

Dibosons at the LHC

Symmetry Restored?

Joachim Kopp

Seminar at Université Libre de Bruxelles | November 18th 2016

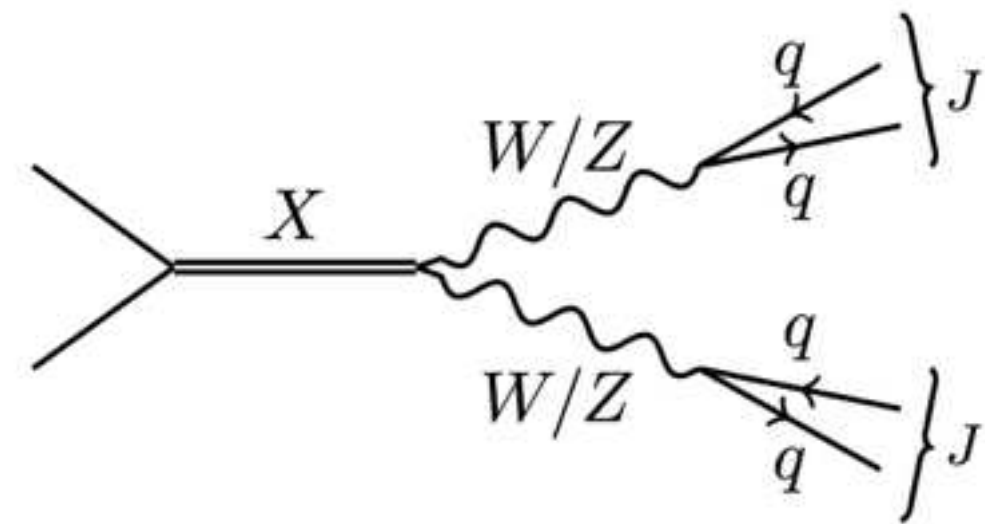
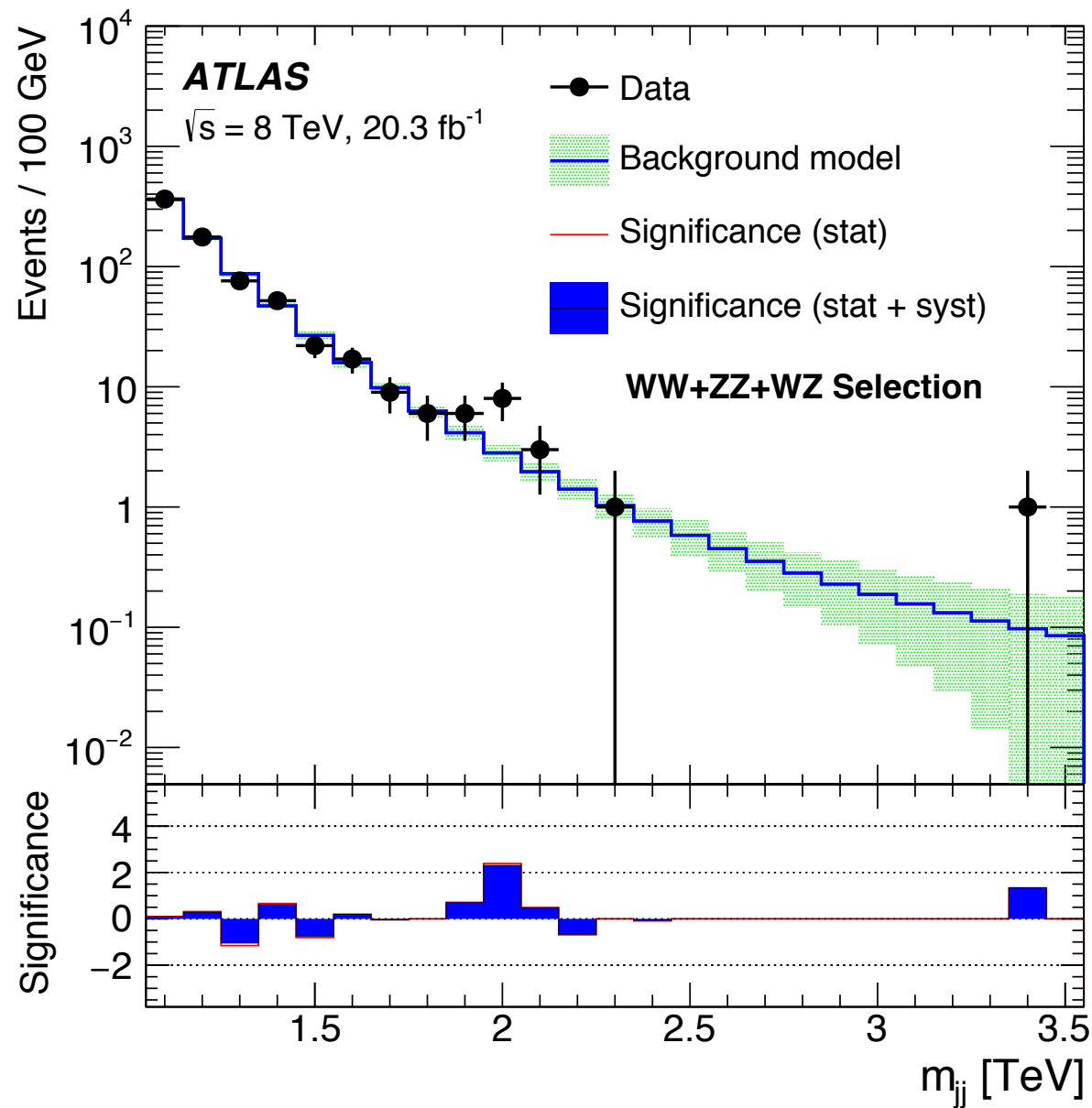
based on [arXiv:1507.00013](https://arxiv.org/abs/1507.00013) (with J. Brehmer, J. Hewett, T. Rizzo, J. Tattersall)

Minute of Silence for the Victims of the Paris Attacks

- ☑ 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

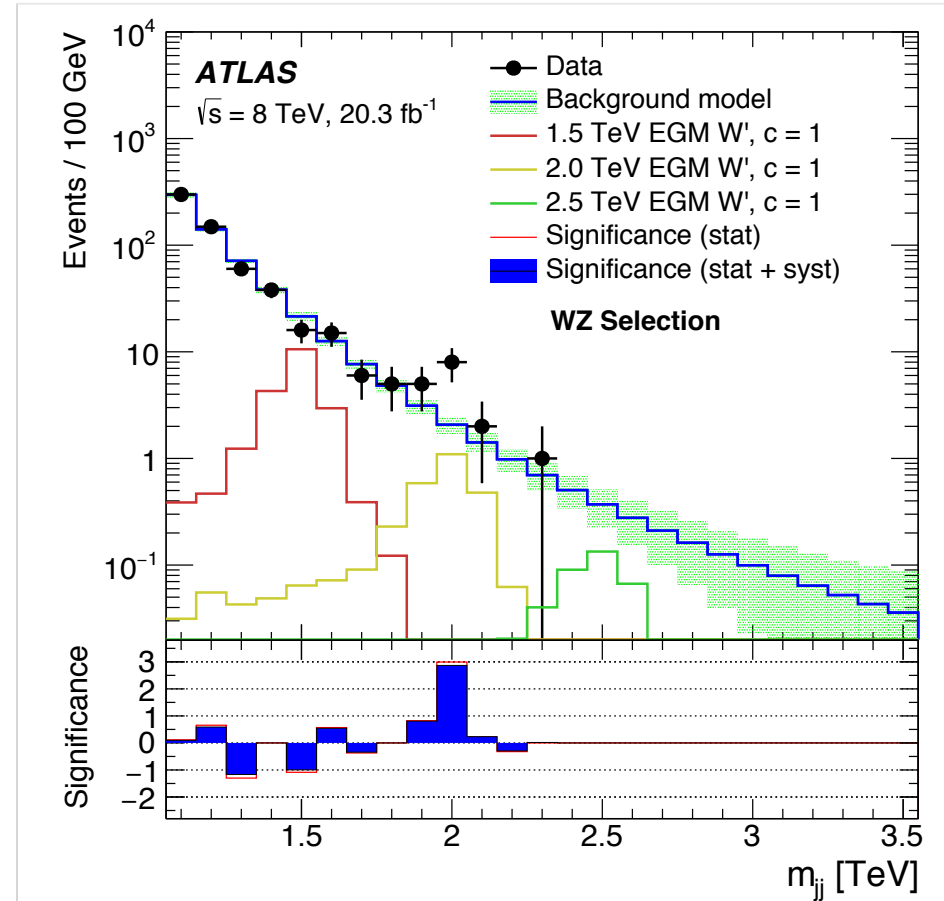
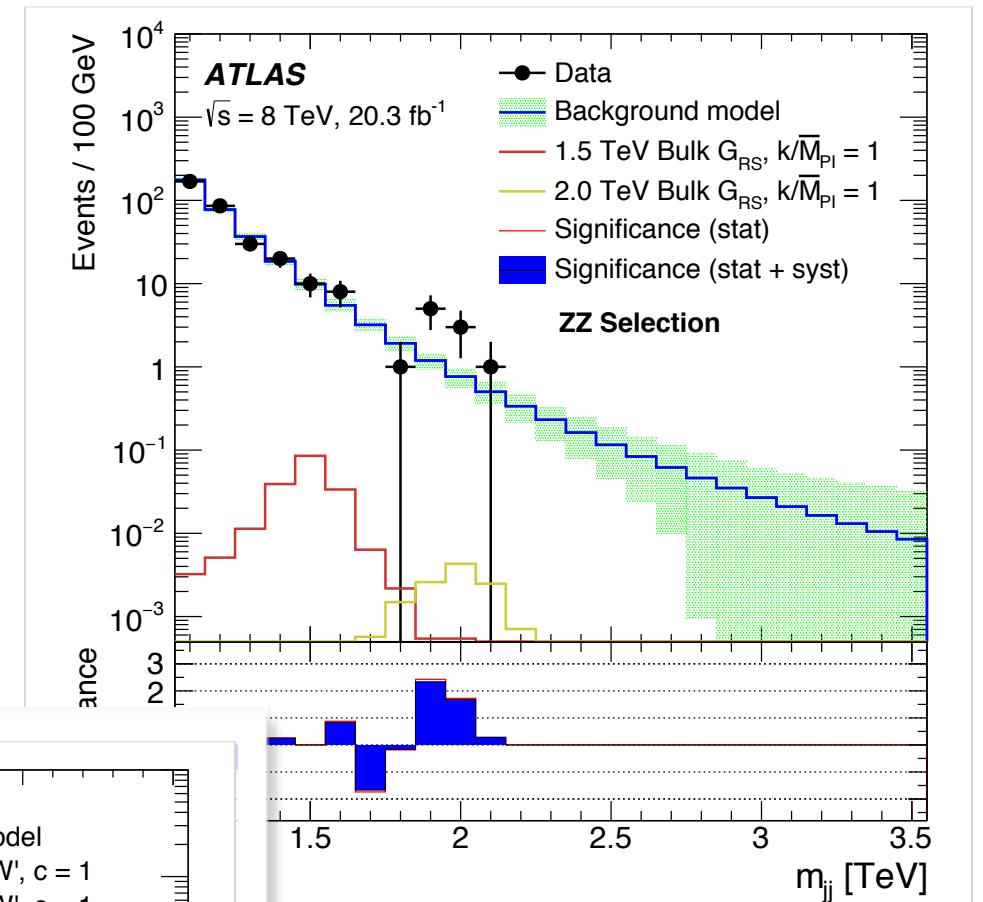
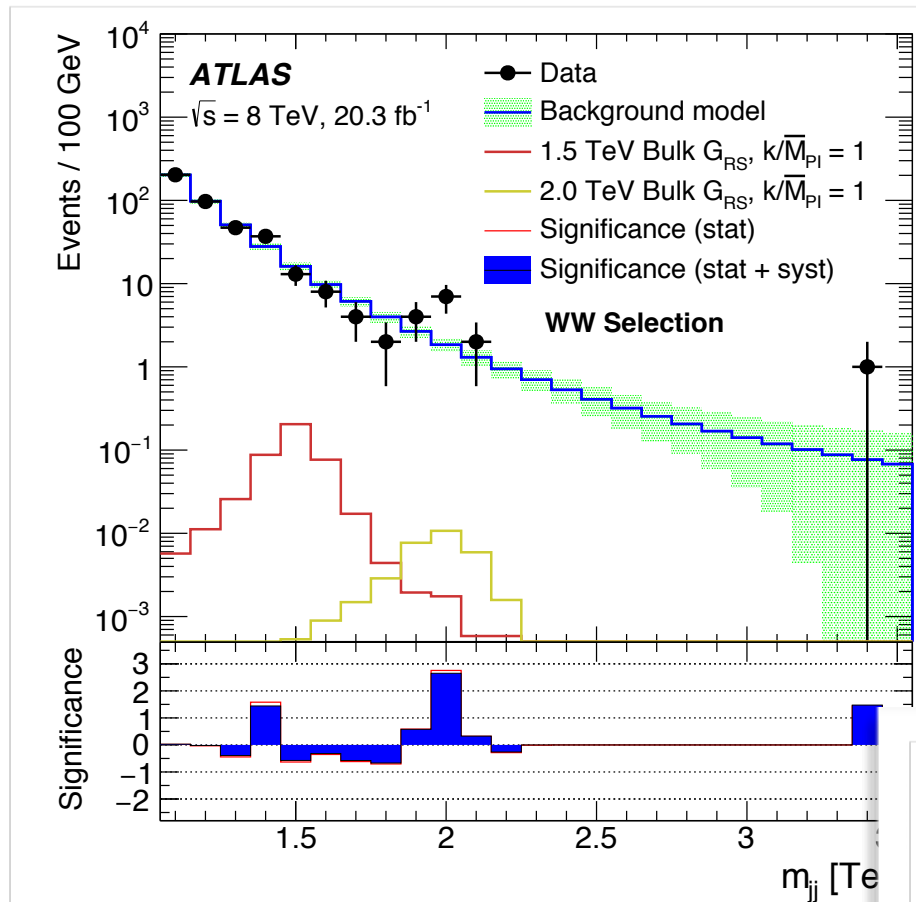
A New Resonance at 1.8–2 TeV?



ATLAS, 1506.00962

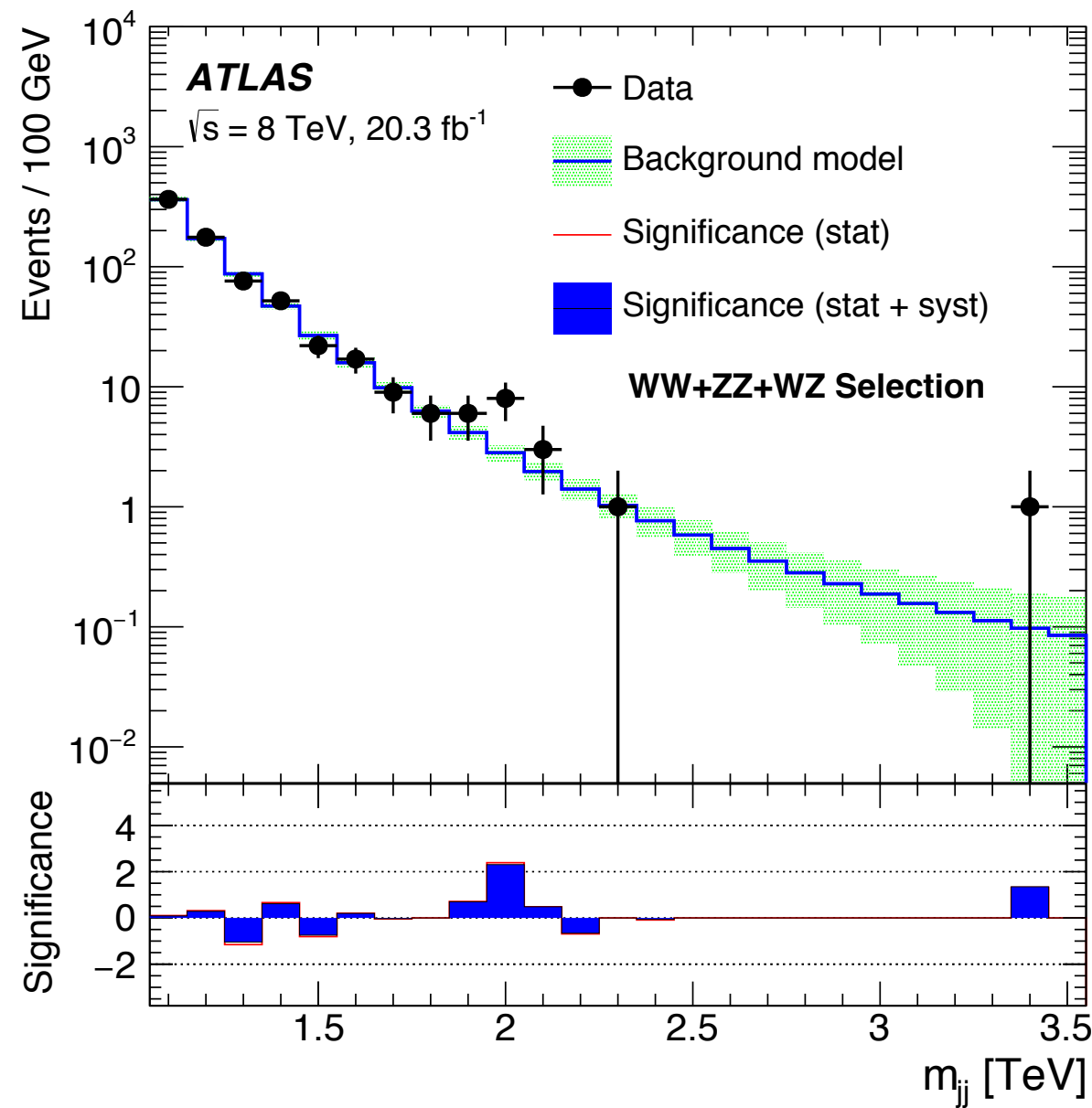
- 3.4σ Resonance in $pp \rightarrow (V \rightarrow jj) + (V \rightarrow jj)$ at 1.8–2 TeV
- Poor discrimination between W and Z

Boosted WW, ZZ and WZ



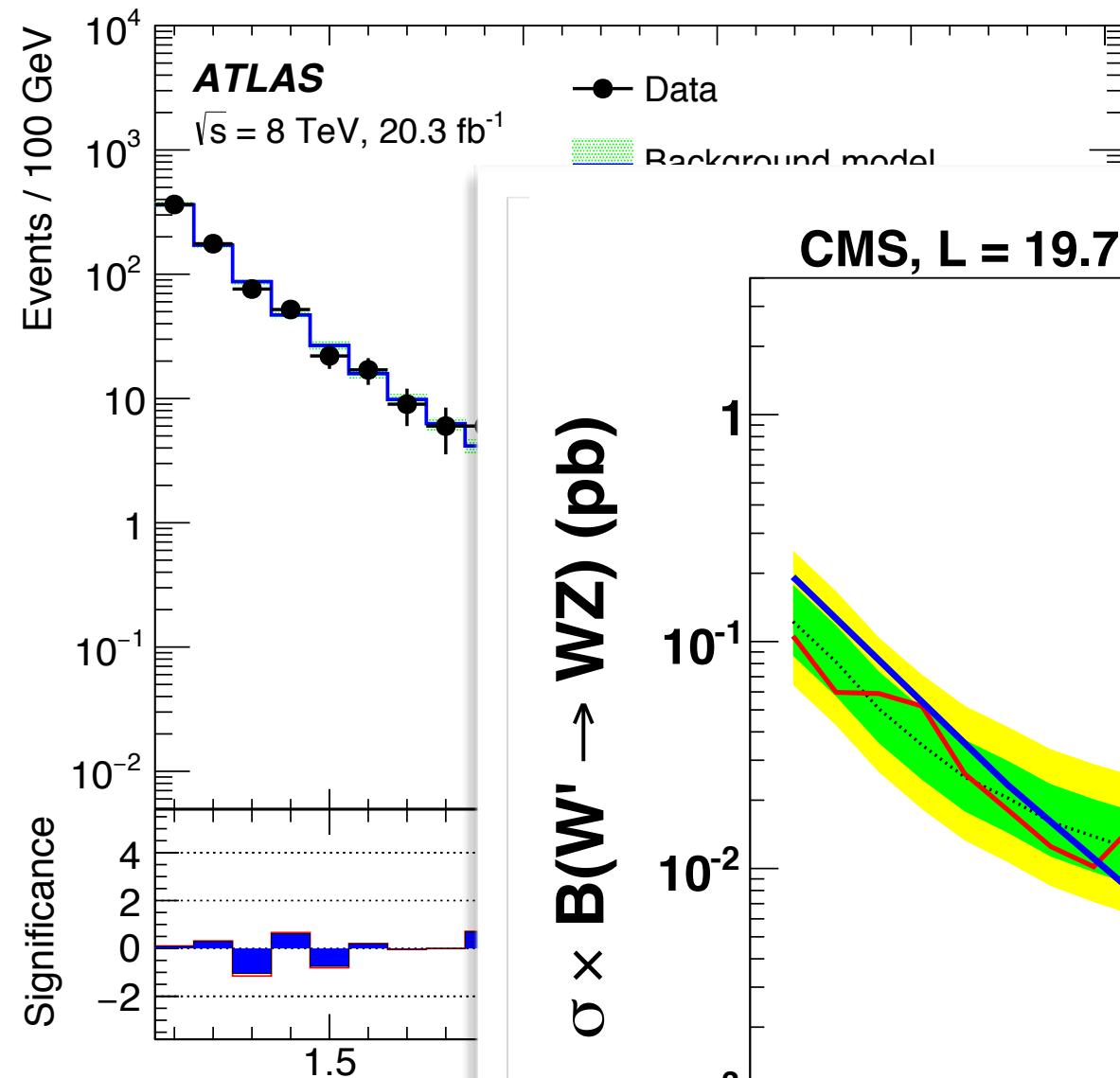
Chasing Ambulances

Chasing Ambulances

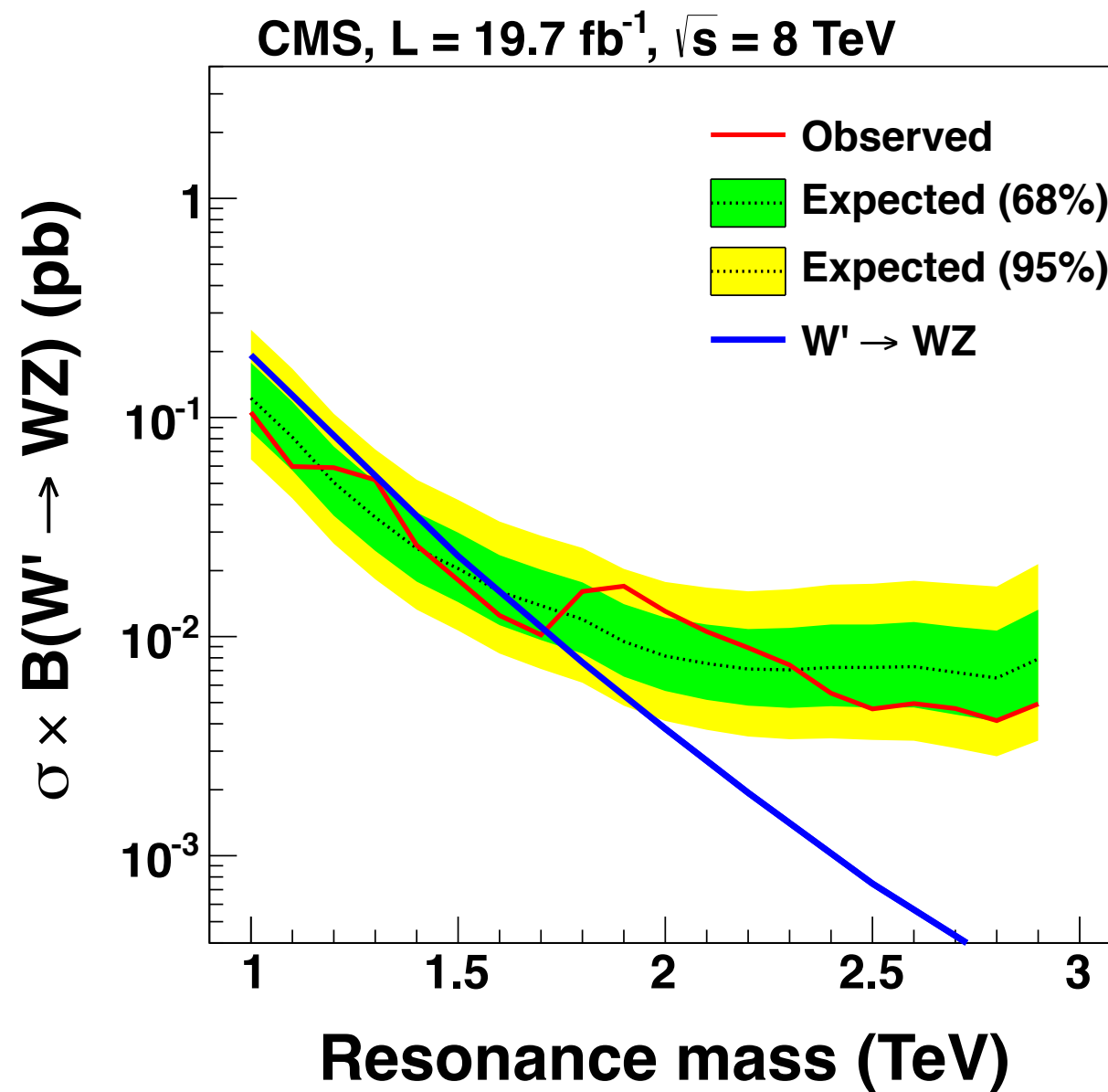


ATLAS $VV \rightarrow JJ$ (3.4σ) 1506.00962

Chasing Ambulances

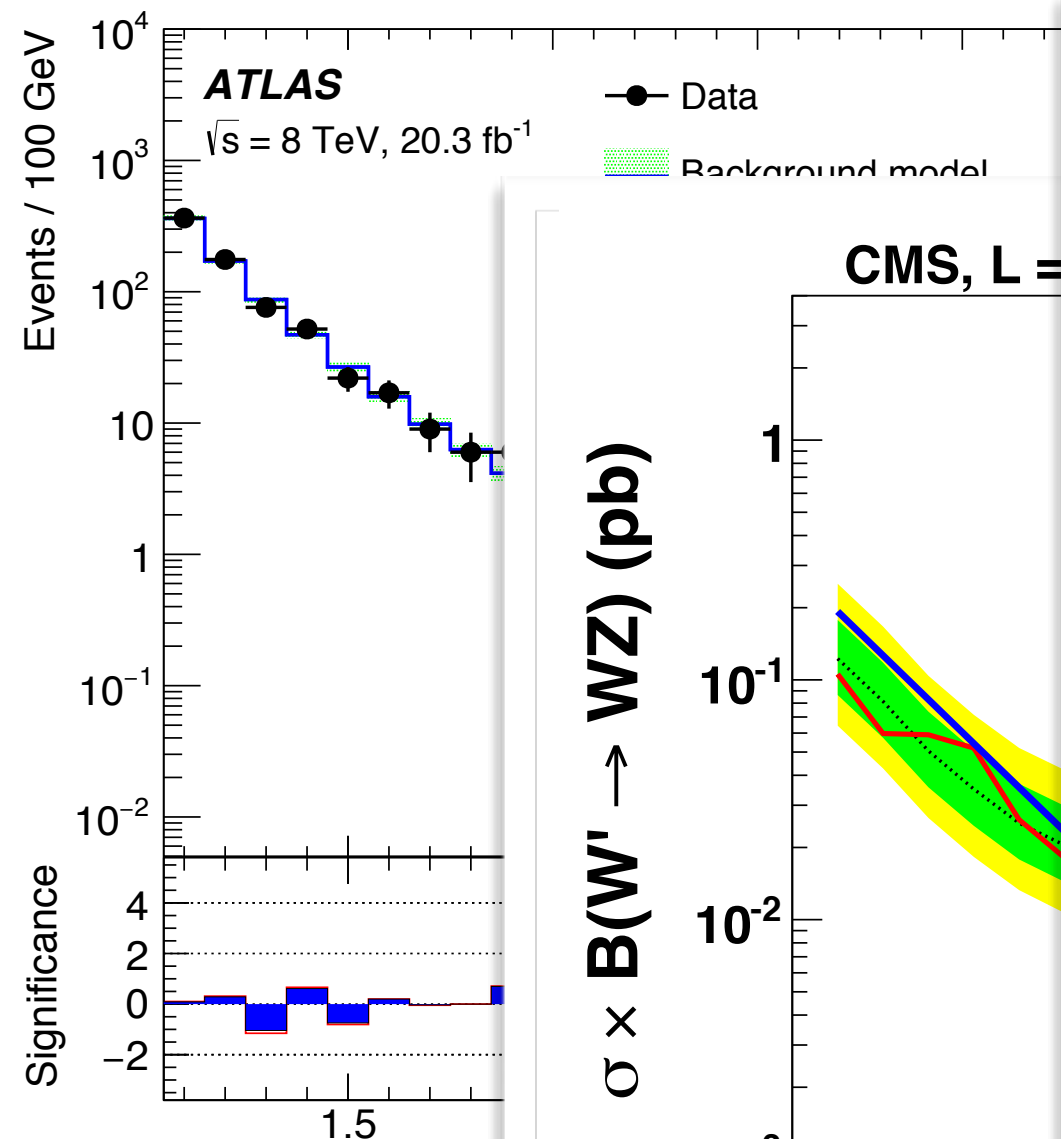


ATLAS $VV \rightarrow$

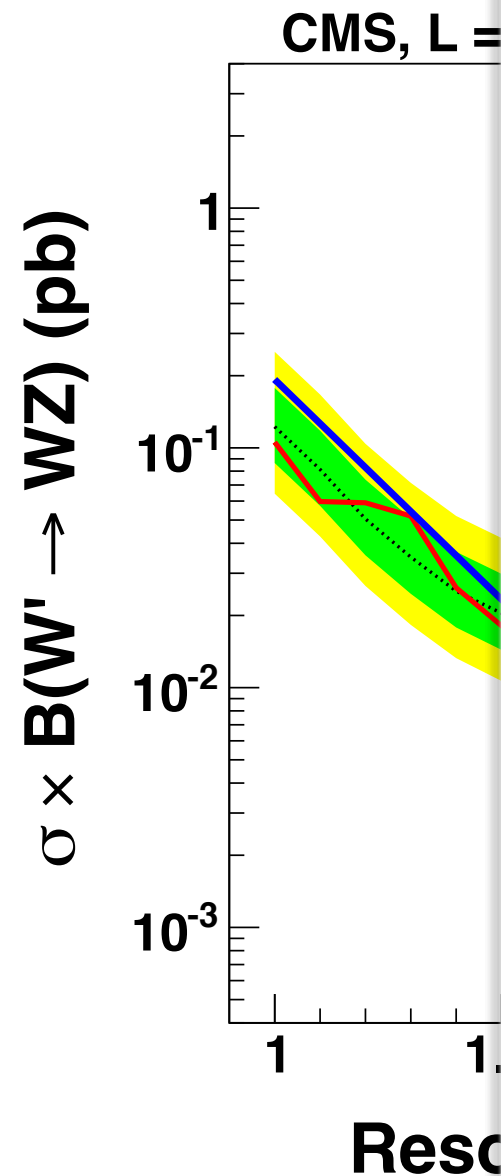


CMS $VV \rightarrow JJ$ ($\sim 1\sigma$) 1405.1994

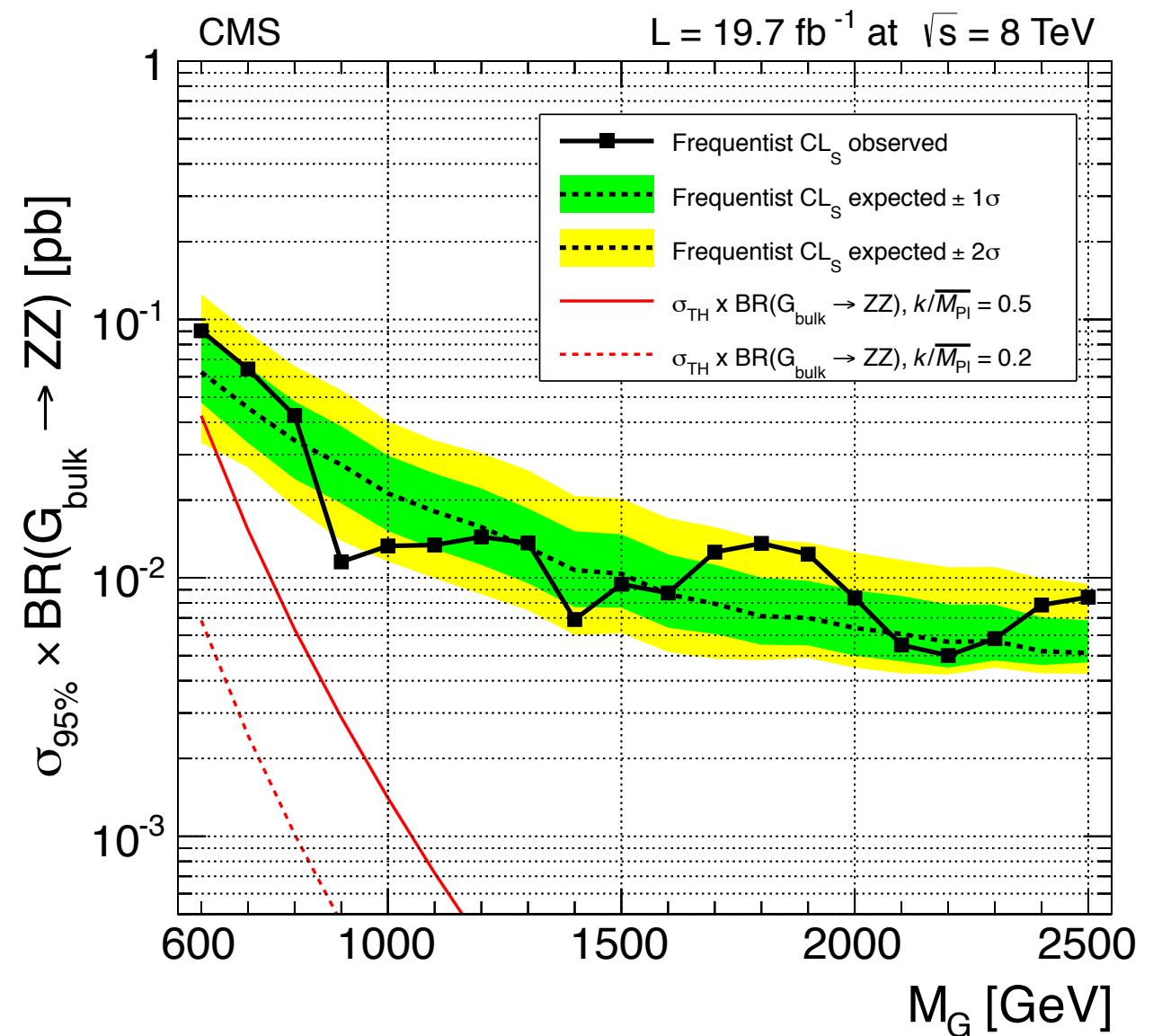
Chasing Ambulances



ATLAS $VV \rightarrow$

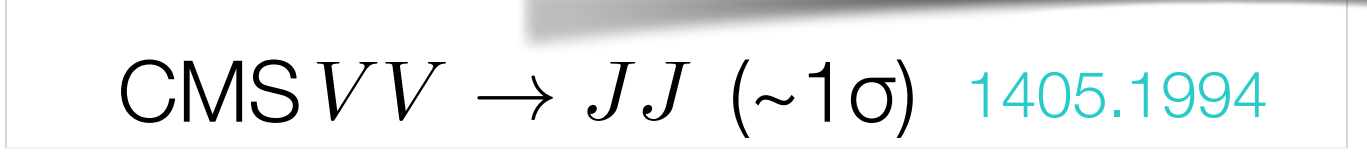
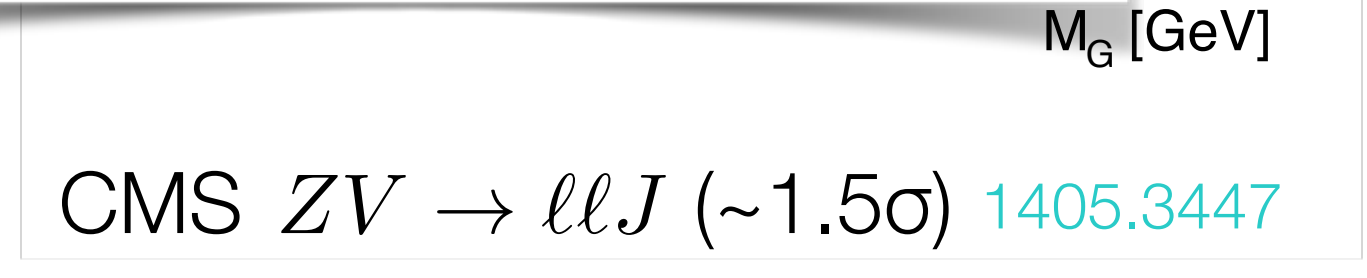
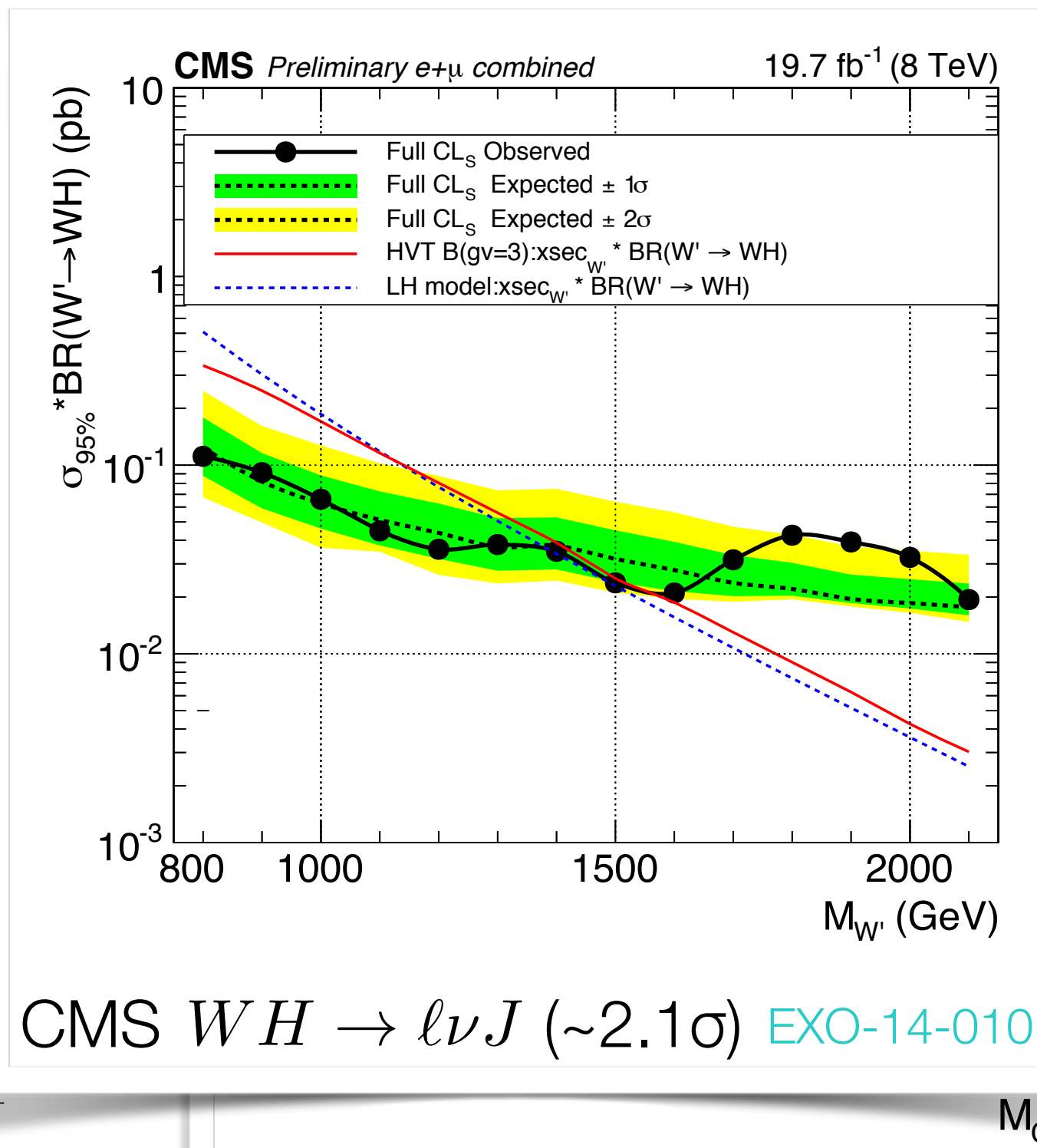
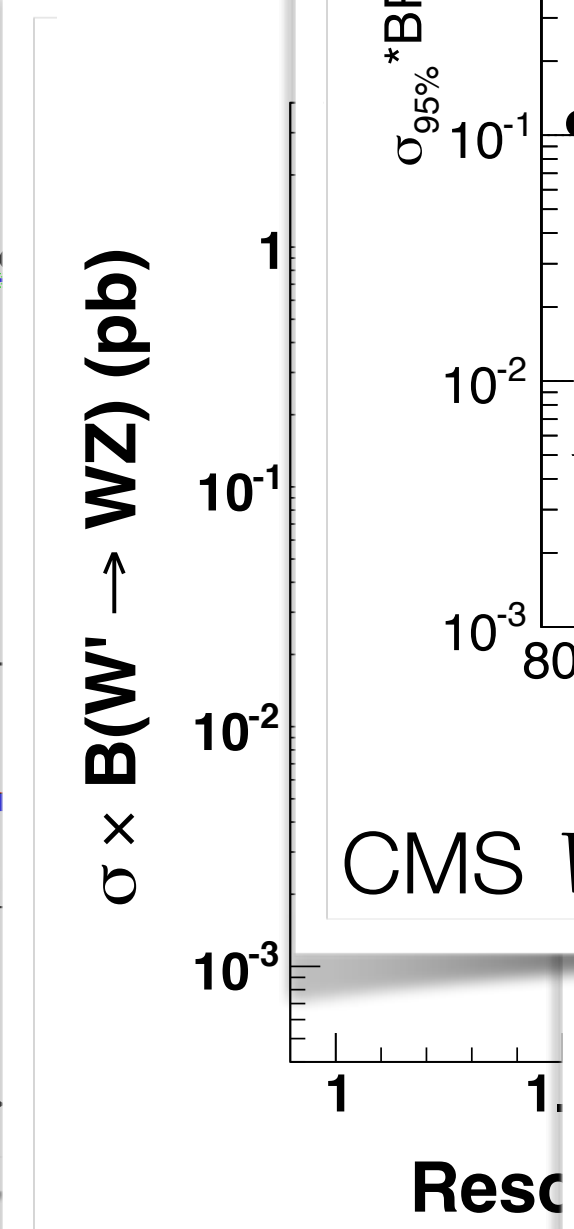
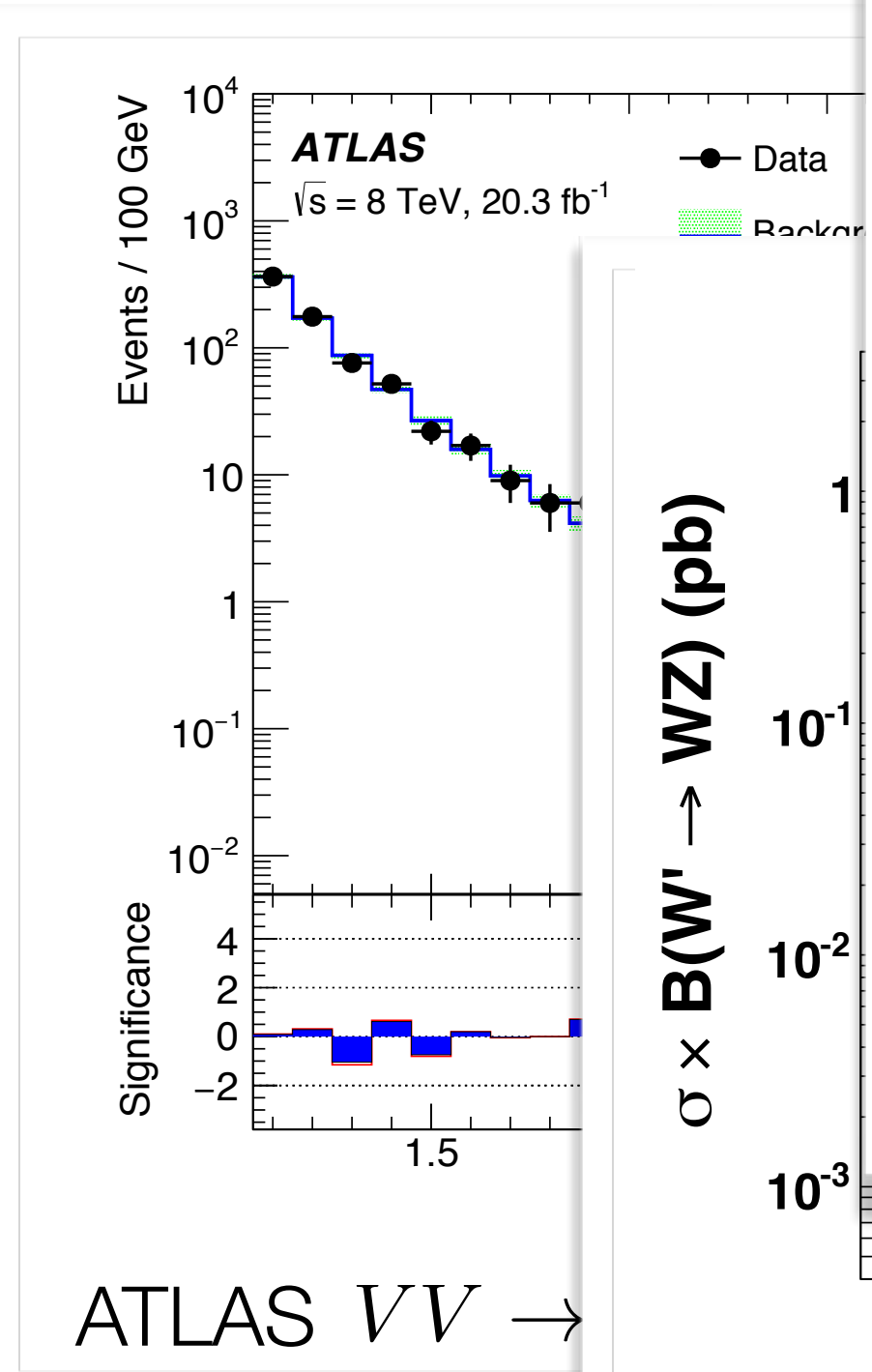


CMS $VV \rightarrow JJ$ ($\sim 1\sigma$) 1405.1994

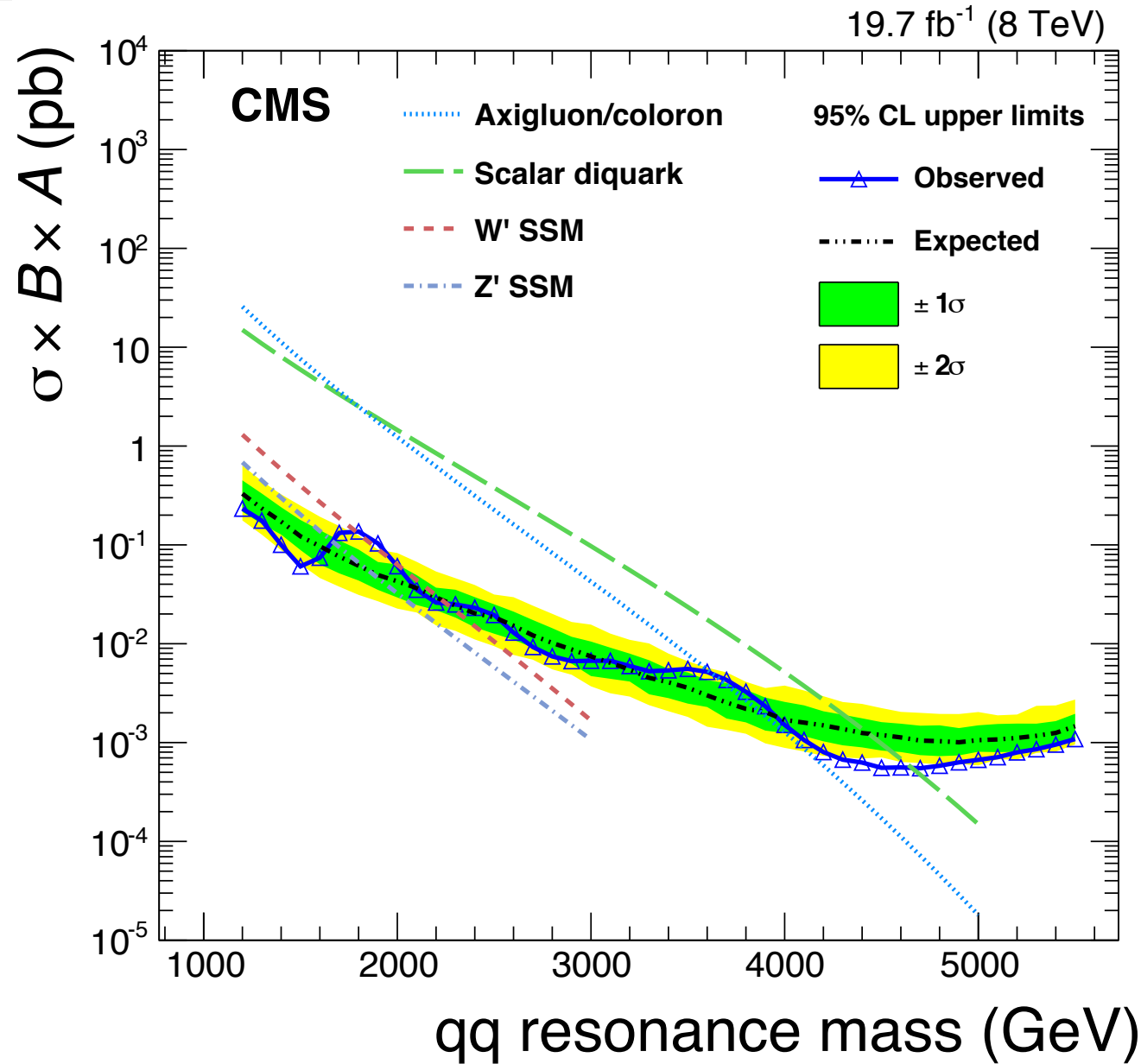


CMS $ZV \rightarrow \ell\ell J$ ($\sim 1.5\sigma$) 1405.3447

Chasing Ambulance

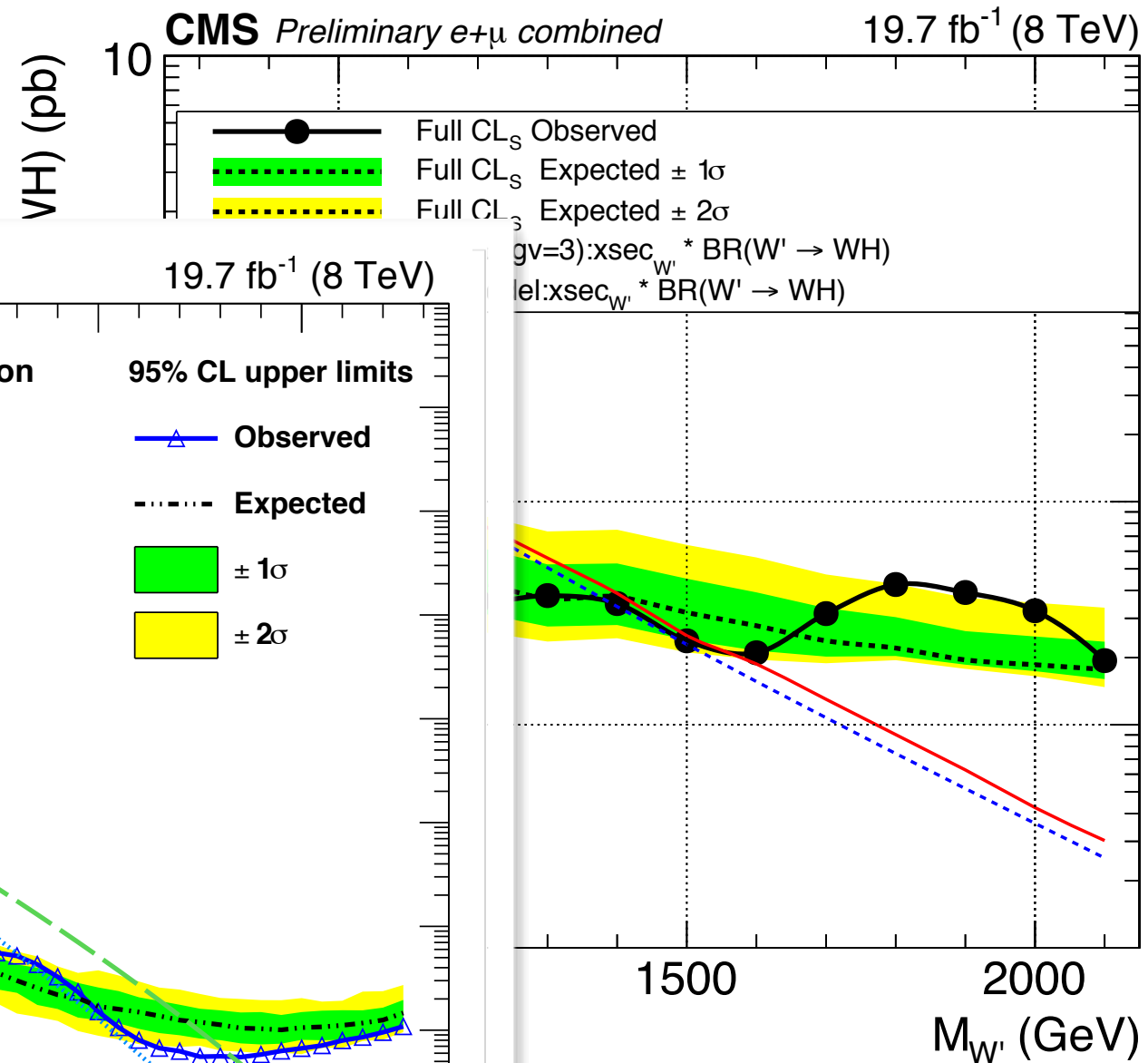


Chasing Ambulance



CMS dijets ($\sim 2\sigma$) 1501.04198

CMS $VV \rightarrow JJ$ ($\sim 1\sigma$) 1405.1994



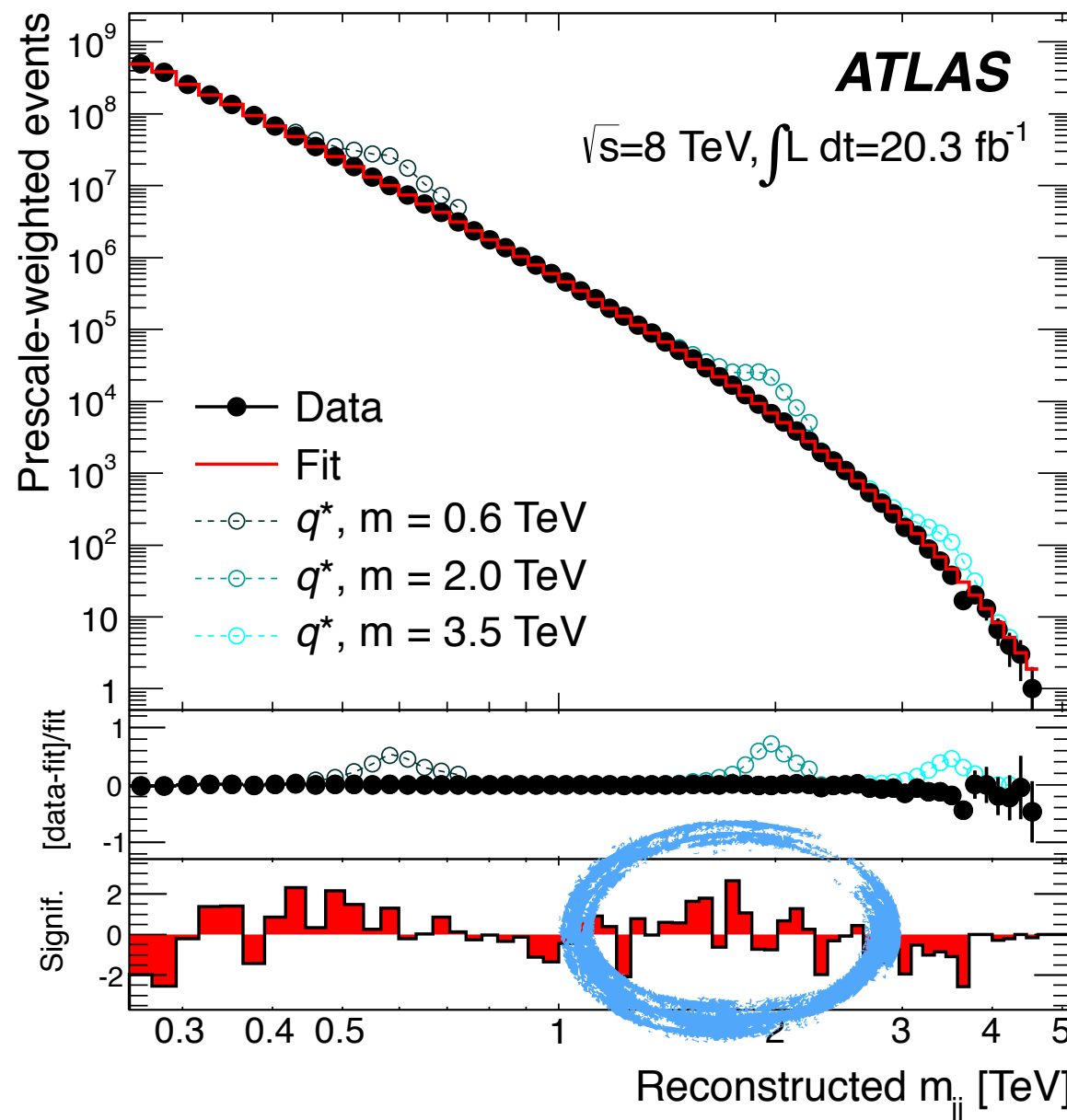
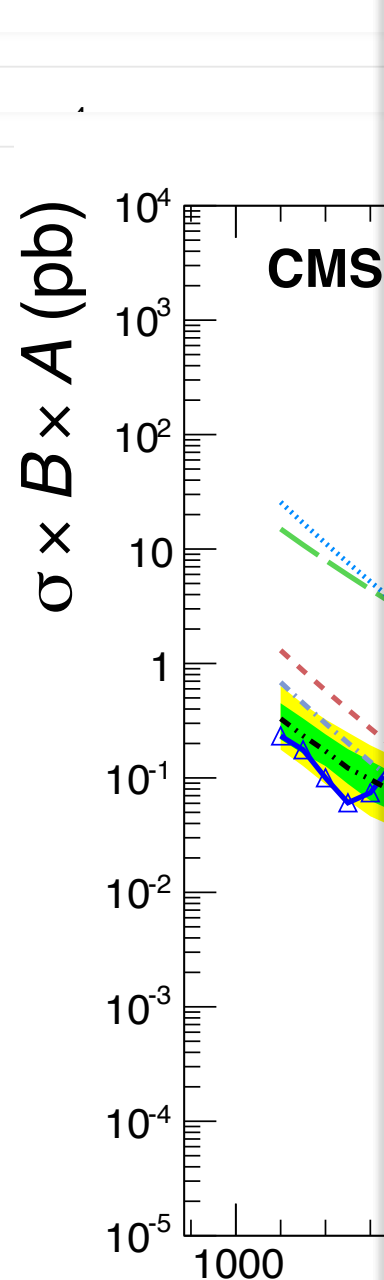
VJ ($\sim 2.1\sigma$) EXO-14-010

$V \rightarrow \ell\ell J$ ($\sim 1.5\sigma$) 1405.3447

Chasing Ambulanc

CMS Preliminary $e+\mu$ combined

19.7 fb⁻¹ (8 TeV)



ATLAS dijets ($\sim 2\sigma$)

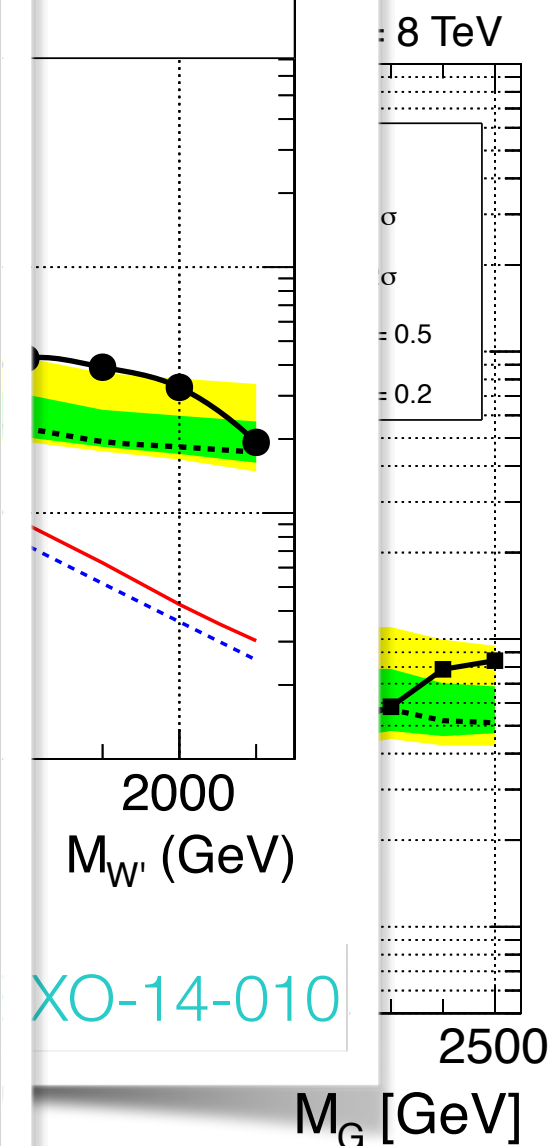
1407.1367

CMS dijets ($\sim 2\sigma$)

1501.04198

$V \rightarrow \ell\ell J$ ($\sim 1.5\sigma$) 1405.3447

CMS $VV \rightarrow JJ$ ($\sim 1\sigma$) 1405.1994

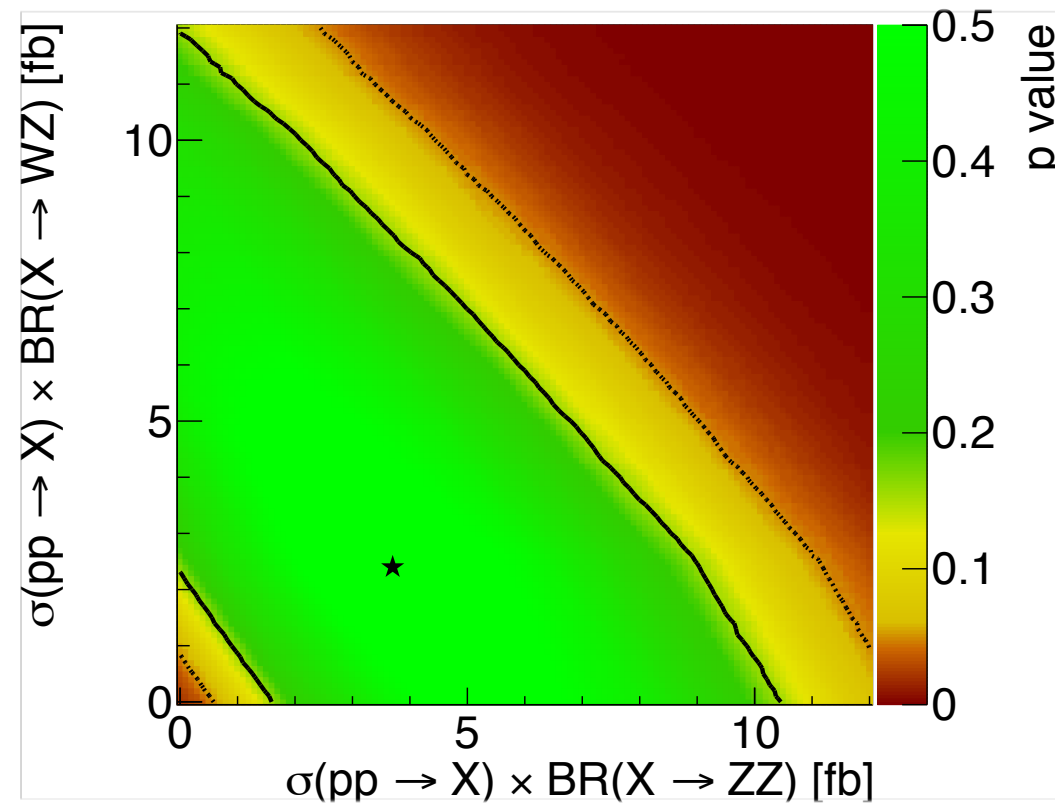
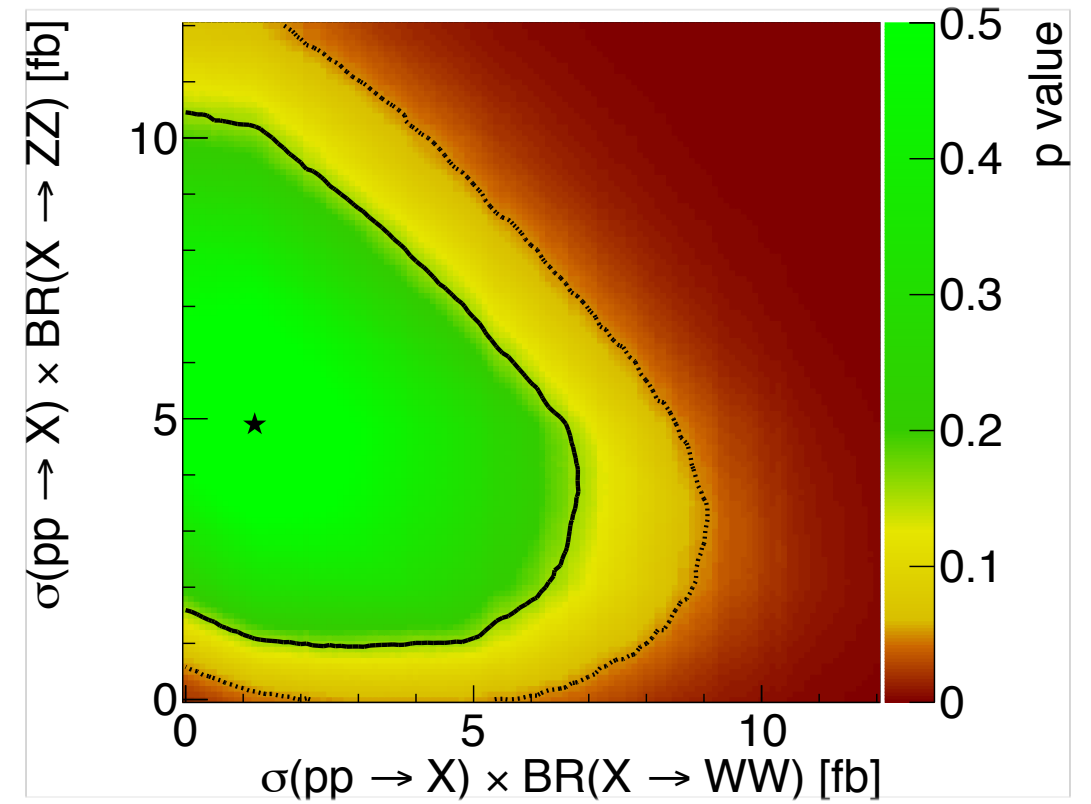
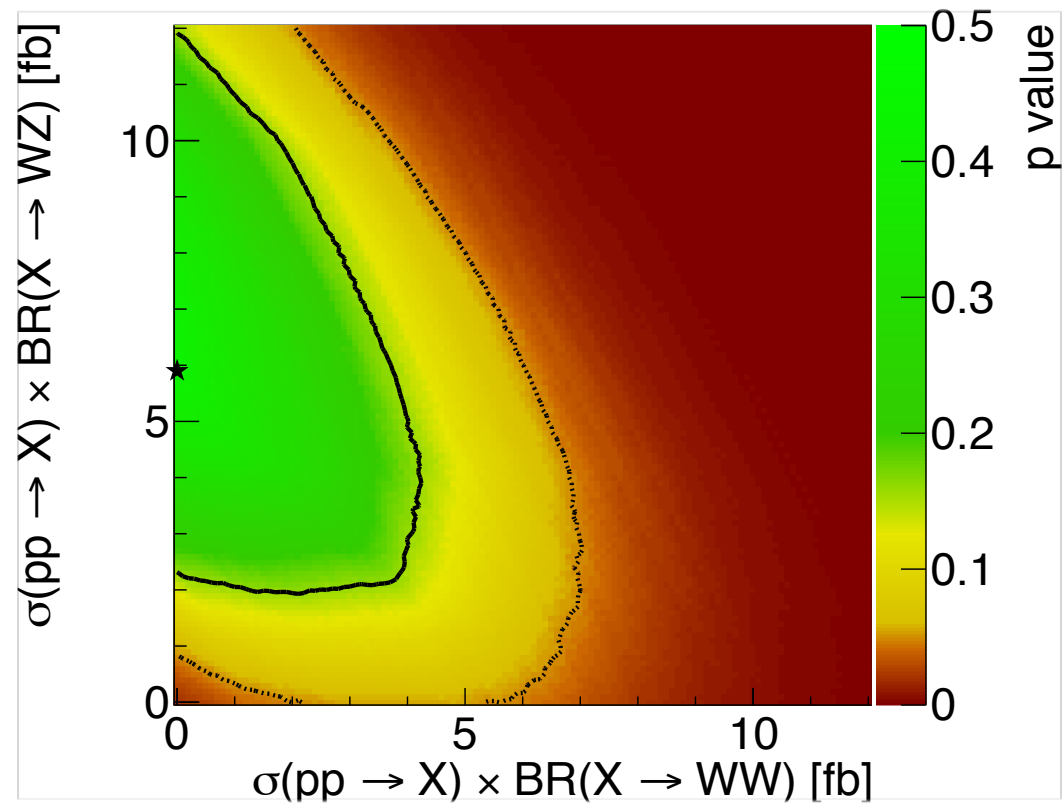


A Global Fit to the Data

Cross Section Fit: Diboson Final States

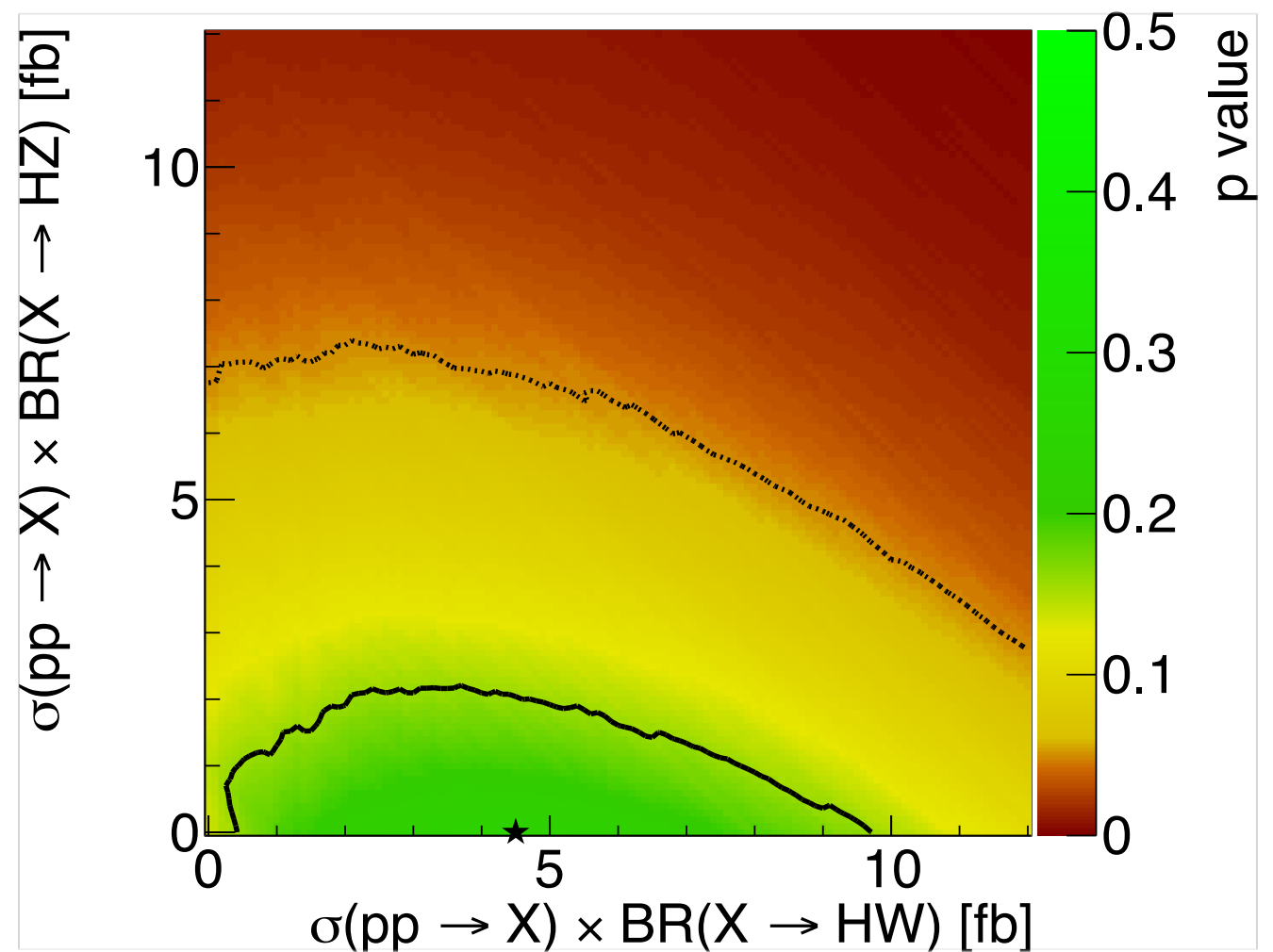
- Assume heavy resonance decaying to WW , ZZ or WZ
- Combine all searches for these final states:
 - ▶ ATLAS $VV \rightarrow JJ$ (3.4σ) 1506.00962
 - ▶ CMS $VV \rightarrow JJ$ ($\sim 1\sigma$) 1405.1994
 - ▶ ATLAS $WW/WZ \rightarrow \ell\nu + \text{jets}$ 1503.04677
 - ▶ CMS $VV \rightarrow \ell\nu/\ell^+\ell^- + \text{jets}$ 1405.3447
 - ▶ ATLAS $VV \rightarrow \ell^+\ell^- + \text{jets}$ 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



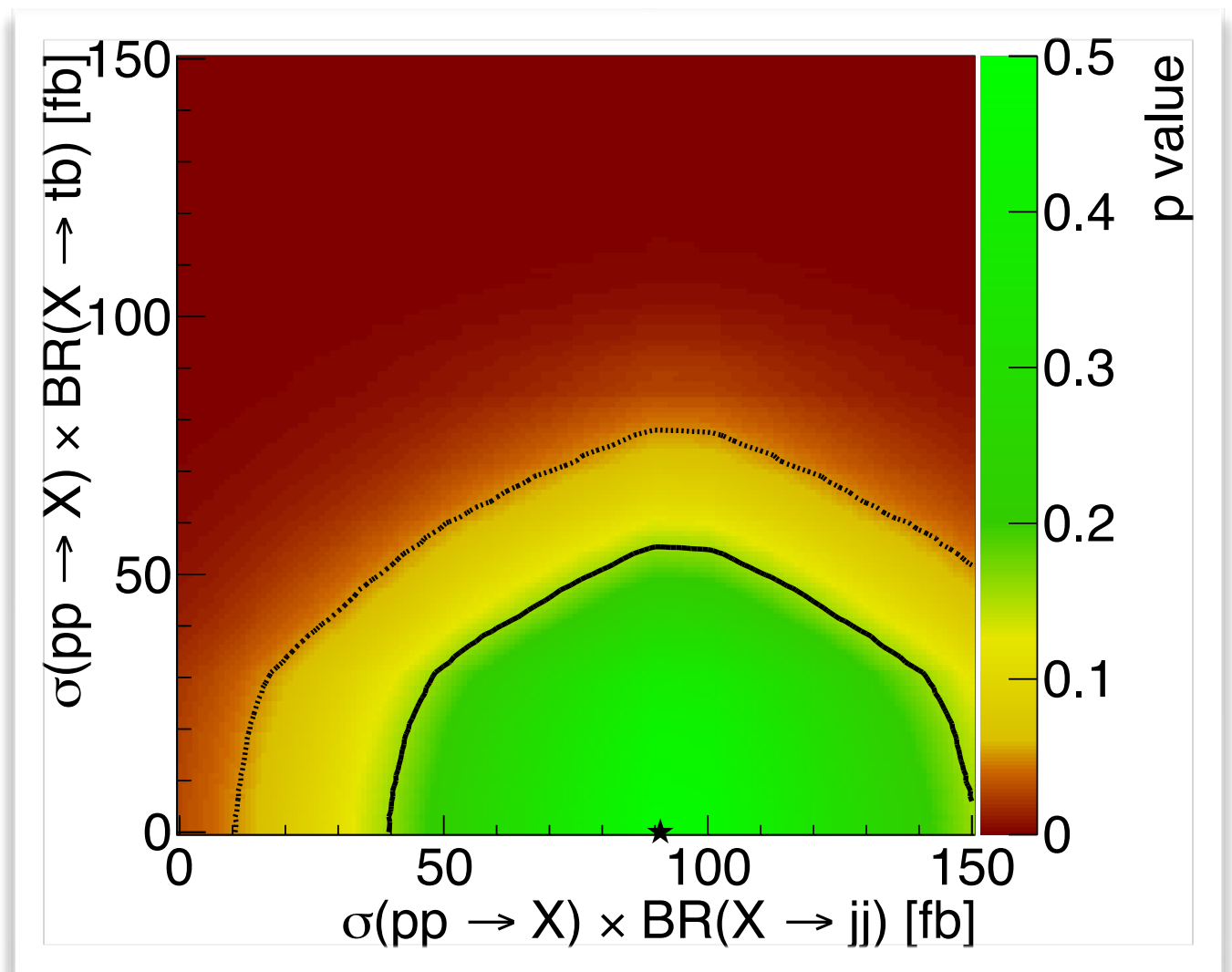
Cross Section Fit: V+H Final States

- Assume heavy resonance decaying to WH or ZH
- Combine all searches for these final states:
 - ▶ ATLAS $VH \rightarrow b\bar{b} + \ell\ell/\ell\nu/\nu\nu$
1503.08089
 - ▶ CMS $WH \rightarrow b\bar{b} + \ell\nu$ ($\sim 2.1\sigma$)
CMS-PAS-EXO-14-010
 - ▶ CMS $VH \rightarrow \tau^+\tau^- + jj$
1502.04994
 - ▶ CMS $VH \rightarrow JJ$
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 ($\sim 2\sigma$)
1407.1376
 - ▶ CMS dijets ($\sim 2\sigma$)
1501.04198
 - ▶ ATLAS $tb \rightarrow$ hadrons
1408.0886
 - ▶ CMS $tb \rightarrow \ell\nu bb$
1402.2176



Consequences of Cross Section Fit

- ZZ or WZ resonance favored over WW
 - $\sigma \sim 5 \text{ fb}$
 - New boson, preferably charged
- Possible resonance in WH (but not ZH)
 - $\sigma \sim 5 \text{ fb}$
- Dijet resonance (constraints from tb channel)
 - $\sigma \sim 100 \text{ fb}$
 - 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 <i>et al.</i> , 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 <i>et al.</i> , 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:	$SU(2)_L \times SU(2)_{L'} \times SU(2)_R \times SU(2)_{R'} \times U(1)_Y$

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)

Other Explanations

Aguilar-Saavedra, 1506.06739:

Cacciapaglia Fransson, 1507.00900:

Fukano Matsuzaki Yamawaki, 1507.03428:

Kim Kong Lee Park, 1507.06312:

Liew Shirai, 1507.08273:

Arnan Espriu Mescia, 1508.00174:

Goncalves Krauss Spannowsky, 1508.04162:

Fichet Gersdorff, 1508.04814:

Petersson Torre, 1508.05632:

Arbuzov Zaitsev, 1510.02312:

Allanach Dev Sakurai, 1511.01483:

Sajjad, 1511.02244:

Bhattacharjee *et al.*, 1511.02797:

triboson final state ($X \rightarrow W + Z + Y$)

effective Lagrangian with heavy vector

effective Lagrangian with heavy vector

EFT analysis

RS graviton

Model-independent unitarity arguments

Model-indep. results on jet substructure

EFT for spin-0 and spin-2 resonances

sgoldstino

Heavy scalar with dim-5 couplings

RPV SUSY with $m_{\tilde{\tau}} \sim m_W, m_Z$

EFT analysis

triboson final state ($X \rightarrow W + Z + Y$)

Composite Higgs Models

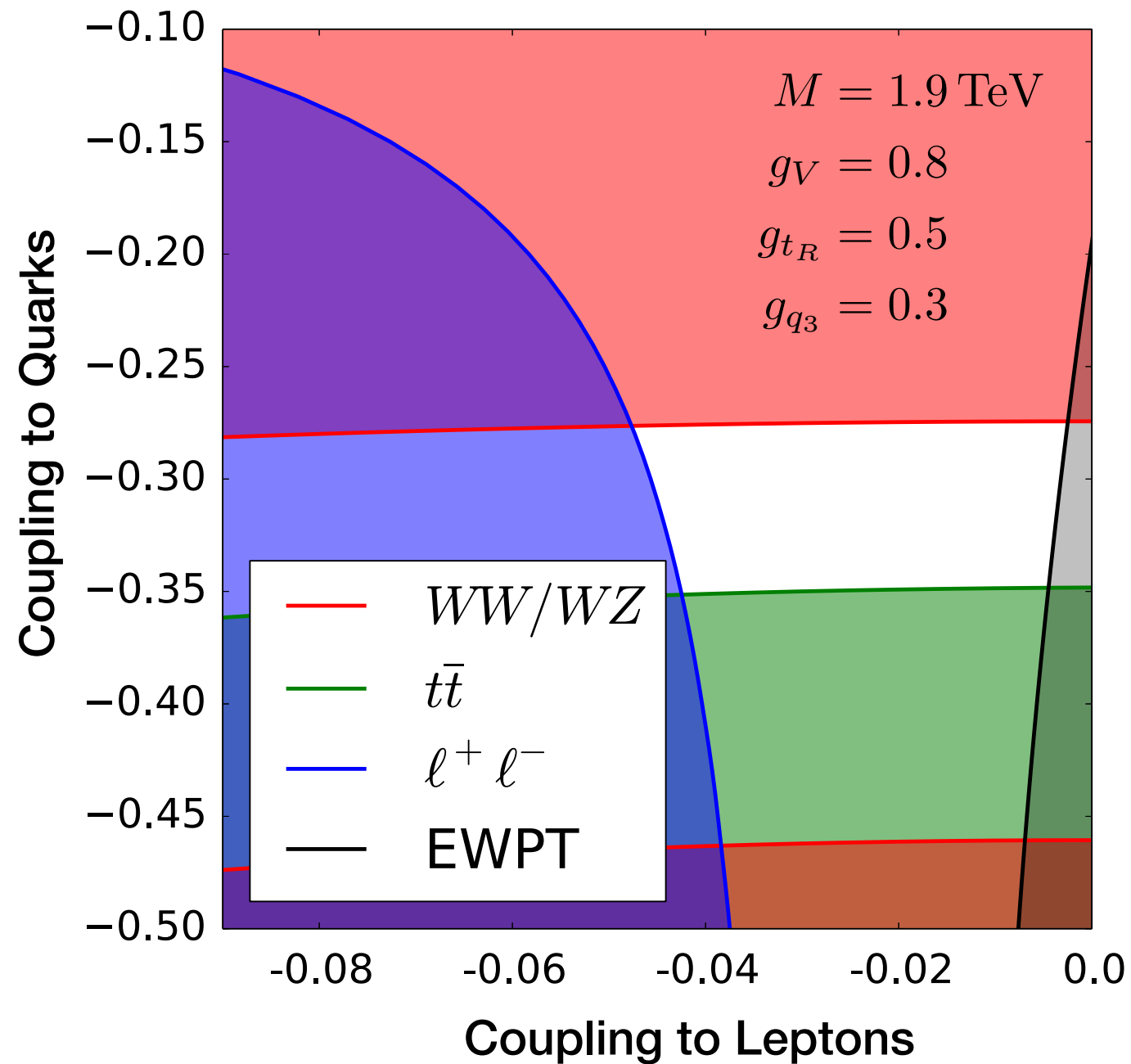
- SM fermions mix with fermions of heavy composite sector
- Symmetry breaking e.g. $SO(5) \rightarrow SO(4)$
 - Higgs as pseudo-Goldstone boson
- Heavy resonances at compositeness scale
 - One of them could explain the diboson anomaly
 - Typically described using a phenomenological Lagrangian

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

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

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



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



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

The Left-Right Symmetric Model

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

g_L

g_R

$$\kappa \equiv g_R/g_L$$



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



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

The Left-Right Symmetric Model

$$W_L, Z_L \quad W_R, Z_R$$

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

$$g_L$$

$$g_R$$

$$\kappa \equiv g_R/g_L$$



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



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

The Left-Right Symmetric Model

W_L, Z_L W_R, Z_R

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

Higgs sector

g_L

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'

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

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

(zero or tiny vev)

The Left-Right Symmetric Model

$$W_L, Z_L \quad W_R, Z_R$$

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

 g_L
 g_R

$$\kappa \equiv g_R/g_L$$

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

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

Fermions

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

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

W / W' Phenomenology in the LR Model

- W boson mass matrix

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

$$\kappa \equiv g_R/g_L$$

- Physical masses

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

- Mixing angle

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

- Z_R mass

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

W / W' Phenomenology in the LR Model

- W boson mass matrix

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

- Physical masses

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

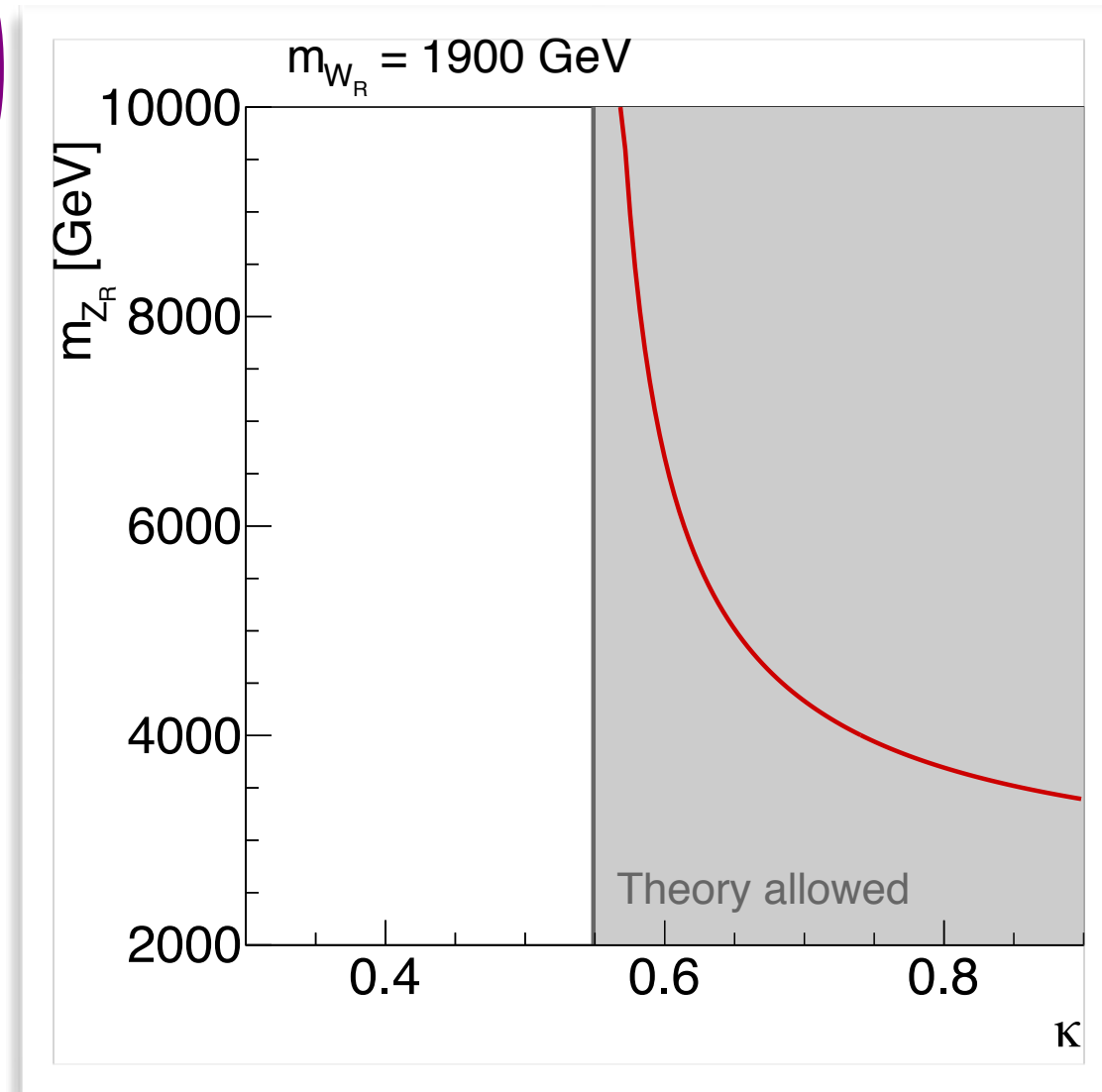
- Mixing angle

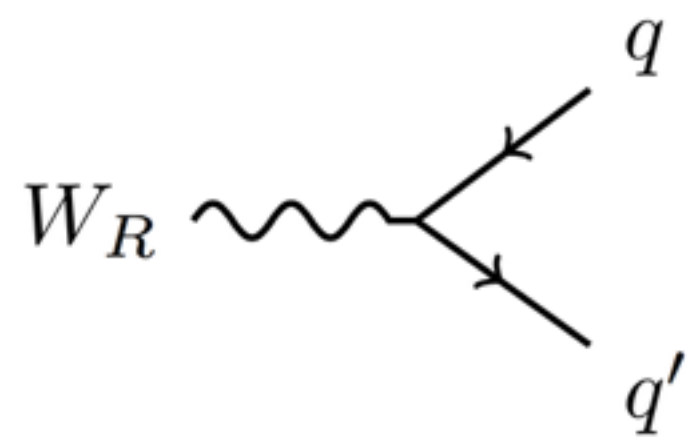
$$\tan 2\phi_w = \frac{-2\beta_w m_{W_L}^2}{m_{W_R}^2 - m_{W_L}^2}$$

- Z_R mass

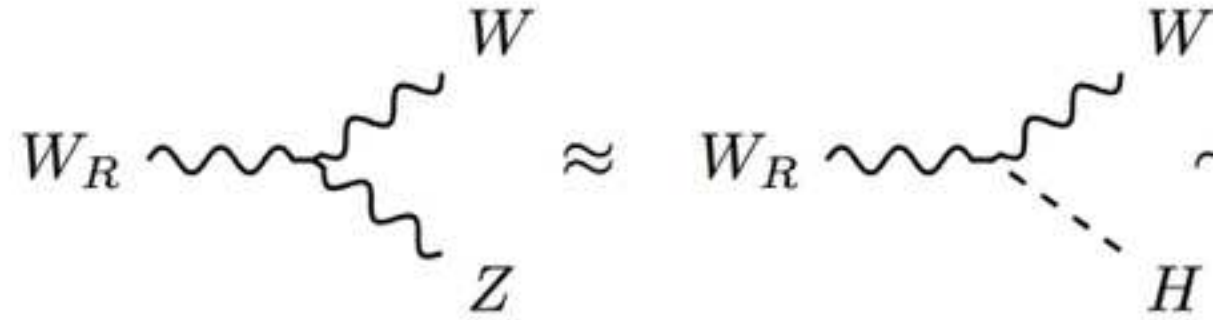
$$\frac{m_{Z_R}^2}{m_{W_R}^2} = \frac{2\kappa^2(1 - \sin^2 \theta_w)}{\kappa^2(1 - \sin^2 \theta_w) - \sin^2 \theta_w} > 1$$

$$\kappa \equiv g_R/g_L$$





W'—W—Z Coupling



- Covariant derivative:

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

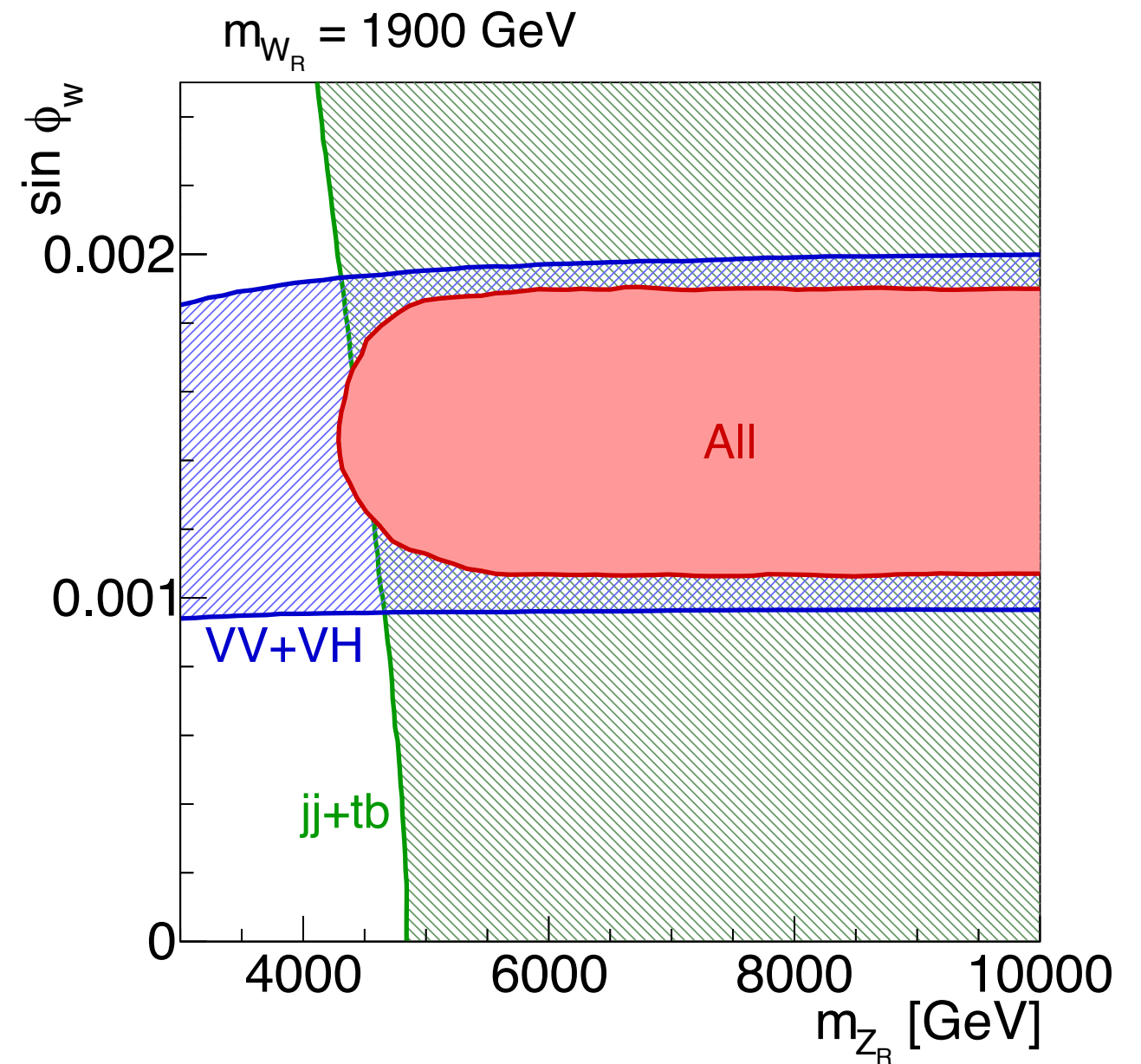
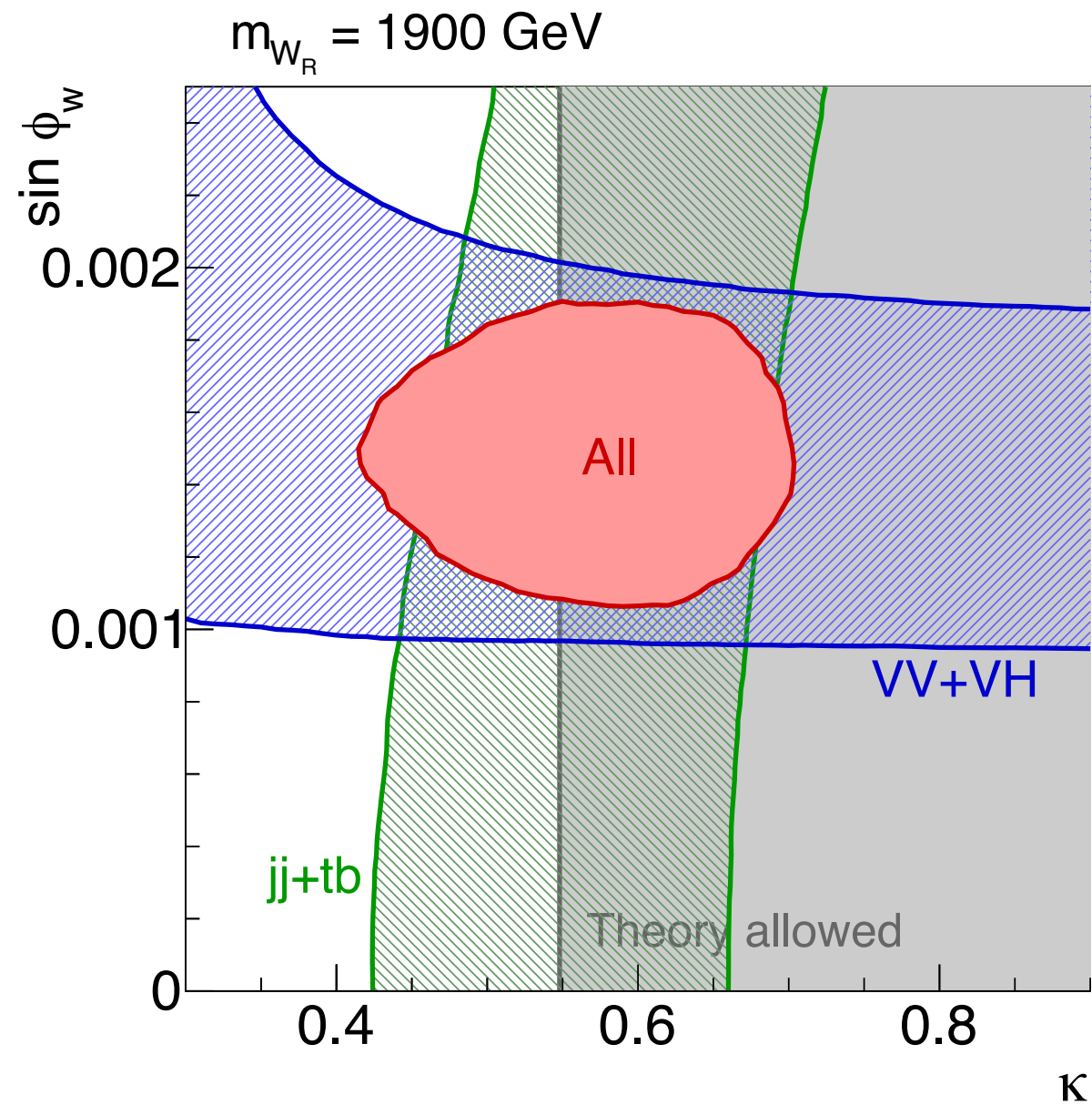
- Two contributions to the W'—W—Z coupling:

▶ $\mathcal{D}$ acting on $W_L^+ W_L^-$: $\sin \phi_w \cos \phi_w \times \frac{g_L}{\cos \theta_w} (1 - \sin^2 \theta_w)$

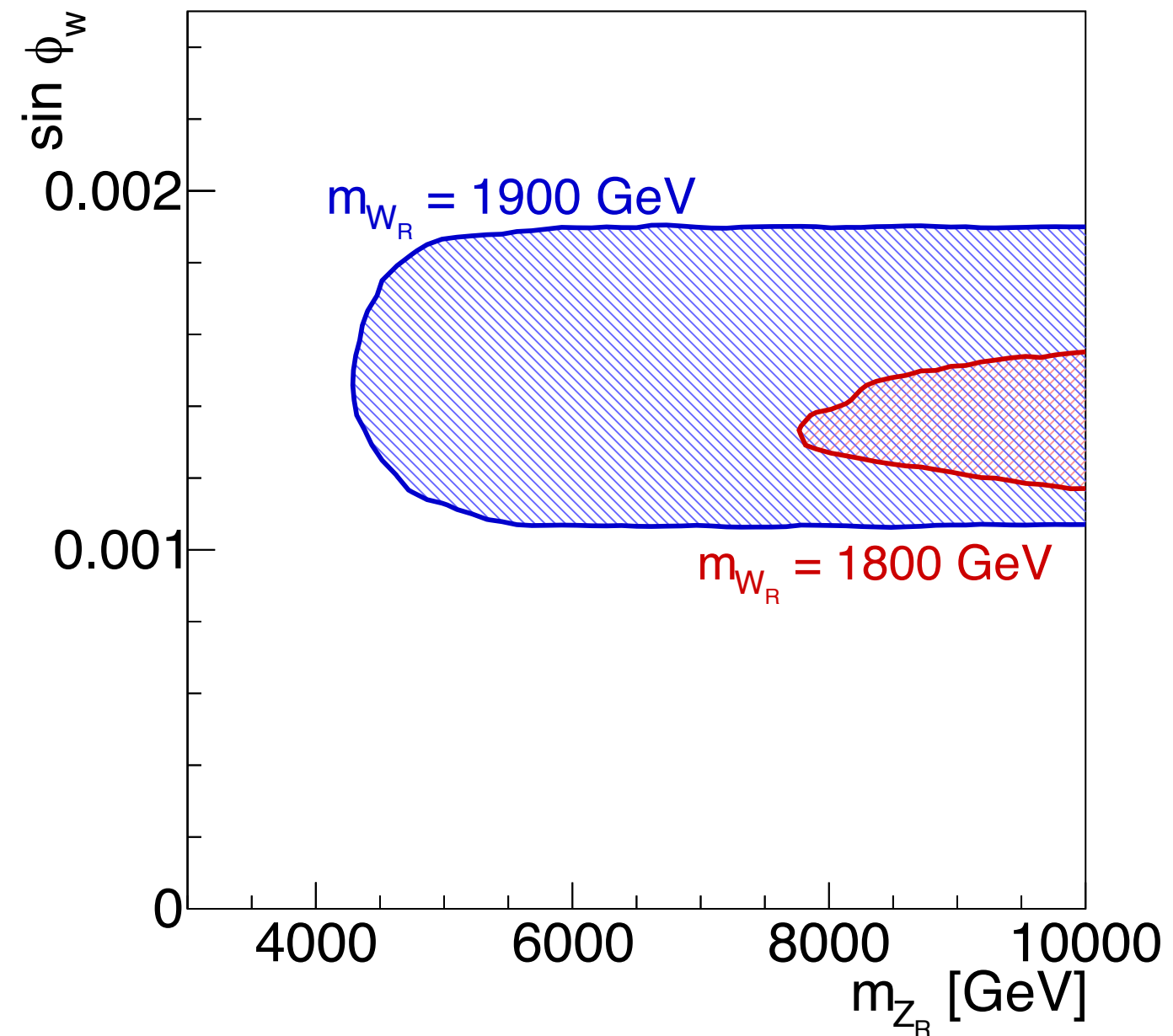
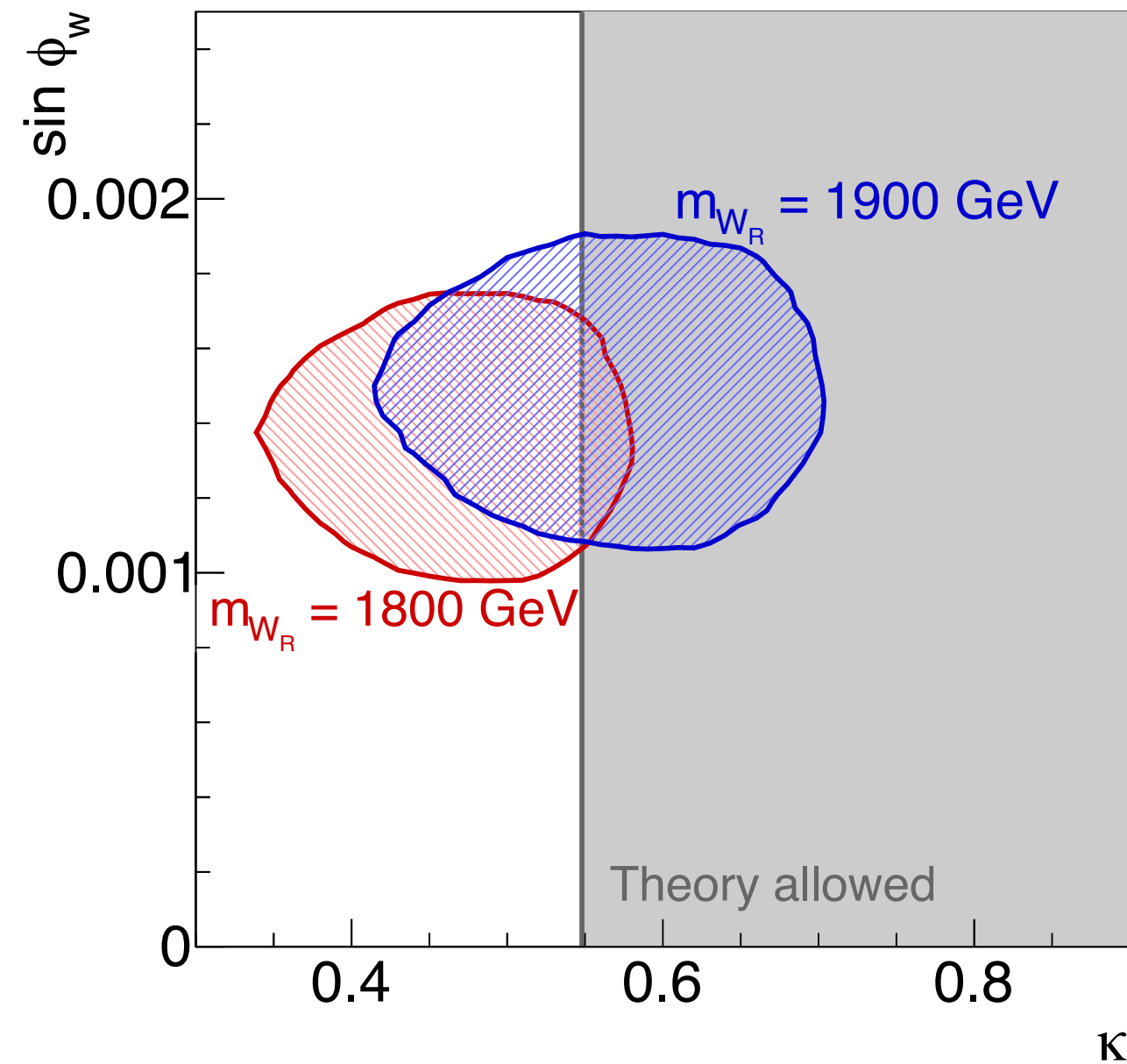
▶ $\mathcal{D}$ acting on $W_R^+ W_R^-$: $\sin \phi_w \cos \phi_w \times \frac{g_L}{\cos \theta_w} (-\sin^2 \theta_w)$


 W_L — W_R mixing angle

Fitting the LR Model



Fitting the LR Model



The CMS $eejj$ anomaly

- Added bonus: explanation of the CMS $eejj$ anomaly (2.8σ) via $W_R \rightarrow eN \rightarrow ee + (W_R^* \rightarrow jj)$

- Potential problems

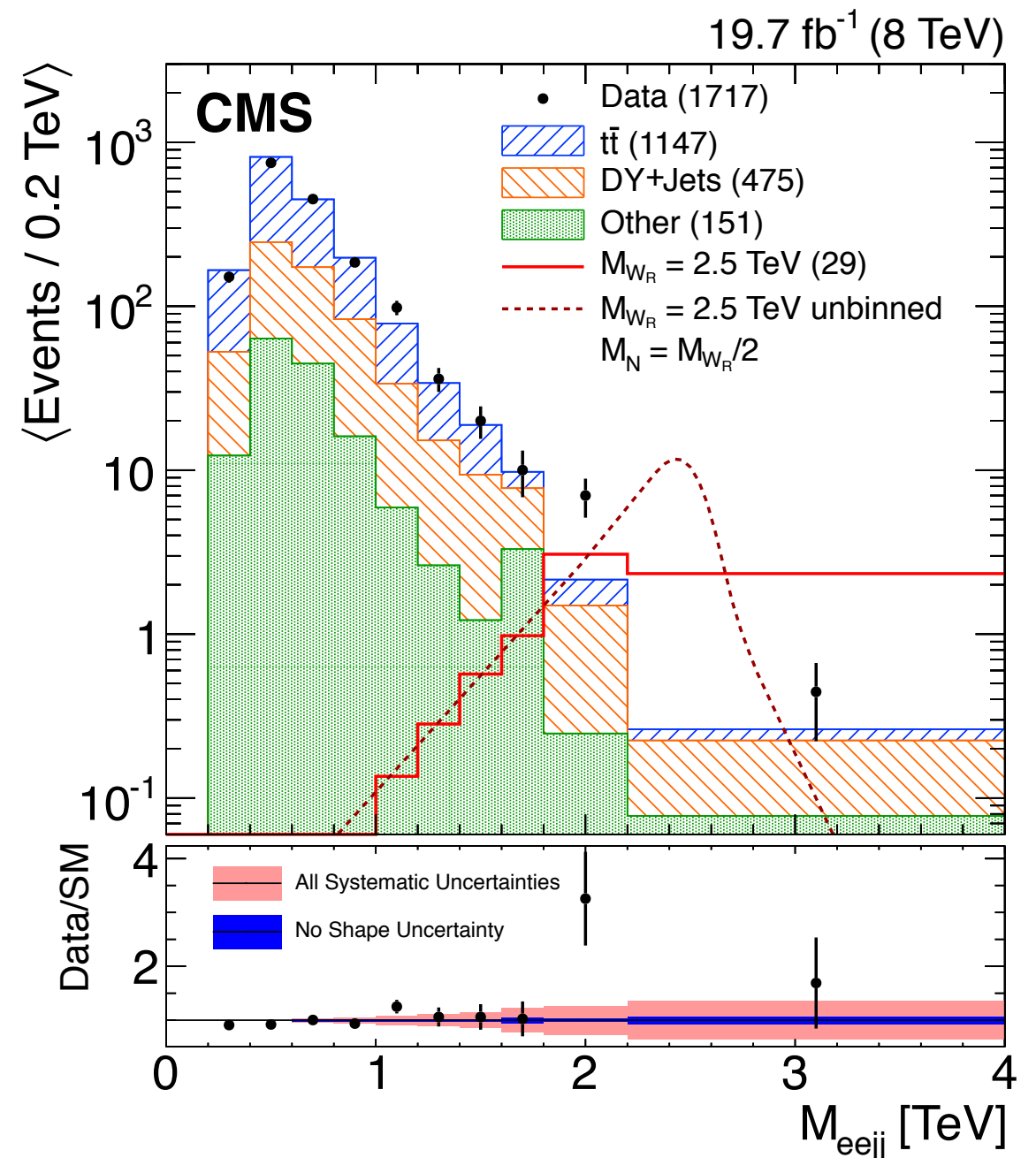
- ▶ Anomaly only in e^+e^- , not $e^\pm e^\pm$
possible remedy: Dirac N
- ▶ No peak in m_{ejj} distribution
- ▶ No signal in $\mu\mu jj$

Dobrescu Liu, 1506.06736

Dobrescu Liu, 1507.01923

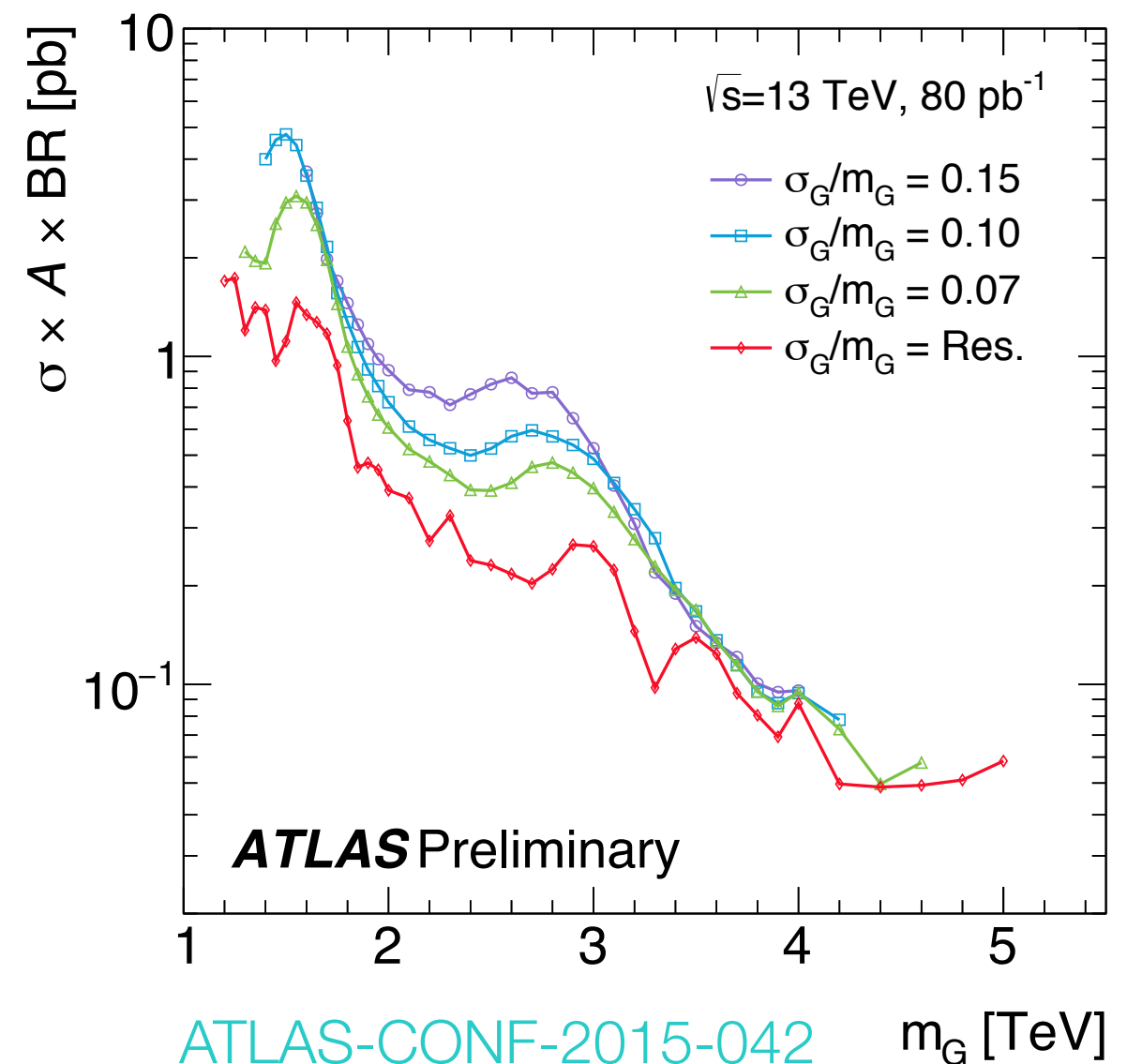
Deppisch *et al.*, 1508.05940

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
 - $\sigma \times \text{BR} \times A \sim 300 \text{ fb}$



Connections to Dark Matter?

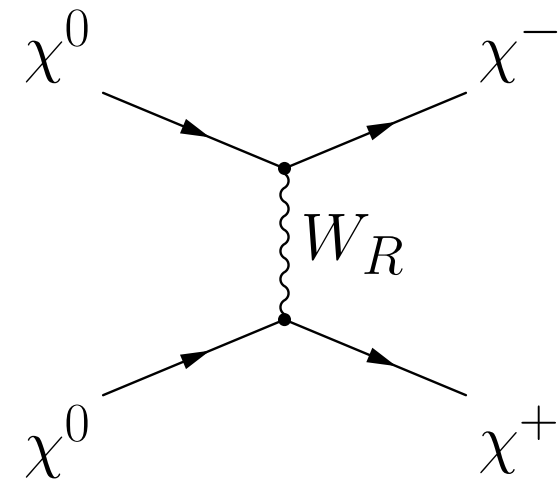
Connections to Dark Matter?

- **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
($\langle \sigma v \rangle (N_3 N_3 \rightarrow \tau^+ \tau^-)$ 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 $\chi^\pm$

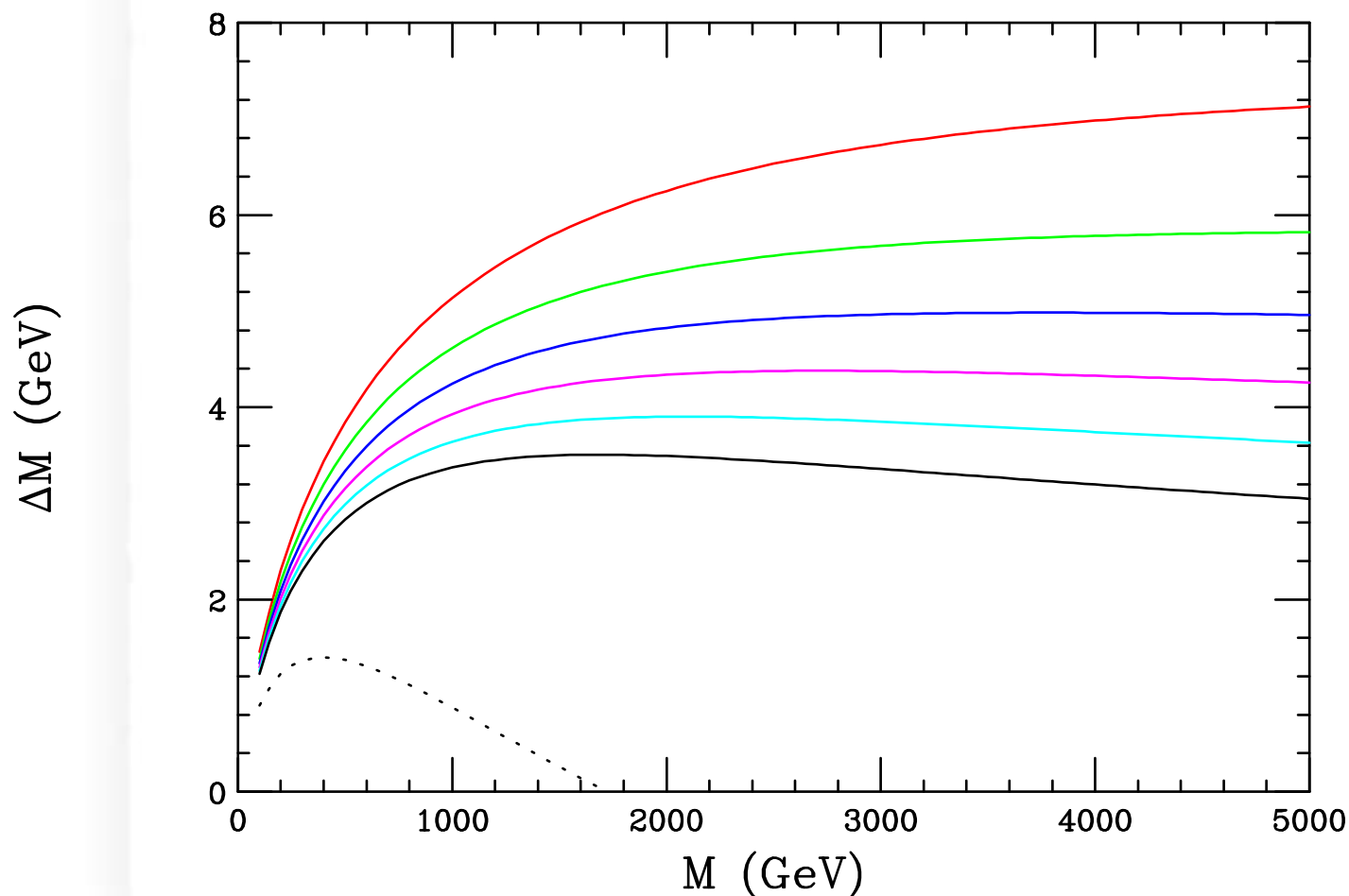
- Features

- ▶ Thermal freeze-out works if $m_{\chi^\pm} \sim m_{\chi^0}$ (coannihilation)
- ▶ No direct or indirect signals
- ▶ $BR(W_R \rightarrow \text{visible})$ reduced $\Rightarrow$ larger k allowed
- ▶ Mixing between χ^0 and N_j must vanish to forbid DM decay

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

- **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 $\chi^0 - N_j$ mixing

- Features

- ▶ χ^0 has Majorana mass $\Rightarrow$ 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

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

Connections to Dark Matter?

- **Z- and Z₂-mediated DM interactions**

- ▶ New SU
- ▶ Extra Z₂

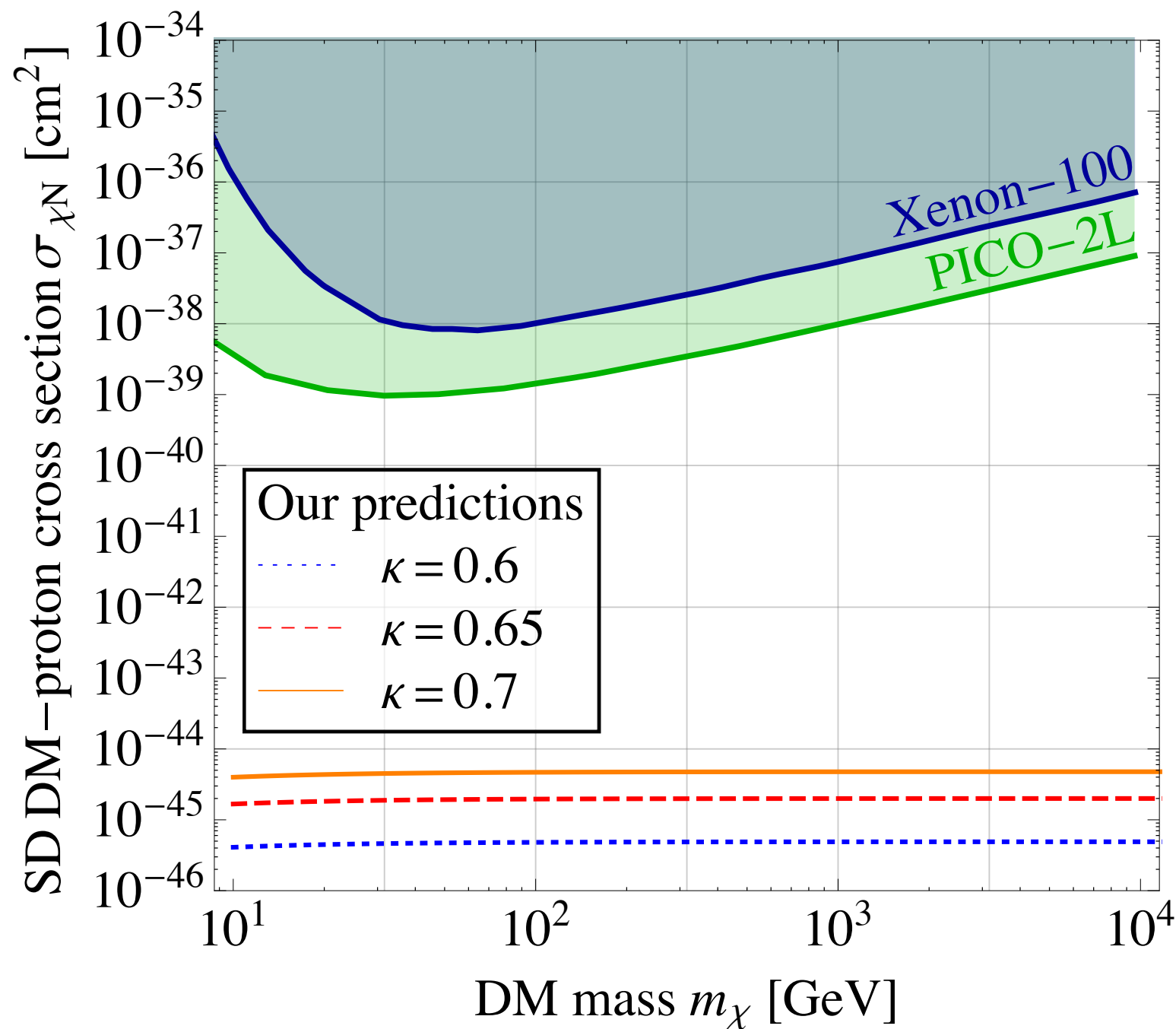
- Features

- ▶ χ^0 has M

$\sigma_{\chi N}$

- ▶ Annihilat

$\langle \sigma v \rangle ($



pendent

$$\left(\frac{\kappa A}{2} \right)^2$$

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Connections to Dark Matter?

- **Z- and Z'-mediated DM interactions**

- ▶ New SU
- ▶ Extra Z_2

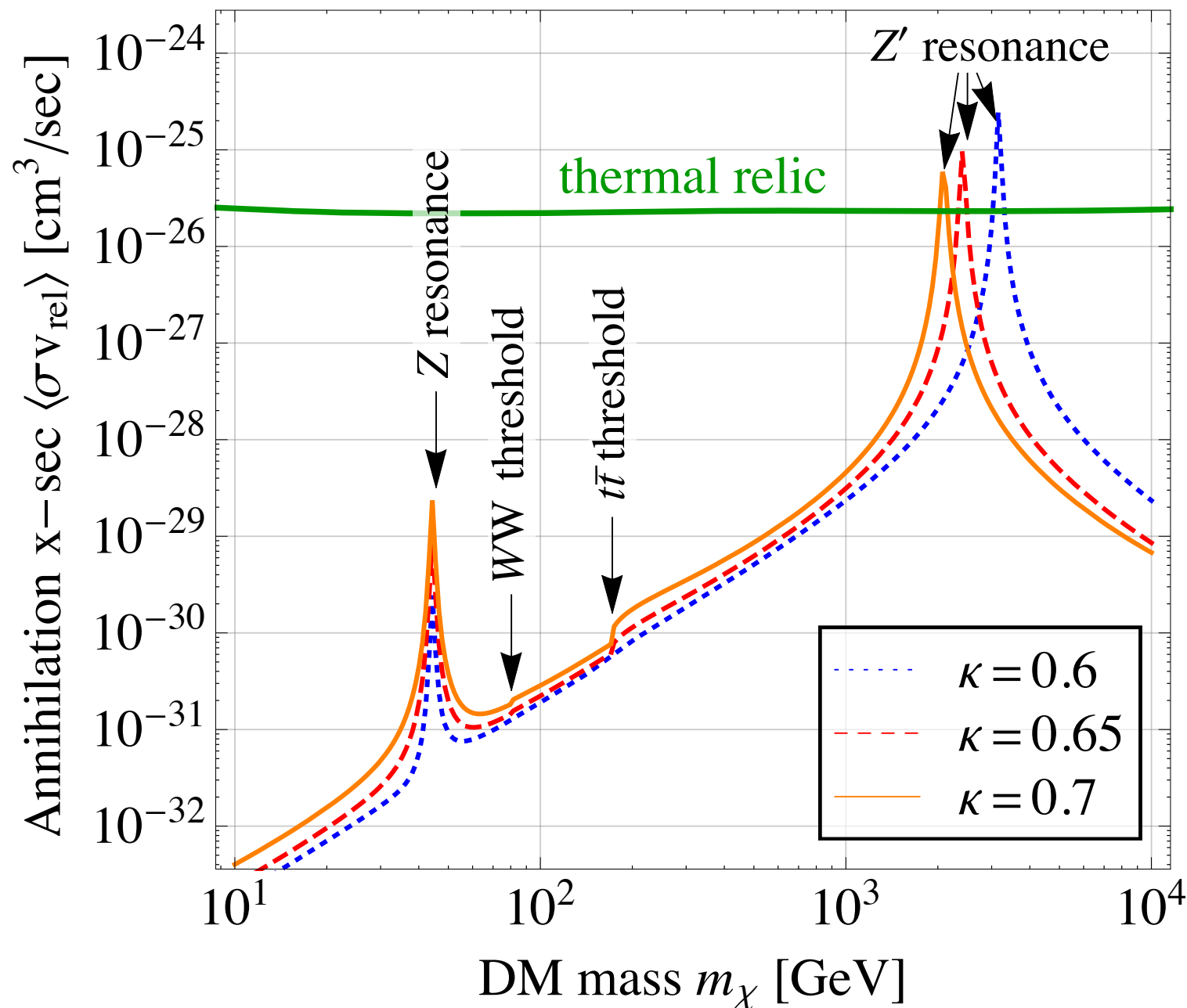
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Conclusions

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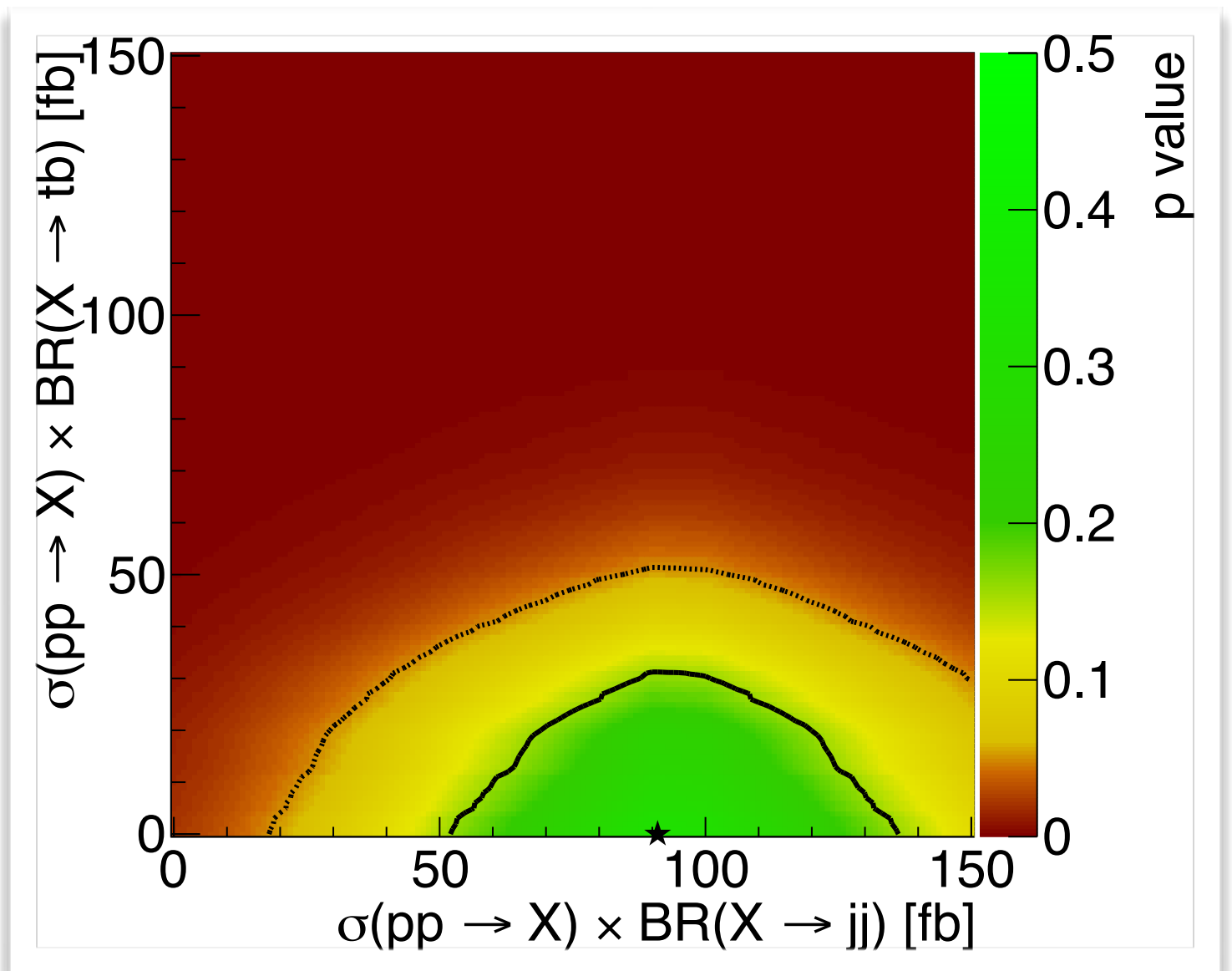
- ☑ An intriguing accumulation of anomalies at $\sim 1.8\text{--}2\text{ TeV}$
 - Signs of a **composite sector**?
 - An **extended Higgs sector**?
 - A **new gauge boson**?
- ☑ Left-right symmetric interpretation
 - Established and well-motivated model
 - Good fit to the data
 - Possible connections 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 ($\sim 2\sigma$)
1407.1376
 - CMS dijets ($\sim 2\sigma$)
1501.04198
 - ATLAS $tb \rightarrow$ hadrons
1408.0886
 - ATLAS $tb \rightarrow \ell\nu bb$
(systematically too strong by $\sim 1.8\sigma$)
1410.4103
 - CMS $tb \rightarrow \ell\nu bb$
1402.2176



Fitting the LR Model

