Solving the wrong problem

Postdicting the top quark mass from the strong CP problem

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Naturalness

- Naturalness : IR physics should not depend sensitively on small variations of UV parameters
- Traditional solutions
  - SUSY, technicolor, Little Higgs, Composite Higgs, Extra dimensions
- Non-Tradiational Solutions
  - Multiverse, Relaxion, NNaturalness

Naturalness

- Focus has been on the Higgs
- If there are any new particles, then their naturalness problems are also solved similarly
- Are there solutions to the hierarchy problem which are unique to these scalars?

Naturalness

- Goal : Add new scalars to the SM without worsening the hierarchy problem
    - If scalars solve other problems, should have O(1) couplings
- Relate the new hierarchy problem to the old hierarchy problem

Naturalness

- Imagine that the new scalar is related to the Higgs by a discrete symmetry
  - Parity or a Z_2 symmetry
- The hierarchy problem is solved completely as long as symmetry is exact
  - Any breaking of the symmetry must be spontaneous
  - Additional scalars re-introduce hierarchy problem

Naturalness

- Exact Parity or Z_2 symmetry
  - No new scalars to break symmetry
- Need Higgs and its copy to spontaneously break the symmetry itself
  - Additional light degrees of freedom (e.g. $SU(2)_R$) : both need non-zero vevs

Classical Analysis

$$V = -\frac{m_H^2}{2}(h^2 + h'^2) + \frac{\lambda}{4}(h^4 + h'^4) + \frac{\delta\lambda}{4}h^2 h'^2$$

- Most general potential allowed by symmetries
- Three classes of solutions

$$\langle h \rangle = \langle h' \rangle = 0 \qquad \langle h \rangle = \langle h' \rangle \neq 0$$

$$m_h^2 = m_{h'}^2 \qquad m_h^2 = m_{h'}^2$$

Classical Analysis

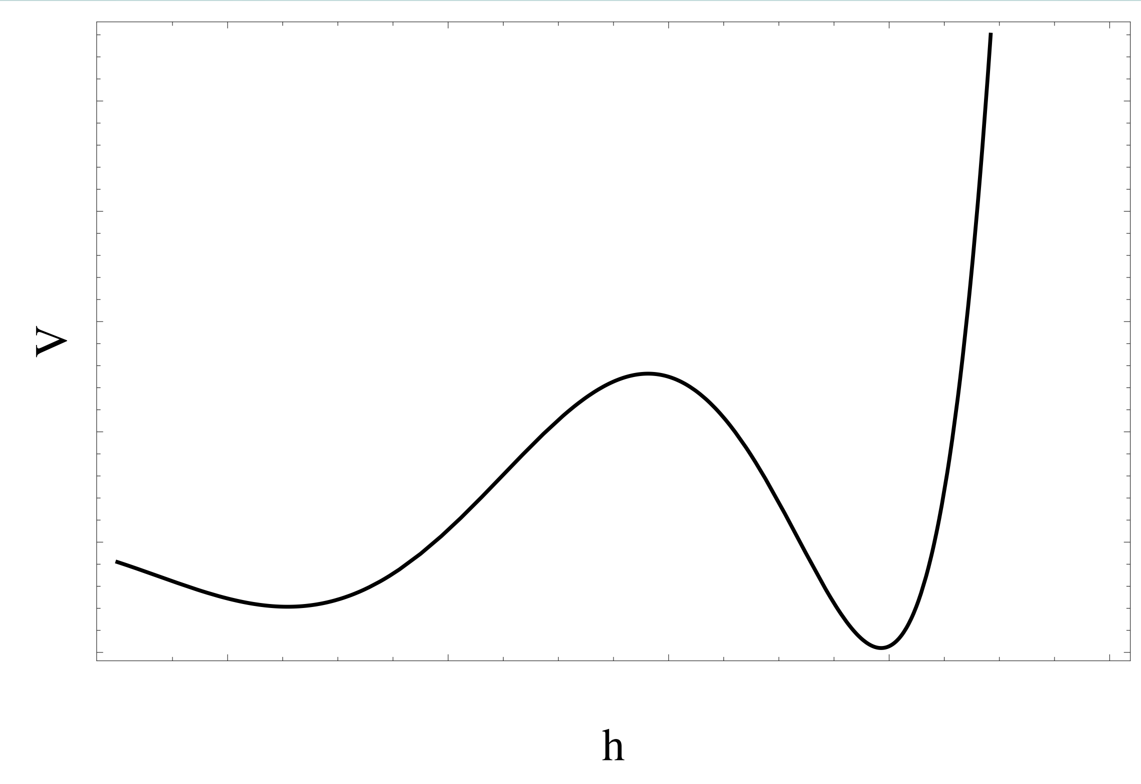
$$V = -\frac{m_H^2}{2}(h^2 + h'^2) + \frac{\lambda}{4}(h^4 + h'^4) + \frac{\delta\lambda}{4}h^2 h'^2$$

$$\langle h \rangle = 0 \qquad \langle h' \rangle \neq 0$$

- Experimentally ruled out due to light degrees of freedom
  - $SU(2)_R$, precision Higgs measurements

Naturalness

- Use RG effects to make sure that Higgs has two minima
  - Our Higgs lives in the vacua close to the origin
  - The parity/Z_2 copy lives in the vacua far from the origin!



Naturalness

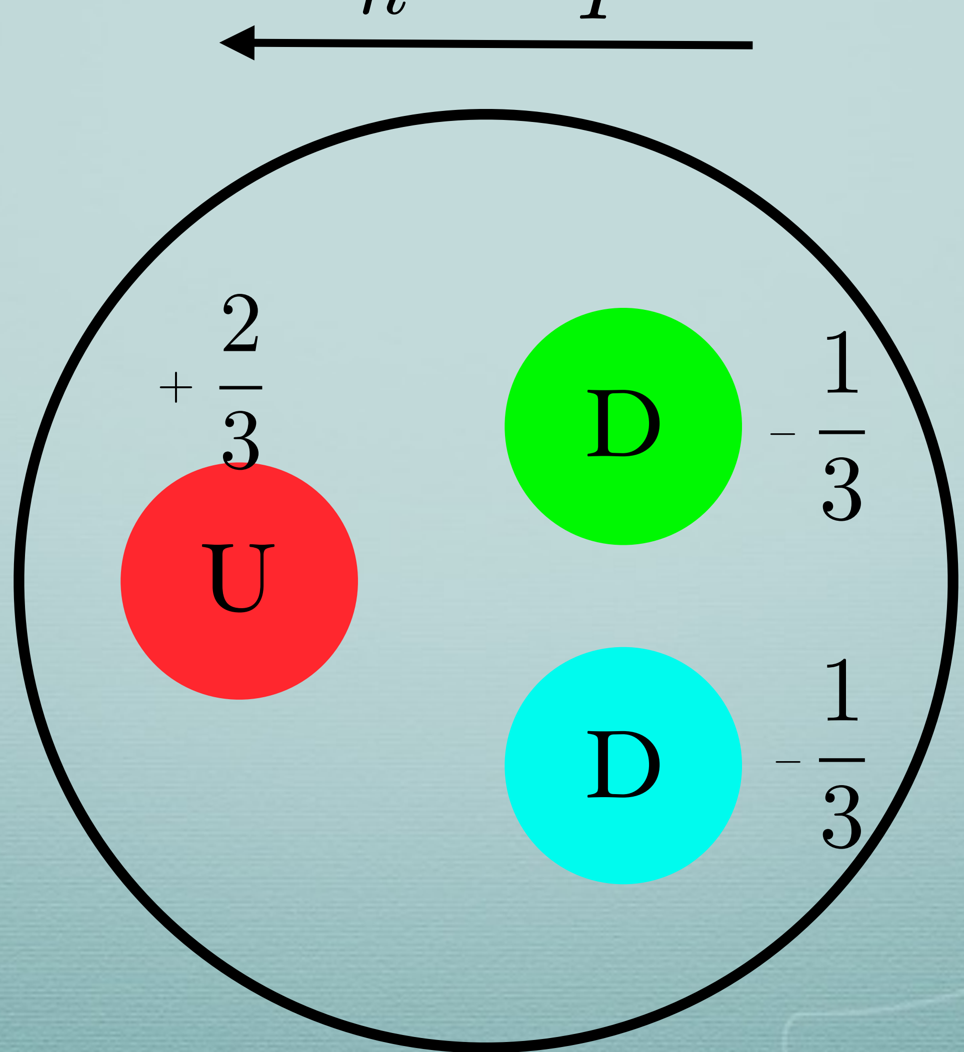
$$V = -\frac{m_H^2}{2} h'^2 + \frac{\lambda[\log(h)]}{4} h^4$$

- No new hierarchy problem!
  - Quadratic divergences set small by discreet symmetry
  - Large vev and mass generated by RG running of quartic

Example : Strong CP problem

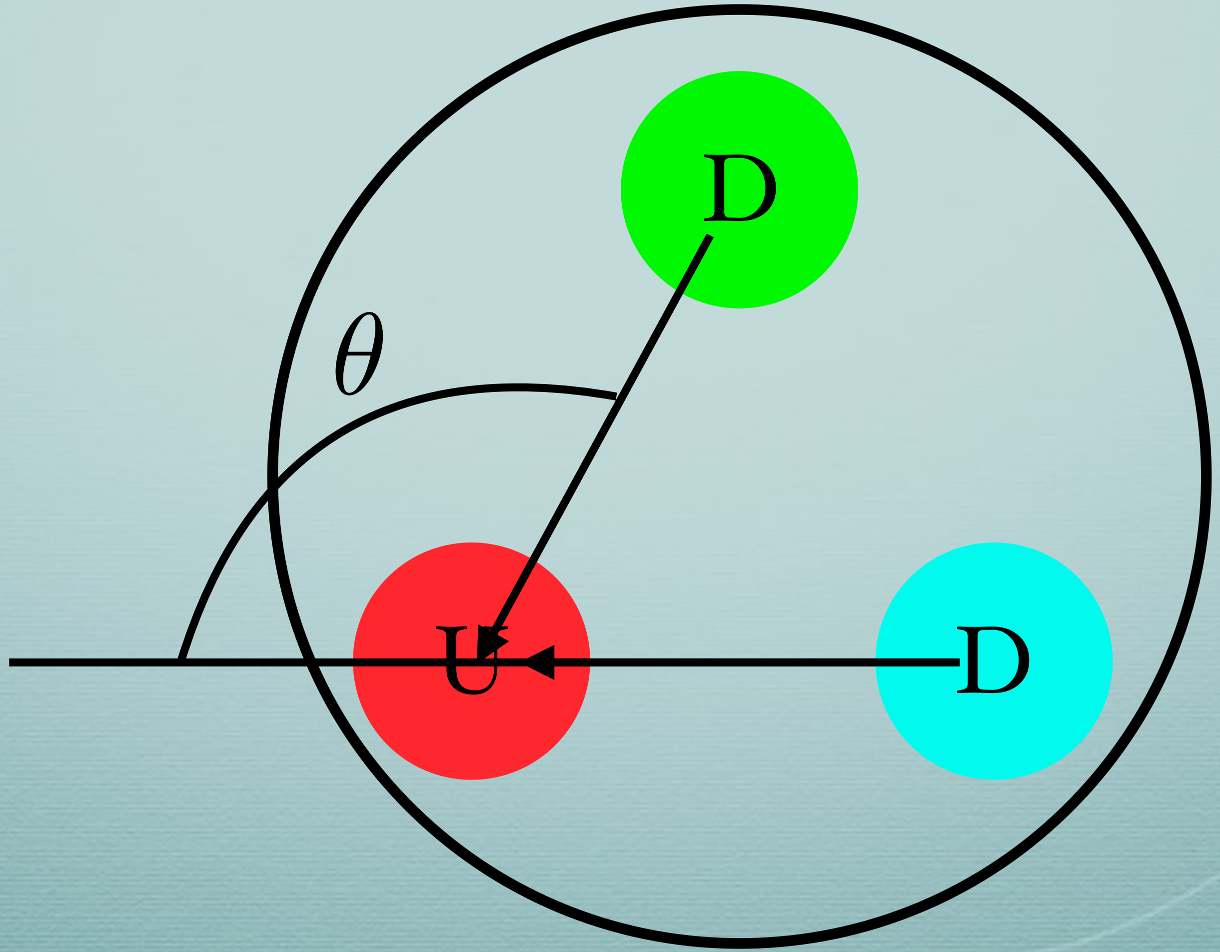
Electric Dipole moment

$$d_n = qx$$



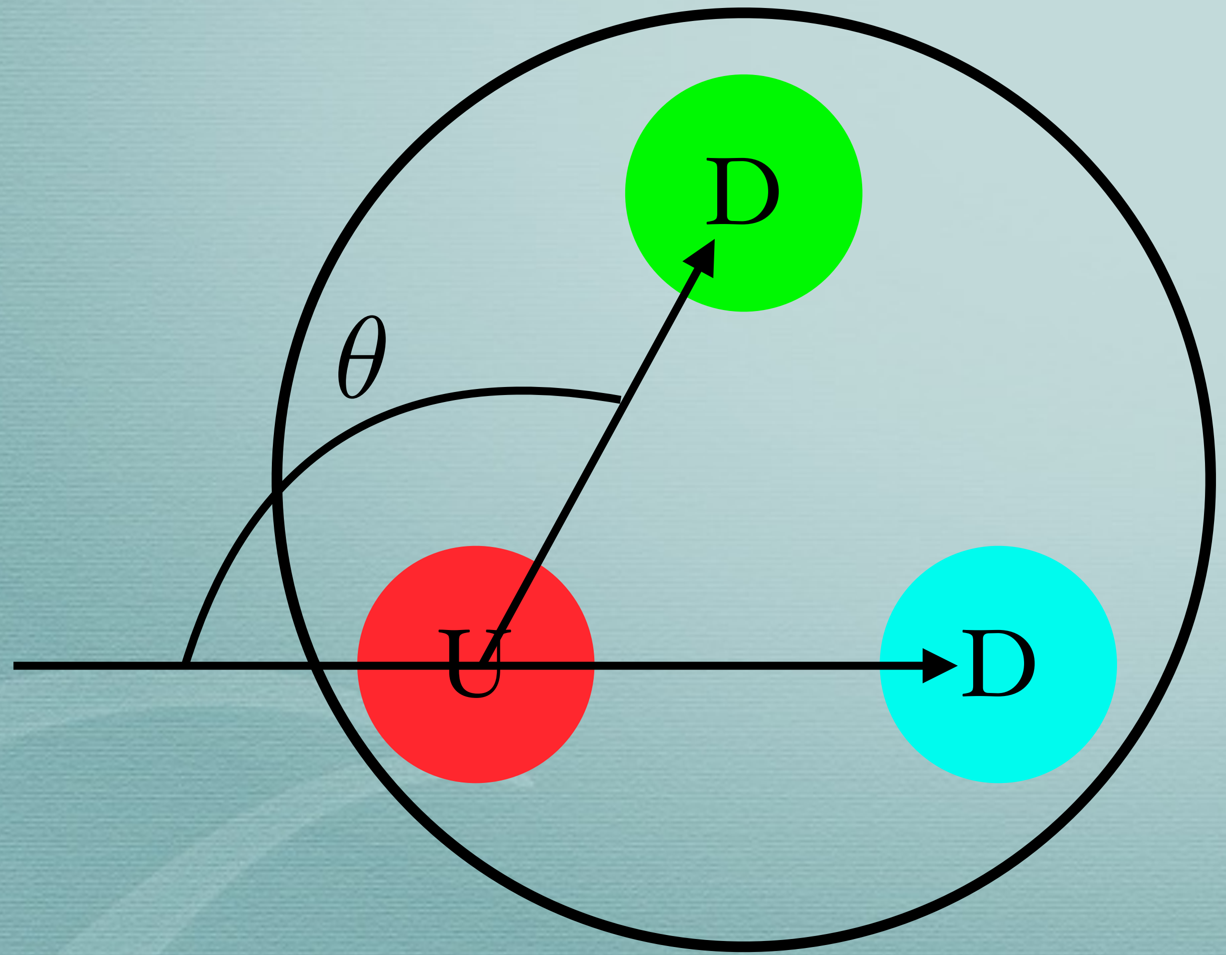
Expected Dipole moment

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



Measured EDM

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

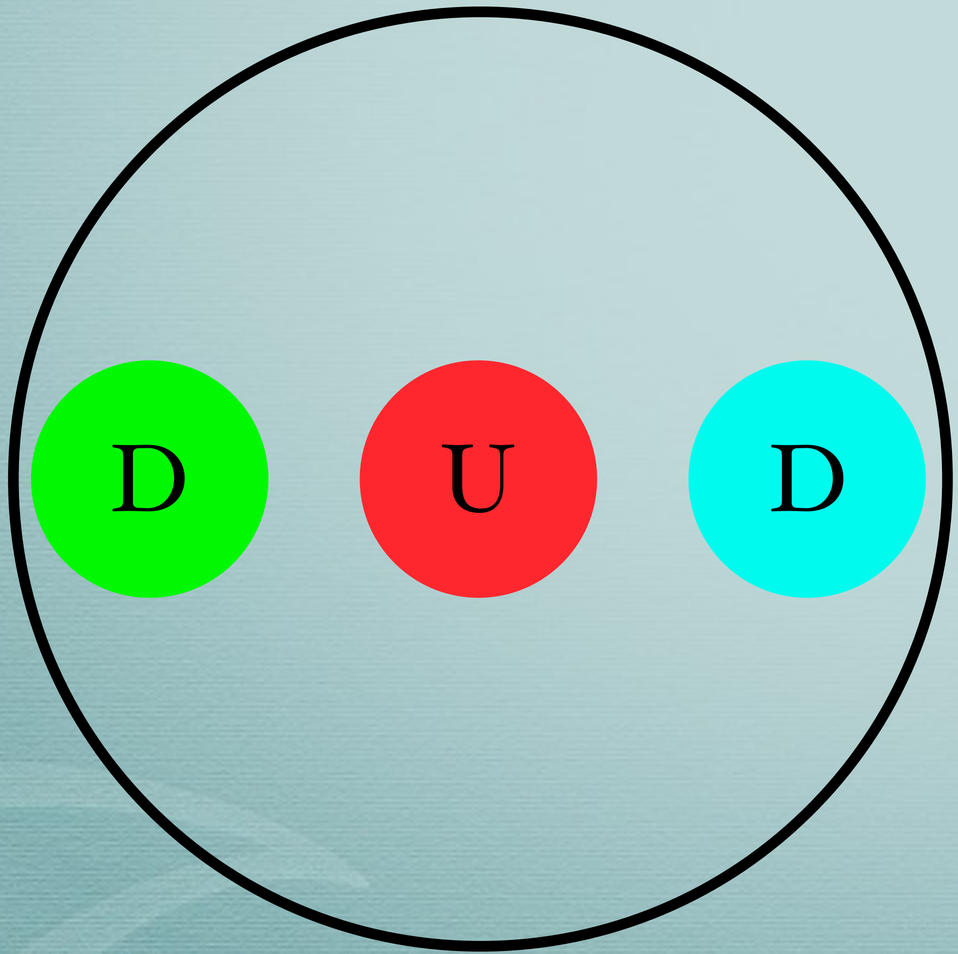


$$|d_n| < 2.9 \times 10^{-26}\, e\, \mathrm{cm}$$

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!

Strong CP problem

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

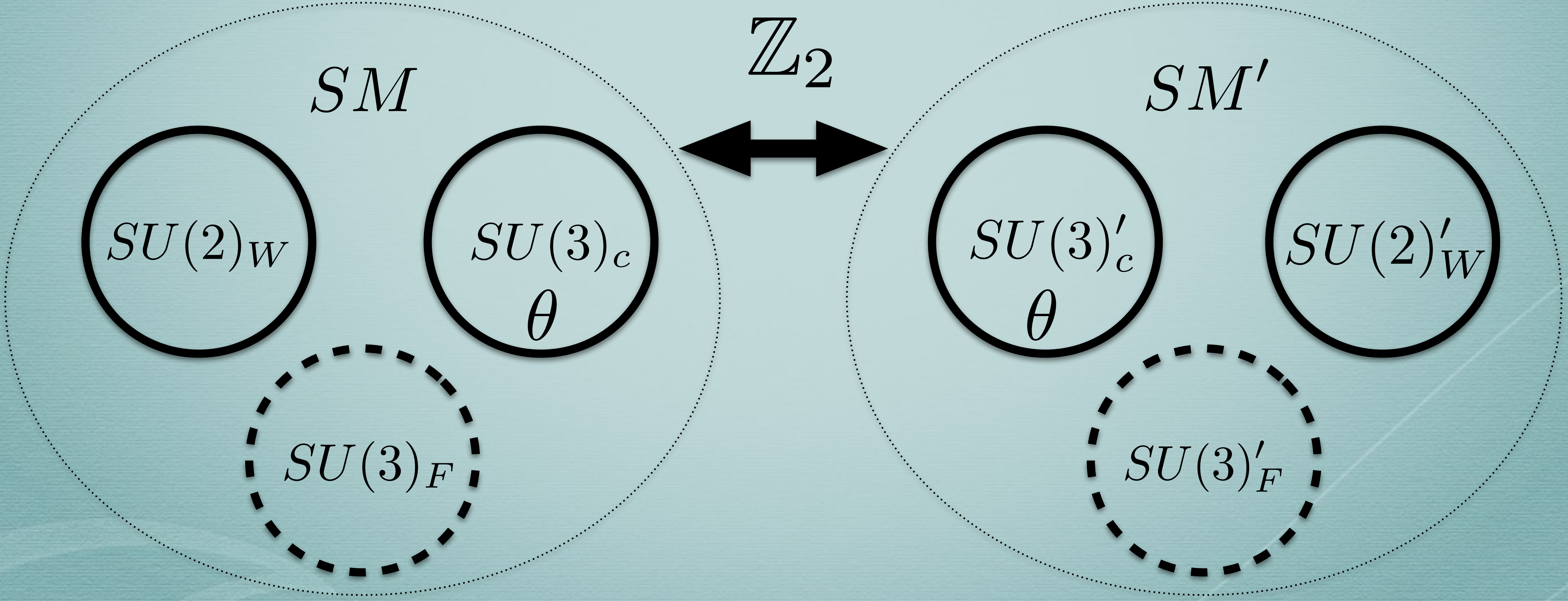
Neutron EDM can be calculated

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

$$|d_n| < 2.9 \times 10^{-26}\,e\,\mathrm{cm} \qquad \theta + \arg\,\det Y_u Y_d \equiv \overline{\theta} < 10^{-10}$$

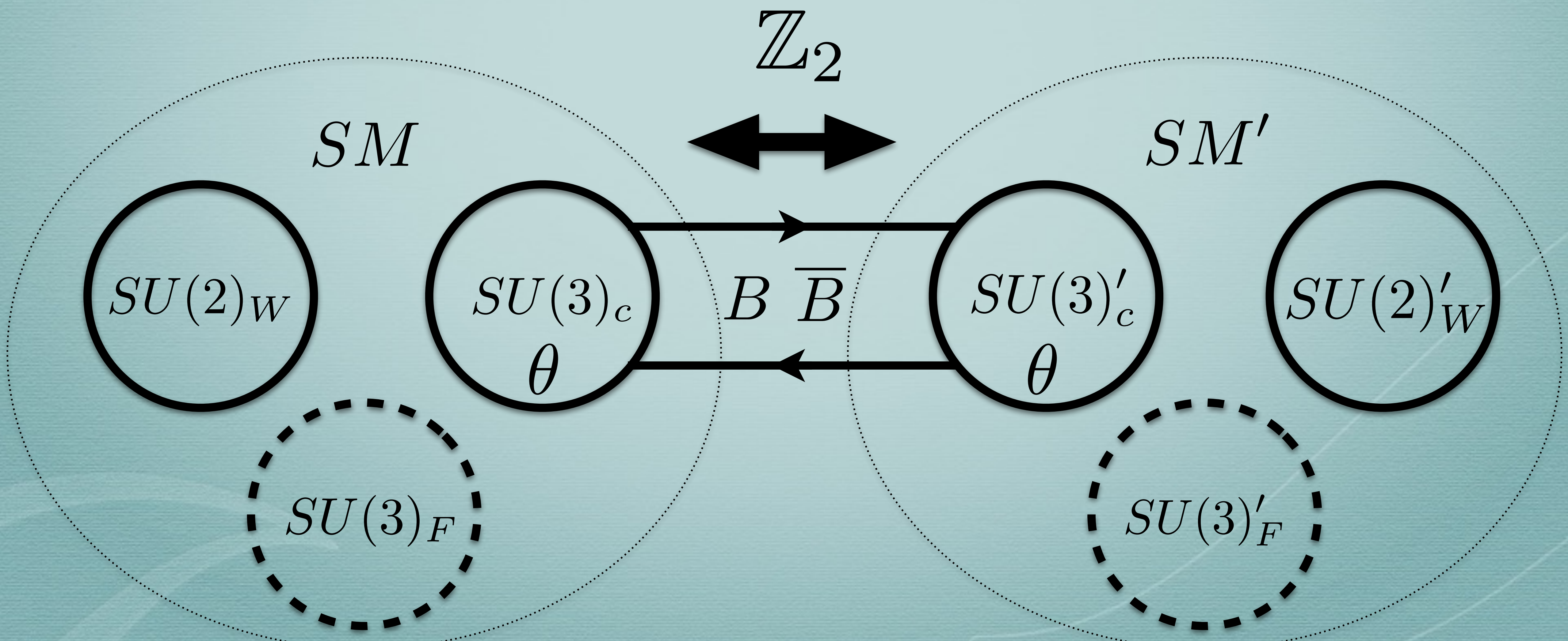
Model

Use a Z_2 theory to solve the strong CP problem



Symmetry explanation

Add Massless Bifundamental under both QCDs

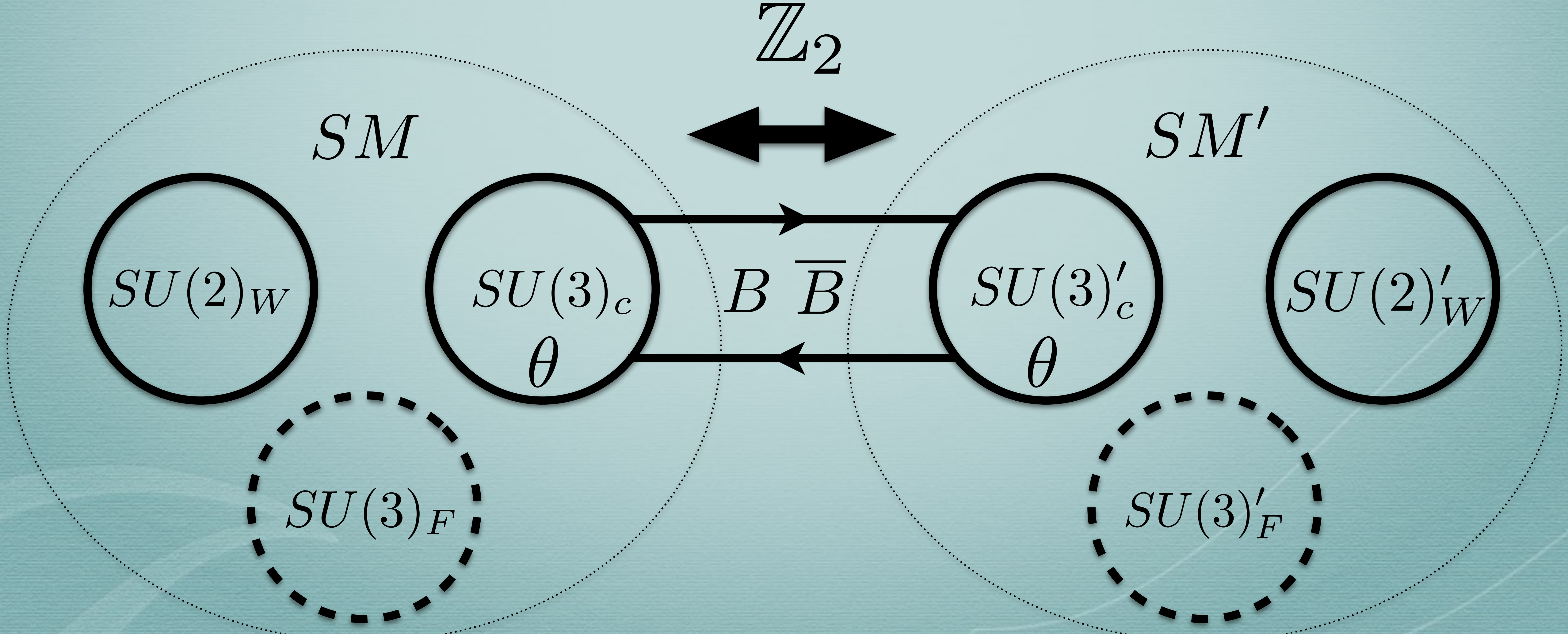


Symmetry explanation

$\theta \to \theta + 6\alpha$

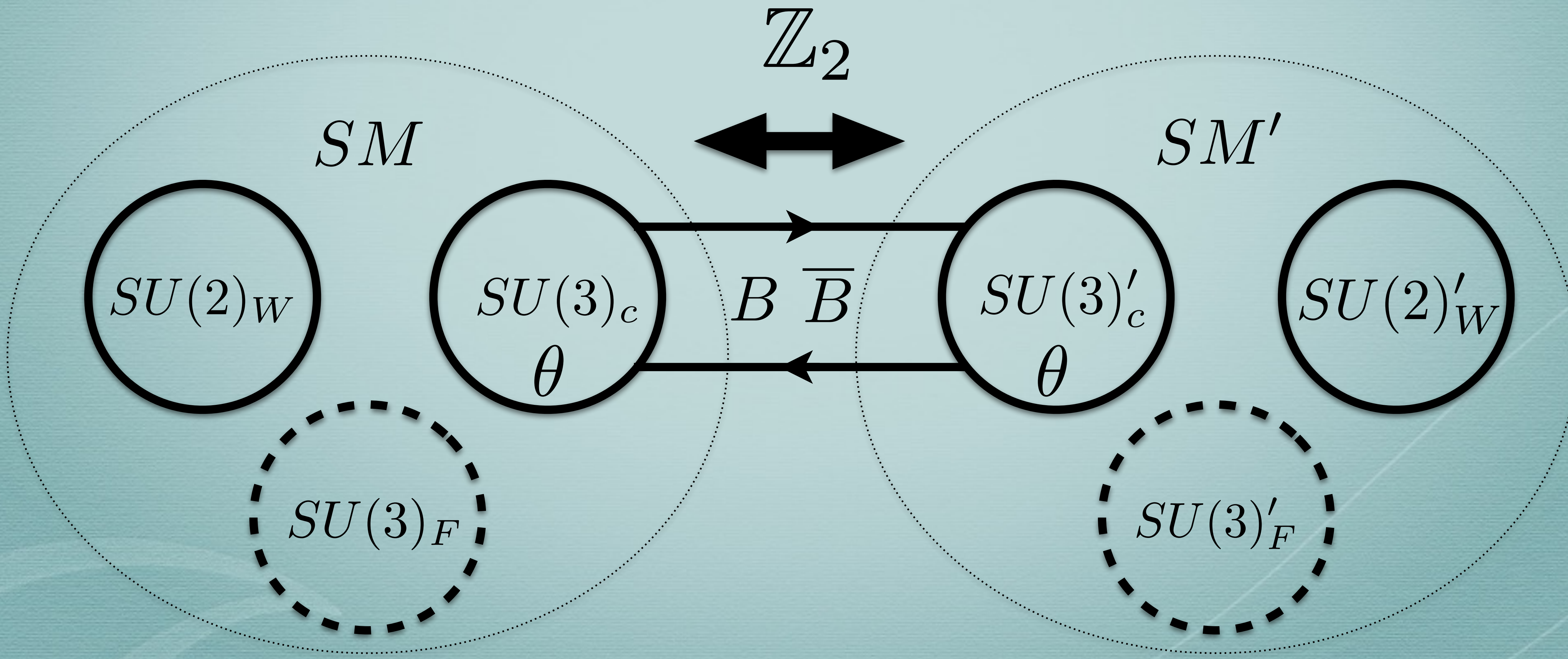
$$B \to B e^{i\alpha}$$
$$\overline{B} \to \overline{B} e^{i\alpha}$$

$\theta \to \theta + 6\alpha$



Constraints

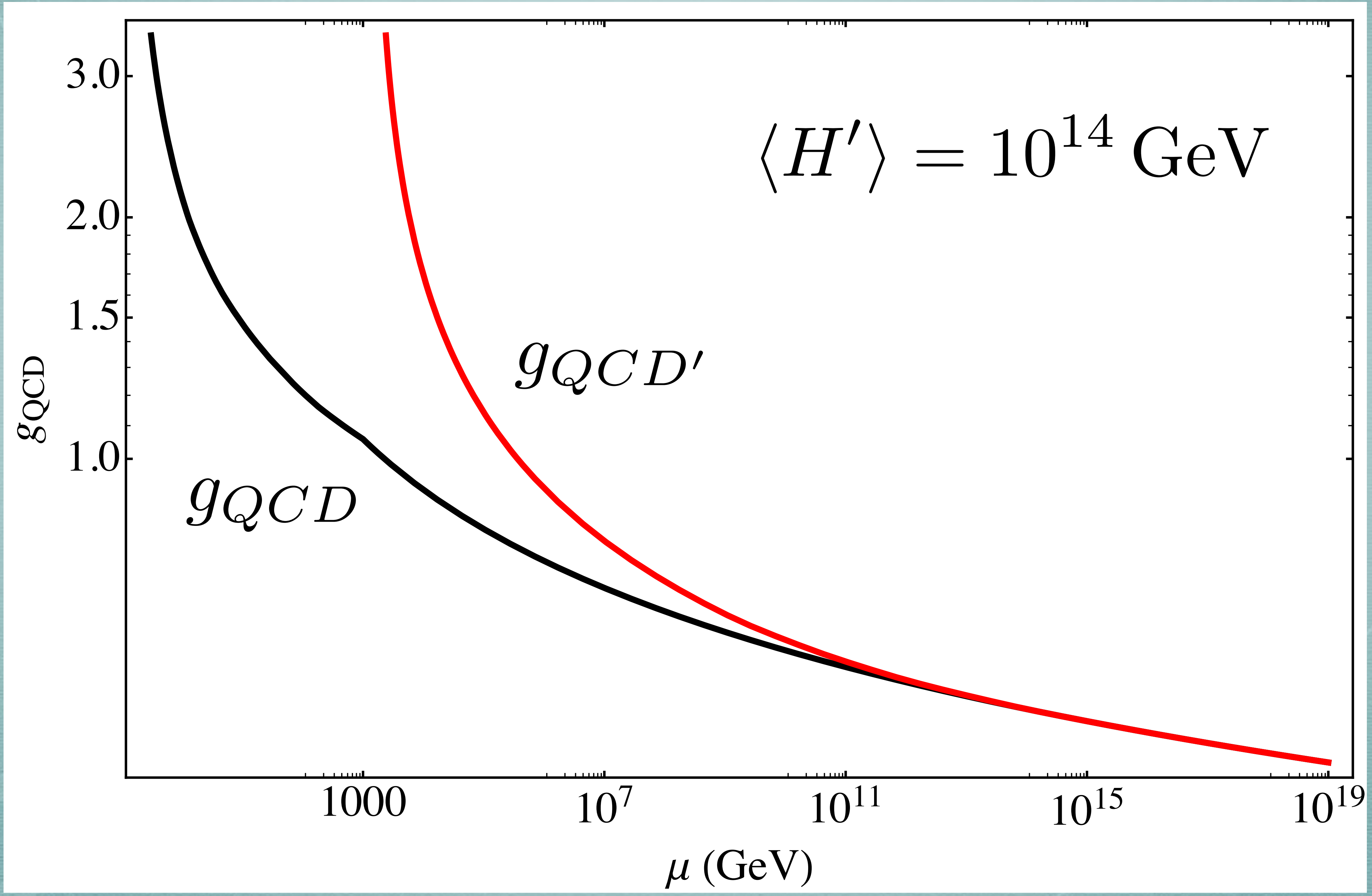
What are the constraints on this model?



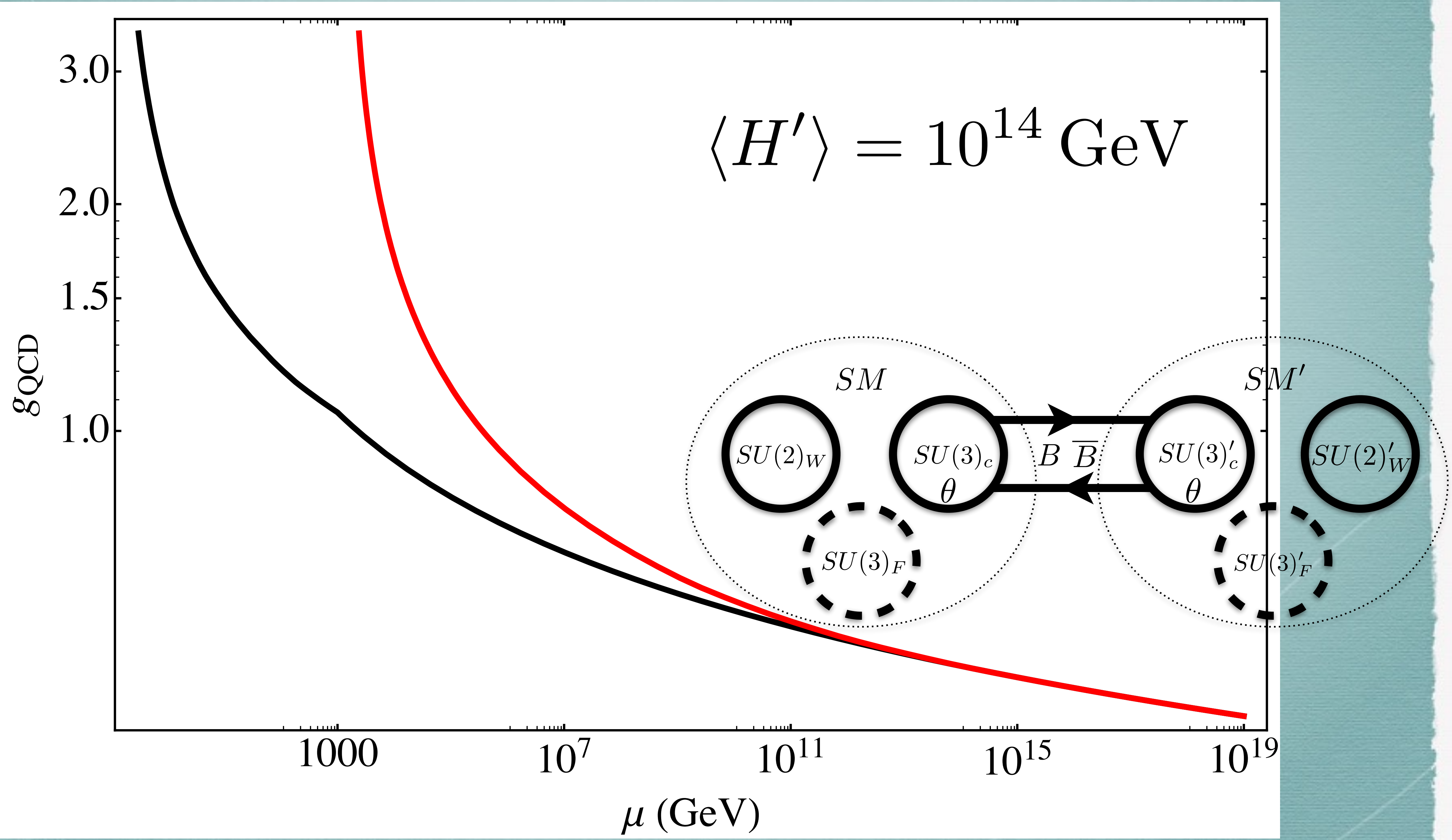
Constraints

- 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

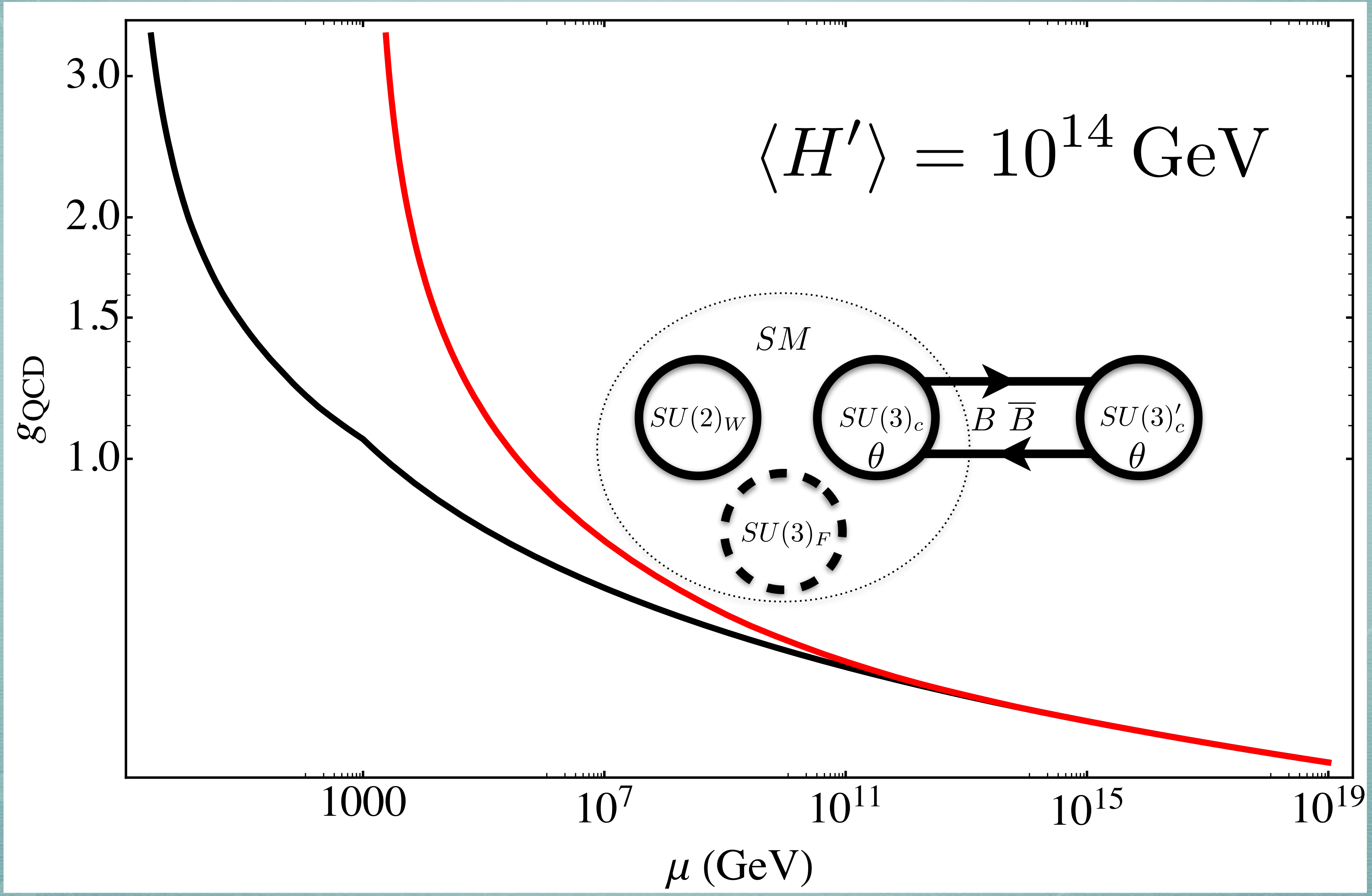
RG evolution



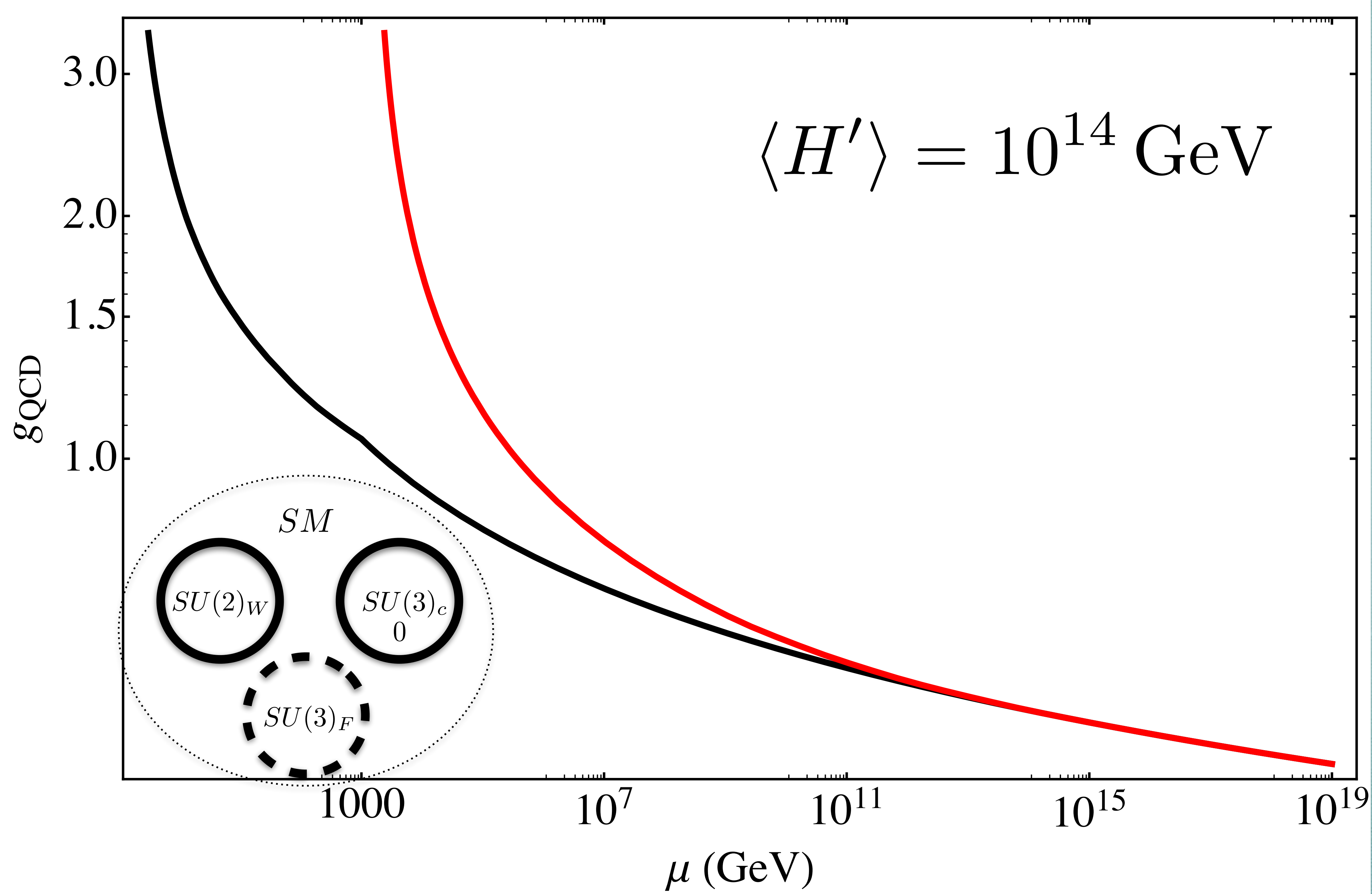
RG evolution



RG evolution



RG evolution



RG running

- Below scale of Z_2 breaking no symmetry protecting neutron EDM
  - RG running potentially reintroduces problem
- Breaking of CP comes from CKM matrix
  - Work in basis where CKM matrix is inside of the Yukawas

J. Ellis, and M.K. Gaillard, Nucl.Phys. B150

RG running

$$\beta_\theta \sim \text{Arg Tr} \prod Y_u Y_d Y_u^\dagger Y_d^\dagger$$

- Need to respect $SU(3)_Q \times SU(3)_u \times SU(3)_d$
- Simple expressions vanish

$$\beta_\theta \sim \text{Arg Tr} Y_u Y_u^\dagger = 0$$

J. Ellis, and M.K. Gaillard, Nucl.Phys. B150

RG running

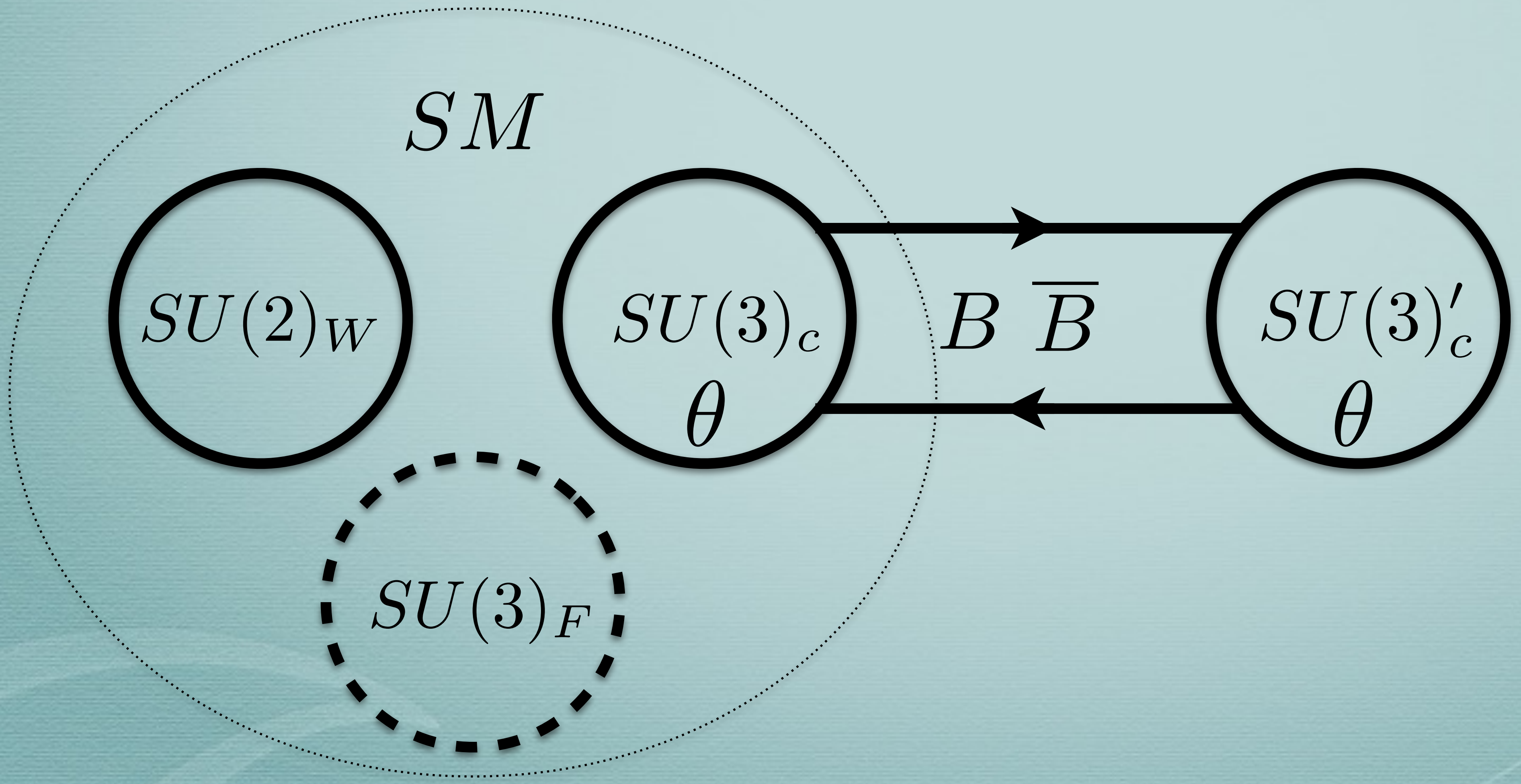
$$\beta_\theta \sim \text{Arg Tr} Y_u^4 Y_d^4 Y_u^2 Y_d^2$$

- Symmetries alone require RG evolution to start at 6 loops
    - Actually need 7 loops because need gauge couplings to see breaking of parity

J. Ellis, and M.K. Gaillard, Nucl.Phys. B150

Low energy Observables

- Observable signatures come from the pseudo-goldstone bosons

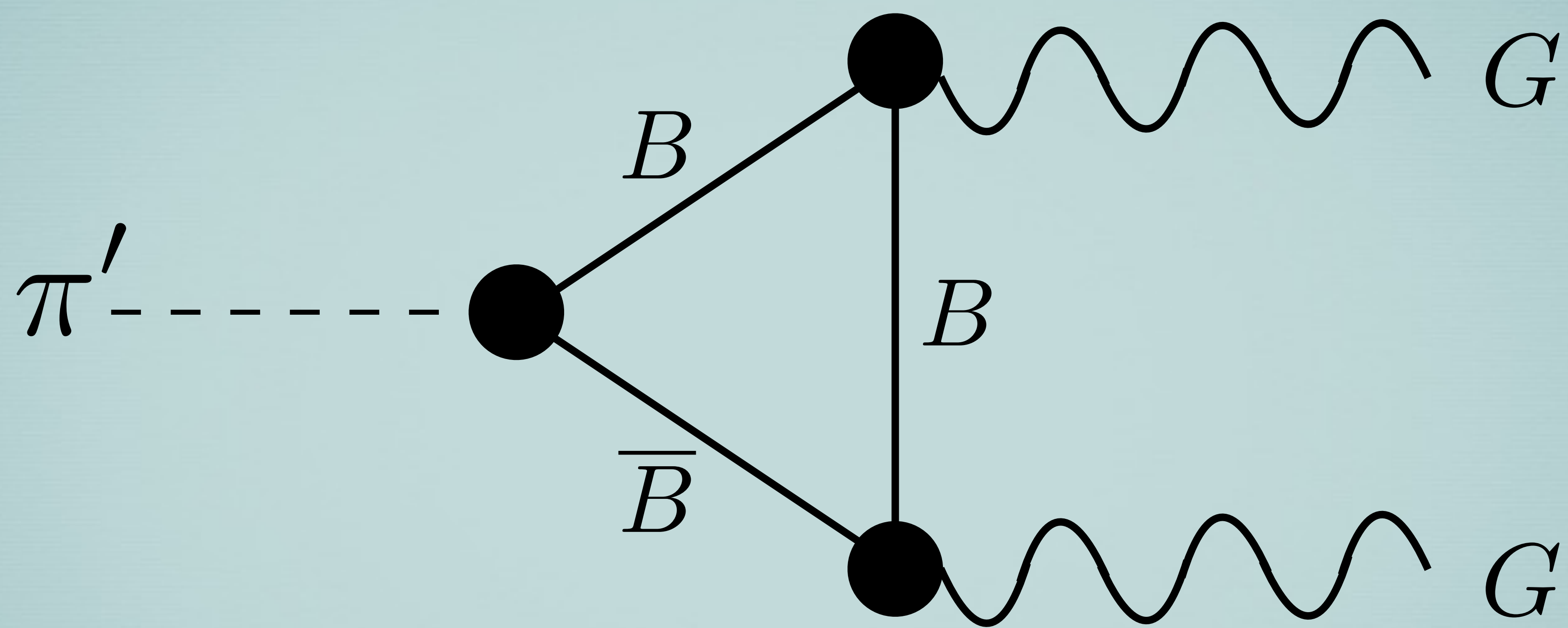


Low energy Observables

- 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

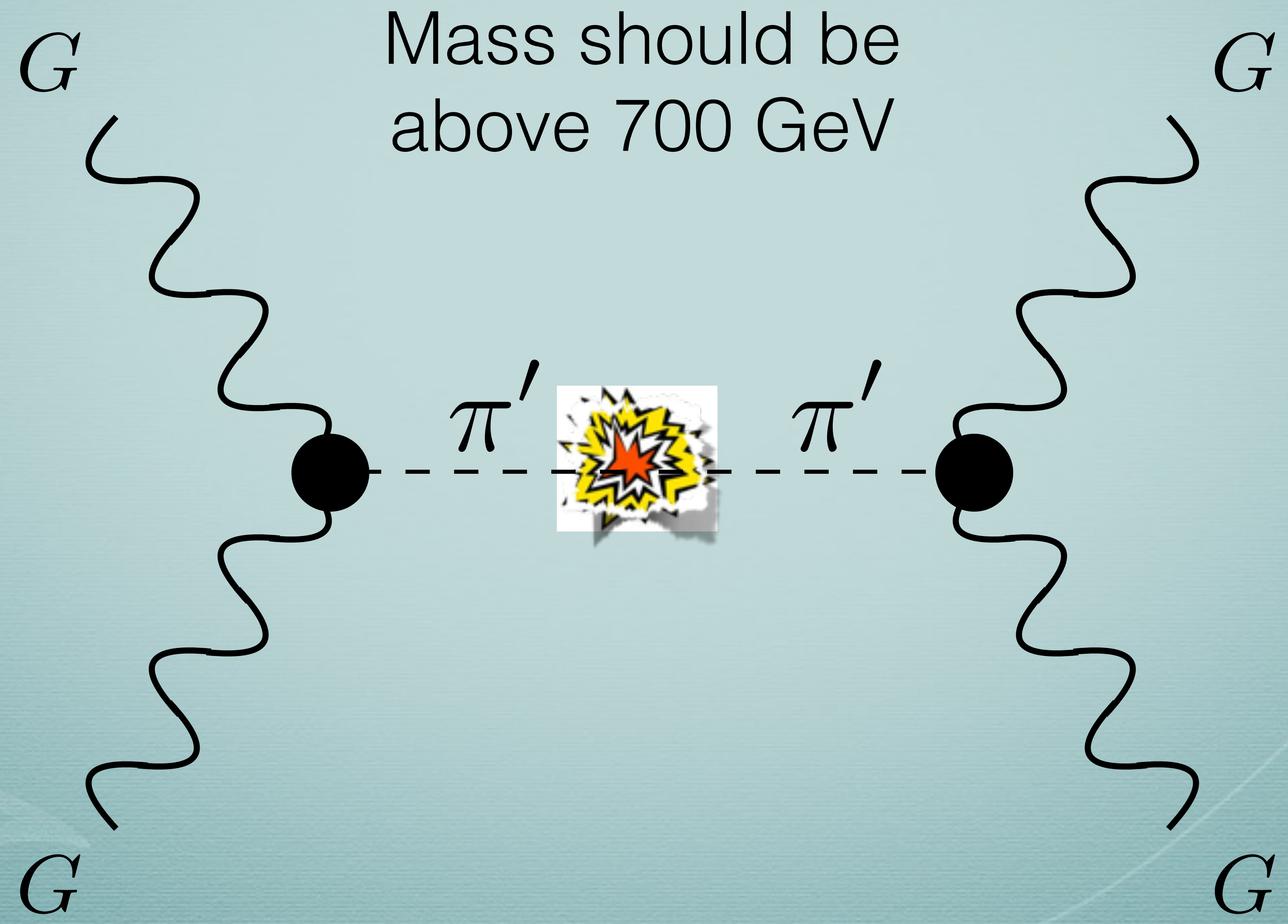
$$m_{\pi'}^2 \approx \frac{9\alpha_s}{4\pi} m_{\rho'}^2$$

Low energy Observables

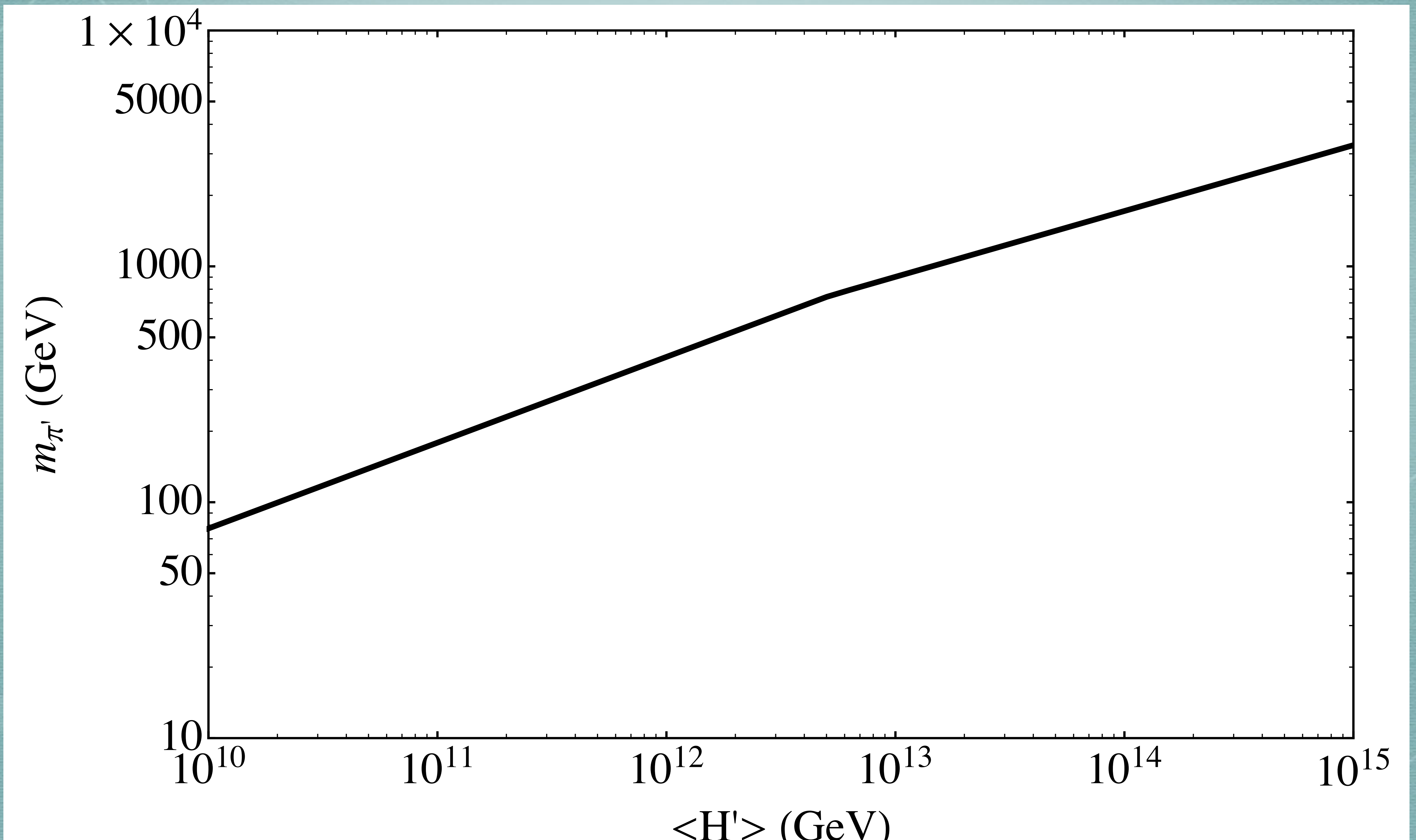


Pions decay through the anomaly into a pair of gluons

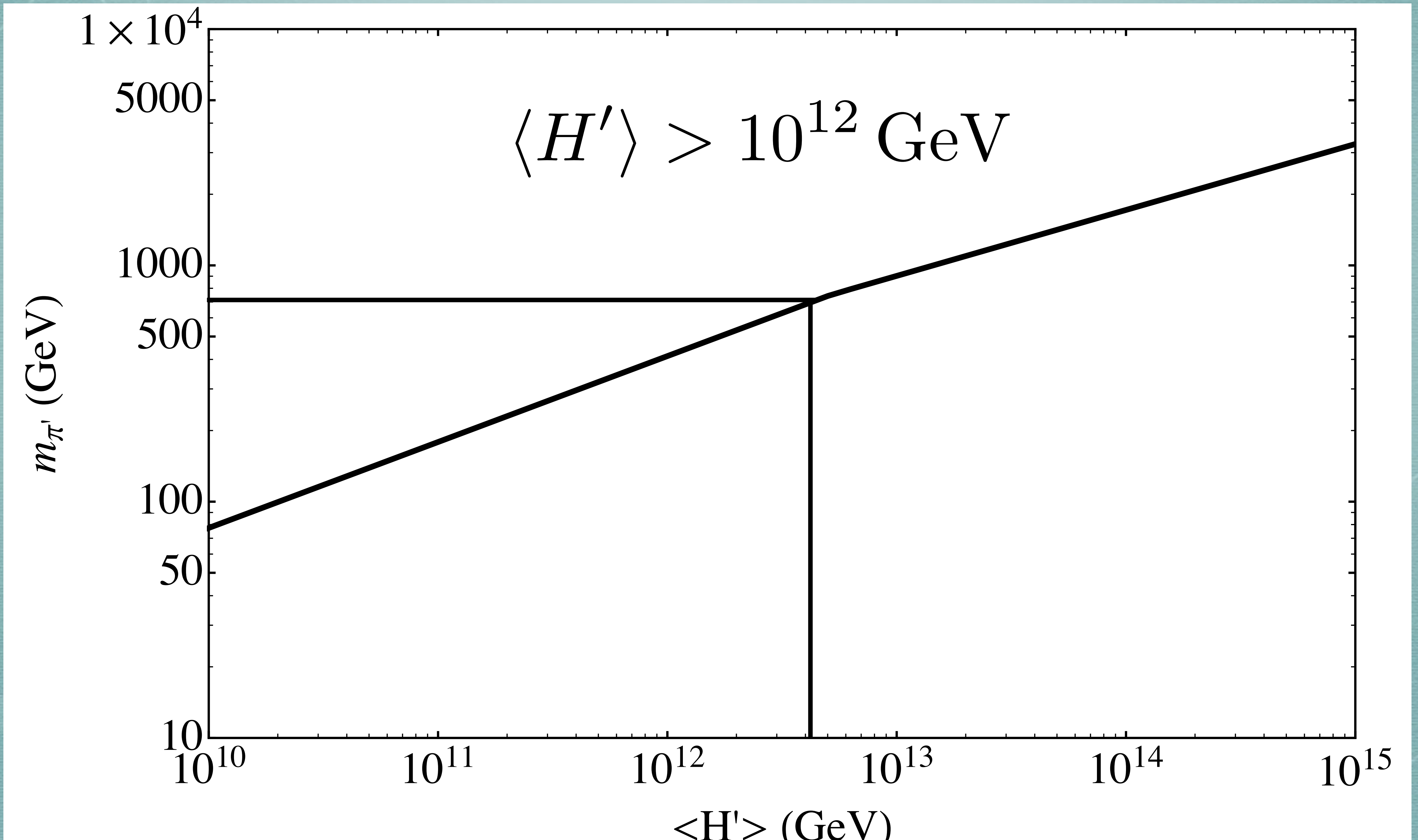
Low energy Observables



Low energy Observables



Low energy Observables

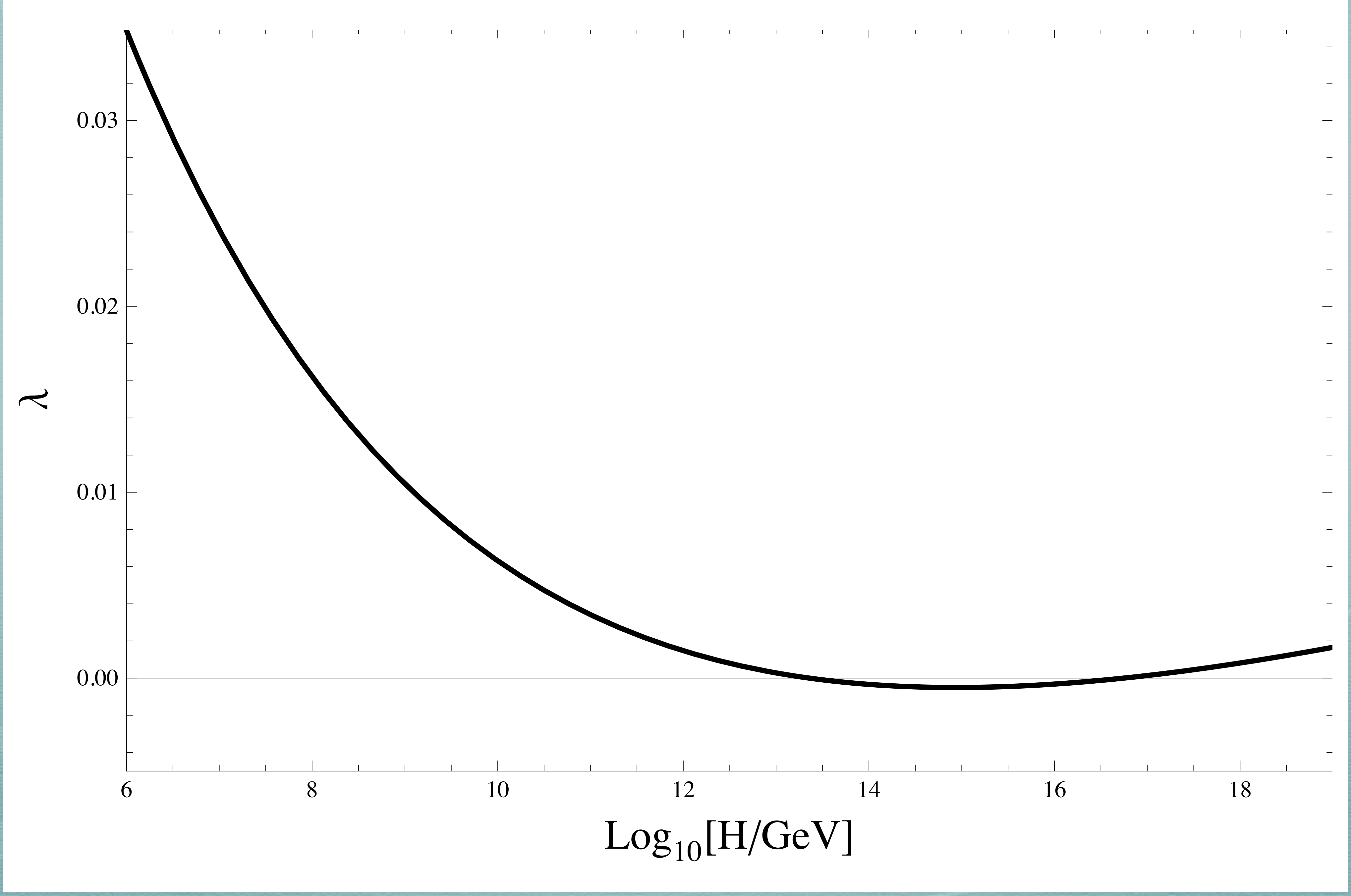


Z_2 symmetry breaking

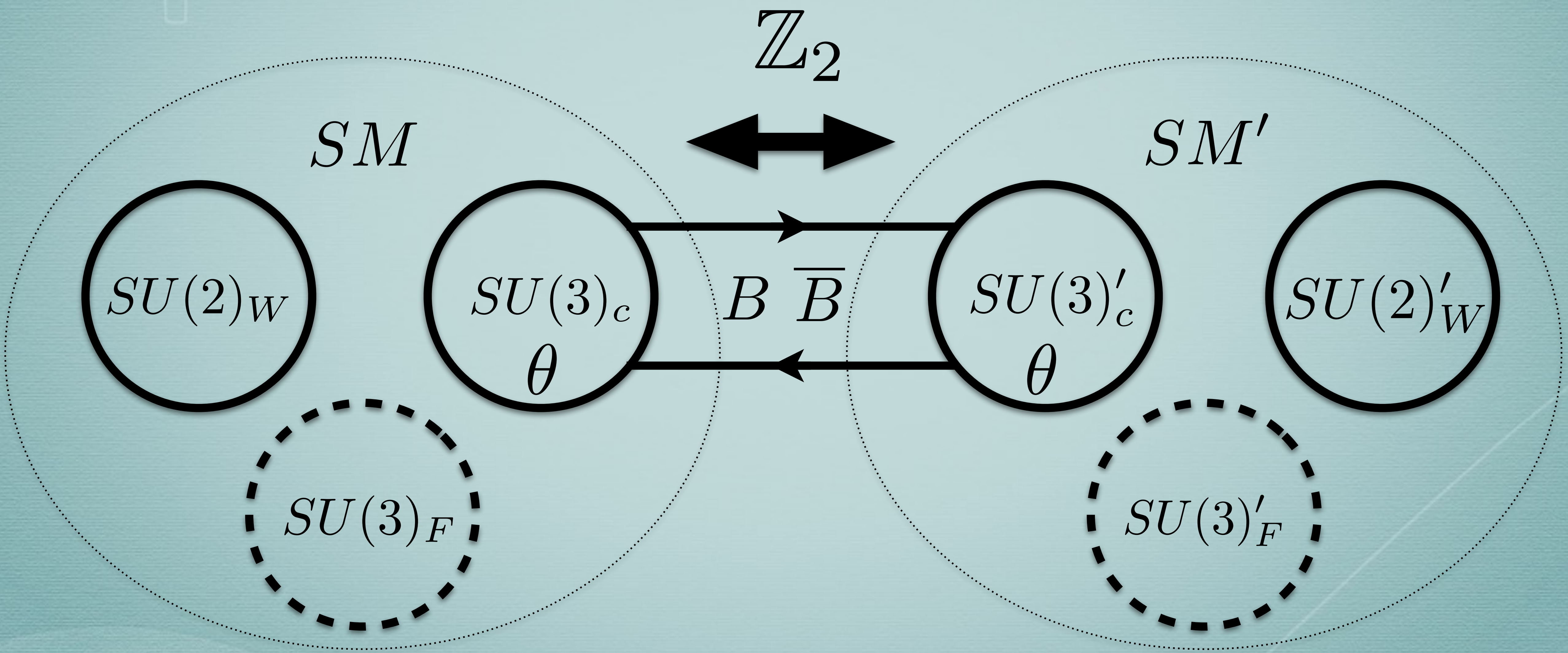
$$\langle H' \rangle > 10^{12}\,\mathrm{GeV}$$

- Z_2 symmetry needs to be broken
  - Second hierarchy problem will be solved using the new mechanism
- Model has two Higgs vacua for certain ranges of parameters
  - Will be slight tension with higher dimensional operators

Z_2 symmetry breaking



Quartic


$\mathbb{Z}_2$
SM
SM'
$SU(2)_W$
$SU(3)_c$
θ
$B\ \overline{B}$
$SU(3)'_c$
θ
$SU(2)'_W$
$SU(3)_F$
$SU(3)'_F$

Quartic

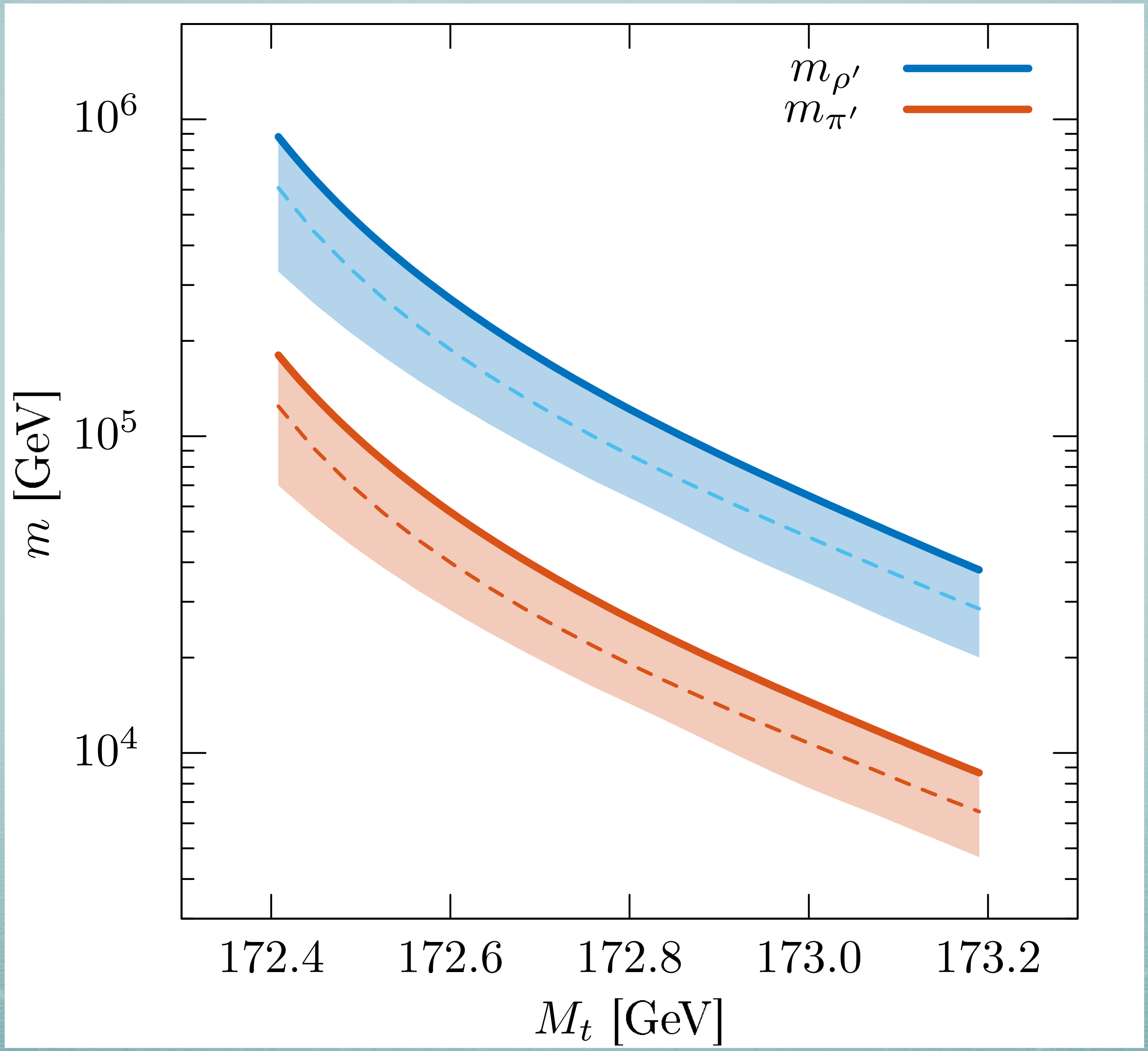
- Bi-fundamentals drive quartic positive at 3-loops
  - New gauge charged matter keeps gauge couplings large
  - SU(3) gauge coupling drives top yukawa small
- Top yukawa drives it negative at 1-loop
- Unlike SM, can have new minimum at sub Planckian field values

Quartic

- Top yukawa + bi-fundamentals determine Higgs vacua
- Higgs vacua determines when bi-fundamentals appear
- Recursively find a solution

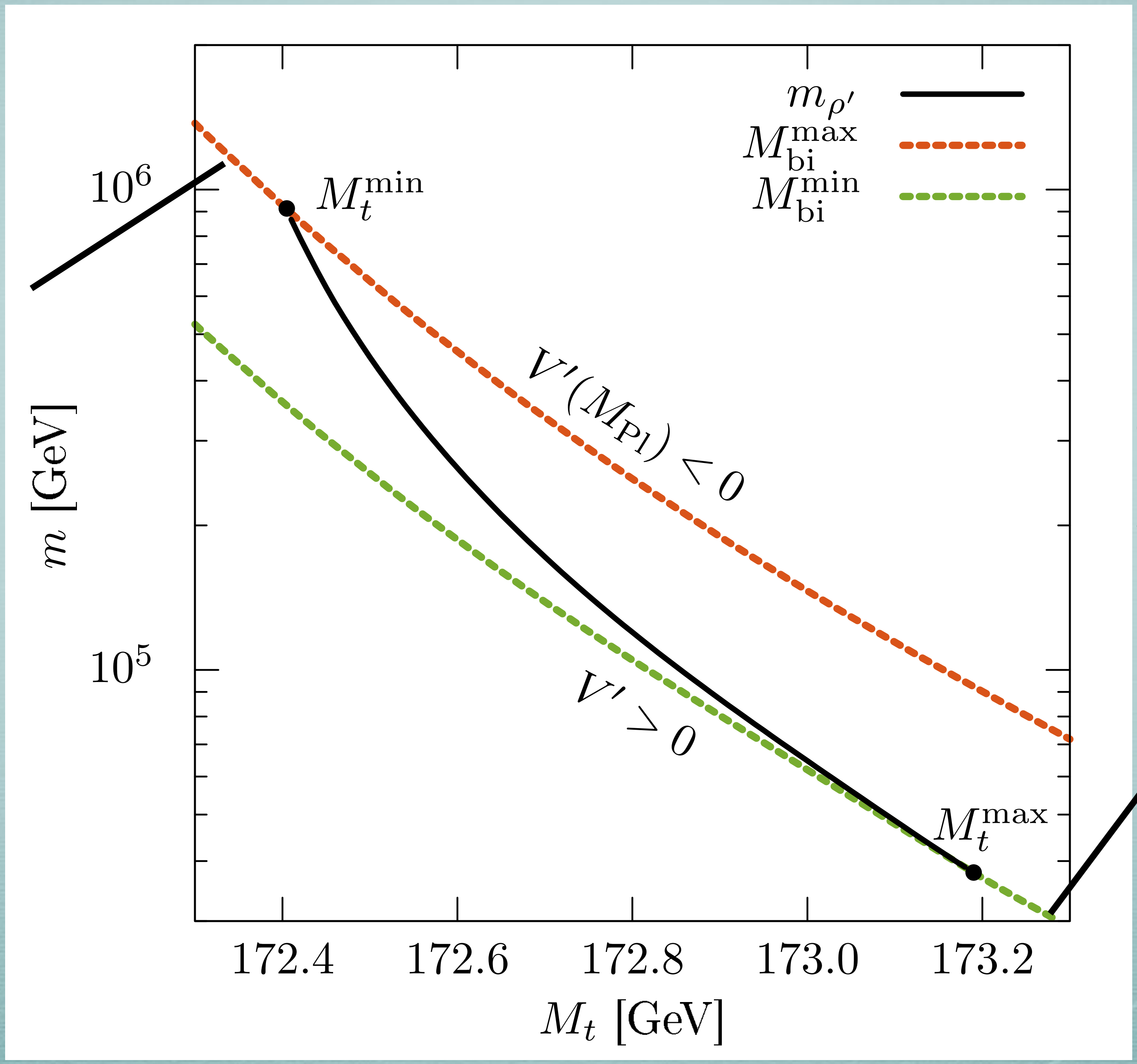
Quartic

New particles at a
100+ TeV collider



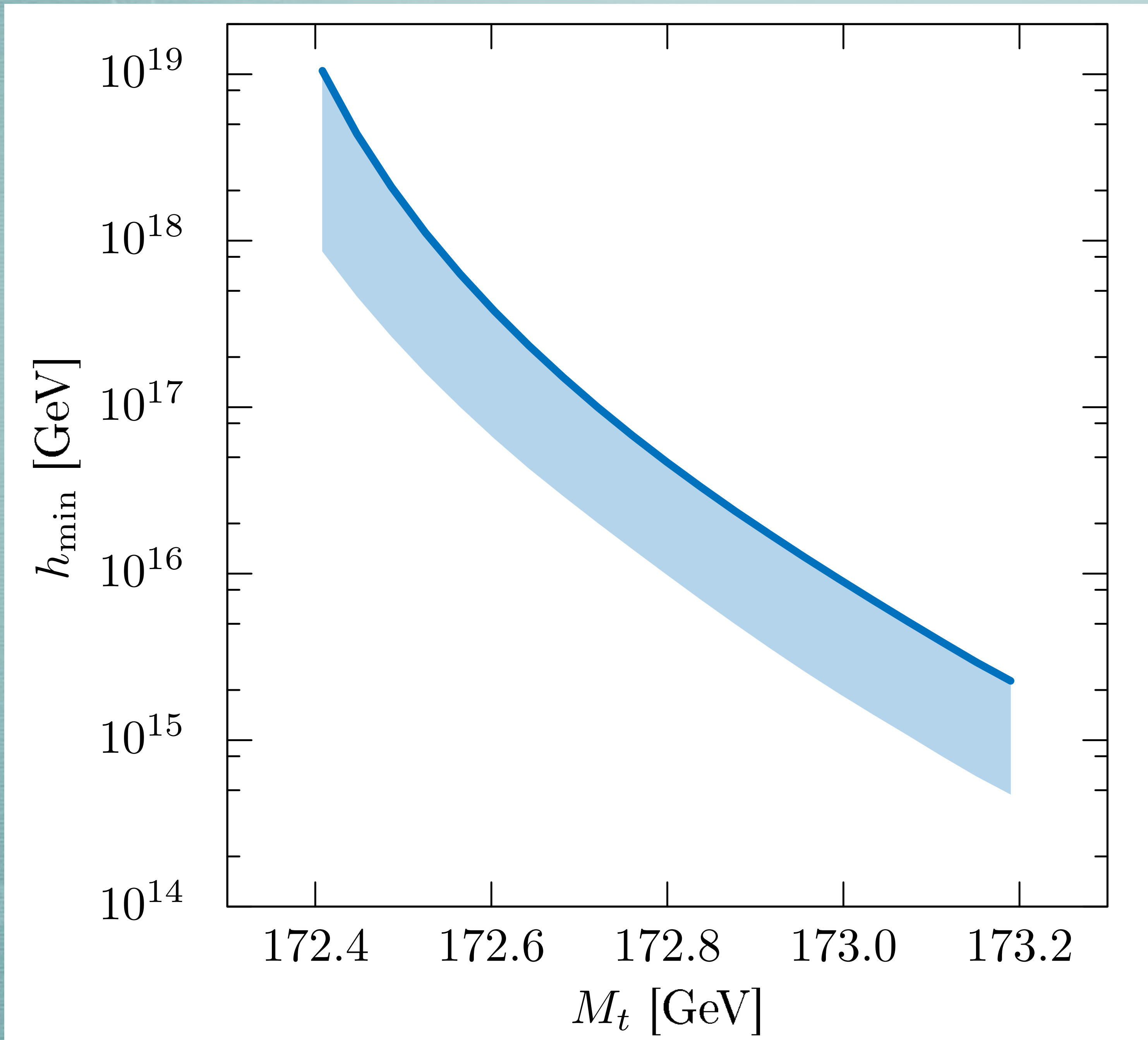
Quartic

Higgs vev at Planck Scale



Bifundamental can no longer stabilize potential

Quartic



Necessarily have problems with higher dimensional operators

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

$$\bar{\theta}=\frac{H'H'^\dagger-HH^\dagger}{M_p^2}\approx\frac{\langle H'\rangle^2}{M_p^2}\gtrsim 10^{-8}$$

Top quark mass

$$172.4\,\mathrm{GeV} < M_t < 173.2\,\mathrm{GeV}$$

$$M_t = 173.34 \pm 0.87\,\mathrm{GeV}$$

Postdict top mass to within 1 sigma!

Conclusion

- Solving the wrong problem can be very productive!
- Strong CP problem postdict top quark mass
    - Dimensional transmutation of Higgs quartic renders theory extremely predictive
    - Top quark mass precisely predicted
    - Color Octets in the 10-100 TeV range
    - Tension with Planck suppressed operators