Strong CP motivations for TeV scale physics

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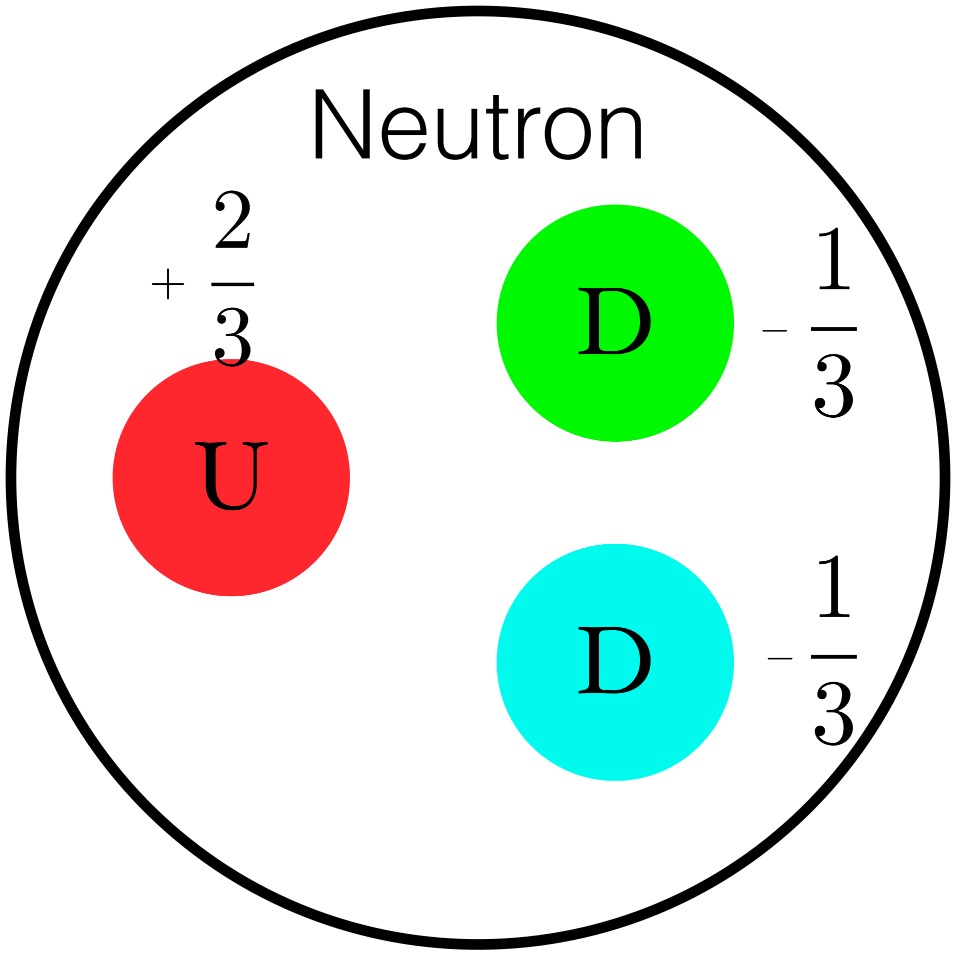
Anson Hook - hep-ph/1411.3325

Outline

- The Strong CP problem
- Previous solutions
- A new solution with colored TeV particles

Classical Strong CP problem

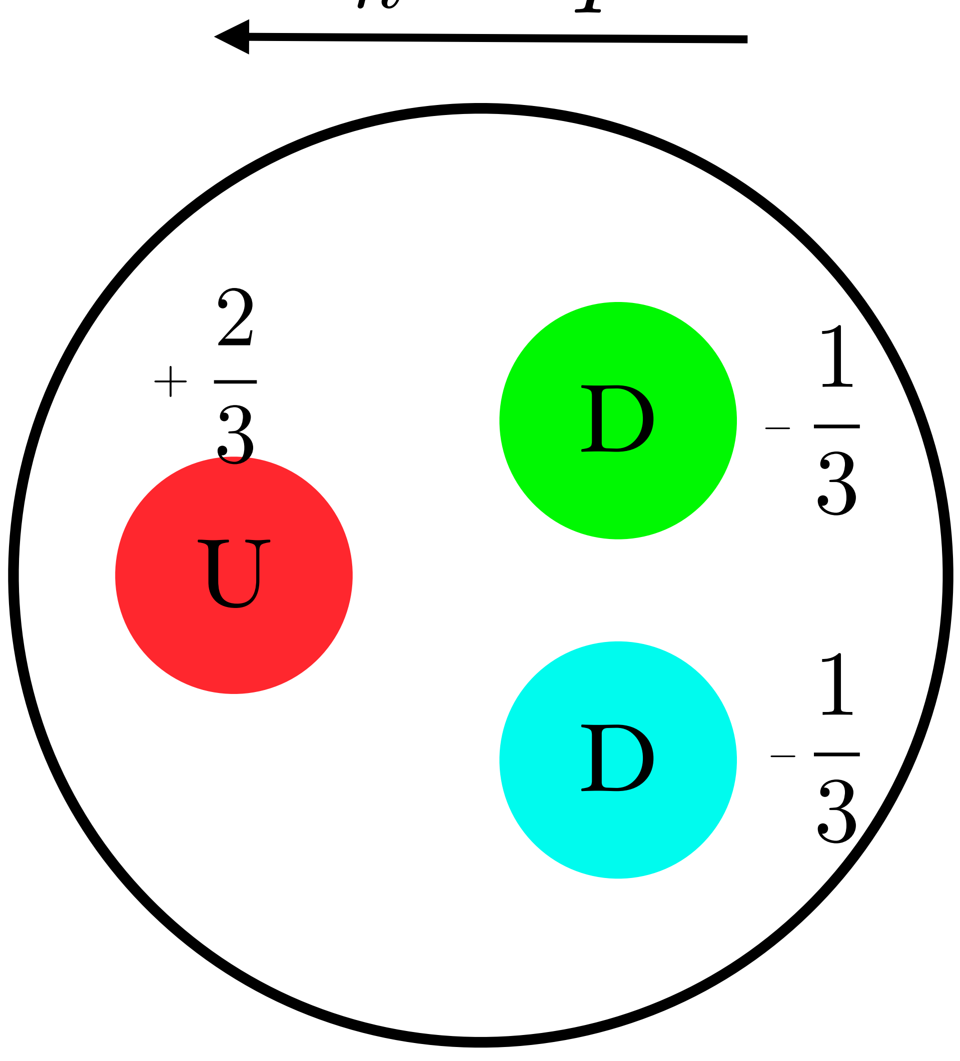
Neutron contains an up quark and two down quarks



Classical Strong CP problem

Electric Dipole moment

$$d_n = qx$$



Expected Dipole moment

- Dimensional analysis suggests

$$d_n \sim 10^{-14} e\,\mathrm{cm}$$

- Observed bound is

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

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

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

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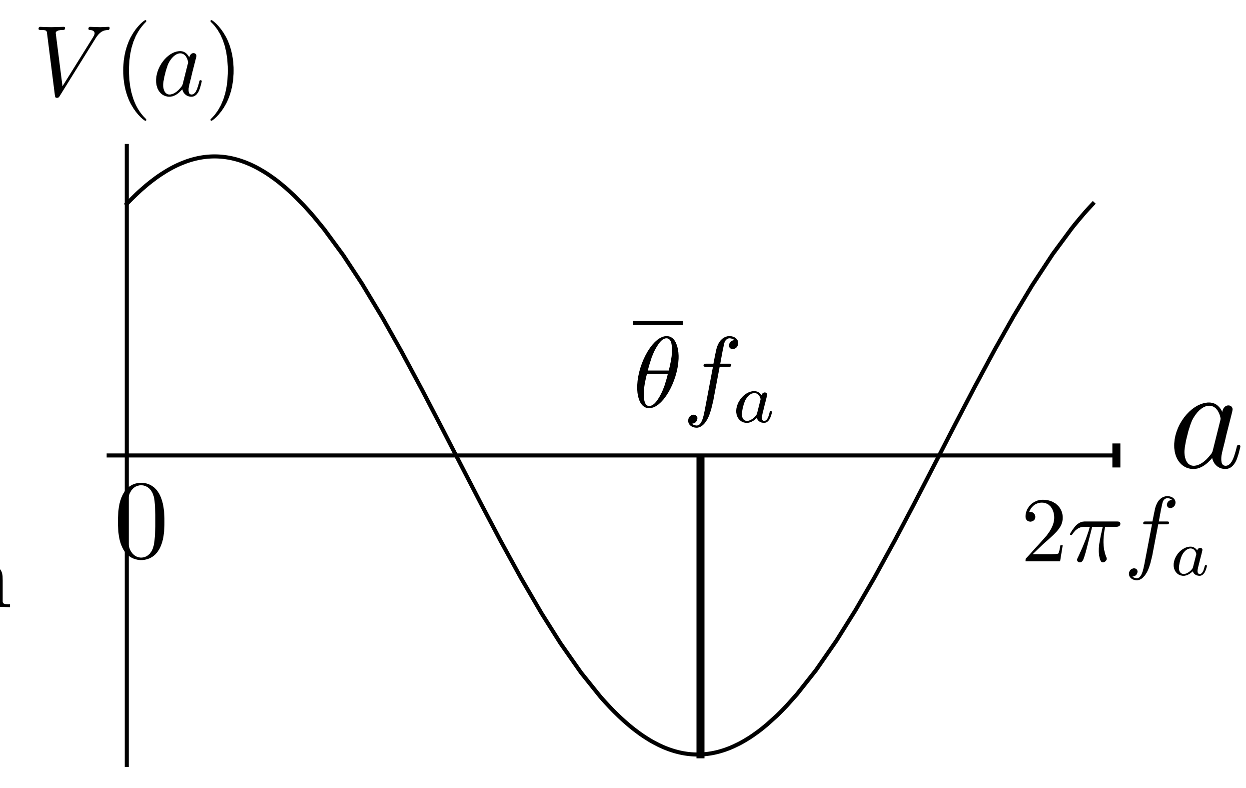
Axion solution

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

Axion dynamically sets the neutron EDM to 0

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



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)

Massless up quark

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

No invariant to construct EDM out of

Must vanish

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

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

Massless up quark solution

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

- In the IR

$$\langle U \overline{U} \rangle \neq 0$$

- Anomalous symmetry is spontaneously broken
    - Looks like axion solution

Massless up quark

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

- η’ boson obtains a vev which removes θ from the IR
  - η’ acts as the axion

Status of the massless up quark

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

Massless up quark solution ruled out

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Generalized massless up quark solution

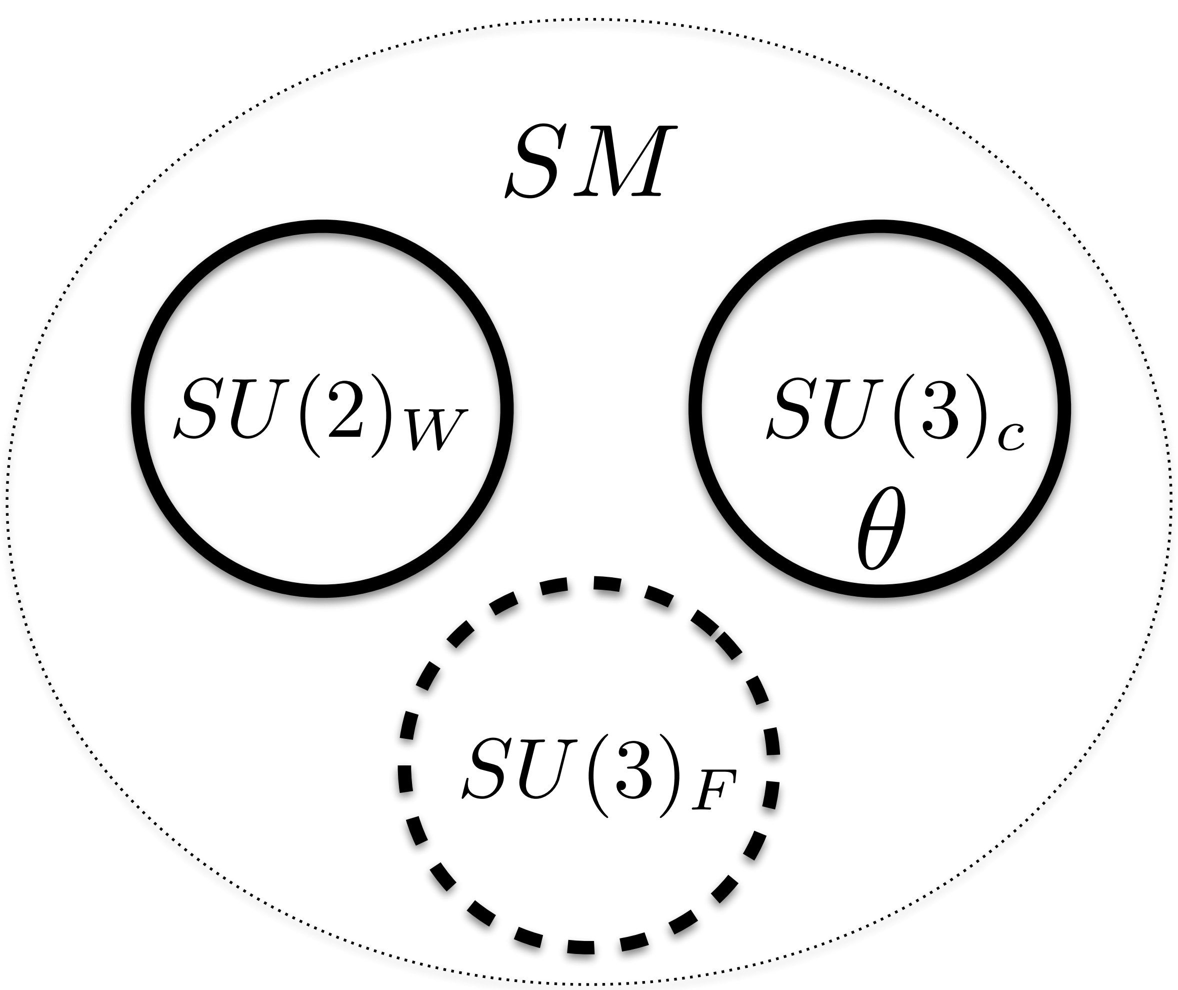
- 40 years since it was invented
  - Why throw away a good idea?
- Simplest generalization of the massless up quark solution

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

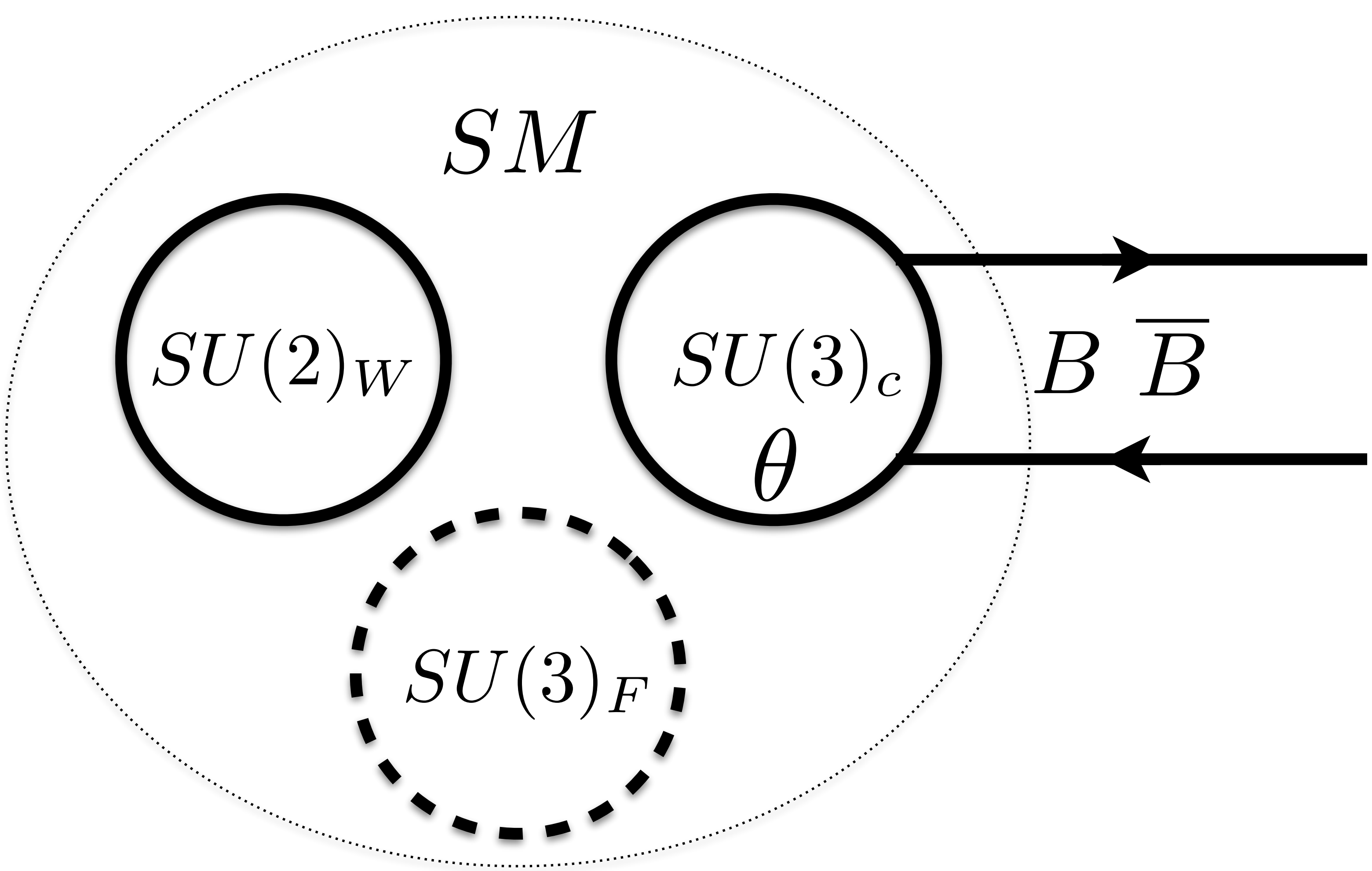
- Before confinement there is a massless quark
- There is a sector which confines
- After confinement, the vev of the η' boson removes θ from the IR



New massless quark solution

Add new massless quarks

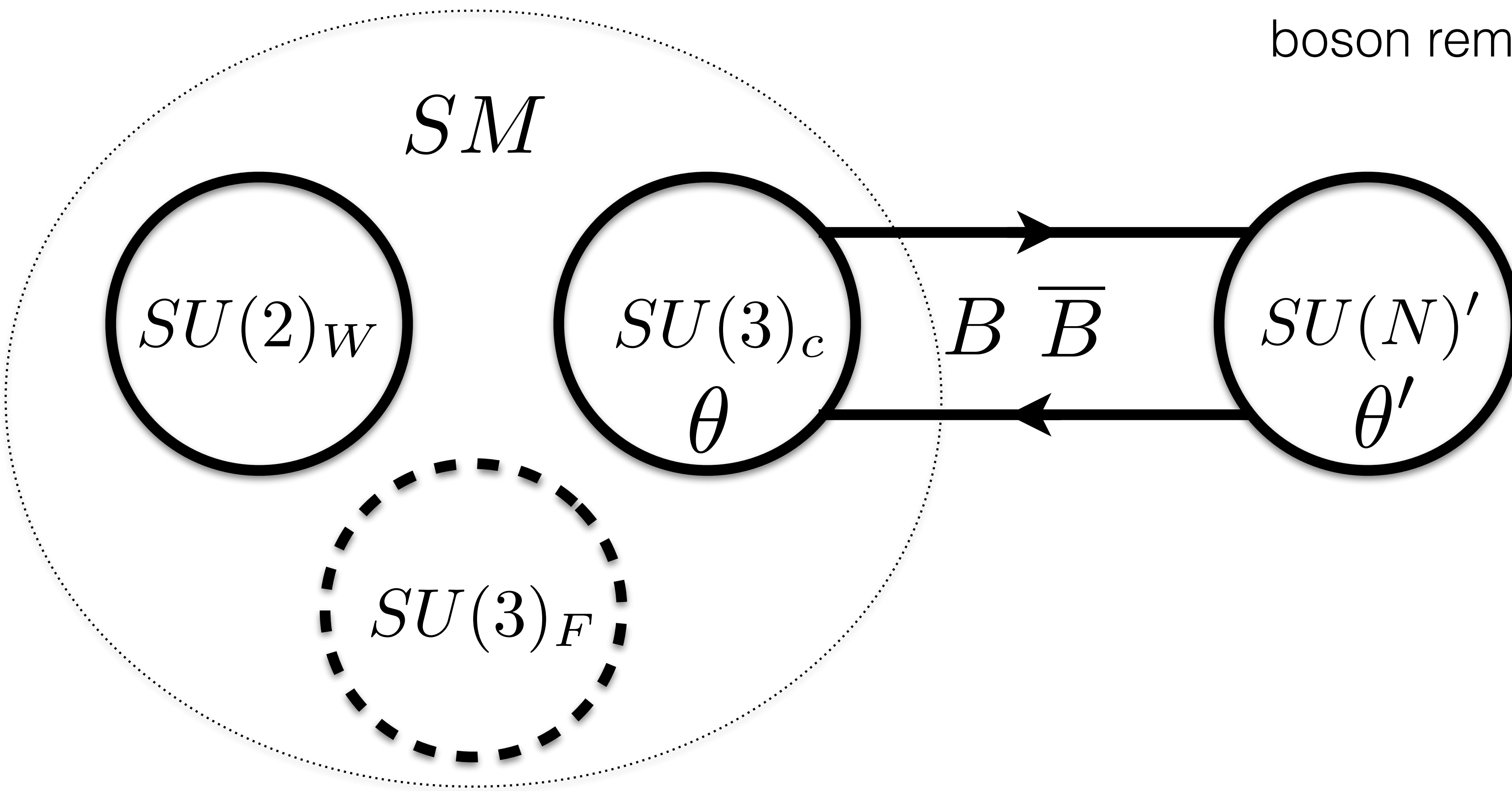
- ✔ Before confinement there is a massless quark
- There is a sector which confines
- After confinement, the vev of the η' boson removes θ from the IR



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

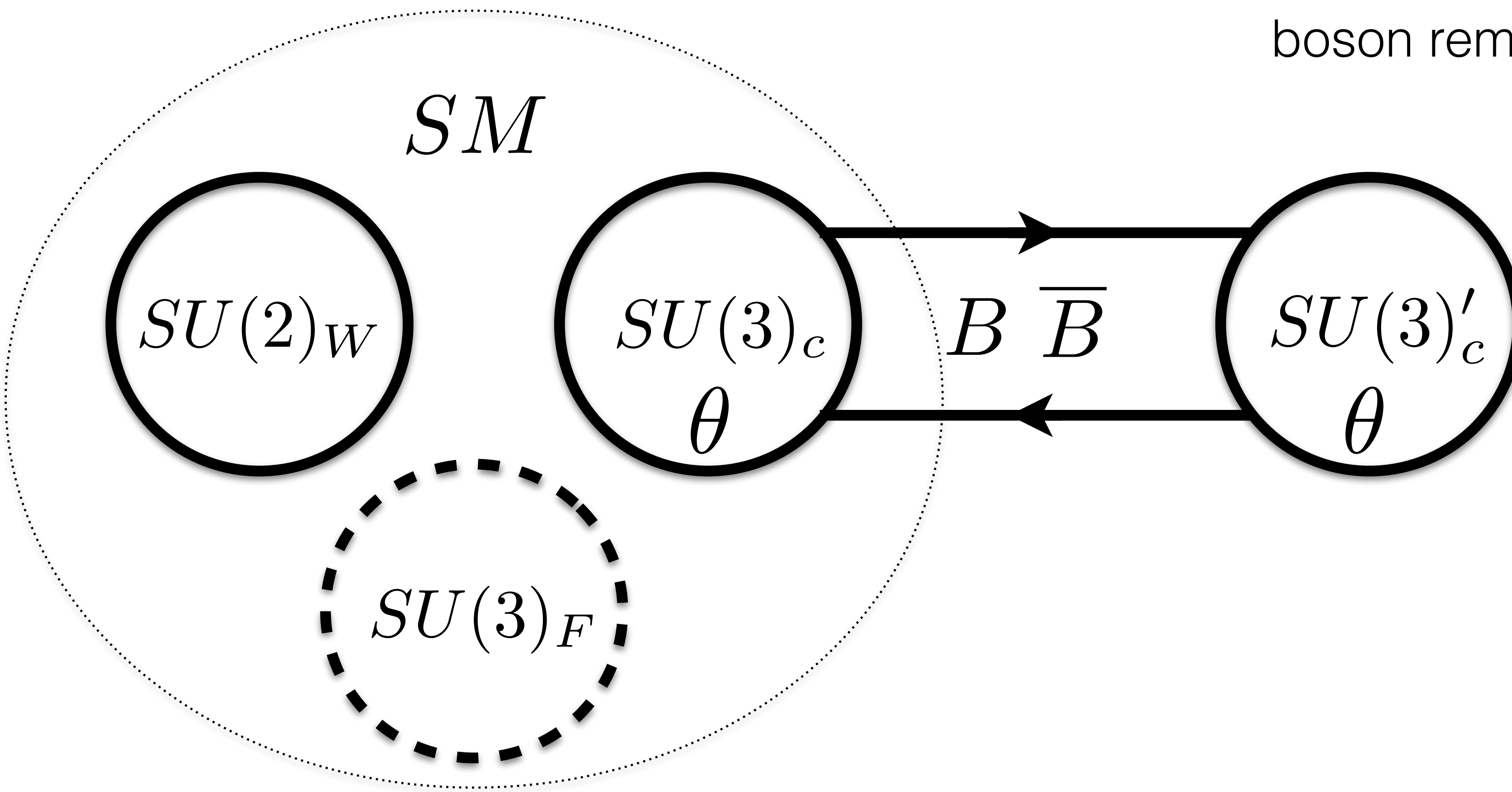
$$\theta' = \frac{3}{N}(\theta + \arg\, \det Y_u Y_d)$$

- 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

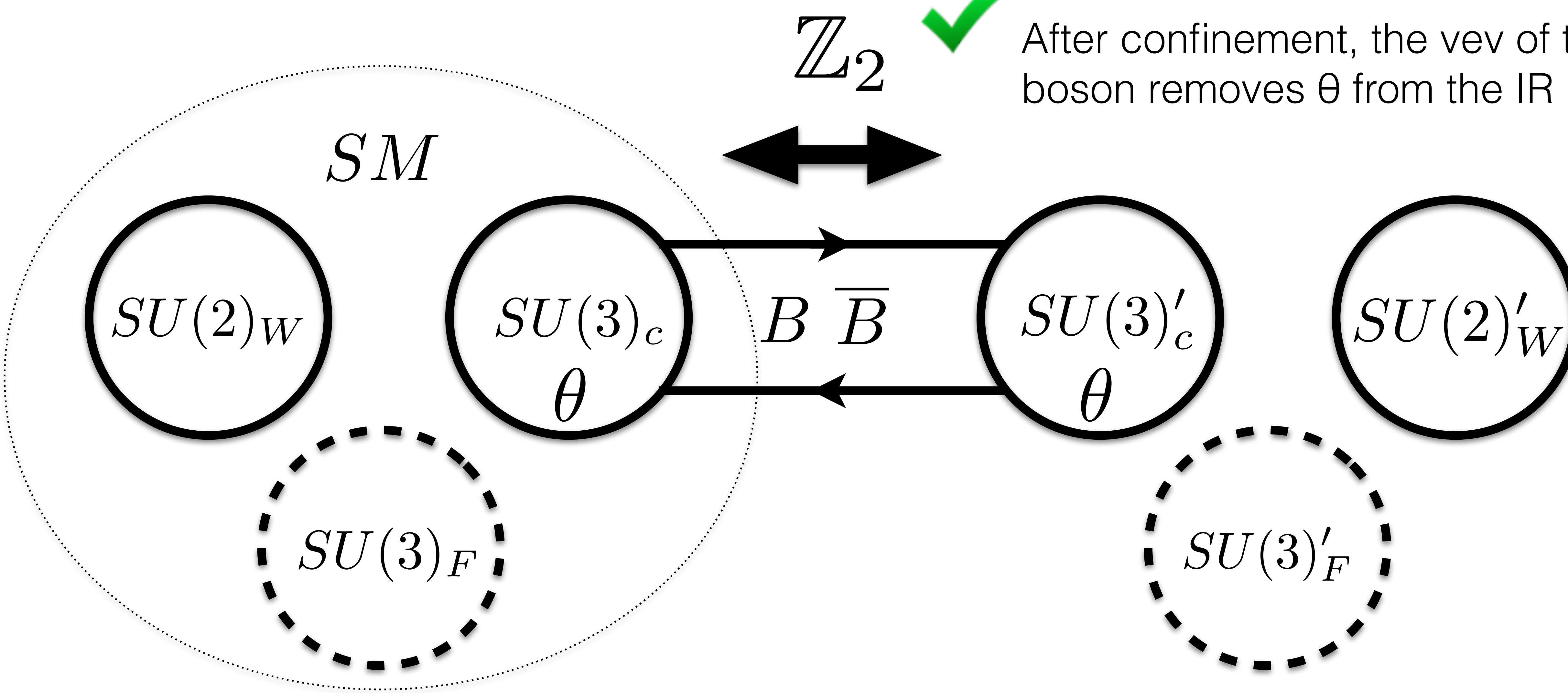


Copying QCD

- 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)

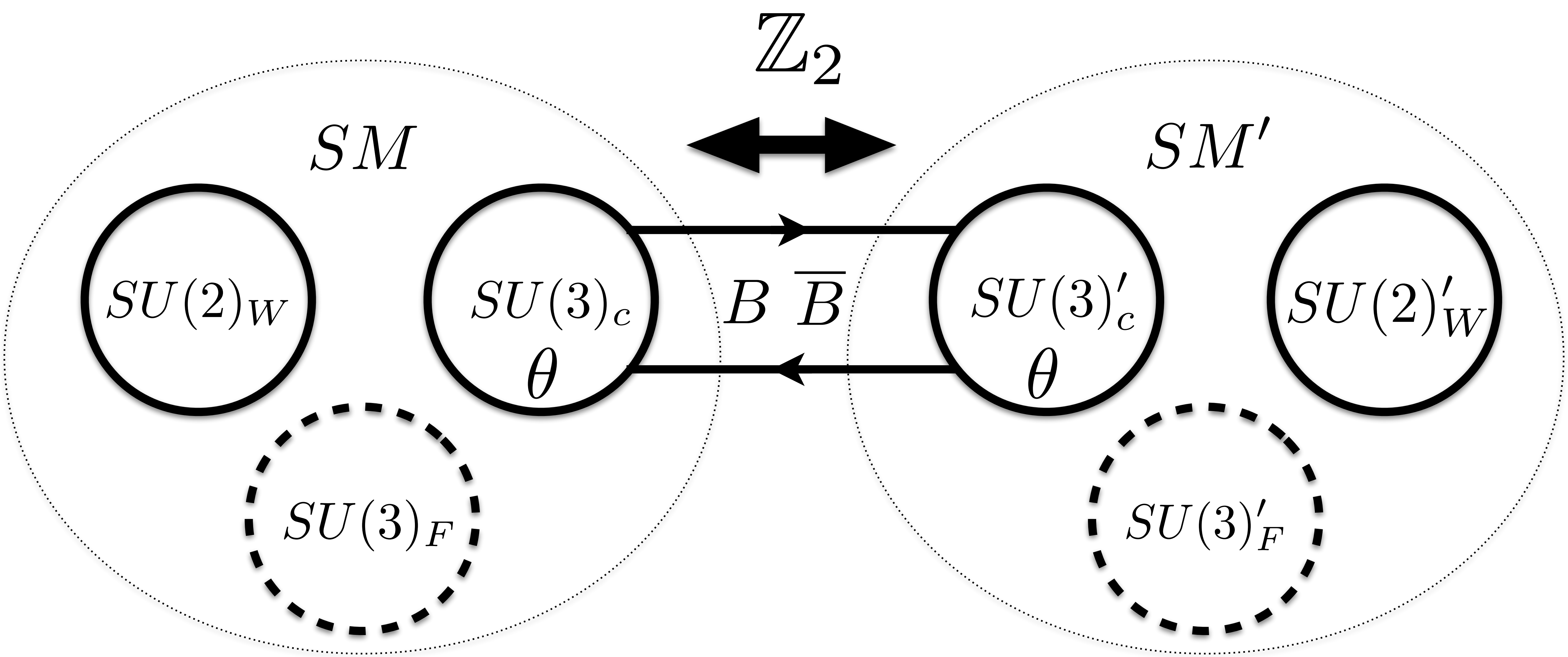
New massless quark solution

- ✓ 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



Constraints

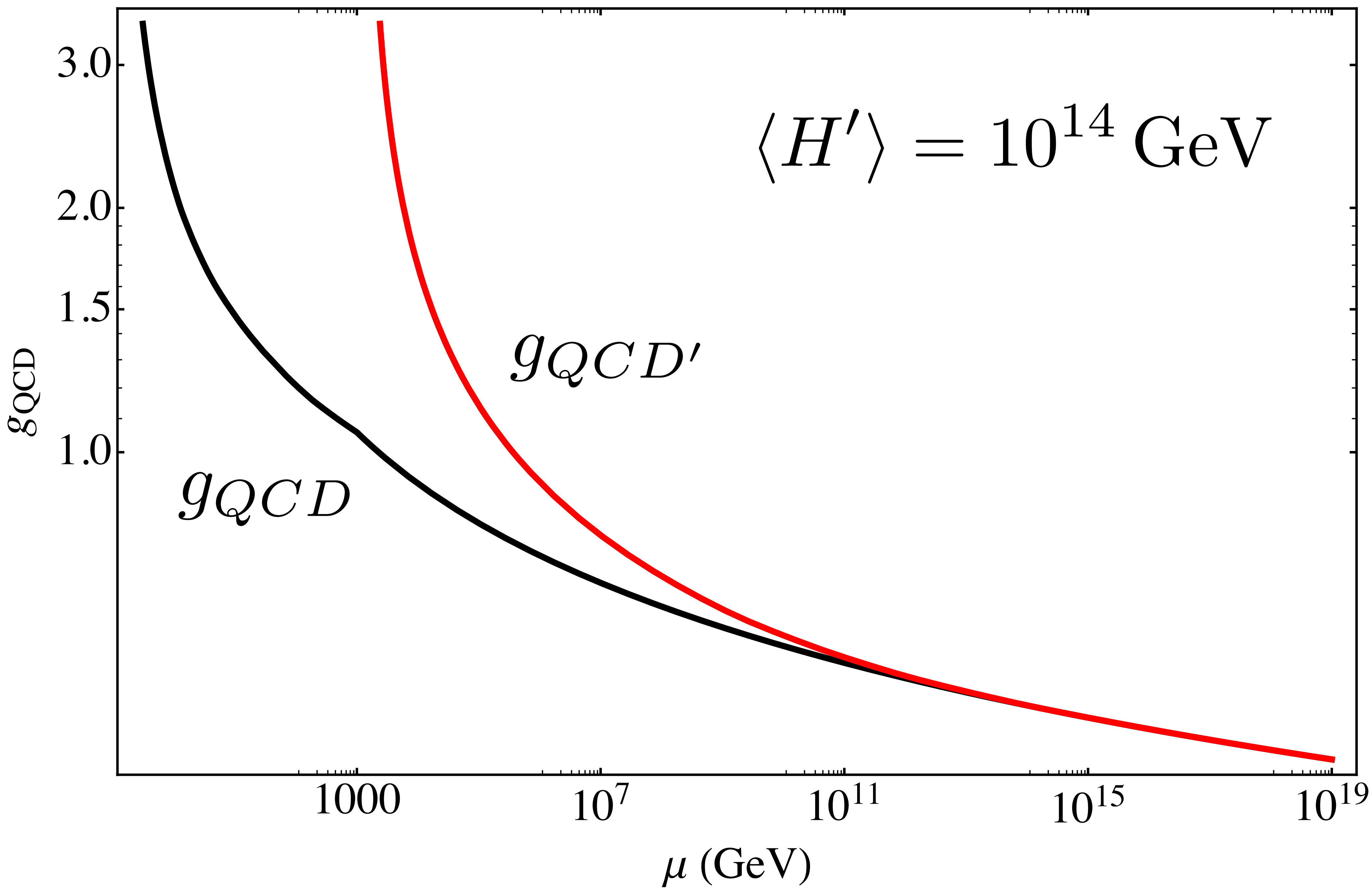
What are the constraints on this model?



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



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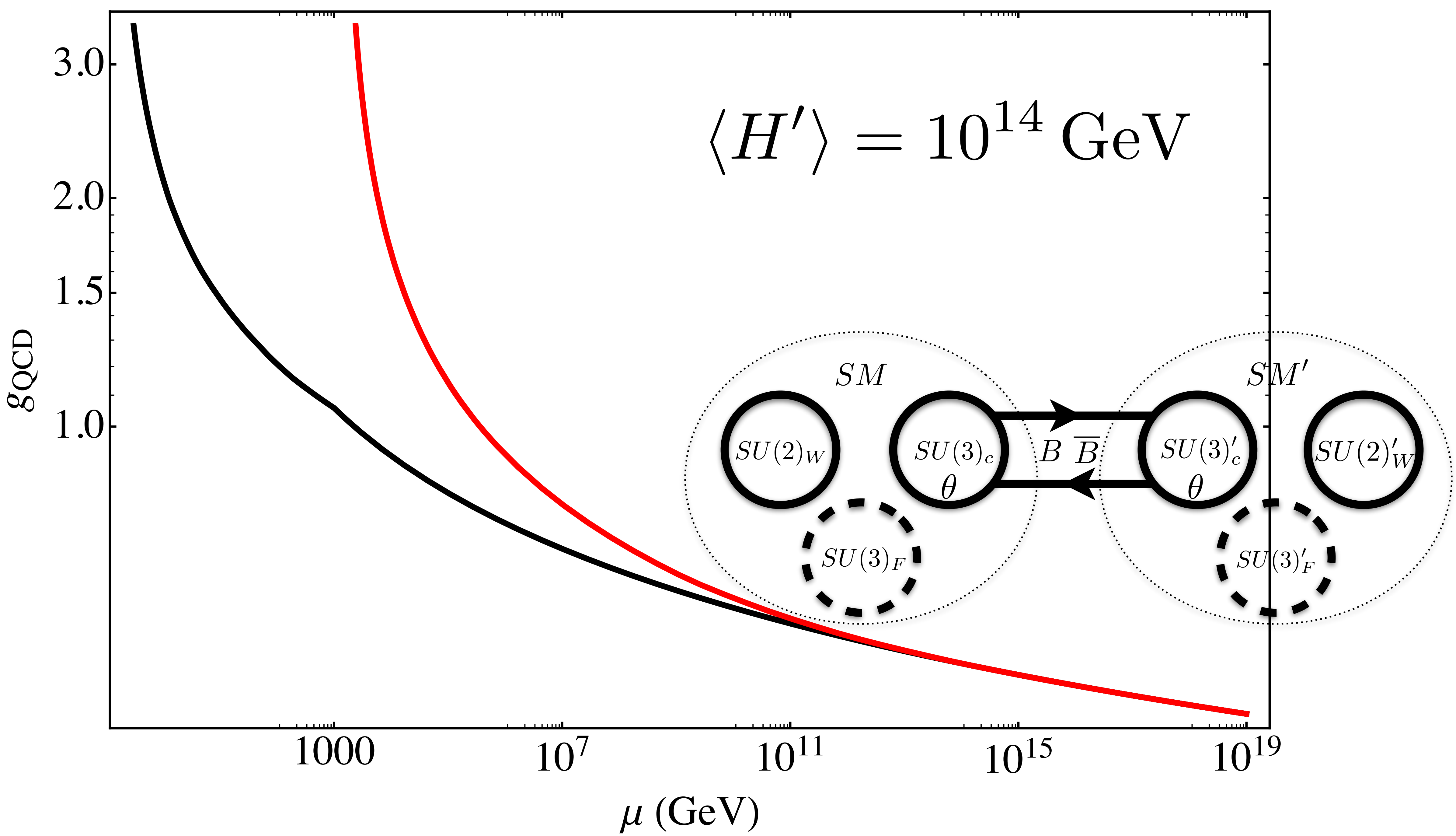

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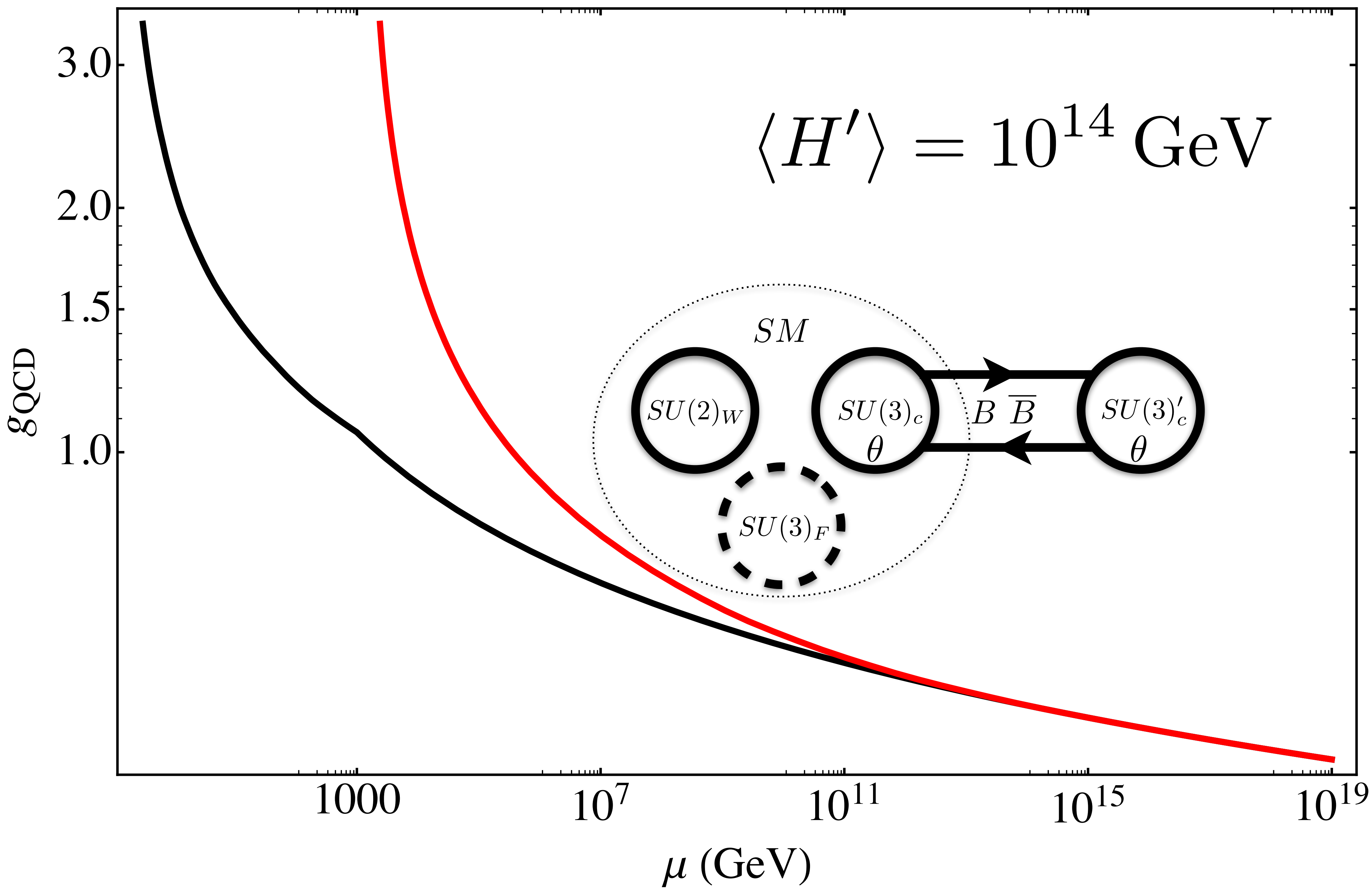

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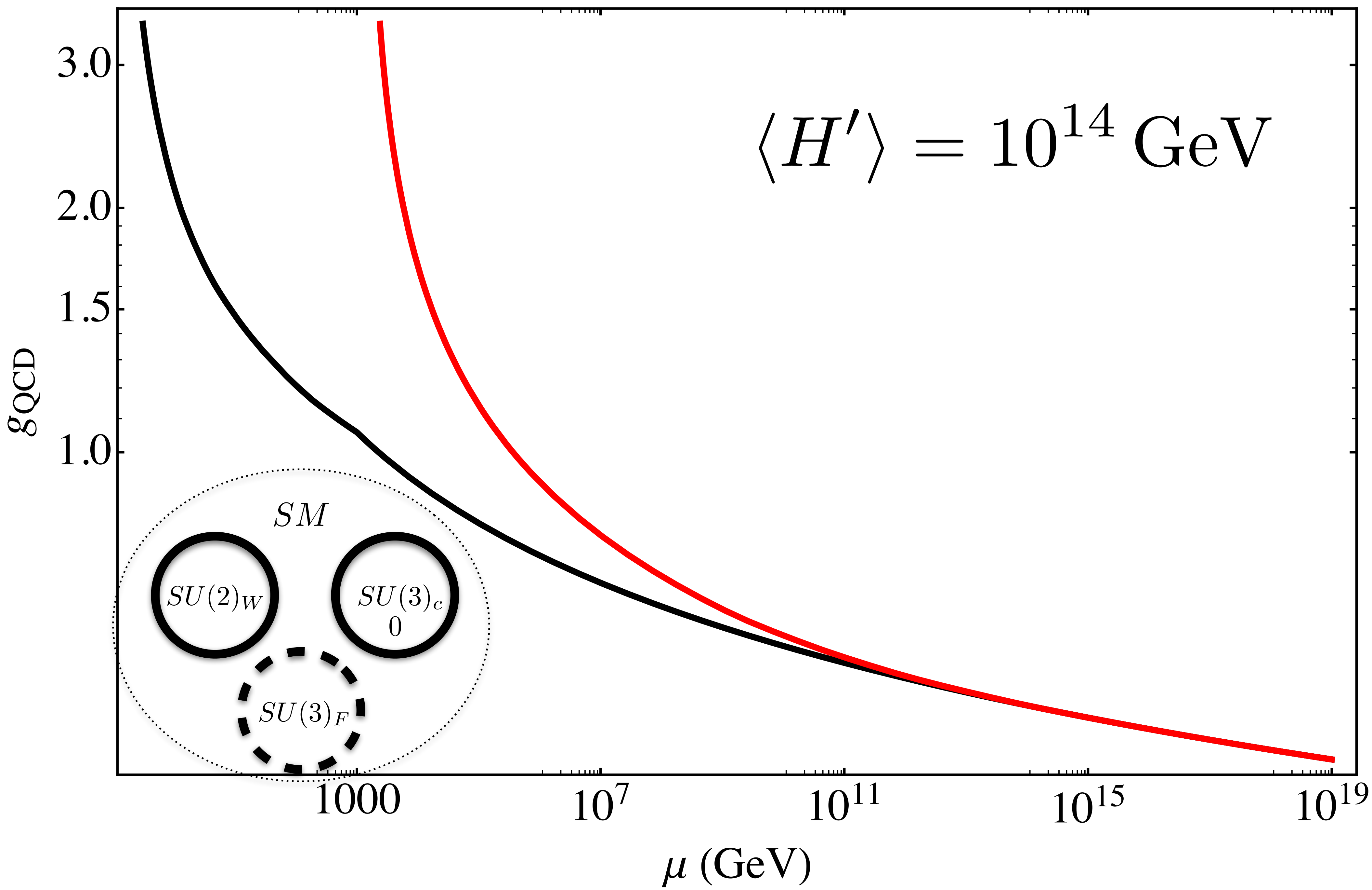


Higher dimensional operators

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

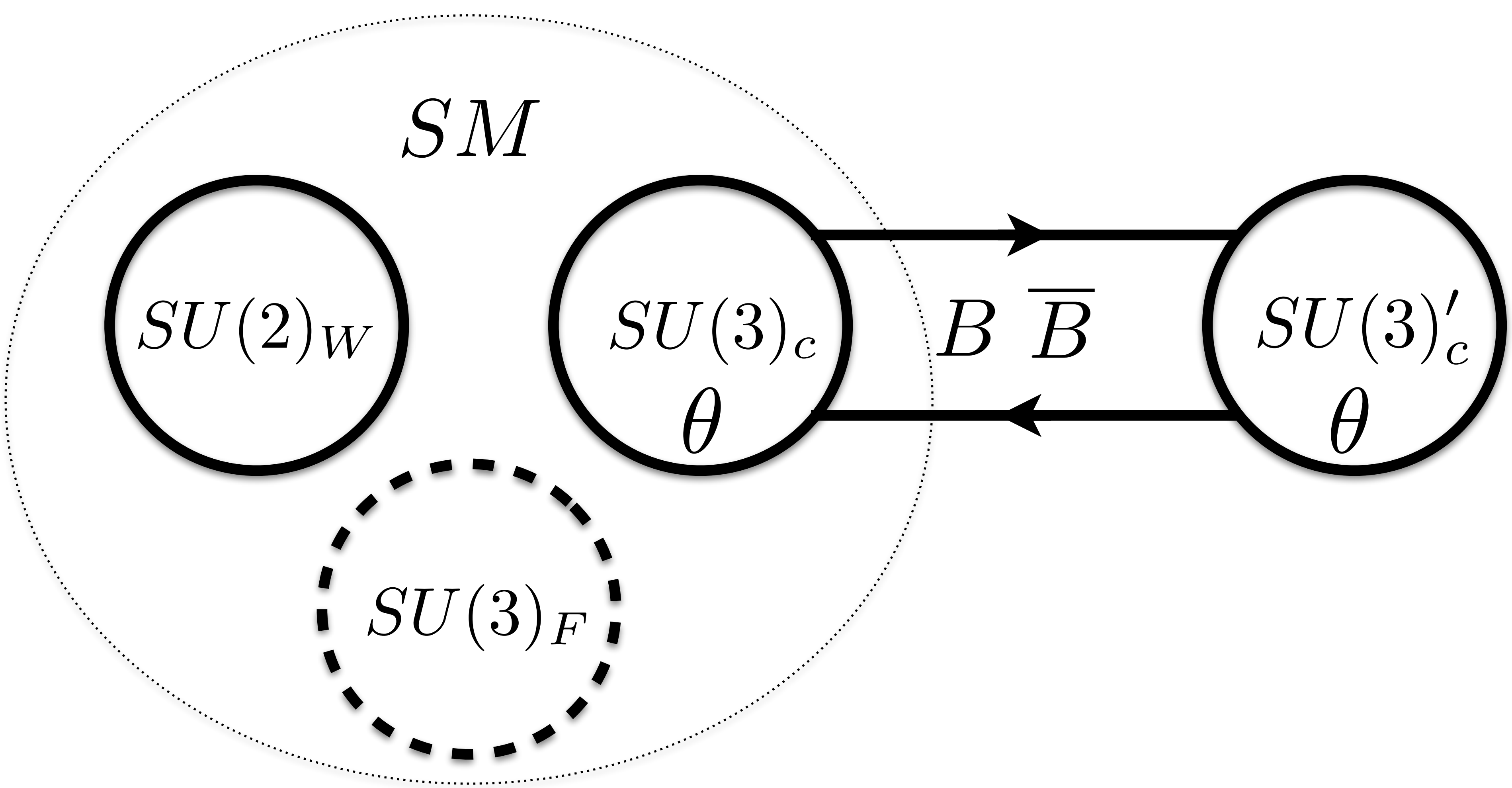
Solutions to the strong CP problem strongly constrained by higher dimensional operators

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

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

Collider Observables

- Observable signatures come from the pseudo-goldstone bosons

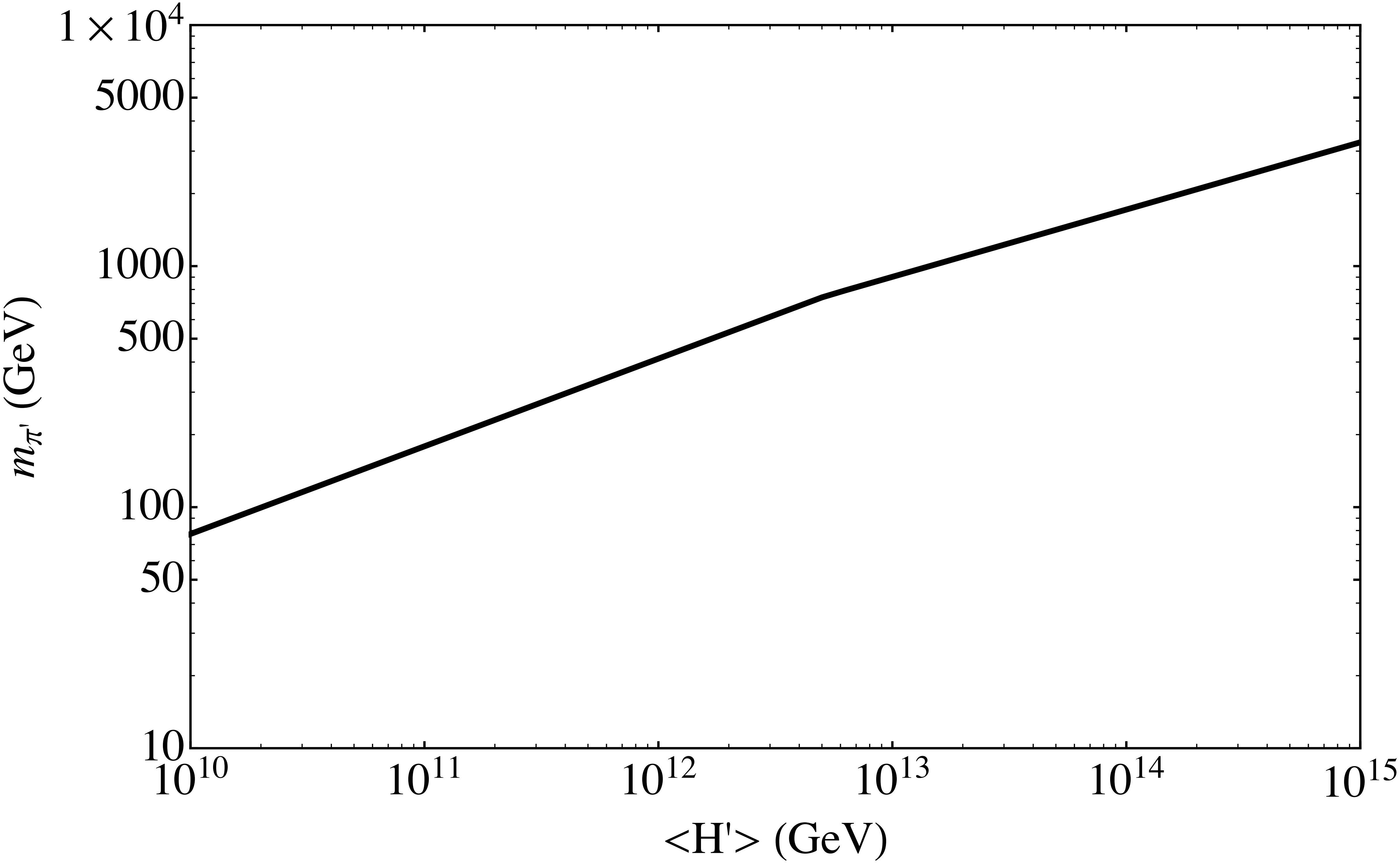


Collider Observables

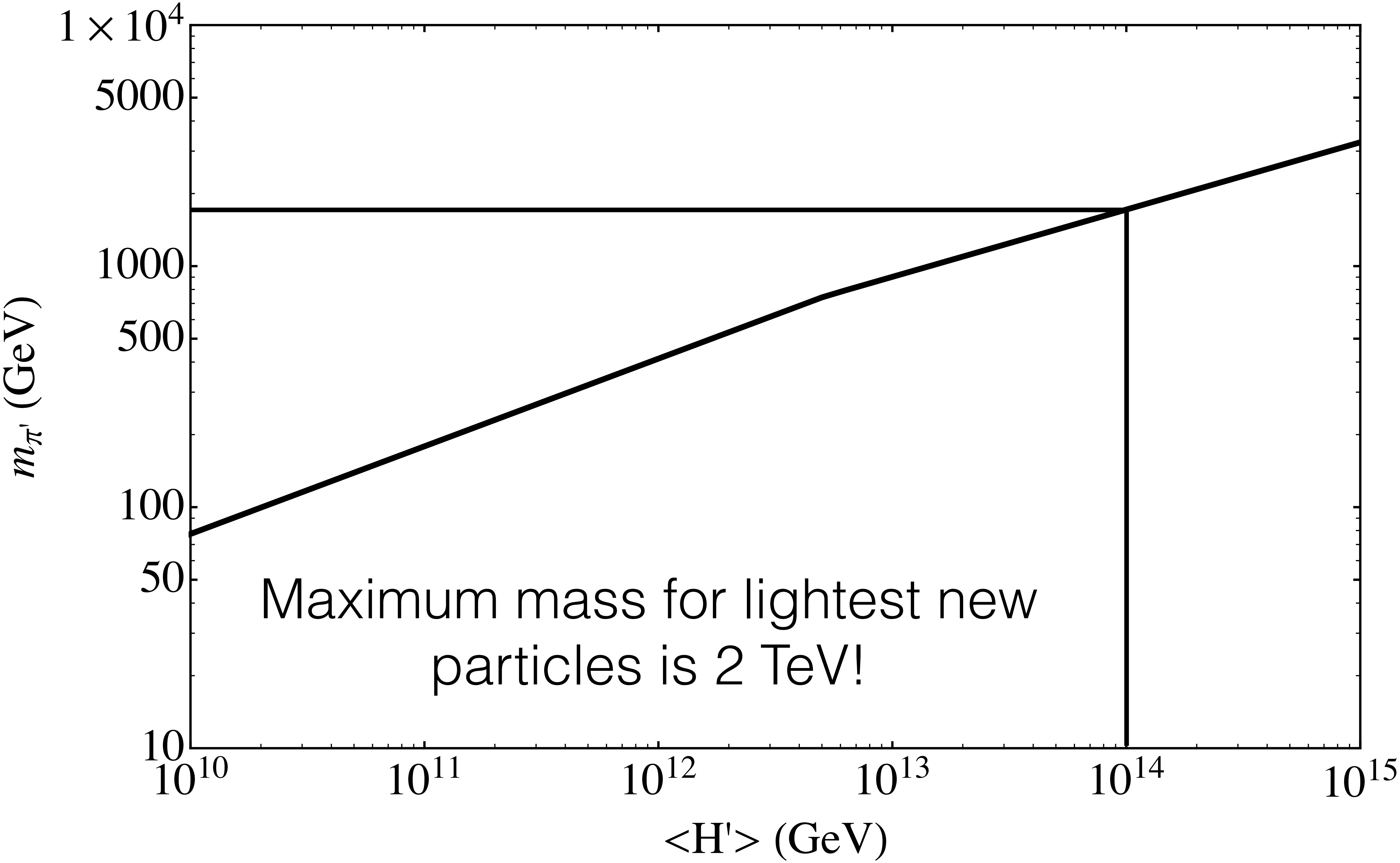
- Observable signatures come from the pseudo-goldstone bosons
  - Color octet scalars
- Obtain a 1-loop mass from gauge boson loops
- Like charged pions, quadratic divergence cut off by rho mesons

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

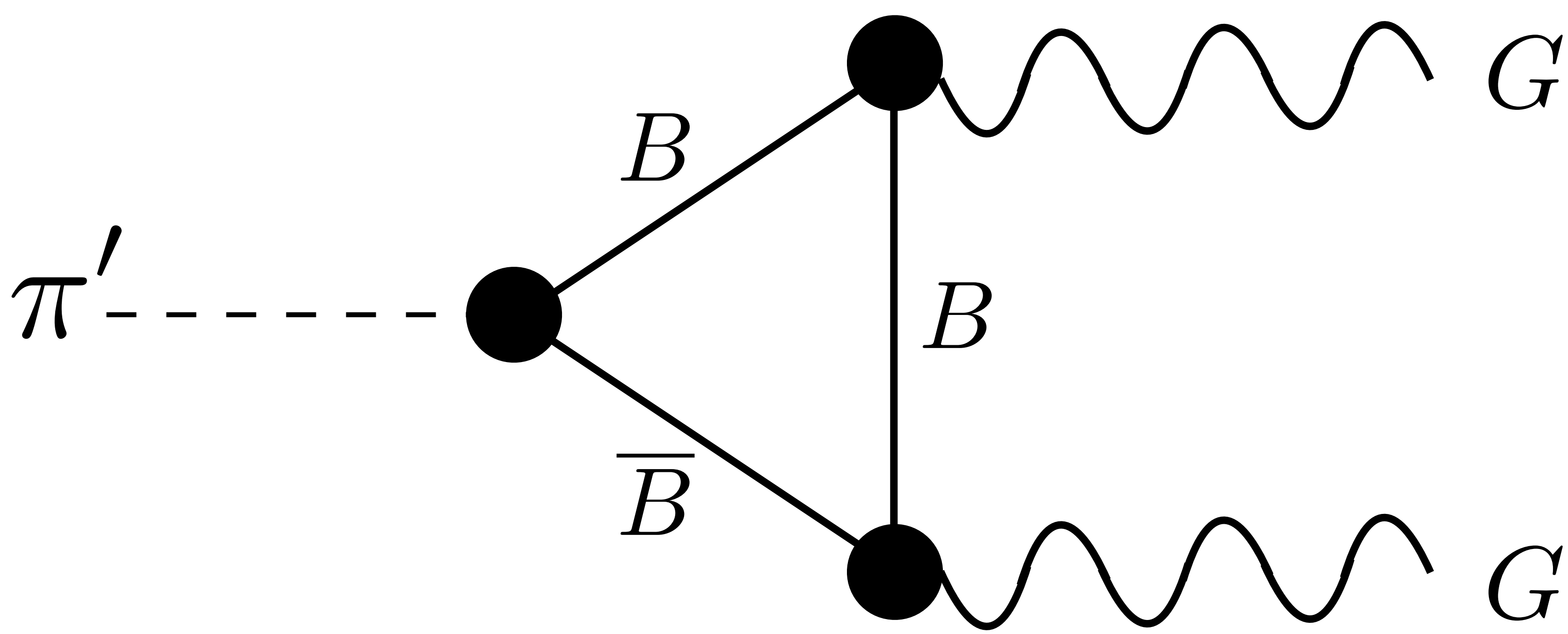
Collider Observables



Collider Observables

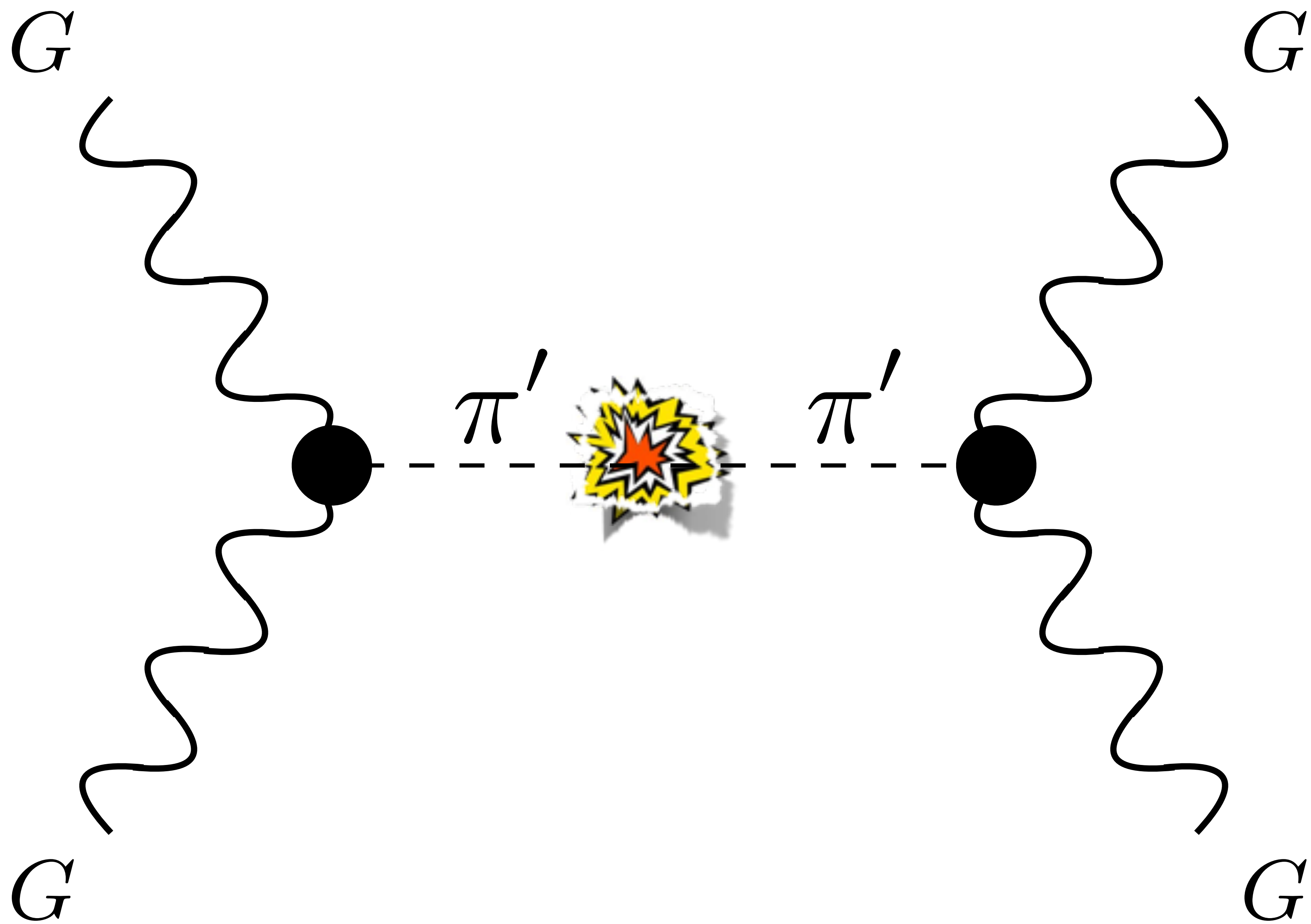


Collider Observables

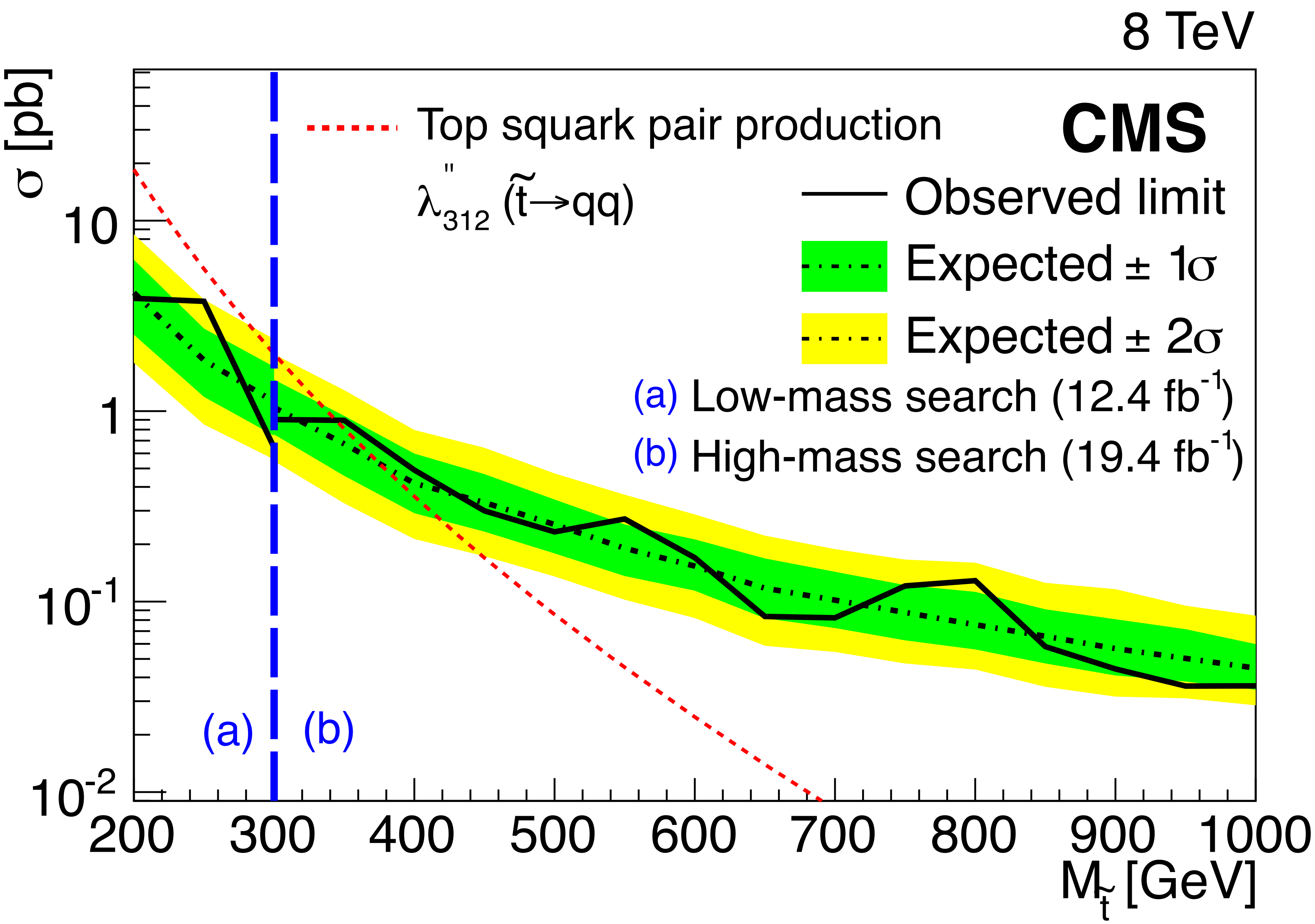


Pions decay through the anomaly into a pair of gluons

Collider Observables



Collider bounds



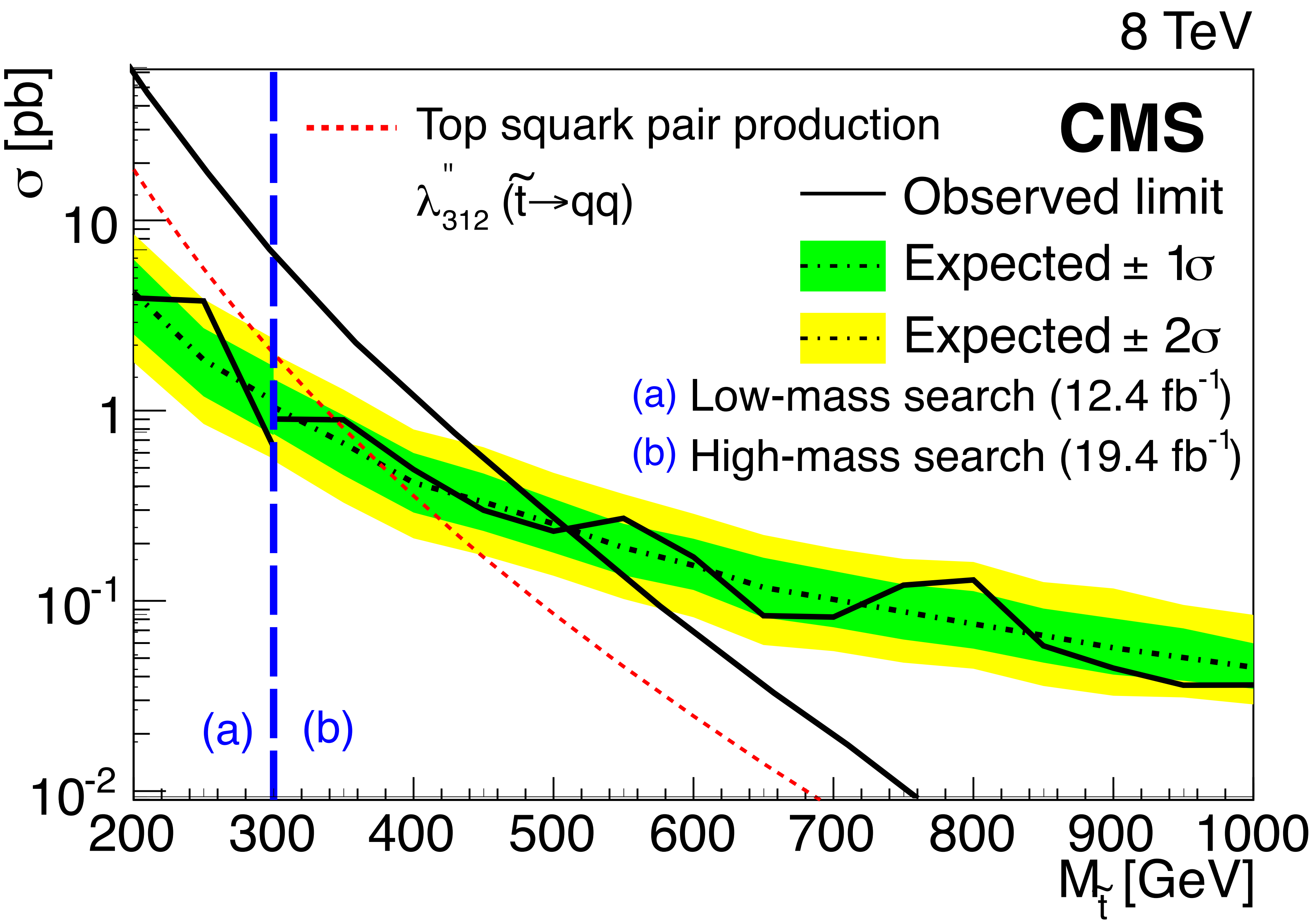
4 jet event with a pair of resonances

New CMS result :

hep-ex / 1412.7706

8 TeV, 19.4 fb^{-1}

Collider bounds



4 jet event with a pair of resonances

New CMS result :

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Conclusion

- A strong CP problem solution which is testable at colliders!
  - 4 jets with two resonances
- Discrete symmetry solutions also subject to the same constraints
  - Some also predict colored particles with mass smaller than 10 TeV
  - 4th generation particles which decay in an unexpected manner