On the Universality of CP Violation in $\Delta F=1$ Processes

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OG, Jernej F. Kamenik, Zoltan Ligeti and Gilad Perez, arXiv:1202.5038

Introduction

- Measurements of flavor changing neutral currents in the quark sector put strong constraints on new physics (NP).
- Models can avoid bounds by aligning the flavor structure with the standard model (SM).
- Yet flavor-breaking sources involving only quark doublets cannot be simultaneously aligned with the up and down sectors.
- Robust constraints come from the *weakest* of the bounds.

Introduction

- Example – combining constraints from *K* and *D* mixing and CP violation (CPV)*.
- We argue that for ΔF=1 processes involving quark doublets CPV is universal.
- Thus, the *strongest* constraint among the up and down sectors applies.

* K. Blum, Y. Grossman, Y. Nir and G. Perez, PRL **102**, 211802 (2009) [arXiv:0903.2118]

Outline

- Two generations
- Examples
  - ϵ'/ϵ => Δa_{CP}
  - $K_L \to \pi^0 e^+ e^-$ => $a_{CP}(D^+ \to \pi^+ e^+ e^-)$
- Three generations
- Example
  - Semileptonic B decay
- Some SUSY implications
- Conclusion

Preliminaries

$$\mathcal{G}_F = SU(3)_Q \times SU(3)_U \times SU(3)_D$$

$$\mathcal{A}_u \equiv (Y_u Y_u^\dagger)_{\cancel{\mathrm{tr}}} \quad \mathcal{A}_d \equiv (Y_d Y_d^\dagger)_{\cancel{\mathrm{tr}}}$$

$$J \equiv i[\mathcal{A}_u, \mathcal{A}_d] \qquad \Rightarrow \qquad (8, 1, 1)$$

* OG, L. Mannelli and G. Perez, PLB **693**, 301 (2010) [arXiv:1002.0778]; JHEP **1010**, 046 (2010) [arXiv:1003.3869]

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SU(2)$_L$-invariant operator:

$$\mathcal{O}_L = \left[(X_L)^{ij}\, \overline{Q}_i \gamma^\mu Q_j \right] L_\mu$$

$$L_\mu = \sum_q \overline{q}\gamma_\mu q\,, \quad \sum_\ell \overline{\ell}\gamma_\mu \ell\,, \quad H^\dagger D_\mu H\,, \quad \ldots$$

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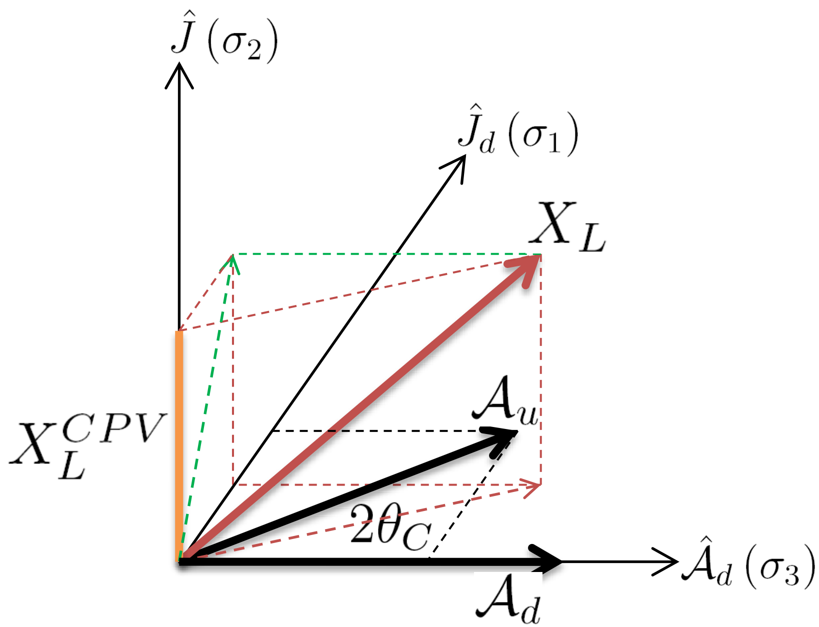
Universality of CPV in Two Generations

- The unique invariant for ΔF=1 CP violation:

$$X_L^{CPV} \equiv \mathrm{Tr}(X_L \cdot J)$$

- CP violation generated by X_L is the same in both up and down transitions!



$$\mathrm{Im}(X_L^u)_{12} = \mathrm{Im}(X_L^d)_{12} \propto \mathrm{Tr}\,(X_L \cdot J)$$

Universality of CPV in Two Generations

$$X_L^d = \begin{pmatrix} a & c + id \\ c - id & -a \end{pmatrix}$$

CP violation in s→d

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CP violation in s⟶d

$$V^{\mathrm{CKM}} = \begin{pmatrix} \cos\theta_C & \sin\theta_C \\ -\sin\theta_C & \cos\theta_C \end{pmatrix}$$

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CP violation in c⟶u

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$$d \propto X_L^{CPV}$$

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CP violation in c→u

Implication of the 3rd Generation

- Decompose X_L in terms of $SU(2)_Q$:

$$X_L = \begin{pmatrix} * & * & * \\ * & * & * \\ * & * & * \end{pmatrix}$$

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adjoint

Doublet $- x_L$

singlet

- Δc, Δs=1 processes are generated at order $x_L{}^2$ independently.
- Our argument applies to both contributions.

Example – Hadronic *K* and *D* Decays

- The bound on left-left (LL) operators from ϵ'/ϵ has been calculated in *.
- The weakest bound: $|\mathrm{Im}(C_2^{(0)})| \lesssim 4.5 \times 10^{-5} \left(\frac{\Lambda_{\mathrm{NP}}}{350\,\mathrm{GeV}}\right)^2$ for $Q_2^{(0)} = (\bar{d}_\alpha s_\beta)_{V-A} \sum_q (\bar{q}_\beta q_\alpha)_{V-A}$
- The contribution to Δa_{CP} is:

$$\Delta a_{CP}^{\mathrm{NP}} \approx 8.9 \sum_i \mathrm{Im}(C_i^{\mathrm{NP}})\,\mathrm{Im}(\Delta R_i^{\mathrm{NP}})$$

- Hence for $\Delta R_i^{\mathrm{NP}} \sim 1$: $\Delta a_{CP}^{\mathrm{NP}} \lesssim 4 \times 10^{-4}$
- The contributions to Δa_{CP} are negligible!

* G. Isidori, J. F. Kamenik, Z. Ligeti and G. Perez, [arXiv:1111.4987]

Example – Semileptonic *K* and *D* Decays

- Analyze the CPV decay $K_L \to \pi^0 e^+ e^-$:

$$\frac{C_{sd}^{\ell_{R/L}}}{\Lambda_{\rm NP}^2} (\bar{s}d)_{V-A}\,(\bar{\ell}\ell)_{V\pm A}$$

$$\mathrm{Br}(K_L \to \pi^0 e^+ e^-) < 2.8 \times 10^{-10}$$

$$|\mathrm{Im}\, C_{sd}^{e_{R/L}}| < 5.5 \times 10^{-4} \left(\frac{\Lambda_{\rm NP}}{1\,\mathrm{TeV}}\right)^2$$

(90% CL)

- Apply the bound to the *D* CP asymmetry:

$$a_e^D \equiv \frac{\mathrm{Br}(D^+ \to \pi^+ e^+ e^-) - \mathrm{Br}(D^- \to \pi^- e^+ e^-)}{\mathrm{Br}(D^+ \to \pi^+ e^+ e^-) + \mathrm{Br}(D^- \to \pi^- e^+ e^-)}$$

Example – Semileptonic *K* and *D* Decays

- Assume that CPV is dominated by NP and decay rate is dominated by long distance SM:

$$|a_e^D| \lesssim \frac{2\int d\rho\,|\mathrm{Im}(\mathcal{A}_{\mathrm{NP}})|\,|\mathcal{A}_{\mathrm{SM}}|}{\int d\rho\,|\mathcal{A}_{\mathrm{SM}}|^2} \lesssim 2\sqrt{\frac{\int d\rho\,|\mathcal{A}_{\mathrm{NP}}|^2}{\int d\rho\,|\mathcal{A}_{\mathrm{SM}}|^2}}$$

- Use the experimental bound for the BR:

$$|a_e^D| \lesssim \left(\frac{1\,\mathrm{TeV}}{\Lambda_{\mathrm{NP}}}\right)^2 \frac{0.1\,|\mathrm{Im}\,C_{sd}^{e_{R/L}}|}{\sqrt{\mathrm{Br}(D^+\to\pi^+e^+e^-)}} \lesssim 0.02$$

- Robust bound on asymmetry from LL ops.

CPV Universality in 3rd Generation Decays

- Neglect the masses of the first 2 generations
  - CKM phase and 1-2 rotation become unphysical
  - Remove the 1-3 entry by additional *SU(2)* rotation
- CKM is reduced to a rotation of $\theta \simeq \sqrt{\theta_{13}^2 + \theta_{23}^2}$

$$\mathcal{A}_d = \frac{y_b^2}{3}\begin{pmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 2 \end{pmatrix} \qquad \mathcal{A}_u = y_t^2 \begin{pmatrix} \spadesuit & 0 & 0 \\ 0 & \spadesuit & \spadesuit \\ 0 & \spadesuit & \spadesuit \end{pmatrix}$$

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q_s

protected by $U(1)_Q$

q_a

- Define "active"/"sterile" light flavors

CPV Universality in 3rd Generation Decays

- The only measure of CPV – $\mathrm{Tr}(X_L \cdot J)$

$$\Longrightarrow \quad \mathrm{Im}(X_L^u)_{a3} = \mathrm{Im}(X_L^d)_{a3}$$

- Active states coincide with 2nd generation quarks up to $\mathcal{O}\left(\lambda_C\right)$.

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- Active states coincide with 2nd generation quarks up to $\mathcal{O}\left(\lambda_C\right)$.
- Corrections – decompose X_L in terms of $SU(2)_{3a}$:
- Doublet constrained by 2→1 CPV transitions
- m_c^2/m_t^2 , m_s^2/m_b^2

$$X_L = \begin{pmatrix} * & * & * \\ * & * & * \\ * & * & * \end{pmatrix}$$

Doublet

singlet

adjoint

Example – Semileptonic *B* Decays

- Observable – $B \to X_s \ell^+ \ell^-$ at $q^2 \equiv (p_{\ell^+} + p_{\ell^-})^2 \in [1, 6]\,\mathrm{GeV}^2$

$$\frac{C^H_{bs}}{\Lambda^2_{\mathrm{NP}}} (\bar{b}s)_{V-A} (H^\dagger D H) \qquad \mathrm{Br}(B \to X_s \ell^+ \ell^-)_{\mathrm{low}} = (1.60 \pm 0.50) \times 10^{-6}$$

$$\Longrightarrow \quad \left|\mathrm{Im}(C^H_{bs})\right| < 8.7 \times 10^{-3} \left(\frac{\Lambda_{\mathrm{NP}}}{1\,\mathrm{TeV}}\right)^2$$

- LHC sensitivity with 100 fb^{-1} at 14 TeV:

$$|C^H_{tc(u)}| \lesssim 0.2\, (\Lambda_{\mathrm{NP}}/\mathrm{TeV})^2$$

- Any CPV signal in t→cZ would have to be from *SU(3)$_U$* breaking NP.

SUSY Implication

- The only source of *SU(3)*$_Q$ breaking is $\tilde{m}_Q^2$, which is approximately *SU(2)*$_L$-invariant.
- Define $\delta_{LL}^{ij} \equiv \left(\tilde{m}_Q^2\right)^{ij} / \, \bar{m}_{\tilde{Q}}^2$ with $\bar{m}_Q \equiv (m_{\tilde{Q}_1} + m_{\tilde{Q}_2})/2$
- Bound from ϵ'/ ϵ: $\mathrm{Im}\,\delta_{LL}^{12} \leq 0.5 \text{ for } \bar{m}_{\tilde{Q}} = m_{\tilde{g}} = 500 \text{ GeV}$

$$\Longrightarrow \quad \delta_Q^{12} \equiv \frac{m_{\tilde{Q}_2} - m_{\tilde{Q}_1}}{m_{\tilde{Q}_2} + m_{\tilde{Q}_1}} \leq 0.25 \left(\frac{500 \text{ GeV}}{\bar{m}_{\tilde{Q}}} \right)$$

- Not the strongest constraint *but* could have been derived more than 20 years ago!

Degeneracy of Squarks

- Bounds on alignment models from *K* and *D* mixing and CPV*:

$$\mathcal{I}m(z_1^K) = -\Lambda_{12}^2 \sin\alpha \sin 2\gamma, \qquad \frac{m_{\tilde{Q}_2} - m_{\tilde{Q}_2}}{m_{\tilde{Q}_1} + m_{\tilde{Q}_2}} \leq \begin{cases} 0.034 & \sin 2\gamma = 1 \\ 0.27 & \sin 2\gamma = 0 \end{cases}$$

$$\mathcal{I}m(z_1^D) = -\Lambda_{12}^2 \sin(\alpha - 2\theta_c) \sin 2\gamma$$

- The maximal phase case does not correspond to an alignment model.
- Alignment makes both real and imaginary parts small.

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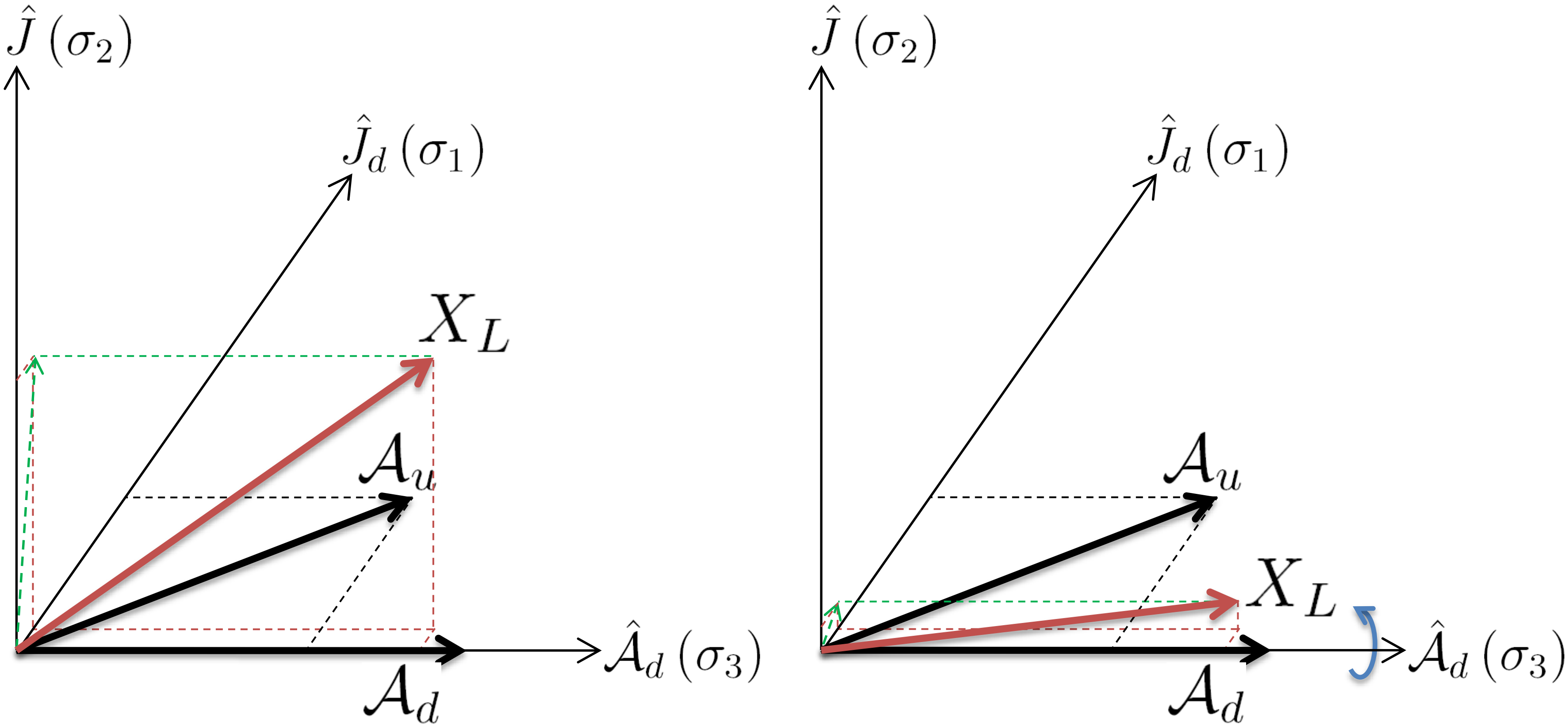
Degeneracy of Squarks



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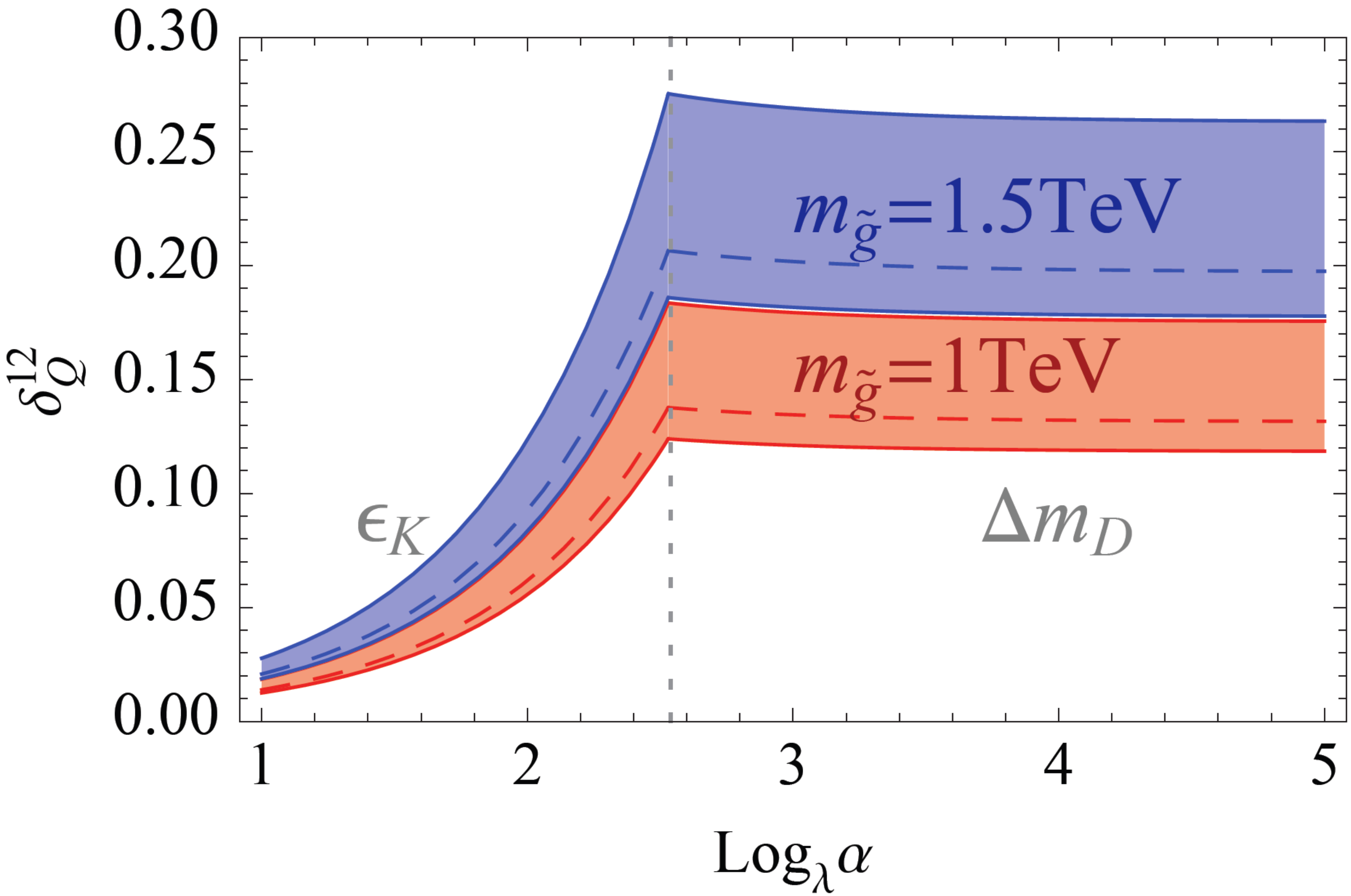
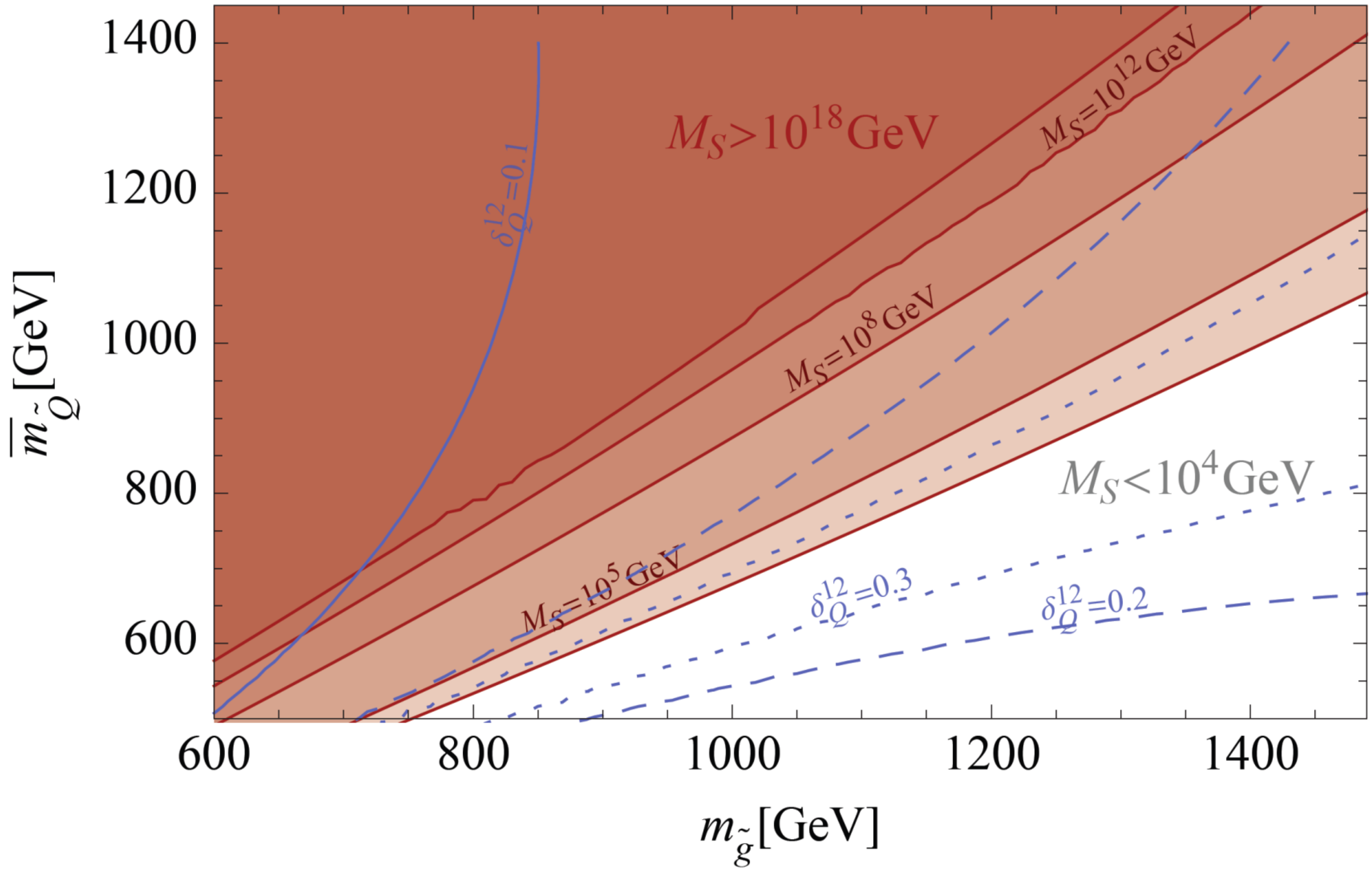


Degeneracy of Squarks

- No strong degeneracy required!
- Ex.: $m_{\tilde{g}}$=1.3 TeV, $m_{\tilde{Q}_1}$=550 GeV, $m_{\tilde{Q}_2}$=950 GeV
- This can be generated by*:
  - Anarchy at the SUSY breaking mediation scale
  - SUSY renormalization group flow to the TeV scale
  - Can lead to modest level of degeneracy

* Y. Nir and G. Raz, PRD **66**, 035007 (2002) [hep-ph/0206064]

Degeneracy of Squarks



Conclusion

- NP sources breaking $SU(3)_Q$ flavor symmetry induce universal CPV in $\Delta F=1$ processes.
- The *strongest* bound between up and down sectors applies.
  - Two generations: ϵ'/ϵ prohibits $SU(3)_Q$-breaking explanations to Δa_{CP} measured by LHCb.
  - Three generations.
- SUSY alignment models can be consistent with data even with a low SUSY breaking mediation scale.

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Goodbye blue stain!

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