
# Searches for Diboson Resonances at the LHC-ATLAS Experiment

Tsukuba Global Science Week, September 30, 2015

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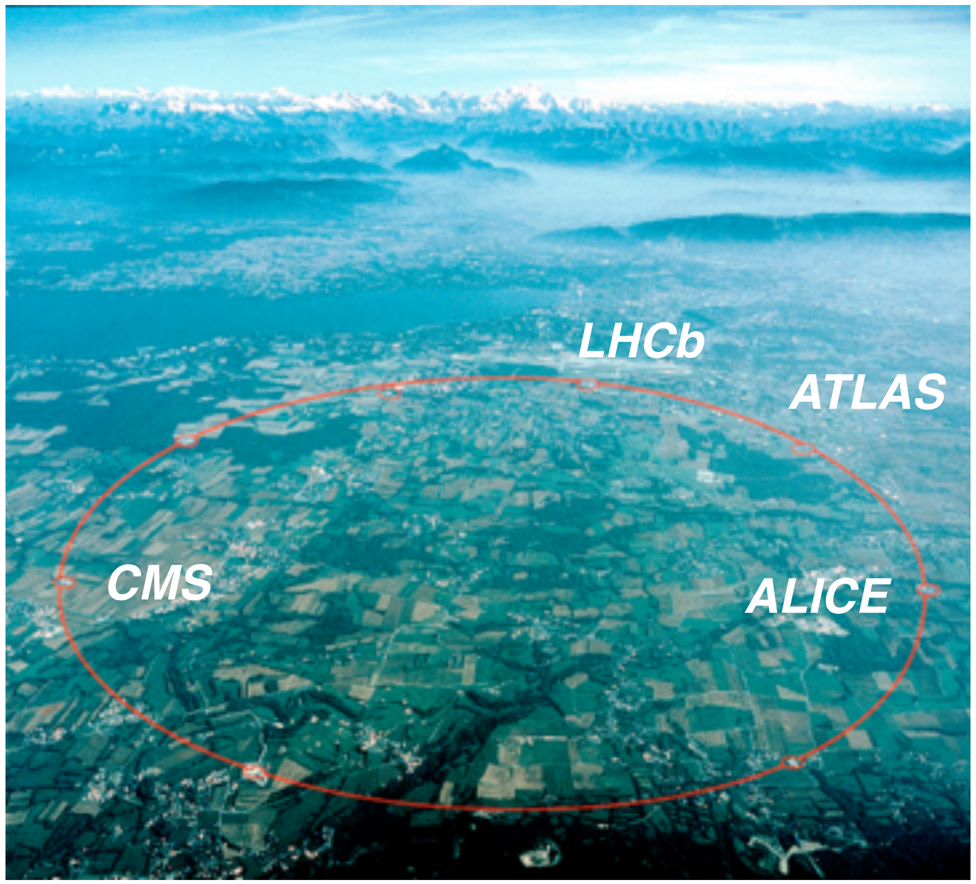
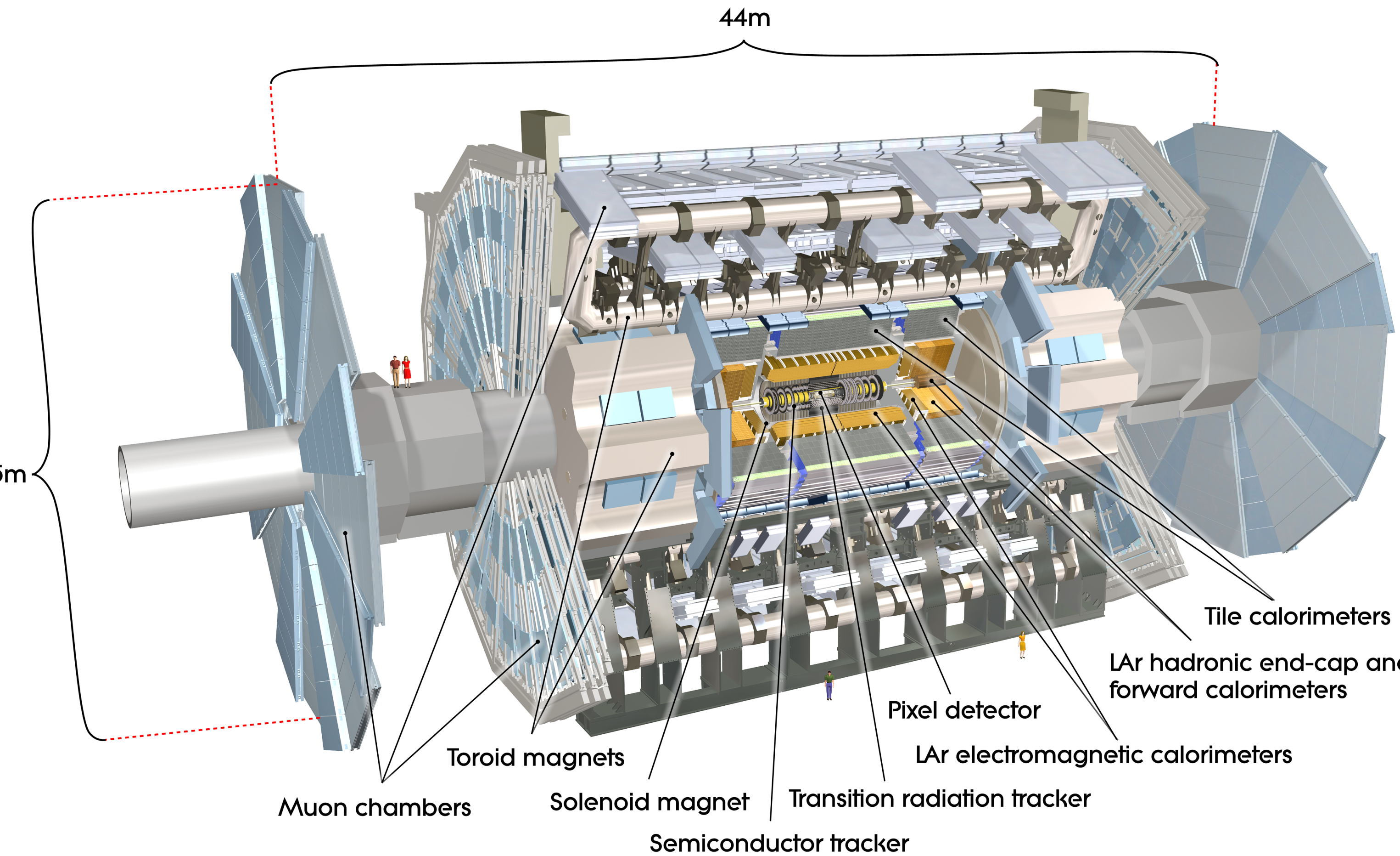
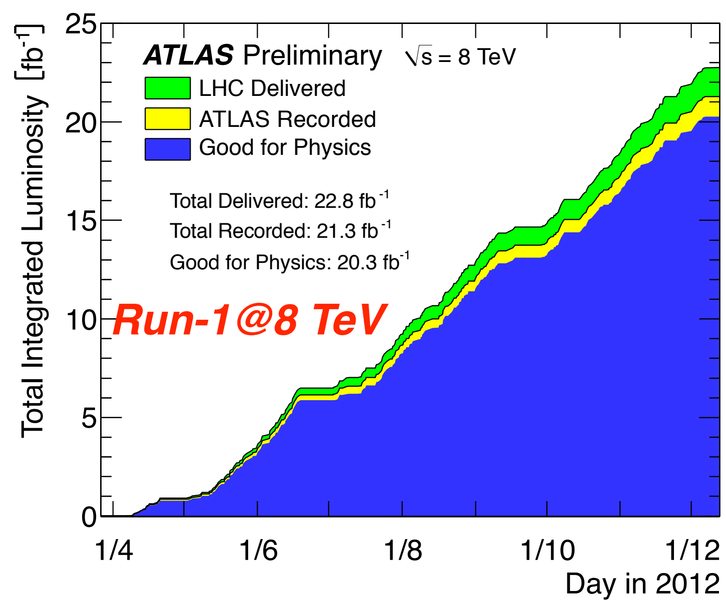
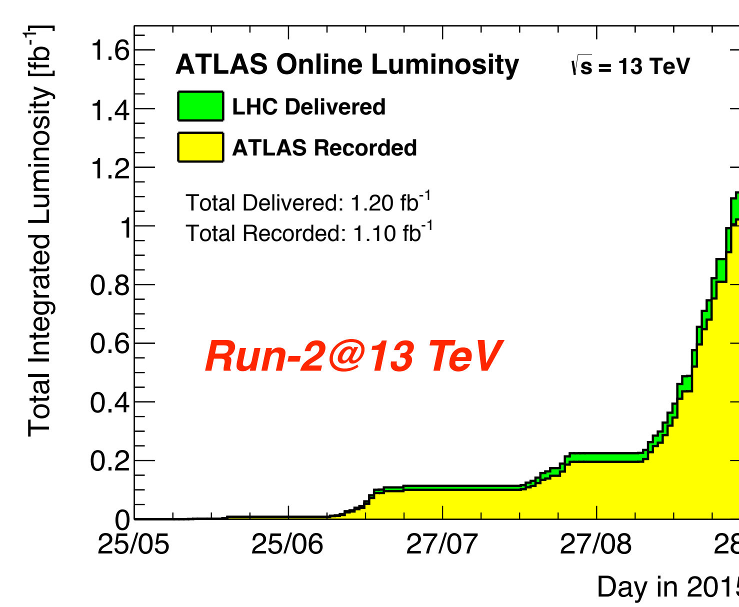
# LHC & ATLAS Experiment



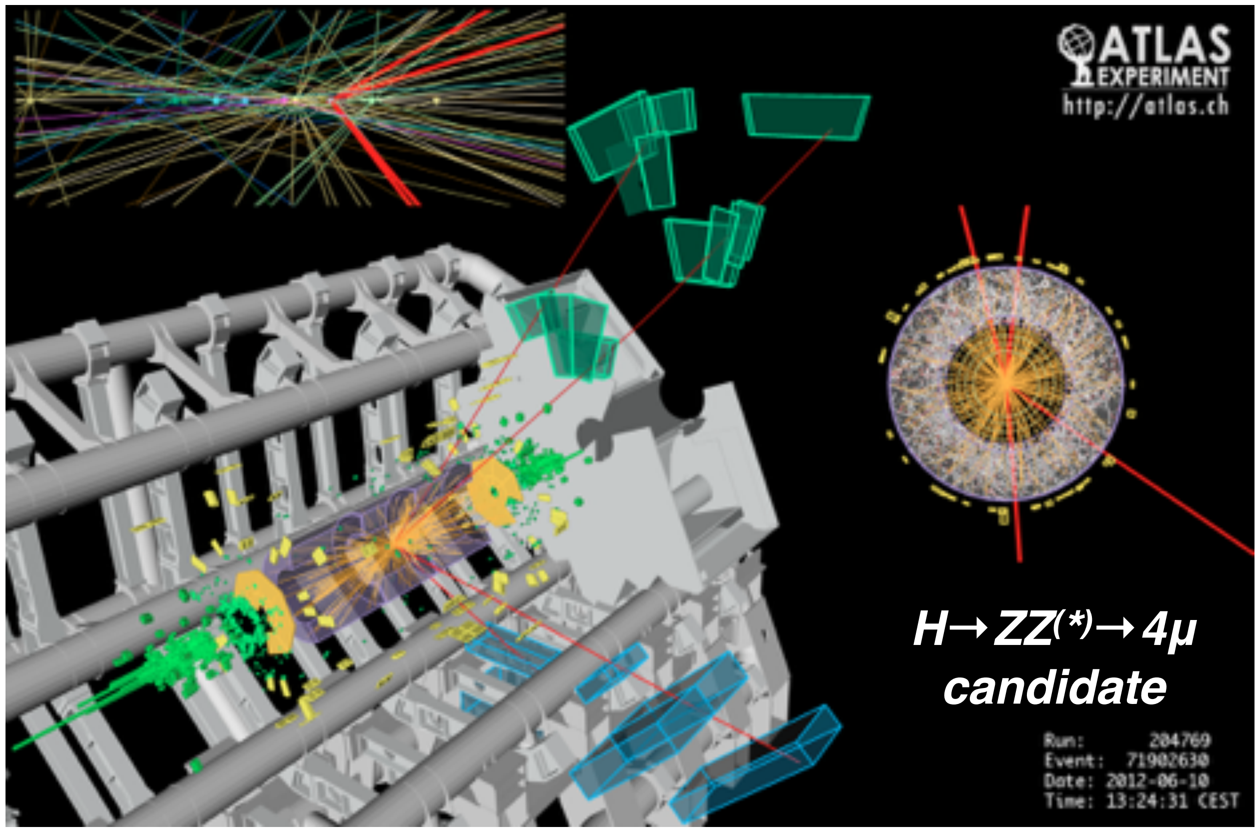



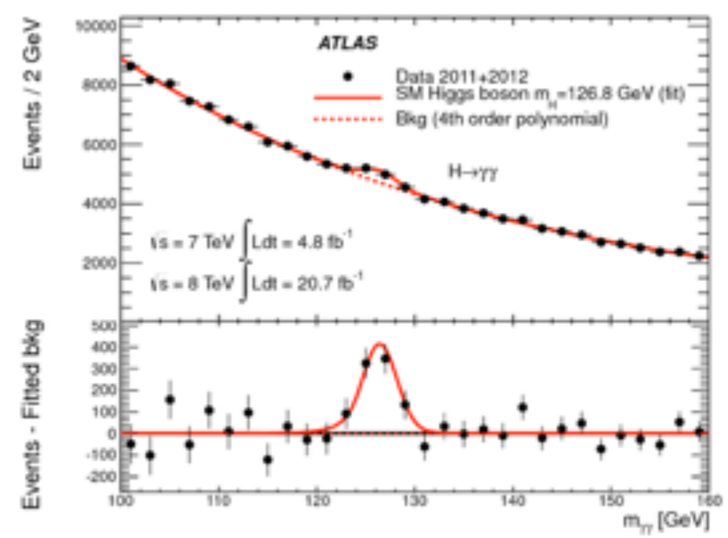

- Large Hadron Collider (LHC) is a pp-collider located at CERN in Geneva, Switzerland.
- ATLAS is among the two generic-purpose detectors at the LHC.
- **Collected 20 $fb^{-1}$ (1.1 $fb^{-1}$)@Run-1(2)**

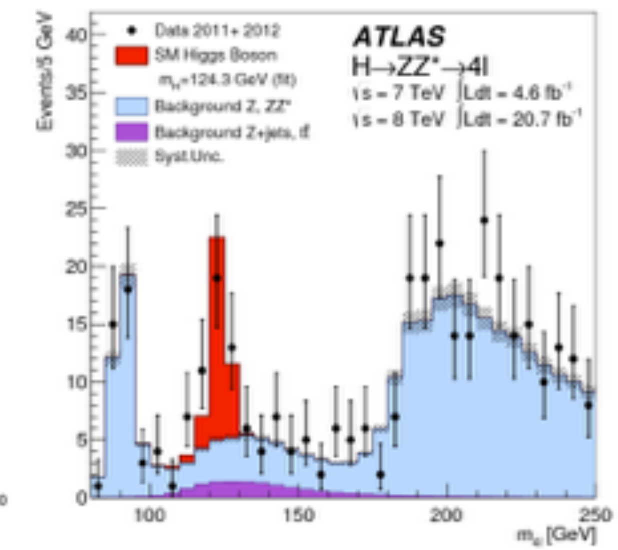


# Higgs Boson & Beyond



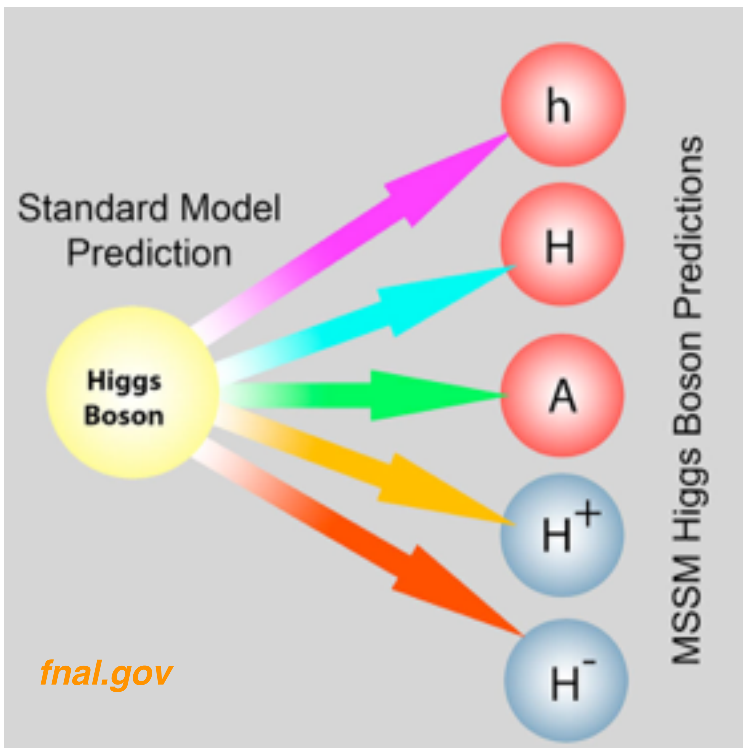

- We have discovered a Higgs boson at 125 GeV. ***What is beyond it?***

- **Is it the Standard Model Higgs boson, or is it part of an extended scalar sector?**
- **Is the discovered Higgs boson elementary or composite?**
- **Any insights from the perspective of naturalness?**

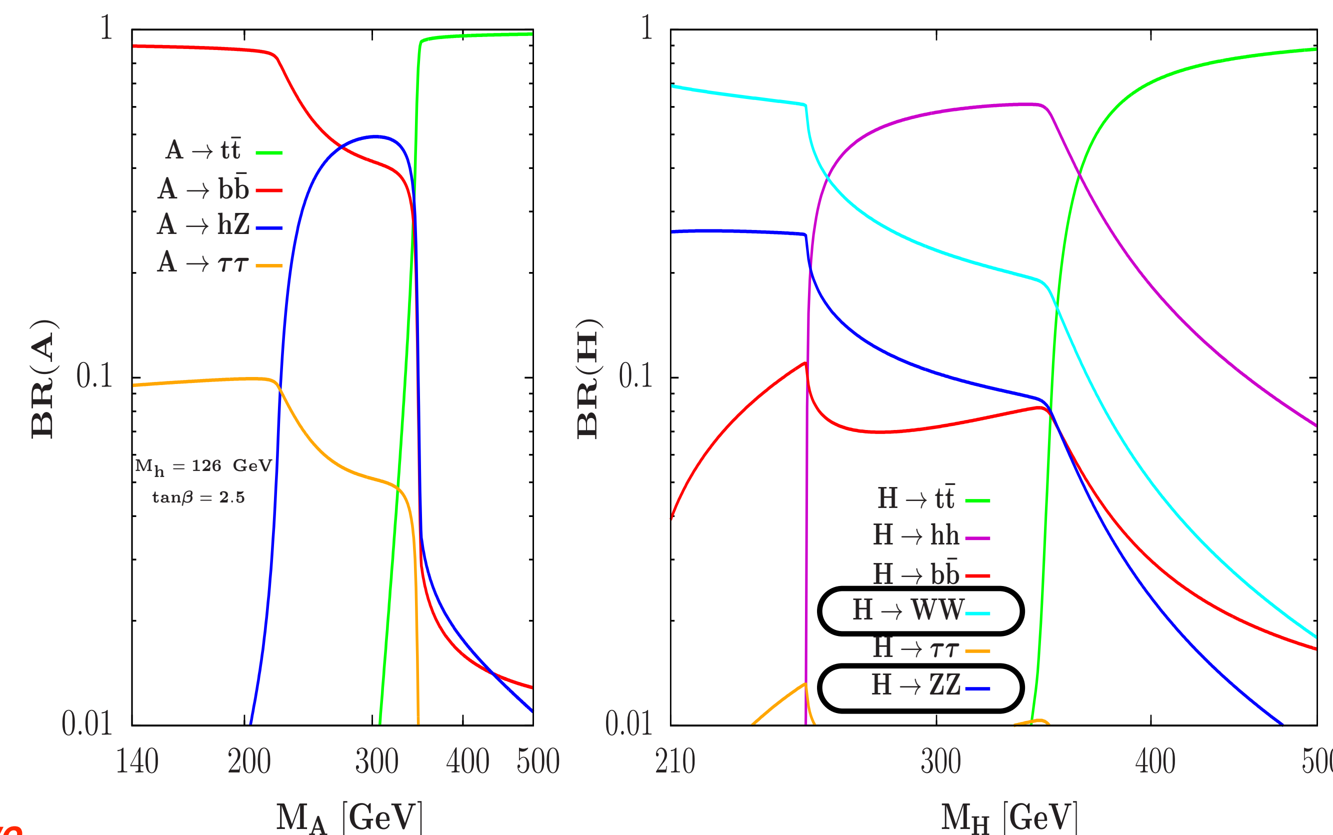
no theoretical fine-tuning to keep the Higgs mass stable

# Extended Scalar Sector

1) **The Higgs boson could be a part of an extended scalar sector.**
→ **There could be more Higgs bosons.**



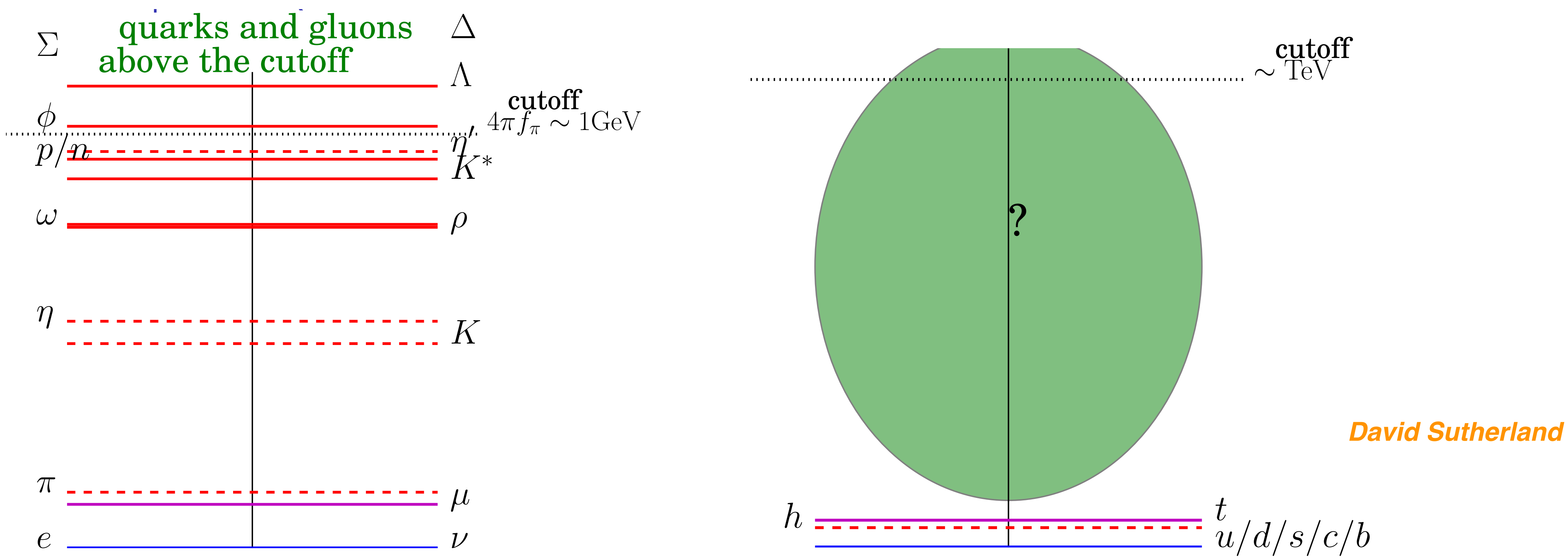

*A. Djouadi & J. Quevillon, arXiv:1304.1787*




# New Particles@TeV Scale

**2) The naturalness implies that there could be additional interactions & particles at the TeV scale.**

**→ Also predicted from composite Higgs models.**




- <u>Composite Higgs models predict high mass resonances decaying to diboson final states.</u>

- Also, extra dimension models (e.g. Randall-Sundrum) predict high mass resonances that decay to diboson final states.

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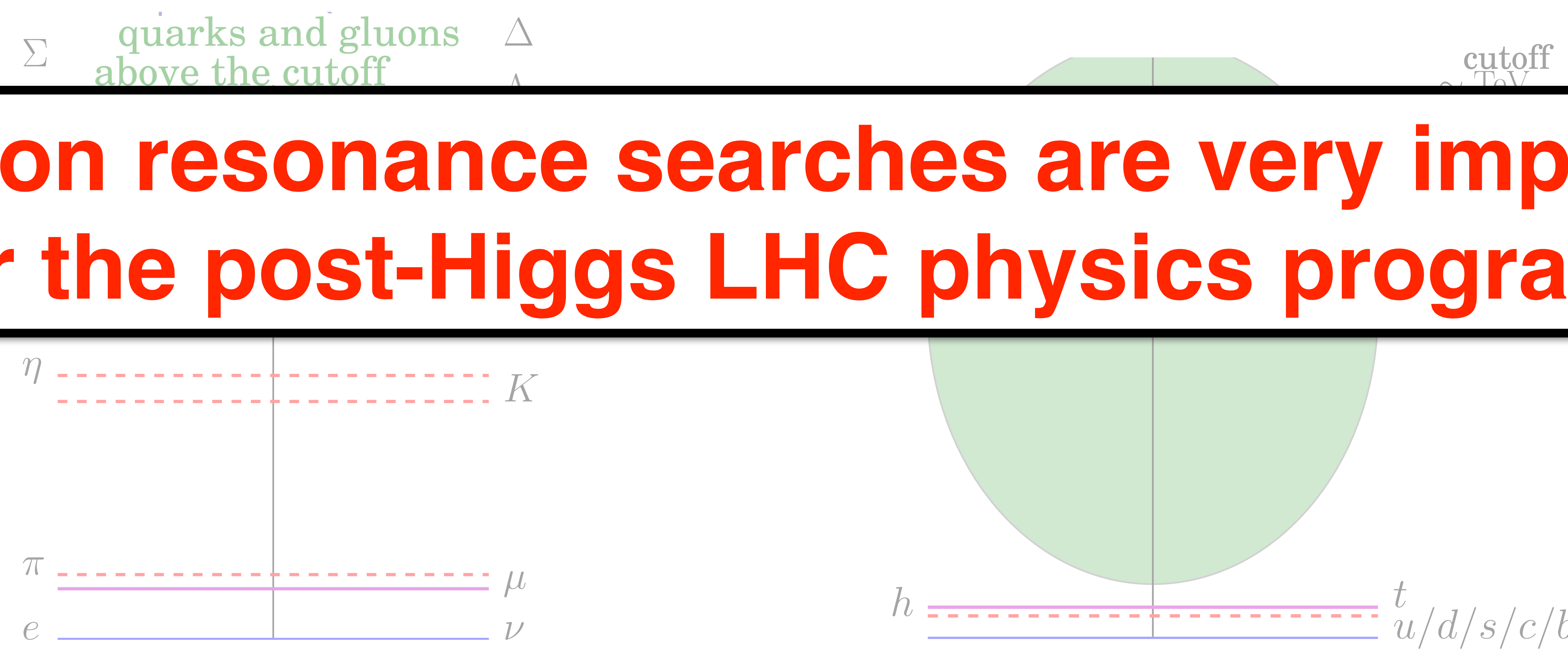


**Diboson resonance searches are very important for the post-Higgs LHC physics program!**

David Sutherland

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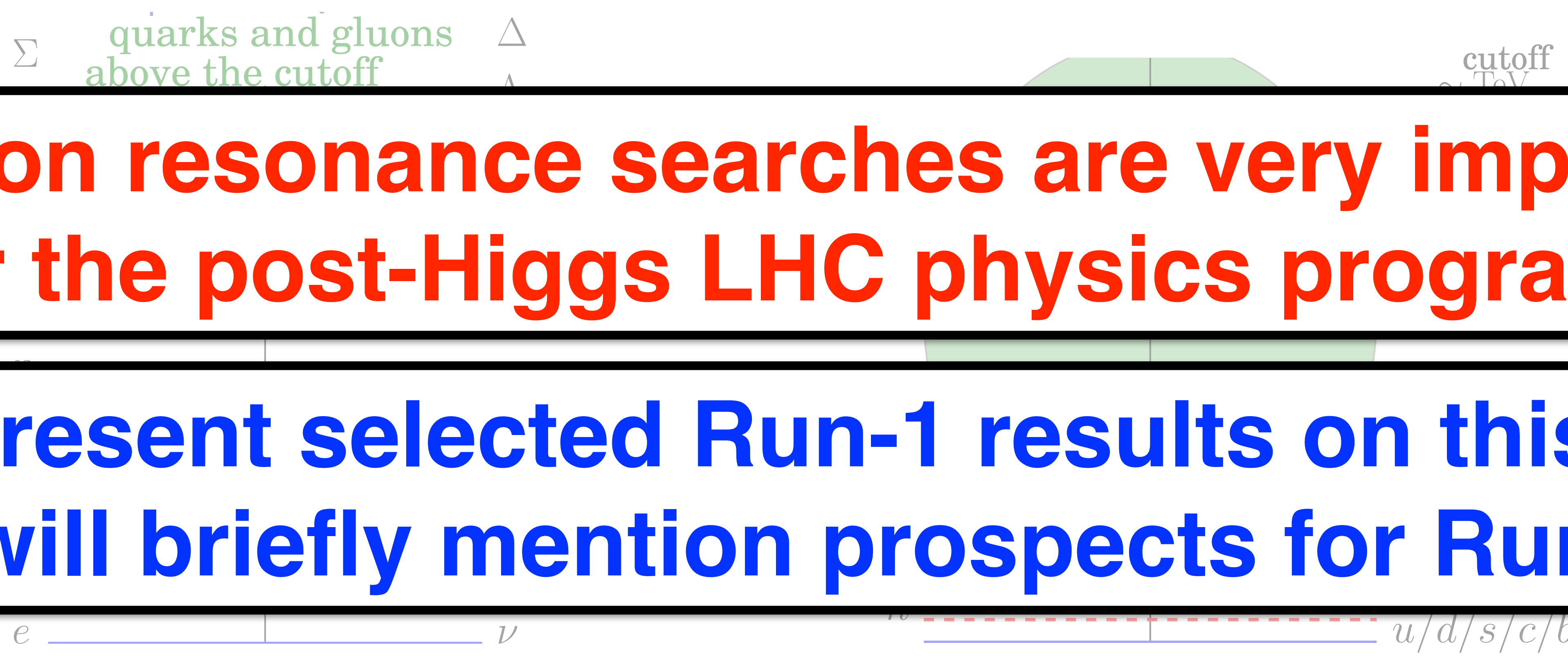



**Diboson resonance searches are very important for the post-Higgs LHC physics program!**

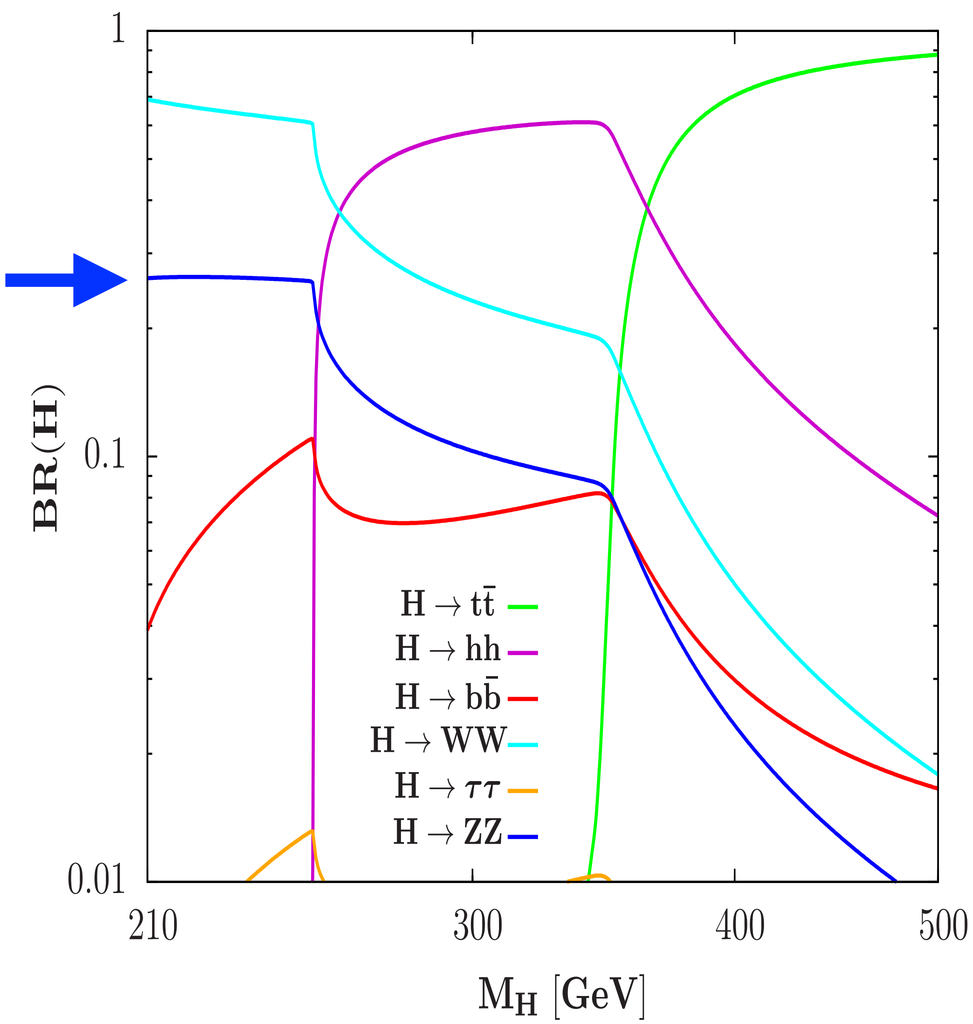
**I will present selected Run-1 results on this topic & will briefly mention prospects for Run-2**

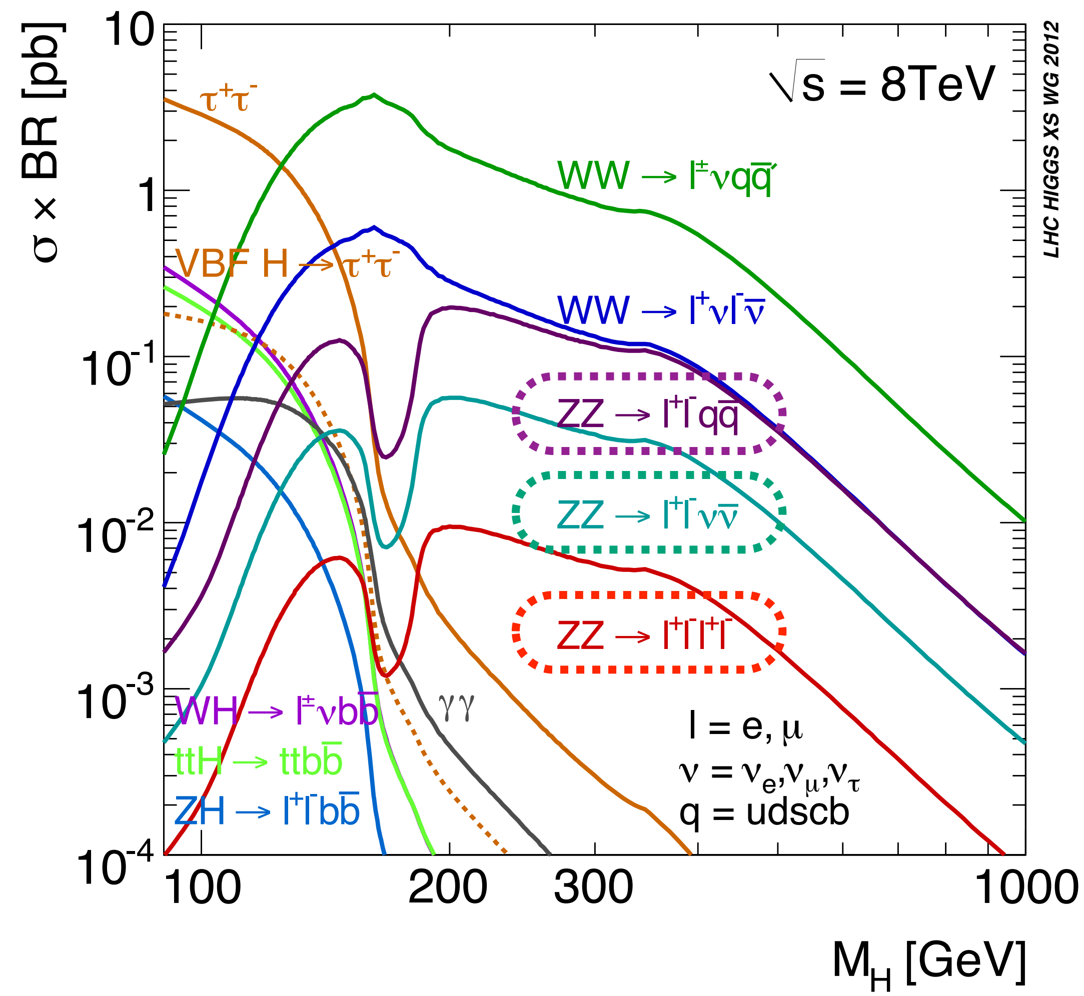
- Composite Higgs models predict high mass resonances decaying to diboson final states.
- Also, extra dimension models (e.g. Randall-Sundrum) predict high mass resonances that decay to diboson final states.

# Dibosons from Heavy Higgs

# Heavy H→ZZ

**H→ZZ**



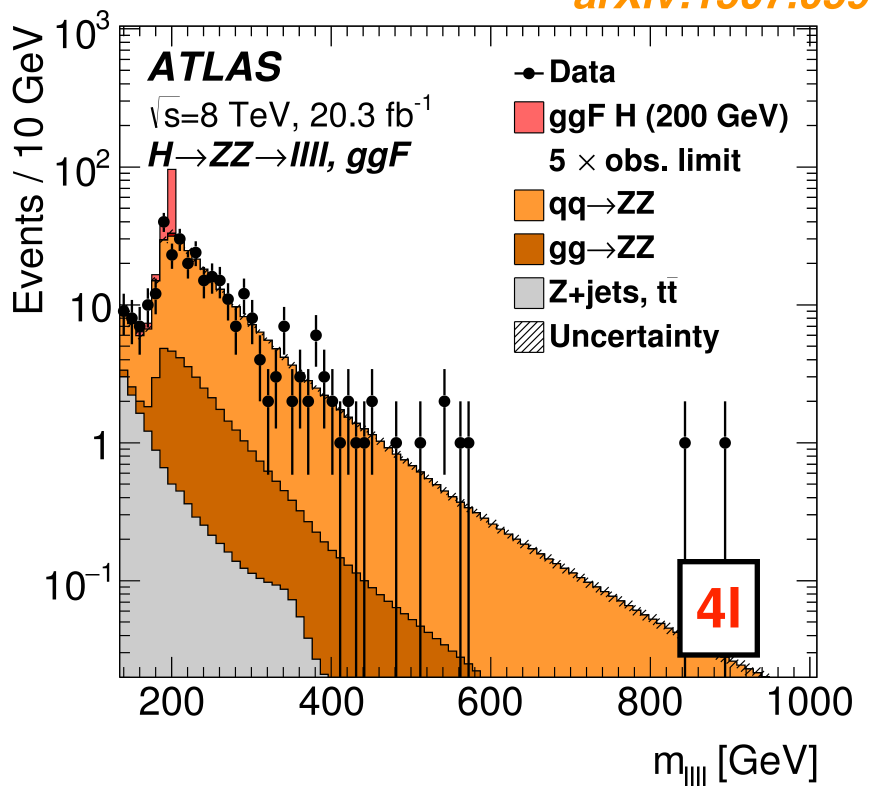



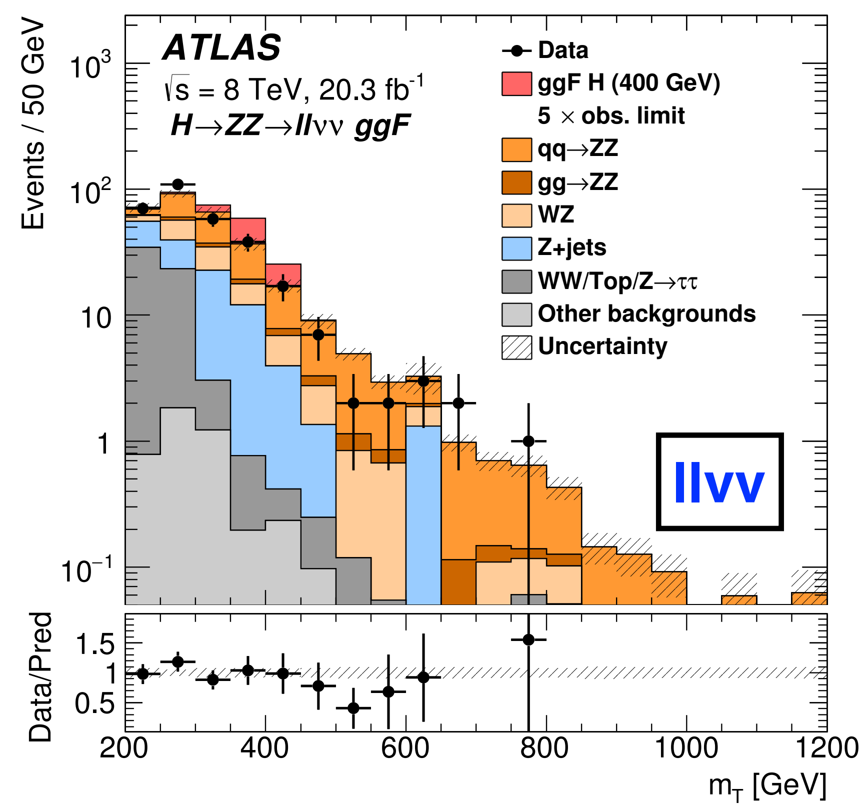

- H→ZZ is a promising channel to search for a heavy Higgs boson in the low tan β case.
- **H→ZZ→4l (e,μ), llvv, llqq, vvqq channels** are considered. **Each channel <u>has different sensitivity in signal mass range & is complementary.</u>**

# H→ZZ→4l & llvv

arXiv:1507.05930

- Leptonic channels have very clean final states & good signal/BG separation.
  - **4l:** Limited event yields, but good mass resolution (1–3.5%) & sensitivity in the low-mass range.
  - **llvv:** High event yields, but limited mass resolution (7–15%), but high signal sensitivity in the intermediate & high masses.
- The most dominant BG is qq→ZZ for both channels. It is estimated at the NNLO including the shape of distributions.
- Non-ZZ BGs are validated or directly estimated from data.

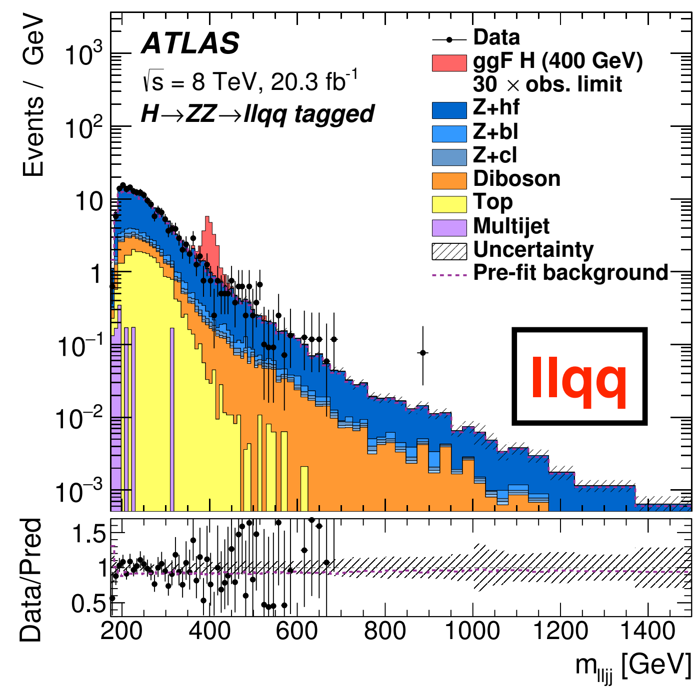


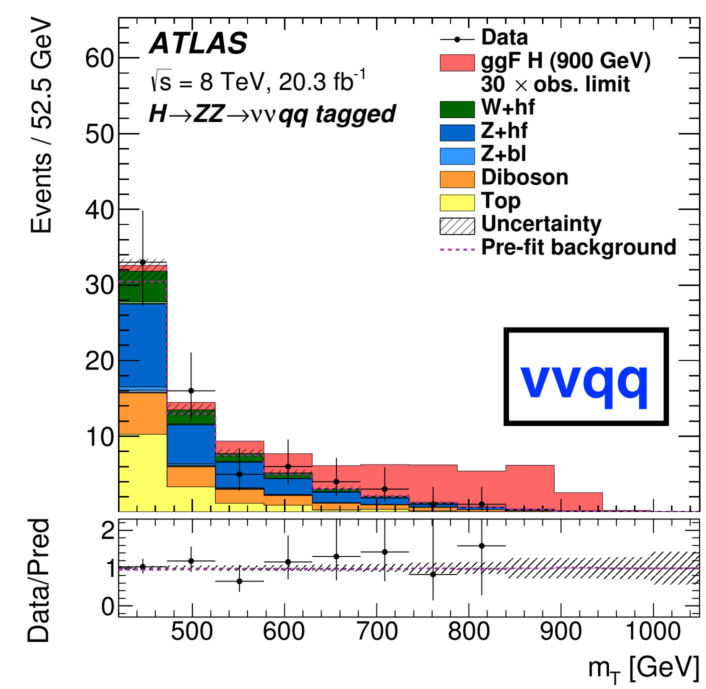



# H→ZZ→llqq & νν qq

arXiv:1507.05930

- **Very high event yields, but also suffer from large backgrounds.**
  - **llqq:** High mass resolution (2–-3%) & high sensitivity in the high mass region.
  - **ννqq:** Limited mass resolution (9–14%), but high sensitivity in the high mass region.

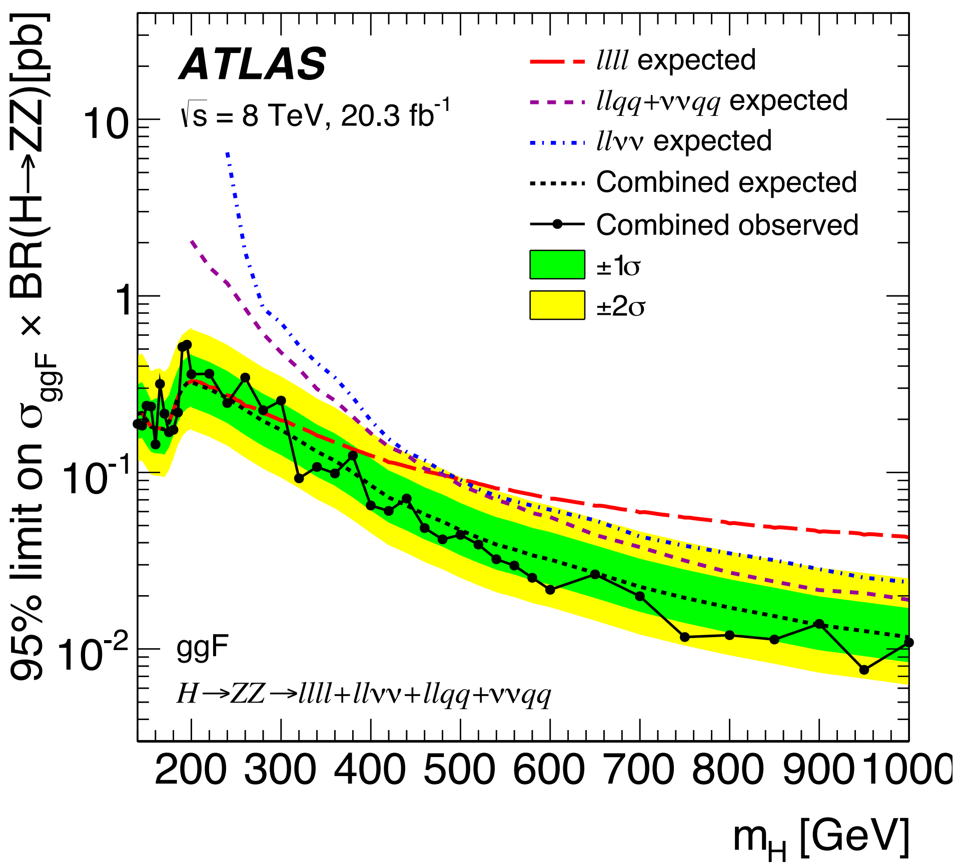


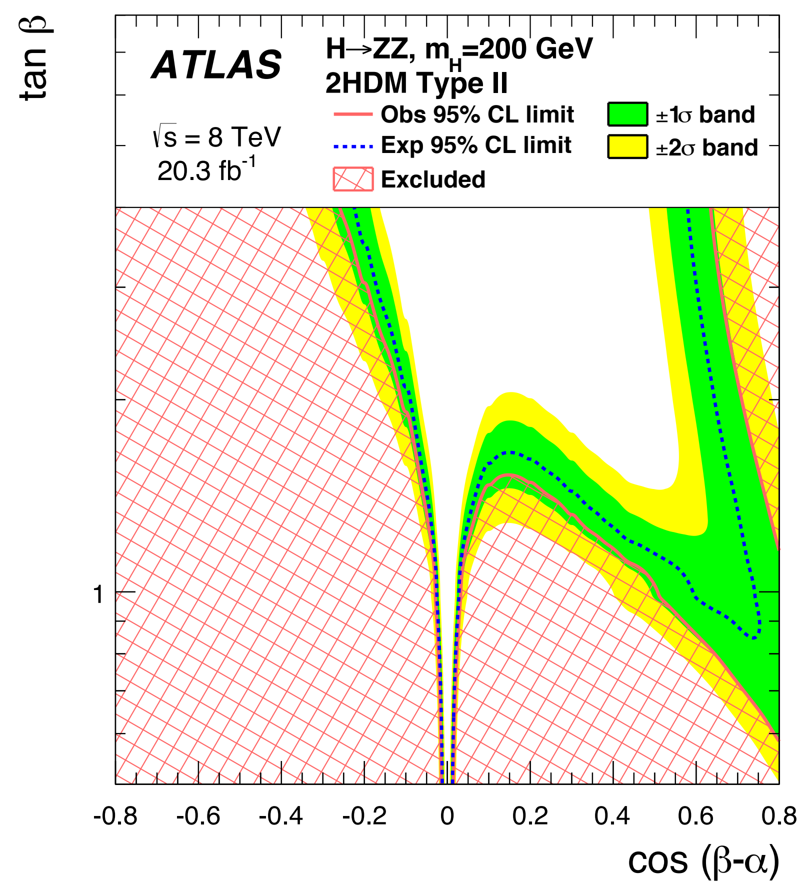



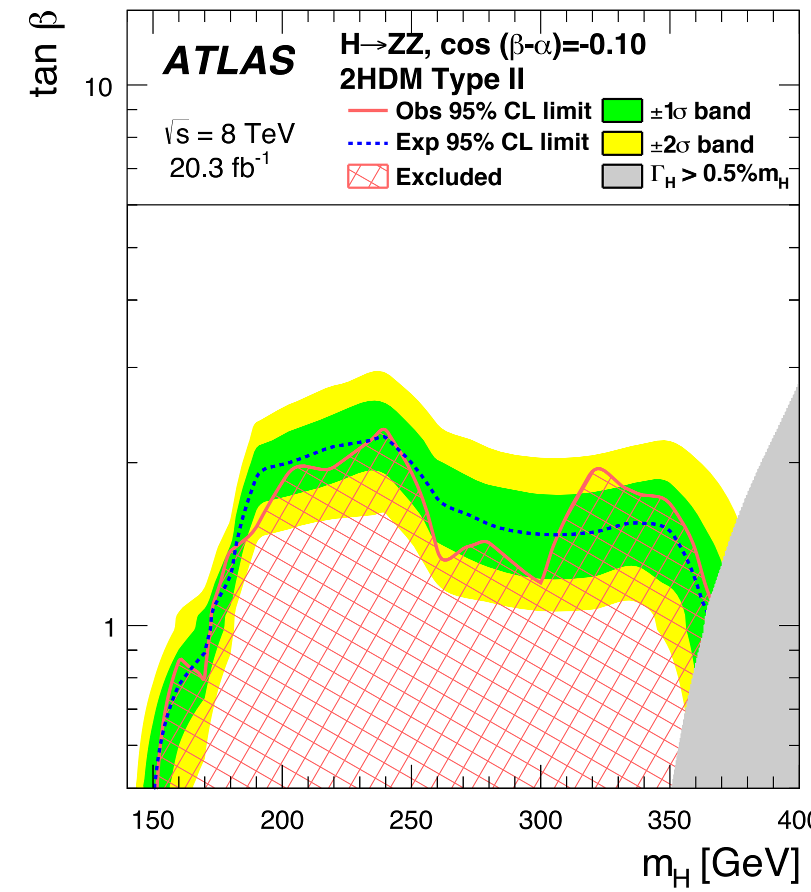

- Signal regions are split into several categories.
  - Untagged (llqq, ννqq): no b-jets.
  - **Tagged (llqq, ννqq): With two b-jets. Better signal over noise than the untagged.**
  - Merged (llqq only): Two partons merged in one jet. Occurs more often in the high mass signals.
- Backgrounds are difficult to model by simulation. Estimated by simultaneous fits in various control regions (Z+jets CR, top CR).

# H→ZZ Results

arXiv:1507.05930



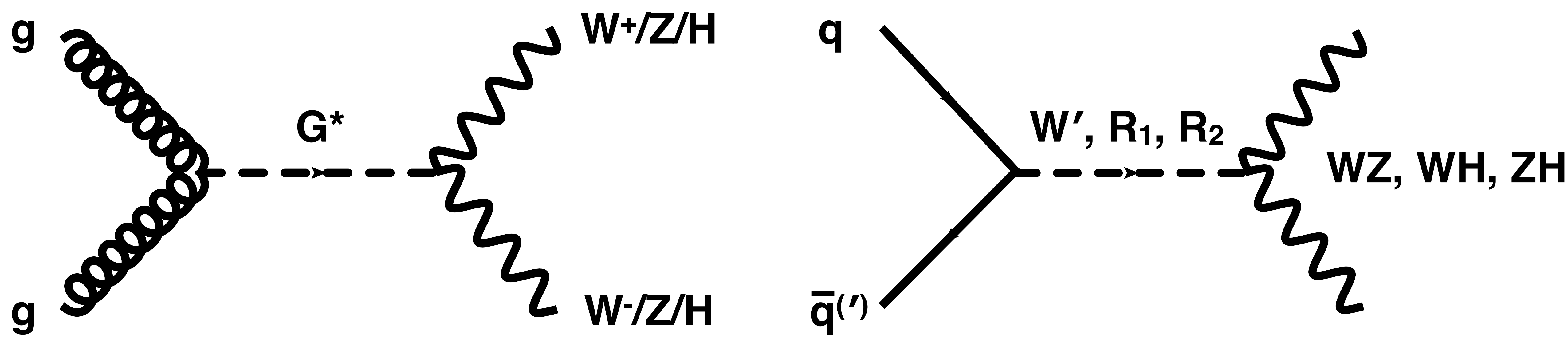




- **No excess is observed in all the 4 channels.** The results are combined to set limits on the heavy Higgs production cross section x BR & Two Higgs Doublet Model (2HDM) scenarios.
- Surpassed the previous results from the Tevatron & LHC@7 TeV & provided constraints on phase space of the extended scalar sector.

# Other Diboson Resonances

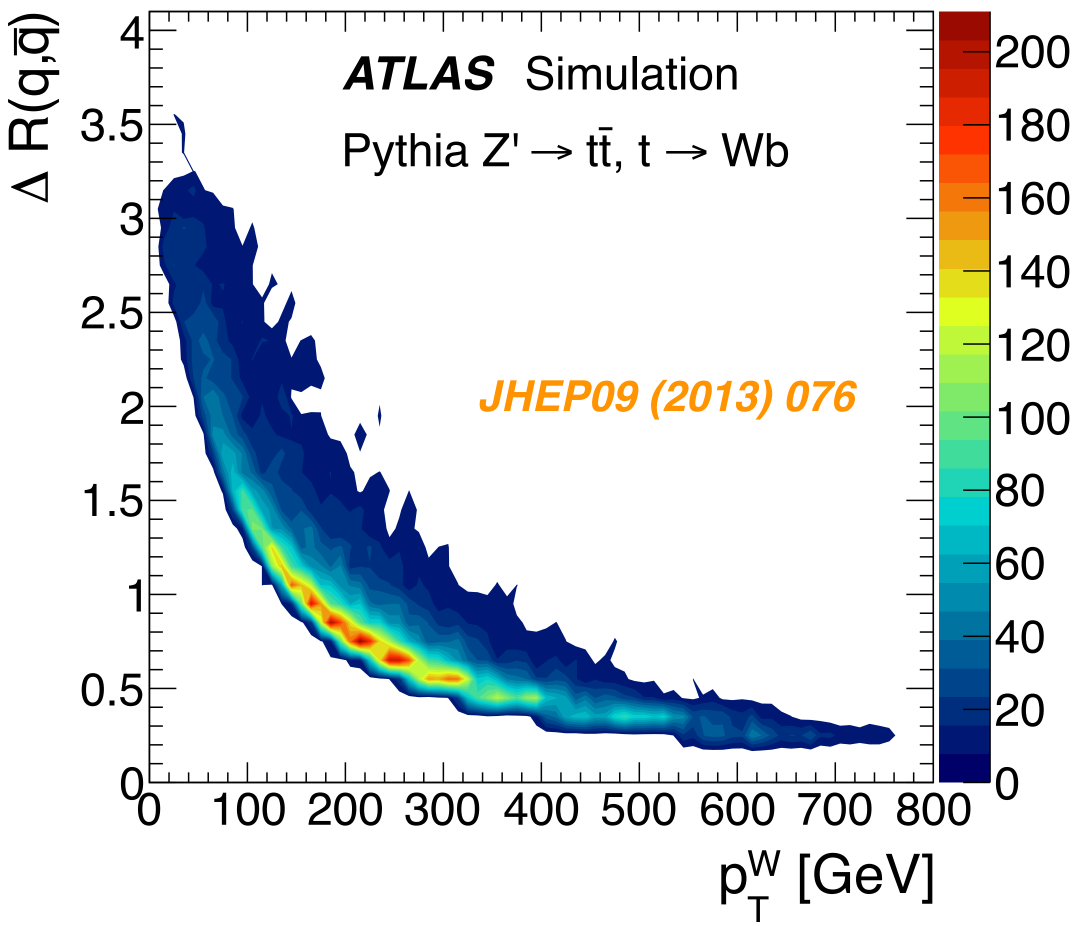
# Other Diboson Resonances

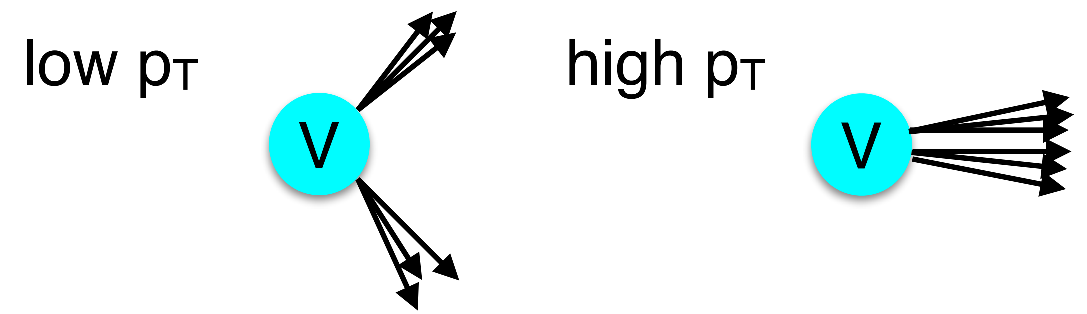



- Various physics beyond the Standard Model (BSM) predicts presence of high mass resonances (e.g. Extended Gauge Model, bulk Randall-Sundrum, minimal walking technicolor, composite Higgs model, etc.)
- **In many cases, the branching ratios to diboson final states are sizable.**
- $m(G^*)=1$ TeV: $BR(G^*\to W^+W^-)\sim 20\%$, $BR(G^*\to ZZ)\sim 10\%$.
- **Due to the large BR, the highest mass reach comes from hadronic decay channels from the W/Z/H bosons.** → **Boosted boson tagging (next slide)**

# Boosted-Boson Tagging

- Bosons decaying from high mass resonances are **highly boosted**.




- High-$p_T$ bosons can be reconstructed as single large-R jets (Cambridge-Aachen, R=1.2).
- Split-filtering algorithm for grooming.
- Require symmetrical splitting between the subjets coming from decay quarks.

$$y_f = \frac{\min(p_{T1}, p_{T2})}{m_{12}} \times \Delta R_{12}, \quad \sqrt{y_f} > 0.45$$

# VV→qqqq (JJ) Search

arXiv:1506.00962

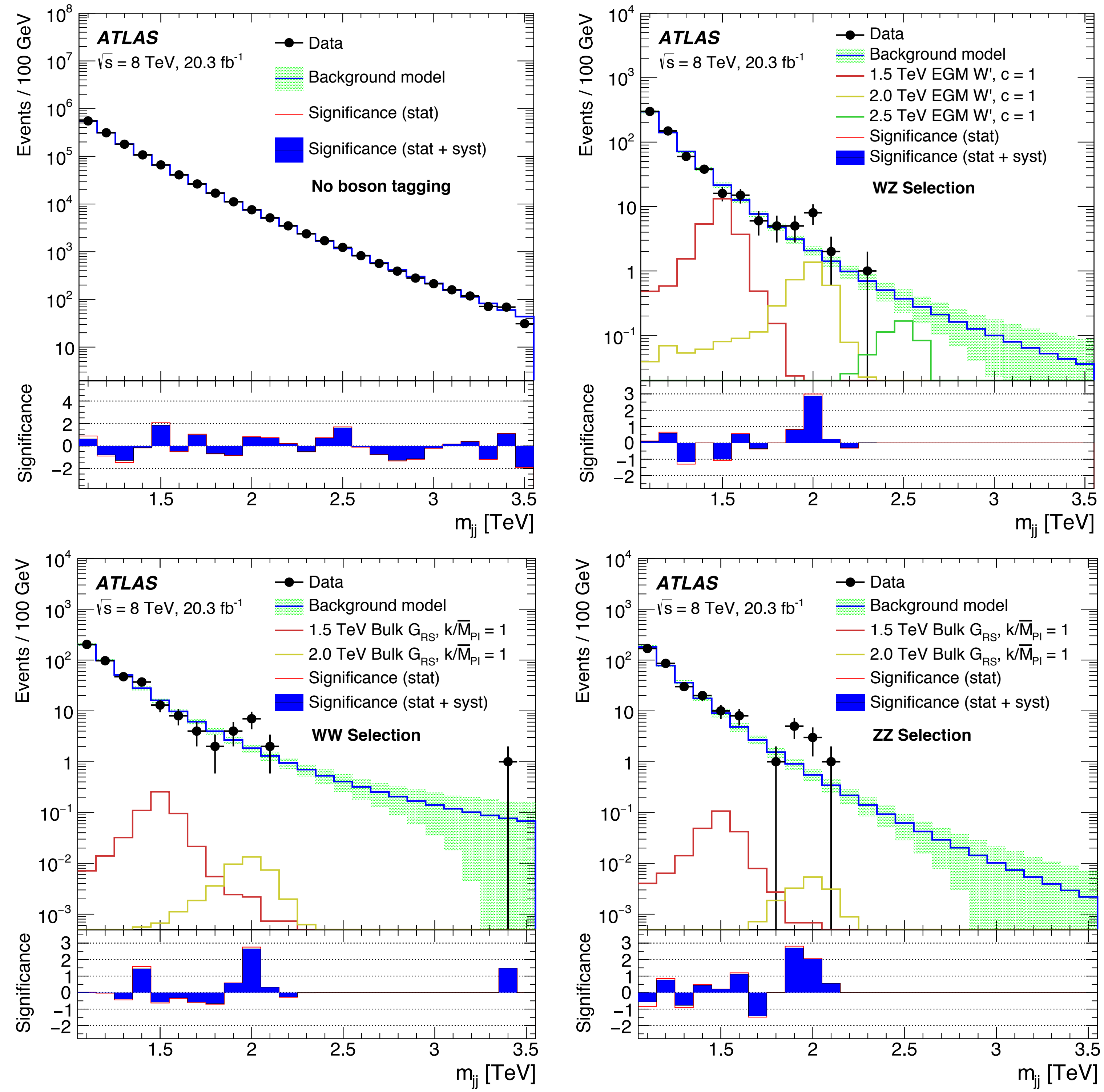
- Fully hadronic final state. **Bump hunting on the invariant mass of two boosted-boson jets**.

$$\frac{\mathrm{d}n}{\mathrm{d}x} = p_1(1-x)^{p_2-\xi p_3} x^{p_3}, \quad x = m_{jj}/\sqrt{s}$$

- Jet mass (26 GeV window around $m_{W/Z}$) → Overlaps between the WZ/WW/ZZ selections.

- **Local significance: WZ (3.4σ), WW (2.6σ), ZZ (2.9σ)**

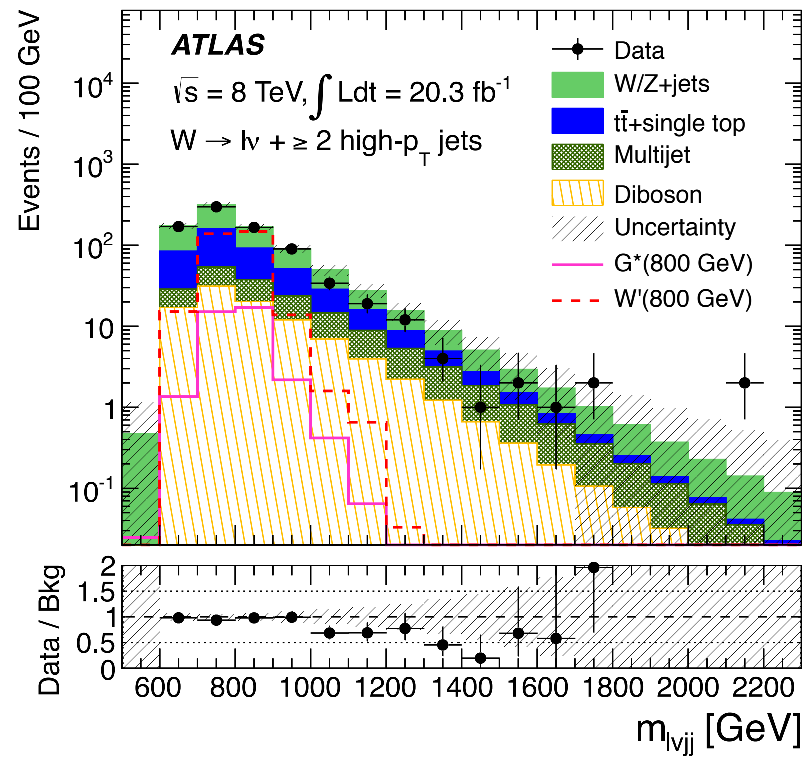
- **Global significance: WZ (2.5σ)**

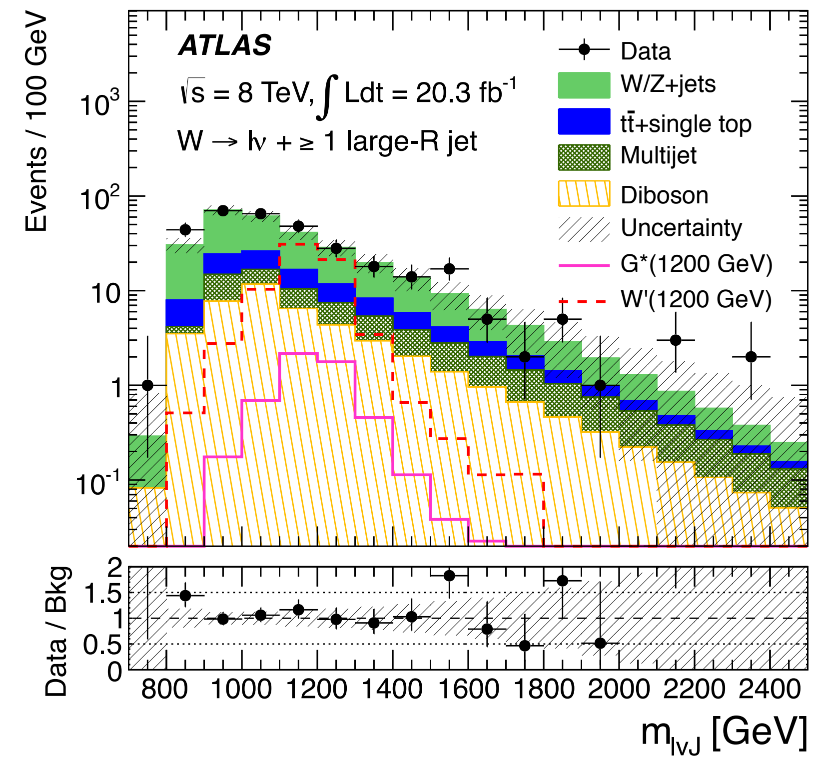


# WV→lvqq (lvjj, lvJ)

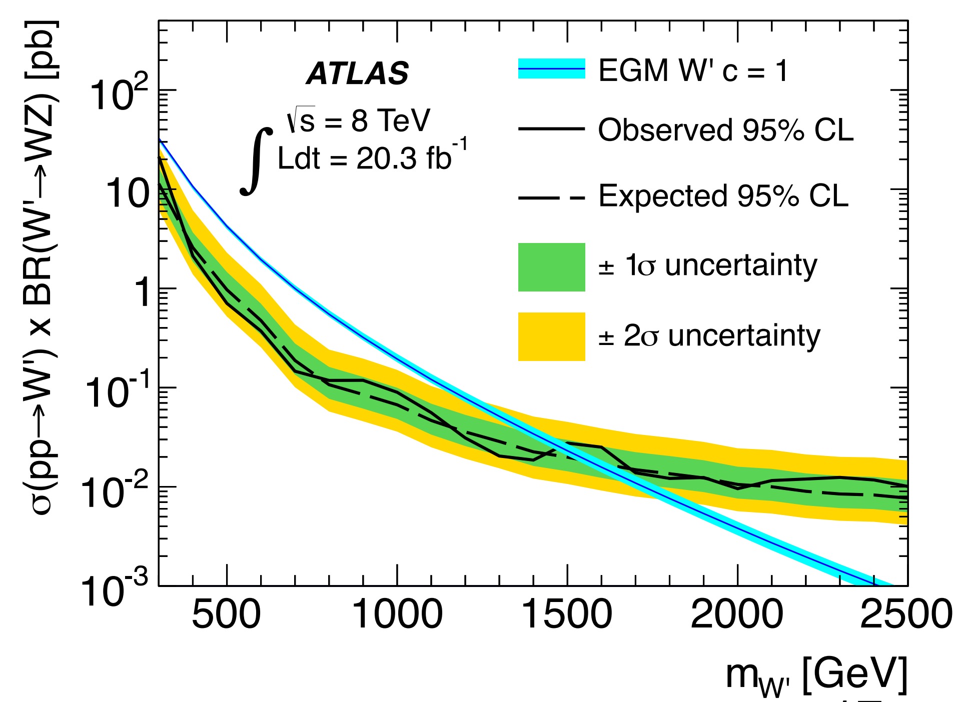
*Eur. Phys. J. C (2015) 75:209*

- 1 lepton+Missing $E_T$+jet(s) final state.
- Signal regions are split into 3 categories.
- Low/high-pT resolved (lvjj) & high-pT merged (lvJ)



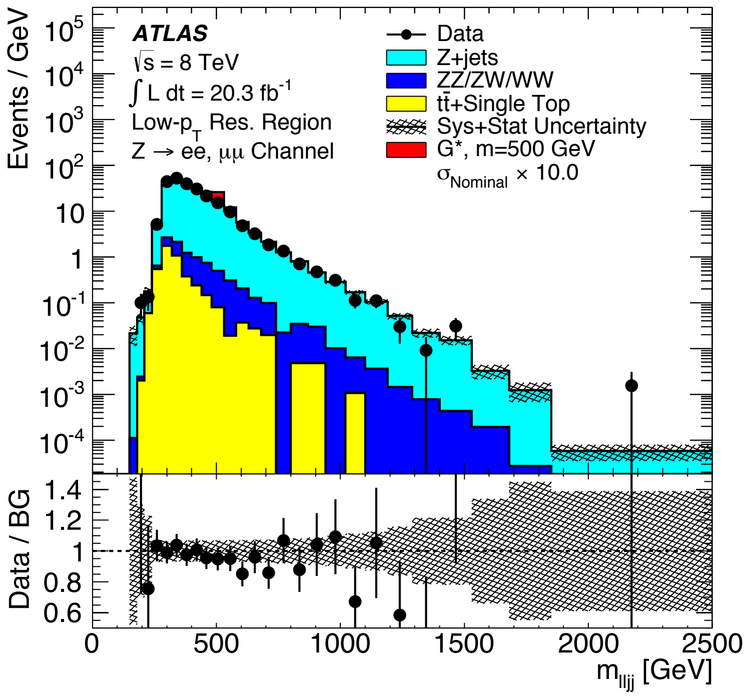



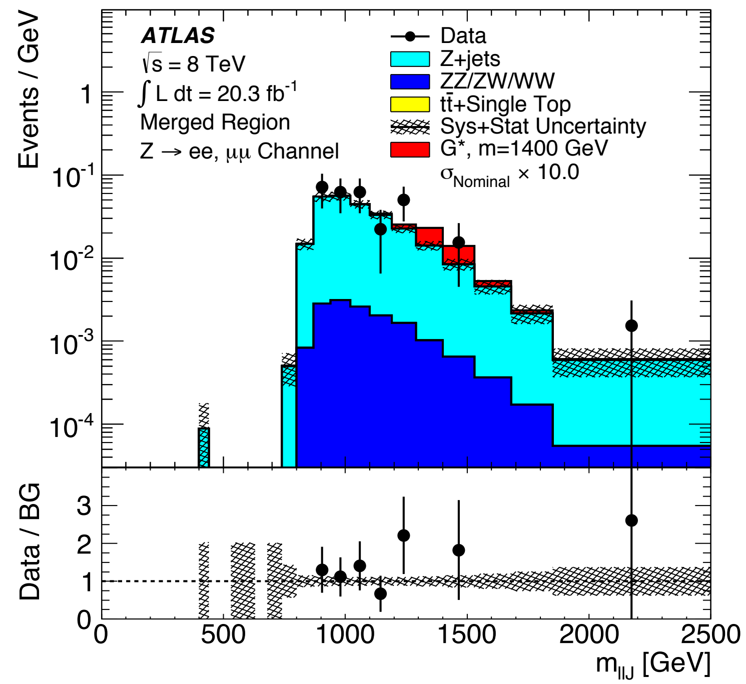

- W/Z+jets, ttbar BGs: estimated from MC simulation.
- Multijet BG: estimated with data.
- **No excesss observed in this channel.** Excluded m(G*) < 760 GeV & m(W′)<1.49 TeV@95% CL.

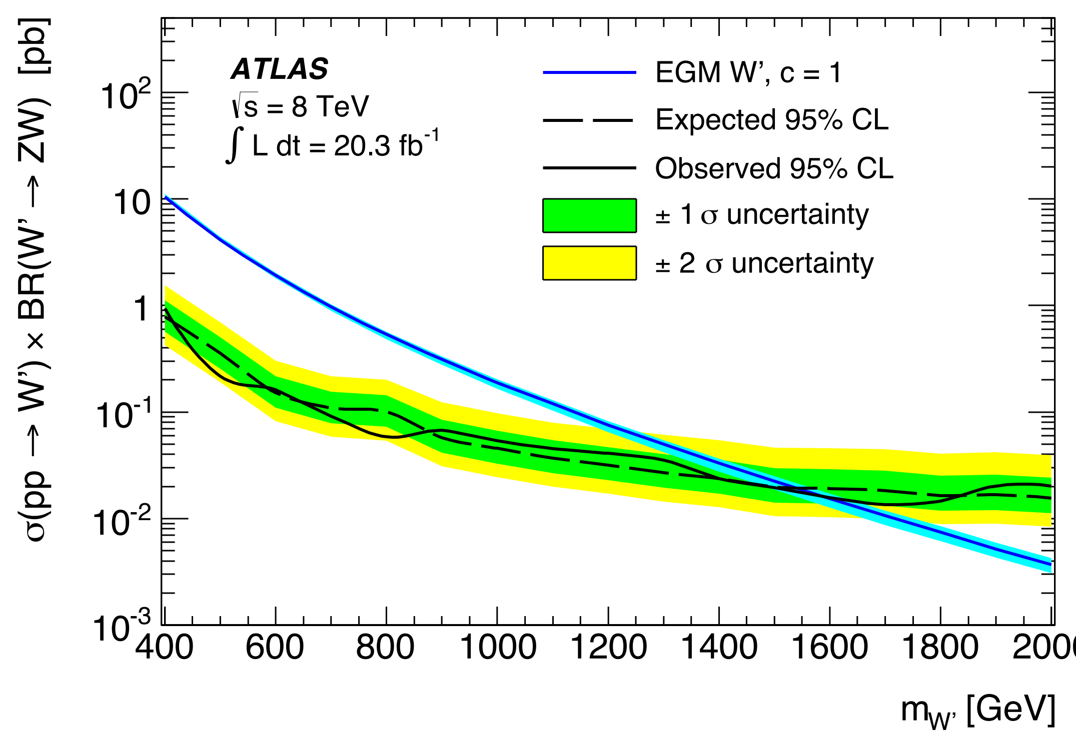


# ZV→llJ Search

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

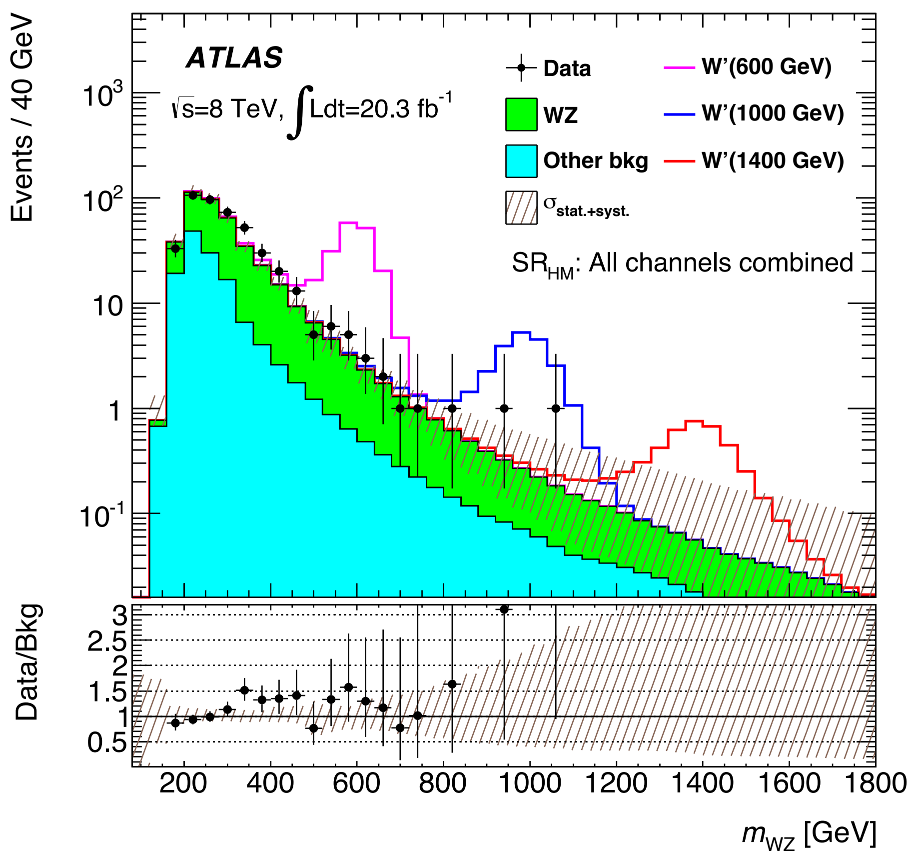


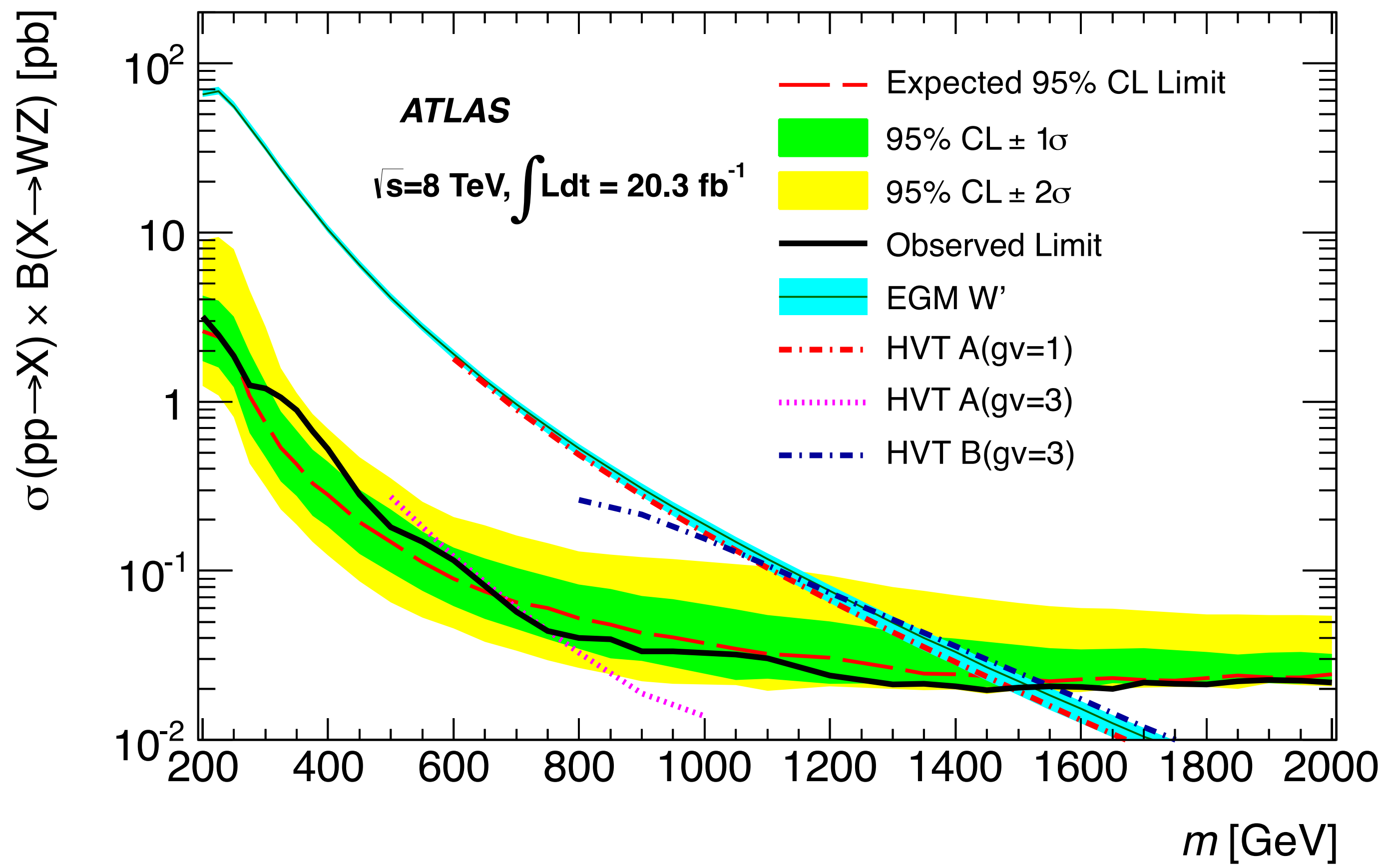




- 2 same-flavor leptons (compatible with Z) & jet(s) final state.
- Signal regions are split into low/high-$p_T$ resolved (lljj) & high-$p_T$ merged (llJ) like the 1-lepton search.
- Dominant BG is Z+jets. Estimated with MC simulation with normalization & shape corrections applied from control regions.
- **No excesss observed in this channel.** Excluded m(G*) < 740 GeV & m(W′)<1.59 TeV@95% CL.

# WZ→lνll Search

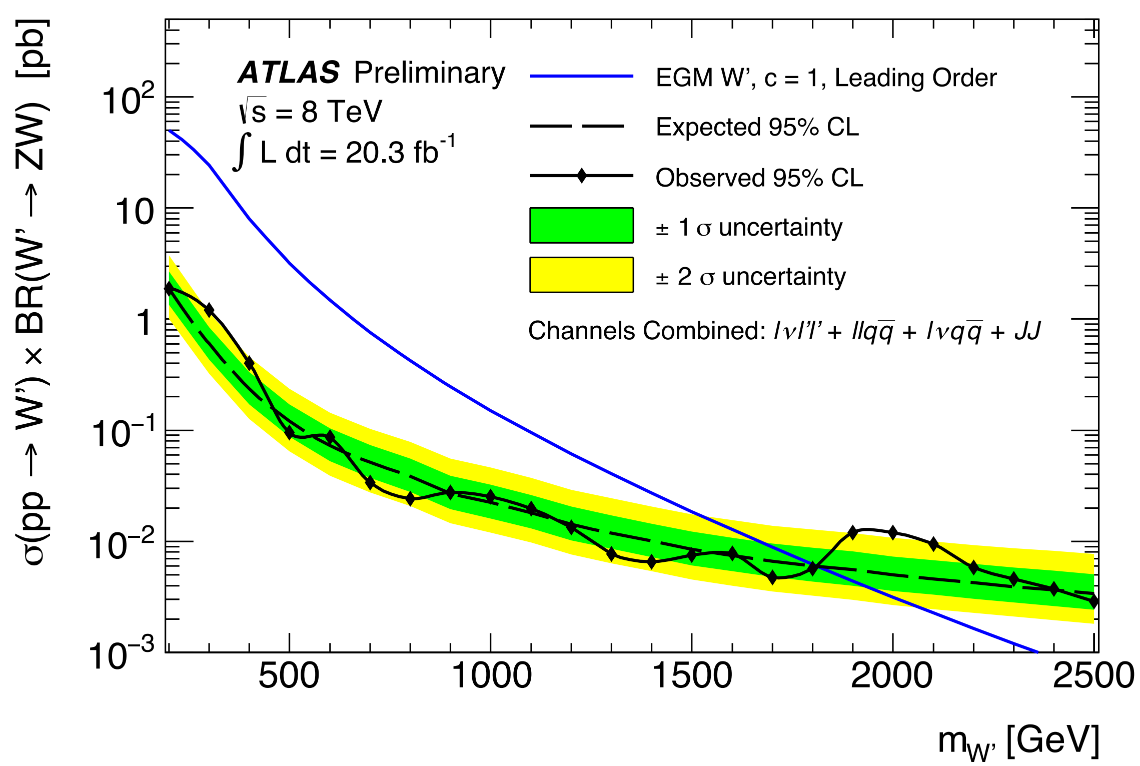


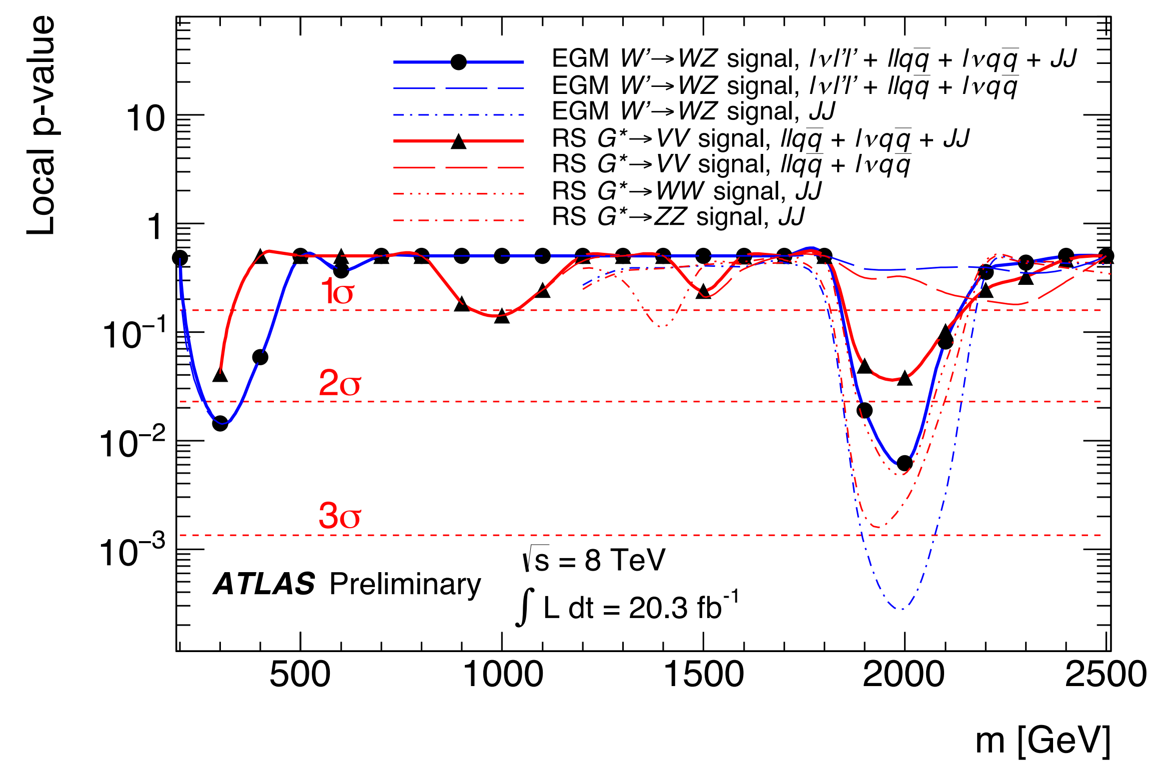




- Fully leptonic (e,μ) channel. Very clean signatures, but low branching fractions.
- Z mass constraint on the 2 same-flavor leptons. W reconstructed from the remaining lepton & Missing $E_T$ using the $m_W$ constraint.
- **No excesss observed in this channel.** Excluded m(W′)<1.52 TeV@95% CL.

# VV Search Combination

ATLAS-CONF-2015-045

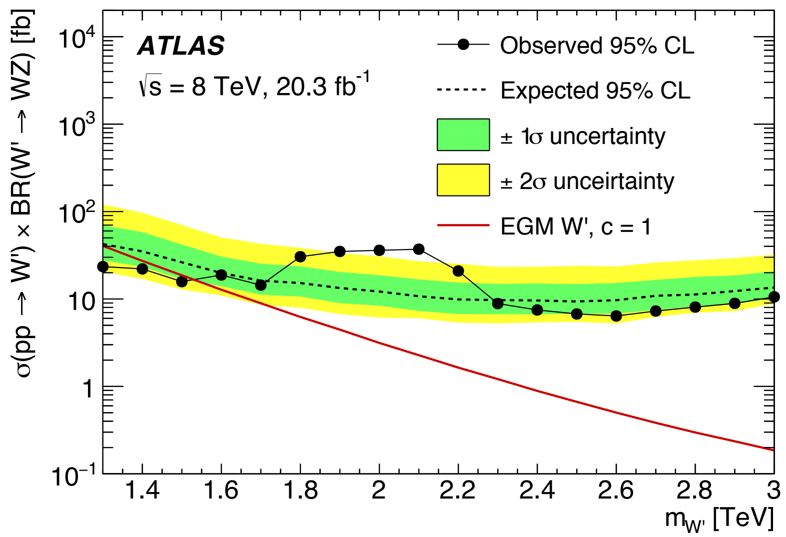
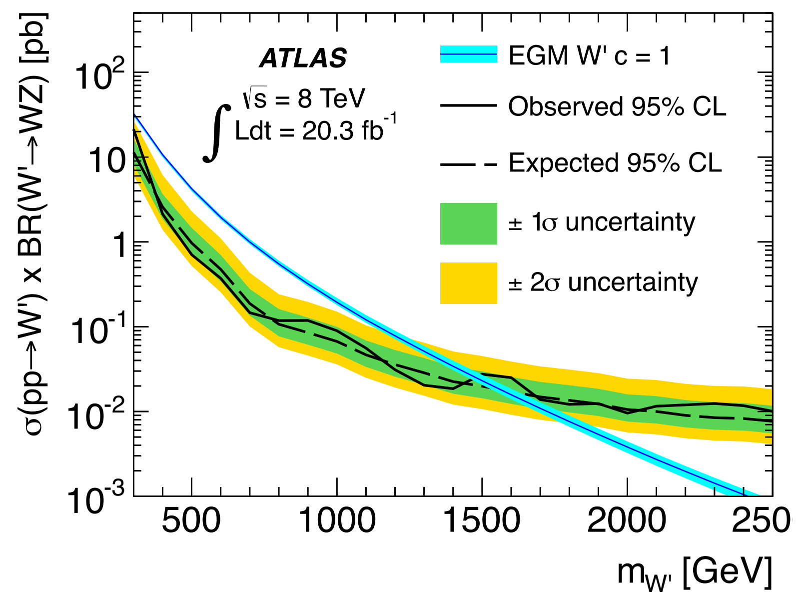
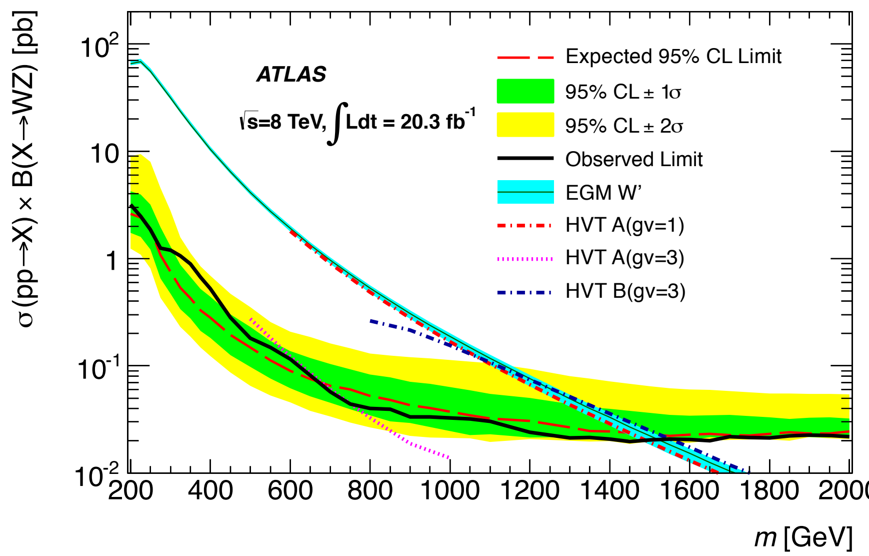
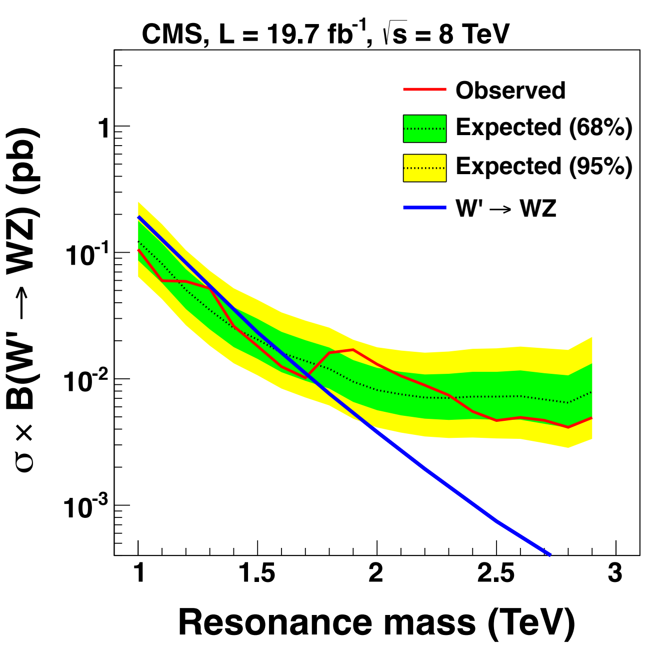
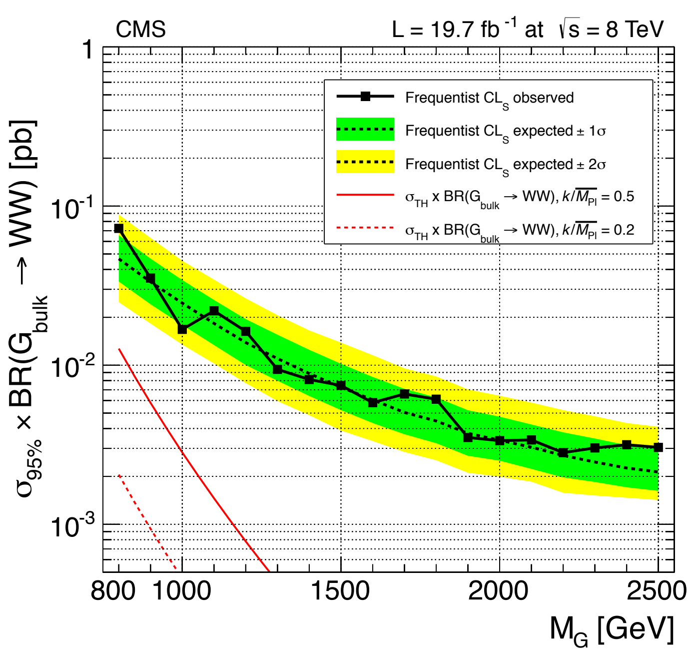
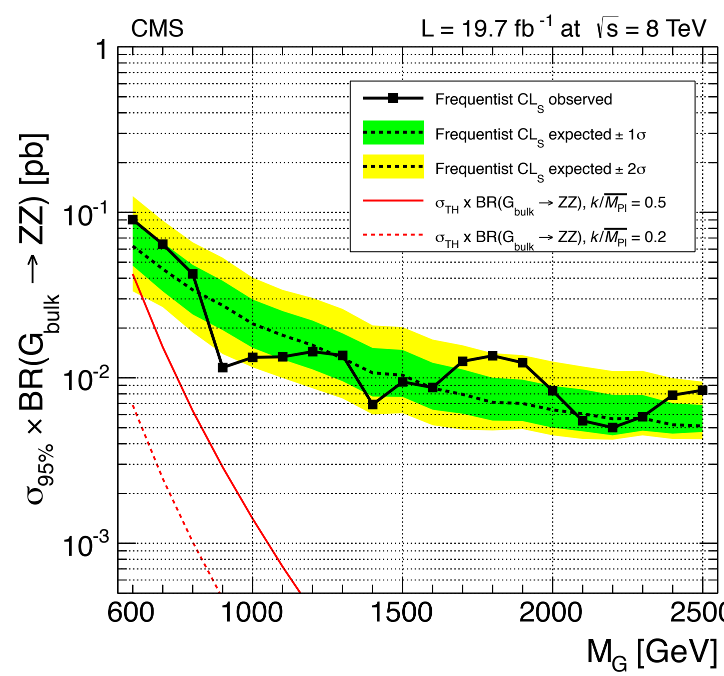



- JJ, lvqq, llqq, lvll channels are combined to search for high mass resonances decaying to WW, WZ, and ZZ.
- No significant excess is observed throughout the mass range. Excluded m(G*) < 810 GeV & m(W')<1.81 TeV@95% CL.
- Local significance on WZ@~2 TeV is reduced from 3.4σ to 2.5σ.

# Run-2 Prospects

# Mysteries to be Resolved

| | JJ | lvqq | llqq |
|---|---|---|---|
| ATLAS |  |  |  |
| CMS |  |  |  |







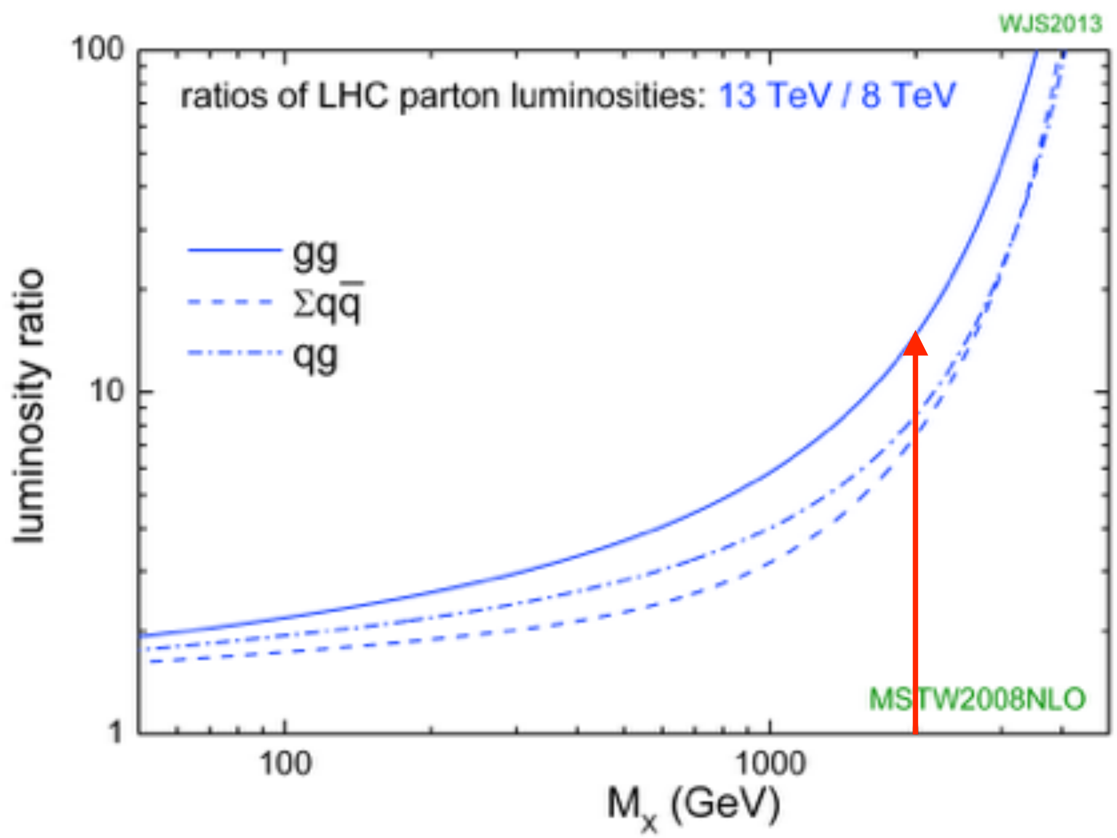


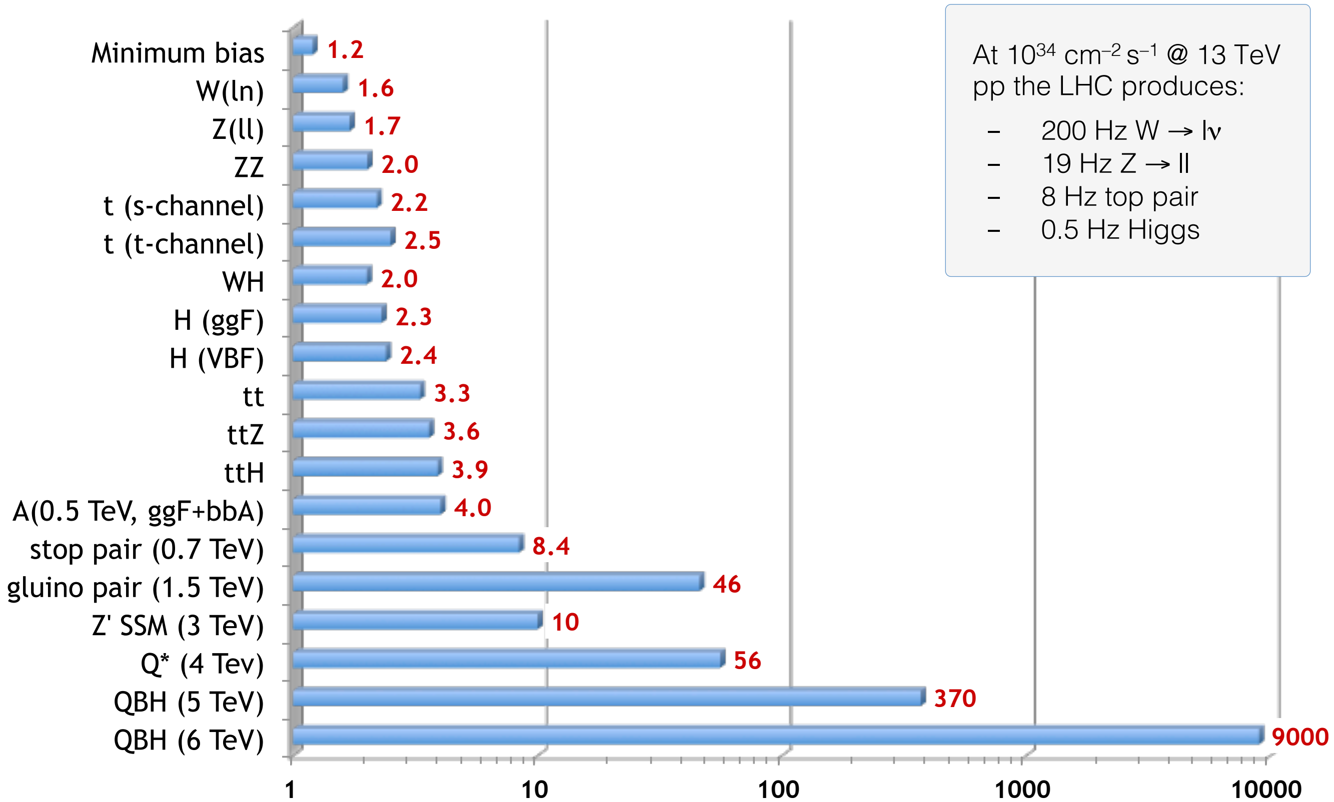




- ATLAS & CMS provided similar results in Run-1, but yields are not consistent among the final states. Increase in statistics will definitely help to understand the excesses.

# LHC@13 TeV



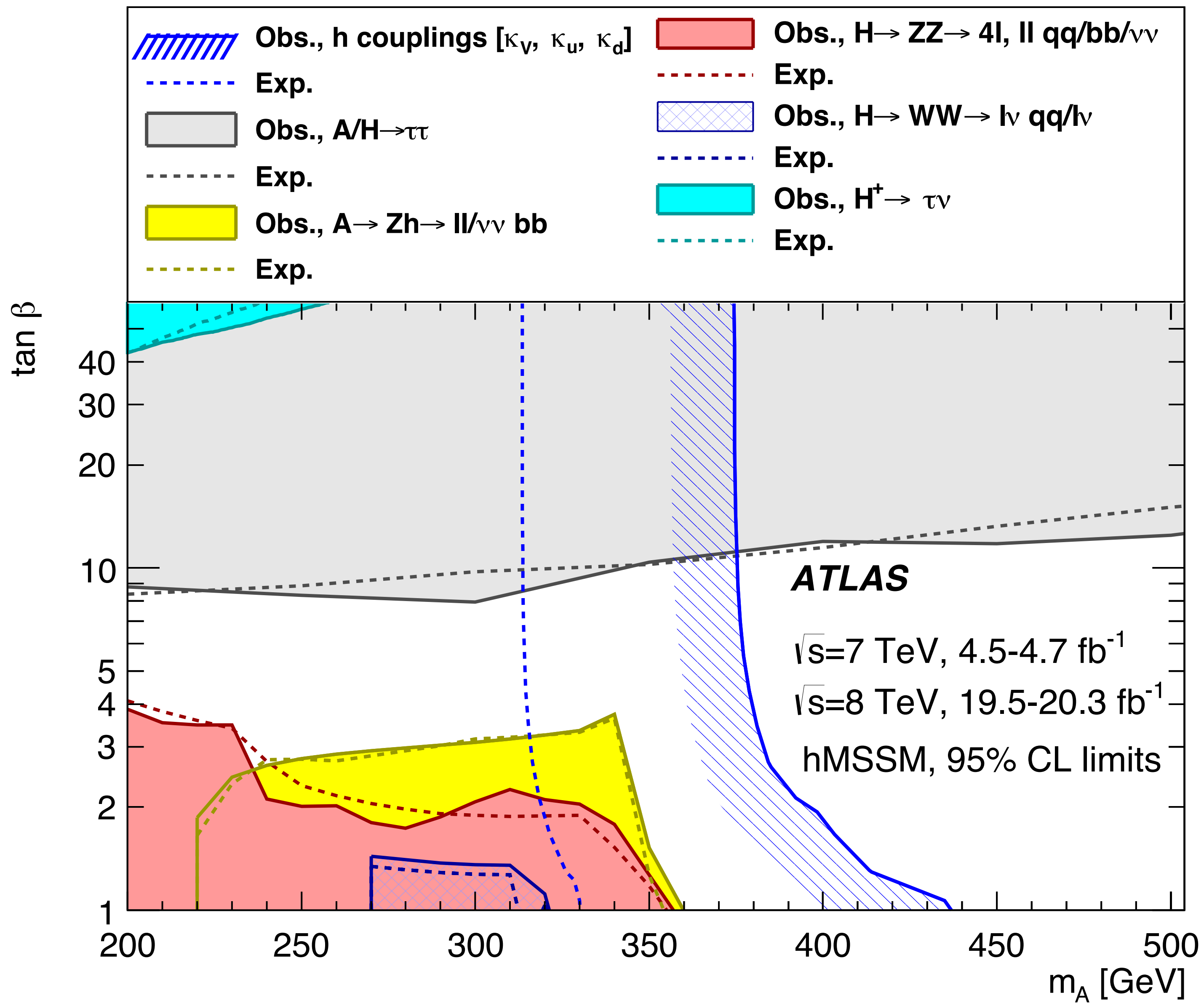

- **Significant increase (a factor~10)** in cross section expected for $M_X$~TeV production@13 TeV.
- **We may be able to confirm/exclude the Run-1 excesses with early Run-2 data!**

# Summary

- Presented Run-1 results with the full 8 TeV dataset (20 $fb^{-1}$) regarding the diboson resonance searches.
- Diboson resonances may arise from heavy Higgs bosons or other new particles predicted from BSM physics.
- Small excesses were observed in the fully hadronic channel using the boosted-boson tagging.
- We may already be able to understand the phenomenon with early Run-2 data.
- Diboson resonance searches are very important & urgent for the post-Higgs LHC physics program in Run-2!

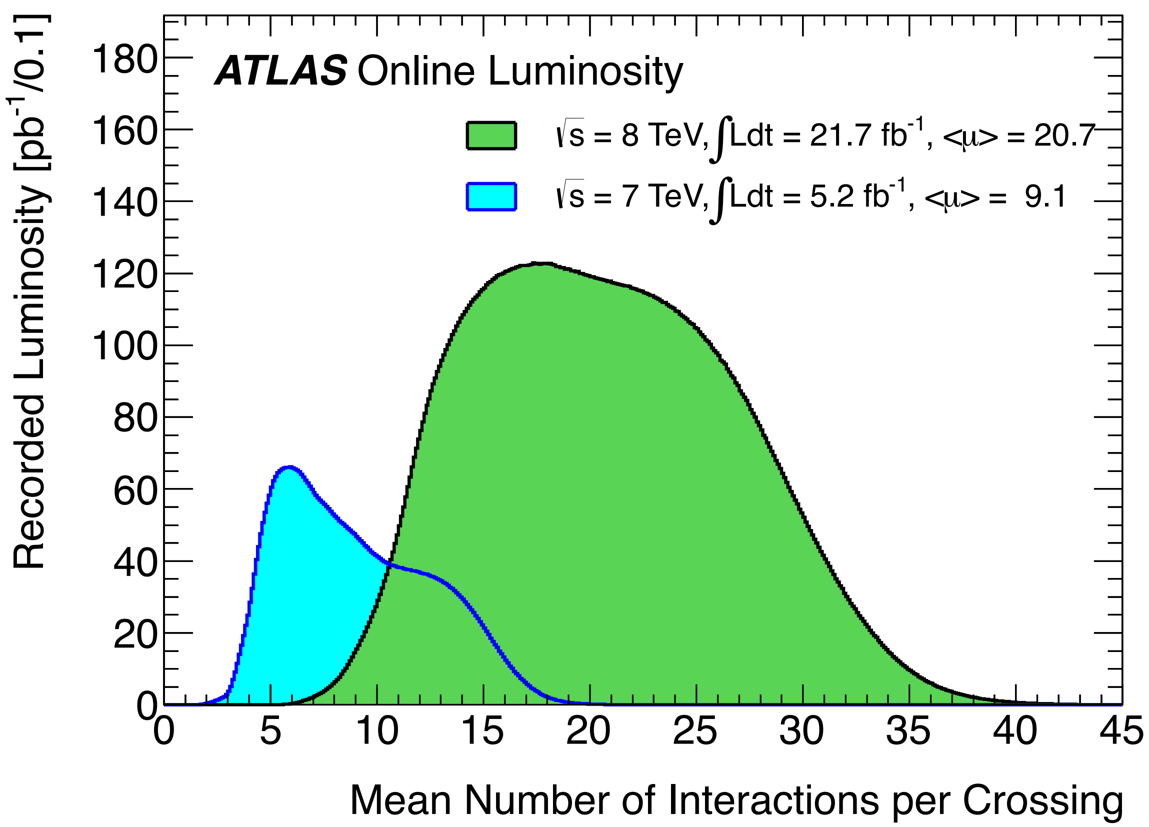
# backups

# hMSSM

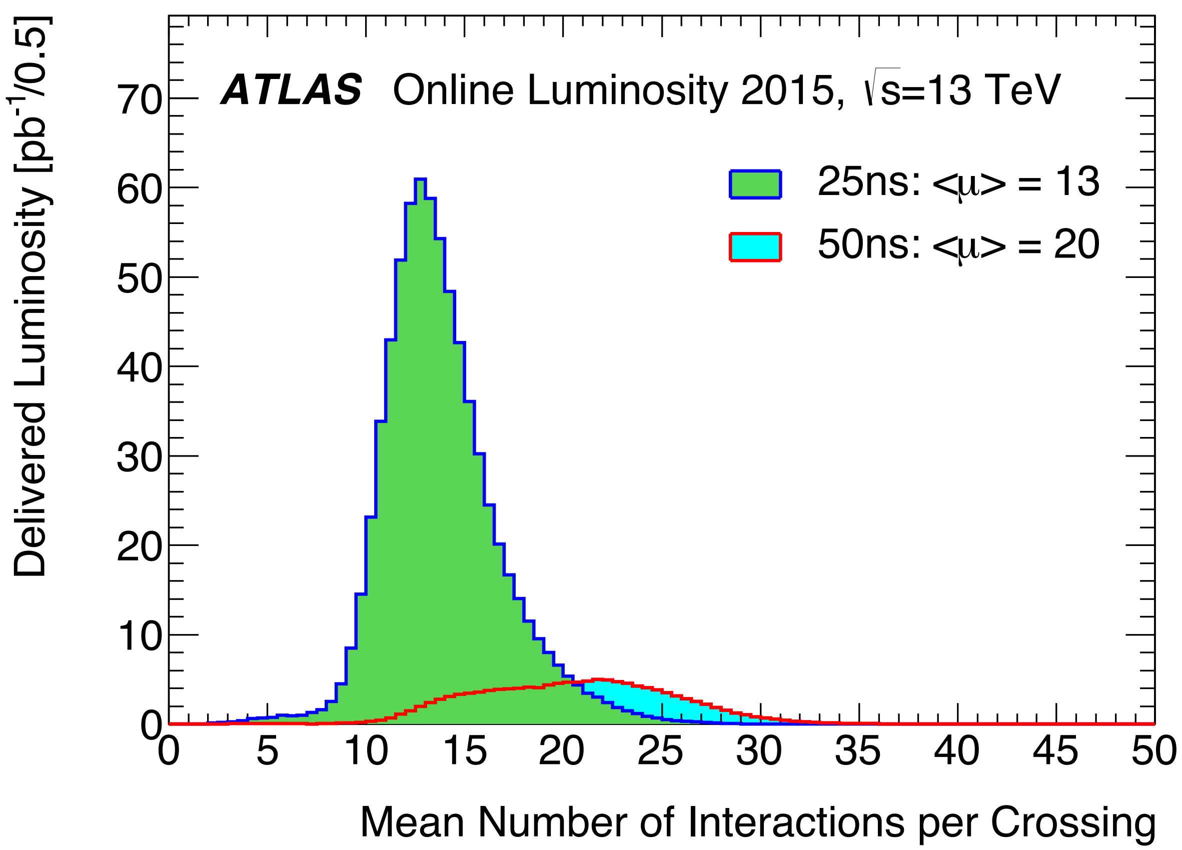


Obs., h couplings [κV, κu, κd]
Exp.
Obs., A/H→ττ
Exp.
Obs., A→ Zh→ ll/νν bb
Exp.
Obs., H→ ZZ→ 4l, ll qq/bb/νν
Exp.
Obs., H→ WW→ lν qq/lν
Exp.
Obs., H+→ τν
Exp.
ATLAS
√s=7 TeV, 4.5-4.7 fb-1
√s=8 TeV, 19.5-20.3 fb-1
hMSSM, 95% CL limits
tan β
m_A [GeV]

# LHC

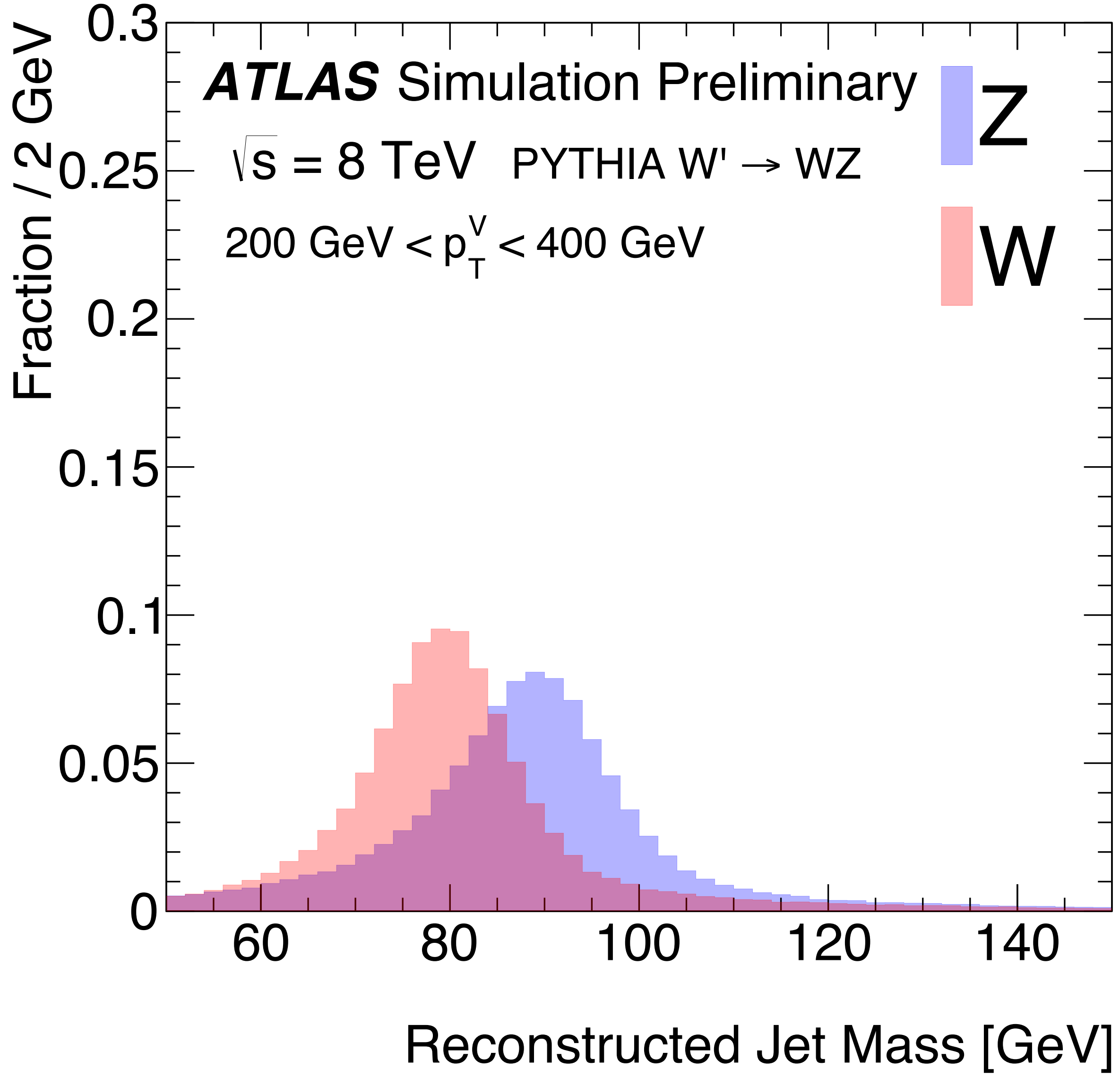


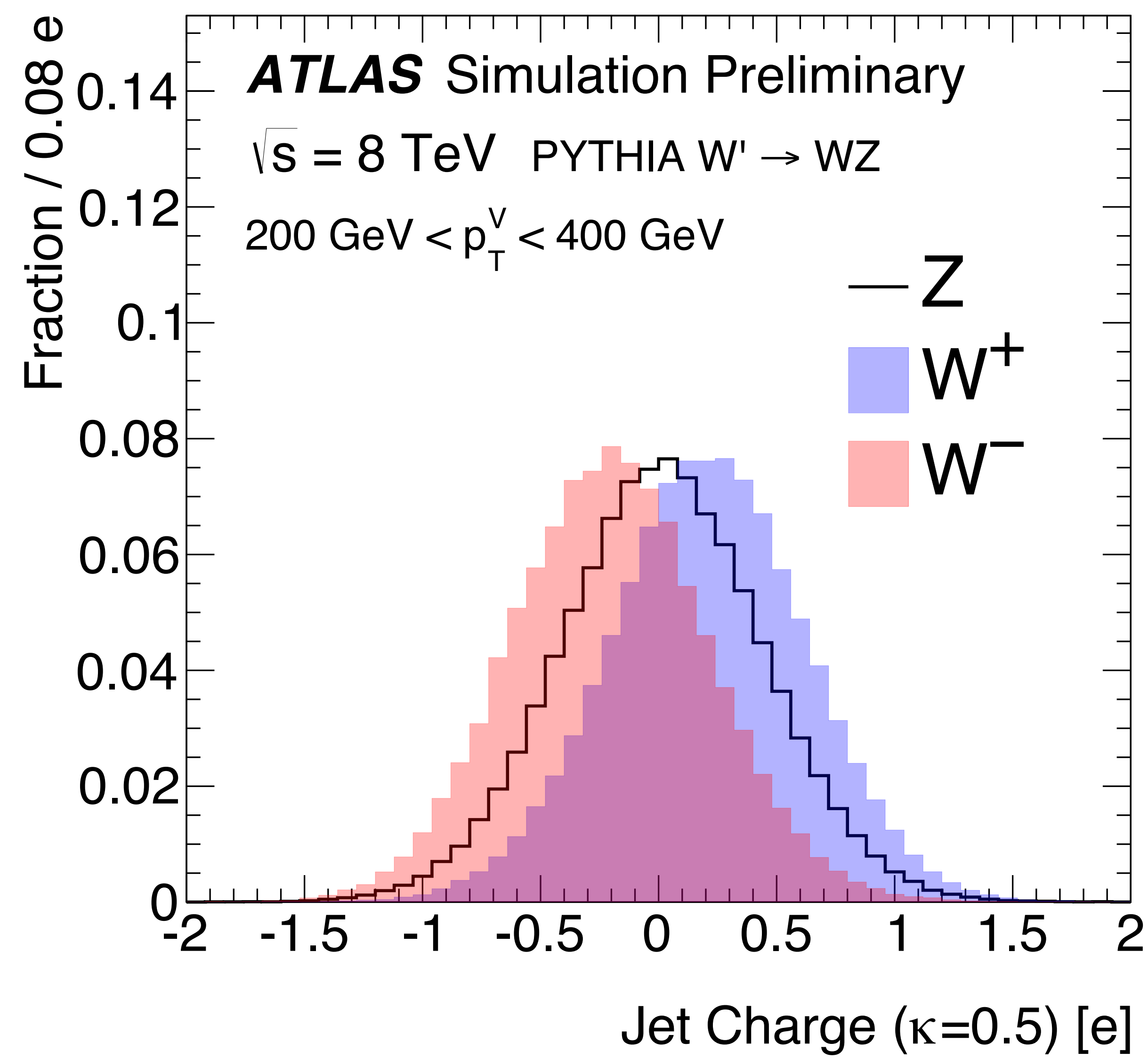
ATLAS Online Luminosity
√s = 8 TeV, ∫Ldt = 21.7 fb-1, <μ> = 20.7
√s = 7 TeV, ∫Ldt = 5.2 fb-1, <μ> = 9.1
Recorded Luminosity [pb-1/0.1]
Mean Number of Interactions per Crossing

ATLAS Online Luminosity 2015, √s=13 TeV
25ns: <μ> = 13
50ns: <μ> = 20
Delivered Luminosity [pb-1/0.5]
Mean Number of Interactions per Crossing

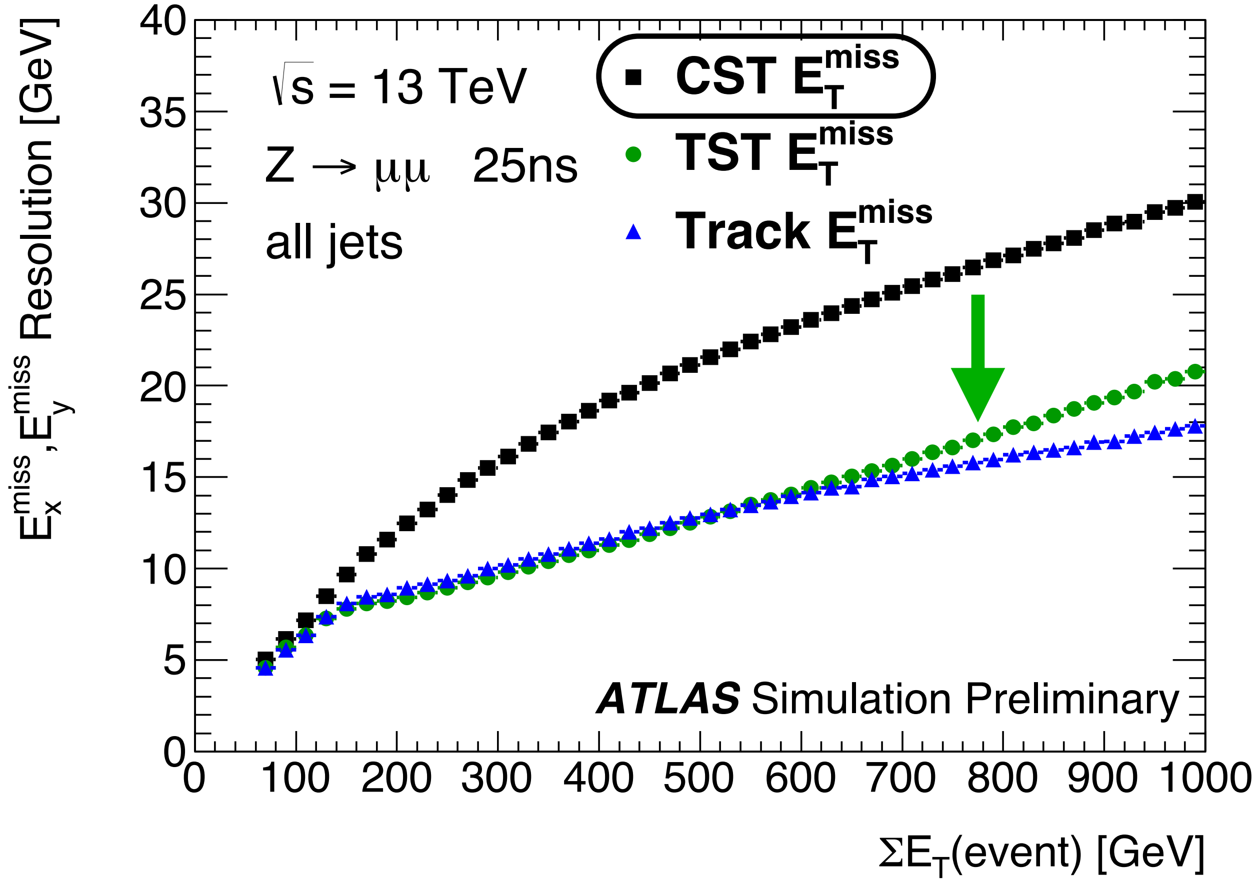
# W/Z Discrimination



# Missing $E_T$ Resolution

$\Sigma E_T$ dependence




Pileup dependence