CP VIOLATION IN CHARM - NP OR SM?

Jure Zupan
U. of Cincinnati

based on J. Brod, A. Kagan, JZ,1111.5000
J. Brod, Y. Grossman, A. Kagan, JZ, 1202.nnnn
see also A. Kagan, talk at FPCP11, May 2011

"Top physics and electroweak symmetry breaking in the LHC era"
workshop, Seoul, Korea Feb 25 2012

OUTLINE

- the topic of the talk

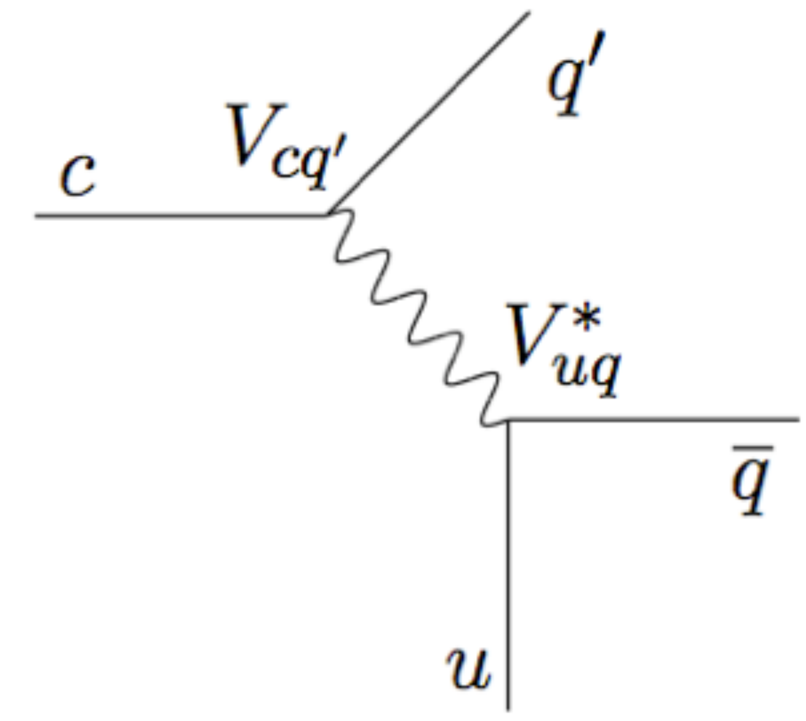
$$\Delta A_{CP} = A_{CP}(D \to K^+K^-) - A_{CP}(D \to \pi^+\pi^-)$$

  - experiment (WA): $\Delta A_{CP} = (-0.65 \pm 0.18)\%$
- could it be New Physics?
- could it be Standard Model?
- could we have anticipated such a large value?
  - how large is the SU(3) breaking in charm?

PRELIMINARIES

SETTING UP THE STAGE

- three classes of *D* decays
  - Cabibbo allowed
    - example: $D^0 \to K^- \pi^+$
      $A_T \sim V_{cs} V_{ud} \sim 1$
  - singly Cabibbo suppressed (SCS)
    - example: $D^0 \to K^- K^+$, $D^0 \to \pi^- \pi^+$
      $A_T \sim V_{cd} V_{ud}, V_{cs} V_{us} \sim \lambda$
  - doubly Cabibbo suppressed
    - example: $D^0 \to \pi^- K^+$
      $A_T \sim V_{cd} V_{us} \sim \lambda^2$



DIRECT CPV

- focus on SCS D decays in the SM

$$A_f(D \to f) = A_f^T[1 + r_f e^{i(\delta_f - \gamma)}],$$
$$\overline{A}_{\bar{f}}(\bar{D} \to \bar{f}) = A_f^T[1 + r_f e^{i(\delta_f + \gamma)}],$$

- A_f^T - tree ampl., r_f - relative “penguin” contrib., δ_f - strong phase
- direct CP asymmetry

$$\mathcal{A}_f^{\rm dir} \equiv \frac{|A_f|^2 - |\bar{A}_{\bar{f}}|^2}{|A_f|^2 + |\bar{A}_{\bar{f}}|^2} = 2 r_f \sin\gamma \sin\delta_f$$

  - sinγ~0.9, so for δ_f~$O(1)$

$$\mathcal{A}_f^{\rm dir} \sim 2 r_f$$

CP VIOLATION IN CHARM

- in charm physics the first 2 gen. dominate
  - $\Rightarrow$ CP conserving to a good approximation in the SM
- CPV is parametrically suppressed
  - in mixing it enters as $\mathcal{O}\big(V_{cb}V_{ub}/V_{cs}V_{us}\big) \sim 10^{-3}$
  - direct CPV in SCS as $\mathcal{O}([V_{cb}V_{ub}/V_{cs}V_{us}]\alpha_s/\pi) \sim 10^{-4}$
- is it possible that it is significantly larger?

Size of P/T needed

- global exp. avers.

$$\mathcal{A}_{K^+K^-} = (-0.23 \pm 0.17)\% \quad \mathcal{A}_{\pi^+\pi^-} = (0.20 \pm 0.22)\%$$

- agree with expect. that A_{KK} and $A_{\pi\pi}$ add up in ΔA_{CP}
  - for O(1) strong phases then

$$\Delta\mathcal{A}_{CP} \sim 4r_f$$

- from experiment thus required

$$r_f \sim 0.15\%$$

- naive estimate

$$r_f \sim \mathcal{O}([V_{cb}V_{ub}/V_{cs}V_{us}]\alpha_s/\pi) \sim 0.01\%$$

- an order of magnitude enhancement over naive estimate required

COULD IT BE NEW PHYSICS?

NEW PHYSICS?

- could it be NP?
- reasonable models of NP can do it
  - model independent NP ops. analysis

    Isidori, Kamenik, Ligeti, Perez, 1111.4987
  - supersymmetric examples

    Grossman, Kagan, Nir, hep-ph/0609178
    Giudice, Isidori, Paradisi, 1201.6204
  - tree level exchanges

    Hochberg, Nir, 1112.5268
    Altmannshofer, Primulando, Yu, Yu, 1202.2866

SUSY?

- SUSY contribs. to QCD penguin particularly interesting

  Grossman, Kagan, Nir, hep-ph/0609178

  - LR mixing in squark matrices

$$Q_8 = \frac{m_c}{4\pi^2}\bar{u}_L \sigma_{\mu\nu} T^a g_s G_a^{\mu\nu} c_R$$

$$\frac{m_c}{m_W^2} \to \frac{v}{\tilde{m}^2}$$

$$Q_8 = \frac{1}{4\pi^2}(\bar{Q}_L H)\sigma_{\mu\nu} T^a g_s G_a^{\mu\nu} c_R$$

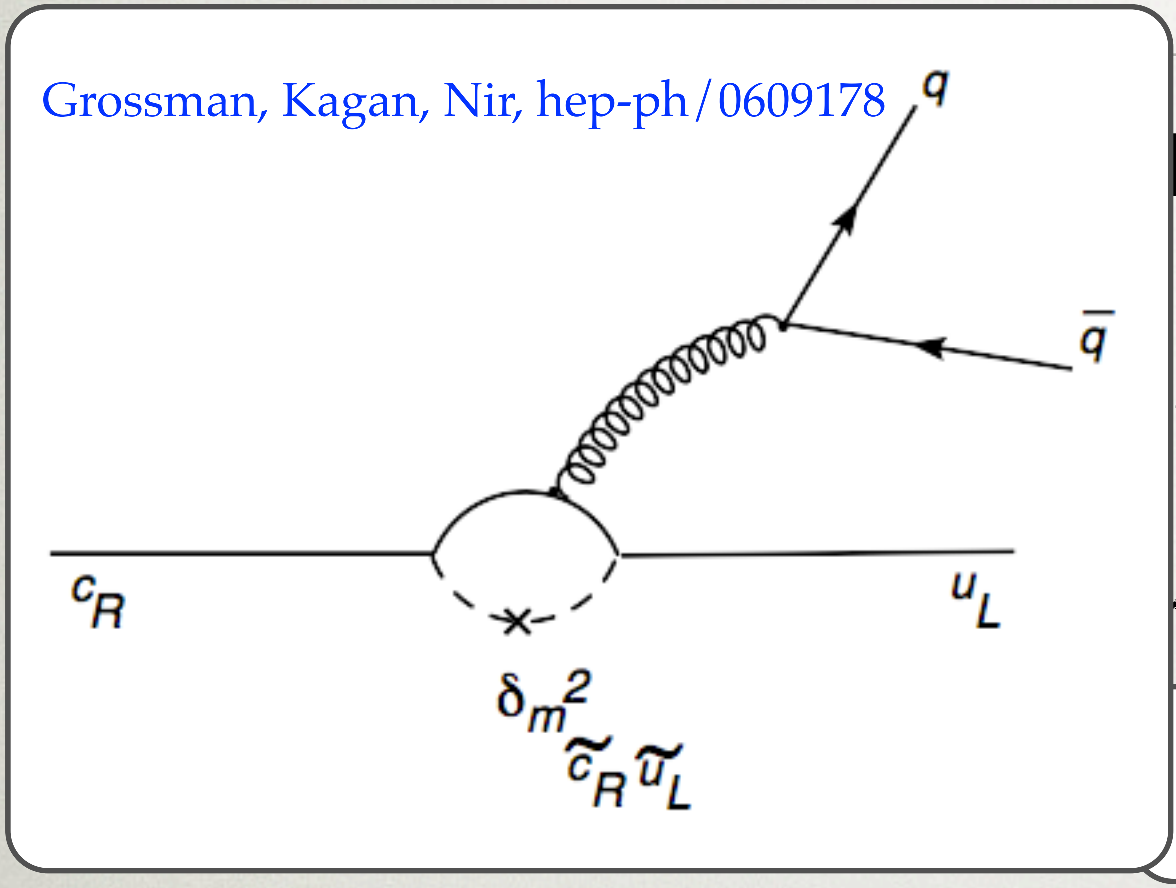
  - for $v \sim m_{susy}$ the op. Q_8 is secretly dim=5

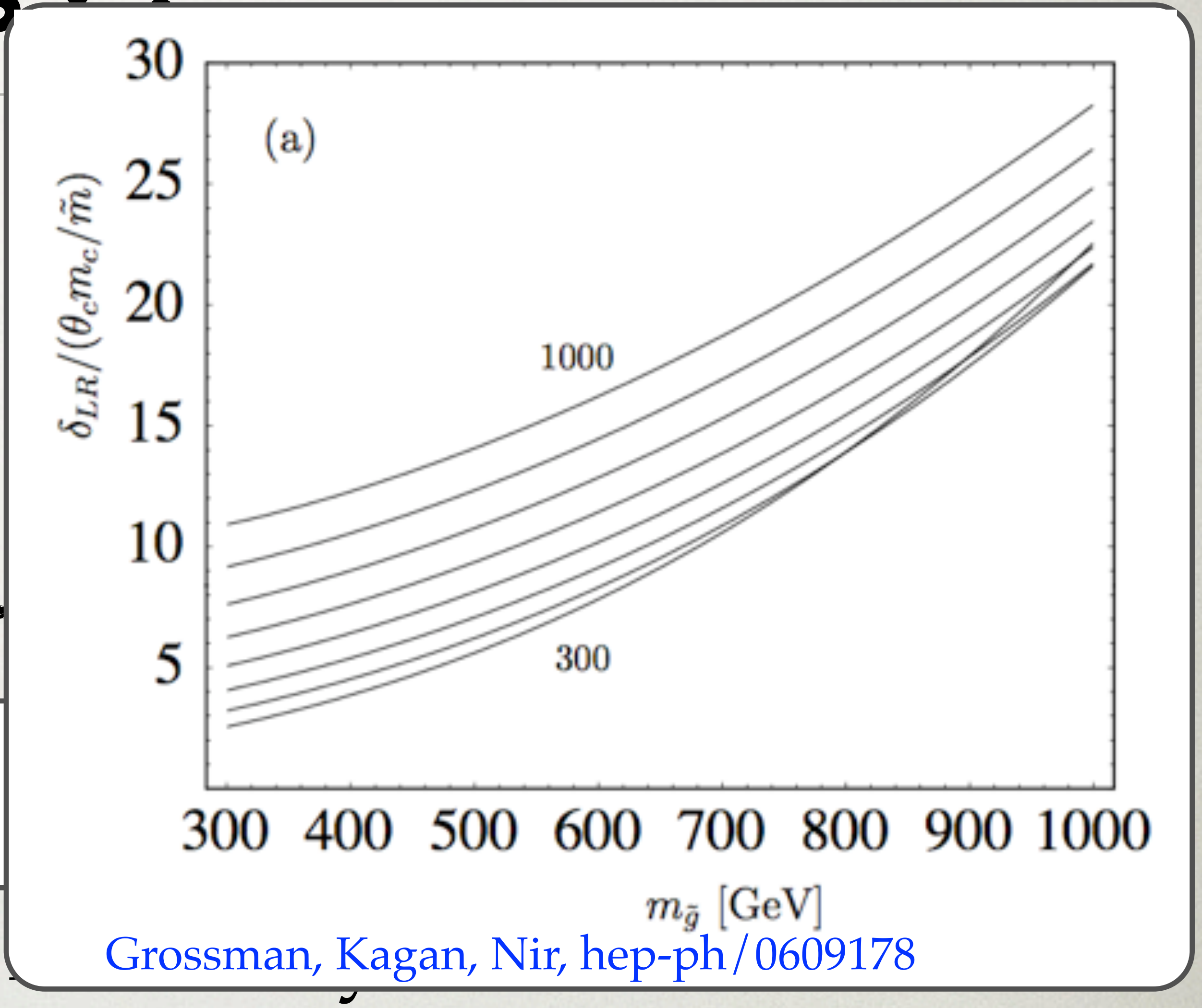
- *D-Dbar* mixing operators are dim=6

$$Q_2^{cu} = \bar{u}_R^\alpha c_L^\alpha \bar{u}_R^\beta c_L^\beta$$

  - SUSY contributions are parametrically smaller

SUSY?





D

k

Q

- for $v \sim m_{susy}$ the op. Q_8

- *D-Dbar* mixing operators are dim=6

$$Q_2^{cu} = \bar{u}_R^\alpha c_L^\alpha \bar{u}_R^\beta c_L^\beta$$

- SUSY contributions are parametrically smaller

SUSY

- Giudice et al. identify two viable scenarios

Giudice, Isidori, Paradisi, 1201.6204

- disoriented *A* terms

$$(\delta^q_{ij})_{LR} \sim \frac{A\theta^q_{ij} m_{q_j}}{\tilde{m}} \qquad q = u, d \ ,$$

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

  - FV only in trilinears

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

- split families

$$(\delta^u_{12})^{\text{eff}}_{RL} = (\delta^u_{13})_{RR}\,(\delta^u_{33})_{RL}\,(\delta^u_{32})_{LL} \ , \qquad (\delta^u_{12})^{\text{eff}}_{LR} = (\delta^u_{13})_{LL}\,(\delta^u_{33})_{RL}\,(\delta^u_{32})_{RR}$$

OTHER EXAMPLES

- SUSY: typically some tuning needed for EDMs
- other examples for Q_8 oper.

  Giudice, Isidori, Paradisi, 1201.6204

  - FCNC in Z, higgs Q_8 at 1-loop
  - same EDM challenge as SUSY
- tree level exchanges

  Altmannshofer, Primulando, Yu, Yu, 1202.2866

  - if vectors (Z, Z′, G′) safest if FV in coupl. to u_R,c_R
    - typically still problems with *D-Dbar* mixing
  - scalars - two viable examples
    - 2HDM with MFV (but very large $tan\beta$)
      - gives only $A_{CP}(K^+K^-)$
    - scalar doublet that can simultaneously explain A_{FB}^{tt}

      Hochberg, Nir, 1112.5268

NEW PHYSICS UPSHOT

- it can be new physics
- but does it have to be?

COULD IT BE STANDARD MODEL?

A REMINDER

- for O(1) strong phases

$$\Delta\mathcal{A}_{CP} \sim 4 r_f$$

- size of P/T needed

$$r_f \sim 0.15\%$$

- naive estimate

$$r_f \sim \mathcal{O}([V_{cb}V_{ub}/V_{cs}V_{us}]\alpha_s/\pi) \sim 0.01\%$$

- an order of magnitude enhancement over naive estimate required

THE STRATEGY

Brod, Kagan, JZ, 1111.5000

- is enhancement of r_f in the SM possible?
- the strategy:
  - tree amplitudes from data
  - relate penguin amplitudes to tree amplitudes
  - try to estimate the ambiguity in doing this

QCD PENGUINS AT LEADING POWER

- as a start evaluate leading power penguin ampls. in QCDfact.
  - naive fact.+ $O(\alpha_S)$ corrections
  - only a rough estimate of true value
- penguin to tree ratio

$$r^{\mathrm{LP}} \equiv \left| \frac{A^P(\text{leading power})}{A^T(\text{exp})} \right|$$

$$r^{\mathrm{LP}}_{K^+K^-} \approx (0.01 - 0.02)\,\%, \quad r^{\mathrm{LP}}_{\pi^+\pi^-} \approx (0.015 - 0.03)\%$$

- assume O(1) phases, then $\Delta A_{CP} \sim 4 r_f$

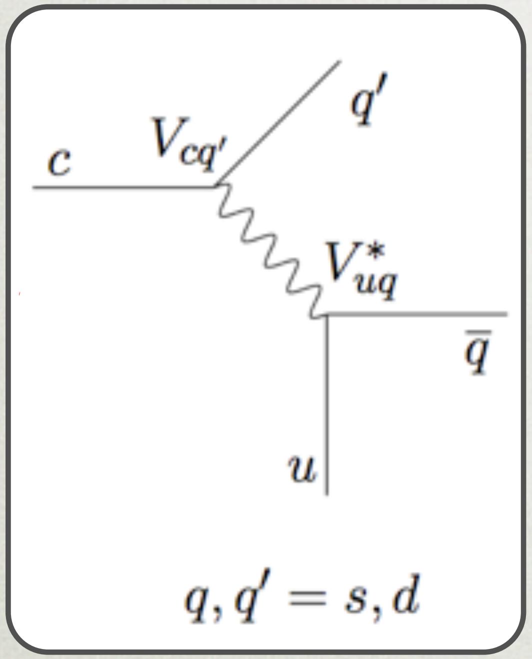
$$\Delta A_{CP}(\text{leading power}) = O(0.05\% - 0.1\%)$$

- order of magnitude below the measurement

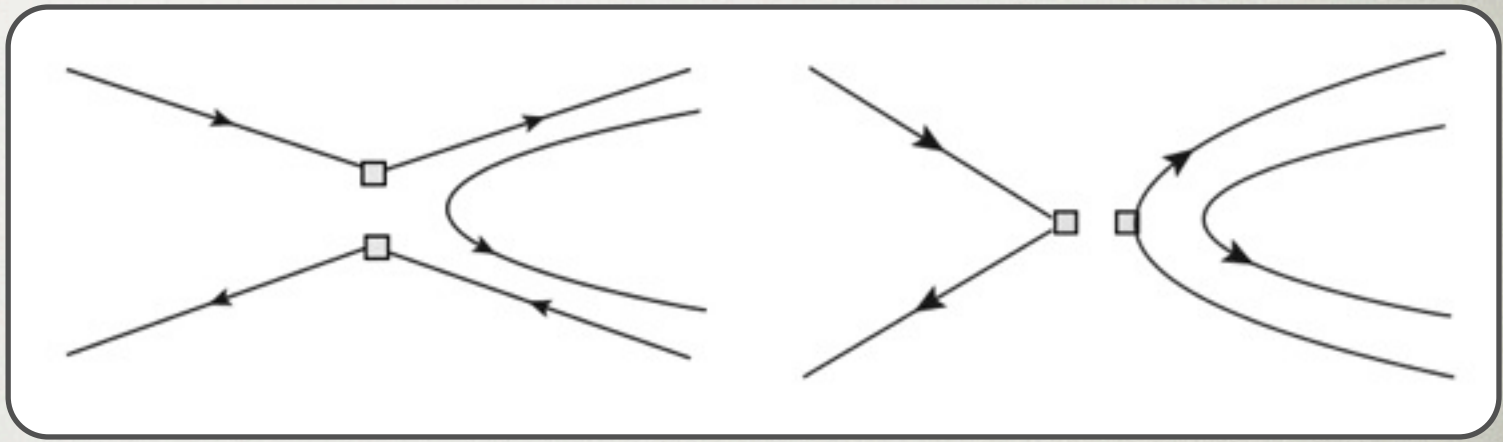
POWER CORRECTIONS

- from SU(3)$_F$ fits to branching ratios we learn:
  - $T_f = A_f[(1/m_c)^0] \sim E_f = A_f[(1/m_c)^1]$

Cheng, Chiang, 1001.0987, 1201.0785
Bhattacharya, Gronau, Rosner, 1201.2351
Pirtskhalava, Uttayarat, 1112.5451



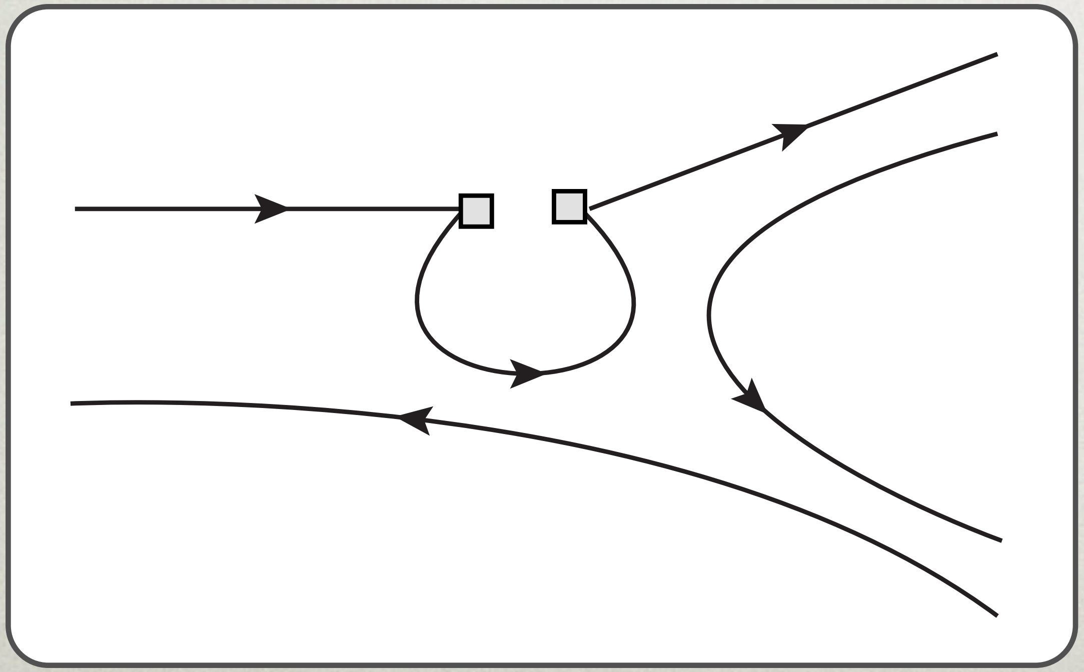
~

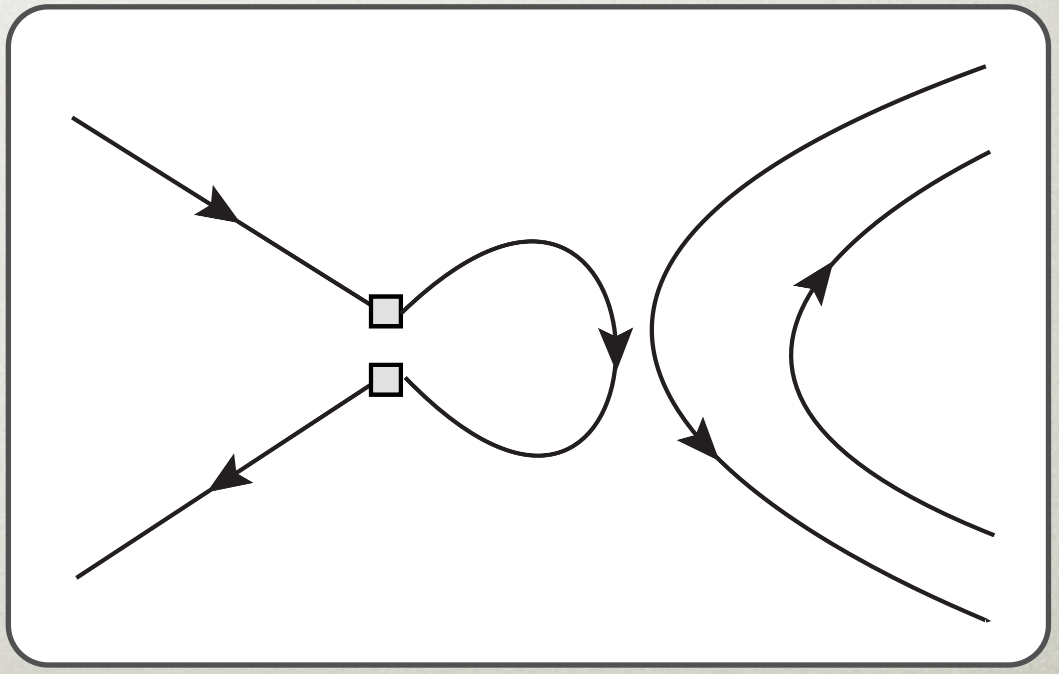


  - $1/m_c$ expansion broken
- will still use N_c counting
- look at two particular $1/m_c$ contribs.

PENGUIN CONTRACTIONS

- penguin contractions of tree op. Q_1
- in partonic picture: $P_{f,1}$ ($P_{f,2}$) ⇔ single gluon exchange between *d,s* loop and spectator ($q\bar{q}$ pair)
- any number of gluons between external legs





ESTIMATING PENGUIN POWER CORRECTIONS

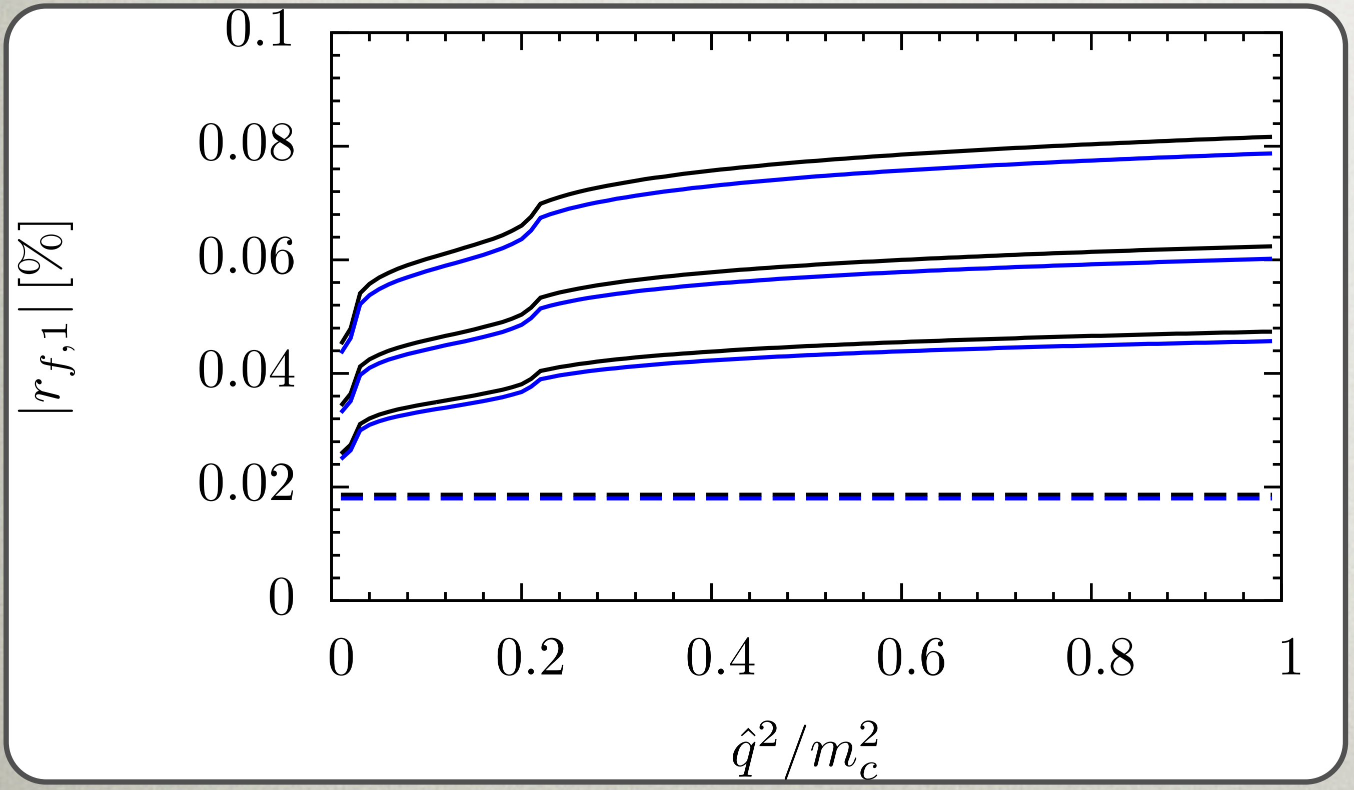
- can define effective Wilson coefficient that depends on gluon's virtuality

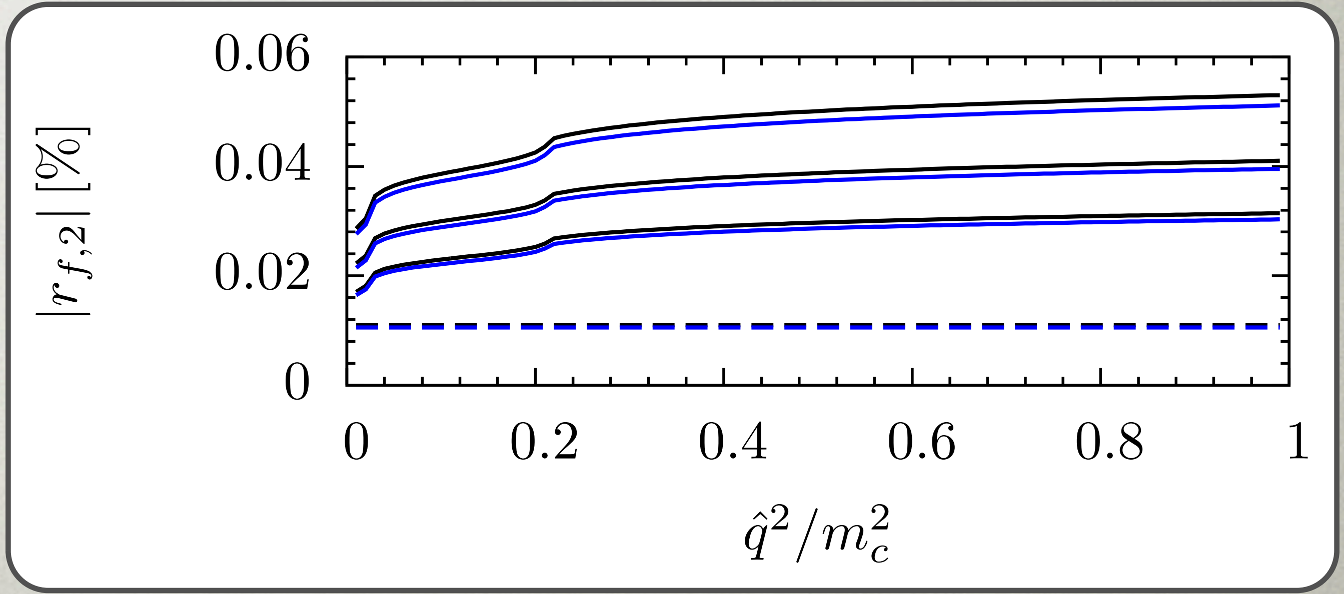
$$C^{\text{eff}}_{6\,(4)}\left(\mu, \frac{q^2}{m_c^2}\right) = C_{6\,(4)}(\mu) + C_1(\mu)\frac{\alpha_s(\mu)}{2\pi}\left(\frac{1}{6} + \frac{1}{3}\log\left(\frac{m_c}{\mu}\right) - \frac{1}{8}G\left[\frac{m_s^2}{m_c^2}, \frac{m_d^2}{m_c^2}, \frac{q^2}{m_c^2}\right]\right)$$

- can roughly estimate penguin contraction contribs. through approximations
  - partonic *G* func. as estimator of hadronic effects, FSI, etc...
  - evaluate *G* func. at particular q^2 (and vary it)
- the related E_f hadronic matrix element from tree level $1/m_c$ amplitude (from data on *Br*)

ORDER OF MAGNITUDE ESTIMATE FOR P/T

- the estimate for $r_{f,1}$, $r_{f,2}$ depends on q^2
  - vary it in $[0,m_c^2]$, choose $m_s=0.3$, $m_d=0.1$
  - $\mu=1$ GeV, m_c, m_D, top-to-bottom
  - dashed curve $G=0$, shows relative importance of penguin contraction contributions





SUMMARY OF SM CONTRIBS.

- individual power corrections could be enhanced by a factor of a few compared to leading power
- using ΔA_{CP}~$4r_f$ and μ=1GeV we obtain

$$\Delta A_{CP} \sim 0.3\% \ \ (P_{f,1}), \quad \Delta A_{CP} \sim 0.2\% \ \ (P_{f,2})$$

- the results are subject to large uncertainties
    - extraction of tree amplitude E_f from data
    - use of N_c counting
    - the modeling of Q_1 penguin contraction matrix elemnts.
- a cumulative uncertainty of a factor of a few is reasonable
- a SM origin for the LHCb measurement is possible

FURTHER INDICATION IN FAVOR OF SM

J. Brod, Y. Grossman, A. Kagan, JZ, 1202.nnnn

- long standing puzzle
  - $Br(D \to K^+K^-) = 2.8\ Br(D \to \pi^+\pi^-)$
  - should be the same in flavor SU(3) limit
- with large SM penguin a consistent picture
  - Br's changed by $P_{break} = \varepsilon_{SU(3)} P \sim T$
  - the fit to four Br confirms $P_{break} \sim T$
- using $P \sim P_{break}/\varepsilon$ one predicts (for $\varepsilon = 0.3$)

$$r_f = \frac{|V_{cb}V_{ub}|}{|V_{cs}V_{us}|}\frac{P}{T} \sim \frac{|V_{cb}V_{ub}|}{|V_{cs}V_{us}|}\frac{1}{\epsilon} \sim 0.2\%$$

  - exactly the required size for ΔA_{CP}

FURTHER INDICATION IN FAVOR OF SM

$$H_{\rm eff}^{\Delta C=1} = \frac{G_F}{\sqrt{2}}\Big(V_{cs}^* V_{us} \sum_{i=1,2} C_i \left(Q_i^s - Q_i^d\right) - V_{cb}^* V_{ub} \Big[\sum_{i=1,2} C_i \left(Q_i^d - Q_i^s\right)/2$$

$$+ \sum_{i=1,2} C_i \left(Q_i^s + Q_i^d\right)/2 + \sum_{i=3}^{6} C_i Q_i + C_{8g} Q_{8g} \Big]\Big) + \text{h.c.},$$

202.nnnn

P_{break}

$$T_{KK} = T_{KK}^s + P_{KK}^{T,s} - P_{KK}^{T,d},$$

$$T_{\pi\pi} = -T_{\pi\pi}^d + P_{\pi\pi}^{T,s} - P_{\pi\pi}^{T,d},$$

- with large SM penguin a
  - *Br*'s cha ... y P_{break}=
  - the fit to four *Br* confi

P

$$A_f^P = -V_{cb}^* V_{ub}\left(P_f + [P_f^{T,s} + P_f^{T,d}]/2 + [P_f^{E,s} + P_f^{E,d}]/2\right)$$

$$r_f = \frac{|V_{cb} V_{ub}|}{|V_{cs} V_{us}|}\frac{P}{T} \sim \frac{|V_{cb} V_{ub}|}{|V_{cs} V_{us}|}\frac{1}{\epsilon} \sim 0.2\%$$

  - exactly the required size for ΔA_{CP}

FURTHER INDICATION IN FAVOR OF SM

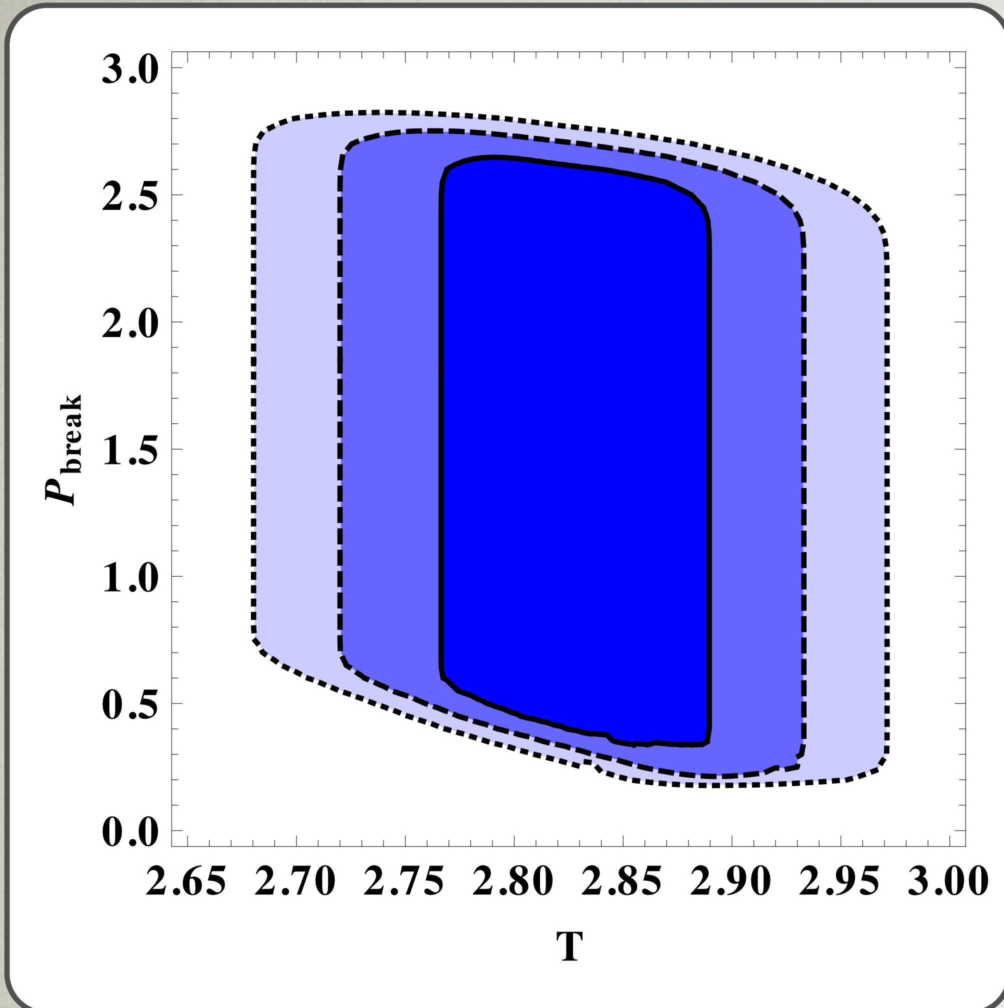
- long standing puzzle

J. Brod, Y. Grossman, A. Kagan, JZ, 1202.nnnn

  - $Br(D \to K^+K^-) = 2.8\, Br(D \to \pi^+\pi^-)$
  - should be the same in flavor SU(3) limit
- with large SM penguin a consistent picture
  - Br's changed by $P_{break} = \varepsilon_{SU(3)} P \sim T$
  - the fit to four Br confirms $P_{break} \sim T$
- using $P \sim P_{break}/\varepsilon$ one predicts (for $\varepsilon = 0.3$)

$$r_f = \frac{|V_{cb}V_{ub}|}{|V_{cs}V_{us}|}\frac{P}{T} \sim \frac{|V_{cb}V_{ub}|}{|V_{cs}V_{us}|}\frac{1}{\epsilon} \sim 0.2\%$$

  - exactly the required size for ΔA_{CP}



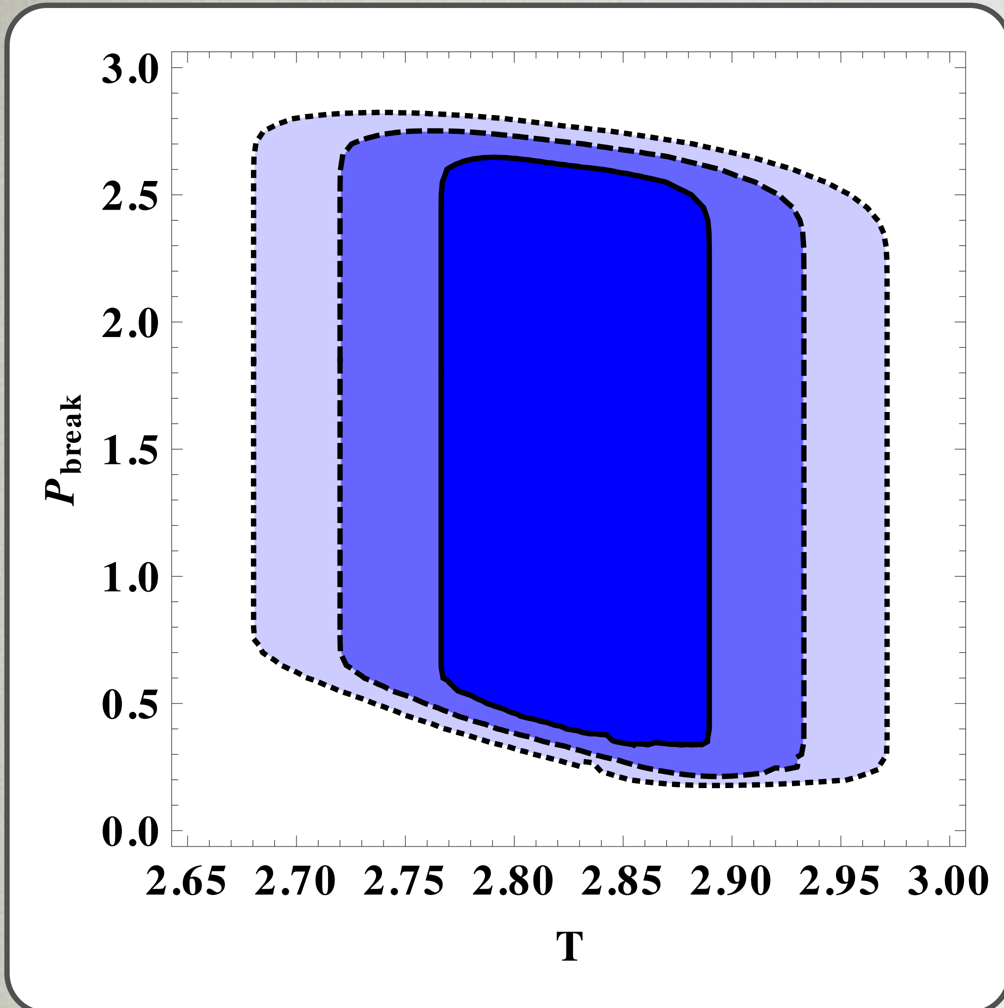
R INDICATION IN
VOR OF SM

J. Brod, Y. Grossman, A. Kagan, JZ, 1202.nnnn

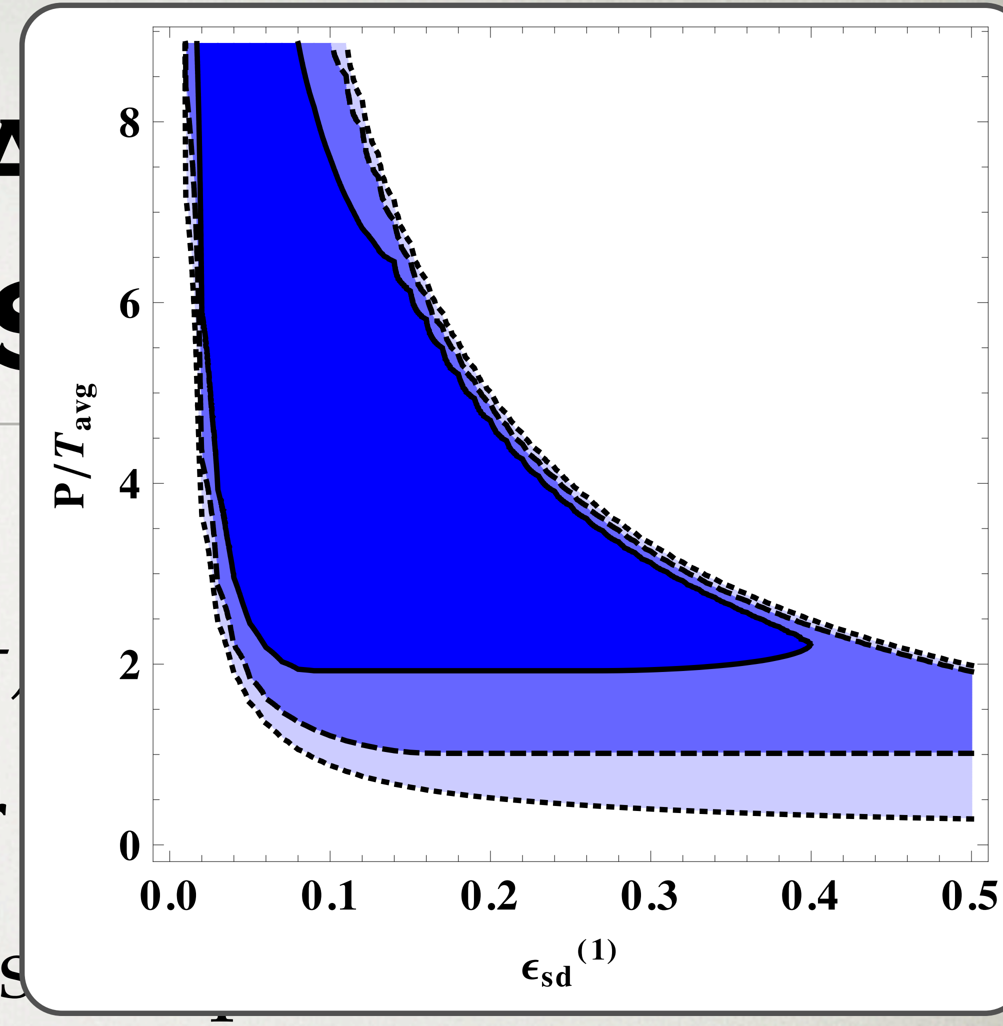
- puzzle
- $=2.8\ Br(D \to \pi^+\pi^-)$
- e same in flavor SU(3) limit
- penguin a consistent picture
  - Br's changed by $P_{break}=\varepsilon_{SU(3)}P \sim T$
  - the fit to four Br confirms $P_{break} \sim T$
- using $P \sim P_{break}/\varepsilon$ one predicts (for $\varepsilon=0.3$)

$$r_f = \frac{|V_{cb}V_{ub}|}{|V_{cs}V_{us}|}\frac{P}{T} \sim \frac{|V_{cb}V_{ub}|}{|V_{cs}V_{us}|}\frac{1}{\epsilon} \sim 0.2\%$$

  - exactly the required size for ΔA_{CP}



R INDICA
VOR OF S



puzzle

$=2.8\ Br(D\to\pi^+\pi^-)$

e same in flavor

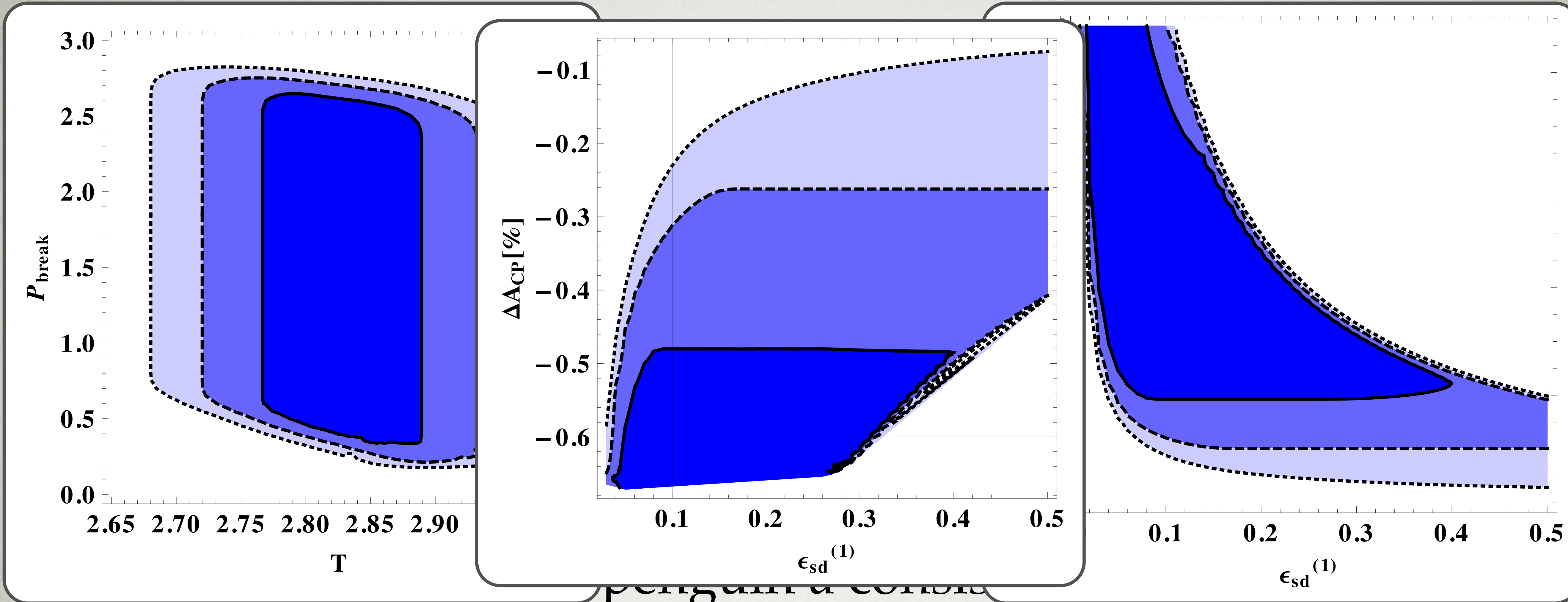
penguin a consis

- *Br*'s changed by $P_{break}=\varepsilon_{SU(3)}P\sim T$
- the fit to four *Br* confirms $P_{break}\sim T$

- using $P\sim P_{break}/\varepsilon$ one predicts (for $\varepsilon=0.3$)

$$r_f=\frac{|V_{cb}V_{ub}|}{|V_{cs}V_{us}|}\frac{P}{T}\sim\frac{|V_{cb}V_{ub}|}{|V_{cs}V_{us}|}\frac{1}{\epsilon}\sim 0.2\%$$

- exactly the required size for ΔA_{CP}



- Br's changed by $P_{break} = \varepsilon_{SU(3)} P \sim T$
- the fit to four Br confirms $P_{break} \sim T$

- using $P \sim P_{break}/\varepsilon$ one predicts (for $\varepsilon = 0.3$)

$$r_f = \frac{|V_{cb}V_{ub}|}{|V_{cs}V_{us}|}\frac{P}{T} \sim \frac{|V_{cb}V_{ub}|}{|V_{cs}V_{us}|}\frac{1}{\epsilon} \sim 0.2\%$$

- exactly the required size for ΔA_{CP}

NP or SM?

- how to distinguish between the two?
- by building NP models
  - search for other signatures (collider or otherwise)
- also using just charm data
  - for a subset of NP models
    - if they lead to $\Delta I=3/2$ operators
    - example: scalar doublet model of Hochberg, Nir
    - possible to write isospin sum rules that would be violated if NP
    - an example: $A_{CP}(D^+\to\pi^+\pi^0)\neq 0$

CONCLUSIONS

- ΔA_{CP} could be due to NP or SM
  - showed additional indications from *Br* that enhanced SM penguin
- to test NP interpretation
  - through models and direct searches
  - isospin sum rules in charm decays

BACKUP SLIDES