Symmetry restored in dibosons at the LHC?

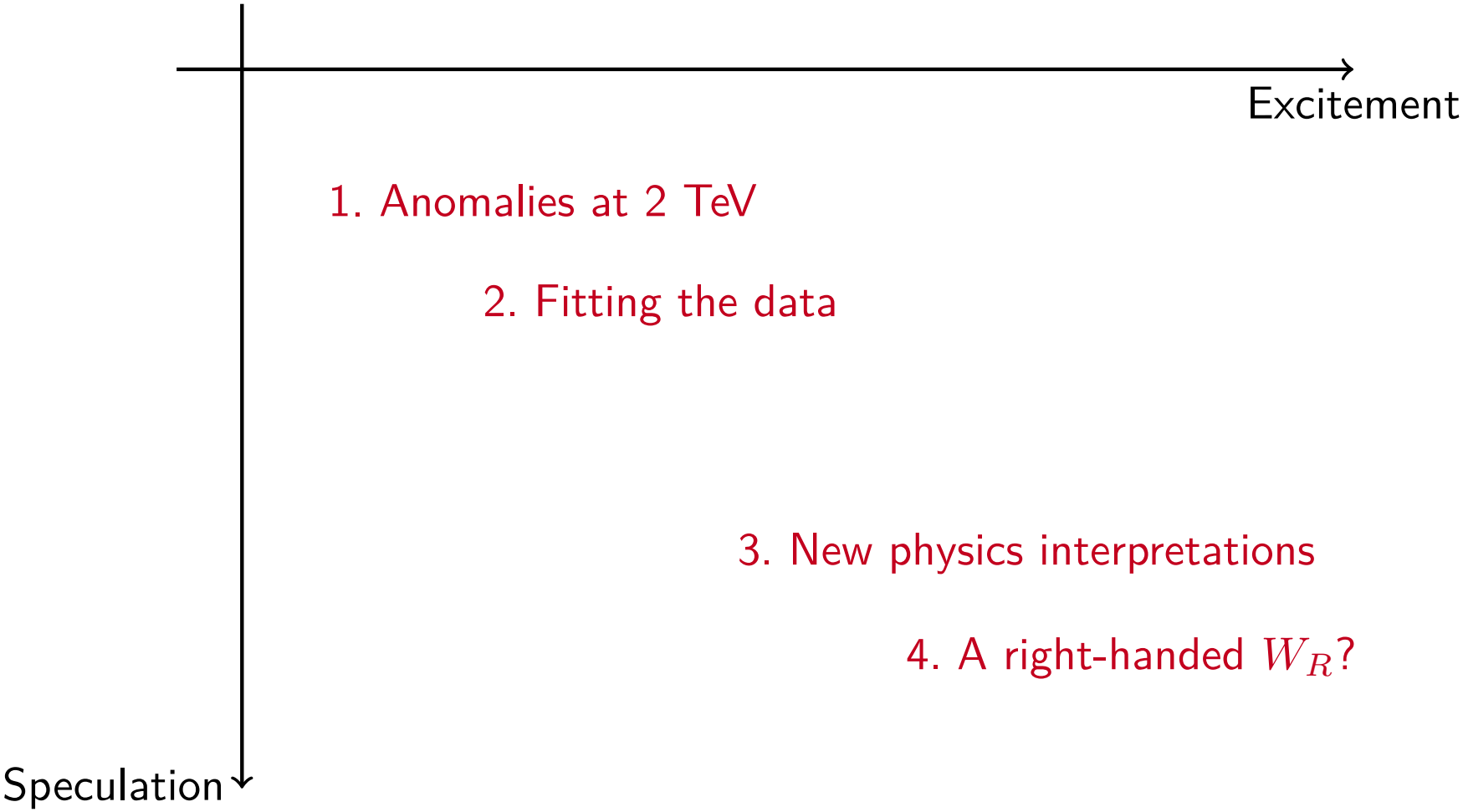
Johann Brehmer

Universität Heidelberg

with JoAnne Hewett, Joachim Kopp, Thomas Rizzo, and Jamie Tattersall

DESY Theory Workshop
October 1, 2015

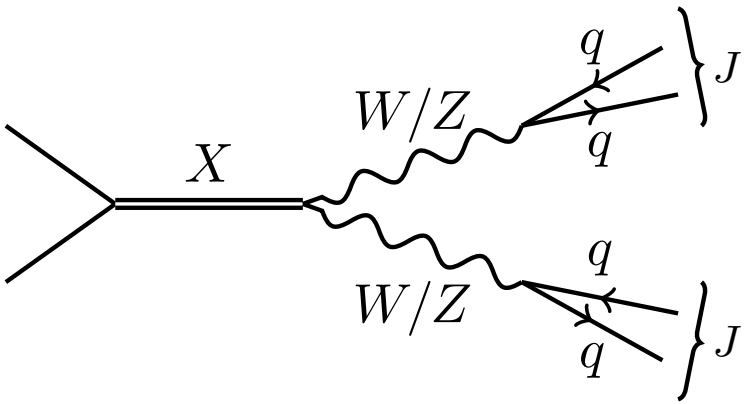
Outline

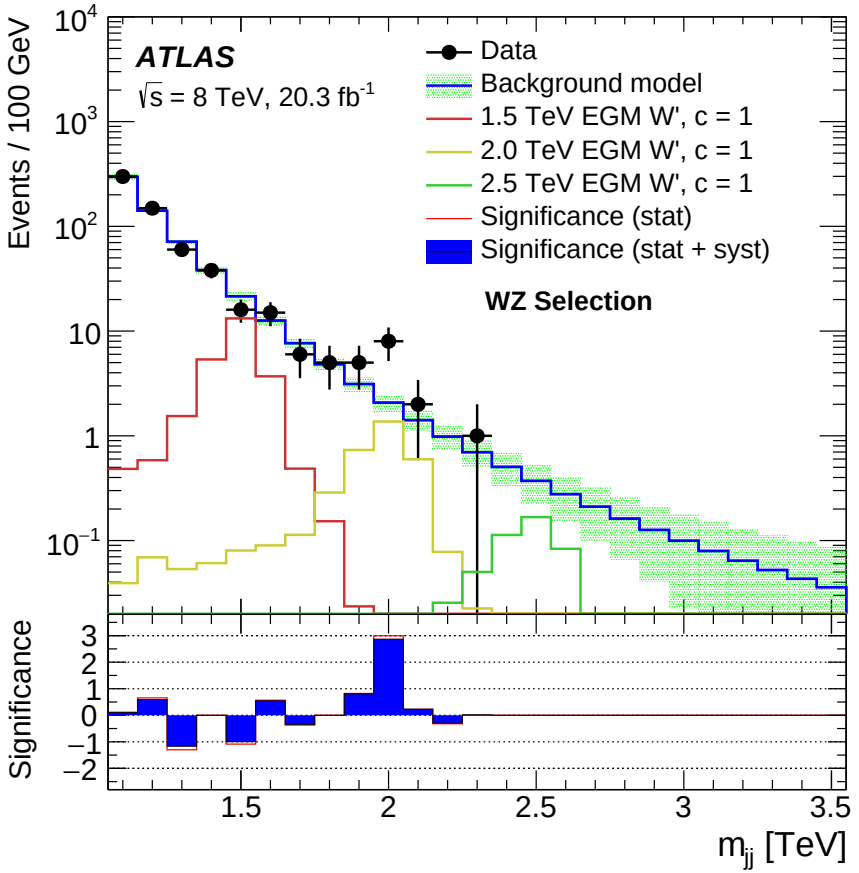

Excitement
1. Anomalies at 2 TeV
2. Fitting the data
3. New physics interpretations
4. A right-handed W_R?
Speculation

A diboson peak (and more) at 1.8…2.0 TeV

- ATLAS $VV \to JJ$: $3.4\,\sigma$

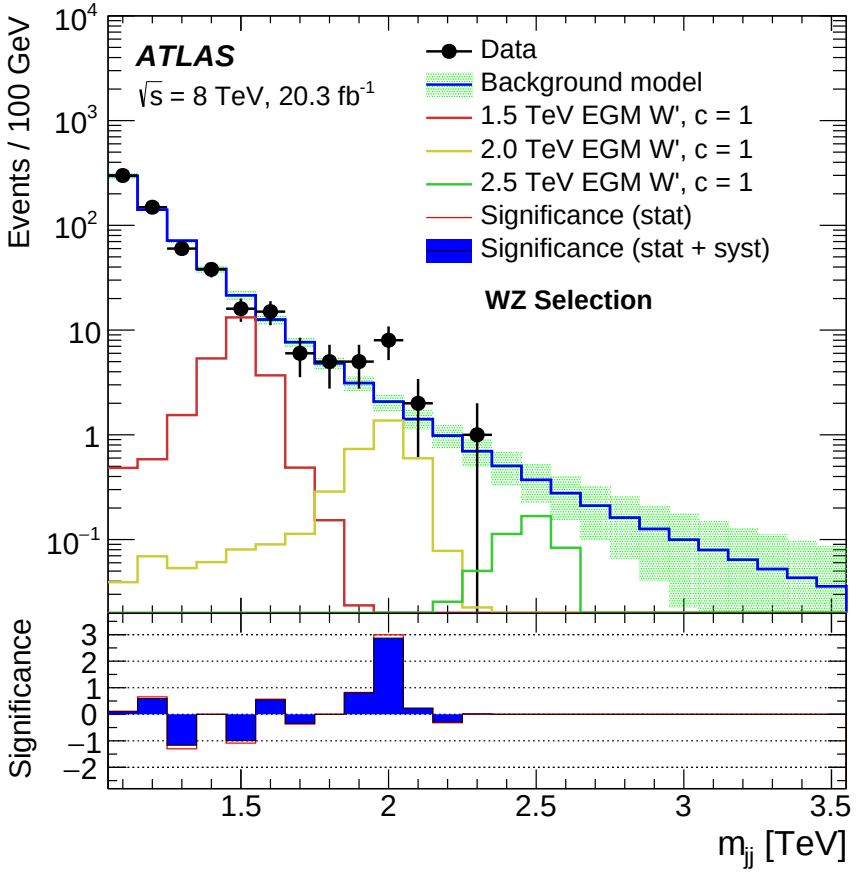
  [1506.00962]





A diboson peak (and more) at 1.8…2.0 TeV

- ATLAS $VV \to JJ$: $3.4\,\sigma$
  [1506.00962]
- CMS $VV \to JJ$: $\sim 1\,\sigma$ [1405.1994]
- CMS $ZV \to \ell\ell J$: $1.5\,\sigma$ [1405.3447]
- CMS $WH \to \ell\nu J$: $2.1\,\sigma$
  [CMS-PAS-EXO-14-010]
- CMS jj: $\sim 2\,\sigma$ [1501.04198]
- ATLAS jj: $\sim 1\,\sigma$ [1407.1376]



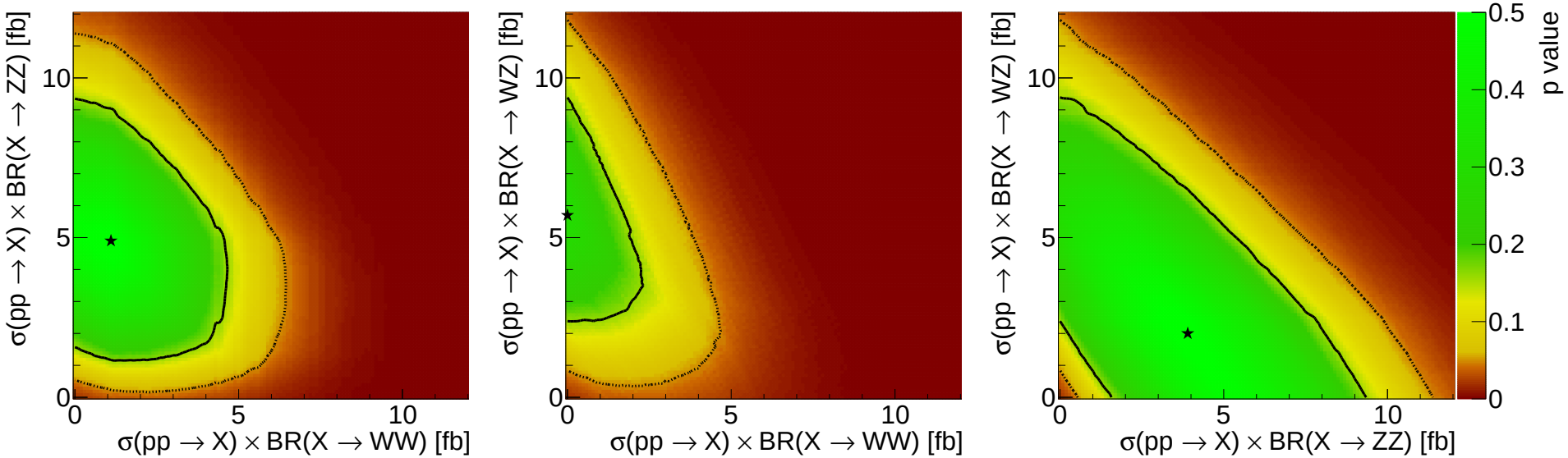
Combining searches in a cross-section fit

- Combining all 8 TeV searches for resonances in...
  - WW, ZZ, WZ (semileptonic and hadronic decays)
  - WH, ZH
  - jj, tb
- Input data:
  - Observed events, expected background in mass window $\sim 1.7 \ldots 2.0$ TeV
  - Acceptance, efficiencies, systematics
- Handle with care: some rough approximations
  - Limits and significances can differ from official results

[JB, J. Hewett, J. Kopp, T. Rizzo, J. Tattersall 1507.00013;
see also B. Allanach, B. Gripaios, D. Sutherland 1507.01638]

Fit results

- VV states (green area: overall agreement with data at 68% CL):



- Other states:
  - HW signal $\sim 1 \ldots 10$ fb
  - jj signal $\sim 50 \ldots 140$ fb
  - tb signal $\sim 0 \ldots 50$ fb

What ~~do we know~~ can we guess?

- ZZ or WZ excess (WW disfavoured), similarly sized WH peak (ZH disfavoured)

  $\Rightarrow$ boson, likely charged

- $\mathcal{O}\,(100\text{ fb})$ production cross section, jj "signal"

  $\Rightarrow$ sizable coupling to quarks or gluons

- Strong $\ell\ell$, $\ell\nu$ limits

  $\Rightarrow$ suppressed leptonic decay mode

Interpretations on the market (1)

UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386

- Spin 1
  - W' [S. Xue 1506.05994; B. Dobrescu, Z. Liu 1506.06736, 1507.01923; Y. Gao, T. Ghosh, K. Sinha, J. Yu 1506.07511; JB, J. Hewett, J. Kopp, T. Rizzo, J. Tattersall 1507.00013; J. Heeck, S. Patra 1507.01584; P. Bhupal Dev, R. Mohapatra 1508.02277; F. Deppisch, L. Graf, S. Kulkarni, S. Patra, W. Rodejohann, N. Sahu, U. Sarkar 1508.05940; U. Aydemir, D. Minic, C. Sun, T. Takeuchi 1509.01606, R. Awasthi, P. Bhupal Dev, M. Mitra 1509.05387]
  - Z' [J. Hisano, N. Nagata, Y. Omura 1506.03931; A. Alves, A. Berlin, S. Profumo, F. Queiroz 1506.06767; L. Anchordoqui, I. Antoniadis, H. Goldberg, X. Huang, D. Lüst, T. Taylor 1507.05299; A. Faraggi, M. Guzzi 1507.07406; T. Li, J. Maxin, V. Mayes, D. Nanopoulos 1509.06821]
  - $W' + Z'$ [K. Cheung, W. Keung, P. Tseng, T. Yuan 1506.06064; Q. Cao, B. Yan, D. Zhang 1507.00268; T. Abe, R. Nagai, S. Okawa, M. Tanabashi 1507.01185; T. Abe, T. Kitahara, M. Nojiri 1507.01681; H. Fukano, S. Matsuzaki, K. Yamawaki 1507.03428]

Interpretations on the market (2)

- Spin 1 (continued)
  - Composite vector triplet [H. Fukano, M. Kurachi, S. Matsuzaki, K. Terashi, K. Yamawaki 1506.03751; D. Franzosi, M. Frandsen, F. Sannino 1506.04392; A. Thamm, R. Torre, A. Wulzer 1506.08688; A. Carmona, A. Delgado, M. Quirós, J. Santiago 1507.01914; L. Bian, D. Liu, J. Shu 1507.06018; H. Fritzsch 1507.06499; K. Lane, L. Pritchett 1507.07102; M. Low, A. Tesi, L. Wang 1507.07557]
  - Generic / EFT [G. Cacciapaglia, M. Frandsen 1507.00900; B. Allanach, B. Gripaios, D. Sutherland 1507.01638; L. Bian, D. Liu, J. Shu, Y. Zhan 1509.02787]

Interpretations on the market (3)

UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386

- Spin 0
  - Higgs singlet [C. Chen, T. Nomura 1509.02039]
  - 2HDM [C. Chen, T. Nomura 1507.04431; Y. Omura, K. Tobe, K. Tsumura 1507.05028; W. Chao 1507.05310]
  - Sparticle [C. Petersson, R. Torre 1508.05632]
  - Composite scalars [C. Chiang, H. Fukada, M. Ibe, T. Yanagida 1507.02483; G. Cacciapaglia, A. Deandrea, M. Hashimoto 1507.03098]
- Other
  - Glueballs [V. Sanz 1507.03553]
  - Excited composite object [H. Terezawa, M. Yasuè 1508.00172]
  - Generic / EFT [J. Aguilar-Saavedra 1506.06739; D. Kim, K. Kong, H. Lee, S. Park 1507.06312; S. Liew, S. Shirai 1507.08273; P. Arnan, D. Espriu, F. Mescia 1508.00174; S. Fichet, G. von Gersdorff 1508.04814]
- No new physics
  - Issues with jet substructure and data-driven background estimation [D. Gonçalves, F. Krauss, M. Spannowsky 1508.04162]

The Left-Right Symmetric Model

$$SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$
$$g_L \qquad\qquad g_R$$
$$\kappa = g_R/g_L$$

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \sim (2, 1, \tfrac{1}{3}) \qquad \begin{pmatrix} u \\ d \end{pmatrix}_R \sim (1, 2, \tfrac{1}{3})$$
$$\begin{pmatrix} \nu \\ \ell \end{pmatrix}_L \sim (2, 1, -1) \qquad \begin{pmatrix} N \\ \ell \end{pmatrix}_R \sim (1, 2, -1)$$
$$\Delta_L \sim (3, 1, -2) \qquad \Delta_R \sim (1, 3, -2)$$
$$\Phi \sim (2, 2, 0)$$

[J. Pati, A. Salam 1974; R. Mohapatra, J. Pati 1977;
G. Senjanovic, R. Mohapatra 1975...]

The Left-Right Symmetric Model

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

$g_L \qquad g_R$

$\kappa = g_R/g_L$

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \sim (2, 1, \tfrac{1}{3}) \qquad \begin{pmatrix} u \\ d \end{pmatrix}_R \sim (1, 2, \tfrac{1}{3})$$

$$\begin{pmatrix} \nu \\ \ell \end{pmatrix}_L \sim (2, 1, -1) \qquad \begin{pmatrix} N \\ \ell \end{pmatrix}_R \sim (1, 2, -1)$$

$$\Delta_L \sim (3, 1, -2) \qquad \Delta_R \sim (1, 3, -2)$$

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

$\downarrow \langle \Delta_R \rangle \rightsquigarrow$ massive W_R, Z_R

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

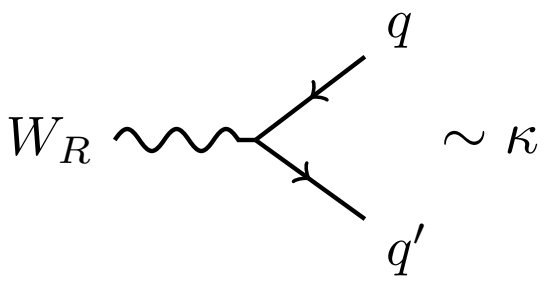
$\downarrow \langle \Phi \rangle \rightsquigarrow W$, Z masses; W-W_R mixing $\sim \phi_w$

$$U(1)_Q$$

[J. Pati, A. Salam 1974; R. Mohapatra, J. Pati 1977;
G. Senjanovic, R. Mohapatra 1975...]

W_R phenomenology

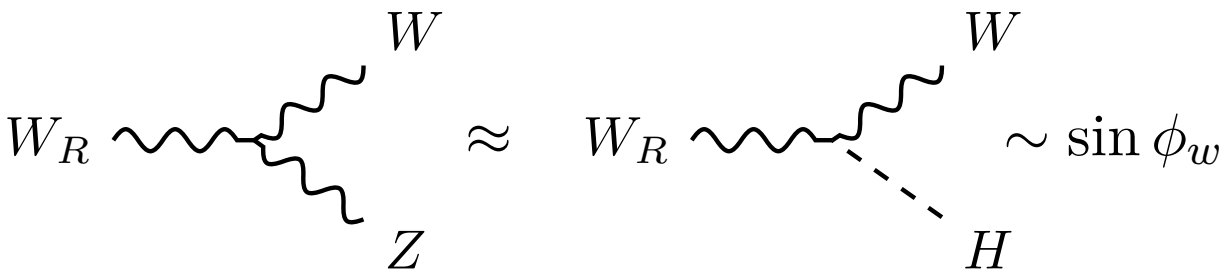
- Direct coupling to RH quarks:



- $m_{N_\ell} > m_{W_R}$ avoids ℓN_ℓ limits

  [see also B. Dobrescu, Z. Liu 1506.06736; F. Deppisch, L. Graf, S. Kulkarni, S. Patra, W. Rodejohann, N. Sahu, U. Sarkar 1508.05940]

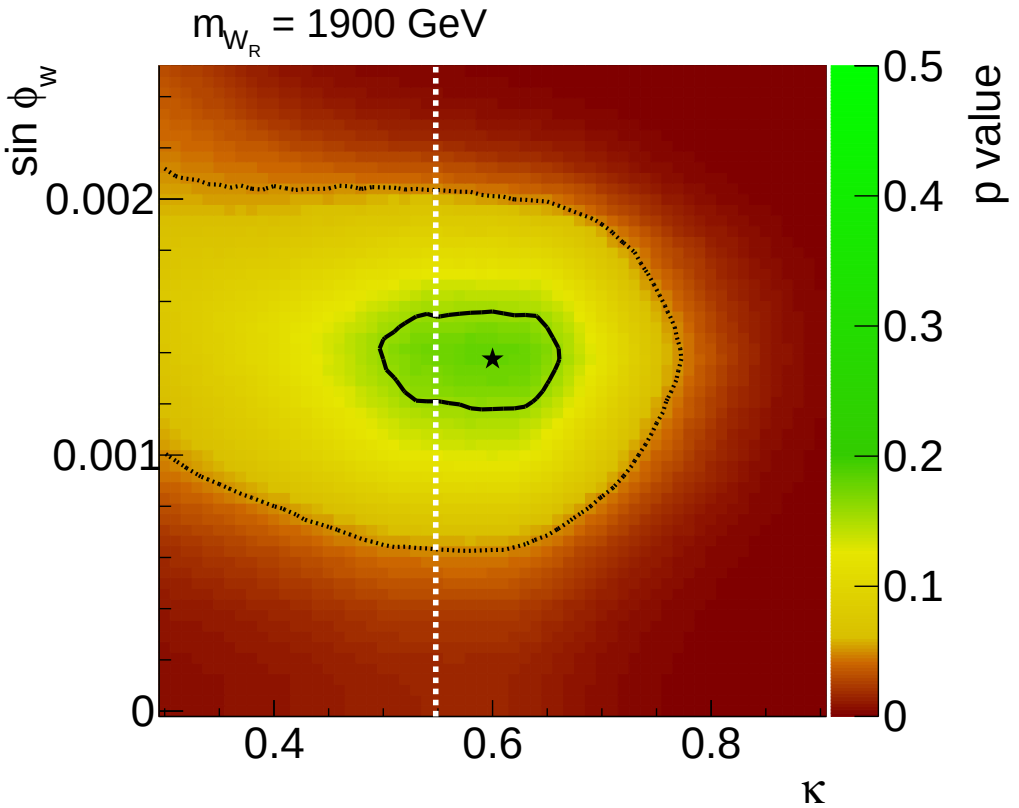
- Mixing gives diboson modes:



$\rightsquigarrow$ candidate for 1.9 TeV excesses

Is That It? Fitting the W_R to data

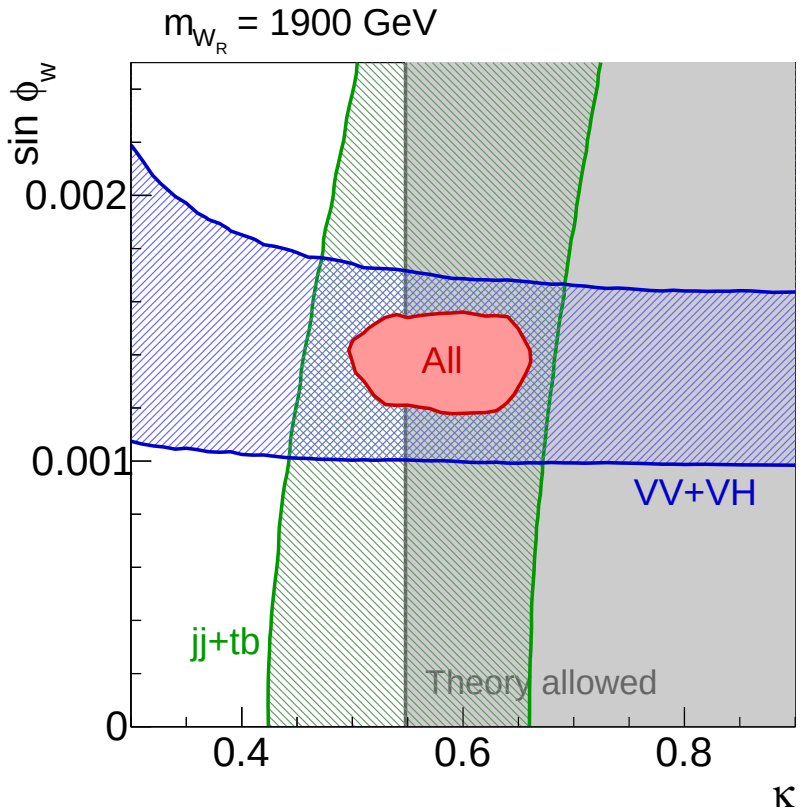
- Same input as before (VV, VH, jj, tb searches)
- Narrow width approximation
- Production cross section based on MMHT2014 NNLO pdfs [1412.3989]



- $W_R \sim 1900$ GeV with coupling $\kappa = g_R/g_L \sim 0.6$ and mixing angle $\sin\phi_w \sim 0.0014$ can explain everything!

Is That It? Fitting the W_R to data

- Same input as before (VV, VH, jj, tb searches)
- Narrow width approximation
- Production cross section based on MMHT2014 NNLO pdfs [1412.3989]



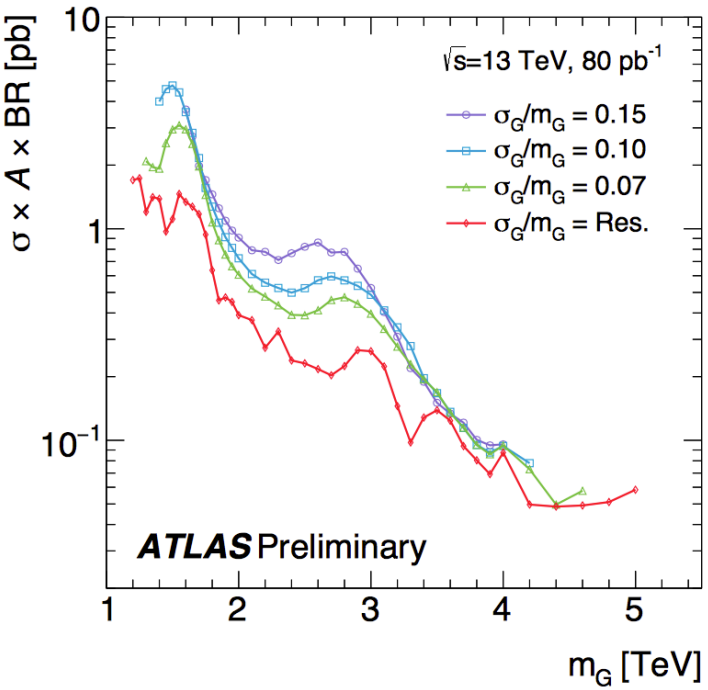
- $W_R \sim 1900$ GeV with coupling $\kappa = g_R/g_L \sim 0.6$ and mixing angle $\sin\phi_w \sim 0.0014$ can explain everything!

13 TeV prospects

- 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)

13 TeV prospects

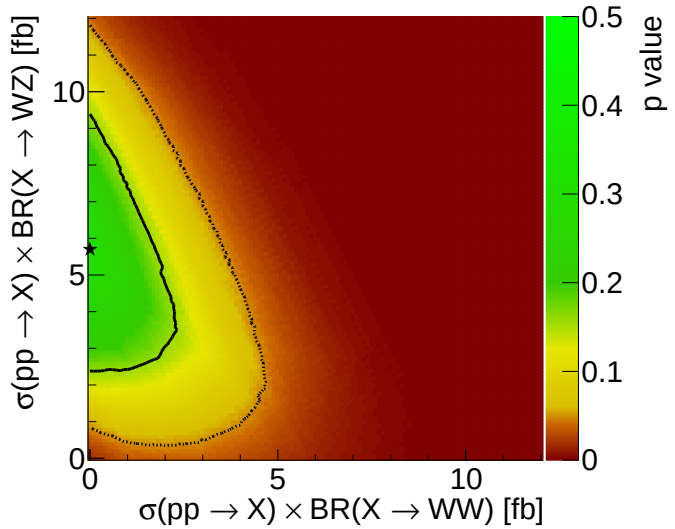
- W_R production cross section > 6 times larger than at 8 TeV
- Best-fit W_R can be excluded with 5 fb^{-1} in jj
  (10 fb^{-1} in tb, 15 fb^{-1} in WZ, WH)
- First result: ATLAS jj with 80 pb^{-1} [ATLAS-CONF-2015-042]

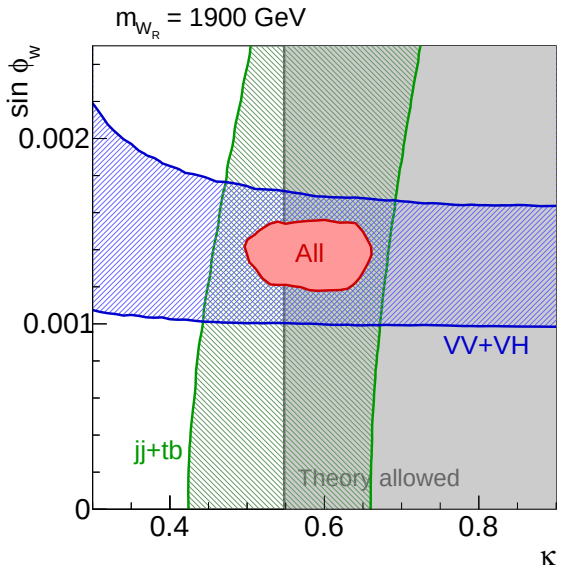


Best-fit W_R prediction:
$\sigma \cdot BR \cdot A \sim 300$ fb

Summary

- Different excesses around $1.8 \ldots 2.0$ TeV in VV, VH, jj searches
- Combined fit to all sensitive searches prefers ~ 5 fb signal in WZ and WH, ~ 100 fb in jj
- In Left-Right Symmetric Model, W_R at 1.9 TeV can explain all measurements
- LHC at 13 TeV will soon be sensitive



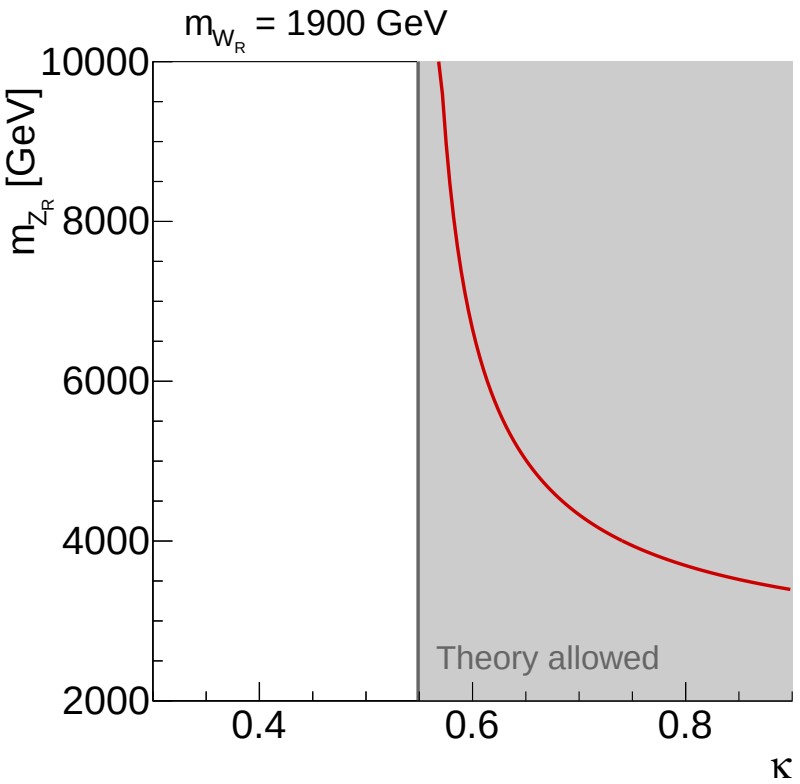


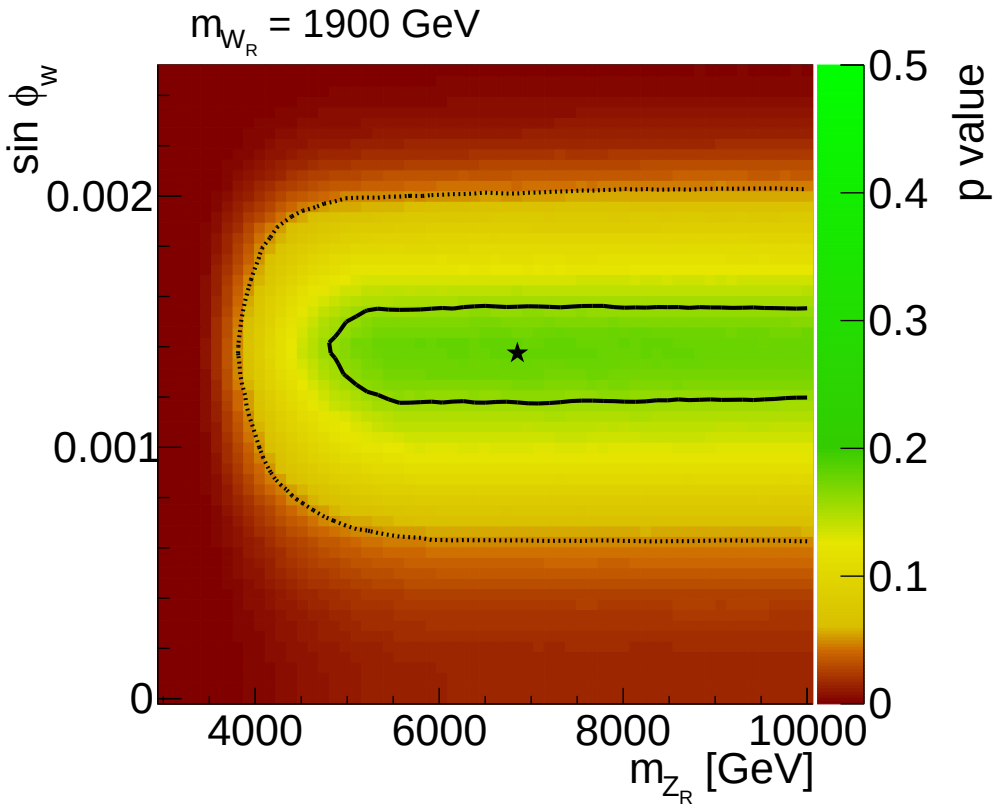
UNIVERSITÄT
HEIDELBERG
ZUKUNFT
SEIT 1386

Backup

Where is the Z_R?

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

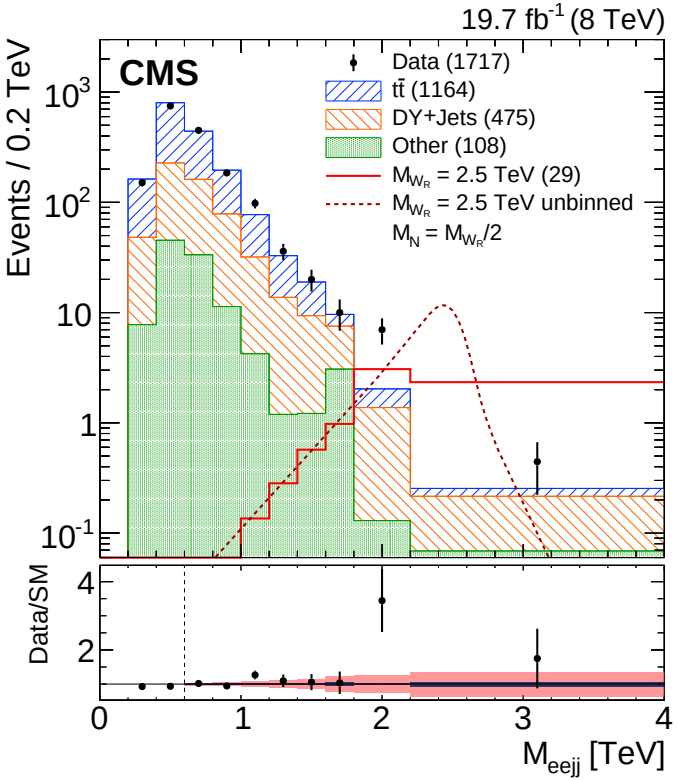




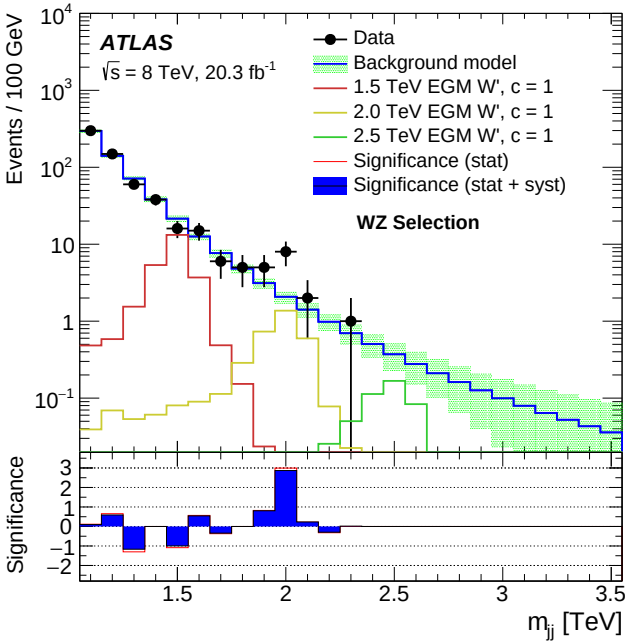
And one more!

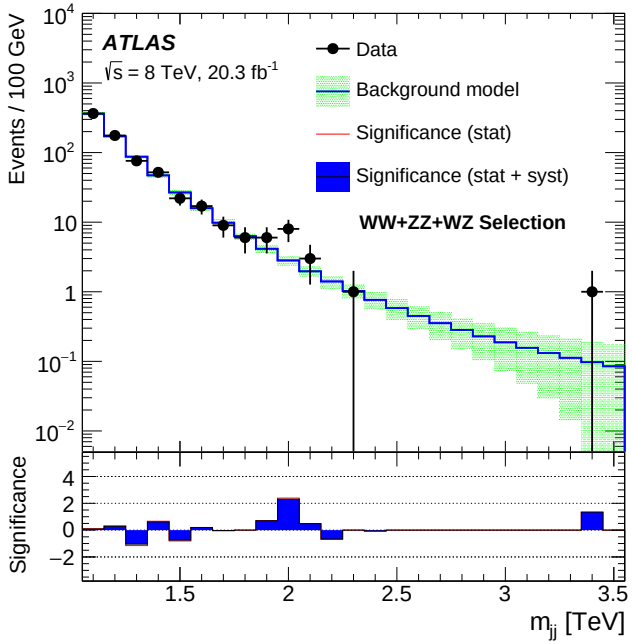
- CMS $e^+e^-\,jj$: $2.8\,\sigma$ excess around 2.0 TeV [1407.3683]
- Could be $W_R \to eN \to ee\,W_R \to ee\,jj$

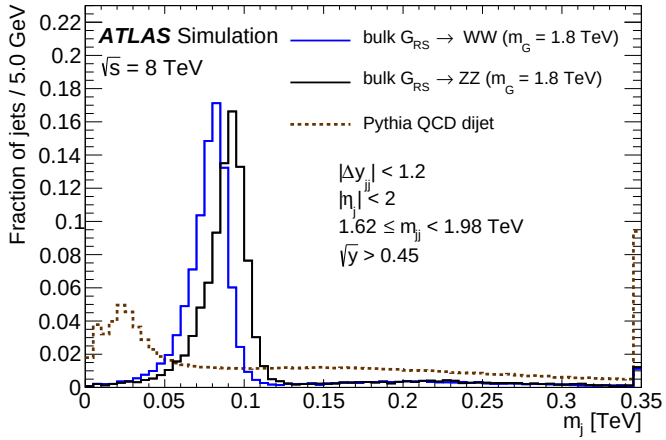
  [B. Dobrescu, Z. Liu 1506.06736; F. Deppisch, L. Graf, S. Kulkarni, S. Patra, W. Rodejohann, N. Sahu, U. Sarkar 1508.05940]
- Issues:
  - Only e^+e^-, no $e^\pm e^\pm$ events (unlike expected from Majorana N_ℓ)
  - No peak in m_{e_2jj} distribution
  - Nothing in $\mu\mu\,jj$ searches
  - Constraints from $\mu \to e\gamma$



ATLAS $VV \to JJ$

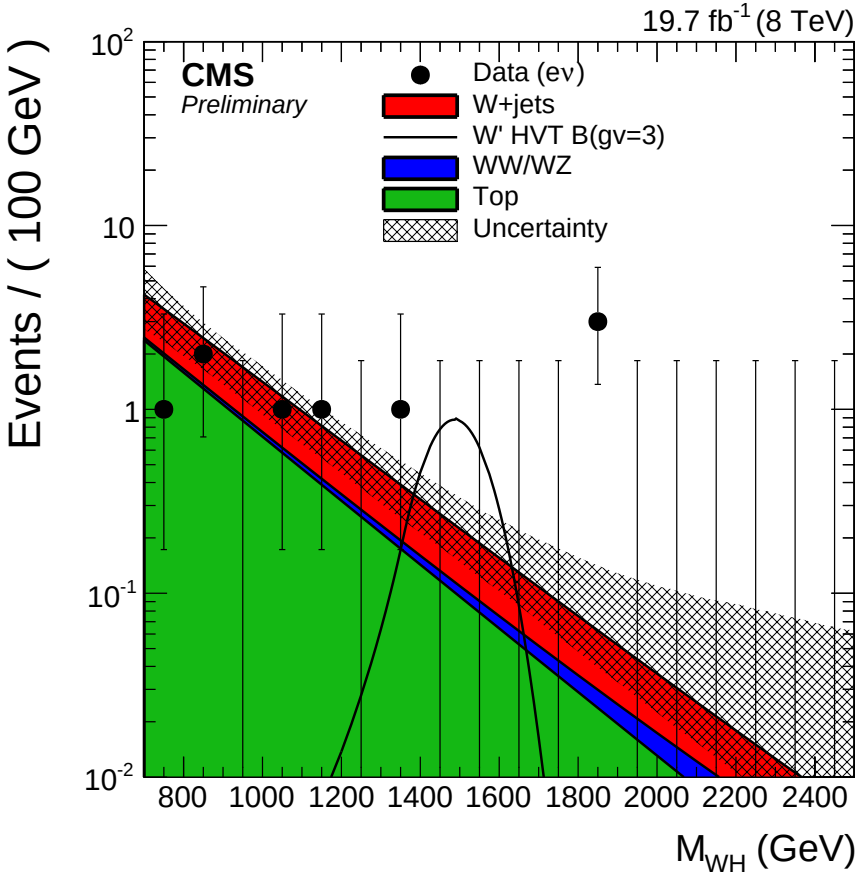






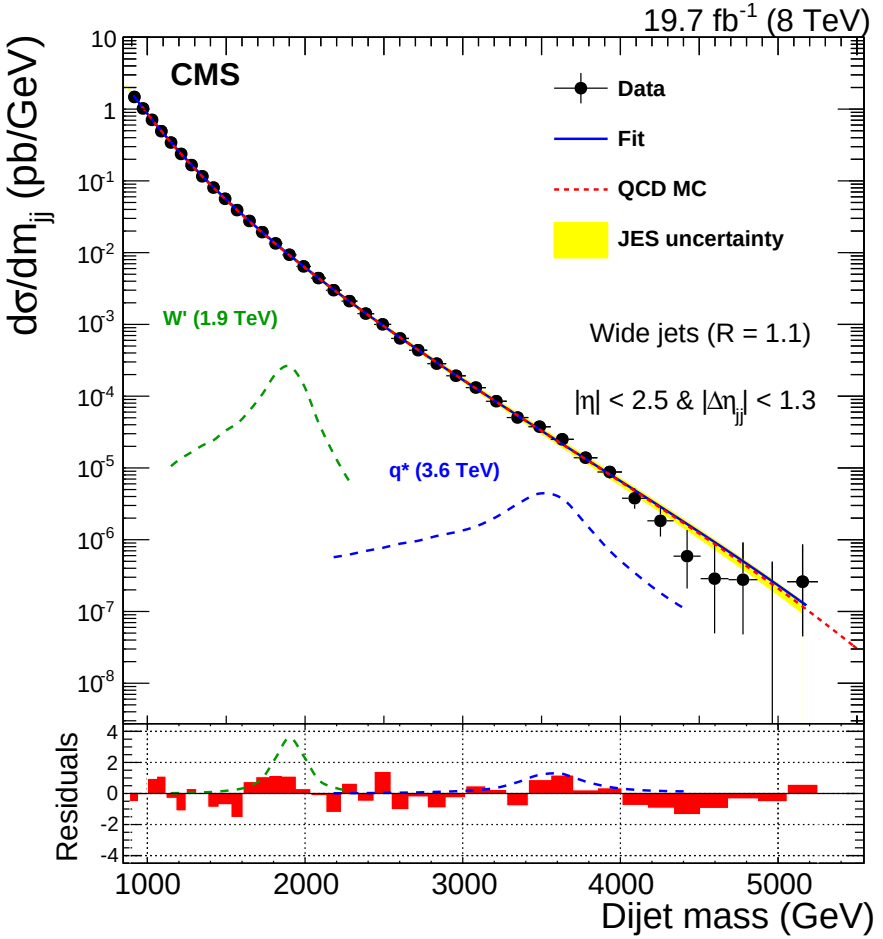
[1506.00962]

More di-things



CMS $WH \to \ell\nu J$: $2.1\,\sigma$

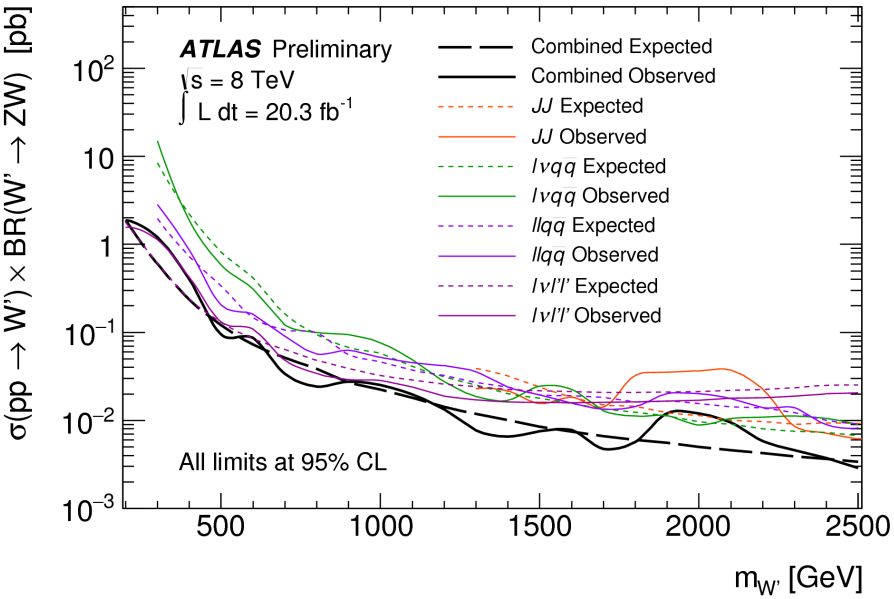
[CMS-PAS-EXO-14-010]

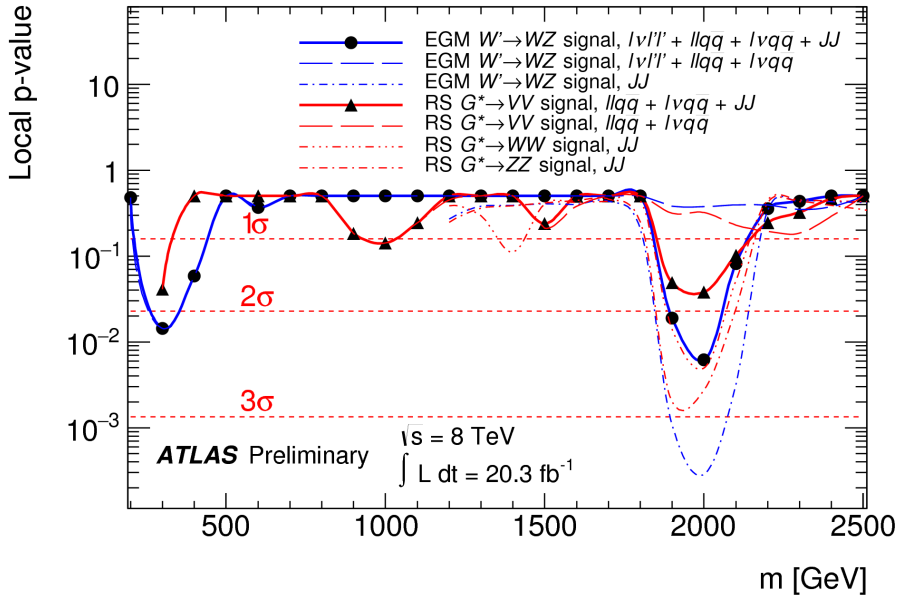


CMS jj: $\sim 2\,\sigma$

[1501.04198]

ATLAS combination





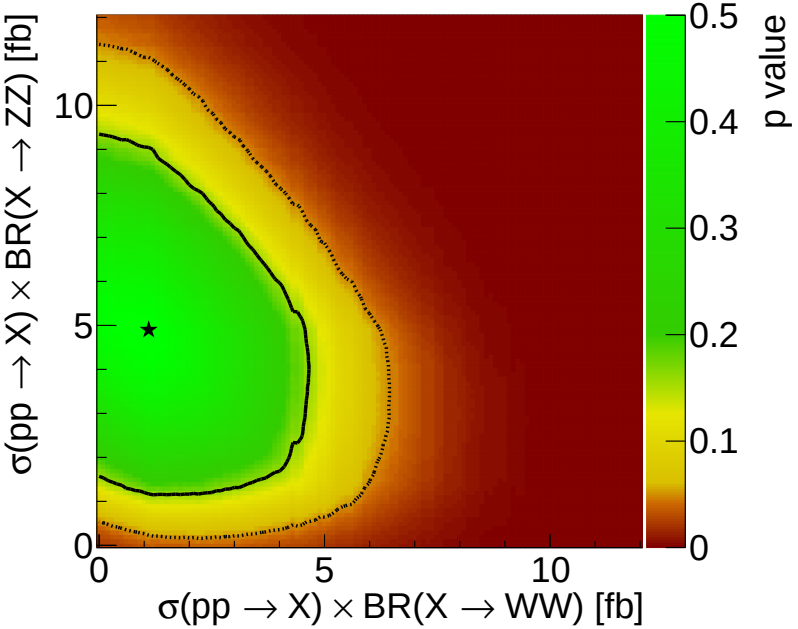
[ATLAS-CONF-2015-045]

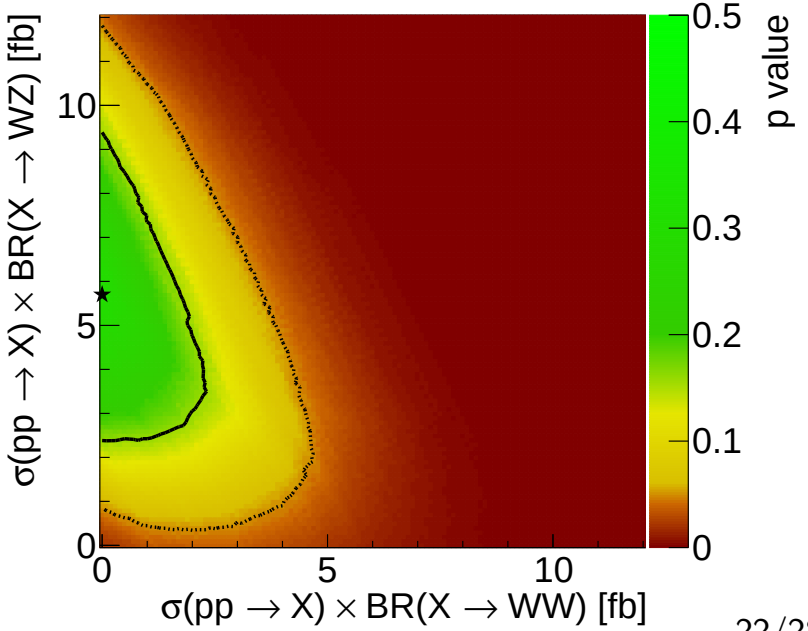
Fit input

Analysis		Selection	Mass bins [GeV]
ATLAS VV hadronic	[1506.00962]	WW selection	1750 – 2050
ATLAS VV hadronic	[1506.00962]	ZZ selection	1750 – 2050
ATLAS VV hadronic	[1506.00962]	WZ selection	1750 – 2050
CMS VV hadronic	[1405.1994]	Double tagged	1780 – 2030
ATLAS VV, single lepton	[1503.04677]	Merged region	1700 – 2000
CMS VV, single lepton	[1405.3447]	High purity	1700 – 2000
ATLAS VV, double lepton	[1409.6190]	Merged region	1680 – 2060
CMS VV, double lepton	[1405.3447]	High purity	1700 – 2000
CMS $VH \to b\bar{b} + \nu\ell$	[PAS-EXO-14-010]		1700 – 2000
CMS $VH \to \tau^+\tau^-$ + hadronic V	[1502.04994]		1500 – 2000
CMS VH hadronic	[1506.01443]	bb selection	1690 – 2030
ATLAS dijet	[1407.1376]		1706 – 2030
CMS dijet	[1501.04198]		1678 – 1945
ATLAS tb, hadronic t	[1408.0886]	Double tagged	1600 – 2000
ATLAS tb, leptonic t	[1410.4103]		1600 – 2000
CMS tb, leptonic t	[1402.2176]		1500 – 2000

VV searches

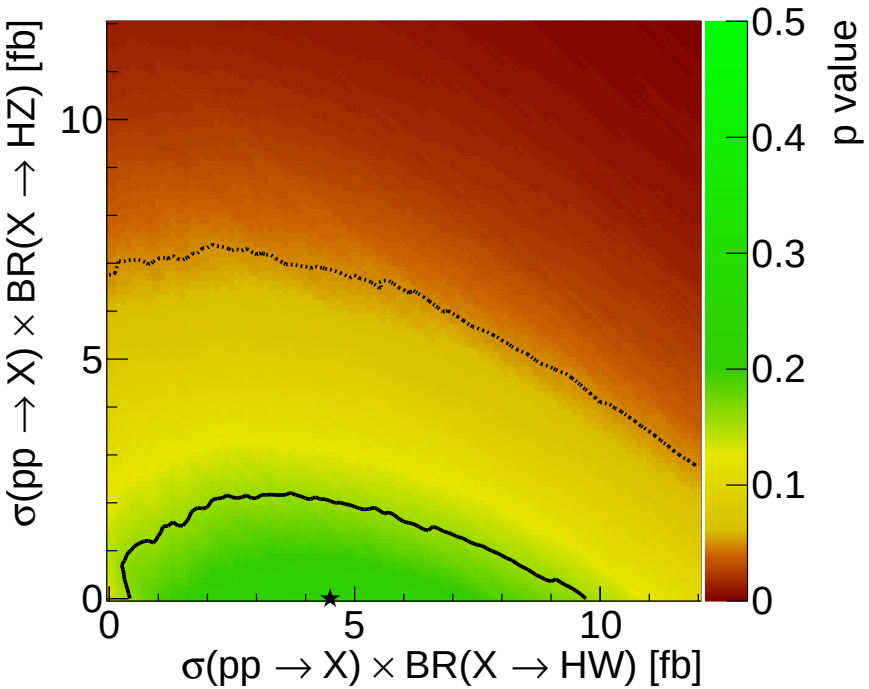
Analysis		Excess [σ]	95% CL_s limits [fb] WW	ZZ	WZ
ATLAS hadronic	[1506.00962]	2.4	20	25	26
CMS hadronic	[1405.1994]	1.0	18	17	18
ATLAS single lepton	[1503.04677]		6		12
CMS single lepton	[1405.3447]		8		17
ATLAS double lepton	[1409.6190]			14	29
CMS double lepton	[1405.3447]	1.5		10	21





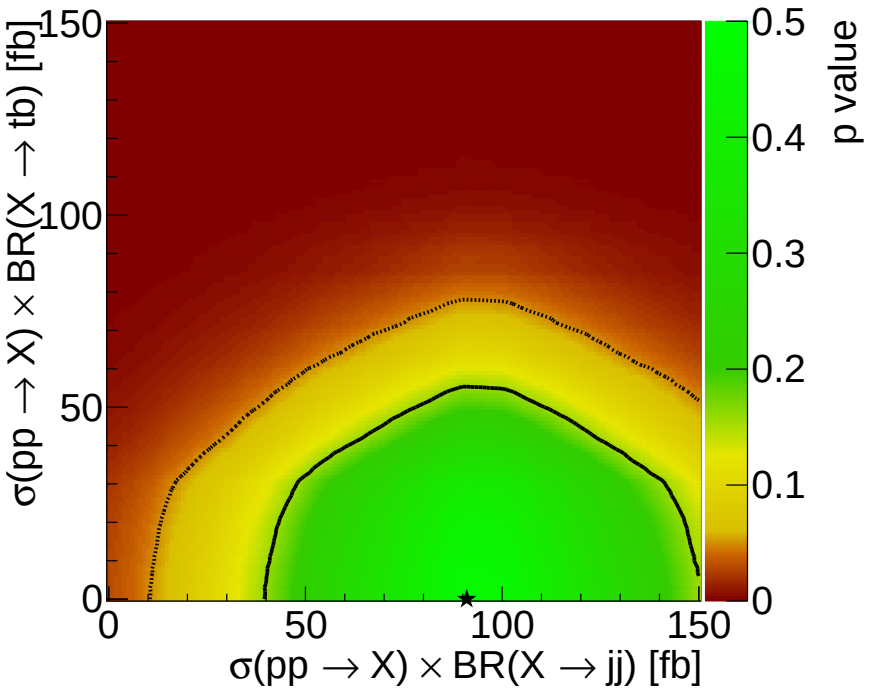
VH searches

Analysis		Excess [σ]	95% CL$_s$ limits [fb] WH	ZH
ATLAS $b\bar{b} + (\ell\ell, \nu\ell, \nu\nu)$	[1503.08089]		30	14
CMS $b\bar{b} + \nu\ell$	[PAS-EXO-14-010]	1.9	44	
CMS $\tau^+\tau^-$ + hadronic vector	[1502.04994]		36	32
CMS hadronic	[1506.01443]		13	13

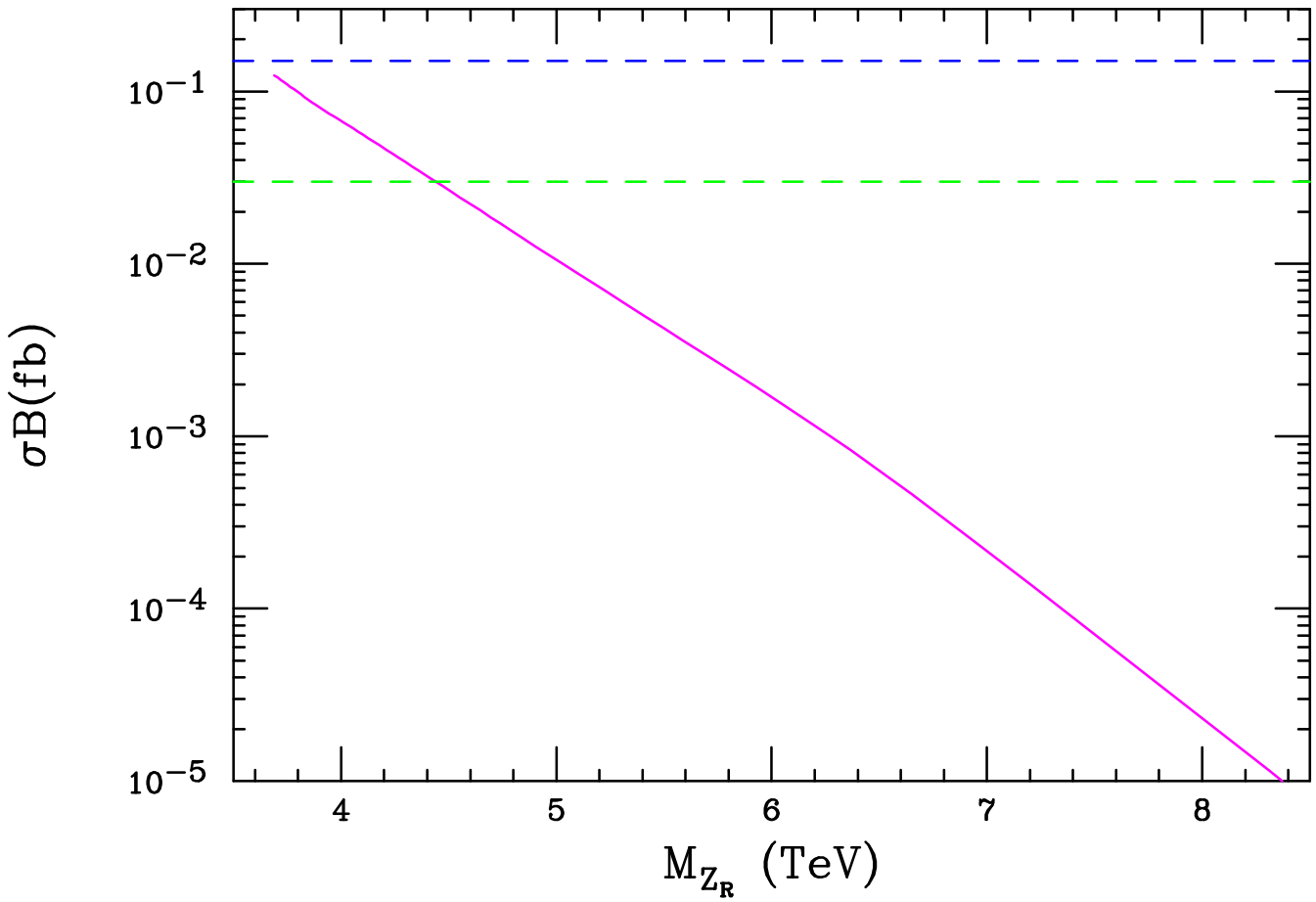


Dijet and tb searches

Analysis		Excess [σ]	95% CL$_s$ limits [fb] jj	tb
ATLAS jj	[1407.1376]	1.5	217	
CMS jj	[1501.04198]	1.9	173	
ATLAS tb, hadronic t	[1408.0886]			203
ATLAS tb, leptonic t	[1410.4103]			101
CMS tb, leptonic t	[1402.2176]			67



$Z_R \to \ell^+\ell^-$ at 13 TeV



(dashed lines: $\sim 95\%$ CLs limits after 20, 100 fb^{-1})

A connection to dark matter? (1)

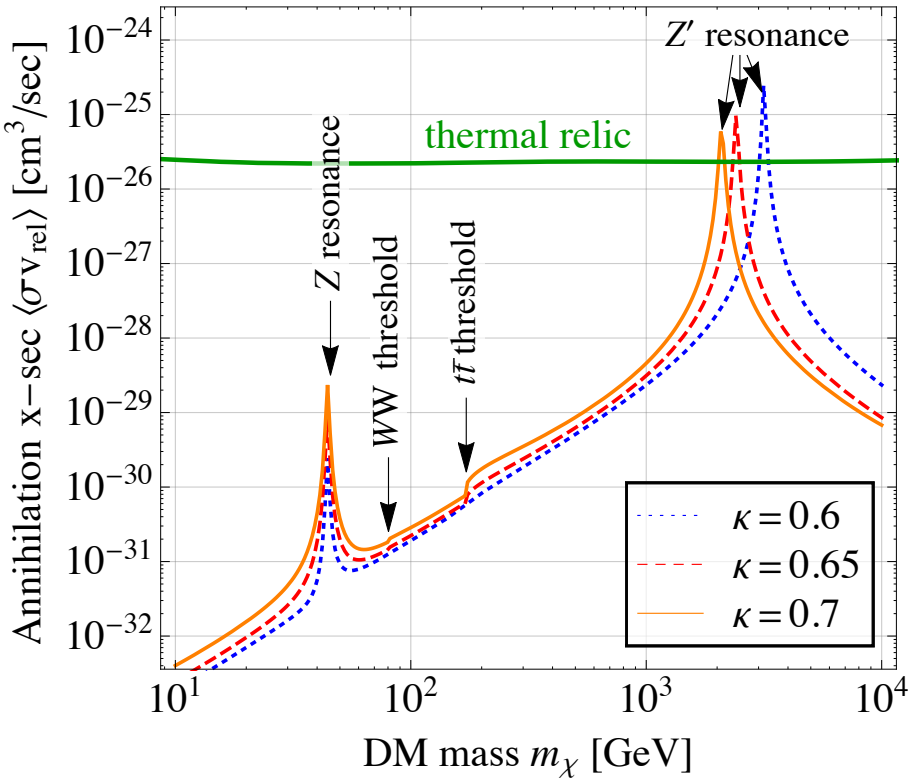
a) W_R-mediated DM interactions with SM partners
- Charged partner χ^+ could be τ
- DM χ^0 could be N_τ (but only if lighter than τ)
- Hard to get relic density right

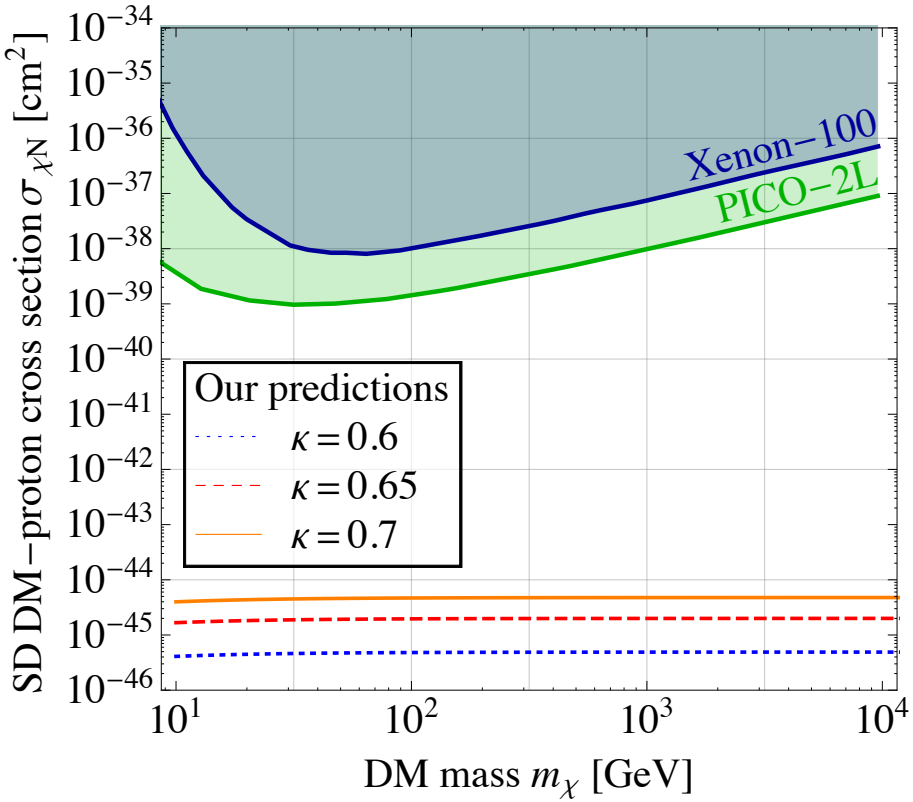
b) W_R-mediated DM interactions with BSM partners
- New particles χ^0, χ^+, with χ^+ slightly heavier
- Freeze-out through χ^0-χ^+ co-annihilation
- Direct and indirect searches probably not sensitive
- Potential LHC signatures: $pp \to W_R \to \chi^0\chi^\pm \to \chi^0\chi^0 qq'$, $\chi^+\chi^-$ pair production

A connection to dark matter? (2)

c) Z- and Z_R-mediated DM interactions

- N_ℓ DM faces same problems as in W_R-mediated scenario
- Alternative: new RH doublet $\chi = (\chi^0, \chi^-) \sim (1, 2, -1)$ with Majorana mass





A connection to dark matter? (3)

d) Minimal Left-Right DM
   - New triplets $\chi_L \sim (3,1,0)$, $\chi_R \sim (1,3,0)$ with common Majorana mass
     [J. Heeck, S. Patra 1507.01584]
   - Electroweak radiative corrections potentially make charged states too light, but safe for $\kappa \sim 0.6$

e) DM in supersymmetric LRM
   - Lightest neutralino is excellent MSSM-like DM candidate