New Physics interpretations at the LHC - ANL

The $\mathcal{F}$ particle

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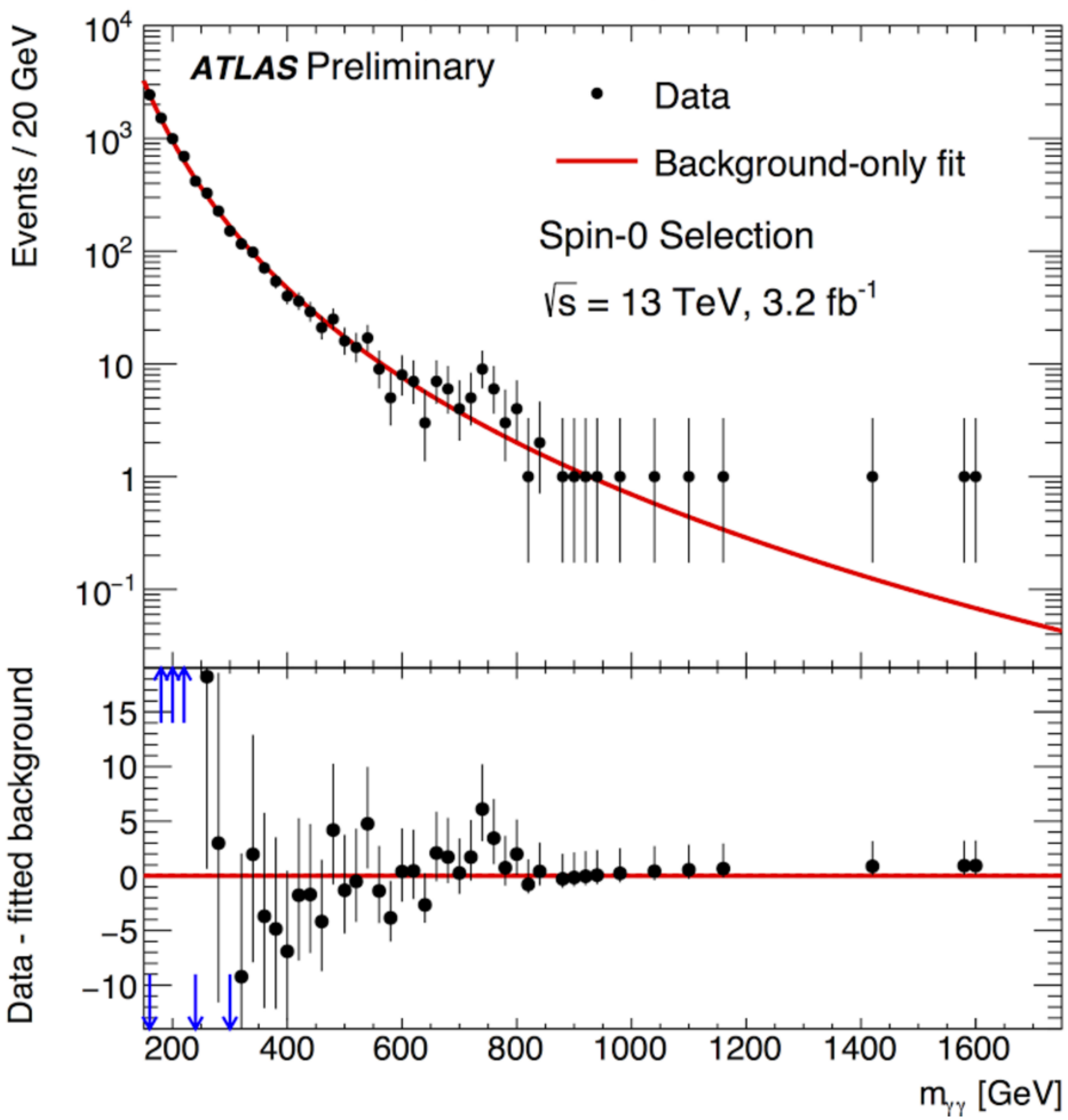
w/ M Low, LT Wang + w/ M Redi, A Strumia, E Vigiani + …

The unexpected might happen

SPIN-0 ANALYSIS

background-only fit



Leicester City @LCFC · May 2

Leicester City. Champions of England.

1 event in 132 years

Starting point

- Digamma is spin-0
- Digamma is a SM singlet
- Resonant production
- Rate 5 fb
- … and it is a real thing

Why 750?

For "natural" theories like SUSY or Compositeness
it is the natural value for scalar masses

$$\delta m_F^2 \simeq \frac{3y_t^2}{4\pi}\left(\frac{m_{\rm LHC}}{2\rm TeV}\right)^2$$ ✓

- After tuning the Higgs, F naturally 750

- A pseudo scalar singlet in Composite Higgs

$$m_\eta \simeq m_h \times \frac{f}{v}$$

Why only digamma (so far)?

A trivial analogy with QCD

- Anomalous (large) decay $\Gamma_{\gamma\gamma} = \frac{\alpha^2}{64\pi^2}\left(\frac{N_c}{3}\right)^2 \frac{m_\pi^3}{f_\pi^2}$
- Quarks confined (not seen at low E)
- \digamma the first (lightest) state

CP-odd to avoid dibosons

$$\mathcal{L} \supset -\frac{1}{16\pi^2}\frac{\eta}{f}\left[g_1^2\, c_B\, B_{\mu\nu}\tilde{B}^{\mu\nu} + g_2^2\, c_W\, W_{\mu\nu}\tilde{W}^{\mu\nu} + g_3^2\, c_G\, G_{\mu\nu}\tilde{G}^{\mu\nu}\right] + \kappa_f y_f \frac{\eta}{f} i\bar{q}Hq$$

← anomaly induced →

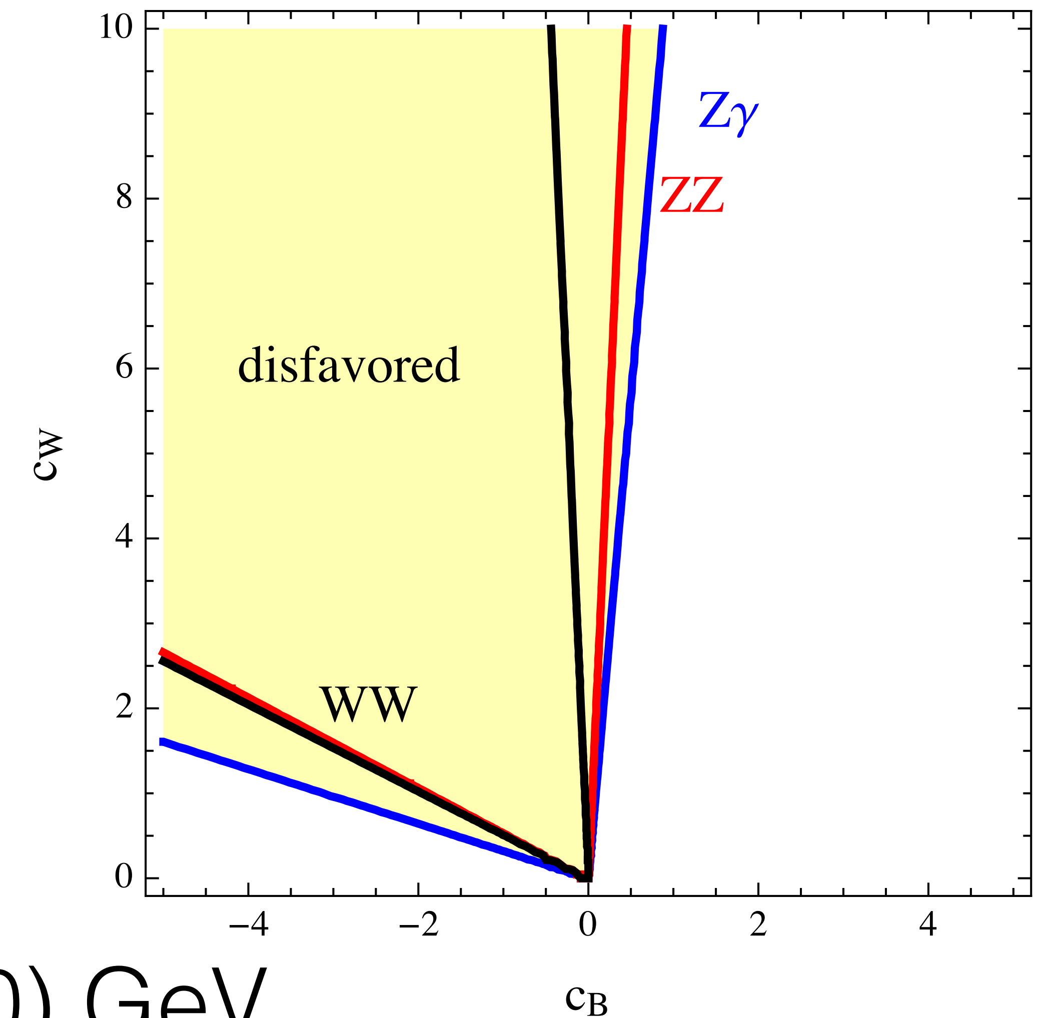
$$c_\gamma = c_W + c_B$$

- CP-even has tree-level coupling to WW, ZZ, hh
- CP selects a few higher order interactions
- Room for sizable diphoton, caveat ttbar

If no coupling to top

$$f \approx 130\ \mathrm{GeV}\sqrt{c_\gamma c_G}\left(\frac{\mathrm{GeV}}{\Gamma_{tot}}\right)^{1/4}$$

w/ Matt Low and Liantao Wang



- Width is small
- For O(1) numbers, f~O(200) GeV

$$\frac{\Gamma_{\gamma Z}}{\Gamma_{\gamma\gamma}} \approx \frac{2(-c_W\cot\theta_W + c_B\tan\theta_W)^2}{c_\gamma^2}, \quad \frac{\Gamma_{ZZ}}{\Gamma_{\gamma\gamma}} \approx \frac{(c_W\cot\theta_W^2 + c_B\tan\theta_W^2)^2}{c_\gamma^2},$$

$$\frac{\Gamma_{WW}}{\Gamma_{\gamma\gamma}} \approx 2\frac{c_W^2}{c_\gamma^2\sin^4\theta_W}, \quad \frac{\Gamma_{gg}}{\Gamma_{\gamma\gamma}} \approx \frac{8\alpha_3^2}{\alpha^2}\frac{c_G^2}{c_\gamma^2} \approx 1300\,\frac{c_G^2}{c_\gamma^2}.$$

Singlet from strong coupling

Composite Higgs - natural

- Higgs and 750 are pNGB, same dynamics
- $m_\eta \simeq m_h \times \frac{f}{v}$
- f>600 GeV, higgs couplings
- ttbar important

New sector - ad hoc

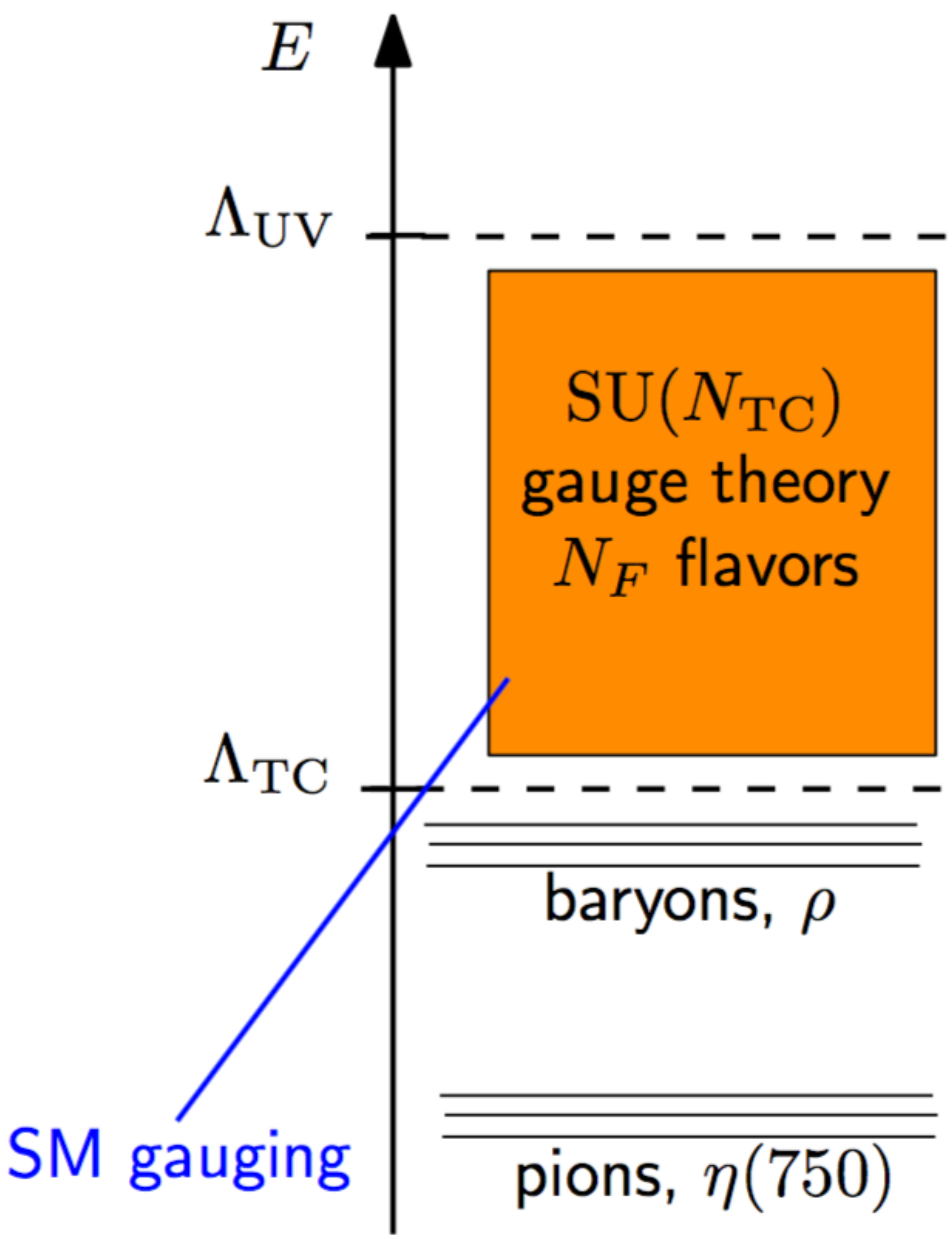
- No link with Higgs
- No ttbar
- No indirect bounds
- Motivated by what?

Vector like confinement

Cilic, Sundrum '09

Harigaya, Nomura
Bai Berger Lu
Craig, Draper, Kilic, Thomas
….

A “pion” from a new sector



- UV gauge theory with fermions $\mathcal{Q}$

$$\mathcal{Q} = \sum_a (N_{\rm TC}, R_a) \oplus (\bar{N}_{\rm TC}, \bar{R}_a)$$

- $\mathcal{Q}_a$ are charged under SM, vector-like
- At low energy theory confines $\langle \mathcal{Q}_i \bar{\mathcal{Q}}^j \rangle = \Lambda^3_{\rm TC} \delta_i^j$
- Vacuum does NOT break SM
- Below $\Lambda_{\rm TC}$, weakly-coupled pions $\mathrm{SU}(N_F)_L \otimes \mathrm{SU}(N_F)_R \to \mathrm{SU}(N_F)$
- Pion can have SM quantum numbers
- η is singlet made of color and ew $\mathcal{Q}_i$

analogy is with QCD-QED

GUT inspired reps

$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	name
1	1	0	N
1	1	1	E
1	2	$-1/2$	L
1	3	0	V
$\bar{3}$	1	$1/3$	D
$\bar{3}$	1	$-2/3$	U
3	2	$1/6$	Q
6	1	$-2/3$	S
8	1	0	G

Simplest scenarios: Q_1, Q_2

- $N_{\rm TF} = \dim(Q_1) + \dim(Q_2)$
- $\eta \sim \frac{1}{\sqrt{d_1}} Q_1 \bar{Q}_1 - \frac{1}{\sqrt{d_2}} Q_2 \bar{Q}_2$
- $\eta' \sim Q_1 \bar{Q}_1 + Q_2 \bar{Q}_2$

$c_B = 2N_{\rm TC}\,{\rm Tr}(T_\eta Y^2)$ $\quad c_W = 2N_{\rm TC}\,{\rm Tr}\left(T_\eta T^a T^a\right)$ $\quad c_G = 2N_{\rm TC}\,{\rm Tr}\left(T_\eta T^A T^A\right)$

Fully determined up to the overall $N_{\rm TC}$

Models with 2 reps

$\mathcal{Q}$	$N_{\rm TF}$	$\frac{c_B^\eta}{N_{\rm TC}}$	$\frac{c_W^\eta}{N_{\rm TC}}$	$\frac{c_G^\eta}{N_{\rm TC}}$	$\frac{\Gamma^\eta_{\gamma Z}}{\Gamma^\eta_{\gamma\gamma}}$	$\frac{\Gamma^\eta_{ZZ}}{\Gamma^\eta_{\gamma\gamma}}$	$\frac{\Gamma^\eta_{GG}}{\Gamma^\eta_{\gamma\gamma}}$	$\frac{f(\text{GeV})}{N_{\rm TC}}$	$\frac{c_B^{\eta'}}{N_{\rm TC}}$	$\frac{c_W^{\eta'}}{N_{\rm TC}}$	$\frac{c_G^{\eta'}}{N_{\rm TC}}$	$\frac{\Gamma^{\eta'}_{\gamma Z}}{\Gamma^{\eta'}_{\gamma\gamma}}$	$\frac{\Gamma^{\eta'}_{ZZ}}{\Gamma^{\eta'}_{\gamma\gamma}}$	$\frac{\Gamma^{\eta'}_{GG}}{\Gamma^{\eta'}_{\gamma\gamma}}$	$\frac{f(\text{GeV})}{N_{\rm TC}}$
$D \oplus L$	5	$\frac{1}{6}\sqrt{\frac{5}{3}}$	$\frac{1}{2}\sqrt{\frac{3}{5}}$	$-\frac{1}{\sqrt{15}}$	1.8	4.7	240	96	$\frac{1}{3}\sqrt{\frac{5}{2}}$	$\frac{1}{\sqrt{10}}$	$\frac{1}{\sqrt{10}}$	0.23	1.9	180	–
$D \oplus U$	6	$\frac{1}{\sqrt{3}}$	0	0	0.57	0.082	0	–	$\frac{5}{3\sqrt{3}}$	0	$\frac{1}{\sqrt{3}}$	0.57	0.082	470	150
$D \oplus E$	4	$\frac{4}{3}\sqrt{\frac{2}{3}}$	0	$-\frac{1}{2\sqrt{6}}$	0.57	0.082	46	170	$\frac{2\sqrt{2}}{3}$	0	$\frac{1}{2\sqrt{2}}$	0.57	0.082	180	–
$D \oplus Q$	9	$-\frac{1}{6}$	$\frac{1}{2}$	0	17	22	0	–	$\frac{1}{3\sqrt{2}}$	$\frac{1}{\sqrt{2}}$	$\frac{1}{\sqrt{2}}$	2.9	6.1	740	150
$D \oplus T$	6	$\frac{8}{3\sqrt{3}}$	$\frac{2}{\sqrt{3}}$	$-\frac{1}{2\sqrt{3}}$	0.43	2.4	15	430	$\frac{10}{3\sqrt{3}}$	$\frac{2}{\sqrt{3}}$	$\frac{1}{2\sqrt{3}}$	0.23	1.9	12	–
$L \oplus U$	5	$\frac{7}{6\sqrt{15}}$	$-\frac{1}{2}\sqrt{\frac{3}{5}}$	$\frac{1}{\sqrt{15}}$	200	180	12000	–	$\frac{11}{3\sqrt{10}}$	$\frac{1}{\sqrt{10}}$	$\frac{1}{\sqrt{10}}$	0.0027	0.83	60	230
$L \oplus Q$	8	$-\frac{2}{3\sqrt{3}}$	0	$\frac{1}{2\sqrt{3}}$	0.57	0.082	740	61	$\frac{1}{3}$	1	$\frac{1}{2}$	2.9	6.1	180	210
$L \oplus S$	8	$\frac{7}{12\sqrt{3}}$	$-\frac{\sqrt{3}}{4}$	$\frac{5}{4\sqrt{3}}$	200	180	74000	–	$\frac{19}{12}$	$\frac{1}{4}$	$\frac{5}{4}$	0.095	0.47	610	290
$U \oplus E$	4	$\frac{5}{3\sqrt{6}}$	0	$-\frac{1}{2\sqrt{6}}$	0.57	0.082	120	110	$\frac{7}{3\sqrt{2}}$	0	$\frac{1}{2\sqrt{2}}$	0.57	0.082	60	260
$U \oplus Q$	9	$-\frac{5}{6}$	$\frac{1}{2}$	0	32	17	0	–	$\frac{1}{\sqrt{2}}$	$\frac{1}{\sqrt{2}}$	$\frac{1}{\sqrt{2}}$	0.79	3.0	330	220
$U \oplus V$	6	$-\frac{4}{3\sqrt{3}}$	$\frac{2}{\sqrt{3}}$	$-\frac{1}{2\sqrt{3}}$	83	82	740	–	$\frac{4}{3\sqrt{3}}$	$\frac{2}{\sqrt{3}}$	$\frac{1}{2\sqrt{3}}$	1.5	4.1	29	310
$U \oplus N$	4	$-\frac{2}{3}\sqrt{\frac{2}{3}}$	0	$-\frac{1}{2\sqrt{6}}$	0.57	0.082	180	87	$\frac{2\sqrt{2}}{3}$	0	$\frac{1}{2\sqrt{2}}$	0.57	0.082	180	–
$E \oplus Q$	7	$-\frac{5}{6}\sqrt{\frac{7}{3}}$	$\frac{1}{2}\sqrt{\frac{3}{7}}$	$\frac{1}{\sqrt{21}}$	3.6	0.52	70	150	$\frac{1}{3}\sqrt{\frac{7}{2}}$	$\frac{3}{\sqrt{14}}$	$\sqrt{\frac{2}{7}}$	1.2	3.7	180	–
$E \oplus S$	7	$-\frac{10}{3\sqrt{21}}$	0	$\frac{5}{2\sqrt{21}}$	0.57	0.082	740	120	$\frac{11}{3}\sqrt{\frac{2}{7}}$	0	$5\sqrt{14}$	0.57	0.082	610	310
$S \oplus V$	9	$-\frac{8}{9}$	$\frac{4}{3}$	$-\frac{5}{6}$	83	82	4600	–	$\frac{8\sqrt{2}}{9}$	$\frac{2\sqrt{2}}{3}$	$\frac{5}{3\sqrt{2}}$	0.43	2.4	380	350
$S \oplus N$	7	$-\frac{8}{3\sqrt{21}}$	0	$-\frac{5}{2\sqrt{21}}$	0.57	0.082	1200	93	$\frac{8}{3}\sqrt{\frac{2}{7}}$	0	$\frac{5}{\sqrt{14}}$	0.57	0.082	1200	230
$N \oplus Q$	7	$\frac{1}{6\sqrt{21}}$	$\frac{1}{2}\sqrt{\frac{3}{7}}$	$\frac{1}{\sqrt{21}}$	4.9	8.5	470	58	$\frac{1}{3\sqrt{14}}$	$\frac{3}{\sqrt{14}}$	$\sqrt{\frac{2}{7}}$	4.9	8.5	470	140

w/ Redi, Strumia Vigiani

Unstable pions

- Interactions from WZW term

$$\mathscr{L}_{\rm WZW} \supset -\frac{1}{16\pi^2}\frac{N_{\rm TC}}{f}{\rm Tr}[\Pi\{F_{\mu\nu},\tilde{F}_{\mu\nu}\}],$$

- (8,1) bound from di-jet and jet+Z,gamma

$$\mathscr{L}_{\chi} \supset -\frac{g_3^2}{32\pi^2}\frac{N_{\rm TC}}{f}\, d^{\alpha\beta\gamma}\chi^{\alpha}G^{\beta}_{\mu\nu}\tilde{G}^{\gamma,\mu\nu} - \frac{g_3 g_Y}{16\pi^2}\frac{N_{\rm TC}}{f}\, q_Y\, \chi^{\alpha}G^{\alpha}_{\mu\nu}\tilde{B}^{\mu\nu},$$

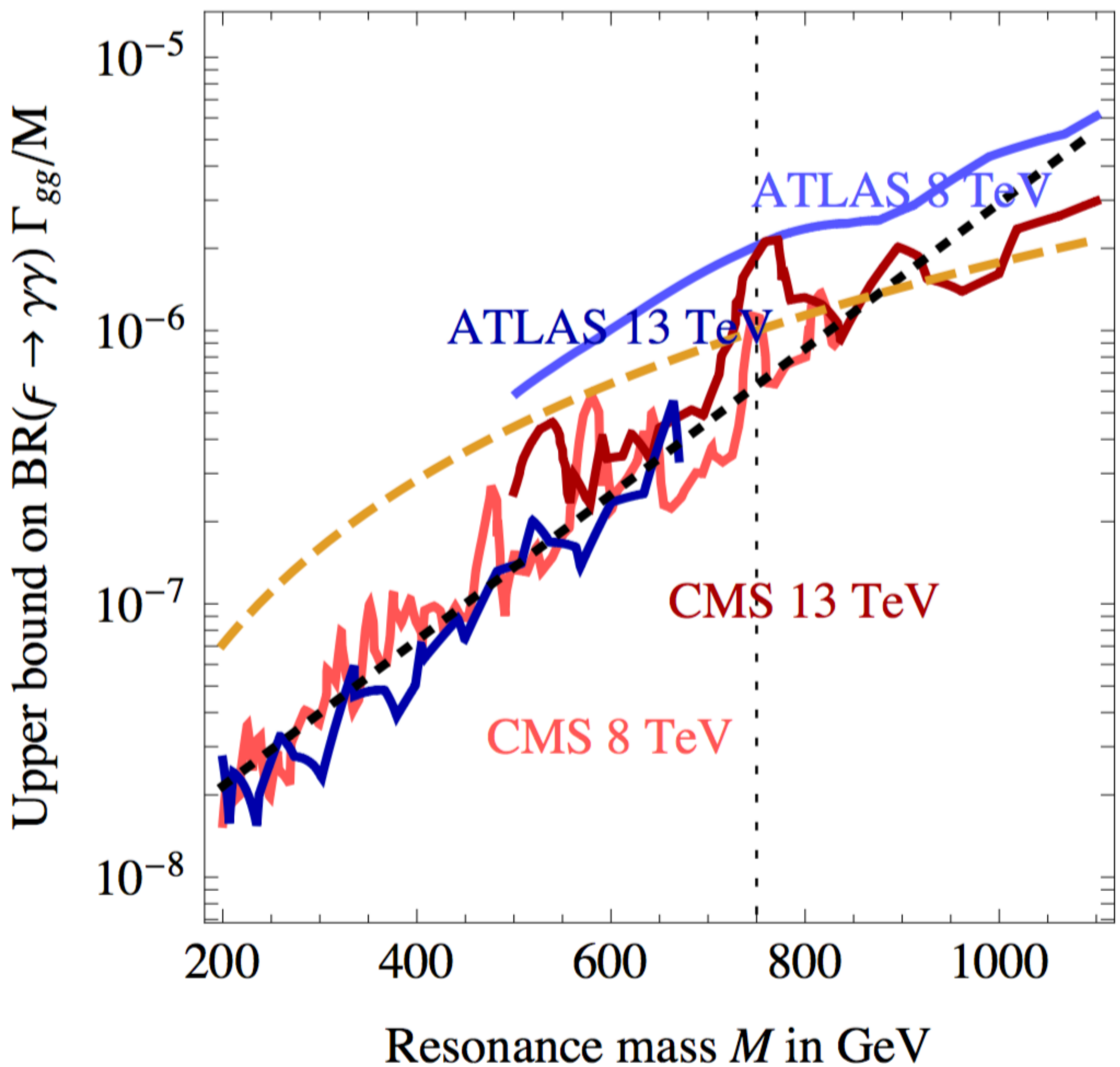
- (8,3) bound from VLQ, T->q+W

$$\mathscr{L}_{\chi^{\alpha}_{a}} \supset -\frac{g_2 g_3}{16\pi^2}\frac{N_{\rm TC}}{f}\, \chi^{\alpha}_{a}G^{\alpha}_{\mu\nu}\tilde{W}^{a,\mu\nu}$$

- Also other singlets η, η'- like

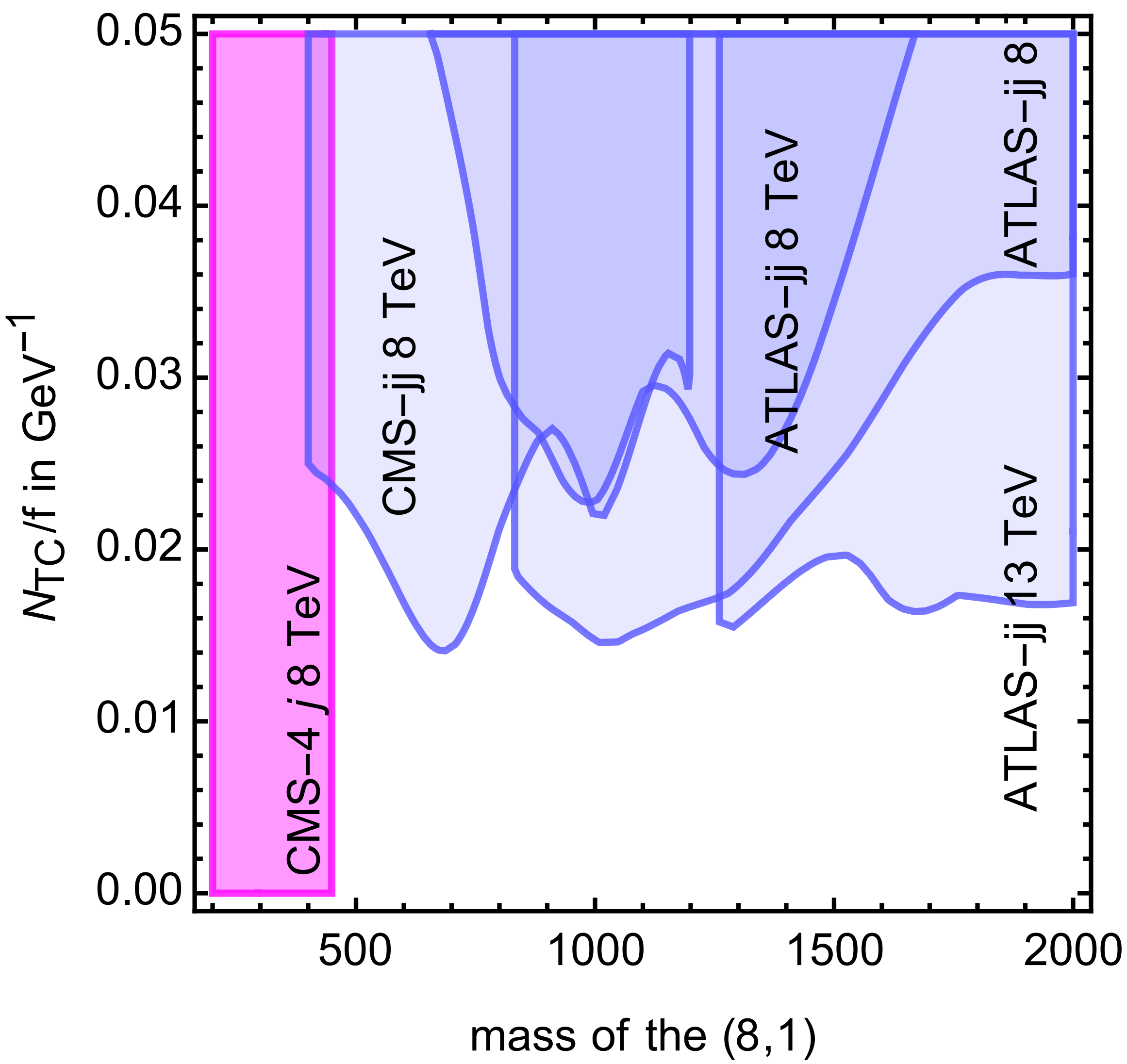
Real pions unstable
(unless G-parity)

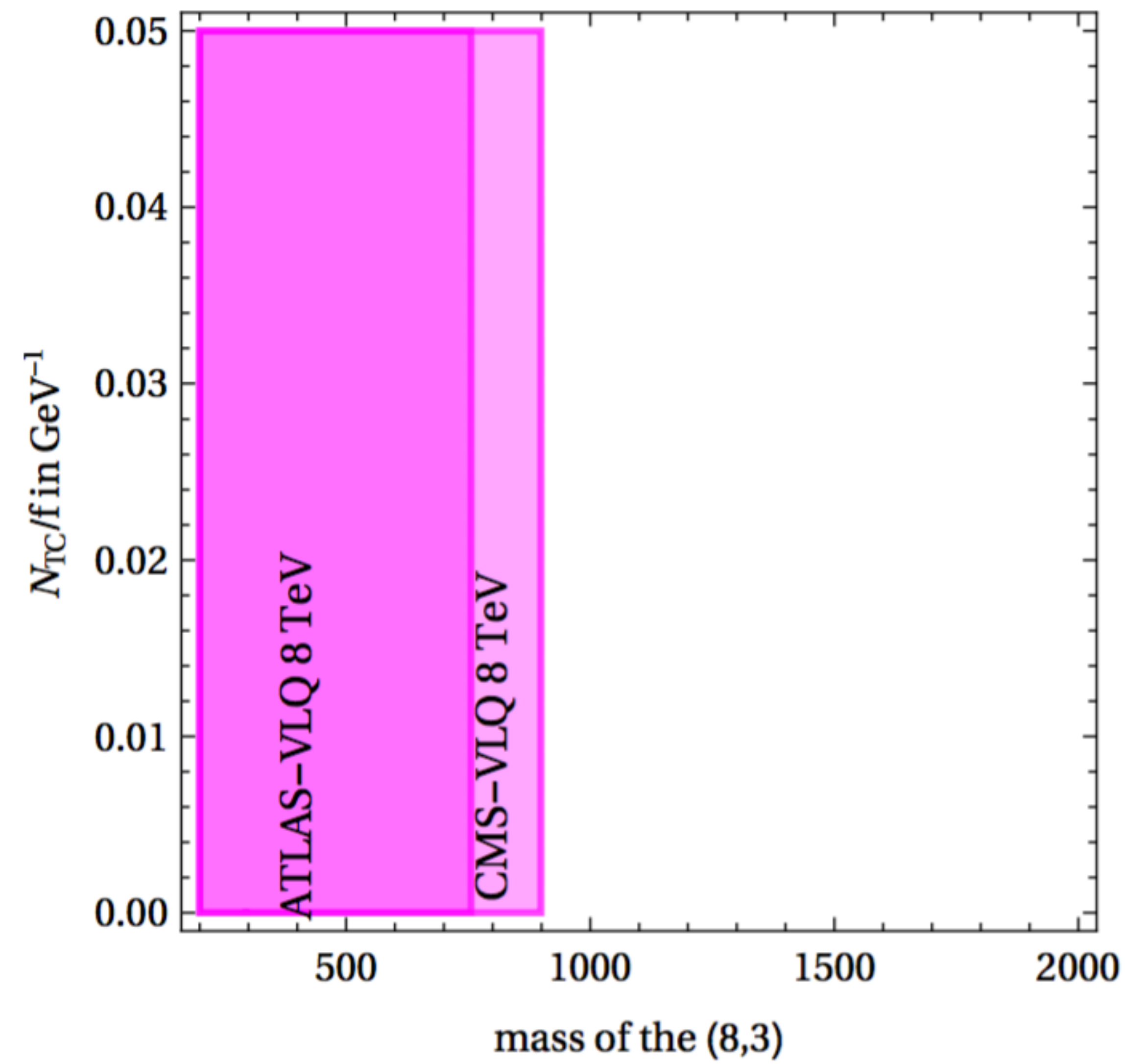
Unstable pions, singlet



Also ew triplets - Howe, Knapen

Unstable pions, colored





Resonances well within the reach of LHC

A few exceptions

Models with no stable particles
can be built involving the Higgs

- In given models, Yukawa terms Q H U
- Funny decay chain, (8,2) —> H* + (8,1)
- Just for fun, in these models one can build a *relaxion* scenario… see Antipin Redi

Other aspects of vector like confinement

Accidental symmetries

(Ex. Imagine QCD is vector like, as our diphoton theories)

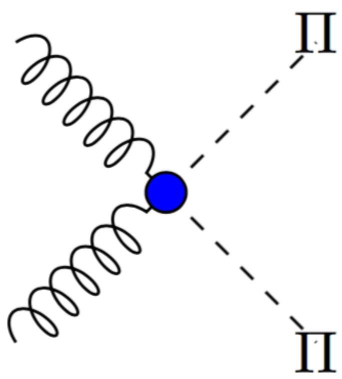
- VL theories with confinement have stable pions
- Species number from UV lagrangian
- Colored pions can be collider stable
- Chance to build a compelling DM model

DM as a heavy pion

- Pions made of different quarks are stable (dim-4)

$$\Pi \sim X_1 X_2^* \qquad U(1)_1 \times U(1)_2$$

- Annihilation to gauge bosons (gluons)



see also Y. Bai

- Thermal relic via hidden theta-term

DM interactions

$$\mathscr{L}_{\rm DM} = \frac{g_3^2}{16\pi^2}\underbrace{\frac{\Pi^2}{fM^2} C_{\eta\Pi\Pi} c_G G^a_{\mu\nu}\tilde{G}^{a,\mu\nu}}_{\theta-\rm term} + \frac{g_3^2}{16\pi^2}\underbrace{C_{\Pi\Pi gg}\frac{\Pi^2}{f^2} G^a_{\mu\nu}G^{a,\mu\nu}}_{\rm Rayleigh}$$

- CPV, 750 mediator $C_{\eta\Pi\Pi} = m_\Pi^2/f\tan(\theta_{\rm TC}/2)$
- Rayleigh $C_{\Pi\Pi gg} \simeq N_{\rm TC}\frac{m_\Pi^2}{\Lambda^2}$
- If Π is not the lightest (also $\pi\pi$ scattering)

Strumia's talk Moriond

A composite model

Over-ambitious model: extra SU($N_{\rm TC}$) with $\mathcal{Q} = N_1 \oplus N_2 \oplus U$ and $\theta_{\rm TC}$.

$$\mathrm{TC}\pi = \underbrace{(8,1)_0}_{\chi\sim U\bar U} \oplus \underbrace{2\times[(\bar 3,1)_{-2/3}+(3,1)_{2/3}]}_{\phi_i\sim U\bar N_i,\ \phi_i^*} \oplus \underbrace{4\times(1,1)_0}_{\Pi\sim N_1\bar N_2,\ \Pi^*,\ \eta_{1,2}}$$

Pseudo-scalars η with couplings to $G\tilde G, W\tilde W, B\tilde B$ predicted by anomalies:
$\eta_2 \sim N_1\bar N_1 - N_2\bar N_2$, $\eta_1 \sim N_i\bar N_i - \frac{3}{2}U\bar U$, $\eta' \sim \mathcal{Q}\bar{\mathcal{Q}}$ up to mixings $\propto m_{N_1} - m_{N_2}$.

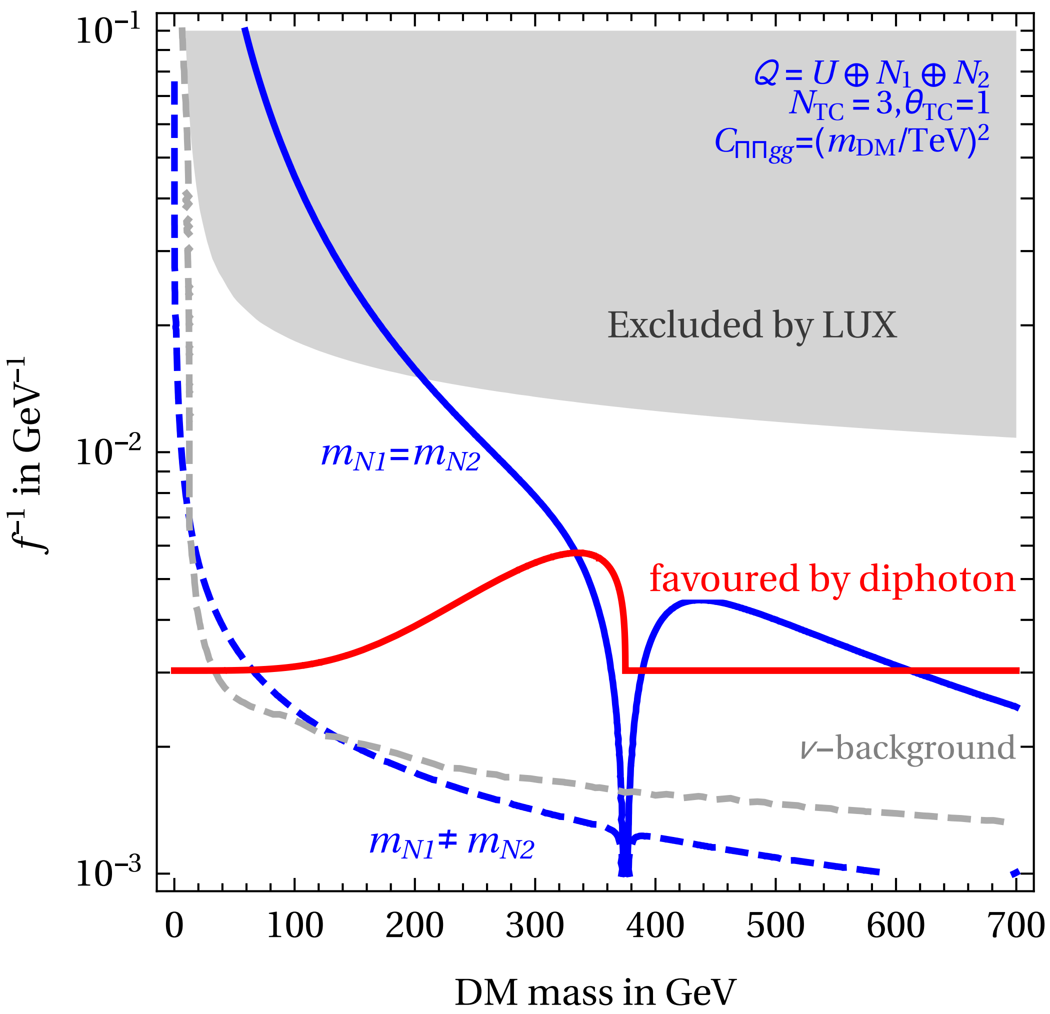
TCπ masses in terms of $B_0 \sim \Lambda_{\rm TC}$ for TC$\mathcal{Q}$ masses $\Lambda_{\rm TC} \sim m_U > \frac{7}{2} m_{N_{1,2}}$

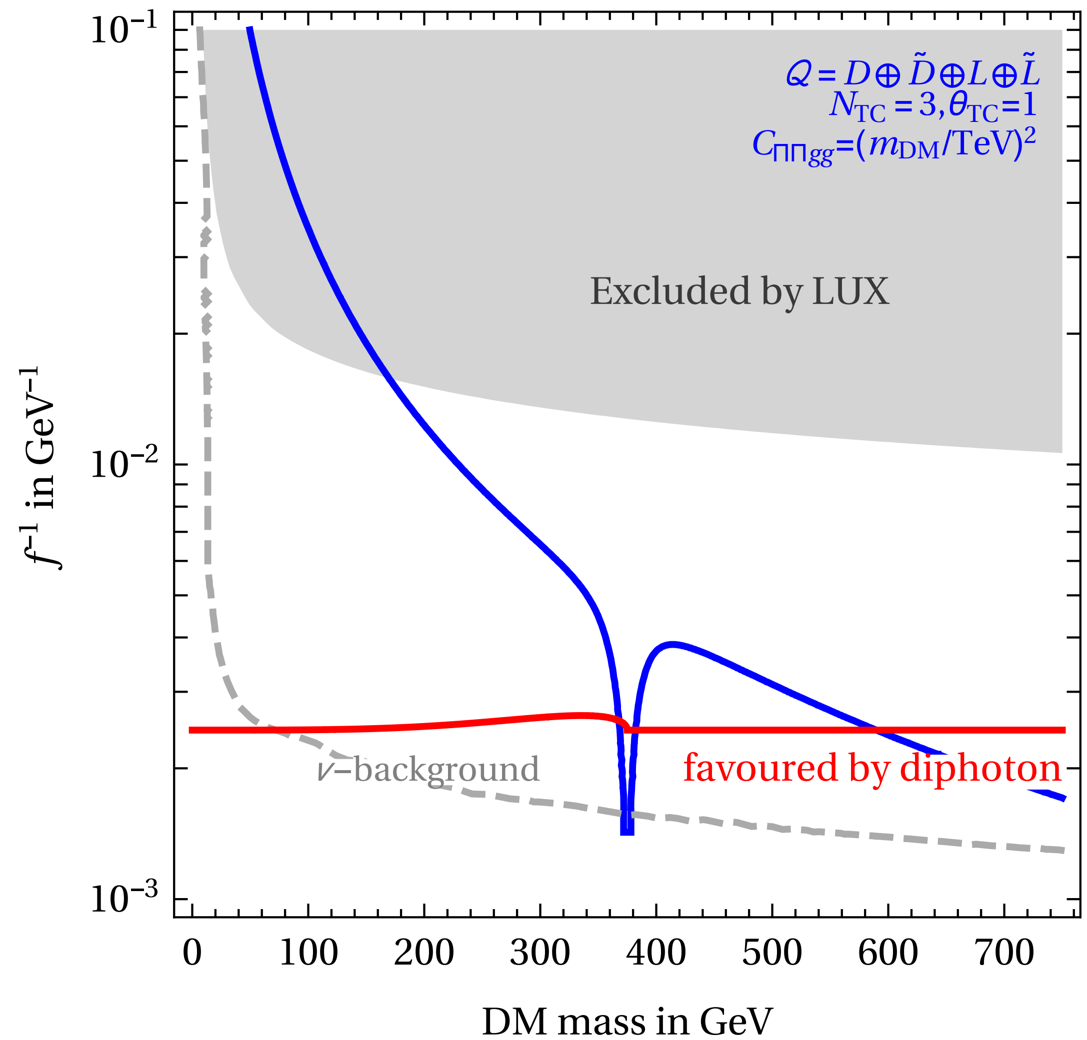
$$\begin{aligned} \text{DM}: &\quad m_\Pi^2 = B_0(m_{N_1}+m_{N_2}), \\ 750\ \text{GeV}\ S: &\quad m_{\eta_1}^2 \approx \tfrac{4}{5}B_0 m_U \qquad m_{\eta'} \sim \Lambda_{\rm TC} \qquad m_{\eta_2} \lesssim m_\Pi \\ \text{Extra colored}: &\quad m_\chi^2 = 2B_0 m_U + \Delta_\chi \qquad m_{\phi_i}^2 = B_0(m_U + m_{N_i}) + \Delta_\phi, \end{aligned}$$

S can $\not{C}$P decay to DM, $\Gamma(\eta_1 \to \Pi\Pi^*) \sim$ GeV $\times\, \theta_{\rm TC}^2 < 45$ GeV.
DM abundance, direct detection: ok. Lightest TCbaryon $N_{1,2}^{N_{\rm TC}}$ can be DM$'$.

Predictive! Look for extra resonances

Thermal relic





- Interesting range, Rayleigh direct detection
- Lower masses if $\pi\pi$ scattering relevant

Conclusions

Confining theories for 750 open "new" interesting directions

- If 750 is real, they become really attractive
- If 750 is not real…
- In both cases they are fun!