

# Color Unified Dynamical Axion

arXiv:1805.06465

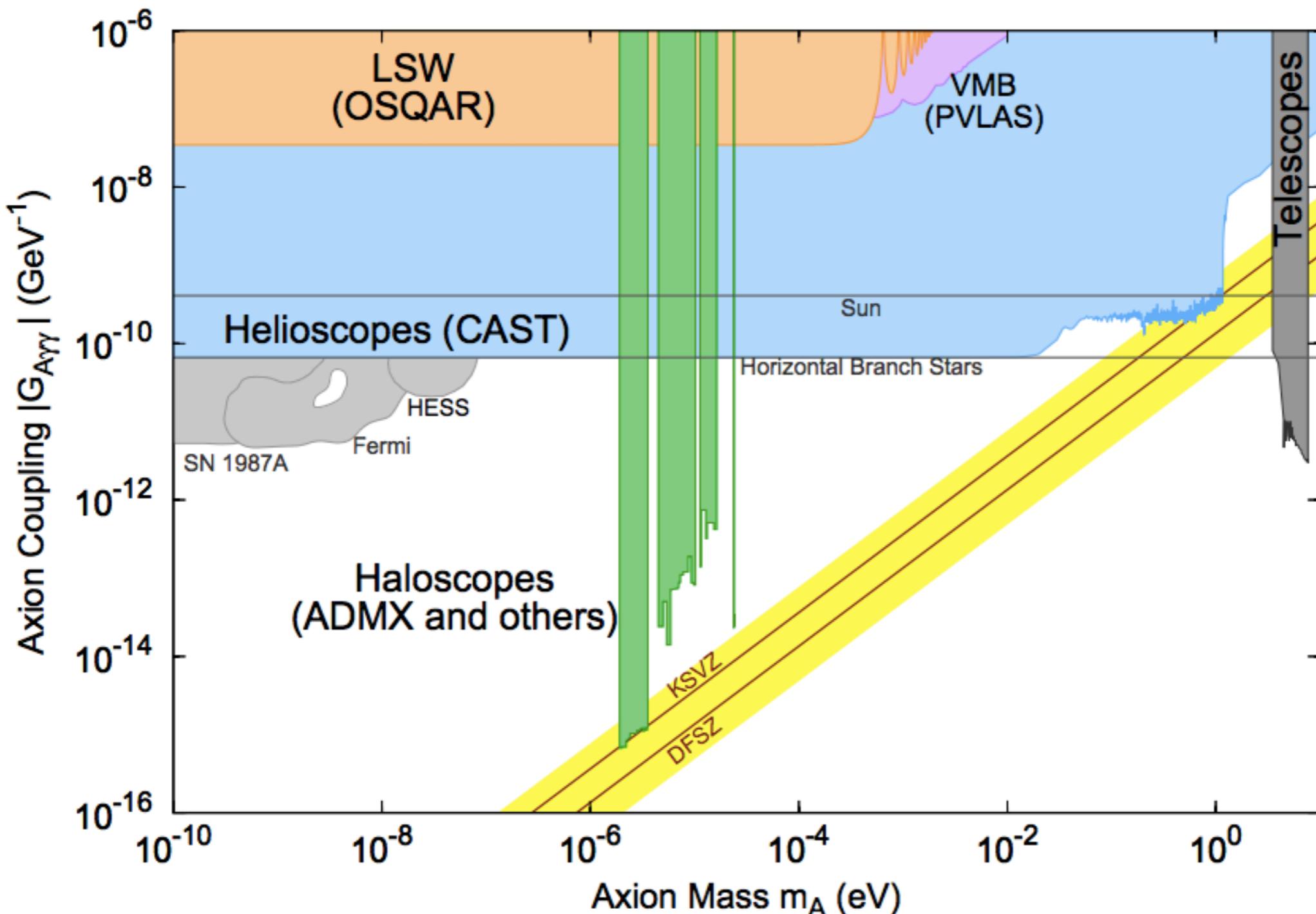


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# Invisible Axion Parameter Space



A. Ringwald, L. J.  
Rosenberg, G.  
Rybka, "Axions and  
Other Similar  
Particles," Particle  
Data Group (2017)

# Strong CP Problem and Massless Quarks

Under a chiral rotation:

$$\begin{aligned}\mathcal{L} \ni -m_q \bar{q} q - \theta \frac{g^2}{32\pi^2} G \tilde{G} \\ \rightarrow -m_q \bar{q} e^{2i\gamma_5 \alpha} q - (\theta - 2\alpha) \frac{g^2}{32\pi^2} G \tilde{G}\end{aligned}$$

If  $m_q = 0$ , then this rotation is just a shift  $\theta \rightarrow \theta - 2\alpha$

- $\theta$  can be removed by field redefinition
- No longer physical
- Strong CP Problem solved

G. 't Hooft. "Computation of the Quantum Effects Due to a Four-Dimensional Pseudoparticle" Phys. Rev. D14 (1976)

# Axicolor

- ❖ Add a massless quark and a new gauge group

$$\tilde{\Lambda} \gg \Lambda_{QCD}$$

Massless quark content

	$su(s)_c$	$su(\tilde{N})$
$\psi$	□	□

K. Choi, J. E. Kim, "Dynamical Axion," Phys. Rev. D32 (1985)

- ❖ When  $SU(\tilde{N})$  confines,  $\psi$  forms bound states  $\sim \tilde{\Lambda}$
- ❖ **Problem:** The new group has its own CP violating angle  $\tilde{\theta}$
- ❖ **Solution:** Absorb  $\tilde{\theta}$  with a new massless quark

# Axicolor

- ❖ Add another massless quark  $\chi$  charged under  $SU(\tilde{N})$

- ❖ When  $SU(\tilde{N})$  confines:

$$SU(4)_L \times SU(4)_R \rightarrow SU(4)_V$$

## Massless quark content

	$su(3)_c$	$su(\tilde{N})$
4	□	□
$\chi$	1	□

$$15 = 8 + 3 + \bar{3} + 1 \quad \leftarrow$$

The  $\eta$  becomes the **dynamical axion**

- ❖ The decay constant is near the very high confinement scale
- ❖ This is then a UV completion for an invisible axion

# Color Unified Dynamical Axion

- ❖ Introduce massless fermion  $\Psi$  to absorb  $\theta_{\text{QCD}}$

$$m_\Psi = 0$$

- ❖ Introduce a new gauge group to allow  $\Psi$  to form bound states near its confinement  $\sim \text{TeV}$
- ❖ The new confining gauge group will be related to QCD through unification
- ❖ This will be an alternative to axicolor:
  - ❖ Different phenomenology
  - ❖ More freedom in  $m_a, f_a$  parameter space

T. Ghergetta, N. Nagata, M. Shifman, “A Visible Axion from an Enlarged Color Group,” Phys. Rev. D93 (2016)

# Color Unification with a Massless Quark

- ❖ The massless quark to absorb the unified group's  $\theta_6$

	$\text{su}(6)$	$\text{su}(2)_L$	$U(1)_Y$
$\Psi_L$	20	1	0

$$SU(6) \xrightarrow{\Lambda_{\text{CUT}}} SU(3)_c \times SU(\tilde{3}) \times U(1)$$

- ❖ Below unification scale:

$$\begin{aligned}\Psi(20) &\rightarrow (1, 1)(-3) + (1, 1)(+3) \\ &+ (3, \bar{3})(-1) + (\bar{3}, 3)(+1)\end{aligned}$$

	$\text{su}(3)_c$	$\text{su}(\tilde{3})$
$\Psi_L$	□	□
$(4^c)_L$	□	□
$\Psi_{v_1}$	1	1
$\Psi_{v_2}$	1	1

# Matter Content Above and Below CUT Breaking

$$SU(6) \xrightarrow{\Lambda_{\text{CUT}}} SU(3)_c \times SU(\tilde{3})$$

	$\text{su}(6)$	$\text{su}(2)_L$		$\text{su}(3)$	$\text{su}(\tilde{3})$	$\text{su}(2)_L$	
$Q_L$	□	□		$g_L$	□	1	□
$\bar{U}_R$	□	1		$\bar{u}_R$	□	1	1
$\bar{D}_R$	□	1		$\bar{d}_R$	□	1	1
$\Psi$	20	1		$\tilde{q}_L$	1	□	□
			$\xrightarrow{\Lambda_{\text{CUT}}}$	$\tilde{q}_L$	1	□	1
				$\tilde{u}_R$	1	□	1
				$\tilde{d}_R$	1	□	1
				4	□	□	1
				24 $\nu$	1	1	1

Goal: provide a mechanism for these fields to form mass terms

# The Prime Sector

$$SU(6) \times SU(3') \xrightarrow{\Lambda_{\text{CUT}}} SU(3)_c \times SU(3)_{\text{diag}}$$

	$\text{su}(6)$	$\text{su}(3')$	$\text{su}(2)_L$
$Q_L$	□	1	□
$\bar{U}_R$	□	1	1
$\bar{D}_R$	□	1	1
$\bar{g}'_R$	1	□	□
$u'_L$	1	□	1
$d'_L$	1	□	1
$\Psi$	20	1	1
$\Delta$	□	□	1

← Scalar field responsible for CUT breaking

These fields pair up with the  
 tilde fields to form masses

# Matter Content Above and Below CUT Breaking

	$\text{su}(6)$	$\text{su}(3')$	$\text{su}(2)_L$	
$Q_L$	□	1	□	
$\bar{U}_R$	□	1	1	
$\bar{D}_R$	□	1	1	
$\bar{q}'_R$	1	□	□	
$u'_L$	1	□	1	
$d''_L$	1	□	1	
$\Xi$	20	1	1	
$\Delta$	□	□	1	

$\xrightarrow{\Lambda_{\text{CUT}}}$

	$\text{su}(3)$	$\text{su}(3)_{\text{diag}}$	$\text{su}(2)_L$
$q_L$	□	1	□
$\bar{u}_R$	□	1	1
$\bar{d}_R$	□	1	1
$4$	□	□	1
$24_L$	1	1	1

$\tilde{q}_L$	1	□	□
$\tilde{u}_R$	1	□	1
$\tilde{d}_R$	1	□	1
$\bar{q}'_R$	1	□	□
$u'_L$	1	□	1
$d''_L$	1	□	1

Prime sector

Massless quark sector

Obtain mass near the CUT breaking scale

# Another Massless Quark

	$\text{su}(6)$	$\text{su}(3')$	$\text{su}(2)_L$			$\text{su}(3)$	$\text{su}(3)_{\text{diag}}$	$\text{su}(2)_L$
$\Psi$	20	1	1			4	1	1
$\chi$	1	1	1			1	1	1

$\xrightarrow{\Lambda_{\text{CUT}}}$

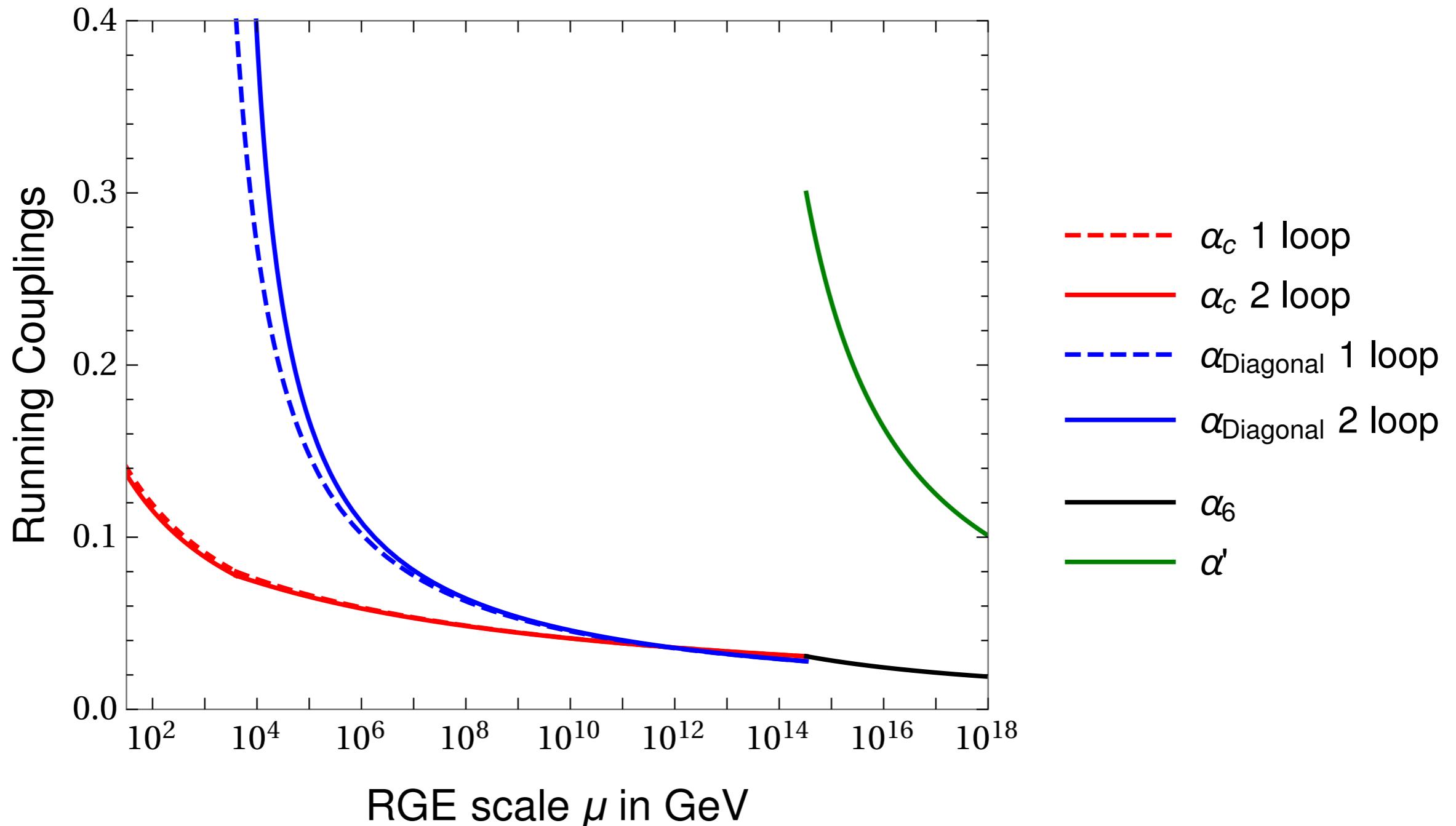
The new massless quark

- Goal:  $SU(3)_{\text{diag}}$  confines at a higher scale than  $SU(3)_c$

$$\frac{1}{\alpha_{\text{diag}}(\mu)} = \frac{1}{\alpha_6(\mu)} + \frac{1}{\alpha'(\mu)} \quad \mu = \Lambda_{\text{CUT}}$$

$$\alpha_c(\Lambda_{\text{CUT}}) = \alpha_6(\Lambda_{\text{CUT}})$$

# Unification and Confinement

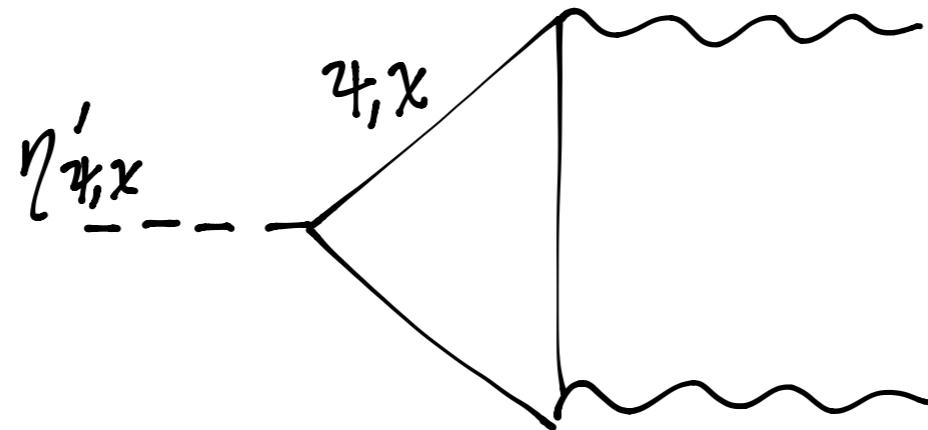


# $SU(3)_{\text{diag}}$ Confinement

- ❖ The  $U(4)$  flavor symmetry is broken by condensates:  $\langle \bar{\psi}\psi \rangle$   $\langle \bar{\chi}\chi \rangle$   
$$U(4)_L \times U(4)_R \rightarrow U(4)_V \qquad \qquad \qquad \langle \bar{\psi}\chi \rangle$$
- ❖ This results in 16 pGB's.  $16 = 8_c + \bar{3}_c + 3_c + 1_c + 1_c$
- ❖ The “pion” masses get pushed up to the cutoff of the theory via interactions with gluons

$$\begin{array}{ccccc} \text{---} & \text{---} & + & \text{---} & \Rightarrow \\ \text{---} & \text{---} & & \text{---} & \\ \text{---} & \text{---} & & \text{---} & \end{array} \qquad \begin{aligned} m^2(8_c) &\approx \frac{9\alpha_c}{4\pi} \Lambda_{\text{diag}}^2 \\ m^2(3_c) &\approx \frac{\alpha_c}{\pi} \Lambda_{\text{diag}}^2 \end{aligned}$$

# Masses of the $\eta'$ Pseudoscalars



$$\mathcal{L} \ni -\frac{\alpha_{\text{diag}}}{8\pi} \left( \frac{2\eta'_\chi}{f_d} + \sqrt{6} \frac{\eta'_\psi}{f_d} \right) G_{\text{diag}} \tilde{G}_{\text{diag}} - \frac{\alpha_c}{8\pi} \left( \frac{2\eta'_{\text{QCD}}}{f_\pi} + \sqrt{6} \frac{\eta'_\psi}{f_d} \right) G_c \tilde{G}_c$$

$$\mathcal{L}_{eff} = \Lambda_{\text{diag}}^4 \cos \left( \frac{2\eta'_\chi}{f_d} + \sqrt{6} \frac{\eta'_\psi}{f_d} \right) + \Lambda_{\text{QCD}}^4 \cos \left( \frac{2\eta'_{\text{QCD}}}{f_\pi} + \sqrt{6} \frac{\eta'_\psi}{f_d} \right)$$

→ This looks like **two** masses for **three**  $\eta'$  pseudoscalars

# Small Size Instantons and Axion Mass

- ❖ Typically, at high scales  $\alpha_c$  is very small
- ❖ If new physics alters RG flow, large couplings can induce new instanton corrections to the axion mass

J. Flynn, L. Randall, “A computation of the small instanton contribution to the axion potential.” Nucl. Phys. B208 (1987)

P. Agrawal, K. Howe. “Factoring the Strong CP Problem,” arXiv/1710.04213

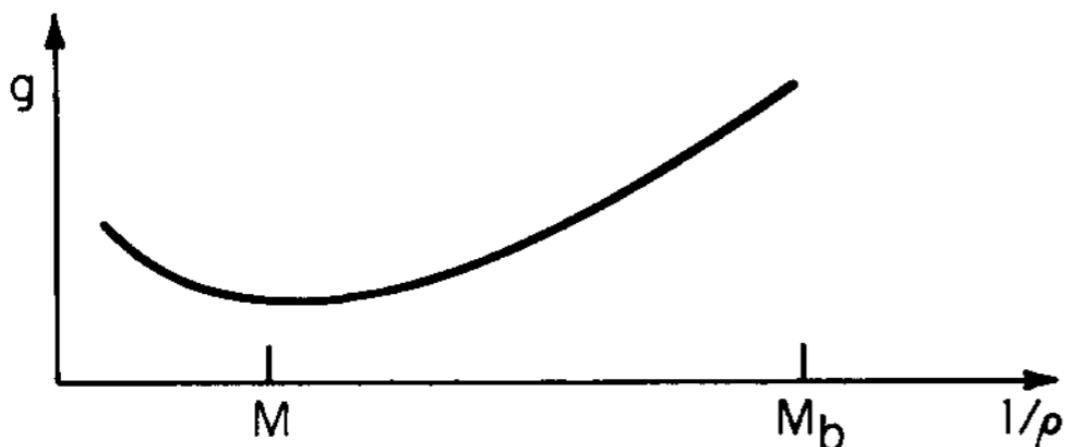


Fig. 1. Coupling  $g$  as a function of  $1/\rho$ .

$$SU(3) \times \dots \times SU(3) \rightarrow SU(3)_c$$

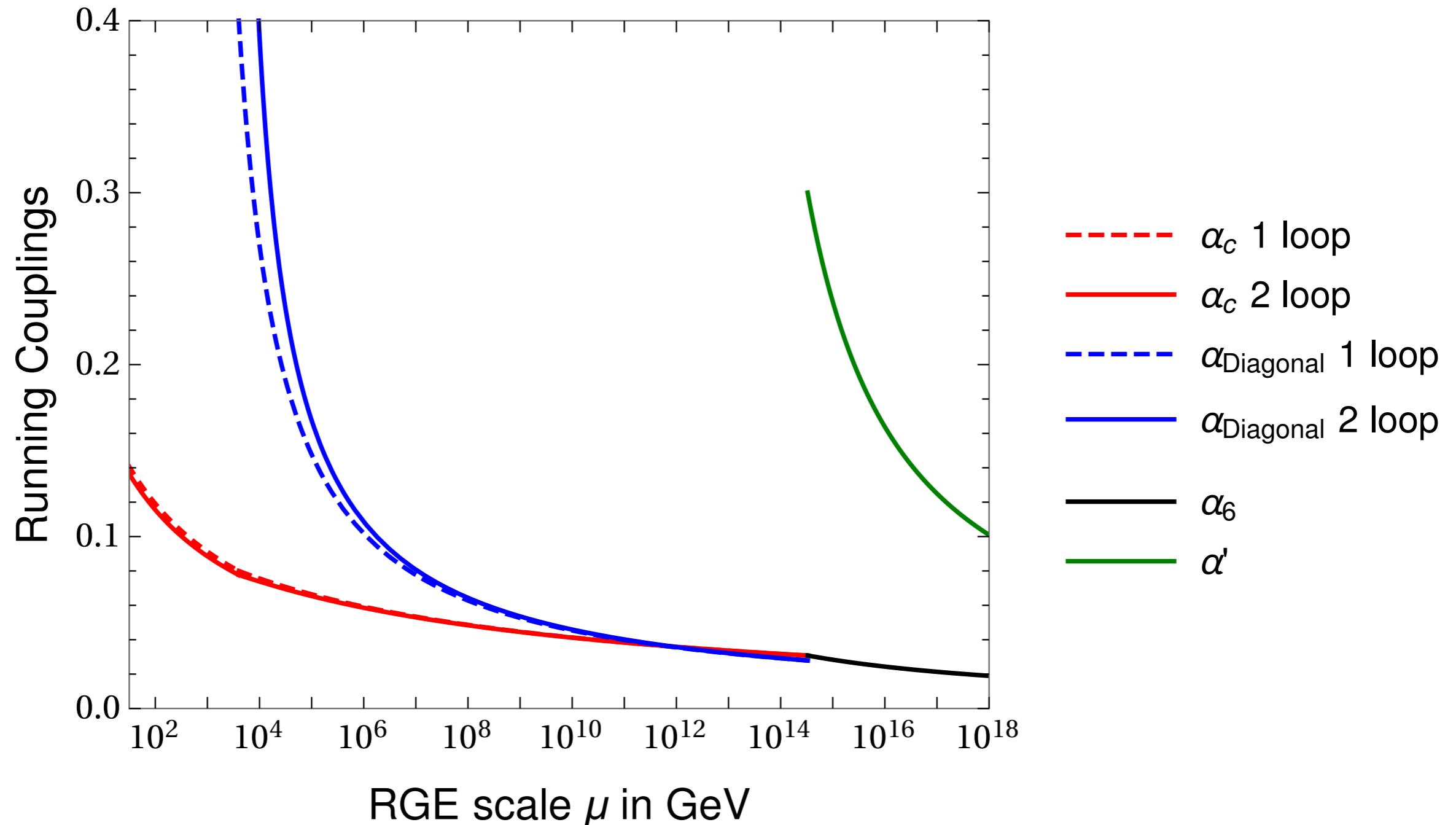
$$\frac{1}{\alpha_s(\mu)} = \frac{1}{\alpha_1(\mu)} + \frac{1}{\alpha_2(\mu)} + \dots + \frac{1}{\alpha_N(\mu)}$$

$$\mu = M_b$$

M. Dine, N. Seiberg, “String Theory and the Strong CP Problem,” Nucl. Phys. B273 (1986)

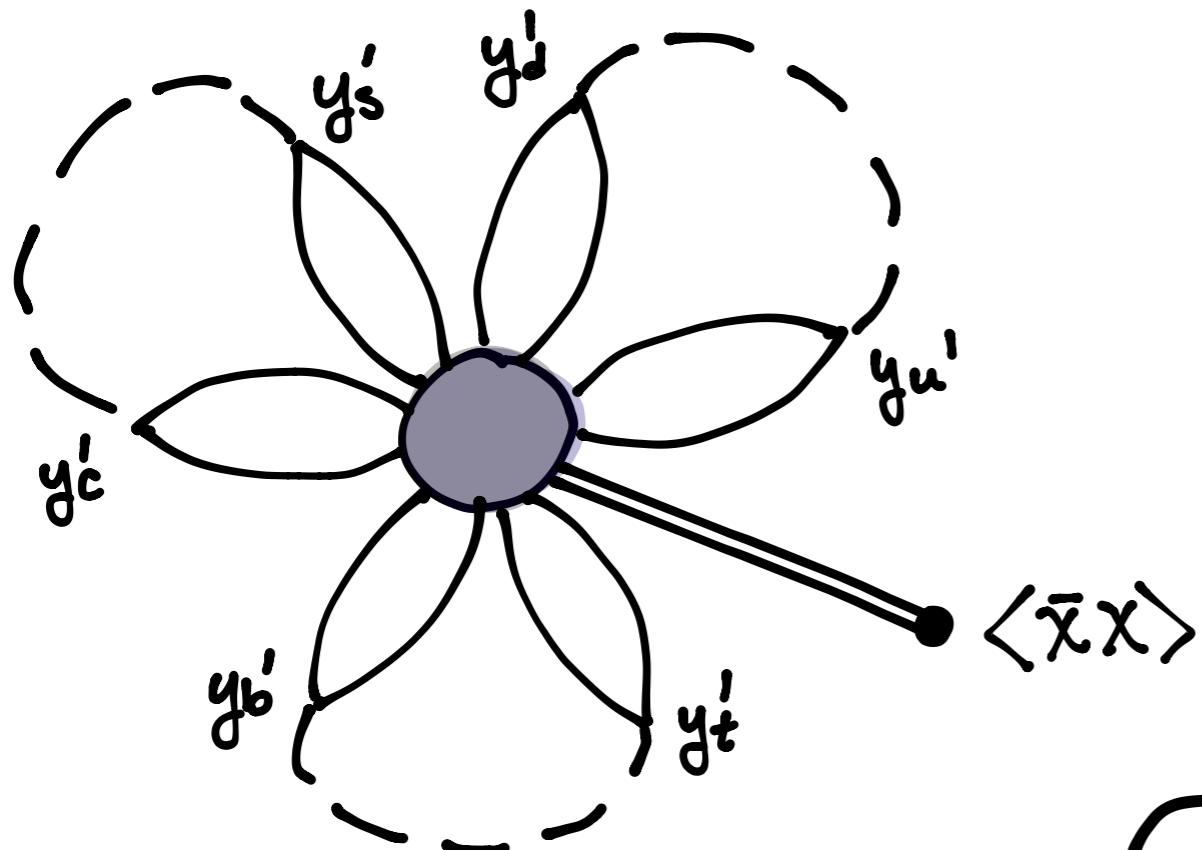
B. Holdom, M. Peskin, “Raising the Axion Mass,” Nucl. Phys. B208 (1982)

# Reminder: Confinement and Unification Scale



# Small Size Instantons with Fermions

- ❖ Adding fermion effects gives an instanton suppression



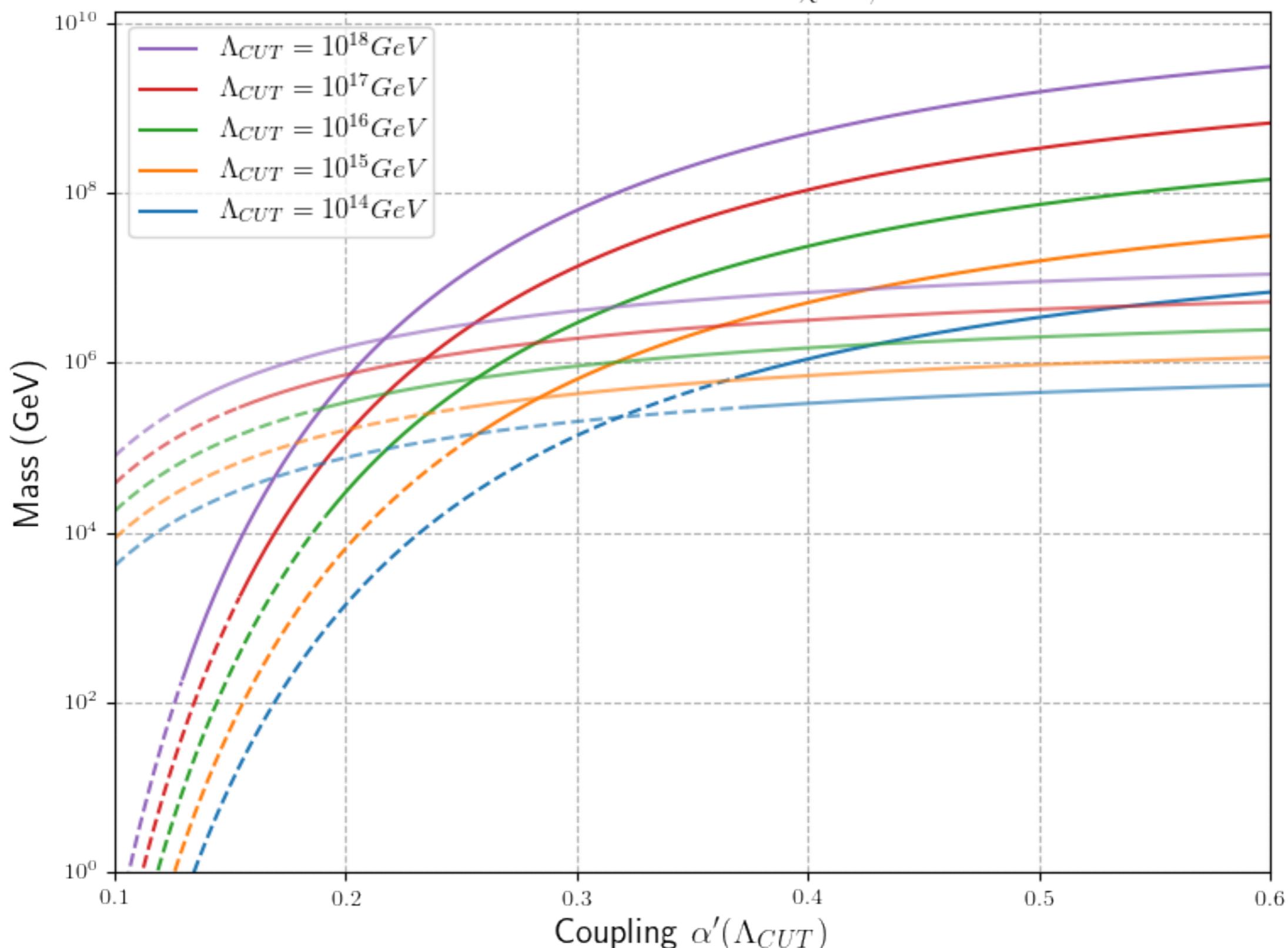
M. A. Shifman, A. I. Vainshtein, V. I. Sakharov,  
“Instanton Density in a Theory with Massless  
Quarks,” Nucl. Phys. B163 (1980)

J. Flynn, L. Randall, “A computation of the  
small instanton contribution to the axion  
potential.” Nucl. Phys. B208 (1987)

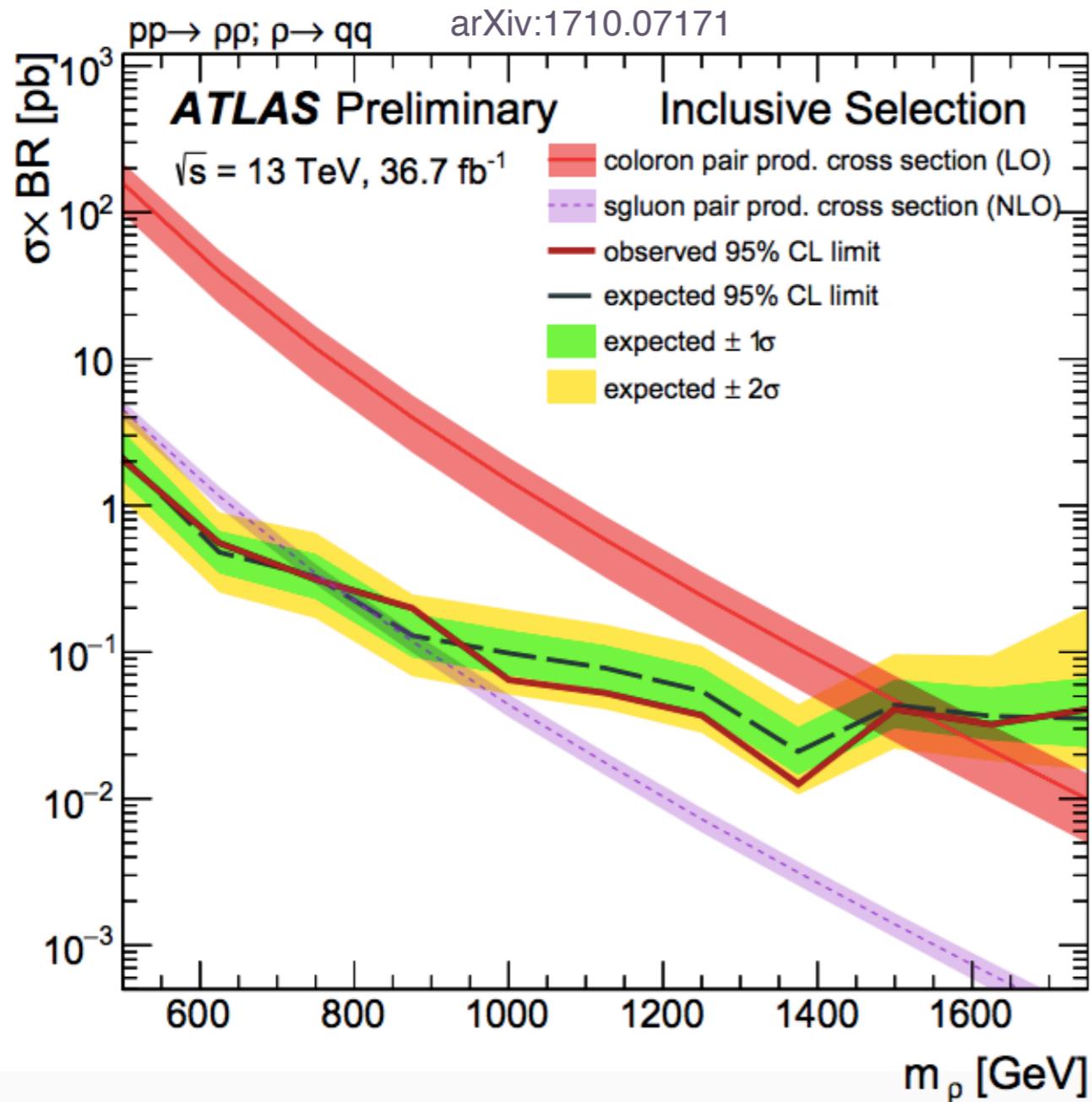
instanton  
suppression factor

$$\Lambda_{SSI}^4 = - \int \frac{d\rho}{\rho^5} D[\alpha'(1/\rho)] \left( \frac{2}{3} \pi^2 \rho^3 \langle \bar{\chi} \chi \rangle \right) \frac{1}{(4\pi)^6} \prod_i y_u'^i y_d'^i$$

## Axion masses: $\eta'_\chi, \eta'_\psi$



# Collider Phenomenology



- ❖ We have a bound on color octet scalars

$$m(\pi_d) \gtrsim 770 \text{ GeV}$$

$$m^2(8_c) \approx \frac{9\alpha_c}{4\pi} \Lambda_{\text{diag}}^2$$

$$\Lambda_{\text{diag}} \gtrsim 2.9 \text{ TeV}$$

# Conclusions

- ❖ The Strong CP Problem can be solved using massless quarks and unification

$$SU(6) \times SU(3') \xrightarrow{\Lambda_{\text{CUT}}} SU(3)_c \times SU(3)_{\text{diag}}$$

- ❖ Arrange  $\Lambda_{\text{diag}} \gg \Lambda_{QCD}$  by decoupling SM quarks
- ❖ The two scales  $\Lambda_{\text{CUT}} \gg \Lambda_{\text{diag}}$  are naturally separated by the running coupling behavior
- ❖ Small size instantons provided an extra source of mass for axions

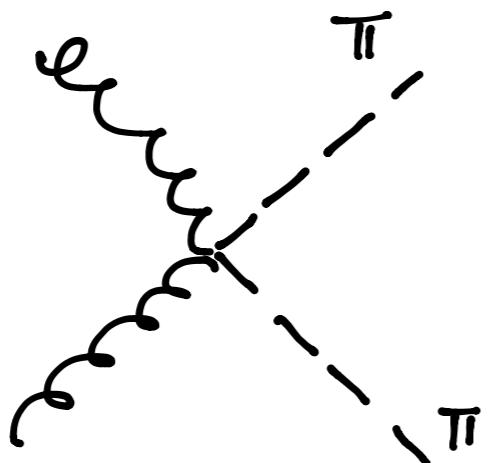
*Thank you!*

# Back-up Slides

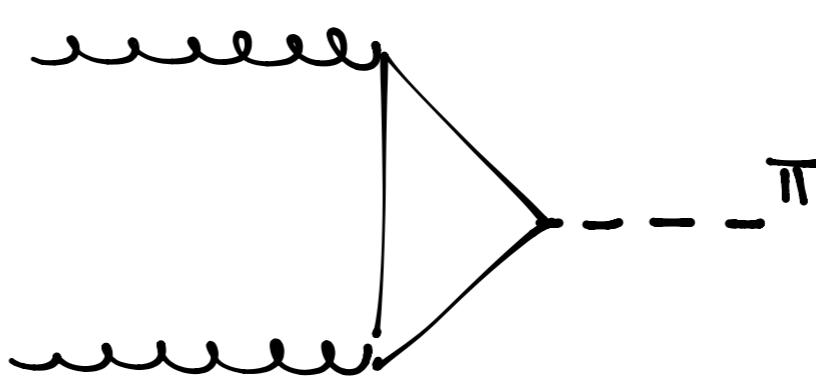
# Collider Phenomenology

- ❖ Collider accessible states are QCD colored “pions” present in Models 1 and 2

$$\mathcal{L} \ni D_\mu \pi_d D^\mu \pi_d + \frac{\pi_d^a}{f_d} \frac{\alpha_s}{16\pi} d_{abc} G_{\mu\nu}^b \tilde{G}^{c\mu\nu}$$

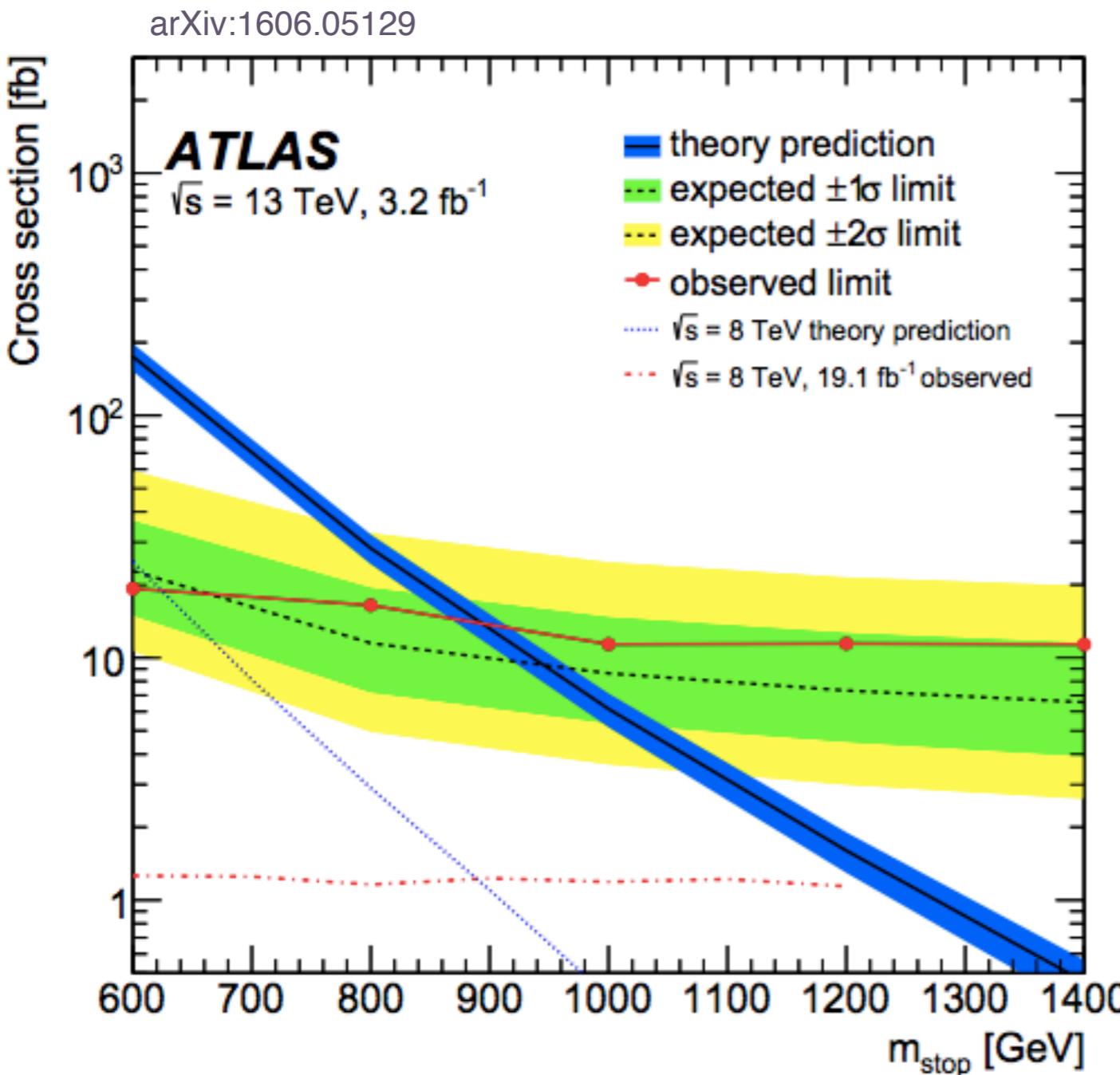


❖ Pair produced



❖ Anomalous production

# Collider Phenomenology: R-Hadron Searches



- ❖ We have a bound on color triplet scalars

$$m(\pi_d) \gtrsim 890 \text{ GeV}$$

$$m^2(3_c) \approx \frac{\alpha_c}{\pi} \Lambda_{\text{diag}}$$

$$\Lambda_{\text{diag}} \gtrsim 3 \text{ TeV}$$

# Small Size Instantons and Axion Mass

- ❖ With the fermion suppression, the benchmark  $\alpha'(\Lambda_{\text{CUT}}) = .3$  gives:

$$\Lambda_{SSI}^4 \simeq 5.8 \times 10^{-11} \Lambda_{\text{diag}}^3 \Lambda_{CUT} \rightarrow \Lambda_{SSI} \sim \text{few TeV}$$

- ❖ The instanton effects generate a new contribution to the effective potential

$$\delta \mathcal{L}_{eff} = \Lambda_{SSI}^4 \cos \left( 2 \frac{\eta'_\chi}{f_d} \right)$$

- ❖ So the axion potential is:

$$\begin{aligned} \mathcal{L}_{eff} = & \Lambda_{SSI}^4 \cos \left( 2 \frac{\eta'_\chi}{f_d} - \bar{\theta}' \right) + \Lambda_{\text{diag}}^4 \cos \left( 2 \frac{\eta'_\chi}{f_d} + \sqrt{6} \frac{\eta'_\psi}{f_d} - \bar{\theta}' - \bar{\theta}_6 \right) \\ & + \Lambda_{\text{QCD}}^4 \cos \left( \sqrt{6} \frac{\eta'_\psi}{f_d} - \bar{\theta}_6 \right) \end{aligned}$$