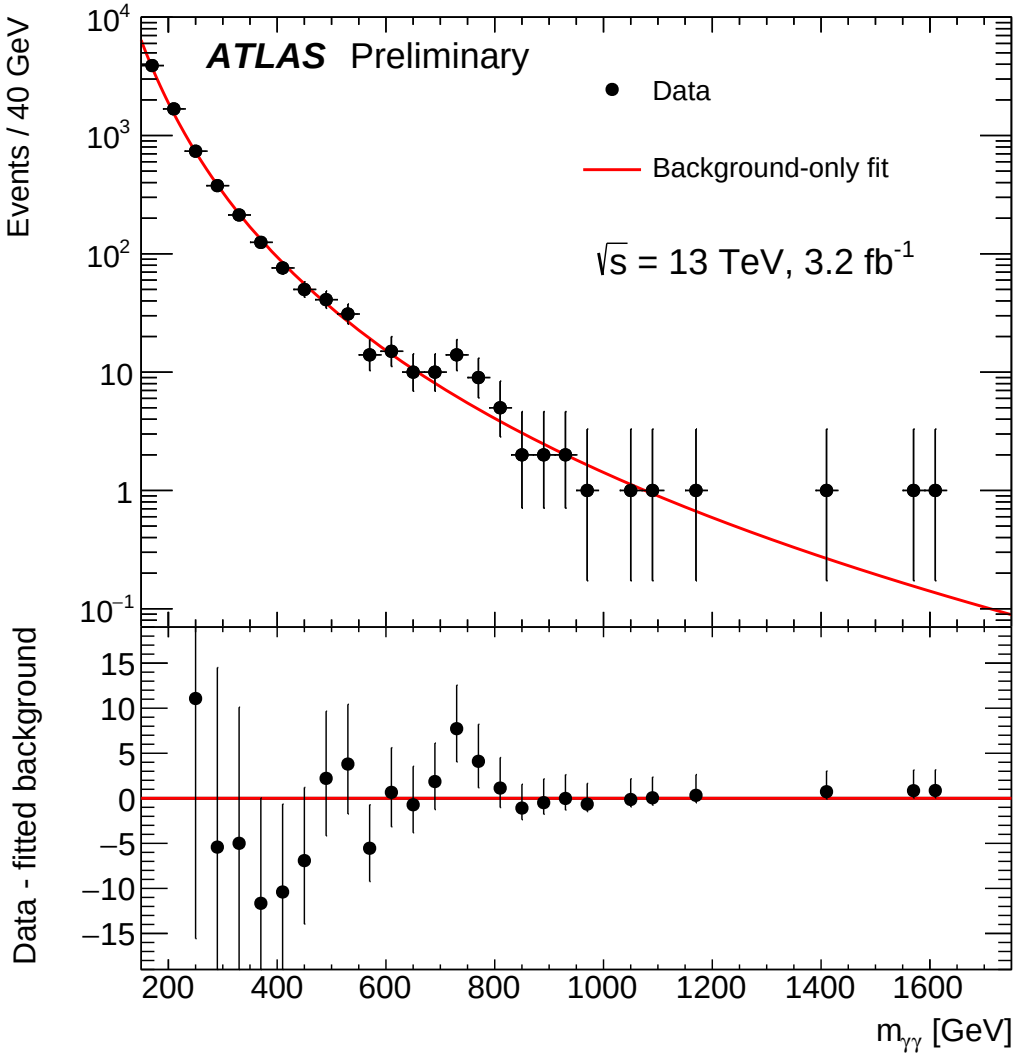
# 750 GeV diphoton excess in unified left-right symmetric models from NCG

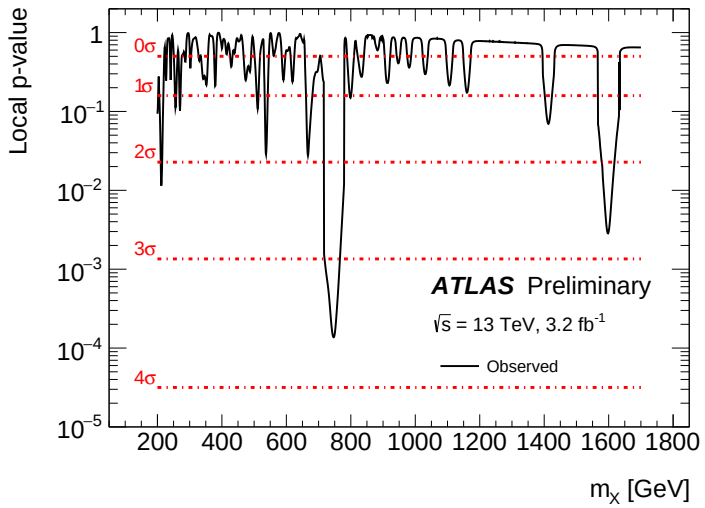
Chen Sun

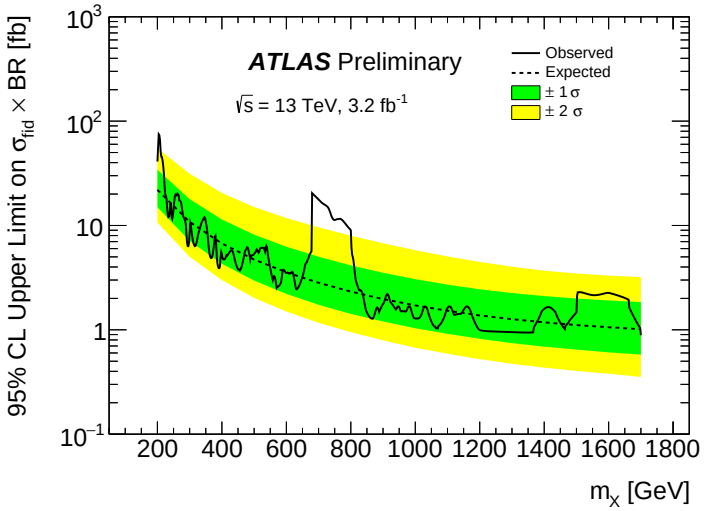
May 10, 2016

*With Ufuk Aydemir, Djordje Minic, Tatsu Takeuchi, arXiv:1603.01756*

# Quick overview of the LHC excess



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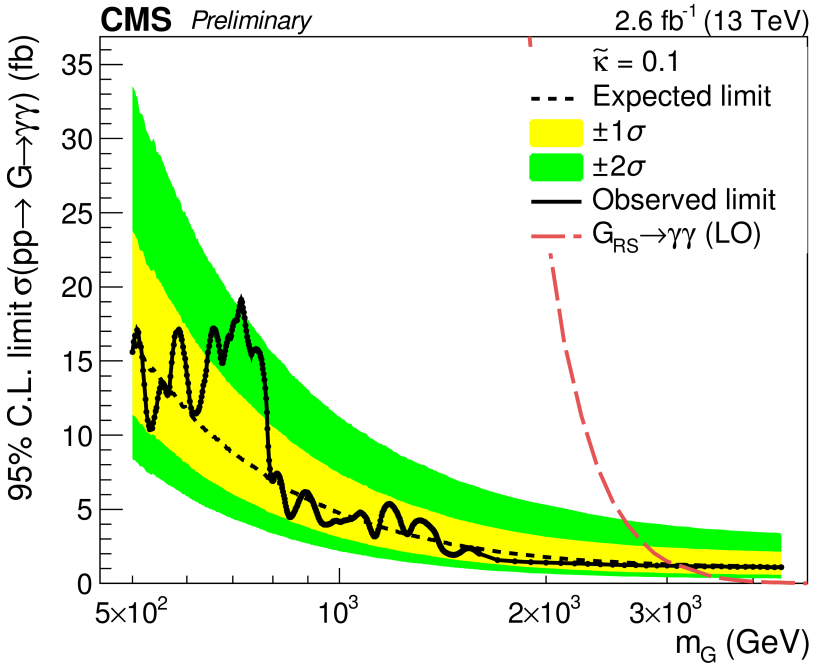
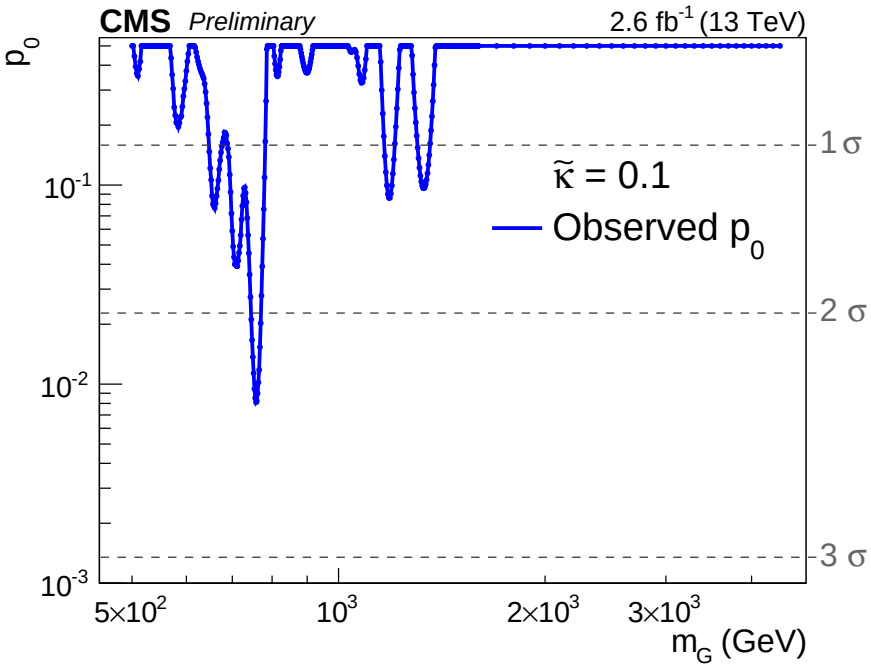


# Quick overview of the LHC excess

The recent diphoton excess:

$$gg \to \gamma\gamma$$

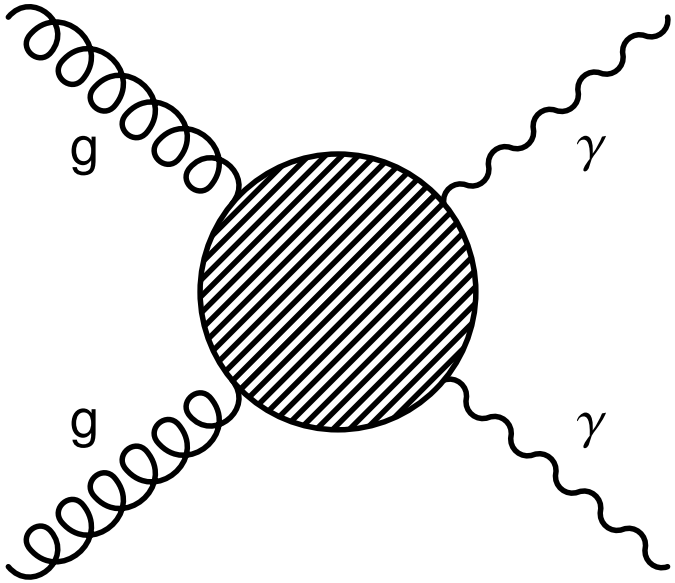
| | Local Significance | Data @ 13 TeV | XSec Upper Limit (95% CL) | Preferred Width |
|---|---|---|---|---|
| ATLAS | $3.6\sigma$ | 3.2 $\text{fb}^{-1}$ | $10 \pm 2.8$ fb | $\sim 45$ GeV |
| CMS | $2.6\sigma$ | 2.6 $\text{fb}^{-1}$ | $6.5 \pm 3.5$ fb | Narrow |

Highlights:

- The anomaly is seen in both ATLAS and CMS.
- Combining Run I and Run II increases the statistical significance.
- Hard to conclude whether it is *narrow* or *wide* at the moment.
- A spin-0 resonance is favored over spin-2. Parity not determined yet.

C.f. Buckley 2016.

# The Effective Vertices



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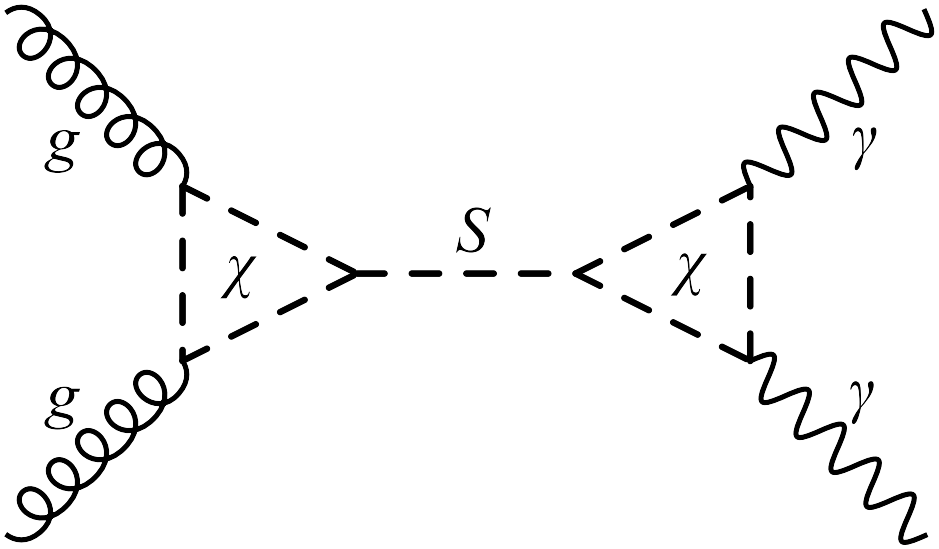


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- $\chi$ is a scalar with EM charge and color.

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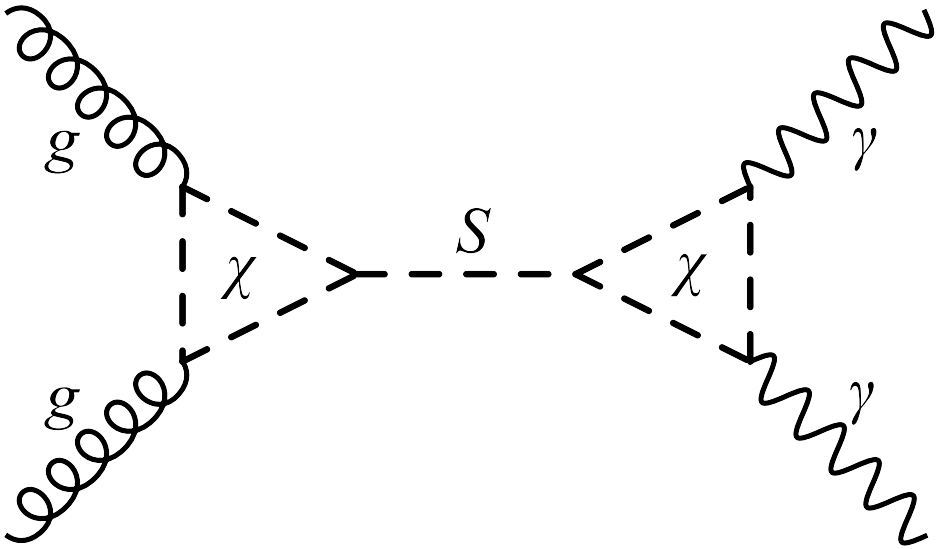


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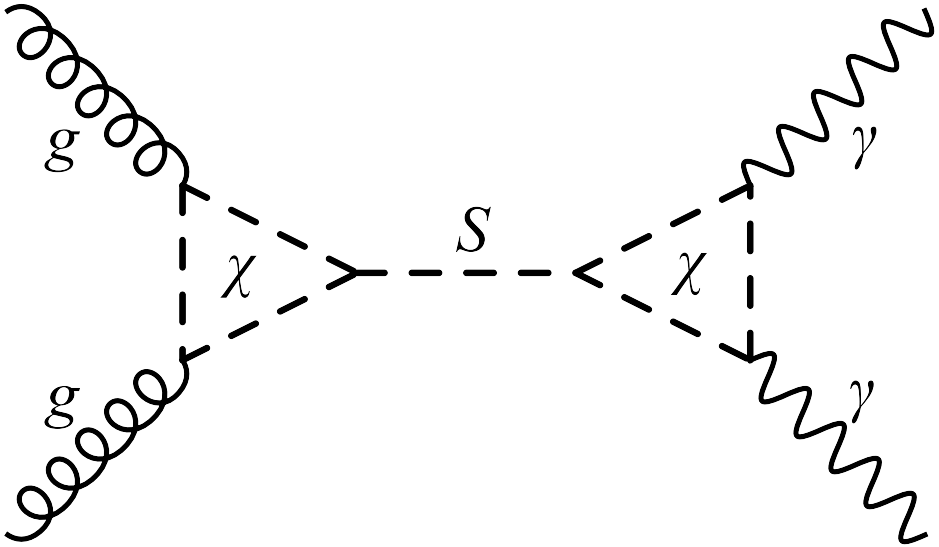


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- Collider analysis shows LHC signal can be reproduced for $\kappa \sim \mathcal{O}(1)$, $M \sim \mathcal{O}(1\ \mathrm{TeV})$ and $M_\chi \sim \mathcal{O}(1\ \mathrm{TeV})$.

(c.f. Aydemir and Mandal 2016)

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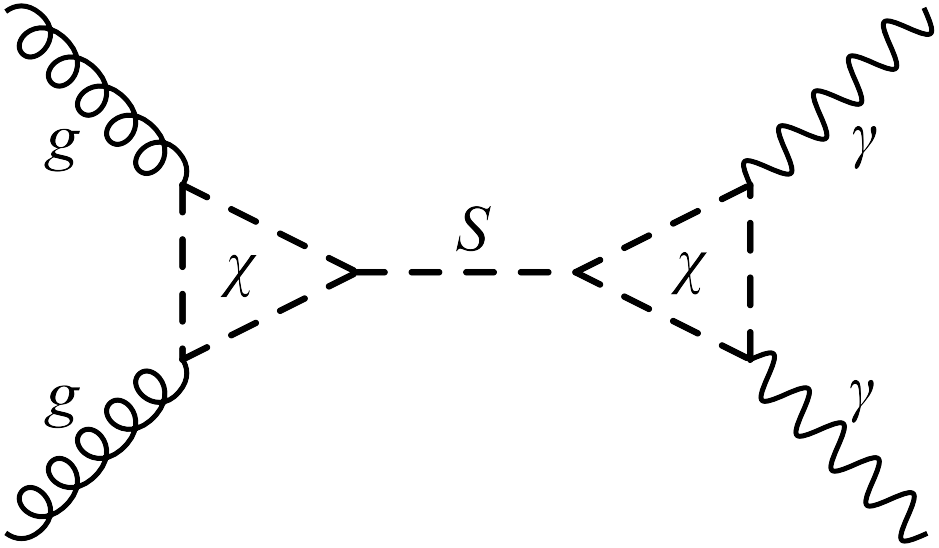


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- Upshot: Unified Pati-Salam through NCG provides $\mathcal{S}$ and $\chi$.

# Vanilla Pati-Salam Model

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- Left right symmetric, but still with three couplings (as opposed to the case of GUTs), and the Higgs content undetermined.

$$SU(4) \times SU(2)_L \times SU(2)_R \to SU(3) \times SU(2)_L \times U(1)_Y$$

$$\begin{aligned}
&(\mathbf{4},\mathbf{2},\mathbf{1}) \to (\mathbf{3},\mathbf{2})_{\frac{1}{6}} \oplus (\mathbf{1},\mathbf{2})_{-\frac{1}{2}},\\
&(\overline{\mathbf{4}},\mathbf{1},\mathbf{2}) \to (\overline{\mathbf{3}},\mathbf{1})_{\frac{1}{3}} \oplus (\overline{\mathbf{3}},\mathbf{1})_{-\frac{2}{3}} \oplus (\mathbf{1},\mathbf{1})_{\mathbf{1}} \oplus (\mathbf{1},\mathbf{1})_{\mathbf{0}},\\
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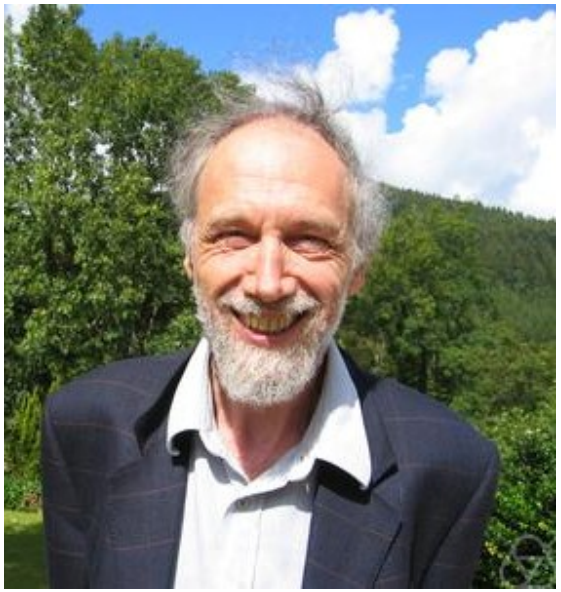
\end{aligned}$$

With arbitrariness in Higgs content and coupling relations, we focus on a specific class of Pati-Salam models that are predicted by noncommutative geometry.

# Pati-Salam from Noncommutative Geometry

Noncommutative geometry was

- mainly developed by Alain Connes in 1980' (cyclic cohomology),
- and applied to particle physics in early 1990'.
- Includes neutrino mass in 2006.



# Pati-Salam from Noncommutative Geometry

Quick Facts from NCG:

- $\partial\!\!\!/ \to D$

$$\overline{\psi}\partial\!\!\!/\psi + m\overline{\psi}\psi \to \begin{bmatrix}\overline{\psi}_R & \overline{\psi}_L\end{bmatrix}\begin{bmatrix}\partial\!\!\!/ & m \\ m & \partial\!\!\!/\end{bmatrix}\begin{bmatrix}\psi_R \\ \psi_L\end{bmatrix}$$

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- Make it gauge invariant.

$\not{\partial}$ generates the ordinary gauge field $W_\mu^\pm / Z_\mu / A_\mu$.

$\begin{bmatrix} & m \\ m & \end{bmatrix}$ generates the discrete gauge field $\phi$.

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- Two sheet picture: left and right, with mass matrix being the discrete derivative connecting the two.

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# Pati-Salam from Noncommutative Geometry

What is this construction good for?

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Among the conclusions from NCG:

- Gauge coupling unification:

$$g^2\mathbb{F}^2 = g_R^2 W_{\mu\nu}W^{\mu\nu} + g_L^2 F_{\mu\nu}F^{\mu\nu} + g_4^2 G_{\mu\nu}G^{\mu\nu},$$

  with $g_L^2 = g_R^2 = g_4^2 \equiv g^2$ at $M_U$.

- Restricted Higgs content. (c.f. Chamseddine et. al. 2015)

# Pati-Salam from Noncommutative Geometry

| Model | Symmetry | Higgs Content |
|---|---|---|
| A | $G_{224}$ | $\phi(2,2,1)$, $\widetilde{\Delta}_R(1,2,4)$, $\Sigma(1,1,15)$ |
| B | $G_{224}$ | $\phi(2,2,1)$, $H(1,1,6)$, $\Delta_R(1,3,10)$, $\widetilde{\Sigma}(2,2,15)$ |
| C | $G_{224D}$ | $\phi(2,2,1)$, $H(1,1,6)\times 2$, $\Delta_R(1,3,10)$, $\Delta_L(3,1,10)$ $\widetilde{\Sigma}(2,2,15)$ |

# Identification of $\mathcal{S}$ and $\chi$

| $G_{224}$ | $G_{2213}$ | $G_{213}$ |
|---|---|---|
| $\phi(2,2,1)$ | $\phi(2,2,0,1)$ | $\phi_2(2,1,1)$, $\phi_2'(2,-1,1)$ |
| $\widetilde{\Delta}_R(1,2,4)$ | $\widetilde{\Delta}_{R1}(1,2,1,1)$ | $\widetilde{\Delta}^0_{R1}(1,0,1)$ , $\widetilde{\Delta}^+_{R1}(1,2,1)$ |
| | $\widetilde{\Delta}_{R3}\left(1,2,-\frac{1}{3},3\right)$ | $\widetilde{\Delta}^{1/3}_{R3}\left(1,\frac{2}{3},3\right)$, $\widetilde{\Delta}^{-2/3}_{R3}\left(1,-\frac{4}{3},3\right)$ |
| $\Delta_R(1,3,10)$ | $\Delta_{R1}(1,3,2,1)$ | $\Delta^0_{R1}(1,0,1)$ , $\Delta^+_{R1}(1,2,1)$, $\Delta^{++}_{R1}(1,4,1)$ |
| | $\Delta_{R3}\left(1,3,\frac{2}{3},3\right)$ | $\Delta^{+4/3}_{R3}\left(1,\frac{8}{3},3\right)$, $\Delta^{+1/3}_{R3}\left(1,\frac{2}{3},3\right)$, $\Delta^{-2/3}_{R3}\left(1,-\frac{4}{3},3\right)$ |
| | $\Delta_{R6}\left(1,3,-\frac{2}{3},6\right)$ | $\Delta^{+2/3}_{R6}\left(1,\frac{4}{3},6\right)$, $\Delta^{-1/3}_{R6}\left(1,-\frac{2}{3},6\right)$, $\Delta^{-4/3}_{R6}\left(1,-\frac{8}{3},6\right)$ |
| $\Delta_L(3,1,10)$ | $\Delta_{L1}(3,1,2,1)$ | $\Delta_{L1}(3,2,1)$ |
| | $\Delta_{L3}\left(3,1,\frac{2}{3},3\right)$ | $\Delta_{L3}\left(3,\frac{2}{3},3\right)$ |
| | $\Delta_{L6}\left(3,1,-\frac{2}{3},6\right)$ | $\Delta_{L6}\left(3,-\frac{2}{3},6\right)$ |

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| $\phi(2,2,1)$ | $\phi(2,2,0,1)$ | $\phi_2(2,1,1)$, $\phi_2'(2,-1,1)$ |
| $\widetilde{\Delta}_R(1,2,4)$ | $\widetilde{\Delta}_{R1}(1,2,1,1)$ | $\widetilde{\Delta}^0_{R1}(1,0,1)$ , $\widetilde{\Delta}^+_{R1}(1,2,1)$ |
| | $\widetilde{\Delta}_{R3}\left(1,2,-\frac{1}{3},3\right)$ | $\widetilde{\Delta}^{1/3}_{R3}\left(1,\frac{2}{3},3\right)$, $\widetilde{\Delta}^{-2/3}_{R3}\left(1,-\frac{4}{3},3\right)$ |
| $\Delta_R(1,3,10)$ | $\Delta_{R1}(1,3,2,1)$ | $\Delta^0_{R1}(1,0,1)$, $\Delta^+_{R1}(1,2,1)$, $\Delta^{++}_{R1}(1,4,1)$ |
| | $\Delta_{R3}\left(1,3,\frac{2}{3},3\right)$ | $\Delta^{+4/3}_{R3}\left(1,\frac{8}{3},3\right)$, $\Delta^{+1/3}_{R3}\left(1,\frac{2}{3},3\right)$, $\Delta^{-2/3}_{R3}\left(1,-\frac{4}{3},3\right)$ |
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| $\Delta_L(3,1,10)$ | $\Delta_{L1}(3,1,2,1)$ | $\Delta_{L1}(3,2,1)$ |
| | $\Delta_{L3}\left(3,1,\frac{2}{3},3\right)$ | $\Delta_{L3}\left(3,\frac{2}{3},3\right)$ |
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# Identification of $\mathcal{S}$ and $\chi$ –Cont'd

| | | |
|---|---|---|
| $H(1,1,6)$ | $H_3\left(1,1,\frac{2}{3},3\right)$ | $H_3^{1/3}\left(1,\frac{2}{3},3\right)$ |
| | $H_{\bar{3}}\left(1,1,-\frac{2}{3},\bar{3}\right)$ | $H_{\bar{3}}^{-1/3}\left(1,-\frac{2}{3},\bar{3}\right)$ |
| $\Sigma(1,1,15)$ | $\Sigma_1(1,1,0,1)$ | $\Sigma_1^0(1,0,1)$ |
| | $\Sigma_3\left(1,1,-\frac{4}{3},3\right)$ | $\Sigma_3^{-2/3}\left(1,-\frac{4}{3},3\right)$ |
| | $\Sigma_{\bar{3}}\left(1,1,\frac{4}{3},\bar{3}\right)$ | $\Sigma_{\bar{3}}^{2/3}\left(1,\frac{4}{3},\bar{3}\right)$ |
| | $\Sigma_8(1,1,0,8)$ | $\Sigma_8^0(1,0,8)$ |
| $\widetilde{\Sigma}(2,2,15)$ | $\widetilde{\Sigma}_1(2,2,0,1)$ | $\widetilde{\Sigma}_1(2,1,1)$, $\widetilde{\Sigma}'_1(2,-1,1)$ |
| | $\widetilde{\Sigma}_3\left(2,2,-\frac{4}{3},3\right)$ | $\widetilde{\Sigma}_3\left(2,-\frac{7}{3},3\right)$, $\widetilde{\Sigma}'_3\left(2,-\frac{1}{3},3\right)$ |
| | $\widetilde{\Sigma}_{\bar{3}}\left(2,2,\frac{4}{3},\bar{3}\right)$ | $\widetilde{\Sigma}_{\bar{3}}\left(2,\frac{7}{3},\bar{3}\right)$, $\widetilde{\Sigma}'_{\bar{3}}\left(2,\frac{1}{3},\bar{3}\right)$ |
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$$M_U \geq M_C \geq M_Z \, .$$

We label the energy intervals in between symmetry breaking scales $[M_Z, M_C]$ and $[M_C, M_U]$ with Roman numerals as

$$\begin{aligned} \mathrm{I} \; &: \; [M_Z, \; M_C] \, , \quad G_{213} \; (\mathrm{SM}) \, , \\ \mathrm{II} \; &: \; [M_C, \; M_U] \, , \quad G_{224} \quad \text{or} \quad G_{224D} \, . \end{aligned}$$

Identify $\mathcal{S}$ with $\widetilde{\Delta}^0_{R1}(1,0,1)$ or $\Delta^0_{R1}(1,0,1)$, with $m_{\mathcal{S}} = 750 \text{ GeV}$.
Identify $\chi$ with $\widetilde{\Delta}^{-2/3}_{R3}\left(1, -\frac{4}{3}, 3\right)$, with $m_\chi \sim 1 \text{ TeV}$.

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- Simplicity.
- Including more intermediate scales do not help.

(c.f. 1509.01606, 1512.00568)

# RG Analysis –Cont'd

## Matching/boundary condition

$$
\begin{aligned}
M_U \quad &: \quad g_L(M_U) \;=\; g_R(M_U) \;=\; g_4(M_U)\,, \\
M_C \quad &: \quad \sqrt{\frac{2}{3}}\, g_{BL}(M_C) \;=\; g_3(M_C) = g_4(M_C)\,, \quad g_2(M_C) \;=\; g_L(M_C)\,, \\
&\quad\; \frac{1}{g_1^2(M_C)} \;=\; \frac{1}{g_R^2(M_C)} + \frac{2}{3}\frac{1}{g_4^2(M_C)}\,, \\
M_Z \quad &: \quad \frac{1}{e^2(M_Z)} \;=\; \frac{1}{g_1^2(M_Z)} + \frac{1}{g_2^2(M_Z)}\,.
\end{aligned}
$$

# RG Analysis –Cont'd
## Low E data

$$\alpha(M_Z) \;=\; 1/127.9\,, \quad \alpha_s(M_Z) \;=\; 0.118\,, \quad \sin^2\theta_W(M_Z) \;=\; 0.2312\,,$$

at $M_Z = 91.1876\,\mathrm{GeV}$, which translates to

$$g_1(M_Z) \;=\; 0.36\,, \quad g_2(M_Z) \;=\; 0.65\,, \quad g_3(M_Z) \;=\; 1.22\,.$$

# RG Analysis –Cont'd

**Requirements**

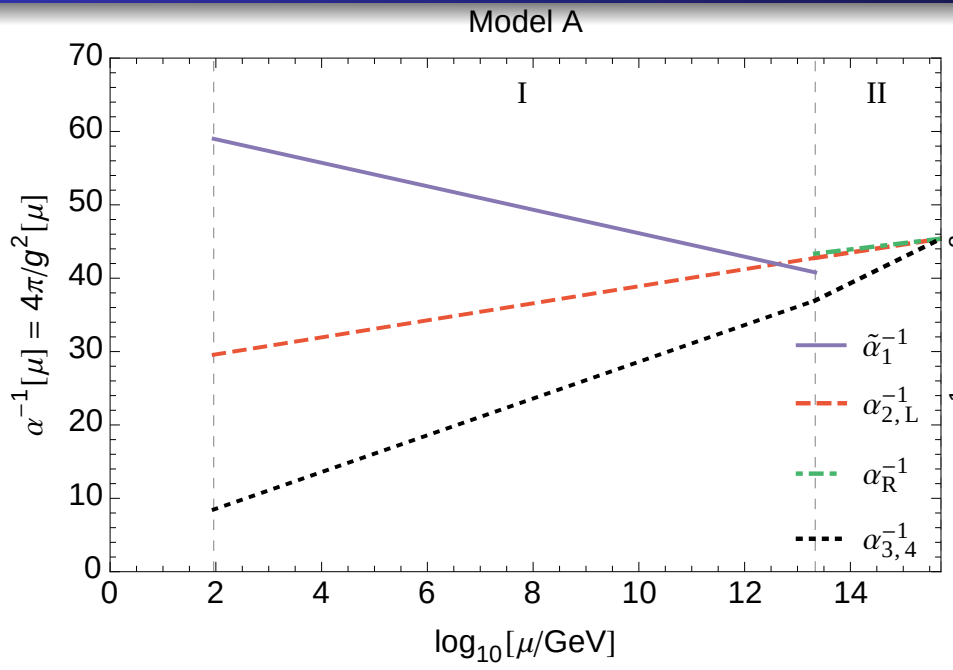
- $M_U \geq M_C \geq M_Z$ is always maintained.
- $M_{Pl} > M_U$.
- Couplings remain perturbative.

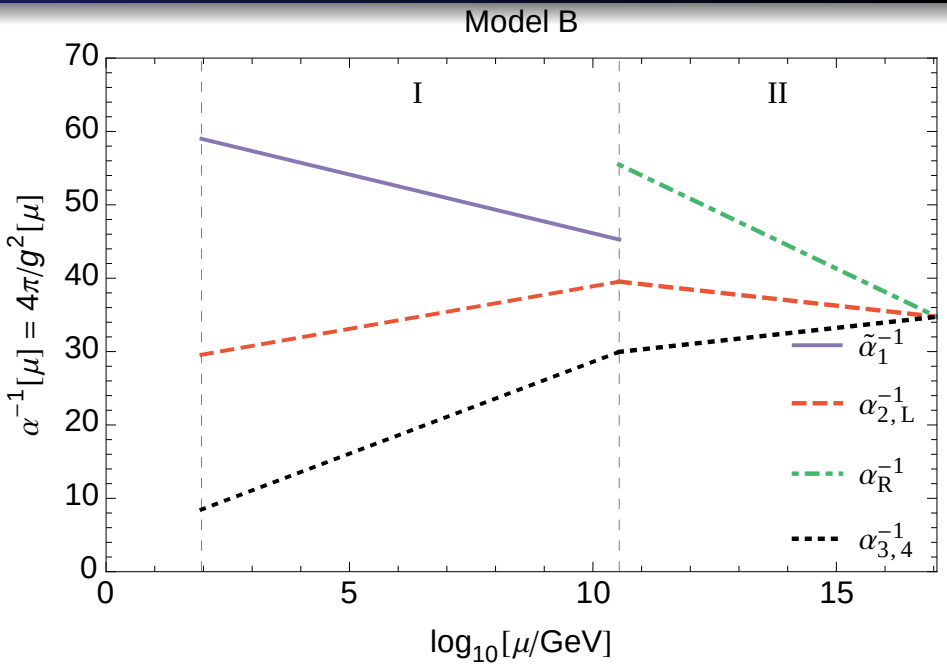
$\mathcal{S}$ does not contribute to RG running of SM gauge couplings because it is a SM singlet.

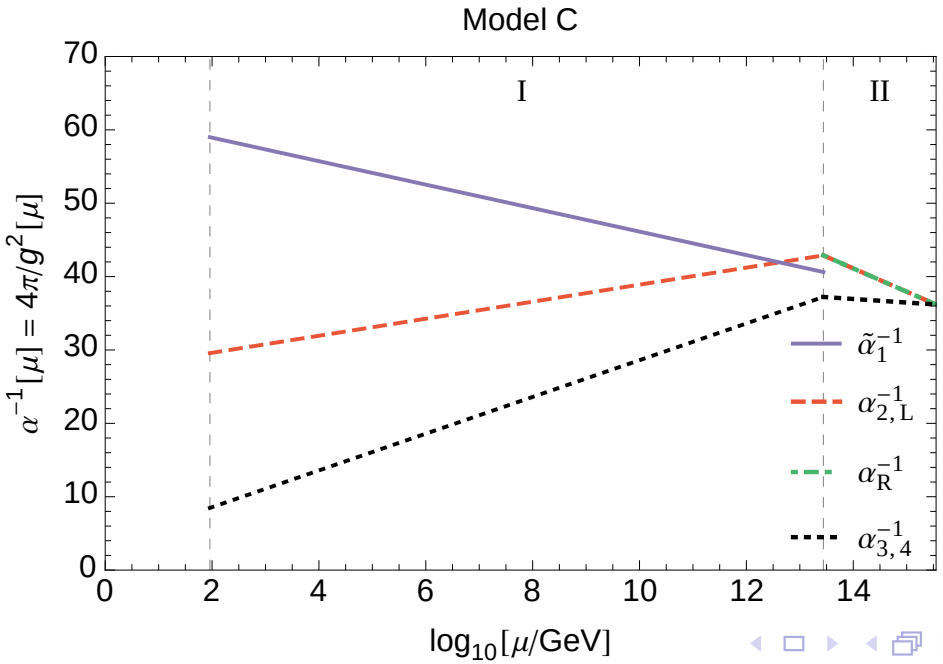
# The results

| Model | A | B | C |
|---|---|---|---|
| Unbroken Symmetry | $G_{224}$ | $G_{224}$ | $G_{224D}$ |
| $\log_{10}(M_U/\mathrm{GeV})$ | 15.7 | 17.1 | 15.6 |
| $\log_{10}(M_C/\mathrm{GeV})$ | 13.3 | 10.5 | 13.4 |
| $\alpha_U^{-1}$ | 45.4 | 34.7 | 36.2 |

# The results –Cont'd



# Fine tuning

Given the fact that

$$M_C \sim 10^{10} GeV - 10^{13} GeV,$$

while the effective coupling $\sim \kappa M \mathcal{S} \chi^\dagger \chi$ has to be very small to produce the observed excess.

**Recall**

$\kappa \sim \mathcal{O}(1)$ only when $M \sim \mathcal{O}(1\mathrm{TeV})$, to reproduce the desired excess.

Fine tuning thus appears.

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On the other hand, all these analysis is based on EFT, while NCG is not an EFT for sure. The conjectures are

- UV/IR,
- Above some scale, the running of coupling is determined by the geometry, instead of EFT loop diagram correction.

The right interpretation should be, the rigidity from phenomenological side may be the price one has to pay to fit a non-EFT/ nonlocal theory into EFT, and could be a hint for the unique nature of NCG approach.

# Conclusions

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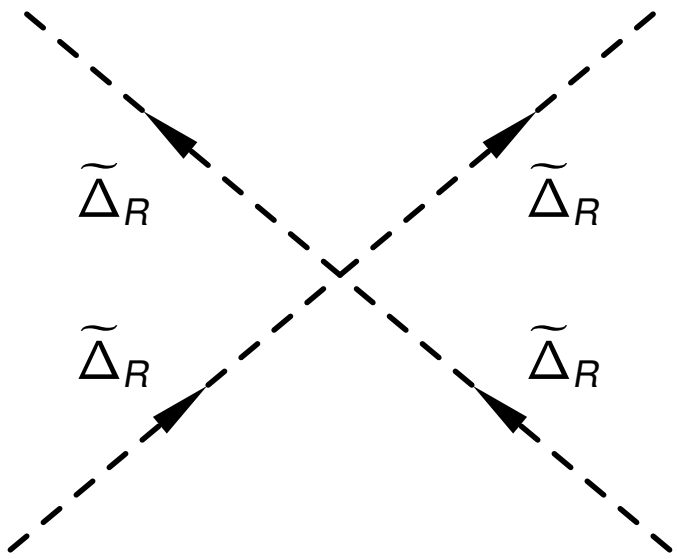
Thank you!

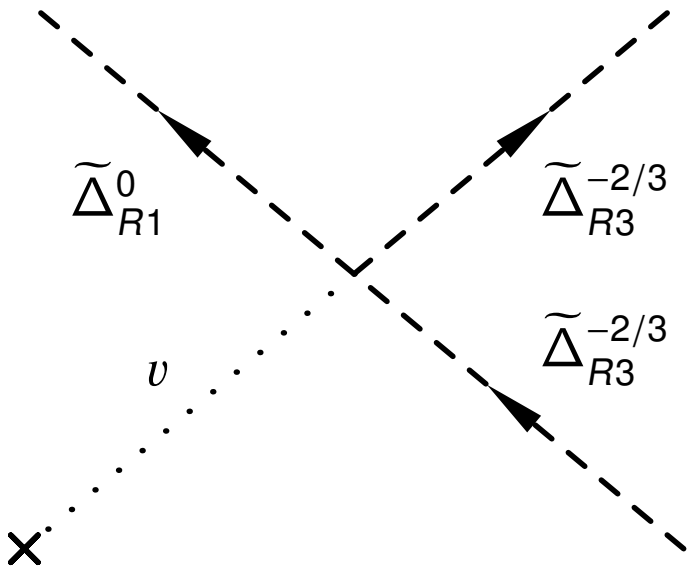
# Back up

$$\widetilde{\Delta}_R(1,2,4) = \widetilde{\Delta}^0_{R1}(1,0,1) + \widetilde{\Delta}^{-2/3}_{R3}(1,-\frac{4}{3},3) + \ldots$$

$(\widetilde{\Delta}_R)^4 \sim$




$\left(\widetilde{\Delta}^0_{R1} + \widetilde{\Delta}^{-2/3}_{R3} + \ldots\right)^4$ contains




$\sim \kappa v \mathcal{S} \chi^\dagger \chi.$