

Supersymmetric, CP violating Charm decays

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October 8th at TWCU

This lecture in 1 slide

2019

LHCb measures too much CP violation in $D^0 \rightarrow K^+K^-$ and $D^0 \rightarrow \pi^+\pi^-$

2023

Kaons and pions, expected to mirror each other, do not quite (U-spin breaking)

Question

Can supersymmetry explain these tensions?

Answer

The CP violation: yes, and it bounds the SUSY masses. The U-spin breaking: unlikely

About me

- EPFL, Switzerland
- First → experimental particle physics with LHCb
- Introduced me to flavor physics
- A semester project at CERN introduced me to CP-violation in charm physics, which is what I'm working on now



The Standard Model is great

Quarks



2.2 MeV



1.27 GeV



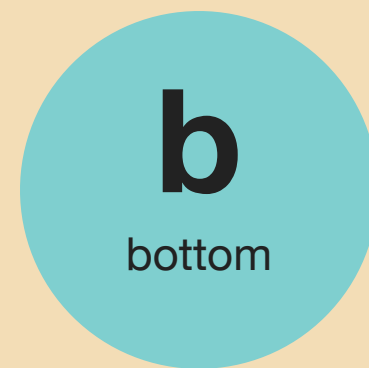
173 GeV



4.7 MeV

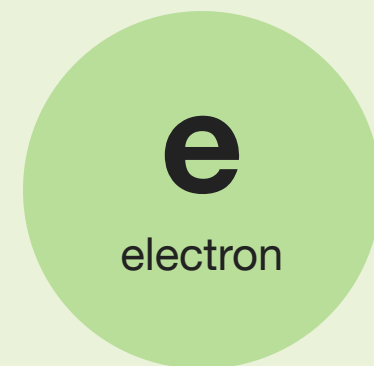


93 MeV



4.18 GeV

Leptons



0.511 MeV



106 MeV



1.78 GeV



< 1 eV



< 1 eV



< 1 eV

FERMIONS

Spin 1/2

The Standard Model is great

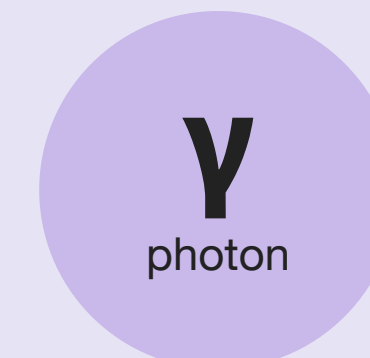
BOSONS

Spin 0 or 1

Forces



0



0



91.2 GeV



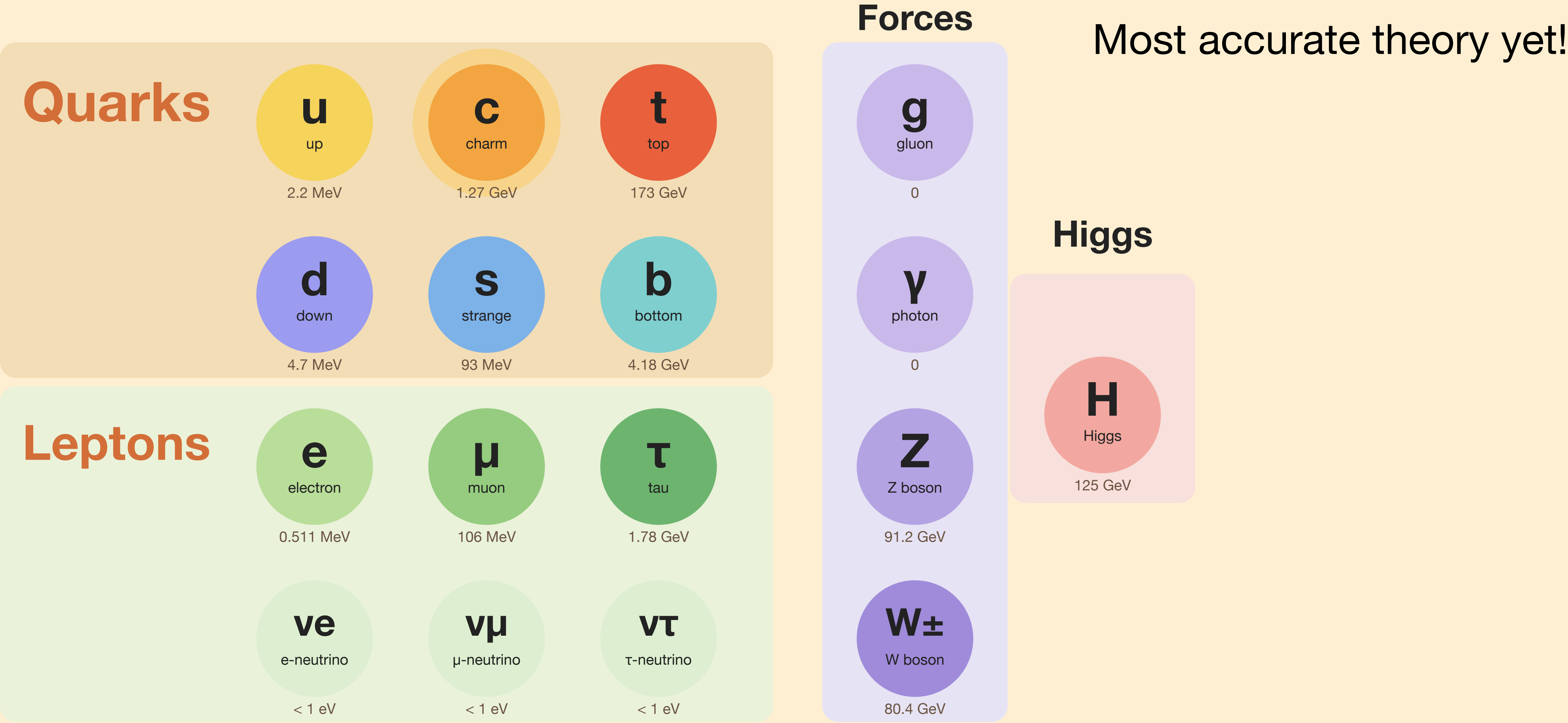
80.4 GeV

Higgs



125 GeV

The Standard Model is great



... but it's not the whole picture

The SM doesn't provide explanations for many observed phenomena: neutrino oscillations, dark matter, matter-antimatter asymmetry....

→ We expect New Physics! (NP)

Supersymmetry is one such theory

What is flavor physics?

Generation:

1st

2nd

3rd

“up” type

u

2.2 MeV

c

1.3 GeV

t

173 GeV

charge $Q = +\frac{2}{3}$

“down” type

d

4.7 MeV

s

96 MeV

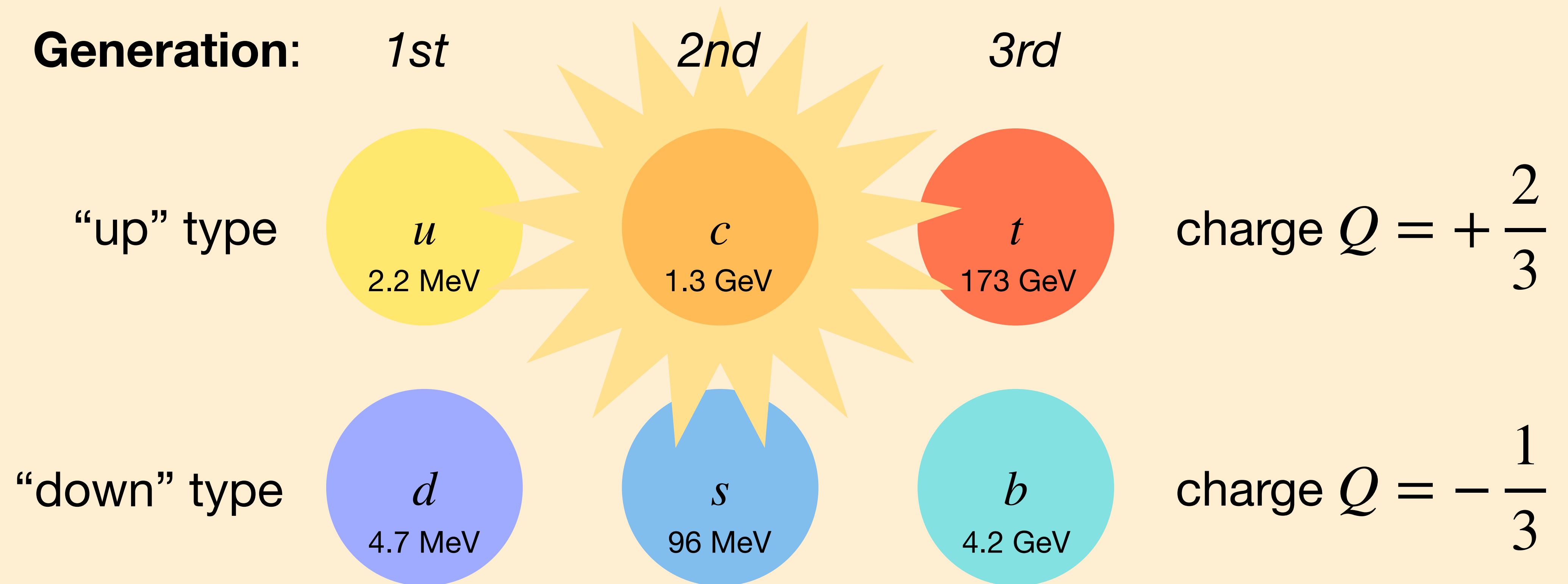
b

4.2 GeV

charge $Q = -\frac{1}{3}$

They are organized into **hadrons**: mesons ($q\bar{q}$) or baryons (qqq)

What is flavor physics?



Why are we interested in charm physics?

- Access to the **up sector**:
 - t doesn't form stable hadrons, and $u\bar{u}$ is not a mass eigenstate
- Flavor changing processes are especially suppressed (within the SM)
 - small deviations from theory are sizable!

But...

- The charm physics sits at an awkward mass scale
 - theoretical predictions have high uncertainty

D^0 decay

$$D^0 \rightarrow K^+ K^-$$

$$D^0 \rightarrow \pi^+ \pi^-$$

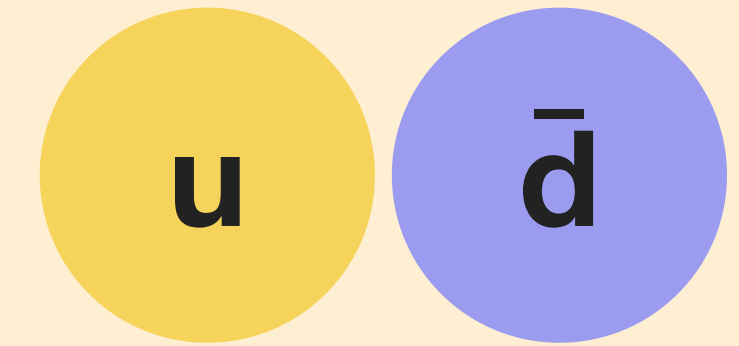
D^0



K^+



π^+



$$D^0 \rightarrow K^+ K^-$$

$$c \bar{u} \rightarrow (u \bar{s}) + (s \bar{u})$$

the charm quark turns into a strange quark or up quark

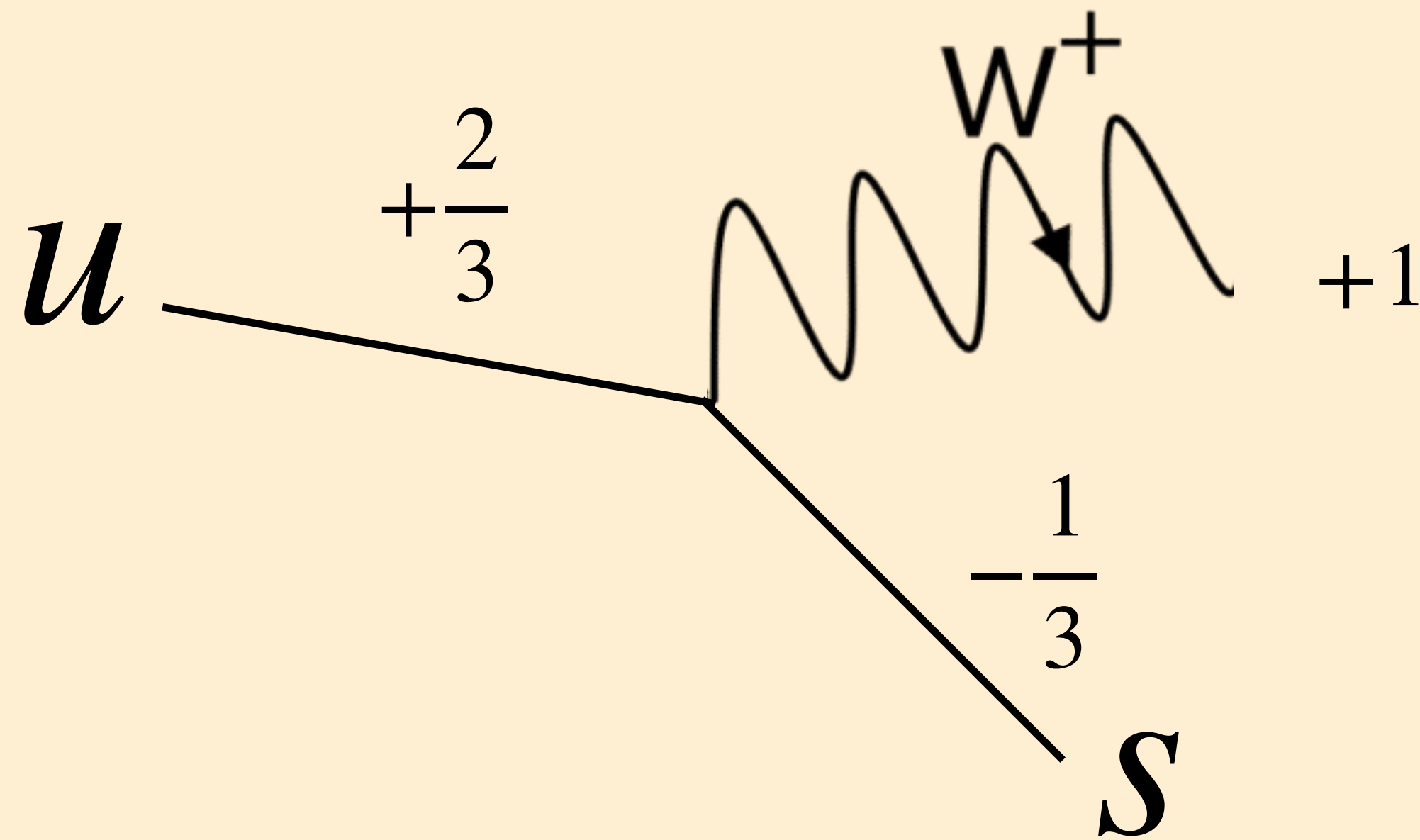
$$D^0 \rightarrow \pi^+ \pi^-$$

$$c \bar{u} \rightarrow (u \bar{d}) + (d \bar{u})$$

the charm quark turns into a down quark or up quark

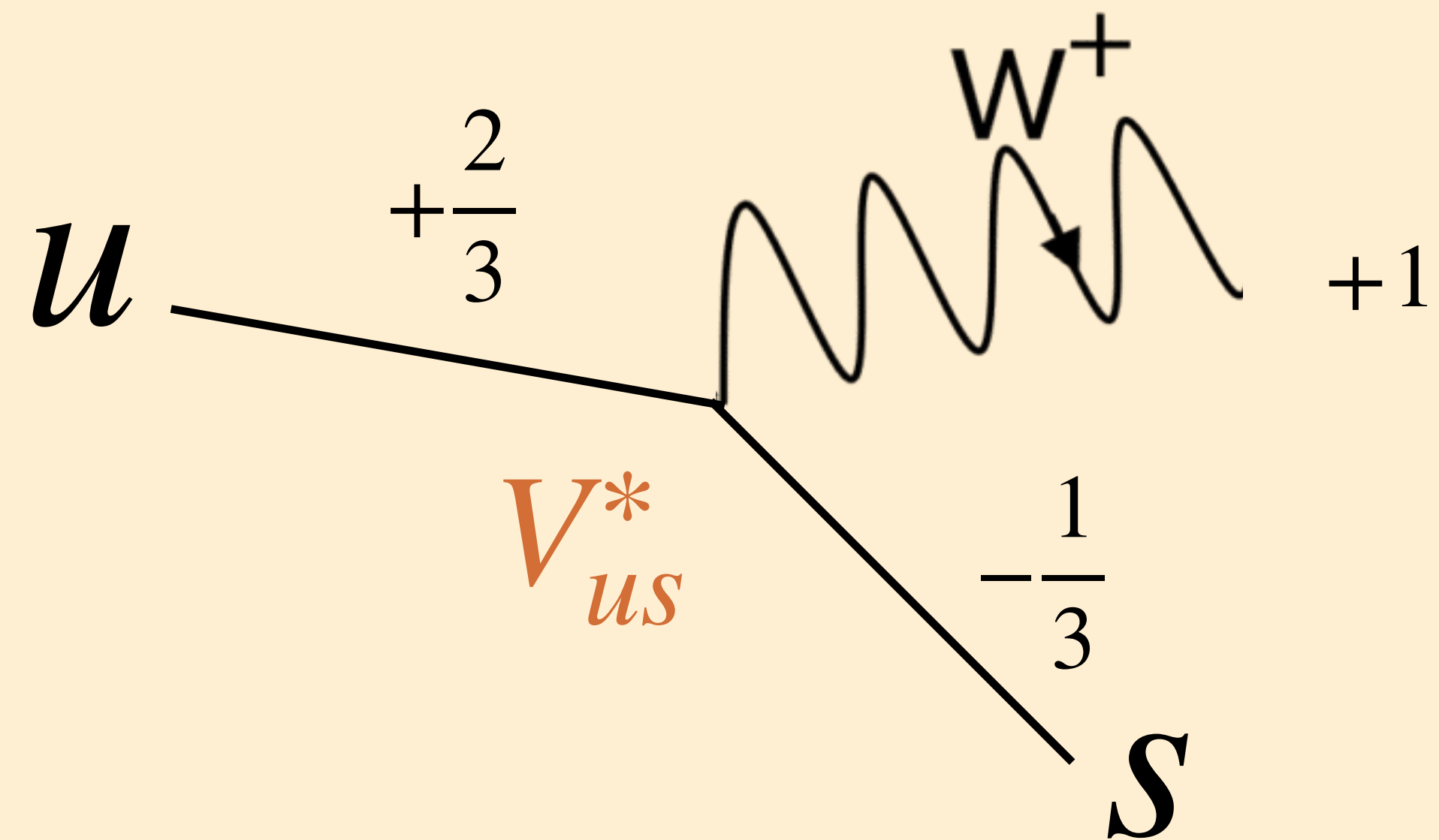
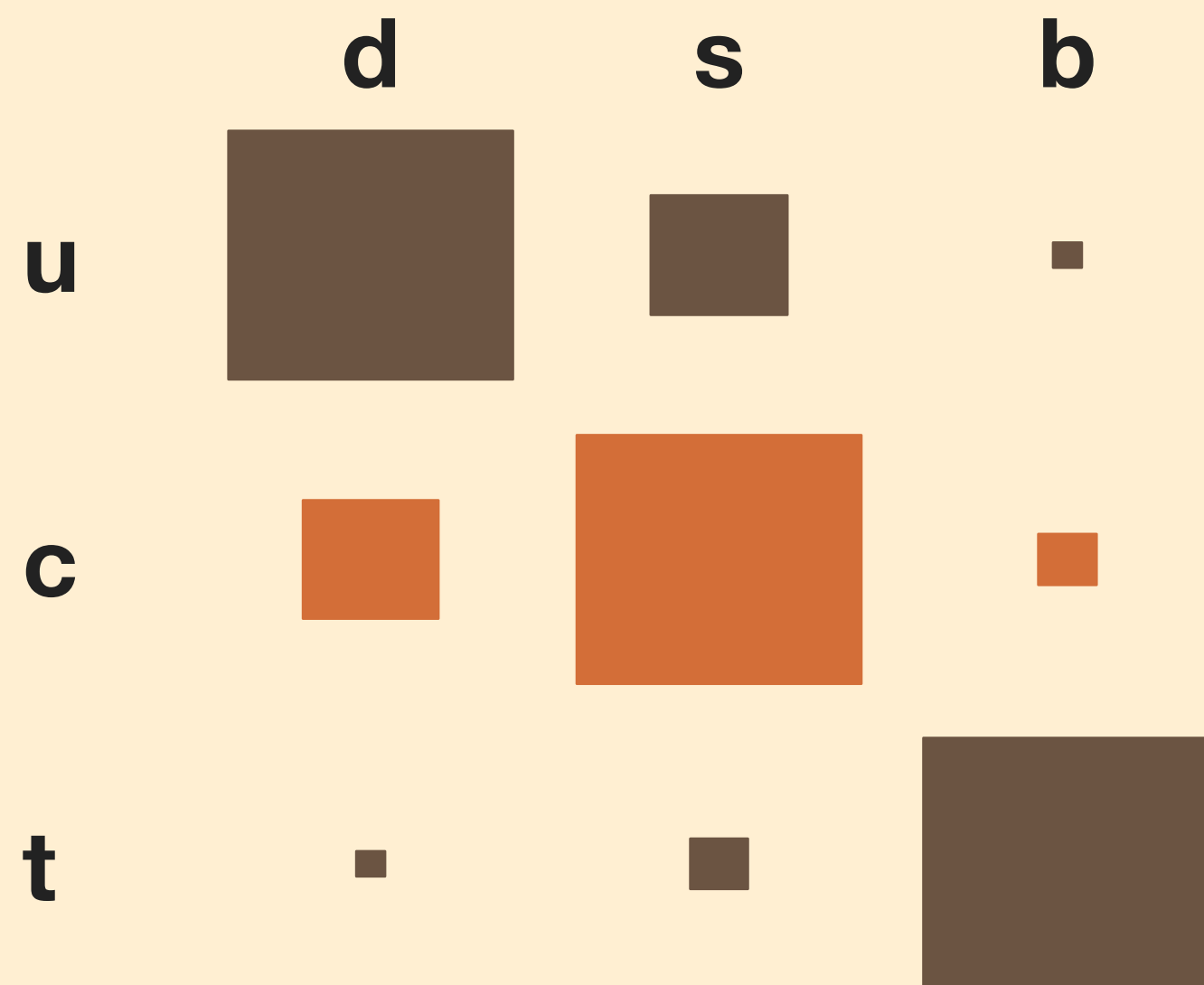
Flavor changing processes in the SM

- They are only mediated by the $W^\pm$ bosons! (Weak interaction)
- $W^\pm$ is charged $\rightarrow$ the interactions change sign



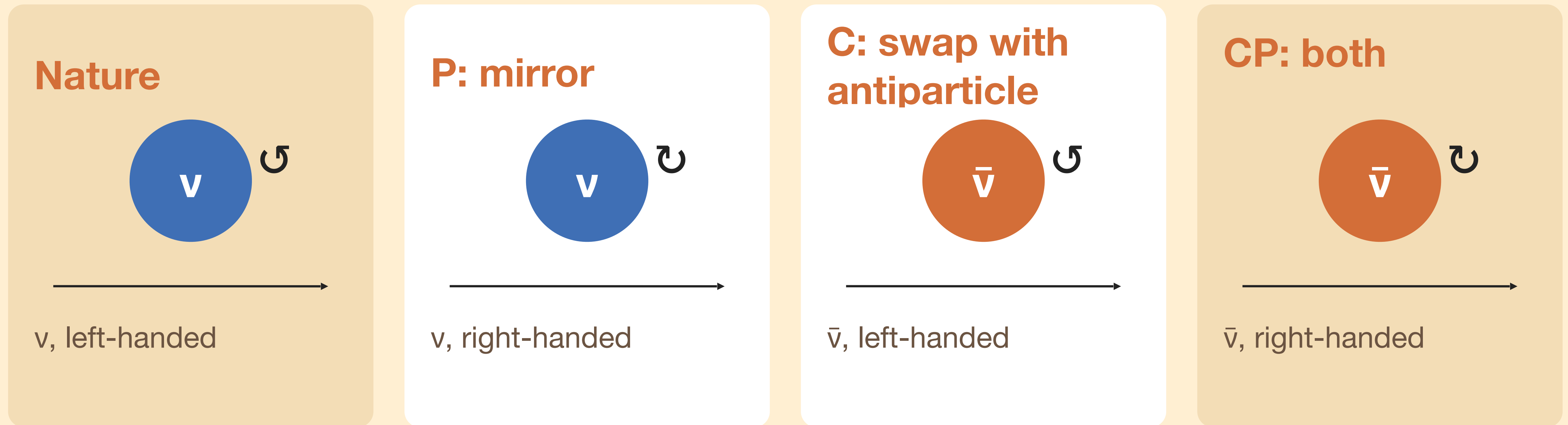
Each flavor change is weighed by the CKM matrix

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$



The CKM matrix has an irreducible phase

CP symmetry



The weak force breaks C and P separately. CP looked like an exact symmetry, until 1964 (kaons): it is broken too, but only slightly.

CP violation (CPV)

- Broken by irreducible phases in the theory

→ the CKM matrix is the only source of CP-violation in the SM
- We need *more* CPV than what the SM provides to explain the matter-antimatter asymmetry of the universe → New physics is probably CPV
- To have CPV, several amplitudes must interfere

How does CPV manifest?

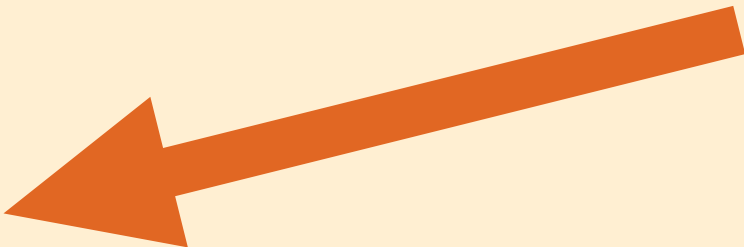
3 types of CPV

1. Direct CPV or CPV in decay

$$|A(D^0 \rightarrow f)| \neq |A(\bar{D}^0 \rightarrow \bar{f})|$$

2. Indirect CPV in mixing

$$P(D^0 \rightarrow \bar{D}^0) \neq P(\bar{D}^0 \rightarrow D^0)$$



Mixing or oscillations refers to when a neutral meson (like D^0) turns into its antiparticle ($\bar{D}^0$)

3. Indirect CPV in interference between mixing and decay

$A(D^0 \rightarrow f)$ and $A(D^0 \rightarrow \bar{D}^0 \rightarrow f)$ interfere

How does CPV manifest?

3 types of CPV

1. **Direct** CPV or CPV in decay

$$|A(D^0 \rightarrow f)| \neq |A(\bar{D}^0 \rightarrow \bar{f})|$$

2. **Indirect** CPV in **mixing**

$$P(D^0 \rightarrow \bar{D}^0) \neq P(\bar{D}^0 \rightarrow D^0)$$

3. **Indirect** CPV in interference between mixing and decay

$$A(D^0 \rightarrow f) \text{ and } A(D^0 \rightarrow \bar{D}^0 \rightarrow f) \text{ interfere}$$

How can we observe it?

CP asymmetry in a D^0 decay to a final state f

- Experimentally, we can access the decay rates Γ

$$A_{CP}(f) = \frac{\Gamma(D^0 \rightarrow f) - \Gamma(\bar{D}^0 \rightarrow f)}{\Gamma(D^0 \rightarrow f) + \Gamma(\bar{D}^0 \rightarrow f)} \quad \text{Measures CPV, both *direct* and *indirect*}$$

$$\Delta A_{CP} = A_{CP}(K^+ K^-) - A_{CP}(\pi^+ \pi^-) \quad \text{Measures *direct* CPV, because indirect effects cancel}$$

2019: the first tension

- CP violation in charm is discovered!



$$\Delta A_{CP}^{exp} = (-15.4 \pm 2.9) \cdot 10^{-4}$$

- But with naive SM calculations, we expect $\Delta A_{CP} \sim 10^{-4}$! (Although theoretical uncertainties are large)

2023: a second tension

$$A_{CP}^{\text{dir}}(K^+K^-) = (7.7 \pm 5.7) \cdot 10^{-4}$$

$$A_{CP}^{\text{dir}}(\pi^+\pi^-) = (23.2 \pm 6.1) \cdot 10^{-4}$$

Under U-spin, we expect

$$\sum_{P=K,\pi} A_{CP}^{\text{dir}}(P^+P^-) = 0$$

→ Exceeds SM predictions at 1.9σ

U-spin refers to the symmetry under

$$d \leftrightarrow s$$

It is an *approximate* symmetry of QCD

(Broken to $\sim 30\%$ in the SM)

How can we explain this?

1. The SM, computed better

- Charm is notoriously hard to calculate
- Non-perturbative effects could enhance the asymmetry
- The U-spin difference could be a statistical fluctuation

2. New physics

- Example: **supersymmetry** (SUSY)
- Every known particle gets a heavier partner: quark $\rightarrow$ squark, gluon $\rightarrow$ gluino
- New particles bring new phases $\rightarrow$ new CP violation

How can we explain this?

1. The SM, computed better

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Now we know:

- The observable from flavor physics
- The experimental results

Next we will see:

- Supersymmetry (SUSY)
- The SUSY contribution to the decay

Questions for now?

Supersymmetry

Standard Model

Superpartners (not yet seen)



Fermion $\rightarrow$ Sfermion

Gauge $\rightarrow$ Gaugino

We consider the most minimal realization of SUSY: the MSSM

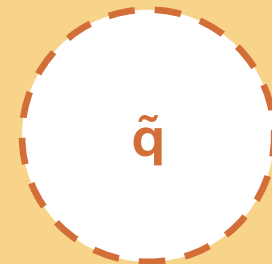
Supersymmetry

Standard Model

Superpartners (not yet seen)



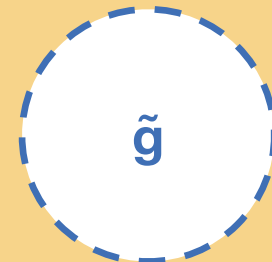
quarks
spin $\frac{1}{2}$



squarks
spin 0



gluon
spin 1



gluino
spin $\frac{1}{2}$

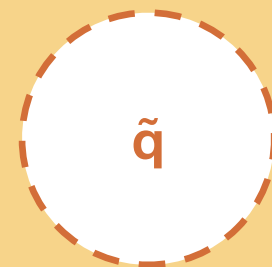
Supersymmetry

Standard Model

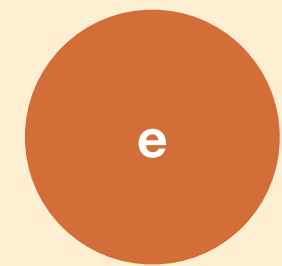
Superpartners (not yet seen)



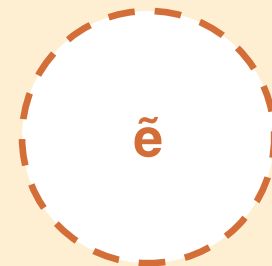
quarks
spin $\frac{1}{2}$



squarks
spin 0



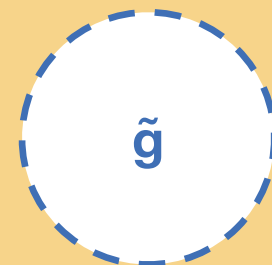
leptons
spin $\frac{1}{2}$



sleptons
spin 0



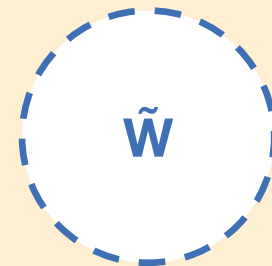
gluon
spin 1



gluino
spin $\frac{1}{2}$



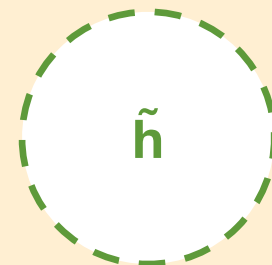
W, Z, photon
spin 1



winos, zino, photino
spin $\frac{1}{2}$



Higgs
spin 0



higgsinos
spin $\frac{1}{2}$

Same charges and couplings

Only the spin differs, so partners interact exactly like the originals (only 1 new parameter in the SUSY Lagrangian)

But not the same mass

Otherwise we would have seen them:

SUSY must be broken!

Soft-SUSY breaking

$$\begin{aligned}\mathcal{L}_{\text{soft}}^{\text{MSSM}} = & -\frac{1}{2} (M_3 \tilde{g} \tilde{g} + M_2 \tilde{W} \tilde{W} + M_1 \tilde{B} \tilde{B} + \text{c.c.}) \\ & - \left(\tilde{u} \mathbf{a}_u \tilde{Q} H_u - \tilde{d} \mathbf{a}_d \tilde{Q} H_d - \tilde{e} \mathbf{a}_e \tilde{L} H_d + \text{c.c.} \right) \\ & - \tilde{Q}^\dagger \mathbf{m}_Q^2 \tilde{Q} - \tilde{L}^\dagger \mathbf{m}_L^2 \tilde{L} - \tilde{u} \mathbf{m}_u^2 \tilde{u}^\dagger - \tilde{d} \mathbf{m}_d^2 \tilde{d}^\dagger - \tilde{e} \mathbf{m}_e^2 \tilde{e}^\dagger \\ & - m_{H_u}^2 H_u^* H_u - m_{H_d}^2 H_d^* H_d - (b H_u H_d + \text{c.c.}) .\end{aligned}$$

“soft” breaking terms = with mass dimension > 0

Soft-SUSY breaking

$$\begin{aligned}\mathcal{L}_{\text{soft}}^{\text{MSSM}} = & -\frac{1}{2} (M_3 \tilde{g} \tilde{g} + M_2 \tilde{W} \tilde{W} + M_1 \tilde{B} \tilde{B} + \text{c.c.}) \\ & - \left(\tilde{u} \mathbf{a}_u \tilde{Q} H_u - \tilde{d} \mathbf{a}_d \tilde{Q} H_d - \tilde{e} \mathbf{a}_e \tilde{L} H_d + \text{c.c.} \right) \\ & - \tilde{Q}^\dagger \mathbf{m}_Q^2 \tilde{Q} - \tilde{L}^\dagger \mathbf{m}_L^2 \tilde{L} - \tilde{u} \mathbf{m}_u^2 \tilde{u}^\dagger - \tilde{d} \mathbf{m}_d^2 \tilde{d}^\dagger - \tilde{e} \mathbf{m}_e^2 \tilde{e}^\dagger \\ & - m_{H_u}^2 H_u^* H_u - m_{H_d}^2 H_d^* H_d - (b H_u H_d + \text{c.c.}) .\end{aligned}$$

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 & - m_{H_u}^2 H_u^* H_u - m_{H_d}^2 H_d^* H_d - (b H_u H_d + \text{c.c.}) .
 \end{aligned}$$

gluino mass

trilinear coupling

LH squark mass

RH up-type squark mass

- They are the contributions to the ***squark mass matrix***
- Non-diagonal entries: flavor changes

$$\begin{aligned}
 \mathcal{L}_{\text{soft}}^{\text{MSSM}} = & -\frac{1}{2} (M_3 \tilde{g} \tilde{g} + M_2 \tilde{W} \tilde{W} + M_1 \tilde{B} \tilde{B} + \text{c.c.}) \\
 & - \left(\tilde{u} \mathbf{a}_u \tilde{Q} H_u - \tilde{d} \mathbf{a}_d \tilde{Q} H_d - \tilde{e} \mathbf{a}_e \tilde{L} H_d + \text{c.c.} \right) \\
 & - \tilde{Q}^\dagger \mathbf{m}_Q^2 \tilde{Q} - \tilde{L}^\dagger \mathbf{m}_L^2 \tilde{L} - \tilde{u} \mathbf{m}_u^2 \tilde{u}^\dagger - \tilde{d} \mathbf{m}_d^2 \tilde{d}^\dagger - \tilde{e} \mathbf{m}_e^2 \tilde{e}^\dagger \\
 & - m_{H_u}^2 H_u^* H_u - m_{H_d}^2 H_d^* H_d - (b H_u H_d + \text{c.c.}) .
 \end{aligned}$$

Chirality-changing →

chirality-conserving

chirality-conserving

- Complex entries = new phases = CPV

The squark squared mass matrix

The contributions from the last slide can be rewritten in the 6x6 matrix

$$\mathcal{M}_{\tilde{q}}^2 = \tilde{m}_q^2 \left[\mathbb{I}_{6 \times 6} + \Delta_q \right], \quad \Delta_q \equiv \begin{pmatrix} \delta_{LL}^q & \delta_{LR}^q \\ \delta_{RL}^q & \delta_{RR}^q \end{pmatrix}$$

- Diagonal: average squark mass $\tilde{m}_q$
- Off-diagonal δ 's $\ll 1$: treat as small “insertions”
- LR, RL block matrices contain chirality changing insertions
- LL, RR block matrices contain chirality conserving insertions

$(\delta_{LR}^u)_{12}$

	$\tilde{u}_L$	$\tilde{c}_L$	$\tilde{t}_L$	$\tilde{u}_R$	$\tilde{c}_R$	$\tilde{t}_R$
$\tilde{u}_L$						
$\tilde{c}_L$		LL			LR	
$\tilde{t}_L$						
$\tilde{u}_R$						
$\tilde{c}_R$		RL			RR	
$\tilde{t}_R$						

The insertion $(\delta_{\Gamma\Gamma'})_{ij}$ changes flavor from j to i

**We have seen the relevant parameters
in SUSY (the mass insertions).**

**How do we compute the contribution
to ΔA_{CP} ?**

To deal with the charm quark calculations, we use:

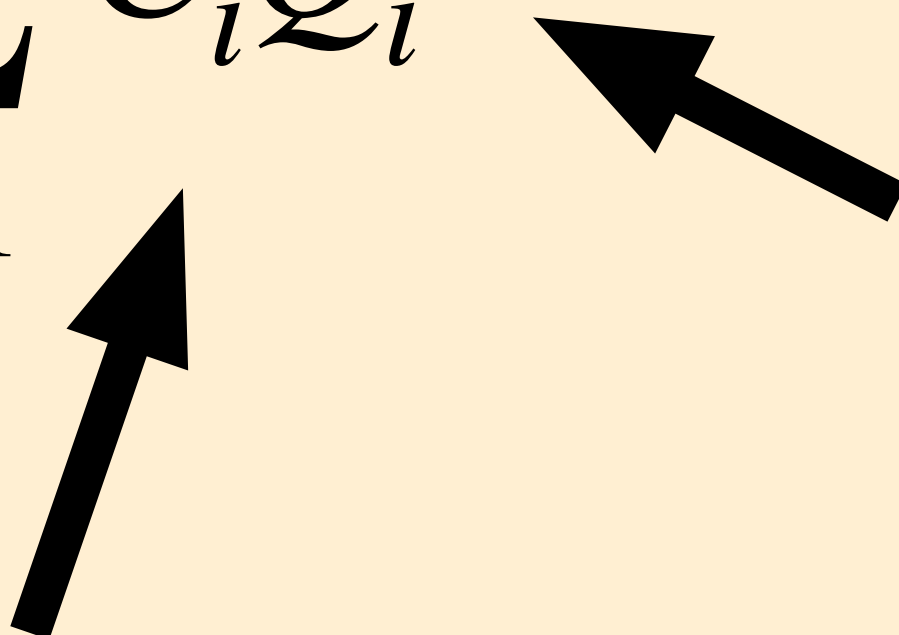
Effective Field Theories

In this approximation, the Hamiltonian is given by a weighed sum of operators

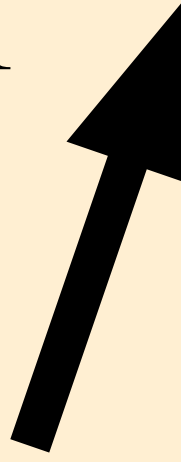
G_F : Fermi Constant

$$H_{eff} = \frac{G_F}{\sqrt{2}} \sum_{i=1} C_i Q_i$$

Operator:
encodes long
distance effects



Wilson coefficient: encodes short distance effects



We can also parametrize ΔA_{CP} like this!

New physics (NP) contribution

$$\Delta A_{CP} \approx \frac{-2}{\sin \theta_C} \left[\text{Im}(V_{cb}^* V_{ub}) \text{Im}(\Delta R^{\text{SM}}) + \sum_i \text{Im}(C_i^{\text{NP}}) \text{Im}(\Delta R^{\text{NP}_i}) \right]$$

SM (assumed negligible)

θ_C : Cabibbo angle

ΔR : Ratios from hadronic physics (we expect around 0.2 for both the SM and NP parts)

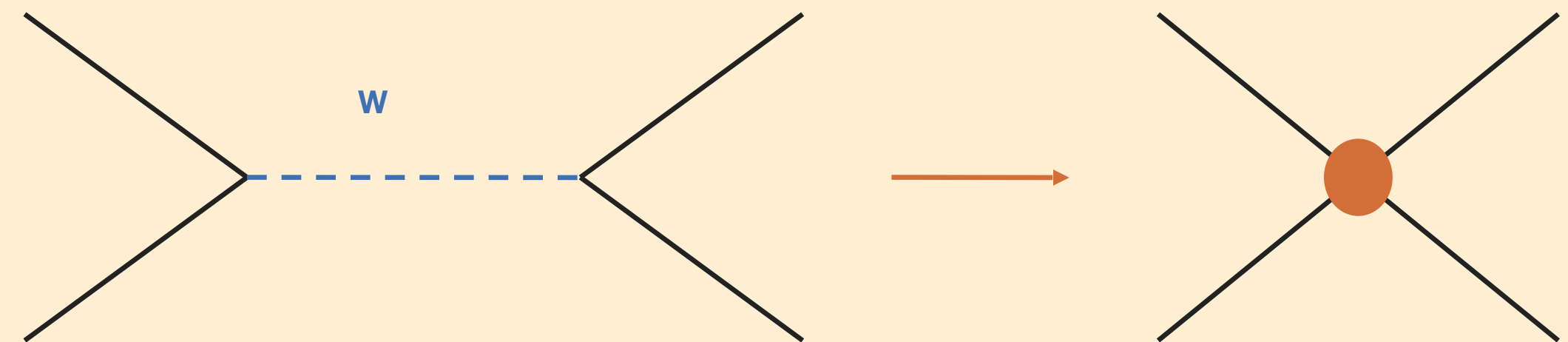
Let's assume ΔA_{CP} is due to SUSY alone.
What can we learn then?

1. What operators are relevant?
2. Do they break U-spin?
3. What constraints can be applied on this model?

What operators are relevant?

4 quark operators

- $Q_i, i = 1, 2, 5, 6$ with Wilson coefficients C_i
- $C_i \propto (\delta_{LL}^u)_{12}$
- *Can* break U-spin



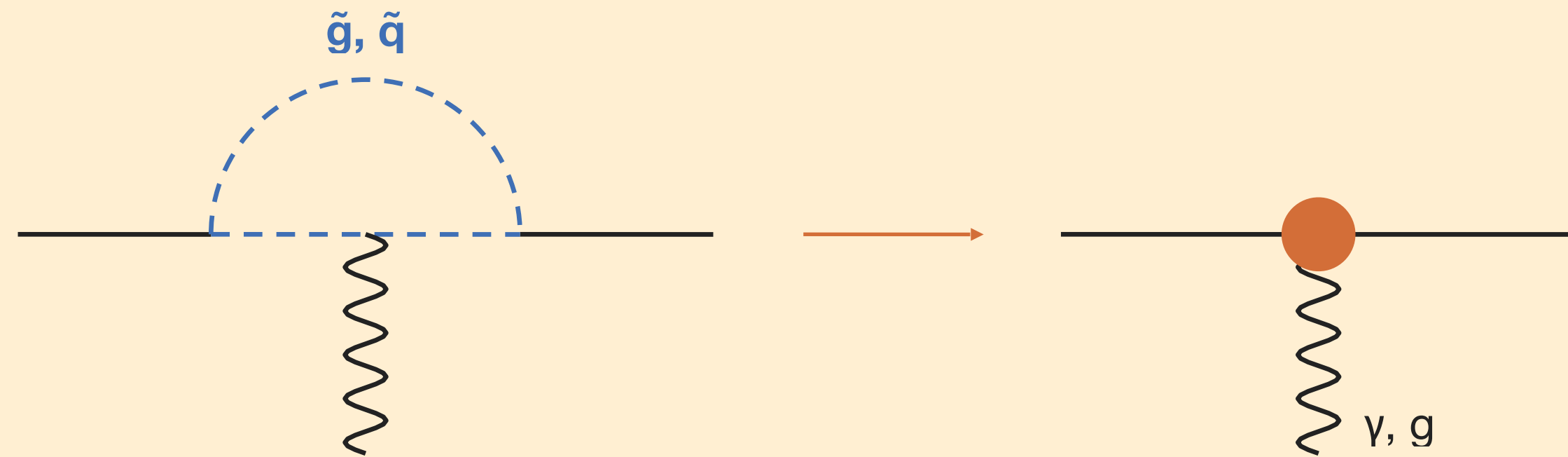
$$Q_1^q = (\bar{u}q)_{V-A}(\bar{q}c)_{V-A},$$

$$Q_2^q = (\bar{u}_\alpha q_\beta)_{V-A}(\bar{q}_\beta c_\alpha)_{V-A},$$

$$Q_5^q = (\bar{u}c)_{V-A}(\bar{q}q)_{V+A},$$

$$Q_6^q = (\bar{u}_\alpha c_\beta)_{V-A}(\bar{q}_\beta q_\alpha)_{V+A}$$

What operators are relevant?



$$Q_7 = -\frac{e}{8\pi^2} m_c \bar{u} \sigma_{\mu\nu} (1 + \gamma_5) F^{\mu\nu} c,$$

$$Q_8 = -\frac{g_s}{8\pi^2} m_c \bar{u} \sigma_{\mu\nu} (1 + \gamma_5) T^a G_a^{\mu\nu} c$$

Magnetic dipole operators

- $Q_i, i = 7, 8$ with Wilson coefficients C_i
- C_i are dominated by chirality-changing mass insertion $(\delta_{LR}^u)_{12}$
- *Cannot* break U-spin

What operators are relevant?

4 quark operators

- $Q_i, i = 1, 2, 5, 6$ with Wilson coefficients C_i
- Dominated by chirality-*conserving* mass insertion $(\delta_{LL}^u)_{12}$
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Magnetic dipole operators

- $Q_i, i = 7, 8$ with Wilson coefficients C_i
- Dominated by chirality-*changing* mass insertion $(\delta_{LR}^u)_{12}$
- *Cannot* break U-spin

The Wilson coefficients are constrained

Constraints on the mass insertions

Collider bounds

Squark masses > 1.9 TeV
Gluino masses > 2.4 TeV

D^0 – $\bar{D}^0$ mixing

Large contributions to
this constrained process
are forbidden

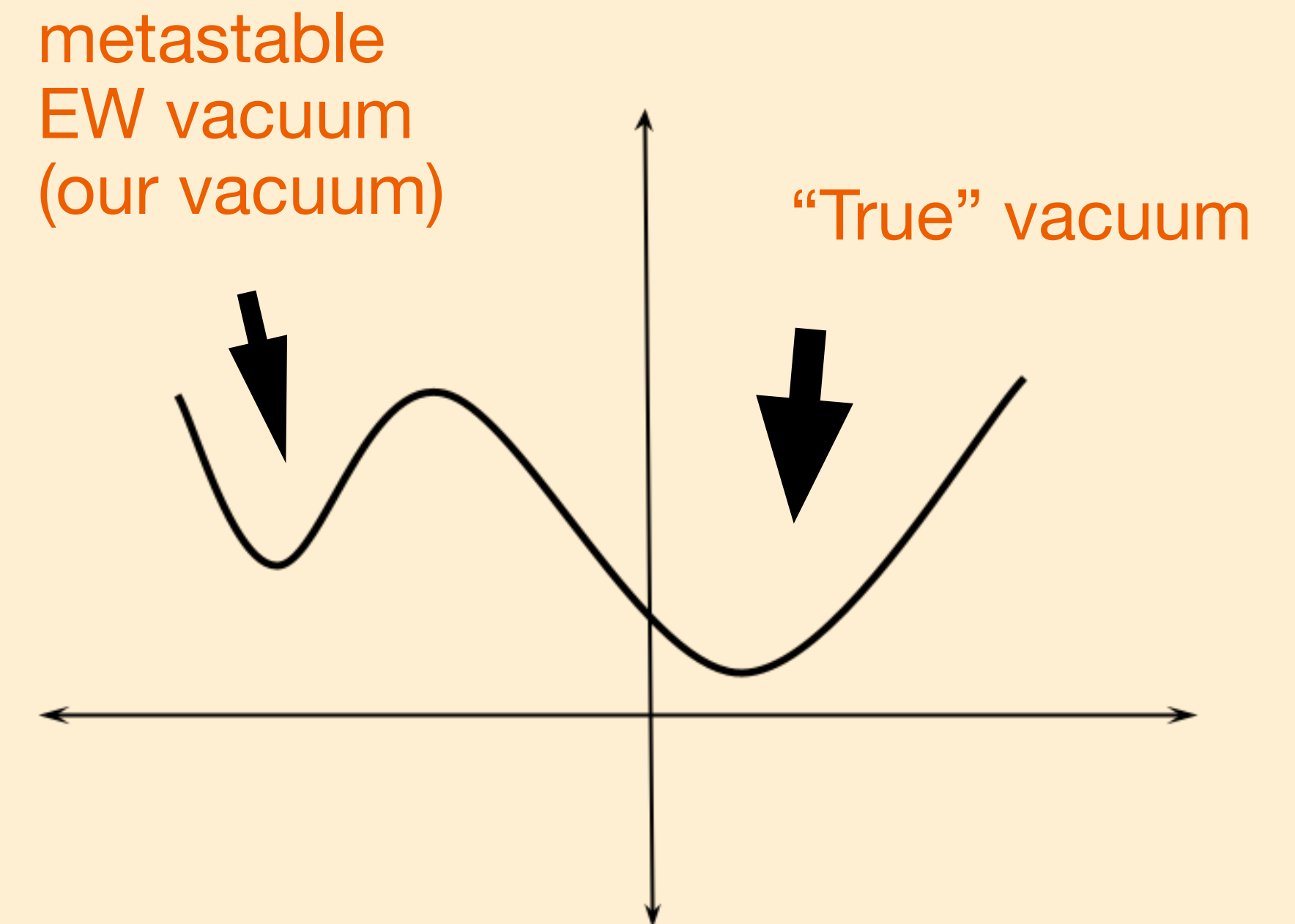
Vacuum (meta)stability

No charge- or color-breaking
vacuum, or one that lives
longer than the universe

Constraints on the particle masses

Vacuum (meta)stability

- The basic idea: a scalar potential $V(\phi) = m^2\phi^2 + \lambda\phi^4 - A\phi^3$ can get a non-0 minimum if the trilinear A is too big
- Squarks are scalars $\rightarrow$ they can spontaneously break color or charge vacuum if they acquire a non-0 VEV
 $\rightarrow$ constraint on the trilinear terms
 $=$ constraint on chirality-changing mass insertions
- This is OK if the vacuum is metastable (lives longer than our universe)

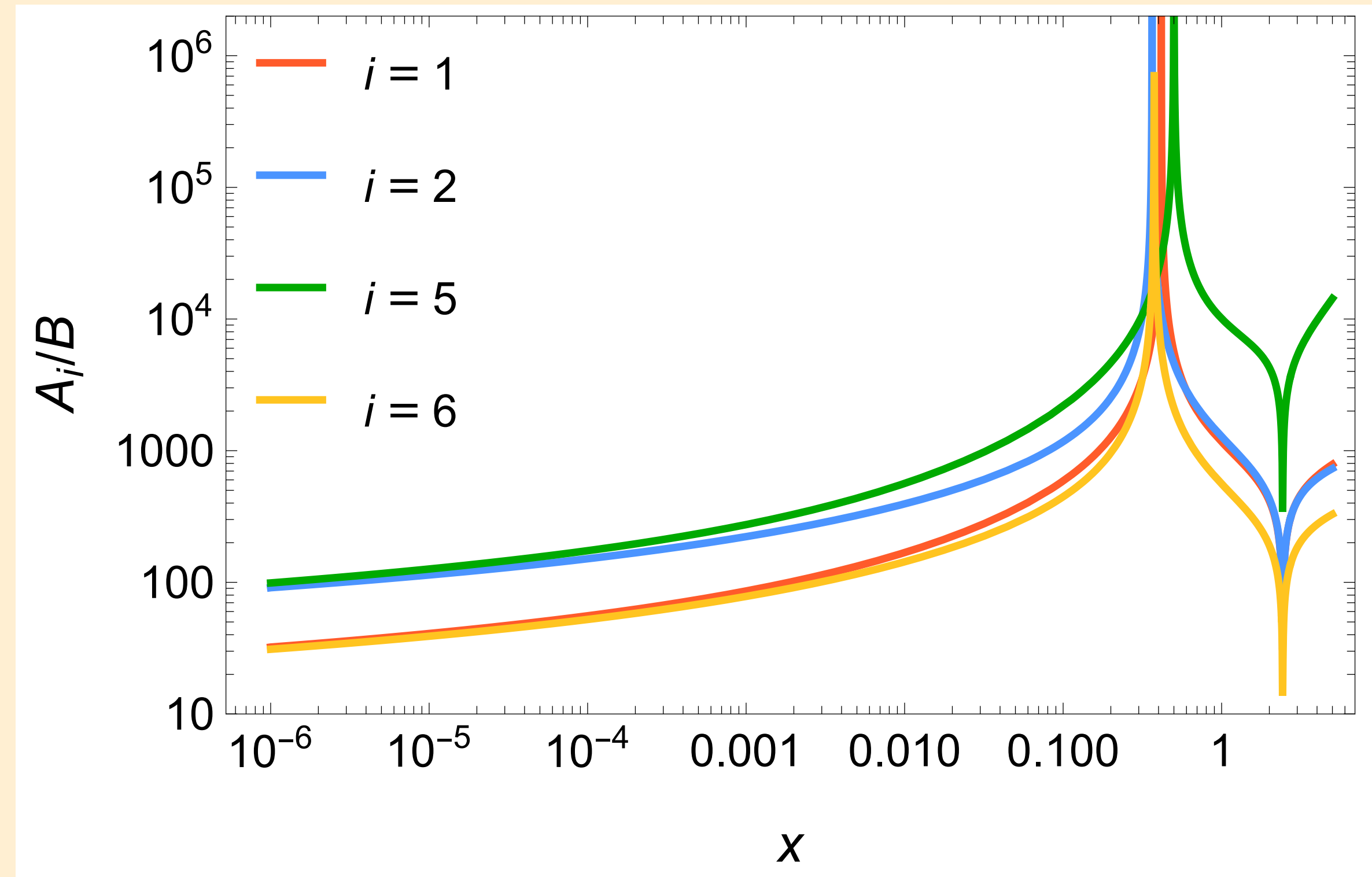


4 quark operators fail (except in a small window)

A_i encodes the contribution of Wilson coef. C_i to ΔA_{CP}

B encodes the contribution of C_i to $D^0 - \bar{D}^0$

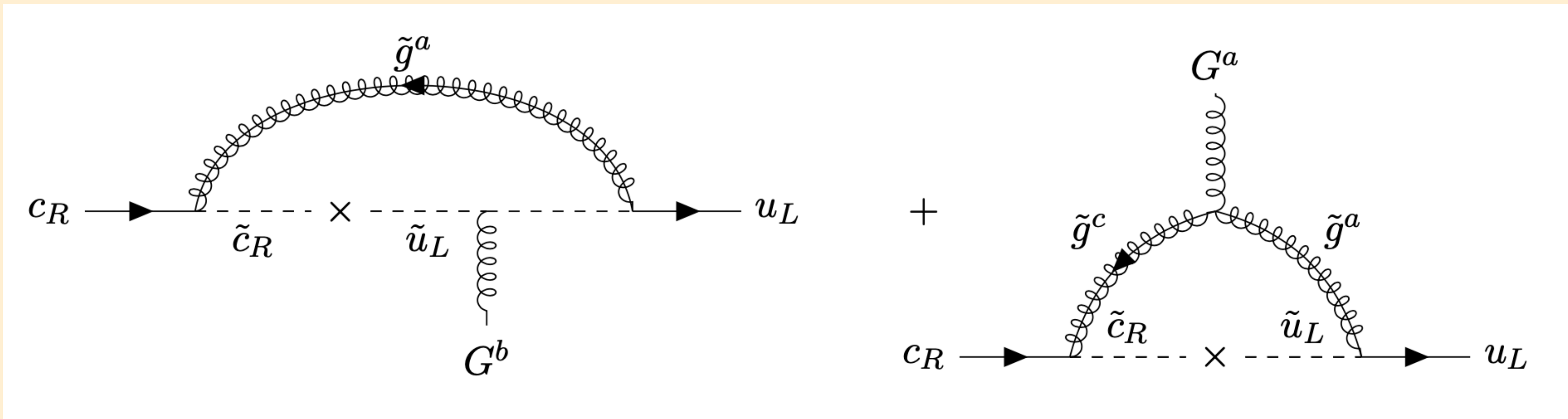
C_i can account for ΔA_{CP}
AND escape bounds from mixing if $A_i/B < 1$



This is only realized at $x \equiv \tilde{m}_g^2/\tilde{m}_q^2 \approx 2.4$

The winner: Q_8

- Mediates the decay through a chirality-*changing* mass insertion $(\delta_{LR}^u)_{12}$
- Gives large contribution to ΔA_{CP} and escapes $D^0 - \bar{D}^0$ bounds



But... does not break U-spin. :(

The SUSY contribution is likely given by Q_8 . Knowing this,

We study...

- Models in which

$$\tilde{m}_g = \tilde{m}_q$$

- Models in which

$$\tilde{m}_g < \tilde{m}_q$$

We assume...

- The SM contribution is negligible
- Squark masses are all nearly degenerate
- $(\delta_{LR}^u)_{12}$ is maximally imaginary

Results for $\tilde{m}_g = \tilde{m}_q$

- Pink region: vacuum **metastability** bound

26 TeV

$\text{Im } \Delta R^{\text{NP}} = 0.1$

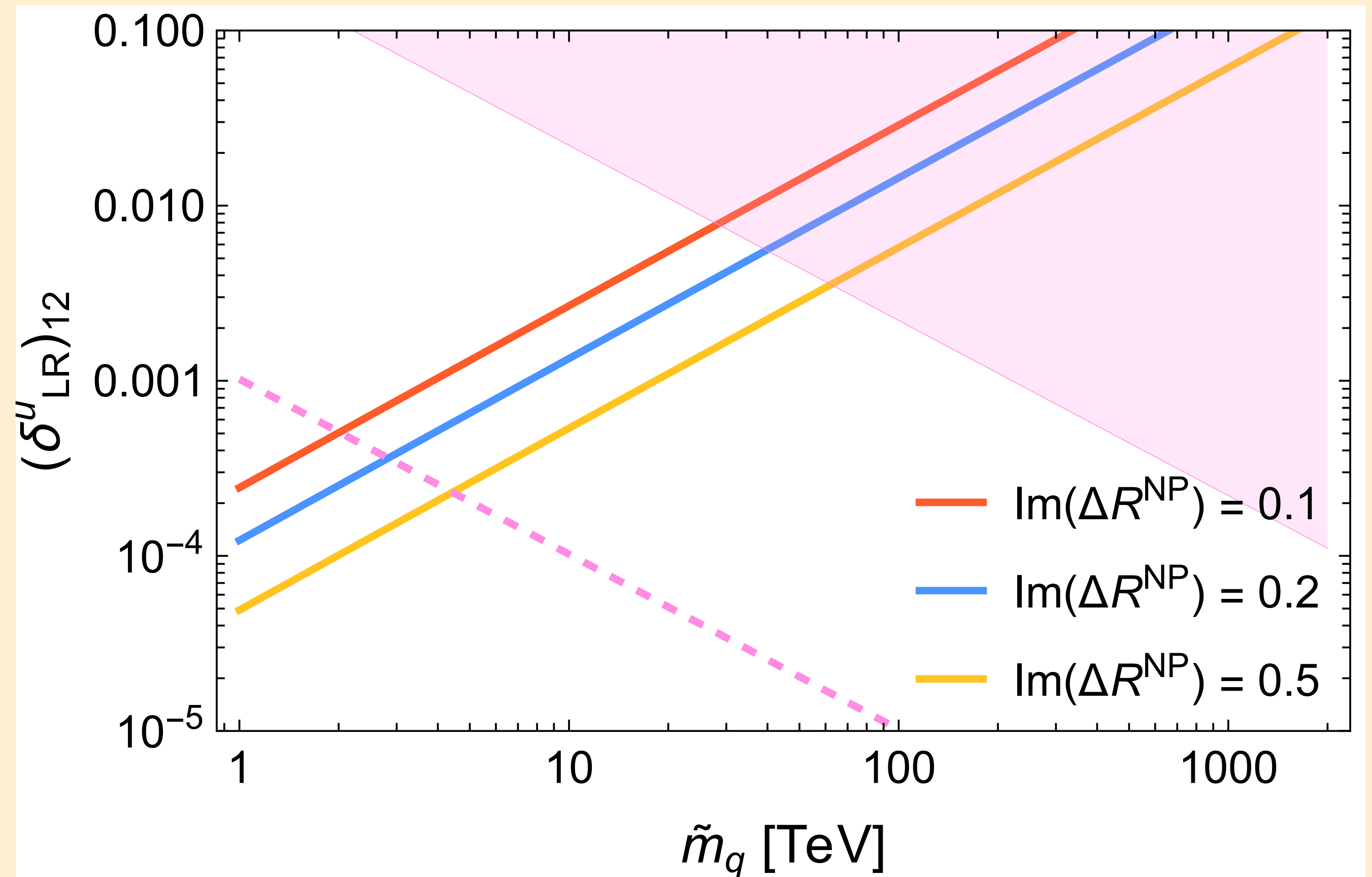
37 TeV

$\text{Im } \Delta R^{\text{NP}} = 0.2$

58 TeV

$\text{Im } \Delta R^{\text{NP}} = 0.5$

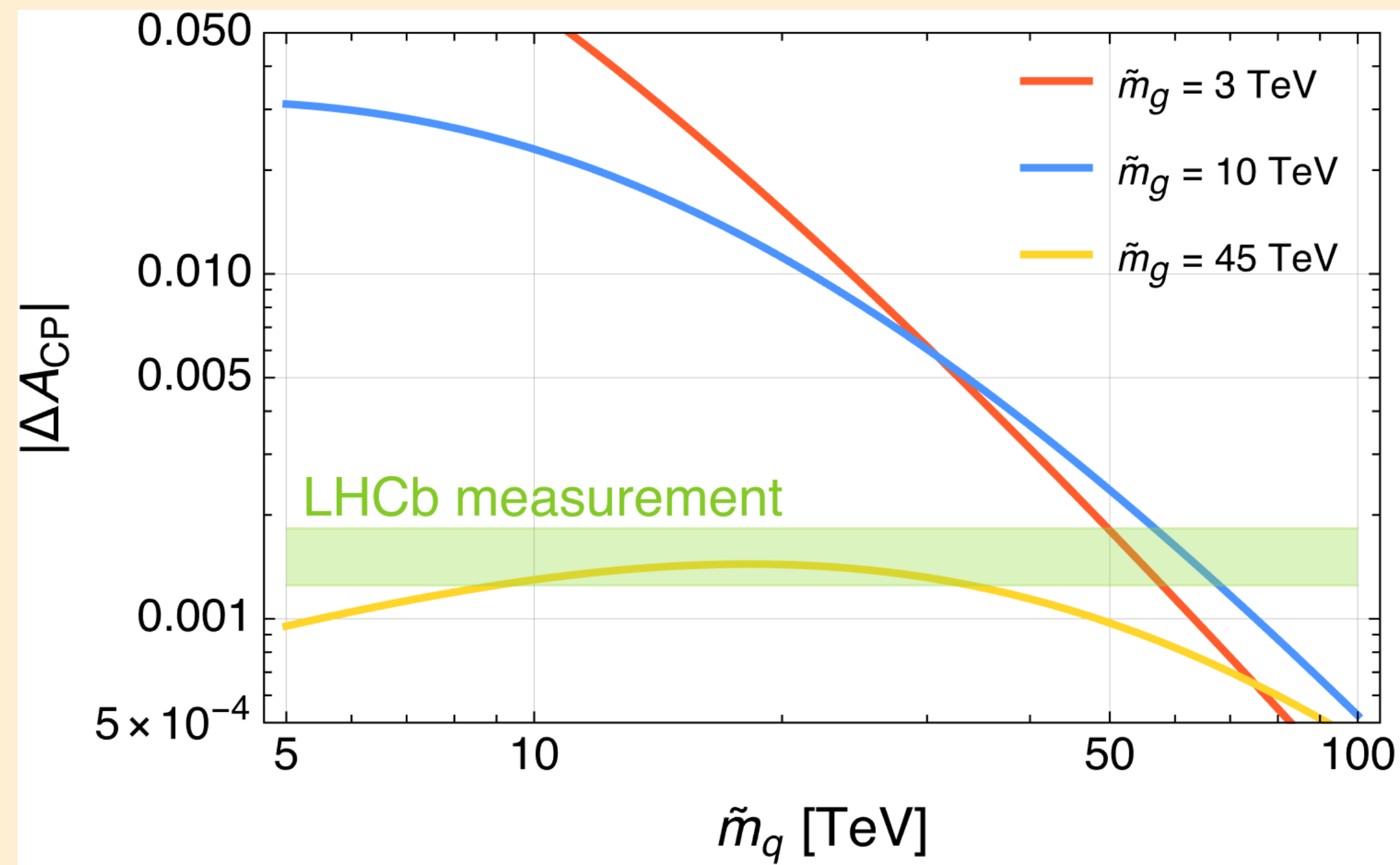
- Pink dashed line: vacuum **stability** bound



The curves correspond to the central value of $\Delta A_{CP}^{\text{exp}}$

Results for $\tilde{m}_g < \tilde{m}_q$

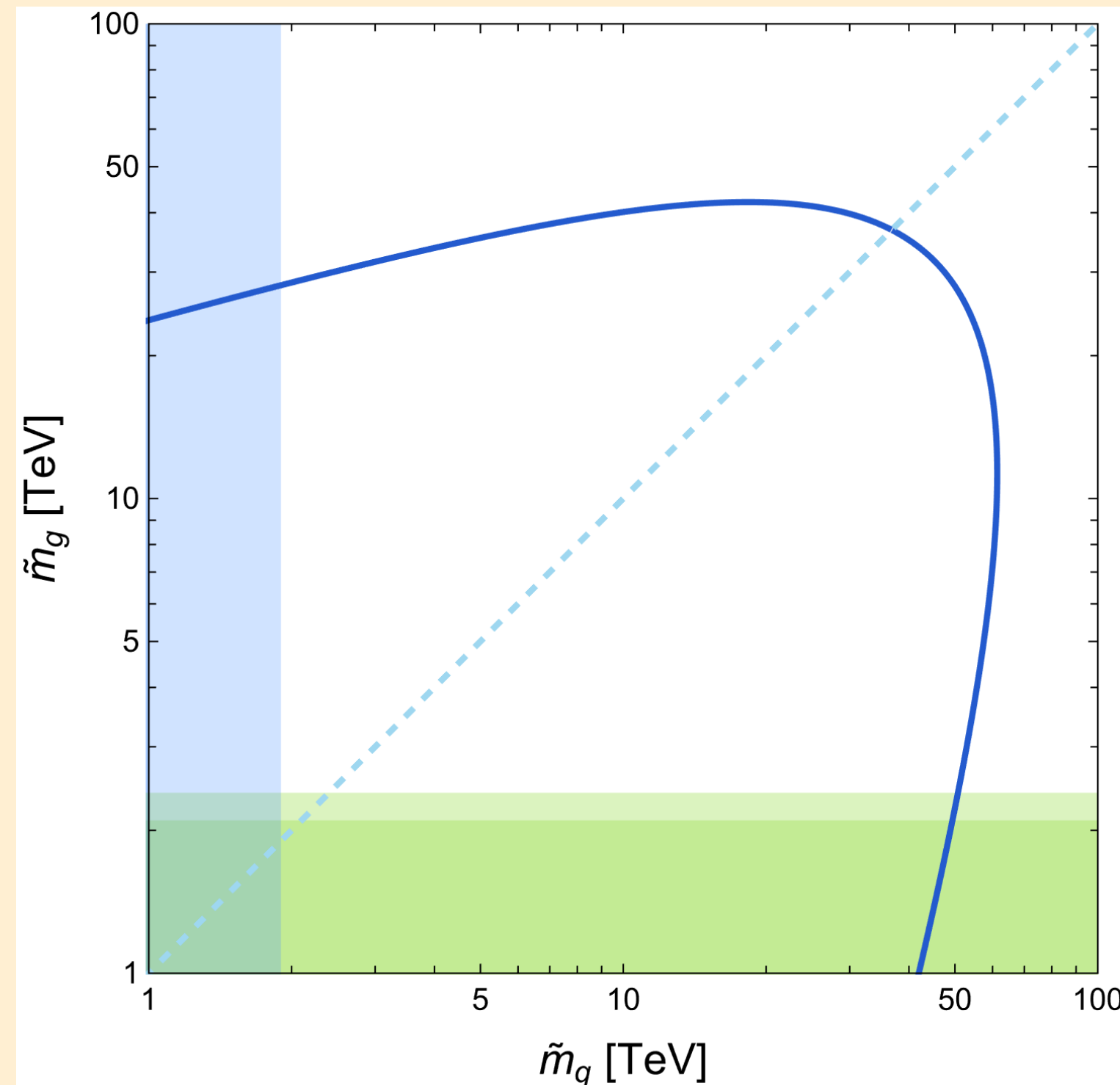
If we assume $(\delta_{LR}^u)_{12}$ is at its maximal metastable value...



Small squark masses overproduce ΔA_{CP}

→ if we observe squarks at the TeV scale, we can place bounds on $\text{Im}(\delta_{LR}^u)_{12}$

If we look at the central value of ΔA_{CP}^{exp}



Blue and green regions are collider bounds

Squark masses allowed up to 65 TeV

Gluino masses up to 45 TeV

Extremely split spectra cannot produce enough ΔA_{CP}

Caveats

$\text{Im}(\delta_{LR}^u)_{12}$ was taken to be maximal: these results are an *upper bound*

We assumed a general flavor model, where all mass insertions except $(\delta_{LR}^u)_{12}$ are 0. If we assume a specific flavor model, bounds from EDM may apply

Take-home messages

1

Charm CP violation is observed, and larger than simple Standard Model estimates.

2

SUSY can produce it through a single gluino–squark dipole, with squarks below ~ 65 TeV and gluinos below ~ 45 TeV.

3

However, it cannot explain the U-spin breaking, and the hadronic uncertainties are large.

Thank you for your attention!

Any questions?

Backup

Wilson coefs for $\Delta C = 1$

$$C_i^q \simeq \frac{\alpha_s^2 (\delta_{LL}^u)_{12}}{\sqrt{2} G_F \tilde{m}_q^2} E_i(x) , \quad i = 1, 2, 5, 6,$$

$$C_7 \simeq -\frac{\sqrt{2} \alpha_s \pi C_F Q_u}{G_F \tilde{m}_q^2} \left[(\delta_{LL}^u)_{12} M_3(x) + \frac{\tilde{m}_g}{m_c} (\delta_{LR}^u)_{12} M_1(x) \right] ,$$

$$C_8 \simeq \frac{\sqrt{2} \alpha_s \pi}{2 G_F \tilde{m}_q^2} \left[(\delta_{LL}^u)_{12} \left(\frac{1}{N_C} M_3(x) + N_C M_4(x) \right) \right. \\ \left. - (\delta_{LR}^u)_{12} \frac{\tilde{m}_g}{m_c} \left(\frac{1}{N_C} M_1(x) + N_C M_2(x) \right) \right] .$$

Operators for $\Delta C = 2$

$$O_1 = (\bar{u}c)_{V-A}(\bar{u}c)_{V-A},$$

$$O_2 = (\bar{u}c)_{S-P}(\bar{u}c)_{S-P},$$

$$O_3 = (\bar{u}_\alpha c_\beta)_{S-P}(\bar{u}_\beta c_\alpha)_{S-P},$$

$$O_4 = (\bar{u}c)_{S-P}(\bar{u}c)_{S+P},$$

$$O_5 = (\bar{u}_\alpha c_\beta)_{S-P}(\bar{u}_\beta c_\alpha)_{S+P},$$

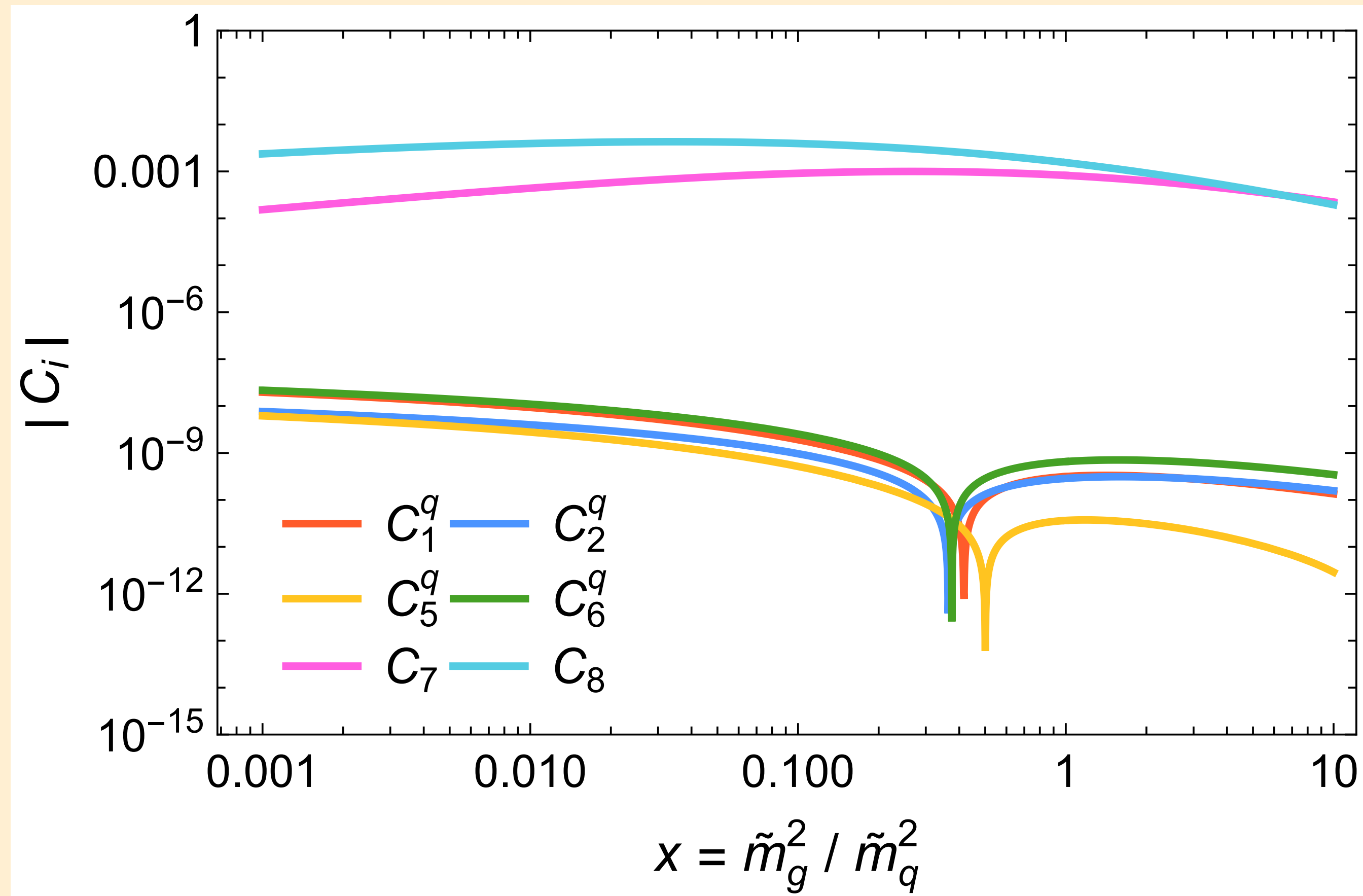
$$c_1 = -\frac{\alpha_s^2 \sqrt{2}}{54 \tilde{m}_q^2 G_F} \left(24x f_6(x) + 66 \tilde{f}_6(x) \right) (\delta_{LL})_{12}^2,$$

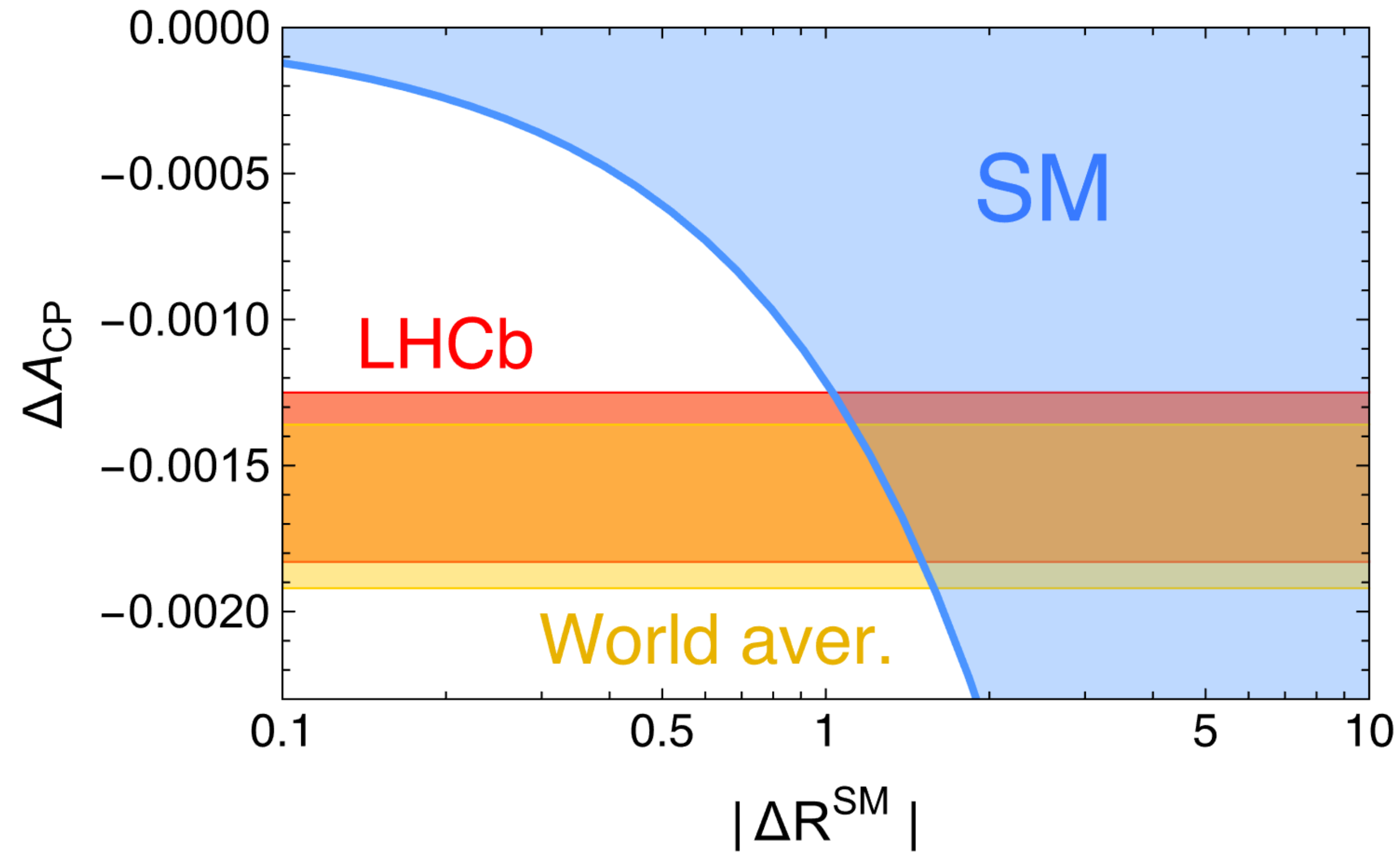
$$c_2 = -\frac{\alpha_s^2 \sqrt{2}}{54 \tilde{m}_q^2 G_F} 204x f_6(x) (\delta_{RL})_{12}^2,$$

$$c_3 = \frac{\alpha_s^2 \sqrt{2}}{54 \tilde{m}_q^2 G_F} 36x f_6(x) (\delta_{RL})_{12}^2,$$

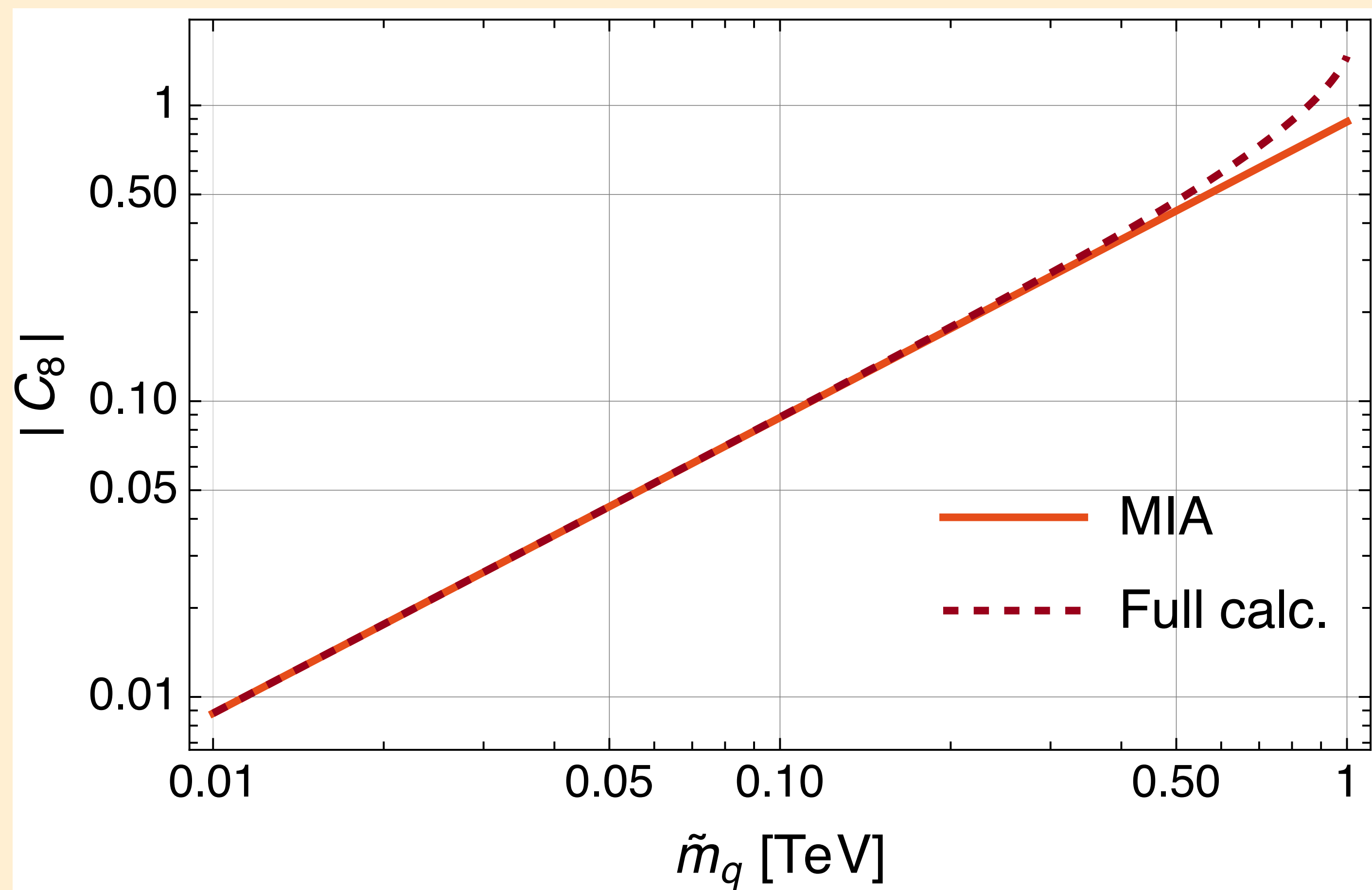
$$c_4 = -\frac{\alpha_s^2 \sqrt{2}}{54 \tilde{m}_q^2 G_F} \left[\left(504x f_6(x) - 72 \tilde{f}_6(x) \right) (\delta_{LL})_{12} (\delta_{RR})_{12} - 132 \tilde{f}_6(x) (\delta_{LR})_{12} (\delta_{RL})_{12} \right],$$

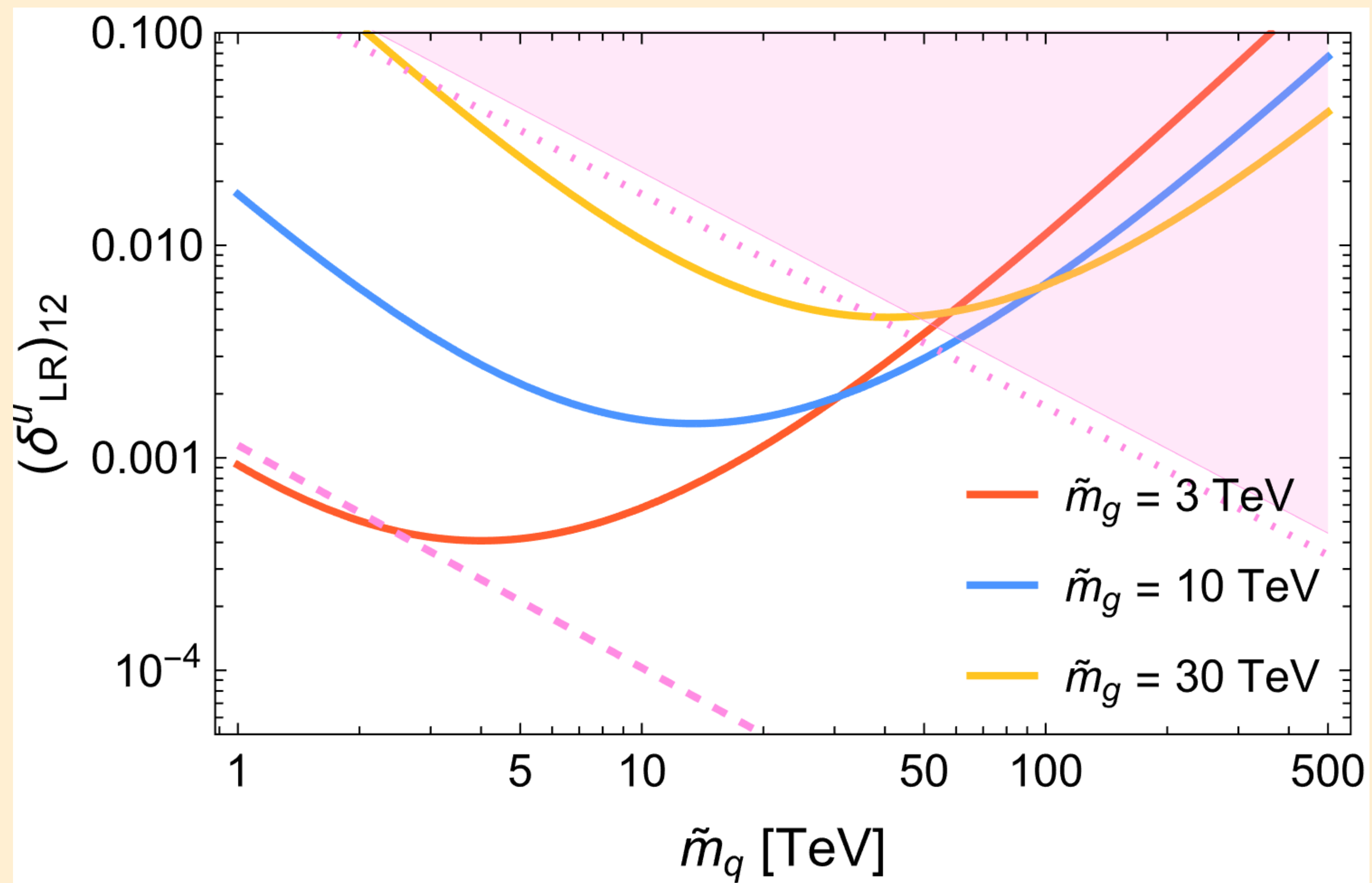
$$c_5 = -\frac{\alpha_s^2 \sqrt{2}}{54 \tilde{m}_q^2 G_F} \left[\left(24x f_6(x) + 120 \tilde{f}_6(x) \right) (\delta_{LL})_{12} (\delta_{RR})_{12} - 180 \tilde{f}_6(x) (\delta_{LR})_{12} (\delta_{RL})_{12} \right],$$



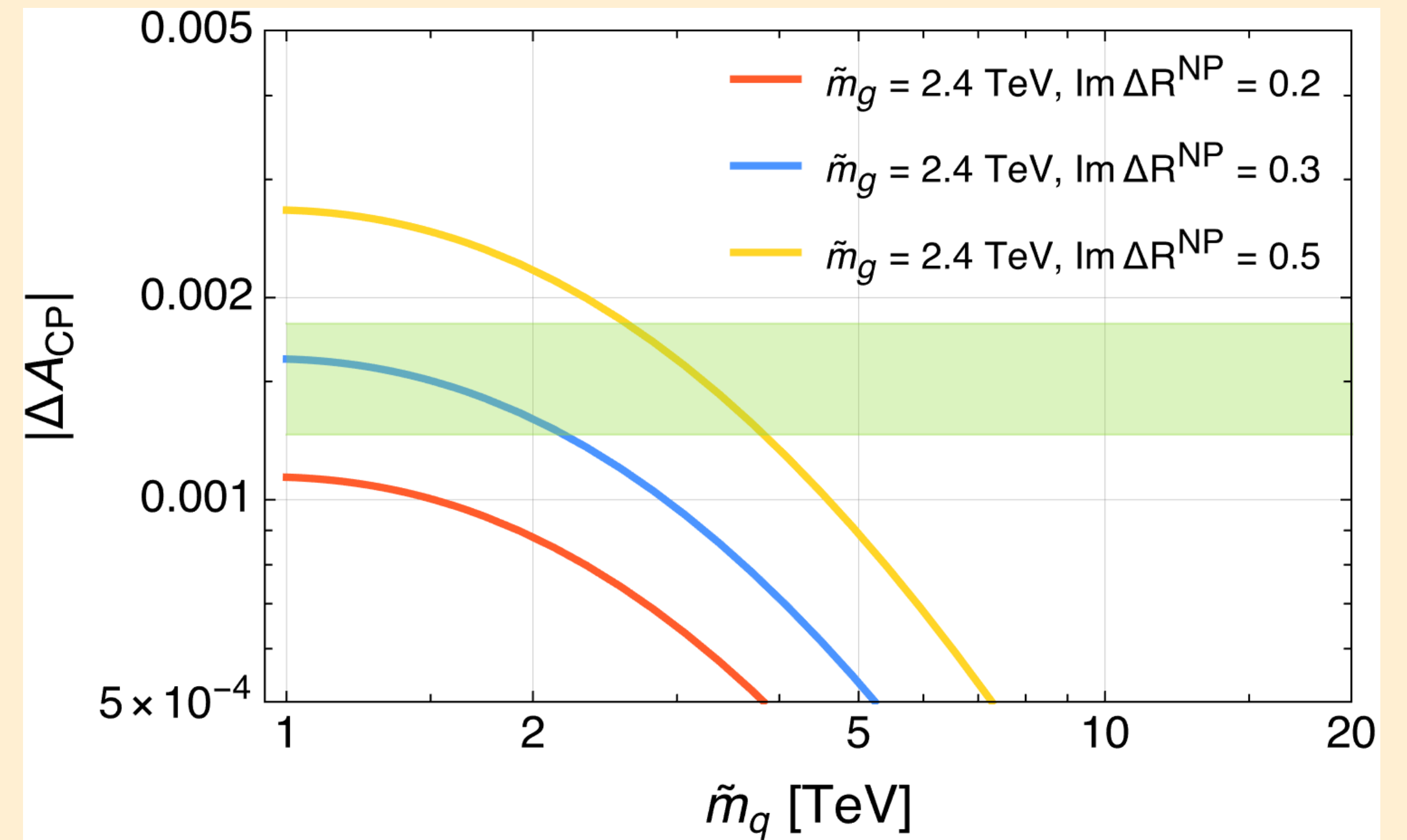
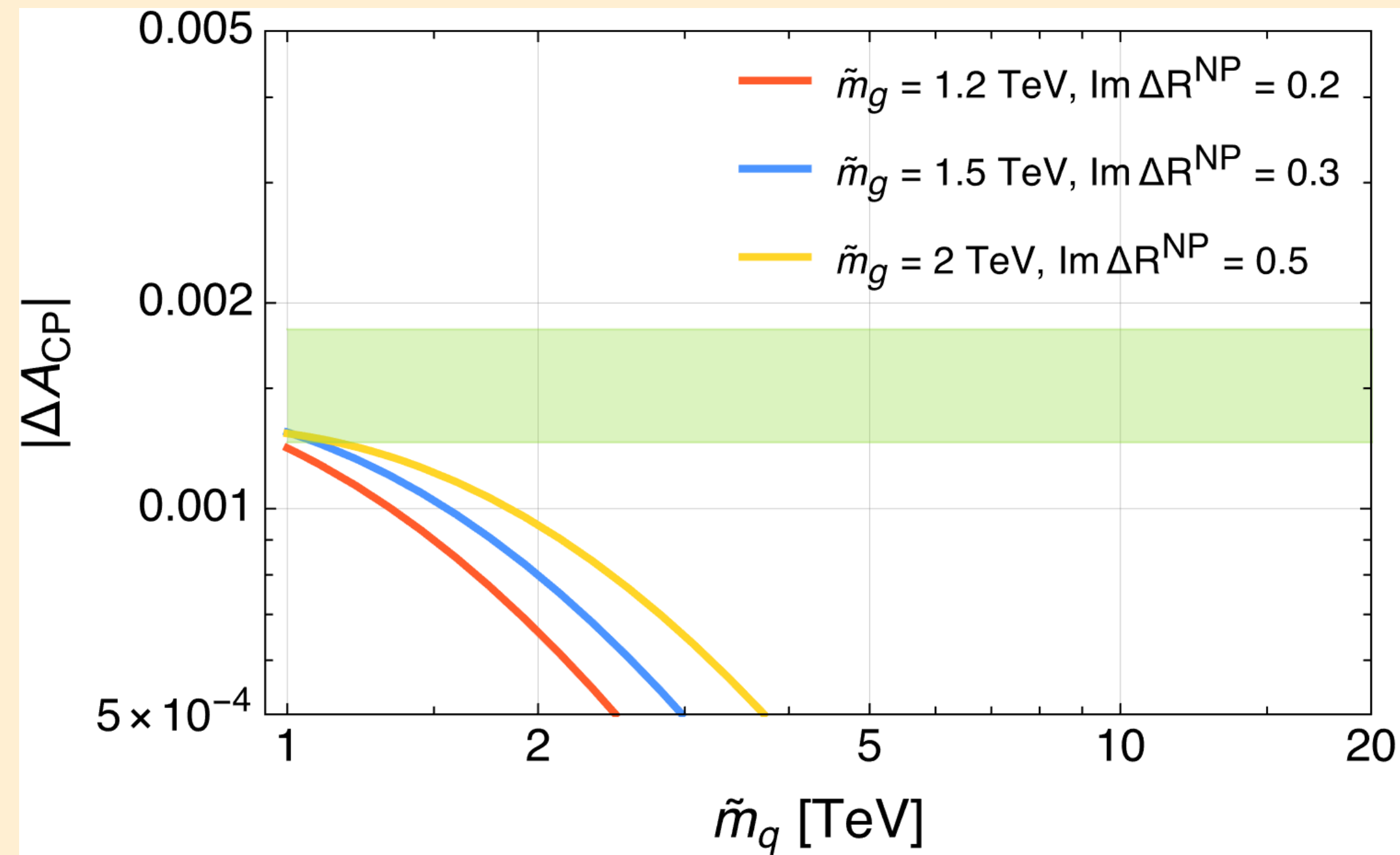


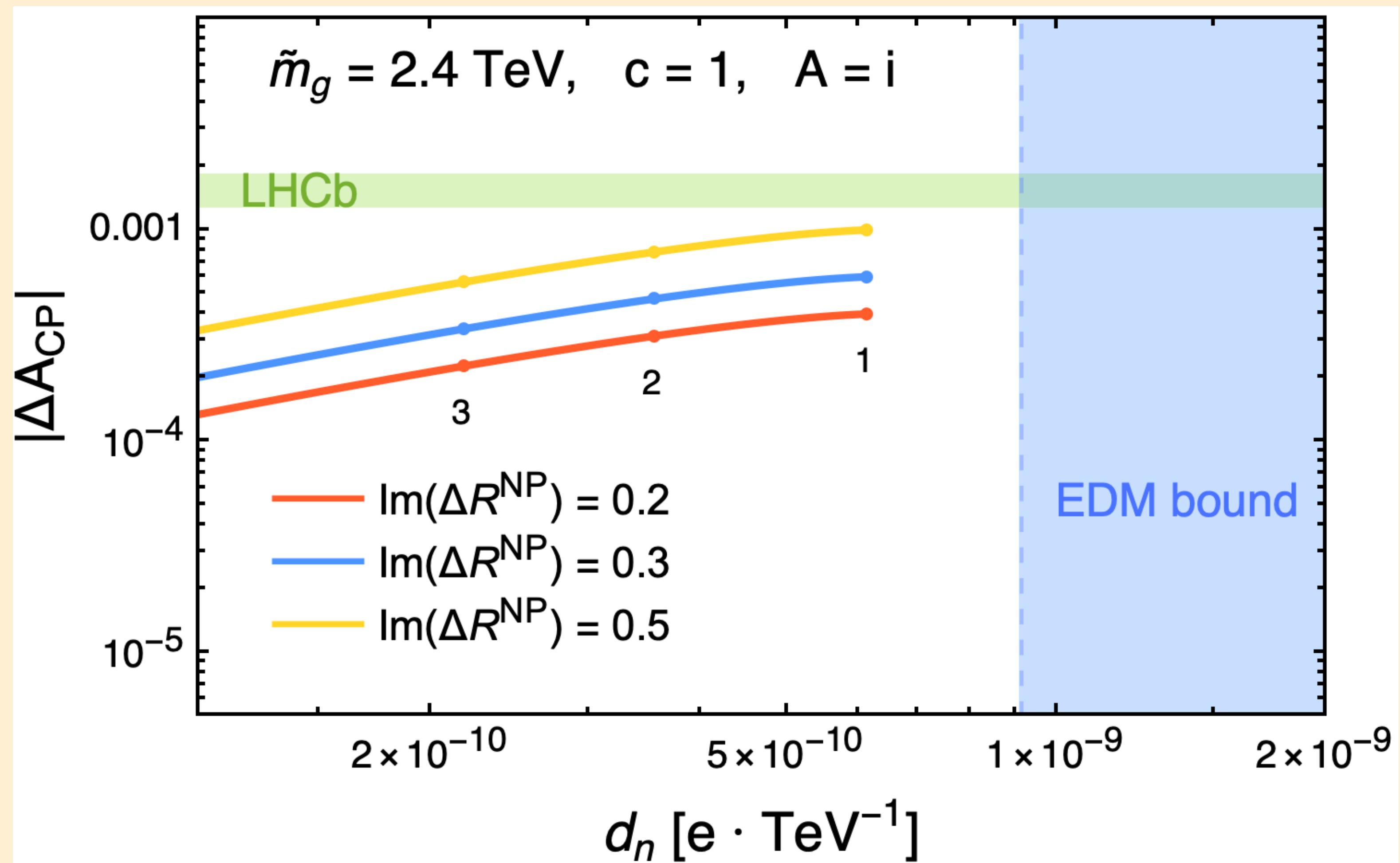
Using this parametrization, we would need $\Delta R^{SM} \sim 1.3$ for the SM to account for the 2019 result!





Froggatt Nielsen





$$(\hat{\mathbf{a}}_{\mathbf{u}})_{12,21} < 1.27 \tilde{m}_q - 44 \text{ GeV},$$

$$\text{Im}(c_1) \lesssim 7.2 \times 10^{-10};$$

$$\text{Im}(c_2) \lesssim 2.0 \times 10^{-10};$$

$$\text{Im}(c_3) \lesssim 7.4 \times 10^{-10};$$

$$\text{Im}(c_4) \lesssim 7.1 \times 10^{-11};$$

$$\text{Im}(c_5) \lesssim 2.0 \times 10^{-10};$$

$$\text{Re}(c_1) \lesssim 2.8 \times 10^{-8},$$

$$\text{Re}(c_2) \lesssim 7.9 \times 10^{-9},$$

$$\text{Re}(c_3) \lesssim 2.9 \times 10^{-8},$$

$$\text{Re}(c_4) \lesssim 2.7 \times 10^{-9},$$

$$\text{Re}(c_5) \lesssim 7.8 \times 10^{-9}.$$