Charming CP & more

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PCPV 2013, Mahabaleshwar, India

Based primarily on Feldman, Nandi, AS, 1202.3795;
Atwood & AS, 1211.1026

MOST IMPORTANT

A NEW FRONTIER FOR TESTING OUR UNDERSTANDING OF CP HAS BEEN OPENED!

THANKS TO LHCb!

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

arXiv. 1112.0938

Experimental status

- **LHCb, CDF, BELLE all have joined in by now.**
- **HFAG: ΔA_{CP} = -0.678 +- 0.147%**
- **In particular Belle gave separate #s for KK and $\pi\pi$ though for now only about 1.5σ significance.**

But SuperKEK B should be able to provide much better numbers a few years from now.

- **Rumours float of LHCb improved results soon**

Outline

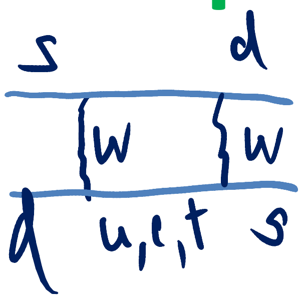
- Intro: D-system is unique: interesting sensitivity to top "compositeness"; BSM connection
- Recapitulate: Brands of CP; K,B CP & UT status
- SM confronts observed charm CP → [F.N.S]
- D-mixing & CP therein: update
- FS with possibly enhanced CP
- CPT constraints
- Possibly "acid" test for SM or NP

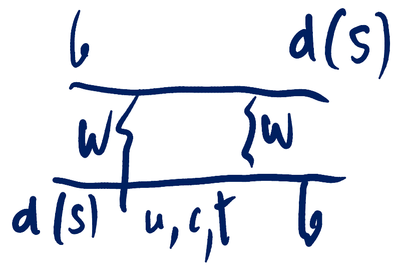
} [A.S]

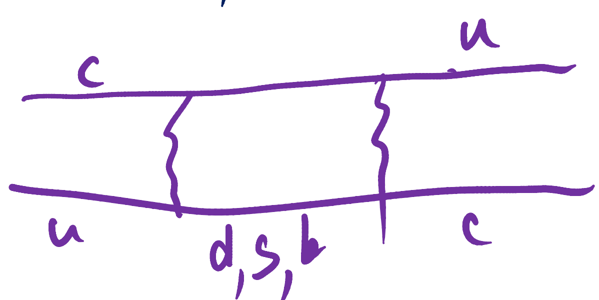
- Summary & Outlook

Charm system is unique

- **Sensitive to top physics, example: warp space theory of flavor, "4G"**



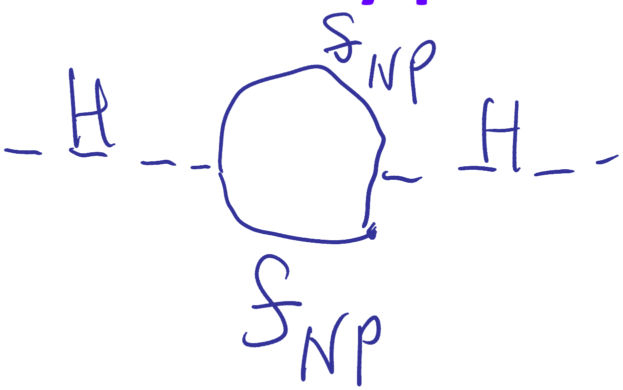




Delta F=2 mixings are an extremely valuable treasure in providing stringent constraints ....

Outstanding Th.puzzles of our times

- **Hierarchy puzzle**

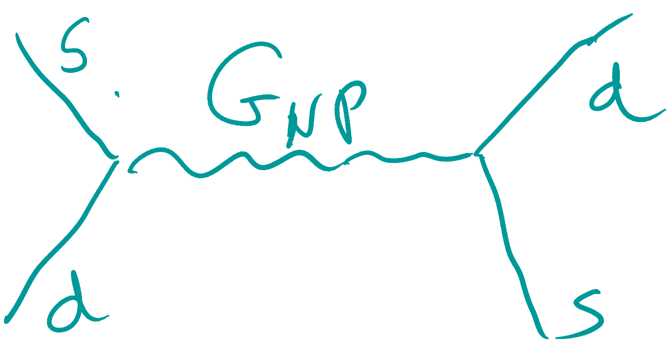


$$\sim \frac{g_{NP}^2}{16\pi^2}\Lambda_{NP}^2 \Rightarrow \Lambda_{NP} \lesssim \text{TeV}$$

to avoid fine tuning m_H

- **Flavor puzzle**

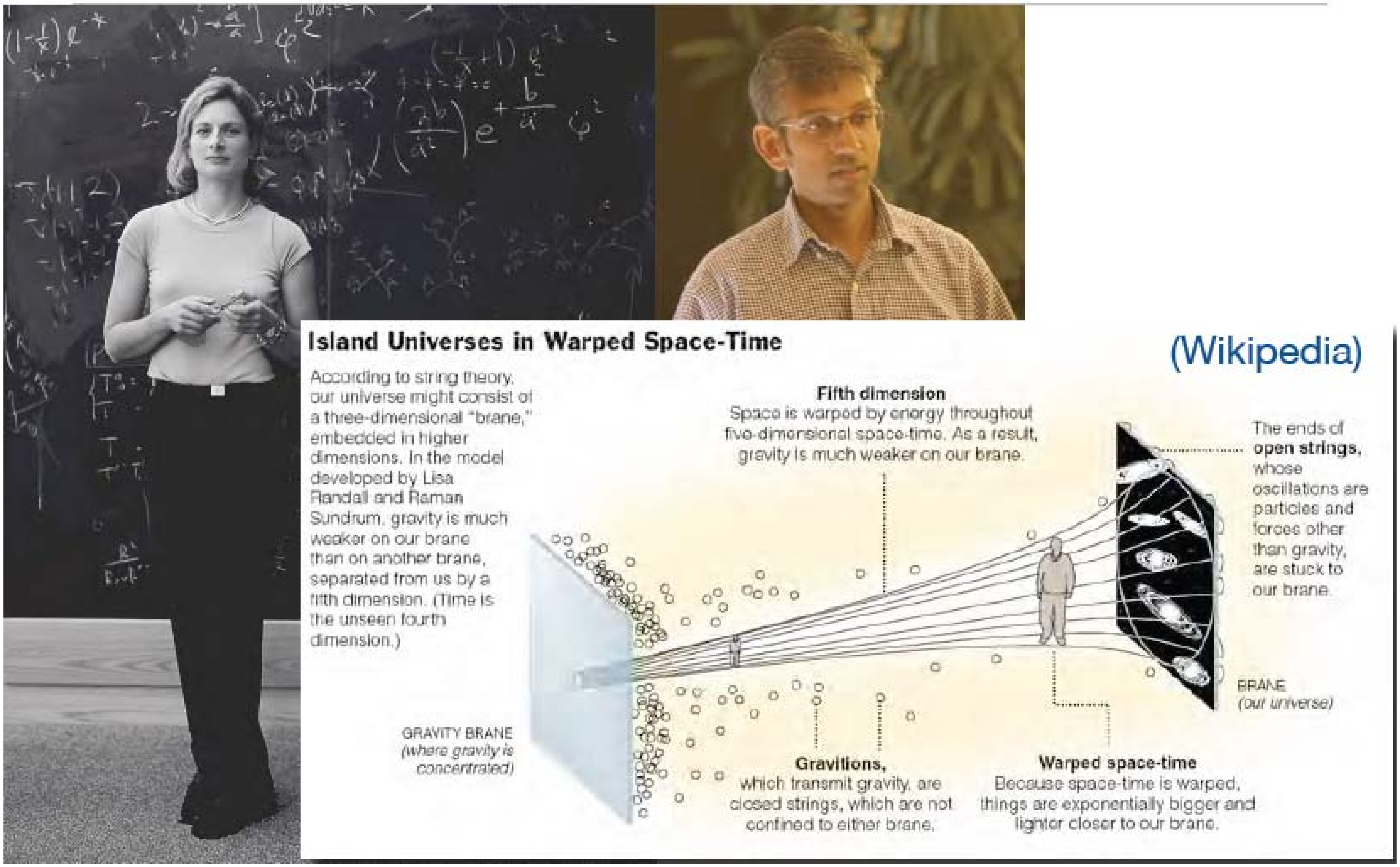
Δ flavor = 2 e.g.



$$\sim \frac{g_{NP}^2}{\Lambda_{NP}^2} \Rightarrow \Lambda_{NP} \gtrsim 10^3 \text{ TeV}$$

to avoid constraint from Δm_K

The Randall-Sundrum (RS) idea

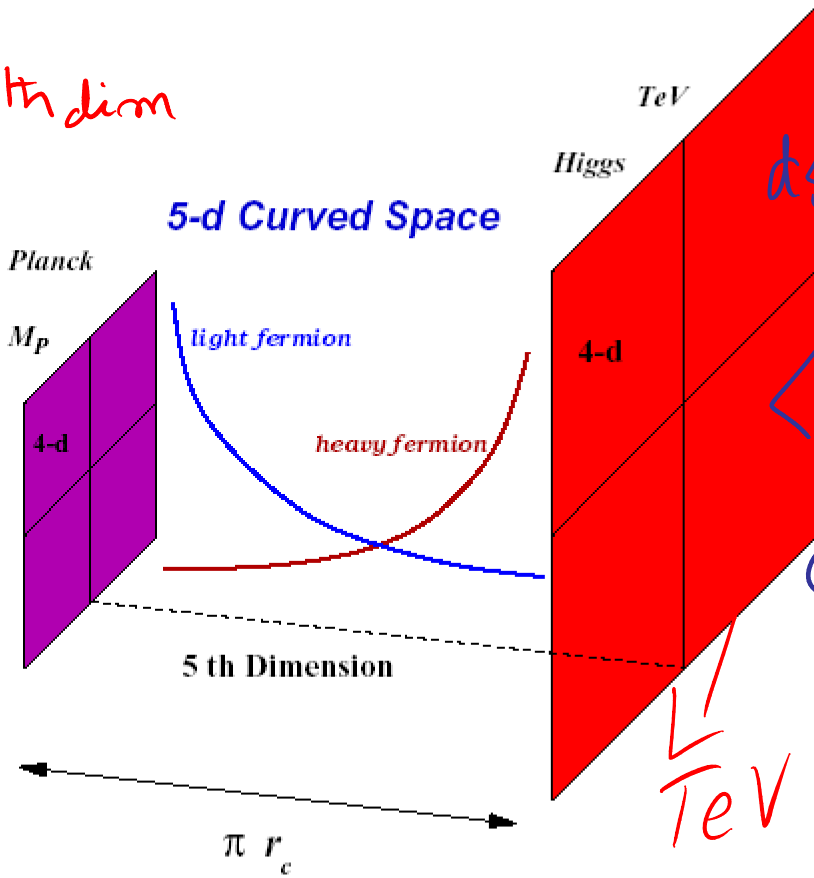


[Stolen from Neubert]

RANDALL+SUNDRUM '99

[FIG BY H DAVOUDIASL]

Points along 5th dim correspond to diff. eff. 4d scale!



$ds^2 = e^{-2\sigma}\eta_{\mu\nu}dx^\mu dx^\nu - r_c^2\, d\phi^2$

$\langle H_4 \rangle = e^{-\sigma}\langle H_5 \rangle$ → M_P ; TeV

$\sigma = k r_c \pi$, $k r_c \sim 12$

Figure 1: Warped geometry with flavor from fermion localization. The Higgs field resides on the TeV-brane. The size of the extra dimension is $\pi r_c \sim M_P^{-1}$.

Simultaneous resolution to hierarchy and flavor puzzles

Fermion "geography" (localization) naturally explains:

Grossman&Neubert; Gherghetta&Pomarol; Davoudiasl, Hewett & Rizzo

- **Why they are light (or heavy)**
- **FCNC for light quarks are severely suppressed automatically**
- **RS-GIM MECHANISM (Agashe, Perez,AS'04) flavor changing transitions though at the *tree level* (resulting from rotation from interaction to mass basis)are suppressed roughly to the same level as the loop in SM=> CKM hierarchy**
- **O(1) CP ubiquitous;…..in fact for neutron a (mild) CP problem**
- **Most flavor violations are driven by the top**

-> ENHANCED t-> cZ, (alsoD^0 mixing w & w/o CP)….A VERY IMPORTANT "GENERIC" PREDICTION..Agashe, Perez, AS'06

Δm_K : 10^3 TeV $\Longrightarrow$ $\sim$ 10 TeV

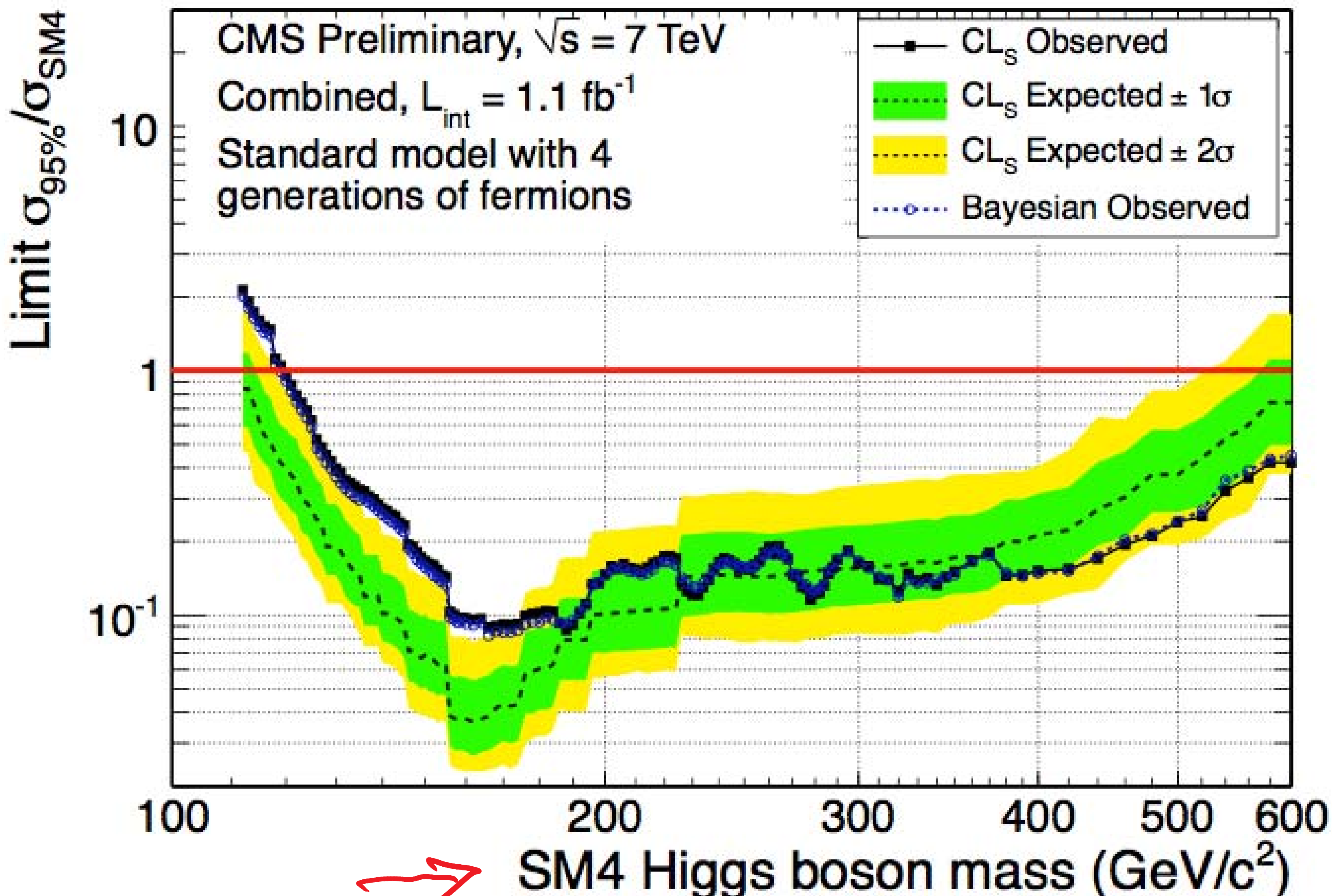
EXTENSIVE RECENT STUDIES by BURAS et al and NEUBERT et al

These theories are supposed to be dual to strong dynamics …The prospects for that get enhanced due heavy quarks via large yukawas if there is a "4th Generation"… Highly intutive picture

Cannot be simple SM4

- **Even if a 4th generation exists it is unlikely to be a simple replica of SM3: Highly implausible that heavy quarks will not be used for DEWSB**
- **Neutrino mass provides a strong clue**
- **DM possibility and baryogenesis both strongly suggest 4G not in SM4…Baryogenesis also needs 2HDM as single Higgs doublet phase transition not strong enough [see e.g. Dine & Kusenko]**
- **[not surprising] Simple SM4 light higgs now strongly disfavored by data**

The Higgs: 4th Generation?



Significant advantages of "4G"

- **I. Baryogenesis : Jarlskog prefactor changes by**

~ 15 orders of magnitude [Hou; Branco et al;Jarskog]

- **II. DEWSB with 4G2HDM {see Geller, Bar-Shalom,AS, arXiv:1302.2915} , simple possible solution to Planck-EW hierarchy**
- **4G2HDM, 125GeV SM-like Higgs, charged and ps 200-300 GeV; Heavier neutral Higgs over 500 GeV**

Thus, using $m_{q'} = v_h g_{q'}(\mu = m_{q'})/\sqrt{2}$, we can obtain the cutoff Λ as a function of $m_{q'}$ and t_β:

Soln to RG eqs

Geller,Bar-Shalom,AS
arXiv:1302.2915

$$\Lambda \approx m_{q'} \cdot exp\left(\frac{2\pi^2 (s_\beta v)^2}{3m_{q'}^2}\right) . \qquad (12)$$

In particular, for $m_{q'} = 400 - 600$ GeV and $t_\beta \sim \mathcal{O}(1)$, for which our low-energy h4G2HDM successfully accounts for the recently discovered 125 GeV Higgs-like particle (see below), we find that $\Lambda \sim 1 - 1.5$ TeV. Remarkably this is some fourteen orders of magnitudes smaller than the cutoff which emerges from a top-condensate scenario: $\Lambda \sim m_t \cdot exp\left(\frac{16\pi^2 v^2}{9m_t^2}\right) \sim 10^{17}$ GeV, i.e., obtained by solving the SM-like RGE for g_t: $\mathcal{D}g_t \approx \frac{9}{2}g_t^3$. Thus, introduction of a heavy quark doublet

Possible NP around few TeV

Brands of CP

- Mixing

$|\epsilon_K| \approx 2.228 \times 10^{-3}$

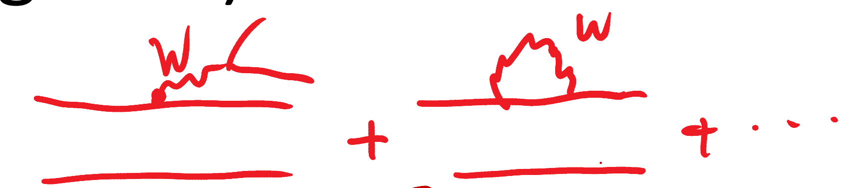
$K_L \to \pi\pi$

BNL '64 CRONIN + FITCH NOBEL

- Decay (direct, time-integrated)

Bander, Silverman, A.S, PRL'79

I. $Re(\epsilon'_K/\epsilon_K) \sim 1.65 \times 10^{-3}$

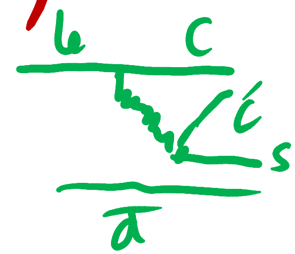


II. $A_{CP}(B^0 \to K^+\pi^-) \approx -0.098$; $A_{CP}(B^+ \to K^+\pi^0) = 0.051 \pm 0.025$

$\Delta A_{CP}(B \to K\pi) \sim (14.4 \pm 2.9)\%$!!

III. $\Delta A_{CP}((D^0 \to K^+K^-) - (D^0 \to \pi^+\pi^-)) = -0.678 \pm 0.147\%$

- Mixing and decay (time-dependent)



$S(B^0 \to \psi K_S) \simeq \sin 2\beta \sim 0.673$

Highly instrumental in the dramatic success of the B-factories and the KM Nobel Prize

Carter & Sanda, PRL'80
Bigi & Sanda, NPB'81

Direct CP: Long² standing challenge for theorists

$$A = |T| + |P| \exp[i\delta_{st} + i\delta_{wk}]$$

(δ_{st}: CP +; δ_{wk}: CP −)

$$\bar{A} = |T| + |P| \exp[i\delta_{st} - i\delta_{wk}]$$

$$a_{CP[PRA]} = \frac{B[i\to f] - B[\bar{i}\to\bar{f}]}{+}$$

$$= \frac{|T||P| \sin\delta_{st} \sin\delta_{wk}}{|T|^2 + |P|^2 + 2|T||P| \cos\delta_{st} \cos\delta_{wk}}$$

$q = u, c, t$ or d, s, b

$(CP)_{odd}$, T_N even

UNKNOWNS 4; $|T|$, $|P|$, δ_{st}, δ_{wk}

OBSERVABLES 3 $|A|^2$; $|\bar{A}|^2$ + a_{CP}

DESEPERATELY NEED δ_{st}!

CP –odd; TN-odd

Data driven "solutions"

- **From Theory need non-perturbative framework..**
- **For K (ε'/ε) on going lattice efforts for ~30 years!**
- **[significant progress [by RBC-UKQCD]in related problem of the $\Delta I = 1/2$ PUZZLE , see arXiv:1212.1474, talk by A. Lytle] Lattice methods not available (yet) for D, B**
- **Resonance dominance ....width contains info of δ_{st}**

Eilam, Hewett, AS, PRL'91; Atwood+AS, Zphys'94

- **B=>D K channels .....most precise determination of γ**

Atwood,Dunietz,AS, PRL'97 ....

Now $\gamma \approx 70 \pm 10°$

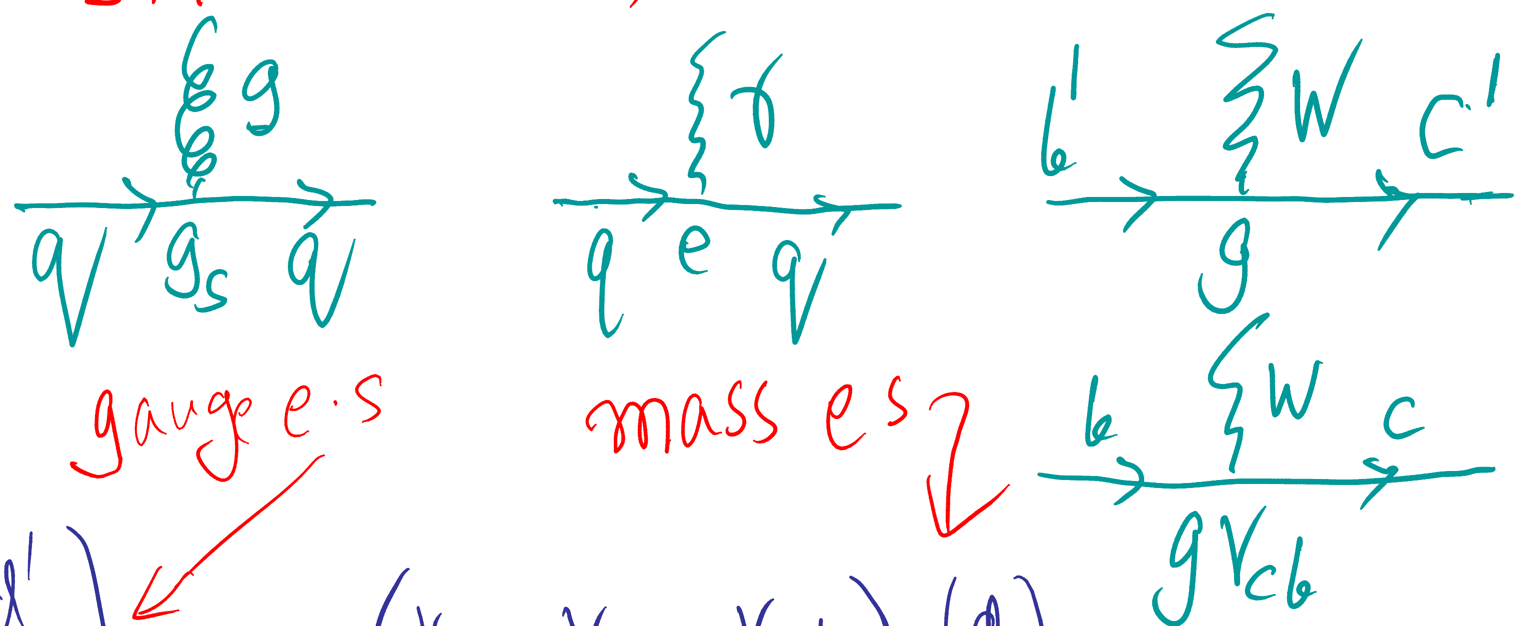
S(LHCb)

Theory precision ~ few $\times 10^{-3}$!! Belle II

CKM –matrix, weak interactions & CPV

CABIBBO, PRL(63); KOBAYASHI-MASKAWA, PTP (72)

$$G_{SM} = SU(3) \times SU(2) \times U(1)$$



$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

CKM MATRIX

Leads to profound repercussions for BSMs: "FLAVOR PUZZLE"

Wolfenstein representation: particularly insightful

PRL '84

$\lambda \cong .22$, EXPANSION PARAMETER

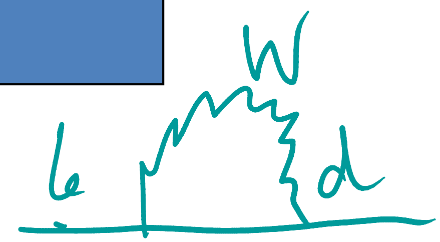
$$V_{WOLF} \equiv \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

e.g.: $V_{ii} \sim 1$, $V_{21} \sim \lambda$; $V_{23} \sim \lambda^2$; $V_{13} \sim \lambda^3$

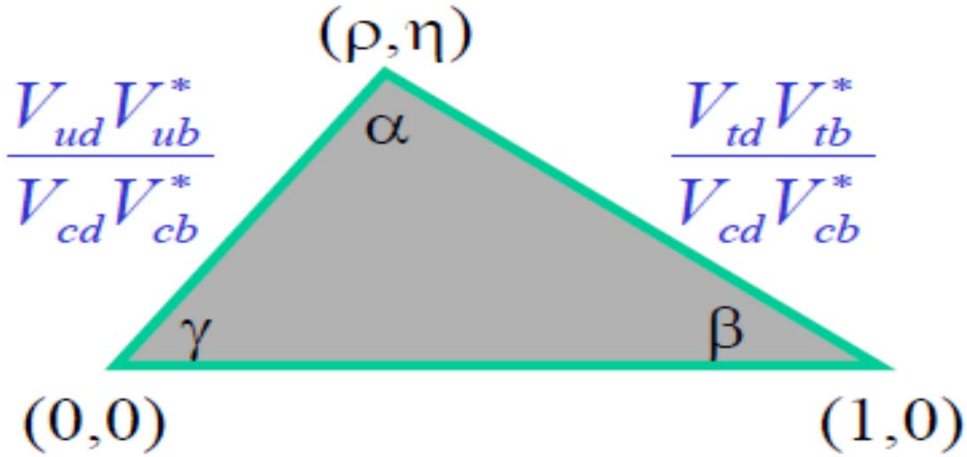
$A, \rho, \eta \sim O(1)$ η is CP-phase

Unitarity triangle(s)

$$V_{ud}V_{ub}^{*} + V_{cd}V_{cb}^{*} + V_{td}V_{tb}^{*} = 0.$$



THE UT



$\alpha, \beta, \gamma \propto \eta$

5 more UTs:

s->d (BNL)

b->s

t->c

t->u

c->u

JARLSKOG INVARIANCE

$$| J_{\mathrm{CP}} | = 2 \cdot A_{\Delta},$$

ALL MUST HAVE The Same J_{CP}

C. J. PRL'85;
See also Chau & Keung, PRL'84

Status of CKM: Marcella Bona talk

Summary of current status of SM-CKM

- **No compelling evidence against SM-CKM**
- **Interesting anomalies persist**
- **1) B=>K π ΔACP**
- **2) Penguin vs tree sin2β**
- **3) sin2β from lattice tends to be higher than from B=> ψ Ks**
- **B=> $\tau\nu$, B=> D(*) $\tau\nu$**
- **Each anomaly is only ~2 σ**
- **Haven't we tested the SM-CKM enough?**

Expected Progress

- **S(LHCb)**
- **Super-KEKB/BELLEII**
- **Lattice [success of Flavor Physics/Intensity Frontier is intricably tied to the developments on the lattice]**

Significant change in the reach of the lattice in place in 2012due X20-50 increase in computing power & improvements in methodology*

* Blum, Izubuchi & Shintani, arXiv:1208.4349; see Eigo's talk

On K=> ππ, see talk by Andrew Lytle
RBC-UKQCD arXiv:1212.1474

QCDOC (~05-'11) -> QCDCQ ('11-?)

$\delta B_K \sim 15\%$ $\quad$ $\lesssim 3\%$ $\Rightarrow \lesssim 1\%$ (2013)

$\delta A_0 \sim O(100\%)$ ChPT $\quad$ $\simeq 25\%$ DIRECT

Re, Im $A_2 \Rightarrow \lesssim 10\%$ (2013)

Recent results from LHCb, CDF

LHCb

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

U Spin ⇒

$$A_{\rm CP}^{\rm dir}(K^+K^-) \simeq -A_{\rm CP}^{\rm dir}(\pi^+\pi^-)$$

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

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

CDF

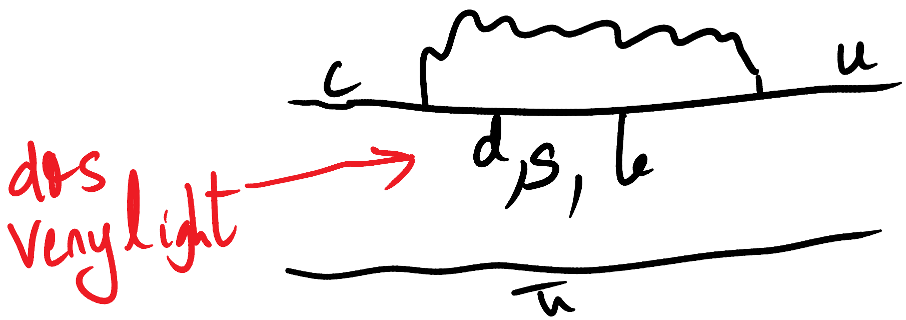
LHCb+CDF ⇒

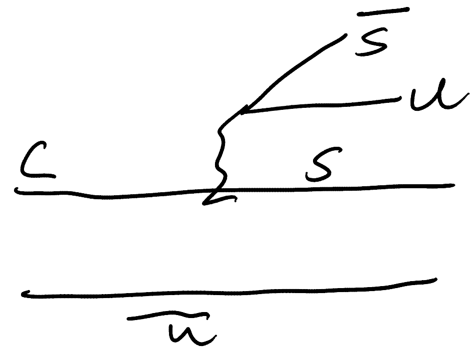
$$\Delta A_{CP}^{\rm dir} = (-0.645 \pm 0.180)\%$$

HFAG

BACK of a NAPKIN

e.g. $D^0 \to K^+ K^-$



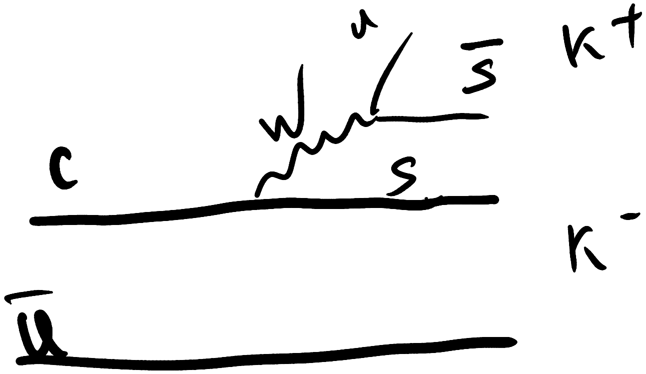


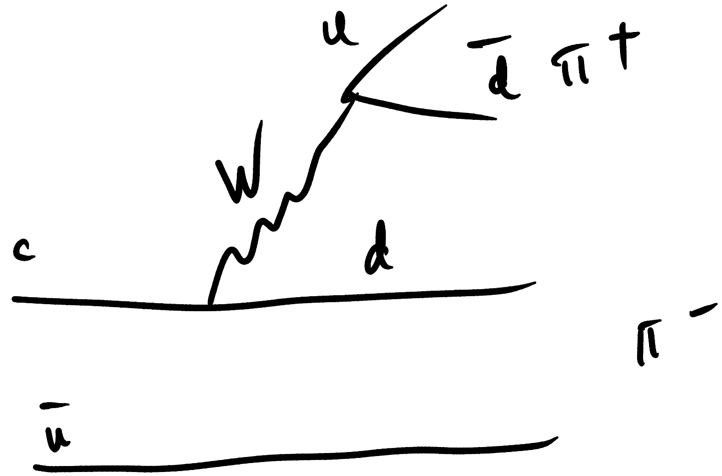
$$\Delta A_{CP} \sim 4 \left(\frac{P}{T}\right) \frac{V_{ub} V_{cb}^*}{V_{cs}^* V_{us}} \Rightarrow \underbrace{4A^2 \lambda^4}_{\sim 1\times 10^{-3}} \eta \sin\delta_{st} \left(\frac{P}{T}\right)$$

HIGHLY Nonperturbative

Naively $\frac{P}{T} \sim \alpha_s(m_c)/\pi \sim 0.3$ **MISLEADING**

U –spin (d ⇔ s)





$$V_{us} = \lambda = -V_{cd}$$

Peek @ PDG: old results

$$\mathrm{BR}[D^0 \to K^-\pi^+] = (3.949 \pm 0.023 \pm 0.040 \pm 0.025)\%\,,$$

$$\mathrm{BR}[D^0 \to \pi^+\pi^-] = (0.1425 \pm 0.0019 \pm 0.0018 \pm 0.0014)\%\,,$$

$$\mathrm{BR}[D^0 \to K^+K^-] = (0.3941 \pm 0.0038 \pm 0.0050 \pm 0.0024)\%\,,$$

$$\frac{\mathrm{BR}[D^0 \to K^+\pi^-]}{\mathrm{BR}[D^0 \to K^-\pi^+]} = (0.331 \pm 0.008)\%\,,$$

$$\mathrm{obs}_1 \equiv \frac{\mathrm{BR}[D^0 \to K^+K^-]/|\vec{p}_K|}{\mathrm{BR}[D^0 \to \pi^+\pi^-]/|\vec{p}_\pi|} \simeq 3.22 \pm 0.09$$

$$\mathrm{obs}_2 \equiv \frac{\mathrm{Br}[D^0 \to K^-\pi^+]/|\vec{p}_{\pi K}|}{\mathrm{Br}[D^0 \to K^+K^-]/|\vec{p}_K|}\,\lambda^2 \simeq 0.47 \pm 0.01\,,$$

$$\mathrm{obs}_3 \equiv \frac{\mathrm{Br}[D^0 \to K^+\pi^-]}{\mathrm{Br}[D^0 \to K^-\pi^+]}\,\lambda^{-4} \simeq 1.28 \pm 0.03\,,$$

} ≠ 1

⇒ U Spin Badly Broken

EXACT U-SPIN LIMIT

$$H_{\rm eff}(c \to us\bar{d}) = -\left(V_{cs}^{*}V_{ud}\right) H_{U=1}^{(U_3=-1)}\,,$$

$$H_{\rm eff}(c \to uq\bar{q}) = \left(\frac{V_{cd}^{*}V_{ud} - V_{cs}^{*}V_{us}}{\sqrt{2}}\right) H_{U=1}^{(U_3=0)} + \left(V_{cd}^{*}V_{ud} + V_{cs}^{*}V_{us}\right) H_{U=0}\,,$$

$$H_{\rm eff}(c \to ud\bar{s}) = \left(V_{cd}^{*}V_{us}\right) H_{U=1}^{(U_3=+1)}\,.$$

$\lambda_q \equiv V_{cq}^{*} V_{uq}$ $q = d, s$

$$\mathcal{A}[D^0 \to K^-\pi^+] = 2\,V_{cs}^{*}V_{ud}\,B_{U=1}\,,$$

$$\mathcal{A}[D^0 \to \pi^+\pi^-] = (\lambda_d + \lambda_s)\,A_{U=0} + (\lambda_d - \lambda_s)\,B_{U=1}\,,$$

→ $O(\lambda^5)$

$$\mathcal{A}[D^0 \to K^+K^-] = (\lambda_d + \lambda_s)\,A_{U=0} - (\lambda_d - \lambda_s)\,B_{U=1}\,,$$

→ $O(\lambda)$

$$\mathcal{A}[D^0 \to K^+\pi^-] = 2\,V_{cd}^{*}V_{us}\,B_{U=1}\,,$$

Taking U-spin breaking into a/c

$$A[D^0 \to K^-\pi^+] \equiv 2\,V_{cs}^* V_{ud}\left(B_{U=1} - \Delta B'_{U=1}\right) = 2\,V_{cs}^* V_{ud}\, B_{U=1}\left[1 - r'_1\, e^{i\,\phi'_1}\right],$$

$$\begin{aligned} A[D^0 \to \pi^+\pi^-] &= (\lambda_d + \lambda_s)\,(A_{U=0} + \Delta B_{U=1}) + (\lambda_d - \lambda_s)\,(B_{U=1} + \Delta A_{U=0}) \\ &= B_{U=1}\left[(\lambda_d + \lambda_s)\left(r\,e^{i\,\phi} + r_1\,e^{i\,\phi_1}\right) + (\lambda_d - \lambda_s)\left(1 + r_0\,e^{i\,\phi_0}\right)\right], \end{aligned}$$

$$\begin{aligned} A[D^0 \to K^+K^-] &= (\lambda_d + \lambda_s)\,(A_{U=0} - \Delta B_{U=1}) - (\lambda_d - \lambda_s)\,(B_{U=1} - \Delta A_{U=0}) \\ &= B_{U=1}\left[(\lambda_d + \lambda_s)\left(r\,e^{i\,\phi} - r_1\,e^{i\,\phi_1}\right) - (\lambda_d - \lambda_s)\left(1 - r_0\,e^{i\,\phi_0}\right)\right], \end{aligned}$$

$$A[D^0 \to K^+\pi^-] = 2\,V_{cd}^* V_{us}\left(B_{U=1} + \Delta B'_{U=1}\right) = 2\,V_{cd}^* V_{us}\, B_{U=1}\left[1 + r'_1\, e^{i\,\phi'_1}\right].$$

SOURCE OF USPIN BREAKING: $m_s \neq m_d$

U-spin violation

U-spin is broken $\mathcal{O}\left(\frac{m_s}{\Lambda_{QCD}}, \frac{f_k}{f_\pi} - 1\right) \Rightarrow \mathcal{H}_{break} \rightarrow$ Tensor operator $\mathcal{O}^{U=1}_{U_3=0}$

$\Rightarrow D^0 \rightarrow P^+P^-$ decays including 1st order U-spin breaking:

$$\mathcal{A}[D^0 \rightarrow K^-\pi^+] = 2V^*_{cs}V_{ud}\, B_{U=1}\left[1 - r'_1\, e^{i\,\phi'_1}\right]$$

$$\mathcal{A}[D^0 \rightarrow \pi^+\pi^-] = B_{U=1}\left[(\lambda_d + \lambda_s)\left(r\, e^{i\,\phi} + r_1\, e^{i\,\phi_1}\right) + (\lambda_d - \lambda_s)\left(1 + r_0\, e^{i\,\phi_0}\right)\right]$$

$$\mathcal{A}[D^0 \rightarrow K^+K^-] = B_{U=1}\left[(\lambda_d + \lambda_s)\left(r\, e^{i\,\phi} - r_1\, e^{i\,\phi_1}\right) - (\lambda_d - \lambda_s)\left(1 - r_0\, e^{i\,\phi_0}\right)\right]$$

$$\mathcal{A}[D^0 \rightarrow K^+\pi^-] = 2V^*_{cd}V_{us}\, B_{U=1}\left[1 + r'_1\, e^{i\,\phi'_1}\right]$$

$\Rightarrow$ Amplitude Ratios: $r_0 = \left|\frac{\Delta A_{U=0}}{B_{U=1}}\right|,\ r_1 = \left|\frac{\Delta B_{U=1}}{B_{U=1}}\right|,\ r = \left|\frac{\Delta A_{U=0}}{B_{U=1}}\right|$

$\Rightarrow D^0 \rightarrow K^\pm\pi^\mp$: No direct CP violation $\Rightarrow$ Only mixing-induced CP violation !!

$\Rightarrow$ Parameters need to fit: $r_0,\ r'_1,\ r_1,\ r,\ \phi_0,\ \phi'_1,\ \phi_1$ and ϕ

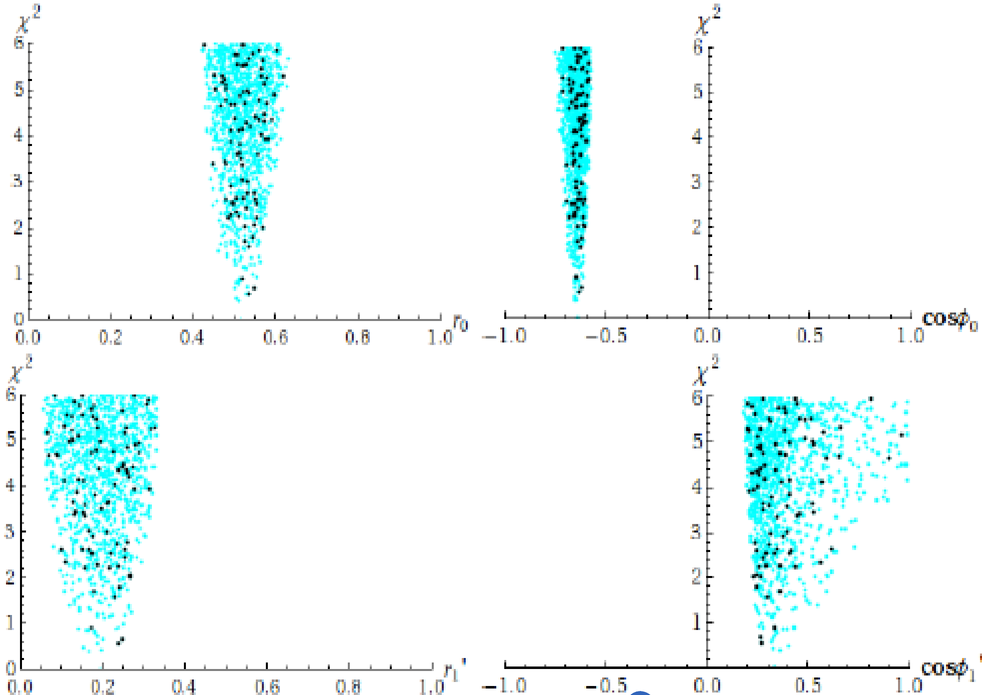
$\Rightarrow$ Available data: $R_1,\ R_2,\ R_3,\ \Delta A_{CP},\ Arg\left(\frac{\mathcal{A}[D^0 \rightarrow K^-\pi^+]}{\mathcal{A}[D^0 \rightarrow K^+\pi^-]}\right) \approx \Delta\phi = 22.4^\circ{}^{+\ 9.7^\circ}_{-11.0^\circ}$

$\Rightarrow$ No priority to a single amplitude ratio !!

$\Rightarrow$ The individual values of r and r_1 can not be fixed from data !!

$\Rightarrow$ Hence, we define $\bar{r} = \sqrt{r^2/2 + r_1^2/2} \Rightarrow$ Sensitive to ΔA_{CP} !!

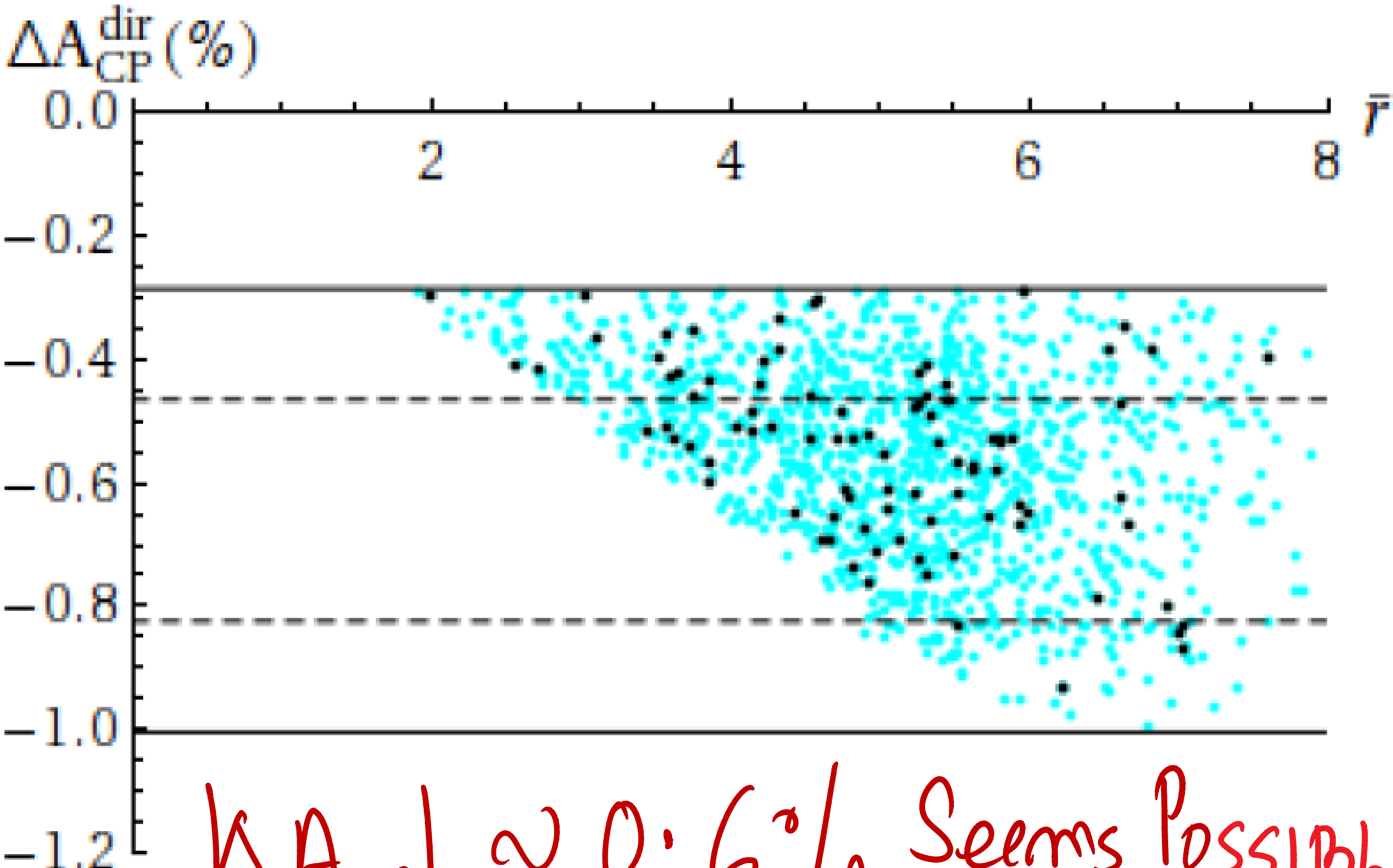
FIT to BRs to Constrain U-Spin Breaking



Amplitude Ratios

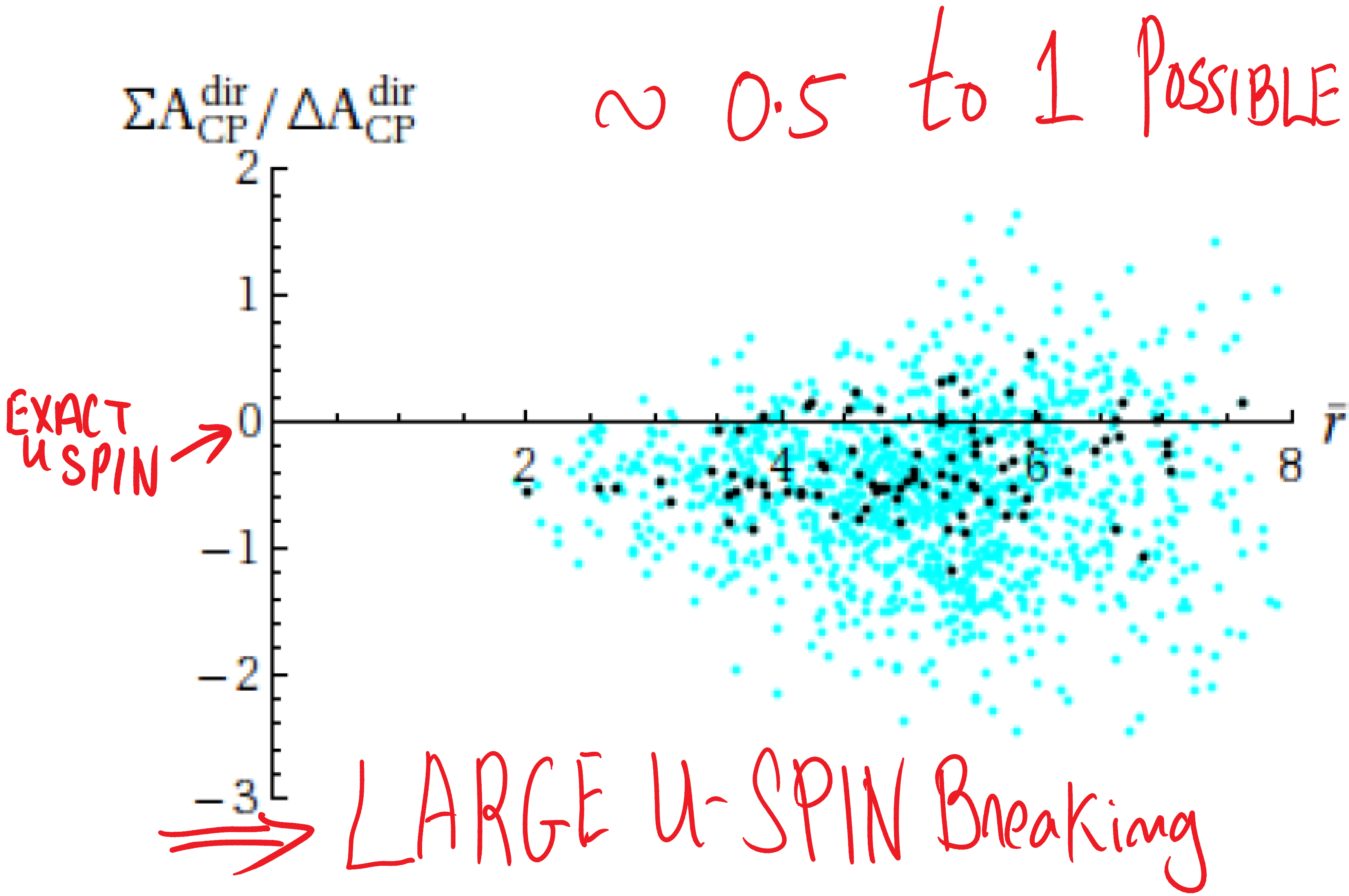
STRONG PHASES

Figure 1. Fit result for the amplitude parameters r_0 and $\cos\phi_0$ (upper row) and r_1' and $\cos\phi_1'$ (lower row), determining the amount of U-spin breaking in $D^0 \to P^+P^-$ BRs. The generic points shown in light blue are consistent with the experimental constraints at the 2σ-level and obey $\chi^2 \leq 6$. The black points denote a subset of points where the strong phase differences between $A_{U=0}$ and $\Delta A_{U=0}$, as well as between $B_{U=1}$ and $\Delta B_{U=1}$ are assumed to be equal within a few percent, $(\phi - \phi_0) = \{0, \pi\}$ and $\phi_1 = \{0, \pi\}$.

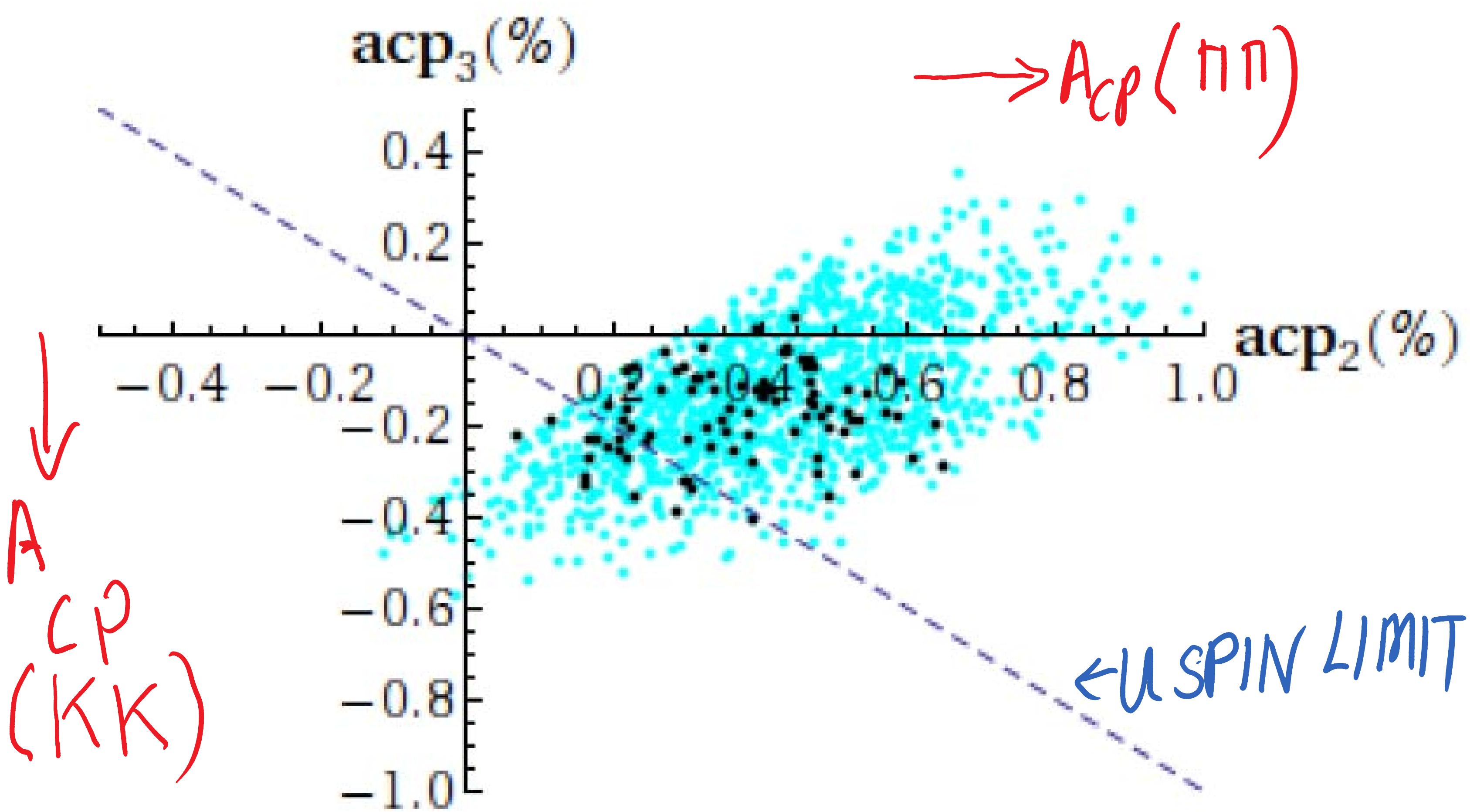


$|\Delta A_{CP}| \sim 0.6\%$ Seems Possible

$\geq 1\%$ HIGHLY UNLIKELY



$\Sigma A_{CP}^{dir} / \Delta A_{CP}^{dir}$
~ 0.5 to 1 POSSIBLE
EXACT U SPIN
LARGE U-SPIN Breaking
$\bar{r}$


acp$_3$(%)
0.4
0.2
−0.2
−0.4
−0.6
−0.8
−1.0
−0.4
−0.2
0.2
0.4
0.6
0.8
1.0
acp$_2$(%)
→ Acp(ππ)
A
CP
(KK)
← U SPIN LIMIT

Summary (so far) on Recent D-CP results

- **SM explanation cannot be ruled out and is quite plausible; *however, a compelling case for SM explanation can also not be made*.**
- ***Unless true result is , for sure, 1% or more , not a compelling sign of new physics***
- **theory estimates plagued by large hadronic (non-perturbative) uncertainties; NO RIGOUROUS METHOD IN SIGHT; LONG-TERM WORRY => Ghost of ε '/ε. However, unlike K-> ππ , lattice methods appear exceedingly difficult** ⇒ DA+AS 2012 See Later
- **More exptal input (many other modes) crucial & could change interpretation…**
-

MORE EXPRIMENTAL INPUT COULD BE VERY USEFUL

(PDG + HFAG ~0(6) $A_{CP} \neq 0$)

Mode	BR	A_{CP} in %	5σ Reach
$D^+ \to K_S \pi^+$	1.47×10^{-2}	-0.52 ± 0.14 [32]	1×10^{-3}
$D_s \to \eta' \pi^+$	3.94×10^{-2}	-6.1 ± 3.0 [63] $-5.5 \pm 3.7 \pm 1.2$ [32]	0.7×10^{-3}
$D_s \to K_S \pi^+$	1.21×10^{-3}	6.6 ± 3.3 [63] 6.53 ± 2.46 [32]	4×10^{-3}

THESE Need clarification.

AT ISSUE IS DIRECT CP ⇒ USE $D^\pm$, D_s

MANY INTERESTING MODES e.g. $D^0 \to K^{*\pm} K^\mp$, $\rho^\pm \pi^\mp$

$D^+ \to K^{*0} \pi^+$, $\phi \pi^+$

$D_s \to \phi \pi^+$, $\eta' \pi^+$, $\bar{K}^{(*)0} \pi^+$, ϕK^+

Important to measure CP in pure trees

Example

$D^0 \to K^- \pi^+$

[NICE FINAL STATE]

NO Penguin

NO CP phase SM

ESPECIALLY IMPORTANT To Search CP since γ extractions ASSUME No CP in D^0

Must try ascertain if D-CP is receiving contribution from BSM

Suggestions:

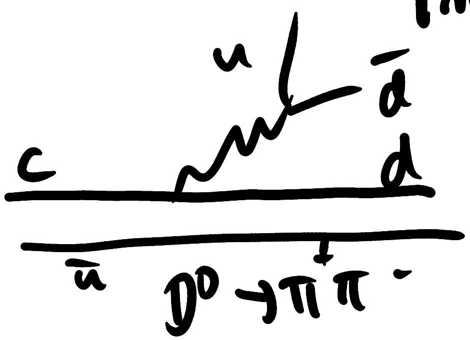
Atwood & AS, arXiv:1211.1026

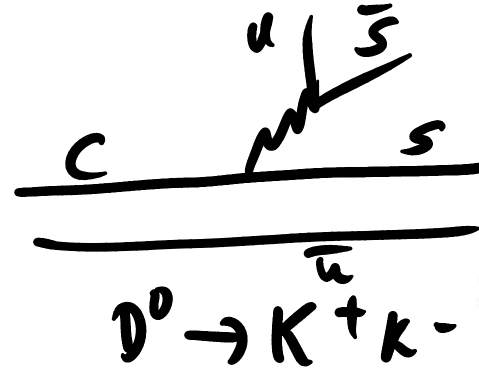
- **Implications of CPT**

- **Final States with enhanced CP**

- **SM or not : A critical test**

Implications of CPT





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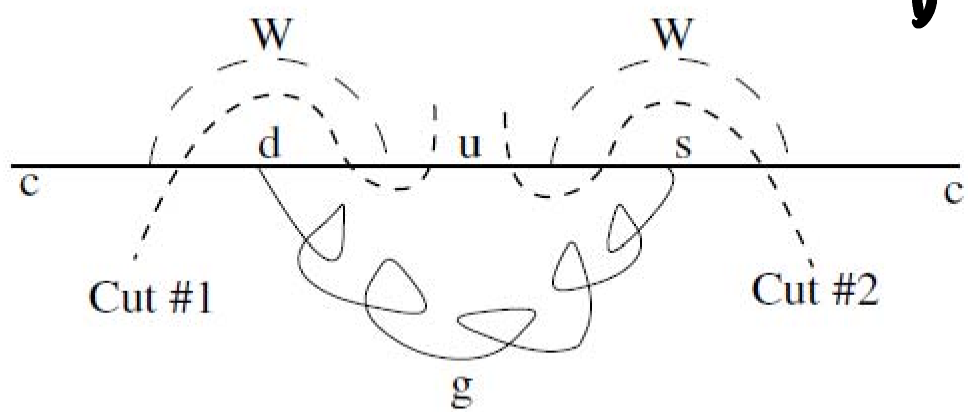

FIG. 1: The unitarity graph showing the CPT identity Eqn. 6 for the quark level SCS charm decay. Cut #1 indicated in the figure shows the case where the decay is $c \to d\bar{d}u$ with a $s\bar{s}u$ intermediate state providing the strong phase. Conversely, cut #2 indicated in the figure shows the case where the decay is $c \to s\bar{s}u$ with a $d\bar{d}u$ intermediate state providing the strong phase. The interfering tree graphs are not shown but are implied

$$\sum_X \Delta\Gamma(D \to X) \equiv \sum_X \left[\Gamma(D \to X) - \Gamma(\bar{D} \to \bar{X})\right] = 0$$

At the quark level: $\Delta\Gamma(c \to d\bar{d}u) = -\Delta\Gamma(c \to s\bar{s}u).$

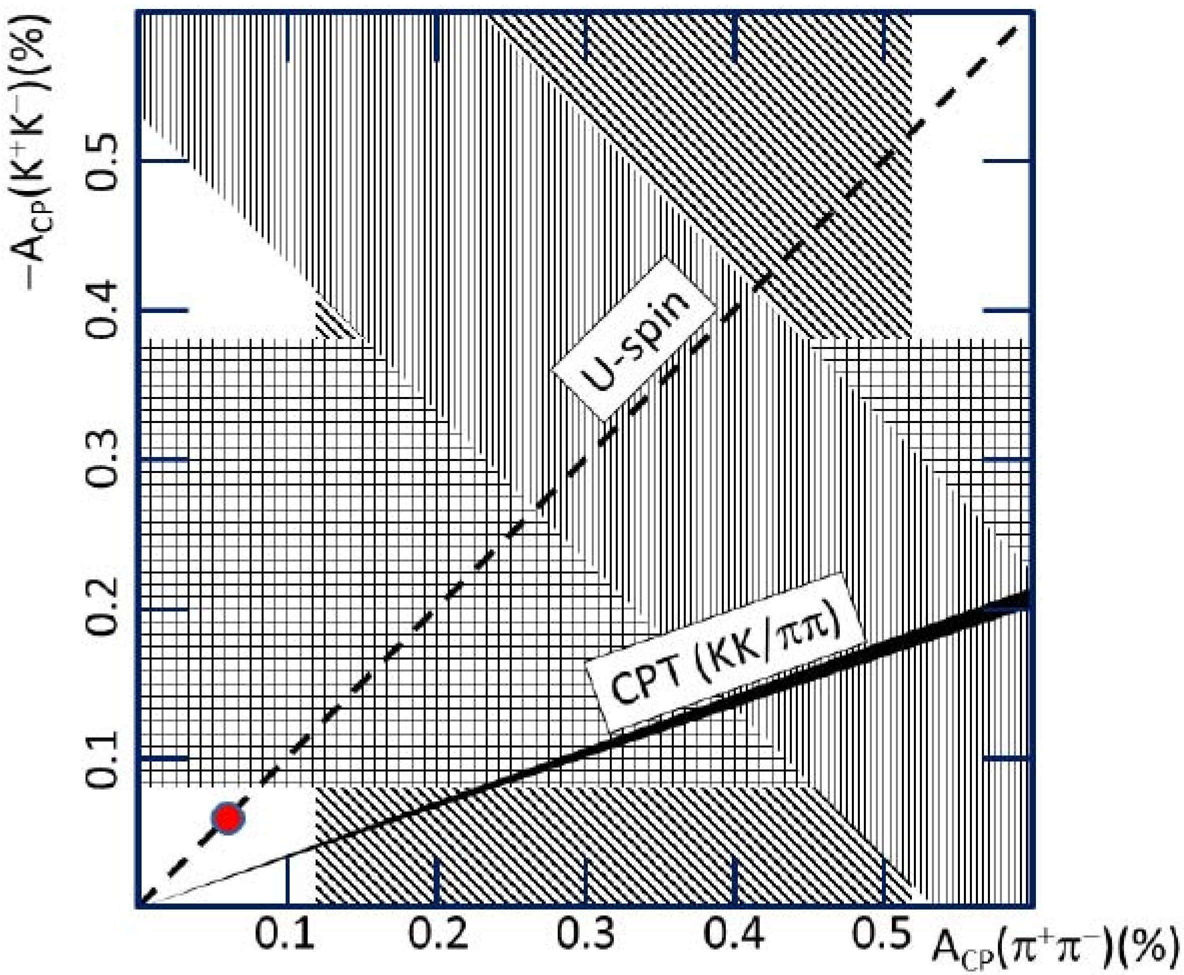

FIG. 2: The current experimental results for $A_{CP}(\pi^+\pi^-)$ and $A_{CP}(K^+K^-)$. The vertically hatched band shows the

Candidates for enhanced CP asymmetry [because of CPT]

- **Since asymmetry arises from T and P interference and as a rule P<<T, need final states where T is suppressed => color suppressed modes: compare $D^0 \Rightarrow \rho^+ + \rho^-$ versus ρ0 ρ0**

- **ρ0 ρ0 also gives 4 charged pi's and possibility of triple correlation asymmetry**
- **Other examples:**

For KEKB D=> π^0 π^0 (η, η')
also imp but may not be CS

Decay	Suppressed Tree	Charged Final State	Favored	Total BR (10^{-3})
$D_s \to \pi^{(*)0} K^{(*)+}$	X	$[\rho^0 \to \pi^+\pi^-]K^+$	X	2.7 ± 0.05
		$[\rho^0 \to \pi^+\pi^-][K^{*+} \to \pi^+[K_s \to \pi^+\pi^-]]$	X	—
$D_s \to \phi^{(*)} K^{(*)+}$		$[\phi \to K^+K^-]K^+$		< 0.3
		$[\phi \to K^+K^-][K^{*+} \to \pi^+[K_s \to \pi^+\pi^-]]$		—
$D^+ \to \pi^{(*)+}\phi^{(*)}$	X	$\pi^+[\phi \to K^+K^-]$	X	2.65 ± 0.08
$D^+ \to K^{(*)+}\overline{K}^{(*)0}$		$K^+[K_s \to \pi^+\pi^-]$		1.98 ± 0.13
		$K^+[\overline{K}^{*0} \to K^+\pi^-]$		$2.45^{.09}_{.14}$
		$[K^{*+} \to \pi^+[K_s \to \pi^+\pi^-]][K_s \to \pi^+\pi^-]$		5.7 ± 2.3
		$[K^{*+} \to \pi^+[K_s \to \pi^+\pi^-]][\overline{K}^{*0} \to K^+\pi^-]$		—
$D^+ \to \pi^{(*)+}\pi^{(*)0}$		$\pi^+[\rho^0 \to \pi^+\pi^-]$		0.81 ± 0.15
$D^0 \to K^{(*)0}\overline{K}^{(*)0}$	XX	$[K_s \to \pi^+\pi^-][K_s \to \pi^+\pi^-]$	X	0.085 ± 0.014
		$[K^{*0} \to K^+\pi^-][K_s \to \pi^+\pi^-]$	X	< 0.2
		$[\overline{K}^{*0} \to K^-\pi^+][K_s \to \pi^+\pi^-]$	X	< 0.35
		$[K^{*0} \to K^+\pi^-][\overline{K}^{*0} \to \pi^+K^-]$	X	$.07 \pm 0.05$
$D^0 \to \pi^{(*)0}\pi^{(*)0}$	X	$[\rho^0 \to \pi^+\pi^-][\rho^0 \to \pi^+\pi^-]$	X	1.82 ± 0.10
$D^0 \to \pi^{(*)+}\pi^{(*)-}$		$\pi^+\pi^-$		$1.400 \pm .026$
$D^0 \to \phi^{(*)}\pi^{(*)0}$	X	$D^0 \to \phi\rho^0$	X	1.40 ± 0.12
$D^0 \to K^{(*)+}K^{(*)-}$		K^+K^-		$3.96 \pm .08$
		$[K^{*+} \to \pi^+[K_s \to \pi^+\pi^-]]K^-$		2.19 ± 0.1
		$K^+[K^{*-} \to \pi^-[K_s \to \pi^+\pi^-]]$		0.78 ± 0.06
		$[K^{*+} \to \pi^+[K_s \to \pi^+\pi^-]][K^{*-} \to \pi^-[K_s \to \pi^+\pi^-]]$		—

TABLE I: The singly Cabibbo suppressed decays of D mesons to two ground state are listed. Note that the notation $\pi^{(*)\pm}$ stands for π^+ or ρ^+; $\pi^{(*)0}$ stands for π^0, ρ^0 or ω^0; $\phi^{(*)}$ stands for ϕ or $\eta^{(\prime)}$ to the extent that $\eta^{(\prime)}$ is an $s\overline{s}$ state. For each group of decays, we have indicated whether the tree contribution is color suppressed with "X" and if it is both color and Zweig suppressed with "XX". The instances which lead to an all charged final state are listed. The favored column are decays where the tree is colored suppressed and the final state has an all charged final state indicated by "X". Where the branching ratios are known from [34] we have included it in the last column; this is the branching ratio including the subsequent decays to the final all charged state indicated.

For details, Atwood + AS 2012

Propose a new "litmus" test for new physics

- Key idea: Hadronic matrix elements enhancement (factor O(5) needed for SM explanation) only operational for EXCLUSIVE (in particular 2 body pseudoscalar) MODES

  e.g. ππ, KK

- Inclusive (multibody) modes should exhibit quark level asymmetry[quark-hadron duality] ~$6X10^{-4}$ if SM is the source, if these also show O($3X10^{-3}$) asymmetry then BSM-CP is the origin
- Look forward to imlementation at LHCb, BF but especially KEKB to get to the bottom this very critical issue

How to look for inclusive final states?

Simple suggestion

- Look for D => K K X
- Operationally KKX is any final state containing a K K with total energy in the 2 kaons less than the energy of the parent D

HAVEN'T WE TESTED THE SM-CKM ENOUGH?

Haven't we tested the SM-CKM enough?

- **Recall current tests around 15-10%**

- **Recall also ε ~ 2 X 10^{-3} ; if BNL had stopped experimental searches at the level of even 1%, history of Particle Physics would have been completely different**

- **ν mass & osc is another example.**

We are looking for small effects

Adapted from Browder

A lesson from history (I)

"A special search at Dubna was carried out by E. Okonov and his group. They did not find a single $K_L \rightarrow \pi^+ \pi^-$ event among 600 decays into charged particles [12] (Anikira et al., JETP 1962). At that stage the search was terminated by the administration of the Lab. The group was unlucky."

-Lev Okun, "The Vacuum as Seen from Moscow"

1964: BF= 2×10^{-3}

A failure of imagination ? Lack of patience ?

Christenson, Cronin, FITCH + TURLAY BNL '64

Lesson learnt from ν's

~ Circa 1983, after long and arduous efforts, Δm^2 upper bound used to be around a few ev^2 but efforts to Search oscillations continued basically because there was no good theoretical reason for m_ν to be zero.

- *Recall it took more than a decade beyond '83* and Δm^2 had to be lowered by almost 4 orders of magnitude (!) before osc were discovered.
- Moral: Physical "principles" shouldn't be abandoned easily

Summary & Outlook

- **Past decade thanks to B-factories milestone in understanding of CP: CKM-paradigm works to an accuracy O(20%)**
- **Few anomalies ~ 2 σ but nothing compelling so far**
- **With 1st observation of CP in charm decays, LHCb has opened a new avenue for probing CP.**
- **Difficulties in hadronic matrix elements makes precise predictions difficult; observed asymmetry (Δ ACP in KK, $\pi\pi$) is somewhat bigger than simple quark level expectations but may be SM (or part of it may be BSM)**
- **Charm system is quite unique and is sensitive to different sources of BSM-CP [WEXD; "4G"…]; therefore extremely important to unambiguously clarify.**
- ***Suggested search in inclusive D=> K K events could shed decisive light; ought to be an imp. target esp. for BELLE II***

EXTRA

Natural Explanation from SM Penguin Enhancement?

[Brod, Grossman, Kagan, Zupan 2012]

- Re-parametrize:

$$r_0/r_1' = \frac{\epsilon\,|2s_1|}{\epsilon\,|t_1|} \gg 1\,, \qquad (\leftarrow \text{BRs})$$

$$r_1 = \frac{\epsilon\,|p_1|}{|t_0|} \sim 1\,, \quad r = \frac{2p_0}{t_0} \gg 1 \qquad (\rightarrow \Delta A_{\mathrm{CP}})$$

  - assign enhancement to penguin contractions of tree operators
  - U-spin breaking (ϵ) of "nominal size"

FROM T. Feldmann

Adapted from Browder

A lesson from history (I)

"A special search at Dubna was carried out by E. Okonov and his group. They did not find a single $K_L \rightarrow \pi^+ \pi^-$ event among 600 decays into charged particles [12] (Anikira et al., JETP 1962). At that stage the search was terminated by the administration of the Lab. The group was unlucky."

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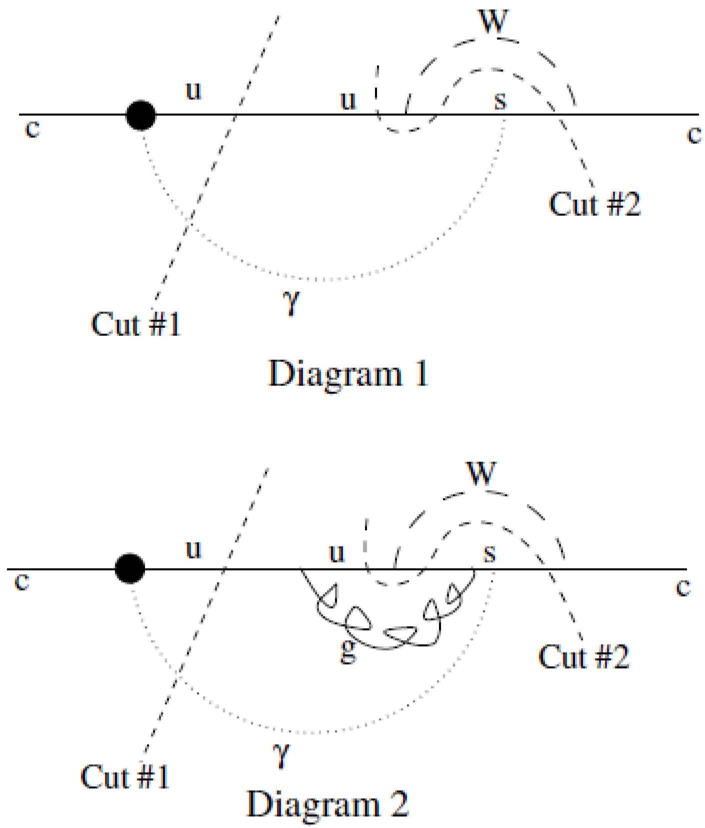
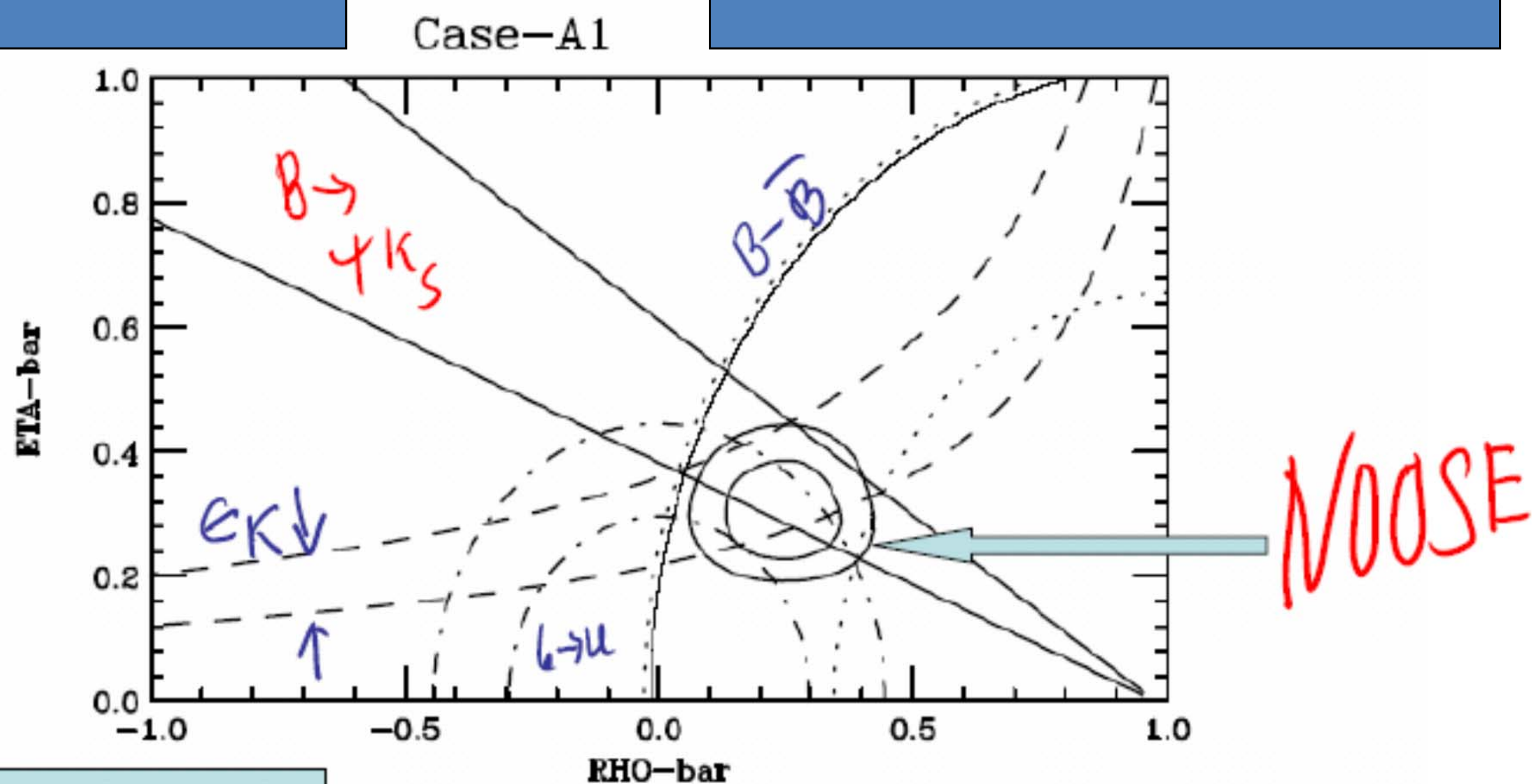


FIG. 3: This unitarity graph illustrates CPT conservation for the quark level process $c \to u\gamma$ due to NP. Diagram 1 shows the lowest order interference between NP and SM where cut #1 is for the $c\gamma$ final state and cut #2 is for a $s\bar{s}u$ final state. Cut #2 cannot be on shell. Diagram 2 shows an example of an order α_s correction to diagram 1 where in contrast cut #2 can be on shell.

1st Hint of confirmation of CKM CP description

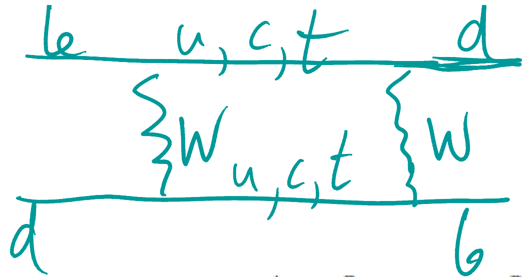
Atwood &AS, hepph/0103197



Most bands due
To theory errors

New physics will be a perturbation, important to use clean theory and lots of statistics.

ALL EXPERIMENTAL DATA MUST REQUIRE UNIQUE values of ρ,η



$$\Rightarrow [\bar{b}\gamma_{\mu L} d]^2$$

$$\Delta M_{B_q} = 2\left|M_{12}^q\right| = \frac{\left|\langle \bar{B}_q^0 | \mathcal{H}_{\rm eff} | B_q^0 \rangle\right|}{m_{B_q}} = \frac{G_F^2}{12\pi^2} m_W^2 m_{B_q} f_{B_q}^2 \hat{B}_{B_q} \eta_B S_0(x_t) \left|V_{tb} V_{tq}^*\right|^2 , \quad (2.1)$$

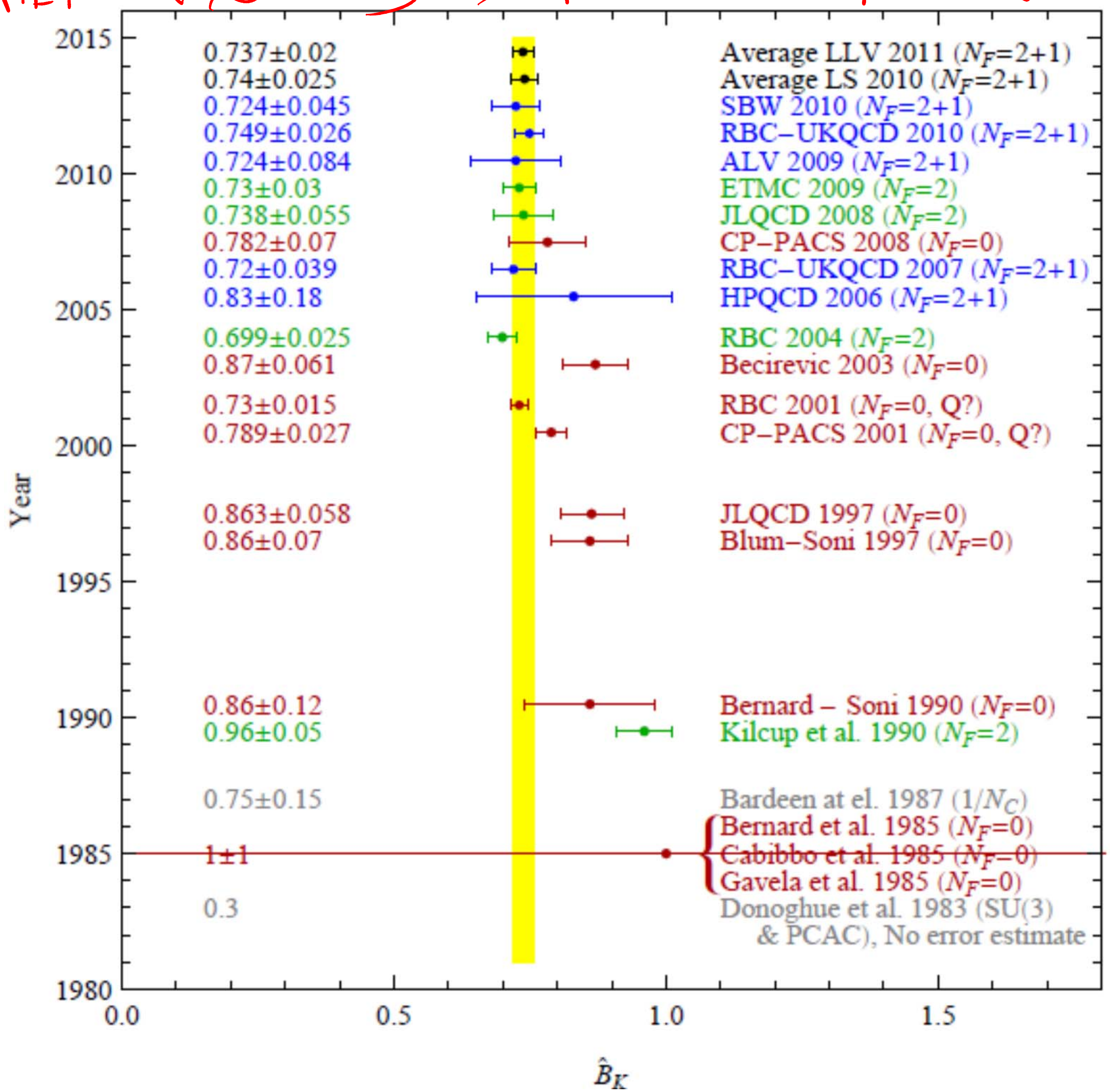
$$\frac{\Delta M_{B_s}}{\Delta M_{B_d}} = \xi^2 \frac{m_{B_s}}{m_{B_d}} \left|\frac{V_{ts}}{V_{td}}\right|^2 , \quad (2.2)$$

$$|\varepsilon_K| = \frac{G_F^2 m_W^2 f_K^2 m_K}{12\sqrt{2}\pi^2 \Delta m_K^{\rm exp}} \hat{B}_K \kappa_\varepsilon \,{\rm Im}\Big(\eta_1 S_0(x_c) \left(V_{cs} V_{cd}^*\right)^2 + 2\eta_3 S_0(x_c, x_t) V_{cs} V_{cd}^* V_{ts} V_{td}^*$$

$$+\eta_2 S_0(x_t) \left(V_{ts} V_{td}^*\right)^2\Big) . \quad (2.3)$$

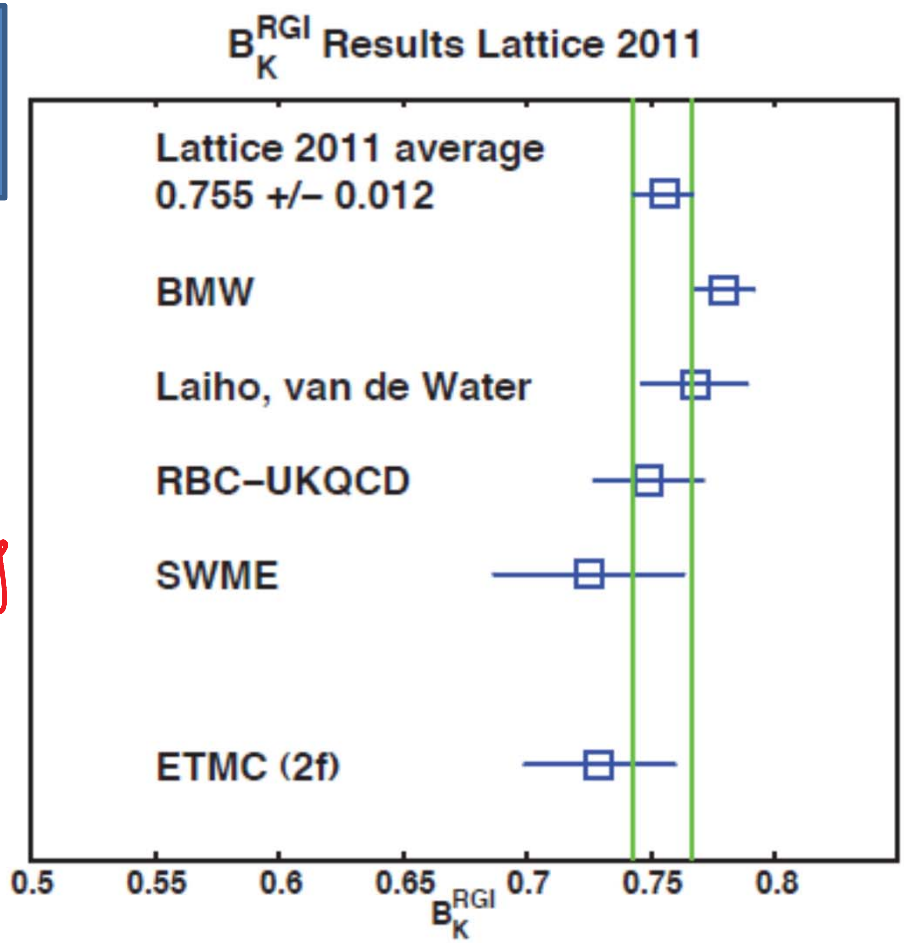
$$\langle \bar{B}_d | [\bar{b}\gamma_{\mu L} d]^2 | B_d \rangle \equiv B_{B_d} / \tfrac{8}{3} f_{B_d}^2 m_{B_d}^2$$

A BRIEF (≈ 25 yrs) HISTORY OF B_K



Mawhinney, plenary LAT'11

Several Lattice groups using completely diff methods reporting B_K with total error $\leq 3\%$!



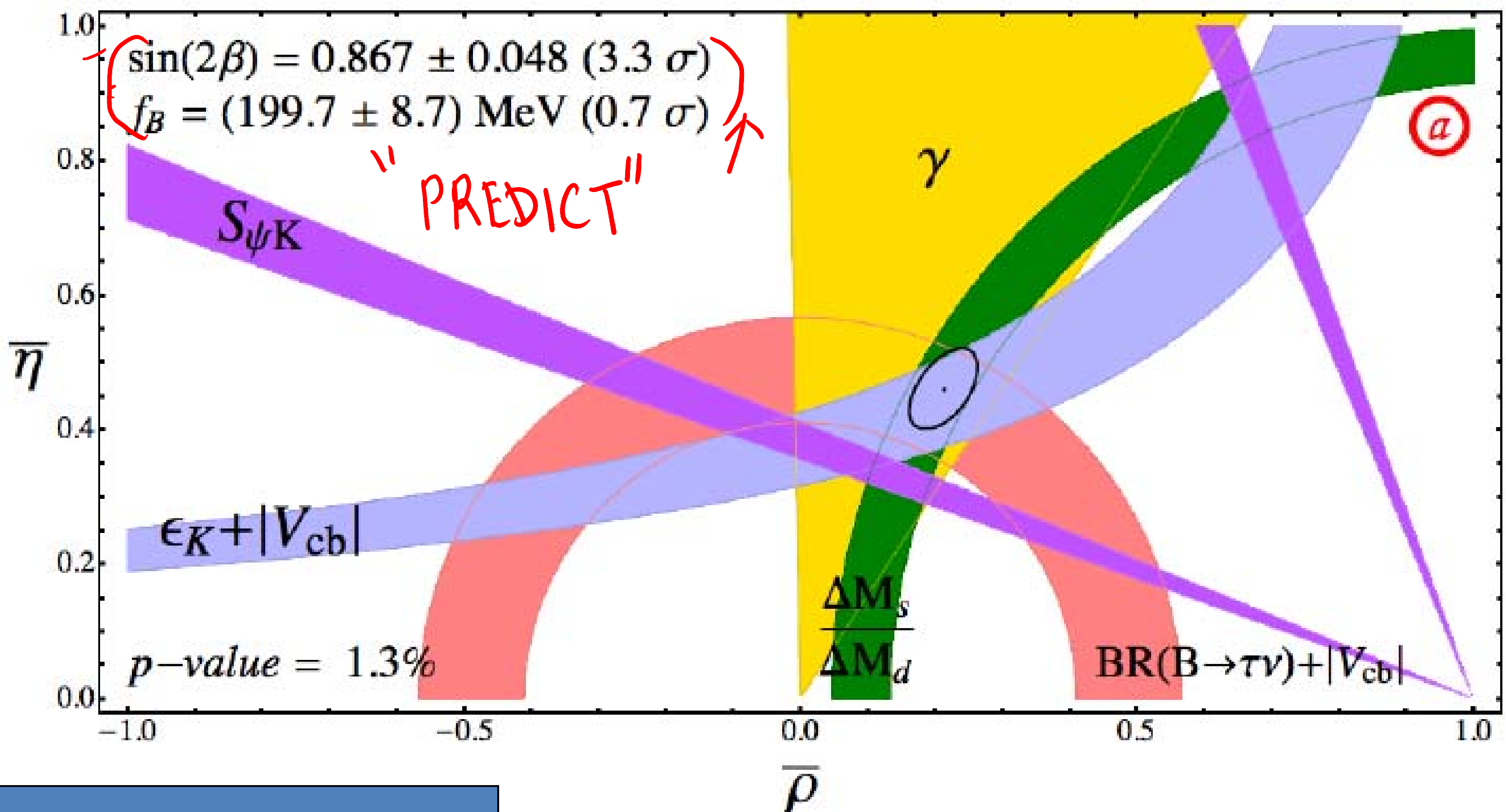
HUGE STRIDES IN LATTICE CALCULATION OF BK!

- Average the four 2+1 flavor calculations presented
- Except for BMW, all are preliminary, although all groups have recently published B_K results from earlier datasets, so preliminary work should be fairly reliable.

See also recent summary by FLAG working group of FLAVIANET (arXiv:1011.4408)
They quote $\hat{B}_K = 0.738(20)$ for $N_f = 2+1$

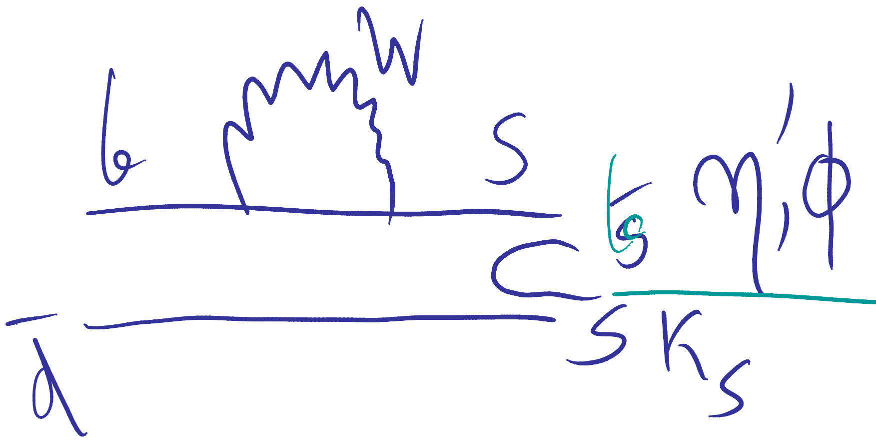
INPUTS ⇒ ε_K - $\Delta M_{Bs}/\Delta M_{Bd}$ - $|V_{cb}|$ - γ $B \to \tau\nu$

4 ΔM_{Bs}



Predict sin2β & fB

$$\Delta S \equiv S_{penguin} - S_{\psi K_S} = O(\lambda^2)$$

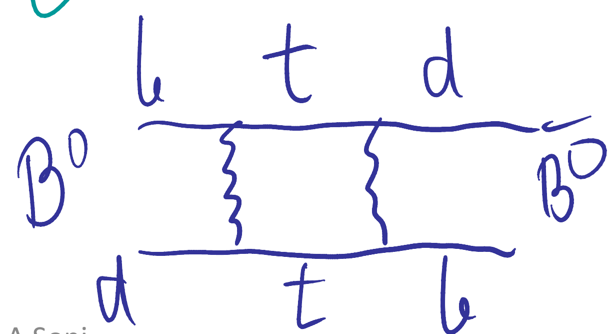


$$S^{Decay}_{peng} \simeq O(\lambda^2) \sim few\,\%$$

Grossman & Worah, hepph/9612269; London & AS,hepph/9704277

$$S^{Decay}_{\psi K_S} = 0$$

OSC is COMMON



Δ Kπ

$$A_{CP}(B^- \to K^-\pi^0) - A_{CP}(\bar{B}^0 \to K^-\pi^+)$$

EXPT ~ 5% − (−9%)

" ~ 14.8 ± 2.8 %

LUNGHI + AS '09 2.8±2.8

Numerous tests to check stability under large variation of inputs.

For other possible explanations see e.g. Gronau and Rosner PLB'07

RTICLE PHYSICS

;ong of the electroweak penguin

chael E. Peskin

ı unexpected imbalance in how particles containing the heaviest quarks decay might reveal exotic fluences — and perhaps help to explain why matter, rather than antimatter, dominates the Universe.

ewhere in this issue, the Belle collaboration, ed at the electron–positron particle collider he high-energy accelerator laboratory KEK Japan, announces their measurement of anomalous asymmetry in the decay rates exotic particles known as B mesons (Lin l., page 332)[1]. Combined with recent meas- ments of the same decays from the BaBar laboration[2,3], a similar experiment at the nford Linear Accelerator Center (SLAC) California, the new finding provides a tan- zing glimpse of a possible new source for a y fundamental asymmetry: the dominance natter over antimatter in our Universe.

The two great principles of modern physics, antum mechanics and Einstein's relativity, ether imply that every particle in nature — ong them the quarks and the leptons, the

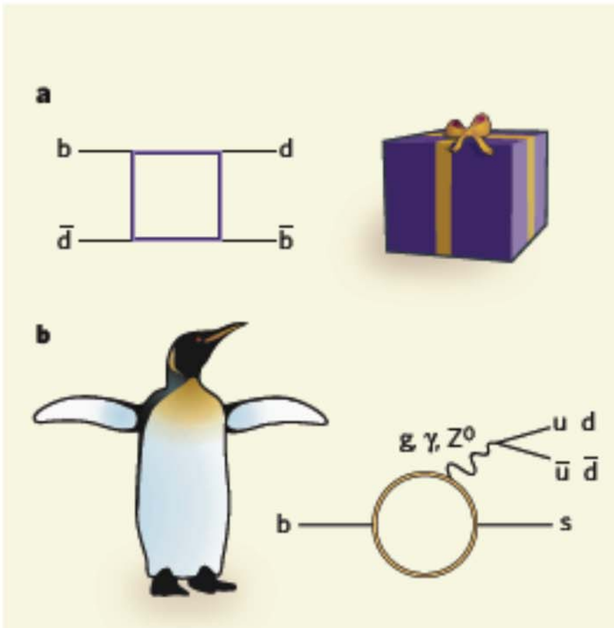


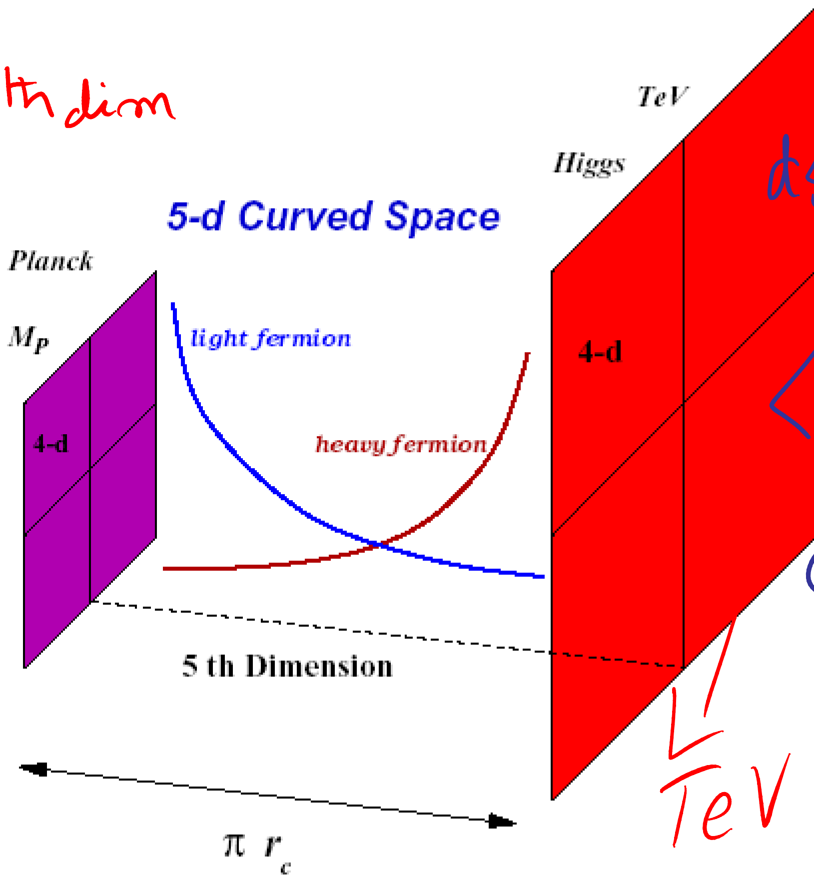
Figure 1 | Weakly decaying. A Feynman diagram represents the time evolution of a particle

time only three types of quark were known: up (u), down (d) and strange (s). But in the following decades, three more were discov- ered: charm (c), and the heavy bottom (b) and top (t) quarks. This astounding success led to the proposal[6,7] that specific experiments on B mesons — quark–antiquark pairings in which one of the particles is a b quark or $\bar{b}$ anti- quark — could test the Kobayashi–Maskawa (KM) theory directly. The idea, proposed by Pier Oddone, that these experiments could be performed by colliding two beams of different energies, one of electrons and one of positrons (the antiparticle of the electron), motivated the construction of new accelerators at KEK and SLAC. In 2002, both BaBar[8] and Belle[9] reported the first observation of a KM asymmetry in a B-meson decay.

RANDALL+SUNDRUM '99

[FIG BY H DAVOUDIASL]

Points along 5th dim correspond to diff. eff. 4d scale!



$$ds^2 = e^{-2\sigma}\eta_{\mu\nu}dx^\mu dx^\nu - r_c^2 d\phi^2$$

$$\langle H_4\rangle = e^{-\sigma}\langle H_5\rangle$$

$\langle H_4\rangle$ ~ TeV; $\langle H_5\rangle$ ~ M_P

$$\sigma = k r_c \pi$$

$k r_c \sim 12$

Figure 1: Warped geometry with flavor from fermion localization. The Higgs field resides on the TeV-brane. The size of the extra dimension is $\pi r_c \sim M_P^{-1}$.

Simultaneous resolution to hierarchy and flavor puzzles

- So heavy quarks may trigger condensation -> STRONG DYNAMICS/ DEWSB,no need 4 fundamental Higgs,SUSY

- 1,2,3, why not 4?

- 4G has significant advantage for baryogenesis over SM3 [Jarlskog & Stora('88); Branco et al('98); Hou('08)]

- Also offers new avenue for DMC

Baryogenesis

- For SM3, there is unique CP invariance [Jarlskog '87]

$$J = \mathrm{Im}\det[M_u M_u^\dagger M_d M_d^\dagger]$$
$$= 2(m_t^2 - m_u^2)(m_t^2 - m_c^2)(m_c^2 - m_u^2)$$
$$(m_b^2 - m_d^2)(m_b^2 - m_s^2)(m_s^2 - m_d^2)A$$

Area of UT

⇒ exceedingly small CP ∵ of small masses

$J/v^{12} \sim 10^{-20}$!

4G facilitates baryogenesis significantly

KM Theorem: 3 Familes 1 CP-odd phase

Family #s 2,3,4 ⇒ J_{234} / J_{123} ;

$$(m_t^2/m_c^2)(m_t'^4/m_t^4)(m_b^2/m_s^2)(m_b'^4/m_b^4) \approx 10^{16}$$!!!

W. S. Hou, arXiv:0803.1234 DIG THIS!!!

DIVINE intervention

See also, F. del Aguila, J. A. Aguilar-Saavedra and G. C. Branco, Nucl. Phys. B **510**, *39 (1998); hep-ph/9703410.*

C. Jarlskog and R. Stora, Phys. Lett. B208, 288 (1988)

Localization parameters

Quarks	c^D	c^S	m_q(SM) (GeV)	m_q^{KK}/m_g^{KK}
$\begin{pmatrix} u \\ d \end{pmatrix}$	0.5	$\begin{pmatrix} -1.4 \\ -0.7 \end{pmatrix}$	$\begin{pmatrix} 3.5 \times 10^{-14} \\ 4.8 \times 10^{-3} \end{pmatrix}$	$1.0, \begin{pmatrix} 1.5 \\ 1.1 \end{pmatrix}$
$\begin{pmatrix} c \\ s \end{pmatrix}$	0.5	$\begin{pmatrix} -0.53 \\ -0.61 \end{pmatrix}$	$\begin{pmatrix} 1.2 \\ 0.11 \end{pmatrix}$	$1.0, \begin{pmatrix} 1.0 \\ 1.0 \end{pmatrix}$
$\begin{pmatrix} t \\ b \end{pmatrix}$	0.4	$\begin{pmatrix} \cdots \\ -0.52 \end{pmatrix}$	$\begin{pmatrix} 170.6 \\ 4.1 \end{pmatrix}$	$1.0, \begin{pmatrix} \cdots \\ 1.0 \end{pmatrix}$

Davoudiasl & A.S. PRD '07

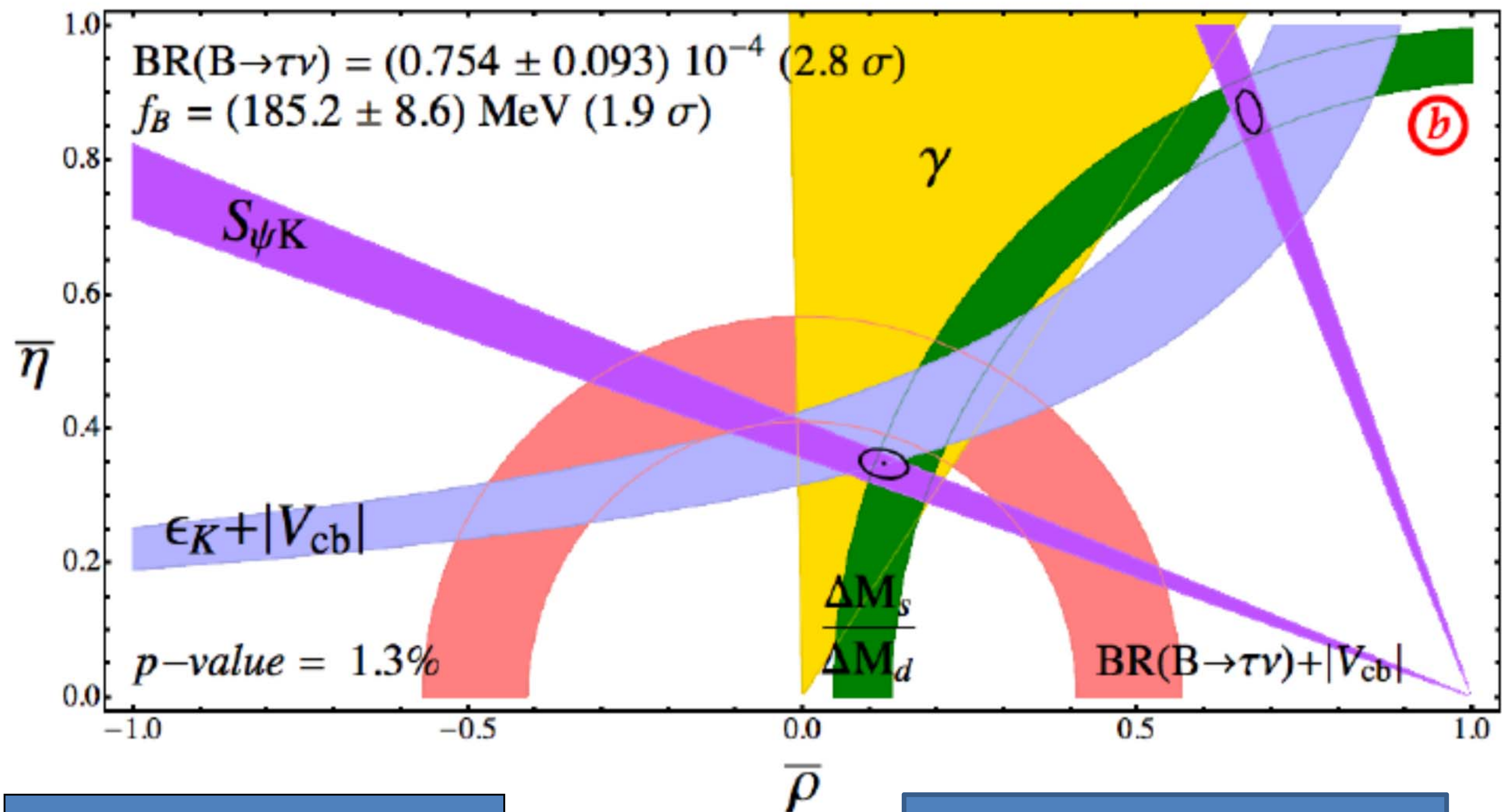
Various explanations

Explanations of the LHCb result in SM, and in NP models:

- Isidori et.al. arxiv:1103.5785 $\Rightarrow$ NP explanation in a model independent way
- Brod et.al. arxiv:1111.4987 $\Rightarrow$ Large $1/m_c$ suppressed amplitude
- Rozanov et.al. arxiv:1111.5000 $\Rightarrow$ Large penguin in sequential 4th generation model
- Pirtskhalava et.al. arxiv:1112.5451 $\Rightarrow$ Badly broken $SU(3)_F$ symmetry
- Cheng et.al. arxiv:1201.0785 $\Rightarrow$ Large weak penguin annihilation contribution
- Bhattacharya et.al. arxiv:1201.2351 $\Rightarrow$ CP conserving NP in penguin
- Giudice et.al arxiv:1201.6204 $\Rightarrow$ Left-right flavour mixing via chromomagnetic operator
- Altmannshofer et.al. arxiv:1202.2866 $\Rightarrow$ Chirally enhanced chromomagnetic penguins

Hopefully many more to come....

Inputs: S(Bd->ψK), εK, ΔMs, ΔMd, Vcb, γ



Predict: Br(B->τν) & fB

Lunghi + AS '10