The 750 GeV diphoton excess and its implications for Z'

Kunio Kaneta (IBS CTPU)

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in collaboration with Subeom Kang and Hye-Sung Lee

Overview on the recent di-photon excess at the LHC Run 2 at IBS CTPU, Jan. 8, 2016

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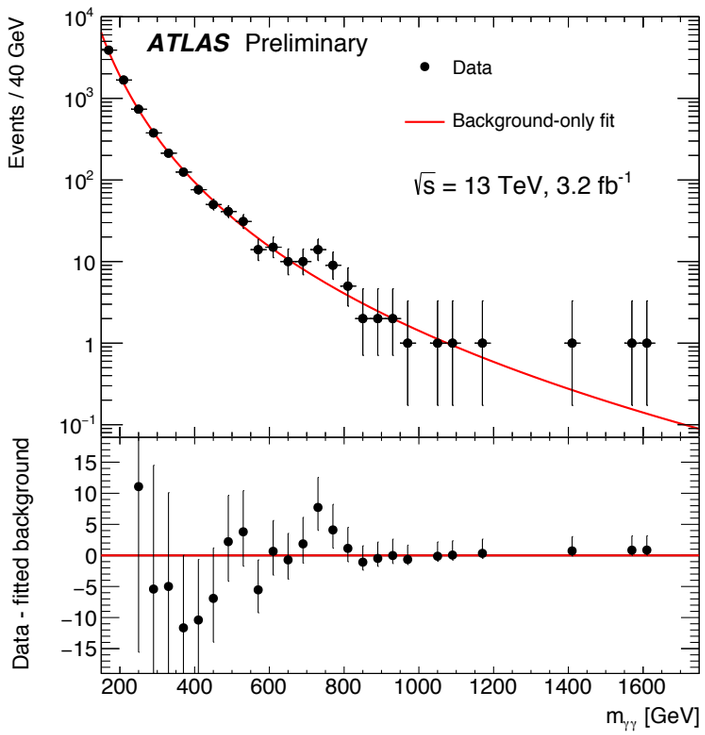
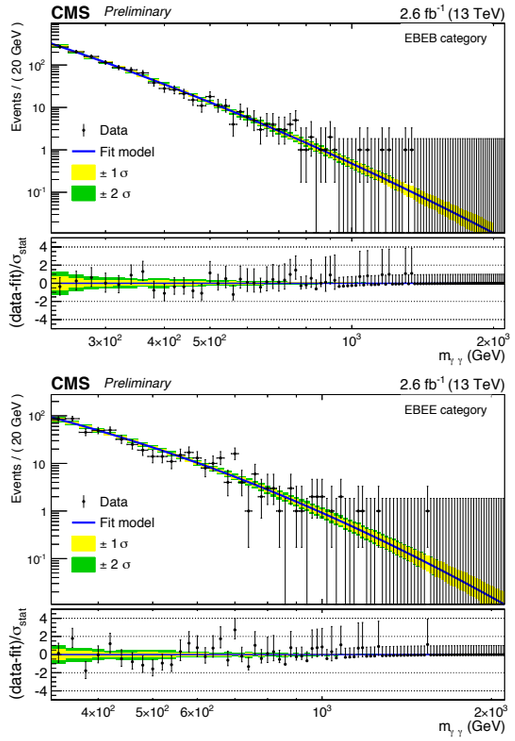
1. Introduction

750 GeV diphoton excess at LHC

[D.Buttazzo, et al. '15]



[ATLAS-CONF-2015-081]



[EXO-15-004]

(ATLAS)

$$\sigma(pp \to s) \times \mathrm{Br}(s \to \gamma\gamma) = 6.0^{+2.4}_{-2.0}\ \mathrm{fb}$$

(CMS)

$$\sigma(pp \to s) \times \mathrm{Br}(s \to \gamma\gamma) = 5.6^{+2.4}_{-2.4}\ \mathrm{fb}$$

- The diphoton excess is not significant yet.
- If confirmed, it would be a strong indication of the existence of a new particle belonging to new physics beyond the SM.
- So, at this stage, it seems reasonable to ask following question:

Who ordered the 750-GeV resonance?

- Our ambitious answer: new gauge symmetry
- The 750-GeV resonance: new scalar field being responsible for the symmetry breaking

- A guiding principle: the unification of the gauge coupling constants (inspired GUTs) (following the success of the unified description of EW theory)
- New charged particles are predicted.
- Prediction of Z' mass as a bonus

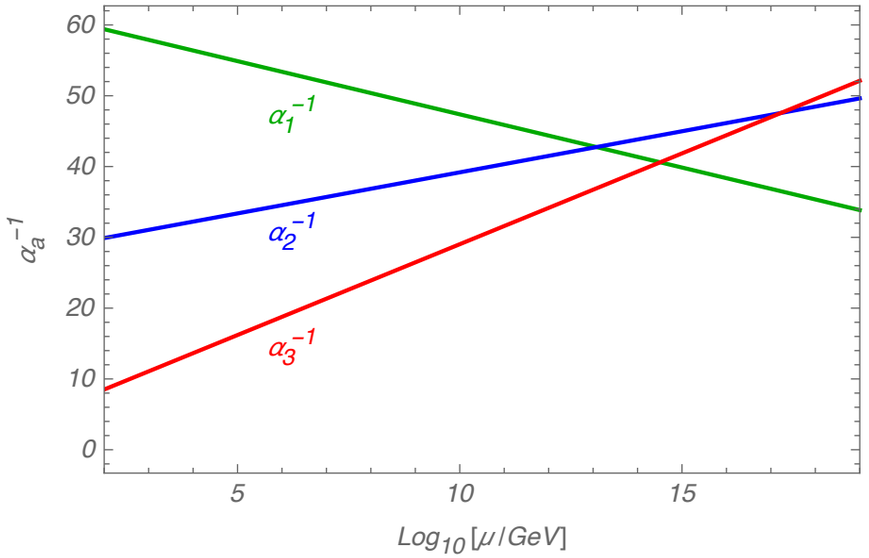
2. The model in view of the unification

The unification of the gauge coupling constants

➢ The SM fails to lead the unification at a certain high energy scale when we simply extrapolate the running couplings toward very high energies.

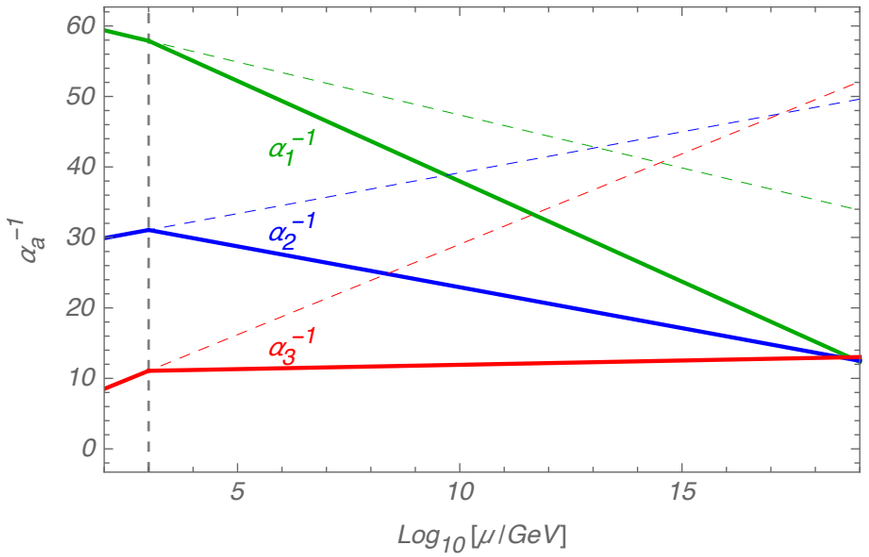
$$\frac{d\alpha_a^{-1}}{d\ln\mu} = \frac{b_a}{2\pi} \qquad (a = 1, 2, 3)$$

$$(b_1^{\mathrm{SM}}, b_2^{\mathrm{SM}}, b_3^{\mathrm{SM}}) = (41/10, -19/6, -7)$$

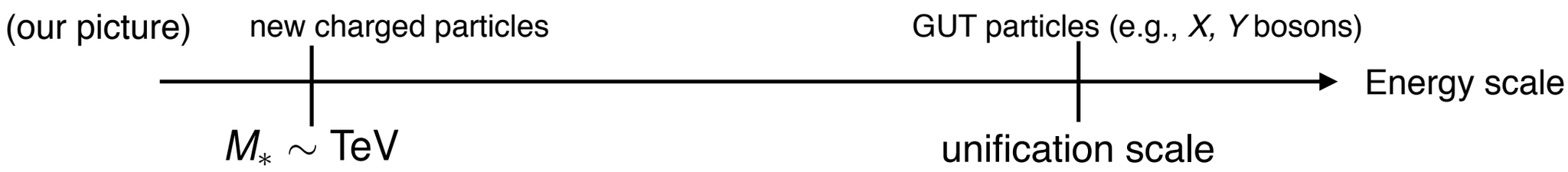


➢ The idea of the grand unified theory inevitably requires new charged particles with masses being in-between the EW scale and the unification scale.

➢ A non-trivial mass spectrum to achieve the unification might guide us to a legitimate effective theory.



➢ In what follows let us suppose that new charged particles have the universal mass scale (M_*) with M_* being TeV scale.



Finding out the model in view of the unification

➢ At one-loop level, the gauge coupling constants at the GUT scale is given by

$$\alpha_a^{-1}(M_{\rm GUT}) = \alpha_a^{-1}(M_Z) - \frac{b_a^{\rm SM}}{2\pi}\ln\frac{M_*}{M_Z} - \frac{\Delta_a}{2\pi}\ln\frac{M_{\rm GUT}}{M_*} \qquad (\Delta_a \equiv b_a - b_a^{\rm SM})$$

where the GUT scale is defined by $\alpha_1^{-1}(M_{\rm GUT}) = \alpha_2^{-1}(M_{\rm GUT})$

➢ By fixing $M_* \sim$ TeV scale, M_{GUT} is determined as

$$M_{\rm GUT} = \left[e^{-(\alpha_2^{-1}-\alpha_1^{-1})} M_Z^{-(b_2^{\rm SM}-b_1^{\rm SM})/(2\pi)} M_*^{-(\Delta_2-\Delta_1)/(2\pi)}\right]^{-\frac{2\pi}{(b_2^{\rm SM}-b_1^{\rm SM})+(\Delta_2-\Delta_1)}}$$

➢ For the unification of three gauge couplings, we usually should take into account threshold corrections by other GUT-scale particles. (necessary to specify a concrete GUT model)

➢ Here, instead of specifying a model, let us discuss the unification based on quantifing the degree of unification in terms of the size of the required threshold correction at M_{GUT}:

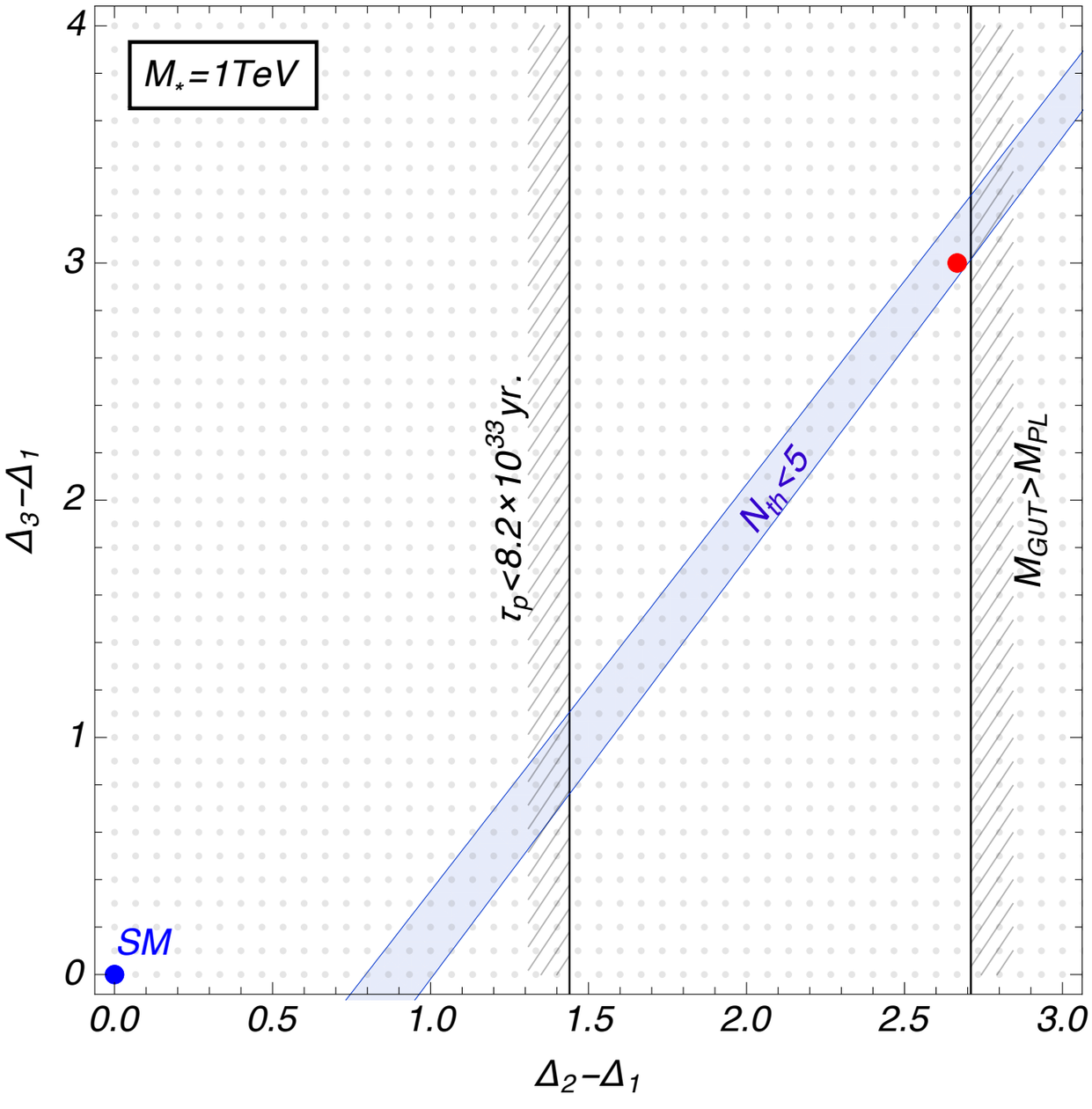
$$N_{\rm th} \equiv 2\pi|\alpha_3^{-1}(M_{\rm GUT}) - \alpha_1^{-1}(M_{\rm GUT})| = |(\Delta_3 - \Delta_1)\ln\frac{M_{\rm GUT}}{M_*} + \cdots|$$

(cf. in MSSM, $N_{\rm th} \lesssim 5$ if SUSY particles are round TeV scale)

[J.Bagger, et al. '95]

Finding out the model in view of the unification

➢ We can find successful models by utilizing M_{GUT} and Nth in terms of Δ_2-Δ_1 and Δ_3-Δ_1.



➢ Each gray dot represents a set of models that lead to the same evolution of the gauge coupling constants.

➢ $N_{th} < 5$ as a reference for the unification

➢ We may need to require $M_{GUT} < M_{PL}$.

➢ Proton life time is also sensitive to the GUT scale if we impose only GUT particles (X, Y bosons) can induce the proton decay.

Finding out the model in view of the unification

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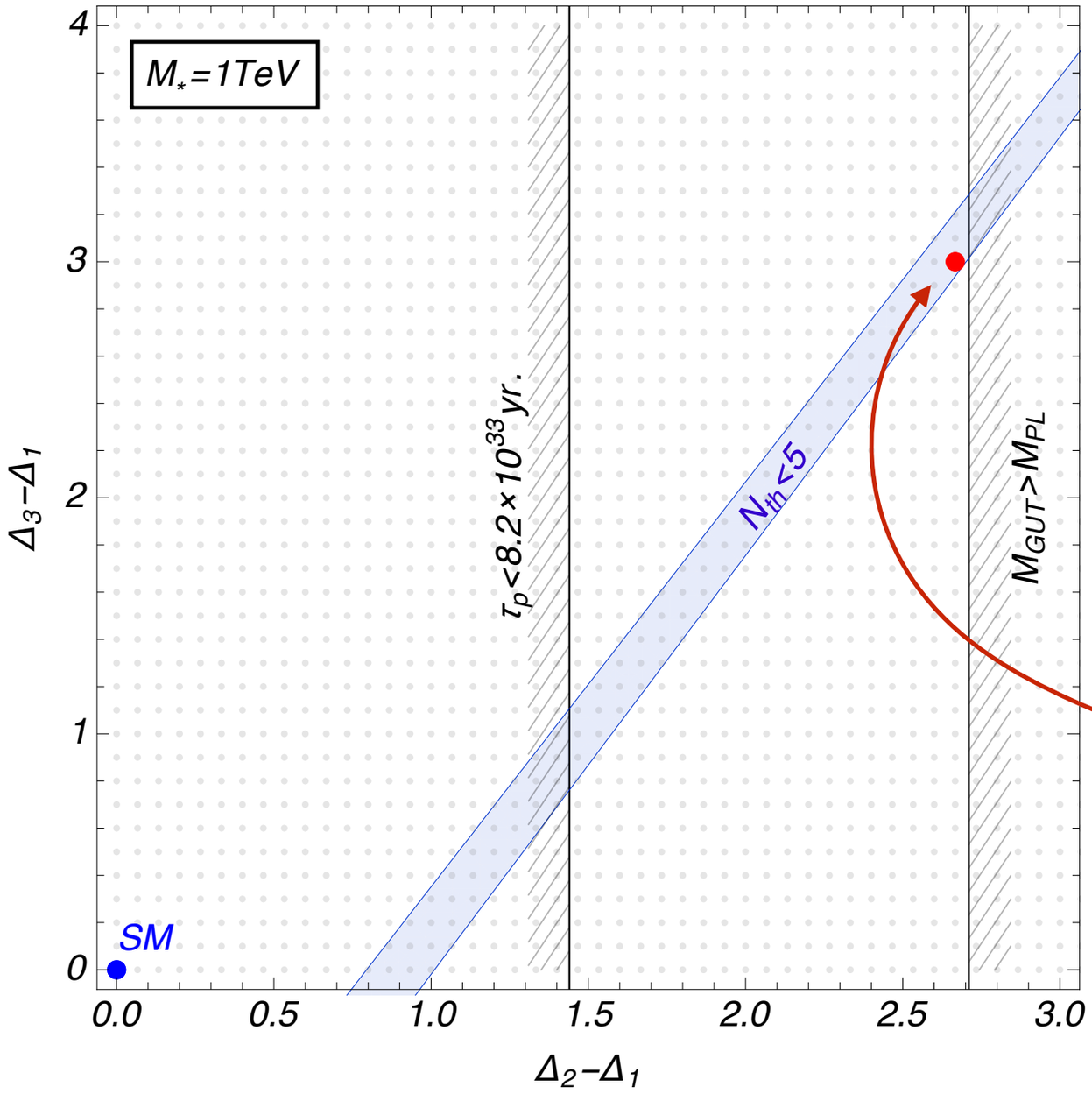


➢ For simplicity, let us introduce only squark-like and wino-like particles:

$$\widetilde{Q} = (3, 2, 1/6),\ \ \widetilde{U} = (3, 1, 2/3),$$
$$\widetilde{D} = (3, 1, -1/3),\ \ \widetilde{W} = (1, 3, 0)$$

$$\Rightarrow \begin{cases} \Delta_2 - \Delta_1 = \frac{1}{15}(7n_{\widetilde{Q}} - 4n_{\widetilde{U}} - n_{\widetilde{D}} + 20n_{\widetilde{W}}), \\ \Delta_3 - \Delta_1 = \frac{1}{10}(3n_{\widetilde{Q}} - n_{\widetilde{U}} + n_{\widetilde{D}}) \end{cases}$$

➢ We can find a solution that the unification can be perturbatively achieved:

$$n_{\widetilde{Q}} = n_{\widetilde{U}} = n_{\widetilde{D}} = 10,\ \ n_{\widetilde{W}} = 1$$

➢ Let us scrutinize this setup in the following.

The model

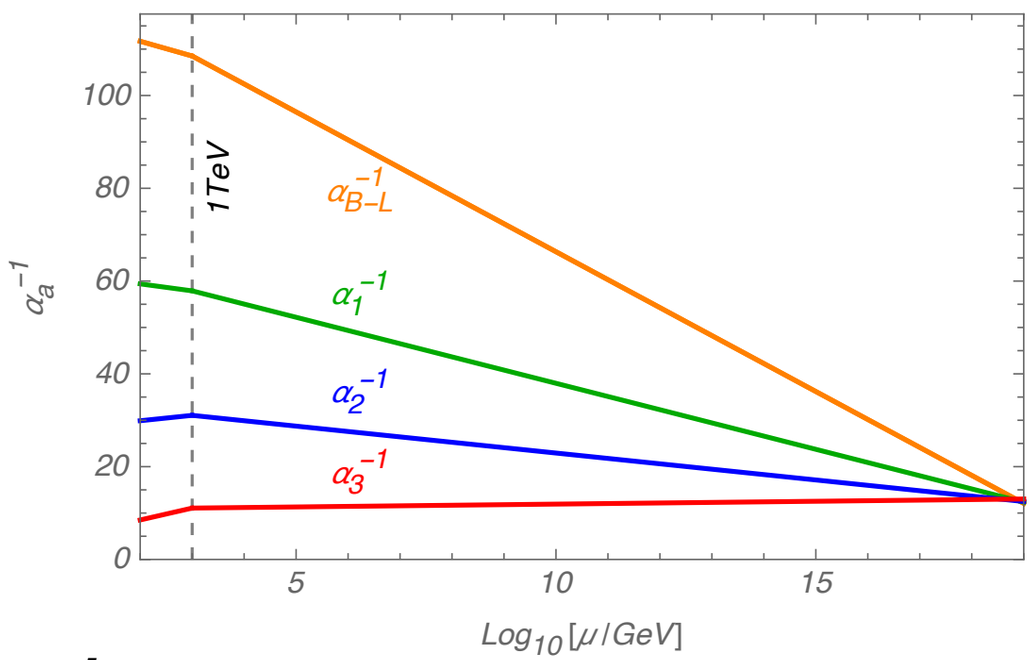
- One important fact of this particle contents is that the rapid proton decay is inevitable due to the tree-level contributions of $\widetilde{D}$ scalars.
- Gauged *B-L* symmetry is a good symmetry to forbid such harmful interactions.
- Now, our model is summarized in the table in which *N* is a right-handed neutrino, and *S* denotes a complex scalar field that spontaneously breaks $U(1)_{B\text{-}L}$ by having a VEV of $\langle S \rangle = f$.

	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_{B-L}$
$\widetilde{Q}$'s	3	2	$1/6$	$1/3$
$\widetilde{U}$'s	3	1	$2/3$	$1/3$
$\widetilde{D}$'s	3	1	$-1/3$	$1/3$
$\widetilde{W}$'s	1	3	0	0
N's	1	1	0	-1
S	1	1	0	2

- Once we introduce *B–L* gauge symmetry, we have an additional gauge boson, *Z′*, whose mass is given by

$$M_{Z'}^2 = 8 g_{B-L}^2 f^2 (= 32\pi\alpha_{B-L} f^2)$$

- In the viewpoint of GUT, we expect that the *B–L* gauge coupling at the EW scale is also derived from the universal coupling at the GUT scale.



- ***This allows us to predict Z' mass at low energies.***

3. Diphoton excess and Z’

The 750-GeV resonance

➢ The potential of scalar fields in the model is given by

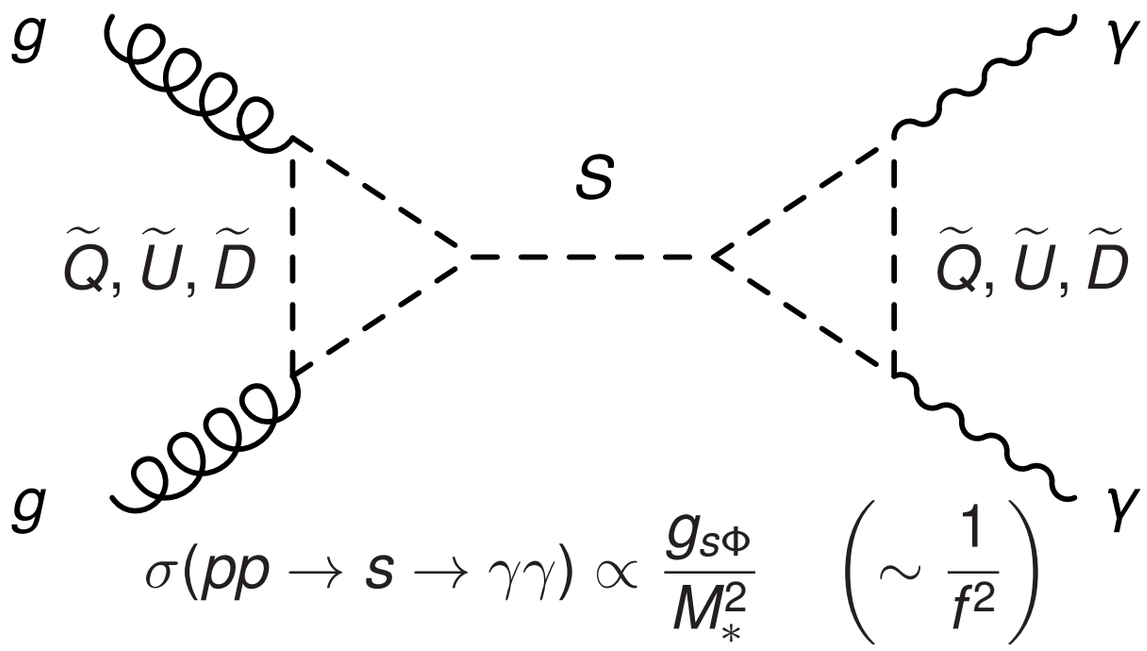
$$V = V_H(H) + V_S(S) + V_{HS}(H,S) + \sum_{\Phi}[V_\Phi(\Phi) + V_{H\Phi}(H,\Phi) + V_{S\Phi}(S,\Phi)]$$

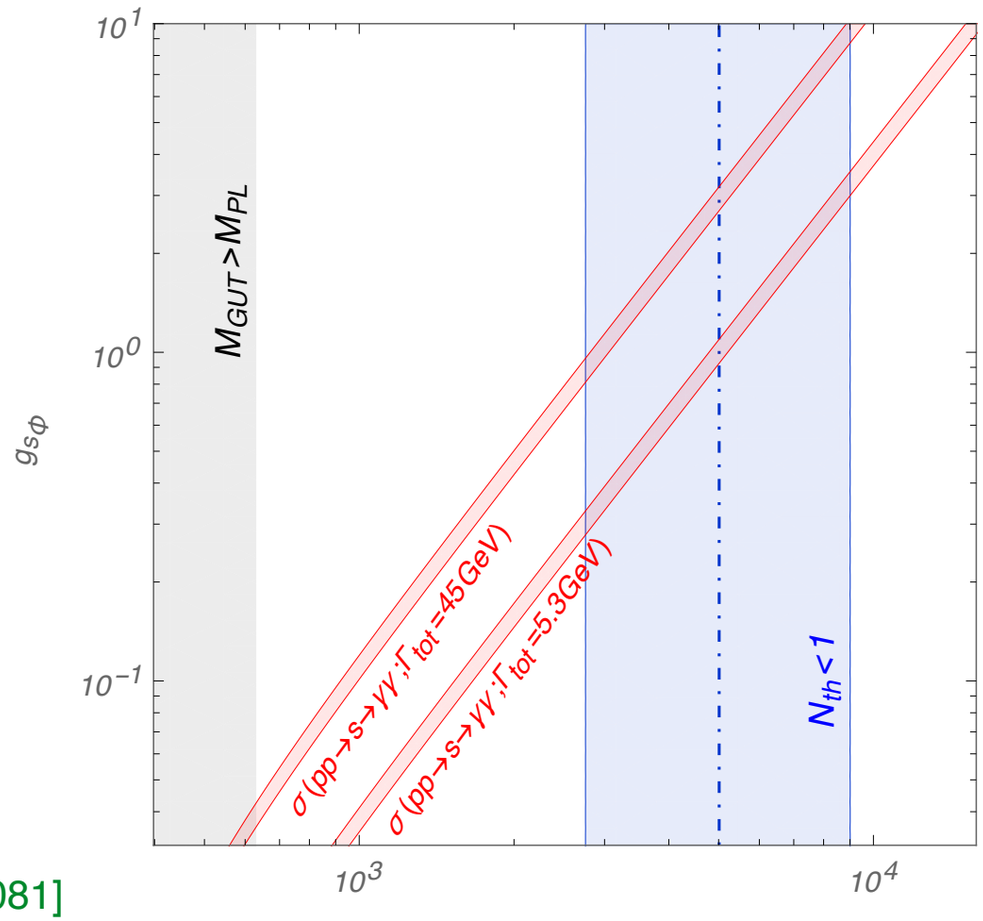
$$(\Phi = \widetilde{Q}'\mathrm{s}, \widetilde{U}'\mathrm{s}, \widetilde{D}'\mathrm{s})$$

➢ The relevant part for diphoton signal is

$$V_{S\Phi}(S,\Phi) = \lambda_{S\Phi}|S|^2|\Phi|^2 \supset g_{s\Phi} f\ s\Phi^\dagger\Phi \qquad (S \sim f + (s+i\rho)/\sqrt{2},\ g_{s\Phi} \simeq \sqrt{2}M_*^2/f^2)$$

➢ The diphoton excess can be induced by s with the mass being M_S = 750 GeV:





➢ $\sigma(pp\to s\to\gamma\gamma) \sim 6 \pm 1$ fb (95%CL, ATLAS+CMS)

[J. Ellis et al., '15]

[ATLAS-CONF-2015-081]

➢ The total decay width:

$\Gamma_{tot} = 45$ GeV (best fit), $5.3GeV$ (diphoton invariant mass resolution)

Other experimental bounds

[R.Franceschini, et al., '15]

- s can also decay into WW/ZZ/Zγ.
- We utilize the bounds on these modes by extrapolating from those at LHC 8TeV.

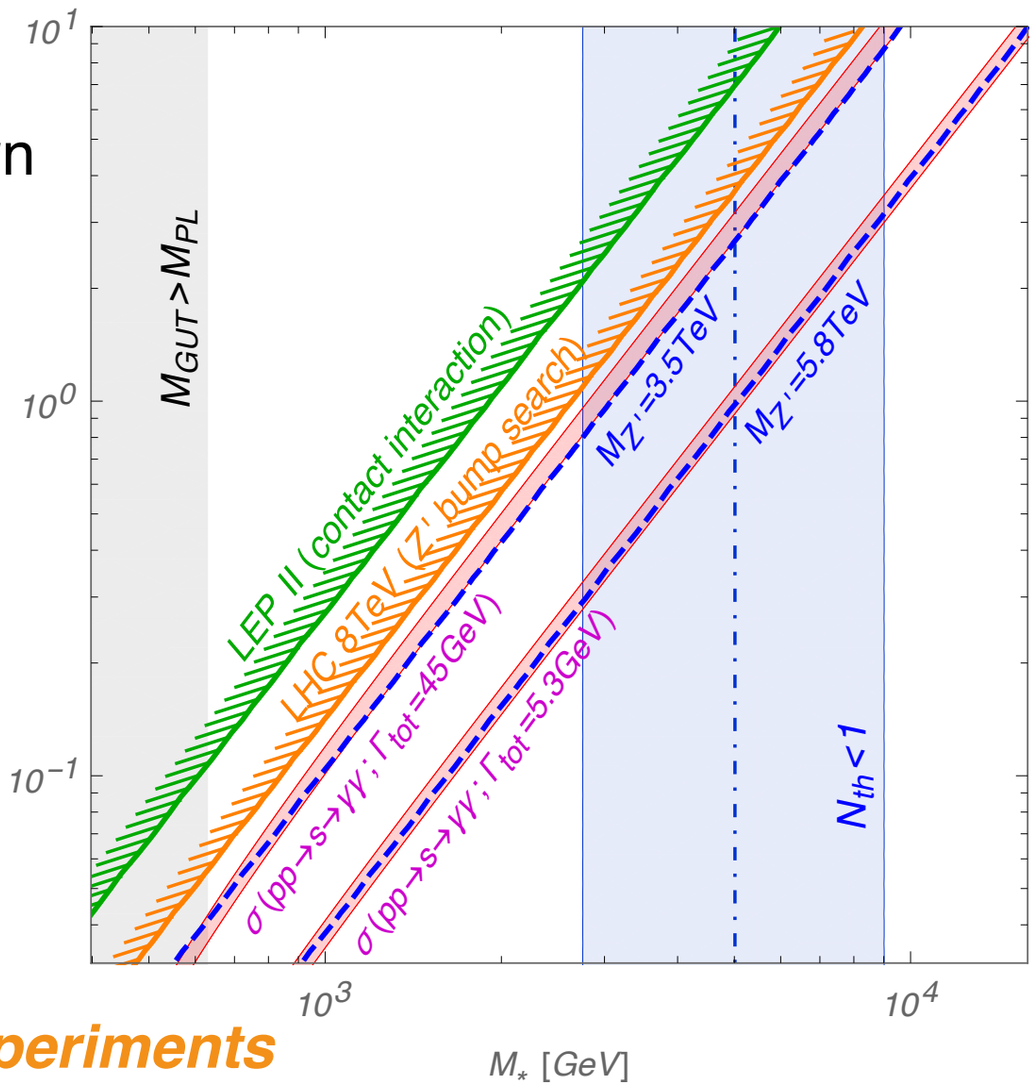
bounds on σ at LHC 8 TeV	implied bounds ($\sigma_{13\text{TeV}}/\sigma_{8\text{TeV}} \sim 5$)	model predictions
$\sigma(pp \to s \to WW) \lesssim 40$ fb	$\Gamma(s \to WW)/\Gamma(s \to \gamma\gamma) \lesssim 20$	$\Gamma(s \to WW)/\Gamma(s \to \gamma\gamma) \sim 7$
$\sigma(pp \to s \to ZZ) \lesssim 12$ fb	$\Gamma(s \to ZZ)/\Gamma(s \to \gamma\gamma) \lesssim 6$	$\Gamma(s \to ZZ)/\Gamma(s \to \gamma\gamma) \sim 3$
$\sigma(pp \to s \to Z\gamma) \lesssim 4$ fb	$\Gamma(s \to Z\gamma)/\Gamma(s \to \gamma\gamma) \lesssim 2$	$\Gamma(s \to Z\gamma)/\Gamma(s \to \gamma\gamma) \sim 0.5$

TeV-scale Z'

- The mass of Z' is induced by spontaneous breakdown of $U(1)_{B\text{-}L}$: $M_{Z'}^2 = 32\pi\alpha_{B-L}f^2$
- LEP II has indirectly put a bound: $M_{Z'}/g_{B-L} \gtrsim 6.7$TeV

  [Carena et al., '04; Cacciapaglia et al., '06]
- The direct observation of Z' at LHC 8TeV gives a bound: $M_{Z'} \gtrsim 3$TeV [Chatrchyan et al. (CMS), '12; Guo et al., '15]
- The condition of the unification leads to $\alpha_{B\text{-}L}(M_Z)$.
- The diphoton excess implies the scale of f .
- Z' mass can be predicted within the range of

  $3.5\text{TeV} \lesssim M_{Z'} \lesssim 5.8\text{TeV}$ (according to the total width)



Z' would be within the reach of the LHC Run 2 experiments

Summary

- We illustrated a possible connection between the 750-GeV diphoton excess and a TeV-scale Z' in view of the unification of the gauge coupling constants.

- New gauge symmetry presumably ordered the 750-GeV scalar as a mass-giver to Z'.

- The unification implies new charged particles, and can also predicts the *B-L* gauge coupling at low energies.

- The diphoton excess can fix the *B-L* breaking scale, which results in the prediction of Z' around just above the current bound (within the reach of LHC Run 2).