ATLAS DiBoson Anomaly

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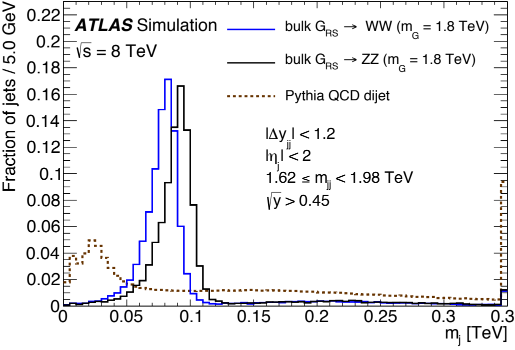
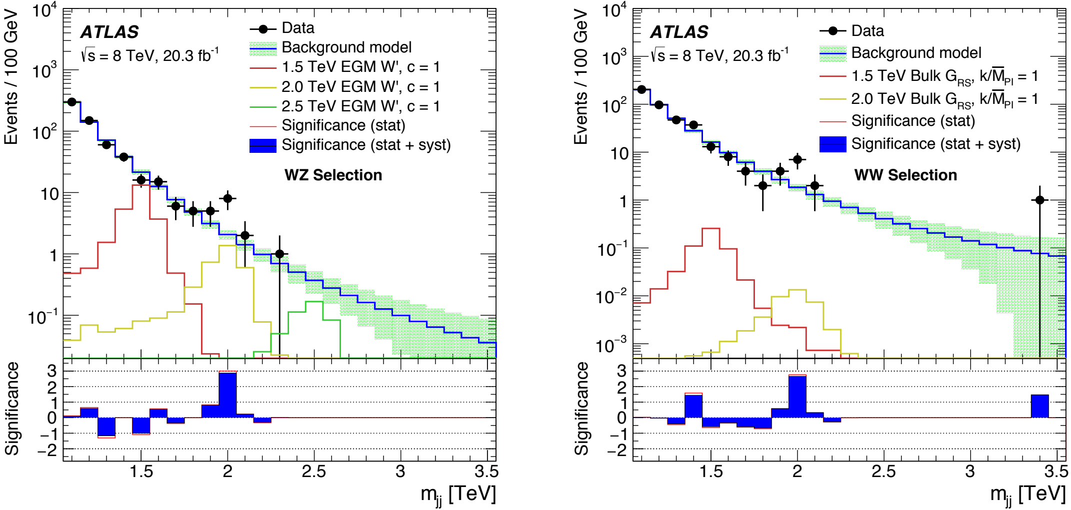
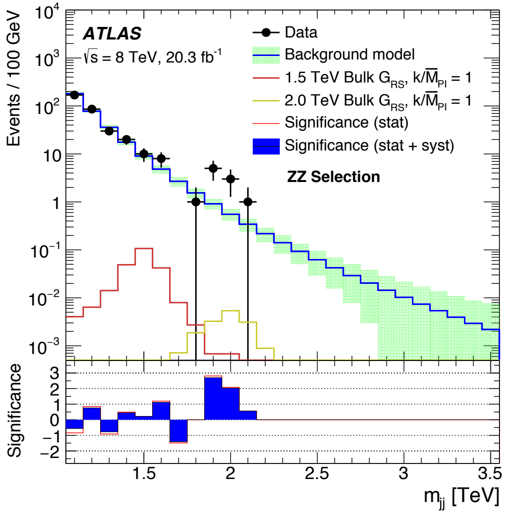


ATLAS Simulation
$\sqrt{s}$ = 8 TeV
bulk $G_{RS} \rightarrow$ WW (m_G = 1.8 TeV)
bulk $G_{RS} \rightarrow$ ZZ (m_G = 1.8 TeV)
Pythia QCD dijet
$|\Delta y_{jj}| < 1.2$
$|\eta_j| < 2$
$1.62 \leq m_{jj} < 1.98$ TeV
$\sqrt{y} > 0.45$
Fraction of jets / 5.0 GeV
m_j [TeV]
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
0.22
0.05
0.15
0.25
0.3
0.35



ATLAS
$\sqrt{s}$ = 8 TeV, 20.3 fb^{-1}
Data
Background model
1.5 TeV EGM W', c = 1
2.0 TeV EGM W', c = 1
2.5 TeV EGM W', c = 1
Significance (stat)
Significance (stat + syst)
WZ Selection
Events / 100 GeV
Significance
m_{jj} [TeV]
ATLAS
$\sqrt{s}$ = 8 TeV, 20.3 fb^{-1}
Data
Background model
1.5 TeV Bulk G_{RS}, $k/\overline{M}_{Pl}$ = 1
2.0 TeV Bulk G_{RS}, $k/\overline{M}_{Pl}$ = 1
Significance (stat)
Significance (stat + syst)
WW Selection
Events / 100 GeV
Significance
m_{jj} [TeV]



ATLAS
$\sqrt{s}$ = 8 TeV, 20.3 fb^{-1}
Data
Background model
1.5 TeV Bulk G_{RS}, $k/\overline{M}_{Pl}$ = 1
2.0 TeV Bulk G_{RS}, $k/\overline{M}_{Pl}$ = 1
Significance (stat)
Significance (stat + syst)
ZZ Selection
Events / 100 GeV
Significance
m_{jj} [TeV]

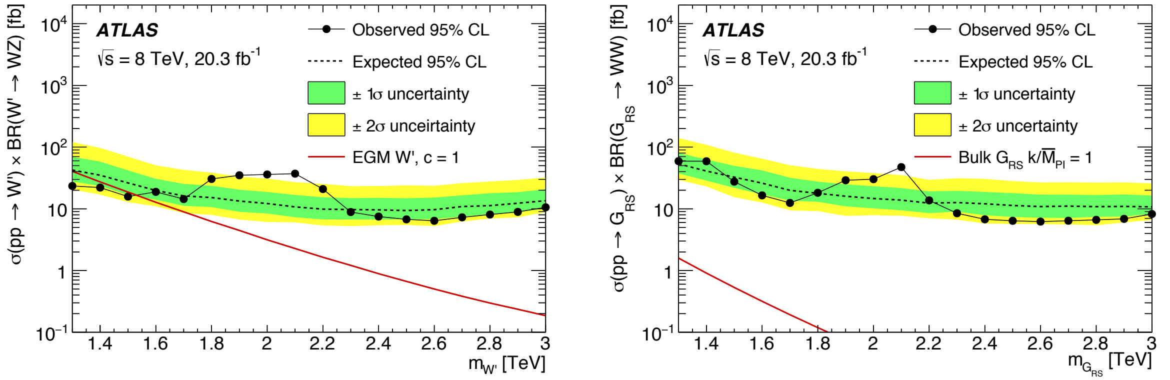
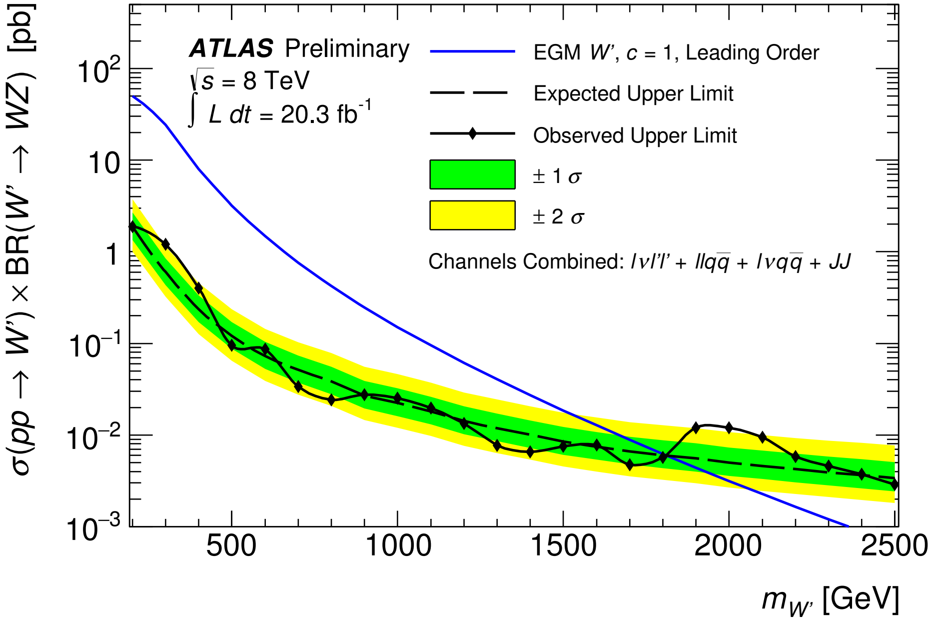
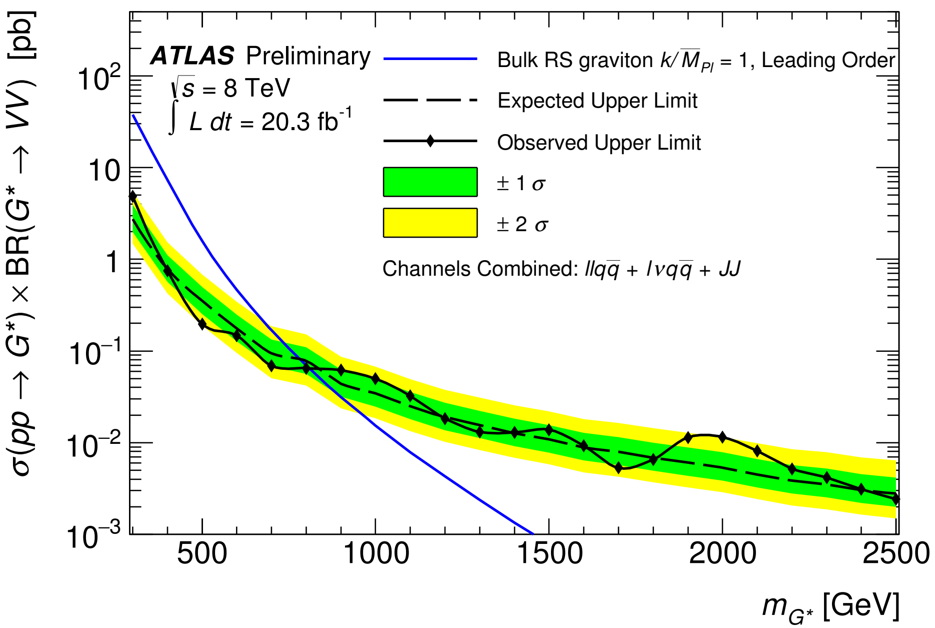

ATLAS
$\sqrt{s}$ = 8 TeV, 20.3 fb^{-1}
Observed 95% CL
Expected 95% CL
± 1σ uncertainty
± 2σ unceirtainty
EGM W', c = 1
$\sigma(pp \rightarrow W') \times BR(W' \rightarrow WZ)$ [fb]
$m_{W'}$ [TeV]
1.4
1.6
1.8
2
2.2
2.4
2.6
2.8
3
10^{-1}
1
10
10^2
10^3
10^4
ATLAS
$\sqrt{s}$ = 8 TeV, 20.3 fb^{-1}
Observed 95% CL
Expected 95% CL
± 1σ uncertainty
± 2σ uncertainty
Bulk G_{RS} $k/\overline{M}_{Pl}$ = 1
$\sigma(pp \rightarrow G_{RS}) \times BR(G_{RS} \rightarrow WW)$ [fb]
$m_{G_{RS}}$ [TeV]
1.4
1.6
1.8
2
2.2
2.4
2.6
2.8
3
10^{-1}
1
10
10^2
10^3
10^4

Table 2: Summary of the event selection requirements in the different search channels. The selected events are further classified into different kinematic categories as listed in Table 3.

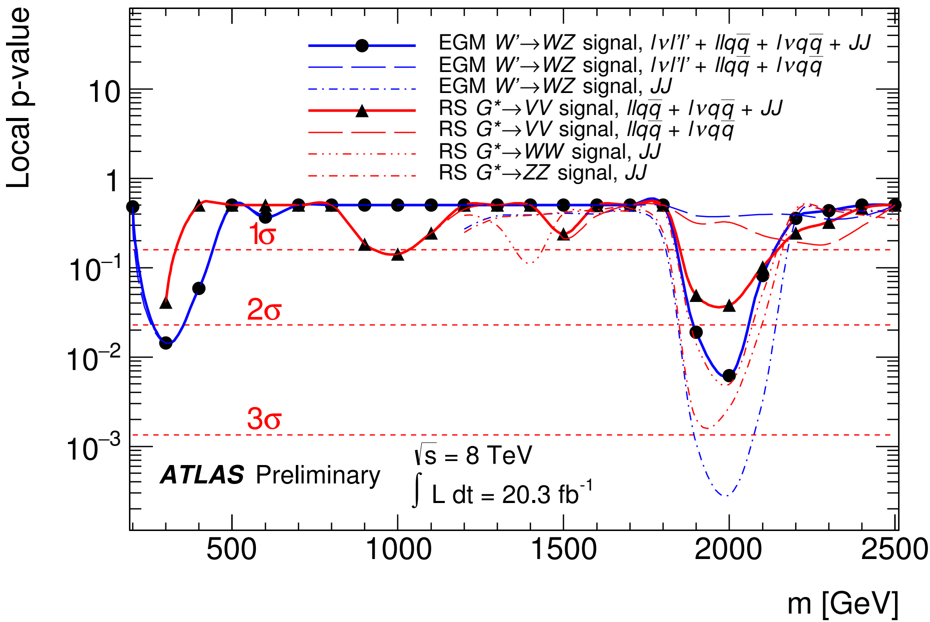
Channel	Leptons	Jets	E_T^{miss}	Boson Identification
$\ell\nu\ell'\ell'$	3 leptons $p_T > 25$ GeV	–	$E_T^{miss} > 25$ GeV	$\|m_{ll} - m_Z\| < 20$ GeV
$\ell\ell q\bar{q}$	2 leptons $p_T > 25$ GeV	2 small-R jets or 1 large-R jet	–	$\|m_{ll} - m_Z\| < 25$ GeV 70 GeV $< m_{jj} <$ 110 GeV 70 GeV $< m_J <$ 110 GeV , $\sqrt{y} > 0.45$
$\ell\nu q\bar{q}$	1 lepton $p_T > 25$ GeV	2 small-R jets or 1 large-R jet No b-jet with $\Delta R(b, W/Z) > 0.8$	$E_T^{miss} > 30$ GeV	65 GeV $< m_{jj} <$ 105 GeV 65 GeV $< m_J <$ 105 GeV, $\sqrt{y} > 0.45$
JJ	0 lepton	2 large-R jets, $\|\eta\| < 2.0$	$E_T^{miss} < 350$ GeV	$\|m_{W/Z} - m_J\| < 13$ GeV $\sqrt{y} > 0.45$, $n_{trk} < 30$



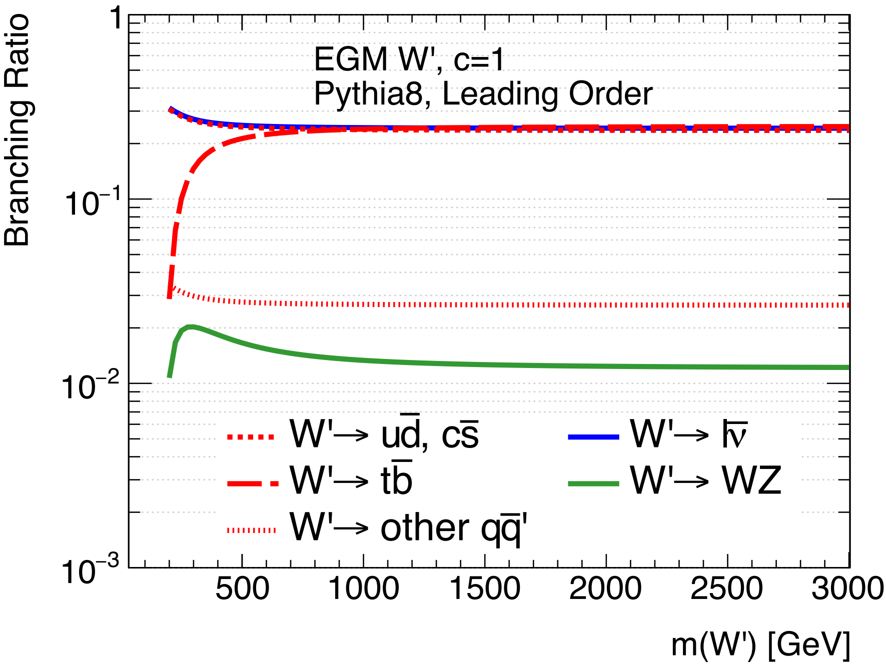
ATLAS Preliminary
$\sqrt{s}$ = 8 TeV
$\int L\, dt$ = 20.3 fb^{-1}
EGM W', c = 1, Leading Order
Expected Upper Limit
Observed Upper Limit
$\pm$ 1 σ
$\pm$ 2 σ
Channels Combined: $l\nu l'l'$ + $llq\bar{q}$ + $l\nu q\bar{q}$ + JJ
$\sigma(pp \rightarrow W') \times BR(W' \rightarrow WZ)$ [pb]
$m_{W'}$ [GeV]
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
500
1000
1500
2000
2500



ATLAS Preliminary
$\sqrt{s}$ = 8 TeV
$\int L\,dt$ = 20.3 fb^{-1}
Bulk RS graviton $k/\overline{M}_{Pl}$ = 1, Leading Order
Expected Upper Limit
Observed Upper Limit
$\pm$ 1 σ
$\pm$ 2 σ
Channels Combined: $llq\bar{q}$ + $l\nu q\bar{q}$ + JJ
$\sigma(pp \to G^*) \times \mathrm{BR}(G^* \to VV)$ [pb]
m_{G^*} [GeV]



Local p-value
EGM W'→WZ signal, lνl'l' + llqq̄ + lνqq̄ + JJ
EGM W'→WZ signal, lνl'l' + llqq̄ + lνqq̄
EGM W'→WZ signal, JJ
RS G*→VV signal, llqq̄ + lνqq̄ + JJ
RS G*→VV signal, llqq̄ + lνqq̄
RS G*→WW signal, JJ
RS G*→ZZ signal, JJ
10
1
10^{-1}
10^{-2}
10^{-3}
1σ
2σ
3σ
ATLAS Preliminary
$\sqrt{s}$ = 8 TeV
$\int L\,dt$ = 20.3 fb^{-1}
500
1000
1500
2000
2500
m [GeV]



EGM W', c=1
Pythia8, Leading Order
Branching Ratio
1
10^{-1}
10^{-2}
10^{-3}
500
1000
1500
2000
2500
3000
m(W') [GeV]
W'→ $u\bar{d}$, $c\bar{s}$
W'→ $t\bar{b}$
W'→ other $q\bar{q}'$
W'→ $l\bar{\nu}$
W'→ WZ

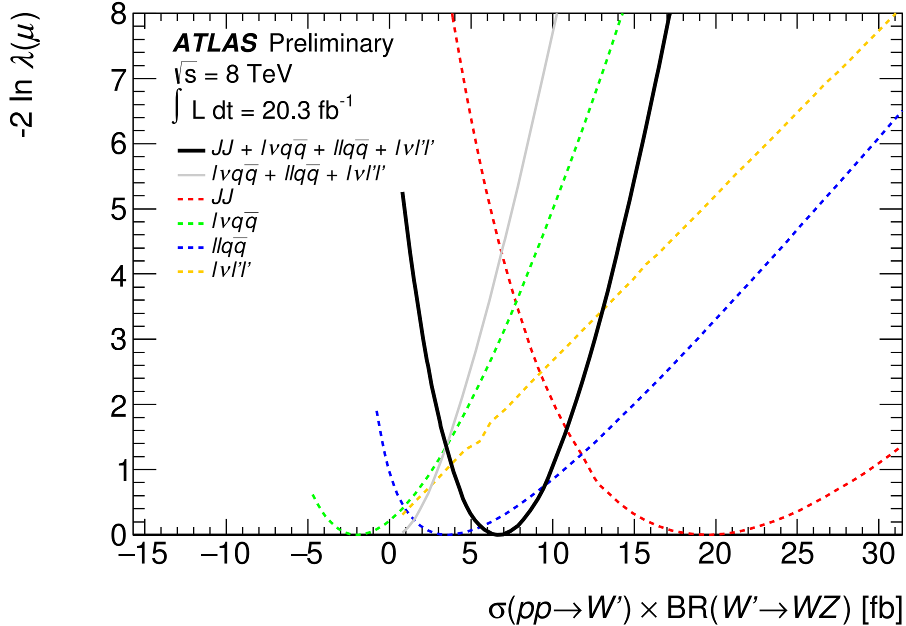


Figure 15: Profile likelihood scans for $\ell\nu\ell'\ell'$, $\ell\ell q\bar{q}$, $\ell\nu q\bar{q}$, and JJ channels separately and in combinations for the EGM W' signal hypothesis for a W' mass of 2 TeV.

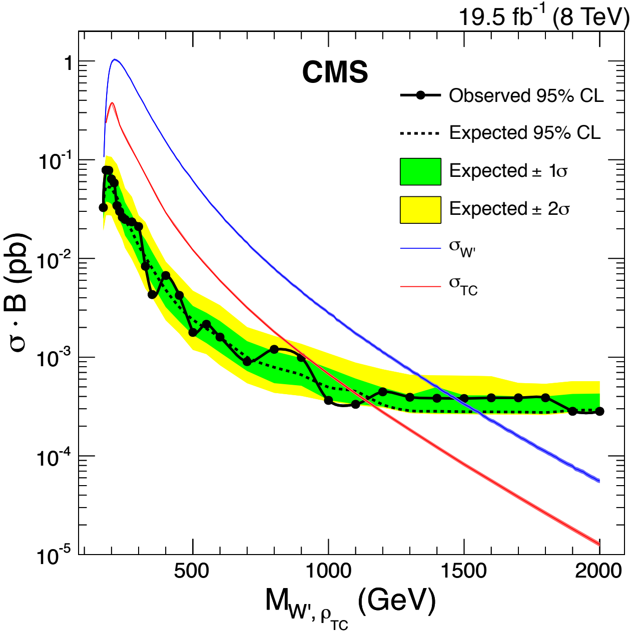
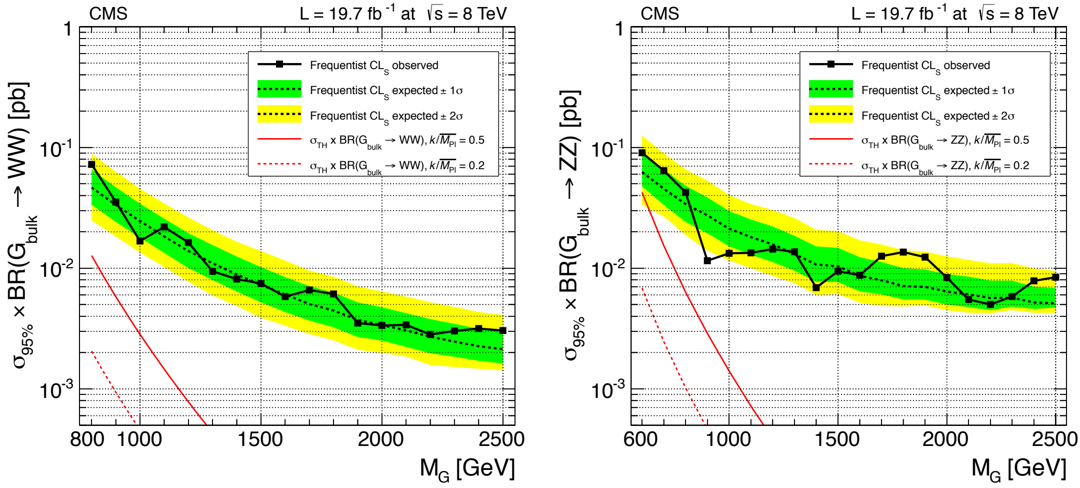
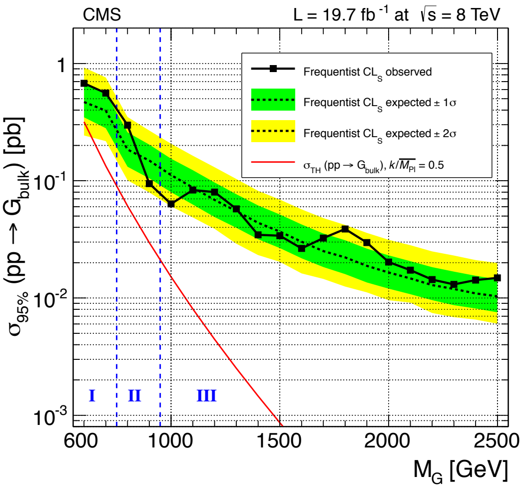
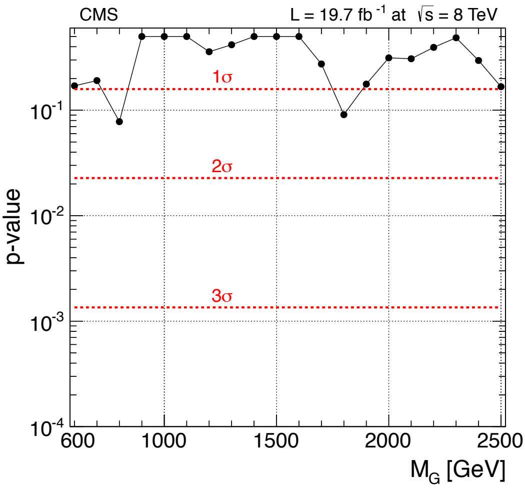
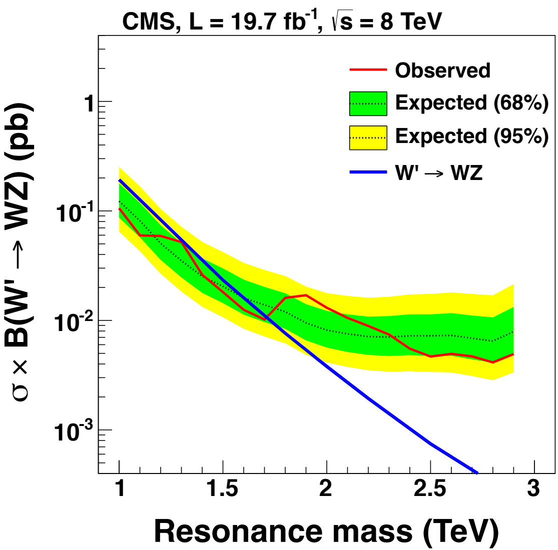


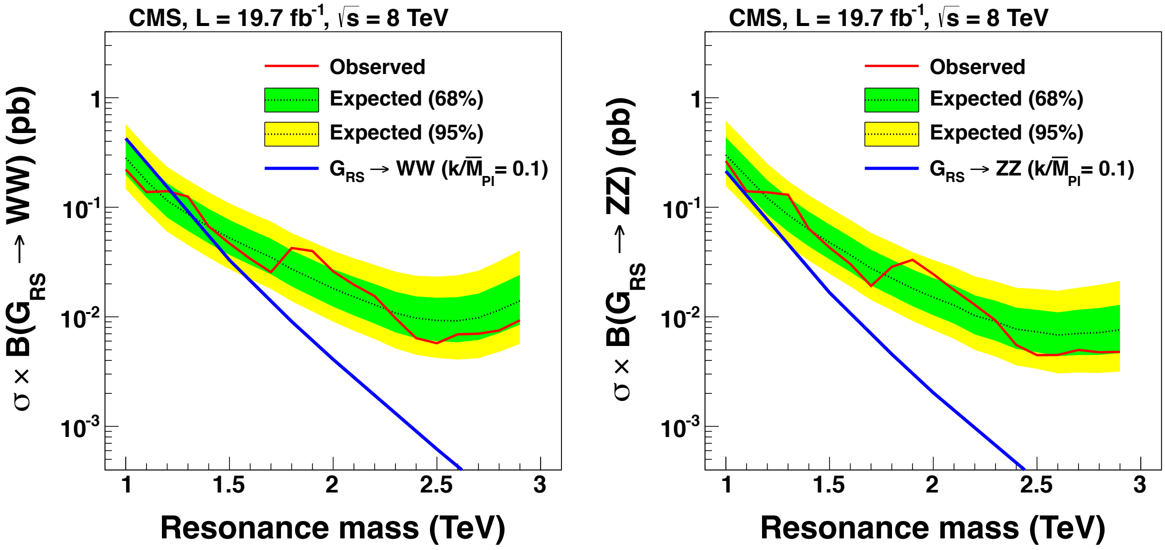
Figure 2: Limits at 95% CL on $\sigma \times \mathcal{B}(\mathrm{W}' \to 3\ell\nu)$ as a function of the mass of the EGM W' (blue) and ρ_{TC} (red), along with the $1\,\sigma$ and $2\,\sigma$ combined statistical and systematic uncertainties in-


CMS
L = 19.7 fb -1 at √s = 8 TeV
Frequentist CLS observed
Frequentist CLS expected ± 1σ
Frequentist CLS expected ± 2σ
σTH x BR(Gbulk → WW), k/M̄Pl = 0.5
σTH x BR(Gbulk → WW), k/M̄Pl = 0.2
σ95% × BR(Gbulk → WW) [pb]
MG [GeV]
CMS
L = 19.7 fb -1 at √s = 8 TeV
Frequentist CLS observed
Frequentist CLS expected ± 1σ
Frequentist CLS expected ± 2σ
σTH x BR(Gbulk → ZZ), k/M̄Pl = 0.5
σTH x BR(Gbulk → ZZ), k/M̄Pl = 0.2
σ95% × BR(Gbulk → ZZ) [pb]
MG [GeV]


CMS
L = 19.7 fb^{-1} at $\sqrt{s}$ = 8 TeV
Frequentist CL$_S$ observed
Frequentist CL$_S$ expected ± 1σ
Frequentist CL$_S$ expected ± 2σ
σ_{TH} (pp → G$_{bulk}$), $k/\overline{M}_{Pl}$ = 0.5
I
II
III
$\sigma_{95\%}$ (pp → G$_{bulk}$) [pb]
M$_G$ [GeV]


CMS
L = 19.7 fb^{-1} at $\sqrt{s}$ = 8 TeV
1σ
2σ
3σ
p-value
M$_G$ [GeV]


CMS, L = 19.7 fb^{-1}, $\sqrt{s}$ = 8 TeV
Observed
Expected (68%)
Expected (95%)
W' → WZ
$\sigma \times$ B(W' → WZ) (pb)
1
10^{-1}
10^{-2}
10^{-3}
1
1.5
2
2.5
3
Resonance mass (TeV)



CMS, L = 19.7 fb^{-1}, $\sqrt{s}$ = 8 TeV
Observed
Expected (68%)
Expected (95%)
$G_{RS} \rightarrow WW$ ($k/\overline{M}_{Pl}$ = 0.1)
$\sigma \times B(G_{RS} \rightarrow WW)$ (pb)
Resonance mass (TeV)
CMS, L = 19.7 fb^{-1}, $\sqrt{s}$ = 8 TeV
Observed
Expected (68%)
Expected (95%)
$G_{RS} \rightarrow ZZ$ ($k/\overline{M}_{Pl}$ = 0.1)
$\sigma \times B(G_{RS} \rightarrow ZZ)$ (pb)
Resonance mass (TeV)

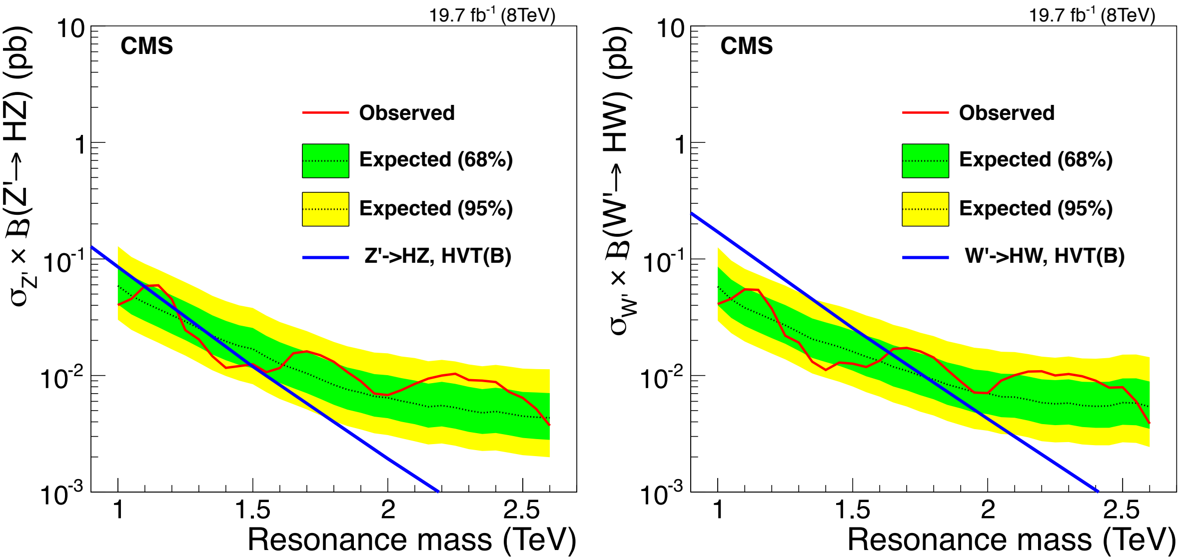
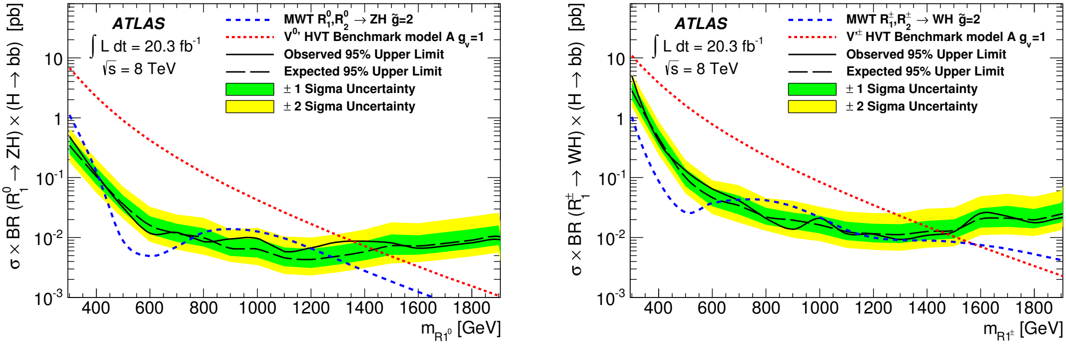
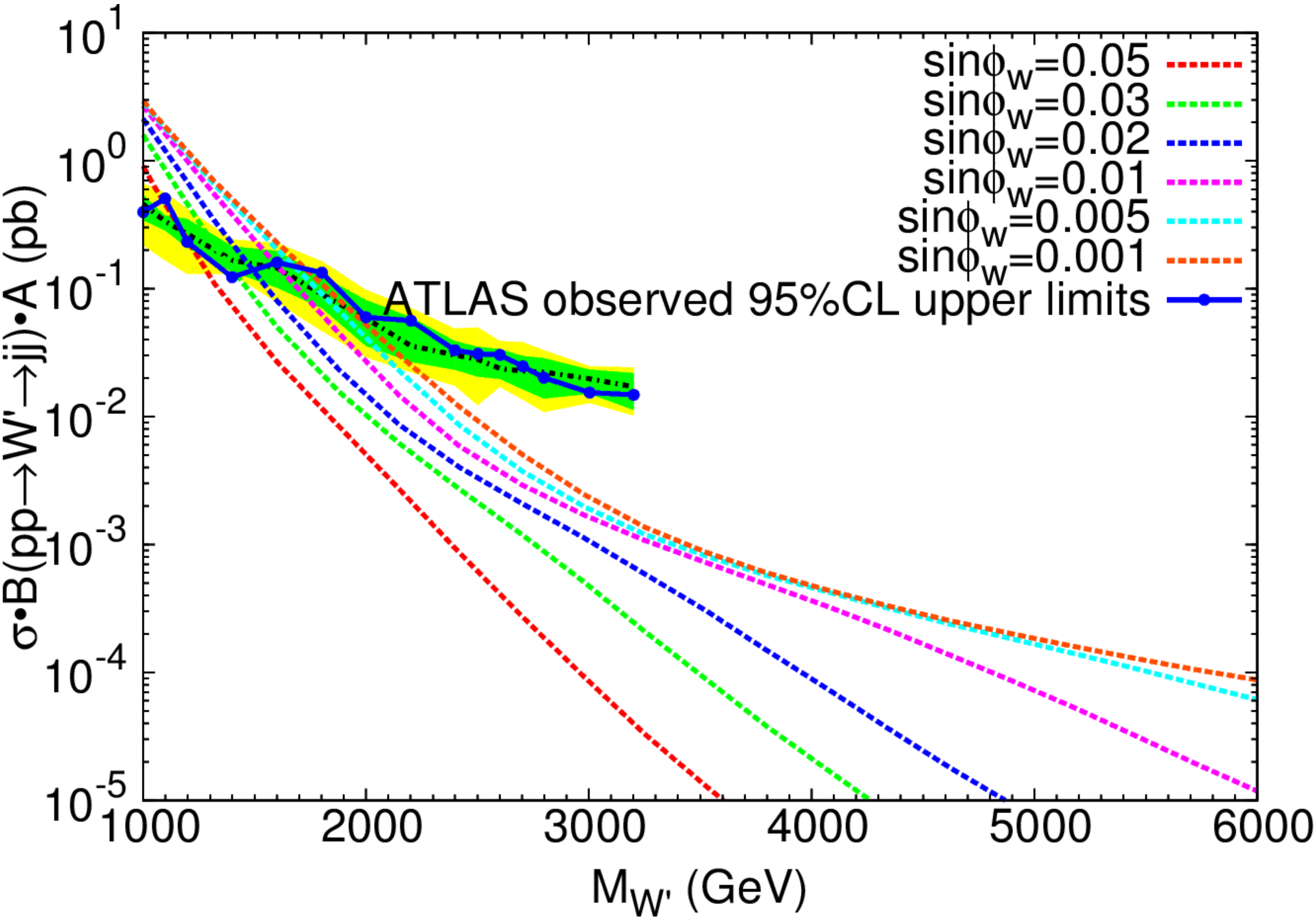


Figure 9: Expected and observed upper limits on the production cross sections for $Z' \to HZ$ (left) and $W' \to HW$ (right), including all five decay categories. Branching fractions of H and V decays have been taken into account. The theoretical predictions of the HVT model scenario

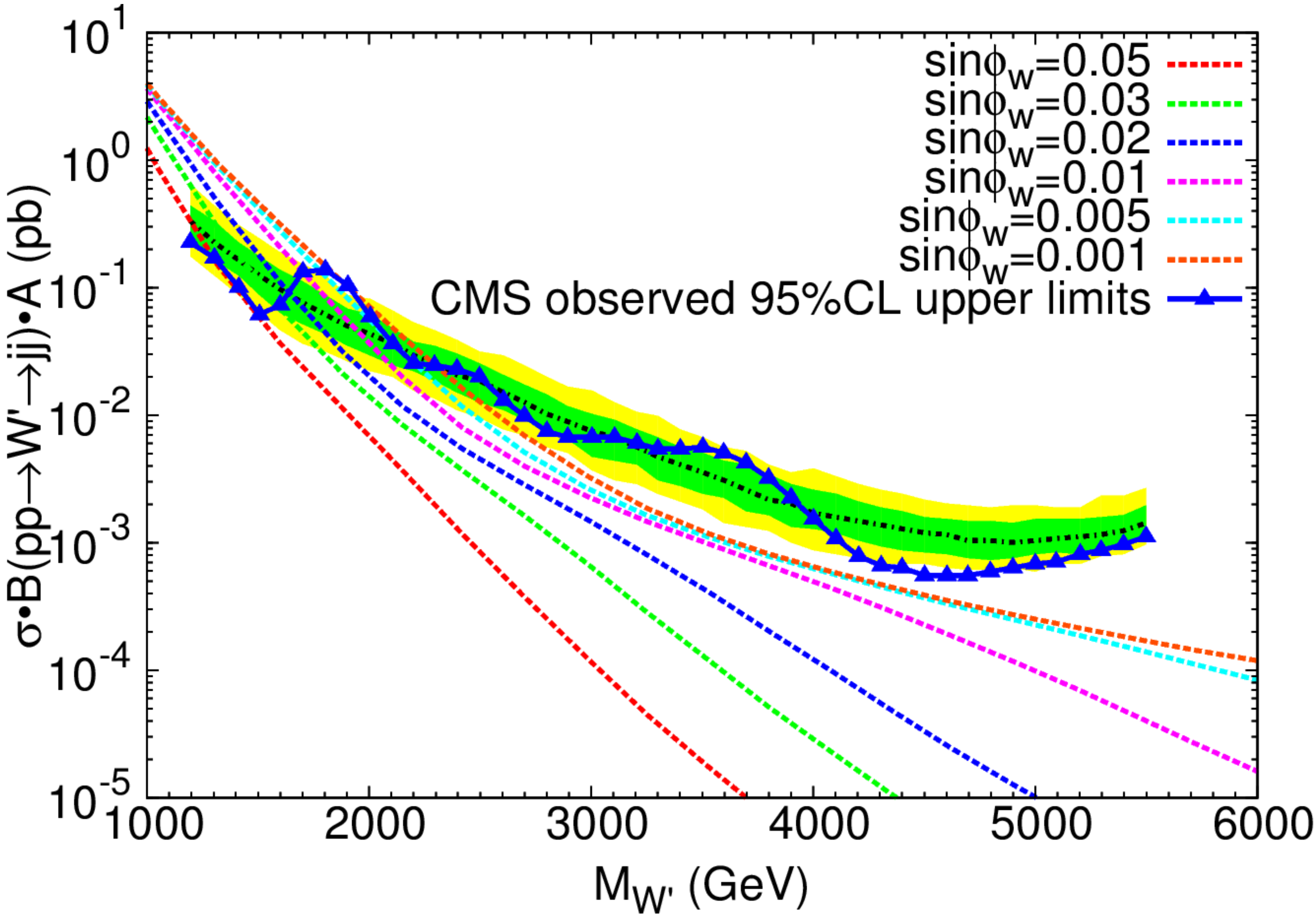


(a) $R_1^0(V'^0) \to ZH$, $H \to b\bar{b}$

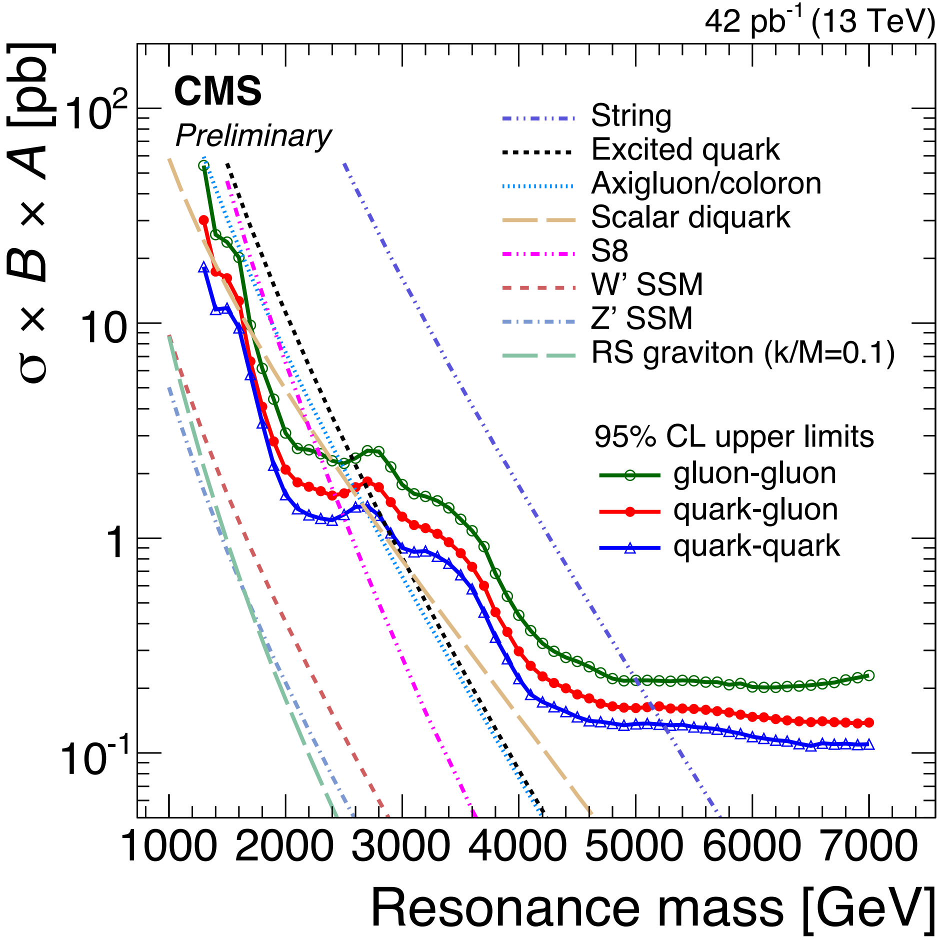
(b) $R_1^\pm(V'^\pm) \to WH$, $H \to b\bar{b}$



sinφw=0.05
sinφw=0.03
sinφw=0.02
sinφw=0.01
sinφw=0.005
sinφw=0.001
ATLAS observed 95%CL upper limits
σ•B(pp→W'→jj)•A (pb)
M_W' (GeV)
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
1000
2000
3000
4000
5000
6000



sinφw=0.05
sinφw=0.03
sinφw=0.02
sinφw=0.01
sinφw=0.005
sinφw=0.001
CMS observed 95%CL upper limits
σ•B(pp→W'→jj)•A (pb)
M_W' (GeV)
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
1000
2000
3000
4000
5000
6000



42 pb^{-1} (13 TeV)
CMS
Preliminary
String
Excited quark
Axigluon/coloron
Scalar diquark
S8
W' SSM
Z' SSM
RS graviton (k/M=0.1)
95% CL upper limits
gluon-gluon
quark-gluon
quark-quark
$\sigma \times B \times A$ [pb]
10^2
10
1
10^{-1}
1000
2000
3000
4000
5000
6000
7000
Resonance mass [GeV]

A short summary of data

- ATLAS $WZ \to JJ$ channel showed a deviation larger than 3σ, but after combining with leptonic and semileptonic channels the deviation reduces to about 2.4σ.
- ATLAS $WW, ZZ \to$ all also reduces to less than 2σ.
- There may be something we do not fully understand the boosted jets of W, Z bosons. Or there may be other exotic particles with similar mass decaying into dijets only.
- The CMS saw something but not as significant in all channels.
- It is a narrow resonance.

A brief summary of possible interpretations

- The baseline is one or more resonance(s) at around 2 TeV that decay into WW, ZZ, and/or WZ.
- A spin-0 resonance - Higgs-like particles. Require a very large Yukawa coupling for the first generation, or many colored scalars running in the loop.
- A spin-1 gauge boson, typically a W' and Z' of some higher symmetry groups, or technirhos from Technicolor theories.
- A spin-2 heavy graviton, e.g., the Randall-Sundrum graviton, but the cross section is not large enough.

Outlines

1. Some existing constraints on W', Z' models
2. $W' \to WZ$
3. $Z' \to WW$
4. A unified model

Existing constraints

- Electroweak precision measurements: W, W' mixing, Z, Z' mixing.
- Leptonic decays of W' and Z'.
- Dijet production, e.g., $\sigma(pp \to W') \times B(W' \to jj)$.
- WH and ZH production that are specific to this work.

W and W' mixing

Limit on W_L-W_R Mixing Angle ζ

Lighter mass eigenstate $W_1 = W_L \cos\zeta - W_R \sin\zeta$. Light ν_R assumed unless noted.
Values in brackets are from cosmological and astrophysical considerations.

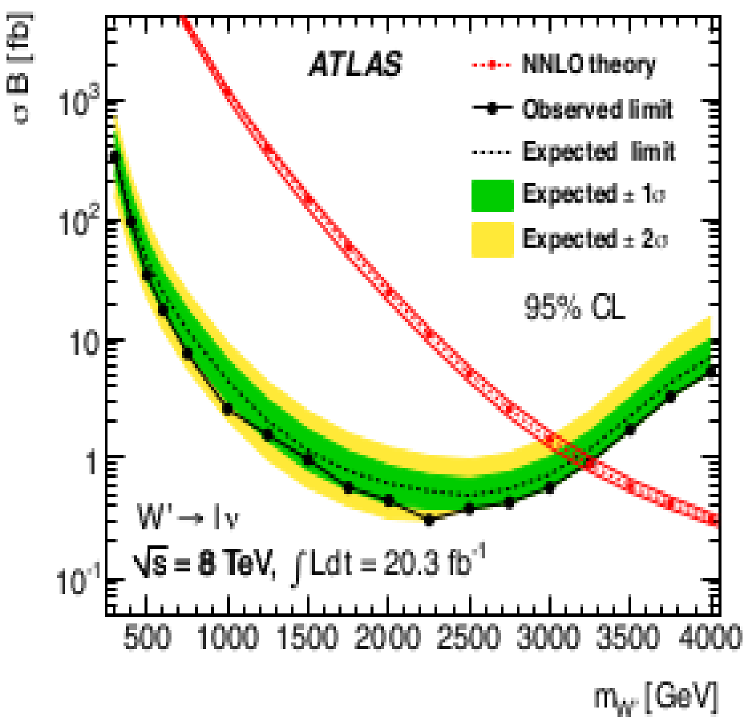
VALUE	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
-0.020 to 0.017	90	BUENO	11	TWST	$\mu \to e\nu\overline{\nu}$
$<$ 0.022	90	MACDONALD	08	TWST	$\mu \to e\nu\overline{\nu}$
$<$ 0.12	95	[1] ACKERSTAFF	99D	OPAL	τ decay
$<$ 0.013	90	[2] CZAKON	99	RVUE	Electroweak
$<$ 0.0333		[3] BARENBOIM	97	RVUE	μ decay
$<$ 0.04	90	[4] MISHRA	92	CCFR	νN scattering
-0.0006 to 0.0028	90	[5] AQUINO	91	RVUE	
[none 0.00001–0.02]		[6] BARBIERI	89B	ASTR	SN 1987A
$<$ 0.040	90	[7] JODIDIO	86	ELEC	μ decay
-0.056 to 0.040	90	[7] JODIDIO	86	ELEC	μ decay

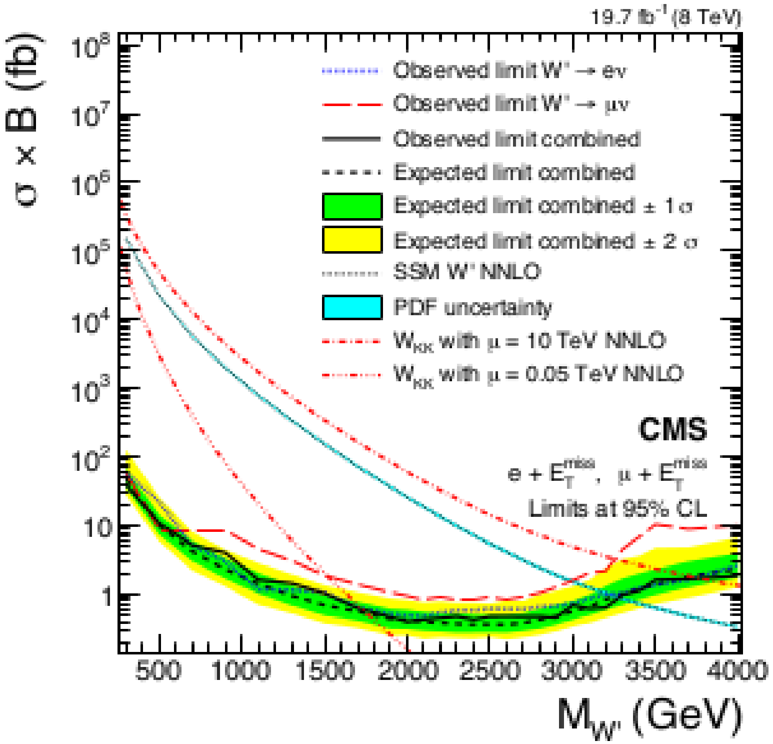
Z and Z' mixing

Z'	$M_{Z'}$ [GeV]				$\sin\theta_{ZZ'}$			$\chi^2_{\min}$
	EW (this work)	CDF	DØ	LEP 2	$\sin\theta_{ZZ'}$	$\sin\theta^{\min}_{ZZ'}$	$\sin\theta^{\max}_{ZZ'}$	
Z_χ	1,141	892	640	673	−0.0004	−0.0016	0.0006	47.3
Z_ψ	147	878	650	481	−0.0005	−0.0018	0.0009	46.5
Z_η	427	982	680	434	−0.0015	−0.0047	0.0021	47.7
Z_I	1,204	789	575		0.0003	−0.0005	0.0012	47.4
Z_S	1,257	821			−0.0003	−0.0013	0.0005	47.3
Z_N	623	861			−0.0004	−0.0015	0.0007	47.4
Z_R	442				−0.0003	−0.0015	0.0009	46.1
Z_{LR}	998	630		804	−0.0004	−0.0013	0.0006	47.3
$Z_{\not{L}}$	(803)	(740)			−0.0015	−0.0094	0.0081	47.7
Z_{SM}	1,403	1,030	780	1,787	−0.0008	−0.0026	0.0006	47.2
Z_{string}	1,362				0.0002	−0.0005	0.0009	47.7
SM	∞				0			48.5

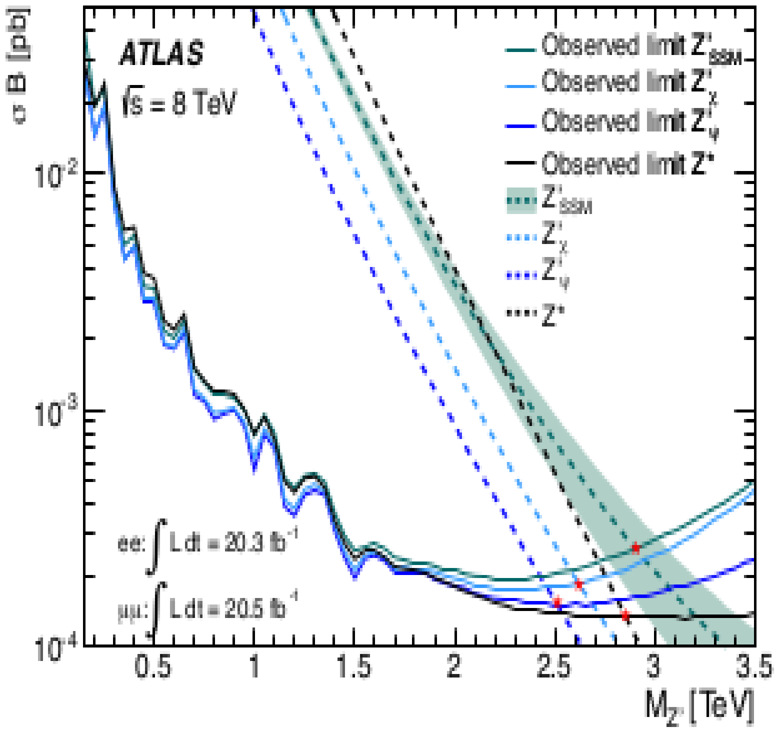
0906.2435

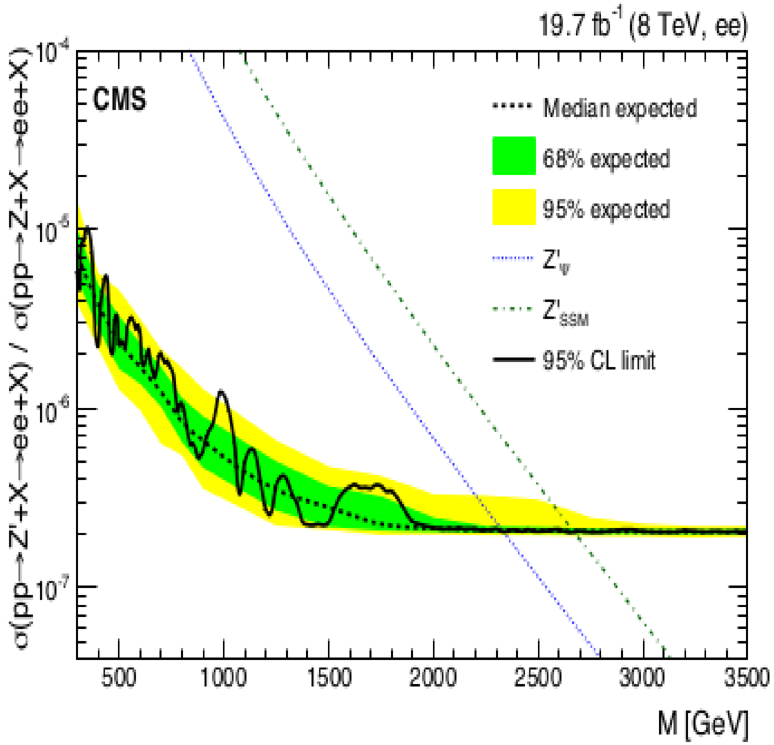
Leptonic W' constraint





Leptonic Z' constraint





Constraint from WH, ZH production

- Due to Equivalence theorem:

$$\Gamma(W'^+ \to W^+ Z) \approx \Gamma(W'^+ \to W^+ H)$$

$$\Gamma(Z' \to W^+ W^-) \approx \Gamma(Z' \to ZH)$$

to LO in $1/M_{W'}^2$.

- The mixing angle ϕ_w between W and W' comes from the off-diagonal mass matrix entry, which also gives the tree-level unsuppressed coupling for W'-W-H.

Leptophobic Z', W' model

- The required mixing angle to explain the anomaly is $10^{-3} - 10^{-2}$. So the usual Z' models cannot work. We need the leptophobic version.

$$\sin\phi_z < 8 \times 10^{-3}$$

- We assume the right-handed neutrinos are heavy enough that

$$W'^{+} \not\to e^{+}\nu_R$$

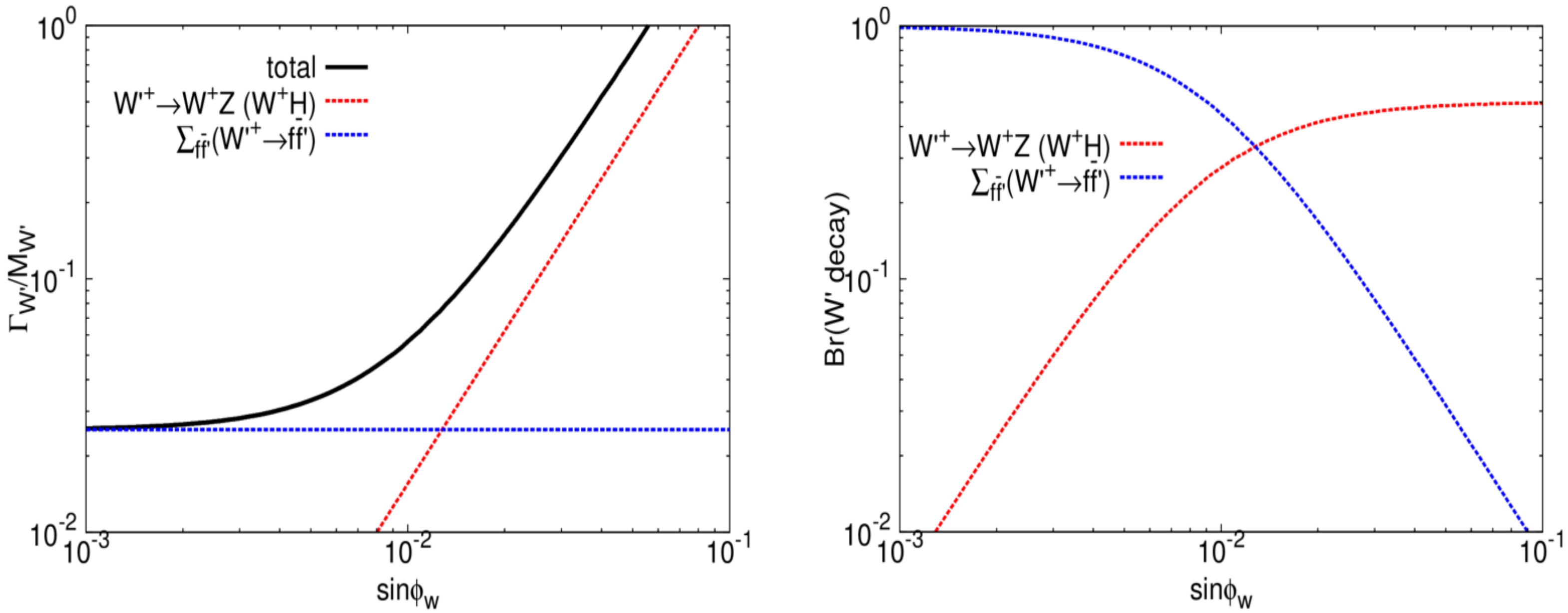
The W' Model

- The extra W_2 arises from $SU(2)_R$. The RH fermions are arranged as $(u_R,\, d_R)^T \quad \nu_R, \quad e_R$.
- W_1 and W_2 mix:

$$\begin{pmatrix} W_1 \\ W_2 \end{pmatrix} = \begin{pmatrix} \cos\phi_w & -\sin\phi_w \\ \sin\phi_w & \cos\phi_w \end{pmatrix} \begin{pmatrix} W \\ W' \end{pmatrix} .$$

- Vertices:

$$\begin{aligned}
\mathcal{V}_{W' f f'} \quad &: \quad -\frac{g_R}{\sqrt{2}} \bar{f}' \gamma^\mu P_R f \, \epsilon_\mu(p_{W'+}) \quad , \\
\mathcal{V}_{W' W Z} \quad &: \quad +g \cos\theta_w \sin\phi_w \left[(p_{W'+} - p_{W-})^\beta g^{\mu\alpha} + (p_{W-} - p_Z)^\mu g^{\alpha\beta} + (p_Z - p_{W'+})^\alpha g^{\mu\beta} \right] \\
&\quad\ \times \epsilon_\mu(p_{W'+}) \, \epsilon_\alpha(p_{W-}) \, \epsilon_\beta(p_Z) \quad , \\
\mathcal{V}_{W' W H} \quad &: \quad +g M_W \sin\phi_w \left(\cos^2\theta_w \frac{M^2_{W'}}{M^2_W} \right) g^{\mu\alpha} \, \epsilon_\mu(p_{W'+}) \, \epsilon_\alpha(p_{W-}) \quad ,
\end{aligned}$$



We require $\Gamma_{W'}/M_{W'} < 0.1$, thus $\sin\phi_w \lesssim 1.5 \times 10^{-2}$.

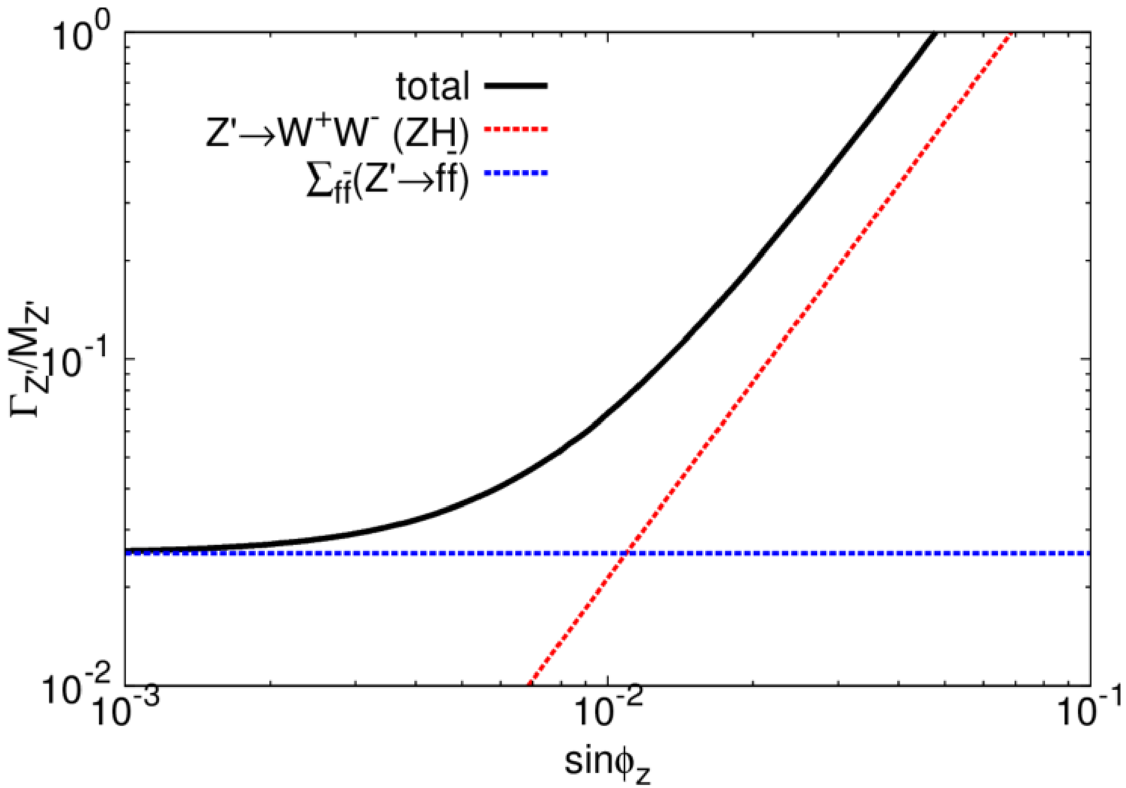
The Z' Model

- $$\begin{aligned}
\mathcal{V}_{Z'ff} &: \quad -\bar{f}\gamma^{\mu}(g_{f,r}P_R + g_{f,l}P_L)f\,\epsilon_{\mu}(p_{Z'}) \quad , \\
\mathcal{V}_{Z'WW} &: \quad +g\cos\theta_w \sin\phi_z \left[(p_{Z'} - p_{W+})^{\beta} g^{\mu\alpha} + (p_{W+} - p_{W-})^{\mu} g^{\alpha\beta} + (p_{W-} - p_{Z'})^{\alpha} g^{\mu\beta}\right] \\
& \quad\quad \times \epsilon_{\mu}(p_{Z'})\,\epsilon_{\alpha}(p_{W+})\,\epsilon_{\beta}(p_{W-}) \quad , \\
\mathcal{V}_{Z'ZH} &: \quad +\frac{g}{\cos\theta_w} M_Z \sin\phi_z \left(\frac{M_{Z'}^2}{M_Z^2}\right) g^{\mu\alpha}\,\epsilon_{\mu}(p_{Z'})\,\epsilon_{\alpha}(p_Z) \quad .
\end{aligned}$$

- We set

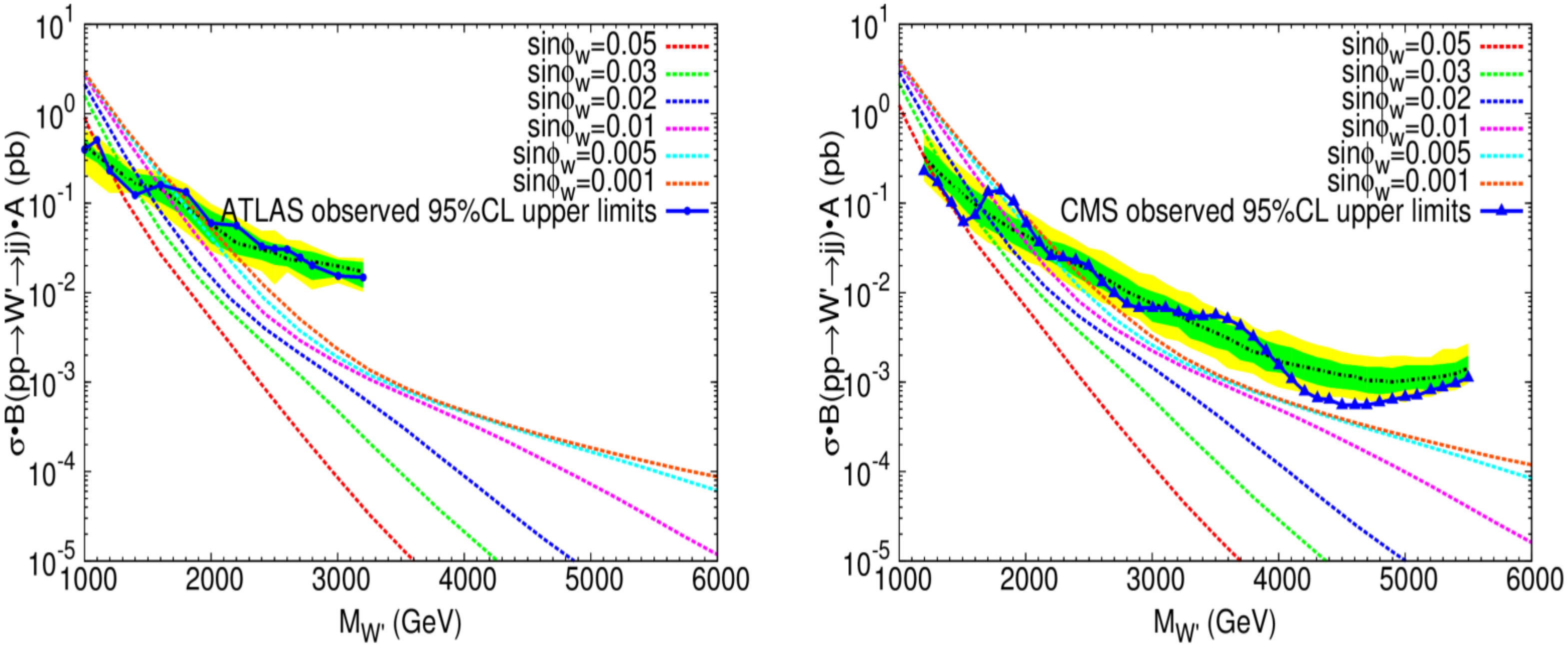
$$g_{f,l} = 0, g_{f,r} = g_R T_{3,f}^{(2)}$$

for leptophobic and only right-handed current $T_3^{(2)}$.



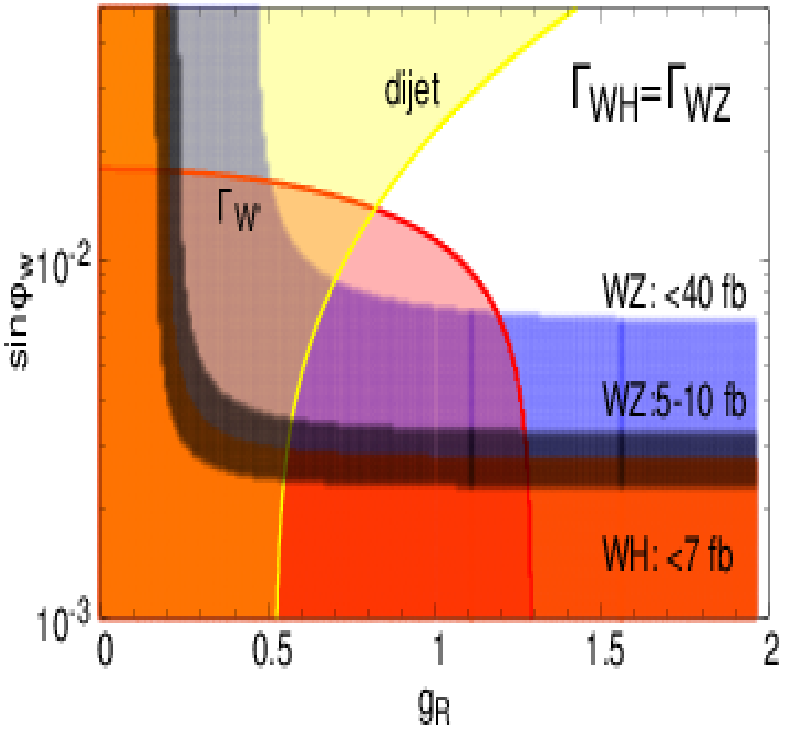
We require $\Gamma_{Z'}/M_{Z'} < 0.1$, thus $\sin\phi_z \lesssim 1.5 \times 10^{-2}$. The Z-Z' mixing needs to be $\lesssim 8 \times 10^{-3}$.

Dijet Constraint



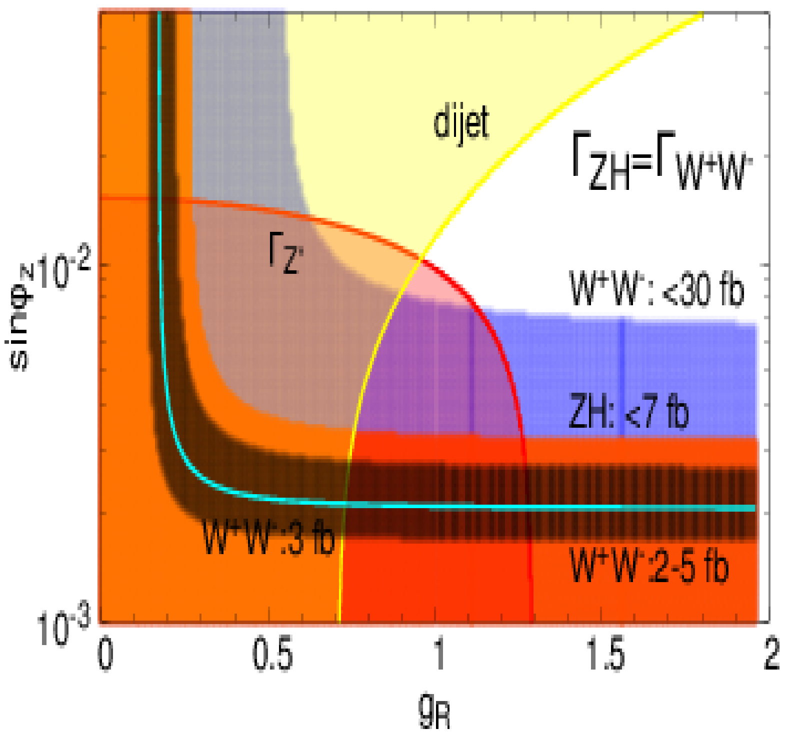
Combined Constraints on W'

1. $\Gamma_{W'}/M_{W'} < 0.1$,
2. $\sigma(W') \times B(W' \to jj) \cdot A < 60$ fb
3. $\sigma(W') \times B(W' \to WZ) < 40$ fb
4. $\sigma(W') \times B(W' \to WH) < 7$ fb



Combined Constraints on Z'

1. $\Gamma_{Z'}/M_{Z'} < 0.1$,
2. $\sigma(Z') \times B(Z' \to jj) \cdot A < 60$ fb
3. $\sigma(Z') \times B(Z' \to W^+W^-) < 30$ fb
4. $\sigma(Z') \times B(Z' \to ZH) < 7$ fb
5. $\sigma(Z') \times B(Z' \to W^+W^-) < 3$ fb



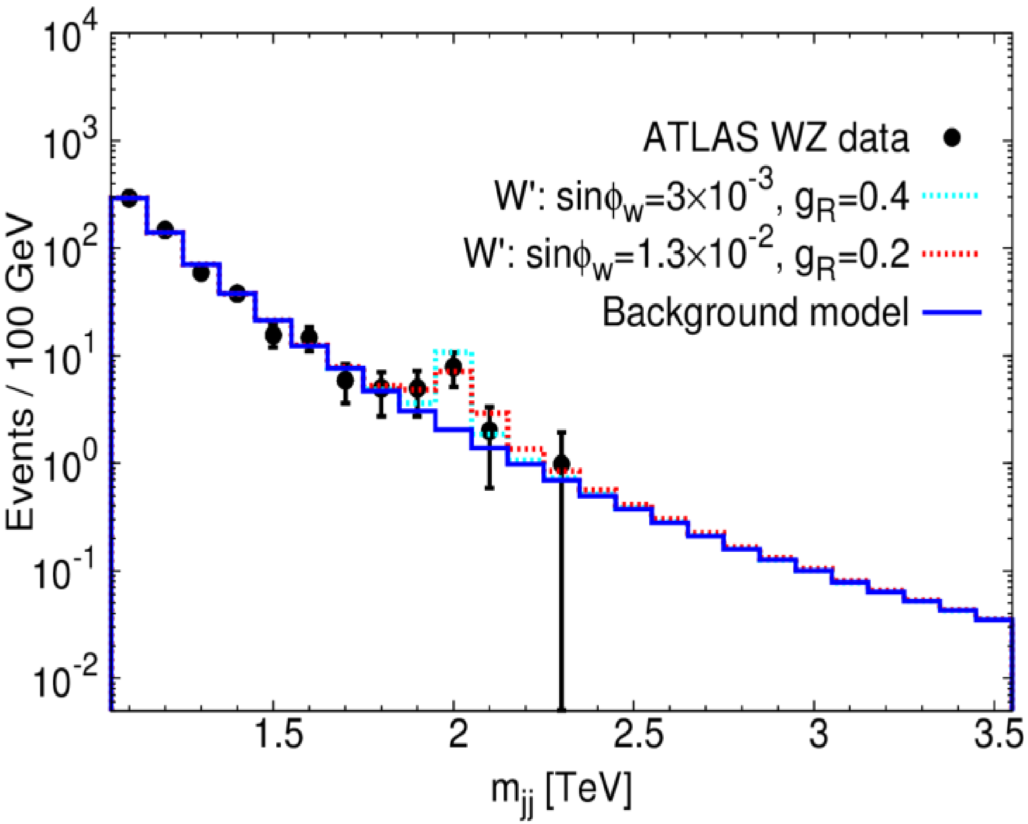
To fit to the WZ Bump

WZ

- Excess events: 8–9
- Convert to

  $\sigma(W').B(W' \to WZ) \approx 6{-}7$

- $\sin\phi_w = 3 \times 10^{-3}$, $g_R = 0.4$
- $\sin\phi_w = 1.3 \times 10^{-2}$, $g_R = 0.2$



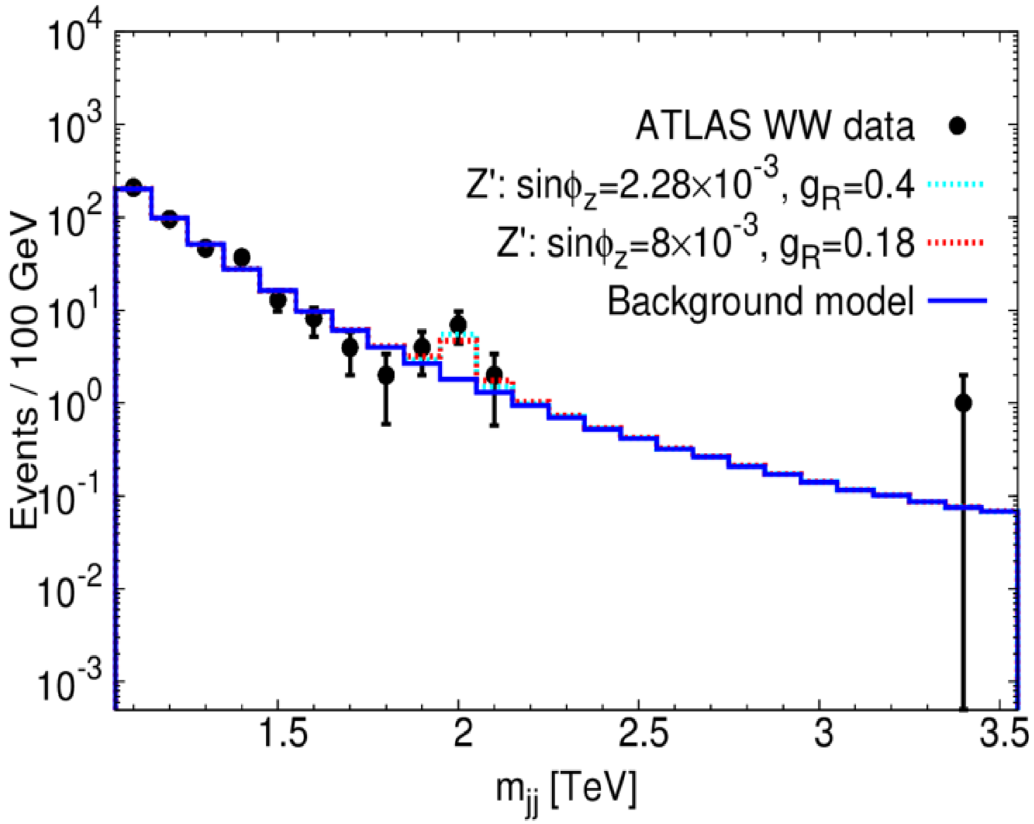
To fit to the WW Bump

WW

- Excess events: 7–8
- Convert to

  $\sigma(W').B(W' \to WZ) \approx 5\text{–}6$

  But restrict it < 3 fb.
- $\sin\phi_w = 2.28 \times 10^{-3}$, $g_R = 0.4$
- $\sin\phi_w = 8 \times 10^{-3}$, $g_R = 0.18$



A unified $SU(2)_1 \times SU(2)_2 \times U(1)_X$ model

- Symmetry breaking pattern:

$$SU(2)_1 \times SU(2)_2 \times U(1)_X \xrightarrow{TeV} SU(2)_L \times U(1)_Y \xrightarrow{EW} U(1)_{\rm em}$$

- The SM hypercharge convention is fixed by

$$Q = T_3^{(1)} + \frac{Y}{2} = T_3^{(1)} + T_3^{(2)} + \frac{Y_X}{2}$$

- Note $(u_R, d_R)^T$, ν_R, e_R:

f	u_R	d_R	ν_R	e_R
$T_3^{(2)}$	$+\frac{1}{2}$	$-\frac{1}{2}$	0	0
$\frac{Y_X}{2}$	$+\frac{1}{6}$	$+\frac{1}{6}$	0	-1

- The first step of symmetry breaking at TeV scale can occur via a

Higgs doublet Φ:

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}, \qquad \langle \Phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ u \end{pmatrix} .$$

- The gauge field B'_μ of the $U(1)_X$ and the W'^3_μ of the $SU(2)_2$ are rotated by angle ϕ into the B_μ of the $U(1)_Y$ and the Z' boson:

$$\begin{pmatrix} B'_\mu \\ W'^3_\mu \end{pmatrix} = \begin{pmatrix} \cos\phi & -\sin\phi \\ \sin\phi & \cos\phi \end{pmatrix} \begin{pmatrix} B_\mu \\ Z'_\mu \end{pmatrix} .$$

- We require for B_μ the same as the SM hypercharge boson:

$$g_X \cos\phi = g_1 , \quad g'_2 \sin\phi = g_1 , \quad \tan\phi = \frac{g_X}{g'_2} , \quad \frac{Y_X}{2} + T_3^{(2)} = \frac{Y}{2} .$$

- The W' and Z' boson masses are

$$M^2_{W'} = \frac{e^2 v^2}{4\cos^2\theta_w \sin^2\phi} (x+1), \quad M^2_{Z'} = \frac{e^2 v^2}{4\cos^2\theta_w \sin^2\phi \cos^2\phi} (x+\cos^4\phi),$$

where $x \equiv u^2/v^2$ is very large. If $\cos\phi \approx 1$, the $M_{Z'} \approx M_{W'}$

- In limit x large: the LH and RH couplings of the W' becomes

$$\frac{g_L^{W'ff'}}{g_R^{W'ff'}} \longrightarrow \frac{1}{x}\,, \quad \text{with } g_R^{W'ff'} = \frac{g_2'}{\sqrt{2}}\,,$$

- In limit x large and $\sin\phi$ small:

$$\begin{aligned} g_{f,l} &\longrightarrow \frac{g_2'}{\cos\phi}(T_3^{(1)} - Q)\,\sin^2\phi \approx 0 \\ g_{f=\ell,r} &\longrightarrow \frac{g_2'}{\cos\phi}(-Q\sin^2\phi) \approx 0 \\ g_{f=q,r} &\longrightarrow \frac{g_2'}{\cos\phi}(T_3^{(2)} - Q\sin^2\phi) \approx g_2' T_3^{(2)} \end{aligned}$$

Conclusions

1. The ATLAS diboson anomaly in WZ is amore than 3σ in the JJ channel. However, if the leptonic and semileptonic channels are included, the sigma level reduces.

2. Thw $W' \to WZ$ and $Z' \to WW$ can explain the WZ and WW bumps, but the ZZ is very difficult. Spin 1 cannot go into ZZ.

3. Spin 0 that decays into WW and ZZ is hard to a narrow width.

4. Spin 2 graviton does not have enough cross sections.

5. The strongest constraint on Z' is the mixing. The $\sin\phi_z \lesssim 10^{-3}$ for a general Z' model. For leptophobic one, $\sin\phi_z \lesssim 8 \times 10^{-3}$.

6. Afterall, we can still find a sweet spot in the parameter space to fit to the $W' \to WZ$ bump and $Z' \to WW$ bump.