Optimizing search strategies for DIR-CP in charm decays

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Outline

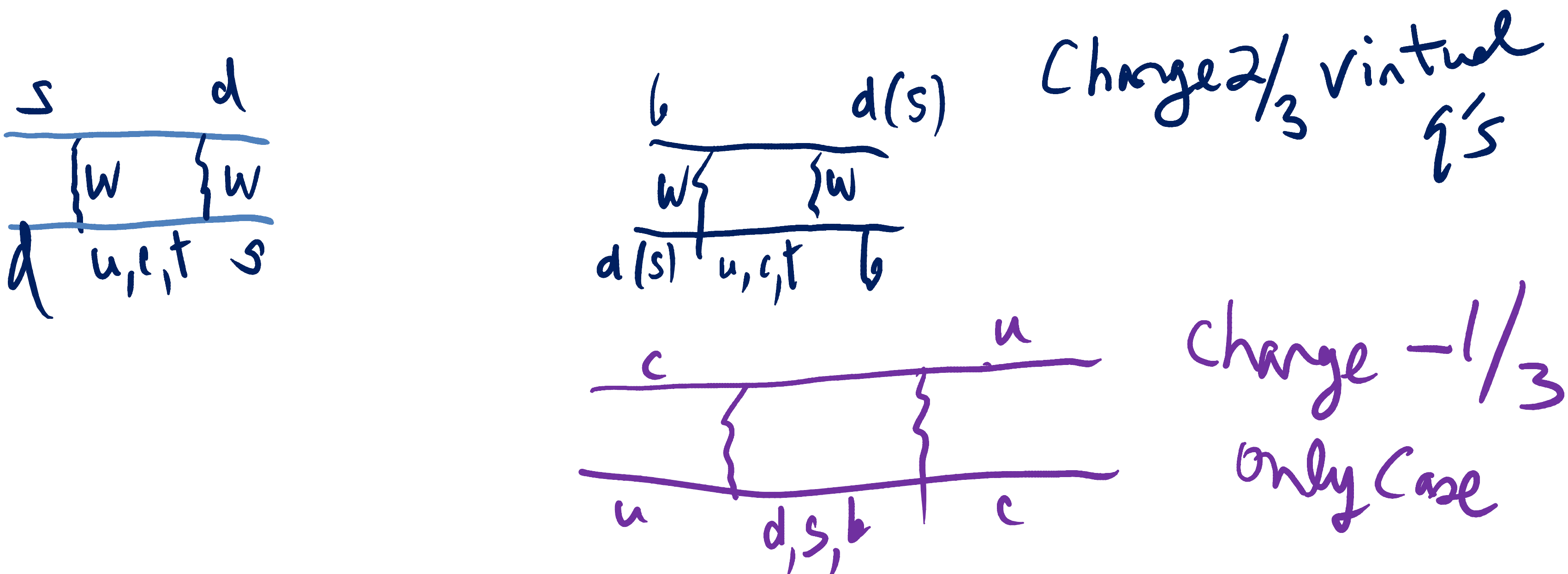
- **Recapitulate: SM expectations => charm physics difficult due to non-perturbative effects**
- **Small [quantify?] CP symmetry violations in SM.**
- **Therefore very good use of charm as null tests**
- **Currently, several indications of BSM =>CP phase**
- **Esp. implications for charm**
- **Also in view of anticipated large increase in data**
- **Strategies to maximize charm- CP [SM and/or BSM]**
- **Illustrative examples**
- **More implications for charm of current BSM-hints**
- **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, systematic implement CPT**
- **Feldmann, Nandi and A.S. JHEP 2012** SM ≤ 1% ΔA_{CP}
- **Atwood + A. S, PTEP 2013…….update now**
- **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**
- **A S lecture III @ 2018 Weihai**

Charm system is unique

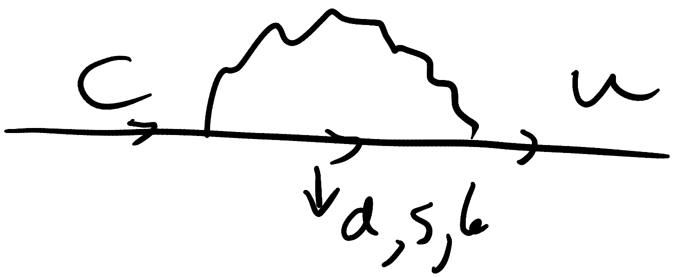
- **Distinct from K and B-mixings**

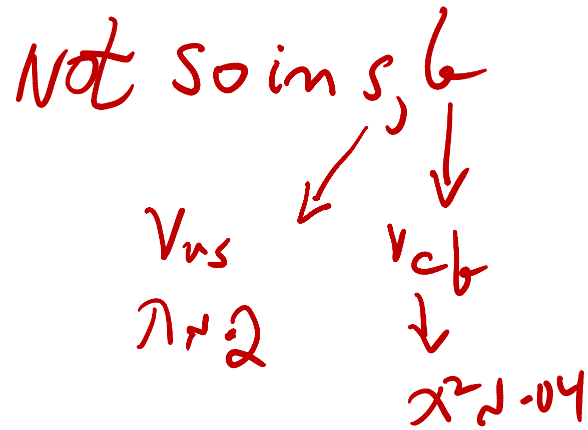


Delta F=2 mixings are an extremely valuable treasure in providing stringent constraints on NP scenarios……….

Tree vs penguin

- **CBA tree**





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

SM expectation…DCP

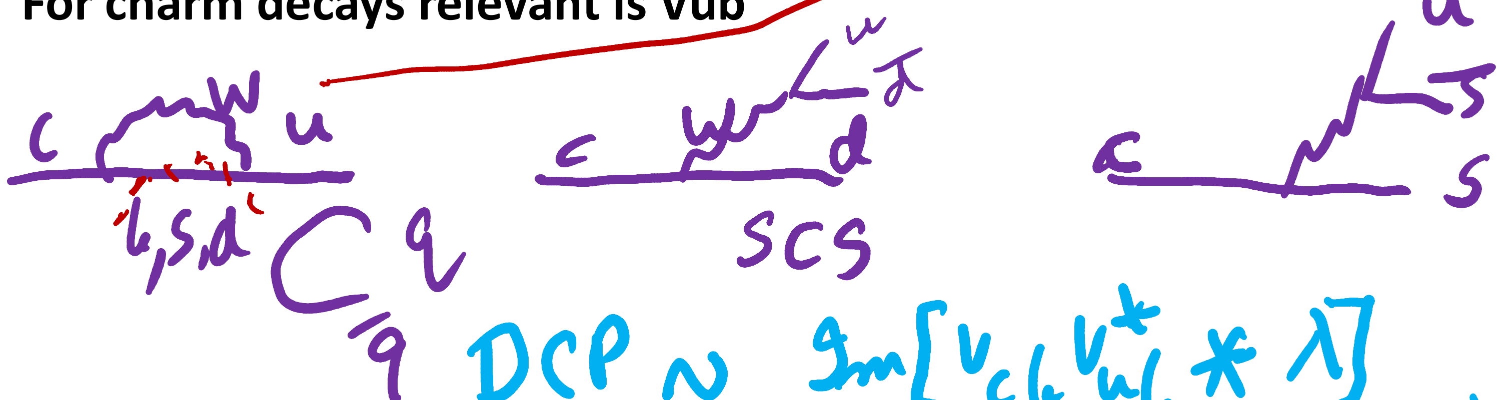
- Dir CP….. See Bander, Silverman + AS, PRL 1979 for DCP when

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

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



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

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

See later

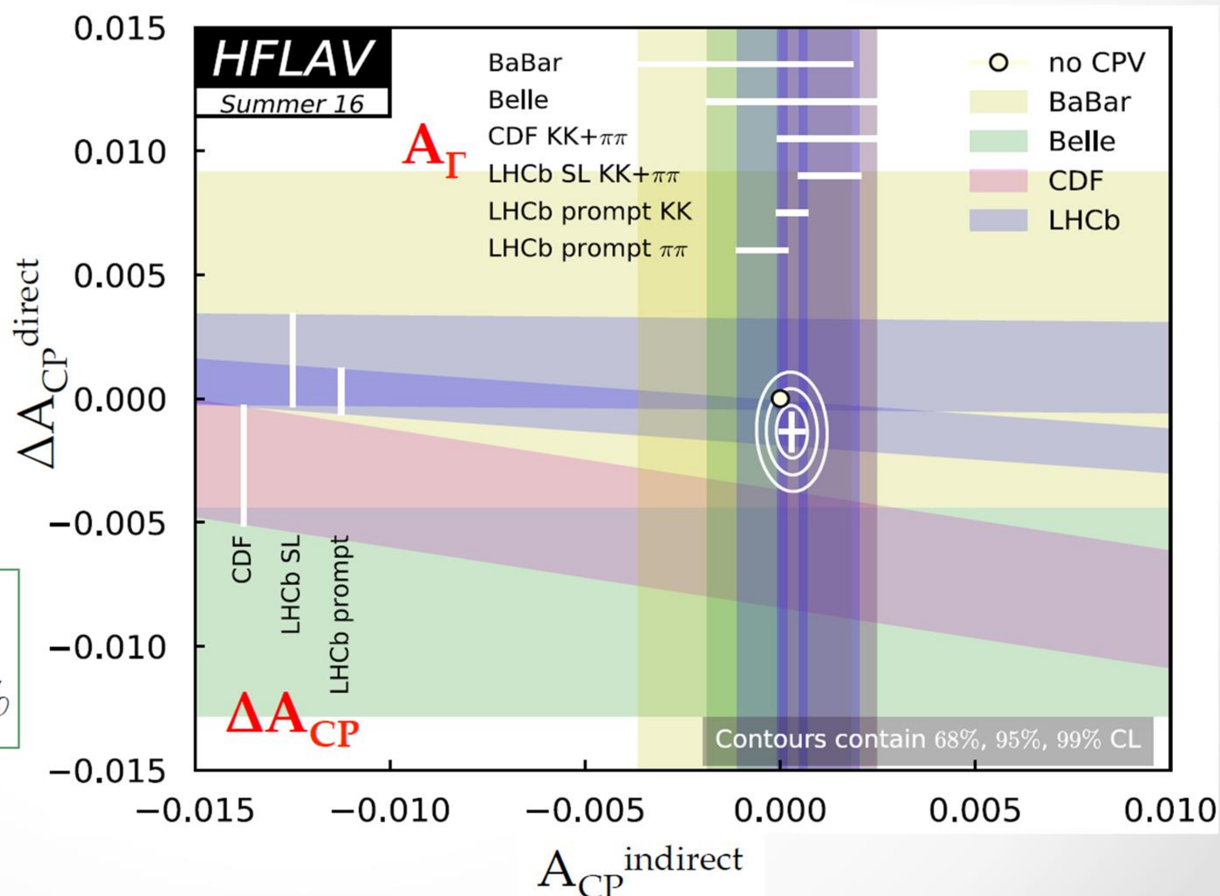
DIFFICULT

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

- 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,

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

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 → h^-h^+ decay rates*, *Phys. Rev. Lett.* **108** (2012) 111602 [arXiv:1112.0938] [INSPIRE].

Unfortunately Short lived excitement

Better understanding of SM Th expectation

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

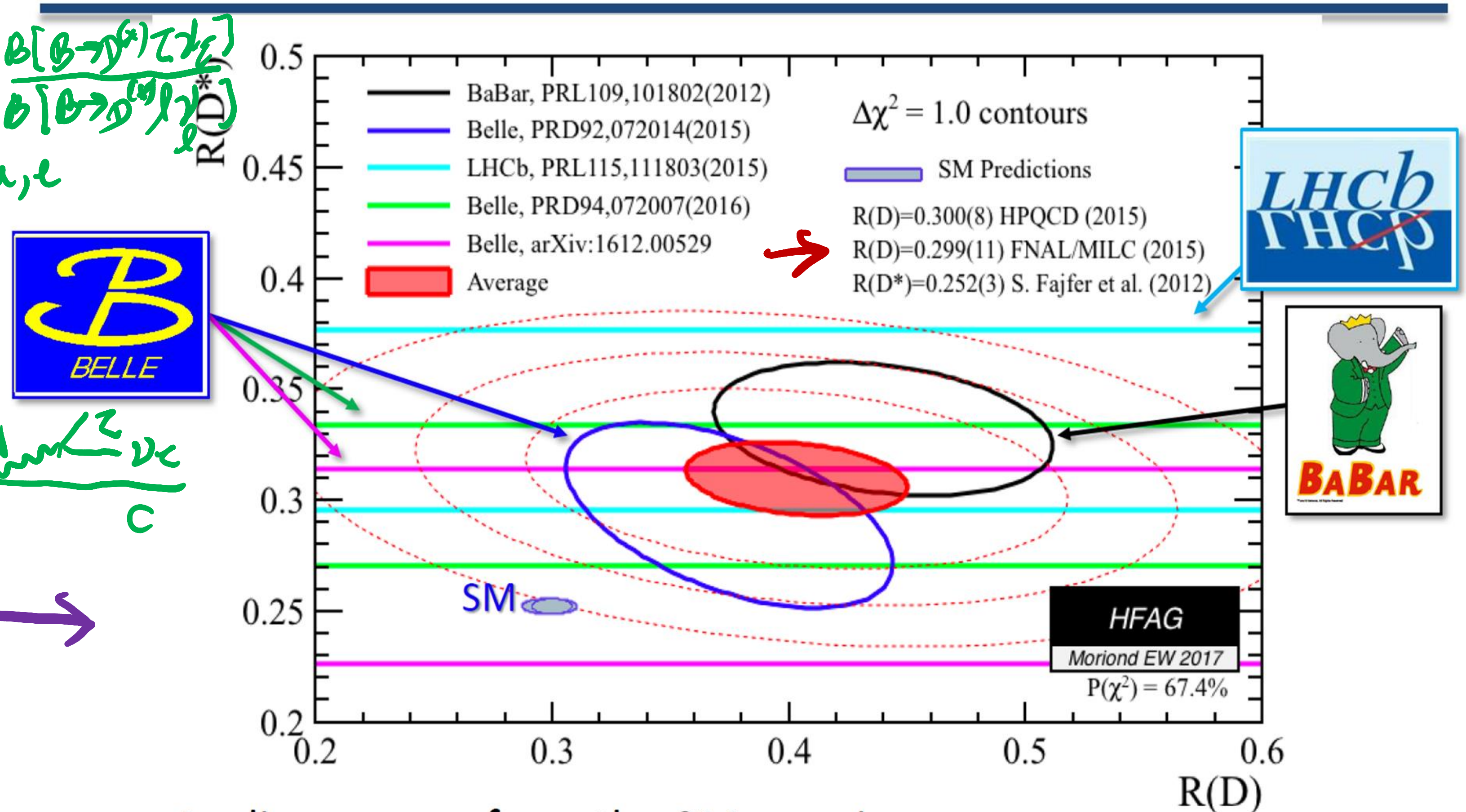
Anomalies galore!

- RD(*) ~ 4σ (?) probably lot less
- RK(*): 2.6σ (R_K); probably ~ 3.5σ but only LHCb

- g -2…BNL =>FNAL expt… ~ 3.6σ major lattice progress by RBC-UKQCD & others

■ $R(D^{(*)})$ by HFAG

Hirose [BELLE]@EW MORIOND Mar. 2017



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

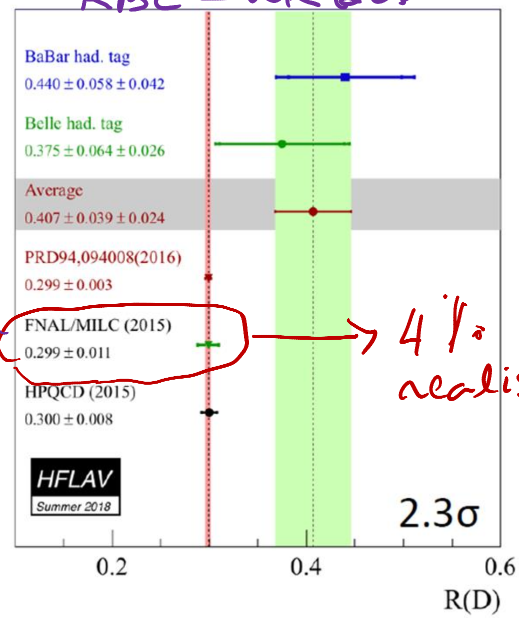
Belle deviations quite mild

Status of R(D$^{(*)}$) results

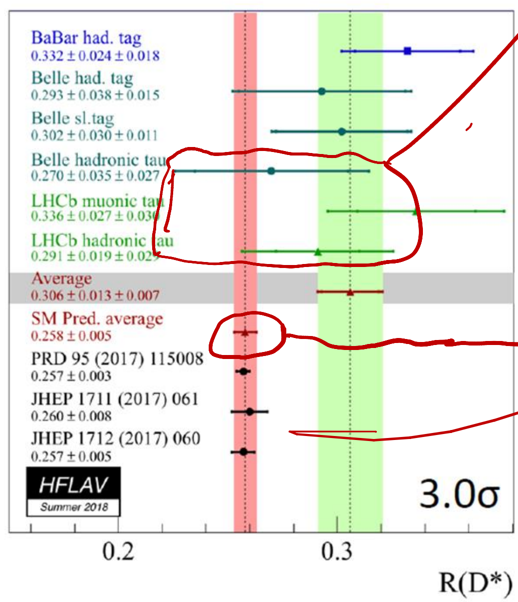
also WITZEL et al RBC – UKQCD

R_D Theory much cleaner but QED radiative corr needed. More expt effort on R_D needed

POTENTIALLY VERY SERIOUS EXPTAL PROBLEM

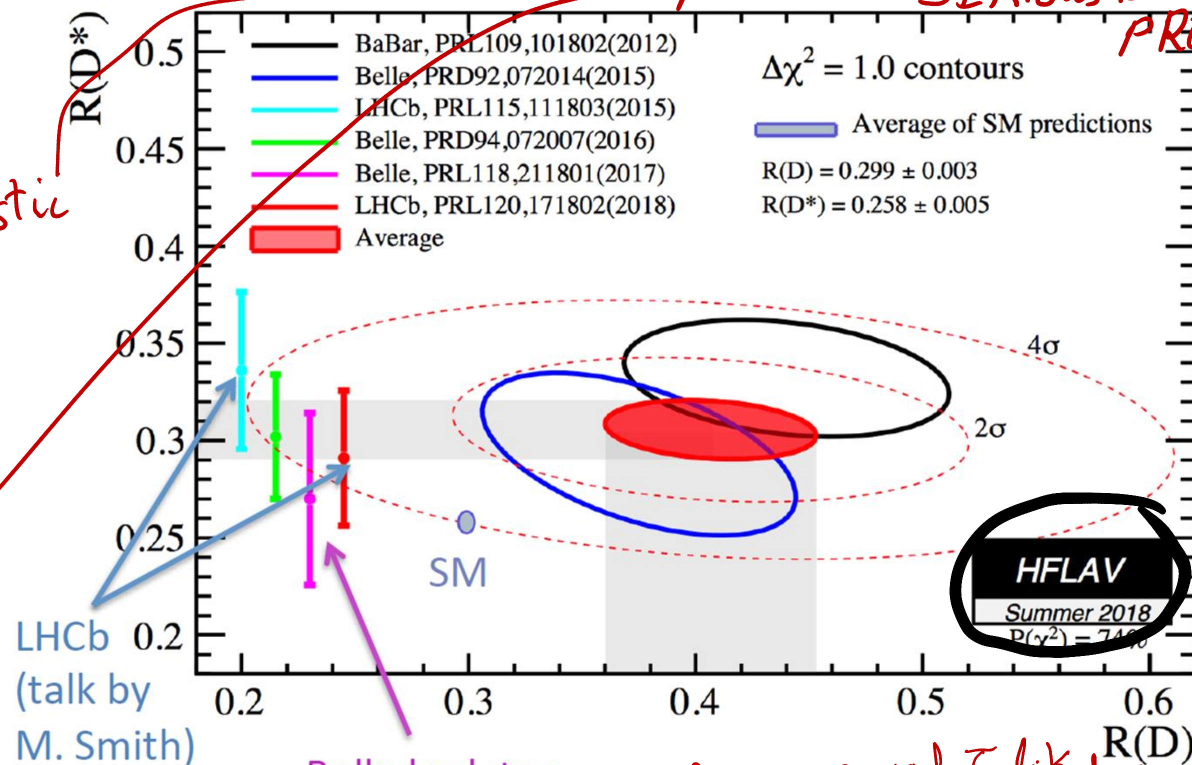


4% realistic



Serious

Likely also affects V_{cb}



also on recoil τ likely problem

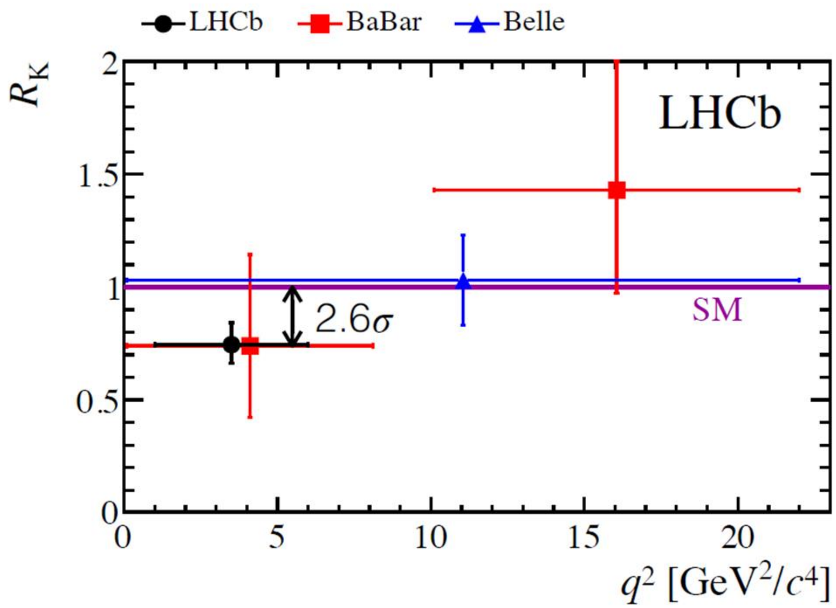
η Theory errors Because D^* has spin

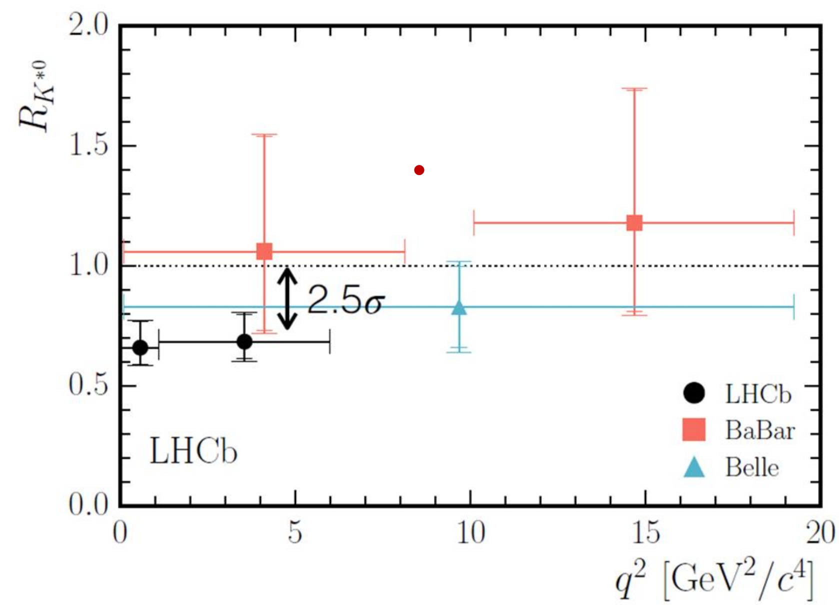
Deviation from SM prediction: 3.9 σ

V Likely OVERESTIMATE

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]

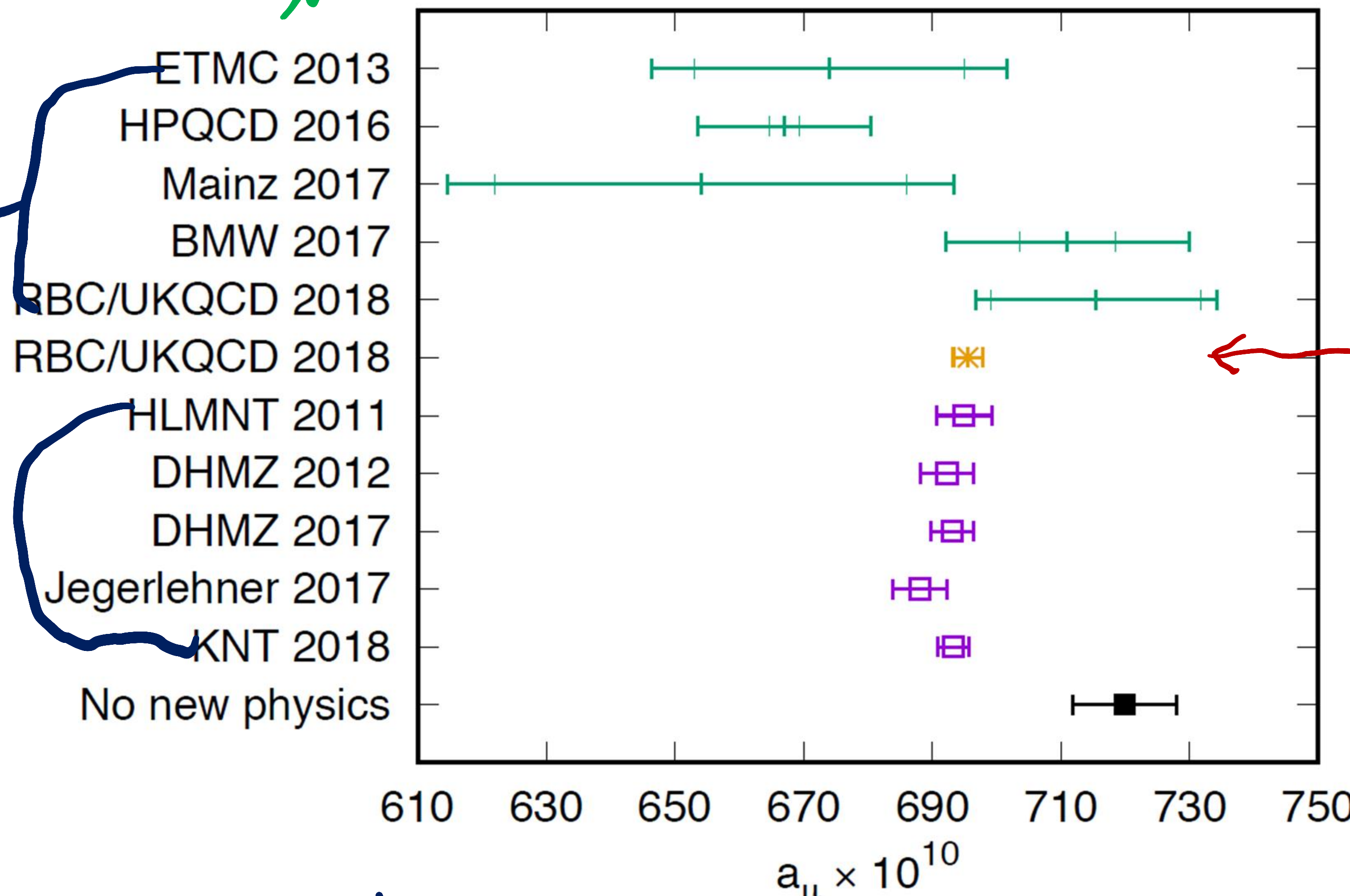
Radiative Correction See Isidori et al

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]

$(g-2)_\mu$ on + off the Lattice

PURE Lattice

Pheno



C Lehner et al RBC-UKQCD HYBRID

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.

HET Lunch Seminar 03/09/18

Possible sightings of new physics

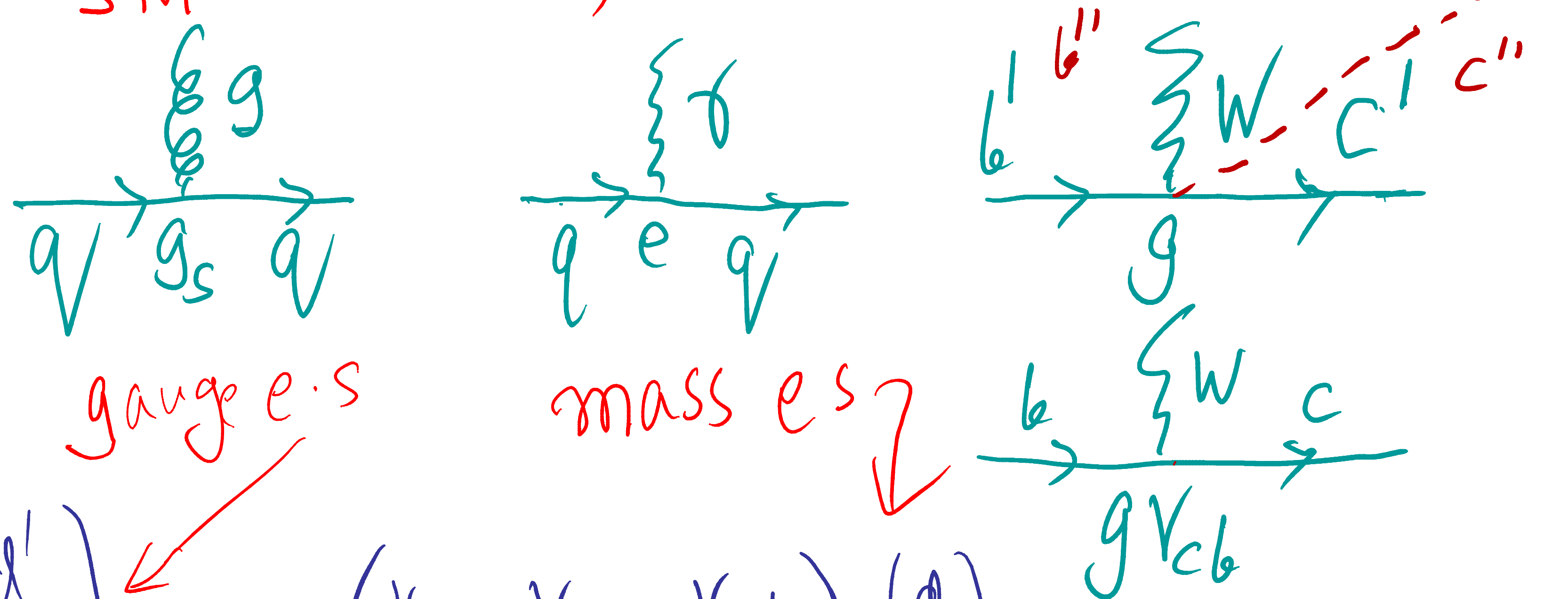
- **An extremely important consequence of NP is that it is highly unlikely (i.e. unnatural) that it will not be accompanied by new CP-odd phase[s]….**

- **This possibility we will explore a bit further**

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"

Since calculations of CPV are not rigorous

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**

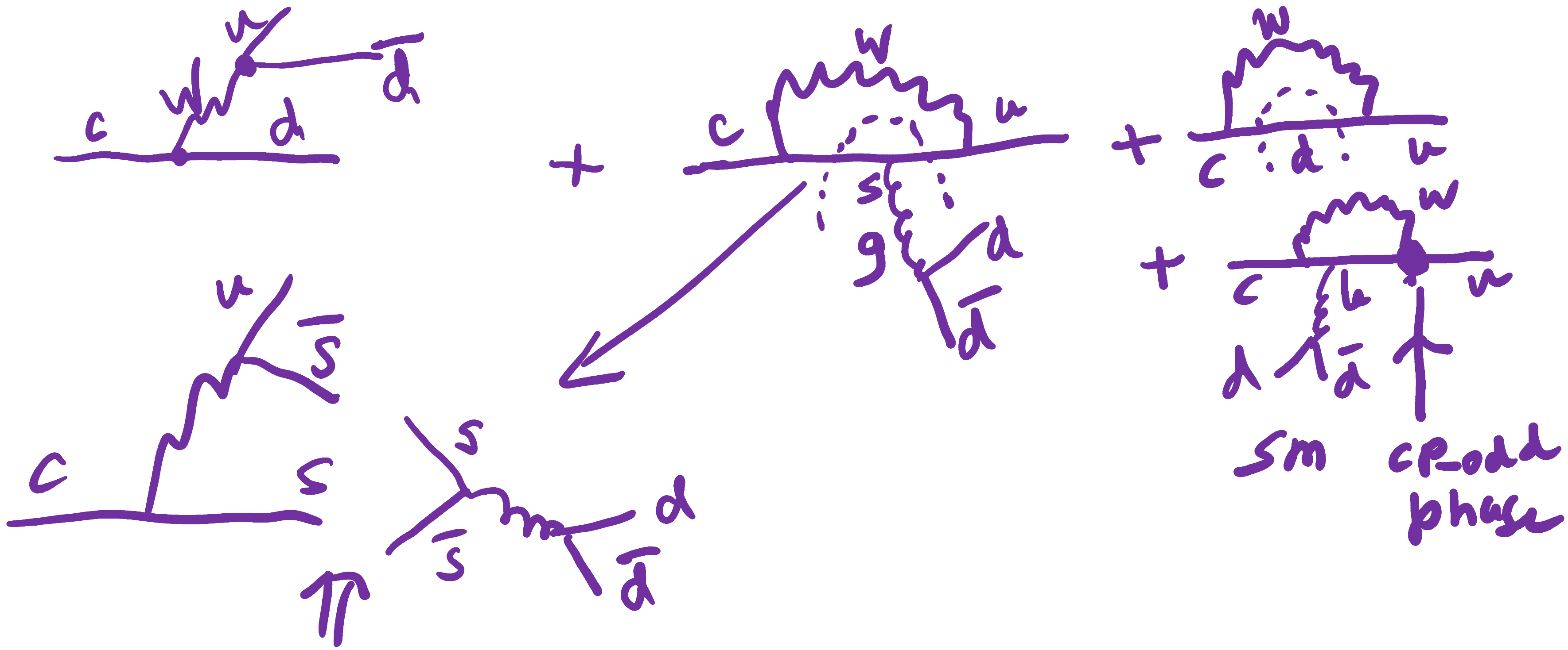
Atwood and A.S, PTEP 2013 (2013) no.9, 093B05

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:

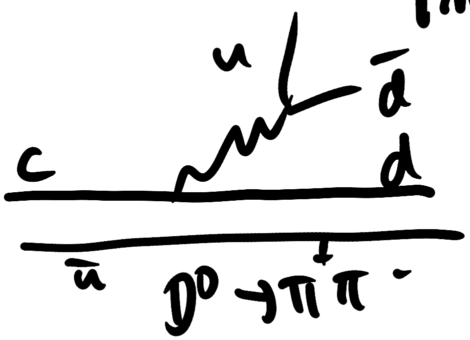
$c \to u s \bar{s}$ & $c \to u d \bar{d}$

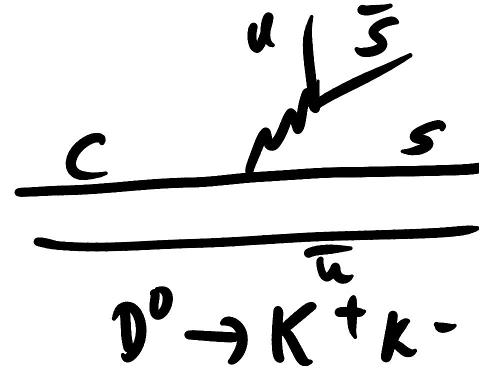


On-shell rescattering phase
CP-even phase ⇒ Total amplitude for $c \to u\, d\, \bar{d}$ is complex

Implications of CPT

ILLUSTRATIVE EXAMPLE





$\Gamma_D = \Gamma_{\bar{D}}$

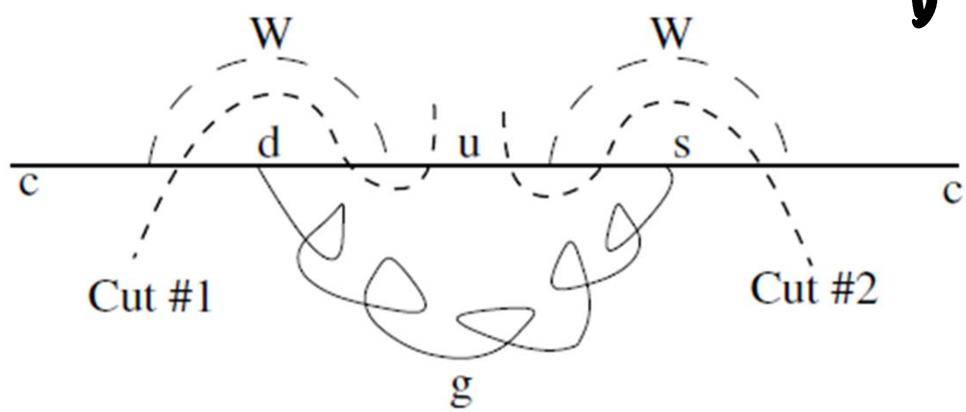


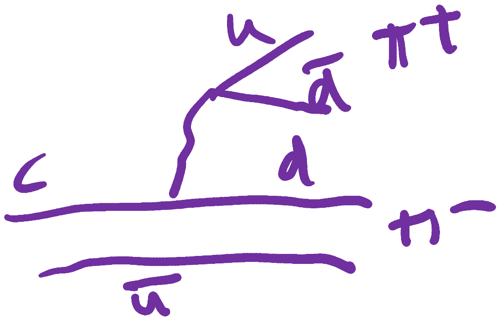
FIG. 1: The unitarity graph showing the CPT identity Eqn. 6 for the quark level SCS charm decay. Cut #1 indicated in the figure shows the case where the decay is $c \to d\bar{d}u$ with a $s\bar{s}u$ intermediate state providing the strong phase. Conversely, cut #2 indicated in the figure shows the case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

See ATWOOD + AS PTEP 2012

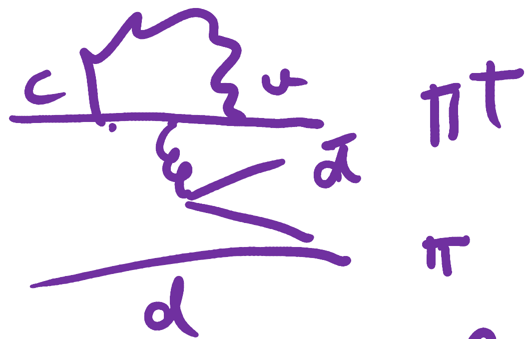
$$\text{CPT} \Rightarrow \sum_X \Delta\Gamma(D \to X) \equiv \sum_X \left[\Gamma(D \to X) - \Gamma(\bar{D} \to \bar{X})\right] = 0$$

AT the quark level:

$$\Delta\Gamma(c \to d\bar{d}u) = -\Delta\Gamma(c \to s\bar{s}u).$$



$T_{\pi\pi}$



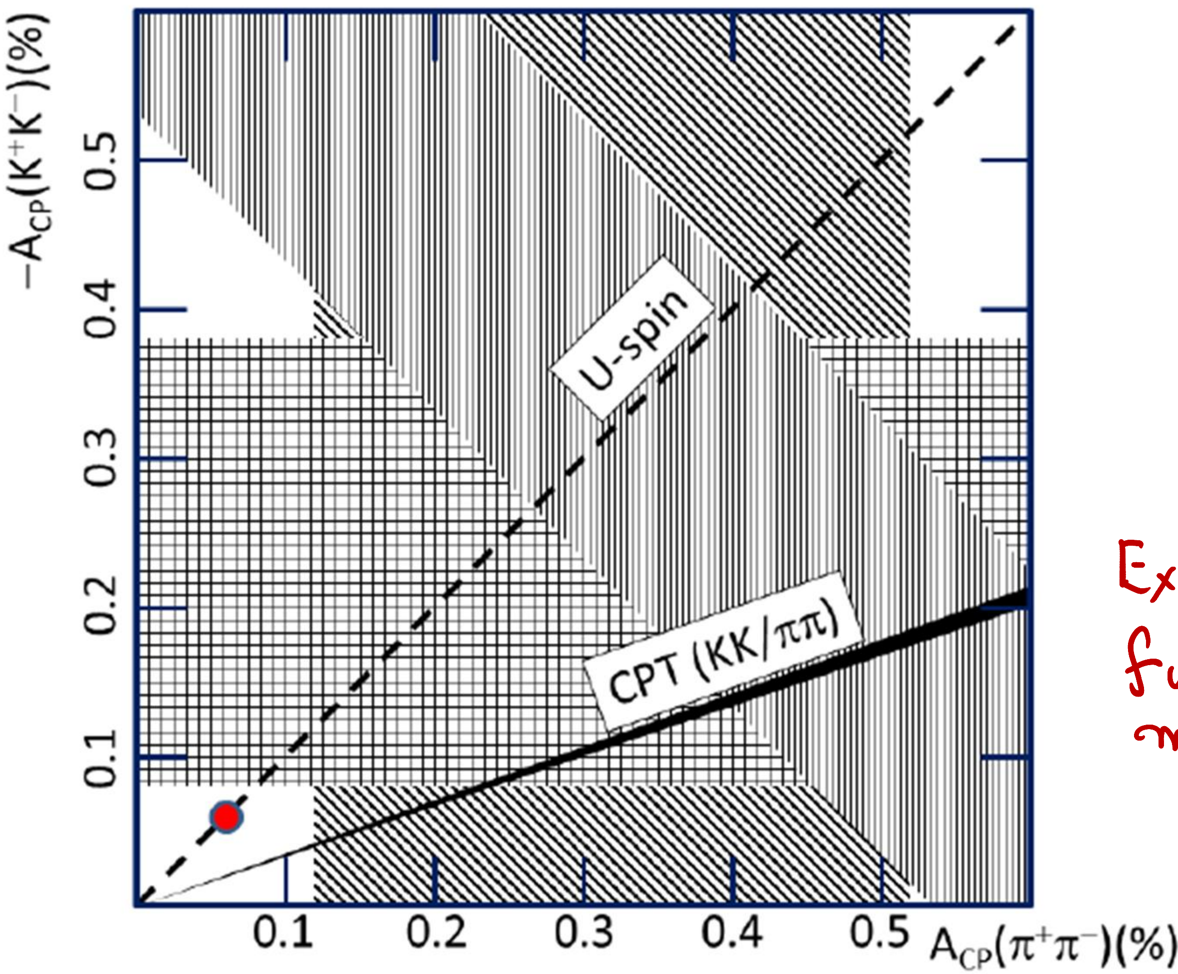
$BR\ D^0 \to K\bar{K} \sim 4\times10^{-3}$

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

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

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

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



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

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

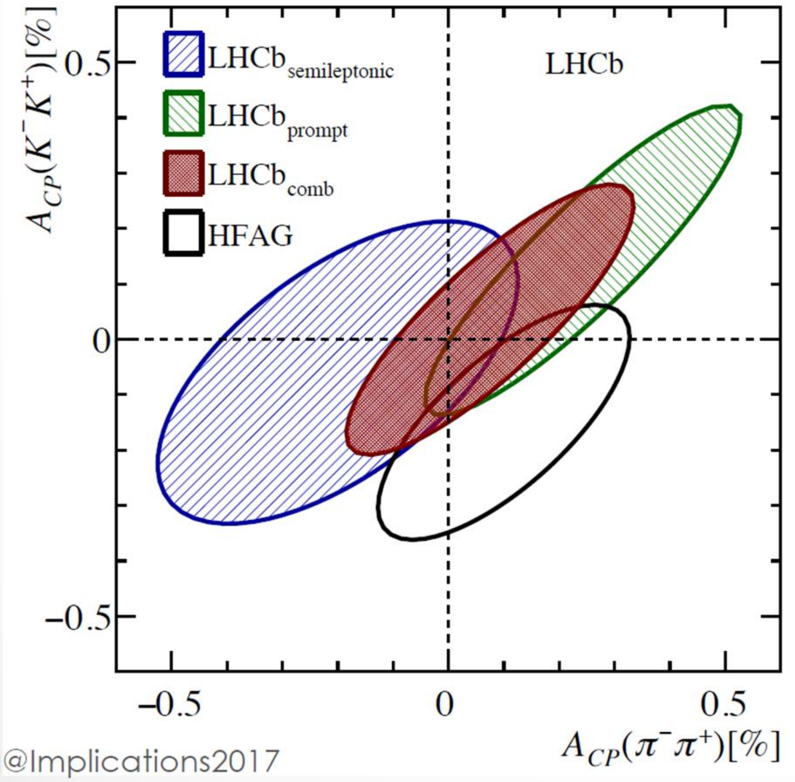
- Individual A_{CP}(KK), pion-tagged sample

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

- 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

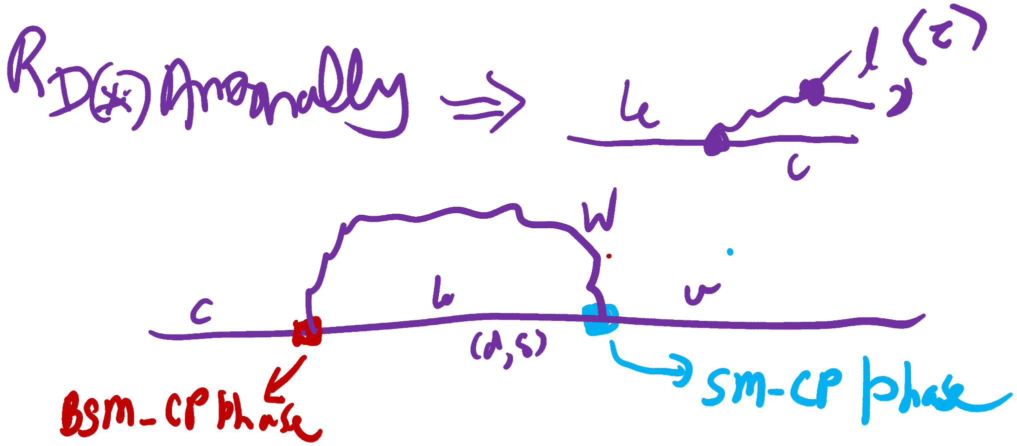


- Combine with results from muon-tagged sample
  JHEP07, 041 (2014)
  ⇨ LHCb combination

- Both A_{CP}'s consistent with zero

STARRING MORE AT CHARMIMG PENGUINS

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



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**

Strategy to enhance charm-CP [$\alpha_{PRA} \sim \frac{Im P}{T}$]

- 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]….**atomatically forced by T-P interference a la Bander, Silverman and A.S PRL 1979**

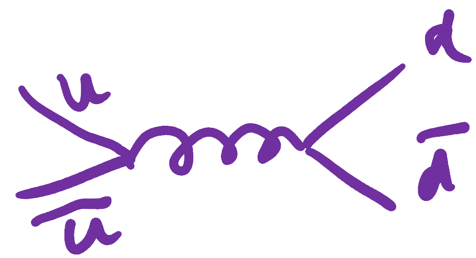
$\pi^0 \pi^0 (\rho^0)$
$\rho^0 \rho^0$

4^{th} rule

See DA+AS PTEP ~ 2012-13

- **Zweig suppressed + CLS**
- **Only class of modes seem possible here:**
- **D0 => Ks Ks, K0 K0*, K0* K0***
- **Feynman graph**

; $\phi\, \pi^0 (\rho^0)$; CLS



CLS+ZWS

$\alpha_{K^+K^-} < \alpha_{\phi \pi^0(\rho^0)} < \alpha_{K_S K_S,\, K_S K_0^*,\, 2K_0^*}$ $\quad K_S K_S, K^0 K^{0(*)}, 2K^{0*}$

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 => $\phi\, \rho^0$; 2K0***
- **3) all π^0 always also imply $\eta^{(')}$;**
- **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
		$[K^{*+} \to \pi^+[K_s \to \pi^+\pi^-]][K^{*-} \to \pi^-[K_s \to \pi^+\pi^-]]$		—

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
d suppressed and the final state has an all charged final state
wn from [34] we have included it in the last column; this is the
nt decays to the final all charged state indicated.

For details, Atwood + AS, PTEP 2012

MANY MORE MODES

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

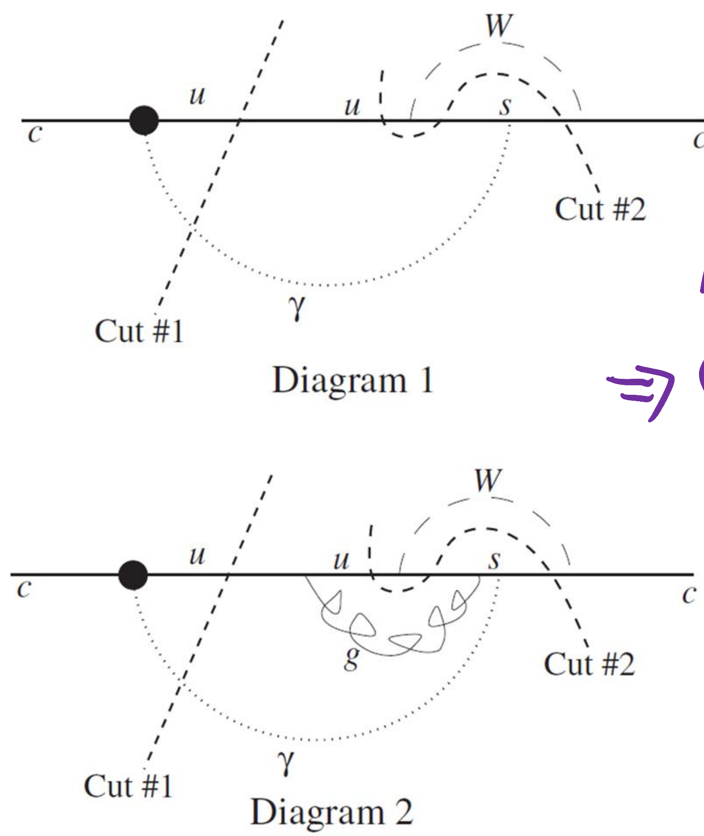
Implications of CPT for CP-violating observables [I]

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). Her
present and N ≡ FSI absent

T_N	CP-violating	CP-conserving
even	Y	N
odd	N	Y

even → Energy, PRA
odd → TCA
Y → Needs FSI phase → requires loop
N → Does not



Implications of CPT
⇒ CPV in on-shell γ small

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

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

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
$\eta e^+ e^-$	*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

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 → 10^7?
$\psi(2S)$	3.686	1.0	~ 640	3.0×10^9
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

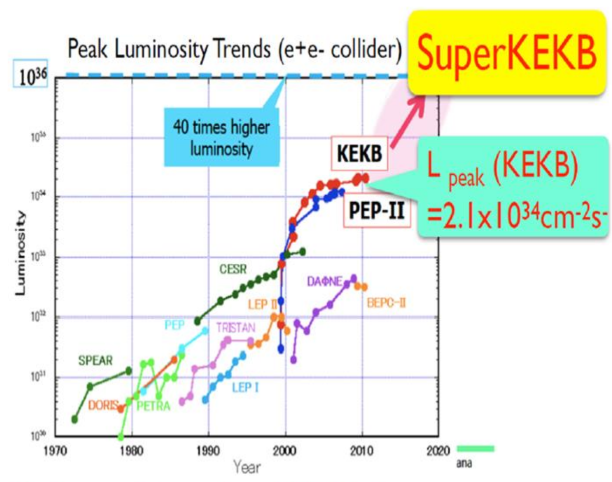
SuperKEKB/Belle II

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

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

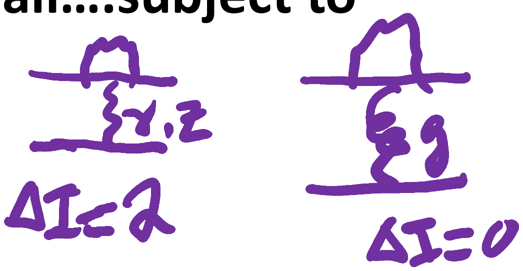
$B_r \sim 10^{-2}$, $A_{cp} \sim 10^{-3}$ $\Rightarrow$ $N \gtrsim 10^{10}$ for 3-σ observation

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

for $\pi^+\pi^0$

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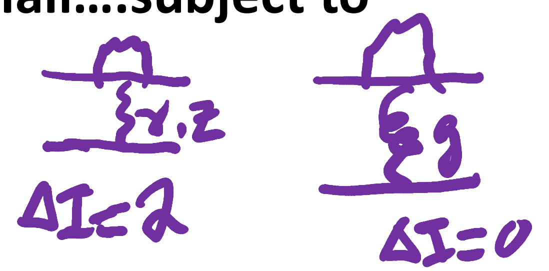

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Null tests:Dir CP

Br ~ 5.5×10^{-6}

- 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 A_{CP}
- 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

$A_{CP}\{B^+ \to \pi^+ \pi^0\} < 1\%$ SM

HYC + Chua + A S, PRD '05

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

SM expectations for DirCP: examples

- **Expected hierarchy:**
- **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

Summary & Outlook

- **SM-CP expectations in charm < ~ 1%....small**
- **Charm serves as a superb null test**
- **Several 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**
- **For purely hadronic modes, expectations for CPAsy from SM**

is a hierarchy (focus here only on CBS mode): CLS+ ZWS > CLS >CLA; also to enhance CPAsy should avoid W^+ => rho^+ or K*+

[there are many other ways of making vector mesons in the final state that should be exploited]

- **D^+ (B^+)=> pi+ pi0 is good way to go after, but precise SM predictions are absent and isospin breakings may be sizeable**
- **Its also important to go after c => u l l, c =u gamma but expected rates**

are rather small.

- **Very good chance that in the next ~5 years, via IF machines, LHCb, Belle-II, STCF along with precise computations …major advances in our understandings of Particle Physics will be made**

EXTRA

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 ~0(2σ) $A_{CP} \neq 0$)

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]

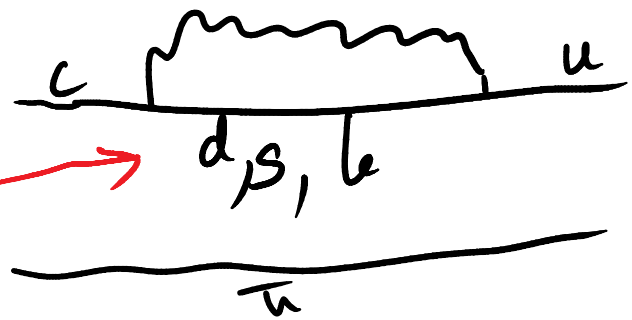
NO Penguin

NO CP phase SM

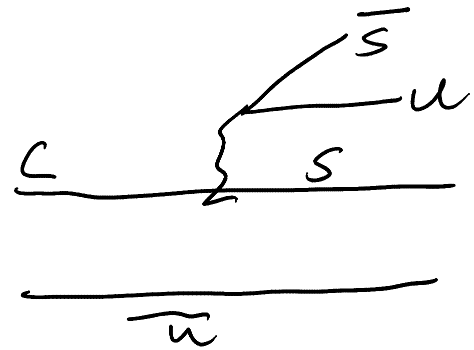
ESPECIALLY IMPORTANT To Search CP since γ extractions ASSUME No CP in D^0

BACK of a NAPKIN

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



d, s very light



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

HIGHLY Nonperturbative

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

- **Implications of CPT**

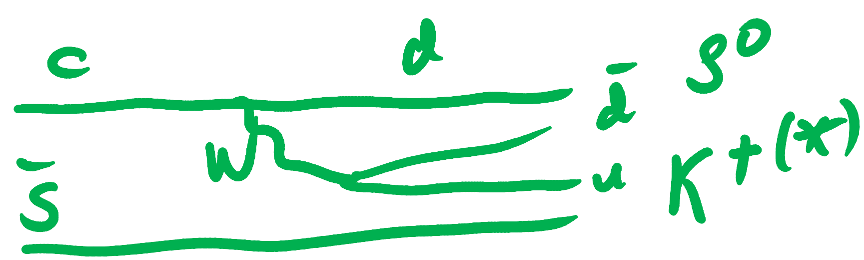
- **Final States with enhanced CP**

- **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 $\rho 0$ $\rho 0$**

- **Other examples:**



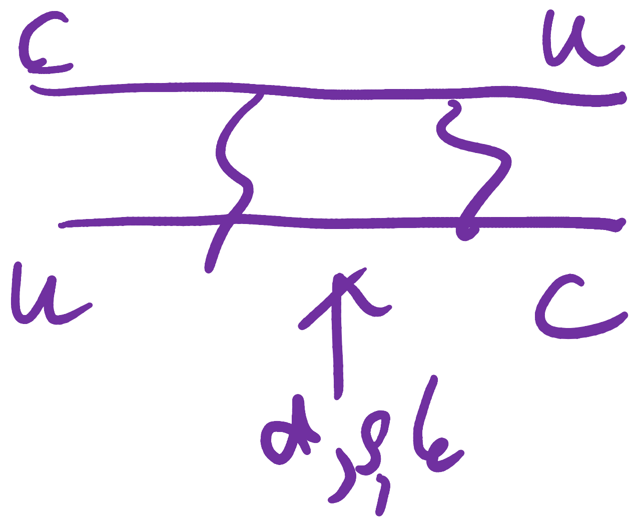
For KEKB D=> π^0 π^0 (η, η') also imp but may not be CS

SM expectation…InDCP

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

$$\frac{Im[V_{cb}V_{ub}^{*}\,V_{us}V_{ud}^{*}]}{Re[\quad " \quad]}$$

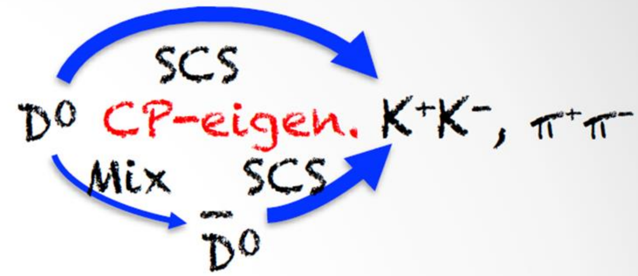
$$\sim O(10^{-4})$$



PRL 118, 261803 (2017)

A_Γ : quest for indirect CPV

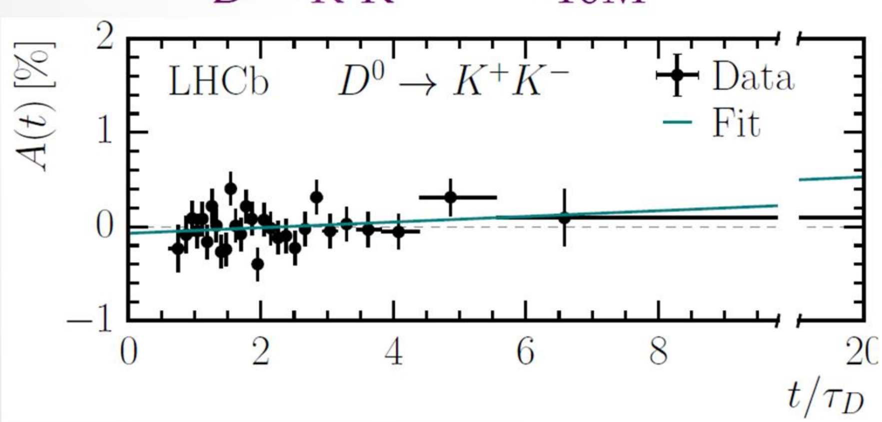
- Does mixing affect D^0 and $\overline{D}^0$ differently?
- Easiest access via A_Γ



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

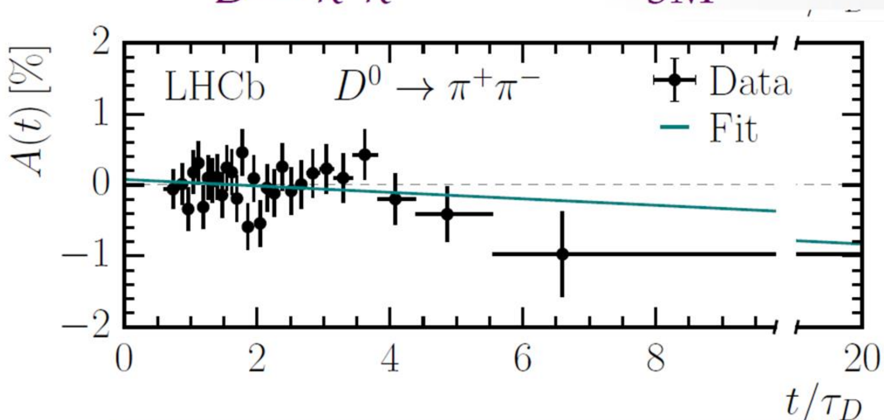
- Asymmetry of yields in t(D) bins: $A_{CP}(t) \simeq A_{CP}^{\text{direct}} - \mathbf{A}_\Gamma \frac{t}{\tau_D}$
- 2011+2012 data, prompt charm

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



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

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



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

A_Γ: entering SM area

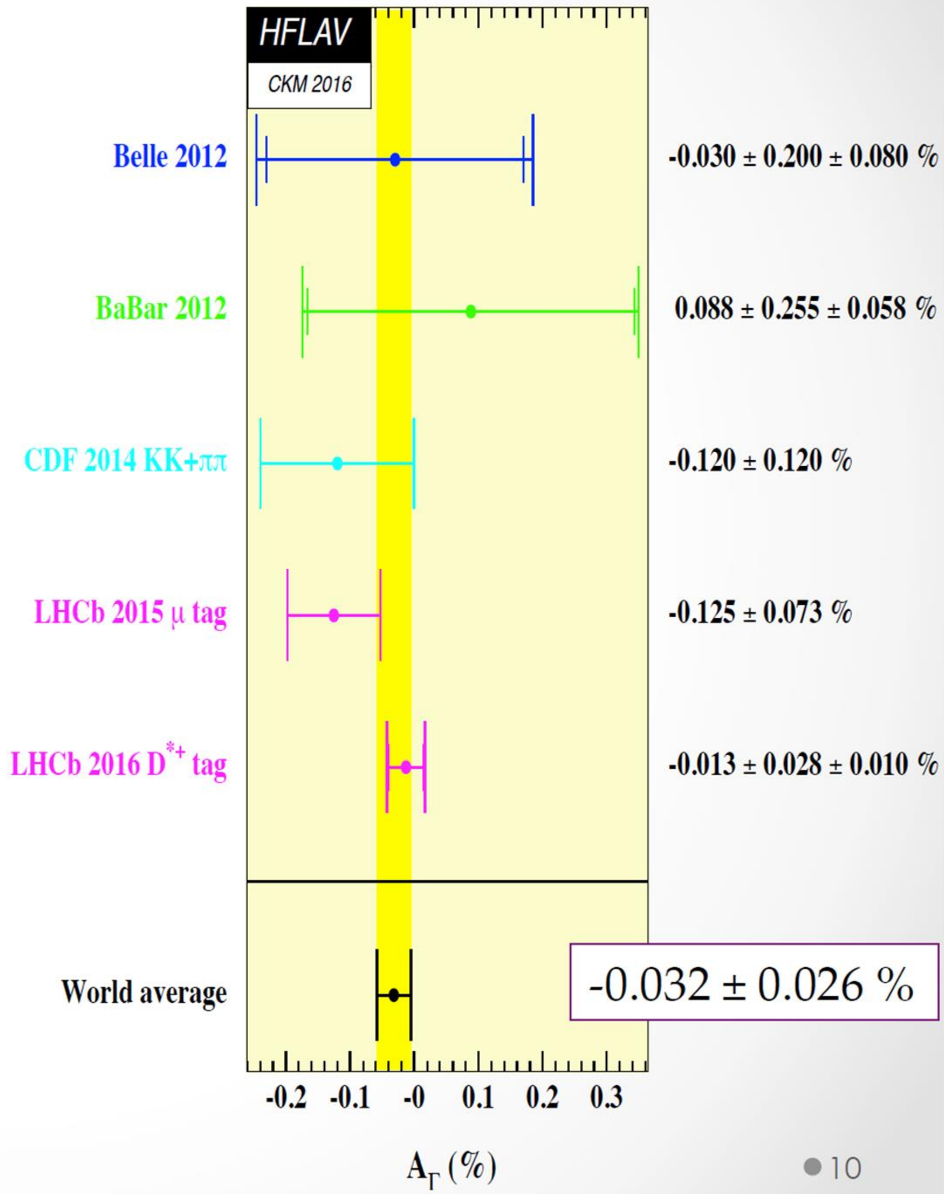
- Sensitivity: $O(10^{-4})$
  Limited by statistics
- Indirect CPV in SM $\sim 10^{-4}$

- 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



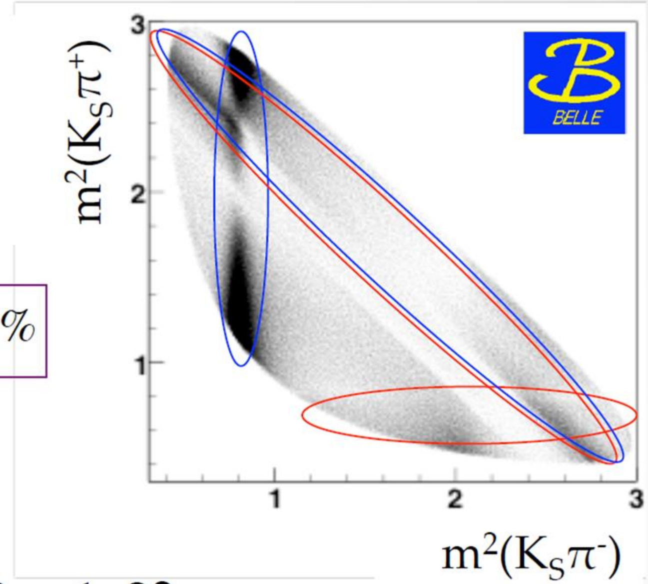
PRD89 091103 (2014)

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

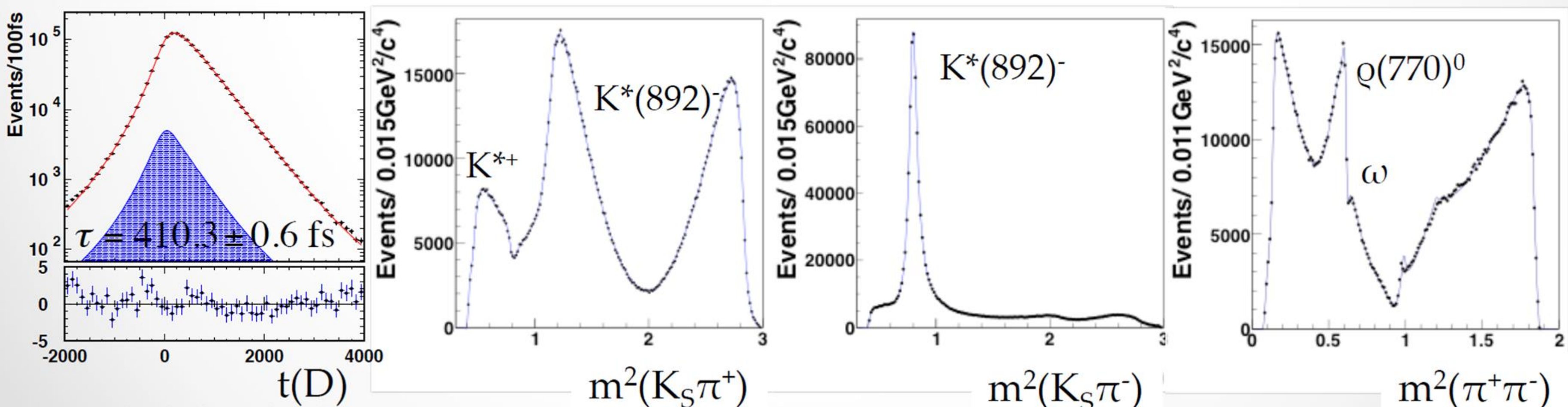
- Large statistics and rich dynamics
- Significant $D^0 \to f$ & $D^0 \to \bar{f}$ interferences
- Most precise x so far

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

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



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



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**

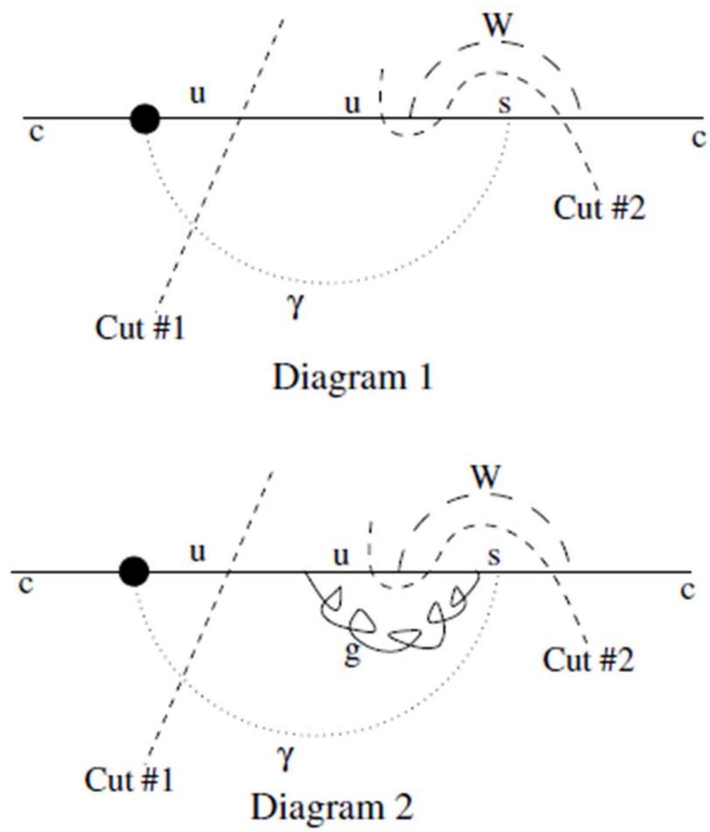


FIG. 3: This unitarity graph illustrates CPT conservation for the quark level process $c \to u\gamma$ due to NP. Diagram 1 shows the lowest order interference between NP and SM where cut #1 is for the $c\gamma$ final state and cut #2 is for a $s\bar{s}u$ final state. Cut #2 cannot be on shell. Diagram 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] ~fewX10^{-4} if SM is the source, if these also show O(5X10^{-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

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

Change to sign of central values; for numerical illustrations take central vaues to be ½ of current value

Brs of some interesting 2-body hadronic modes

Expected hierarchy of CPA

$Amp \sim a + A$ $a \ll A$

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 $N = N_\sigma^2/({\rm Br} A_{\rm CP}^2)$. In terms of the amplitudes then,

D(s)

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

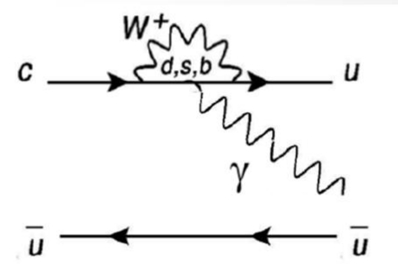
So that, generally, N depends on a but is independent of A, but a smaller value of A does enhance $A_{\rm CP}$; N is not affected because this is at the expense of the branching ratio. Going to a mode that has a smaller branching ratio with higher asymmetry has the advantage of reducing the effects of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

Going rare

More by Simone Bifani on Wednesday

- The larger penguin contribution, the larger CPV

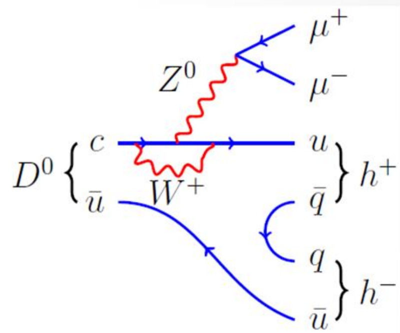
Radiative decays: there are signals to explore



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

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

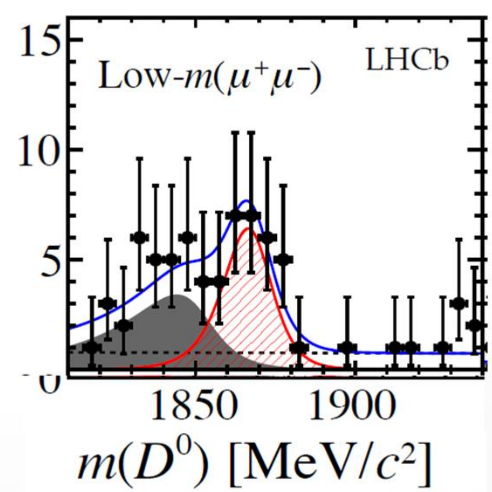
- LHCb Run2: at least double Belle signals



Leptonic decays: first signal!

- $D^0 \to \pi^+\pi^- \mu^+\mu^-$
  with $m(\mu^+\mu^-) < 525$ MeV
  $S = 27 \pm 6$ (5.4σ)

  PRL119, 181805 (2017)



signal
$D^0 \to 4\pi$

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