Exo-Higgs at 750 GeV and Genesis of Baryons

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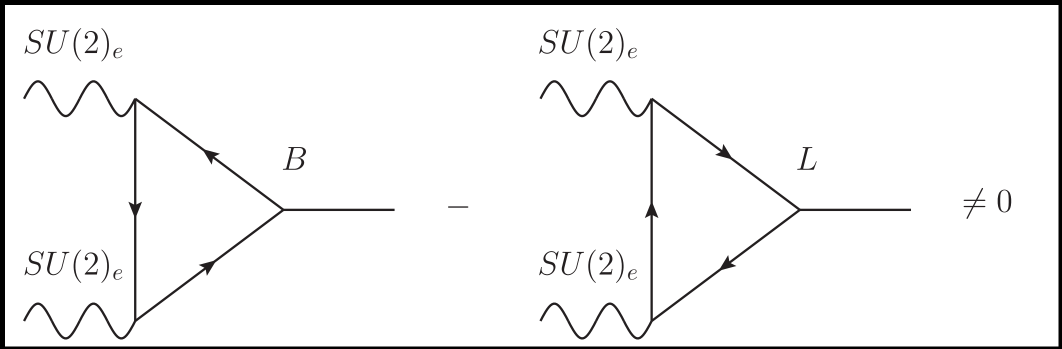


Based on: H. D., P. P. Giardino and C. Zhang, arXiv:1605.00037 [hep-ph]

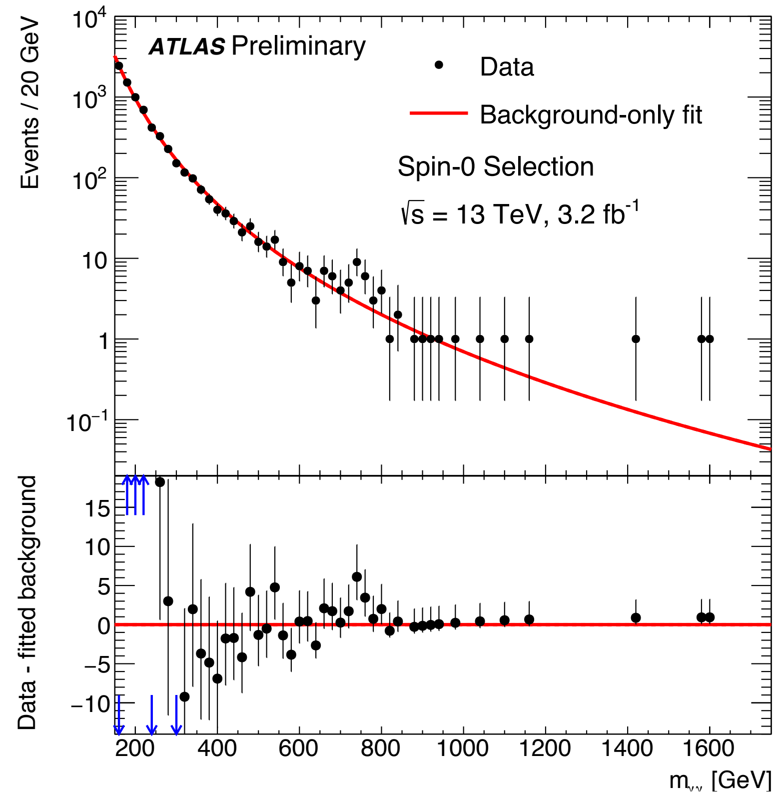
Exploring the Energy Ladder of the Universe

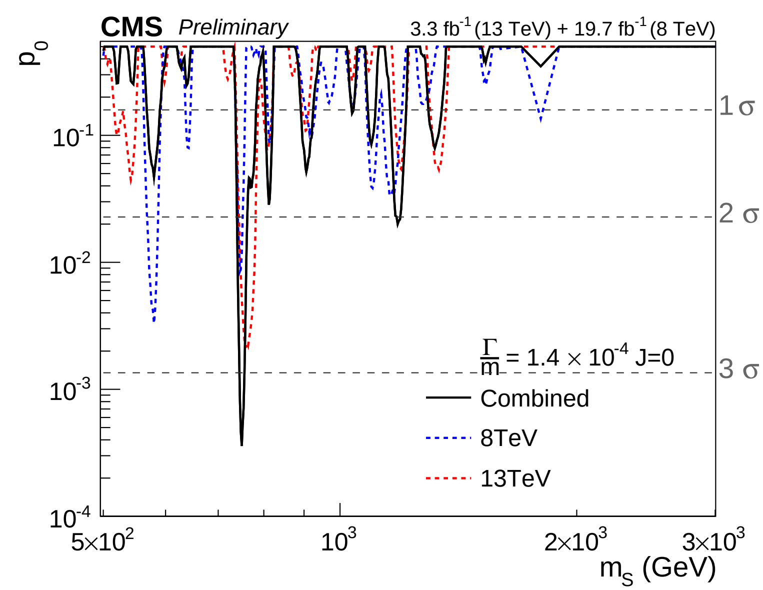
Workshop at the Mainz Institute for Theoretical Physics

Johannes Gutenberg University, Mainz, Germany, May 30 - June 10, 2016

The Data

- Diphoton excess at ~ 750 GeV
- Both ATLAS and CMS
- Local significance $> 3\sigma$
- Spin-0 or spin-2 possible
- $\lesssim 2\sigma$ compatible with 8 TeV data
  - Gluon initiated production favored
- Data not yet conclusive
- Encouraging features
  - Both experiments see it
  - Simple final state
  - Survived further analysis (Moriond 2016)





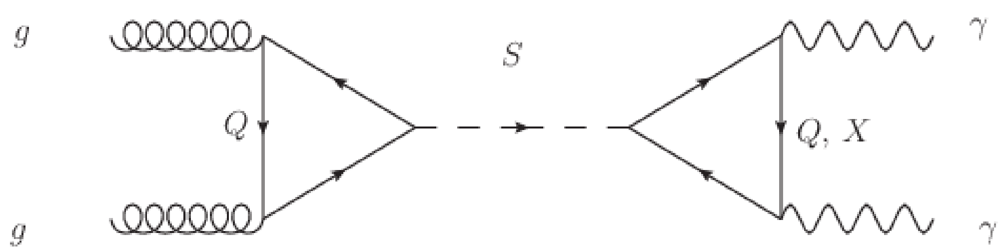
ATLAS and CMS presentations, Moriond 2016

Phenomenology

- Low statistics: presently several ideas are viable
- Composite or elementary states, spin-0, spin-2, 4γ final states (boost),. . .
- A large number of papers

- Very modest preference for wide width $\sim$ %6 (ATLAS)

- Simple popular model: scalar coupled to gg and $\gamma\gamma$ via loops
- Often a singlet scalar
- Experimental constraints disfavor only SM in the loops
- Generically, new heavy ($m \gtrsim 375$ GeV) states wuth color and charge needed



This Talk

- Consider a scalar resonance η at 750 GeV
- Natural assumption: η a Higgs boson   Exo: Greek for outside
- Gauged $SU(2)_e$ *exo-spin* breaking via *exo-Higgs* vev $\langle\eta\rangle \neq 0$
- New chiral *exo-fermions* with masses $\propto \langle\eta\rangle$ and charges
- Exo-spin (chiral); color, and hypercharge (vector-like)
- $B - L$ anomaly under $SU(2)_e$
- Assume $SU(2)_e$ breaking a first order phase transition (PT):
- Early universe: $\Delta(B-L) \neq 0 \xrightarrow{EW\, sphalerons} \Delta B \neq 0$ Harvey, Turner, 1990
- Analogy with EW baryogenesis

- Heavy exo-fermions, non-decoupling for large mass
- Similar to SM Higgs with heavy top
- Signal strength for $gg \to \eta \to \gamma\gamma$ mostly set by $\langle\eta\rangle$
- Given m_η and $\langle\eta\rangle \to$ Self coupling λ_η
- The signal strength determines the η potential
- Further assume that $\eta^\dagger \eta H^\dagger H$ sets SM Higgs mass parameter
- Reduce parameters
- Relative proximity of η and H mass scales
- Strong first order PT $\to$ lower bound on $SU(2)_e$ coupling g_e

The Model

HD, Giardino, Zhang, 1605.00037

- $SU(2)_e$ completely broken by $\langle \eta \rangle = v_\eta/\sqrt{2}$
- Three degenerate gauge bosons ω_1, ω_2, ω_3
- Exo-fermion charges under $SU(2)_e \otimes SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$

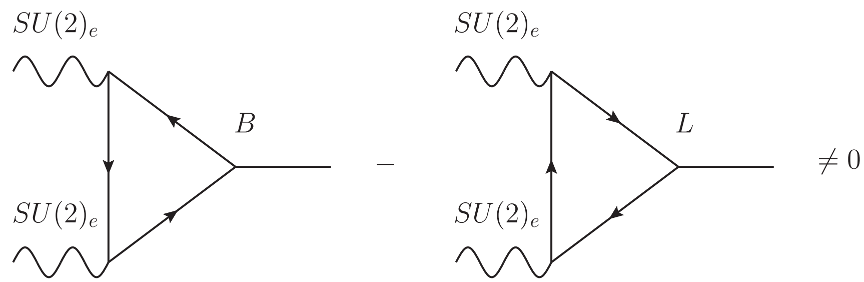
$$\begin{aligned} \text{ϙ}_L &= (2, 3, 1, -\tfrac{1}{3}) && \textit{exo-quarks} \\ \text{ϙ}_R &= (1, 3, 1, -\tfrac{1}{3}) \quad (\times 2) \\ \Lambda_L &= (1, 1, 1, -1) \quad (\times 2) \\ \Lambda_R &= (2, 1, 1, -1) && \textit{exo-leptons} \end{aligned}$$

ϙ: Archaic Greek letter Qoppa

- Three generations of exo-quarks and exo-leptons
- ϙ_L (Λ_R) exo-doublet components: $\text{ϙ}_R^{\wedge,\vee}$ ($\Lambda_L^{\wedge,\vee}$)

- No gauge or Witten anomaly (even number of exo-doublets)

- Global $B-L$ anomaly if $\mathbf{\Upsilon}$ and $\mathbf{\Lambda}$ assigned B and L



- $B+L$ preserved under $SU(2)_e$

- Scalar potential: $\boxed{V = \lambda_H |H^\dagger H|^2 - \mu_\eta^2 \eta^\dagger \eta + \lambda_\eta |\eta^\dagger \eta|^2 - 2 k_{\eta H} \eta^\dagger \eta H^\dagger H}$

- $\mu_H^2 H^\dagger H = k_{\eta H} v_\eta^2$ induced by the "Higgs portal"

- $\mu_H = \sqrt{\lambda v_H^2}$, with $v_H \approx 246$ GeV the SM Higgs vev

- Stable potential since $k_{\eta H}^2 \ll \lambda_H \lambda_\eta$ with our parameters

- Yukawa and mixing terms

$$\begin{aligned}\mathcal{L}_Y &= -Y_{\Koppa}^{\vee;i,j}\eta\bar{\Koppa}^i_L\Koppa_R^{\vee;j} - Y_{\Koppa}^{\wedge;i,j}\tilde{\eta}\bar{\Koppa}^i_L\Koppa_R^{\wedge;j} \\ &- Y_{\Lambda}^{\vee;i,j}\eta\bar{\Lambda}^i_R\Lambda_L^{\vee;j} - Y_{\Lambda}^{\wedge;i,j}\tilde{\eta}\bar{\Lambda}^i_R\Lambda_L^{\wedge;j}\end{aligned}$$

$$\begin{aligned}\mathcal{L}_m &= -Y_{\Koppa q}^{\vee;i,j}\eta\,\bar{\Koppa}^i_L d^j_R - Y_{\Koppa q}^{\wedge;i,j}\;\tilde{\eta}\,\bar{\Koppa}^i_L d^j_R \\ &- Y_{q\Koppa}^{\vee;i,j}H\bar{q}^i_L\Koppa_R^{\vee;j} - Y_{q\Koppa}^{\wedge;i,j}H\bar{q}^i_L\Koppa_R^{\wedge;j} \\ &- \mathcal{M}_{\Lambda}^{\wedge;i,j}\bar{\Lambda}_L^{\wedge;i}e^j_R - \mathcal{M}_{\Lambda}^{\vee;i,j}\bar{\Lambda}_L^{\vee;i}e^j_R.\end{aligned}$$

- $\mathcal{M}_\Lambda \ll v_H$: a new mass scale
  - May descend from higher dimension operators
- To avoid FCNCs, Yukawa and mixing terms assumed diagonal
  - Small off-diagonal terms do not change our main conclusions
- Degeneracy (simplicity): within a generation, also $\mathbf{\Lambda^i}$, and $\Koppa^{1,2}$

Relevance to Cosmology

- Strong first order $SU(2)_e$ PT at $T \sim 1$ TeV: possible $\Delta(B-L) \neq 0$
- Similar to EW baryogenesis via charge transport; extra CPV from the exo-sector
- SM electroweak sphalerons: $\Delta(B-L) \neq 0 \to \Delta B \neq 0$
- SM Higgs: EWSB not a strong first order PT, $ET\phi^3$ term too small
- In our model: $E = \frac{3\, m_\omega^3}{4\pi v_\eta^3} = \frac{3\, g_e^3}{32\pi}$
- Strong first order PT: $\eta(T_c)/T_c \gtrsim 1 \Rightarrow 2E/\lambda_\eta(T_c) \gtrsim 1$
- $\lambda_\eta(T_c) \approx \lambda_\eta \Rightarrow \dfrac{3\, g_e^3}{16\pi\, \lambda_\eta} \gtrsim 1$ See, *e.g.*, Quiros, hep-ph/9901312
- Signal strength $\to v_\eta$ and λ_η ($m_\eta = 750$ GeV) $\to$ lower bound on g_e
- May be possible to test this baryogenesis scenario at colliders

Signal Strength

- For heavy fermions, signal strength largely set by $\langle\eta\rangle$

- Interaction with gluons and photons:

$$\mathcal{L} = \frac{\alpha_s}{3\pi v_\eta} N_{♀} \frac{1}{4} G^A_{\mu\nu} G^{A\mu\nu} \eta + \frac{2\alpha}{3\pi v_\eta} \sum_{♀,\Lambda} N_c Q_f^2 \frac{1}{4} F_{\mu\nu} F^{\mu\nu} \eta$$

- Benchmark values

v_η	=	1.2TeV	Vev of the η field
$m_{♀}^{>}$	=	800GeV	Mass of the heavier ♀
$m_{♀}^{<}$	=	500GeV	Mass of the lighter ♀'s
m_Λ	=	380GeV	Mass of Λ's
$\mathcal{M}_\Lambda$	=	1GeV	$\Lambda - l$ mixing mass parameter
$\theta^{♀}_{L,R}$	=	10^{-3}	$♀ - q$ mixing angles
g_e	=	2	$SU(2)_e$ gauge coupling

- Cross section of 4.1 fb, with NLO+NNLL K-factor of 1.56

- Weighted average of ATLAS and CMS data: 4.6 ± 1.3 fb.

Higgs Portal Signals

- H-η mixing from $-2k_{\eta H}\eta^\dagger\eta H^\dagger H$:
  - $\sin\theta_{\eta H} = 0.006$
  - Set to get the correct μ_H^2 for EWSB
  - Allows η to couple to W^+W^-, ZZ, $t\bar{t}$, and HH
  - Benchmark consistent with Run 1 data
  - Larger $\theta_{\eta H}$ would suppress signal strength

Mode	BR
gg	82.1%
W^+W^-	7.4%
HH	4.2%
ZZ	3.7%
$t\bar{t}$	1.8%
$\gamma\gamma$	0.81%
γZ	0.47%
$l\Lambda$	0.12%
Γ_η	0.060 GeV

- Benchmark $ZZ(WW)$ BR 4 (9) times larger than BR($\eta \to \gamma\gamma$)
  - Loops of only hypercharged fermions:
  - Suppression by $\tan^2\theta_W$ of ZZ coupling compared to $\gamma\gamma$
  - No significant coupling to WW

- Measuring BR($\eta \to ZZ$)/BR($\eta \to \gamma\gamma$) can yield H-η mixing

- Mixing-dominated W and Z couplings to η: $\frac{\text{BR}(\eta\to WW)}{\text{BR}(\eta\to ZZ)} \approx 2$

Fermion Decays

- Third generation exo-quarks:

- $♀ \to tW^-, bZ, bH$, with BRs $\sim 50\%$, $\sim 25\%$, and $\sim 25\%$, respectively
- Mass $m_{♀}^{>} = 800$ GeV

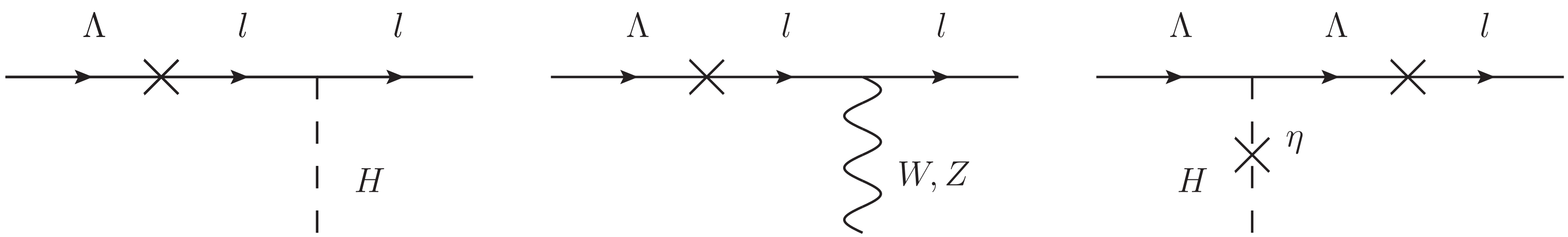
\- Run 1 vector-like B quark mass bound: 790 GeV CMS Collaboration, 2015

- First two exo-quark generations: main decays into Wj, Zj, and Hj

- Avoid $\eta \to ♀♀$: $m_{♀} > m_\eta/2$
- Bounds not very restrictive
- $\theta^{♀}_{L,R} = 10^{-3}$ ($\lesssim \mathcal{O}(1\%)$: $\eta \to q\bar{♀}, ♀\bar{q}$ would not suppress signal)

- Exo-leptons: $m_\Lambda > m_\eta/2$

- We choose 380 GeV to enhance the signal (no significant tuning needed)
- Λ_L-l_R mass coupling, but Λ_R-l_L not allowed: $\dfrac{\tan\theta^\Lambda_L}{\tan\theta^\Lambda_R} = \dfrac{m_l}{m_\Lambda}$
- We choose $\mathcal{M}_\Lambda = 1$ GeV: $\theta^\Lambda_R \approx 2.7 \times 10^{-3}$



Decays of a Λ into a lepton. The decay into τ is mostly mediated by the first two processes, while the decays into μ and e are mostly mediated by the third, since the first two are suppressed by m_e and m_μ.

Mode	$\Lambda^{\wedge,\vee;1}$	$\Lambda^{\wedge,\vee;2}$	$\Lambda^{\wedge,\vee;3}$
Hl	100%	84.0%	22.0%
$W^-\nu$	$\sim 10^{-6}$	10.6%	52.1%
Zl	$\sim 10^{-6}$	5.3%	25.9%

Λ branching ratios

Predictions

- Exo-fermions $\female$ and Λ similar to usual vector-like fermions

- Distinct signature: exo-gauge bosons $\omega^{\uparrow,\downarrow} = (\omega^1 \mp i\omega^2)/\sqrt{2}$ and ω^3

- Production via $gg \to \omega\omega$ and $gg \to \omega j$, mediated by $\female$ loops

- Single ω production traced over T^3, vanishing for degenerate $\female^\wedge$ and $\female^\vee$
- For this process, we assume $\female^\wedge$ 300 GeV heavier

- Tree-level single production negligible for $\theta^{\female}_{L,R} \lesssim 10^{-2}$

- $q\bar{q} \to \omega$ suppressed by $(\theta^{\female}_{L,R})^4$
- $gq \to \female\omega$ suppressed by $(\theta^{\female}_{L,R})^2$
- Benchmark: $\theta^{\female}_{L,R} = 10^{-3}$

Process	8 TeV	13 TeV	14 TeV
$gg \to \omega^3 j$	0.016 fb	0.16 fb	0.26 fb
$gg \to \omega\omega$	0.003 fb	0.11 fb	0.17 fb

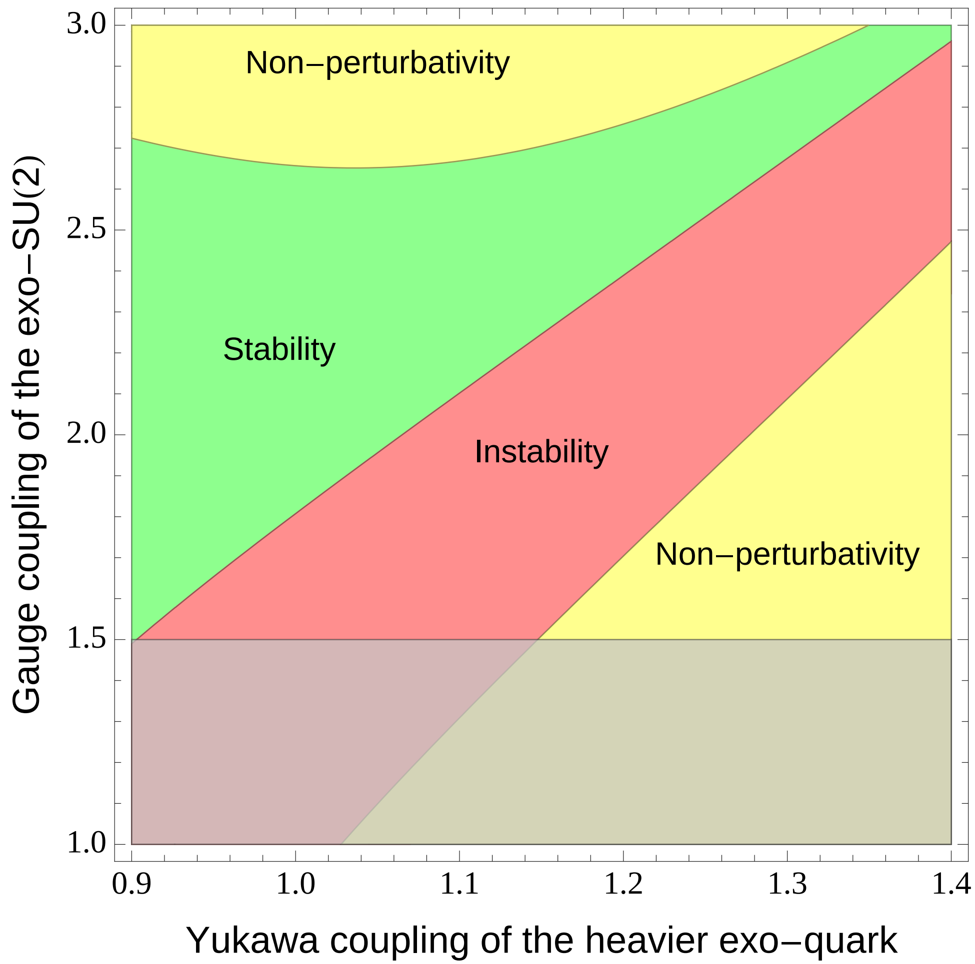
LHC cross sections for ω production. Double production summed over all exo-vector bosons.

- Focus on double-ω production (less sensitive to exo-quark spectrum)
- For example, $\omega^3 \to \Lambda^{\wedge,\vee;i+}\Lambda^{\wedge,\vee;i-}$ for $i = 1,2$ (e,μ); BR $\sim 28.8\%$
- $0.17 \times 300 \times 28.8\%^2 = 4.2$ events with 4 Λ's for 300 fb^{-1} of data at 14 TeV
- $\Lambda^{\wedge,\vee;1}$ ($\Lambda^{\wedge,\vee;2}$) BR into eH $(\mu H/Z) \sim 100\%(90\%)$
- ~ 3.5 signal events: 4 hard leptons, $p_T \sim 100-200$ GeV, additional jets or leptons

- Irreducible and reducible backgrounds, *e.g.* $tt\overline{tt}$, negligible or can be suppressed
- $p_T(l) > 80$ GeV, no missing E_T, additional jet/lepton requirements
- SM $4l$: remove l^+l^- from Z's, $p_T(l) > 80$ GeV, require additional jets

UV Behavior

- Stability: $\lambda_\eta > 0$ and no $y_♀$ (800 GeV) or λ_η Landau poles
- UV completion scale: $\bar{\mu} = 10^5$ TeV
- Gray region: disfavored if requiring strong first order transition
- Coincides with "Stability" (larger g_e)



Concluding Remarks

- Diphoton excess may be due to an exo-Higgs η at 750 GeV

- We considered a gauged $SU(2)_e$ broken by $\langle\eta\rangle \sim 1$ TeV

- Suitable charge assignments yield a $B-L$ anomaly under $SU(2)_e$

- Strong first order PT mediated by η may yield $\Delta(B-L) \neq 0$
- Possible gravitational wave signals within the reach of LISA

- Distinct signature: $SU(2)_e$ exo-vector bosons at ~ 1 TeV
- Within reach at LHC with 300 fb^{-1}

- $SU(2)_e$ breaking may trigger EWSB via the Higgs portal