Low Scale Composite Higgs and 2 TeV Diboson Excess

Jing Shu

ITP-CAS

L-G.Bian, D. Liu, J.S, arXiv: 1507.06018

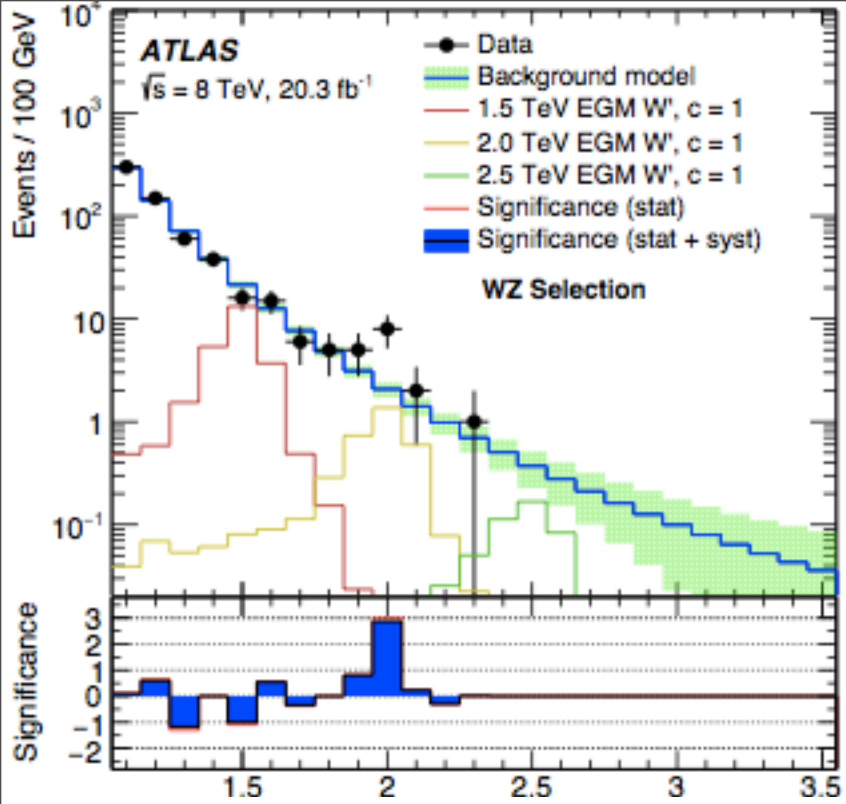
L-G.Bian, D. Liu, J.S, Y.-C. Zhang arXiv: 1508.XXXXX

Outline

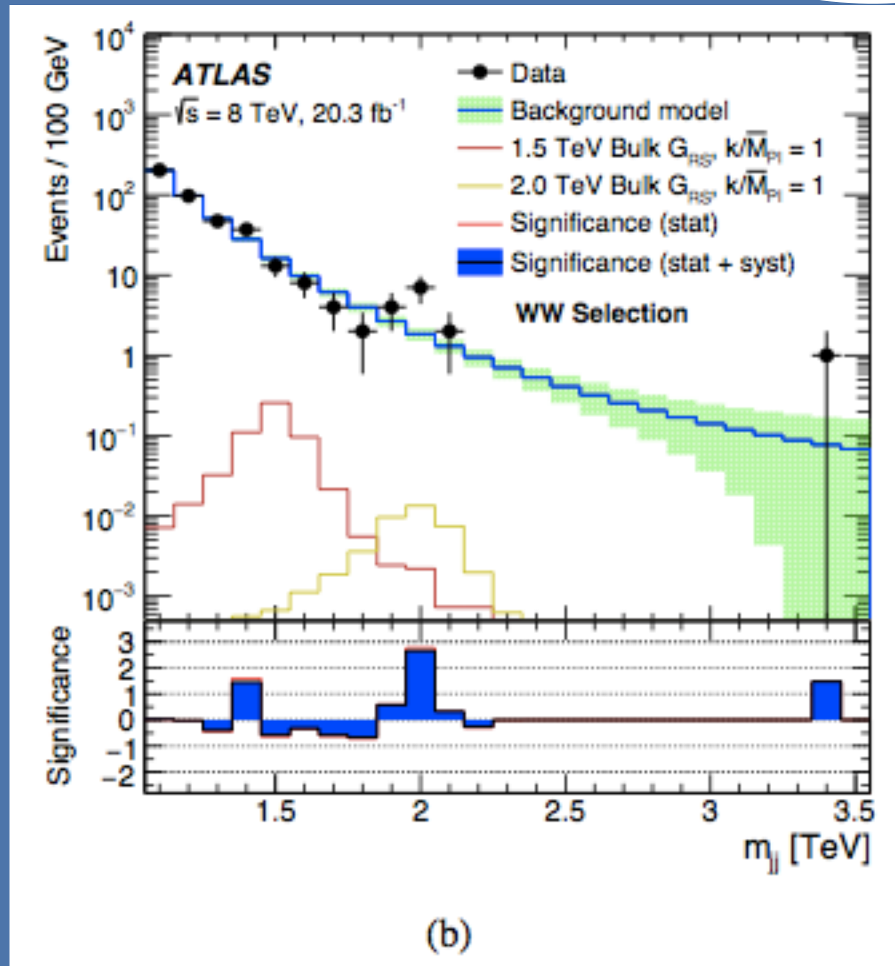
- Di-boson Excess ?
- Model setup in GCHM
- EWPT with axial-vector field “a”
- Fit the Excess & Other predictions.
- Future Prospects.
- Comment on resonance search and Interference effects

Di-boson Excess

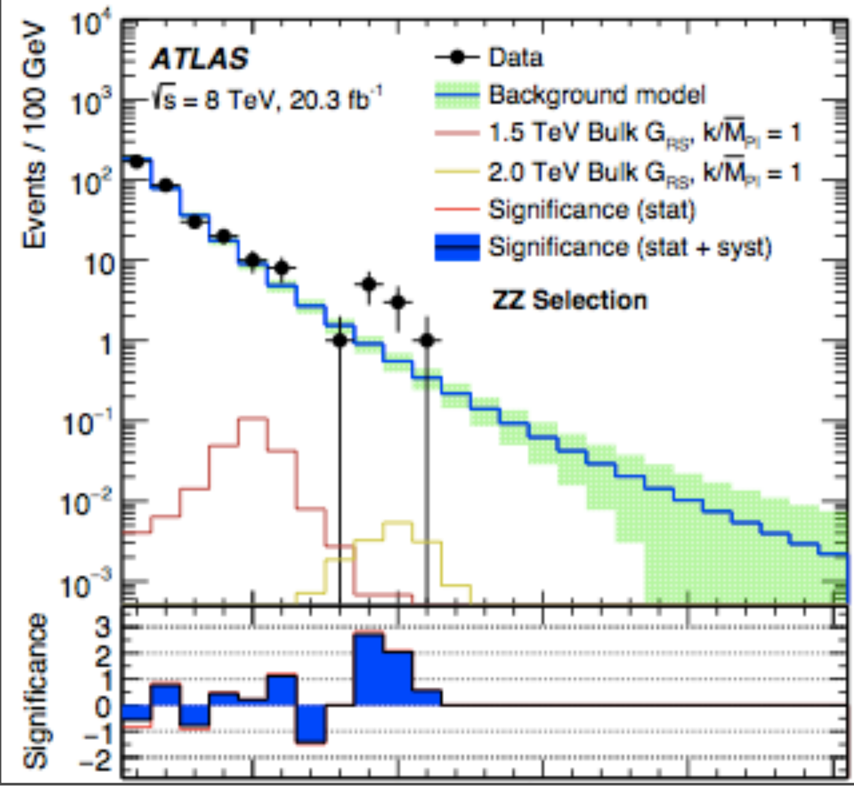
WZ



WW



ZZ



Many Channels

It is interesting to see small "bumps" in many channels around 2 TeV.

- Di-bosons: ATALS WZ 3.4, WW 2.6, ZZ 2.9 sigma; (sigma 2.5 sigma);
- VH channel: CMS 2 sigma
- Di-leptons: tiny bumps around 1~2 sigma.
- Di-jets: CMS 1~ 2 sigma

New game begin?

What is our attitude?

- True excitement haven't begun: (stay stunned as in Adam's blog)
- However, there might be some thing at 2 TeV that we can think about; What if ???
- Therefore, I believe it is not very meaningful to consider a global fit on ALL excess right now since some actually conflict with others. Let's think about SOME possible excesses right now.

CCWZ

- Di-bosons: Without distinguish the W, Z (10 GeV errors); Excess
- VH channel: Excess
- Di-leptons: very small bumps around 2 sigma. Excess or Constraint
- Di-jets: CMS ~ 2 sigma (too large to be consistent with Di-leptons) Constraint

Explanation with EWSB

It is natural to think about the resonance here has something to do with EWSB since it is so close related to W/Z

Let's consider a spin-one SU(2)_L weak triplet resonance, which is actually from many models explain the EWSB with custodial symmetry;

However, the 1st obvious obscure is the S parameter and EWPT

EWPT

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

$$\Big\downarrow \Delta$$

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

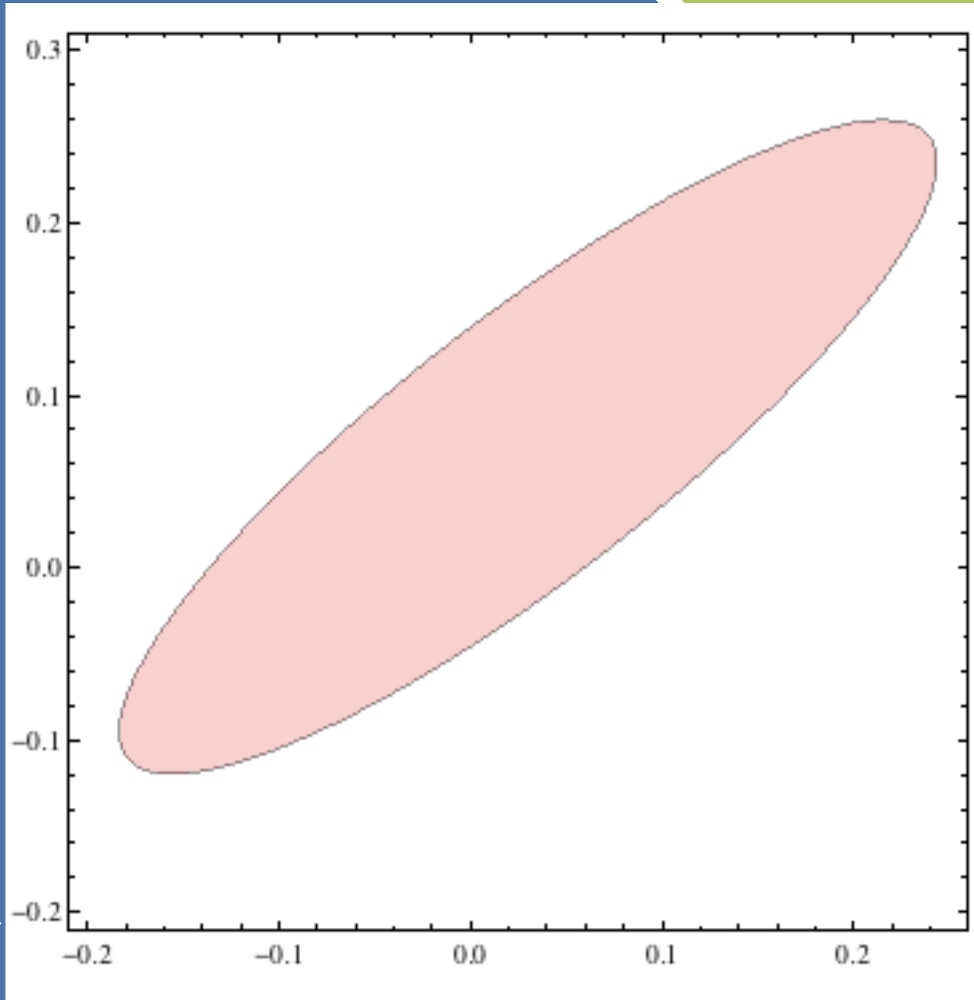
Kinetic term of Δ and Higgs gives you S

$$S = \frac{4\pi v^2}{m_\rho^2} = 0.2$$

Marginal fit

Multi-moose or RS model usually has a factor more than one

T



S

Why reject marginal fit?

There are actually more reasons to consider beyond this marginal fit.

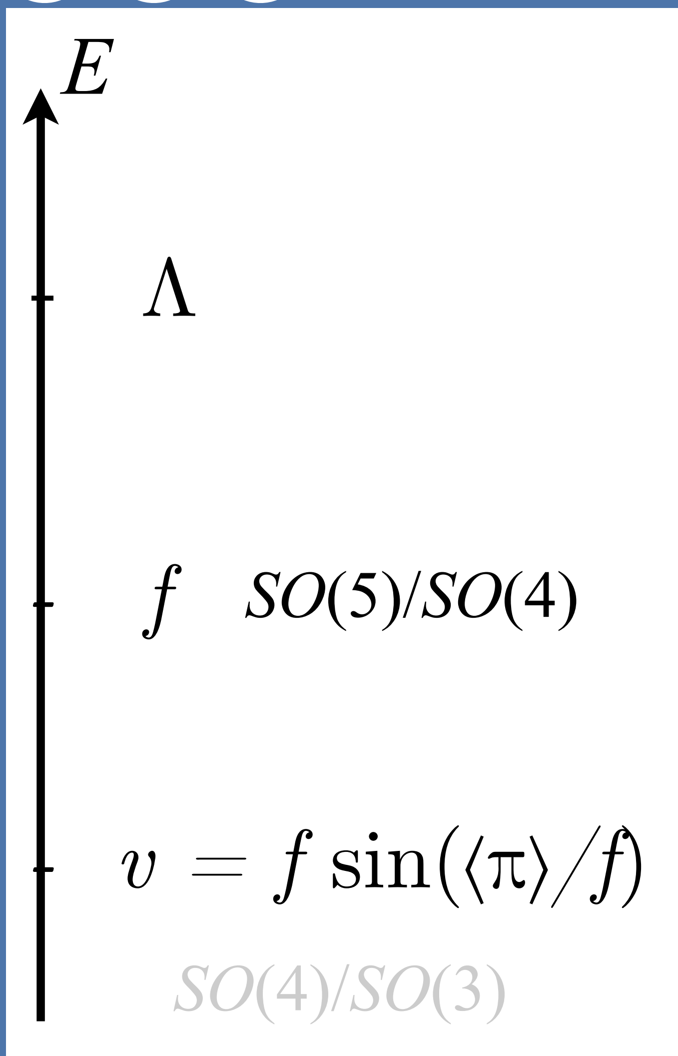
- Weak triplet vector meson alone can not trigger EWSB, we need other sources.
- Those other sources usually gives you more positive S and other EW precision deviations: Like a composite Higgs, top partner, etc.
- If one requires more room to fit the diboson excess, that may gives extra EW precision deviations: partially composite fermions.

Solution

With axial vector mesons transform as the (2,2) of (SU(2)_L, SU(2)_R)

- Small positive S (can be negative)
- Arbitrary rho fermion couplings (split the lepton quark couplings)
- Small or zero shift on the couplings between partially composite fermion and SM W/Z gauge bosons

Higgs as pNGB



Consider the minimal group G/H

$$SO(5) \times U(1)_X \to SO(4) \times U(1)_X$$

at the scale f > v

$$\xi \equiv \frac{v^2}{f^2}$$

There are four NGBs: $\pi^{\hat{a}}$, with $\hat{a} = 1, 2, 3, 4.$

They transform as a 4 of $SO(4)$

(2,2) of $SU(2)$ x $SU(2)$ ~ $SO(4)$.

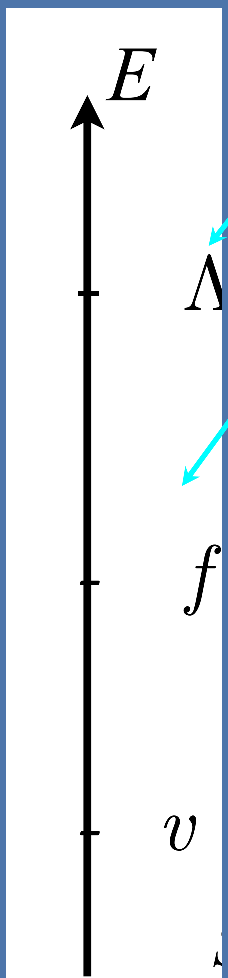
$$Y = T_{3R} + X$$

$SU(2)_L \times U(1)_Y \subset SU(2)_L \times SU(2)_R \times U(1)_X \sim SO(4)' \times U(1)_X$

$$U = \exp(i\sqrt{2}\pi^{\hat{a}}T^{\hat{a}}/f)$$

GCHMs

The theory make sense up to $\Lambda = 4\,\pi\,\mathrm{f}$



We assume that a given number of resonances in the composite sector are lighter than Λ so that it appears in the effective action.

Consider Spin-1 resonances in the $SU(2)_L \times SU(2)_R$ representation

$\rho_L\!:\ (\mathbf{3},\mathbf{1})$ $\rho_R\!:\ (\mathbf{1},\mathbf{3})$ $a\!:\ (\mathbf{2},\mathbf{2})$

``Vector Resonances'' ``Axial Resonances''

$1 \ll g_\rho,\, g_a \ll 4\,\pi$ strong but perturbative

Spin-one Resonances

$$\mathcal{L}_g = \mathcal{L}^{v_L} + \mathcal{L}^{v_R} + \mathcal{L}^{a},$$

$$\begin{aligned}
\mathcal{L}^{v_L} &= -\frac{1}{4}\rho^{i,2}_{L,\mu\nu} + \frac{f_\rho^2}{2}\left(g_\rho \rho^i_L - \hat{E}^L\right)^2, \\
\mathcal{L}^{v_R} &= \mathcal{L}^{v_L}, \text{ with } L \to R, \\
\mathcal{L}^{a} &= -\frac{1}{4}a^{i,2}_{\mu\nu} + \frac{f_a^2}{2\Delta_i^2}\left(g_a a^i - \Delta_i \hat{d}\right)^2.
\end{aligned}$$

$$iU^\dagger D_\mu U = d_\mu^{\hat{a}} T^{\hat{a}} + E_\mu^a T^a \text{ with } T^{\hat{a}}$$

ρ-SM gauge boson mixing terms

$$\begin{aligned}
d_\mu &= -\frac{\sqrt{2}}{f}\partial_\mu h^0 T^{\hat{4}} + \left(\frac{h^0}{\sqrt{2}f} - \frac{(h^0)^3}{6\sqrt{2}f^3}\right)\left(g_0 \tilde{W}^a_\mu - \right. \\
&\quad \left. g_0' \tilde{B}_\mu \delta^{a3}\right)\delta^{a\hat{a}} T^{\hat{a}} + \cdots \\
E_\mu &= \left(g_0 \tilde{W}^a_\mu T^a_L + g_0' \tilde{B}_\mu T^3_R\right) - \frac{(h^0)^2}{4f^2}\left(g_0 \tilde{W}^a_\mu - g_0' \tilde{B}_\mu \delta^{a3}\right) \\
&\quad (T^a_L - T^a_R) + \cdots \qquad (4)
\end{aligned}$$

$$m^2_{\rho^i_L} = f^2_{\rho^i_L} g^2_{\rho^i_L} \qquad m^2_{\rho^i_R} = f^2_{\rho^i_R} g^2_{\rho^i_R} \qquad m^2_{a_i} = \frac{f^2_{a_i} g^2_{a_i}}{\Delta_i^2}$$

SM gauge boson form factors

Effective Langragian for SM gauge fields in SO(5)/SO(4)

$$\mathcal{L}^{eff} = \frac{P_T^{\mu\nu}}{2}\Big(\Pi_0 W_\mu^a W_\nu^a + \Pi_1 \frac{s_h^2}{4}\left(W_\mu^1 W_\nu^1 + W_\mu^2 W_\nu^2\right) +$$
$$\Pi_B B_\mu B_\nu + \Pi_1 \frac{s_h^2}{4}\left(\frac{g_0'}{g_0}B_\mu - W_\mu^3\right)\left(\frac{g_0'}{g_0}B_\nu - W_\nu^3\right)$$
$$+c_h \Pi_{LR}\left(W_\mu^a W_\nu^a - \frac{g_0'^2}{g_0^2}B_\mu B_\nu\right)\Big), \qquad (7$$

$$\Pi_B = g_0'^2/g_0^2 \Pi_0.$$

Integrating out the spin one field

$$\Pi_1(p^2) = g_0^2 f^2 + 2g_0^2 p^2 \left[\frac{f_a^2}{(p^2+m_a^2)} - \frac{f_\rho^2}{(p^2+m_\rho^2)}\right]$$
$$\Pi_0(p^2) = p^2 + g_0^2 p^2 \frac{f_\rho^2}{(p^2+m_\rho^2)}, \quad \Pi_0^X(p^2) = p^2 .$$

SM gauge boson form factors

$\Pi_1(p^2)$ is critical since it is the one related to EWSB (The Goldstones), which affect the Higgs potential

Regulating the UV behavior

$$\lim_{p^2\to+\infty} g_0^{-2}\Pi_1(p^2) = f^2 + 2f_a^2 - 2f_\rho^2 \equiv 0\,. \quad \text{(I)}$$

1st Weinberg sum rule

$$\Pi_1(p^2) \geqslant 0$$

suggested by Witten's theorem for vector confinement

Relaxing the 2nd Weinberg sum rule

$$\lim_{p^2\to+\infty} g_0^{-2}p^2\Pi_1(p^2) = 2(f_\rho^2 m_\rho^2 - f_a^2 m_a^2) = 2\alpha^2 f^4.$$

Allow small S

If vector confining?

If the underlying theory is vector confining:

Witten's theorem suggest that:

$$\Pi_1(p^2) \geqslant 0$$

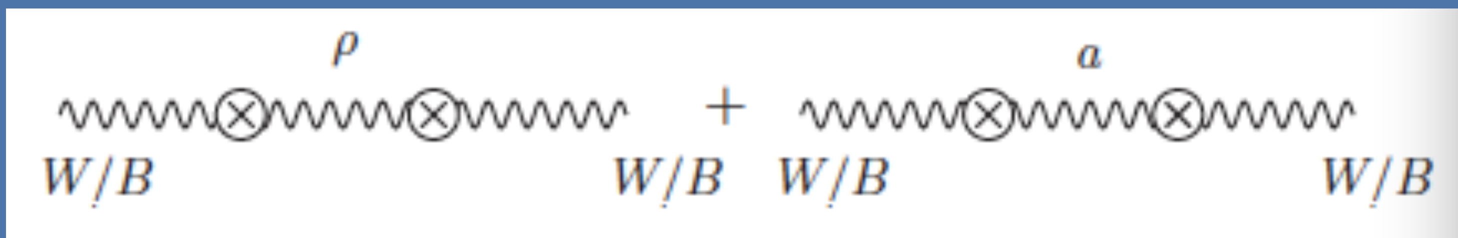
S is positive

S is negative but

$m_\rho > m_a$

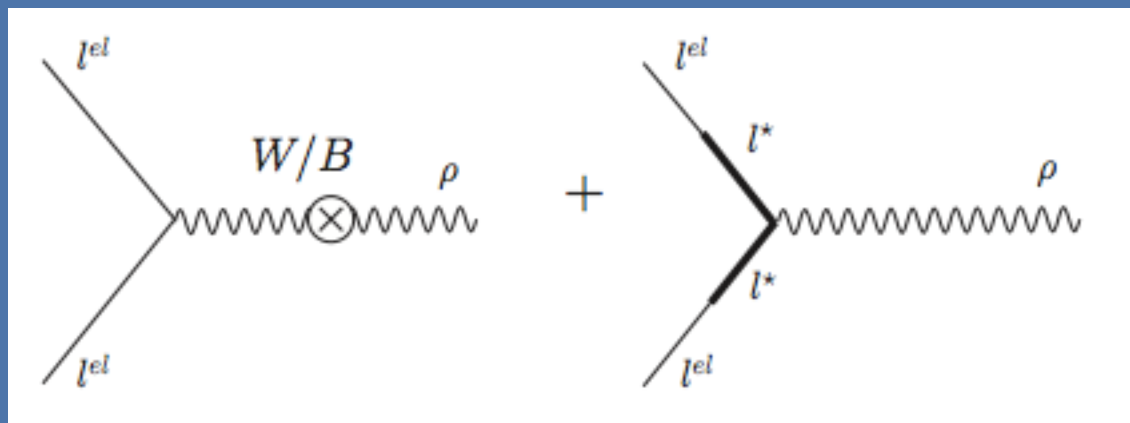
S is always positive if $m_\rho < m_a$.

Cancellation of S



$$S \simeq 8\pi s_h^2 \left(\frac{f_\rho^2}{m_\rho^2} - \frac{f_a^2}{m_a^2}\right)$$

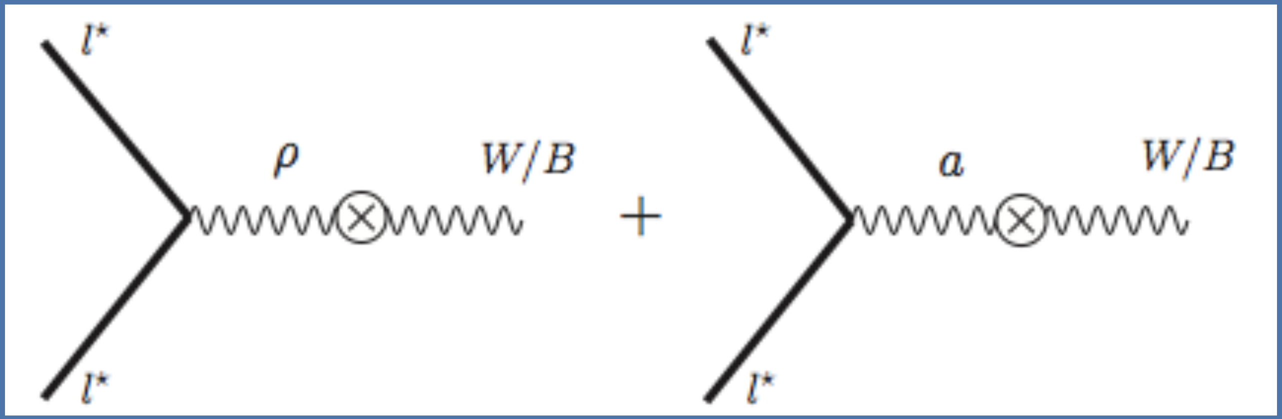
Adjusting the rho-f-f couplings



Mixture is ~ $g/\sqrt{g_\rho g_\rho^{l*}}$

Complete cancellation

Cancellation of EW observables



a small composite fermion component for SM fermions would result a deviation on the SM fermion and gauge boson

$$i(f^\dagger \gamma^\mu f)(H^\dagger D_\mu H)$$

$$(g_\rho^{l*}(\xi/2)m_\rho^2/g_\rho \sim g_a^{l*}\sqrt{\xi/2}m_a^2 g_a)$$ Complete cancellation

Couplings

$$\mathcal{L}_\rho = i g_{\rho^+ WZ} \left[(\partial_\mu \rho_\nu^+ - \partial_\nu \rho_\mu^+) W^{\mu-} Z^\nu - (\partial_\mu W_\nu^- - \partial_\nu W_\mu^-) \rho^{\mu+} Z^\nu + (\partial_\mu Z_\nu - \partial_\nu Z_\mu) \rho^{\mu+} W^{\nu-} + h.c. \right]$$
$$+ i g_{\rho^0 WW} \left[(\partial_\mu W_\nu^+ - \partial_\nu W_\mu^+) W^{\mu-} \rho^{0\nu} + \frac{1}{2} (\partial_\mu \rho_\nu^0 - \partial_\nu \rho_\mu^0) W^{\mu+} W^{\nu-} + h.c. \right]$$
$$+ g_{\rho^+ Wh} (h \rho_\mu^+ W^{\mu-} + h.c.) + g_{\rho^0 Zh} h \rho_\mu^0 Z^\mu$$
$$+ \frac{1}{\sqrt{2}} g_{\rho^+ ff'} (\rho_\mu^+ \bar{f} \gamma^\mu f' + h.c.)$$
$$+ g_{\rho^+ ff} (\rho_\mu^+ \bar{f} \gamma^\mu f + h.c.)$$

$$g_{\rho^+ f_{el} f'_{el}} \sim -\frac{g^2}{g_\rho}, \quad g_{\rho^+ t_L b_L} \sim -\frac{g^2}{g_\rho} + g_\rho \epsilon_{t_L}^2$$
$$g_{\rho^0 f_{el} f_{el}} \sim -T_f^{3L} \frac{g^2}{g_\rho},$$
$$g_{\rho^0 t_L t_L} \sim \frac{1}{2}\left(-\frac{g^2}{g_\rho} + g_\rho \epsilon_{t_L}^2\right),$$
$$g_{\rho^0 b_L b_L} \sim -\frac{1}{2}\left(-\frac{g^2}{g_\rho} + g_\rho \epsilon_{t_L}^2\right),$$

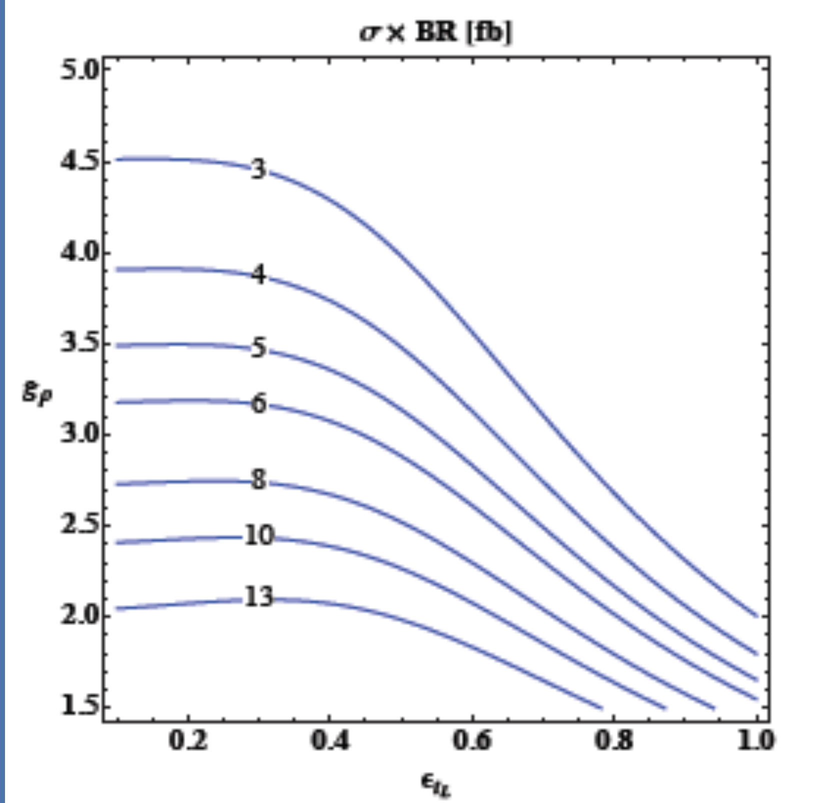
$$g_{\rho^+ WZ} \sim \frac{m_Z m_W}{m_\rho^2} g_\rho, \quad g_{\rho^+ Wh} \sim m_W g_\rho,$$
$$g_{\rho^0 WW} \sim \frac{m_W^2}{m_\rho^2} g_\rho, \quad g_{\rho^0 Zh} \sim m_Z g_\rho.$$

Drell-Yan of a is v/f suppressed, a order lower

Production and Decay

$$\Gamma(\rho^+ \to W^+Z) = M^5_{\rho^+} g^2_{\rho^+WZ}/(192\pi m_W^2 m_Z^2),$$
$$\Gamma(\rho^+ \to W^+h) = M_{\rho^+} g^2_{\rho^+Wh}/(192\pi m_W^2),$$
$$\Gamma(\rho^+ \to \psi_f \bar{\psi}_{f'}) = N_c M_{\rho^+} g^2_{\rho^+ff'}/48\pi,$$
$$\Gamma(\rho^0 \to W^+W^-) = M^5_{\rho^0} g^2_{\rho^0WW}/(192\pi m_W^4),$$
$$\Gamma(\rho^0 \to Zh) = M_{\rho^0} g^2_{\rho^0Zh}/(192\pi m_Z^2),$$
$$\Gamma(\rho^0 \to \psi_f \bar{\psi}_f) = N_c M_{\rho^0} g^2_{\rho^0ff}/24\pi.$$

$$\sigma(pp \to \rho^+) \sim \frac{g^4}{g_\rho^2} \times 528\,\text{fb},$$
$$\sigma(pp \to \rho^-) \sim \frac{g^4}{g_\rho^2} \times 132\,\text{fb}$$



Including the composite fermions

$$(\sigma(pp \to \rho^+) + \sigma(pp \to \rho^-)) \times \text{BR}(\rho^+ \to W^+Z)$$
$$\sim 282\,\text{fb} \times \frac{\epsilon_g^2(1+\epsilon_g^2)^2}{(1+\epsilon_g^2)^2 + 1 + 48\epsilon_g^4 + 12\epsilon_{t_L}^4 - 24\epsilon_g^2\epsilon_{t_L}^2}$$

Two benchmarks

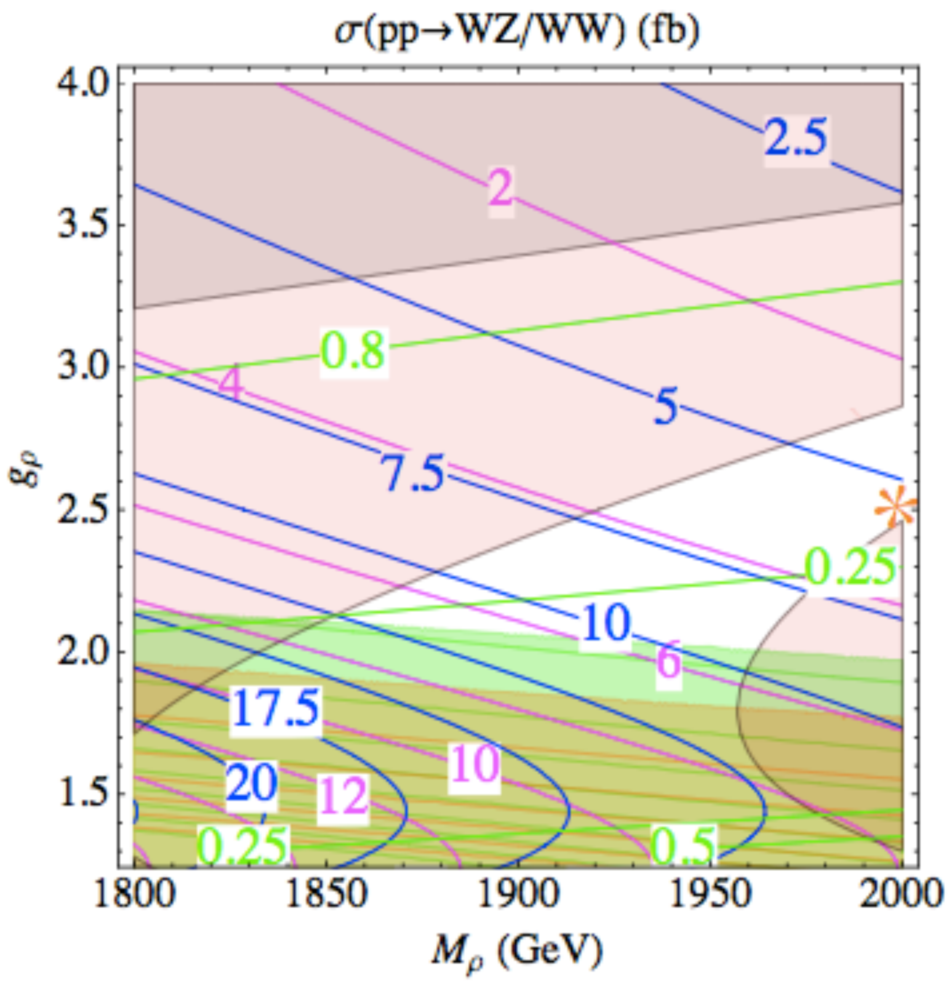
h to Z gamma

If diboson is confirmed, or our underlying theory does have the "a" field, then ?

Besides the VBF search channels

The nonzero aWZ terms make a largely contribute to the h Z gamma loops, can be order one large

Elementary light fermions



1st Weinberg sum rule

EWPT constrain

Benchmark point A

h Z gamma

charged lepton neutrino

di charged lepton

lepton bound can be regarded as the excess

$(M_\rho[\text{TeV}], g_\rho)$	$\sigma(WZ)$	$\sigma(WW)$	m_a [TeV]	g_a	$\frac{\Gamma(h\to Z\gamma)}{\Gamma(h\to Z\gamma)_{SM}}$
(2.0, 2.5)	6.78	3.74	1.46	2.68	0.38
(1.85, 2.0)	4.23	3.32	1.29	1.87	0.17

Partial composite leptons

1st Weinberg sum rule

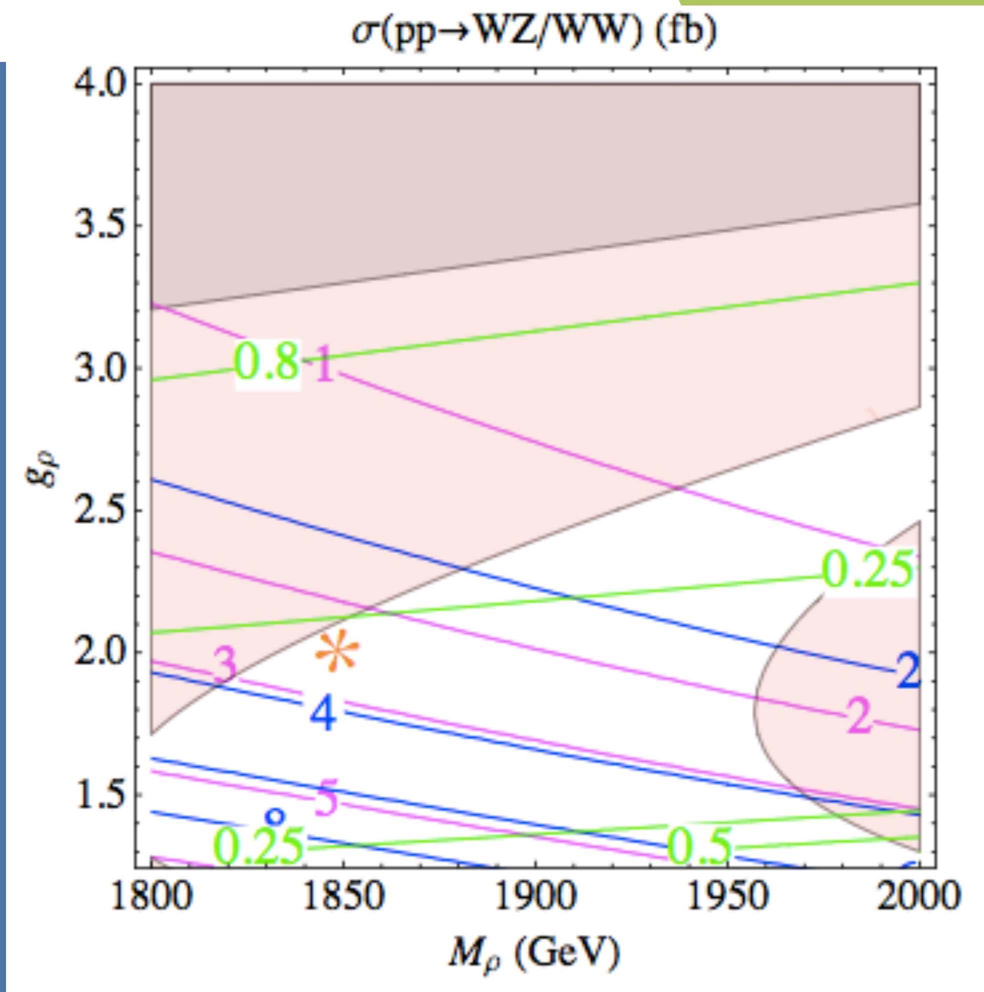
$$g_\rho < \frac{\sqrt{2} m_\rho}{f}$$

EWPT constrain

h Z gamma

Benchmark point B

No lepton constrain

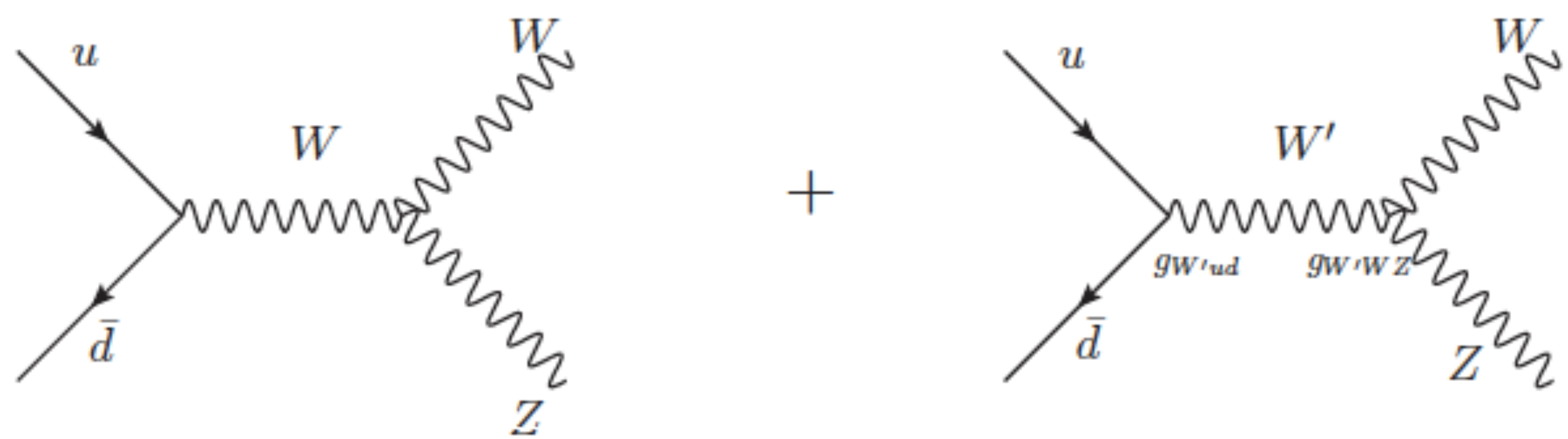


$(M_\rho[\text{TeV}], g_\rho)$	$\sigma(WZ)$	$\sigma(WW)$	m_a [TeV]	g_a	$\frac{\Gamma(h\to Z\gamma)}{\Gamma(h\to Z\gamma)_{SM}}$
(2.0, 2.5)	6.78	3.74	1.46	2.68	0.38
(1.85, 2.0)	4.23	3.32	1.29	1.87	0.17

Many future works to be done

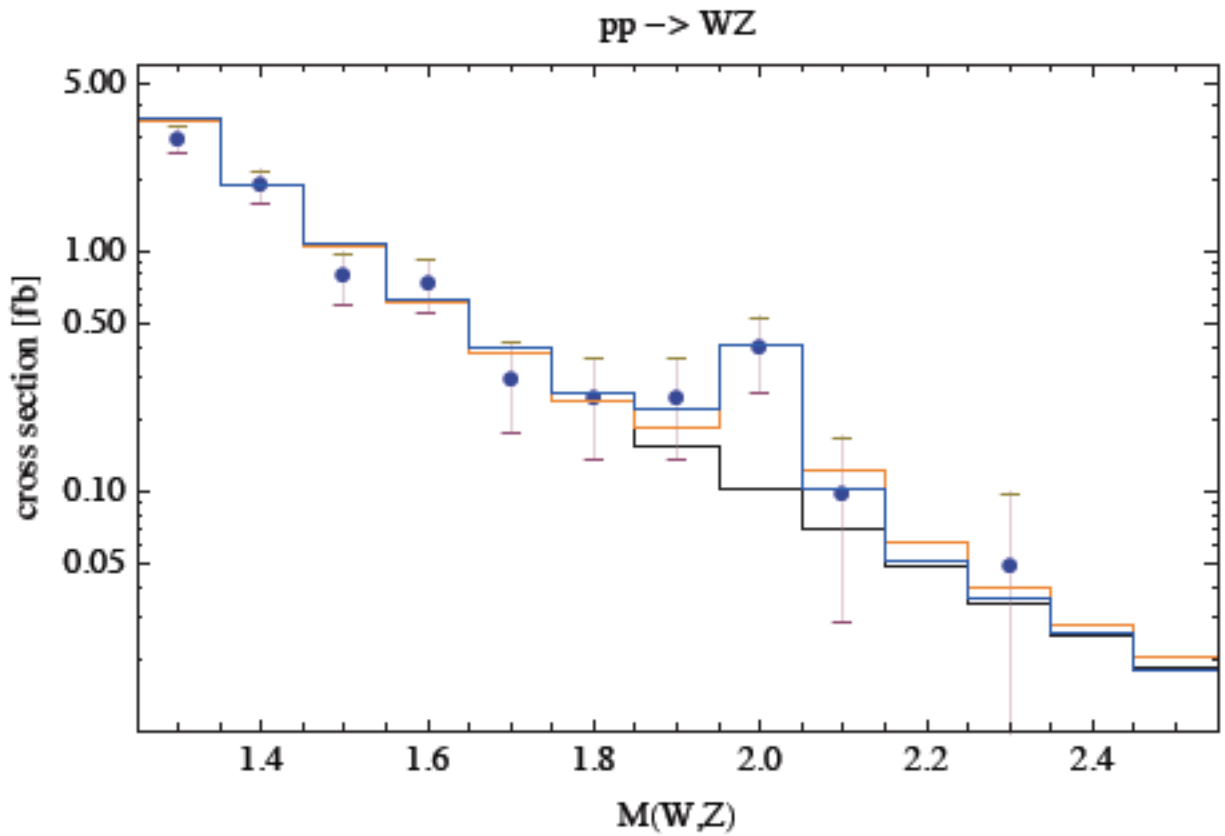
- Unitarity cut off with a (make it lower)
- Viable Coleman-Weinberg Higgs potential
- Full EWPT with axial-vector field "a"
- LHC direct searches on "a".
- Full h-gammma-gamma, h-Z-gamma loops.
- More need to think about it

Resonance Interference



Relative sign does matter!

Resonance Interference



$$A_i = -\frac{\int \mathrm{d}M_{AB}\left(\frac{\mathrm{d}\sigma}{\mathrm{d}M_{AB}} - \frac{\mathrm{d}\sigma}{\mathrm{d}M_{AB}}_{\mathrm{SM}}\right) * \Theta(M_{AB} - M_X)}{\int \mathrm{d}M_{AB}\left|\frac{\mathrm{d}\sigma}{\mathrm{d}M_{AB}} - \frac{\mathrm{d}\sigma}{\mathrm{d}M_{AB}}_{\mathrm{SM}}\right|}.$$

$$\Theta(x) = \begin{cases} -1, & x < 0 \\ 1, & x > 0 \end{cases}$$

Resonance Interference

interference	Mass	$\Gamma_{W'}$	$g_{W'WZ}$	$g_{W'ud}$	χ^2_{local}
constructive	2 TeV	50 GeV	0.005	-0.085	0.45
destructive	2 TeV	50 GeV	0.005	0.085	0.069

	constructive	destructive	data
local A_i	0.27	-0.34	$-0.52^{+1.52}_{-0.48}$

Resonance Interference