Michigan State University
High Energy Physics Seminar

# INTERPRETING RECENT ~2 TEV EXCESSES AT THE LHC

Zhen Liu
(Fermilab)

Talk based on recent work with B. Dobrescu,
**arXiv:1506.06736** and **arXiv:1507.01923**

# LHC

Well-controlled testing ground for high energy physics.

Run 1 being extremely successful, Run 2 just started and we are understanding nature better with our efforts.

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Run 1 being extremely successful, Run 2 just started and we are understanding nature better with our efforts.

Nature maybe more kind to us, leaving us some hint in the Run 1 data.

# Outline

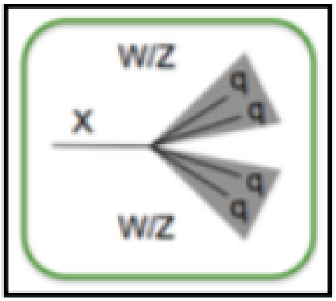
- Excesses
- Models
  - Interpretations
  - Model details
  - Other aspects
- Summary and outlook

# Excesses

- Diboson
- llqq
- Dijet
- WH
- eejj

# Diboson Excess (why people are excited)

V-jet + V-jet




- Searched for a pair of boosted fat jets.
- Using jet substructure to suppress QCD background.
- Mass window for jets are weak boson mass $\pm 13$ GeV. WW, ZZ, WZ signal regions overlap.(More details later.)

**arXiv:1506.00962**, more details and additional material, see http://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/EXOT-2013-08/#auxstuff

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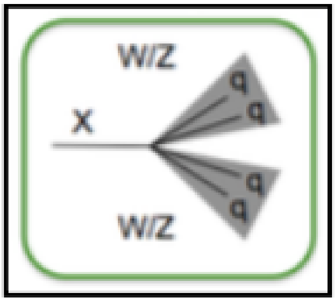


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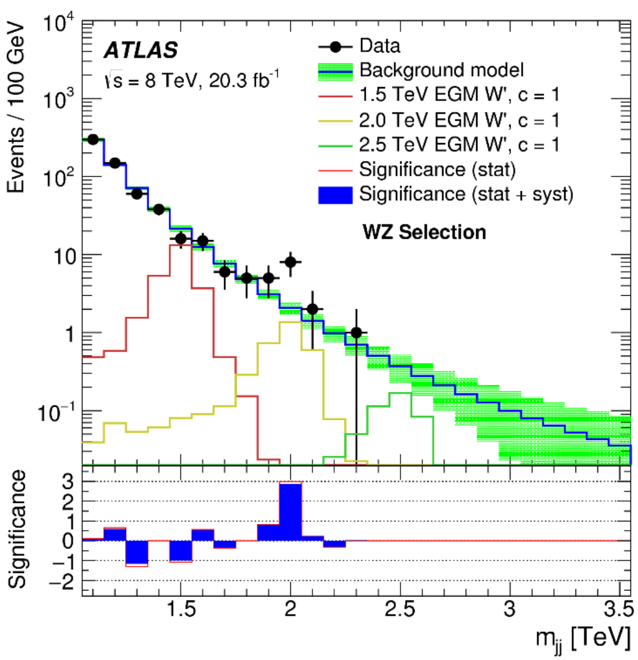


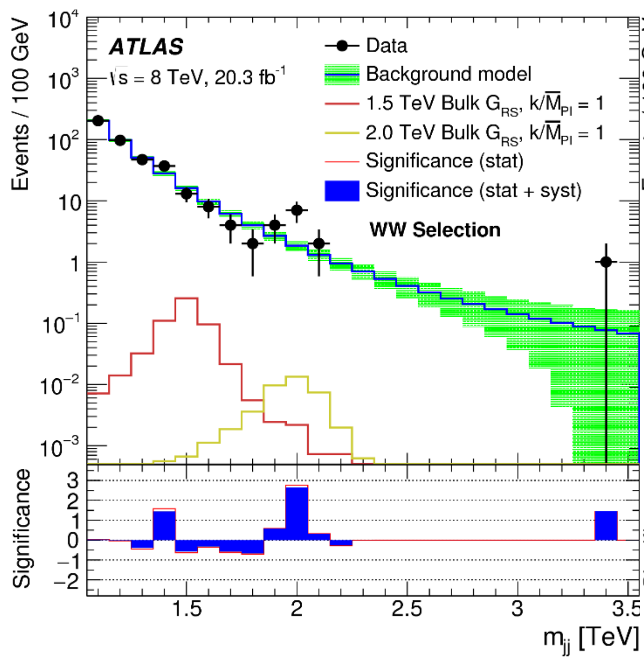


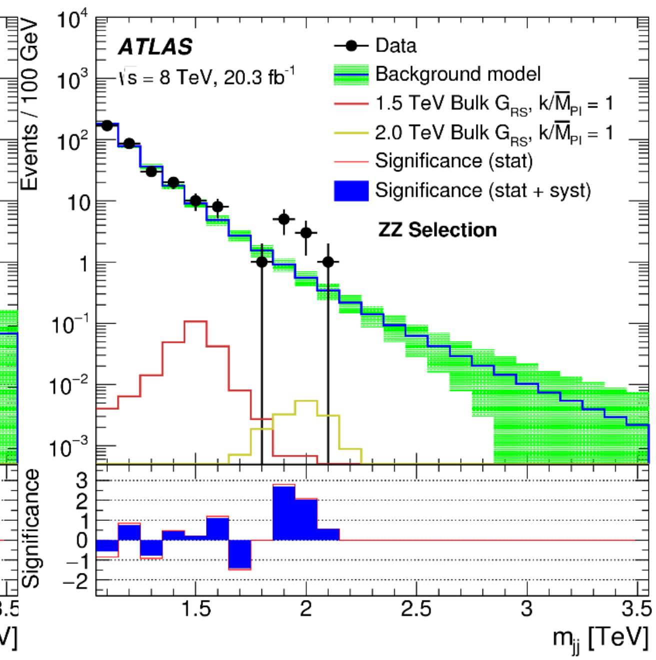


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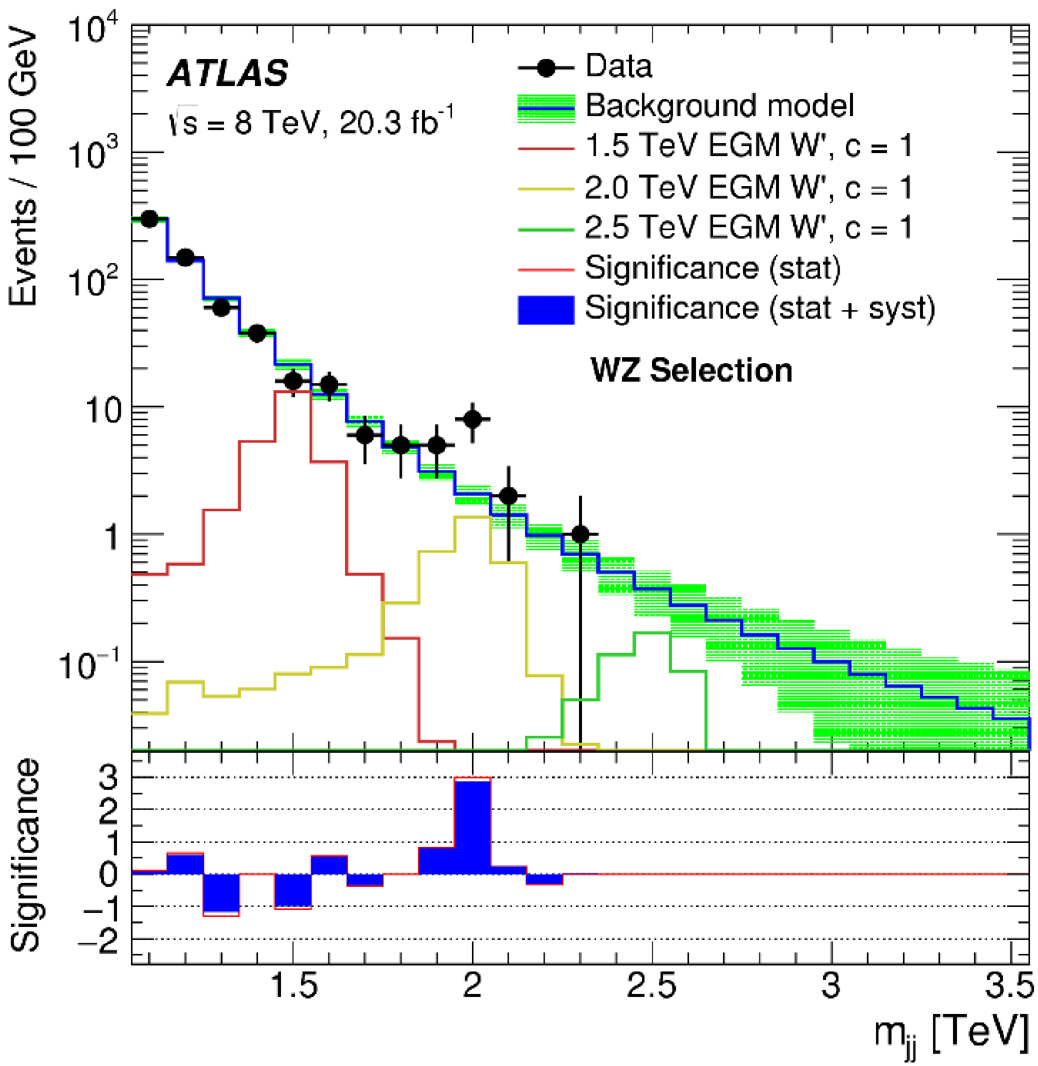
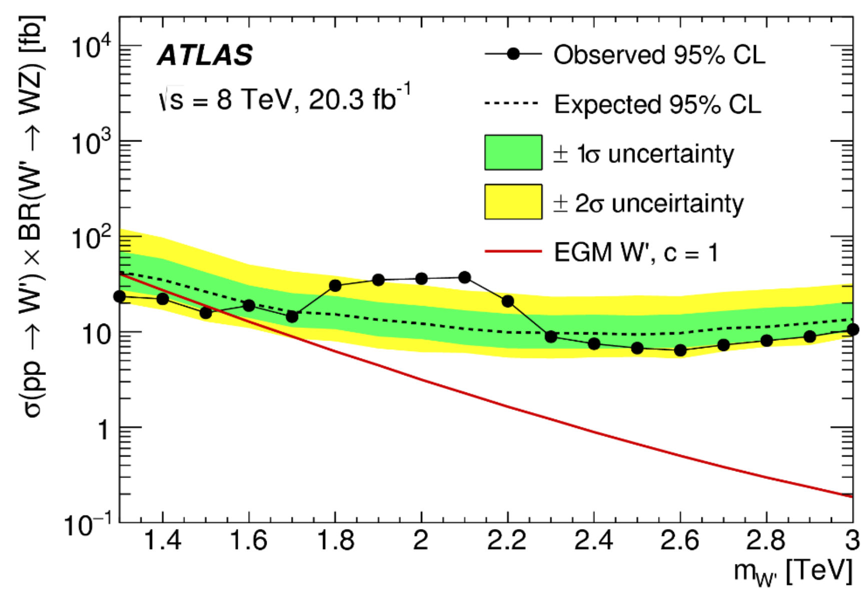
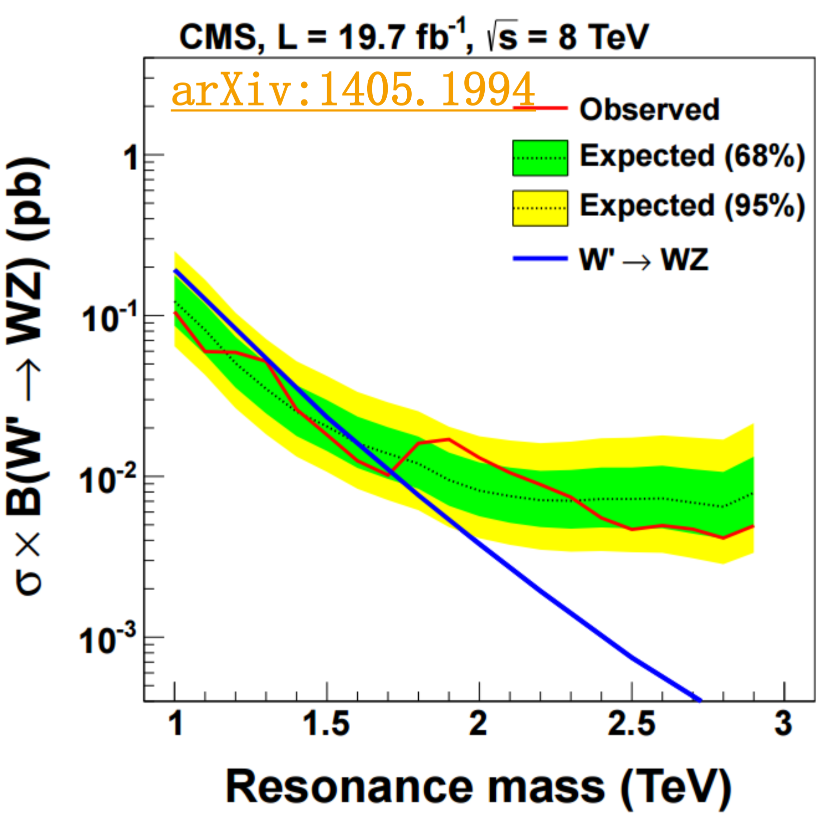



Local significance 3.4 sigma
Global significance 2.5 sigma

An "obvious" bump near 2 TeV. Due to resolution, anywhere between ~1.8-2.1 TeV has more than 2 sigma significance.

# Diboson excess (CMS)

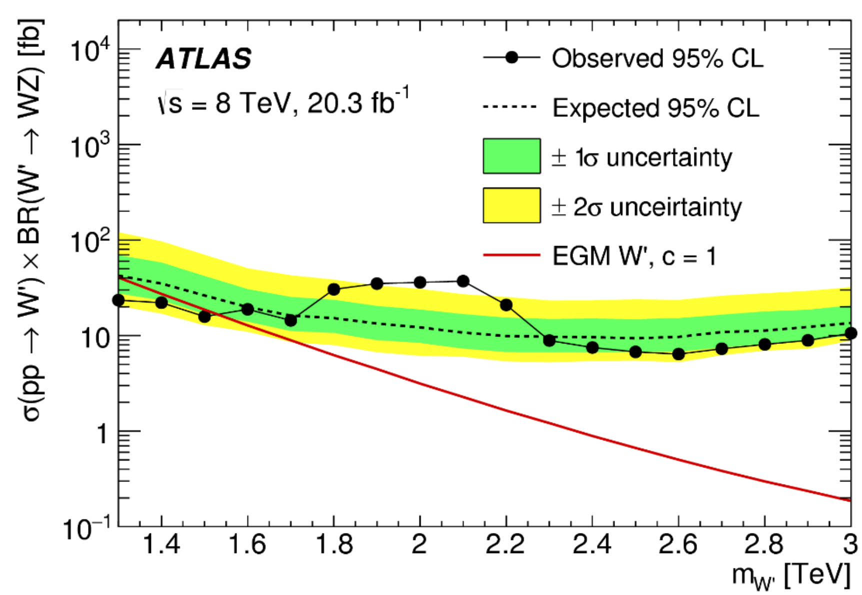



## ATLAS vs CMS

- C/A R=1.2, split-filtered,|η| <2.0,
- sub-jet pT balance / **Trk. Multi./** Mass (**2 overlapping mass window**)
- Trk mult. not always well modelled
- Tagging eff: 25-45% (pT dependent)
- 2 leading jets with |y1-y2| <1.2: s-channel vs t-channel
- **Optimised using longitudinal polarised signal**

- C/A R=0.8, pruned,|η| <2.5,
- $\tau_{21}$/ Mass (single mass window)
- Tagging eff.: 20-50% (pT dependent)
- 2 leading jets with $|\eta_1-\eta_2|$ <1.3
- **2 signal regions with different sensitivy for longitudinal and transverly polarised bosons**

Reina Camacho@Boost2015



# Diboson—Other channels

| | W | Z |
|---|---|---|
| W | qqqq (EXO-12-024)<br>lvqq (EXO-13-009, HIG-13-031) | qqqq (EXO-12-024)<br>lvqq (EXO-13-009)<br>llqq (EXO-13-009)<br>lvll (EXO-12-025) |
| Z | CMS<br>11 Aug 2015 | qqqq (EXO-12-024)<br>llqq (EXO-13-009, HIG-13-031)<br>Andreas Hinzmann |

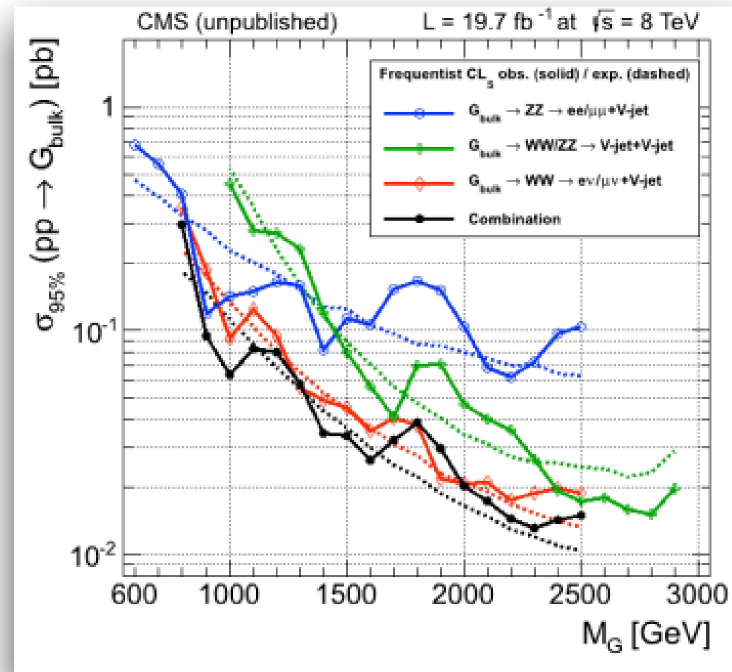
Establishment of the VV->JJ excesses requires consistent observation in all different channels, including leptonic, semi-leptonic decays of the weak boson pairs.

Both ATLAS and CMS has done a very thorough job in searching for resonances in these channels.

# Diboson-Other channels

- Improves sensitivity to new physics!
- Best sensitivity from lepton+$E_T^{miss}$+V-jet channel over the whole mass range, followed by the all-hadronic channel at higher masses
- Good sensitivity from the 2 leptons+V-jet channel at low masses
- Interesting deviation from expected background (1.3σ) in all channels at M ~ 1.8 - 2 TeV!

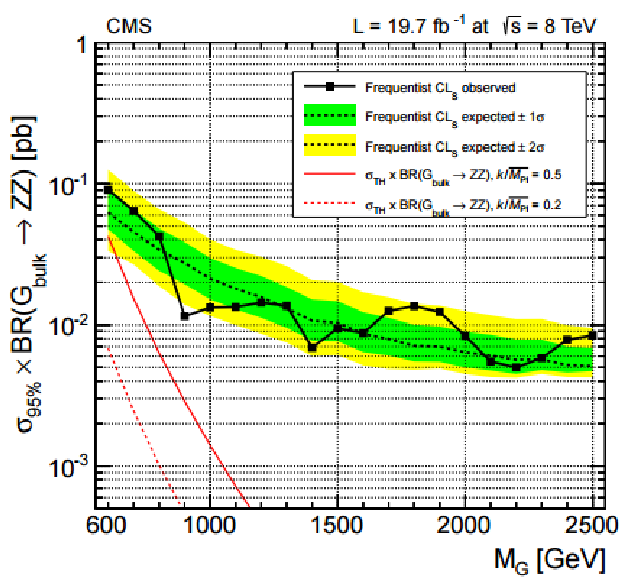
J. Ngadiuba    Resonant di-boson searches with CMS



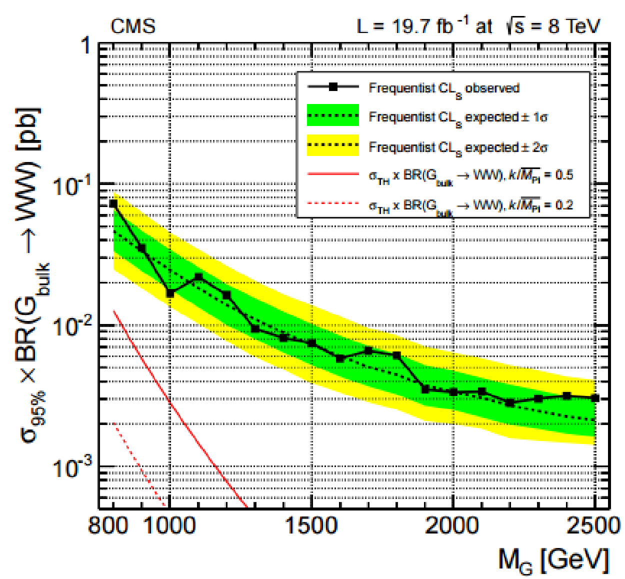

EXO-13-009 public twiki

# WZ->qq ll

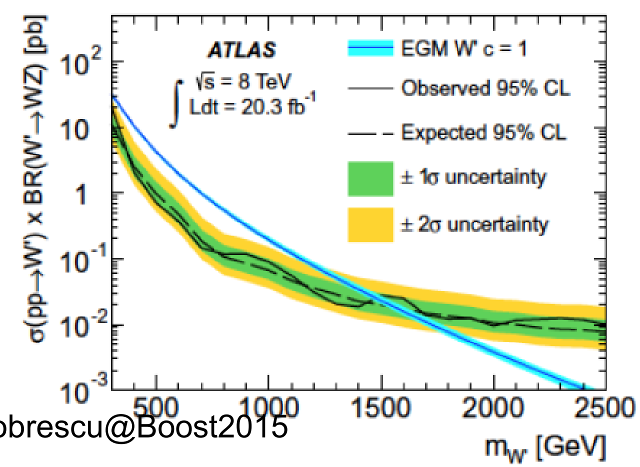
$W' \to WZ \to J(\ell^+\ell^-)$




$W' \to WZ \to (\ell\nu)J$




**CMS (1405.3447): limit on $WZ$ weaker by a factor of 2 (2.3) compared to $ZZ$ ($WW$)**

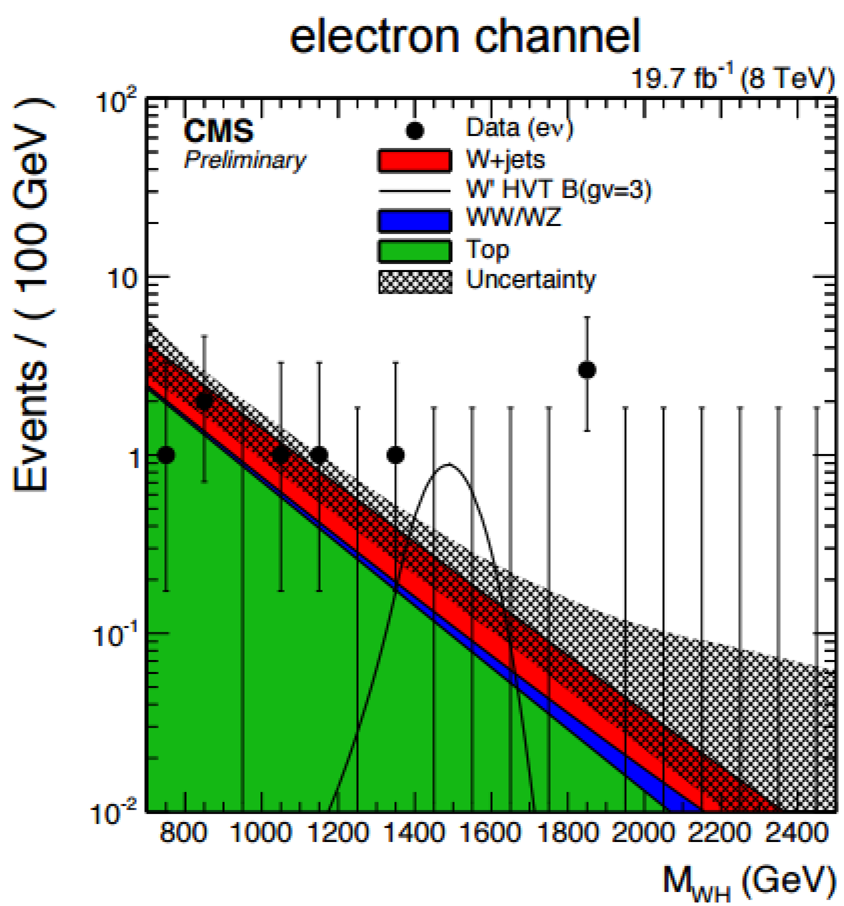


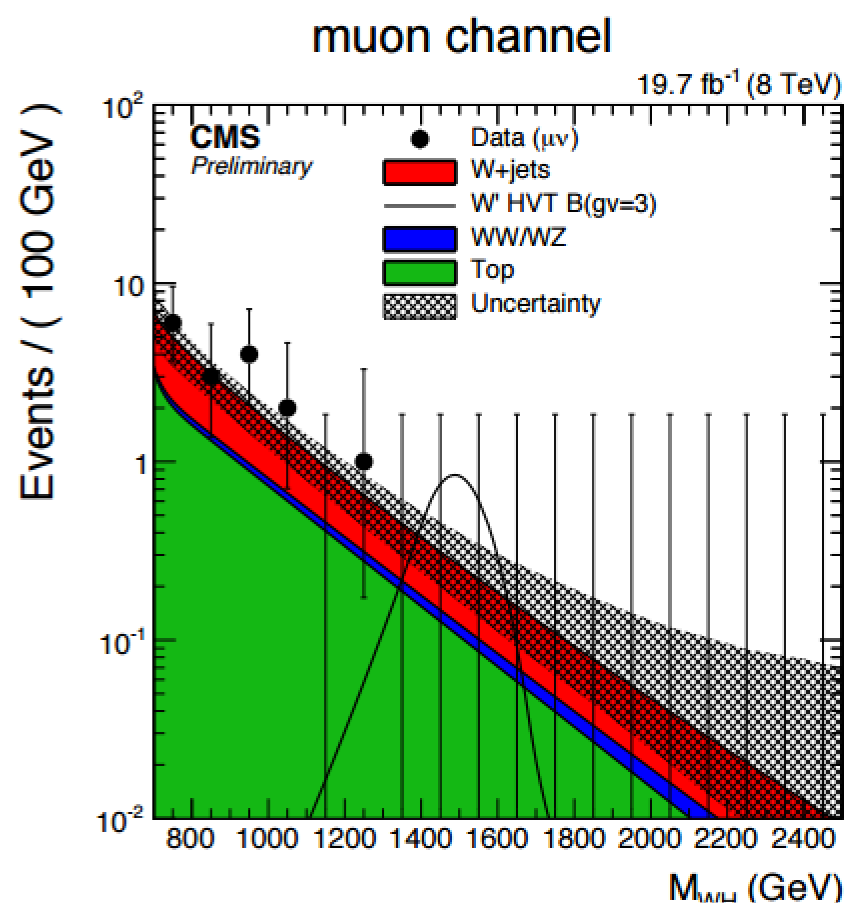

**ATLAS 1503.04677:**

$\sigma(pp \to W' \to WZ) > 12$ fb

Dobrescu@Boost2015

# WH->lv bb



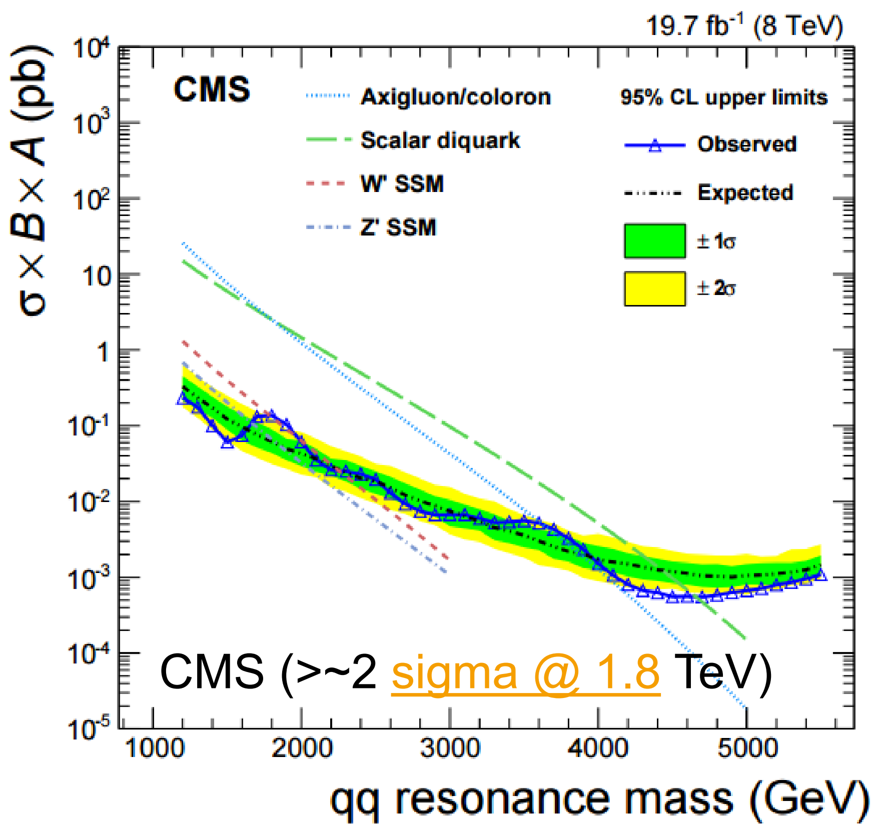




CMS-PAS-EXO-14-010

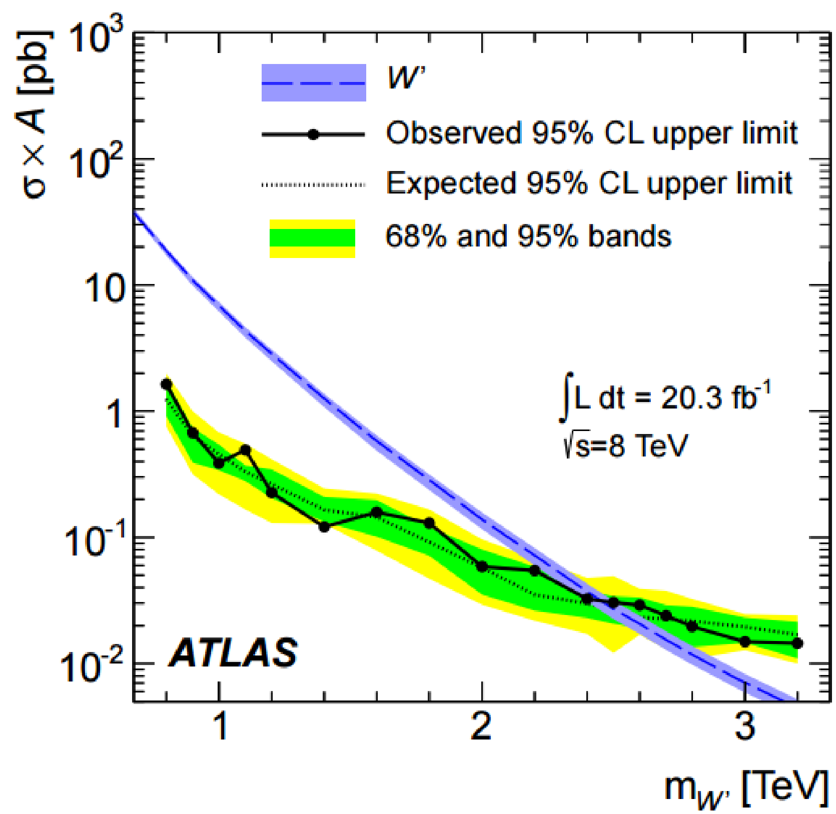
Same search techniques as W(lv)V(qq) search
Lower backgrounds due to better background rejection of H(bb)-tagger compared to W(qq)/Z(qq)-tagger
Excess in W(lv)H(bb) at 1.8 TeV has a global significance of 2.2 s.d.

# Dijets

**CMS (1501.04198):**



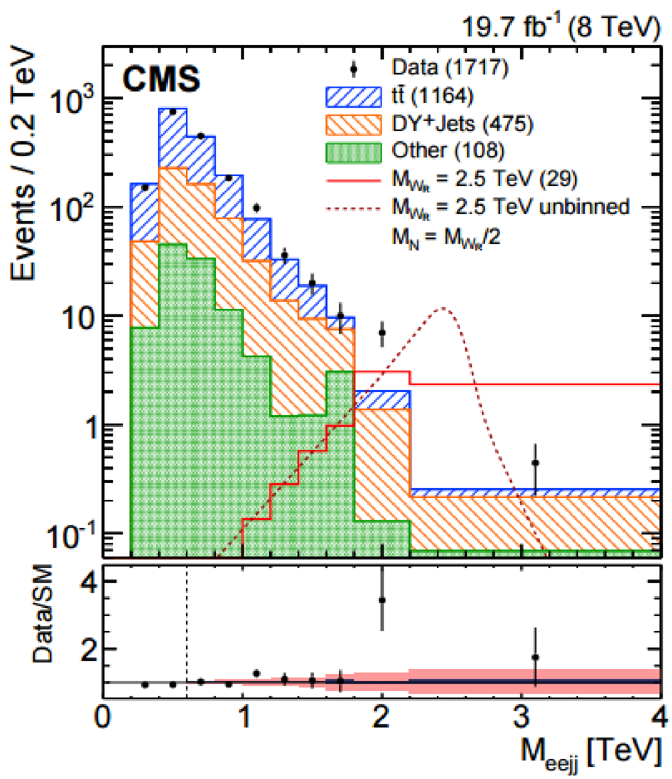

**ATLAS (1407.1376):**



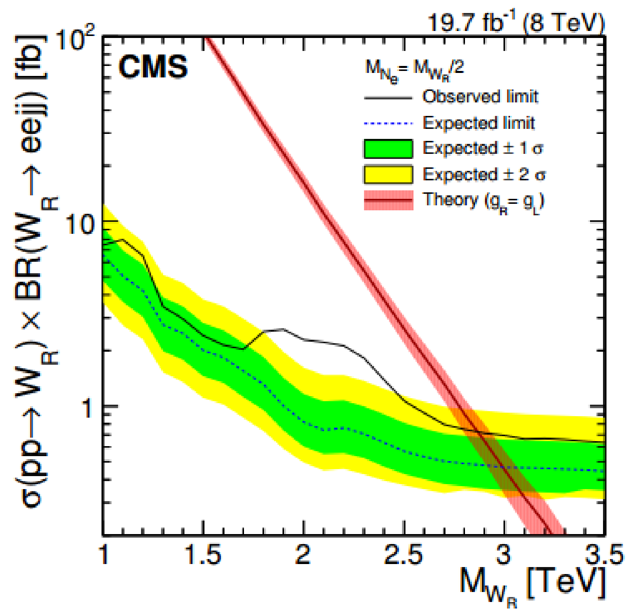
# eejj

$\underline{W' \to eN \to e^+e^-jj}$ (no $e^+e^+jj$ signal → Dirac mass for $N$)

CMS (1407.3683):




14 observed with 5 expected bkg. One event has same-sign dilepton.



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Z-dilepton peak vetoed.

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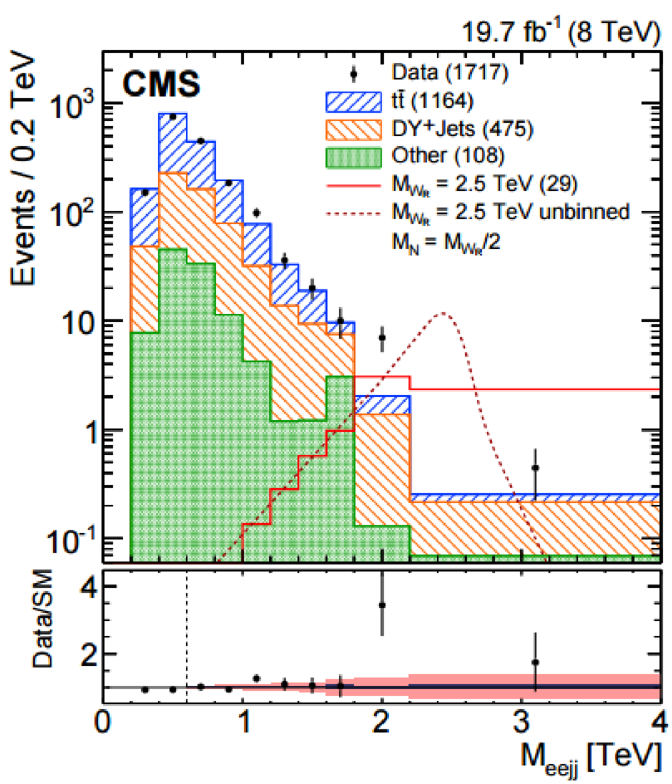


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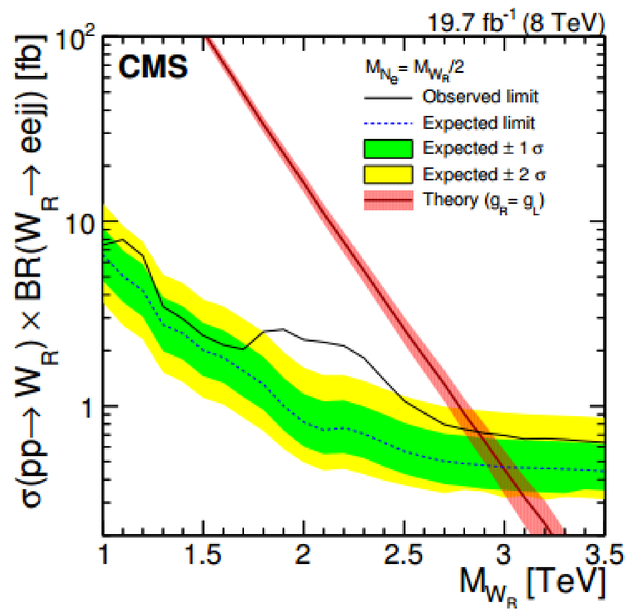

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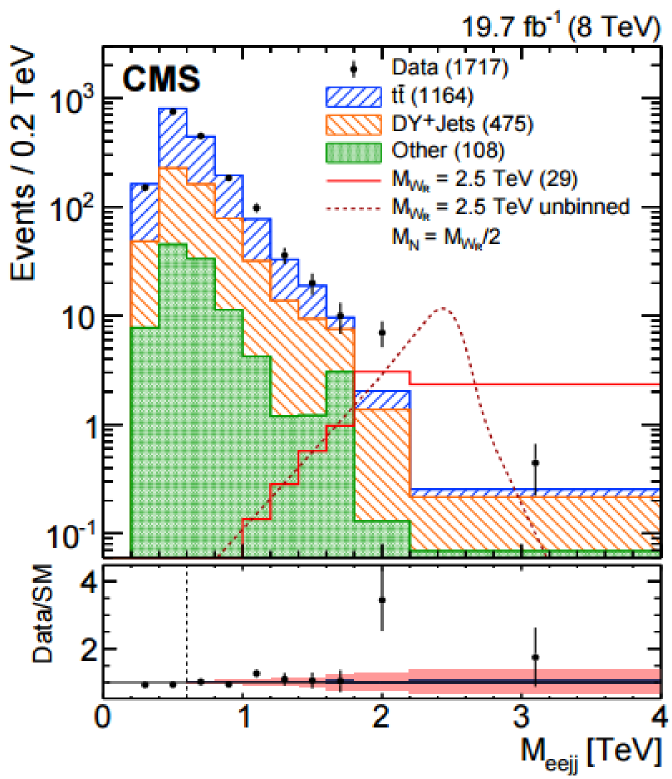
**CMS (1407.3683):**

This excess does not appear to be consistent with $W_R \to eN_e$ decay. We examined additional distributions for events with $1.8 < M_{eejj} < 2.2$ TeV, including the mass distributions $M_{ejj}$ (for both the leading and subleading electrons), $M_{ee}$, and $M_{jj}$, as well as the $p_T$ distributions for each of the final state particles. In this examination, we find no compelling evidence in favor of the signal hypothesis over the assumption of an excess of SM background events in this region.

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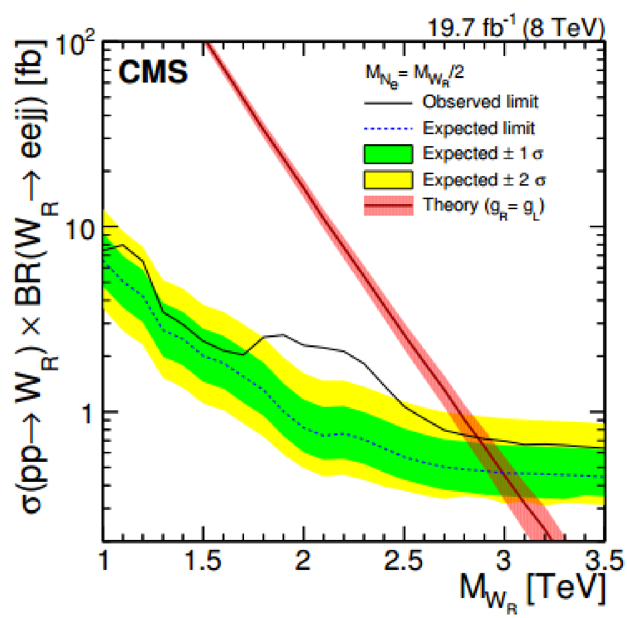

# Summary of excesses

- $e^+e^-jj$ (CMS) $2.8\sigma$ "peak" @ 1.8–2.2 TeV
- $jj$ (CMS) $\sim 2\sigma$ "peak" @ 1.8–1.9 TeV
- $JJ$ (ATLAS) $2.5\sigma$ (global) peak @ 1.8–2.1 TeV
- $J(\ell^+\ell^-)$ (CMS) $\sim 2\sigma$ "peak" @ 1.8–1.9 TeV
- $Wh \to (\ell\nu)(b\bar{b})$ (CMS) $2.2\sigma$ "peak" @ 1.8–1.9 TeV

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For these excesses, other experiments see compatible excesses with less significance (jj, JJ), or not explicit search result not available (eejj), or no excesses seen but sensitivity is worse with little tension (lvbb, lvjj).

# Interpretations

- SM
- Effective Operators
- Composite Resonances
- Gauge Boson

# SM Interpretation

Statistical fluctuations?

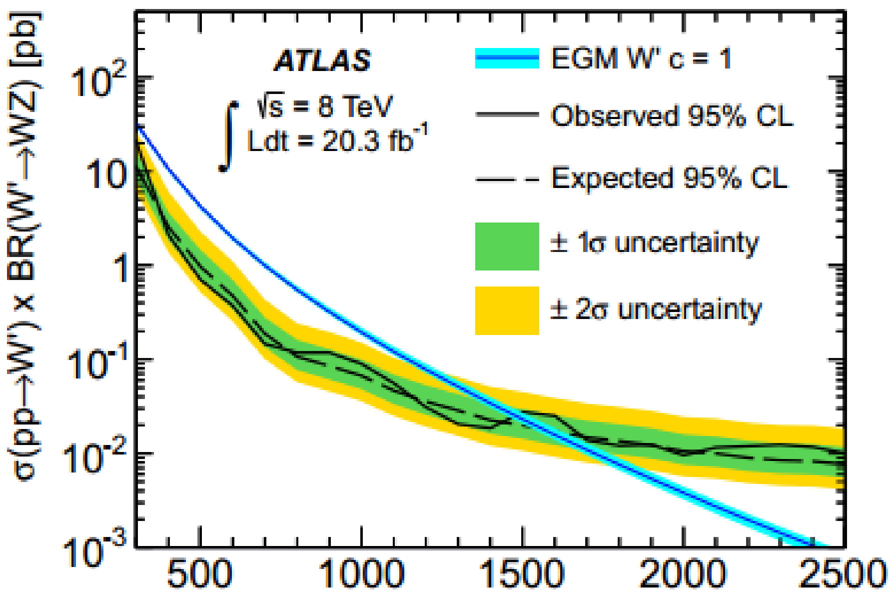
Pros:

- “bumps are everywhere” (e.g. dijets, diboson)
- “never trust last bin” (e.g. WH->lvbb, eN->eejj)

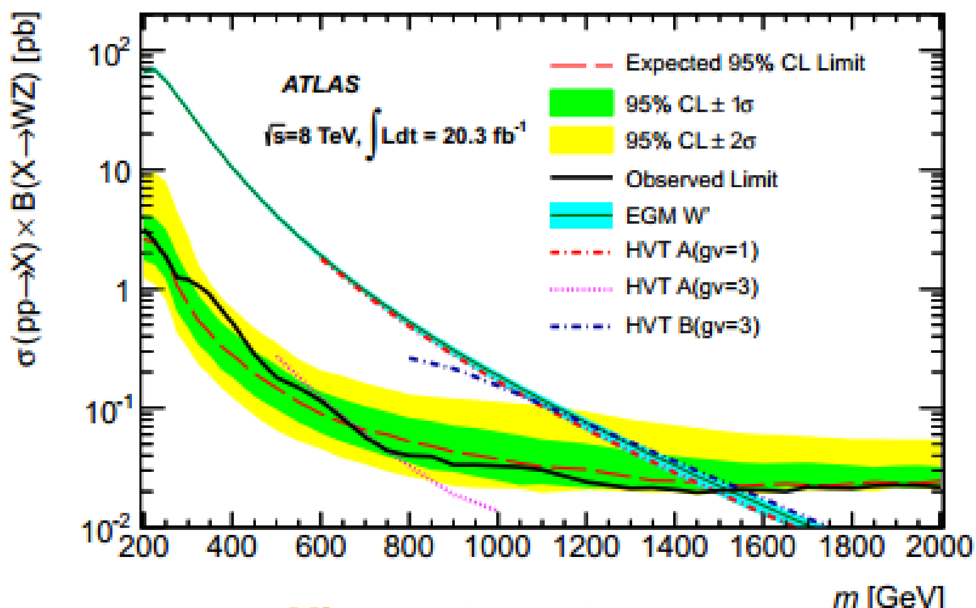
Cons:

- Experimentally un-correlated channels all see bumps near 2 TeV, some by both experiment?
- Especially when all these fits in very simple extension of the SM?

# Diboson-Other channels (ATLAS)

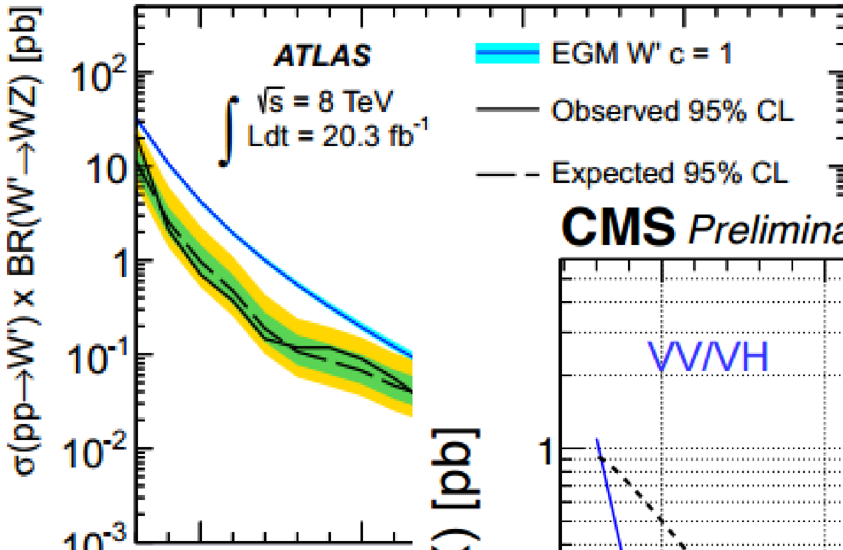



lvjj, arXiv:1503.04677

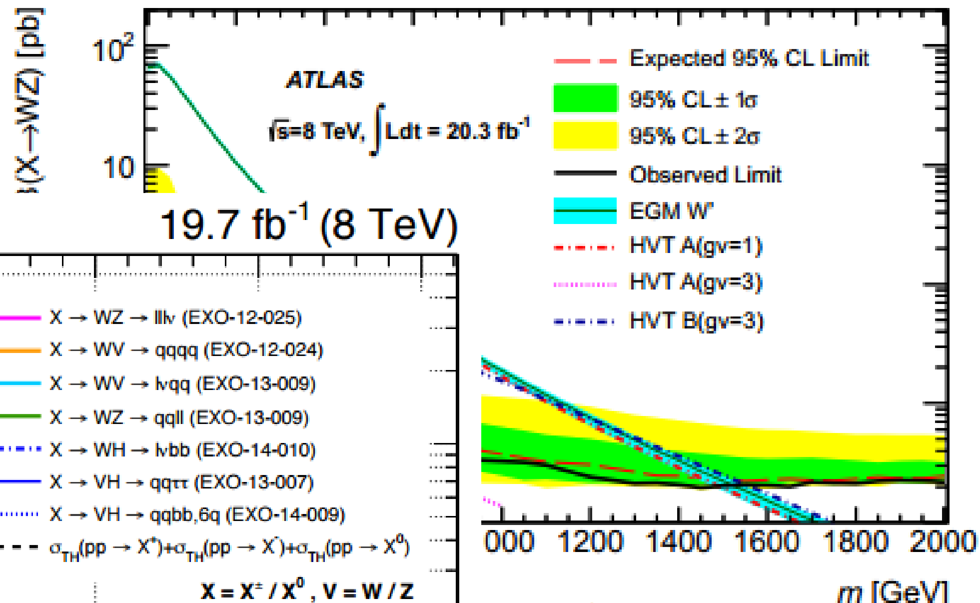



lvll, arXiv:1406.4456

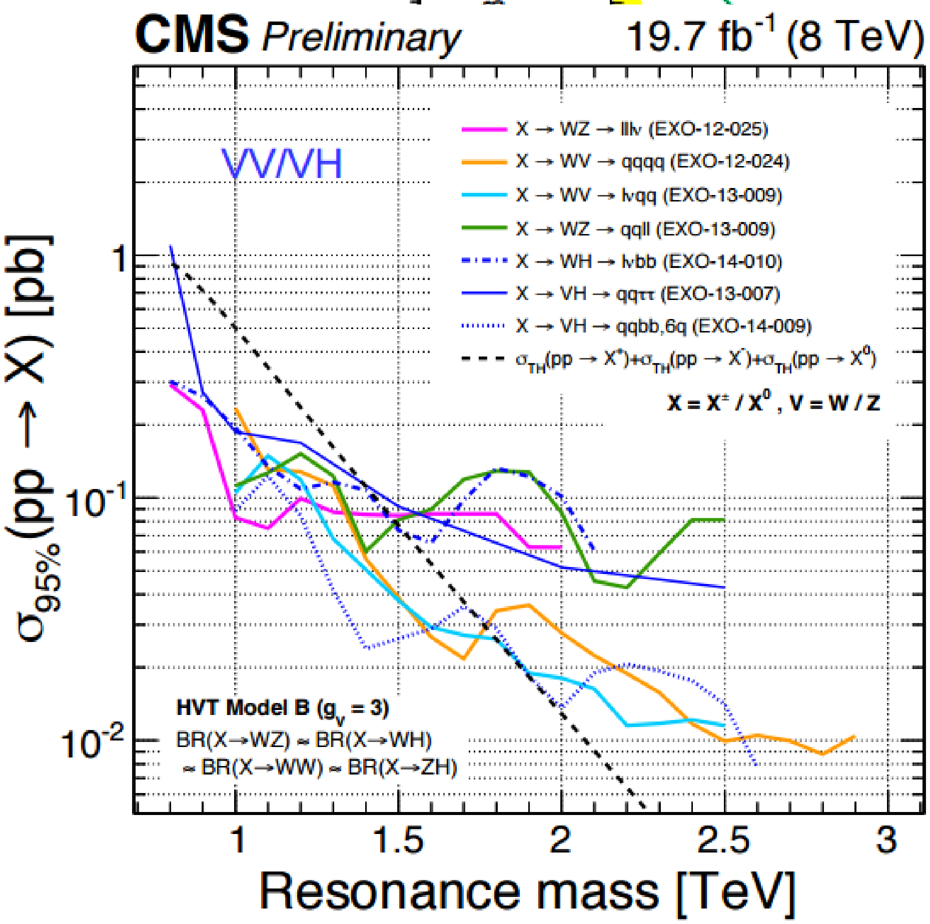
# Diboson-Other channels (ATLAS)




lvjj, arXiv:150




.4456




No excess seen, not excluding.

CMS plot only exclusion, no expected limit, so hard to tell excess.

But WZ->lvjj does have minor tension.

# Effective Operators

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$J(\ell^+\ell^-)$ (CMS) $\sim 2\sigma$ "peak" @ 1.8–1.9 TeV

$Wh \to (\ell\nu)(b\bar{b})$ (CMS) 2.2$\sigma$ "peak" @ 1.8–1.9 TeV

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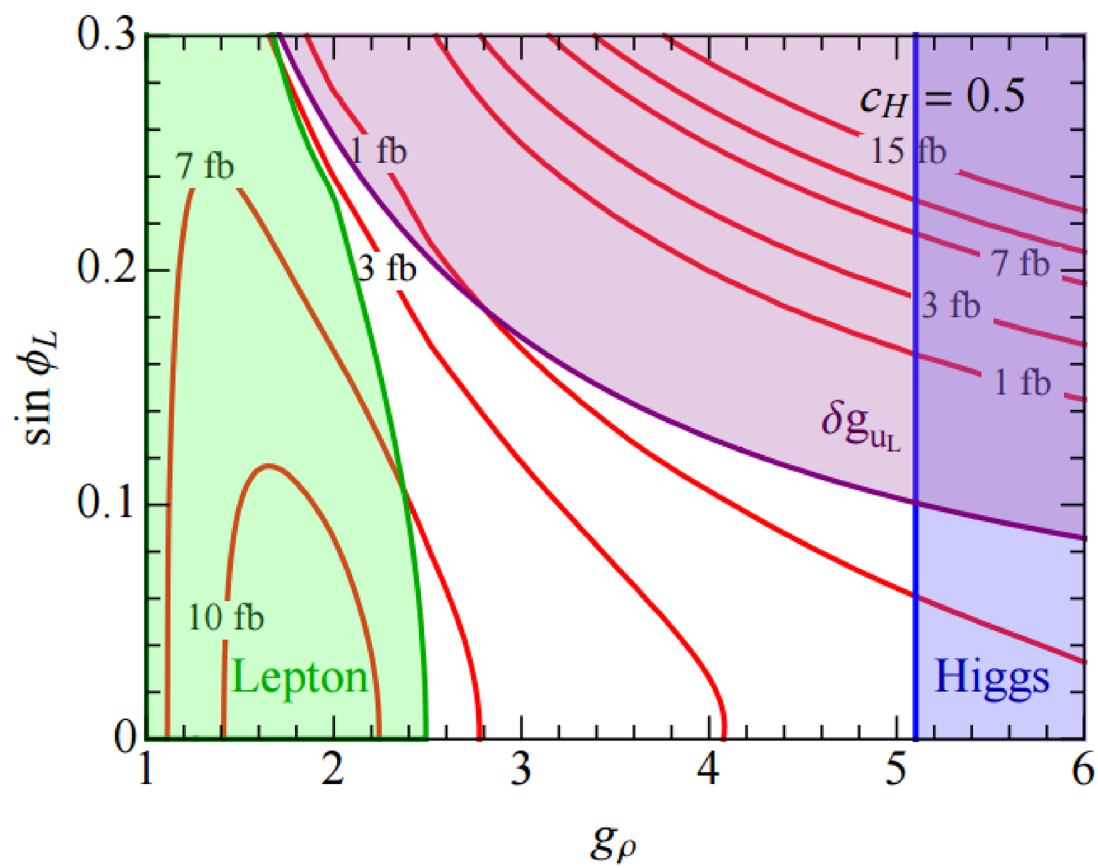
Quite a few attempts to fit JJ resonances (essentially with effective interactions), a production term and a decay interaction term.

Examples are walking technicolor interpretation, lepto-phobic Z' interpretation (due to dilepton constraints), heavy-vector-triplet interpretation, spin-0/1/2 effective operator interpretation, WBF production interpretation, and so on.

# Composite Resonance




Composite resonances, unitarize weak boson scattering, decays dominantly to weak boson pairs.

Production are mainly from quark-heavy quark mixing. (receives constrains from EWPO)

An argument for composite resonance is in composite Higgs models, the tuning is large if not the composite scalar below a few TeV.

M. Low, A. Tesi, L.-T. Wang, arXiv:1507.07557

# Gauge Boson

$e^+e^-jj$ (CMS) $2.8\sigma$ “peak” @ 1.8–2.2 TeV

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# Gauge Boson

| | | |
|---|---|---|
| $e^+e^-jj$ | (CMS) $2.8\sigma$ "peak" @ 1.8–2.2 TeV | 1~2 fb |
| $jj$ | (CMS) $\sim 2\sigma$ "peak" @ 1.8–1.9 TeV | 100~200 fb |
| $JJ$ | (ATLAS) $2.5\sigma$ (global) peak @ 1.8–2.1 TeV | 3~10 fb |
| $J(\ell^+\ell^-)$ | (CMS) $\sim 2\sigma$ "peak" @ 1.8–1.9 TeV | ~few fb |
| $Wh \to (\ell\nu)(b\bar{b})$ | (CMS) $2.2\sigma$ "peak" @ 1.8–1.9 TeV | ~few fb |

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Many aspects point us toward a charged gauge boson explanation:

- Sizable production, dominant decays into dijet
- Decays to Wh
- accommodates eejj

# Gauge Boson

| | |
|---|---|
| $W' \to eN \to e^+e^-jj$ (CMS) $2.8\sigma$ "peak" @ 1.8–2.2 TeV | 1~2 fb |
| $W' \to jj$ (CMS) $\sim 2\sigma$ "peak" @ 1.8–1.9 TeV | 100~200 fb |
| $W' \to WZ \to JJ$ (ATLAS) $2.5\sigma$ (global) peak @ 1.8–2.1 TeV | 3~10 fb |
| $W' \to WZ \to J(\ell^+\ell^-)$ (CMS) $\sim 2\sigma$ "peak" @ 1.8–1.9 TeV | ~few fb |
| $W' \to Wh \to (\ell\nu)(b\bar{b})$ (CMS) $2.2\sigma$ "peak" @ 1.8–1.9 TeV | ~few fb |

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# $W_R$—works out of the box

Due to constraints from lepton+Missing Energy search, W' should have little/no couplings to SM lepton and neutrino.

Right-handed W' is a very straight forward choice and works out of the box.

Simply count by degree of freedom, ignoring the phase space factors, partial widths

$$jj: tb: lN: WZ: Wh = 24: 12: 4: 1: 1$$

and branching fractions

$$jj: tb: WZ: Wh = \sim 60\%: 30\%: 3\%: 3\%$$

*assuming W-W' mass mixing; WZ and Wh only longtitugonal modes counts; lN has a bit more complexities.

# $SU(2)_R$ extension (LR-symmetric model)

$$SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

$$\downarrow W_R, Z_R \qquad g_R, g_{B-L} \to g', \quad g_L \to g$$

$$SU(2)_L \times U(1)_Y$$

$$\downarrow W, Z$$

$$U(1)_{em}$$

$g_R$ is the only free parameter in gauge couplings, others are fixed by SM condition.

Masses and mixings determined by details of the symmetry breaking.

LR-symmetric standard model as very long history. Our proposal is one variation. See Mohapatra's book and earlier works. For many detailed properties of this model, see Q.-H. Cao, Z. Li, J.-H. Yu and C.P. Yuan arXiv:1205.3769.

# $W_R$—model details

**$W_R$ arises from (almost minimal) gauge extension of the SM.**

| Fields | $SU(2)_L$ | $SU(2)_R$ | $U(1)_{B-L}$ |
|---|---|---|---|
| $(u_L,\ d_L)$ | 2 | 1 | $+1/3$ |
| $(u_R,\ d_R)$ | 1 | 2 | $+1/3$ |
| $(\nu_L,\ \ell_L)$ | 2 | 1 | $-1$ |
| $(N_R,\ \ell_R)$ | 1 | 2 | $-1$ |
| $\psi_L\ ,\ \psi_R$ | 1 | 2 | $+1$ |
| $\Sigma$ | 2 | 2 | 0 |
| $T$ | 1 | 3 | $+2$ |

A simple anomaly free assignment of the quantum number for extended SM particle content.

Right-handed heavy neutrinos introduced to form $SU(2)_R$ doublet.

Bi-doublet Higgs introduced to induce $W_L - W_R$ mass mixing.

Triplet Scalar introduced to break $SU(2)_R$, granting mass to W' and Z'.

Additional vector fermion introduce to give raise to Dirac mass of the right-handed neutrino.

# $\boldsymbol{W_L - W_R}$ mixing and masses

Higgs Triplet $T \rightarrow U_R^{+} T U_R$, after spontaneous symmetry breaking $SU(2)_R$, grants masses for $W_R, Z_R$

Higgs $\Sigma \rightarrow U_L^{+} \Sigma U_R$, its kinetic term induces mass mixing of the $W_L$ and $W_R$, and a direct coupling between them with the Higgs boson.

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$$\langle\Sigma\rangle = v_H \begin{pmatrix} \cos\beta & 0 \\ 0 & e^{i\alpha_\Sigma}\sin\beta \end{pmatrix} \qquad T = \sum_{i=1}^{3} T_i \sigma_i \equiv \begin{pmatrix} \frac{1}{\sqrt{2}} G_R^+ & T^{++} \\ u_T + \frac{1}{\sqrt{2}}(T^0 + i G_R^0) & -\frac{1}{\sqrt{2}} G_R^+ \end{pmatrix}$$

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$$\langle \Sigma \rangle = v_H \begin{pmatrix} \cos\beta & 0 \\ 0 & e^{i\alpha_\Sigma} \sin\beta \end{pmatrix} \qquad T = \sum_{i=1}^{3} T_i \sigma_i \equiv \begin{pmatrix} \frac{1}{\sqrt{2}} G_R^+ & T^{++} \\ u_T + \frac{1}{\sqrt{2}}(T^0 + i G_R^0) & -\frac{1}{\sqrt{2}} G_R^+ \end{pmatrix}$$

$$(W_L^{+\mu}, W_R^{+\mu}) \begin{pmatrix} g_{2_L}^2 \frac{v_H^2}{2} & -g_{2_L} g_{2_R} \frac{v_H^2}{2} \sin 2\beta \\ -g_{2_L} g_{2_R} \frac{v_H^2}{2} \sin 2\beta & g_{2_R}^2 \left( u_T^2 + \frac{v_H^2}{2} \right) \end{pmatrix} \begin{pmatrix} W_{L\mu}^- \\ W_{R\mu}^- \end{pmatrix}$$

# $W_L - W_R$ mixing and masses

Higgs Triplet $T \to U_R^{+} T U_R$, after spontaneous symmetry breaking $SU(2)_R$, grants masses for $W_R, Z_R$

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$$M_W = \frac{g\, v_H}{\sqrt{2}}$$

$$M_{W'} = g_{\rm R}\, u_T$$

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Higgs Triplet $T \to U_R^+ T U_R$, after spontaneous symmetry breaking $SU(2)_R$, grants masses for $W_R, Z_R$

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$$\begin{aligned} W_\mu^\pm &= W_{L\mu}^\pm \cos\theta_+ + W_{R\mu}^\pm \sin\theta_+ \\ W_\mu'^\pm &= -W_{L\mu}^\pm \sin\theta_+ + W_{R\mu}^\pm \cos\theta_+ \end{aligned} \qquad \sin\theta_+ = \frac{g_R}{g} \left(\frac{M_W}{M_{W'}}\right)^2 \sin 2\beta \qquad \begin{aligned} M_W &= \frac{g\, v_H}{\sqrt{2}} \\ M_{W'} &= g_R\, u_T \end{aligned}$$

# W' decays

$$
\begin{aligned}
\Gamma(W_R^\pm \to N_i \ell^\pm) &= \frac{g_R^2}{48\pi} |U'_{\ell N_i}|^2 M_{W_R} \left(1 + \frac{M_{N_i}^2}{2M_{W_R}^2}\right)\left(1 - \frac{M_{N_i}^2}{M_{W_R}^2}\right)^2 , \\
\Gamma(W_R^+ \to t\bar{b}) &= \frac{g_R^2}{16\pi} M_{W_R} \left(1 + \frac{M_t^2}{2M_{W_R}^2}\right)\left(1 - \frac{M_t^2}{M_{W_R}^2}\right)^2 , \\
\Gamma(W_R^+ \to u\bar{d}) &= \Gamma(W_R^+ \to c\bar{s}) \;=\; \frac{g_R^2}{16\pi} M_{W_R} , \\
\Gamma(W_R^\pm \to W^\pm Z) &= \frac{g_R^2}{192\pi} M_{W_R} \sin^2 2\beta \left(1 - 2\frac{M_W^2 + M_Z^2}{M_{W_R}^2} + \frac{(M_W^2 - M_Z^2)^2}{M_{W_R}^4}\right)^{3/2} \\
&\quad \times \left(1 + 10\frac{M_W^2 + M_Z^2}{M_{W_R}^2} + \frac{M_W^4 + 10M_W^2 M_Z^2 + M_Z^4}{M_{W_R}^4}\right) , \\
\Gamma(W_R^\pm \to W^\pm H) &= \frac{g_R^2}{192\pi} M_{W_R} \cos^2(\alpha + \beta) \left(1 - 2\frac{M_W^2 + M_H^2}{M_{W_R}^2} + \frac{(M_W^2 - M_H^2)^2}{M_{W_R}^4}\right)^{1/2} \\
&\quad \times \left(1 + \frac{10M_W^2 - 2M_H^2}{M_{W_R}^2} + \frac{(M_W^2 - M_Z^2)^2}{M_{W_R}^4}\right) ,
\end{aligned}
$$

# W’ decays

$$\Gamma(W_R^\pm \to N_i \ell^\pm) = \frac{g_R^2}{48\pi} M_{W_R}$$

$$\Gamma(W_R^+ \to t\bar{b}) = \frac{g_R^2}{16\pi} M_{W_R}$$

$$\Gamma(W_R^+ \to u\bar{d}) = \Gamma(W_R^+ \to c\bar{s}) = \frac{g_R^2}{16\pi} M_{W_R} ,$$

$$\Gamma(W_R^\pm \to W^\pm Z) = \frac{g_R^2}{192\pi} M_{W_R} \sin^2 2\beta$$

$$\Gamma(W_R^\pm \to W^\pm H) = \frac{g_R^2}{192\pi} M_{W_R} \cos^2(\alpha+\beta)$$

# W' decays

$$\Gamma(W' \to Wh) \approx \frac{1}{192\pi} g^2_{W'Wh} \frac{v^2}{m^2_W} m_{W'}$$

$$\Gamma(W' \to WZ) \approx \frac{1}{192\pi} g^2_{W'WZ} \frac{m^4_{W'}}{m^2_W m^2_Z} m_{W'}$$

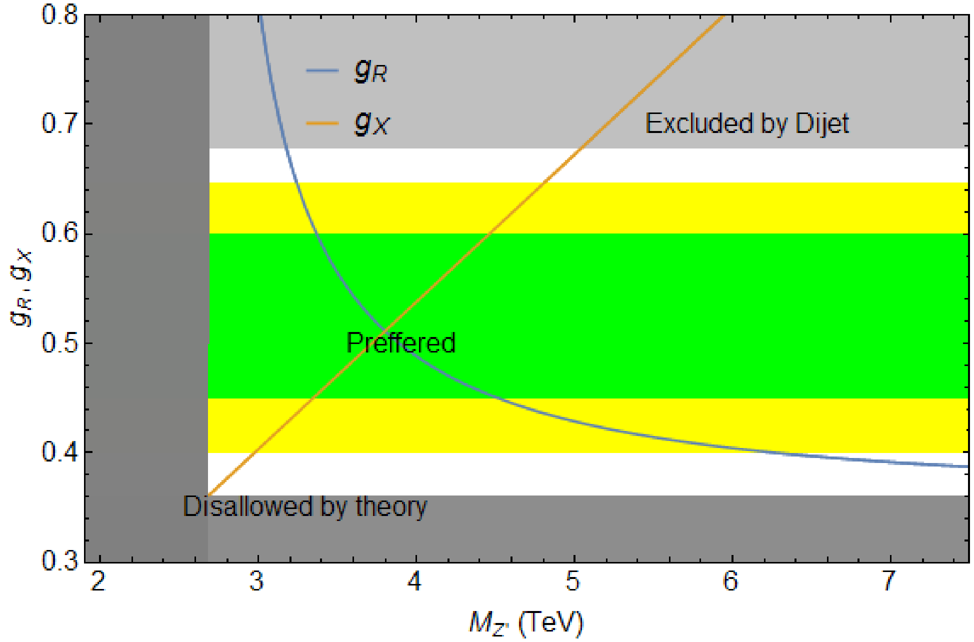
$W' \to Wh$ has one power of longtitugonal enhancement
$W' \to WZ$ has two power of such enhancement, and a derivative in enhancement in the couplings, but suppressed by the $W_L - W_R$ mixing squared.

Such that they end up being equivalent.

# Preferred values

For fixed W’ mass (as observed), only one free-parameter left $g_R$, which can be represented by Z’ mass.

# Preferred values

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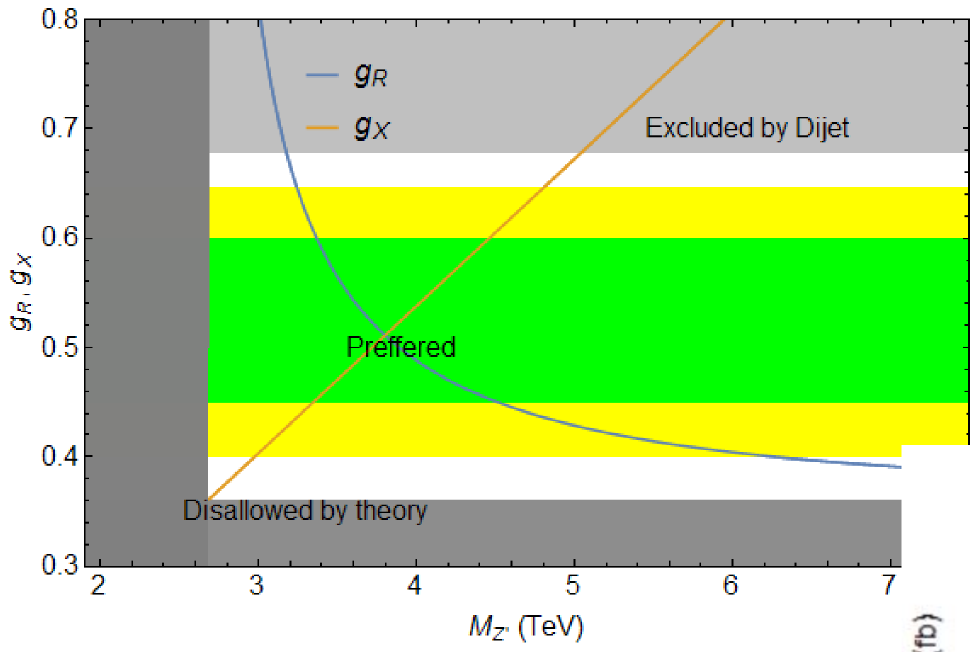


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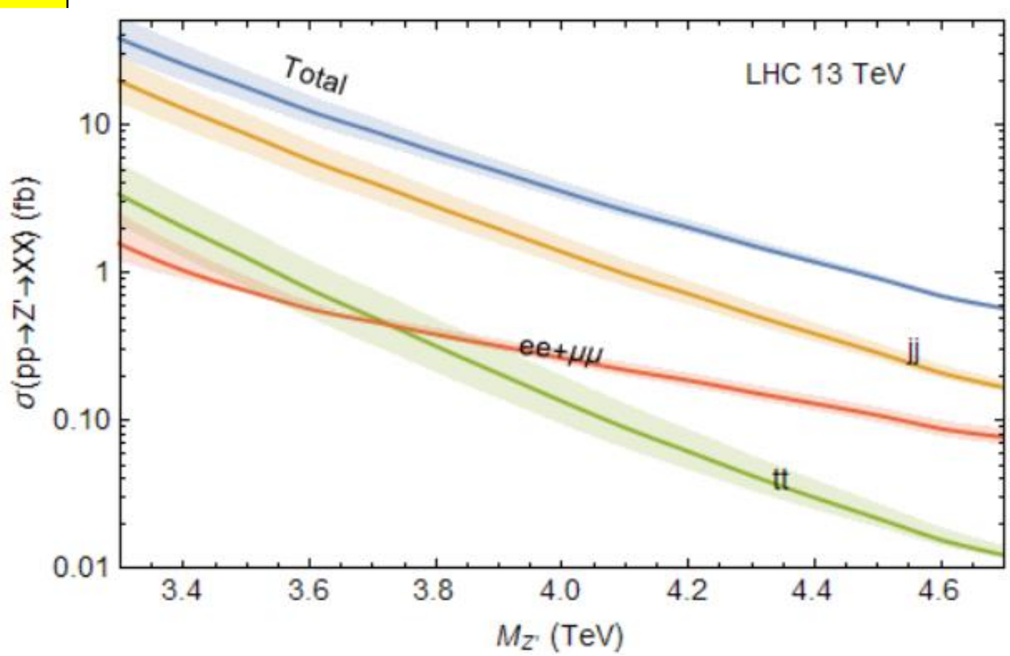
Z' properties predicted, up to heavy neutrino sector, vector fermions and heavy Higgs boson branching fractions.



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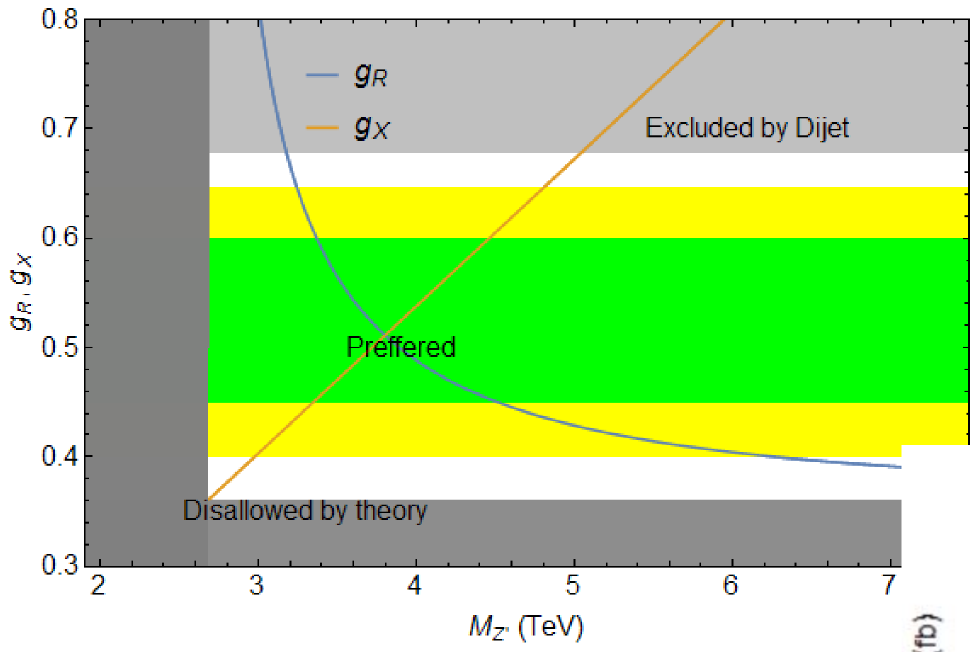
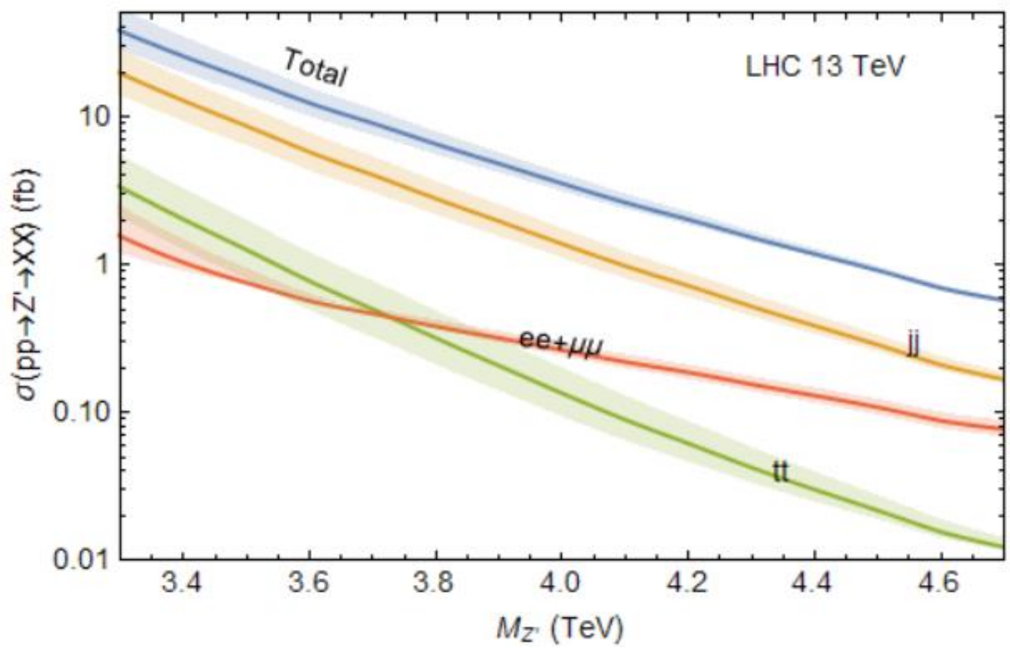



For fixed W’ mass (as observed), only one free-parameter left $g_R$, which can be represented by Z’ mass.

Z’ properties predicted, up to heavy neutrino sector, vector fermions and heavy Higgs boson branching fractions.

If $SU(2)_R$ is broken by a doublet Higgs, then W’ an will be degenerate in mass; dilepton resonant sear puts strong constraints on it, e.g., see study by Q.-Cao, B. Yan and D.M. Zhang, **arXiv:1507.00268**



# Heavy Higgs Physics

The bidoublet Higgs $\Sigma$ after $SU(2)_R$ breaking becomes essentially two-Higgs-doublet model with less parameters in the Higgs potential due to additional symmetries before breaking.

Its mass are in general in TeV scale.

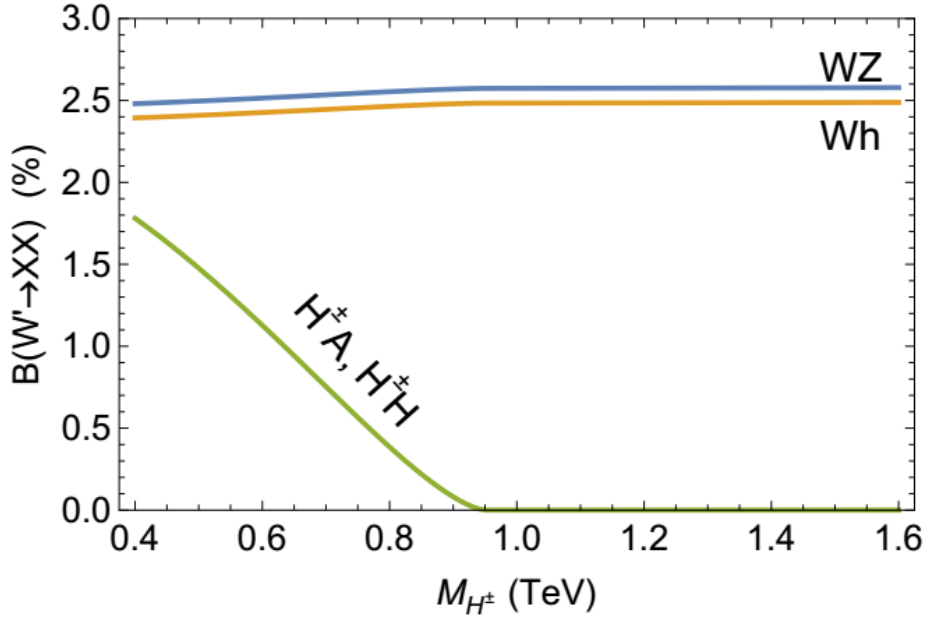
W' can then decay to heavy Higgs bosons.

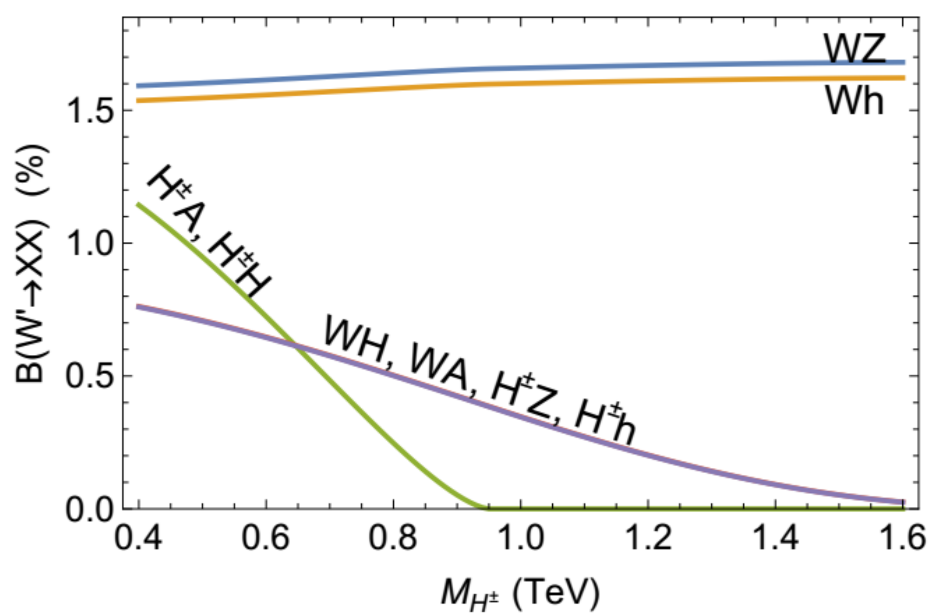
# W' decay to Higgs bosons

For different values of $tan\beta$, rich phenomenology can be achieved.

The sum of W' decays to boson are fixed, due to equivalence theorem.

# W' decay to Higgs bosons

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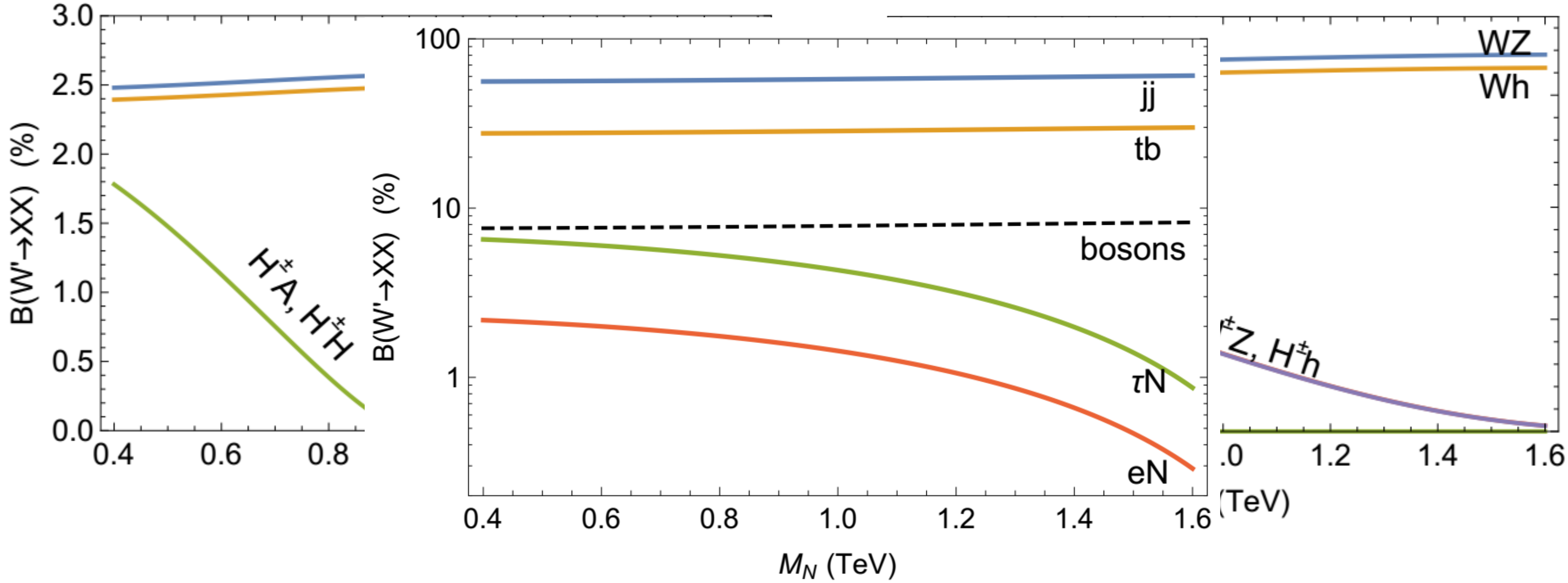


For different values of $tan\beta$, rich phenomenology can be achieved.

The sum of W’ decays to boson are fixed, due to equivalence theorem.

# W' to Higgs bosons, another excess?

| Signal | channel | efficiency | signal events | | obs. (background) |
|---|---|---|---|---|---|
| $bb\ell^\pm\ell^\pm$ | $H^\pm H^0, H^\pm A^0 \to 3t+b$ | $2.5\times10^{-4}$ | 1.0-1.8 | 4.2-6.5 | 12 $(4.3\pm1.1\pm1.1)$ |
| | $\tau N^\tau, eN^\tau \to (\tau/e)(\tau/e)tb$ | $5.2\times10^{-4}$ | 2.1-3.7 | | |
| | $t\bar{t}A^0, t\bar{t}H^0 \to 4t$ | $1.6\times10^{-2}$ | 1.1 | | |
| $\geq 3b\,\ell^\pm\ell^\pm$ | $H^\pm H^0, H^\pm A^0 \to 3t+b$ | $6.2\times10^{-4}$ | 2.5-4.4 | 5.1-7.0 | 6 $(1.1\pm0.9\pm0.4)$ |
| | $t\bar{t}A^0, t\bar{t}H^0 \to 4t$ | $4.1\times10^{-2}$ | 2.6 | | |
| $bb\ell^\pm\ell^\pm$ | $H^\pm H^0, H^\pm A^0 \to 3t+b$ | $1.6\times10^{-4}$ | 0.7-1.1 | 4.2-7.2 | 12 $(4.3\pm1.1\pm1.1)$ |
| | $WH^0,\ WA^0 \to Wt\bar{t}$ | $2.2\times10^{-4}$ | 0.9-1.6 | | |
| | $H^\pm h, H^\pm Z \to \ell tb+X$ | $0.7\times10^{-4}$ | 0.3-0.5 | | |
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| | $t\bar{t}A^0, t\bar{t}H^0 \to 4t$ | $4.1\times10^{-2}$ | 0.7 | | |

Same-sign leptons plus b-jets by ATLAS.

**ATLAS 1504.04605**

$\ell^+\ell^+ + (\geq 3)b$ **and** $\ell^+\ell^+bb$

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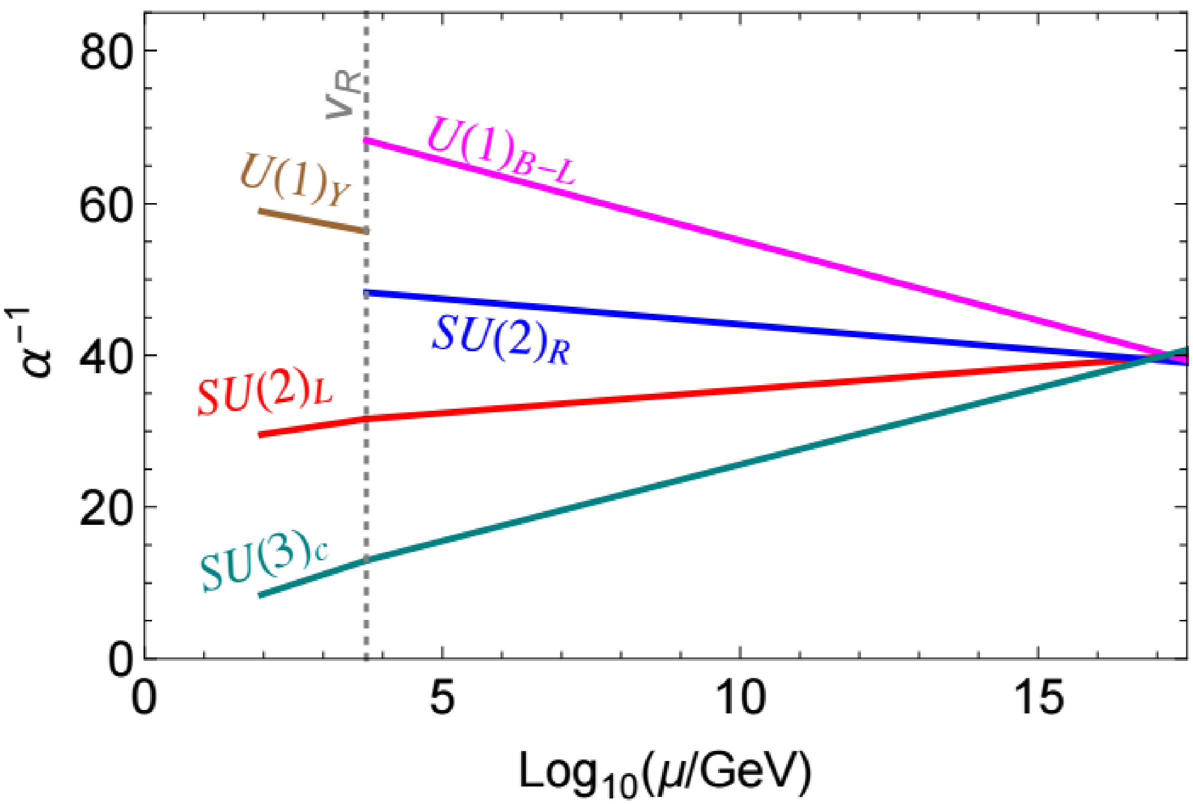
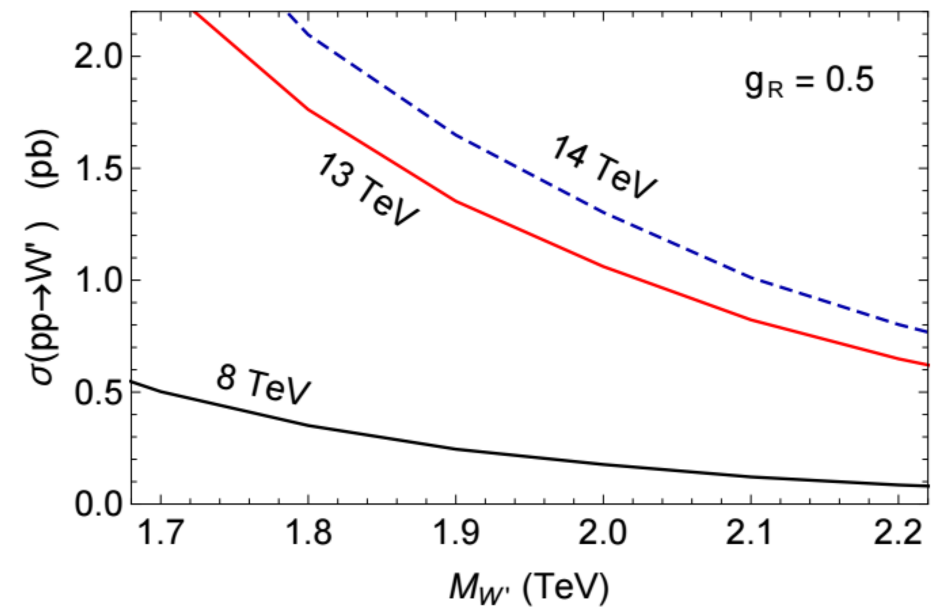
# Gauge coupling unification

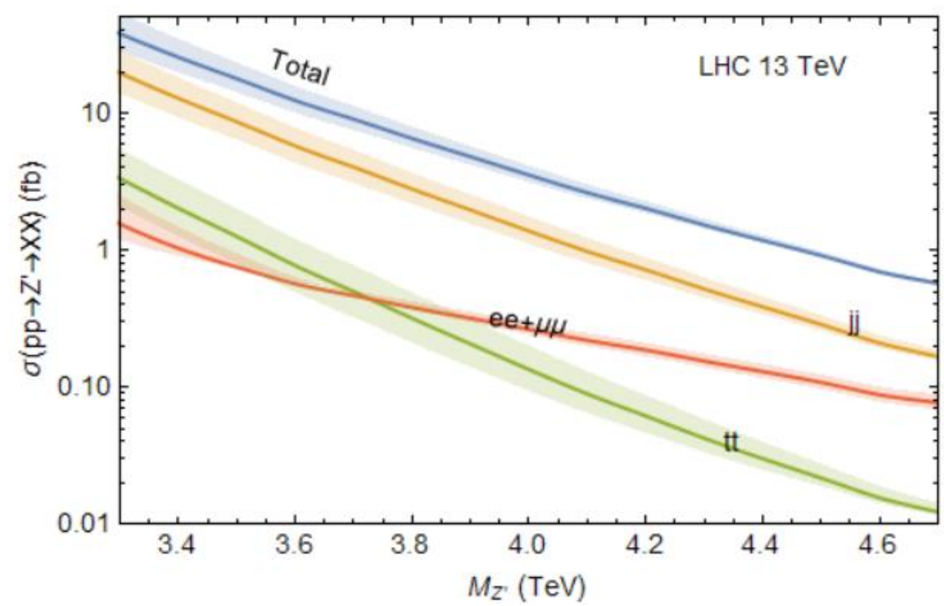



With slightly modified scalar sector and out preferred values of the gauge couplings, gauge coupling unification can be achieved, by B. Dev., R. Mohapatra, **arXiv:1508.02277**

and many related studies on best fit coupling strength, electroweak precision and dark matter (Brehmer, Hewett, Kopp, Rizzo, Tattersall, **arXiv:1507.00013**), alternative setup for eejj excess (J. Gluza, T. Jelinski, **arXiv:1504.05568**, Coloma, Dobrescu and Lopez-Pavon, **arXiv:1508.04129**, Q.-H. Cao, B. Yan and D.M. Zhang, **arXiv:1507.00268**), and many efforts from different groups.

# Run-II Prospective



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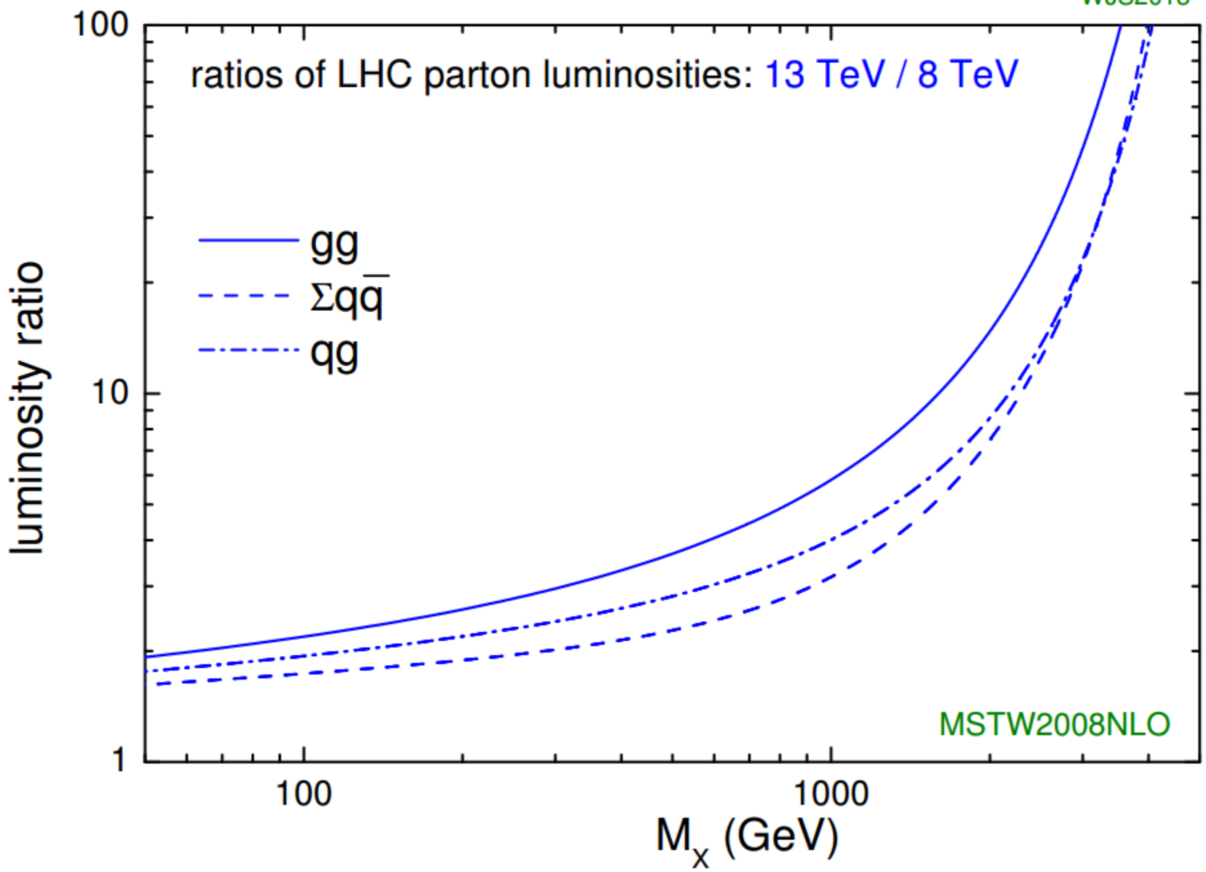


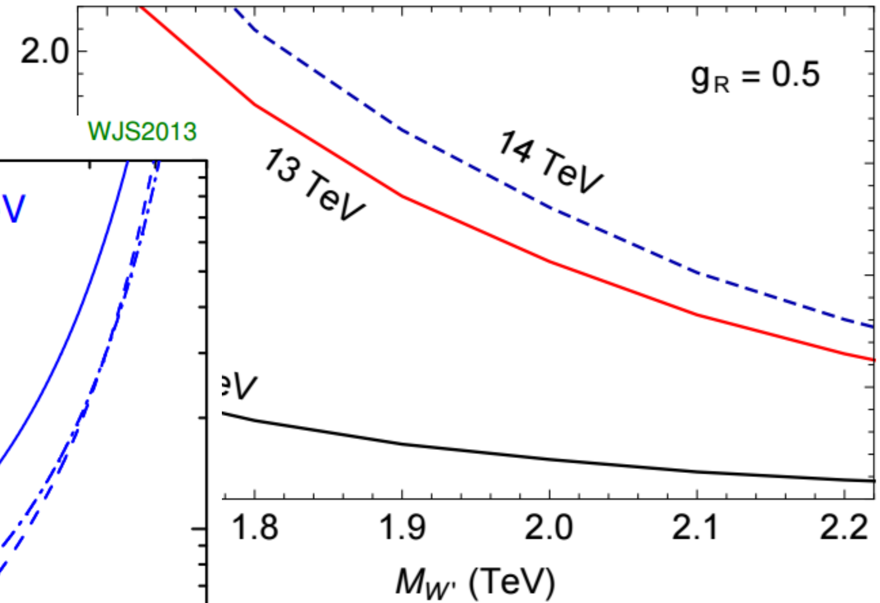


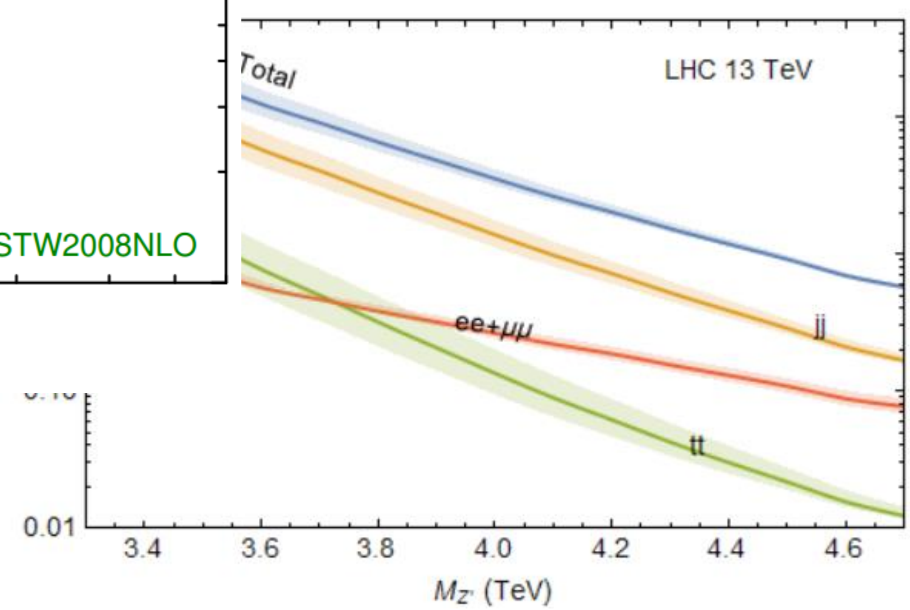


For 2 TeV resonances, the parton luminosity increases by factor of 5 or more. Assuming similar S/B at LHC 13 TeV to LHC 8 TeV, 4 fb^-1 would be able to check the consistency.

# Run-II data

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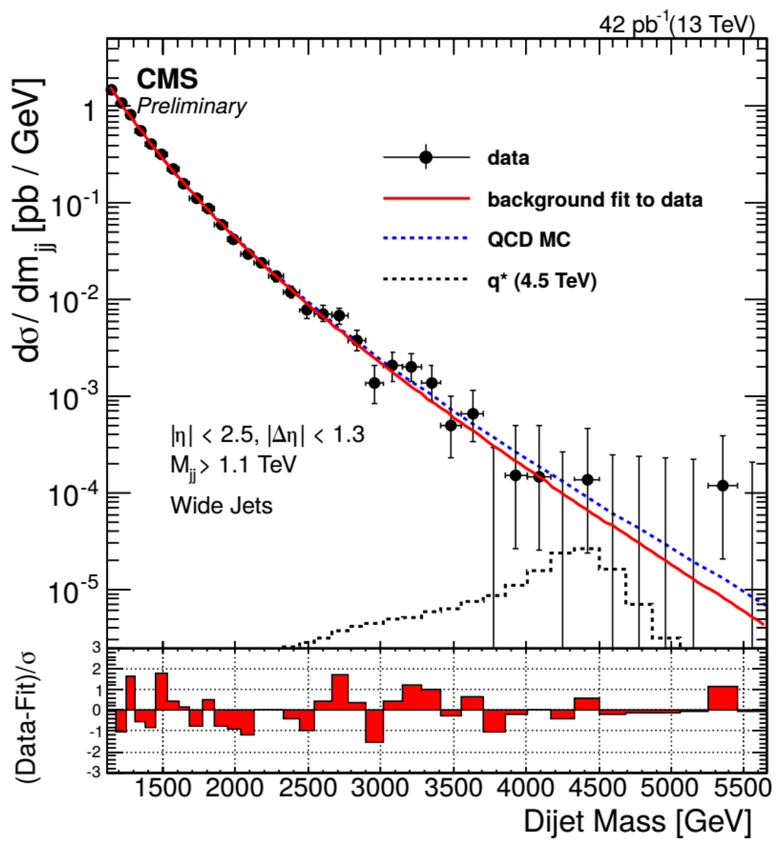


CMS-EXO-15-001-PAS

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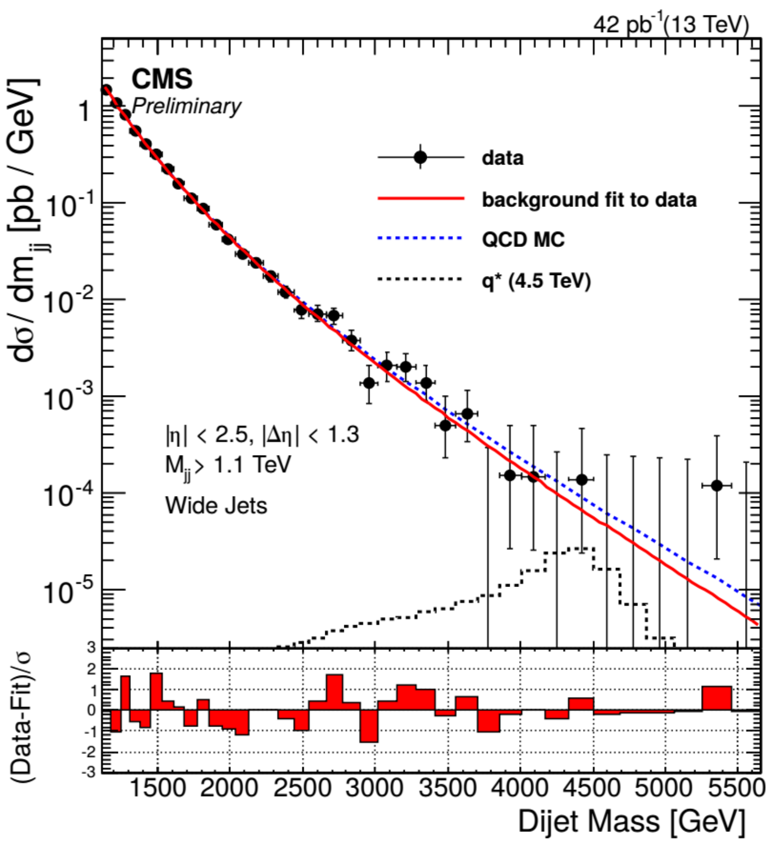
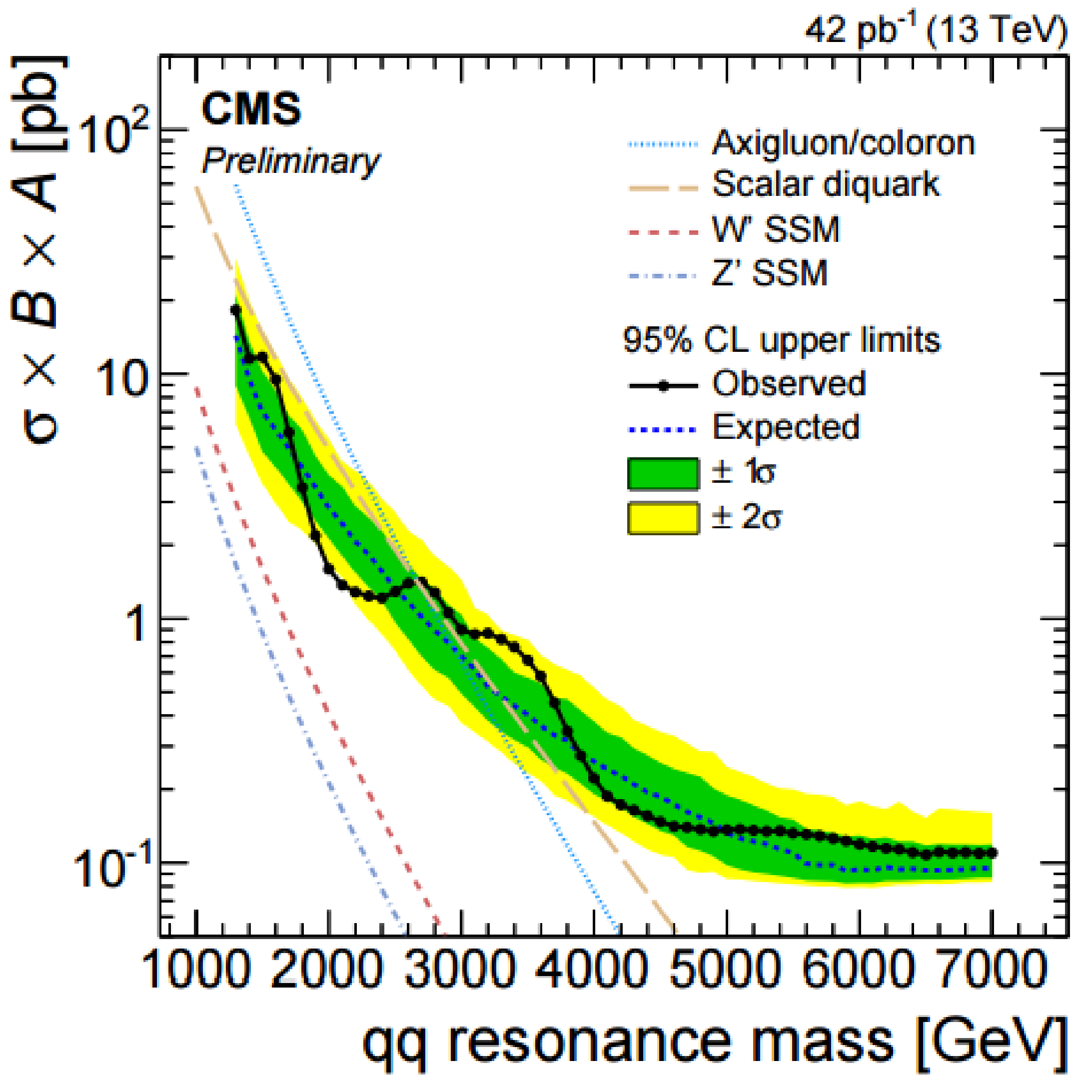
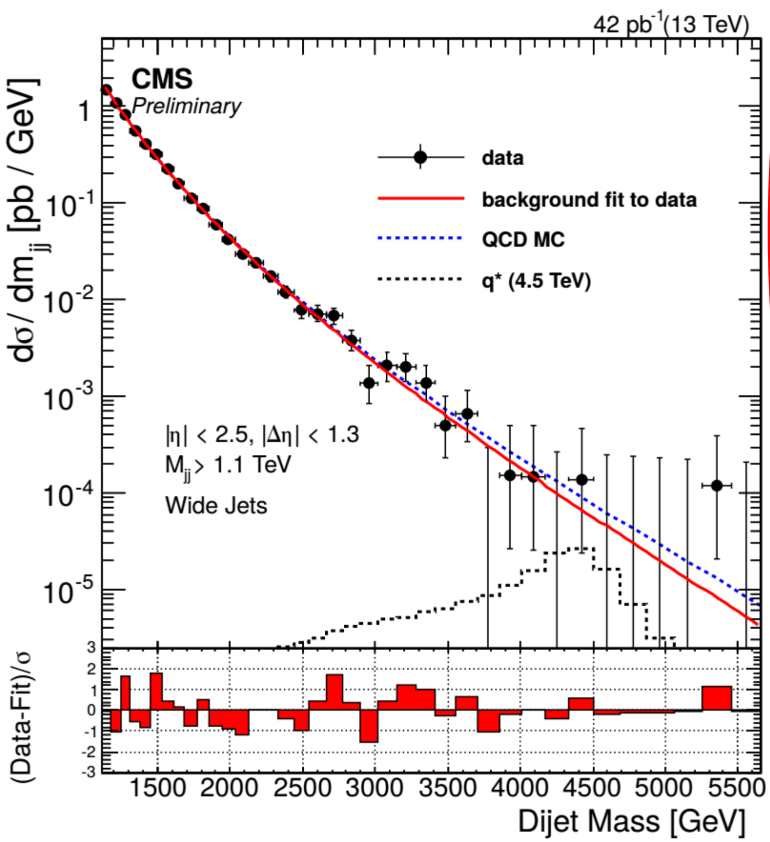


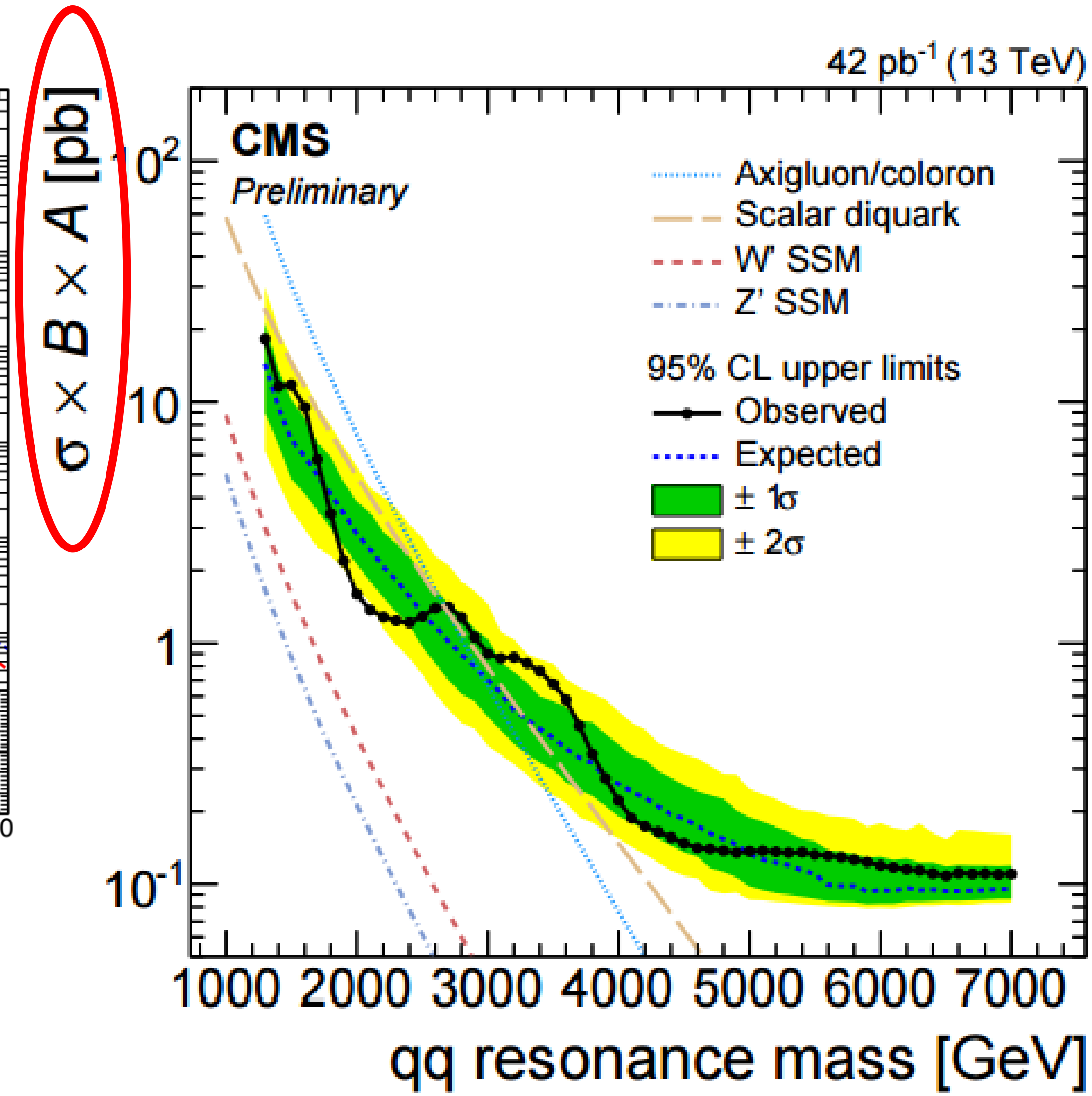




CMS-EXO-15-001-PAS

# Run-II data

$$\sigma BA \approx \sim 0.2\, pb$$




CMS-EXO-15-001-PAS

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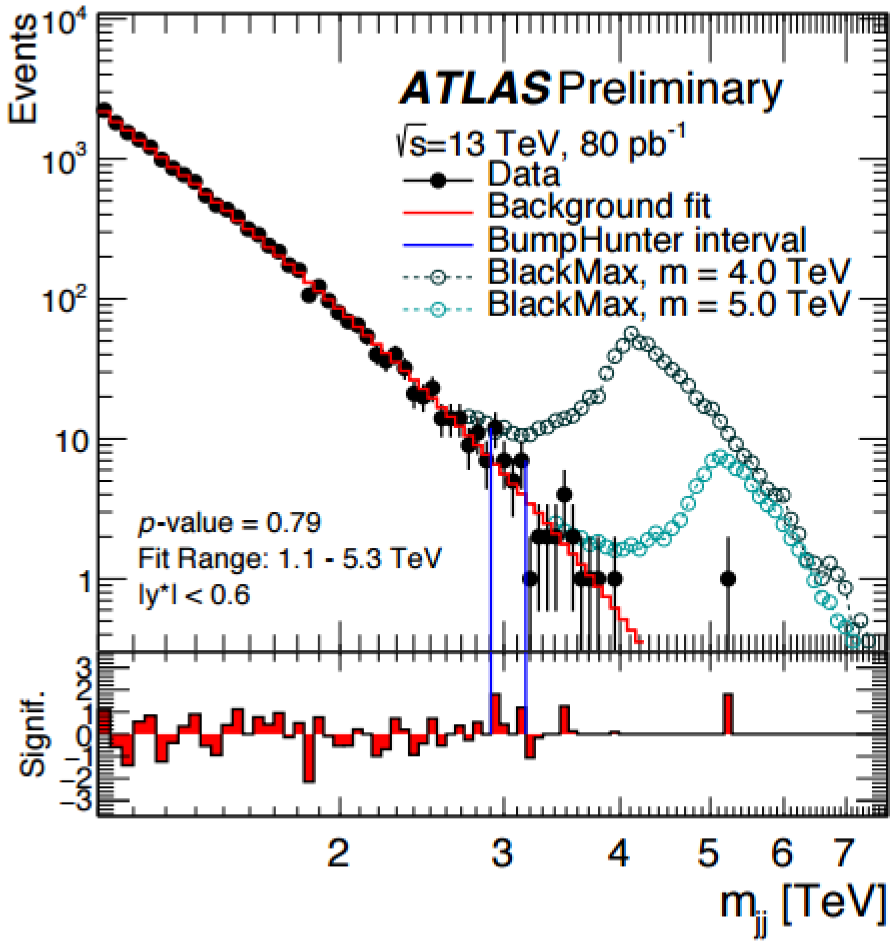
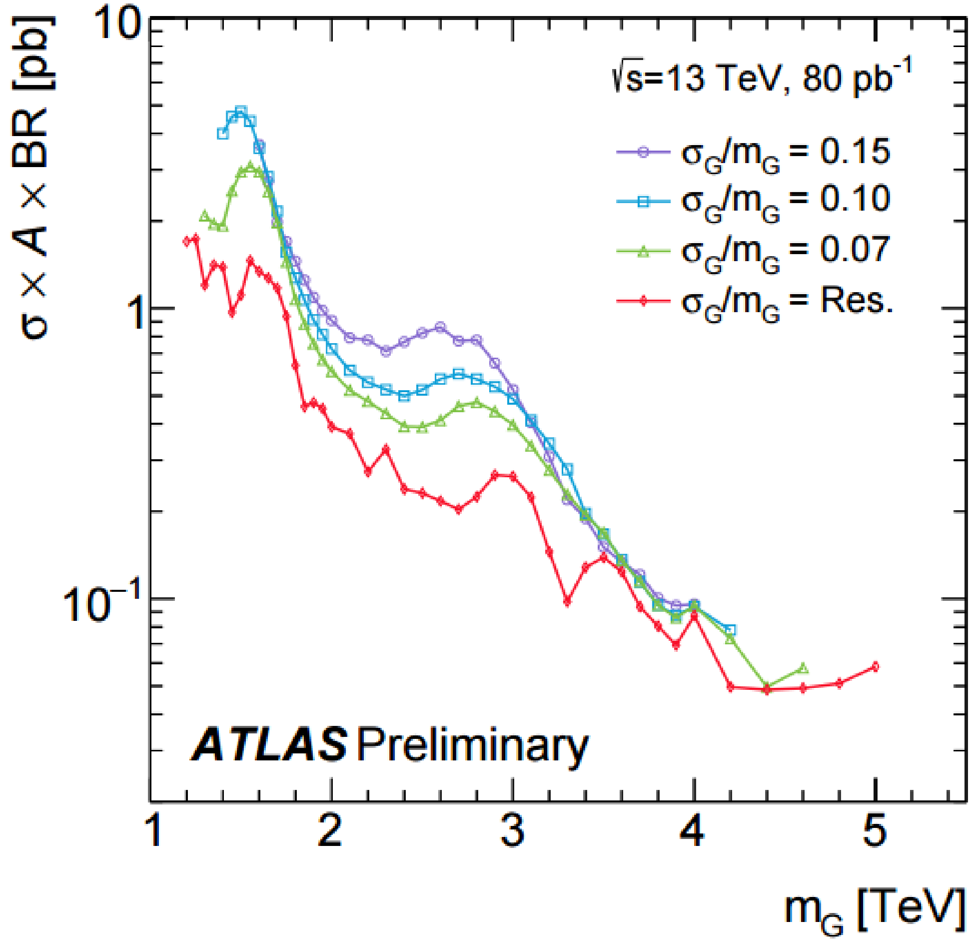

ATLAS Preliminary
√s=13 TeV, 80 pb-1
Data
Background fit
BumpHunter interval
BlackMax, m = 4.0 TeV
BlackMax, m = 5.0 TeV
p-value = 0.79
Fit Range: 1.1 - 5.3 TeV
|y*| < 0.6
Events
Signif.
m_jj [TeV]


√s=13 TeV, 80 pb-1
σ_G/m_G = 0.15
σ_G/m_G = 0.10
σ_G/m_G = 0.07
σ_G/m_G = Res.
ATLAS Preliminary
σ × A × BR [pb]
m_G [TeV]

# Summary and outlook

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# Summary and outlook

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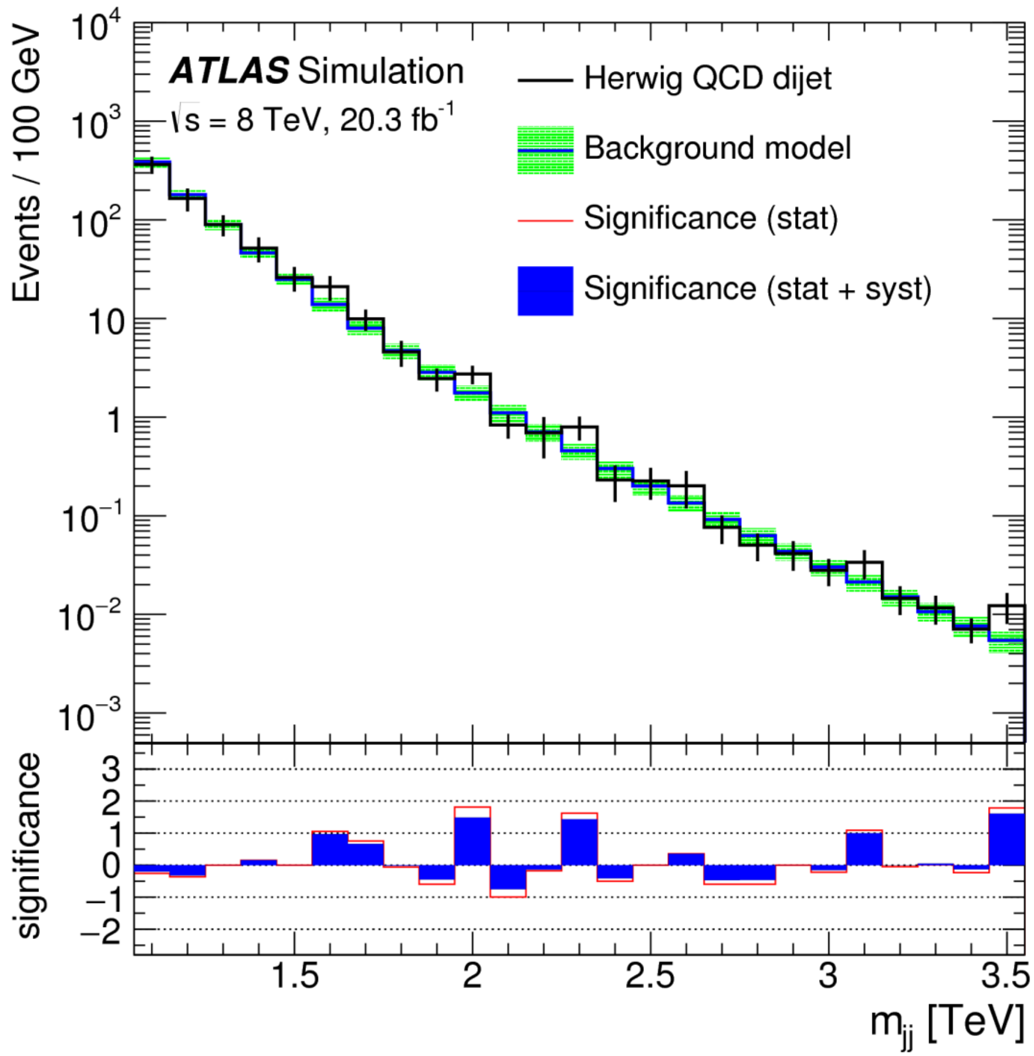
- Alternatively, all these excess may not persist simultaneously. In this case, many other possibilities will be open. Many tests, including color, width, initial state, and so on need to be performed to identify its physical origin, see many works from our MSU group (R. Sekhar Chivukula, E. Simmons, N. Vignaroli, P. Ittisamai, K. Mohan, arXiv:1406.2003, arXiv:1412.3094, arXiv:1507.06676)

Thank you!

# Backup

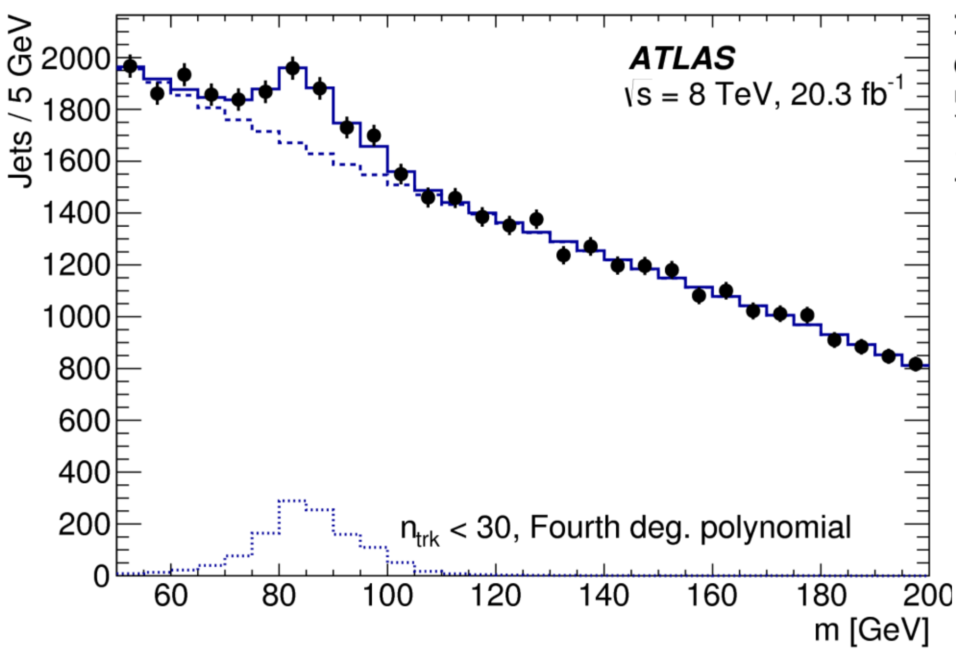
# Boosted Hadronic Diboson

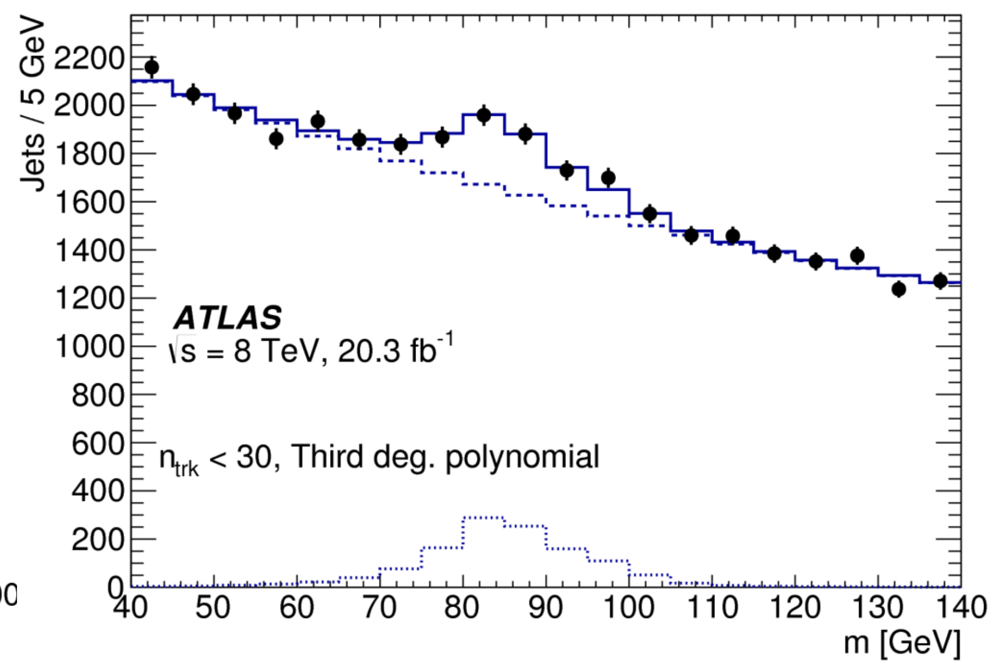



ATLAS simulation

Leading Log, Sudakov effect properly taken into account.

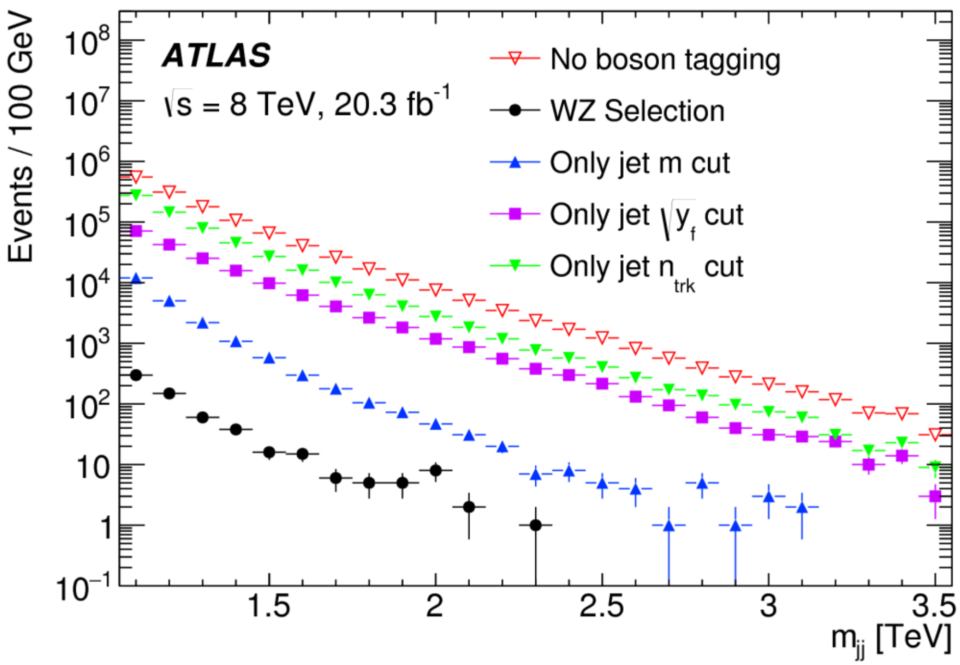
# Boost Hadronic Diboson

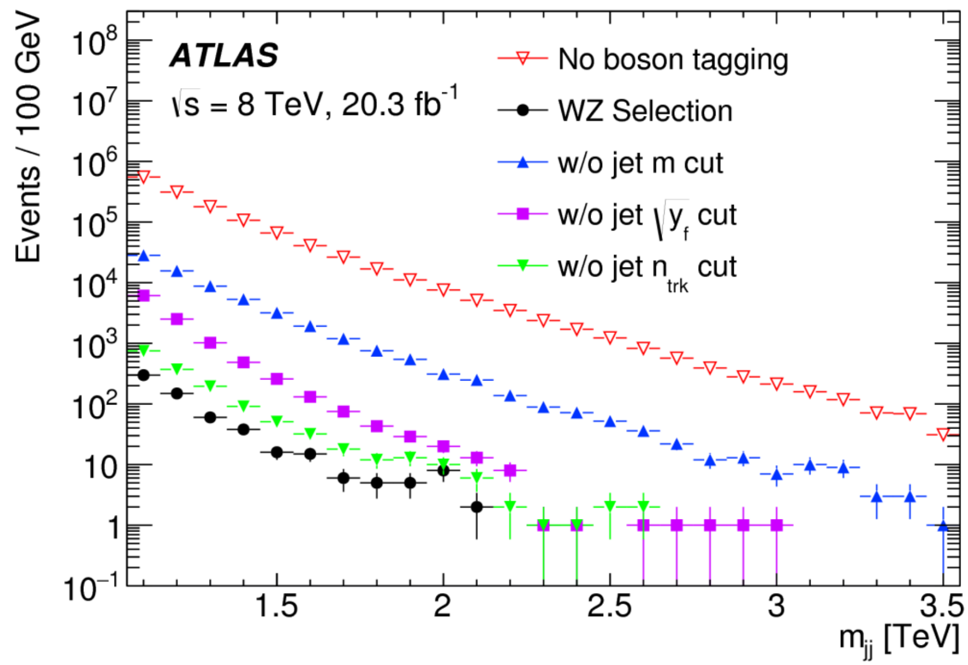


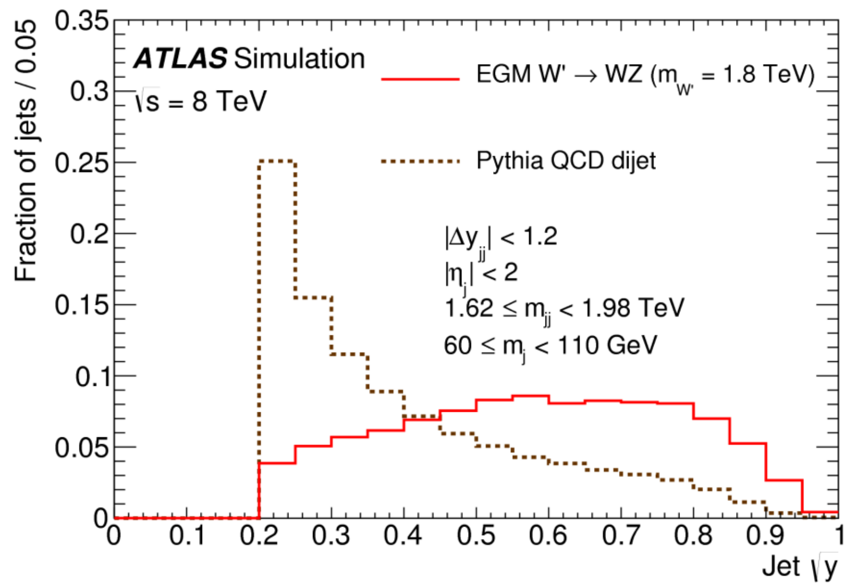

Validated data in V+j sample

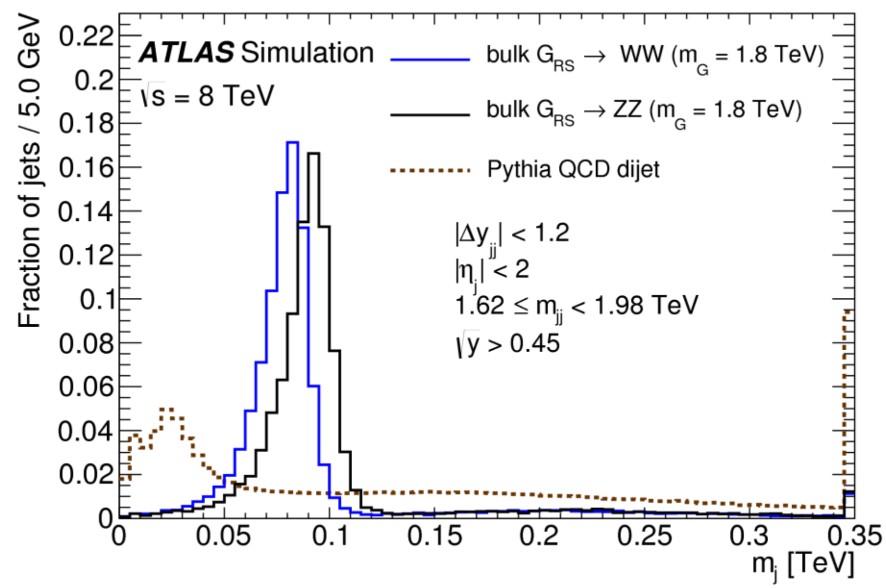
# Boosted Hadronic Diboson



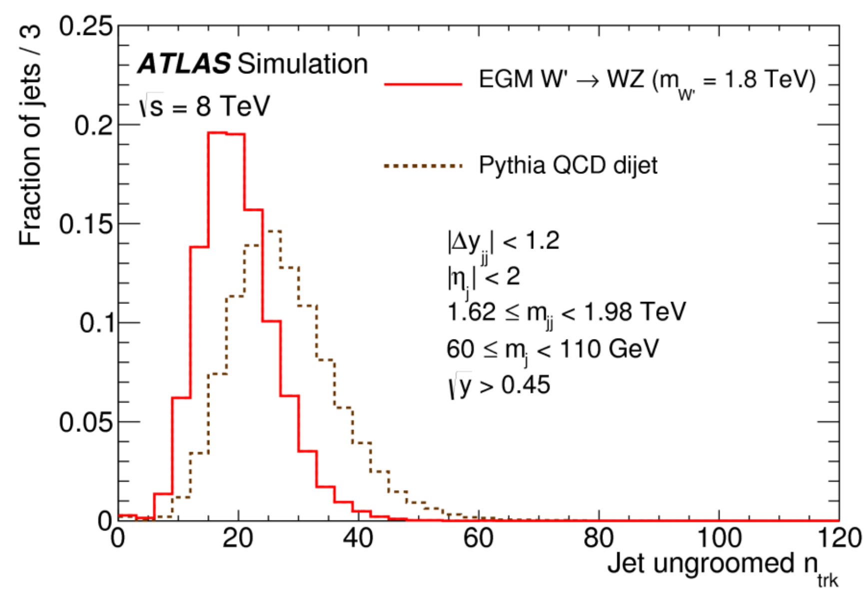



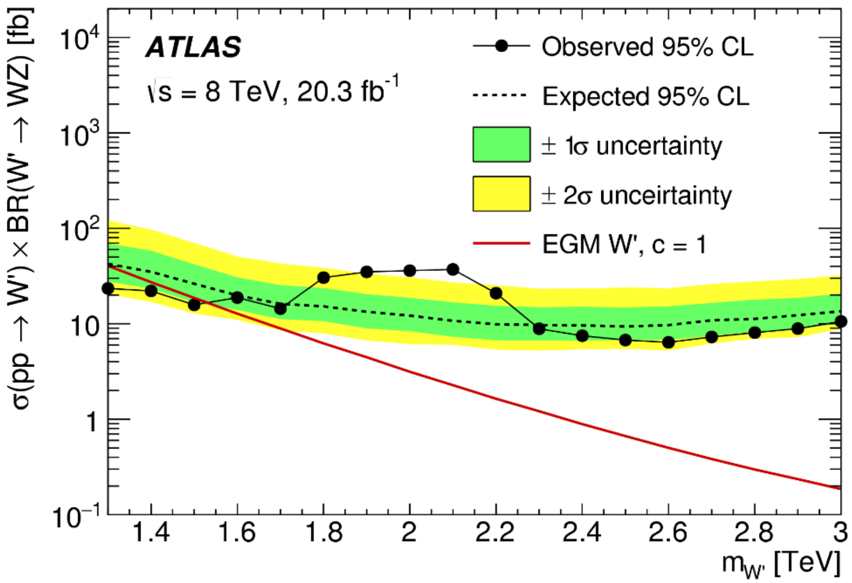

Cut Flow

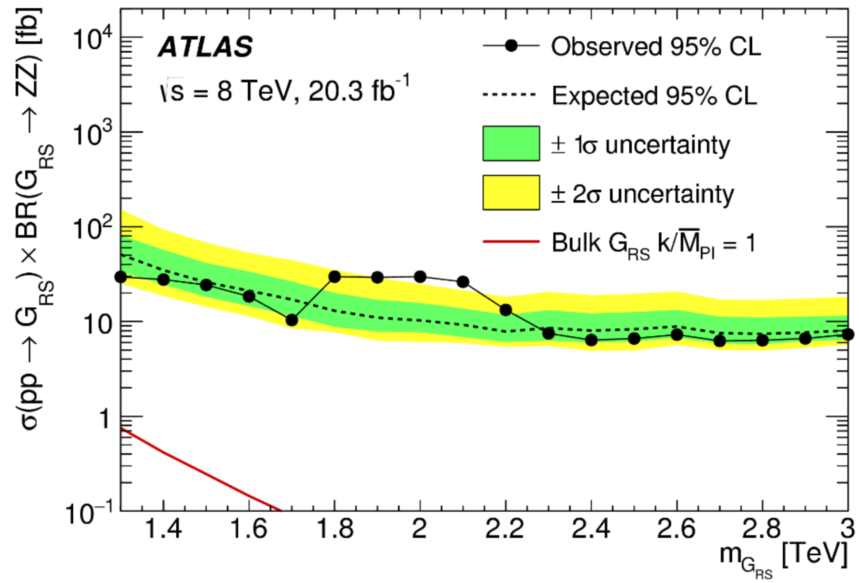


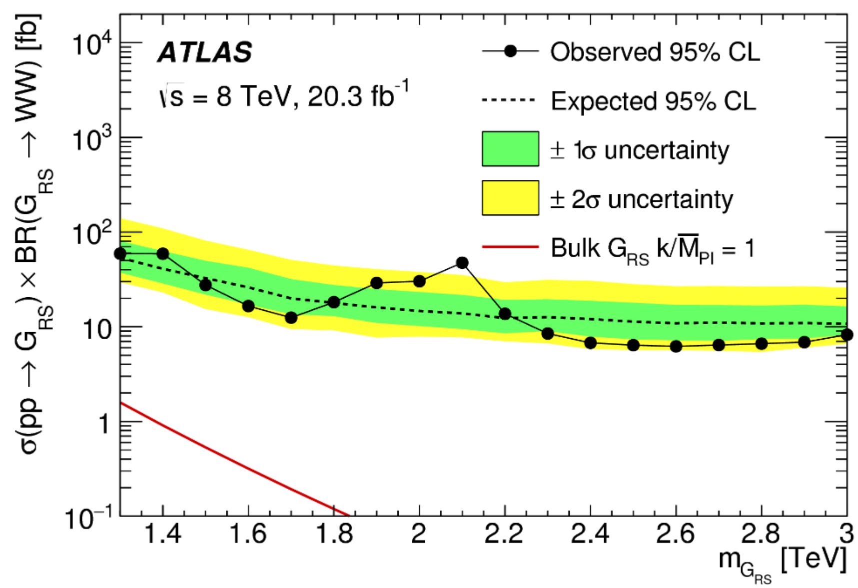




Jet variable distribution




ATLAS
√s = 8 TeV, 20.3 fb-1
Observed 95% CL
Expected 95% CL
± 1σ uncertainty
± 2σ unceirtainty
EGM W', c = 1
σ(pp → W') × BR(W' → WZ) [fb]
m_W' [TeV]


ATLAS
√s = 8 TeV, 20.3 fb-1
Observed 95% CL
Expected 95% CL
± 1σ uncertainty
± 2σ uncertainty
Bulk G_RS k/M̄_Pl = 1
σ(pp → G_RS) × BR(G_RS → ZZ) [fb]
m_G_RS [TeV]


ATLAS
√s = 8 TeV, 20.3 fb-1
Observed 95% CL
Expected 95% CL
± 1σ uncertainty
± 2σ uncertainty
Bulk G_RS k/M̄_Pl = 1
σ(pp → G_RS) × BR(G_RS → WW) [fb]
m_G_RS [TeV]

Based mostly on this prompt…
Plausibility of the anomaly as detector effect vs. statistical fluctuation vs. new physics

Nhan Tran

Some of us had this
conversation 2 years ago!

T. Lecompte

## Priors and Prejudice

- I asked about two dozen people if they would believe a result only on a boosted signature
  - Nobody gave an unqualified "yes"
  - Everyone said "it would depend what it was"
  - There was a desire for a confirming result
    - A second channel
    - Interestingly, the same thing from the other experiment was viewed as weak confirmation. The concern is that there is some common systematic.

- Better integration of the "boosted community" in the experiments can only help
  - People need to get comfortable with these new ideas, and this is one way to do this
  - A parade of SM results using boostology would be helpful
  - Top Group sociology enters into this in non-trivial ways

$W' \to eN \to e^+e^-jj$ (CMS) $2.8\sigma$ "peak" @ 1.8–2.2 TeV

$W' \to jj$ (CMS) $\sim 2\sigma$ "peak" @ 1.8–1.9 TeV

$W' \to WZ \to JJ$ (ATLAS) $2.5\sigma$ (global) peak @ 1.8–2.1 TeV

$W' \to WZ \to J(\ell^+\ell^-)$ (CMS) $\sim 2\sigma$ "peak" @ 1.8–1.9 TeV

$W' \to Wh \to (\ell\nu)(b\bar{b})$ (CMS) $2.2\sigma$ "peak" @ 1.8–1.9 TeV

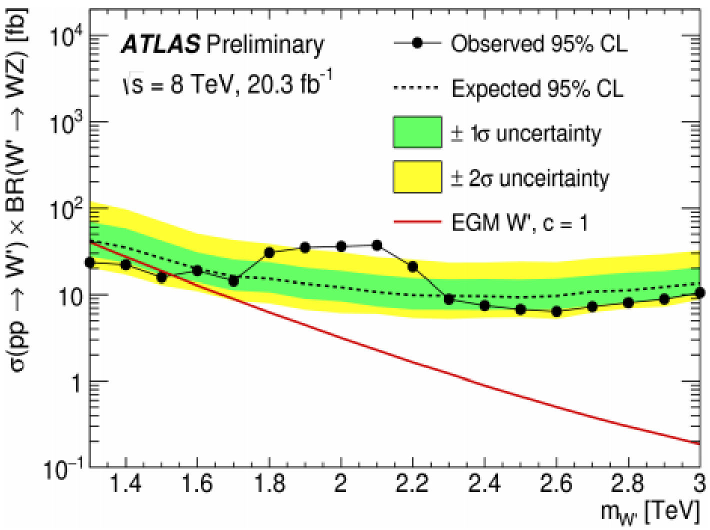
**Rates consistent with an $SU(2)_R$ gauge theory** *(1506.06736)*.

*Parameters:* $M_{W'} \approx 1.9$ *TeV*, $g_R = 0.5$, $\tan\beta \approx 1$, $s_\theta \approx 1/2$.

*Predictions*

**More final states:** $W' \to e\tau jj$ , $\tau\tau jj$ , $eetb$, $tb$ , ...

Full hadronic ATLAS search

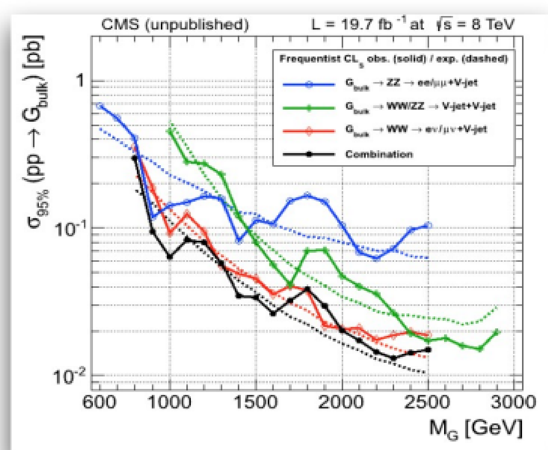



## ATLAS vs CMS

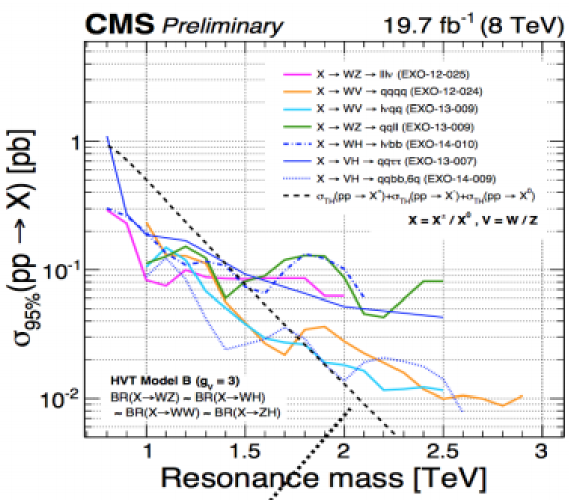
- C/A R=1.2, split-filtered,|η| <2.0,
- sub-jet pT balance / **Trk. Multi./** Mass (**2 overlapping mass window**)
- Trk mult. not always well modelled
- Tagging eff: 25-45% (pT dependent)
- 2 leading jets with |y1-y2| <1.2: s-channel vs t-channel
- **Optimised using longitudinal polarised signal**

- C/A R=0.8, pruned,|η| <2.5,
- $\tau_{21}$/ Mass (single mass window)
- Tagging eff.: 20-50% (pT dependent)
- 2 leading jets with $|\eta_1-\eta_2|$ <1.3
- **2 signal regions with different sensitivy for longitudinal and transverly polarised bosons**

CMS sees excess in similar regions: 1.8 vs 2.0 TeV




EXO-13-009 public twiki




EXO14010 public twiki

**Consistency?**

- Tension with lnuqq channel in ATLAS: no excess observed
- Shift could be explained by jet energy scale and resolution differences?
- Better sensitivity observed by CMS

**Too early to conclude → We need Run-2!**

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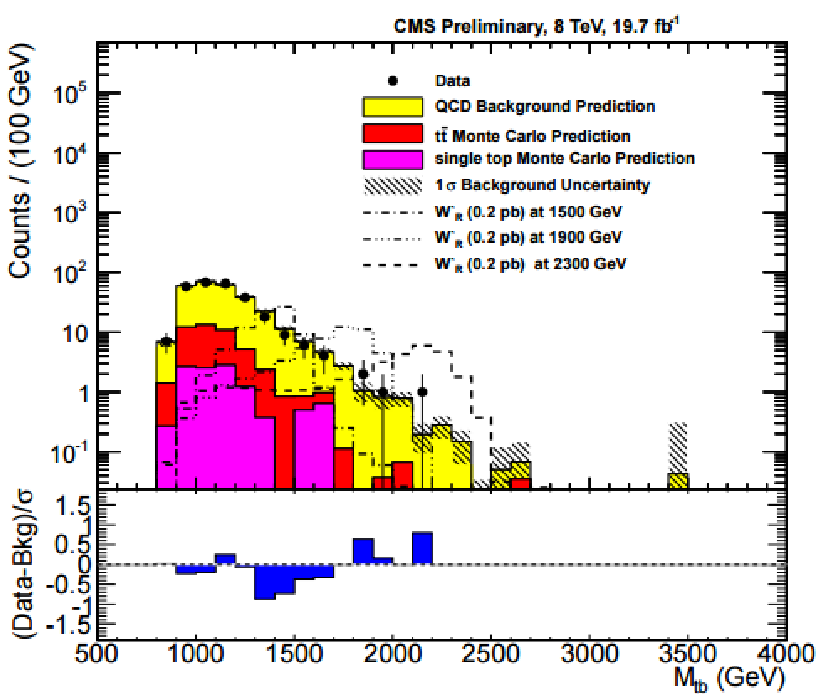
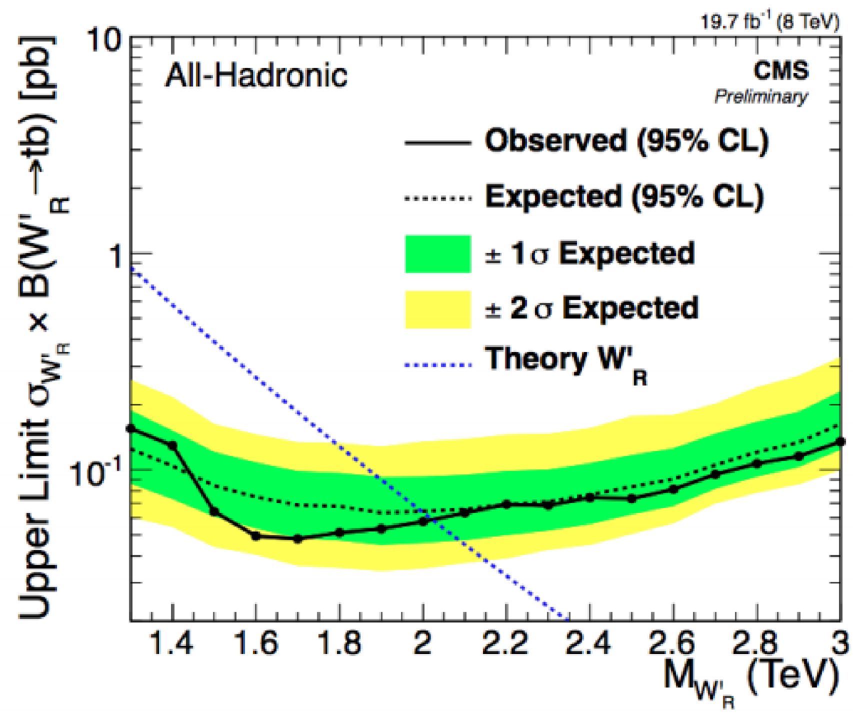
Reina Camacho

# W'->tb

$$W' \to t\bar{b} \to (jjb)\bar{b}$$

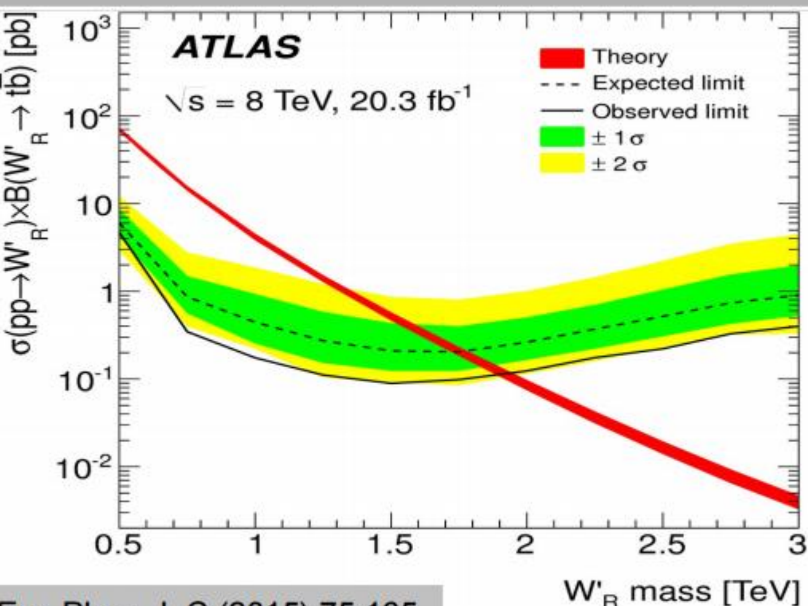
**CMS (B2G-009):**



# $W' \rightarrow tb$

PLB 743, 235 (2015)

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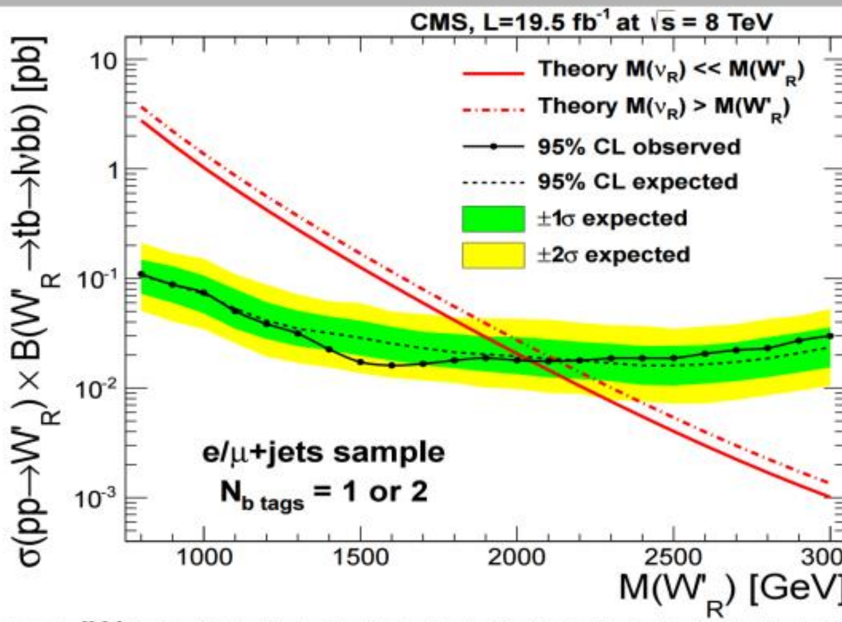


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