The Strong CP Problem at the LHC

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IAS

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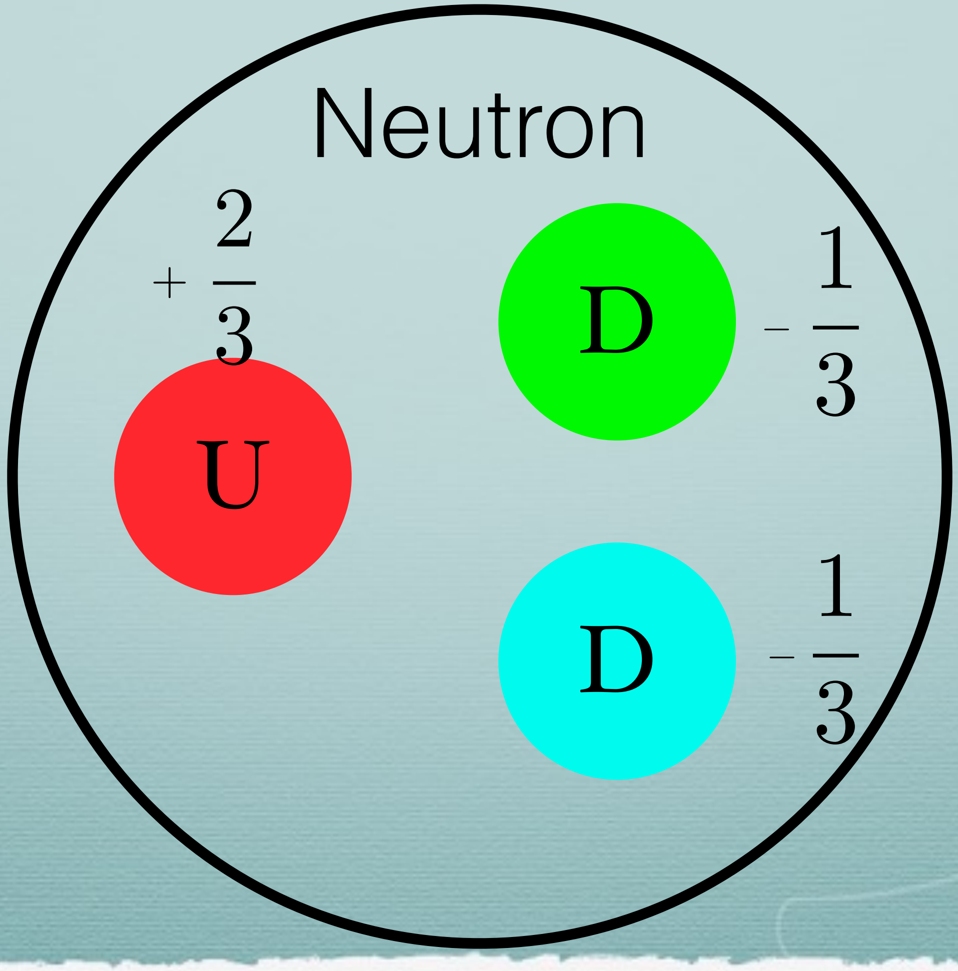
Anomalous solutions to the strong CP problem
hep-ph/1411.3325

Outline

- The Strong CP problem
- Previous solutions
- New solutions with LHC observable signatures

Classical Strong CP problem

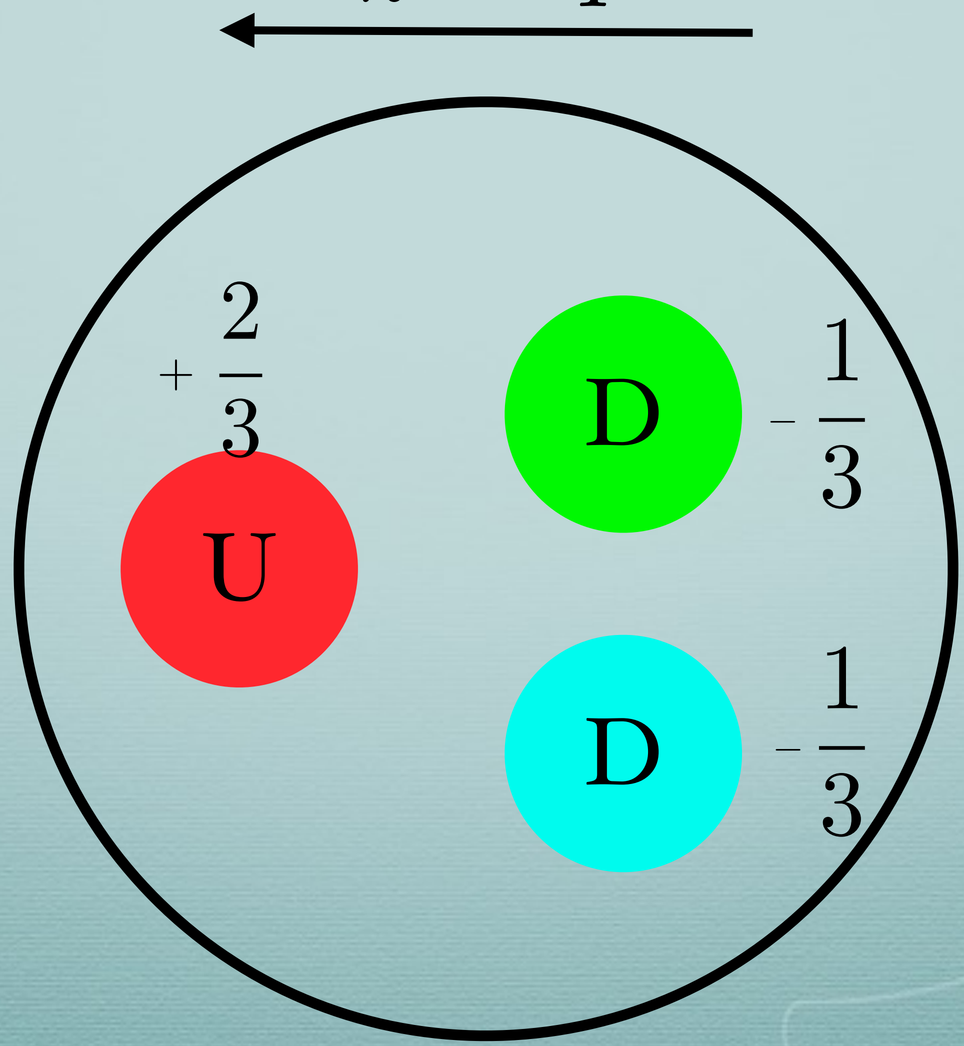
Neutron contains an up quark and two down quarks



Classical Strong CP problem

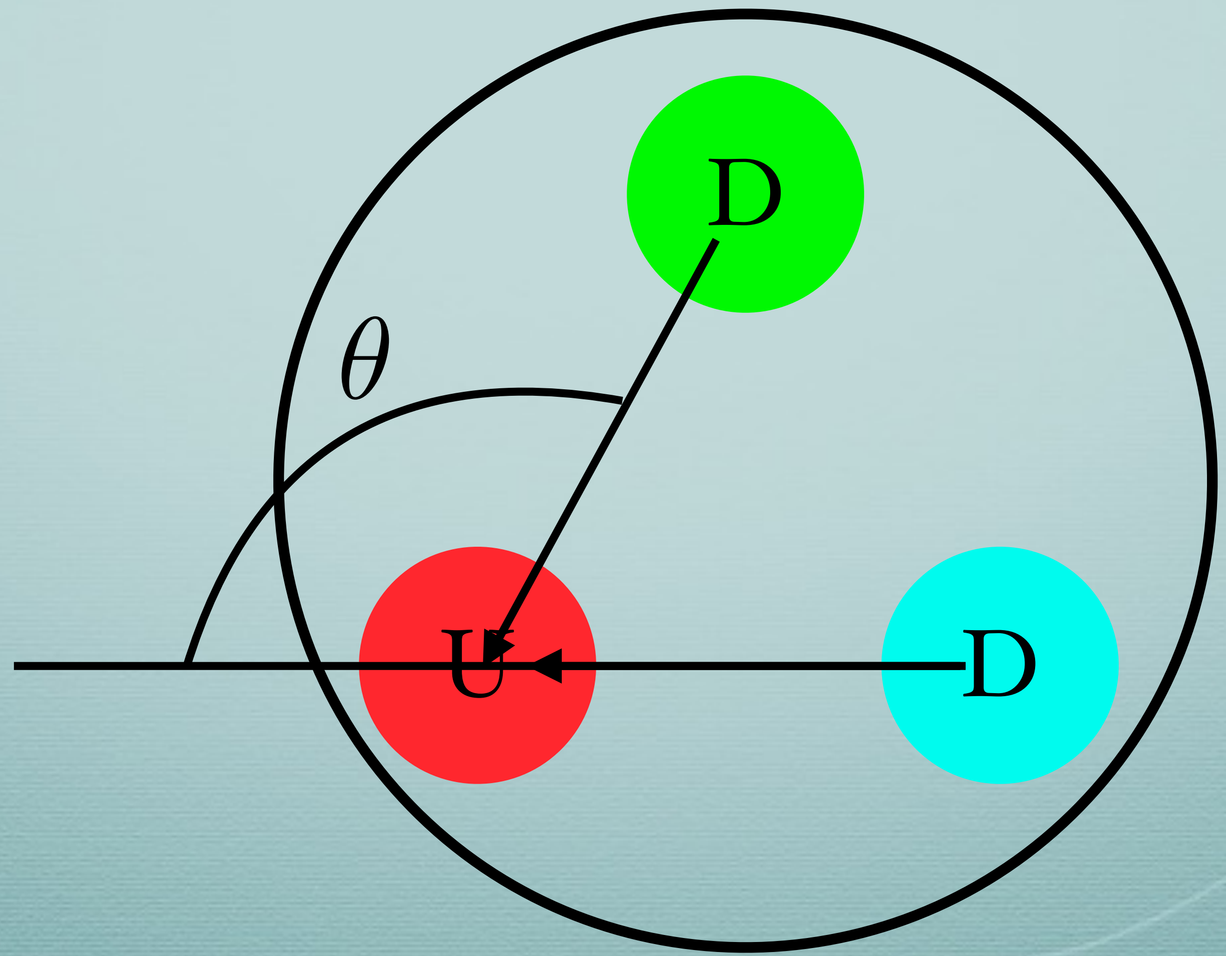
Electric Dipole moment

$$d_n = qx$$



Expected Dipole moment

$$
\begin{aligned}
|d_n| &\approx ex\sqrt{1-\cos\theta} \\
&\approx 10^{-14}\, e\, \sqrt{1-\cos\theta}\ \mathrm{cm}
\end{aligned}
$$



Measurement of EDM

- Measurement via Larmor frequency

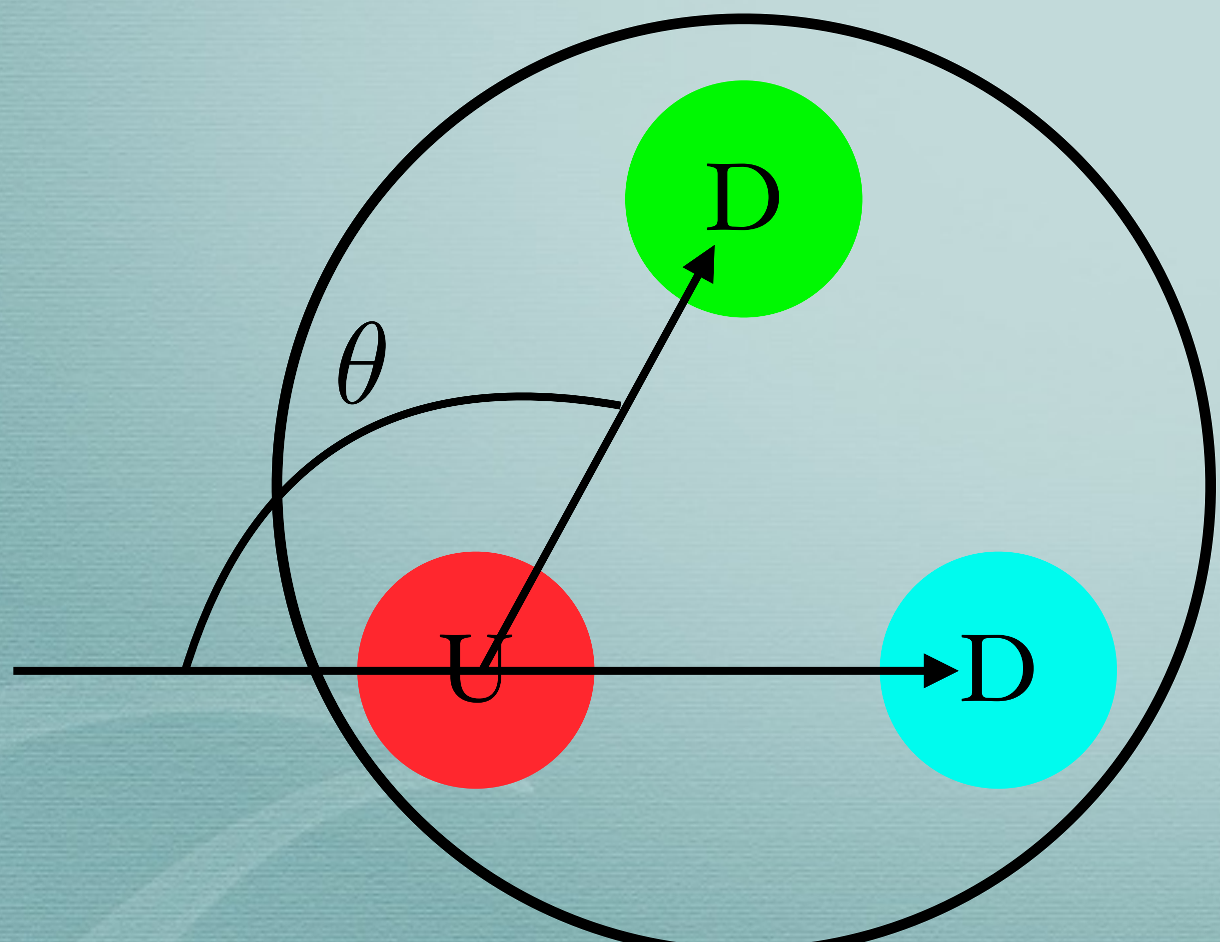
$$h\nu_{\uparrow\uparrow} = |2\mu_n B + 2d_n E|$$

$$h\nu_{\uparrow\downarrow} = |2\mu_n B - 2d_n E|$$

- Measure number of spin up versus spin down neutrons for parallel and anti-parallel electric and magnetic fields

Measured EDM

$$|d_n| \approx ex\sqrt{1-\cos\theta}$$
$$\approx 10^{-14}\, e\,\sqrt{1-\cos\theta}\ \text{cm}$$

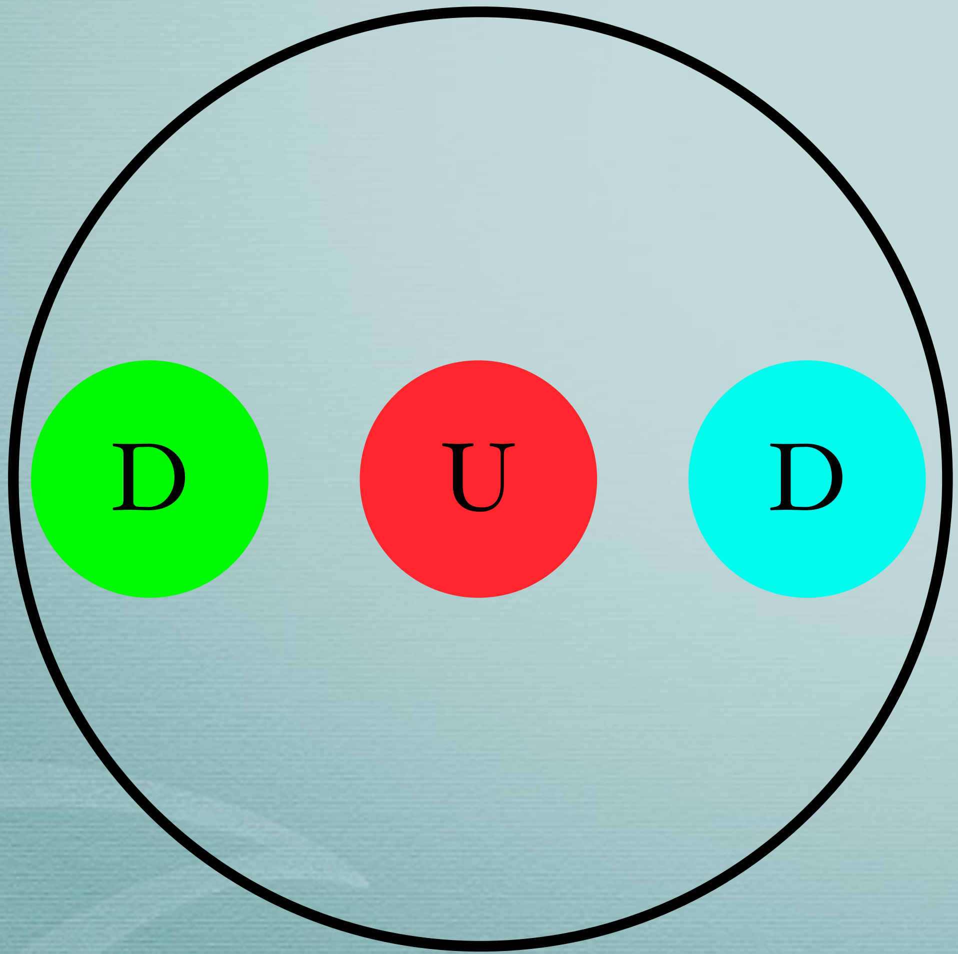


$$|d_n| < 2.9 \times 10^{-26}\, e\,\text{cm}$$

Baker et. al. hep-ex/0602020 :
Institut Laue-Langevin, Grenoble

Classical Strong CP problem

Measurement indicates a small theta



$$\theta < 10^{-12}$$

Must be a reason!

Quantum Strong CP problem

$$\mathcal{L} \supset \frac{g^2}{32\pi^2}\theta G_{\mu\nu}\tilde{G}^{\mu\nu} + Y_u H Q u^c + Y_d H^\dagger Q d^c$$

Neutron EDM can be calculated

Quantum calculation $$|d_n| = 3.2 \times 10^{-16}\,(\theta + \arg\,\det Y_u Y_d)\,e\,\mathrm{cm}$$

Classical estimate $$|d_n| \approx 10^{-14}\,\theta\,e\,\mathrm{cm}$$

Quantum Strong CP problem

$$|d_n| < 2.9 \times 10^{-26}\, e\,\mathrm{cm}$$

$$\theta + \arg\, \det Y_u Y_d \equiv \bar{\theta} < 10^{-10}$$

QFT formulation of the Strong CP problem

Discrete symmetries

$$\theta + \arg\ \det Y_u Y_d \equiv \bar{\theta} < 10^{-10}$$

$$\begin{pmatrix} \cos\theta_{12} & -\sin\theta_{12} & 0 \\ \sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & -\sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ \sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & -\sin\theta_{23} \\ 0 & \sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} y_d e^{i\theta_d} & 0 & 0 \\ 0 & y_s e^{i\theta_s} & 0 \\ 0 & 0 & y_b e^{i\theta_b} \end{pmatrix}$$

$$\delta \sim \frac{\pi}{3}$$

Anomalous symmetry

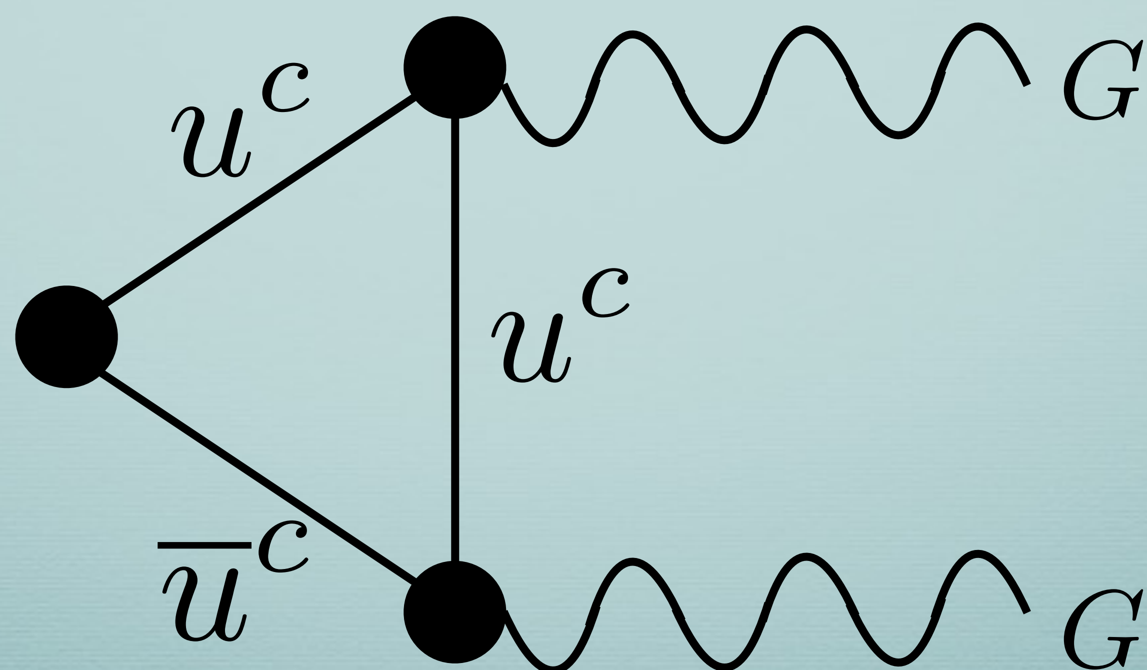
$$\theta + \arg\,\det Y_u Y_d$$

- Strange combination appears in the EDM
- Reason is that there exists a symmetry

$$u_c \to e^{i\alpha} u_c \qquad Y_u \to e^{-i\alpha} Y_u \qquad \theta \to \theta + \alpha$$

Anomalous symmetry

$$\mathcal{L} \supset \frac{g^2}{32\pi^2}\theta G_{\mu\nu}\tilde{G}^{\mu\nu} + Y_u H Q u^c + Y_d H^\dagger Q d^c$$



Anomalous symmetry

$$u_c \to e^{i\alpha} u_c \qquad Y_u \to e^{-i\alpha} Y_u \qquad \theta \to \theta + \alpha$$

- Physical quantities must be invariant
- Only the combination $\theta + \arg\,\det Y_u Y_d$ is invariant under the symmetry

Outline

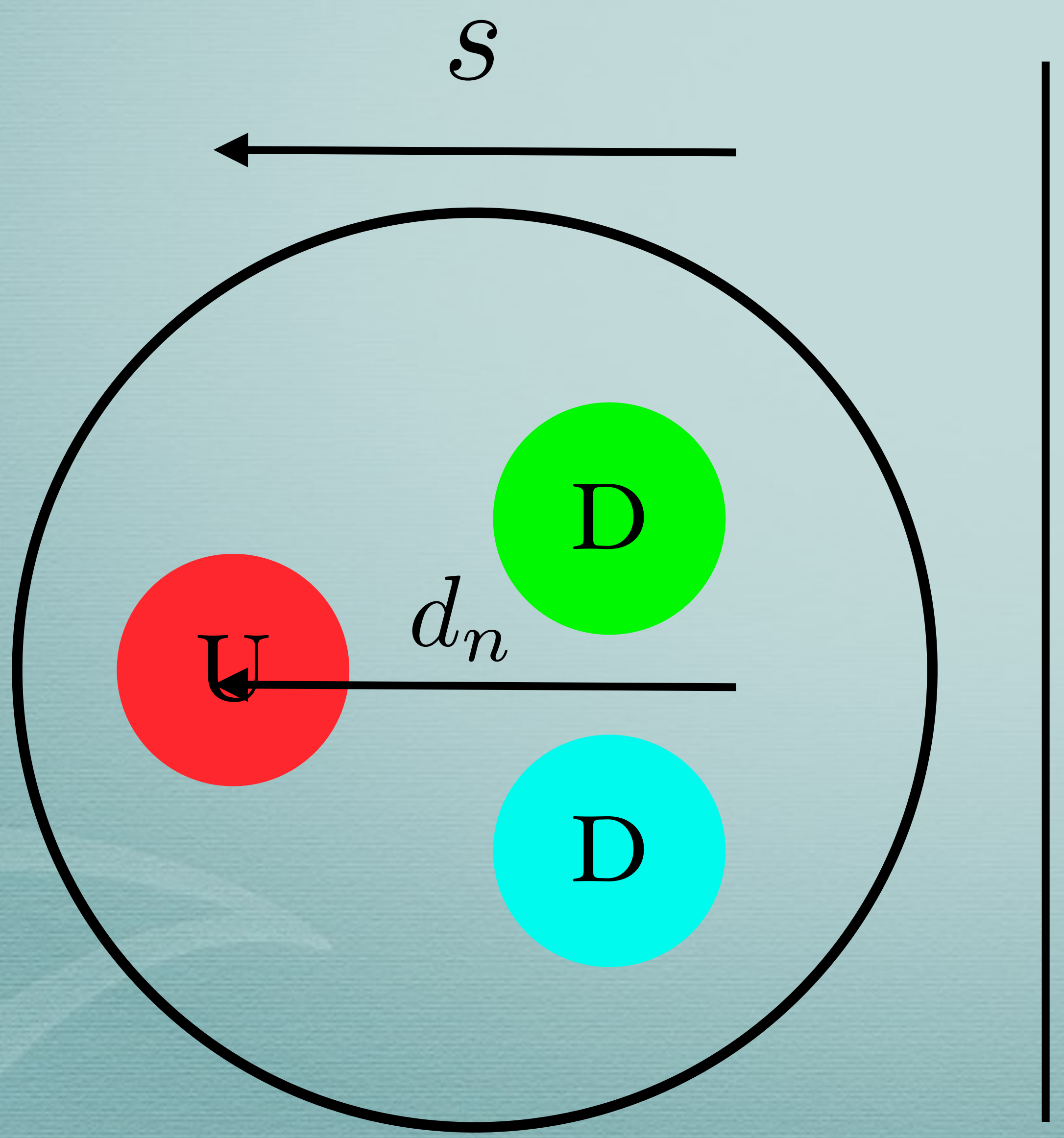
- ~~The Strong CP problem~~
- Previous solutions
- New solutions with LHC observable signatures

Discrete Symmetries

- CP and P can both set the neutron EDM to 0
- Require one to be a good symmetry of nature

Parity

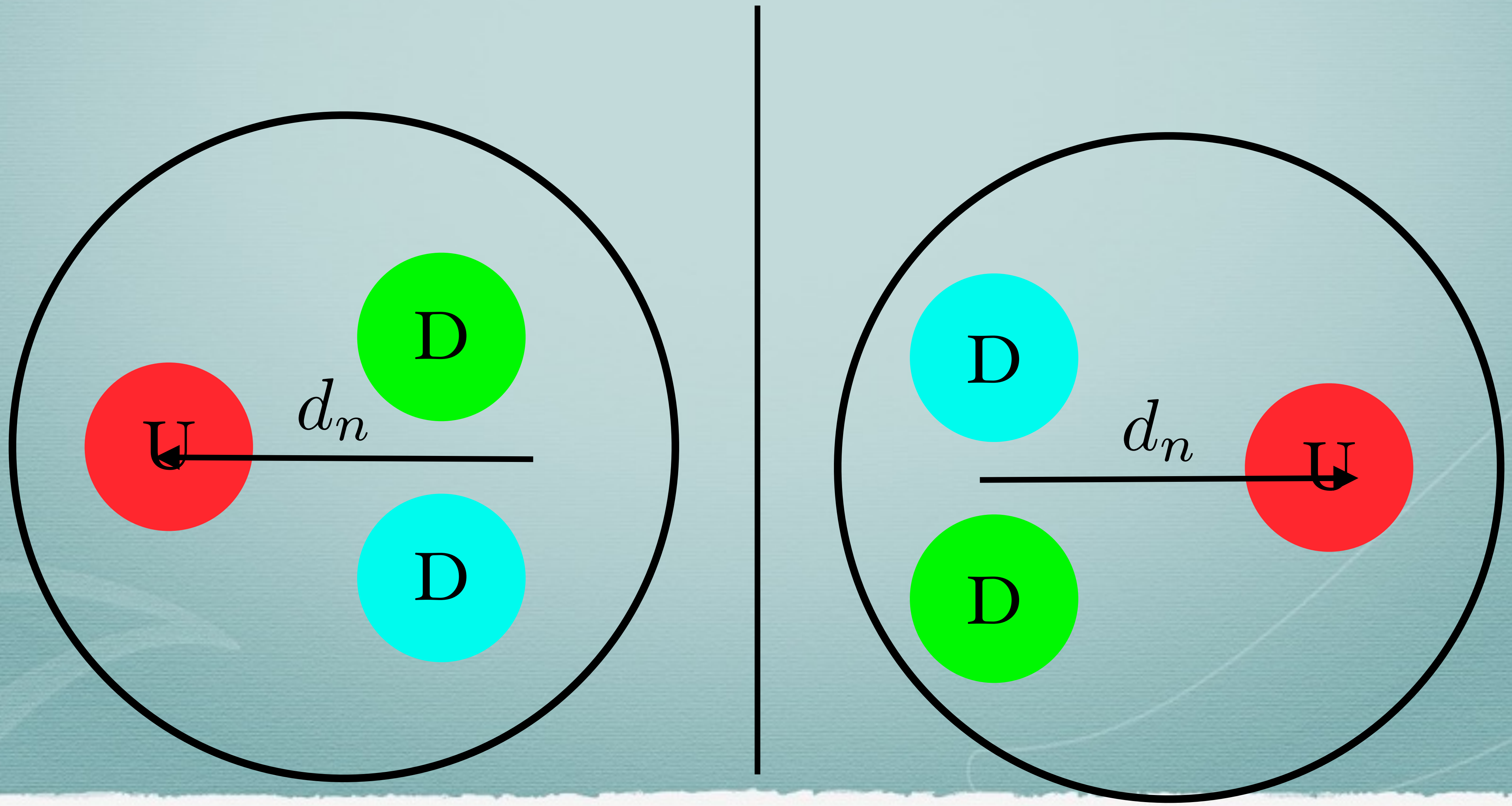
$$\vec{x} \Rightarrow -\vec{x}$$



Parity

$$\vec{d}_n = q\vec{x}$$

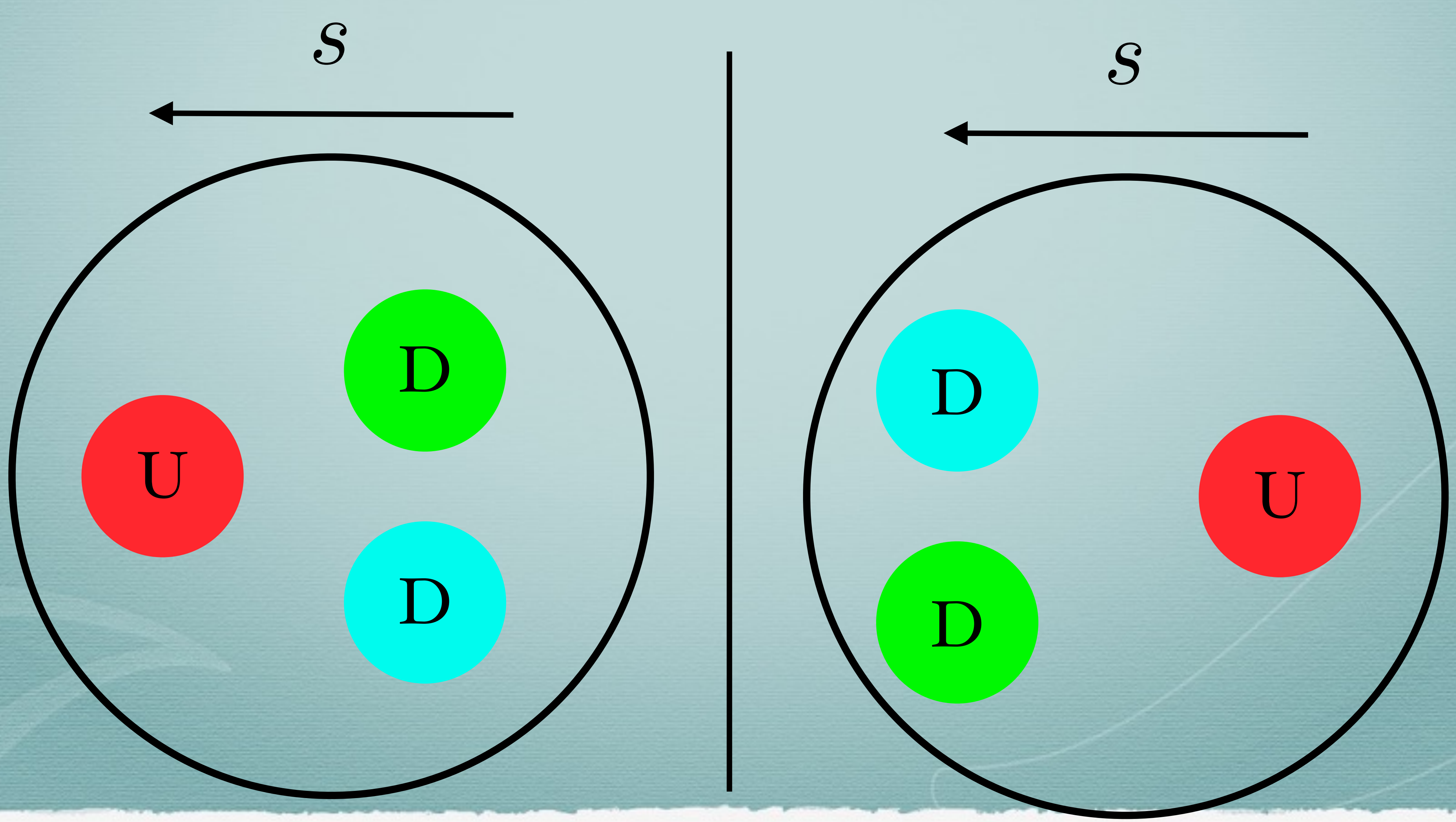
$$\vec{d}_n \Rightarrow -\vec{d}_n$$



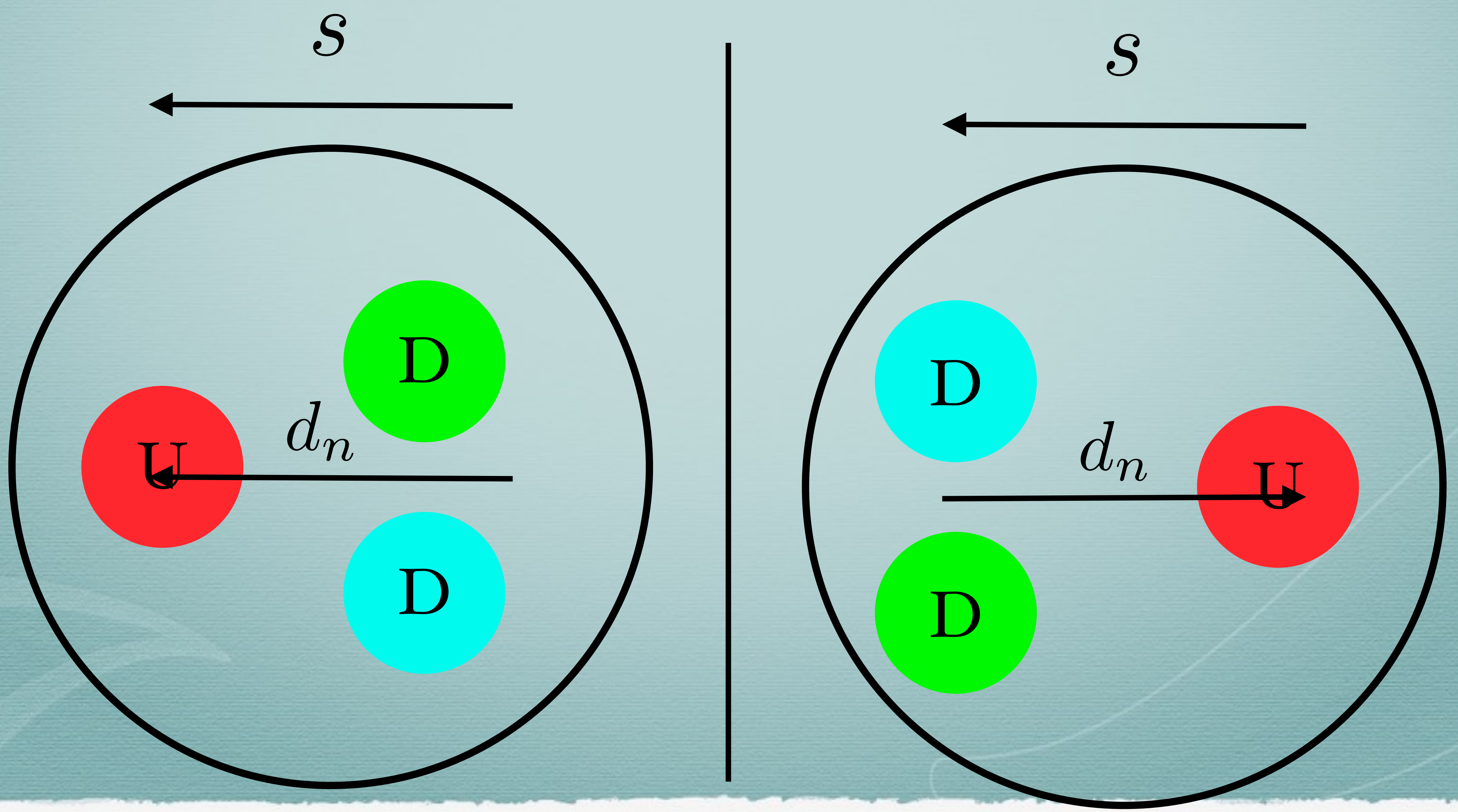
Parity

$$\vec{s} \Rightarrow \vec{s}$$

$$\vec{s} = \vec{r} \times \vec{p}$$

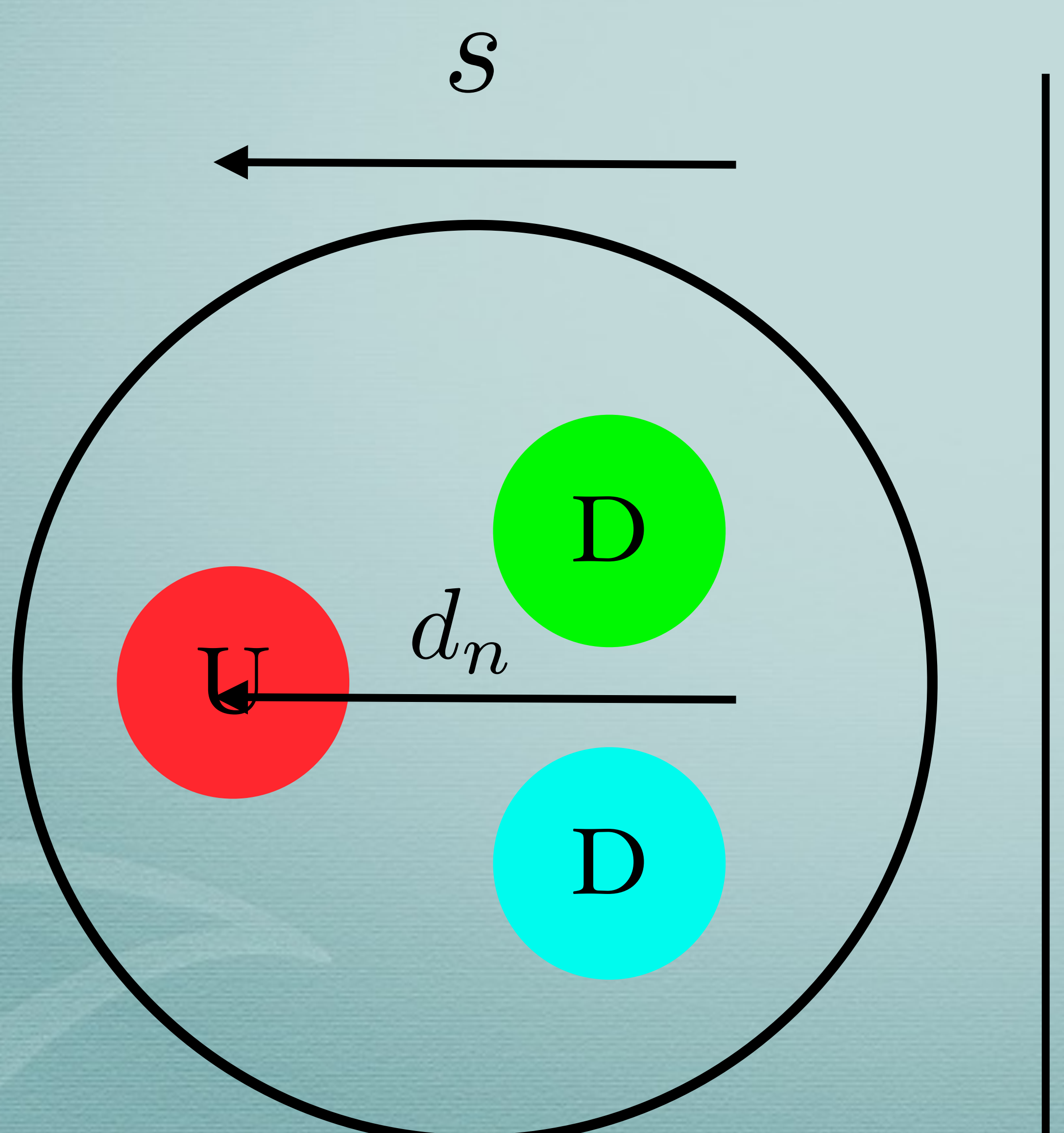


Parity



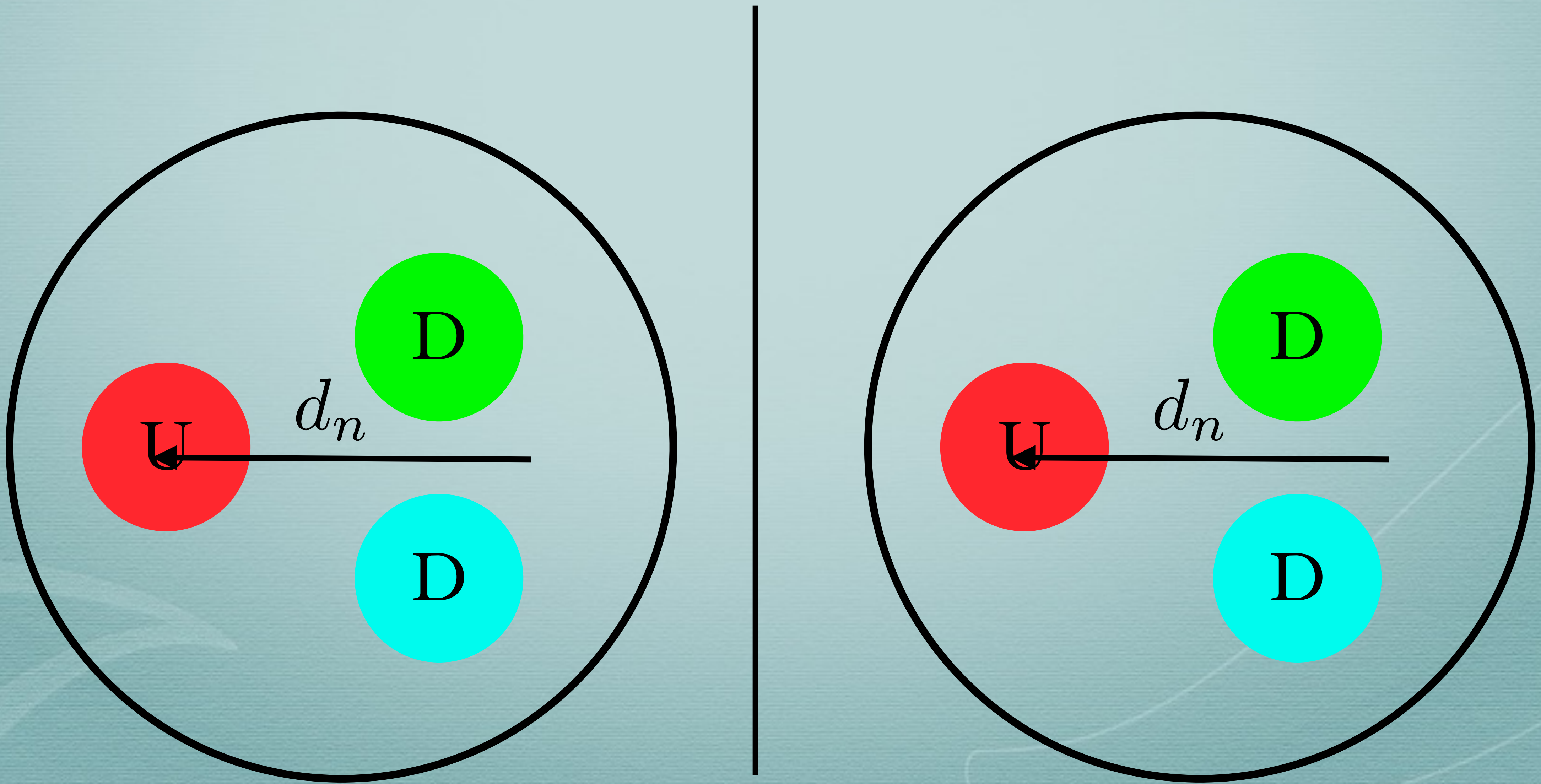
Time reversal

$$t \Rightarrow -t$$



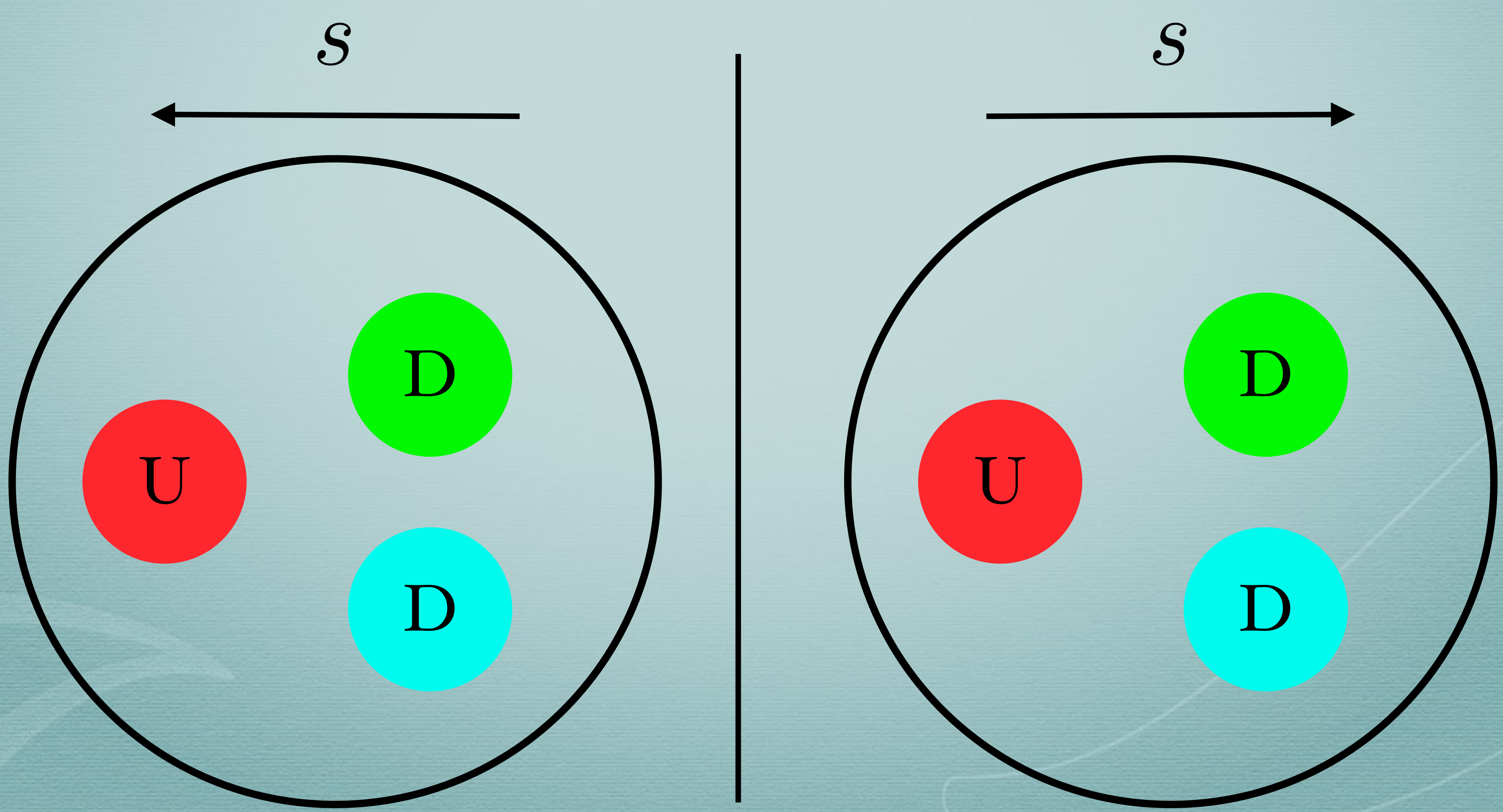
Time reversal

$$\vec{d}_n = q\vec{x} \qquad \vec{d}_n \Rightarrow \vec{d}_n$$

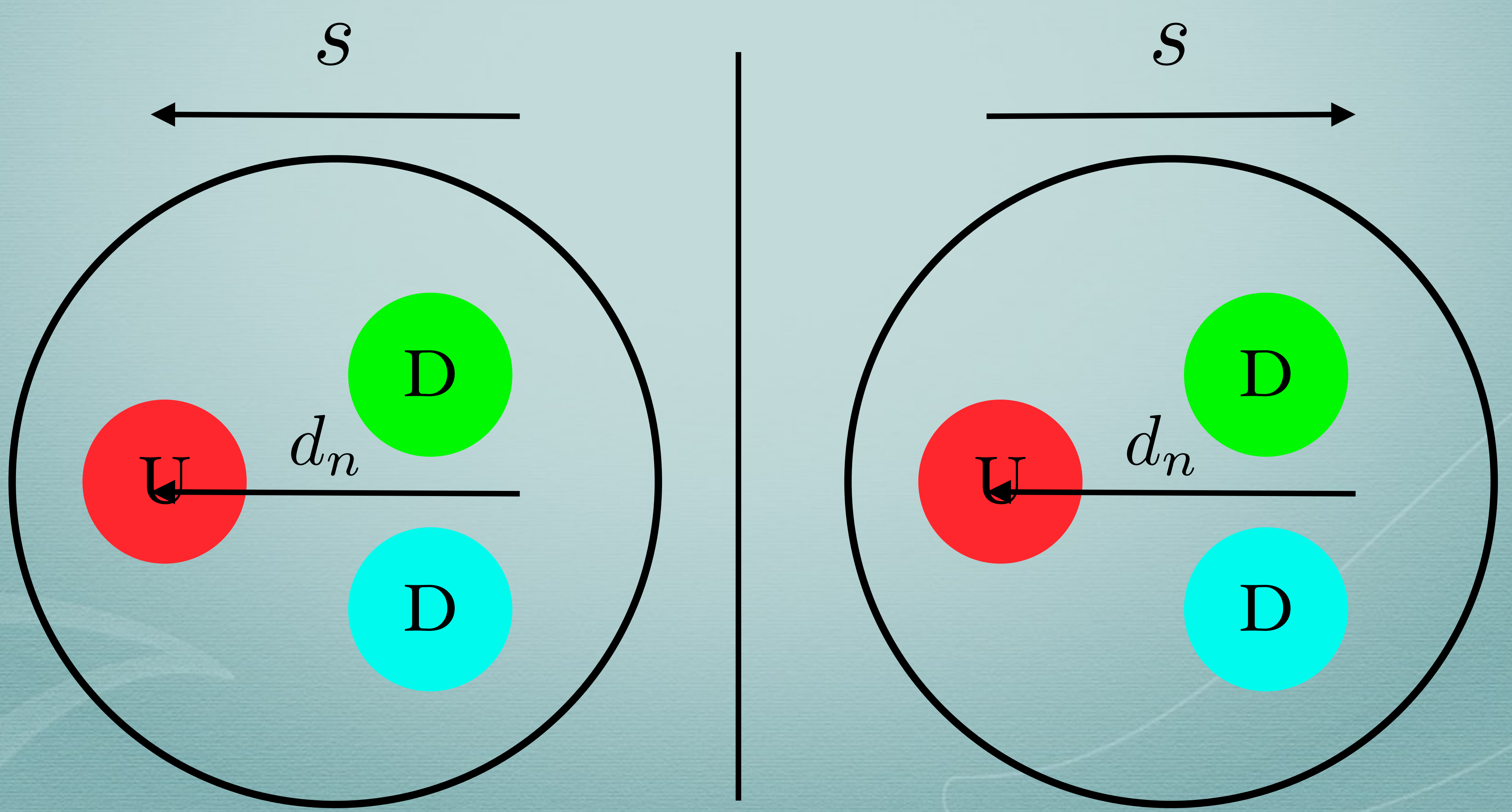


Time reversal

$$\vec{s} = \vec{r} \times \vec{p} \quad \vec{s} \Rightarrow -\vec{s}$$



Time reversal



Discrete Symmetries

- CP and P can both set the neutron EDM to 0
- Require one to be a good symmetry of nature
  - Spontaneously break the symmetry while
    - Arranging for CKM phase to be large
    - Arranging for neutron EDM to be small
- Nelson-Barr approach

A. E. Nelson, Phys.Lett. B136, 387 (1984)

S. M. Barr, Phys.Rev.Lett. 53, 329 (1984)

Discrete Symmetries

- Supersymmetry makes this natural
  - CKM phase is in the Kahler potential
  - Theta angle is not renormalized
  - Use loops to connect SM to CP breaking sector

G. Hiller and M. Schmaltz, Phys. Lett. B 514, 263 (2001)

Running of theta

$$\tau = \frac{1}{g^2} + i\frac{\theta}{8\pi^2}$$

$$\tau(\mu) = \tau(\mu_0) - \frac{b_0}{8\pi^2} log(\mu/\mu_0)$$

- Gauge coupling runs a one loop
- Imaginary part implies theta angle does not run

Running of CKM phase

$$\int d^4\theta Z Q^\dagger Q = \int d^4\theta (T_Q^{-1} Q)^\dagger (T_Q^{-1} Q)$$

$$Y_u = T_Q \hat{Y}_u T_u$$

$$\mathrm{argdet} Y_u = \mathrm{argdet} \hat{Y}_u + \mathrm{argdet} T_u + \mathrm{argdet} T_Q = 0$$

- Wave function renormalization results in non-vanishing CKM phase
    - Because T are hermitian, does not change invariant theta angle

Axion solution

CP Conservation in the Presence of Pseudoparticles*

R. D. Peccei and Helen R. Quinn†
Institute of Theoretical Physics, Department of Physics, Stanford University, Stanford, California 94305
(Received 31 March 1977)

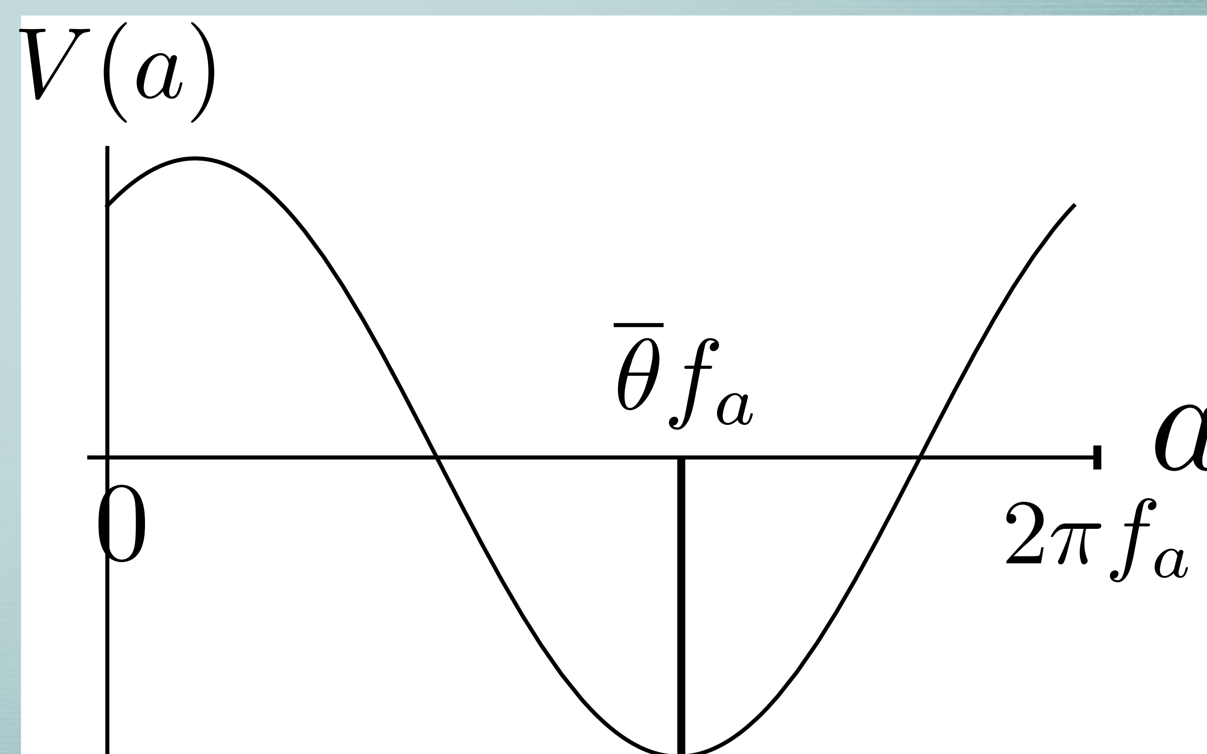
We give an explanation of the CP conservation of strong interactions which includes the effects of pseudoparticles. We find it is a natural result for any theory where at least one flavor of fermion acquires its mass through a Yukawa coupling to a scalar field which has nonvanishing vacuum expectation value.

Axion solution

$$\mathcal{L} \supset \frac{g^2}{32\pi^2}(\theta - \frac{a}{f_a})G_{\mu\nu}\tilde{G}^{\mu\nu} + \frac{1}{2}\partial_\mu a \partial^\mu a$$

Axion dynamically sets the neutron EDM to 0

$$|d_n| = 3.2 \times 10^{-16}\,(\overline{\theta} - \langle\frac{a}{f_a}\rangle)\,e\,\mathrm{cm}$$



Axion solution

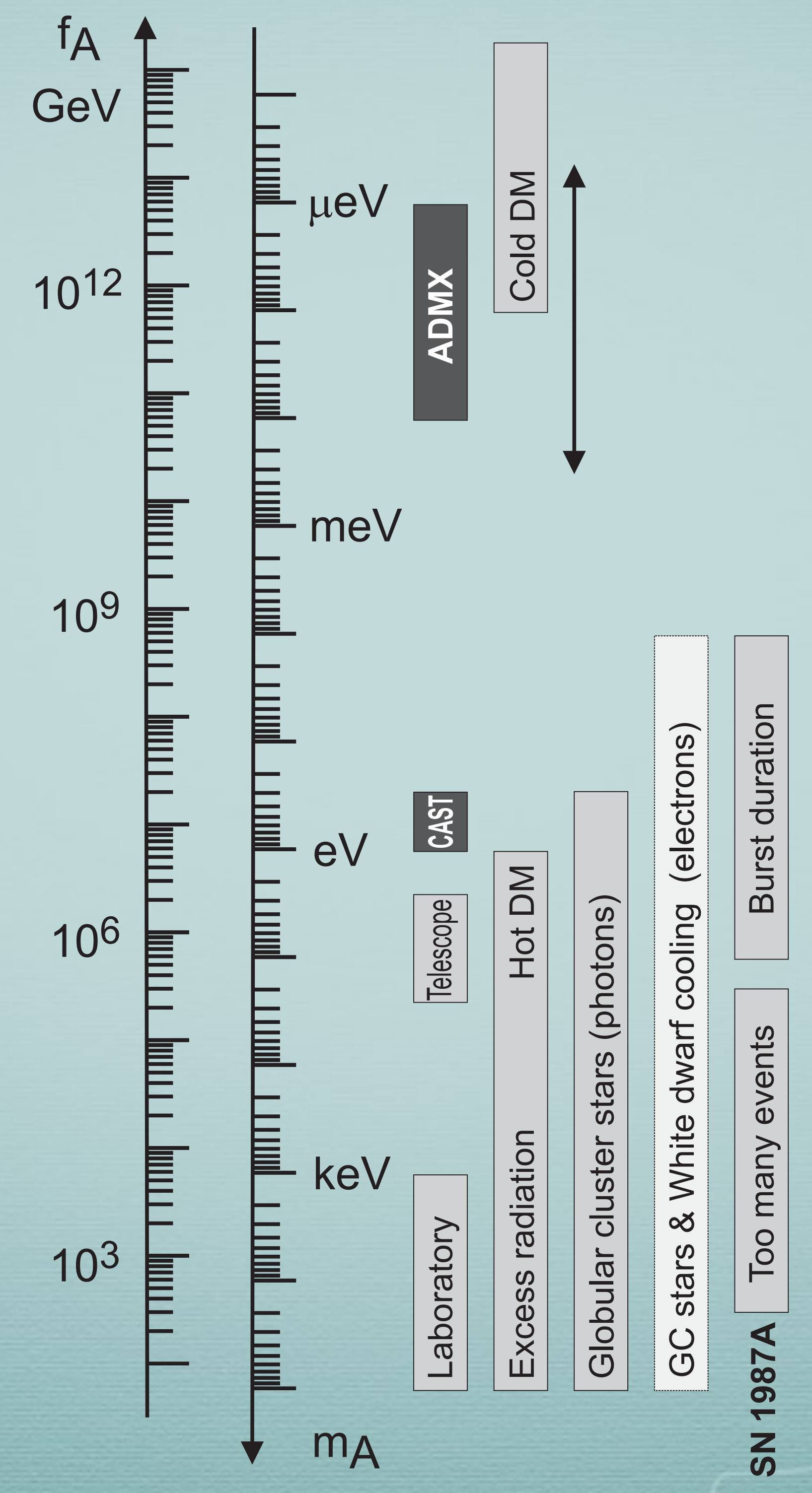
$$\mathcal{L} \supset \frac{g^2}{32\pi^2}(\theta - \frac{a}{f_a})G_{\mu\nu}\tilde{G}^{\mu\nu} + \frac{1}{2}\partial_\mu a \partial^\mu a$$

- One parameter solution (KSVZ axion)
- Also a dark matter candidate
- String theory motivation for not just one axion, but many many axions

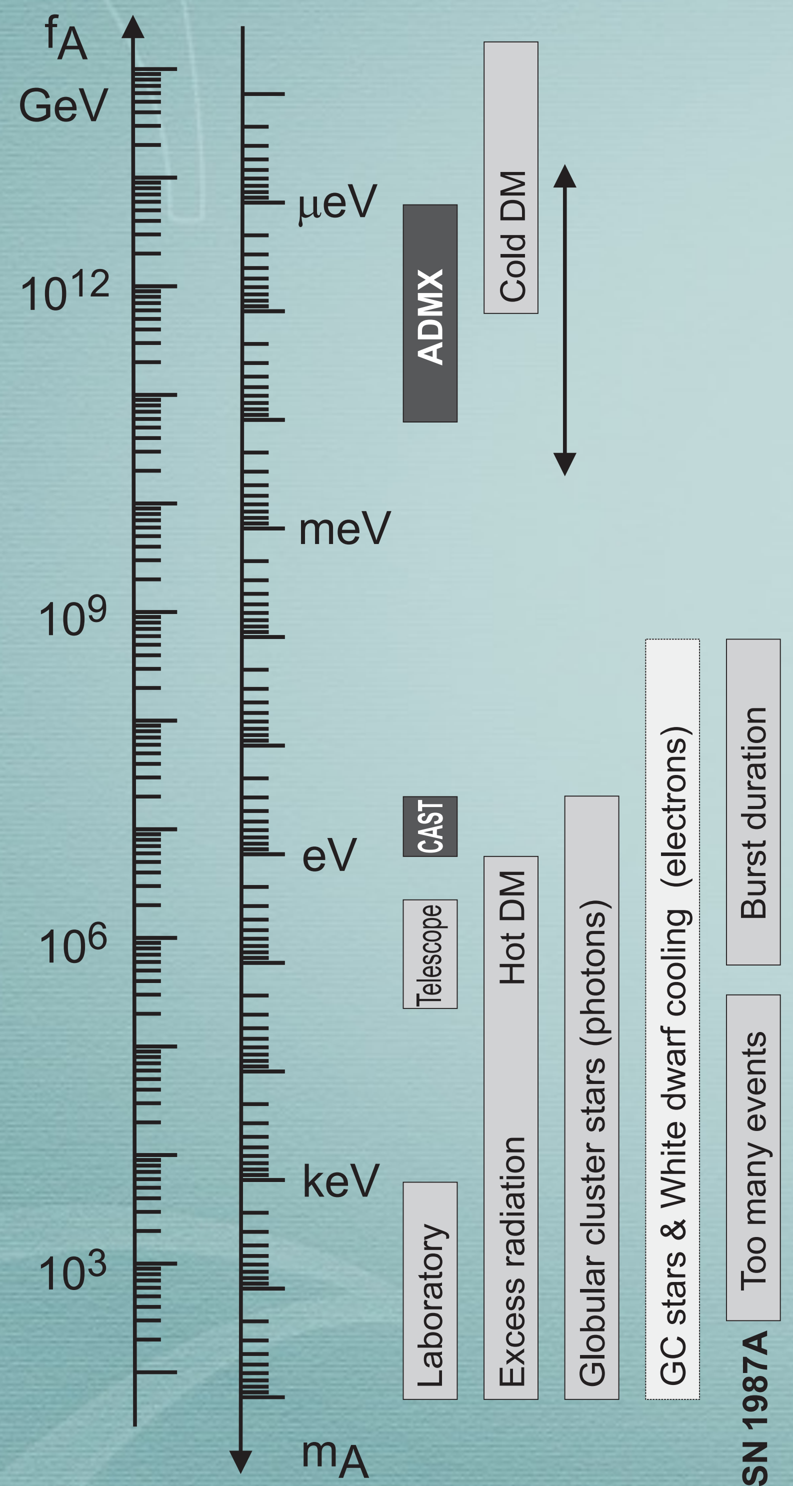
Kim, J.E. (1979). *Phys. Rev. Lett.* **43**: 103.
Shifman, M.; Vainshtein, A.; Zakharov, V. (1980). *Nucl. Phys.* **B166**: 493.

Arvanitaki, A.; Dimopoulos, S.; Dubovsky, S.; Kaloper, N.; March-Russell, J. *(2010) Phys.Rev. D81*

Testing the axion



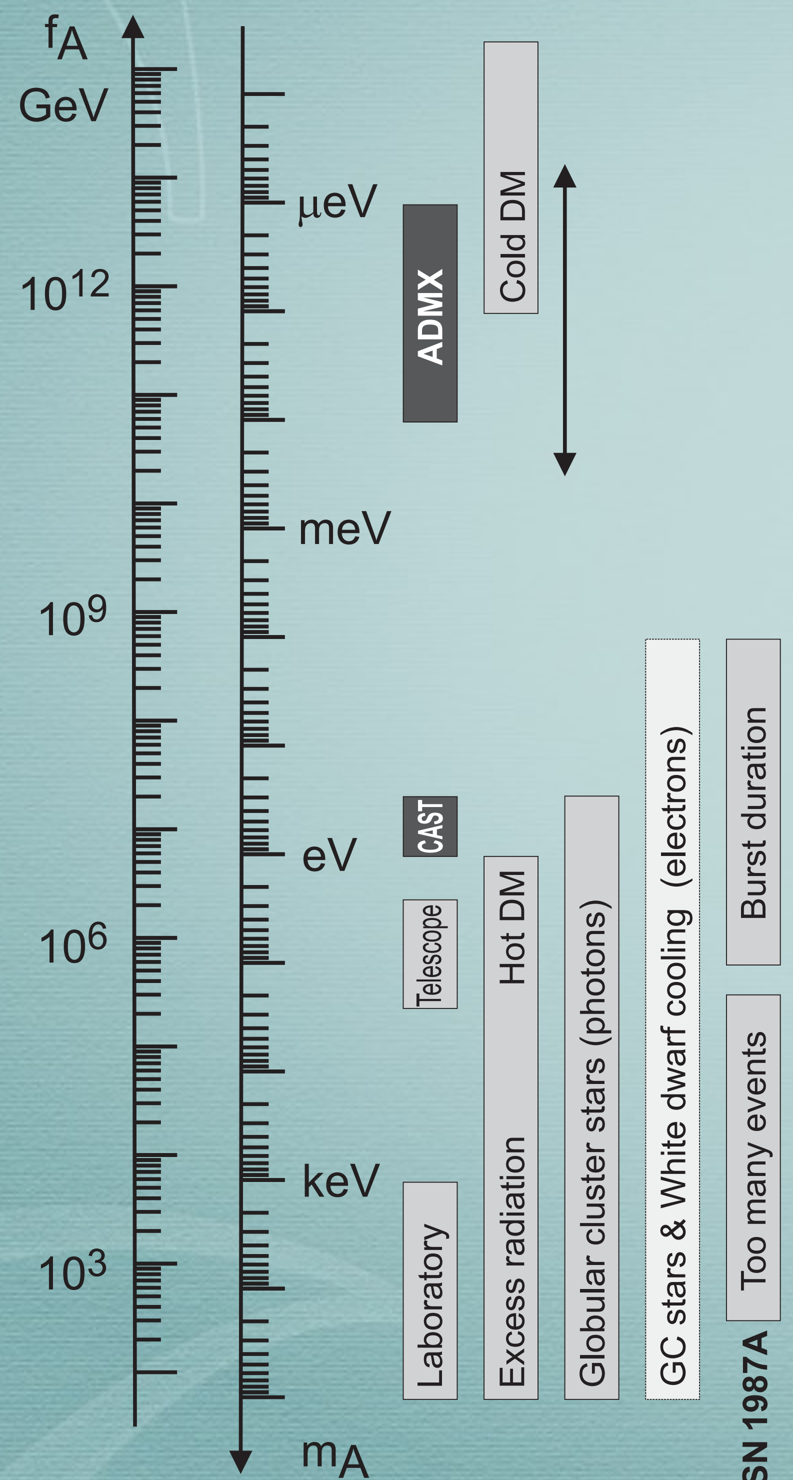
Testing the axion



- ADMX
  - Microwave cavity

S. Asztalos et al., Phys. Rev. D69, 011101 (2004)

Testing the axion



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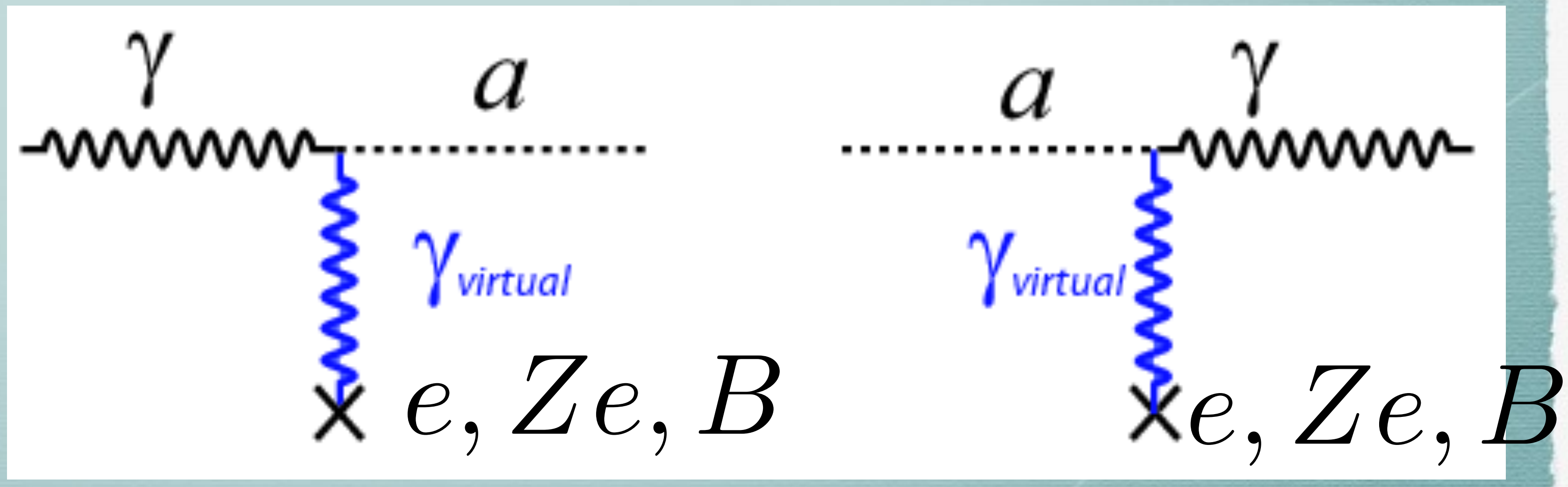

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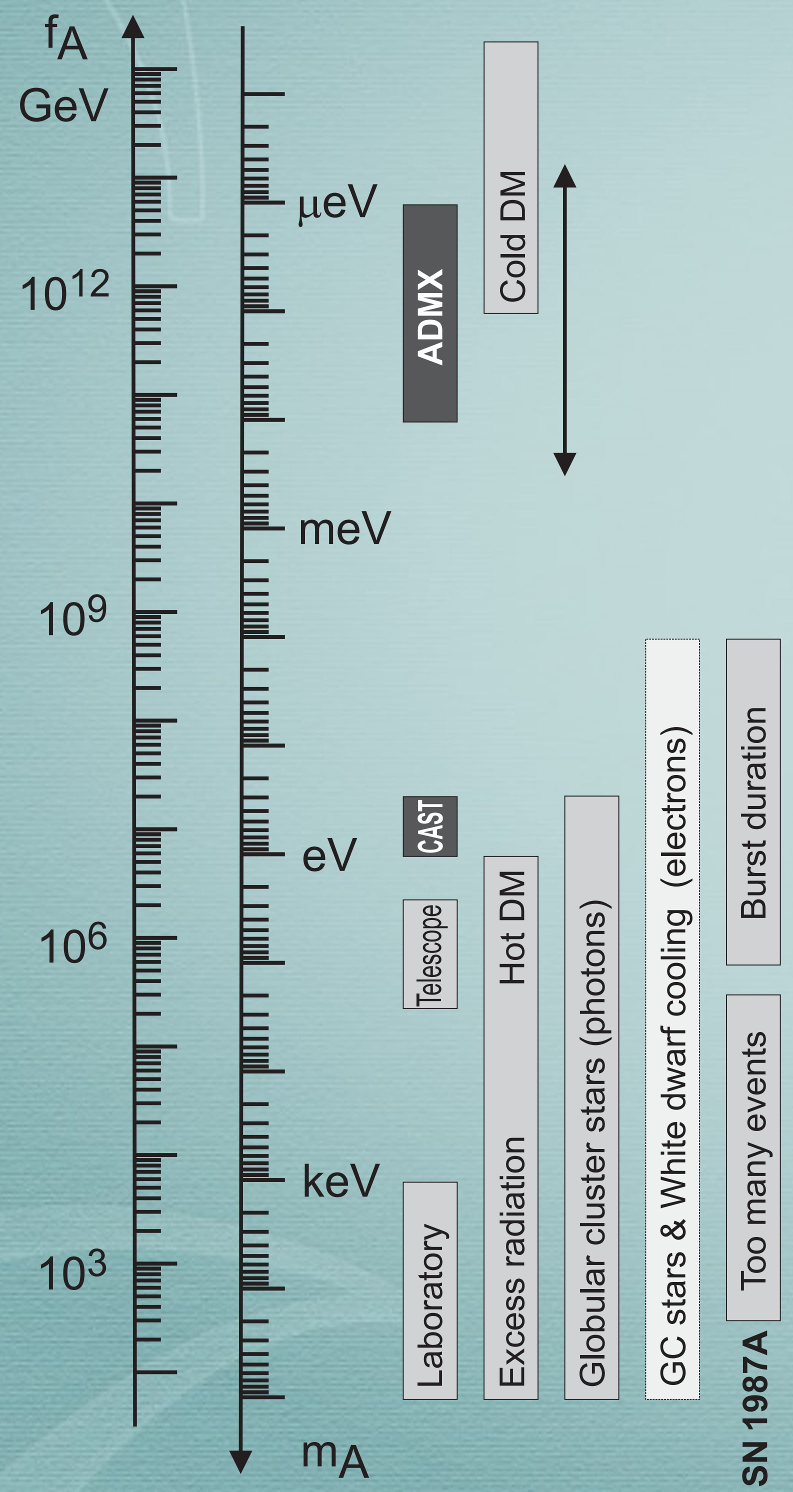
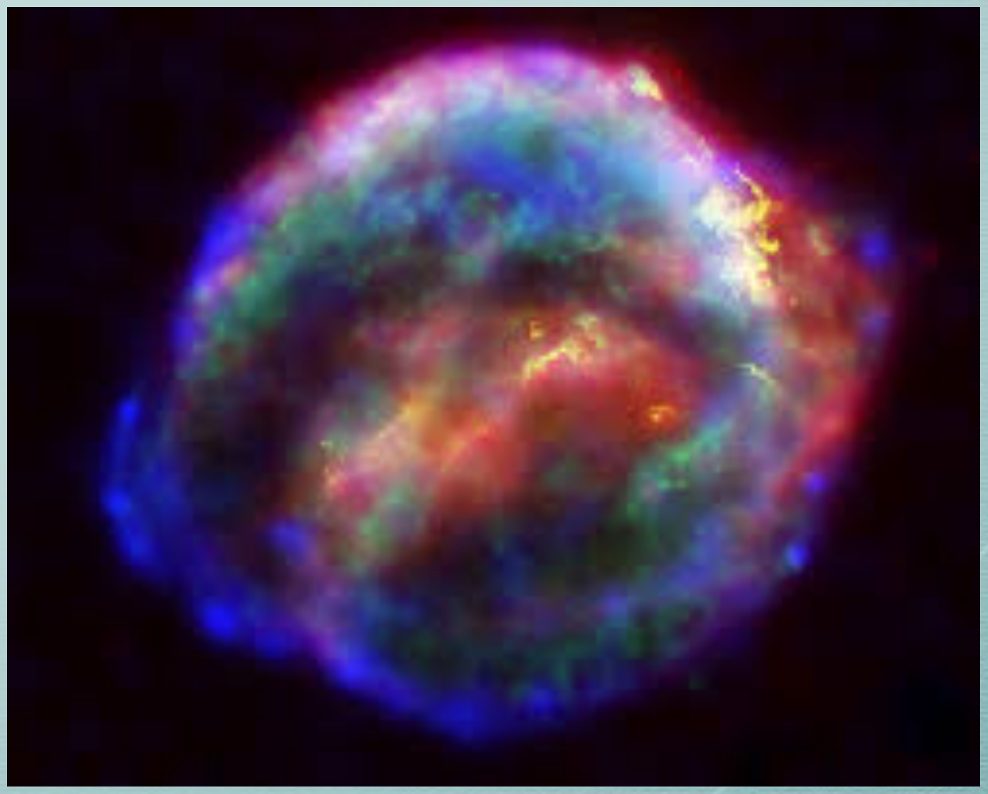
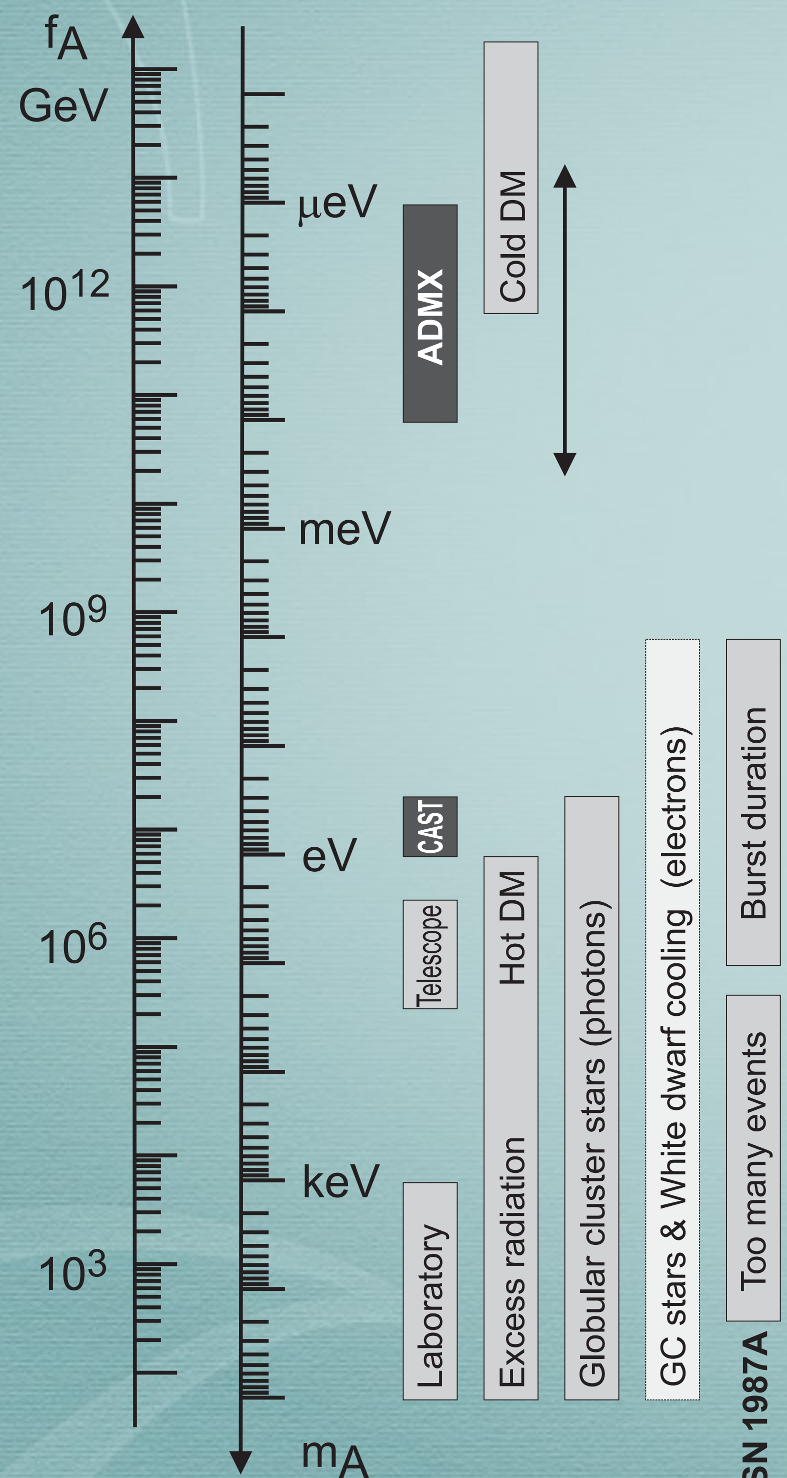


- SuperNova 1987A
  - Axions carry away too much energy

G.G. Raffelt, Lect. Notes Phys. 741, 51 (2008)

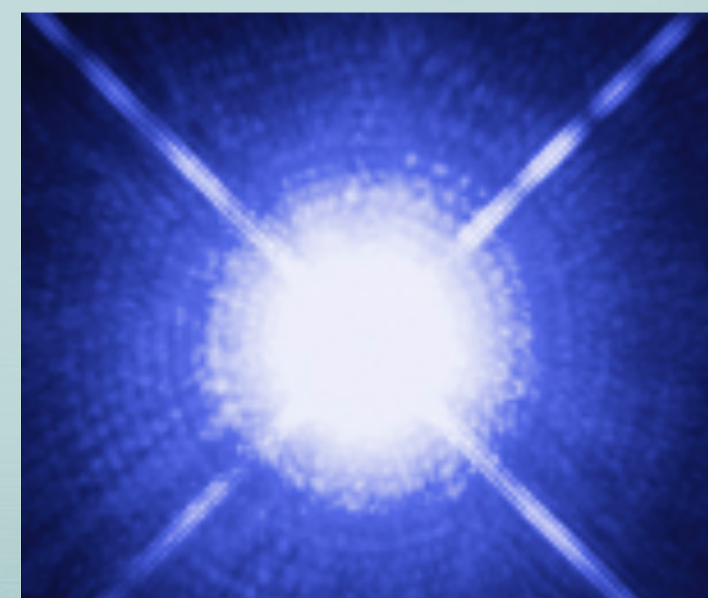


Testing the axion

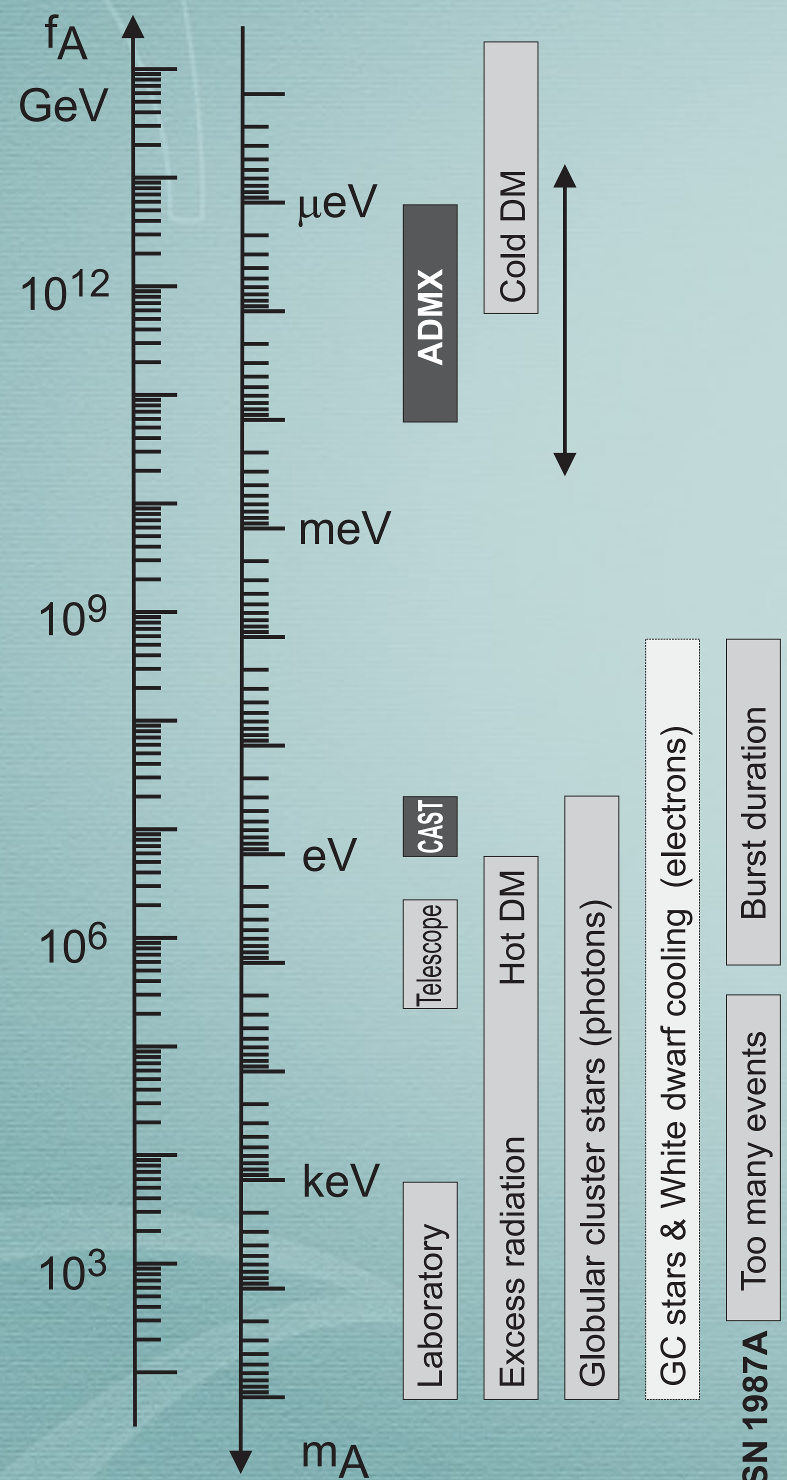


- Globular cluster stars/ White dwarf
  - Alters stellar evolution

G.G. Raffelt, Stars as Laboratories for Fundamental Physics, (1996)

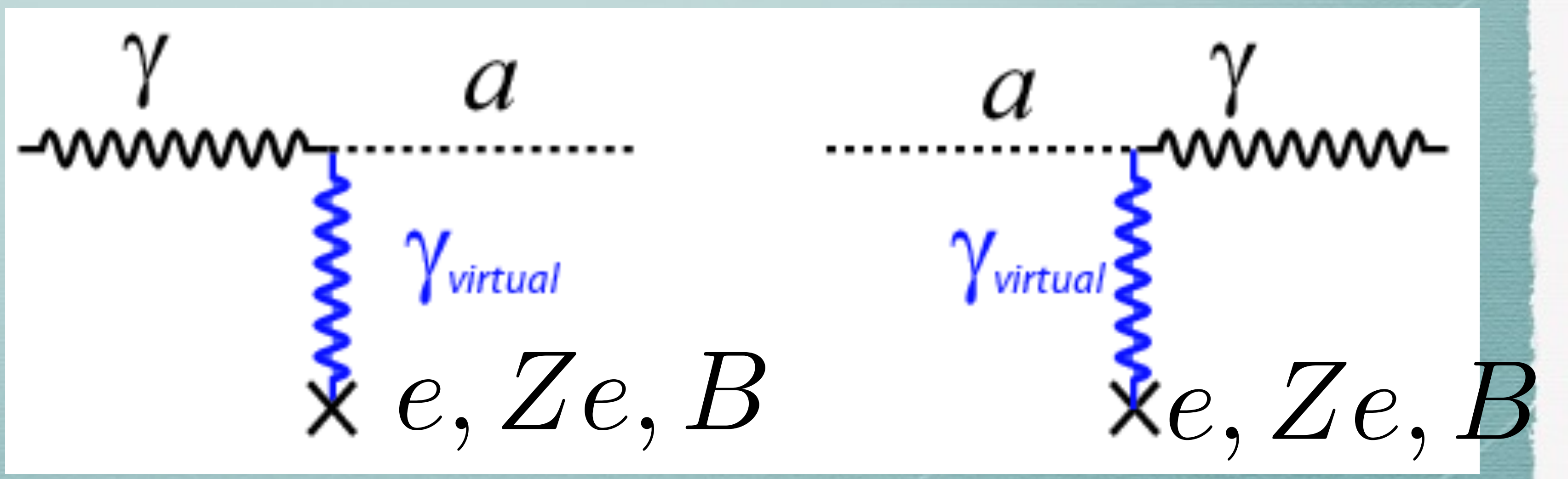


Testing the axion



- Laboratory experiments
  - Photon regeneration - ála neutrino flavor oscillations

$$\gamma + Ze \leftrightarrow Ze + A$$



G. Raffelt and L. Stodolsky, Phys. Rev. D37, 1237 (1988)

Outline

- ~~The Strong CP problem~~
- ~~Previous solutions~~
- New solutions with LHC observable signatures

Massless up quark

Symmetry Breaking through Bell-Jackiw Anomalies*

G. 't Hooft†
Department of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 22 March 1976)

In models of fermions coupled to gauge fields certain current-conservation laws are violated by Bell-Jackiw anomalies. In perturbation theory the total charge corresponding to such currents seems to be still conserved, but here it is shown that nonperturbative effects can give rise to interactions that violate the charge conservation. One consequence is baryon and lepton number nonconservation in $V-A$ gauge theories with charm. Another is the nonvanishing mass squared of the η.

$$U \to e^{i\alpha} U \qquad \overline{U} \to e^{i\alpha} \overline{U} \qquad \theta \to \theta + 2\alpha$$

No invariant to construct EDM out of

Must vanish

Massless up quark

$$|d_n| = 3.2 \times 10^{-16} \, (\theta + \arg\,\det Y_u Y_d) \frac{m_u m_d}{(m_u + m_d)} \frac{1}{1.6\,\mathrm{MeV}} \, e\,\mathrm{cm}$$

$$m_u \to 0 \qquad \Rightarrow \qquad d_n \to 0$$

Massless up quark

$$\mathcal{L}_{IR} = \frac{m_{\eta'}^2}{2}\left(\eta' - f_{\eta'}\overline{\theta}\right)^2 + f(\eta' - f_{\eta'}\overline{\theta})$$

- Signatures of the massless up quark solution
  - Before confinement there is a massless quark
  - There is a sector which confines - QCD
  - After confinement, the vev of the η' boson removes θ from the IR

Status of the massless up quark

$$m_u = 2.3^{+0.7}_{-0.5}\ \text{MeV}$$

Massless up quark solution “strongly disfavored”

J. Beringer *et al.* (Particle Data Group) (2012). "PDGLive Particle Summary 'Quarks (u, d, s, c, b, t, b', t', Free)'"

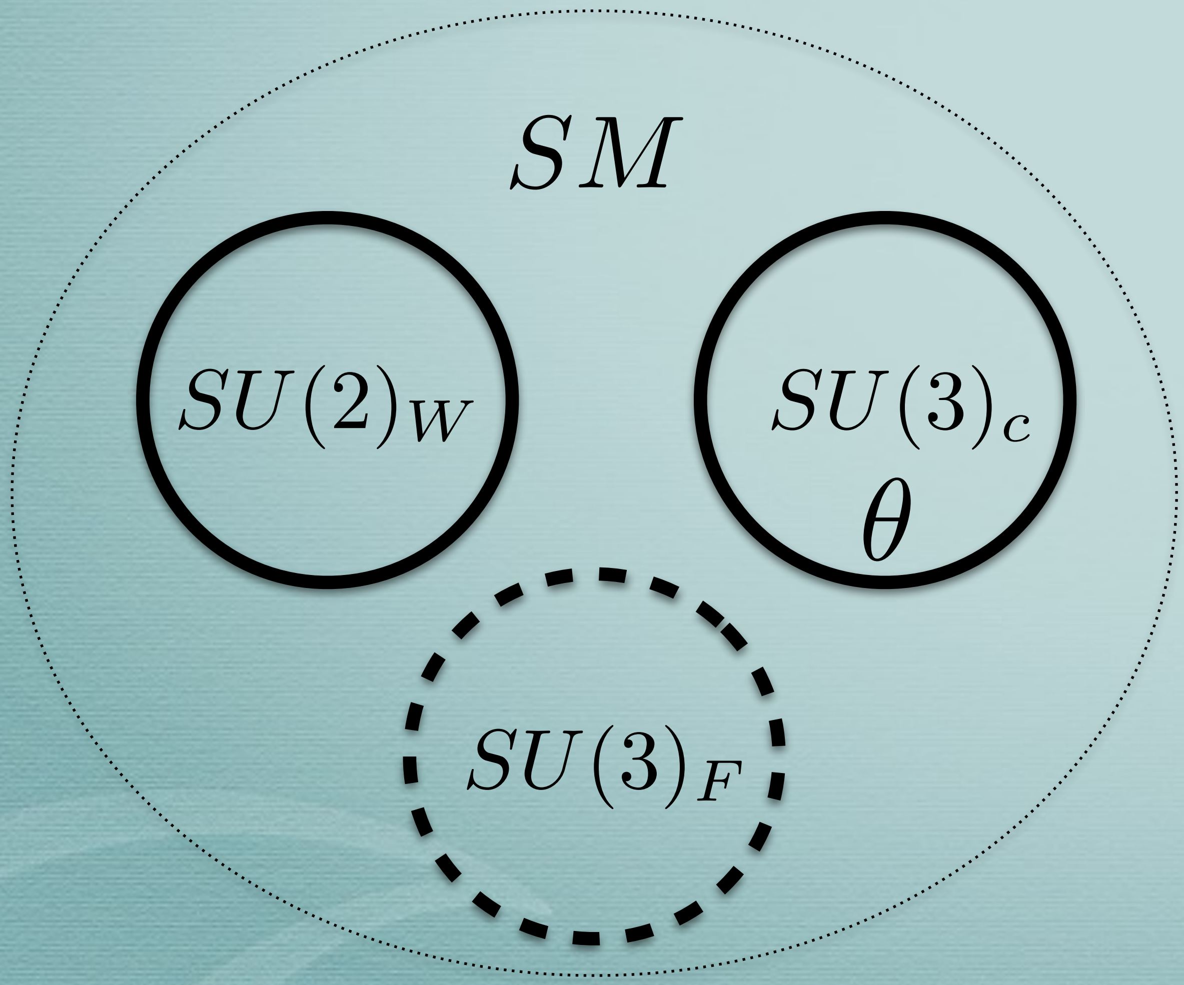
Generalized massless up quark solution

- 40 years since it was invented
  - Why throw away a good idea?
- Simplest generalization of the massless up quark solution

Generalized massless up quark solution

- Before confinement there is a massless quark
- There is a sector which confines
- After confinement, the vev of the η' boson removes θ from the IR

New massless quark solution



- Before confinement there is a massless quark
- There is a sector which confines
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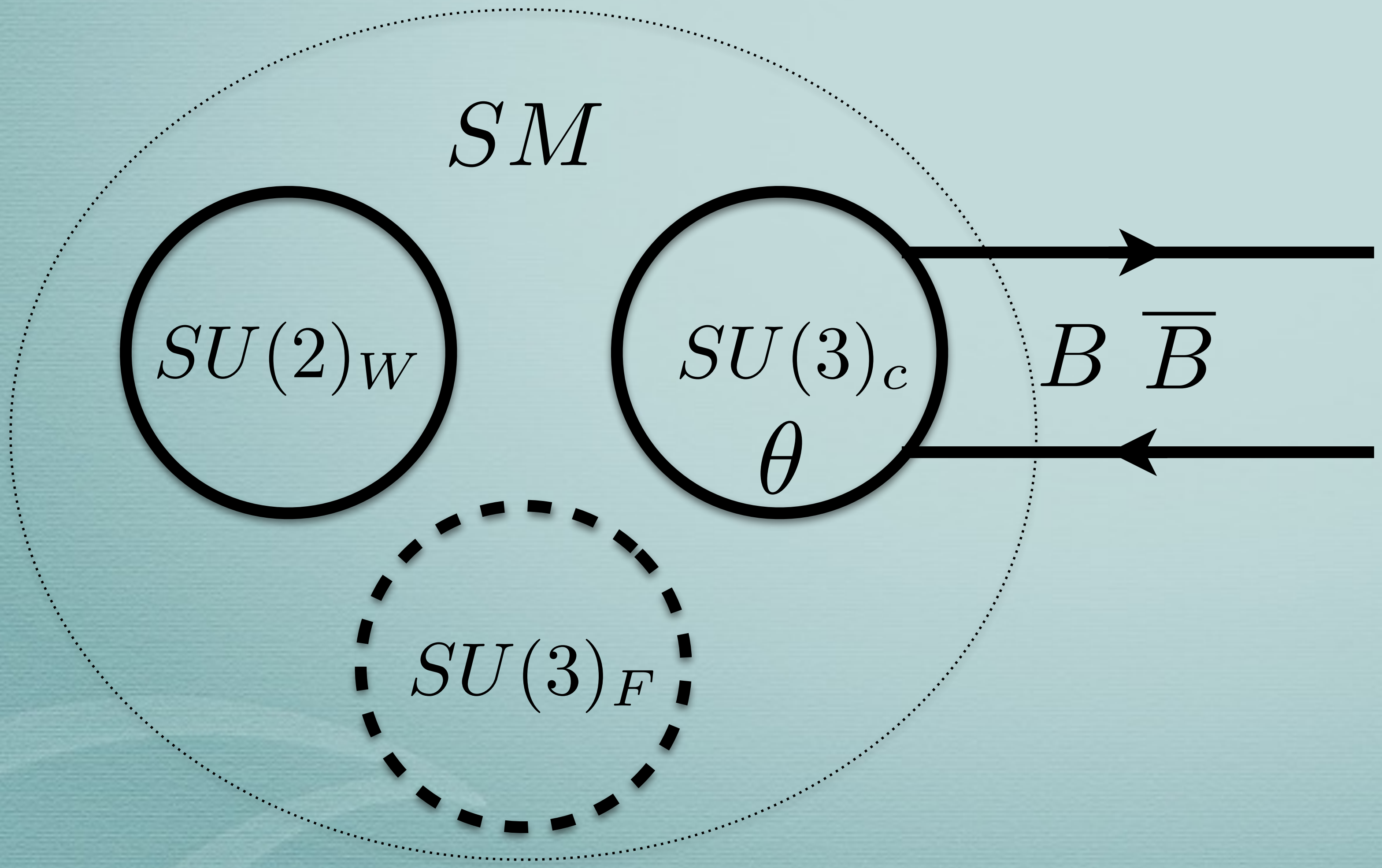
New massless quark solution

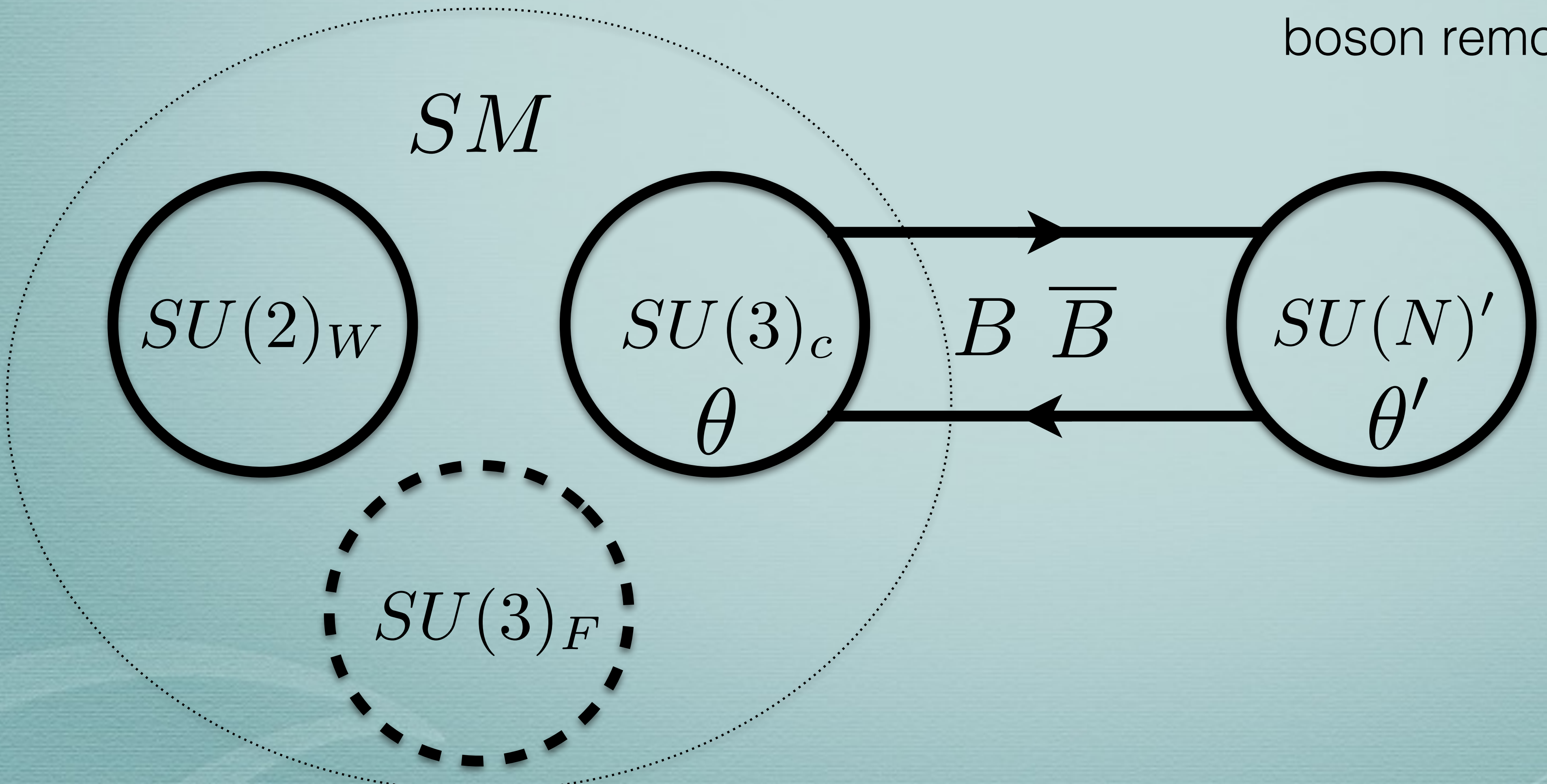
Add new massless quarks



- ✔ Before confinement there is a massless quark
- There is a sector which confines
- After confinement, the vev of the η' boson removes θ from the IR

New massless quark solution

Add a new confining gauge group



- ✓ Before confinement there is a massless quark
- ✓ There is a sector which confines
- After confinement, the vev of the η' boson removes θ from the IR

Effect of confinement

$$\mathcal{L} \supset \frac{g^2}{32\pi^2}\left(\theta - \frac{N}{3}\frac{\eta'}{f_{\eta'}}\right) G_{\mu\nu}\tilde{G}^{\mu\nu} + \frac{m_{\eta'}^2}{2}\left(\eta' - f_{\eta'}\theta'\right)^2 + \cdots$$

The eta prime boson changes our theta angle

$$\overline{\theta} = \theta + \arg\, \det Y_u Y_d - \frac{N}{3}\theta'$$

Effect of confinement

- To solve Strong CP problem, we need

$$\theta' = \frac{3}{N}(\theta + \arg\,\det Y_u Y_d)$$

- Seems strange to have a new gauge group with exactly this theta angle

Effect of confinement

- To solve Strong CP problem, we need

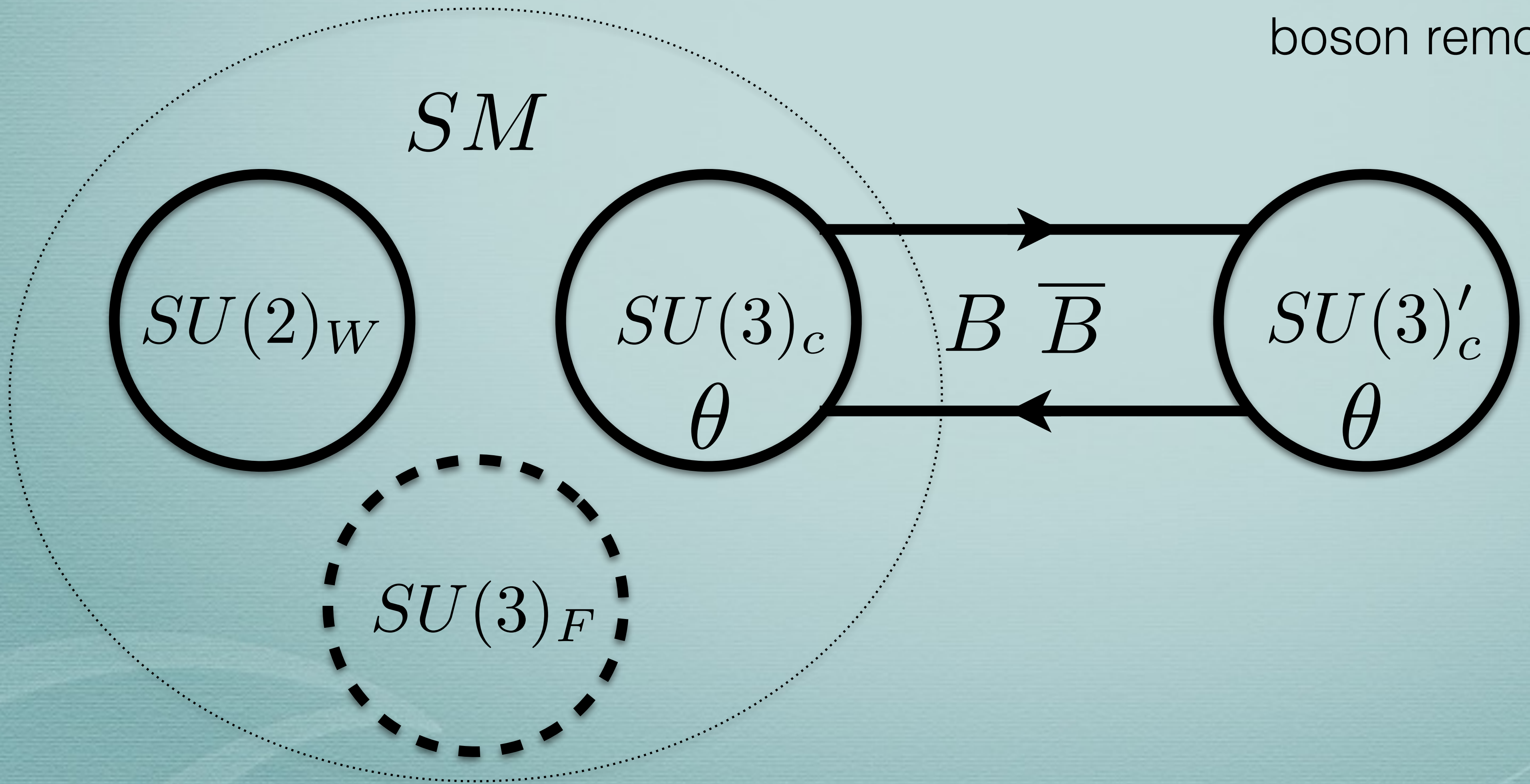
$$\theta' = \frac{3}{N}(\theta + \arg\,\det Y_u Y_d)$$

- Seems strange to have a new gauge group with exactly this theta angle
- We know of a gauge group with exactly this theta angle: QCD!

Effect of confinement

New confined gauge group is a copy of QCD

- ✔ Before confinement there is a massless quark
- ✔ There is a sector which confines
- After confinement, the vev of the η' boson removes θ from the IR

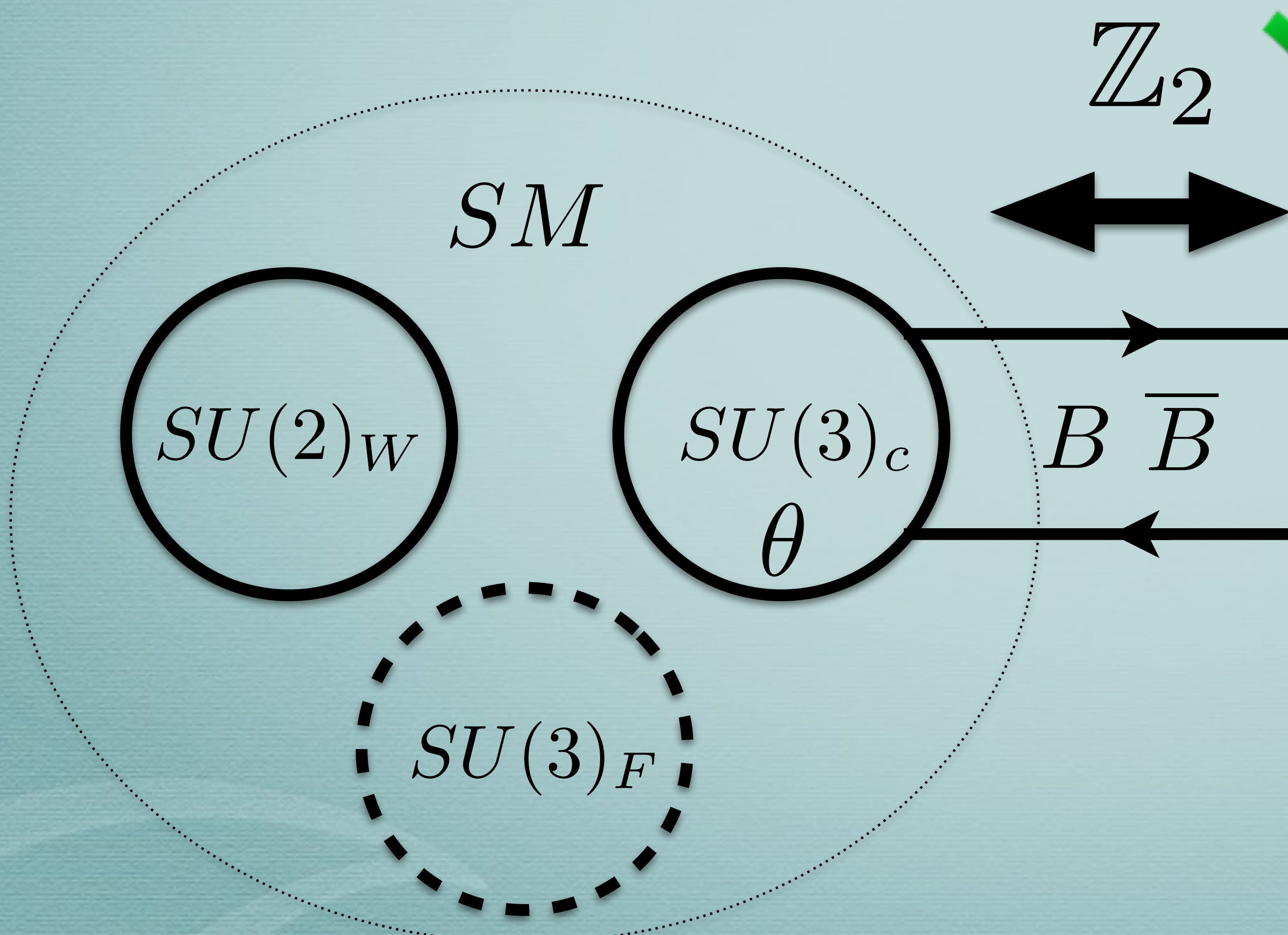


Copying QCD

- How much do we need to copy?
- Copy leptons
  - Anomaly considerations
- Mirror QCD spontaneously breaks SU(2)
  - Copy Higgs and SU(2)
- Everything but U(1)

New massless quark solution

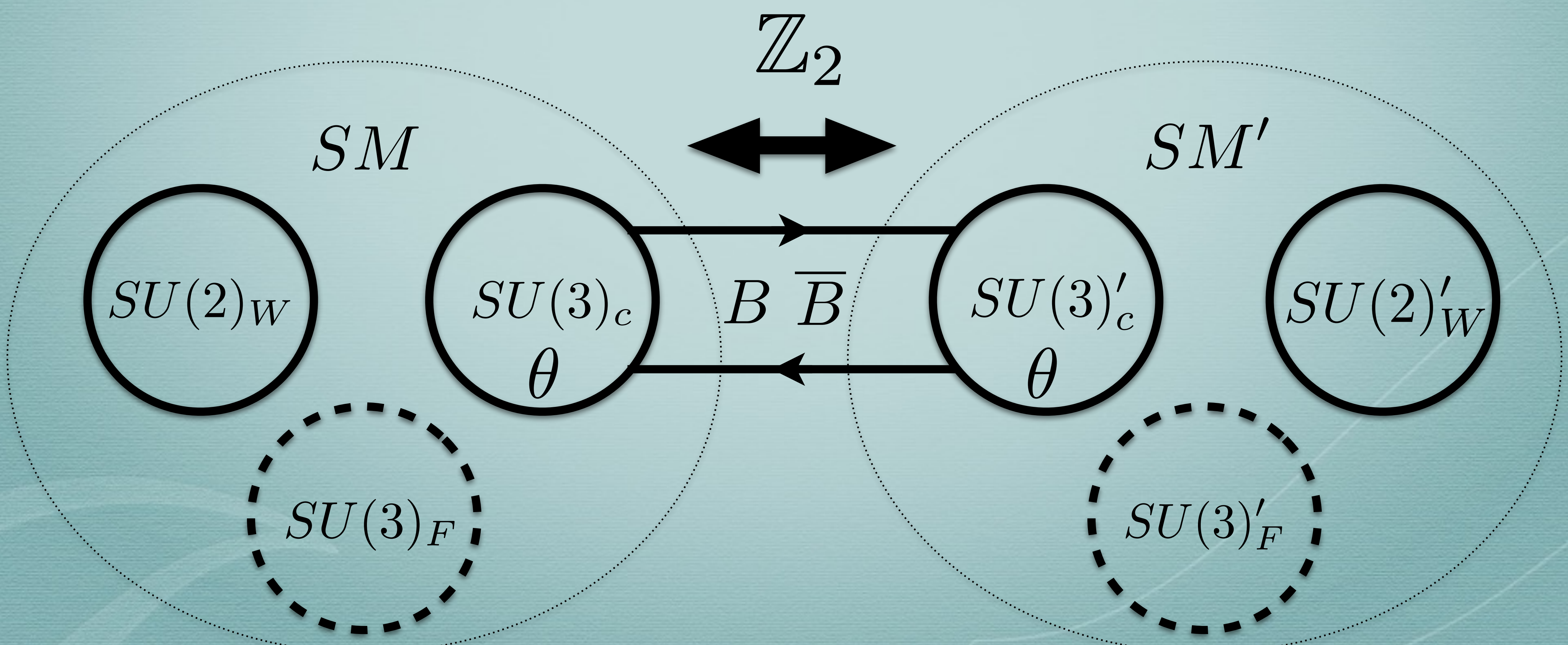
- Before confinement there is a massless quark
- There is a sector which confines
- After confinement, the vev of the η' boson removes θ from the IR



Symmetry explanation

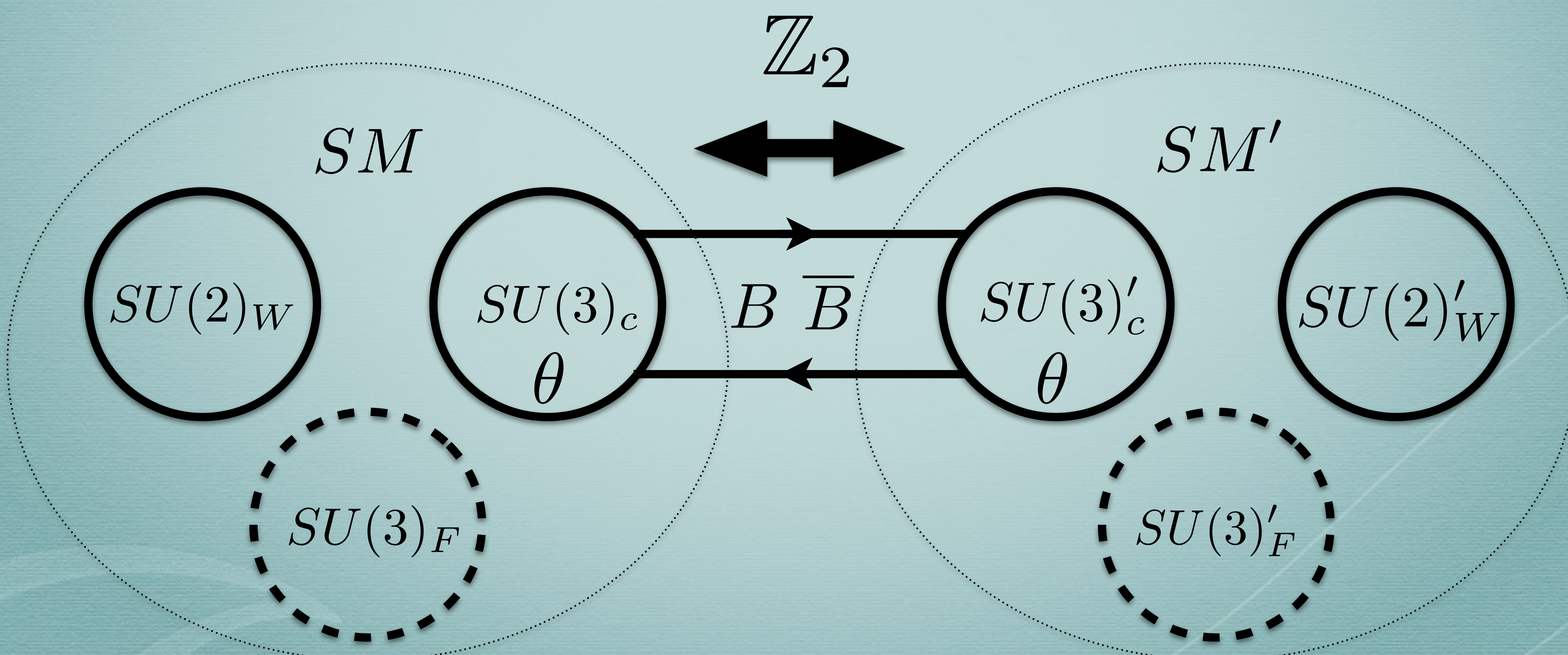
Anomalous symmetry renders sum of angles unphysical and difference physical

Discrete symmetry results in the difference being zero



Constraints

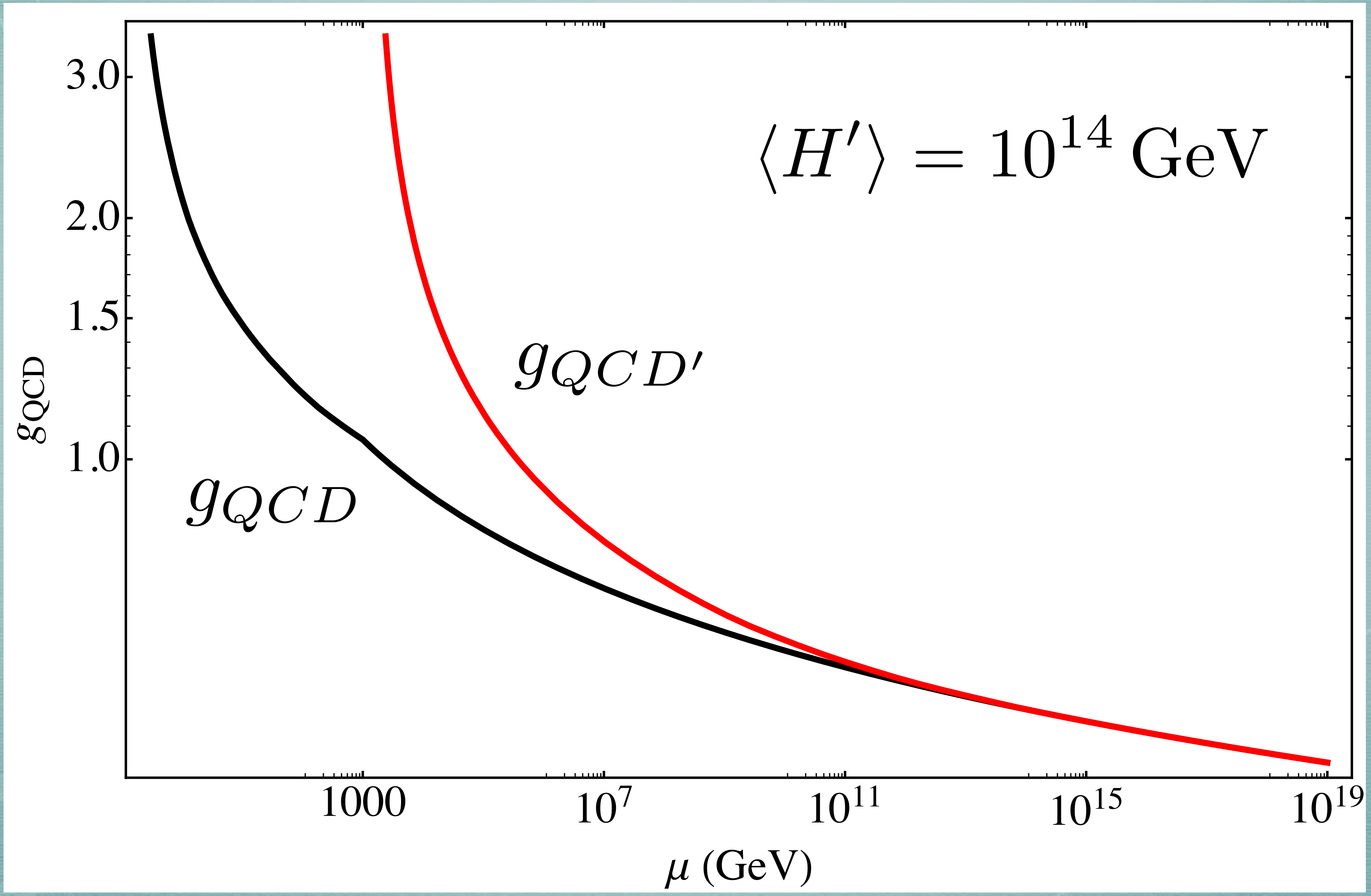
What are the constraints on this model?



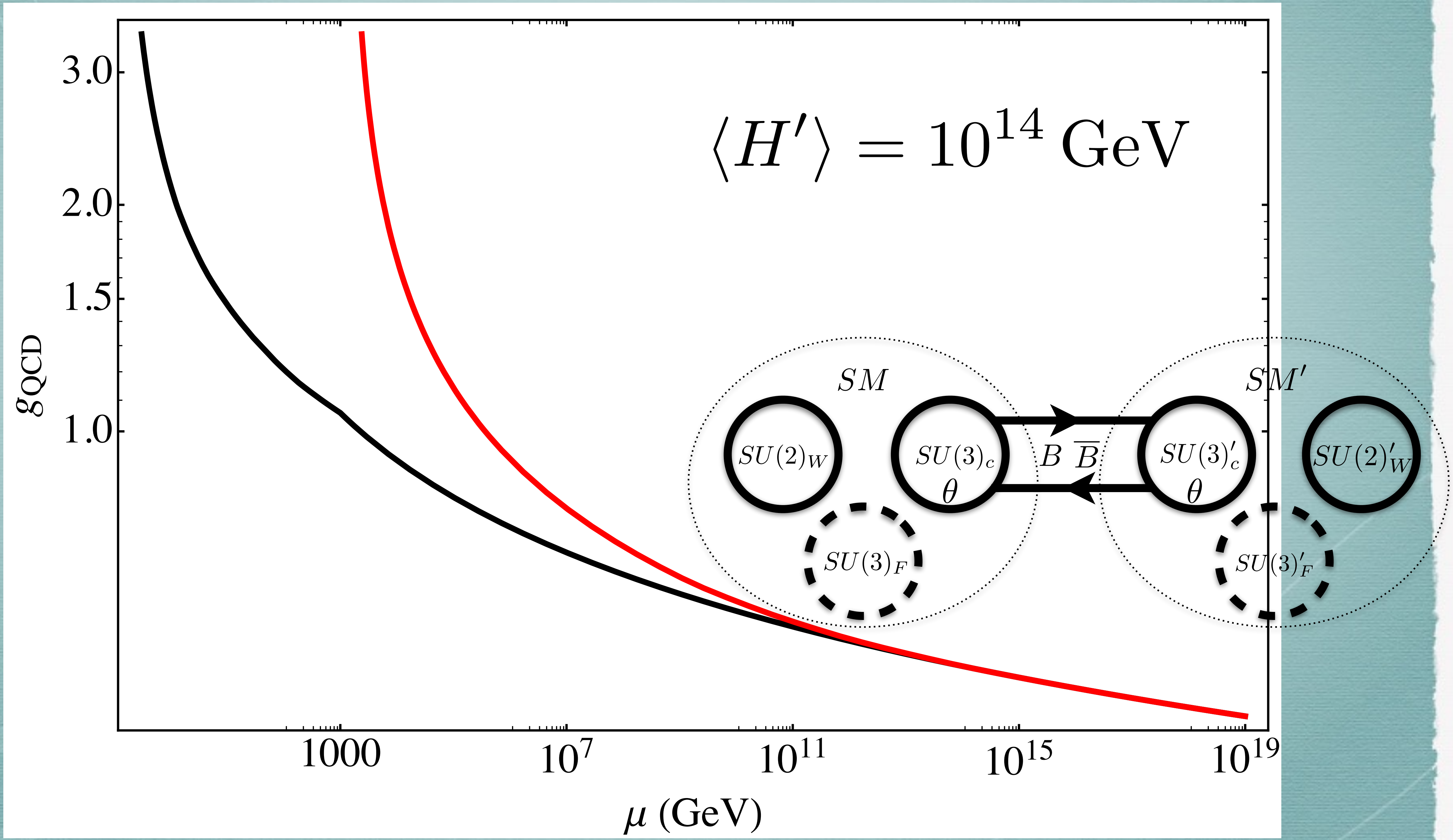
Constraints

- We do not see a mirror sector
- The mirror sector must have larger masses
- The Higgs vev in the other sector must be much larger than ours!
  - For the sake of plotting results, set it to 10^{14} GeV

RG evolution



RG evolution



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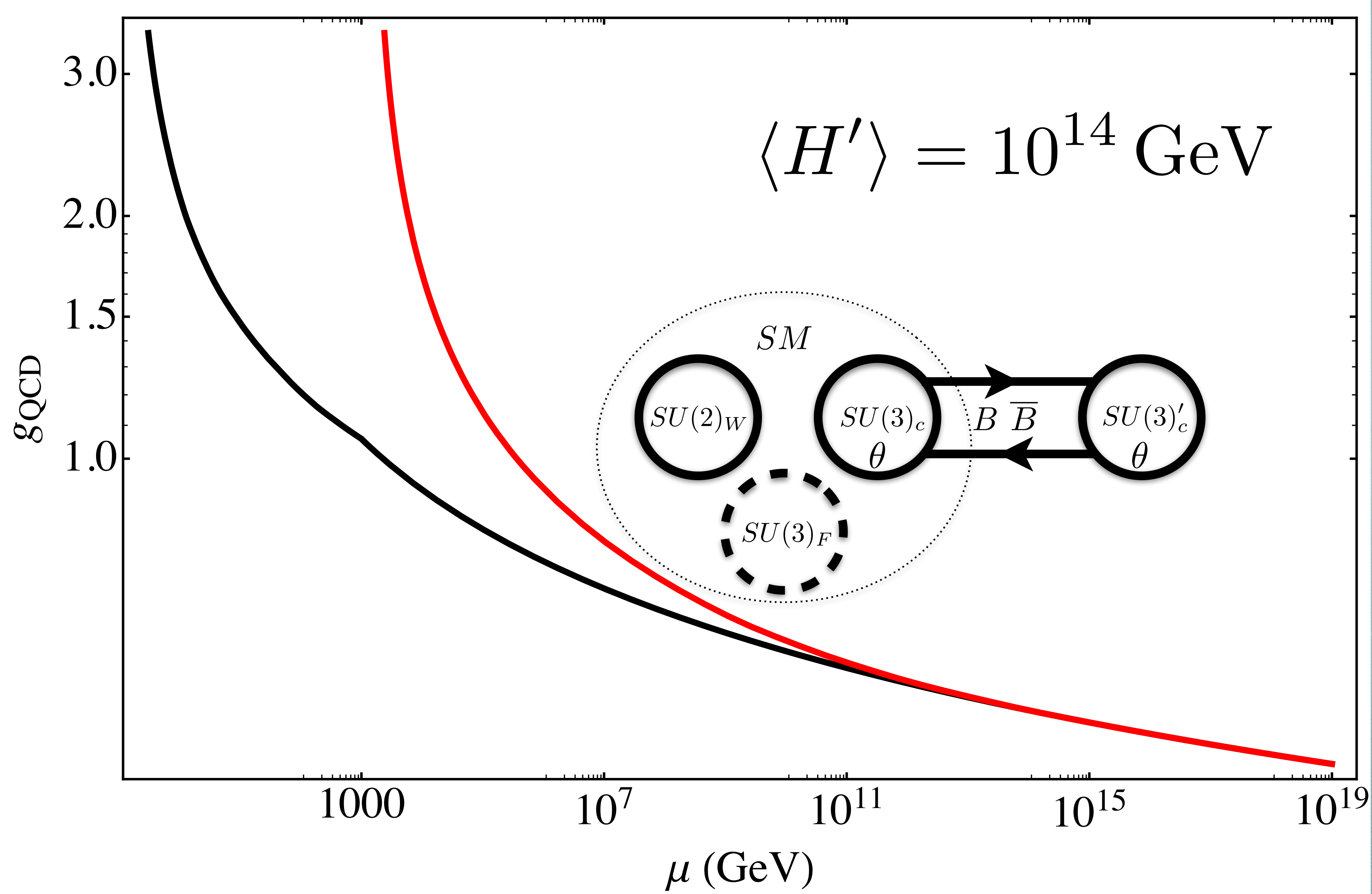

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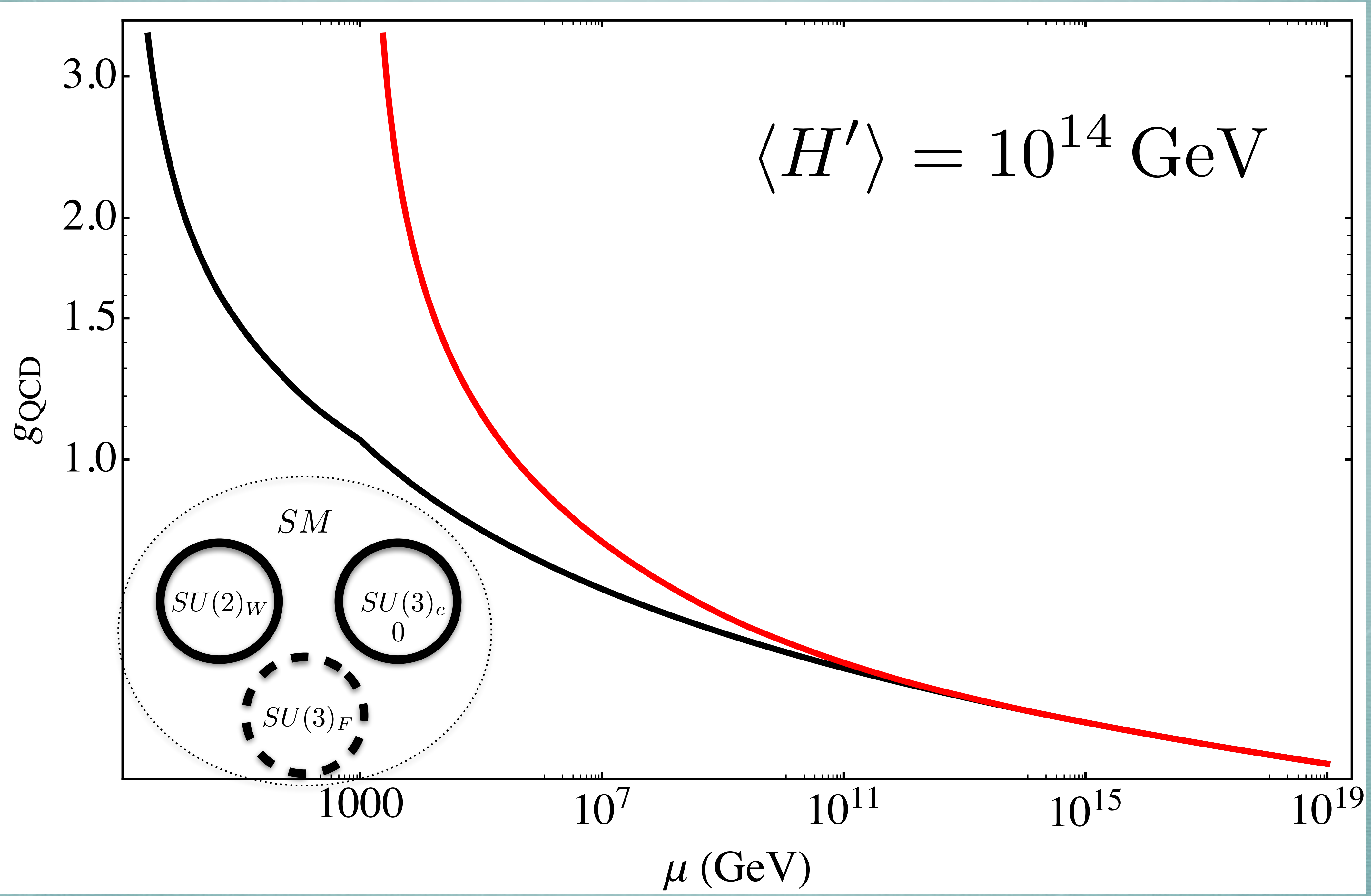


Higher dimensional operators

$$\frac{g^2}{32\pi^2}\left(\frac{HH^\dagger}{M_{pl}^2}G\tilde{G}+\frac{H'H'^\dagger}{M_{pl}^2}G'\tilde{G}'\right)$$

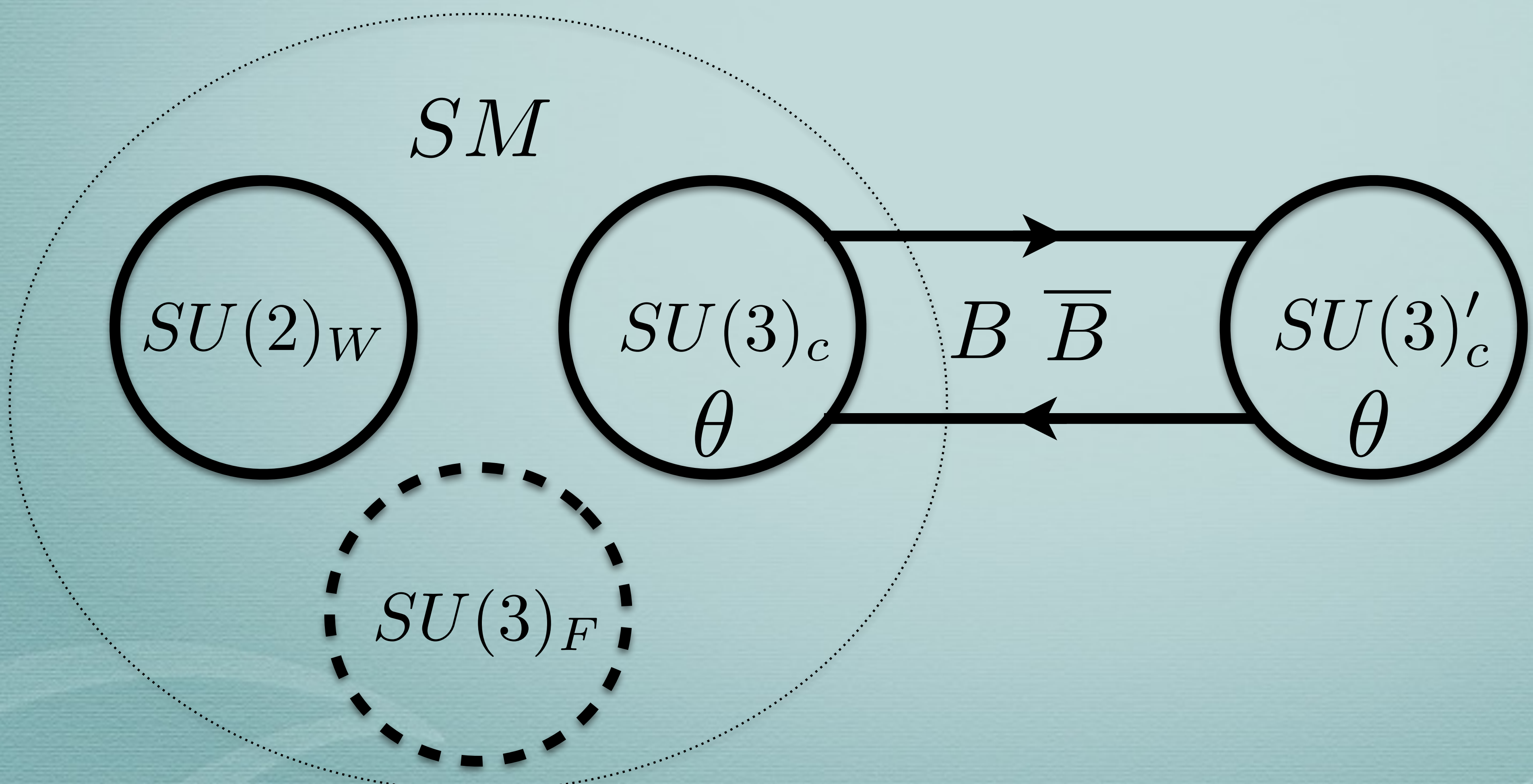
Solutions to the strong CP problem strongly constrained by higher dimensional operators

$$\bar{\theta}=\frac{H'H'^\dagger-HH^\dagger}{M_p^2}\approx\frac{\langle H'\rangle^2}{10^{38}\mathrm{GeV}^2}<10^{-10}$$

$$H'\lesssim 10^{14}\,\mathrm{GeV}$$

LHC Observables

- Observable signatures come from the pseudo-goldstone bosons

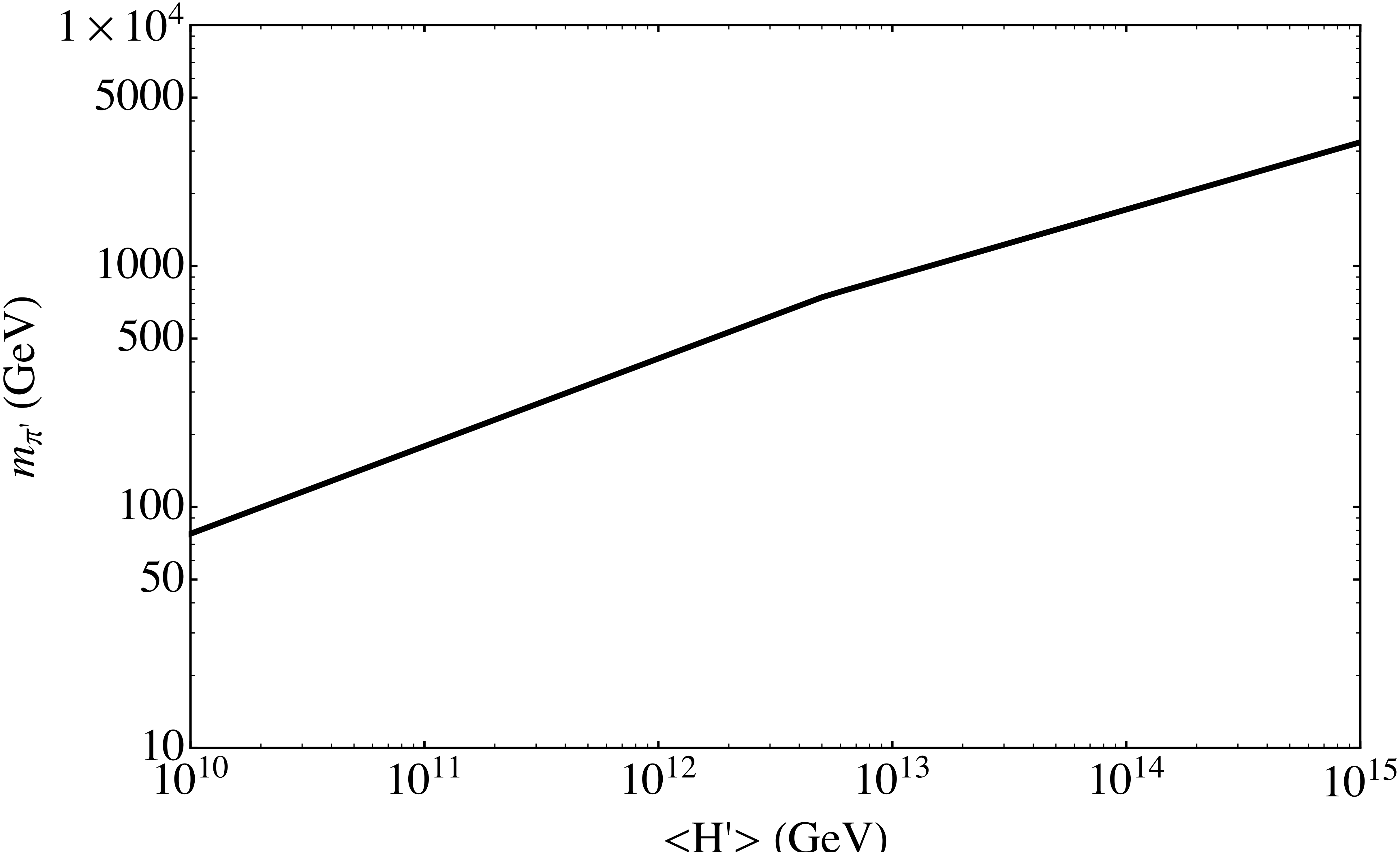


LHC Observables

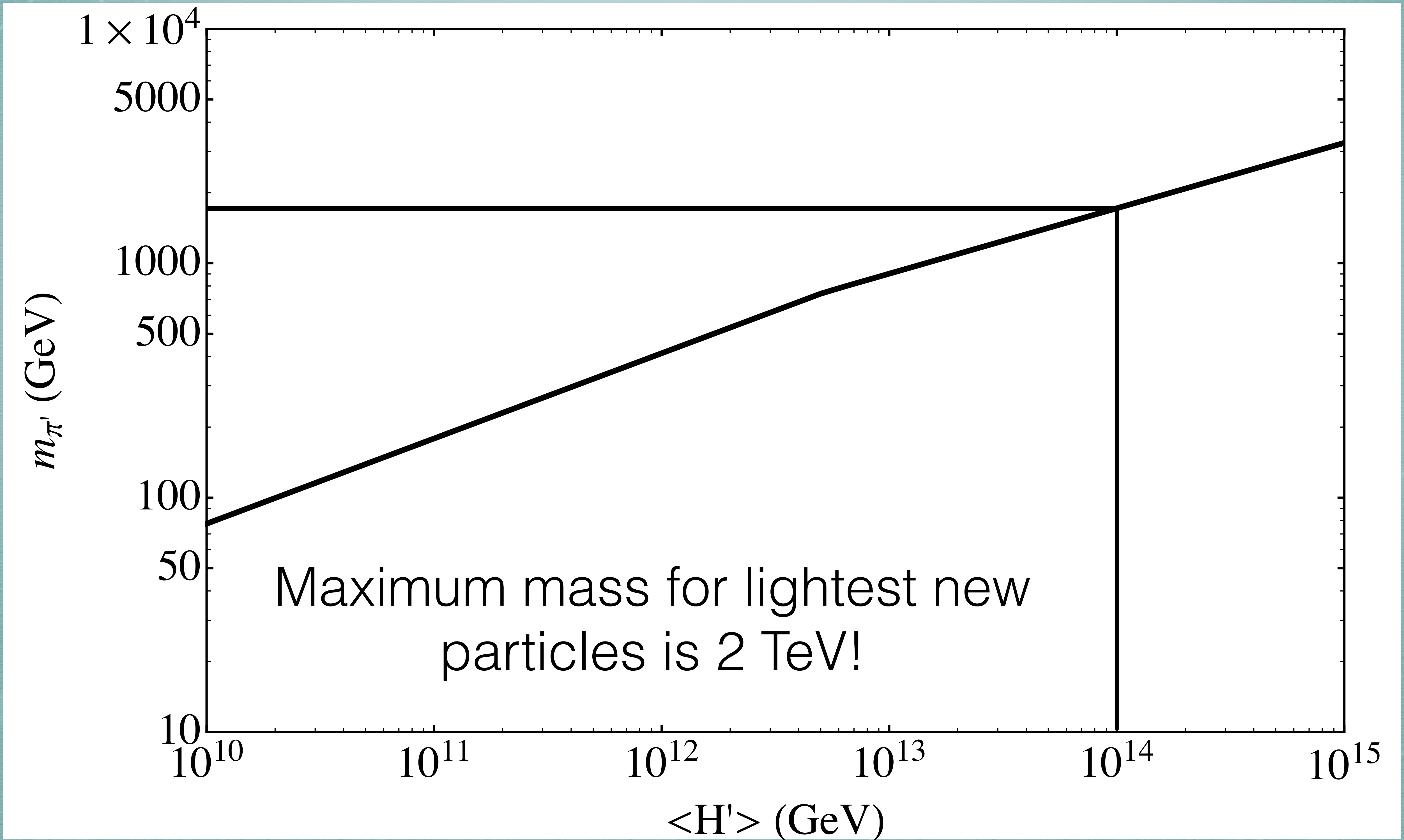
- Observable signatures come from the pseudo-goldstone bosons
    - Color octet scalars
- Obtain a 1-loop mass from gauge boson loops
- Like charged pions, quadratic divergence cut off by rho mesons

$$m_{\pi'}^2 \approx \frac{9\alpha_s}{4\pi} m_{\rho'}^2$$

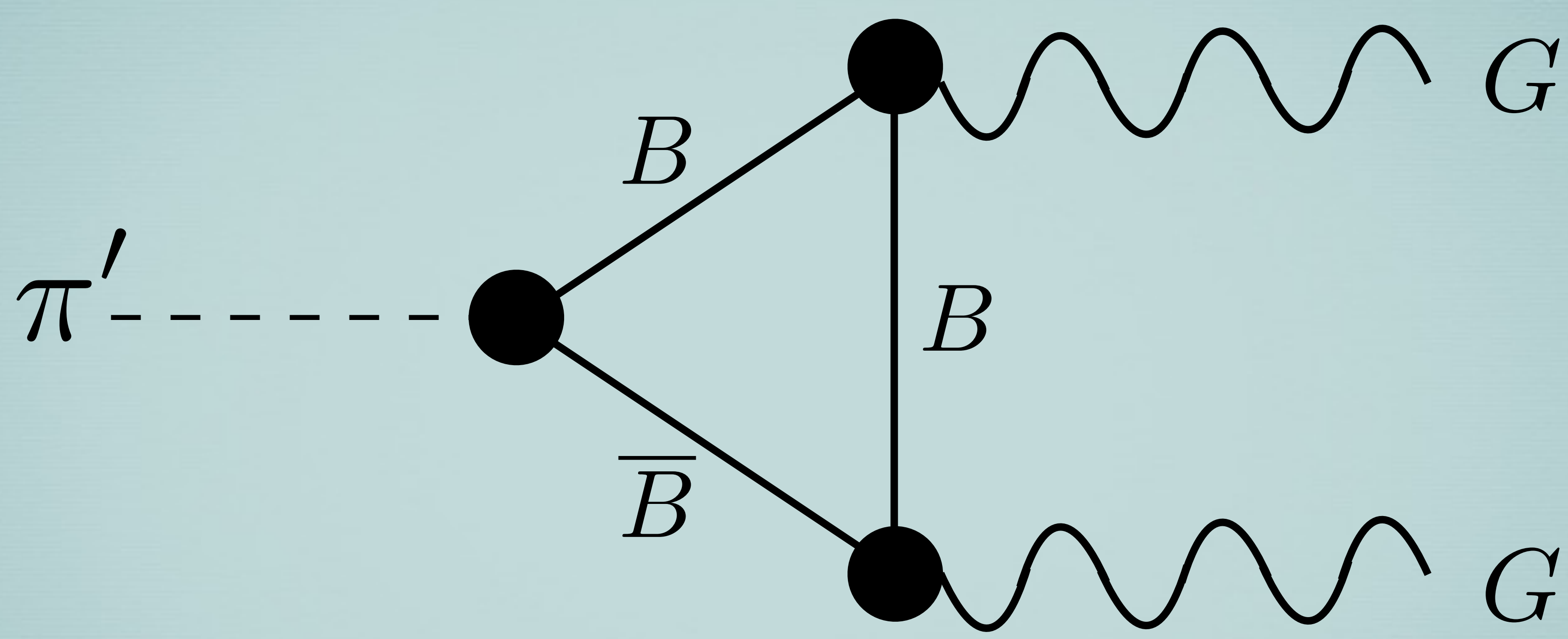
LHC Observables



LHC Observables



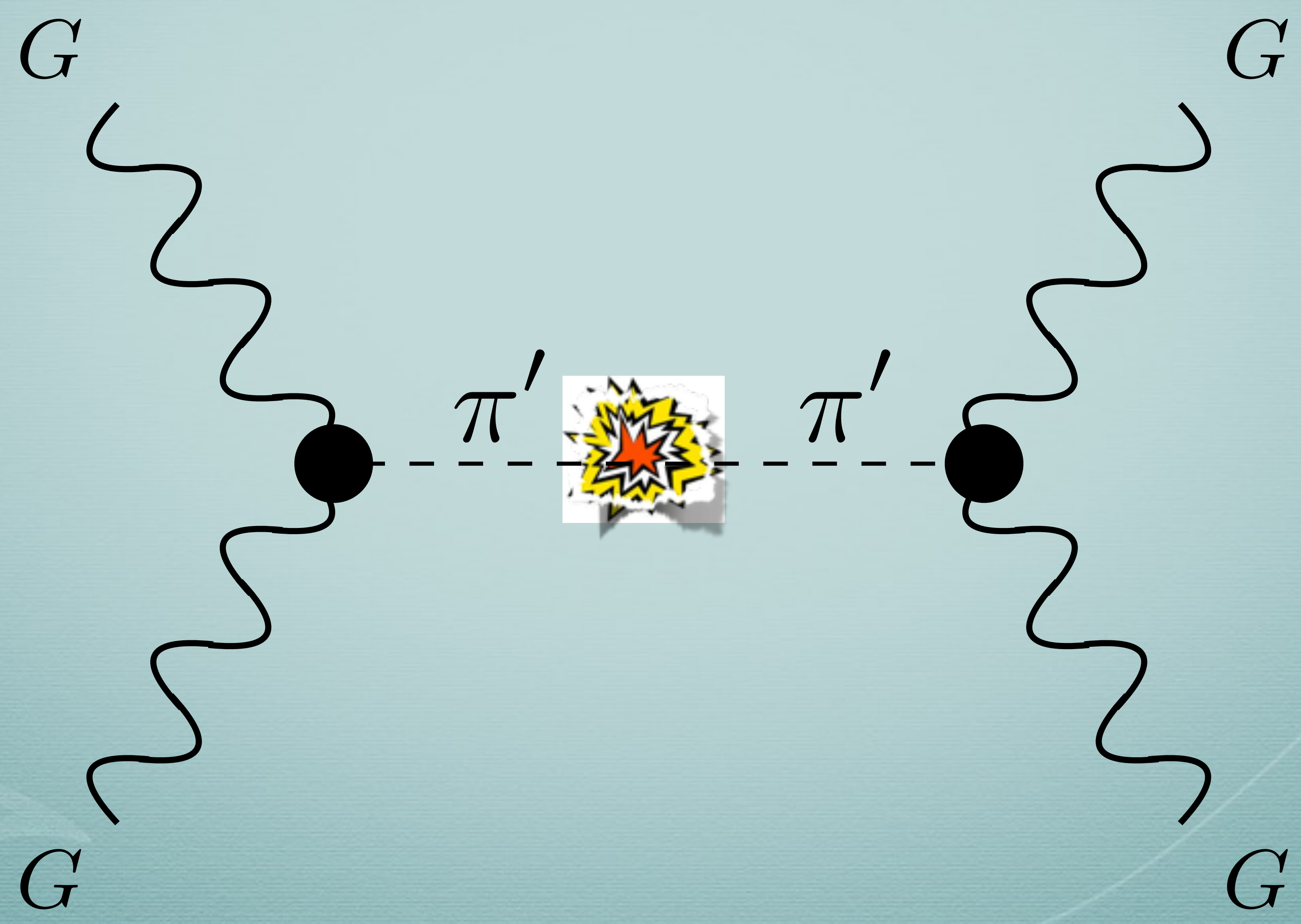
LHC Observables



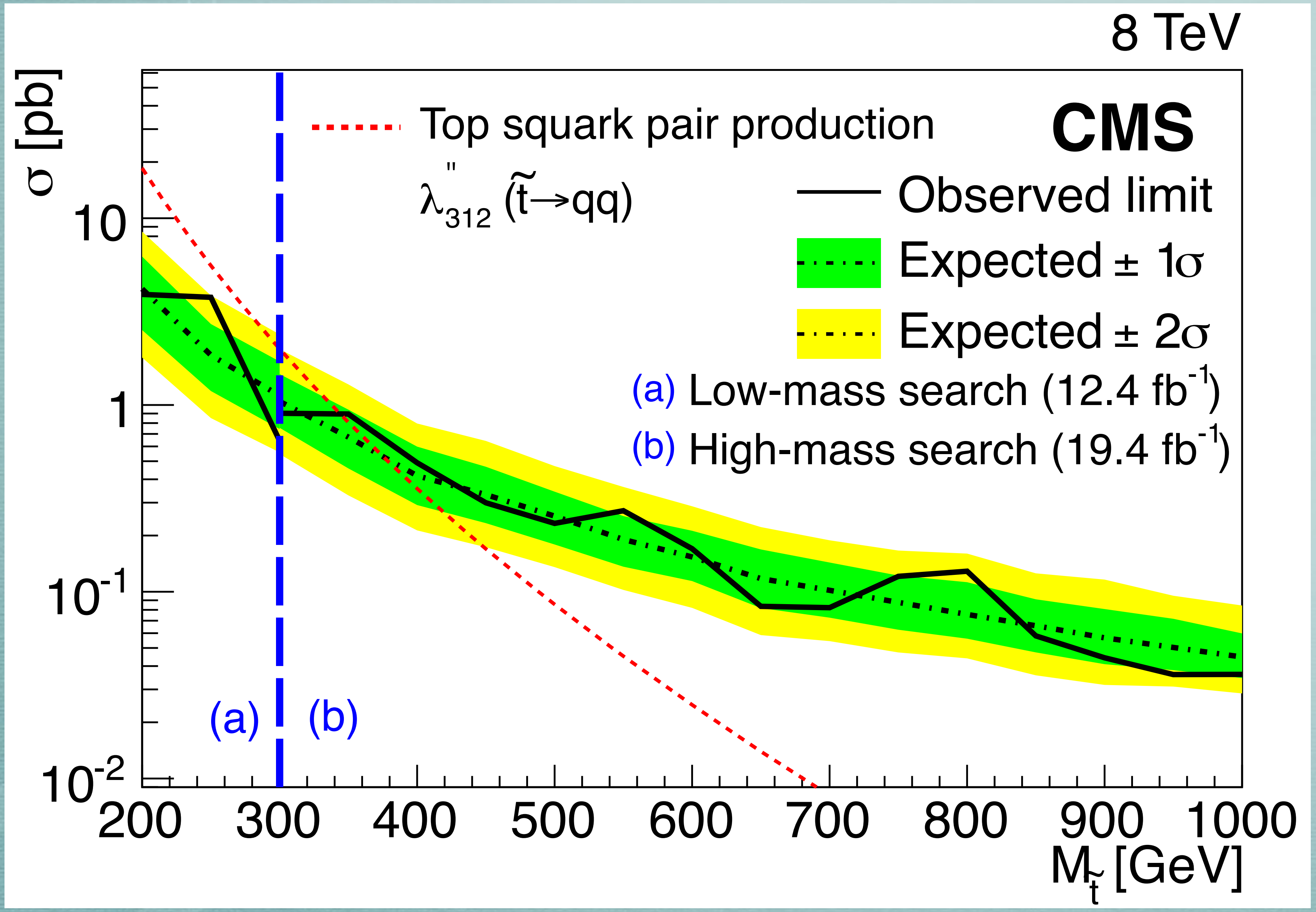
Pions decay through the anomaly into a pair of gluons

LHC signature

LHC observable signatures



LHC signature



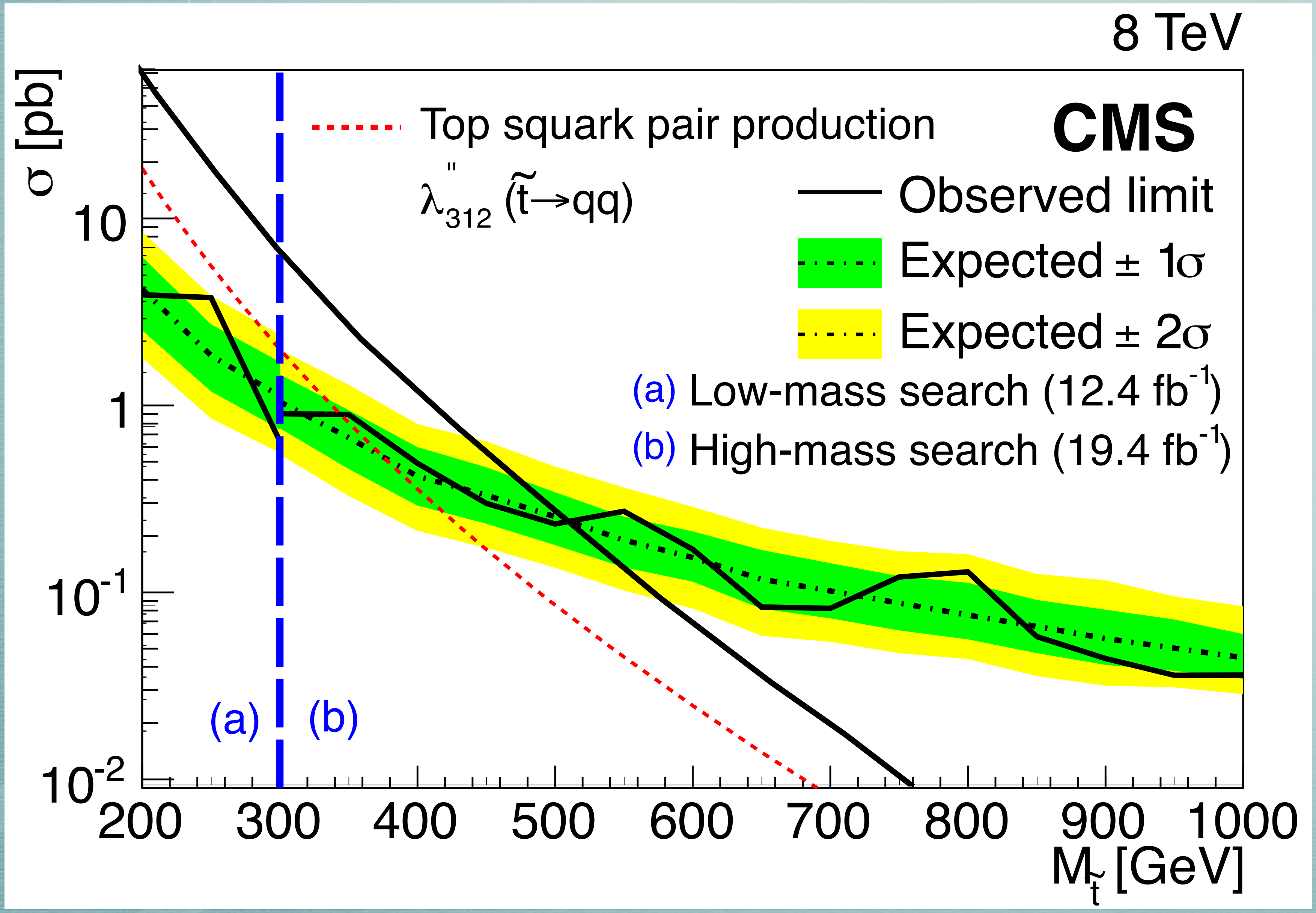
4 jet event with a pair of resonances

New CMS result :

hep-ex / 1412.7706

8 TeV, 19.4 fb^{-1}

LHC signature



4 jet event with a pair of resonances

New CMS result :

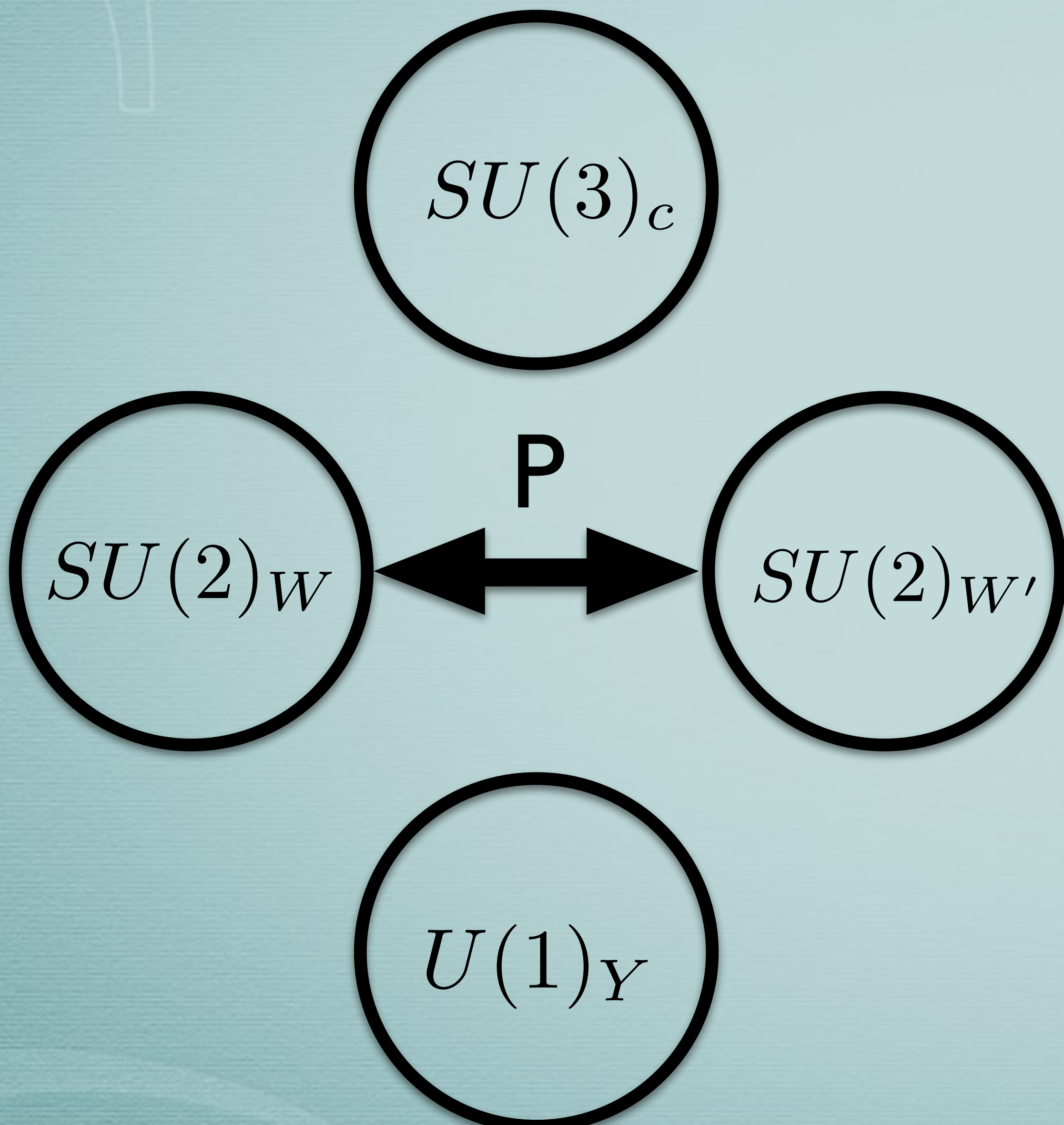
hep-ex / 1412.7706

8 TeV, 19.4 fb^{-1}

Testable strong CP

- A strong CP problem solution which is testable at the LHC!
    - An existing search places bounds
    - 4 jets with two resonances
- What about a solution which is not being looked for at the LHC?

Parity



SU(3)xU(1) goes to itself under parity so that their theta angles vanish

S. M. Barr, D. Chang, and G. Senjanovic, Phys.Rev.Lett. 67, 2765 (1991)

Parity

$$Q, u^c, d^c, H, L, e^c \overset{\textsf{P}}{\longleftrightarrow} Q', u'^c, d'^c, H', L', e'^c$$

Parity acts non-trivially on space-time indices

$$L_\alpha \overset{\textsf{P}}{\longleftrightarrow} L'^\dagger_{\dot\alpha}$$

Parity

$$Y_u H Q u^c \Rightarrow Y_u H'^{\dagger} Q'^{\dagger} u'^{c,\dagger}$$

$$Y_u' = Y_u^\star$$

CKM phase and arg det Y is non-zero

Parity

$$\text{arg}\det Y_u = -\text{arg}\det Y'_u$$

$$\overline{\theta} = \theta + \text{arg}\det Y_u + \text{arg}\det Y'_u = 0$$

Invariant theta angle vanishes!

Breaking of parity

$$\Phi \overset{P}{\longleftrightarrow} -\Phi$$

$$\langle \Phi \rangle \neq 0$$

- No mirror quarks observed
- Mirror quarks are heavy
- Mirror Higgs vev is large

Higher dimensional operators

$$\frac{g^2}{32\pi^2}\frac{\Phi}{M_p}G_{\mu\nu}\tilde{G}^{\mu\nu}$$

$$\frac{\Phi}{M_p} < 10^{-10}$$

Testability comes from Higher dimensional operators

LHC signatures

$$10^9\,\mathrm{GeV} > \Phi \sim H'$$

$$m_{u'} = y_u H' < 10\,\mathrm{TeV}$$

- New colored particles observable at the LHC!
- New colored particles with mass ratios equal to the Standard Model mass ratios

LHC signatures

$$\mathcal{L} \supset m u^c u'^c + h.c.$$

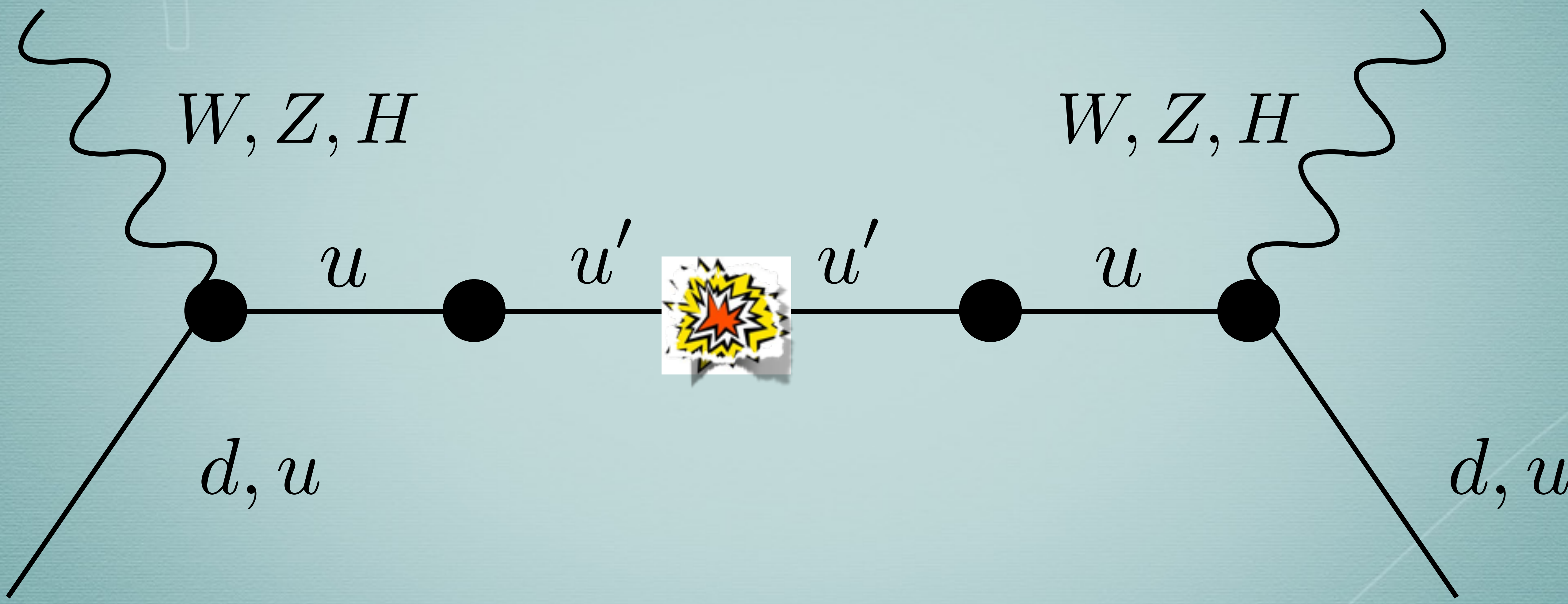
- Mixing allowed by symmetries
  - Technically natural to keep them small
  - If matrix is random, need to be smaller than 100 GeV from FCNC bounds
  - Could be like Yukawas and be almost diagonal

LHC signatures

$$\mathcal{L} \supset m u^c u'^c + h.c.$$

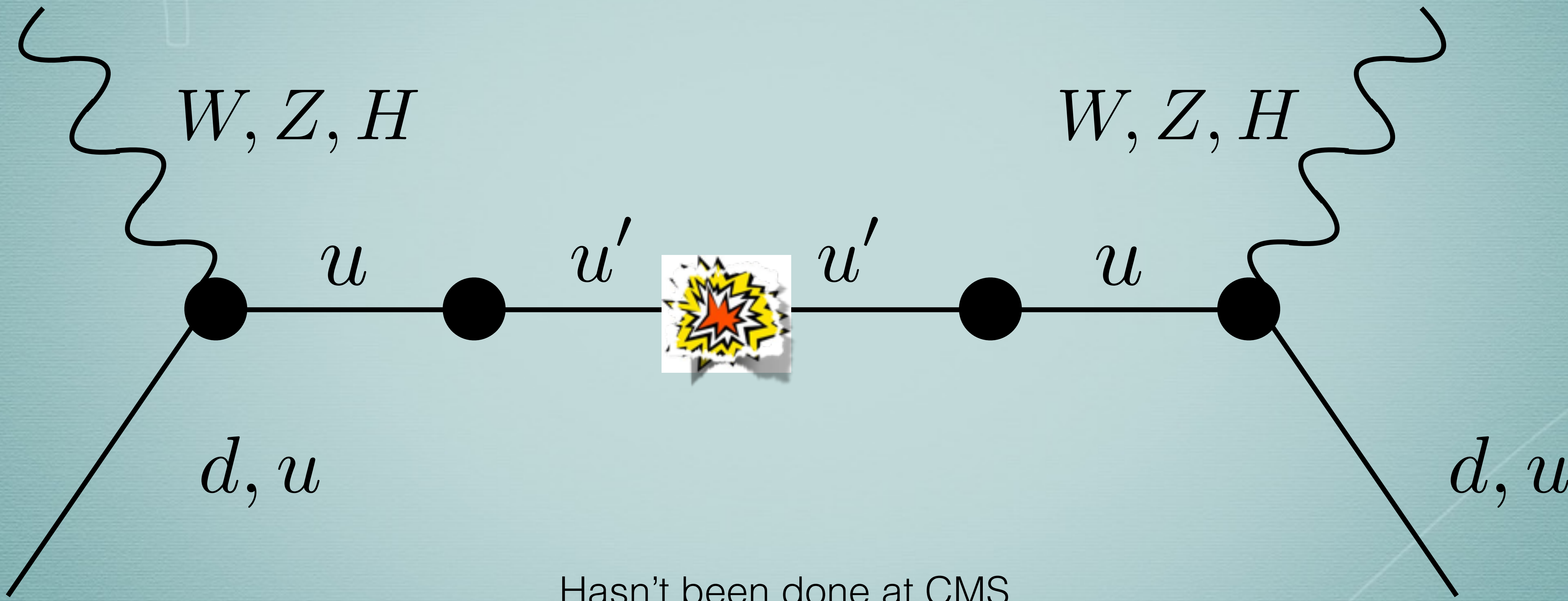
- m = 0
  - R Hadron type searches
- m is flavor anarchic
  - Mixing in right handed quarks : decays through yukawa interactions
  - Preferentially decay into 3rd generation : Standard T' searches

LHC signatures



Decay of fourth generation quarks which is exactly opposite the current intuition!

LHC signatures

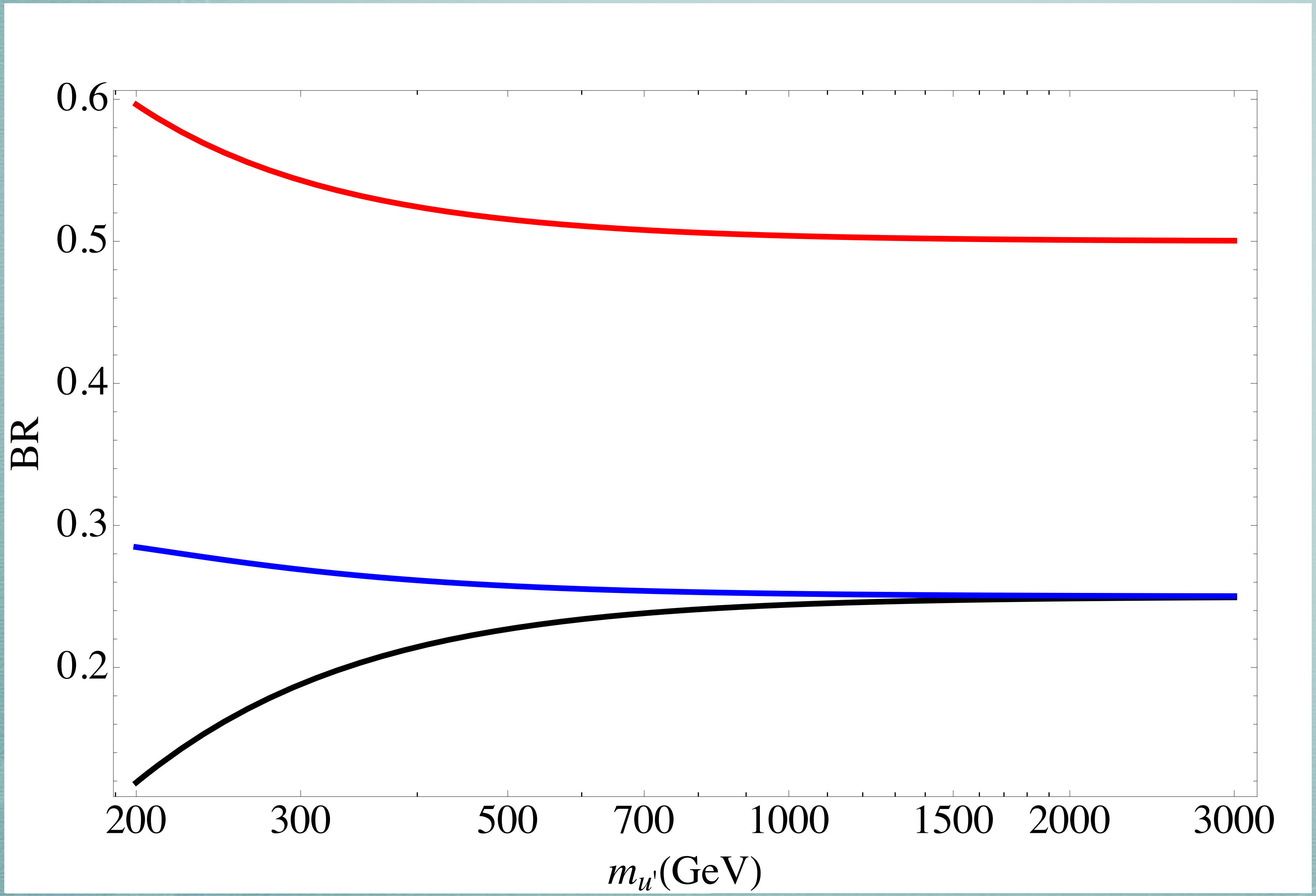


Hasn't been done at CMS

ATLAS-CONF-2011-022, 7 TeV 37 pb^{-1}

Bounds of 270 GeV - new decay involving Z,H isn't being searched for

LHC signatures



Red : W q

Blue : Z q

Black : H q

Conclusion

- Solutions to the Strong CP problem are testable at the LHC
    - Two solutions each reaching TeV scale by different mechanisms
- Generalized massless up quark solution
    - 2 TeV color octets - 4 jet search with 2 resonances
- Parity based solution
    - Fourth generation quarks that preferentially decay into first generation quarks - 2 weak gauge bosons or Higgs, plus 2 jets with 2 resonances