

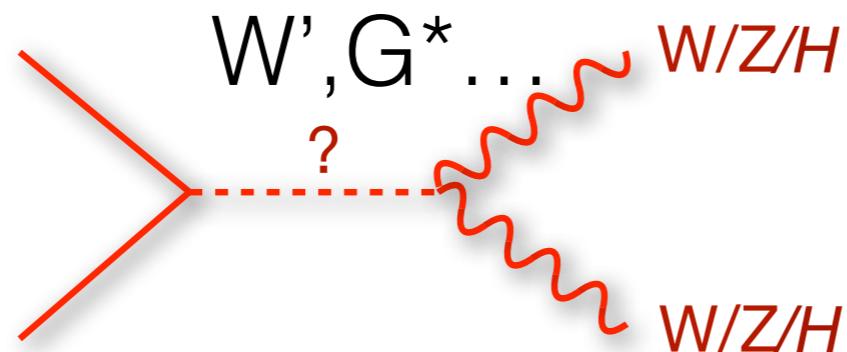
Search for new phenomena in diboson final states in ATLAS and CMS

Viviana Cavaliere (University of Illinois at Urbana-Champaign)
on behalf of ATLAS and CMS collaborations

EPS-HEP 2015
25/07/2015

Diboson resonances

- Several extension of the SM predict new resonances decaying into pair of bosons (including the Higgs)



Clear experimental signature
– Known properties and decay kinematics

M	M	M
$W \rightarrow q\bar{q} \sim 67\%$	$Z \rightarrow q\bar{q} \sim 70\%$	$H \rightarrow b\bar{b} \sim 57\%$
$W \rightarrow l\nu \sim 33\%$	$Z \rightarrow \nu\nu \sim 20\%$	$H \rightarrow WW \sim 21.5\%$ $H \rightarrow ZZ \sim 2.5\%$
$Z \rightarrow ll \sim 10\%$		$H \rightarrow \tau\tau \sim 6\%$
		$H \rightarrow \gamma\gamma \sim 0.2\%$

To fully exploit potential signatures (at high mass) from new physics at LHC

novel reconstruction techniques to handle highly boosted objects

Resonance models

Charged (WZ)

Sequential Standard Model (W', spin-1)

- * Trilinear $W'WZ$ coupling set by Extended Gauge Model: $\sim (M_W/M_{W'})^2$

Neutral (WW, ZZ, HH)

Randall-Sundrum graviton (RS G*, spin-2)

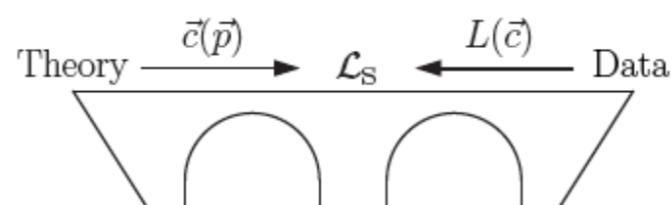
- * Traditional benchmark model with extra dimensions

Bulk RS graviton (Bulk G*, spin-2)

- * Graviton couples more with heavy particles (W, Z, t)
- * Smaller σ , but larger branching ratio to WW, ZZ

Minimal Walking Technicolor (R₁, R₂, charged and neutral)

- * Technicolor with minimal ingredients, can decay to ZH and WH



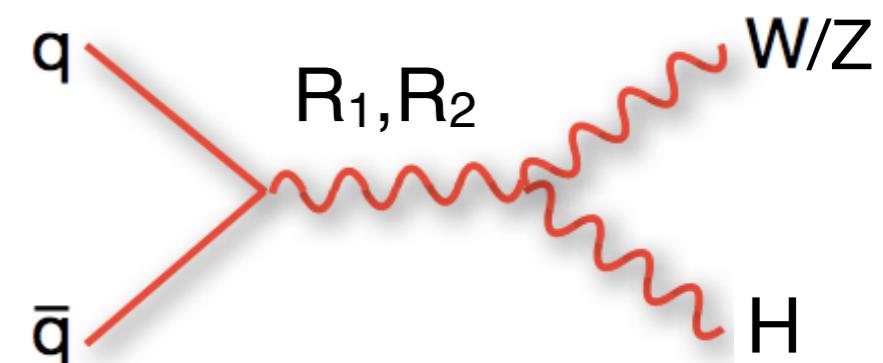
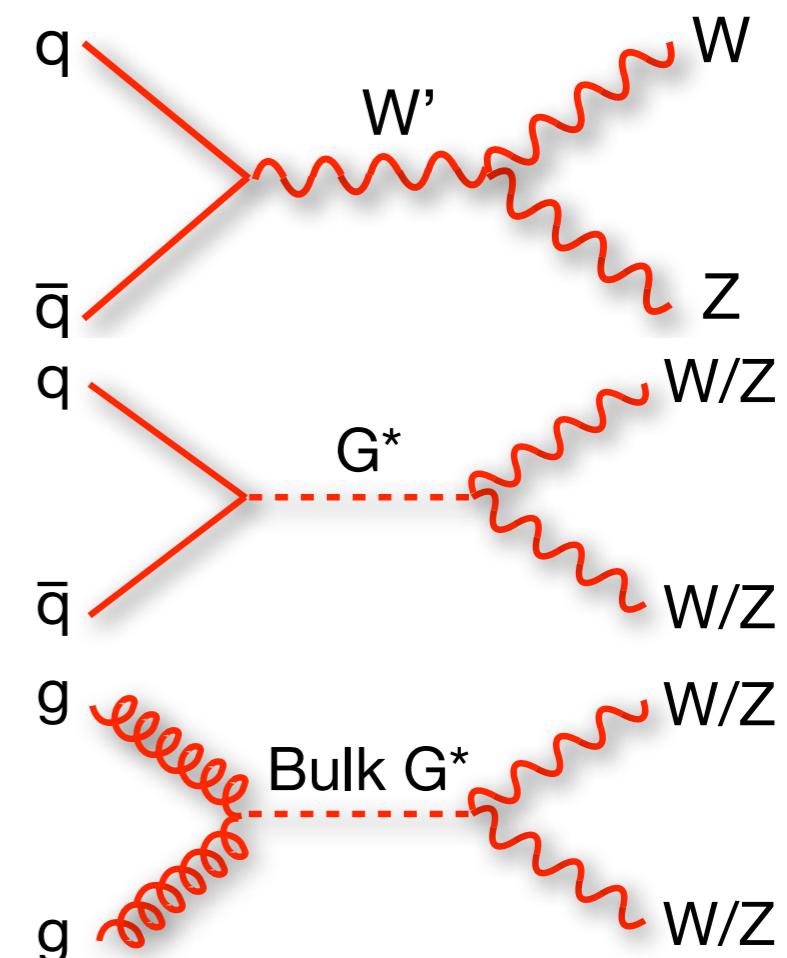
HVT (Simplified Lagrangian)

Model A

- * weakly coupled vector resonances from extension of the gauge group

Model B

- * produced in a strong scenario e.g. composite higgs model

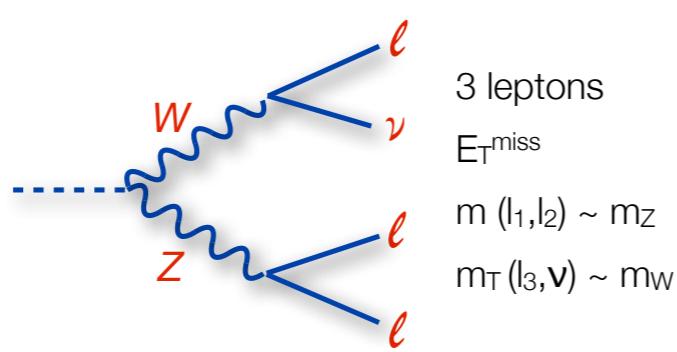


Summary of diboson analysis

Final State	Channel	Reference (ATLAS)	Reference (CMS)
l _v ll	WZ	ATLAS: arxiv.1406.4456	CMS: arxiv:1407.3476
ll γ , l $\nu\gamma$	Z γ , W γ	ATLAS:arxiv.1407.8150	
llqq	ZZ	ATLAS:arxiv.1409.6190	CMS: arxiv1405.3447
lvqq	WZ/WW	ATLAS:arxiv.1503.04677	CMS: arxiv1405.3447
qqqq	WW/WZ/ZZ	ATLAS: arxiv:1506.00962	CMS: arxiv:1405.1994
lvbb/llbb/vvb	WH/ZH	ATLAS: arxiv1503.08089	CMS PAS EXO-14-010
qqbb	WH/ZH		CMS: arxiv1506.01443
bbbb	HH	ATLAS: arxiv. 1506.00285	
bb $\gamma\gamma$	HH	ATLAS: arxiv. 1406.5053	CMS-HIG-13-032

All results based on full Run1 dataset

Final states



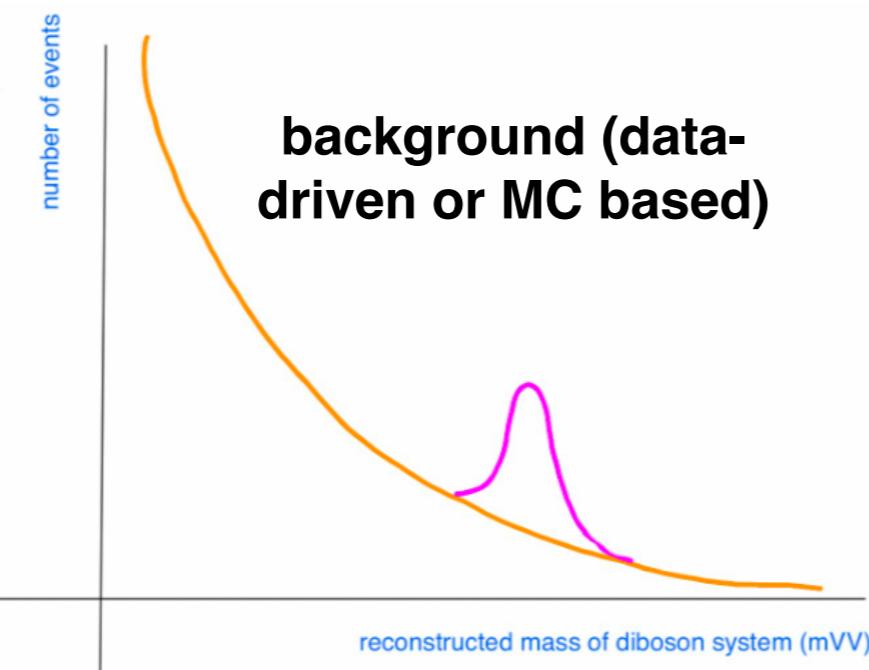
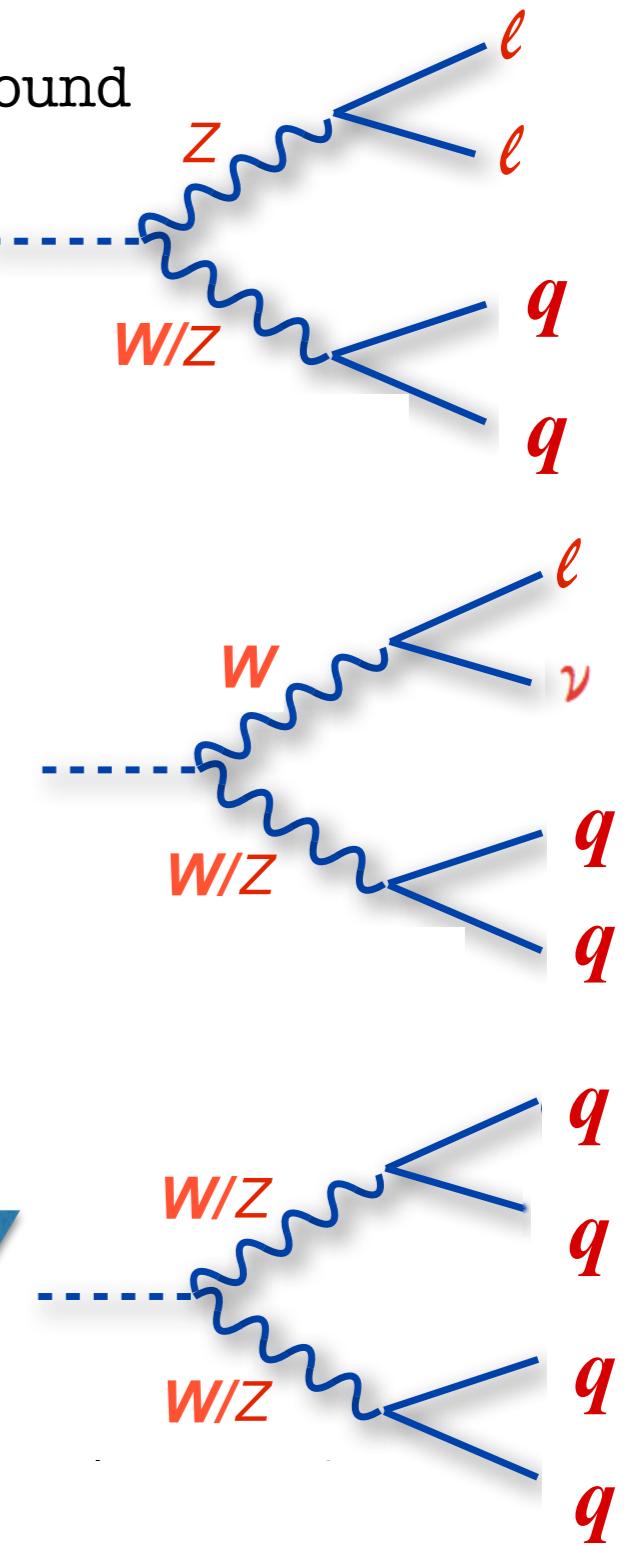
- Fully leptonic \rightarrow Low backgrounds, high purity, low branching fraction
- **Semileptonic final states**
- Fully hadronic
 - Advantages:
 - good kinematic resolution
 - High branching fractions
 - Access to $H \rightarrow b\bar{b}$
 - Disadvantages:
 - higher background although steeply falling at high mass
- Physics observable: invariant mass of diboson system

Signal (BR)

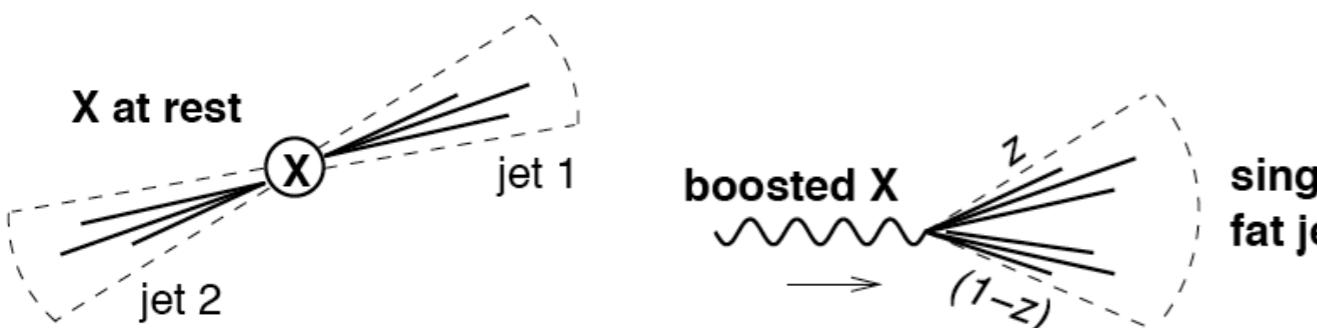
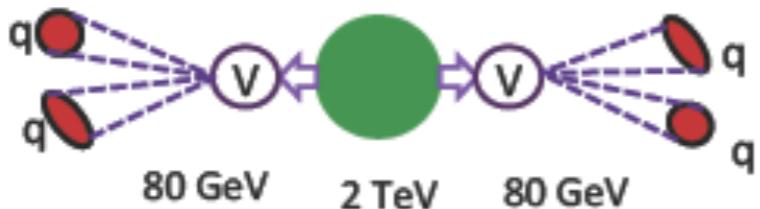
Background

increasing

increasing



Boson jets



- “Natural” angular separation $dR \sim 2m/p_T$
- Resolved regime: the boson has relative low momentum in the lab frame so we are able to reconstruct one jet for each quark
- Boosted Regime: the boson has high momentum in the lab frame - the outgoing quarks are very close so the jets begin to merge

1. **Fat jet:** large distance parameter to pick up all the radiation from the original decay
2. **Grooming:**
 - Signal: take out jet constituents that don't belong to the signal decay
 - Background -Preserve background characteristics in the jet
3. **Tagging:**
 - Use differences in Signal and Background jet characteristics to reject background jets

Boson jets



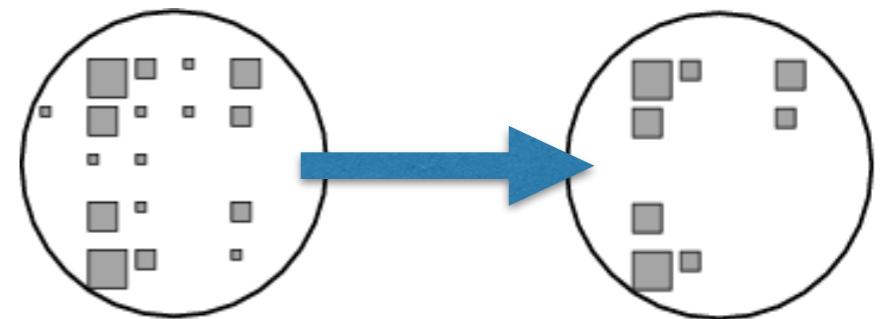
QCD jets



Jet substructure

Jet Pruning: (Phys. Rev. D 80 051501, arXiv:0912.0033)

- Recluster jet constituents, applying additional conditions at each recombination
- $$z = \frac{\min(p_{T,i}, p_{T,j})}{p_{T,jet}} > 0.1 \quad \Delta R < 0.5 \frac{M_{jet}}{p_{T,jet}}$$
- Filter out soft and large angle QCD emissions



Mass Drop: (PRL 100 240001)

- de-cluster jet by stopping jet algo before last iteration → two subjets
- jet is V-tagged if its mass drop $\mu_D <$ (analysis dependent) cut value

$$\mu_D = \frac{M_1}{M_{jet}}$$

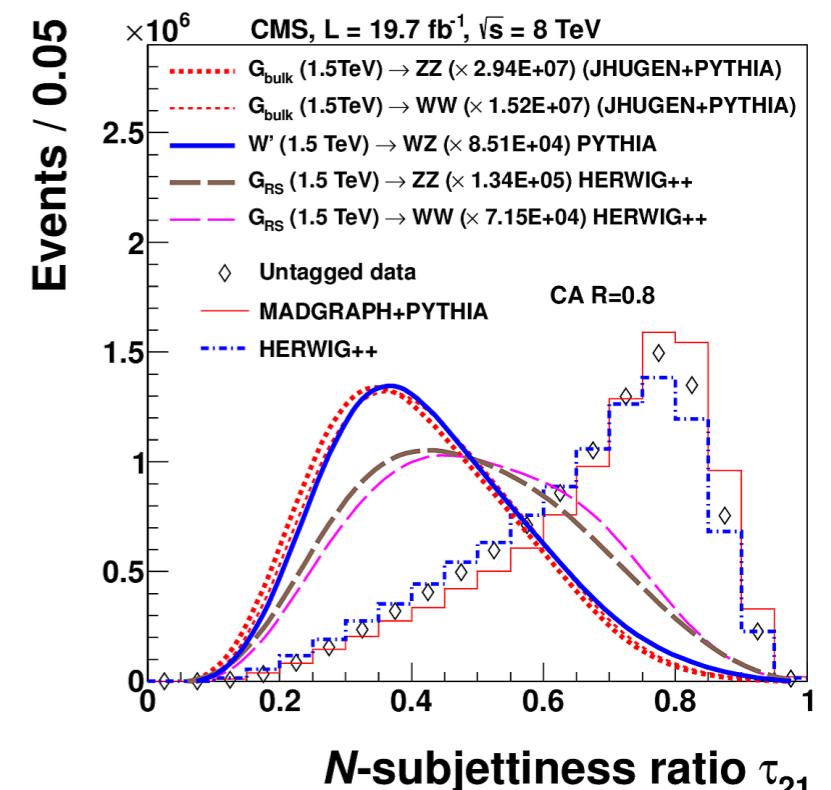
N-subjettiness: (JHEP03(2011)240001)

- Topological compatibility with hyp of N subjets
- τ_N : pT-weighted sum over jet constituents of distances from closest subjet axis

Momentum balance: (PRL 100(2008)24200)

- boson jets tend to have symmetric momentum distribution among the two quarks

Plenty of alternatives at [CMS-JME-13-006](#) and [ATL-PHYS-PUB-2014-004](#)



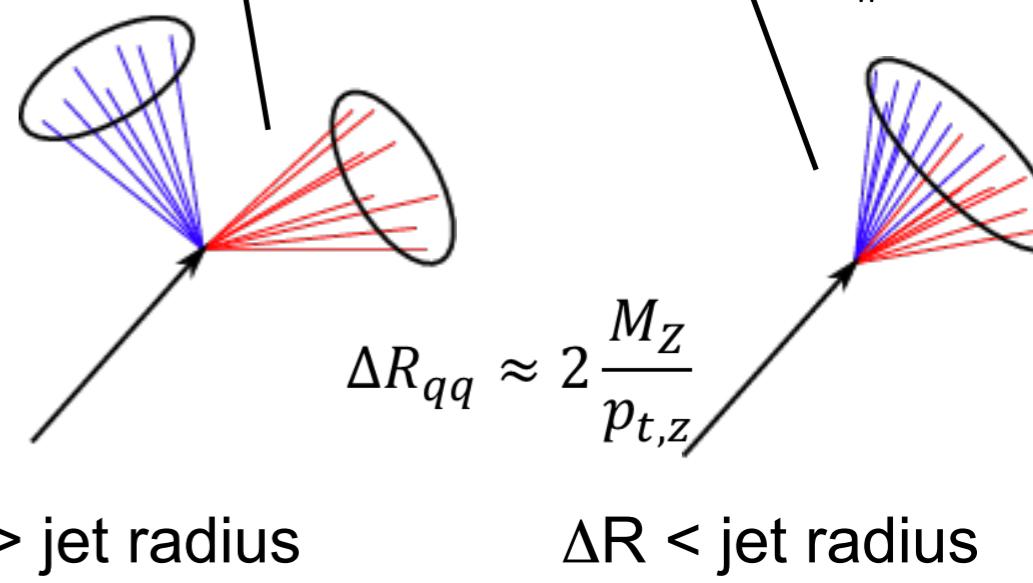
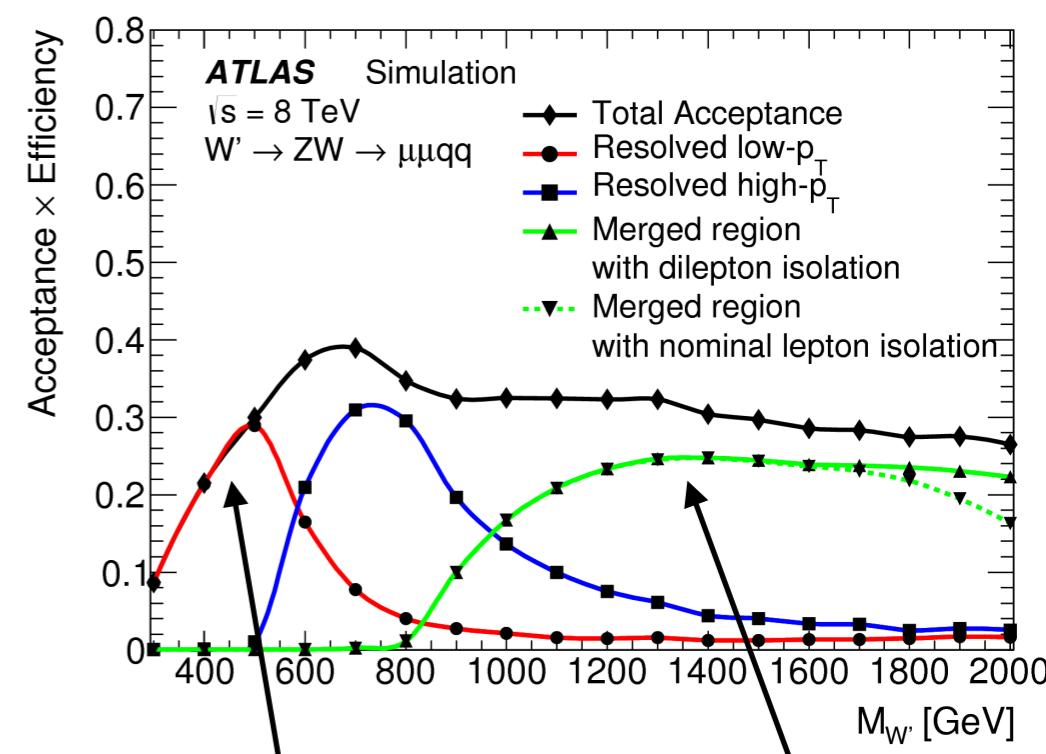
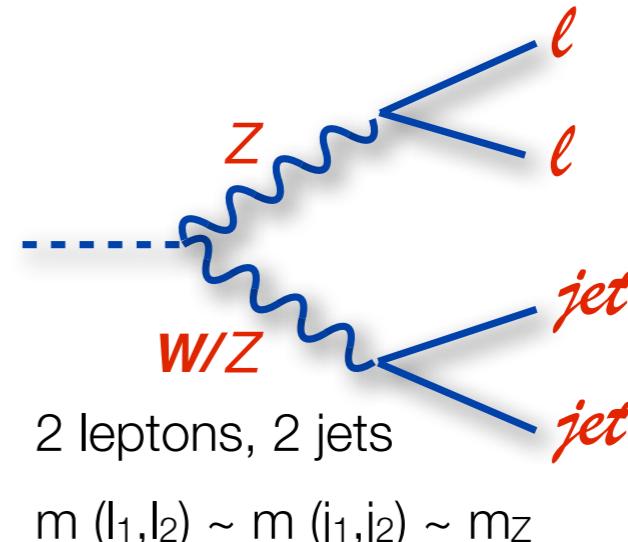
ZV->llqq

$Z \rightarrow ll:$

- 2 leptons, same flavor, compatible with the Z mass
- Leptons are collimated and interfere with each other's isolation cones
 - Subtract the other lepton's track pT from the isolation cone

$Z/W \rightarrow \text{hadronic}:$

- **ATLAS:**
 - Low pt resolved : 2 jets with $p_T > 100 \text{ GeV}$
 - High pt resolved
 - 2 jets with $p_T > 250 \text{ GeV}$ to gain efficiency in the intermediate region
 - Merged Region: 1 fatjet with $p_T > 400 \text{ GeV}$
- **CMS:**
 - high-purity (HP) category: $\tau_{21} \leq 0.5$;
 - low-purity (LP) category: $0.5 < \tau_{21} < 0.75$.
 - ATLAS: Use C/A R=1.2 jets with modified BDRS filtering
 - CMS: Use C/A R=0.8 pruned jets

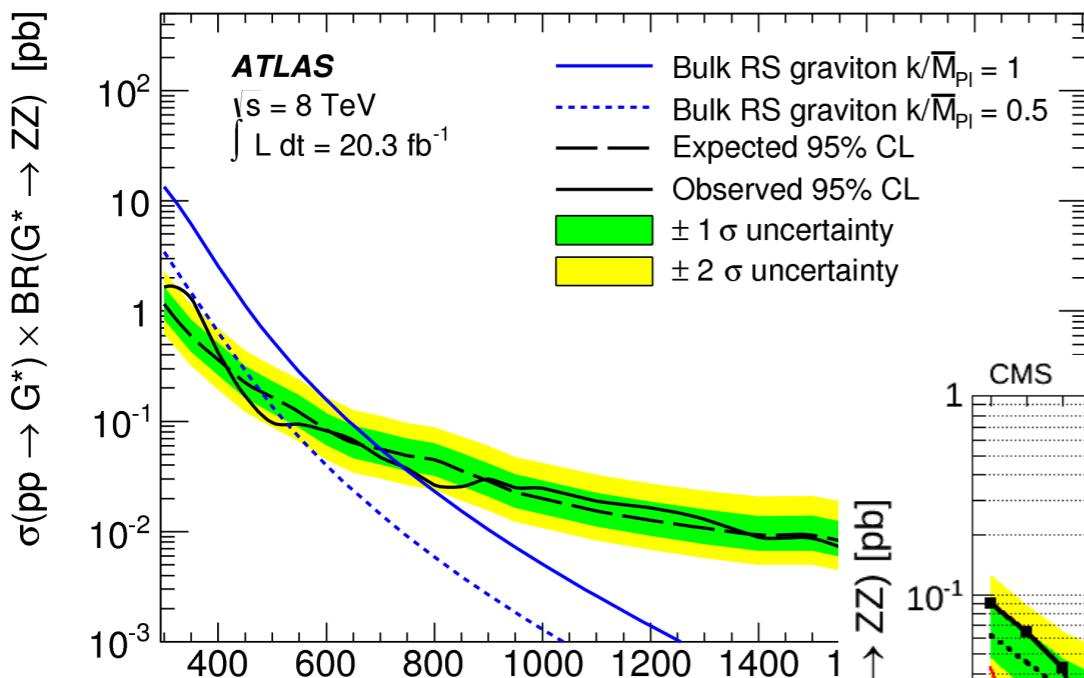


ZV->llqq

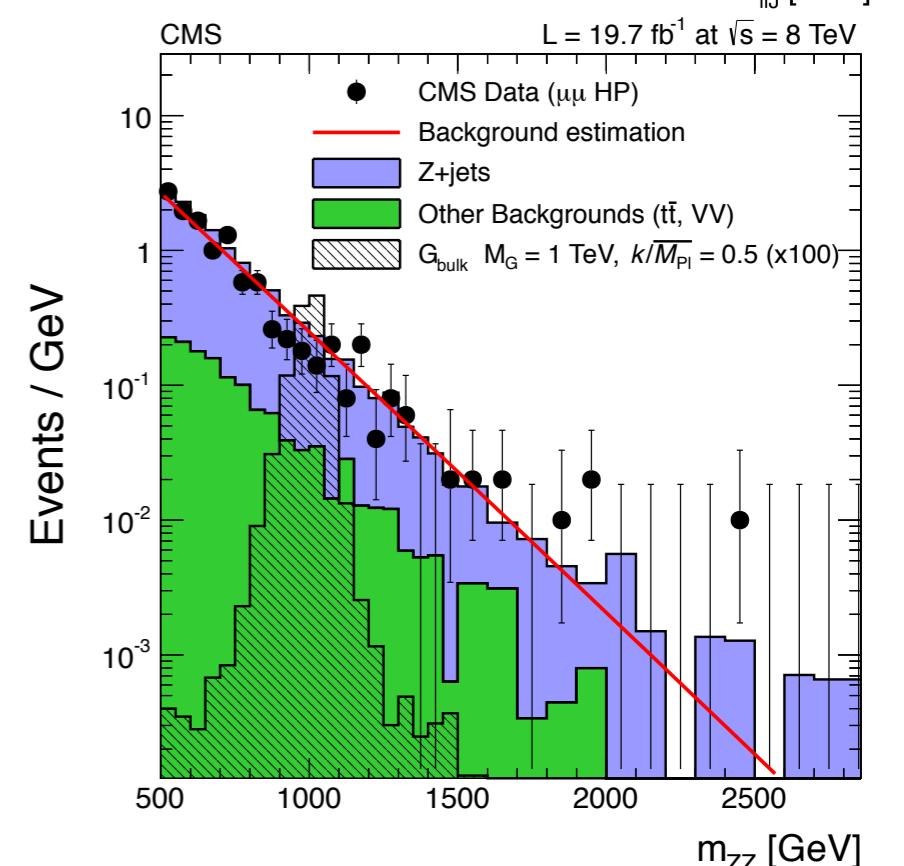
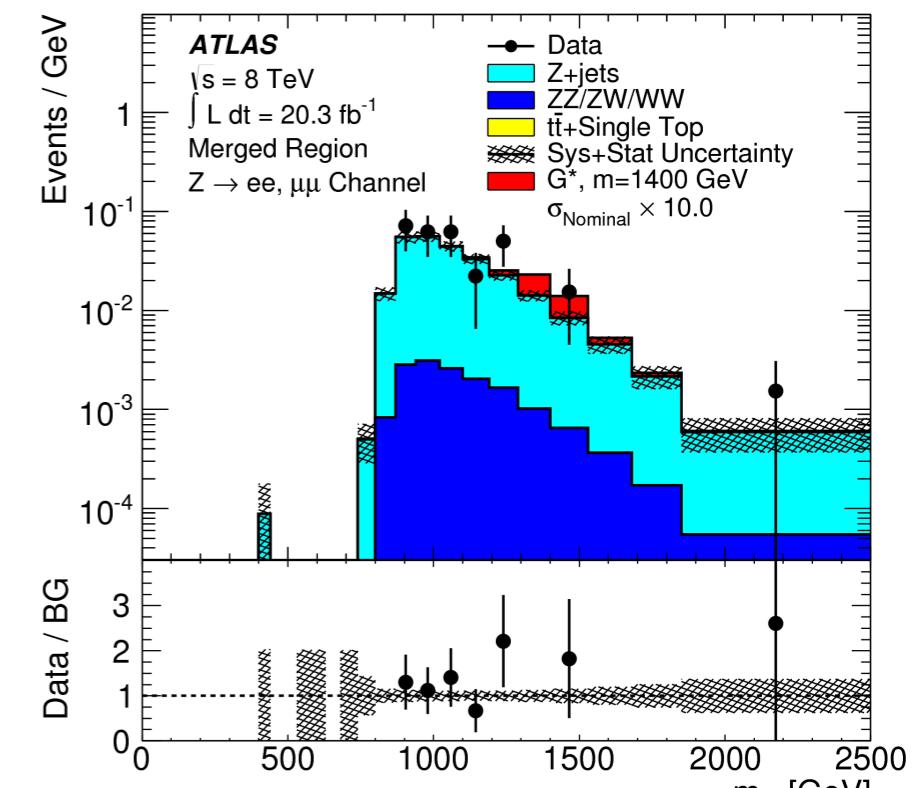
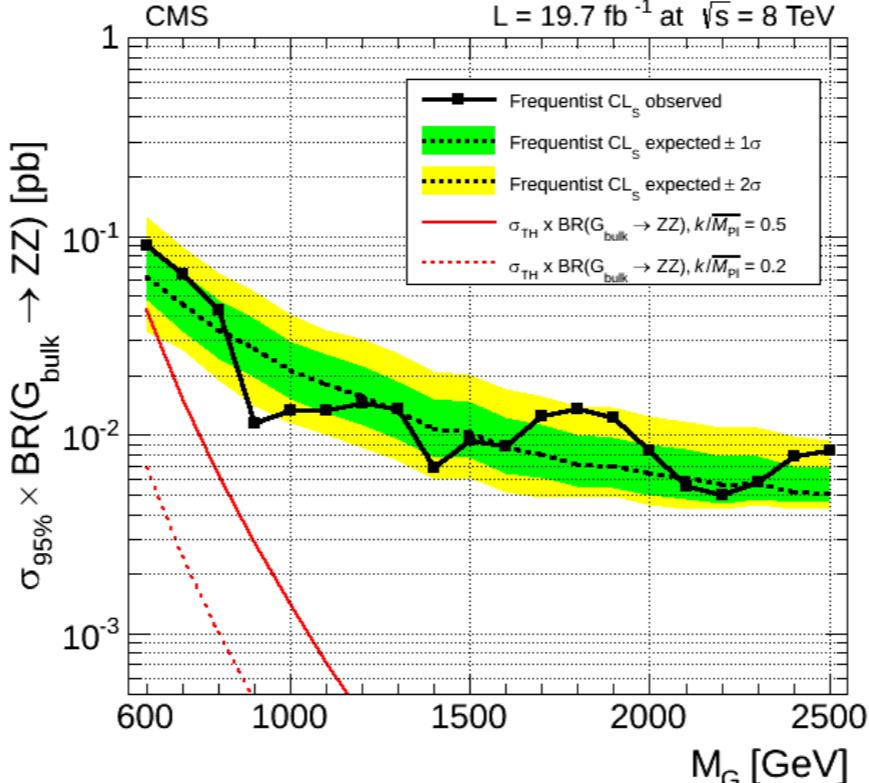
No significant deviations from Standard Model expectation observed

- $M(G^*) > 730 \text{ GeV}, M(W') > 1590 \text{ GeV}$

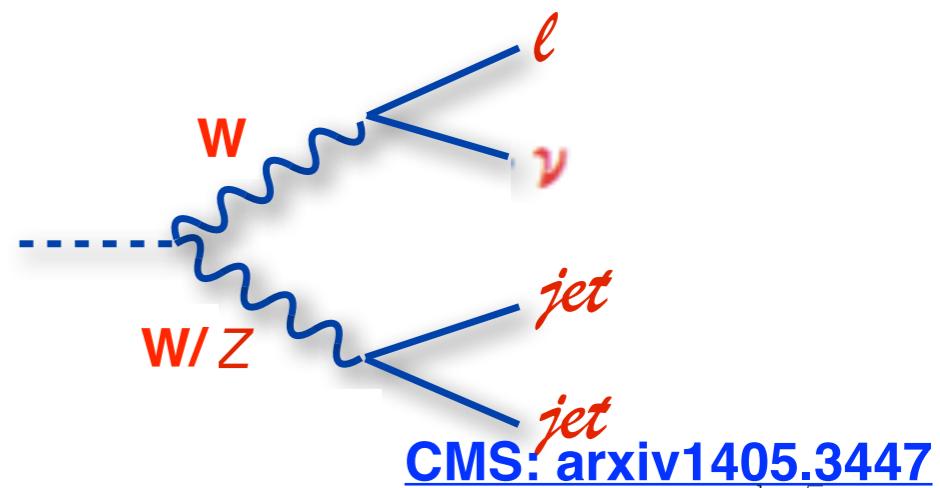
[ATLAS:arxiv.1409.6190](#)



[CMS: arxiv1405.3447](#)



$WV \rightarrow l\nu qq$



$W \rightarrow l\nu$ selection: $\text{MET} > 30 \text{ GeV}$ (100 GeV for CMS) and exactly one lepton

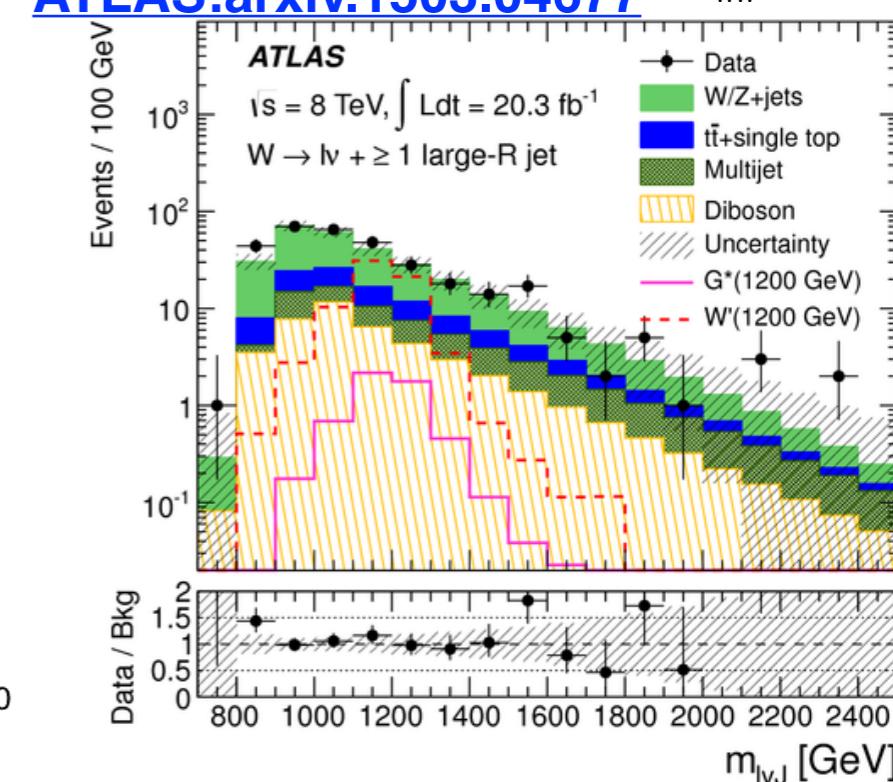
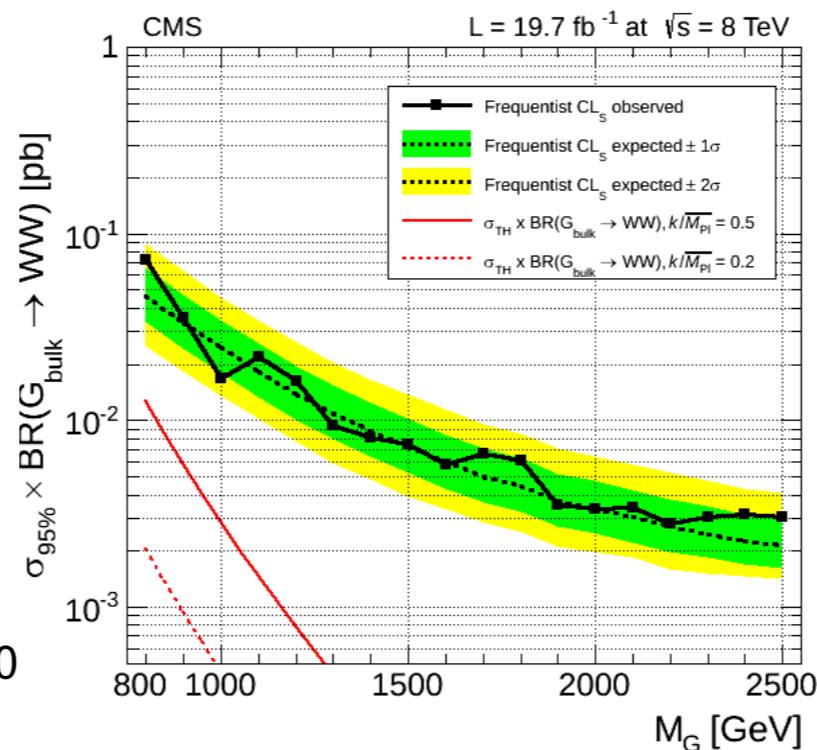
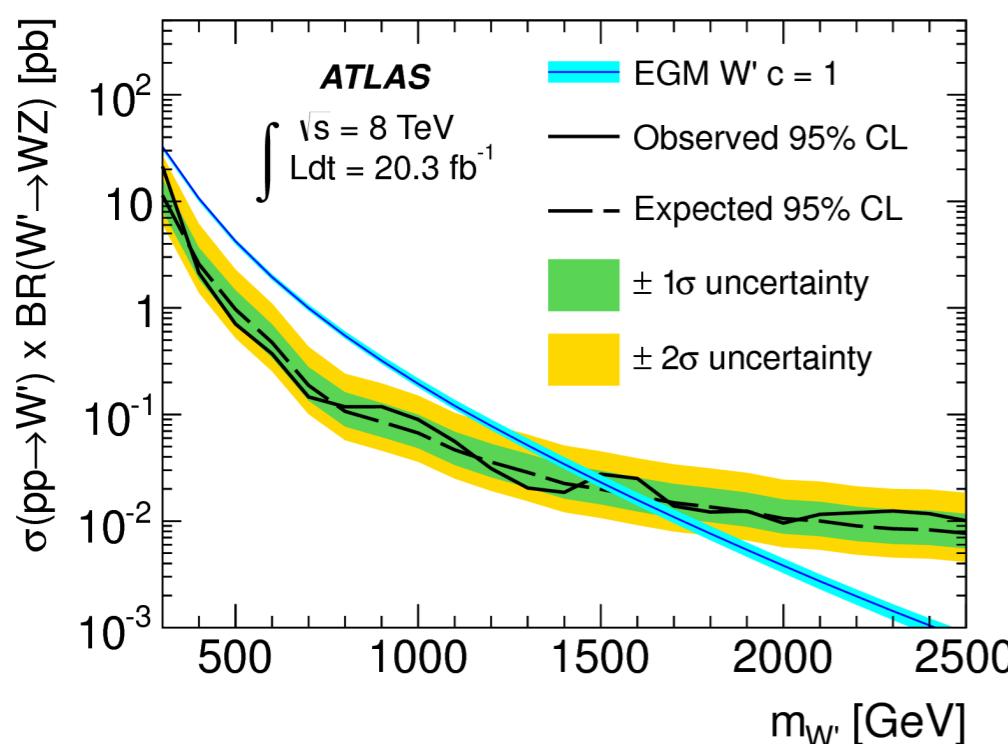
Hadronic side, same selection as for llqq

Main Backgrounds:

MC: $W/Z + \text{jets}$, $t\bar{t}$

Data driven: Multijet QCD \rightarrow loosened lepton selection to extract template and fit to the Met to extract normalization

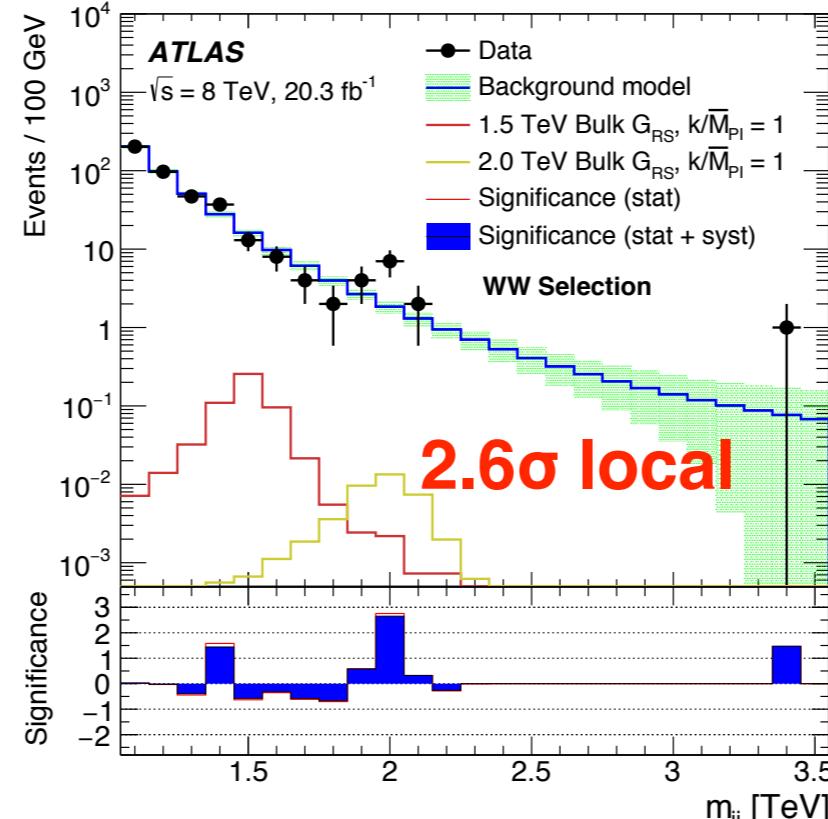
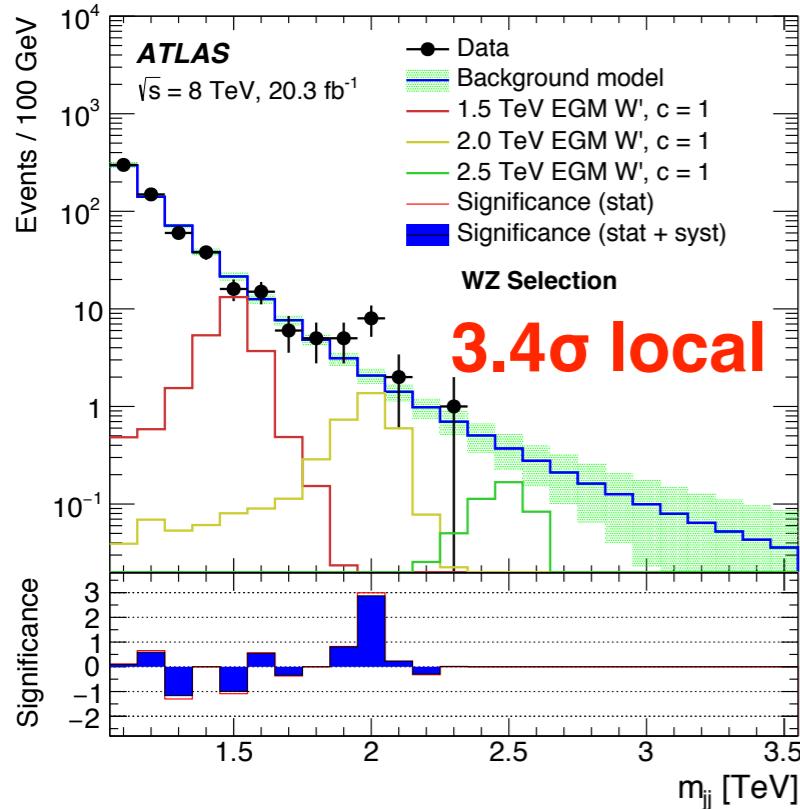
Since no excess is seen,
limits are set using W' and G



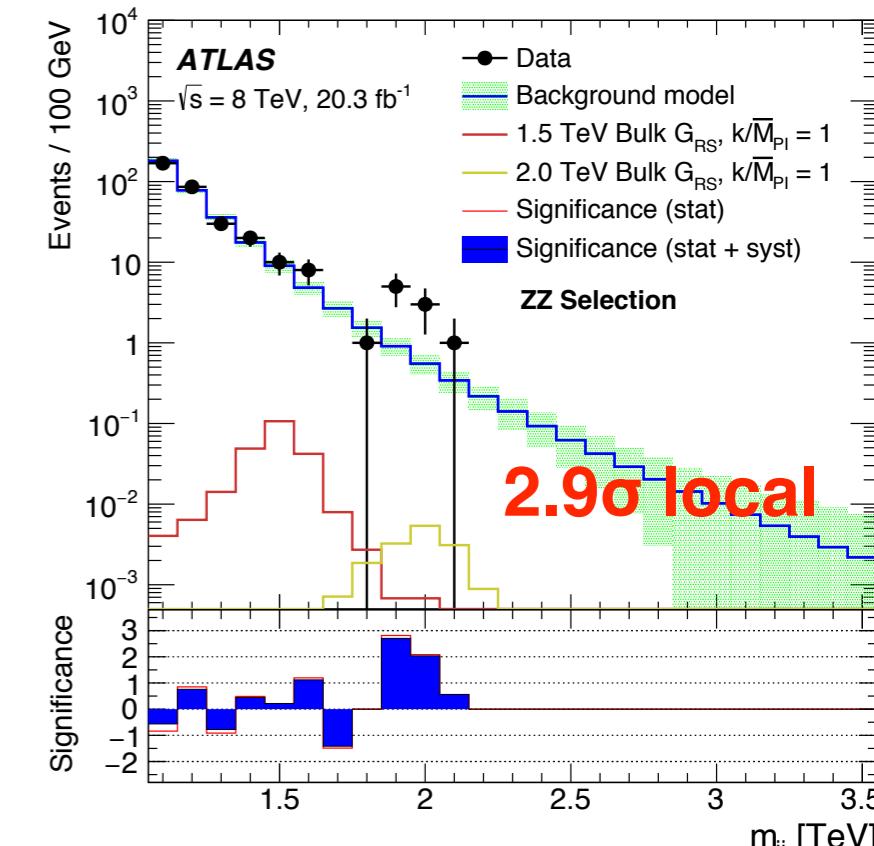
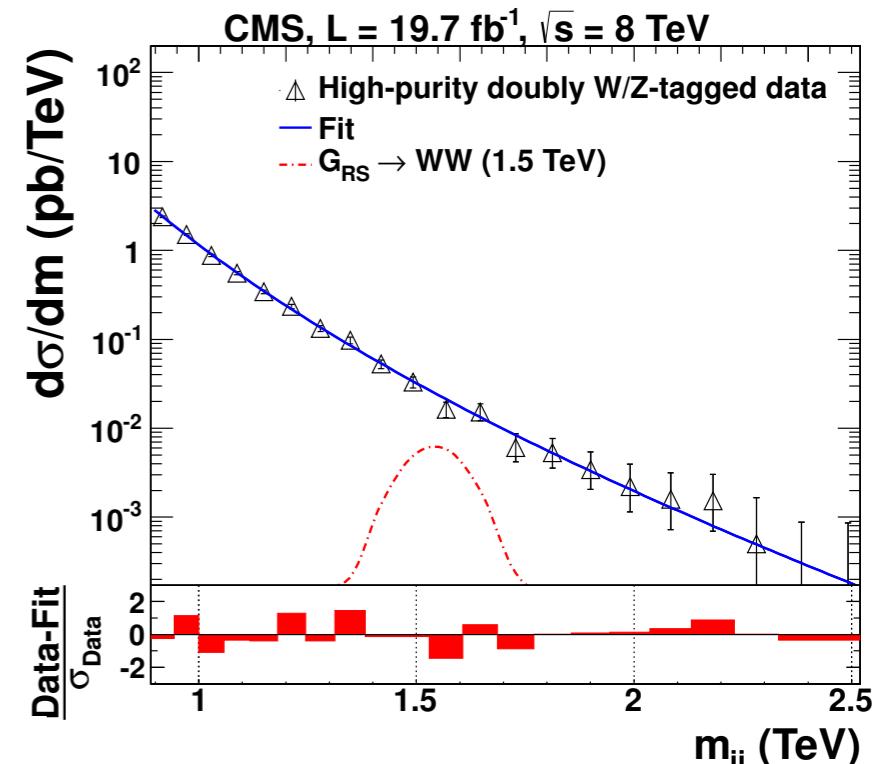
VV->qqqq

- ATLAS: Trigger on a jet with $p_T > 360$ GeV CMS: Trigger on HT
- Only boosted region considered (low mass QCD dominated)
- Select events with M_{jj} within the W/Z mass window
 - ATLAS: $|y_1 - y_2| < 1.2$, Pt Asymmetry < 0.15 to reject events where one of the jets is poorly measured
 - 3 overlapping signal regions/non statistically independent
- Additional cuts to reduce QCD (ntrk, nsubjettiness...)
- The background is estimated by fitting the data

[ATLAS: arxiv:1506.00962](#)



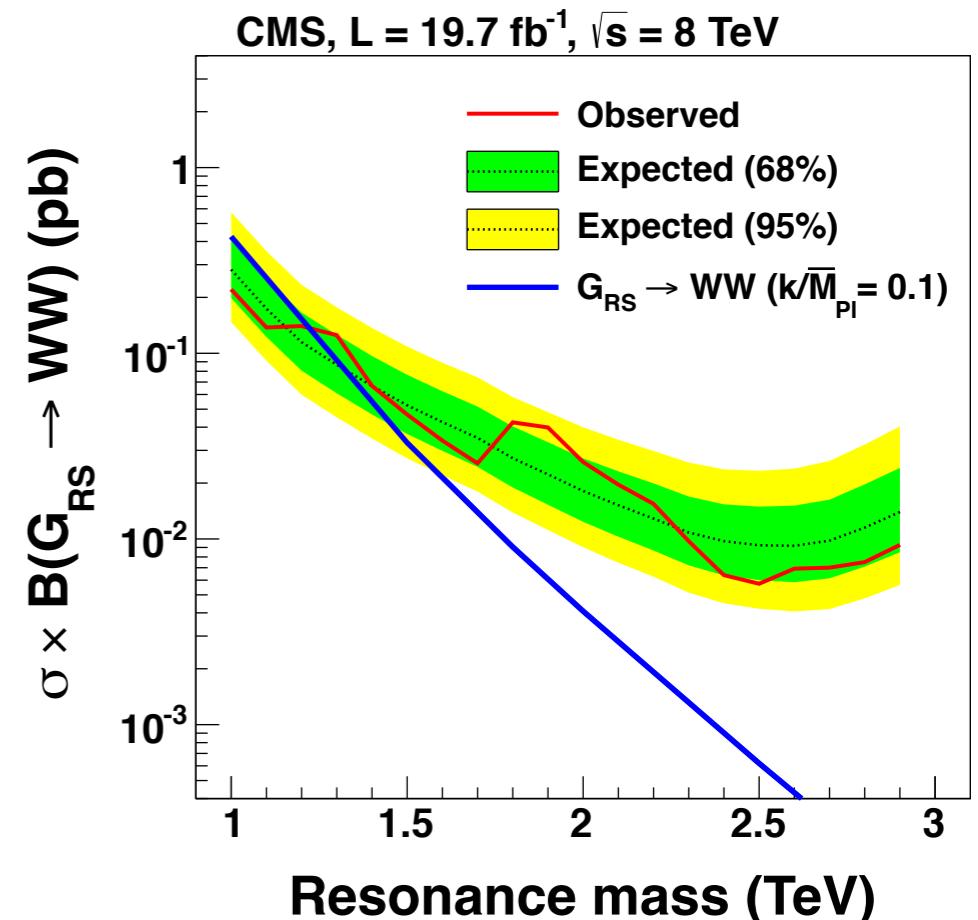
[CMS: arxiv:1405.1994](#)



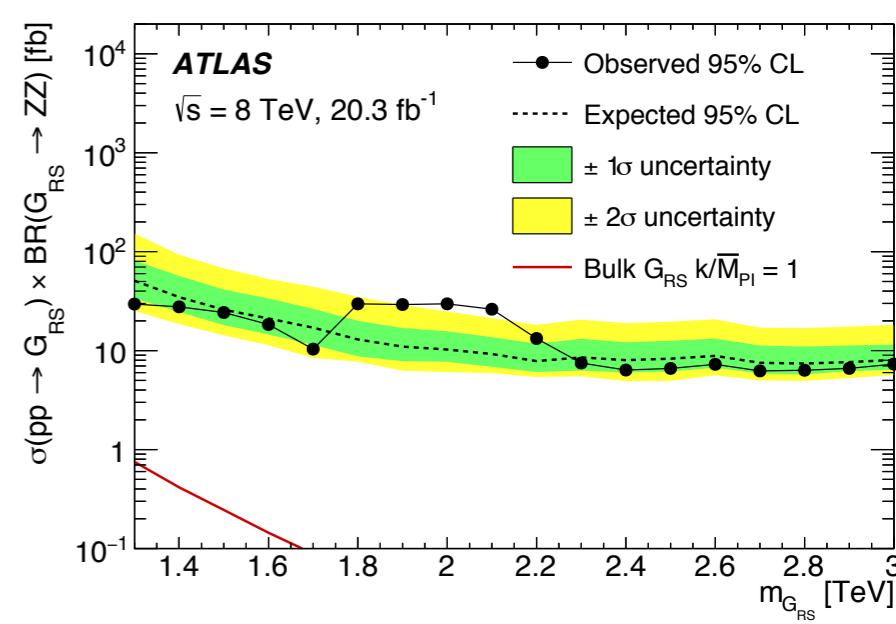
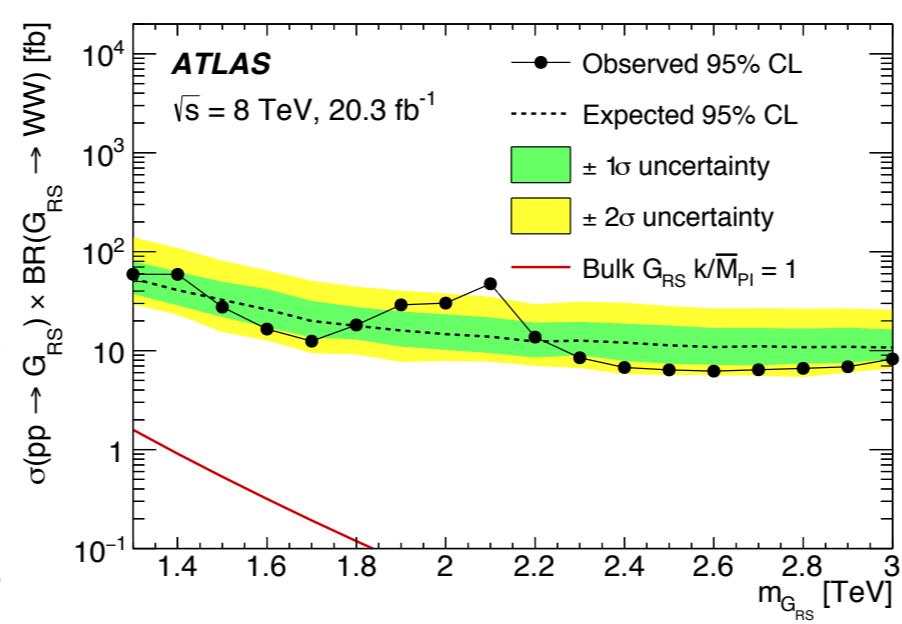
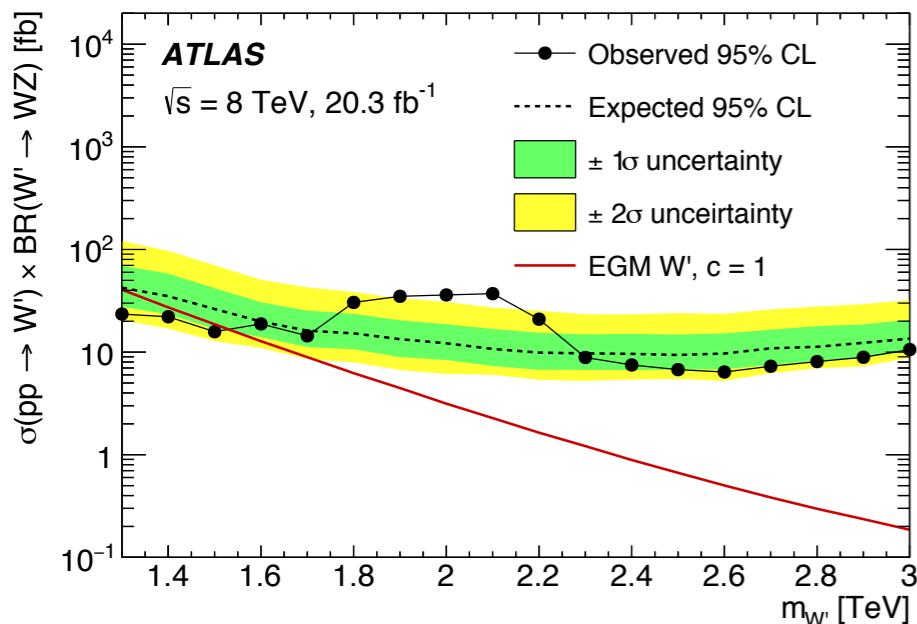
VV->qqqq

- ATLAS: Trigger on a jet with $\text{pt} > 360 \text{ GeV}$ CMS: Trigger on HT
- Only boosted region considered (low mass QCD dominated)
- Select events with M_j within the W/Z mass window
 - ATLAS: $|y_1 - y_2| < 1.2$, Pt Asymmetry < 0.15 to reject events where one of the jets is poorly measured
 - 3 overlapping signal regions/non statistically independent
- Additional cuts to reduce QCD (ntrk, nsubjettiness...)
- The background is estimated by fitting the data

CMS: arxiv:1405.1994



ATLAS: arxiv:1506.00962



2.5 σ global significance in WZ selection

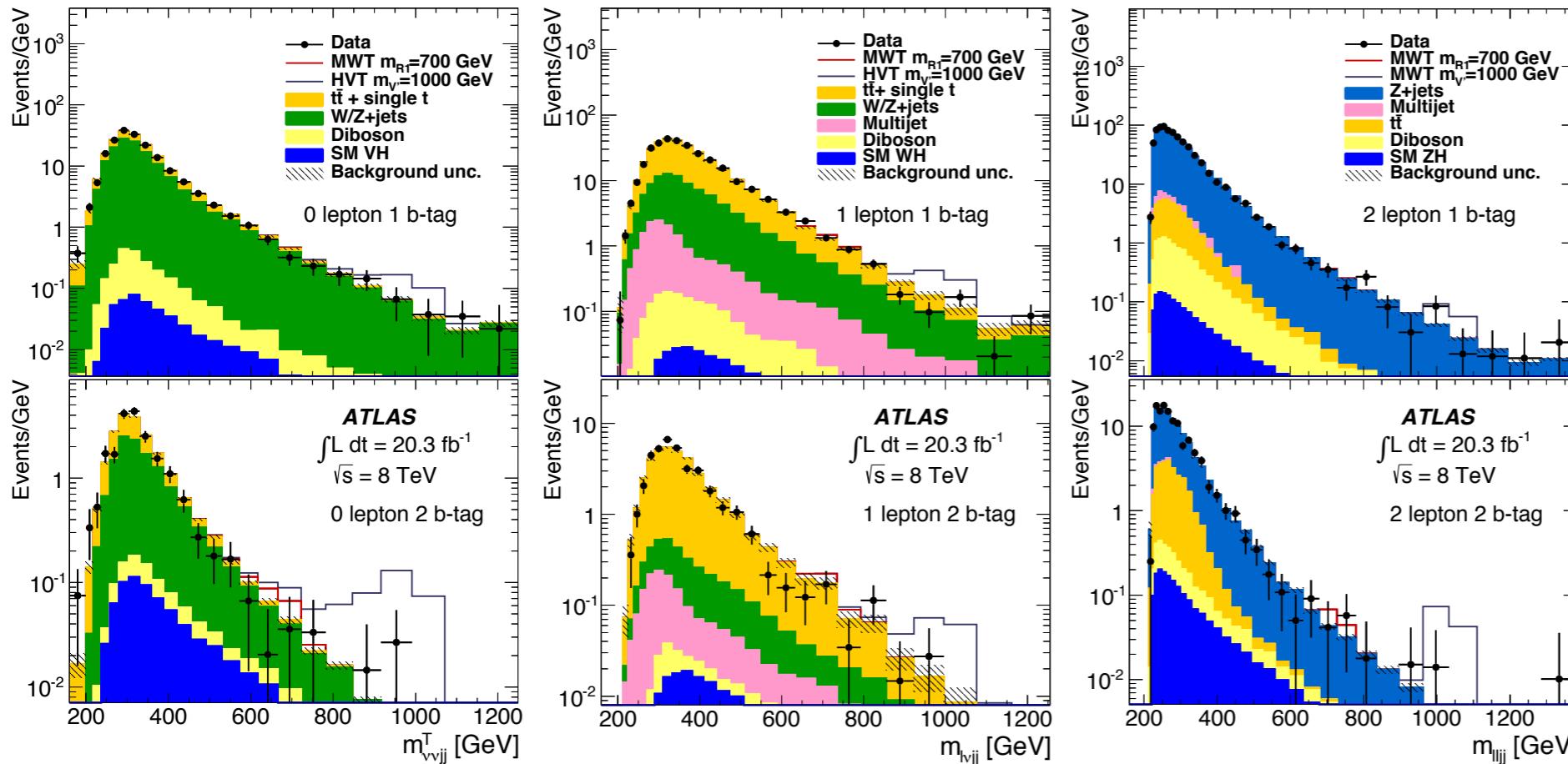
VH \rightarrow lν/ll/vv/bb (ATLAS)

Higgs as a discovery tool

- Discovery of the Higgs opened up other final states to look for diboson resonances
 - Examine the VH mass and look for a localized excess
- Categorize events according to the number of charged leptons
- Further subdivision according to number of b-tagged jets (1 to 2 btags)
- Only antikt0.4 jets considered



ATLAS: arxiv1503.08089



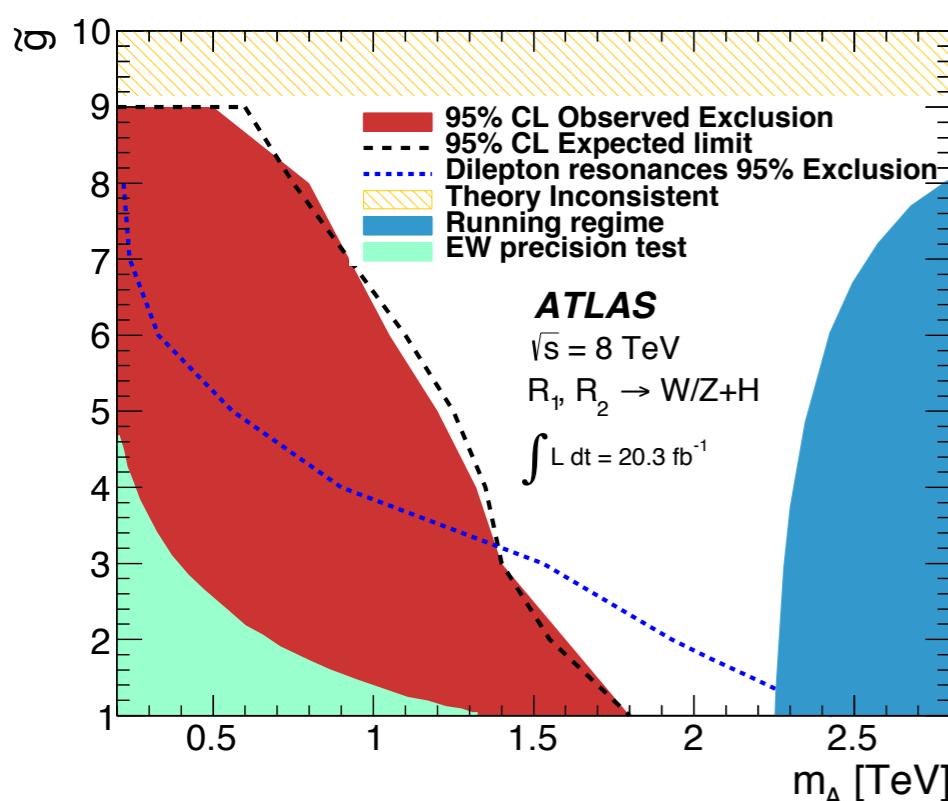
- Dominant background is W/Z+j; simulation with data-based corrections
- Multi-jet background; data driven
- tt/single top; normalized using control region fit

VH \rightarrow lν/lℓ/vv/bb (ATLAS)

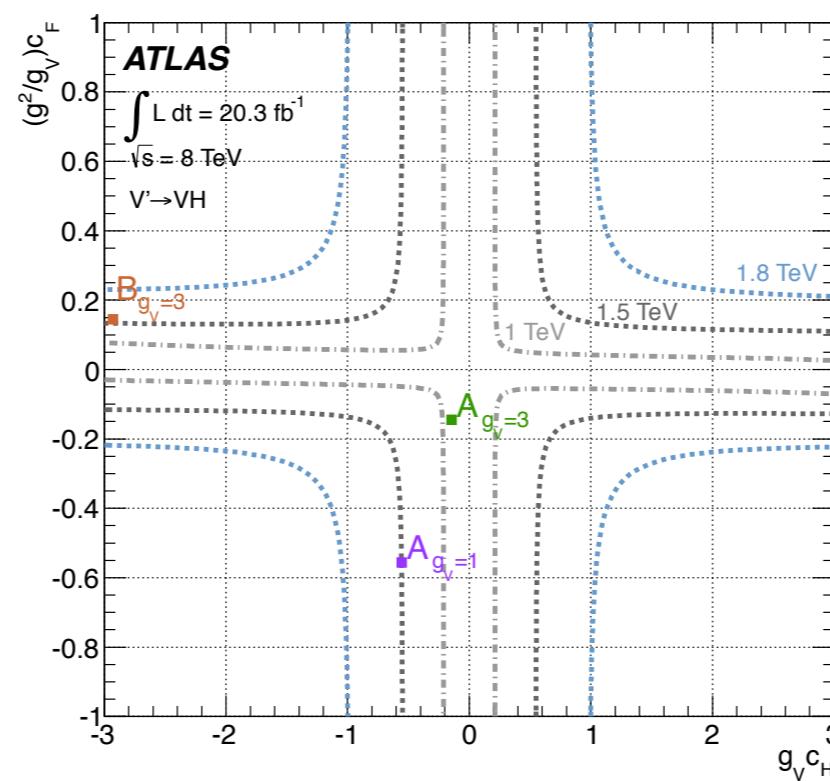
Higgs as a discovery tool

- Discovery of the Higgs opened up other final states to look for diboson resonances
 - Examine the VH mass and look for a localized excess
- Categorize events according to the number of charged leptons
- Further subdivision according to number of b-tagged jets (1 to 2 btags)

[ATLAS: arxiv1503.08089](https://arxiv.org/abs/1503.08089)



Minimal Walking Technicolor

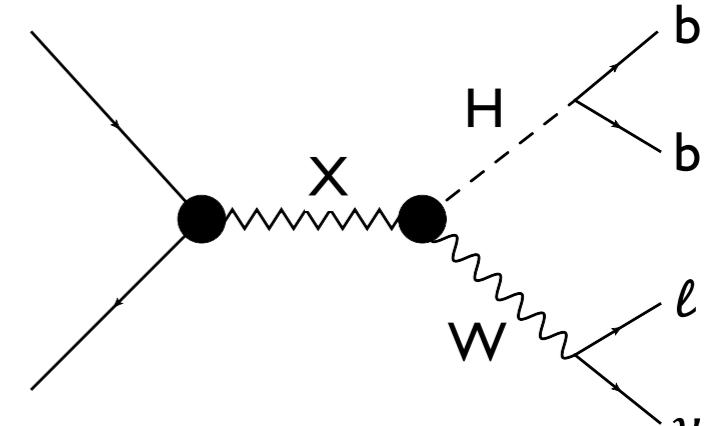


HVT

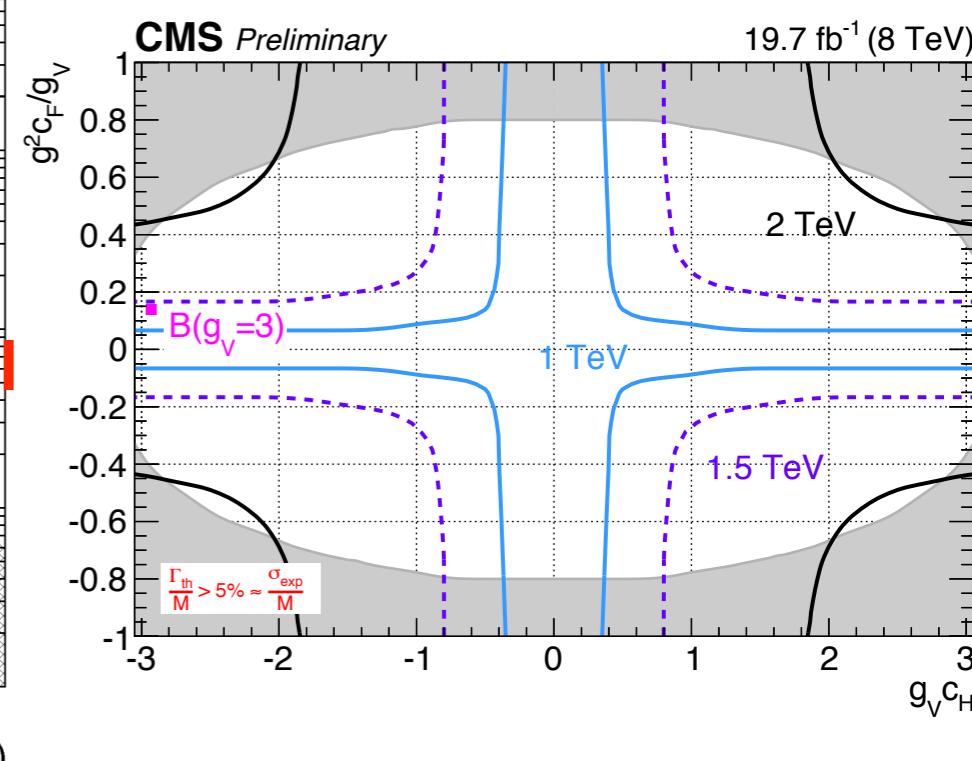
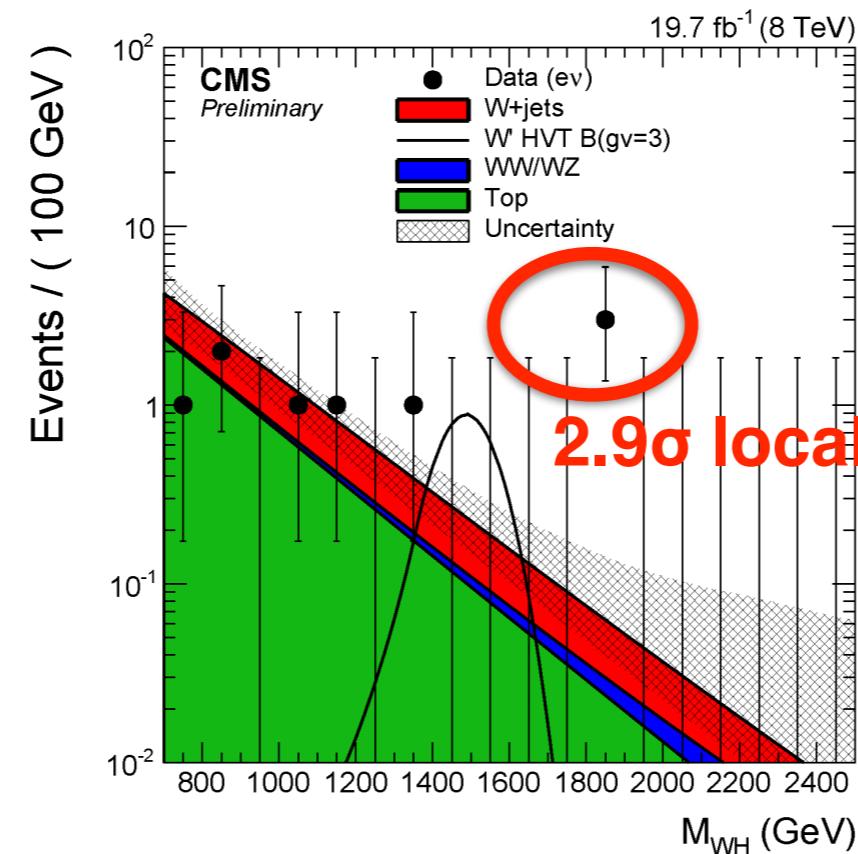
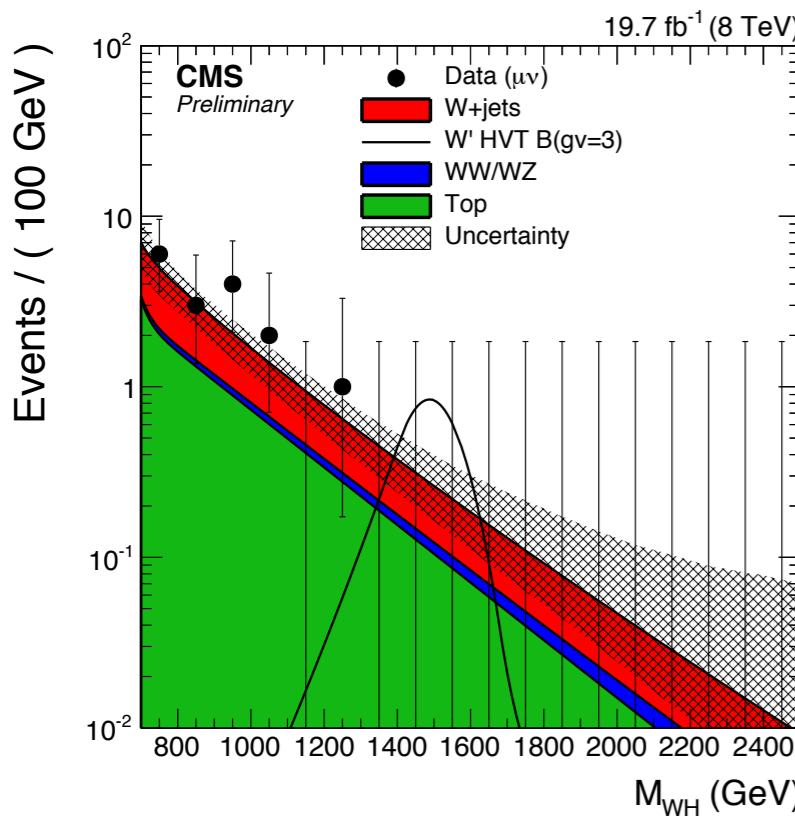
-for each line corresponding to a $M_{V'}$ mass, the area outsides the curves is excluded

WH- \rightarrow lvbb (CMS)

- 1 lepton +MET + reconstruct H- \rightarrow bb using pruned jets
- 1 CA0.8 jet
- $110 < m_{jet} < 135$ GeV.
- Split pruned jet:
 - if the subjets' $\Delta R > 0.3$ b-tagging applied to individual sub-jets
 - if the subjets' $\Delta R < 0.3$ b-tagging applied to the CA0.8 jet
- Special topological requirements to avoid possible instrumental backgrounds
- The shape of the mWH distribution of the W+jets background in the signal region is estimated from data from the lower sideband region while correction for the extrapolation are taken from the simulation.



CMS PAS EXO-14-010

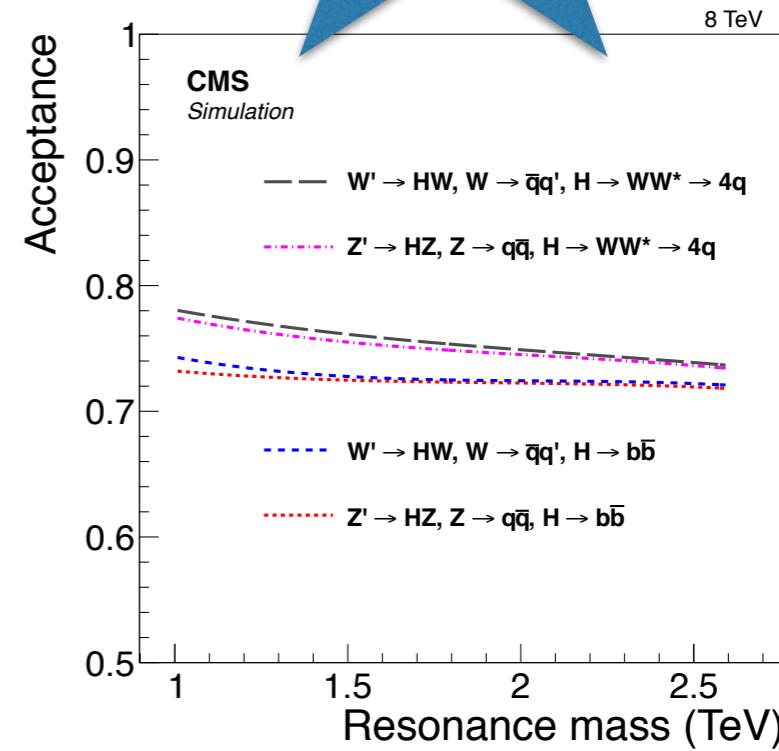
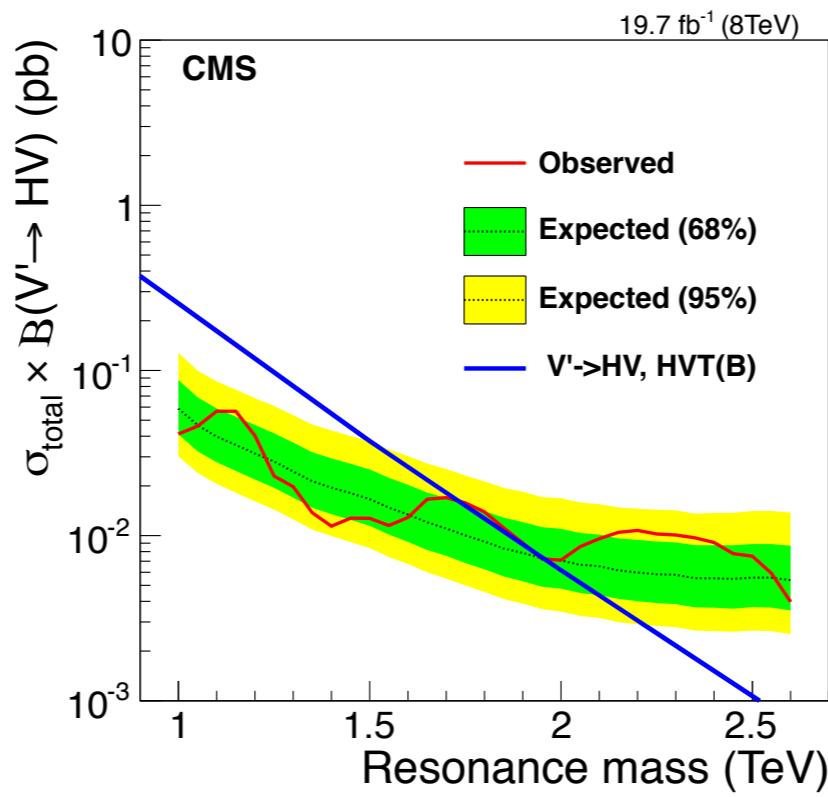
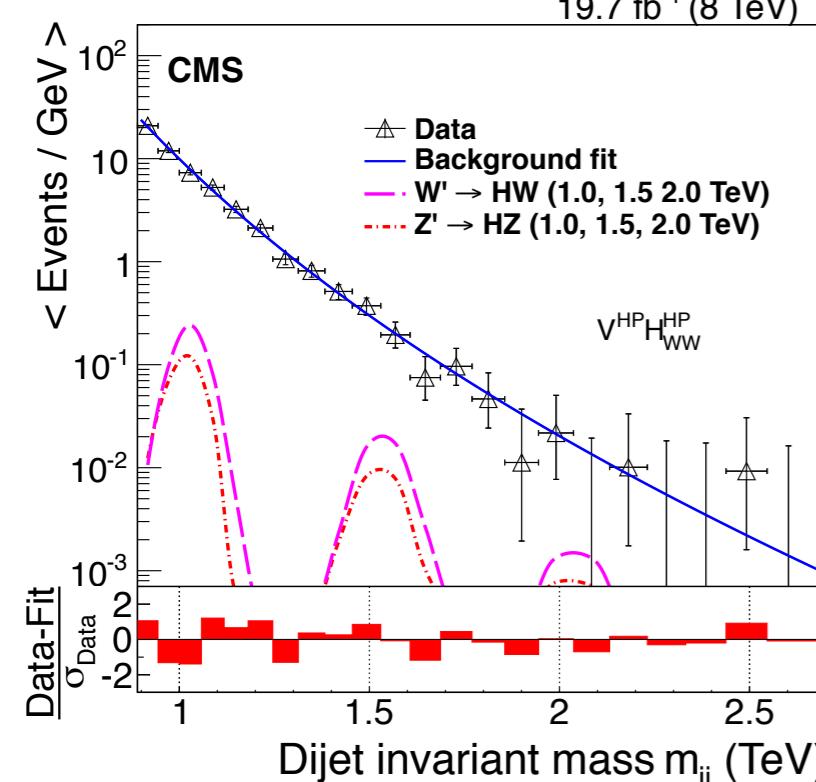


W/ZH->hadronic (CMS)

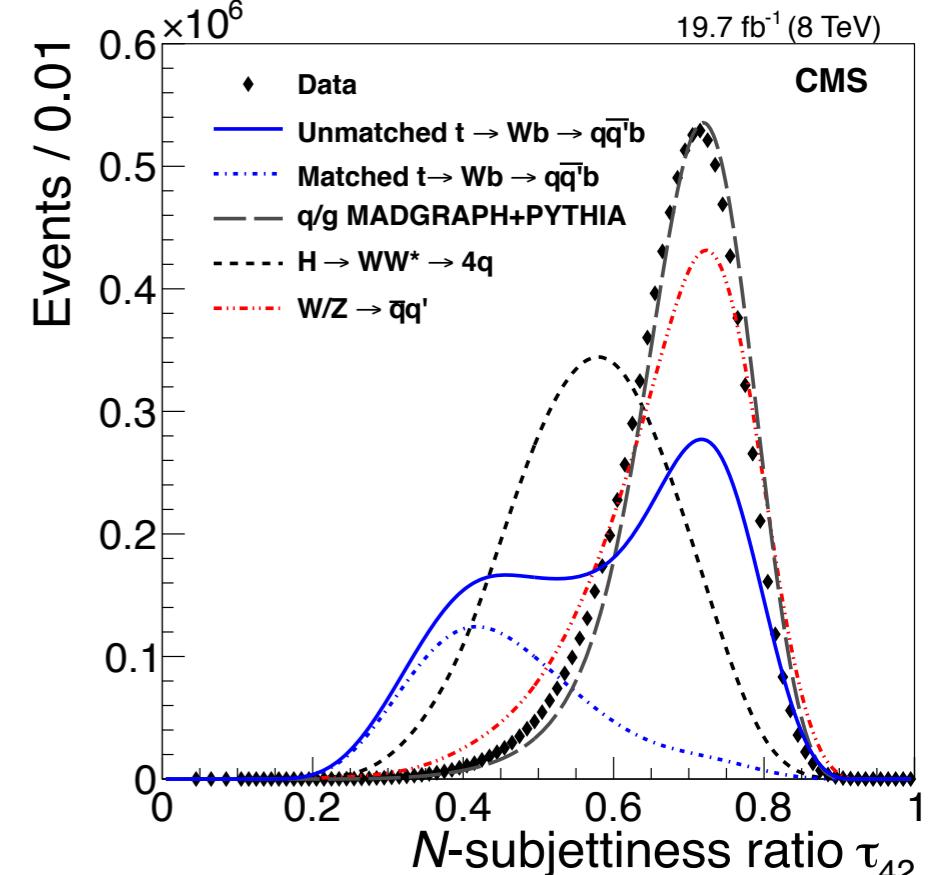


- First analysis to include H->WW->4 q decays
- 2 CA0.8 jet, $70 < m_j < 100 \text{ GeV}/c^2$ for W/Z, $110 < m_j < 135 \text{ GeV}/c^2$ for H
- Split pruned jet:
 - if the subjets' $\Delta R > 0.3$ b-tagging applied to individual sub-jets
 - if the subjets' $\Delta R < 0.3$ b-tagging applied to the CA0.8 jet
- tau42 used to discriminate H->WW->4q from QCD jets

Categories	V tag	H tag
$V^{HP}H_{bb}$	$\tau_{21} \leq 0.5$	b tag
$V^{LP}H_{bb}$	$0.5 < \tau_{21} < 0.75$	b tag
$V^{HP}H_{WW}^{HP}$	$\tau_{21} \leq 0.5$	$\tau_{42} \leq 0.55$
$V^{LP}H_{WW}^{HP}$	$0.5 < \tau_{21} < 0.75$	$\tau_{42} \leq 0.55$
$V^{HP}H_{WW}^{LP}$	$\tau_{21} \leq 0.5$	$0.55 < \tau_{42} < 0.65$



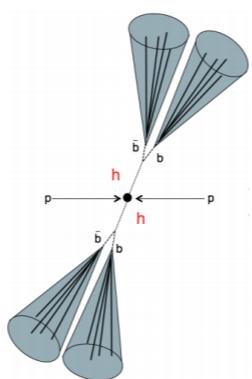
[CMS: arxiv1506.01443](https://arxiv.org/abs/1506.01443)



HH->4b (ATLAS)

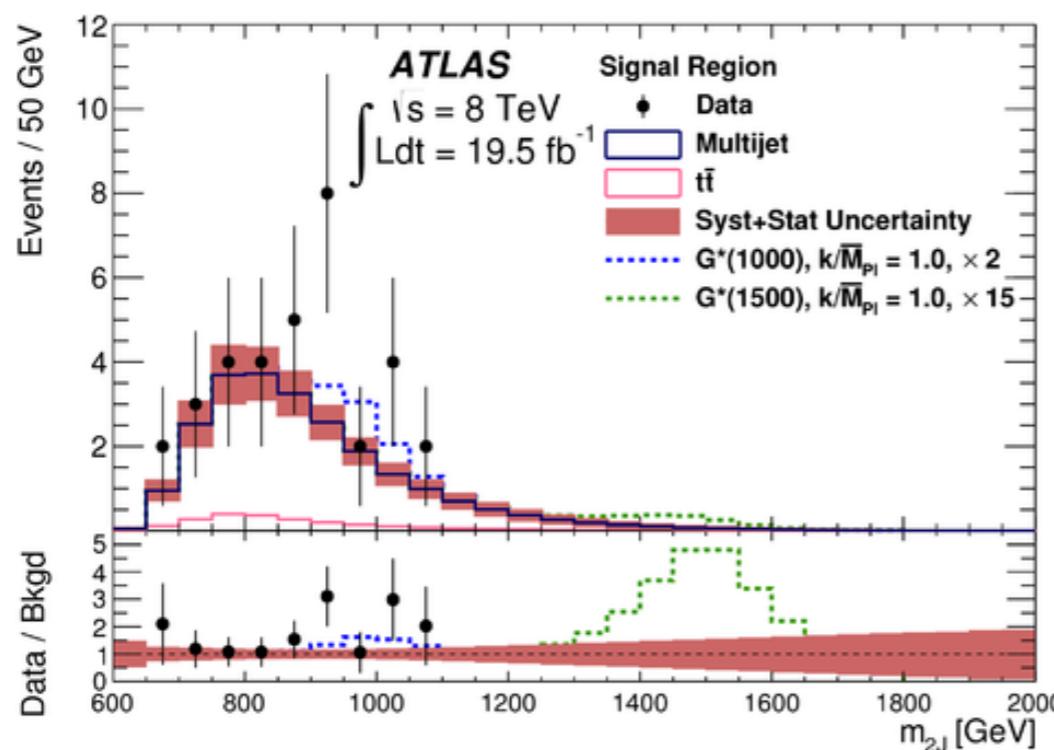
Resolved

- 4 b-jets
- 2 dijets with $M_{jj} \sim MH$
- ttbar veto



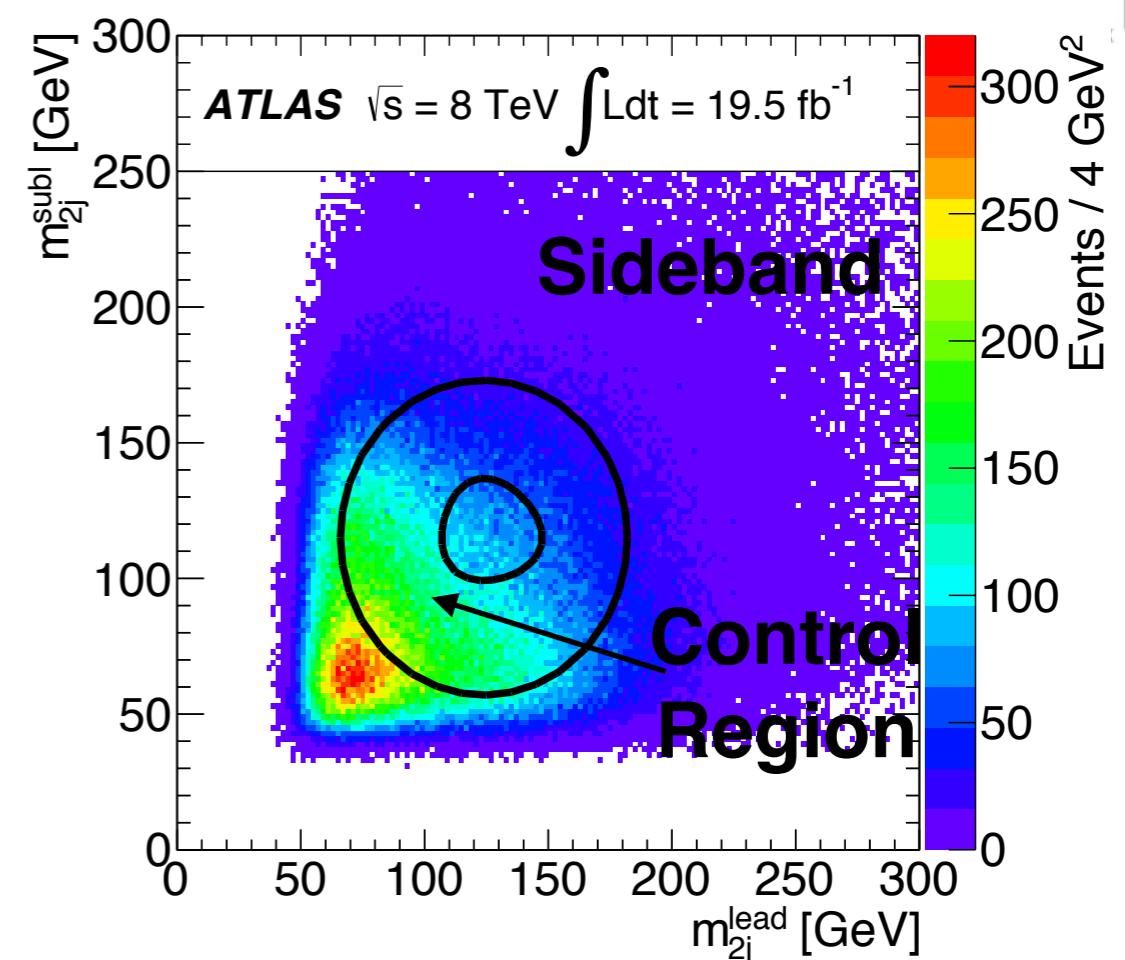
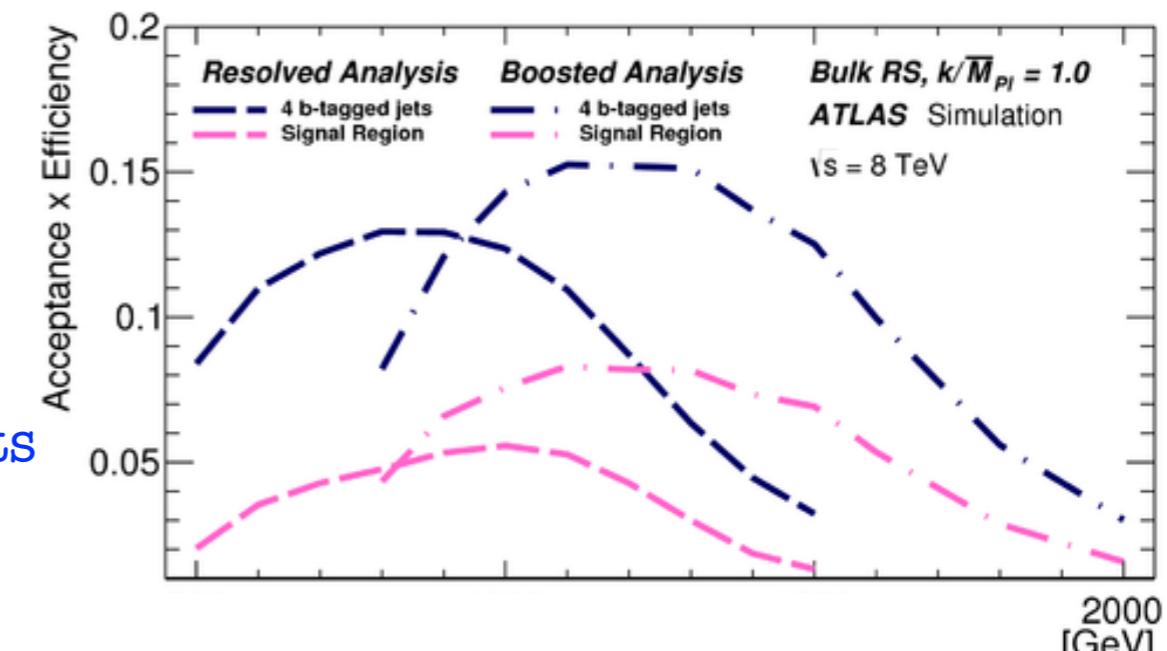
Boosted:

- Select events with two large-R jets, build from their tracks AntiKt jets $\Delta R = 1.0$ and trim them, using $\Delta R = 0.3$ subjets to get rid of QCD, find b-jets among the subjets
- Validation in signal-depleted sidebands
- **M4b resolution ~15% at 1 TeV**



17

<http://arxiv.org/abs/1506.00285>

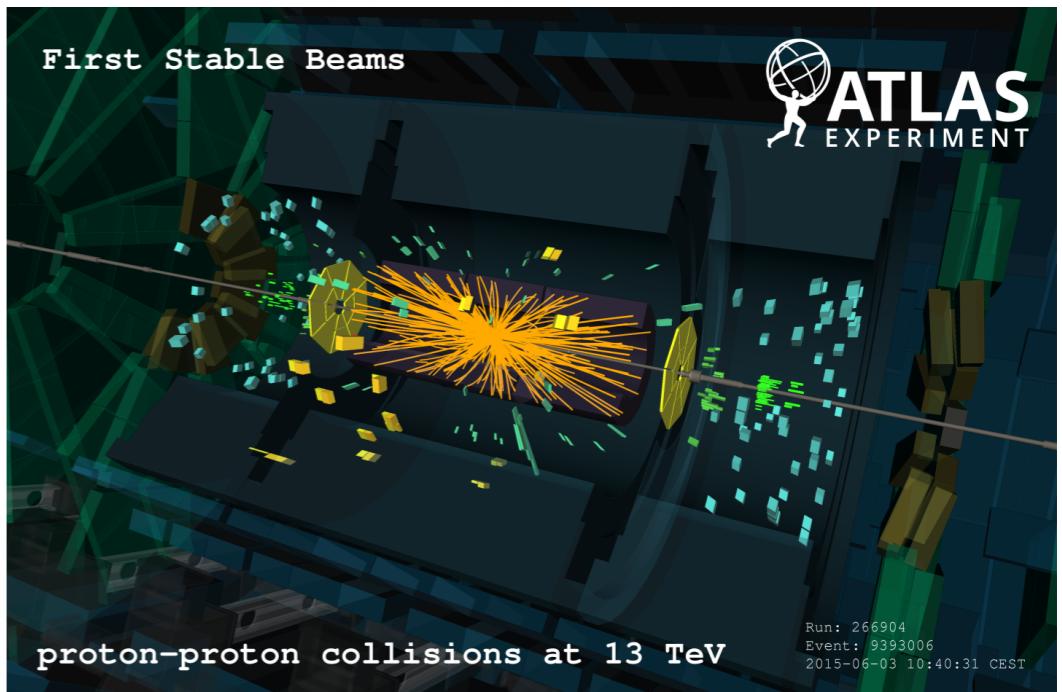


Conclusion

Search for **heavy resonances** is one of the most direct ways to find new physics at TeV scale

Diboson final state provides clear experimental signature and allows cross check among different channels

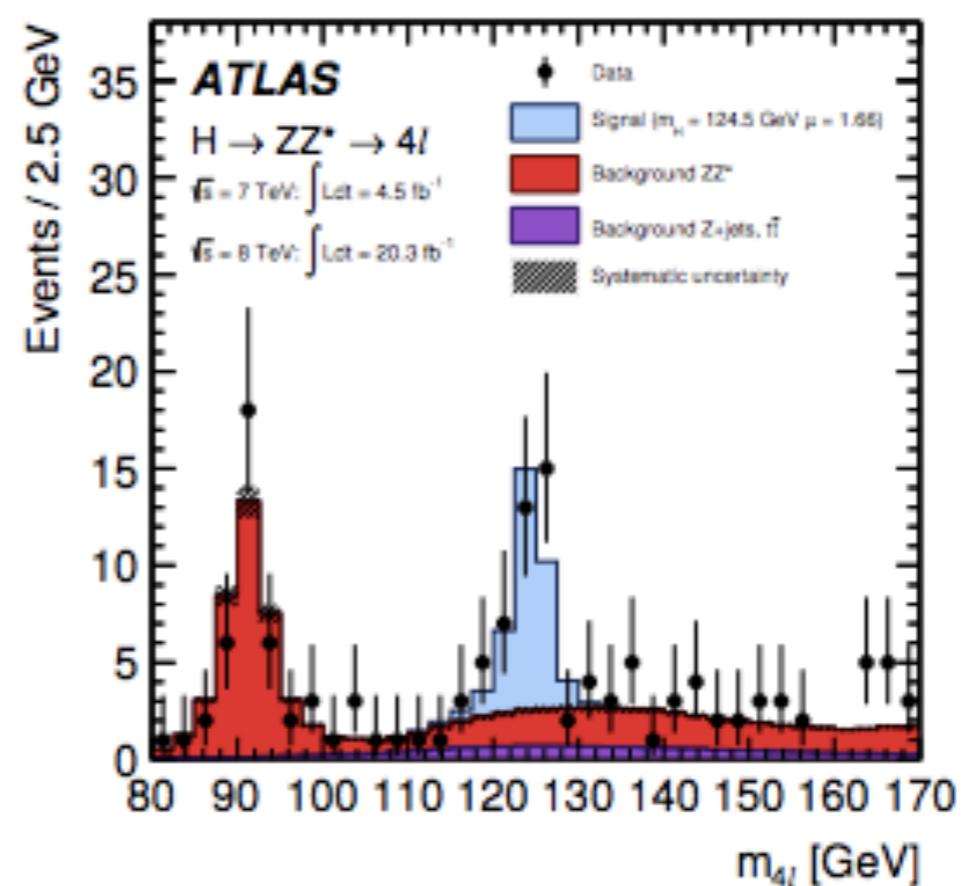
- Some interesting excess need to be checked with 13 TeV data
- Run2 offers new opportunity for discoveries:
 - Increase in CM energy ->Increase the mass discovery reach
 - Increase in integrated luminosity ->enhance sensitivity for rare processes
- Need to be ready for the unexpected
 - Analyze all feasible final state to make sure we leave no stone unturned





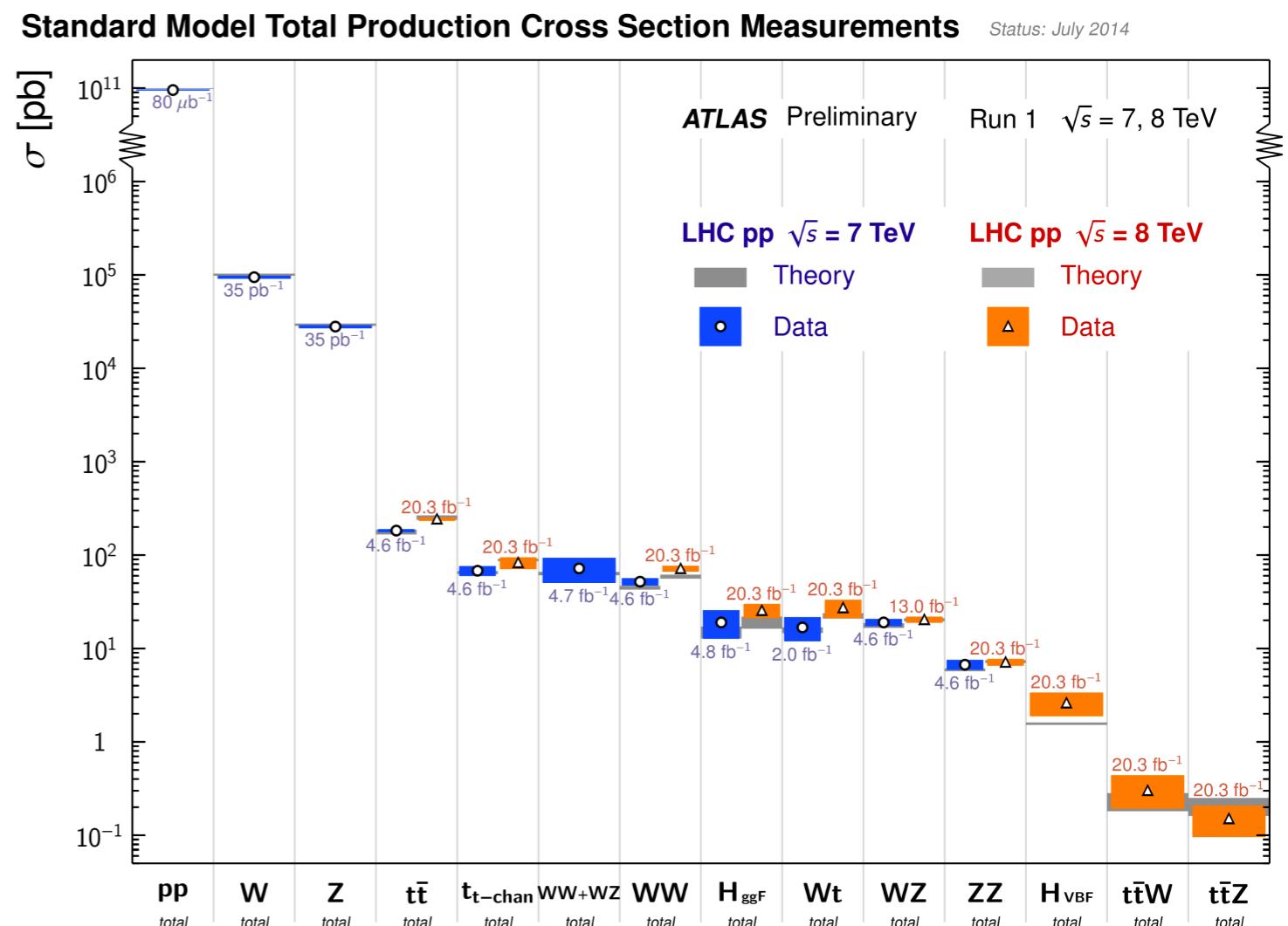
Lessons from Run1

1. Detectors perform very well in challenging LHC environment → Higgs discovery with ~half the energy, less luminosity



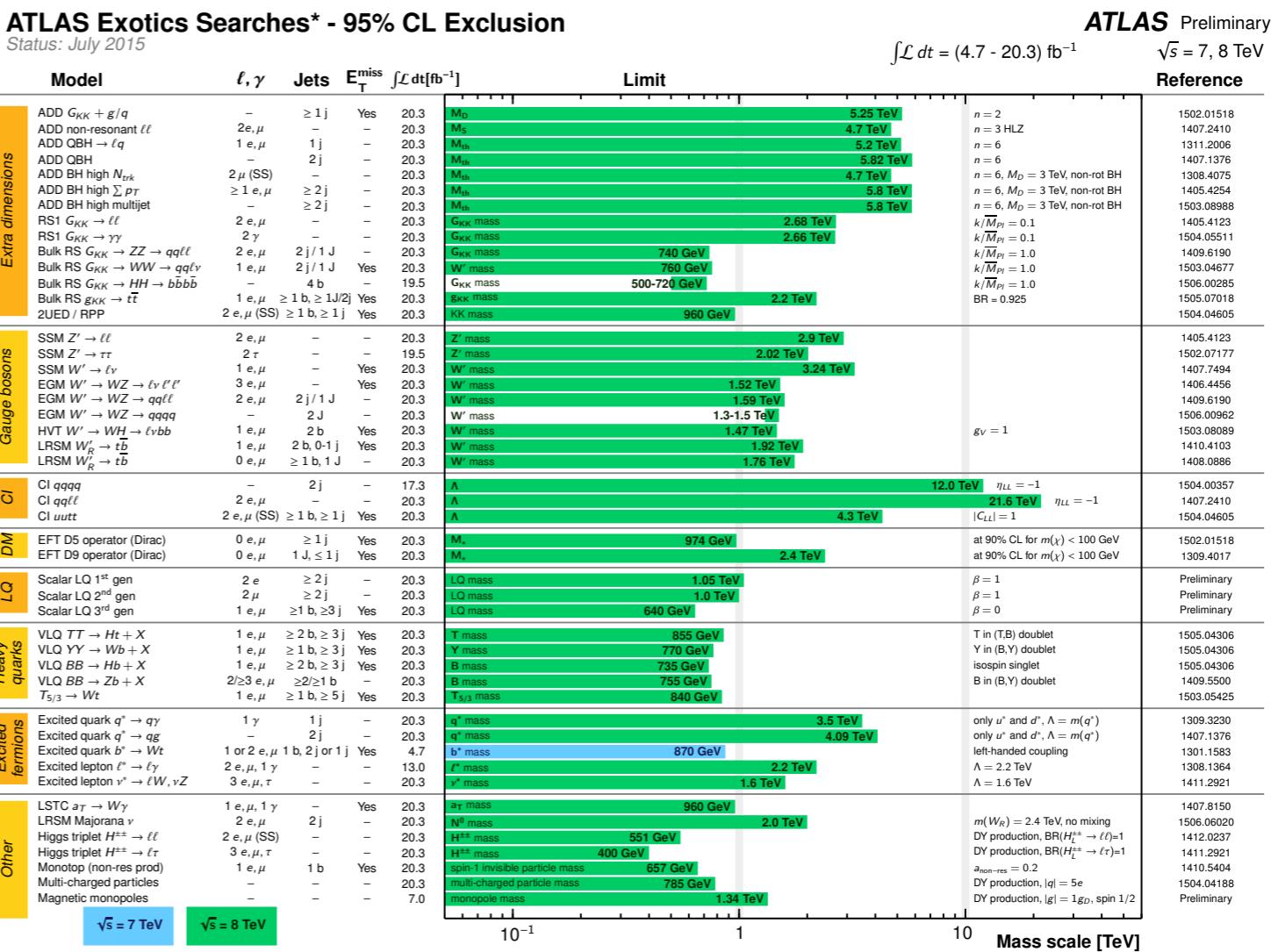
Lessons from Run1

1. Detectors perform very well in challenging LHC environment → Higgs discovery with ~half the energy, less luminosity
2. Plethora of SM precision measurement



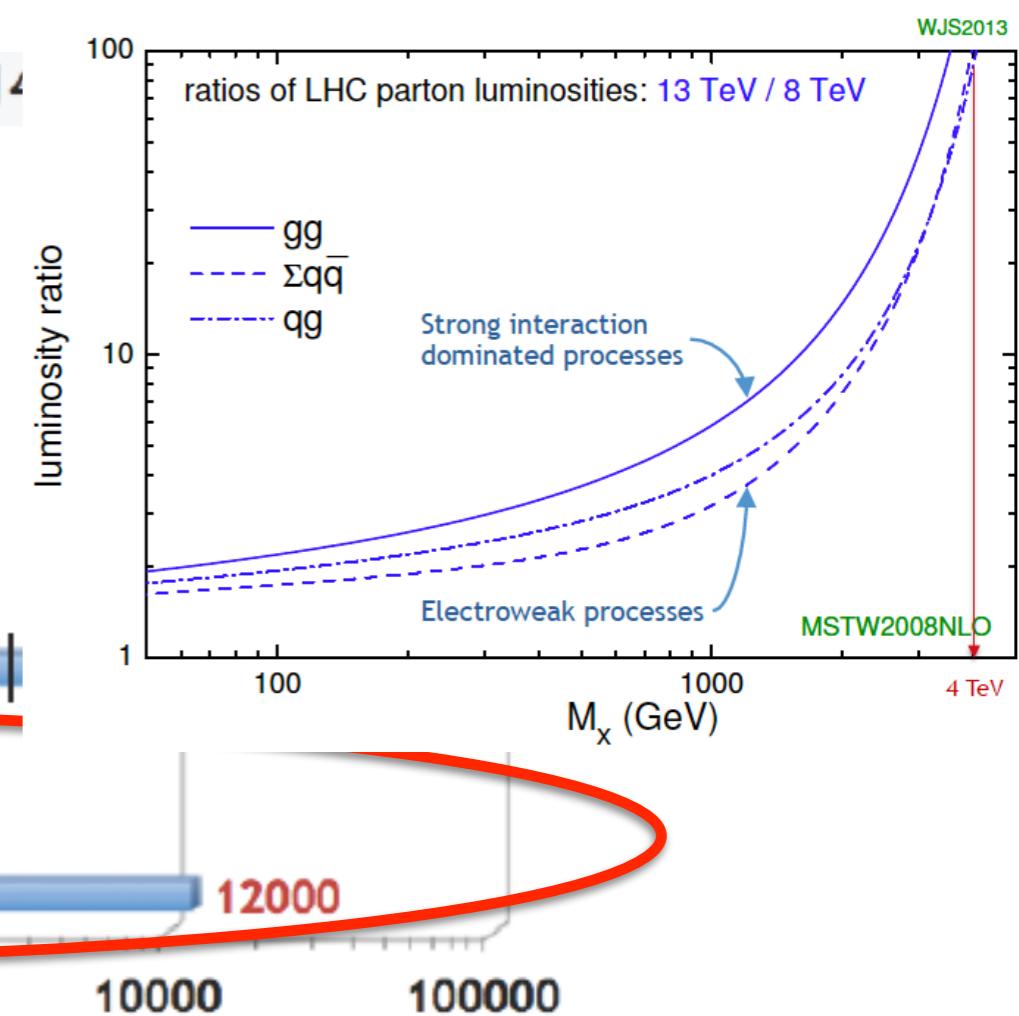
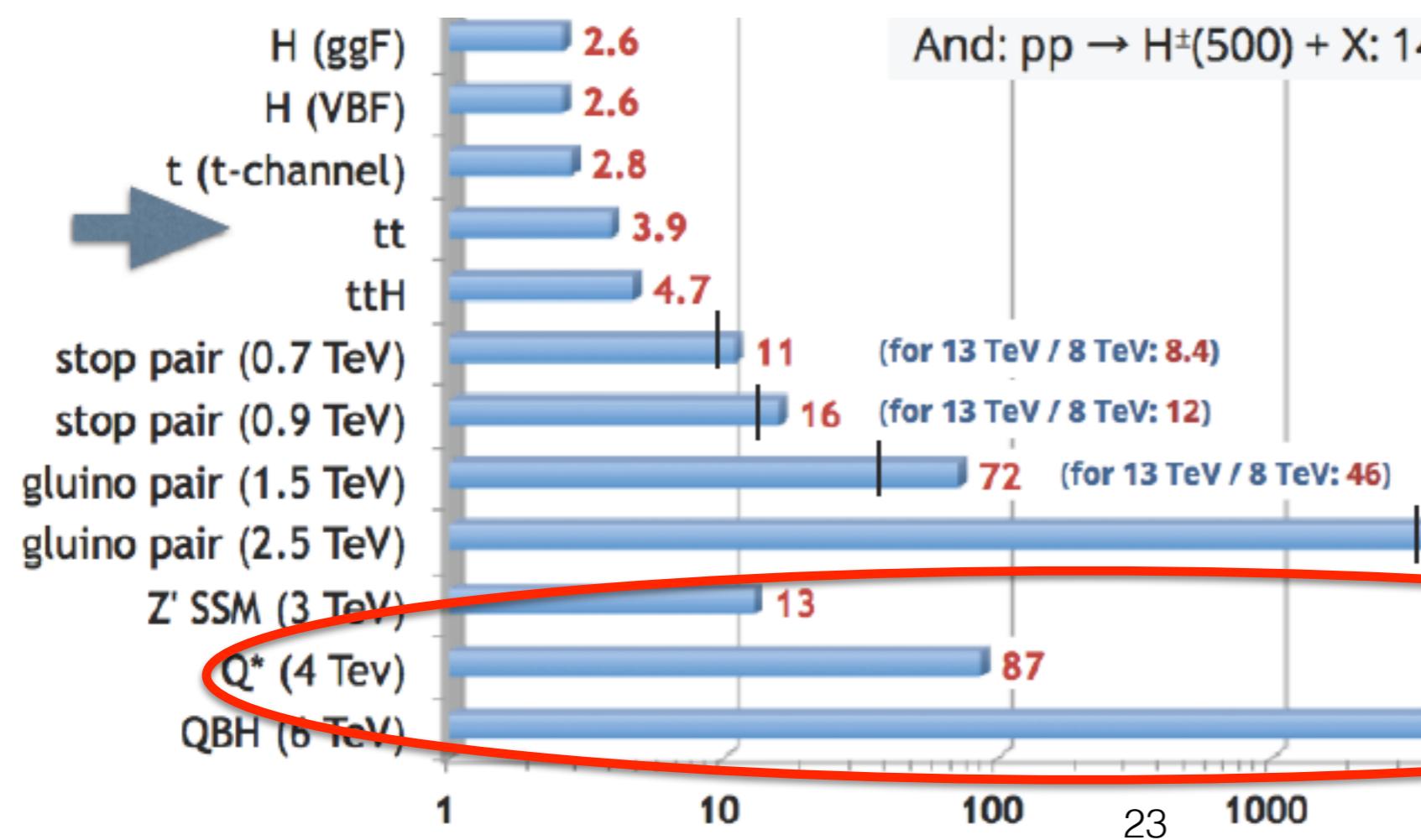
Lessons from Run 1

1. Detectors perform very well in challenging LHC environment → Higgs discovery with ~half the energy, less luminosity
2. Plethora of SM precision measurement
3. No hints of BSM (at least not significant)



Hail to Run2

- Substantial increase in energy for the world's highest energy collider
- Largest jump in sensitivity to BSM
 - 20 fb^{-1} @8TeV $\rightarrow 100 \text{ fb}^{-1}$ @13/14 TeV
 - Will not happen again for another 2+ decades!!!
- New territory explored essentially for all BSM searches with 0.1-10.0 fb-1 (2015)

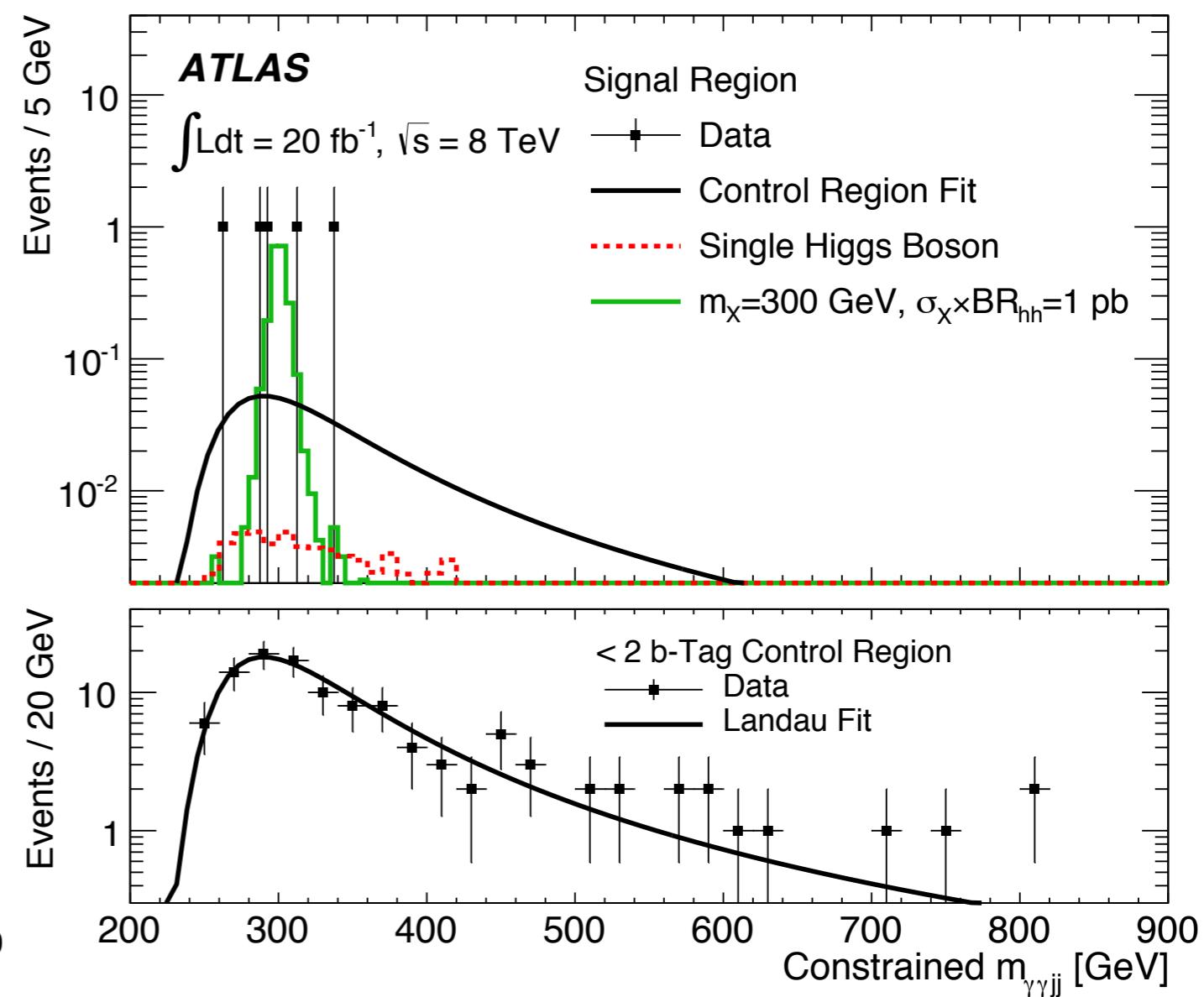
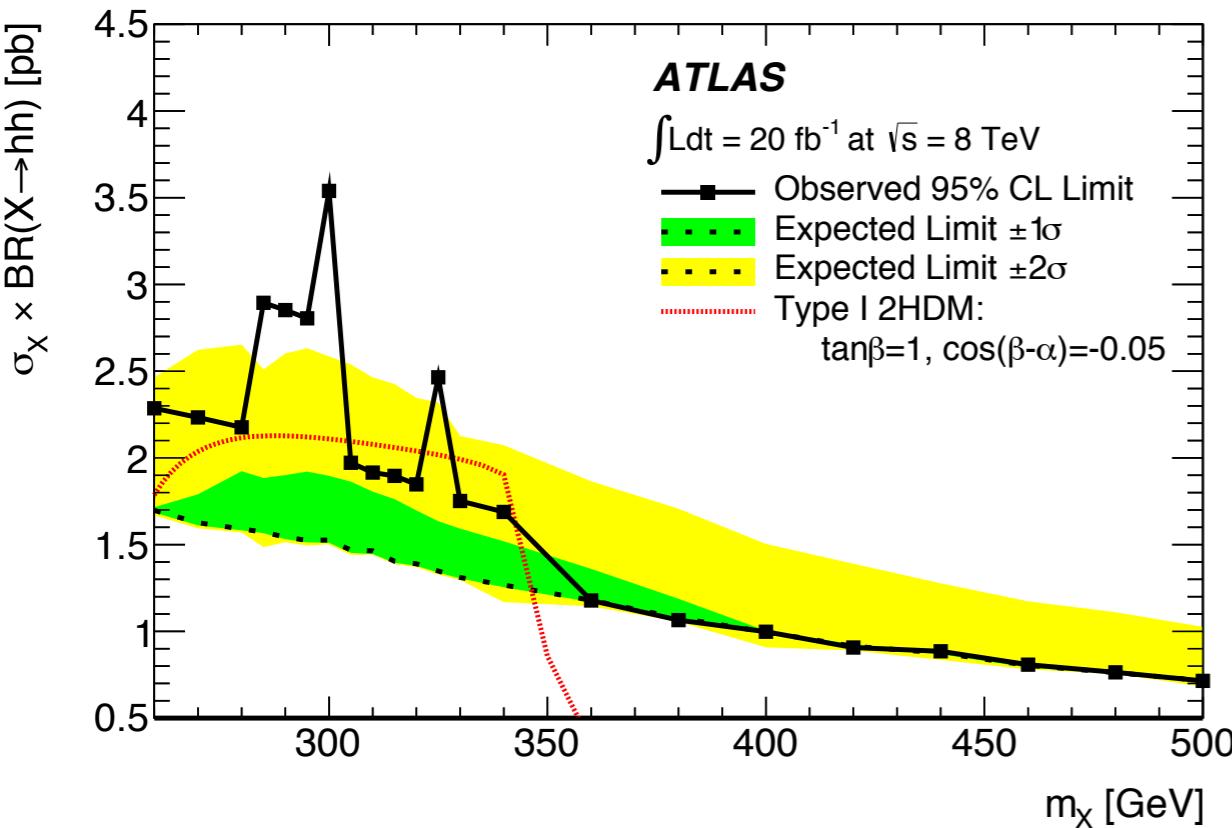


HH \rightarrow bb $\gamma\gamma$ (ATLAS)

[ATLAS: arxiv. 1406.5053](https://arxiv.org/abs/1406.5053)

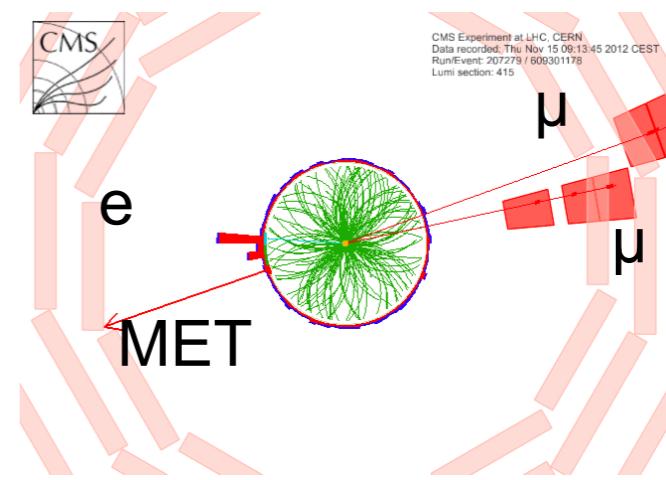
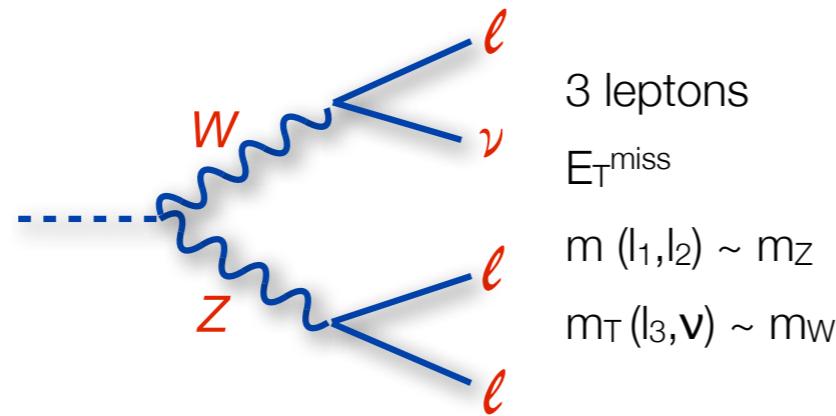
Standard H $\rightarrow\gamma\gamma$ sel. + 2 b-jets

- $|m_{\gamma\gamma}-m_H|<2\sigma m$ & $95 < m_{jj} < 135$ GeV
- $|m_{\gamma\gamma bb}-MX|<$ optimized cut, MX dependent
- Counting experiment
- Background estimated from $\gamma\gamma$ sideband and events with <2 b-jets



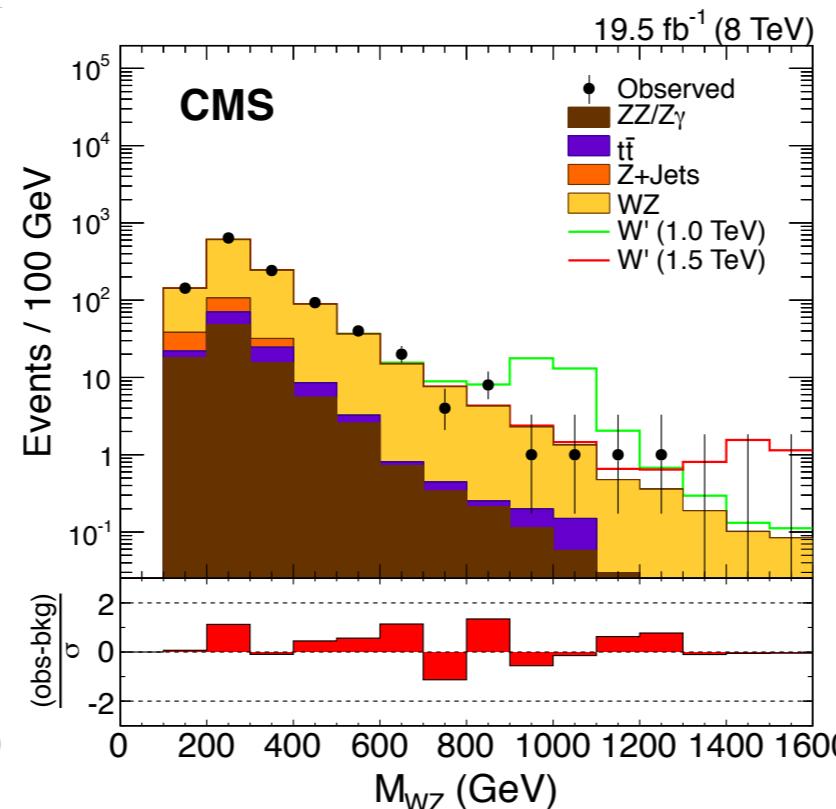
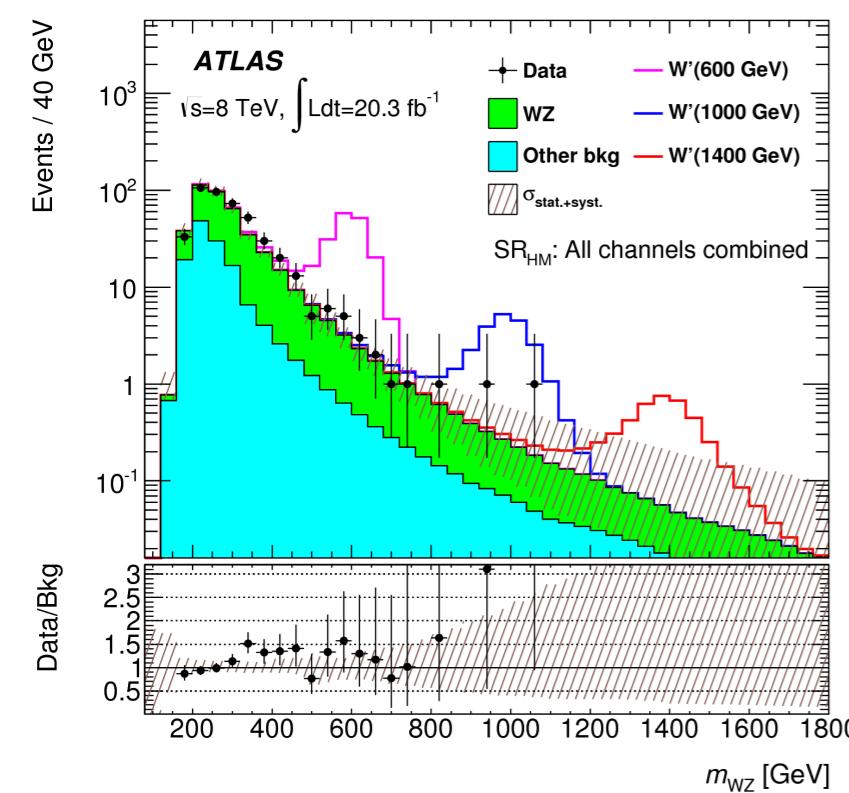
All leptonic final states

- Advantages:
 - Low backgrounds, high purity
- Disadvantages:
 - Low branching fraction
 - Kinematic reconstruction with at least one neutrino



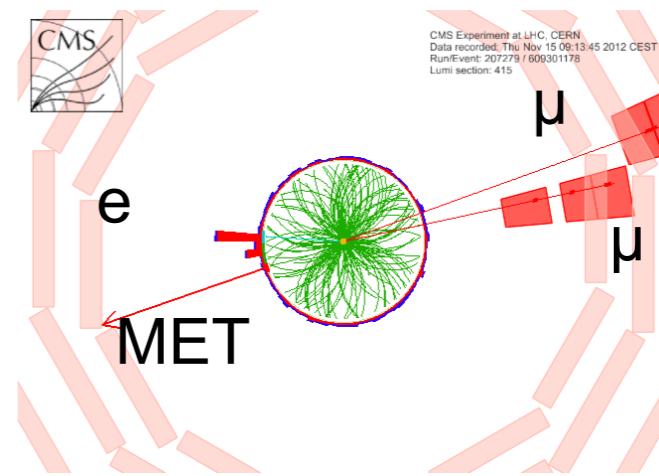
$WZ \rightarrow lll\nu$

- Analysis Strategy:
 - Select three leptons
 - Compute M_{WZ} from MET and W mass constraint
 - Search for bump in M_{WZ} spectrum

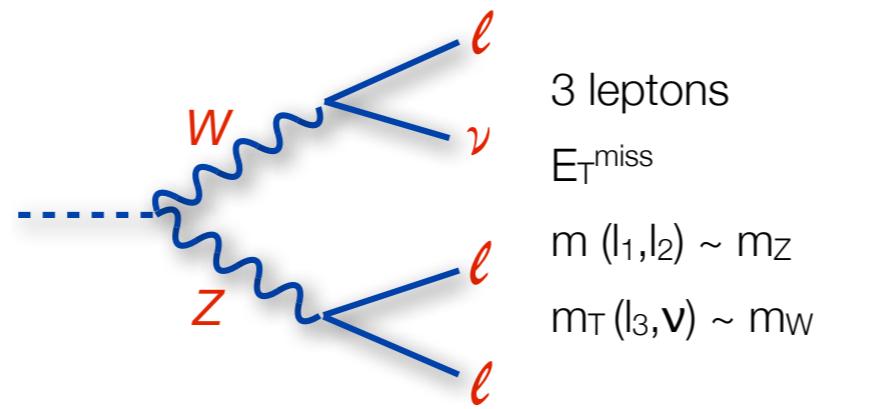
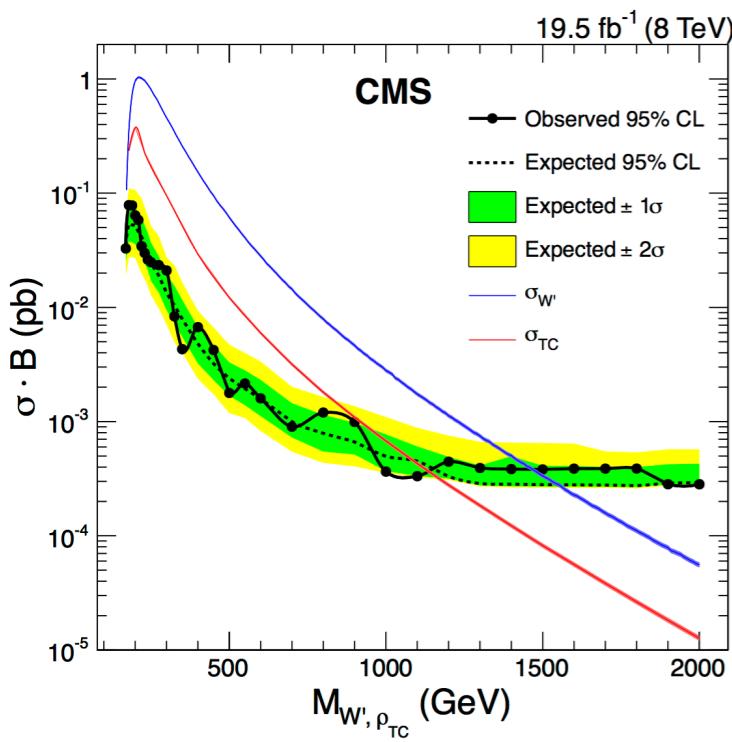


All leptonic final states

- Advantages:
 - Low backgrounds, high purity
- Disadvantages:
 - Low branching fraction
 - Kinematic reconstruction with more than one neutrino



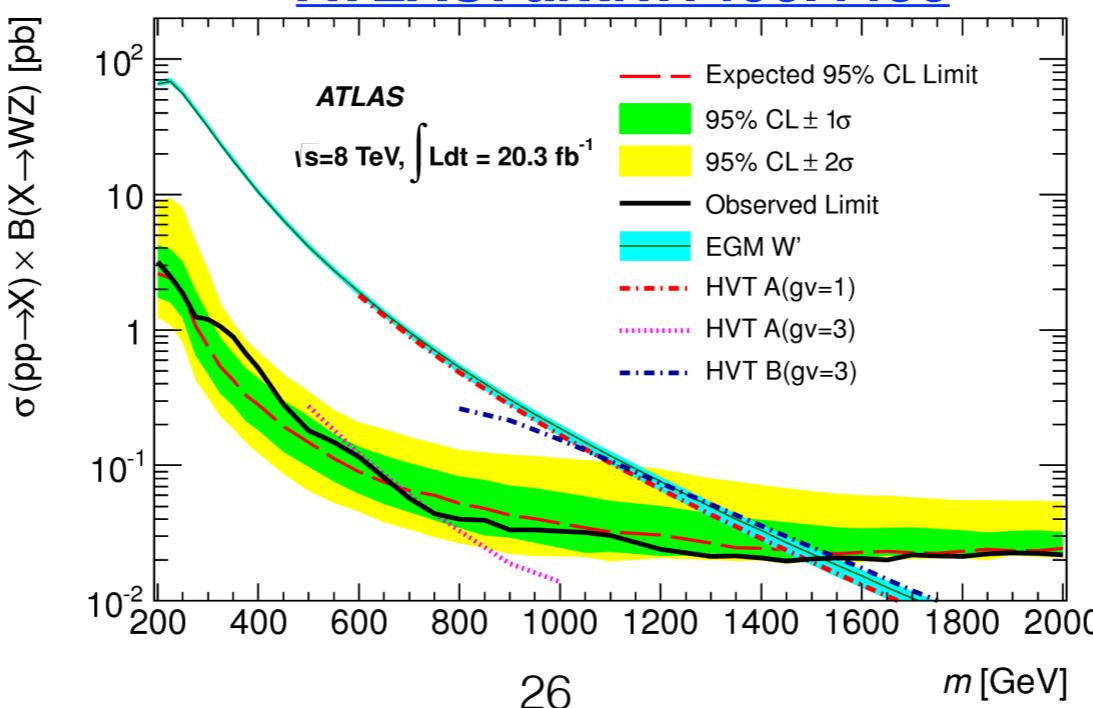
[CMS: arxiv:1407.3476](https://arxiv.org/abs/1407.3476)



$WZ \rightarrow l l l \nu$

- Interpretations:
 - Sequential SM W'
 - Heavy vector triplet (weakly coupled resonance and composite Higgs)
 - Technicolor

[ATLAS: arxiv.1406.4456](https://arxiv.org/abs/1406.4456)



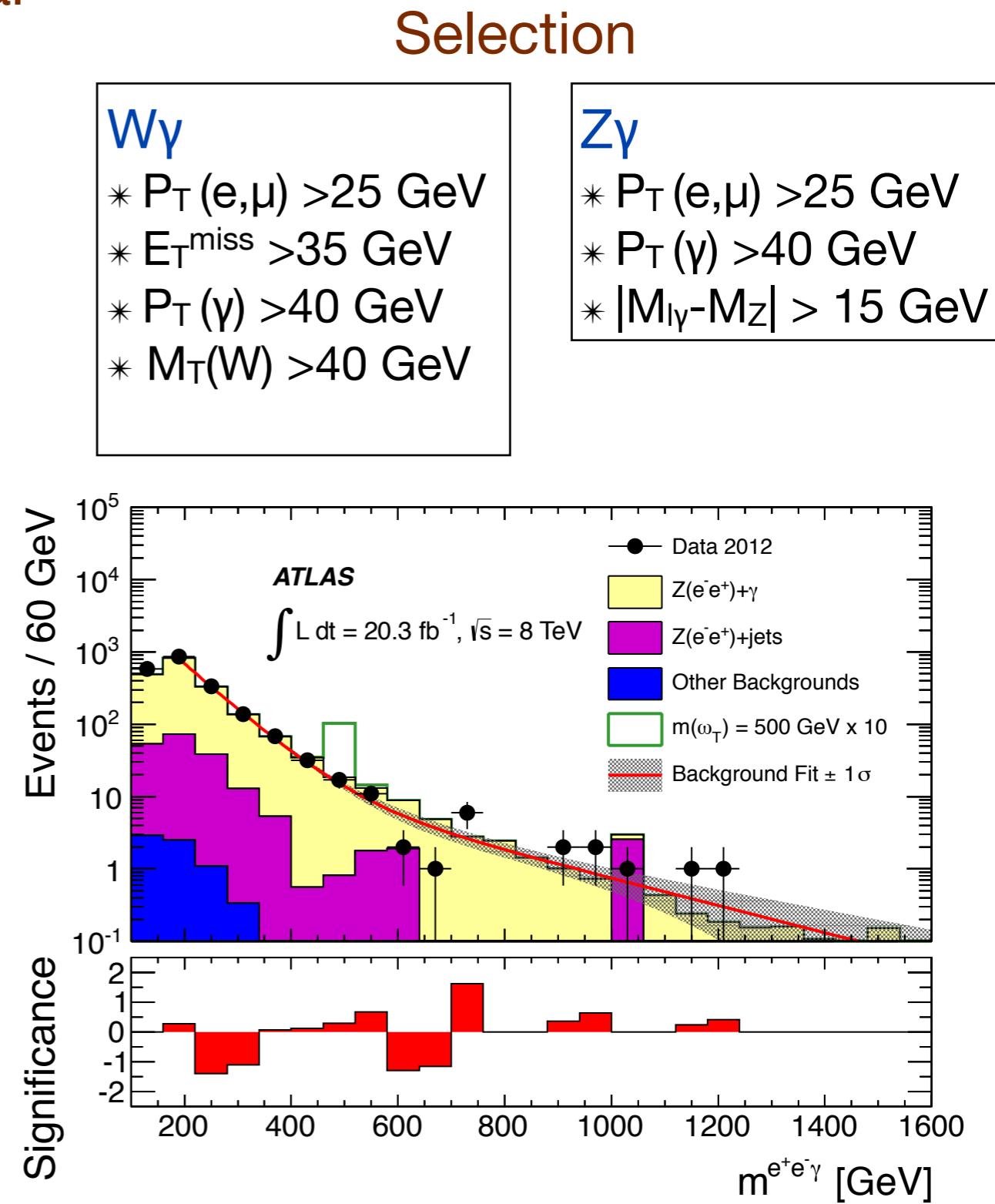
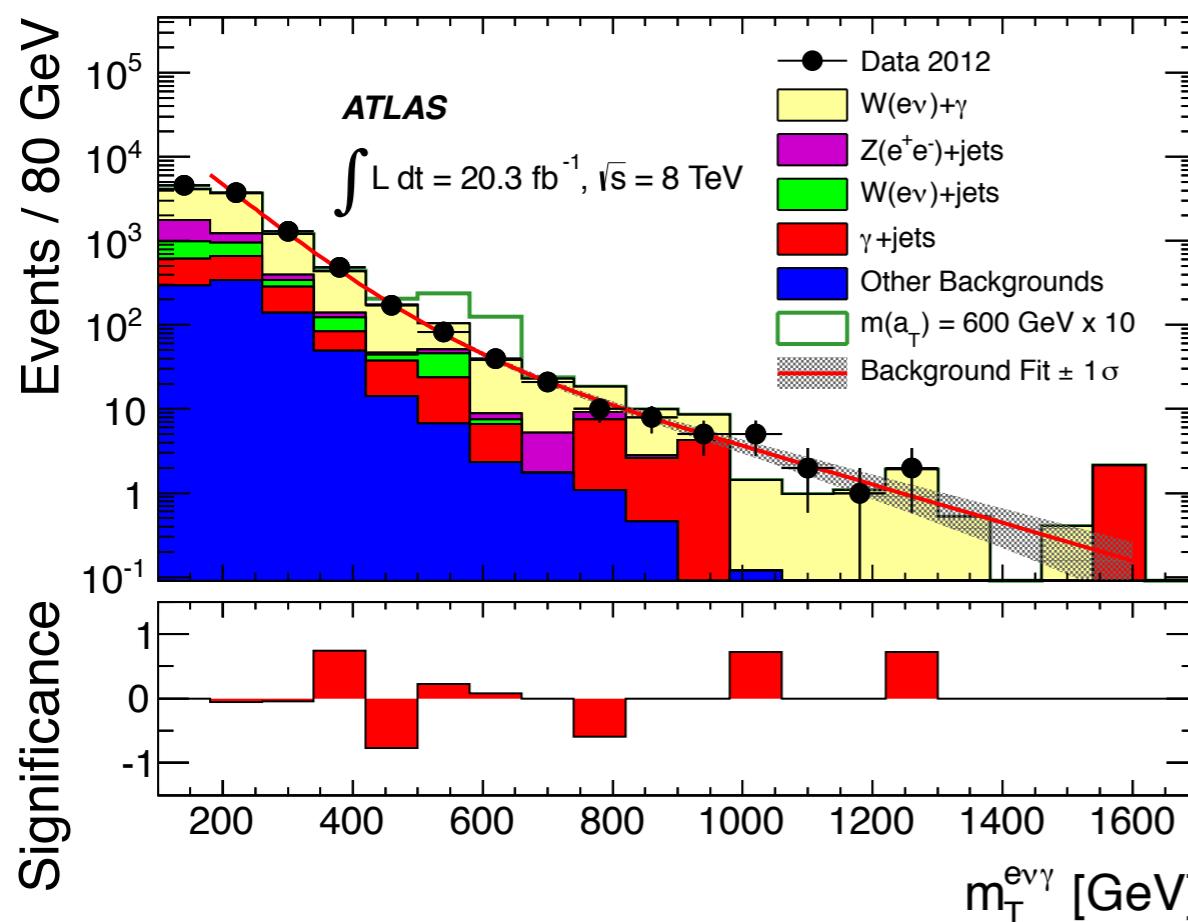
$Z\gamma, W\gamma$

Standard Model inclusive and differential cross sections are measured

Here focus on non-SM part of the analysis

First $V\gamma$ search at LHC

Technicolor models give $a_T \rightarrow W\gamma$ and
 $\omega_T \rightarrow Z\gamma$



Selection

$W\gamma$

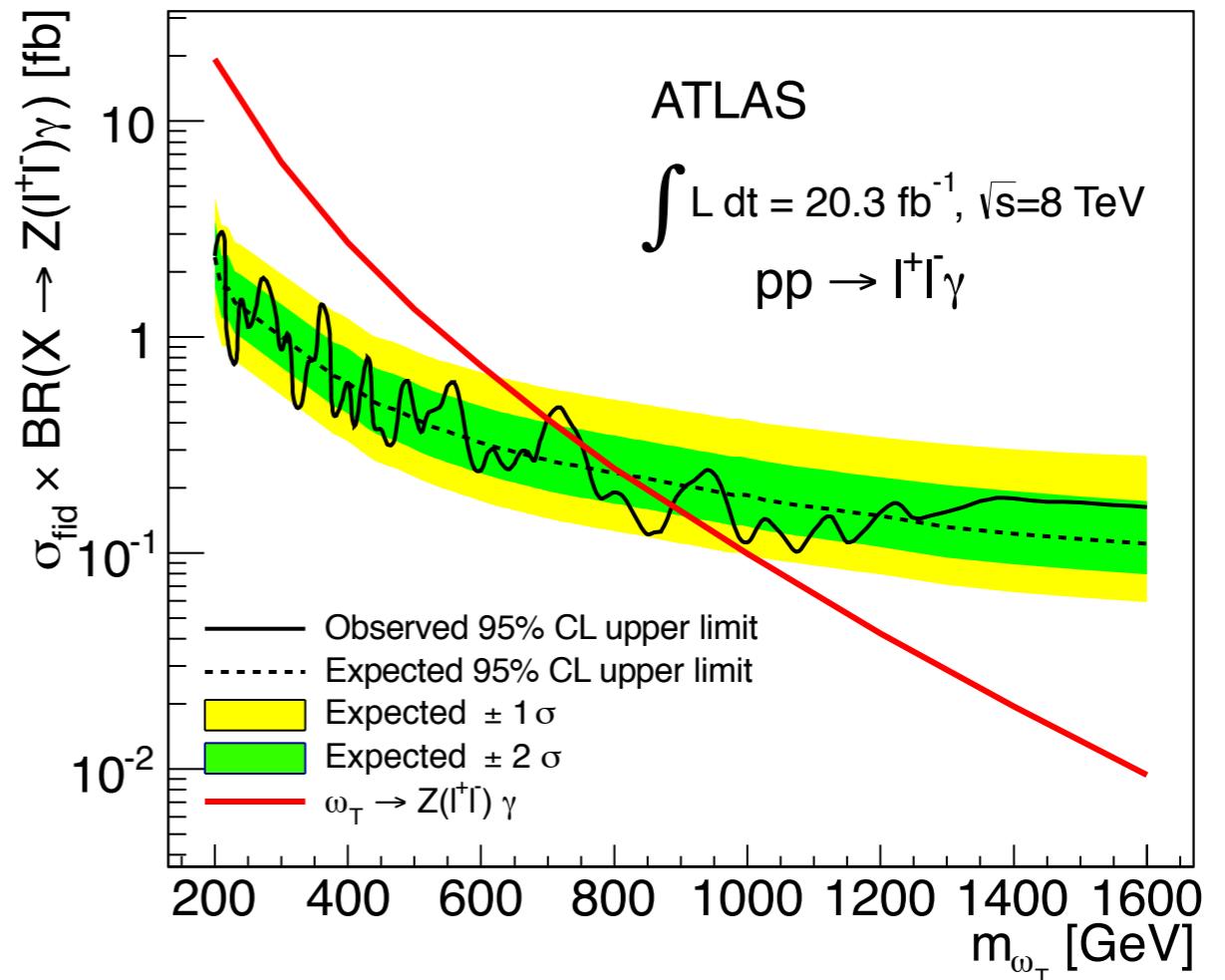
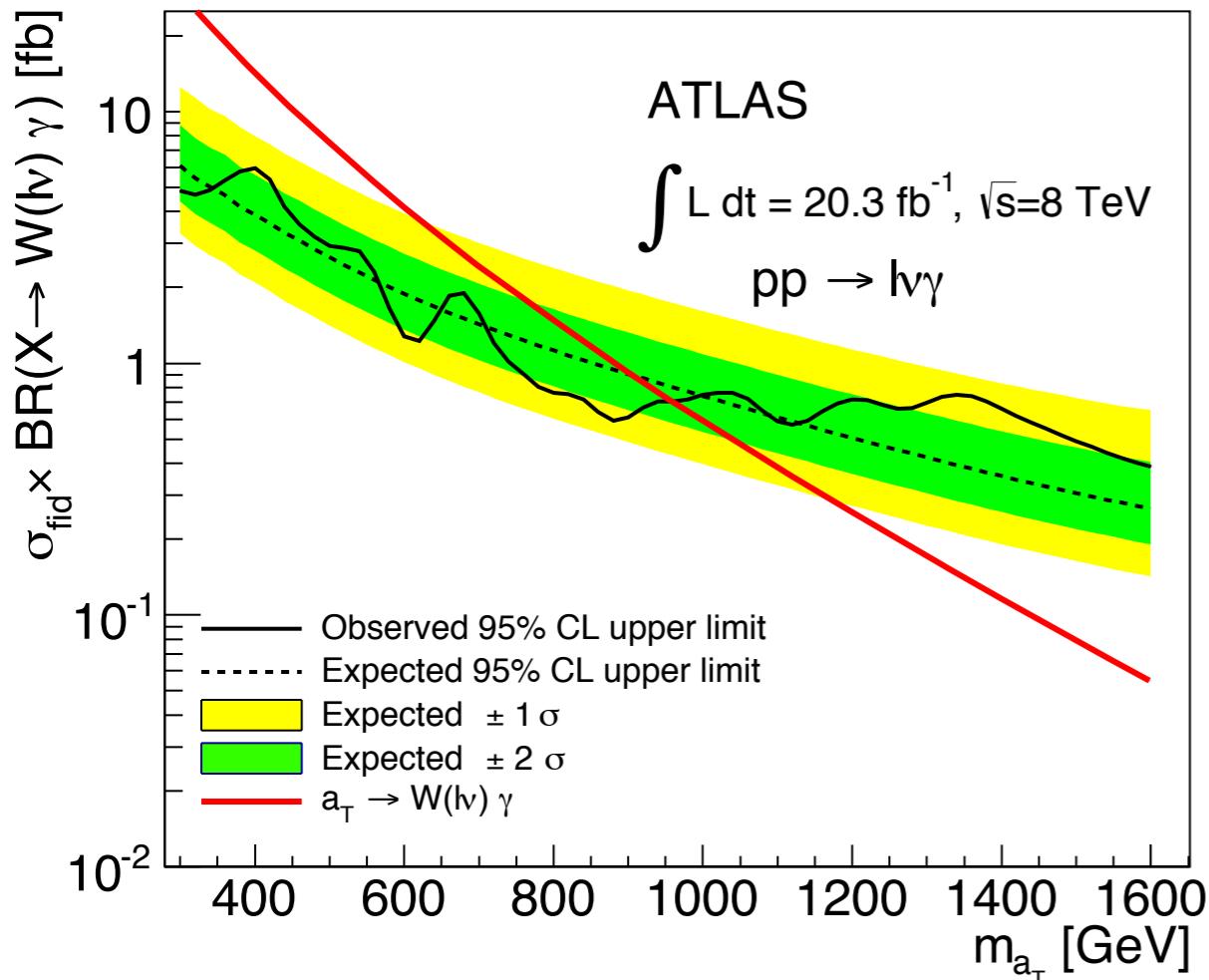
- * $P_T(e, \mu) > 25 \text{ GeV}$
- * $E_T^{\text{miss}} > 35 \text{ GeV}$
- * $P_T(\gamma) > 40 \text{ GeV}$
- * $M_T(W) > 40 \text{ GeV}$

$Z\gamma$

- * $P_T(e, \mu) > 25 \text{ GeV}$
- * $P_T(\gamma) > 40 \text{ GeV}$
- * $|M_{\gamma\gamma} - M_Z| > 15 \text{ GeV}$



$Z\gamma, W\gamma$



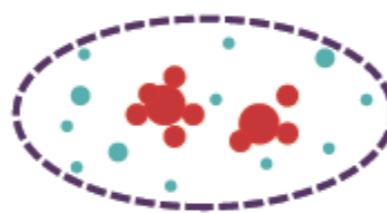
* data well described by SM backgrounds

- * Exclude: $m(\omega_T) < 900 \text{ GeV}$
- * Exclude: $m(a_T) < 1000 \text{ GeV}$

Boosted boson tagging

Boson jets

- Two narrow regions with high energy for each quark
- Each of the quark carries comparable fraction of the boson momentum in the lab frame



QCD jets

- Narrow region with high energy density
- High energy density region has most of the momentum of the jet



1. **Fat jet:** large distance parameter to pick up all the radiation from the original decay

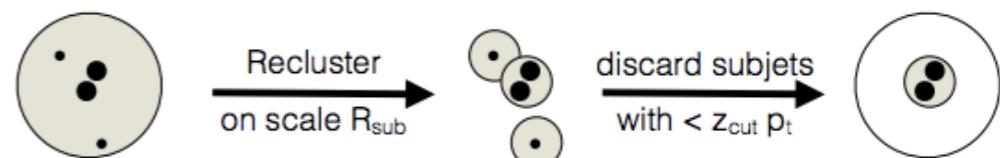
Grooming:

- Signal: take out jet constituents that don't belong to the signal decay
- Background - Preserve background characteristics in the jet

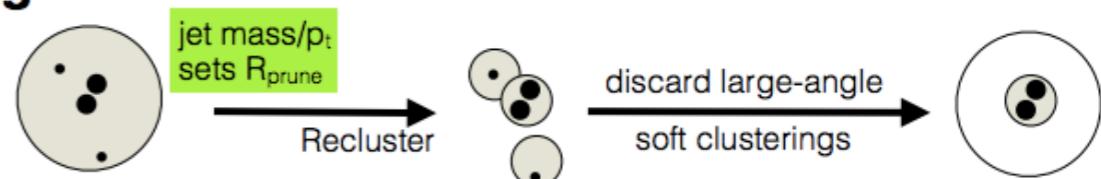
Tagging:

- Use differences in Signal and Background jet characteristics to reject background jets

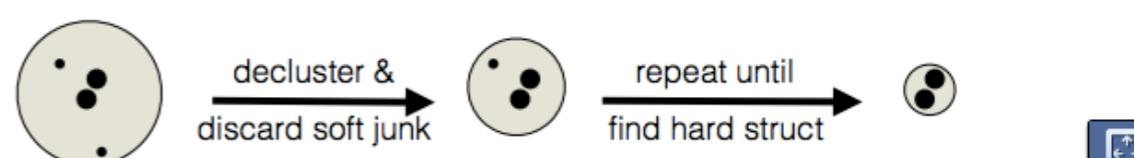
Trimming



Pruning

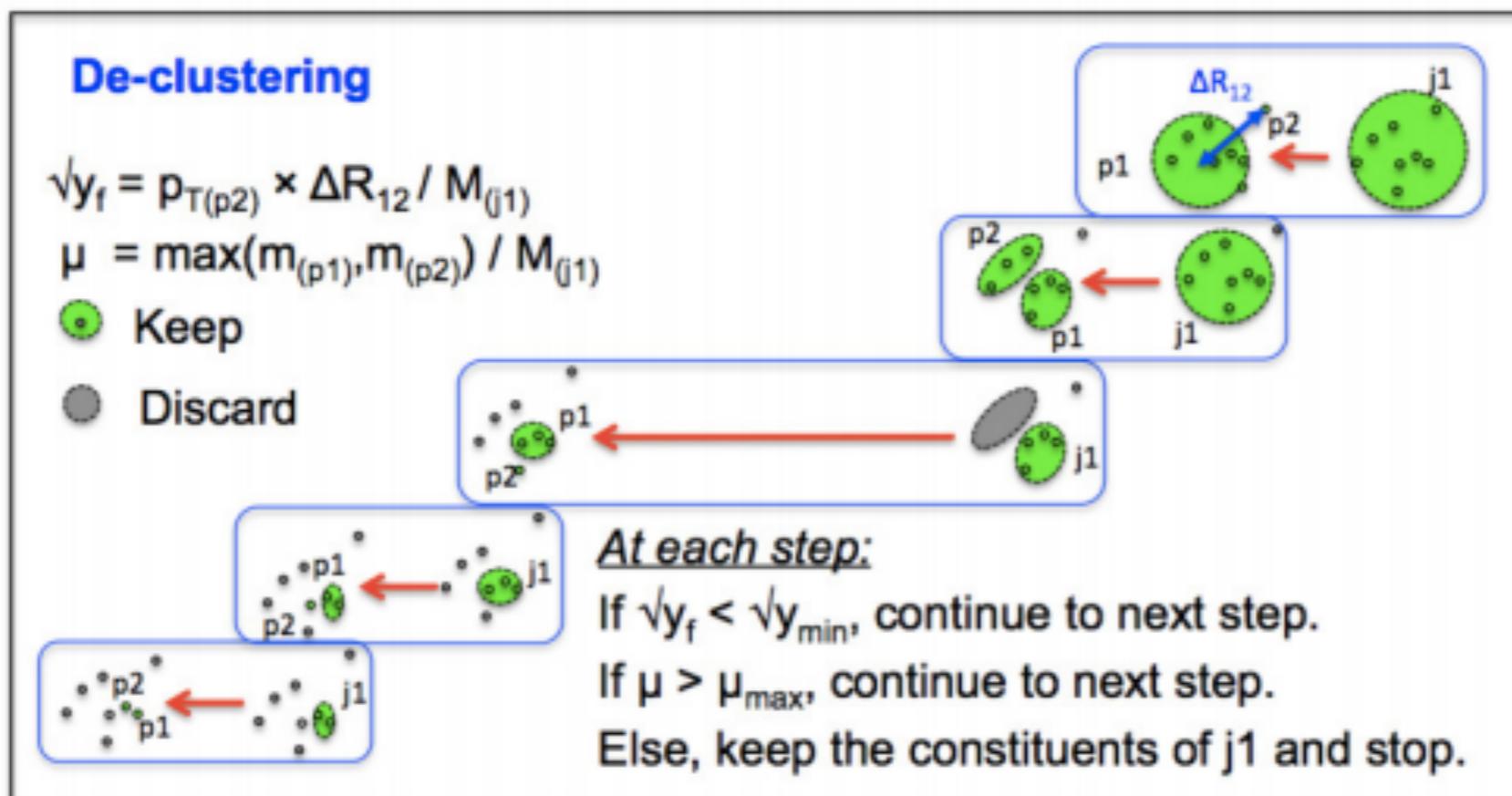


Mass-drop tagger (MDT, aka BDRS)



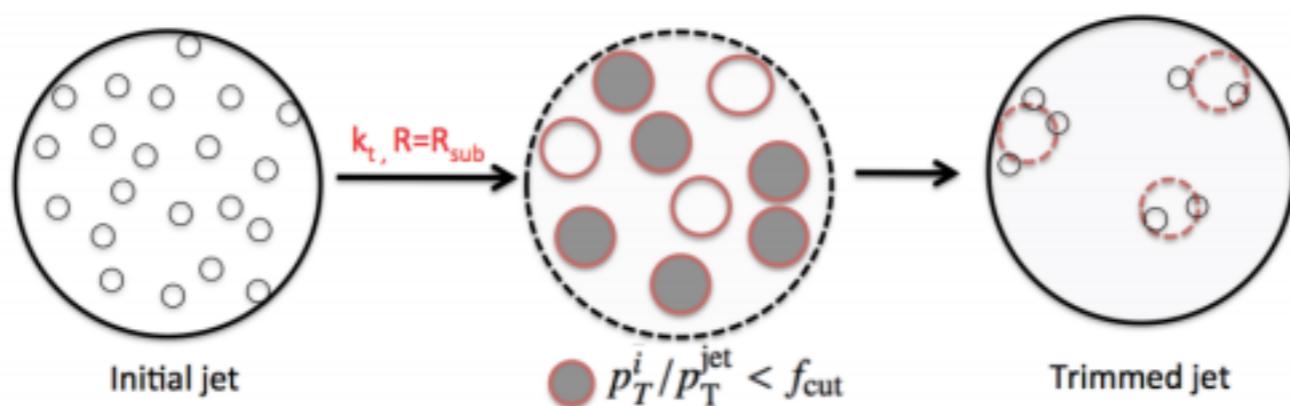
JetMass grooming

- Mass drop/filtering (<http://arxiv.org/abs/0802.2470>)
- Splitting: use substructure of jet: $\sqrt{y_s}$ and mass drop
- Filtering: remove soft radiation



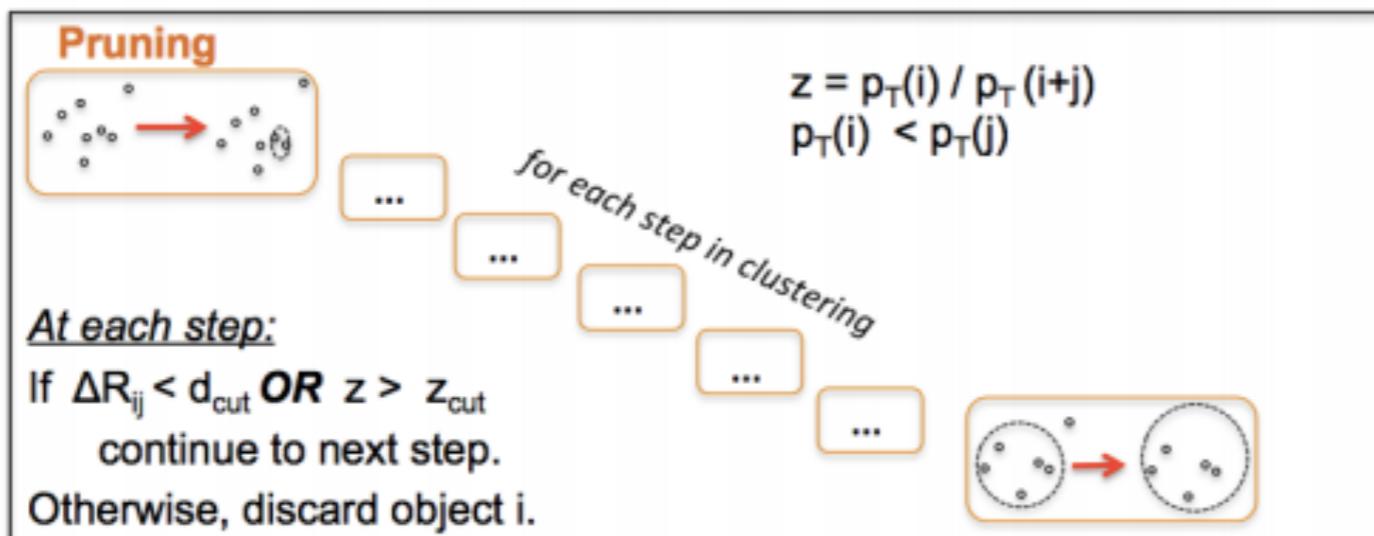
JetMass grooming

- Trimming (<http://arxiv.org/abs/0912.1342>)
- Removes soft constituents from pile-up, ISR and multiple parton interaction by comparing the pT of each constituents to the jet pT: $p_T^i/p_{\text{jet}}^T < f_{\text{cut}}$



JetMass grooming

- Pruning <http://arxiv.org/abs/0912.0033>
- For each jet in reclustering, remove softer constituent from jet if wide-angled: $R_{12} > R_{\text{cut}} \cdot 2m/p_T$ or
- soft: $\min(p_{T,1}, p_{T,2}) / p_{T,1} + p_{T,2} < Z_{\text{cut}}$



Definition of substructure variables

- **Splitting scale** Phys. Rev. D65 (2002) 096014

- k_t distance between the two proto-jets of the final clustering step:

$$\sqrt{d_{12}} = \min(p_{T1}, p_{T2}) \times \Delta R_{12}$$

- Hardest proto-jets are combined in last step of reclustering for k_t algorithm
- Symmetric energy distribution for W-jets, asymmetric for QCD jets

- **Momentum balance** Phys. Rev. Lett. 100 (2008) 24200

$$\sqrt{y_f} = \frac{\min(p_{T1}, p_{T2})}{m_{12}} \times \Delta R_{12}$$

- **N-subjettiness** JHEP 03 (2011) 015

- Describes how likely it is that a jet is composed out of N subjets:

$$\tau_N = \frac{\sum_k p_{T,k} (\min(\Delta R_{1,k}, R_{2,k}, \dots, R_{N,k}))^\beta}{\sum_k p_T(R_0)^\beta}$$

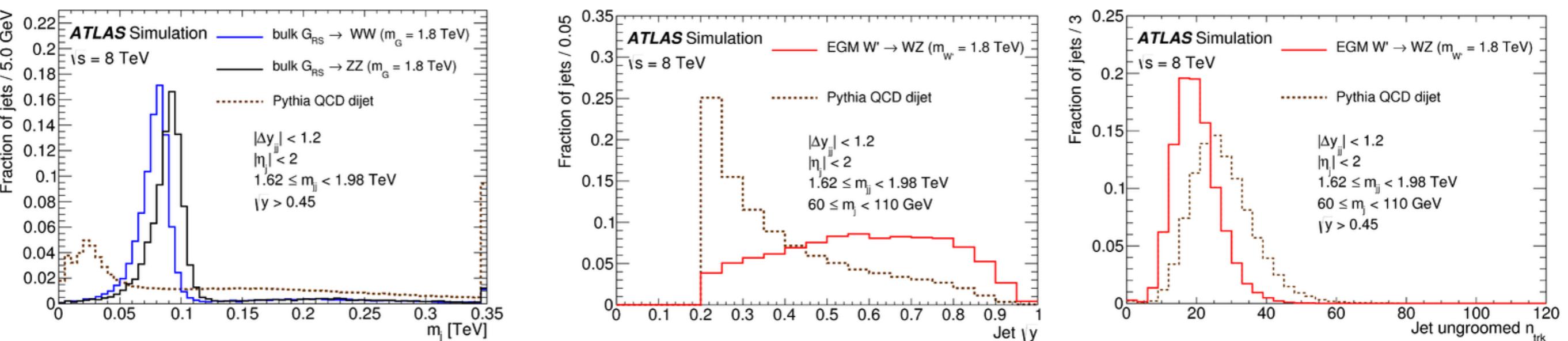
- Powerful discrimination using the ratio: τ_2/τ_1

Run2: Energy correlator functions (<http://arxiv.org/abs/1305.0007>)

VV->qqqq (ATLAS)

Table 4: Summary of the systematic uncertainties affecting the shape of the signal dijet mass distribution and their corresponding models. $G(x|\mu, \sigma)$ in the table denotes a Gaussian distribution for the variable x with mean μ and standard deviation σ .

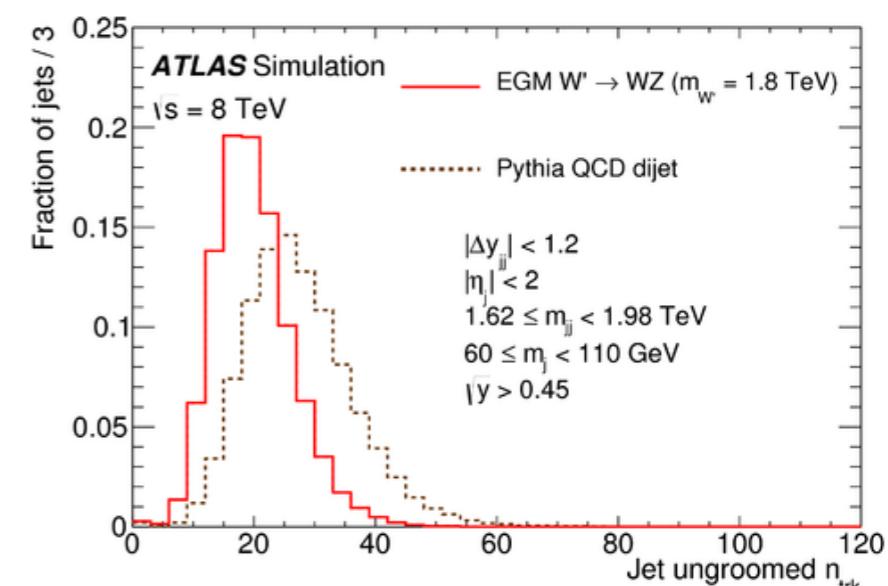
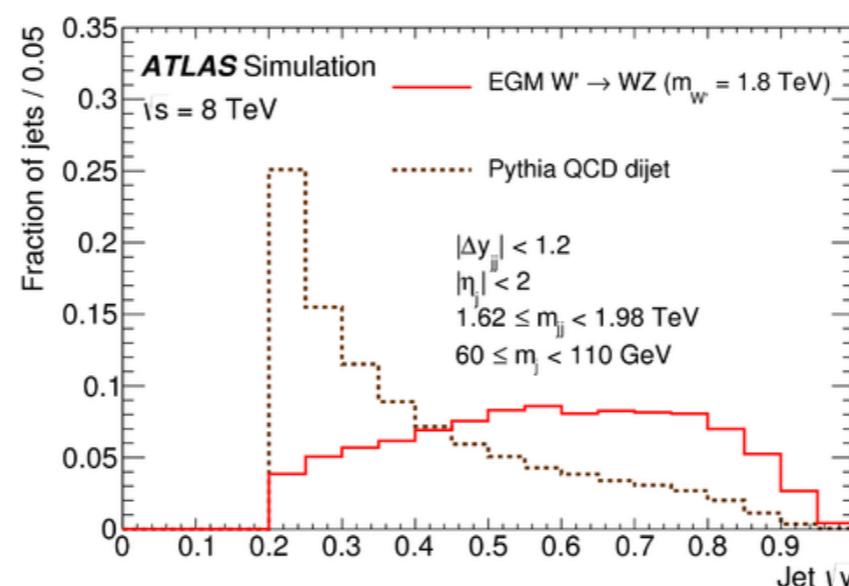
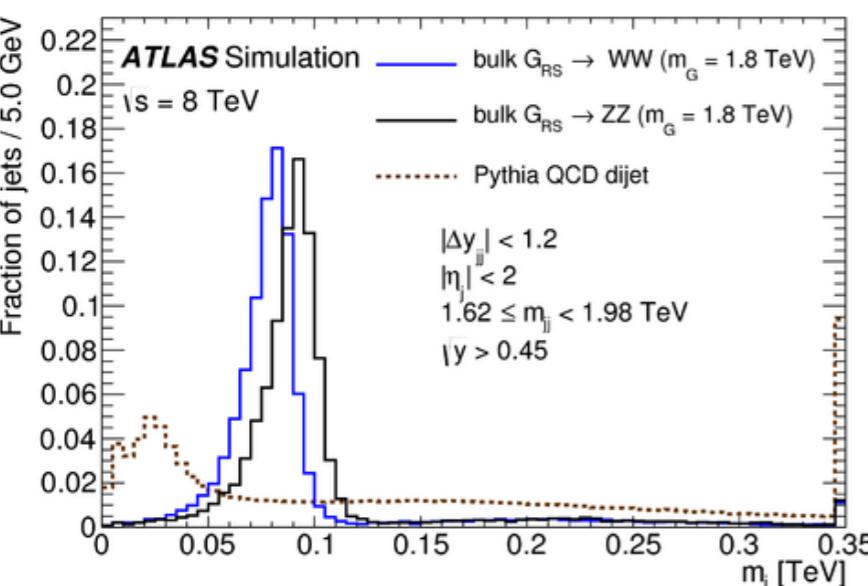
Source	Uncertainty	Constraining pdf
Jet p_T scale	2%	$G(\alpha_{\text{PT}} 1, 0.02)$
Jet p_T resolution	20%	$G(\sigma_{r_E} 0, 0.05 \times \sqrt{1.2^2 - 1^2})$
Jet mass scale	3%	$G(\alpha_m 1, 0.03)$



VV->qqqq (ATLAS)

Table 5: Summary of the systematic uncertainties affecting the signal normalisation and their impact on the signal.

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%



Track jet double ratio method

In situ method using track jets in dijet sample: [JetMassScaleUncertaintyGuide](#)

- Ratio of calorimeter and track jet mass:

$$r_{\text{track jet}}^{m,\text{data/MC}} = \frac{m_{\text{jet}}^{\text{data/MC}}}{m_{\text{track jet}}^{\text{data/MC}}}$$

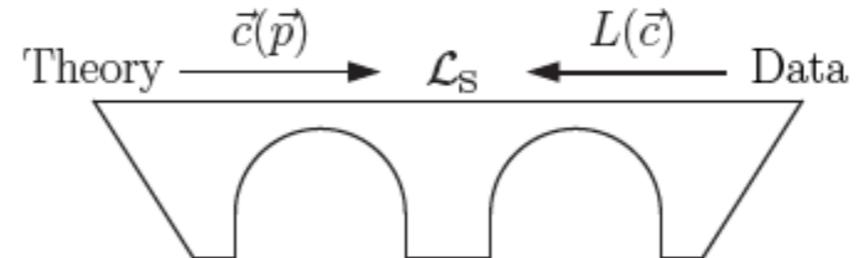
- If detector effects are well modeled in simulation, the ratios in data and MC should be in decent agreement
- Data/MC comparison:

$$R_{\text{track jet}}^m = \frac{r_{\text{track jet}}^{m,\text{data}}}{r_{\text{track jet}}^{m,\text{MC}}}$$

- The comparison of data and MC as a function of kinematic jet variables provides an estimation of the calibration uncertainty
- The jet mass calibration is probed in different kinematic regions (η , p_T)

Technicolor Models, Heavy Vector Triplet

- Technicolor (TC): effective theories with a new strong force dynamics to provide mechanism for EWSB
 - Composite Higgs state for EWSB, no hierarchy problem
 - Explorable at LHC: Minimal Walking Technicolor (MWT)
 - Search for narrow resonances in dilepton, diboson final states or WH/ZH associate production
- HVT:
 - not sensitive to details of underlying model
 - A simplified Lagrangian can be used, limits derived on $\sigma \times \text{BR}$ can then be translated into any specific model



- Works for on shell resonances, it doesn't include off-shell effects!
- Two benchmark models
 - Model A —> weakly coupled vector resonances from extension of the gauge group
 - Model B —> HVT are produced in a strong scenario e.g. composite higgs model

Heavy vector triplet

- ★ New heavy vector boson triplet V_μ^a ($a = 1, 2, 3$) and the simplest Lagrangian

$$\begin{aligned} \mathcal{L}_V = & -\frac{1}{4}D_{[\mu}V_{\nu]}^a D^{[\mu}V^{\nu]}{}^a + \frac{m_V^2}{2}V_\mu^a V^\mu{}^a \\ & + i g_V c_H V_\mu^a H^\dagger \tau^a \overset{\leftrightarrow}{D}^\mu H + \frac{g^2}{g_V} c_F V_\mu^a J_F^\mu{}^a \\ & + \frac{g_V}{2} c_{VVV} \epsilon_{abc} V_\mu^a V_\nu^b D^{[\mu}V^{\nu]}{}^c + g_V^2 c_{VHH} V_\mu^a V^\mu{}^a H^\dagger H - \frac{g}{2} c_{VWW} \epsilon_{abc} W^{\mu\nu}{}^a V_\mu^b V_\nu^c \end{aligned}$$

where g_V represent the “typical” strength of V interactions (“weakly coupled” $g_V \simeq 1$, “strongly coupled” $g_V \simeq 4\pi$) and the parameters c (c_H , c_ℓ , c_q , c_3) define deviation from “typical” size

- ★ This \mathcal{L} is the most general compatible with SM gauge invariance and CP symmetry for operators of energy dimension ≤ 4
- ★ This is justified if the effect of higher dimensional operators is negligible (especially for the strong coupling case) and this is the case if $\xi = v^2/f^2$ is small (EWPT demands $\xi \lesssim 0.2$)
- ★ Production is mainly Drell-Yan while VBF could be interesting at LHC run-2 for a scenario with suppressed coupling to fermions ...

