Topical lectures on flavor physics & CP-violation

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The 2018 Weihai High-Energy Physics School (WHEPS)

LECTURE III: OPPORTUNITIES FOR NEW PHYSICS/CP SEARCHES IN CHARM AND TAU DECAYS

Outline

- **Recapitulate: SM expectations => charm physics difficult due to non-perturbative effects**
- **Small CP symmetry violations in SM.**
- **Therefore excellent use of charm as null tests**
- **Currently, strong indications of BSM =>CP phase**
- **Esp. implications for charm**
- **Strategies to maximize charm- CP [SM and/or BSM]**
- **Illustrative examples**
- **More implications for charm of current BSM-hints**
- **In fact tau is a central player in current anomalies**
- **Possibility of BSM [-CP] in tau**
- **Illustrative examples in tau-decays**

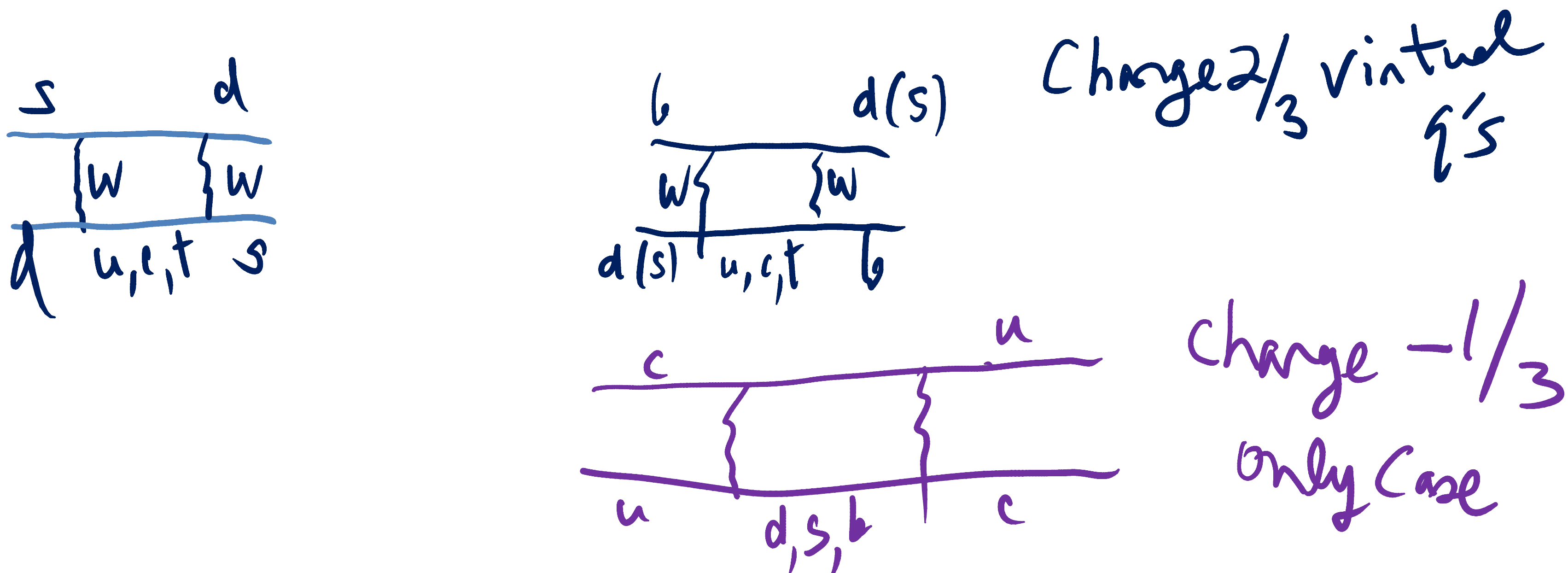
- **Summary and outlook**

Useful literature for CPV

- **Bander, Silverman and A.S., PRL 1979**
- **Bigi et al; in particular Bigi + Ayan Paul, Several papers**
- **Hou & Gerard; PRL, 1989.**
- **Feldmann, Nandi and A.S. JHEP 2012**
- **Atwood + A. S, PTEP 2013**
- **Atwood, Bar-Shalom, Eilam and A.S, Phys Rept 2001**
- **W. Altmannshofer, CKM-Vienna 2014 [talk]**
- **Jolanta Brodzicka, Implications workshop, CERN, 2017 [talk]….many very useful experimental updates**
- **Marco Gersabeck, talks at FPCP 18 & at Weihai-18**

Charm system is unique

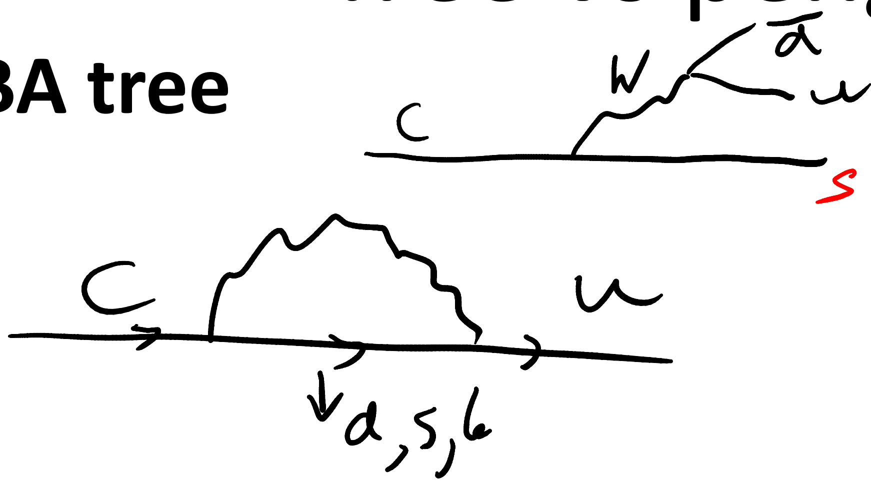
- **Distinct from K and B-mixings**



Delta F=2 mixings are an extremely valuable treasure in providing stringent constraints on NP scenarios……….

Tree vs penguin

- **CBA tree**



Not so in s, b

V_{us} $\lambda \sim .2$

V_{cb} $\lambda^2 \sim .04$

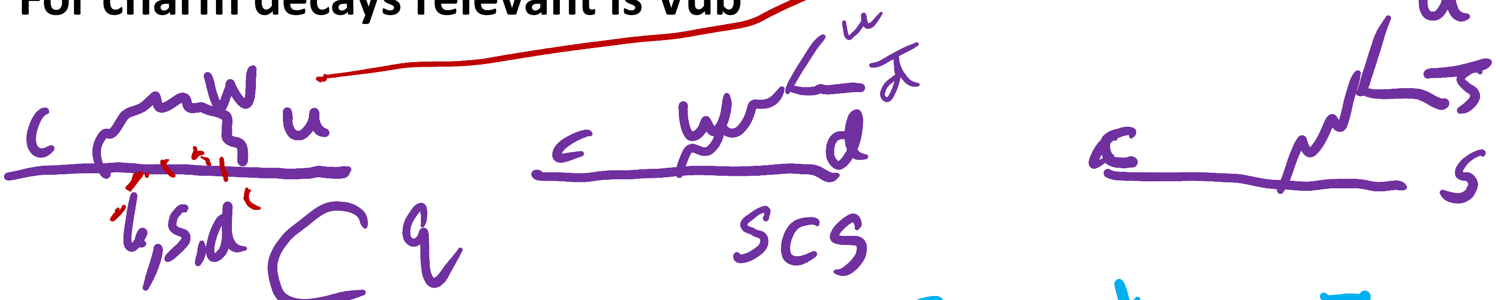
- **Penguin..partial cancellation between d,s**
- **Also $(mb/mW)^2 \ll (mt/mW)^2$**
- **So corrections due to c-penguin are much muted compared K and B decays**

SM expectation…DCP

- Dir CP….. See Bander, Silverman + AS, PRL 1979 for DCP when mq >> lamda_QCD…anticipate large corrections for charm from s-quark[K-decays]
- Key points: Penguin-Tree interference; SCS modes……Hall mark of BSS'79
- Need suitable simple changes
- SM CKM phase either in Vub or in Vtd
- For charm decays relevant is Vub

non-perturbative

$\rightarrow m_c^2 > 4[m_s^2, m_d^2]$



C_9

$DCP \sim \frac{Im[V_{cb} V_{ub}^* * \lambda]}{\lambda^2} \sim \lambda^4 \sim 10^{-3}$

ENhance by CLS Tree etc $\propto N^2 \lambda^4 \sim 10^{-2}$!!

DIFFICULT

See later

$\Delta A_{CP} = A_{CP}(D^0 \rightarrow K^+K^-) - A_{CP}(D^0 \rightarrow \pi^+\pi^-)$

- Simple & sensitive

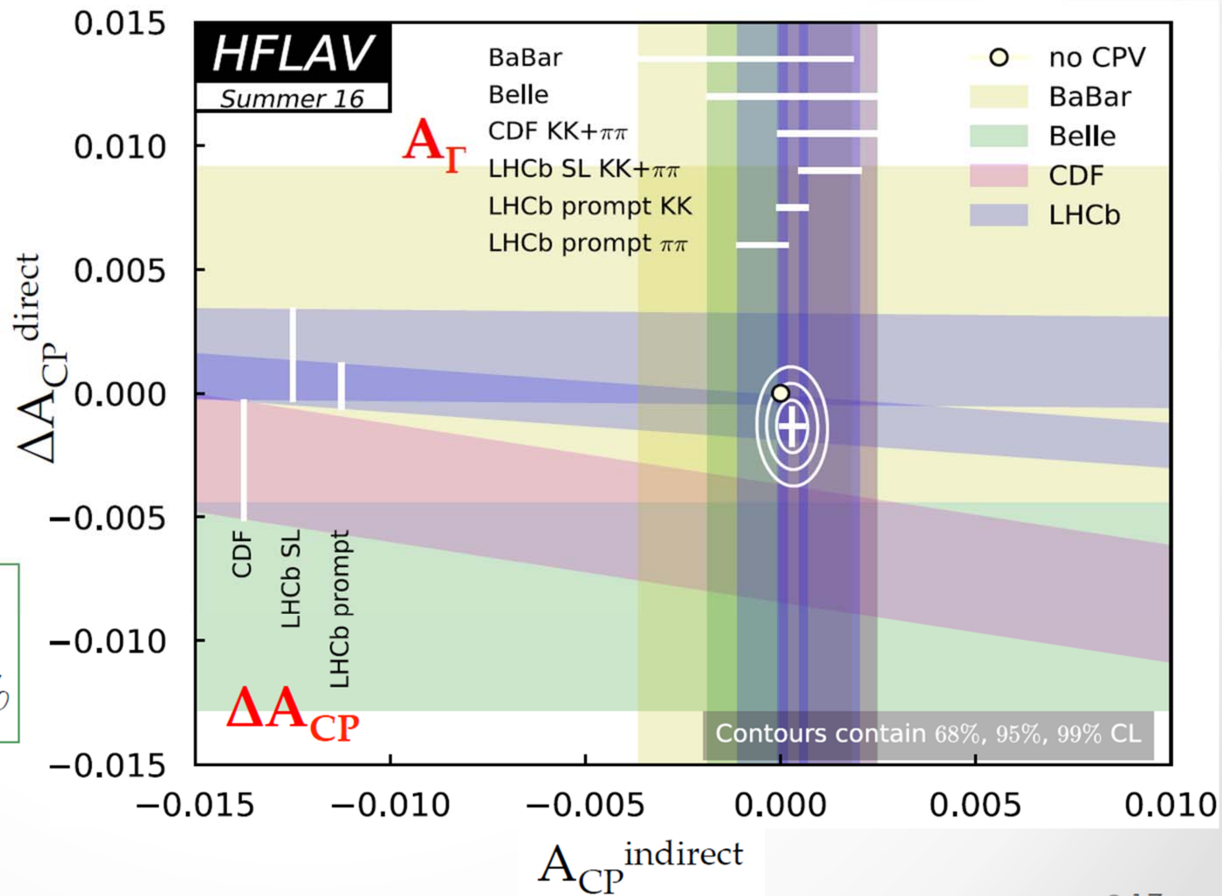
$$\Delta A_{CP} \simeq \left[A_{CP}^{\text{direct}}(KK) - A_{CP}^{\text{direct}}(\pi\pi)\right] + \frac{\Delta\langle t\rangle}{\tau_D} A_{CP}^{\text{indirect}}$$

- In SM: $|\Delta A_{CP}^{\text{direct}}| \leq 0.6\%$

?

- HFLAV average

$$\Delta A_{CP}^{direct} = (-0.13 \pm 0.07)\%$$
$$A_{CP}^{indirect} = (0.030 \pm 0.026)\%$$



Excitement from LHCb : CIRCA 2012

from D^0-$\bar{D}^0$ mixing, and $A_{\rm CP}^{\rm ind}$ stems from the interference of mixing and decay. Recent results from the LHCb experiment [18] on CP asymmetries in D^0 decays,

$$\Delta A_{\rm CP}^{\rm dir} \equiv A_{\rm CP}^{\rm dir}(K^+K^-) - A_{\rm CP}^{\rm dir}(\pi^+\pi^-) = -\,(0.82 \pm 0.21 \pm 0.11)\,\%\,, \quad (1.3)$$

indicate a 3.5σ deviation from 0, with a large amount of experimental systematics cancelling

[18] LHCb collaboration, R. Aaij et al., *Evidence for CP-violation in time-integrated $D0 \to h^-h^+$ decay rates*, *Phys. Rev. Lett.* **108** (2012) 111602 [arXiv:1112.0938] [INSPIRE].

Unfortunately Short lived excitement

BEST CHANCE IN A VERY LONG TIME OF POSSIBLE SIGHTINGS OF BSM

Anomalies galore!

- RD(*) ~ 4σ(?)
- RK(*): 2.6σ(R_K);
- g -2…BNL =>FNAL expt… ~ 3.6σ major lattice progress by RBC-UKQCD & others
- Ɛ': a personal obsession….for a long^3 time=>'cause of the strong conviction that it is super-sensitive to NP EVER LOOMING

216[PRL 2015] => ~1200 now => ~1400

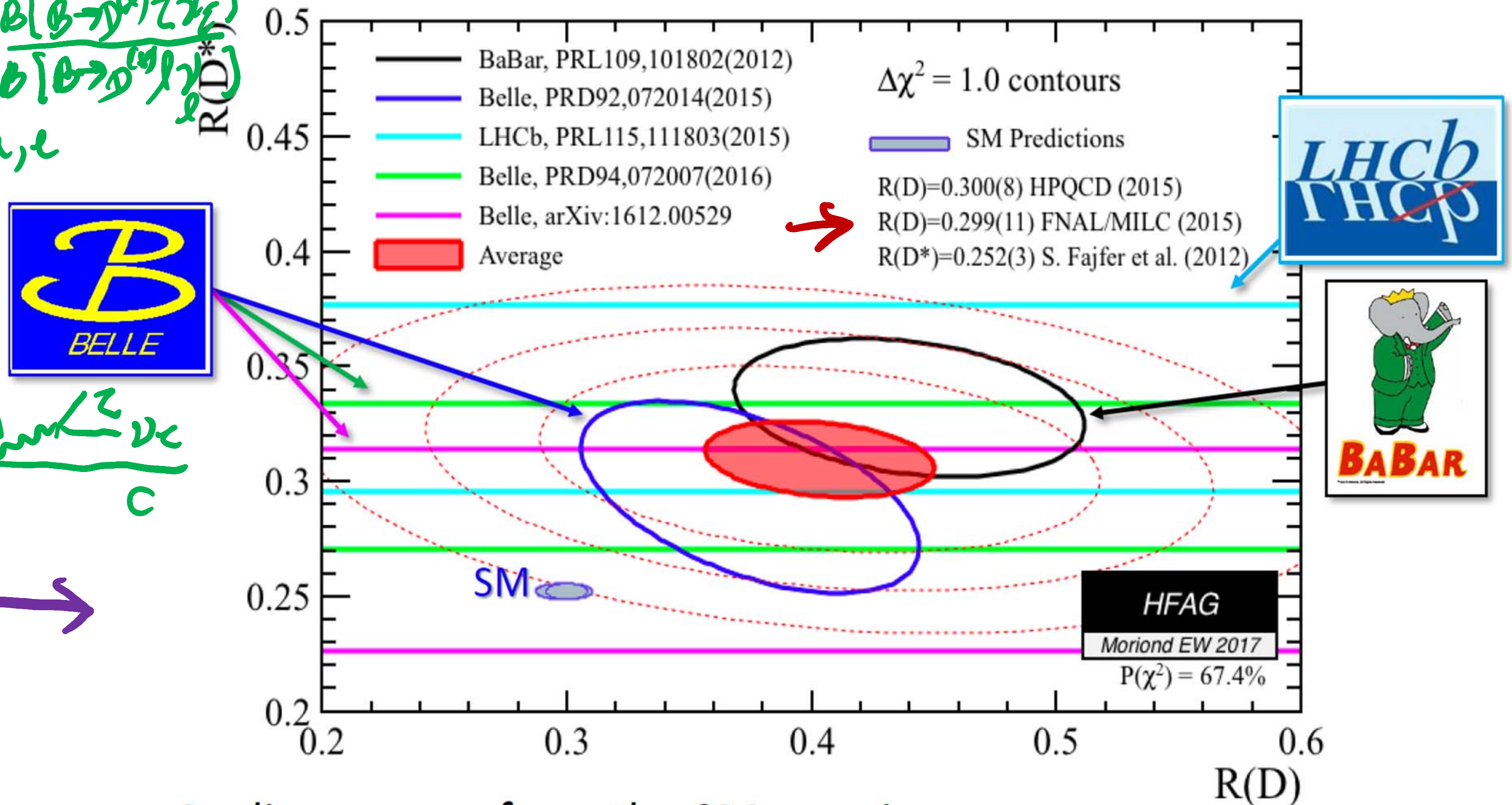
[2.1σ (2.9σ?) => ??] …..few more months to new results

In seeking BSM scenarios it is important to keep all these [INCLUDING ε'] + Higgs radiative stability in mind

■ $R\left(D^{(*)}\right)$ by HFAG

Hirose [BELLE]@EW MORIOND Mar. 2017

11/15



- ~4σ discrepancy from the SM remains
  - All the experiments show the larger $R\left(D^{(*)}\right)$ than the SM
- More precise measurements at Belle II and LHCb are essential

Belle deviations quite mild

Lepton universality tests

LHCb introduced such v. well defined ratios

- In the SM, ratios

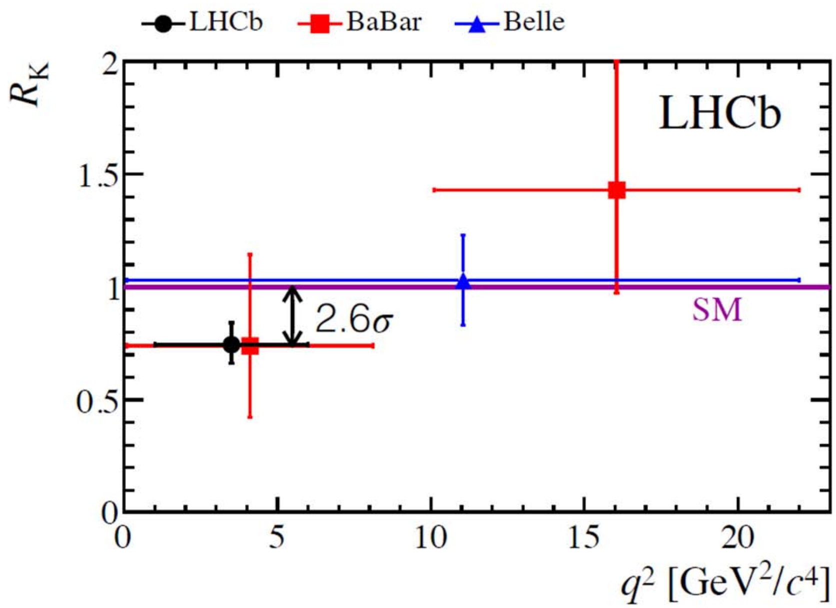
$$R_K = \frac{\int d\Gamma[B^+ \to K^+\mu^+\mu^-]/dq^2 \cdot dq^2}{\int d\Gamma[B^+ \to K^+e^+e^-]/dq^2 \cdot dq^2}$$

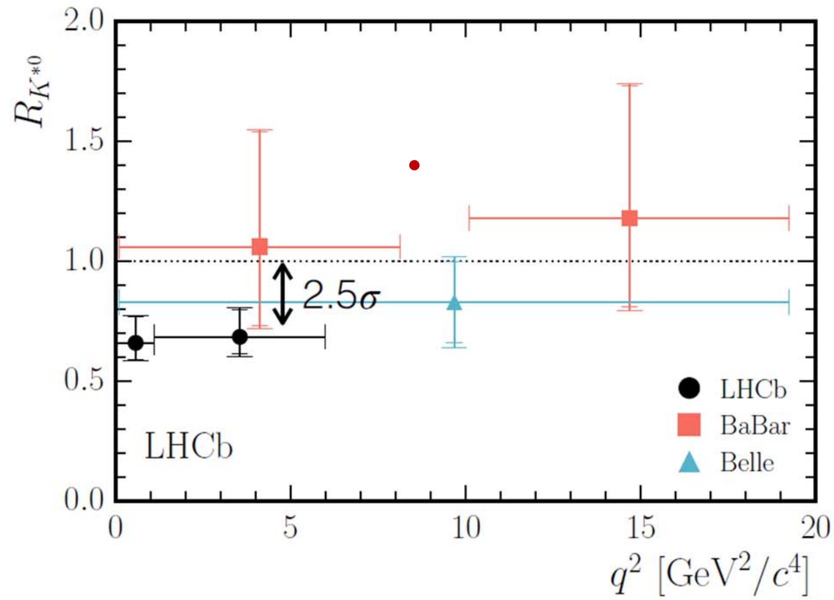
only differ from unity by phase space — the dominant SM processes couple equally to the different lepton flavours.

- Theoretically clean since hadronic uncertainties cancel in the ratio.
- Experimentally challenging due to differences in muon/electron reconstruction (in particular Bremsstrahlung from the electrons).
    - ➡ Take double ratios with $B \to J/\psi X$ decays to cancel possible sources of systematic uncertainty.
    - ➡ Correct for migration of events in q^2 due to FSR/Bremsstrahlung using MC (with PHOTOS).

Lepton universality tests

- We have interesting hints of non-universal lepton couplings in LHCb run 1 dataset:





[LHCb , PRL113 (2014) 151601]
[LHCb, LHCb-PAPER-2017-013]
[BaBar, PRD 86 (2012) 032012]
[Belle, PRL 103 (2009) 171801]

Radiative Correction See Isidori et al

NB $R_K \simeq 0.8$ is a prediction of one class of model explaining the $B^0 \to K^{*0}\mu^+\mu^-$ angular observables, see L_μ - L_τ models
W. Altmannshofer et al. [PRD 89 (2014) 095033]

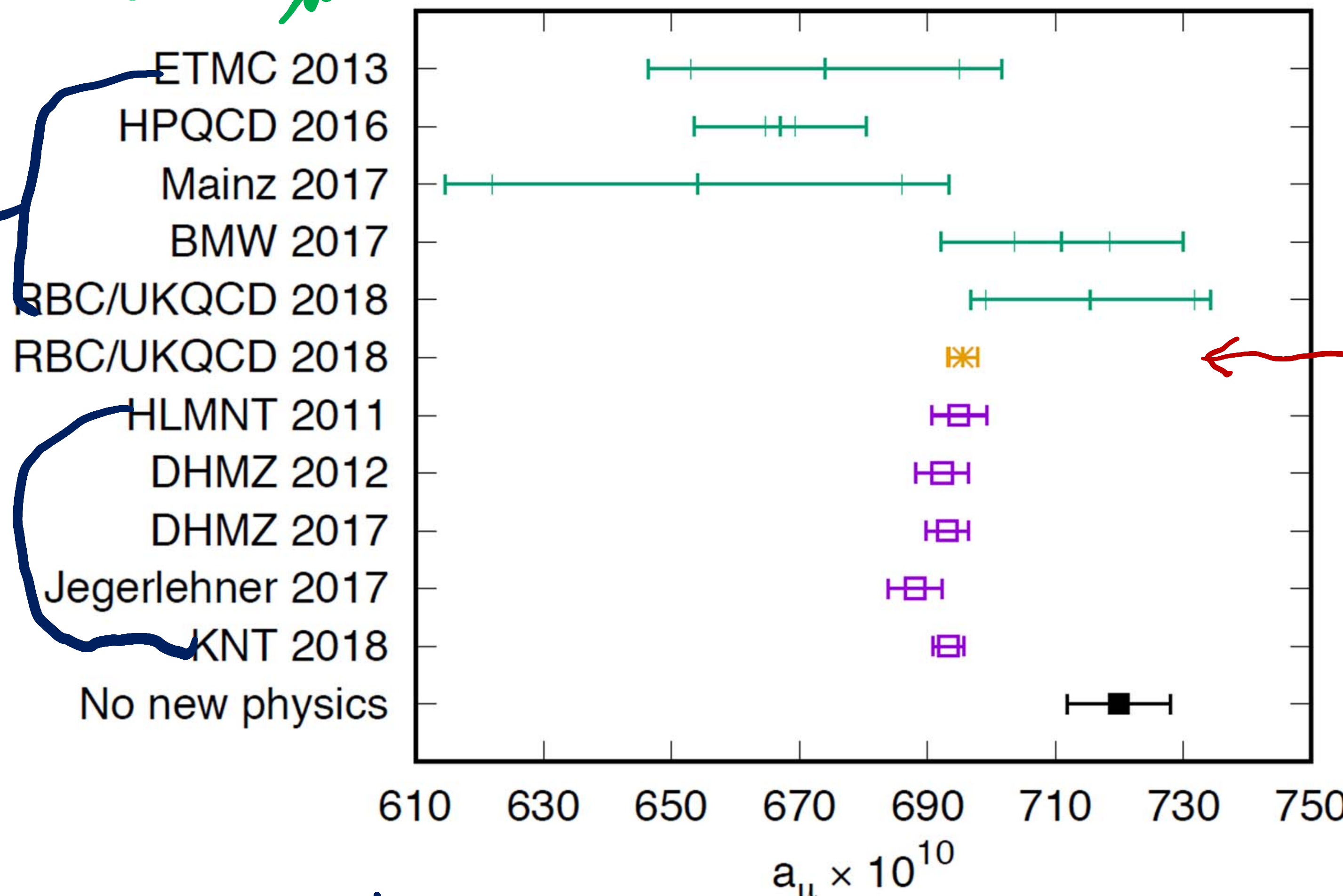
Rusa Mandal, PhD Thesis [IMSc Chennai]

- Another hint of deviation (at a level of more than 3σ), for a particular neutral-current decay mode is evinced by $B_s \to \phi\mu\mu$ [8, 62, 63]. LHCb

$$\Phi \equiv \frac{d}{dq^2}\mathrm{BR}(B_s \to \phi\mu\mu)\Big|_{q^2\in[1:6]\,\mathrm{GeV}^2} = \begin{cases} \left(2.58^{+0.33}_{-0.31} \pm 0.08 \pm 0.19\right) \times 10^{-8}\ \mathrm{GeV}^{-2} & \text{(exp.)} \\ (4.81 \pm 0.56) \times 10^{-8}\ \mathrm{GeV}^{-2} & \text{(SM)}\,. \end{cases} \quad (6.2.3)$$

where $q^2 = m^2_{\mu\mu}$. Intriguingly, the q^2 region where this measurement has relatively low error (and data is quoted) is virtually the same as that for R_K and $R^{\mathrm{central}}_{K^*}$. This (g-2)$_\mu$ on + off the Lattice

PURE Lattice



Pheno

C Lehner et al RBC-UKQCD HYBERID

SUMMARY: C. LEHNER (BNL)

We need to improve the precision of our pure lattice result so that it can distinguish the "no new physics" results from the cluster of precise R-ratio results.

Lunch Seminar 03/09/18

Possible sightings of new physics

- An important consequence of NP is that will also be accompanied by new CP-odd phase[s]….

- This possibility we will explore a bit further

Implications of CPT

Based on

Hou and Gerard, **Phys.Rev.Lett. 62 (1989) 855**

Atwood, Bar-Shalom, Eilam and A.S, **Phys.Rept. 347 (2001) 1-222**

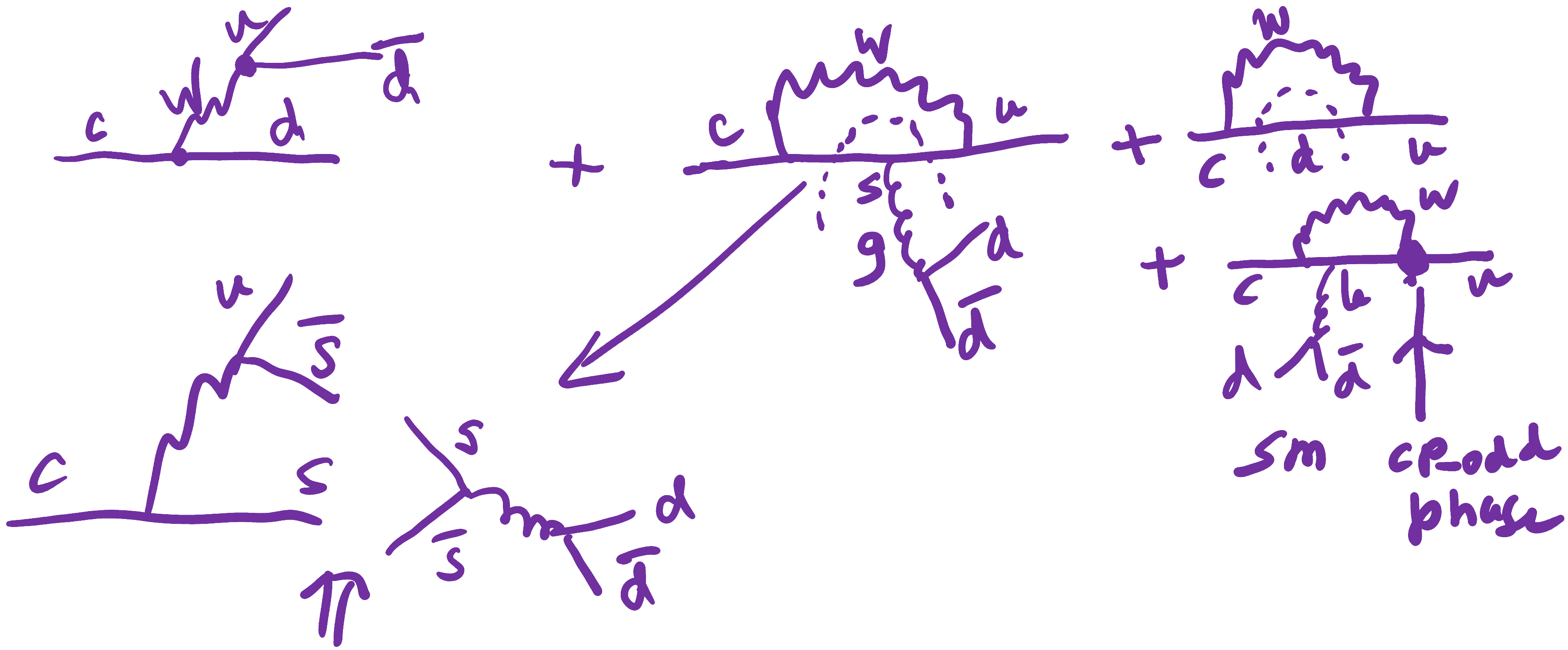
Atwood and A.S, PTEP 2013 (2013) no.9, 093B05

CP ⇔ CPT

- A classic test for CPV is the partial rate asymmetry:
- $$\alpha_x = \frac{\Gamma(D \to X) - \Gamma(\bar{D} \to \bar{X})}{\Gamma(D \to X) + \Gamma(\bar{D} \to \bar{X})}$$

Consider such rate asymmetries in 2 final states:

$c \to u s \bar{s}$ & $c \to u d \bar{d}$

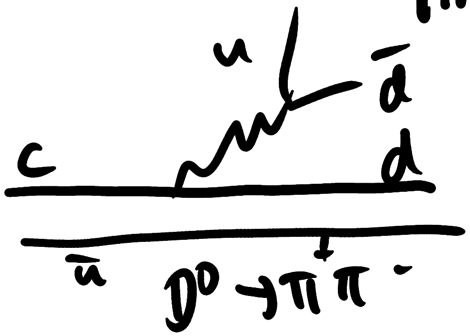


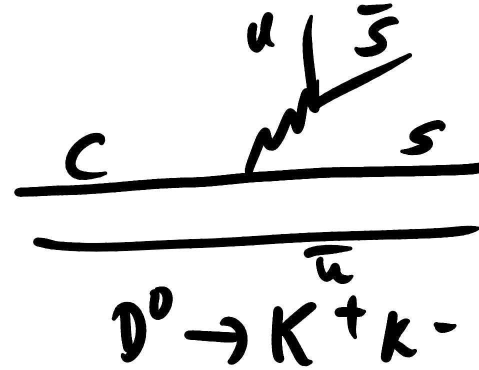
on-shell rescattering phase

CP-even phase ⇒ Total amplitude for $c \to u d \bar{d}$ is complex

Implications of CPT

ILLUSTRATIVE EXAMPLE





$\Gamma_D = \Gamma_{\bar{D}}$ ↑

See ATWOOD + AS PTEP 2012

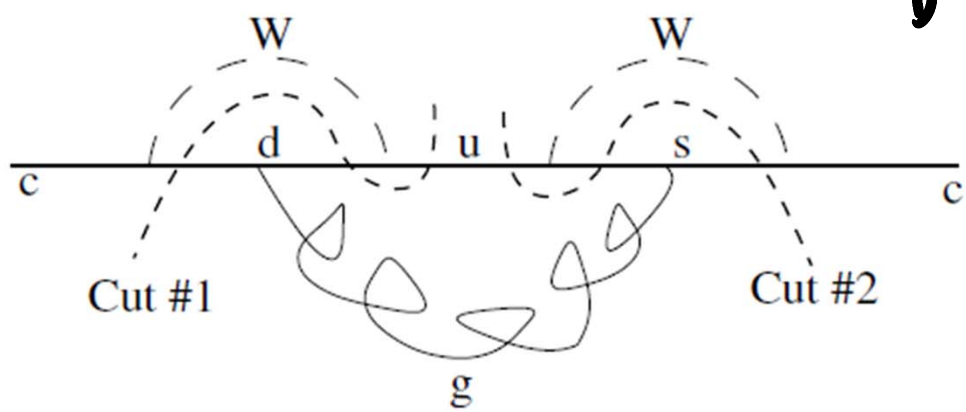


FIG. 1: The unitarity graph showing the CPT identity Eqn. 6 for the quark level SCS charm decay. Cut #1 indicated in the figure shows the case where the decay is $c \to d\bar{d}u$ with a $s\bar{s}u$ intermediate state providing the strong phase. Conversely, cut #2 indicated in the figure shows the case 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

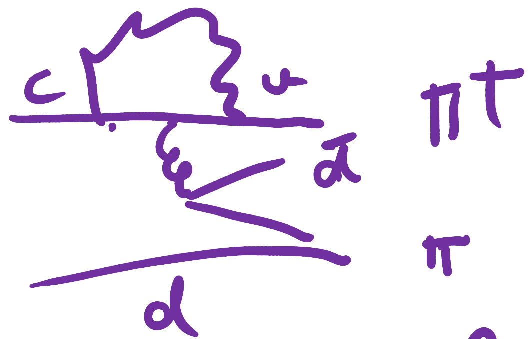
CPT $\Rightarrow$ $\sum_X \Delta\Gamma(D \to X) \equiv \sum_X [\Gamma(D \to X) - \Gamma(\bar{D} \to \bar{X})] = 0$

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

$BR\ D^0 \to K\bar{K} \sim 4\times10^{-3}$

$D^0 \to \pi\pi \quad 1.4\times10^{-3}$

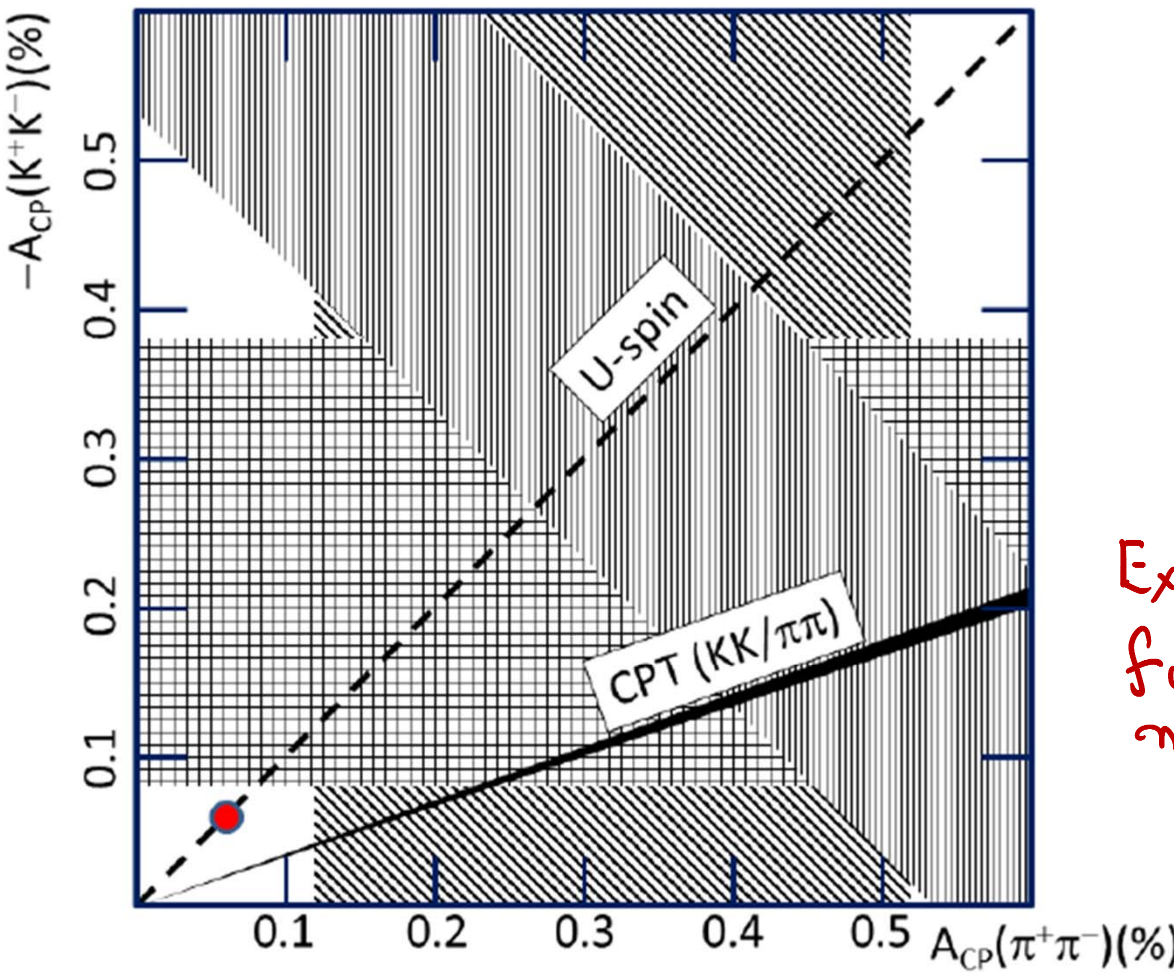
$T_{\pi\pi}$



$$\alpha_{\pi\pi} \Rightarrow \frac{\mathrm{Im}\,P * T_{\pi\pi}}{|T_{\pi\pi}|^2} \sim \frac{\mathrm{Im}\,P}{T_{\pi\pi}} \sim \frac{\mathrm{Im}\,P}{\sqrt{Br\ D\to\pi\pi}}$$

$$\frac{\alpha_{\pi\pi}}{\alpha_{KK}} \sim \sqrt{\frac{4}{1.4}} \sim 1.7$$

$$\alpha_{KK} \Rightarrow \frac{\mathrm{Im}\,P * T_{KK}}{|T_{KK}|^2} \sim \frac{\mathrm{Im}\,P}{T_{KK}} \sim \frac{\mathrm{Im}\,P}{\sqrt{Br\ D\to KK}}$$



Expectation for future measurements

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

PLB 767 (2017) 177-187

$A_{CP}(D^0 \to K^+K^-)$ & $A_{CP}(D^0 \to \pi^+\pi^-)$

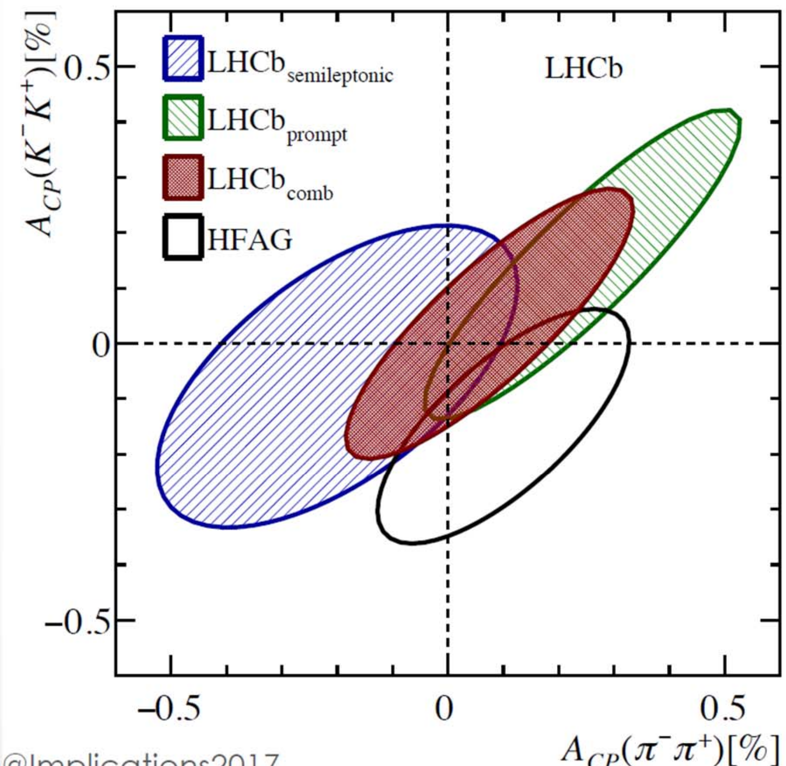
- Individual A_{CP}(KK), pion-tagged sample

$$A_{CP}(K^+K^-) = (0.14 \pm 0.15 \pm 0.10)\%$$

- Combine with ΔA_{CP} ⇨

$$A_{CP}(\pi^+\pi^-) = A_{CP}(K^+K^-) - \Delta A_{CP} = (0.24 \pm 0.15 \pm 0.11)\%$$

Central values seem consistent with expectation from CPT but errors large



- Combine with results from muon-tagged sample
  JHEP07, 041 (2014)
  ⇨ LHCb combination

- Both A_{CP}'s consistent with zero

Amp ~ a + A   a << A

Atwood + AS PTEP'12

→ smaller amplitude
→ larger "

while $A_{\rm CP}(f) \propto a/A$. If we want to observe the CP violation with a significance of N_σ, the number of mesons required is $N = N_\sigma^2/(\mathrm{Br}A_{\rm CP}^2)$. In terms of the amplitudes then,

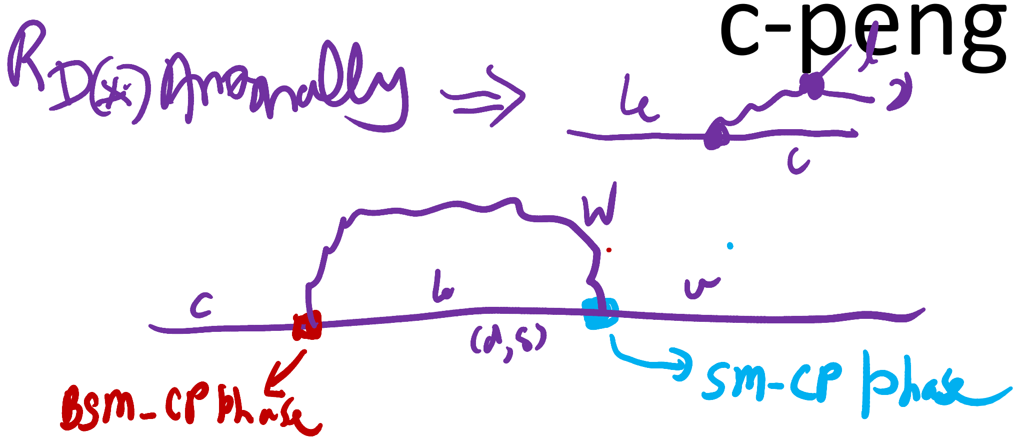
D(s)

$$N = N_\sigma^2/(\mathrm{Br}A_{\rm CP}^2) \propto \frac{N_\sigma^2}{|A|^2|a/A|^2} \propto \frac{N_\sigma^2}{|a|^2}. \tag{11}$$

So that, generally, N depends on a but is independent of A, but a smaller value of A does enhance $A_{\rm CP}$; N is not affected because this is at the expense of the branching ratio. Going to a mode that has a smaller branching ratio with higher asymmetry has the advantage of reducing the effects of systematic errors and other errors that are not statistical in nature, *all other things being equal*.

Bearing all that in mind, Let's stare some at c-penguin

come



Charming Penguin

- cb has no SM-CP …whereas likely it has BSM-CP

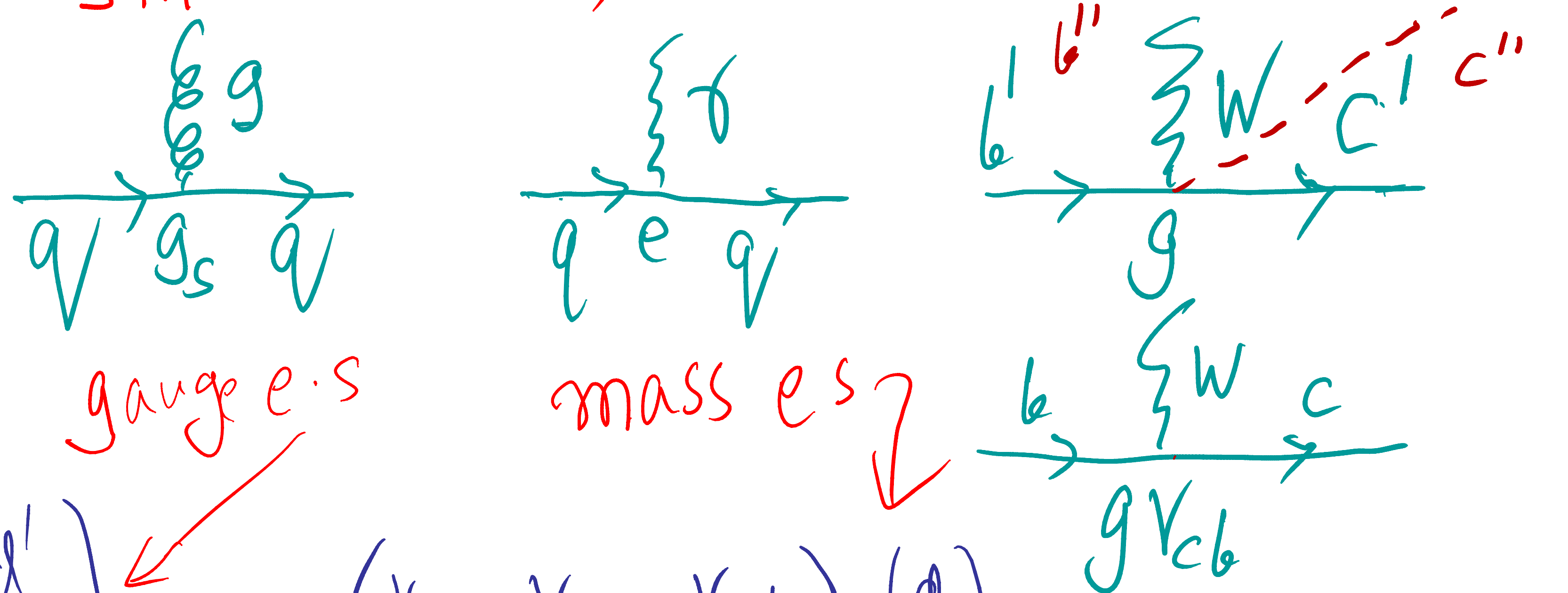
Because of B→Dτν anomally

- ub does have SM-CP …whereas likely it has no BSM-CP
- **MORAL…no matter what charm –penguin is; it is essential for DCP observation**

CKM –matrix and weak interactions

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

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



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

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

Strategy to enhance charm-CP

- Enhance penguin as much as you can
- **For charm-CP extremely important to suppress tree as much as possible:**
- A) avoid W-> ud or us making charge vector state…. e.g. rho^{+-} or K$^{*(+-)}$ …..field-current ….Sakurai VMD ideas B) go for CLS ….color suppressed FS…from tree
- C) go for CBS….cabibbo suppressed FS =>Singly Cabibbo Suppressed [SCS]….follows from Bander, Silverman and A.S PRL 1979

Improved strategy for DCP

- Improved a bit over DA+AS, PTEP 2013, Tab I
- Ds=> ρ^0 $K^{+(*)}$; $K^+ \phi$ [NOT K+*]
- D+ => $\phi\,\pi^+$ (ρ^+) ; $K^{0(*)}$ K^+ [NOT K+*]
- D+ => $\rho^0\,\pi^+$; $\pi^0\,\pi^+$ ...;[NOT ρ+]
- D0 => $K^+ K^{-(*)}$ [NOT K+*] ; $\phi\,\rho^0$
- D0 => $\rho^0\,\rho^0$; $\rho^0\,\pi^0$; $\pi^+\pi^-$; $\pi^+\rho^-$ [Not $\rho^+\,\pi^-$; $\rho^+\,\rho^-$]
- NOTES:
- 1)many FS all charged;
- 2) Some VV good for TCA esp. Ds=> ρ^0 $K^{+(*)}$, D0 => $\phi\,\rho^0$;
- 3) all π^0 always also imply $\eta^{(\prime)}$;
- 4) Special Note: ρ^0 broad width not a problem for CP tests as can always replace it with $\pi^+\pi^-$ in a mass window so long as done C-symmetrically with the antiparticle decay as well.

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
		$[K^{*+} \to \pi^+[K_s \to \pi^+\pi^-]][K^{*-} \to \pi^-[K_s \to \pi^+\pi^-]]$		—

MANY MORE MODES

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, PTEP 2012

Direct CPV in 4-body decays

- Access to P-odd amplitudes ⇨ CPV via P-violation
  [P-odd amplitude e.g. D→VV in P-wave] $D^0 \to \rho^0\rho^0, \rho^0\phi^0 \ldots$
- 2&3-body D decays: P-even ampl. only ⇨ CPV via C-violation
  [Baryons: P-odd also in 2&3-body decays]
- CPV in P-even ampl: $A_{CP} \sim \sin\Delta\phi_{weak}\ \mathbf{\sin\Delta\phi_{strong}}$
  P-odd ampl: $A_{CP} \sim \sin\Delta\phi_{weak}\ \mathbf{\cos\Delta\phi_{strong}}$ ⇦ complementary
- Triple-product method (aka T-odd): sensitive to P-odd CPV **only**

Mode	$A_{CP}^{P\text{-odd}}$ [10^{-3}]	Exp	Ref
$D^0 \to K_S\pi^+\pi^-\pi^0$	$-0.3 \pm 1.4^{+0.2}_{-0.8}$	Belle	arXiv:1703.05721
$D^0 \to K^+K^-\pi^+\pi^-$	$1.8 \pm 2.9 \pm 0.4$	LHCb	JHEP10 (2014) 005
$D^+ \to K_SK^+\pi^+\pi^-$	$-12 \pm 10 \pm 5$	Babar	PRD84 031103(2011)

Triple product:

$$C_T \equiv \vec{p}_1 \cdot \left(\vec{p}_2 \times \vec{p}_3\right)$$

Implications of CPT for CP-violating observables [I]

D. Atwood et al. / Physics Reports 347 (2001) 1–222

Table 1
Transformation properties under T_N and CP and presence or absence of final state interactions (FSI). He
present and N ≡ FSI absent

T_N	CP-violating	CP-conserving
even → Energy, PRA	Y → Needs FSI phase → requires loop	N
odd → TCA	N → Does not	Y

PTEP **2013**, 093B05 D. Atwood and A. Soni

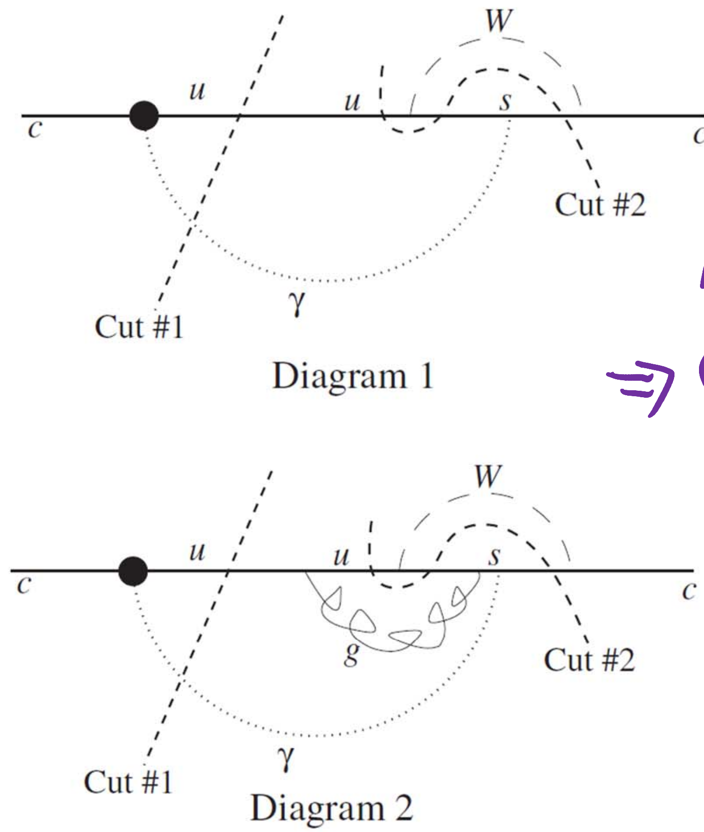


Fig. 3. This unitarity graph illustrates CPT conservation for the quark level process $c \to u\gamma$ due to NP. Diagram 1 shows the lowest order interference between NP and SM where cut #1 is for the $c\gamma$ final state and cut #2 is for an $s\bar{s}u$ final state. Cut #2 cannot be on shell. Diagram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

Implications of CPT

⇒ CPV in on-shell γ small

Off-shell gamma, Z esp. important in light of current LHCb hints of LUV

- D(s) => [π(K),ρ(K*)] + $l^+ l^-$

For l=mu, e….for LUV tests

Many ways to test CP, for example,

Compare lepton pair invariant mass

From particle to anti-particle decays

Going rare

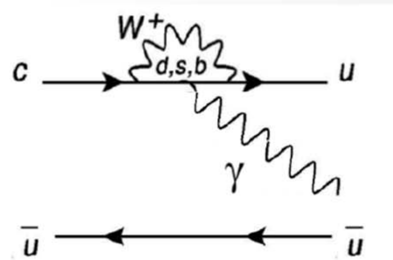
More by Simone Bifani on Wednesday

- The larger penguin contribution, the larger CPV

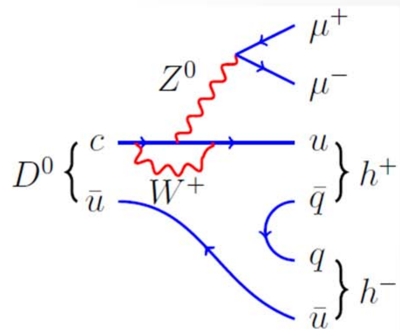
Radiative decays: there are signals to explore

- $A_{CP}(D^0 \to \rho^0\gamma) \leq 10\%$ de Boer, Hiller arXiv:1701.06392
- Full Belle data PRL118, 051801 (2017)

$$A_{CP}(D^0 \to \phi\gamma) = (-9.4 \pm 6.6 \pm 0.1)\%$$
$$A_{CP}(D^0 \to \rho^0\gamma) = (+5.6 \pm 15.1 \pm 0.6)\%$$

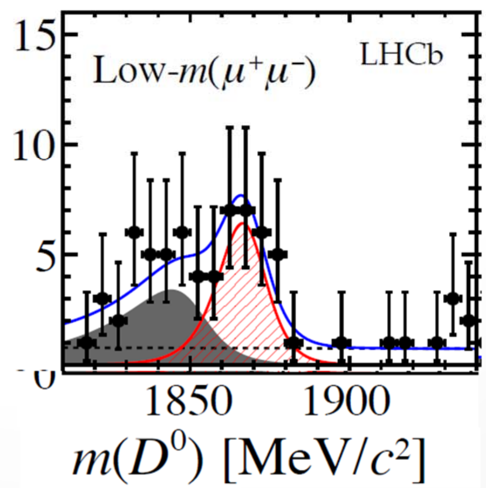


- LHCb Run2: at least double Belle signals



Leptonic decays: first signal!

- $D^0 \to \pi^+\pi^- \mu^+\mu^-$ with $m(\mu^+\mu^-) < 525$ MeV
  S = 27±6 (5.4σ)
  PRL119, 181805 (2017)



signal
$D^0 \to 4\pi$

Radiative modes

$\rho^0\gamma$	< 2.4	$\times 10^{-4}$	CL=90%	771
$\omega\gamma$	< 2.4	$\times 10^{-4}$	CL=90%	768
$\phi\gamma$	(2.73 ± 0.35)	$\times 10^{-5}$		654
$\overline{K}^*(892)^0\gamma$	(3.31 ± 0.34)	$\times 10^{-4}$		719

$\gamma\gamma$	*C1*	< 2.2	$\times 10^{-6}$	CL=90%	932
e^+e^-	*C1*	< 7.9	$\times 10^{-8}$	CL=90%	932
$\mu^+\mu^-$	*C1*	< 6.2	$\times 10^{-9}$	CL=90%	926
$\pi^0 e^+e^-$	*C1*	< 4.5	$\times 10^{-5}$	CL=90%	928
$\pi^0\mu^+\mu^-$	*C1*	< 1.8	$\times 10^{-4}$	CL=90%	915
ηe^+e^-	*C1*	< 1.1	$\times 10^{-4}$	CL=90%	852
$\eta\mu^+\mu^-$	*C1*	< 5.3	$\times 10^{-4}$	CL=90%	838
$\pi^+\pi^- e^+e^-$	*C1*	< 3.73	$\times 10^{-4}$	CL=90%	922
$\rho^0 e^+e^-$	*C1*	< 1.0	$\times 10^{-4}$	CL=90%	771
$\pi^+\pi^-\mu^+\mu^-$	*C1*	< 5.5	$\times 10^{-7}$	CL=90%	894
$\rho^0\mu^+\mu^-$	*C1*	< 2.2	$\times 10^{-5}$	CL=90%	754

350 F.A. Harris / Nuclear Physics B (Proc. Suppl.) 162 (2006) 345–350 → 2006

Table 1
Number of events expected for one year of running. STCF expectations

Physics channel	Center-of-mass energy (GeV)	Peak luminosity (10^{33} cm^{-2} s^{-1})	Physics cross section (nb)	Number of events per year
J/ψ	3.097	0.6	~ 3400	10×10^9
τ	3.67	1.0	~ 2.4	12×10^6 →
$\psi(2S)$	3.686	1.0	~ 640	3.0×10^9 10^7?
D	3.770	1.0	~ 5	25×10^6 →
D_s	4.030	0.6	~ 0.32	1.0×10^6
D_s	4.140	0.6	~ 0.67	2.0×10^6

Expect # of τ's, D's $\gtrsim 10^9$ in the coming years

Toru Iijima @ SCGP May 31, 2018

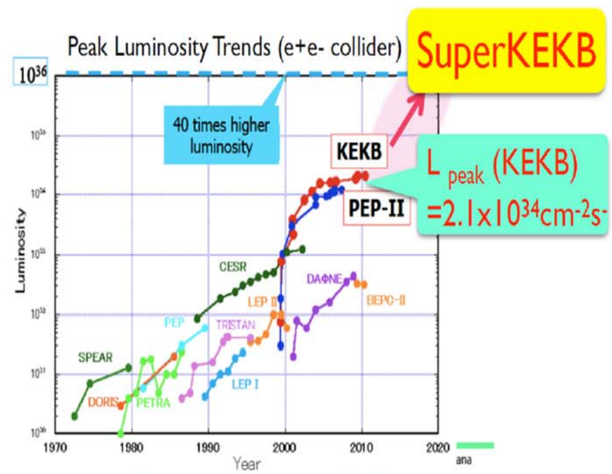
SuperKEKB/Belle II

New intensity frontier facility at KEK

- Target luminosity ; $L_{peak} = 8 \times 10^{35} cm^{-2}s^{-1}$

  $\Rightarrow \sim 10^{10}$ $B\bar{B}$, $\tau^+\tau^-$ and charms per year !

  $L_{int} > 50\ ab^{-1}$



The first particle collider after the LHC !

of D's vs Br & Asymm

$$N = N_\sigma^2/(\mathrm{Br}A_{\mathrm{CP}}^2) \propto \frac{N_\sigma^2}{|A|^2|a/A|^2} \propto \frac{N_\sigma^2}{|a|^2}. \qquad (11)$$

So that, generally, N depends on a but is independent of A, but a smaller value of A does enhance A_{CP}; N is not affected because this is at the expense of the branching ratio. Going to a mode that has a smaller branching ratio with higher asymmetry has the advantage of reducing the effects of systematic errors and other errors that are not statistical in nature, *all other things being equal*.

With $Br \sim O(10^{-3})$, $A_{CP} \sim 10^{-2}$; $N_\sigma = 3$, $\eta_{eff} \sim \frac{1}{10}$

$N \gtrsim 10^9$ puts things in interesting region

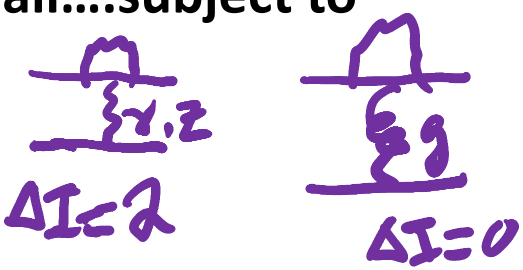
$Br \sim 10^{-2}$, $A_{cp} \sim 10^{-3} \Rightarrow N \gtrsim 10^{10}$ for 3-σ observation

CPV in charm a powerful null test

- **All CP asymmetries in charm should be vanishingly small [how small? ..Devil is in ….] ΔACP[pipi – KK] a case in point. Some theorists 1st predicted any non-vanishing**

measurement would signal genuine NP. This is based on naïve thinking w/o understanding of non-perturbative effects. Consensus now is only if its >1% a compelling case for NP

- **D=>pi+ pi0 is another very interesting case.**
- **K+, D+, B+ => pi+ pi0 are all vanishingly small….subject to considerable non perurbative corrections**



But QED, EW, $m_u \neq m_d$ break Isospin

$A_{CP}(B^+) > A_{CP}(D^+) > A_{CP}(K^+)$ SM

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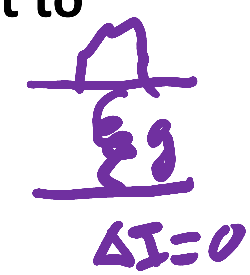

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SM expectations for DirCP: examples

- **ACP[b=>s]>ACP[c=>u] [l l]**
- **ACP[b=>d]>ACP[b=>s][l l]**
- **ACP[b=>d]>ACP[b=>s] [q q']**

All follow from CPT

Null tests:Dir CP

- A very powerful class of null tests relevant for the era of the huge data sets on the horizon and esp suited for lattice calculations is
- D, B => pi[K] l^+ l^- [diff. rate and Dir CP]
- K+, D+, B+ => pi^+ pi0
- FS is I=2 and transitions are all Delta I=3/2
- Therefore to the extent isospin is conserved
- gluonic penguins cannot contribute [only tree + (8,8) ops enter]
- Calculations are a lot simpler than eps' because disconnected diagrams cannot contribute
- However EMIV [electro –mag + isospin violations] are essential for non-vanshing SM-CPV thus rendering these as approx null tests….
- Quantitative calculation of these non-perturbative effects become essential
- One is encouraged by the fact that calculations of EMIV are becoming standard tools in many lattice calculations

Br ~ 5.5x10^-6

A_{CP} {B+ → π+ π0} < 1%. SM HYC+Chua+AS, PRD'05

DIR-CP Great Null tests now due Belle-II & LHCb

Opportunities in tau: few illustrative examples

- **1. Improving determination of magnetic and electric diploe moments.**
- **Key point : Borrow ideas determination for the top quark….i.e an "elementary fermion"**

PHYSICAL REVIEW D VOLUME 45, NUMBER 7 1 APRIL

Analysis for magnetic moment and electric dipole moment form factors of the top quark via $e^+e^- \to t\bar{t}$

D. Atwood and A. Soni
Department of Physics, Brookhaven National Laboratory, Upton, New York 11973

(Received 15 November 1991)

Phenomenological analysis for determining the magnetic moment and electic dipole moment form factors of the top quark via the reaction $e^+e^- \to t\bar{t}$, followed by the decays $t \to bW^+$ and $\bar{t} \to \bar{b}W^-$, is presented, with analytic expressions for the differential cross section and decay given. Various experimental observables are studied and their efficacy for the determination of form factors is considered and compared with the optimal resolution of form factors in the $t\bar{t}\gamma$ and $t\bar{t}Z$ vertices. We find that with a sample of 10 000 events it is possible to put limits of 10^{-18}–10^{-19} e cm for the form factors considered, evaluated at $q^2=s$ when $\sqrt{s} \approx 500$ GeV.

PACS number(s): 13.40.Fn, 13.10.+q, 14.80.Dq

Beams may be polarised

$t\bar{t}$ @ LC

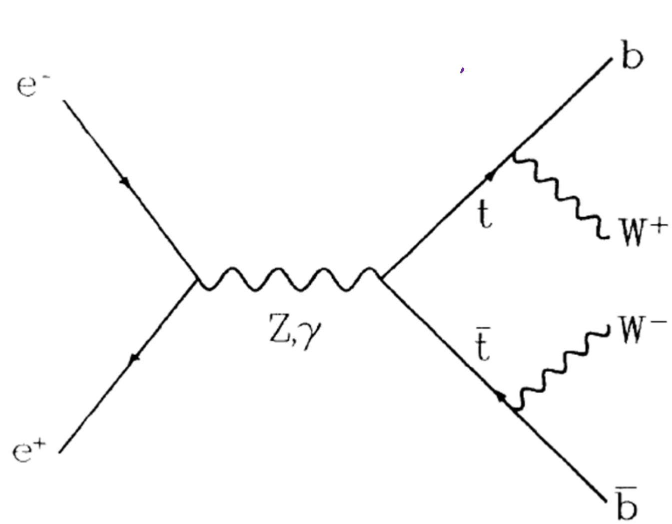
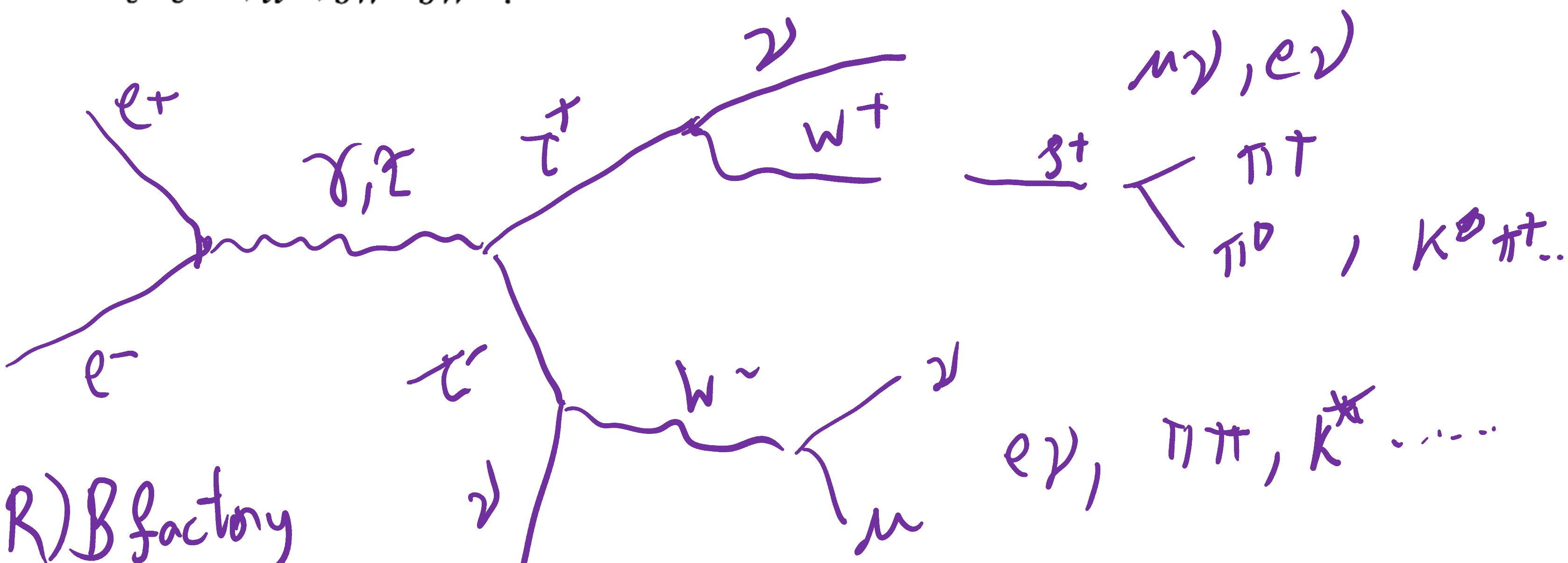


FIG. 1. Feynman diagrams for the process $e^+e^- \to t\bar{t} \to bW^+\bar{b}W^-$.



(SUPER) B factory

Many possible decay channels

- Allows you to construct many observables

- So both TN-even [e.g. energy asymmetry] as well as TN-odd [Triple Correlation Asymmetries]....are possible complicated equations given in the Appendix. It would also be desirable to consider an observable which, although not optimal, is of a simple form. Consider first the case of the imaginary MDM-type couplings [$\mathrm{Im}(C_t)$]. In this case we have considered observables of the form

$$\epsilon_{\mu\nu\sigma\rho} k_1^\mu k_2^\nu k_3^\sigma k_4^\rho (k_5 \cdot k_6) , \tag{25}$$

where

$$k_i \in \{ P_t, Q_Z, P_e, P_b, Q_b, H^+, H^- \} , \tag{26}$$

which have the correct symmetry (even under CP, odd under P_n). The momenta mentioned above in the notation of the Appendix are

$$\begin{aligned} & P_t = \bar{p}_t - p_t, \quad Q_z = p_e^+ + p_e^- , \\ & P_e = p_e^+ - p_e^- , \\ & H^\pm = 2E_W^+ \cdot p_t \, E_W^+ \pm 2E_W^- \cdot p_t \, E_W^- . \end{aligned} \tag{27}$$

Of all the operators of the above type, it was found that the operator

$$\epsilon_{\mu\nu\sigma\rho} P_b^\mu Q_z^\nu H^{+\sigma} H^{-\rho} (P_b \cdot Q_z) \tag{28}$$

is the best in both the cases of $\mathrm{Im}(C_t^\gamma)$ and $\mathrm{Im}(C_t^Z)$. The results for this operator are shown with the dashed curve in Fig. 3(a) for the case of $\mathrm{Im}(C_t^\gamma)$ and Fig. 3(b) for the case of $\mathrm{Im}(C_t^Z)$ assuming unpolarized e^+e^- beams. Note that this operator gives precision a factor of 5–10 poorer than the optimal operator.

In Fig. 3(c) we consider the measurement of the EDM, $\mathrm{Re}(D_t^\gamma)$. The curves we give are similar to those described above except that the form of the best simple operator indicated on the graph by the dashed line is

$$\epsilon_{\mu\nu\sigma\rho}P_b^\mu Q_z^\nu H^{+\sigma}H^{-\rho}\ . \tag{29}$$

Likewise, Fig. 3(d) shows a similar set of curves for the coupling $\mathrm{Re}(D_t^Z)$, where the best simple operator represented by the dashed curve is

$$\epsilon_{\mu\nu\sigma\rho}P_e^\mu Q_z^\nu H^{+\sigma}H^{-\rho}\ . \tag{30}$$

For the case of the imaginary EDM couplings, we have considered operators of either the form

$$(k_1\cdot k_2)(k_3\cdot k_4)$$

or

$$k_1\cdot k_2\ , \tag{31}$$

with the correct symmetry (CP odd, P_n even), k_i chosen as above. In both the γ and Z cases, the best operator of this form we found was

$$H^-\cdot Q_z\ . \tag{32}$$

In Figs. 3(e) and 3(f) we produce the corresponding dashed curves for the couplings $\mathrm{Im}(D_t^\gamma)$ and $\mathrm{Im}(D_t^Z)$, respectively.

From the above calculations we conclude that in the case of the real MDM couplings, $\mathrm{Re}(C_t)$, the use of an optimized operator instead of just looking at the change in the total cross section gives a factor of about 3 improvement in resolution, while using right-polarized beams gives another factor of about 3, giving a total gain using both improvements of about an order of magnitude. In the cases of $\mathrm{Im}(C_t)$, $\mathrm{Re}(D_t)$, and $\mathrm{Im}(D_t)$, we wish to

Magnetic Dipole moment determinations

unpolarised

polarized

polarized

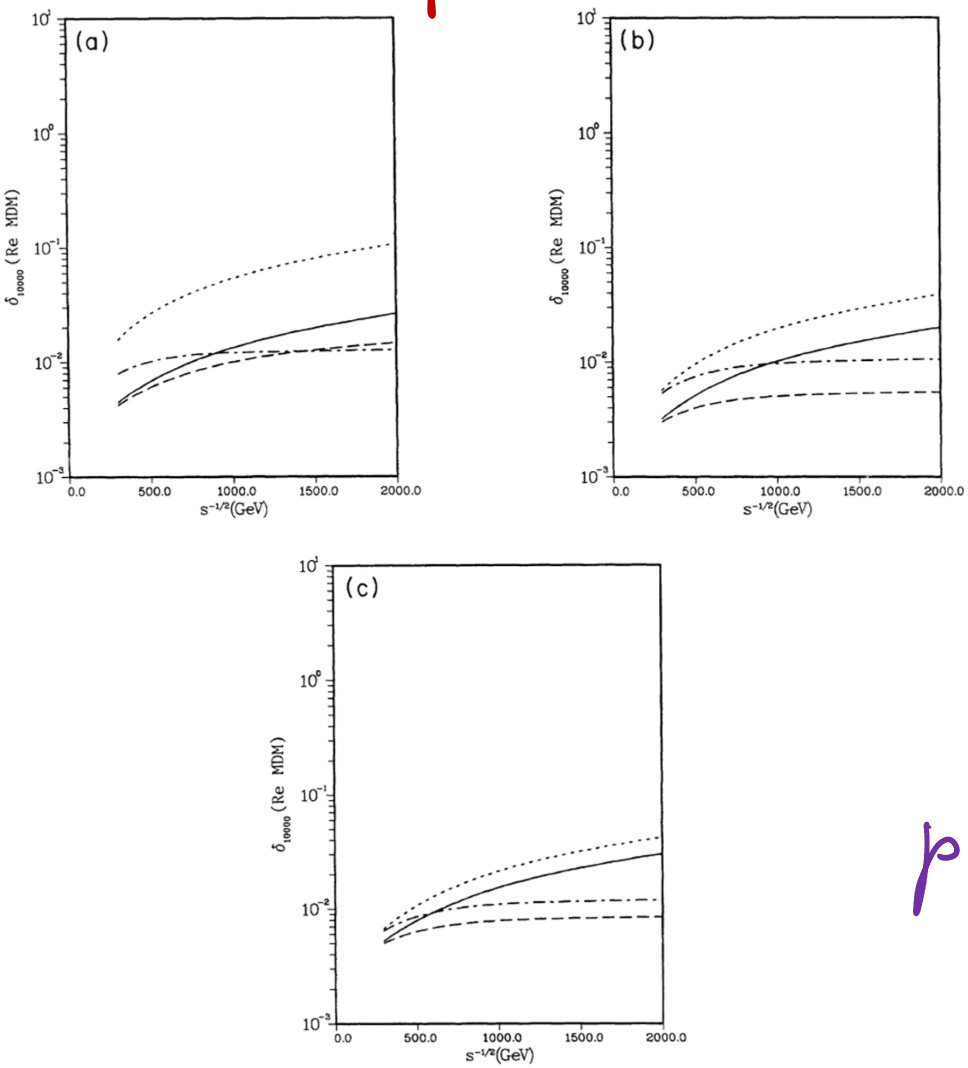


FIG. 2. δ_{10000} vs $\sqrt{s}$ is shown for various observables sensitive to Re(C). The curves shown are as follows: the dashed curve is δ_{10000} for the optimized observable for Re(C_t^γ); the solid curve is δ_{10000} using the total cross section to measure Re(C_t^γ); the dash-dot curve is δ_{10000} for the optimized observable for Re(C_t^Z); and the dotted curve is δ_{10000} using the total cross section to measure Re(C_t^Z). The polarization of the e^+e^- beams is taken to be unpolarized in (a), right polarized in (b), and left polarized in (c).

Magnetic γ

Z

Electric γ

Z

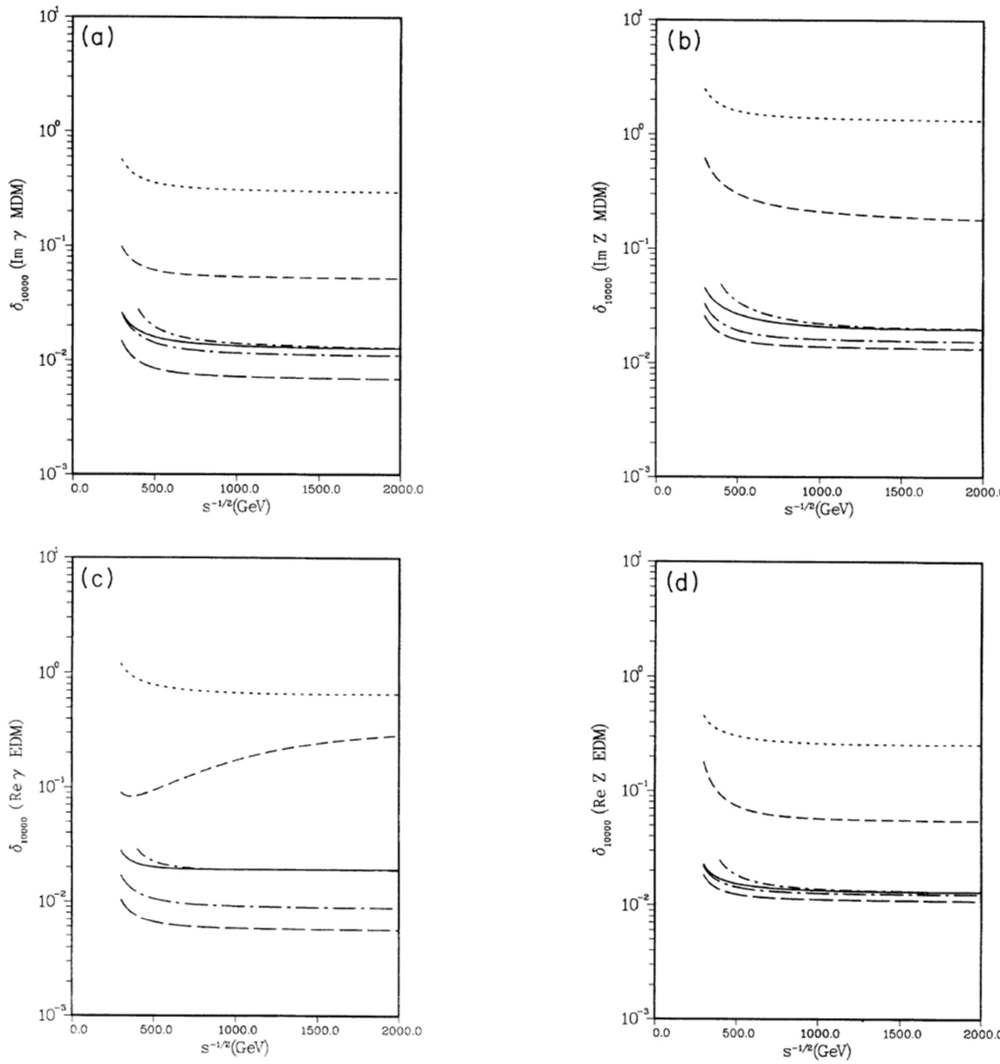


FIG. 3. Shown here is $\delta_{10\,000}$ vs $\sqrt{s}$ with respect to various couplings. The cases shown are (a) $\mathrm{Im}(C_t^\gamma)$; (b) $\mathrm{Im}(C_t^Z)$; (c) $\mathrm{Re}(D_t^\gamma)$; (d) $\mathrm{Re}(D_t^Z)$; (e) $\mathrm{Im}(D_t^\gamma)$; and (f) $\mathrm{Im}(D_t^Z)$. In each case the optimal observable for unpolarized beams using $m_t = 120$ GeV is shown with the solid curve; the optimal with left-polarized beams is shown with the long dash-dot curve; the optimal with right-polarized beams is shown with the long dash curve. The optimal curve using unpolarized beams and $m_t = 160$ GeV is shown with the short dash-dot curve; the optimal case where W-boson polarization is not measured is shown with the dotted curve. The best that can be achieved with the simple operators described in the text is shown with the dashed curve.

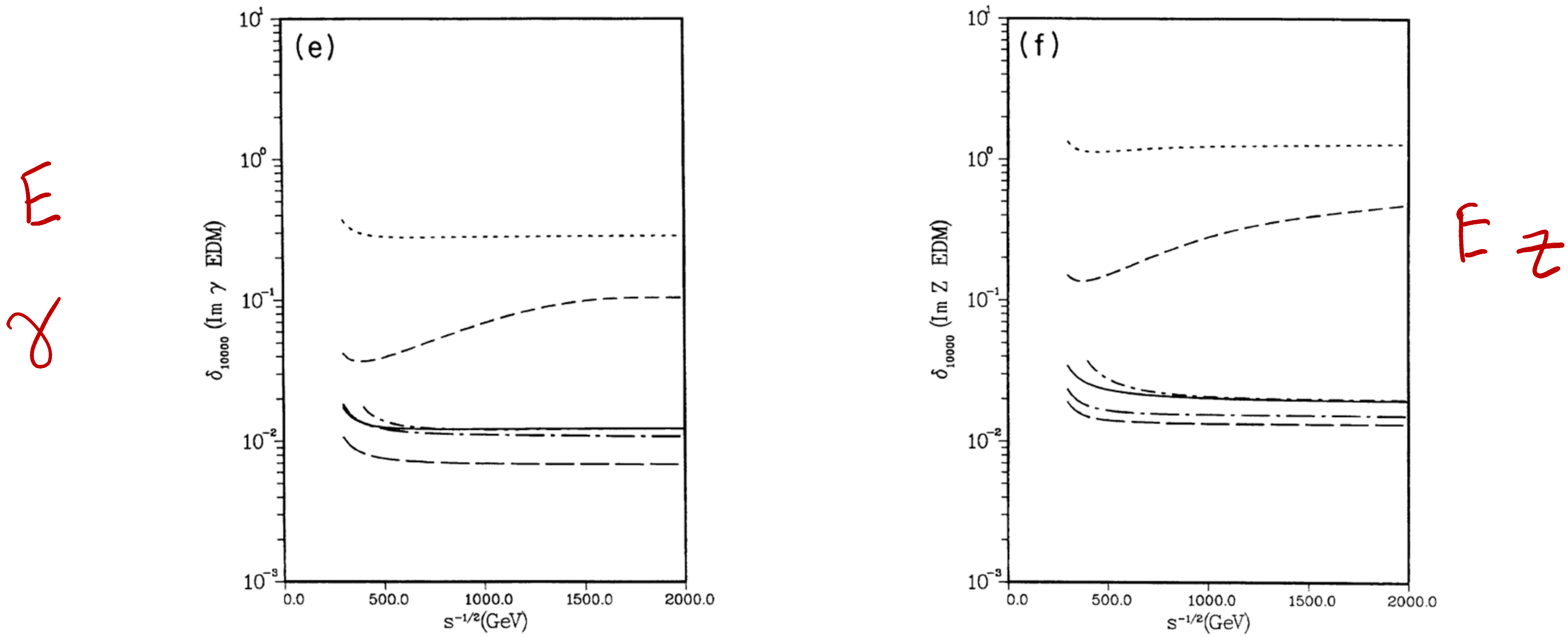


FIG. 3. (*Continued*).

III. OPTIMIZED OBSERVABLE QUANTITIES

Before defining how to measure the EDM or MDM couplings, let us consider the general problem of observing the change in the differential cross section due to the addition of any small coupling. Here, we denote the differential cross section by

$$\Sigma(\phi)d\phi \ , \tag{5}$$

where ϕ represents the relevant phase-space variables being considered (including angular and polarization variables). Suppose now that there is a small contribution to this differential cross section controlled by a parameter λ (for example, λ could be the EDM or MDM) so that if we expand the total differential cross section in terms of λ we have

$$\Sigma = \Sigma_0 + \lambda \Sigma_1 \ . \tag{6}$$

Theorem on optimised observables.

See Atwood + S
PRD 92

$$f = f_{\text{opt}} = \frac{\Sigma_1}{\Sigma_0} \ . \tag{17}$$

Usually Σ_1 is a linear combination of naive observables.

II. tau => Ks pi^- nu on and off the lattice

- **Motivation ……**
- **tau plays a central role in indications of LUV from semi-leptonic charge current RD(*) anomaly**
- **If these indications of new physics become a reality, then naturalness arguments strongly**

suggest the new physics will entail also a new CP-odd phase.

tau => Ks pi nu is an excellent final state for experimental study and a good candidate for such a BSM phase

$\tau \to \nu K^- \rho^0$ Also very good

tau=> Ks pi nu

- **Babar seems to have ~3 sigma indication of BSM CP in this channel.**

- **The role of the lattice here is envisioned for**

a precise calculation of the BR as well as

the differential rate. The rate calculation can be

normalized to tau=>K nu ….another strikingly

simple lattice calculation

Great for BELLE-II & STCF

PHYSICAL REVIEW D **85,** 031102(R) (2012)

Search for *CP* violation in the decay $\tau^- \to \pi^- K_s^0 (\geq 0\pi^0) \nu_\tau$

(*BABAR* Collaboration)

Asy ~ -4×10^{-3}

(Received 9 September 2011; published 13 February 2012)

We report a search for *CP* violation in the decay $\tau^- \to \pi^- K_S^0 (\geq 0\pi^0)\nu_\tau$ using a data set of 437×10^6 τ-lepton pairs, corresponding to an integrated luminosity of 476 fb^{-1}, collected with the *BABAR* detector at the PEP-II asymmetric-energy e^+e^- storage rings. The *CP*-violating decay-rate asymmetry is determined to be $(-0.36 \pm 0.23 \pm 0.11)\%$ approximately 2.8 standard deviations from the standard model prediction of $(0.36 \pm 0.01)\%$.

NOTE $B_r[\tau \to \nu \pi^- K^0] \sim 8 \times 10^{-3}$

$N_\tau \sim 10^9$ needed

relevant weak hadronic current is just

$$J^{W,S}_{\mu} = \bar{u}\gamma_{\mu}(1-\gamma_5)s$$

leads to one major well known exclusive mode

$$\tau \to \nu K^{+} \quad \text{via} \quad \langle 0|\bar{u}\gamma_{\mu}\gamma_5 s|K\rangle$$

From expt. : $B_r(\tau \to \nu K) = 6.96 \times 10^{-3}$

So now we also want $\langle 0 | J_\mu^{W,S} | K_S \pi^+ \rangle$

Normalizing with experimental measured Br

$$Br[\tau \to \nu K_S \pi^+] / Br[\tau \to \nu K^+]$$

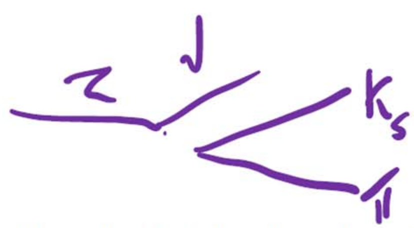
we may be able to get rid of several of the errors.

A precise calculation of the rate provides an important test of the SM in itself.

There is an interesting Crossing-Symmetry connection between the K=> pi semi-leptonic [Kl3] form factors and tau => nu Ks pi^+ ....~~by exploiting flavor SU3~~. For Kl3

Related by X Sym

q^2 [with q= p_K – p_pi], q^2 >~ 0 is positive, while in the decay amplitude relevant to tau => nu Ks pi, Q^2 [with Q = p_K + p_pi], Q^2 > ~0, is positive.



Complex amplitude

In the tau decay calculation, final-state interaction phase enters and it'd be very interesting if this complex amplitude can be calculated on the lattice.

It'd also be very useful to study the case when pi^+ can be replaced with rho^+,

if possible.

Strong [i.e. CP-conserving] FS interaction phases

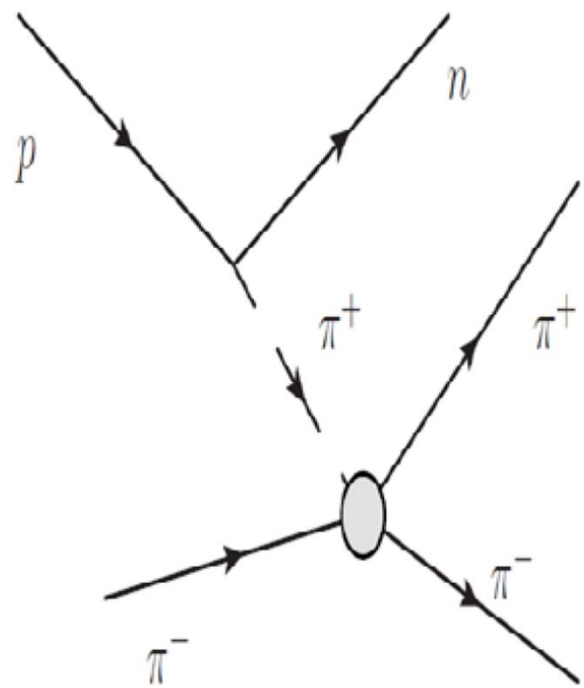
- We can calculate these phases on the lattice

for K, pi scattering see RBC-UKQCD for K-pi

and also now for pi pi

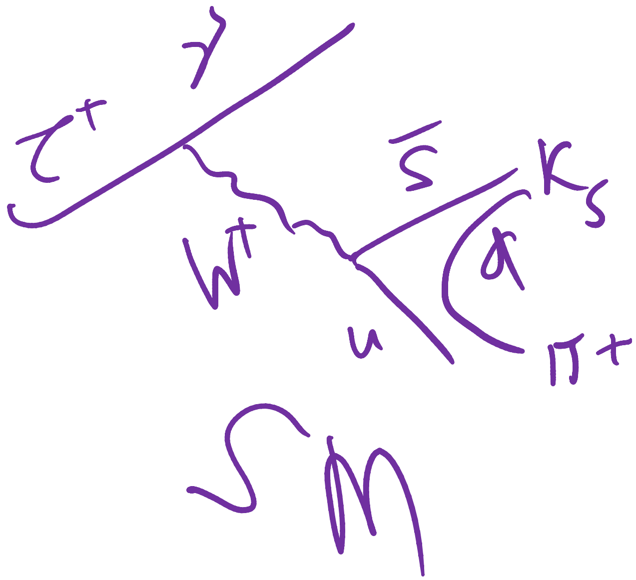
Tianle Wang [RBC-UKQCD]
Talk @ Lattice 2018

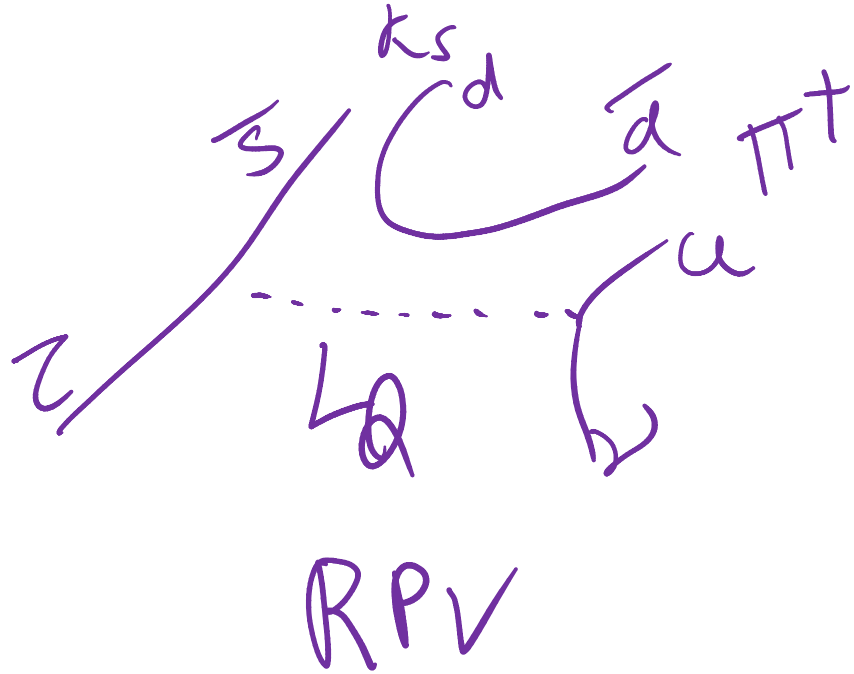
However, flavor SU(3) can also be used to relate them to pi pi scattering phases from Kl4 and from pi N => N pi pi following Colangelo et al.....get K pi phases upto SU(3) corrrections



p
n
π^+
π^+
π^-
π^-

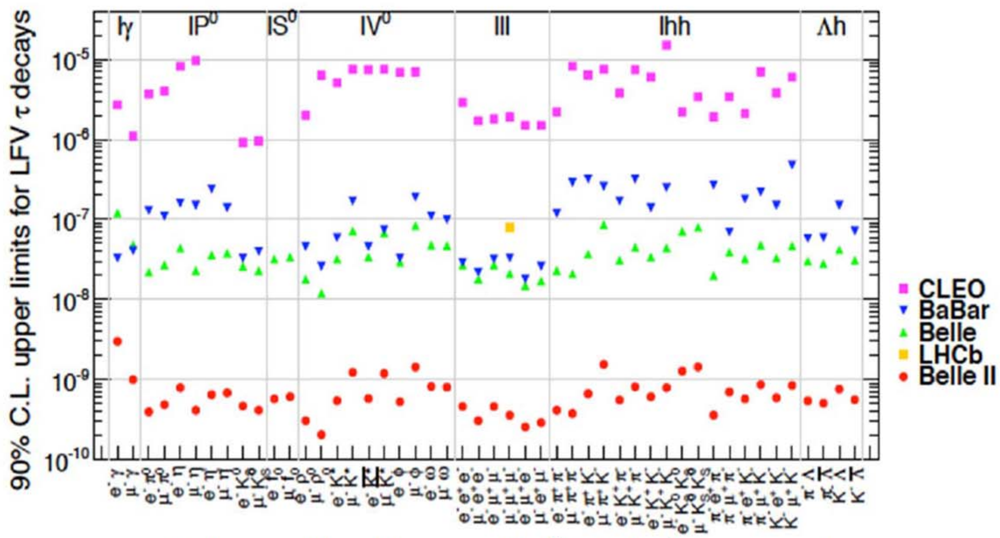
Possible NP in tau=> Ks pi nu





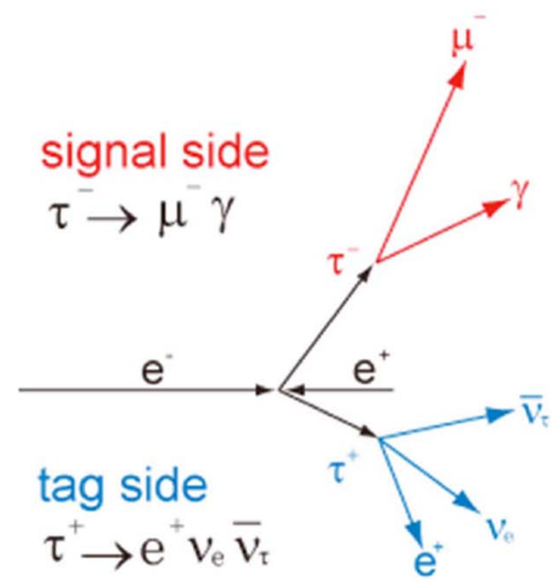
WIP ON AND OFF THE LATTICE ON THIS CLASS OF STUDY

τ Lepton Flavor Violation



Note vertical log-scale (50 ab^{-1} assumed for Belle II; 3 fb^{-1} result for LHCb

Example of the decay topology



<u>Belle II will push many limits below 10^{-9}</u> ;

LHCb, CMS and ATLAS have very *limited* capabilities.

Also $\tau \to 3\mu$ $\to \mu ee$

LHC high pt: The modes $\tau \to \mu\gamma$ and $\tau \to \mu\, h^+ h^-$ provide important constraints on $H \to \mu\tau$

GORRILLA + GODZILLA

LFUV WITH $B^0_s \rightarrow K^{*0}\,\mu^+\mu^-$

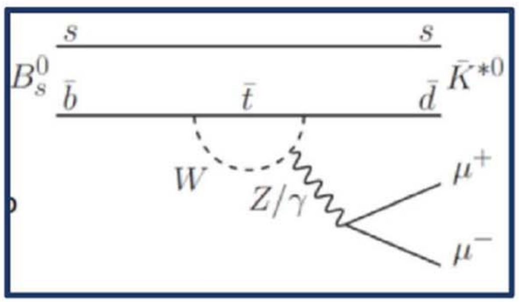
- Heavily suppressed b → dll transition in Standard Model
  - complementary to b → sll transitions in B^0_d decays

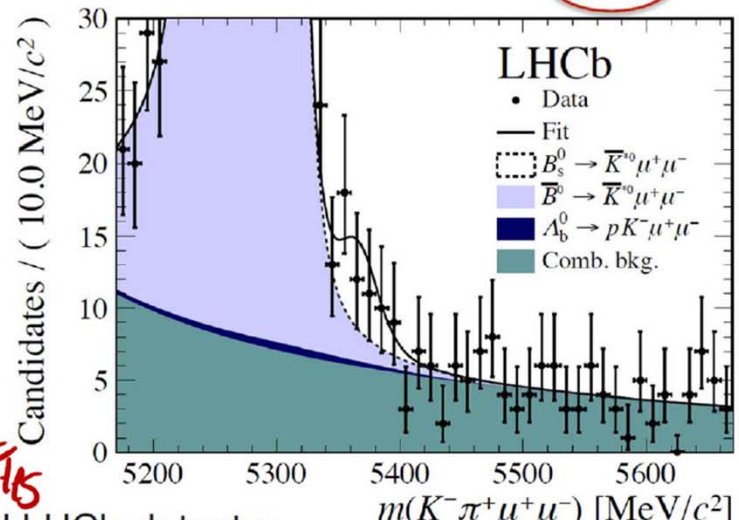
arXiv:1804.07167,
Run 1+2, 4.6 fb^{-1}

- Evidence of 3.4σ (38 ± 12 events) consistent with prediction

$$\mathcal{B}(B^0_s \to \overline{K}^{*0}\mu^+\mu^-) = [2.9 \pm 1.0\,(\text{stat}) \pm 0.2\,(\text{syst}) \pm 0.3\,(\text{norm})] \times 10^{-8}$$

CONGRATS LHCb





b → d!! CPT guarantees

- Angular analysis with upgraded LHCb detector
  - Sensitivity with Run3 possibly better than current B_d measurement

Large CP Asymmetries SIGNIFIES IMPORTANCE 4 LHCb upGs

Contrarian/Complementary view

- **flavor physics is actually hanging by perhaps the weakest link i.e. a single CP-phase endowed by the 3g –SM.**

- **In many ways this is a contrarian (or complementary) point of view, in sharp contrast to the overwhelming majority following the naturalness lamp post via Higgs radiative stability.**

- **In this context it is useful to stress**

Importance of the “IF”: score card

- Beta decay => Gf => W….
- Huge suppression of KL => mu mu; miniscule ΔmK=> charm
- KL =>2 pi but very rarely; mostly to 3pi =>CP violation => 3 families
- Largish Bd –mixing => large top mass
- etc…….
- => extremely unwise to put all eggs in HEF
- Complementary info from IF can be a crucial guide

for pointing to new thresholds as well as provide important clues to the nature of the signals there from

Summary & Outlook

- **SM-CP expectations in charm < ~ 1%....small**
- **Charm serves as a superb null test**
- **Strong indications of new physics around now**
- **Can have major repercussions for charm decays**
- **In particular with some insight focussing on selected modes may pay good rewards..gave several examples of hadronic modes**
- **Its also important to go after c => u l l, and after τ decays for CP-tests as well as LUV, LFV…searches**
- **Excellent chance that in the next ~5 years, via IF machines, LHCb, Belle-II, STCF along with precise computations …major [if not revolutionalry] advances in our fundamental understandings of Particle Physics will be made**

EXTRA

- **ASSUMING the anomaly is REAL & HERE TO STAY [BIG ASSUMPTION due to caveats mentioned]**
- **Anomaly involves simple tree-level semi-leptonic decays**
- **Also b => tau (3rd family)**
- **Speculate: May be related to Higgs naturalness**
- **Seek minimal solution: perhaps 3rd family super-partners(a lot) lighter than other 2 gens > proton decay concerns may not be relevant=> RPV ["natural" SUSY as argued also in Brust, Katz, Lawrence and Sundrum 1110.6670 …….]**
- **RPV natural setting for LUV …can accommodate g-2 and eps' if needs be**
- **Collider signals tend to get a lot harder than (usual-RPC) SUSY**

Haven't we tested the SM-CKM enough?

- **Recall current tests around 15-10%**
- **Recall also $\varepsilon \sim 2 \times 10^{-3}$; 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

Topics

- D => h h l l bigi + A and Gronu + R
- b => c and anomally
- D => hadronic 4-body FS
- D=> K +X and A+S point
- CPT a la DA + AS; Bigi +
- DA + AS Table
- Delta I=1/2 enhancement; RBC-UKQCD prl
- Emerging figure at mpi phy and heavier
- Likely affects all 2 pi exclusive modes
- For PV and VV color counting likely works a lot better…anticipated by DA+AS PTEP

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-> $\pi\pi$, lattice methods appear exceedingly difficult** => DA+AS 2012 See Later
- **More exptal input (many other modes) crucial & could change interpretation…**
-

MORE EXPRIMNTAL INPUT COULD BE VERY USEFUL

(PDG + HFAG ~ O(2 σ) $A_{CP} \neq 0$)

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 clarificaton.

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

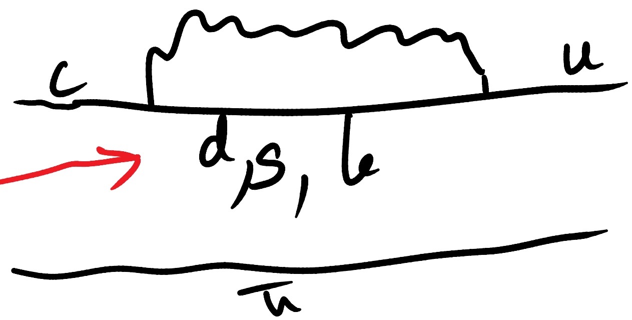
ESPECIALLY IMPORTANT To Search CP

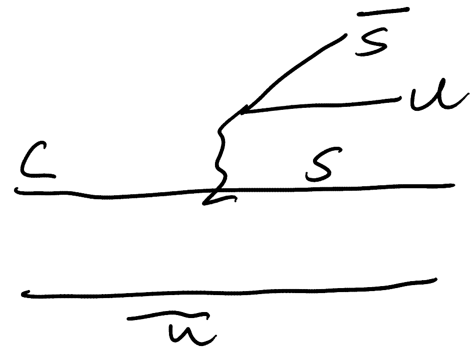
since γ extractions ASSUME No CP in D^0

BACK of a NAPKIN

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

d&s very light





$$\Delta A_{CP} \sim 4\left(\frac{P}{T}\right)\frac{V_{ub}V_{cb}^*}{V_{cs}^*V_{us}} \Rightarrow 4A^2\lambda^4\eta\,\sin\delta_{st}\left(\frac{P}{T}\right)$$

$\sim 1\times10^{-3}$

HIGHLY Nonperturbative ⇑

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

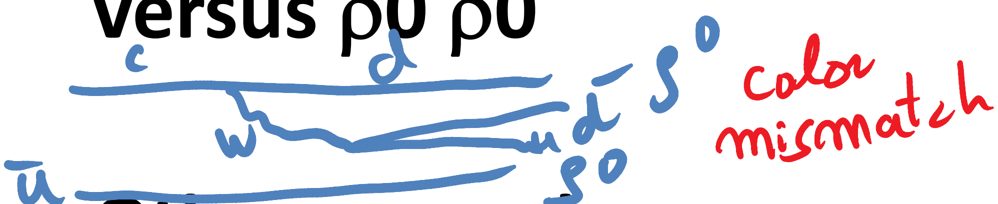
- **Implications of CPT**

- **Final States with enhanced CP**

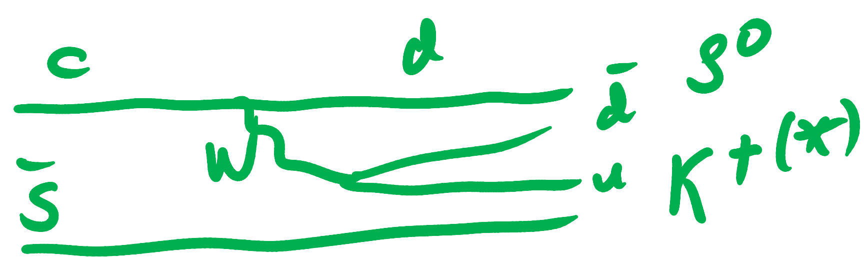
- **SM or not : A critical test**

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**



- **Other examples:**



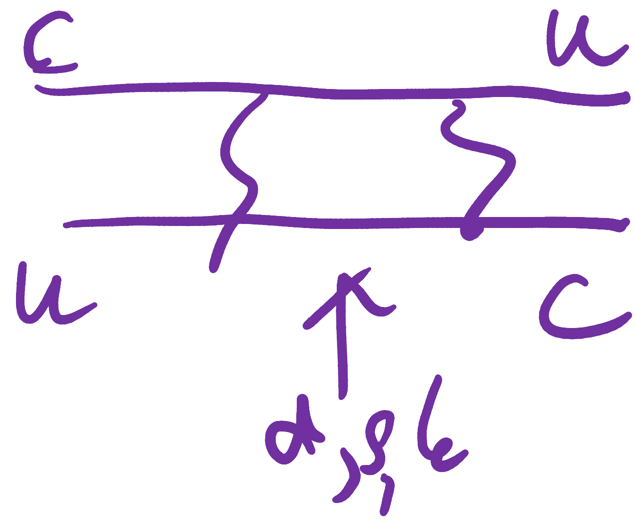
For KEKB D=> π^0 π^0 (η, η') also imp but may not be CS

SM expectation…InDCP

- Indirect CP…..Im[D0-mixing-Box graph]/Re[ ]

$$\frac{Im[V_{cb} V_{ub}^{*} V_{us} V_{ua}^{*}]}{Re[\quad '' \quad]}$$

$$\sim O(10^{-4})$$



PRL 118, 261803 (2017)

A_Γ : quest for indirect CPV

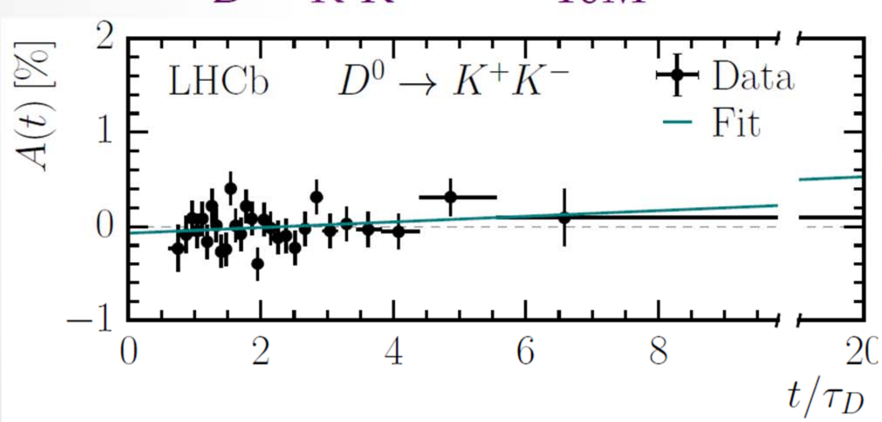
- Does mixing affect D^0 and $\bar{D}^0$ differently?
- Easiest access via A_Γ

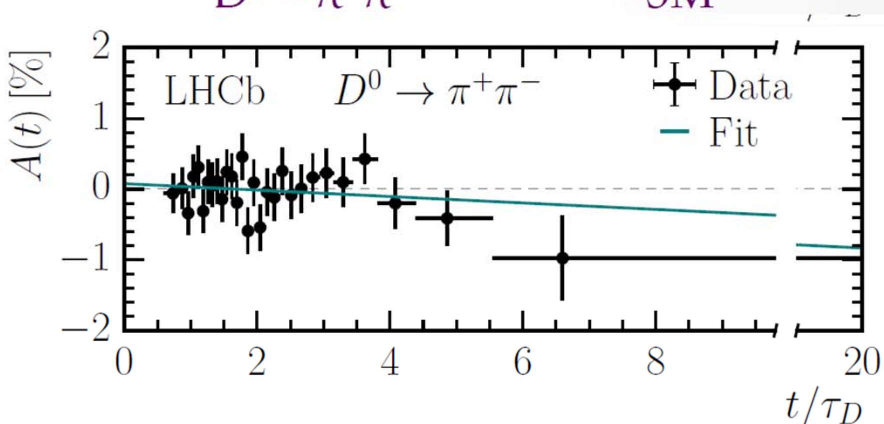
$$A_\Gamma = \frac{\tau(\overline{D}^0 \to h^+h^-) - \tau(D^0 \to h^+h^-)}{\tau(\overline{D}^0 \to h^+h^-) + \tau(D^0 \to h^+h^-)} \simeq -A_{CP}^{\text{indirect}}$$

- Asymmetry of yields in t(D) bins: $A_{CP}(t) \simeq A_{CP}^{\text{direct}} - \mathbf{A}_\Gamma \frac{t}{\tau_D}$
- 2011+2012 data, prompt charm

$D^0 \to K^+K^-$ ~10M

$D^0 \to \pi^+\pi^-$ ~3M





$A_\Gamma(KK) = (-0.030 \pm 0.032 \pm 0.010)\%$

$A_\Gamma(\pi\pi) = (+0.046 \pm 0.058 \pm 0.012)\%$

A_Γ: entering SM area

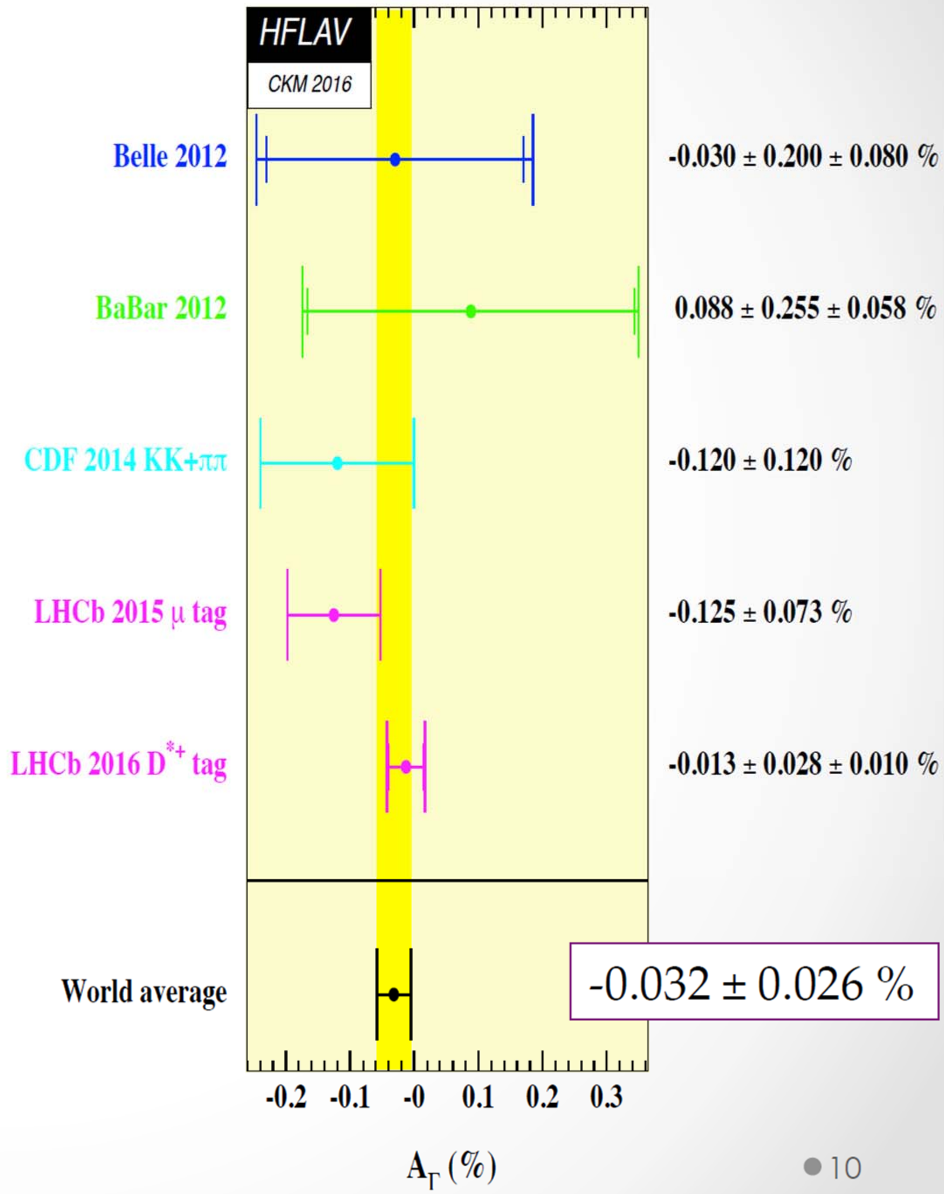
- Sensitivity: $O(10^{-4})$
  Limited by statistics
- Indirect CPV in SM ~10^{-4}

- A_Γ in terms of basic parameters

$$A_\Gamma = \frac{1}{2}\left[\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) y\cos\phi - \left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) x\sin\phi\right]$$

CPV in mixing — in mixing-decay interference

⇨ sensitivity to q/p depends on x



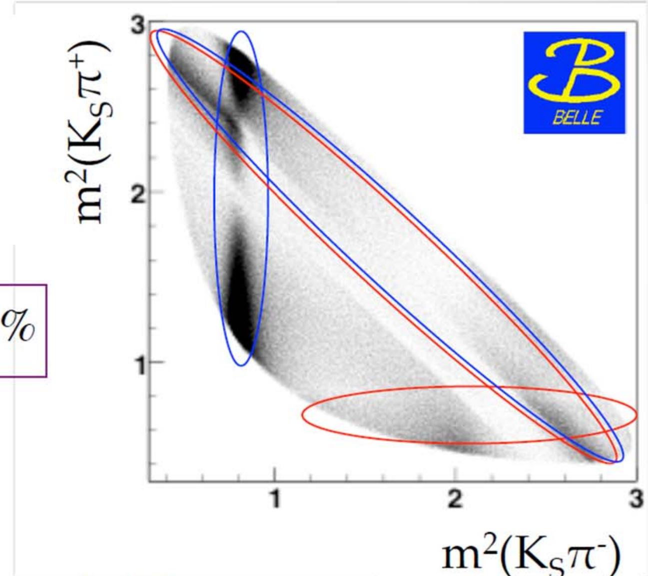
PRD89 091103 (2014)

Dalitz(t) of $D^0 \to K_S \pi^+ \pi^-$ golden mode

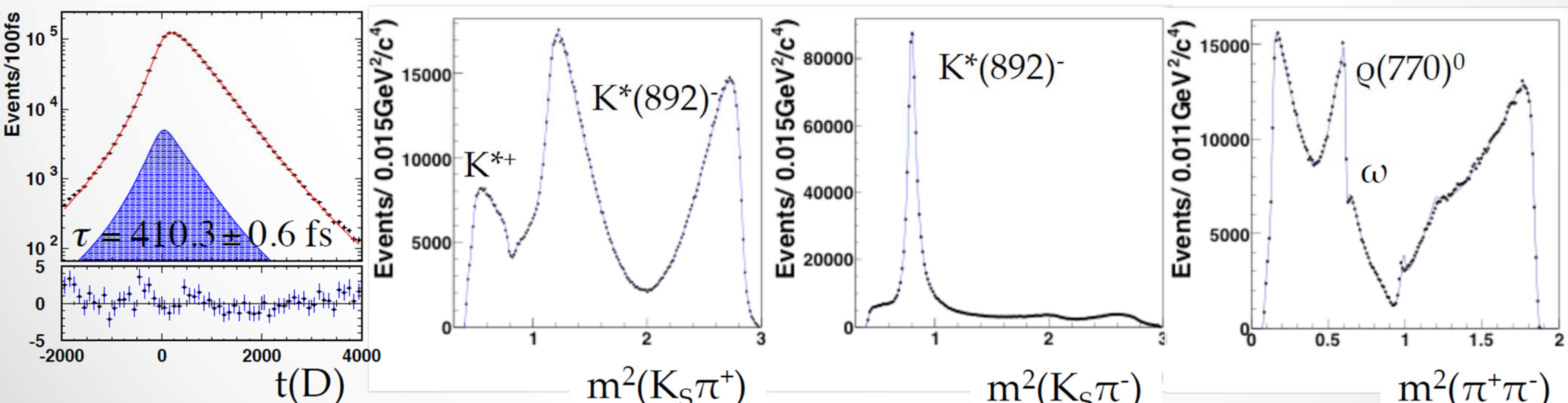
- Large statistics and rich dynamics
- Significant $D^0 \to f$ & $D^0 \to \bar{f}$ interferences
- Most precise x so far

$$x = \left(0.56 \pm 0.19^{+0.04}_{-0.08}{}^{+0.06}_{-0.08}\right)\% \quad y = \left(0.30 \pm 0.15^{+0.04}_{-0.05}{}^{+0.03}_{-0.07}\right)\%$$

$$|q/p| = 0.90^{+0.16}_{-0.15}{}^{+0.05}_{-0.04}{}^{+0.06}_{-0.05} \quad \phi = \left(-6 \pm 11 \pm 3^{+3}_{-4}\right)^\circ$$



- Belle: 1.2M signal events
- LHCb: 2M in Run1. Significant x with Run1+2?



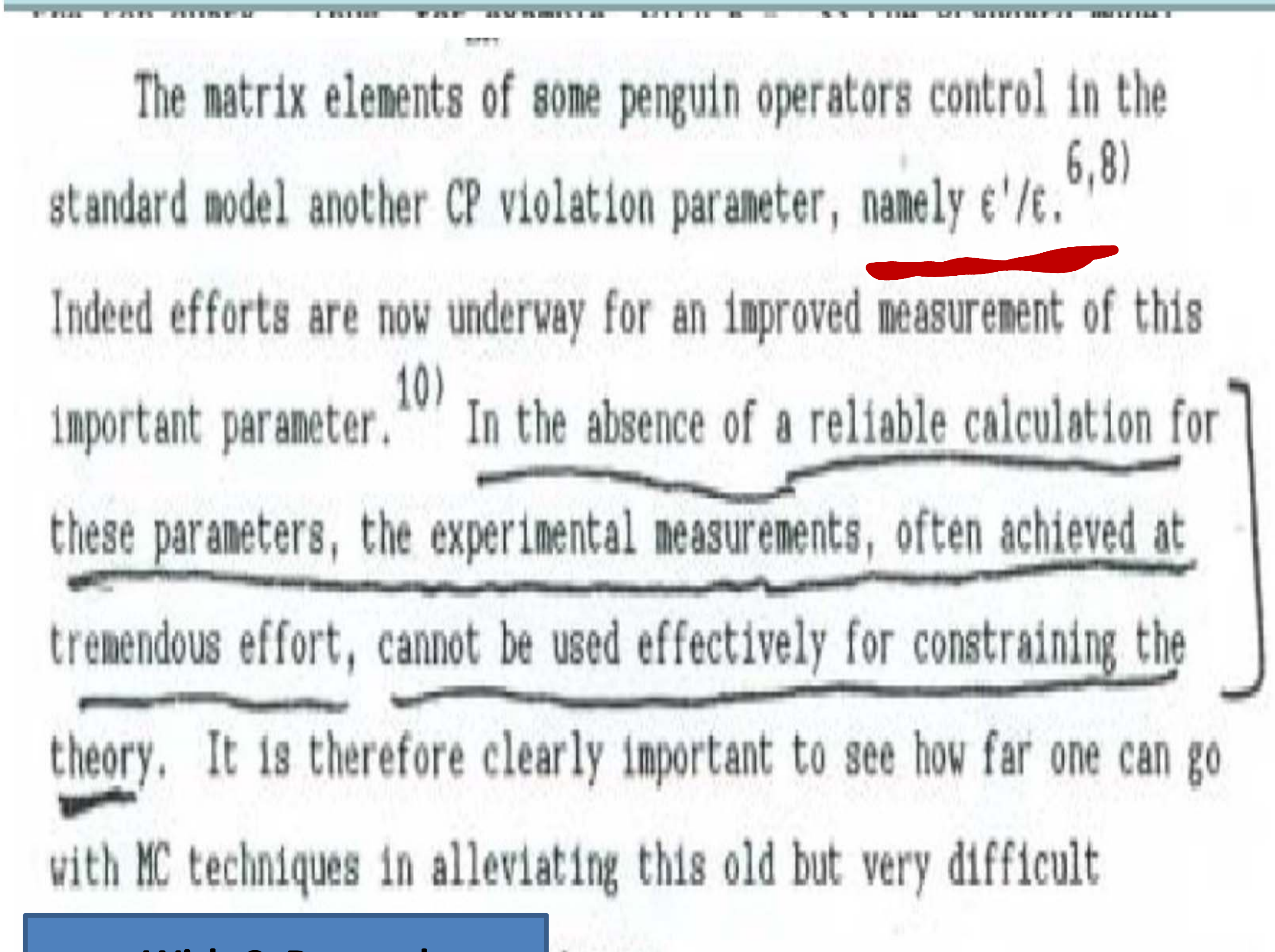
REMARKABLY: FOR RD* CENTRAL VALUE OF BEST THEORY ESTIMATE APPEARS BIT HIGHER THAN ALL ~6 MEASUREMENTS!

Bottom line

- **NP or not depends critically not just on precise experiment but also reliable SM prediction from the lattice become mandatory**
- **Experiment + hadronic ME from Lattice has the last word….[does often require sophisticated and demanding input from perturbation theory]**

- **Experimental results often attained at huge cost can be used effectively, iff commensurate theory predictions are available…….mantra for past several decades**

A.S. in Proceedings of Lattice '85 (FSU)..1st Lattice meeting ever attended


The matrix elements of some penguin operators control in the standard model another CP violation parameter, namely ϵ'/ϵ.[6,8] Indeed efforts are now underway for an improved measurement of this important parameter.[10] In the absence of a reliable calculation for these parameters, the experimental measurements, often achieved at tremendous effort, cannot be used effectively for constraining the theory. It is therefore clearly important to see how far one can go with MC techniques in alleviating this old but very difficult

With C. Bernard [UCLA]

ITS MY ~36TH YEAR ON EPS' …..WHY?

WHY FOCUS with SUCH intense DETERMINATION
All these many many years?

UNDERLYING REALIZATION

ε': MOST LIKELY A GEM IN SEARCH OF NEW PHENOMENA

Contrarian/Complementary view

- **flavor physics is actually hanging by perhaps the weakest link i.e. a single CP-phase endowed by the 3g –SM.**

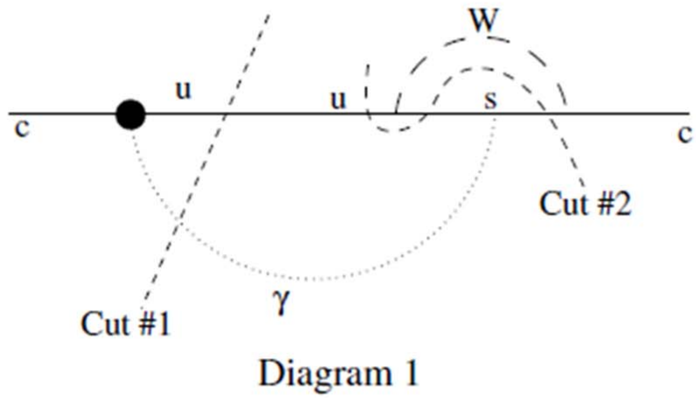
- **In many ways this is a contrarian (or complementary) point of view, in sharp contrast to the overwhelming majority following the naturalness lamp post via Higgs radiative stability.**

- **Ɛ' due to its miniscule value, esp because it results from unnatural large cancellations seemed clearly highly vulnerable…The mantra being followed for a very very long time**

Extremely important consequence of CPT

- Since Br(D0 => pi+ pi-) ~Br(D0=>K+ K-)X[1.40/3.96=0.35]

- # of D0 needed for CP-observability in pi^+ pi^- modes
  ~ 1/3 needed for K^+ K-
- Note: This only accounts for statistical errors



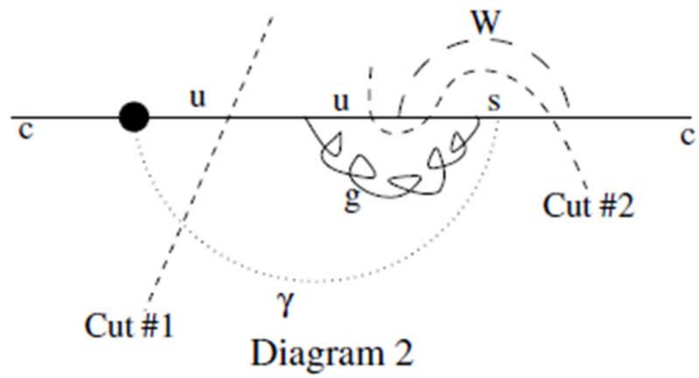


FIG. 3: This unitarity graph illustrates CPT conservation for the quark level process $c \to u\gamma$ due to NP. Diagram 1 shows the lowest order interference between NP and SM where cut #1 is for the $c\gamma$ final state and cut #2 is for a $s\bar{s}u$ final state. Cut #2 cannot be on shell. Diagram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

Propose a new test for new physics see Atwood + AS, PTEP 2012

- **Key idea: Hadronic matrix elements enhancement only operational for EXCLUSIVE [few body] MODES,** e.g $\pi\pi$, KK

- **Inclusive (multibody) modes should exhibit quark level asymmetry[quark-hadron duality] ~few$\times 10^{-4}$ if SM is the source, if these also show $O(5\times 10^{-3})$ asymmetry then BSM-CP is the origin**
- **Look forward to implementation at LHCb, but esp at KEKB(II), BESIII, STCF….**

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
- Limitation=> charm mass is a bit light