Dibosons at the LHC

Symmetry Restored?

Joachim Kopp

Invisibles Webinar | November 24^{th} 2015

based on arXiv:1507.00013 (with J. Brehmer, J. Hewett, T. Rizzo, J. Tattersall)

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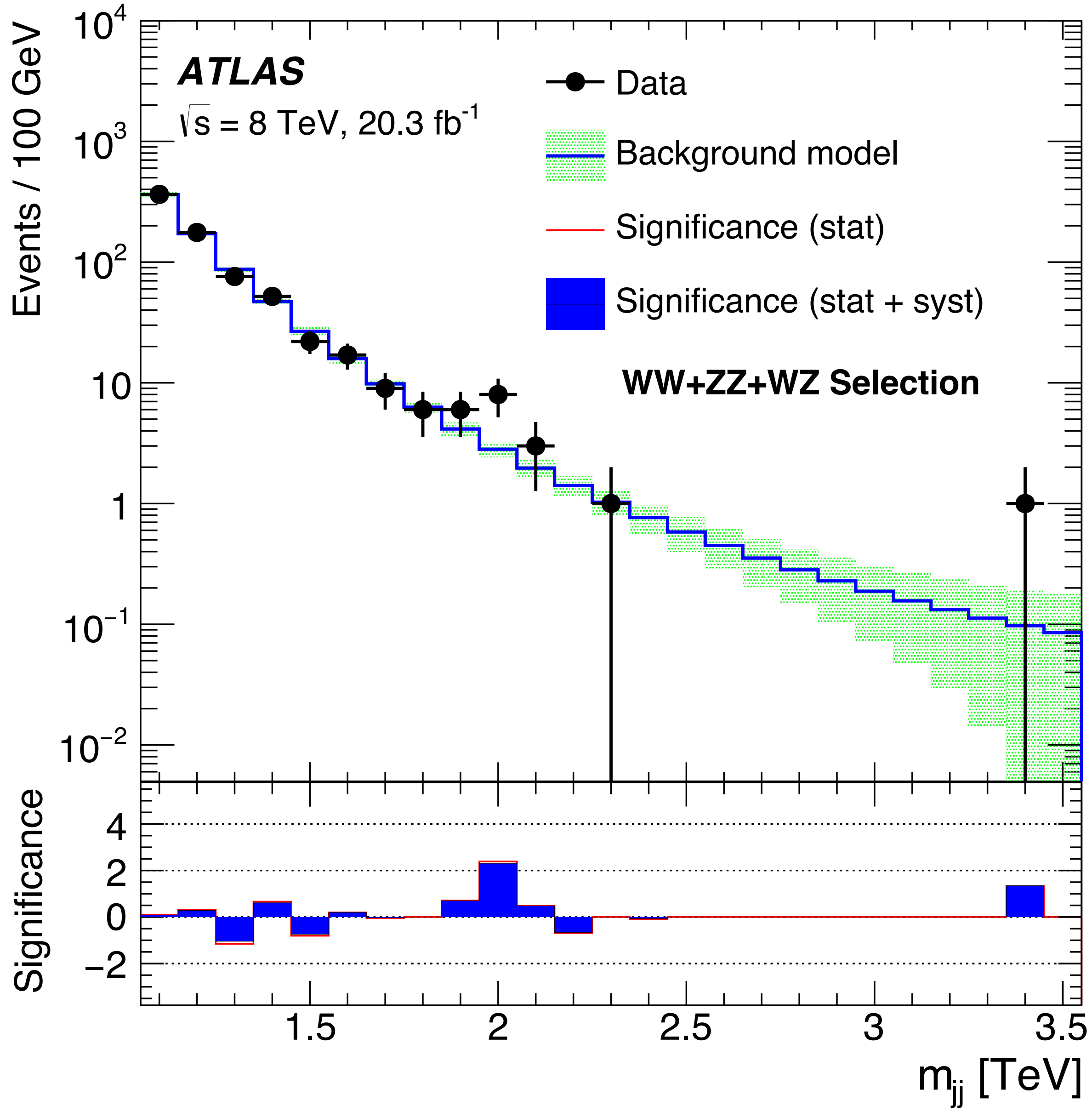
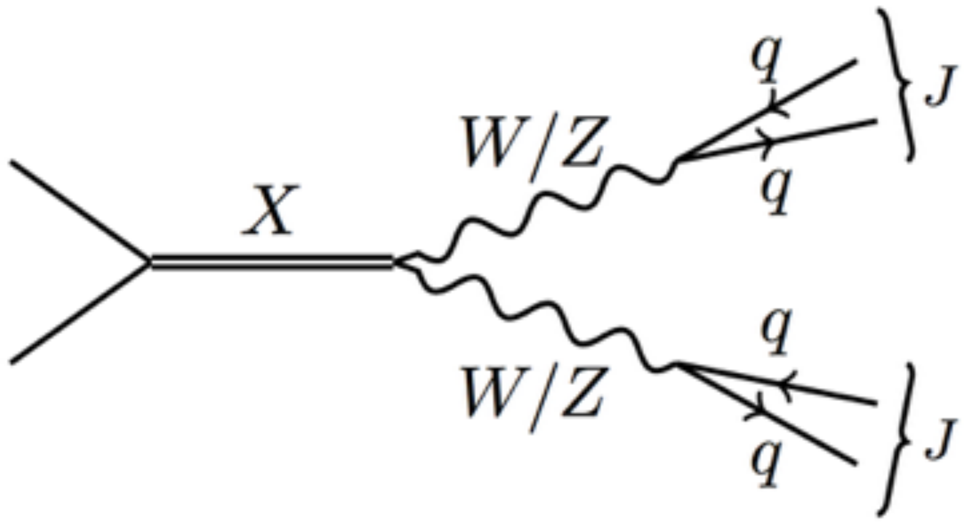
Outline

- Diboson Anomalies at the LHC
- A Global Fit to the Data
- Theoretical Explanations on the Market
- Left-Right Symmetric Models
- Conclusions

Diboson Anomalies at the LHC

A New Resonance at 1.8—2 TeV?





ATLAS, 1506.00962

- 3.4σ Resonance in $pp \to (V \to jj) + (V \to jj)$ at 1.8—2 TeV
- Poor discrimination between W and Z

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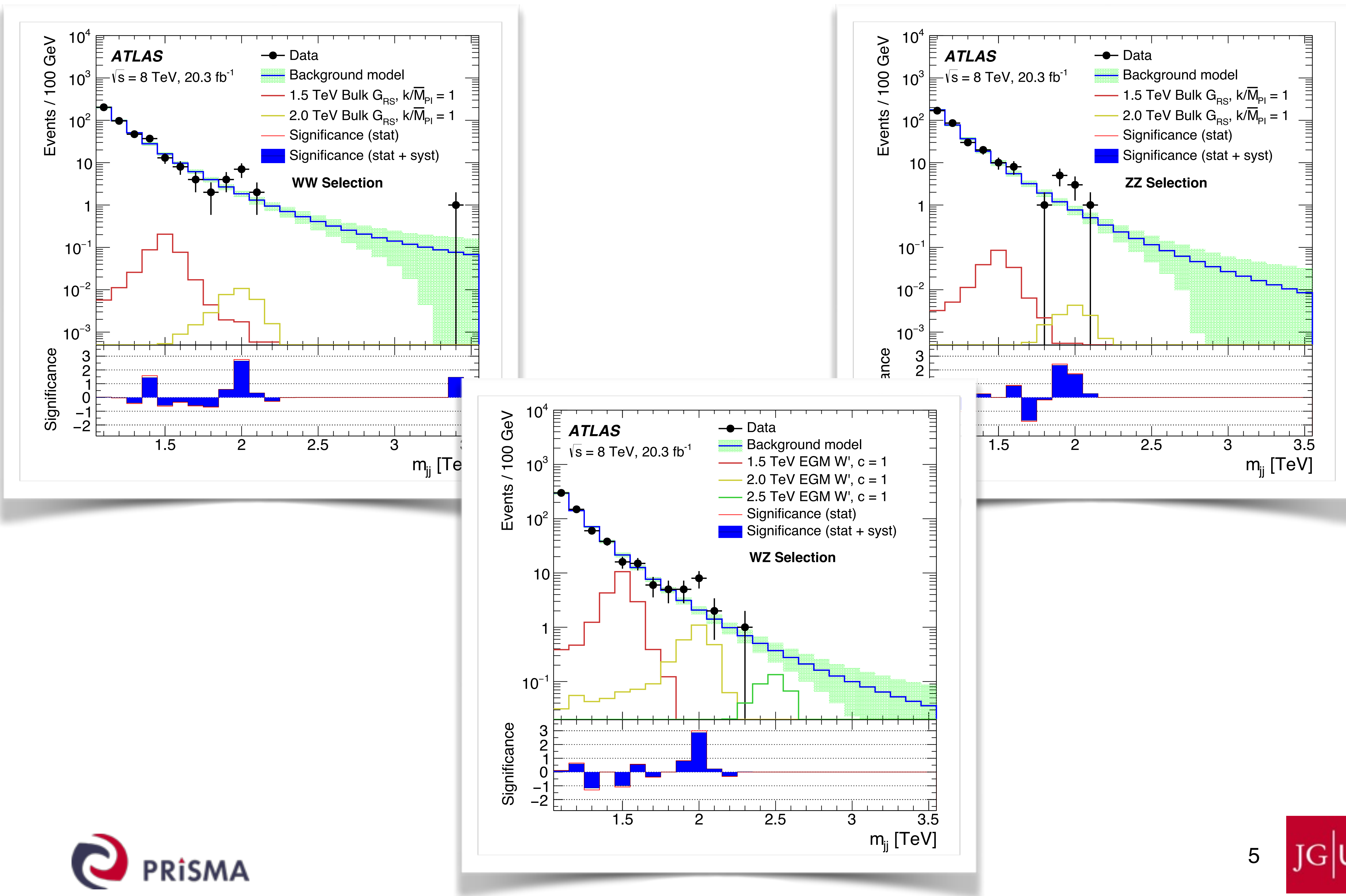
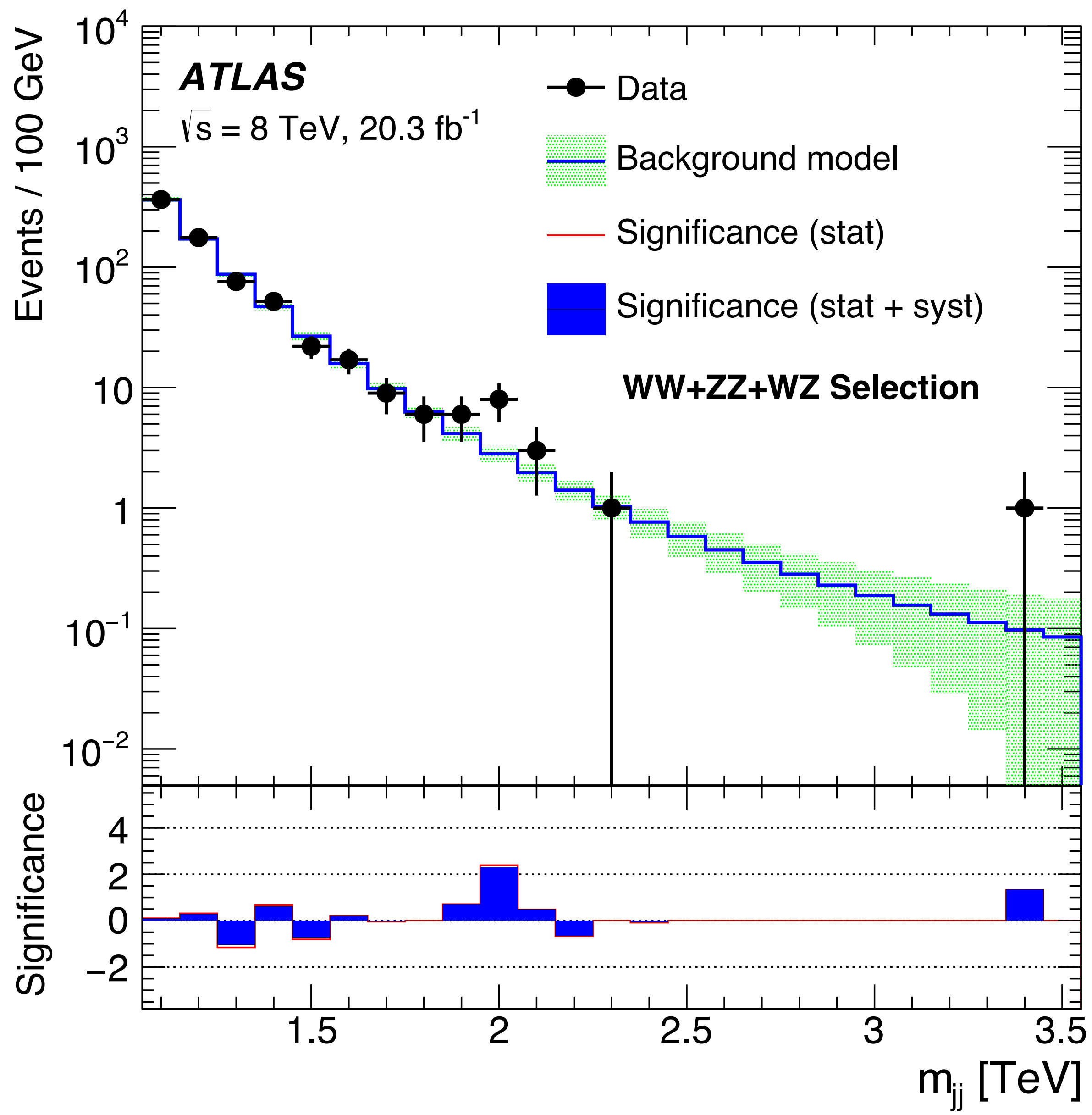
Boosted WW, ZZ and WZ



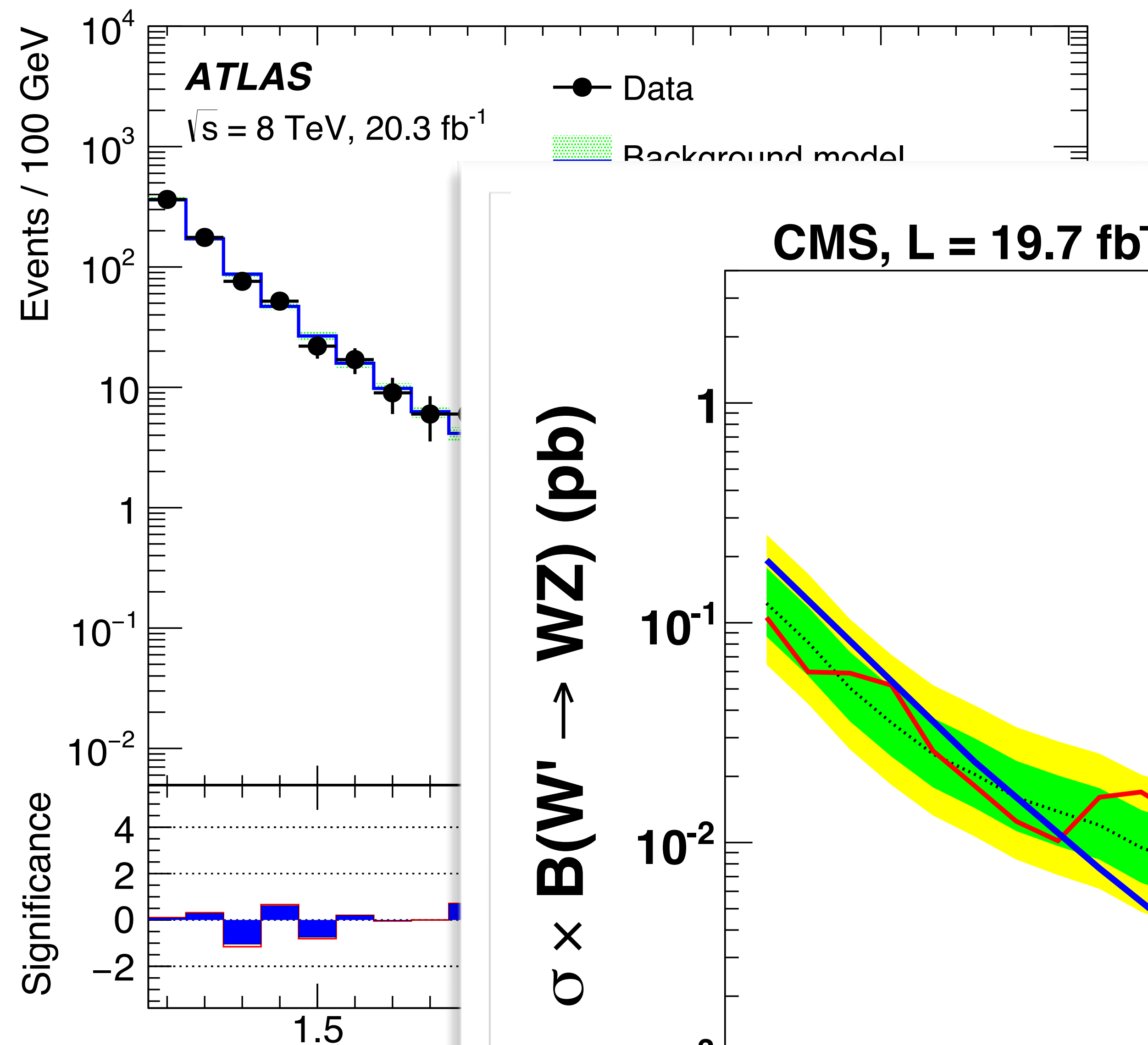
Chasing Ambulances

Chasing Ambulances

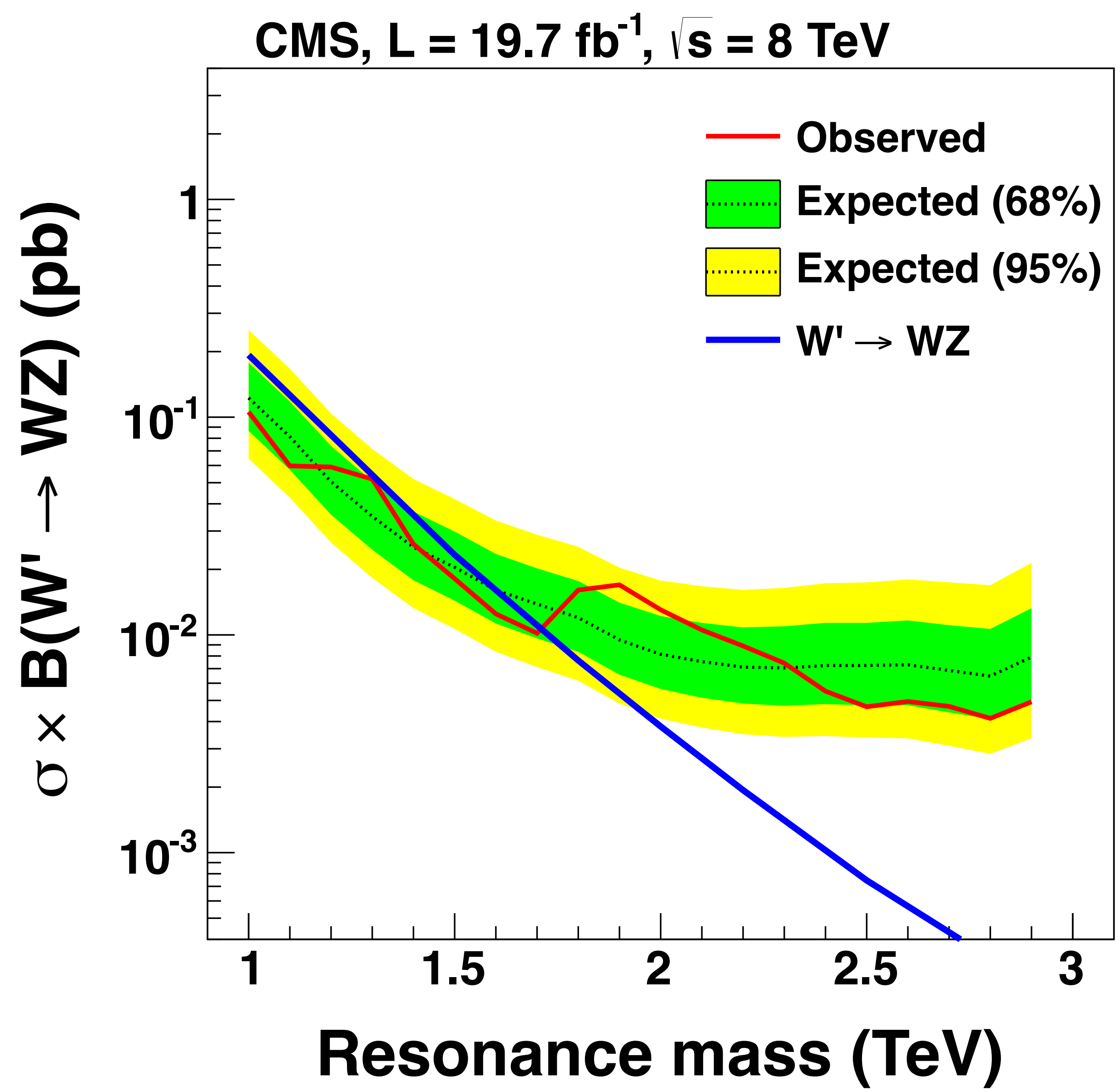


ATLAS $VV \to JJ$ (3.4σ) 1506.00962

Chasing Ambulances

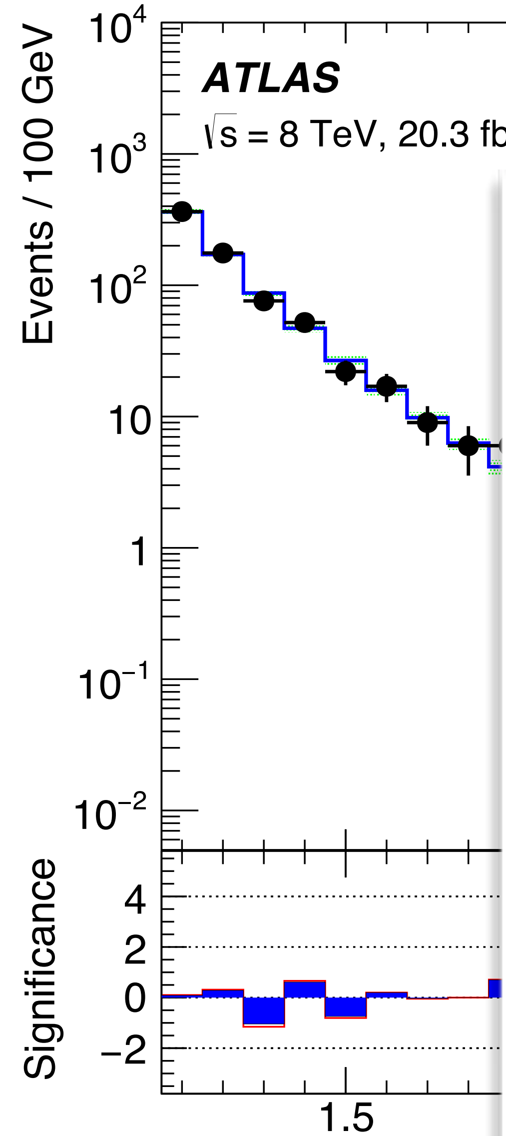


ATLAS $VV \rightarrow$

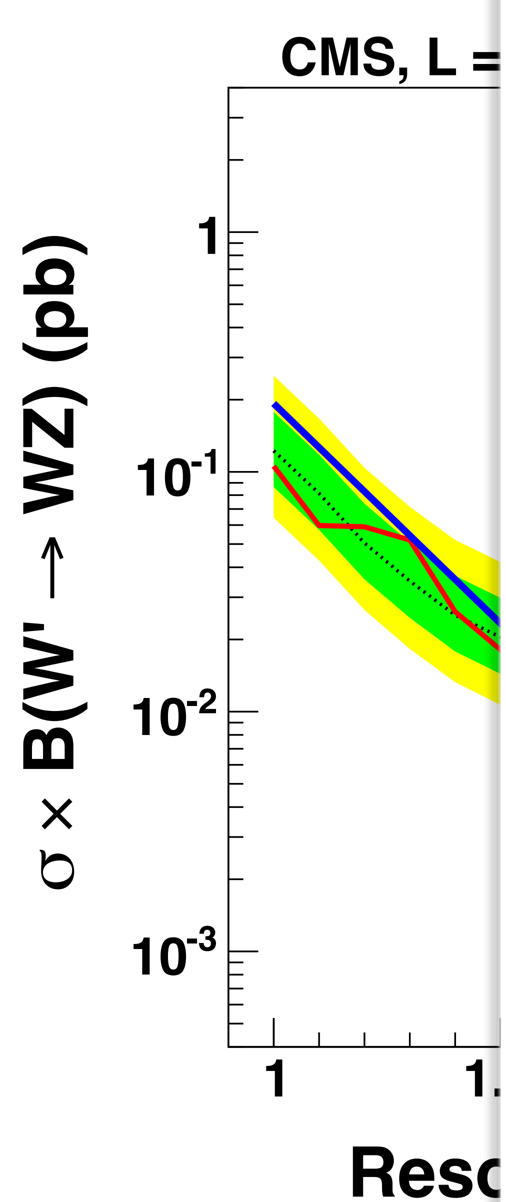


CMS $VV \rightarrow JJ$ (~1σ) 1405.1994

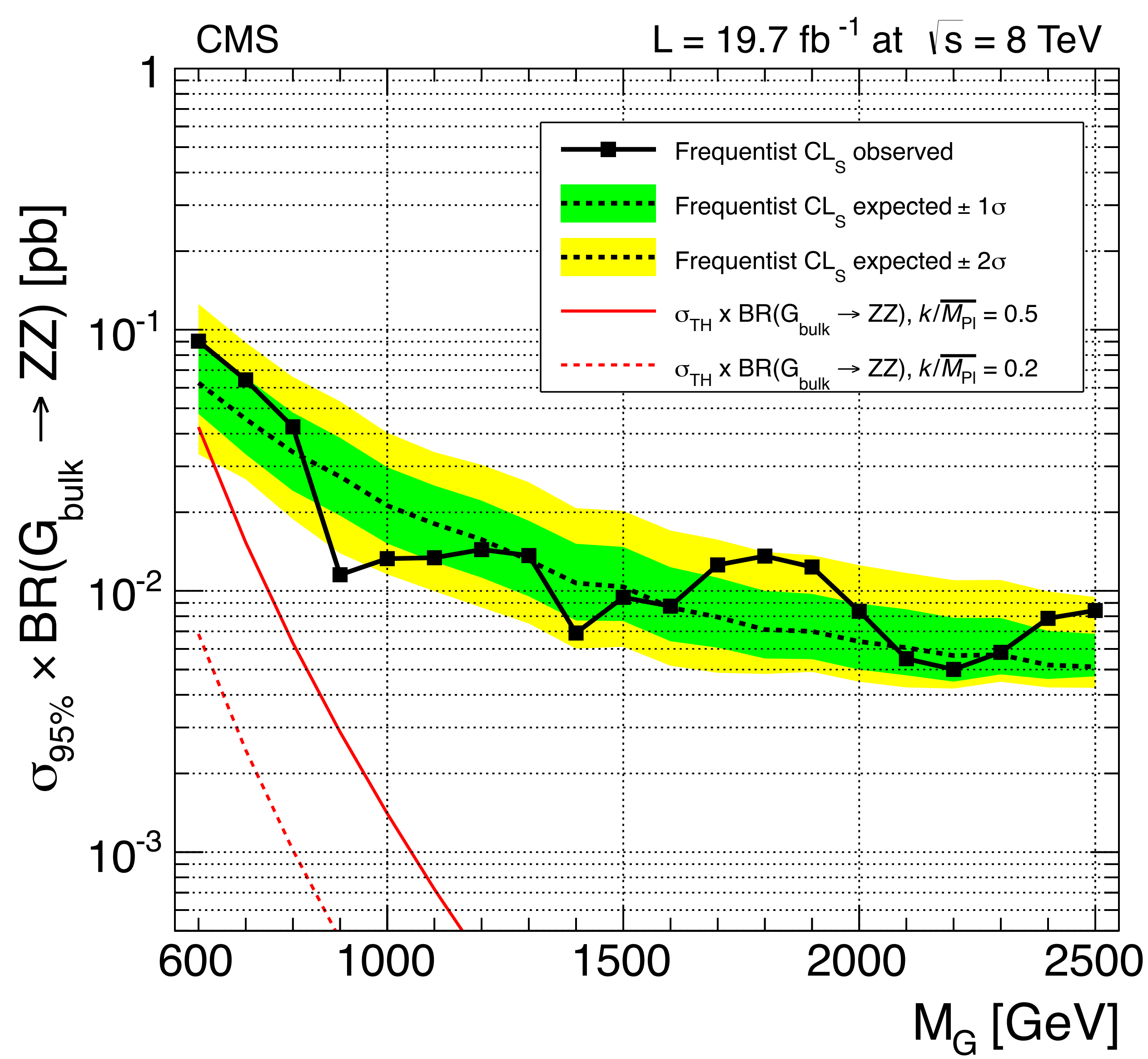
Chasing Ambulances



ATLAS $VV \to$



CMS $VV \to JJ$ (~1σ) 1405.1994



CMS $ZV \to \ell\ell J$ (~1.5σ) 1405.3447

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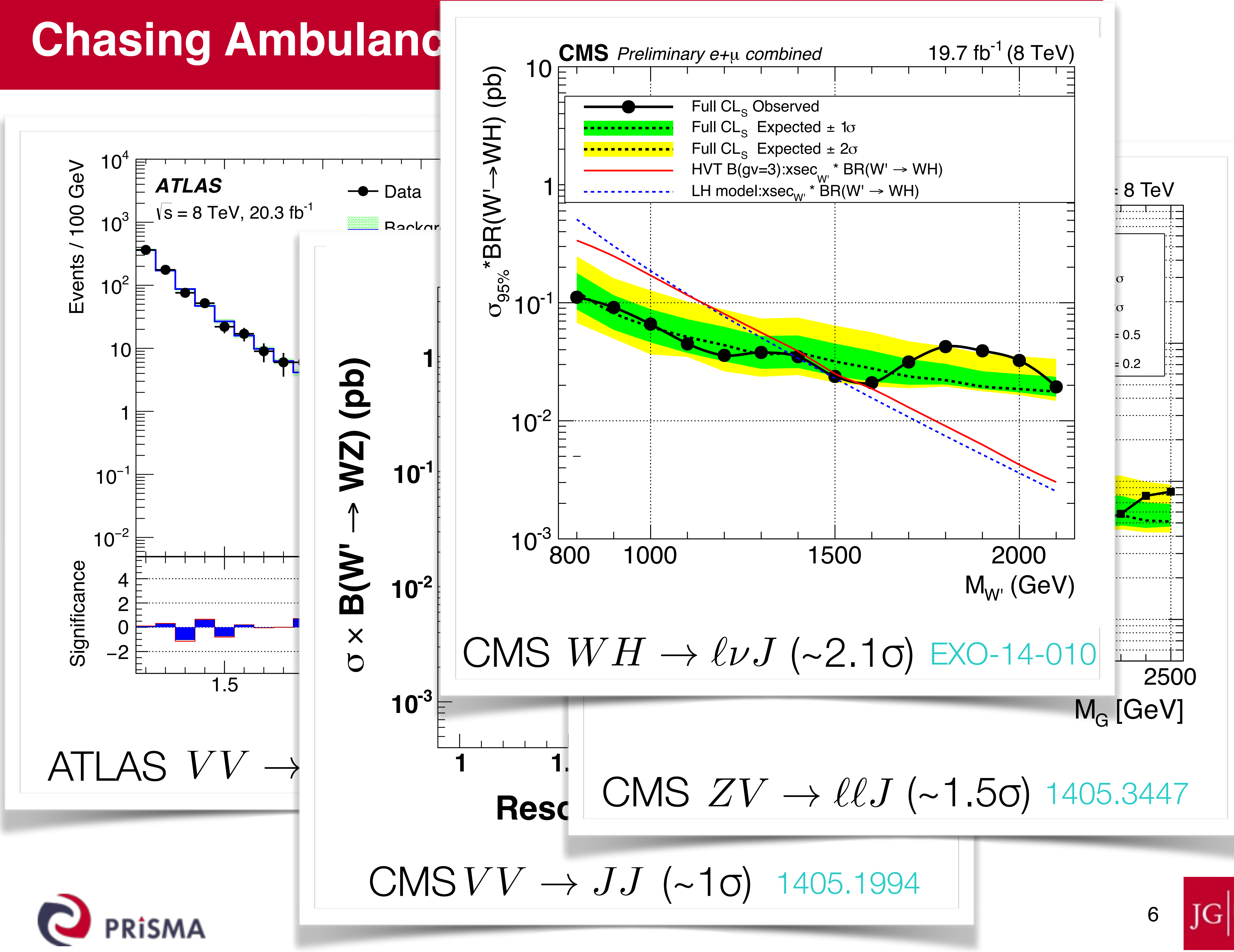

ATLAS $VV \to$

CMS $WH \to \ell\nu J$ (~2.1σ) EXO-14-010

CMS $ZV \to \ell\ell J$ (~1.5σ) 1405.3447

CMS $VV \to JJ$ (~1σ) 1405.1994

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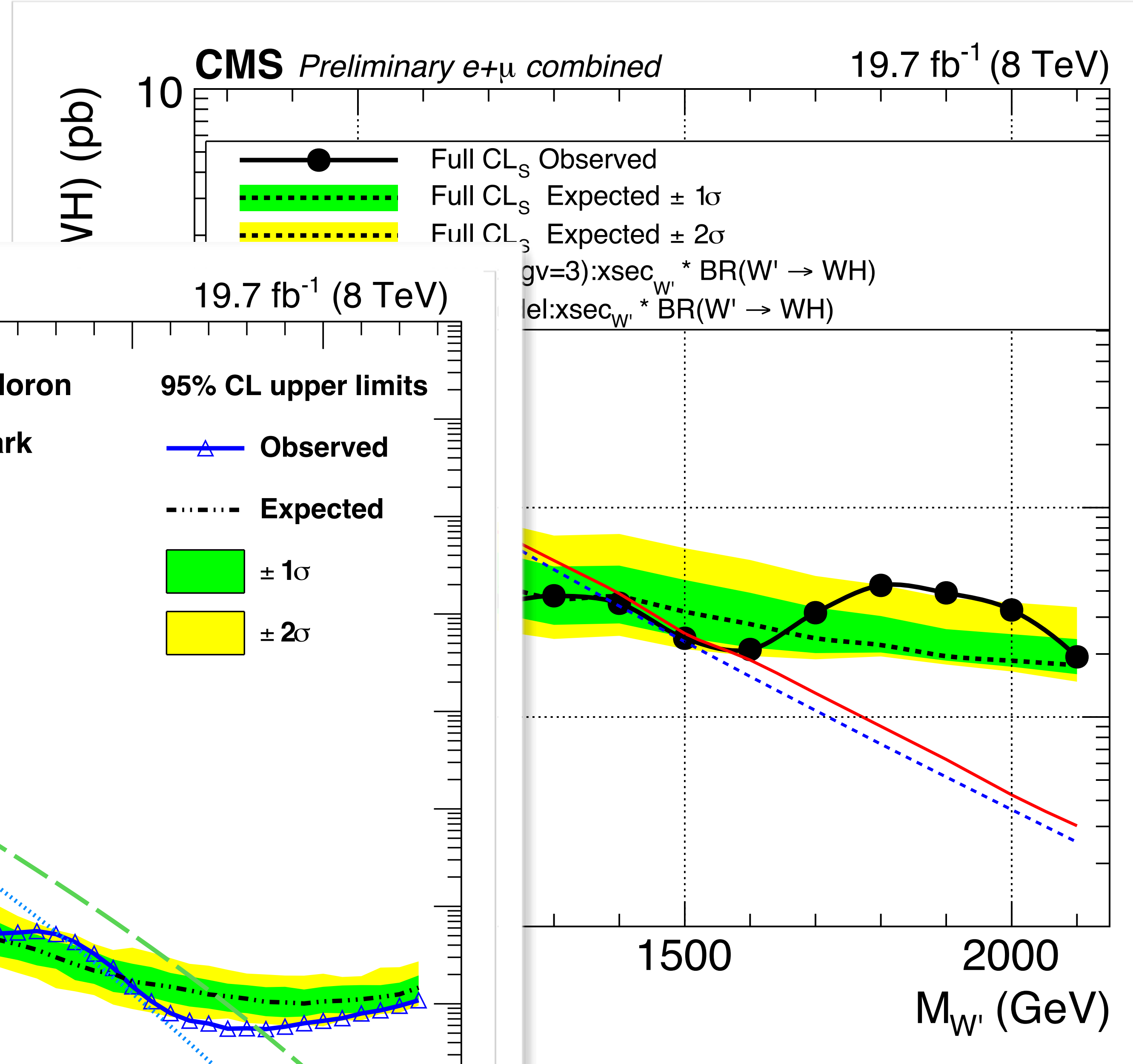
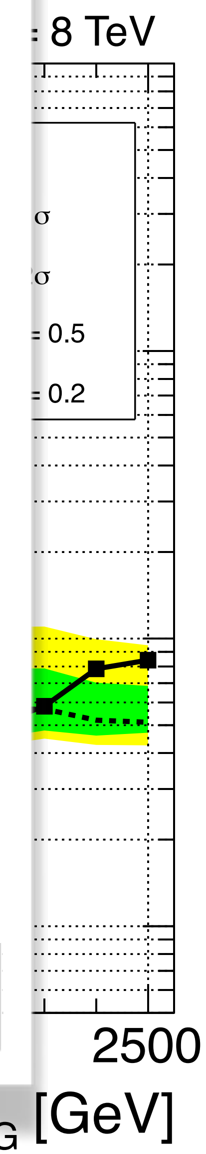
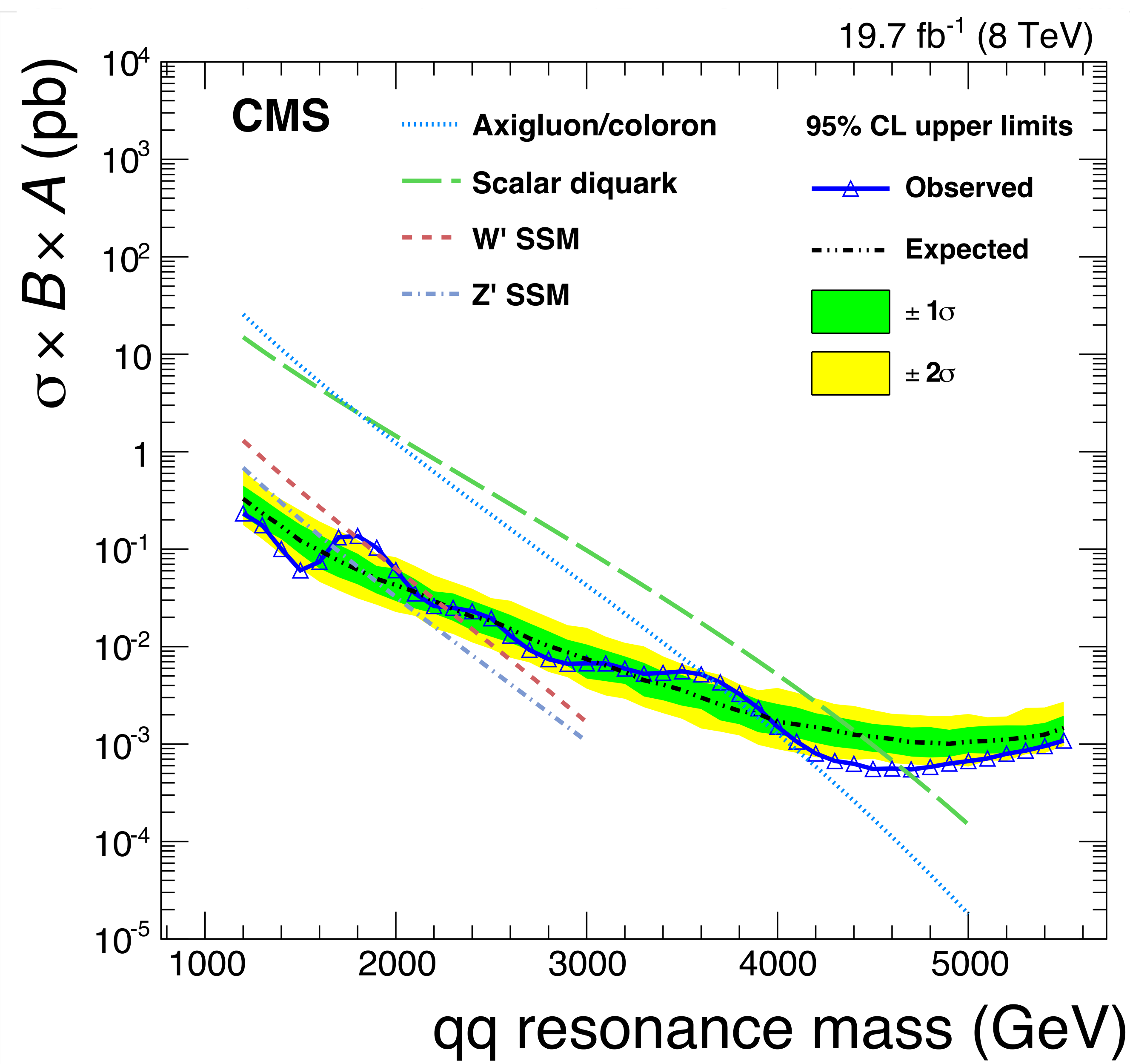


J (~2.1σ) EXO-14-010



$V \to \ell\ell J$ (~1.5σ) 1405.3447



CMS dijets (~2σ) 1501.04198

A

CMS $VV \to JJ$ (~1σ) 1405.1994

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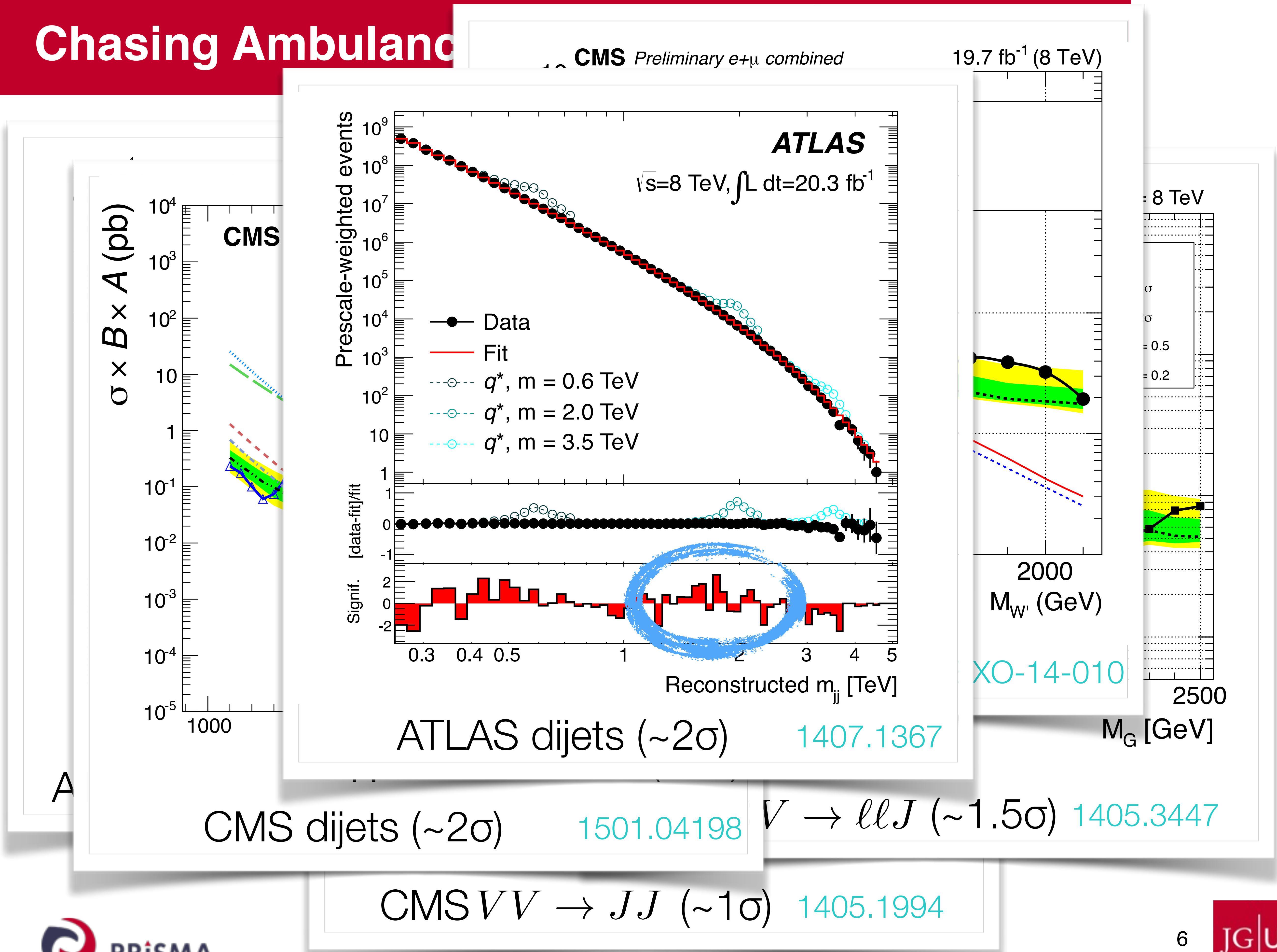
Chasing Ambulanc



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A Global Fit to the Data

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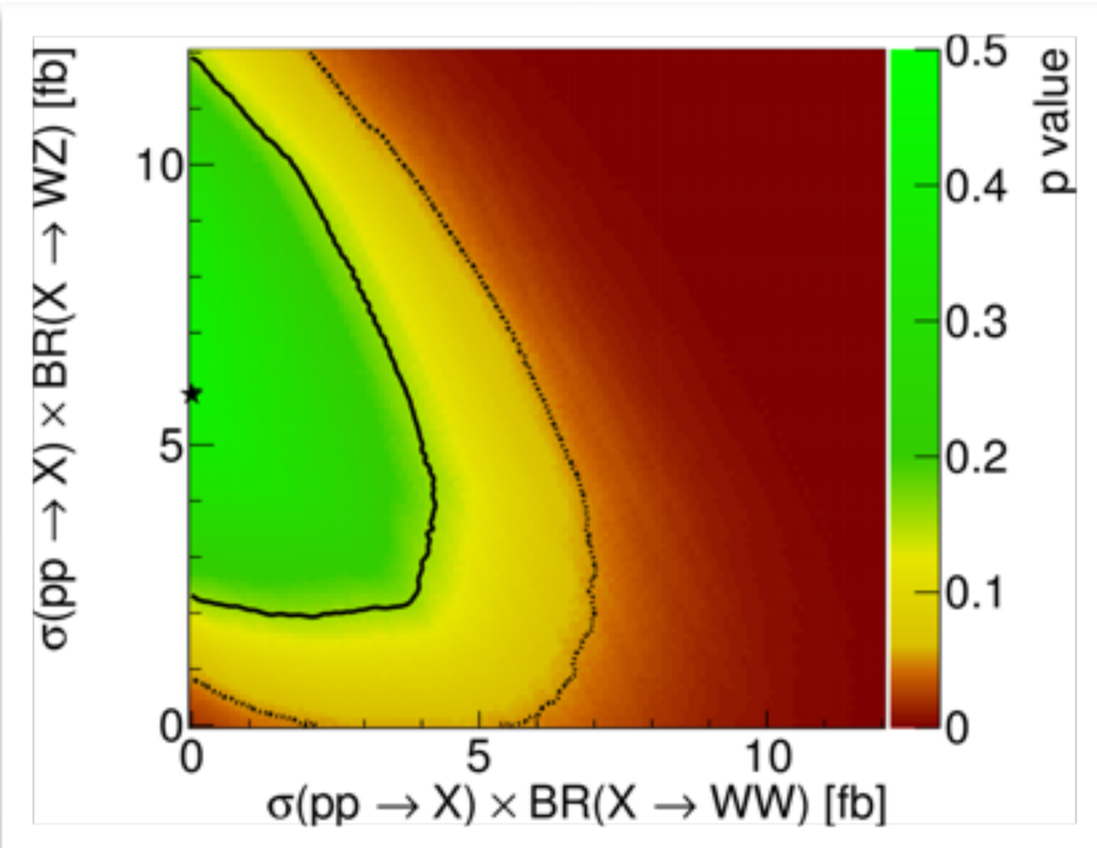
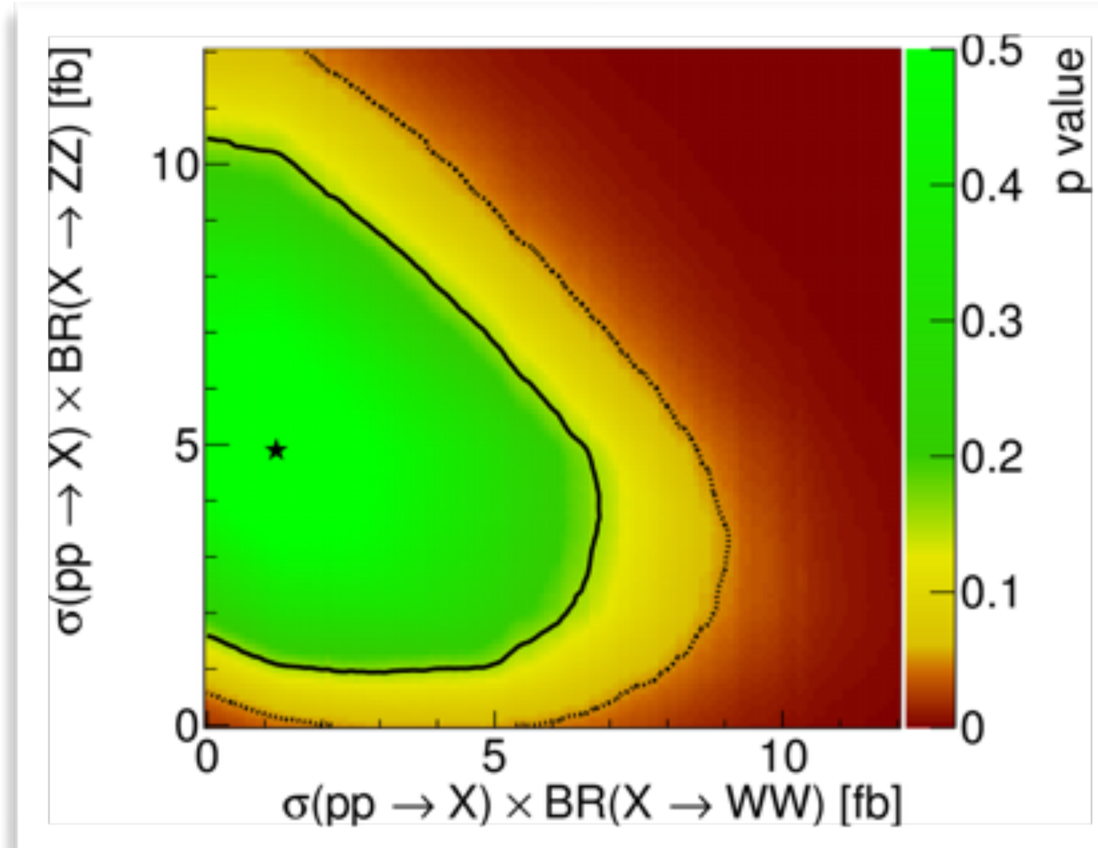
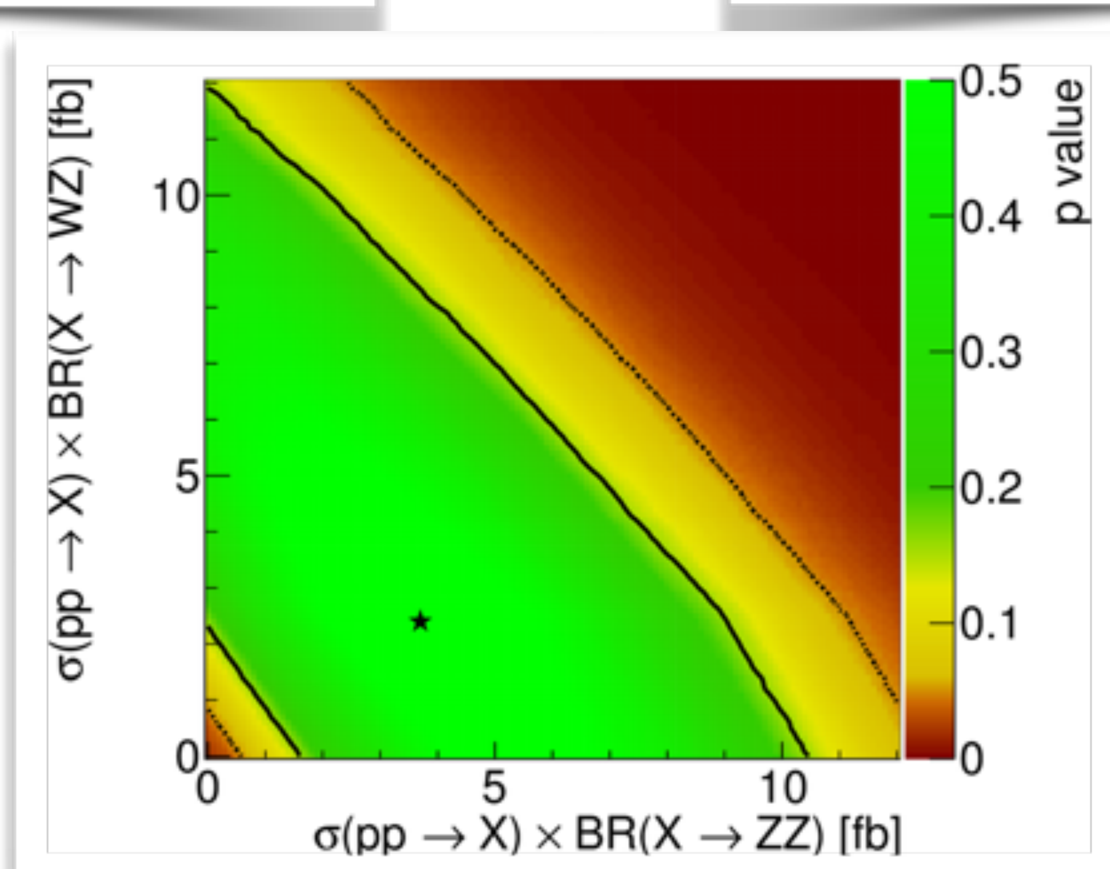
Cross Section Fit: Diboson Final States

- Assume heavy resonance decaying to WW, ZZ or WZ
- Combine all searches for these final states:
  - ATLAS $VV \to JJ$ (3.4σ) 1506.00962
  - CMS $VV \to JJ$ (~1σ) 1405.1994
  - ATLAS $WW/WZ \to \ell\nu + \mathrm{jets}$ 1503.04677
  - CMS $VV \to \ell\nu/\ell^+\ell^- + \mathrm{jets}$ 1405.3447
  - ATLAS $VV \to \ell^+\ell^- + \mathrm{jets}$ 1409.6190
- Input Data
  - # of events + predicted BG in mass window [1.7 … 2.0 TeV]
  - Acceptance, Efficiency, Systematics where available
  - where not: tune to reproduce experimental limits

Cross Section Fit: Diboson Final States







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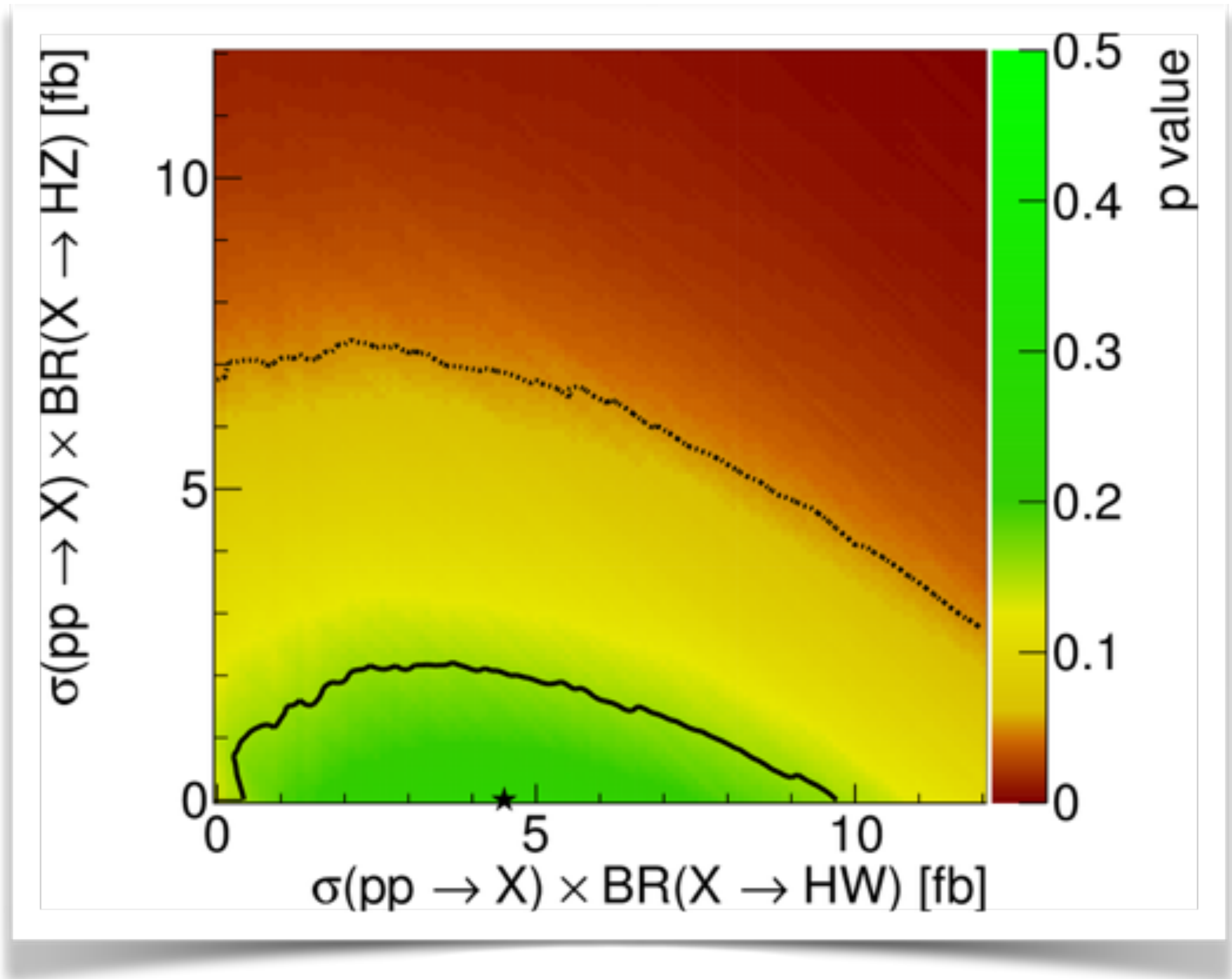
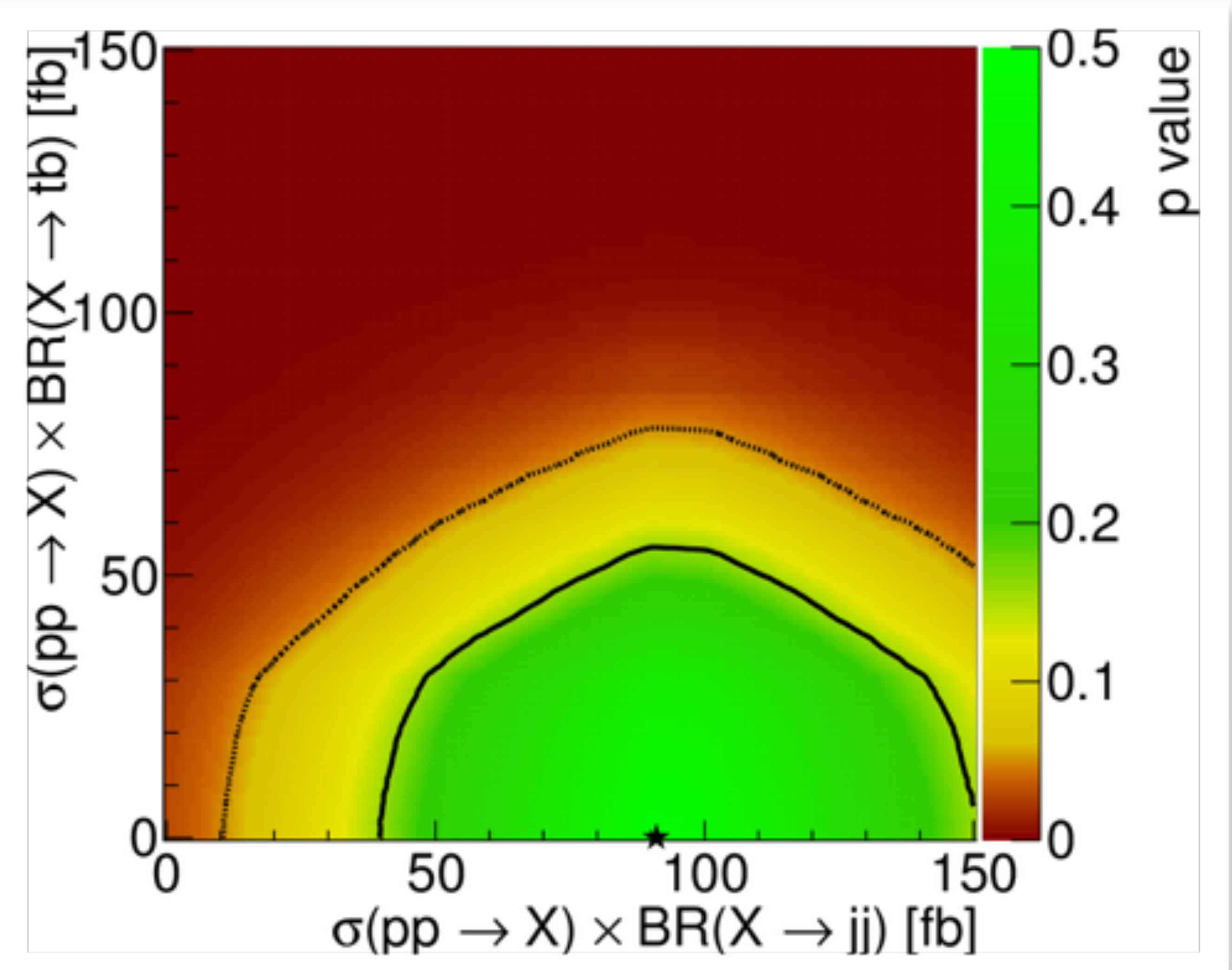
Cross Section Fit: V+H Final States

- Assume heavy resonance decaying to WH or ZH
- Combine all searches for these final states:
  - ATLAS $VH \to b\bar{b} + \ell\ell/\ell\nu/\nu\nu$
    1503.08089
  - CMS $WH \to b\bar{b} + \ell\nu$ (~2.1σ)
    CMS-PAS-EXO-14-010
  - CMS $VH \to \tau^+\tau^- + jj$
    1502.04994
  - CMS $VH \to JJ$
    1506.1443



Cross Section Fit: Dijet and t+b Resonances

- Assume heavy resonance decaying to jj or tb
- Combine all searches for these final states:
  - ATLAS dijet (~2σ)
    1407.1376
  - CMS dijets (~2σ)
    1501.04198
  - ATLAS $tb \to \text{hadrons}$
    1408.0886
  - CMS $tb \to \ell\nu bb$
    1402.2176



Consequences of Cross Section Fit

- ZZ or WZ resonance favored over WW
  - σ ~ 5 fb
  - New boson, preferably charged
- Possible resonance in WH (but not ZH)
  - σ ~ 5 fb
- Dijet resonance (constraints form tb channel)
  - σ ~ 100 fb
  - Strong coupling to quarks
- No resonance observed in (semi)leptonic final states
  - suppressed couplings to leptons

Explanations

Explanations in the Literature

- A new composite sector
- An enlarged scalar sector
- Extended gauge groups
- Others

Composite Dynamics

Fukano *et al.*, 1506.03751:	techni-rho
Thamm Torre Wulzer, 1506.08688:	composite Higgs sector
Carmona Delgadod Quiros Santiago,1507.01914:	composite Higgs sector
Chiang Fukuda Harigaya Ibe Yanagida, 1507.02483:	composite scalar
Cacciapaglia Deandrea Hashimoto, 1507.03098:	composite pseudoscalar, WZW term
Sanz, 1507.03553:	glueball in new composite sector
Bian Liu Shu, 1507.06018:	composite Higgs sector
Low Tesi Wang, 1507.07557:	composite Higgs sector
Dobadu Guo Llanes-Estrada, 1508.03544:	composite Higgs sector

Extended Gauge Sectors

Hisano Nagata Omura, 1506.03931:	Leptophobic Z' or W'
Cheung Keung Tseng Yuan, 1506.06064:	Z' or W_R
Dobrescu Liu, 1506.06736 / 1507.01923:	W' in LR model
Gao Ghosh Sinha Yu, 1506.07511:	W' in LR model
Brehmer Hewett JK Rizzo Tattersall, 1507.00013:	W' in LR model
Abe Nagai Okawa Tanabashi, 1507.0115:	KK-W in 3-site moose model
Cao Yan Zhang, 1507.00268:	Various 221 and 331 models
Heeck Patra, 1507.01584:	W' in LR model
Abe Kitahara Nojiri, 1507.01681:	strongly interacting SU(2)'
Anchordoqui *et al.*, 1507.05299:	stringy U(1)'
Dhuria Hati Sarkar, 1507.08297:	string-inspired U(1)'
Dev Mohapatra, 1508.02277:	W' in LR model
Coloma Dobrescu Lopez-Pavon, 1508.04129:	W' in LR model
Deppisch *et al.*, 1508.05940:	W' in LR model

Extended Gauge Sectors (contd.)

Bian Liu Shu Zhang, 1509.02787:	W’
Bandyopadhyay *et al.*, 1509.03232:	W’ in LR model / SO(10) context
Avasthi Dev Mitra, 1509.05387:	W’ in LR model
Li Maxin Mayes Nanopoulos, 1509.06821:	stringy leptophobic U(1)’
Ko Nomura, 1510.07872:	W’ in LR model
Collins Ng, 1510.08083:	W’ in SUSY LR model
Dobrescu Fox, 1511.02148:	W’ in LR model
Wang Sage Steele Mann, 1511.02531:	U(1)’ + classical conformal symmetry
Appelquist Bai Ingoldby Piai, 1511.05473:	$SU(2)_L \times SU(2)_{L'} \times SU(2)_R \times SU(2)_{R'} \times U(1)_Y$

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Extended Higgs Sectors

Chen Nomura, 1507.04431:	2HDM
Omura Tobe Tsumura, 1507.05028:	2HDM (H^0 with large up-Yukawa)
Chao, 1507.05310:	2HDM
Chen Nomura, 1509.02039:	Higgs singlet (+ vector-like fermions)
Sierra *et al.*, 1510.03437:	2HDM
Alves Camargo Dias, 1511.04449:	Heavy Higgs (+ vector-like fermions)

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Other Explanations

Aguilar-Saavedra, 1506.06739:	triboson final state (X -> W + Z + Y)
Cacciapaglia Franssen, 1507.00900:	effective Lagrangian with heavy vector
Fukano Matsuzaki Yamawaki, 1507.03428:	effective Lagrangian with heavy vector
Kim Kong Lee Park, 1507.06312:	EFT analysis
Liew Shirai, 1507.08273:	RS graviton
Arnan Espriu Mescia, 1508.00174:	Model-independent unitarity arguments
Goncalves Krauss Spannowsky, 1508.04162:	Model-indep. results on jet substructure
Fichet Gersdorff, 1508.04814:	EFT for spin-0 and spin-2 resonances
Petersson Torre, 1508.05632:	sgoldstino
Arbuzov Zaitsev, 1510.02312:	Heavy scalar with dim-5 couplings
Allanach Dev Sakurai, 1511.01483:	RPV SUSY with $m_{\tilde{\tau}} \sim m_W, m_Z$
Sajjad, 1511.02244:	EFT analysis
Bhattacherjee *et al.*, 1511.02797:	triboson final state (X -> W + Z + Y)

Composite Higgs Models

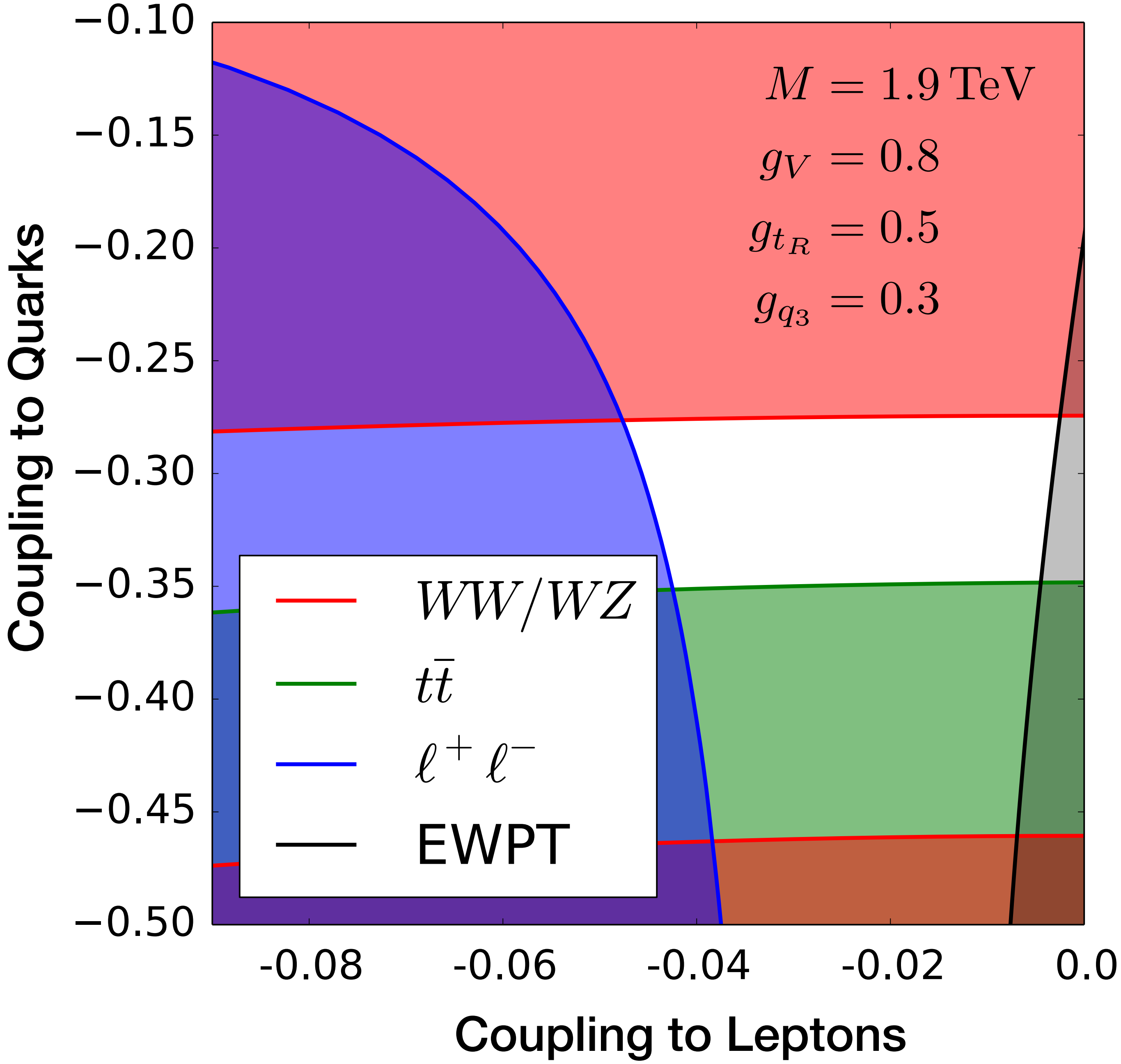
- SM fermions mix with fermions of heavy composite sector
- Symmetry breaking e.g. SO(5) → SO(4)
  - Higgs as pseudo-Goldstone boson
- Heavy resonances at compositeness scale
  - One of them could explain the diboson anomaly
  - Typically described using a phenomenological Lagrangian

$$
\begin{aligned}
\mathcal{L} \supset & -\frac{1}{4} D_{[\mu} V_{\nu]}^{a} D^{[\mu} V^{\nu]\,a} + \frac{m_V^2}{2} V_\mu^a V^{\mu\,a} \\
& + i\, g_V c_H V_\mu^a H^\dagger \tau^a \overleftrightarrow{D}^\mu H + \frac{g^2}{g_V} c_F V_\mu^a J_F^{\mu\,a} \\
& + \frac{g_V}{2} c_{VVV}\, \epsilon_{abc} V_\mu^a V_\nu^b D^{[\mu} V^{\nu]\,c} + g_V^2 c_{VVHH} V_\mu^a V^{\mu\,a} H^\dagger H \\
& - \frac{g}{2} c_{VVW} \epsilon_{abc} W^{\mu\nu\,a} V_\mu^b V_\nu^c
\end{aligned}
$$

Thamm Torre Wulzer, 1506.08688

Carmona Delgadod Quiros Santiago,1507.01914

Fit of a Composite Vector Resonance



Carmona Delgadod Quiros Santiago,1507.01914

Left-Right Symmetry

The Left-Right Symmetric Model

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

$$\downarrow$$

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

$$\downarrow$$

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

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The Left-Right Symmetric Model

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

g_L g_R

$\kappa \equiv g_R/g_L$

$$\downarrow$$

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

$$\downarrow$$

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

The Left-Right Symmetric Model

$W_L,\ Z_L \qquad W_R,\ Z_R$

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

$g_L \qquad g_R$

$\kappa \equiv g_R/g_L$

$$\downarrow$$

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

$$\downarrow$$

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

The Left-Right Symmetric Model

$W_L,\ Z_L \qquad W_R,\ Z_R$

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

$g_L \qquad g_R$

$\kappa \equiv g_R/g_L$

$W_R,\ Z_R$ mass ← $\Delta_R \sim (1,3,2)$

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

$W_L,\ Z_L$ mass ← $\Phi\ (2,2,0)$

W_L–W_R, Z_L–Z_R mixing

physical states $W,\ W'$

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

Higgs sector

$\Delta_R \sim (1,3,2)$

$\Phi\ (2,2,0)$

$\Delta_L \sim (3,1,2)$

(zero or tiny vev)

The Left-Right Symmetric Model

$W_L,\ Z_L \qquad W_R,\ Z_R$

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

$g_L \qquad g_R$

$\kappa \equiv g_R/g_L$

$\downarrow$

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

$\downarrow$

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

Fermions

$$\begin{pmatrix} \nu_L \\ \ell_L \end{pmatrix} \sim (2,1,-1) \qquad \begin{pmatrix} N \\ \ell_R \end{pmatrix} \sim (1,2,-1)$$

$$\begin{pmatrix} u_L \\ d_L \end{pmatrix} \sim (2,1,\tfrac{1}{3}) \qquad \begin{pmatrix} u_R \\ d_R \end{pmatrix} \sim (1,2,\tfrac{1}{3})$$

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W / W’ Phenomenology in the LR Model

$\kappa \equiv g_R/g_L$

- W boson mass matrix

$$\mathcal{M}_{\mathcal{W}}{}^2 = \begin{pmatrix} m_{W_L}^2 & \beta_w m_{W_L}^2 \\ \beta_w m_{W_L}^2 & m_{W_R}^2 \end{pmatrix}$$

- Physical masses

$$m_1 \sim m_{W_L} \qquad m_2 \sim m_{W_R}$$

- Mixing angle

$$\tan 2\phi_w = \frac{-2\beta_w m_W^2}{m_{W_R}^2 - m_W^2}$$

- Z_R mass

$$\frac{m_{Z_R}^2}{m_{W_R}^2} = \frac{2\kappa^2(1-\sin^2\theta_w)}{\kappa^2(1-\sin^2\theta_w)-\sin^2\theta_w} > 1$$

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W / W' Phenomenology in the LR Model

- W boson mass matrix

$$\mathcal{M}_{\mathcal{W}}{}^2 = \begin{pmatrix} m_{W_L}^2 & \beta_w m_{W_L}^2 \\ \beta_w m_{W_L}^2 & m_{W_R}^2 \end{pmatrix}$$

- Physical masses

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$$\tan 2\phi_w = \frac{-2\beta_w m_W^2}{m_{W_R}^2 - m_W^2}$$

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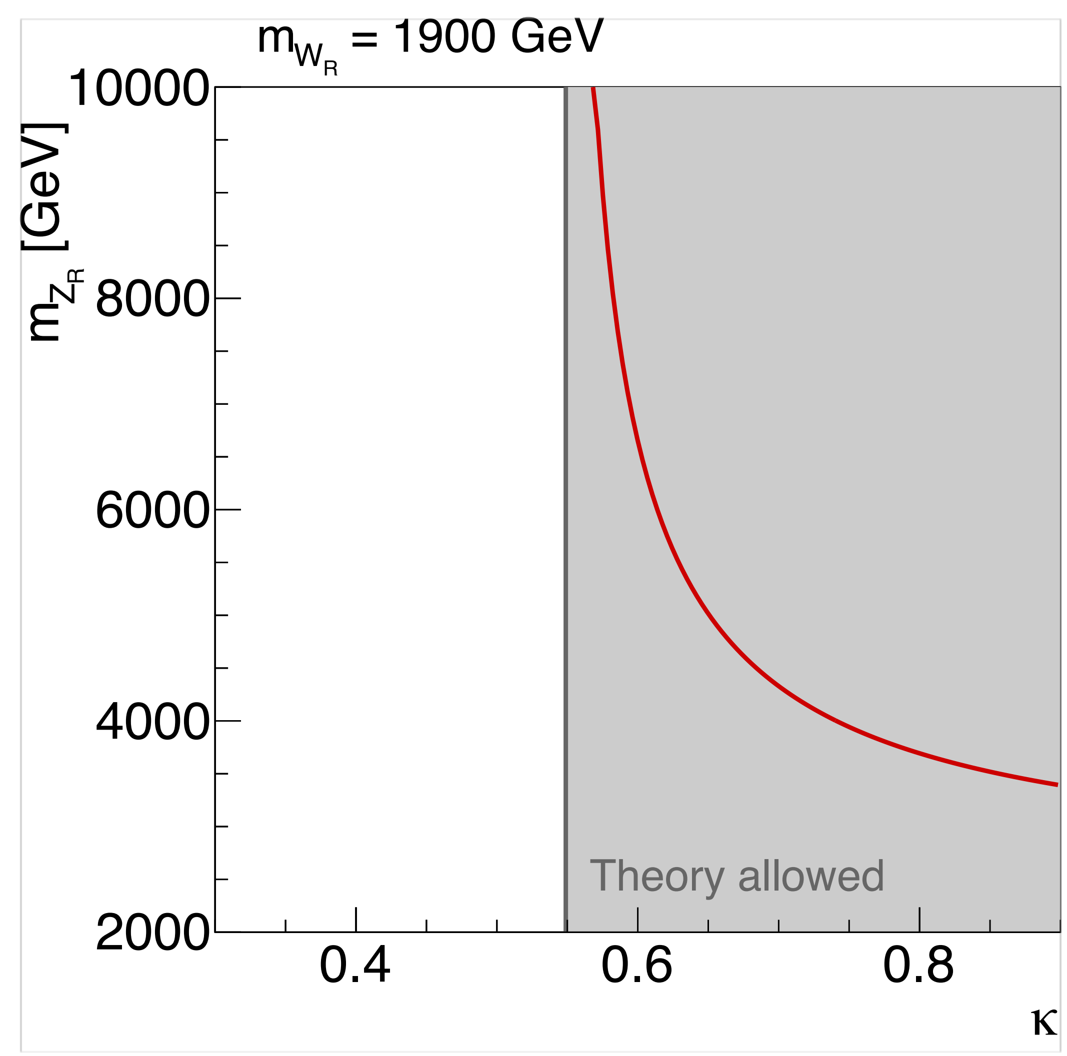
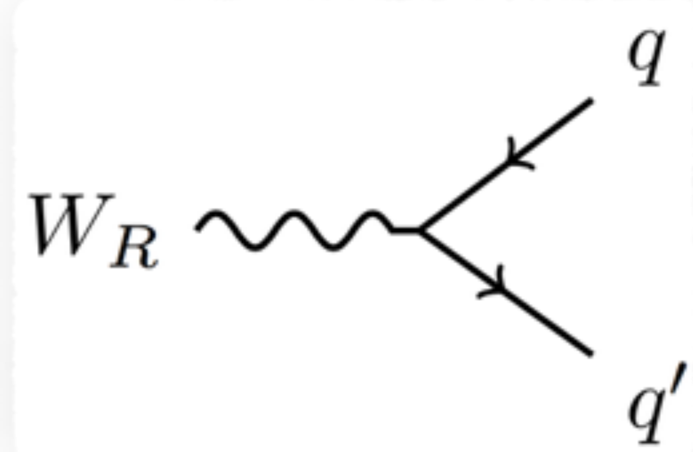
$$\kappa \equiv g_R/g_L$$



W' and Z' Couplings to Fermions

$$Q = T_{3L} + T_{3R} + (B-L)/2$$

- W' couplings

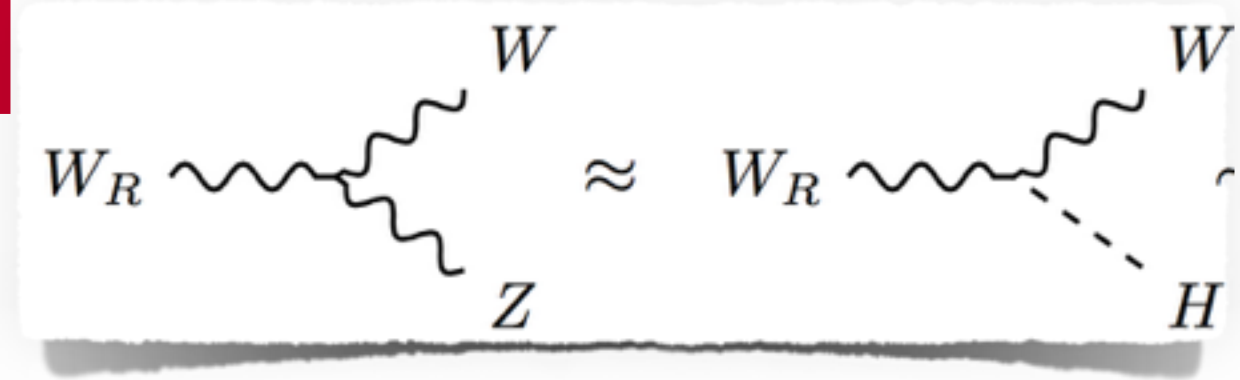


$$\mathcal{O}_{W'} \simeq \frac{g_R}{\sqrt{2}}$$ (neglecting W–W' mixing)

- Z' couplings

$$\mathcal{O}_{Z_R} = \frac{g_R}{\cos\alpha}\left[T_{3R} + Y\sin^2\alpha\right]$$ with $$\tan\alpha \equiv \frac{g_{B-L}}{g_R}$$

W'—W—Z Coupling



- Covariant derivative:

$$\mathcal{D} = \partial - ieQA - \frac{i}{\sqrt{2}} g_L T_L^{\pm} \cdot W^{\mp} + (L \to R)$$
$$- i \frac{g_L}{\cos\theta_w}(T_{3L} - \sin^2\theta_w Q) Z - i \mathcal{O}_{Z_R} Z_R$$

- Two contributions to the W'—W—Z coupling:
  - $\mathcal{D}$ acting on $W_L^+ W_L^-$: $\sin\phi_w \cos\phi_w \times \frac{g_L}{\cos\theta_w}(1 - \sin^2\theta_w)$
  - $\mathcal{D}$ acting on $W_R^+ W_R^-$: $\sin\phi_w \cos\phi_w \times \frac{g_L}{\cos\theta_w}(- \sin^2\theta_w)$

W_L–W_R mixing angle

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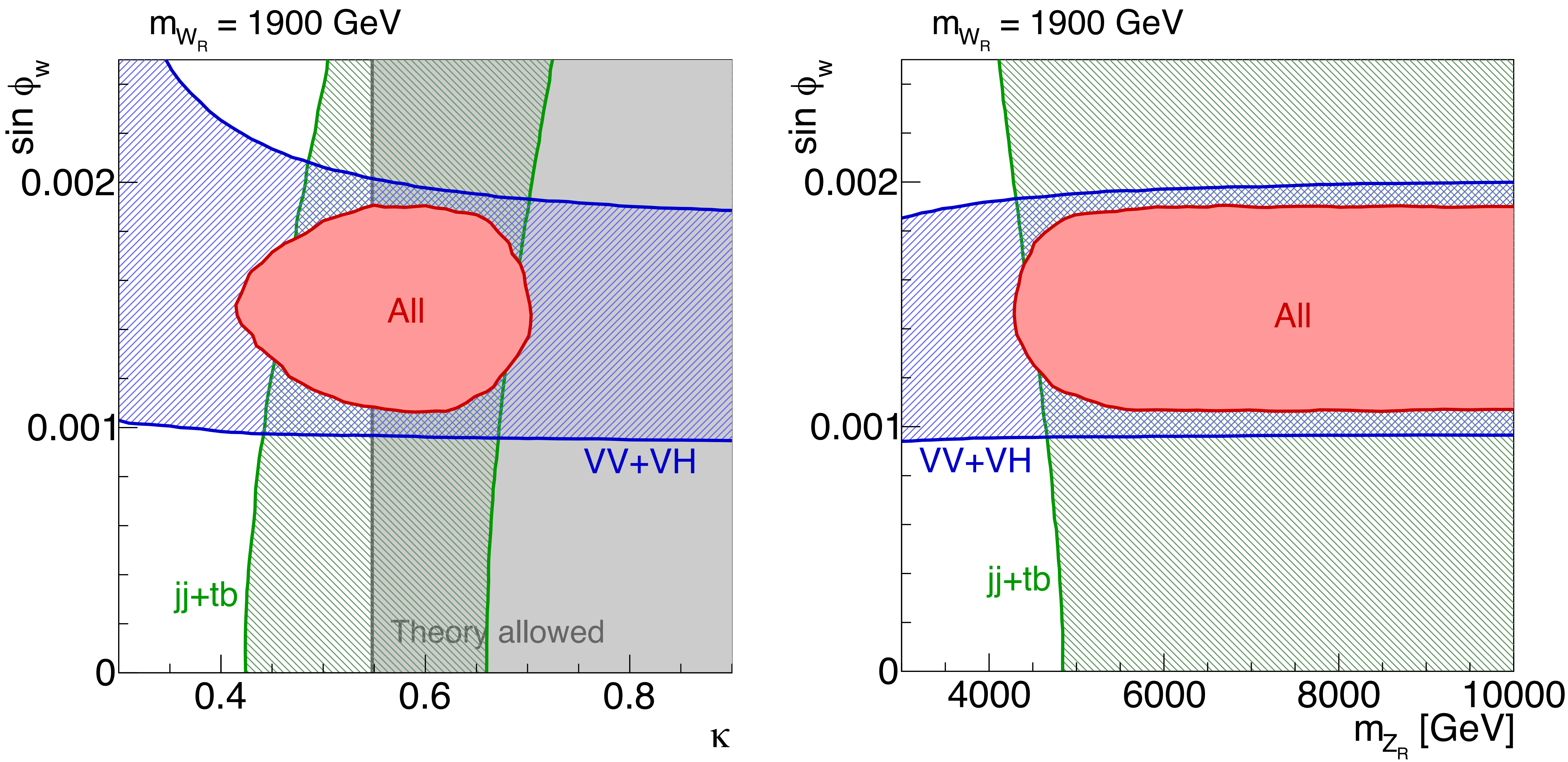
Fitting the LR Model



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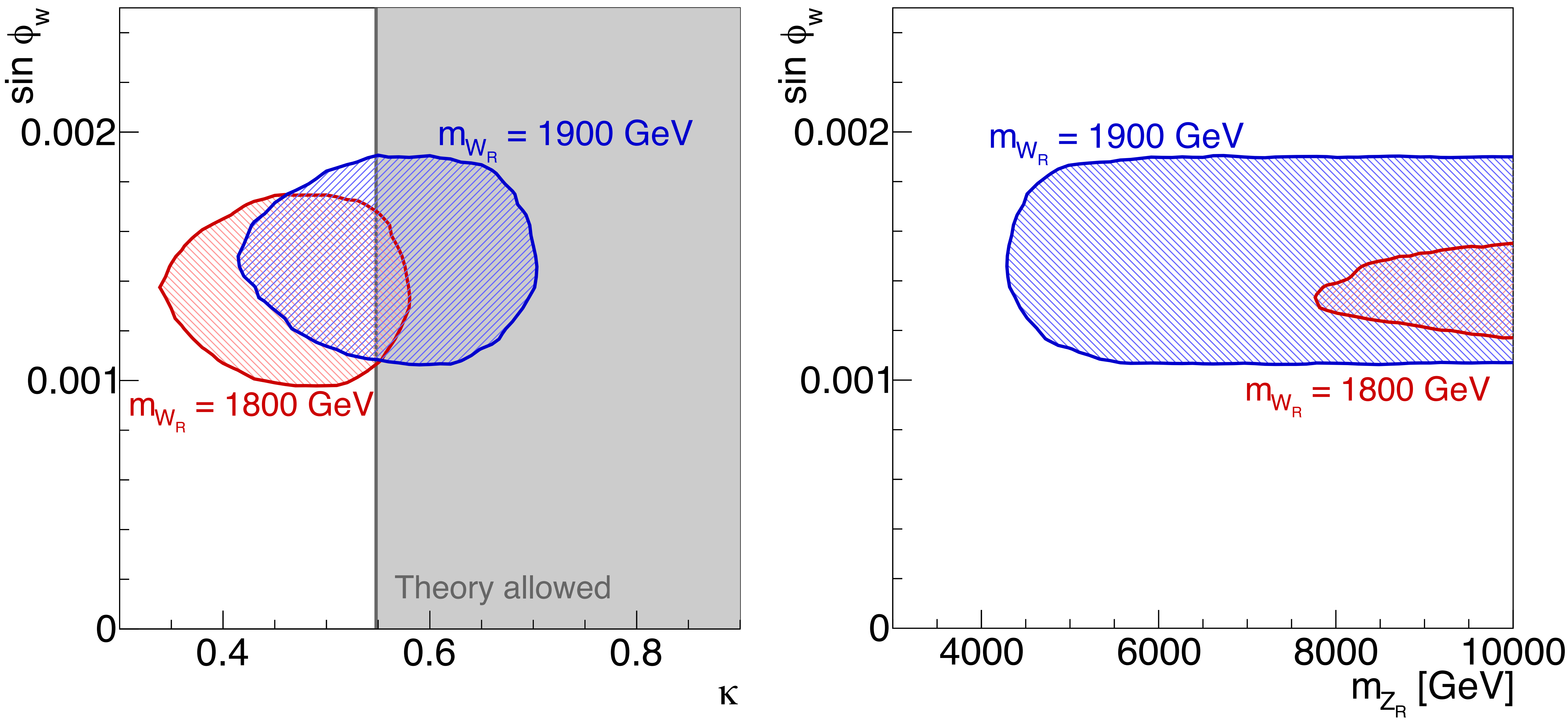
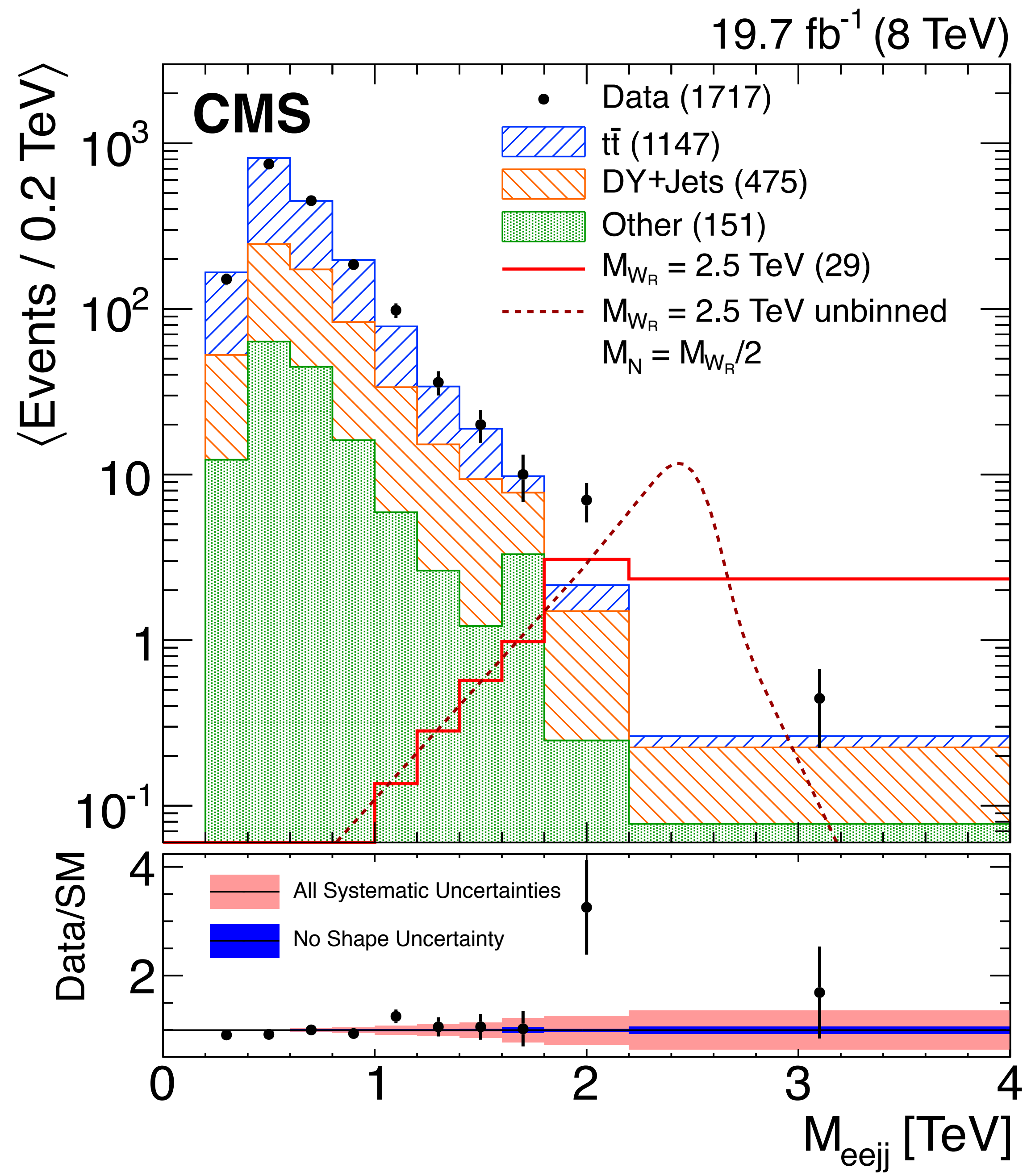
Fitting the LR Model



The CMS eejj anomaly

- Added bonus: explanation of the CMS eejj anomaly (2.8σ) via $W_R \to eN \to ee + (W_R^* \to jj)$
- Potential problems
  - Anomaly only in e^+e^-, not $e^\pm e^\pm$ possible remedy: Dirac N
  - No peak in m_{ejj} distribution
  - No signal in μμjj



Dobrescu Liu, 1506.06736

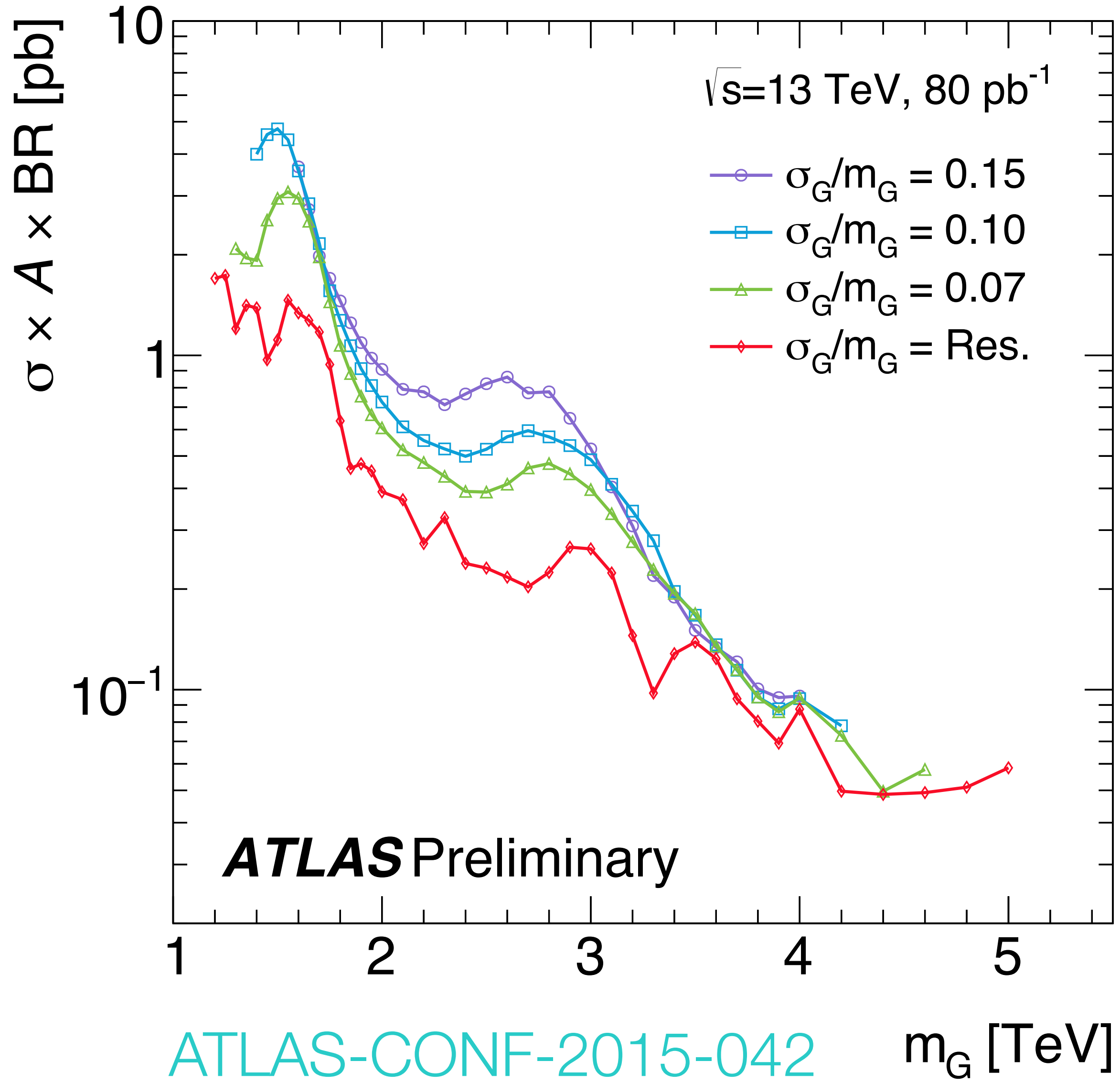
Dobrescu Liu, 1507.01923

Deppisch *et al.*, 1508.05940

Dobrescu Fox, 1511.02148

Prospects at 13 TeV

- W_R production cross section ~6 times larger than at 8 TeV
- Best fit W_R can be excluded with
  - 5 fb^{-1} in jj
  - 10 fb^{-1} in tb
  - 15 fb^{-1} in WZ, WH
- Predictions for jj at best fit
  - $\sigma \times BR \times A \sim 300$ fb



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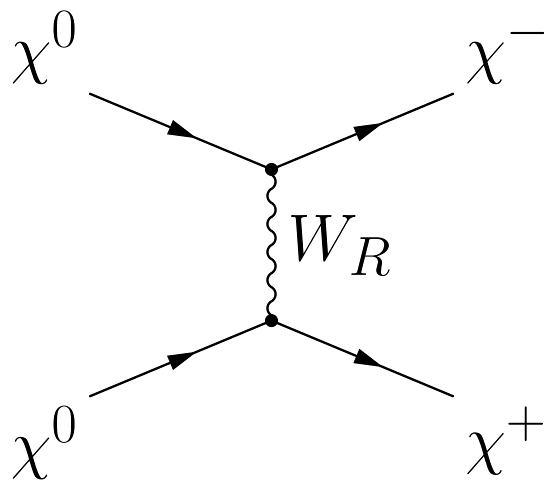
Connections to Dark Matter?

Connections to Dark Matter?



- **W'-mediated coupling to SM fields**
  - DM candidate χ^0 (e.g. N_3)
  - $SU(2)_R$ partner $\chi^{\pm}$ (e.g. τ_R)
- Requirements
  - $m_{N_3} < m_\tau$ to prevent DM decay through off-shell W_R
  - No mixing between N_3 and $N_{1,2}$ to forbid fast decay to $e/\mu + W_R^*$
  - Entropy production after DM freeze-out
    ($\langle \sigma v \rangle (N_3 N_3 \to \tau^+ \tau^-)$ too small)

Connections to Dark Matter?

- **A new SU(2)$_R$ doublet**
  - DM candidate χ^0
  - In new SU(2)$_R$ doublet with charged partner $\chi^\pm$
- Features
  - Thermal freeze-out works if $m_{\chi^\pm} \sim m_{\chi^0}$ (coannihilation)
  - No direct or indirect signals
  - $BR(W_R \to \text{visible})$ reduced => larger κ allowed
  - Mixing between χ^0 and N_j must vanish to forbid DM decay

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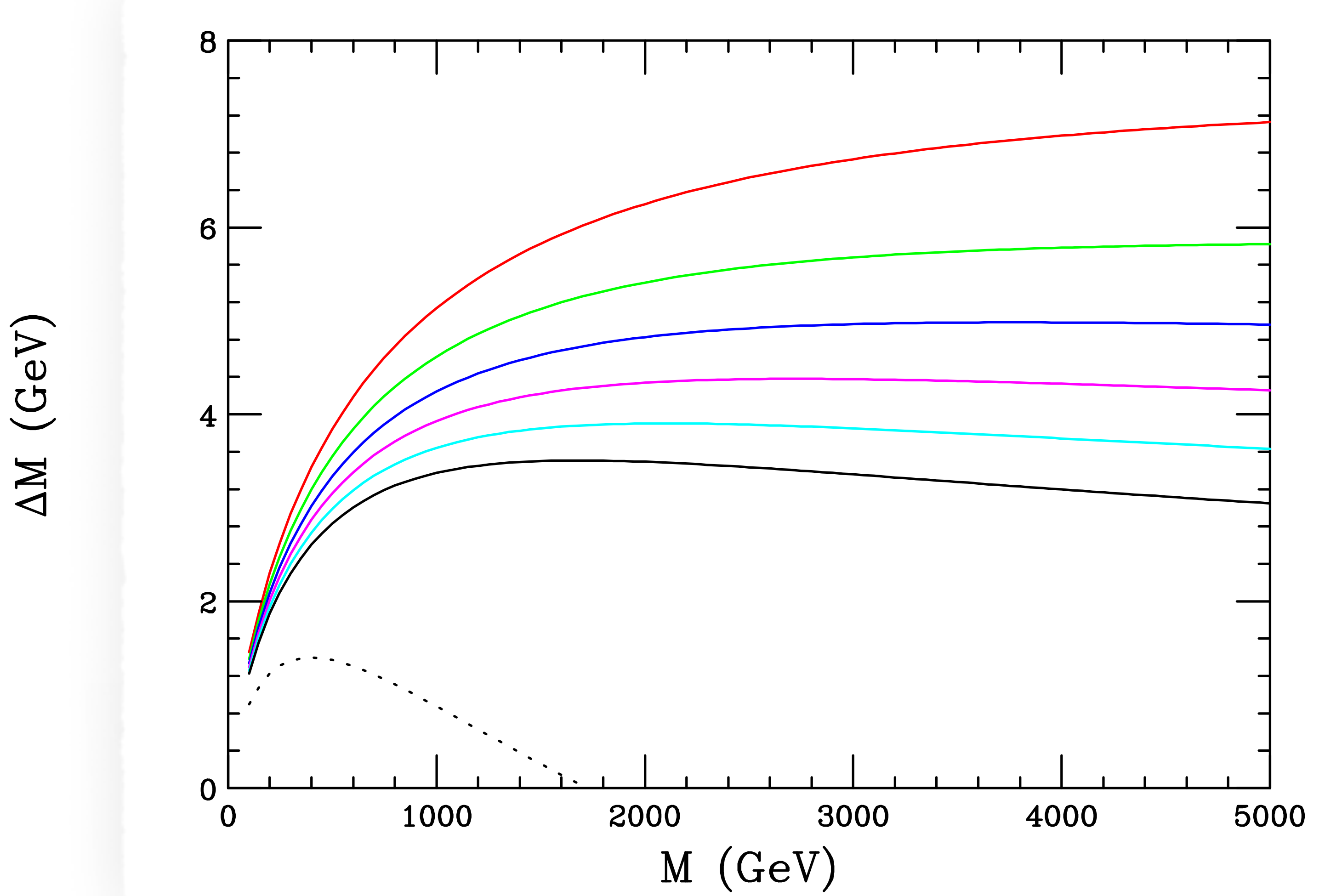
Connections to Dark Matter?

- **Minimal Left-Right Symmetric Dark Matter**
  - New $SU(2)_R$ triplet or quintuplet
  - Mass splitting between χ^0, $\chi^\pm$, $\chi^{\pm\pm}$ from radiative corrections



Heeck Patra, 1507.01584

Ko, Nomura, 1510.07872

Connections to Dark Matter?

- **DM in SUSY LR Models**
  - SUSY versions of the $SU(2)_L \times SU(2)_R$ model admit the usual SUSY DM candidates

Connections to Dark Matter?

- **Z- and Z_R-mediated DM interactions**
  - New $SU(2)_R$ multiplet $(\chi^0, \chi^\pm)$
  - Extra $\mathbb{Z}_2$ symmetry forbids χ^0–N_j mixing
- Features
  - χ^0 has Majorana mass => DM—nucleus scattering spin-dependent

$$\sigma_{\chi N} = \frac{3m_N^2 m_\chi^2}{\pi(m_N + m_\chi)^2}\left[\sum_{q=u,d,s} \Delta_{Nq}\left(\frac{g_{qA}g_{\chi A}}{M_Z^2} + \frac{g'_{qA}g'_{\chi A}}{M_Z'^2}\right)\right]^2$$

  - Annihilation through Z and Z_R

$$\langle\sigma v\rangle(\chi\chi \to f\bar{f}) \simeq \frac{n_c v_{\rm rel}^2}{6\pi}\frac{g'^2_{\chi A}(g'^2_{fV} + g'^2_{fA})m_\chi^2}{(4m_\chi^2 - m_{Z_R}^2)^2 + m_{Z_R}^2\Gamma_{Z_R}^2}$$

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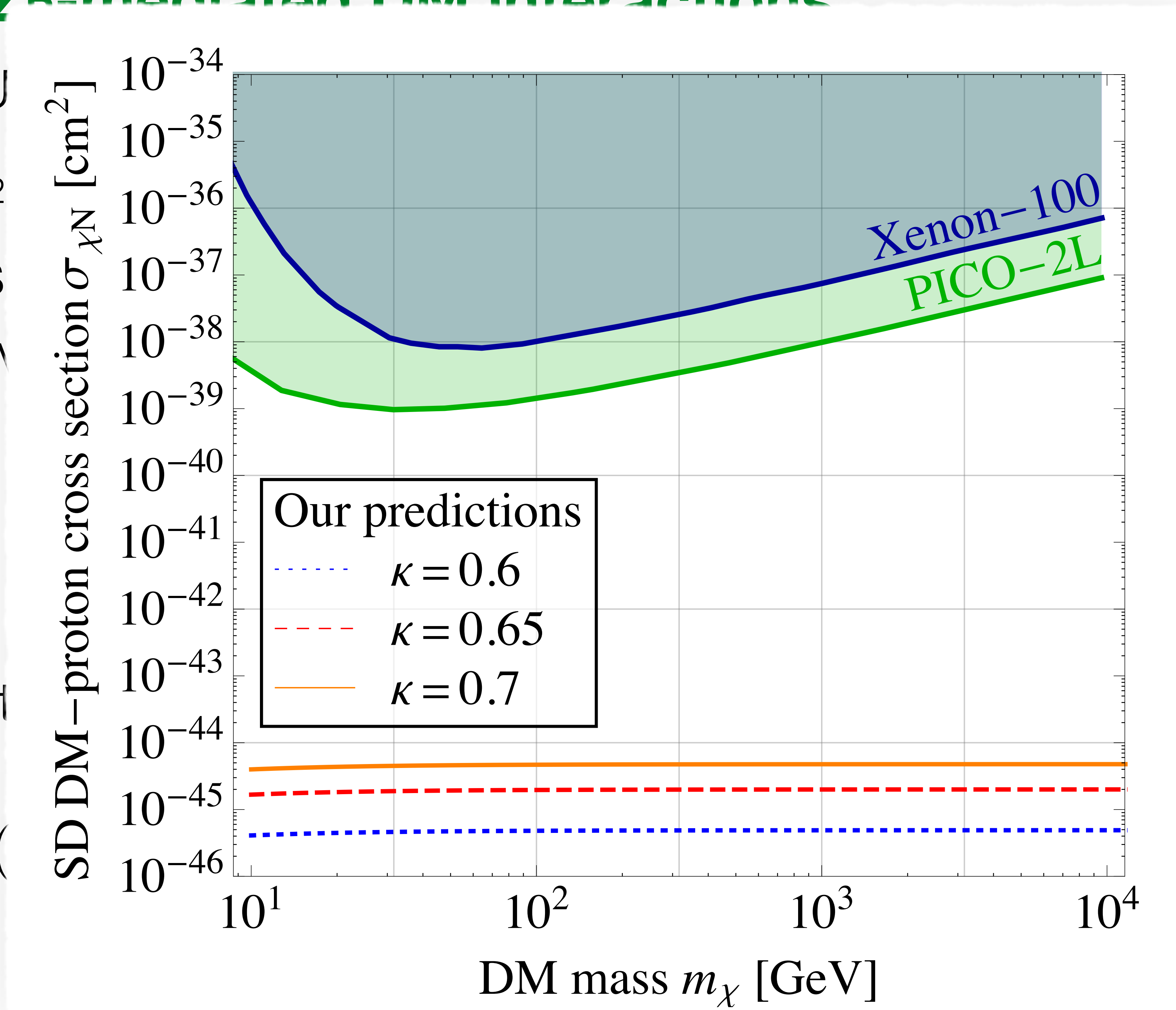
Connections to Dark Matter?

- **Z- and Z₂-mediated DM interactions**
  - New SU
  - Extra $\mathbb{Z}_2$
- Features
  - χ^0 has N … pendent

$$\sigma_{\chi N} \quad \ldots \quad \Big)\Big]^2$$

  - Annihilat

$$\langle \sigma v \rangle (\ldots$$



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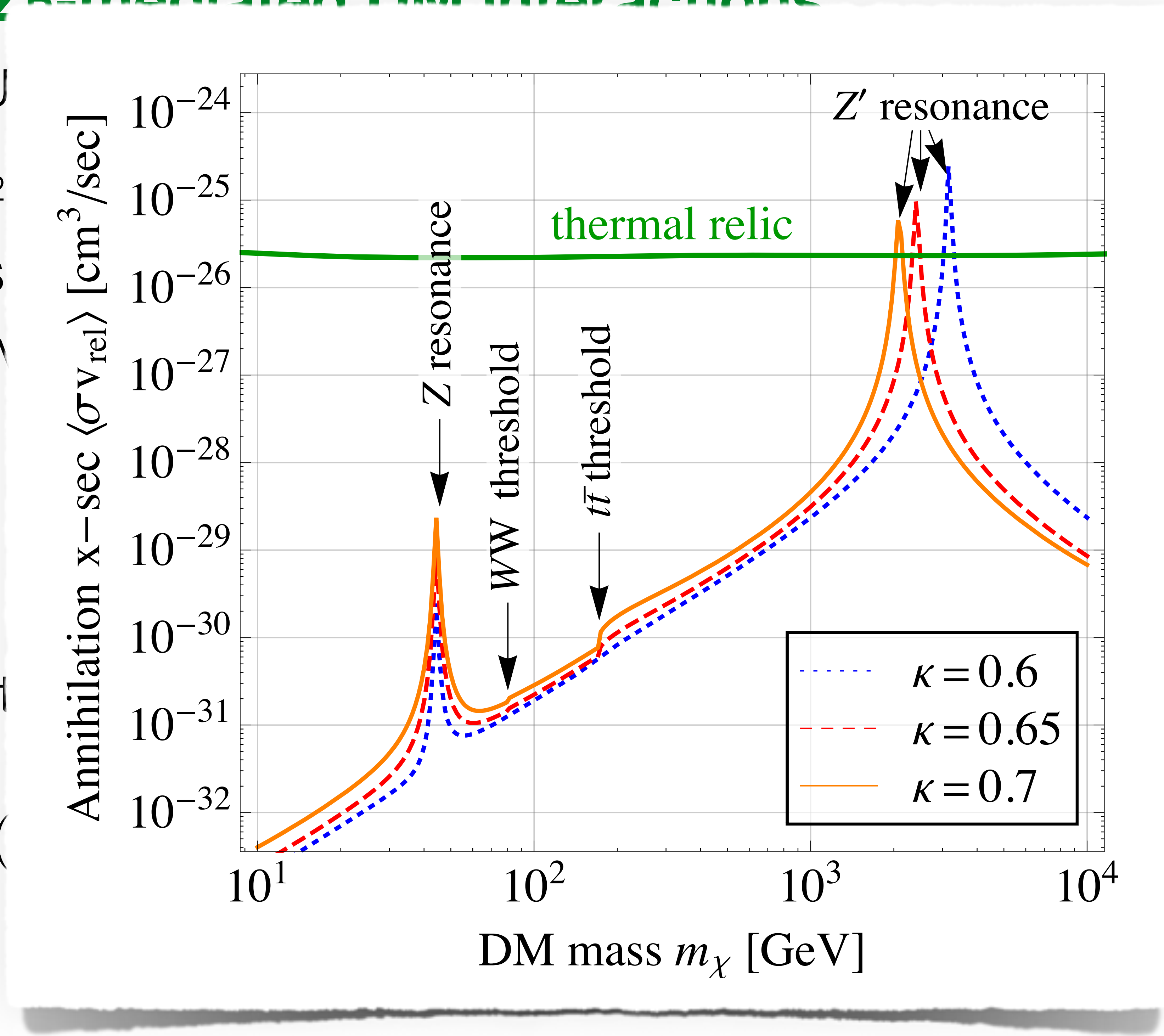
Connections to Dark Matter?

- **Z- and Z$_B$-mediated DM interactions**
  - New SU
  - Extra $\mathbb{Z}_2$
- Features
  - χ^0 has N ... pendent

$\sigma_{\chi N}$ ... $\left.\frac{\chi A}{2}\right)\Big]^2$

  - Annihilat

$\langle \sigma v \rangle($



Connections to Dark Matter?

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Conclusions

Conclusions

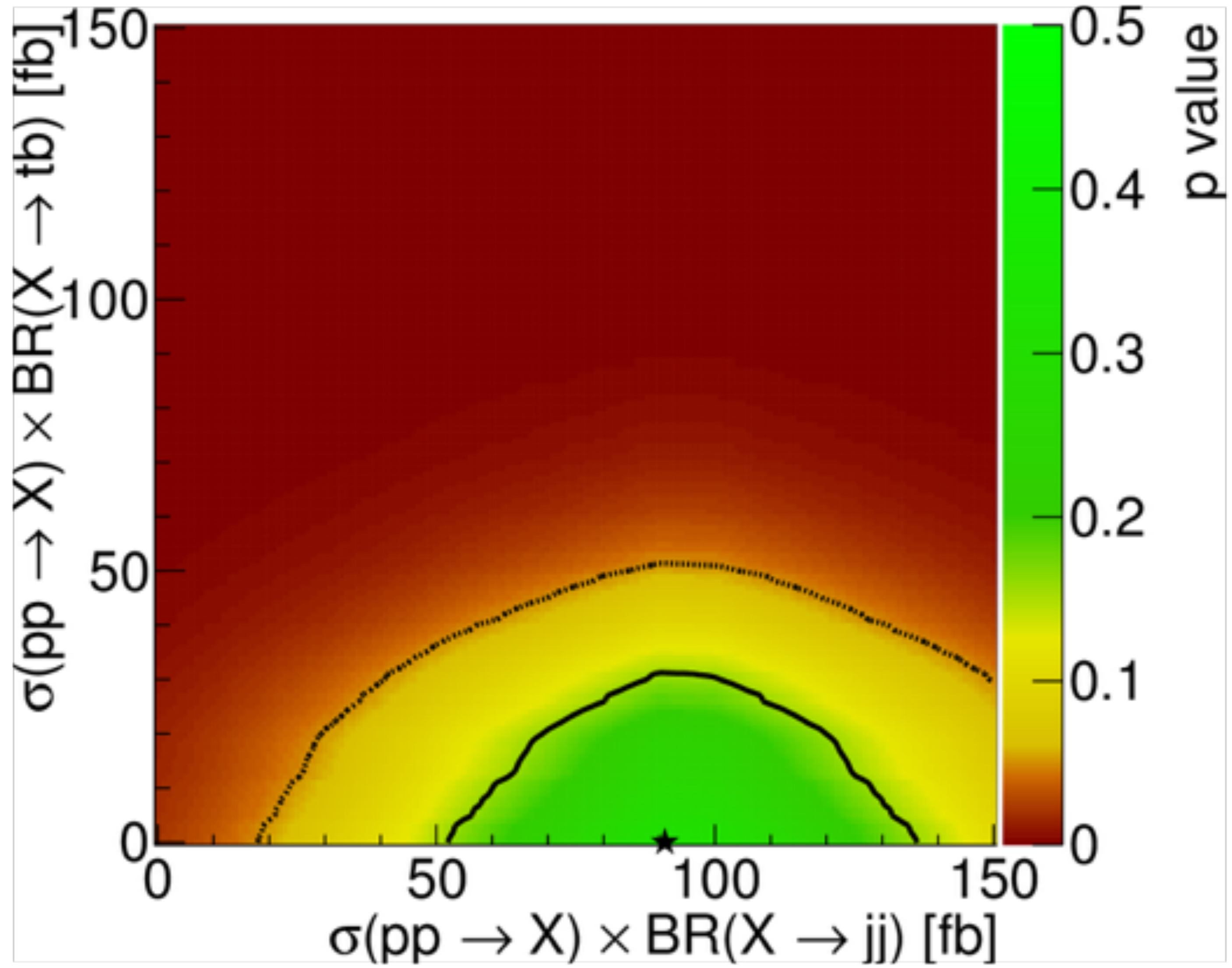
- An intriguing accumulation of anomalies at ~1.8—2 TeV
  - Signs of a composite sector?
  - An extended Higgs sector?
  - A new gauge boson?
- Left-right symmetric interpretation
  - Established and well-motivated model
  - Good fit to the data
  - Possible connections to the dark sector

Thank You!

Bonus Slides

Cross Section Fit: Dijet and t+b Resonances

- Assume heavy resonance decaying to jj or tb
- Combine all searches for these final states:
  - ATLAS dijet (~2σ) 1407.1376
  - CMS dijets (~2σ) 1501.04198
  - ATLAS $tb \to \text{hadrons}$ 1408.0886
  - ATLAS $tb \to \ell\nu bb$ (systematically too strong by ~1.8σ) 1410.4103
  - CMS $tb \to \ell\nu bb$ 1402.2176



Fitting the LR Model