Symmetry restored in dibosons at the LHC?

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based on 1507.00013
(with JoAnne Hewett, Joachim Kopp, Thomas Rizzo, Jamie Tattersall)

ABHM agenda meeting, November 25, 2015

Outline

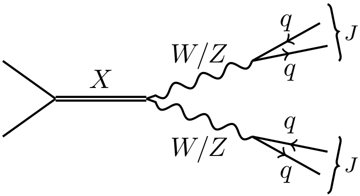
Excitement

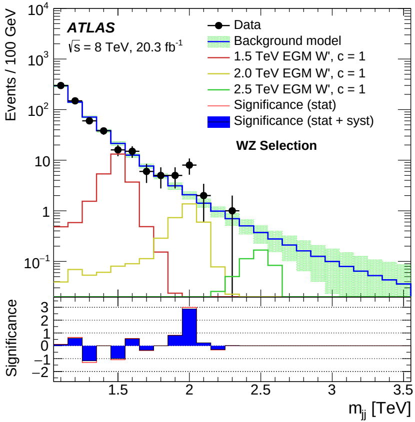
1. Anomalies at 2 TeV
2. Fitting the data
3. New physics interpretations
4. A right-handed W_R?

Speculation

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

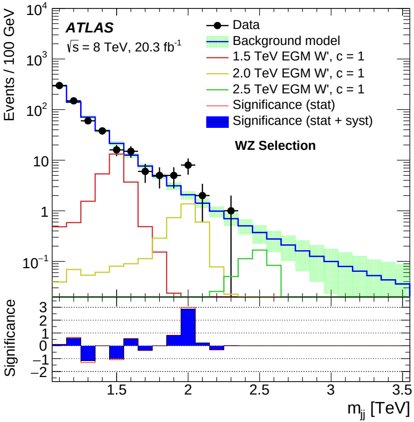
- ATLAS $VV \to JJ$: $3.4\,\sigma$
  [1506.00962]





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

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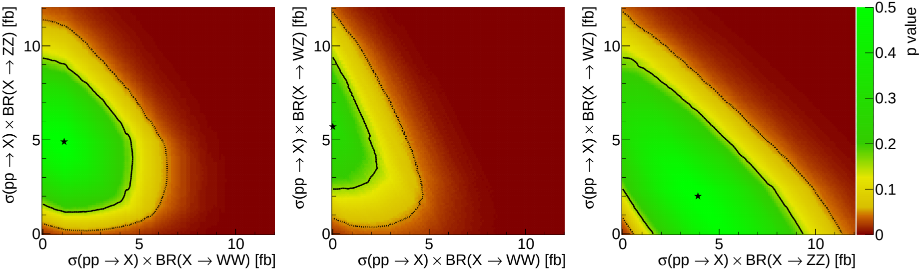
- Combining all 8 TeV searches for resonances in...
  - WW, ZZ, WZ (semileptonic and hadronic decays)
  - WH, ZH
  - jj, tb
- Input data:
  - Observed events, expected background in mass window $\sim 1.7 \ldots 2.0$ TeV
  - Acceptance, efficiencies, systematics
- Handle with care: some rough approximations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

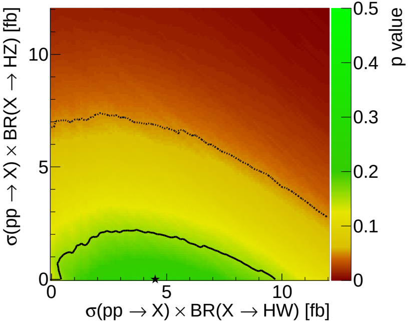
[JB, J. Hewett, J. Kopp, T. Rizzo, J. Tattersall 1507.00013;
see also B. Allanach, B. Gripaios, D. Sutherland 1507.01638]

Fit results: VV



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

Fit results: VH, jj, tb



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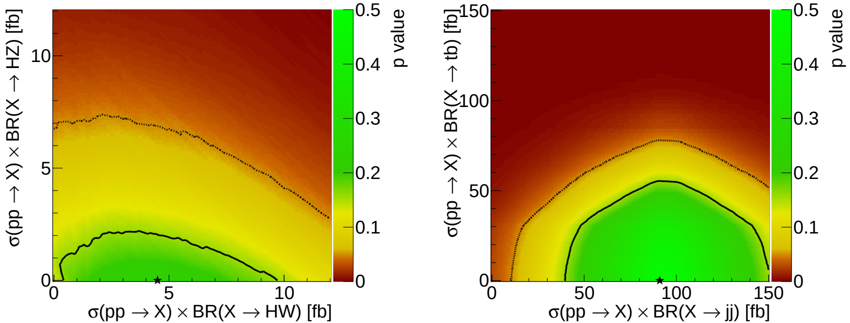
Fit results: VH, jj, tb



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

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

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

$\Rightarrow$ boson, likely charged

- $\mathcal{O}\left(100\ \text{fb}\right)$ 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)

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- 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; D. Sierre, J. Herrero-Garcia, D. Restrepo, A. Vicente 1510.03437]
  - Sparticle [C. Petersson, R. Torre 1508.05632; B. Allanach, P. Bhupal Dev, K. Sakurai 1511.01483]
  - Composite scalar [C. Chiang, H. Fukada, M. Ibe, T. Yanagida 1507.02483; G. Cacciapaglia, A. Deandrea, M. Hashimoto 1507.03098]

Interpretations on the market (2)

- 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; P. Ko, T. Nomura 1510.07872; J. Collins, W. Ng 1510.08083; B. Dobrescu, P. Fox 1511.02148]
  - 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; Z. Wang, F. Sage, T. Steele, R. Mann 1511.02531]
  - $W' + Z'$ [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; T. Appelquist, Y. Bai, J. Ingoldby, M. Piai 1511.05473]

Interpretations on the market (3)

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- Spin 1 (continued)
  - Composite vector [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. Quiròs, 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; H. Fukano, S. Matsuzaki, K. Terashi, K. Yamawaki 1510.08184]
  - 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; B. Bhattacherjee, P. Byakti, C. Khosa, J. Lahiri, G. Mendiratta 1511.02797]

Interpretations on the market (4)

- Different spins
  - 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; A. Sajjad 1511.02244]
- 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 g_R

$$\kappa = g_R/g_L$$

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

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

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

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

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

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

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

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

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

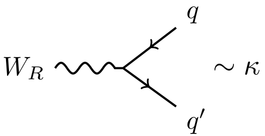
↓ $\langle \Phi \rangle \rightsquigarrow W$, Z masses; W-W_R mixing $\sim \phi_w$

$U(1)_Q$

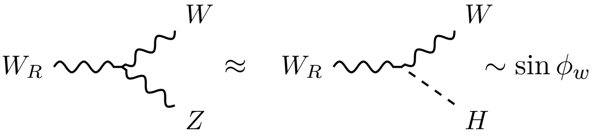
[J. Pati, A. Salam 1974; R. Mohapatra, J. Pati 1977; G. Senjanovic, R. Mohapatra 1975. . .]

W_R phenomenology

- Direct coupling to RH quarks:



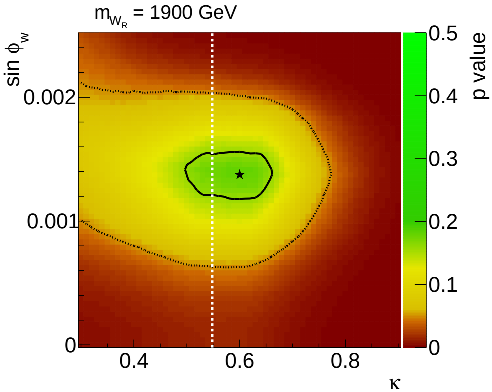
- $m_{N_\ell} > m_{W_R}$ avoids ℓN_ℓ limits
  [see also B. Dobrescu, Z. Liu 1506.06736; F. Deppisch, L. Graf, S. Kulkarni, S. Patra, W. Rodejohann, N. Sahu, U. Sarkar 1508.05940]
- Mixing gives diboson modes:



$\rightsquigarrow$ 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

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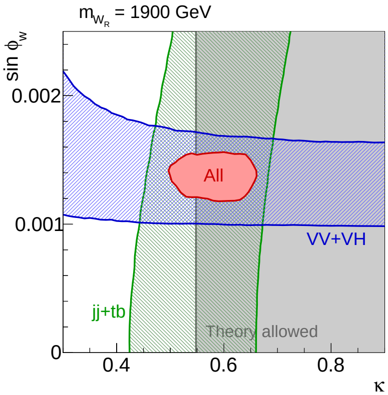

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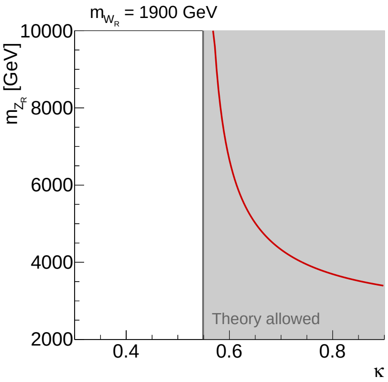
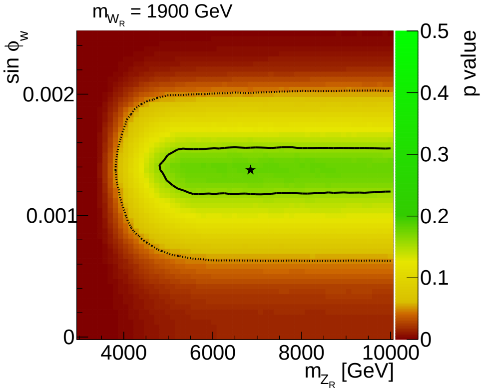
Where is the Z_R?

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





13 TeV prospects

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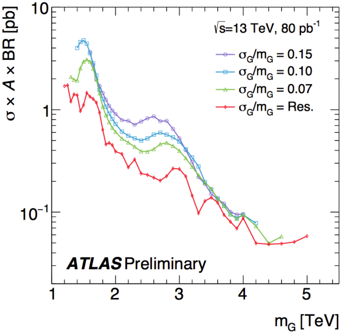
- W_R production cross section > 6 times larger than at 8 TeV
- Best-fit W_R can be excluded with 5 fb^{-1} in jj (10 fb^{-1} in tb, 15 fb^{-1} in WZ, WH)

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]

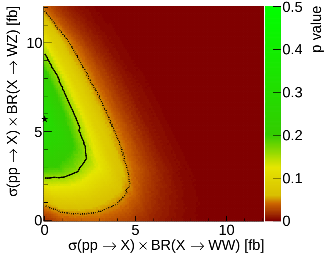


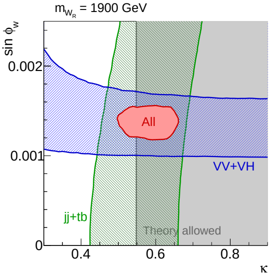
Best-fit W_R prediction:
$\sigma \cdot BR \cdot A \sim 300$ fb

- Full 2015 sample: 4.0 fb^{-1} (ATLAS) + 3.7 fb^{-1} (CMS)

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

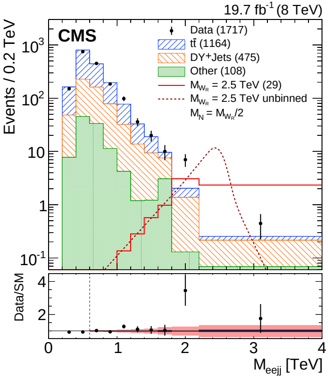




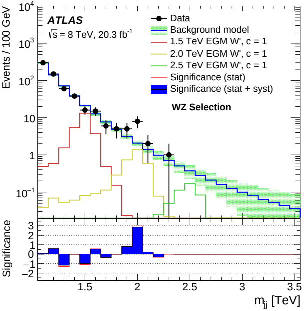
Backup

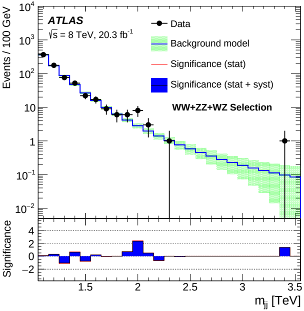
The one (anomaly) that got away

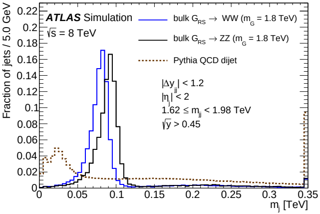
- CMS $e^+e^- jj$: $2.8\,\sigma$ excess around 2.0 TeV [1407.3683]
- Could be $W_R \to eN \to ee\, W_R \to ee\, jj$
  [B. Dobrescu, Z. Liu 1506.06736; F. Deppisch, L. Graf, S. Kulkarni, S. Patra, W. Rodejohann, N. Sahu, U. Sarkar 1508.05940]
- Issues:
  - Only e^+e^-, no $e^\pm e^\pm$ events (unlike 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

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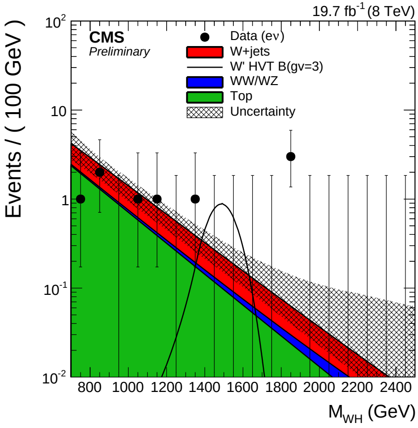
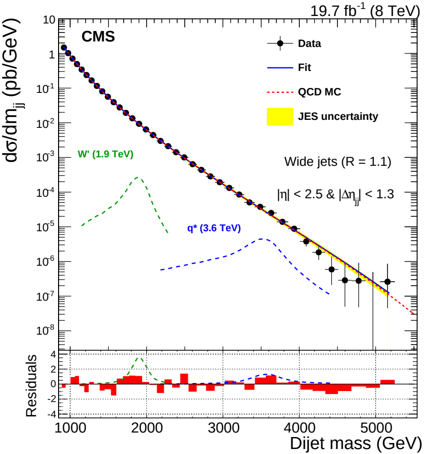


CMS $WH \to \ell\nu J$: $2.1\,\sigma$

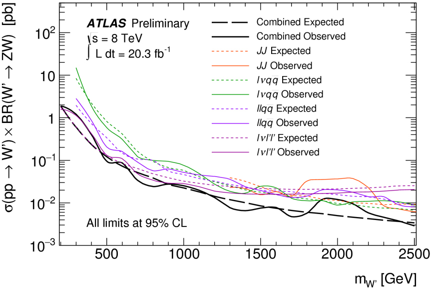
[CMS-PAS-EXO-14-010]

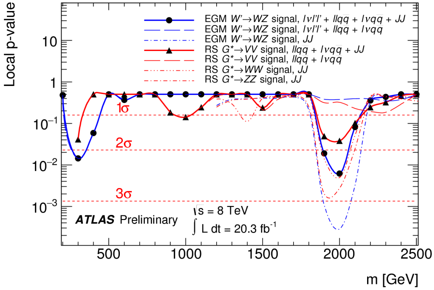


CMS jj: $\sim 2\,\sigma$

[1501.04198]

ATLAS combination





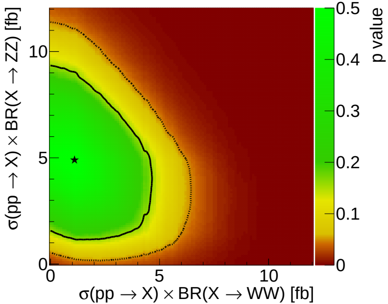
[ATLAS-CONF-2015-045]

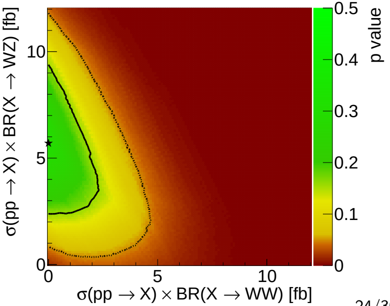
Fit input

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

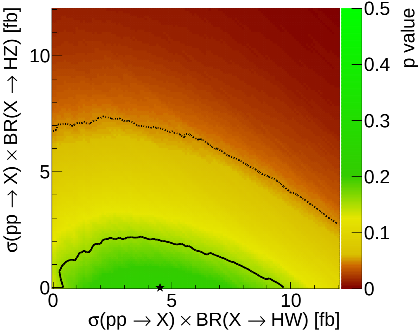
Analysis		Excess [σ]	95% CL_s limits [fb]		
			WW	ZZ	WZ
ATLAS hadronic	[1506.00962]	2.4	20	25	26
CMS hadronic	[1405.1994]	1.0	18	17	18
ATLAS single lepton	[1503.04677]		6		12
CMS single lepton	[1405.3447]		8		17
ATLAS double lepton	[1409.6190]			14	29
CMS double lepton	[1405.3447]	1.5		10	21





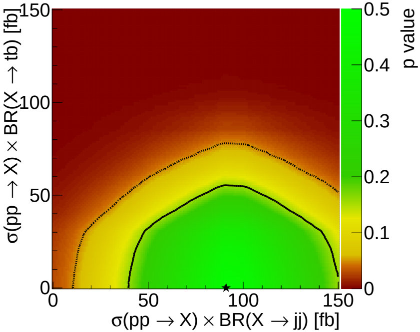
VH searches

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

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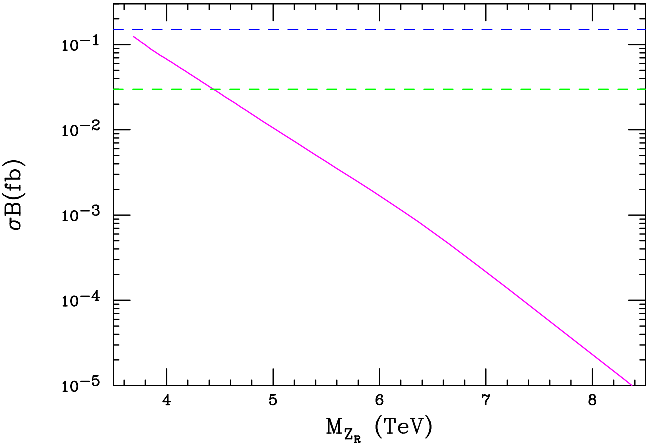


(dashed lines: $\sim 95\%$ CLs limits after 20, 100 fb^{-1})

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

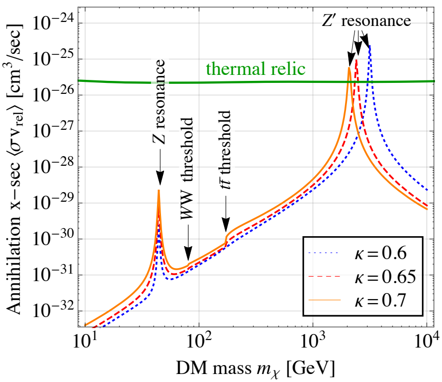
b) W_R-mediated DM interactions with BSM partners

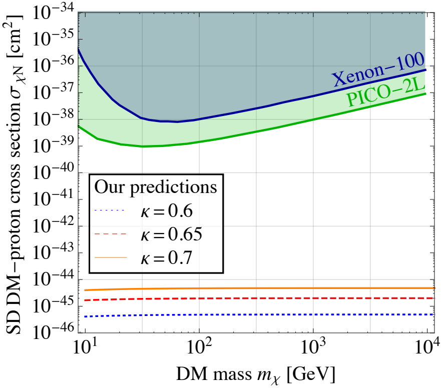
- New particles χ^0, χ^+, with χ^+ slightly heavier
- Freeze-out through χ^0-χ^+ co-annihilation
- Direct and indirect searches probably not sensitive
- Potential LHC signatures: $pp \to W_R \to \chi^0\chi^\pm \to \chi^0\chi^0 qq'$, $\chi^+\chi^-$ pair production

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)

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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