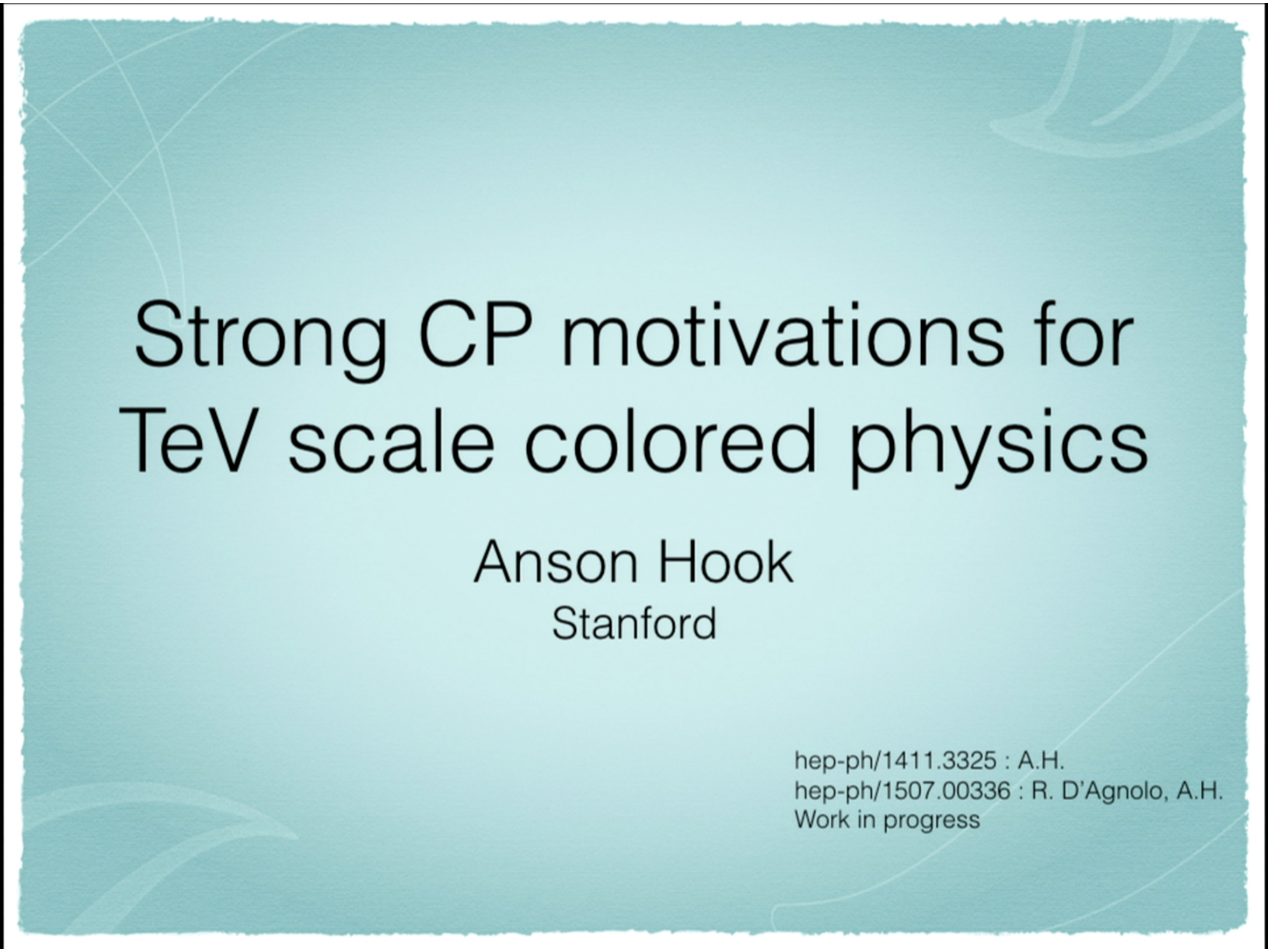
Title: Confronting the strong CP problem at the LHC

Date: Nov 17, 2015 01:00 PM

URL: http://pirsa.org/15110065

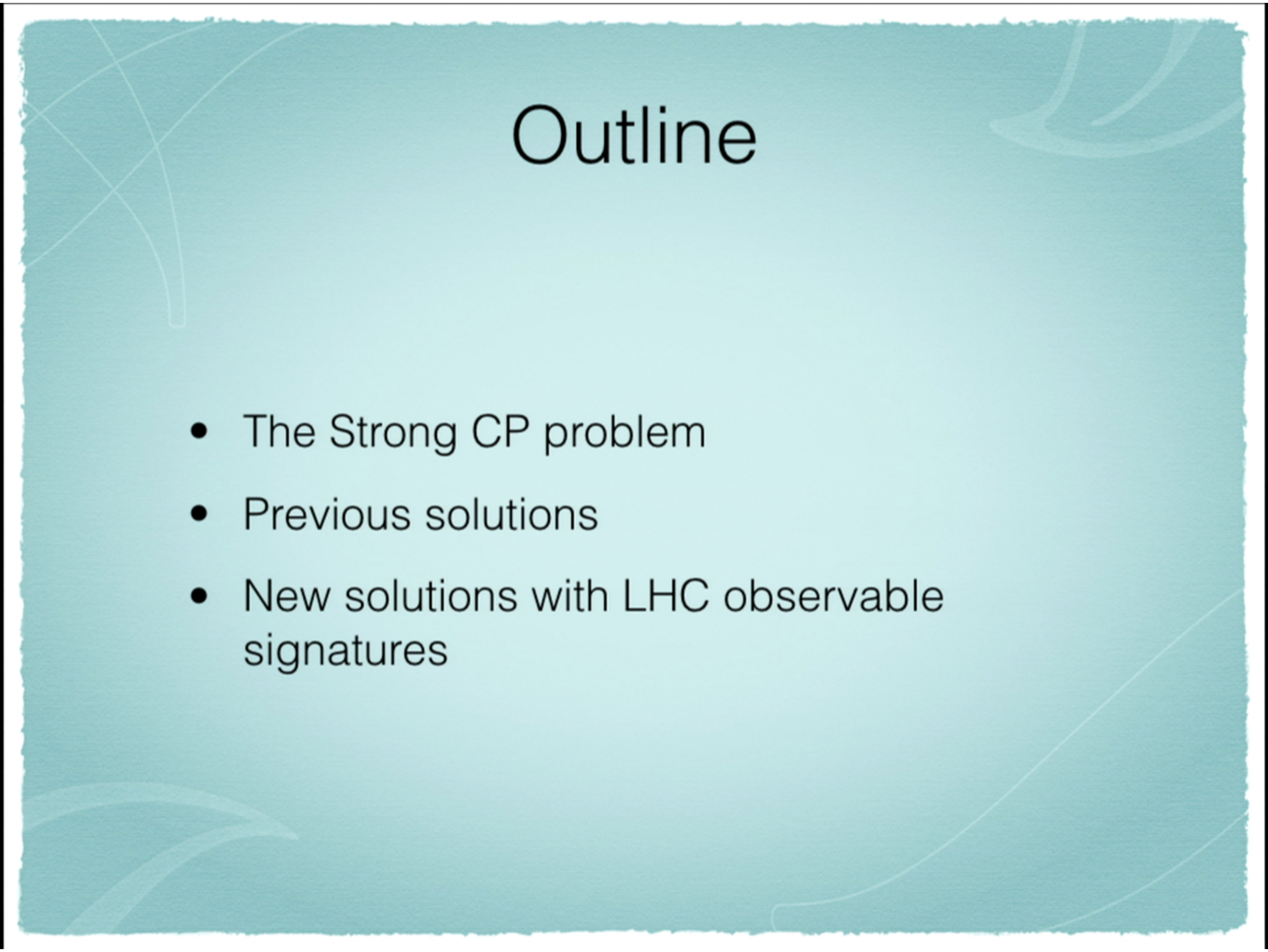
Abstract: <p>We argue that solutions to the strong CP problem motivate different searches for TeV scale physics at the LHC than are currently being emphasized. We present two solutions to the strong CP problem that require the existence of new colored particles with masses below 10 TeV. New motivated searches at the LHC would provide a strong constraint on these solutions to the strong CP problem.</p>



Strong CP motivations for TeV scale colored physics

Anson Hook
Stanford

hep-ph/1411.3325 : A.H.
hep-ph/1507.00336 : R. D'Agnolo, A.H.
Work in progress

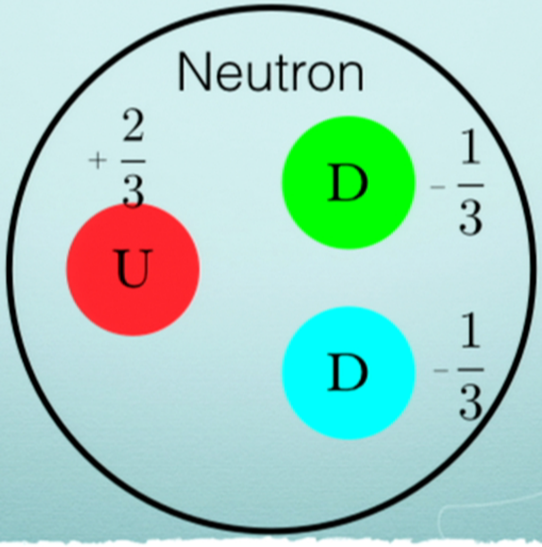


Outline

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

Classical Strong CP problem

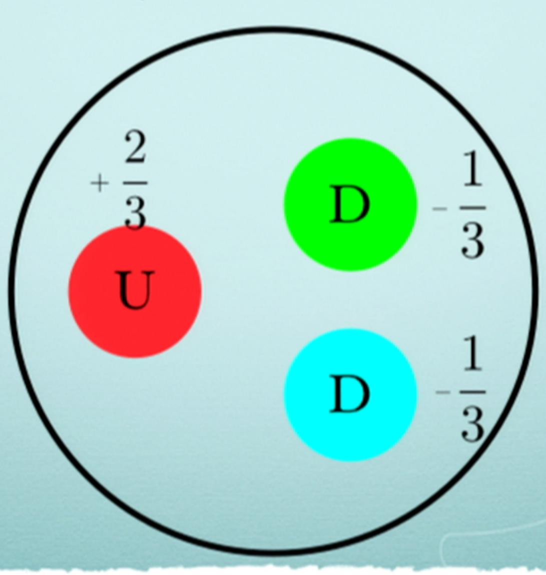
Neutron contains an up quark and two down quarks

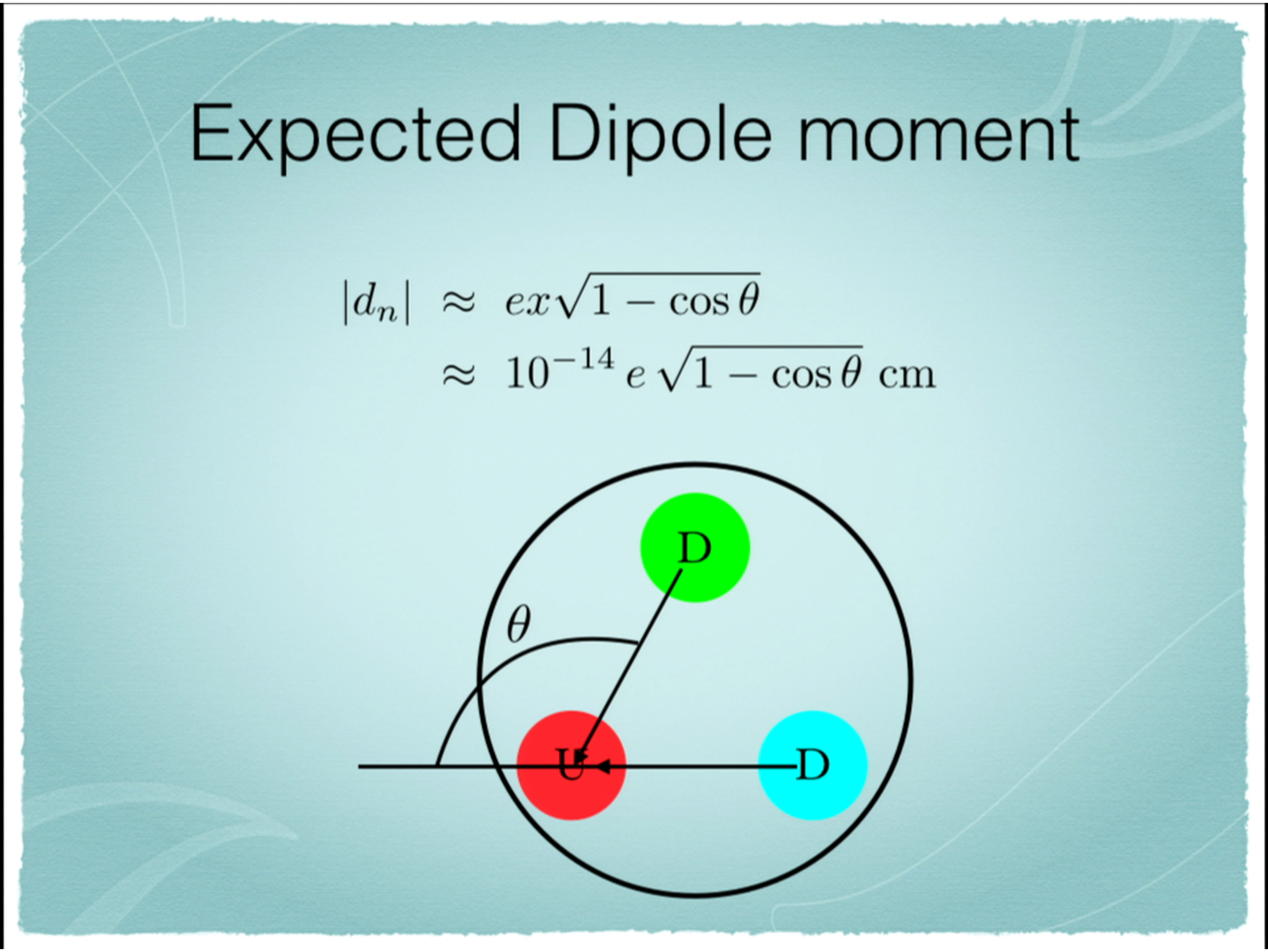


Classical Strong CP problem

Electric Dipole moment

$$d_n = qx$$





Expected Dipole moment

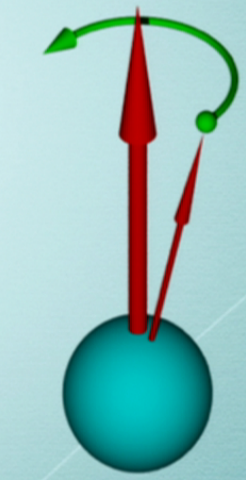
$$\begin{aligned} |d_n| &\approx ex\sqrt{1-\cos\theta} \\ &\approx 10^{-14}\,e\,\sqrt{1-\cos\theta}\ \mathrm{cm} \end{aligned}$$

Measurement of EDM

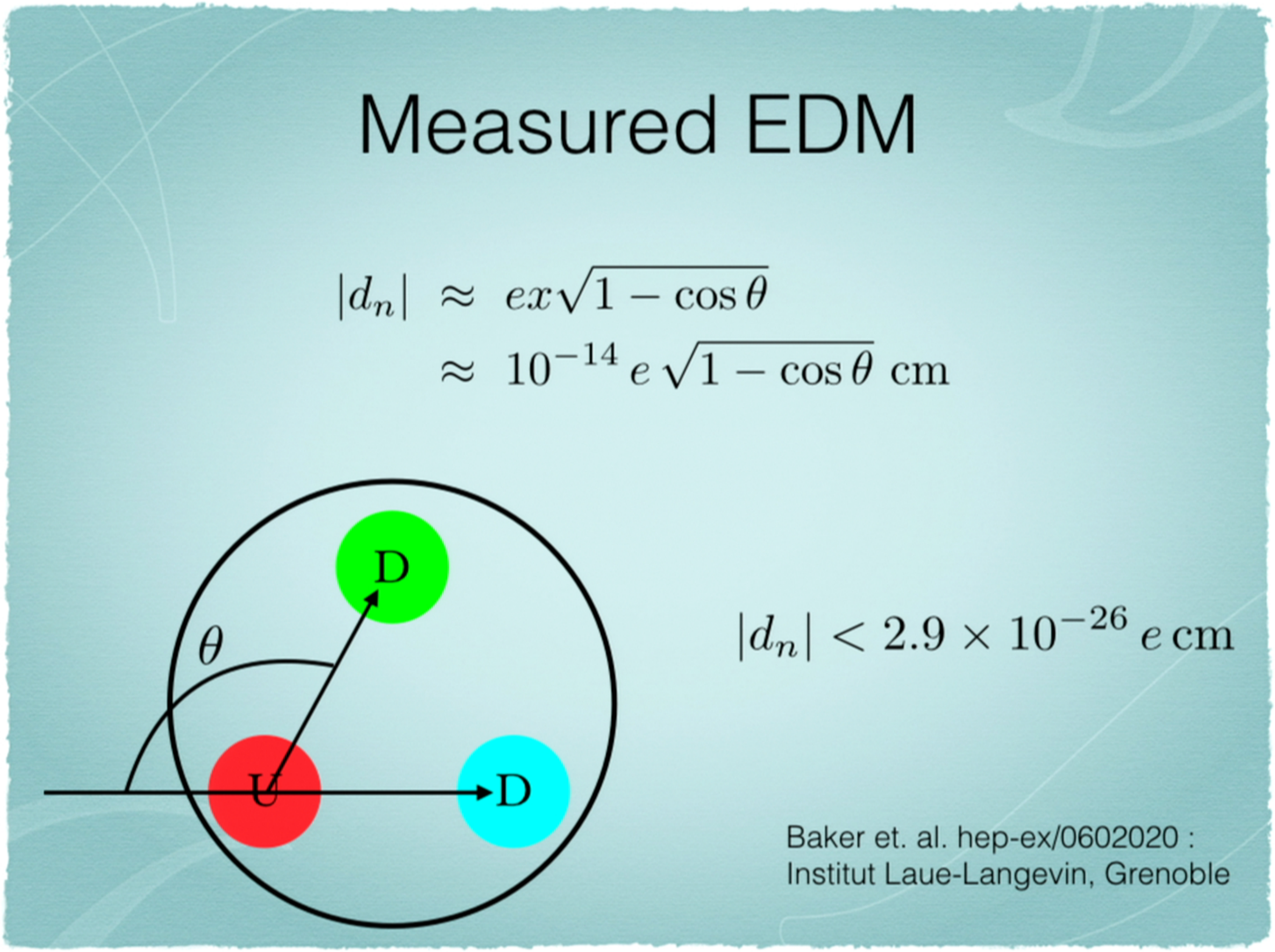
- Measurement via Larmor frequency

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

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



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



Measured EDM

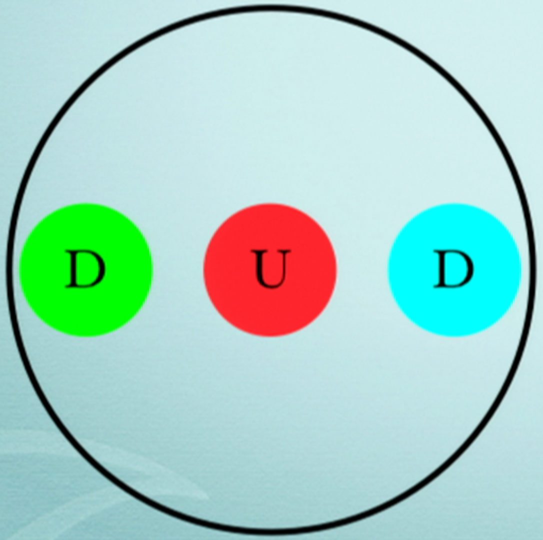
$$
\begin{aligned}
|d_n| &\approx ex\sqrt{1-\cos\theta} \\
&\approx 10^{-14}\,e\,\sqrt{1-\cos\theta}\ \mathrm{cm}
\end{aligned}
$$

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

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!

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

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

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

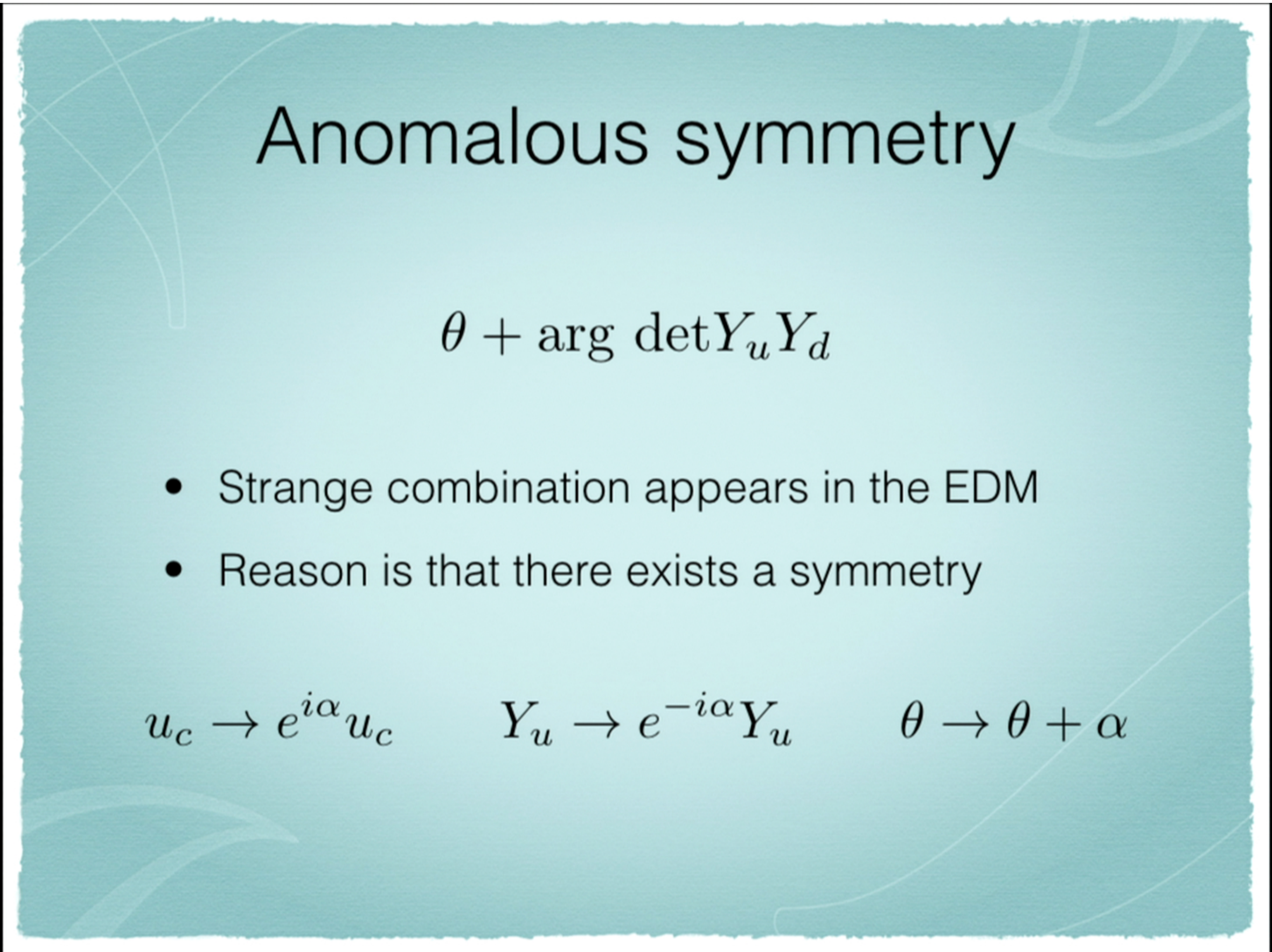
QFT formulation of the Strong CP problem

Discrete symmetries

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

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

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



Anomalous symmetry

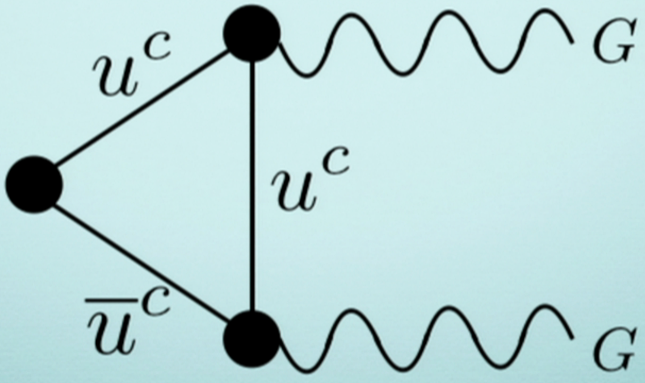
$$\theta + \arg\,\det Y_u Y_d$$

- 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

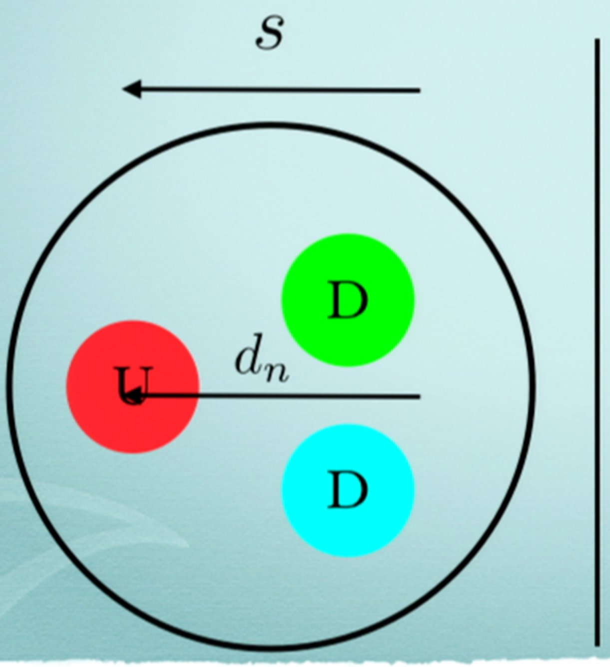
- ~~The Strong CP problem~~
- Previous solutions
- New solutions with LHC observable signatures

Discrete Symmetries

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

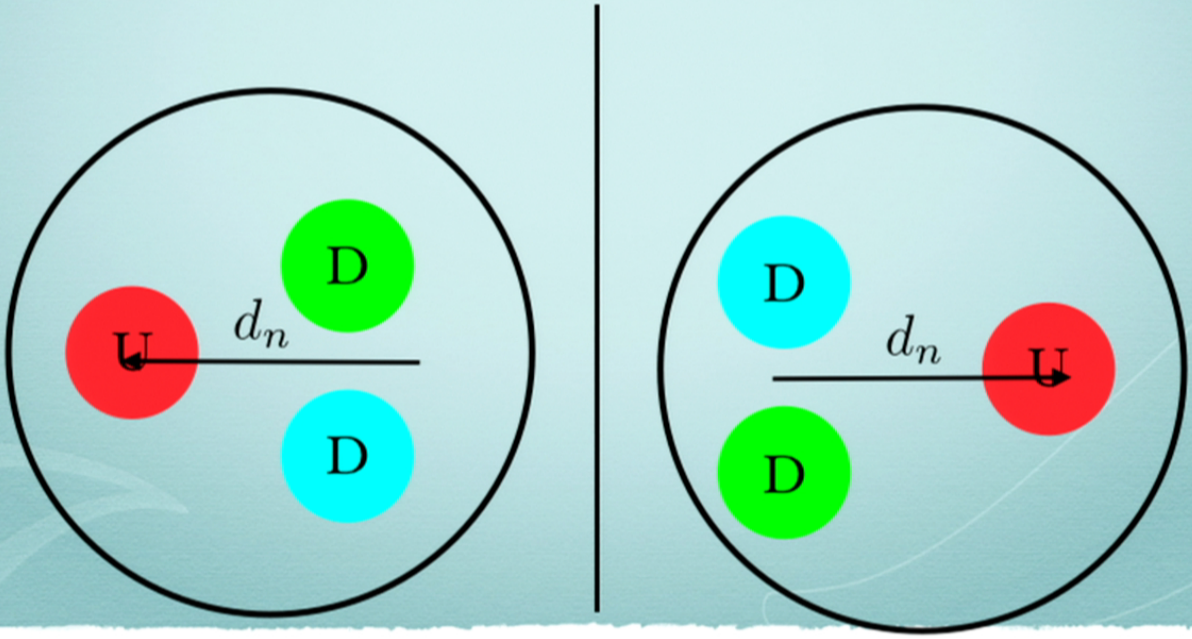
Parity

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

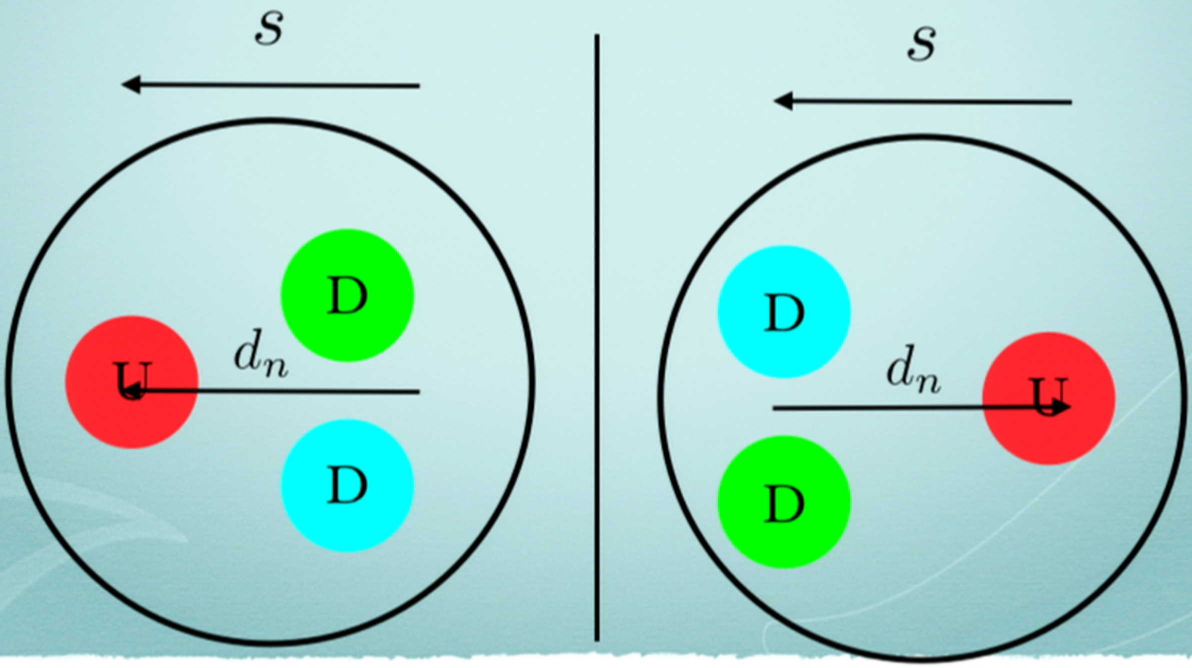


Parity

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

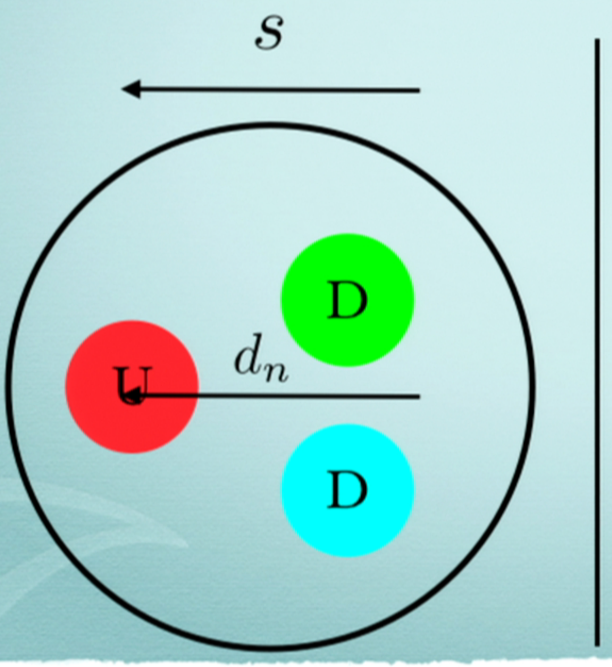


Parity



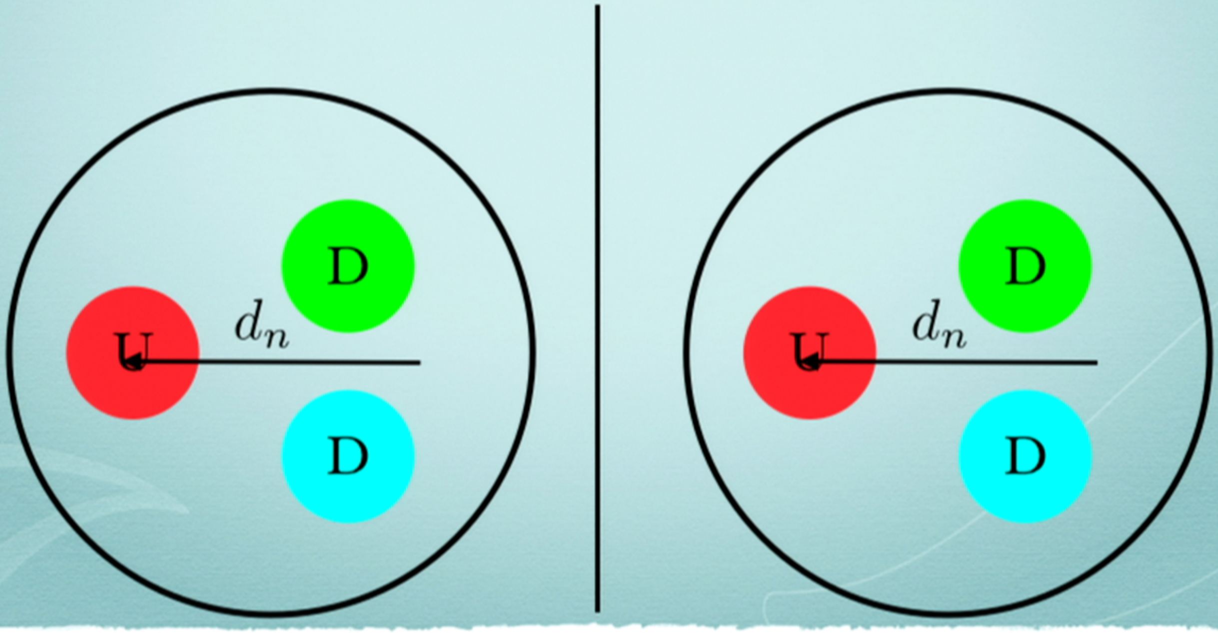
Time reversal

$$t \Rightarrow -t$$



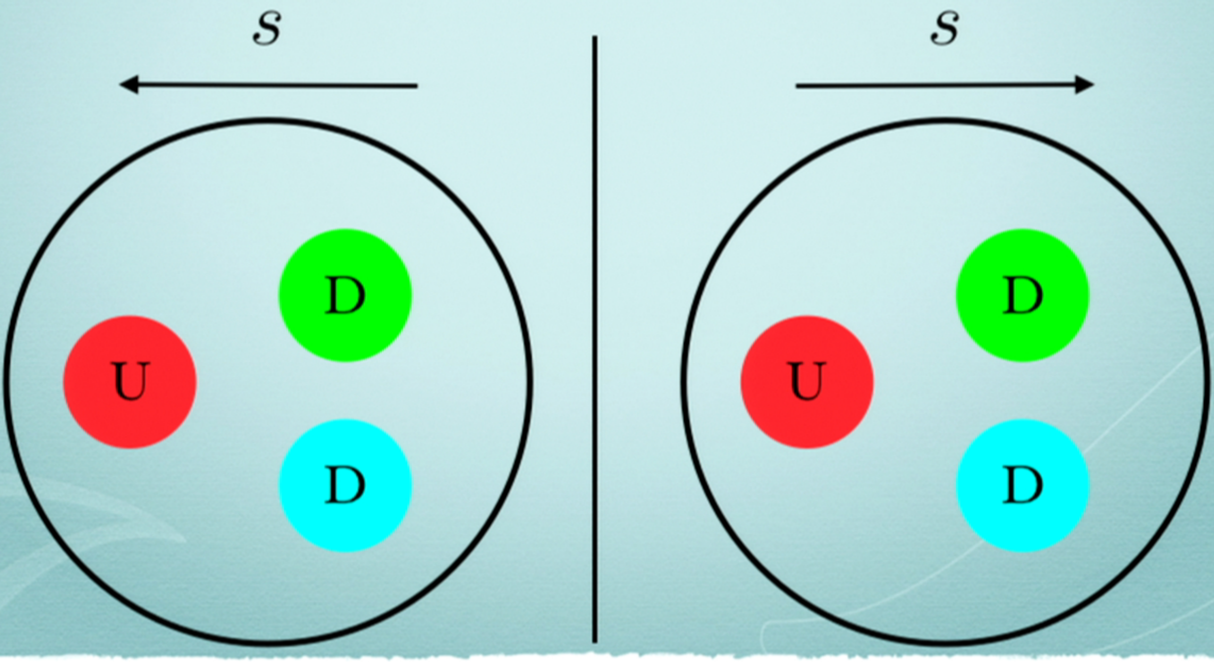
Time reversal

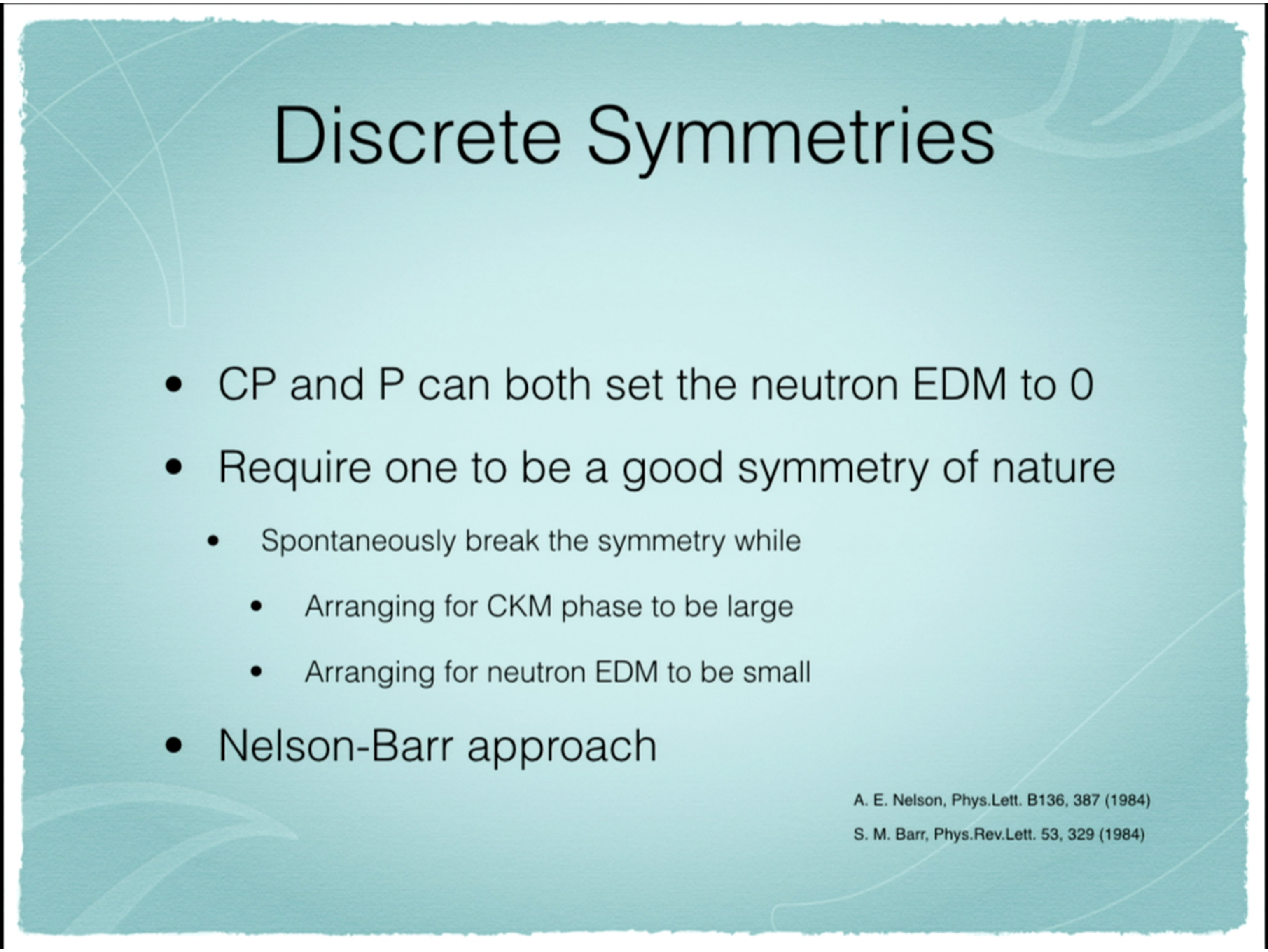
$$\vec{d}_n = q\vec{x} \qquad \vec{d}_n \Rightarrow \vec{d}_n$$



Time reversal

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





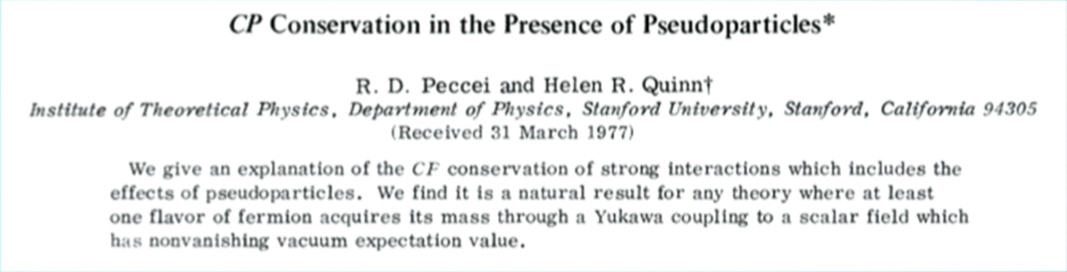
Discrete Symmetries

- 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)

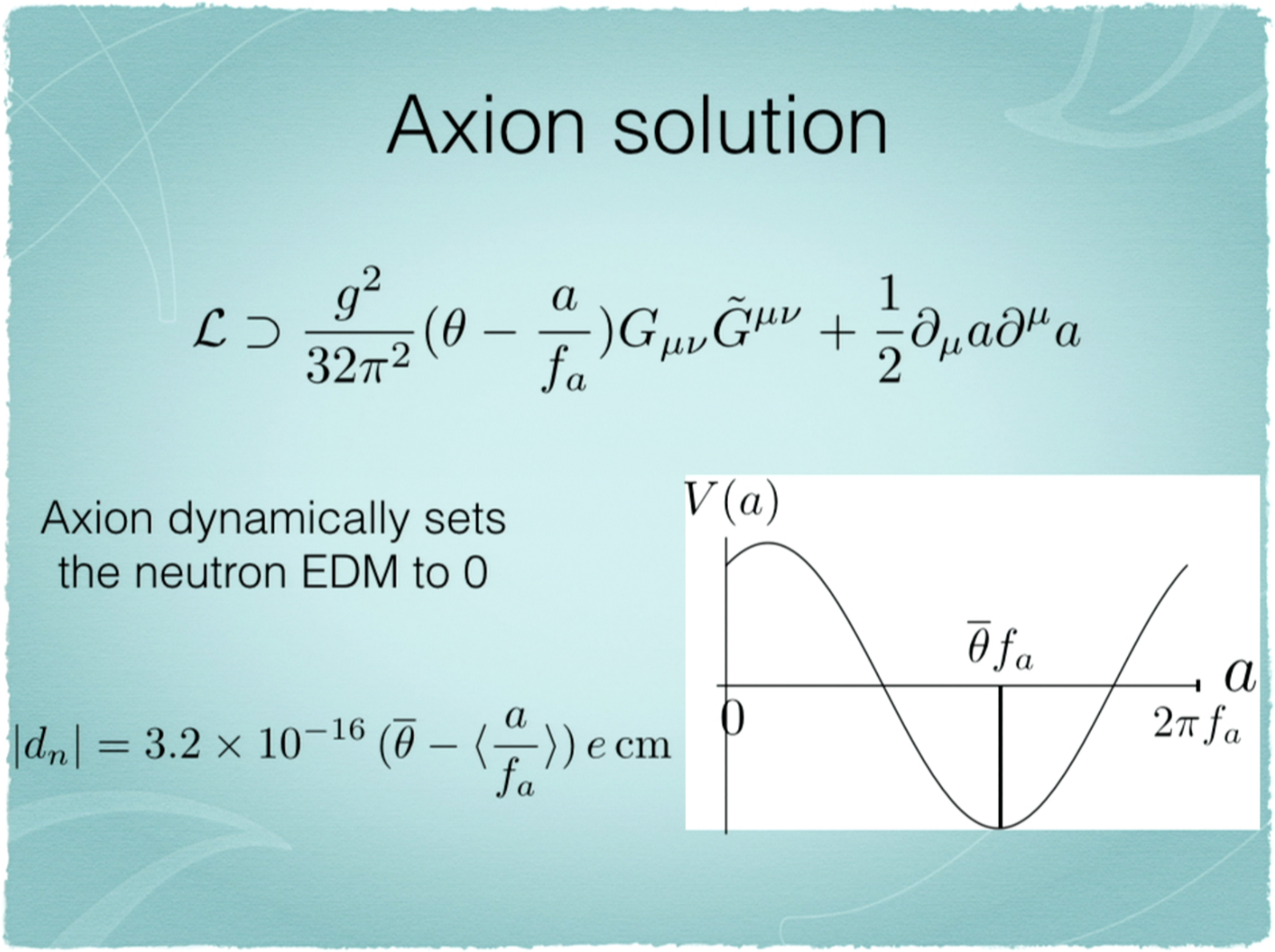
Axion solution



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 *CF* 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.

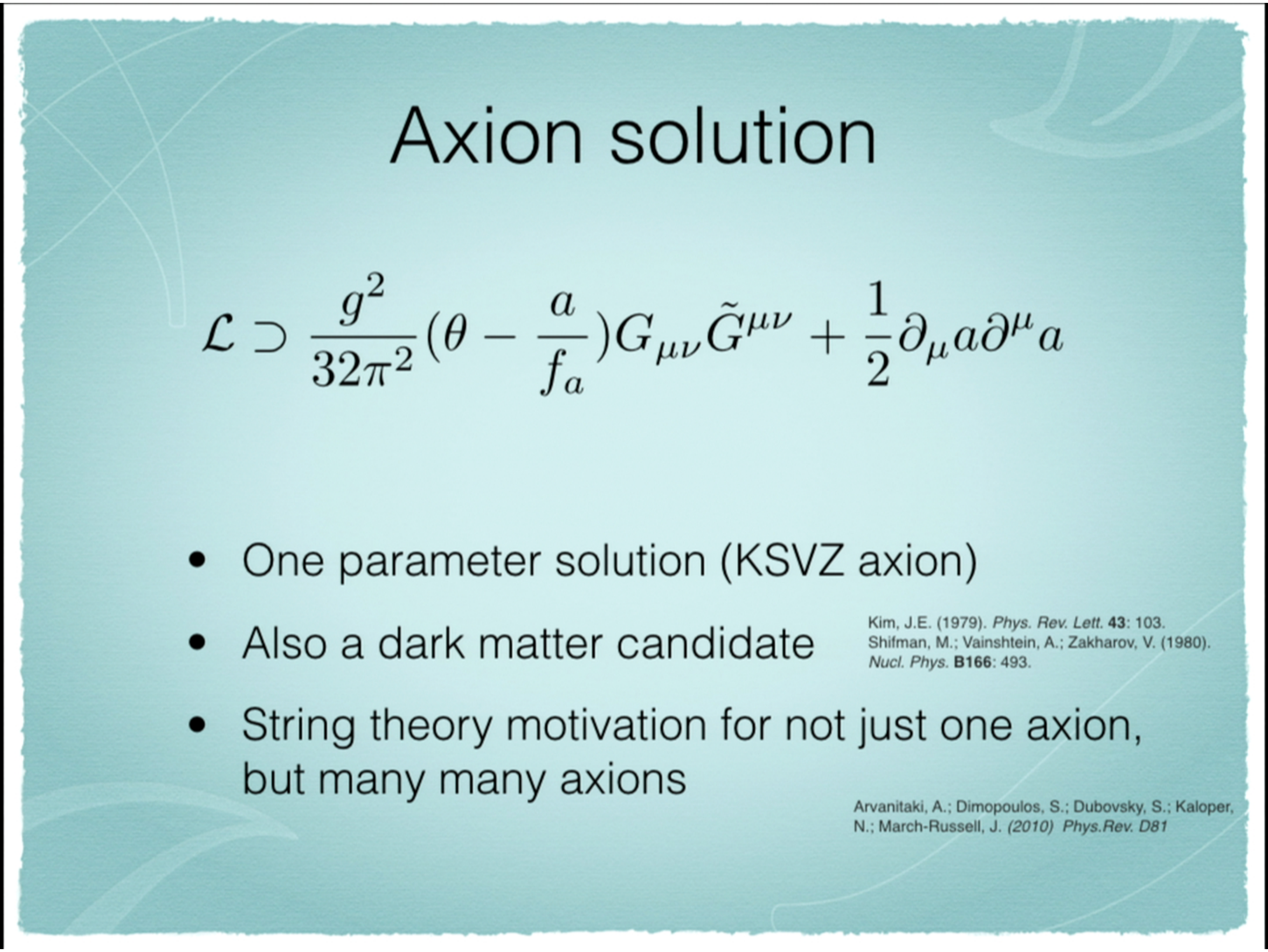


Axion solution

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

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

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

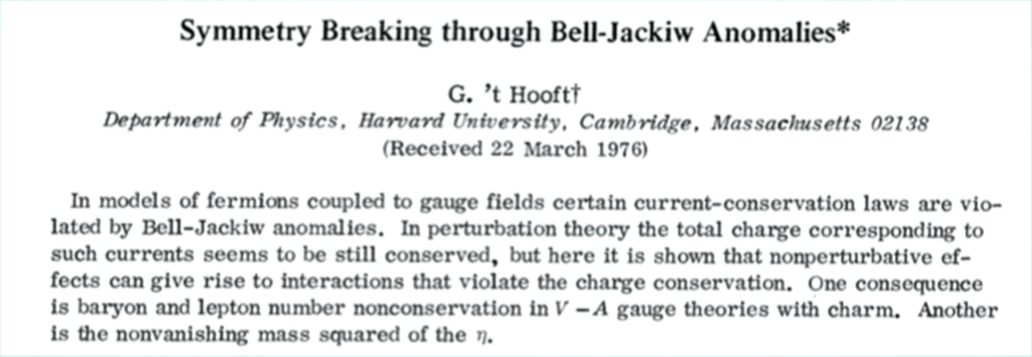
- String theory motivation for not just one axion, but many many axions

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

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.

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

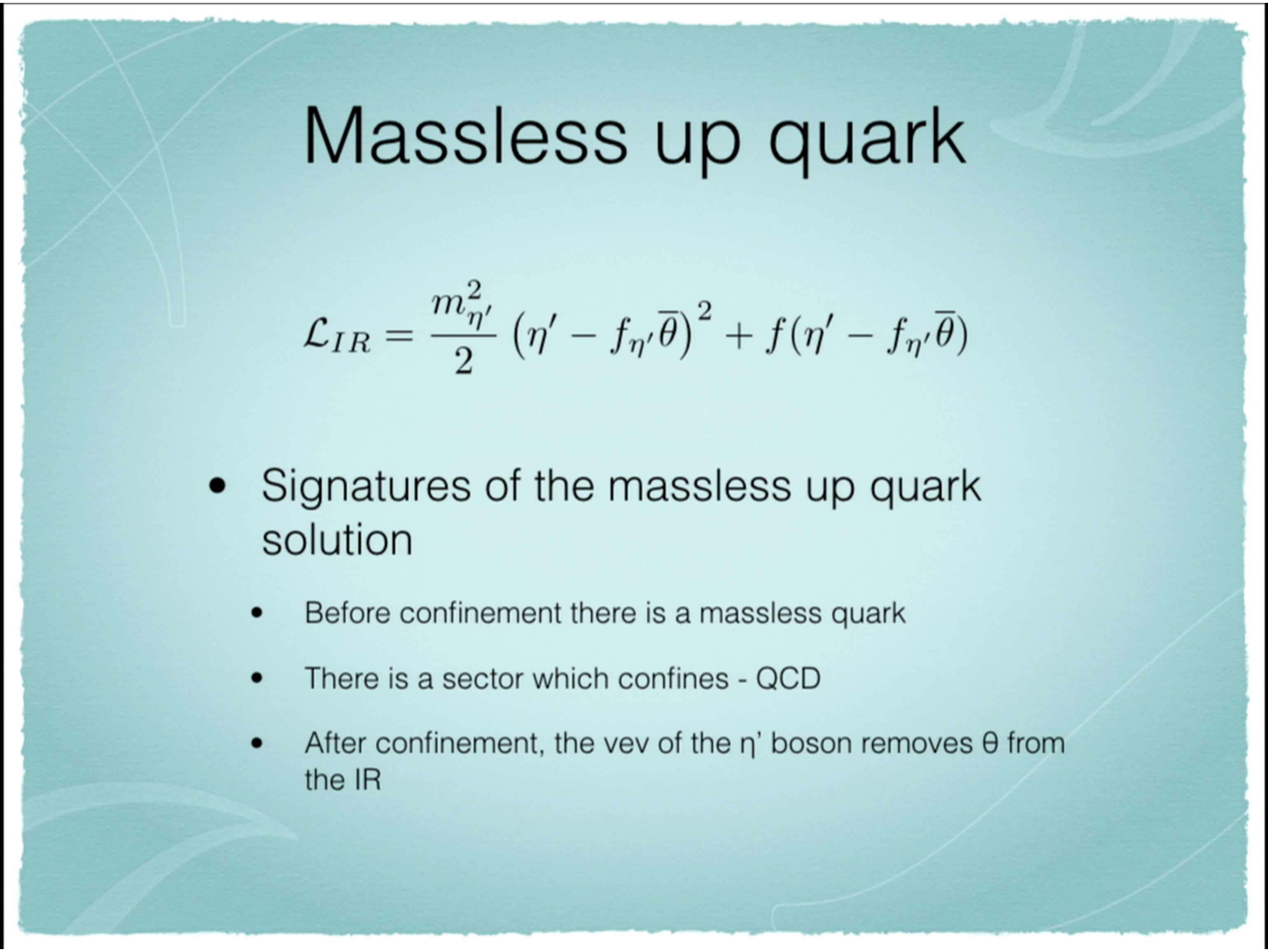
No invariant to construct EDM out of

Must vanish

Massless up quark

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

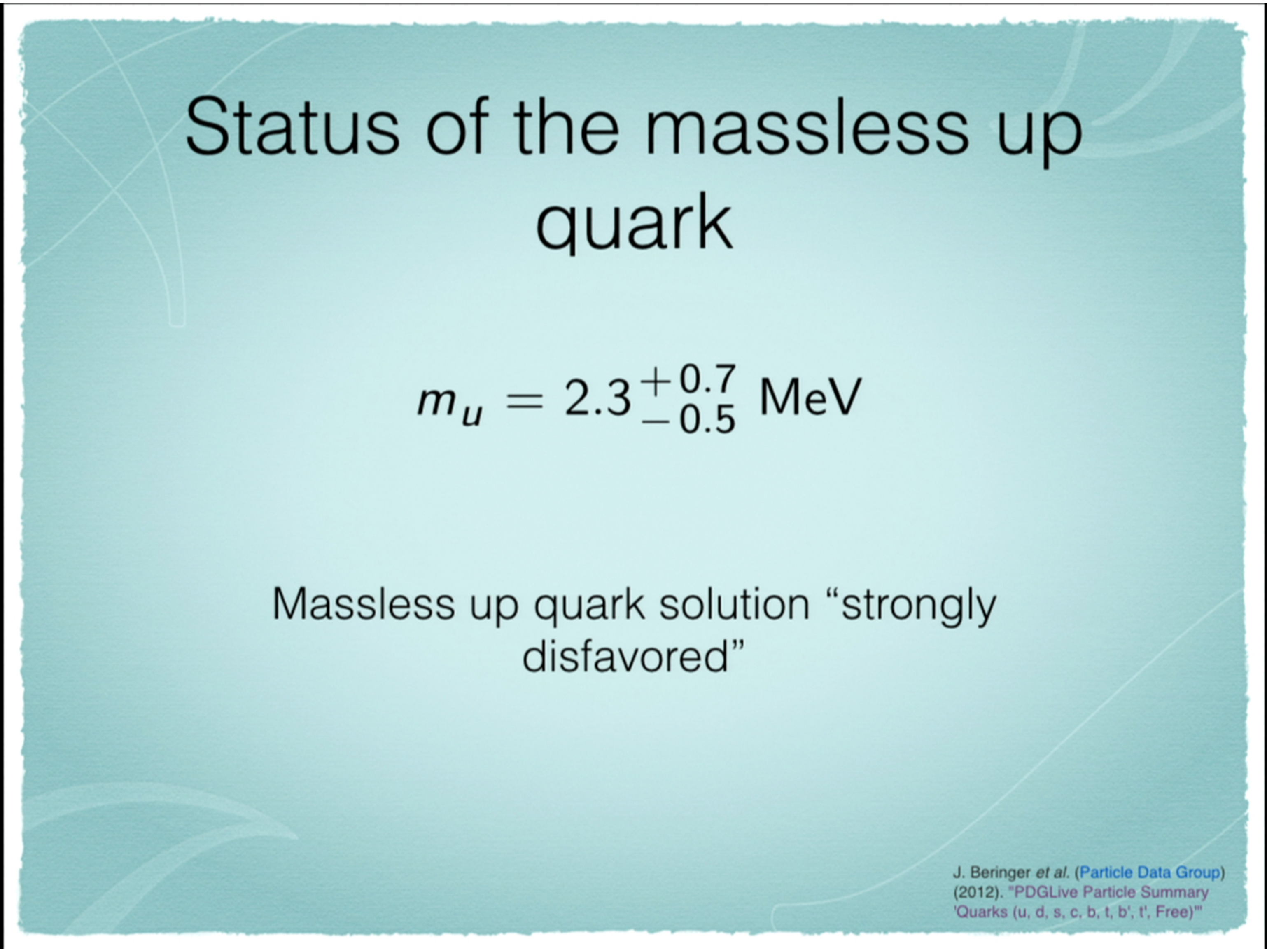
$$m_u \to 0 \qquad \Rightarrow \qquad d_n \to 0$$



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)'"

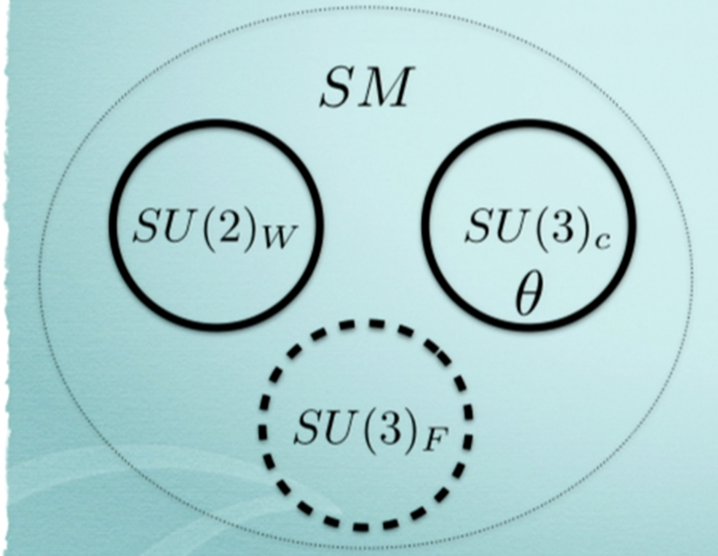
Generalized massless up quark solution

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

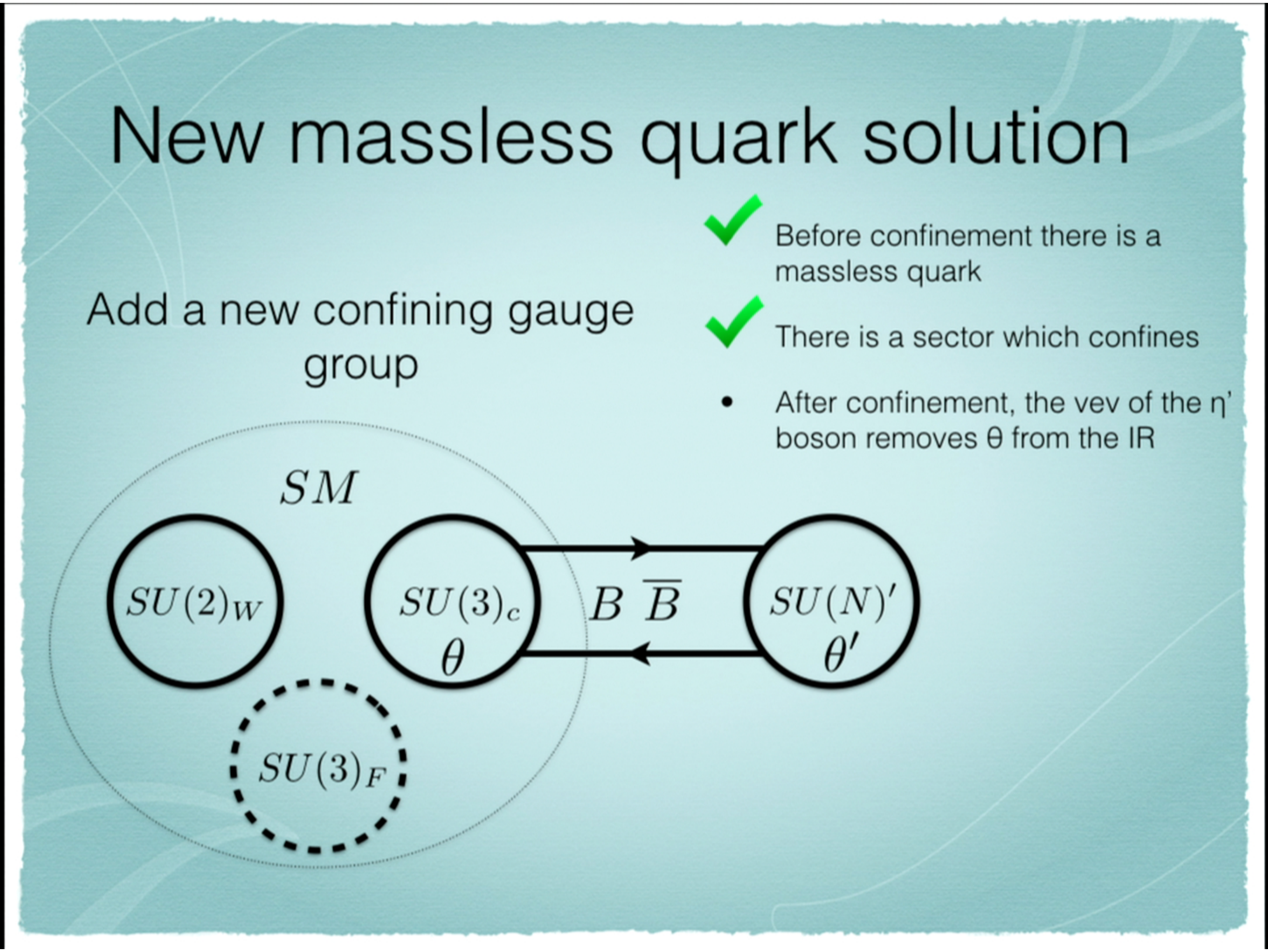
Generalized massless up quark solution

- 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
- 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

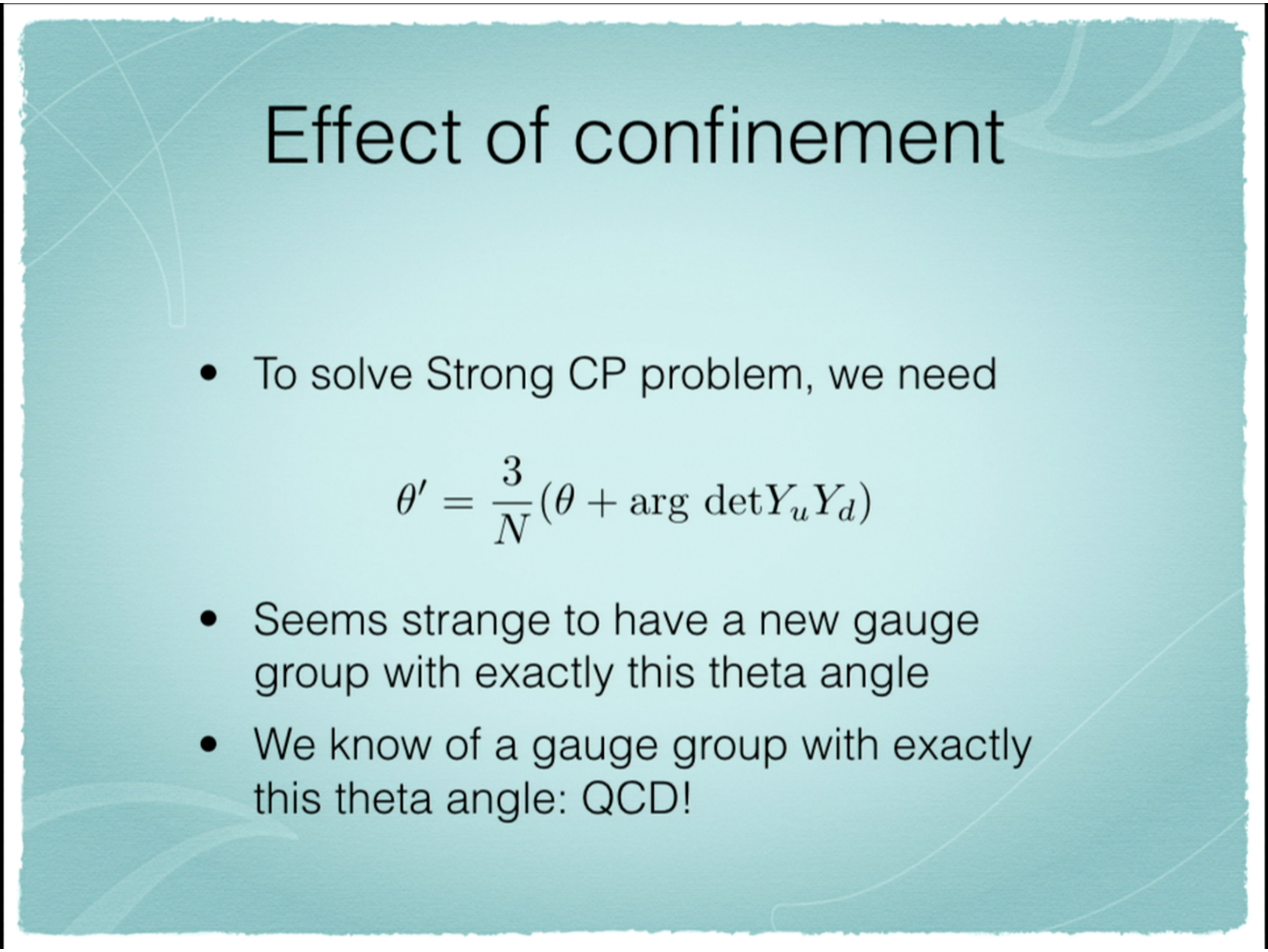
$$\overline{\theta} = \theta + \arg\,\det Y_u Y_d - \frac{N}{3}\theta'$$

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

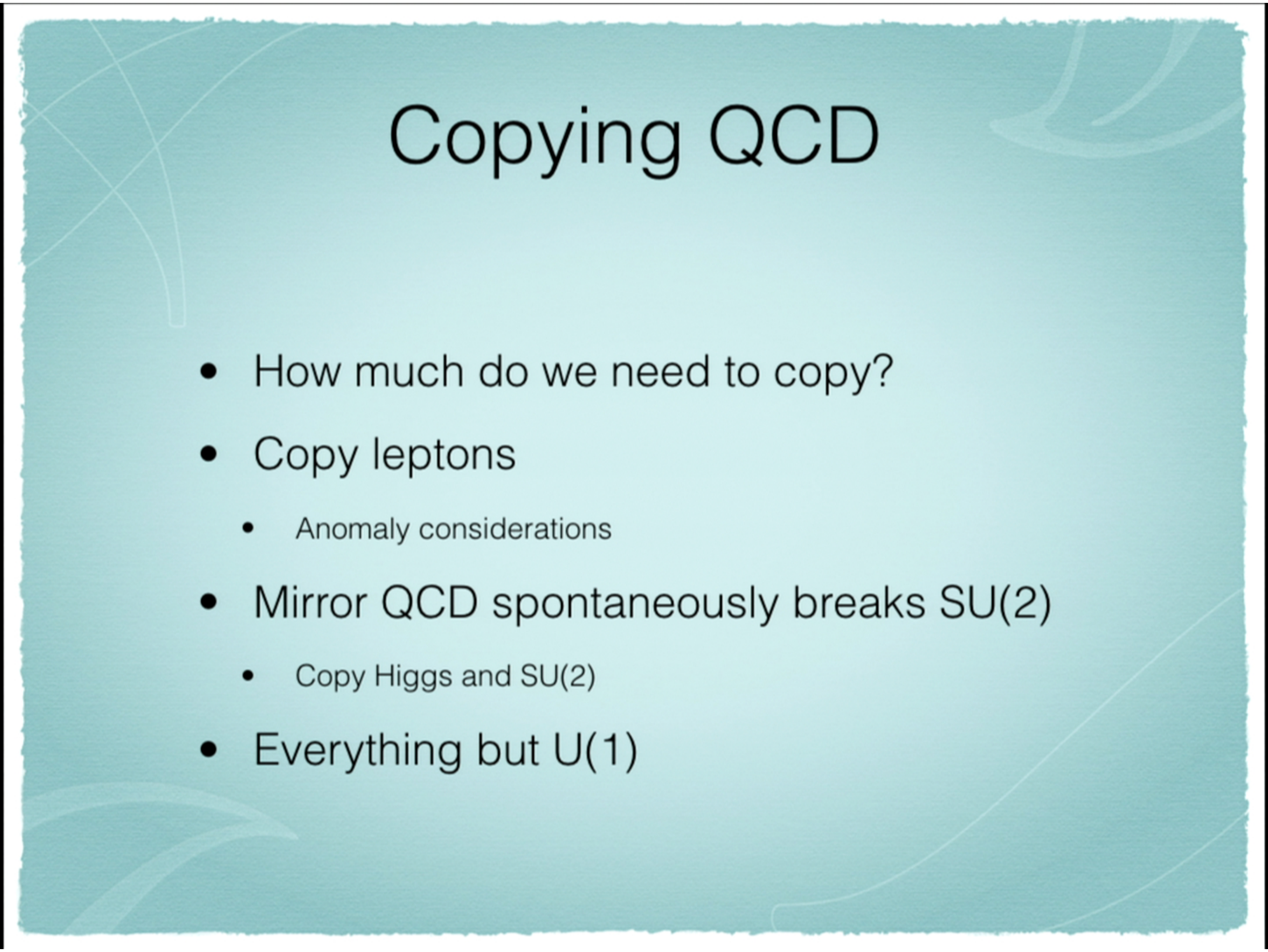


Effect of confinement

- To solve Strong CP problem, we need

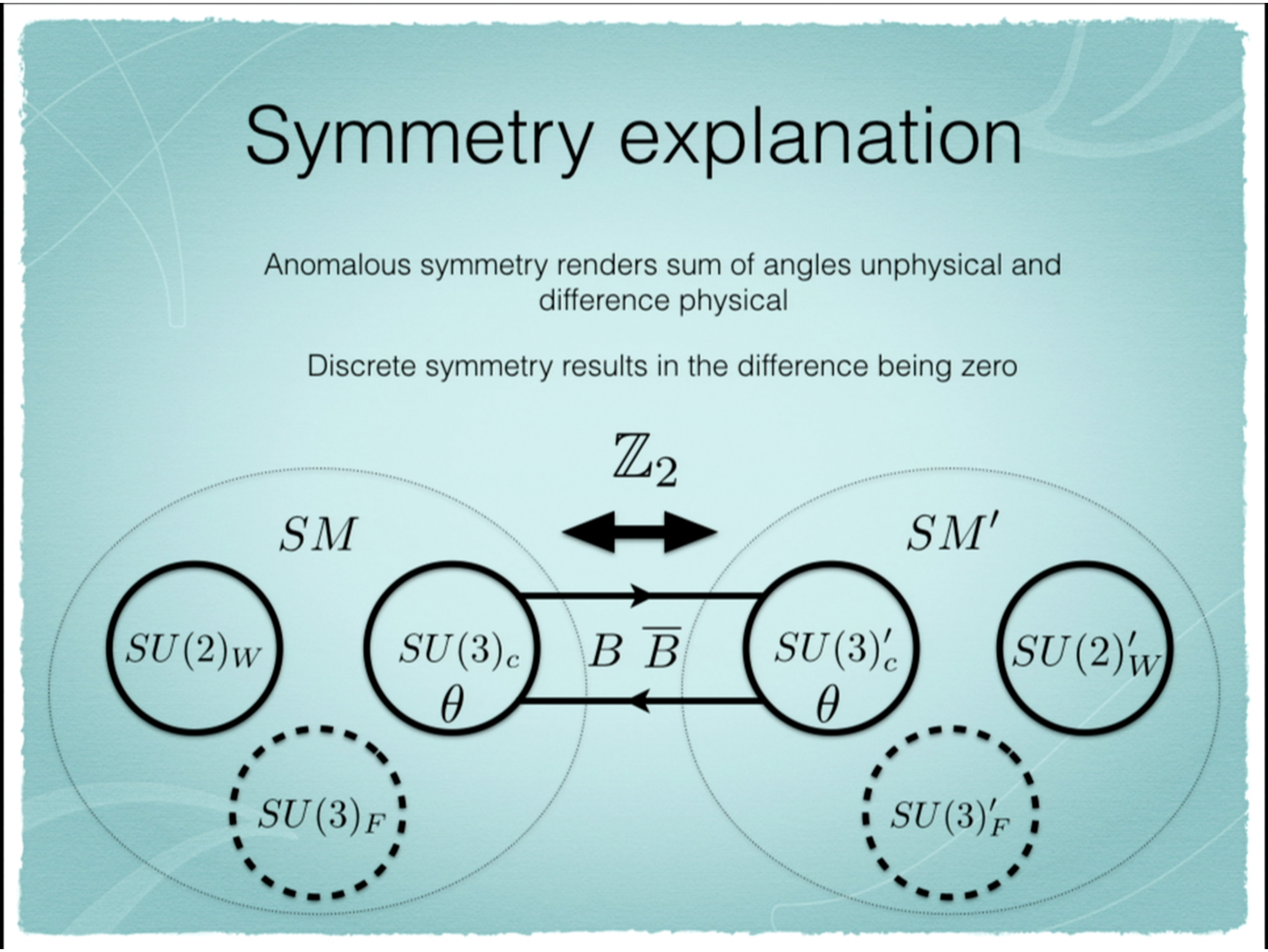
$$\theta' = \frac{3}{N}(\theta + \arg\,\det Y_u Y_d)$$

- 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!



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)



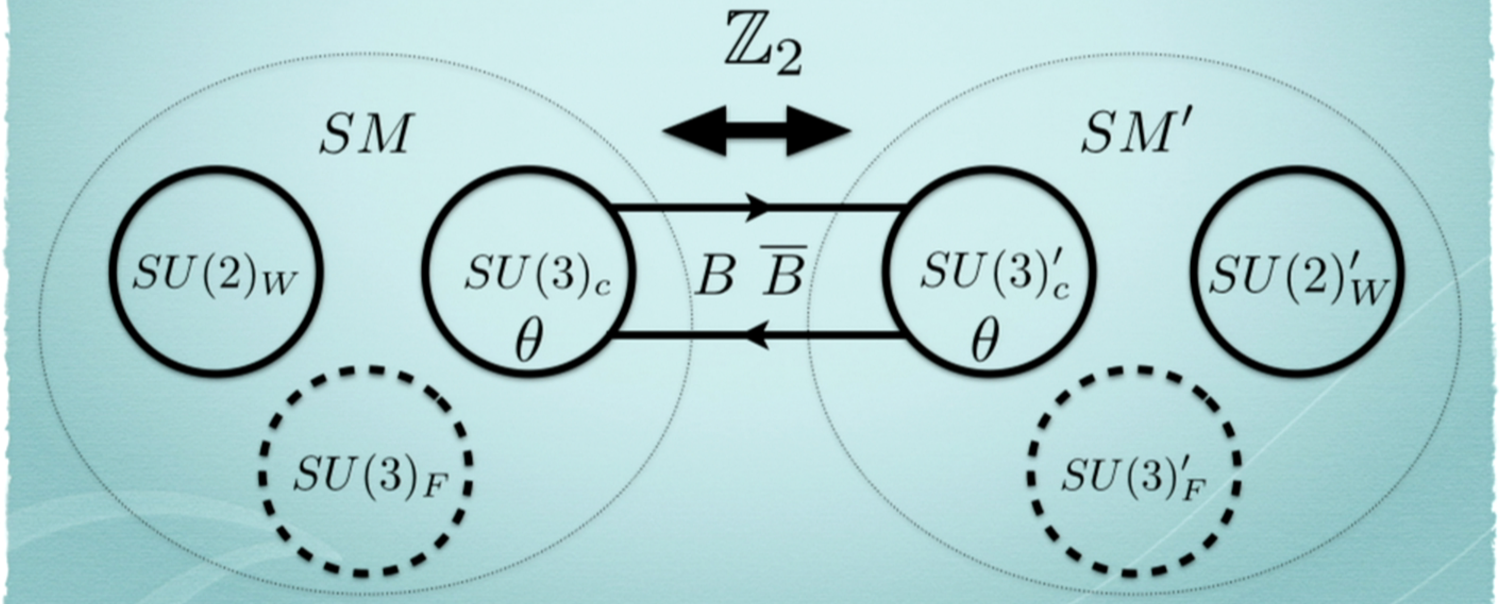
Symmetry explanation

Anomalous symmetry renders sum of angles unphysical and difference physical

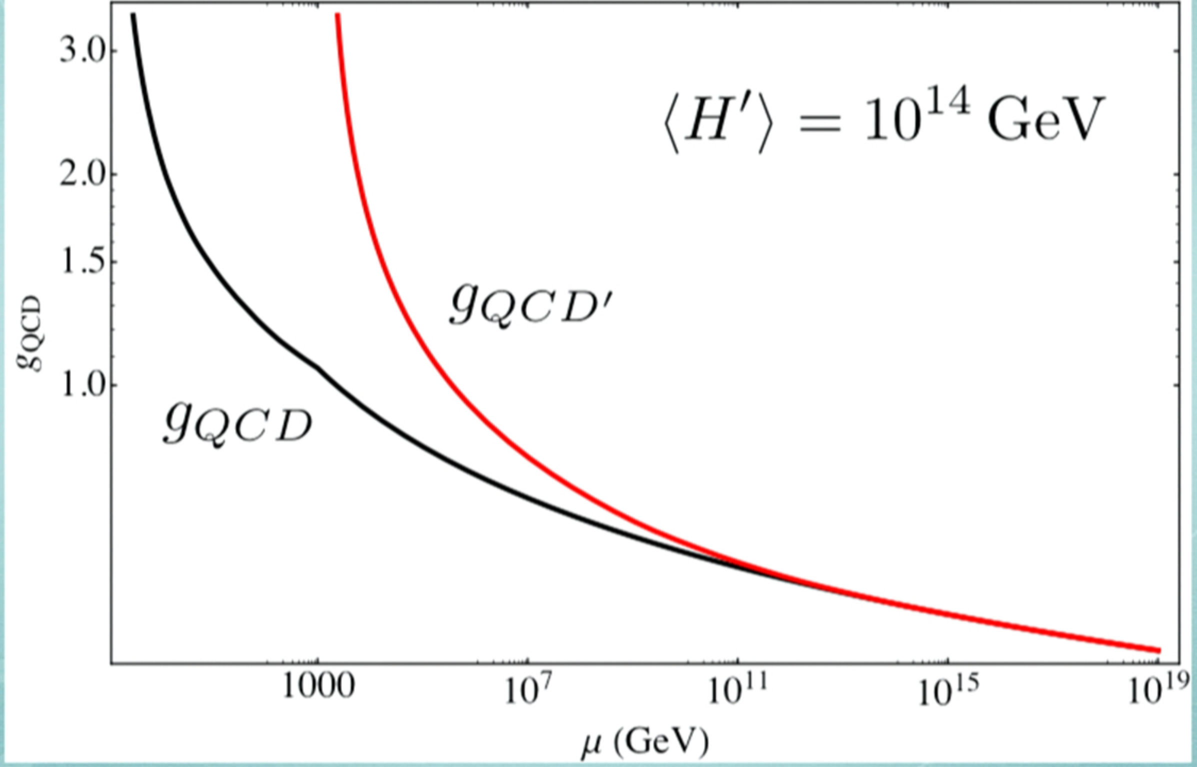
Discrete symmetry results in the difference being zero

Constraints

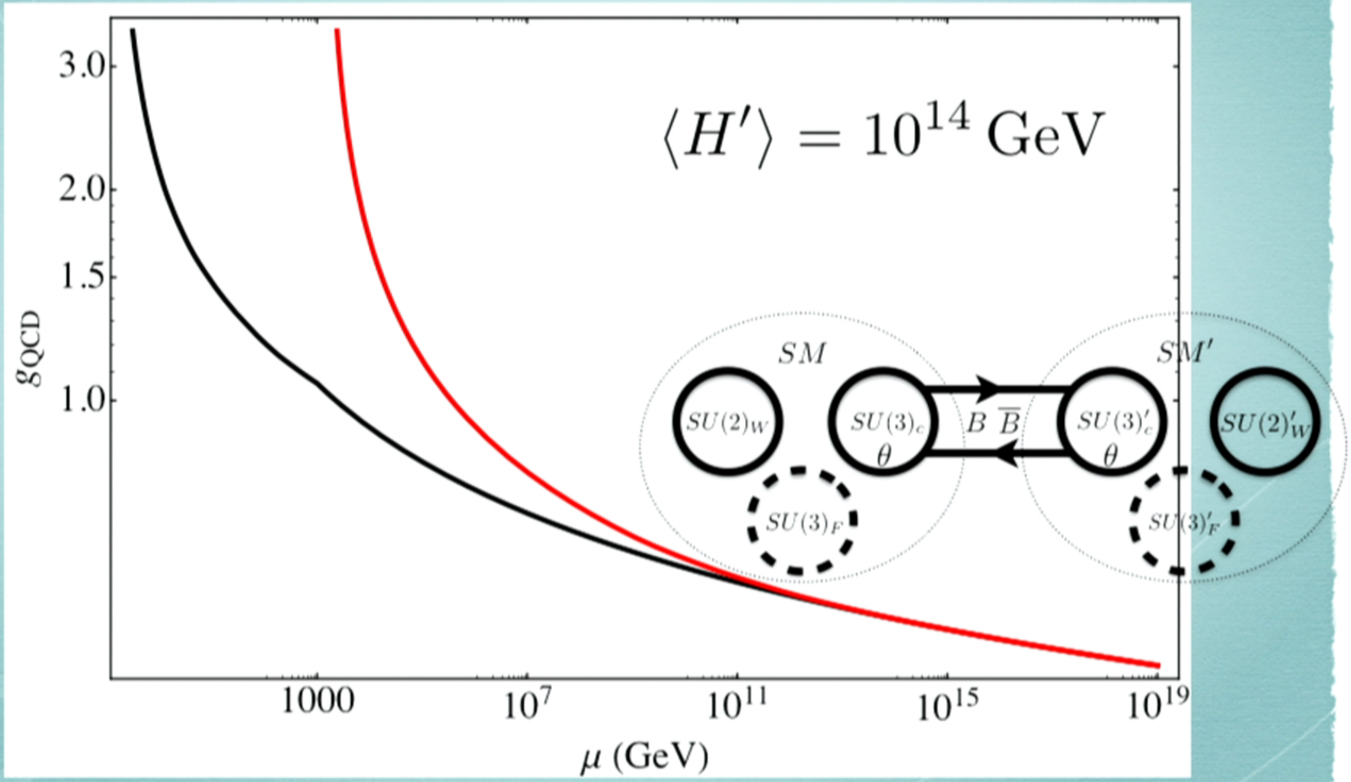
What are the constraints on this model?



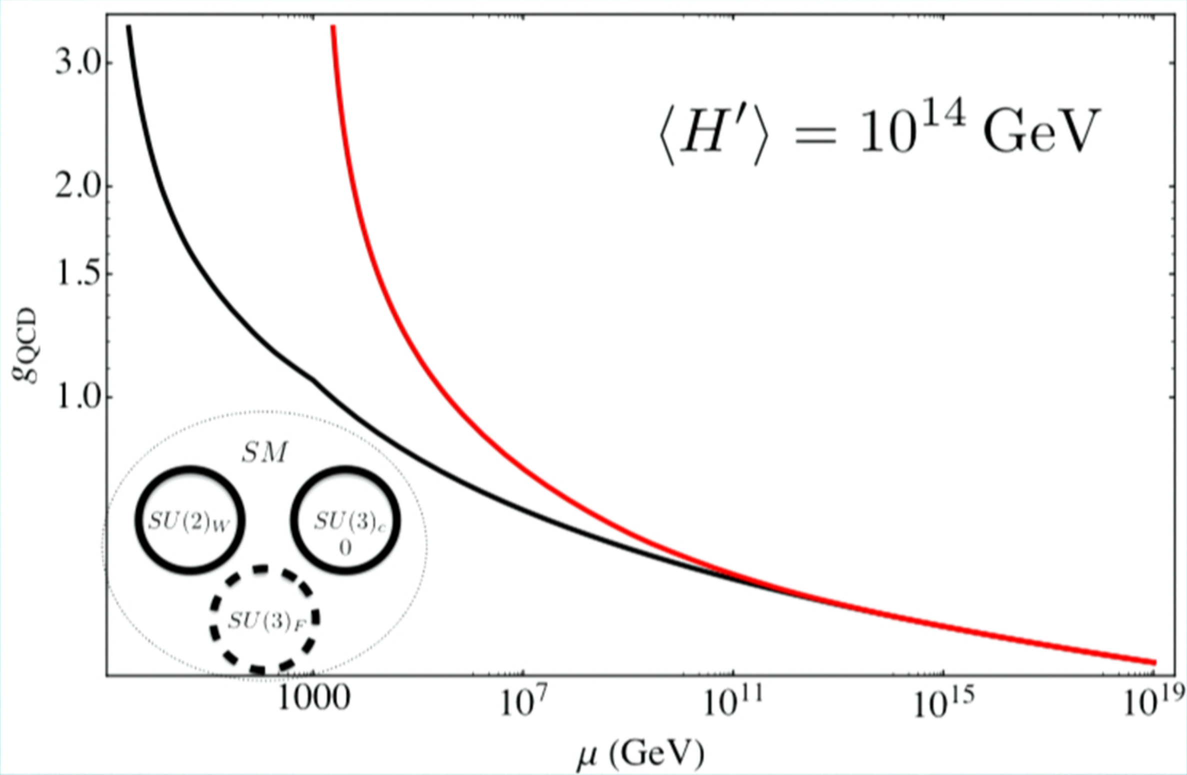
RG evolution



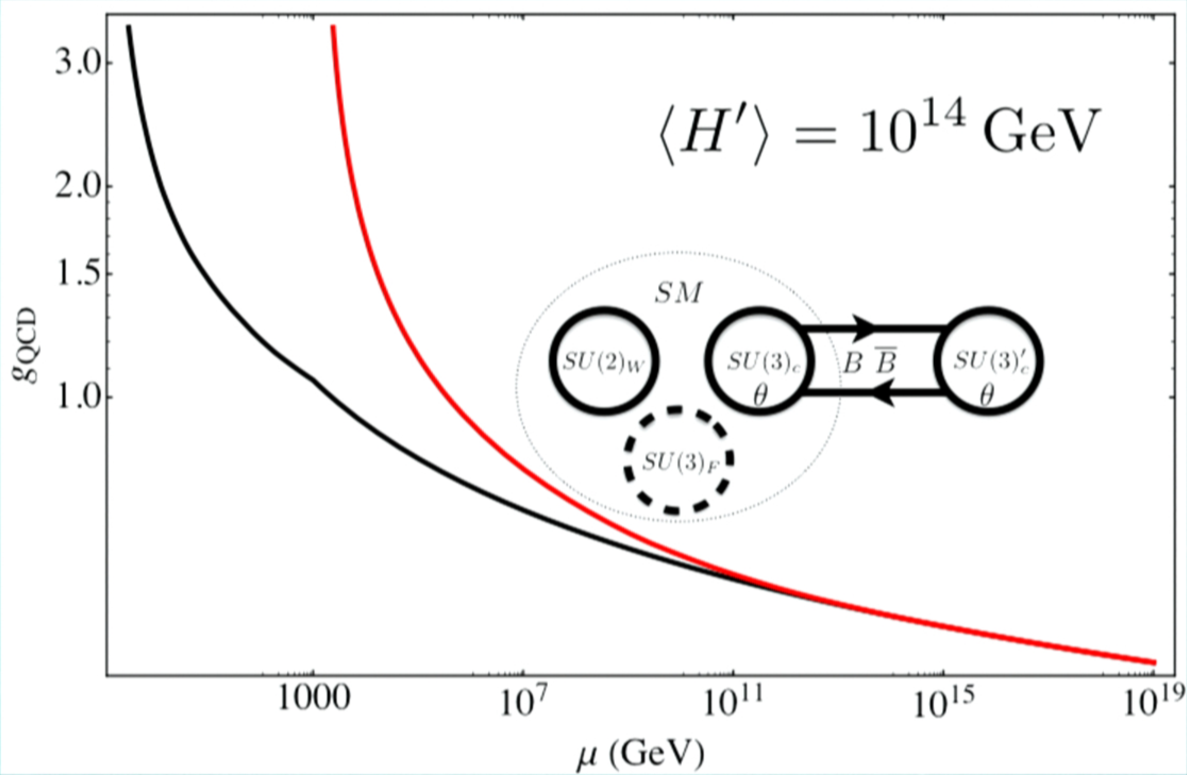
RG evolution

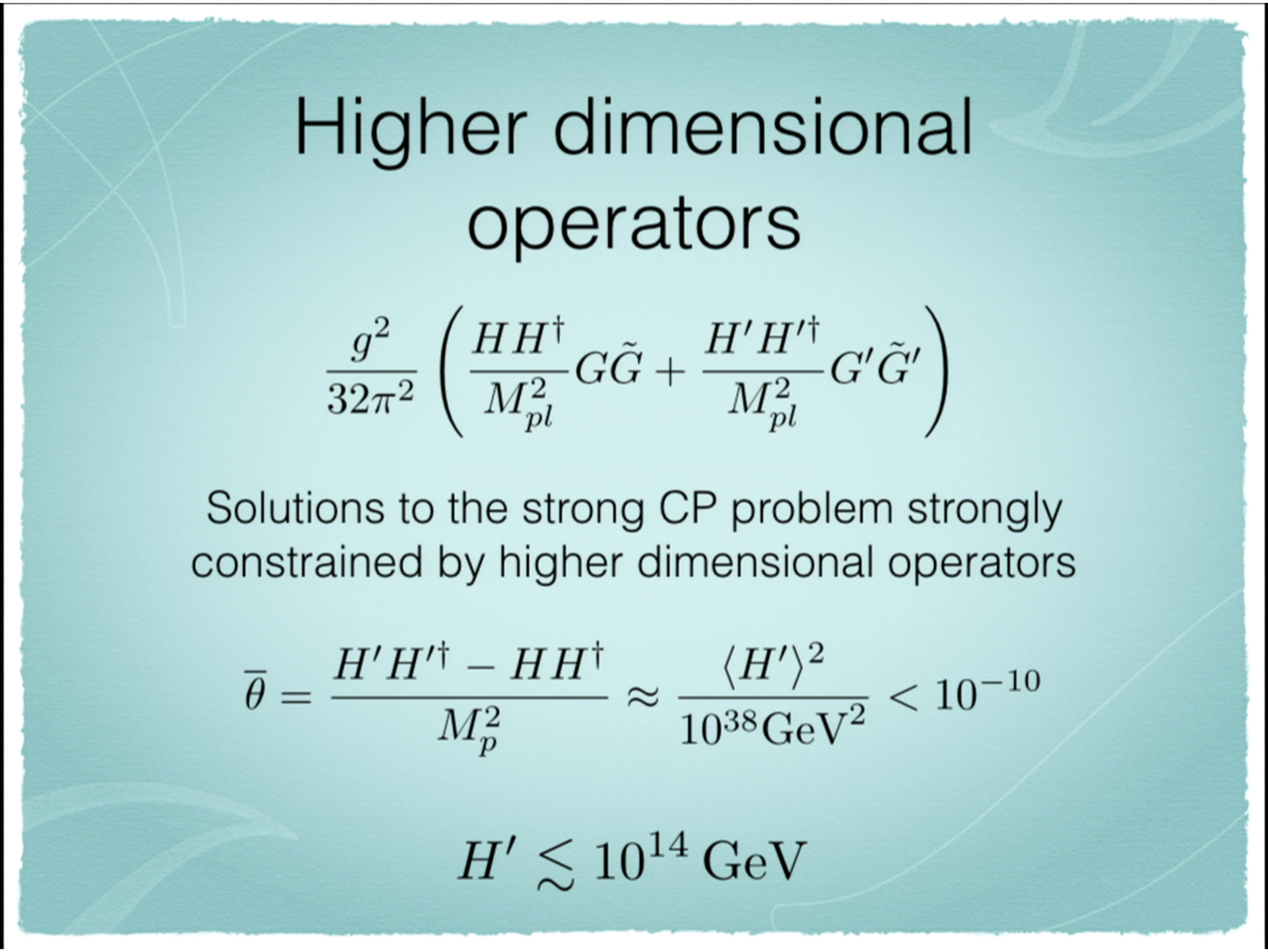


RG evolution



RG evolution





Higher dimensional operators

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

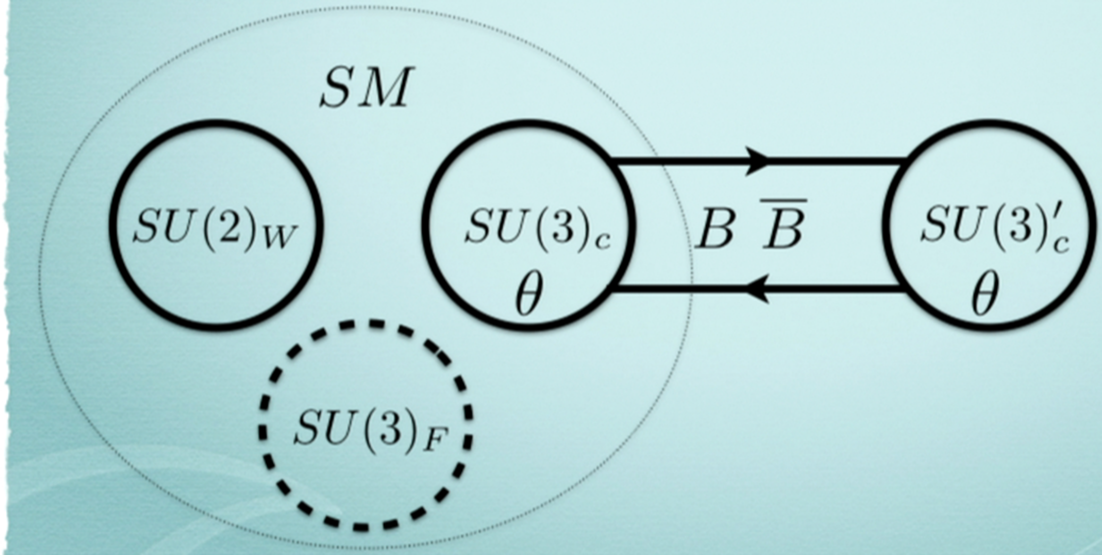
Solutions to the strong CP problem strongly constrained by higher dimensional operators

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

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

LHC Observables

- Observable signatures come from the pseudo-goldstone bosons

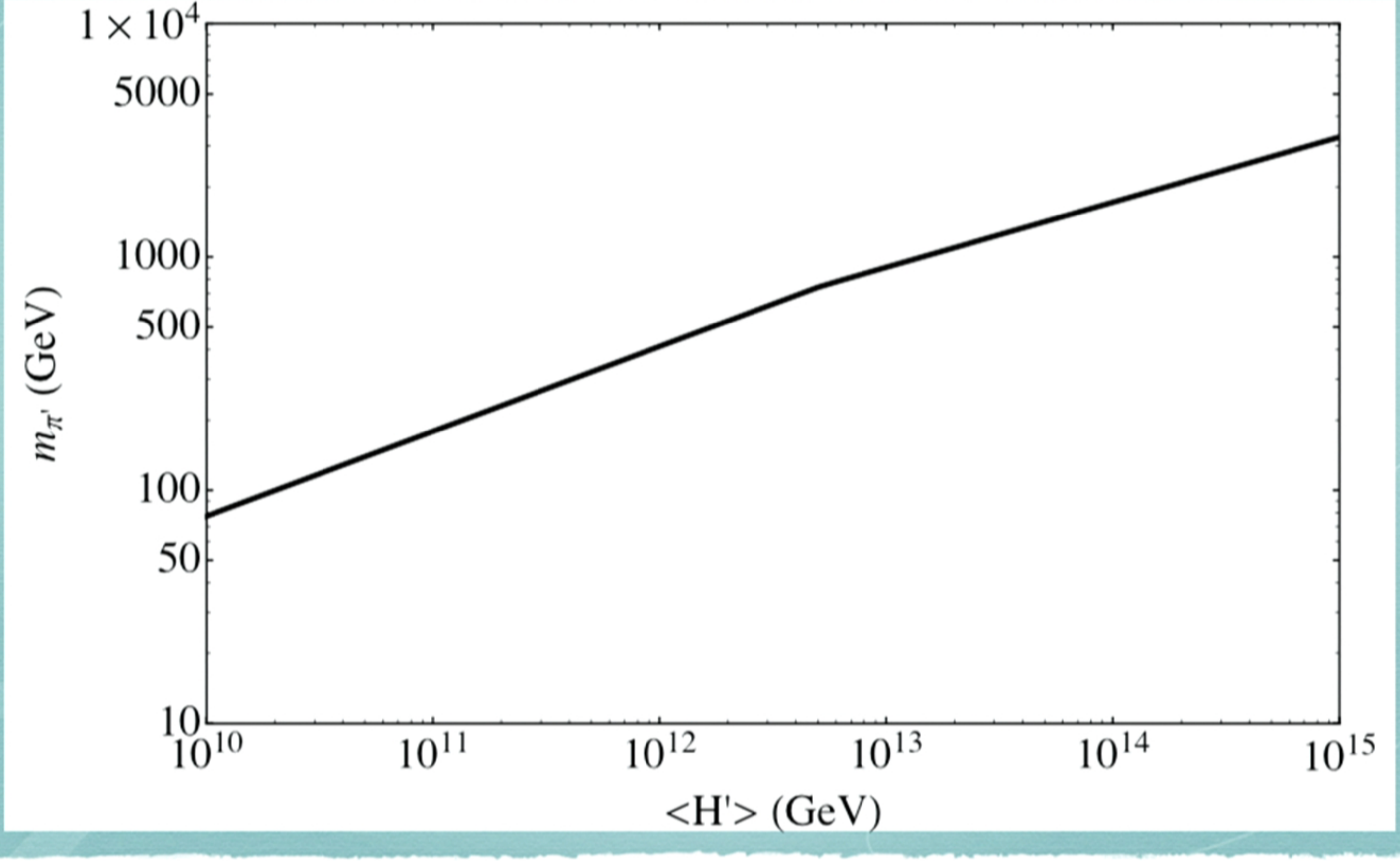


LHC Observables

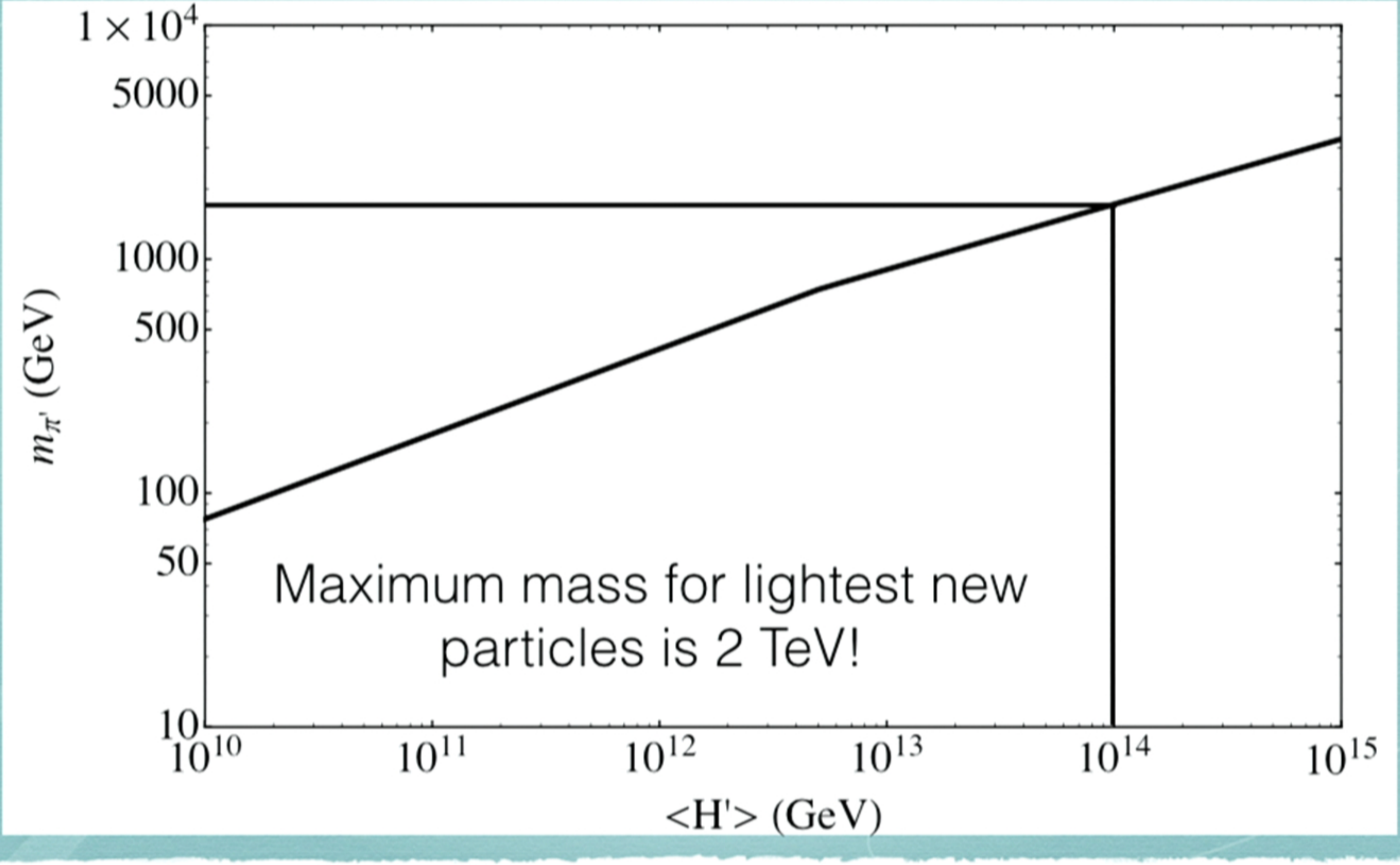
- Observable signatures come from the pseudo-goldstone bosons
    - Color octet scalars
- Obtain a 1-loop mass from gauge boson loops
- Like charged pions, quadratic divergence cut off by rho mesons

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

LHC Observables

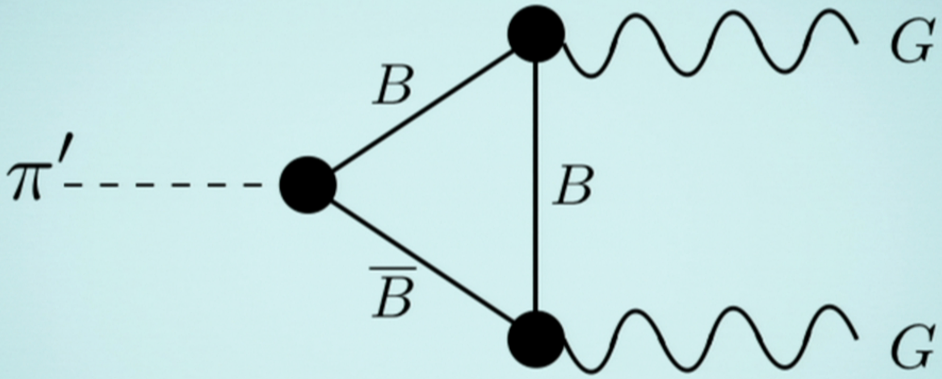


LHC Observables



Maximum mass for lightest new particles is 2 TeV!

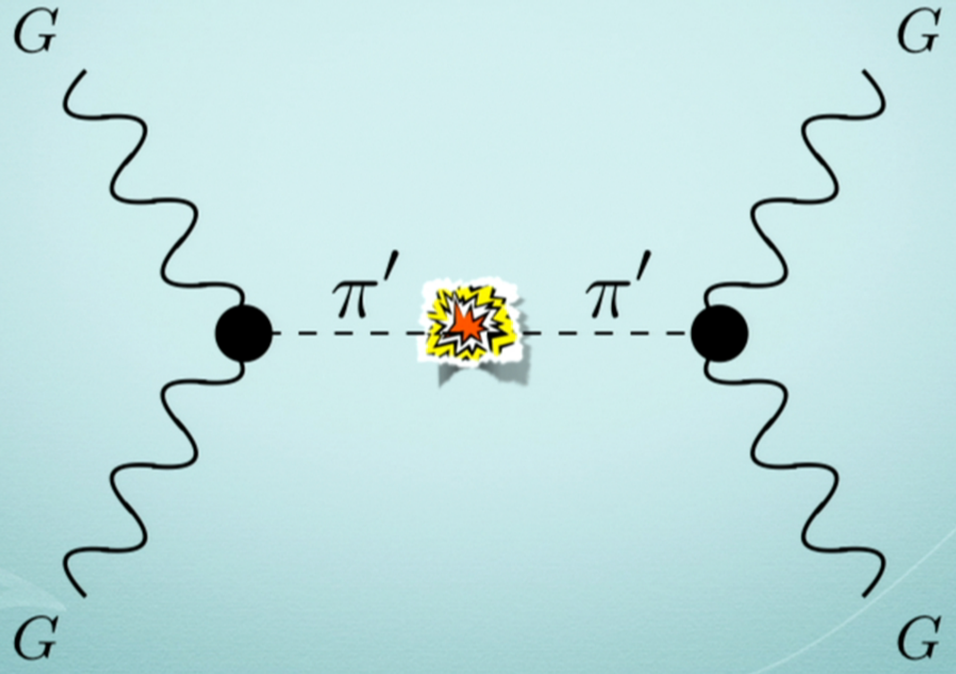
LHC Observables



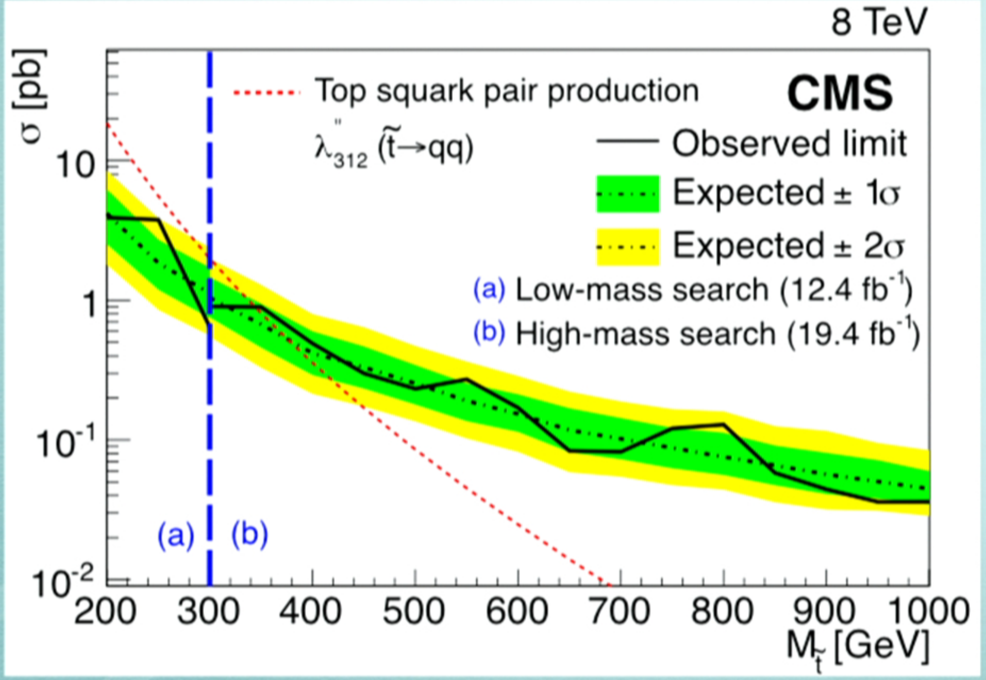
Pions decay through the anomaly into a pair of gluons

LHC signature

LHC observable signatures



LHC signature



4 jet event with a pair of resonances

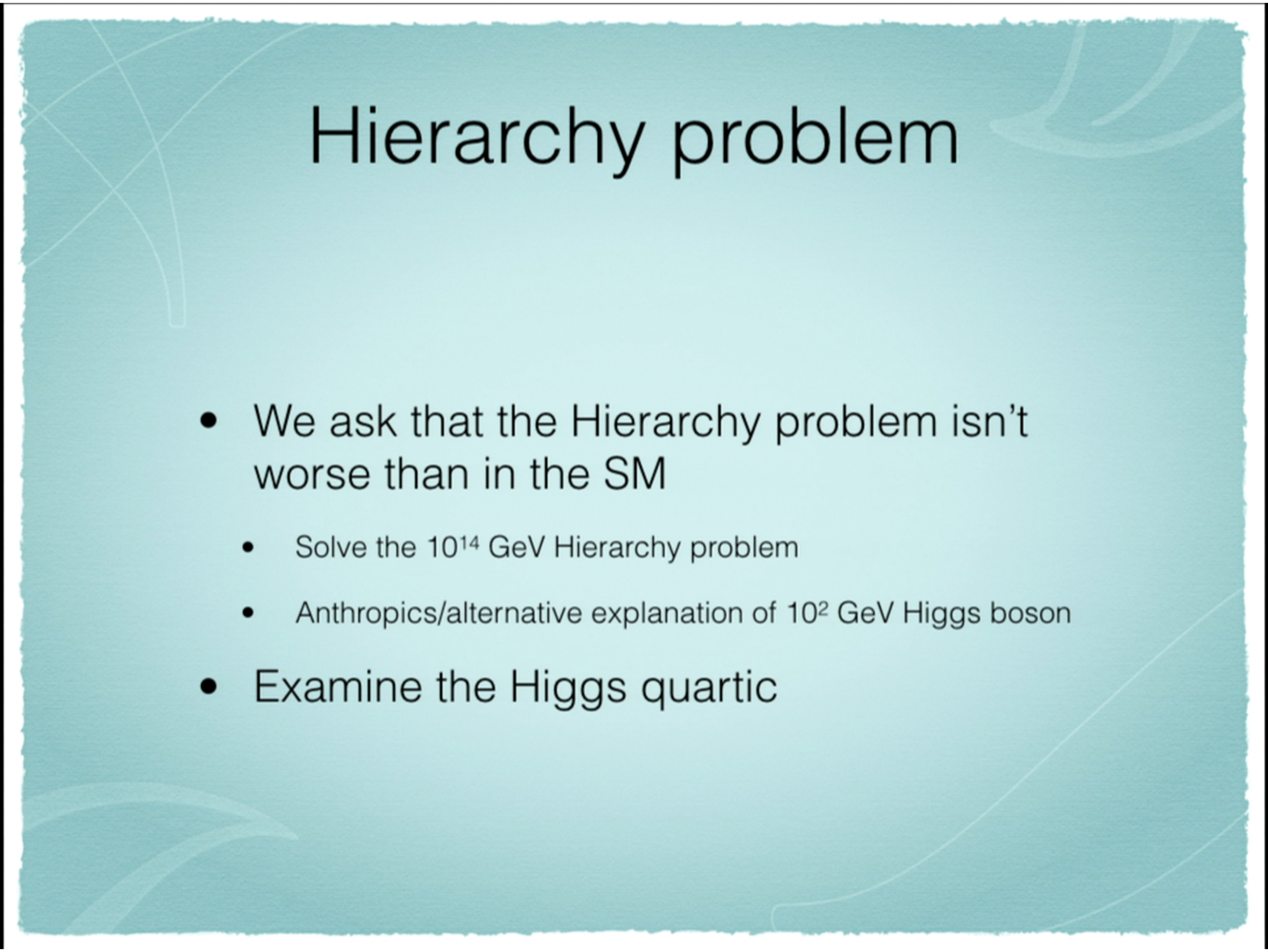
New CMS result :

hep-ex / 1412.7706

8 TeV, 19.4 fb^{-1}

Hierarchy problem

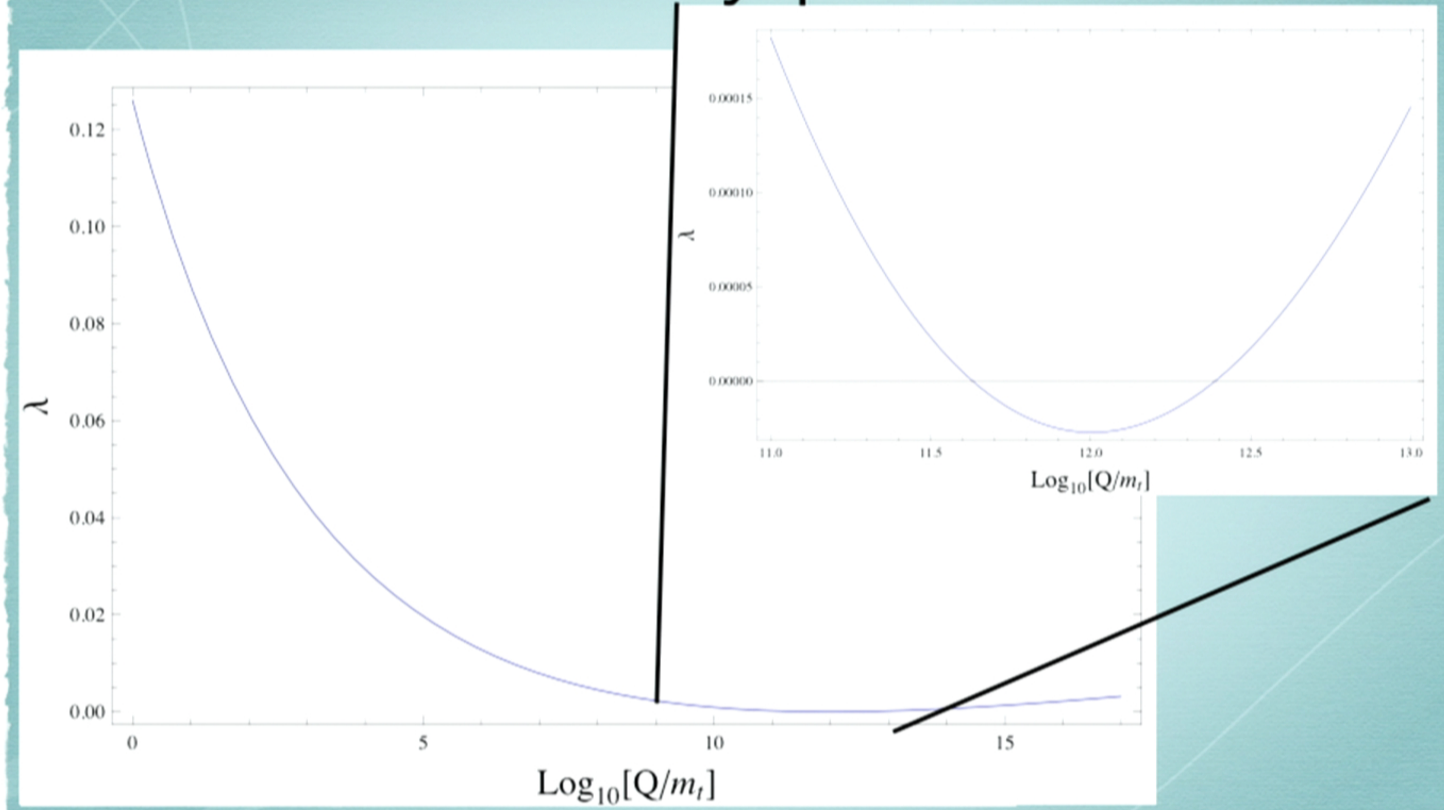
- How bad is the hierarchy problem in this scenario?
    - 10^2 GeV Higgs and 10^{14} GeV Higgs
- We have simply pushed the strong CP problem into the Hierarchy problem
    - Not the end of the world as we have many solutions to the hierarchy problem

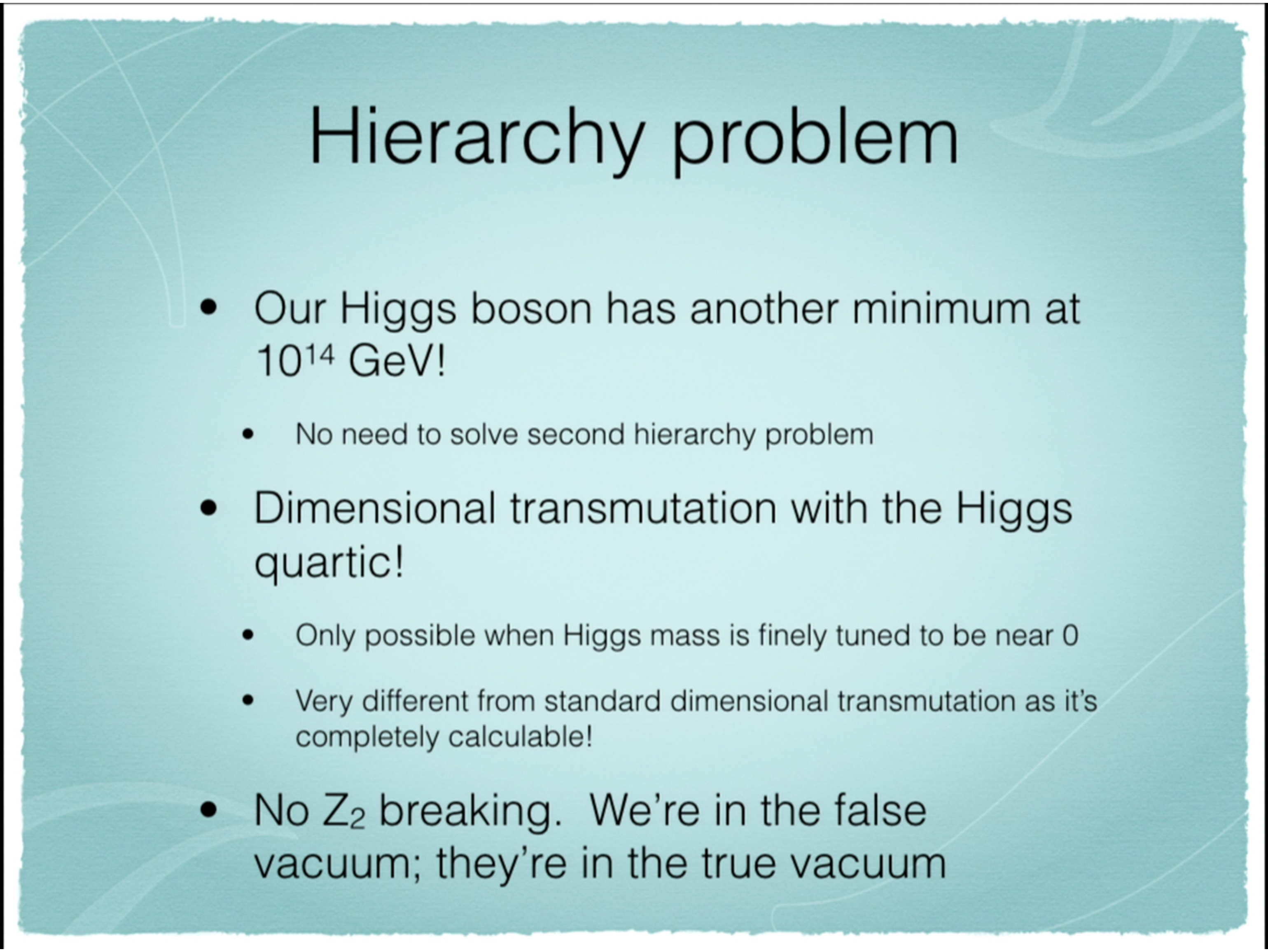


Hierarchy problem

- We ask that the Hierarchy problem isn't worse than in the SM
  - Solve the 10^{14} GeV Hierarchy problem
  - Anthropics/alternative explanation of 10^{2} GeV Higgs boson
- Examine the Higgs quartic

Hierarchy problem





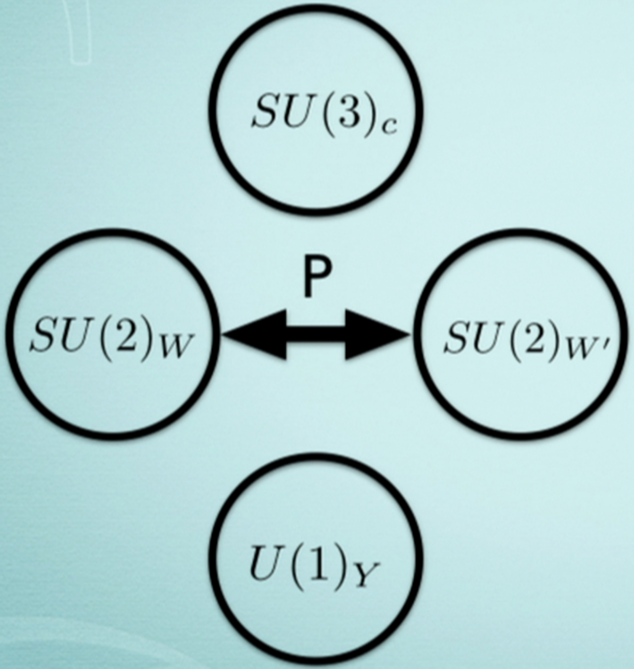
Hierarchy problem

- Our Higgs boson has another minimum at 10^{14} GeV!
  - No need to solve second hierarchy problem
- Dimensional transmutation with the Higgs quartic!
  - Only possible when Higgs mass is finely tuned to be near 0
  - Very different from standard dimensional transmutation as it's completely calculable!
- No Z_2 breaking. We're in the false vacuum; they're in the true vacuum

Testable strong CP

- A solution to the strong CP problem which is testable at the LHC!
    - An existing search places bounds
    - 4 jets with two resonances
- Other LHC testable solutions to the strong CP problem?

Parity



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

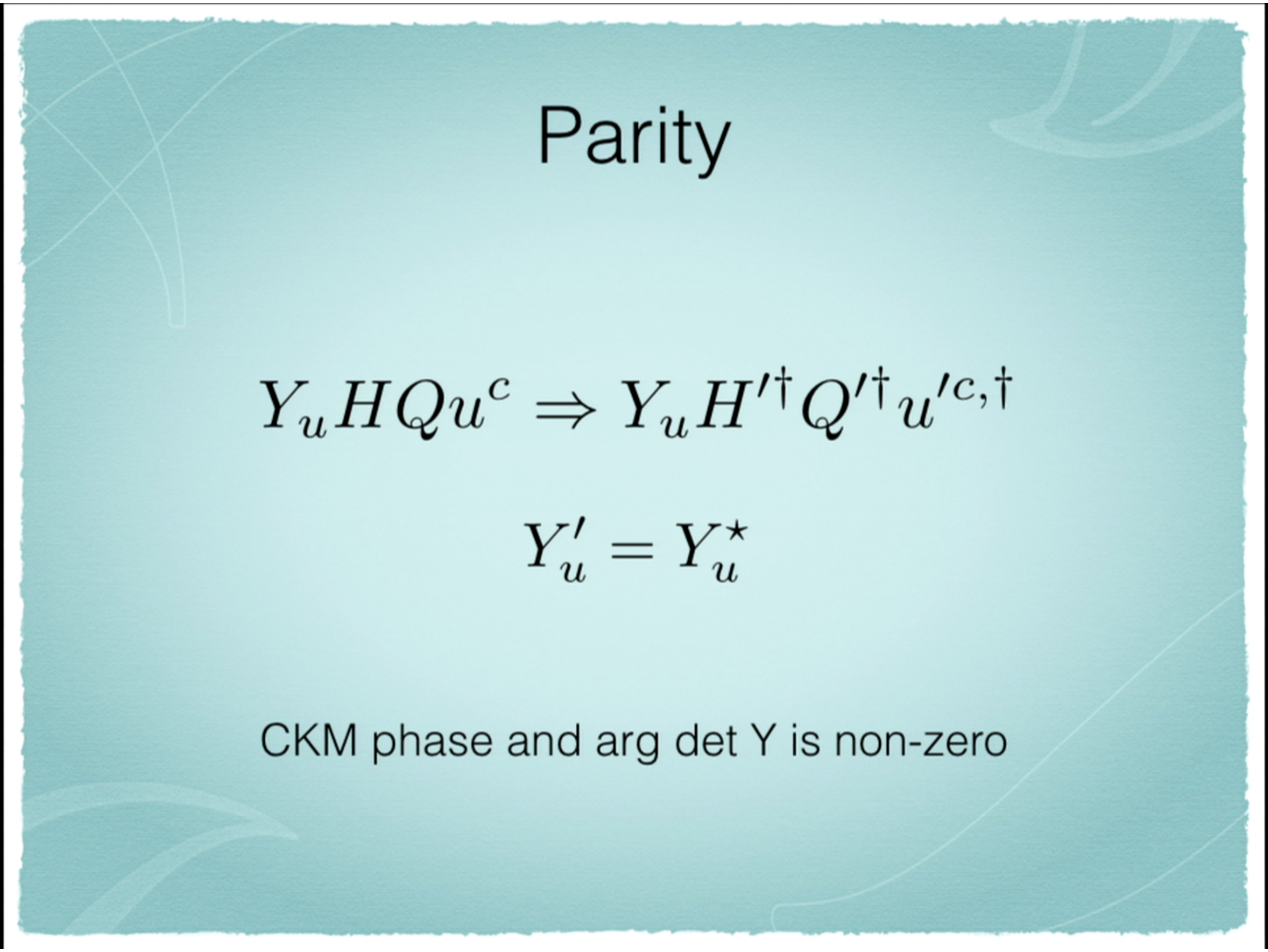
S. M. Barr, D. Chang, and G. Senjanovic,
Phys.Rev.Lett. 67, 2765 (1991)

Parity

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

Parity acts non-trivially on space-time indices

$$L_\alpha \overset{\mathsf{P}}{\longleftrightarrow} L'^{\dagger}_{\dot{\alpha}}$$



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

$$\mathrm{argdet} Y_u = -\mathrm{argdet} Y_u'$$

$$\bar{\theta} = \theta + \mathrm{argdet} Y_u + \mathrm{argdet} Y_u' = 0$$

Invariant theta angle vanishes!

Breaking of parity

$$\Phi \xleftrightarrow{P} -\Phi$$

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

- 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

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

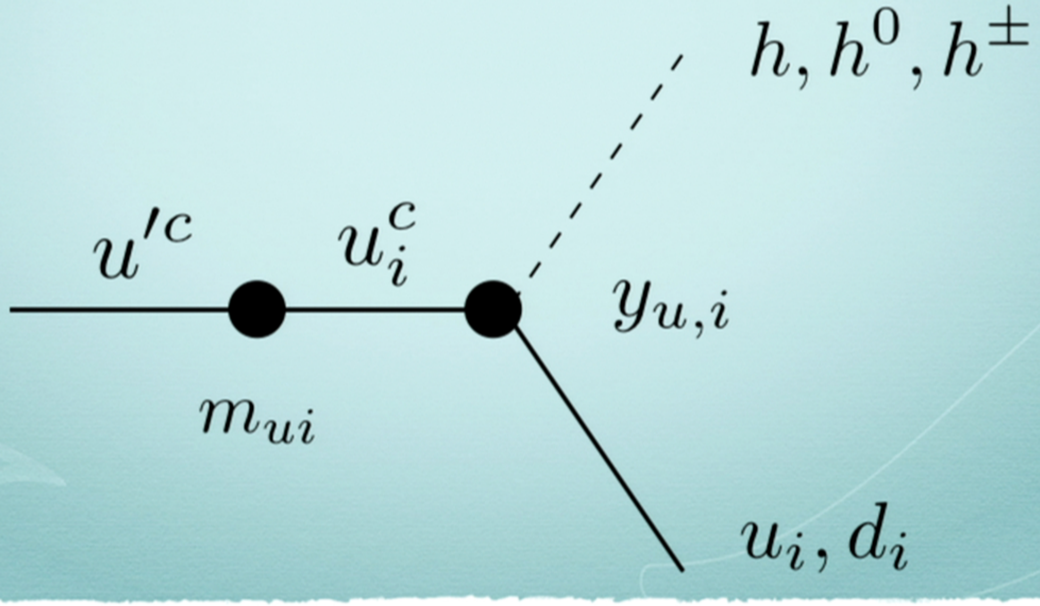
- Mixing allowed by symmetries
  - Technically natural to keep them small
  - If matrix is random, need to be smaller than 100 GeV from FCNC bounds
  - Could be like Yukawas and be almost diagonal

Vanishing m

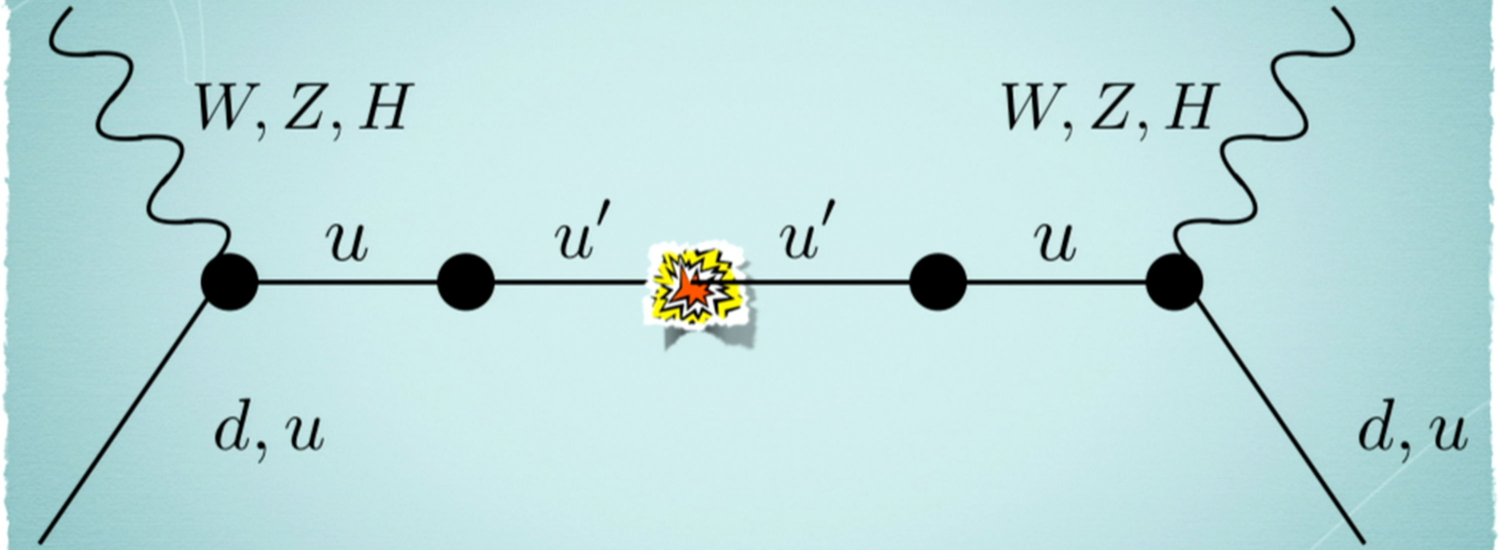
- Stable fourth generation particles
  - Pair produced
  - R hadron search
  - Current bound ~ TeV

m as a Random Matrix

- Decays dominated by the third generation
- Can be prompt or displaced depending on value of m
- Decays via transverse gauge bosons suppressed



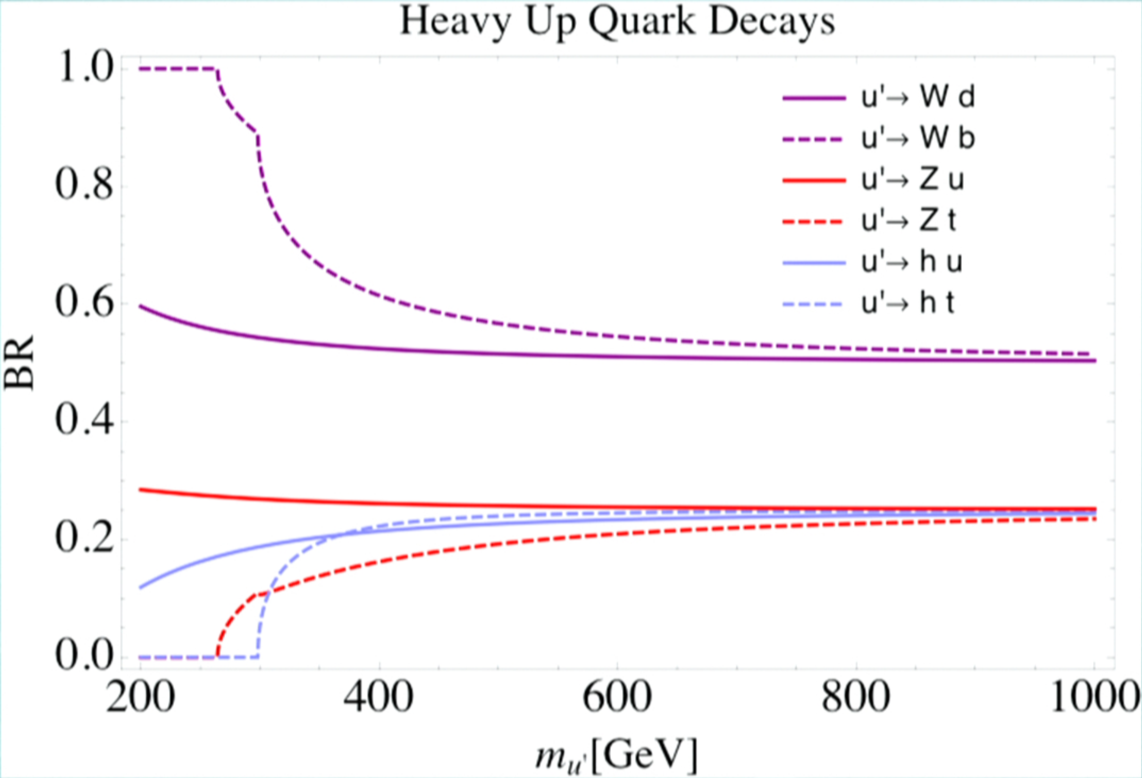
LHC signatures



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

No dedicated search

Branching ratios

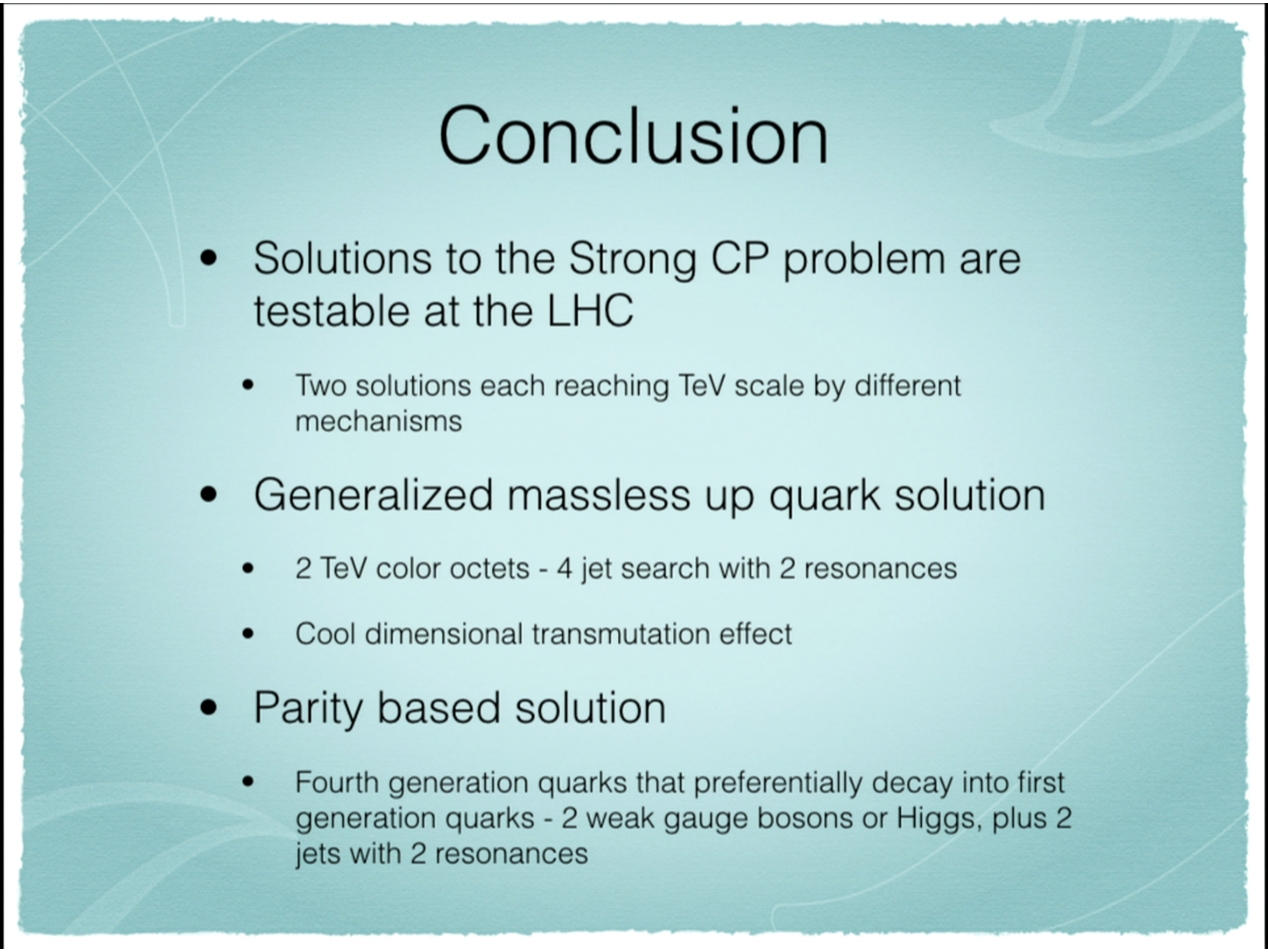


Cosmology

- Reheating smaller than Z_2 breaking scale f ~ 10^9 GeV : domain walls
- m = 0
  - Reheat smaller than 10 TeV to avoid overclosing universe from stable mirror particles

Cosmology

- $m \neq 0$
    - Mirror particles must decay before BBN
    - Mirror neutrinos either decay or act as right handed neutrinos
- Mirror sector has 1st order phase transition
    - EW baryogenesis in mirror sector then have baryons decay to us after sphalerons freeze out
    - LHC signals are displaced vertices or long lived particles



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
  - Cool dimensional transmutation effect
- 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