宇宙の進化と素粒子模型

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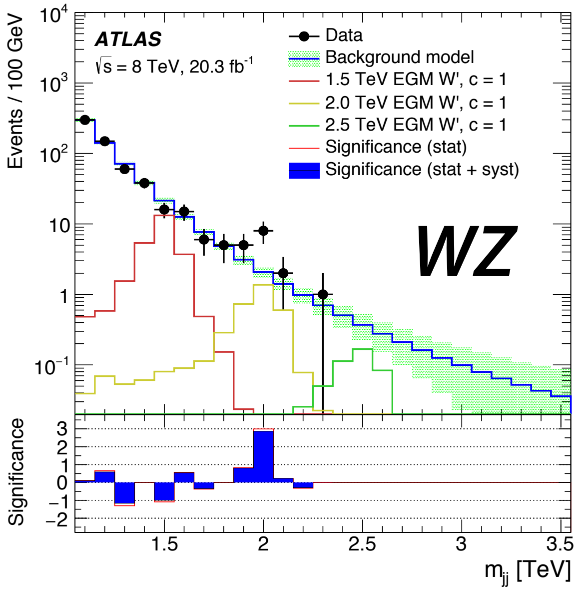
Diboson Resonance as a Portal to Hidden Strong Dynamics

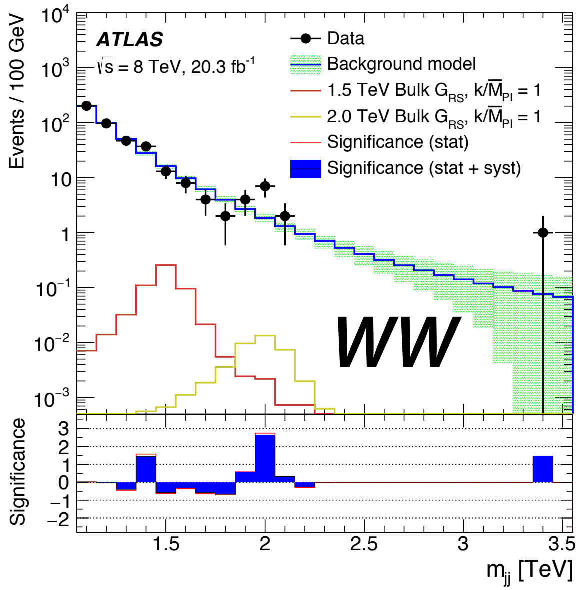
with C.W. Chiang (TNCU), H. Fukuda (IPMU), K. Harigaya(UC Berkeley), T.T.Yanagida (IPMU)

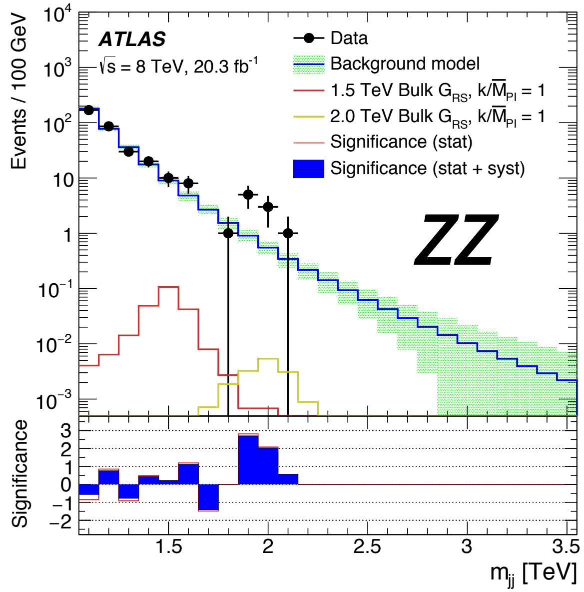
JHEP 1511 (2015) 015 (arXiv:1507.02483)

Diboson Excesses !

[ATLAS arXiv:1506.00962]





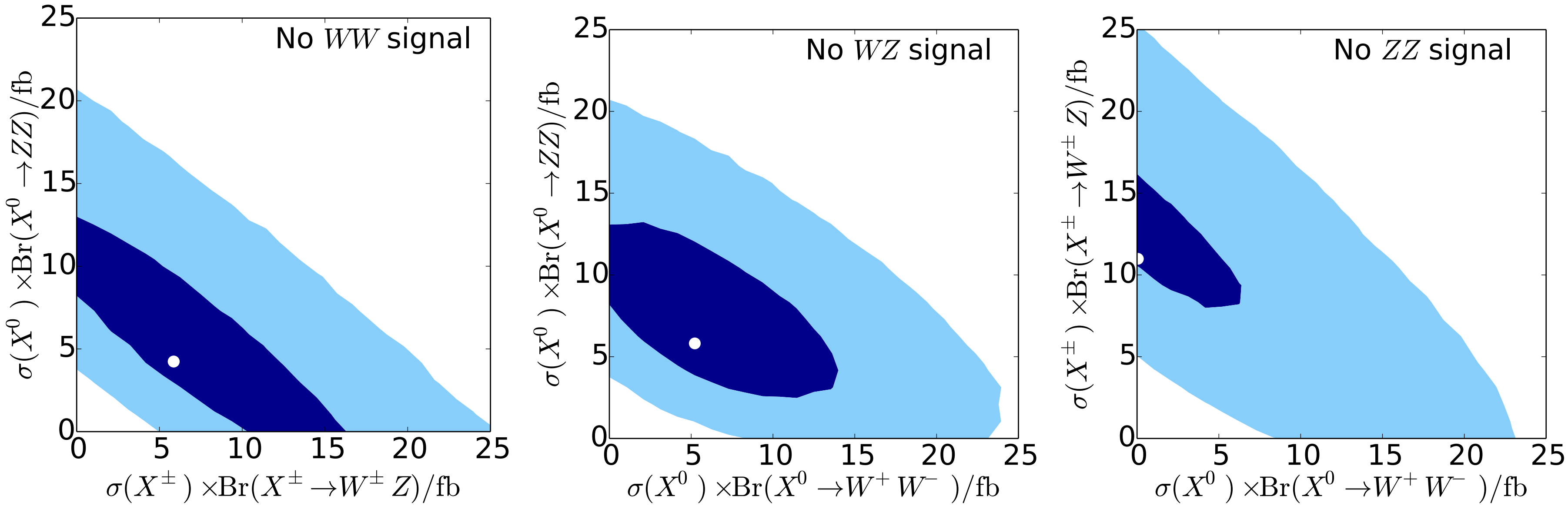


$pp \to X \to ZZ/WW/WZ \to$ Two Fat Jets ($|m_J - m_V| < 13$ GeV)

- ✔ *local significances : ZZ(2.6σ)/WW(2.9σ)/WZ(3.4σ)*
- ✔ *$m_X \sim 2$ TeV*
- ✔ *$\Gamma_X \lesssim 100$ GeV (narrow width)*

Who is X ?

B.C. Allanach, B. Gripaios and D. Sutherland, [arXiv:1507.01638]



[preferred region : dark blue 70%CL, light blue 95%CL]

✔ *WZ signals are not well separated from ZZ, WW*

For example, the signal can be explained without ***WZ*** channel by

$$\sigma_{WW} + \sigma_{ZZ} \sim 5\text{-}15\ \mathrm{fb}$$

✓ ***No excesses in leptonic modes @ 2TeV…***

(CMS 1405.3447,ATLAS 1503.04677)

$$\sigma_{WZ}\,(WZ \to l\nu + jets) \lesssim 10\ fb$$

$$\sigma_{WW}\,(WW \to lepton + jets) \lesssim 3\text{-}5\ fb$$

$$\sigma_{ZZ}\,(ZZ \to lepton + jets) \lesssim 10\ fb$$

[No BR's of Z,W are multiplied]

✓ ***No excesses in dijet modes @ CMS (CMS 1405.1994)***

$$\sigma_{ZZ,WW,WZ}\,(ZZ,WW,WZ \to dijet) \lesssim 10\ fb$$

✓ These constraints do not immediately conflict with the ATLAS dijet excesses.

→ We need to wait for Run 2 results !

Spin-0 from Hidden Strong Dynamics

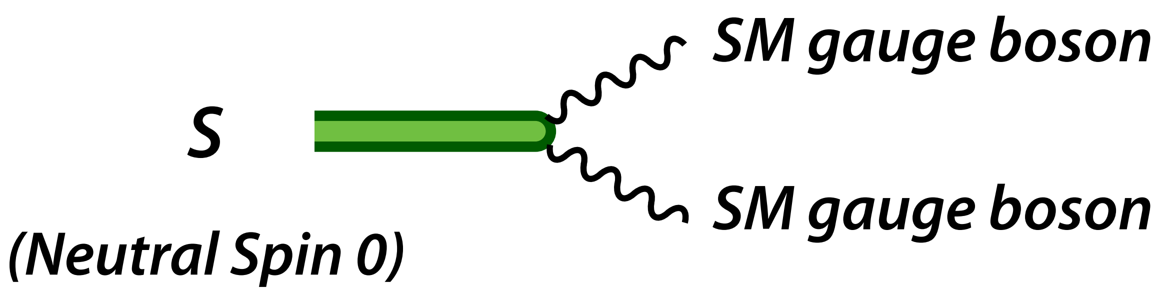
If the ***spin-0*** boson is a composite particle resulting from strong dynamics ***at the TeV scale***, the production cross section can be sizable !

Effective theory (*S* : composite ***spin-0*** neutral boson)

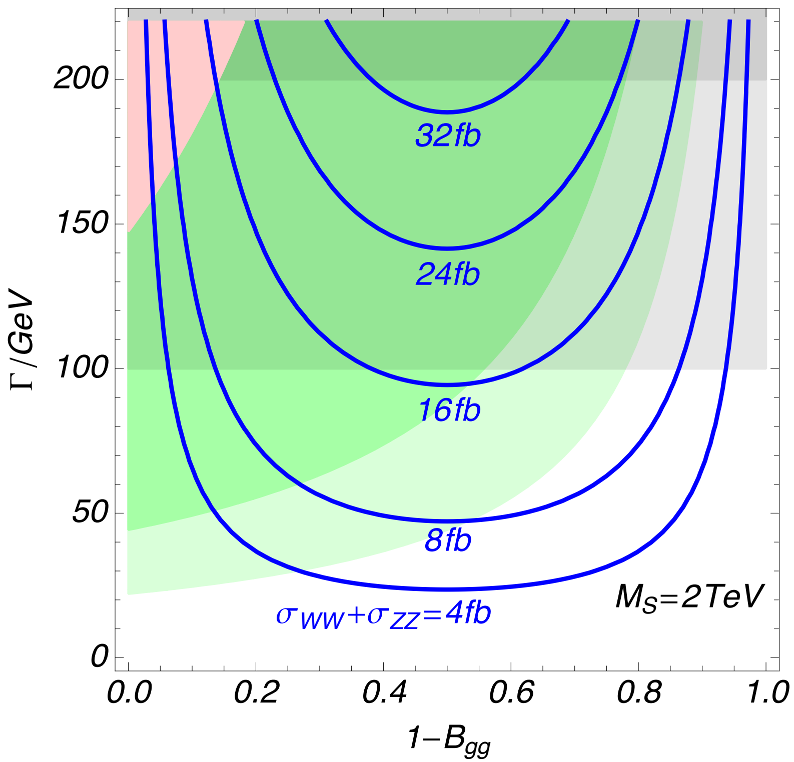
$$\mathcal{L}_{\rm eff} = \frac{\kappa_3}{\Lambda} S G^a_{\mu\nu} G^{a\,\mu\nu} + \frac{\kappa_2}{\Lambda} S W^i_{\mu\nu} W^{i\,\mu\nu} + \frac{5}{3}\frac{\kappa_1}{\Lambda} S B_{\mu\nu} B^{\mu\nu}$$

(Normalization : $\mathcal{L} = -\frac{1}{4g_s^2} G^a_{\mu\nu} G^{a\,\mu\nu} - \frac{1}{4g^2} W^i_{\mu\nu} W^{i\,\mu\nu} - \frac{1}{4g'^2} B_{\mu\nu} B^{\mu\nu}$)

($\Lambda = O(1)$*TeV* : dynamical scale)



Predicted cross section (8TeV)



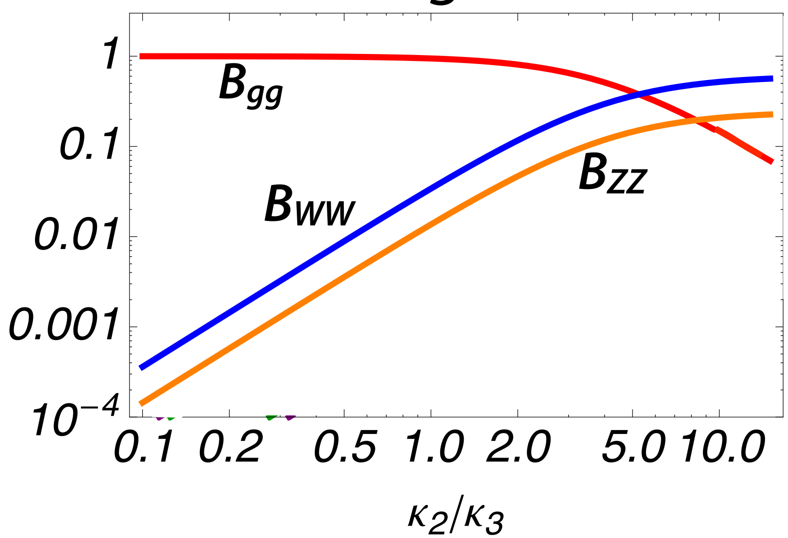
- Gray shaded region $\Gamma_S > 100$ GeV
- (light) Green shaded region $\sigma_{\gamma\gamma} > 0.3$ fb for $B_{\gamma\gamma} = 1\%$ (2%) [ATLAS, 1504.05511]
- Pink shaded region $\sigma_{gg} > 100$ fb [ATLAS, 1407.1376, CMS, 1501.04198]

- Allowed region with

  $\sigma_{WW+ZZ} \sim 5$ - 10 fb

  $\Gamma_S = O(10)$GeV

  $B_{WW}+B_{ZZ} \gtrsim 0.4$



- $B_{WW}+B_{ZZ} > 0.4$ is achieved for $\kappa_2/\kappa_3 > 2$ - 3 .

$$\left(\mathcal{L}_{\rm eff} = \frac{\kappa_3}{\Lambda} S G^a_{\mu\nu} G^{a\,\mu\nu} + \frac{\kappa_2}{\Lambda} S W^i_{\mu\nu} W^{i\,\mu\nu} \right)$$

Model of Hidden Dynamics

- Gauge Group : ***$SU(N)_H$ x SM Gauge group***
- Matter field : ***5 scalars in fundamental representations of $SU(N)_H$***

	$SU(N)_H$	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
Q_L	N	1	2	1/2
Q_D	N	3	1	1/3

- ***5*** scalars are in ***$(3,1)_{1/3}$, $(1,2)_{1/2}$*** reps. of ***$SU(3)_c$ x $SU(2)_L$ x $U(1)_Y$***
- Explicit Mass term of ***O(1) TeV*** ($m_L^2 < m_D^2$)

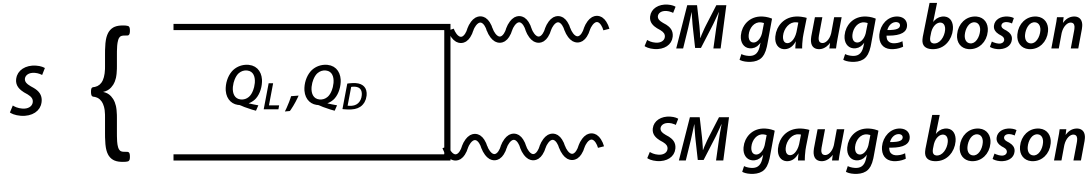
$$\mathcal{L} \supset -m_D^2 Q_D^\dagger Q_D - m_L^2 Q_L^\dagger Q_L$$

- Dynamical Scale : $\Lambda_{dyn} = O(1)\,TeV$

✔ By taking $m_{D,L} \lesssim \Lambda_{dyn}$, we assume that $Q_L^\dagger Q_L$ and $Q_D^\dagger Q_D$ dominate S.

$$S \propto \cos\theta_Q \times [Q_L^\dagger Q_L] + \sin\theta_Q \times [Q_D^\dagger Q_D]$$

(θ_Q decreases for $m_D \gg m_L$)



✔ Effective Lagrangian is given by

$$\mathcal{L}_{\rm eff} = \frac{\kappa_3}{\Lambda} S G^a_{\mu\nu} G^{a\,\mu\nu} + \frac{\kappa_2}{\Lambda} S W^i_{\mu\nu} W^{i\,\mu\nu} + \frac{5}{3}\frac{\kappa_1}{\Lambda} S B_{\mu\nu} B^{\mu\nu}$$

$$\frac{\kappa_3}{\Lambda} = \frac{\kappa \sin\theta_Q}{4\pi\Lambda_{\rm dyn}}\,, \quad \frac{\kappa_2}{\Lambda} = \frac{\kappa \cos\theta_Q}{4\pi\Lambda_{\rm dyn}}\,, \quad \frac{\kappa_1}{\Lambda} = \frac{\kappa}{4\pi\Lambda_{\rm dyn}} \frac{6}{5}\left(\frac{\sin\theta_Q}{3} + \frac{\cos\theta_Q}{2}\right)$$

[Naive dimensional analysis (NDA) ('97 Luty, '97 Cohen,Kaplan,Nelson)]

$\Lambda/\kappa = O(1)$TeV is possible within uncertainties !

$B_{WW}+B_{ZZ} > 0.4$ is possible for a small θ_Q ($m_D \gg m_L$) !

[If we do not use, NDA, we don't have ***4π*** suppressions.]

Dark Matter Candidate ?

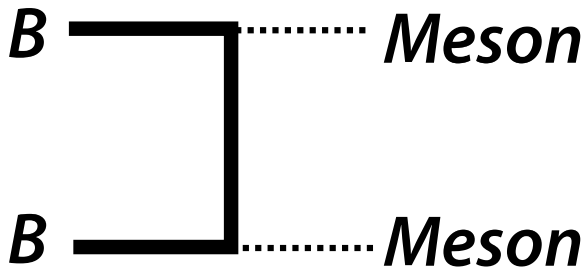
- ✓ Hidden sector so far has a global ***U(1)*** symmetry.
- ✓ The lightest ***U(1)*** charged composite field = ***Baryon*** !

For ***N*** **=** ***5*** , the lightest baryon is a neutral scalar !

$$B \propto QQQQQ$$

→ Dark matter candidate !

Abundance ?



- ✓ If $\sigma_{ann} \sim 4\pi/m_B^2$ (unitarity limit)

$$\Omega h^2 \sim 10^{-3} (10\mathrm{TeV}/m_B)^2$$

- ✓ However, since $m_B > \Lambda_{dyn}$, σ_{ann} can be suppressed by form factors $F(m_B)^4$:

$$\Omega h^2 \propto F(m_B)^{-4}$$

The thermal relic density of ***B*** can be consistent with the observed relic density !

(Detection is very difficult … heavy and suppressed interactions)

Summary

- ATLAS reported excesses in diboson resonance search.
  (No excesses in leptonic modes nor dijet modes at CMS)

- Standard Model ***neutral Spin-0*** resonance requires dynamical scale in the TeV range.

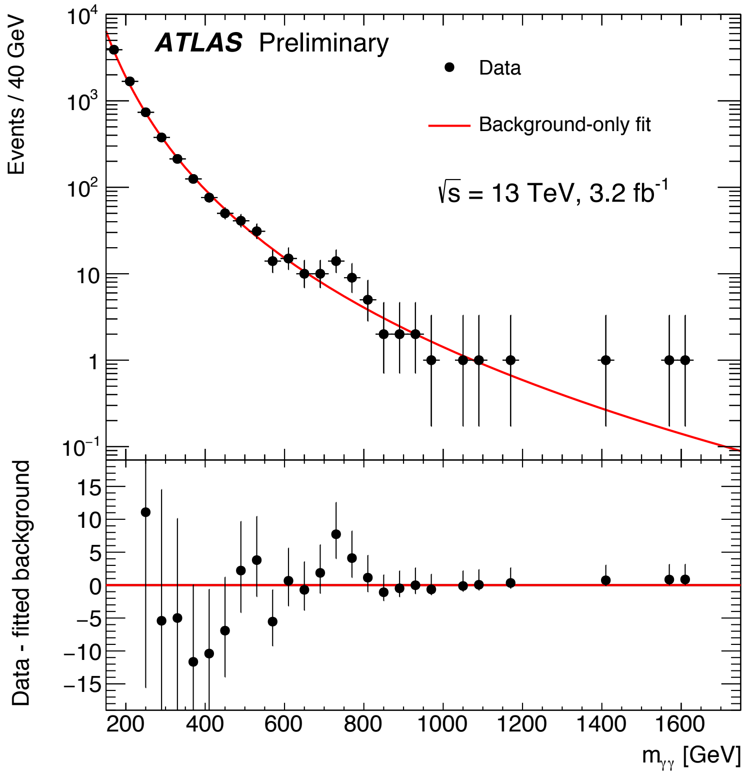
- Simple dynamical model can provide the desired ***spin-0*** particle for $m_{L,D} < \Lambda_{dyn}$.

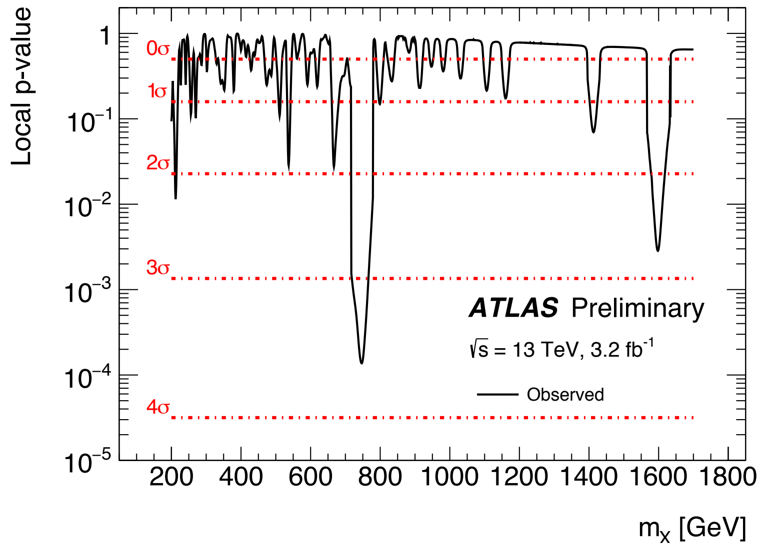
- The model predicts a lot of new charged particles in the TeV region!

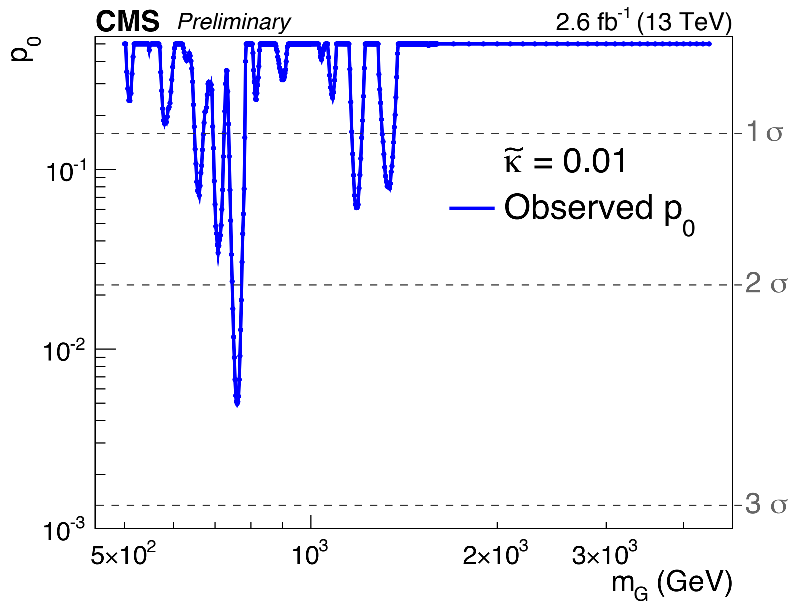
- Dark Matter can be provided as a lightest neutral baryon in the dynamical sector.

The diboson resonance can be a portal to a hidden strong dynamics !

News ! ✓ Apart from the 2TeV excess, ***both*** ATLAS and CMS reported an excess at 750GeV in di-photon search (2015/12/15)!







We could have some dynamics within a TeV range?

(Our model can be tuned to explain this 750GeV signal.)

Backup Slides

Partial Decay Widths

$$\Gamma(S \to g + g) = \frac{2}{\pi}\left(\frac{g_s^2 \kappa_3}{\Lambda}\right)^2 M_S^3$$

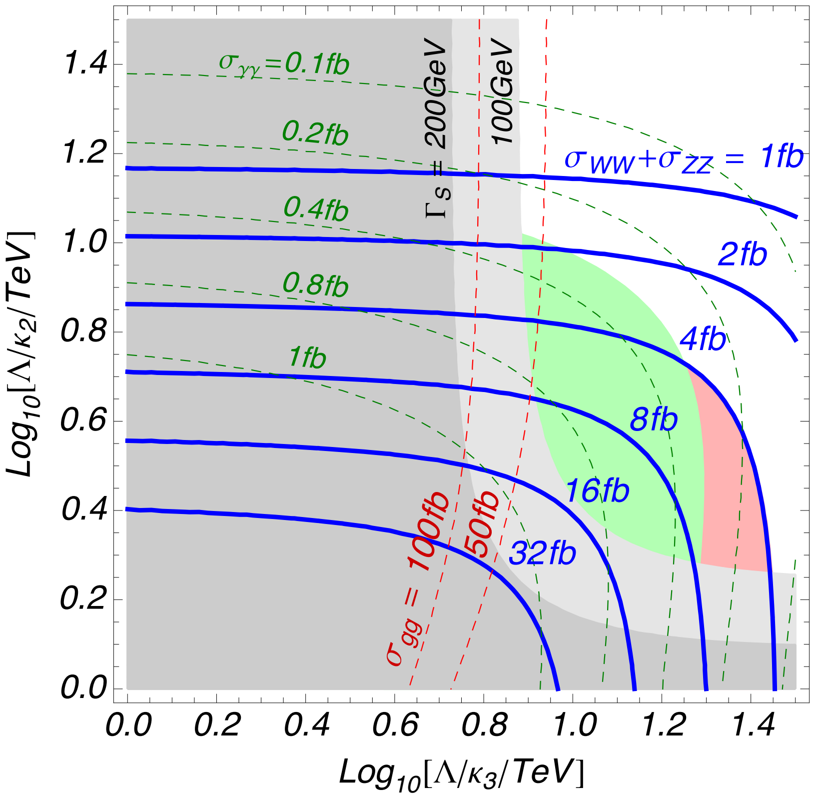
$$\Gamma(S \to W^+ + W^-) = \frac{1}{2}\frac{1}{\pi}\left(\frac{g^2 \kappa_2}{\Lambda}\right)^2 M_S^3 \ ,$$

$$\Gamma(S \to Z + Z) = \frac{1}{4}\frac{1}{\pi}\left[\left(\frac{g^2 \kappa_2}{\Lambda}\right) c_W^2 + \frac{3}{5}\left(\frac{g'^2 \kappa_1}{\Lambda}\right) s_W^2\right]^2 M_S^3 \ ,$$

$$\Gamma(S \to \gamma + \gamma) = \frac{1}{4}\frac{1}{\pi}\left[\left(\frac{g^2 \kappa_2}{\Lambda}\right) s_W^2 + \frac{3}{5}\left(\frac{g'^2 \kappa_1}{\Lambda}\right) c_W^2\right]^2 M_S^3 \ ,$$

$$\Gamma(S \to Z + \gamma) = \frac{1}{2}\frac{1}{\pi}\left[\left(\frac{g^2 \kappa_2}{\Lambda}\right) - \frac{3}{5}\left(\frac{g'^2 \kappa_1}{\Lambda}\right)\right]^2 c_W^2 s_W^2 M_S^3 \ ,$$

Cross section in terms of the model parameters



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- Pink shaded region $\sigma_{gg} > 100$ fb

✓ $\sigma_{WW}+\sigma_{ZZ} \sim 5$ -10 fb is allowed $\Lambda/\kappa \sim$ 1-1.4TeV

Naive Dimensional Counting ('97 Luty, '97 Cohen, Kaplan, Nelson)

$$S \propto \cos\theta_Q \times [Q_L^\dagger Q_L] + \sin\theta_Q \times [Q_D^\dagger Q_D]$$

(**θ_Q** decreases for $m_D \gg m_L$)

Operator Matching

$$S \simeq \frac{4\pi}{\kappa\Lambda_{\rm dyn}} \cos\theta_Q \times [Q_L^\dagger Q_L] + \frac{4\pi}{\kappa\Lambda_{\rm dyn}} \sin\theta_Q \times [Q_D^\dagger Q_D]$$

Effective Lagrangian is given by

$$\mathcal{L}_{\rm eff} = \frac{\kappa_3}{\Lambda} S G^a_{\mu\nu} G^{a\,\mu\nu} + \frac{\kappa_2}{\Lambda} S W^i_{\mu\nu} W^{i\,\mu\nu} + \frac{5}{3}\frac{\kappa_1}{\Lambda} S B_{\mu\nu} B^{\mu\nu}$$

$$\frac{\kappa_3}{\Lambda} = \frac{\kappa \sin\theta_Q}{4\pi\Lambda_{\rm dyn}}\,, \quad \frac{\kappa_2}{\Lambda} = \frac{\kappa \cos\theta_Q}{4\pi\Lambda_{\rm dyn}}\,, \quad \frac{\kappa_1}{\Lambda} = \frac{\kappa}{4\pi\Lambda_{\rm dyn}} \frac{6}{5}\left(\frac{\sin\theta_Q}{3} + \frac{\cos\theta_Q}{2}\right)$$

S is accompanied by charged spin-0 particles

$Q_{L,D}^{\dagger}Q_{L,D} \sim (1,1)_0 \times 2,\ (1,3)_0,\ (8,1)_0,\ (3,2)_{5/6}$ [25 states]

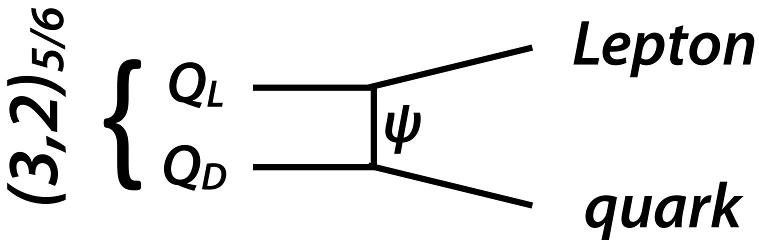
✓ Heavier singlets : ***$Q_D^{\dagger}Q_D$*** dominated but decaying to ***S***.

✓ Octet : decaying to two gluons [***$\sigma_{gg} < 30\text{fb}$ for $M_8 > 3\text{TeV}$***]

✓ Triplet : decaying to ***HH, WZ*** via $L = (H^{\dagger}\sigma^i H)(Q_L^{\dagger}\sigma^i Q_L)$

(produced via Drell-Yan process at the LHC)

✓ ***$(3,2)_{5/6}$*** : we need new particle to make ***$(3,2)_{5/6}$*** decay



$$\mathcal{L} \supset y\, Q_D^{\dagger}\, \psi_Q\, \bar{d}_R + y\, Q_L^{\dagger}\, \psi_Q\, \ell_L + M\psi\bar{\psi}$$

(***ψ*** : ***$SU(N)_H$*** fundamental fermion)

Higher spin modes are heavier and decay immediately .

Electroweak Precision Constraints 1

The decay operator

$$L = (H^\dagger \sigma^i H)(Q_L^\dagger \sigma^i Q_L)$$

leads to a tadpole to the triplet scalar

$$\mathcal{L} \simeq \frac{\lambda}{4\pi} \Lambda_{\rm dyn} H^\dagger \sigma^i H T^i \ ,$$

Thus, the triplet obtains a small VEV,

$$\langle T^3 \rangle \simeq \frac{\lambda v_{\rm EW}^2 \Lambda_{\rm dyn}}{4\pi M_T^2} = 0.6 \text{ GeV} \times \lambda \frac{\Lambda_{\rm dyn}}{1 \text{ TeV}} \left(\frac{M_T}{2 \text{ TeV}}\right)^{-2}$$

whose contribution to ***T***-parameter is small enough.

Electroweak Precision Constraints 2

The decay operator

$$L = (H^\dagger \sigma^i H)(Q_L^\dagger \sigma^i Q_L)$$

also induces

$$\frac{g^2}{16\pi^2}\frac{1}{m_L^2}(H^\dagger W^i_{\mu\nu}\sigma^i H)B^{\mu\nu}$$

which contributes to ***S***-parameter.

Again, it is very small.

Electroweak Precision Constraints 3

Spin-1 composite fields may have kinetic mixing
to the SM gauge boson

e.g. $\epsilon F^{'}_{\mu\nu} F^{\mu\nu}$

After removing the kinetic mixing and integrating out ***F'***,
we end up with

$$\frac{\epsilon^2}{M_F^2}(H^\dagger D H)^2 \qquad \frac{\epsilon^2}{M_F^2} J J$$

Both contributes to the electroweak precision measurements
but they are small enough for ***M_F > a few TeV.***