Constraints on New Physics Explanations for CP Violation in D^0 Decays From LHCb

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Motivation – LHCb Result

- Recently, the LHCb collaboration reported a measurement of ΔA_{CP} for time-integrated singly-suppressed Cabibbo decays of D^0 mesons

$$\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-)$$
$$= (-0.82 \pm 0.21 \pm 0.11)\%$$

- This result differs from the CP conserving hypothesis at **3.5σ**

$$A_{CP}(f) = \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to f)}$$

LHCb-CONF-2011-061
LHCb, 1112.0938 [hep-ex]

Previous measurements

- This result is consistent (at about 1σ) with the previous measurements from CDF and the world average performed by the Heavy Flavor Averaging Group

LHCb

0.62 fb^{-1}

$$\begin{aligned}\Delta A_{CP} &= A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) \\ &= (-0.82 \pm 0.21 \pm 0.11)\%\end{aligned}$$

LHCb-CONF-2011-061

LHCb, 1112.0938 [hep-ex]

CDF

5.9 fb^{-1}

$$A_{CP}(\pi^+\pi^-) = (+0.22 \pm 0.24\ (\text{stat}) \pm 0.11\ (\text{syst}))\%$$

$$A_{CP}(K^+K^-) = (-0.24 \pm 0.22\ (\text{stat}) \pm 0.09\ (\text{syst}))\%$$

$$\Delta A_{CP} = (-0.46 \pm 0.31\ (\text{stat}) \pm 0.12\ (\text{syst}))\%$$

CDF, 1111.5023 [hep-ex]

HFAG

$A_{CP}^{ind} = (-0.030 \pm 0.232)\%$, $\Delta A_{CP}^{dir} = (-0.423 \pm 0.270)\%$

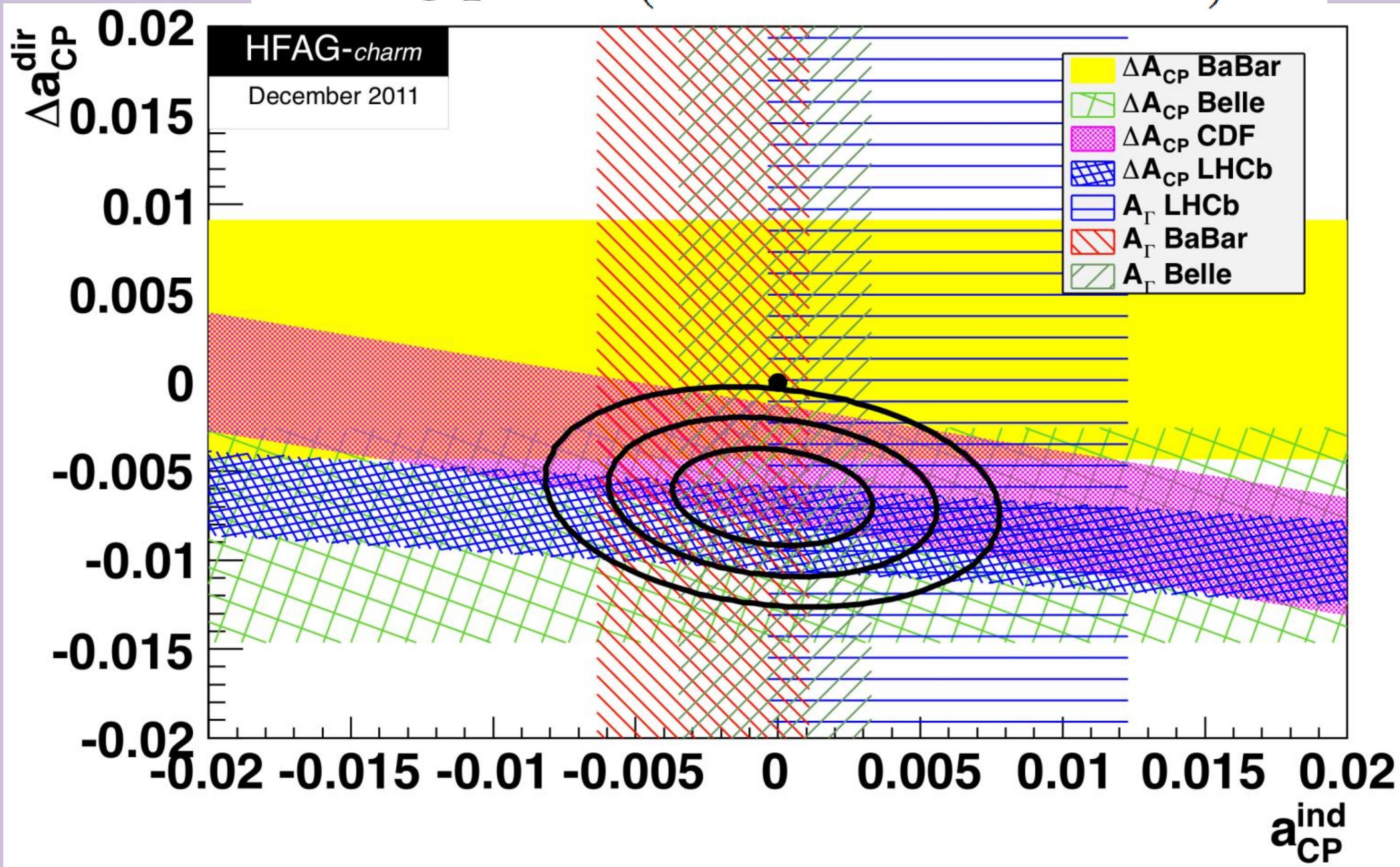
HFAG, http://www.slac.stanford.edu/xorg/hfag/charm/Dec11/DCPV/direct_indirect_cpv.html

Updated World Average

- Updated in December 2011: CL(no CPV) = 0.128%

$$\Delta A_{CP} = (-0.645 \pm 0.180)\%$$

Ellipses denote 68%, 95%, 99.7% CL



HFAG, http://www.slac.stanford.edu/xorg/hfag/charm/Dec11/DCPV/direct_indirect_cpv.html

Motivation – New Physics Flavor Puzzle

- The hierarchy problem motivates the presence of TeV-scale New Physics at the LHC
- Without additional assumptions, generic NP couplings give large flavor violation and large CP violation
  - Low energy flavor measurements provide strong constraints on the flavor structure of NP
  - Conversely, a signal of flavor violation or CP violation provides strong motivation for NP
- We already know more CP violation is needed for baryogenesis

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  - Conversely, a signal of flavor violation or CP violation provides strong motivation for NP
- We already know more CP violation is needed for baryogenesis – This result is *really* exciting!

Outline

- Motivation
- LHCb Measurement Details
- The SM CP Asymmetry Calculation
  - Hadronic Matrix Element Uncertainty
- Calculating New Physics Contributions to the CP Asymmetry
  - Effective Hamiltonian Approach
- New Physics Models and Constraints
  - Tree-level NP Contributions
  - Gluonic Penguin Contributions
- Conclusions

LHCb Analysis

- In general, A_{CP} has direct and indirect components
  - Direct contribution comes from CPV in the decay amplitudes
  - Indirect contributions come from CPV in mixing as well as CPV from the interference between mixing and decay
- – To first order, $A_{CP}(f) = a_{CP}^{\mathrm{dir}}(f) + \frac{\langle t \rangle}{\tau} a_{CP}^{\mathrm{ind}},$
- – Since the indirect component is largely universal

$$\begin{aligned} \Delta A_{CP} &\equiv A_{CP}(K^- K^+) - A_{CP}(\pi^- \pi^+) \\ &= \left[a_{CP}^{\mathrm{dir}}(K^- K^+) - a_{CP}^{\mathrm{dir}}(\pi^- \pi^+)\right] + \frac{\Delta \langle t \rangle}{\tau} a_{CP}^{\mathrm{ind}}, \end{aligned}$$

- – LHCb measured $\Delta\langle t\rangle/\tau = [9.83 \pm 0.22(\mathrm{stat.}) \pm 0.19(\mathrm{syst.})]\,\%$ indicating the direct CPV contribution is responsible

LHCb Analysis

- LHCb measures a "raw" asymmetry in each mode (N is calculated after background subtraction)

$$A_{\mathrm{raw}}(f) \equiv \frac{N(D^{*+} \to D^0(f)\pi_s^+) - N(D^{*-} \to \overline{D}^0(\bar{f})\pi_s^-)}{N(D^{*+} \to D^0(f)\pi_s^+) + N(D^{*-} \to \overline{D}^0(\bar{f})\pi_s^-)},$$

which can be decomposed into

$$A_{\mathrm{raw}}(f) = A_{CP}(f) + A_{\mathrm{D}}(f) + A_{\mathrm{D}}(\pi_{\mathrm{s}}^+) + A_{\mathrm{P}}(D^{*+})$$

  - $A_D(f)$ is the selection asymmetry for D^0 decay to f
  - $A_D(\pi_s^+)$ is the selection asymmetry for the slow pion
  - $A_P(D^{*+})$ is the production asymmetry for D^{*+}

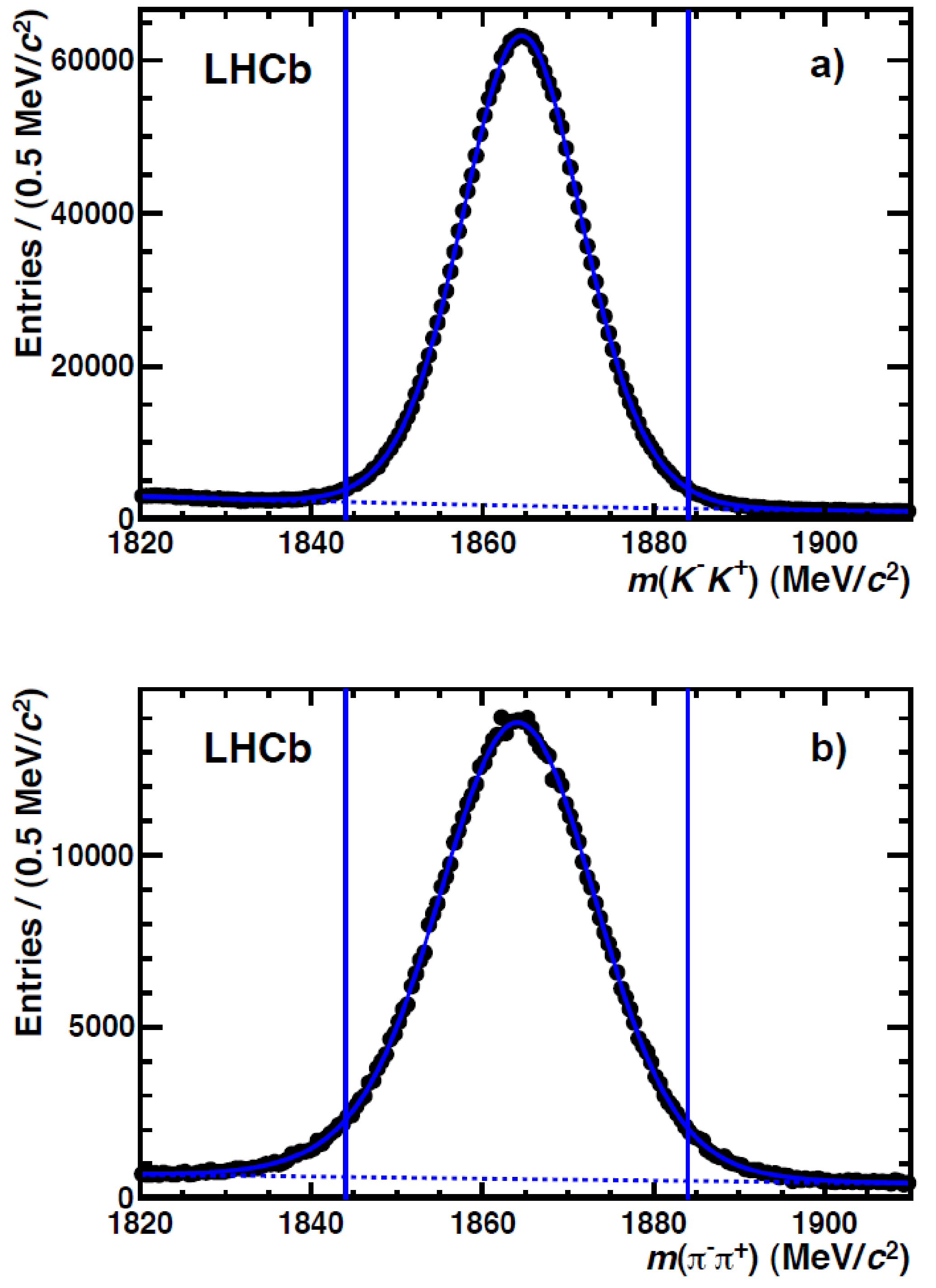
LHCb Analysis

$$A_{\mathrm{raw}}(f) = A_{CP}(f) + A_{\mathrm{D}}(f) + A_{\mathrm{D}}(\pi_s^+) + A_{\mathrm{P}}(D^{*+})$$

- Since the K^+K^- and $\pi^+\pi^-$ modes are self-conjugate, there is no $A_D(f)$
- The difference ΔA_{CP} causes $A_D(\pi_s^+)$ and $A_P(D^{*+})$ to largely cancel
  - Yet, slightly different kinematics between the two modes lead to imperfect cancellation for $A_D(\pi_s^+)$ and $A_P(D^{*+})$
  - This is taken into account via fiducial region requirements for the slow pion and 54 kinematic bins
    - Also switch magnetic polarity

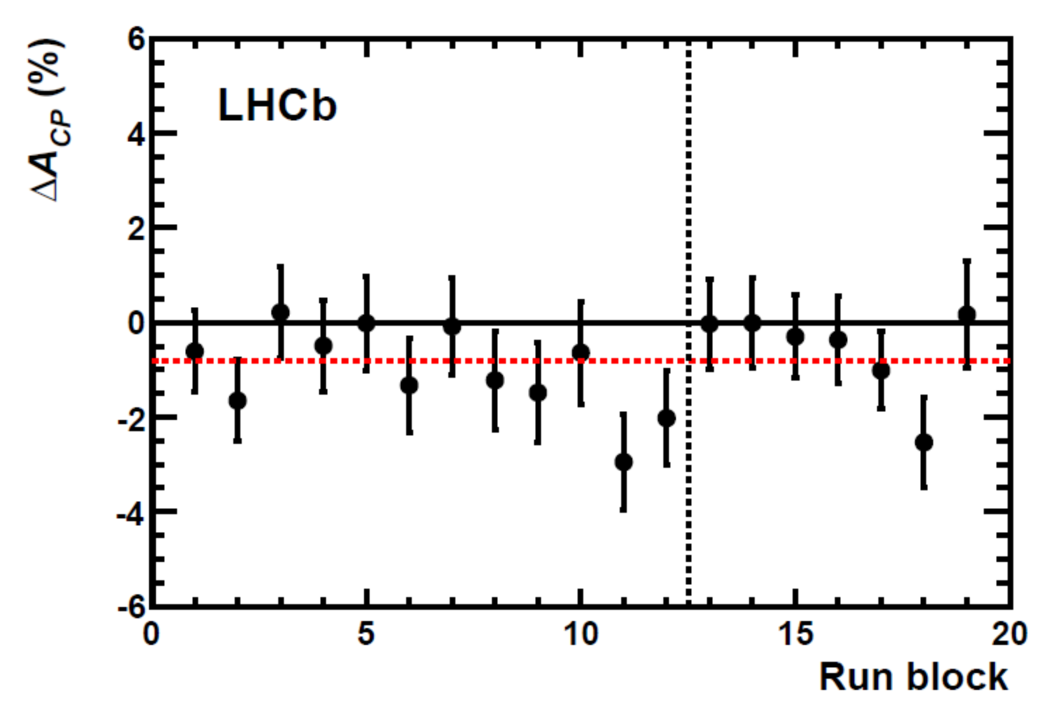
LHCb Analysis

- With 0.62 fb^{-1}, LHCb obtains 1.44×10^{6} $K^{+}K^{-}$ and 0.38×10^{6} $\pi^{+}\pi^{-}$ samples



LHCb Analysis

- Check time dependence



- Systematic uncertainties

Source	Uncertainty
Fiducial requirement	0.01%
Peaking background asymmetry	0.04%
Fit procedure	0.08%
Multiple candidates	0.06%
Kinematic binning	0.02%
Total	0.11%

CPV in D decays in the SM

- SM expectation for CPV in D decays is very small
  - Both D^0-$\bar{D}^0$ mixing and singly Cabibbo suppressed (SCS) D decays involve only first two quark generations and are therefore CP conserving
  - Resulting CPV in the SM is necessarily CKM suppressed
    - For D^0-$\bar{D}^0$ mixing, CPV enters at $O[(V_{cb} V_{ub})/(V_{cs} V_{us})] \approx 10^{-3}$
    - For $c \rightarrow u \bar{s} s$ and $c \rightarrow u \bar{d} d$ decays, CPV is both CKM and loop suppressed

Grossman, Kagan, Nir (2006)

Naïve Factorization

- In our work, we assume naïve factorization of the hadronic matrix element

$$\langle K^+ K^- | (\bar{u}\Gamma_1 s)(\bar{s}\Gamma_2 c) | D^0 \rangle$$
$$\simeq \langle K^+ | (\bar{u}\Gamma_1 s) | 0 \rangle \langle K^- | (\bar{s}\Gamma_2 c) | D^0 \rangle$$

  - Disregards the contribution of long-distance QCD physics, which can be estimated to give O(1) corrections to the Wilson coefficient for the operator
  - Studies of known branching ratios as an estimate of the ratio between decay amplitudes demonstrate an enhancement of a few is possible

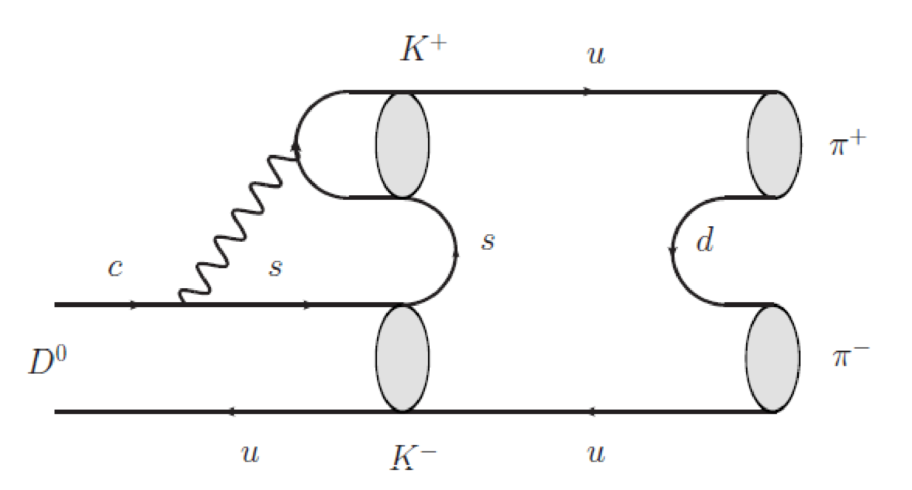
Brod, Kagan, Zupan (2011)
Isidori, Kamenik, Ligeti, Perez (2011)

Hadronic Matrix Element Uncertainty

- A different approach using the topological-diagram approach gives an estimate of the maximal as $\Delta A_{cp}^{dir} \approx -0.25\%$, still more than 2σ from the world average

Cheng, Chiang (2012)

  - based on $SU(3)_F$ symmetry, classify diagrams according to topologies of weak interactions with all strong interaction effects included)



Brod, Kagan, Zupan (2011)
Pirtskhalava, Uttayarat (2011)
Bhattacharya, Gronau, Rosner (2012)

Sociology

- “We conclude that CP violation in SCS D decays at the percent level signals new physics.” – Grossman, Kagan, Nir [hep-ph/0609178]
- “Observation of CP violation in D^0-$\overline{D}^0$ mixing (at a level much higher than $O(10^{-3})$) will constitute an unambiguous signal of new physics.” – Kirkby, Nir – PDG 2009 – “CP Violation in Meson Decays”

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- "We have shown that it is plausible that the standard model accounts for the measured value of ΔA_{CP}." – Brod, Kagan, Zupan [arXiv:1111.5000 [hep-ph]]

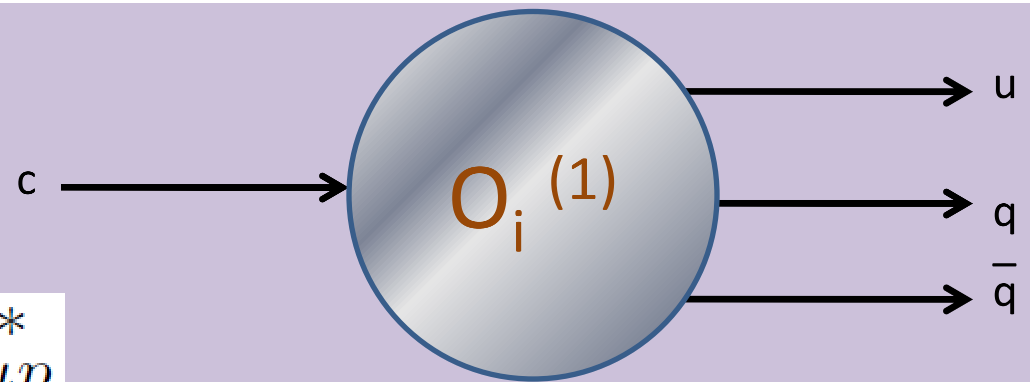
Our Approach

- If this is a sign of New Physics, what possibilities exist and what should we look for in direct searches?
  - We use naïve factorization, allow for 1×, 3×, and 10× enhancement of ΔA_{CP} from the hadronic matrix element
  - Impose relevant constraints to see if each scenario remains viable
  - (Future work will discuss the phenomenology of the remaining viable models)

Effective Hamiltonian for ΔF = 1

- We adopt an effective Hamiltonian approach to characterize $D \to K^+K^-$ and $D \to \pi^+\pi^-$ decays

$$\mathcal{H}_{\rm eff} = \Big(\sum_p \lambda_p \sum_{i=1}^{2} \Big(C_i^{(1)p} O_i^{(1)p} + \tilde{C}_i^{(1)p} \tilde{O}_i^{(1)p} \Big) + \sum_i \Big(C_i^{(1)} O_i^{(1)} + \tilde{C}_i^{(1)} \tilde{O}_i^{(1)} \Big) \Big) + \text{ h.c.}$$



$$\lambda_p = V_{cp} V_{up}^*$$

Effective Hamiltonian for ΔF = 1

- List of operators

$$O_1^{(1)p} = (\bar{u}p)_{V-A}(\bar{p}c)_{V-A} \ , \qquad (15a)$$

$$O_2^{(1)p} = (\bar{u}_\alpha p_\beta)_{V-A}(\bar{p}_\beta c_\alpha)_{V-A} \ , \qquad (15b)$$

$$O_3^{(1)} = (\bar{u}c)_{V-A}\sum_q (\bar{q}q)_{V-A} \ , \qquad (15c)$$

$$O_4^{(1)} = (\bar{u}_\alpha c_\beta)_{V-A}\sum_q (\bar{q}_\beta q_\alpha)_{V-A} \ , \qquad (15d)$$

$$O_5^{(1)} = (\bar{u}c)_{V-A}\sum_q (\bar{q}q)_{V+A} \ , \qquad (15e)$$

$$O_6^{(1)} = (\bar{u}_\alpha c_\beta)_{V-A}\sum_q (\bar{q}_\beta q_\alpha)_{V+A} \ , \qquad (15f)$$

$$O_7^{(1)} = \frac{3}{2}(\bar{u}c)_{V-A}\sum_q e_q(\bar{q}q)_{V+A} \ , \qquad (15g)$$

$$O_8^{(1)} = \frac{3}{2}(\bar{u}_\alpha c_\beta)_{V-A}\sum_q e_q(\bar{q}_\beta q_\alpha)_{V+A} \ , \qquad (15h)$$

$$O_9^{(1)} = \frac{3}{2}(\bar{u}c)_{V-A}\sum_q e_q(\bar{q}q)_{V-A} \ , \qquad (15i)$$

$$O_{10}^{(1)} = \frac{3}{2}(\bar{u}_\alpha c_\beta)_{V-A}\sum_q e_q(\bar{q}_\beta q_\alpha)_{V-A} \ , \qquad (15j)$$

$$O_{8g}^{(1)} = \frac{g_s}{8\pi^2} m_c \bar{u}\sigma^{\mu\nu}(1+\gamma_5)T^A_{\alpha\beta}c_\beta G^A_{\mu\nu} \ , \qquad (15k)$$

$$O_{S1}^{(1)} = (\bar{u}s)_{S-P}(\bar{s}c)_{S-P} \ , \qquad (15l)$$

$$O_{S2}^{(1)} = (\bar{u}_\alpha s_\beta)_{S-P}(\bar{s}_\beta c_\alpha)_{S-P} \ . \qquad (15m)$$

The operators $\tilde{O}_i^{(1)\{p\}}$ are obtained from $O_i^{(1)\{p\}}$ by replacing $\gamma_5 \to -\gamma_5$.

Effective Hamiltonian for ΔF = 1

Current-current operators

$$O_1^{(1)p} = (\bar u p)_{V-A}(\bar p c)_{V-A}\ , \tag{15a}$$

$$O_2^{(1)p} = (\bar u_\alpha p_\beta)_{V-A}(\bar p_\beta c_\alpha)_{V-A}\ , \tag{15b}$$

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Effective Hamiltonian for ΔF = 1

QCD penguin

$$O_1^{(1)p} = (\bar{u}p)_{V-A}(\bar{p}c)_{V-A} \ , \quad (15a)$$

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Effective Hamiltonian for ΔF = 1

EW penguin

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Effective Hamiltonian for ΔF = 1

Chromomagnetic operator

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Effective Hamiltonian for ΔF = 1

Scalar operators

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$$\boxed{\begin{aligned} O_{S1}^{(1)} &= (\bar{u}s)_{S-P}(\bar{s}c)_{S-P} \ , \quad (15l) \\ O_{S2}^{(1)} &= (\bar{u}_\alpha s_\beta)_{S-P}(\bar{s}_\beta c_\alpha)_{S-P} \ . \quad (15m) \end{aligned}}$$

The operators $\tilde{O}_i^{(1)\{p\}}$ are obtained from $O_i^{(1)\{p\}}$ by replacing $\gamma_5 \to -\gamma_5$.

Effective Hamiltonian for ΔF = 1

Odd # = no color exchange; **Even #** = color exchange

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$$O_9^{(1)} = \frac{3}{2}(\bar{u}c)_{V-A}\sum_q e_q(\bar{q}q)_{V-A} \,, \tag{15i}$$

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$$O_{8g}^{(1)} = \frac{g_s}{8\pi^2} m_c \bar{u}\sigma^{\mu\nu}(1+\gamma_5)T^A_{\alpha\beta}c_\beta G^A_{\mu\nu} \,, \tag{15k}$$

$$O_{S1}^{(1)} = (\bar{u}s)_{S-P}(\bar{s}c)_{S-P} \,, \tag{15l}$$

$$O_{S2}^{(1)} = (\bar{u}_\alpha s_\beta)_{S-P}(\bar{s}_\beta c_\alpha)_{S-P} \,. \tag{15m}$$

The operators $\tilde{O}_i^{(1)\{p\}}$ are obtained from $O_i^{(1)\{p\}}$ by replacing $\gamma_5 \to -\gamma_5$.

Effective Hamiltonian for ΔF = 1

Left-Left (or Right-Right, if tilded)

$$O_1^{(1)p} = (\bar{u}p)_{V-A}(\bar{p}c)_{V-A} \ , \qquad (15a)$$

$$O_2^{(1)p} = (\bar{u}_\alpha p_\beta)_{V-A}(\bar{p}_\beta c_\alpha)_{V-A} \ , \qquad (15b)$$

$$O_3^{(1)} = (\bar{u}c)_{V-A}\sum_q (\bar{q}q)_{V-A} \ , \qquad (15c)$$

$$O_4^{(1)} = (\bar{u}_\alpha c_\beta)_{V-A}\sum_q (\bar{q}_\beta q_\alpha)_{V-A} \ , \qquad (15d)$$

$$O_5^{(1)} = (\bar{u}c)_{V-A}\sum_q (\bar{q}q)_{V+A} \ , \qquad (15e)$$

$$O_6^{(1)} = (\bar{u}_\alpha c_\beta)_{V-A}\sum_q (\bar{q}_\beta q_\alpha)_{V+A} \ , \qquad (15f)$$

$$O_7^{(1)} = \frac{3}{2}(\bar{u}c)_{V-A}\sum_q e_q(\bar{q}q)_{V+A} \ , \qquad (15g)$$

$$O_8^{(1)} = \frac{3}{2}(\bar{u}_\alpha c_\beta)_{V-A}\sum_q e_q(\bar{q}_\beta q_\alpha)_{V+A} \ , \qquad (15h)$$

$$O_9^{(1)} = \frac{3}{2}(\bar{u}c)_{V-A}\sum_q e_q(\bar{q}q)_{V-A} \ , \qquad (15i)$$

$$O_{10}^{(1)} = \frac{3}{2}(\bar{u}_\alpha c_\beta)_{V-A}\sum_q e_q(\bar{q}_\beta q_\alpha)_{V-A} \ , \qquad (15j)$$

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$$O_{S1}^{(1)} = (\bar{u}s)_{S-P}(\bar{s}c)_{S-P} \ , \qquad (15l)$$

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The operators $\tilde{O}_i^{(1)\{p\}}$ are obtained from $O_i^{(1)\{p\}}$ by replacing $\gamma_5 \to -\gamma_5$.

Effective Hamiltonian for ΔF = 1

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$$O_2^{(1)p} = (\bar{u}_\alpha p_\beta)_{V-A}(\bar{p}_\beta c_\alpha)_{V-A} \ , \quad (15b)$$

$$O_3^{(1)} = (\bar{u}c)_{V-A}\sum_q(\bar{q}q)_{V-A} \ , \quad (15c)$$

$$O_4^{(1)} = (\bar{u}_\alpha c_\beta)_{V-A}\sum_q(\bar{q}_\beta q_\alpha)_{V-A} \ , \quad (15d)$$

$$O_5^{(1)} = (\bar{u}c)_{V-A}\sum_q(\bar{q}q)_{V+A} \ , \quad (15e)$$

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$$O_{S2}^{(1)} = (\bar{u}_\alpha s_\beta)_{S-P}(\bar{s}_\beta c_\alpha)_{S-P} \ . \quad (15m)$$

The operators $\tilde{O}_i^{(1)\{p\}}$ are obtained from $O_i^{(1)\{p\}}$ by replacing $\gamma_5 \to -\gamma_5$.

Effective Hamiltonian for ΔF = 1

- Consider the decay amplitudes

$$A_f = A_f^T\left(1 + r_f e^{i(\delta_f+\phi_f)}\right) ,$$
$$\bar{A}_f = \eta_{CP}^f A_f^T\left(1 + r_f e^{i(\delta_f-\phi_f)}\right) ,$$

  - Taking r_f small, we obtain $A_f^d = 2r_f \sin\delta_f \sin\phi_f$

- In our effective operator language, we get

$$r_f e^{i\phi_f} \simeq \frac{1}{\lambda_p}\left(C_1^{(1)p} + \frac{C_2^{(1)p}}{N_c}\right)^{-1}\left(\frac{\lambda_p (C_2^{(1)p})_{NP}}{N_c} + C_4^{(1)} + \frac{C_3^{(1)}}{N_c} - \frac{C_{10}^{(1)}}{2} - \frac{C_9^{(1)}}{2N_c} - \frac{3\alpha_s}{4\pi}\frac{N_c^2-1}{N_c^2}C_{8g}^{(1)}\right.$$
$$\left. + \chi_f\left(C_6^{(1)} + \frac{C_5^{(1)}}{N_c} - \frac{C_8^{(1)}}{2} - \frac{C_7^{(1)}}{2N_c} - \frac{C_{S1}^{(1)}}{2N_c} - \frac{C_{S2}^{(1)}}{2} - \frac{\alpha_s}{4\pi}\frac{N_c^2-1}{N_c^2}C_{8g}^{(1)}\right) + (C_i^{(1)} \leftrightarrow \tilde{C}_i^{(1)})\right)$$

- We evaluate at the scale

$$\mu \simeq m_D \simeq 1.8 \text{ GeV}$$

$$\chi_{K^+K^-} = \frac{2m_K^2}{(m_c - m_s)(m_s + m_u)}$$
$$\chi_{\pi^+\pi^-} = \frac{2m_\pi^2}{(m_c - m_s)(m_d + m_u)}$$

Effective Hamiltonian for ΔF=2

- Strong constraints arise from the ΔF=2 operators

$$\mathcal{H}_{\text{eff}} = \sum_{i=1}^{5} C_i^{(2)} O_i^{(2)} + \sum_{i=1}^{3} \tilde{C}_i^{(2)} \tilde{O}_i^{(2)} + \text{h.c.}$$

- We calculate the contribution to D^0- $\overline{D}^0$ mixing

$$\tilde{O}_1^{(2)D} = (\bar{u}^\alpha \gamma_\mu P_R c^\alpha)(\bar{u}^\beta \gamma^\mu P_R c^\beta)$$

as well as K^0-$\overline{K}^0$ mixing where necessary

$$\begin{aligned}
\tilde{O}_1^{(2)K} &= (\bar{d}^\alpha \gamma_\mu P_R s^\alpha)(\bar{d}^\beta \gamma^\mu P_R s^\beta)\ , \\
O_4^{(2)K} &= (\bar{d}^\alpha P_L s^\alpha)(\bar{d}^\beta P_R s^\beta)\ , \\
O_5^{(2)K} &= (\bar{d}^\alpha P_L s^\beta)(\bar{d}^\beta P_R s^\alpha)\ .
\end{aligned}$$

New Physics Models

- We consider a large variety of tree-level and loop-level NP models
- Tree level
  - Flavor changing Z
  - Flavor changing Z’ (W’)
  - Flavor changing heavy gluon
  - 2 Higgs doublet model
  - (Scalar octet, scalar sextet)
- Loop level
  - Fermion + scalar loop without GIM in gluonic penguin
  - Fermion + scalar loop with GIM in gluonic penguin
  - (Chirally enhanced magnetic penguin)

Flavor Changing Z

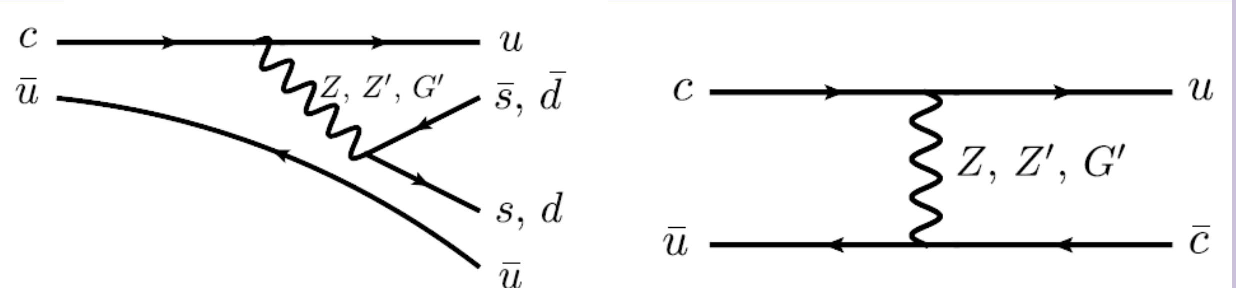
- Introduce flavor changing Z couplings (*e.g.* generated from RS with non-universal bulk masses) given by

$$\mathcal{L} = X_{cu}\bar{c}_R\gamma^\mu u_R Z_\mu \; + \; \text{h.c.}$$

- Calculate Wilson coefficients for ΔF=1 and ΔF=2 and obtain

$$\tilde{C}_5^{(1)} = -\frac{1}{3}\frac{g}{2c_W}\frac{X_{cu}}{4M_Z^2}\,,$$
$$\tilde{C}_7^{(1)} = \frac{2}{3}g c_W\frac{X_{cu}}{4M_Z^2}\,,$$
$$\tilde{C}_9^{(1)} = -\frac{2}{3}\frac{g s_W^2}{c_W}\frac{X_{cu}}{4M_Z^2}$$

$$\tilde{C}_1^{(2)D} = \frac{X_{cu}^2}{2M_Z^2}$$

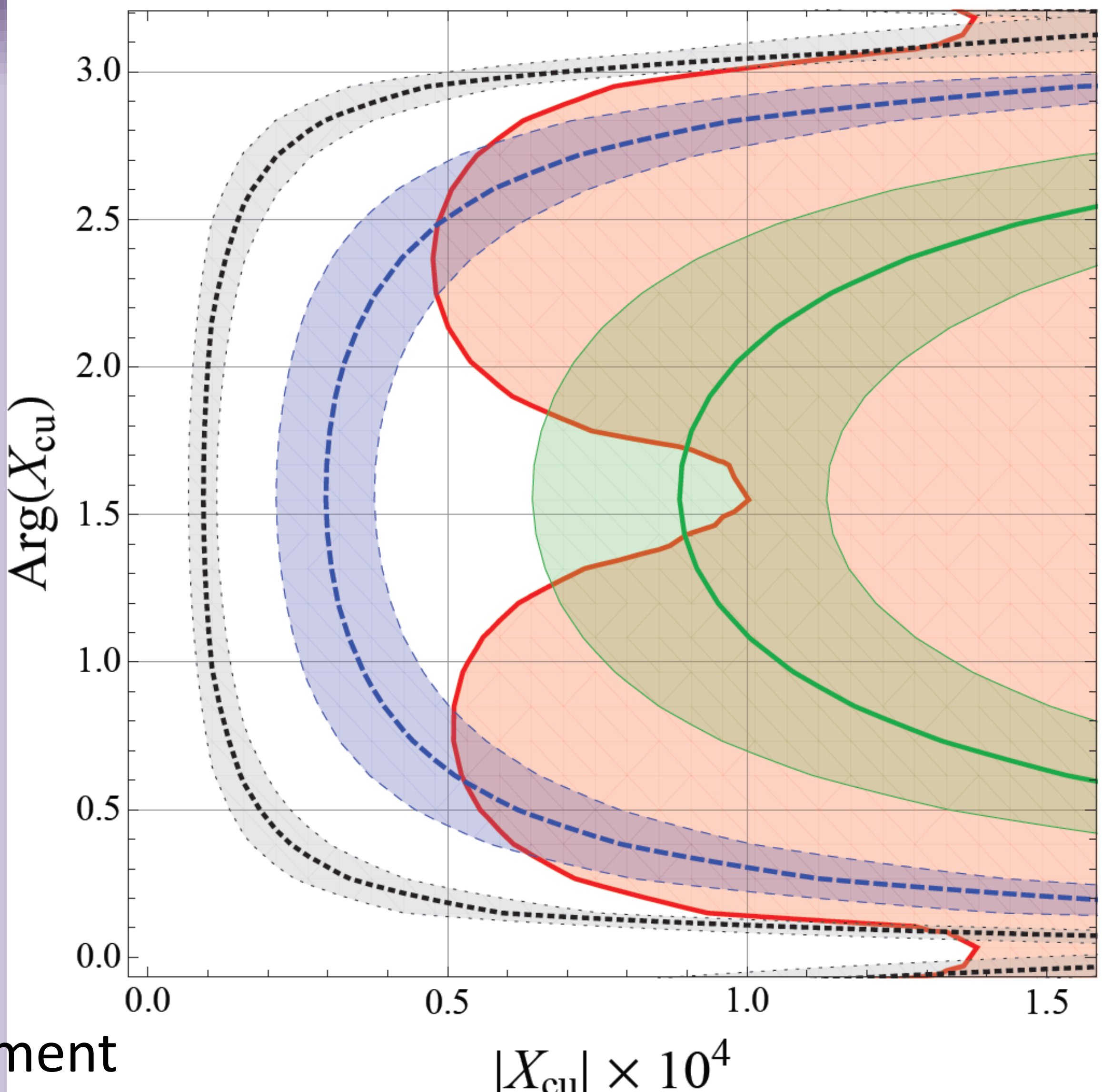


(a) (b)

PRELIMINARY

Constraints – Z

Only have small viable parameter space around $\mathrm{Arg}(X_{cu}) = \pi/2, 3\pi/2$



Green = 1× enhancement
Blue dashed = 3× enhancement
Black dotted = 10× enhancement
Bands correspond to 1σ for ΔA_{CP}
Red = excluded by D^0-$\bar{D}^0$ mixing

PRELIMINARY

Flavor Changing Z'

- Introduce flavor changing Z' with couplings given by

$$\begin{aligned}\mathcal{L} = & \, g_L \bar{u}_L^i \gamma^\mu u_L^i Z'_\mu + g_u \bar{u}_R^i \gamma^\mu u_R^i Z'_\mu \\ & + g_L \bar{d}_L^i \gamma^\mu d_L^i Z'_\mu + g_d \bar{d}_R^i \gamma^\mu d_R^i Z'_\mu \\ & + X_{cu} \bar{c}_R \gamma^\mu u_R Z'_\mu \; + \; \text{h.c.} \; .\end{aligned}$$

- Obtain Wilson coefficients for ΔF=1 and ΔF=2

From RH couplings

$$\tilde{C}_3^{(1)} = \frac{(g_u + 2g_d)}{3} \frac{X_{cu}}{4M_{Z'}^2} \, ,$$

$$\tilde{C}_9^{(1)} = \frac{2(g_u - g_d)}{3} \frac{X_{cu}}{4M_{Z'}^2} \, ,$$

From LH couplings

$$\tilde{C}_5^{(1)} = \frac{g_L X_{cu}}{4M_{Z'}^2} \, .$$

$$\tilde{C}_1^{(2)D} = \frac{X_{cu}^2}{2M_{Z'}^2}$$

PRELIMINARY

Constraints – Z'

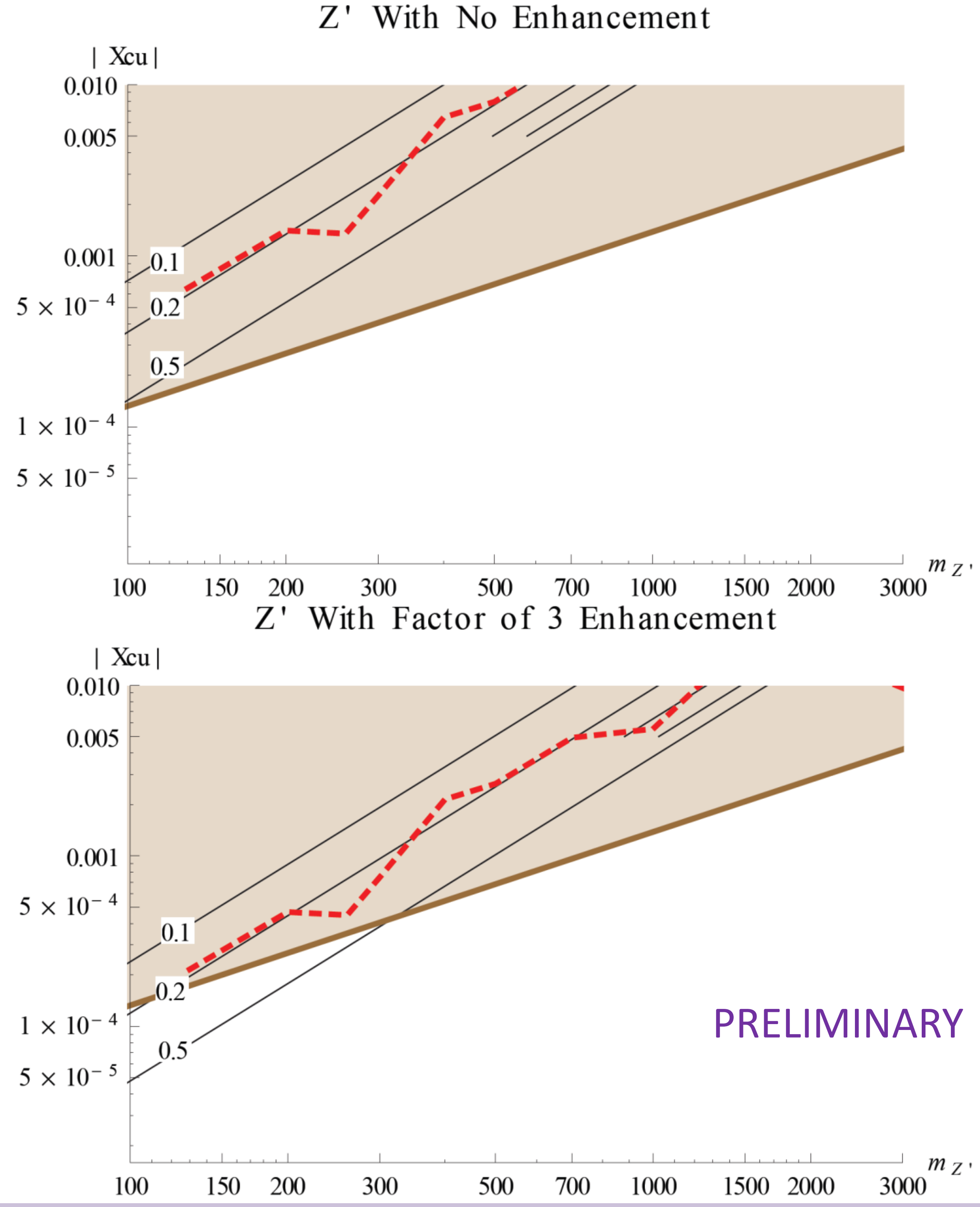
Set $\mathrm{Arg}(X_{cu}) = \pi/2$

Vary $g_L = g_u = g_d$

A W' model would necessarily be constrained by kaon mixing

Below red line = excluded by dijet searches

Shaded = excluded by D^0-D^0 mixing



Flavor Changing Heavy Gluon

- Introduce flavor changing heavy gluon with couplings given by

$$\mathcal{L} = g_L \bar{u}^i_L \gamma^\mu T^a u^i_L (G')^a_\mu + g_u \bar{u}^i_R \gamma^\mu T^a u^i_R (G')^a_\mu \\ + g_L \bar{d}^i_L \gamma^\mu T^a d^i_L (G')^a_\mu + g_d \bar{d}^i_R \gamma^\mu T^a d^i_R (G')^a_\mu \\ + X_{cu} \bar{c}_R \gamma^\mu T^a u_R (G')^a_\mu \; + \; \text{h.c.} \, . \qquad (27)$$

- Obtain Wilson coefficients

From RH g_u and g_d couplings

$$\tilde{C}^{(1)}_4 = \frac{(g_u + 2g_d)}{3} \frac{X_{cu}}{8M^2_{G'}} \, , \quad \tilde{C}^{(1)}_3 = \frac{-1}{N_c} \tilde{C}^{(1)}_4 \, ,$$

$$\tilde{C}^{(1)}_{10} = \frac{2(g_u - g_d)}{g_u + 2g_d} \tilde{C}^{(1)}_4 \, , \quad \tilde{C}^{(1)}_9 = \frac{-1}{N_c} \tilde{C}^{(1)}_{10} \, ,$$

From LH g_L couplings

$$\tilde{C}^{(1)}_6 = \frac{g_L X_{cu}}{8M^2_{G'}} \, , \quad \tilde{C}^{(1)}_5 = \frac{-1}{N_c} \tilde{C}^{(1)}_6 \, . \qquad (28)$$

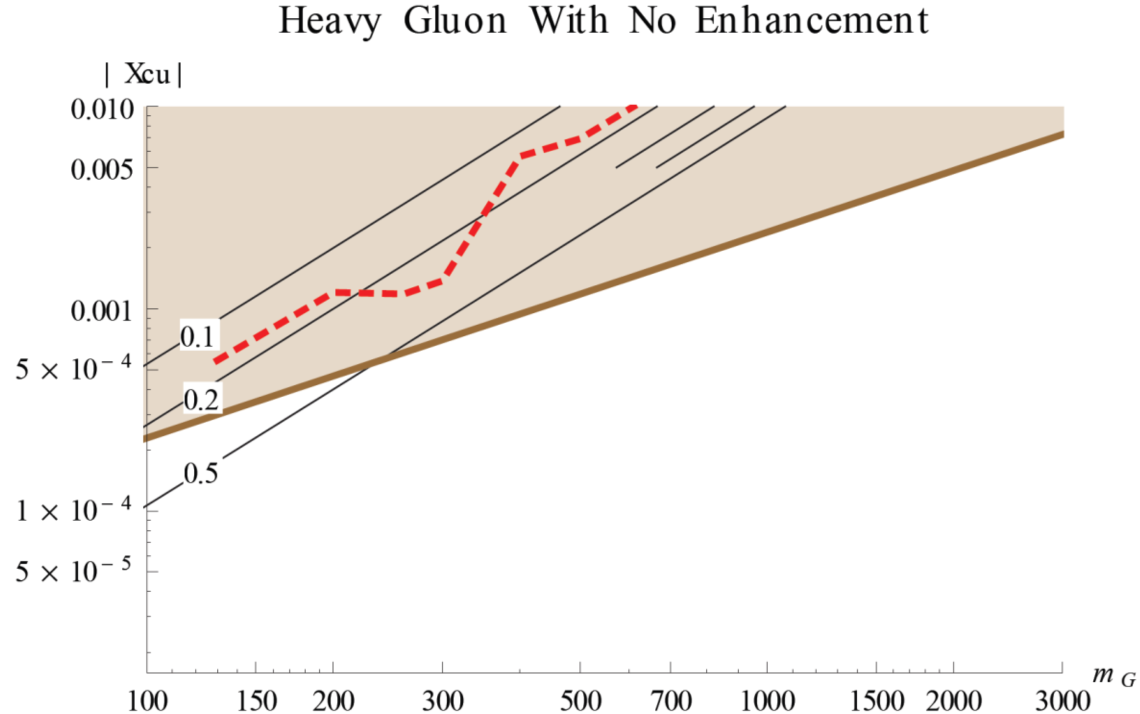
$$\tilde{C}^{(2)D}_1 = \frac{1 - N_c}{2N_c} \frac{X^2_{cu}}{2M^2_{G'}}$$

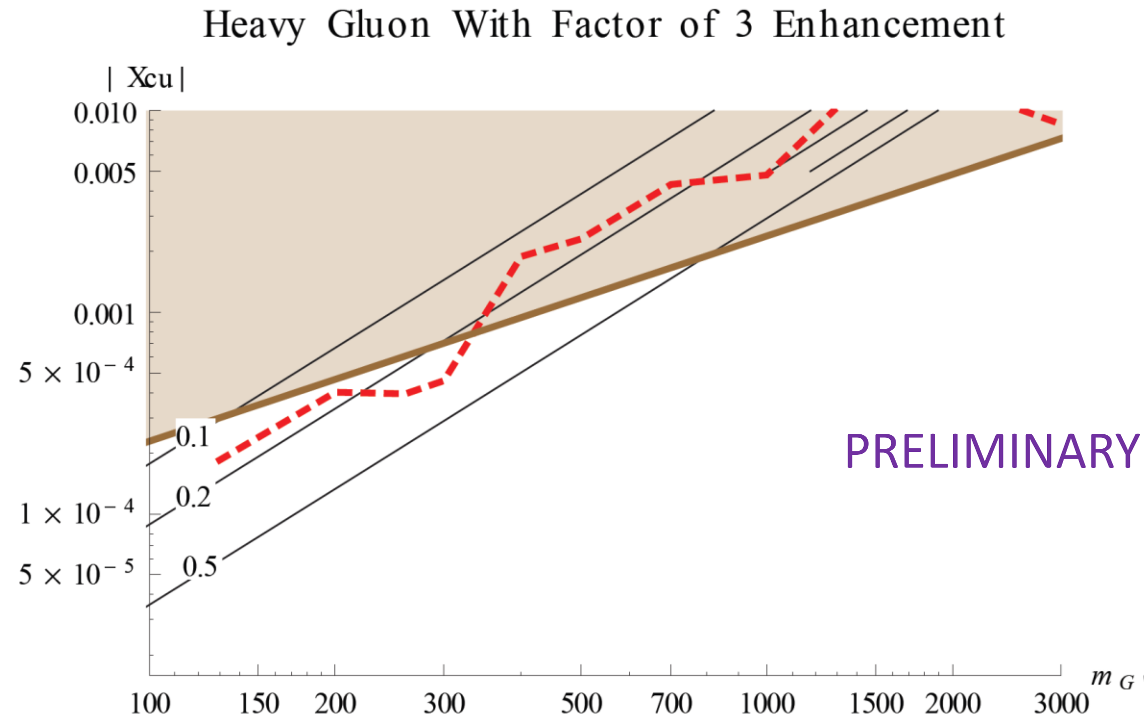
PRELIMINARY

Constraints – Heavy Gluon

Set Arg(X_{cu}) = $\pi/2$

Vary $g_L = g_u = g_d \equiv g$





PRELIMINARY

Black line = constant g

Below red line = excluded by dijet searches

Shaded = excluded by D^0-D^0 mixing

Two Higgs Doublet Model with MFV

- Introduce general 2HDM, allowing "wrong" Yukawas

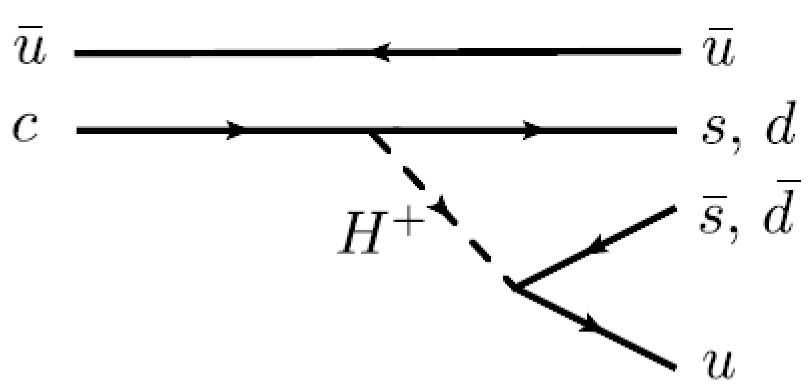
$$\mathcal{L} = Y_u \bar{Q} U H_u + Y_d \bar{Q} D H_d + Y_\ell \bar{L} E H_d \qquad (30)$$
$$+ X_u \bar{Q} U H_d^\dagger + X_d \bar{Q} D H_u^\dagger + X_\ell \bar{L} E H_u^\dagger + \text{ h.c.}$$

- Use Minimal Flavor Violation ansatz for X_u and X_d matrices

$$X_u = \epsilon_u Y_u + \epsilon'_u Y_u Y_u^\dagger Y_u + \epsilon''_u Y_u Y_d^\dagger Y_d + \ldots \ ,$$
$$X_d = \epsilon_d Y_d + \epsilon'_d Y_d Y_u^\dagger Y_u + \epsilon''_d Y_d Y_d^\dagger Y_d + \ldots (31)$$
$$X_\ell = \epsilon_\ell Y_\ell$$

- Focus on large tan β region,

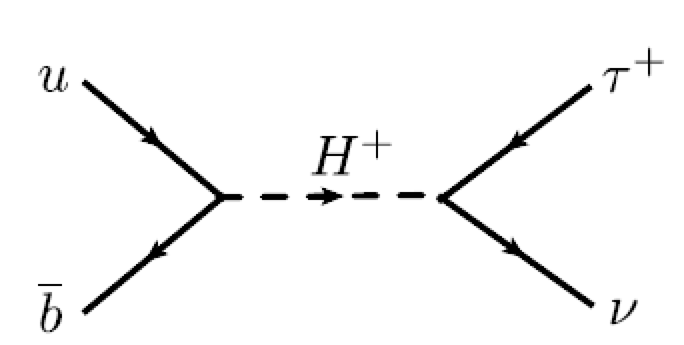
$$C_{S1}^{(1)} = \frac{m_c m_s}{v^2} \epsilon_u \tan\beta \frac{V_{us} V_{cs}^*}{4 M_{H^\pm}^2}$$



(a)

PRELIMINARY

Constraints – 2HDM



- Constraints from B^+ and K^+ decays
  - Measured ratio of branching ratios

$$R_{B\tau\nu} = \frac{\mathrm{Br}(B \to \tau\nu)_{\mathrm{exp}}}{\mathrm{Br}(B \to \tau\nu)_{\mathrm{SM}}} = 1.58 \pm 0.32$$

  - For our model

$$R_{B\tau\nu} = \left| 1 - \frac{m_B^2}{M_{H^\pm}^2} \frac{\tan\beta}{1 + \epsilon_b \tan\beta} \frac{1}{\epsilon_\ell} \right|^2$$

  - Satisfied from $\varepsilon_b \equiv (\varepsilon_d + \varepsilon_d'' y_b^2) \approx 10^{-2}$ - 10^{-1} given $\varepsilon_d \ll 1$ since $\tan\beta$ large, $m_B \ll M_H^\pm$
- Model is only constrained from R_{l23} if $\tan\beta$ is very high
  - Measured ratio

$$R_{\ell 23} = 0.999 \pm 0.007$$

  - Our calculation

$$R_{\ell 23} = \left| 1 - \frac{m_K^2}{M_{H^\pm}^2} \frac{\tan\beta}{\epsilon_\ell} \right|$$

PRELIMINARY

Constraints – 2HDM

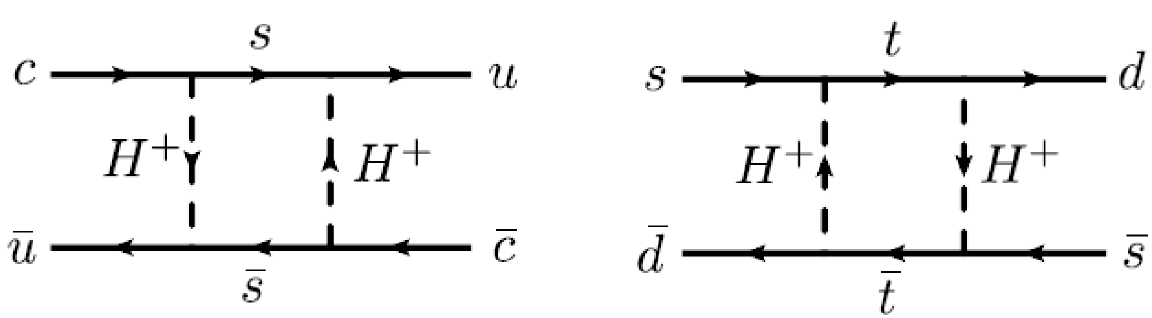
- Constraints from D and K mixing

$$C_1^{(2)D} \simeq \frac{1}{16\pi^2}\frac{m_s^4}{v^4}(V_{cs}V_{us}^*)^2\frac{\tan\beta^4}{2M_{H^\pm}^2}\ ,$$

$$C_1^{(2)K} \simeq \frac{1}{16\pi^2}\frac{m_t^4}{v^4}(V_{ts}V_{td}^*)^2\frac{1}{M_{H^\pm}^2}$$

$$\left(|\epsilon_t|^4 h_1(x_t) - |\epsilon_t|^2 h_2(x_t, x_W)\right)$$

  - $\varepsilon_t \equiv \varepsilon_u + \varepsilon_u' y_t^2$; $x_t = m_t^2/M_{H\pm}^2$; $x_W = m_W^2/M_{H\pm}^2$;
  - h_1 and h_2 are loop functions calculated numerically



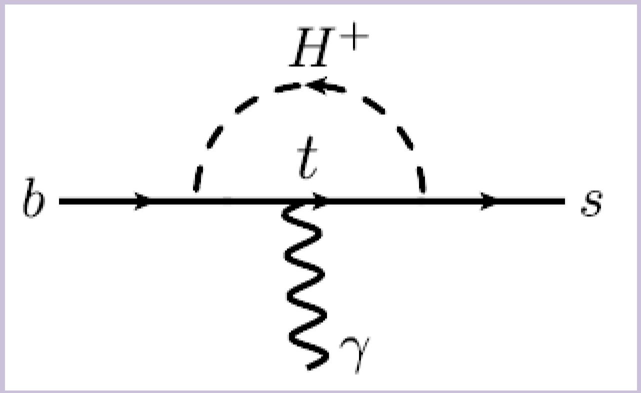
(b) (c)

PRELIMINARY

Constraints – 2HDM

- Have 1-loop charged Higgs contributions to $B_d \rightarrow X_s\gamma$
  - Bound does not apply here, since

$$\frac{A(b \to s\gamma)}{A(b \to s\gamma)_{\rm II}} = \frac{\epsilon_t \tan\beta}{1+\epsilon_b \tan\beta} + |\epsilon_t|^2 f(x_t)$$



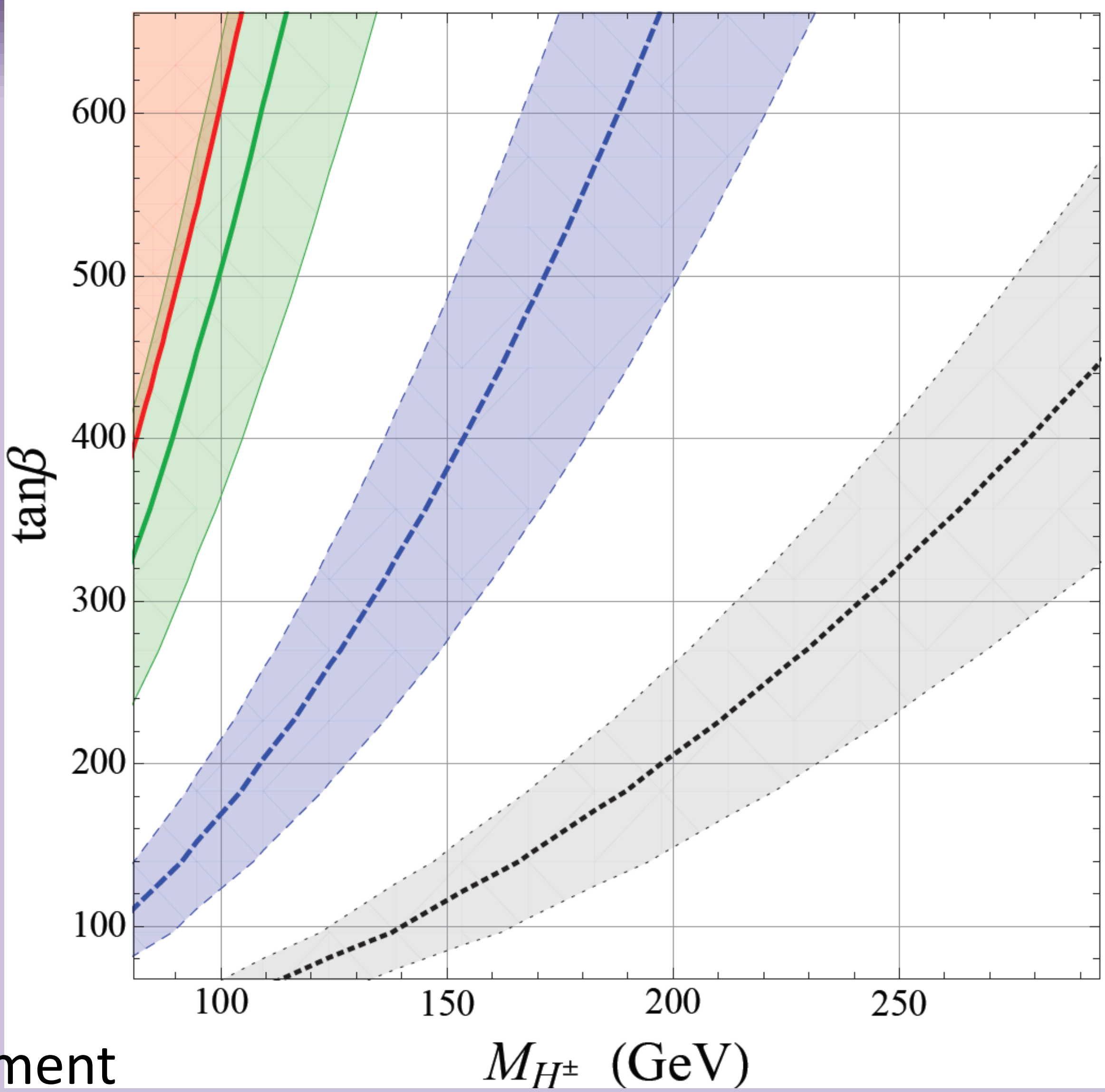
  - Since ε_t and ε_b can be complex, the amplitude can be complex, relaxing the constraint considerably

Altmannshofer, Paradisi, Straub (2011)

PRELIMINARY

Constraints – 2HDM

- Set ε_u=0.5i, ε_d=2, ε_l=1
- 2HDM can only affect $D^0 \rightarrow K^+K^-$



Green = 1× enhancement
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Bands correspond to 1σ for ΔA_{CP}
Red = excluded by $K \rightarrow \mu\nu$ decay

PRELIMINARY

Loop level – scalar+fermion, no GIM

- Add one heavy fermion and one heavy colored scalar that only couple to RH up and charm quarks

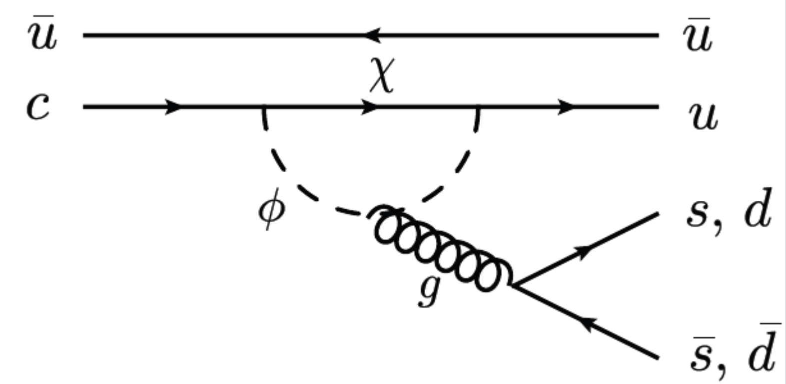
$$\mathcal{L} = X_u \bar{u}_R \chi \phi + X_c \bar{c}_R \chi \phi \; + \; \text{h.c.}$$

- Calculate Wilson coefficients

$$\tilde{C}_6^{(1)} = \frac{\alpha_s}{4\pi} X_u X_c^* \frac{1}{m_\phi^2} p(z) \; ,$$

$$\tilde{C}_3^{(1)} = \tilde{C}_5^{(1)} = -\frac{1}{N_c} \tilde{C}_4^{(1)} = -\frac{1}{N_c} \tilde{C}_6^{(1)} \; ,$$

$$\tilde{C}_{8g}^{(1)} = X_u X_c^* \frac{1}{m_\phi^2} g(z) \; .$$



$$z = m_\chi^2 / m_\phi^2$$

PRELIMINARY

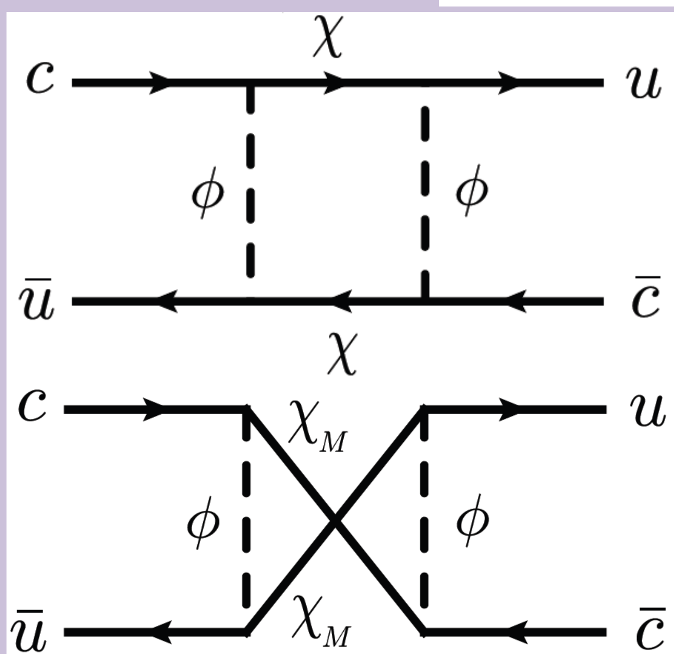
Constraints – scalar+fermion, no GIM

- Calculate Wilson coefficient for ΔF=2
  - Dirac fermion

$$\tilde{C}_1^{(2)D} = \frac{(X_u X_c^*)^2}{16\pi^2} \frac{1}{m_\phi^2} \frac{1}{8} f(z)$$

  - Majorana fermion

$$\tilde{C}_1^{(2)D} = \frac{(X_u X_c^*)^2}{16\pi^2} \frac{1}{m_\phi^2} \left(\frac{1}{8} f(z) + \frac{1}{4} \tilde{f}(z) \right)$$



$$f(z) = -\frac{1+z}{4(1-z)^2} - \frac{z}{2(1-z)^3} \log(z) \ ,$$

$$\tilde{f}(z) = -\frac{2z}{(1-z)^2} - \frac{z(1+z)}{(1-z)^3} \log(z) \ ,$$

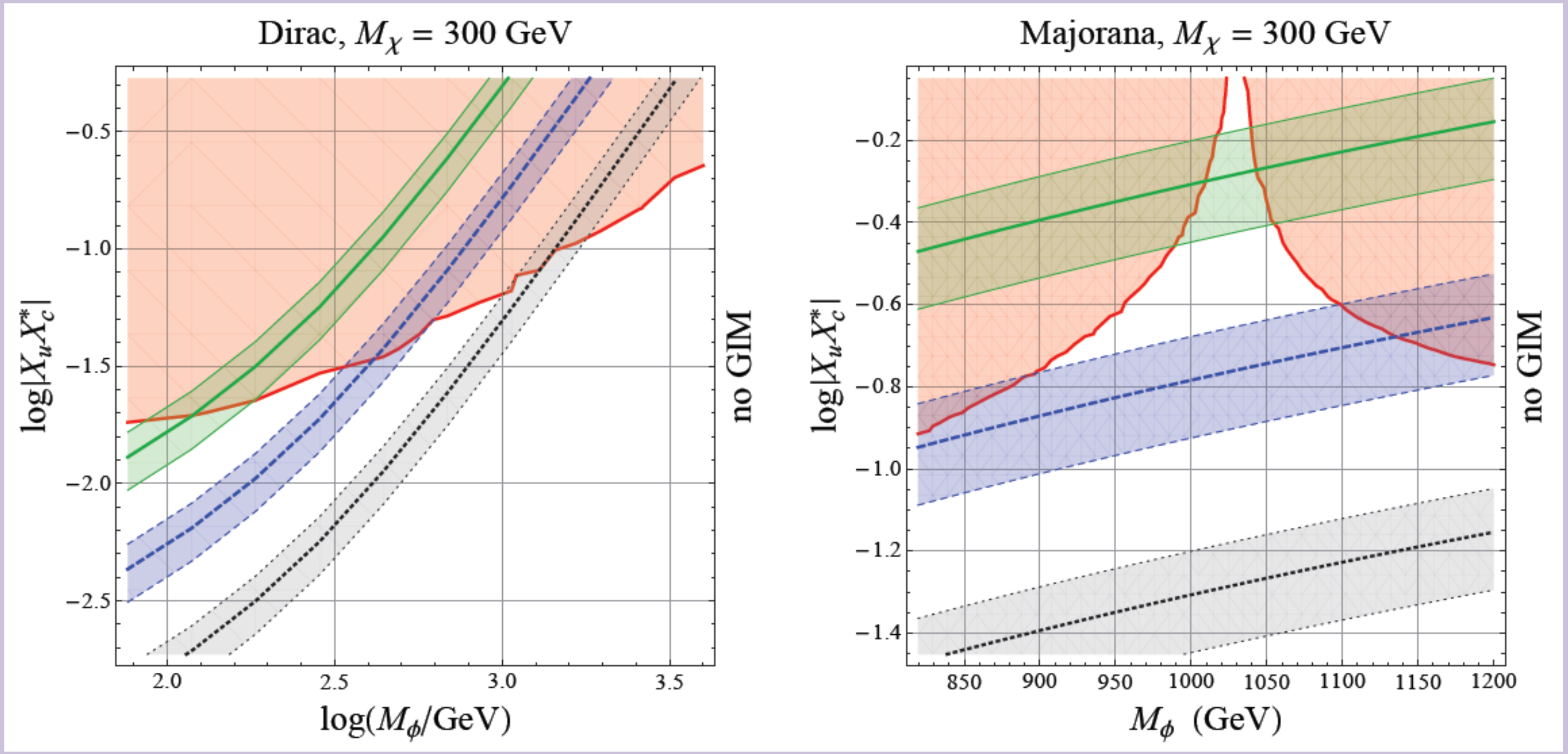
PRELIMINARY

Constraints – no GIM

Cancellation in D mixing constraint in Majorana case when $m_\phi \approx X\, m_\chi$

Have some viable areas of parameter space

Caveat: Have not included direct search constraints



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Black dotted = 10× enhancement; Red = excluded by D^0-D^0 mixing

PRELIMINARY

Loop level – scalar+fermion, with GIM

- Add one heavy fermion and two heavy colored scalar that only couple to RH up and charm quarks

$$\mathcal{L} = g_{\phi_u} \bar{u}_R \chi \phi_u + g_{\phi_c} \bar{c}_R \chi \phi_c \ + \ \text{h.c.}$$

- To have an efficient GIM mechanism, assume $g_{\phi_u} = g_{\phi_c} = g_\phi$ and $m^2_{\phi_u} = m^2_{\phi_c} = m^2_\phi$
- Write scalar mass matrix (in basis where quark masses are diagonal)

$$\hat{m}^2_\phi = \begin{pmatrix} m^2_{\phi_u} & m^2_{uc} \\ (m^2_{uc})^* & m^2_{\phi_c} \end{pmatrix}$$

PRELIMINARY

Loop level – scalar+fermion, with GIM

- Calculate Wilson coefficients

$$\tilde{C}_6^{(1)} = \frac{\alpha_s}{4\pi}\delta_{uc}\frac{g_\phi^2}{m_\phi^2}P(z) \, ,$$

$$\tilde{C}_3^{(1)} = \tilde{C}_5^{(1)} = -\frac{1}{N_c}\tilde{C}_4^{(1)} = -\frac{1}{N_c}\tilde{C}_6^{(1)} \, ,$$

$$\tilde{C}_{8g}^{(1)} = \delta_{uc}\frac{g_\phi^2}{m_\phi^2}G(z) \, .$$

$$\delta_{uc} = m_{uc}^2/m_\phi^2$$

$$z = m_\chi^2/m_\phi^2$$

- Also have one-loop contributions to ΔF=1 which induce contributions to D → K^+K^- and $\pi^+\pi^-$ decays from RGE running

$$\tilde{C}_4^{(1)} = \frac{1}{2}\tilde{C}_{10}^{(1)} = \frac{g_\phi^4}{16\pi^2}\frac{\delta_{cu}}{3m_\phi^2}B(z)$$

PRELIMINARY

Loop level – scalar+fermion, with GIM

- Also have one-loop contributions to ΔF=1 which induce contributions to $D \to K^+K^-$ and $\pi^+\pi^-$ decays from RGE running

- Dirac

$$\tilde{C}_4^{(1)} = \frac{1}{2}\tilde{C}_{10}^{(1)} = \frac{g_\phi^4}{16\pi^2}\frac{\delta_{cu}}{3m_\phi^2}B(z)$$

$$\tilde{C}_1^{(2)D} = \frac{\delta_{uc}^2}{16\pi^2}\frac{g_\phi^4}{m_\phi^2}\frac{1}{8}F(z)$$

- Majorana case

$$\tilde{C}_4^{(1)} = \frac{1}{2}\tilde{C}_{10}^{(1)} = \frac{g_\phi^4}{16\pi^2}\frac{\delta_{cu}}{3m_\phi^2}\left(B(z) + \frac{1}{2}\tilde{B}(z)\right)$$

$$\tilde{C}_1^{(2)D} = \frac{\delta_{uc}^2}{16\pi^2}\frac{g_\phi^4}{m_\phi^2}\left(\frac{1}{8}F(z) + \frac{1}{4}\tilde{F}(z)\right)$$

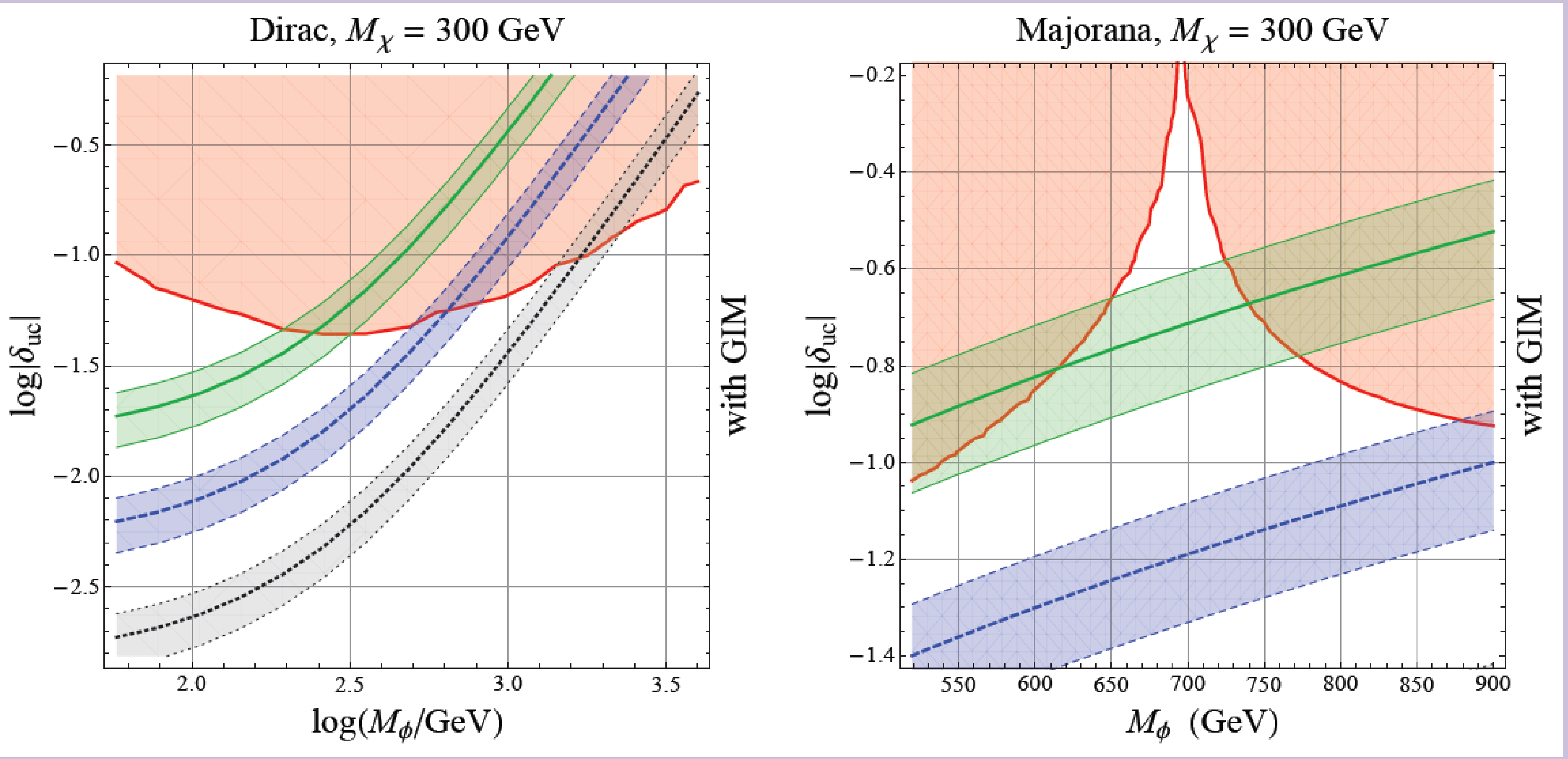
PRELIMINARY

Constraints – with GIM

Cancellation in D mixing constraint in Majorana case when $m_\phi \approx X\, m_\chi$

Also have some viable areas of parameter space

Caveat: Have not included direct search constraints



Green = 1× enhancement; Blue dashed = 3× enhancement

Black dotted = 10× enhancement; Red = excluded by D^0-D^0 mixing

PRELIMINARY

Conclusions

- Have a new result from LHCb that may be the first hint of New Physics
  - Could be a SM effect, large hadronic matrix element uncertainty
- Our work aims to isolate viable and reasonable areas of NP parameter space to focus for direct searches
  - Penguin models and 2HDM with MFV have easiest time accommodating the LHCb result
  - Follow up work will focus on phenomenology and propose new search strategies for these viable models