combined Search
- 2 Looking ahead to Run 2 (and beyond)

ATLAS Exotics Searches* - 95% CL Exclusion

Status: ICHEP 2014

ATLAS Preliminary

$\int \mathcal{L}\, dt = (1.0 - 20.3)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 7, 8$ TeV

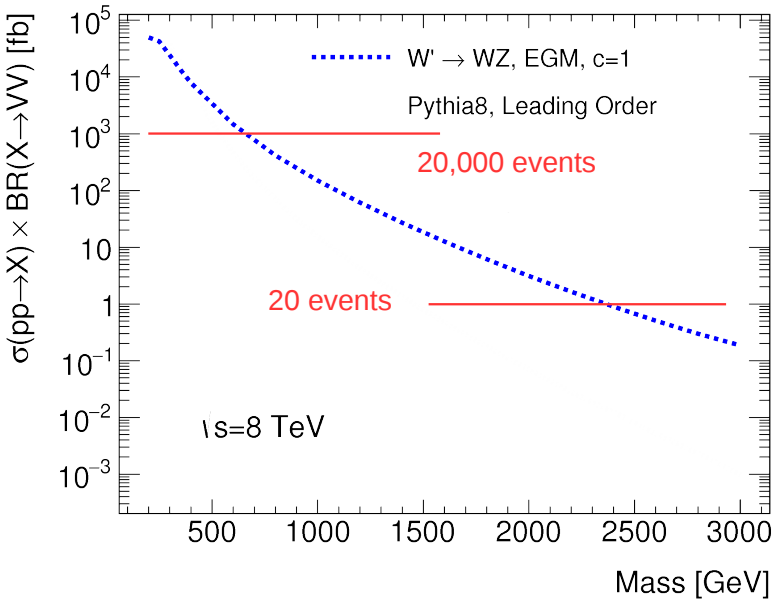
	Model	ℓ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$	Mass limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	–	1-2 j	Yes	4.7	M_D 4.37 TeV	$n = 2$	1210.4491
	ADD non-resonant $\ell\ell$	$2e, \mu$	–	–	20.3	M_S 5.2 TeV	$n = 3$ HLZ	ATLAS-CONF-2014-030
	ADD QBH $\to \ell q$	$1\ e, \mu$	1 j	–	20.3	M_{th} 5.2 TeV	$n = 6$	1311.2006
	ADD QBH	–	2 j	–	20.3	M_{th} 5.82 TeV	$n = 6$	to be submitted to PRD
	ADD BH high N_{trk}	$2\ \mu$ (SS)	–	–	20.3	M_{th} 5.7 TeV	$n = 6$, $M_D = 1.5$ TeV, non-rot BH	1308.4075
	ADD BH high $\sum p_T$	$\geq 1\ e, \mu$	≥ 2 j	–	20.3	M_{th} 6.2 TeV	$n = 6$, $M_D = 1.5$ TeV, non-rot BH	1405.4254
	RS1 $G_{KK} \to \ell\ell$	$2\ e, \mu$	–	–	20.3	G_{KK} mass 2.68 TeV	$k/\overline{M}_{Pl} = 0.1$	1405.4123
	RS1 $G_{KK} \to WW \to \ell\nu\ell\nu$	$2\ e, \mu$	–	Yes	4.7	G_{KK} mass 1.23 TeV	$k/\overline{M}_{Pl} = 0.1$	1208.2880
	Bulk RS $G_{KK} \to ZZ \to \ell\ell qq$	$2\ e, \mu$	2 j / 1 J	–	20.3	G_{KK} mass 730 GeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2014-039
	Bulk RS $G_{KK} \to HH \to b\bar{b}b\bar{b}$	–	4 b	–	19.5	G_{KK} mass 590-710 GeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2014-005
	Bulk RS $g_{KK} \to t\bar{t}$	$1\ e, \mu$	≥ 1 b, ≥ 1J/2j	Yes	14.3	g_{KK} mass 2.0 TeV	BR = 0.925	ATLAS-CONF-2013-052
	S^1/Z_2 ED	$2\ e, \mu$	–	–	5.0	$M_{KK} \approx R^{-1}$ 4.71 TeV		1209.2535
	UED	$2\ \gamma$	–	Yes	4.8	Compact. scale R^{-1} 1.41 TeV		ATLAS-CONF-2012-072
Gauge bosons	SSM $Z' \to \ell\ell$	$2\ e, \mu$	–	–	20.3	Z' mass 2.9 TeV		1405.4123
	SSM $Z' \to \tau\tau$	$2\ \tau$	–	–	19.5	Z' mass 1.9 TeV		ATLAS-CONF-2013-066
	SSM $W' \to \ell\nu$	$1\ e, \mu$	–	Yes	20.3	W' mass 3.28 TeV		ATLAS-CONF-2014-017
	EGM $W' \to WZ \to \ell\nu\ell'\ell'$	$3\ e, \mu$	–	Yes	20.3	W' mass 1.52 TeV		1406.4456
	EGM $W' \to WZ \to qq\ell\ell$	$2\ e, \mu$	2 j / 1 J	–	20.3	W' mass 1.59 TeV		ATLAS-CONF-2014-039
	LRSM $W'_R \to t\bar{b}$	$1\ e, \mu$	2 b, 0-1 j	Yes	14.3	W' mass 1.84 TeV		ATLAS-CONF-2013-050
	LRSM $W'_R \to t\bar{b}$	$0\ e, \mu$	≥ 1 b, 1 J	–	20.3	W' mass 1.77 TeV		to be submitted to EPJC
CI	CI $qqqq$	–	2 j	–	4.8	Λ 7.6 TeV	$\eta = +1$	1210.1718
	CI $qq\ell\ell$	$2\ e, \mu$	–	–	20.3	Λ 21.6 TeV	$\eta_{LL} = -1$	ATLAS-CONF-2014-030
	CI $uutt$	$2\ e, \mu$ (SS)	≥ 1 b, ≥ 1 j	Yes	14.3	Λ 3.3 TeV	$\lvert C \rvert = 1$	ATLAS-CONF-2013-051
DM	EFT D5 operator (Dirac)	$0\ e, \mu$	1-2 j	Yes	10.5	M_* 731 GeV	at 90% CL for $m(\chi) < 80$ GeV	ATLAS-CONF-2012-147
	EFT D9 operator (Dirac)	$0\ e, \mu$	1 J, ≤ 1 j	Yes	20.3	M_* 2.4 TeV	at 90% CL for $m(\chi) < 100$ GeV	1309.4017
LQ	Scalar LQ 1st gen	$2\ e$	≥ 2 j	–	1.0	LQ mass 660 GeV	$\beta = 1$	1112.4828
	Scalar LQ 2nd gen	$2\ \mu$	≥ 2 j	–	1.0	LQ mass 685 GeV	$\beta = 1$	1203.3172
	Scalar LQ 3rd gen	$1\ e, \mu, 1\ \tau$	1 b, 1 j	–	4.7	LQ mass 534 GeV	$\beta = 1$	1303.0526
Heavy quarks	Vector-like quark $TT \to Ht + X$	$1\ e, \mu$	≥ 2 b, ≥ 4 j	Yes	14.3	T mass 790 GeV	T in (T,B) doublet	ATLAS-CONF-2013-018
	Vector-like quark $TT \to Wb + X$	$1\ e, \mu$	≥ 1 b, ≥ 3 j	Yes	14.3	T mass 670 GeV	isospin singlet	ATLAS-CONF-2013-060
	Vector-like quark $TT \to Zt + X$	$2/\geq 3\ e, \mu$	$\geq 2/\geq 1$ b	–	20.3	T mass 735 GeV	T in (T,B) doublet	ATLAS-CONF-2014-036
	Vector-like quark $BB \to Zb + X$	$2/\geq 3\ e, \mu$	$\geq 2/\geq 1$ b	–	20.3	B mass 755 GeV	B in (B,Y) doublet	ATLAS-CONF-2014-036
	Vector-like quark $BB \to Wt + X$	$2\ e, \mu$ (SS)	≥ 1 b, ≥ 1 j	Yes	14.3	B mass 720 GeV	B in (T,B) doublet	ATLAS-CONF-2013-051
Excited fermions	Excited quark $q^* \to q\gamma$	$1\ \gamma$	1 j	–	20.3	q^* mass 3.5 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1309.3230
	Excited quark $q^* \to qg$	–	2 j	–	20.3	q^* mass 4.09 TeV	only u^* and d^*, $\Lambda = m(q^*)$	to be submitted to PRD
	Excited quark $b^* \to Wt$	1 or 2 e, μ	1 b, 2 j or 1 j	Yes	4.7	b^* mass 870 GeV	left-handed coupling	1301.1583
	Excited lepton $\ell^* \to \ell\gamma$	$2\ e, \mu, 1\ \gamma$	–	–	13.0	ℓ^* mass 2.2 TeV	$\Lambda = 2.2$ TeV	1308.1364
Other	LSTC $a_T \to W\gamma$	$1\ e, \mu, 1\ \gamma$	–	Yes	20.3	a_T mass 960 GeV		to be submitted to PLB
	LRSM Majorana ν	$2\ e, \mu$	2 j	–	2.1	N^0 mass 1.5 TeV	$m(W_R) = 2$ TeV, no mixing	1203.5420
	Type III Seesaw	$2\ e, \mu$	–	–	5.8	$N^\pm$ mass 245 GeV	$\lvert V_e \rvert$=0.055, $\lvert V_\mu \rvert$=0.063, $\lvert V_\tau \rvert$=0	ATLAS-CONF-2013-019
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	$2\ e, \mu$ (SS)	–	–	4.7	$H^{\pm\pm}$ mass 409 GeV	DY production, BR($H^{\pm\pm} \to \ell\ell$)=1	1210.5070
	Multi-charged particles	–	–	–	4.4	multi-charged particle mass 490 GeV	DY production, $\lvert q \rvert = 4e$	1301.5272
	Magnetic monopoles	–	–	–	2.0	monopole mass 862 GeV	DY production, $\lvert g \rvert = 1g_D$	1207.6411

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

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

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

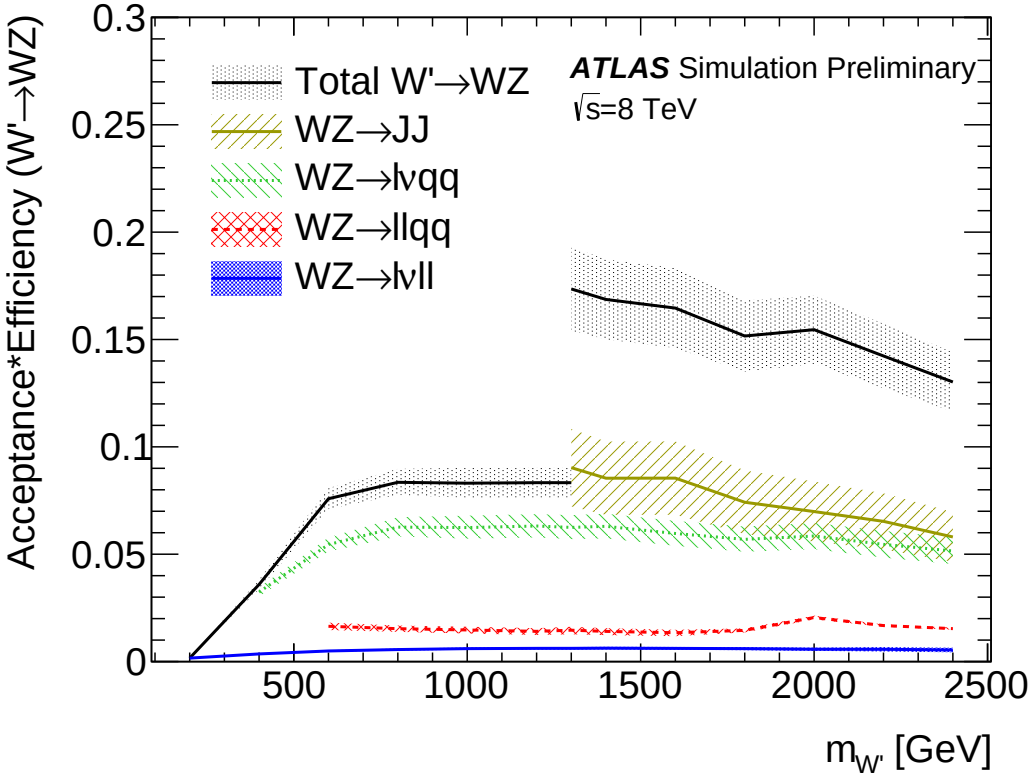
Searches for heavy W' bosons



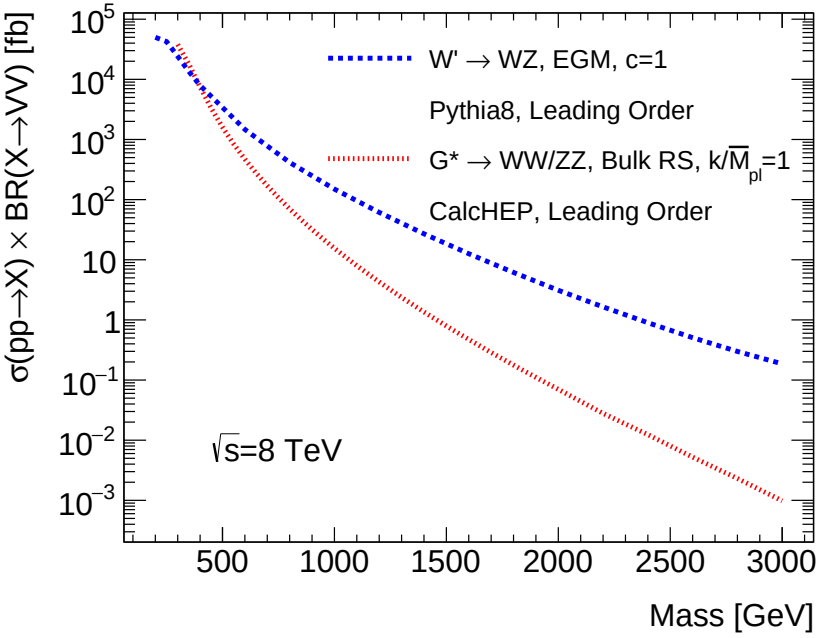
Extended Gauge Model (EGM) - large production rates!

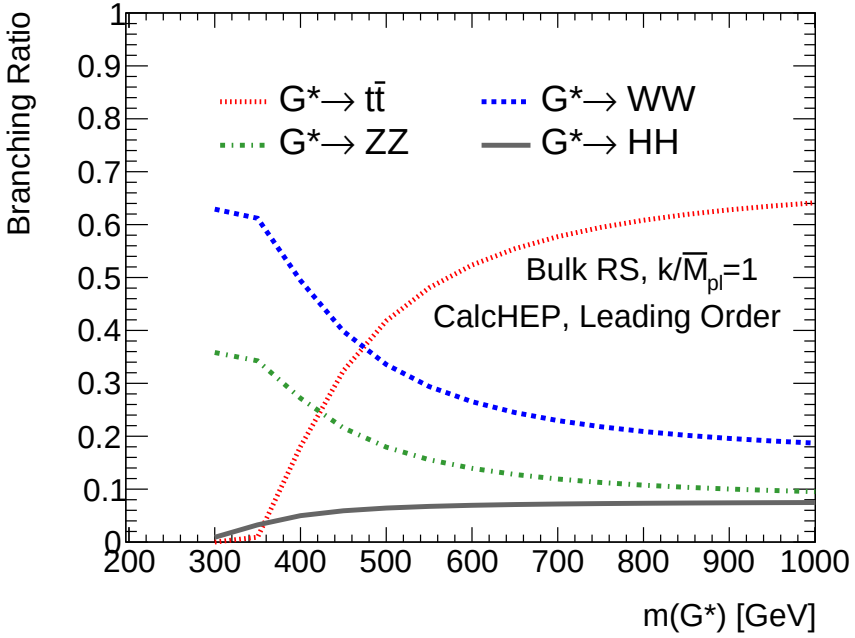
- 20k events for $m(W') = 700$ GeV
- 20 events for $m(W') = 2.4$ TeV

$W \rightarrow$	$Z \rightarrow$	BR
$\ell\nu$	$\ell\ell$	3.2%
qq	$\ell\ell$	6.8%
$\ell\nu$	qq	22.4%
qq	qq	47.6%



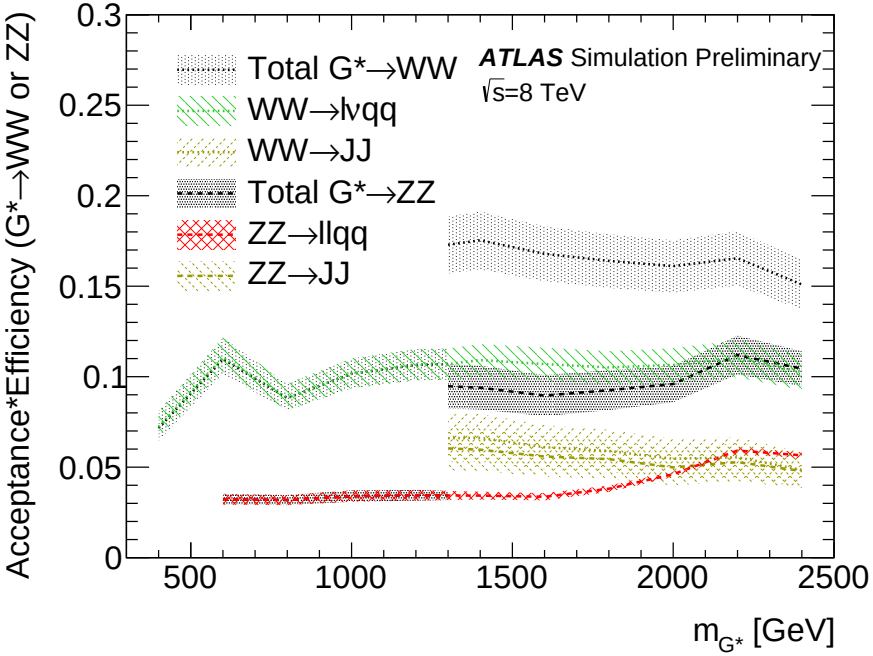
Searches for Bulk-RS Gravitons





$W \rightarrow$	$W \rightarrow$	BR
$\ell\nu$	qq	21.9%
qq	qq	45.7%

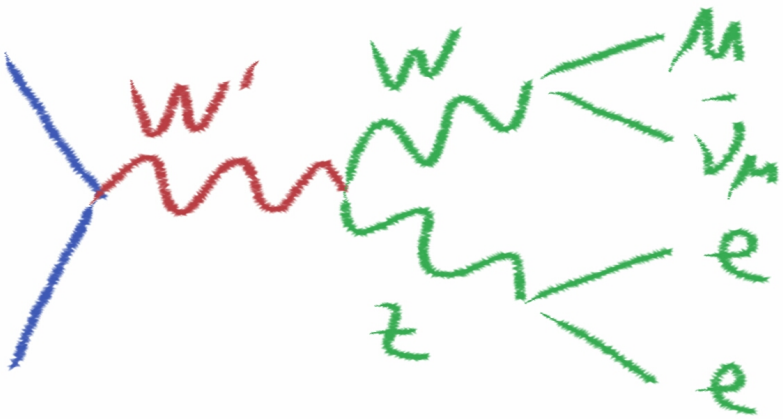
$Z \rightarrow$	$Z \rightarrow$	BR
$\ell\ell$	qq	7.7%
qq	qq	48.9%



$W' \to WZ \to \ell\nu\ell\ell$

PLB 737, 223 (2014)

- $= 3\ e/\mu + E_{\mathrm{T}}^{\mathrm{miss}} > 25$ GeV
- Reconstruct $m(WZ)$ using W-mass constraint
- SM WZ modeled with MC, tested in $\Delta\phi(\ell_3, E_{\mathrm{T}}^{\mathrm{miss}}) > 1.5$
- Require $\Delta y(W, Z) < 1.5$



$W' \to WZ \to \ell\nu\ell\ell$

PLB 737, 223 (2014)

- $= 3\ e/\mu + E_{\mathrm{T}}^{\mathrm{miss}} > 25$ GeV
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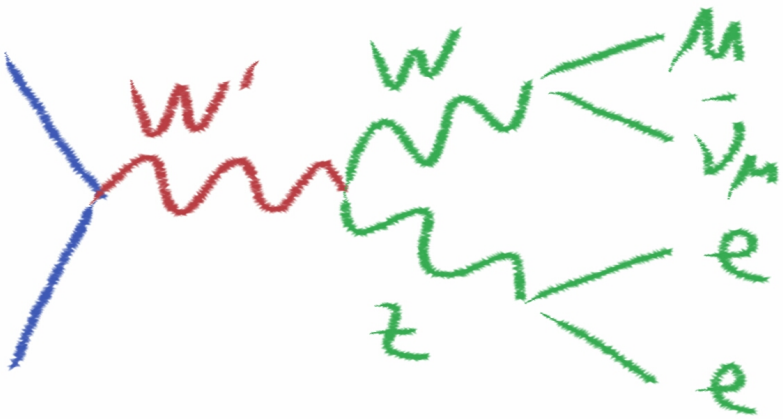
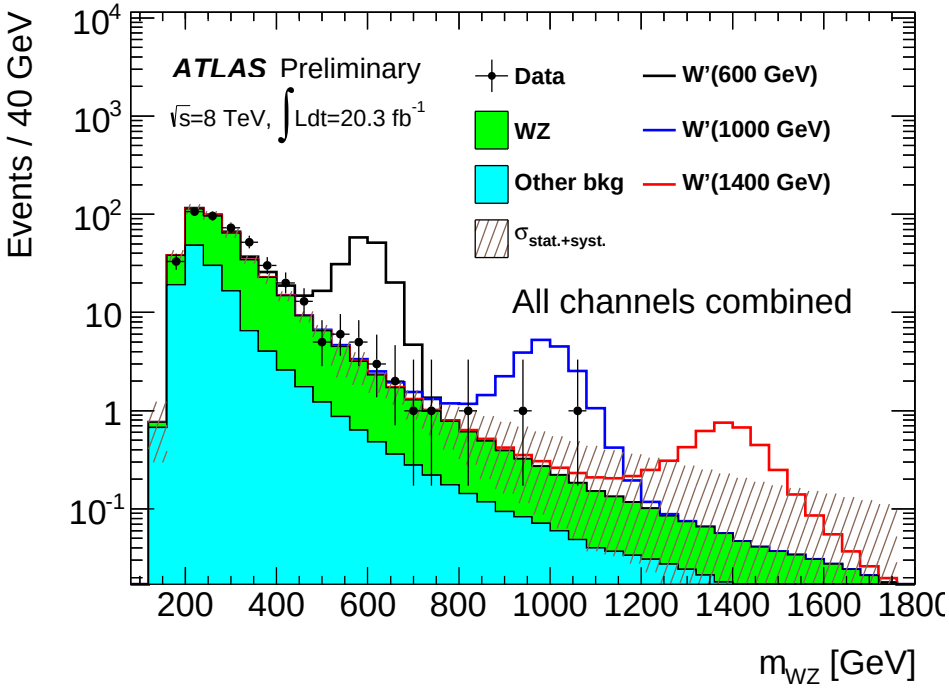
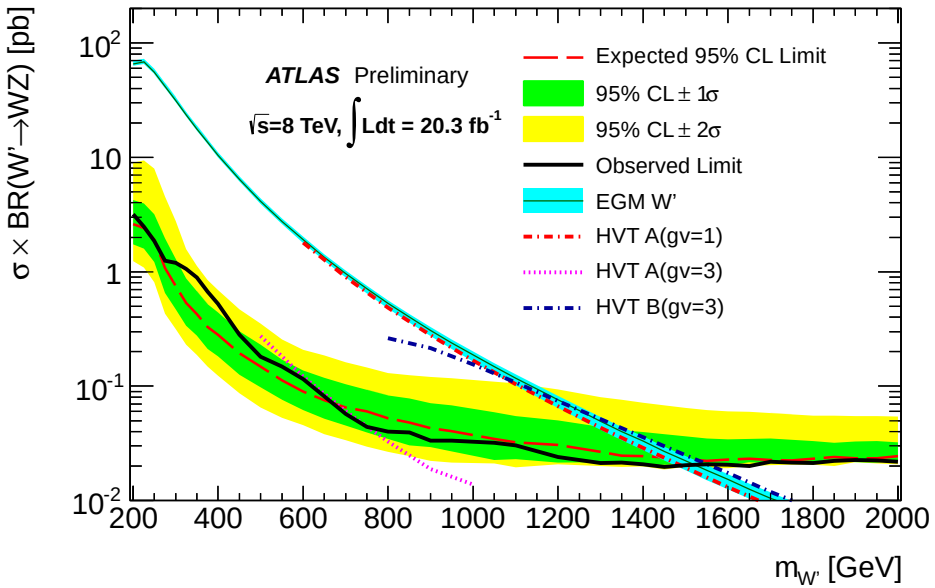




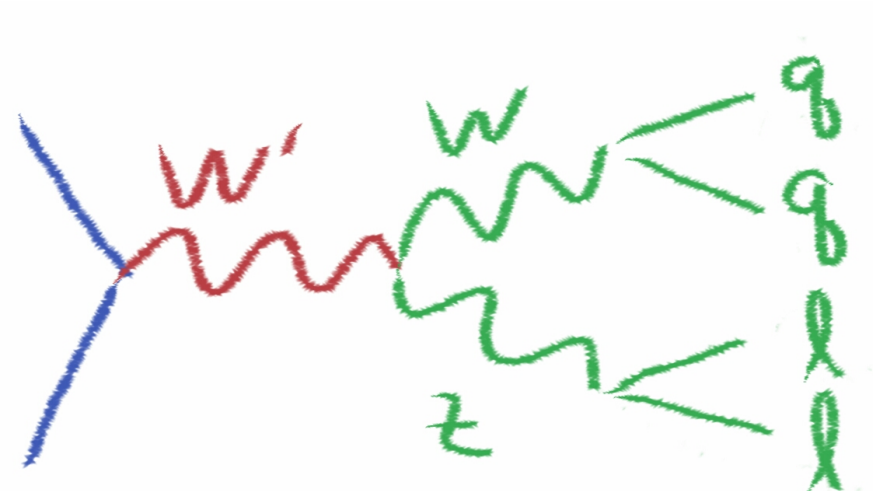


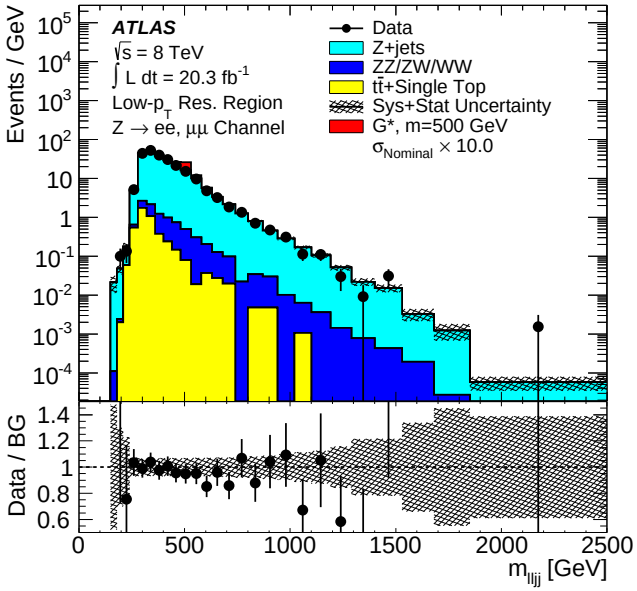
$V' \to ZV \to \ell\ell qq$

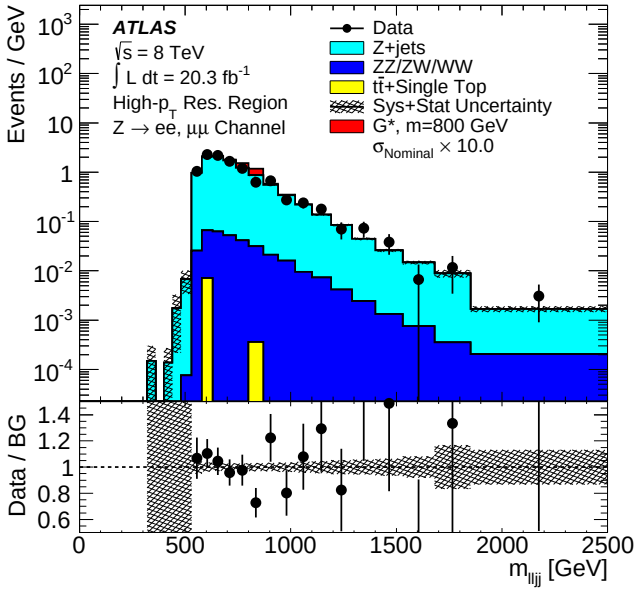
Eur. Phys. J. C (2015) 75:69

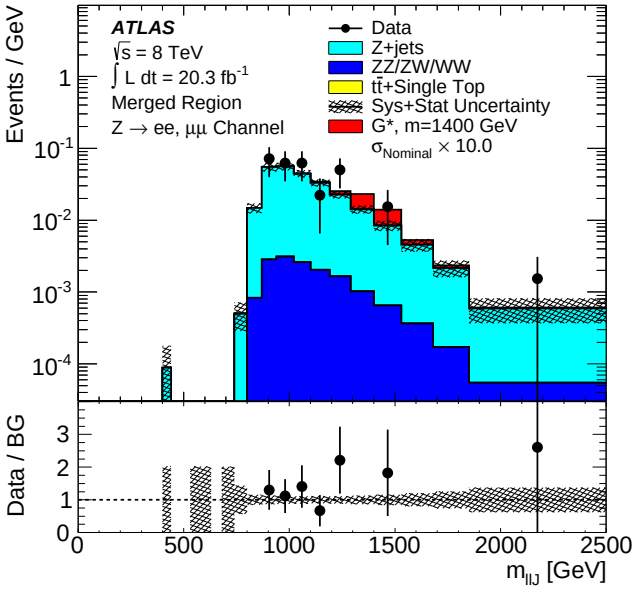
Search for $V' \to ZZ/WZ \to \ell\ell qq$:

- ee or $\mu\mu$ pair, with $66 < m(\ell\ell) < 116$ GeV
- 3 categories cover 0.3-2.0 TeV
- CR using mass sidebands
- W' and G^* interpretations

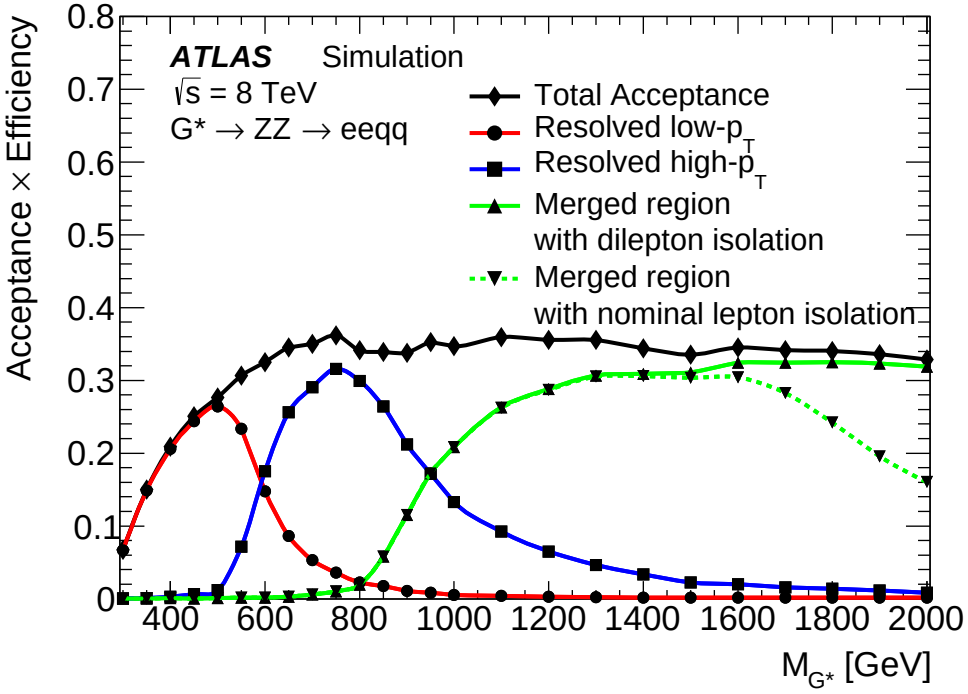


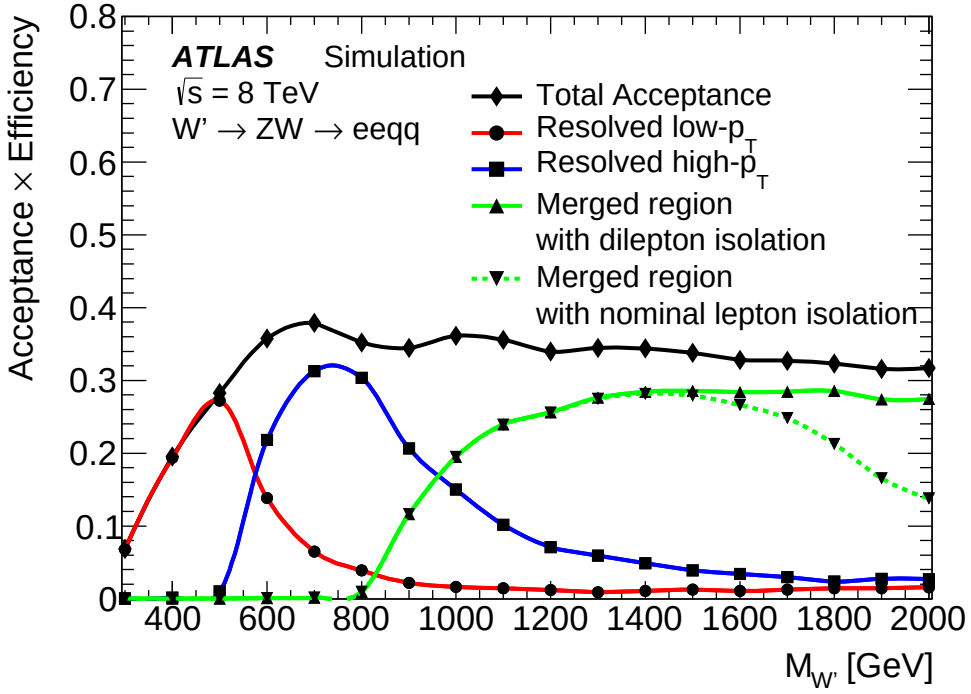






$ZV \to \ell\ell qq$

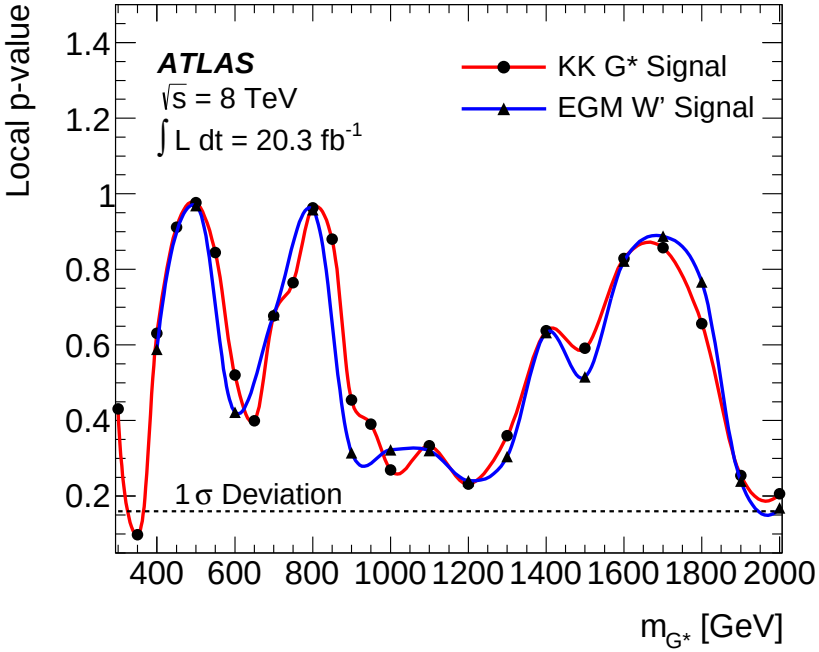




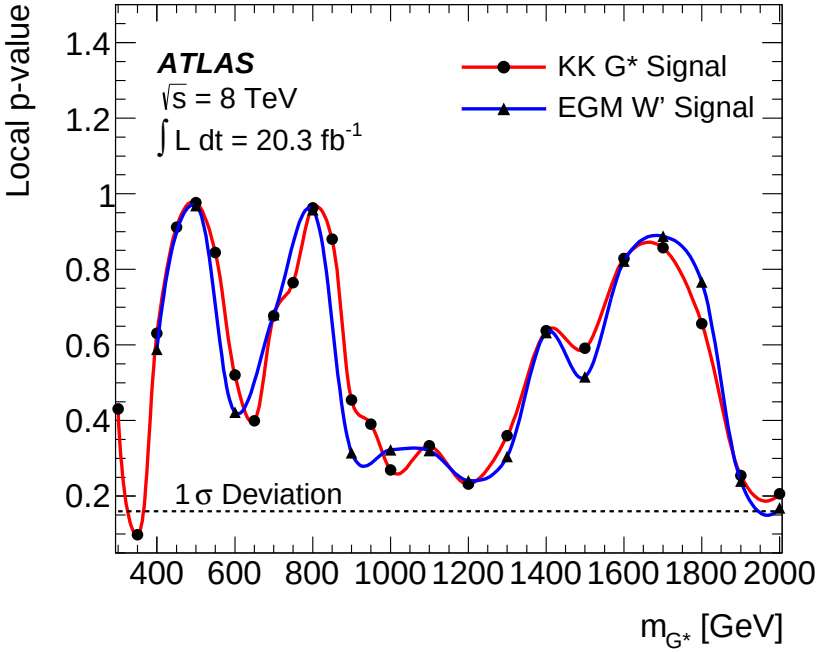
Categorized selection: good acceptance∗efficiency across wide mass range

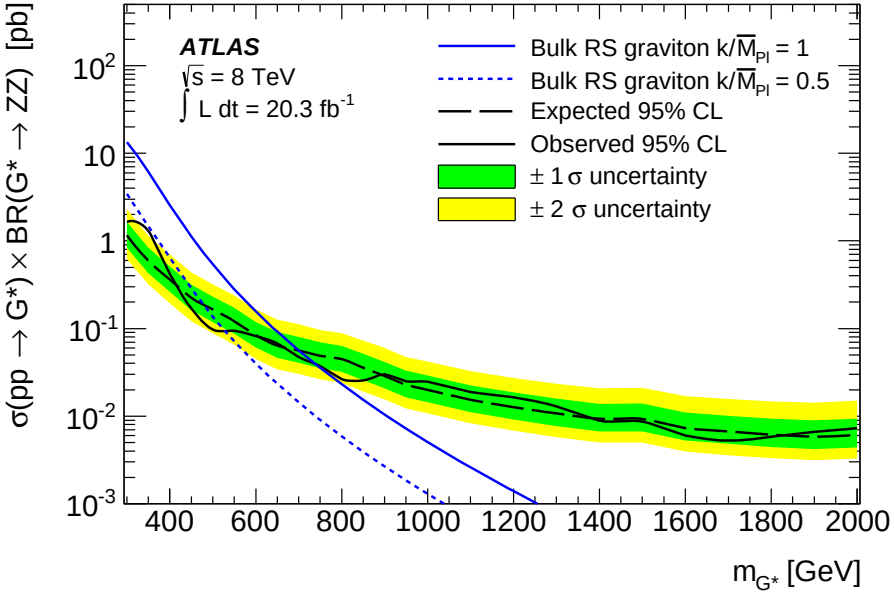
- Low-p_{T}: $p_{\mathrm{T}}^{\ell\ell} > 100$ GeV, $p_{\mathrm{T}}^{jj} >$100 GeV, resolved dijet pair
- High-p_{T}: $p_{\mathrm{T}}^{\ell\ell} > 250$ GeV, $p_{\mathrm{T}}^{jj} >$250 GeV, resolved dijet pair
- Merged: $p_{\mathrm{T}}^{\ell\ell} > 400$ GeV, $p_{\mathrm{T}}^{J} >$400 GeV, large-R jet

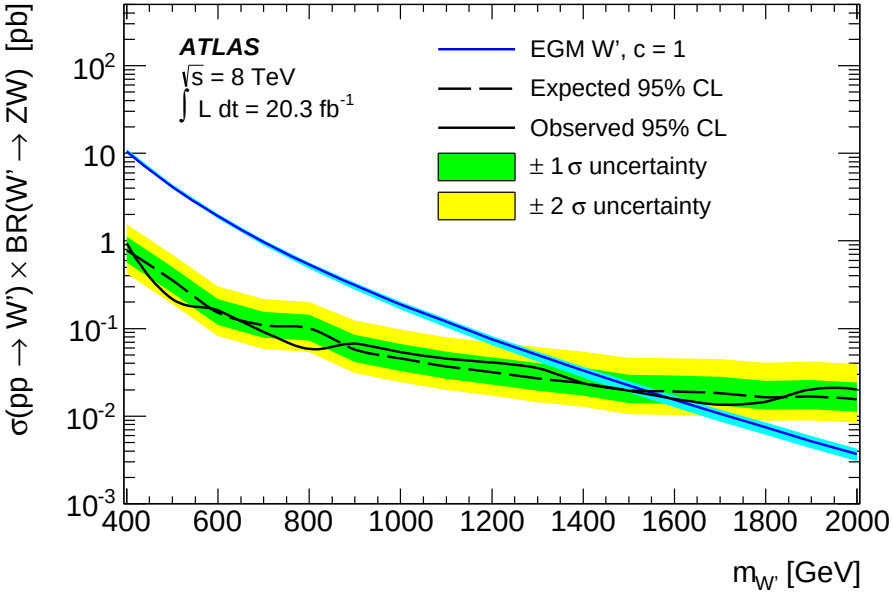
$ZV \to \ell\ell qq$ Results



$ZV \to \ell\ell qq$ Results





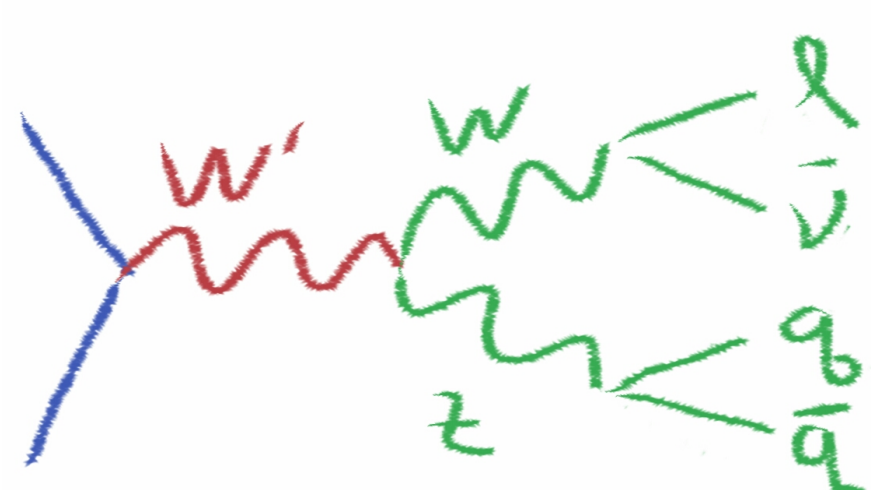


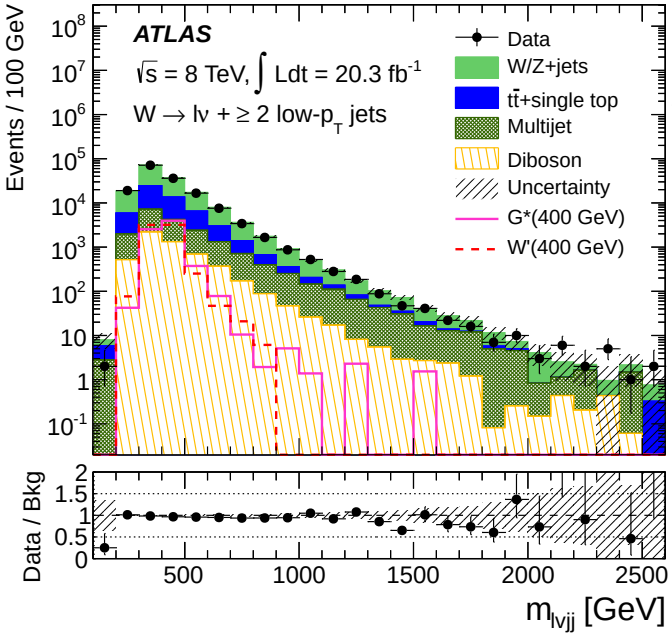
$V' \to WV \to \ell\nu qq$

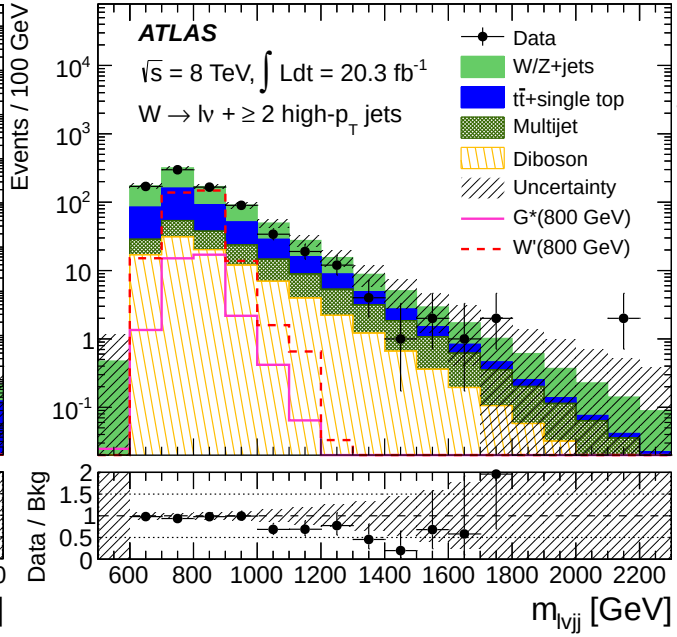
Eur. Phys. J. C (2015) 75:209

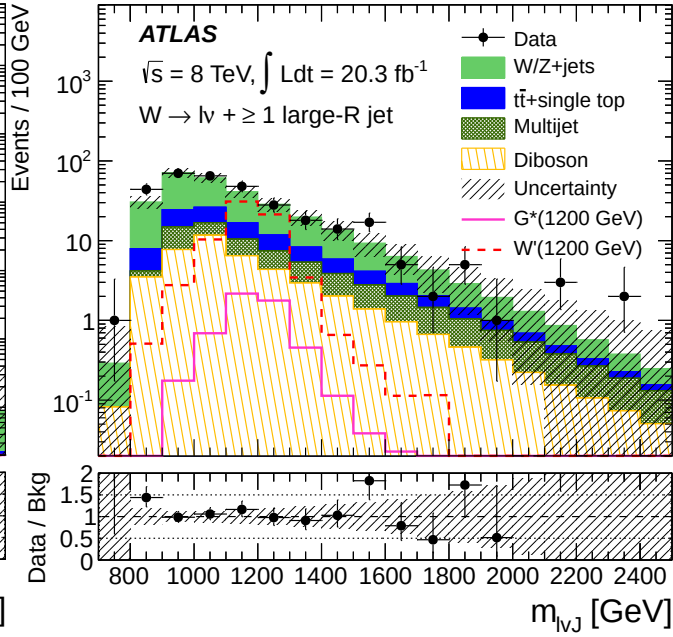
Search for $ZZ/WZ \to \ell\ell qq$ resonances:

- Single e or μ + $E_{\mathrm{T}}^{\mathrm{miss}} > 30$ GeV
- 3 categories cover 0.3-2.0 TeV
- CR using mass sidebands
- W' and G^* interpretations

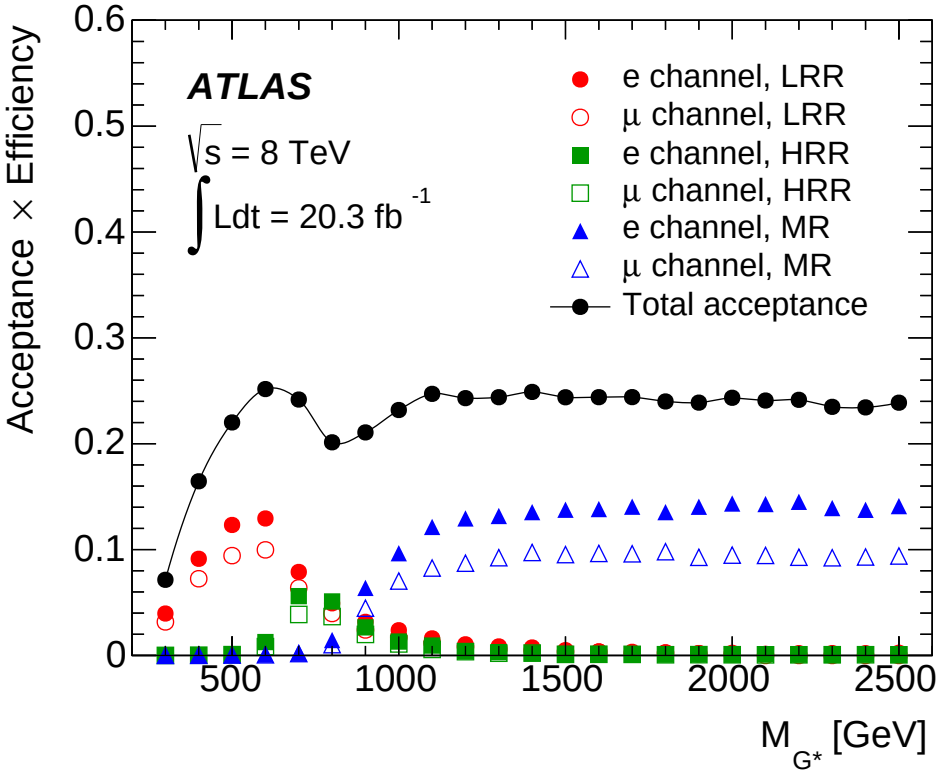


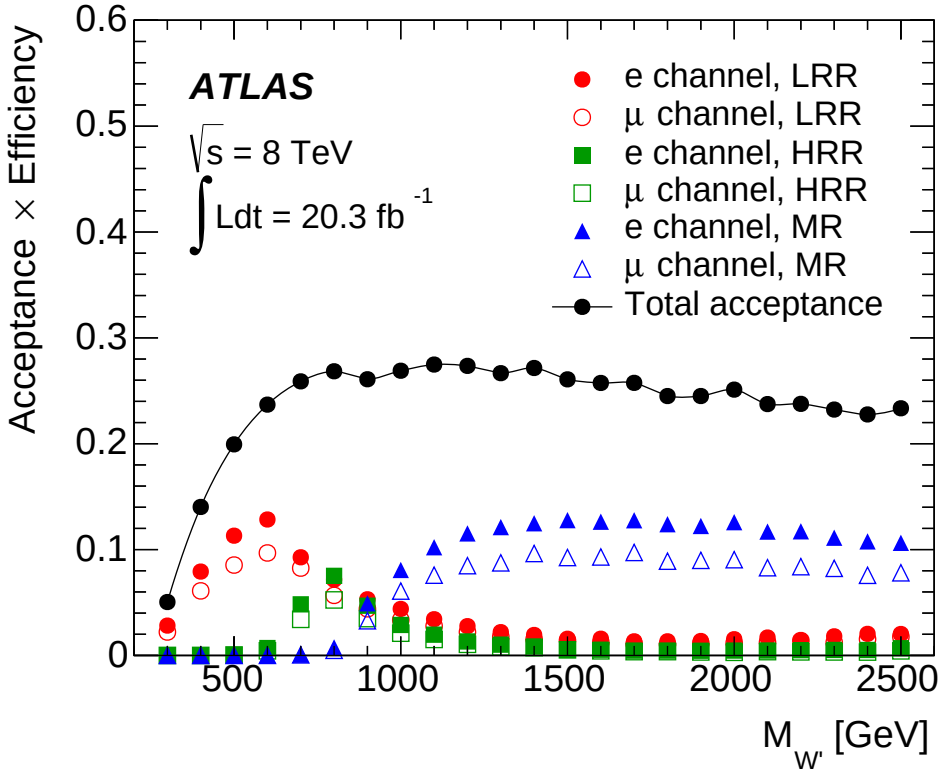






$WV \to \ell\nu qq$





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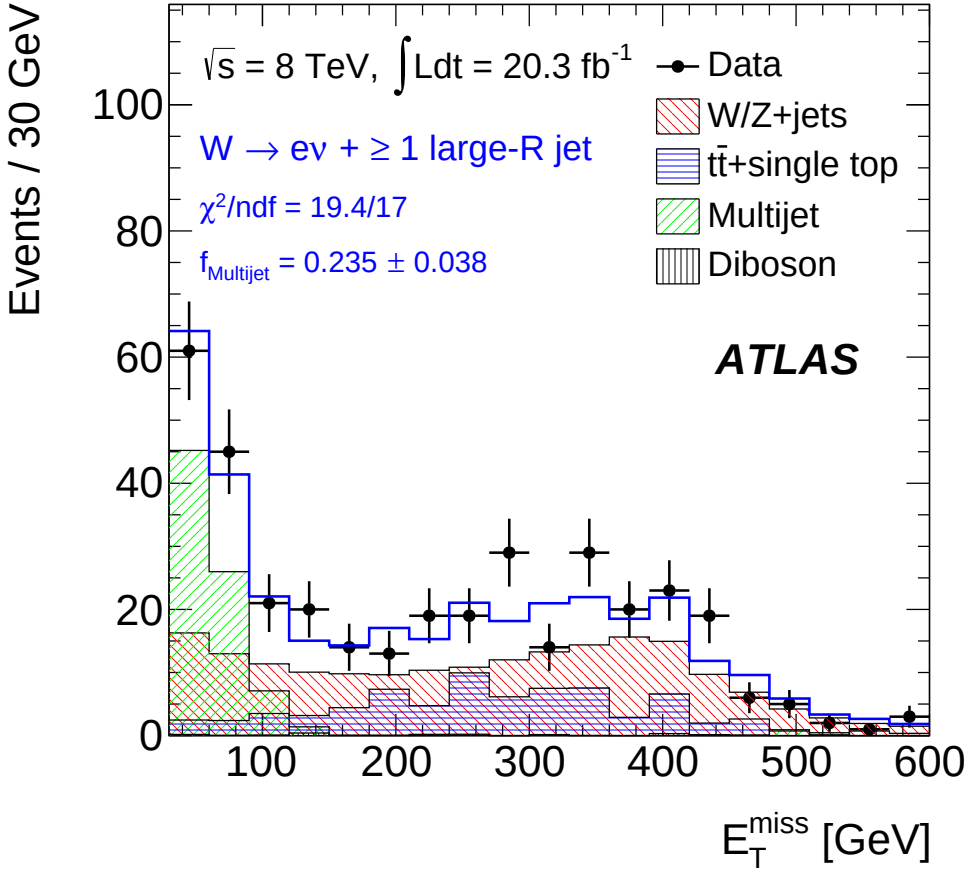
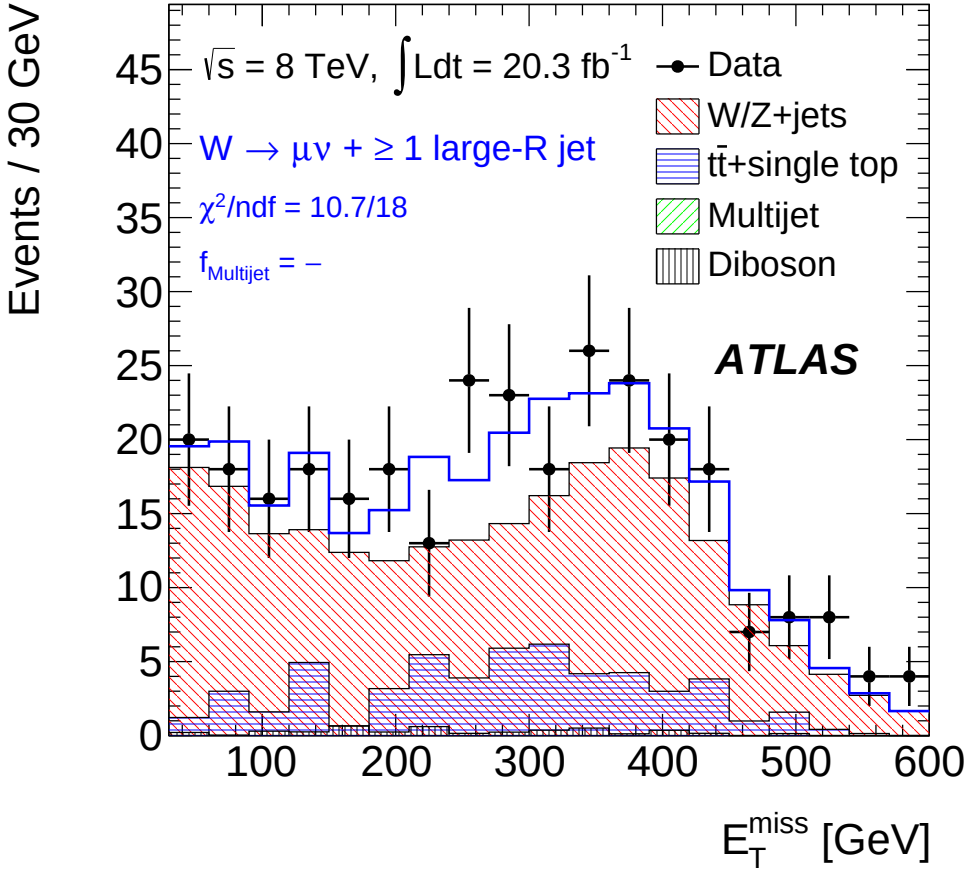
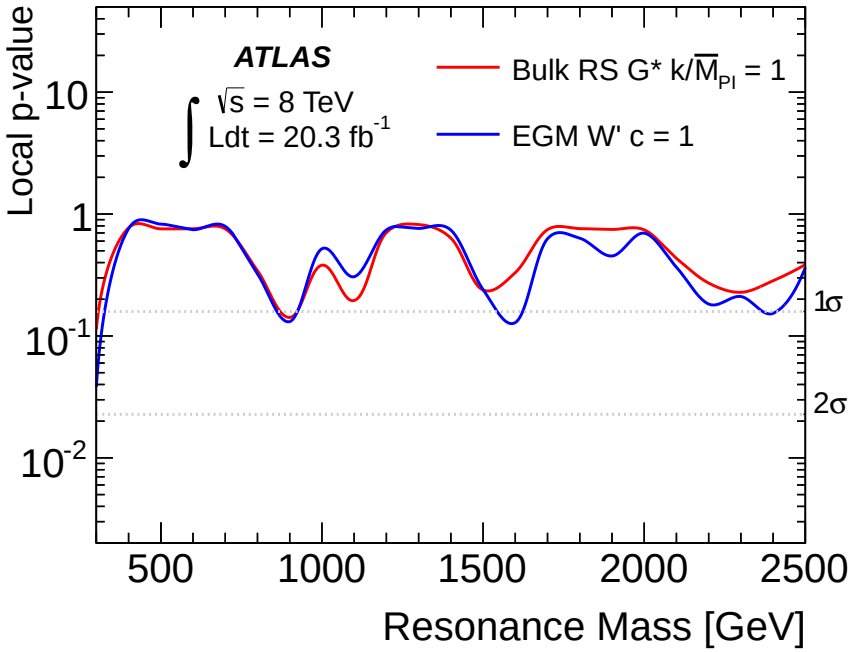
- Merged: $p_{\mathrm{T}}^{\ell\nu} > 400$ GeV, $p_{\mathrm{T}}^{J} >$400 GeV, large-R jet

Check background model in large-R jet mass sidebands

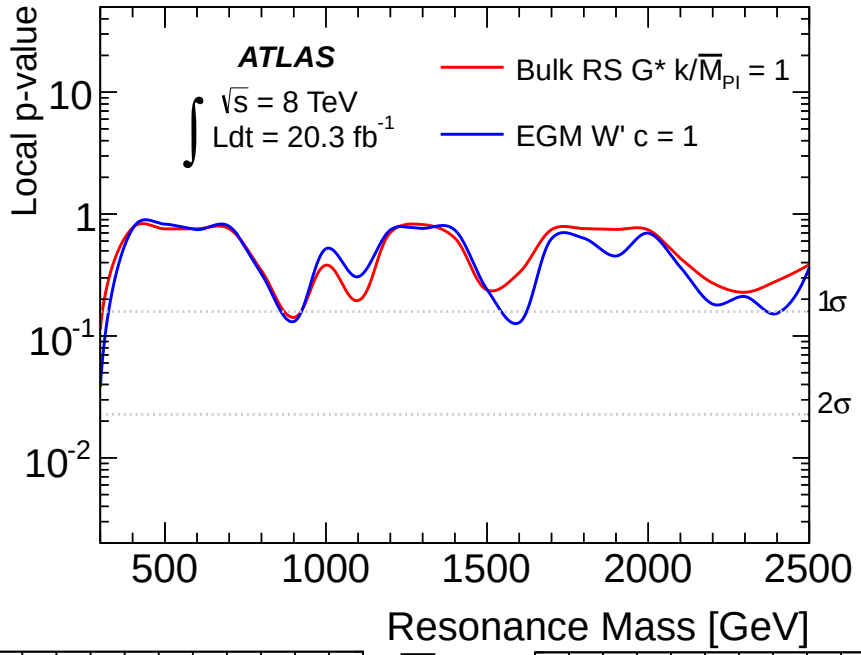


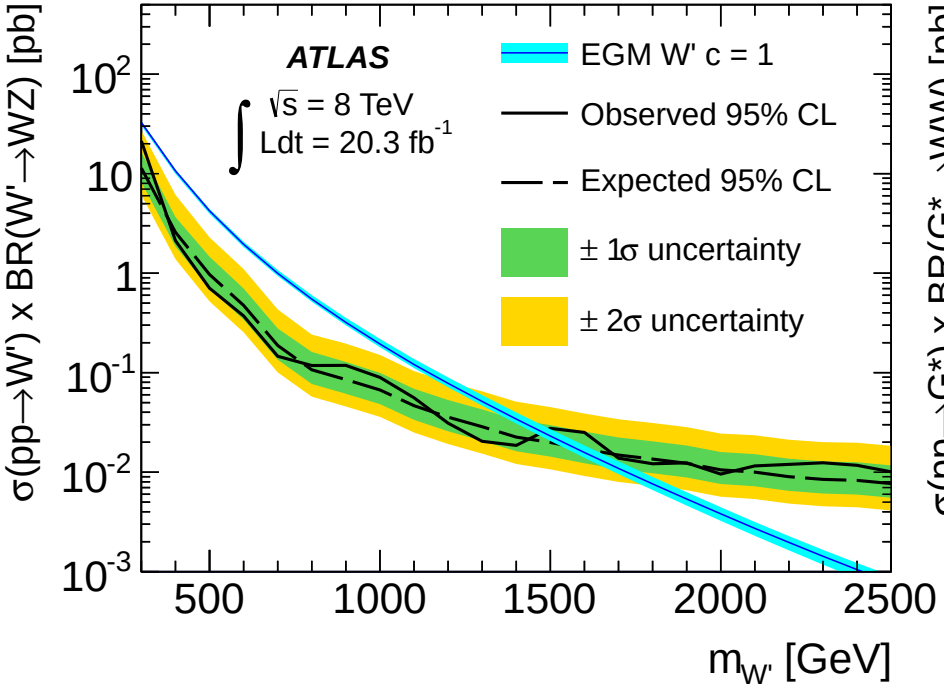


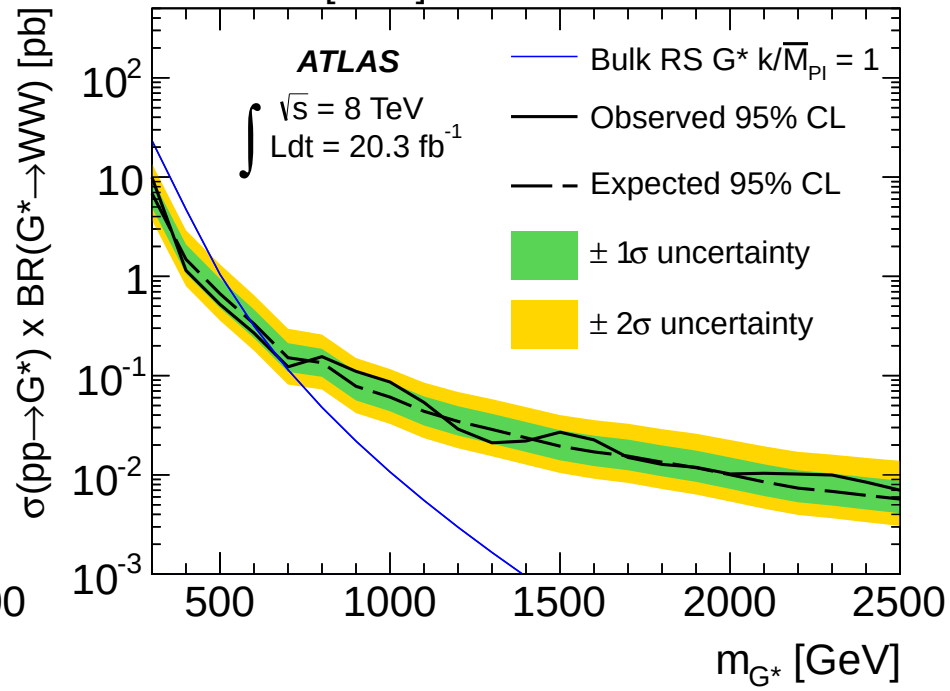
$W' \to WZ \to \ell\nu qq$



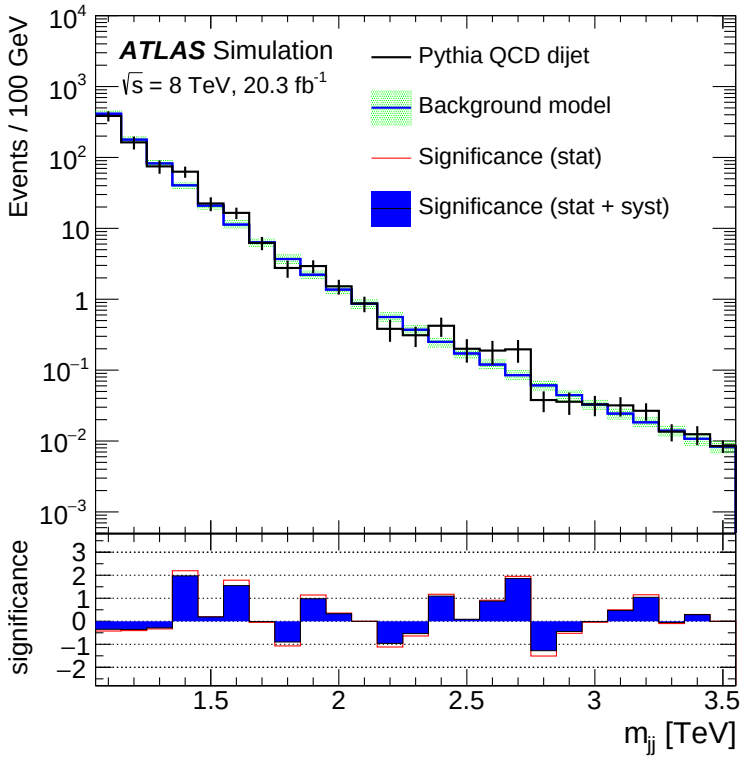
$W' \to WZ \to \ell\nu qq$







All Hadronic $WZ \to qqqq$ Search



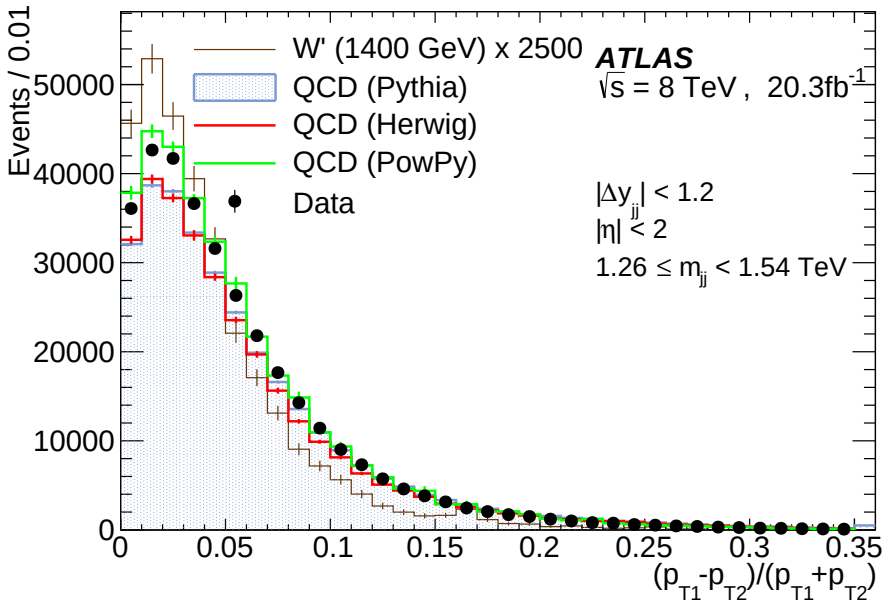
All-hadronic channel:

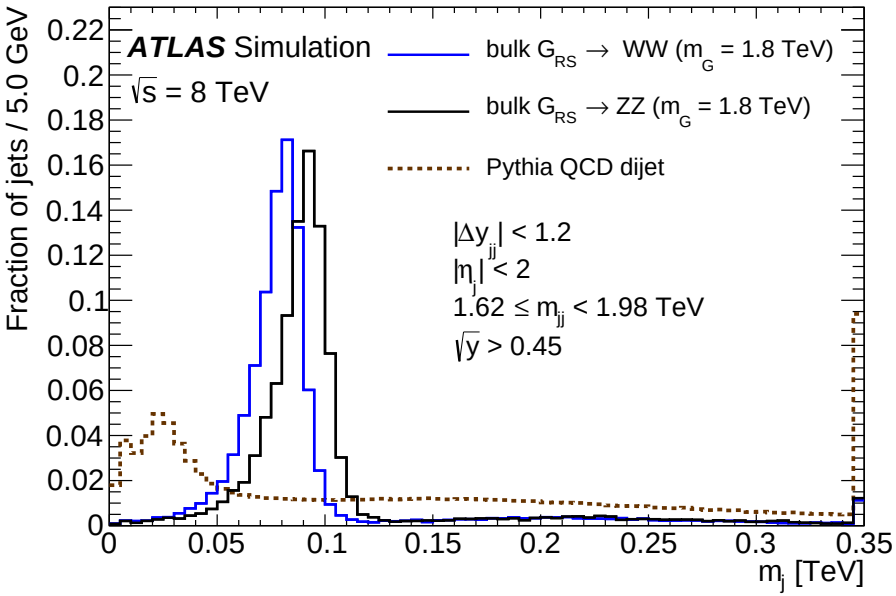
- Background: QCD dijets
  - Model with data: $\frac{\mathrm{d}n}{\mathrm{d}x} = p_1(1-x)^{p_2-\xi p_3}x^{p_3}$
- Discriminating variables: W and W' mass
  - Substructure and tracking cuts too

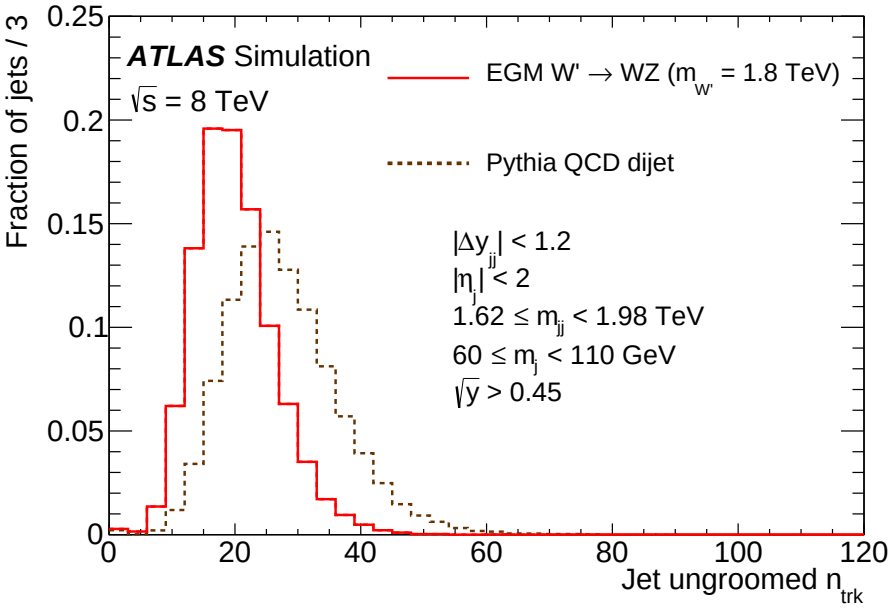
Filtering parameter	Value
$\sqrt{y_\mathrm{f}}$	0.2
μ_f	1
R_r	0.3
n_r	3

Additional Selection Criteria

- $|m_J - m_V| < 13$ GeV
- $n_{trk} < 30$
- $(p_{\mathrm{T1}} - p_{\mathrm{T2}})/(p_{\mathrm{T1}} + p_{\mathrm{T2}}) < 0.15$

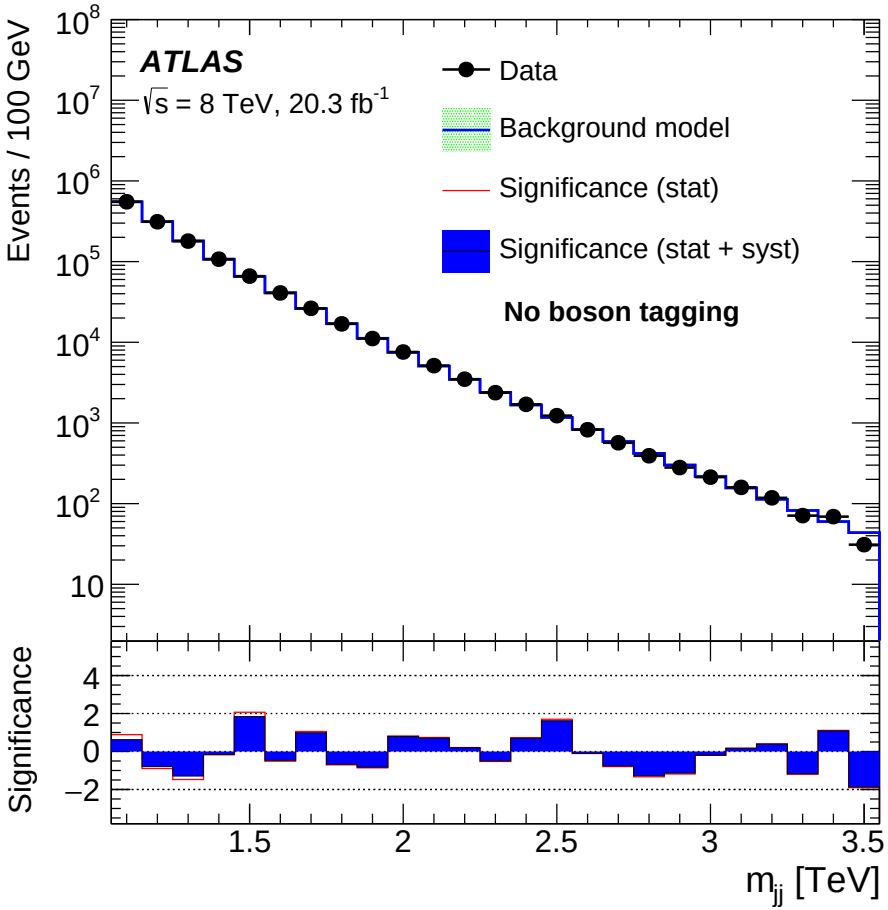


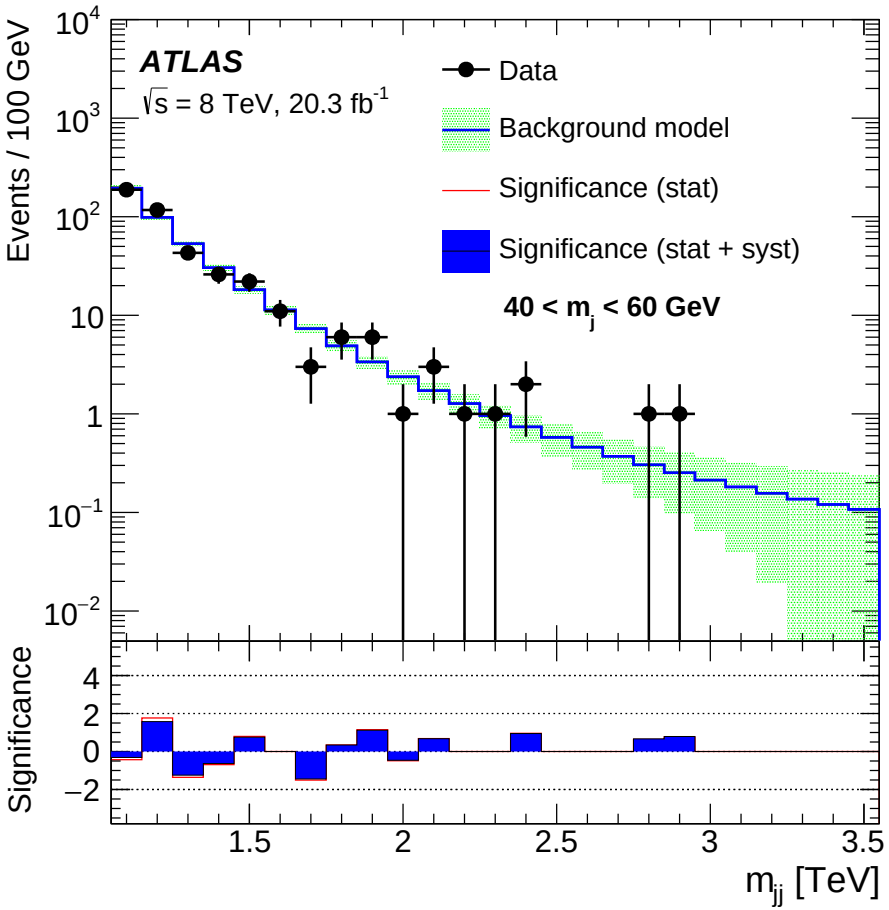




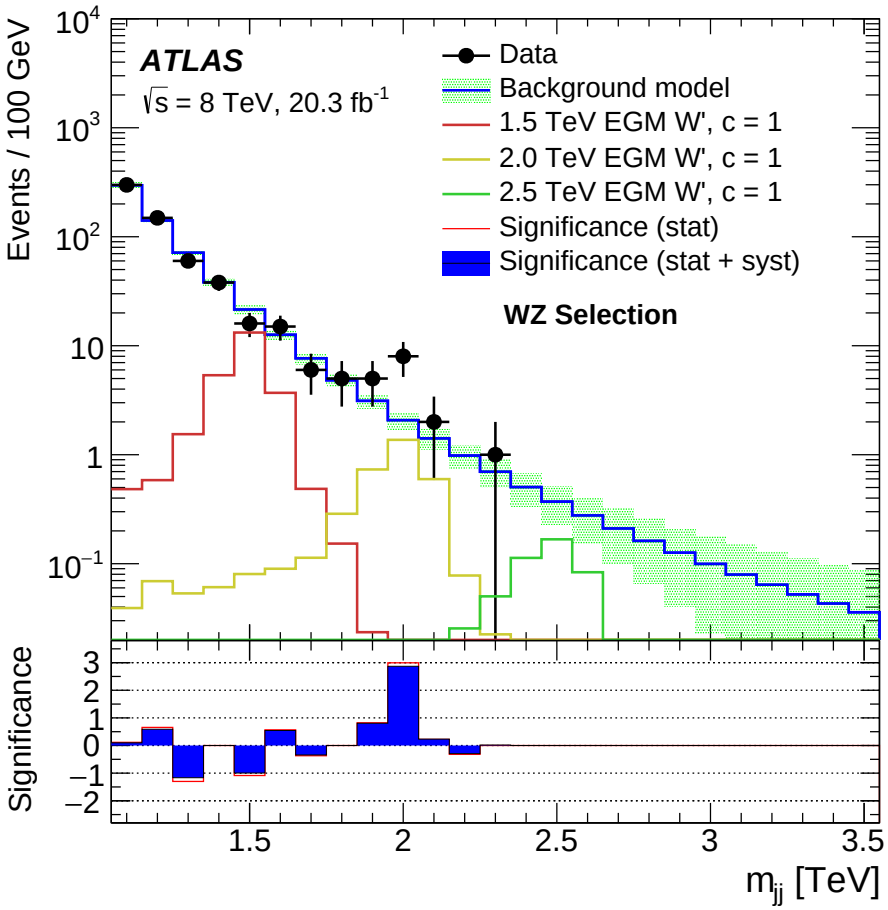
Validation

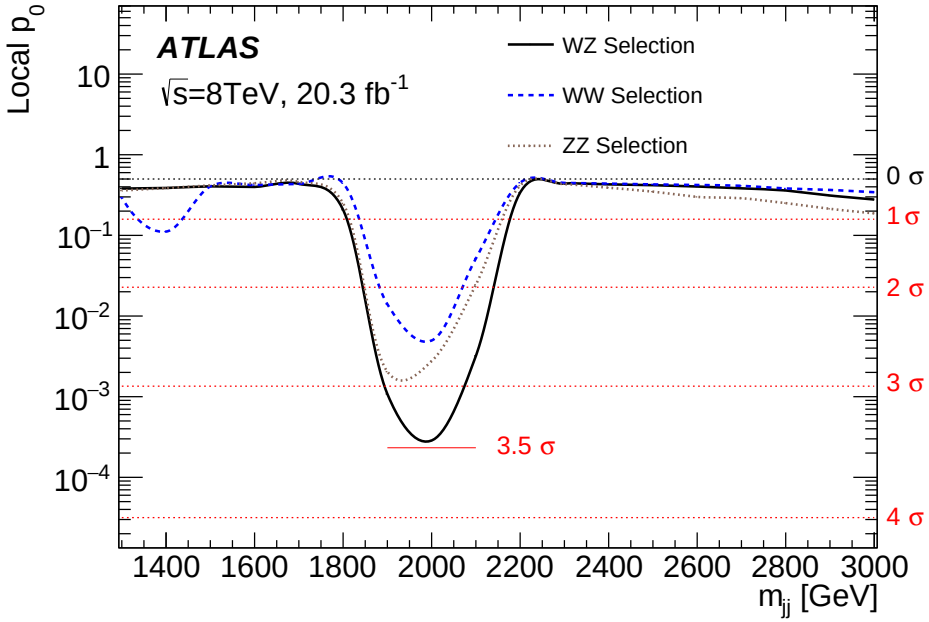
Check background model in large-R jet mass sidebands





Results



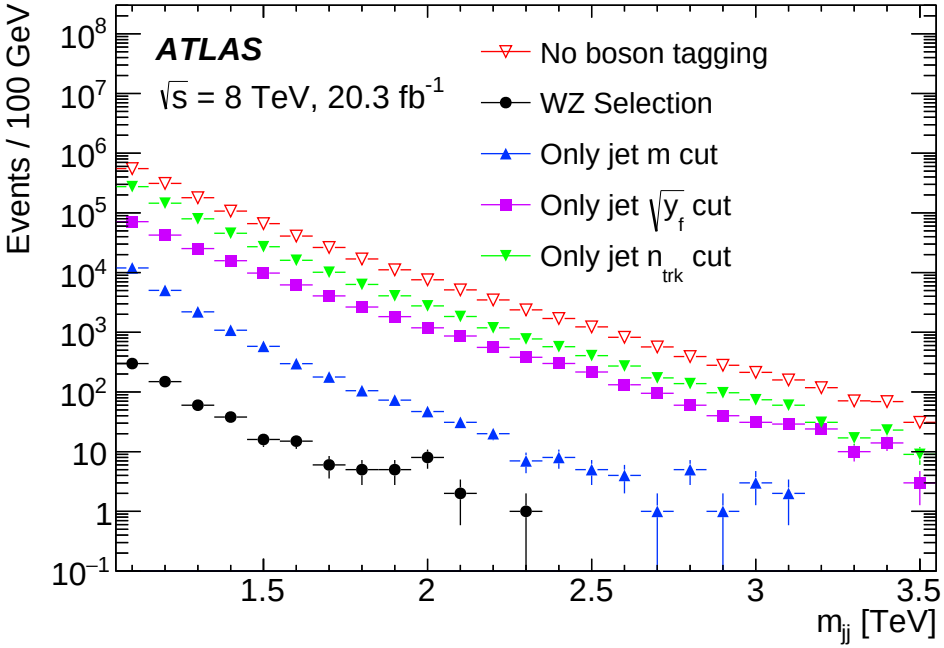


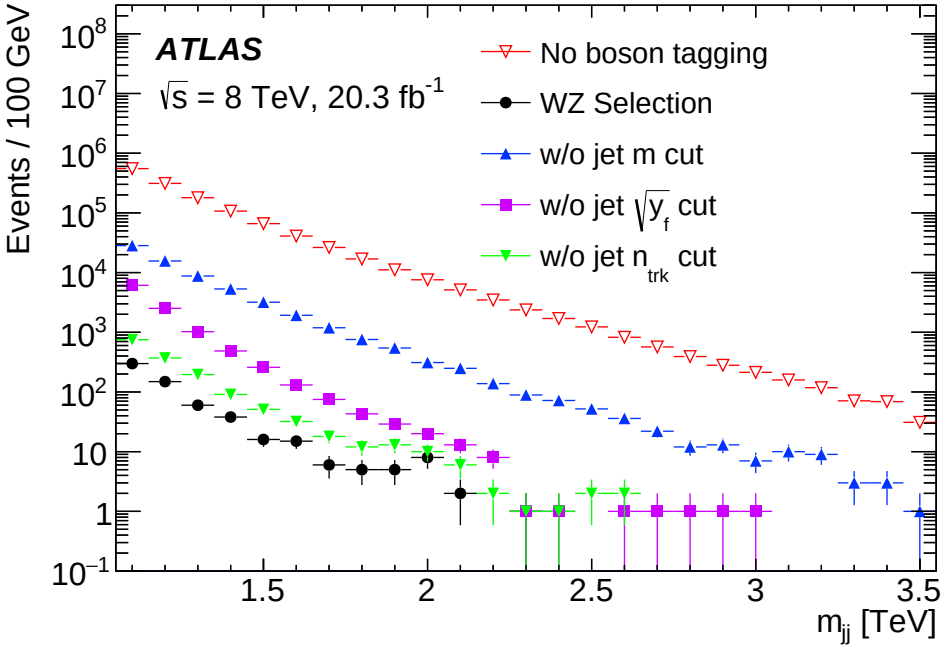
That looks interesting!

- "Local" significance: 3.4σ
- "Global" significance: 2.5σ ("Look Elsewhere Effect")

Impact of different cuts

No obvious sculpting induced by tagging or event selection criteria





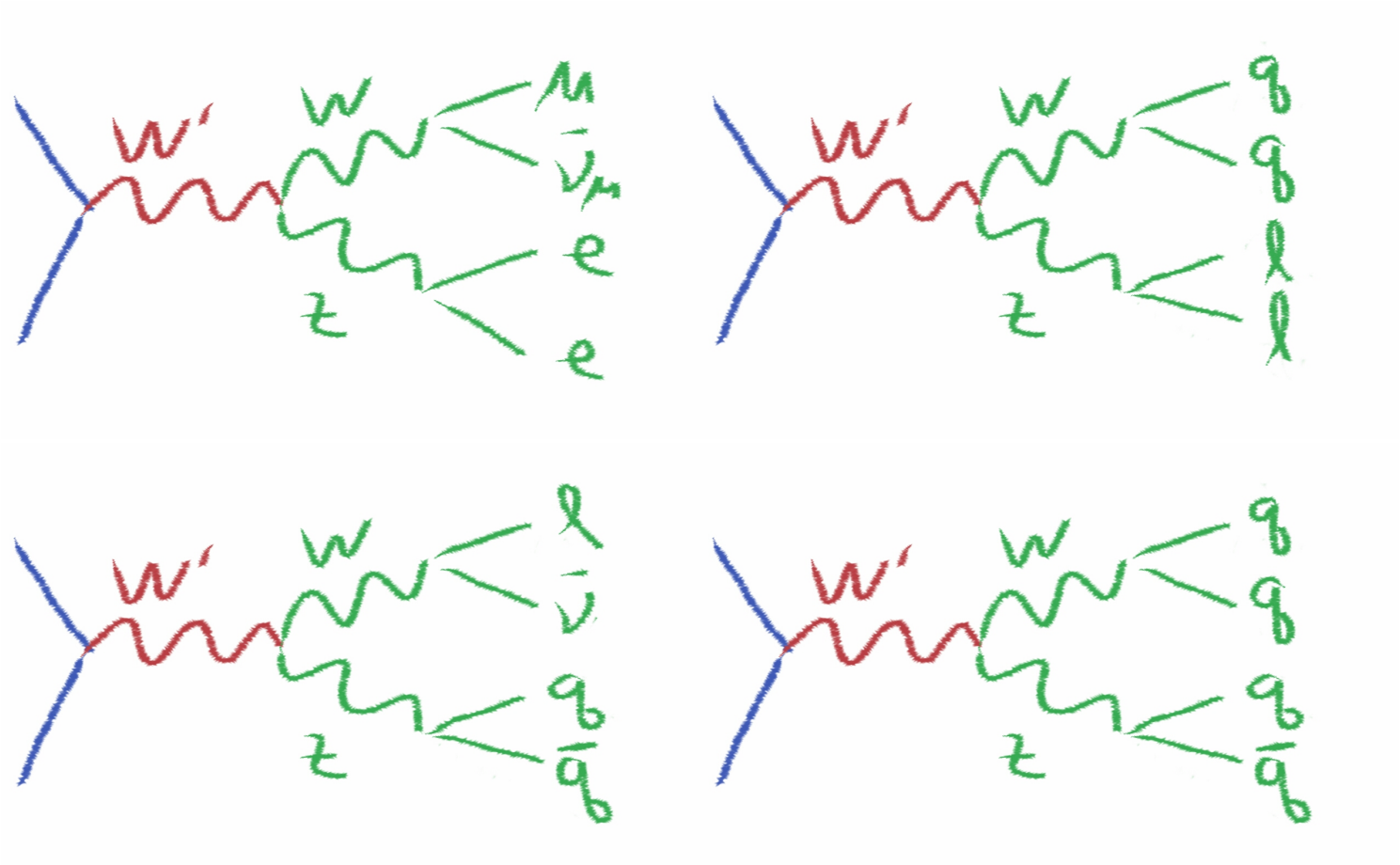
Do you mind if we call this a W'?

Do you mind if we call this a W'?
Yes, I do mind!

Combined Analysis

Treat both analyses on an equal footing, and perform the search in a combined model:

$$\mathcal{L} = \Pi_c \Pi_{i_c} \, \mathrm{Pois}\left(n_{i_c}^{\mathrm{obs}} \middle| n_{i_c}^{\mathrm{exp}}(\mu, \theta_k)\right) \Pi_k \, f_k(\theta_k)$$



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Channels distinguished by number of leptons

- Orthogonality enforced via lepton requirements/vetoes

Channel	Leptons	Jets	$E_{\text{T}}^{\text{miss}}$	Boson Identification
$\ell\nu\ell'\ell'$	3 leptons $p_{\text{T}} > 25$ GeV	–	$E_{\text{T}}^{\text{miss}} > 25$ GeV	$\lvert m_{ll} - m_Z \rvert < 20$ GeV
$\ell\ell q\bar{q}$	2 leptons $p_{\text{T}} > 25$ GeV	2 small-R jets or 1 large-R jet	–	$\lvert m_{ll} - m_Z \rvert < 25$ GeV 70 GeV$< m_{jj} <$ 110 GeV 70 GeV$< m_J <$ 110 GeV , $\sqrt{y} > 0.45$
$\ell\nu q\bar{q}$	1 lepton $p_{\text{T}} > 25$ GeV	2 small-R jets or 1 large-R jet No b-jet with $\Delta R(b, W/Z) > 0.8$	$E_{\text{T}}^{\text{miss}} > 30$ GeV	65 GeV$< m_{jj} <$ 105 GeV 65 GeV$< m_J <$ 105 GeV, $\sqrt{y} > 0.45$
JJ	0 lepton	2 large-R jets, $\lvert\eta\rvert < 2.0$	$E_{\text{T}}^{\text{miss}} < 350$ GeV	$\lvert m_{W/Z} - m_J \rvert < 13$ GeV $\sqrt{y} > 0.45$, $n_{\text{trk}} < 30$

Combined Analysis

Treat both analyses on an equal footing, and perform the search in a combined model:

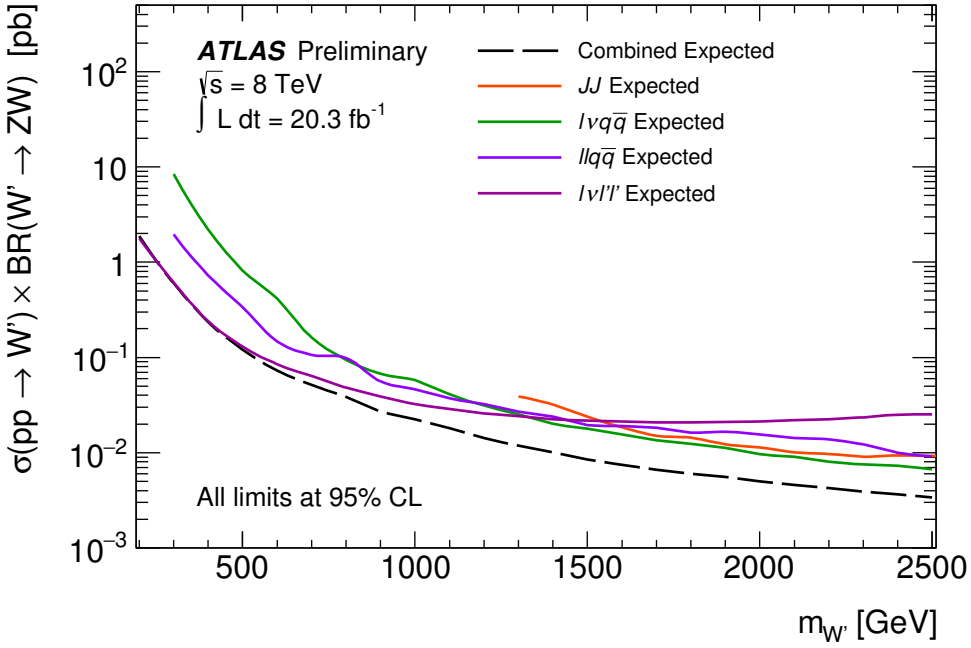
$$\mathcal{L} = \Pi_c \Pi_{i_c} \text{Pois}\left(n_{i_c}^{\text{obs}} \middle| n_{i_c}^{\text{exp}}(\mu, \theta_k)\right) \Pi_k f_k(\theta_k)$$

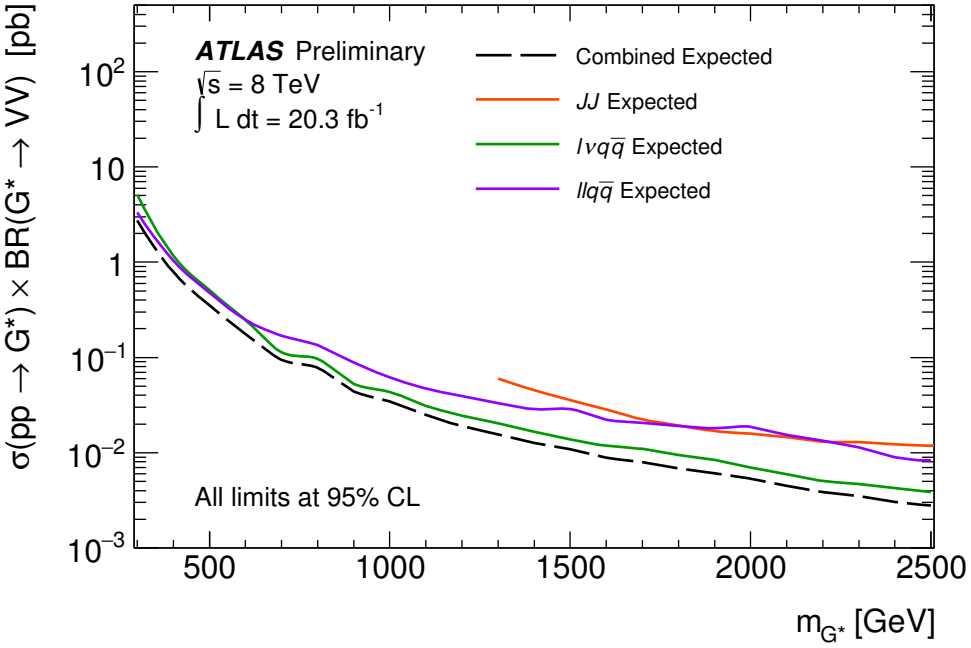
Channel	Signal Region	W' mass range [TeV]	G^* mass range [TeV]
$\ell\nu\ell'\ell'$	low-mass	0.2-1.9	–
	high-mass	0.2-2.5	–
$\ell\ell q\bar{q}$	low- resolved	0.3-0.9	0.2-0.9
	high- resolved	0.6-2.5	0.6-0.9
	merged	0.9-2.5	0.9-2.5
$\ell\nu q\bar{q}$	low- resolved	0.3-0.8	0.2-0.7
	high- resolved	0.6-1.1	0.6-0.9
	merged	0.8-2.5	0.8-2.5
JJ	WZ selection	1.3-3.0	–
	WW+ZZ selection	–	1.3-3.0

Combined Analysis

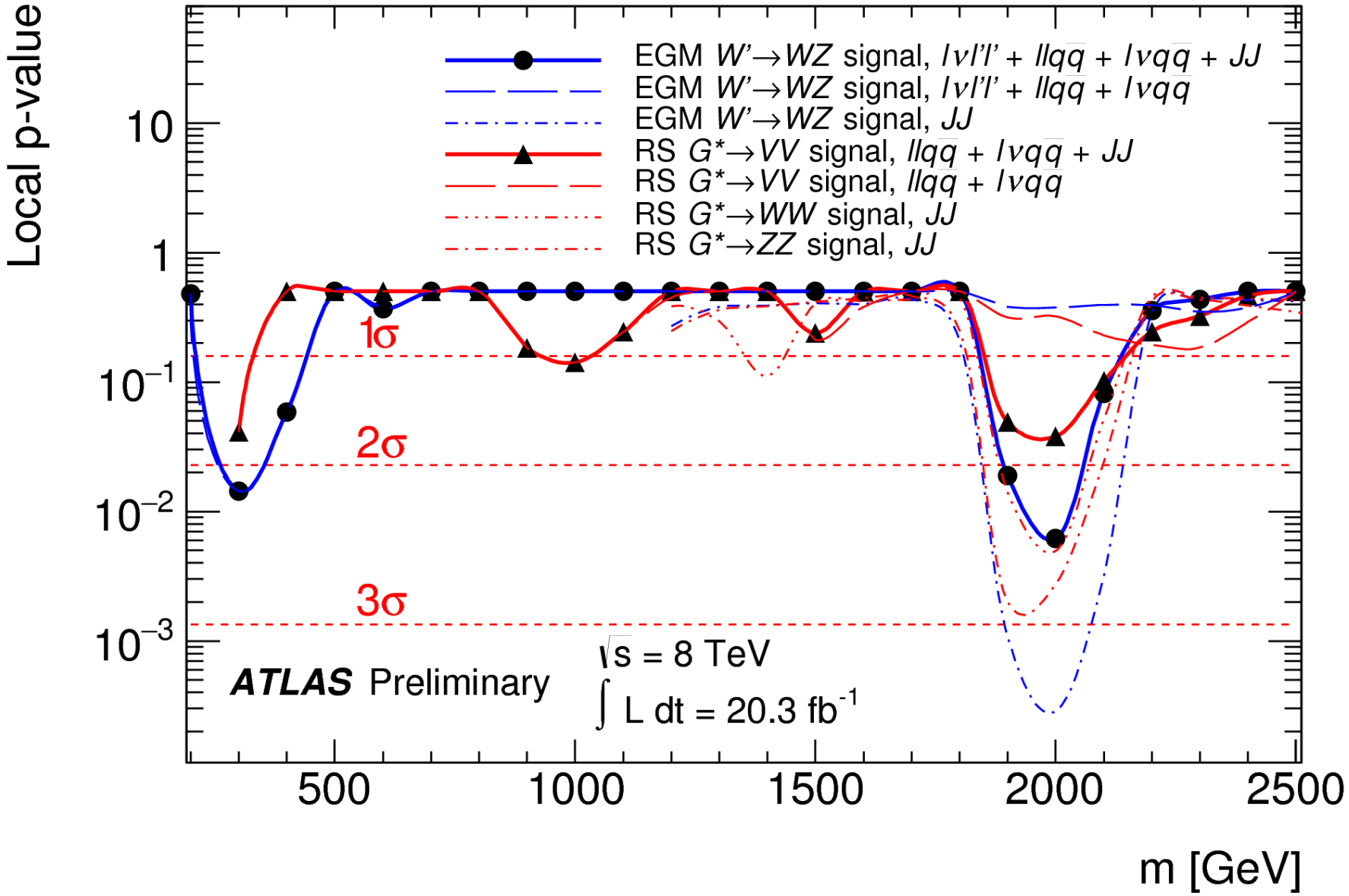
Treat both analyses on an equal footing, and perform the search in a combined model:

$$\mathcal{L} = \Pi_c \Pi_{i_c} \text{Pois}\left(n_{i_c}^{\text{obs}} \middle| n_{i_c}^{\text{exp}}(\mu, \theta_k)\right) \Pi_k f_k(\theta_k)$$

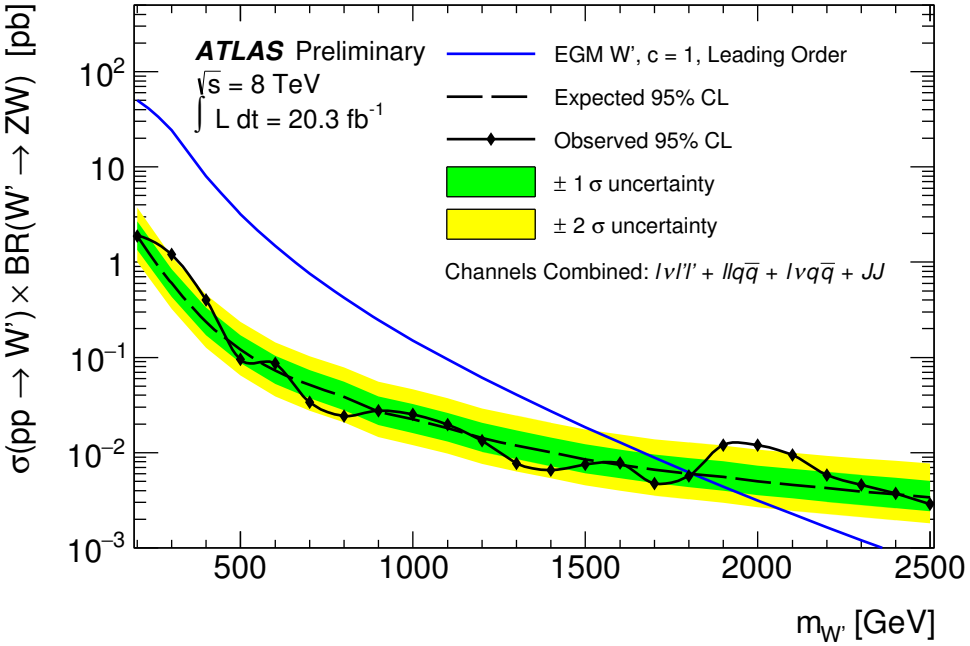


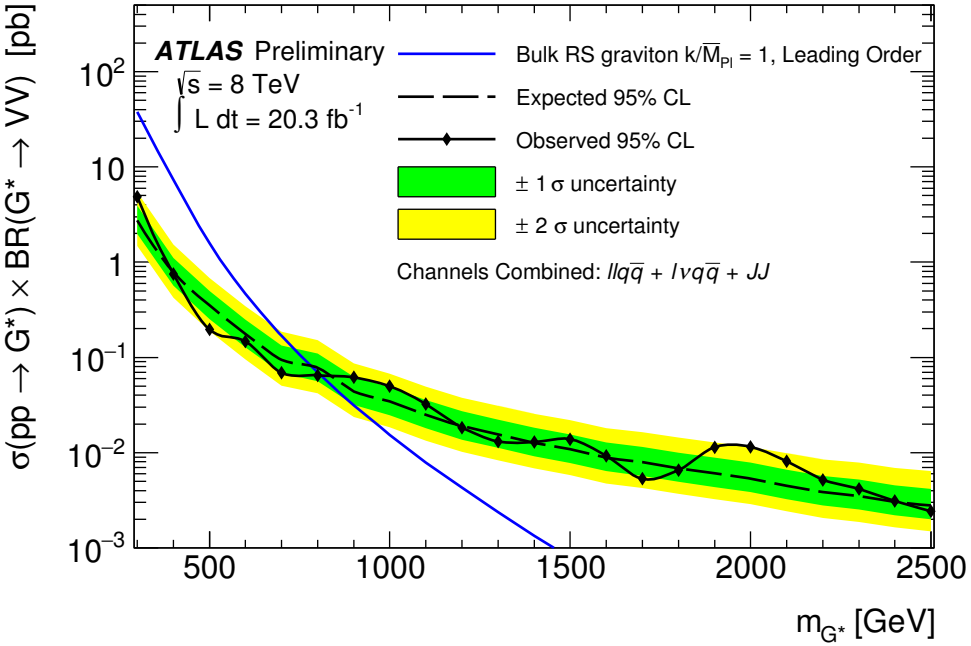


Combined Analysis



Combined Analysis



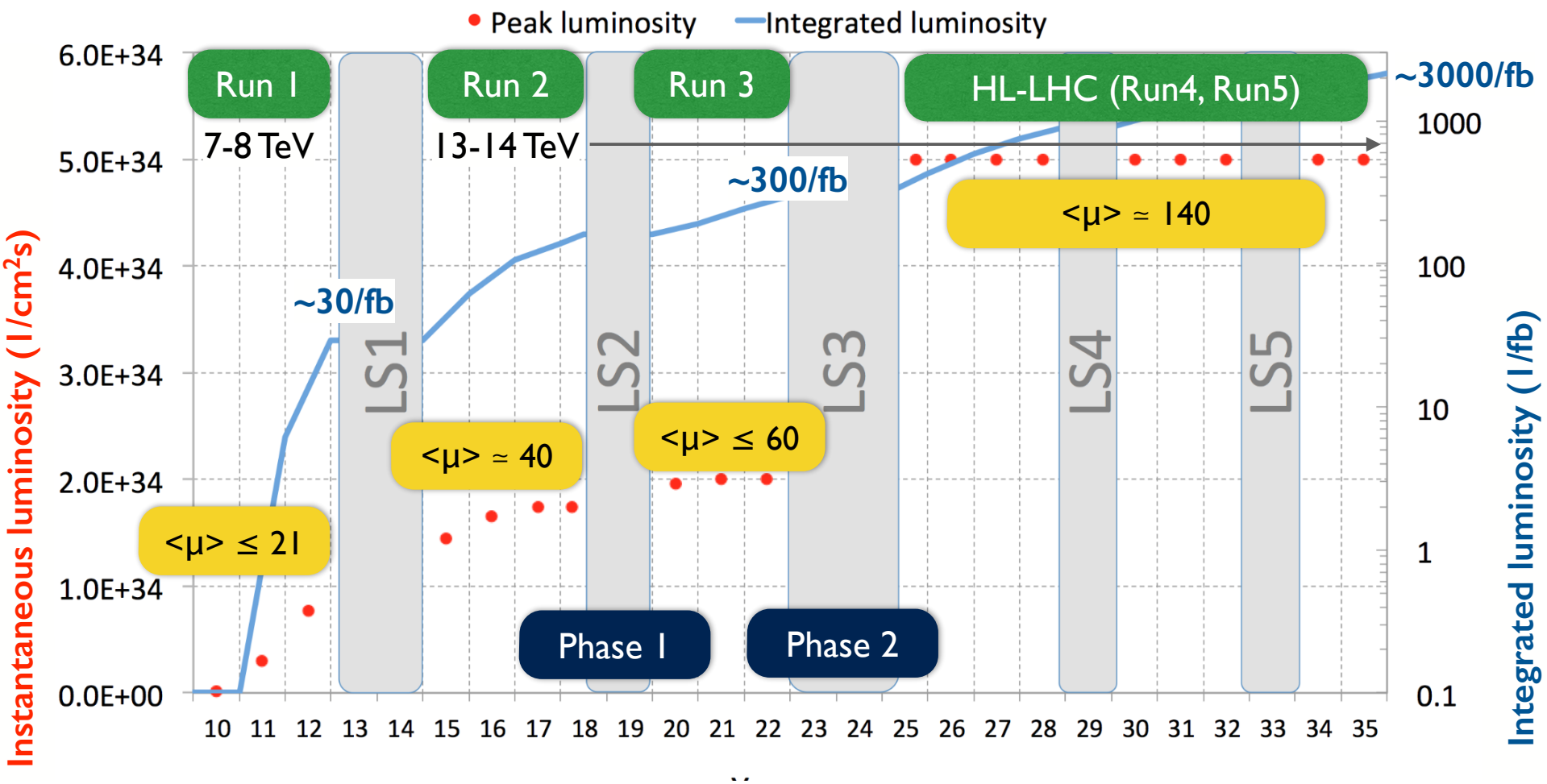


Excess at 2 TeV drops to 2.5σ local significance.

- EGM W': Expected limit at 1.81 TeV, observed at 1.81 TeV.
- Bulk RS G^*: Expected limit at 0.79 TeV, observed at 0.81 TeV.

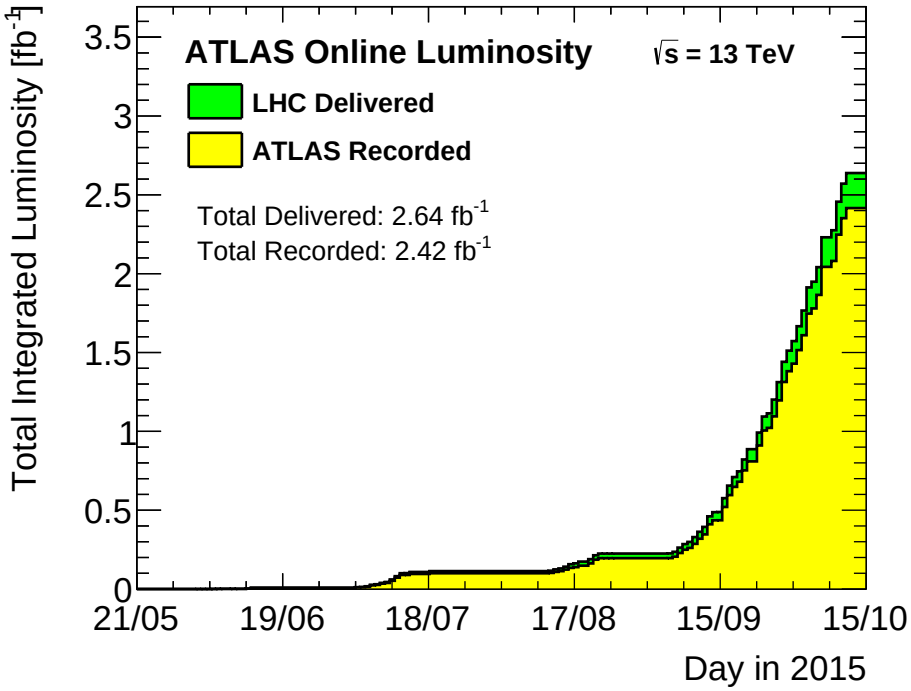
Prospects for Discovery in Run 2 and Beyond

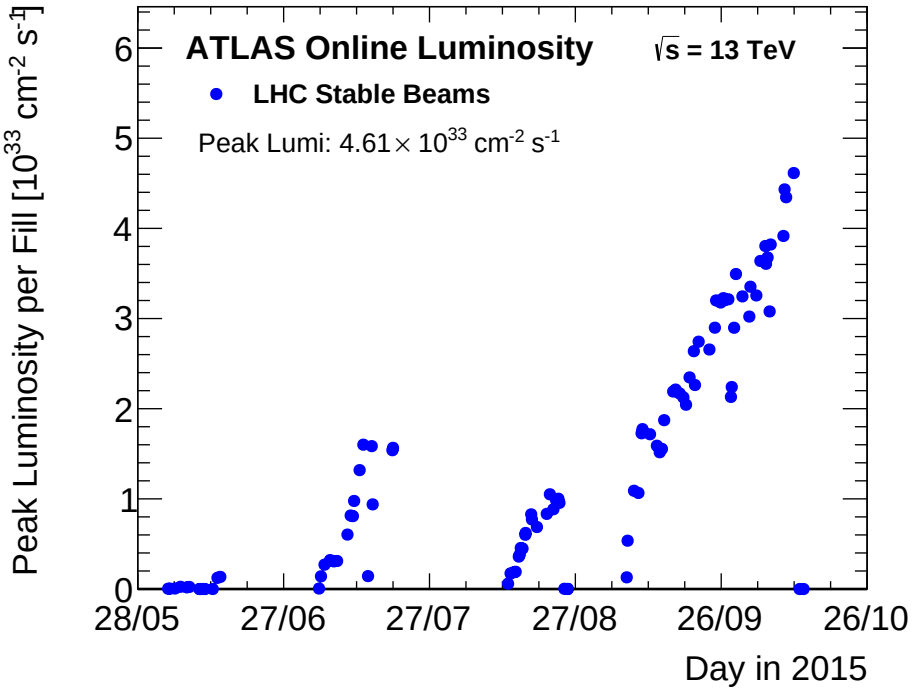
The Road to 13 TeV

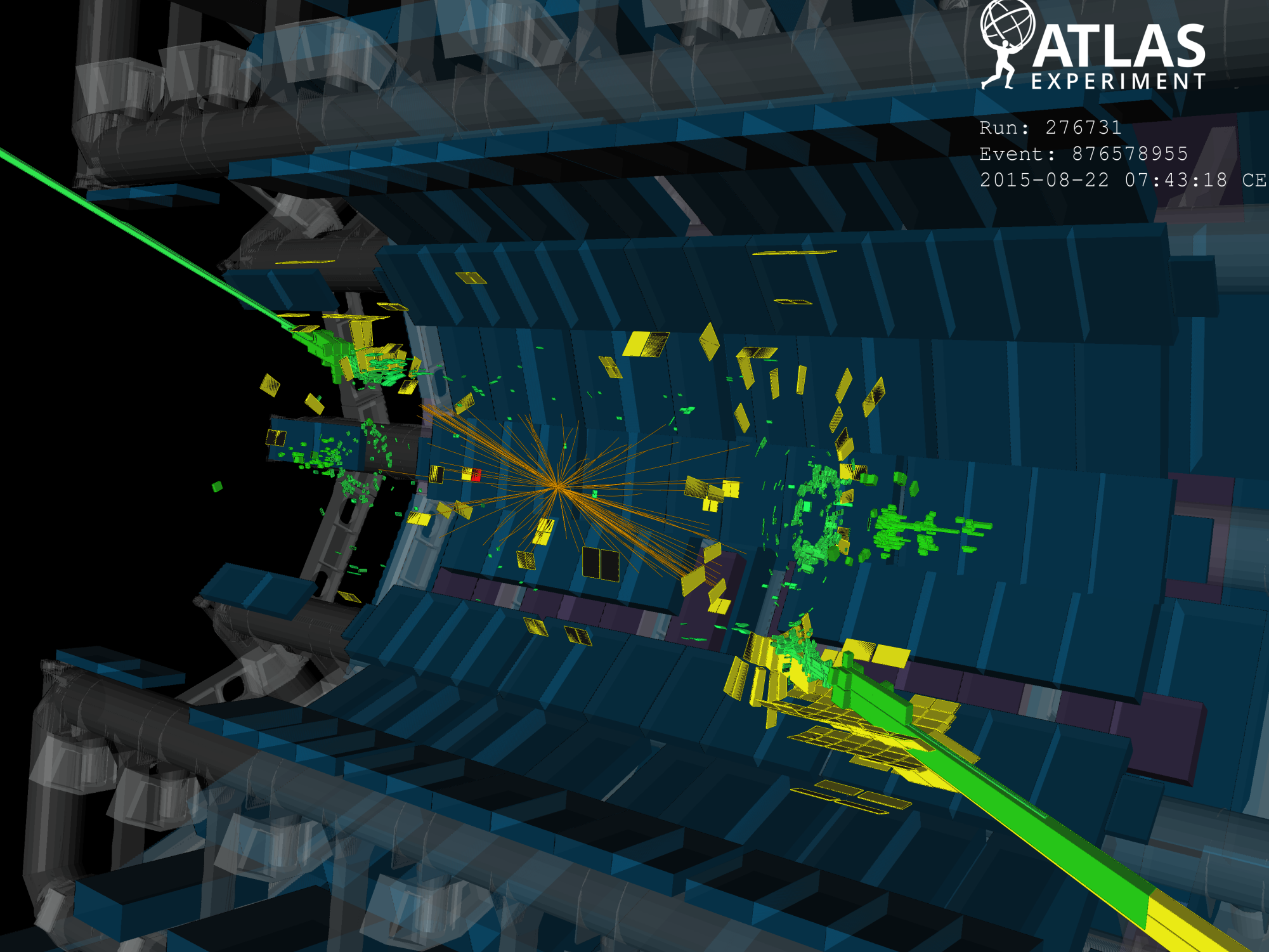


The Road to 13 TeV

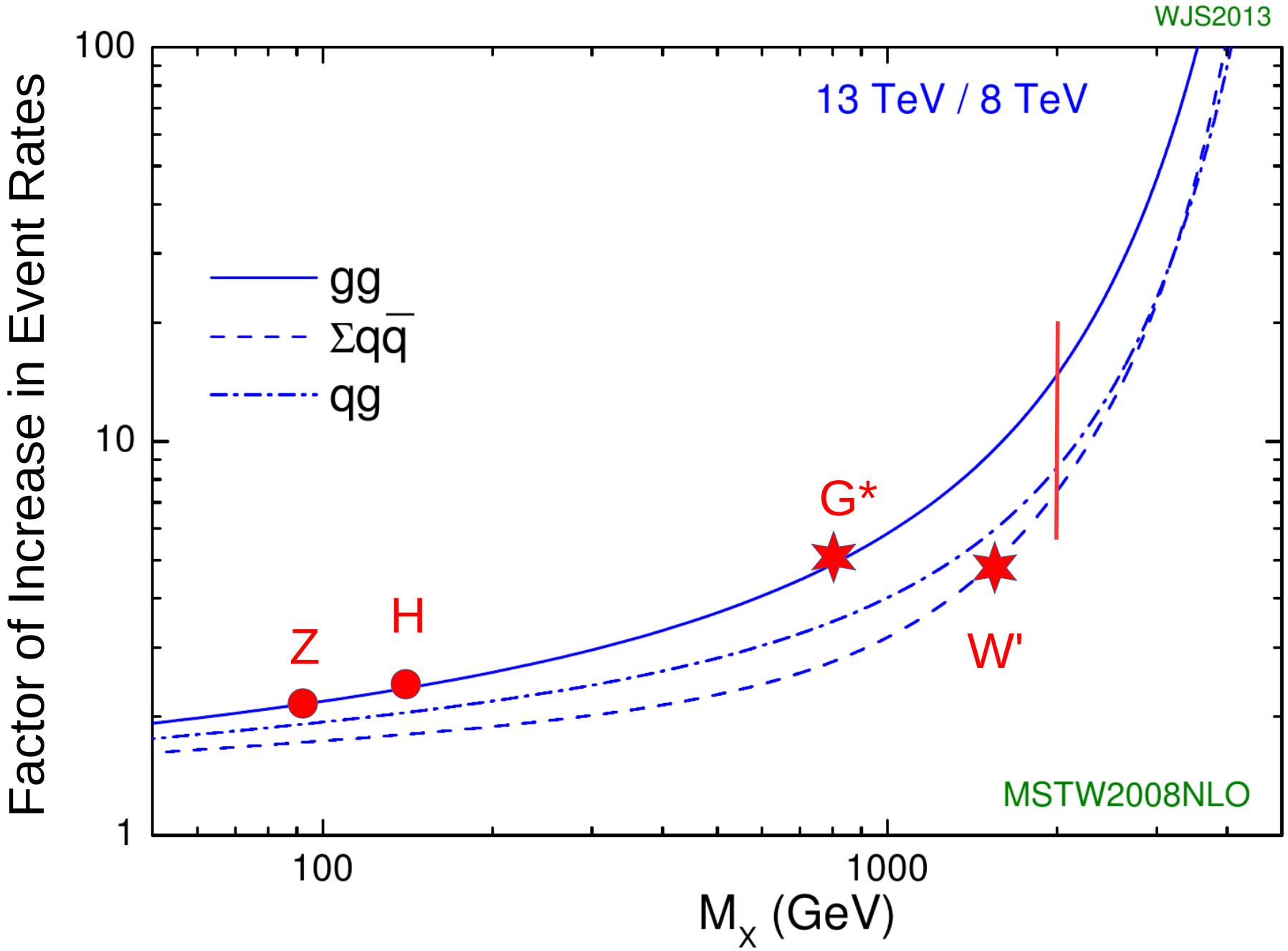
$$\boxed{\text{LHC Running at } \sqrt{s} = 13 \text{ TeV!}}$$






ATLAS
EXPERIMENT
Run: 276731
Event: 876578955
2015-08-22 07:43:18 CE

Physics Reach



Reach in Run 2 and Beyond

	8 TeV	13 TeV			
	20 fb^{-1}	3 fb^{-1}	10 fb^{-1}	300 fb^{-1}	3000 fb^{-1}
BSM	**95% CL Mass Limits [TeV]**				
$G^* \to VV$	0.8	0.8	1.0	**1.7**	**2.4**
$W' \to VV$	1.8	1.8	2.1	**3.8**	**5.1**
SM	**Events**				
Z bosons	6×10^8	2×10^8	7×10^8	2×10^{10}	$\mathbf{2 \times 10^{11}}$
W bosons	2×10^9	6×10^8	2×10^9	6×10^{10}	$\mathbf{6 \times 10^{11}}$
H bosons	5×10^5	1.5×10^5	5×10^5	1.5×10^7	$\mathbf{1.5 \times 10^8}$
$H \to \gamma\gamma$	1×10^3	3×10^2	1×10^3	3×10^4	$\mathbf{3 \times 10^5}$

Reach in Run 2 and Beyond

	8 TeV	13 TeV			
	2012	soon!	2016	2022	2035
BSM			**95% CL Mass Limits [TeV]**		
$G^* \to VV$	0.8	0.8	1.0	**1.7**	**2.4**
$W' \to VV$	1.8	1.8	2.1	**3.8**	**5.1**
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Conclusion

Conclusions

Our searches for new physics at high energies continue...

- Standard Model provides a good description for (almost) all LHC results so far
- Excellent detector calibration using "Standard candles" like single W and Z production
- Improved constraints on BSM physics
  - Heavy partners of SM gauge bosons (W', Z')
  - Extra dimensions, extended gauge models, many many others
- Reach is up to $\sim$2 TeV in diboson mass for models with large cross sections and narrow widths
- Additional interpretations to follow in Run 2

Conclusions

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- Additional interpretations to follow in Run 2

- Run 2 will be even more exciting!
  - Last (big) jump in energy for a long time!
  - Large $\sqrt{s}$ and $\int_{2015}^{2035} \mathcal{L} dt$ = lots of interesting data to come

ATLAS Exotics Searches* - 95% CL Exclusion

Status: ICHEP 2014

ATLAS Preliminary

$\int \mathcal{L}\, dt = (1.0 - 20.3)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 7, 8$ TeV

	Model	ℓ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$	Mass limit			Reference
Extra dimensions	ADD $G_{KK} + g/q$	–	1-2 j	Yes	4.7	M_D	4.37 TeV	$n = 2$	1210.4491
	ADD non-resonant $\ell\ell$	$2e, \mu$	–	–	20.3	M_S	5.2 TeV	$n = 3$ HLZ	ATLAS-CONF-2014-030
	ADD QBH $\to \ell q$	$1\ e, \mu$	1 j	–	20.3	M_{th}	5.2 TeV	$n = 6$	1311.2006
	ADD QBH	–	2 j	–	20.3	M_{th}	5.82 TeV	$n = 6$	to be submitted to PRD
	ADD BH high N_{trk}	$2\ \mu$ (SS)	–	–	20.3	M_{th}	5.7 TeV	$n = 6$, $M_D = 1.5$ TeV, non-rot BH	1308.4075
	ADD BH high $\sum p_T$	$\geq 1\ e, \mu$	≥ 2 j	–	20.3	M_{th}	6.2 TeV	$n = 6$, $M_D = 1.5$ TeV, non-rot BH	1405.4254
	RS1 $G_{KK} \to \ell\ell$	$2\ e, \mu$	–	–	20.3	G_{KK} mass	2.68 TeV	$k/\overline{M}_{Pl} = 0.1$	1405.4123
	RS1 $G_{KK} \to WW \to \ell\nu\ell\nu$	$2\ e, \mu$	–	Yes	4.7	G_{KK} mass	1.23 TeV	$k/\overline{M}_{Pl} = 0.1$	1208.2880
	Bulk RS $G_{KK} \to ZZ \to \ell\ell qq$	$2\ e, \mu$	2 j / 1 J	–	20.3	G_{KK} mass	730 GeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2014-039
	Bulk RS $G_{KK} \to HH \to b\bar{b}b\bar{b}$	–	4 b	–	19.5	G_{KK} mass	590-710 GeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2014-005
	Bulk RS $g_{KK} \to t\bar{t}$	$1\ e, \mu$	≥ 1 b, ≥ 1J/2j	Yes	14.3	g_{KK} mass	2.0 TeV	BR = 0.925	ATLAS-CONF-2013-052
	S^1/Z_2 ED	$2\ e, \mu$	–	–	5.0	$M_{KK} \approx R^{-1}$	4.71 TeV		1209.2535
	UED	$2\ \gamma$	–	Yes	4.8	Compact. scale R^{-1}	1.41 TeV		ATLAS-CONF-2012-072
Gauge bosons	SSM $Z' \to \ell\ell$	$2\ e, \mu$	–	–	20.3	Z' mass	2.9 TeV		1405.4123
	SSM $Z' \to \tau\tau$	$2\ \tau$	–	–	19.5	Z' mass	1.9 TeV		ATLAS-CONF-2013-066
	SSM $W' \to \ell\nu$	$1\ e, \mu$	–	Yes	20.3	W' mass	3.28 TeV		ATLAS-CONF-2014-017
	EGM $W' \to WZ \to \ell\nu\ell'\ell'$	$3\ e, \mu$	–	Yes	20.3				1406.4456
	EGM $W' \to WZ \to qq\ell\ell$	$2\ e, \mu$	2 j / 1 J	–	20.3				ATLAS-CONF-2014-039
	LRSM $W'_R \to t\bar{b}$	$1\ e, \mu$	2 b, 0-1 j	Yes	14.3				ATLAS-CONF-2013-050
	LRSM $W'_R \to t\bar{b}$	$0\ e, \mu$	≥ 1 b, 1 J	–	20.3				to be submitted to EPJC
CI	CI $qqqq$	–	2 j	–	4.8		7.6 TeV	$\eta = +1$	1210.1718
	CI $qq\ell\ell$	$2\ e, \mu$	–	–	20.3	Λ	21.6 TeV	$\eta_{LL} = -1$	ATLAS-CONF-2014-030
	CI $uutt$	$2\ e, \mu$ (SS)	≥ 1 b, ≥ 1 j	Yes	14.3	Λ	3.3 TeV	$\lvert C \rvert = 1$	ATLAS-CONF-2013-051
DM	EFT D5 operator (Dirac)	$0\ e, \mu$	1-2 j	Yes	10.5	M_*	731 GeV	at 90% CL for $m(\chi) < 80$ GeV	ATLAS-CONF-2012-147
	EFT D9 operator (Dirac)	$0\ e, \mu$	1 J, ≤ 1 j	Yes	20.3	M_*	2.4 TeV	at 90% CL for $m(\chi) < 100$ GeV	1309.4017
LQ	Scalar LQ 1st gen	$2\ e$	≥ 2 j	–	1.0	LQ mass	660 GeV	$\beta = 1$	1112.4828
	Scalar LQ 2nd gen	$2\ \mu$	≥ 2 j	–	1.0	LQ mass	685 GeV	$\beta = 1$	1203.3172
	Scalar LQ 3rd gen	$1\ e, \mu, 1\ \tau$	1 b, 1 j	–	4.7	LQ mass	534 GeV	$\beta = 1$	1303.0526
Heavy quarks	Vector-like quark $TT \to Ht + X$	$1\ e, \mu$	≥ 2 b, ≥ 4 j	Yes	14.3	T mass	790 GeV	T in (T,B) doublet	ATLAS-CONF-2013-018
	Vector-like quark $TT \to Wb + X$	$1\ e, \mu$	≥ 1 b, ≥ 3 j	Yes	14.3	T mass	670 GeV	isospin singlet	ATLAS-CONF-2013-060
	Vector-like quark $TT \to Zt + X$	$2/\geq 3\ e, \mu$	$\geq 2/\geq 1$ b	–	20.3	T mass	735 GeV	T in (T,B) doublet	ATLAS-CONF-2014-036
	Vector-like quark $BB \to Zb + X$	$2/\geq 3\ e, \mu$	$\geq 2/\geq 1$ b	–	20.3	B mass	755 GeV	B in (B,Y) doublet	ATLAS-CONF-2014-036
	Vector-like quark $BB \to Wt + X$	$2\ e, \mu$ (SS)	≥ 1 b, ≥ 1 j	Yes	14.3	B mass	720 GeV	B in (T,B) doublet	ATLAS-CONF-2013-051
Excited fermions	Excited quark $q^* \to q\gamma$	$1\ \gamma$	1 j	–	20.3	q^* mass	3.5 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1309.3230
	Excited quark $q^* \to qg$	–	2 j	–	20.3	q^* mass	4.09 TeV	only u^* and d^*, $\Lambda = m(q^*)$	to be submitted to PRD
	Excited quark $b^* \to Wt$	1 or 2 e, μ	1 b, 2 j or 1 j	Yes	4.7	b^* mass	870 GeV	left-handed coupling	1301.1583
	Excited lepton $\ell^* \to \ell\gamma$	$2\ e, \mu, 1\ \gamma$	–	–	13.0	ℓ^* mass	2.2 TeV	$\Lambda = 2.2$ TeV	1308.1364
Other	LSTC $a_T \to W\gamma$	$1\ e, \mu, 1\ \gamma$	–	Yes	20.3	a_T mass	960 GeV		to be submitted to PLB
	LRSM Majorana ν	$2\ e, \mu$	2 j	–	2.1	N^0 mass	1.5 TeV	$m(W_R) = 2$ TeV, no mixing	1203.5420
	Type III Seesaw	$2\ e, \mu$	–	–	5.8	$N^\pm$ mass	245 GeV	$\lvert V_e \rvert$=0.055, $\lvert V_\mu \rvert$=0.063, $\lvert V_\tau \rvert$=0	ATLAS-CONF-2013-019
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	$2\ e, \mu$ (SS)	–	–	4.7	$H^{\pm\pm}$ mass	409 GeV	DY production, BR($H^{\pm\pm} \to \ell\ell$)=1	1210.5070
	Multi-charged particle	–	–	–	4.4	multi-charged particle mass	490 GeV	DY production, $\lvert q \rvert = 4e$	1301.5272
	Magnetic monopoles	–	–	–	2.0	monopole mass	862 GeV	DY production, $\lvert g \rvert = 1g_D$	1207.6411

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

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

Thanks!

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

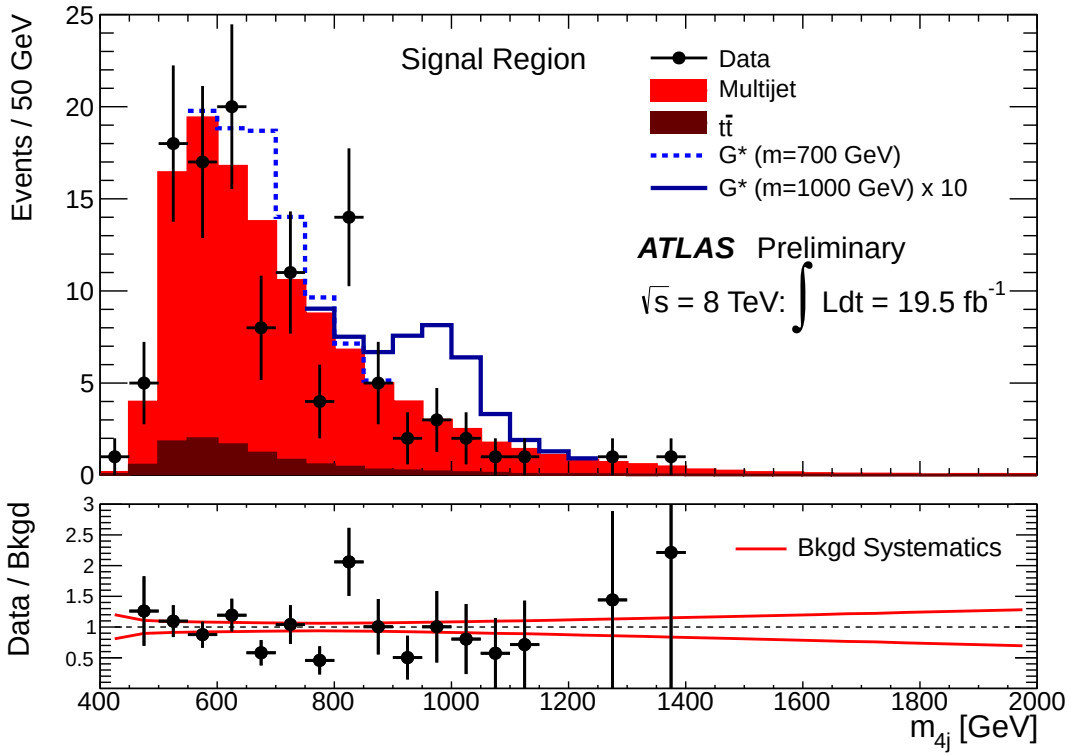
Bonus Slides!

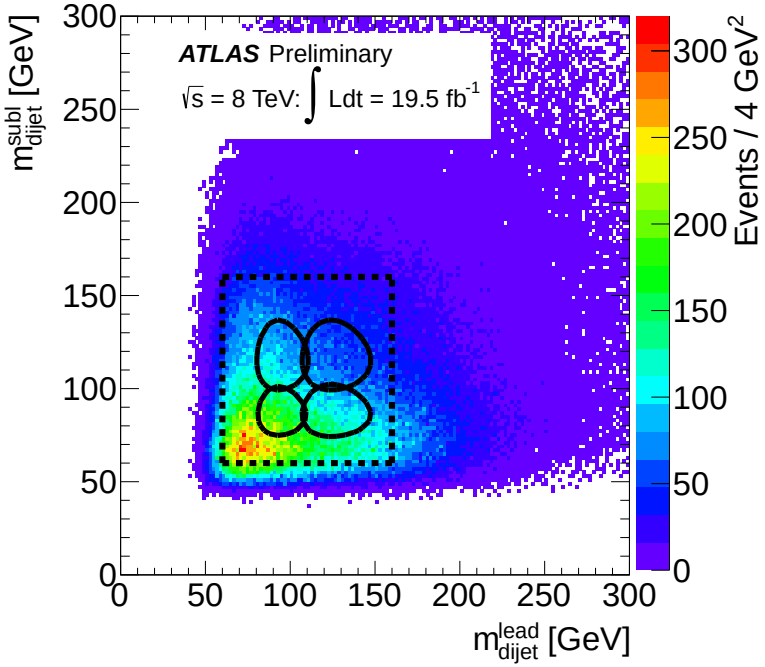
$V' \to HH \to 4b$

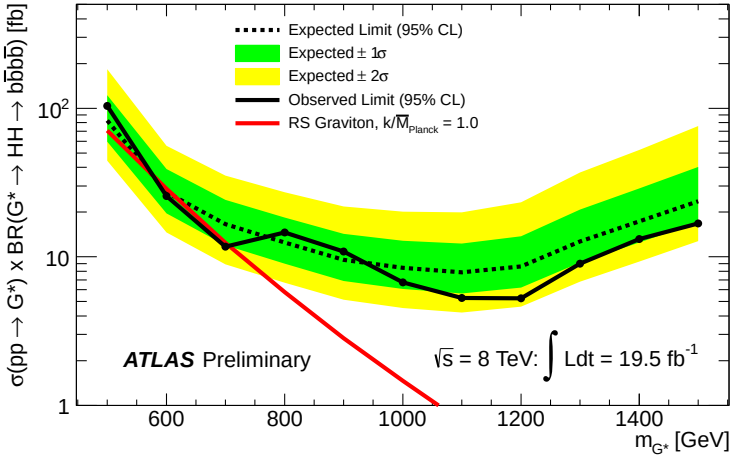
ATLAS-CONF-2014-005

Search for TeV resonance $\to HH$

- Require two pairs of anti-k_tR=0.4 b-tagged jets, dijet masses $\approx m(H)$
- b-tag triggers provide excellent coverage from 0.5 to 1.5 TeV

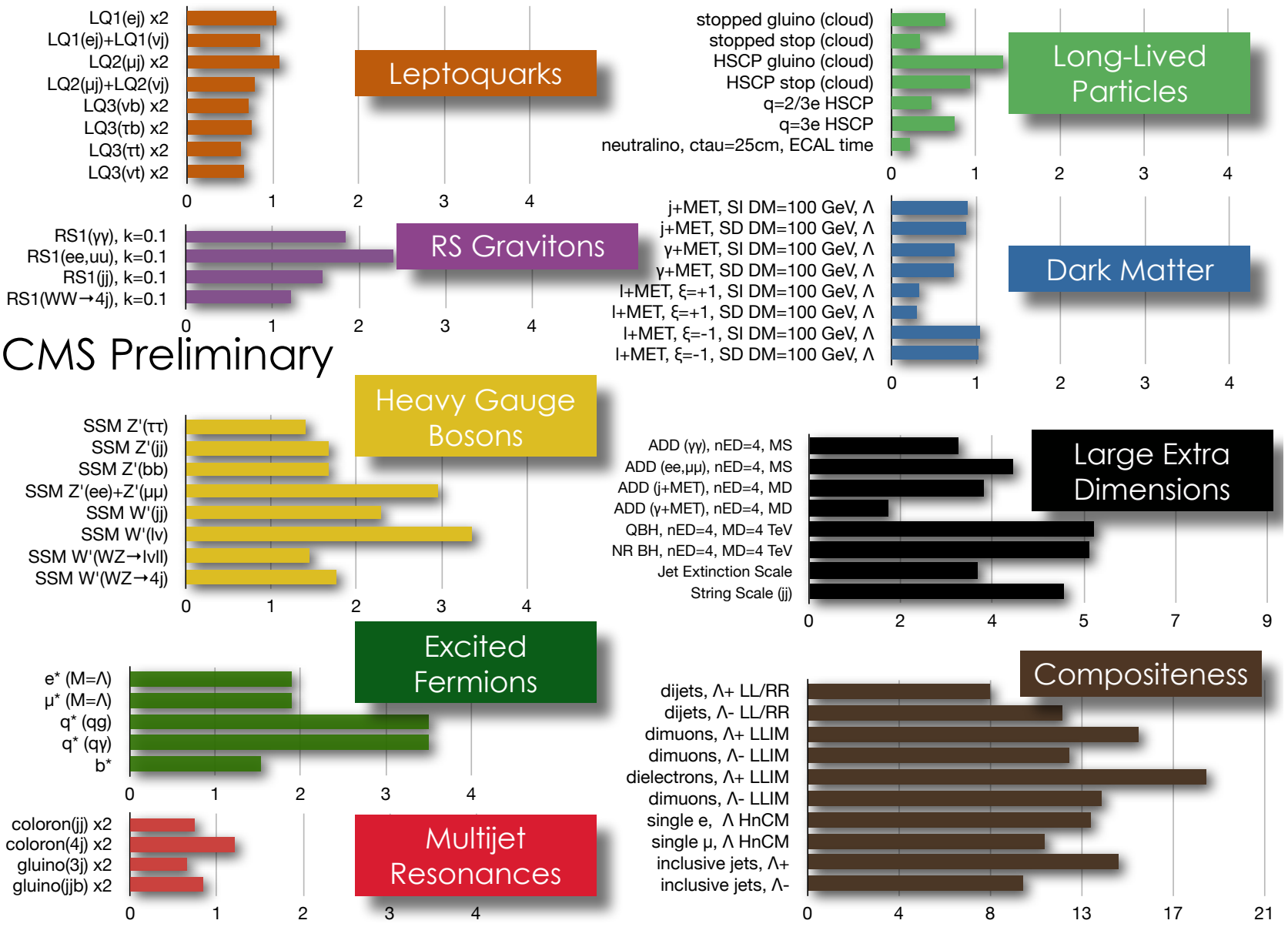






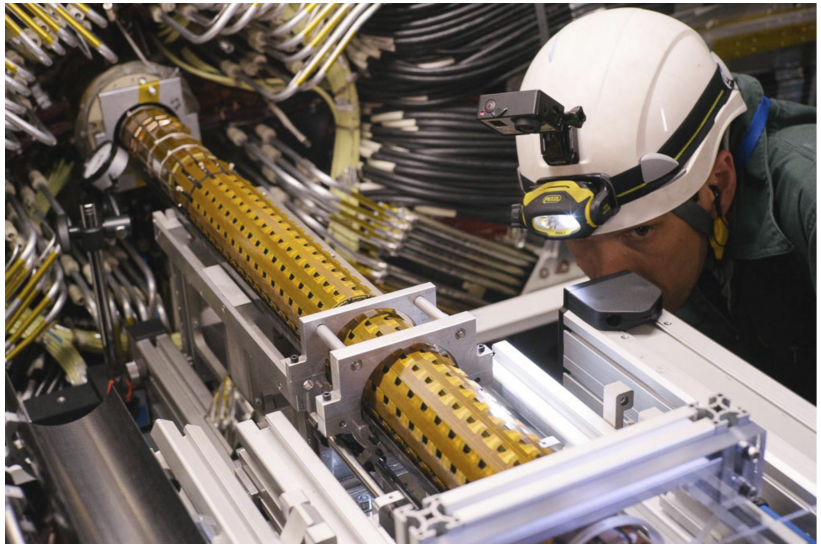
- No excess observed, limits on KK G^* in warped (RS) ED : 0.59 to 0.71 TeV

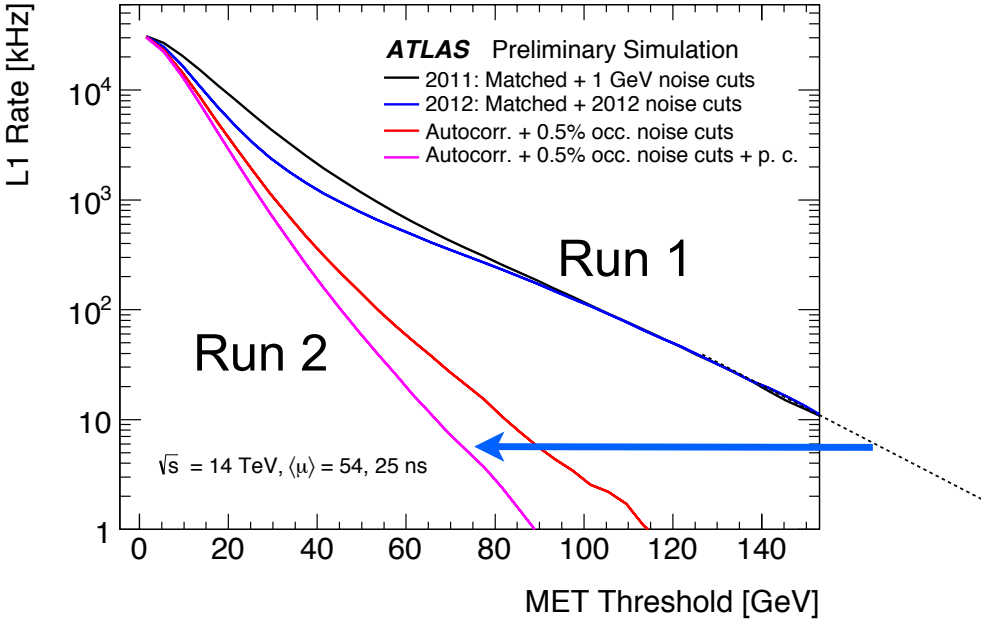
CMS Summary

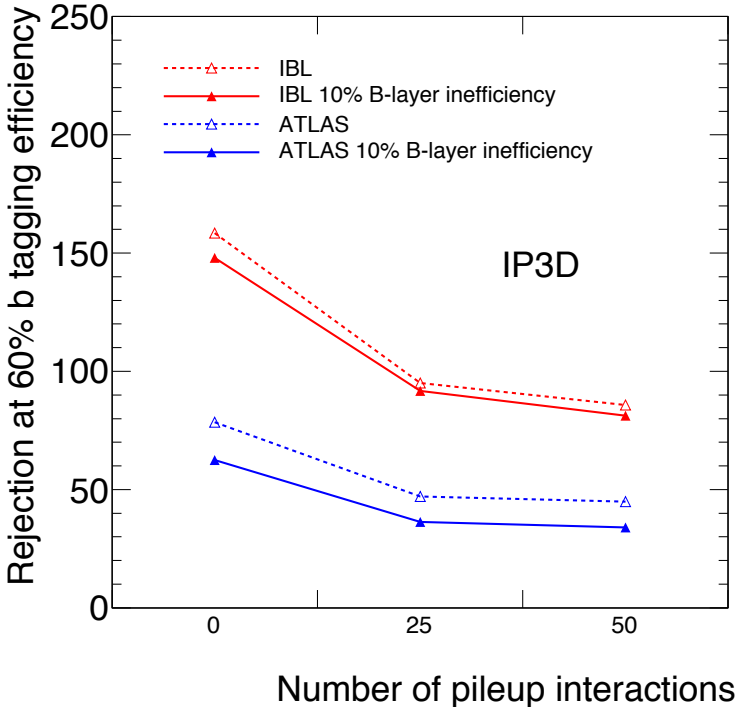

Leptoquarks
LQ1(ej) x2
LQ1(ej)+LQ1(vj)
LQ2(μj) x2
LQ2(μj)+LQ2(vj)
LQ3(vb) x2
LQ3(τb) x2
LQ3(τt) x2
LQ3(vt) x2
Long-Lived Particles
stopped gluino (cloud)
stopped stop (cloud)
HSCP gluino (cloud)
HSCP stop (cloud)
q=2/3e HSCP
q=3e HSCP
neutralino, ctau=25cm, ECAL time
RS Gravitons
RS1(γγ), k=0.1
RS1(ee,uu), k=0.1
RS1(jj), k=0.1
RS1(WW→4j), k=0.1
Dark Matter
j+MET, SI DM=100 GeV, Λ
j+MET, SD DM=100 GeV, Λ
γ+MET, SI DM=100 GeV, Λ
γ+MET, SD DM=100 GeV, Λ
l+MET, ξ=+1, SI DM=100 GeV, Λ
l+MET, ξ=+1, SD DM=100 GeV, Λ
l+MET, ξ=-1, SI DM=100 GeV, Λ
l+MET, ξ=-1, SD DM=100 GeV, Λ
CMS Preliminary
Heavy Gauge Bosons
SSM Z'(ττ)
SSM Z'(jj)
SSM Z'(bb)
SSM Z'(ee)+Z'(μμ)
SSM W'(jj)
SSM W'(lv)
SSM W'(WZ→lvll)
SSM W'(WZ→4j)
Large Extra Dimensions
ADD (γγ), nED=4, MS
ADD (ee,μμ), nED=4, MS
ADD (j+MET), nED=4, MD
ADD (γ+MET), nED=4, MD
QBH, nED=4, MD=4 TeV
NR BH, nED=4, MD=4 TeV
Jet Extinction Scale
String Scale (jj)
Excited Fermions
e* (M=Λ)
μ* (M=Λ)
q* (qg)
q* (qγ)
b*
Compositeness
dijets, Λ+ LL/RR
dijets, Λ- LL/RR
dimuons, Λ+ LLIM
dimuons, Λ- LLIM
dielectrons, Λ+ LLIM
dimuons, Λ- LLIM
single e, Λ HnCM
single μ, Λ HnCM
inclusive jets, Λ+
inclusive jets, Λ-
Multijet Resonances
coloron(jj) x2
coloron(4j) x2
gluino(3j) x2
gluino(jjb) x2
CMS Exotica Physics Group Summary – ICHEP, 2014

Ready for Run 2

- Detector repairs
- Trigger improvements
  - Consolidation
  - pileup suppression
  - **400 Hz → 1000 Hz** to tape
- New tracking layer (IBL)





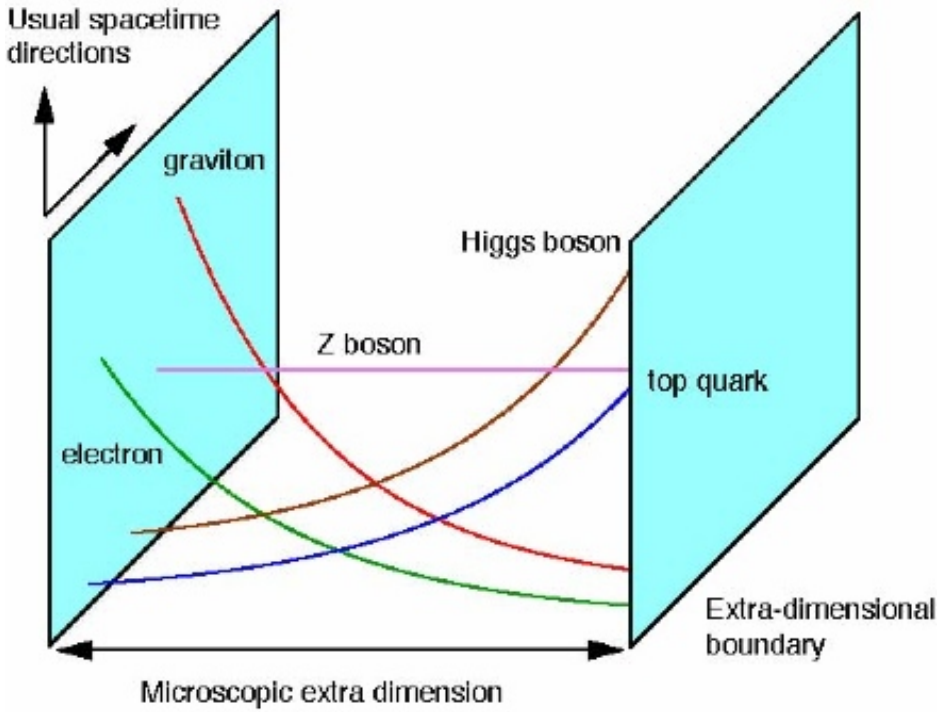


Diboson Resonances

Many BSM theories predict new resonances decaying to 2 $\times \{\gamma,\ \mathbf{W},\ \mathbf{Z},\ \mathbf{H}\}$

Randall-Sundrum extra dimensions

- SM particles can propagate with different strengths in bulk
- Predicts excited states of spin-2 gravitons (G^*)
- Bulk-RS model has large BR's to diboson decays



Other models:

- Extended gauge sector: W', Z'
- Technicolor: $a_{\mathrm{TC}} \to Z\gamma, \omega_{\mathrm{TC}} \to W\gamma, \rho_{\mathrm{TC}} \to WZ$

Spin 2 : $G^* \to ZZ \to \ell\ell qq$

arXiv:1409.6190

Search for resonance in $ZZ \to \ell\ell qq$

- $\times 10$ better BR than $ZZ \to \ell\ell\ell\ell$

Spin 2 : $G^* \to ZZ \to \ell\ell qq$

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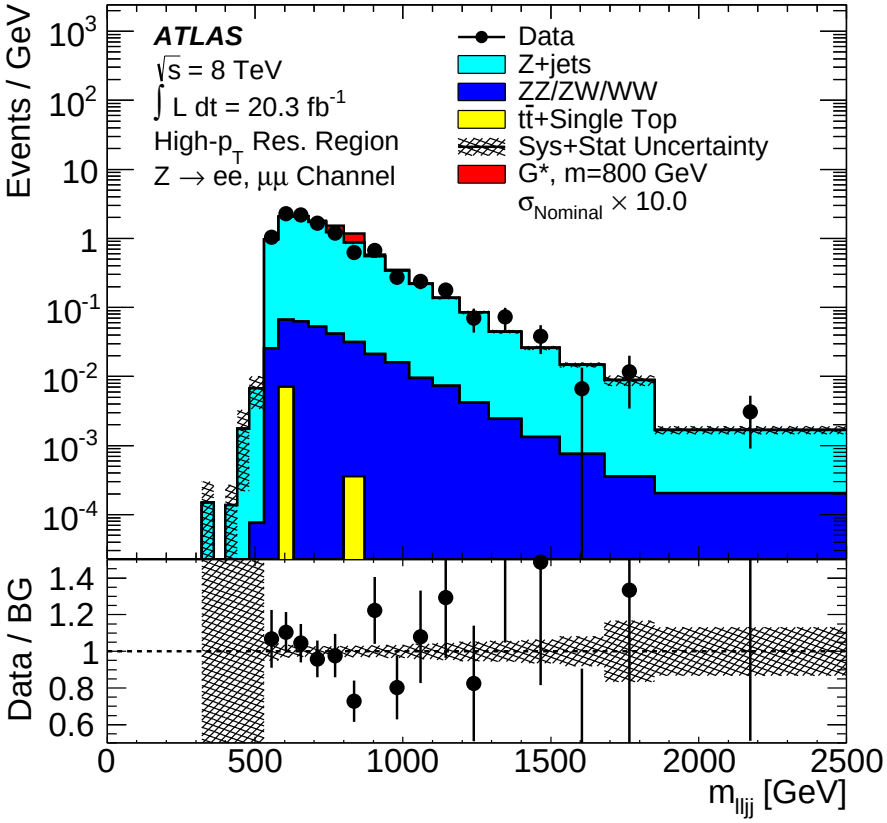

Spin 2 : $G^* \to ZZ \to \ell\ell qq$

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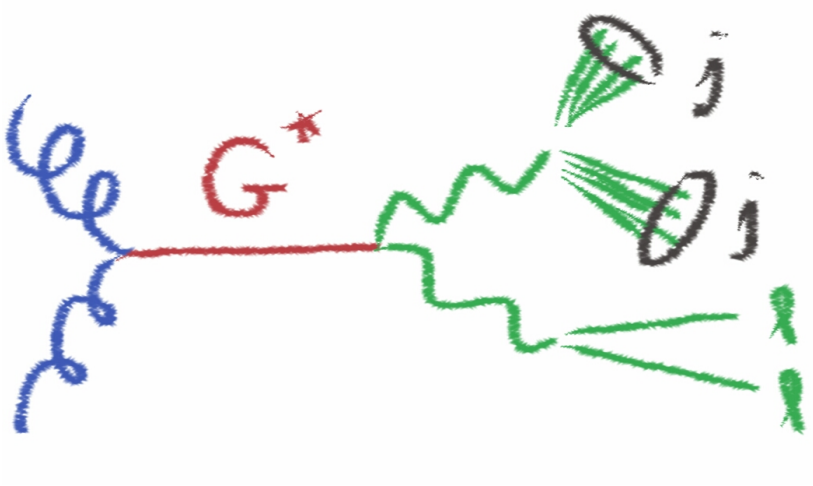
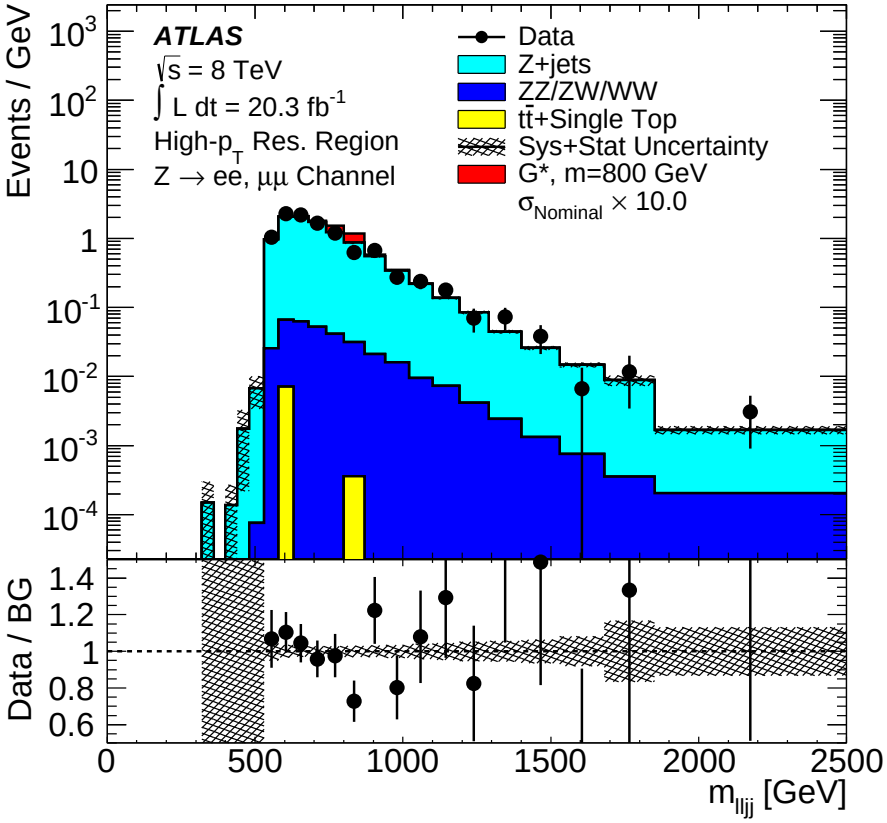
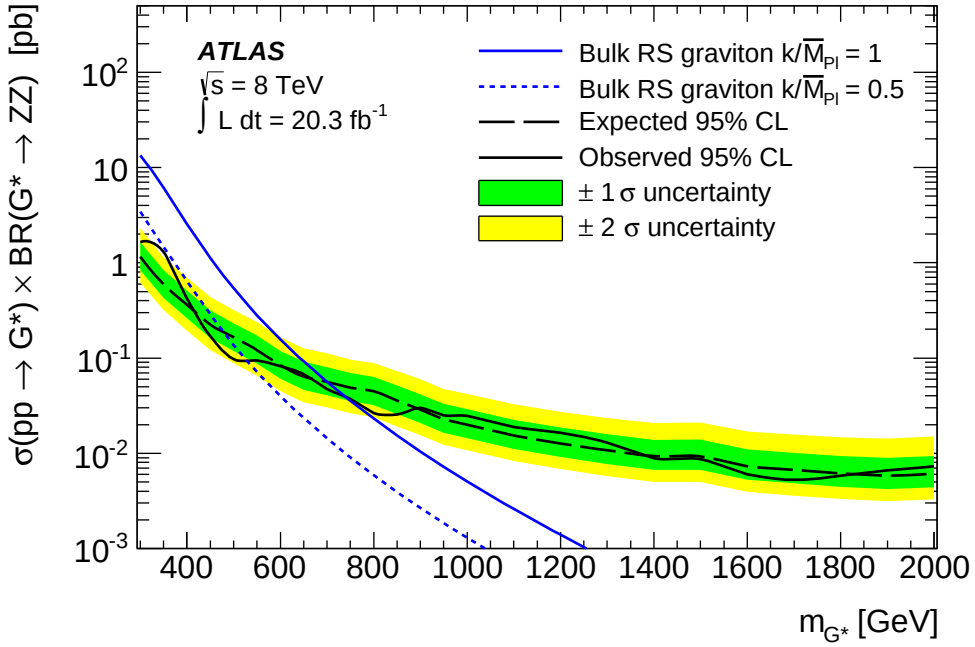
- $\times 10$ better BR than $ZZ \to \ell\ell\ell\ell$







$m(G^*) > 0.8$ TeV!

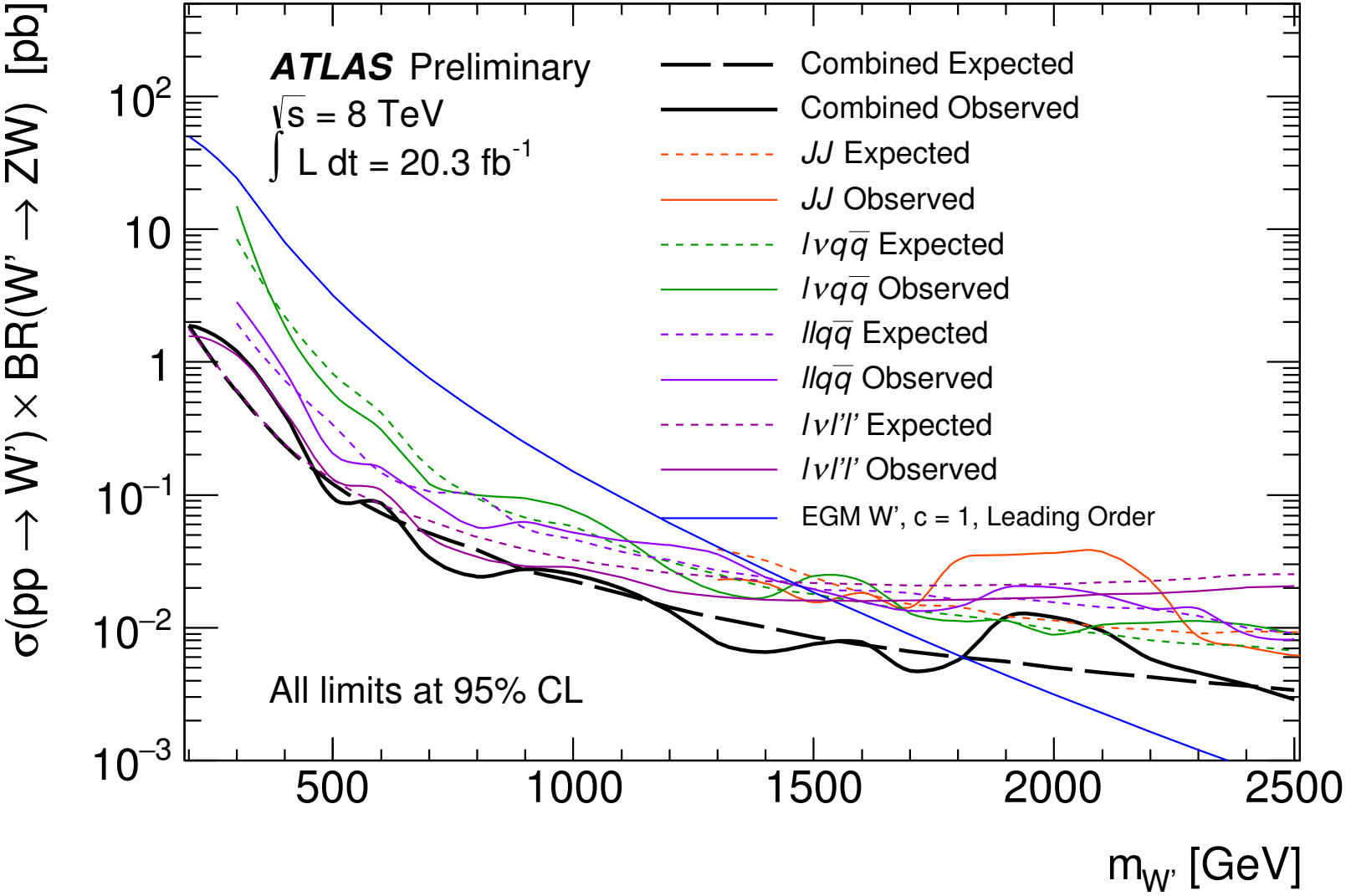
Diboson Resonance Summary

	γ	W	Z	H
γ	G*	TC	TC	A
W		G* (3)	W' (4)	A/TC
Z			G* (3)	A/TC (2)
H				G*

Complete suite of diboson resonance searches

- Many analyses not described here
- Some more to come from Run 1

Combination



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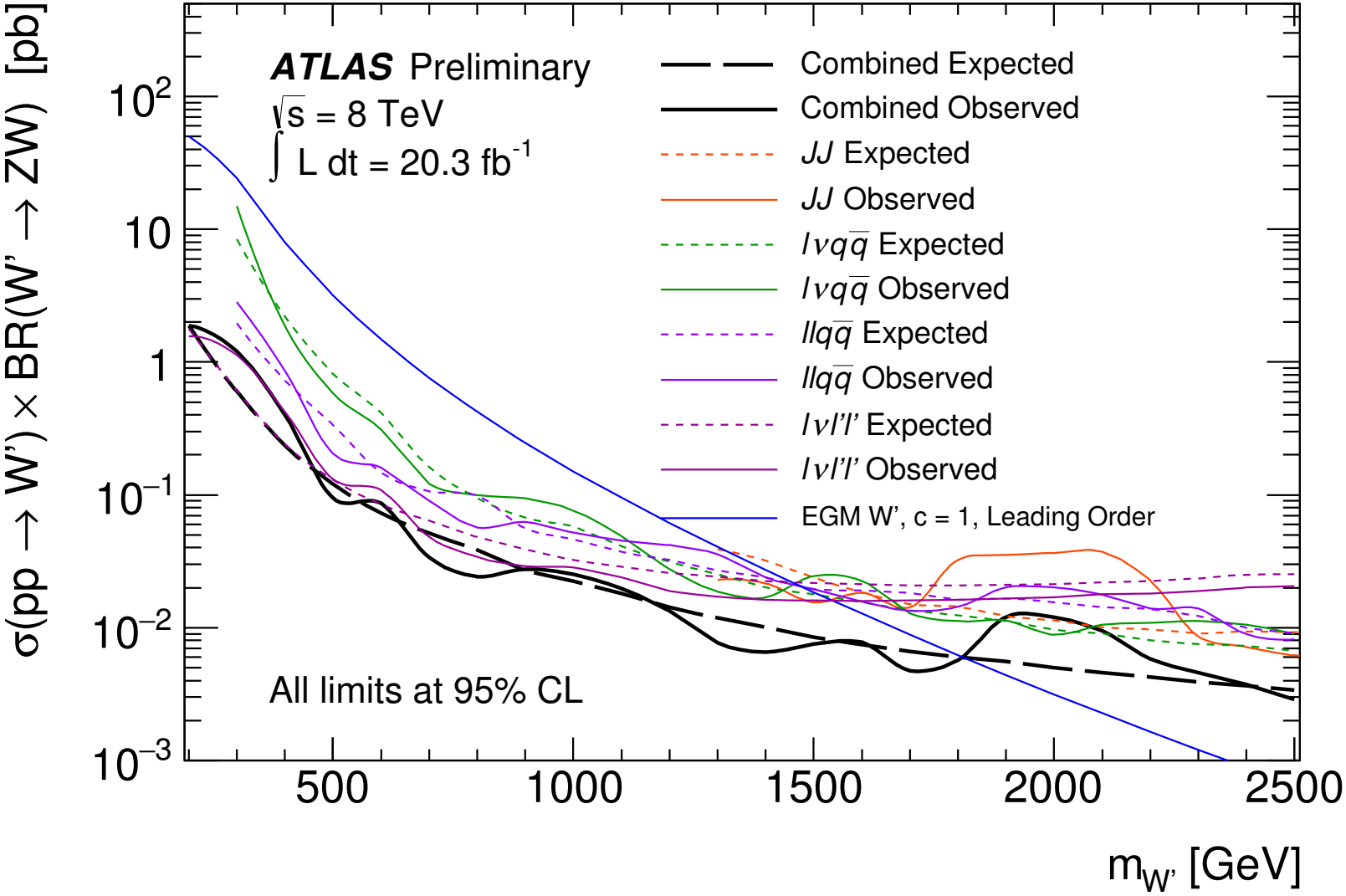
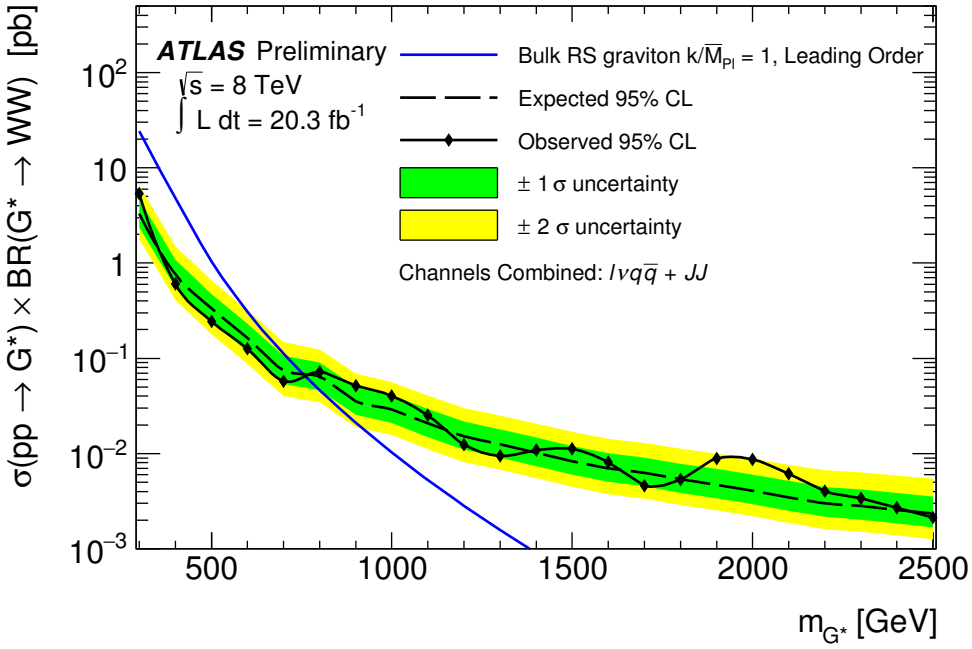
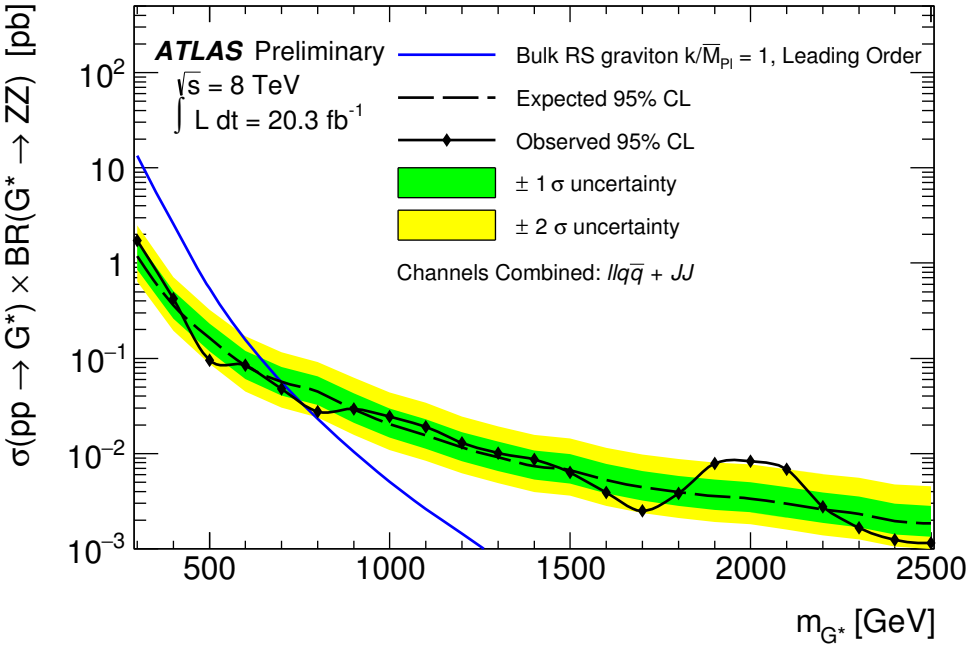


Combination





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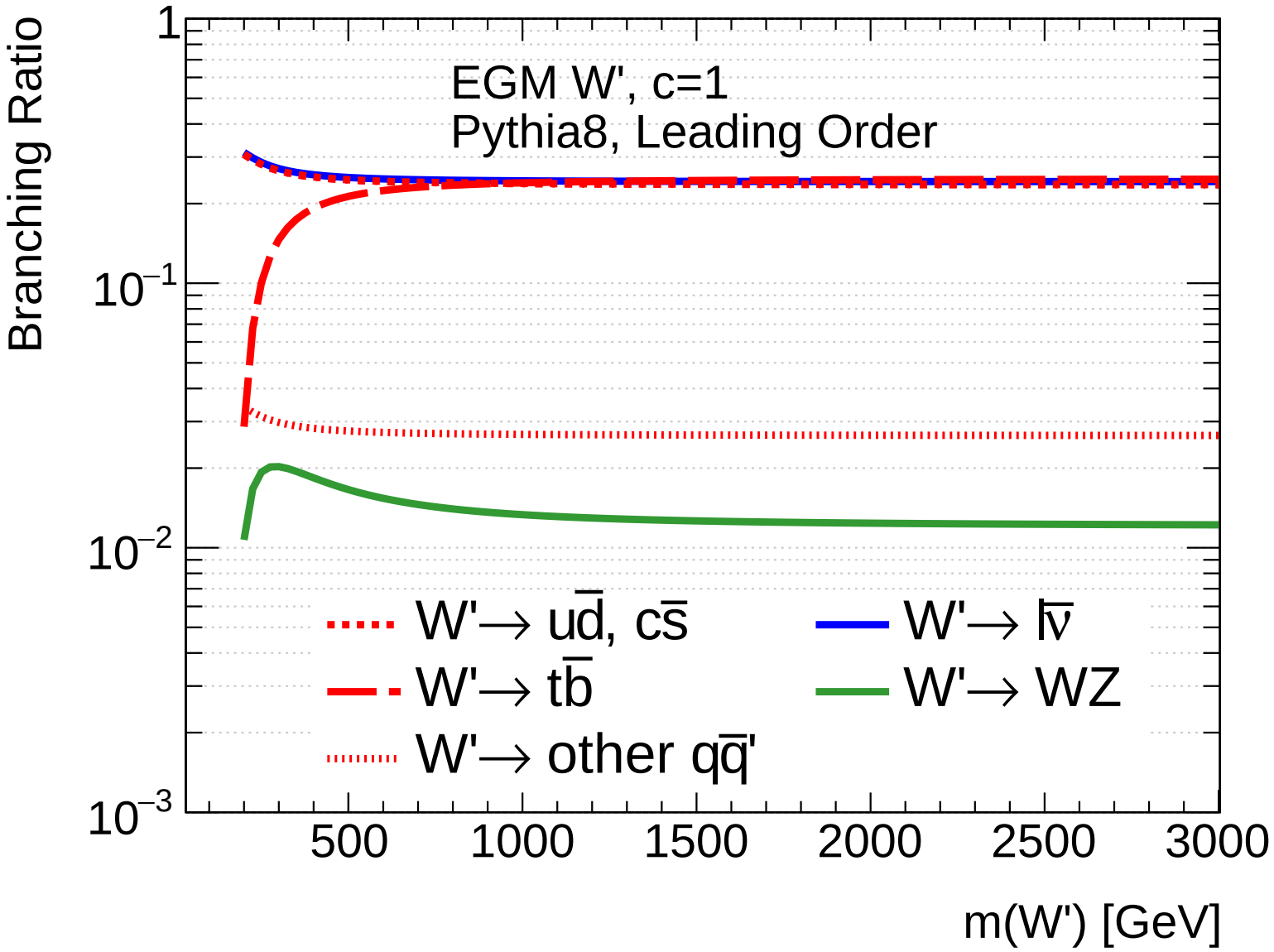

$W' \to WZ \to \ell\nu\ell\ell$

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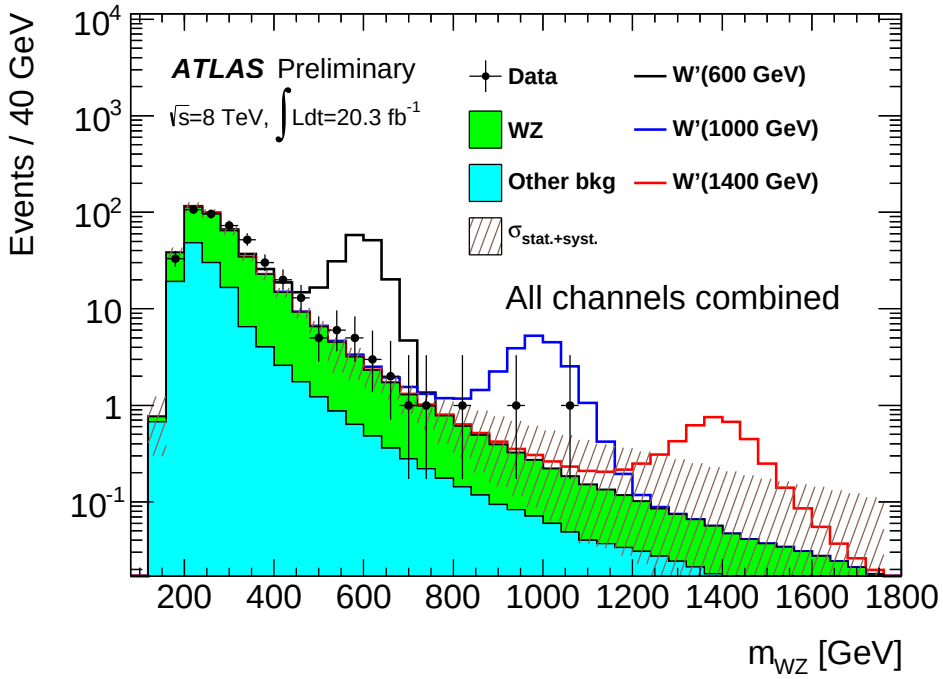
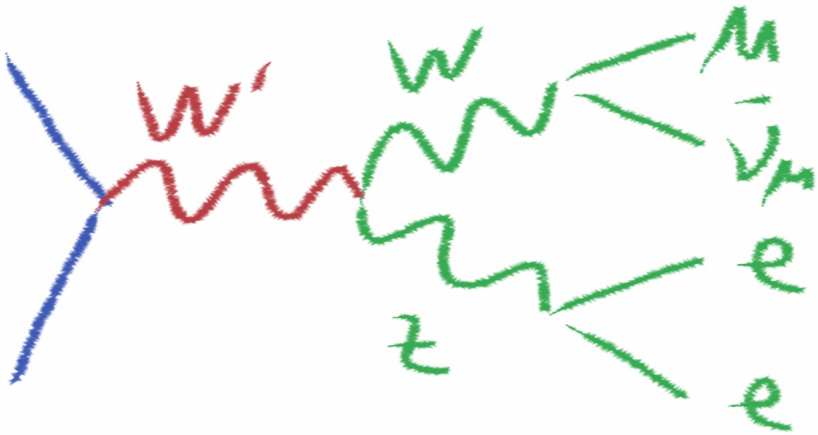
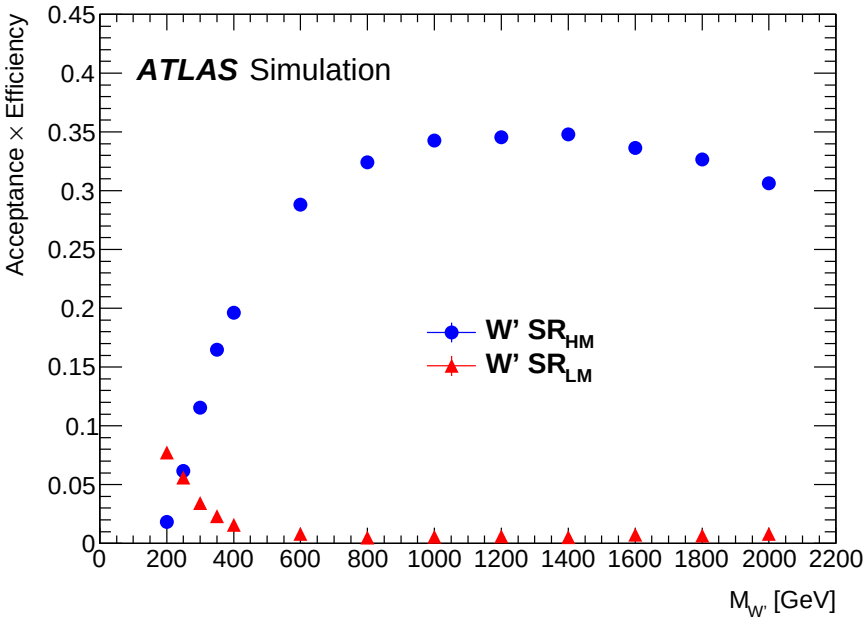
- Leptonic decays best at low masses
- Reconstruct $m(WZ)$ using W-mass constraint
- Resolution: ≈ 100 GeV at $m(W') = 1$ TeV
- No significant excess observed. Interpretations in:
  - EGM W'
  - Heavy Vector Triplet



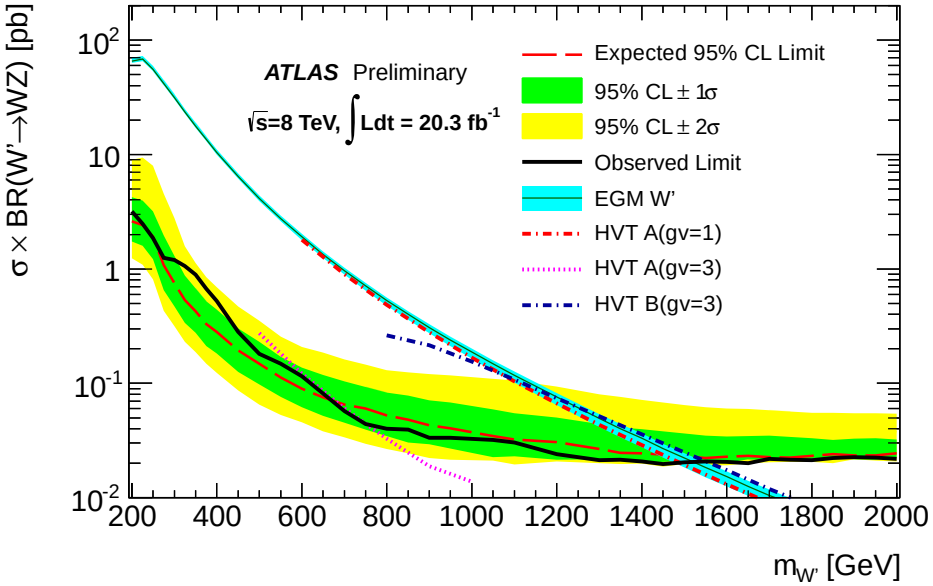


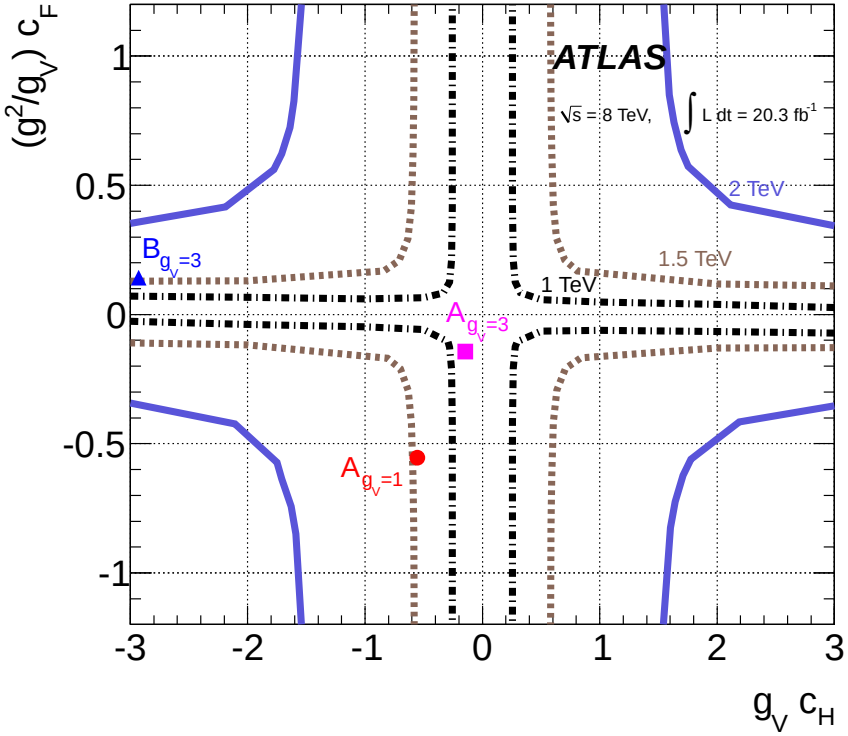


$W' \to WZ \to \ell\nu\ell\ell$ - Results

95% CL limit on $m(W')$ [TeV]

	Expected	Observed
$e\nu ee$	1.21	1.20
$\mu\nu ee$	1.16	1.19
$e\nu\mu\mu$	1.17	1.06
$\mu\nu\mu\mu$	1.16	1.17
Combined	1.49	1.52





- A (B) has standard (enhanced) couplings to W/Z
- g_V: strength of V interactions
  - $g_V \sim 1$: weakly coupled
  - $g_V \sim 4\pi$: strongly coupled
- c_F: fermion coupling
- c_H: Higgs coupling