

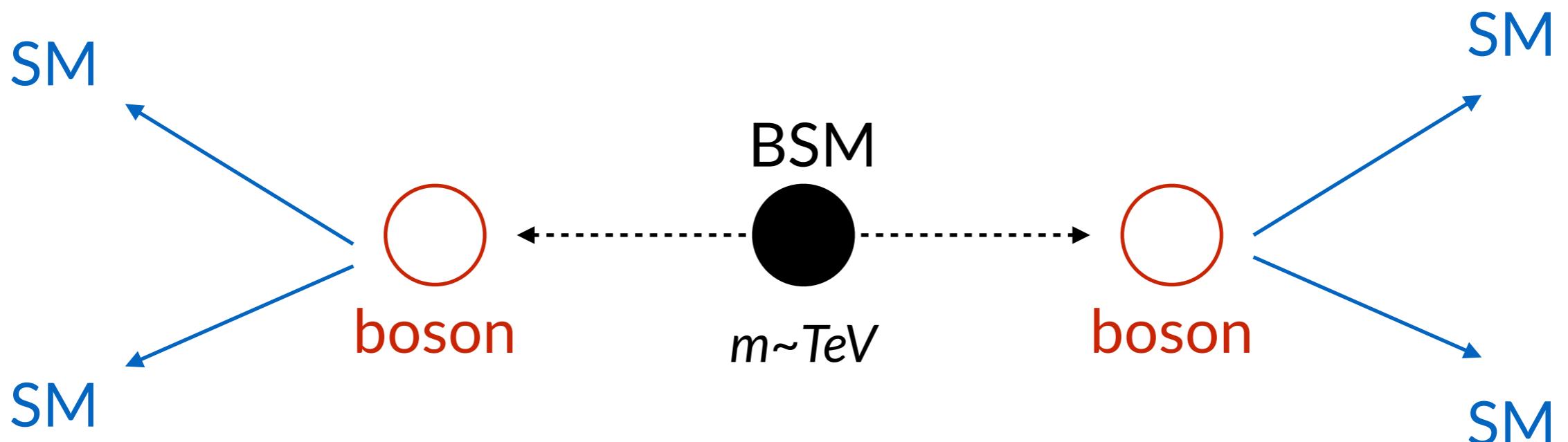
DIBOSON RESONANCE SEARCHES AT ATLAS

Run-1 results

Valerio Ippolito
Harvard University
on behalf of the ATLAS collaboration

WHY?

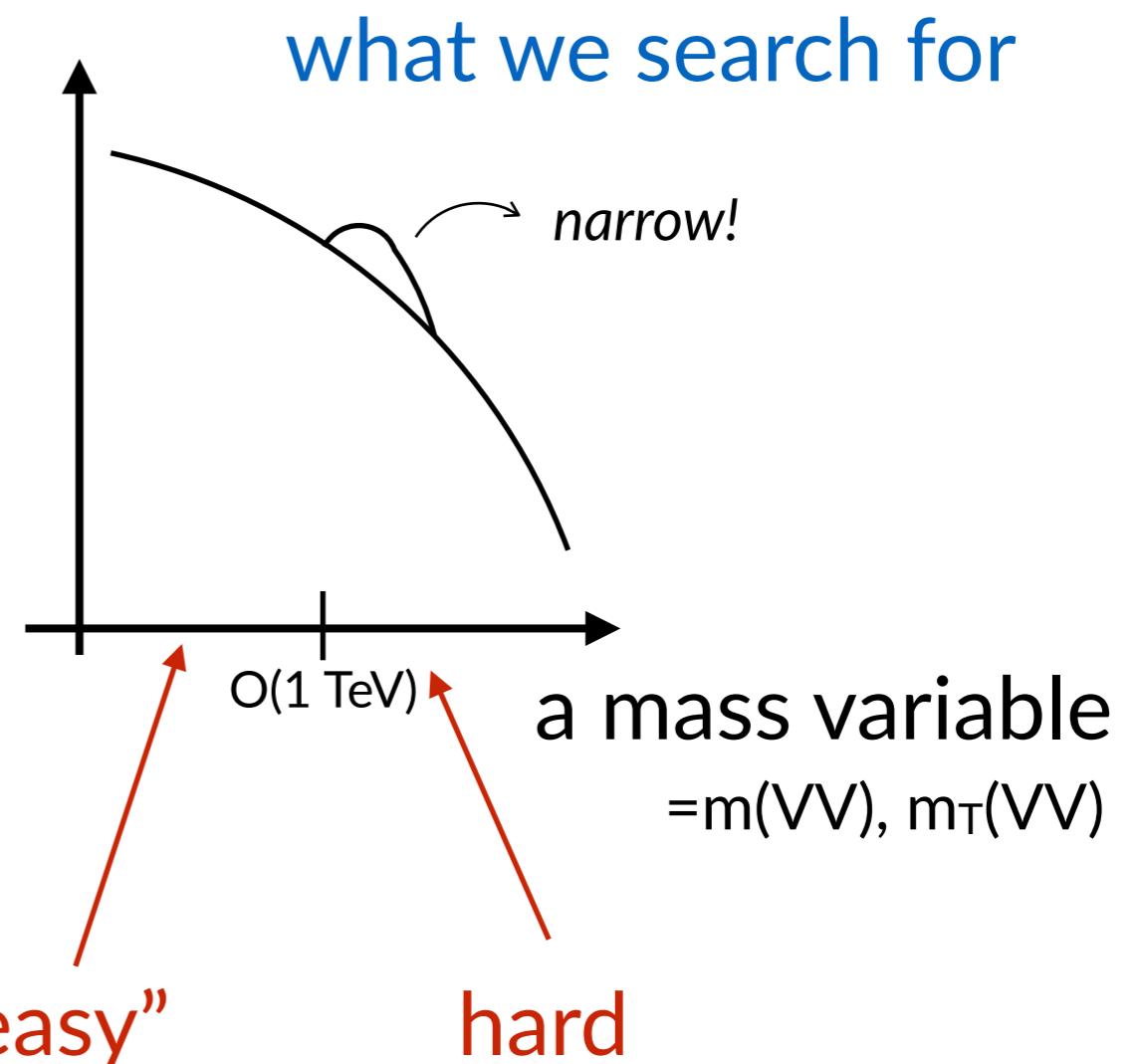
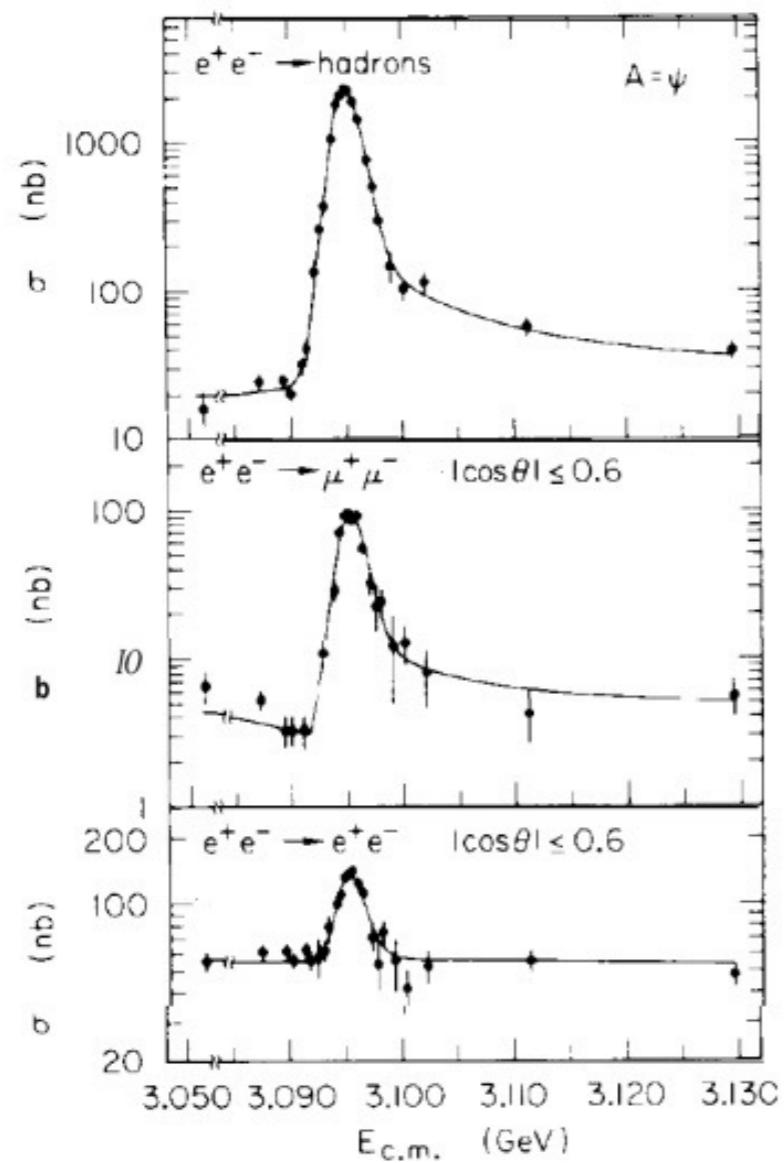
look for new physics



- predicted by many SM extensions
- clean final states
 - ▶ but probing high- m is challenging!

EXPECTATIONS

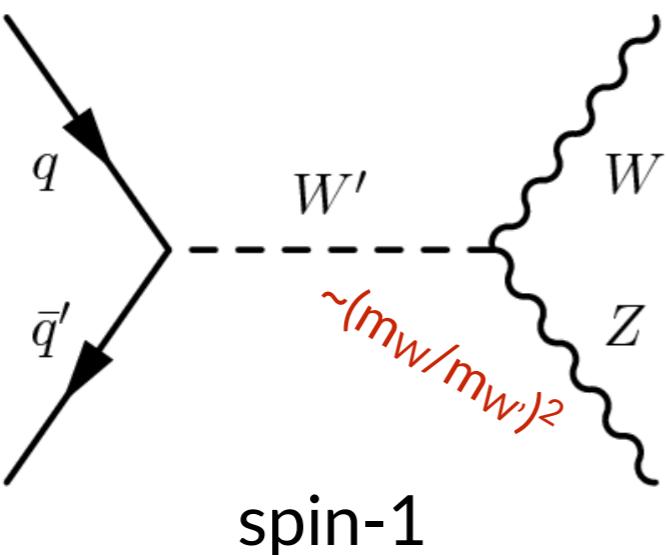
what we dream



BENCHMARK MODELS

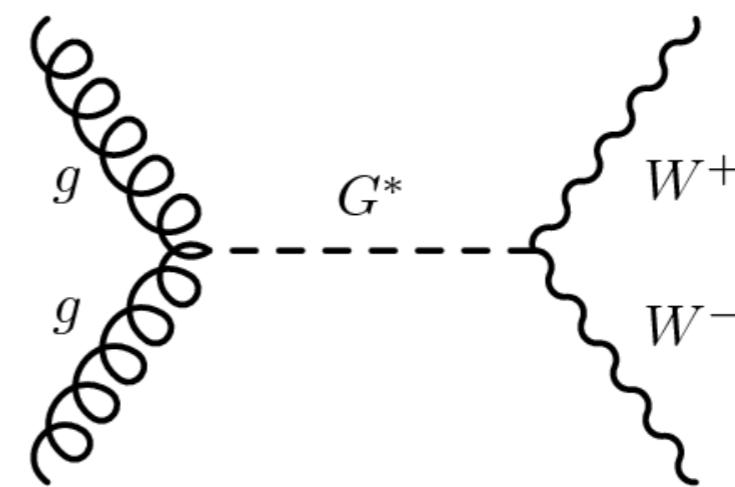
main models used for Run-1

Extended Gauge Model



@ $m=1\text{TeV}$: $\text{BR}(W' \rightarrow WW/ZZ) \sim 1.3\%$

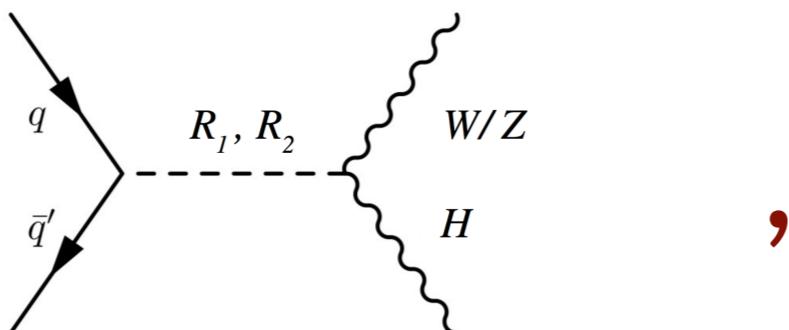
Bulk Randall-Sundrum



spin-2

$\text{BR}(W' \rightarrow WW/ZZ) \sim 20/10\%$

Minimal Walking Technicolour



Heavy Vector Triplet

arXiv:1402.4431

- heavy vector
- couplings gv_{CH} and $(g^2gv)_{\text{CF}}$
- model A: comparable W and Z couplings
- model B: fermionic coupling = 0 (à la composite Higgs)

+

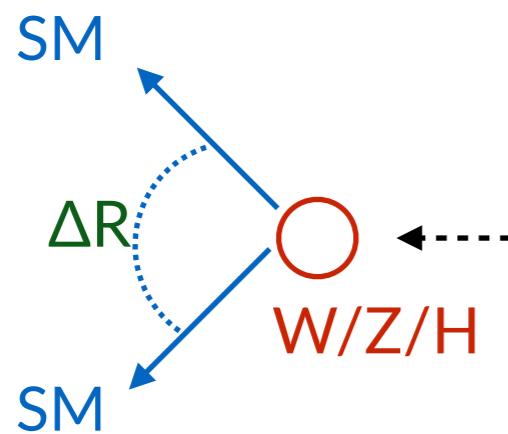
HIGH-MASS IS A CHALLENGE!

* clean or dirty?

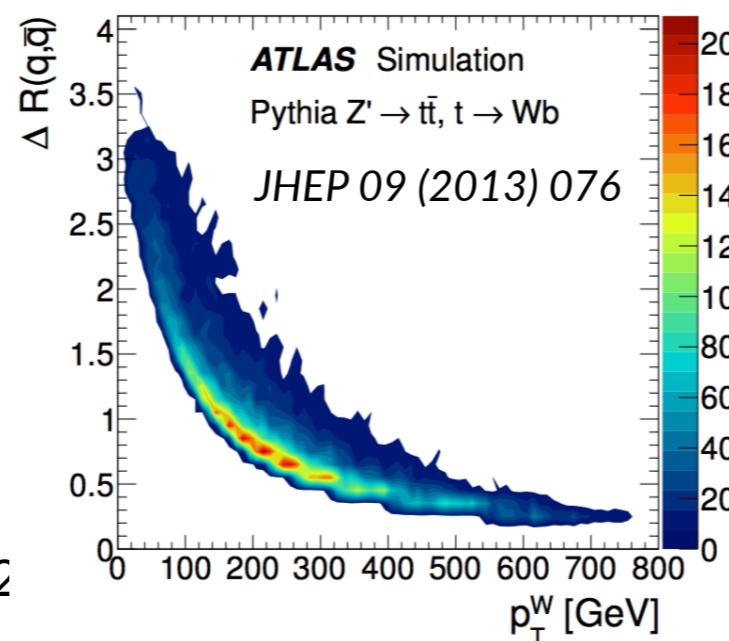
- lepton decays: clean, low BR
- hadronic decays: delicate, higher BR, gives access to H(bb)

	mass	leptonic	hadronic
W	~80 GeV	33%	67%
Z	~91 GeV	20% (vv) 10% (ll)	70%
H	~125 GeV	hopeless	57% (bb)

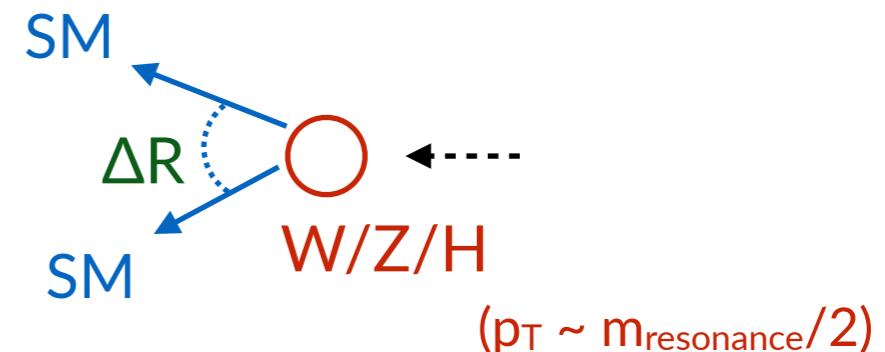
* low resonance mass



$\Delta R \sim 2m_V/p_T$



high resonance mass



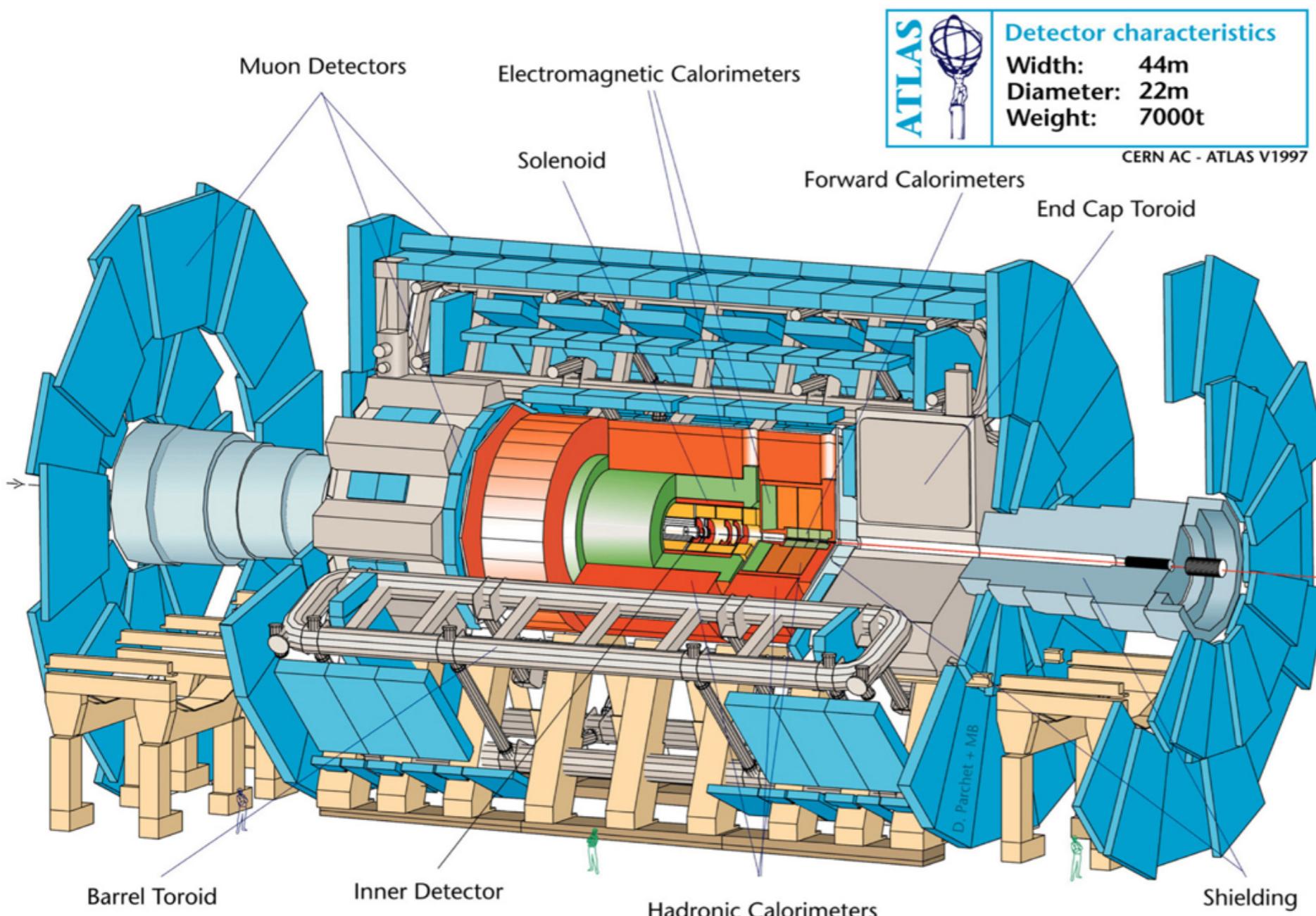
- jet reconstruction $\sim R!$
- lepton isolation $\sim R!$

ATLAS SEARCHES IN RUN-1

final state	channel	reference
lvll	WZ	Physics Letters B 737 (2014) 223–243
llqq	ZZ/ZW	Eur. Phys. J. C (2015) 75:69
lvqq	WZ/WW	Eur. Phys. J. C (2015) 75:370
qqqq	WZ/WW/ZZ	arXiv:1506.00962 (accepted by JHEP)
combination	WZ/WW/ZZ	ATLAS-CONF-2015-045
vvbb/lvbb/lbb	VH	Eur. Phys. J. C (2015) 75:263
bbbb	HH	Eur. Phys. J. C (2015) 75:412
lvγ, llγ	$W\gamma, Z\gamma$	Physics Letters B 738 (2014) 428–447
$\gamma\gamma bb$	HH	Phys. Rev. Lett. 144, 081802
llll/lvvv/lqqq/vvqq	H->ZZ	arXiv:1507.05930

→ not in this talk

THE INSTRUMENT



[ID]
 $B = 2 \text{ T}$, up to $|\eta| < 2.5$
 $\sigma/p_T \sim 3.4 \times 10^{-4} p_T + 0.015$

[ECAL]
up to $|\eta| < 3.2$
 $\sigma/E \sim 10\%/\sqrt{E} + 1\div3\%$
 $\Delta\eta \times \Delta\Phi \sim 0.025 \times 0.025$
 $\sigma(\eta) \sim 40 \text{ mrad}/[E \text{ in GeV}]$

[HCAL]
up to $|\eta| < 3.2$ (FCAL: 4.9)
 $\sigma/E \sim 50\%/\sqrt{E} + 0.03$
 $\Delta\eta \times \Delta\Phi = 0.1 \times 0.1 \text{ for } (|\eta| < 2.5)$

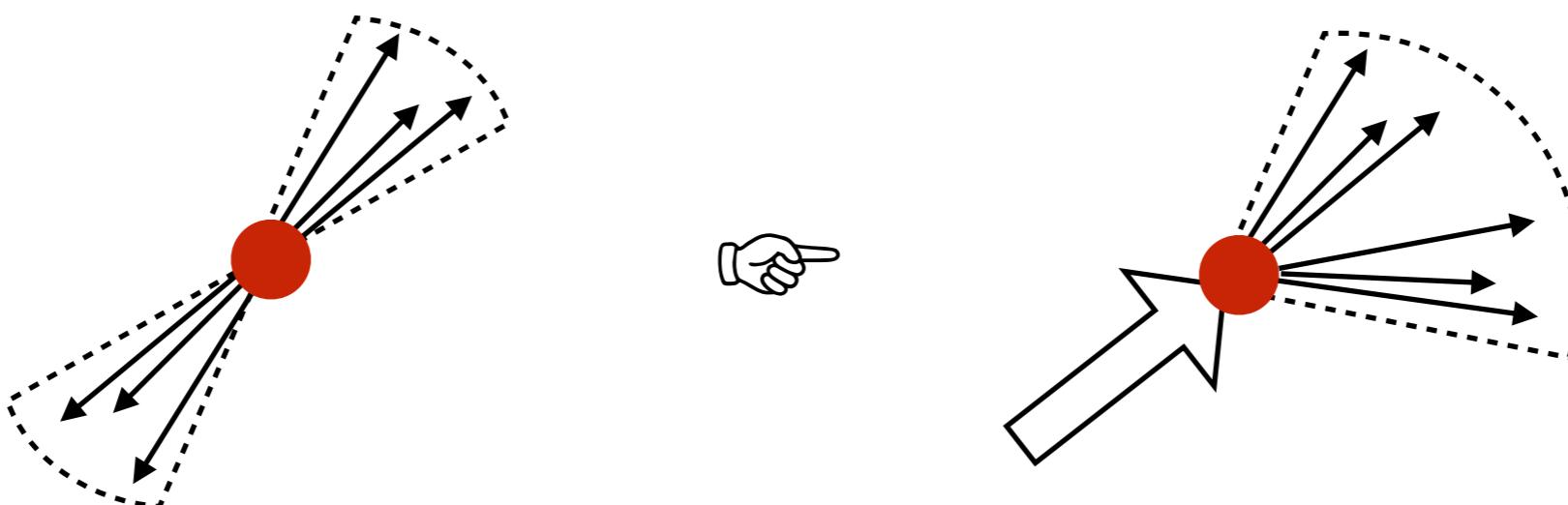
[MS]
up to $|\eta| < 2.7$
 $\sigma/p_T < 10\% \text{ up to } 1 \text{ TeV}$

inner detector (ID) pseudo-rapidity region offers best handles against pile-up and QCD

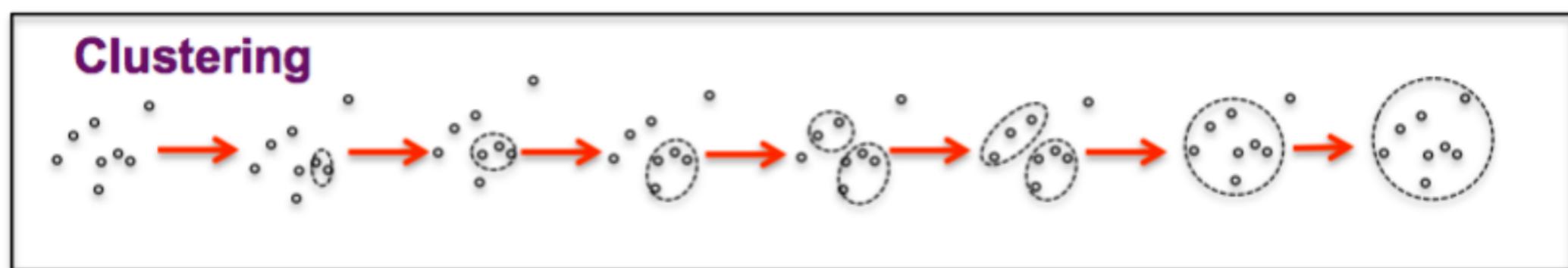
GETTING FAT

* jet reconstruction is based on topological clusters

- anti- k_T algorithm, $R=0.4$ for ordinary, resolved jets
- need different clustering strategy at high- p_T



* boosted jets: Cambridge-Aachen algorithm, $R=1.2$

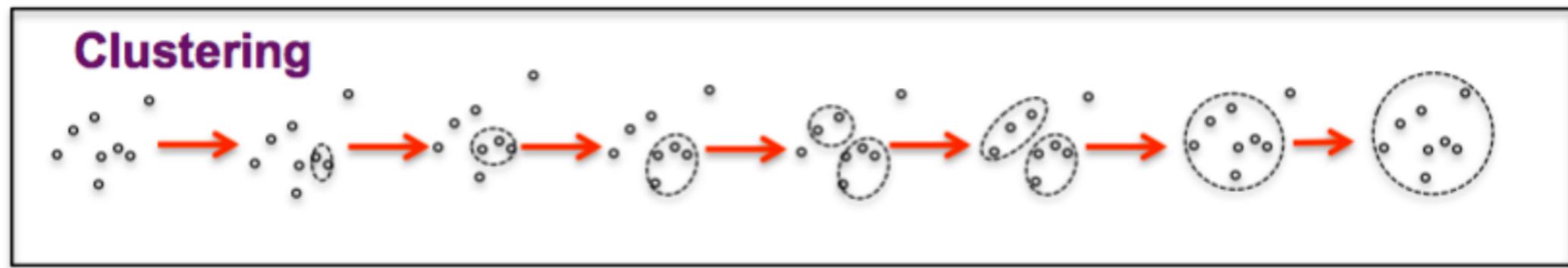


ATL-PHYS-
PUB-2014-004

distance parameter = $\Delta R(j_1, j_2)$

GETTING FAT

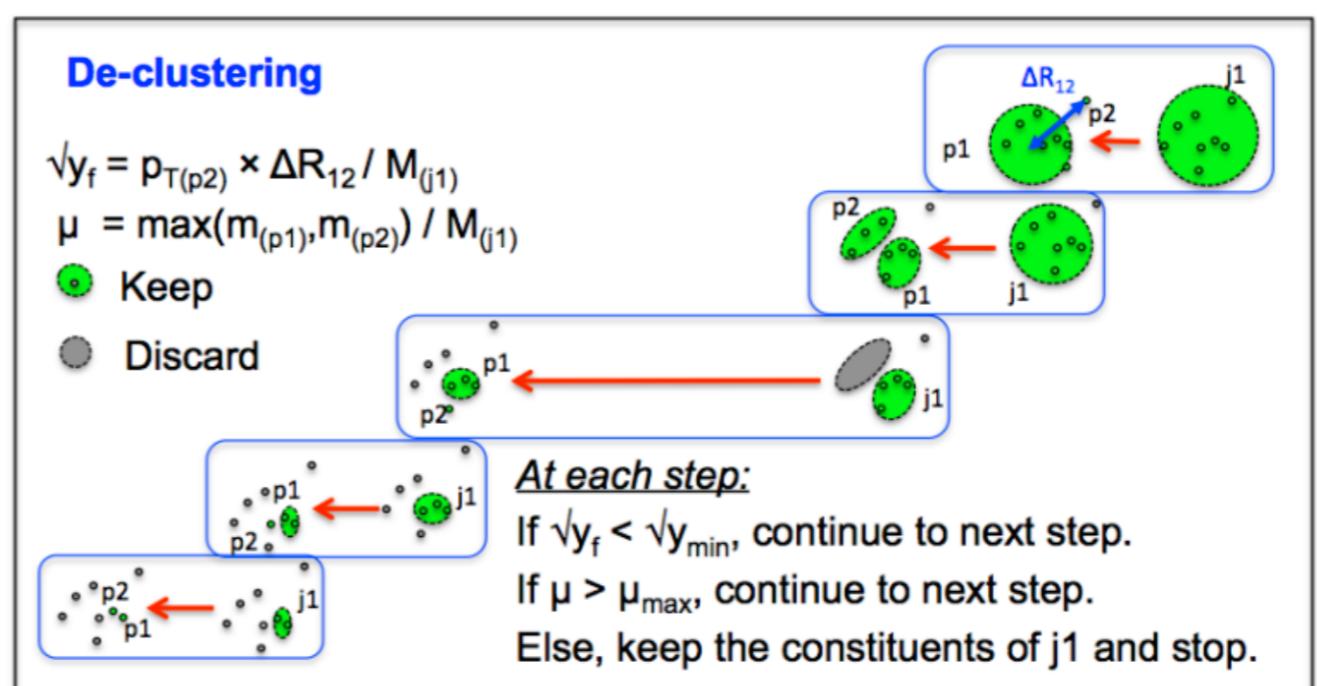
- * boosted jets: Cambridge-Aachen algorithm, $R=1.2$



distance parameter = $\Delta R(j_1, j_2)$

- * iteratively declustered into two symmetric smaller jets, and “groomed”

- BDRS-A splitting, based on $\sqrt{y_f}$ (subjet momentum balance)
- filtering: constituents of the two subjets are reclustered with C/A $R=0.3$, and up to 3 of these are retained
 - remove soft gluon radiation, pile-up



or: anti- k_T $R=1.0$, reclustered with k_T $R=0.3$ and “trimmed” based on subjet p_T fraction

BOSON TAGGING

W, Z, H or multi-jet?  **use substructure information**

clean environment,
~2-prong decays

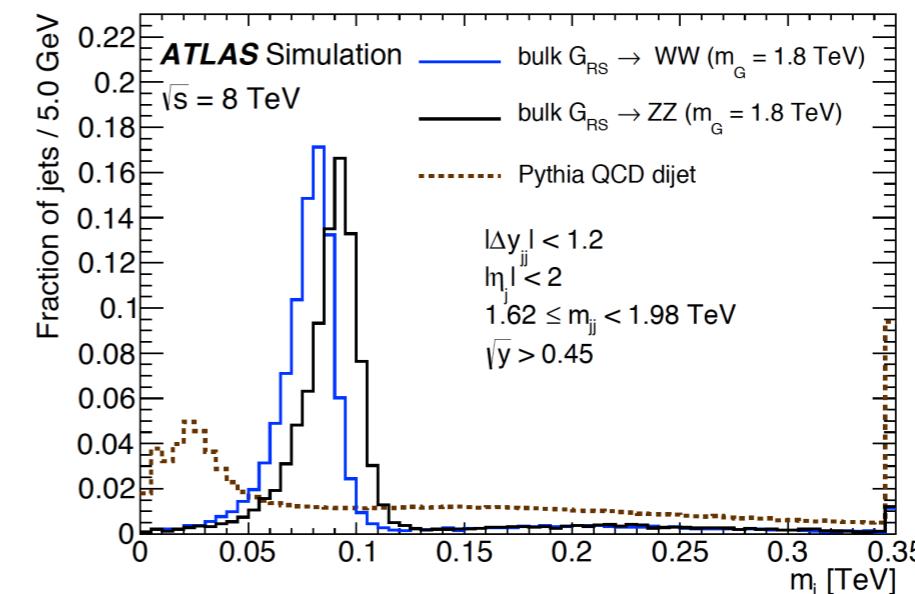
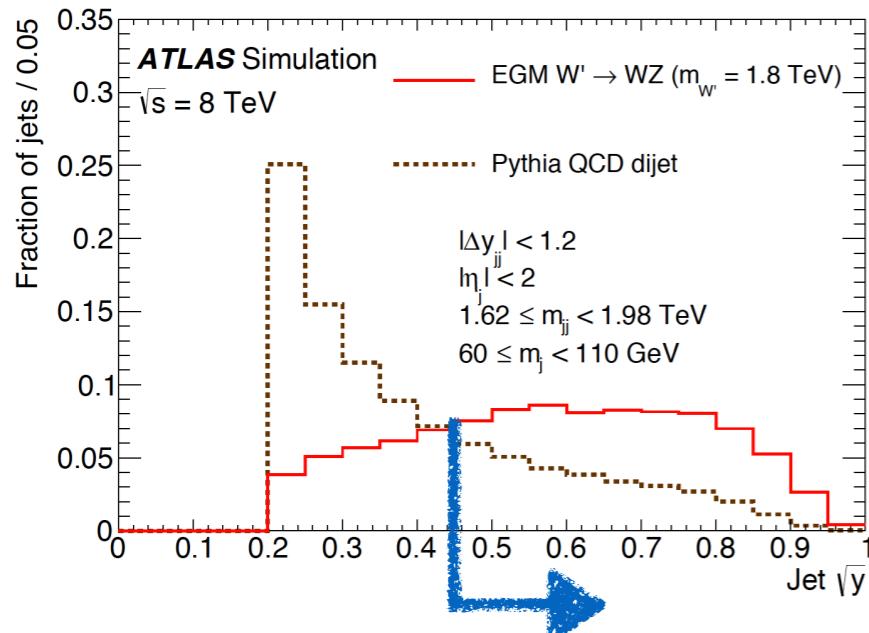
soft and large-angle
gluon radiation

fat-jet mass

w/dedicated calibration

subjet momentum balance

$$\sqrt{y_f} = p_T(j_2) \times \frac{\Delta R(j_1, j_2)}{M(j_1)}$$



charged track multiplicity

inner detector information as a proxy for higher hadronic activity in multi-jet background jets

WHAT ABOUT LEPTONS?

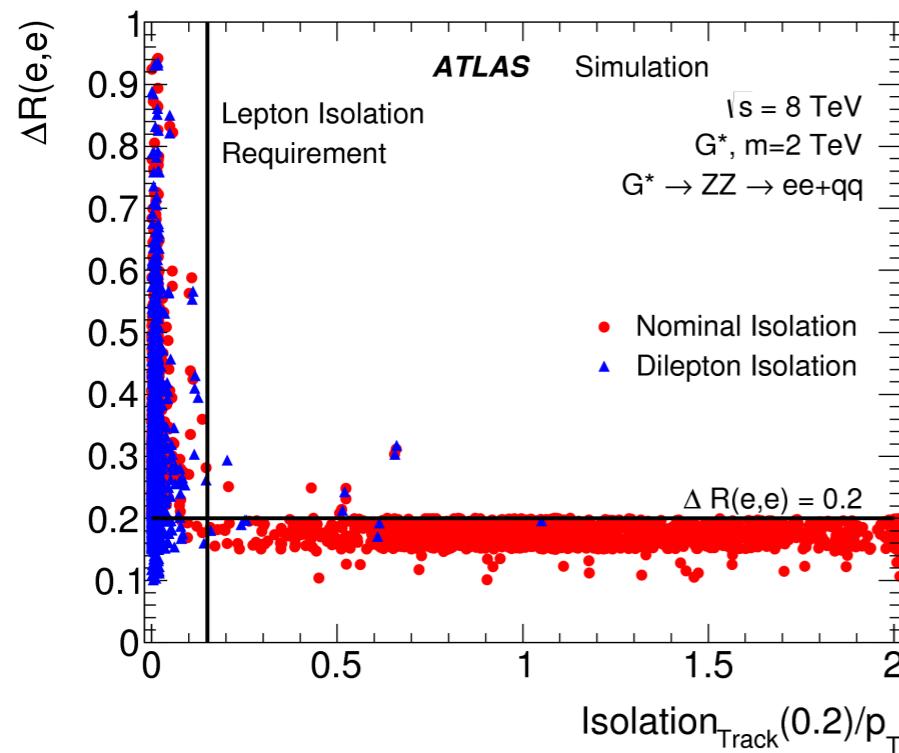
lepton isolation in a cone helps identify leptonic boson decays

- based on ID and ECAL/HCAL information, pile-up rejection
- strategy needs to be adapted to boosted Z decays

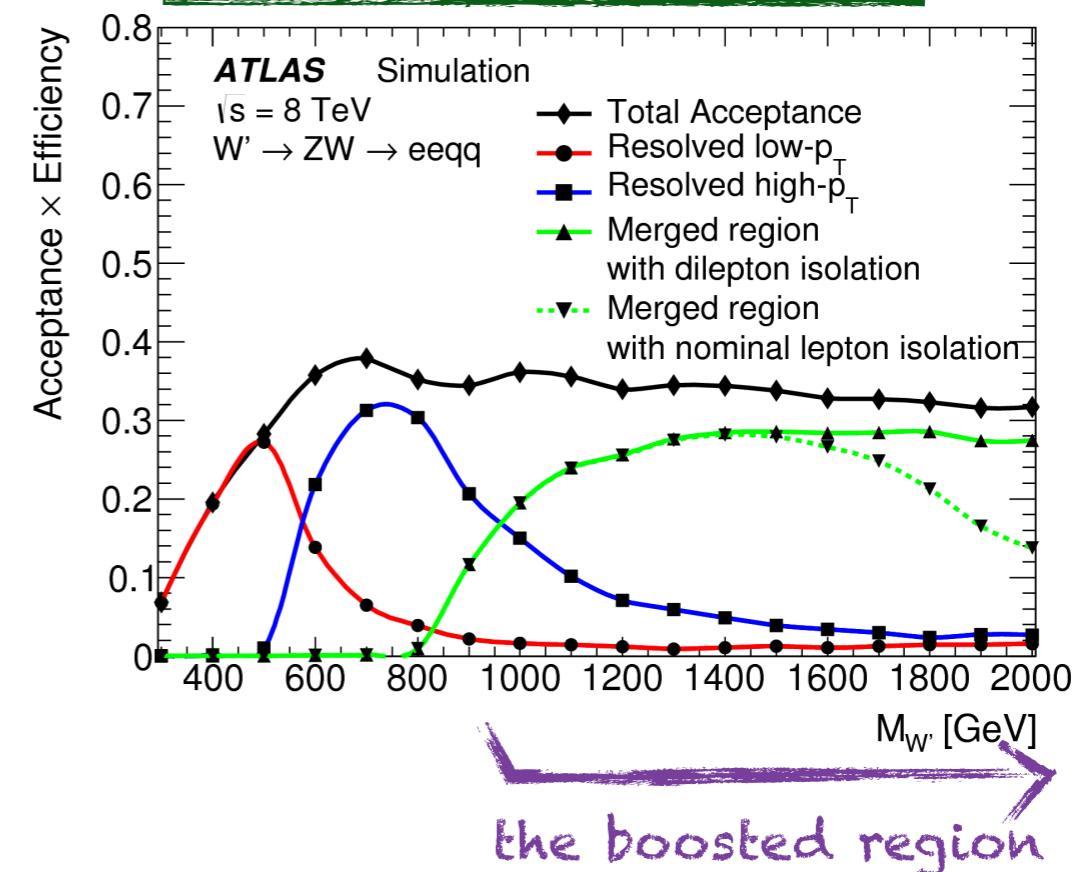
$$\Delta R(\ell_1, \ell_2) > 0.25 : \sum_{\Delta R < 0.2} p_T^{(i)} < 0.15 \cdot p_T(\ell)$$

$$\Delta R(\ell_1, \ell_2) < 0.25 : \sum_{\Delta R < 0.2} p_T^{(i)} - p_T(\ell_2) < 0.15 \cdot p_T(\ell_1)$$

$\Delta R(ee)$ vs isolation in
 $G^* \rightarrow ZZ \rightarrow llqq$ simulation



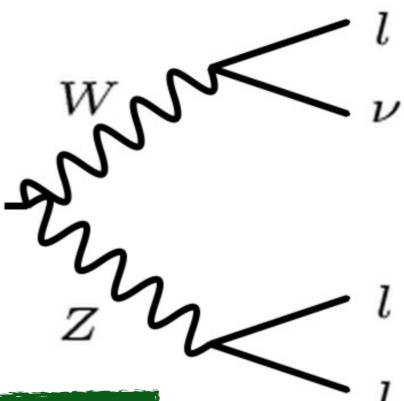
improvement in $A \times \epsilon$, vs
 $m_W \sim 2p_T(Z)$



$X \rightarrow WZ \rightarrow \ell\nu\ell'\ell'$, THE CLEAN CHANNEL

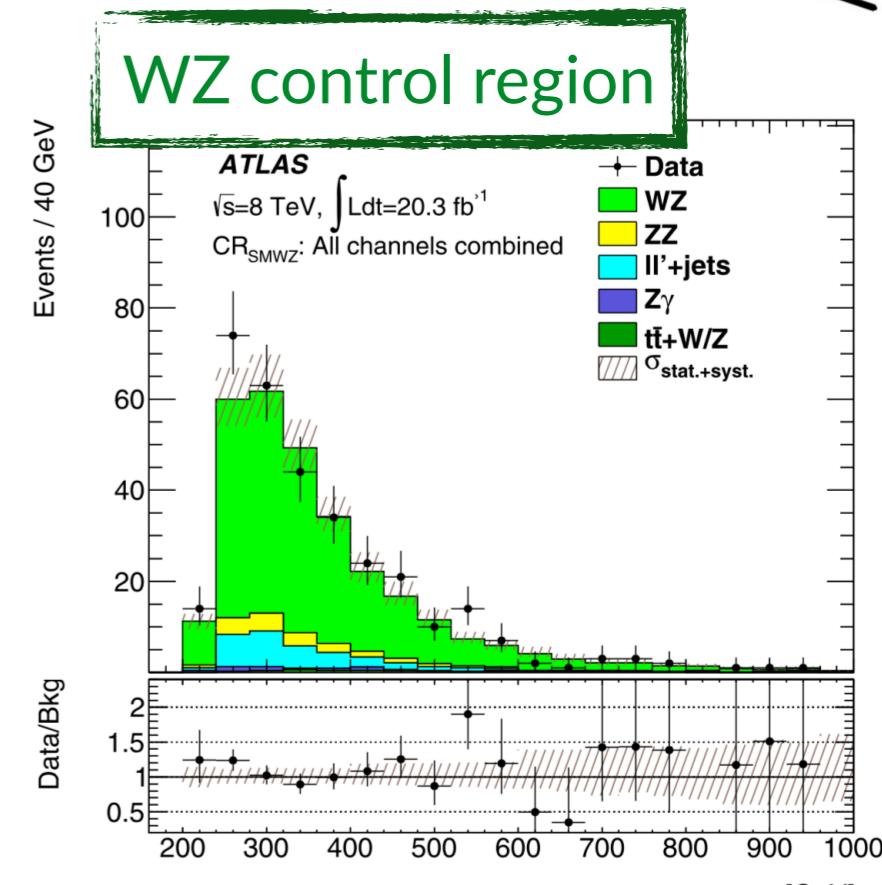
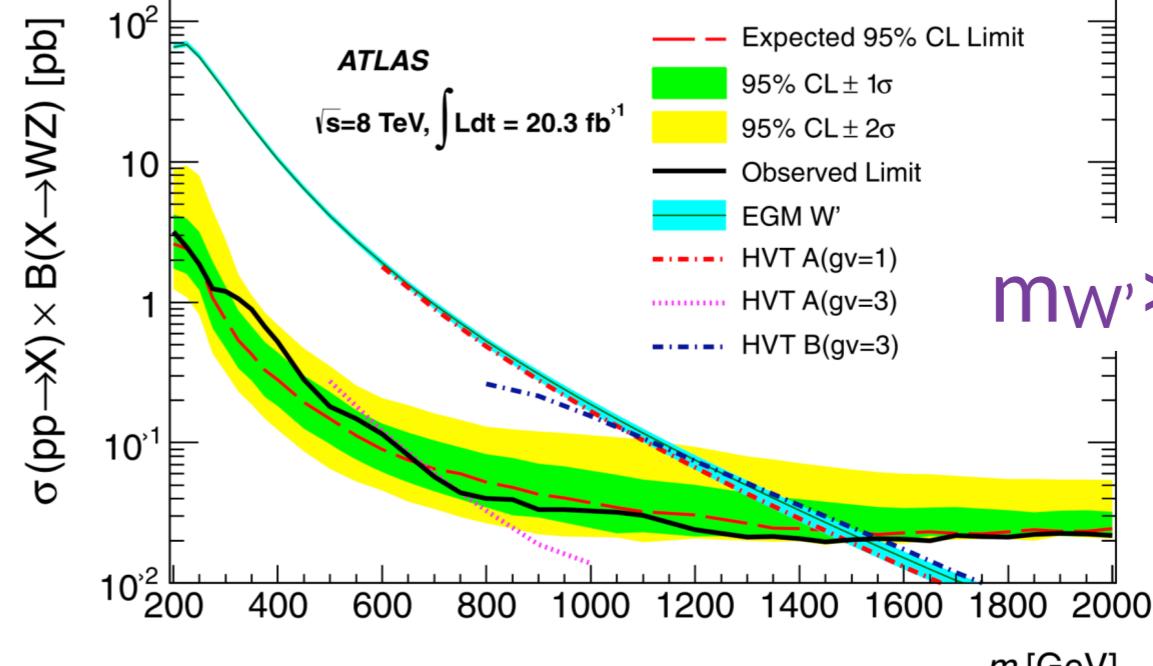
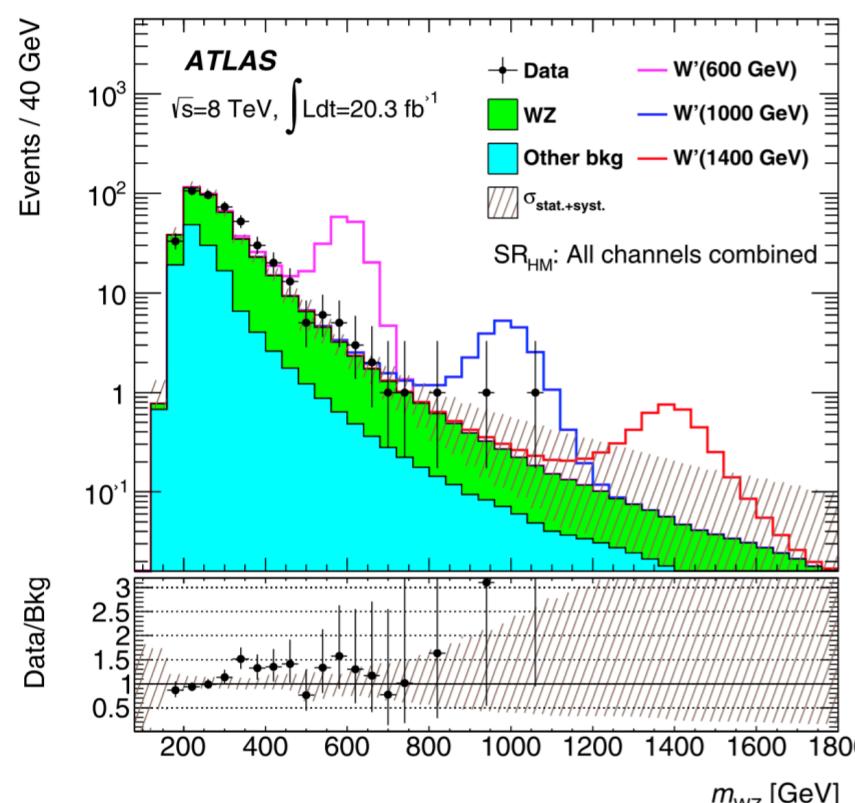
event selection

- lepton trigger, 3 isolated leptons (e, μ)
- m_{ll} cut, W mass constraint on $\ell\nu$ pair
- $\Delta y(W, Z) < 1.5$
- low/high $m_{W'}$ SRs with $\Delta\Phi(\text{MET}, l) > (<) 1.5$



main background from SM WZ

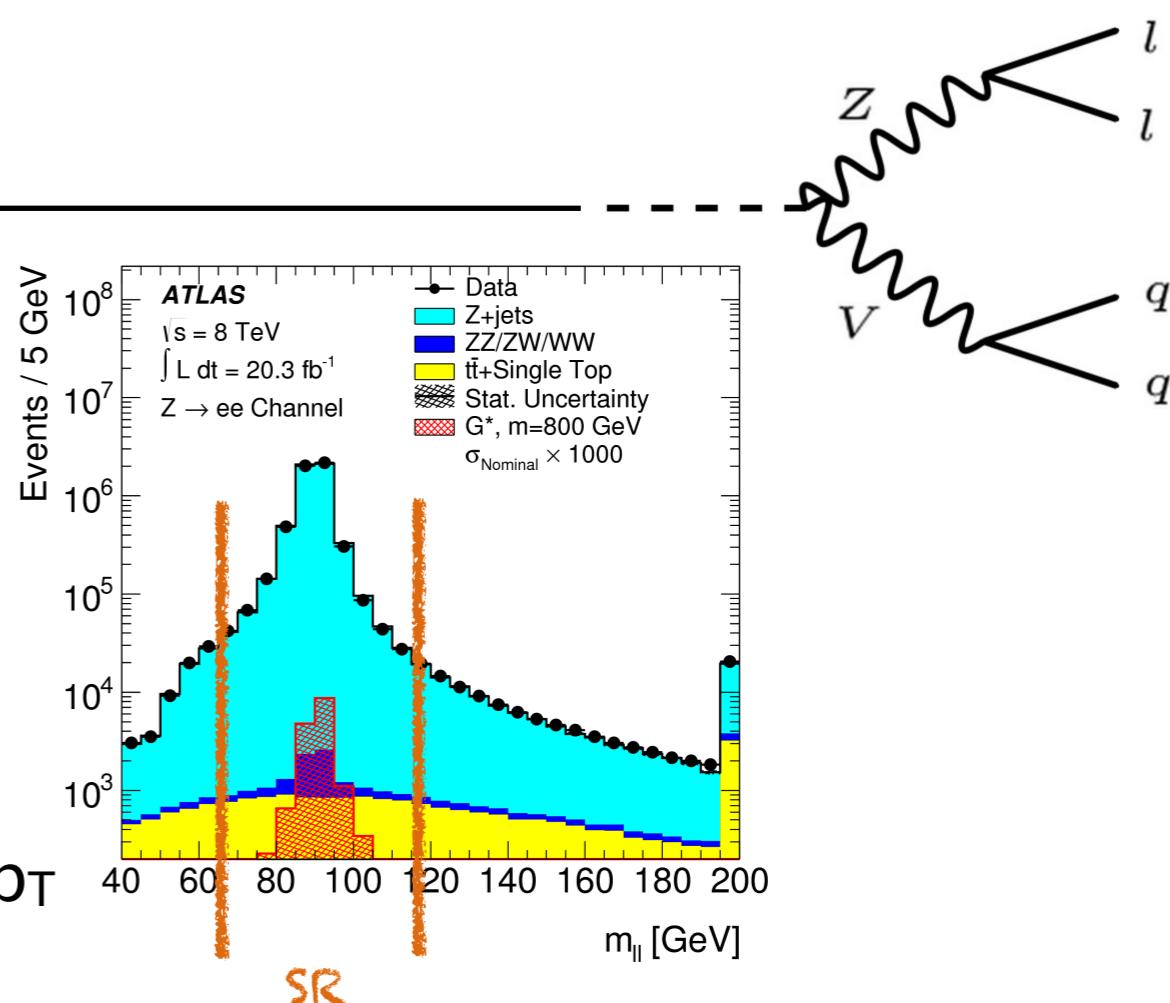
- ▶ validated in data (inverting $\Delta y, \Delta\Phi$ cuts)
- ▶ dominant uncertainty from MC normalisation



$X \rightarrow VZ \rightarrow qq\ell\ell$: EVENT SELECTION

leptonic leg

- isolated ee/ $\mu\mu$ pair
- dilepton isolation for $p_T(\ell\ell) > 800$ GeV



hadronic leg

- different exclusive selection criteria vs p_T
- $70 < m_{\text{had}} < 110$ GeV

merged

- $p_T(\ell\ell)$, $p_T(\text{had}) > 400$ GeV
- C/A R=1.2 jets, $|\eta| < 1.2$, BDRS-A, $\sqrt{y_f} > 0.45$

high- p_T resolved

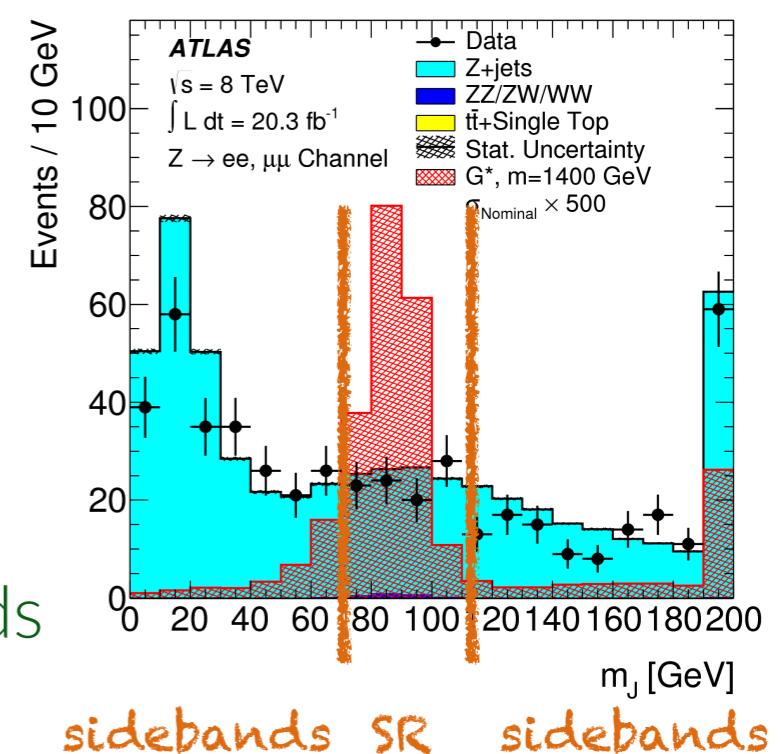
- $p_T(\ell\ell)$, $p_T(\text{had}) > 250$ GeV
- anti- k_T R=0.4 jets, $|\eta| < 2.1$

low- p_T resolved

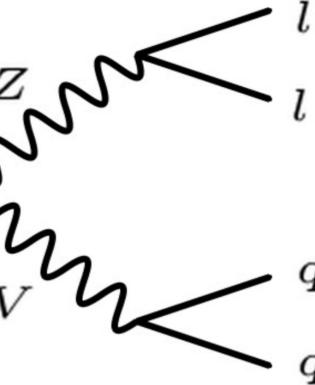
- $p_T(\ell\ell)$, $p_T(\text{had}) > 100$ GeV

○ dominant background from Z+jets

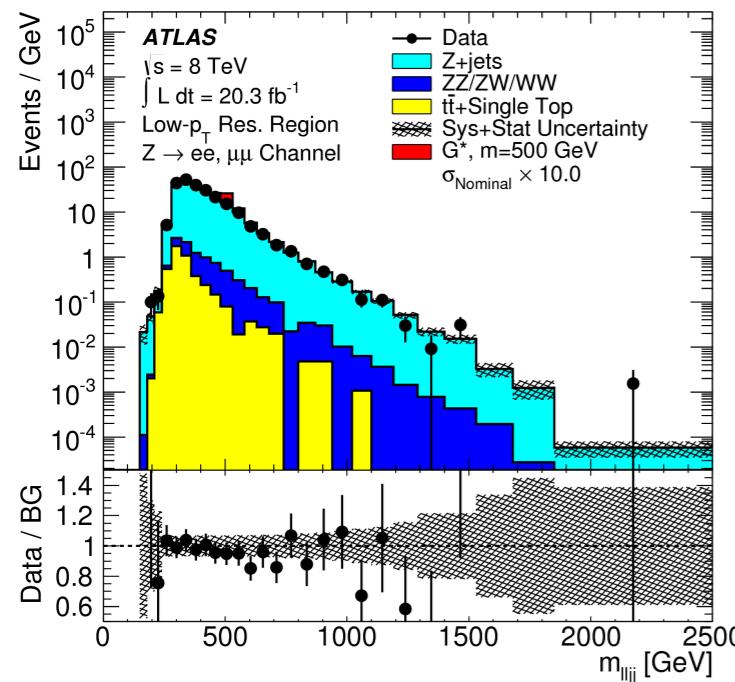
- norm, m_{qqll} shape from m_{had} sidebands



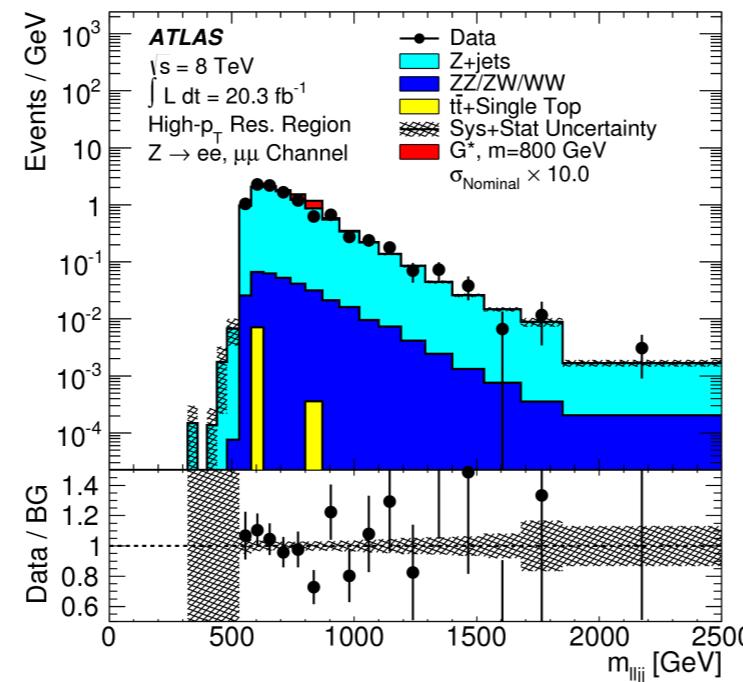
$X \rightarrow VZ \rightarrow qq\ell\ell$: RESULTS



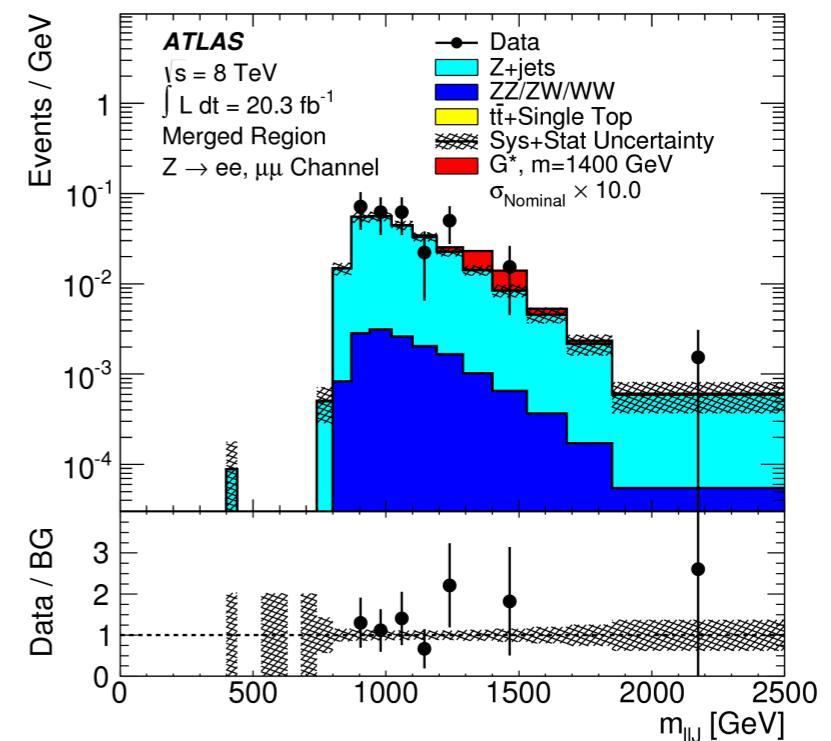
low p_T resolved



high p_T resolved

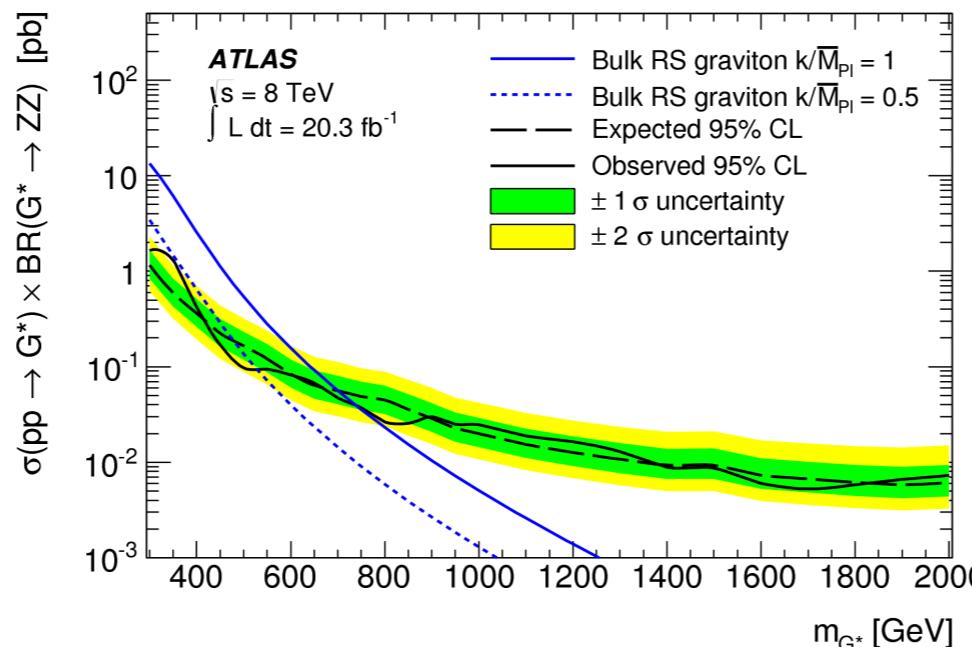


high p_T merged

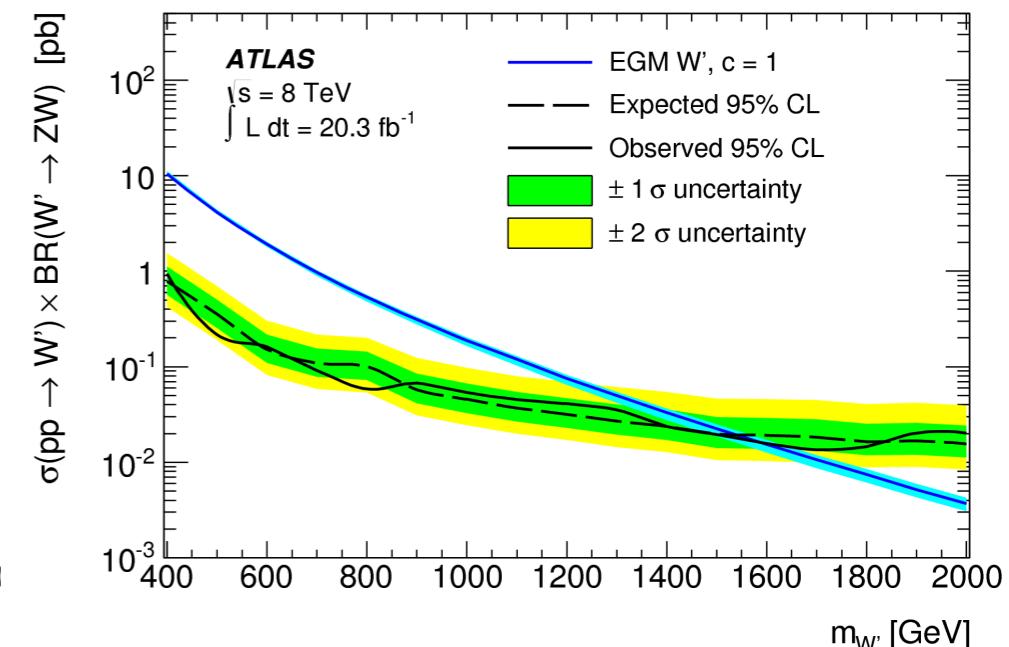


- dominant syst uncertainty from Z +jets data-driven estimation
 - 11-47% [merged]

$m_{G^*}(k/M_{Pl})=1.0 > 740 \text{ GeV}$



$m_{W'} > 1590 \text{ GeV}$



$X \rightarrow VV \rightarrow qq\ell\nu$: EVENT SELECTION

event selection

- one lepton + MET > 30 GeV
- $65 < m_{had} < 105$ GeV, $m(\ell\nu)$ constrained to m_W
- $\Delta\Phi(\text{jet, MET}) > 1$

merged

- $p_T(\ell\nu), p_T(\text{had}) > 400$ GeV
- C/A R=1.2 jets, $|\eta| < 2.0$, BDRS-A, $\sqrt{y_f} > 0.45$

high- p_T resolved

- $p_T(\ell\nu), p_T(\text{had}) > 300$ GeV
- anti- k_T R=0.4 jets, $p_T > 80$ GeV

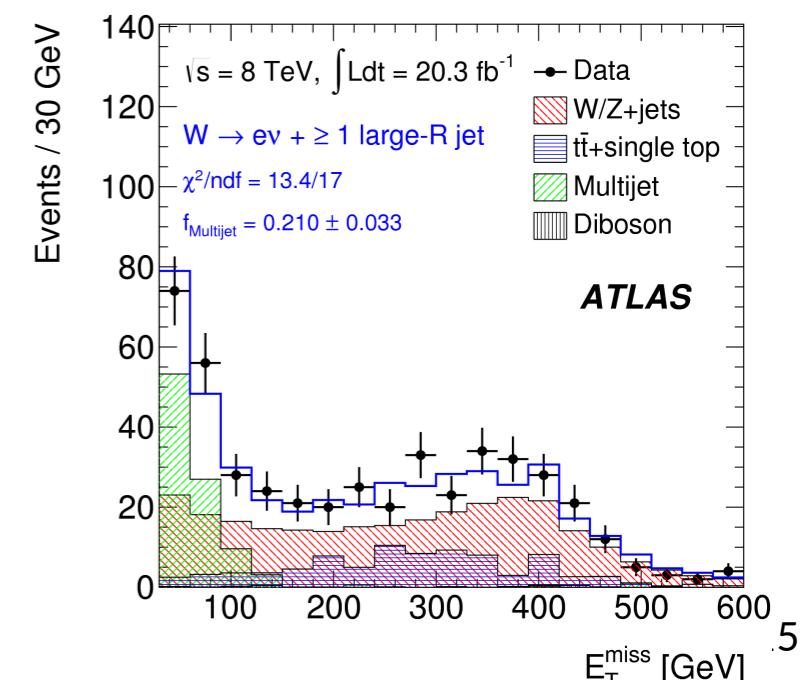
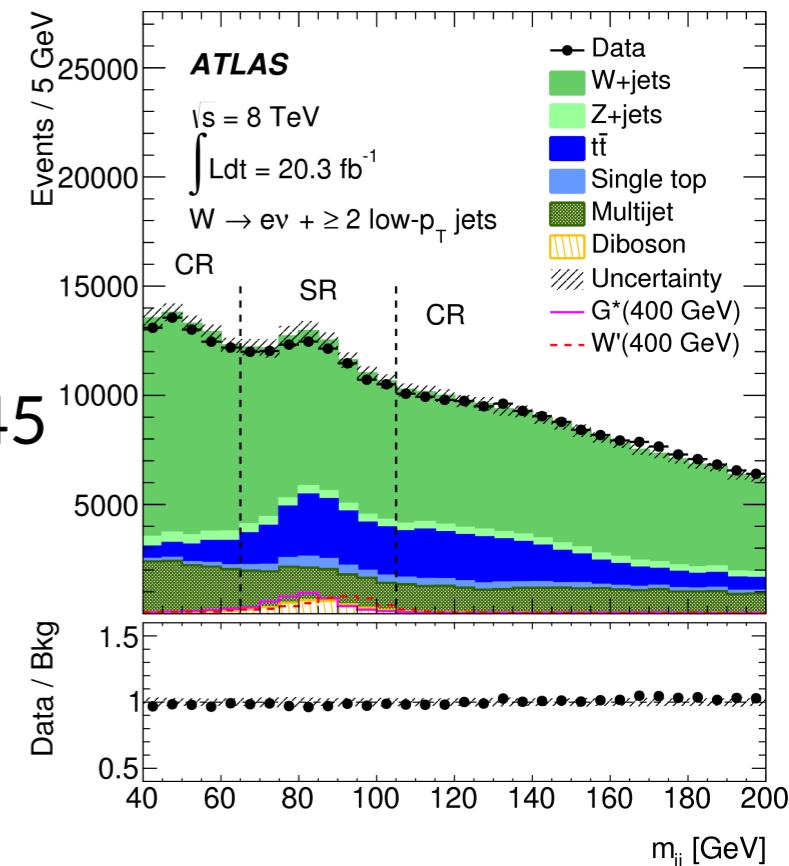
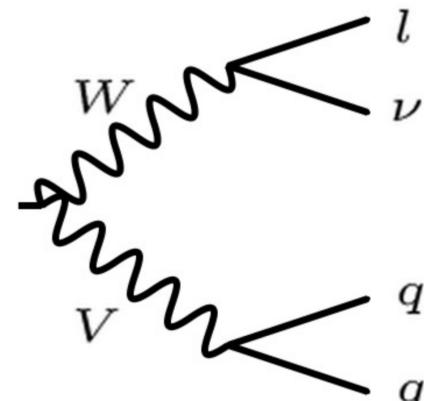
low- p_T resolved

- $p_T(\ell\nu), p_T(\text{had}) > 100$ GeV

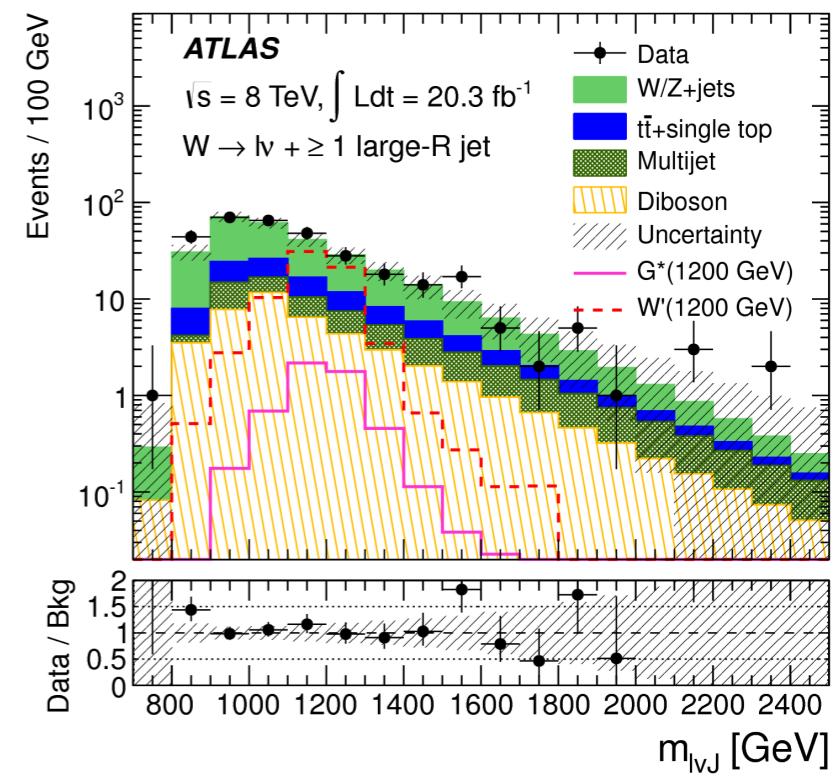
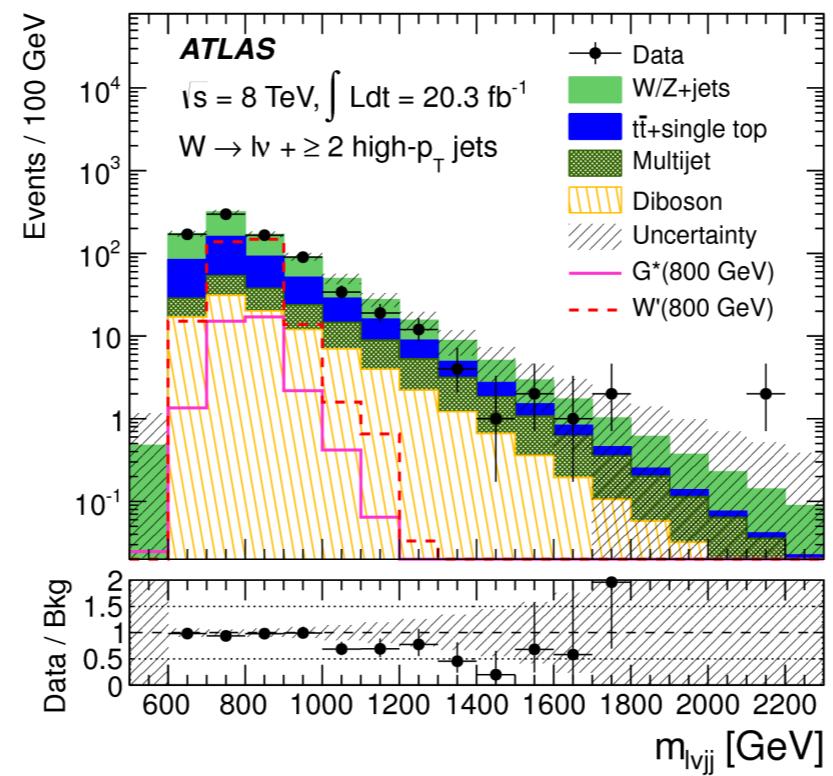
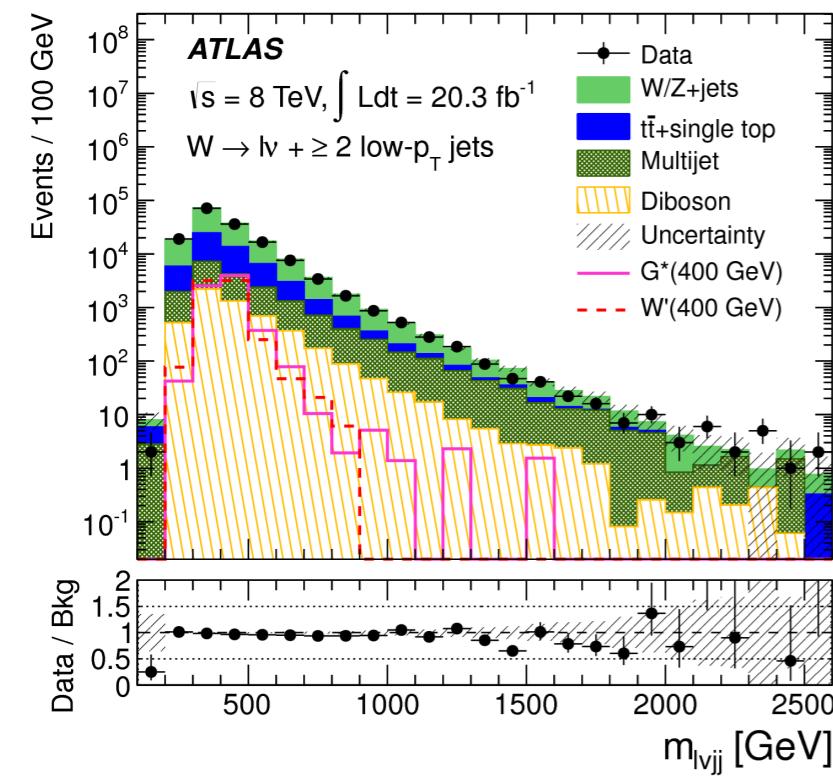
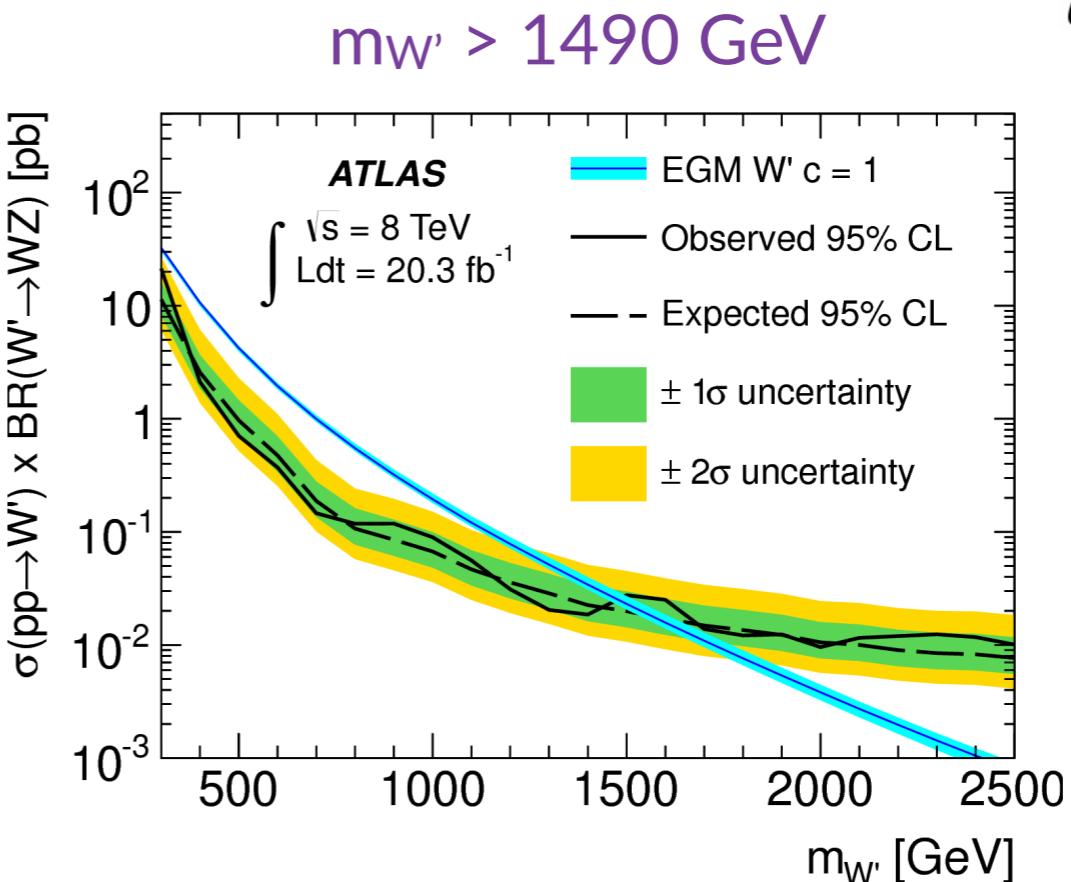
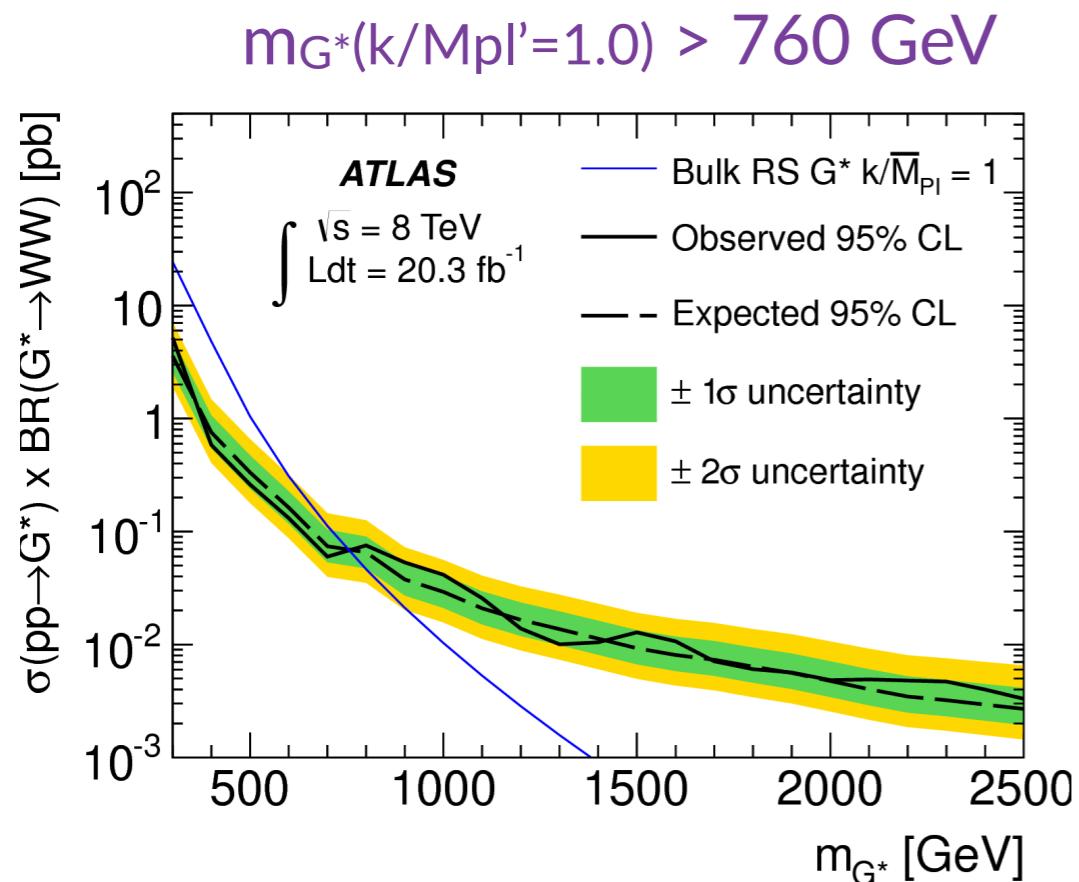
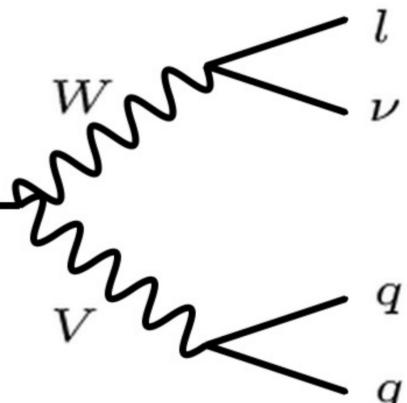
○ W/Z+jets, multijet norm from MET fit to m_{had} sidebands

- multi-jet $m_{qq\ell\nu}$ shape from inverted lepton quality
- top from MC, validated with 1 b-tag

○ main uncertainty from sideband fit (3-20%)



$X \rightarrow VV \rightarrow qq\ell\nu$: RESULTS



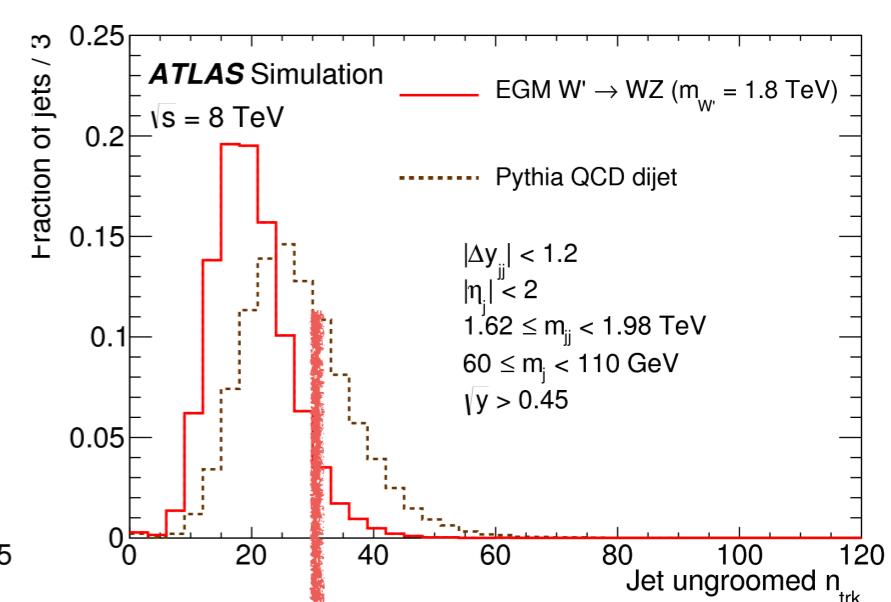
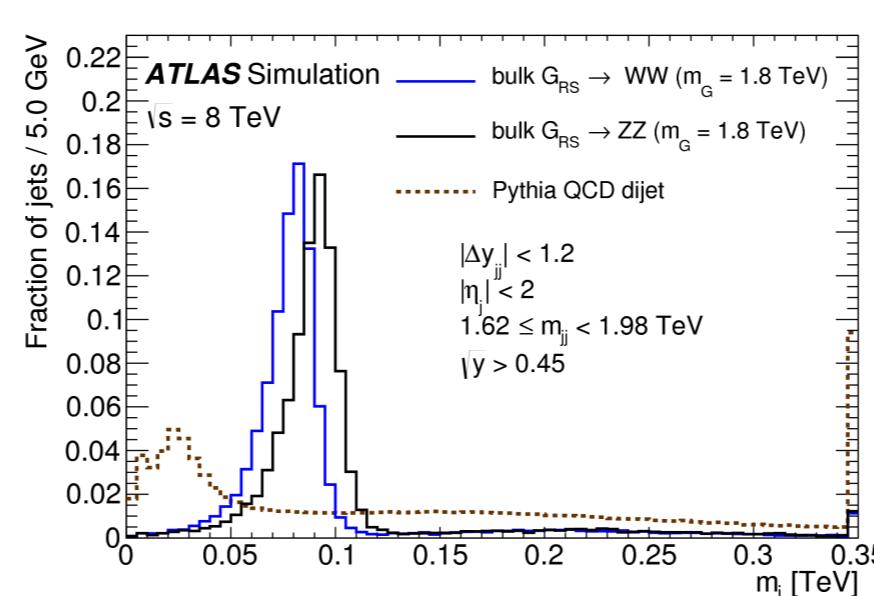
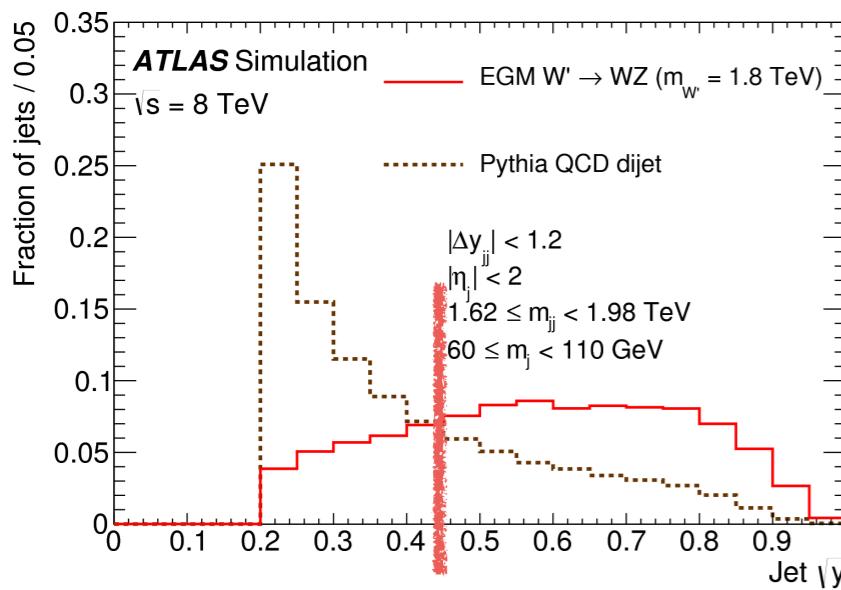
$X \rightarrow WZ/WW/ZZ \rightarrow qqqq$: EVENT SELECTION

boosted regime only

- jet trigger, lepton veto, MET < 350 GeV (orthogonality)
- C/A R=1.2 jets, $|\eta| < 2.0$, BDRS-A
- dominated by multi-jet, fitted with $(1-x)^{p_2-kp_3} x^{p_3}$ ($x = m_{JJ}/\sqrt{s}$)
 - fit tested on m_J sidebands, MC

background rejection

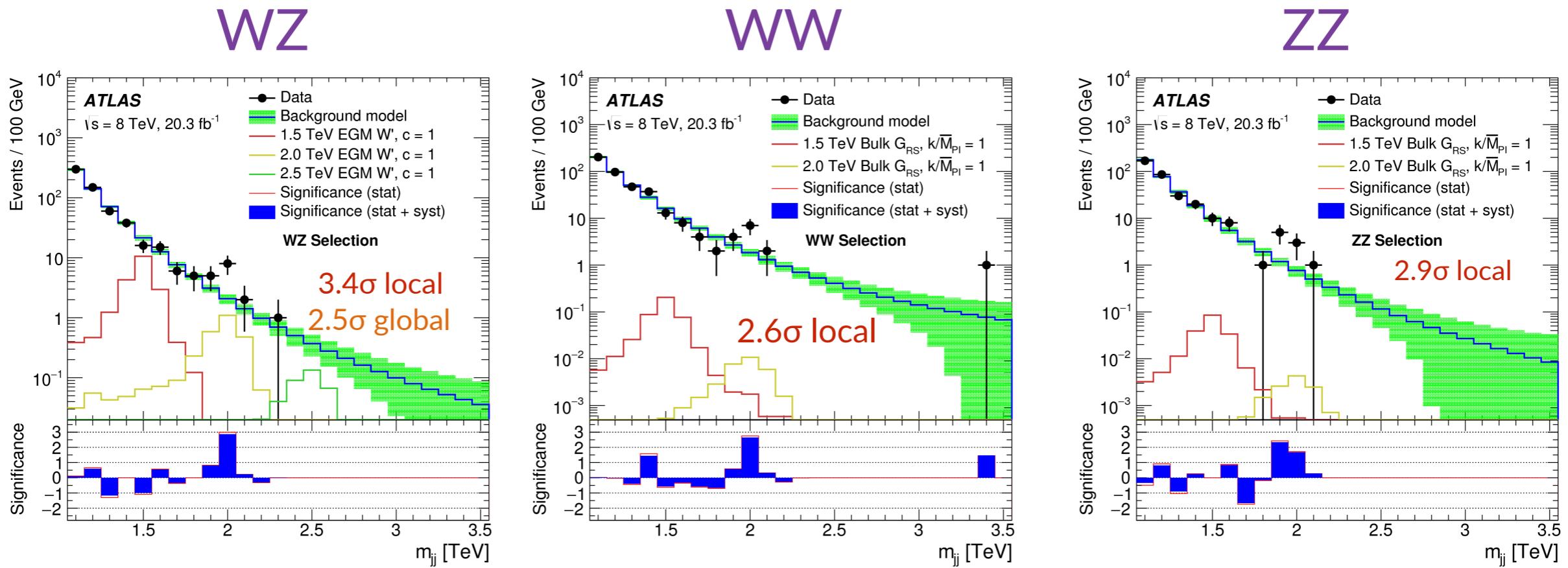
- $\sqrt{y_f} > 0.45$
- $|y_1 - y_2| < 1.2$
- $|(\mathbf{p}_T^{(1)} - \mathbf{p}_T^{(2)}) / (\mathbf{p}_T^{(1)} + \mathbf{p}_T^{(2)})| < 0.15$
- $|m_J - m_V| < 13$ GeV
- $n_{trk} < 30$, efficiency from m_J fit to $W/Z + \text{jets}$ data/MC



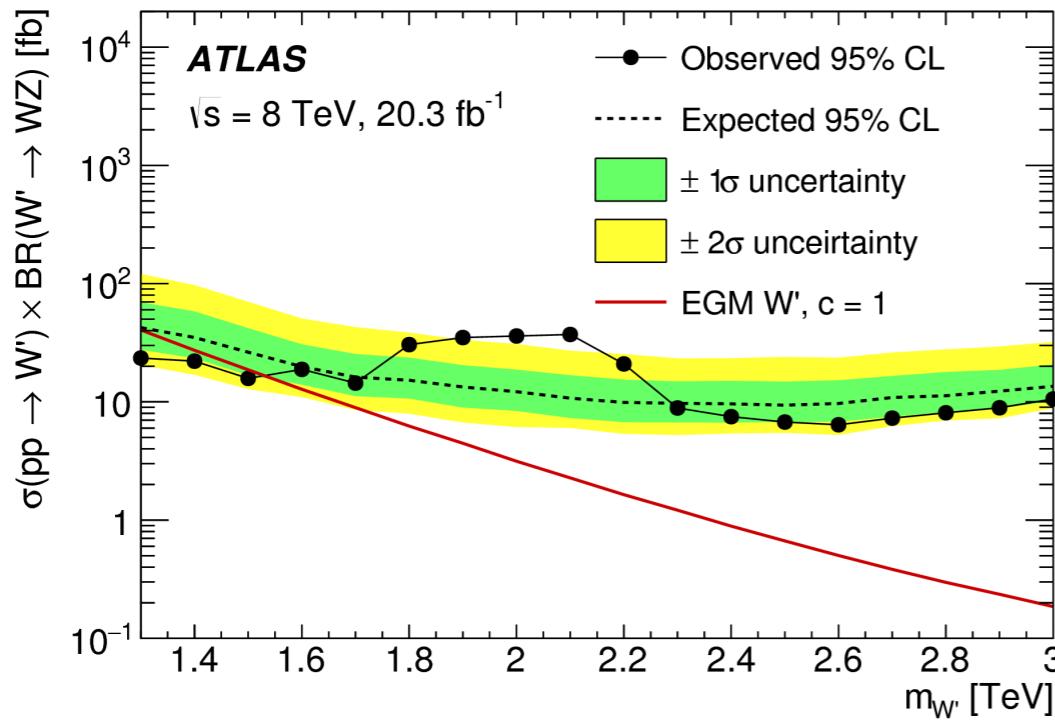
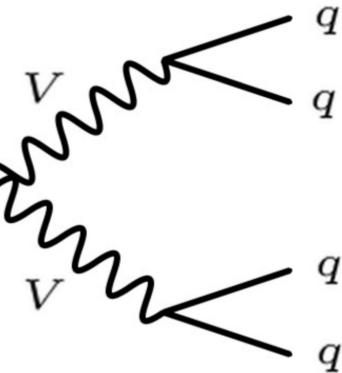
$X \rightarrow WZ/WW/ZZ \rightarrow qqqq$: RESULTS

- dominant signal norm uncertainty from n_{trk} cut efficiency (20%)
 - ISR/FSR $\sim 5\%$, parton shower $\sim 5\%$, jet mass scale/reso 5% each
 - shape: 5% from p_T reso

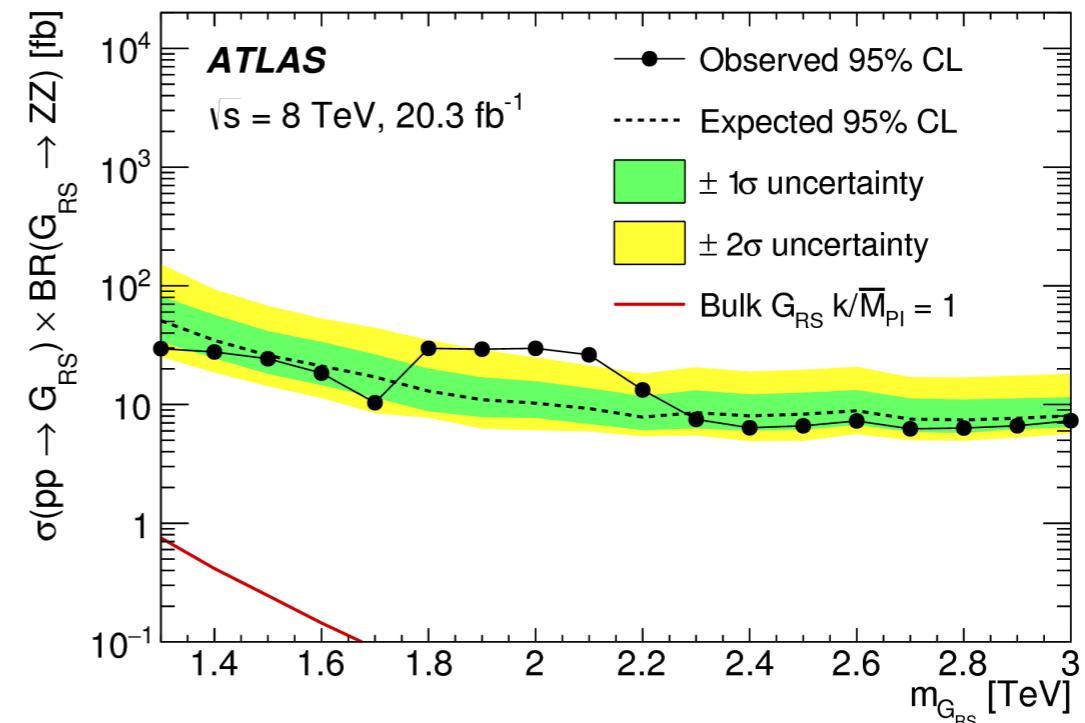
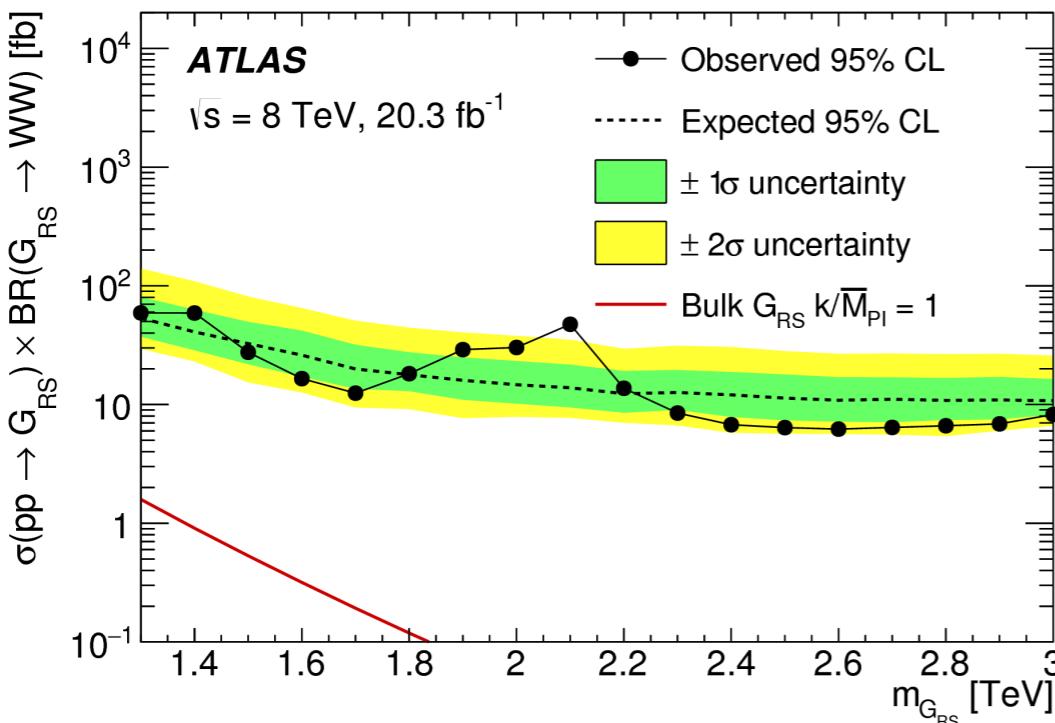
3 ~overlapping channels: WZ , WW , ZZ



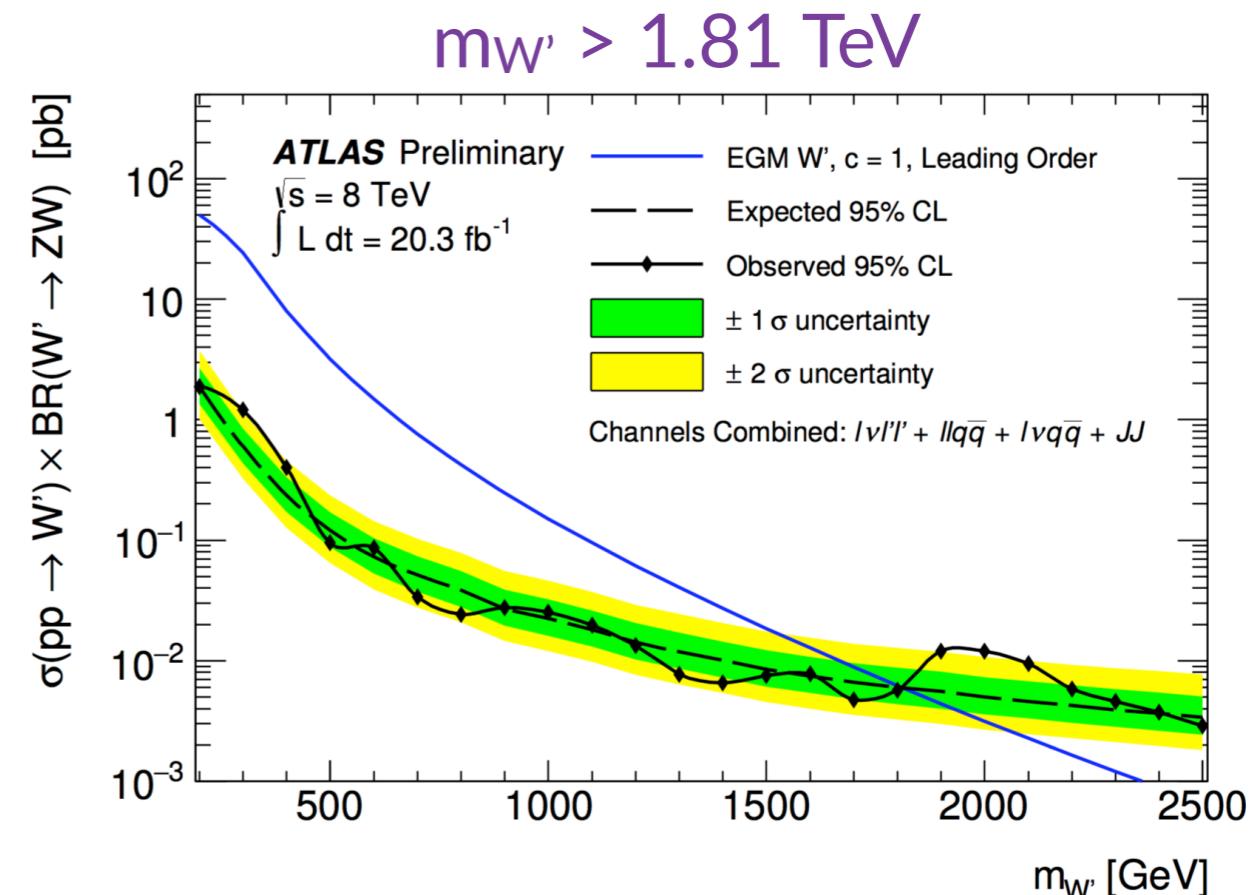
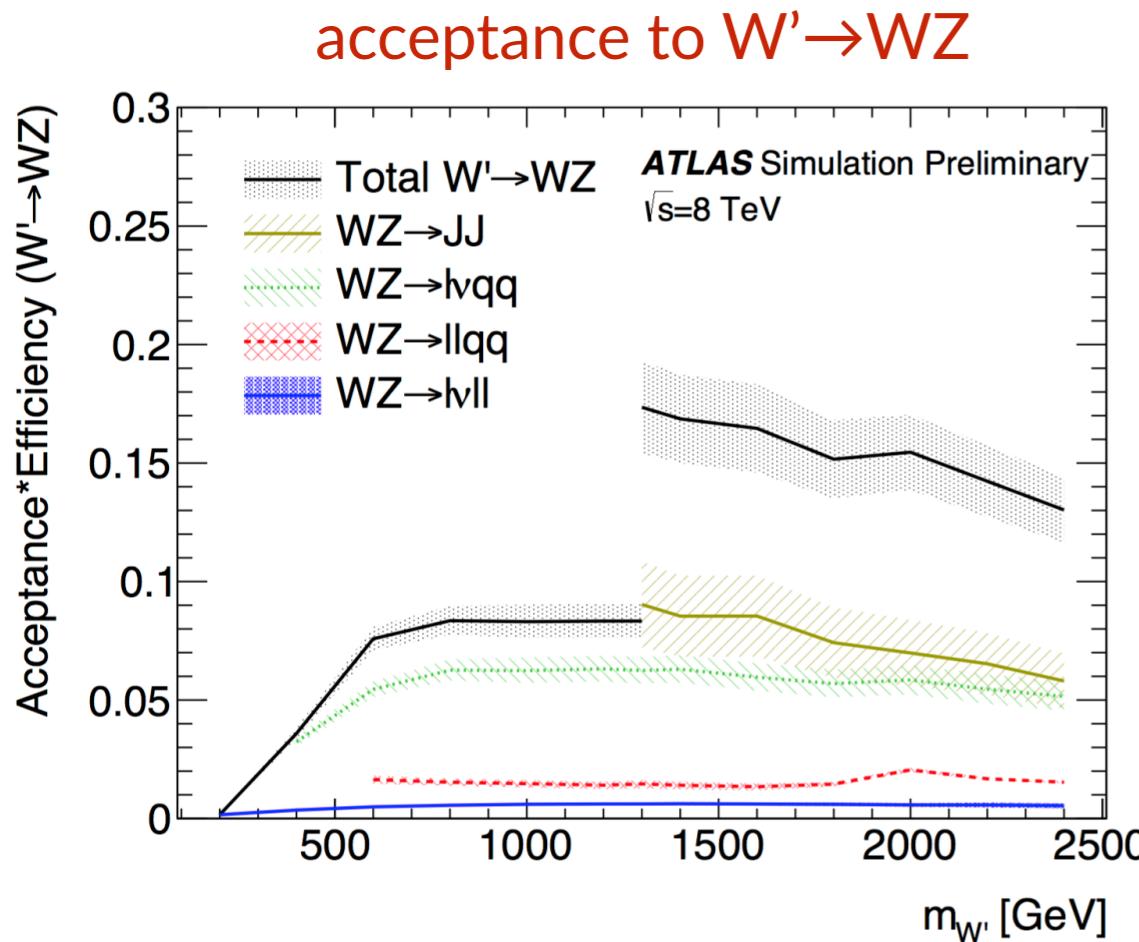
$X \rightarrow WZ/WW/ZZ \rightarrow qqqq$: LIMITS



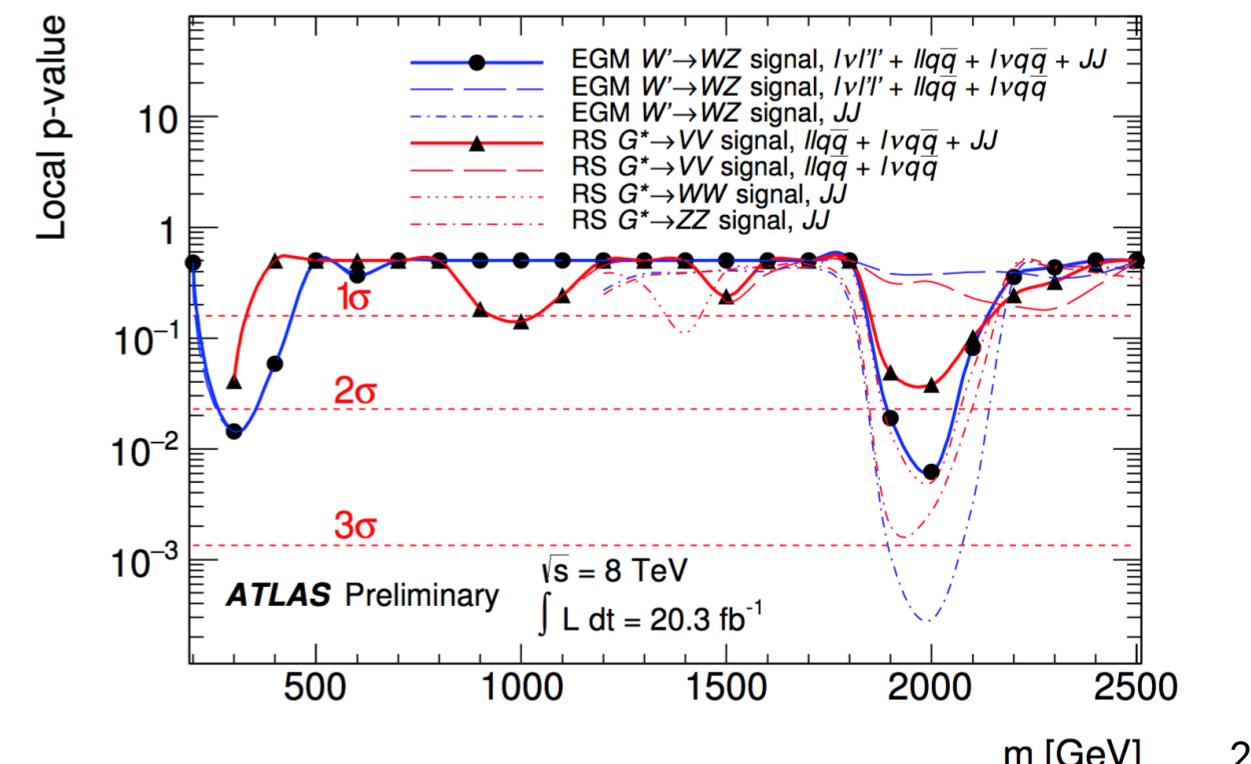
- WZ: $m_{W'} > 1.5 \text{ TeV}$
- WW, ZZ: no sensitivity to tested model



COMBINATION



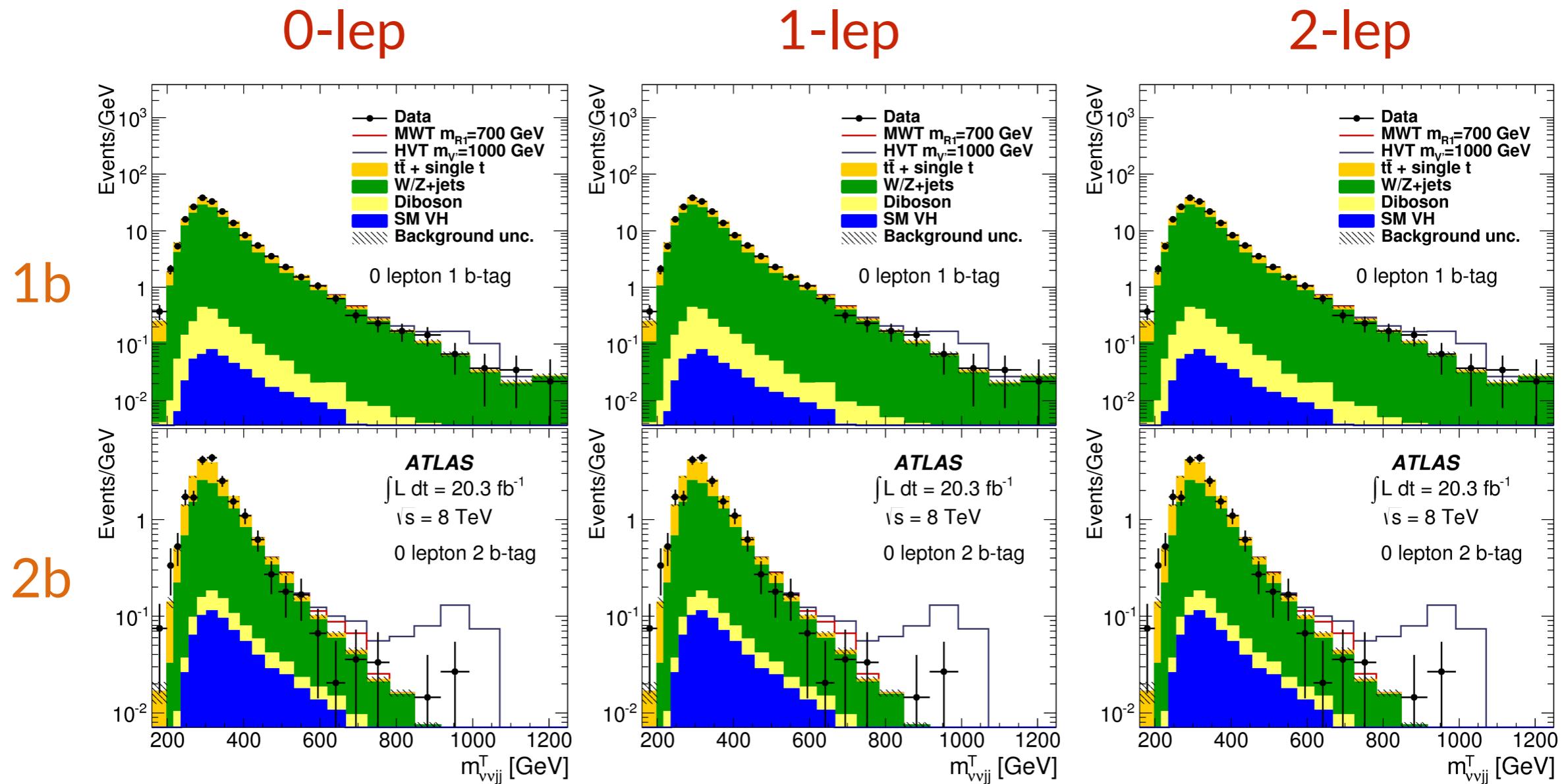
- 2 TeV: local p0 reduced to 2.5σ (other channels more bkg-like)
- best sensitivity from $l\nu qq / qqqq, l\nu ll$ at low mass
- $MG^*(k/Mpl=1.0) > 810 \text{ GeV}$



$X \rightarrow VH \rightarrow VVBB/\ell vbb/\ell\ell bb$: EVENT SELECTION



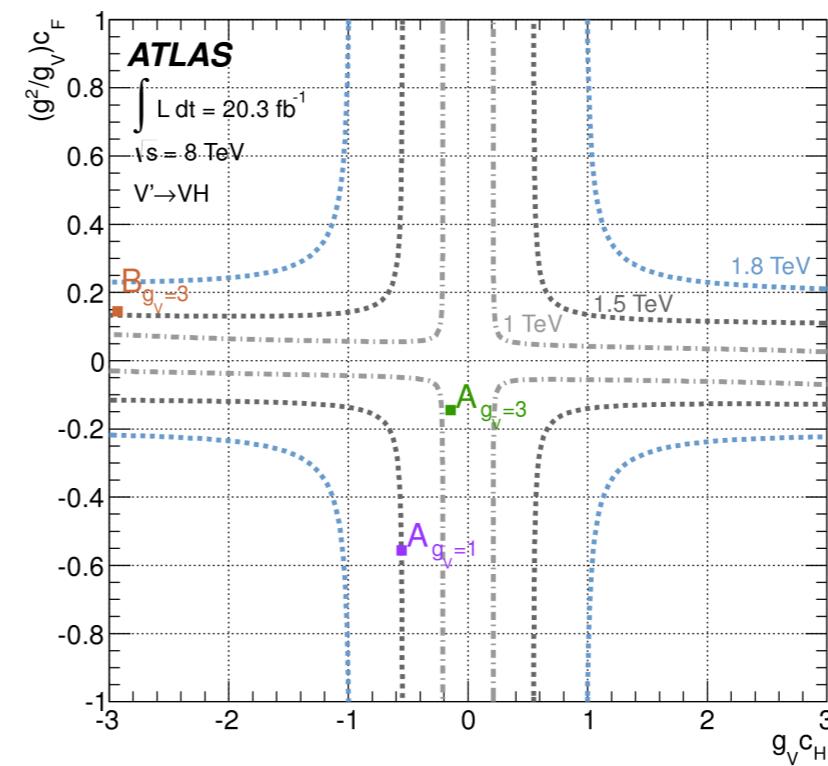
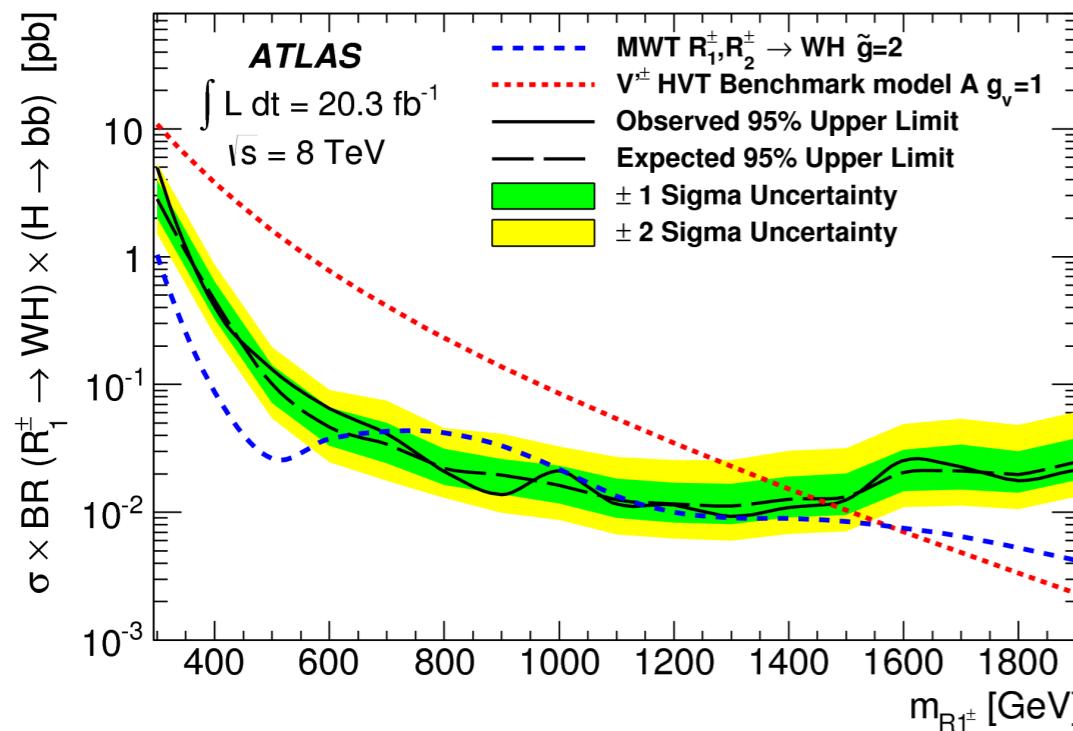
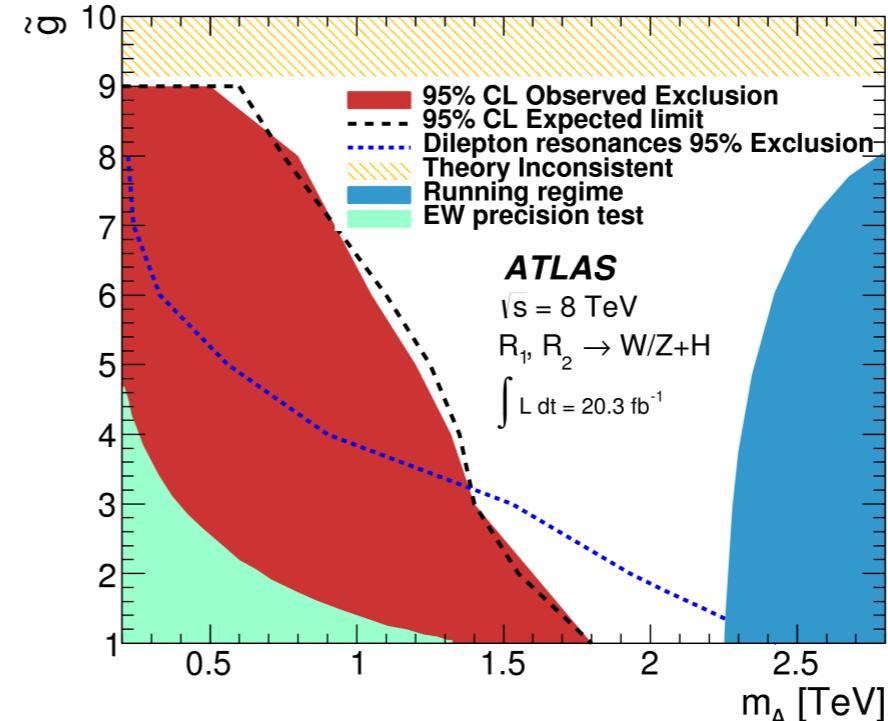
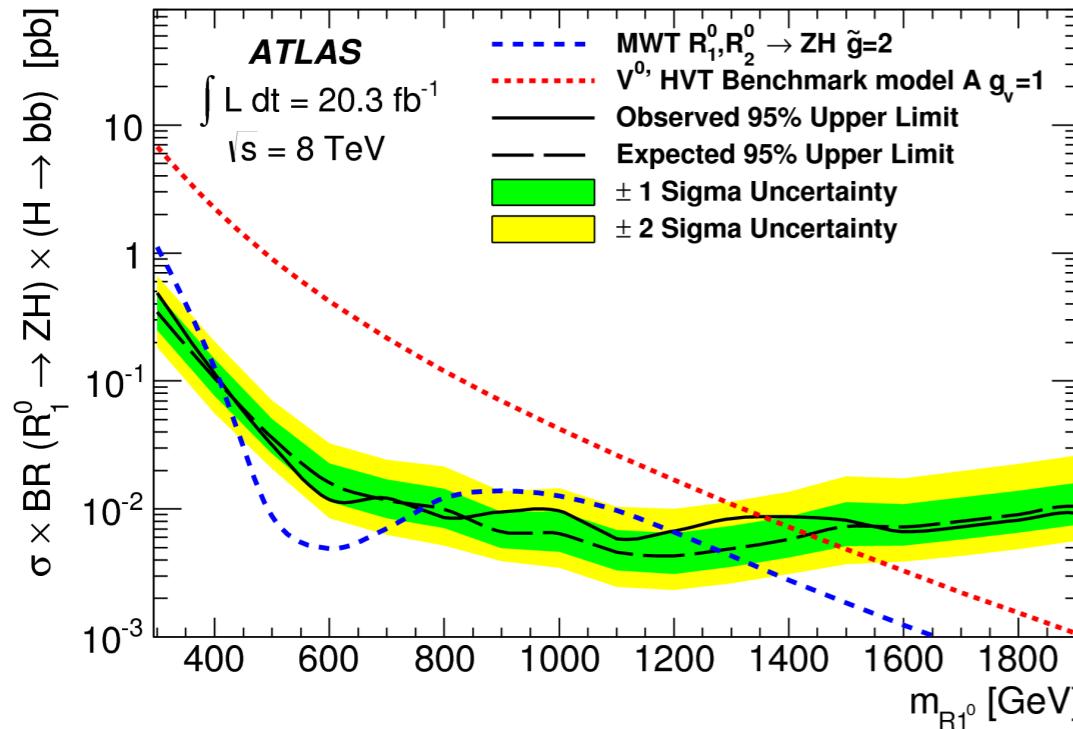
- resolved channel only
- anti- k_T R=0.4 jets, 1-2 b-tags, 0-1-2 leptons
- backgrounds:
 - W/Z+jets (semi data-driven)
 - multijet (data-driven), top (CR fit)



$X \rightarrow VH \rightarrow VVBB/\ell\nu bb/\ell\ell bb$: RESULTS



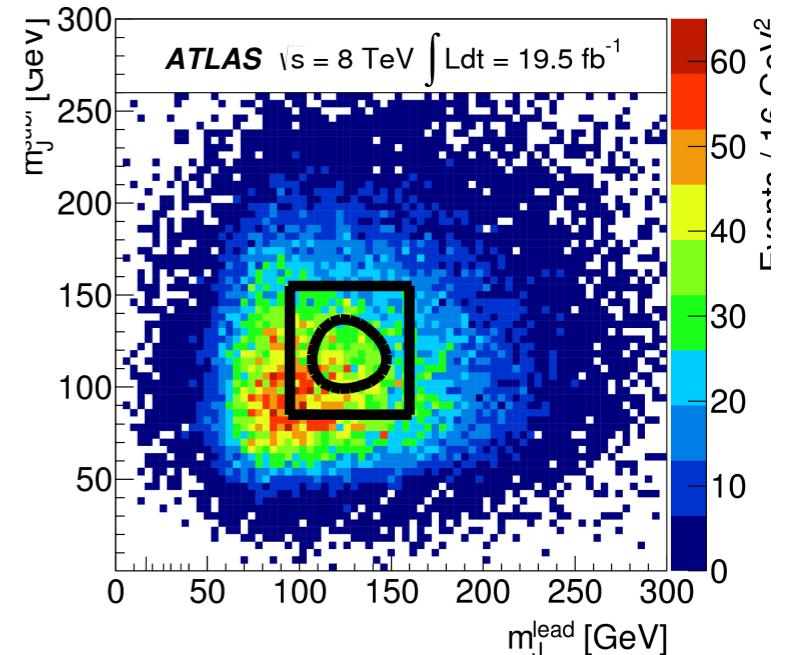
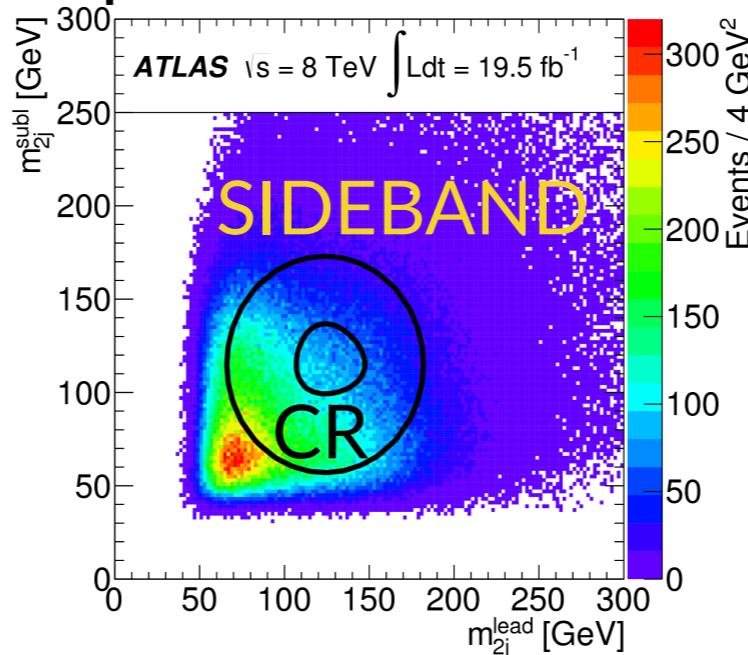
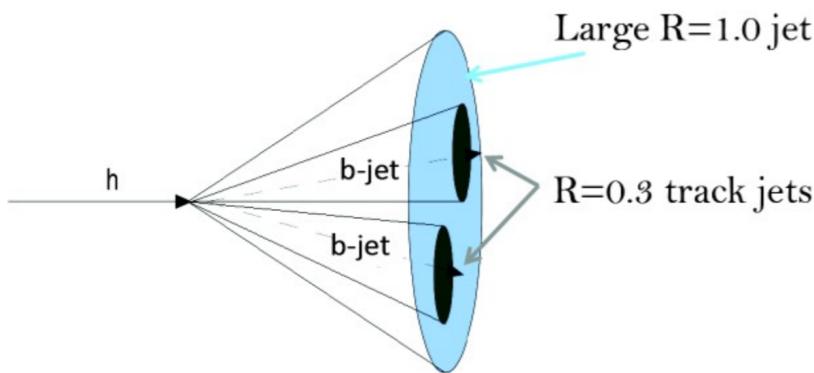
limits on neutral/charged resonance masses



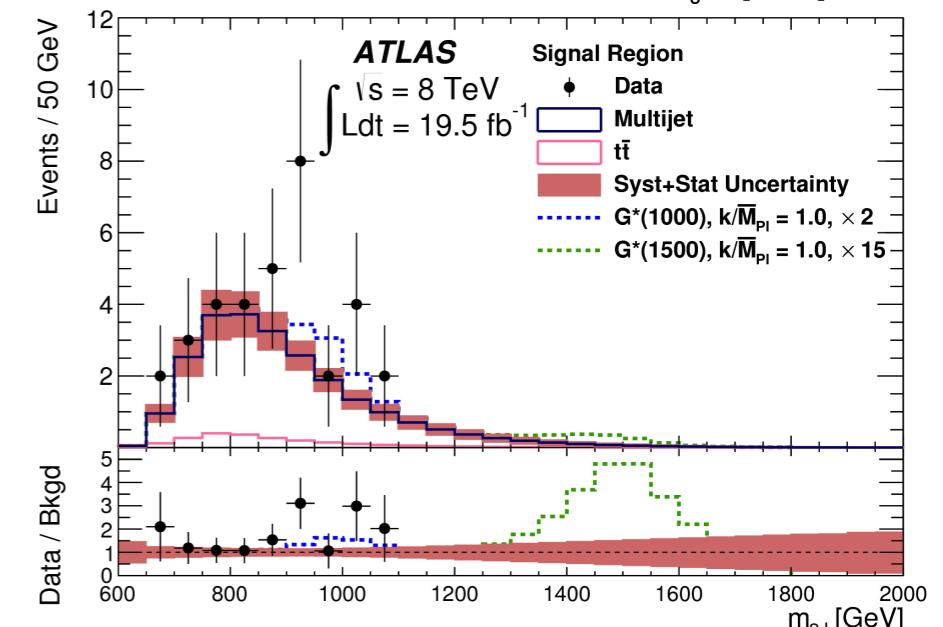
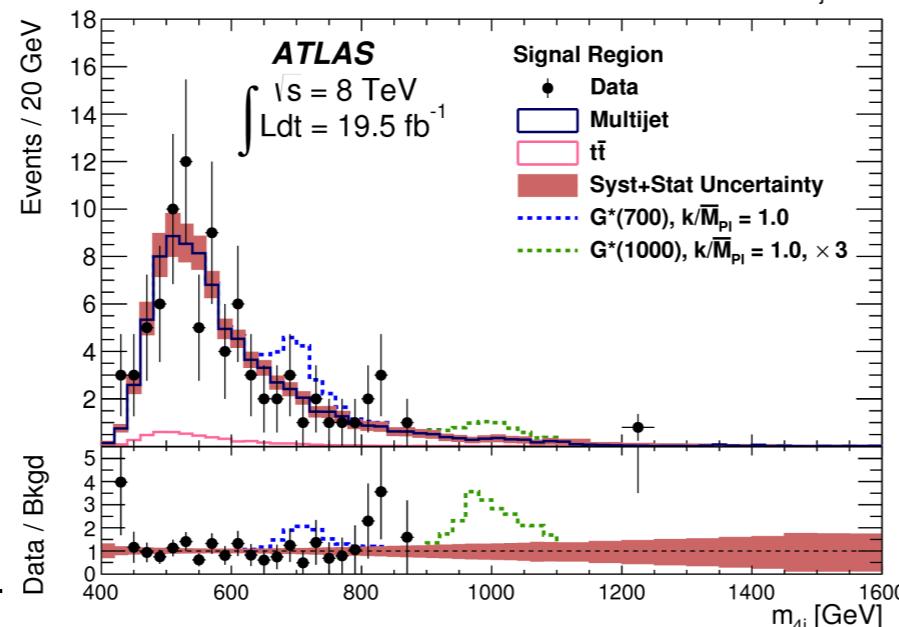
HVT: for each $m_{V'}$,
 area outside the
 curves is excluded



- resolved
 - 4 b-jets, $m_{bb} \sim m_H$, ttbar veto
- boosted
 - 2 trimmed anti- k_T $R=1.0$ jets, m_J cut, 2 b-tagged $R=0.3$ track-jets
- multijet from 2b \rightarrow 4b extrapolation



@1 TeV: $\sigma(m_{4b}) \sim 15\%$

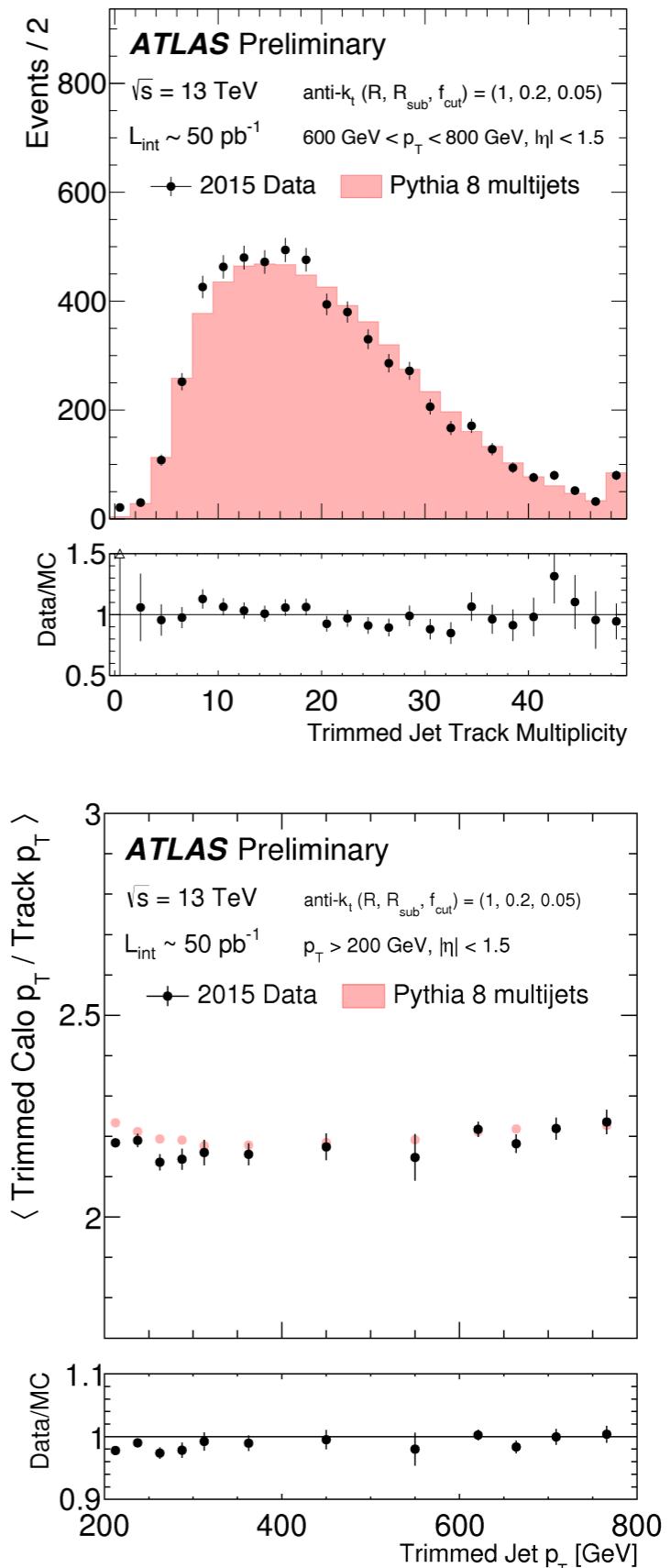
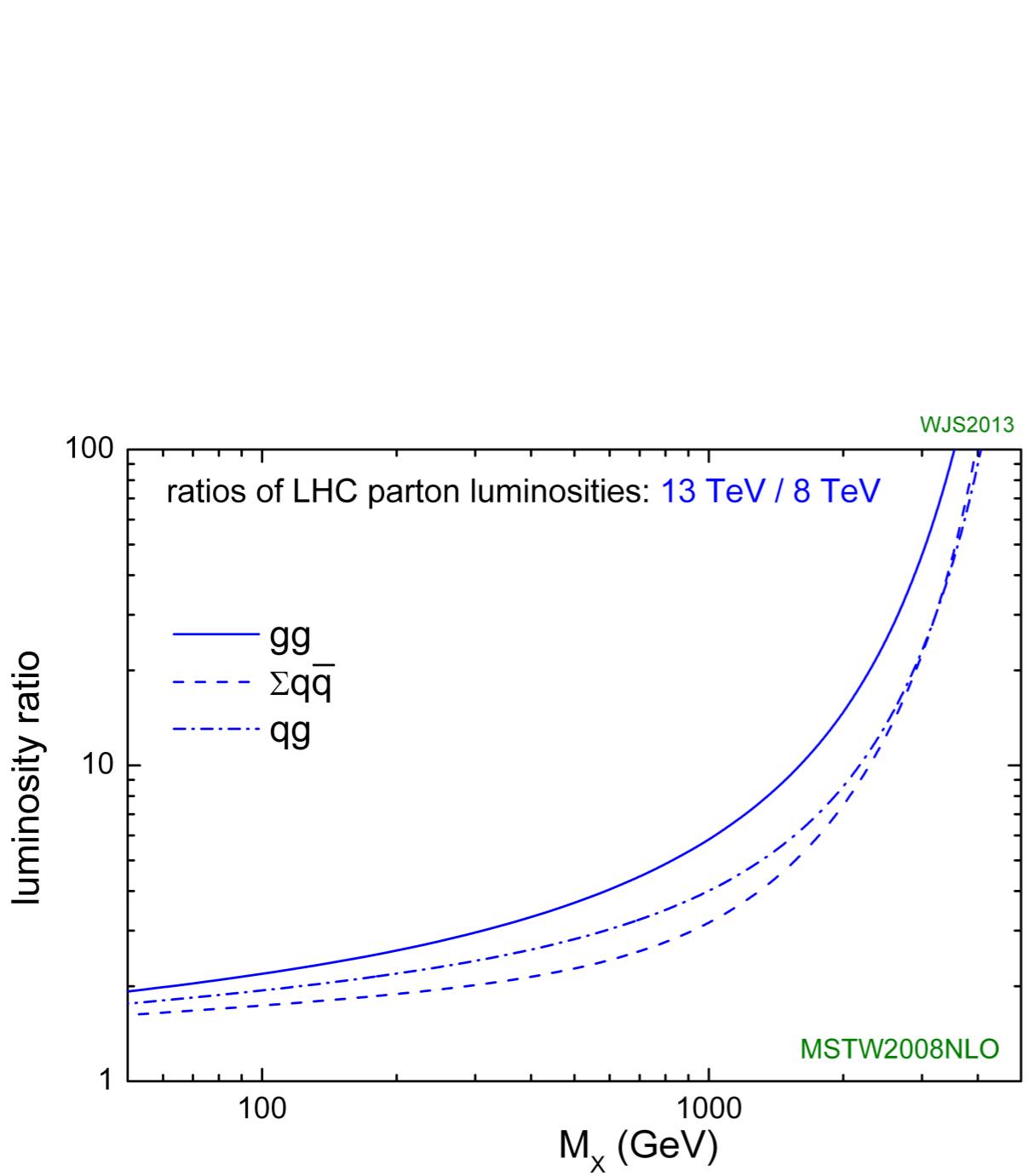


CONCLUSIONS

- ▶ plethora of final states probed at ATLAS during LHC Run-1
 - ❖ a few tantalising excesses, but no smoking gun for new physics
- ▶ detector, analyses and tools ready for 13 TeV data
 - ❖ parton luminosity should help!
- ▶ let's stay tuned!
 - The hardest thing of all is to find a black cat in a dark room, especially if there is no cat.

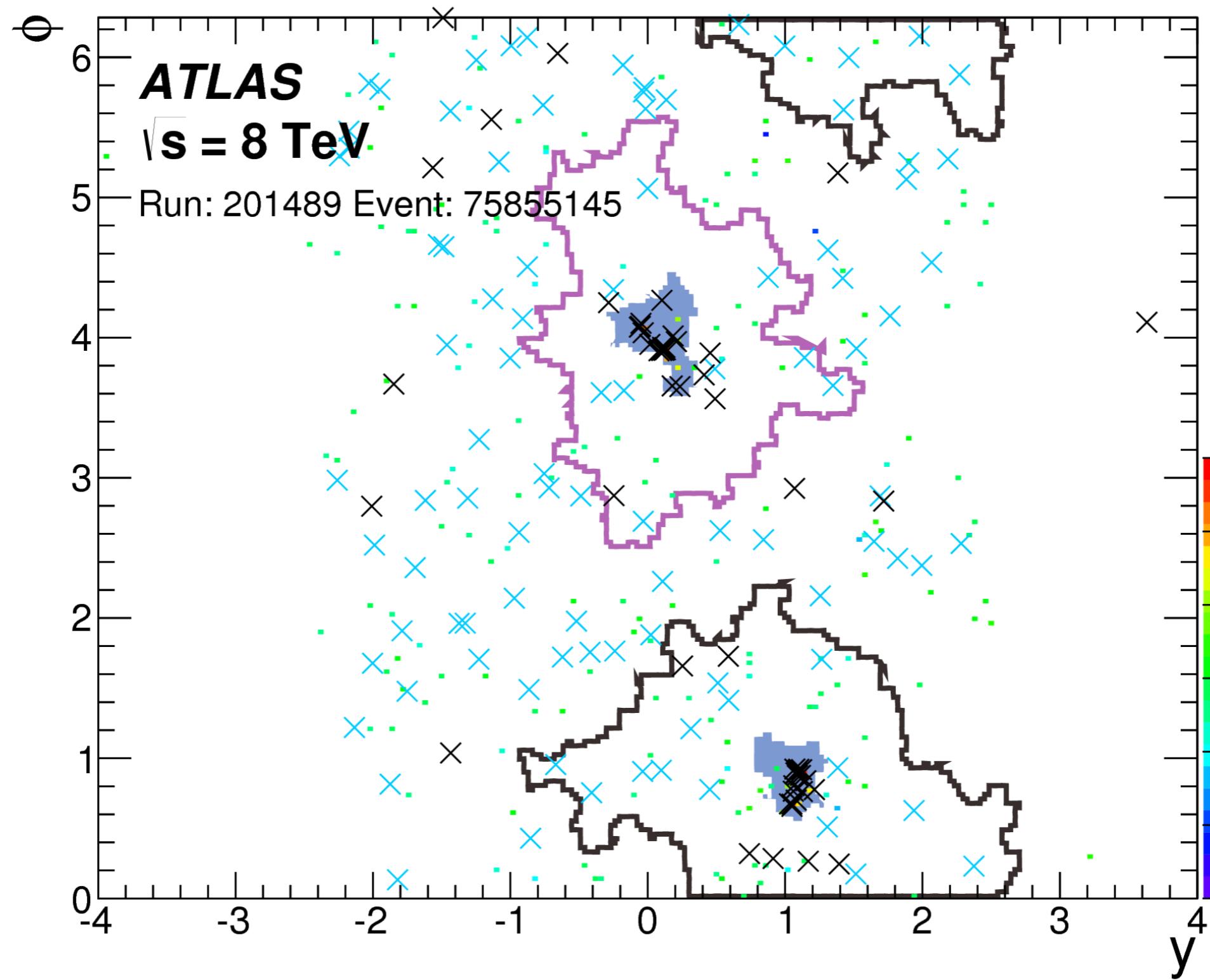
BACKUP

READY FOR RUN-2?

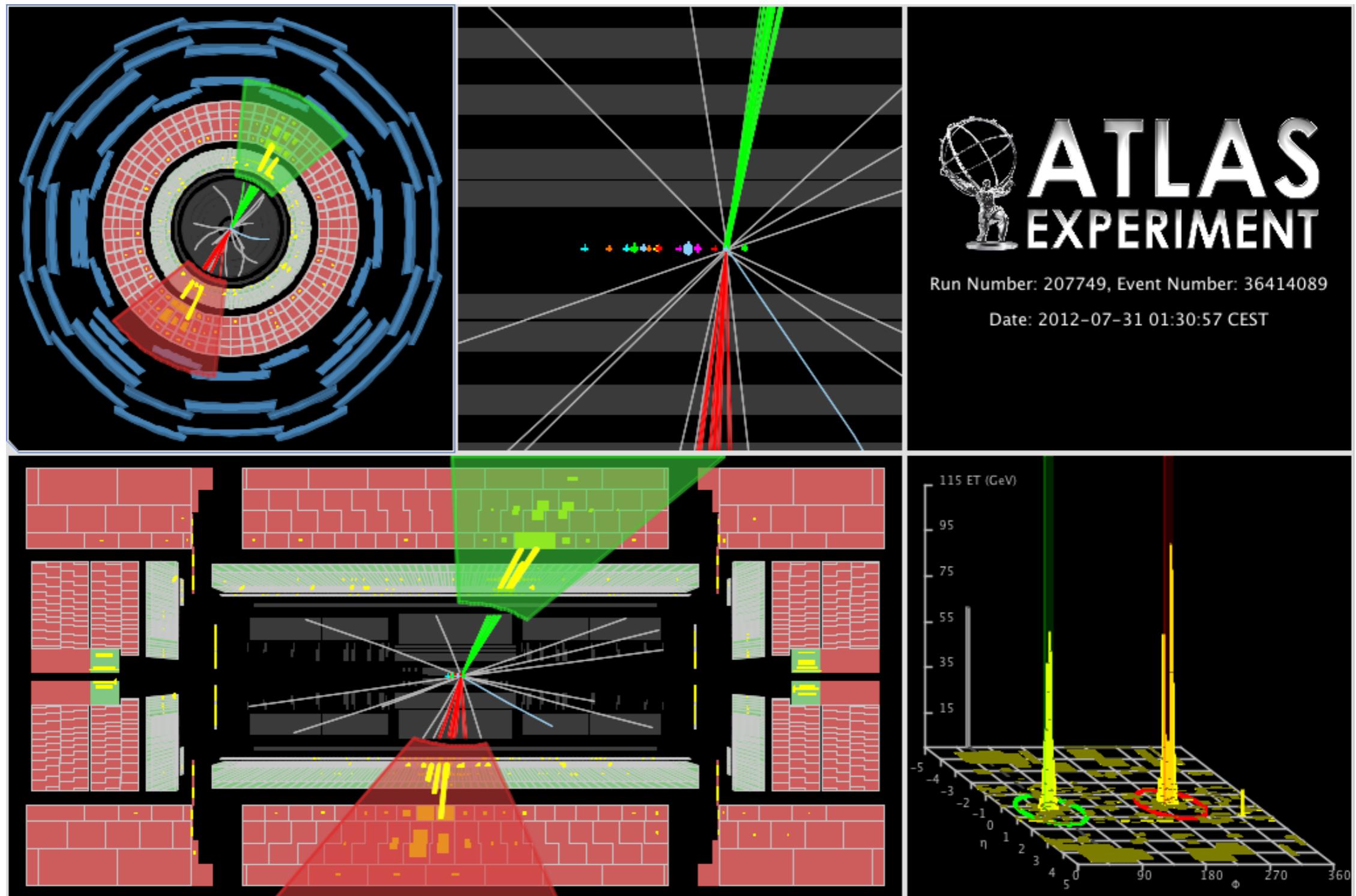


ATLAS-CONF-2015-035

How Two (FAT) JETS LOOK LIKE



How Two (FAT) JETS LOOK LIKE



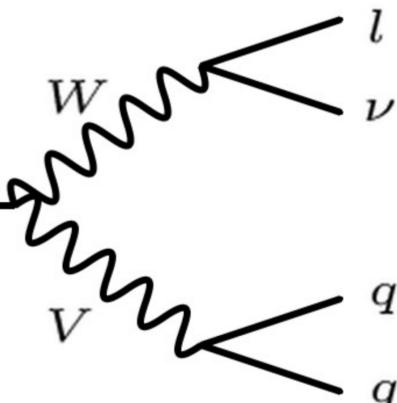
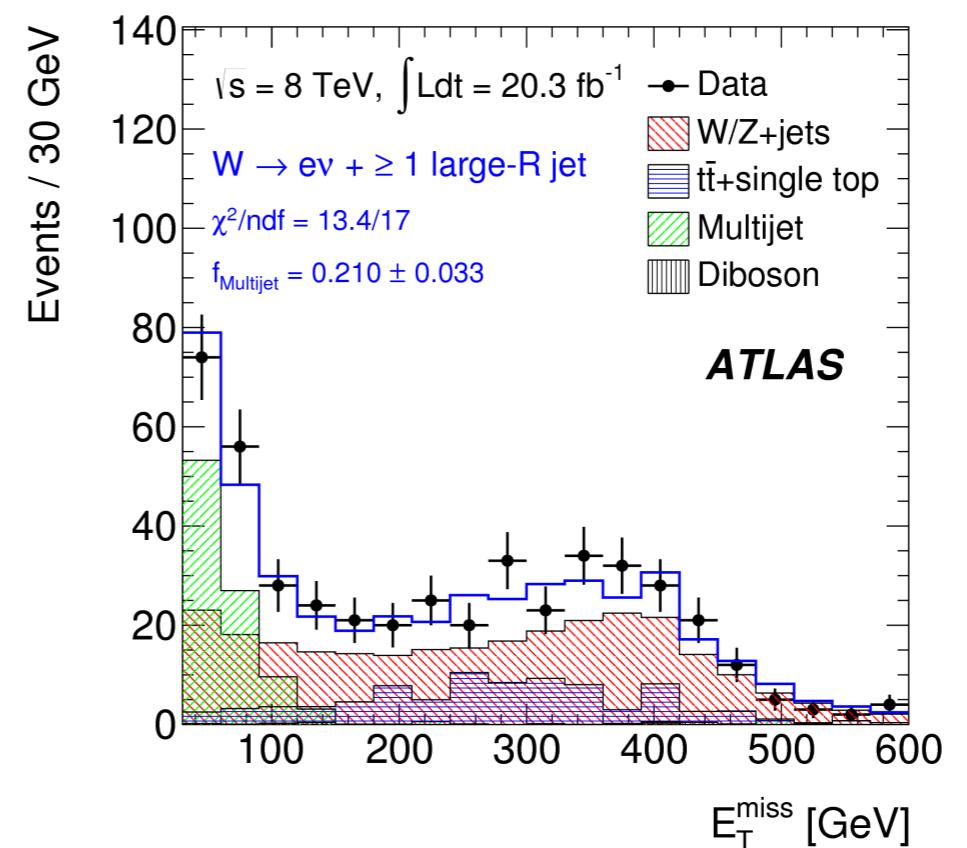
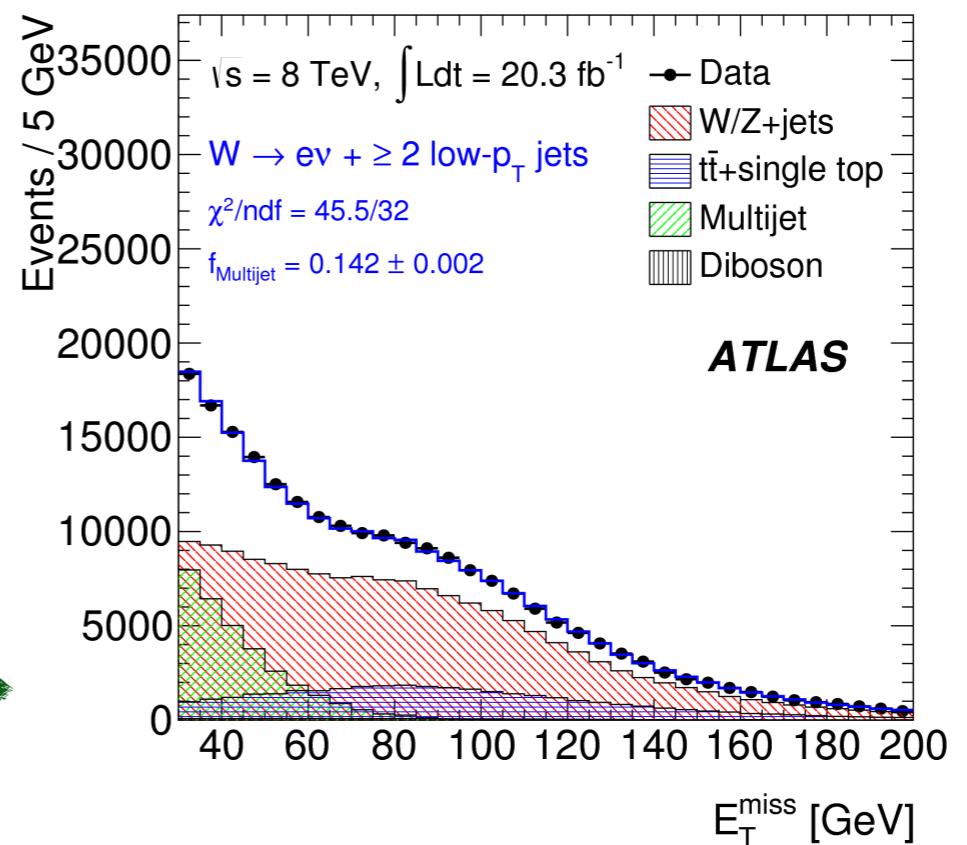
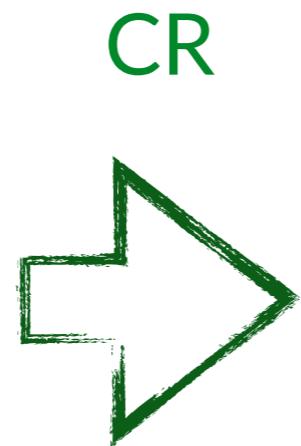
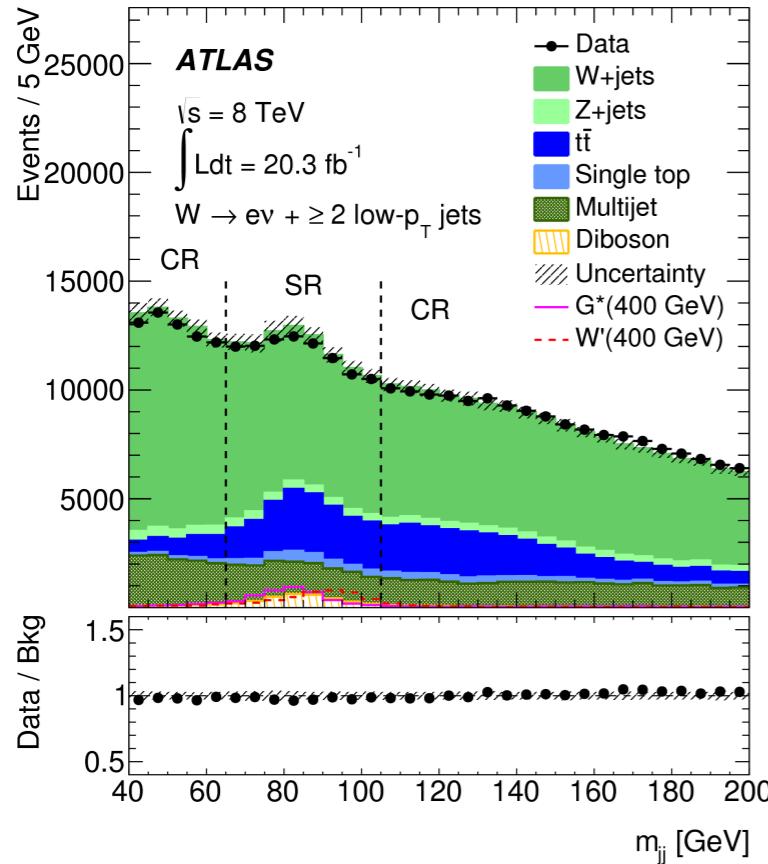
SYSTEMATICS FOR FAT JETS: THE R-TRACK METHOD

- ▶ mass/ p_T calibration of large-R jets is MC-based
- ▶ energy and mass-scale uncertainties derived using track-jets
 - ❖ calorimeter-related effects cancel out!
- ▶ e.g. mass response evaluated in MC and W/Z+jets-enriched data sample
 - ❖ average of ratio between response for calo and track jets is taken
 - ❖ ratio between this number in data and MC is checked for stability against observables
 - ◆ systematic uncertainty from mismodeling, if significant

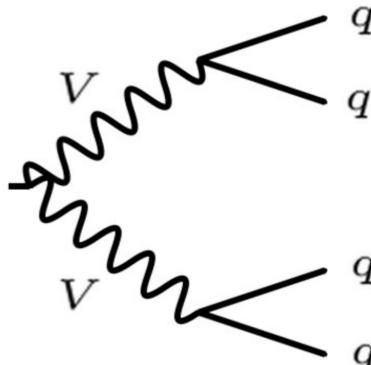
$X \rightarrow WZ \rightarrow \ell^{\pm} \nu \ell'^{\mp} \ell'$: BACKGROUND ESTIMATION

- ▶ WZ
 - ❖ from CR with inverted $\Delta\text{eta}(W, Z)$, $\Delta\phi(l, \text{MET})$ cuts
 - ❖ dominant source of uncertainty
- ▶ $l l' + \text{jets}$ (≥ 1 lepton from jet)
 - ❖ select events with lepton trigger, less stringent lepton cuts (no iso/IP)
 - ❖ measure fake factor on $Z + \text{jets}$ ($\text{MET} < X$ cut), dijet samples
 - ◆ enforced topology, fake = $0.10 \pm 30\%$
 - ➡ uncertainty due to $Z + \text{jets}$ vs dijet
 - ❖ apply it in $|l| > l'$ and $|l'| > l$ regions
 - ◆ validated in low-MET CR

$X \rightarrow VV \rightarrow qq\ell\nu$: BACKGROUND ESTIMATION

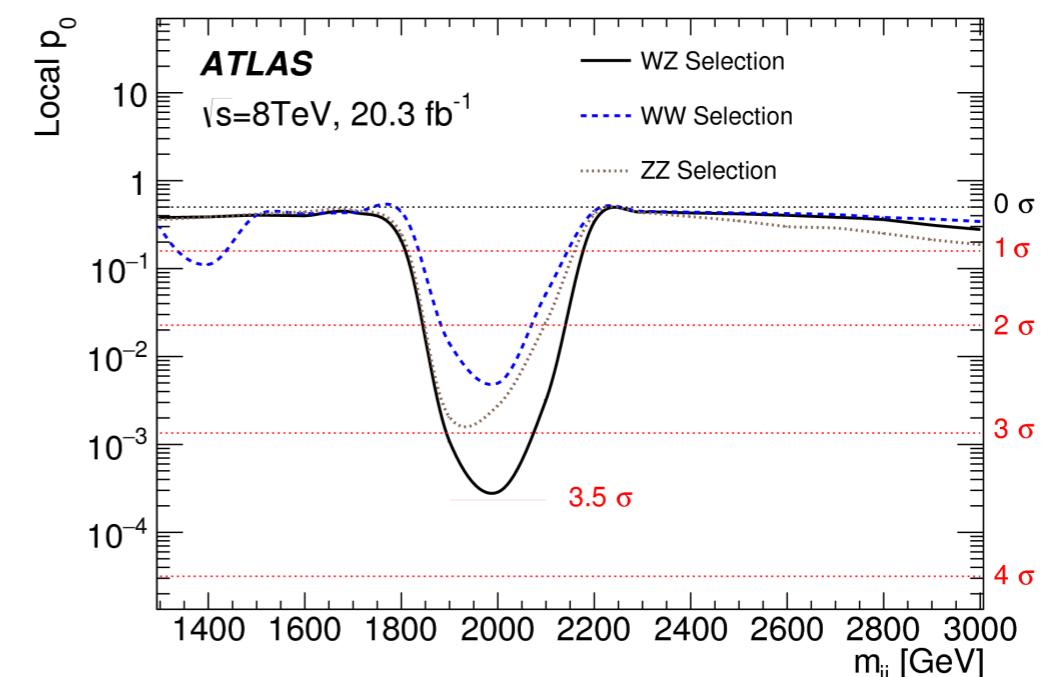


$X \rightarrow WZ/WW/ZZ \rightarrow qqqq$: MORE DETAILS

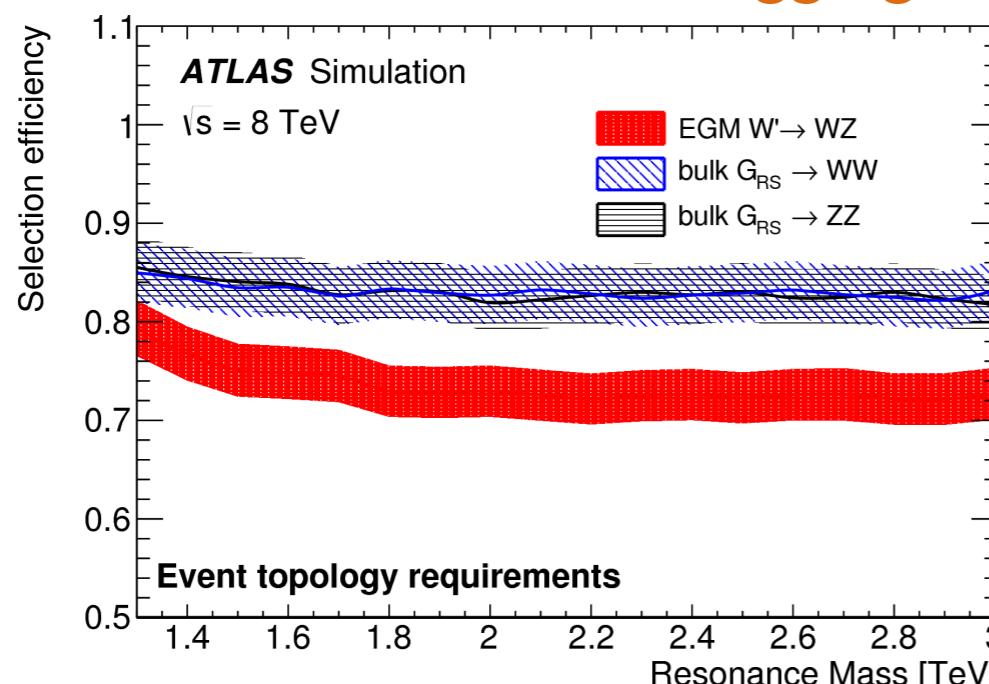


Source	Uncertainty	Constraining pdf
Jet p_T scale	2%	$G(\alpha_{PT} 1, 0.02)$
Jet p_T resolution	20%	$G(\sigma_{r_E} 0, 0.05 \times \sqrt{1.2^2 - 1^2})$
Jet mass scale	3%	$G(\alpha_m 1, 0.03)$

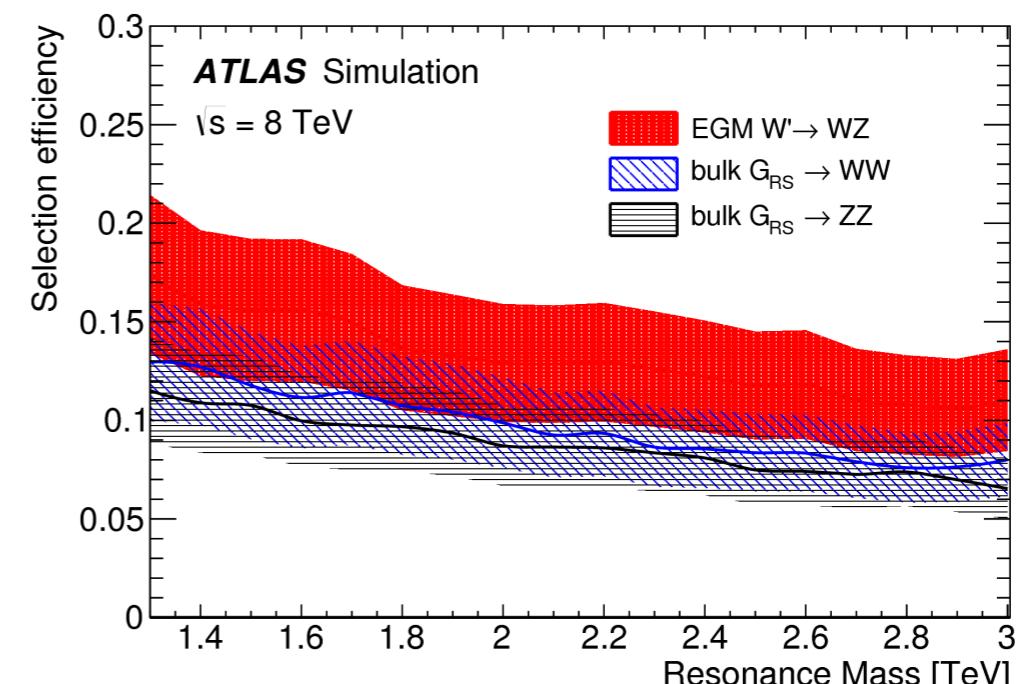
Source	Uncertainty
Efficiency of the track-multiplicity cut	20.0%
Jet mass scale	5.0%
Jet mass resolution	5.5%
Subjet momentum-balance scale	3.5%
Subjet momentum-balance resolution	2.0%
Parton shower model	5.0%
Parton distribution functions	3.5%
Luminosity	2.8%



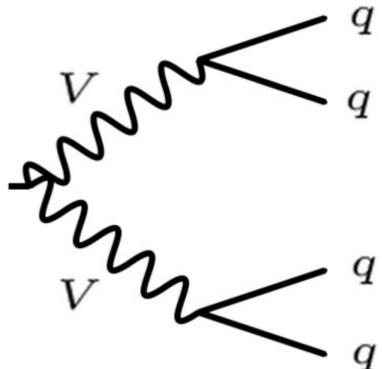
all but boson tagging



full selection



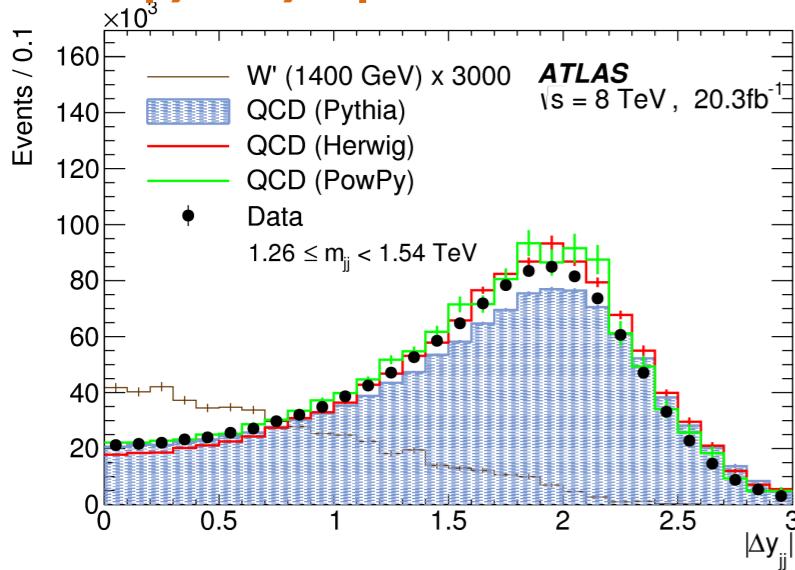
$X \rightarrow WZ/WW/ZZ \rightarrow qqqq$: MORE DETAILS



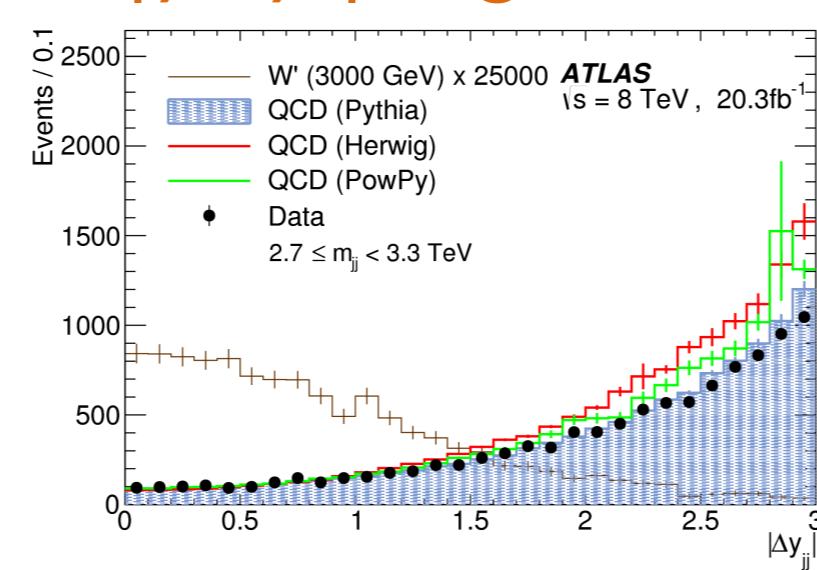
signals

m [TeV]	$\Gamma_{W'}$ [GeV]	$\Gamma_{G_{\text{RS}}}$ [GeV]	$W' \rightarrow WZ$		$G_{\text{RS}} \rightarrow WW$		$G_{\text{RS}} \rightarrow ZZ$	
			$\sigma \times \text{BR}$ [fb]	$f_{10\%}$	$\sigma \times \text{BR}$ [fb]	$f_{10\%}$	$\sigma \times \text{BR}$ [fb]	$f_{10\%}$
1.3	47	76	19.1	0.83	0.73	0.85	0.37	0.84
1.6	58	96	6.04	0.79	0.14	0.83	0.071	0.84
2.0	72	123	1.50	0.72	0.022	0.83	0.010	0.82
2.5	91	155	0.31	0.54	0.0025	0.78	0.0011	0.78
3.0	109	187	0.088	0.31	0.00034	0.72	0.00017	0.71

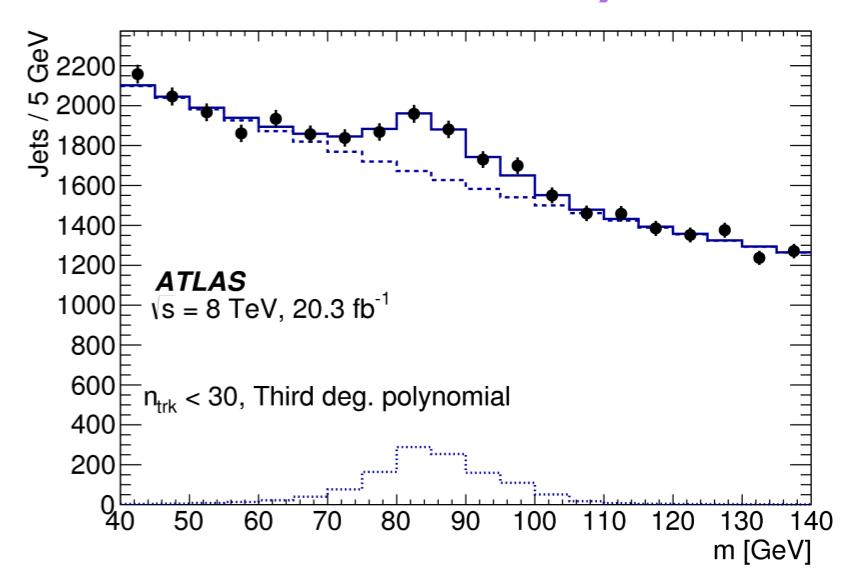
$|y_1 - y_2|$, low mass



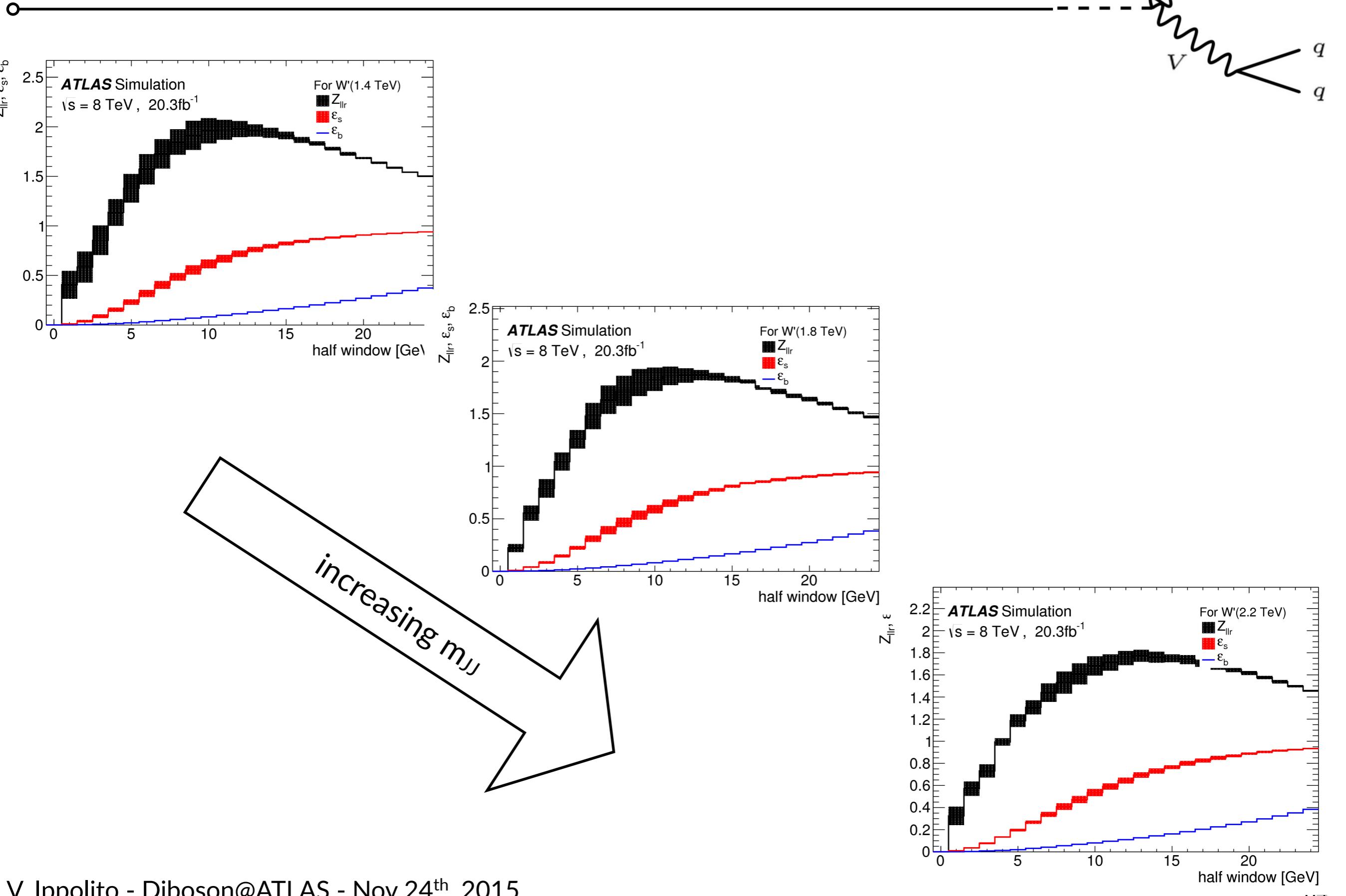
$|y_1 - y_2|$, high mass



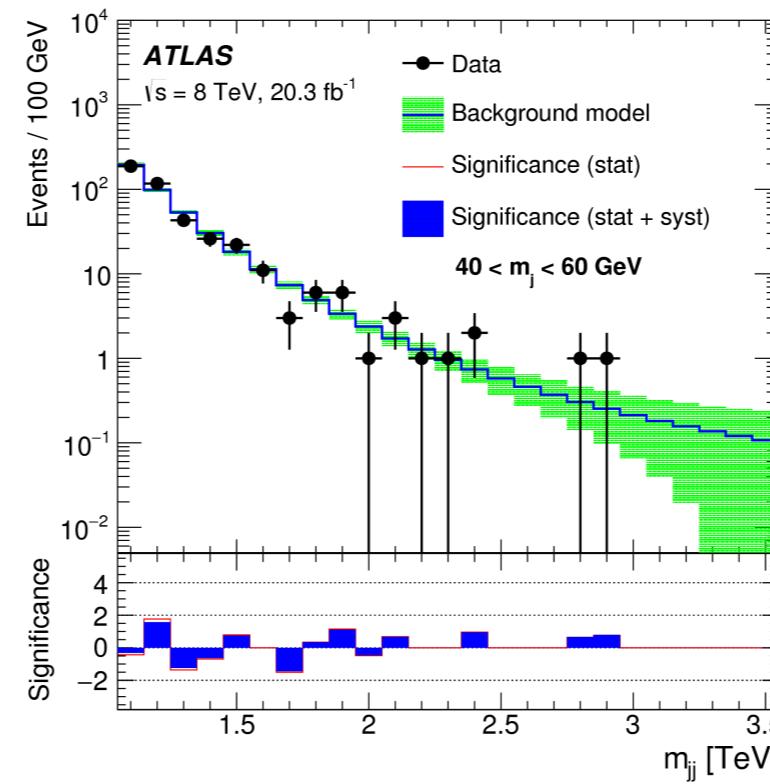
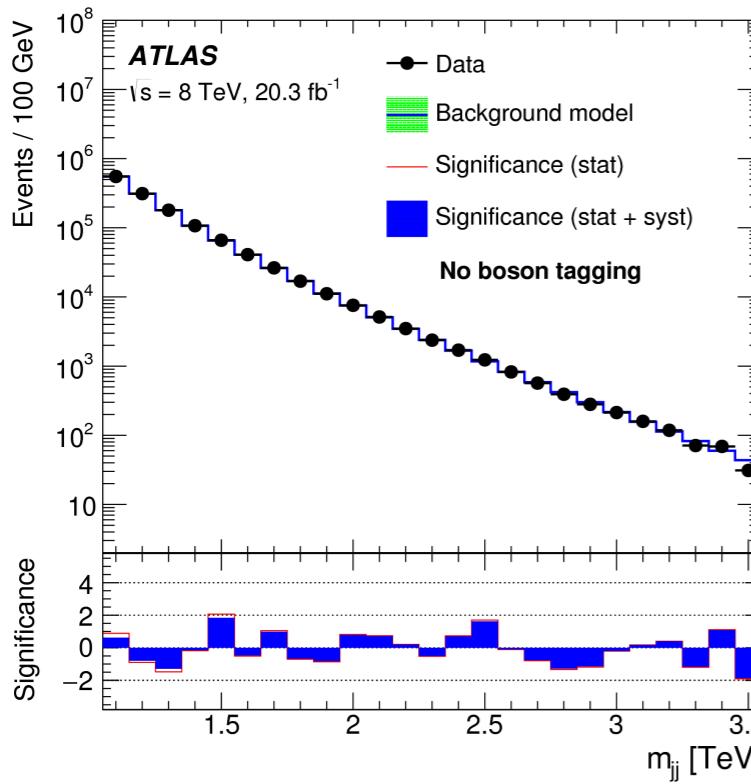
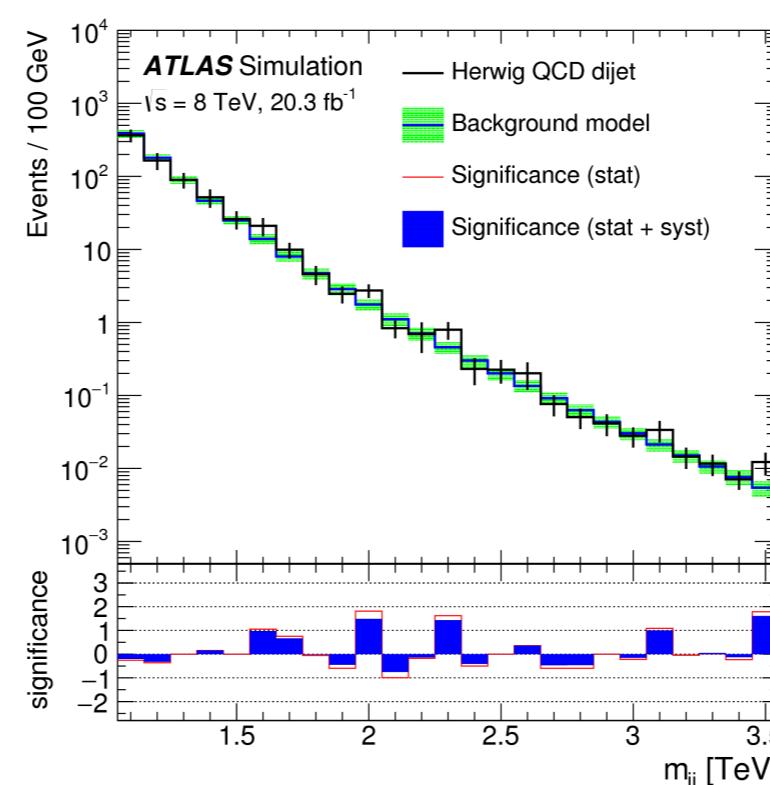
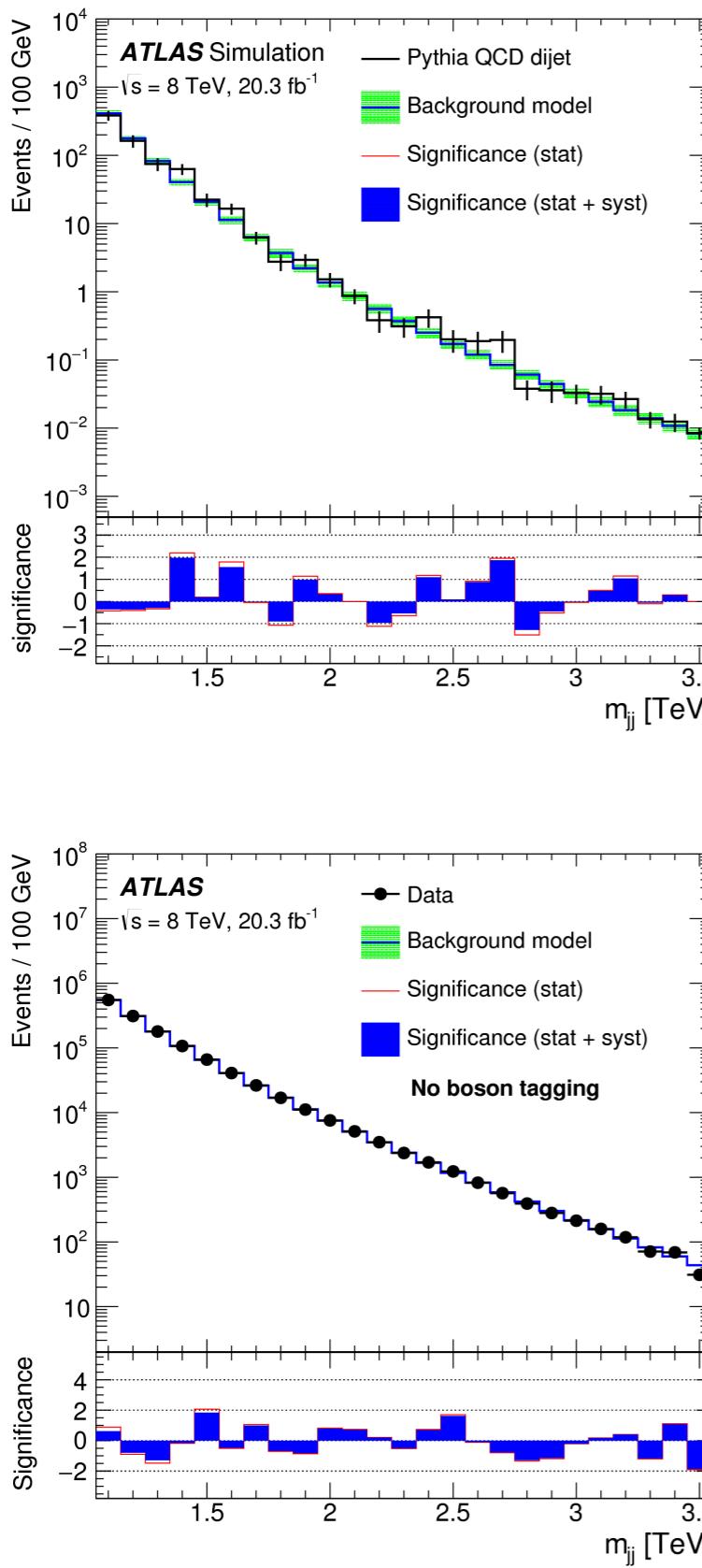
n_{trk} efficiency fit



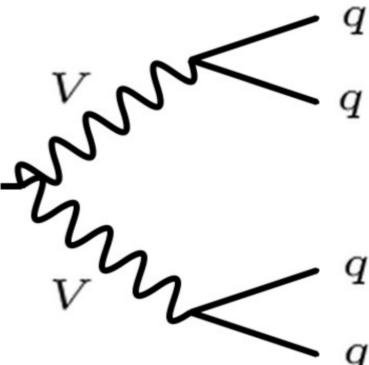
$X \rightarrow WZ/WW/ZZ \rightarrow qqqq$: M_J CUT CHOICE



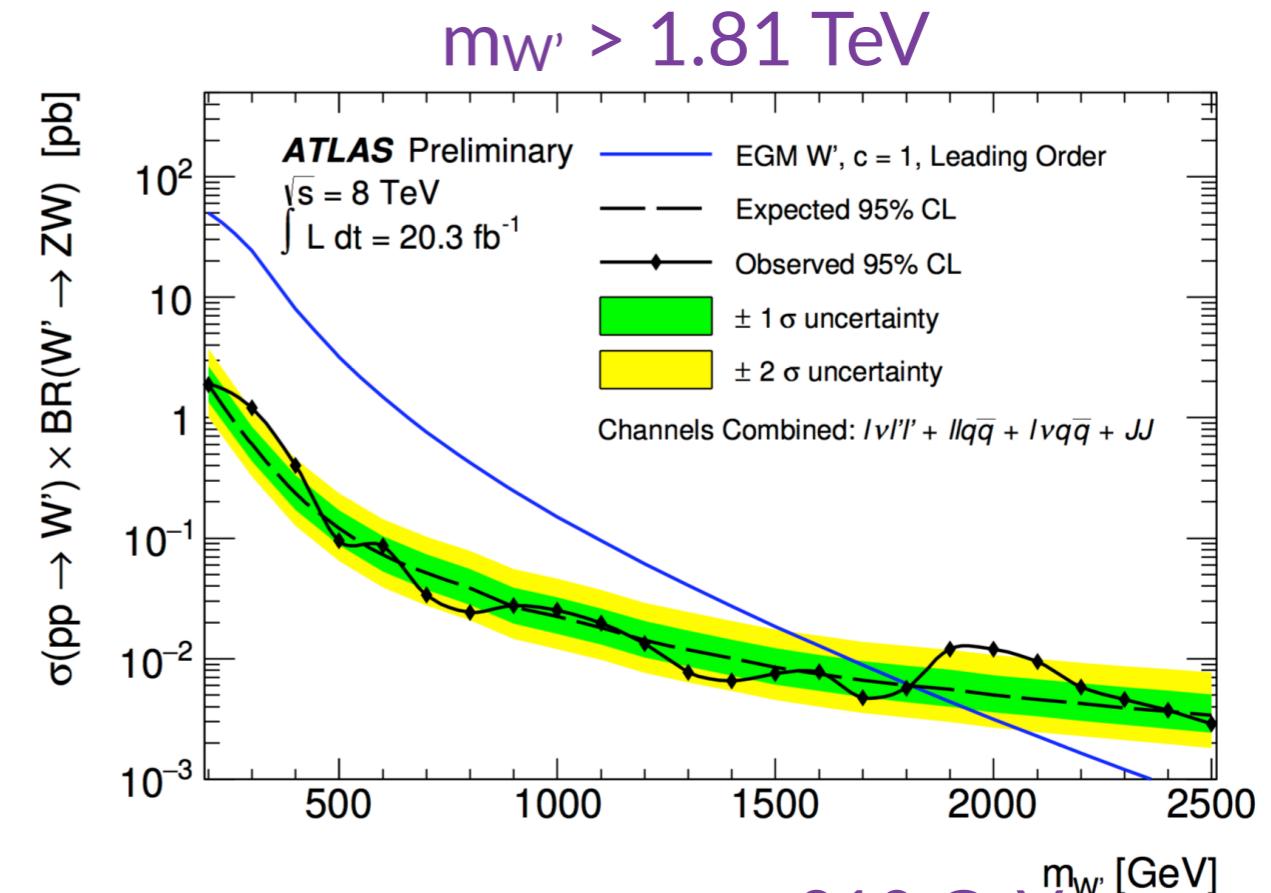
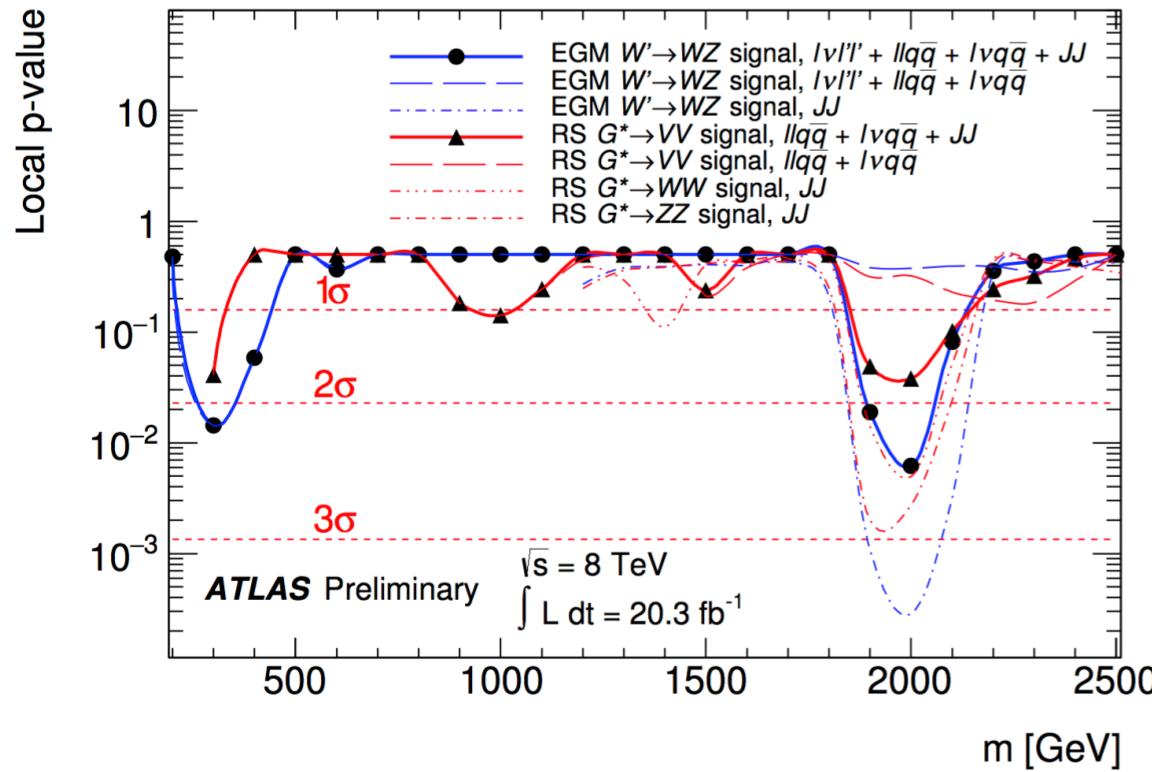
$X \rightarrow WZ/WW/ZZ \rightarrow qqqq$: FIT VALIDATION



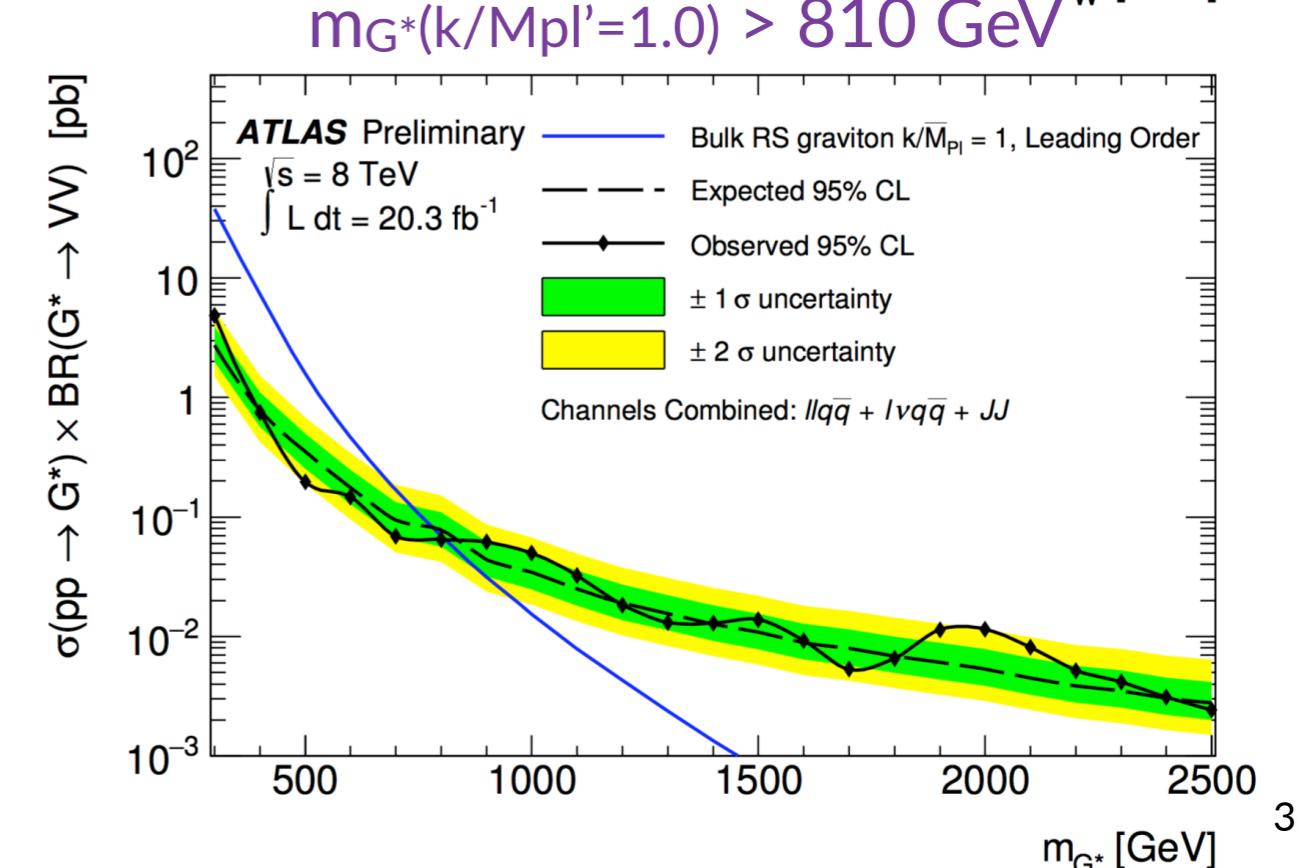
Parameter	Before tagging	WZ	WW	ZZ
ξ	4.3	3.8	4.2	4.5
p_2	30.95 ± 0.03	31.0 ± 1.4	32.5 ± 1.5	39.5 ± 2.0
p_3	-5.54 ± 0.03	-9.1 ± 1.5	-9.4 ± 1.6	-9.5 ± 2.3
Observed events	1335762	604	425	333



COMBINATION

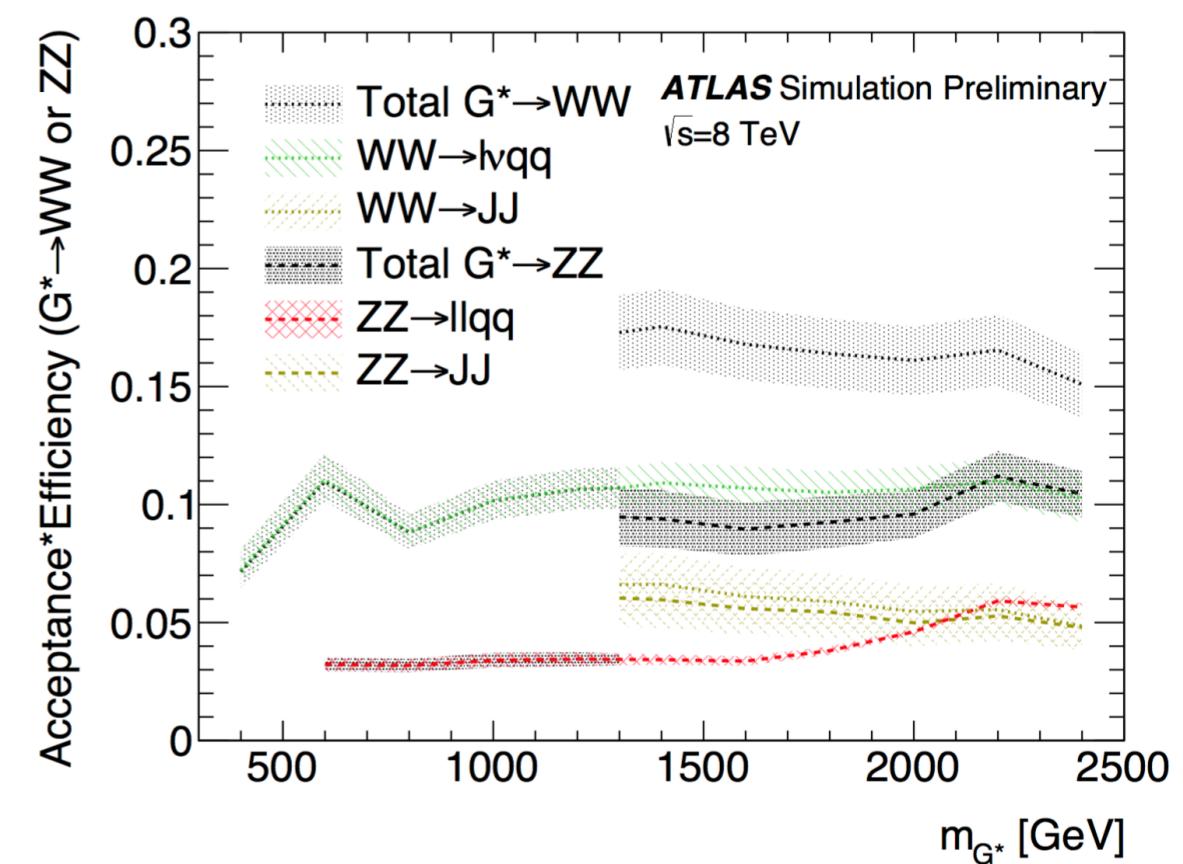
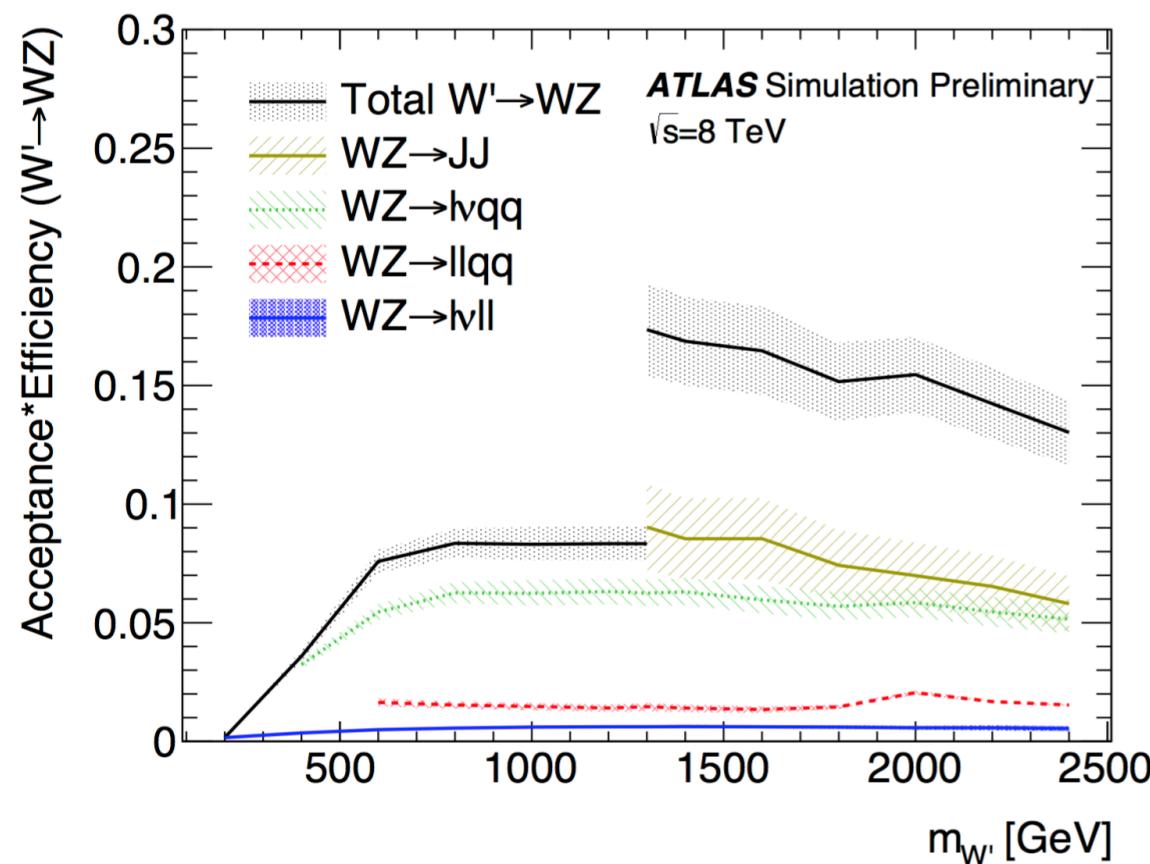


- 2 TeV: local p0 reduced to 2.5σ (other channels more bkg-like)
- best sensitivity from $l\nu qq$ /
 $qqqq$, $l\nu ll$ at low mass



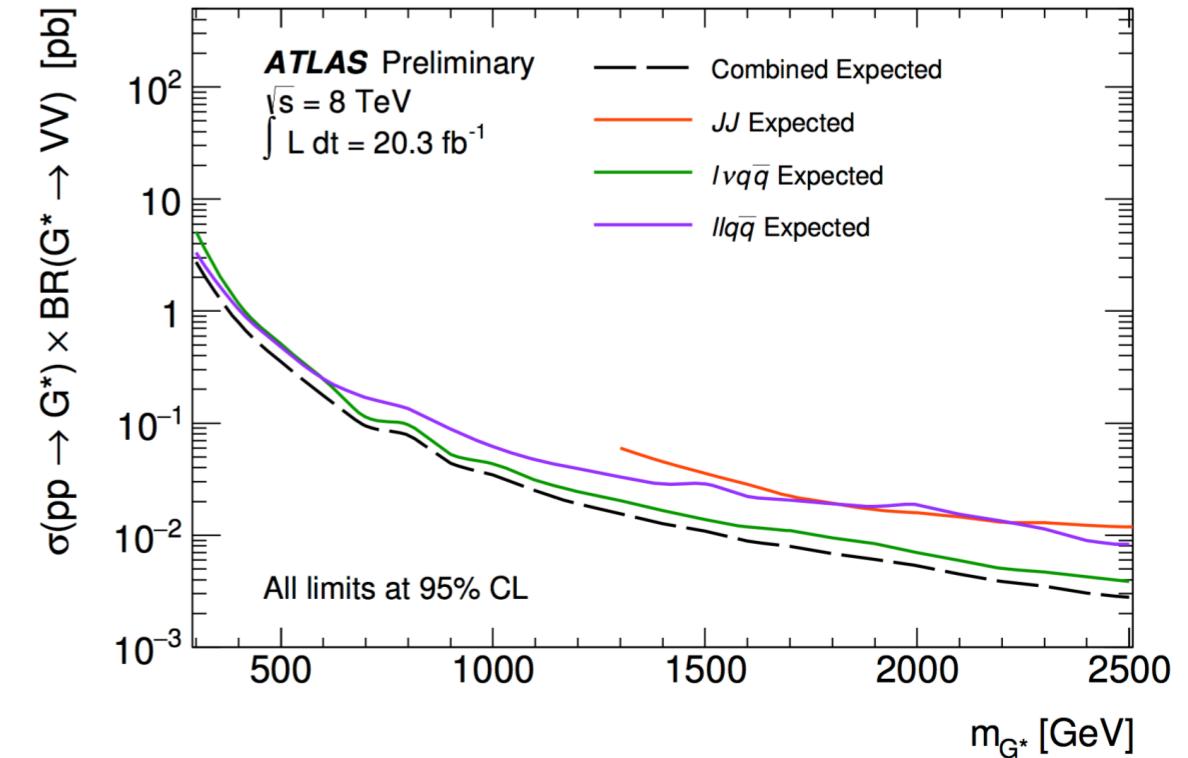
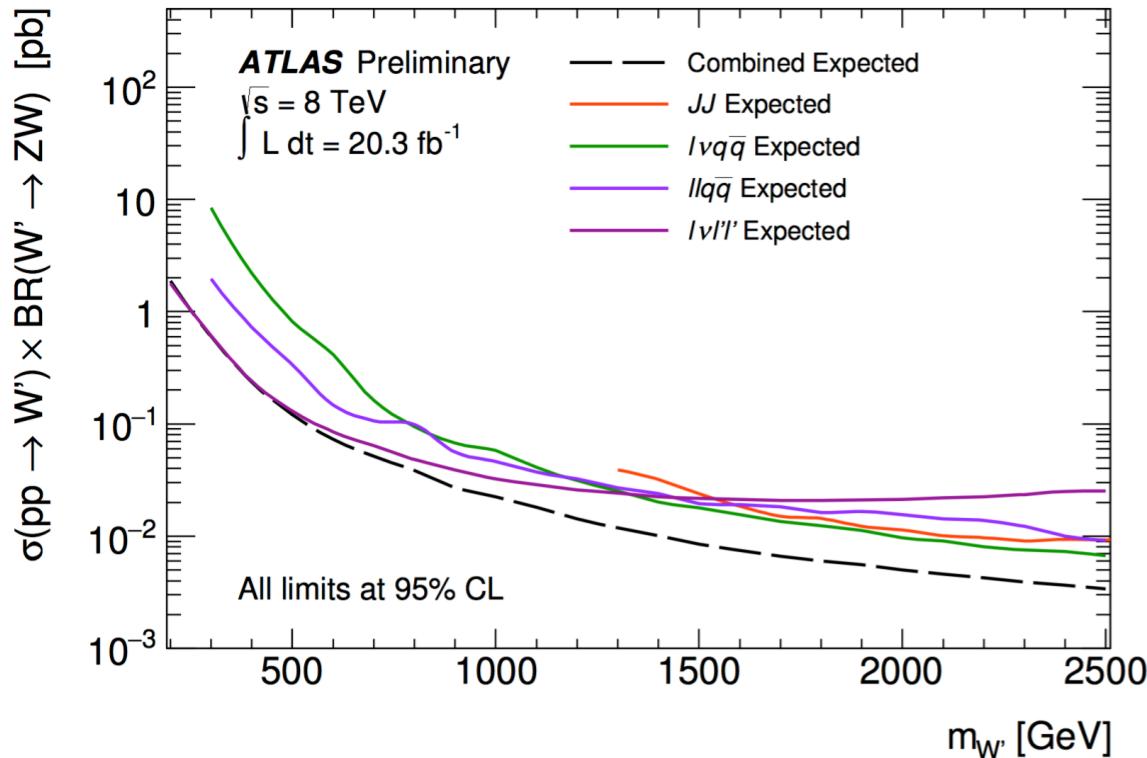
COMBINATION

W' : best sensitivity from $l\nu ll$ (low mass), $l\nu qq/qqqq$ (high mass)
 G^* : best sensitivity from $l\nu qq$



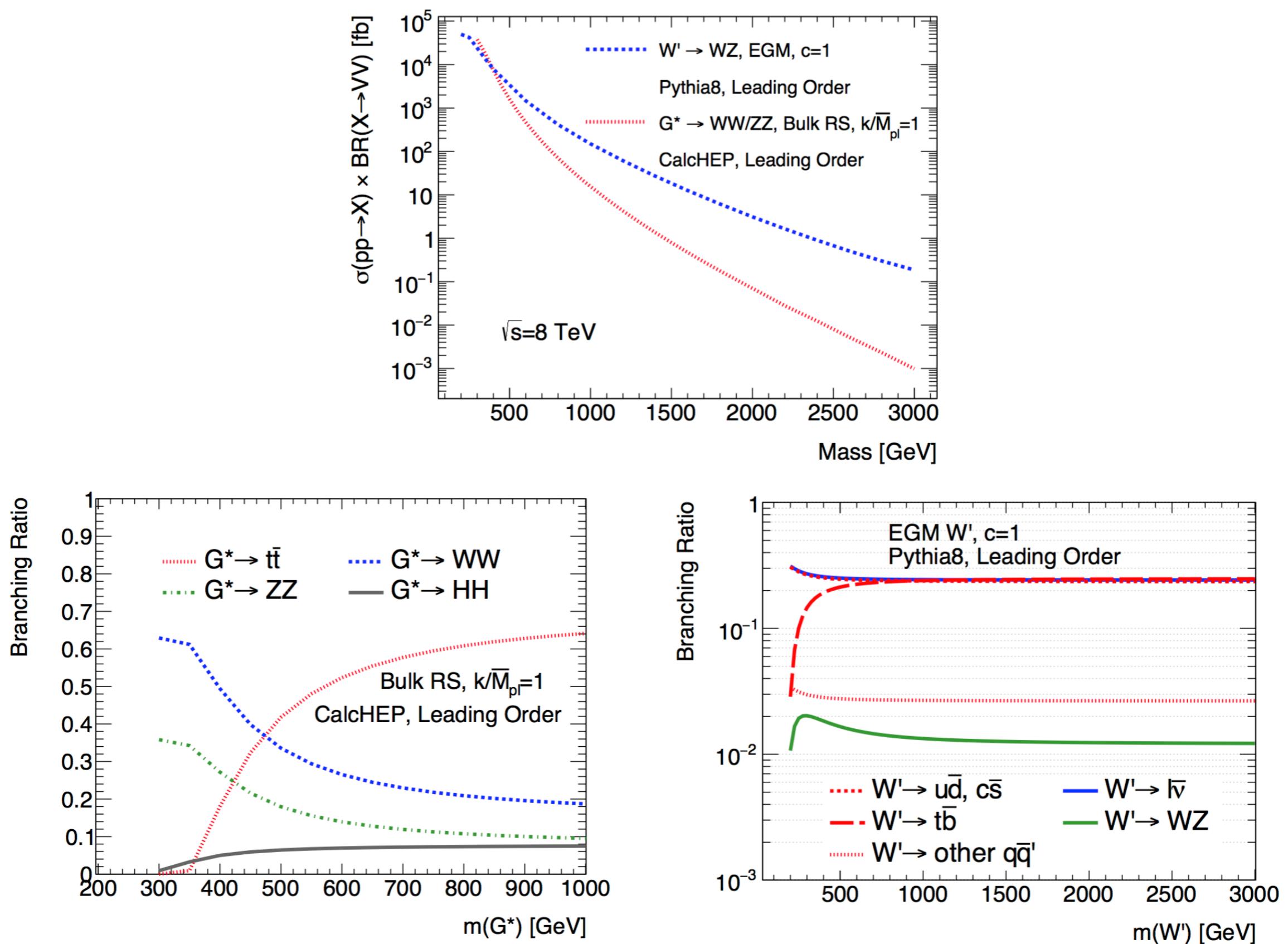
COMBINATION

W' : best sensitivity from $\ell\nu\ell'\ell'$ (low mass), $\ell\nu q\bar{q}$ / $qq\bar{q}q$ (high mass)
 G^* : best sensitivity from $\ell\nu q\bar{q}$



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- p_T resolved	0.3-0.9	0.2-0.9
	high- p_T resolved	0.6-2.5	0.6-0.9
	merged	0.9-2.5	0.9-2.5
$\ell\nu q\bar{q}$	low- p_T resolved	0.3-0.8	0.2-0.7
	high- p_T 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

COMBINATION: CROSS-SECTION & BRANCHING RATIOS





0-lepton (20/30/2% efficiency at 0.4/1/2 TeV)

- MET, TrackMET cuts (close by 45°, no jet within 85°)
- MET-dependent bb ΔR cut
- MET back-to-back w.r.t. bb system

1-lepton (8/20/2% efficiency at 0.4/1/2 TeV)

- tight lepton definitions
- no jet close to MET, $\text{MET}/m_T > 30/20$ GeV, m_W mass constraint
- enhance signal with $p_T(W) > 0.4 \times m_{VH}$

2-leptons (18/30/1% efficiency at 0.4/1/2 TeV)

- dilepton mass cut
- reject ttbar with $\text{MET} < 60$ GeV
- enhance signal with $p_T(Z) > 0.4 \times m_{VH}$

+ m_{bb} constraint to m_H



multijet: data-driven

- 0-lep: ABCD with $\Delta\Phi(\text{MET}, \text{jet})$ vs $\Delta\Phi(\text{MET}, \text{TrackMET})$
- 1-lep: template for MET fit from inverted lepton criteria ($\sim \text{lvqq}$)
- 2-e ($\mu \sim 0$): shape from inverted isolation, norm from m_{ee} fit

W/Z+jets

- fit for W/Z+cq, W/Z+hf normalisations
- modeling checked in CRs with no b-tag or with m_{bb} sidebands
 - W/Z+qq corrected vs jet $p_T(j_1)$, $p_T(j_2)$, $\Delta\Phi(j_1, j_2)$ [0-tag]
 - then, Z+cq, Z+hf corrected [2-lep]
- ttbar is fitted in $e\mu+bb$ CR, shape validated in CR

systematics

- JES [3-1% for 0.02-1 TeV $p_T(\text{jet})$], JER[20-5%] b-tagging efficiency



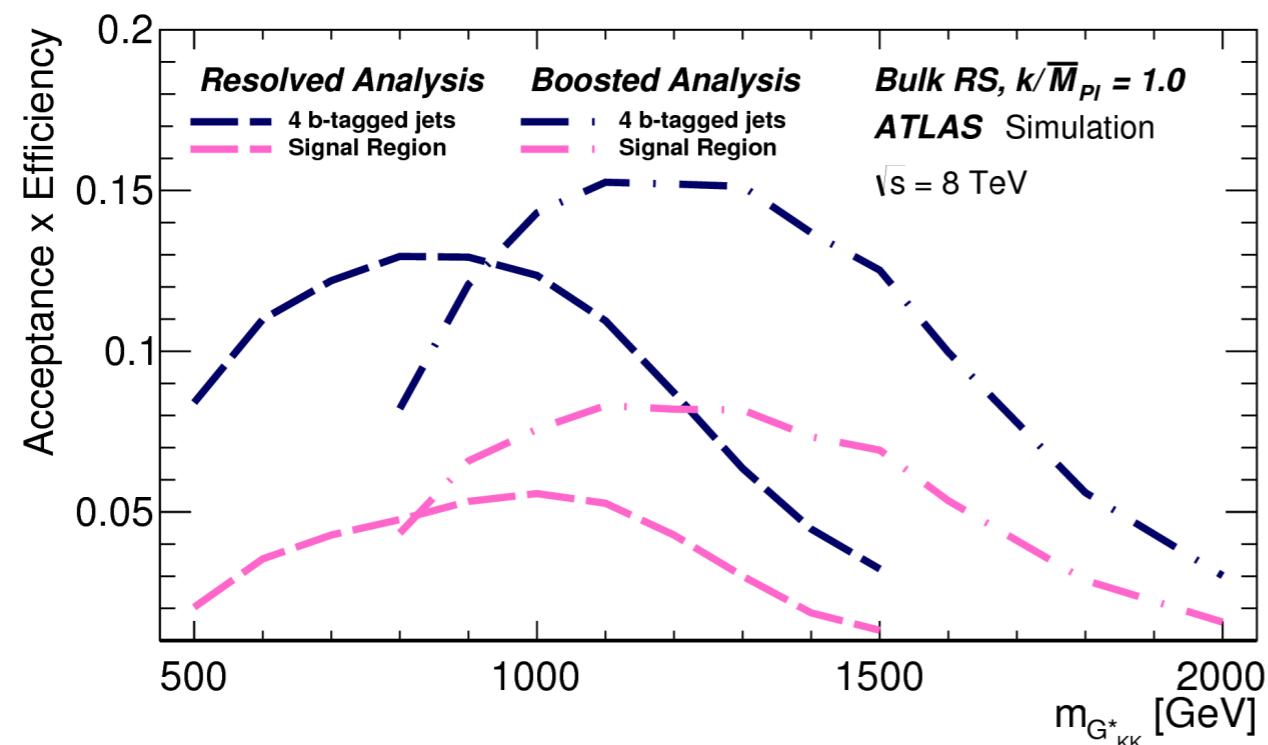
resolved

- 4 b-jets (MV1 70%/5x c-rejection/140x q,g-rejection)
- back-to-back dijets, ΔR cut between two b's
 - m_{4j} -dependent p_T and $\Delta\eta$ cuts
- top veto (most of ttbar from b-fakes from c), based on additional jets
- m_{bb} cut and then constraint to m_H
- multi-jet from ($>=$)2-tag sample, corrected from sidebands
 - and validated in CR corrected via $p_T(\text{dijet})$, $\Delta R(\text{subjets})$, $\Delta R(\text{dijets})$
- ttbar from inverted veto, $N_{SR} = e^2 / (1 - e^2) N_{CR}$ [e from semi-leptonic decays]

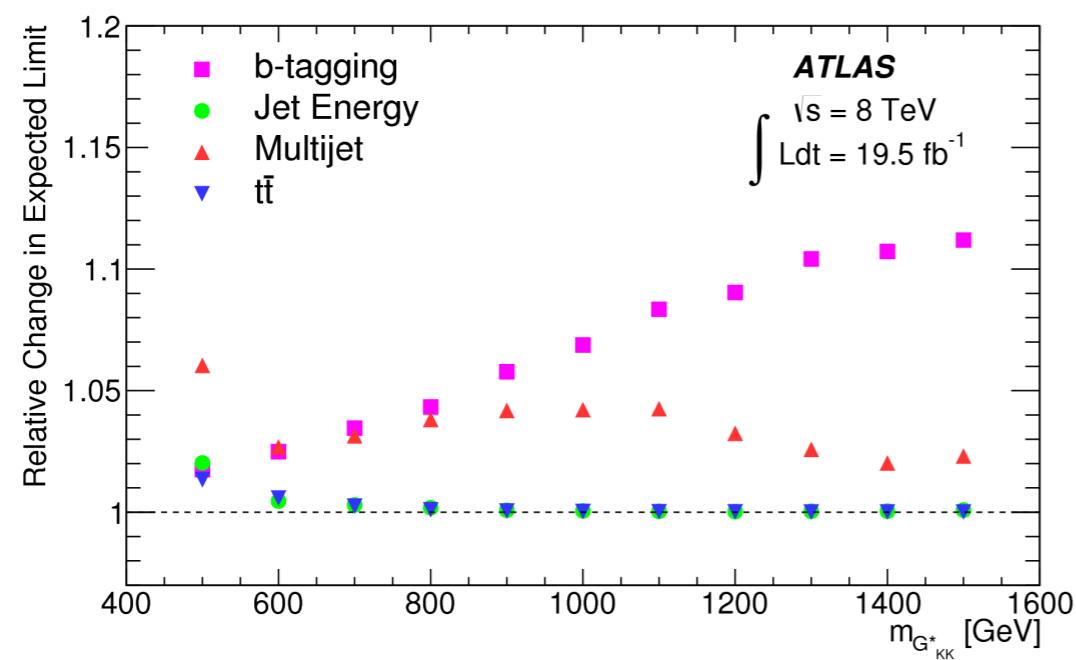
boosted

- anti- k_T $R=1.0$ trimmed jets, matched to 0.3 anti- k_T track jets
- similar bkg strategy, but merging 2 and 3-tag samples

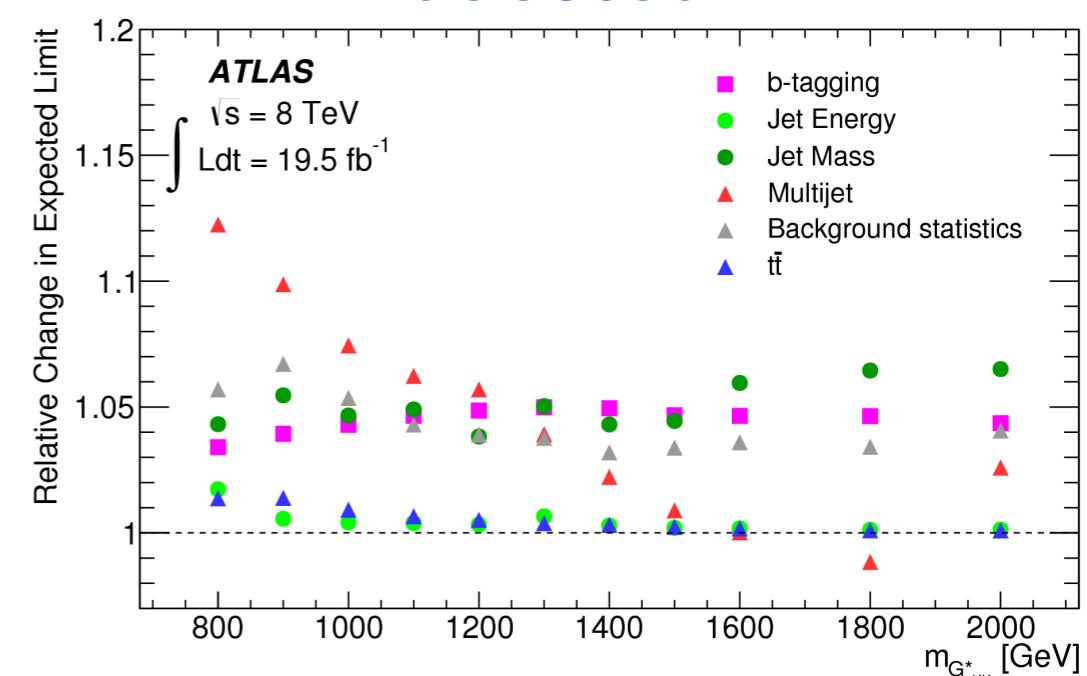
$X \rightarrow HH \rightarrow BBBB$: ACCEPTANCE & SYSTEMATICS



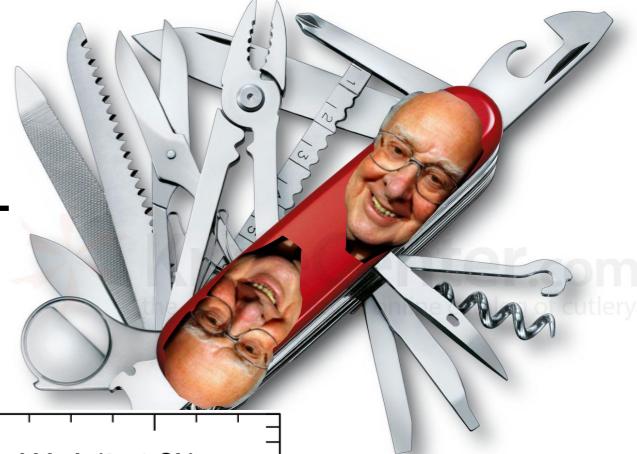
resolved



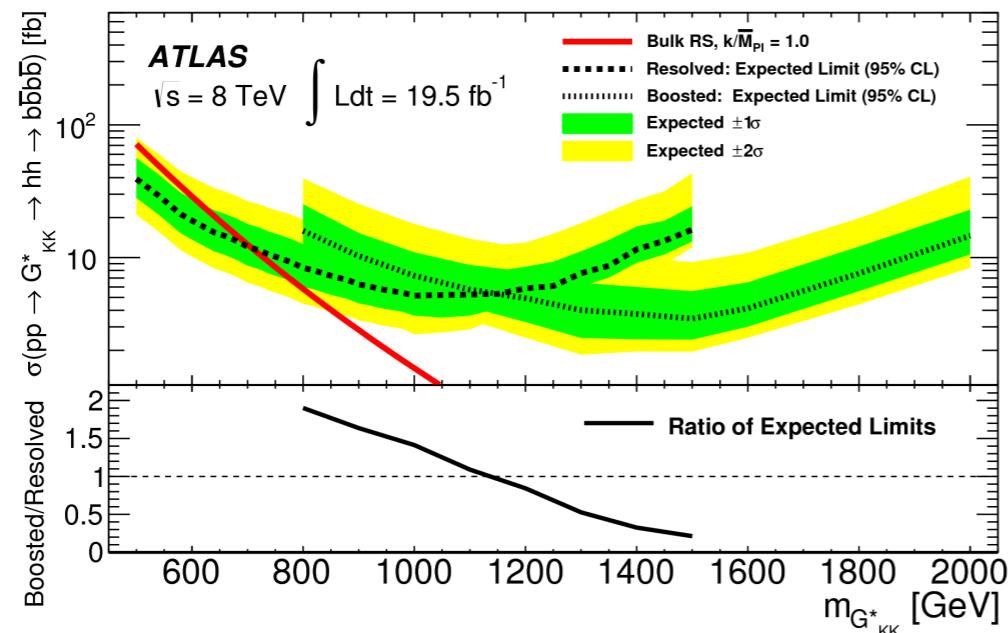
boosted



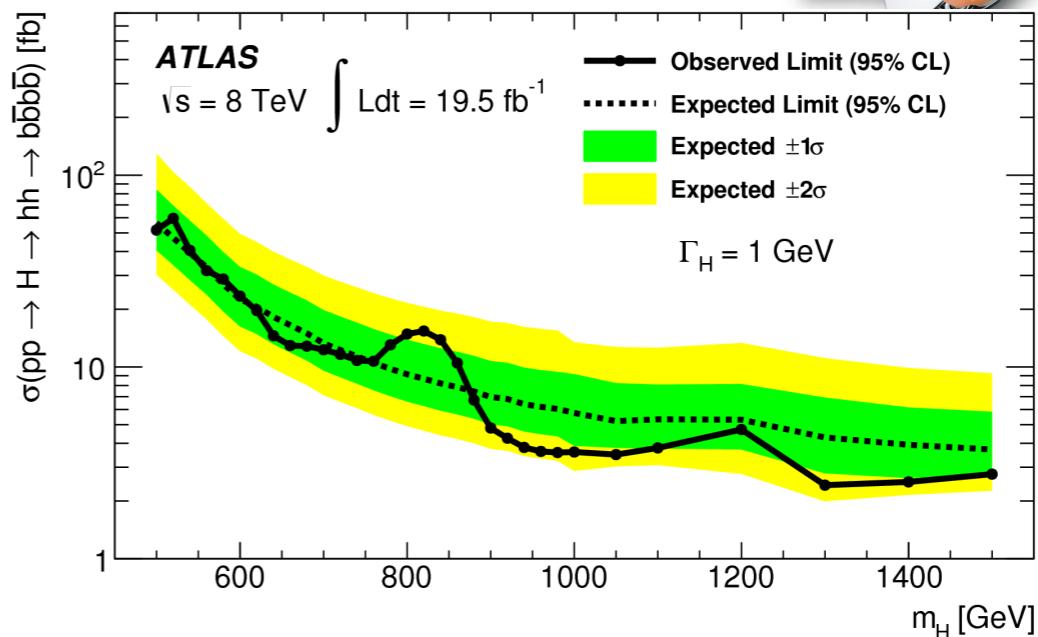
$X \rightarrow HH \rightarrow BBBB$: LIMITS



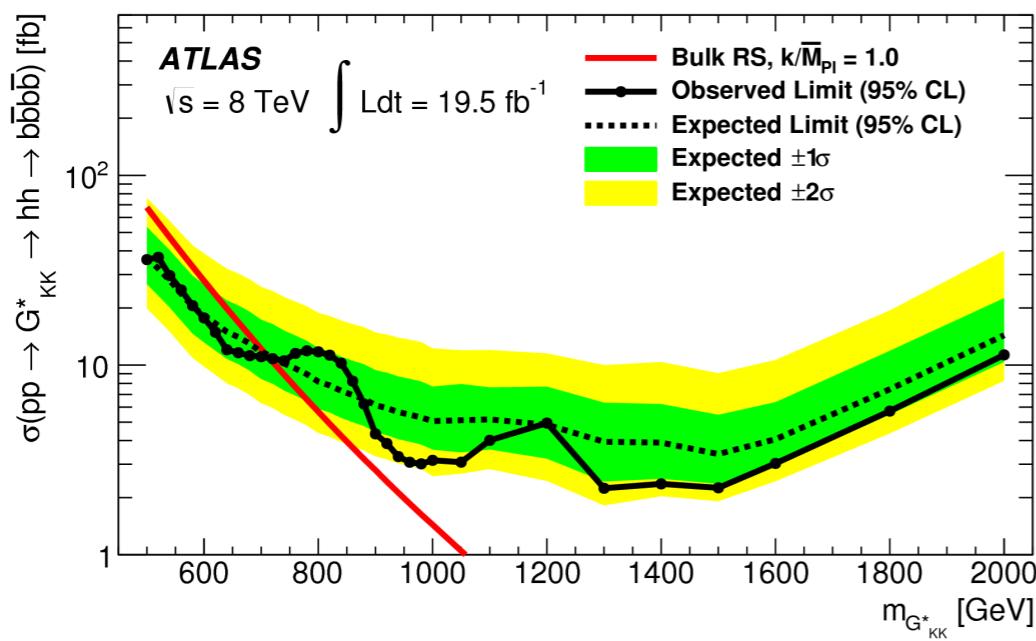
complementarity



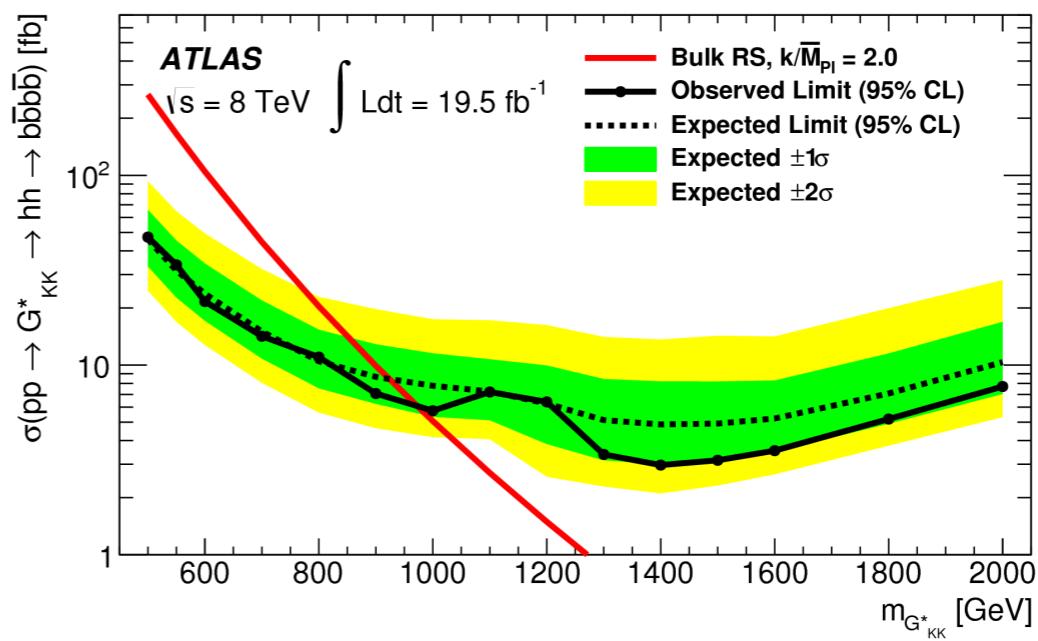
2HDM $H \rightarrow hh$



$m_{G^*}(k/MPl=1.0) > 720 \text{ GeV}$



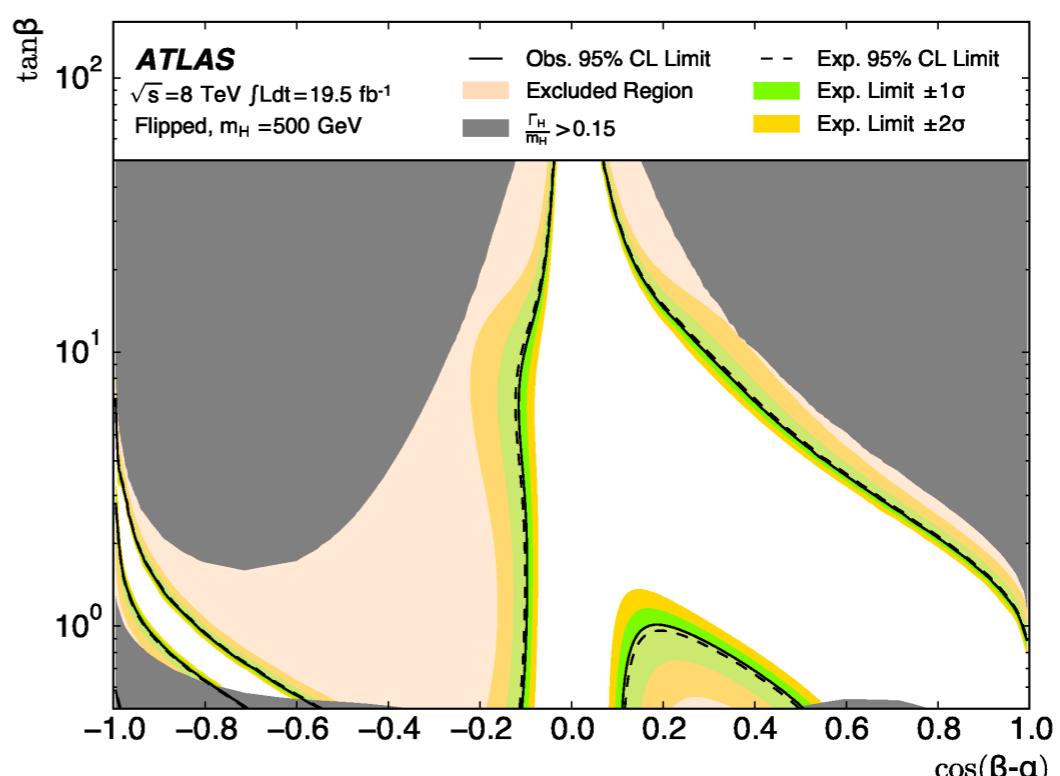
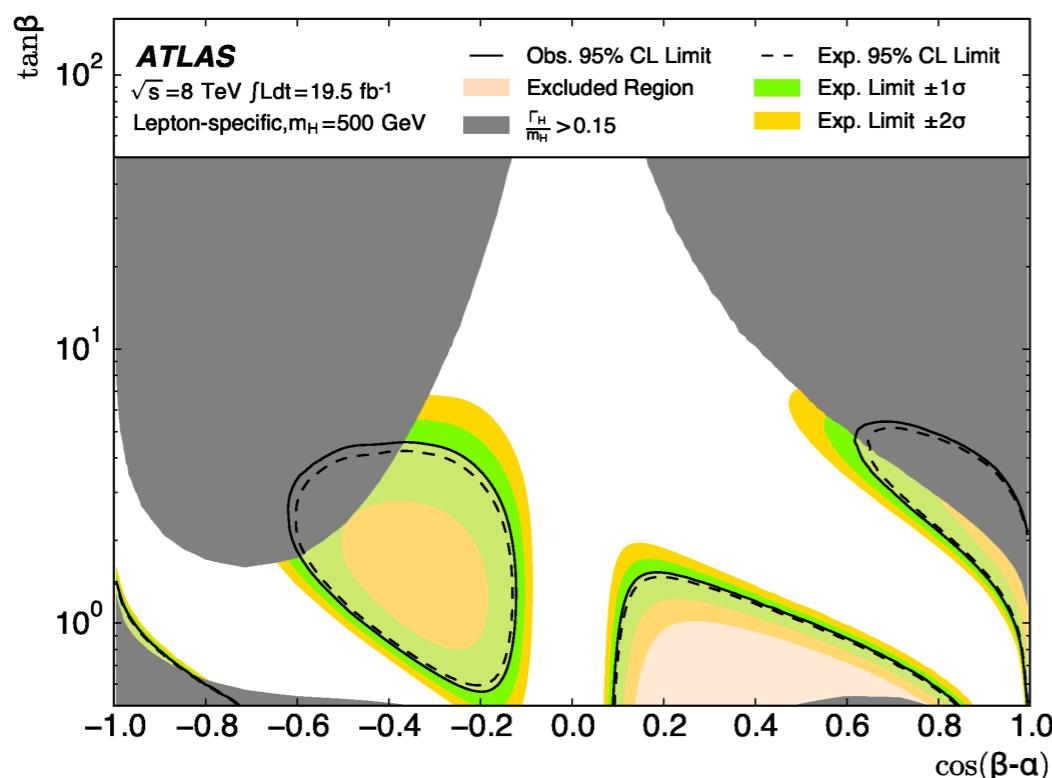
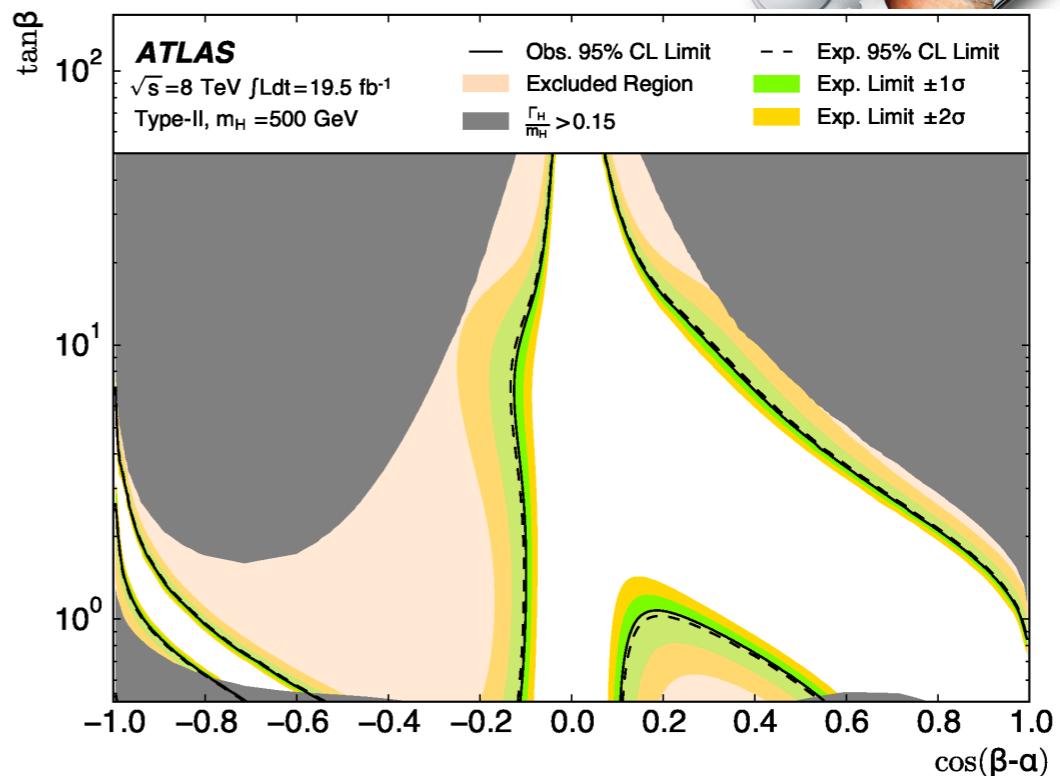
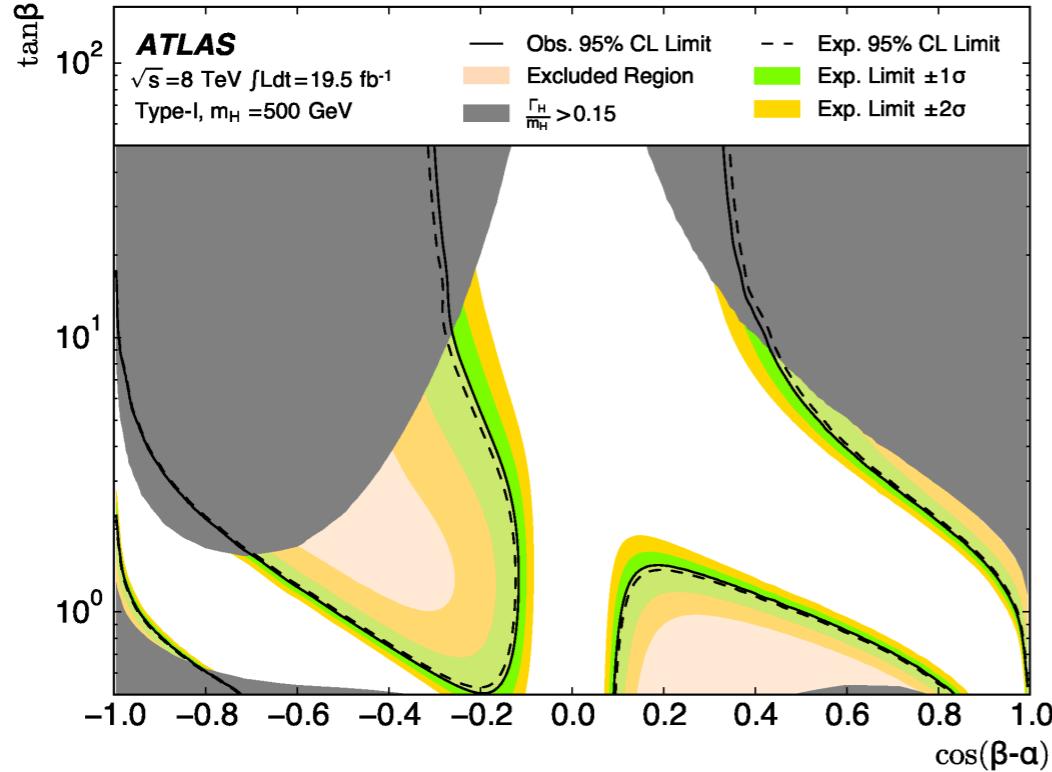
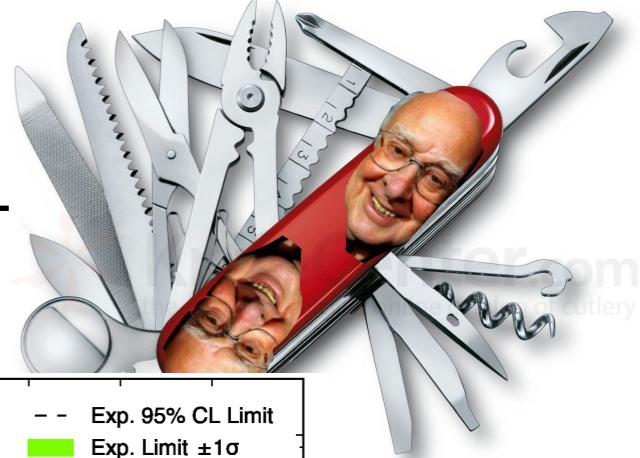
$m_{G^*}(k/MPl=2.0) > 990 \text{ GeV}$



$X \rightarrow HH \rightarrow BBBB$: 2HDM EXCLUSIONS

grey=limit not reliable

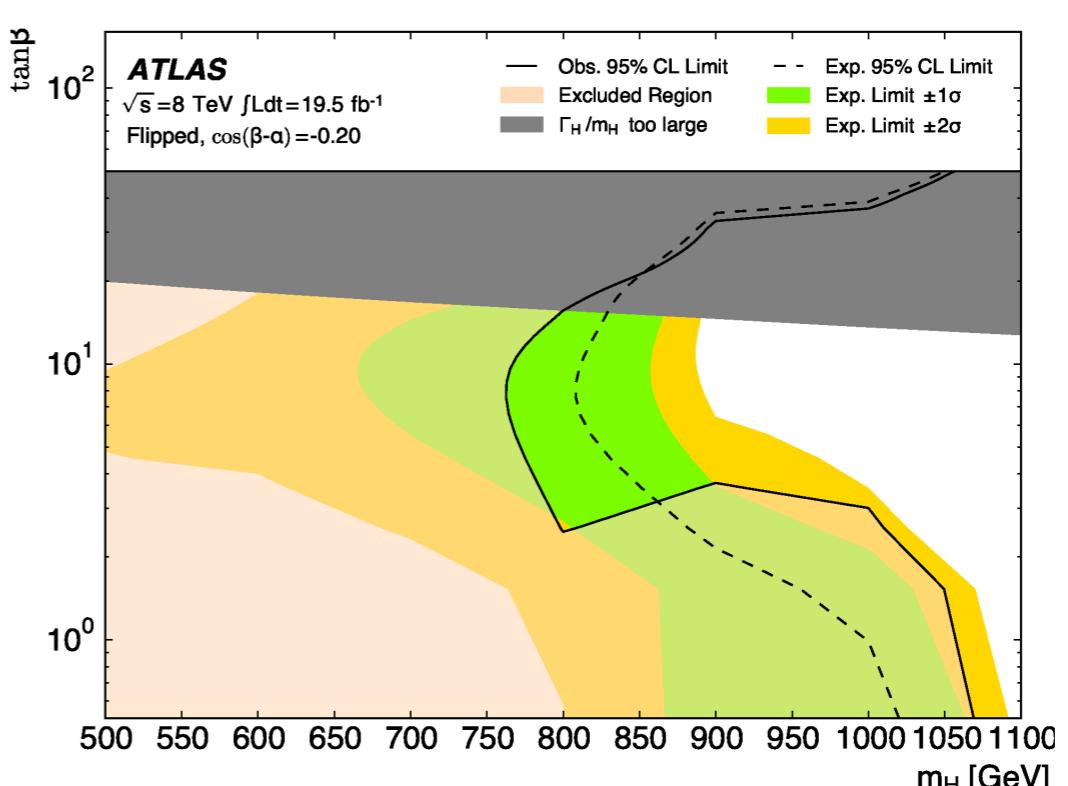
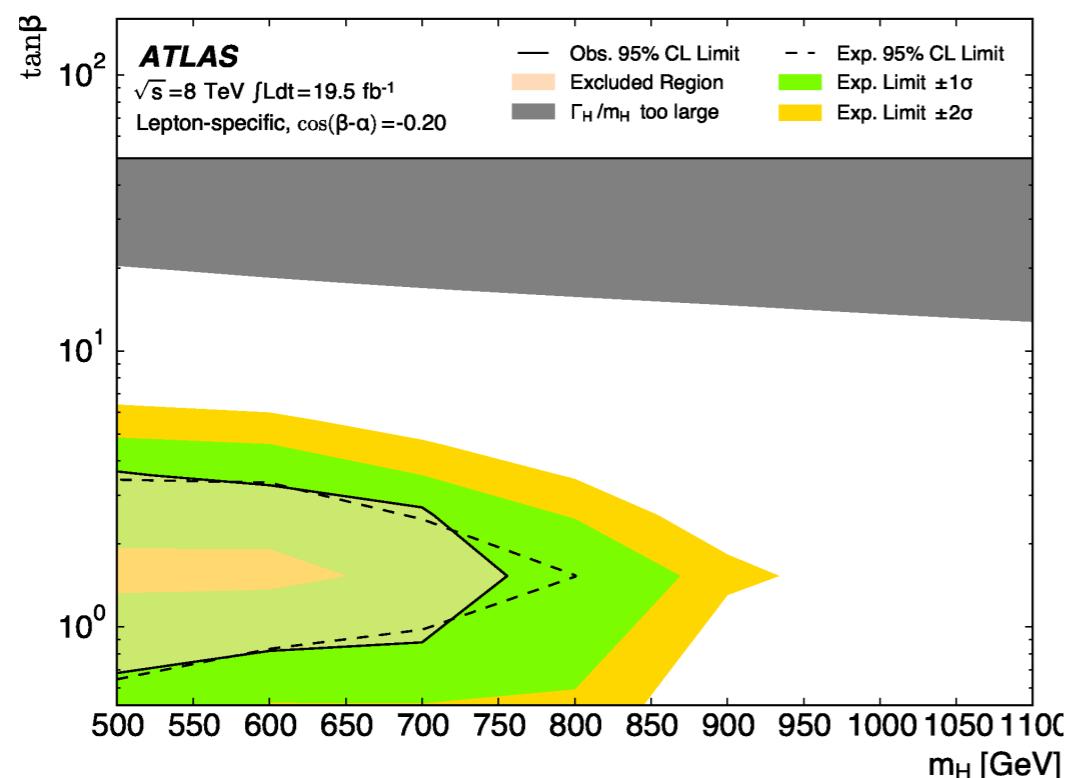
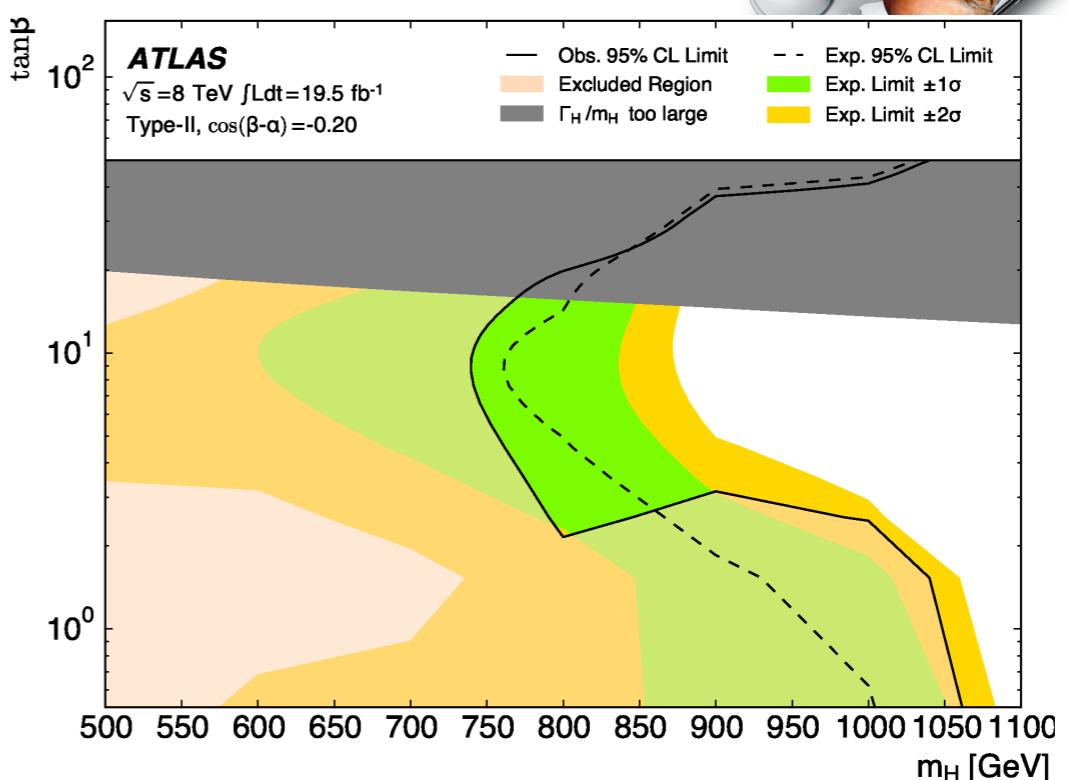
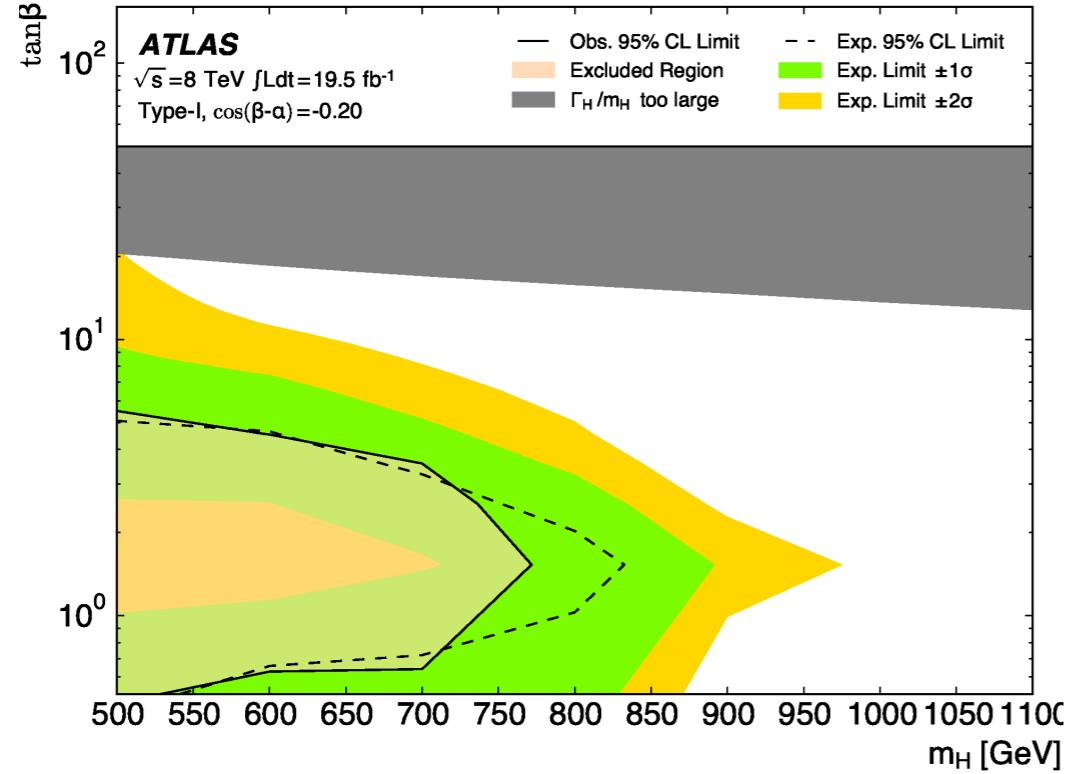
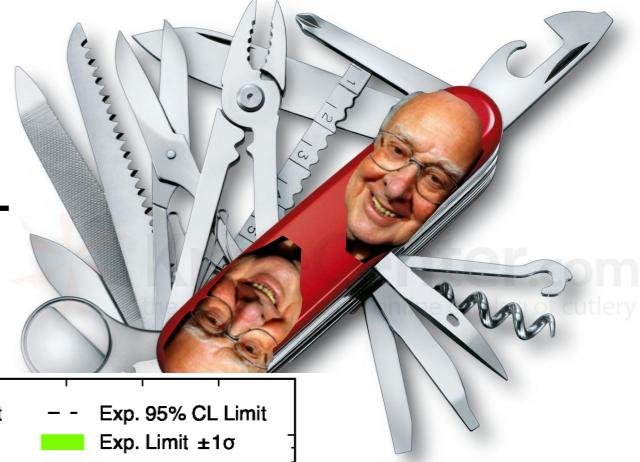
$\tan\beta, \cos(\beta-\alpha)$



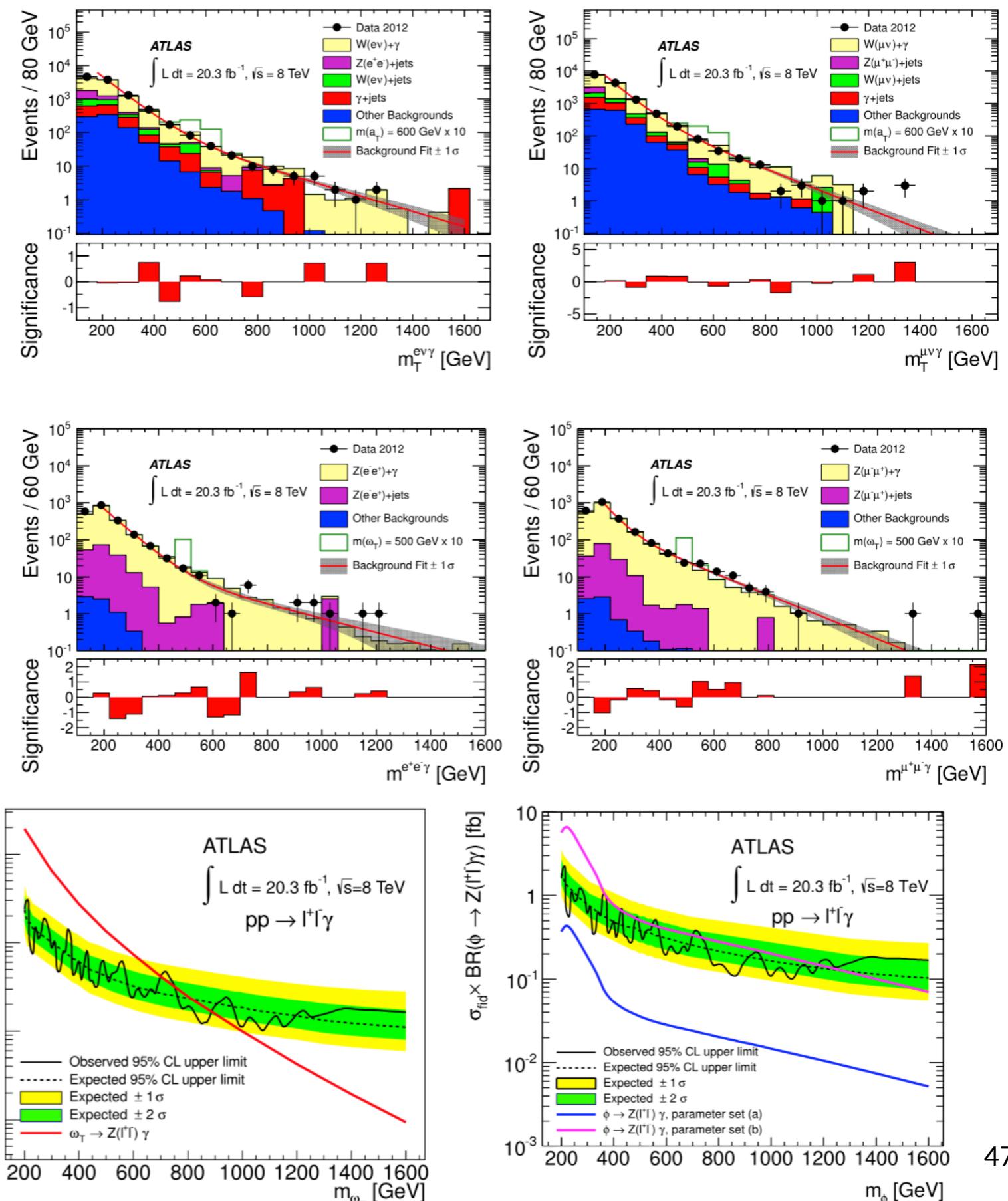
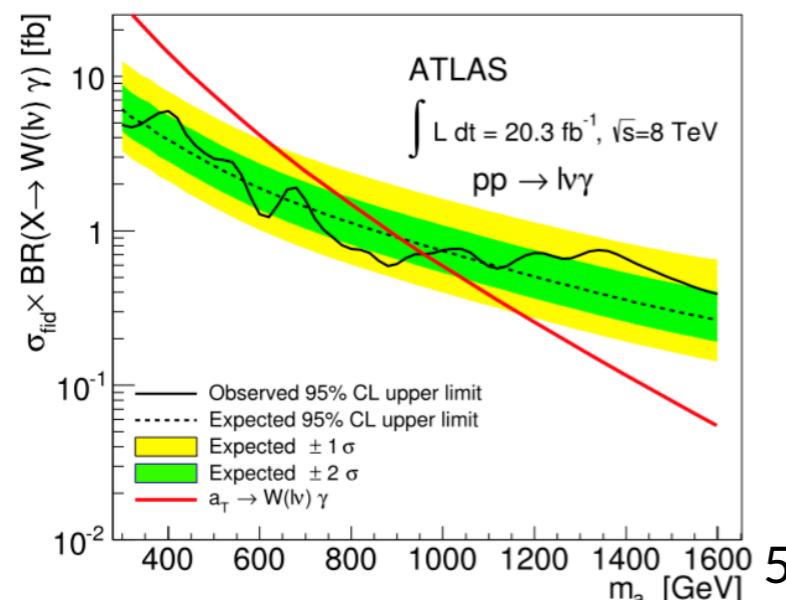
$X \rightarrow HH \rightarrow BBBB$: 2HDM EXCLUSIONS

grey=limit not reliable

$\tan\beta, m_H$



- ▶ leptonic W/Z ($l=e,\mu$) + photon
 - ❖ $l\nu: p_T(l) > 25 \text{ GeV}, E(\gamma) > 40 \text{ GeV}, \text{MET} > 35 \text{ GeV}, m_T(l, \text{MET}) > 40 \text{ GeV}$, Z veto on $e\gamma$
 - ❖ $ll: 65 < m_{ll} < 105 \text{ GeV}$
 - ❖ $\Delta R(l, \gamma) > 0.7$ to reject photon radiation
- ▶ $W/Z + \text{jets}$ from data-driven
- ▶ fit to mass distributions



THE HVT FRAMEWORK (ARXIV:1402.4431)

- ▶ heavy vector triplet benchmark model

- ❖ $V^0, V^{+/-}$

- ❖ phenomenological lagrangian, assuming on-shell production (insensitive to underlying details of the actual theory)

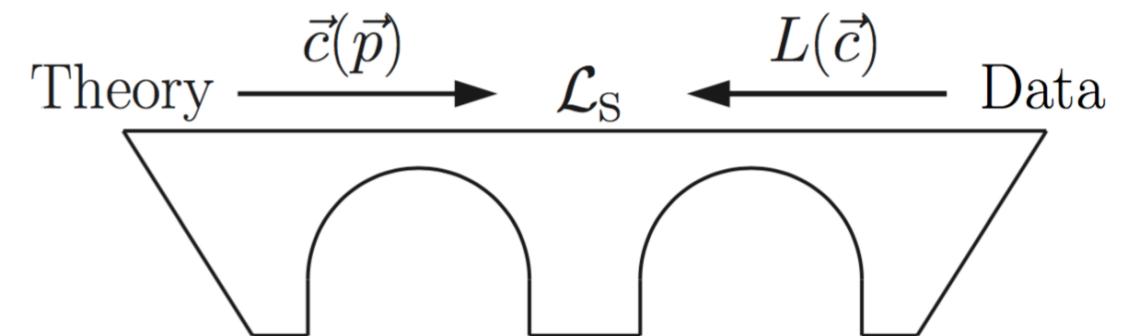
- ▶ couples to fermions through $g c_F / g_V$

- ▶ couples to Higgs, vector bosons through $g_V c_H$

- ▶ c_F, c_H close to unity in most models

- ❖ model A: weakly-coupled vector resonances from extension of the gauge group

- ❖ model B: strong scenario (e.g. composite Higgs)



MINIMAL WALKING TECHNICOLOR

- ▶ strongly coupled dynamics
- ▶ predicts two triplets of resonances (masses ~ 2 TeV)
 - ❖ vector, axial-vector
 - ❖ $R_1^{\pm,0}, R_2^{\pm,0}$
 - ❖ charged bosons decay to WH, neutral bosons to ZH
- ▶ coupling to vector bosons with \sim non-running strength $g\tilde{}$
 - ❖ to fermions with $g/g\tilde{}$
 - ◆ $g \Rightarrow SU_2(L)$
- ▶ axial-vector bare mass determines R_1, R_2 masses

SPARES