Spin-1 particle and the ATLAS Diboson excess

Tomohiro Abe (KEK)

based on the works

1507.01185: **TA, Ryo Nagai, Shohei Okawa, Masaharu Tanabashi**

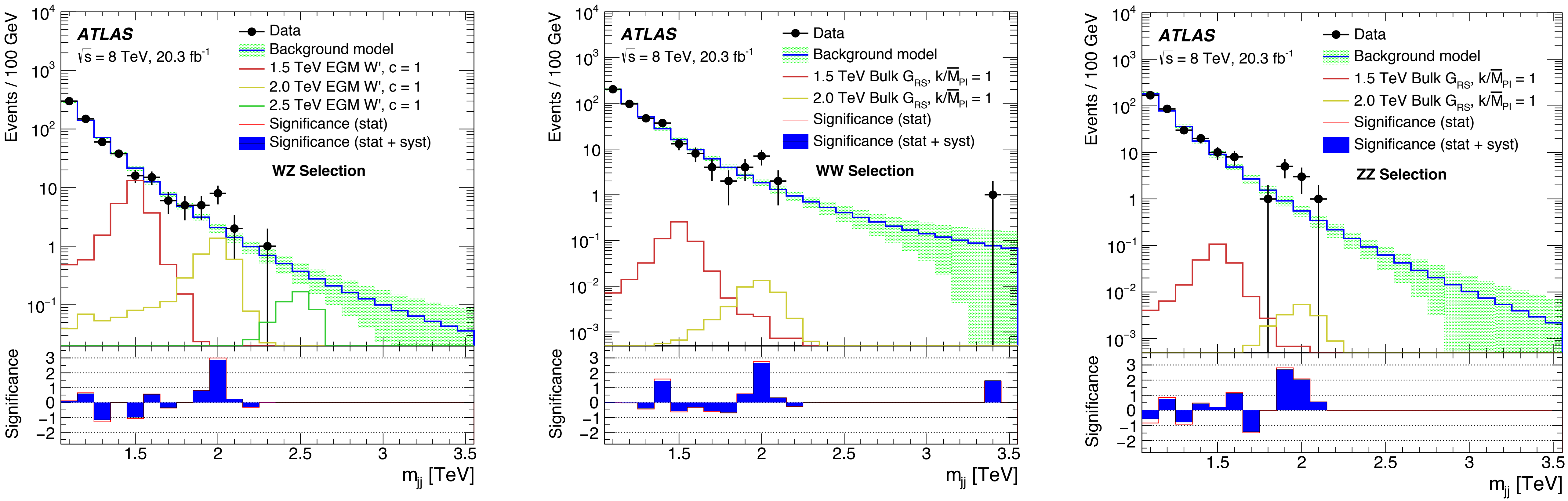
1507.01681: **TA, Teppei Kitahara, Mihoko Nojiri**

seminar at ICRR

2015.8.6

ATLAS diboson excess

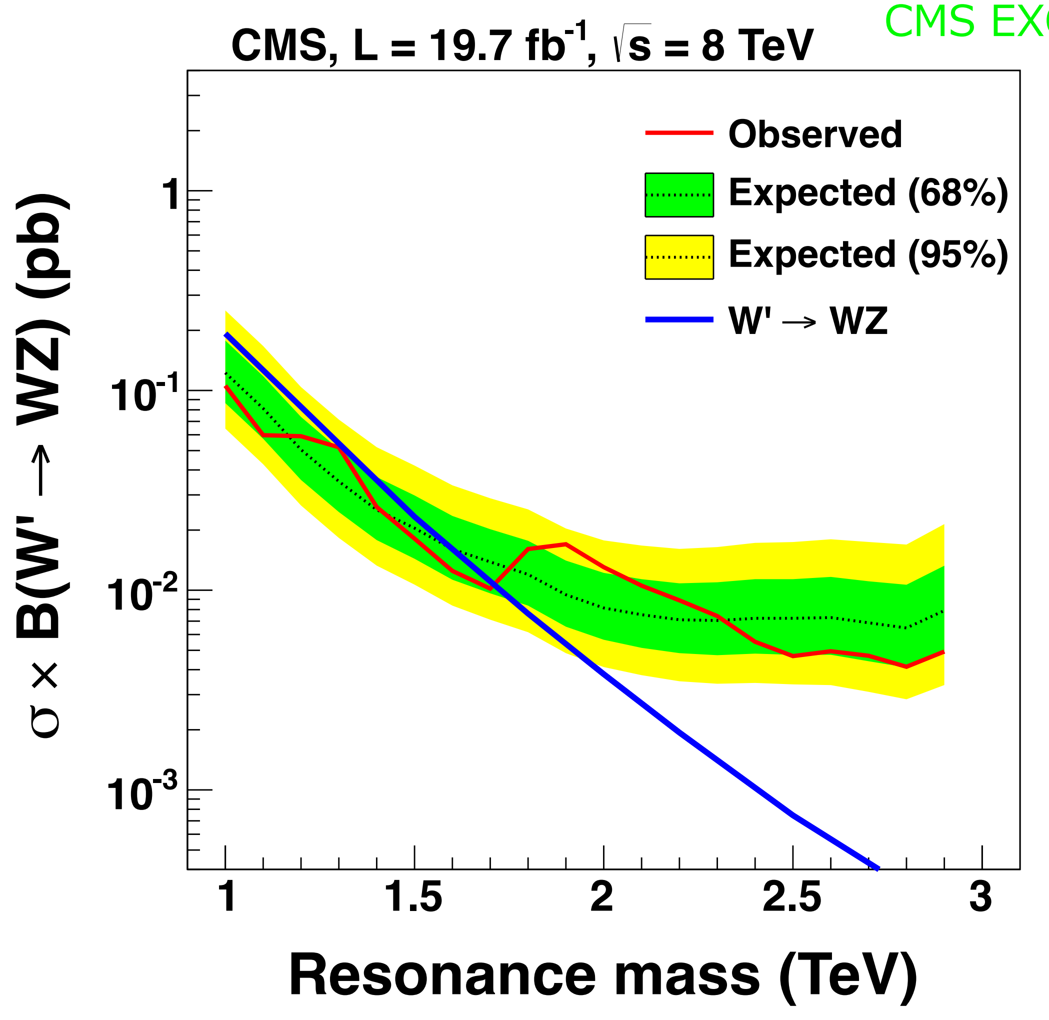
ATLAS EXOT-2013-008



- **pp → X → WZ/WW/ZZ → two fat jets**
  - ★ mass of X ~ 2TeV ?
  - ★ local significance: WZ 3.4σ, WW 2.6σ, ZZ 2.9σ
  - ★ global significance: WZ 2.5σ

Same process in CMS

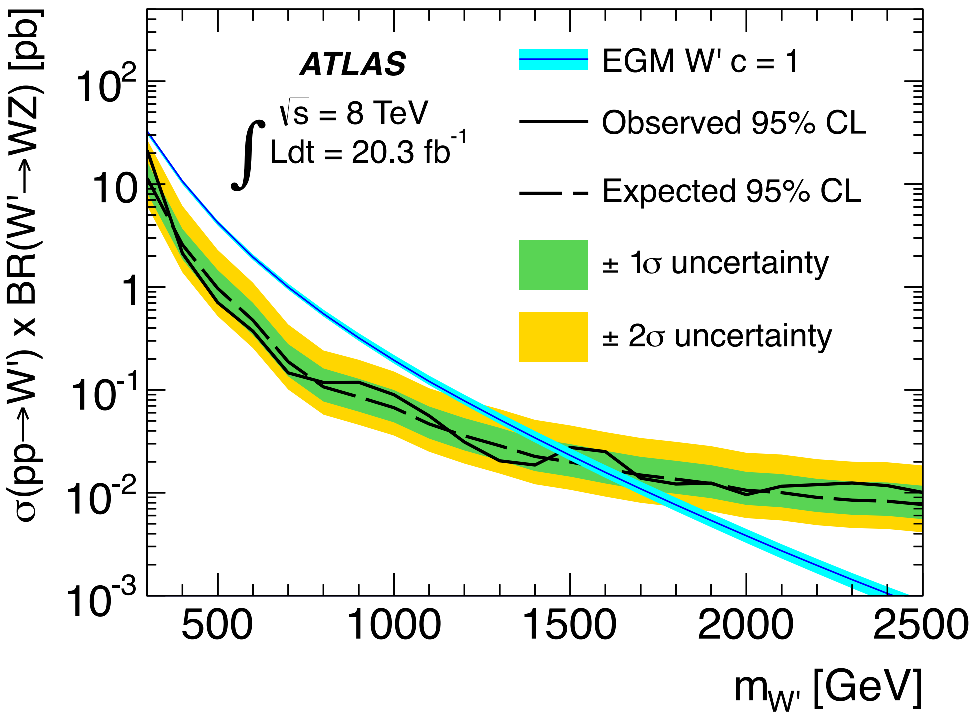
CMS EXO-12-024



Other final states from diboson

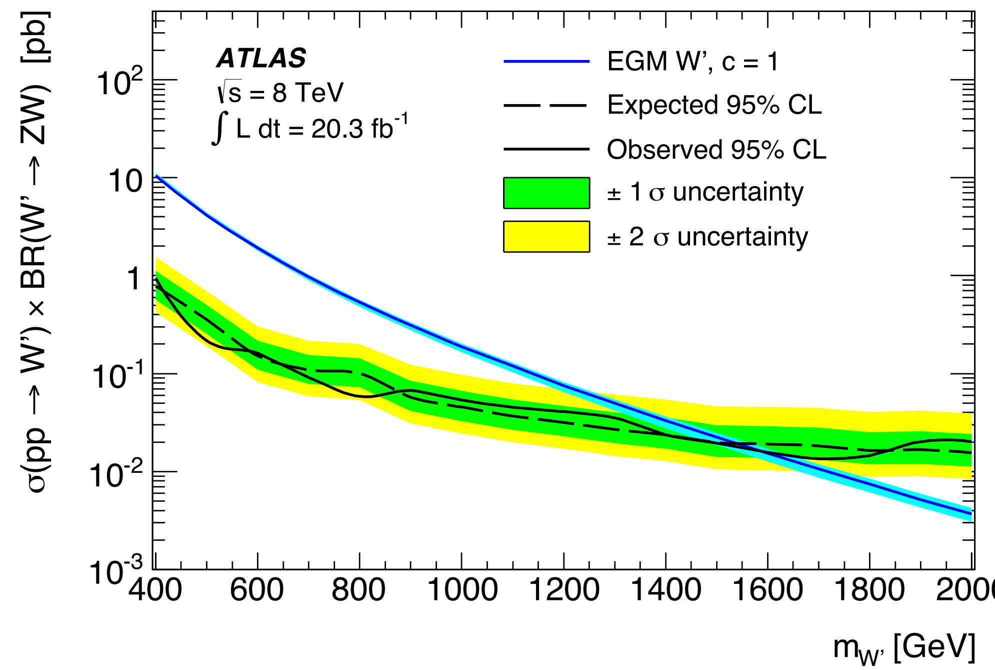
ATLAS EXOT-2013-001

ATLAS(WZ →lv + jets)



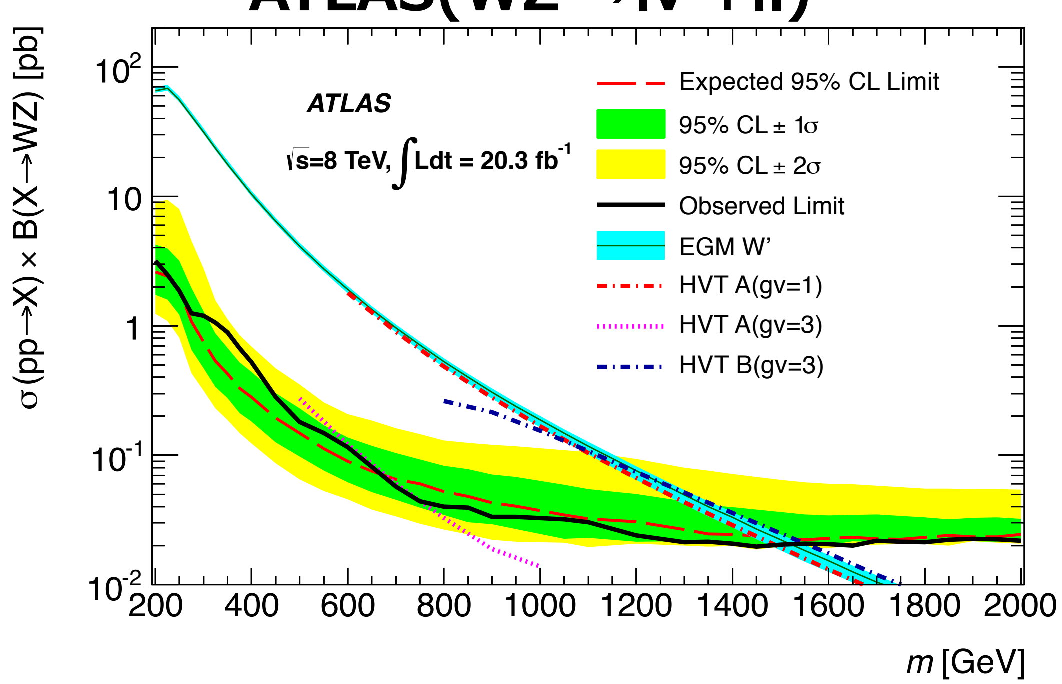
ATLAS EXOT-2013-006

ATLAS(WZ → jets + leptons)



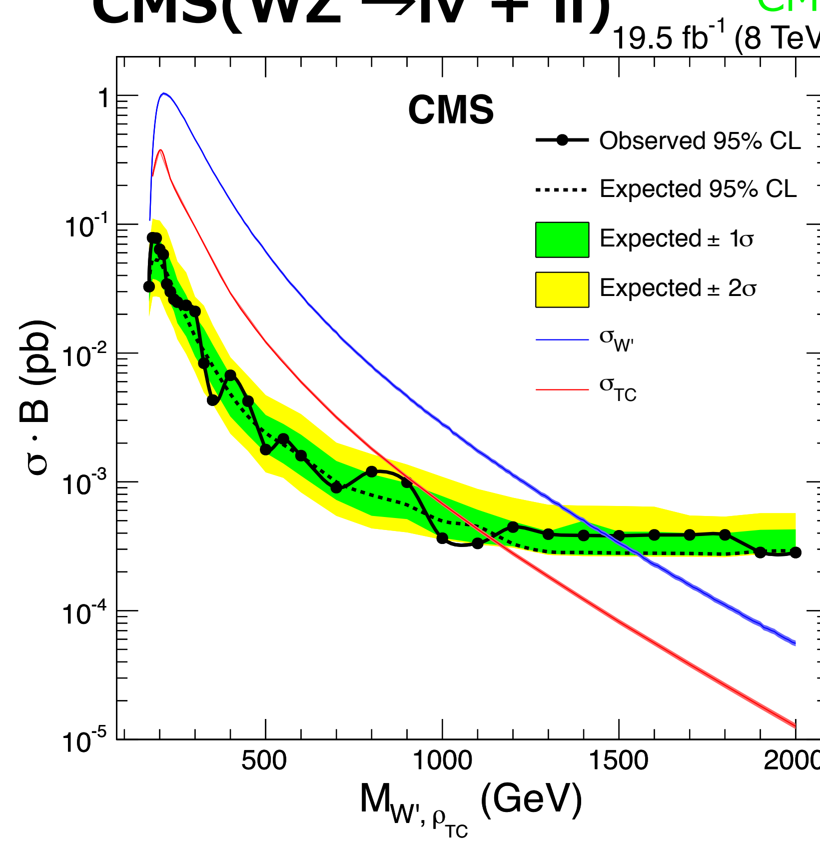
ATLAS EXOT-2013-007

ATLAS(WZ →lv +ll)



CMS(WZ →lv + ll)

CMS EXO-12-025



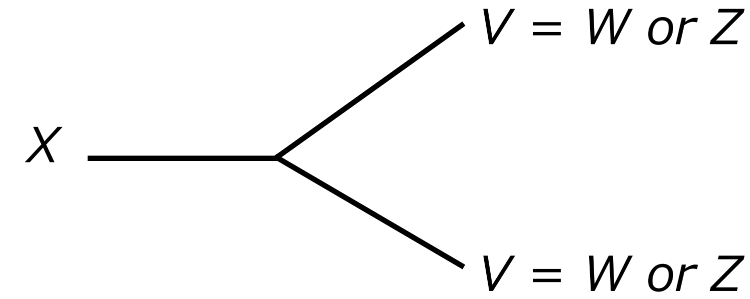
Situation of diboson in each channel

final states	ATLAS	CMS
only jets	excess	no excess
with leptons	no excess	no excess

- **Excess is only in pp → VV → jets at the ATLAS**
  - ⋆ logal: WZ 3.4σ, WW 2.6σ, ZZ 2.9σ
  - ⋆ global: WZ 2.5σ
- **Excess might be statistical fluctuation**
- **But it is good exercise to consider what kind of BSM can explain the excess**

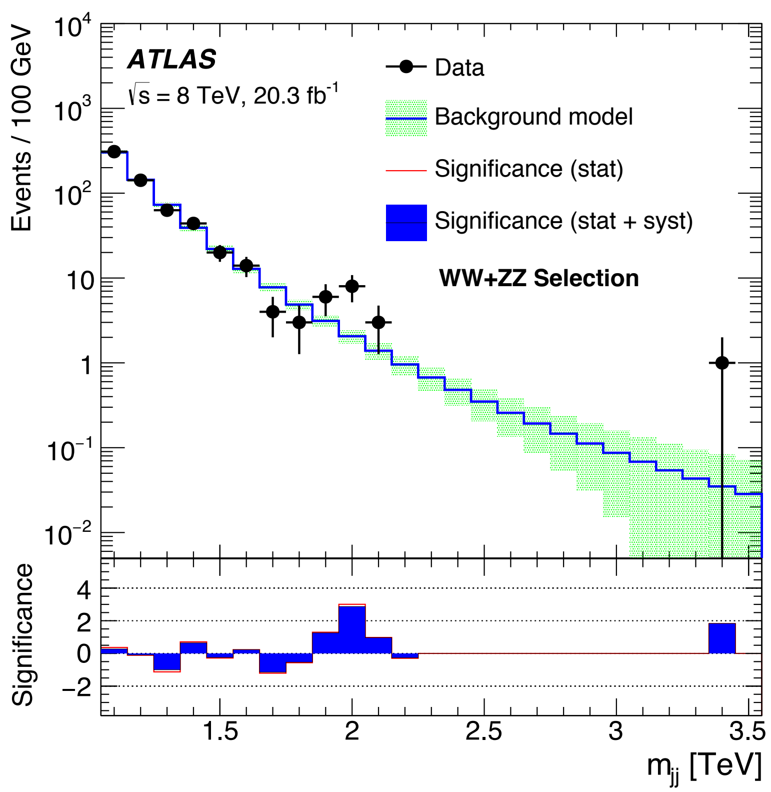
What we know about the excess

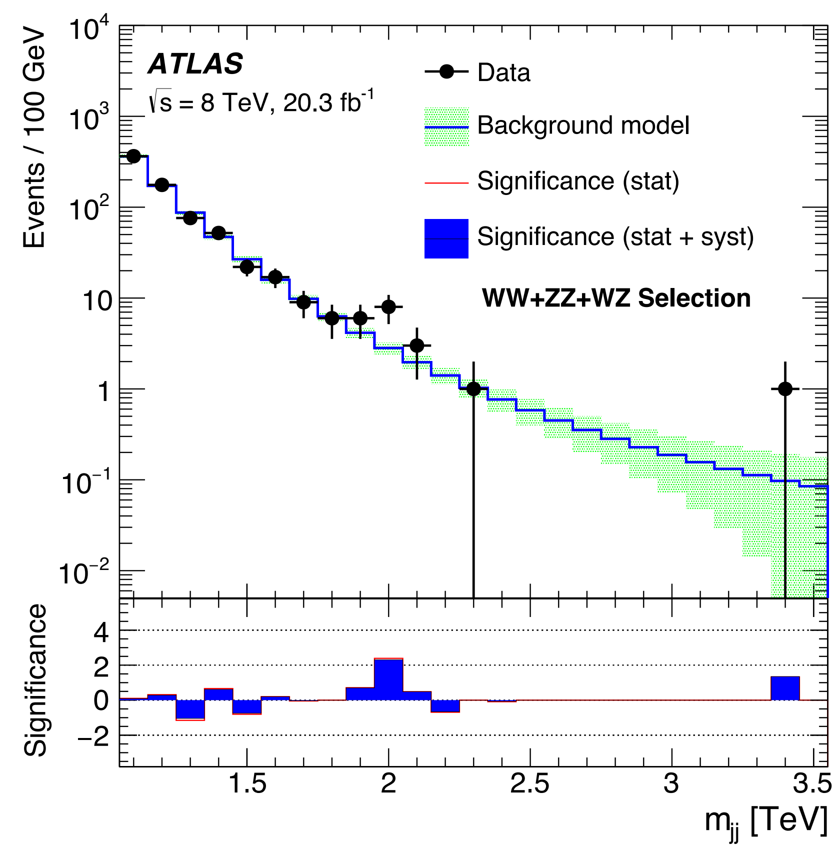
- **New particles (*X*) is a boson**
  - ★ It decays into *WZ/WW/ZZ*



- **WZ/WW/ZZ are not good separation**
  - ★ $|m_j - m_V| < 13\text{GeV}$
  - ★ one or two channels are enough to be explained

ATLAS EXOT-2013-008





Works in market (more than 30 papers)

- **Spin 0 ($S \to WW$, $S \to ZZ$)**

  1507.02483, 1507.03553, 1507.04431, 1507.05028, 1507.05310, 1507.06312

- **Spin 1 ($W' \to WZ$, $Z' \to WW$)**

  1506.03751, 1506.03931, 1506.04392, 1506.05994, 1506.06064, 1506.06736, 1506.06767, 1506.07511, 1506.08688, 1507.00013, 1507.00268, 1507.00900, 1507.01185, 1507.01638, 1507.01681, 1507.01914, 1507.01914, 1507.01923, 1507.02483, 1507.03098, 1507.03428, 1507.03553, 1507.03940, 1507.04431, 1507.05028, 1507.05299, 1507.05310, 1507.06018, 1507.06312, 1507.07102, 1507.07406, 1507.07557, 1507.08273, 1508.00174

- **Spin 2**

  1507.03553, 1507.06312

- **others (tri-boson can mimic diboson signal)**

  1506.06739

In this talk

- **focus on spin 1 new particle**
  - ★ add new SU(2) gauge symmetry
  - ★ many models can be constructed (choice of Higgs and fermion sectors)

- **discuss model independent features**
  - ★ perturbative unitarity 1507.01185 (TA, Nagai, Okawa, Tanabashi)
  - ★ prospect for 13TeV 1507.01681 (TA, Kitahara, Nojiri)

- **discuss two example models**
  - ★ 221 (or 3-site) model JHEP 1301 082 (TA, Chen, He)
  - ★ partially composite (or triangle) model PRD88 015019 (TA, Kitano)

talk plan

- **perturbative unitarity**
  - ⋆ show some relations among couplings
- **221 model**
  - ⋆ as an example satisfying the coupling relations derived from perturbative unitary
  - ⋆ model is not renormalizable
- **partially composite model**
  - ⋆ model is renormalizable
- **prospect for LHC 13 TeV**
- **Summary**

talk plan

- **perturbative unitarity**
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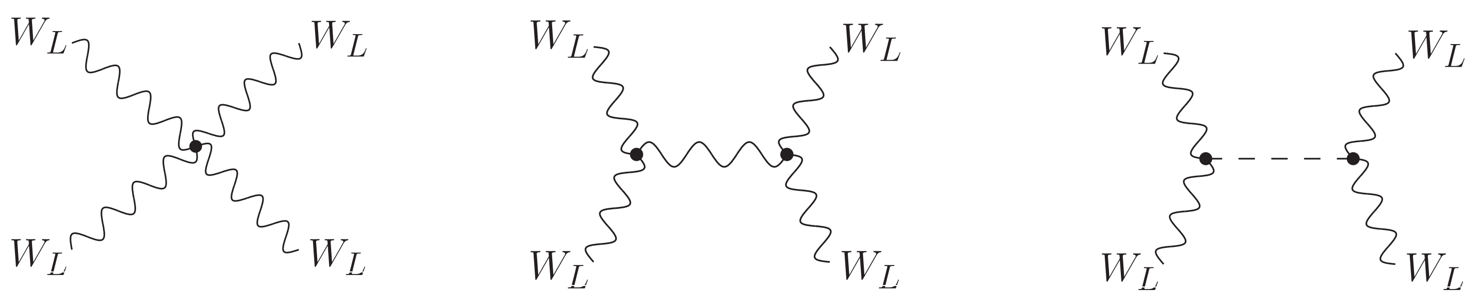
WW scattering at high energy (longitudinal modes)



- **naively, amplitude ~ a E^4 + b E^2 + ···**
  - ★ if a ≠ 0, b ≠ 0 then perturbative unitarity is broken
  - ★ a = 0 and b= 0 are required to keep perturbative calculation

- **Unitarity sum rules**
  - ★ some coupling relations are required for a = b = 0
  - ★ example in SM (U(1) gauge coupling =0 for simplicity)

$$\mathcal{M} \simeq (g_{WWWW} - g_{WWW}^2)\frac{\mathbf{E^4}}{\mathbf{m_W^4}} + \frac{1}{m_W^2}(4m_W^2 g_{WWWW} - 3m_W^2 g_{WWW}^2 - g_{WWh}^2)\frac{\mathbf{E^2}}{\mathbf{m_W^2}} + \cdots$$

$$\Rightarrow \quad \begin{aligned} 0 &= g_{WWWW} - g_{WWW}^2 \\ 0 &= 4m_W^2 g_{WWWW} - 3m_W^2 g_{WWW}^2 - g_{WWh}^2 \end{aligned}$$

Unitarity sum rules with *W'*

- **In SM example**
  - ⋆ *WWh* coupling relates with *WWW* coupling

$$
\begin{aligned}
0 =& g_{WWWW} - g_{WWW}^2 \\
0 =& 4m_W^2 g_{WWWW} - 3m_W^2 g_{WWW}^2 - g_{WWh}^2
\end{aligned}
\quad \Rightarrow \quad m_W^2 g_{WWW} = g_{WWh}^2
$$

- **unitarity sum rules with *W'***
  - ⋆ *WWh* and *WW'h* couplings relate with *WWW, WWW'* couplings
  - ⋆ model independent feature
  - ⋆ **assumption**: theory keeps “perturbative” unitarity

Sum rules in *W*, *W'*, and *CP-even Higgses* system

- **WW → WW**

$$g_{WWWW} = \sum_V g_{WWV}^2$$
$$4m_W^2 g_{WWWW} = \sum_V 3m_V^2 g_{WWV}^2 + \sum_h g_{WWh}^2$$

- **WW → WW'**

$$g_{WWWW'} = \sum_V g_{WWV} g_{WW'V}$$
$$(3m_W^2 + m_{W'}^2) g_{WWWW'} = \sum_V 3m_V^2 g_{WWV} g_{WW'V} + \sum_h g_{WWh} g_{WW'h}$$

- **WW → W'W', WW' → WW'**

$$\begin{aligned} g_{WWW'W'} &= \sum_V g_{WWV} g_{W'W'V} \\ &= \sum_V g_{WW'V} g_{WW'V} \\ (2m_W^2 + 2m_{W'}^2) g_{WWW'W'} &= \sum_V \left(3m_V^2 g_{WW'V}^2 - \frac{1}{m_V^2} 2 g_{WW'V}^2 (m_W^2 - m_{W'}^2)^2 \right) + \sum_h g_{WW'h}^2 \end{aligned}$$

WW → *WW* and *WWW'* *coupling*

- ***WW* → *WW* amplitude**
  - ⋆ require this satisfies perturbative unitarity at $m_W << E << m_{W'}$

$$\mathcal{M} \sim (g_{WWWW} - g_{WWW}^2)\frac{E^4}{m_W^4} \qquad (g_{WWWW} - g_{WWW}^2)\frac{m_{W'}^4}{m_W^4} < 32\pi$$

  - ⋆ from this relation and sum rule

$$g_{WWW'}^2 = (g_{WWWW} - g_{WWW}^2) < 32\pi\frac{m_W^4}{m_{W'}^4}$$

  - ⋆ order $g_{WWW'} \sim (m_w/m_{W'})^2$

- **introduce O(1) parameter: ξ_V**

$$g_{WWW'} = \xi_V \frac{m_W^2}{m_{W'}^2} g_{WWW}$$

Sum rules in *W*, *W'*, and *CP*-even *Higgses* system

- **WW → WW**

$$g_{WWWW} = \sum_V g_{WWV}^2$$

$$4m_W^2 g_{WWWW} = \sum_V 3m_V^2 g_{WWV}^2 + \boxed{\sum_h g_{WWh}^2}$$

- **WW → WW'**

$$g_{WWWW'} = \sum_V g_{WWV} g_{WW'V}$$

$$(3m_W^2 + m_{W'}^2) g_{WWWW'} = \sum_V 3m_V^2 g_{WWV} g_{WW'V} \boxed{+ \sum_h g_{WWh} g_{WW'h}}$$

- **WW → W'W', WW' → WW'**

$$g_{WWW'W'} = \sum_V g_{WWV} g_{W'W'V}$$

$$= \sum_V g_{WW'V} g_{WW'V}$$

$$(2m_W^2 + 2m_{W'}^2) g_{WWW'W'} = \sum_V \left(3m_V^2 g_{WW'V}^2 - \frac{1}{m_V^2} 2 g_{WW'V}^2 (m_W^2 - m_{W'}^2)^2 \right) + \boxed{\sum_h g_{WW'h}^2}$$

WW'h coupling and *WWh* coupling

- **combine sum rules and ξ_V, we find**

$$g_{WW'h}^2 = \xi_V^2 g_{WWh}^2$$

  - ⋆ $\xi_V = O(1)$
  - ⋆ $g_{WWW'} = \xi_V (m_w/m_{W'})^2 g_{WWW}$

Γ(W' → Wh) ~ Γ(W' → WW)

- **Γ(W′ → WW)**

$$\Gamma(W' \to WW) \simeq \frac{1}{192\pi} m_{W'} \xi_V^2 g_{WWW}^2$$

- **Γ(W′ → Wh)**

$$\begin{aligned}\Gamma(W' \to Wh) &\simeq \frac{1}{192\pi} m_{W'} g_{WW'h}^2 \frac{1}{m_W^2} \\ &= \frac{1}{192\pi} m_{W'} \xi_V^2 g_{WWh}^2 \frac{1}{m_W^2} \\ &= \frac{1}{192\pi} m_{W'} \xi_V^2 g_{WWW}^2 \frac{g_{WWh}^2}{g_{WWW}^2} \left(\frac{g_{WWW}^{\mathrm{SM}}}{g_{WWh}^{\mathrm{SM}}}\right)^2\end{aligned}$$

- **we find Γ(W′ → Wh) ~ Γ(W′ → WW)**

$$\frac{\Gamma(W' \to Wh)}{\Gamma(W' \to WW)} \simeq \left(\frac{g_{WWh}}{g_{WWh}^{\mathrm{SM}}}\right)^2 \left(\frac{g_{WWW}^{\mathrm{SM}}}{g_{WWW}}\right)^2$$

- **Br(W′ → Wh) ~ Br(W′ → WW)**

Consequences of the sum rules

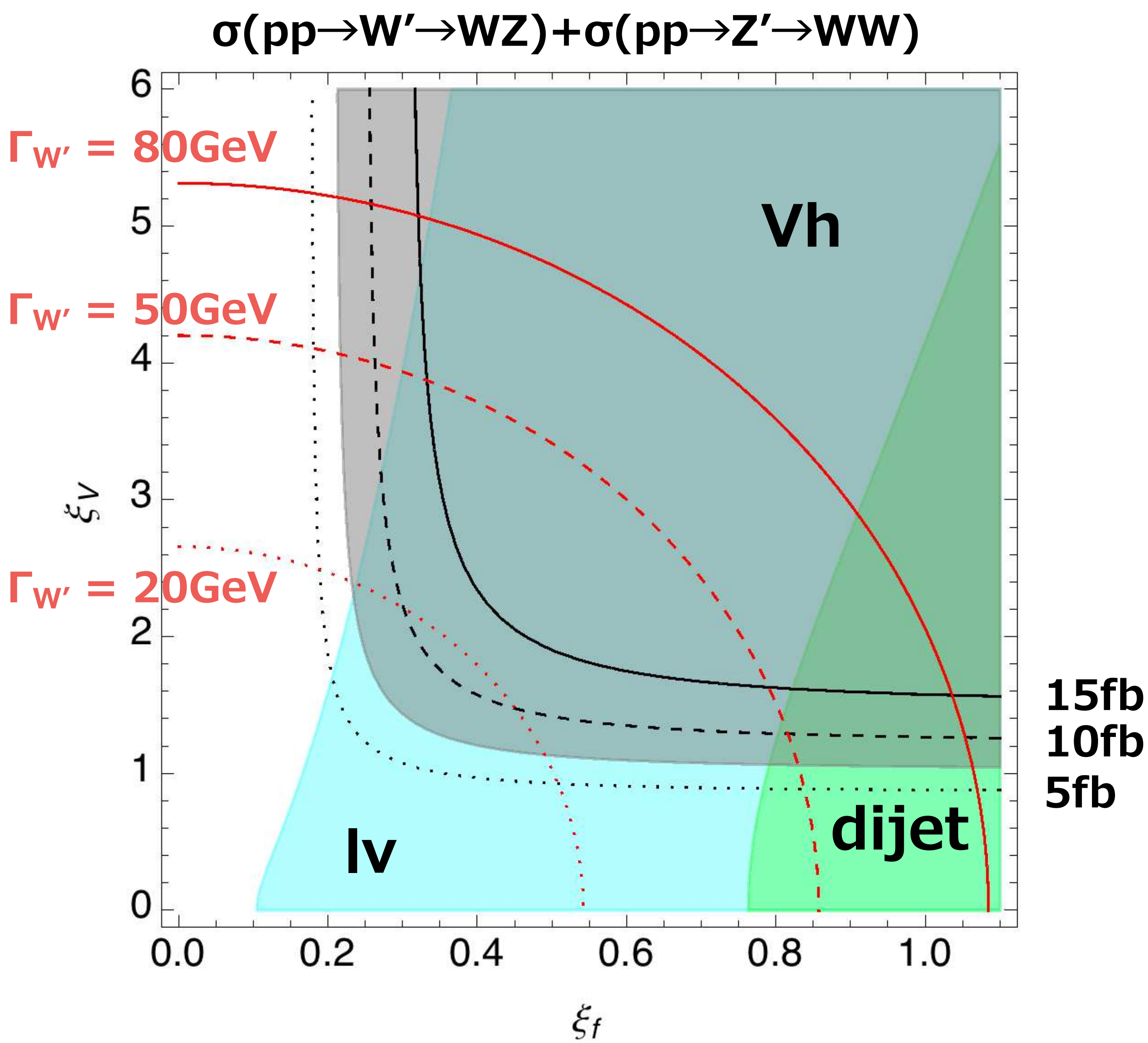
- $g_{WWW'} = \xi_V\,(m_W/m_{W'})^2\, g_{WWW}$
- $(g_{WW'h})^2 = \xi_V^2\,(g_{WWh})^2$
- $\mathrm{Br}(W' \to Wh) \sim \mathrm{Br}(W' \to WW)$

  ⋆ these relation are true in models which respect perturbative calculations

  ⋆ the third relation is usually explained as a consequence of the equivalence theorem

  ⋆ non-perturbative models does not respect these relations

constraint on parameter space



- **parameter choice**
  - ★ $m_{W'}$ = 2TeV
  - ★ $g_{WWh} = g_{WWh}^{SM}$
  - ★ $g_{W'ff} = \xi_f\, g_{Wff}^{SM}$
- **exclusion**
  - ★ cyan: $W' \to l\nu$
  - ★ green: $W' \to$ di-jets
  - ★ gray : $W' \to Wh$
- **Vh exclude σ > 7fb**
- **small width prefere small ξ_V**

talk plan

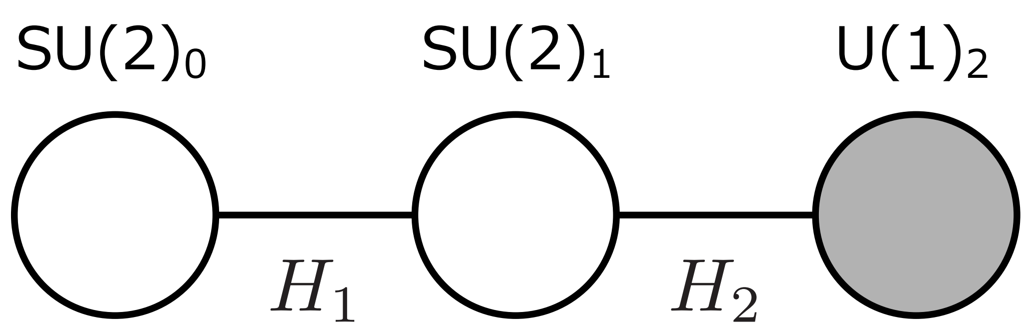
- **perturbative unitarity**
  - ⋆ show some relations among couplings
- **221 model**
  - ⋆ as an example satisfying the coupling relations derived from perturbative unitary
  - ⋆ model is not renormalizable
- **partially composite model**
  - ⋆ model is renormalizable
- **prospect for LHC 13 TeV**
- **Summary**

221 model (or 3-site model)

- **$SU(2)_0$ x $SU(2)_1$ x $U(1)_2$ → $U(1)_{QED}$**

- **two Higgs doublet**
  - ★ H_1 : $SU(2)_0$ x $SU(2)_1$ → $SU(2)_v$
  - ★ H_2 : $SU(2)_1$ x $U(1)_2$ → $U(1)_v$
  - ★ two CP-even scalars
  - ★ six would-be NG bosons

- **schematic picture** (moose notation)



221 model (or 3-site model)

- **boson sector**
  - ⋆ spin 1: W', Z', W, Z, photon
  - ⋆ spin 0: two CP-even
  - ⋆ we can use the results from perturbative unitarity
  - ⋆ $h = h_1 \cos\alpha + h_2 \sin\alpha$

- **fermion**
  - ⋆ ψ_L: ($SU(2)_0$, $SU(2)_1$, $U(1)_2$) =(2, 1, 1/6) or (2, 1, -1/2)
  - ⋆ ψ_R: ($SU(2)_0$, $SU(2)_1$, $U(1)_2$) =(1, 1, Q_{QED})
  - ⋆ coupling to $SU(2)_1$ is given by higher dimensional operator

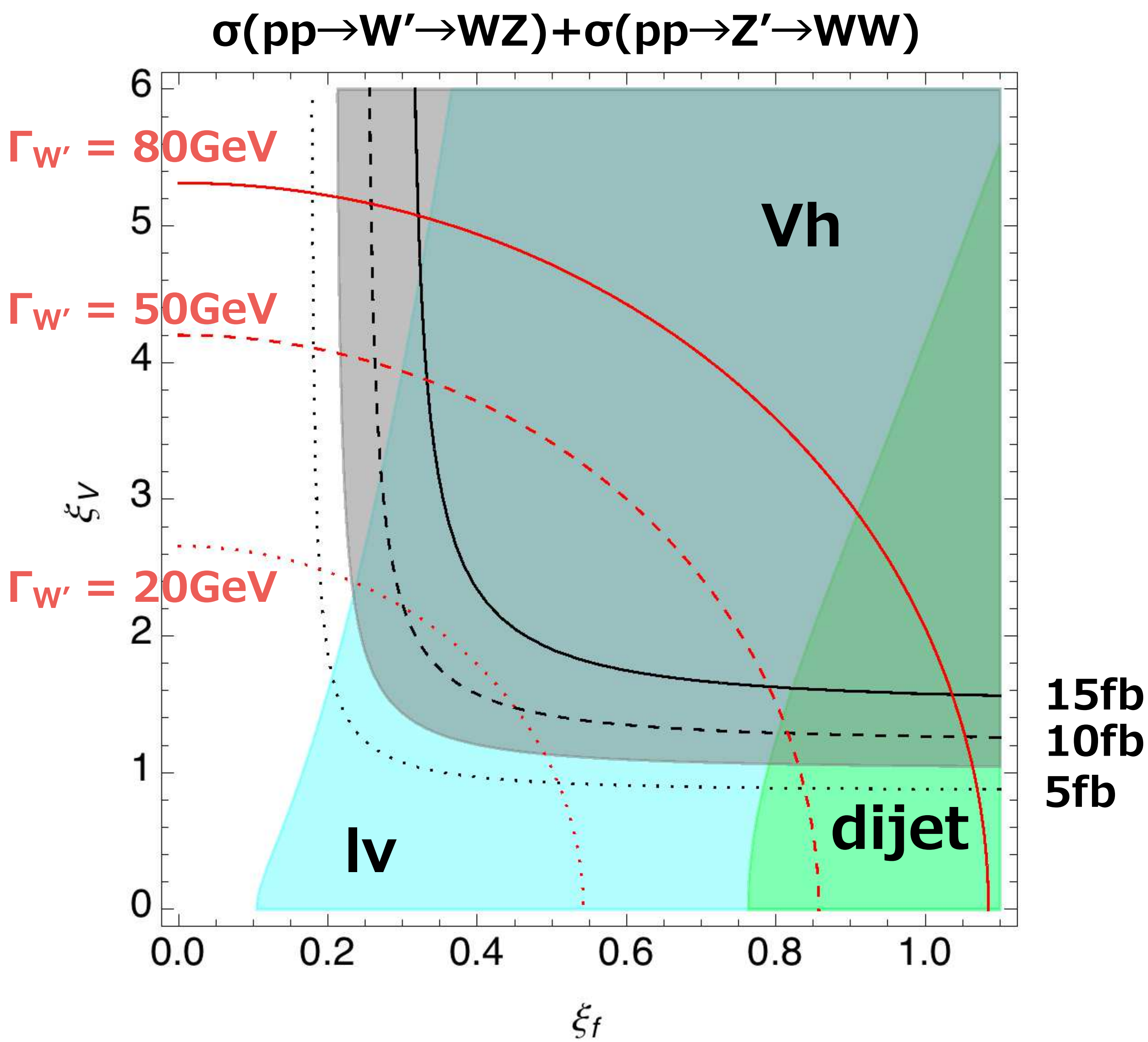
$$\frac{x_f}{v_1^2}\ \bar{\psi}_L i\gamma^\mu (H_1 \overleftrightarrow{D}_\mu H_1^\dagger)\bar{\psi}_L$$

  - ⋆ Yukawa is also given by higher dimensional operator

$$\frac{1}{\Lambda}\bar{q}_L H_1 H_2 \begin{pmatrix} y_u & 0 \\ 0 & y_d \end{pmatrix} \begin{pmatrix} u_R \\ d_R \end{pmatrix} + (h.c.) + (\text{lepton sector})$$

A benchmark: $v_1 >> v_2$ $(v_i = \langle H_i \rangle)$

$$\xi_V = \frac{g_{W1}}{g_{W0}}, \qquad \xi_f = \frac{1}{\xi_V}\left(1 - x_f(1+\xi_V^2)\right)$$



- **σ > 5fb** at $\xi_f = 0.2$

- If $x_f = 0$
  - ★ $\xi_V \xi_f = 1$
  - ★ $\xi_V = 5$, $\xi_f = 0.2$ for σ>5fb
  - ★ width = 80GeV

- If $0 < x_f << 1$
  - ★ $\xi_V \xi_f < 1$
  - ★ $\xi_V < 5$, $\xi_f = 0.2$ for σ>5fb
  - ★ width < 80GeV
  - ★ (width = 20GeV for $x_f = 0.08$)
  - ★ (width = 50GeV for $x_f = 0.01$)

summary of 221 model

- **satisfies sum rules**
- **some parameter space where σ(WZ+WW) > 5fb**

- **model is non-renormalizable**
  - ⋆ Yukawa is dim5 operator
  - ⋆ dim6 operator for the fermion coupling to $SU(2)_1$ to get narrow width

- **several ways to make model renormalizable**
  - ⋆ add new scalar for Yukawa interaction
  - ⋆ or add $SU(2)_1$ vector like fermions

talk plan

- **perturbative unitarity**
  - ⋆ show some relations among couplings
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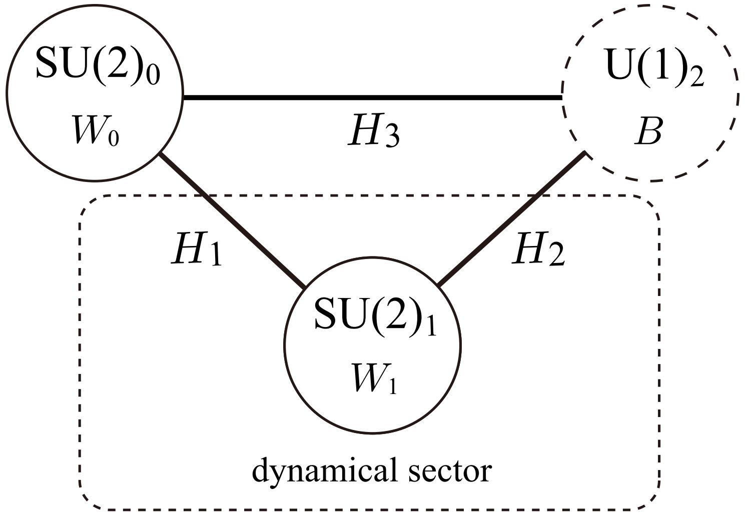
- **partially composite model**
  - ⋆ model is renormalizable
- **prospect for LHC 13 TeV**
- **Summary**

partially composite model

- **$SU(2)_0 \times SU(2)_1 \times U(1)_2 \rightarrow U(1)_{QED}$**

- **three Higgs doublet**
  - ★ H_1 : $SU(2)_0 \times SU(2)_1 \rightarrow SU(2)_V$
  - ★ H_2 : $SU(2)_1 \times U(1)_2 \rightarrow U(1)_V$
  - ★ H_3 : $SU(2)_0 \times U(1)_2 \rightarrow U(1)_V$
  - ★ three CP-even scalars + one CP-odd + charged Higgs
  - ★ six would-be NG bosons

- **schematic picture** (moose notation)



partially composite model

- **boson sector**
  - ⋆ spin 1: W′, Z′, W, Z, photon
  - ⋆ spin 0: h, H, H′, A^0, $H^\pm$
  - ⋆ we *cannot* use the results from sum rules (due to CP-odd and charged Higges)

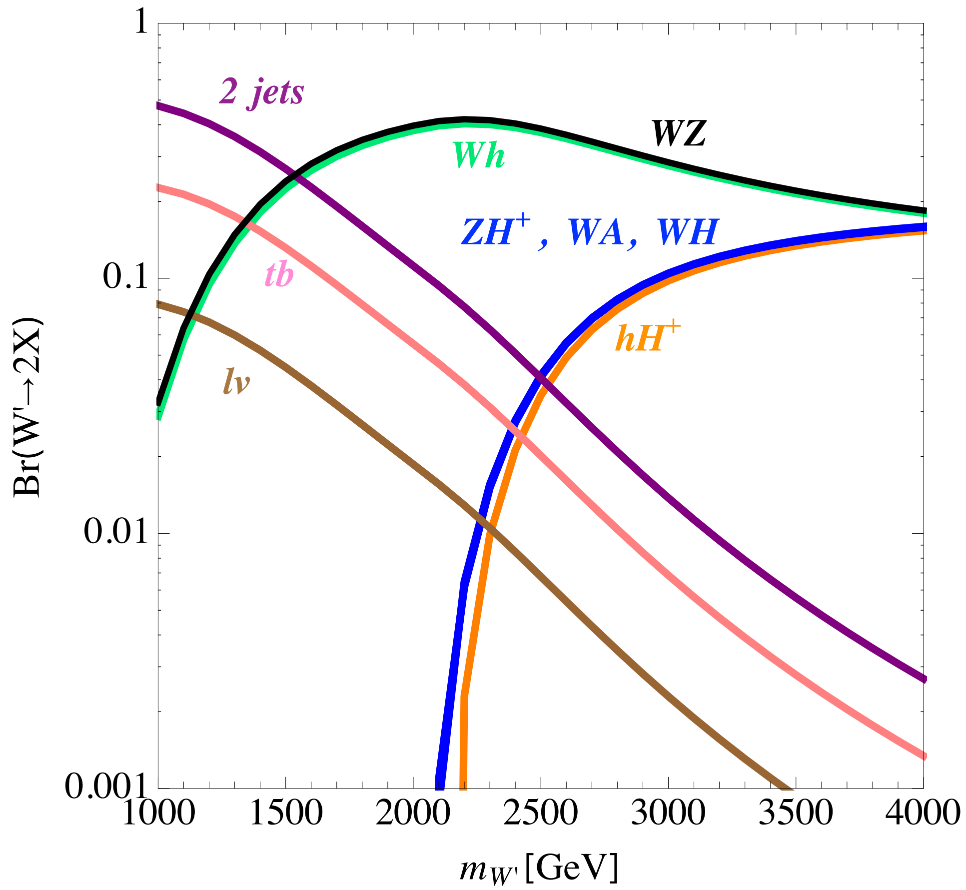
- **fermion**
  - ⋆ ψ_L: $(SU(2)_0, SU(2)_1, U(1)_2) = (2, 1, 1/6)$ or $(2, 1, -1/2)$
  - ⋆ ψ_R: $(SU(2)_0, SU(2)_1, U(1)_2) = (1, 1, Q_{QED})$
  - ⋆ Yukawa is given by H_3

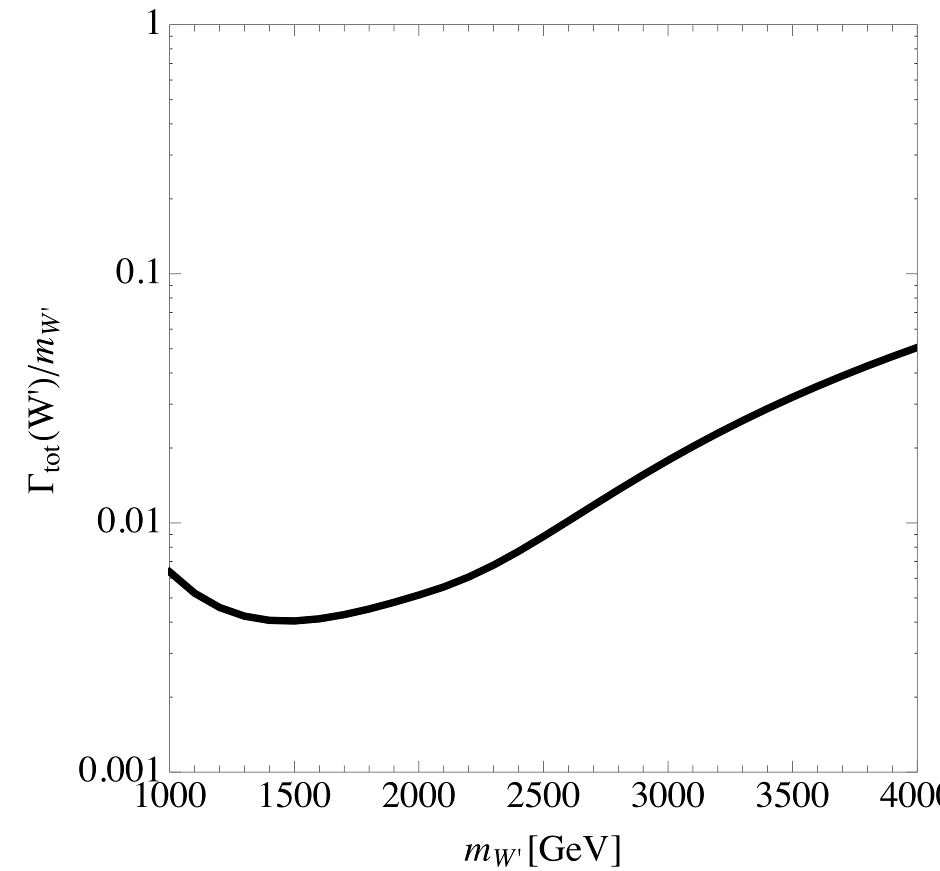
$$\mathcal{L}^{\rm Yukawa} = -\bar{Q}^i H_3 \begin{pmatrix} y_u^{ij} & 0 \\ 0 & y_d^{ij} \end{pmatrix} \begin{pmatrix} u_R^j \\ d_R^j \end{pmatrix} + (h.c.) + (\text{lepton sector})$$

model parameters

- **13 parameters**
  - ⋆ 4 known parameters: $v,\ \alpha,\ m_Z,\ m_h,$
  - ⋆ 4 unknown masses: $m_{Z'}, m_{H'},\ m_H,\ m_A,$
  - ⋆ three couplings: $\kappa_F,\ \kappa_Z,\ g_{WW'H'}.$ ($\kappa_F = g_{hff}/g_{hff}^{SM}$, $\kappa_Z = g_{hZZ}/g_{hZZ}^{SM}$)
  - ⋆ two others: $r,\ v_3,$ ($r = v_2/v_1$)
- **We take**
  - ⋆ $m_H = m_{H'} = m_A = 2\text{TeV}$
  - ⋆ $\kappa_F = 1$, $\kappa_Z \sim 1$, $g_{WW'H'} = 0$

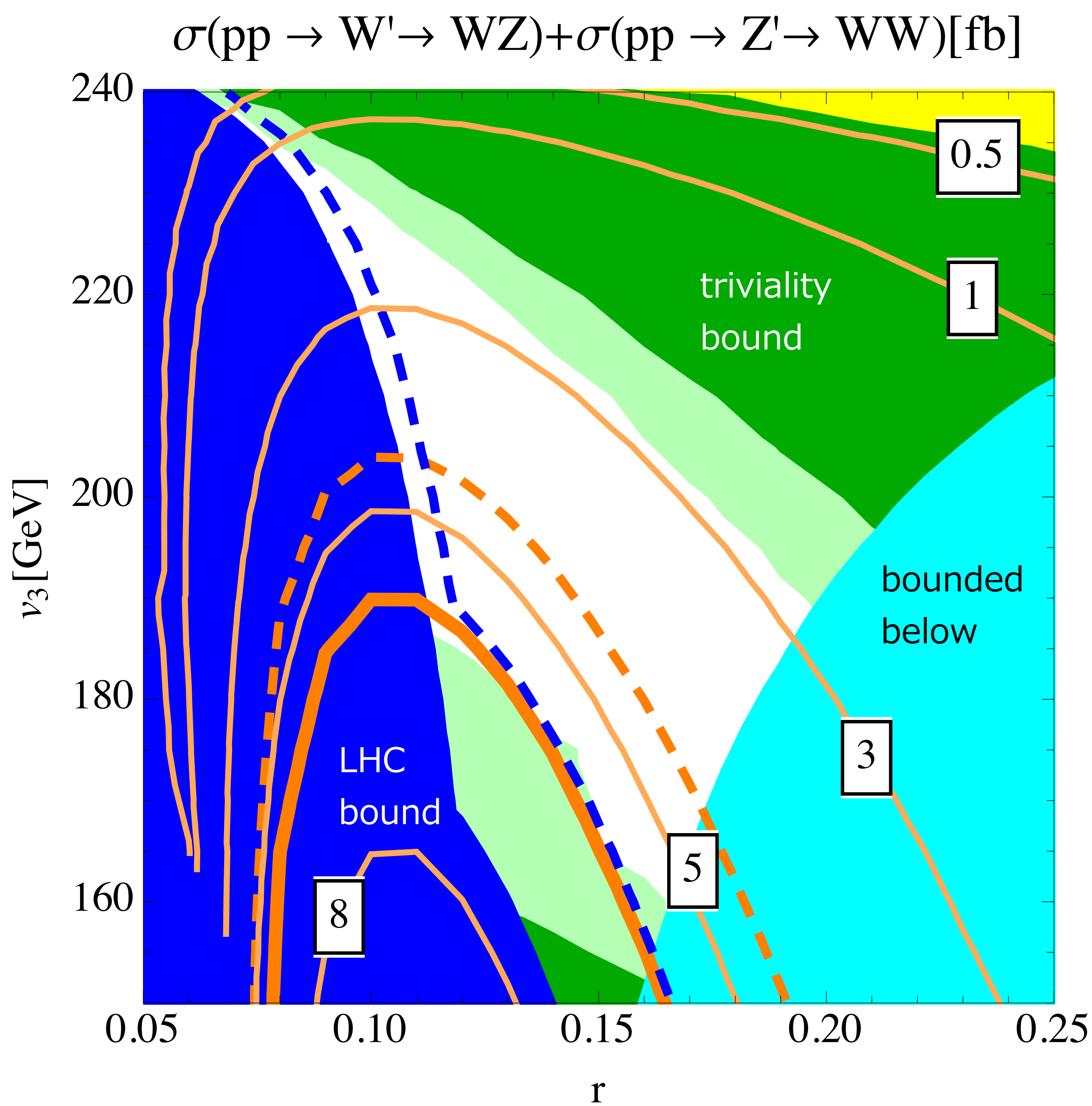
W' branching ration and width





- ★ $m_H = m_{H'} = m_A = 2\text{TeV}$, $r = 0.13$, $v_3 = 200$ GeV
- ★ width is narrow (20 GeV for $m_{W'} = 2\text{TeV}$)

results



★ colored region is excluded

★ orange lines are σ

★ σ = 6fb on bold orange line
(possiblly explain the excess)

★ dashed lines are with K-factor
(K ~ 1.3)
0711.0749, 1410.4692

talk plan

- **perturbative unitarity**
  - ⋆ show some relations among couplings
- **221 model**
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  - ⋆ model is not renormalizable
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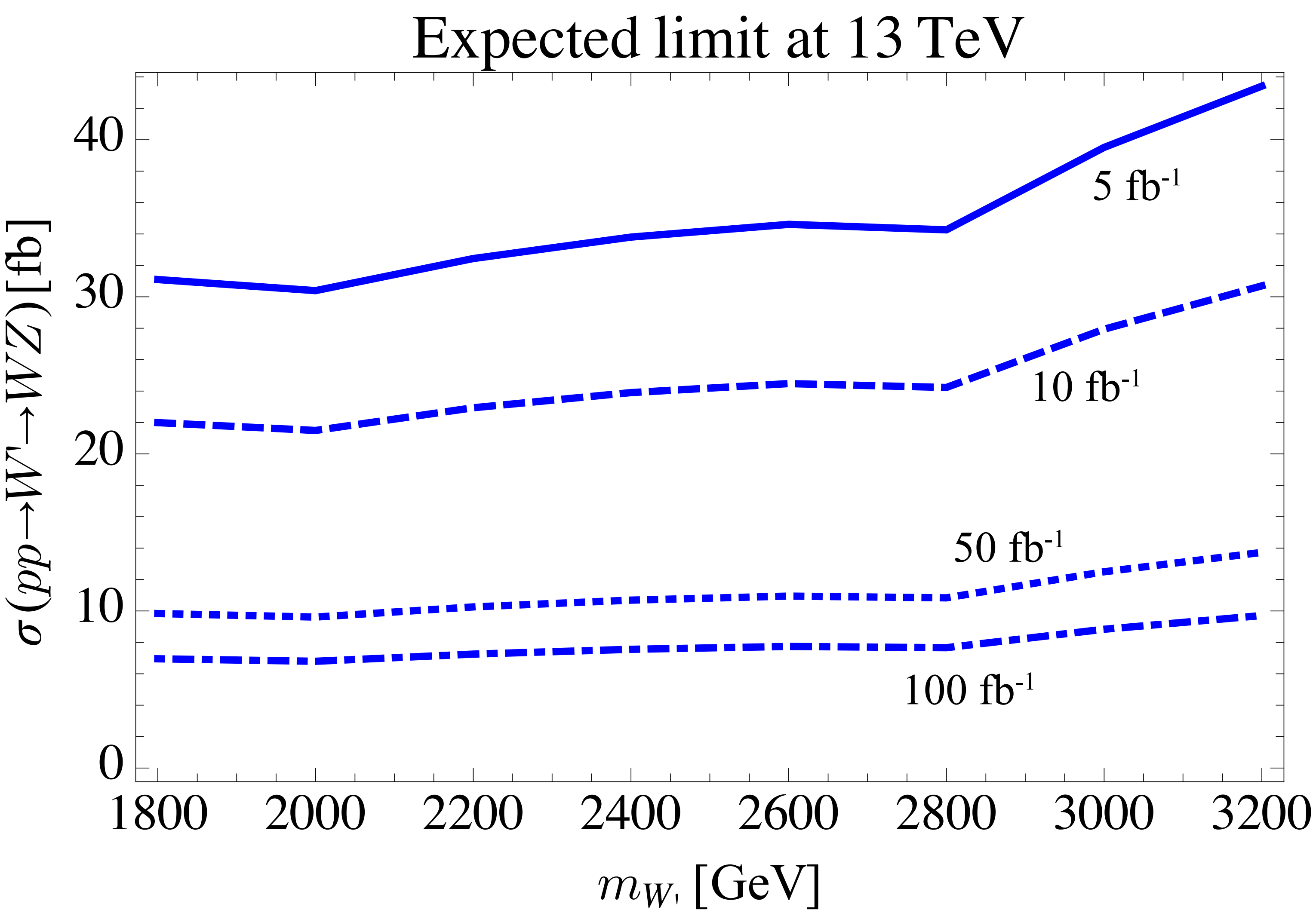
- **prospect for LHC 13 TeV**
- **Summary**

95% exclusion limit



★ W' width = 25GeV

★ This is model independent result

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Summary

- **diboson excess around 2TeV by the ATLAS**
  - ⋆ CMS does not find the excess
  - ⋆ no excess with leptonic decay channel
  - ⋆ In this talk we discussed spin-1 new particles (W’, Z’)

- **perturbative unitarity**
  - ⋆ $g_{WWW'_2} = \xi_{V_2} (m_W/m_{W'_2})^2 g_{WWW}$
  - ⋆ $g_{WW'h} = \xi_V \; g_{WWh}$
  - ⋆ Br(W’ → Wh) ~ Br(W’ → WW)
  - ⋆ if these are not satisfied, then we need non-perturbative calculations

- **two model examples**
  - ⋆ 221 model
    - ✴ satisfying the perturbative unitarity sum rules
    - ✴ UV completion is needed to make model renormalizable
  - ⋆ partially composite model
    - ✴ renormalizable model

- **prospect for LHC 13 TeV**
  - ⋆ less than 10 fb-1 is enough to exclude the 2TeV excess