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
  \[ \text{sm} \leq 1.1 \% \Delta A_{CP} \]
• 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 \((mb/mW)^2 \ll (mt/mW)^2\)
- 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 $m_q >> \lambda_{QCD}$...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

\[ m_c^2 > 4 \left( m_s^2, m_d^2 \right) \]

ENhance by CLS Tree et al $N^2 \lambda^4 \sim 10^{21}$

See Later

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

- Simple & sensitive

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

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

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

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

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


Unfortunately, short lived excitement

Better understanding of SM theoretical expectation
BEST CHANCE IN A VERY LONG TIME OF POSSIBLE SIGHTINGS OF BSM
Anomalies galore!

- RD(*) \( \sim 46(?) \) probably not less
- RK(*) \( 2.66(R_k) \) probably \( 3.56 \) but only LHC

- \( g -2 \) BNL => FNAL expt... \( \sim 3.66 \) mean lattice progress by
  RBC-UKQCD & others

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$R(D^{(*)})$ by HFAG

- ~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**

- R_{D(∗)}: Theory much cleaner but QED radiative correction needed.
- More experimental effort needed.
- Potentially very serious experimental problem.

**Figure Details**

- **HFLAV (Summer 2018)**
- **Belle had. tag** (τ polarization) is also overestimated likely because theory error is not included.
- **Belle had. tag** affects V_{c}V_{L}.
- Deviation from SM prediction 3.9σ, likely an overestimate.

**Table Data**

<table>
<thead>
<tr>
<th>Experiment</th>
<th>R(D)</th>
<th>R(D*)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BaBar PRL109,101802(2012)</td>
<td>0.299 ± 0.003</td>
<td>R(D*) = 0.259 ± 0.005</td>
</tr>
<tr>
<td>Belle PRD92,072104(2015)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LHCb PRL115,111803(2015)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LHCb PRD94,072007(2016)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Belle PRL118,211801(2017)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LHCb PRL120,171802(2018)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Other Notes**

- Also WITZEL et al.
- R_{D(∗)} = 0.299 ± 0.003
- POTENTIAL C. V. E. X. E. P. T. A. L
- 4.1% realistic
Lepton universality tests

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

\[ R_K = 0.8 \] is a prediction of one class of model explaining the \( B^0 \rightarrow K^{*0} \mu^+\mu^- \) angular observables, see \( L_\mu - L_\tau \) models

\[ R_{K^0} = 2.5 \sigma \]

W. Altmannshofer et al. [PRD 89 (2014) 095033]

Radiative correction Seisidomi et al.
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.
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)

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

Masses

CKM matrix

Leads to profound repercussions for BSMs: “FLAVOR PUZZLE”
Implications of CPT
Based on
Atwood and A.S, PTEP 2013 (2013) no.9, 093B05
A classic test for CPV is the partial rate asymmetry:

\[ \alpha_x = \frac{\Gamma (e^+ \rightarrow x) - \Gamma (\bar{e}^\rightarrow \bar{x})}{\Gamma (e^+ \rightarrow x) + \Gamma (\bar{e} \rightarrow \bar{x})} \]

Consider such rate asymmetry in a final state:

\[ c \rightarrow u s \bar{s} \bar{s} \quad \text{and} \quad c \rightarrow u d d \bar{d} \]

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On-shell rescattering phase

CP-even phase \( \Rightarrow \) Total amplitude

\( \text{fn} \ c \Rightarrow u \ d \bar{d} \text{ is complex} \)
Implications of CPT

ILLUSTRATIVE EXAMPLE

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 $c \rightarrow d \bar{d}u$ 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 $c \rightarrow s\bar{s}u$ with a $d\bar{d}u$ intermediate state providing the strong phase. The interfering tree graphs are not shown but are implied.

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

AT the quark level:

\[ \Delta \Gamma (c \rightarrow \bar{d}du) = -\Delta \Gamma (c \rightarrow s\bar{s}u). \]
FIG. 9: The current experimental results for $A_{\mathrm{CP}}(\pi^+\pi^-)\times 10^3$ and $A_{\mathrm{CP}}(K^+K^-)\times 10^3$. The vertically hatched band shows the expectation for future measurements.
\[ A_{CP}(D^0 \rightarrow K^+K^-) \text{ & } A_{CP}(D^0 \rightarrow \pi^+\pi^-) \]

- **Individual** \( A_{CP}(KK) \), pion-tagged sample
  \[ A_{CP}(K^+K^-) = (0.14 \pm 0.15 \pm 0.10)\% \]

- **Combine with** \( \Delta A_{CP} \Rightarrow \)
  \[ A_{CP}(\pi^+\pi^-) = A_{CP}(K^+K^-) - \Delta A_{CP} = (0.24 \pm 0.15 \pm 0.11)\% \]

- **Central Values** seem consistent with expectation from CPT but errors Orange

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

- **Both** \( A_{CP} \)'s consistent with zero
STARRING MORE AT CHARMMING PENGUINS
Bearing all that in mind, Let’s stare some more at c-penguin

• cb has no SM-CP ...whereas likely it has BSM-CP
• 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

• Enhance penguin as much as you can

• **For charm-CP extremely important to suppress tree as much as possible:**
  
  • A) avoid $W \rightarrow ud$ or $us$ making charge vector state.... e.g. $\rho^+$ or $K^{*(+)}$ .....field-current ....Sakurai

  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
4\textsuperscript{th} rule

- Zweig suppressed + CLS
- Only class of modes seem possible here:
  - $D0 \Rightarrow Ks\ Ks, \ K0\ K0^*, \ K0^*\ K0^*$
- Feynman graph

\[ \text{See DA+AS PTEP\ 2012-13} \]
Improved strategy for DCP

- Improved a bit over DA+AS, PTEP 2013, Tab I
- Ds => $\rho^0 K^{(*)}$ ; $K^+ \phi$ [NOT $K^+$]
- D+ => $\phi \pi^+$ ($\rho^+$) ; $K^{0(*)} K^+$ [NOT $K^+$]
- D+ => $\rho^0 \pi^+ ; \pi^0 \pi^+ ...$; [ NOT $\rho^+$ ]
- D0 => $K^+ K^{-(*)}$ [NOT $K^+$] ; $\phi \rho^0$
- D0 => $\rho^0 \rho^0 ; \rho^0 \pi^0 ; \pi^+ \pi^- ; \pi^+ \rho^- [\text{Not} \rho^+ \pi^-; \rho^+ \rho^-]$
- NOTES:
  1) many FS all charged;
  2) Some VV good for TCA esp. Ds=> $\rho^0 K^{(*)}$ , D0 => $\phi \rho^0$; 2K0*
  3) all $\pi^0$ always also imply $\eta (')$ ;
  4) Special Note: $\rho^0$ 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.
<table>
<thead>
<tr>
<th>Decay</th>
<th>Suppressed Tree</th>
<th>Charged Final State</th>
<th>Favored</th>
<th>Total BR (10^{-3})</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_s \to \pi^{(<em>)0} K^{(</em>)+}$</td>
<td>X</td>
<td>$[\rho^0 \to \pi^+ \pi^-] K^+$</td>
<td>X</td>
<td>2.7 ± 0.05</td>
</tr>
<tr>
<td>$D_s \to \phi^{(<em>)} K^{(</em>)+}$</td>
<td></td>
<td>$[\phi \to K^+ K^-] K^+$</td>
<td>X</td>
<td>&lt; 0.3</td>
</tr>
<tr>
<td>$D^+ \to \pi^{(<em>)+} \phi^{(</em>)}$</td>
<td></td>
<td>$\pi^0 [\rho^0 \to \pi^+ \pi^-]$</td>
<td>X</td>
<td>2.65 ± 0.08</td>
</tr>
<tr>
<td>$D^+ \to K^{(<em>)+} K^{(</em>)0}$</td>
<td></td>
<td>$K^+[K_s \to \pi^+ \pi^-] K^+$</td>
<td>X</td>
<td>1.98 ± 0.13</td>
</tr>
<tr>
<td>$D^0 \to K^{(<em>)0} K^{(</em>)0}$</td>
<td>XX</td>
<td>$K^+[K_s \to \pi^+ \pi^-] K^+$</td>
<td>X</td>
<td>0.81 ± 0.15</td>
</tr>
<tr>
<td>$D^0 \to \pi^{(<em>)0} \pi^{(</em>)0}$</td>
<td></td>
<td>$K^+[K_s \to \pi^+ \pi^-] K^+$</td>
<td>X</td>
<td>&lt; 0.2</td>
</tr>
<tr>
<td>$D^+ \to \phi^{(<em>)} \pi^{(</em>)}$</td>
<td></td>
<td>$K^+[K_s \to \pi^+ \pi^-] K^+$</td>
<td>X</td>
<td>&lt; 0.35</td>
</tr>
<tr>
<td>$D^0 \to \phi^{(<em>)} \pi^{(</em>)}$</td>
<td></td>
<td>$K^+[K_s \to \pi^+ \pi^-] K^+$</td>
<td>X</td>
<td>0.7 ± 0.05</td>
</tr>
<tr>
<td>$D^0 \to K^{(<em>)0} K^{(</em>)+}$</td>
<td></td>
<td>$K^+[K_s \to \pi^+ \pi^-] K^+$</td>
<td>X</td>
<td>1.82 ± 0.10</td>
</tr>
<tr>
<td>$D^0 \to \phi^{(*)} \rho^0$</td>
<td></td>
<td>$K^+[K_s \to \pi^+ \pi^-] K^+$</td>
<td>X</td>
<td>1.40 ± 0.12</td>
</tr>
</tbody>
</table>

**TABLE I:** The singly Cabibbo suppressed decays of $D$ mesons to two ground state are listed. Note that the notation $\pi^{(*)0}$ stands for $\pi^+$ or $\rho$; $\pi^{(*)0}$ stands for $\pi^0$, $\rho^0$ or $\omega$; $\phi^{(*)}$ stands for $\phi$ or $\eta(0)$ to the extent that $\eta(0)$ is an $s\bar{s}$ 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 singly suppressed and the final state has an all charged final state. The decays down from [34] we have included it in the last column; this is the only singly suppressed 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. $D \rightarrow VV$ in P-wave]

• 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: $A_{CP} \sim \sin \Delta \phi_{weak}$
  $\sin \Delta \phi_{strong}$
  P-odd ampl: $A_{CP} \sim \sin \Delta \phi_{weak}$
  $\cos \Delta \phi_{strong}$
  complementary

• Triple-product method (aka T-odd): sensitive to P-odd CPV only

<table>
<thead>
<tr>
<th>Mode</th>
<th>$A_{CP}^{P-odd} \times 10^{-3}$</th>
<th>Exp</th>
<th>Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^0 \rightarrow K_S \pi^+ \pi^- \pi^0$</td>
<td>$-0.3 \pm 1.4^{+0.2}_{-0.8}$</td>
<td>Belle</td>
<td>arXiv:1703.05721</td>
</tr>
<tr>
<td>$D^0 \rightarrow K^+ K^- \pi^+ \pi^-$</td>
<td>$1.8 \pm 2.9 \pm 0.4$</td>
<td>LHCb</td>
<td>JHEP10 (2014) 005</td>
</tr>
<tr>
<td>$D^+ \rightarrow K_S K^+ \pi^+ \pi^-$</td>
<td>$-12 \pm 10 \pm 5$</td>
<td>Babar</td>
<td>PRD84 031103(2011)</td>
</tr>
</tbody>
</table>

**Triple product:**
$$C_T \equiv \vec{p}_1 \cdot (\vec{p}_2 \times \vec{p}_3)$$
Implications of CPT for CP-violating observables [I]

Table 1
Transformation properties under $T_N$ and CP and presence or absence of final state interactions (FSI). Here, $H$ present and $N \equiv$ FSI absent

<table>
<thead>
<tr>
<th>$T_N$</th>
<th>CP-violating</th>
<th>CP-conserving</th>
</tr>
</thead>
<tbody>
<tr>
<td>even</td>
<td>Y $\rightarrow$ Needs FSI phase</td>
<td>N</td>
</tr>
<tr>
<td>odd</td>
<td>N $\rightarrow$ TCA $\rightarrow$ Energy, PRA</td>
<td>Y $\rightarrow$ Does not Requires Loop</td>
</tr>
</tbody>
</table>

D. Atwood et al. / Physics Reports 347 (2001) 1–222
**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 $\alpha_s$ correction to diagram 1 where the intermediate cut #2 is on shell.

**Implications of CPT**

$\Rightarrow$ $\text{CRV in on-shell } \gamma$

$\text{small}$
Off-shell gamma, Z esp. important in light of current LHCb hints of LUV

• \( D(s) \Rightarrow [\pi(K),\rho(K^*)] + l^+ \ l^- \)

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

<table>
<thead>
<tr>
<th>Process</th>
<th>Upper Limit $\times 10^{-4}$</th>
<th>CL (%)</th>
<th>Expt.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho^0 \gamma$</td>
<td>$2.4$</td>
<td>90</td>
<td>771</td>
</tr>
<tr>
<td>$\omega \gamma$</td>
<td>$2.4$</td>
<td>90</td>
<td>768</td>
</tr>
<tr>
<td>$\phi \gamma$</td>
<td>$(2.73 \pm 0.35) \times 10^{-5}$</td>
<td>90</td>
<td>654</td>
</tr>
<tr>
<td>$K^*(892)^0 \gamma$</td>
<td>$(3.31 \pm 0.34) \times 10^{-4}$</td>
<td>90</td>
<td>719</td>
</tr>
</tbody>
</table>

### Other Radiative Decays

<table>
<thead>
<tr>
<th>Process</th>
<th>Upper Limit $\times 10^{-6}$</th>
<th>CL (%)</th>
<th>Expt.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma \gamma$</td>
<td>$2.2$</td>
<td>90</td>
<td>932</td>
</tr>
<tr>
<td>$e^+ e^-$</td>
<td>$7.9$</td>
<td>90</td>
<td>932</td>
</tr>
<tr>
<td>$\mu^+ \mu^-$</td>
<td>$6.2$</td>
<td>90</td>
<td>926</td>
</tr>
<tr>
<td>$\pi^0 e^+ e^-$</td>
<td>$4.5$</td>
<td>90</td>
<td>928</td>
</tr>
<tr>
<td>$\pi^0 \mu^+ \mu^-$</td>
<td>$1.8$</td>
<td>90</td>
<td>915</td>
</tr>
<tr>
<td>$\eta e^+ e^-$</td>
<td>$1.1$</td>
<td>90</td>
<td>852</td>
</tr>
<tr>
<td>$\eta \mu^+ \mu^-$</td>
<td>$5.3$</td>
<td>90</td>
<td>838</td>
</tr>
<tr>
<td>$\pi^+ \pi^- e^+ e^-$</td>
<td>$3.73$</td>
<td>90</td>
<td>922</td>
</tr>
<tr>
<td>$\rho^0 e^+ e^-$</td>
<td>$1.0$</td>
<td>90</td>
<td>771</td>
</tr>
<tr>
<td>$\pi^+ \pi^- \mu^+ \mu^-$</td>
<td>$5.5$</td>
<td>90</td>
<td>894</td>
</tr>
<tr>
<td>$\rho^0 \mu^+ \mu^-$</td>
<td>$2.2$</td>
<td>90</td>
<td>754</td>
</tr>
</tbody>
</table>
Table 1
Number of events expected for one year of running.

<table>
<thead>
<tr>
<th>Physics channel</th>
<th>Center-of-mass energy (GeV)</th>
<th>Peak luminosity (10^{33}) cm(^{-2}) s(^{-1})</th>
<th>Physics cross section (nb)</th>
<th>Number of events per year</th>
</tr>
</thead>
<tbody>
<tr>
<td>(J/\psi)</td>
<td>3.097</td>
<td>0.6</td>
<td>(\sim 3400)</td>
<td>(10 \times 10^9)</td>
</tr>
<tr>
<td>(\tau)</td>
<td>3.67</td>
<td>1.0</td>
<td>(\sim 2.4)</td>
<td>(12 \times 10^6)</td>
</tr>
<tr>
<td>(\psi(2S))</td>
<td>3.686</td>
<td>1.0</td>
<td>(\sim 640)</td>
<td>(3.0 \times 10^9)</td>
</tr>
<tr>
<td>(D)</td>
<td>3.770</td>
<td>1.0</td>
<td>(\sim 5)</td>
<td>(25 \times 10^6)</td>
</tr>
<tr>
<td>(D_s)</td>
<td>4.030</td>
<td>0.6</td>
<td>(\sim 0.32)</td>
<td>(1.0 \times 10^6)</td>
</tr>
<tr>
<td>(D_s)</td>
<td>4.140</td>
<td>0.6</td>
<td>(\sim 0.67)</td>
<td>(2.0 \times 10^6)</td>
</tr>
</tbody>
</table>

Expect \# of \(\pi S\), \(D_s\)'s \(\geq 10^9\) in the coming years.
**SuperKEKB/Belle II**

New intensity frontier facility at KEK

- Target luminosity: \( L_{\text{peak}} = 8 \times 10^{35} \text{cm}^{-2}\text{s}^{-1} \)
  \[ \Rightarrow \sim 10^{10} \, \text{B\bar{B}}, \, \Upsilon^+\Upsilon^- \text{ and charms per year} ! \]

\[ L_{\text{int}} > 50 \, \text{ab}^{-1} \]

*The first particle collider after the LHC!*

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*Theo Summary; 16th FPCP; A Soni*
\# of D’s vs Br & Asymm

\[ N = \frac{N_\sigma^2}{(\text{Br}A_{\text{CP}}^2)} \propto \frac{N_\sigma^2}{|A|^2 |a/A|^2} \propto \frac{N_\sigma^2}{|a|^2}. \] (11)

So that, generally, \( N \) depends on \( a \) but is independent of \( A \), but a smaller value of \( A \) does enhance \( A_{\text{CP}} \); \( N \) 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 \( B_{\text{Br}} \approx 0(10^{-3}) \), \( A_{\text{CP}} \approx 10^{-2} \), \( N_6 = 3 \), \( n_{\text{eff}} \approx \frac{1}{10} \)

\[ N \gtrsim 10^9 \]

puts things in interesting region

\( B_{\text{Br}} \approx 10^{-2}, A_{\text{CP}} \approx 10^{-3} \Rightarrow N \gtrsim 10^{10} \) fn3-6 observation
CPV in charm a powerful null test

- All CP asymmetries in charm should be vanishingly small [how small? ..Devil is in ....] $\Delta ACP[\pi\pi - KK]$ a case in point. Some theorists $1^{st}$ 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

- $D \Rightarrow \pi^+ \pi^0$ is another very interesting case.

- $K^+, D^+, B^+ \Rightarrow \pi^+ \pi^0$ are all vanishingly small....subject to considerable non perurbative corrections

\[
\text{But QED, EW, } m_n \neq m_{\ell} \text{ break Isospin} \quad A_{CP} (B^+) > A_{CP} (D^+) > A_{CP}(K^+) \quad \text{SM}
\]

$\Delta I = 2$ \quad $\Delta I = 0$.
CPV in charm a powerful null test

• All CP asymmetries in charm should be vanishingly small [how small? ..Devil is in ....] ΔACP[ππ – 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→π+ π0 is another very interesting case.
• K+, D+, B+ => π+ π0 are all vanishingly small….subject to considerable non perturbative corrections

But QED, EW, mν ≠ mχ

break Isospin

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

CKM-2018; soni-BNL
Null tests: Dir CP

- A very powerful class of null tests relevant for the era of the huge data sets on the horizon and especially suited for lattice calculations is
- $D, B \rightarrow \pi[K] l^+ l^-$ [diff. rate and Dir CP]
- $K^+, D^+, B^+ \rightarrow \pi^+ \pi^0$
- 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 $\epsilon$'s because disconnected diagrams cannot contribute
  - However EMIV [electro – mag + isospin violations] are essential for non-vanishing 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

$B^+ \rightarrow \pi^+ \pi^0 \left< 1 \right>$

$A_{CP}(B^+ \rightarrow \pi^+ \pi^0) \left< 1 \right.$

Electro – mag + isospin violations

Calculations are a lot simpler than $\epsilon$'s because disconnected diagrams cannot contribute
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 $\varepsilon'/\varepsilon$. However, unlike $K\to \pi\pi$, lattice methods appear exceedingly difficult $\Rightarrow$ DATAAS 2017 See Later
- More exptal input (many other modes) crucial & could change interpretation...

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MURE EXPERIMENTAL INPUT COULD BE VERY USEFUL

(PDG + HFA  90%) $A_{CP} \neq 0$

<table>
<thead>
<tr>
<th>Mode</th>
<th>BR</th>
<th>$A_{CP}$ in %</th>
<th>5σ Reach</th>
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</thead>
<tbody>
<tr>
<td>$D^+ \rightarrow K_S \pi^+$</td>
<td>$1.47 \times 10^{-2}$</td>
<td>$-0.52 \pm 0.14$ [32]</td>
<td>$1 \times 10^{-3}$</td>
</tr>
</tbody>
</table>
| $D_s \rightarrow \eta' \pi^+$ | $3.94 \times 10^{-2}$ | $-6.1 \pm 3.0$ [63]  
               |               | $-5.5 \pm 3.7 \pm 1.2$ [32] | $0.7 \times 10^{-3}$ |
| $D_s \rightarrow K_S \pi^+$ | $1.21 \times 10^{-3}$ | $6.6 \pm 3.3$ [63]  
               |               | $6.53 \pm 2.46$ [32] | $4 \times 10^{-3}$ |

These need clarification.

AT ISSUE IS DIRECT CP $\Rightarrow$ USE $D^+$, $D_s$

MANY INTERESTING MODES $\cdot$ $D^+ \rightarrow K^{*+} K^0 \pi^+$

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

$D_s \rightarrow \phi \pi^+$, $\eta' \pi^+$, $K^{*0} \pi^+$, $\phi K^+$
Important to measure CP in pure trees

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

Example

$C \bar{c}$

$\bar{u} u$

NO Penguin
NO CP phase SM

ESPECIALLY IMPORTANT to search CP
Since 7 extractions ASSUME No CP in $D^0$

CKM-2018; soni-BNL
BACK of a NAPKIN

\[ e.g. \, D^0 \rightarrow K^+ K^- \]

\[ d s, b \]

\[ u \]

\[ d \]

\[ \bar{s} \]

\[ s \]

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• 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 $D \rightarrow \pi^0 \pi^0 \ (\eta, \eta')$ also imp but may not be CS
SM expectation...InDCP

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

\[ \frac{\text{Im}[V_{cb}V_{ub}^* V_{us}V_{ub}^*]}{\text{Re}[]} \approx 0 \left(10^{-4}\right) \]
$A_T$ : quest for indirect CPV

- Does mixing affect $D^0$ and $\bar{D}^0$ differently?
- Easiest access via $A_T$
  
  $$A_T = \frac{\tau(D^0 \to h^+h^-) - \tau(D^0 \to h^+h^-)}{\tau(D^0 \to h^+h^-) + \tau(D^0 \to h^+h^-)} \approx -A_{CP}^{\text{indirect}}$$

- Asymmetry of yields in $t(D)$ bins:
  
  $$A_{CP}(t) \approx A_{CP}^{\text{direct}} - A_T \frac{t}{\tau_D}$$

- 2011+2012 data, prompt charm
  
  $D^0 \to K^+K^- \quad \sim10M$
  
  $D^0 \to \pi^+\pi^- \quad \sim3M$

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

$A_T(\pi\pi) = (+0.046 \pm 0.058 \pm 0.012)\%$
$A_T$: entering SM area

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

- $A_T$ in terms of basic parameters

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

CPV in mixing in mixing-decay interference

⇒ sensitivity to $q/p$ depends on $x$

World average: $-0.032 \pm 0.026 \%$

Belle 2012: $-0.030 \pm 0.200 \pm 0.080 \%$
BaBar 2012: $0.088 \pm 0.255 \pm 0.058 \%$
CDF 2014 KK+πτ: $-0.120 \pm 0.120 \%$
LHCb 2015 $\mu$ tag: $-0.125 \pm 0.073 \%$
LHCb 2016 $D_{s}^{+}$ tag: $-0.013 \pm 0.028 \pm 0.010 \%$
Dalitz(t) of $D^0 \rightarrow K_S \pi^+ \pi^-$ golden mode

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

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

\[ \left| \frac{q}{p} \right| = 0.90^{+0.16}_{-0.15} \quad 0.05 \quad 0.05 \]
\[ \phi = (-6 \pm 11 \quad 3^{+3}_{-4})^\circ \]

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

\[
\begin{array}{c}
\text{Events/100fs} \\
\begin{array}{c}
\tau = 410.3 \pm 0.6 \text{ fs} \\
\end{array}
\end{array}
\]

\[
\begin{array}{c}
\text{Events/0.015GeV/c}^2 \\
\begin{array}{c}
K^{*+} \\
K^*(892)^+ \\
K^*(892)^- \\
\phi(770)^0 \\
\end{array}
\end{array}
\]

\[
\begin{array}{c}
\text{Events/0.011GeV/c}^2 \\
\begin{array}{c}
m^2(K_S \pi^+) \\
m^2(K_S \pi^-) \\
m^2(\pi^+ \pi^-) \\
\end{array}
\end{array}
\]
Extremely important consequence of CPT

- Since $\text{Br}(D0 \Rightarrow \pi^+ \pi^-) \sim \text{Br}(D0 \Rightarrow K^+ K^-) \times [1.40/3.96 = 0.35]$

- # of D0 needed for CP-observability in $\pi^+ \pi^-$ modes
  $\sim 1/3$ 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 $\alpha_s$ 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_j m_j K \K 

• Inclusive (multibody) modes should exhibit quark level asymmetry [quark-hadron duality] \( \sim \text{few} \times 10^{-4} \) 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....

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How to look for inclusive final states?

Simple suggestion

• Look for $D \rightarrow K K X$

• Operationally $K K X$ 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

\[ \lambda \equiv 0.22 \quad , \quad \text{EXPANSION PARAMETER} \]

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

e.g., \( V_{11} \sim 1 \), \( V_{21} \sim \lambda \); \( V_{23} \sim \lambda^2 \), \( V_{13} \sim \lambda^3 \)

\( A, s, \eta \sim O(1) \) \( \eta \) is CP-phase
Change to sign of central values; for numerical illustrations take central values to be $\frac{1}{2}$ of current value
Brs of some interesting 2-body hadronic modes
Expected hierarchy of CPA
while $A_{CP}(f) \propto a/A$. If we want to observe the CP violation with a significance of $N_{\sigma}$, the number of mesons required is $N = N_{\sigma}^2/(\text{Br}A_{CP}^2)$. In terms of the amplitudes then,

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

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.*
Going rare

- The larger penguin contribution, the larger CPV

**Radiative decays:** there are signals to explore
- $A_{CP}(D^0 \rightarrow q^0 \gamma) \leq 10\%$  de Boer, Hiller arXiv:1701.06392
- Full Belle data  PRL118, 051801 (2017)

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

- LHCb Run2: at least double Belle signals

**Leptonic decays:** first signal!
- $D^0 \rightarrow \pi^+\pi^- \mu^+\mu^-$
  with $m(\mu^+\mu^-) < 525$ MeV
  $S = 27 \pm 6$ (5.4$\sigma$)
  PRL119, 181805 (2017)
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