Dynamical generation of the weak and Dark Matter scales

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Based on: arxiv 1410.1817 [hep-ph]
in collaboration with A. Strumia and M.Redi

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Outline

- Introduction to electroweak-preserving strong sector
- Electroweak symmetry breaking
- Phenomenological constrains and LHC signals
- Predictions for Dark Matter
- In progress: Hyperquark masses and θ-angle
- Conclusions

TC - QCD

2 Dirac flavors

$$\mathcal{L}_{\text{fermion}} = i\bar{u}_L\gamma_\mu D^\mu u_L + i\bar{d}_L\gamma_\mu D^\mu d_L + i\bar{u}_R\gamma_\mu D^\mu u_R + i\bar{d}_R\gamma_\mu D^\mu d_R$$

$$D^\mu = \partial^\mu - igA^\mu$$

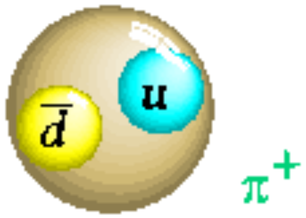
Lagrangian has $SU(2)_L \times SU(2)_R$ chiral symmetry

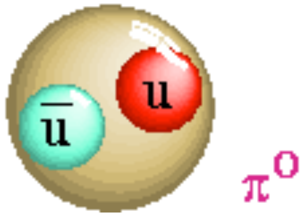
$$\bar{q}_L = (\bar{u}_L, \bar{d}_L) \quad \text{and} \quad \bar{q}_R = (\bar{u}_R, \bar{d}_R)$$

When the QCD gauge coupling becomes strong: $\langle \bar{q}_L q_R \rangle \neq 0$

$\langle \bar{q}_L q_R \rangle \neq 0$ breaks $SU(2)_L \times SU(2)_R \rightarrow SU(2)_{L+R}$

$\bar{q}_L q_R$ pions are associated Goldstone bosons





But $\bar{q}_L = (\bar{u}_L, \bar{d}_L)$ is electroweak doublet while

$\bar{u}_R, \bar{d}_R$ are electroweak singlets

$\langle \bar{q}_L q_R \rangle \neq 0$

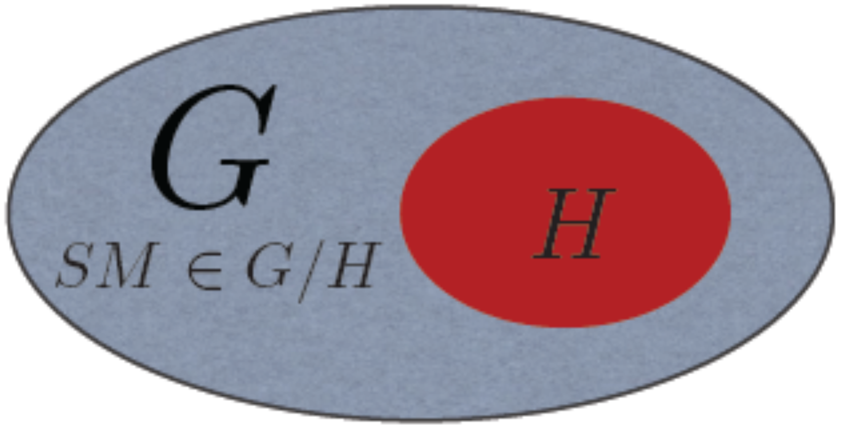
⇒ electroweak symmetry is broken

$$SU(2)_L \times SU(2)_R \to SU(2)_{L+R} \quad (SU(2)_L \times U(1)_Y \to U(1)_{\mathrm{EM}})$$

Pions belong to the “coset space”

$$\frac{G}{H} = \frac{SU(2)_L \times SU(2)_R}{SU(2)_{L+R}}$$

and are “eaten” by W and Z

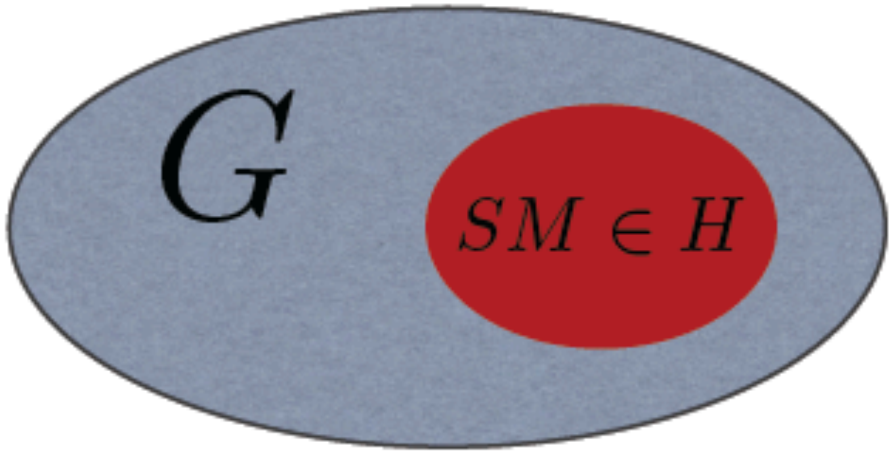


Higgs is the composite scalar resonance

Next, idea of Goldstone boson Higgs appeared

Higgs could be an approximate GB

Georgi, Kaplan 80's



$$m_\rho = g_\rho f$$

Ex:

Agashe , Contino,
Pomarol, '04

$$\frac{SO(5)}{SO(4)} \xrightarrow{f > v} \mathrm{GB} = 4$$

Electro-weak scale determined by vacuum alignment.

- Hard to construct UV theories.
  Typically postulate effective theories with correct features.

We consider different paradigm...

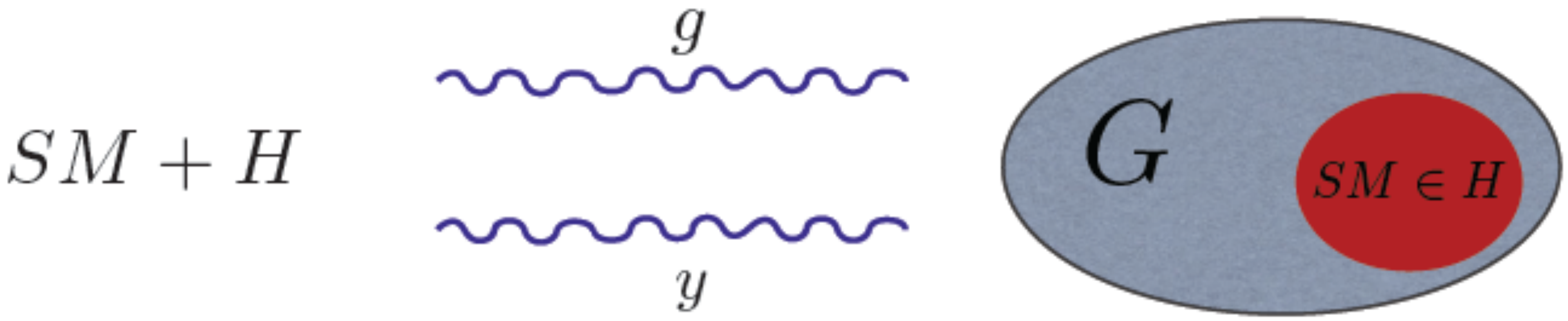
Electroweak-preserving strong sector

For 2 Dirac flavors

Kilic, Okui, Sundrum '09

$\bar{q}_L = (\bar{u}_L, \bar{d}_L) \quad \text{and} \quad \bar{q}_R = (\bar{u}_R, \bar{d}_R)$

are <u>both</u> electroweak doublets now



<u>Higgs is massless and elementary</u> and couples to the strong sector with renormalizable interactions:

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4\, g_{TC}} G^a_{\mu\nu} G^{a\,\mu\nu} + i\bar{\Psi}\gamma_\mu(\partial_\mu - iA_\mu - iG_\mu)\Psi$$

❗ <u>Additional assumption:</u> no hyperquark mass terms

Electroweak-preserving strong sector

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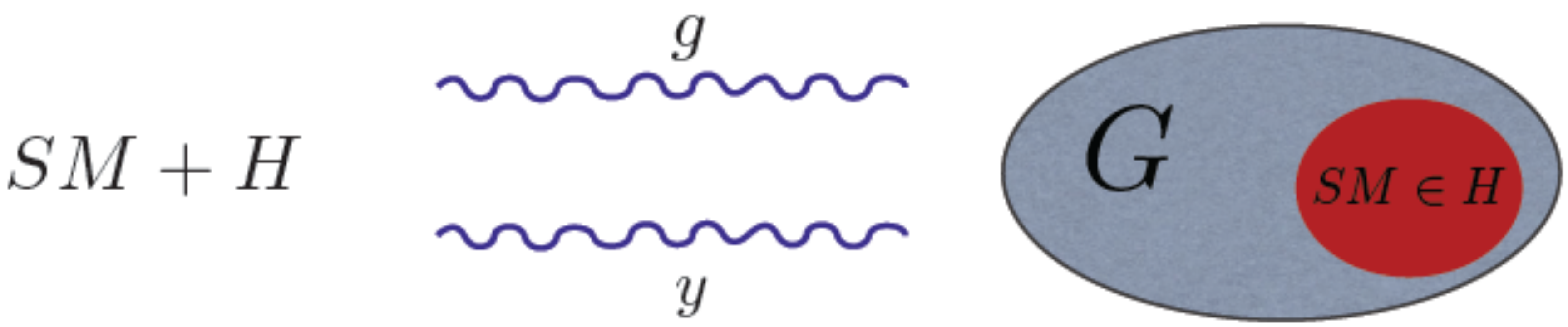
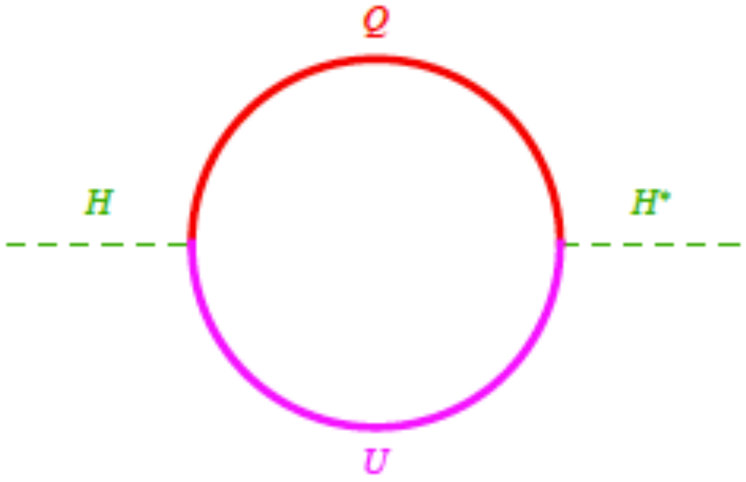
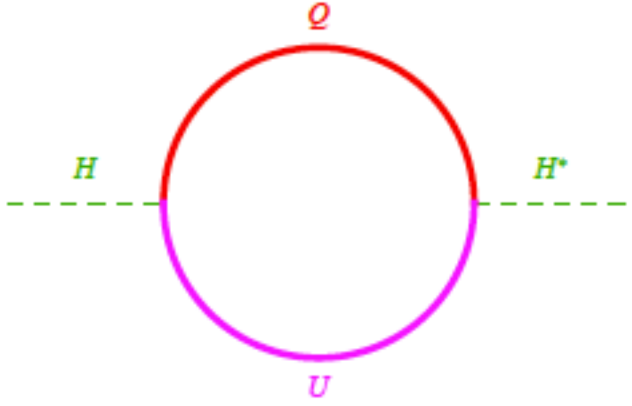


Higgs is massless and elementary and couples to the strong sector with renormalizable interactions:

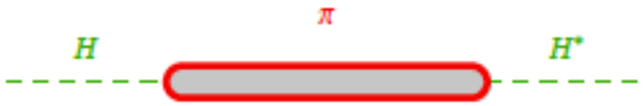
For example,
Yukawa couplings



Weak coupling



Strong coupling



$$yHQ_LQ_R$$

Chiral lagrangian,

$$U = \exp(i\pi^{\hat{a}}T^{\hat{a}}/f) \qquad y\, m_\rho f^2\, \mathrm{Tr}[HU] + \mathrm{h.c.} \quad \Rightarrow \quad y m_\rho f H \pi^*$$

Seesaw-like mass matrix

$$\begin{array}{c} \\ \pi \\ H \end{array} \begin{array}{c} \begin{array}{cc} \qquad\qquad \pi^* \qquad\qquad & \qquad\qquad H^* \qquad\qquad \end{array} \\ \begin{pmatrix} \mathcal{O}(g_2^2)/(4\pi)^2 & \mathcal{O}(y)\sqrt{N}/(4\pi) \\ \mathcal{O}(y)\sqrt{N}/(4\pi) & 0 \end{pmatrix} m_\rho^2 \end{array}$$

Mixing induces negative Higgs mass

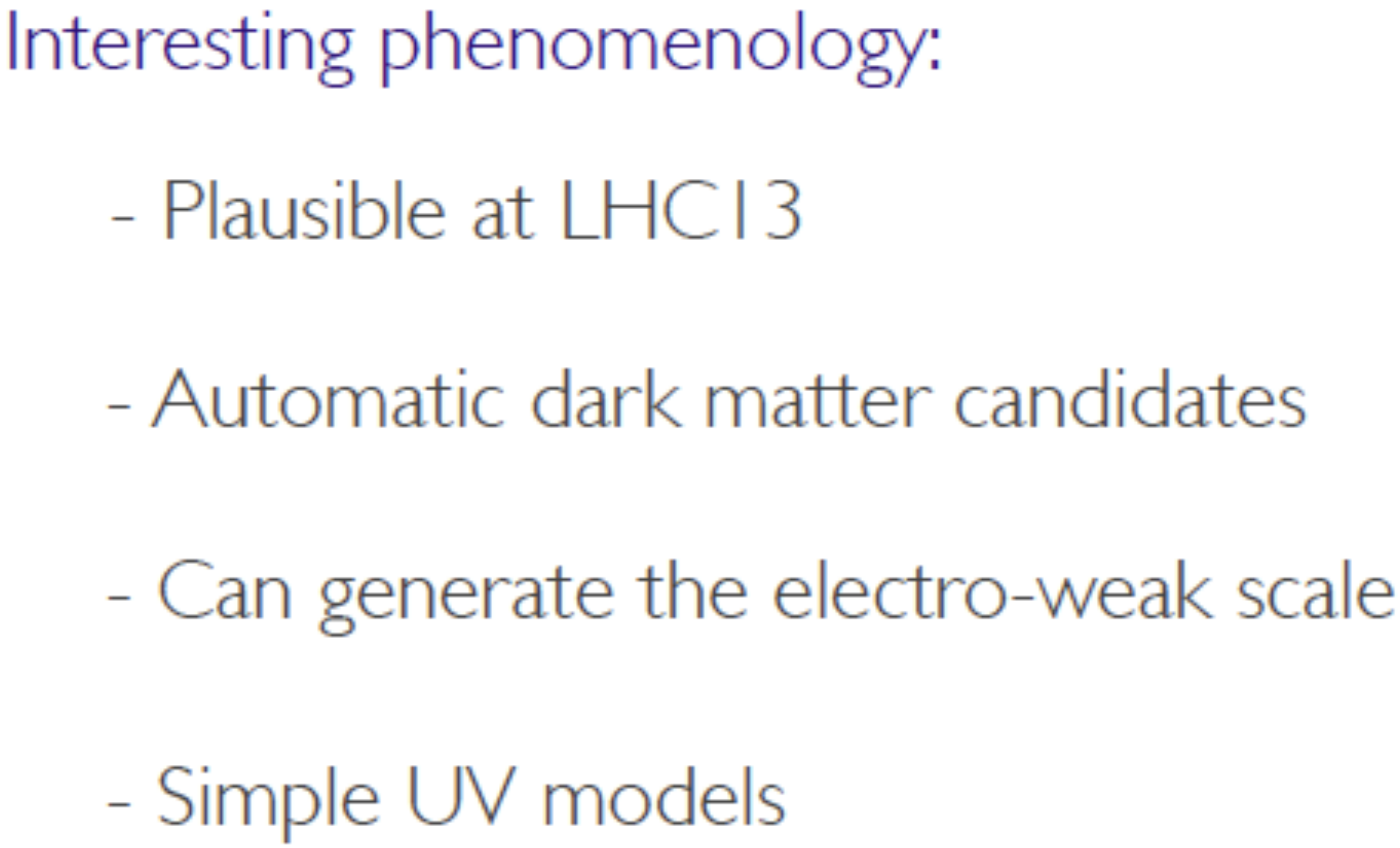
$$m_H^2 \approx -\frac{y^2 N}{(4\pi)^2}\frac{m_\rho^4}{m_\pi^2} \sim \Lambda_{TC}^2 \quad \Rightarrow$$

for measured Higgs mass, strong scale is in the multi-TeV range

Phenomenology and Constraints

Experimental bounds are weak:

- Precision tests are OK
- LHC: “strong” resonances in the multi-TeV range



Interesting phenomenology:

- Plausible at LHC13

- Automatic dark matter candidates

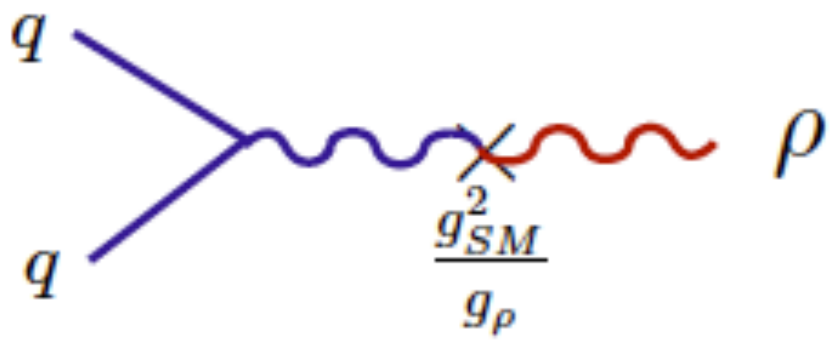
- Can generate the electro-weak scale

- Simple UV models

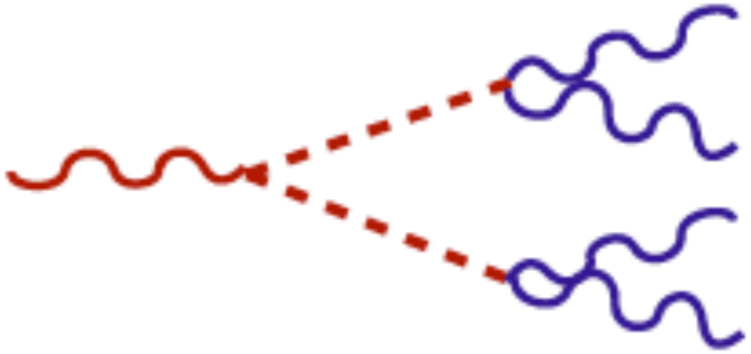
COLLIDER SIGNATURES

Kilic, Okui, Sundrum '09

Vector resonances with SM quantum numbers predicted



Decay to hidden pions and back to SM gauge bosons,



Pions can also be stable or long lived.

- Models

SU(N) gauge theory with NF flavors

Techni-quarks are vectorial with respect to SM.

Fermions	SM	SU(N)
Ψ_L	$\sum_i r_i$	n
Ψ_R	$\sum_i \bar{r}_i$	$\bar{n}$

$$\sum_i d[r_i] = N_F$$

Spontaneous symmetry breaking respects electro-weak.

Massless Goldstone bosons: $N_F^2 - 1$

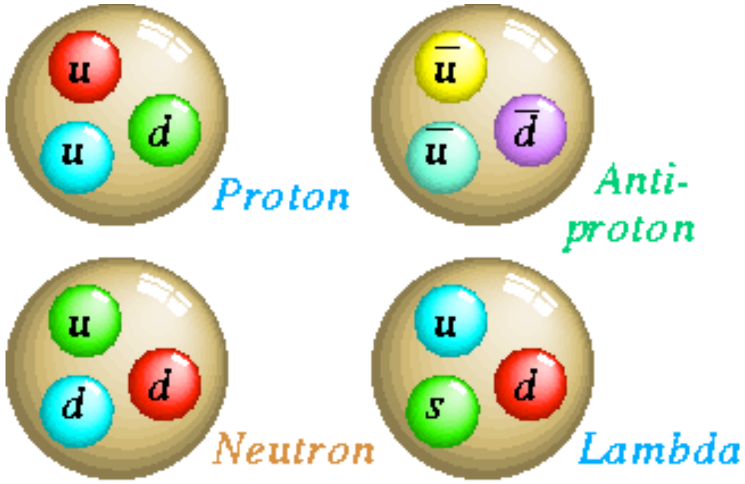
$$\frac{SU(N_F) \times SU(N_F)}{SU(N_F)}$$

DM candidates

- Baryons

$$m_B \sim N m_\rho$$

Baryons are products of n quarks symmetric in flavor and spin("eightfold way").



$$(\text{spin}, \text{flavor}) =$$

N=3 N=4

To be DM, demand:

$$Q_{TB} = T_3 + Y_{TB} = 0$$
$$Y_{TB} = 0$$

→ multiplets with integer isospin J=0,1,2,..

DM candidates

Pions

Bai, Hill '10

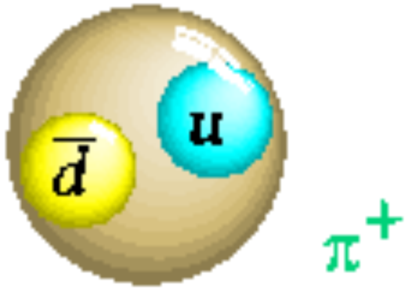
Pions can be stable due to G-parity:

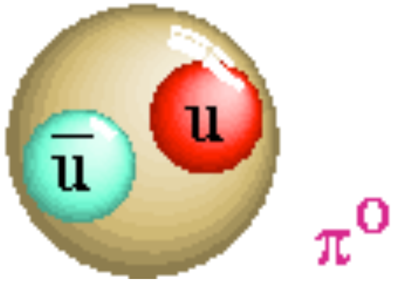
$$\psi \to S\,\psi^C$$

$$W^a_\mu J^a \to W^a_\mu J^a$$

$$A^a t^a \to A^a(-t^a)^*$$

$$S^\dagger J^a S = -J^{a*}$$





$$\pi^0 \not\to \gamma\gamma \qquad \Pi^J \to (-1)^J \Pi^J$$

J= total weak isospin of the pion multiplet

- Techni-pion singlets under $\mathrm{SU}(2)_L$ are G-even, do not acquire masses from SM gauge interactions and can have anomalous couplings to $\mathrm{SU}(2)_L$ vectors: they are excluded in our framework unless Yukawa couplings make them massive. They are absent if techni-quarks fill a single irreducible representation of $\mathrm{SU}(2)_L$.

- Techni-pions in the 5 of $\mathrm{SU}(2)_L$ are G-even and are heavier, $m_{\pi_5} \approx \sqrt{3} m_{\pi_3}$: they undergo anomalous decays into electro-weak vectors, $\pi_5 \to WW$.

- Techni-pions in higher representations of $\mathrm{SU}(2)_L$, if present, decay into lighter techni-pions respecting G-parity by emitting two $\mathrm{SU}(2)_L$ vectors, e.g. $\pi_7 \to \pi_3 WW$.

Example:
N=NF=3

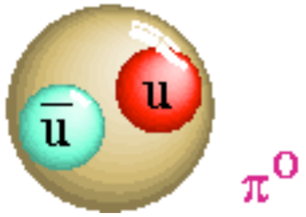
number of techni-flavors	Yukawa	$N=3$		
		TCb	TCπ	
$N_F=3$		8	8	under TC-flavor SU(3)
model 1: $Q=1_Y+2_{Y'}$	1	1	no	DM, under SU(2)$_L$
model 2: $Q=3_{Y=0}$	0	3	3	DM, under SU(2)$_L$

Q=3

- $SU(2)_L \subset SU(3)_F$

$$J = 1 \quad 2$$
$$\mathbf{8} = \mathbf{3} + \mathbf{5}$$

Scalar triplet is stable and is dominant dark matter.



$m_{\pi^0} \sim 2.5$ TeV

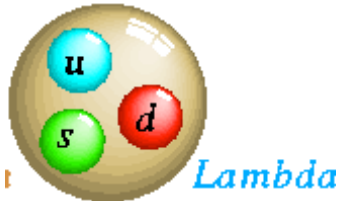
Q=2+1

- $SU(2)_L \times U(1)_Y \subset SU(3)_F$

$$3 = 2_{\frac{1}{2}} + 1_{-1}$$

Same as QCD quantum numbers.

$$\mathbf{8} = \mathbf{2}(\mathrm{p},\mathrm{n}) + \mathbf{3}(\Sigma^{\pm,0}) + \mathbf{2}(\Xi^0,\Xi^-) + \mathbf{1}(\Lambda_0)$$
$$\mathbf{8} = \mathbf{2}(\mathrm{K}^0,\mathrm{K}^+) + \mathbf{3}(\pi^{\pm,0}) + \mathbf{2}(K^-,\bar{K}^0) + \mathbf{1}(\eta)$$



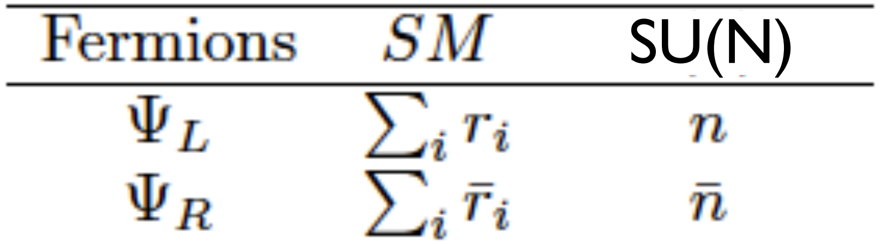
Quantum numbers allow for Yukawa interactions.
Singlet GB acquires mass and triplet decays.

$m_{\Lambda^0} \sim 200$ TeV

Dark matter is a technibaryon.

SU(N) gauge theory with NF flavors

Techni-quarks are vectorial with respect to SM.



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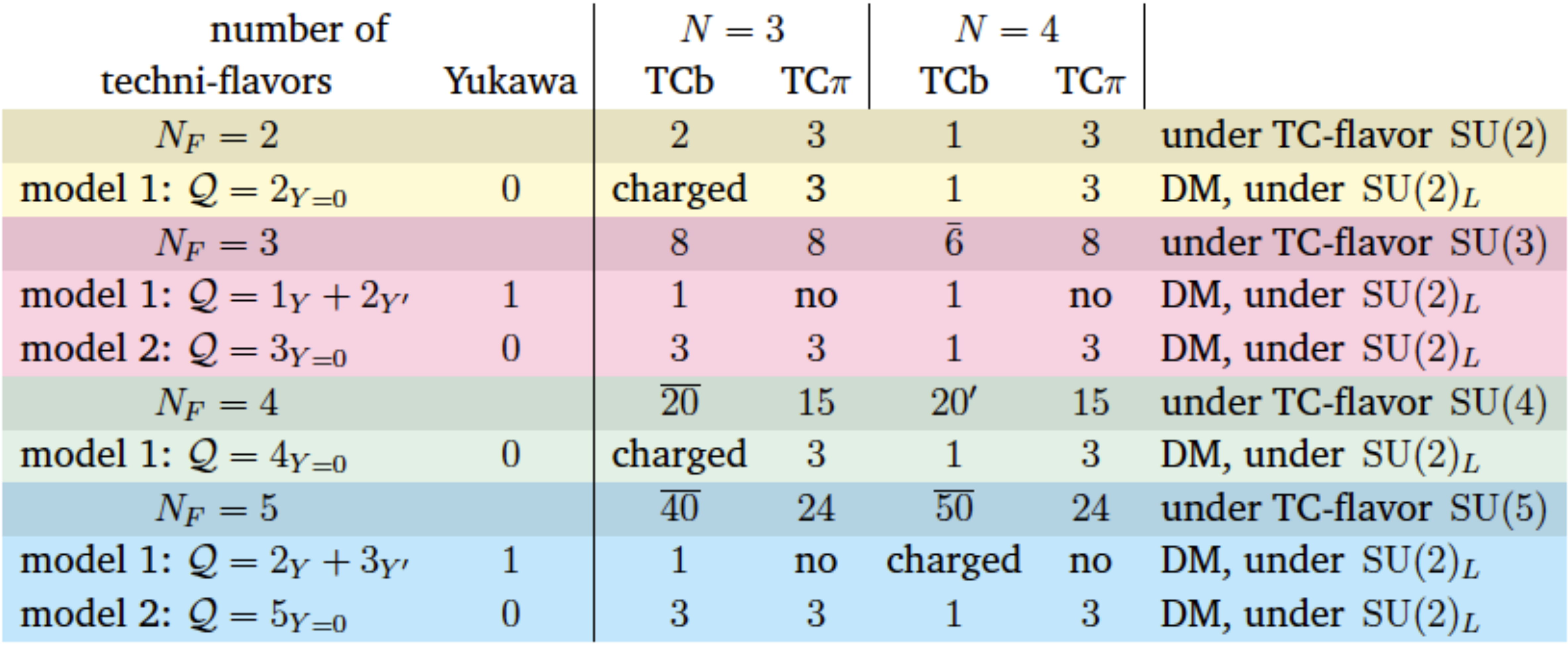
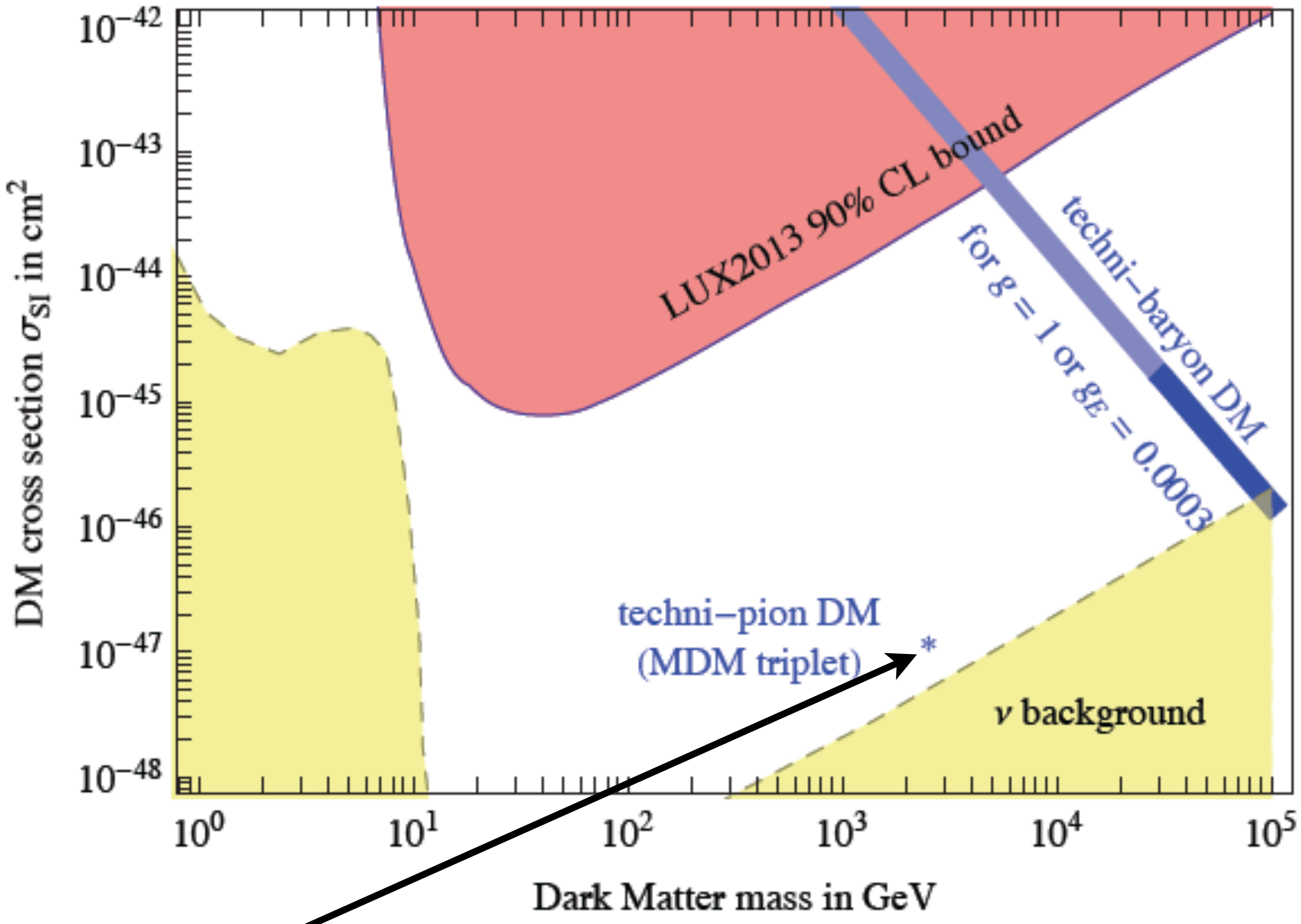


number of techni-flavors	Yukawa	$N=3$ TCb	$N=3$ TCπ	$N=4$ TCb	$N=4$ TCπ	
$N_F = 2$		2	3	1	3	under TC-flavor $\mathrm{SU}(2)$
model 1: $Q = 2_{Y=0}$	0	charged	3	1	3	DM, under $\mathrm{SU}(2)_L$
$N_F = 3$		8	8	$\bar{6}$	8	under TC-flavor $\mathrm{SU}(3)$
model 1: $Q = 1_Y + 2_{Y'}$	1	1	no	1	no	DM, under $\mathrm{SU}(2)_L$
model 2: $Q = 3_{Y=0}$	0	3	3	1	3	DM, under $\mathrm{SU}(2)_L$
$N_F = 4$		$\overline{20}$	15	$20'$	15	under TC-flavor $\mathrm{SU}(4)$
model 1: $Q = 4_{Y=0}$	0	charged	3	1	3	DM, under $\mathrm{SU}(2)_L$
$N_F = 5$		$\overline{40}$	24	$\overline{50}$	24	under TC-flavor $\mathrm{SU}(5)$
model 1: $Q = 2_Y + 3_{Y'}$	1	1	no	charged	no	DM, under $\mathrm{SU}(2)_L$
model 2: $Q = 5_{Y=0}$	0	3	3	1	3	DM, under $\mathrm{SU}(2)_L$

In the models with single SU(2)L reps DM has two components (TB and Tpions)

The 1+2 and 2+3 models allow to write Yukawa interactions and DM is only TB

Direct detection of Dark Matter



- Pions

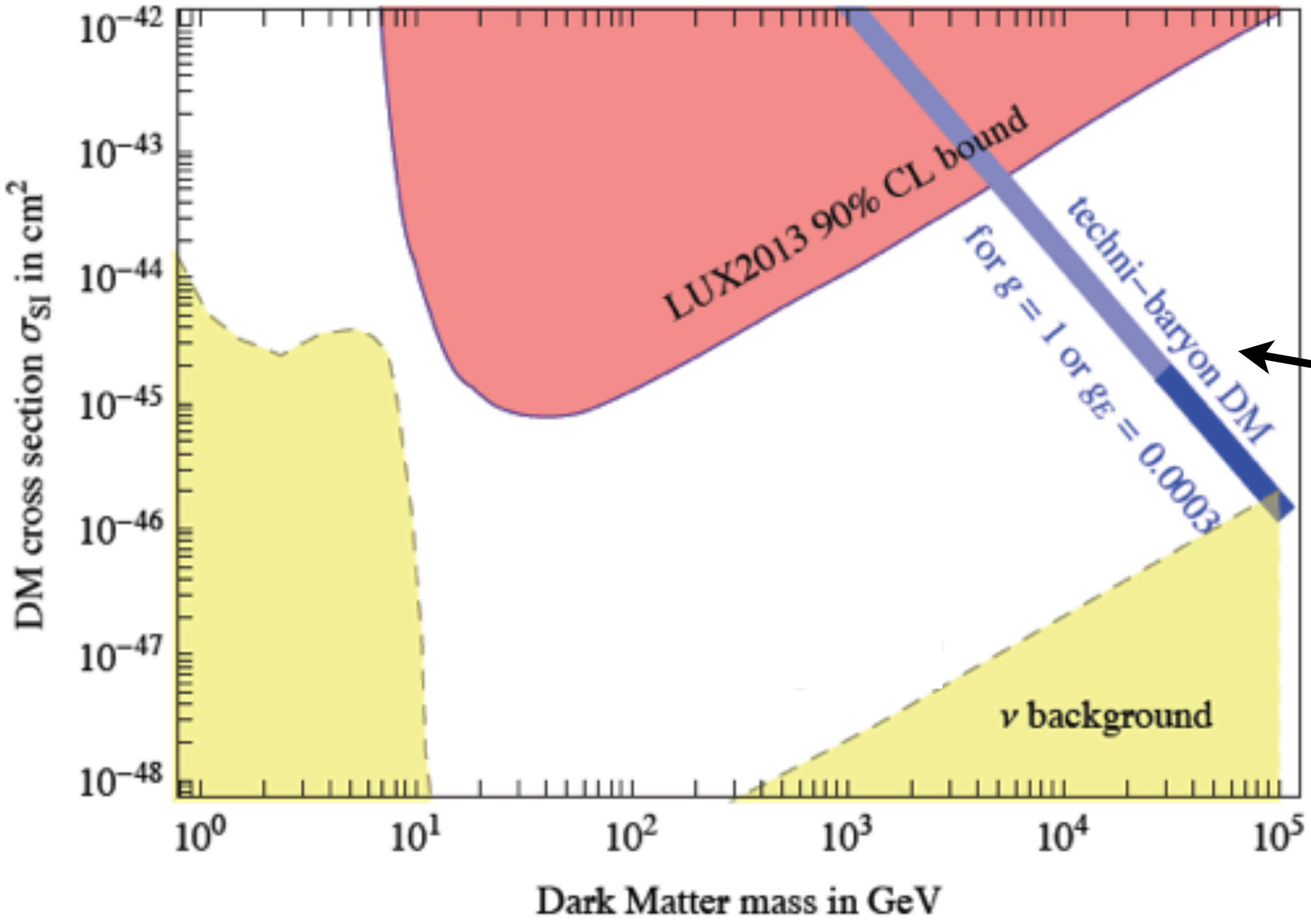
Strumia, Cirelli '05

$$m_{J=1} \sim 2.5\ \mathrm{TeV}$$

Behave as Minimal DM

$$\sigma_{SI} = 0.12 \pm 0.03 \times 10^{-46}\ \mathrm{cm}^2$$

Direct detection of Dark Matter



- Baryons

Dipole interactions: $$\bar{B}\sigma_{\mu\nu}\frac{\mu + id\gamma_5}{2}B\,F_{\mu\nu}.$$

$$\frac{d\sigma}{dE_R} \approx \frac{e^2Z^2}{4\pi E_R}(\mu^2 + \frac{d^2}{v^2}).$$

$$\mu = ge/2m_B \qquad d = g_E e/2m_B$$

LUX data: $$g^2 + 1.2\ 10^7 g_E^2 < \left(\frac{m_B}{5.1\,\mathrm{TeV}}\right)^3$$

Baryons-anti-baryon annihilate mostly into pions

$$\langle\sigma_{B\bar{B}}^{ANN}v\rangle \sim \frac{4\pi}{m_B^2}$$

THERMAL ABUNDANCE

$$m_B \sim 50 - 100\,\mathrm{TeV}$$

An electric dipole moment needs CP-violation. In our context, techni-quarks are strictly massless, such that the CP-violating techni-strong θ term is not physical. A small g_E could be generated if techni-quark masses are included.

In progress: Hyperquark masses

$$M = M^\dagger = diag(m_u, m_d, m_s, ...)$$

Mass of the pions:

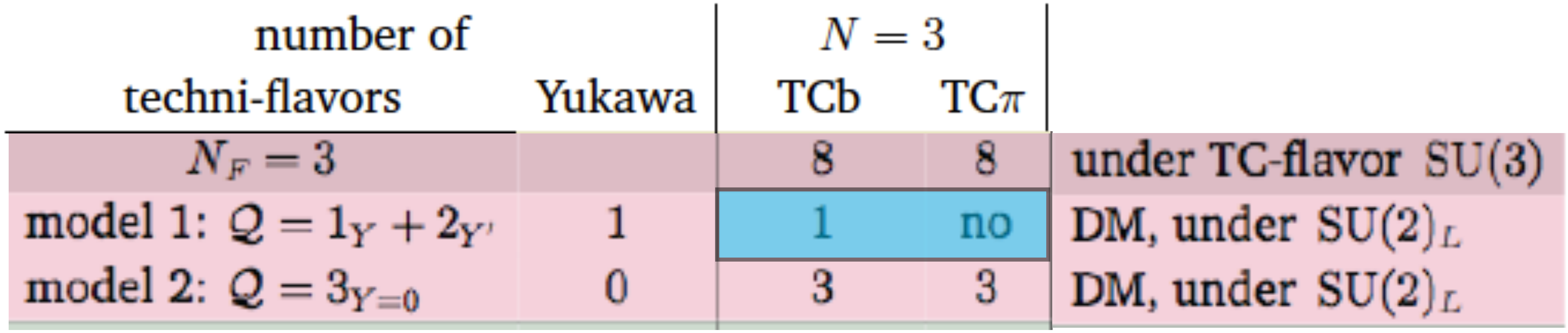
$$Tr[MU + M^\dagger U^\dagger]$$

Mass of the baryons:

$$b_1 Tr[\bar{B}MB] + b_2 Tr[\bar{B}BM]$$

Baryons also get mass from the strong interactions

Example: N=NF=3



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Q=2+1: we can write <u>two</u> masses (doublet + singlet)

$$m_u = m_d = m$$

- Pions

$$Tr[MU + M^\dagger U^\dagger] \Longrightarrow$$

$$m^2_{\pi^+} = m^2_{\pi^0} = \frac{4v}{F^2_\pi}[m_u+m_d]\,,$$

$$m^2_{K^+} = \frac{4v}{F^2_\pi}[m_u+m_s]\,,$$

$$m^2_{K^0} = \frac{4v}{F^2_\pi}[m_d+m_s]\,,$$

$$m^2_{\eta^0} = \frac{4v}{F^2_\pi}\left[\frac{4m_s+m_d+m_u}{3}\right]$$

$$U = \begin{pmatrix} \pi^0/\sqrt{2}+\eta_0/\sqrt{6} & \pi^+ & K^+ \\ \pi^- & -\pi^0/\sqrt{2}+\eta_0/\sqrt{6} & K^0 \\ K^- & \bar{K}^0 & -2\eta_0/\sqrt{6} \end{pmatrix}$$

- Baryons

$$b_1 Tr[\bar{B}MB] + b_2 Tr[\bar{B}BM] \Longrightarrow$$

$$m_p = b_2 m + b_1 m_s$$

$$m_\Xi = b_1 m + b_2 m_s$$

$$m_\Sigma = (b_1+b_2)m$$

$$m_\Lambda = 1/3(m+2m_s)(b_1+b_2)$$

$$B = \begin{pmatrix} \Sigma^0/\sqrt{2}+\Lambda/\sqrt{6} & \Sigma^+ & P \\ \Sigma^- & -\Sigma^0/\sqrt{2}+\Lambda/\sqrt{6} & N \\ \Xi^- & \Xi^0 & -2\Lambda/\sqrt{6} \end{pmatrix}$$

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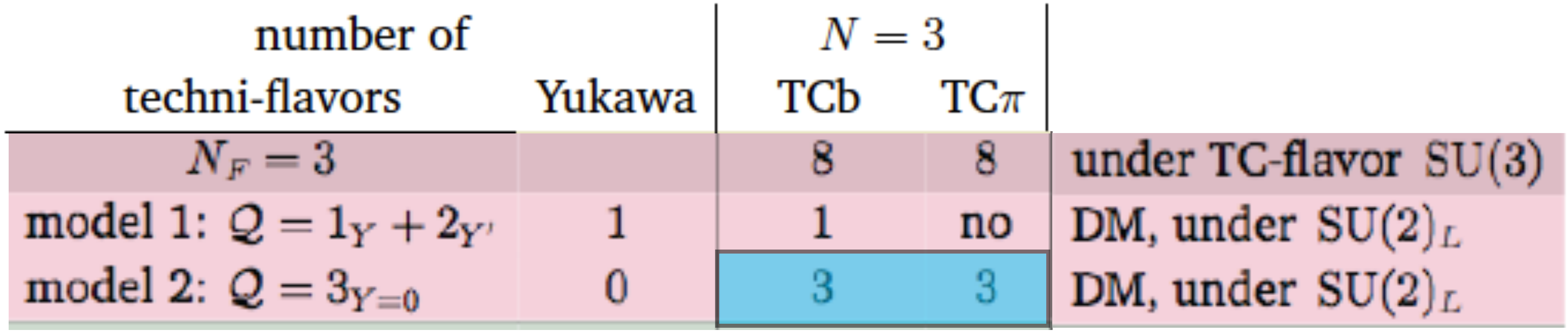
N=NF=3



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Q=3 we can write only one (triplet) hyperquark mass m

$$8=3+5$$

- Pions $M^2_{\pi_3}=M^2_{\pi_5}\sim mF_\pi$

- Baryons $M_{B_3}=M_{B_5}\sim m(b_1+b_2)$

θ-angle

We have to account for axial anomaly

$$L = \frac{F_\pi{}^2}{2}\Big(\mathrm{Tr}\,\partial_\mu U\,\partial_\mu U^{-1} + (\mathrm{Tr}\,MU + \mathrm{Tr}\,MU^\dagger)$$

$$-\frac{a}{N}(-i\ln\det U - \theta)^2\Big).$$

Minimizing potential energy with: $< U >= diag(e^{-i\phi_1}, e^{-i\phi_2}, e^{-i\phi_3}, ...)$

$$V(\phi_i) = F_\pi{}^2\left(-\sum \mu_i{}^2\cos\phi_i + \frac{a}{2N}\left(\sum\phi_i - \theta\right)^2\right)$$

⇒

$$\mu_i{}^2\sin\phi_i = \frac{a}{N}\left(\theta - \sum\phi_j\right)$$

θ-angle

Rotate to the physical basis: $$<V> = diag(e^{i\phi_1}, e^{i\phi_2}, e^{i\phi_3}, ...)U$$

Expand around the vacuum: $$V = e^{iT^a\pi^a}$$

$$\Longrightarrow \qquad \mathcal{L} = 2\,Tr[\mu_i^2 \cos\phi_i \cos T^a\pi^a] + \frac{a}{N} Tr(T^a\pi^a)^2 + \cdots$$

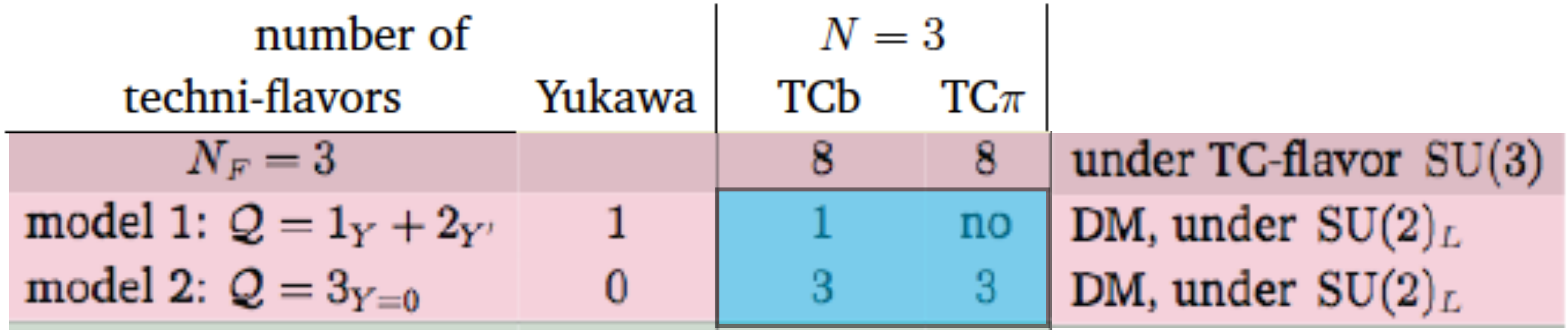
Quadratic terms define the masses of the Goldstones:

$$T^a\pi^a = \pi_a^d \times (\text{diagonal generator})_a + \pi_a^{nd} \times (\text{non-diagonal generator})_a$$

$$\begin{aligned} M^2_{\pi_i^d} &= \begin{pmatrix} \mu_u^2\cos\phi_u & ... & 0 \\ : & ... & : \\ 0 & ... & \mu_{N_F}^2\cos\phi_{N_F} \end{pmatrix} + \frac{a}{N}\begin{pmatrix} 1 & ... & 1 \\ : & ... & : \\ 1 & ... & 1 \end{pmatrix} \\ (M^2_{\pi_i^{nd}})_{\alpha\beta} &= \frac{1}{2}(\mu_\alpha^2\cos\phi_\alpha + \mu_\beta^2\cos\phi_\beta) \end{aligned}$$

need to
diagonalize

Example:
N=NF=3



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$$\mu_i^2 \sin\phi_i = \frac{a}{N}\left(\theta - \sum \phi_j\right)$$

Q=3

$$\mu^2 \sin\phi \;=\; \tfrac{a}{N}(\theta - 3\phi)$$

Solve for angle ϕ

Physical "diagonal" pions masses:

$$(\mu^2\cos\phi, \mu^2\cos\phi, 3a/N + \mu^2\cos\phi)$$

Q=2+1

$$\mu^2 \sin\phi = \frac{a}{N}(\theta - 2\phi - \phi_s) \qquad \mu_s^2 \sin\phi_s = \frac{a}{N}(\theta - 2\phi - \phi_s)$$

Solve for angles ϕ and ϕs

Physical "diagonal" pions masses: μ^2 and $\frac{1}{2}\left(3a/N + \mu^2 + \mu_s^2 \pm \sqrt{9a^2/N^2 + 2a\mu^2/N + \mu^4 - 2(a/N + \mu^2)\mu_s^2 + \mu_s^4}\right)$

In conclusions...

- We discussed electroweak-preserving strong sector
- We showed that these theories naturally lead to EWSB, have interesting collider signatures at LHC 13 and feature DM candidates to be probed in the next round of DM experiments
- Hyperquark masses and θ-angle can modify the spectrum and therefore change predictions!