Direct CP-violation in nonleptonic charm decays: New Physics

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01/10/2012, Cincinnati

Outline

- Significance of CPV in Charm within and beyond SM
  - Quantify (parametrize) theory expectations of direct CPV in charm decays
- Δa_{CP} implications for weak scale NP
  - EFT & models

Why CP Violation in Charm?

- CPV in charm provides a unique probe of New Physics (NP)
  - sensitive to NP in the up sector
  - SM charm physics is CP conserving to first approximation (2 generation dominance, no hard GIM breaking)
- Common lore "any signal for CPV would be NP":
  - In the SM, CPV in mixing enters at $\mathcal{O}(V_{cb}V_{ub}/V_{cs}V_{us}) \sim 10^{-3}$
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Experimental observables

- **CPV in decays (direct CPV)**
  - Time-integrated CPV decay asymmetries to CP eigenstates

$$a_f \equiv \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to f)}\,.$$

  - Focus on K^+K^- and $\pi^+\pi^-$ final states: $\Delta a_{CP} \equiv a_{K^+K^-} - a_{\pi^+\pi^-}$

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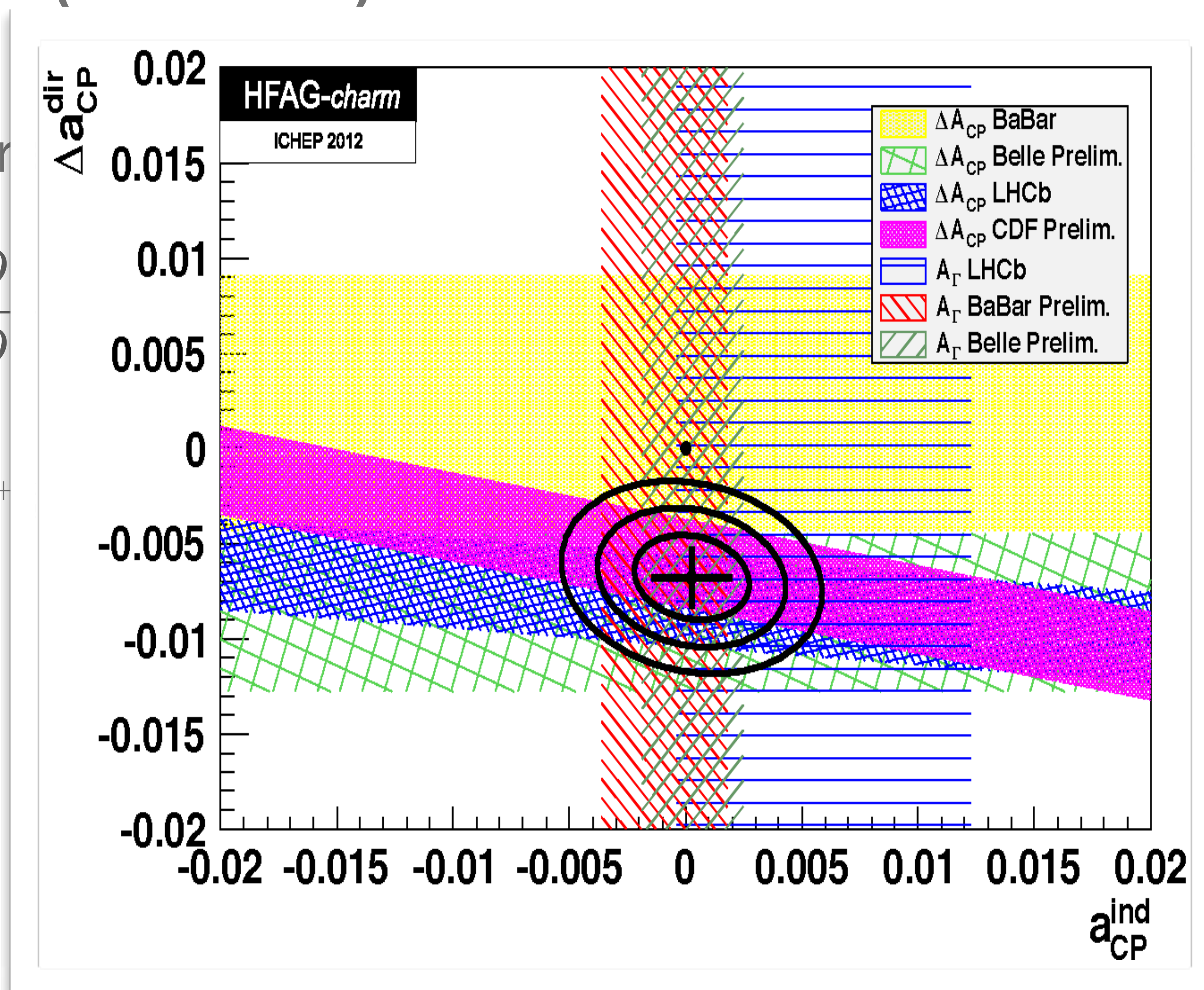

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$$\boxed{\Delta a_{CP}^{\text{World}} = -(0.68 \pm 0.15)\% \qquad \text{(\textasciitilde}4.3\sigma \text{ from 0)}}$$

see talks by Ko, Parkes & Mattson

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Grossman et al., hep-ph/0609178
Cheng & Chiang, 1201.0785
Franco, Mishima & Silvestrini, 1203.3131
Li, Lu & Yu, 1203.3120

  - ...beyond natural expectation within the SM
  - but not possible to prove from first principles, and SM-like explanation cannot be excluded

Golden & Grinstein Phys. Lett. B 222 (1989)
Brod, Kagan & Zupan 1111.5000
Brod, Grossman, Kagan & Zupan 1203.6659
Feldmann, Nandi & Soni, 1202.3795
Bhattacharya, Gronau & Rosner, 1201.2351

see talks by Bhattacharya & Brod

Quantifying theoretical predictions

- SM expectations for $a_f^{\mathrm{dir.}} \simeq 2 r_f \sin\phi_f \sin\delta_f \qquad f = K, \pi$

absolute ratio of interf. decay amplitudes

CPV & strong phase differences

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$$A_K = \lambda_s A_K^{(1)} + \lambda_b A_K^{(2)}$$
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- naive expectation $A_f^{(2)}/A_f^{(1)} \sim \dfrac{\alpha_s(m_c)}{\pi}$

(assuming $m_c >> \Lambda_{QCD}$)

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$\longrightarrow$

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$$\begin{aligned} \phi_K^{\text{SM}} &= \arg(\lambda_b/\lambda_s) \\ &\approx -\arg(\lambda_b/\lambda_d) = -\phi_\pi^{\text{SM}} \\ &\approx 70^\circ \end{aligned}$$

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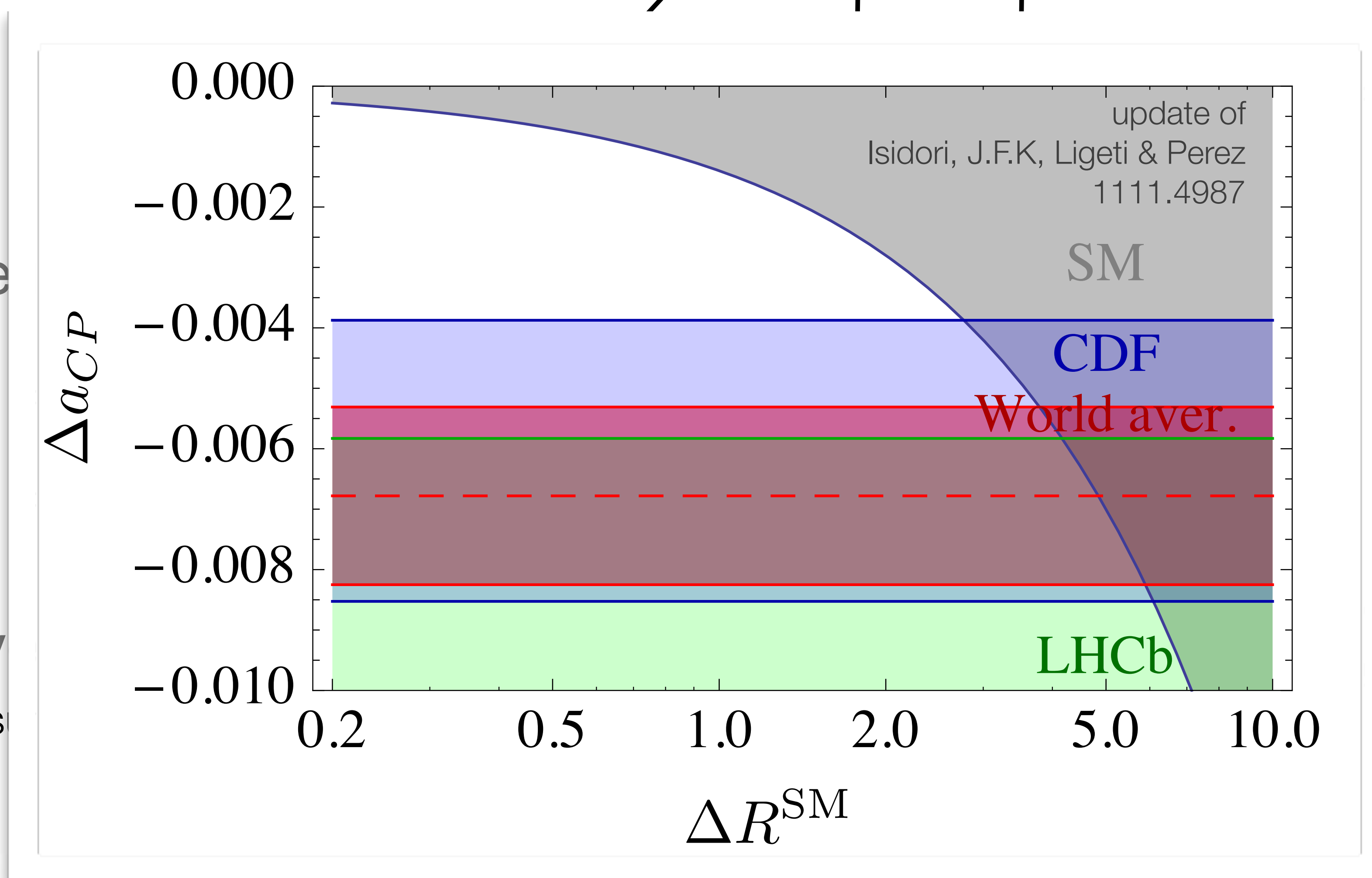

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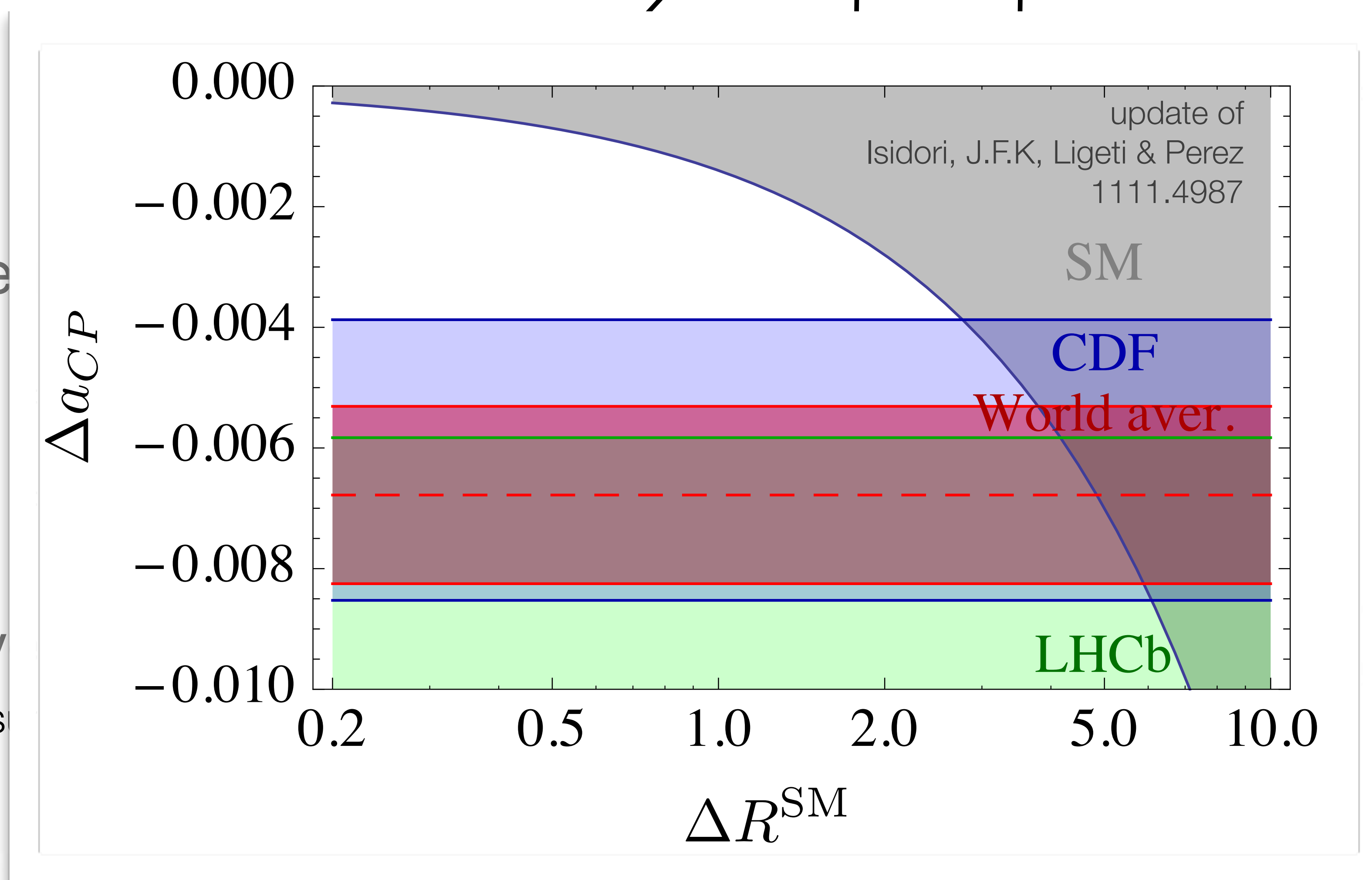

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O(4−6) values of $|\Delta R^{\text{SM}}|$ needed

Δa_{CP} and New Physics

- Assume SM does not saturate the experimental value

- Parametrize NP contributions in EFT normalized to the effective SM scale

$$\mathcal{H}^{\mathrm{eff-NP}}_{|\Delta c|=1} = \frac{G_F}{\sqrt{2}} \sum_i C_i^{\mathrm{NP}} Q_i$$

$$\begin{aligned}
Q_1^q &= (\bar{u}q)_{V-A}\,(\bar{q}c)_{V-A} \\
Q_2^q &= (\bar{u}_\alpha q_\beta)_{V-A}\,(\bar{q}_\beta c_\alpha)_{V-A}\,, \\
Q_5^q &= (\bar{u}c)_{V-A}\,(\bar{q}q)_{V+A}\,, \\
Q_6^q &= (\bar{u}_\alpha c_\beta)_{V-A}\,(\bar{q}_\beta q_\alpha)_{V+A}\,, \\
Q_7 &= -\frac{e}{8\pi^2}\, m_c\, \bar{u}\sigma_{\mu\nu}(1+\gamma_5)F^{\mu\nu}\, c\,, \\
Q_8 &= -\frac{g_s}{8\pi^2}\, m_c\, \bar{u}\sigma_{\mu\nu}(1+\gamma_5)T^a G_a^{\mu\nu} c\,,
\end{aligned}$$

+ Ops. with V↔A

x 5 q$\bar{\text{q}}$ flavor structures

  - most general dim 6 Hamiltonian at $\mu < m_{W,t}$

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$$\Delta a_{CP} \approx (0.13\%)\mathrm{Im}(\Delta R^{\mathrm{SM}}) + 9\sum_i \mathrm{Im}(C_i^{\mathrm{NP}})\,\mathrm{Im}(\Delta R_i^{\mathrm{NP}}) \qquad \Delta R_i^{\mathrm{NP}} \equiv \frac{G_F}{\sqrt{2}} \sum_{f=\pi,K} \frac{\langle Q_i \rangle_f}{A_f^{(1)}}$$

- for $\mathrm{Im}(C_i^{\mathrm{NP}}) = \dfrac{v^2}{\Lambda^2}$: $\dfrac{(10\ \mathrm{TeV})^2}{\Lambda^2} = \dfrac{(0.61 \pm 0.17) - 0.12\,\mathrm{Im}(\Delta R^{\mathrm{SM}})}{\mathrm{Im}(\Delta R^{\mathrm{NP}})}$

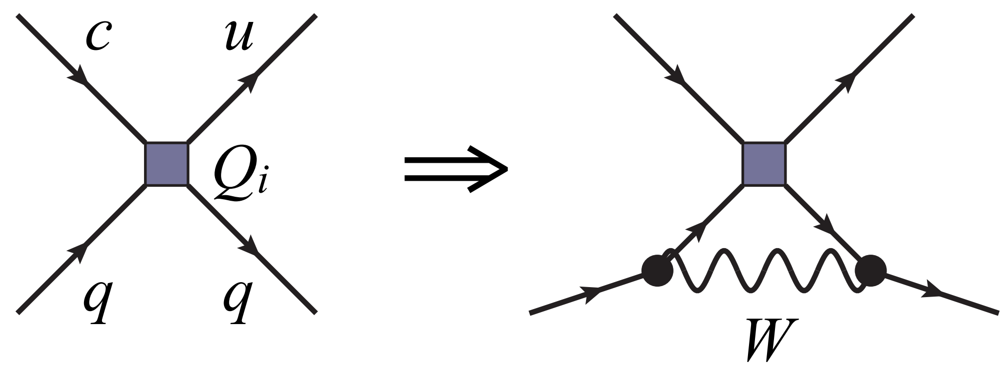
Are such contributions allowed by other flavor constraints?

Δa_{CP} and New Physics

Isidori, J.F.K, Ligeti & Perez
1111.4987

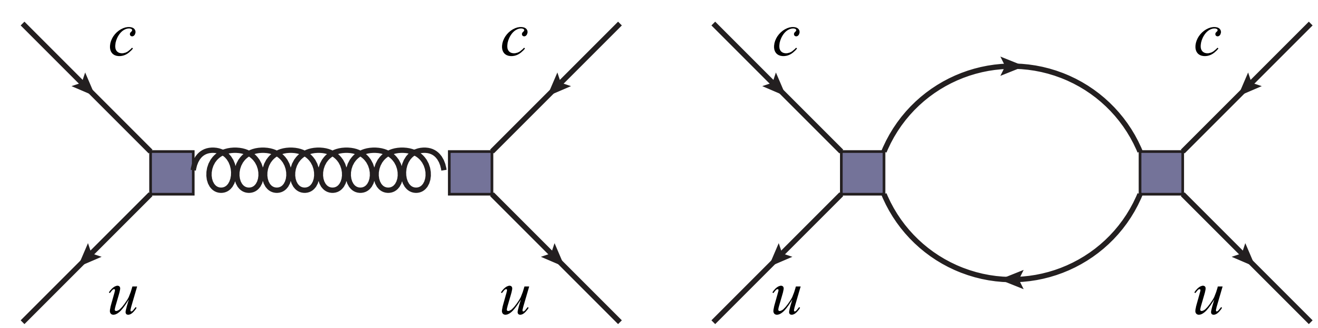
- In EFT can be estimated via "weak mixing" of operators

$$T\left\{\mathcal{H}^{\mathrm{eff-NP}}_{|\Delta c|=1}(0), \mathcal{H}^{\mathrm{SM}}(x)\right\}$$



  - Important constraints expected from **D-$\bar{\text{D}}$ mixing** and direct CPV in $K^0 \to \pi^+\pi^-$ **(ε'/ε)**

- Quadratic NP contributions
  - either chirally suppressed...
  - ...or highly UV sensitive



$\propto \alpha\, m_c^2/v^2$ $\qquad$ $\propto \Lambda^2$

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On Universality of CPV in SU(3)$_Q$ breaking NP

- SM quark flavor symmetry $\mathcal{G}_F = \boxed{SU(3)_Q} \times SU(3)_U \times SU(3)_D$
  - two sources of breaking: $\mathcal{A}_u \equiv (Y_u Y_u^\dagger)_{\not{\mathrm{tr}}}\,, \qquad \mathcal{A}_d \equiv (Y_d Y_d^\dagger)_{\not{\mathrm{tr}}}$

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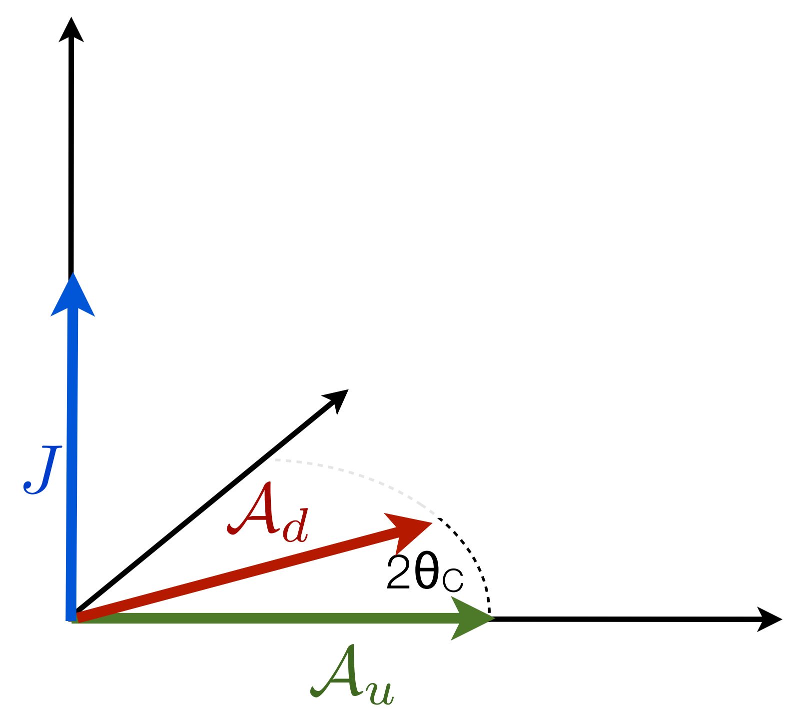
  - in the 2-gen limit single source of CPV: $J \equiv i[\mathcal{A}_u, \mathcal{A}_d]$ Gedalia, Mannelli & Perez 1002.0778, 1003.3869
    - invariant under SO(2) rotations between up-down mass bases



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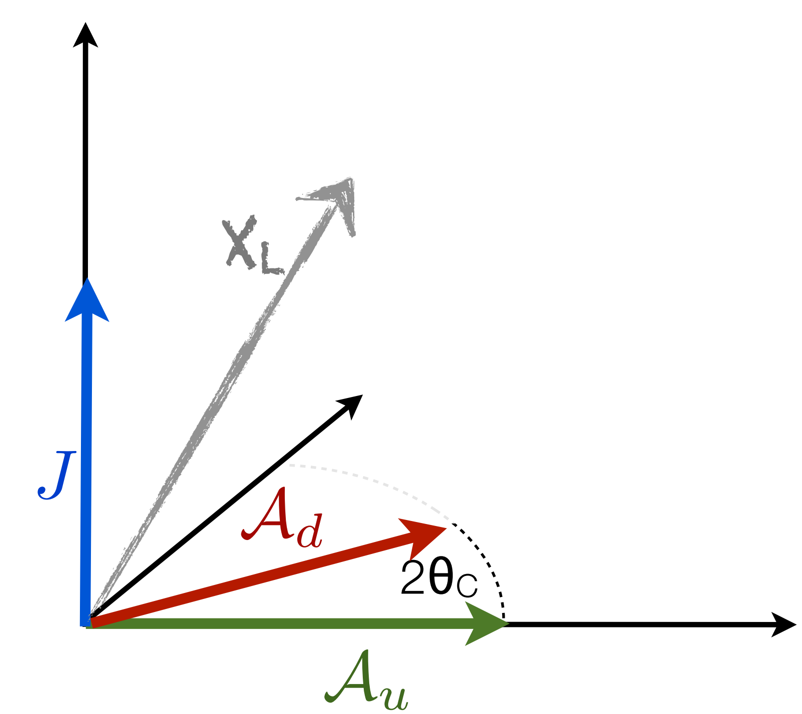
        - invariant under SO(2) rotations between up-down mass bases
- SU(2)$_Q$ breaking NP $\mathcal{O}_L = \left[(X_L)^{ij}\,\overline{Q}_i\gamma^\mu Q_j\right] L_\mu$

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



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  - SM 3-gen case characterized by SU(3)/SU(2) breaking pattern by $Y_{b,t}$

Kagan et al., 0903.1794

- 3-gen X_L can be decomposed under SU(2)$_Q$, constrained separately

(barring cancelations)

- SM breaking of residual SU(2)$_Q$ suppressed by m_c/m_t, m_s/m_b, θ_{13}, θ_{23}

(charm and kaon sectors dominated by 2-gen physics)

On Universality of CPV in $SU(3)_Q$ breaking NP

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  - **Implication (1):** direct correspondence between Δa_{CP} and ε'/ε

    (no weak loop suppression)

    - constraint on $SU(3)_Q$ breaking NP contributions

Gedalia, J.F.K, Ligeti & Perez
1202.5038

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      1202.5038

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  - **Implication (2):** bounds on degeneracy in SUSY alignment models
    - CPV constraints less stringent than previously thought

      see talk by G. Perez

}

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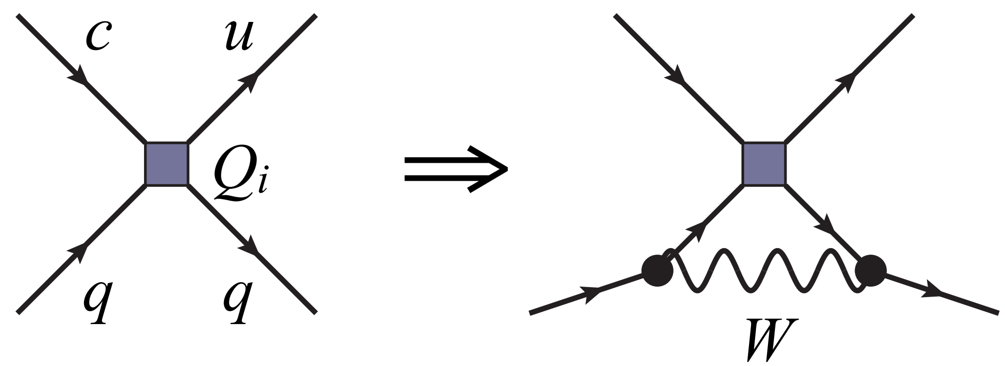

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  - **LL 4q operators:** excluded
  - **LR 4q operators:** ajar - potentially visible effects in D-$\overline{\text{D}}$ and/or ε’/ε

Model example:
Hochberg, Nir, 1112.5268

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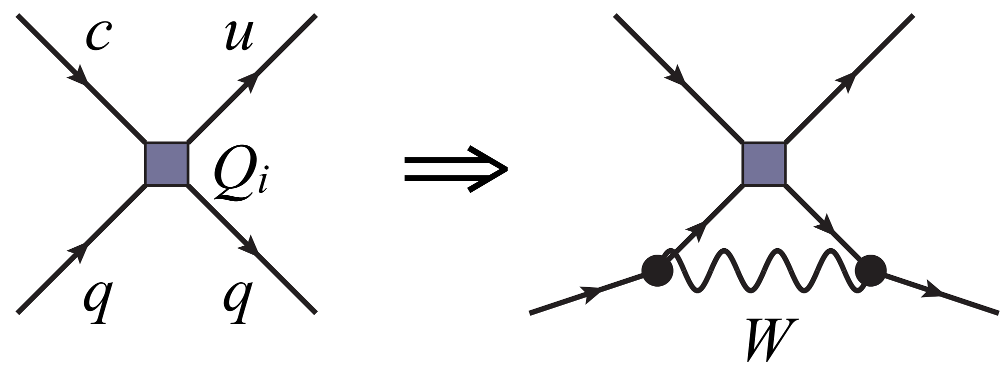

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  - **RR 4q operators:** unconstrained in EFT - UV sensitive contributions?

Model example:
Da Rold et al., 1208.1499

Dipole operators only weakly constrained (edm's)

Δa_{CP} in (enter favorite NP model name)

Before LHCb result,

DCPV in charm not on top of NP theorists expectations

Δa_{CP} in (enter favorite NP model name)

Before LHCb result,

DCPV in charm not on top of NP theorists expectations

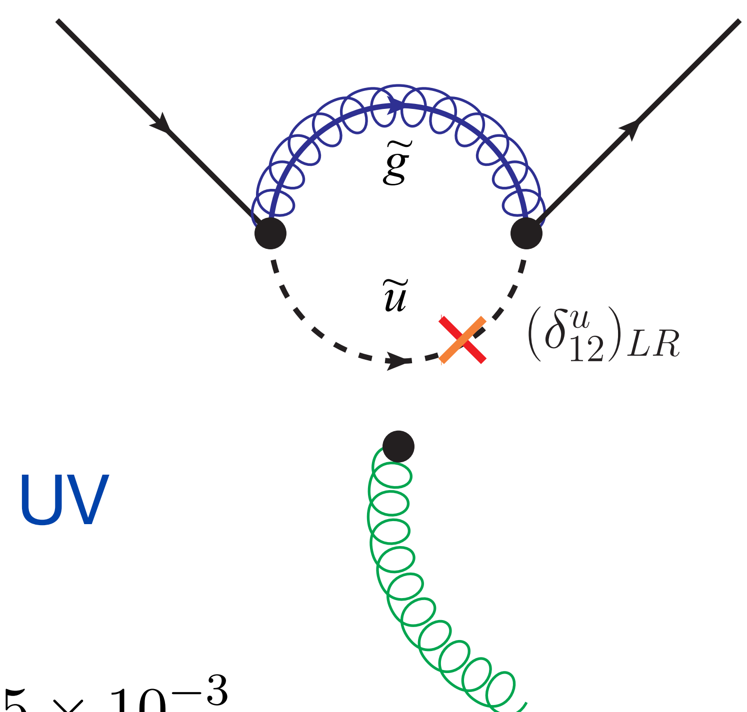
In last year, situation has improved considerably

Δa_{CP} in SUSY Models

- Left-right up-type squark mixing contributions

Grossman, Kagan & Nir, hep-ph/0609178
Giudice, Isidori & Paradisi, 1201.6204
Hiller, Hochberg, Nir, 1204.1046

$$\left|\Delta a_{CP}^{\mathrm{SUSY}}\right| \approx 0.6\% \left(\frac{\left|\mathrm{Im}\,(\delta^u_{12})_{LR}\right|}{10^{-3}}\right)\left(\frac{\mathrm{TeV}}{\tilde{m}}\right)$$



- contributions to ΔF=2 helicity suppressed

- requires large trilinear (A) terms, non-trivial flavor in UV

$$\mathrm{Im}\,(\delta^u_{12})_{LR} \approx \frac{\mathrm{Im}(A)\ \theta_{12}\ m_c}{\tilde{m}} \approx \left(\frac{\mathrm{Im}(A)}{3}\right)\left(\frac{\theta_{12}}{0.3}\right)\left(\frac{\mathrm{TeV}}{\tilde{m}}\right) 0.5 \times 10^{-3}$$

Giudice, Isidori & Paradisi, 1201.6204
see also Keren-Zur et al., 1205.5803

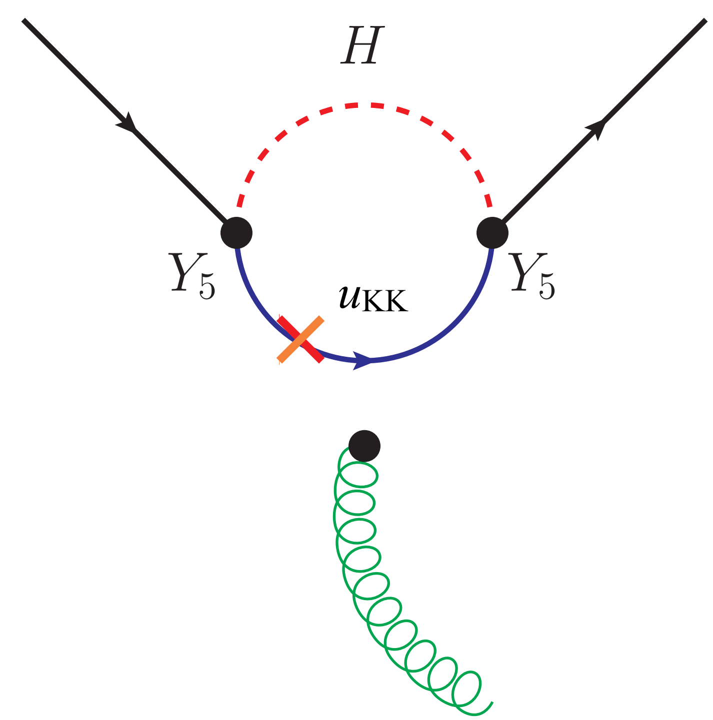
Δa_{CP} in Warped Extra-Dim. Models

- Anarchic flavor with bulk Higgs

Delaunay, J.F.K., Perez & Randall
1207.0474

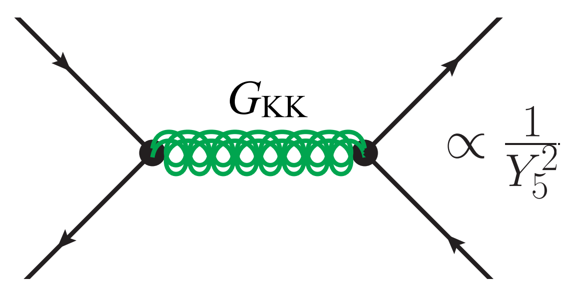
$$\left|\Delta a_{CP}^{\text{chromo}}\right|_{\text{RS}} \simeq 0.6\% \times \left(\frac{\mathcal{O}_\beta}{0.1}\right)\left(\frac{Y_5}{6}\right)^2\left(\frac{3\,\text{TeV}}{m_{\text{KK}}}\right)^2$$

Higgs wavefunction overlap



- requires very large 5D Yukawas
  - helps to avoid D-$\overline{\text{D}}$ mixing constraints

    Gedalia et al., 0906.1879



  - implies low UV cut-off $\frac{1}{2} \lesssim Y_5 \lesssim \frac{4\pi}{\sqrt{N_{KK}}}$

Agashe, Azatov & Zhu, 0810.1016
Csaki et al., 0907.0474

- Can be mapped to 4D partial compositeness models (for localized Higgs $\mathcal{O}_\beta \sim 1$)

Keren-Zur et al., 1205.5803

Δa_{CP} and 4th Generation

- 3-gen CKM non-unitarity and b' penguins

Feldmann, Nandi & Soni
1202.3795

$$\Delta a_{CP} \propto \ 4\,\mathrm{Im}\left[\frac{\lambda_{b'}}{\lambda_d - \lambda_s}\right] \simeq \frac{2\ \sin\theta_{14}\sin\theta_{24}\sin(\delta_{14}-\delta_{24})}{\sin\theta_{12}}$$

- No parametric enhancement allowed due to existing ΔF=2 CPV bounds

Nandi & Soni, 1011.6091
Buras et al., 1002.2126

  - Effects comparable to SM still allowed

- Similar conclusions for generic mixing with vector-like quarks

Grossman, Kagan & Nir
hep-ph/0609178
Altmannshofer et al.
1202.2866

Generic Implications for Experiment

- correlations with EDM's, rare top & down-type quark processes

Giudice, Isidori & Paradisi, 1201.6204
Hochberg & Nir, 1112.5268
Altmannshofer et al., 1202.2866

very model dependent

- NP explanations of Δa_{CP} via chromo-magnetic dipole operators
  - generically predict EM dipoles - rare radiative charm decays

$$D^0 \to X\gamma \qquad\qquad D^0 \to X e^+ e^-$$

Delaunay, J.F.K., Perez & Randall
1207.0474

Expected NP rates few orders below SM LD contributions

- possibility to access CPV observables

Isidori & J.F.K., 1205.3164
Fajfer & Kosnik, 1208.0759
Cappiello, Cata & D' Ambrosio, 1209.4235

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Fajfer & Kosnik, 1208.0759
Cappiello, Cata & D' Ambrosio, 1209.4235

- NP explanations of Δa_{CP} via ΔI=3/2 contributions
  - SM contributions to $A_f^{(2)}$ purely ΔI=1/2

Grossman, Kagan & Zupan, 1204.3557

No CPV expected in pure ΔI=3/2 decays

see also later talk by Grossman

Conclusions

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    see talks by Bhattacharya & Brod
- If NP, points towards new flavor structures in u_R sector at the TeV scale
- More experimental observables could clarify the picture

  Grossman, Kagan & Zupan, 1204.3557
  Isidori & J.F.K., 1205.3164
  - (CPV in) rare radiative charm decays - sensitive to NP in dipole ops.
  - CPV in isospin related 2-, 3-body modes - can test $\Delta I=3/2$ NP

Backup

CPV in $|\Delta c|=2$

- **CPV in Mixing** $|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$

$$m \equiv \frac{m_1 + m_2}{2}\,, \qquad \Gamma \equiv \frac{\Gamma_1 + \Gamma_2}{2}\,,$$
$$x \equiv \frac{m_2 - m_1}{\Gamma}\,, \qquad y \equiv \frac{\Gamma_2 - \Gamma_1}{2\Gamma}\,.$$

- Experimentally accessible mixing quantities:
  - x,y (CP conserving)

    Cannot be estimated accurately within SM

    NP contributions are predictable
  - flavor specific time-dependent CPV decay asymmetries [sensitive to q/p]

$$a_f(t) \equiv \frac{\Gamma(D^0(t) \to f) - \Gamma(\bar{D}^0(t) \to f)}{\Gamma(D^0(t) \to f) + \Gamma(\bar{D}^0(t) \to f)}\,,$$

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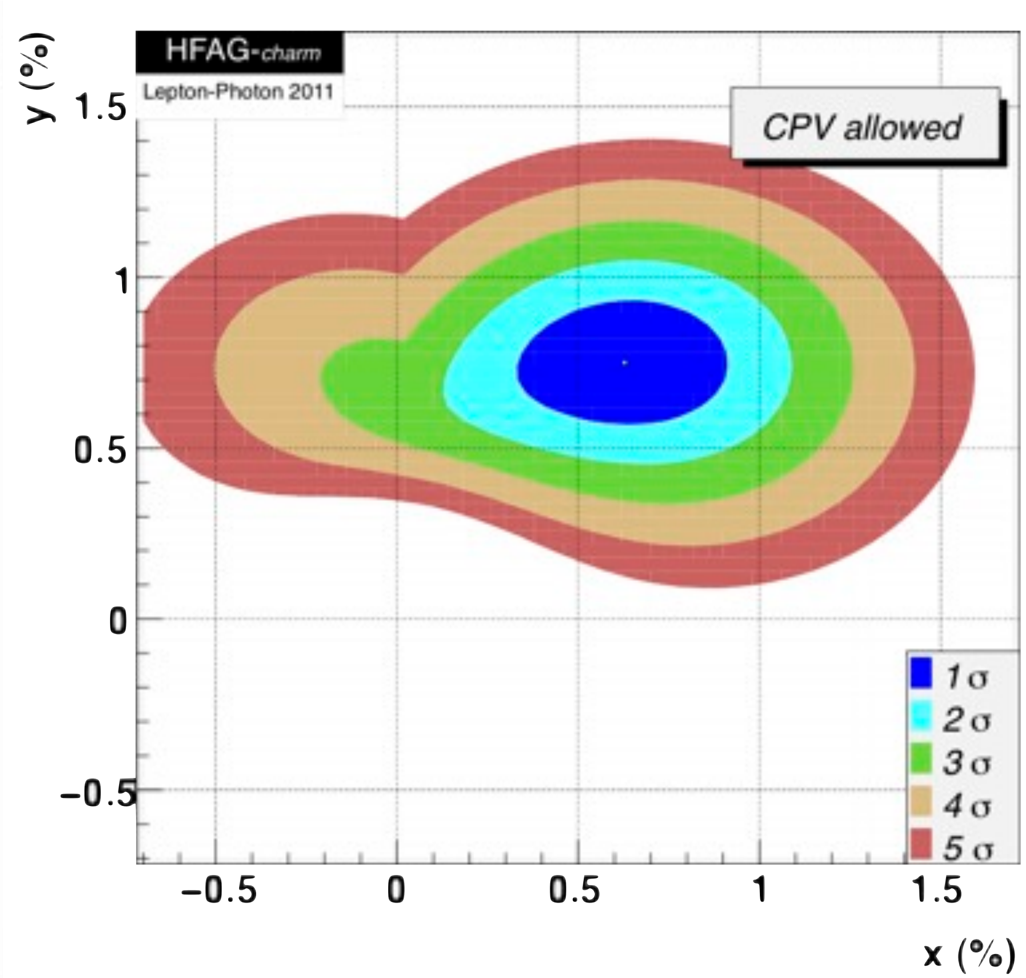

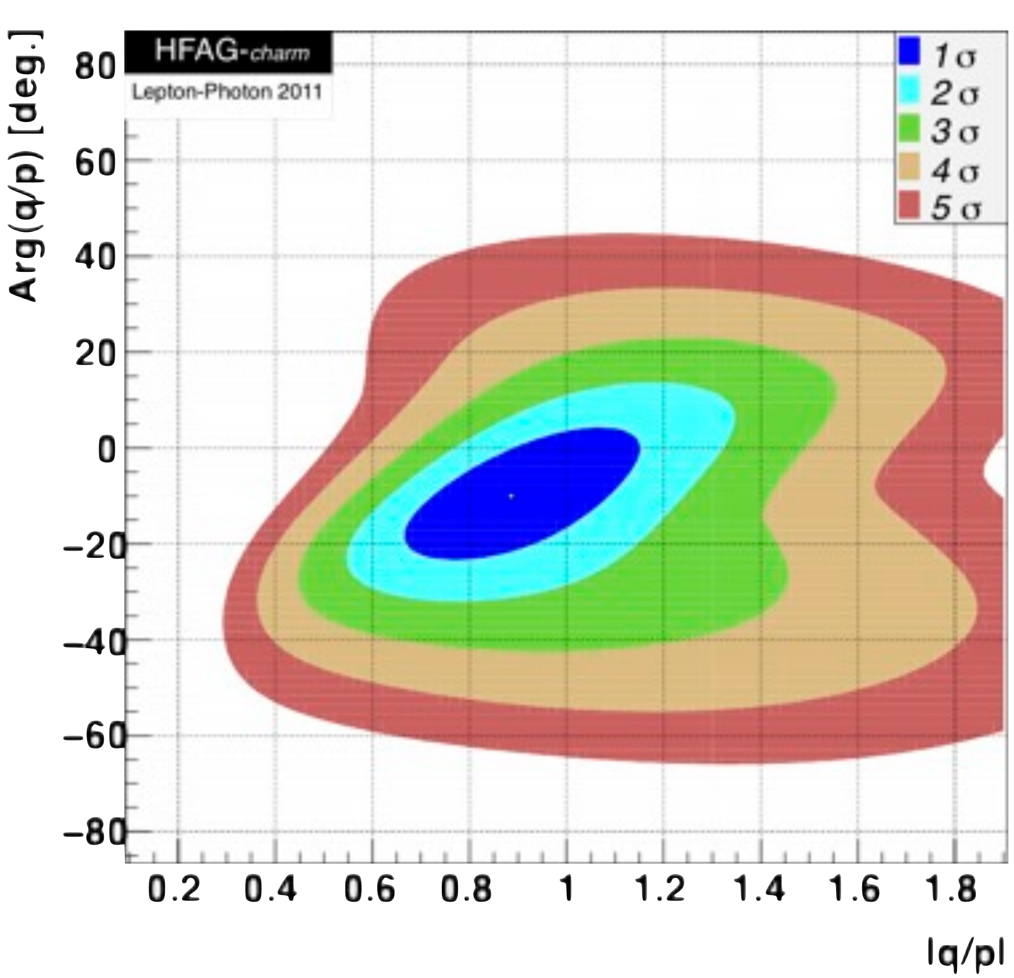

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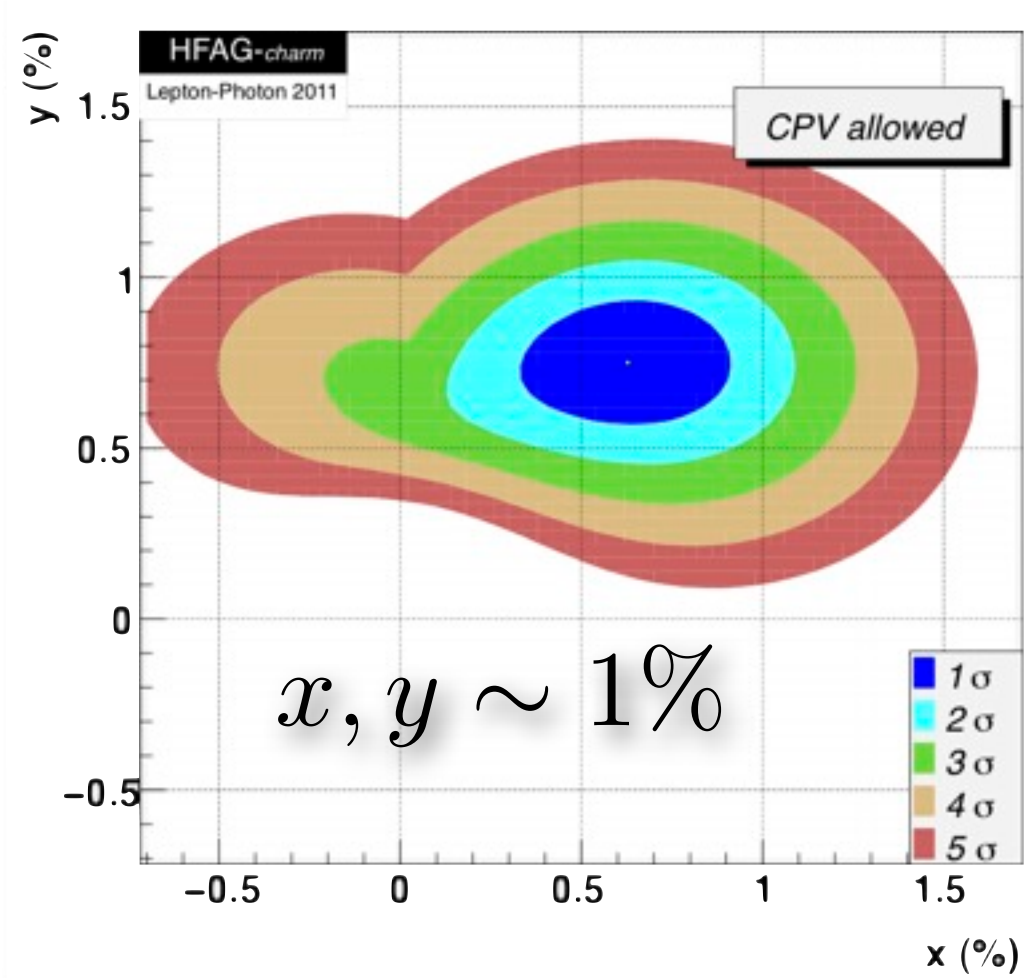

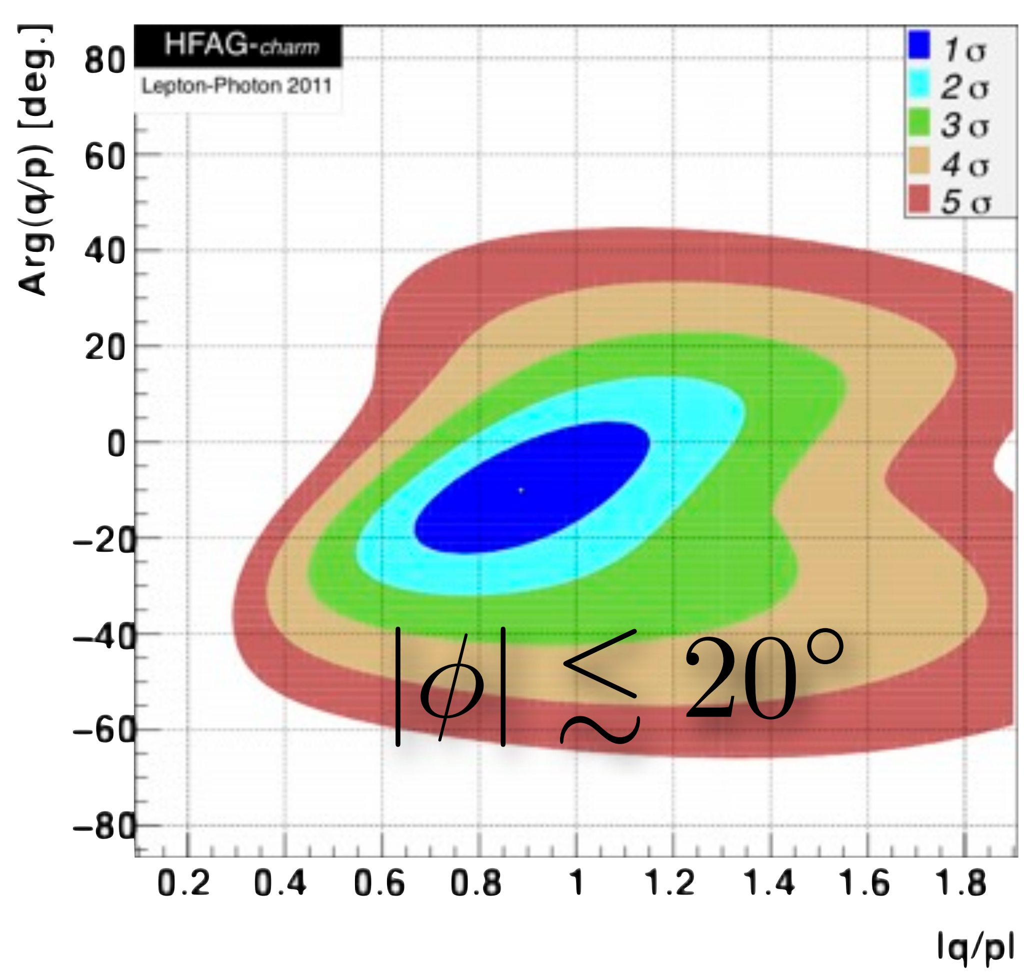

CPV in $|\Delta c|=2$

- **CPV in Mixing**

Isidori, Nir & Perez 1002.0900

Operator	Bounds on Λ (TeV)		Bounds on c_{ij} ($\Lambda = 1$ TeV)		Observables
	Re	Im	Re	Im	
$(\bar{s}_L \gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	Δm_K; ε_K
$(\bar{s}_R d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	Δm_K; ε_K
$(\bar{c}_L \gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	Δm_D; $\lvert q/p \rvert$, ϕ_D
$(\bar{c}_R u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	Δm_D; $\lvert q/p \rvert$, ϕ_D
$(\bar{b}_L \gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2	3.3×10^{-6}	1.0×10^{-6}	Δm_{B_d}; $S_{B_d \to \psi K}$
$(\bar{b}_R d_L)(\bar{b}_L d_R)$	1.9×10^3	3.6×10^3	5.6×10^{-7}	1.7×10^{-7}	Δm_{B_d}; $S_{B_d \to \psi K}$
$(\bar{b}_L \gamma^\mu s_L)^2$	1.1×10^2	1.1×10^2	7.6×10^{-5}	7.6×10^{-5}	Δm_{B_s}
$(\bar{b}_R s_L)(\bar{b}_L s_R)$	3.7×10^2	3.7×10^2	1.3×10^{-5}	1.3×10^{-5}	Δm_{B_s}

$$x, y \sim 1\%$$

$$|\phi| \lesssim 20^\circ$$

Imply significant constraints on CPV NP contributions, second only to kaon sector

On Universality of CPV in SU(3)$_Q$ breaking NP

- SM quark flavor symmetry $\mathcal{G}_F = \boxed{SU(3)_Q} \times SU(3)_U \times SU(3)_D$
  - two sources of breaking: $\mathcal{A}_u \equiv (Y_u Y_u^\dagger)_{\cancel{\mathrm{tr}}}\,, \qquad \mathcal{A}_d \equiv (Y_d Y_d^\dagger)_{\cancel{\mathrm{tr}}}$
  - **Implication (1):** direct correspondence between Δa_{CP} and ε'/ε (no weak loop suppression)
    - constraint on SU(3)$_Q$ breaking NP: $\Delta a_{CP}^{\mathrm{NP}} \lesssim 4 \times 10^{-4}$ Gedalia, J.F.K, Ligeti & Perez 1202.5038
  - Similarly for rare semileptonic decays:

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

$$\Downarrow$$

$$a_e^D \equiv \frac{\mathrm{Br}(D^+ \to \pi^+ e^+ e^-) - \mathrm{Br}(D^- \to \pi^- e^+ e^-)}{\mathrm{Br}(D^+ \to \pi^+ e^+ e^-) + \mathrm{Br}(D^- \to \pi^- e^+ e^-)} \lesssim 0.02$$ for SU(3)$_Q$ breaking NP

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  - **Implication (2):** bounds on degeneracy in SUSY alignment models

    - SUSY effects in flavor ~ masses, splittings (degeneracy); mixing angles $(\text{e.g.}\quad \bar{q}_i \tilde{q}_j \tilde{g})$

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    - D & K mixing said to imply that alignment not viable w/o degeneracy

(Nir & Seiberg, hep-ph/9304307) Blum et al., 0903.2118

      - based on assumption of ~ maximal CPV in K & D mixing
      - not actually attainable in alignment due to CPV universality

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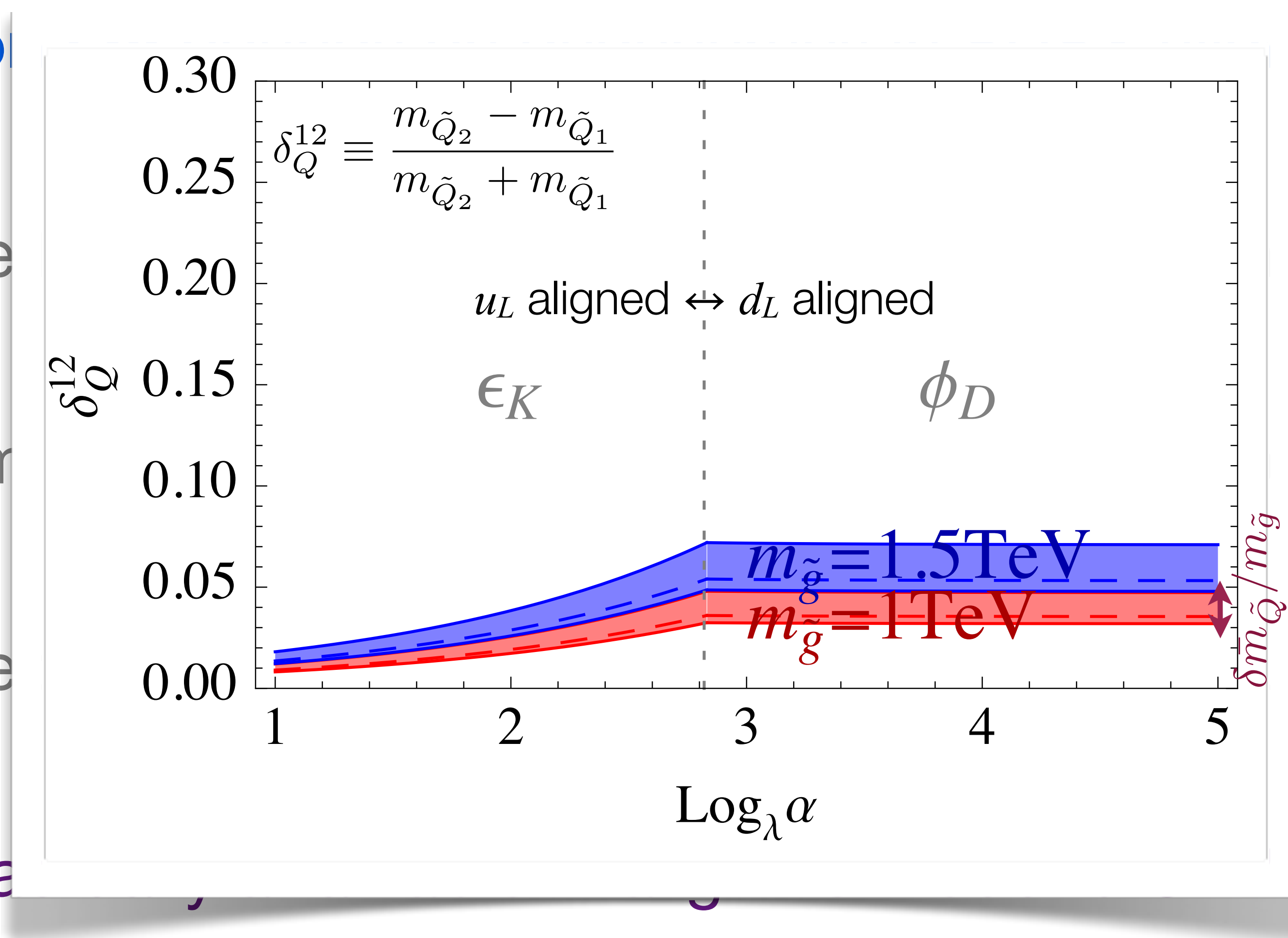
Blum et al., 0903.2118



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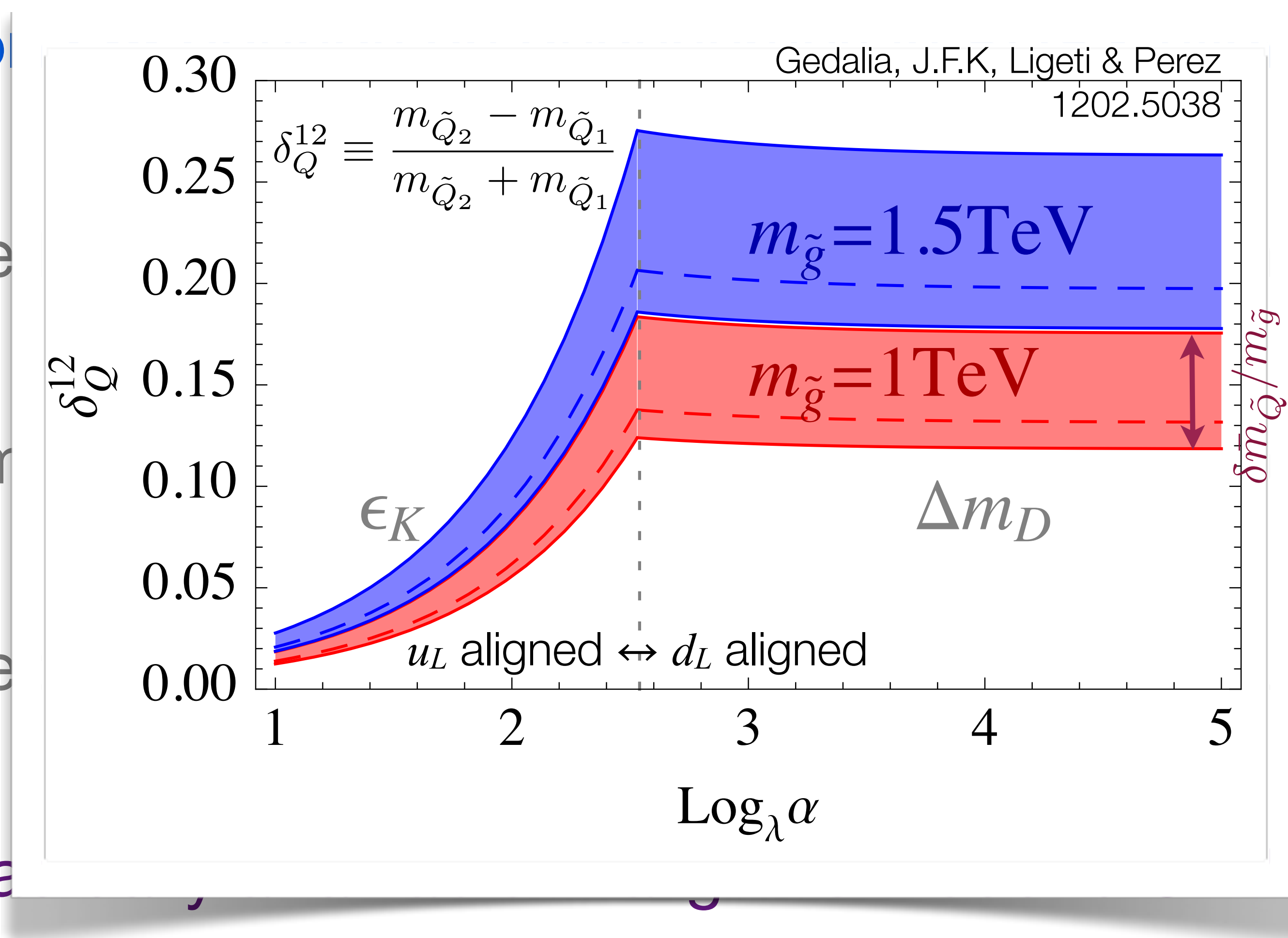

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    - viable SUSY spectra can be generated from complete anarchy at moderate mediation scales (M_S) (SUSY QCD RGE)

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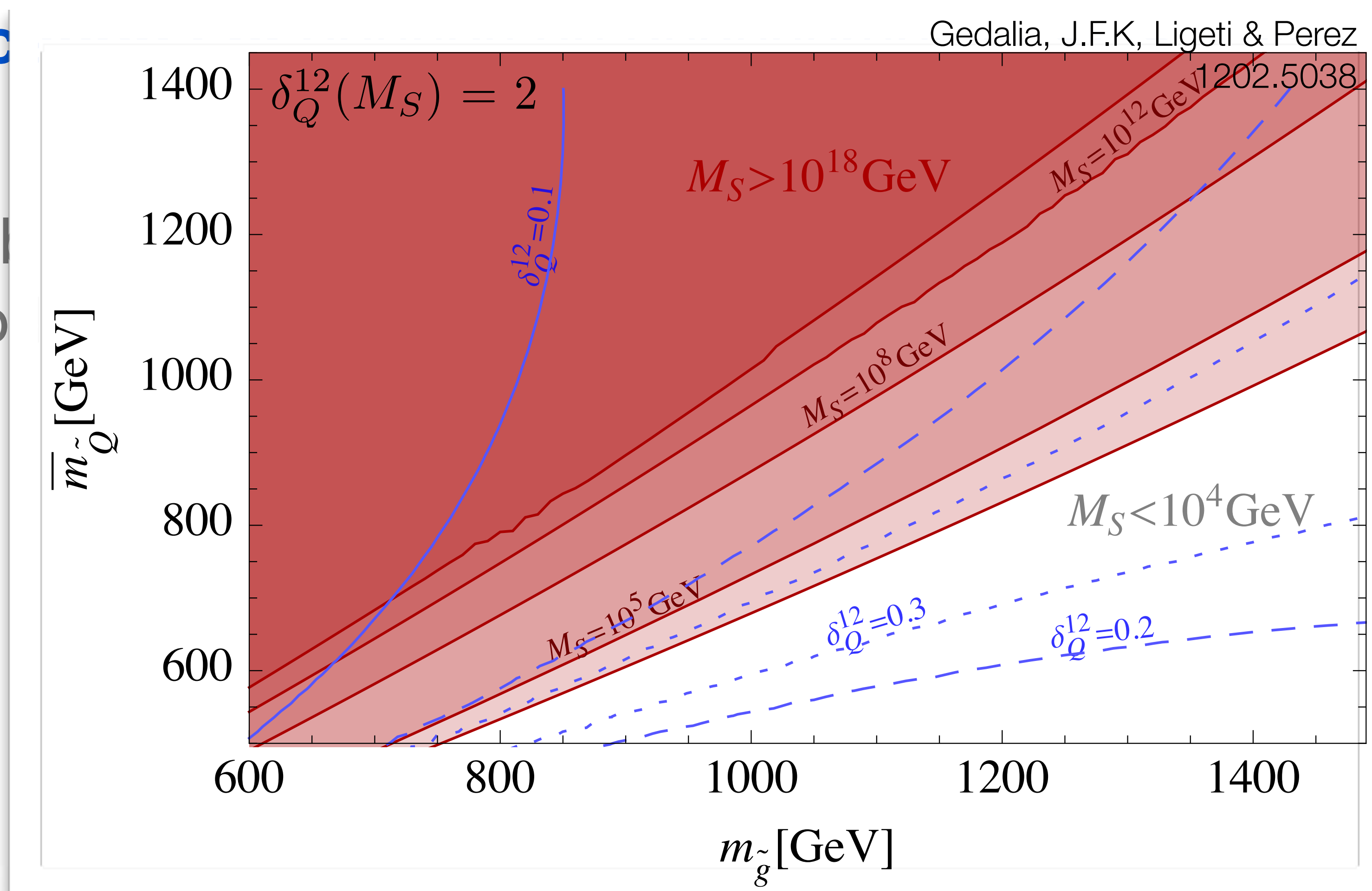

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  - **Implication (2):** bounds on degeneracy in SUSY alignment models
    - viable SUSY spectra can be generated from complete anarchy at moderate mediation scales (SUSY QCD RGE)
    - surprising mass hierarchies still viable, e.g.

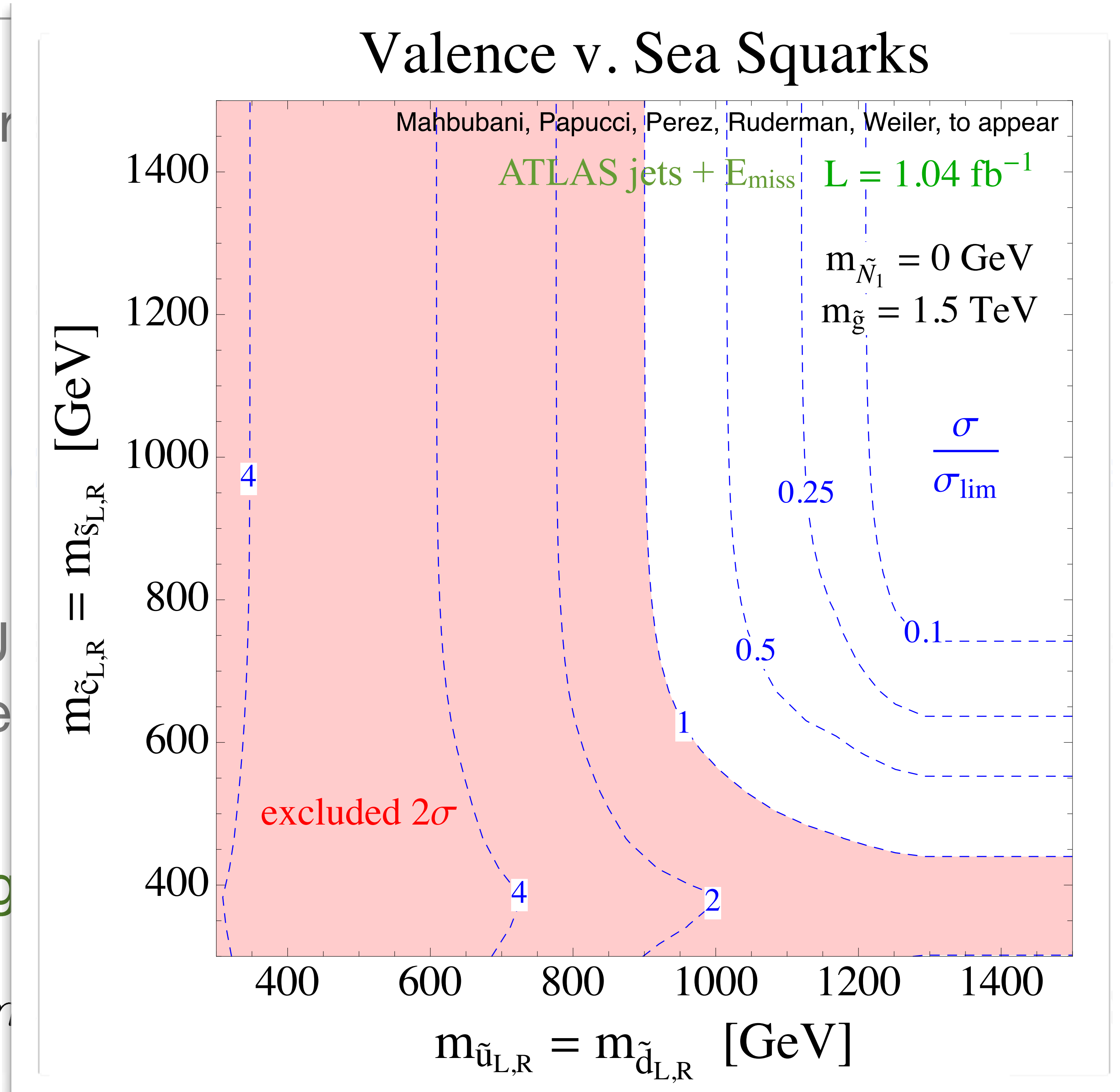
$$m_{\tilde{g}} = 1.3\,\mathrm{TeV}, m_{\tilde{Q}_1} = 550\,\mathrm{GeV}, m_{\tilde{Q}_2} = 950\,\mathrm{GeV}$$

Important implications for LHC searches

On Universality of CPV in SU(3)$_Q$ breaking NP

- SM quark flavor … $\times SU(3)_D$
  - two sources … $Y_d^\dagger)_{t\!\!/r}$
  - **Implication** … nt models
    - viable SU … anarchy at moderate …
    - surprising …

n … eV



Important implications for LHC searches

Generic Implications for Experiment

- NP explanations of Δa_{CP} via chromo-magnetic dipole operators

Grossman, Kagan & Nir, hep-ph/0609178
Giudice, Isidori & Paradisi, 1201.6204

$$|\Delta a_{CP}^{\rm NP}| \approx -1.8 |{\rm Im}[C_8^{\rm NP}(m_c)]| \ ,$$

(estimate of matrix element in QCD fact.)

  - generically predict EM dipoles

$$|{\rm Im}[C_7^{\rm NP}(m_c)]| \approx |{\rm Im}[C_8^{\rm NP}(m_c)]| \approx 0.4 \times 10^{-2} \ .$$

(QCD RGE evolution with TeV NP)   Isidori & J.F.K., 1205.3164

    - possibility to access CPV observables in $D^0 \to \pi\pi\gamma,\ KK\gamma$
      - in SM CPV expected similar as in $D^0 \to \pi\pi,\ KK$
      - large strong phases natural for LD SM contributions

$$\boxed{|a_{(\rho,\omega)\gamma}|^{\rm max} = 0.04(1) \left|\frac{{\rm Im}[C_7(m_c)]}{0.4\times 10^{-2}}\right| \left[\frac{10^{-5}}{\mathcal{B}(D\to(\rho,\omega)\gamma)}\right]^{1/2} \lesssim 10\% \ .}$$

(smaller effects also in $D^0 \to KK\gamma$ *with* m_{KK} around Φ mass)

Generic Implications for Experiment

- NP explanations of Δa_{CP} via $\Delta I = 3/2$ contributions

Grossman, Kagan & Zupan, 1204.3557

  - SM contributions to $A_{K^{(d)}}$, $A_{\pi^{(s)}}$ purely $\Delta I = 1/2$

No CPV expected in pure ΔI=3/2 decays

$$\Gamma(D^+ \to \pi^+ \pi^0) - \Gamma(D^- \to \pi^- \pi^0) = 0$$

(up to small isospin breaking)

  - nonzero difference would point towards CPV $\Delta I = 3/2$ NP contributions

  - decay amplitude sum-rules even in presence isospin breaking

$$\frac{1}{\sqrt{2}} \left| A_{\pi^+\pi^-} - \bar{A}_{\pi^-\pi^+} \right| \neq \left| A_{\pi^0\pi^0} - \bar{A}_{\pi^0\pi^0} \right|, \quad \rightarrow \quad \text{signal of } \Delta I = 3/2 \text{ CPV NP}$$

    - experimentally accessible with time-dependent measurements

    (also Dalitz plot analyses in $D \to 3\pi$, $D \to KK\pi$)