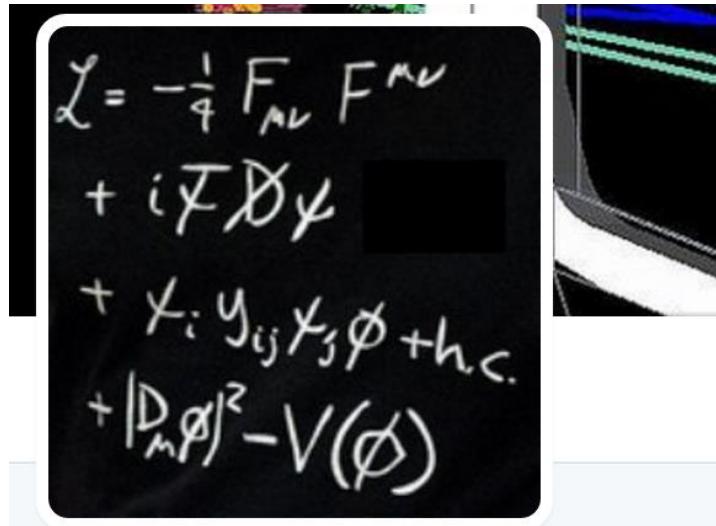


Triboson Signatures at the LHC

Jack Collins,
University of Maryland & Johns Hopkins University

J.A. Aguilar-Saavedra, JC, S. Lombardo, arXiv:1607.08911

BSM faces LHC run-2 realities



Smug Standard Model

@smugsmphys

I win... always.

📍 Geneva, Switzerland

📅 Joined August 2016



Tweet to Smug Standard M...

Smug Standard Model @smugsmphys · Aug 5

Once again, I win. #ICHEP2016 #diphoton



71



81



$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$
+ $i \bar{F} D_\mu F$
+ $\lambda_i \bar{\chi}_i \chi_j \phi + h.c.$
+ $|D_\mu \phi|^2 - V(\phi)$

Smug Standard Model @smugsmphys · Aug 8

Maybe you'd do a better job finding NP if you weren't all so busy dancing and tweeting about how awesome science is. #justsaying



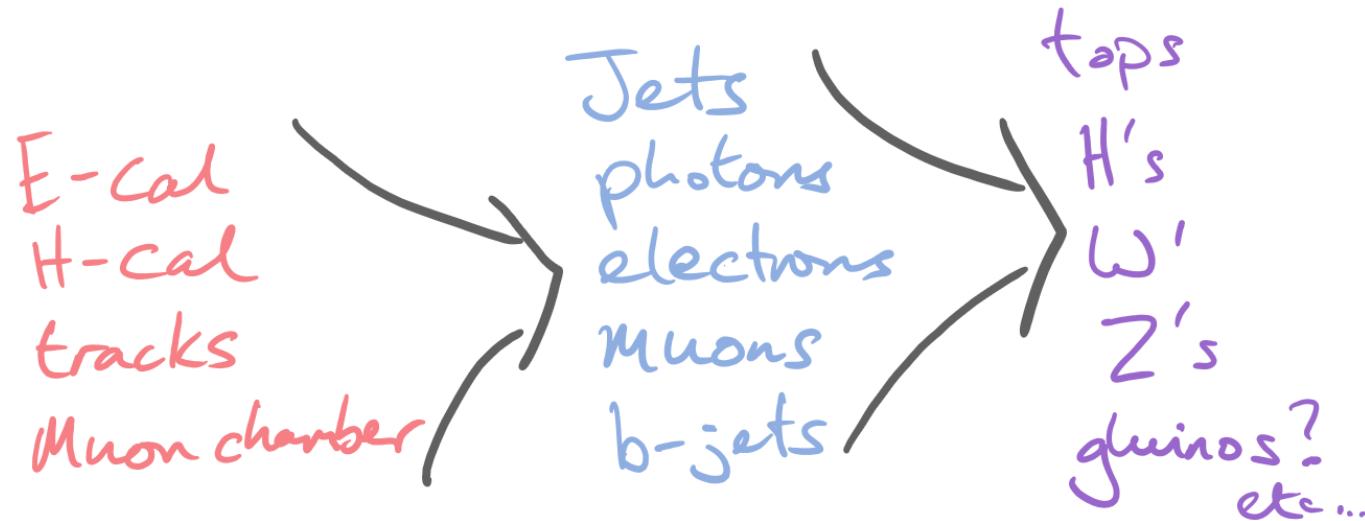
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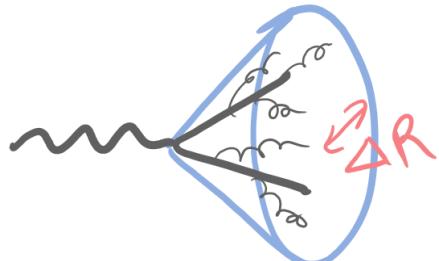
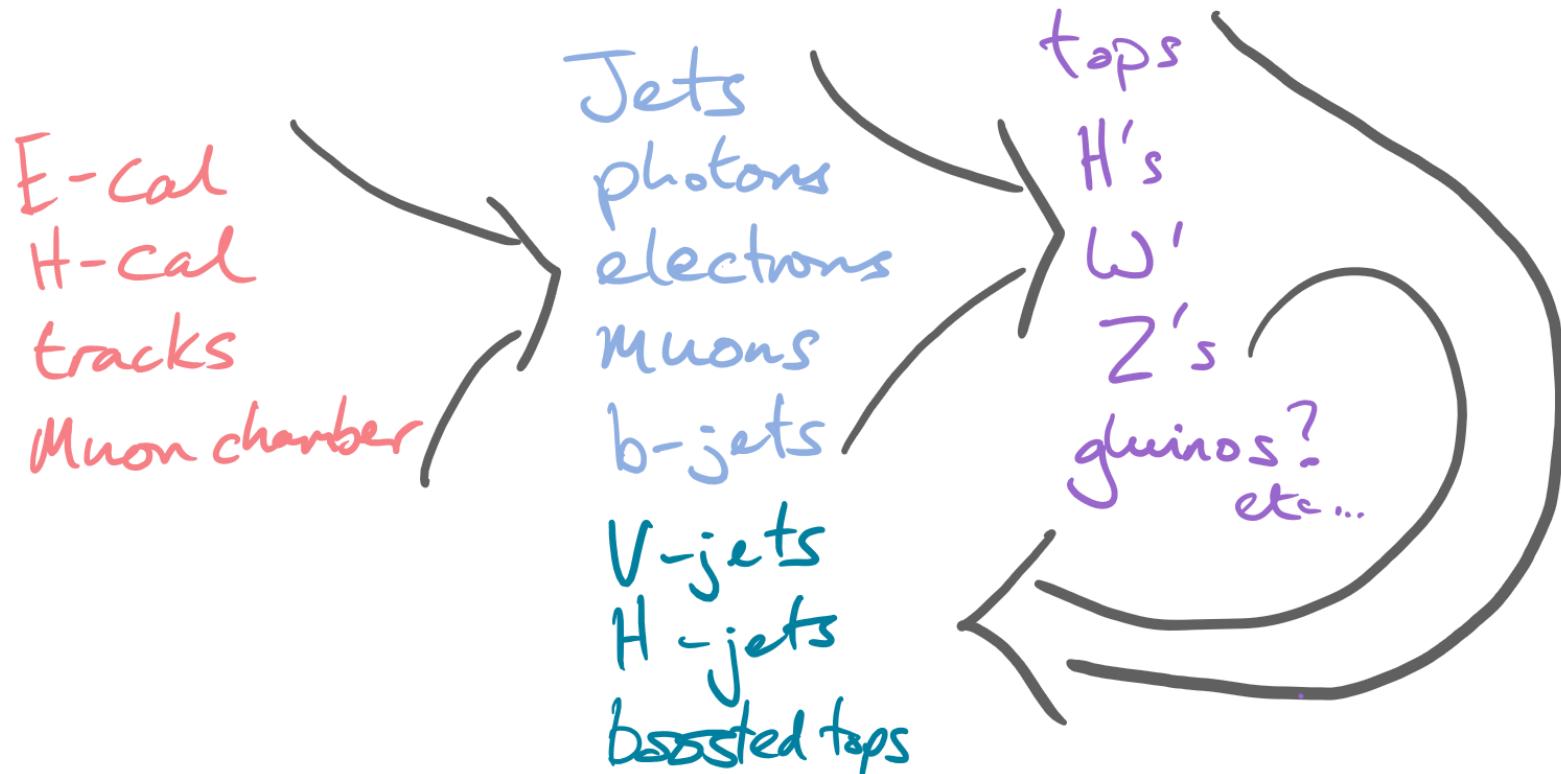
5



Physics Objects



Physics Objects

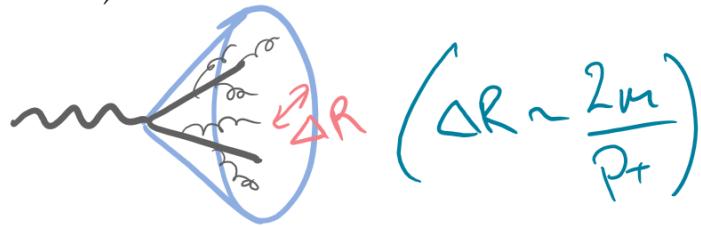


$$\left(\Delta R \sim \frac{2m}{P_T} \right)$$

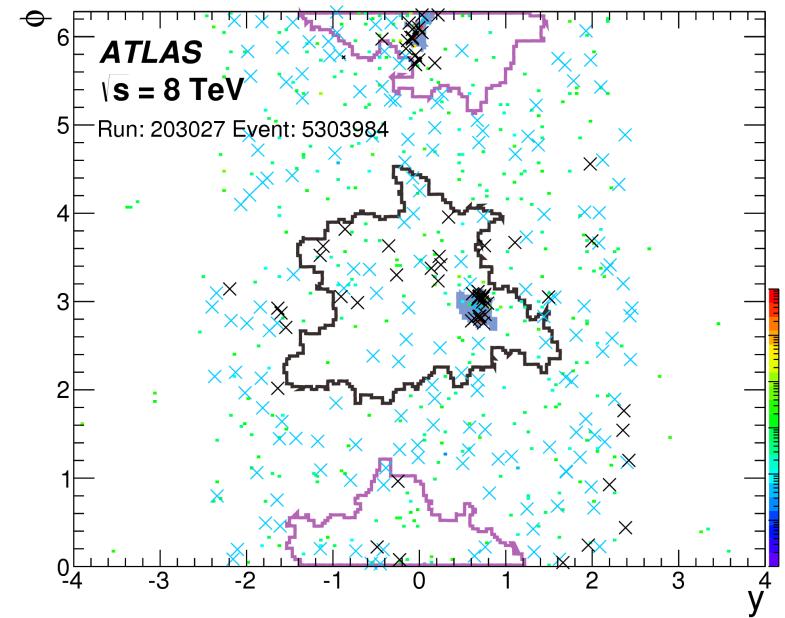
$\Delta R \sim 0.5$ for
 $P_T \sim 400$ GeV

Vector Boson Tagging

	ΔR	Crossing	Mass	Shape	Tracks
CMS	0.8	Pruning	$\sim 65\text{-}105 \text{ GeV}$	N-sub-jet-ness	—
ATLAS Run 1	1.2	MD filtering	(W/Z)	\sqrt{g}	< 30
ATLAS Run 2	1.0	Trimming	$\sim 105\text{-}145 \text{ GeV}$ (H)	D_2	—



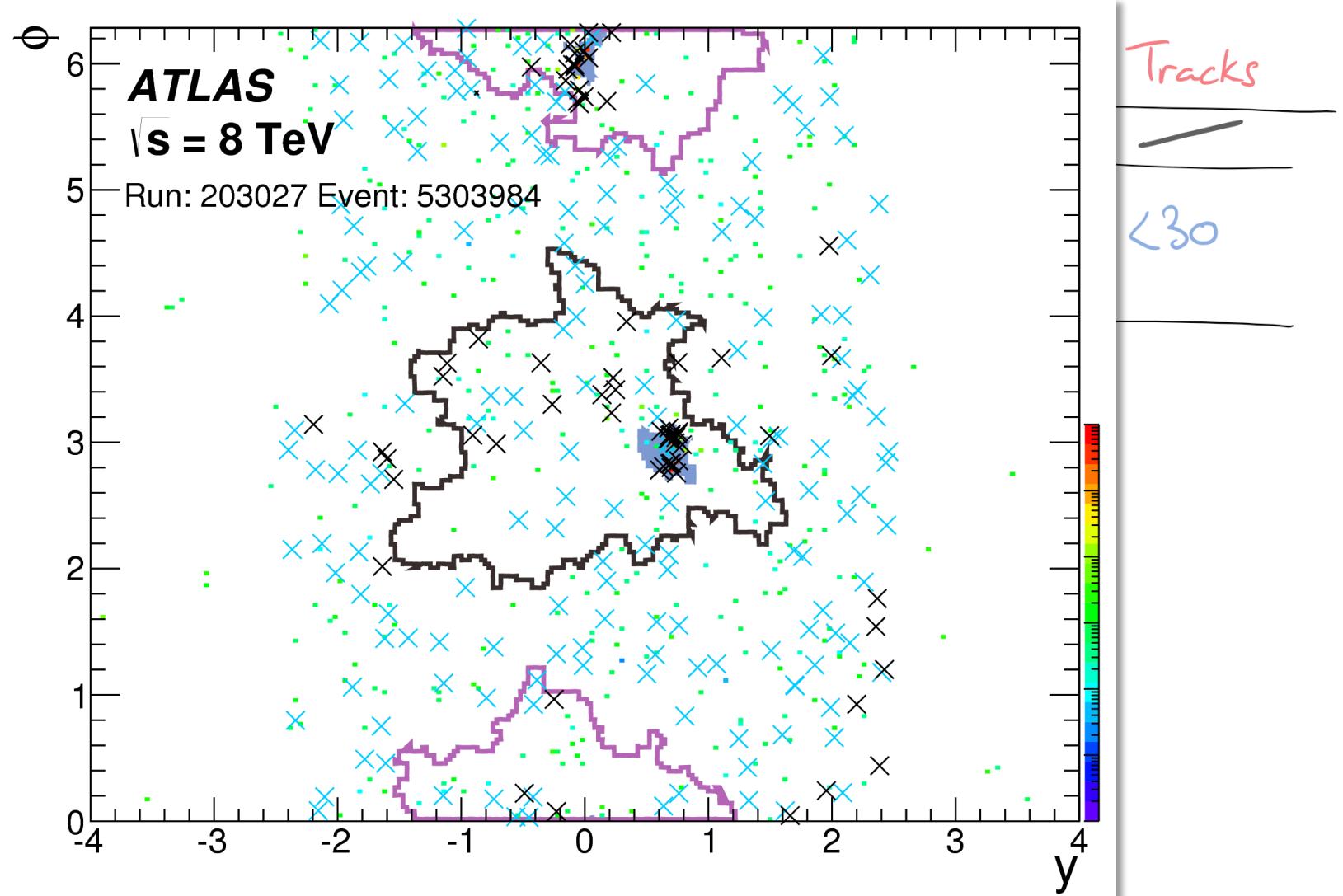
(Also b-tagged subjects)



Vector Boson Tagging

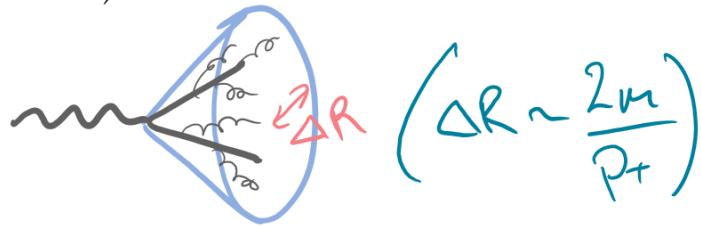
CMS

ATLAS

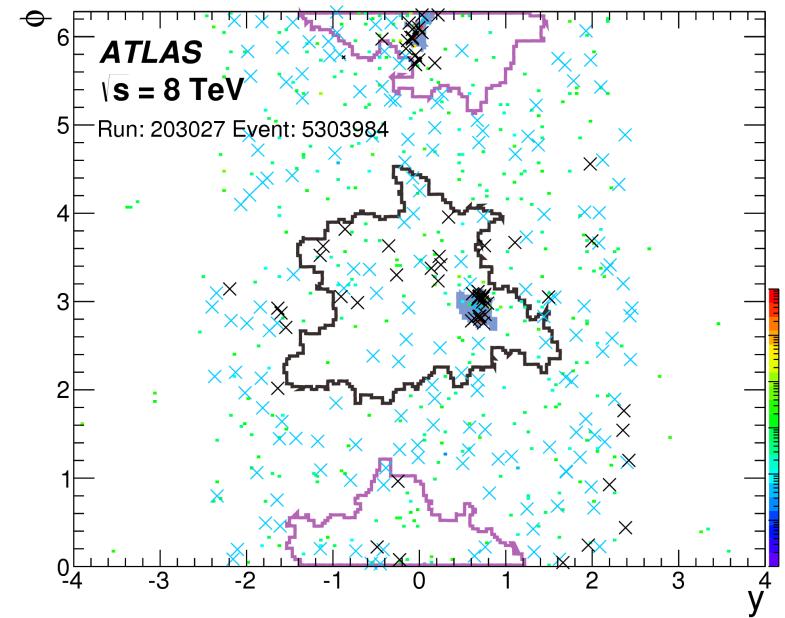


Vector Boson Tagging

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(Also b-tagged subjects)



Boosted Boson Searches

ATLAS Exotics Public Results, 2016 Data

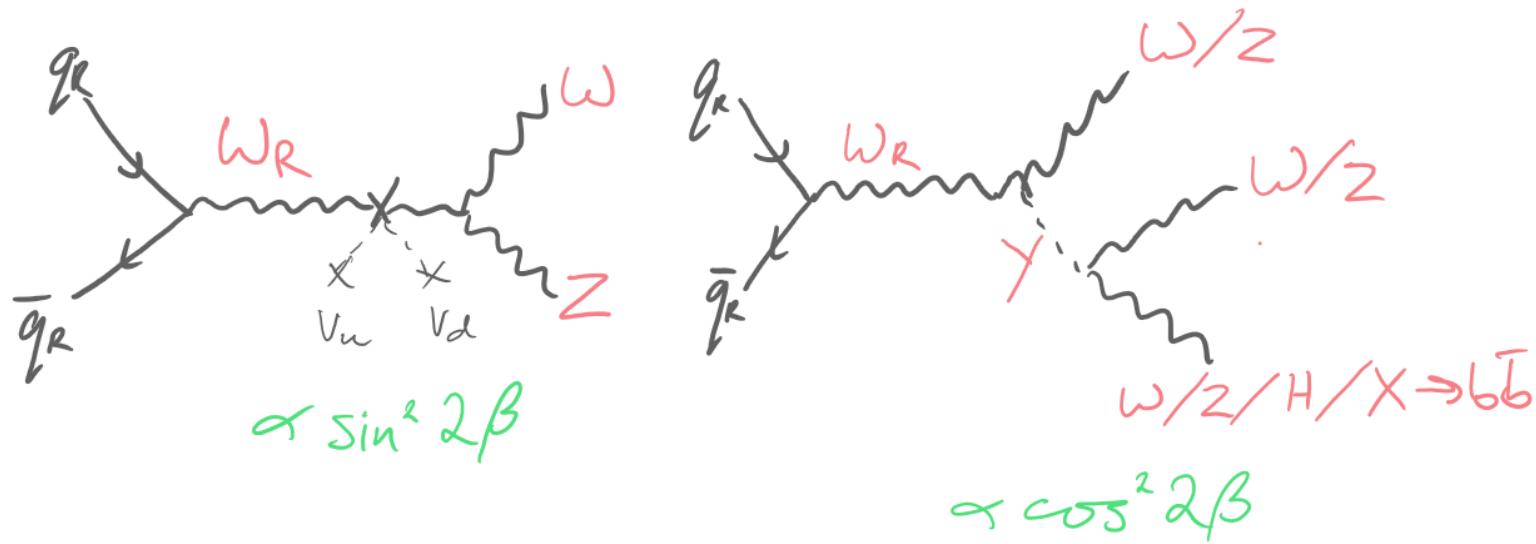
Search for Dark Matter production associated with bottom quarks in 13.3 fb ⁻¹ of pp collisions at $\sqrt{s}=13$ TeV with the ATLAS detector at the LHC		ATLAS-CONF-2016-086	13.3/fb	Aug 2016
A search for pair-produced resonances in four jets final states at $\sqrt{s}=13$ TeV with the ATLAS detector		ATLAS-CONF-2016-084	15.4/fb	Aug 2016
A Search for Resonances Decaying to a W or Z Boson and a Higgs Boson in the qqbarbbbar Final State		ATLAS-CONF-2016-083	13.3/fb	Aug 2016
Searches for heavy ZZ and ZW resonances in the llqq and vvqq final states in pp collisions at $\sqrt{s}=13$ TeV with the ATLAS detector		ATLAS-CONF-2016-082	13.2/fb	Aug 2016
Search for new light resonances decaying to jet pairs and produced in association with a photon or a jet in proton-proton collisions at $\sqrt{s}=13$ TeV with the ATLAS detector		ATLAS-CONF-2016-070	15.5/fb	Aug 2016
Search for new phenomena in dijet events collected in 2015 and 2016 pp collisions with the ATLAS detector at $\sqrt{s}=13$ TeV		ATLAS-CONF-2016-069	15.7/fb	Aug 2016
Search for diboson resonance production in the lnuqq final state using pp collisions at $\sqrt{s}=13$ TeV with the ATLAS detector at the LHC		ATLAS-CONF-2016-062	13.2/fb	Aug 2016
Search for new resonances decaying to a charged lepton and a neutrino in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector		ATLAS-CONF-2016-061	13.3/fb	Aug 2016
Search for resonances in the mass distribution of jet pairs with one or two jets identified as b-jets with the ATLAS detector with 2015 and 2016 data		ATLAS-CONF-2016-060	13.3/fb	Aug 2016
Search for scalar diphoton resonances with 15.4/fb of data collected at $\sqrt{s}=13$ TeV in 2015 and 2016 with the ATLAS detector		ATLAS-CONF-2016-059	15.4/fb	Aug 2016
Search for resonances with boson-tagged jets in 15.5/fb of pp collisions at $\sqrt{s}=13$ TeV collected with the ATLAS detector		ATLAS-CONF-2016-055	15.5/fb	Aug 2016
Search for doubly-charged Higgs bosons in same-charge electron pair final states using proton-proton collisions at $\sqrt{s}=13$ TeV with the ATLAS detector		ATLAS-CONF-2016-051	13.9/fb	Aug 2016
Search for pair production of Higgs bosons in the bbbar final state using proton–proton collisions at $\sqrt{s}=13$ TeV with the ATLAS detector		ATLAS-CONF-2016-049	13.3/fb	Aug 2016
Search for new high-mass resonances in the dilepton final state using proton–proton collisions at $\sqrt{s}=13$ TeV with the ATLAS detector		ATLAS-CONF-2016-045	13.3/fb	Aug 2016

Boosted Boson Searches

		CMS.	A _T LAS	
VV		2015	2016	2015
↳	gggg	✓	✗	✓
↳	lgg	✓	✓	✓
↳	ννgg	✗	✗	✓
↳	llgg	✓	✗	✓
VH				
↳	ggbb	✓	✗	✓
↳	lvbb	✓	✗	✓
↳	llbb	✓	✗	✓
↳	ννbb	✓	✗	✓
HH				
↳	bbbb	✓	✗	✓

Theory Motivation

Left-Right symmetry

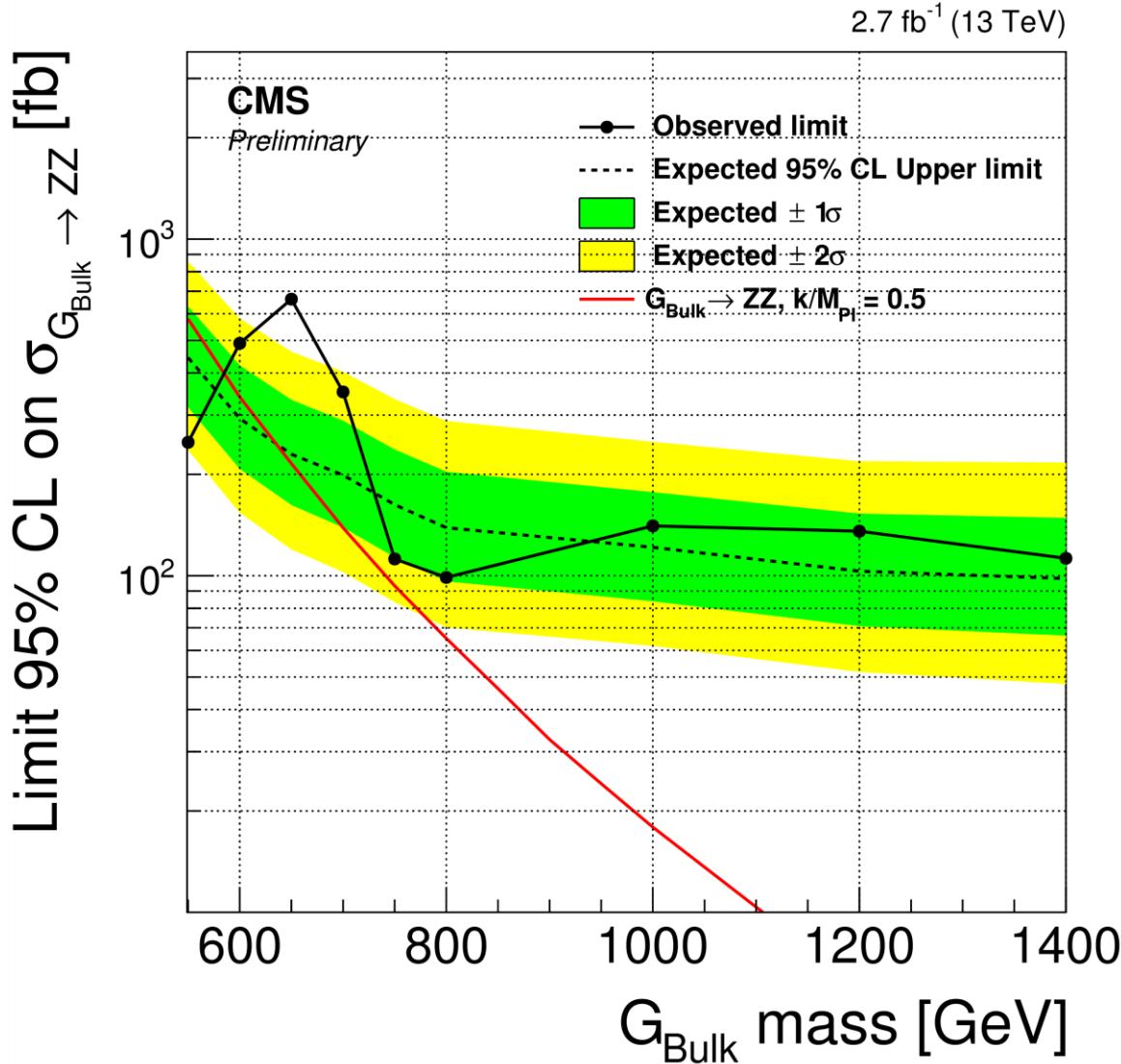


Motivations for large $\cos^2 2\beta$:

- $\frac{M_t}{M_b} \sim \tan\beta$

- SUSY Higgs mass $\sim (g^2 + g_R^2) v^2 \cos^2 2\beta$

CMS 650 GeV ($R > ZV > llqq$)

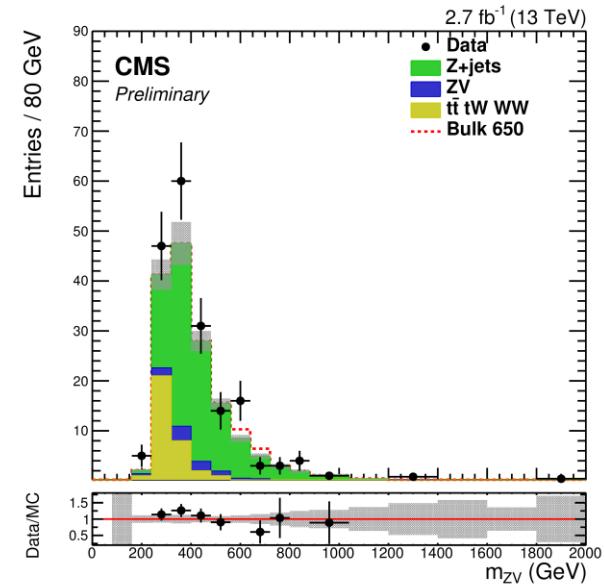
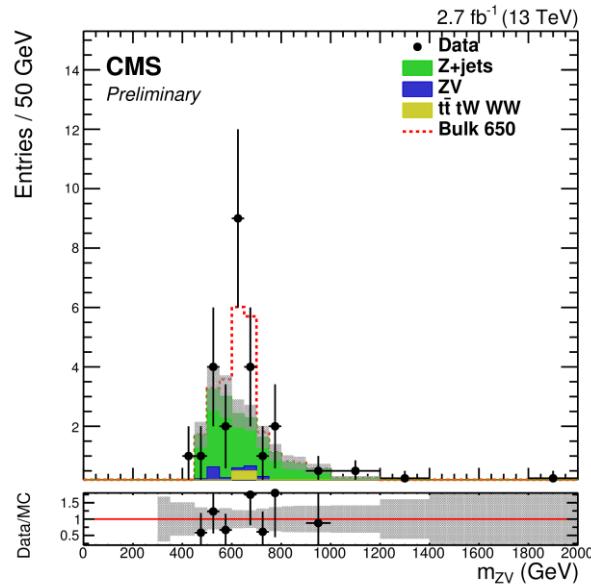
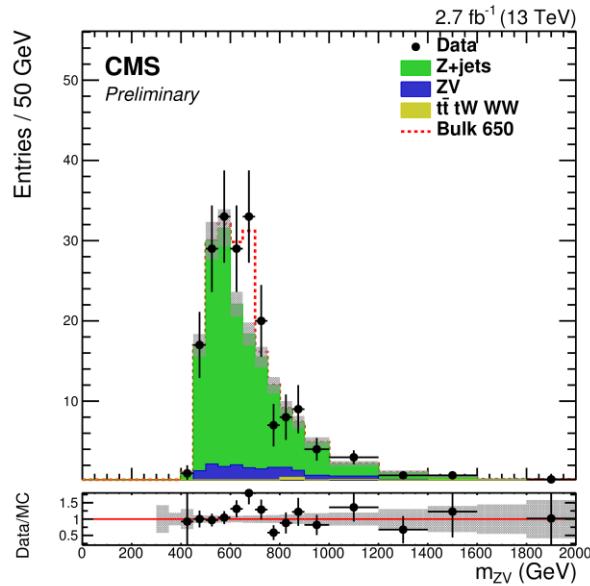


For KK graviton hypothesis:

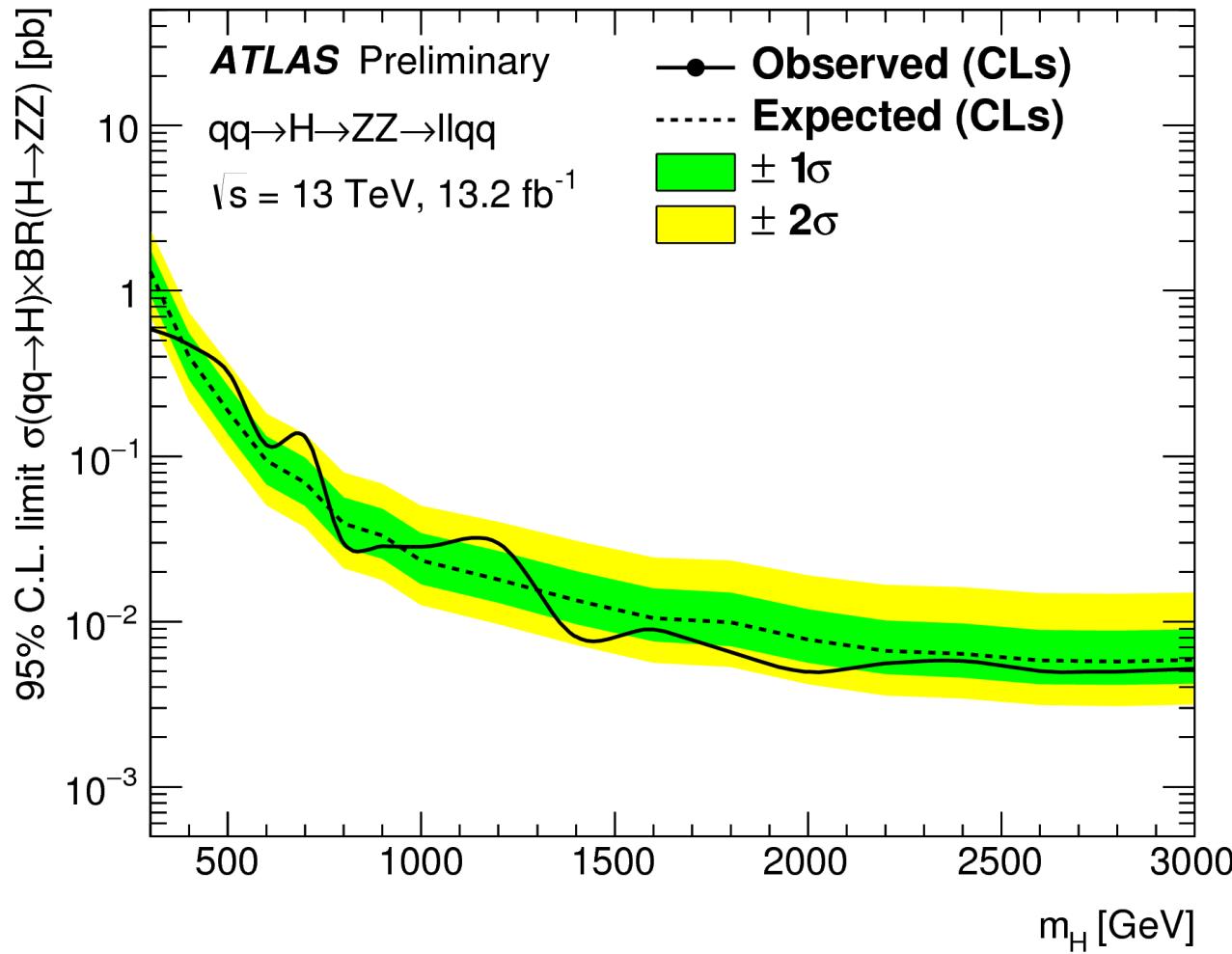
3.9 σ local

3.5 σ global

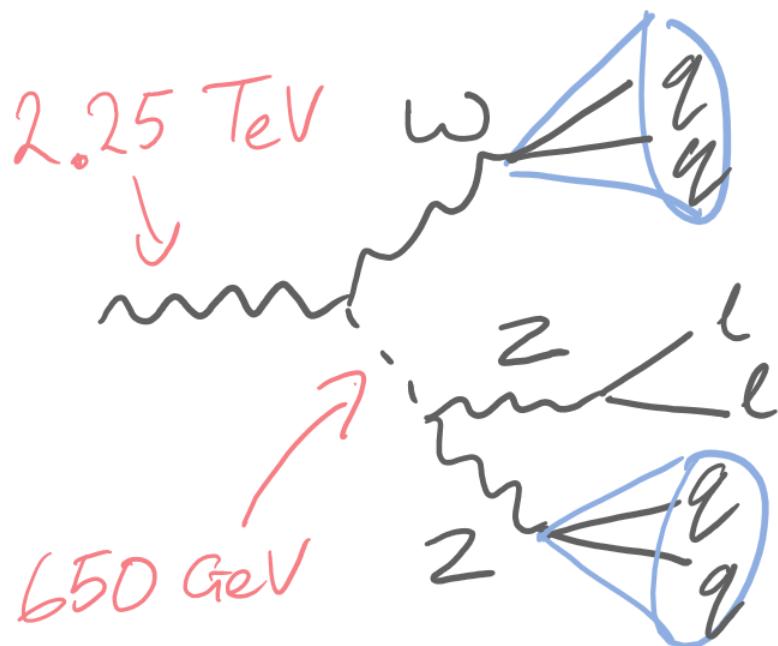
CMS 650 GeV ($R > ZV > llqq$)



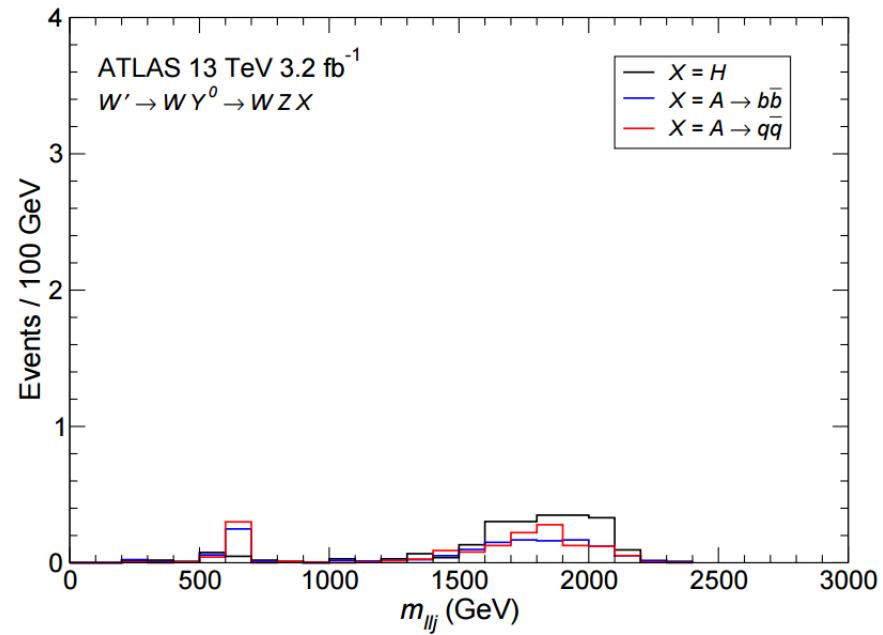
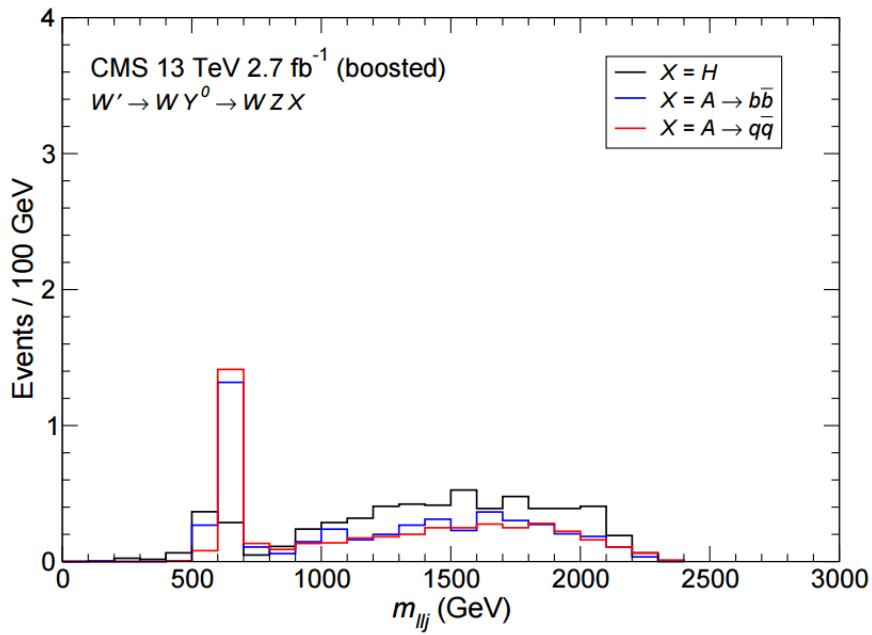
ATLAS 650 GeV ($R > ZV > llqq$)



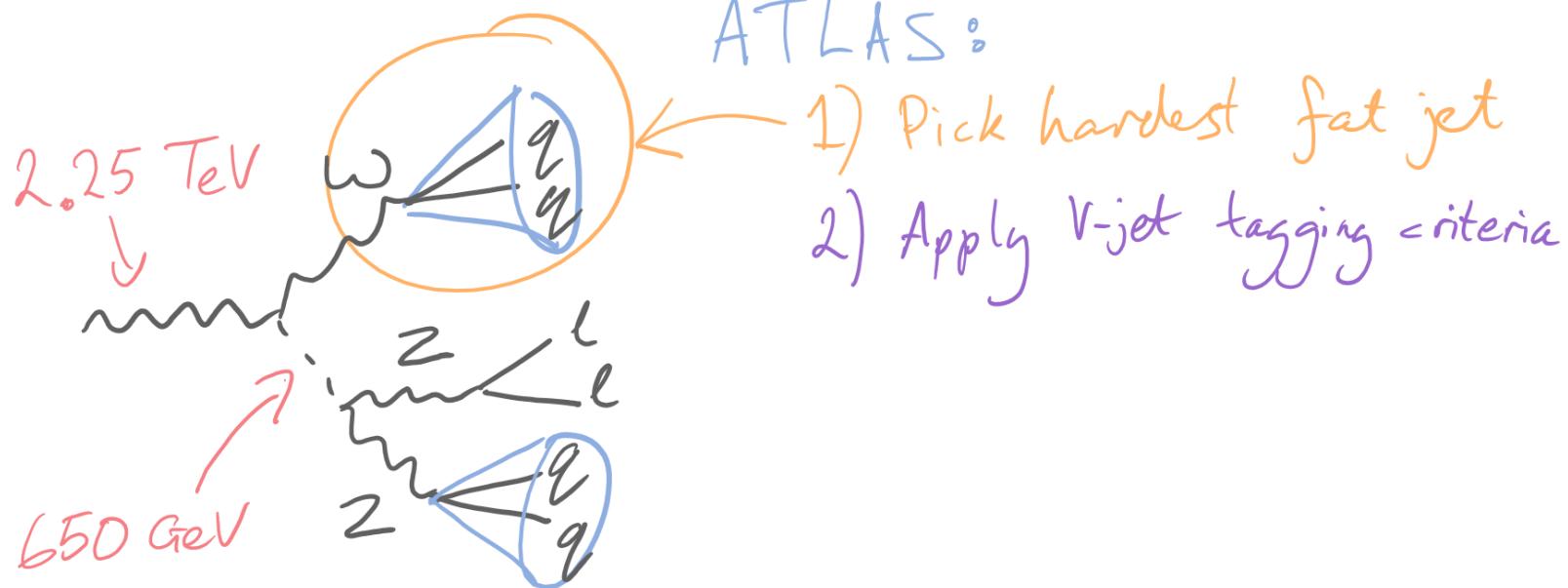
650 GeV ($R > ZV > llqq$)



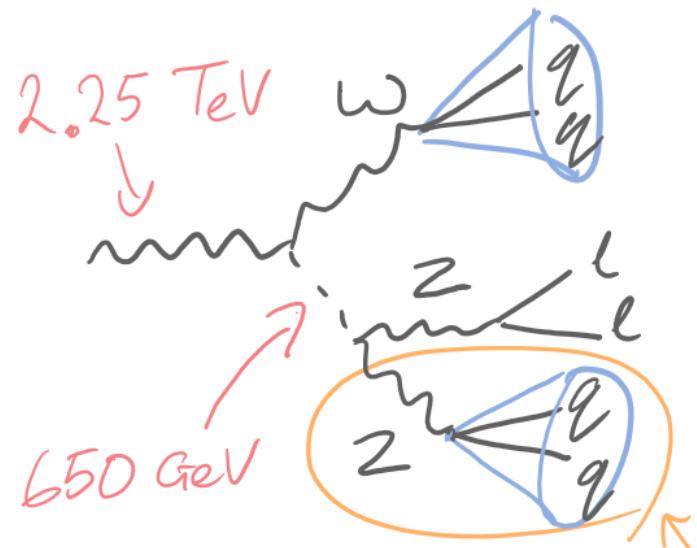
650 GeV ($R > ZV > llqq$)



650 GeV ($R > ZV > llqq$)



650 GeV ($R > ZV > llqq$)



ATLAS:

- 1) Pick hardest fat jet
- 2) Apply V-jet tagging criteria

CMS:

- 1) Apply V-jet tagging criteria to all jets
- 2) Find hardest V-jet

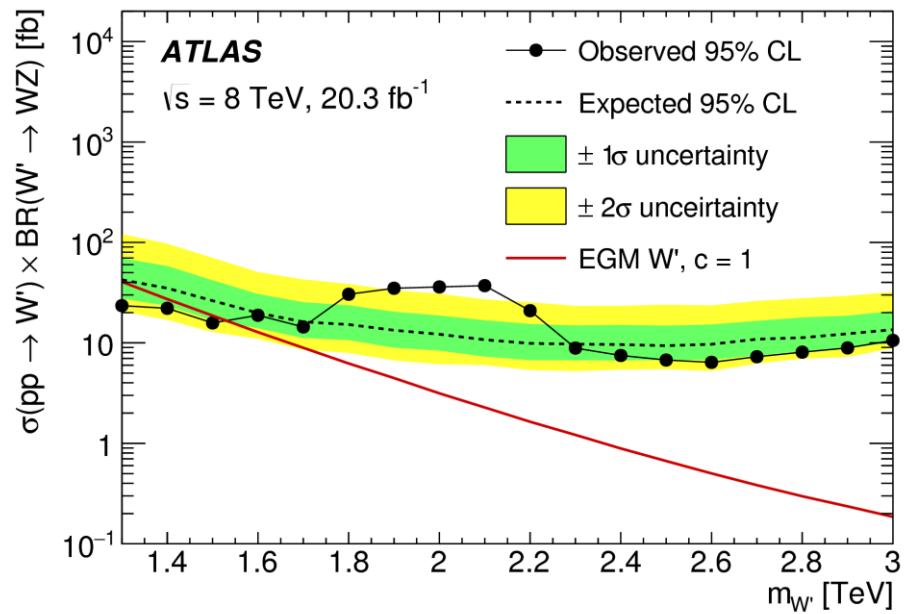
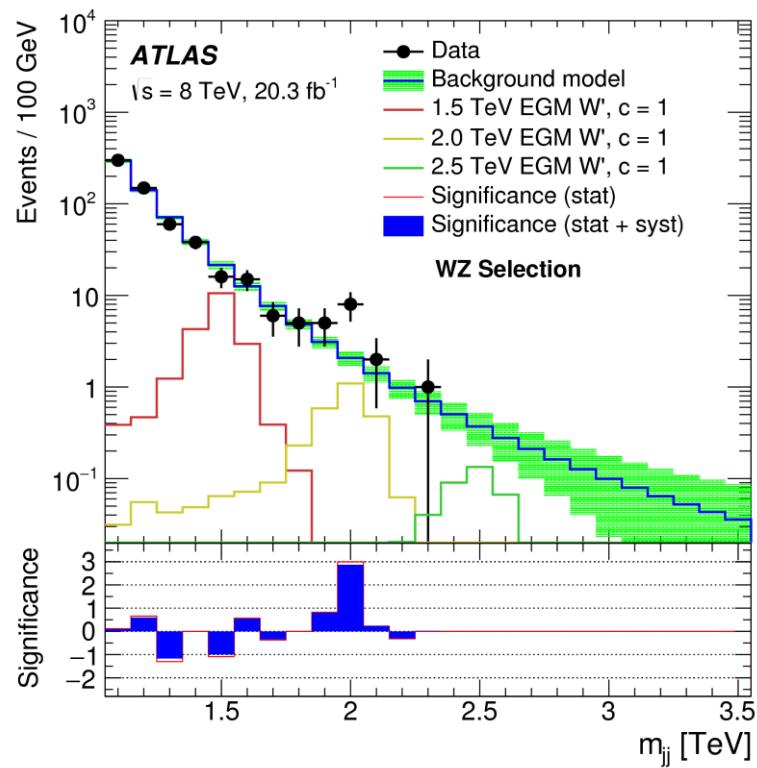
$P_{Z>W \cdot \epsilon_{V\text{-tag}}}$

vs

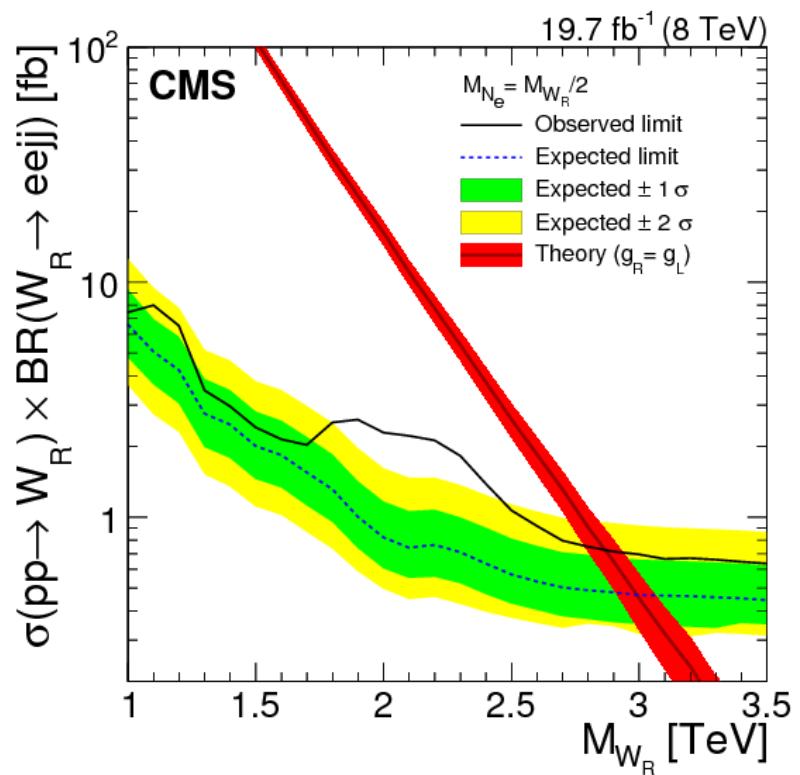
$$\epsilon_{V\text{-tag}} \cdot [(1 - \epsilon_{V\text{-tag}}) + P_{Z>W} \epsilon_{V\text{-tag}}]$$

Ordering matters!

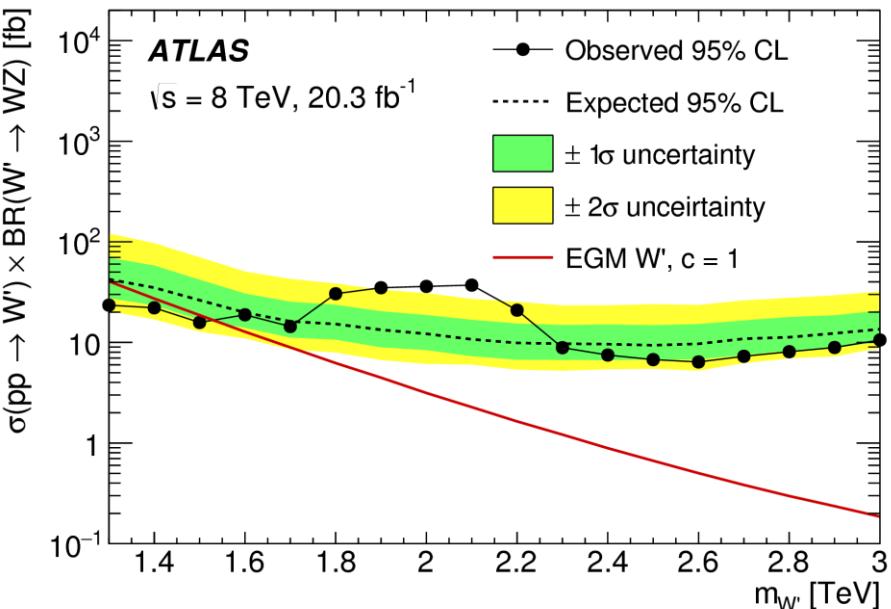
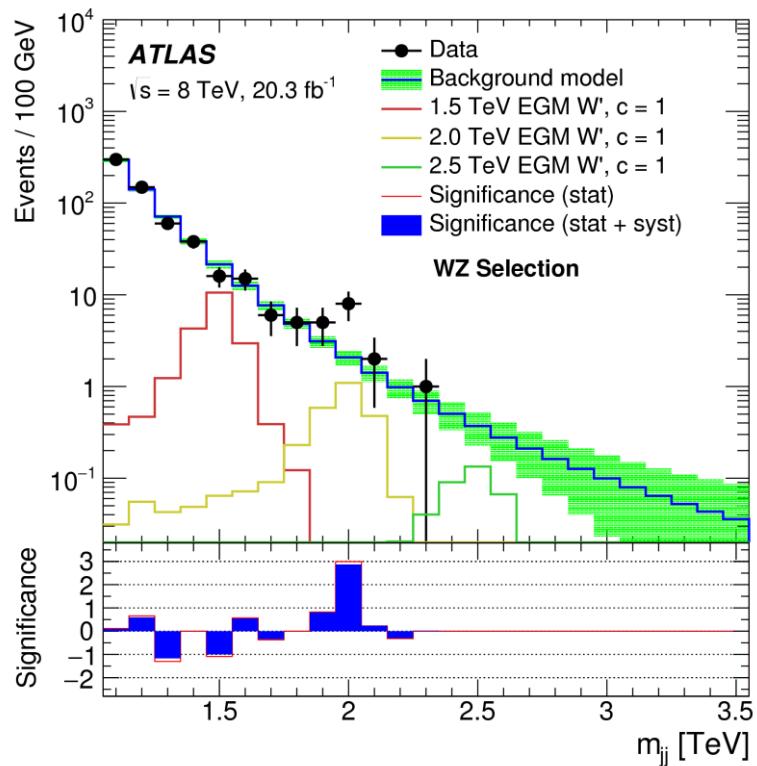
2 TeV (run 1)



2 TeV (run 1)

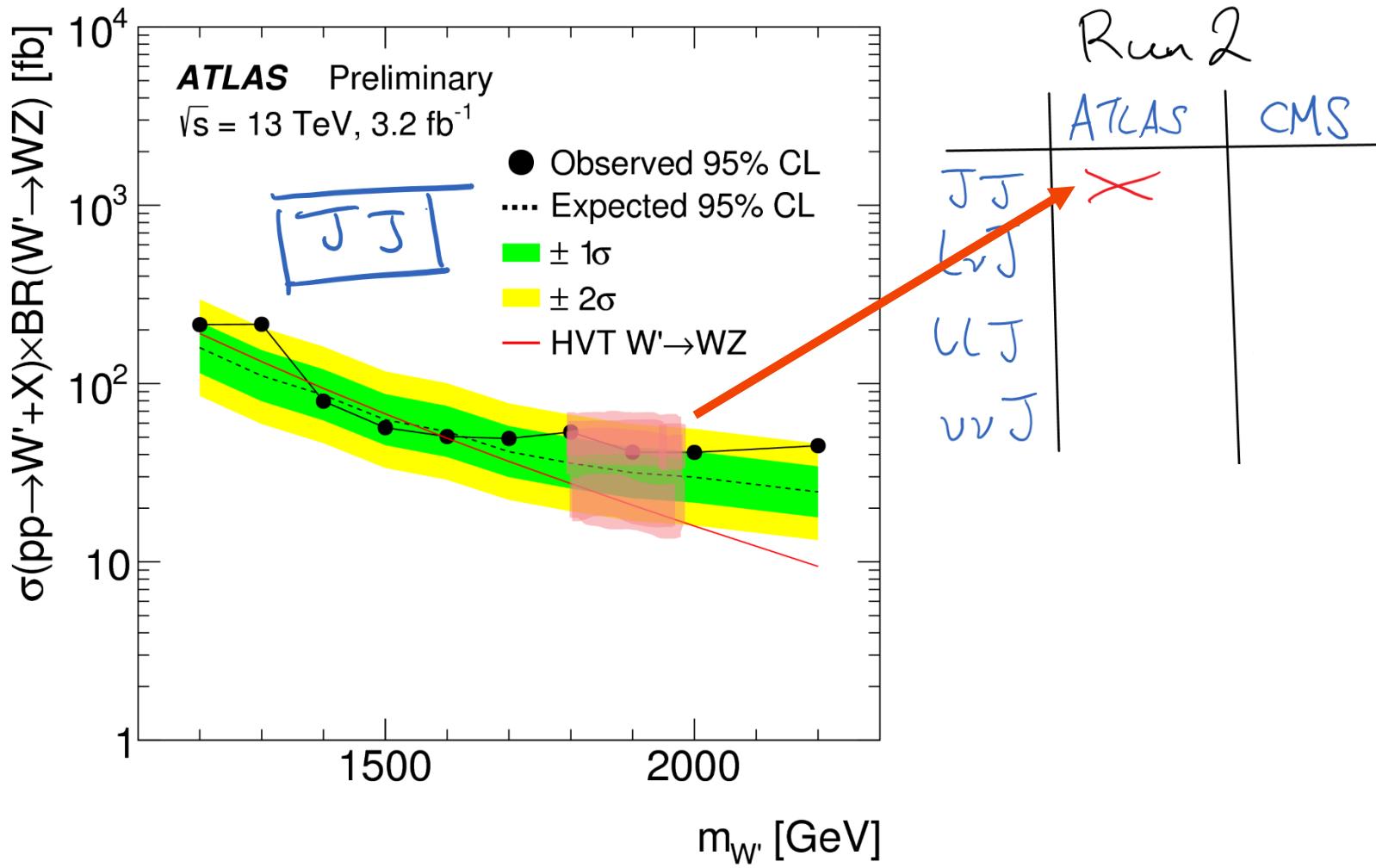


2 TeV (run 1)

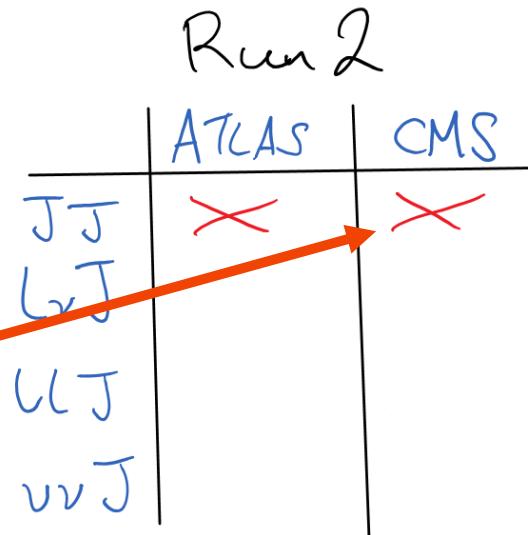
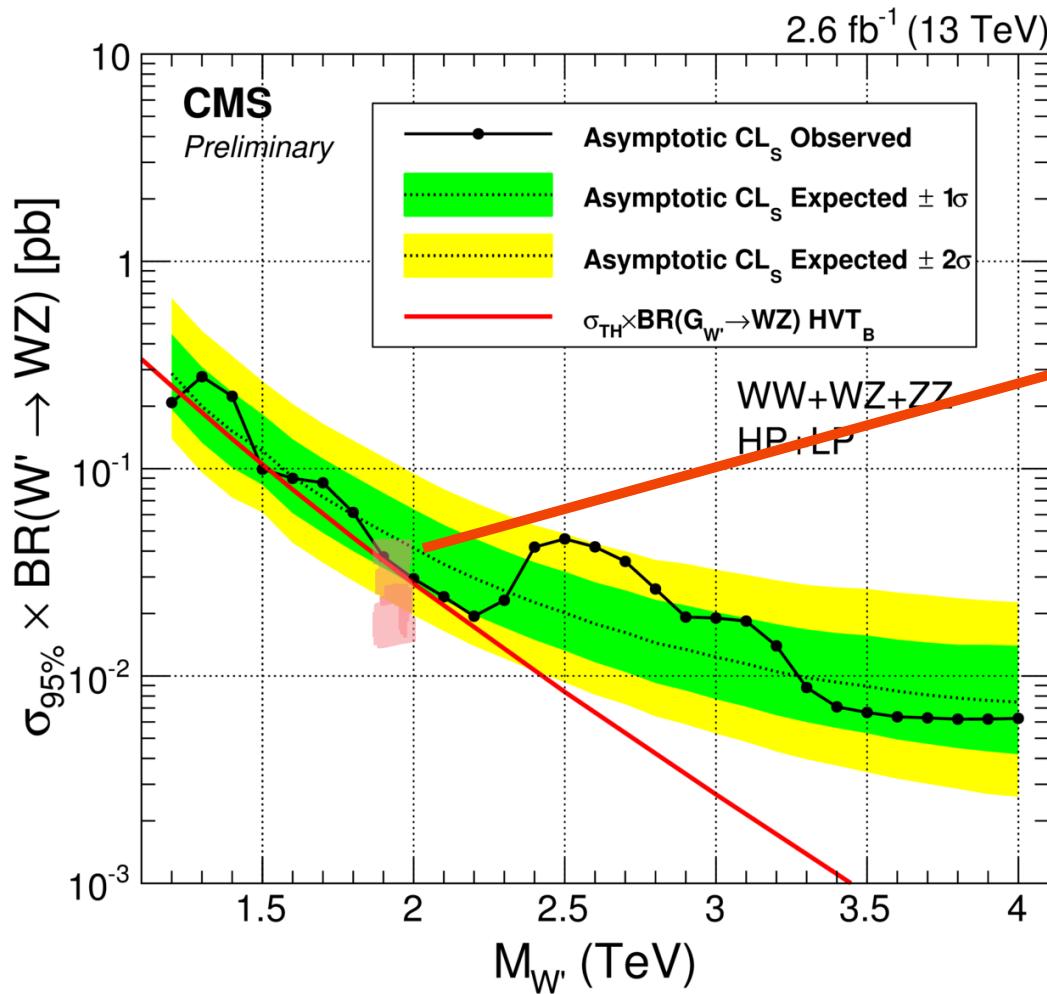


	ATLAS	CMS
JJ	3 σ	2 σ
L ν J	✓	✓
LLJ	✓	2 σ

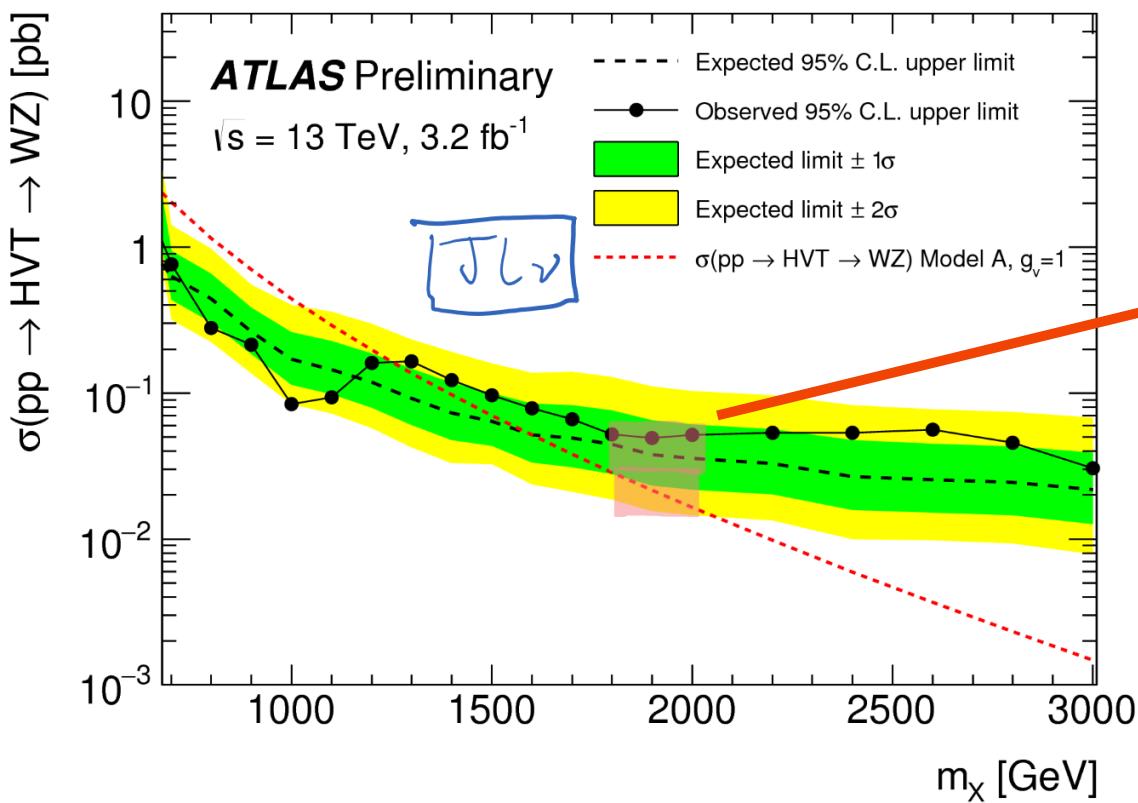
2 TeV (run 2, December 2015)



2 TeV (run 2, December 2015)



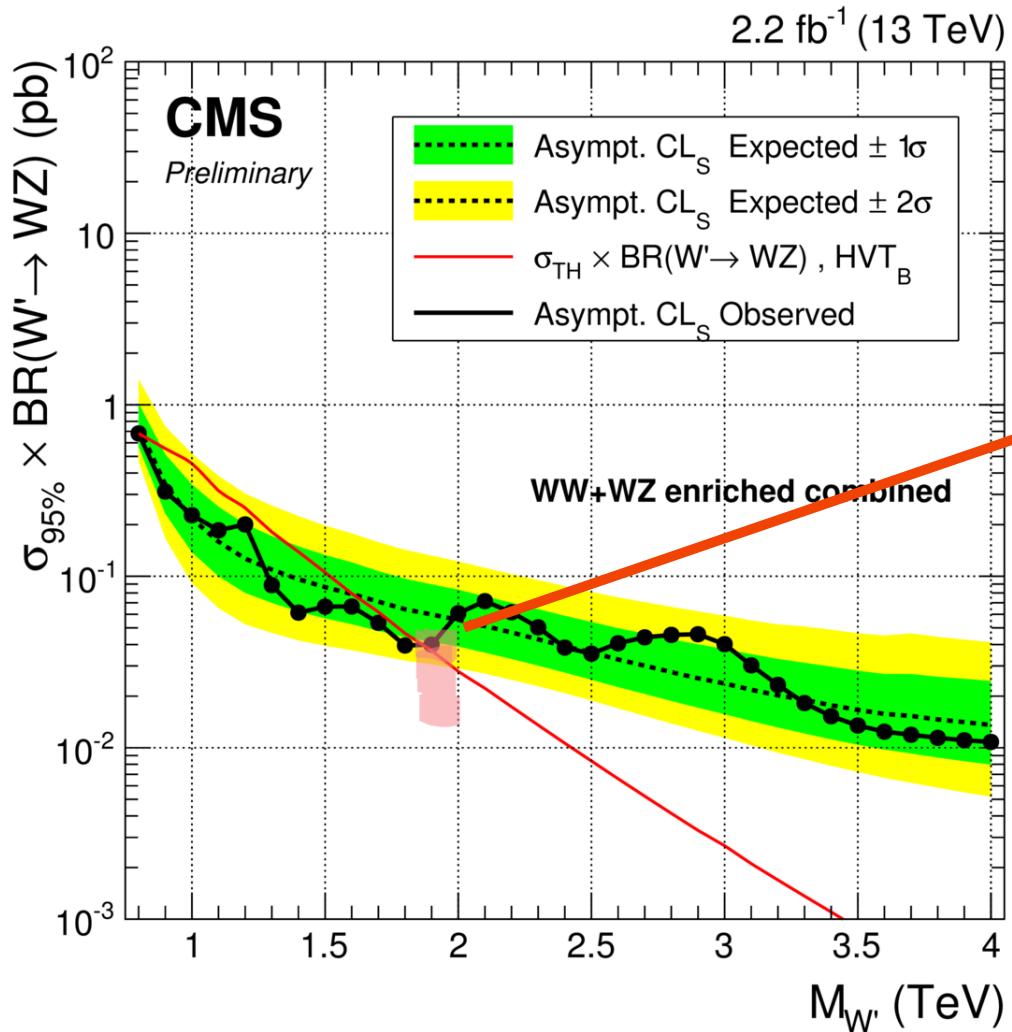
2 TeV (run 2, December 2015)



Run 2

	ATLAS	CMS
JJ	✗	✗
L _v J	✗	✗
LLJ		
vvJ		

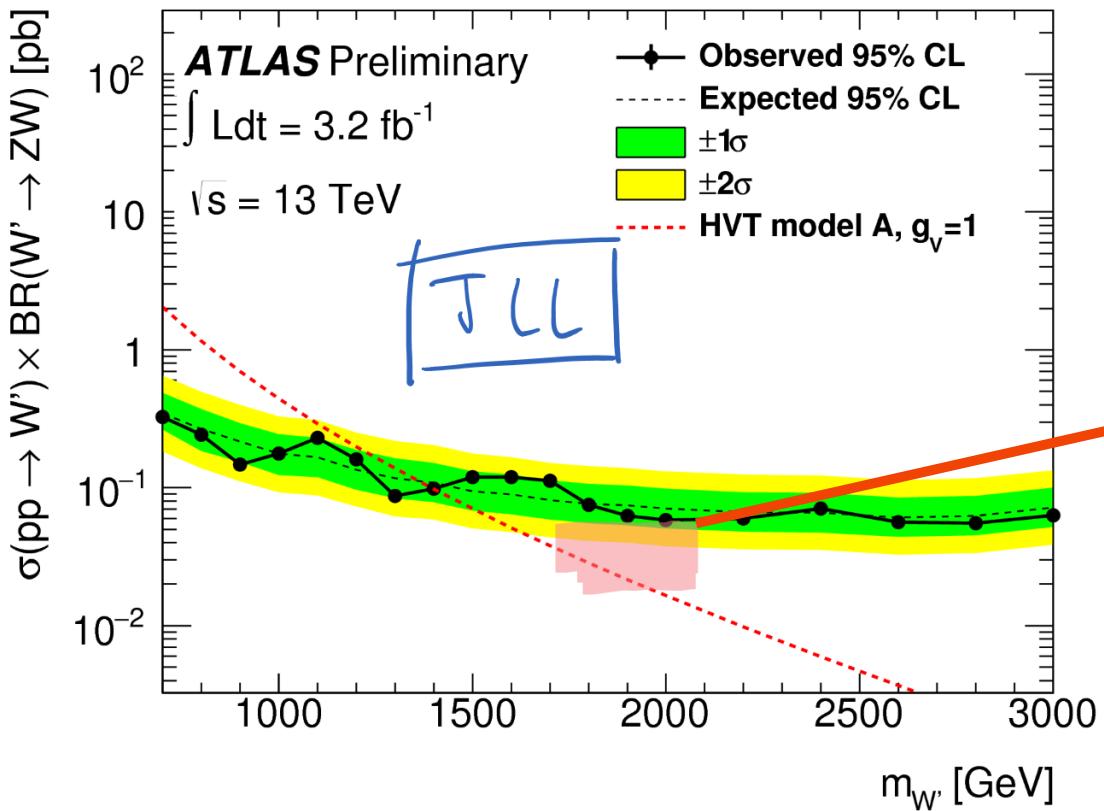
2 TeV (run 2, December 2015)



Run 2

	ATLAS	CMS
JJ	✗	✗
L ν J	✗	✗
L $\bar{\nu}$ J		
$\nu\nu J$		

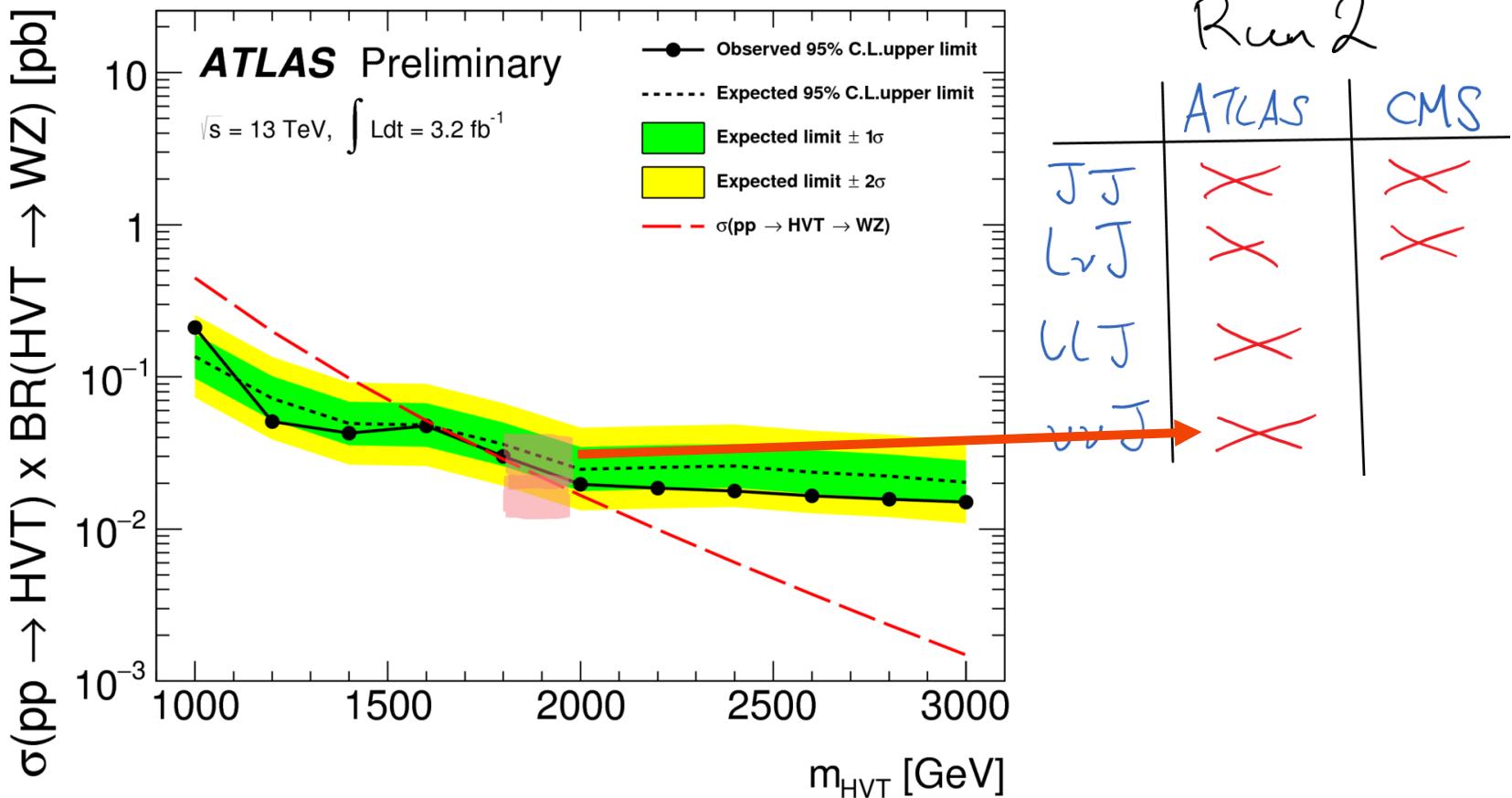
2 TeV (run 2, December 2015)



Run 2

	ATLAS	CMS
JJ	✗	✗
L _v J	✗	✗
U _v J	✗	✗
UJ	→	
vvJ		

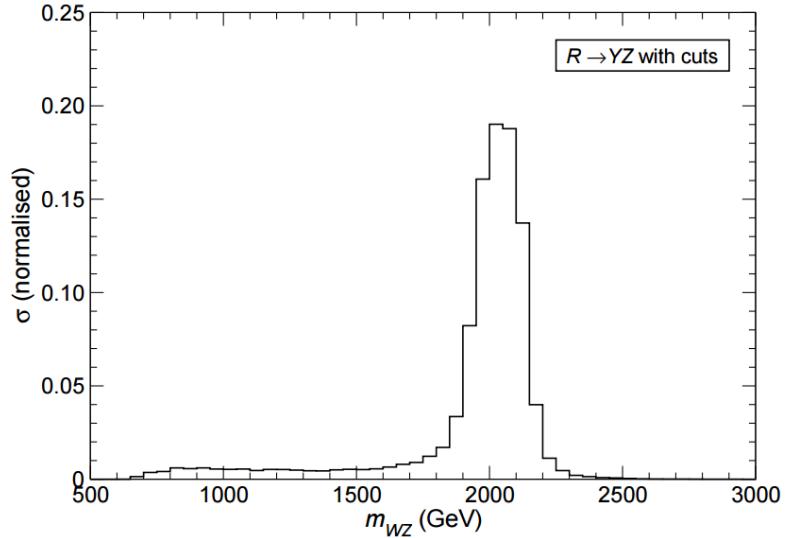
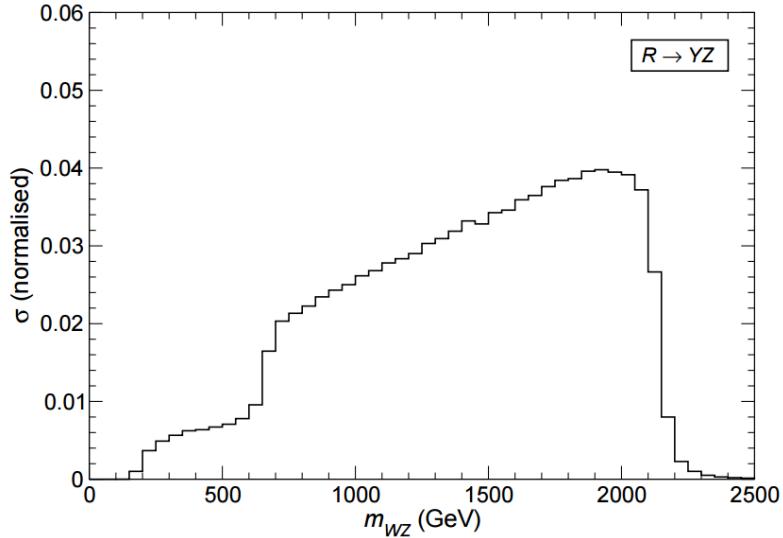
2 TeV (run 2, December 2015)



2 TeV (run 2, December 2015)

	Run 1		Run 2	
	ATLAS	CMS	ATLAS	CMS
JJ	3σ	2σ	JJ	✗
LvJ	✗	✗	LvJ	✗
LLJ	✗	2σ	LLJ	✗
			vvJ	✗

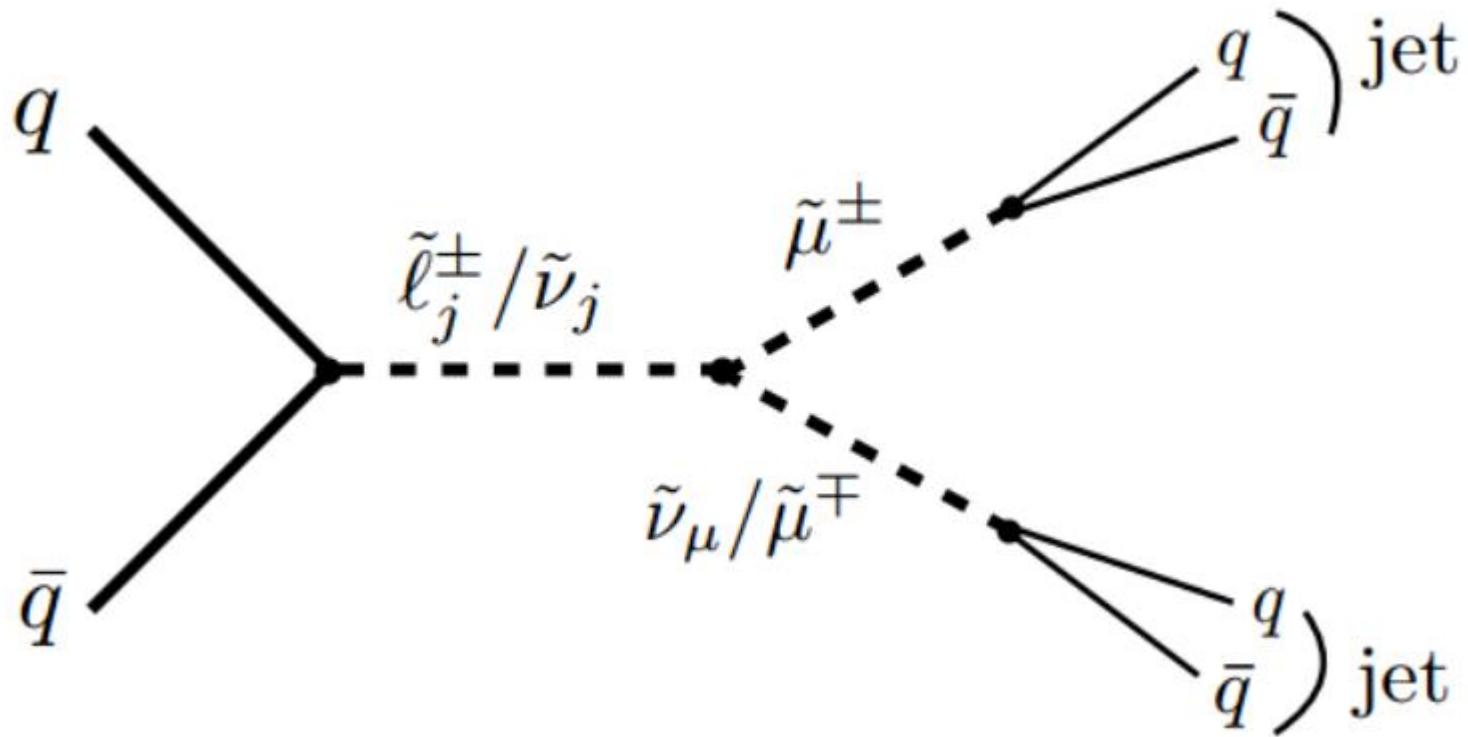
Tribosons for the 2 TeV JJ bump



$$\frac{p_{T1} - p_{T2}}{p_{T1} + p_{T2}} < 0.15$$

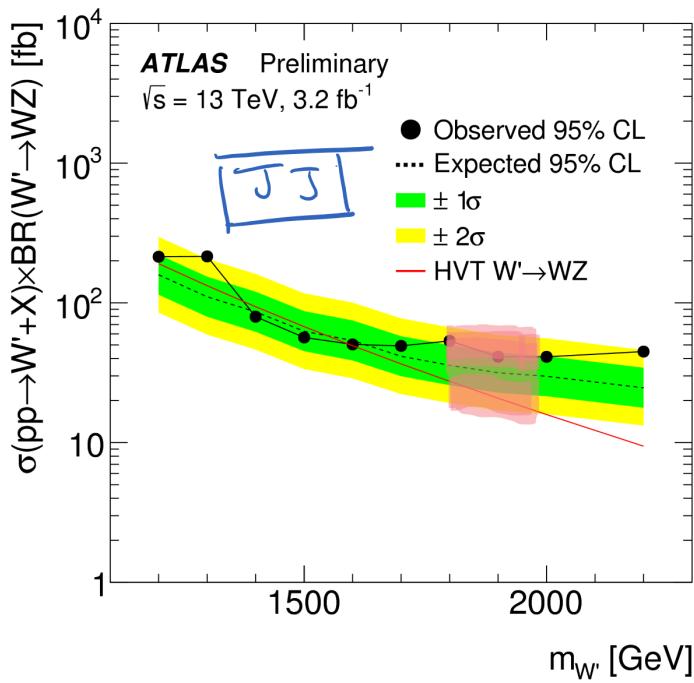
J. A. Aguilar-Saavedra, arXiv:1506.06739

Another idea for the 2 TeV JJ bump

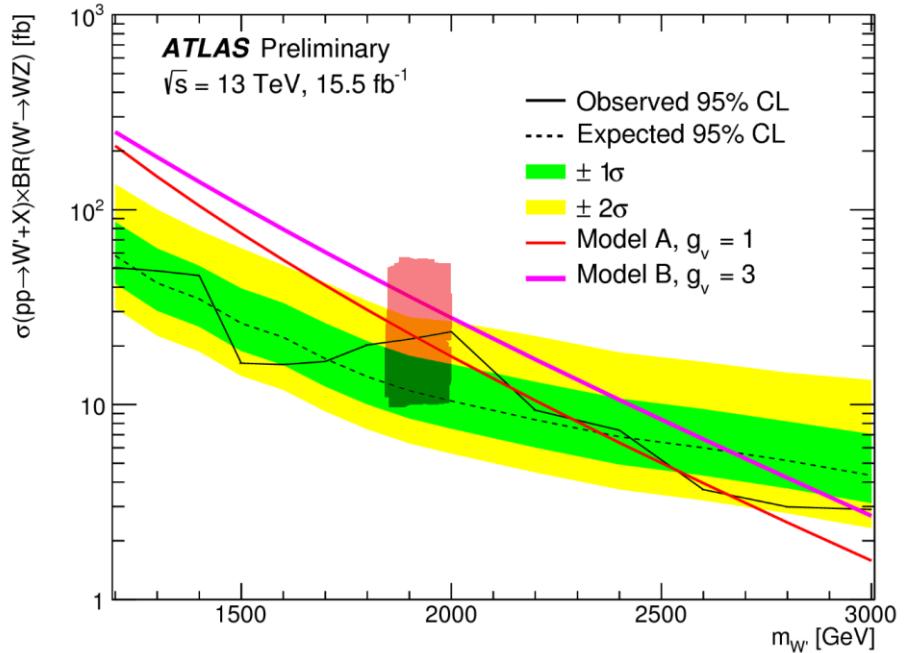


Fully hadronic 2 TeV data (2016)

Dec 2015

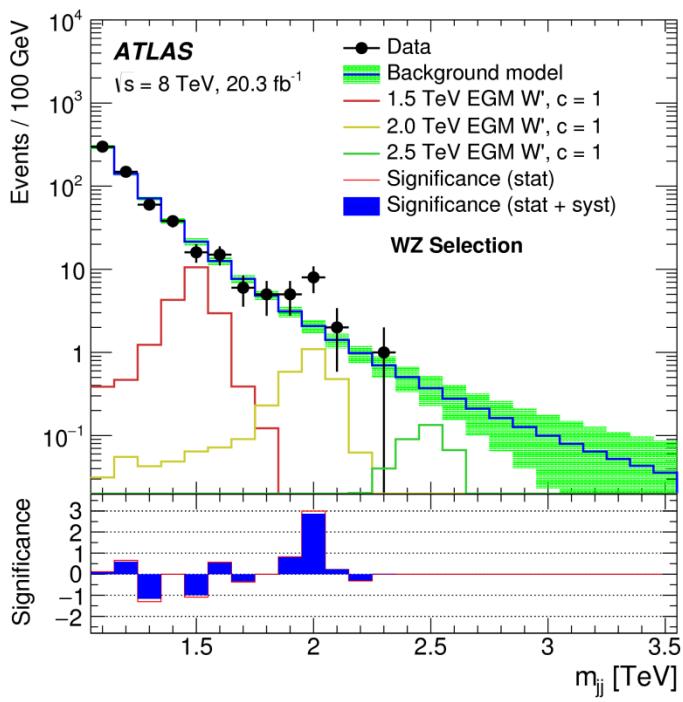


August 2016

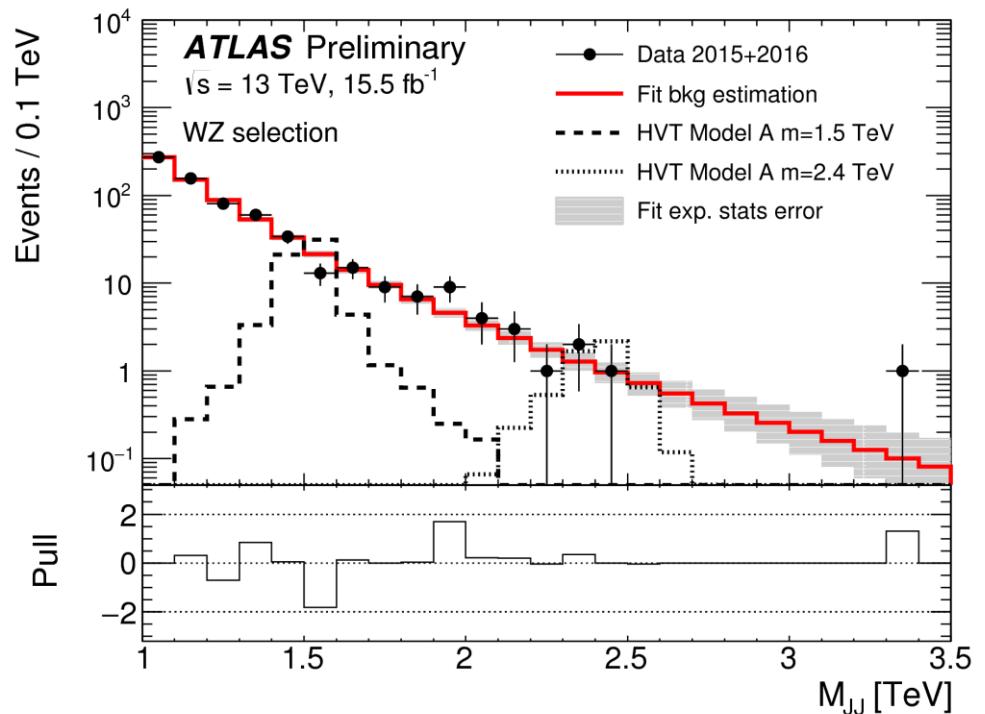


Fully hadronic 2 TeV data (2016)

Run 1

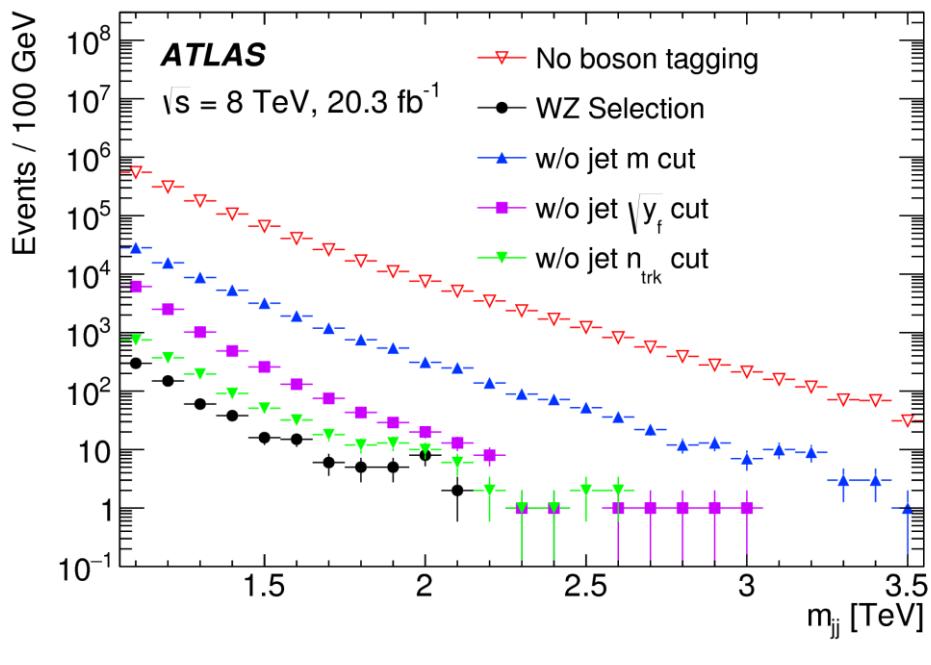


Run 2 (15.5/fb)

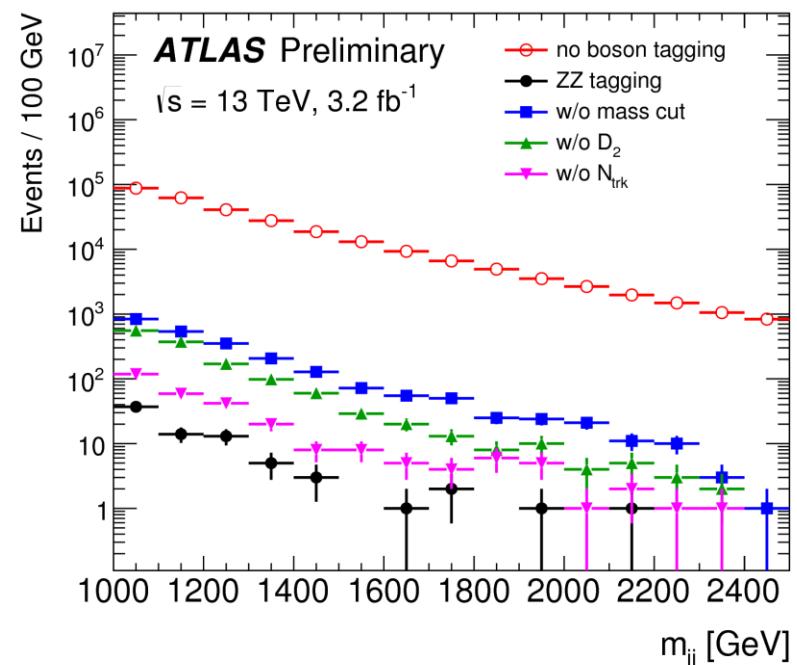


Fully hadronic 2 TeV data (N_{track})

Run 1



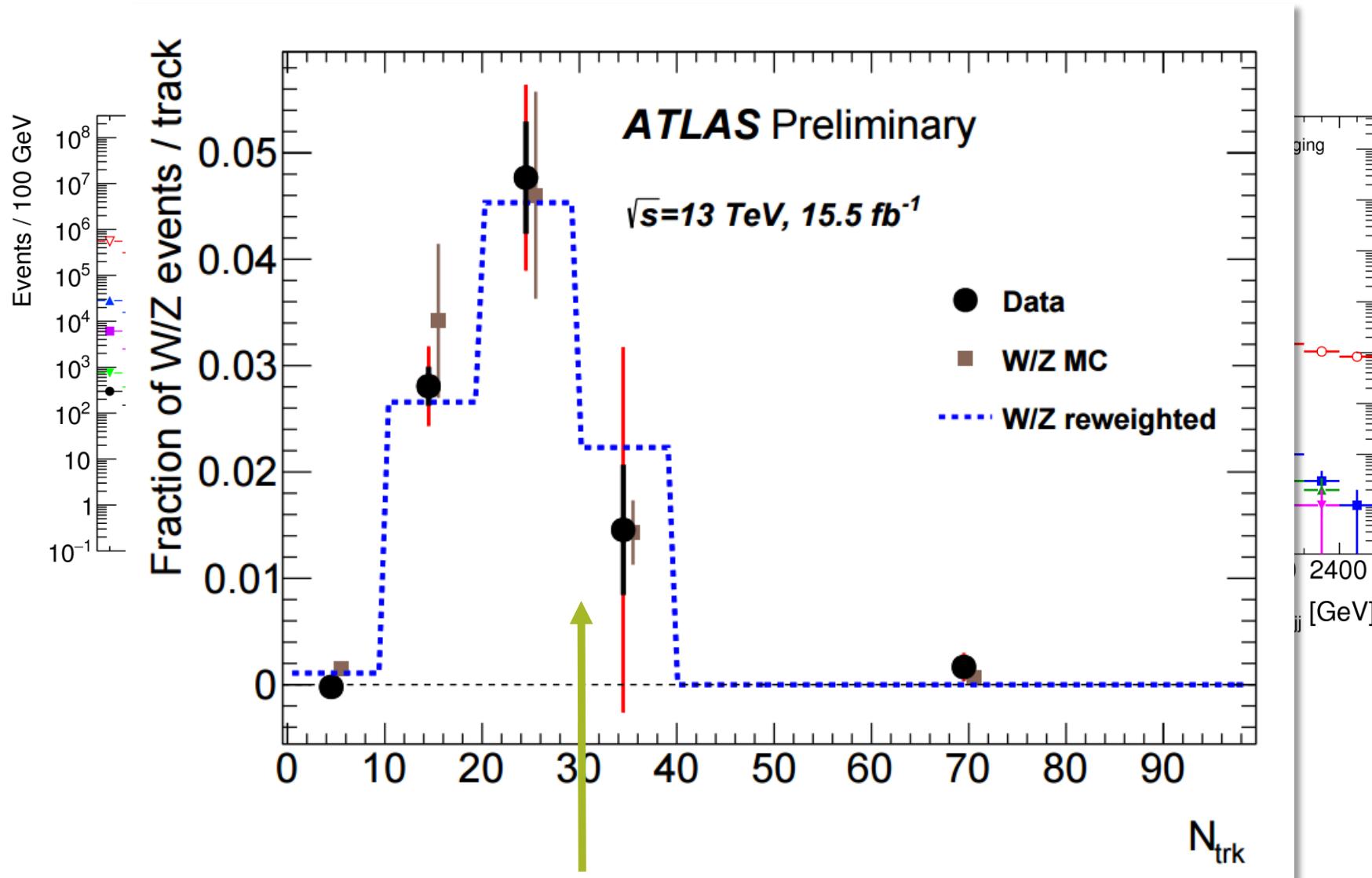
Run 2 (3.2/fb)



Run 2 (15/fb)

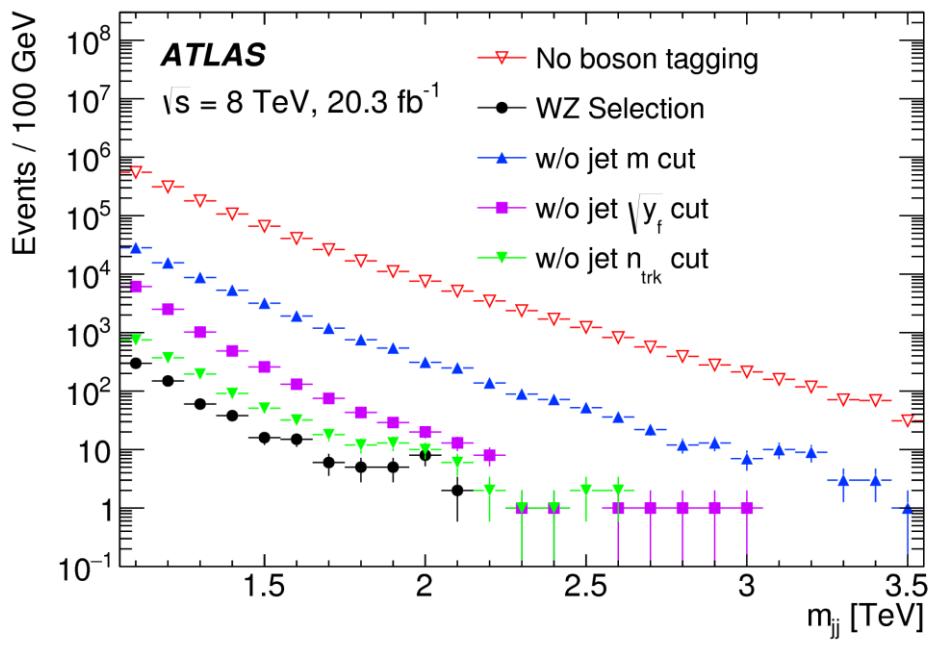
????

Fully hadronic 2 TeV data (N_{track})

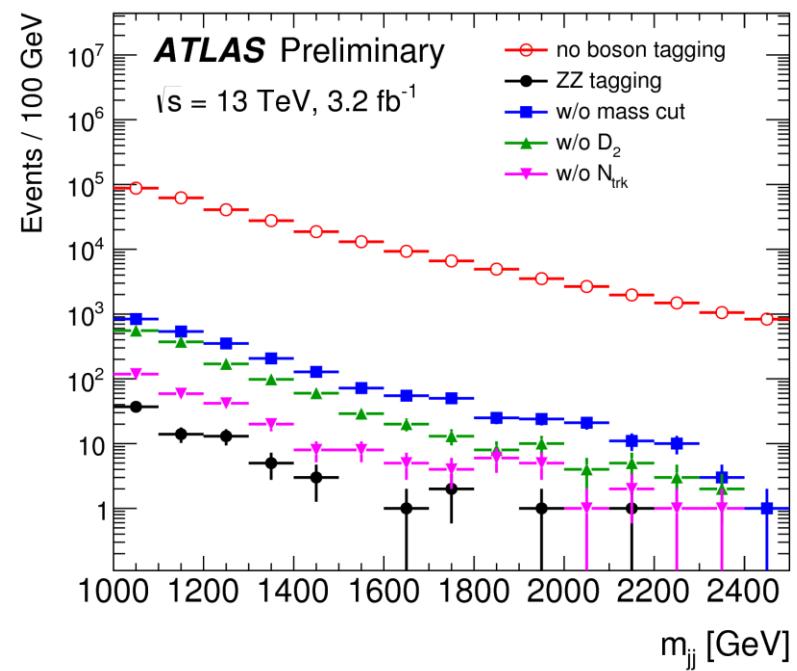


Fully hadronic 2 TeV data (N_{track})

Run 1



Run 2 (3.2/fb)



Run 2 (15/fb)

????

Summary

- Boosted vector boson searches are young and immature, there is scope for exploring their potential to discover BSM physics
- The diboson resonance program is reaching maturity, but there are well motivated BSM models whose first signature would be a collection of confusing and seemingly contradictory anomalies in with the character of statistical fluctuations.
- This motivates an exploration for a broader extension of the search for new physics in boosted bosons.
- In the meantime, there are some curious anomalies that can provide cheap entertainment.