XXIX ciclo di dottorato

Università di Pisa

Accidental Composite Dark Matter
(and the di-photon resonance)

Elena Vigiani

Pisa, 31/03/2016

Outline

- Vectorlike Confinement
- Techni-baryons as Dark Matter candidates
    - Dark Matter phenomenology
- Techni-pions as Dark Matter and di-photon candidates
    - Dark Matter and di-photon phenomenology
- Conclusions

Vectorlike Confinement

Kilic, Okui, Sundrum (arXiv:0906.0577)

$$\mathcal{Q} = \sum_i (N_{\rm TC}, r_i) \oplus (\bar{N}_{\rm TC}, \bar{r}_i)$$

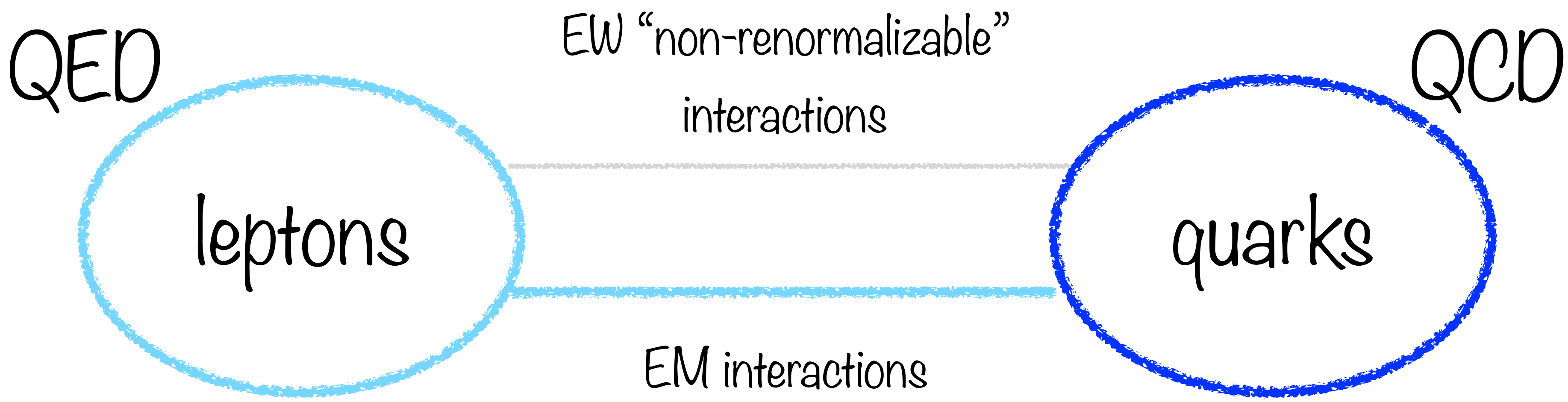
new fermions in a vectorial rep of the SM
charged under a new strong interaction (fundamental of $\mathrm{SU}(N_{\rm TC})$)
that confines without breaking the SM

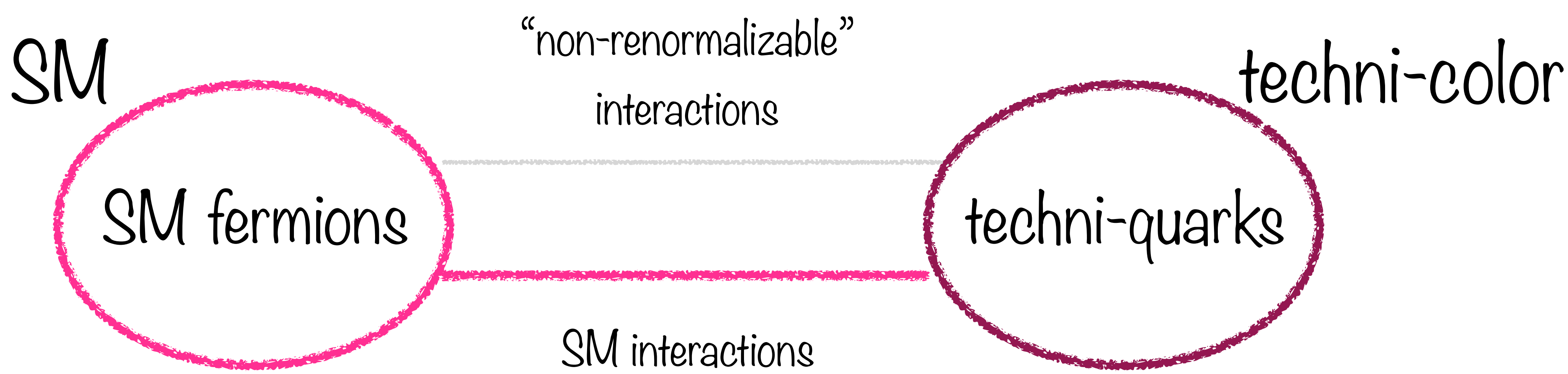
$\langle \mathcal{Q}\bar{\mathcal{Q}} \rangle \sim$ SM singlet

let's call it "techni-color" ($\neq$ old Technicolor theories !!!)

EWPT : ok , flavor : ok (MFV)
LHC bounds : new particles at the TeV scale
DM candidates : stable thanks to accidental symmetries

Vectorlike Confinement





Vectorlike Confinement

$\mathrm{SU}(N_{\mathrm{TC}})$

with N_{TF} techni-flavors

→ SSB of the chiral symmetry

$$\mathrm{SU}(N_{\mathrm{TF}})_L \otimes \mathrm{SU}(N_{\mathrm{TF}})_R \to \mathrm{SU}(N_{\mathrm{TF}})$$

$N_{\mathrm{TF}}^2 - 1$ techni-pions $(\mathcal{Q}\bar{\mathcal{Q}})$

pseudo Goldstone Bosons

$$m_{\mathrm{TC}\pi}^2 \sim m_{\mathcal{Q}} \Lambda_{\mathrm{TC}} + \underbrace{\Delta_{\mathrm{gauge}}}_{\sim 1/100 \Lambda_{\mathrm{TC}}^2}$$

mass of techni-pions

$\sim 1/10$ of the mass of techni-baryons

↓

techni-baryons

techni-color singlets made of

N_{TC} techni-quarks

depend on the details of the models

fermion if N_{TC} odd, boson if N_{TC} even

Accidental Symmetries

techni-baryon number : $\mathcal{Q} \to e^{i\alpha} \mathcal{Q}$

the lightest techni-baryon is stable

species number : $\mathcal{Q}_i \to e^{i\alpha_i} \mathcal{Q}_i \, , \quad i = 1, \ldots, N_s$

the lightest $\bar{\mathcal{Q}}_i \mathcal{Q}_j \, , \quad i \neq j$

is stable, in analogy with $\pi^+ (u\bar{d})$

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dim-6 (or more) operators

species number :

$$\mathcal{Q}_i \to e^{i\alpha_i} \mathcal{Q}_i \,, \quad i = 1, \ldots, N_s$$

the lightest $\bar{\mathcal{Q}}_i \mathcal{Q}_j \,, \quad i \neq j$

is stable, in analogy with $\pi^+(u\bar{d})$

dim-5 operators

Techni-baryons as DM candidates

Antipin, Redi, Strumia, Vigiani (arXiv:1503.08749)

SU(5)	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	name	$\Delta b_3/N_{TC}$	$\Delta b_2/N_{TC}$	$\Delta b_Y/N_{TC}$
1	1	1	0	N	0	0	0
$\bar{5}$	$\bar{3}$	1	1/3	D	1/3	0	2/9
	1	2	−1/2	L	0	1/3	1/3
10	$\bar{3}$	1	−2/3	U	1/3	0	8/9
	1	1	1	E	0	0	2/3
	3	2	1/6	Q	2/3	1	1/9
15	3	2	1/6	Q	2/3	1	1/9
	1	3	1	T	0	4/3	2
	6	1	−2/3	S	5/3	0	8/9
24	1	3	0	V	0	4/3	0
	8	1	0	G	2	0	0
	$\bar{3}$	2	5/6	X	2/3	1	25/9
	1	1	0	N	0	0	0

techni-baryon DM candidate
(no color, no charge, no hypercharge)
no unwanted stable particles
(Yukawa couplings break unwanted accidental symmetries)

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	1	2	−1/2	L	0	1/3	1/3
10	$\bar{3}$	1	−2/3	U	1/3	0	8/9
	1	1					
	3	2					
15	3	2					
	1	3					
	6	1					
24	1	3					
	8	1					
	$\bar{3}$	2					
	1	1					

$SU(N_{TC})$ techni-color Techni-quarks	Yukawa couplings	Allowed N_{TC}	Techni-pions	Techni-baryons	under
$N_{TF}=3$			8	$8, \bar{6}, \ldots$ for $N_{TC}=3,4,\ldots$	$SU(3)_{TF}$
$\mathcal{Q}=V$	0	3	3	$VVV=3$	$SU(2)_L$
$\mathcal{Q}=N\oplus L$	1	3 − 14	unstable	$(N^{N_{TC}})^*=1$	=
$N_{TF}=4$			15	$\overline{20}, 20', \ldots$	$SU(4)_{TF}$
$\mathcal{Q}=V\oplus N$	0	3	3 × 3	$VVV, VNN=3,\ VVN=1$	$SU(2)_L$
$\mathcal{Q}=N\oplus L\oplus\tilde{E}$	2	3, 4, 5	unstable	$(N^{N_{TC}})^*=1$	=
$N_{TF}=5$			24	$\overline{40}, \overline{50}$	$SU(5)_{TF}$
$\mathcal{Q}=V\oplus L$	1	3	unstable	$VVV=3$	$SU(2)_L$
$\mathcal{Q}=N\oplus L\oplus\tilde{L}$	2	3	unstable	$NL\tilde{L}=1$	=
=	2	4	unstable	$NNL\tilde{L}, L\tilde{L}L\tilde{L}=1$	=
$N_{TF}=6$			35	$70, \overline{105'}$	$SU(6)_{TF}$
$\mathcal{Q}=V\oplus L\oplus N$	2	3	unstable	$VVV, VNN=3, VVN=1$	$SU(2)_L$
$\mathcal{Q}=V\oplus L\oplus\tilde{E}$	2	3	unstable	$VVV=3$	=
$\mathcal{Q}=N\oplus L\oplus\tilde{L}\oplus\tilde{E}$	3	3	unstable	$NL\tilde{L}, \tilde{L}\tilde{L}\tilde{E}=1$	=
=	3	4	unstable	$NNL\tilde{L}, L\tilde{L}L\tilde{L}, N\tilde{E}\tilde{L}\tilde{L}=1$	=
$N_{TF}=7$			48	112	$SU(7)_{TF}$
$\mathcal{Q}=L\oplus\tilde{L}\oplus E\oplus\tilde{E}\oplus N$	4	3	unstable	$LLE, \tilde{L}\tilde{L}\tilde{E}, L\tilde{L}N, E\tilde{E}N=1$	$SU(2)_L$
$\mathcal{Q}=N\oplus L\oplus\tilde{E}\oplus V$	3	3	unstable	$VVV, VNN=3,\ VVN=1$	=
$N_{TF}=9$			80	240	$SU(9)_{TF}$
$\mathcal{Q}=Q\oplus\tilde{D}$	1	3	unstable	$QQ\tilde{D}=1$	$SU(2)_L$
$N_{TF}=12$			143	572	$SU(12)_{TF}$
$\mathcal{Q}=Q\oplus\tilde{D}\oplus\tilde{U}$	2	3	unstable	$QQ\tilde{D}, \tilde{D}\tilde{D}\tilde{U}=1$	$SU(2)_L$

techni-baryon DM car
(no color, no charge, n
no unwanted stable pa
(Yukawa couplings bre

DM phenomenology

DM as a thermal relic : non relativistic annihilation of techni-baryons to techni-pions via techni-strong interactions

$\sigma_{p\bar{p}}^{\text{ann}}\, v \sim 100/m_p^2$ → $M_{\text{DM}} \sim 100\,\text{TeV}$

too high for usual direct detection interactions!

but fermionic DM, even if a SM singlet, can have typical interactions with photons

↓

Magnetic and Electric Dipole Moments

$\frac{1}{2}\bar{\Psi}\gamma_{\mu\nu}(\mu_M + i d_E \gamma_5)\Psi F^{\mu\nu}$

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Magnetic and Electric Dipole Moments

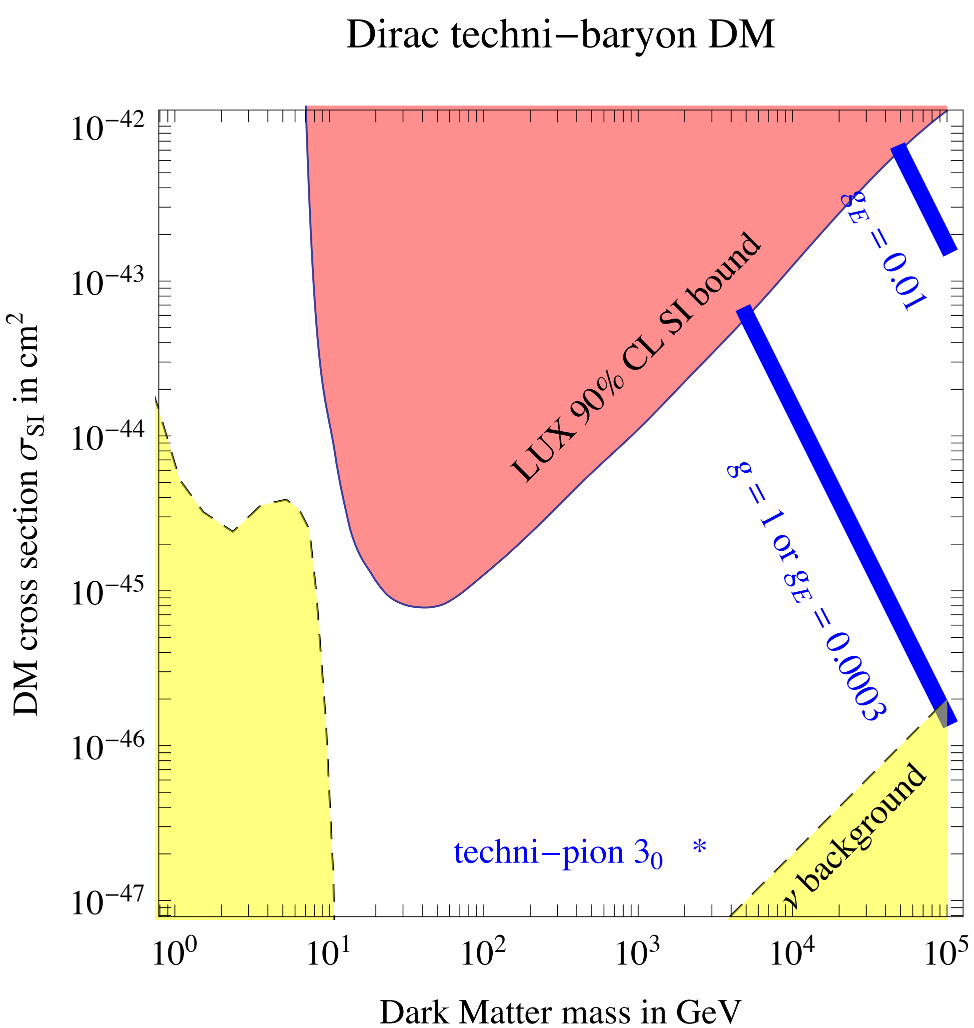
$$\frac{1}{2}\bar{\Psi}\gamma_{\mu\nu}(\mu_M + i d_E \gamma_5)\Psi F^{\mu\nu}$$

$C\!\!\!/P\!\!\!/$

$\mu_M \sim \frac{e}{2M_{\rm DM}}$

$d_E \sim \theta_{\rm TC}\, \frac{e}{2M_{\rm DM}}\, \frac{\min[m_Q]}{M_{\rm DM}}$

DM phenomenology



$$\frac{d\sigma}{dE_R} \approx \frac{e^2 Z^2}{4\pi E_R v^2}\left(\mu_M^2 v^2 + d_E^2\right)$$

compared to the usual direct detection cross section

$$\frac{d\sigma}{dE_R} \approx \frac{M_{\mathcal{N}} \sigma_{\rm SI} A^2}{2v^2} \frac{(M_{\mathcal{N}} + M_{\rm DM})^2}{M_{\mathcal{N}}^2 M_{\rm DM}^2}$$

characteristic enhancement at low E_R

characteristic v^2 suppression for μ_M

testable with seasonal variation of v

SO(N_{TC}) models

SO($N_{\rm TC}$) techni-color Techni-quarks	Yukawa couplings	Allowed $N_{\rm TC}$	Techni-pions	Techni-baryons	under
$N_{\rm TF}=3$			5	$3,1,\ldots$ for $N_{\rm TC}=3,4,\ldots$	SO(3)$_{\rm TF}$
$Q=V$	0	$3,4,..,7$	unstable	$V_{\rm TC}^{N}=3,1,\ldots$	SU(2)$_L$
$N_{\rm TF}=4$			9	$4,1,\ldots$	SO(4)$_{\rm TF}$
$Q=N\oplus V$	0	$3,4,..,7$	3	$VVN=1, V(VV+NN)=3,$	SU(2)$_L$
				$VV(VV+NN)=1,\ldots$	=
$N_{\rm TF}=5$			14	$5,1\ldots$	SO(5)$_{\rm TF}$
$Q=L\oplus N$	1	$3,4,..,14$	unstable	$L\bar{L}N=1,$	SU(2)$_L$
				$L\bar{L}(L\bar{L}+NN)=1,\ldots$	=
$N_{\rm TF}=7$			27	$1,\ldots$	SO(7)$_{\rm TF}$
$Q=L\oplus V$	1	4	unstable	$(L\bar{L}+VV)^2=1$	SU(2)$_L$
$Q=L\oplus E\oplus N$	2	$4,5$	unstable	$(E\bar{E}+L\bar{L})^2+NN(L\bar{L}+E\bar{E})=1$	=
$N_{\rm TF}=8$			35	1	SO(8)$_{\rm TF}$
$Q=G$	0	4	unstable	$GGGG=1$	SU(2)$_L$
$Q=L\oplus N\oplus V$	2	4	unstable	$(L\bar{L}+VV)^2+NN(L\bar{L}+VV)=1$	=
$N_{\rm TF}=9$			44	1	SO(9)$_{\rm TF}$
$Q=L\oplus E\oplus V$	2	4	unstable	$(E\bar{E}+L\bar{L}+VV)^2=1$	SU(2)$_L$
$N_{\rm TF}=10$			54	1	SO(10)$_{\rm TF}$
$Q=L\oplus E\oplus V\oplus N$	3	4	unstable	as $L\oplus E\oplus V+NN(L\bar{L}+E\bar{E}+VV)=1$	SU(2)$_L$

all the models contain a real techni-quark → real techni-baryon DM candidate

interesting spin dependent cross section !

Techni-pions at collider

$m_{\mathrm{TC}b} \sim 1\,\mathrm{TeV}$ → too low for a thermal relic

$m_{\mathrm{TC}\pi} < 1\,\mathrm{TeV}$

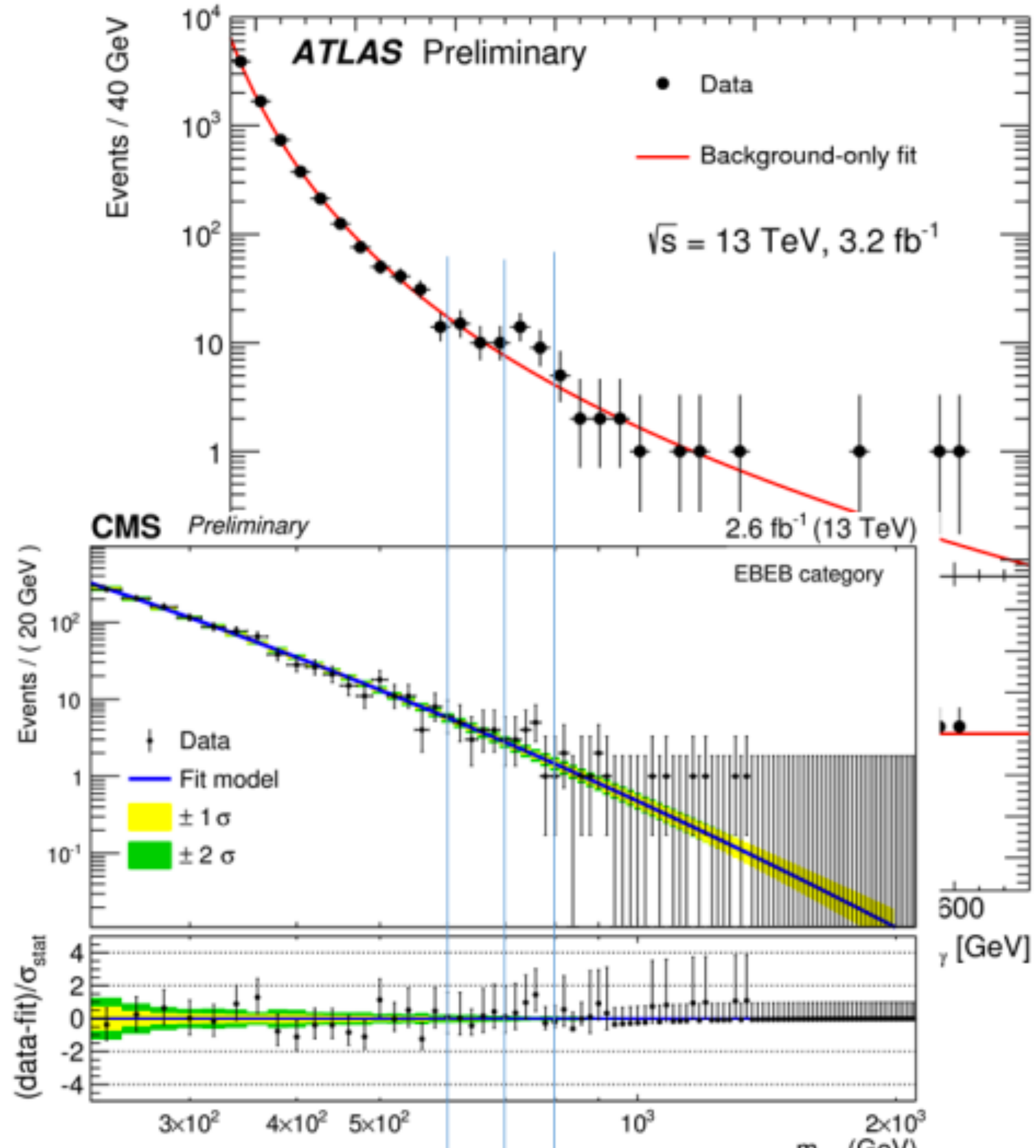
↓

accessible at LHC...

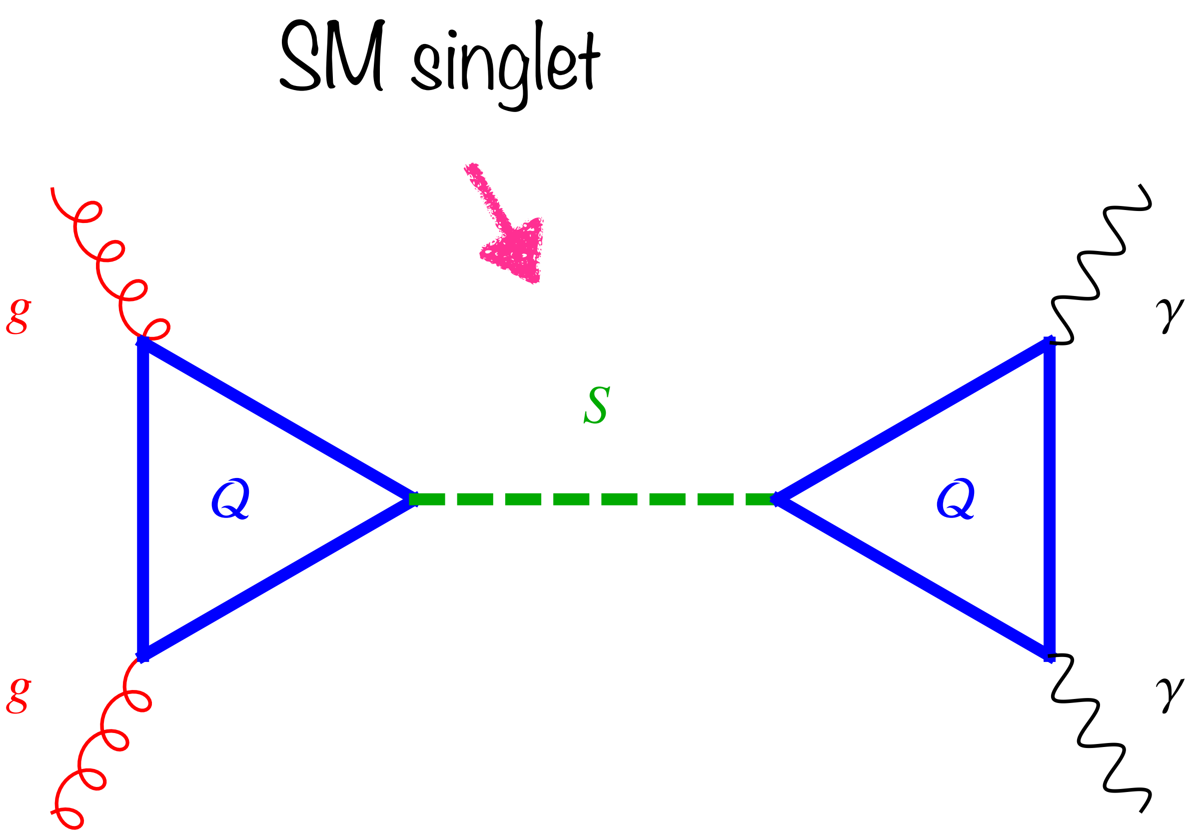
maybe already seen?

di-photon excess at

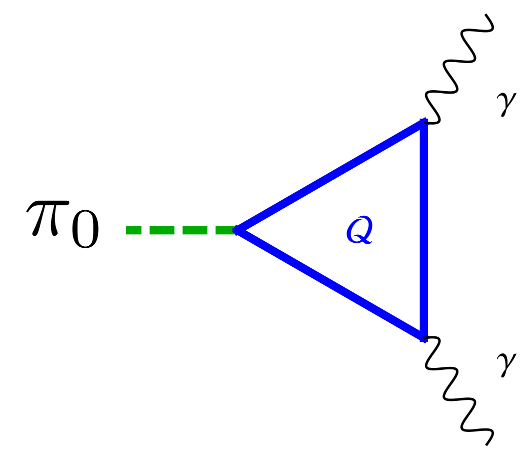
$750\,\mathrm{GeV}$



Simple and predictive



scalar or pseudo-scalar



$$\mathcal{L}_{\text{anomalies}} \supset -\frac{1}{16\pi^2}\frac{S}{f}\left[g_1^2 c_B B_{\mu\nu}\tilde{B}^{\mu\nu} + g_2^2 c_W W^a_{\mu\nu}\tilde{W}^{\mu\nu}_a + g_3^2 c_G G^a_{\mu\nu}\tilde{G}^{\mu\nu}_a\right]$$

$$c_B = 2N_{\text{TC}}\text{Tr}(T_S Y^2) \qquad c_W\delta^{ab} = 2N_{\text{TC}}\text{Tr}(T_S T^a T^b) \qquad c_G\delta^{AB} = 2N_{\text{TC}}\text{Tr}(T_S T^A T^B)$$

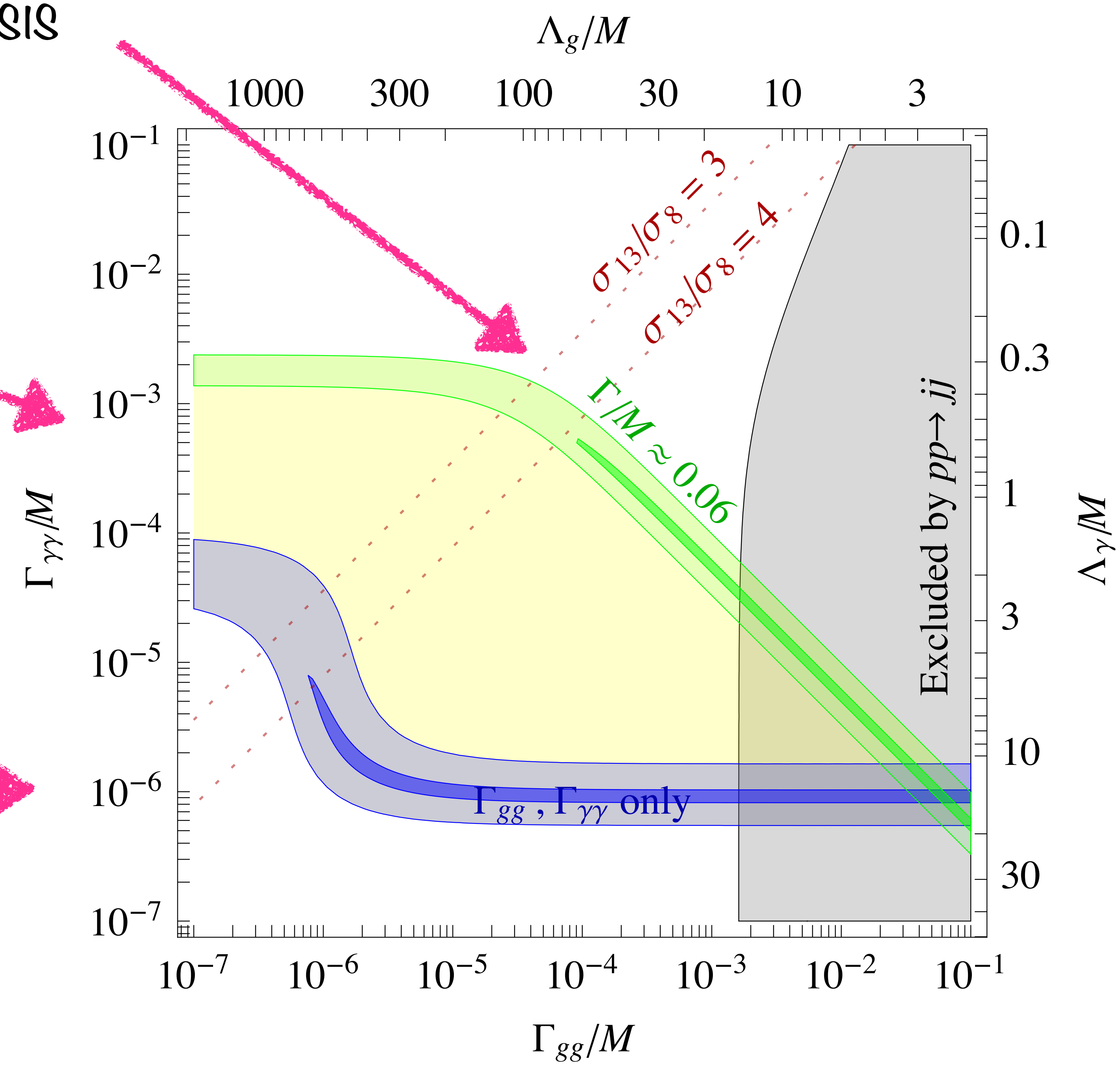
$$\frac{\Gamma(S\to VV)}{M_S} = c_V^2\,\frac{\kappa_V\,\alpha_V^2}{64\pi^3}\,\frac{M_S^2}{f^2}$$

Reproducing the signal

large width hypothesis

another decay channel
maybe DM ?

$\Gamma_S \approx \Gamma_{gg} < 1\,\mathrm{GeV}$



Franceschini et al. (arXiv:1512.04933)

Di-photon and DM in VC models

Redi, Strumia, Tesi, Vigiani (arXiv:1602.07297)

$$\underline{\mathcal{Q} = N_1 \oplus N_2 \oplus U} = (1,1)_0 \oplus (1,1)_0 \oplus (\bar{3},1)_{-2/3}$$

$\Pi \sim N_1 \bar{N}_2\,,\ \Pi^*$ stable because of species number → DM candidate

pseudo-scalars with given anomalous couplings to SM gauge bosons, up to mixing effects

$$\eta' \sim U\bar{U} + N_1\bar{N}_1 + N_2\bar{N}_2$$

$$\eta_1 \sim U\bar{U} - 3/2(N_1\bar{N}_1 + N_2\bar{N}_2)$$

$$\eta_2 \sim N_1\bar{N}_1 - N_2\bar{N}_2$$

$$m_{\eta'} \sim \Lambda_{\rm TC}$$

$$m^2_{\eta_1} \approx 4/5\, B_0 m_U\,,\ B_0 \sim \mathcal{O}(\Lambda_{\rm TC})$$

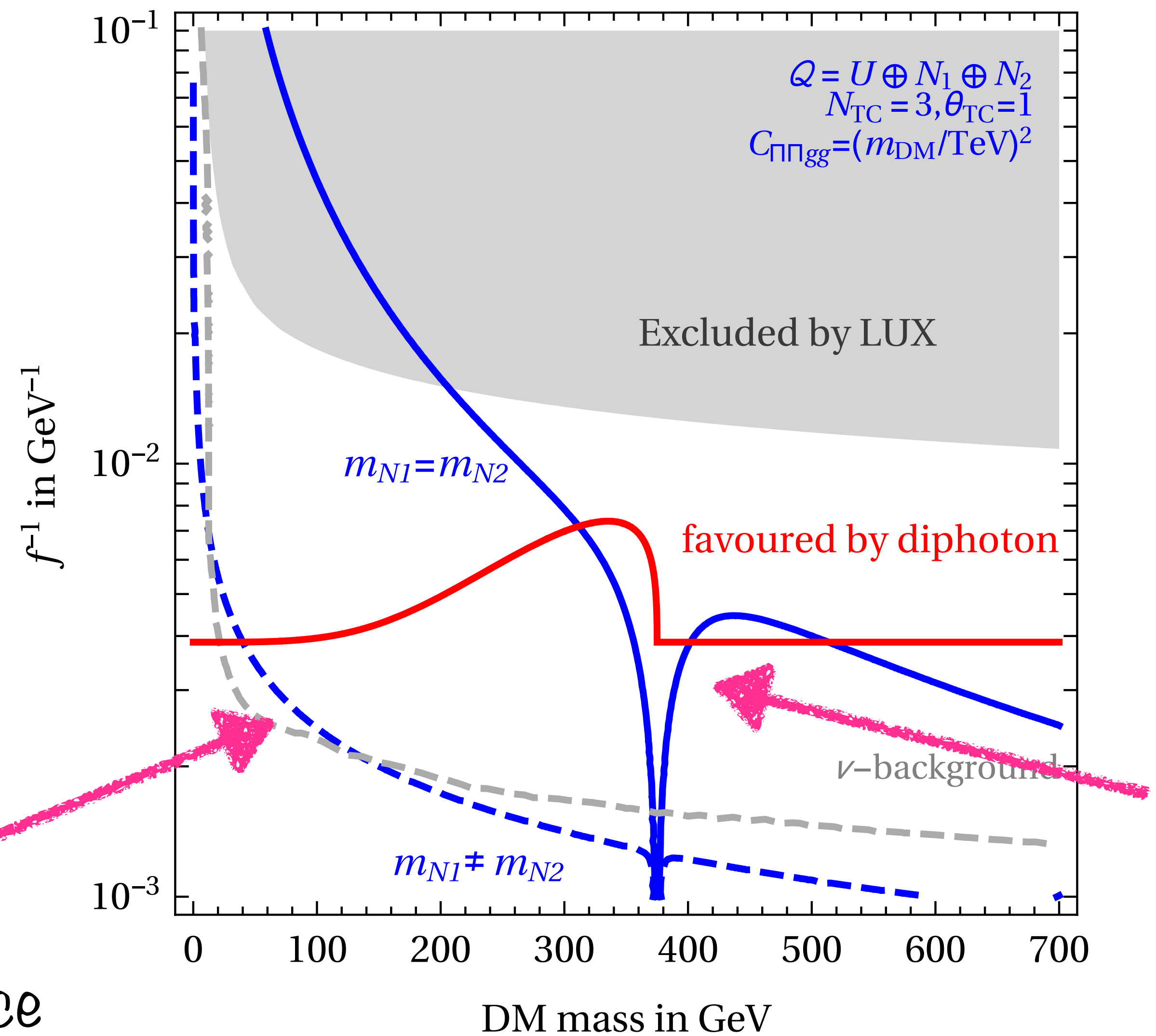
$$m^2_{\eta_2} \lesssim m^2_\Pi = B_0(m_{N_1} + m_{N_2})$$

di-photon resonance

$\not{C}\not{P}$ decays of di-photon into DM induced by the $\theta_{\rm TC}$ angle of the new strong sector

$$\Gamma_{\eta_1 \to \Pi\Pi^*} \sim \theta^2_{\rm TC}\,{\rm GeV} \ < \ 45{\rm GeV}$$

Phenomenology



$\Pi\Pi^* \to \eta_2\eta_2$ dominates, relic abundance reproduced for $m_\Pi < 100\,\text{GeV}$

$m_{\eta_2} = m_\Pi$ and $\eta_2,\ \Pi,\ \Pi^*$ becomes a triplet of DM candidates

$\text{DM DM} \to \eta_1 \to gg$ dominates, relic abundance reproduced for $m_{DM} \approx 750\,\text{GeV}/2$

search for colored resonances !

Conclusions

→ Vectorlike Confinement as interesting scenario for BSM physics and DM

→ Dark Matter as a composite techni-baryon with mass of order $100\,\mathrm{TeV}$ with a peculiar phenomenology

→ Techni-pions below the TeV as Dark Matter and di-photon candidates

if the di-photon excess will survive, this would be one of the most simple and predictive scenarios ! With more data in the di-photon and other channels we would be able to get the right model !

Thanks for the attention !

Backup slides

Techni-baryons as DM candidates

goal :

find all possible renormalizable models that contain a techni-baryon
that is a good DM candidate (no color, no charge, no hypercharge)
and no unwanted stable particles

rules :

techni-quarks from $\mathrm{SU}(5)$ irreducible reps
asymptotic freedom for $\mathrm{SU}(N_{\mathrm{TC}})$
no Landau poles for SM couplings at low scales

Yukawa couplings break accidental symmetries that make
unwanted particles stable

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$$\frac{d\alpha_{\rm TC}^{-1}}{d\log Q} = -\frac{b_{\rm TC}}{2\pi}$$

$$b_{\rm TC} = -\frac{11}{3}N_{\rm TC} + \frac{2}{3}N_{\rm TF} < 0\,, \rightarrow \; N_{\rm TF} < \frac{11}{2}N_{\rm TC}$$

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no Landau poles for SM couplings at low scales →

$$b_3 = -7 + \Delta b_3 \lesssim 3$$

$$b_2 = -\frac{19}{6} + \Delta b_2 \lesssim 6.5$$

$$b_Y = \frac{41}{6} + \Delta b_Y \lesssim 18$$

Yukawa couplings break accidental symmetries that make unwanted particles stable

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Yukawa couplings break accidental symmetries that make unwanted particles stable →

constraint on techni-quarks quantum numbers

$SO(N_{TC})$ models

$$\mathcal{Q} = \sum_i (N_{\rm TC}, R_i) \oplus \sum_j (N_{\rm TC}, C_j) \oplus (N_{\rm TC}, \bar{C}_j)$$

fundamental of $\mathrm{SO}(N_{\rm TC})$

(real)

techni-baryons

no distinction between techni-baryons

and anti techni-baryons

can be real scalar or majorana fermions

no techni-baryon number,

stability from $\mathbb{Z}_2 = \frac{\mathrm{O}(N_{\rm TC})}{\mathrm{SO}(N_{\rm TC})}$

SSB of the chiral symmetry

$$\mathrm{SU}(N_{\rm TF}) \to \mathrm{SO}(N_{\rm TF})$$

$\frac{N_{\rm TF}(N_{\rm TF}+1)}{2} - 1$ techni-pions $(\mathcal{Q}\mathcal{Q})$

species number symmetry

only for complex SM reps

DM phenomenology

if DM is a majorana fermion : $Z_\mu \bar{\chi}\gamma^\mu\chi\,,\ \ \frac{1}{2}\bar{\chi}\gamma_{\mu\nu}(\mu_M + i d_E\gamma_5)\chi F^{\mu\nu}$

Yukawa couplings → mixing between the neutral components of states with $Y=0$ and $Y\neq 0$ after EWSB

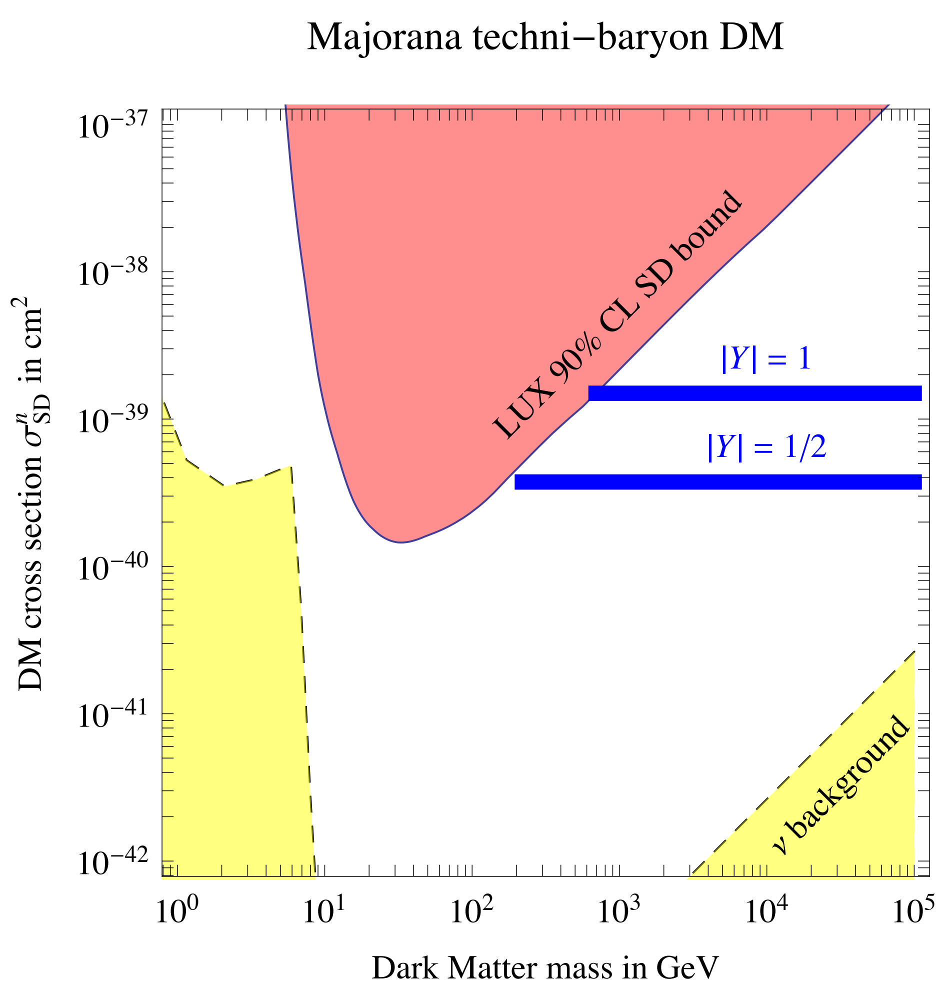
the lightest eigenstate is a majorana fermion

↓

axial coupling to the Z

$$-\frac{g_A\, g_2}{2\cos\theta_W} Z_\mu \bar{\chi}\gamma^\mu\gamma_5\chi$$

spin dependent cross section



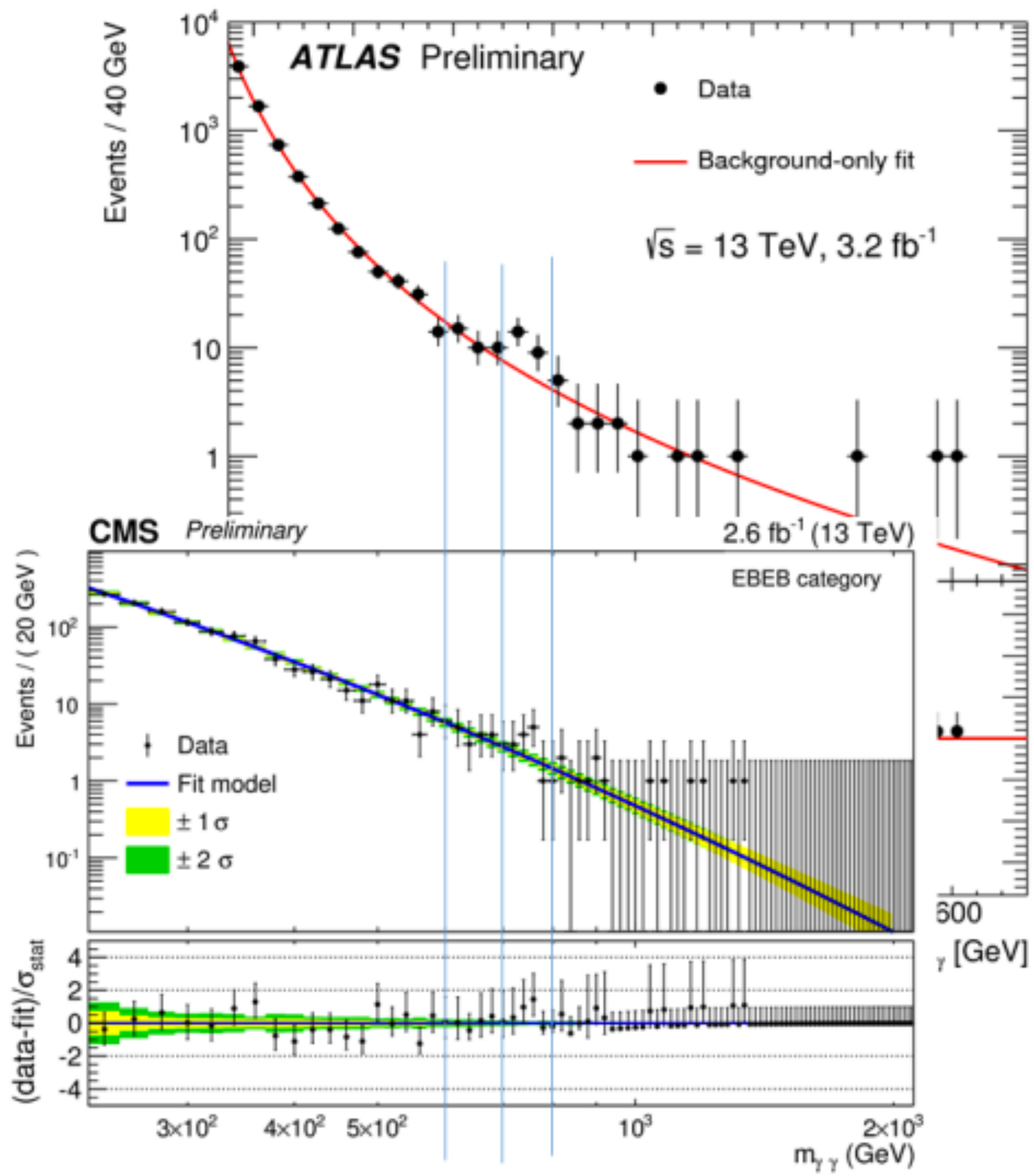
Di-photon excess

ATLAS: $3.9\,\sigma$ (local)
$2.0\,\sigma$ (global)

large width $\Gamma/M \approx 6\%$

CMS: $3.4\,\sigma$ (local)
$1.6\,\sigma$ (global)

narrow width

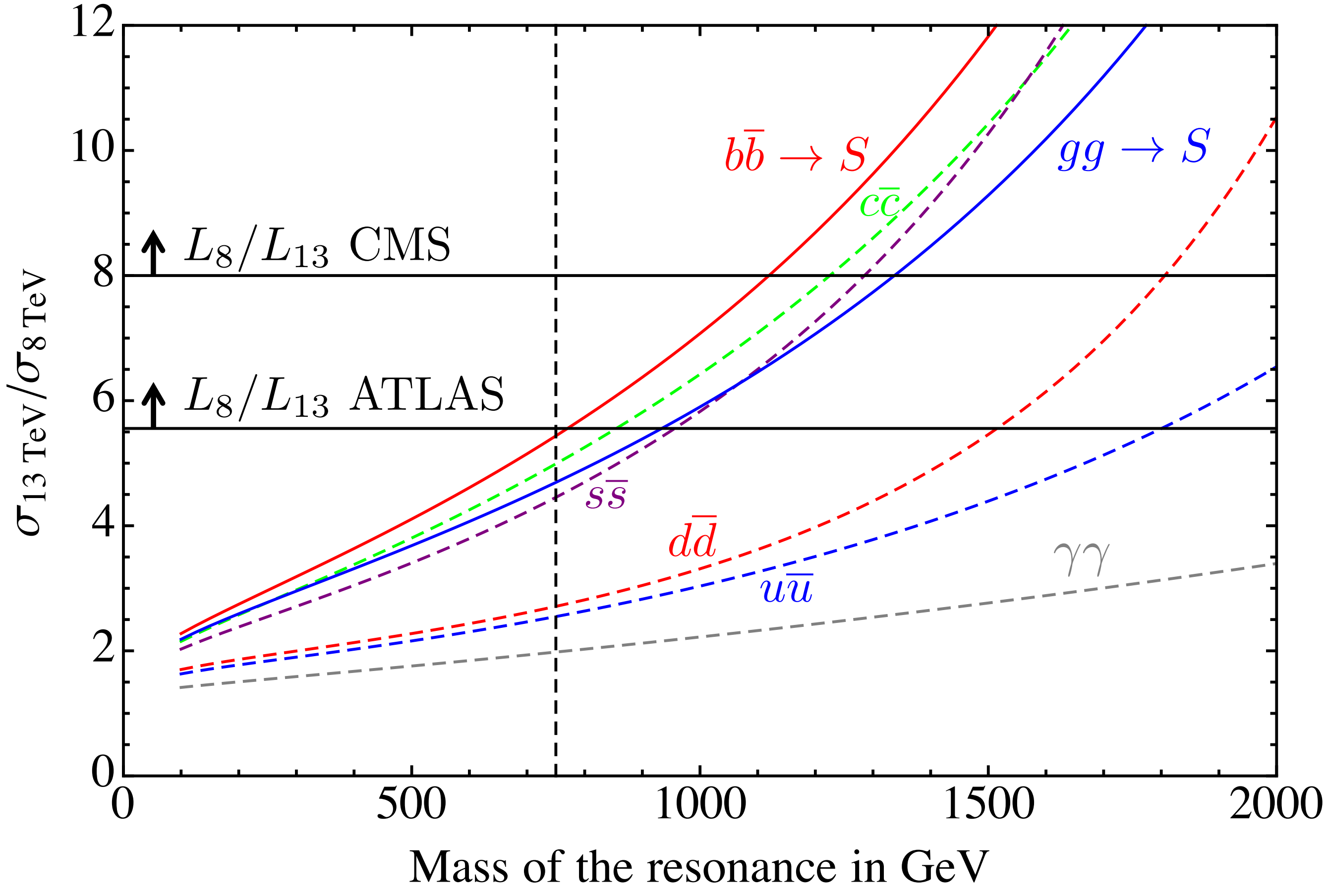


not enough significance so far! but if it was true...

why anything at Run-1 ?

the background grows by 2.3 at $750\,\mathrm{GeV}$

the signal grows by 5 if produced by $gg, b\bar{b}, c\bar{c}, s\bar{s}$



Di-photon and DM in VC models

Redi, Strumia, Tesi, Vigiani (arXiv:1602.07297)

$$\underline{\mathcal{Q} = N_1 \oplus N_2 \oplus U} = (1,1)_0 \oplus (1,1)_0 \oplus (\bar{3},1)_{-2/3}$$

SM singlets :

$$\eta' \sim U\bar{U} + N_1\bar{N}_1 + N_2\bar{N}_2 \qquad m_{\eta'} \sim \Lambda_{\rm TC} \sim {\rm TeV}$$

$$\eta_1 \sim U\bar{U} - 3/2(N_1\bar{N}_1 + N_2\bar{N}_2) \qquad m^2_{\eta_1} \approx 4/5\, B_0 m_U \approx (750\,{\rm GeV})^2$$

$$\eta_2 \sim N_1\bar{N}_1 - N_2\bar{N}_2 \qquad m^2_{\eta_2} \lesssim m^2_\Pi = B_0(m_{N_1} + m_{N_2})$$

DM : $\Pi \sim N_1\bar{N}_2\,,\ \Pi^*$ → $\sim 50\,{\rm GeV}$ / $\sim 350\,{\rm GeV}$ (depending on the regime)

colored objects :

$\chi \sim U\bar{U}$

$\phi_{1,2} \sim U\bar{N}_{1,2}\,,\ \phi^*_{1,2}$ → $\gtrsim {\rm TeV}$ to be compatible with di-jet bounds