LHC Run1 anomalies @ high mass and summary of Run2 observations

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One remark before starting

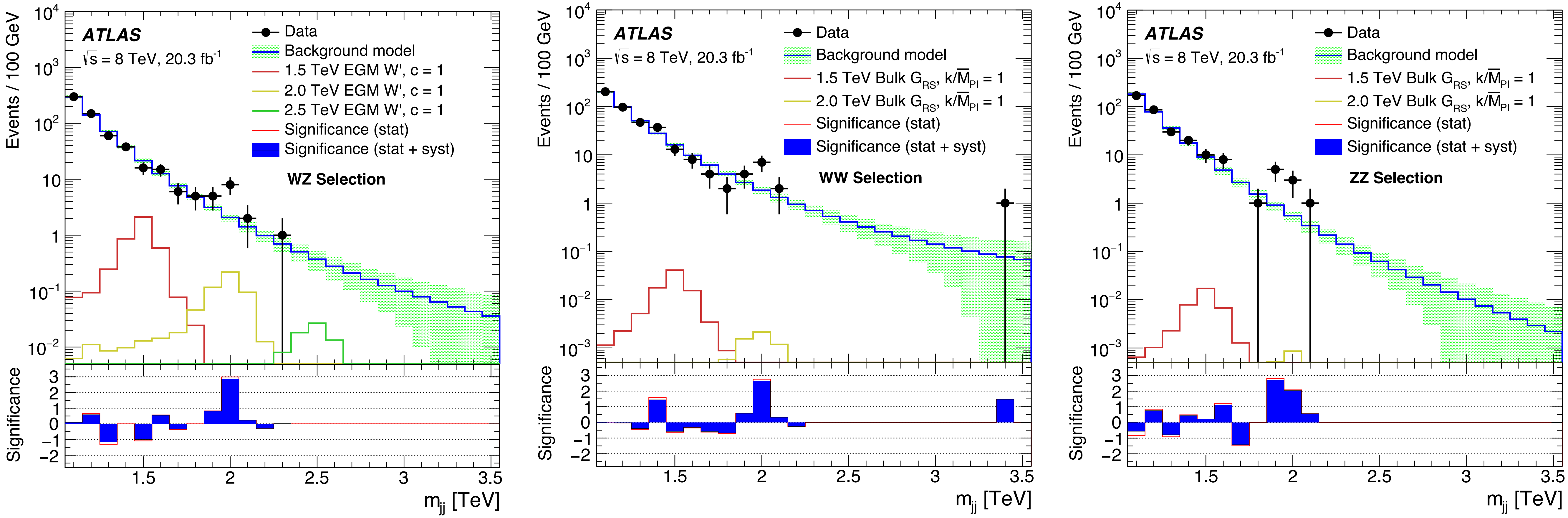
- Despite being member of one LHC experiment, I am here speaking for myself
- I prepared this talk as any outsider would have done
- The main purpose is to stimulate a discussion on this topic and use Moriond as an opportunity to make the point on this long standing puzzle
- Will show some combination performed by experimentalists (ATLAS & CMS individual members collaborating on their own) or theorists, using public information provided by the experiments
    - When I do so, I make it clear with a symbol

- As this is not an ATLAS/CMS talk, no new results shown

DiBoson resonance Searches

The ATLAS Dijet Diboson excess

- ATLAS reported an excess in the Run I all-jet Diboson search



- Excess seen at ≈2 TeV in three overlapping analyses (i.e., not independent results)
- 3.4σ in the WZ channel, 2.6σ in WW, 2.9σ in ZZ
- Global significance evaluated to 2.5σ after Look Elsewhere effect

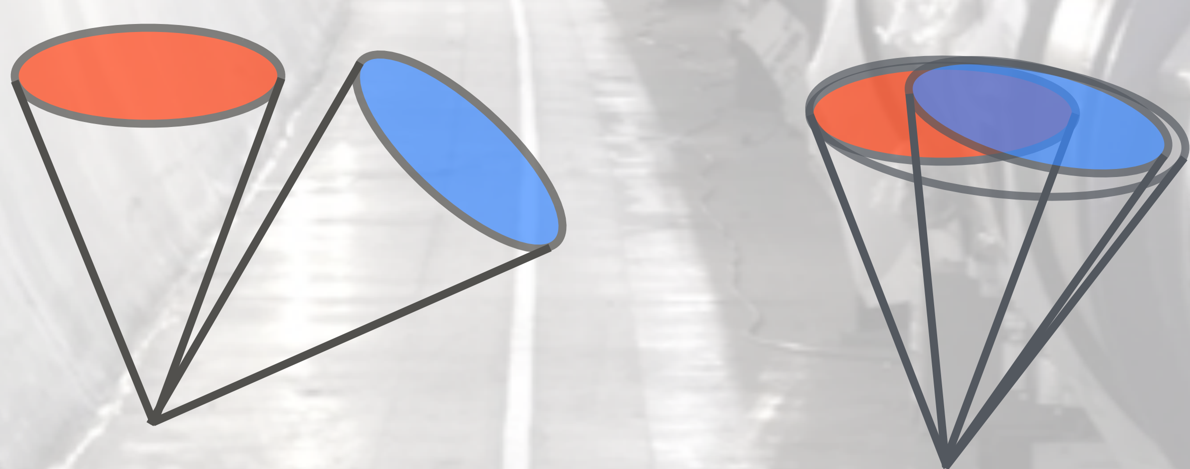
ATLAS arXiv:1506.00962

How does it work? Boosted jets

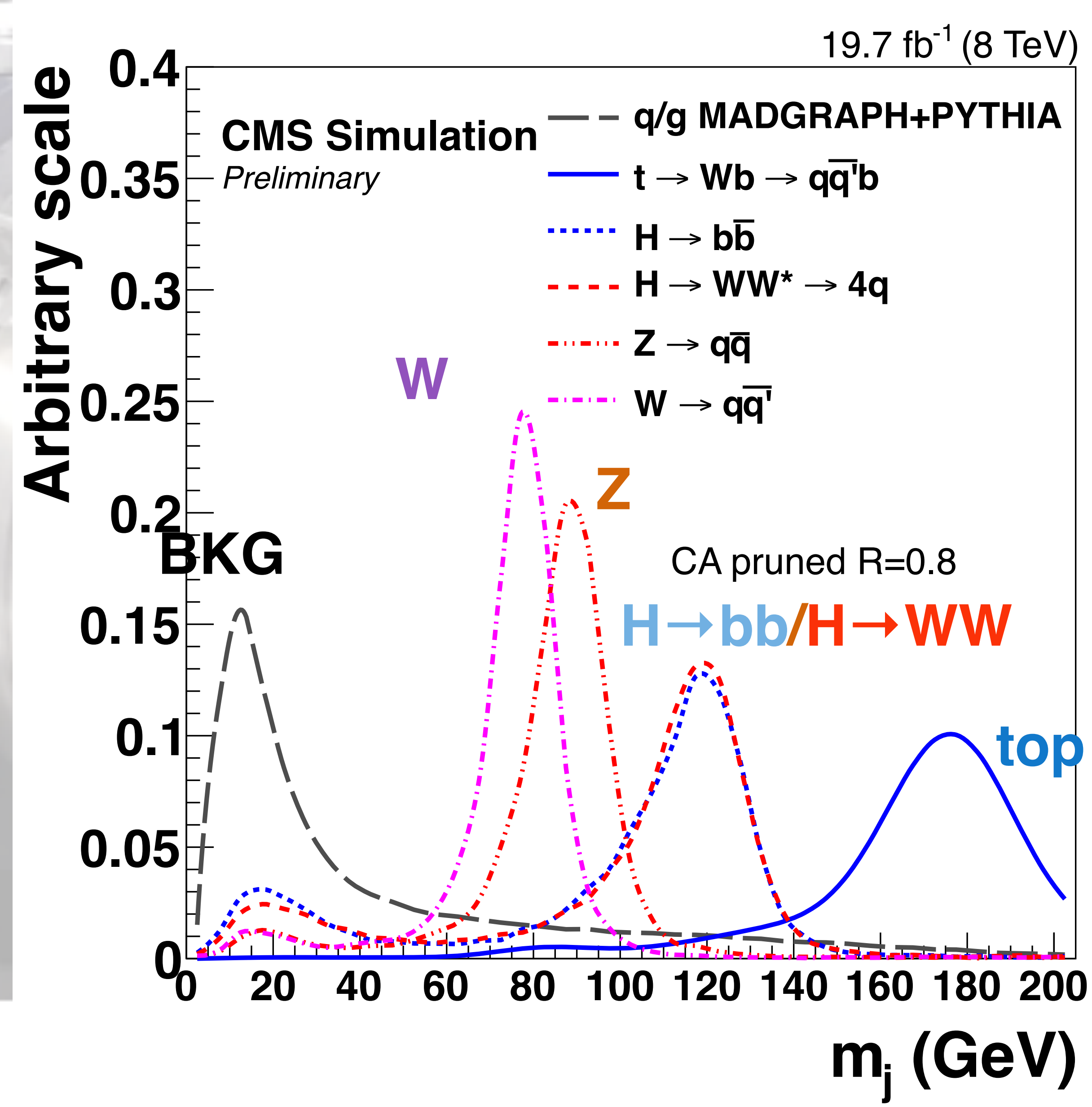
- SM bosons decay to 2q final states, giving usually 2 jets
- For large enough p_T, decay products merge into a single massive jet
- Jet Mass main tool for discriminating signal vs. background

Low energy W/Z/H

High energy W/Z/H

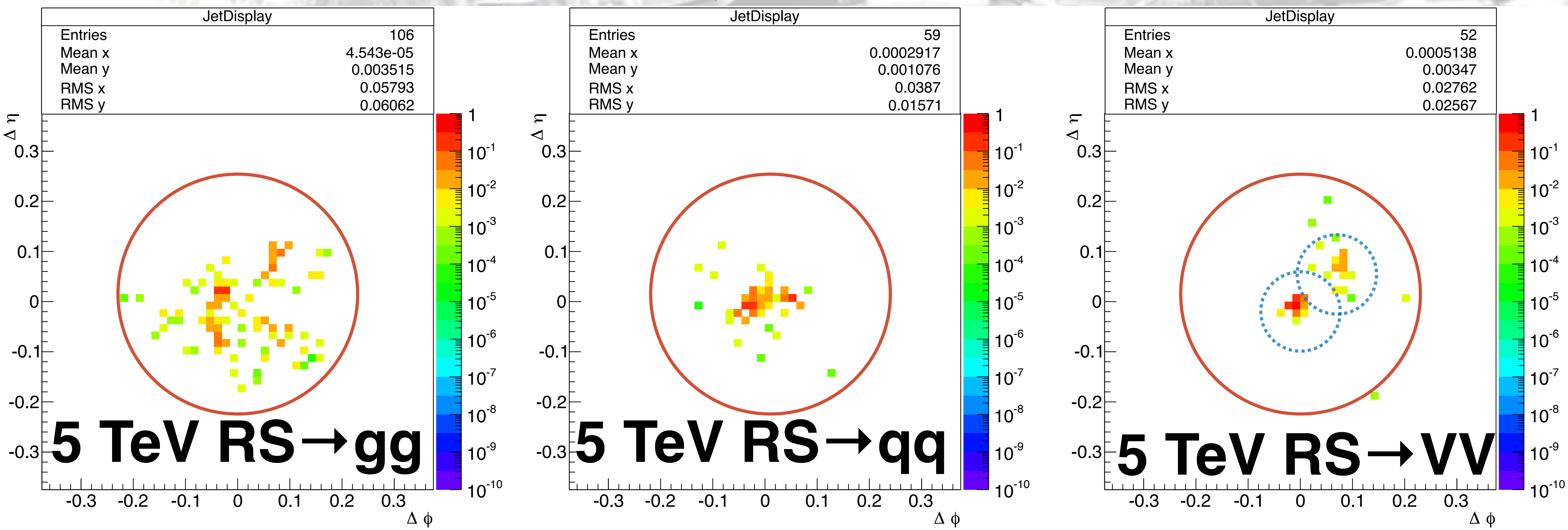


For $X \rightarrow VV$, $\Delta R(q,q) \sim 4\, M_V/M_X$



How does it work? Boosted jets

- Further discrimination from pT & angular distribution of jet constituents (so-called jet substructure)
- Unlike classic QCD jets, two collimated clusters of particles inside jet
- Several variables proposed to quantify this behavior



pT distribution of jet constituents at Generator-Level (PYTHIA8) from boosted gluons/ quarks / Z->qq bosons (from RS gravitons)

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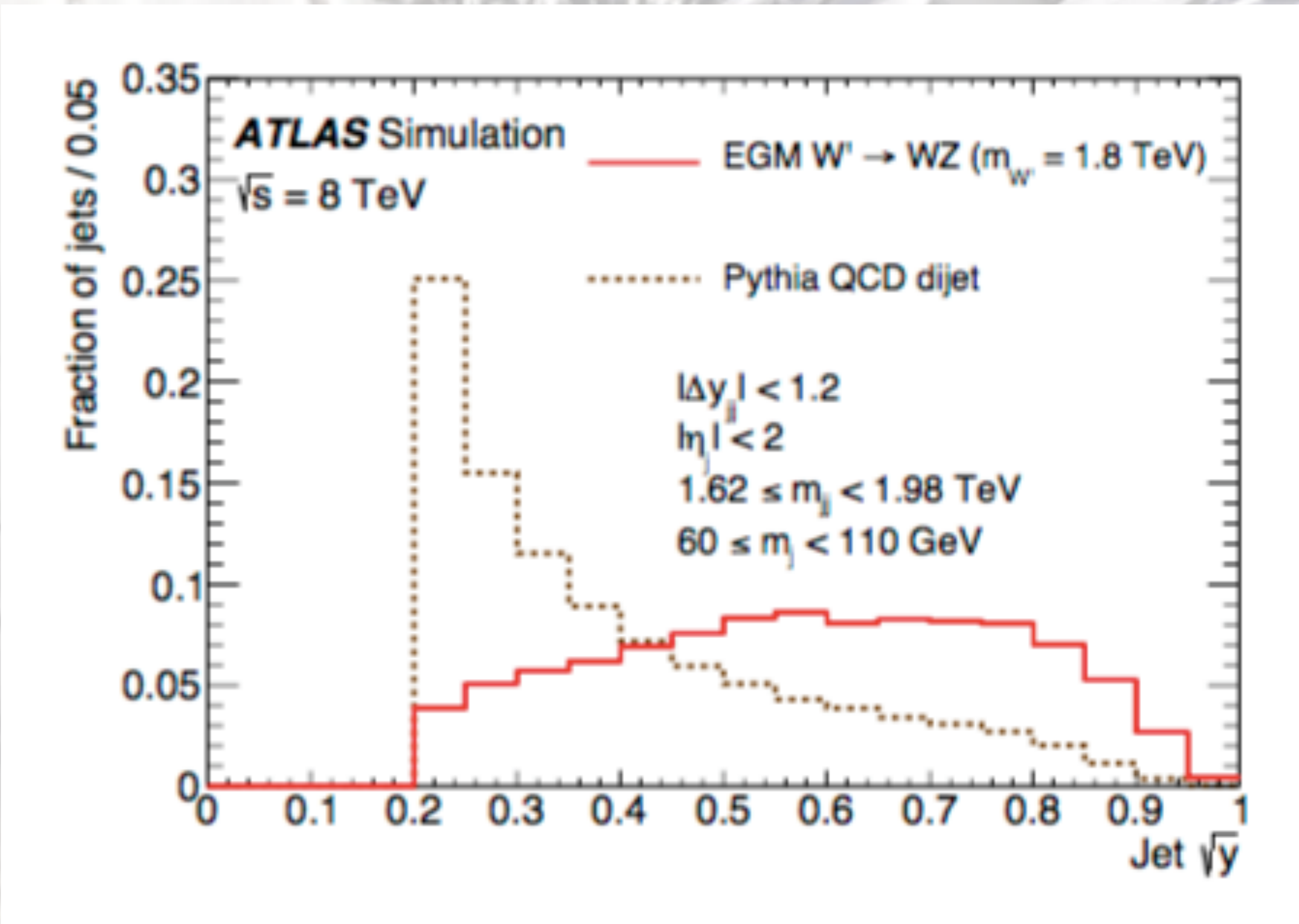
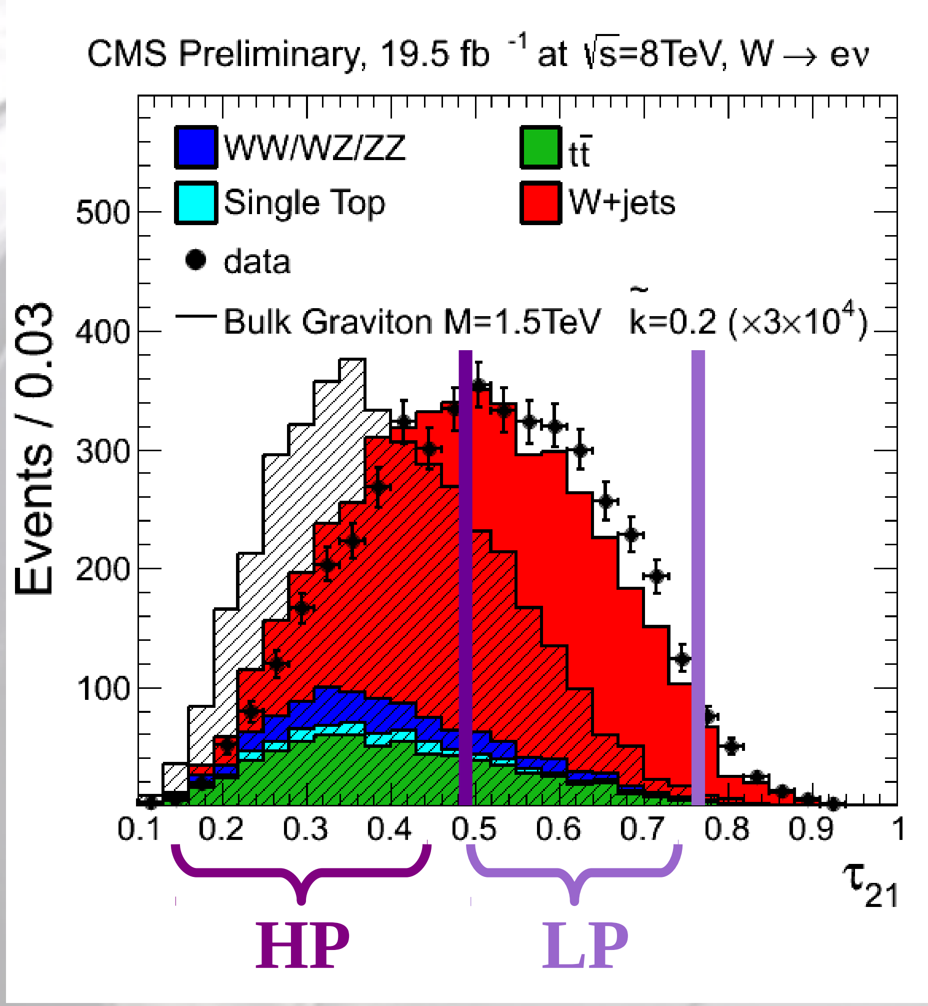


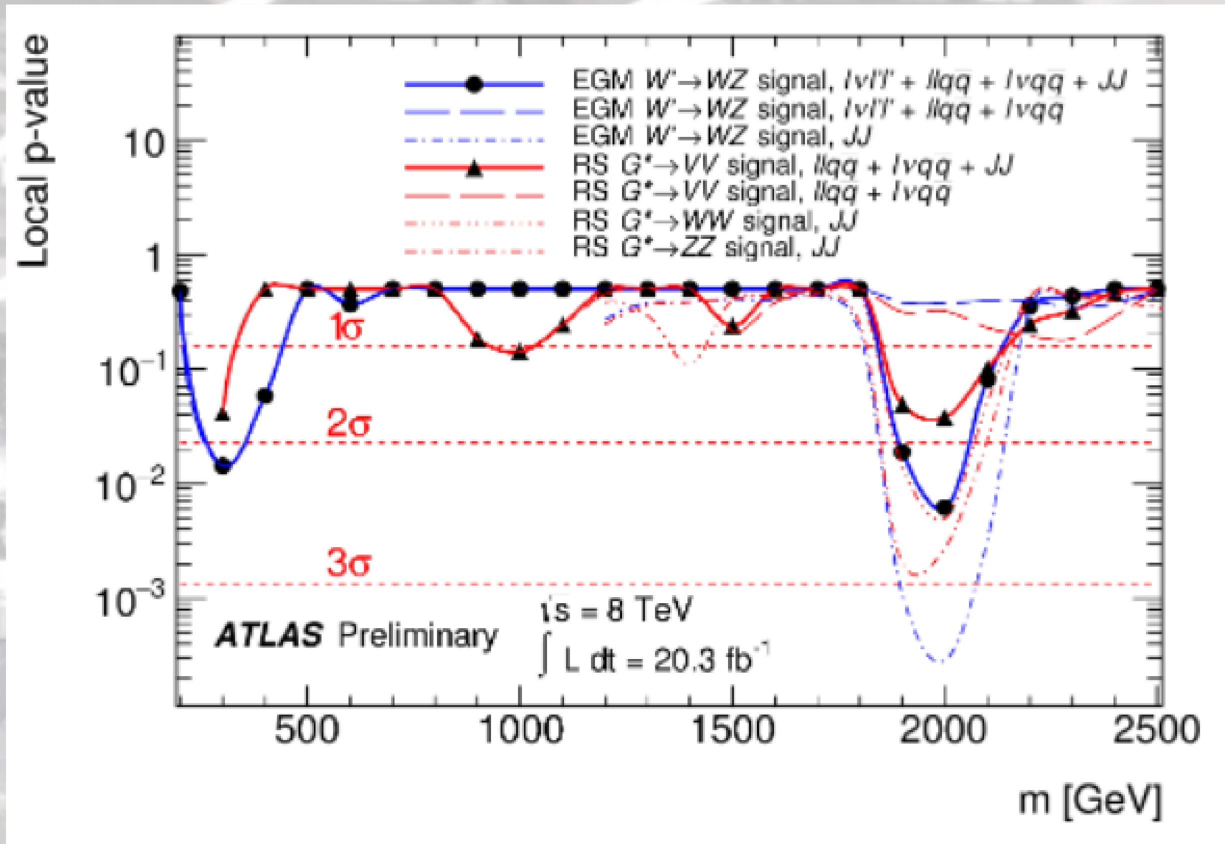


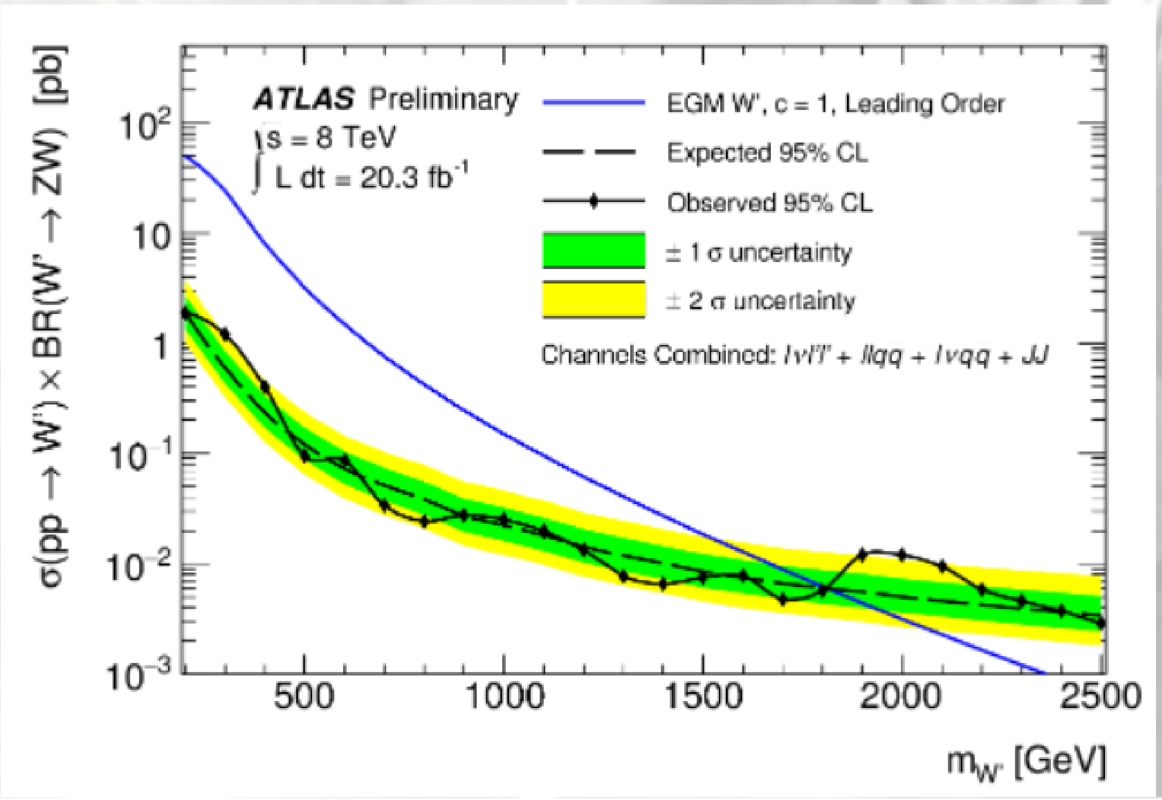
Jet √y introduced by J. Butterworth et al .

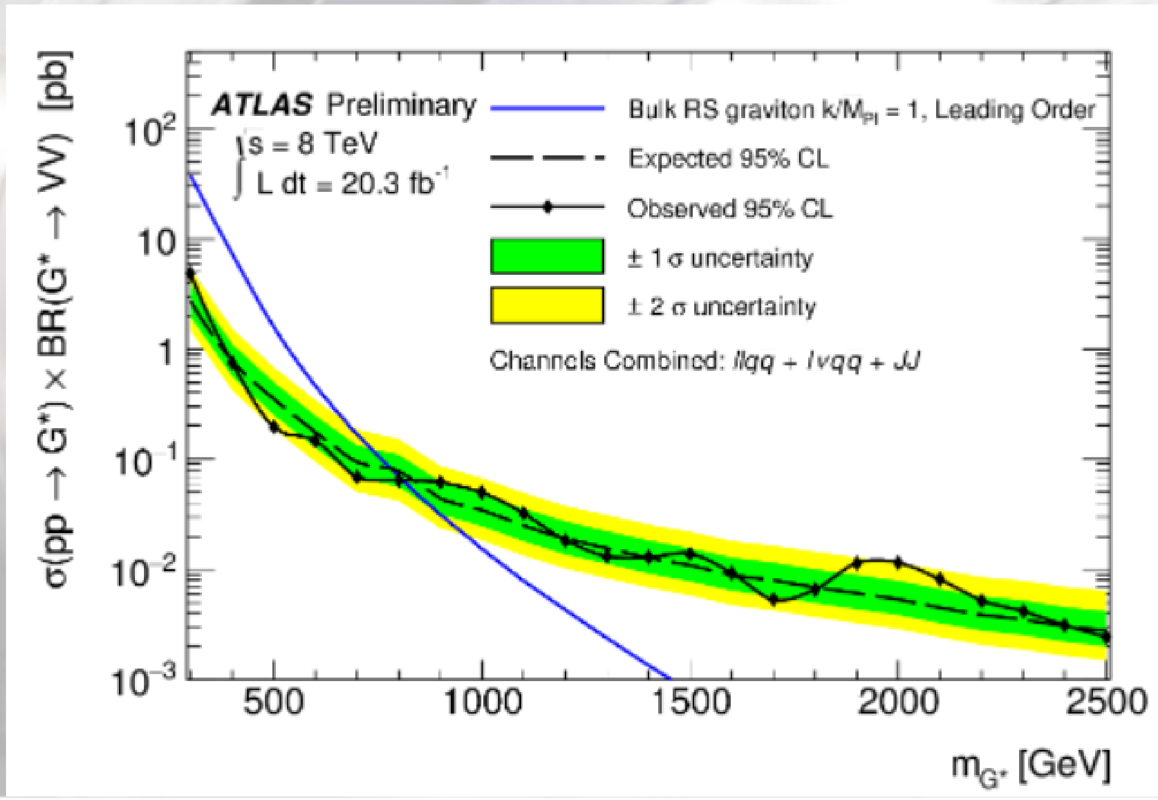
N-Subjettiness introduced by J. Thaler and K. Van Tilburg

Other ATLAS Diboson Searches

- Lack of a signal in other channels reduces the excess
- This was known (the other searches are older). Not everybody payed attention to that
- Now ATLAS quantified the reduction: significance drop by 1σ, i.e. at most 2.4σ (depending on signal hypothesis)

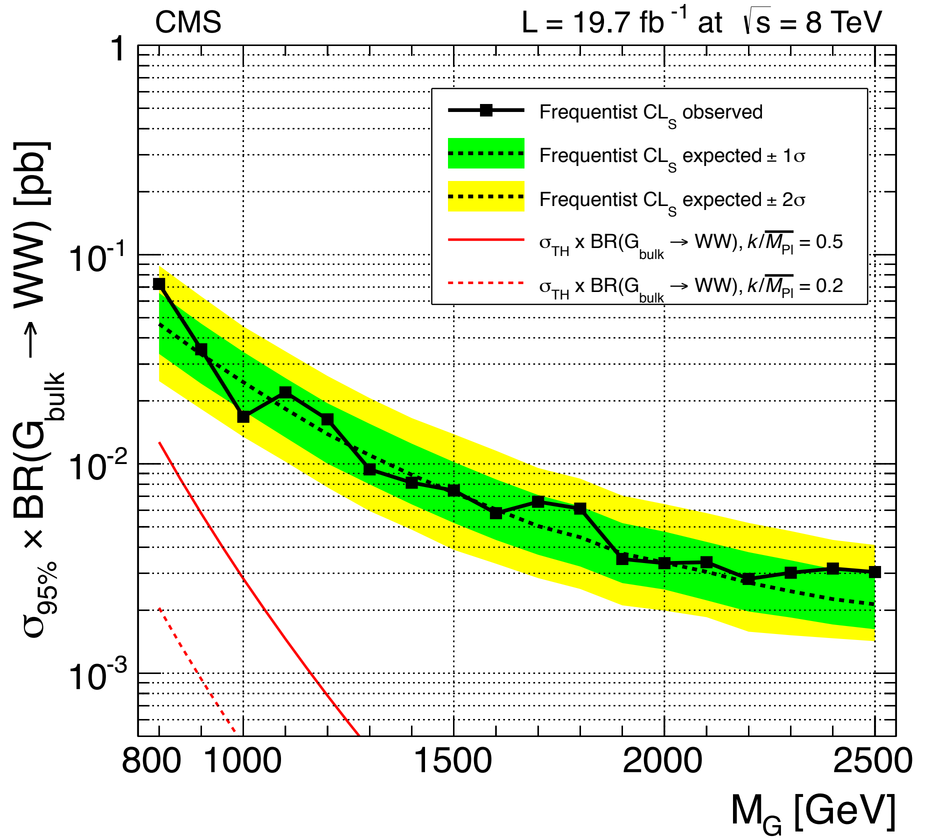


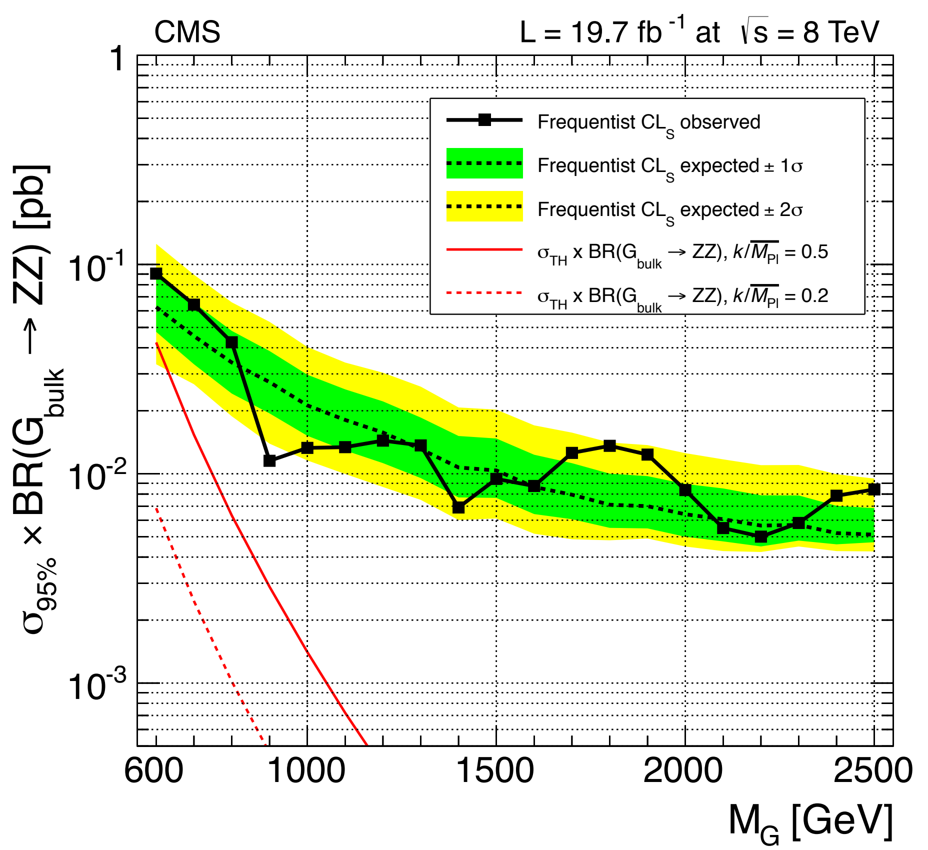


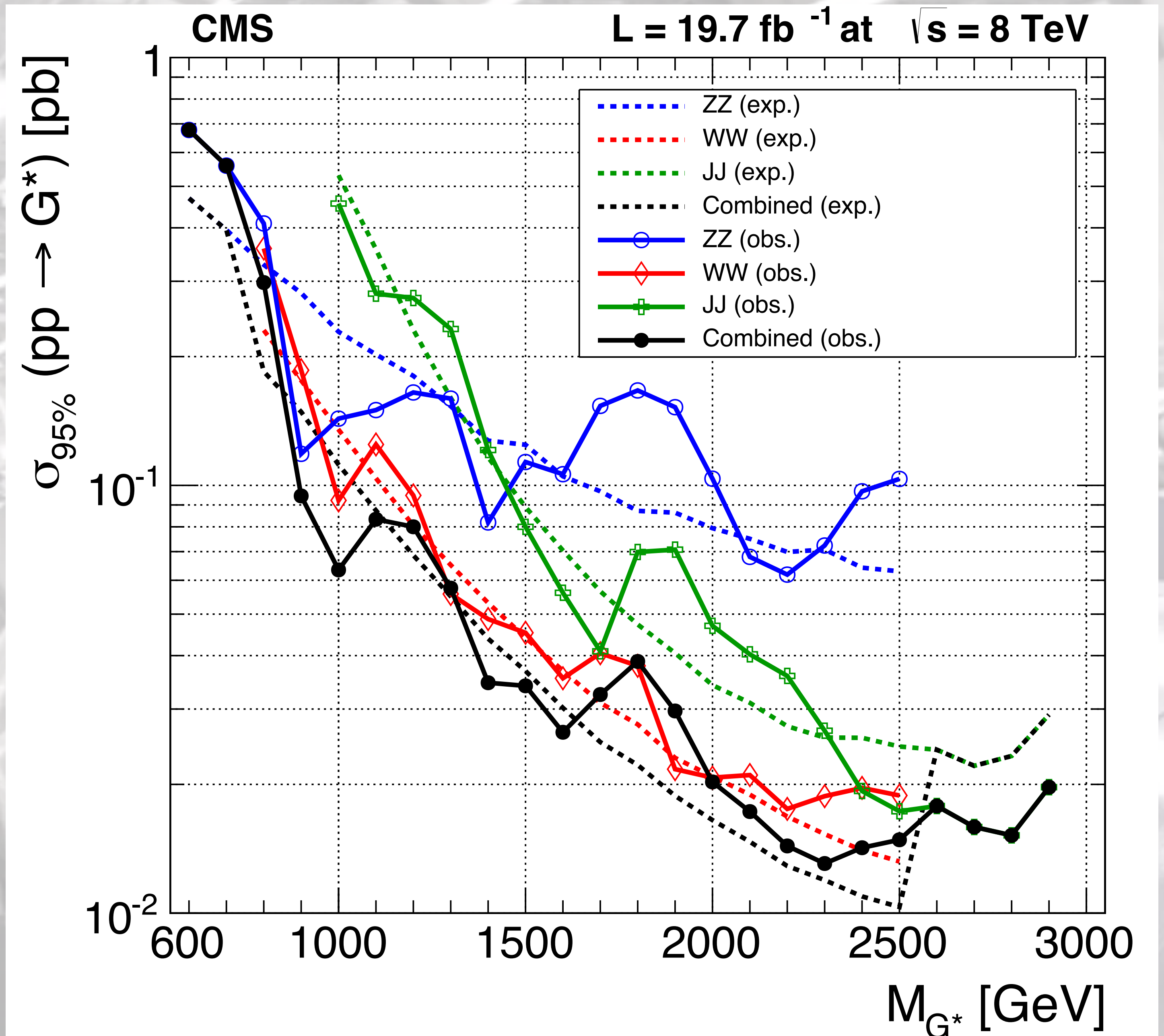


ATLAS arXiv:1506.00962

CMS Diboson Searches







Not as spectacular as ATLAS JJ, but similar to ATLAS combination

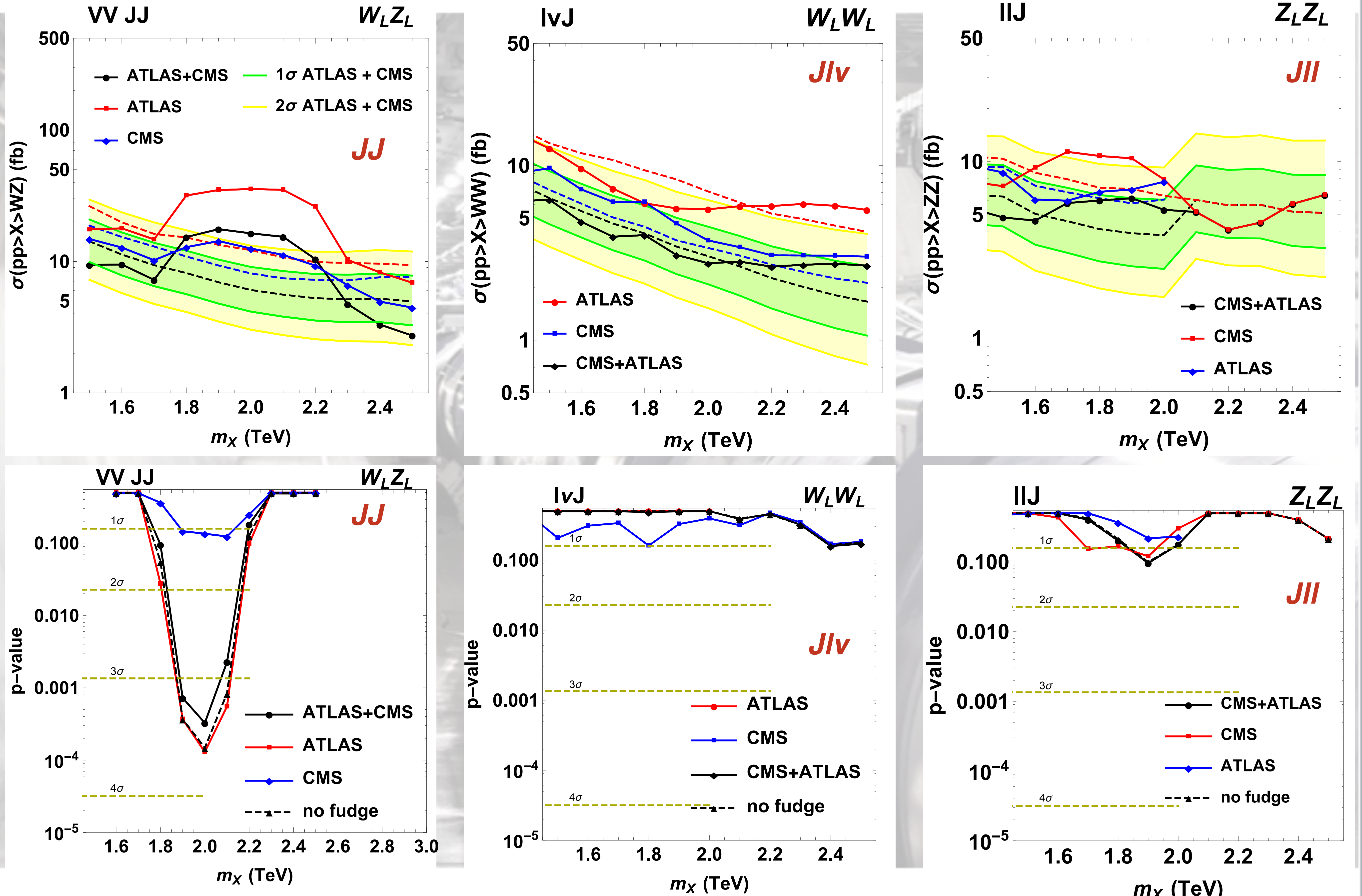
Interestingly enough, @ same mass value

Interestingly enough, not coming from a single analysis

CMS arXiv:1405.1994

CMS arXiv:1405.3447

A combination of VV searches



F. Dias et al. http://arxiv.org/abs/1512.03371

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JJ/lnJ/llJ compatibility @2 TeV

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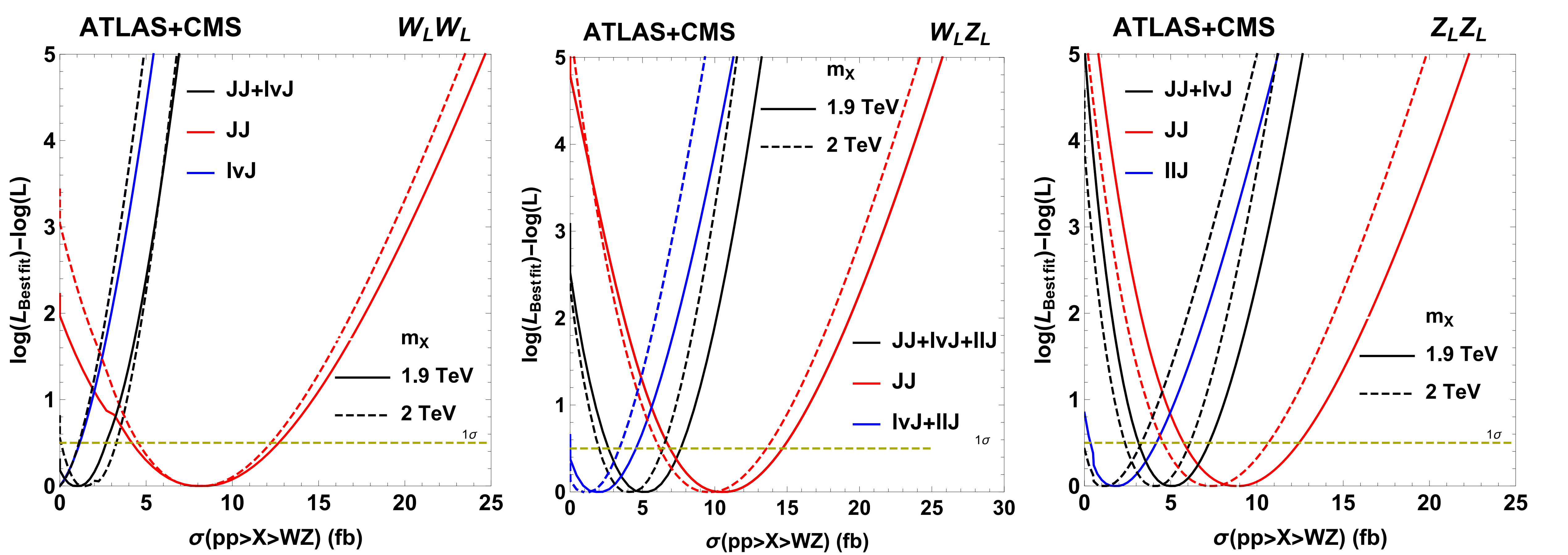

- If one assumes BR(X->WW)=100%, the experimental results make no sense
  - no signal in lνJ analyses, the strongest
  - The lνJ result is then capable of excluding the JJ ATLAS excess
- If instead BR(X->ZZ)=100%, lνJ plays no role
  - the small excess in llJ reinforce the JJ excess
  - the signal xsec is reduced
- The W'->WZ is the ideal test of compatibility
  - interestingly, the picture is similar to ZZ

F. Dias et al.

http://arxiv.org/abs/1512.03371

Combination under WZ hypothesis

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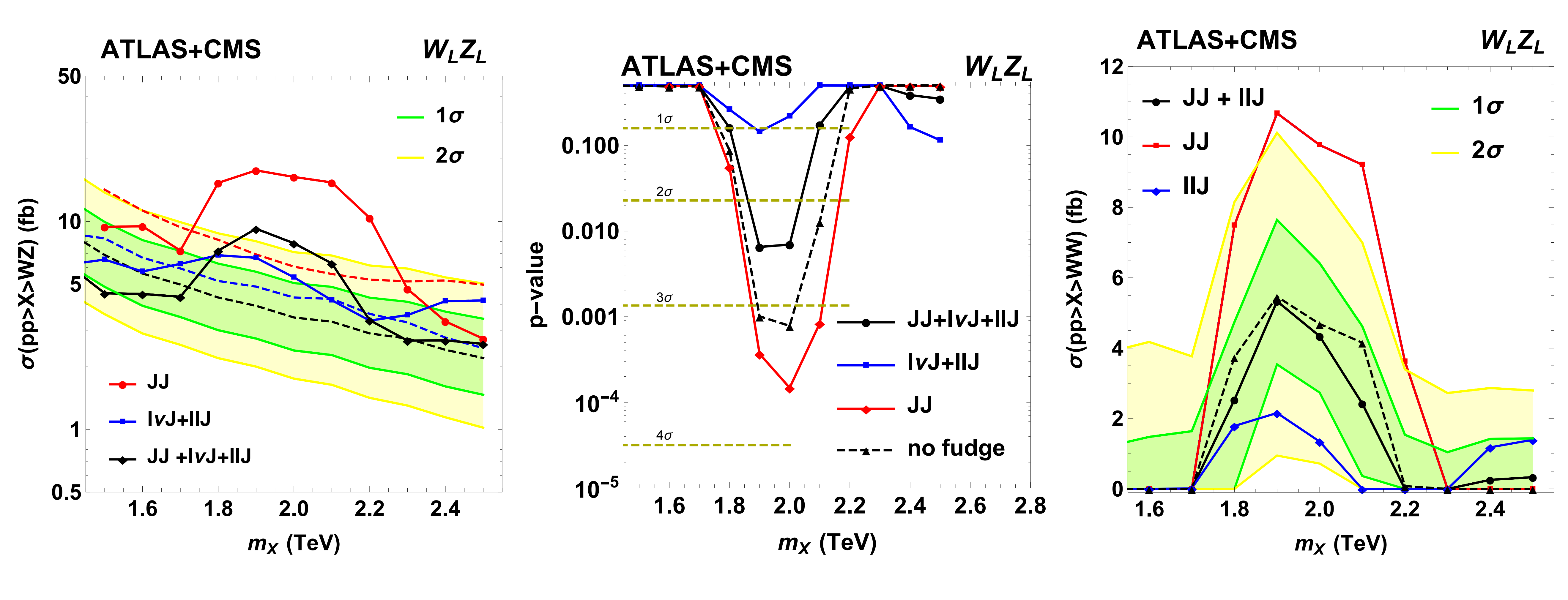
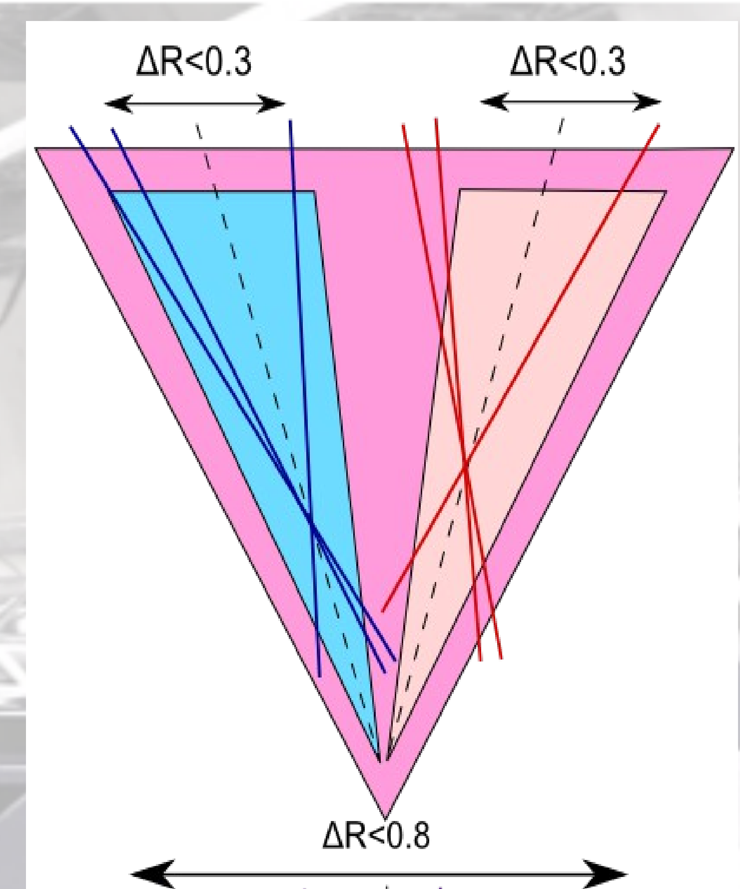


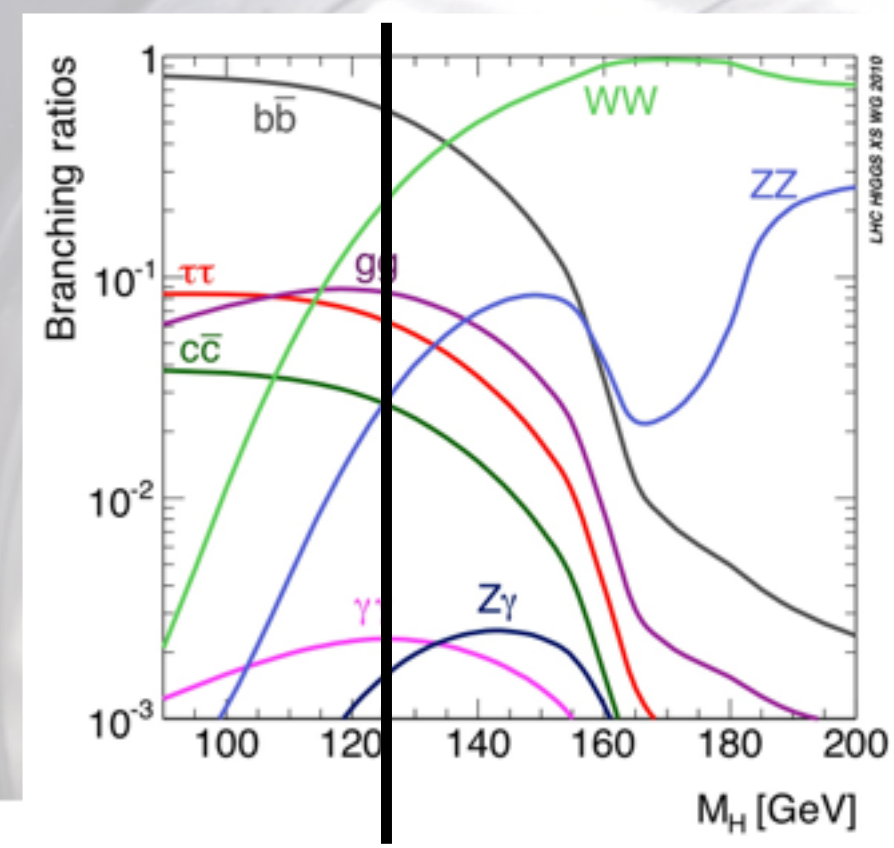
- Combination points to a signal strength 1/2 smaller than ATLAS JJ excess
- (Local) Significance ≈2.5σ

Adding BEH boson to final states

Boosted BEH bosons

- Boosted BEH bosons → bb are even cleaner than W/Z bosons
  - larger mass means less QCD background
  - possibility of tagging one or two b "subjets"
- More than bb final states
  - gg/qq final states can be treated like for V mesons
  - $\tau\tau$ decays offer special signatures (jets with few tracks)
  - fully hadronic WW decays (massive jet with multiple subjets)

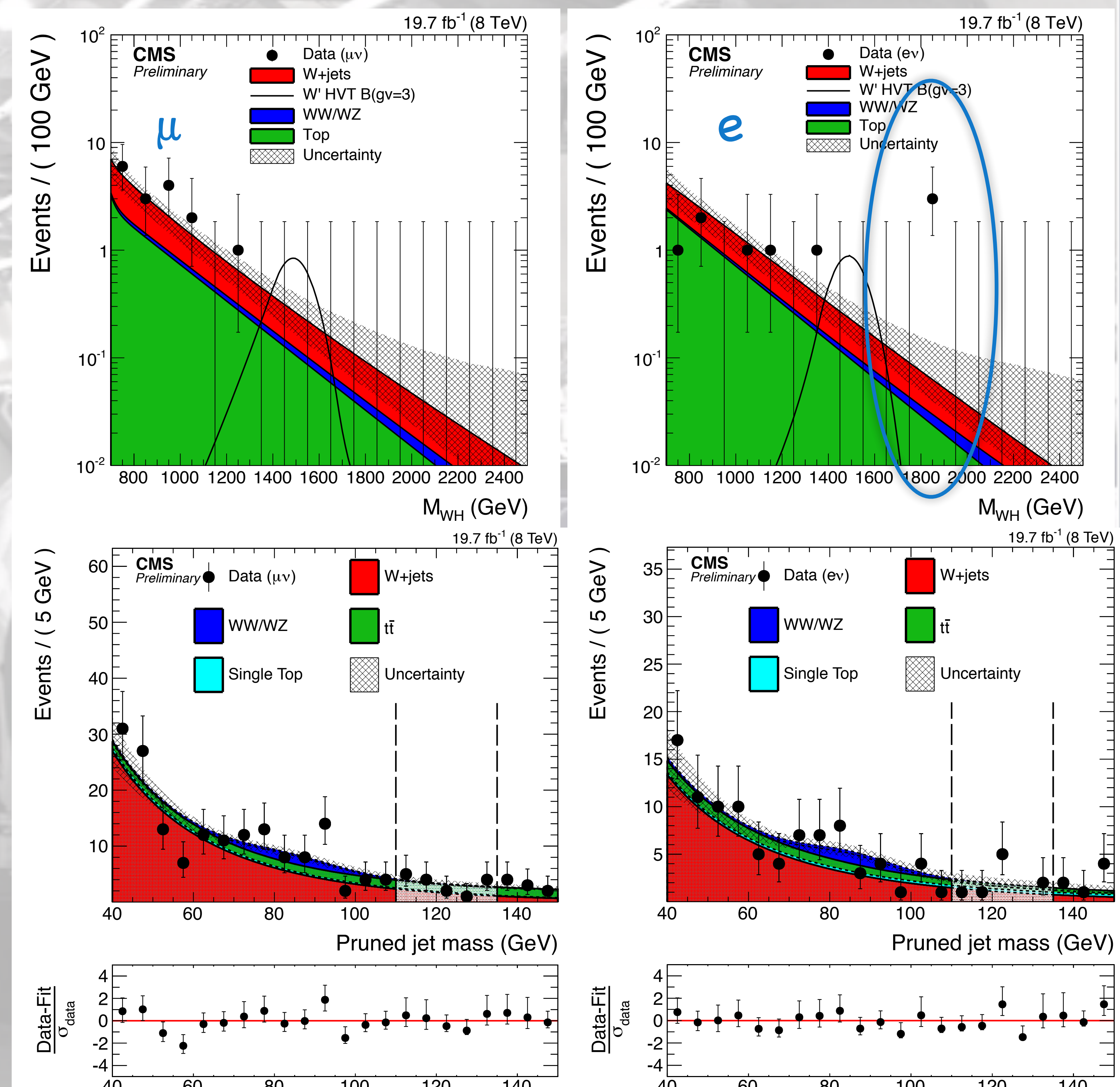




CMS-BTV-13-001

X→H(bb)W(lν) CMS search

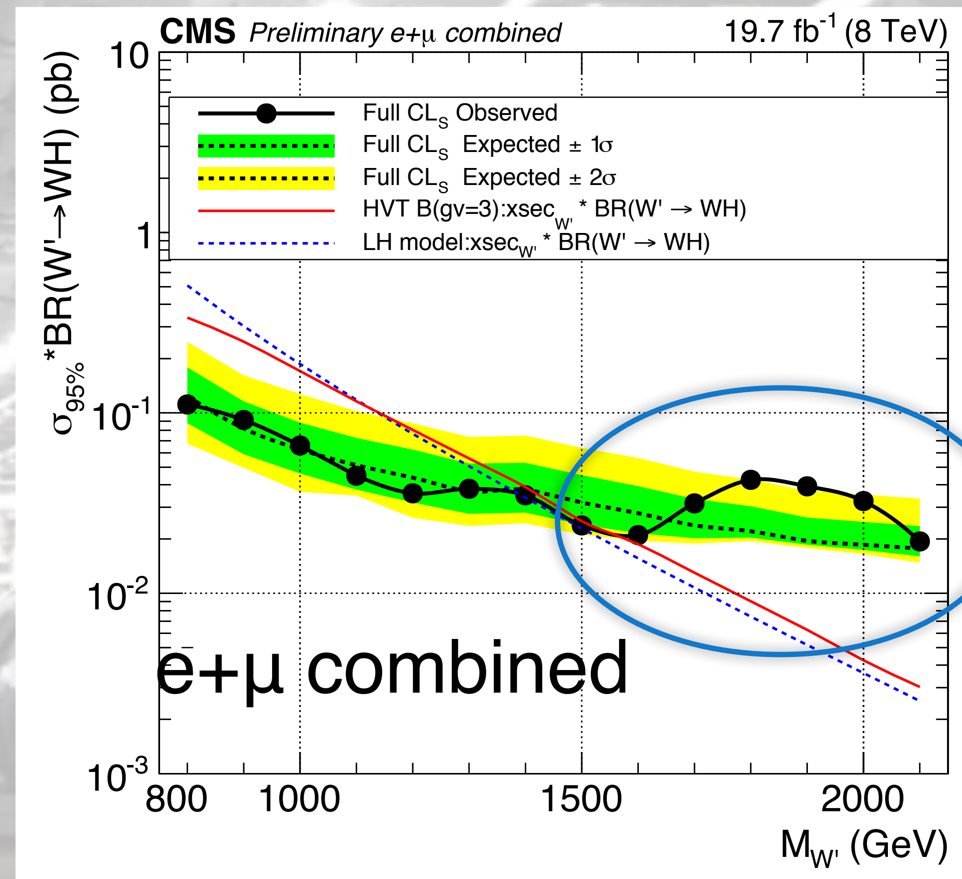
- Same analysis strategy as V(qq)W($\ell\nu$). Better S/B
  - Added b-tagging for Higgs: large suppression factor to bkg
  - Tuned the jet mass window around 125 GeV: more bkg suppression
- Observed 4 events at $M_{WH} \approx$ 1800 GeV in electron channel (2.9σ local significance). Nothing in the muon channel
- Combination gives 2σ significance for local significance

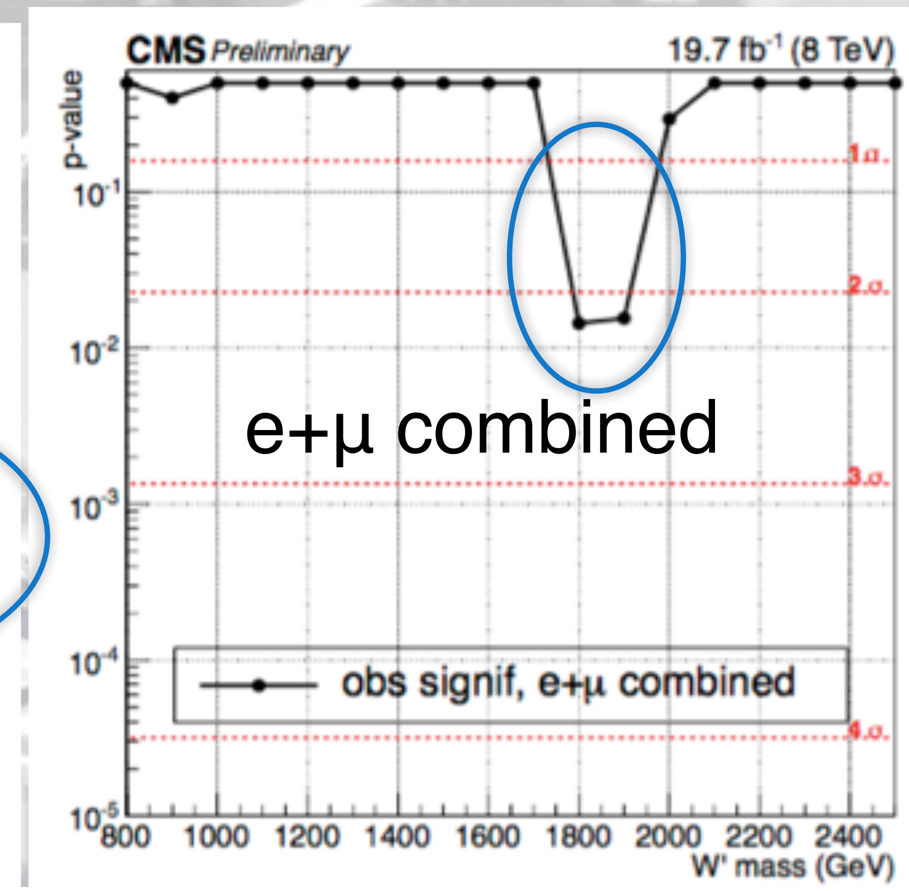


CMS-EXO-14-010

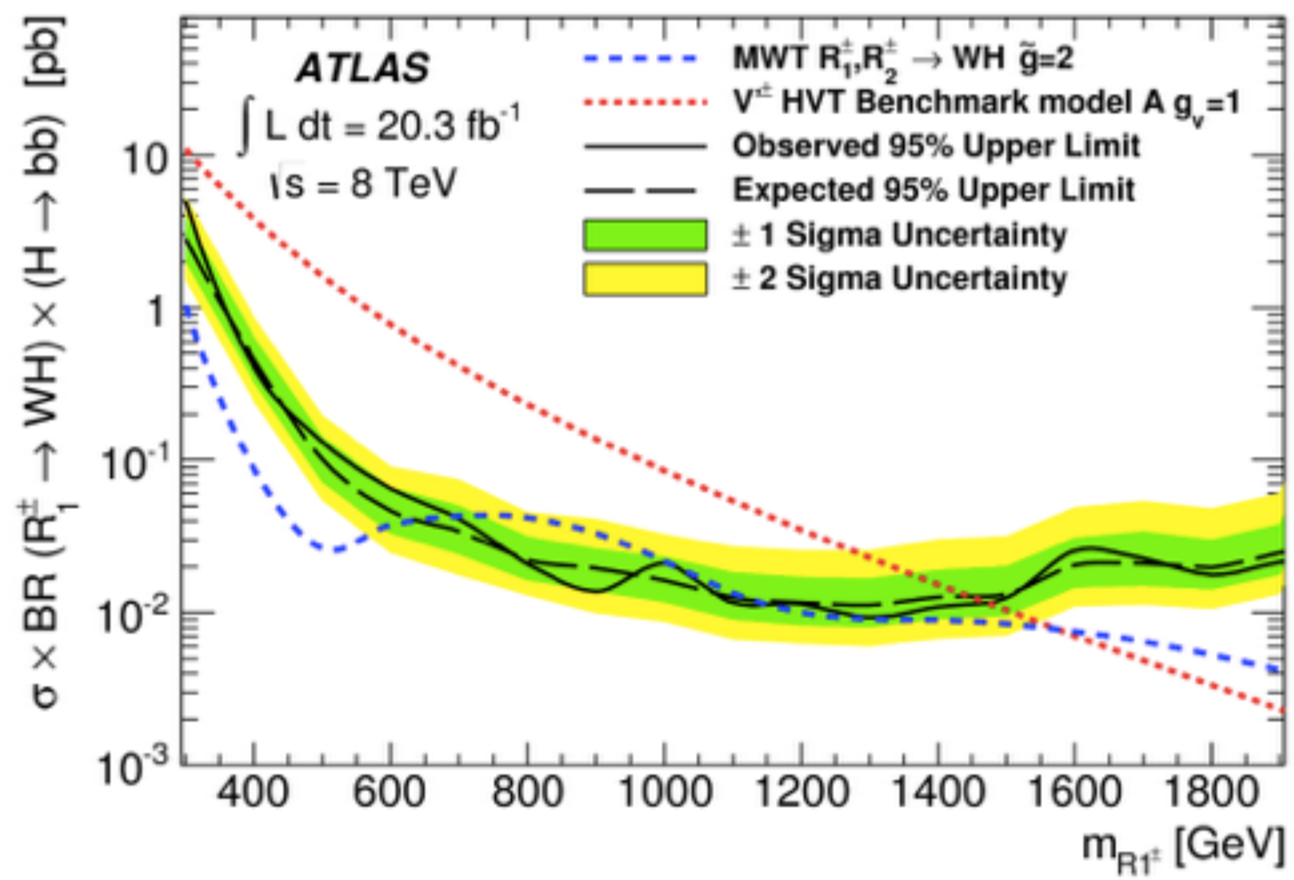
ATLAS vs CMS comparison

- ATLAS plots stop right at the interesting region
    - Highest observed HW mass is 1350 GeV





- Once divided by BR(Hbb), ATLAS limits is around observed CMS limit, i.e. ATLAS result cannot exclude the excess

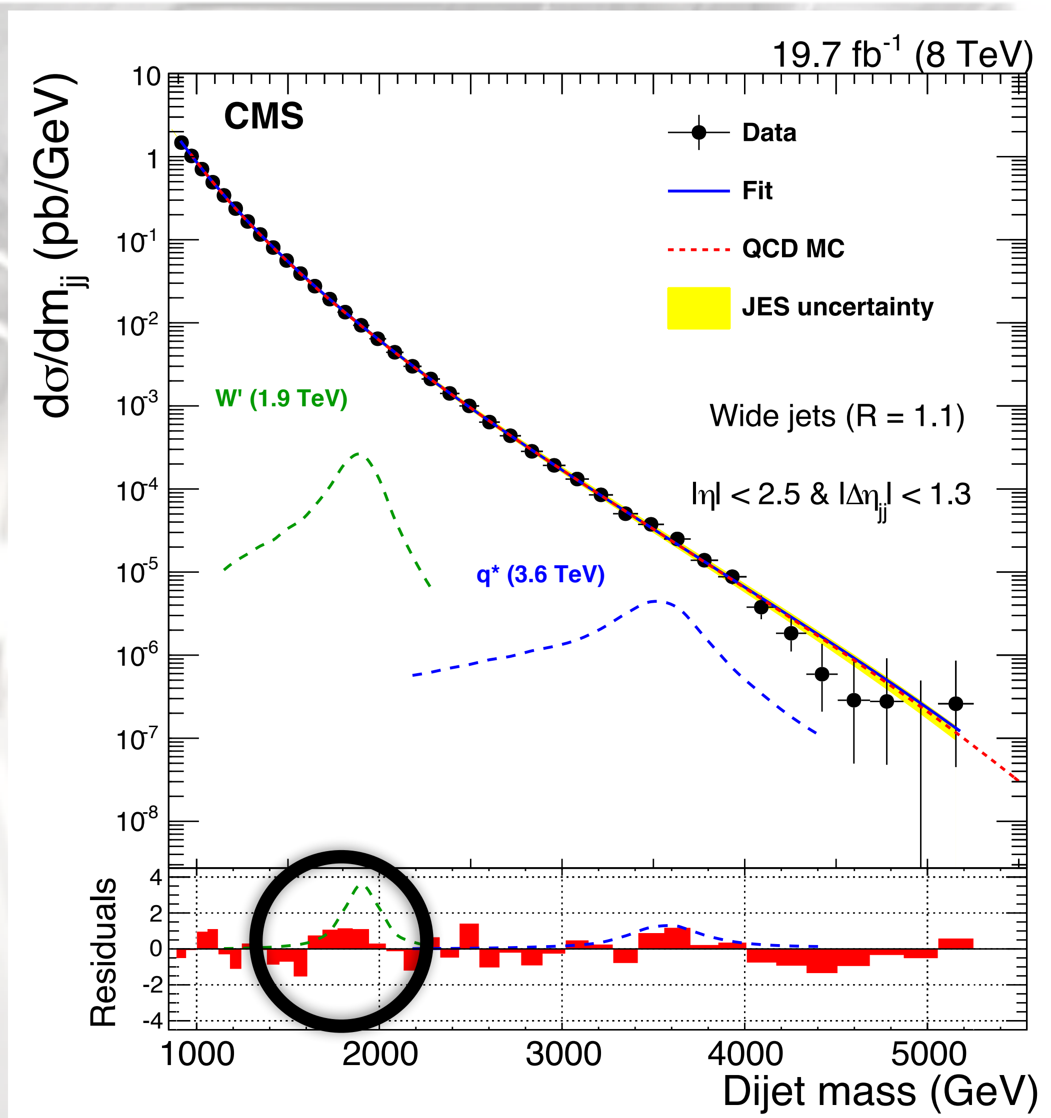


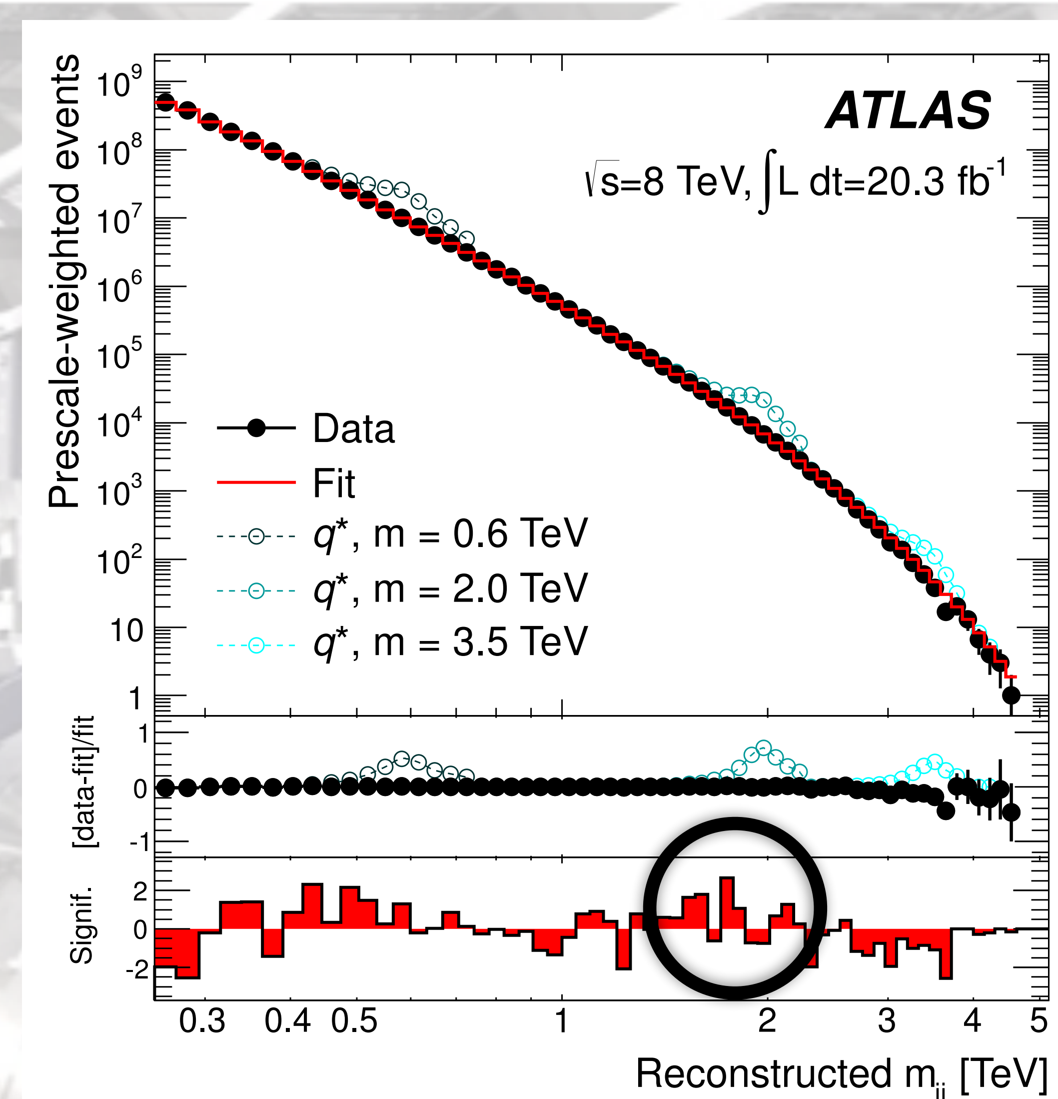
- Two results are NOT in contradiction

- Other searches (e.g. in HZ and HH) don't see an excess

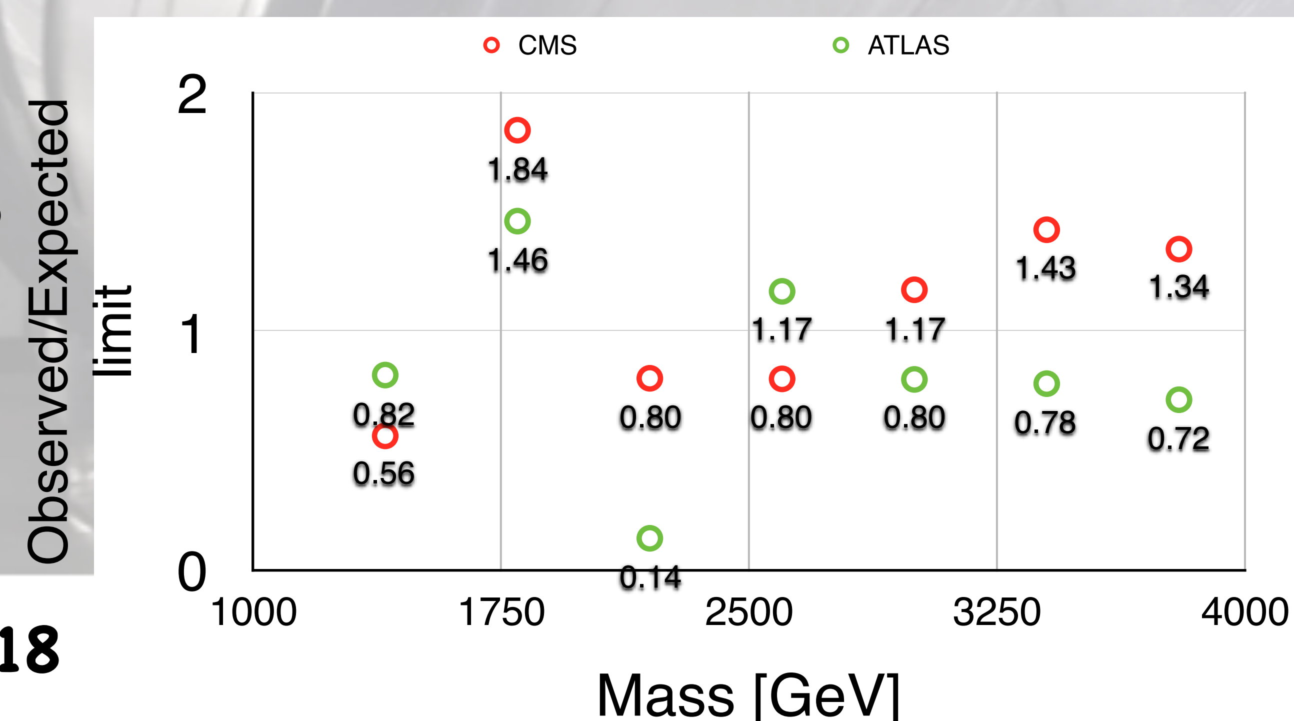
Seen in Other Searches?

Dijet





- ≈2σ (local) in CMS
- much smaller "excess" in ATLAS
- Only place where both experiments have observed limit > expectation



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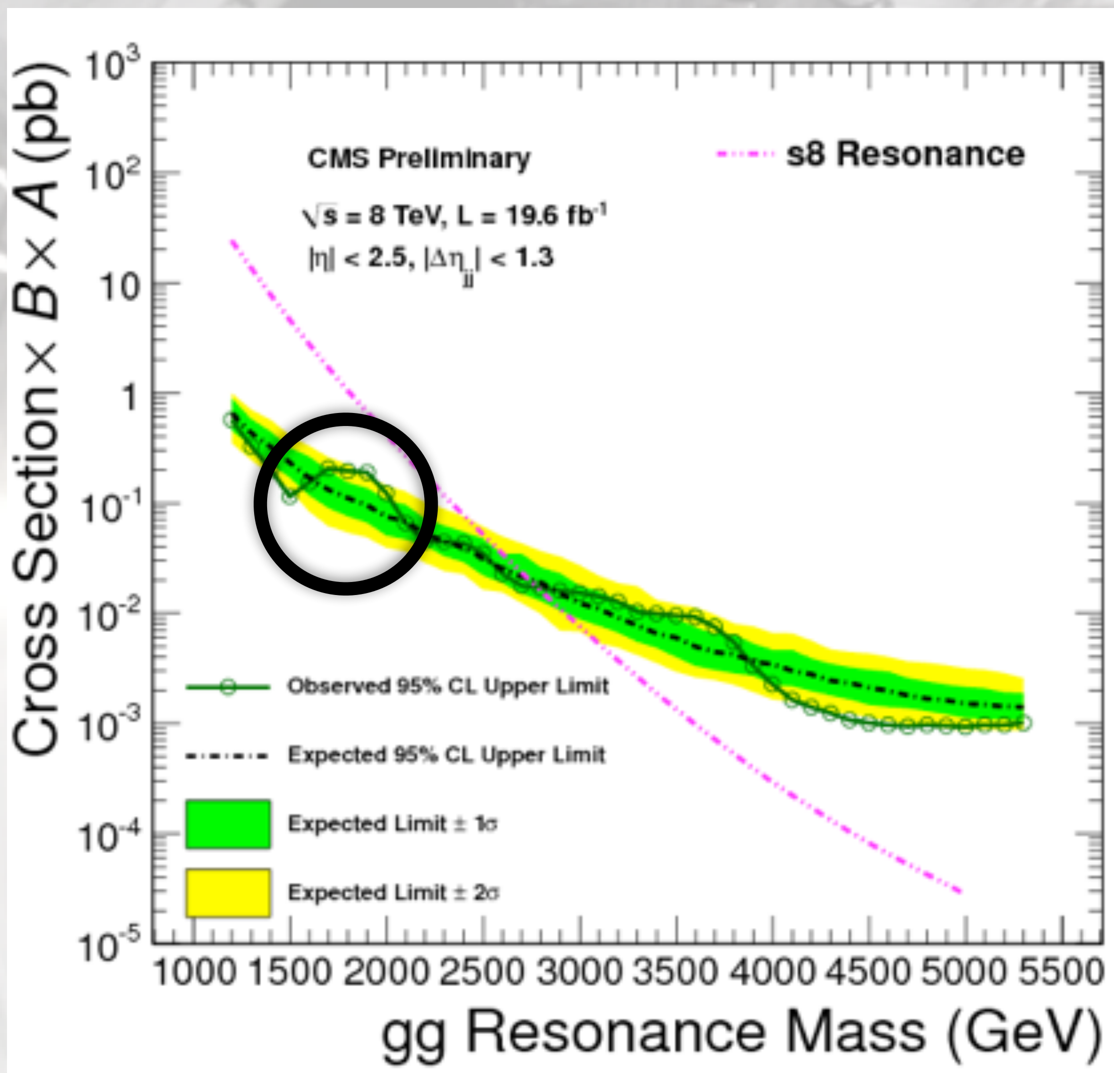

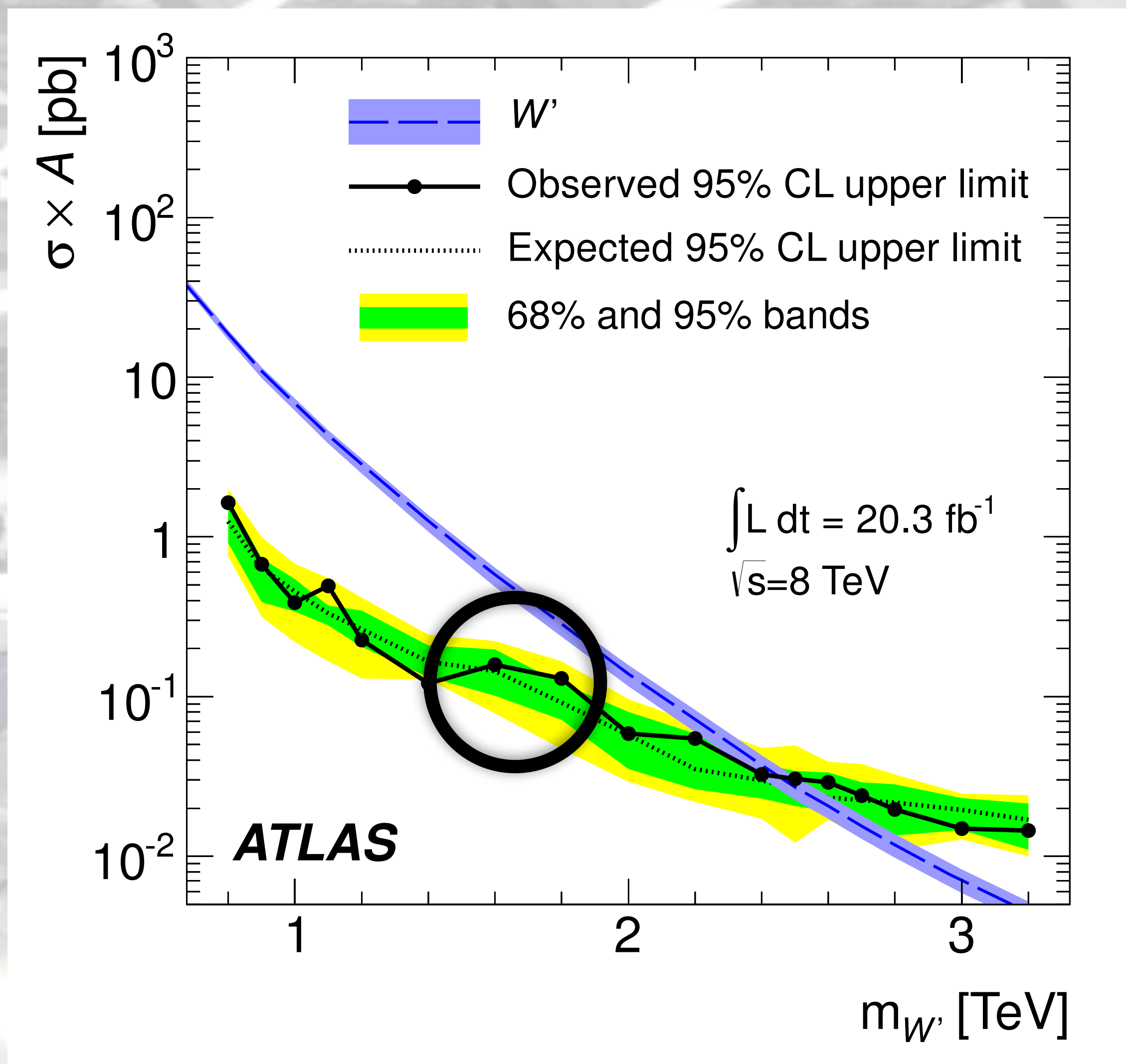

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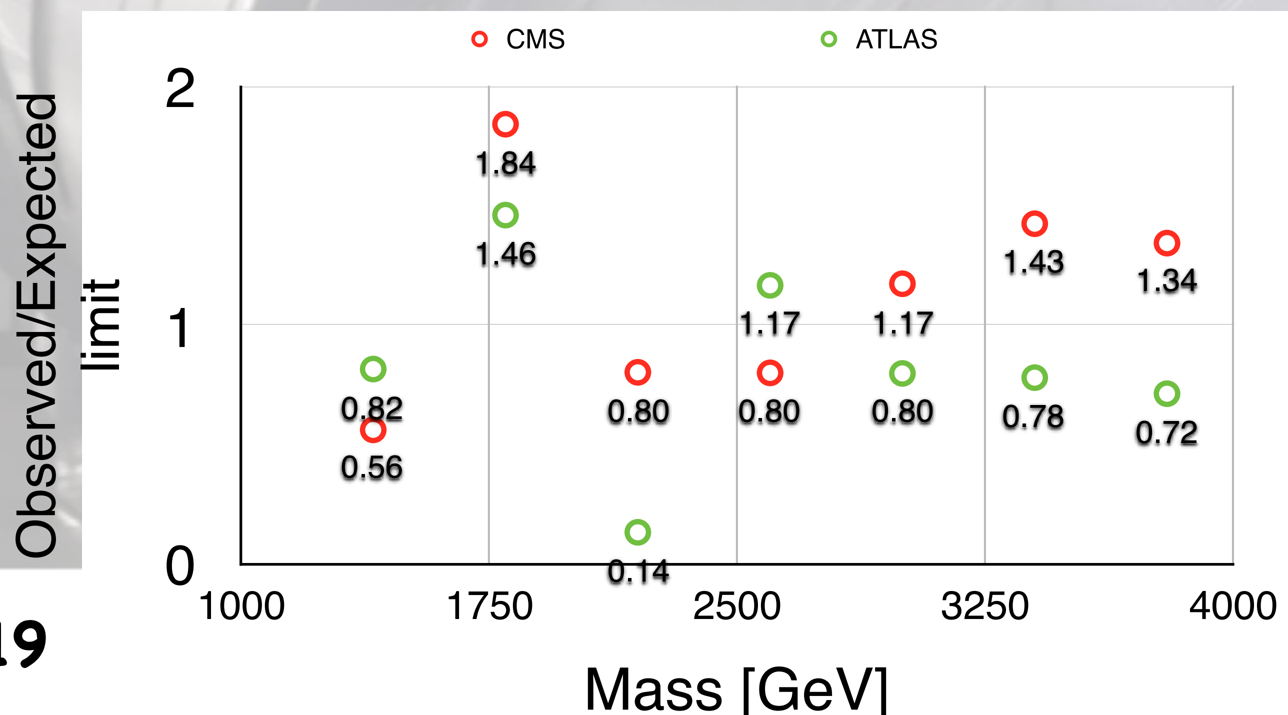
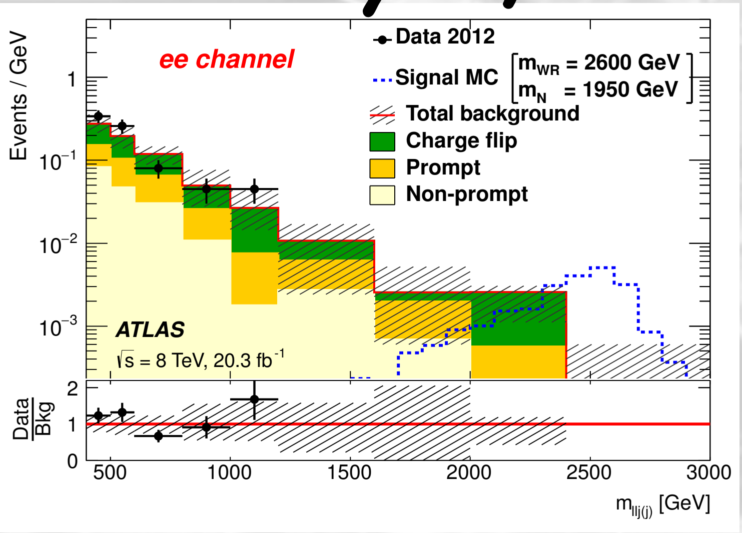


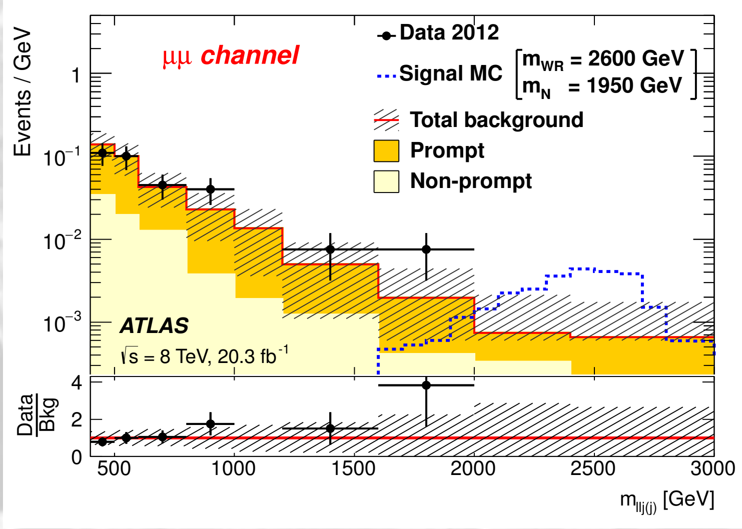
More exotic signatures

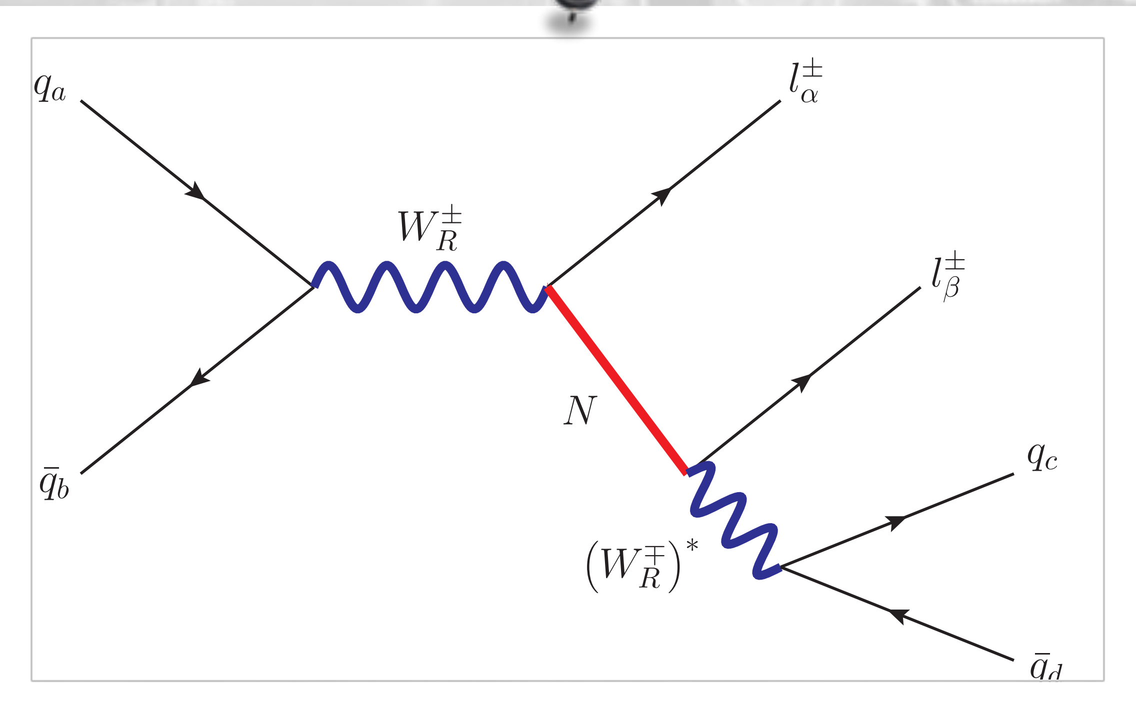
- Excess seen by CMS
    - one flavor only (OK for this model)
    - one bin only
    - No excess in ATLAS
- To be checked, but not very promising

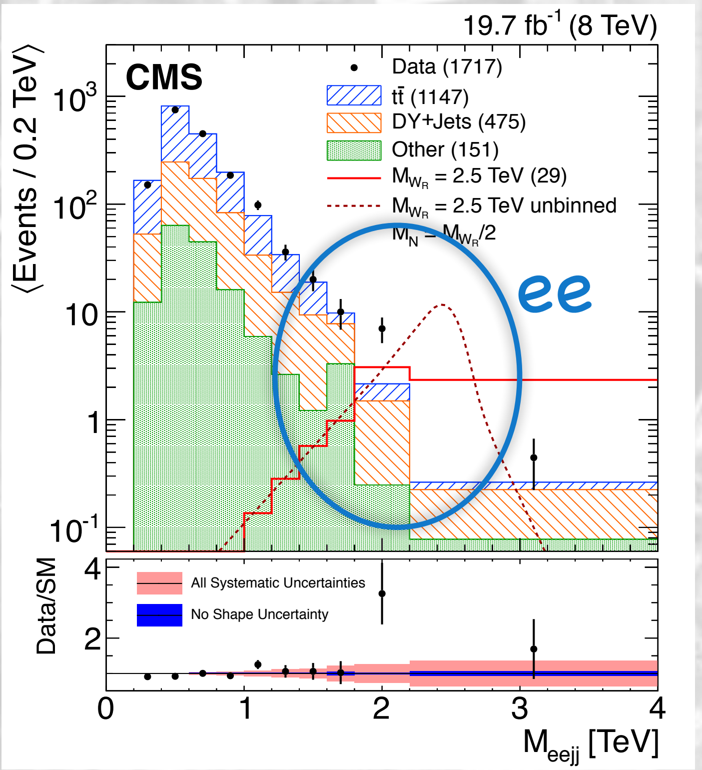
ATLAS arXiv:1506.06020

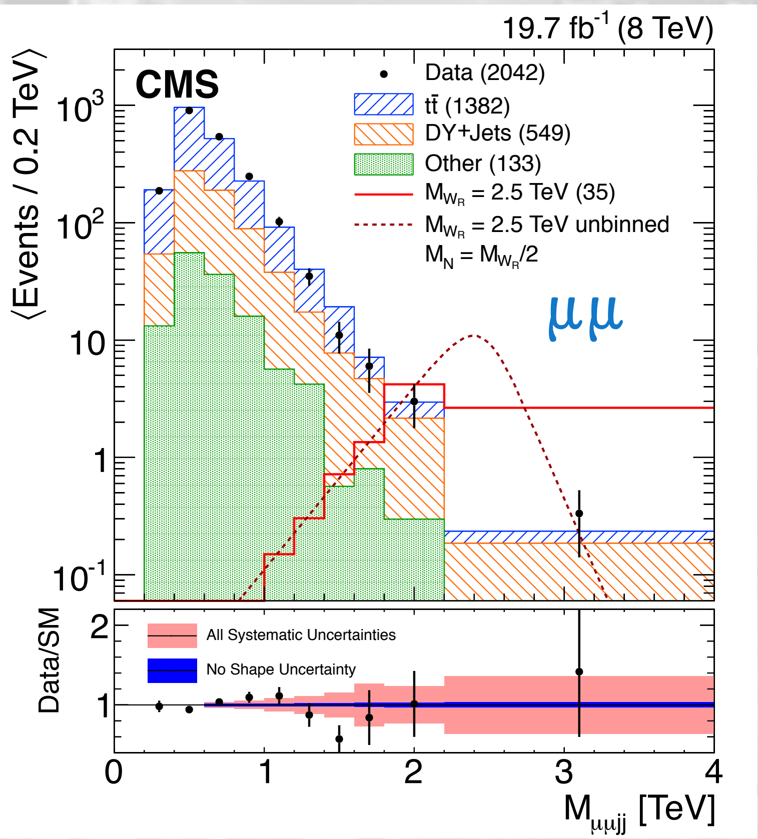
SS analysis, sees no excess seen











CMS arXiv:1407.3683

No charge requirement here

local significance of 2.8σ

Lesson from Run I

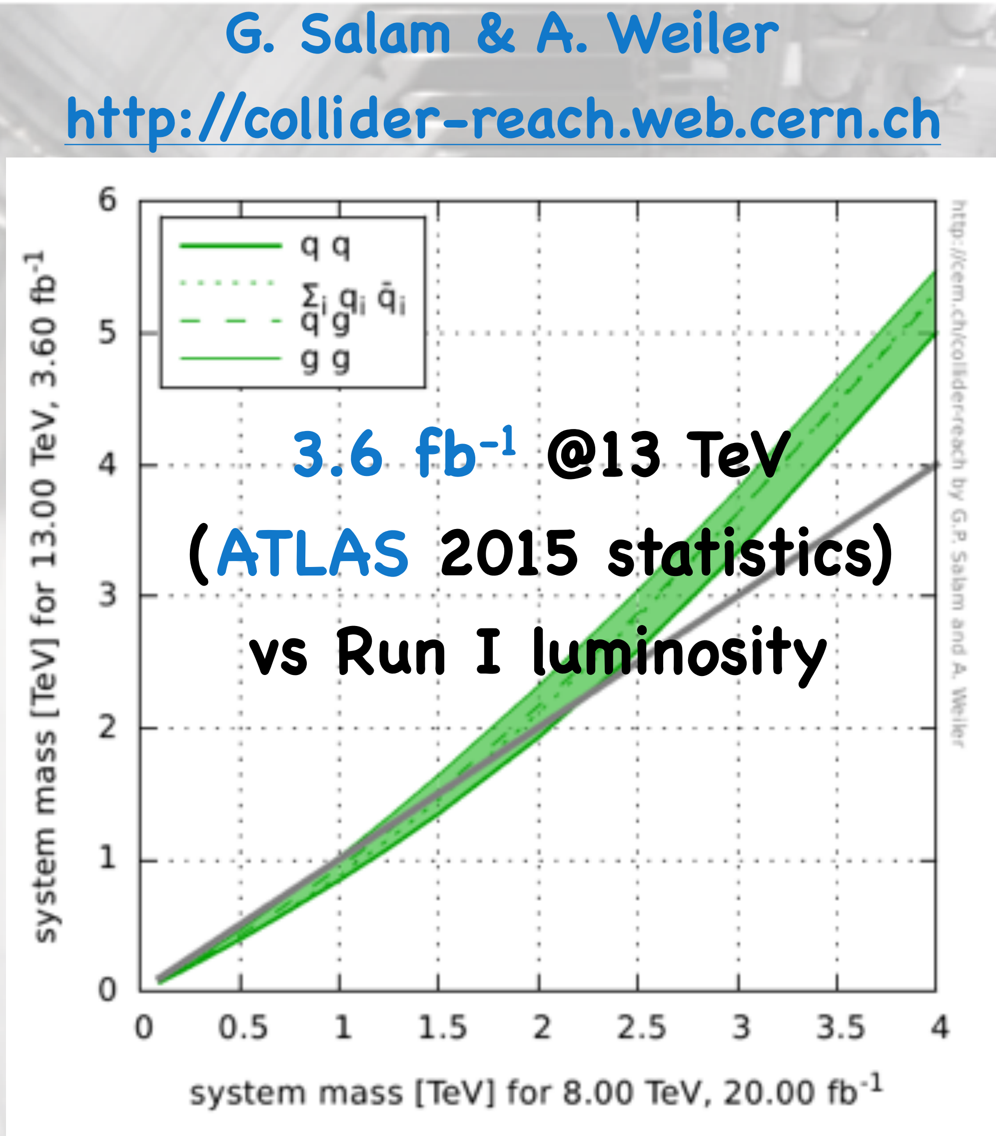
- Interesting situation overall
- Level of attention raised. The full story made it to the press
- Interesting “exercise” in view off what happened after (e.g. 750 GeV bump)
  - The theory community shows immediate interest on the large excess. The series of small excesses becomes “THE ATLAS EXCESS”
  - Everyone forget that the other channels are pushing the big excess down
    - … despite individual averages by ATLAS and CMS
    - eventually proven by the unofficial combination
- Lesson to be learned
  - Let’s stay calm
  - Let’s look around
  - Don’t sit on the best case scenario ignoring the rest
- Lesson learned? Not really …

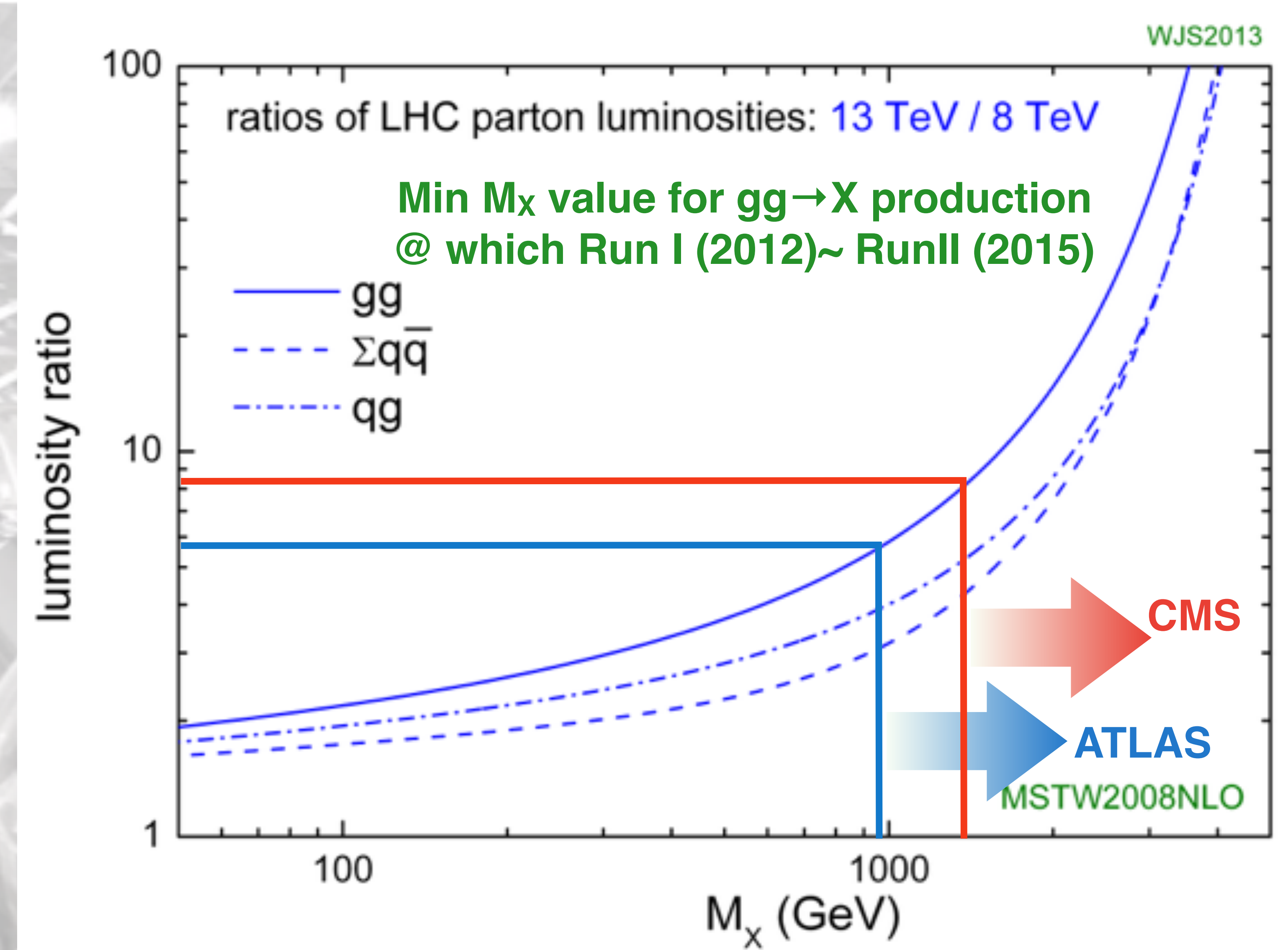
Open questions

- Is the overall VV/VH picture consistent?
  - Excess is driven by a few channels (JJ for VV, $\ell\nu J$ for VH) but not seen in others (e.g., $\ell\nu J$, the most sensitive VV search)
  - ("unofficial") combination brings the signal strength in VV down by a factor ≈2
- How solid is the background estimate? Is the jet-mass cut biasing the diboson mass shape?
  - All all-jet analyses (VV and JJ) use essentially a common empirical function
  - Other searches use instead MC-assisted bkg predictions
  - different selection variables in different experiments: would be interesting to see an ATLAS-like search in CMS and vice versa
- Is jet substructure helping or biasing the search?
  - Not essential @ 2 TeV (e.g., not used in some semileptonic searches)

Run II results (as presented in December)

From Run I to Run II



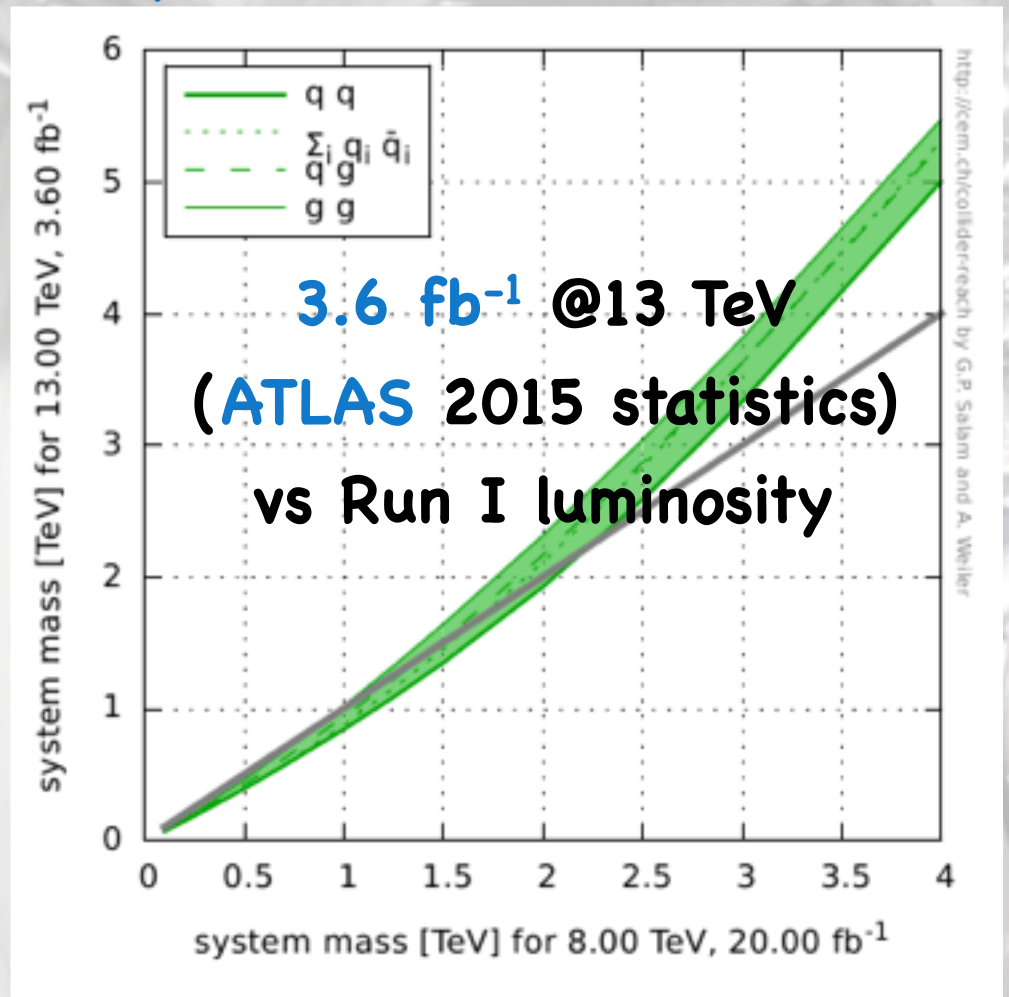


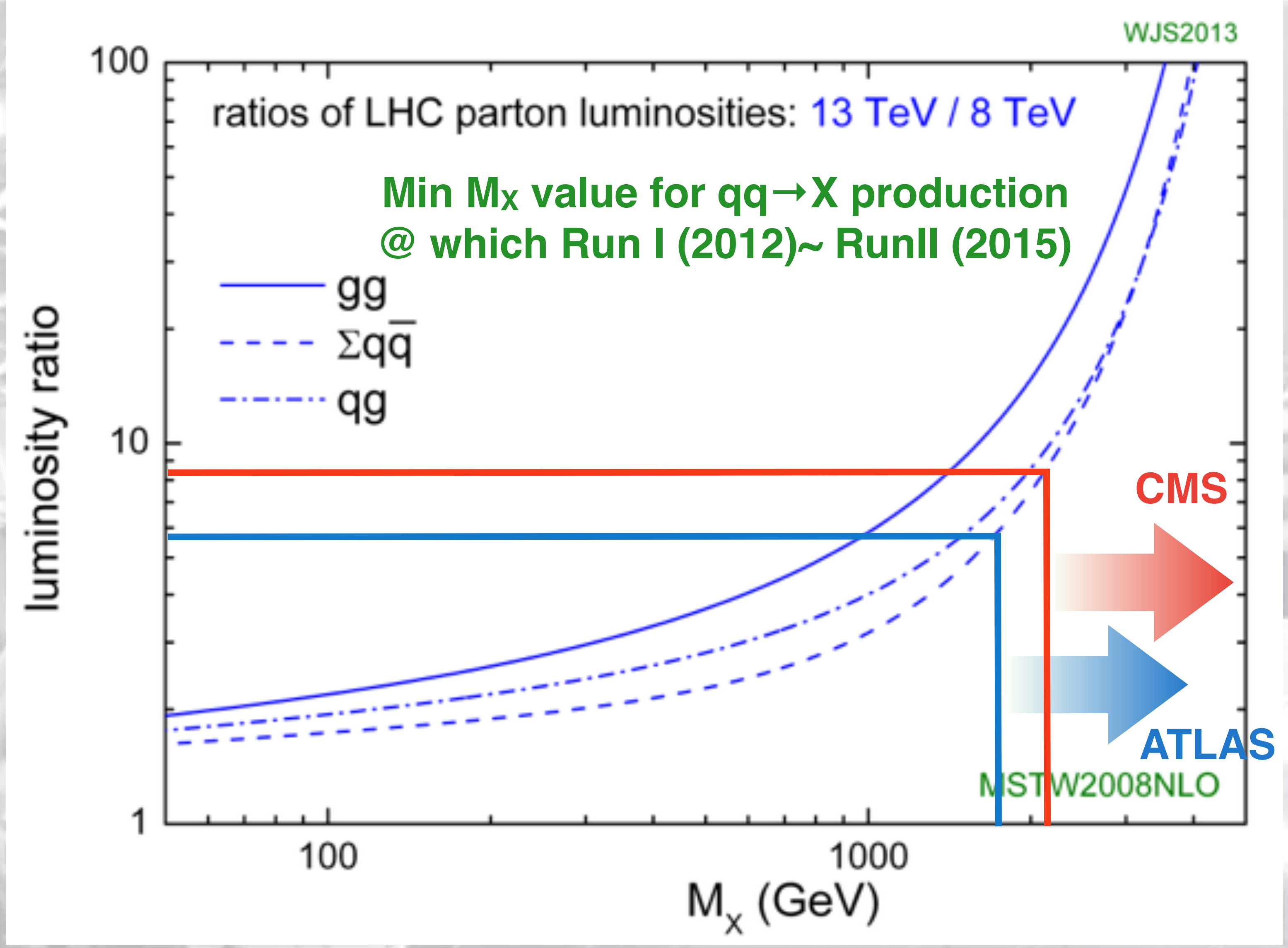
- Increase in energy compensates the lower luminosity
- Effectively, the new dataset should be comparable to what we saw in RunI
- While we are dealing with small numbers (small excesses), the result of RunII are already significative for a better understanding of the situation

From Run I to Run II

G. Salam & A. Weiler

http://collider-reach.web.cern.ch





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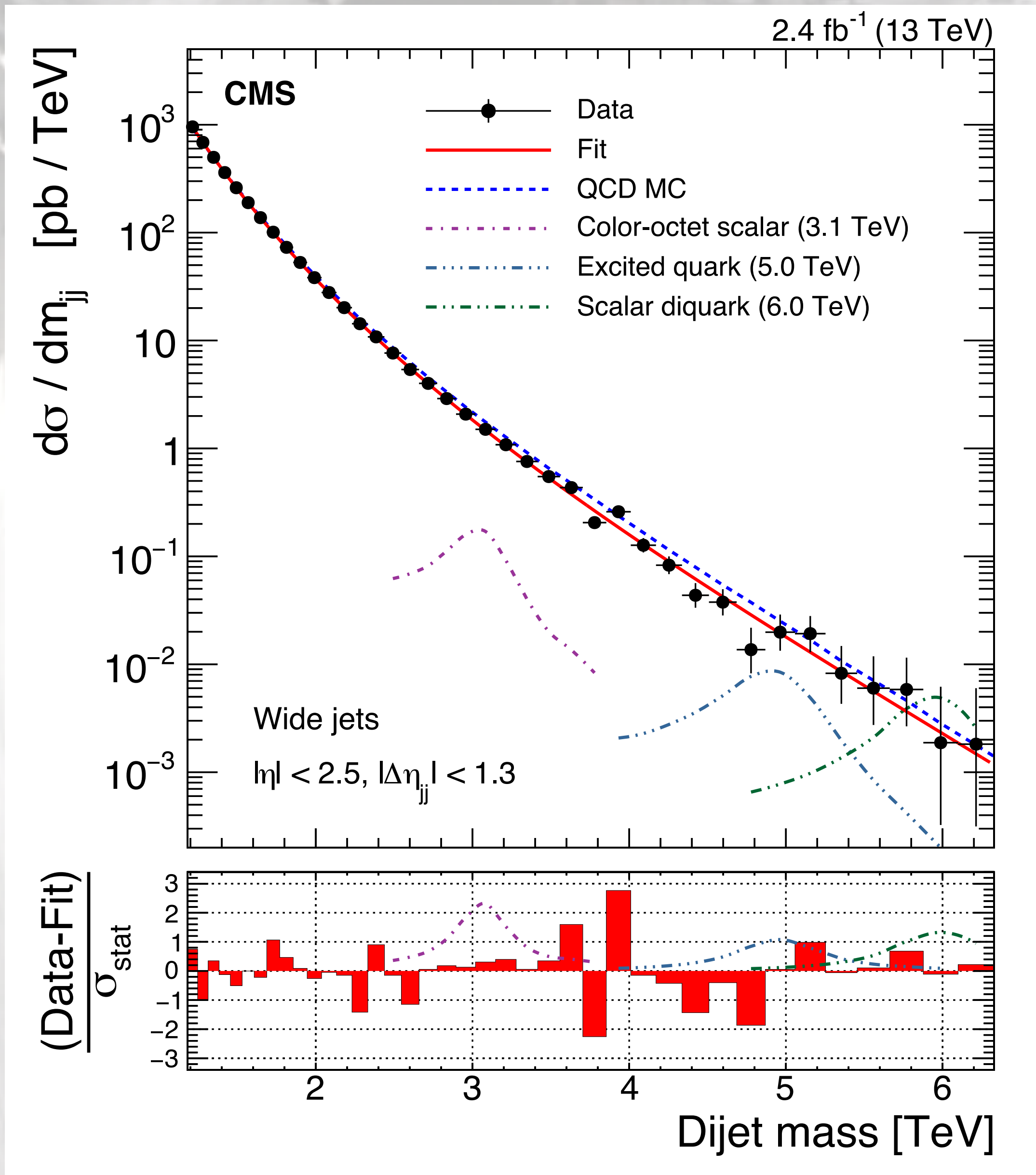
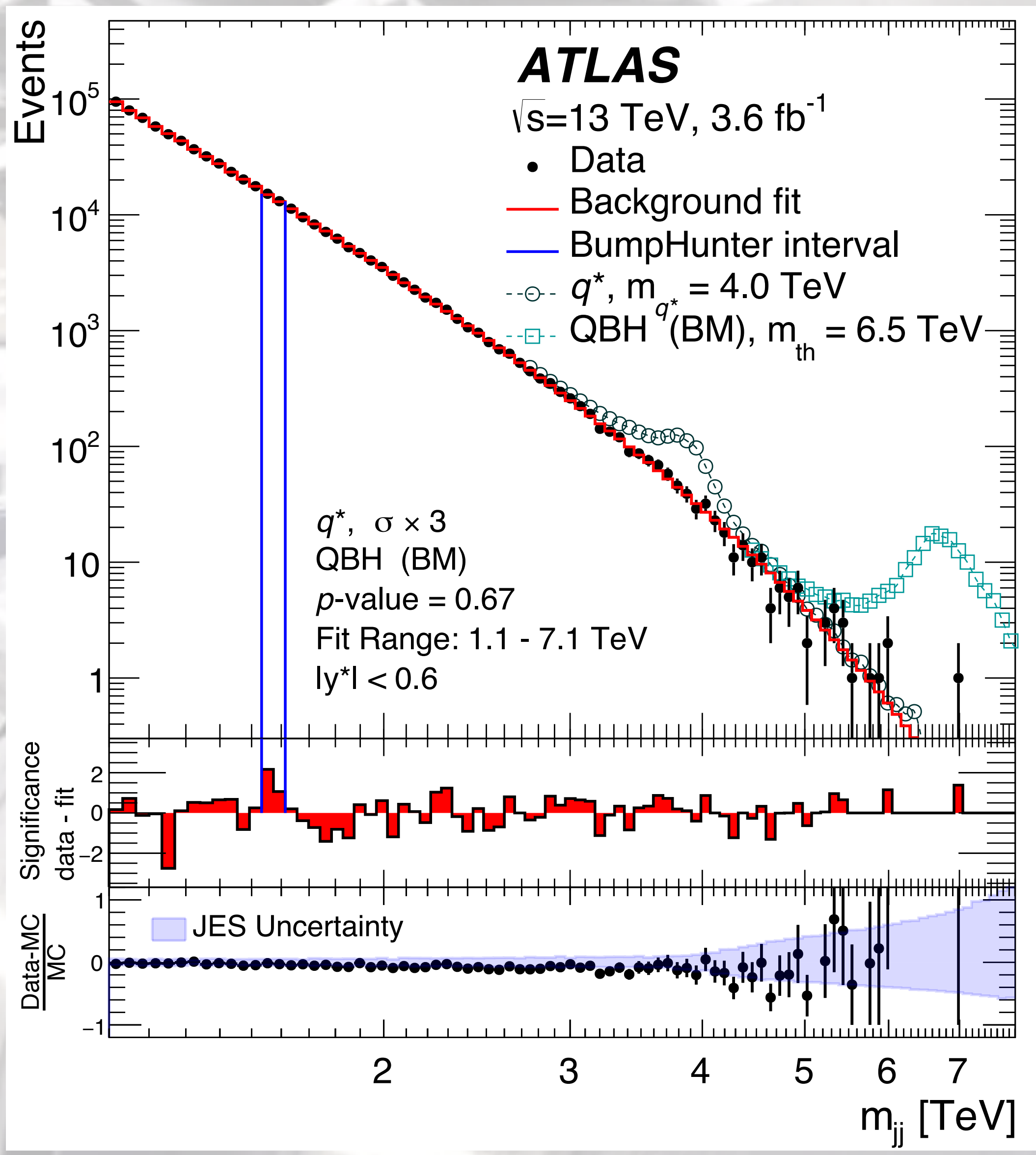
Dijet Resonance Search

http://arxiv.org/abs/1512.01224



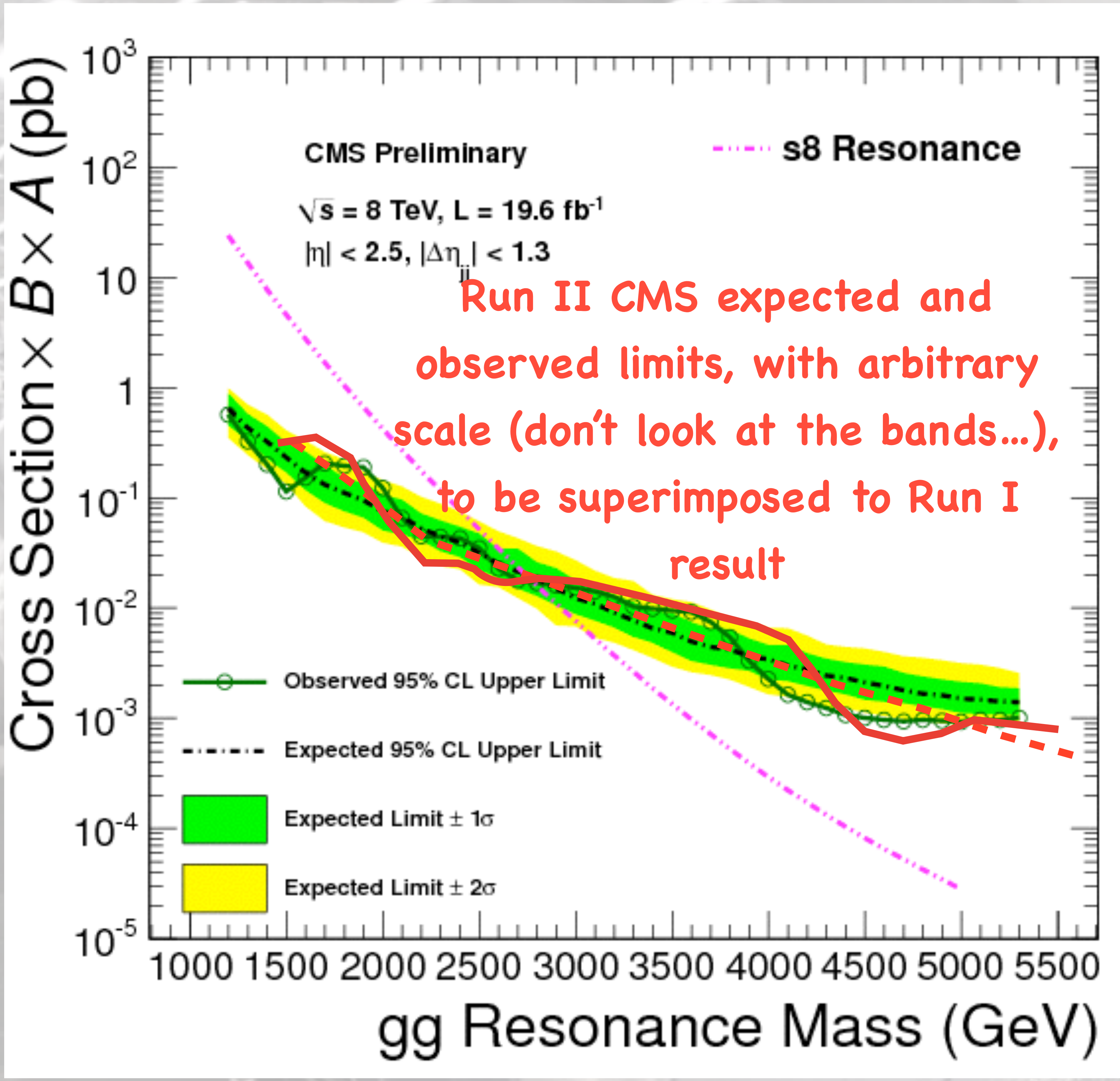
http://arxiv.org/abs/1512.01530



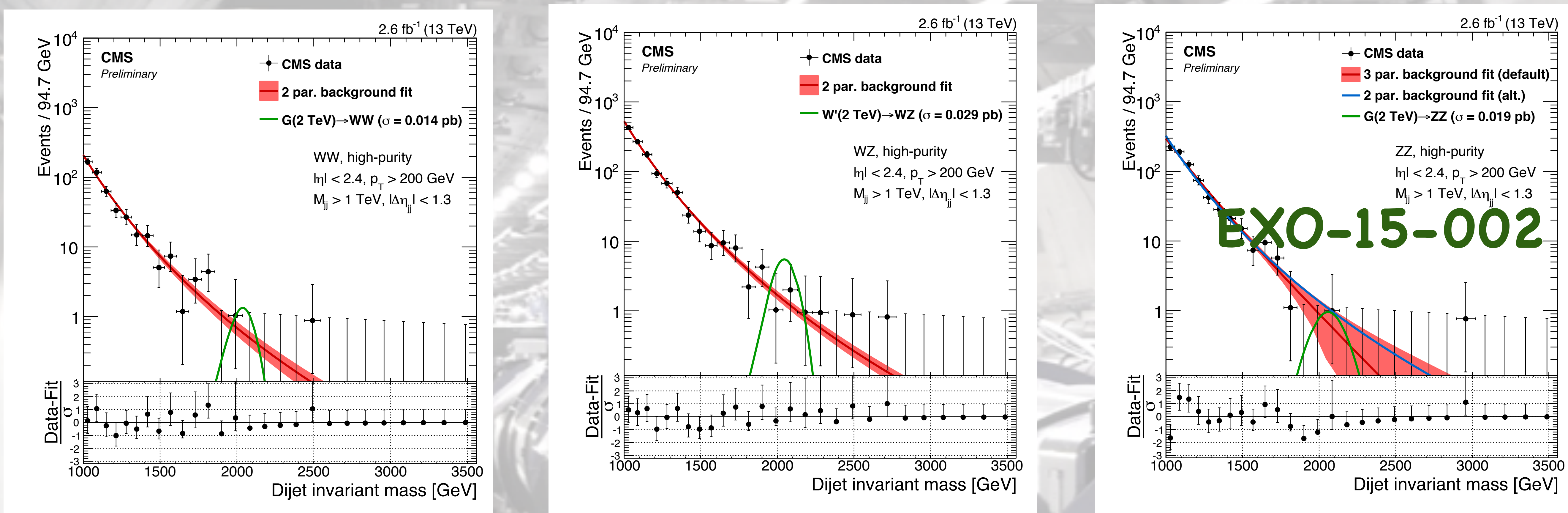
- DiJet Run II results confirm the Run I picture
  - moderate excess around 1.8 TeV. Nothing spectacular enough to claim anything
- Maybe Run II confirms too much of Run I. Are we seeing an issue with the analyses

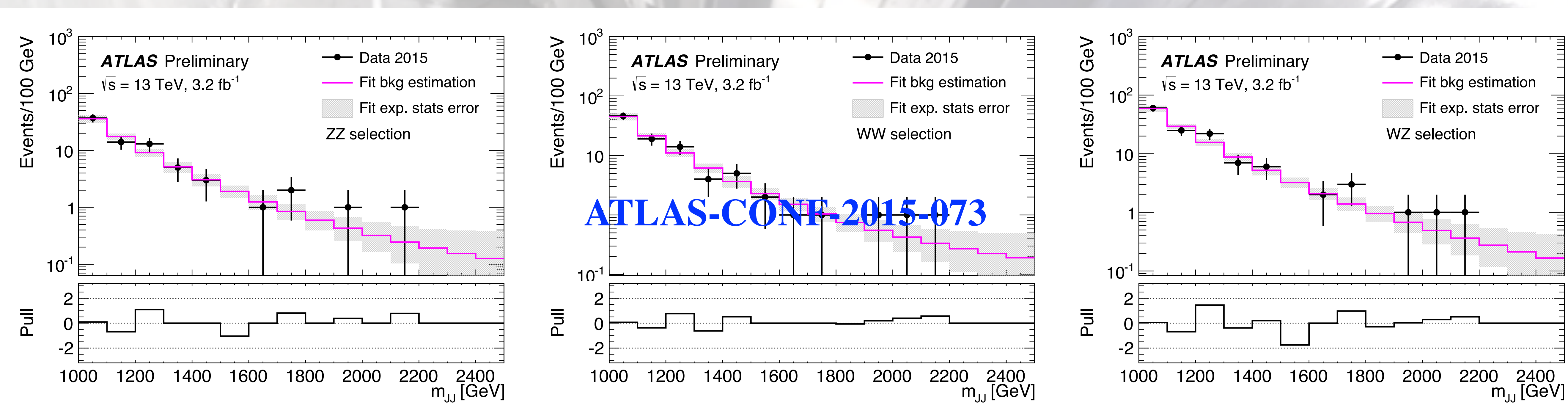
CMS Run I vs Run II

- Up & Down fluctuations qualitatively "in sync" between Run I and Run II
- Are we seeing a discrepancy between fit lineshape and data?
  - Not according to the QCD MC ...
- Should we look for alternative background predictions?



Diboson @13 TeV





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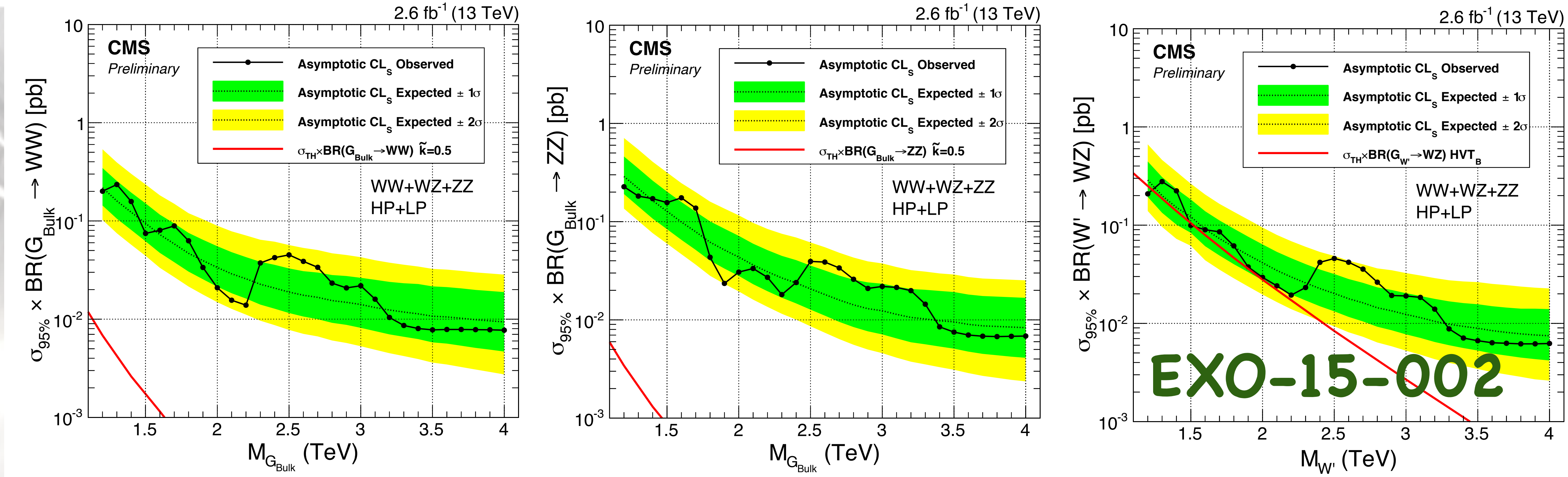
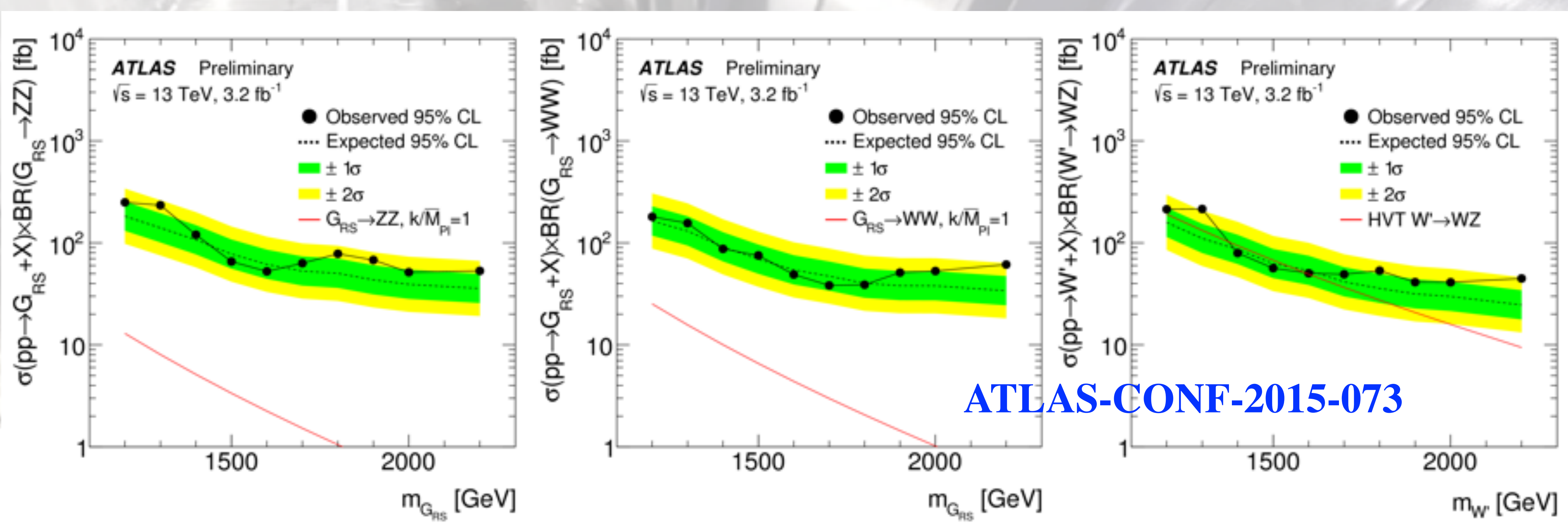
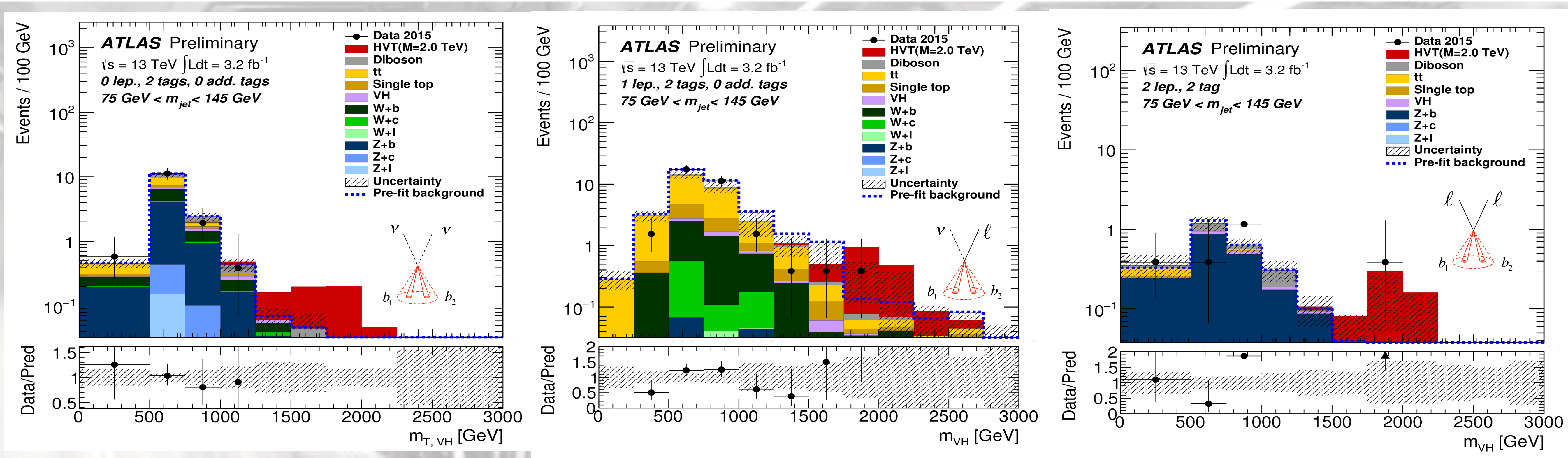


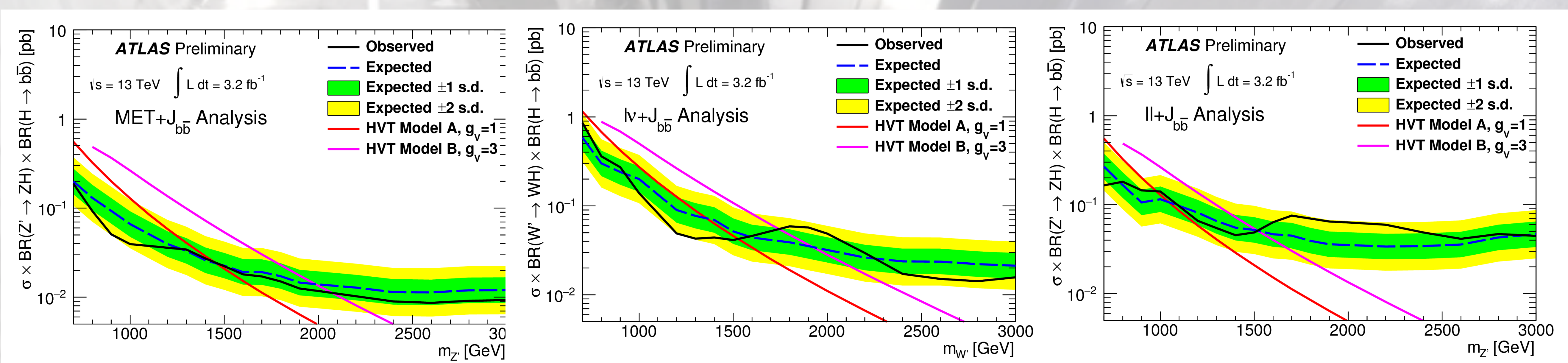
- Not much of an excess
- Still, not enough lumi to exclude the Run I excess or to confirm it
    - (particularly the 1/2 reduced cross section after combination)



VH Search by ATLAS @ 13 TeV



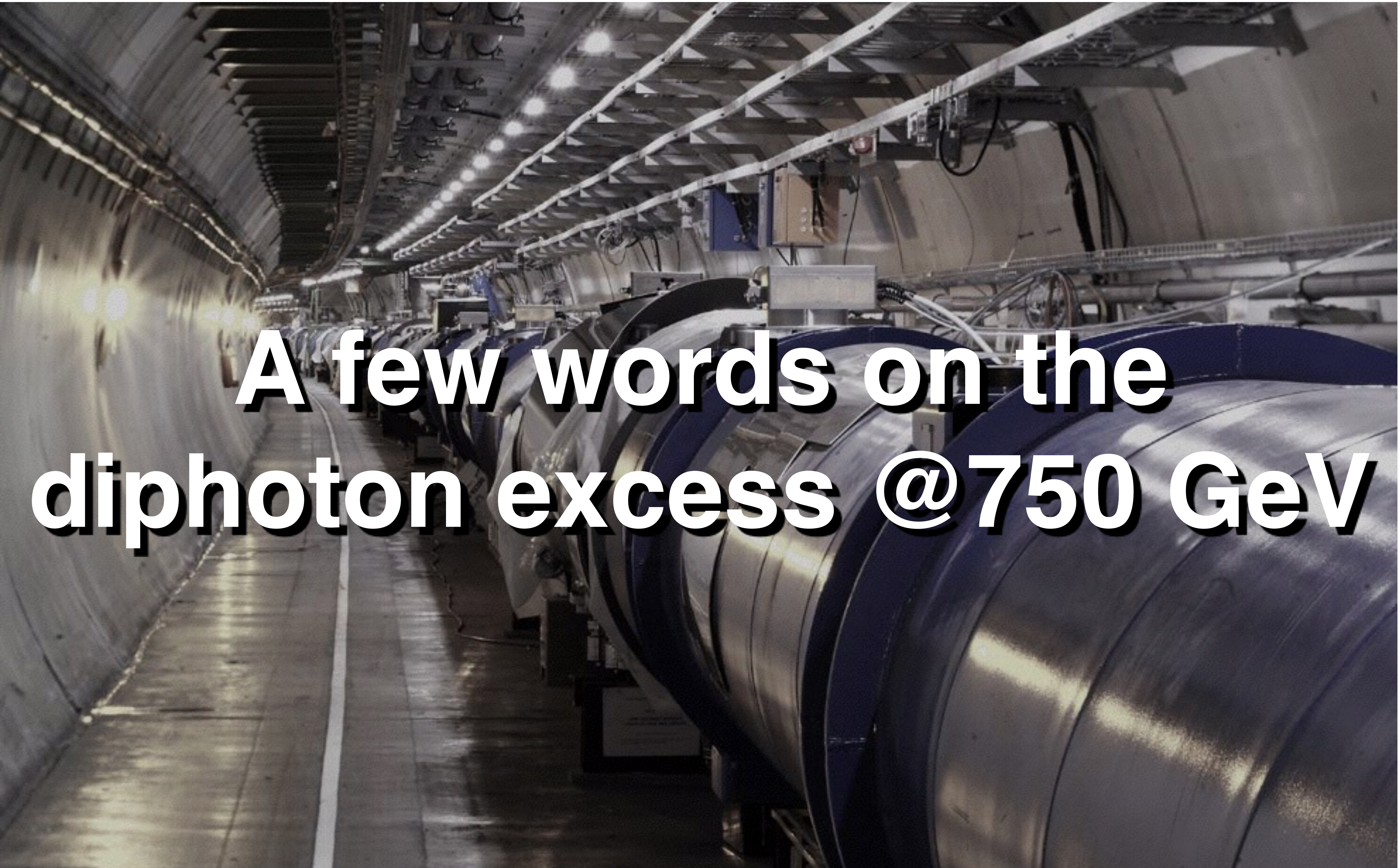
- No confirmation of the excess seen by CMS
- Some low-significance upper fluctuation in the "right" spot
- Still, not enough lumi to exclude the Run I excess or to confirm it



ATLAS-CONF-2015-074

A VV/VH short summary

- The physics lesson
  - The 2 TeV Run I excess is not dead, but certainly it doesn't live its best moment
  - Run II data are giving us useful information
    - gg/qq-> X -> WW/WZ hypothesis strongly challenged
    - qq->X-> WZ scenario still alive
    - search in $\nu\nu J$ final state puts string bounds
  - Still, lumi is too small to conclude anything
  - 2016 Data will be fundamental
- And the sociology one
  - We should take a deep breath and stop jumping up and down at the minimal opportunity (to me the "ATLAS excess" thing was a very poor choice of words)
  - This is a marathon. We just don't know if we are at Km 1 or Km 38



A few words on the diphoton excess @750 GeV

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A Private CMS+ATLAS Combination

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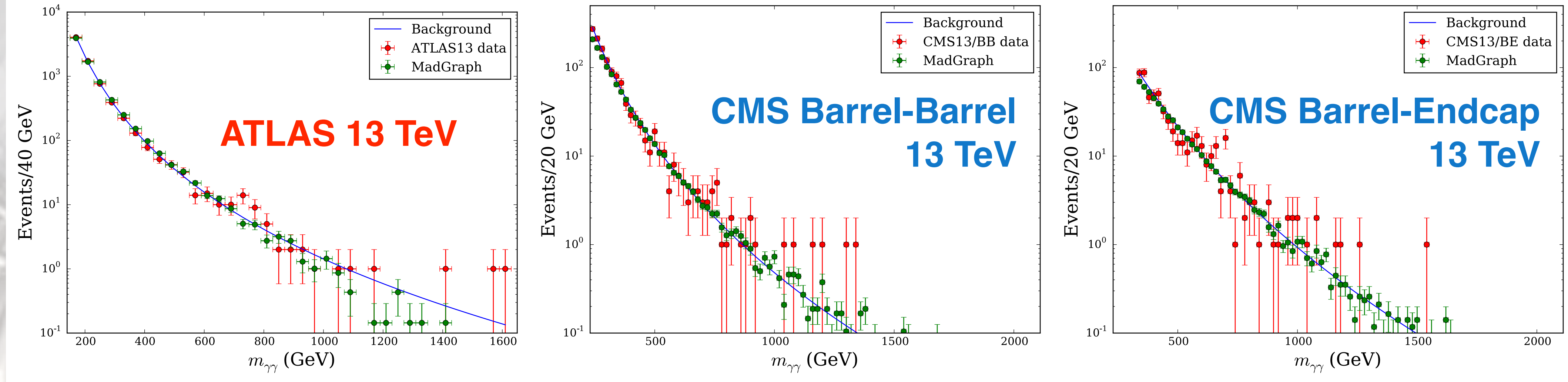

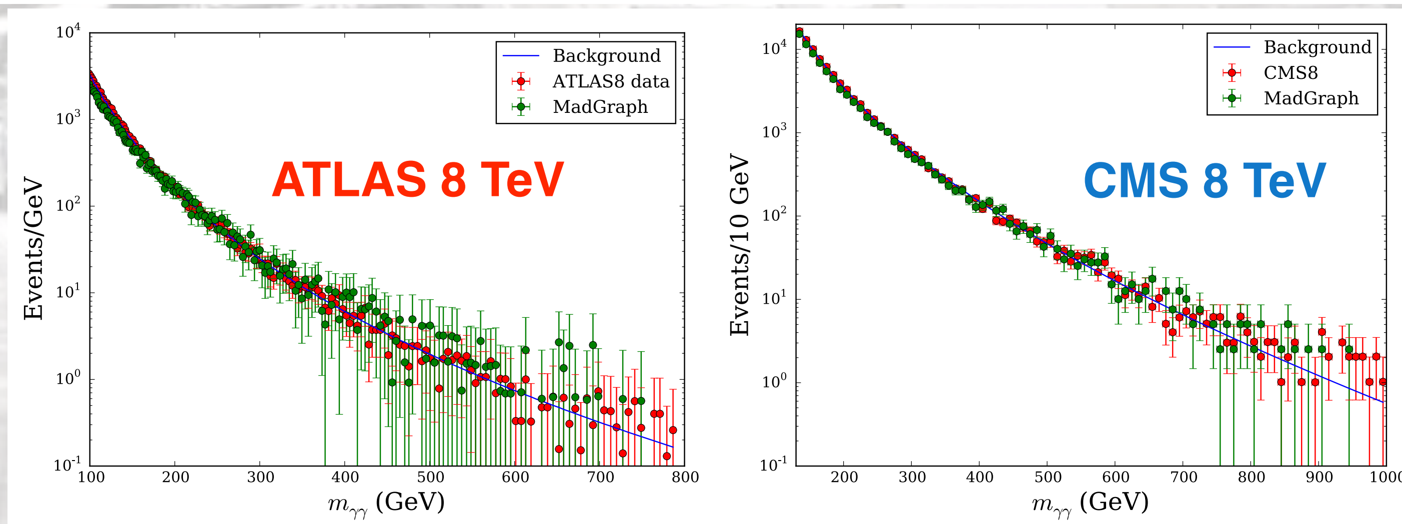

- Repeat fits from digitised plots @13 TeV and @8TeV [Jamboree analyses]
- Compute significance vs experiment, energy, production mechanism, and width
  - in general, quoted significance smaller than what experiments quote
  - exercise is conservative and valid beyond just the qualitative level

M. Buckley, arXiv:1601.04751

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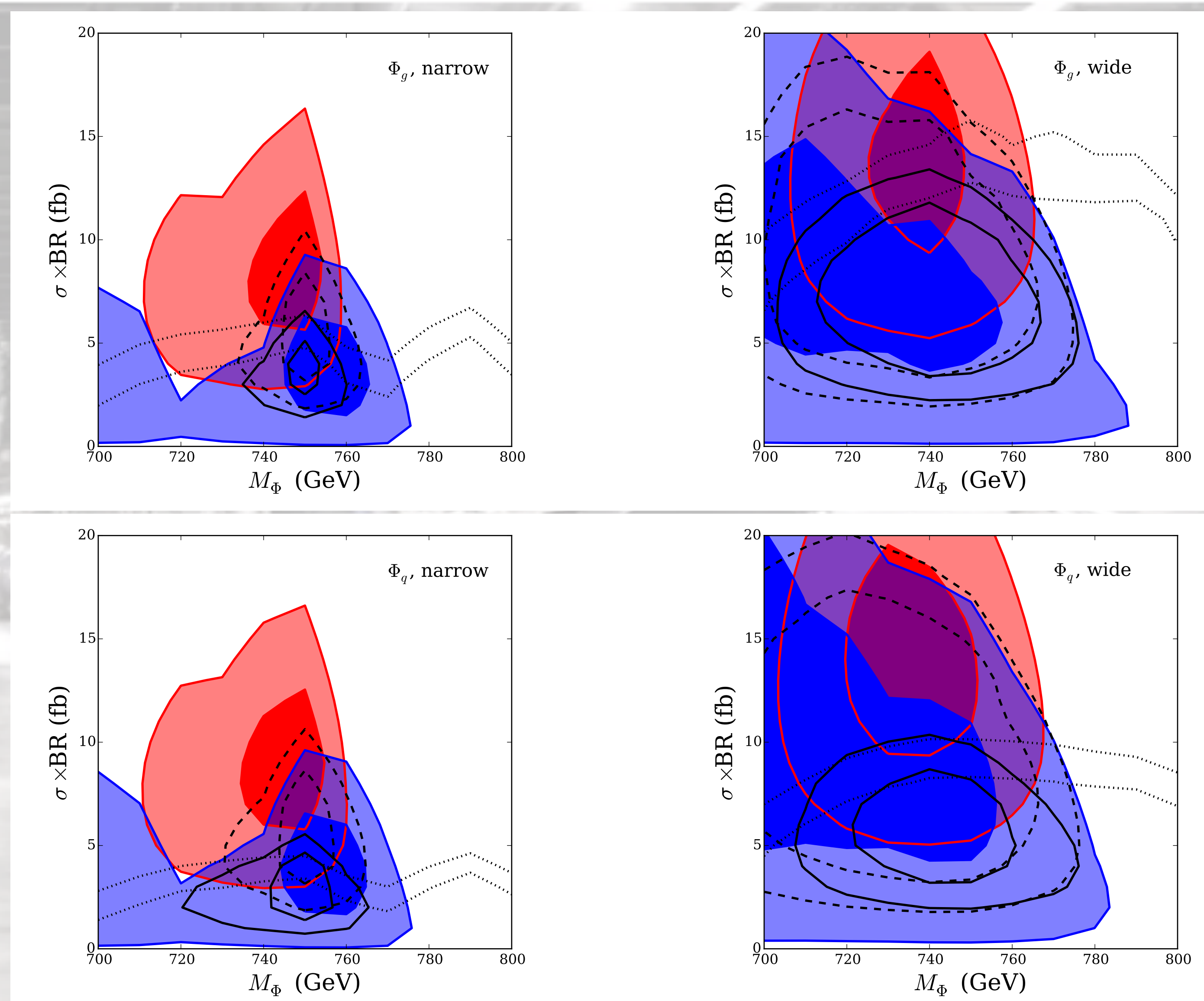

- Both for large and small width, the large ATLAS Run II excess is pushed down by CMS Run II + CMS/ATLAS Run I
- The average close to CMS central value, but with reduced uncertainty
- Overall, the significance increases (not as much the naive/wrong expectation

M. Buckley, arXiv:1601.04751

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Spin 0 Narrow	ATLAS narrow	CMS narrow	Combined narrow	ATLAS wide	CMS wide	Combined wide
8 TeV	-	1.2 σ	1.2 σ	-	1.7 σ	1.7 σ
13 TeV	3.2 σ	2.0 σ	3.4 σ	3.5 σ	2.0 σ	3.0 σ
Combined	n.a.	n.a.	3.4 σ	n.a.	n.a.	3.4 σ

- Both for large and small width, the large ATLAS Run II excess is pushed down by CMS Run II + CMS/ATLAS Run I
- The average close to CMS central value, but with reduced uncertainty
- Overall, the significance increases (not as much the naive/wrong expectation

M. Buckley, arXiv:1601.04751

Open Questions & More Info Needed

- Clearly very exiting, but with some open question
    - Is the large-width scenario really preferred (larger LEE might compensate larger significance)
    - Could we see a profile in width, at fixed or profiled mass?
- Run I vs Run II
    - CMS result more significant when Run I is added
    - ATLAS claims “2σ compatibility” in absence of a Run I excess
        - with which PDF assumption? gg or qq?
        - What’s the local/global significance when Run I and Run II are combined
    - In general, why do we present things so that people (i.e., theorists) feel allowed to forget about Run I?
        - The paper I showed is quite a rare exception


Backup Slides

Bkg estimate from bump-hunt fit

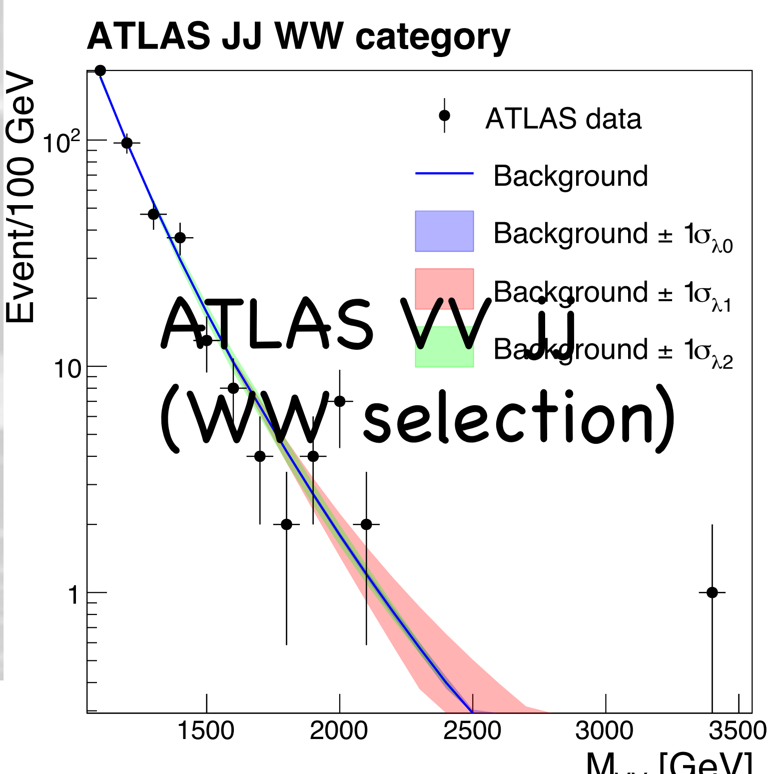
- Start from the published data (hep format or plots)
- Bkg estimate problematic
  - missing correlations, which often matter
  - (sometimes) bkg uncertainties not quoted

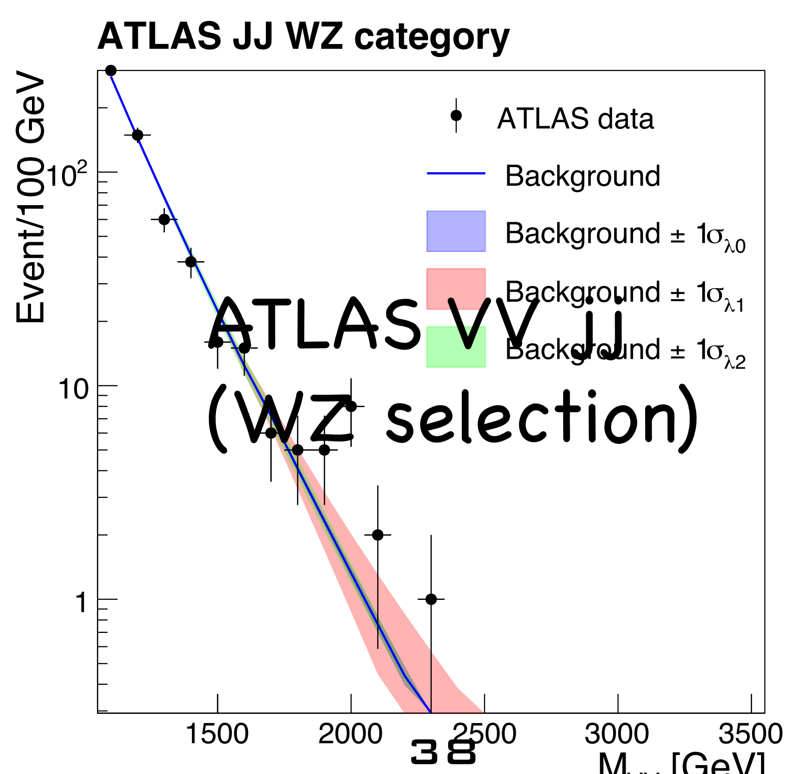
$$\frac{d\sigma}{dm_{jj}} = \frac{P_0(1-x)^{P_1}}{x^{P_2+P_3\ln(x)}}$$

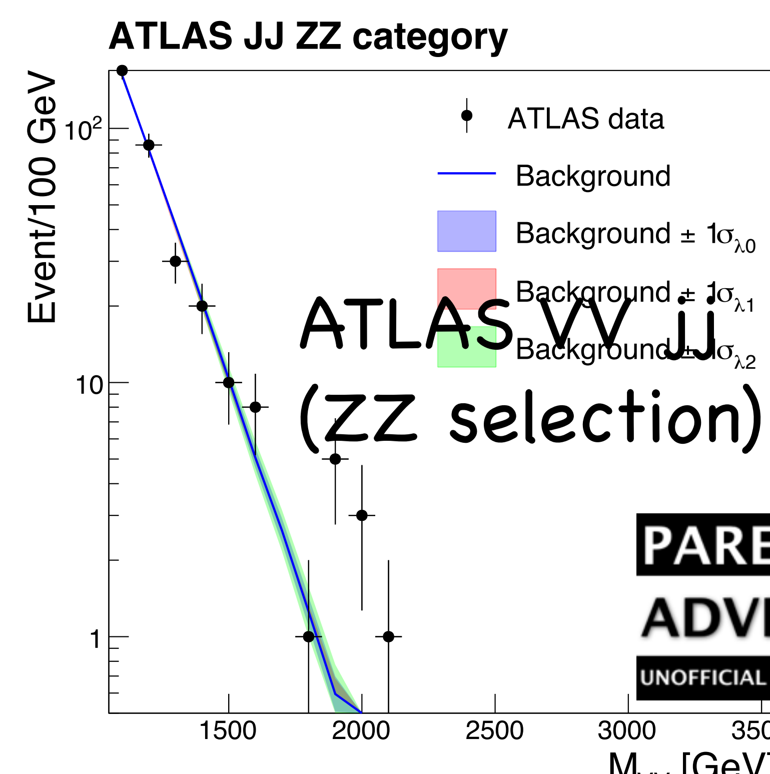
- When info missing, bkg estimate using a dijet-like bump hunt
  - fit in sideband vs full region give similar results
  - Simpler function (expo) used for low-stat channels (llJ)
  - For ATLAS VV fully hadronic, simplified function used according to ATLAS prescription

$$x = m_{jj}/\sqrt{s}$$

- Diagonalize covariance matrix + Bkg systematic for eigenvalues







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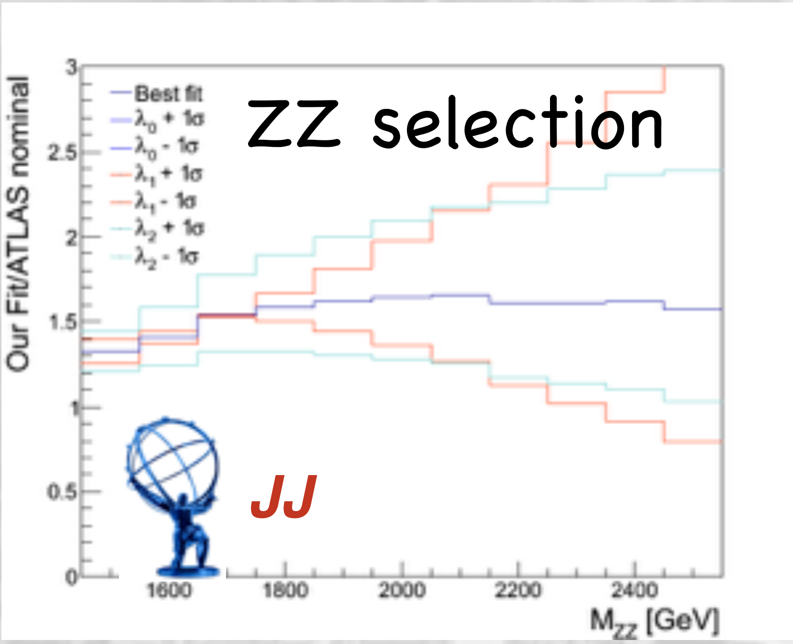
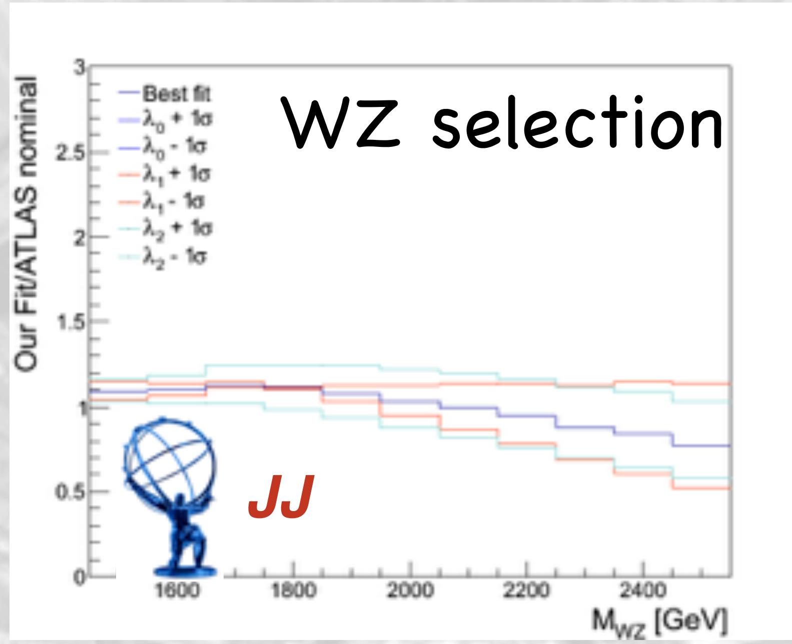
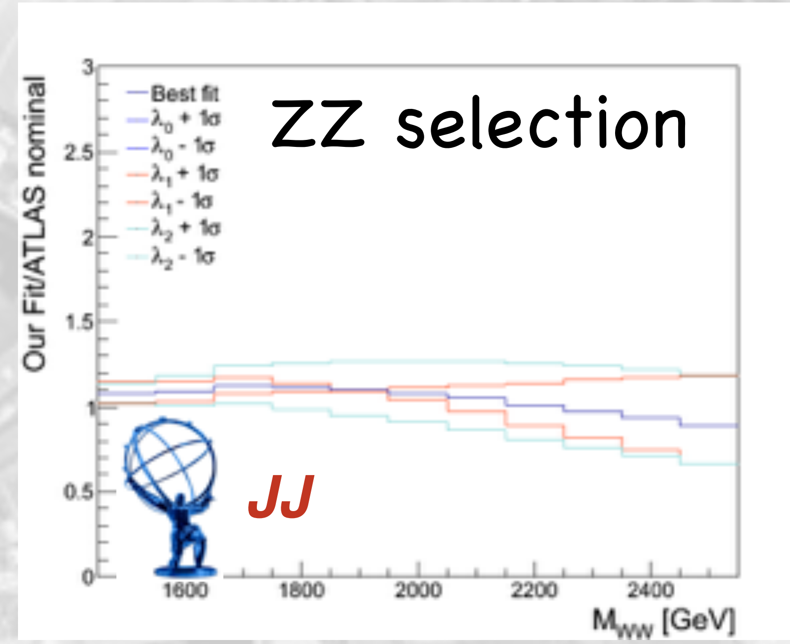
Comparison with nominal result

- In general, nominal bkg (from ATLAS or CMS) within our fit+systematic







- Sometimes (e.g. ATLAS ZZ) larger deviations observed
  - We use the nominal result as a background estimate
  - We rescale the systematic variations by nominal/our fit ratio
- Rescaling not always needed (e.g. CMS lνJ & llJ)

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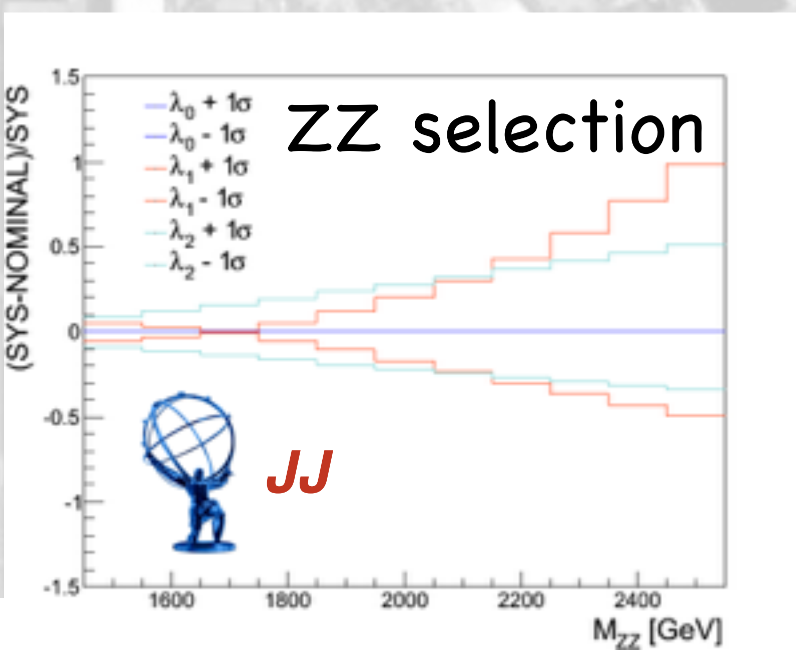

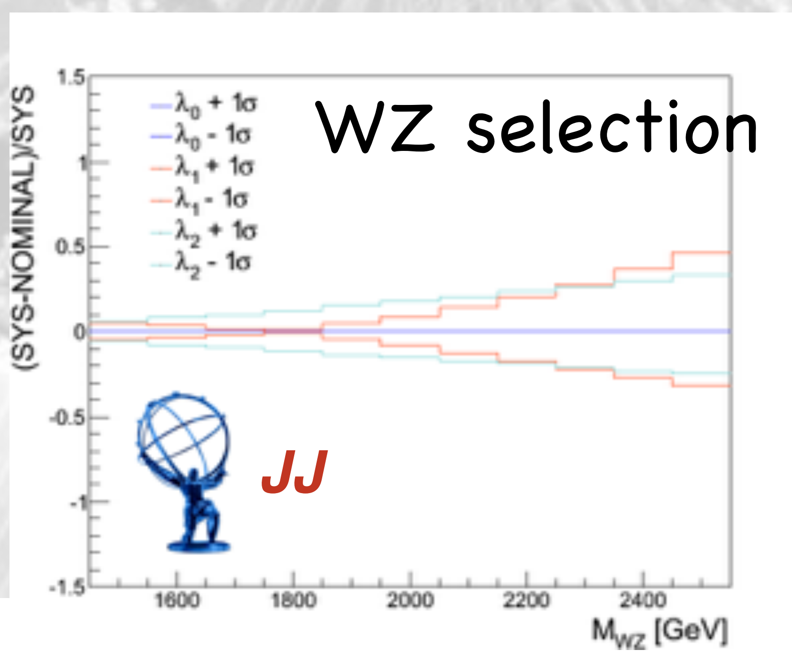

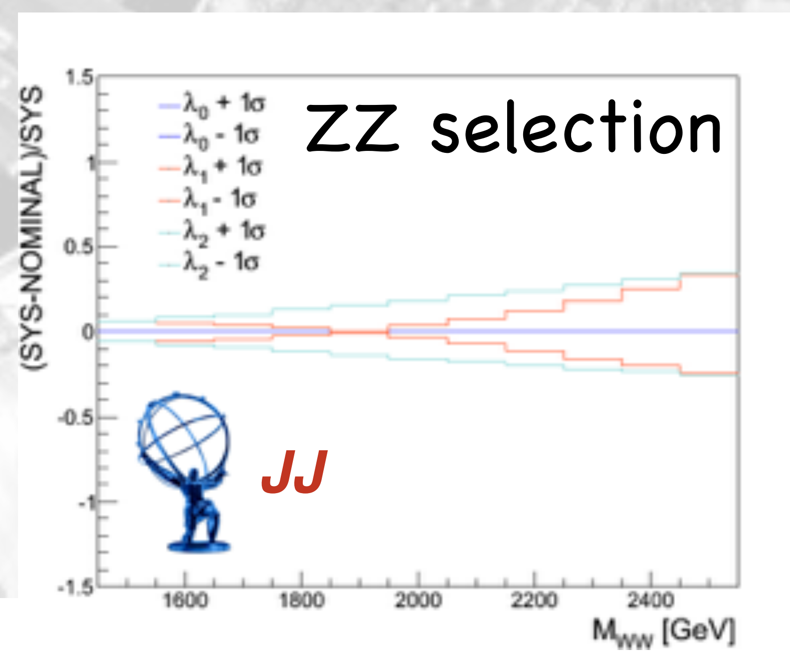

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Limit Comparison

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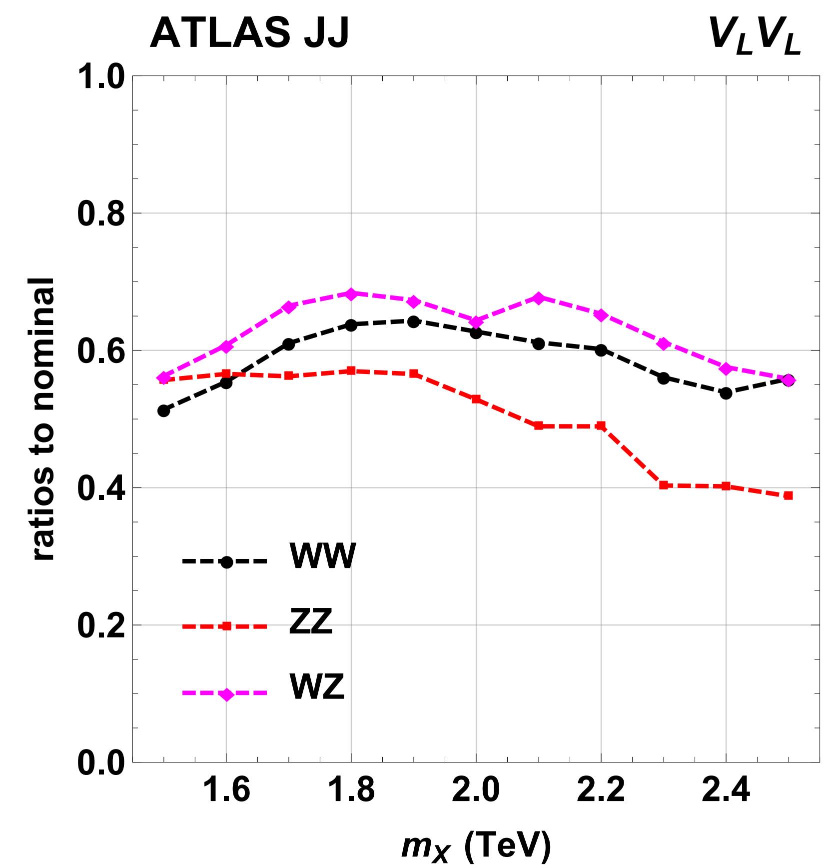
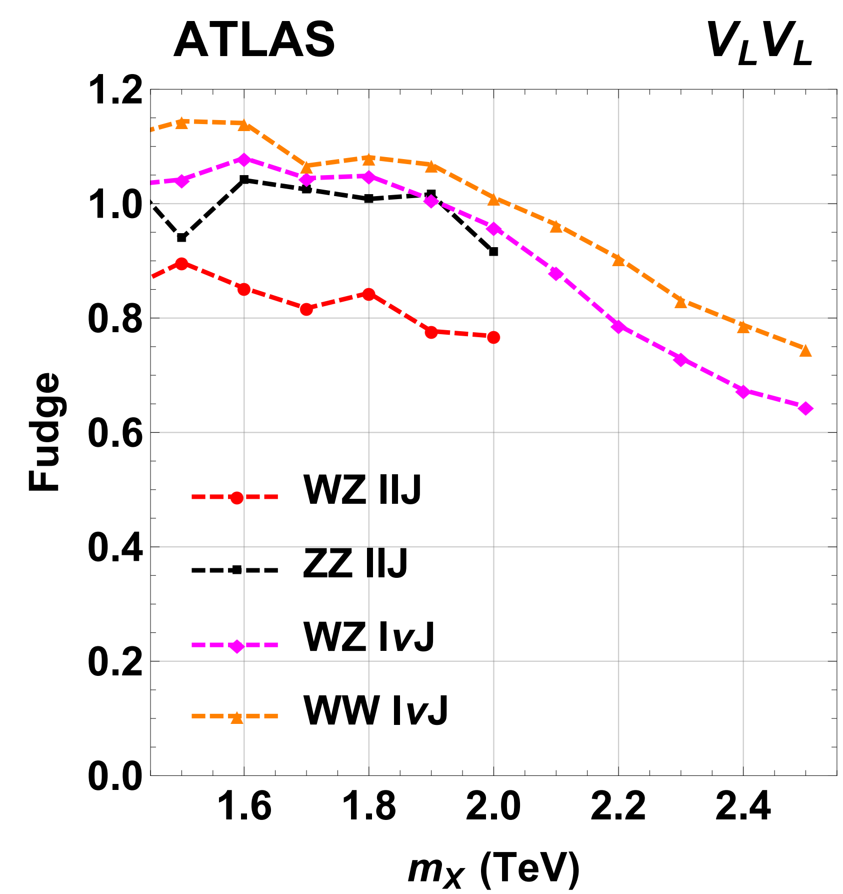
- Nominal+systematics estimate used in a template fit
- Signal parameterized from available information
  - signal efficiency
  - benchmark models for specific mass values
  - linear interpolation within benchmarks for generic mass values
- Limit extraction with asymptotic CLs reproduces trends in nominal result
- Discrepancies between nominal results & out fit (channel dependent)
  - approximately mass independent
- Rescale the expected limit by constant factor to match nominal
- Good agreement observed after rescaling (fudge factor)





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Limit Comparison

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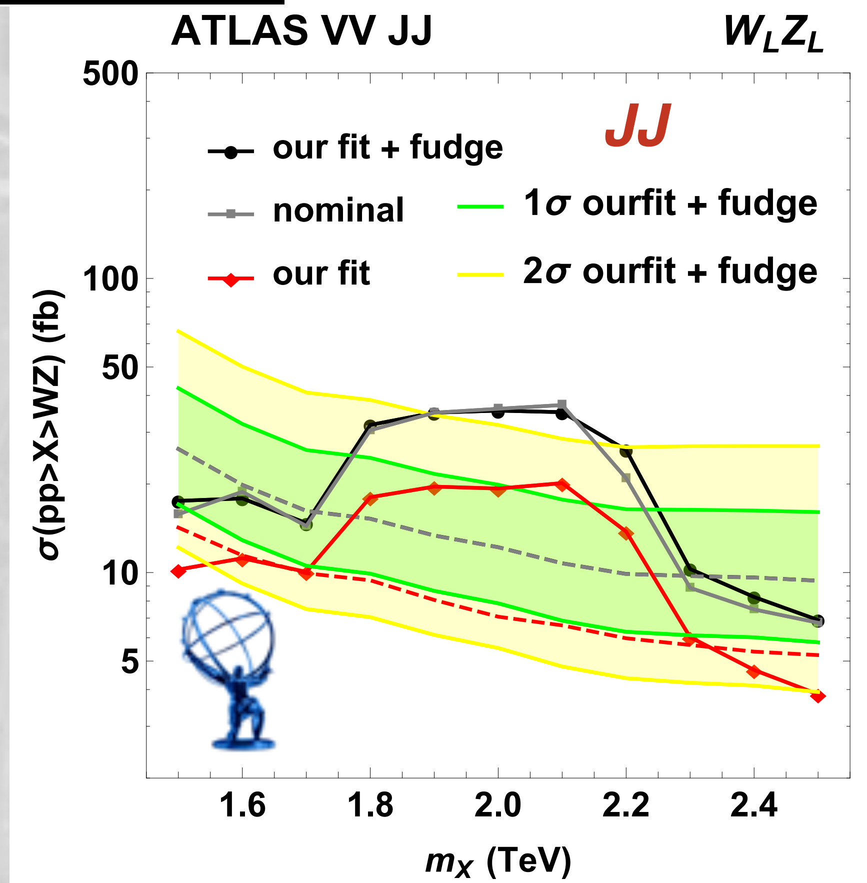

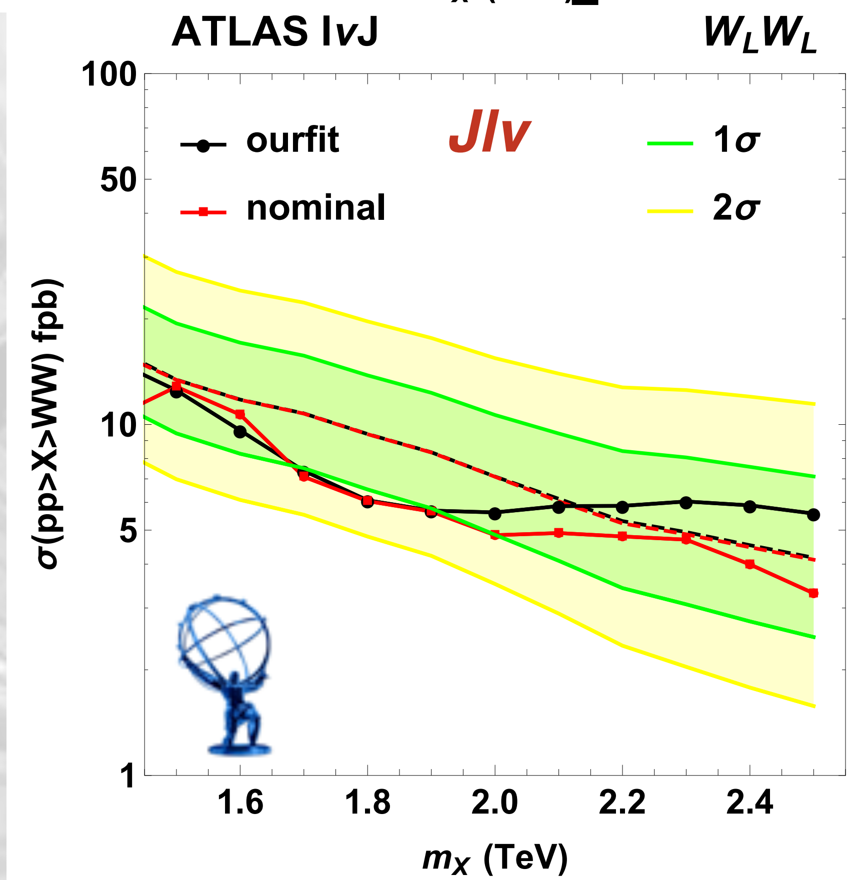

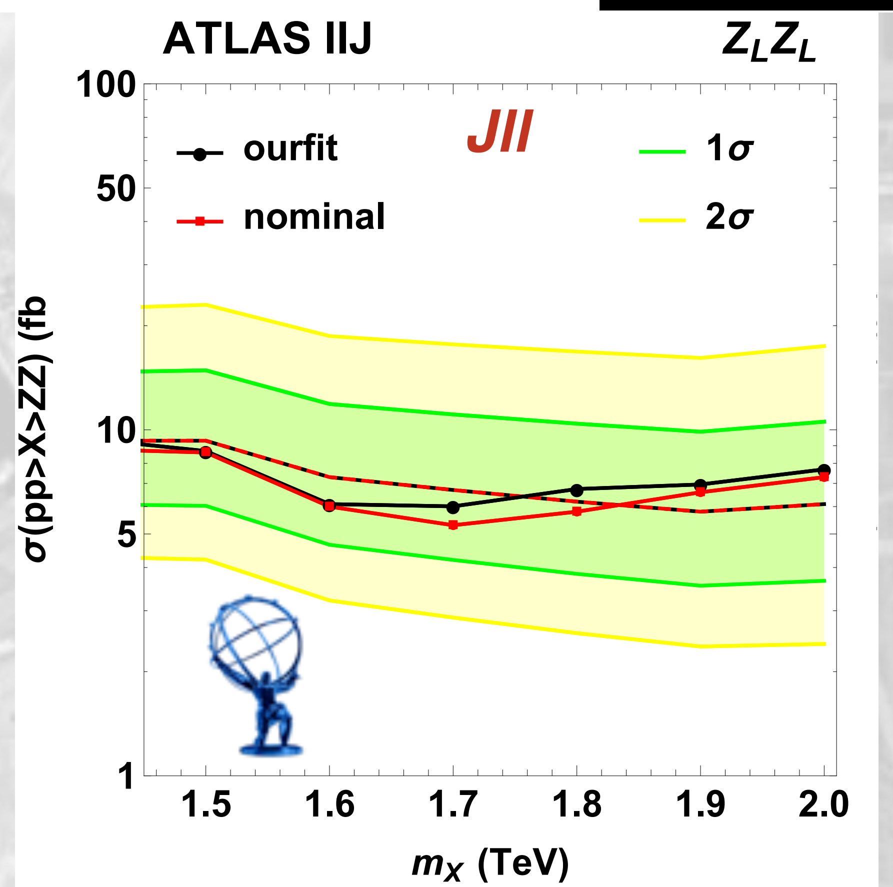

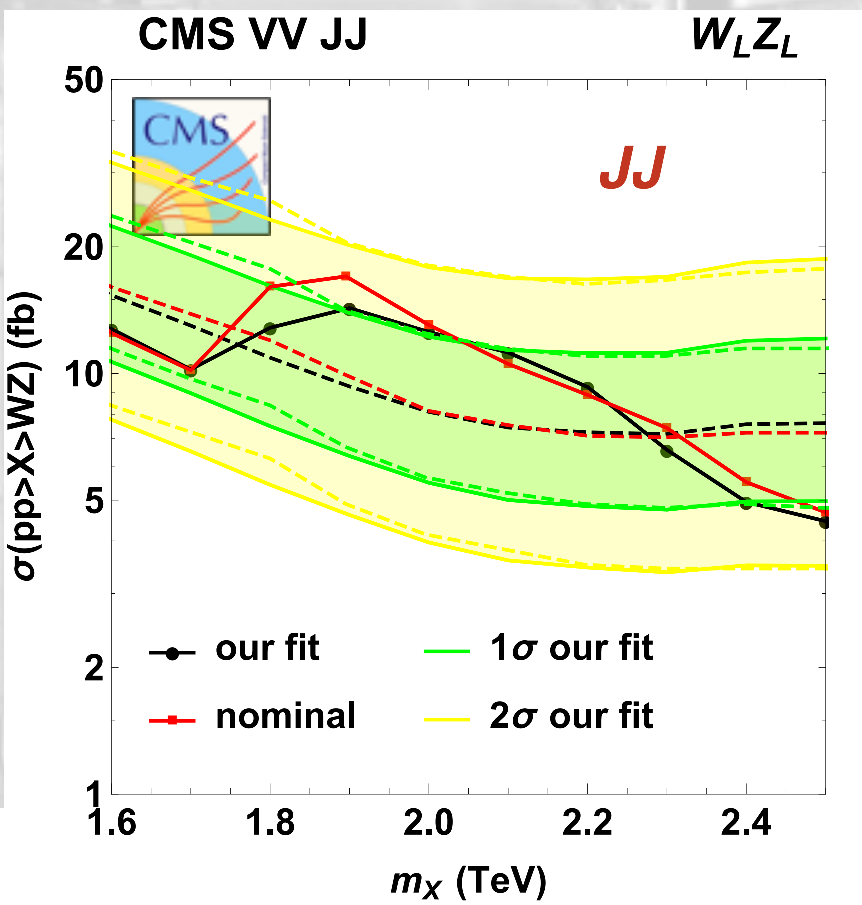

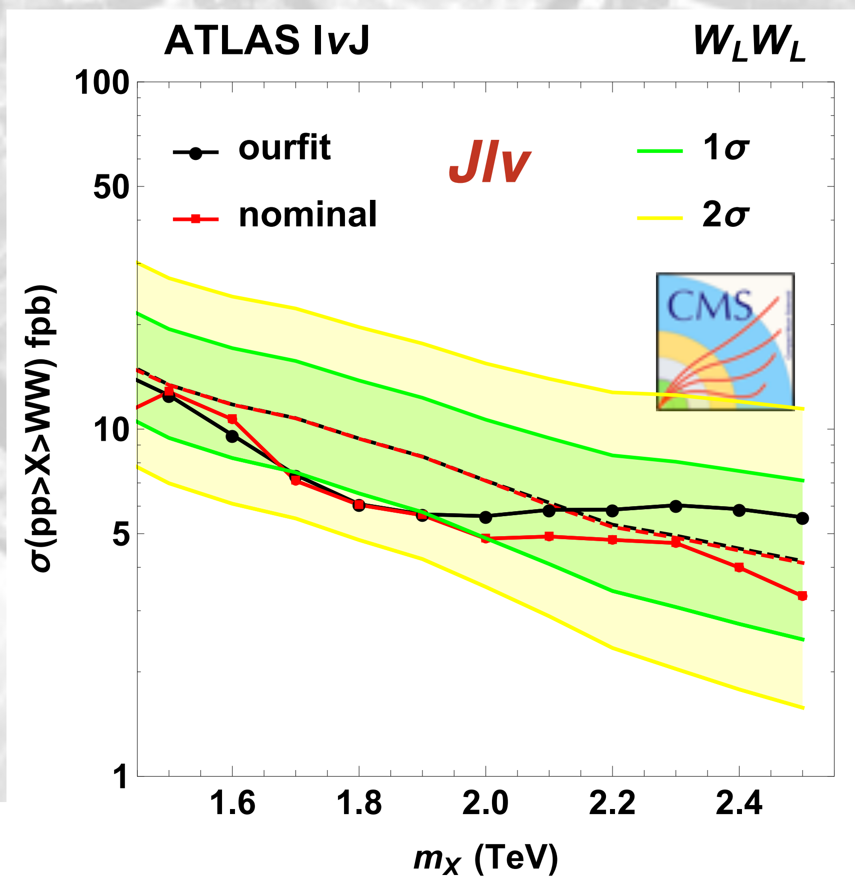

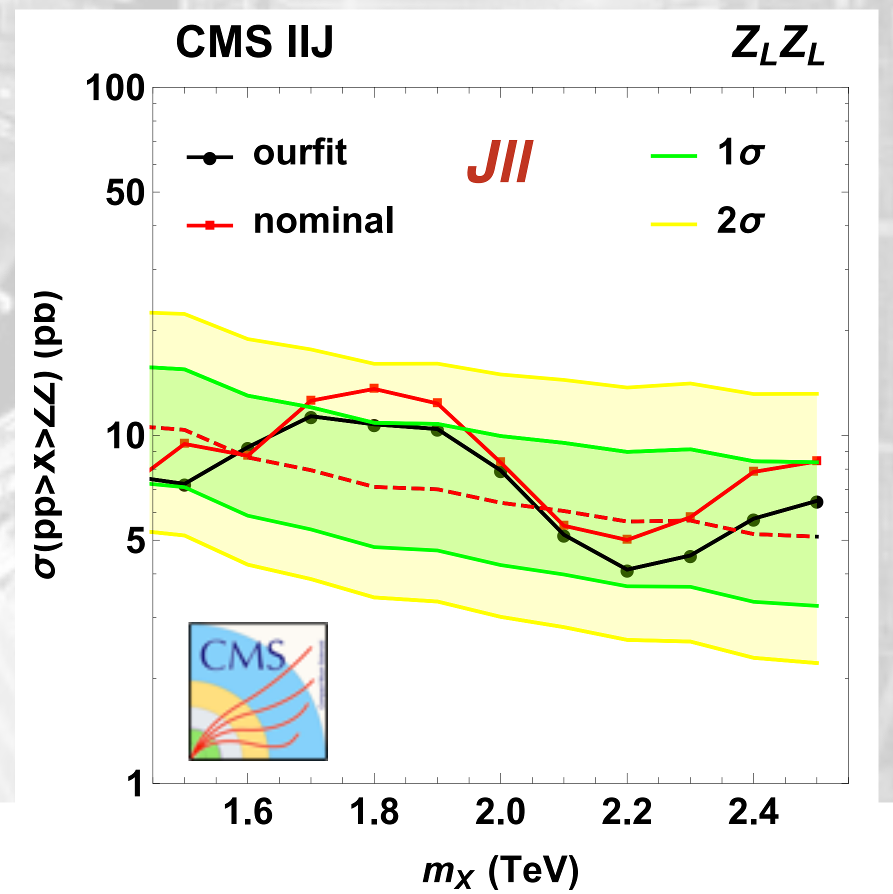

ATLAS+CMS “unofficial” combo: WW hypothesis

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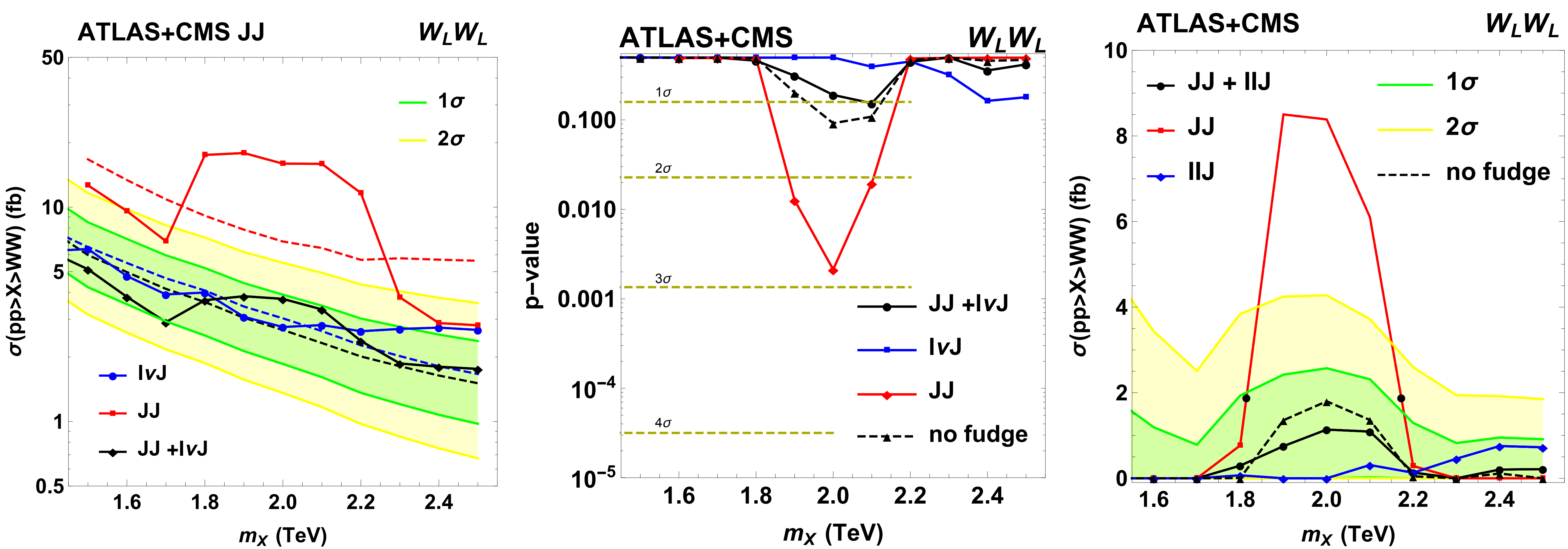

ATLAS+CMS "unofficial" combo: ZZ hypothesis

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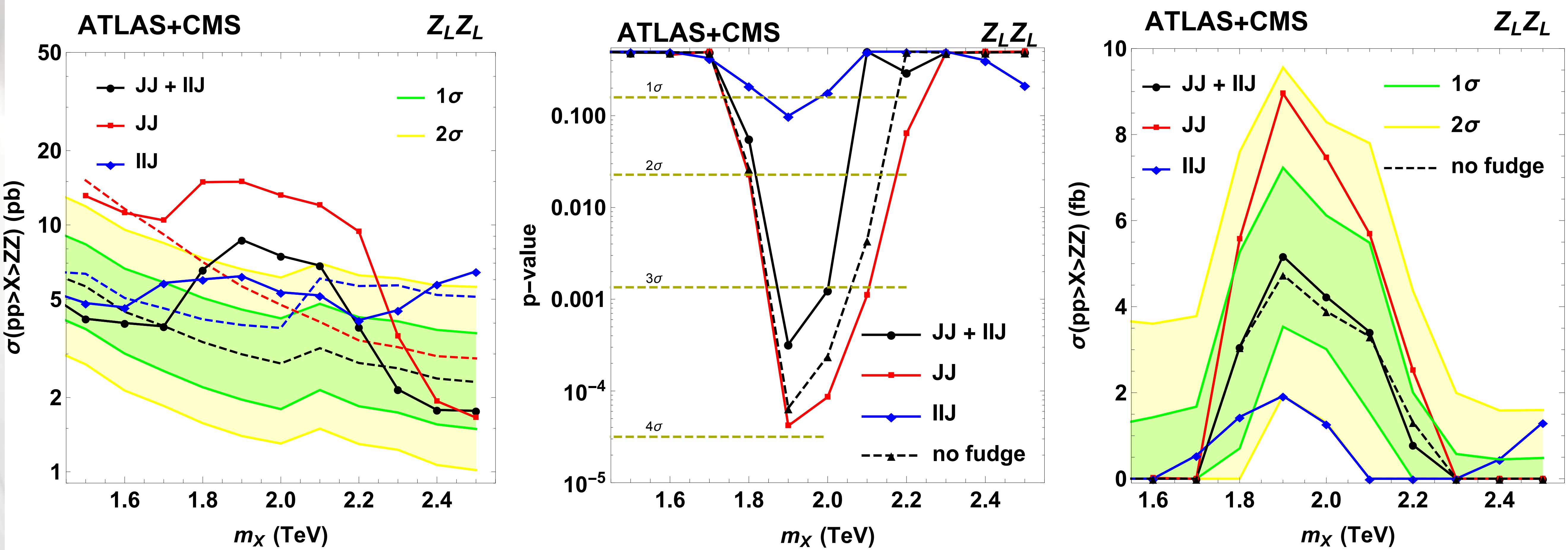
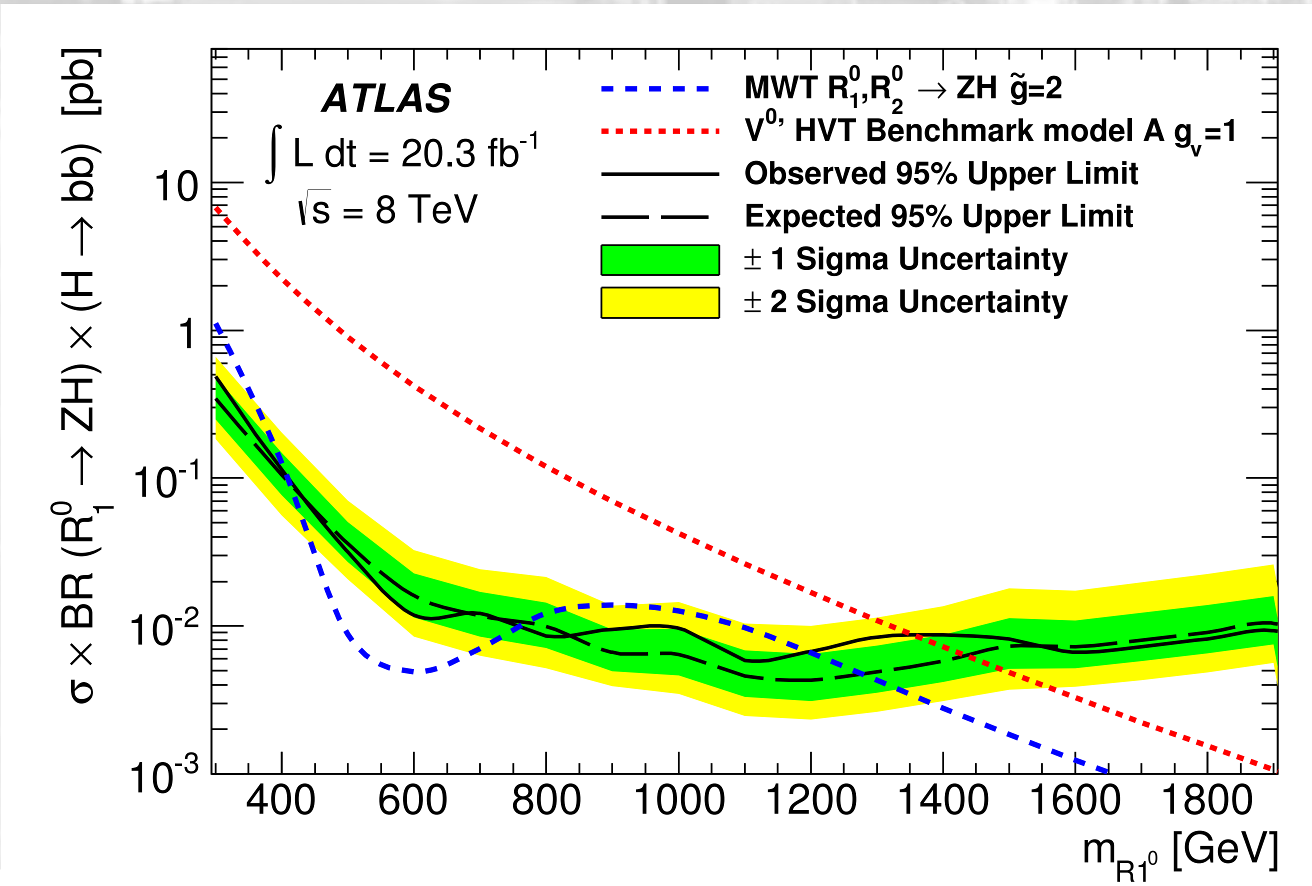


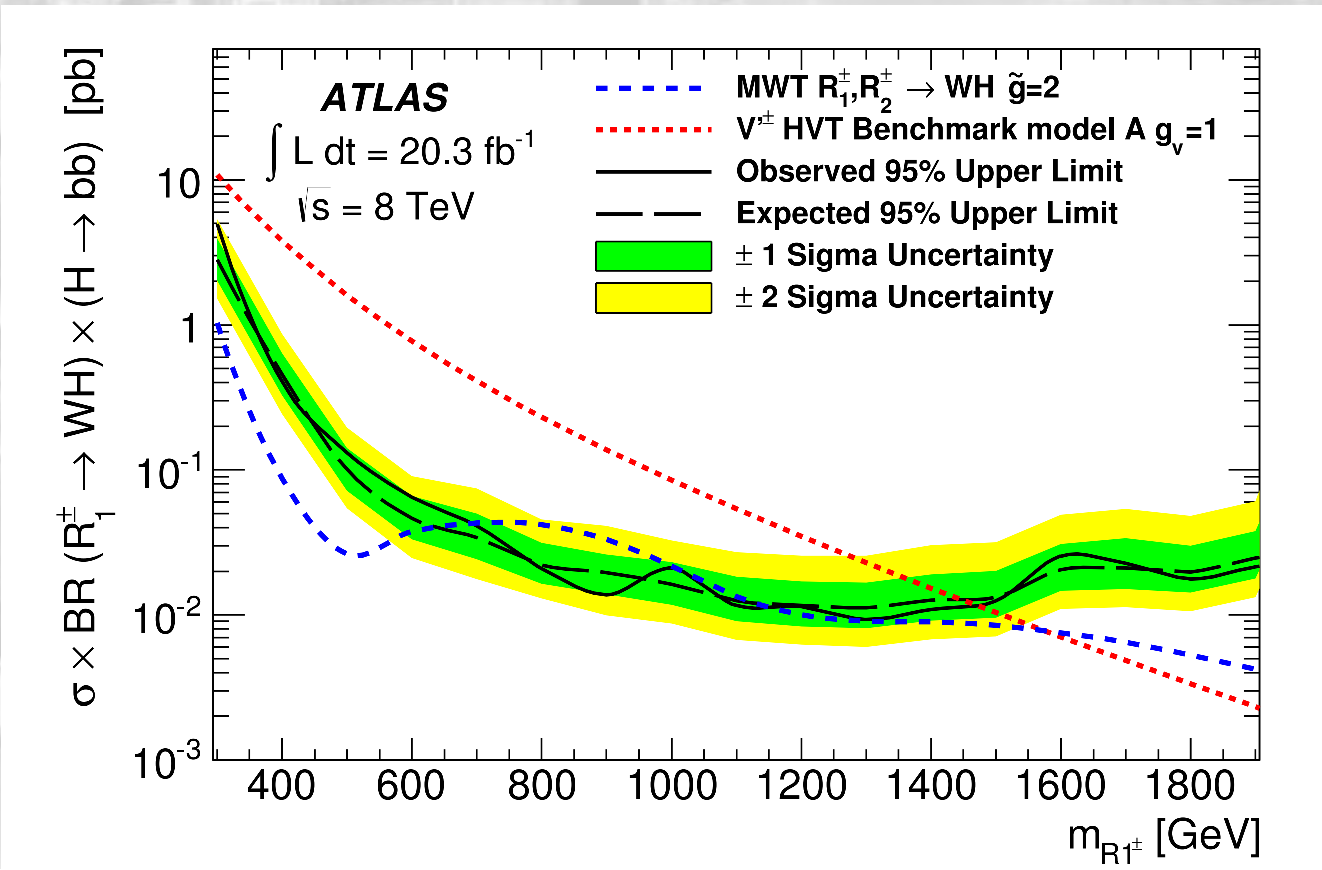
$X \to H(bb)W(l\nu)/Z(ll)/Z(\nu\nu)$ ATLAS search

- ATLAS searched for $X \to VH$ final states with resolved $H \to bb$
- Several V final states combined: $Z(l\nu)/Z(ll)/Z(\nu\nu)$
- No dedicated boosted topology. Use instead dijet system (with Anti-kT jets with R=0.4)
- Analysis sensitive to resonances $\lesssim$ 2 TeV
  - result quoted as cross section exclusion for masses up to 1900 GeV
  - no evidence for a signal

ATLAS 1503.08089



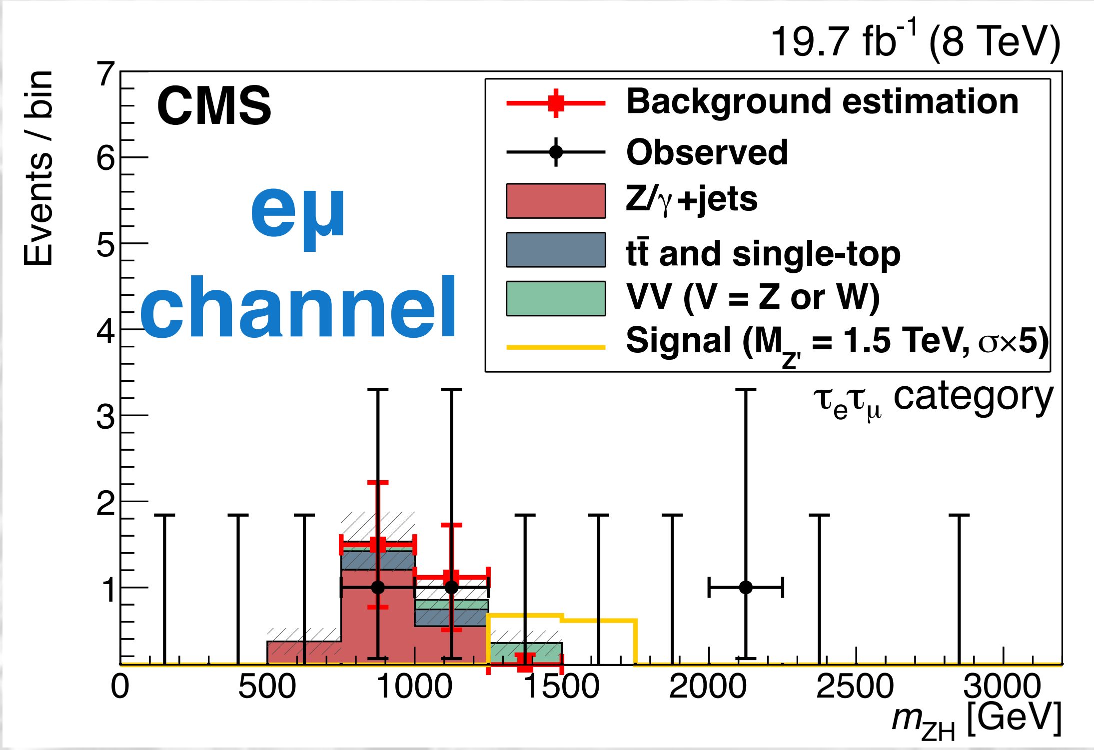
(a) $R_1^0(V'^0) \to ZH, H \to b\bar{b}$

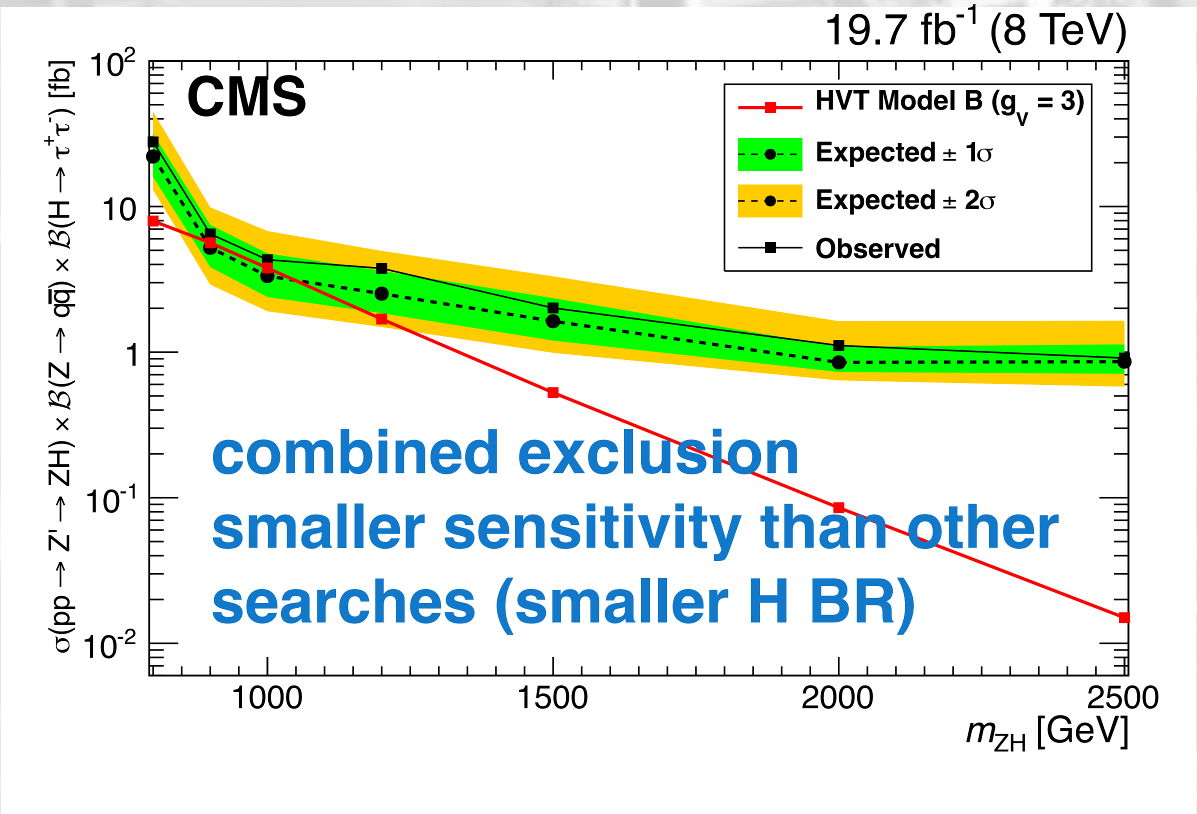


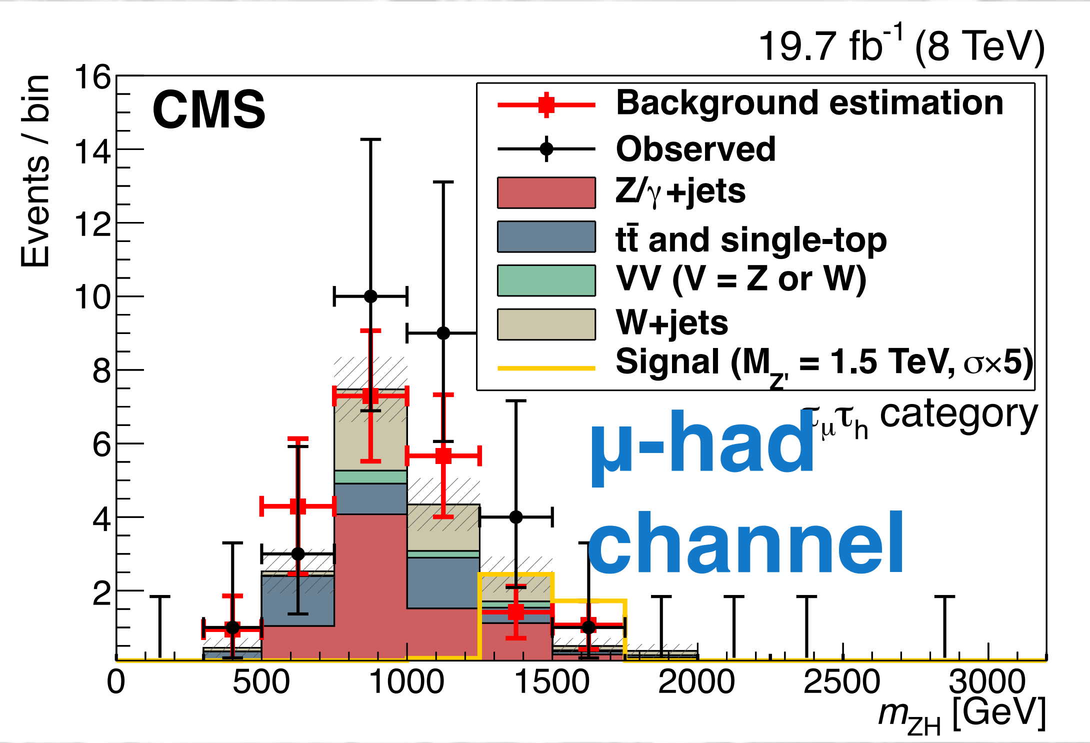
(b) $R_1^\pm(V'^\pm) \to WH, H \to b\bar{b}$

X→H(ττ)V(qq) CMS search

- Same V tagger as other analyses
- Special reconstruction of boosted taus
- Background predicted from data sidebands
  - low jet mass window
  - ditau mass window below the Z
- No excess observed



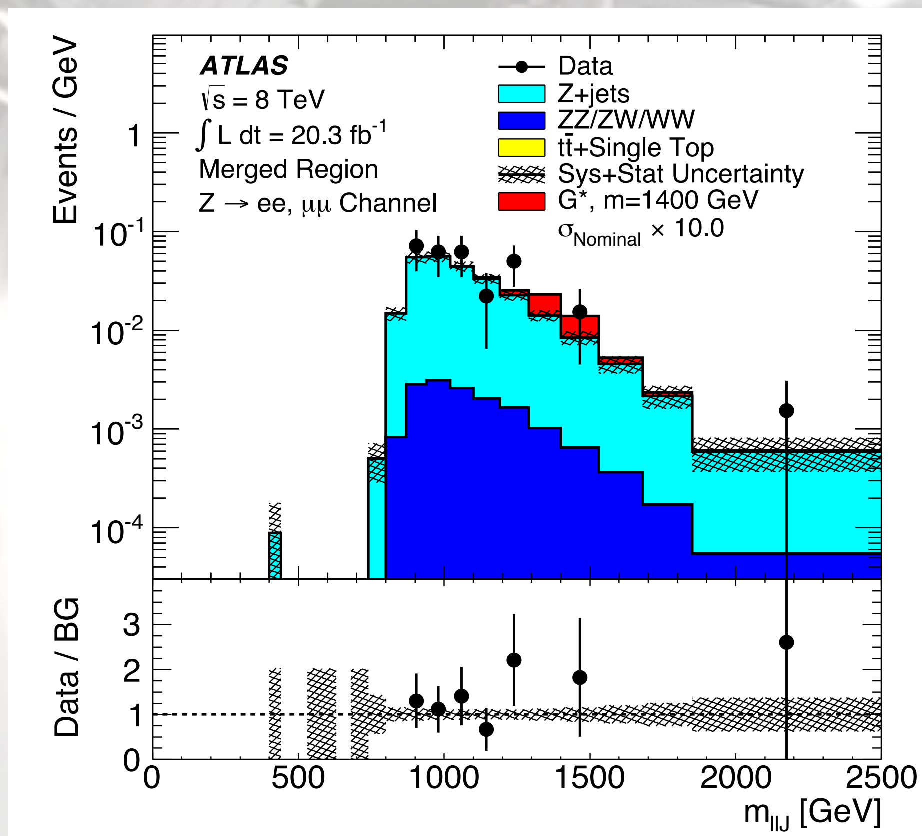


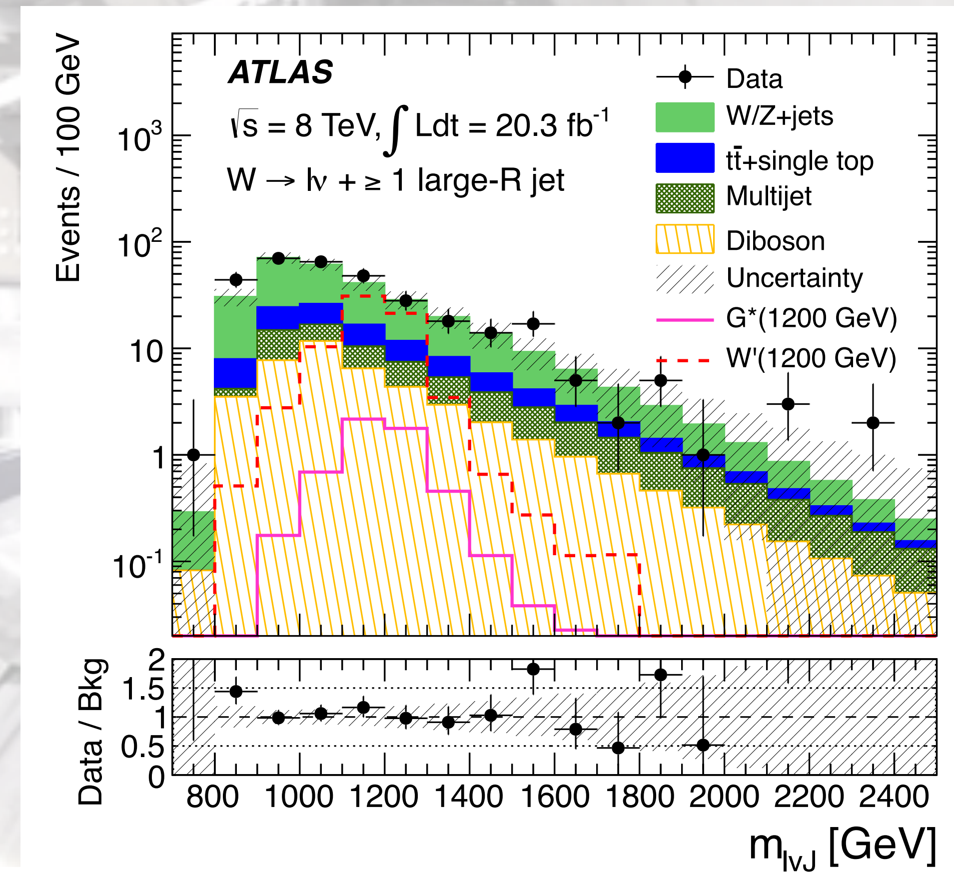


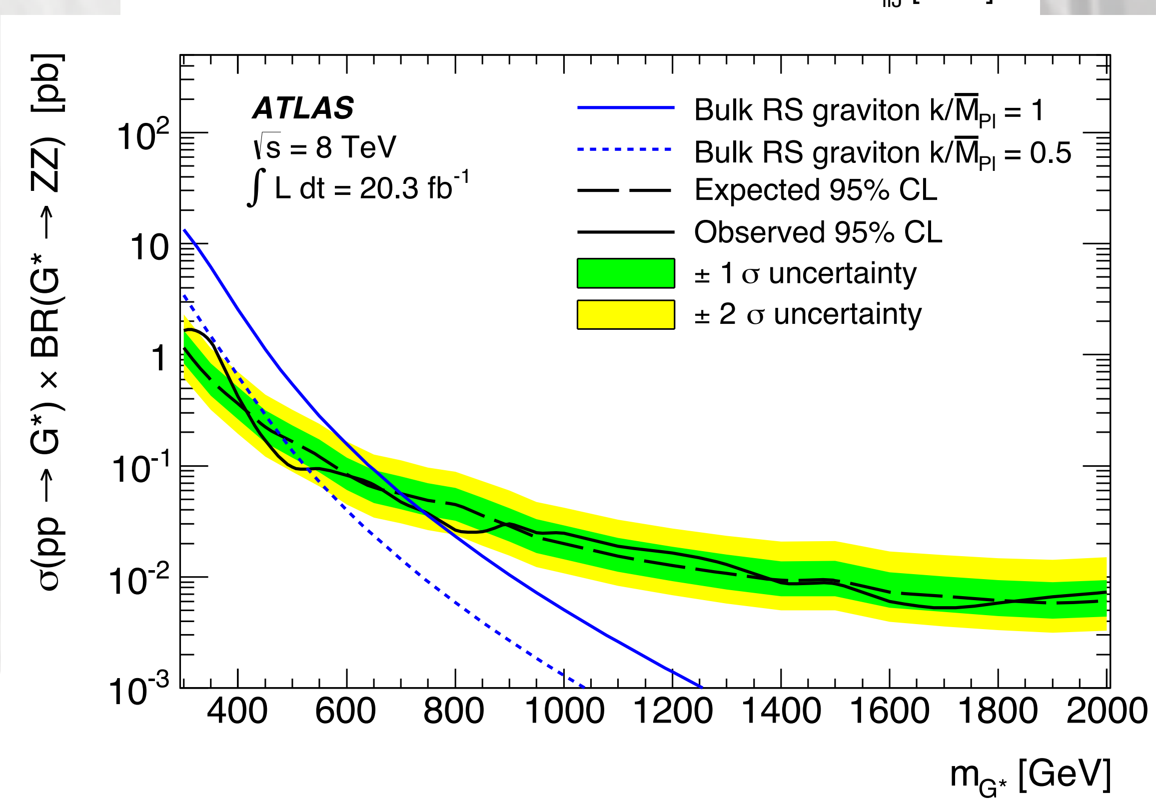
CMS-EXO-13-007

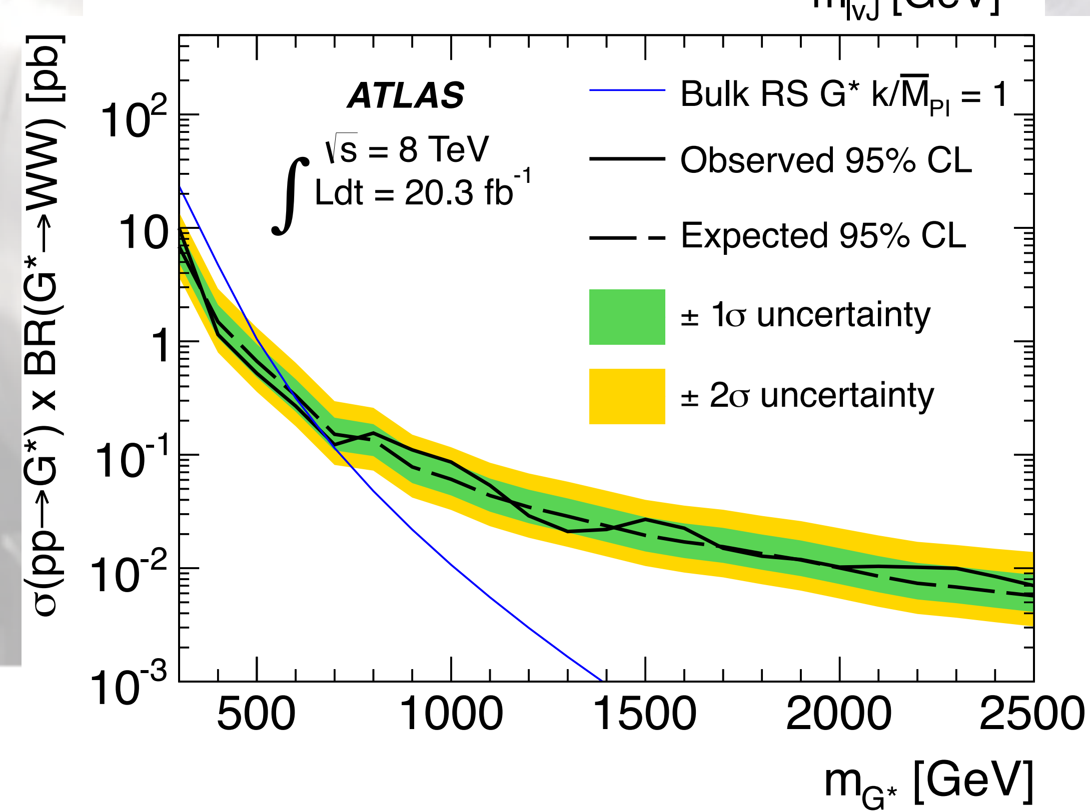
Other ATLAS Diboson Searches

- One should see something in the leptonic channels
  - at least if we are seeing vector bosons



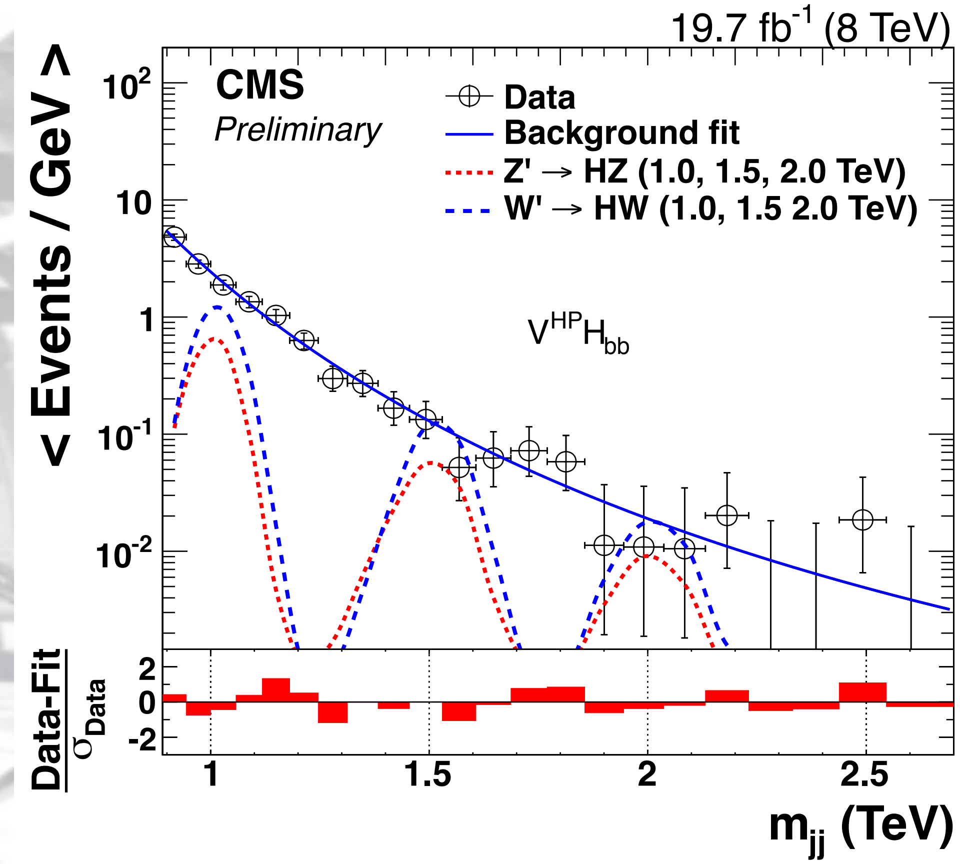


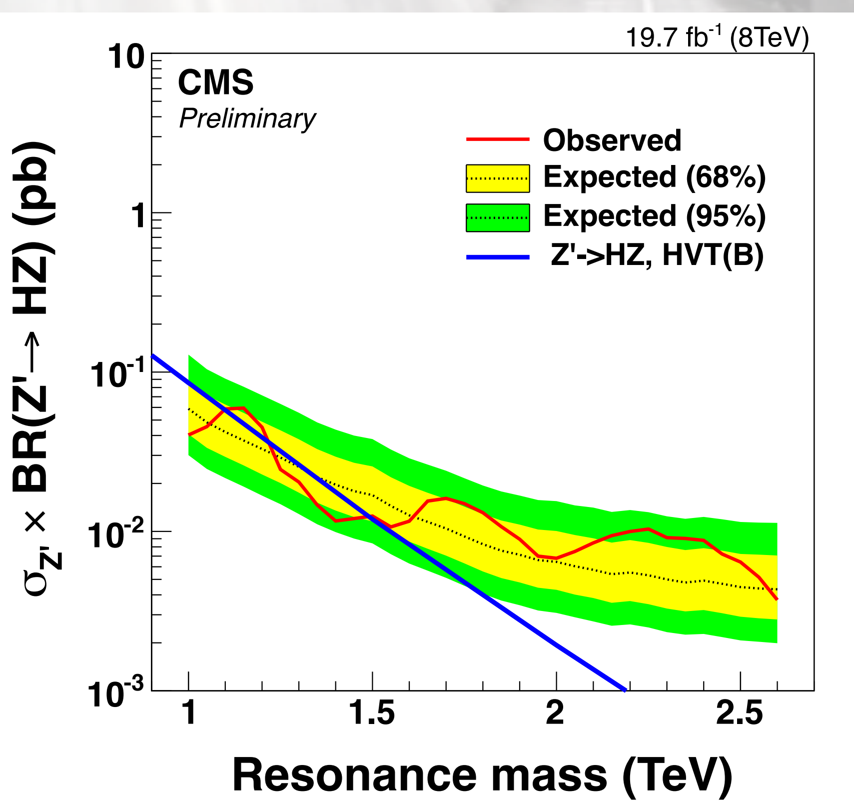


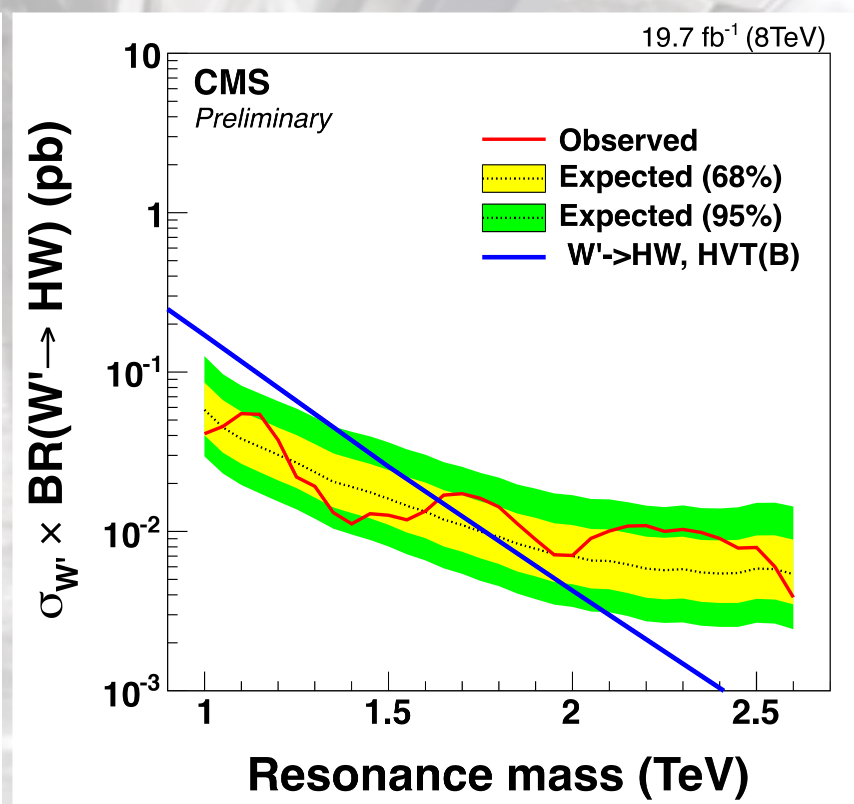


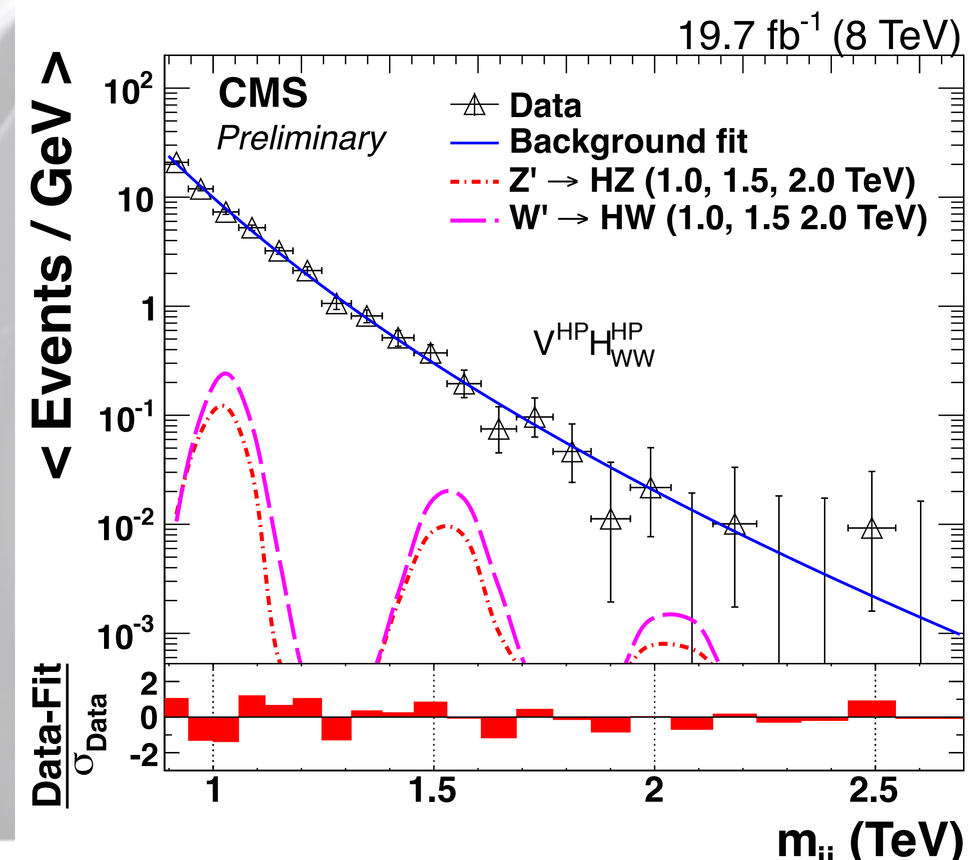
CMS HZ Search

- Same strategy as fully hadronic VV search
- Sensitive to both WH and ZH (no discrimination)
- No significant excess seen: some hint of a bump, but uncertainty on bkg shape “covers” it
- Results combined assuming Higgs SM BRs





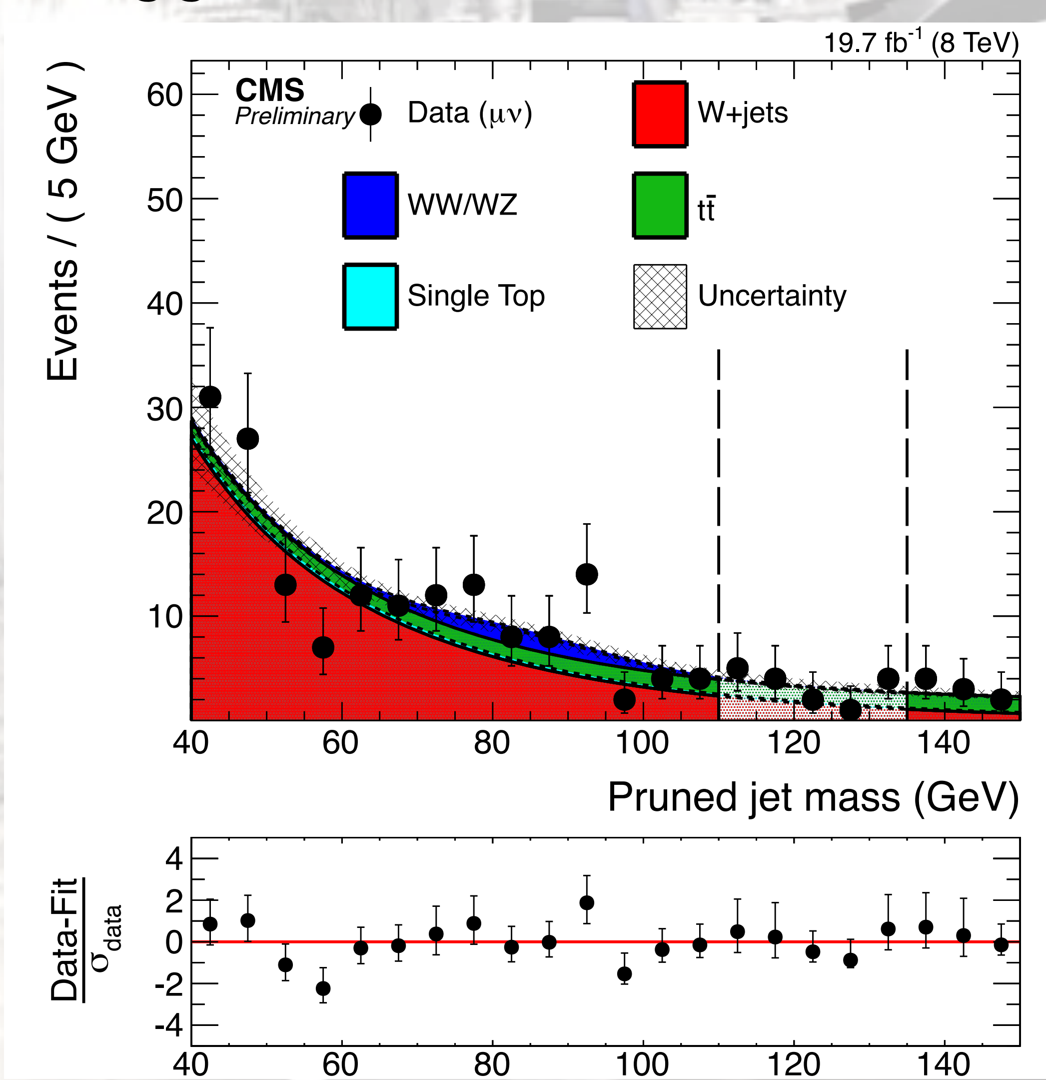


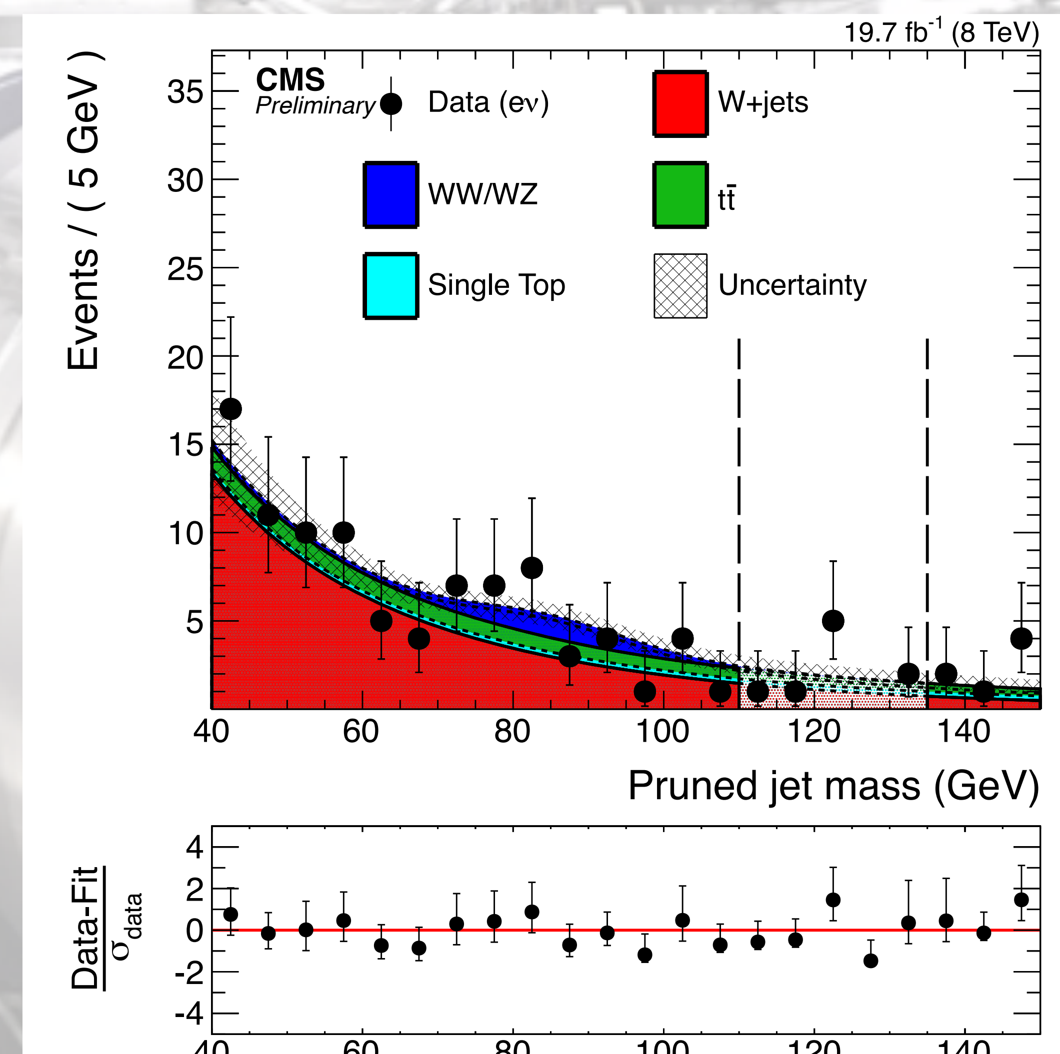


CMS-EXO-14-009

X→H(bb)W(lν) CMS search

- Jet mass compatible with bkg-only distribution for muon sample
  - expected, since the bkg is from fake Hbb candidates
- Interestingly, the excess events translate into a signal-like bump also in the Higgs mass

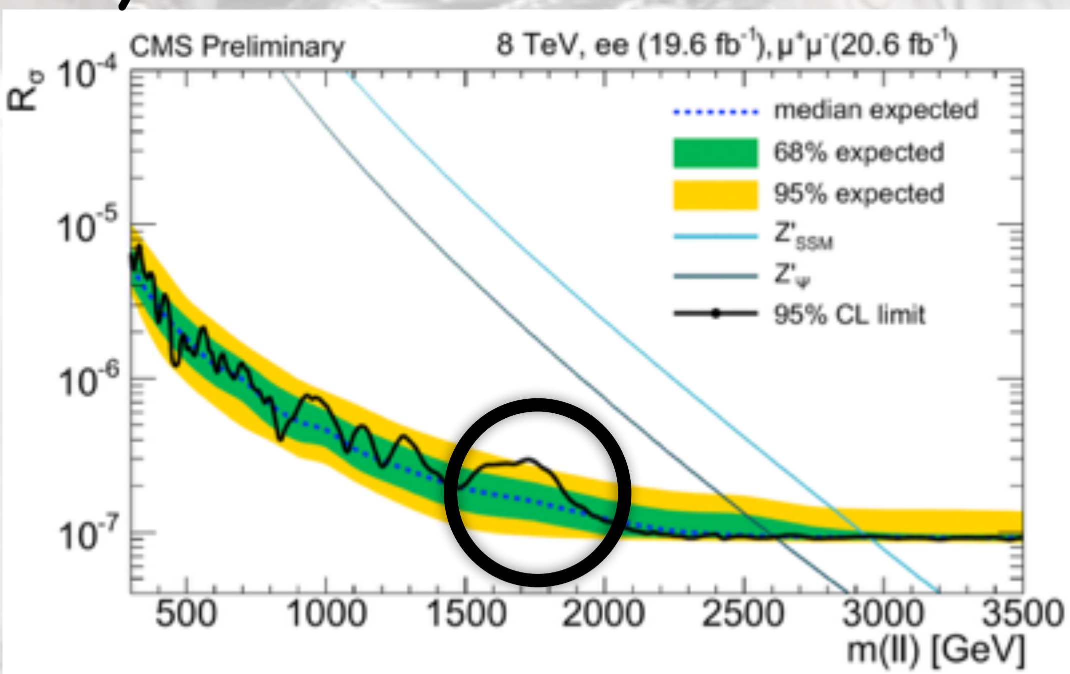


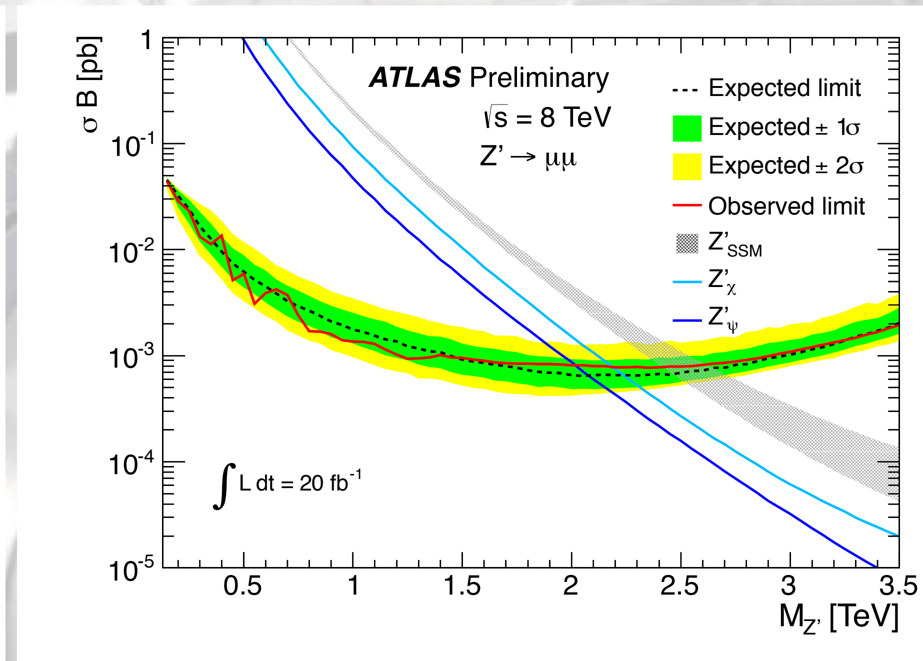


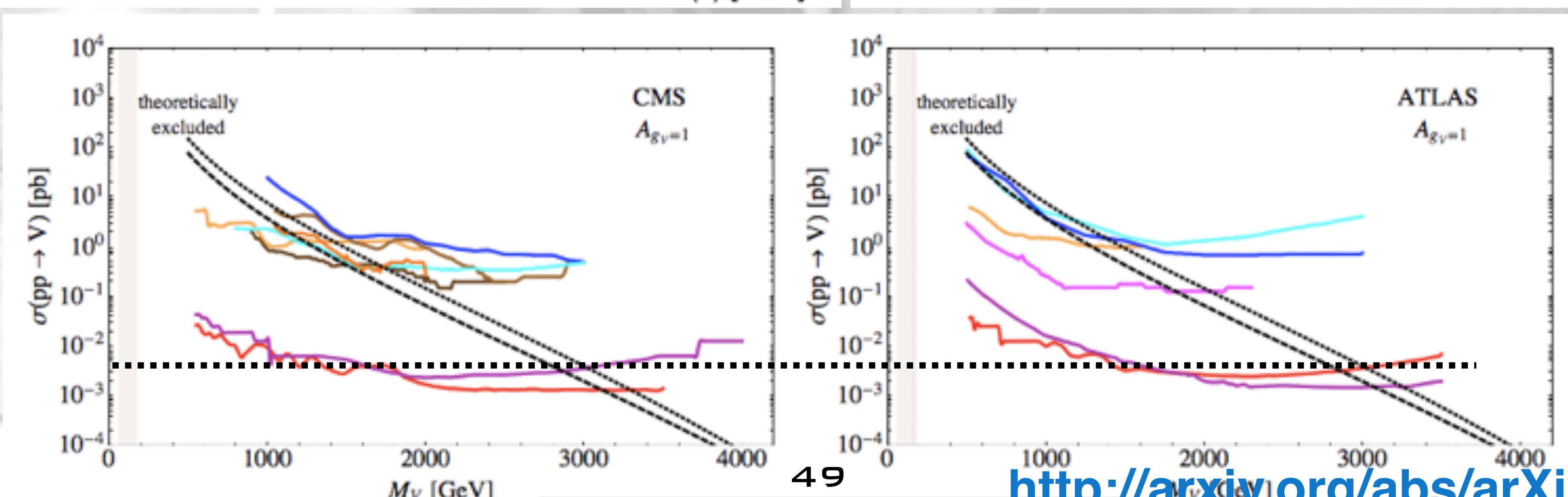
CMS-EXO-14-010

Dilepton

- CMS sees excess around 2 TeV vs ATLAS sees no excess
- Many other excesses seen (narrow resonance, each fluctuation is signal like, i.e. LEE)
- Two statements are not in contradiction: same observed limits
- Not very conclusive







http://arxiv.org/abs/arXiv:1402.4431

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Likelihood Scan vs Mass

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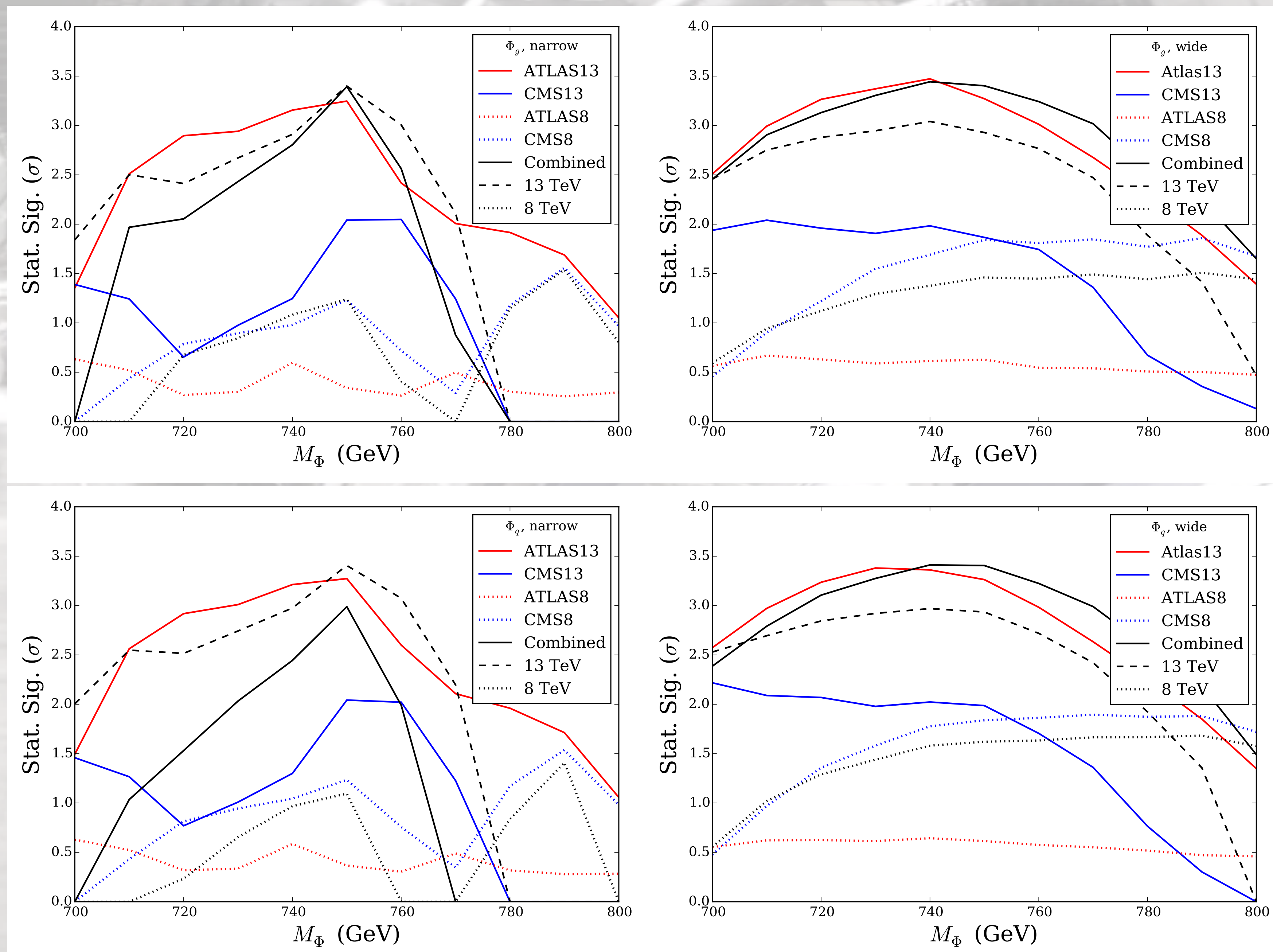

M. Buckley, arXiv:1601.04751