Novel sources and uses of quantum-correlated charm systems

IOP HEPP

Paras Naik

JHEP 03 (2023) 038 (arXiv:2102.07729)

UNIVERSITY OF LIVERPOOL

What is a quantum-correlated (QC) charm system?

- When part of a two-meson system, $D^0\bar{D}^0$ exists in eigenstates of C and P:

$$C_{D^0\bar{D}^0} = P_{D^0\bar{D}^0} = (-1)^{L_{D^0\bar{D}^0}}$$

- Such a system only exists in two quantum states (each correlated):

symmetric

$$\frac{|D^0\bar{D}^0\rangle + |\bar{D}^0 D^0\rangle}{\sqrt{2}} \text{ when } C_{D^0\bar{D}^0} = P_{D^0\bar{D}^0} = +1$$

asymmetric

$$\frac{|D^0\bar{D}^0\rangle - |\bar{D}^0 D^0\rangle}{\sqrt{2}} \text{ when } C_{D^0\bar{D}^0} = P_{D^0\bar{D}^0} = -1$$

- Correlations allow us to access **D decay strong phases** via interference

Goldhaber and Rosner Phys. Rev. D 15, 1254

- D^0 is a charmed meson ($c\bar{u}$)

Consequences of a transformation to the CP basis

- Define a new basis of **CP eigenstates***, ***D*₋** and ***D*₊**, from flavour states.

CP-odd
$$D_- = \frac{|D^0\rangle + |\overline{D}^0\rangle}{\sqrt{2}}$$

CP-even
$$D_+ = \frac{|D^0\rangle - |\overline{D}^0\rangle}{\sqrt{2}}$$

phase convention
$$CP|D^0\rangle = -|\overline{D}^0\rangle$$

- Re-write the quantum states of the $D^0\overline{D}^0$ system in this basis:

opposite
$$\frac{|D_-D_+\rangle - |D_+D_-\rangle}{\sqrt{2}} \text{ when } C_{D^0\overline{D}^0} = -1$$

Both D in same CP state is forbidden

same
$$\frac{|D_+D_+\rangle - |D_-D_-\rangle}{\sqrt{2}} \text{ when } C_{D^0\overline{D}^0} = +1$$

Both D must be in same CP state, product branching fraction is enhanced

Asner and Sun Phys. Rev. D 77, 019902

* assuming no CP violation, through can be corrected

How to prepare QC $D^0\overline{D}^0$ systems (traditional)

Goldhaber and Rosner
Phys. Rev. D 15, 1254

- At an $e^+ e^-$ collider running at **open charm threshold**, $D^0\overline{D}^0$ systems will be produced via the reaction:

$$e^+e^- \xrightarrow{\gamma^*} D^0\,\overline{D}^0$$

$J^{PC} = 1^{--}$

$C = -1$

- Currently, **the entire quantum correlated D decay sample** studied by BES III [2.93 fb^{-1} analysed, 16 fb^{-1} available, 20 fb^{-1} expected] (and formerly, CLEO-c [818 pb^{-1}]) has been collected at threshold.

Current applications of QC $D^0\bar{D}^0$

- **QC $D^0\bar{D}^0$ systems** have been used to obtain:
  - Time-integrated measurements of **charm mixing** PRD 86, 112001 (2012)
  - **Strong decay phase differences** (e.g. $\delta_{K\pi}$, $\delta_{KK\pi0}(\Phi)$)
    - Input for measurements of charm mixing and the CKM phase γ
    - Reduce/replace systematics due to D decay models

Simultaneous determination of the CKM angle γ and parameters related to mixing and *CP* violation in the charm sector

LHCb-CONF-2022-003

(using CLEO-c, BES III & HFLAV inputs)

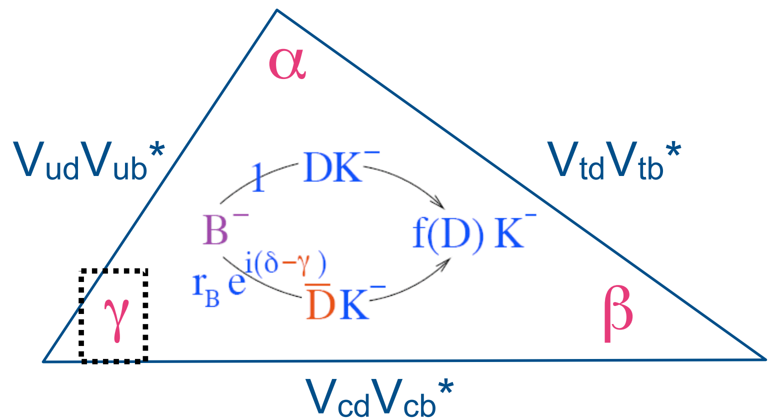
Many input analyses and theory/phenomenology contributions! (see CONF note references)

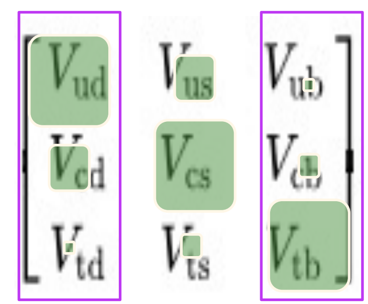
(Belle II making similar measurements!)

$$\gamma = (63.8\,^{+3.5}_{-3.7})^\circ$$

$$x = (0.398\,^{+0.050}_{-0.049})\% \qquad x \equiv \frac{\Delta m}{\Gamma}$$

$$y = (0.636\,^{+0.020}_{-0.019})\% \qquad y \equiv \frac{\Delta\Gamma}{2\Gamma}$$





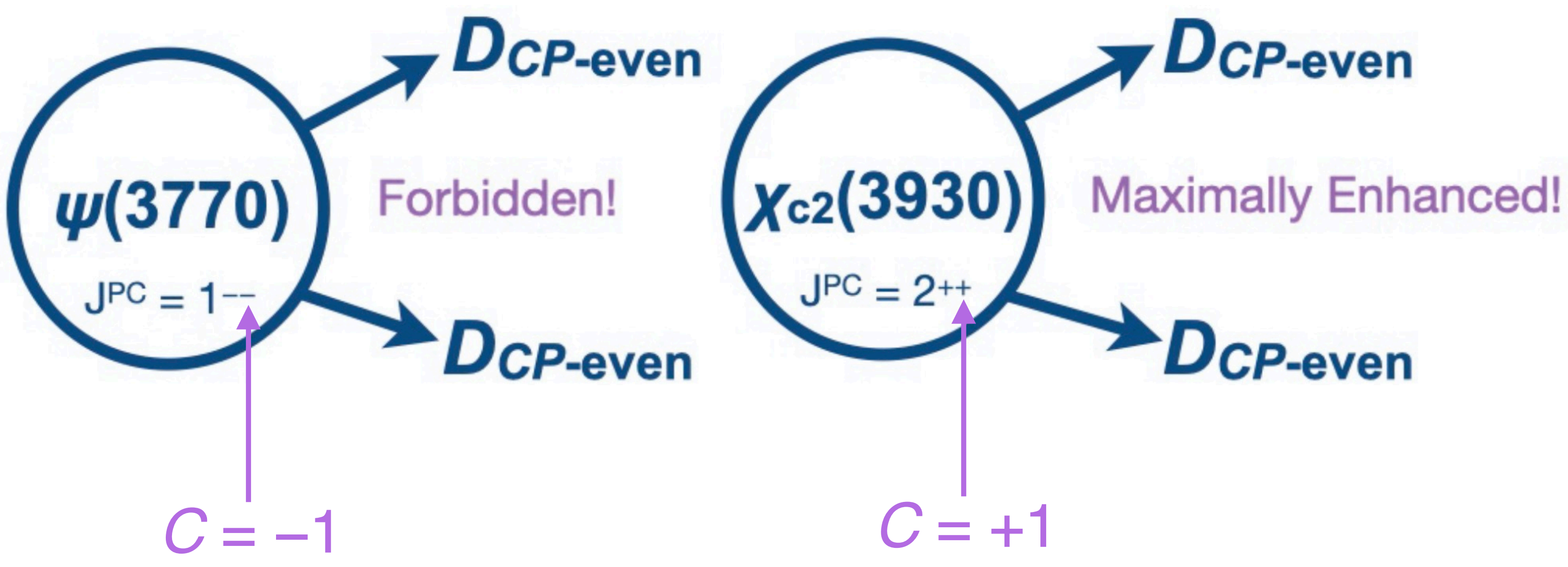
Quantum correlations extended

JHEP 03 (2023) 038

- The full BES III sample (20/fb), while large, is limited… as LHCb & Belle II collect more data systematics from charm input limits the precision on γ.

- There are also some other interesting things you can do with QC systems. Also other interesting places to obtain them.

- Apply the same logic to other C conserving reactions: **strong decays**



Yet another source of QC $D^0\bar{D}^0$

JHEP 03 (2023) 038

- Also a C conserving reaction:

$$\chi_{c1}(3872) \to D^0\bar{D}^0 + m\gamma + n\pi^0$$

$J^{PC} = 1^{++}$

[49] LHCb collaboration, *Determination of the $X(3872)$ meson quantum numbers*, *Phys. Rev. Lett.* **110** (2013) 222001 [1302.6269]. (Cited in section 2.)

- $\chi_{c1}(3872)$ is known to decay primarily to DD* G. Gokhroo *et al.*, Phys. Rev. Lett. **97**, 162002 (2006).

$$\chi_{c1}(3872) \to D^0\bar{D}^0\pi^0 \qquad C_{D^0\bar{D}^0} = +1$$

$$\chi_{c1}(3872) \to D^0\bar{D}^0\gamma \qquad C_{D^0\bar{D}^0} = -1$$

- Off-shell DD* also possible, but also produced strongly, C must be conserved!

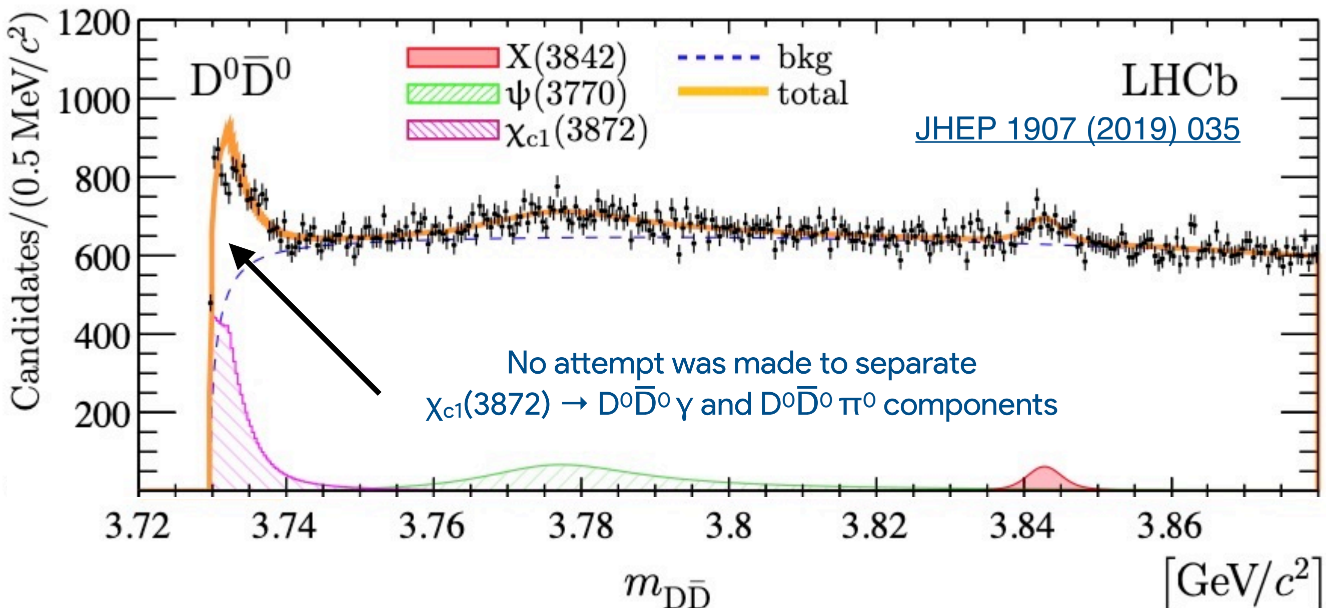
$$m_{\chi_{c1}(3872)} = 3871.59 \pm 0.06 \pm 0.03 \pm 0.01\ \text{MeV}/c^2$$
$$\Gamma_{\chi_{c1}(3872)} = 0.96\,^{+0.19}_{-0.18} \pm 0.21\ \text{MeV}$$

LHCb, PRL 122 (2019) 211803

Prompt Charmonia at LHCb

- LHCb, 9 fb^{-1} data, JHEP 1907 (2019) 035, reconstructing $D^0 \to K^-\pi^+$ only
  - Plot of $m(D^0\bar{D}^0)$, $\chi_{c1}(3872) \to (D^0\bar{D}^0$ + light neutral) seen as a reflection
  - O(10^4) $D^0\bar{D}^0$ systems from $\chi_{c1}(3872)$ seen in prompt decays.
    - ~4x more expected from LHCb by 2025, similar amount to BES III*

- Possible to separate C components using $p_{D^0}^{D\bar{D}}$ JHEP 03 (2023) 038 — invariant & does not require a mass constraint



*my estimate: BES III 20/fb will collect ~ 5×10^4 C = –1 $D^0\bar{D}^0$, $D^0 \to K^-\pi^+$ only, extrapolated from Chin.Phys.C 42 (2018) 8, 083001 (BES III)

What else can we do with QC $D^0\bar{D}^0$?

JHEP 03 (2023) 038

- Certainly would be interesting to extract quantum correlated $D^0\bar{D}^0$ systems from wherever we could find them for further studies on γ and D mixing.

- Interesting consequences due to the correlations:

$C = -1$

$$\chi_{c1}(3872) \rightarrow D^0\bar{D}^0\gamma$$

Forbidden by CP conservation	***CP+***	***CP+***
	CP–	***CP–***
Maximal enhancement	*CP+*	*CP–*
	CP–	*CP+*

$C = +1$

$$\chi_{c1}(3872) \rightarrow D^0\bar{D}^0\pi^0$$

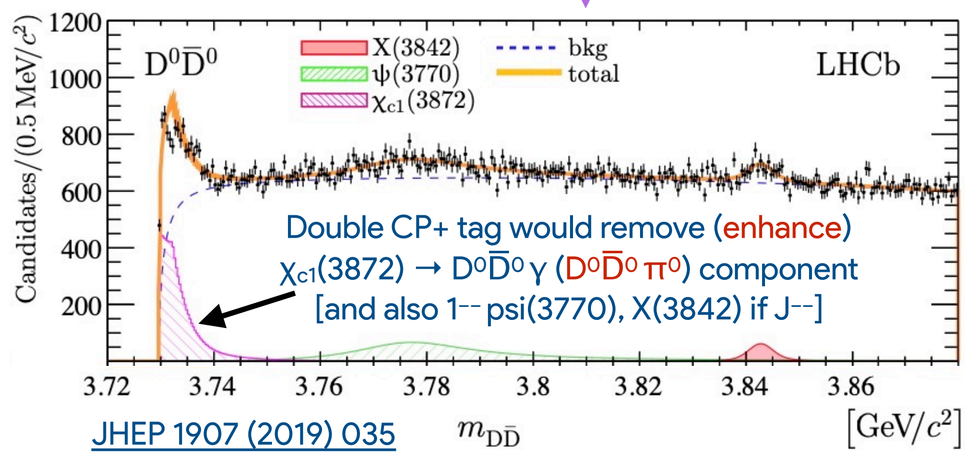
Forbidden by CP conservation	*CP+*	*CP–*
	CP–	*CP+*
Maximal enhancement	***CP+***	***CP+***
	CP–	***CP–***

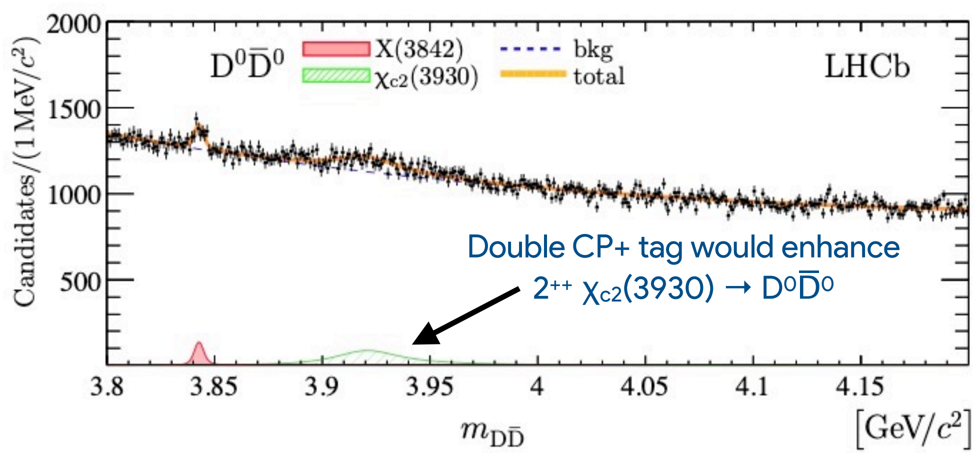
- Reconstructing **both D decays** with **CP-even states** (e.g. **$K^+ K^-$**, **$\pi^+ \pi^-$**) is effectively a **filter preserving only C = +1 $D^0\bar{D}^0$**

Prompt Charmonia at LHCb, and a filtering idea

- LHCb, 9 fb^{-1} data, JHEP 1907 (2019) 035, reconstructing $D^0 \to K^-\pi^+$ only

- Idea: Reconstructing both D in **CP+** modes (K^+K^-, $\pi^+\pi^-$) means **branching fraction for $\chi_{c1}(3872) \to D^0\bar{D}^0\gamma$ will be zero.**
  JHEP 03 (2023) 038
  $\chi_{c1}(3872) \to D^0\bar{D}^0\pi^0$ will "only" be ~**25** times smaller than $K^-\pi^+$ case (50x smaller if no correlation).





- Will help access the $\chi_{c1}(3872) \to D^0\bar{D}^0\pi^0$ line shape.

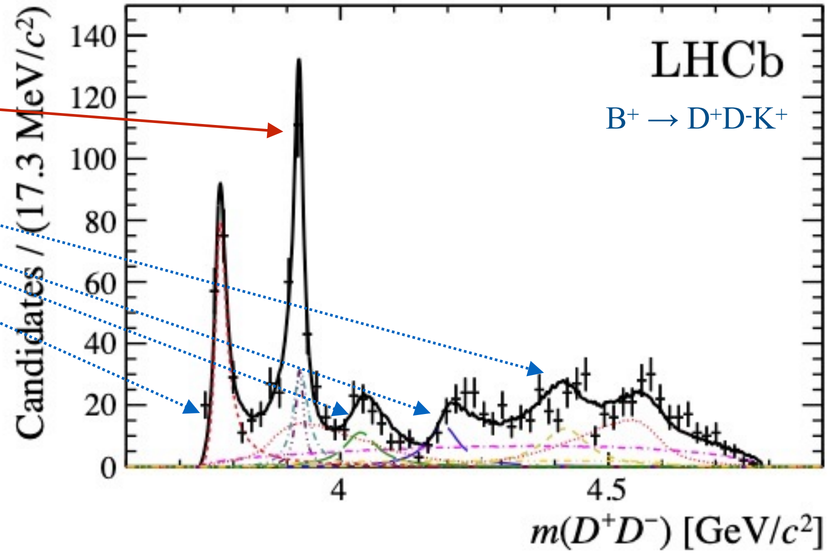
- *Other charmonia affected similarly.*

Amplitude analysis filtering idea

JHEP 03 (2023) 038

- In the LHCb **$B^+ \to D^+D^-K^+$** amplitude analysis [PRD 102 (2020) 112003] the following **$m(D^+D^-)$ Dalitz plot projection** is observed:

In $D^0\bar{D}^0K^+$ case, double CP+ tag would remove (enhance) J^{--} (J^{++}) components



- Bondar and Milstein [JHEP 12 (2020) 015] notice (compared to $B^+ \to D^+D^-K^+$)
  - In $B^+ \to D^0\bar{D}^0K^+$, $\psi(3770)$ branching fraction is ~ 4 times the size
  - In $B^+ \to D^0\bar{D}^0K^+$, $\chi_{c2}(3930)$ is suppressed (not observed by BaBar)

PRD 91 (2015) 052002

- Reconstruct D mesons in K^+K^-, $\pi^+\pi^-$ states in $B^+ \to D^0\bar{D}^0K^+$
  - Expect mainly DK^+ resonance (+ non-resonant) amplitudes.

Quantum correlations in weak decay

JHEP 03 (2023) 038

- Idea: find the first evidence for quantum correlations generated from a weak decay. $B^0_{(s)} \to D^0 \overline{D}^0$ $C_{D^0\overline{D}^0} = +1$ Angular momentum conservation alone dictates this!
- Proof would be demonstrating (approximately*) for $h^+h^- = \{K^+K^-, \pi^+\pi^-\}$:

$$\frac{\mathscr{B}(B^0_{(s)} \to [D^0 \to h^+h^-][\overline{D}^0 \to h^+h^-])}{\mathscr{B}(B^0_{(s)} \to [D^0 \to K^-\pi^+][\overline{D}^0 \to K^+\pi^-])} = \frac{\mathbf{2}\,[\mathscr{B}(D^0 \to h^+h^-)]^2}{[\mathscr{B}(D^0 \to K^-\pi^+)]^2}$$

Maximally (slightly) affected by quantum correlations

* really this is slightly less than 2 due to mixing

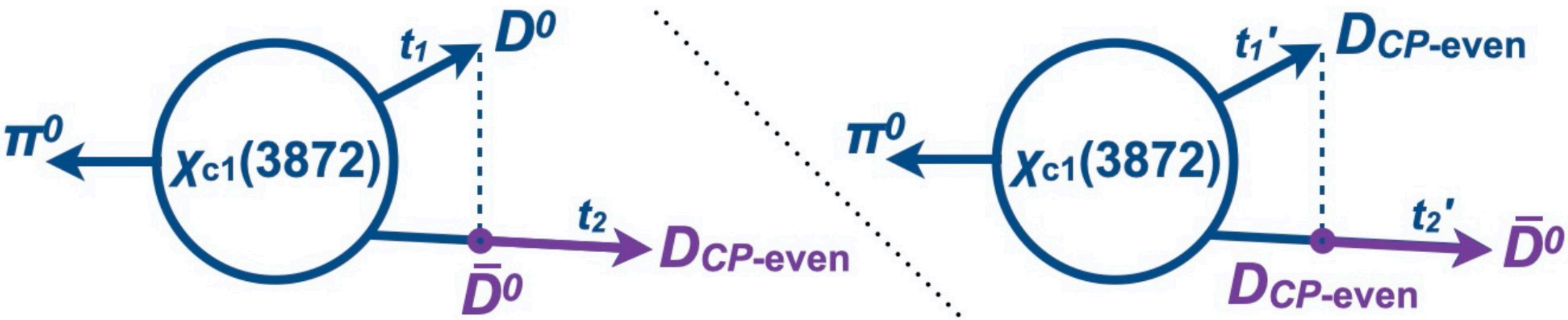
- Should be able to observe this effect with the Run 3 (2024-2025) LHCb data*:

* 2000 (600) B^0_s (B^0) $\to [D^0 \to K^-\pi^+][\overline{D}^0 \to K^+\pi^-]$
and
80 (24) B^0_s (B^0) $\to [D^0 \to h^+h^-][\overline{D}^0 \to h^+h^-]$
extrapolating from LHCb collab., PRD 87 (2013) 092007 [1302.5854] and arXiv:1808.08865.

Time-reversal violation in charm

JHEP 03 (2023) 038
J. Bernabeu et al., JHEP 1208(2012) 064

- CP violation implies T violation (or CPT violation, or both) —
  - CPT Theorem: CP and T violations equal; obligated to demonstrate this.
- Similar method to
  - T violation observation in the B system **[BaBar PRL 109, 211801 (2012)]**
  - Time-reversal search in the K system **[KLOE PLB 845 (2023) 138164]**
- Reconstruct flavour (e.g. $\mathbf{K^- \pi^+}$) and CP-even final states (e.g. $\mathbf{K^+ K^-}$, $\mathbf{\pi^+ \pi^-}$)



Two T-conjugate D transitions within $\chi_{c1}(3872)$ decays

Summary

- Reconstructing neutral D mesons in CP=+1 eigenstates, within the charmonia spectrum can enhance or eliminate components with specific C
  - study $\chi_{c1}(3872) \rightarrow D^0\overline{D}^0 \pi^0$ line shape
  - $b \rightarrow D^0\overline{D}^0X$ amplitude analyses
  - observe quantum correlations in weak decay

- Possibility to study T (and CPT) reversed processes in the charm system.

- BES III (20/fb) C = -1 $D^0\overline{D}^0$ sample and analyses still on the way!
- Opportunities for QC $D^0\overline{D}^0$ at BES III (above threshold), BELLE II, PANDA
  - Full set of suggestions in JHEP 03 (2023) 038

- It's ambitious — but if more quantum correlated $D^0\overline{D}^0$ is desired the LHC is *no doubt* producing them in quantity, and LHCb can collect them — analyzing them will be a challenge worth looking forward to.

Backup Slides

P. Naik, JHEP 03 (2023) 038

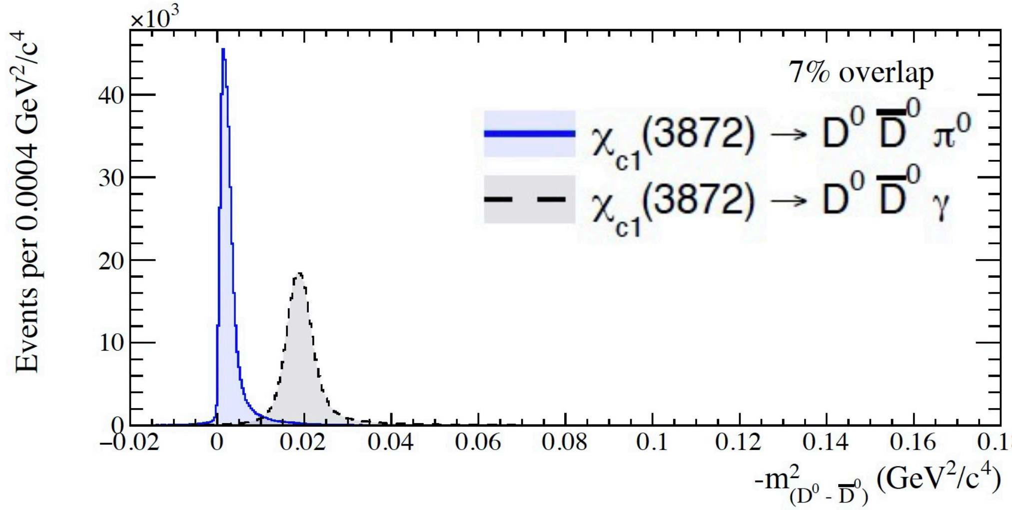
Separating $\chi_{c1}(3872) \to D^0\bar{D}^0\pi^0$ & $D^0\bar{D}^0\gamma$

- A variable based on the $D^0\bar{D}^0$ frame energy release, closely approximates the light neutral's momentum and is frame invariant:

$$\left(2\,p_{D^0}^{D\bar{D}}/c\right)^2 = -m^2_{(D^0-\bar{D}^0)}$$

- No D mass-constraint is required for this variable to be useful.

- Only the D^0 and $\bar{D}^0$ are required - the light neutral does not need to be reconstructed.



Study using **toy** signal MC designed to simulate LHCb detector effects ("RapidSim")

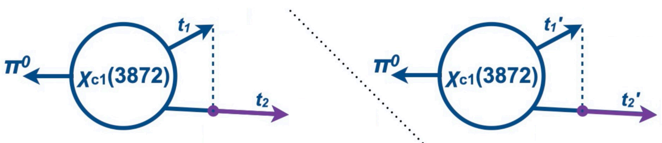
$\chi_{c1}(3872)$ decays only via D*D in S-wave

Real $\chi_{c1}(3872)$ decays will also have off-shell components

Time-reversal violation

P. Naik, JHEP 03 (2023) 038
A.J. Bevan, Front. Phys.(Beijing) 11 (2016) 111401

- Can form many testable symmetry pairs.



- Need small corrections if using $D^0 \to K^-\pi^+$ as a flavor tag

- Could try a time-integrated measurement first, since D mixing is slow

Testable Symmetry S	Reference Transition $a \to b$	Conjugate Transition $a' \to b'$	$(D^0\overline{D}^0)_{C=-1}$ Detection Modes at (t_1, t_2, t_1', t_2')	$(D^0\overline{D}^0)_{C=+1}$ Detection Modes at (t_1, t_2, t_1', t_2')
CP and T	$D^0 \to \overline{D}^0$	$\overline{D}^0 \to D^0$	$(\boldsymbol{\overline{D}^0, \overline{D}^0, D^0, D^0})$	$(\boldsymbol{\overline{D}^0, \overline{D}^0, D^0, D^0})$
CP and CPT	$D^0 \to D^0$	$\overline{D}^0 \to \overline{D}^0$	$(\boldsymbol{\overline{D}^0, D^0, D^0, \overline{D}^0})$	$(\boldsymbol{\overline{D}^0, D^0, D^0, \overline{D}^0})$
T and CPT	$D_+ \to D_-$	$D_- \to D_+$	(D_-, D_-, D_+, D_+)	(D_+, D_-, D_-, D_+)
CP	$\overline{D}^0 \to D_-$	$D^0 \to D_-$	$(D^0, D_-, \overline{D}^0, D_-)$	$(D^0, D_-, \overline{D}^0, D_-)$
	$D_+ \to D^0$	$D_+ \to \overline{D}^0$	$(D_-, D^0, D_-, \overline{D}^0)$	$(\boldsymbol{D_+, D^0, D_+, \overline{D}^0})$
	$\overline{D}^0 \to D_+$	$D^0 \to D_+$	$(\boldsymbol{D^0, D_+, \overline{D}^0, D_+})$	$(\boldsymbol{D^0, D_+, \overline{D}^0, D_+})$
	$D_- \to D^0$	$D_- \to \overline{D}^0$	$(\boldsymbol{D_+, D^0, D_+, \overline{D}^0})$	$(D_-, D^0, D_-, \overline{D}^0)$
T	$\overline{D}^0 \to D_-$	$D_- \to \overline{D}^0$	$(D^0, D_-, D_+, \overline{D}^0)$	$(D^0, D_-, D_-, \overline{D}^0)$
	$D_+ \to D^0$	$D^0 \to D_+$	$(D_-, D^0, \overline{D}^0, D_+)$	$(\boldsymbol{D_+, D^0, \overline{D}^0, D_+})$
	$\overline{D}^0 \to D_+$	$D_+ \to \overline{D}^0$	$(D^0, D_+, D_-, \overline{D}^0)$	$(\boldsymbol{D^0, D_+, D_+, \overline{D}^0})$
	$D_- \to D^0$	$D^0 \to D_-$	$(D_+, D^0, \overline{D}^0, D_-)$	$(D_-, D^0, \overline{D}^0, D_-)$
CPT	$\overline{D}^0 \to D_-$	$D_- \to D^0$	(D^0, D_-, D_+, D^0)	(D^0, D_-, D_-, D^0)
	$D_+ \to D^0$	$\overline{D}^0 \to D_+$	(D_-, D^0, D^0, D_+)	$(\boldsymbol{D_+, D^0, D^0, D_+})$
	$D^0 \to D_-$	$D_- \to \overline{D}^0$	$(\overline{D}^0, D_-, D_+, \overline{D}^0)$	$(\overline{D}^0, D_-, D_-, \overline{D}^0)$
	$D_+ \to \overline{D}^0$	$D^0 \to D_+$	$(D_-, \overline{D}^0, \overline{D}^0, D_+)$	$(\boldsymbol{D_+, \overline{D}^0, \overline{D}^0, D_+})$

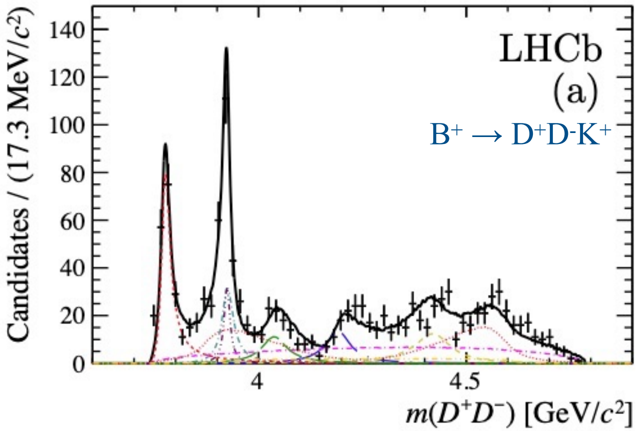
Table 4. The fifteen possible pairings of reference and symmetry conjugated transitions used to study CP, T and CPT for pairs of neutral D mesons, as demonstrated by Bevan [76, 77]. In four of these pairings, both a and a' can be established without the use of C-correlated charm (e.g. via $D^{*+} \to D^0\pi^+$ flavor tags) and thus the symmetry can also be tested elsewhere. Listed next to these pairings are the states that must be measured at (t_1, t_2, t_1', t_2') for $C = -1$ and $C = +1$ correlated $D^0\overline{D}^0$ systems, to establish the conjugated-transitions pair (see fig. 6). Sets of states that do not require D_- to be reconstructed are highlighted in **bold**; only $C = +1$ correlated $D^0\overline{D}^0$ allow tests of T and CPT without the use of the more difficult-to-reconstruct D_- states.

Another filtering idea

P. Naik, JHEP 03 (2023) 038

- In the LHCb $B^+ \to D^+D^-K^+$ amplitude analysis [PRD 102 (2020) 112003] the following fit fractions were observed:

Resonance	Magnitude	Phase (rad)	Fit fraction (%)
D^+D^- resonances			
$\psi(3770)$	1 (fixed)	0 (fixed)	$14.5 \pm 1.2 \pm 0.8$
$\chi_{c0}(3930)$	$0.51 \pm 0.06 \pm 0.02$	$2.16 \pm 0.18 \pm 0.03$	$3.7 \pm 0.9 \pm 0.2$
$\chi_{c2}(3930)$	$0.70 \pm 0.06 \pm 0.01$	$0.83 \pm 0.17 \pm 0.13$	$7.2 \pm 1.2 \pm 0.3$
$\psi(4040)$	$0.59 \pm 0.08 \pm 0.04$	$1.42 \pm 0.18 \pm 0.08$	$5.0 \pm 1.3 \pm 0.4$
$\psi(4160)$	$0.67 \pm 0.08 \pm 0.05$	$0.90 \pm 0.23 \pm 0.09$	$6.6 \pm 1.5 \pm 1.2$
$\psi(4415)$	$0.80 \pm 0.08 \pm 0.06$	$-1.46 \pm 0.20 \pm 0.09$	$9.2 \pm 1.4 \pm 1.5$
D^-K^+ resonances			
$X_0(2900)$	$0.62 \pm 0.08 \pm 0.03$	$1.09 \pm 0.19 \pm 0.10$	$5.6 \pm 1.4 \pm 0.5$
$X_1(2900)$	$1.45 \pm 0.09 \pm 0.03$	$0.37 \pm 0.10 \pm 0.05$	$30.6 \pm 2.4 \pm 2.1$
Nonresonant	$1.29 \pm 0.09 \pm 0.04$	$-2.41 \pm 0.12 \pm 0.51$	$24.2 \pm 2.2 \pm 0.5$



The $\chi_{c1}(3872)$ exotic meson

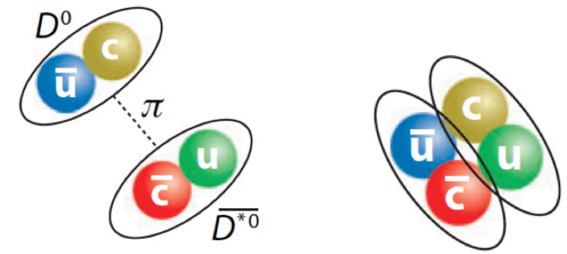
- The **χ_{c1}(3872) exotic meson** was first discovered by Belle in 2003
- Rapidly confirmed by CDF, D0, and BaBar

[41] BELLE collaboration, *Observation of a narrow charmonium - like state in exclusive $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}J/\psi$ decays*, *Phys. Rev. Lett.* **91** (2003) 262001 [hep-ex/0309032]. (Cited in section 2.)

[42] CDF collaboration, *Observation of the narrow state $X(3872) \to J/\psi\pi^{+}\pi^{-}$ in $\bar{p}p$ collisions at $\sqrt{s} = 1.96$ TeV*, *Phys. Rev. Lett.* **93** (2004) 072001 [hep-ex/0312021]. (Cited in section 2.)

[43] D0 collaboration, *Observation and properties of the $X(3872)$ decaying to $J/\psi\pi^{+}\pi^{-}$ in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV*, *Phys. Rev. Lett.* **93** (2004) 162002 [hep-ex/0405004]. (Cited in section 2.)

[44] BABAR collaboration, *Study of the $B \to J/\psi K^{-}\pi^{+}\pi^{-}$ decay and measurement of the $B \to X(3872)K^{-}$ branching fraction*, *Phys. Rev.* **D71** (2005) 071103 [hep-ex/0406022]. (Cited in section 2.)



D^0–$\overline{D^{*0}}$ "molecule" **Diquark–diantiquark**

$$m_{\chi_{c1}(3872)} = 3871.59 \pm 0.06 \pm 0.03 \pm 0.01\ \mathrm{MeV}/c^2$$
$$\Gamma_{\chi_{c1}(3872)} = 0.96^{+0.19}_{-0.18} \pm 0.21\ \mathrm{MeV}$$

LHCb, PRL 122 (2019) 211803

- Observation of $\chi_{c1}(3872) \to J/\psi\,\gamma$ established that χ_{c1}(3872) was **C = +1**

[48] BELLE collaboration, *Observation of $X(3872) \to J/\psi\gamma$ and search for $X(3872) \to \psi'\gamma$ in B decays*, *Phys. Rev. Lett.* **107** (2011) 091803 [1105.0177]. (Cited in section 2.)

- In 2013, LHCb established full quantum numbers **$J^{PC} = 1^{++}$**

[49] LHCB collaboration, *Determination of the $X(3872)$ meson quantum numbers*, *Phys. Rev. Lett.* **110** (2013) 222001 [1302.6269]. (Cited in section 2.)

- **Narrow width**; mass *coincident* with the sum of D^0 and D^{*0} mesons' masses
- Has isospin violating decays — P. del Amo Sanchez *et al.* [BABAR Collaboration], Phys. Rev. D **82**, 011101 (2010) [arXiv:1005.5190 [hep-ex]].
- χ_{c1}(3872) is known to decay primarily to **DD*** — G. Gokhroo *et al.*, Phys. Rev. Lett. **97**, 162002 (2006).
- Branching fraction of $\chi_{c1}(3872) \to D^*\bar{D}$ is $(52.4^{+25.3}_{-14.3})\%$ — C. Li and C.-Z. Yuan, *Determination of the abs* *Phys. Rev. D* **100** (2019) 094003 [1907.09149].

Light neutral kinematics in X decays

- $\chi_{c1}(3872)$ expected to decay through $D^*\overline{D}$ + c.c., at $D^*\overline{D}$ threshold.
    - However, an "off-shell" (non-res) component is possible / expected
- For D* we know breakup energies and momenta for the photon/pion.
- Major bonus: The X and neutral D* rest frames "coincide"…
  the D break-up momentum defines the kinematics*
    - Thus, the π^0/γ momentum is smoking gun, if we can reconstruct.

Decay	$E_{\pi^0/\gamma}$ (MeV/c^2)	$\lvert p_{\pi^0/\gamma}\rvert$ (MeV/c)
$X(3872) \to D^0\overline{D}^0\pi^0$	141.5	42.6
$X(3872) \to D^0\overline{D}^0\gamma$	137.0	137.0

- There is a variable that approximates the light neutral momentum without having to reconstruct it. **P. Naik, JHEP 03 (2023) 038**

- For off-shell $D^0\overline{D}^0\pi^0$, *p* still small, between the pion mass and threshold
- For off-shell $D^0\overline{D}^0\gamma$, *p* can take a larger set of values, very distinguishable.

Quantum numbers

$$\chi_{c1}(3872) \rightarrow (D^0\overline{D}^0)_{L_{D^0\overline{D}^0}}\pi^0 \quad :: \quad 1^{++} \rightarrow \underbrace{J^{PC}_{D^0\overline{D}^0} \oplus 0^{-+}}_{L_R}$$

$$\chi_{c1}(3872) \rightarrow (D^0\overline{D}^0)_{L'_{D^0\overline{D}^0}}\gamma \quad :: \quad 1^{++} \rightarrow \underbrace{J'^{P'C'}_{D^0\overline{D}^0} \oplus 1^{--}}_{L'_R}$$

Decay	$J_{D^0\overline{D}^0}$	L_R
$\chi_{c1}(3872) \rightarrow D^0\overline{D}^0\pi^0$	0	1
$\chi_{c1}(3872) \rightarrow D^0\overline{D}^0\pi^0$	2	1 or 3
$\chi_{c1}(3872) \rightarrow D^0\overline{D}^0\gamma$	1	0 or 2

$\chi_{c1}(3872)$ mass is at $D^0\overline{D}^{*0}$ threshold

Higher J and L unlikely

Table 1. Allowed angular momentum configurations for $J_{D^0\overline{D}^0} \leq 2$

CP violation in the charm system

- LHCb recently made the first observation of CP violation in the charm system

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

$$\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$$

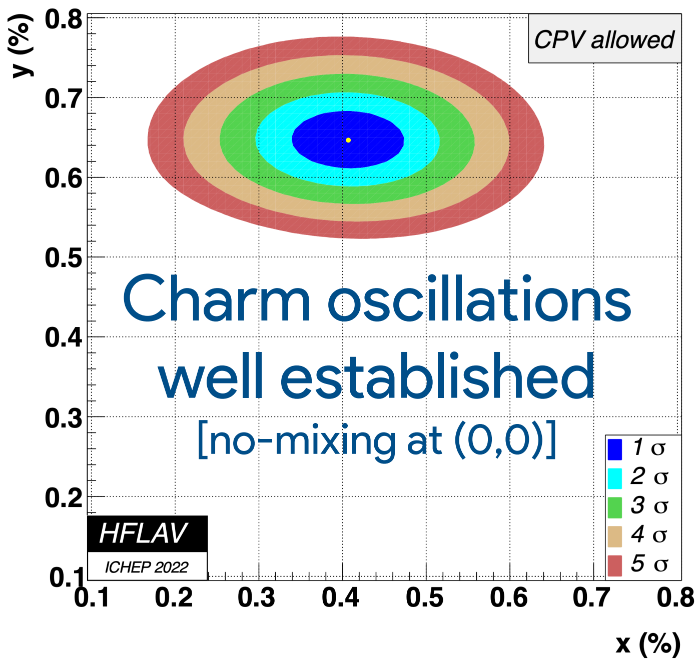
PRL 122 (2019) 211803

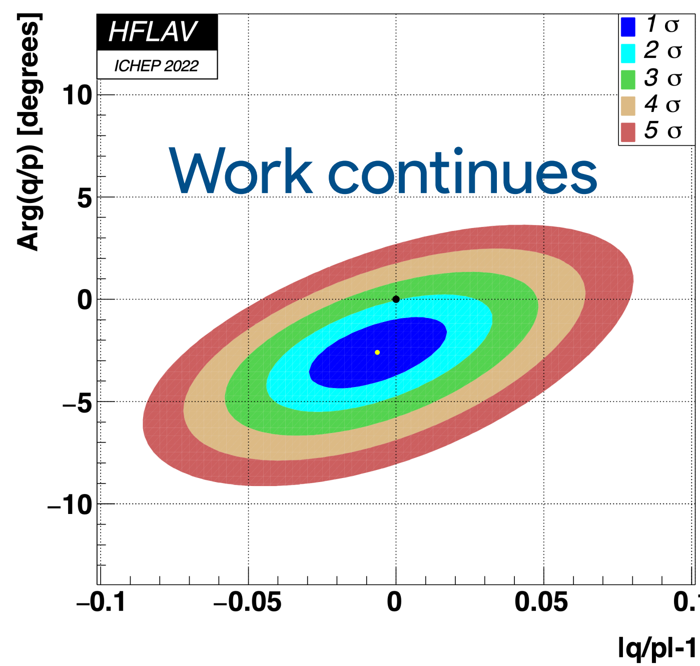
$$a^d_{\pi^-\pi^+} = (23.2 \pm 6.1) \times 10^{-4}$$

Evidence in a single decay channel at 3.8 std. dev.

PRL 131 (2023) 091802

- Global fits across several decay modes have clearly established charm oscillations, and are getting closer to establishing CP violation.

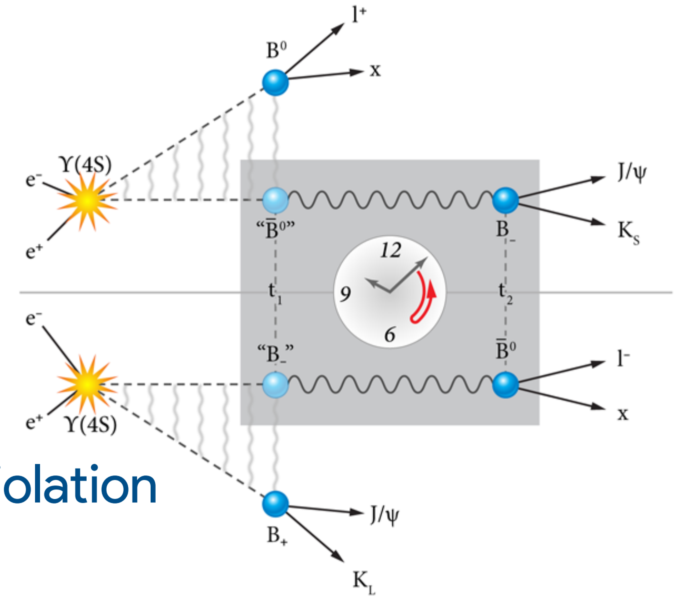




HFLAV ICHEP 2022 update

Time-reversal violation

- CP violation implies T violation (or CPT violation or both)
  - Since CPT supremacy implies the CP and T violations must be equal, we are obligated to demonstrate this.
- T violation seen in the Beauty system!
  - need one Asymmetric B-factory (BaBar)
  - prepare T (& CPT)-reversed processes
  - Measure T & CPT violation (14 & 0.3 σ)
  - Measure CP violation consistent with T violation



PRL 109, 211801 (2012)

- T violation being tested in the Kaon system!
  - need one Asymmetric kaon-factory (KLOE-2)
  - Recent results published with KLOE sample! - T/CPT violation not seen yet

PLB 845 (2023) 138164

- Can we see T violation in the Charm system?
  - *(No one has built me my asymmetric (tau-)charm factory)*
  - So I propose looking at LHCb

$D^0\bar{D}^0$ Product Branching fractions

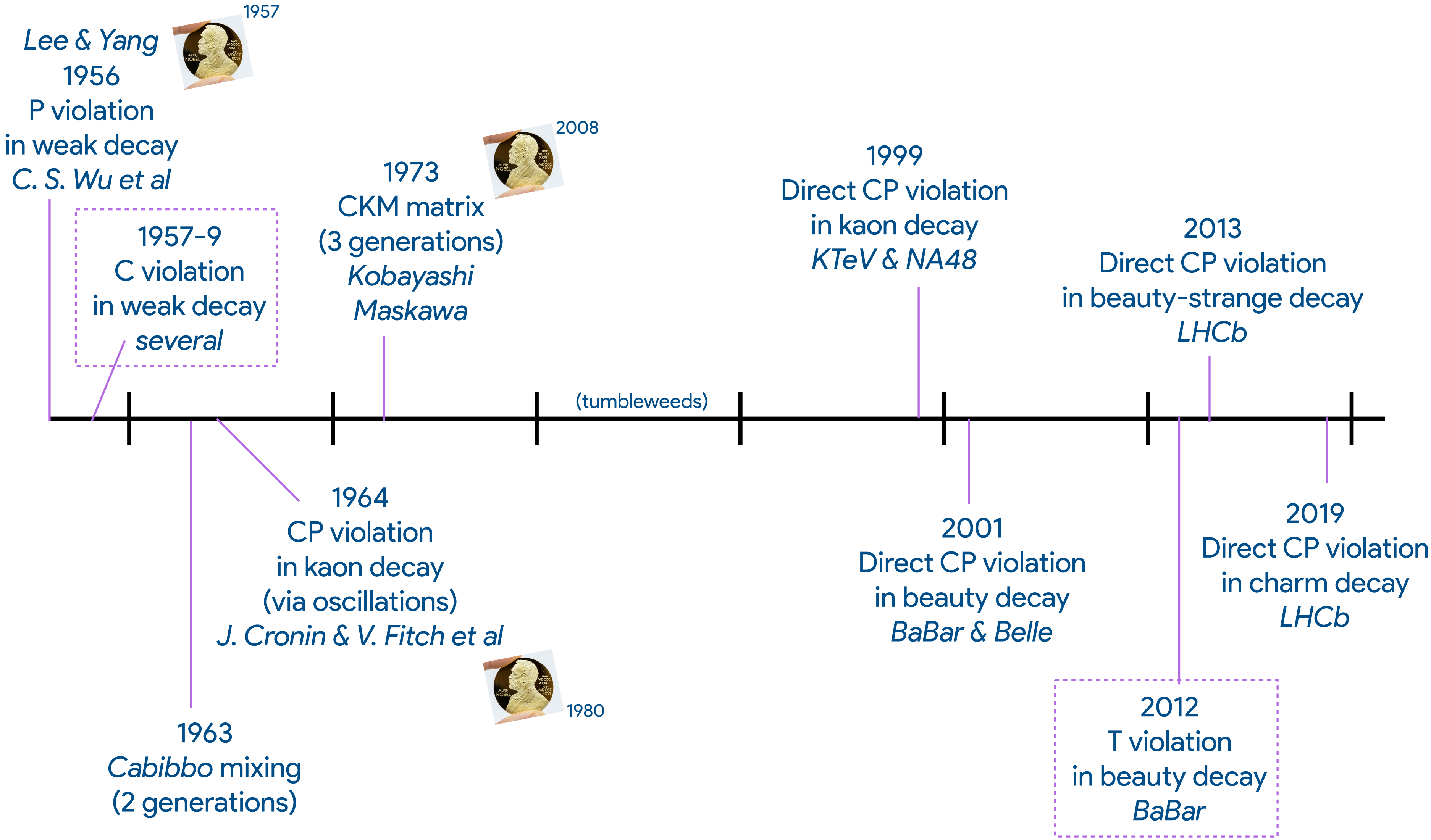
- There are fewer statistics in CP+ eigenstates, compared to flavour modes.
- However, remember that C=+1 $D^0\bar{D}^0$ to {CP+, CP+} is enhanced.
  The product branching fraction approximately doubles.

	D decay mode	$\bar{D}$ decay mode	$\mathcal{B}$ (naive)	$\mathcal{B}$ (including correlations)	
	$K^-\pi^+$	$K^+\pi^-$	1.60×10^{-3}	1.60×10^{-3}	
CP+, CP+ modes	$K^+K^-, \pi^+\pi^-$	$\pi^+\pi^-, K^+K^-$	1.23×10^{-5}	2.45×10^{-5}	Total = 6.27×10^{-5}
	K^+K^-	K^+K^-	1.69×10^{-5}	3.38×10^{-5}	
	$\pi^+\pi^-$	$\pi^+\pi^-$	2.22×10^{-6}	4.44×10^{-6}	

Table 2. Approximate product branching fractions $\mathcal{B}$ of a $C = +1$ $D^0\bar{D}^0$ pair reconstructed in the corresponding $D\bar{D}$ decay mode, both under the naive expectation [2] and after the effects of quantum correlation [23, 53], excluding small effects due to charm mixing and ignoring doubly-Cabibbo suppressed decays.

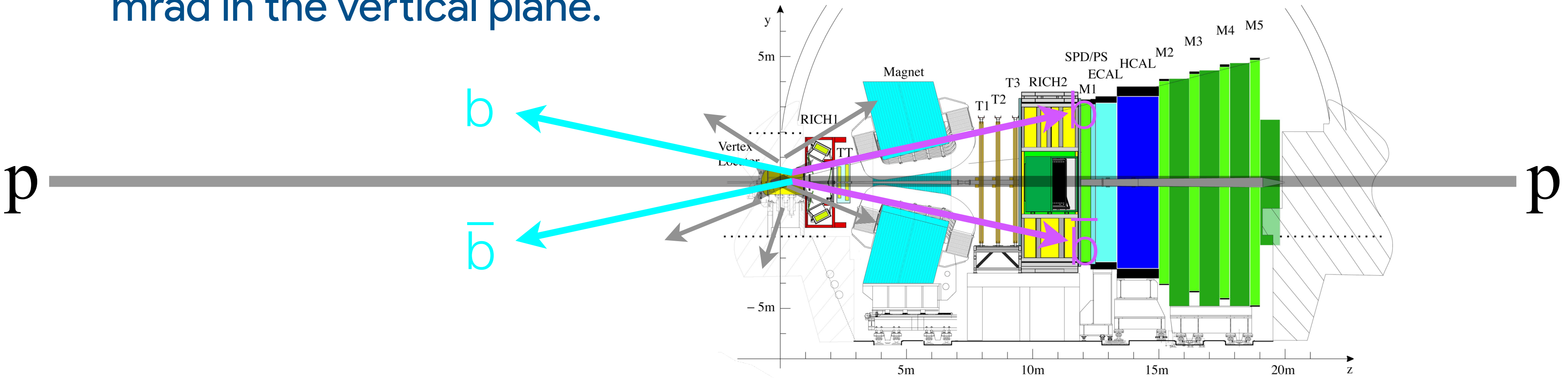
- Total product branching fraction ~25 times smaller for {CP+, CP+} tag than for {$K^-\pi^+$, $K^+\pi^-$} tag. [6.27×10^{-5} / 1.60×10^{-3} = ~ (1 / 25)]
- CP projections can give better access to phases / remove opposite C content

Discrete Symmetries Timeline

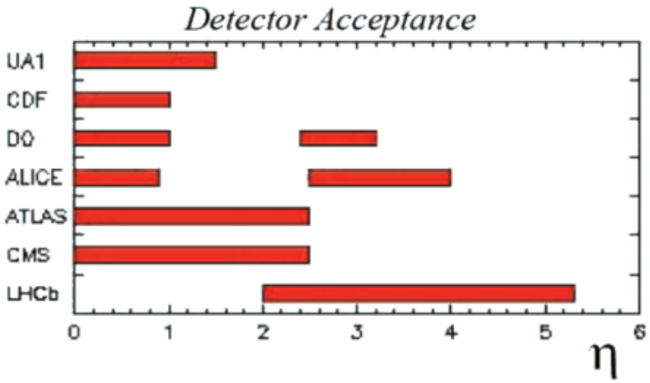


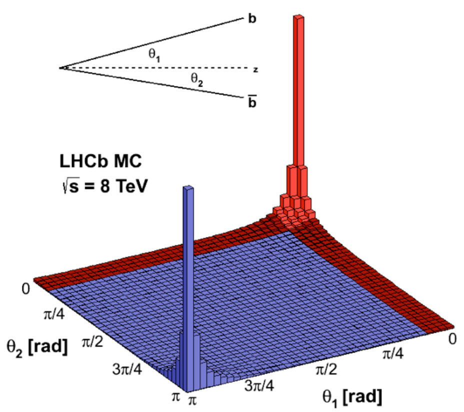
LHCb Experiment Overview

- The LHCb detector is a single arm forward spectrometer with a polar angular coverage from 10 to 300 mrad in the horizontal plane and 250 mrad in the vertical plane.



- Unique regime: $2 < \eta < 5$, down to $p_T \sim 0$

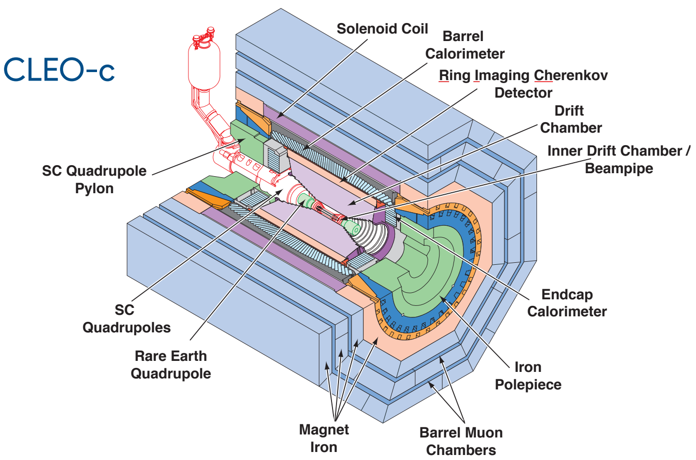


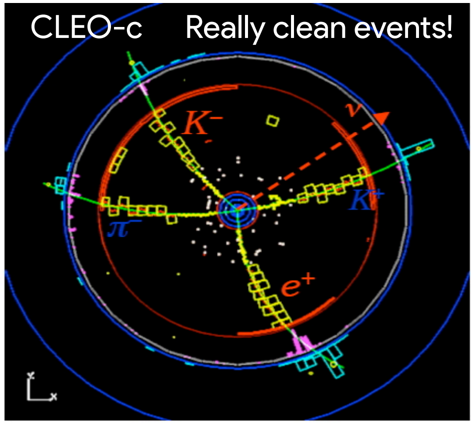


CLEO-c (2003-2008) / BES III (2008-)

- CLEO-c studied
  $e^+e^- \rightarrow \psi(3770) \rightarrow D^0\bar{D}^0$ decays
  - Total integrated luminosity of this sample is **818 pb^{-1} (3 million D pairs)**

CLEO-c

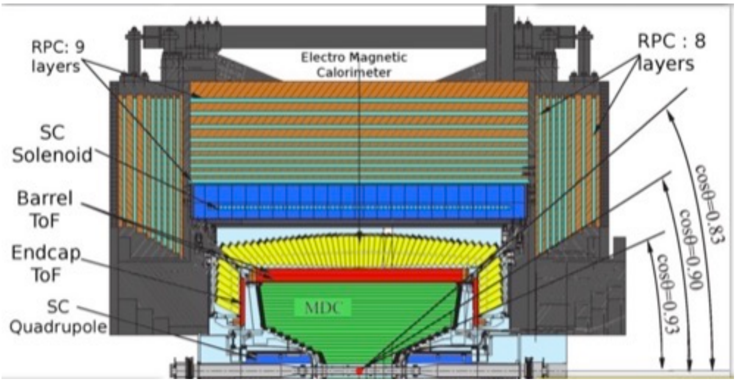




$K^- e^+ \nu$ vs. $K^+ \pi^-$

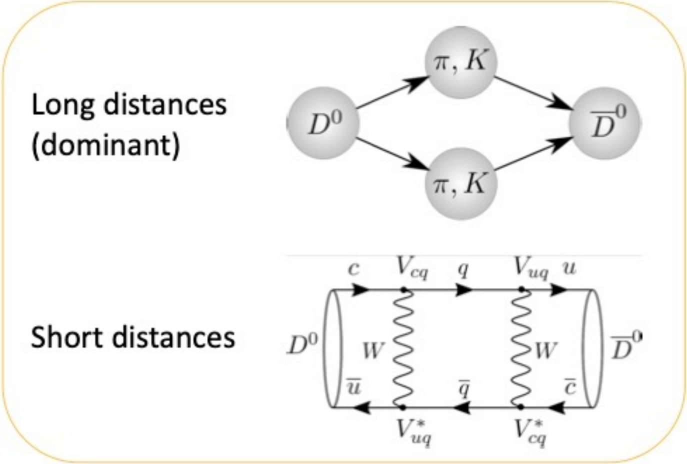
- BES III studies
  $e^+e^- \rightarrow \psi(3770) \rightarrow D^0\bar{D}^0$ decays
  - Total integrated luminosity of this sample is **2.93 fb^{-1} (10.6 million D pairs)**
  - **Soon to be 20 fb^{-1} (~72 million D pairs)**

BES-III



Playing a movie in reverse

- Since the dawn of time, man has yearned to reverse the arrow of time
- On the elementary particle scale we can return to where it all started via meson oscillations



$$i\frac{\partial}{\partial t}\begin{pmatrix} D^0(t) \\ \overline{D}^0(t) \end{pmatrix} = \left(\mathbf{M} - \frac{i}{2}\mathbf{\Gamma}\right)\begin{pmatrix} D^0(t) \\ \overline{D}^0(t) \end{pmatrix}$$

$$|D_{1,2}\rangle \equiv p|D^0\rangle \pm q|\overline{D}^0\rangle$$

$$m_{1,2} - \frac{i}{2}\Gamma_{1,2}$$

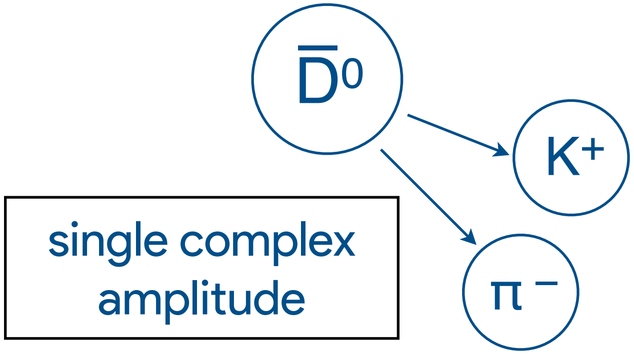
$$x \equiv \frac{\Delta m}{\Gamma}$$

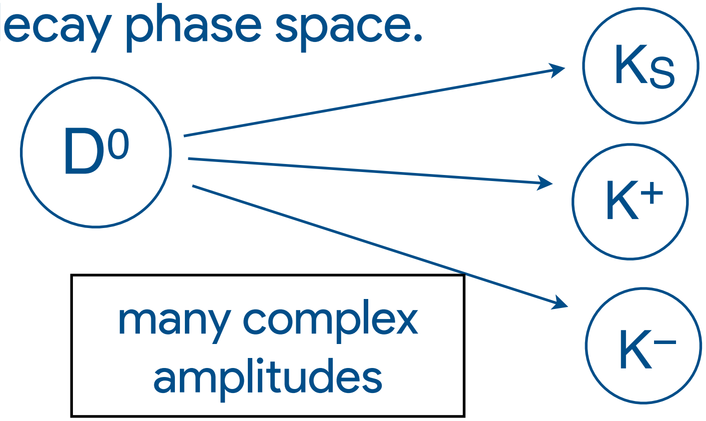
$$y \equiv \frac{\Delta\Gamma}{2\Gamma}$$

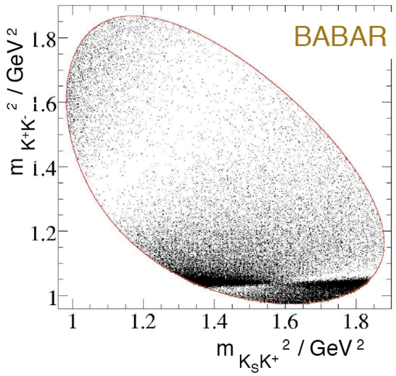
- We can study $D^0 \to \overline{D}^0$ and $\overline{D}^0 \to D^0$. These are T-reversed processes.
- However these are *also* CP-reversed, so what symmetry would we be testing?
  - Can we isolate T? (yes, let's come back to this later)

What are strong phases?

- When a hadron decays, the decay amplitude has a “strong” phase associated with hadronisation of the final state particles.
- For a multi-body final state, there can be a different amplitude and strong phase for every point in the decay phase space.







- The relative amplitude (r) and relative phase (δ), between $\overline{D}^0$ and D^0 decays to the same final state j are key parameters in studies of D mixing & CPV in B.

$$r_j \equiv \left| \frac{\langle j | \overline{D}^0 \rangle}{\langle j | D^0 \rangle} \right|$$

$$-\delta_j \equiv \arg\left(\frac{\langle j | \overline{D}^0 \rangle}{\langle j | D^0 \rangle} \right)$$

So how exactly does QC $D^0\overline{D}^0$ provide the phases?

- For D decays, Asner & Sun neatly relate the r (relative amplitudes) and δ (relative phase), along with x and y, to decay rates of quantum correlated $D^0\overline{D}^0$ systems.

$$r_j \equiv \left|\frac{\langle j|\overline{D}^0\rangle}{\langle j|D^0\rangle}\right|$$

$$-\delta_j \equiv \arg\left(\frac{\langle j|\overline{D}^0\rangle}{\langle j|D^0\rangle}\right)$$

D. Asner and W. Sun,
Phys. Rev. D73, 034024 (2006)
Phys. Rev. D77, 019901(E) (2008)
[built on upon work by many others]

$$C_{D^0\overline{D}^0} = -1 \qquad \Gamma^{C-}(j,k) = Q_M\left|A^{(-)}(j,k)\right|^2 + R_M\left|B^{(-)}(j,k)\right|^2$$

$$C_{D^0\overline{D}^0} = +1 \qquad \Gamma^{C+}(j,k) = Q'_M\left|A^{(+)}(j,k)\right|^2 + R'_M\left|B^{(+)}(j,k)\right|^2 + C^{(+)}(j,k)$$

$$A^{(\pm)}(j,k) \equiv \langle j|D^0\rangle\langle k|\overline{D}^0\rangle \pm \langle j|\overline{D}^0\rangle\langle k|D^0\rangle$$

$$B^{(\pm)}(j,k) \equiv \frac{p}{q}\langle j|D^0\rangle\langle k|D^0\rangle \pm \frac{q}{p}\langle j|\overline{D}^0\rangle\langle k|\overline{D}^0\rangle$$

$$C^{(+)}(j,k) \equiv 2\Re\left\{A^{(+)*}(j,k)B^{(+)}(j,k)\left[\frac{y}{(1-y^2)^2}+\frac{ix}{(1+x^2)^2}\right]\right\}$$

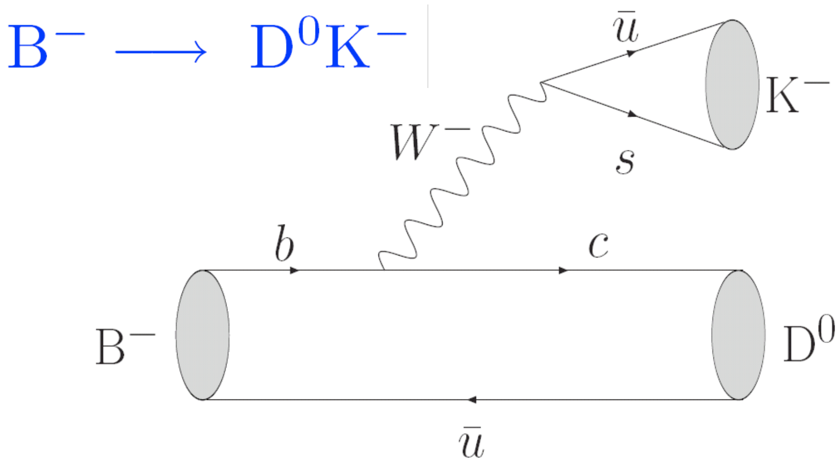
$$Q_M \equiv \frac{1}{2}\left[\frac{1}{1-y^2}+\frac{1}{1+x^2}\right] \approx 1-\frac{x^2-y^2}{2}$$

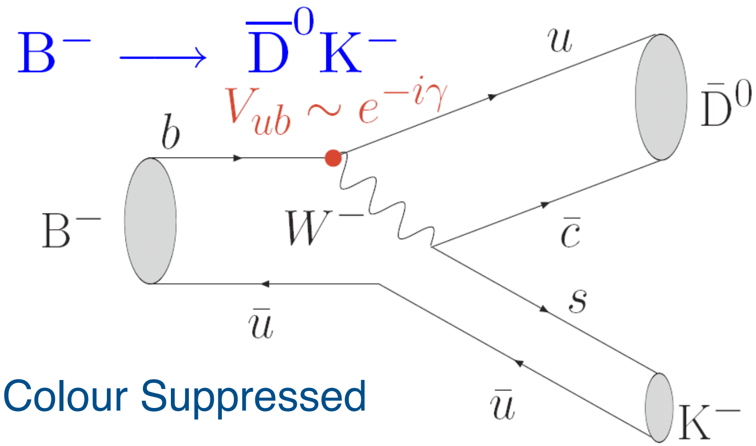
$$R_M \equiv \frac{1}{2}\left[\frac{1}{1-y^2}-\frac{1}{1+x^2}\right] \approx \frac{x^2+y^2}{2}$$

$$Q'_M \equiv \frac{1}{2}\left[\frac{1+y^2}{(1-y^2)^2}+\frac{1-x^2}{(1+x^2)^2}\right] \approx Q_M - x^2 + y^2$$

$$R'_M \equiv \frac{1}{2}\left[\frac{1+y^2}{(1-y^2)^2}-\frac{1-x^2}{(1+x^2)^2}\right] \approx 3R_M.$$

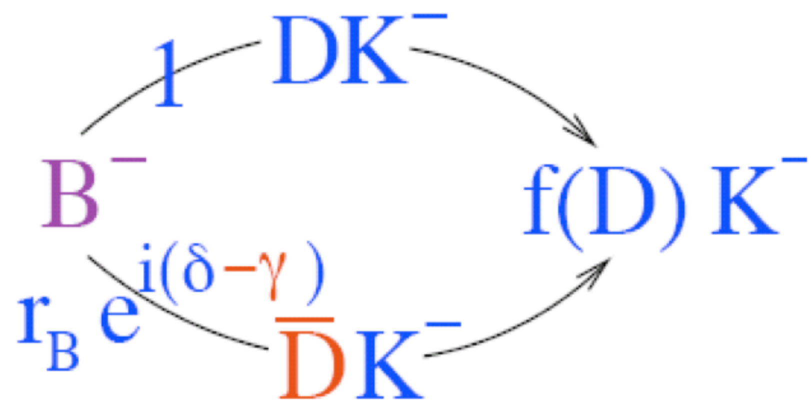
The CKM phase γ





Colour Suppressed

- The CKM phase γ can be determined through the **interference** between the $b \to c$ and $b \to u$ transitions
- Require the neutral D mesons to decay to the same final state f(D)



- This method is theoretically clean
- **Success of this method requires that the D decay is well understood**

The LHCb gamma combination

LHCb-CONF-2022-003

LHCb input measurements

B decay	D decay	Ref.	Dataset	Status since Ref. [14]
$B^\pm \to Dh^\pm$	$D \to h^+h^-$	[29]	Run 1&2	As before
$B^\pm \to Dh^\pm$	$D \to h^+\pi^-\pi^+\pi^-$	[30]	Run 1	As before
$B^\pm \to Dh^\pm$	$D \to K^\pm\pi^\mp\pi^+\pi^-$	[18]	Run 1&2	**New**
$B^\pm \to Dh^\pm$	$D \to h^+h^-\pi^0$	[19]	Run 1&2	**Updated**
$B^\pm \to Dh^\pm$	$D \to K^0_S h^+h^-$	[31]	Run 1&2	As before
$B^\pm \to Dh^\pm$	$D \to K^0_S K^\pm\pi^\mp$	[32]	Run 1&2	As before
$B^\pm \to D^*h^\pm$	$D \to h^+h^-$	[29]	Run 1&2	As before
$B^\pm \to DK^{*\pm}$	$D \to h^+h^-$	[33]	Run 1&2(*)	As before
$B^\pm \to DK^{*\pm}$	$D \to h^+\pi^-\pi^+\pi^-$	[33]	Run 1&2(*)	As before
$B^\pm \to Dh^\pm\pi^+\pi^-$	$D \to h^+h^-$	[34]	Run 1	As before
$B^0 \to DK^{*0}$	$D \to h^+h^-$	[35]	Run 1&2(*)	As before
$B^0 \to DK^{*0}$	$D \to h^+\pi^-\pi^+\pi^-$	[35]	Run 1&2(*)	As before
$B^0 \to DK^{*0}$	$D \to K^0_S\pi^+\pi^-$	[36]	Run 1	As before
$B^0 \to D^\mp\pi^\pm$	$D^+ \to K^-\pi^+\pi^+$	[37]	Run 1	As before
$B^0_s \to D^\mp_s K^\pm$	$D^+_s \to h^+h^-\pi^+$	[38]	Run 1	As before
$B^0_s \to D^\mp_s K^\pm\pi^+\pi^-$	$D^+_s \to h^+h^-\pi^+$	[39]	Run 1&2	As before

D decay	Observable(s)	Ref.	Dataset	Status since Ref. [14]
$D^0 \to h^+h^-$	ΔA_{CP}	[24, 40, 41]	Run 1&2	As before
$D^0 \to K^+K^-$	$A_{CP}(K^+K^-)$	[16, 24, 25]	Run 2	**New**
$D^0 \to h^+h^-$	$y_{CP} - y_{CP}^{K^-\pi^+}$	[42]	Run 1	As before
$D^0 \to h^+h^-$	$y_{CP} - y_{CP}^{K^-\pi^+}$	[15]	Run 2	**New**
$D^0 \to h^+h^-$	ΔY	[43–46]	Run 1&2	As before
$D^0 \to K^+\pi^-$ (Single Tag)	$R^\pm$, $(x'^\pm)^2$, $y'^\pm$	[47]	Run 1	As before
$D^0 \to K^+\pi^-$ (Double Tag)	$R^\pm$, $(x'^\pm)^2$, $y'^\pm$	[48]	Run 1&2(*)	As before
$D^0 \to K^\pm\pi^\mp\pi^+\pi^-$	$(x^2+y^2)/4$	[49]	Run 1	As before
$D^0 \to K^0_S\pi^+\pi^-$	x, y	[50]	Run 1	As before
$D^0 \to K^0_S\pi^+\pi^-$	x_{CP}, y_{CP}, Δx, Δy	[51]	Run 1	As before
$D^0 \to K^0_S\pi^+\pi^-$	x_{CP}, y_{CP}, Δx, Δy	[52]	Run 2	As before
$D^0 \to K^0_S\pi^+\pi^-$ (μ^- tag)	x_{CP}, y_{CP}, Δx, Δy	[17]	Run 2	**New**

"Auxiliary" inputs

Decay	Parameters	Source	Ref.	Status since Ref. [14]
$B^\pm \to DK^{*\pm}$	$\kappa_{B^\pm}^{DK^{*\pm}}$	LHCb	[33]	As before
$B^0 \to DK^{*0}$	$\kappa_{B^0}^{DK^{*0}}$	LHCb	[53]	As before
$B^0 \to D^\mp\pi^\pm$	β	HFLAV	[13]	As before
$B^0_s \to D^\mp_s K^\pm(\pi\pi)$	ϕ_s	HFLAV	[13]	As before
$D \to K^+\pi^-$	$\cos\delta_D^{K\pi}$, $\sin\delta_D^{K\pi}$, $(r_D^{K\pi})^2$, x^2, y	CLEO-c	[27]	**New**
$D \to K^+\pi^-$	$A_{K\pi}$, $A_{K\pi}^{\pi\pi\pi^0}$, $r_D^{K\pi}\cos\delta_D^{K\pi}$, $r_D^{K\pi}\sin\delta_D^{K\pi}$	BESIII	[28]	**New**
$D \to h^+h^-\pi^0$	$F^+_{\pi\pi\pi^0}$, $F^+_{KK\pi^0}$	CLEO-c	[54]	As before
$D \to \pi^+\pi^-\pi^+\pi^-$	$F^+_{4\pi}$	CLEO-c+BESIII	[26, 54]	**Updated**
$D \to K^+\pi^-\pi^0$	$r_D^{K\pi\pi^0}$, $\delta_D^{K\pi\pi^0}$, $\kappa_D^{K\pi\pi^0}$	CLEO-c+LHCb+BESIII	[55–57]	As before
$D \to K^\pm\pi^\mp\pi^+\pi^-$	$r_D^{K3\pi}$, $\delta_D^{K3\pi}$, $\kappa_D^{K3\pi}$	CLEO-c+LHCb+BESIII	[49, 55–57]	As before
$D \to K^0_S K^\pm\pi^\mp$	$r_D^{K^0_S K\pi}$, $\delta_D^{K^0_S K\pi}$, $\kappa_D^{K^0_S K\pi}$	CLEO	[58]	As before
$D \to K^0_S K^\pm\pi^\mp$	$r_D^{K^0_S K\pi}$	LHCb	[59]	As before

Crucial quantum correlated charm inputs (sometimes combined with D-mixing input from LHCb)

Acrylic felt/fur with poly bead fill for medium mass.

Measuring the CKM unitarity triangle phase γ

- Measuring the CKM phase γ from tree decays is possible via B → Dh (and similar e.g. B → D*h & B → Dh*).

  The measurement requires B decay information and:
  - **D** decay **strong phase difference** between $D^0 \to f$ and $\overline{D}^0 \to f$
  - **D** decay **relative magnitude ratio** between $D^0 \to f$ and $\overline{D}^0 \to f$
  - **D** decay **coherence factors**

$$\Gamma(B^\pm \to Dh^\pm) \propto |r_D e^{-i\delta_D} + r_B e^{i(\delta_B \pm \gamma)}|^2 \Rightarrow r_D^2 + r_B^2 + 2\kappa_D \kappa_B r_D r_B \cos(\delta_B + \delta_D \pm \gamma)$$

  - **Coherence factor**: Dilution of the interference term due to incoherence (strong phase variation) between contributing intermediate resonances in multi-body decays
    - Can be determined by integrating the amplitude over parts of the (or the entire) D decay phase space **or** by counting (model-indep.)
    - Performing the analysis in bins allows focus on regions where coherence is high (if coherence is low, still get constraints on r_B).

Relationship of γ to D mixing

- **Non-negligible** correction to the B decay rates due to D mixing
  - x, proportional to D^0 and $\overline{D}^0$ mass difference
  - y, proportional to D^0 and $\overline{D}^0$ decay width difference

$$\begin{aligned}\Gamma(B^\pm \to Dh^\pm) \propto\ & r_D^2 + r_B^2 + 2\kappa_D\kappa_B r_D r_B \cos(\delta_B + \delta_D \pm \gamma) \\ & - \alpha\left[(1+r_B^2)\kappa_D r_D \cos(\delta_D) + (1+r_D^2)\kappa_B r_B \cos(\delta_B \pm \gamma)\right] y \\ & + \alpha\left[(1-r_B^2)\kappa_D r_D\ \sin(\delta_D) - (1-r_D^2)\kappa_B r_B \sin(\delta_B \pm \gamma)\right] x\end{aligned}$$

  - Hence a simultaneous fit is required to get the best result.
- Many B decay states already used, more will be added
- Many D decay states already used, more will be added
- The fit is nicely over-constrained
- Even more over-constrained when including information from time-dependent charm decay rates, e.g.

$$R^\pm(t) \approx R^\pm + \sqrt{R^\pm} y'^\pm \left(\frac{t}{\tau}\right) + \frac{(x'^\pm)^2 + (y'^\pm)^2}{4}\left(\frac{t}{\tau}\right)^2$$

$$x'^\pm \equiv -|q/p|^{\pm 1}\left[x\cos(\delta_D^{K\pi} \pm \phi) + y\sin(\delta_D^{K\pi} \pm \phi)\right]$$

$$y'^\pm \equiv -|q/p|^{\pm 1}\left[y\cos(\delta_D^{K\pi} \pm \phi) - x\sin(\delta_D^{K\pi} \pm \phi)\right]$$

$$|D_{1,2}\rangle \equiv p|D^0\rangle \pm q|\overline{D}^0\rangle \qquad \phi = \mathrm{Arg}(q/p)$$

mass eigenstates

Impact of C-even $D^0\bar{D}^0$ [22]

D. Asner and W. Sun,
Phys. Rev. D73, 034024 (2006)
Phys. Rev. D77, 019901(E) (2008)

- The possible impact of C-even states should not be understated
- Recall the Kπ strong phase measurement. Asner and Sun did a study for not only the C = -1 decays obtained by CLEO, but also C = +1 and a sample where the C = -1 decays outnumber the C = +1 decays by 10 to 1

TABLE VII: Estimated uncertainties (statistical and systematic, respectively) for different C configurations, with branching fractions constrained to the world averages. We include C-even ST yields in the second column, but not the third.

Parameter	Value	$\mathcal{N}^{C-} = 3 \times 10^6$	$\mathcal{N}^{C+} = 3 \times 10^6$	$\mathcal{N}^{C-} = 10 \cdot \mathcal{N}^{C+} = 3 \times 10^6$
y	0	$\pm 0.015 \pm 0.008$	$\pm 0.007 \pm 0.003$	$\pm 0.012 \pm 0.005$
$x^2\ (10^{-3})$	0	$\pm 0.6 \pm 0.6$	$\pm 0.3 \pm 0.3$	$\pm 0.6 \pm 0.6$
$\cos\delta_{K\pi}$	1	$\pm 0.21 \pm 0.04$	$\pm 0.27 \pm 0.05$	$\pm 0.20 \pm 0.04$
$x \sin\delta_{K\pi}$	0	—	$\pm 0.022 \pm 0.003$	$\pm 0.027 \pm 0.005$
$r^2\ (10^{-3})$	3.74	$\pm 1.0 \pm 0.0$	$\pm 1.7 \pm 0.1$	$\pm 1.0 \pm 0.0$

FYI
CLEO 2012 final, C-odd only
(NB: includes more modes)

Parameter	Standard Fit
$\mathcal{N}\ (10^6)$	$3.092 \pm 0.050 \pm 0.040$
$y\ (\%)$	$4.2 \pm 2.0 \pm 1.0$
$r^2\ (\%)$	$0.533 \pm 0.107 \pm 0.045$
$\cos\delta$	$0.81^{+0.22+0.07}_{-0.18-0.05}$
$\sin\delta$	$-0.01 \pm 0.41 \pm 0.04$
$x^2\ (\%)$	$0.06 \pm 0.23 \pm 0.11$

- Notable:
  - C-even alone offers about a factor of two better sensitivity to y
    - C-even, even in small quantity, provides strong constraint on C-odd.
  - Direct access to x sin δ (with original set of modes)
    - (CLEO-philes know: can get this in C-odd by adding $K_S\pi\pi$ tags)

Sources of quantum correlated $D^0\bar{D}^0$ [24]

PhysRevD.86.112001
PhysLettB.734.227-233
P. Naik, JHEP 03 (2023) 038

- Most easily reconstructible final states at LHCb: $K^- h^+$, $\pi^+ \pi^-$, $h^- h^+ \pi^- \pi^+$
- From B2OC, my rough through-Run 3 estimates w/ $[D^0 \to K\pi][\bar{D}^0 \to K\pi]$:
  C = +1 yields: 2000 $B_s \to D^0\bar{D}^0$, 600 $B^0 \to D^0\bar{D}^0$
  C = –1 yields: 3000 $B^+ \to [D^0\bar{D}^0]_{\psi(3770)}K^+$
- Can get more from other resonances (e.g. $[D^0\bar{D}^0]_{\psi(4040)}$) and decays:
  $B^0_{(s)} \to D^0\bar{D}^0K^+\pi^-$, $B^0_{(s)} \to D^0\bar{D}^0K_S$
  $B^+ \to D^0\bar{D}^0\pi^0/\gamma K^+$, $B^0_{(s)} \to D^0\bar{D}^0\pi^0/\gamma K^+\pi^-$, $B^0_{(s)} \to D^0\bar{D}^0\pi^0/\gamma K_S$
  $\Lambda_b \to D^0\bar{D}^0\Lambda$, $\Lambda_b \to D^0\bar{D}^0 pK^-$, $\Lambda_b \to D^0\bar{D}^0\pi^0/\gamma\Lambda$, $\Lambda_b \to D^0\bar{D}^0\pi^0/\gamma pK^-$
- Could add up quickly, but of course backgrounds, interferences to deal with.
- Need to be creative to obtain equivalents to "single-tag" normalizations.

What are the enhancements? [36a]

- More precisely, the enhancements or suppressions are detailed in Asner & Sun (Phys. Rev. D73:034024, 2006; Erratum-ibid. D77:019902, 2008)
  - For C = –1, to leading order in the charm mixing parameters x and y, the rate of both D mesons decaying to CP+ (e.g. $K^+ K^-$, $\pi^+ \pi^-$) is zero.
  - For C = +1, to leading order in the charm mixing parameters x and y, the rate of both D mesons decaying to CP+ is practically doubled.

TABLE III: $D^0\overline{D}^0$ DT branching fractions for semileptonic modes and CP eigenstates, to leading order in x and y.

	ℓ^+	ℓ^-	S_+	S_-
		$C=-1$		
ℓ^+	$A_\ell^4 R_M$			
ℓ^-	A_ℓ^4	$A_\ell^4 R_M$		
S_+	$A_\ell^2 A_{S_+}^2$	$A_\ell^2 A_{S_+}^2$	0	
S_-	$A_\ell^2 A_{S_-}^2$	$A_\ell^2 A_{S_-}^2$	$4A_{S_+}^2 A_{S_-}^2$	0
		$C=+1$		
ℓ^+	$3A_\ell^4 R_M$			
ℓ^-	A_ℓ^4	$3A_\ell^4 R_M$		
S_+	$A_\ell^2 A_{S_+}^2(1-2y)$	$A_\ell^2 A_{S_+}^2(1-2y)$	$2A_{S_+}^4(1-2y)$	
S_-	$A_\ell^2 A_{S_-}^2(1+2y)$	$A_\ell^2 A_{S_-}^2(1+2y)$	0	$2A_{S_-}^4(1+2y)$
S'_+	$A_\ell^2 A_{S'_+}^2(1-2y)$	$A_\ell^2 A_{S'_+}^2(1-2y)$	$4A_{S_+}^2 A_{S'_+}^2(1-2y)$	0
S'_-	$A_\ell^2 A_{S'_-}^2(1+2y)$	$A_\ell^2 A_{S'_-}^2(1+2y)$	0	$4A_{S_-}^2 A_{S'_-}^2(1+2y)$

y

$0.615\,^{+0.056}_{-0.055}\,(\%)$

HFLAV 2021

Effect on double Kpi ; Kpi vs CP+ [36b]

TABLE II: $D^0\overline{D}^0$ DT branching fractions for modes containing f or $\bar{f}$, to leading order in x and y.

	f	$\bar{f}$
	$C = -1$	
f	$A_f^4 R_M \left[1 + r_f^2(2 - z_f^2) + r_f^4\right]$	
$\bar{f}$	$A_f^4 \left[1 + r_f^2(2 - z_f^2) + r_f^4\right]$	$A_f^4 R_M \left[1 + r_f^2(2 - z_f^2) + r_f^4\right]$
f'	$A_f^2 A_{f'}^2 \left(r_f^2 + r_{f'}^2 - r_f r_{f'} v_{ff'}^+\right)$	$A_f^2 A_{f'}^2 \left(1 + r_f^2 r_{f'}^2 - r_f r_{f'} v_{ff'}^-\right)$
$\bar{f}'$	$A_f^2 A_{f'}^2 \left(1 + r_f^2 r_{f'}^2 - r_f r_{f'} v_{ff'}^-\right)$	$A_f^2 A_{f'}^2 \left(r_f^2 + r_{f'}^2 - r_f r_{f'} v_{ff'}^+\right)$
ℓ^+	$A_f^2 A_\ell^2 r_f^2$	$A_f^2 A_\ell^2$
ℓ^-	$A_f^2 A_\ell^2$	$A_f^2 A_\ell^2 r_f^2$
S_+	$A_f^2 A_{S_+}^2 \left[1 + r_f(r_f + z_f)\right]$	$A_f^2 A_{S_+}^2 \left[1 + r_f(r_f + z_f)\right]$
S_-	$A_f^2 A_{S_-}^2 \left[1 + r_f(r_f - z_f)\right]$	$A_f^2 A_{S_-}^2 \left[1 + r_f(r_f - z_f)\right]$
	$C = +1$	
f	$2A_f^4 r_f \left(r_f + y'_f + r_f^2 \tilde{y}_f\right)$	
$\bar{f}$	$A_f^4 \left[1 - r_f^2(2 - z_f^2) + r_f^4 + 4r_f(\tilde{y}_f + r_f^2 y'_f)\right]$	$2A_f^4 r_f \left(r_f + y'_f + r_f^2 \tilde{y}_f\right)$
f'	$A_f^2 A_{f'}^2 \left(r_f^2 + r_{f'}^2 + r_f r_{f'} v_{ff'}^+ + 2c_{ff'}^-\right)$	$A_f^2 A_{f'}^2 \left(1 + r_f^2 r_{f'}^2 + r_f r_{f'} v_{ff'}^- + 2c_{ff'}^+\right)$
$\bar{f}'$	$A_f^2 A_{f'}^2 \left(1 + r_f^2 r_{f'}^2 + r_f r_{f'} v_{ff'}^- + 2c_{ff'}^+\right)$	$A_f^2 A_{f'}^2 \left(r_f^2 + r_{f'}^2 + r_f r_{f'} v_{ff'}^+ + 2c_{ff'}^-\right)$
ℓ^+	$A_f^2 A_\ell^2 \left(r_f^2 + 2r_f y'_f\right)$	$A_f^2 A_\ell^2 (1 + 2r_f \tilde{y}_f)$
ℓ^-	$A_f^2 A_\ell^2 (1 + 2r_f \tilde{y}_f)$	$A_f^2 A_\ell^2 \left(r_f^2 + 2r_f y'_f\right)$
S_+	$A_f^2 A_{S_+}^2 \left[1 + r_f(r_f - z_f)\right](1 - 2y)$	$A_f^2 A_{S_+}^2 \left[1 + r_f(r_f - z_f)\right](1 - 2y)$
S_-	$A_f^2 A_{S_-}^2 \left[1 + r_f(r_f + z_f)\right](1 + 2y)$	$A_f^2 A_{S_-}^2 \left[1 + r_f(r_f + z_f)\right](1 + 2y)$

C = -1 correlated branching fractions

Mode	Correlated	Uncorrelated
$K^-\pi^+,\ K^-\pi^+$	$R_M[(1 + R_{WS})^2 - 4r\cos\delta(r\cos\delta + y)]$	R_{WS}
$K^-\pi^+,\ K^+\pi^-$	$(1 + R_{WS})^2 - 4r\cos\delta(r\cos\delta + y)$	$1 + R_{WS}^2$
$K^-\pi^+,\ S_+$	$1 + R_{WS} + 2r\cos\delta + y$	$1 + R_{WS}$

C = +1 correlated branching fractions

Mode	Correlated	Uncorrelated
$K^-\pi^+,\ K^-\pi^+$	[illegible]	R_{WS}
$K^-\pi^+,\ K^+\pi^-$	[illegible]	$1 + R_{WS}^2$
$K^-\pi^+,\ S_+$	[illegible]	$1 + R_{WS}$

Homework...

What if we can't separate easily? [32]

D. Asner and W. Sun,
Phys. Rev. D73, 034024 (2006)
Phys. Rev. D77, 019901(E) (2008)

- For $\chi_{c1}(3872)$ decays, recall that it is possible to have C = +1 or C = –1 states.
  - Ideally we extract the C = +1 states cleanly, this should be fairly possible looking for a π^0 reflection peak or managing to fully reconstruct the decay.
  - However, if one thinks their sample is predominately QC, then it is possible to look at double-tags which would be otherwise forbidden to help determine the C = –1 contamination (and then exploit that for analysis as well), assuming CP conservation of course:

$$\frac{\Gamma(S_+,S'_+)\Gamma(S_-,S'_-)}{\Gamma(S_+,S_-)\Gamma(S'_+,S'_-)} = \frac{\Gamma(S_+,S'_+)\Gamma(S_-,S'_-)}{\Gamma(S_+,S'_-)\Gamma(S'_+,S_-)} = \frac{4\Gamma(S_+,S_+)\Gamma(S_-,S_-)}{\Gamma^2(S_+,S_-)} = \left(\frac{\mathcal{N}^{C+}}{\mathcal{N}^{C-}}\right)^2$$

S_+ or S_-: CP-even and CP-odd eigenstates, respectively.

  - Hard to reconstruct S_- at LHCb… $K_S\,\varphi$?
  - Would have to include another component for dilution if there are any uncorrelated backgrounds.

Abstract (Talk)

Quantum-correlated (entangled) systems of charmed mesons have been a focus area for flavour physicists, providing input for measurements of the CKM phase gamma and for studies of charm oscillations. Considered previously only from a single source, there is a novel opportunity to perform additional types of analyses with these systems, in several experimental environments [JHEP 03 (2023) 038].

For systems from charmonia decays, it is advantageous to isolate these systems in their C = +1 components for studies of lineshapes and, within b-hadron decays, amplitude analyses. Studies of T and CPT conservation in C = +1 correlated charm systems can be performed with more easily reconstructible final states, when compared to C = -1 correlated charm systems, leading to an opportunity for LHCb — understanding the C = +/– 1 correlated charm components from chi_c1(3872) exotic meson decay samples is crucial to this task.

Abstract (Paper)

Decays of charmonia(-like) particles with definite J, P, and C quantum numbers (e.g. chi_c1(3872)), to a neutral charmed meson, neutral anti-charmed meson, and any combination of C-definite decay particles, are sources of quantum-correlated charm systems of definite C and P.

Methods to separate the C = +/– 1 correlated charm components from chi_c1(3872) decay samples are presented.

Several b-hadron decays also produce quantum-correlated charm systems.

Advantages of isolating these systems in their C = +1 components for amplitude analyses and studies of lineshapes are discussed.

Studies of T and CPT conservation in C = +1 correlated charm systems can be performed with more easily reconstructible final states, when compared to C = -1 correlated charm systems.

Biography

Before arriving in Liverpool in 2023, Paras did his Bachelor's (Engineering Physics), Master's, and PhD degrees at the University of Illinois. For his PhD he worked on charm decay Amplitude Analysis (Dalitz Plot Analysis) with data from the CLEO III experiment.

He then spent a short ~year as a postdoc with Carleton University (Ottawa, Canada) and then started with the University of Bristol, both while based at CLEO-c. He then spent two years at CERN before moving to Bristol. During his time with Bristol, Paras worked on several charm amplitude analyses and charm decay strong phase measurements with several incarnations of CLEO data.

Along with this he transitioned into working at LHCb, where he has been involved with the Charm decays and B decays to Open Charm working groups. He also led a project to perform the LHCb Cherenkov detectors' mirror alignment in software, and as a member of the Heavy Flavour Averaging Group (HFLAV), he is responsible for correctly accounting for final state radiation in averages of key charm meson decay branching fractions (crucial reference modes used in many publications).

Paras was most recently the LHCb B decays to Open Charm working group convener and remains convener of the HFLAV Charm Decays working group. He was recently appointed to the LHCb Speakers' Bureau.

Plans at Liverpool

- Steps in progress
  - Evaluate the impact of CP-tagged decays in B decay amplitude analyses
  - Look at Run 2 data where already ~100 events should be expected in $\chi_{c1}(3872) \rightarrow D^0\bar{D}^0\pi^0$ when reconstructing both D mesons in CP states
  - Add trigger lines with D CP states for Run 3+ (done)

UNIVERSITY OF LIVERPOOL




- Future steps
  - Collect Run 3 (+ 4) [+5 +6] data
  - Establish correlations
  - Study $\chi_{c1}(3872) \rightarrow D^0\bar{D}^0\pi^0$ and $\chi_{c1}(3872) \rightarrow D^0\bar{D}^0\gamma$
  - Study resonances in B-decay amplitude analyses
    - Measure branching fractions where unmeasured
  - Quantify direct T/CPT violation in charm