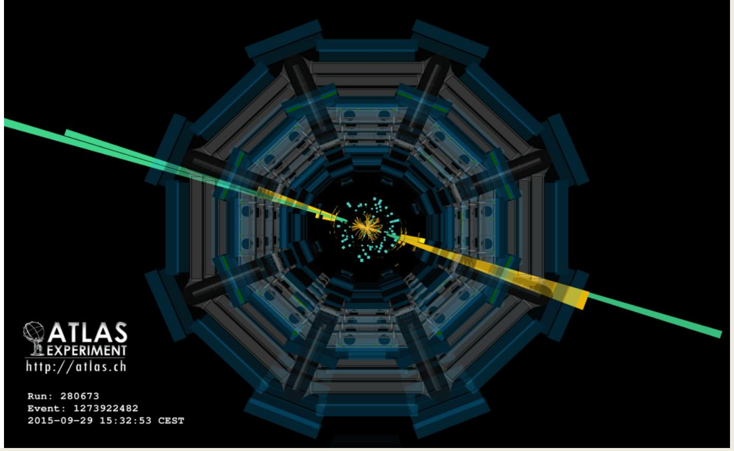


Explaining the 750 GeV diphoton excess with scalar particles charged under new confining gauge interaction

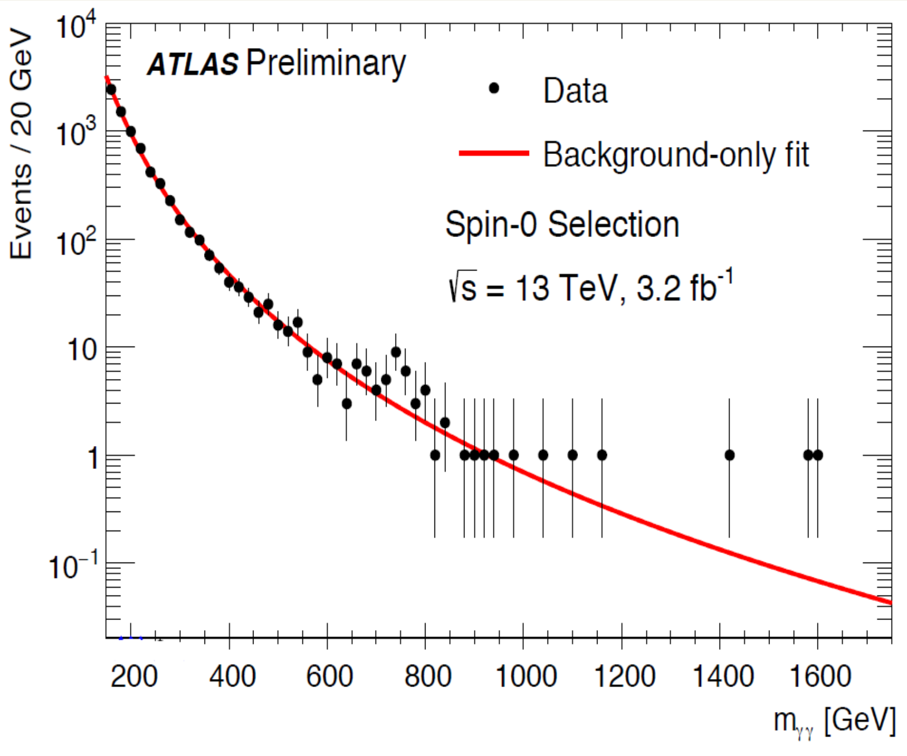
Robert Foot

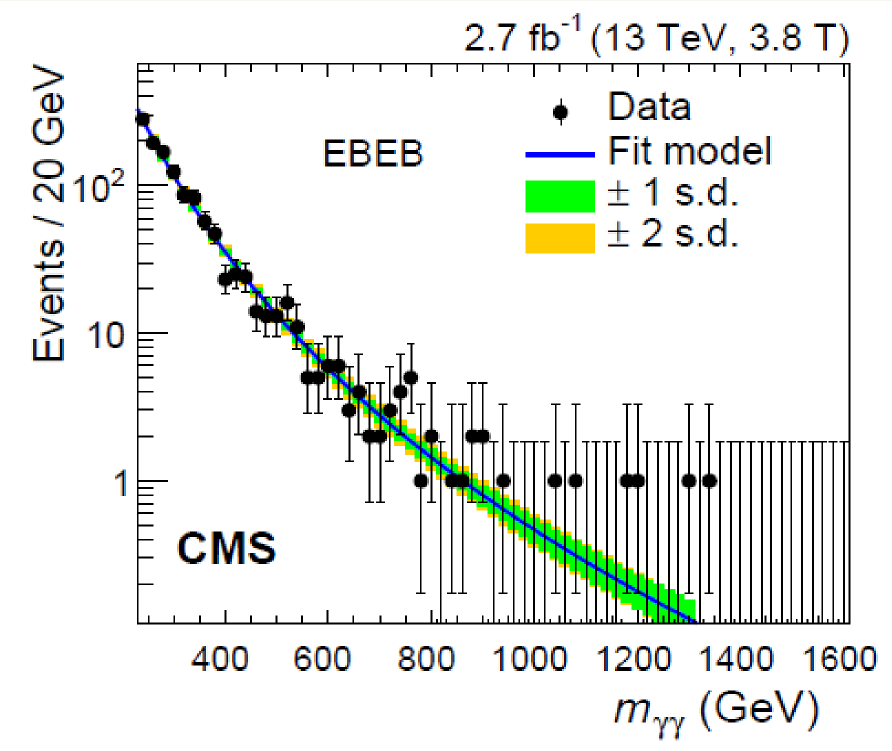
COEPP, University of Melbourne

SUSY 2016, Melbourne, July 3-8.

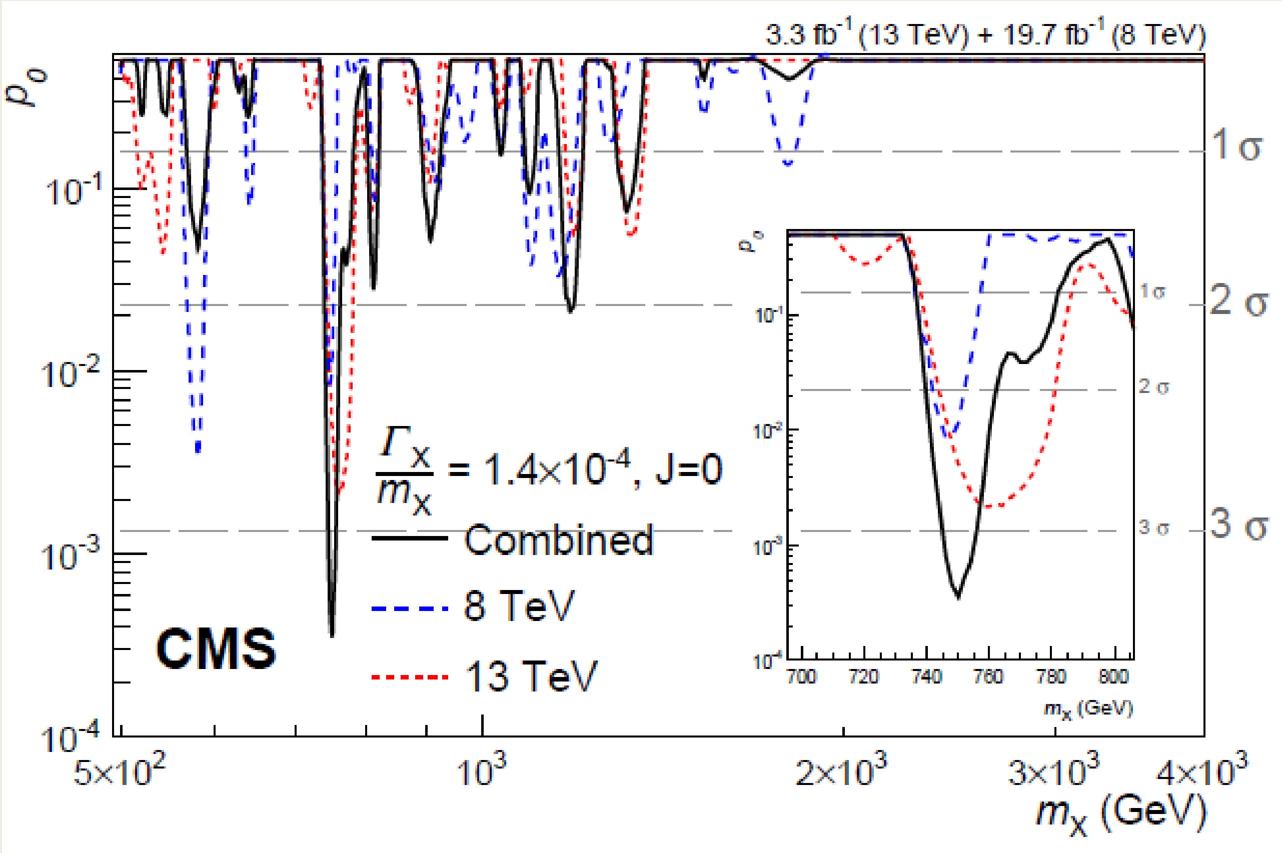
Based on arXiv: 1604.06180, work in collaboration with John Gargalionis.

ATLAS and CMS data: diphoton excess





ATLAS and CMS each have > 3σ excess at around 750 GeV invariant mass



A simple explanation...

Add extra unbroken confining gauge interaction, taken to be SU(N), so that gauge symmetry of the standard model is extended to:

$$\mathrm{SU}(3)_{\mathrm{C}} \otimes \mathrm{SU}(2)_{\mathrm{L}} \otimes \mathrm{U}(1)_{\mathrm{Y}} \otimes \mathrm{SU}(N)$$

Consider a <u>scalar</u> particle, charged under both $SU(3)_c$, $U(1)_Y$ and SU(N):

$$\chi \sim (\mathbf{3}, \mathbf{1}, Y; \mathbf{N})$$

We consider the 'perturbative regime' where $\alpha_N \lesssim \alpha_s$ at a renormalization scale $\mu \sim m_\chi$.

<u>Claim:</u> This simple model provides a consistent explanation for the diphoton excess, in terms of diphoton decays of bound states formed from $\chi^\dagger\chi$

<u>Old claim:</u> Having a fermionic χ could not explain the diphoton excess, as dilepton decay channel would dominate over diphoton.

E. Carlson *et al.*, PRD, 1991.

Two production mechanisms:

Direct resonance production:

$$gg \to \Pi$$

$$\sqrt{s_{gg}} \simeq M_{\Pi}$$

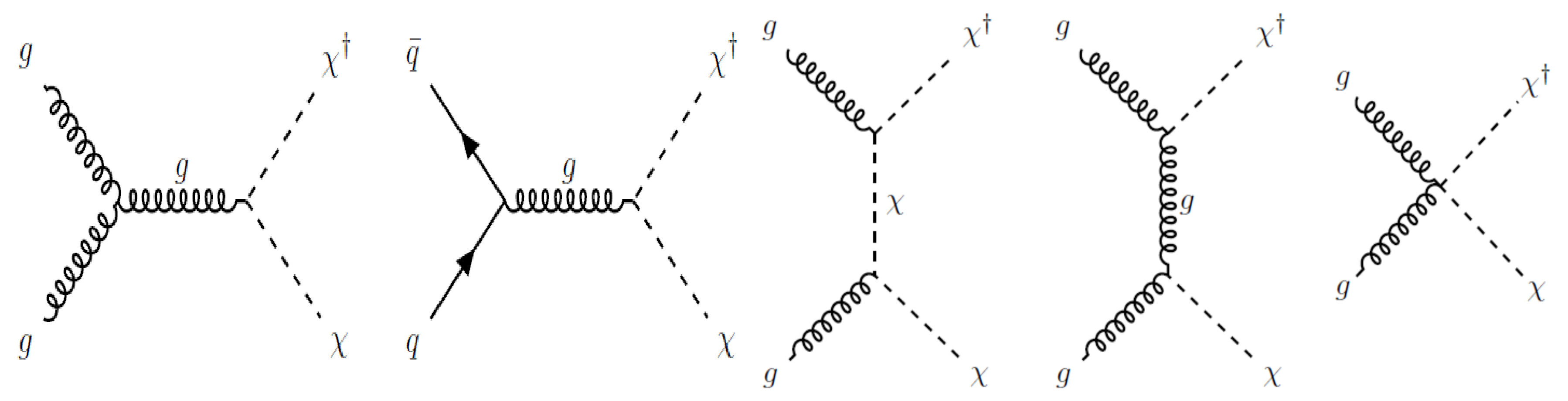
Indirect resonance production

$$gg \to \chi^{\dagger}\chi \to \Pi + soft\ quanta$$

$$\sqrt{s_{gg}} > M_{\Pi}$$

Turns out that indirect resonance production dominates! Not analogous to QCD processes like gg → upsilon: difference QCD has light quarks which can be produced out of vacuum .

Production of the bound state at the LHC



Tree level + higher order processes give:

$$\sigma(pp \to \chi^\dagger \chi) \approx \begin{cases} 2.6N \text{ pb} & \text{at } 13 \text{ TeV} \\ 0.5N \text{ pb} & \text{at } \ \ 8 \text{ TeV} \end{cases}$$

C. Borschensky et al. , 2014

Decay of the ground state

Ground state has L=J=0 and can decay: $\Pi \to gg, \mathcal{H}\mathcal{H}, \gamma\gamma, Z\gamma, ZZ, hh$

a) $\Lambda_{\mathrm{N}} \approx \Lambda_{\mathrm{QCD}}$ ⇒ χ pairs form a bound state: $\chi^\dagger \chi$.

$\Pi \to gg$ rate given by: $\Gamma(\Pi \to gg) = \frac{4}{3} M_\Pi N \alpha_{\mathrm{s}}^2 \frac{|R(0)|^2}{M_\Pi^3}$

Radial wave function at origin can be calculated:

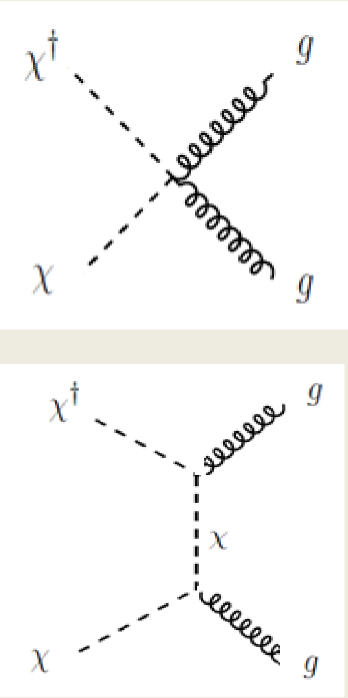
$$\frac{|R(0)|^2}{M_\Pi^3} = \frac{1}{16}\left[\frac{4}{3}\bar{\alpha}_s + C_{\mathrm{N}}\bar{\alpha}_{\mathrm{N}} + Q^2\bar{\alpha}\right]^3$$

b) $\Lambda_{\mathrm{N}} \lesssim \Lambda_{\mathrm{QCD}}$ ⇒ Bound state is composed of $\chi\bar{q}$ and $\chi^\dagger q$.

Rate is modified due to different color structure.

New decay mode arises in this case: $\Pi \to g\gamma$

$\Pi \to gg$



Decays: $\Pi \to \mathcal{H}\mathcal{H}$ and $\Pi \to \gamma\gamma$ very similar, only group theory factor changes.

SU(N) gauge boson (Huon)

Diphoton cross section

$$\sigma(pp \to \gamma\gamma) \approx \sigma(pp \to \chi^\dagger\chi) \times \mathrm{Br}(\Pi \to \gamma\gamma)$$

Two cases:

a) $\Lambda_\mathrm{N} \approx \Lambda_\mathrm{QCD}$ ⇨ χ pairs form a bound state: $\chi^\dagger\chi$

Bound state decays: $\Pi \to gg, \mathcal{H}\mathcal{H}, \gamma\gamma, Z\gamma, ZZ, hh$, with diphoton branching fraction:

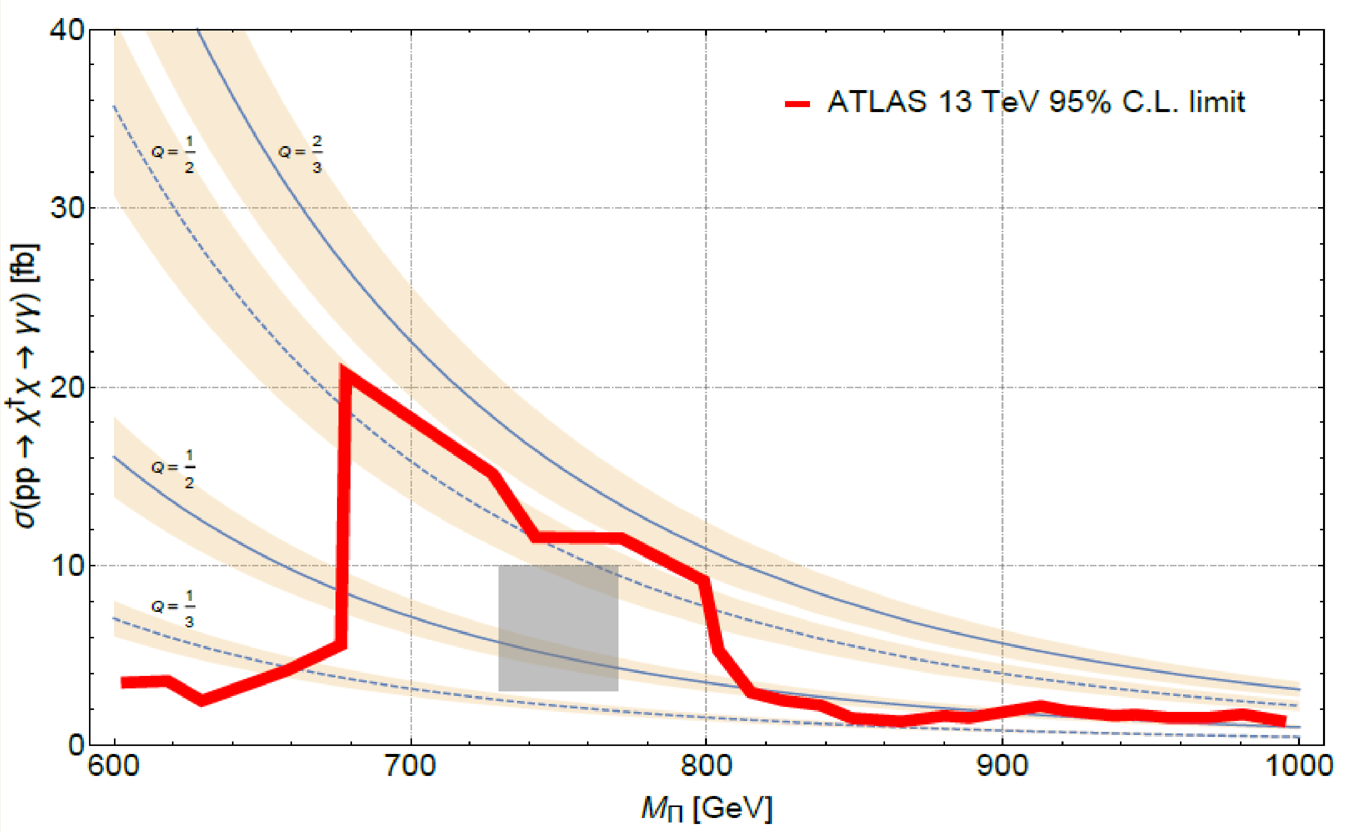
$$\mathrm{Br}(\Pi \to \gamma\gamma) \simeq \frac{3NQ^4\alpha^2}{\frac{2}{3}N\alpha_\mathrm{S}^2 + \frac{3}{2}C_\mathrm{N}\alpha_\mathrm{N}^2 + 3NQ^4\alpha^2}$$

b) $\Lambda_\mathrm{N} \lesssim \Lambda_\mathrm{QCD}$, ⇨ bound state is composed of $\chi\bar{q}$ and $\chi^\dagger q$, and due to the different color structure has a somewhat modified branching fraction:

$$\mathrm{Br}(\Pi \to \gamma\gamma) \simeq \frac{3NQ^4\alpha^2}{\frac{7}{3}N\alpha_\mathrm{S}^2 + \frac{3}{2}C_\mathrm{N}\alpha_\mathrm{N}^2 + 3NQ^4\alpha^2}$$

Diphoton cross section

For $\alpha_N = \alpha_s$ at $\mu \sim m_\chi$ and for case a) $\Lambda_N \approx \Lambda_{QCD}$



Thus, for N=2, the diphoton excess suggests Q ~ ½.

In case b) $\Lambda_N \lesssim \Lambda_{QCD}$, somewhat larger values of Q ~ 1 are indicated.

Other signatures of this $\mathrm{SU}(3)_C \otimes \mathrm{SU}(2)_L \otimes \mathrm{U}(1)_Y \otimes \mathrm{SU}(N)$ gauge model

Dominate decays of the bound state are: $\Pi \to gg$ and $\Pi \to \mathcal{H}\mathcal{H}$

Dijet $\Pi \to gg$

First gives dijet signal with invariant mass around 750 GeV:

$$\sigma(pp \to jj) \approx \begin{cases} 2.6N \times \mathrm{Br}(\Pi \to gg)\ \mathrm{pb} & \text{at } 13\ \mathrm{TeV} \\ 0.5N \times \mathrm{Br}(\Pi \to gg)\ \mathrm{pb} & \text{at } \ 8\ \mathrm{TeV} \end{cases}$$

Current limit on $\sigma(pp \to jj)$ is around 5 pb at 13 TeV. Ok for N=2.

ATLAS-CONF-2016-030

Monojet+MET

ATLAS-CONF-2016-030

The invisible decays $\Pi \to \mathcal{H}\mathcal{H}$ not expected to give observable signal, but bremsstrahlung of hard gluon off initial state will lead to monojet+MET:

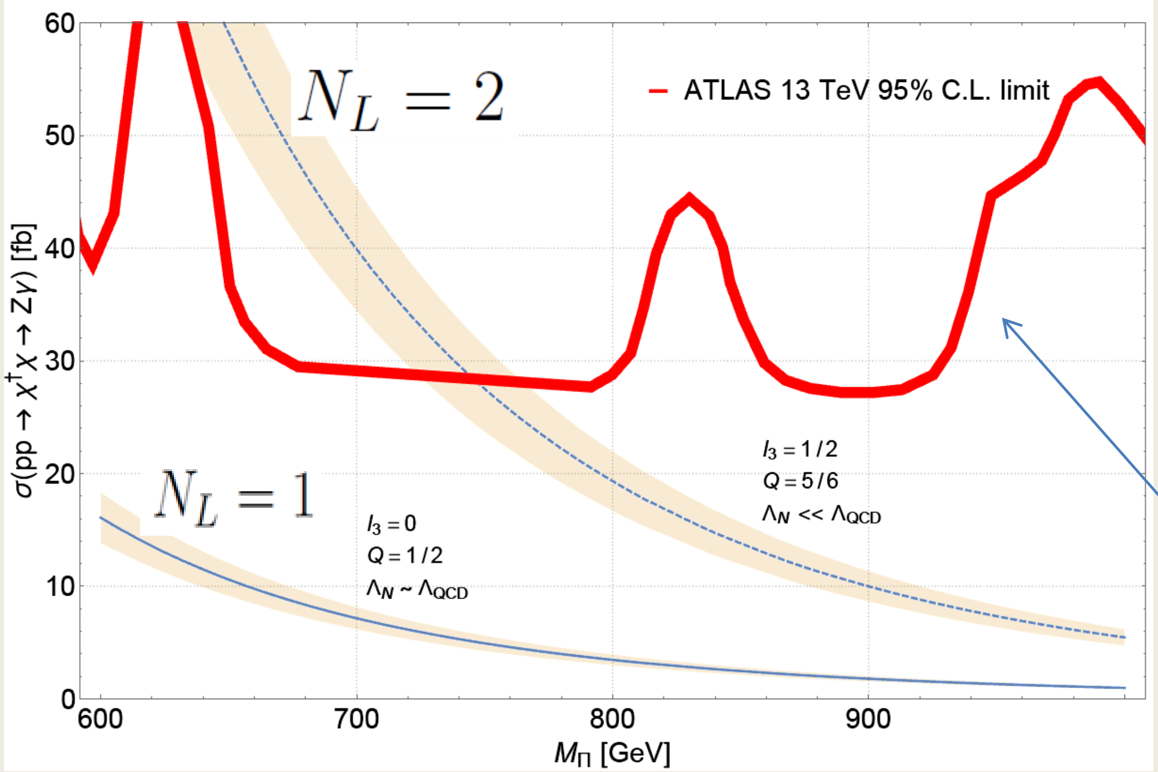
$$pp \to \Pi g \to \mathcal{H}\mathcal{H}g$$

Other signatures

For $\chi \sim (3, N_L, Y; N)$ under $\mathrm{SU}(3)_C \otimes \mathrm{SU}(2)_L \otimes \mathrm{U}(1)_Y \otimes \mathrm{SU}(N)$ have decays:

$pp \to \Pi \to Z\gamma$ and $pp \to \Pi \to ZZ$. Only $N_L = 1, 2$ still consistent with data.

If $N_L = 2$ have: $\chi = \begin{pmatrix} \chi_1[Q] \\ \chi_2[Q-1] \end{pmatrix}$



$N_L \geq 3$

Already excluded for m_χ ~ 375 GeV.

ATLAS-CONF-2016-010

Credit to: John Gargalionis for this plot.

Some premature speculations…

For N=2 case, $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y \otimes SU(2)$ gauge symmetry can arise from extended color models, such as SU(5) color:

$$\begin{aligned} f_L &= \begin{pmatrix} \nu \\ e \end{pmatrix}_L \sim (1,2,-1),\ e_R \sim (1,1,-2), \\ Q_L &= \begin{pmatrix} u \\ d \end{pmatrix}_L \sim (5,2,1/5),\ u_R \sim (5,1,6/5),\ d_R \sim (5,1,-4/5) \end{aligned}$$

O.Hernandez+R.F. PRD 1990,
E. Carlson *et al.,* PRD 1991.

$$\begin{array}{c} SU(5)_c \otimes SU(2)_L \otimes U(1)_{Y'} \\ \downarrow \langle\chi\rangle \\ SU(3)_c \otimes SU(2)_L \otimes U(1)_Y \otimes SU(2) \\ \downarrow \langle\phi\rangle \\ SU(3)_c \otimes U(1)_Q \otimes SU(2) \end{array}$$

Model has exotic fermions charged under the unbroken SU(2), and also exotic gauge bosons that are charged under SU(2) and $SU(3)_c$. Such fermions were called ‘quirks’ by Carlson *et al*. 1991.

The minimal model does <u>not</u> feature scalars like the required: $\chi \sim (\mathbf{3}, \mathbf{1}, Y; \mathbf{N})$

Some premature speculations…(cont.)

But, $SU(5)_c$ model can be partially unified in extended Pati-Salam gauge models:

$$\begin{tikzcd}[row sep=small] \mathrm{SU}(6)\otimes \mathrm{SU}(2)_L \otimes \mathrm{SU}(2)_R \arrow[d, "M_1"] \\ \mathrm{SU}(5)\otimes \mathrm{SU}(2)_L \otimes \mathrm{U}(1)_{Y'} \arrow[d, "M_2"] \\ \mathrm{SU}(3)_c\otimes \mathrm{SU}(2)_L \otimes \mathrm{U}(1)_Y \otimes \mathrm{SU}(2) \end{tikzcd}$$

H. Lew, R. Volkas, R.F., PRD 1991

SM fermions + 2 exotic colored states contained in

$$F_L \sim (6,2,1), \quad F_R \sim (6,1,2)$$

The symmetry breaking scale M_1 is implemented via a $\rho \sim (15,1,1)$, and

$$H_L \sim (21,3,1), \quad H_R \sim (21,1,3)$$

$$L_{\mathrm{Yuk}} = \lambda_1 \bar{F}_L H_L (F_L)^c + \lambda_1 \bar{F}_R H_R (F_R)^c + \mathrm{H.c.}$$

H_R is $SU(2)_R$ triplet: $\chi = \begin{pmatrix} \chi_1[Q = 7/6] \\ \chi_2[Q = 1/6] \\ \chi_2[Q = -5/6] \end{pmatrix}$ and $\chi_{1,2,3} \sim (3, 2)$ under $SU(3)_c \otimes SU(2)$

It is possible that the 3 components have similar masses and contribute to the diphoton excess, effectively broadening the feature…

Conclusion:

The LHC diphoton excess might arise from particles charged under a new SU(N) unbroken gauge interaction, so that the SM is extended to:

$$\mathrm{SU}(3)_{\mathrm{C}} \otimes \mathrm{SU}(2)_{\mathrm{L}} \otimes \mathrm{U}(1)_{\mathrm{Y}} \otimes \mathrm{SU}(N)$$

We have considered a scalar particle, charged under both $\mathrm{SU}(3)_c$, $\mathrm{U}(1)_Y$ and SU(N):

$$\chi \sim (\mathbf{3}, \mathbf{1}, Y ; \mathbf{N})$$

The bound states formed from χ : can be copiously produced at the LHC. We assumed the 'perturbative regime' where $\alpha_N \lesssim \alpha_s$ and found that the excess could be reproduced for Q ~ [½ - 1] and N = 2.

This particular idea can be tested further with new data from LHC, pp → jj, MET+j, …

A few (premature) speculations about a deeper origin of this model were made in the framework of extended color models.