Correlated charm systems for fun and profit

Liverpool Seminar

Paras Naik

JHEP 03 (2023) 038 (arXiv:2102.07729)

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I lied

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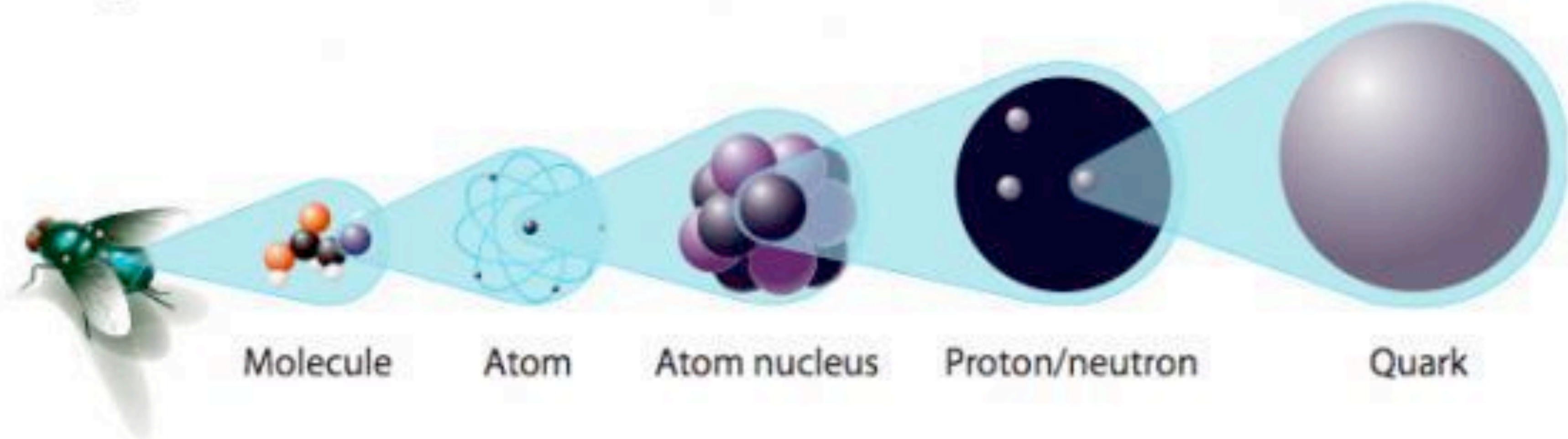
Outline

- Context: flavour physics / discrete symmetries / charm oscillations
- What is a quantum-correlated (QC) charm system / how do we make them?
- What are QC charm systems good for? Part 1
  - Charm mixing / strong phases
  - Input to measurements of the CKM phase gamma
- How else can we make QC charm systems?
- What are QC charm systems good for? Part 2
  - As a means to establish new sources
  - As a filter for C = +1 charmonium resonance content
  - For tests of time-reversal and CPT conservation

The Standard Model

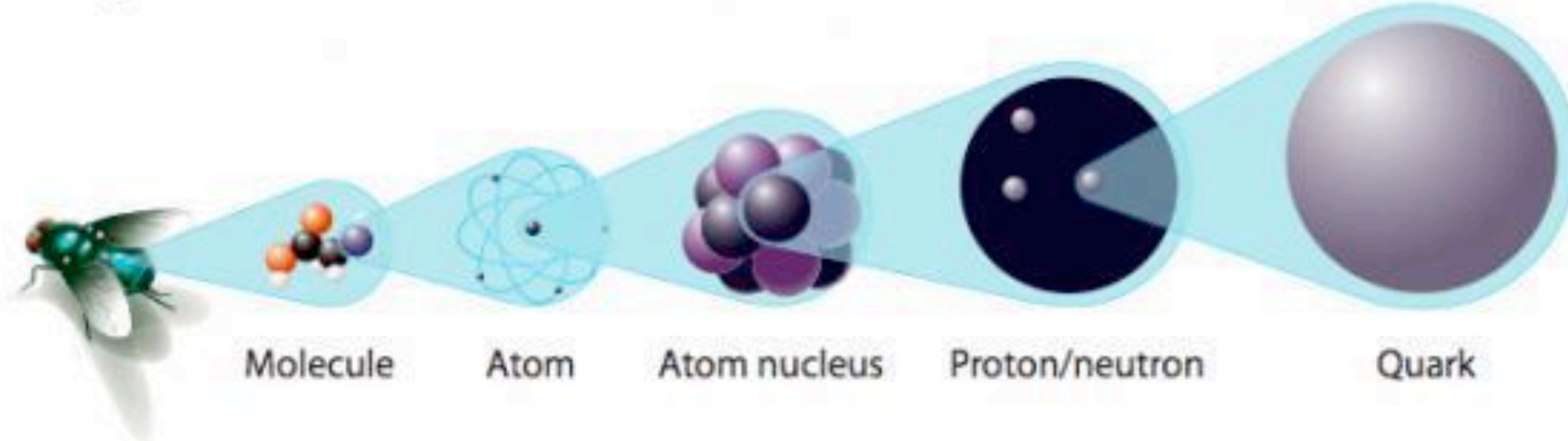


Elementary particles

Ordinary Matter

	First family	charge	Second family	Third family		Forces	Messenger particles
Leptons	electron neutrino	0	muon neutrino	tau neutrino		electromagnetic force	photon
Leptons	electron	−1	muon	tau	Higgs	weak force	W, Z
Quarks	up	+2/3	charm	top		strong force	gluons
Quarks	down	−1/3	strange	bottom			

The Standard Model



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	down	−1/3	strange	bottom	strong force	gluons

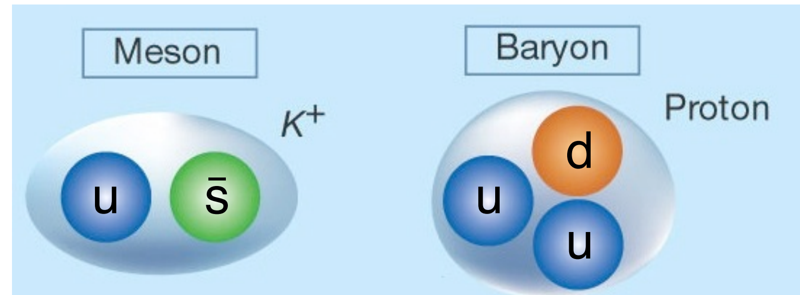
Higgs

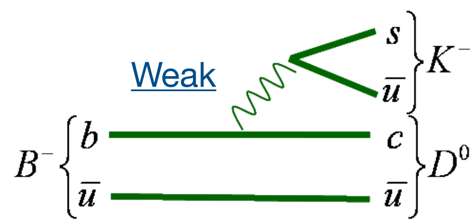
Flavour Changing Quark Decays

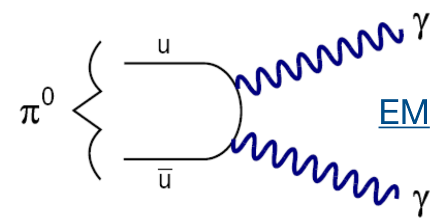
The Standard Model

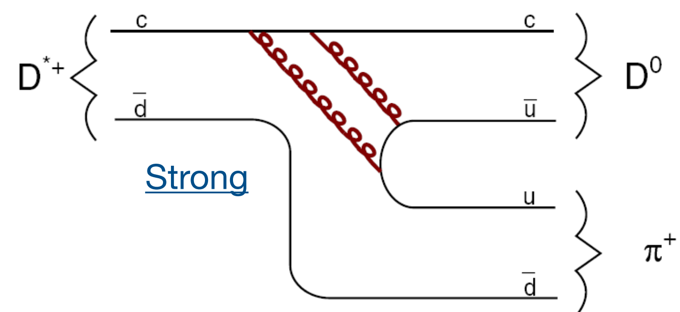
- Mesons
  - Strongly interacting bound state of a quark and antiquark
  - Decay
    - Strong
    - Electromagnetic
    - Weak (Can change flavour)
- Some mesons I will mention
  - B^+ (5279 MeV/c^2) - $u\bar{b}$
  - D^0 (1865 MeV/c^2) - $c\bar{u}$
  - K^+ (494 MeV/c^2) - $u\bar{s}$
  - π^+ (140 MeV/c^2) - $u\bar{d}$
  - π^0 (135 MeV/c^2) - $(u\bar{u}-d\bar{d})/\sqrt{2}$
  - $\psi(3770)$ (3774 MeV/c^2) - $c\bar{c}$
  - $\chi_{c1}(3872)$ (3872 MeV/c^2) - $c\bar{c}[u\bar{u}]$ ("exotic")

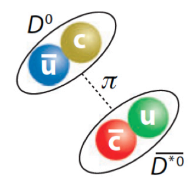
Hadrons



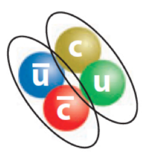






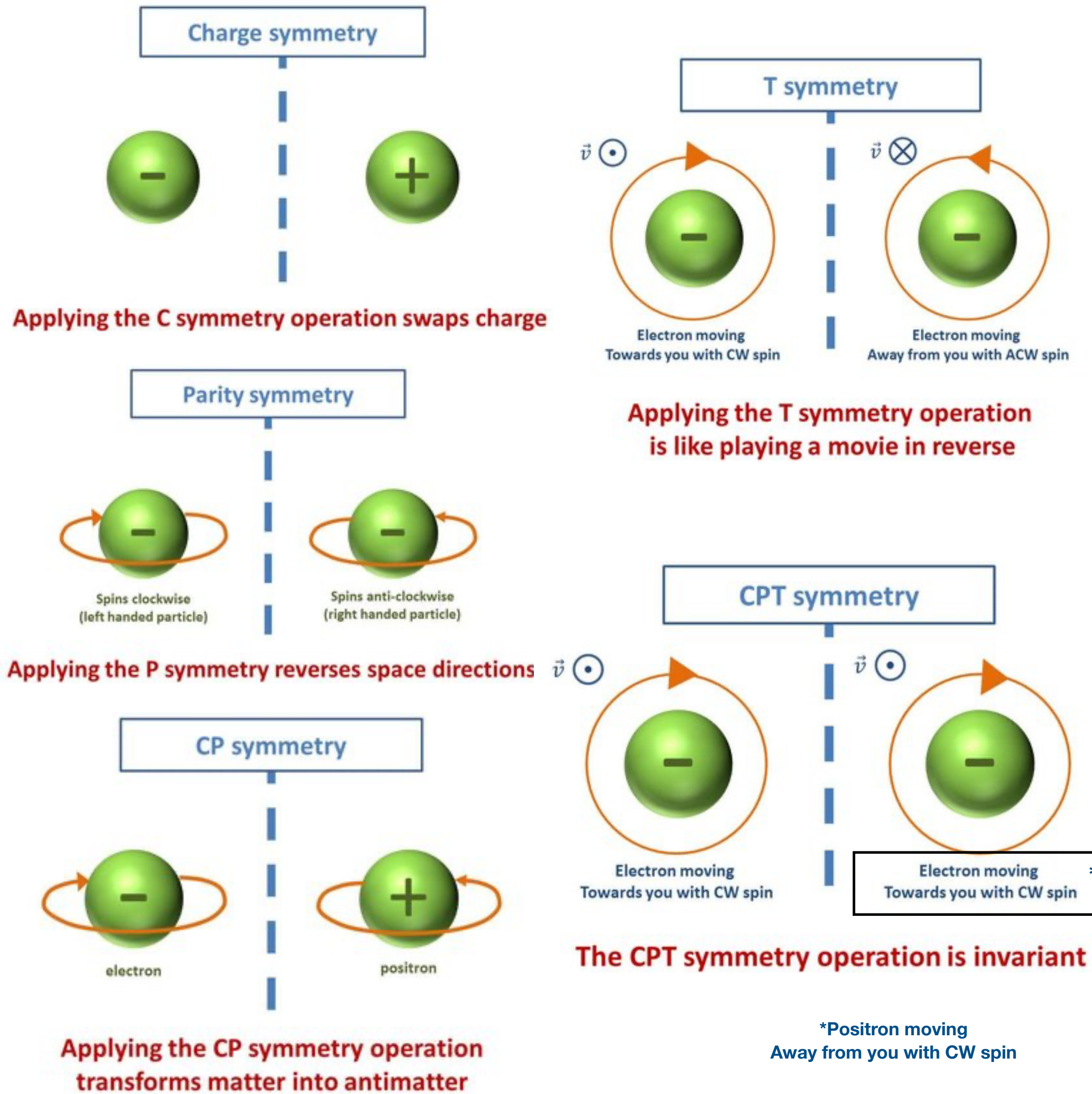


D^0–$\bar{D}^{*0}$ "molecule"



Diquark–diantiquark

Discrete Symmetries



- Discrete Symmetries
  - C: Charge reversal
  - P: Parity reversal
  - T: Time reversal
- C, P maximally violated in weak decay
- CP seems mostly conserved in weak decay, but the closer we look, the more we can isolate large CP violating effects (particularly in beauty)
- CPT is conserved in all Lorentz invariant theories. If it is found to be violated: Congratulations, here is the Nobel prize.
- CP violation implies T violation

Discrete Symmetries Timeline

Lee & Yang
1956
P violation
in weak decay
C. S. Wu et al


1957

1957-9
C violation
in weak decay
several

1963
Cabibbo mixing
(2 generations)

1964
CP violation
in kaon decay
(via oscillations)
J. Cronin & V. Fitch et al


1980

1973
CKM matrix
(3 generations)
Kobayashi
Maskawa


2008

(tumbleweeds)

1999
Direct CP violation
in kaon decay
KTeV & NA48

2001
Direct CP violation
in beauty decay
BaBar & Belle

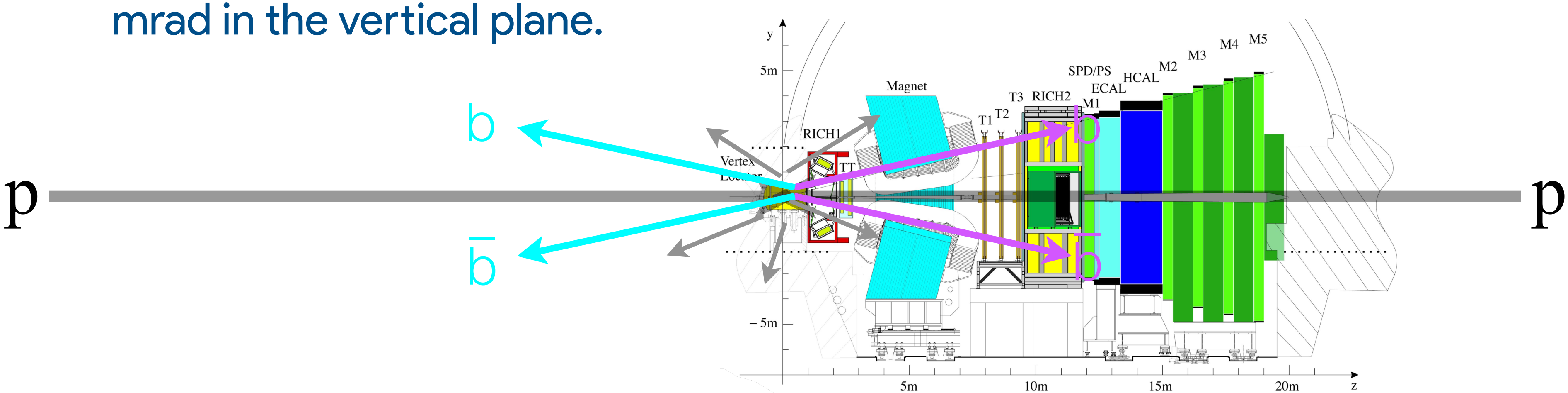
2012
T violation
in beauty decay
BaBar

2013
Direct CP violation
in beauty-strange decay
LHCb

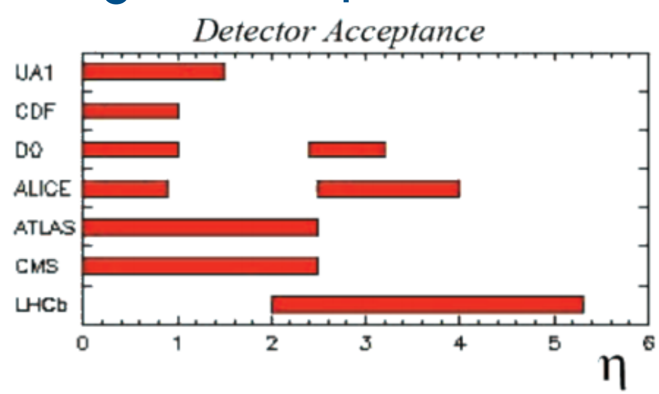
2019
Direct CP violation
in charm decay
LHCb

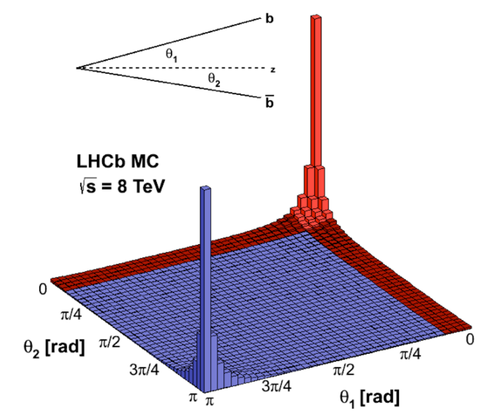
LHCb Experiment Overview

- 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.



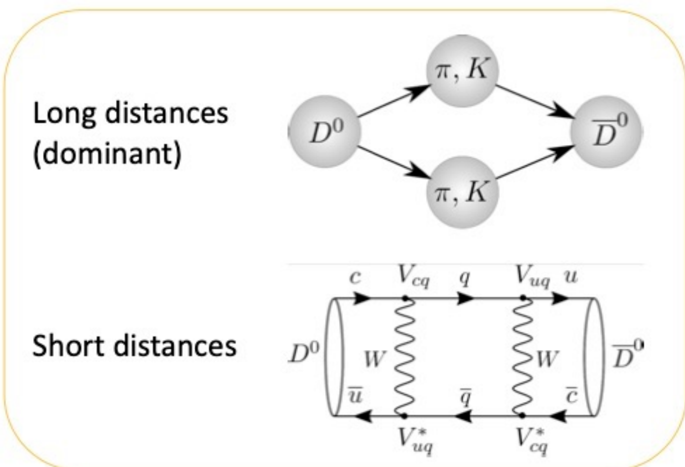
- Unique regime: $2 < \eta < 5$, down to $p_T \sim 0$





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 $D^0 \rightarrow \overline{D}^0$ and $\overline{D}^0 \rightarrow D^0$. 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 is a quantum-correlated charm system?

- As a two-meson system, $D^0\overline{D}^0$ exists in an eigenstate of C and P. Both eigenvalues depend on the relative orbital angular momentum.

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

- The system thus can only exist in two quantum states:

$$\frac{|D^0\overline{D}^0\rangle + |\overline{D}^0 D^0\rangle}{\sqrt{2}} \text{ when } C_{D^0\overline{D}^0} = P_{D^0\overline{D}^0} = +1,\ L_{D^0\overline{D}^0} \text{ is even}$$

$$\frac{|D^0\overline{D}^0\rangle - |\overline{D}^0 D^0\rangle}{\sqrt{2}} \text{ when } C_{D^0\overline{D}^0} = P_{D^0\overline{D}^0} = -1,\ L_{D^0\overline{D}^0} \text{ is odd.}$$

Consequences of a transformation to the CP basis

- Can rewrite in a basis of D decays to CP eigenstates, D_+ and D_-.

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

phase convention

- The quantum state dictates that the D mesons must be found decaying in *opposite* states of CP, or the *same* states of CP, depending on the C eigenvalue of the $D^0\overline{D}^0$ system.

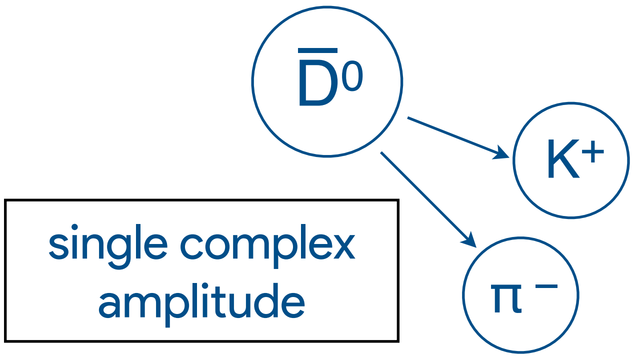
$$\frac{|D^0\overline{D}^0\rangle - |\overline{D}^0 D^0\rangle}{\sqrt{2}} = \frac{|D_-D_+\rangle - |D_+D_-\rangle}{\sqrt{2}} \text{ when } C_{D^0\overline{D}^0} = -1$$

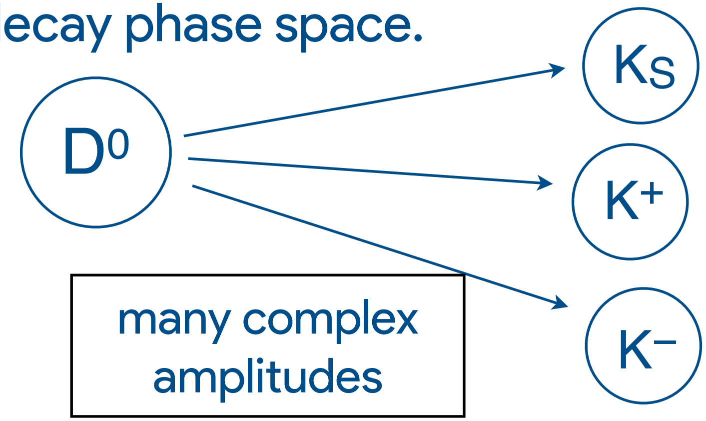
$$\frac{|D^0\overline{D}^0\rangle + |\overline{D}^0 D^0\rangle}{\sqrt{2}} = \frac{|D_+D_+\rangle - |D_-D_-\rangle}{\sqrt{2}} \text{ when } C_{D^0\overline{D}^0} = +1$$

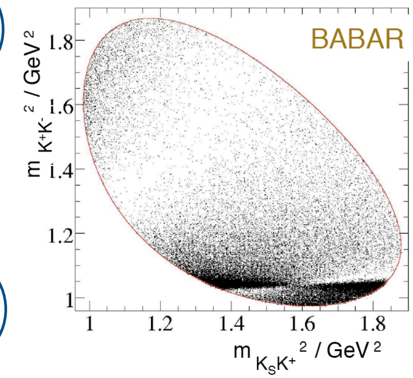
- The resulting decay interference gives access to **D^0 decay strong phases.** CP "tags" of one D decay leads to a projection of the other decay into the opposite or same CP state.

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]

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

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

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

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

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

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

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

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

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

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

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

$$e^+e^- \xrightarrow[J^{PC} = 1^{--}]{\gamma^*} D^0\overline{D}^0 + m\gamma + n\pi^0$$

- C conservation in this reaction dictates that the $D^0\overline{D}^0$ system must be formed with the following eigenvalue:

$$C_{D^0\overline{D}^0} = (-1)^{m+1}$$

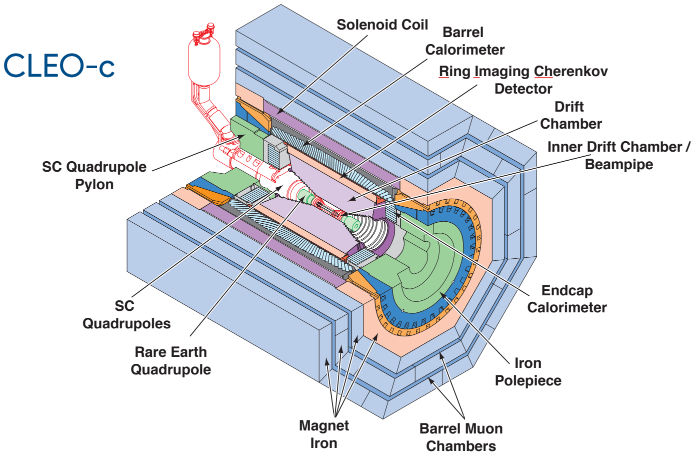
Goldhaber and Jonathan L. Rosner
Phys. Rev. D 15, 1254

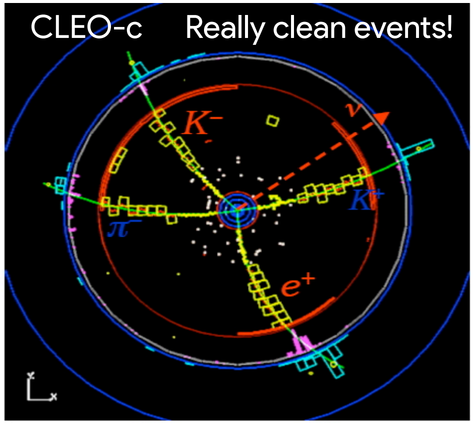
- Currently, the entire quantum correlated sample studied by BES III (and formerly, CLEO-c) has been collected at **open charm threshold** (m = 0) and thus is C = –1 correlated.

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)**

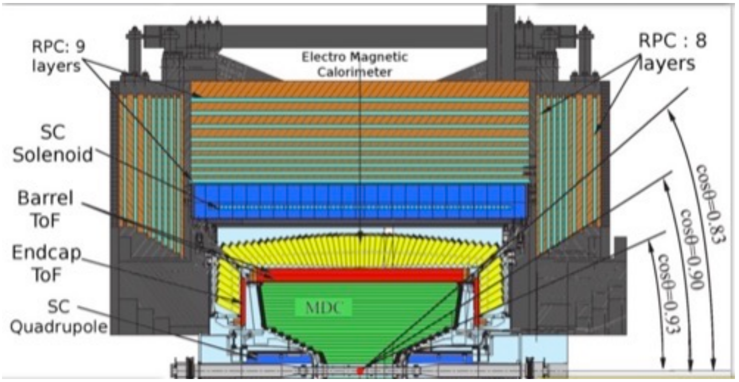
CLEO-c





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

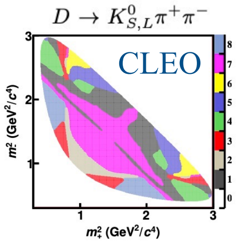
BES-III



- 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)**

Application of QC $D^0\overline{D}^0$: State-of-the-art

- **Quantum-correlated (QC) $D^0\overline{D}^0$ systems** have been exploited to obtain:
  - Time-integrated measurements of **charm mixing** PRD 86, 112001 (2012)
  - **Strong decay phase differences** (e.g. $\delta_{K\pi}$, $\delta_{KK\pi0}(\Phi)$)
  - *Coherence factors / CP-even fractions* for multi-body decays
  - Bin-integrated strong phase differences and coherence factors
  - Input for measurements of charm mixing and the CKM phase γ



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

$$x = (0.398\,^{+0.050}_{-0.049})\%$$
$$y = (0.636\,^{+0.020}_{-0.019})\%$$

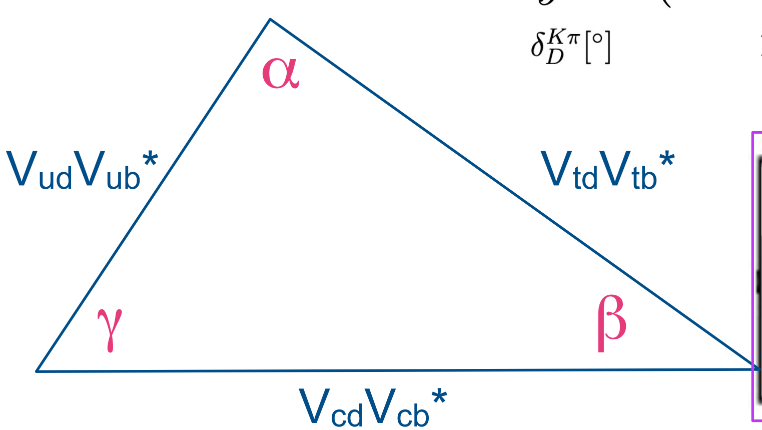
$\delta_D^{K\pi}[^\circ]$ 190.2 $^{+2.8}_{-2.8}$

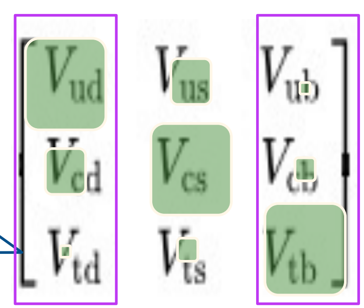
Simultaneous determination of the CKM angle γ and parameters related to mixing and *CP* violation in the charm sector

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

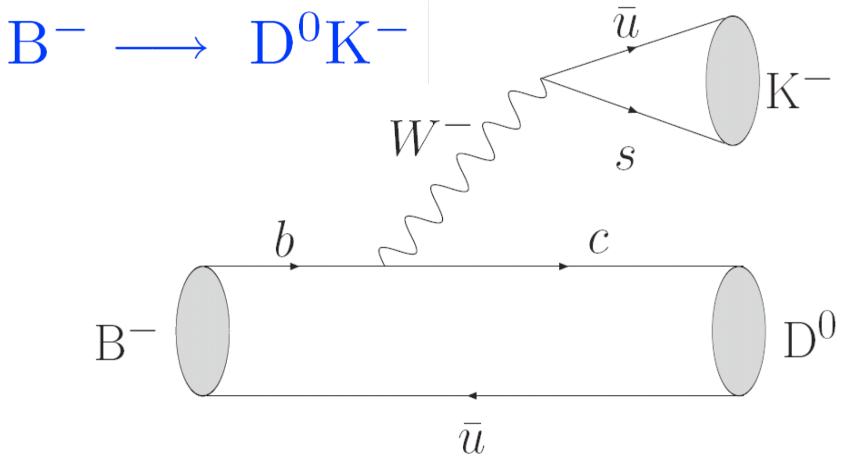
LHCb-CONF-2022-003

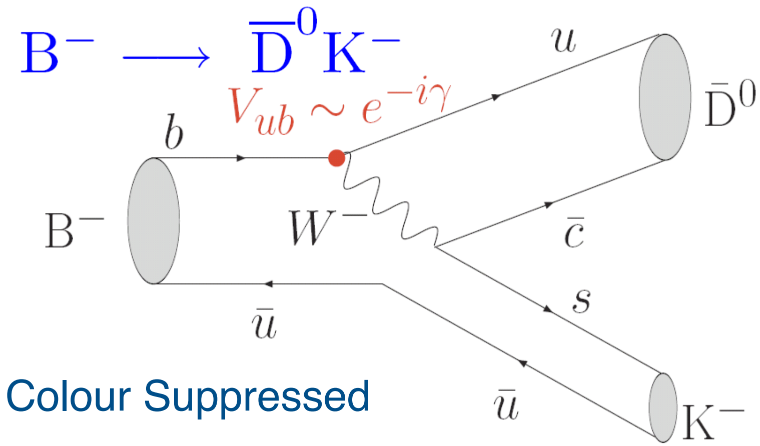
Many input analyses and theory/phenomenology contributions! (see references)





The CKM phase γ

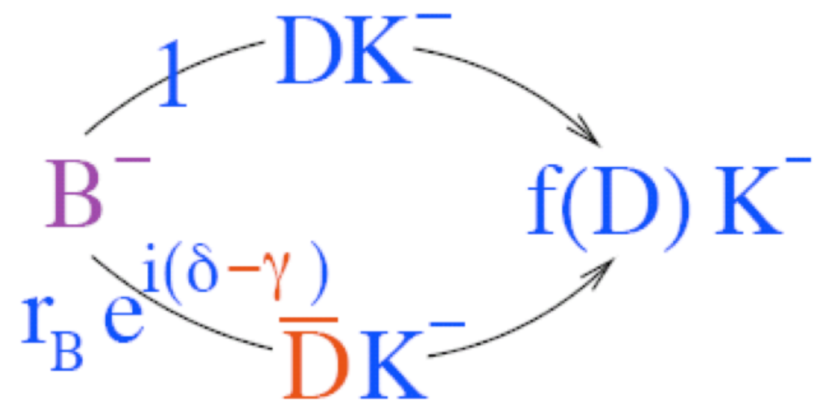




- The CKM phase γ can be determined through the **interference** between the *b*→*c* and *b*→*u* transitions

- 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

Alright, now what?

- **Quantum-correlated (QC) $D^0\overline{D}^0$ systems** have been exploited to obtain:
  - Time-integrated measurements of **charm mixing**
  - **Strong decay phase differences** (e.g. $\delta_{D\rightarrow K\pi}$, $\delta_{D\rightarrow KK\pi}(\Phi)$)
    - Coherence factors / CP-even fractions for multi-body decays
    - Bin-integrated strong phase differences and coherence factors
    - Input for measurements of charm mixing and the CKM phase γ

- We "always" need more of these decays to reduce errors and test the SM.

- The BES III sample, while large, is limited… as LHCb collects more and more data systematics from charm input will limit the precision on γ.

- There are also some other interesting things you can do with them.

- So where can we look?

Alternative sources of QC $D^0\overline{D}^0$

BES III, Belle II

$$e^+e^- \xrightarrow{\gamma^*} D^0\overline{D}^0 + m\gamma + n\pi^0$$

BES III is actively looking into this

$$C_{D^0\overline{D}^0} = (-1)^{m+1}$$

$$e^+e^- \xrightarrow{\Upsilon(1S)} D^0\overline{D}^0 + m\gamma + n\pi^0$$

This won't happen in the Belle II run plan

At full Belle II luminosity
(@ Υ(1S), ~10^{36} $cm^{-2}s^{-1}$)
expect ~4x yearly QC $D^0\overline{D}^0$ of BES III
(@ 3.77 GeV, 10^{33} $cm^{-2}s^{-1}$)

Li & Yang, Phys. Rev. D 74 (2006) 094016 [hep-ph/0610073].

and many more
(Must be some [Υ(4S) → $D^0\overline{D}^0$ + C-definite] in Belle II 50/ab ?)

Even more alternative sources of QC $D^0\overline{D}^0$

LHCb, Belle II

$$B^0_{(s)} \to D^0 \overline{D}^0 \qquad C_{D^0\overline{D}^0} = +1$$

Angular momentum conservation alone dictates this!
P. Naik, JHEP 03 (2023) 038

LHCb observed 13±6 (45±8) $B^0_{(s)} \to D^0 \overline{D}^0$ in 1/fb of Run 1 data*

LHCb is running without a hardware trigger in Run 3.
Expect over 2 orders of magnitude more of these decays.

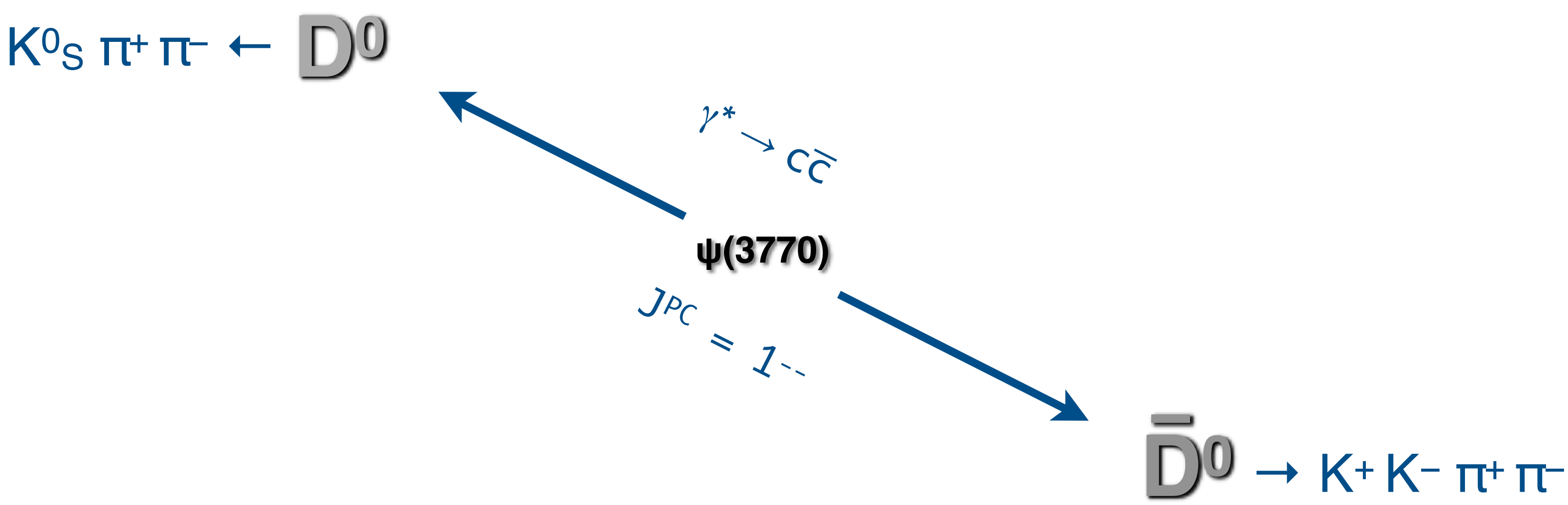
*Run 1 LHCb Paper: PRD 87, 092007 (2013)

$$B^+ \to \psi(3770) K^+ \qquad C_{D^0\overline{D}^0} = -1$$

Also will be C=+1 resonances in the $D^0\overline{D}^0$ spectra
Need to consider “backgrounds” from resonances in the DK spectra

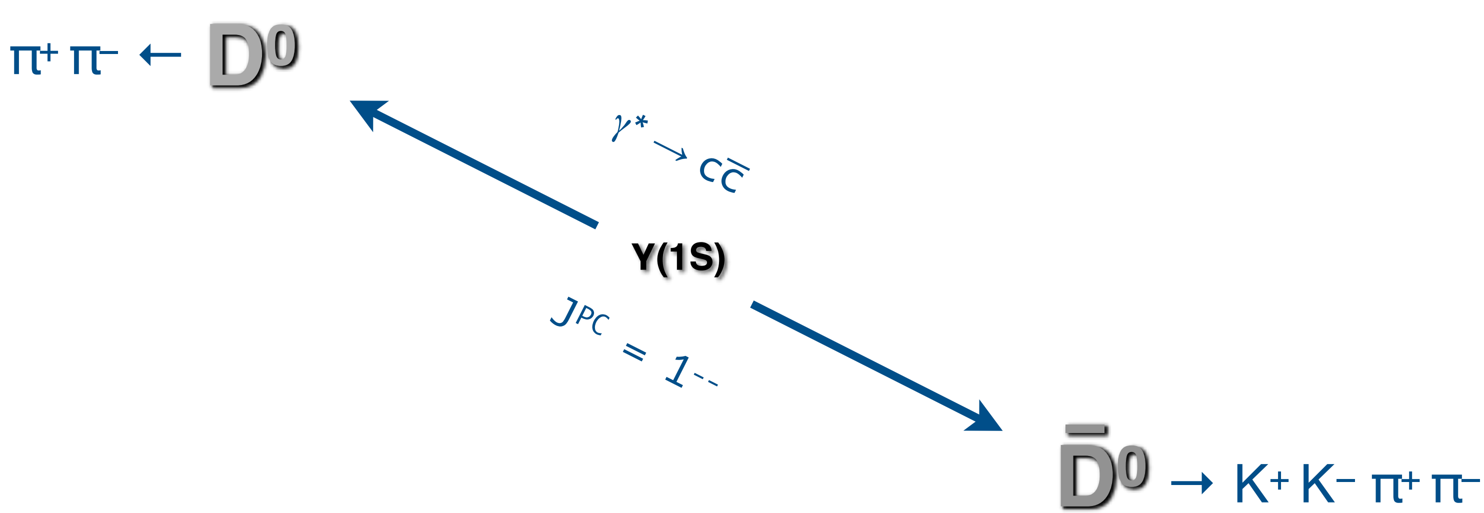
and many more

Aside: A reason one might want boosted QC $D^0\bar{D}^0$



At a symmetric charm factory,
low momentum D-frame tracks have lower lab frame efficiencies

Another reason one might want boosted QC $D^0\bar{D}^0$



At an asymmetric charm or B factory,
low momentum D-frame tracks have higher lab frame efficiencies
and you can do time-dependent analysis
(e.g. CP-tagged time-dependent amplitude analysis, ...)

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

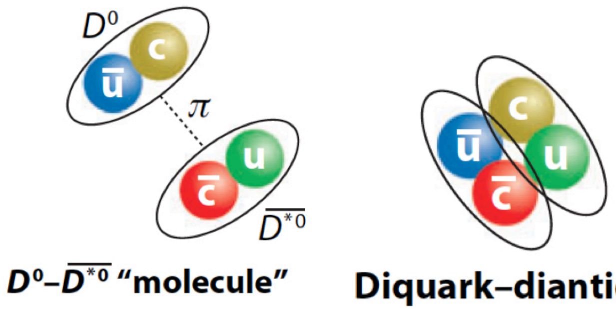
- The $\chi_{c1}(3872)$ exotic meson was first discovered by Belle in 2003
- Rapidly confirmed by CDF, D0, and BaBar

[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.)



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

LHCb, PRL 122 (2019) 211803

- Observation of $\chi_{c1}(3872) \to J/\psi\,\gamma$ established that $\chi_{c1}(3872)$ 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]].
- $\chi_{c1}(3872)$ 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].

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

P. Naik, JHEP 03 (2023) 038

- I recently proposed an extension to other C conserving reactions:

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

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

- C conservation in this reaction means the $D^0\overline{D}^0$ system will be formed with the following eigenvalue:

$$C_{D^0\overline{D}^0} = (-1)^m$$

- $\chi_{c1}(3872)$ is known to decay primarily to DD* where the D* decays to a neutral D and a neutral photon/pion. So the final states will be:

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

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

- Off-shell DD* possible…. but however the final state is produced, if it is produced strongly, C must be conserved!

Quantum numbers

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

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

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

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

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

Higher J and L unlikely

Light neutral kinematics in X decays

- $\chi_{c1}(3872)$ expected to decay through $D^*\bar{D}$ + c.c., at $D^*\bar{D}$ 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)
$X(3872) \to D^0\bar{D}^0\pi^0$	141.5	42.6
$X(3872) \to D^0\bar{D}^0\gamma$	137.0	137.0

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

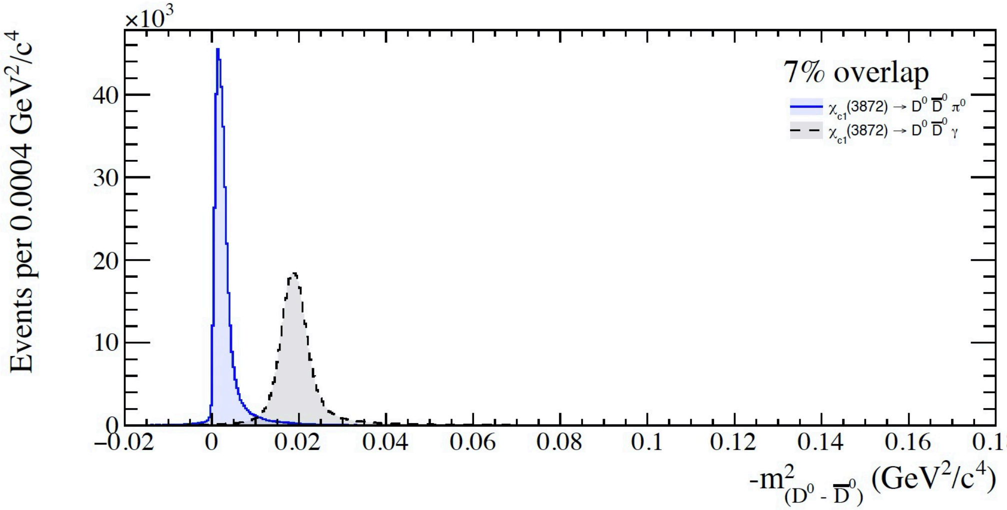
- For off-shell $D^0\bar{D}^0\pi^0$, *p* still small, between the pion mass and threshold
- For off-shell $D^0\bar{D}^0\gamma$, *p* can take a larger set of values, very distinguishable.

P. Naik, JHEP 03 (2023) 038

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

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

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



Study using **toy** MC designed to simulate LHCb detector effects ("RapidSim")
No D mass-constraints

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

Real performance NOT expected to be this good

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

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

(internal tests with LHCb MC don't look too bad though... but real $\chi_{c1}(3872)$ decays will have off-shell components that make it harder)

P. Naik, JHEP 03 (2023) 038

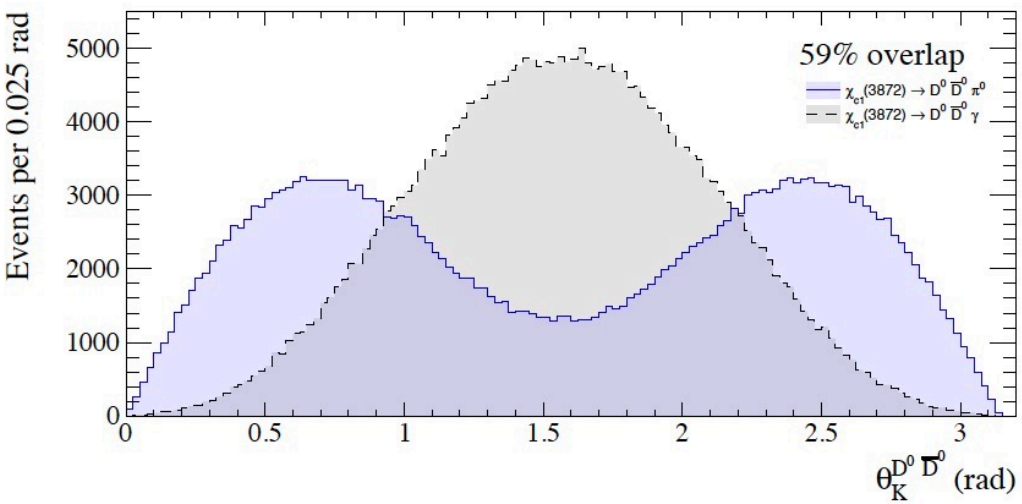
How to separate $\chi_{c1}(3872) \rightarrow D^0\bar{D}^0\pi^0$ & $D^0\bar{D}^0\gamma$

- If we have

  $$B \rightarrow \chi_{c1}(3872)K$$

  Can also look at the angle between the K and either D in the $D^0\bar{D}^0$ frame and get extra separation from helicity-related effects.

- Again, the light neutral does not need to be reconstructed.



Study using **toy** MC designed to simulate LHCb detector effects (“RapidSim”)
No D mass-constraints

Real performance NOT expected to be this good

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

To the ends of the earth (or Germany) for QC $D^0\bar{D}^0$

$\overline{\text{P}}$ANDA

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

$$\sigma(p\bar{p} \to \chi_{c1}(3872)) < 68 \text{ nb}$$

$$p\bar{p} \to \psi(3770) \qquad C_{D^0\bar{D}^0} = -1$$

$$\sigma[p\bar{p} \to \psi(3770)] = (9.8^{+11.8}_{-3.9}) \text{ nb } (< 27.5 \text{ nb at } 90\% \text{ C.L.}) \text{ or } (425.6^{+42.9}_{-43.7}) \text{ nb}$$

$$\sqrt{s} = 3.774 \text{ GeV}$$

[101] BESIII collaboration, *Study of $e^+e^- \to p\bar{p}$ in the vicinity of $\psi(3770)$*, *Phys. Lett.* **B735** (2014) 101 [1403.6011]. (Cited in section 5.2.1.)

[106] $\overline{\text{P}}$ANDA collaboration, *New spectroscopy with $\bar{\text{P}}$ANDA at FAIR: X, Y, Z and the F-wave charmonium states*, *AIP Conf. Proc.* **1735** (2016) 060011 [1512.05496]. (Cited in section 5.2.3.)

and many more

Quantum correlations extended

P. Naik, JHEP 03 (2023) 038

- Apply the same logic to other C conserving reactions:

$$\psi(3770) \to D^0\overline{D}^0 \qquad \chi_{c2}(3930) \to D^0\overline{D}^0$$

$$C_{D^0\overline{D}^0} = (-1) \qquad C_{D^0\overline{D}^0} = +1$$

- The D mesons must be found decaying in opposite states of CP or in states of the same CP, depending on the initial state.

$$\frac{|D^0\overline{D}^0\rangle - |\overline{D}^0D^0\rangle}{\sqrt{2}} = \frac{|D_-D_+\rangle - |D_+D_-\rangle}{\sqrt{2}} \text{ when } C_{D^0\overline{D}^0} = -1 \qquad \psi(3770) \to D^0\overline{D}^0$$

$$\frac{|D^0\overline{D}^0\rangle + |\overline{D}^0D^0\rangle}{\sqrt{2}} = \frac{|D_+D_+\rangle - |D_-D_-\rangle}{\sqrt{2}} \text{ when } C_{D^0\overline{D}^0} = +1 \qquad \chi_{c2}(3930) \to D^0\overline{D}^0$$

- Every charmonia state that can decay to $D^0\overline{D}^0$ will have the D mesons in a CP-anticorrelated or a CP-correlated state.

And what else can we do with these?

P. Naik, 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

- Also, as said before the two D mesons must exist in either CP-correlated or CP-anticorrelated states — which has interesting consequences, e.g.:

$C = -1$

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

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

$C = +1$

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

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

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

$D^0\bar{D}^0$ 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}	

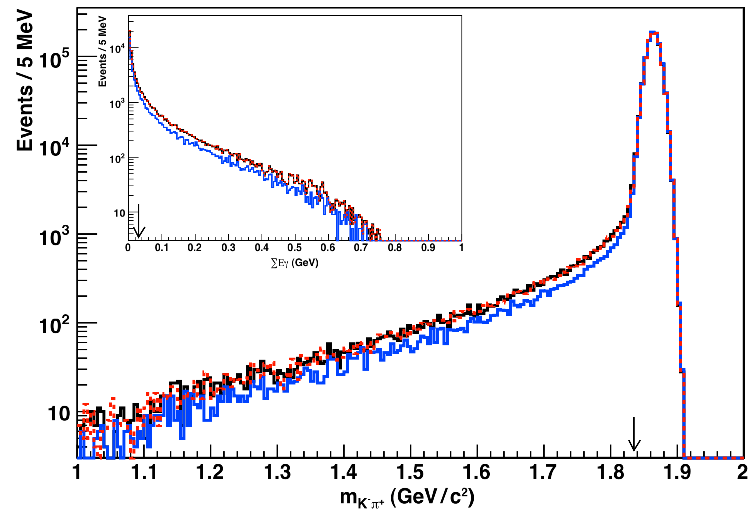
Table 2. Approximate product branching fractions $\mathcal{B}$ of a $C = +1$ $D^0\bar{D}^0$ pair reconstructed in the corresponding $D\bar{D}$ decay mode, both under the naive expectation [2] and after the effects of quantum correlation [23, 53], excluding small effects due to charm mixing and ignoring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

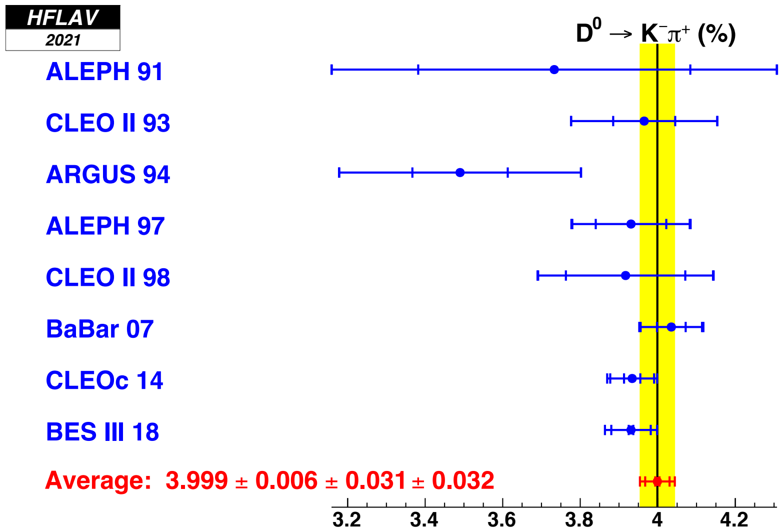
- Total product branching fraction ~25 times smaller for {CP+, CP+} tag than for {$K^-\pi^+$, $K^+\pi^-$} tag. [6.27×10^{-5} / 1.60×10^{-3} = ~ (1 / 25)]
- CP projections can give better access to phases / remove opposite C content

HFLAV D⁰ branching fraction averages

- The Heavy Flavour Averaging Group provides informed averages of quantities relevant to flavour physics experiments
- We provide world averages of branching fractions for two-body hadronic D⁰ decays, treating final state radiation (FSR) consistently so the accuracy of these averages matches their precision
- These averages can be useful in predicting the expected rates of quantum-correlated decays

average branching fractions accurately by correcting those with poorly modeled efficiency





PRD 107, 052008 (2023)

Quantum correlations in weak decay

P. Naik, JHEP 03 (2023) 038

- Idea: find the first evidence for quantum correlations generated from a weak decay.

$$B^0_{(s)} \to D^0 \overline{D}^0 \qquad C_{D^0\overline{D}^0} = +1$$

- Proof would be demonstrating (approximately*) for $h^+h^- = \{K^+K^-, \pi^+\pi^-\}$:

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

* really this is slightly less than 2 due to mixing

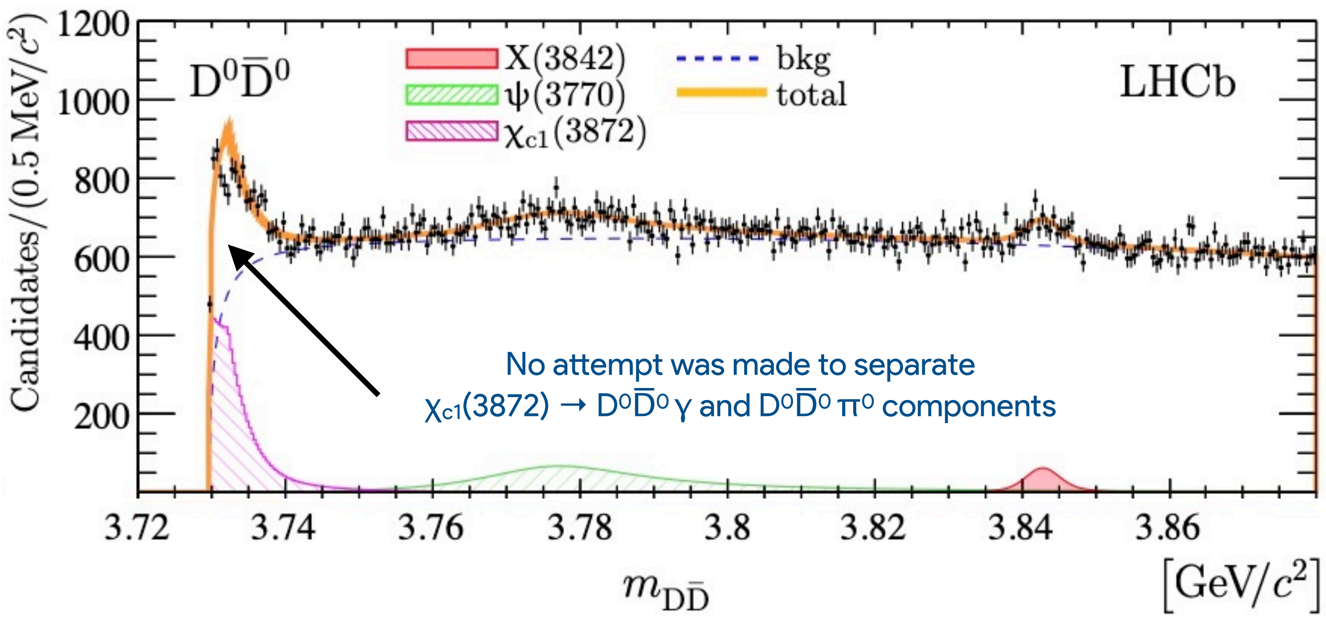
- My rough estimate*:
  expect
  2000 (600) B^0_s (B^0) $\to [D^0 \to K^-\pi^+][\overline{D}^0 \to K^+\pi^-]$
  and
  80 (24) B^0_s (B^0) $\to [D^0 \to h^+h^-][\overline{D}^0 \to h^+h^-]$
  total decays through LHCb Run 3.

* extrapolating from LHCb collab., PRD 87 (2013) 092007 [1302.5854] and arXiv:1808.08865.

Prompt Charmonia at LHCb, and a filtering idea

- LHCb, Run 2 data, JHEP 1907 (2019) 035, reconstructing $D^0 \to K^-\pi^+$ only
  - $O(10^4)$ $D^0\bar{D}^0$ systems from $\chi_{c1}(3872)$ seen in prompt decays.
  - I estimate 4x more in Run 3

(my estimate: BES III 20/fb will collect ~ 9×10^4 $C = -1$ $D^0\bar{D}^0$, $D^0 \to K^-\pi^+$ only, extrapolated from BES III PLB 734 (2014) 227)



JHEP 1907 (2019) 035

Prompt Charmonia at LHCb, and a filtering idea

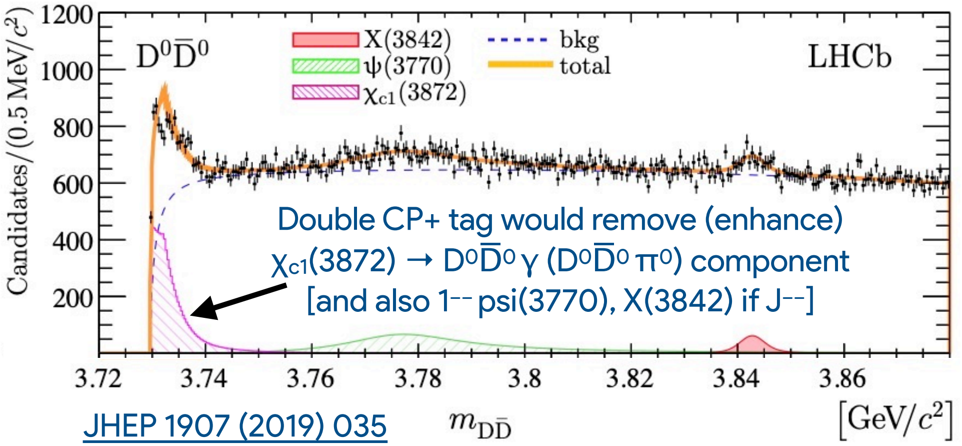
- LHCb, Run 2 data, JHEP 1907 (2019) 035, reconstructing $D^0 \to K^- \pi^+$ only
  - $O(10^4)$ $D^0\bar{D}^0$ systems from $\chi_{c1}(3872)$ seen in prompt decays.

(my estimate: BES III 20/fb will collect ~ 9×10^4 $C = -1$ $D^0\bar{D}^0$, $D^0 \to K^-\pi^+$ only, extrapolated from BES III PLB 734 (2014) 227)

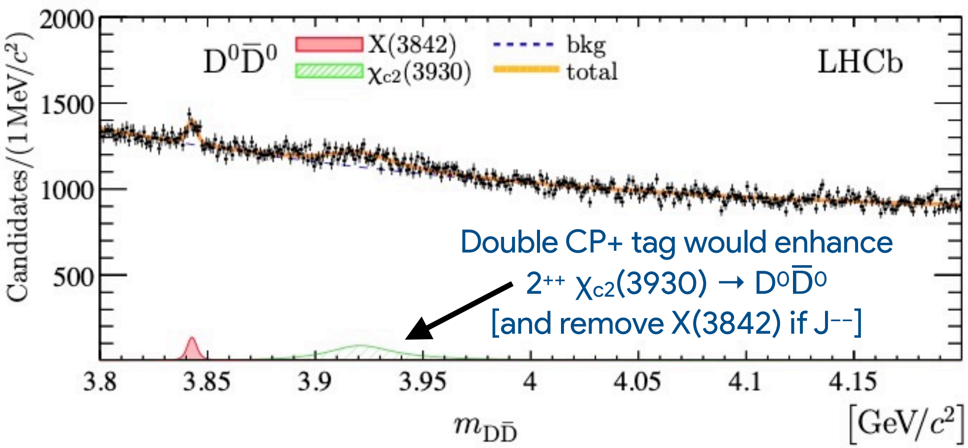
- Idea: Reconstructing both D in K^+K^-, $\pi^+\pi^-$ modes means **branching fraction for $\chi_{c1}(3872) \to D^0\bar{D}^0\gamma$ will be zero.** $\chi_{c1}(3872) \to D^0\bar{D}^0\pi^0$ will "only" be **~25** times smaller than $K^-\pi^+$ case.

P. Naik, JHEP 03 (2023) 038

- Could help constrain line shapes.
- *Other charmonia affected similarly.*
- *If these behaviors not observed…*



JHEP 1907 (2019) 035



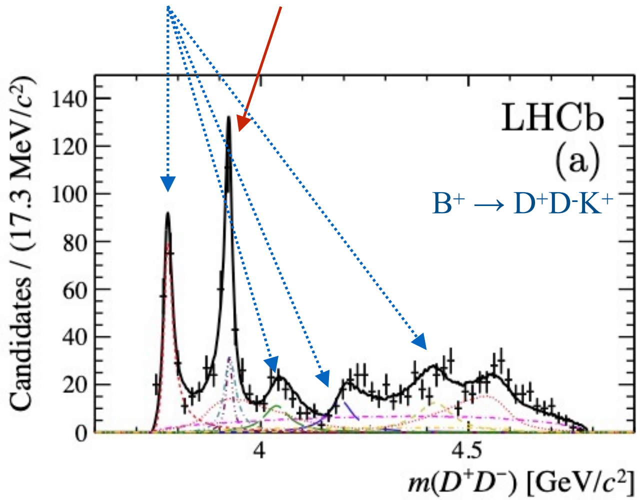
Another filtering idea

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	$1.29 \pm 0.09 \pm 0.04$	$-2.41 \pm 0.12 \pm 0.51$	$24.2 \pm 2.2 \pm 0.5$

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



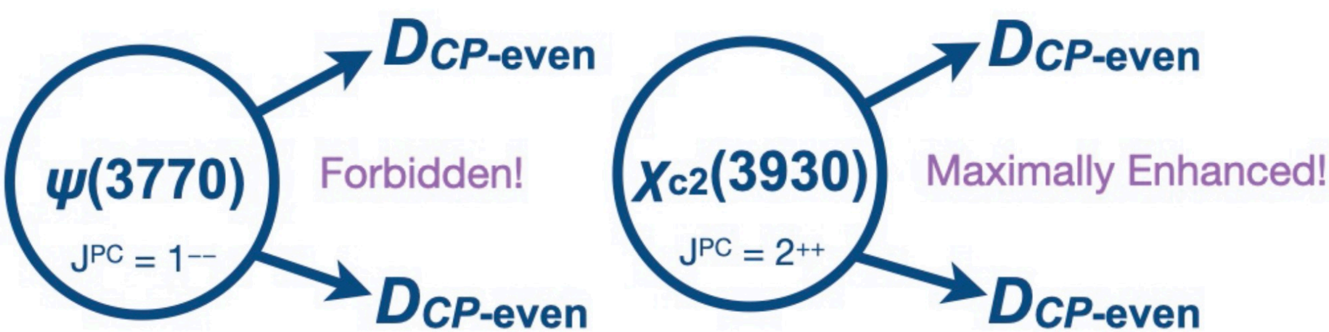
- Bondar and Milstein [JHEP 12 (2020) 015] notice (compared to $B^+ \to D^+D^-K^+$)
  - In $B^+ \to D^0\bar{D}^0K^+$, $\psi(3770)$ branching fraction is ~ 4 times the size
  - In $B^+ \to D^0\bar{D}^0K^+$, $\chi_{c2}(3930)$ is suppressed (not observed by BaBar) PRD 91 (2015) 052002
- Reconstructing D mesons in K^+K^-, $\pi^+\pi^-$ states in $B^+ \to D^0\bar{D}^0K^+$ should leave the decay dominated by the DK^+ resonance (+ non-resonant) amplitudes.

In b-hadron Amplitude Analysis

P. Naik, JHEP 03 (2023) 038

- Could envision a future $B \to D^0\overline{D}^0 \pi^0 K$ amplitude analysis where:
  - Reconstructing D mesons with $K^+ K^-$, $\pi^+ \pi^-$ states only would mean:
    - All 1^{--} $D^0\overline{D}^0$ states [e.g. psi(3770)] **would not be observed**
    - Rate of $B \to (\chi_{c1}(3872) \to D^0\overline{D}^0 \pi^0) K$ component ~doubled
    - Rate of $B \to (D^0\overline{D}^0)_{C=+1} \pi^0 K$ components [e.g. $\chi_{c2}(3930)$] ~doubled

- **Provides an alternative (albeit lower-statistics) environment to study DK resonances with fewer interfering charmonia components.**



CP violation in the charm system

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

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

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

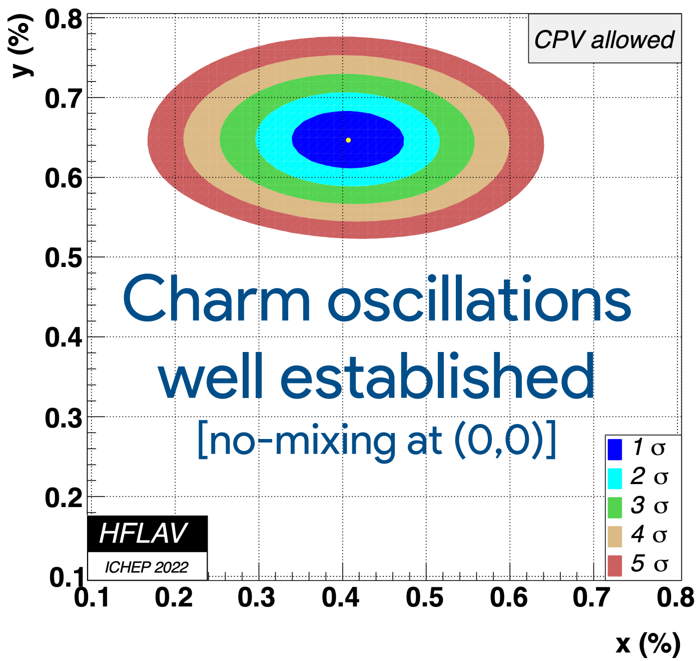
PRL 122 (2019) 211803

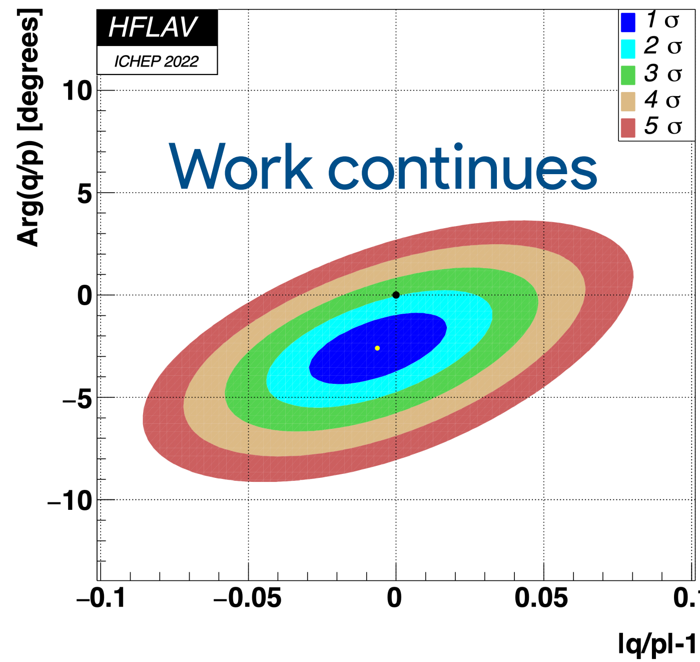
$$a^d_{\pi^-\pi^+} = (23.2 \pm 6.1) \times 10^{-4}$$

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.

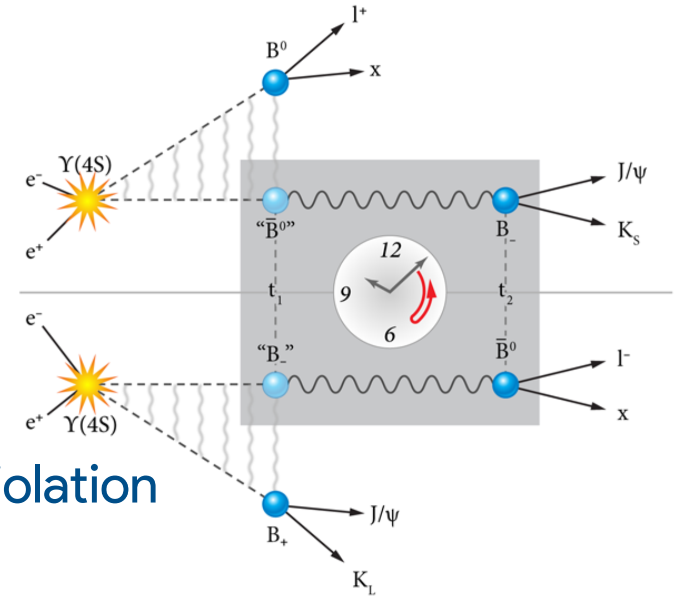




HFLAV ICHEP 2022 update

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
- 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
- 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



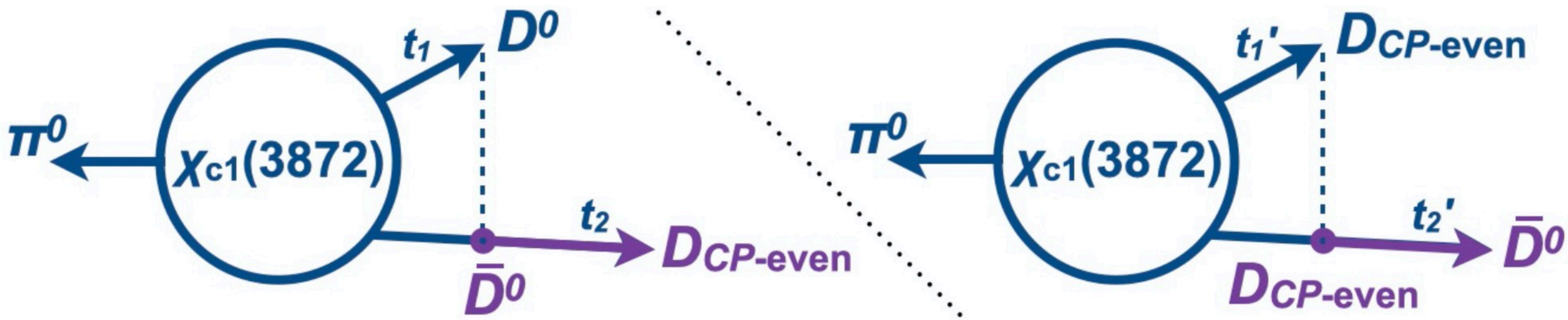
PRL 109, 211801 (2012)

PLB 845 (2023) 138164

Time-reversal violation

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

- "All" we need to do is look at samples of time-reversed D^0 decay process and compare their rates.
- Follow similar method to time-reversal measurement in the B system [BaBar Phys. Rev. Lett. 109, 211801 (2012)], but use $\chi_{c1}(3872)$.

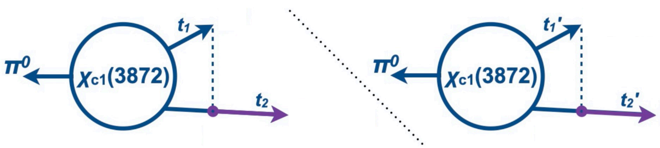


Two T-conjugate D transitions within $\chi_{c1}(3872)$ decays

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	$D^0 \to \overline{D}^0$	$\overline{D}^0 \to D^0$	$(\mathbf{\overline{D}^0, \overline{D}^0, D^0, D^0})$	$(\mathbf{\overline{D}^0, \overline{D}^0, D^0, D^0})$
CP and CPT	$D^0 \to D^0$	$\overline{D}^0 \to \overline{D}^0$	$(\mathbf{\overline{D}^0, D^0, D^0, \overline{D}^0})$	$(\mathbf{\overline{D}^0, D^0, D^0, \overline{D}^0})$
T and CPT	$D_+ \to D_-$	$D_- \to D_+$	(D_-, D_-, D_+, D_+)	(D_+, D_-, D_-, D_+)
CP	$\overline{D}^0 \to D_-$	$D^0 \to D_-$	$(D^0, D_-, \overline{D}^0, D_-)$	$(D^0, D_-, \overline{D}^0, D_-)$
	$D_+ \to D^0$	$D_+ \to \overline{D}^0$	$(D_-, D^0, D_-, \overline{D}^0)$	$(\mathbf{D_+, D^0, D_+, \overline{D}^0})$
	$\overline{D}^0 \to D_+$	$D^0 \to D_+$	$(\mathbf{D^0, D_+, \overline{D}^0, D_+})$	$(\mathbf{D^0, D_+, \overline{D}^0, D_+})$
	$D_- \to D^0$	$D_- \to \overline{D}^0$	$(\mathbf{D_+, D^0, D_+, \overline{D}^0})$	$(D_-, D^0, D_-, \overline{D}^0)$
T	$\overline{D}^0 \to D_-$	$D_- \to \overline{D}^0$	$(D^0, D_-, D_+, \overline{D}^0)$	$(D^0, D_-, D_-, \overline{D}^0)$
	$D_+ \to D^0$	$D^0 \to D_+$	$(D_-, D^0, \overline{D}^0, D_+)$	$(\mathbf{D_+, D^0, \overline{D}^0, D_+})$
	$\overline{D}^0 \to D_+$	$D_+ \to \overline{D}^0$	$(D^0, D_+, D_-, \overline{D}^0)$	$(\mathbf{D^0, D_+, D_+, \overline{D}^0})$
	$D_- \to D^0$	$D^0 \to D_-$	$(D_+, D^0, \overline{D}^0, D_-)$	$(D_-, D^0, \overline{D}^0, D_-)$
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_+)	$(\mathbf{D_+, D^0, D^0, D_+})$
	$D^0 \to D_-$	$D_- \to \overline{D}^0$	$(\overline{D}^0, D_-, D_+, \overline{D}^0)$	$(\overline{D}^0, D_-, D_-, \overline{D}^0)$
	$D_+ \to \overline{D}^0$	$D^0 \to D_+$	$(D_-, \overline{D}^0, \overline{D}^0, D_+)$	$(\mathbf{D_+, \overline{D}^0, \overline{D}^0, D_+})$

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.

Mechanisms for CPT violation in charm

- Yes it's unlikely
- Not an expert on these mechanisms... but here are some examples
- Strings are not point particles —> can elude Lorentz invariance requirement
- Can violate particle Lorentz invariance (although not observer Lorentz invariance)

[79] D. Colladay and V.A. Kostelecký, *Testing CPT with the neutral D system*, Phys. Rev. D **52** (1995) 6224 [hep-ph/9510365] [INSPIRE].

[80] V.A. Kostelecký and R. Potting, *CPT, strings, and meson factories*, Phys. Rev. D **51** (1995) 3923 [hep-ph/9501341] [INSPIRE].

[81] V.A. Kostelecký, *Formalism for CPT, T, and Lorentz violation in neutral meson oscillations*, Phys. Rev. D **64** (2001) 076001 [hep-ph/0104120] [INSPIRE].

[82] J. Bernabeu, N.E. Mavromatos and J. Papavassiliou, *Novel type of CPT violation for correlated EPR states*, Phys. Rev. Lett. **92** (2004) 131601 [hep-ph/0310180] [INSPIRE].

[83] J. Bernabeu, N.E. Mavromatos and S. Sarkar, *Decoherence induced CPT violation and entangled neutral mesons*, Phys. Rev. D **74** (2006) 045014 [hep-th/0606137] [INSPIRE].

[84] Y. Shi, *Exact Theorems Concerning CP and CPT Violations in C=-1 Entangled State of Pseudoscalar Neutral Mesons*, Eur. Phys. J. C **72** (2012) 1907 [arXiv:1112.2828] [INSPIRE].

[85] Y. Shi, *Some exact results on CP and CPT violations in a $C = -1$ entangled pseudoscalar neutral meson pair*, Eur. Phys. J. C **73** (2013) 2506 [arXiv:1306.2676] [INSPIRE].

https://doi.org/10.1140/epjc/s10052-012-1907-3

[86] Z. Huang and Y. Shi, *CP and CPT Violating Parameters Determined from the Joint Decays of $C = +1$ Entangled Neutral Pseudoscalar Mesons*, Phys. Rev. D **89** (2014) 016018 [arXiv:1307.4459] [INSPIRE].

[87] Á. Roberts, *Testing CPT symmetry with correlated neutral mesons*, Phys. Rev. D **96** (2017) 116015 [arXiv:1706.03378] [INSPIRE].

[88] B.R. Edwards and V.A. Kostelecký, *Searching for CPT Violation with Neutral-Meson Oscillations*, Phys. Lett. B **795** (2019) 620 [arXiv:1907.05206] [INSPIRE].

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 are 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 data
- Future steps
  - Collect Run 3 (+ 4) 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

UNIVERSITY OF LIVERPOOL




Conclusion

P. Naik, JHEP 03 (2023) 038

- Reconstructing neutral D mesons in CP=+1 eigenstates, within the charmonia spectrum can enhance or eliminate components with specific C; within $b \to D^0\overline{D}^0X$ amplitude analyses, allows the possibility of an alternative environment to study DX resonances.

- Opportunity to observe C = +1 quantum correlations in $B^0_{(s)} \to D^0\overline{D}^0$.

- 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 on the way!
- Opportunities for QC $D^0\overline{D}^0$ at BES III (above threshold), BELLE II, PANDA

- It's ambitious — but if we want more quantum correlated $D^0\overline{D}^0$ 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 [51-75]

LHCb [9]

- LHCb is a B physics experiment at CERN
- We have substantial beauty and charm samples...
  - **$\sigma(b\overline{b})_{LHCb}$ = 75.3 ± 14.1 μb (Phys. Lett. B 694 (2010), 209)**
  - **$\sigma(c\overline{c})_{LHCb}$ = 1419 ± 133 μb (Nucl. Phys. B 871 (2013), 1)**
- In 2011 roughly a trillion $c\bar{c}$ were produced!
- LHCb can make precision measurements in beauty with high sensitivity to New Physics...
  - We can measure γ from trees to high precision
  - Will there be a difference between tree and loop measurements?

Phase convention for D→Kπ [13]

It should be noted that there are multiple conventions in the literature for the strong phase $\delta_D^{K\pi}$, depending on whether the discussion involves the CKM angle γ or charm mixing. The convention in which $\delta_D \to \pi$ in the SU(3) limit is used, which is shifted by π with respect to the convention employed by the HFLAV Charm group.

How to prepare QC $D^0\overline{D}^0$ systems (traditional) [15]

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

$$e^+e^- \xrightarrow{\gamma^*} D^0\overline{D}^0 + m\gamma + n\pi^0 + a\,J/\psi + b\,\rho$$

- C conservation in this reaction dictates that the $D^0\overline{D}^0$ system must be formed with the following eigenvalue:

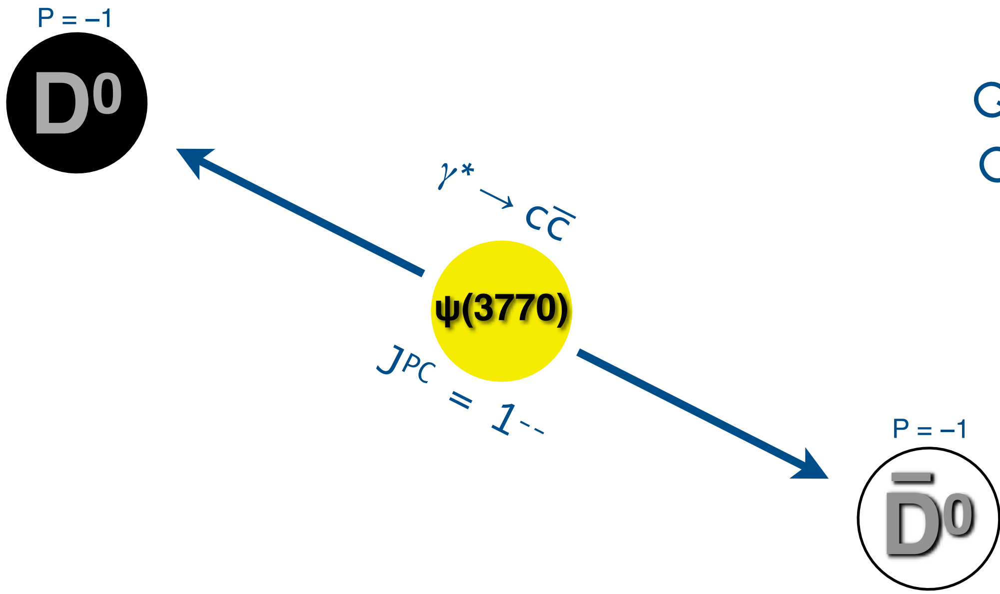
$$C_{D^0\overline{D}^0} = (-1)^{m+1+a+b}$$

Very special case: ($e^+e^- \xrightarrow{\gamma^*}$) $\psi(3770) \to D^0\bar{D}^0$ [16a]

$$C|\gamma^*\rangle = C|D^0\bar{D}^0\rangle \xrightarrow{C|\gamma^*\rangle \equiv -1} C\,|D^0\bar{D}^0\rangle = -1$$

Quantum Correlations

$|D^0(\hat{p})\rangle|\bar{D}^0(-\hat{p})\rangle - |\bar{D}^0(-\hat{p})\rangle|D^0(\hat{p})\rangle$



Forbidden by CP conservation	*CP+*	*CP+*
	CP−	*CP−*
Maximal enhancement	*CP+*	*CP−*
Forbidden if no mixing	$K^-\pi^+$	$K^-\pi^+$
Interference of CF with DCS	$K^-\pi^+$	*CP±*
	CP±	$K^-\pi^+$
Rates Unaffected	*CP±*	X
	$K^-\pi^+$	
	SL	

$$P\,|D^0\bar{D}^0\rangle \equiv (-1)^J \times P\,|D^0\rangle \times P\,|\bar{D}^0\rangle = -1$$

$$CP_{sys} = +1$$

$BR[\psi(3770) \to D^0\bar{D}^0] = (52 \pm 5)\%$

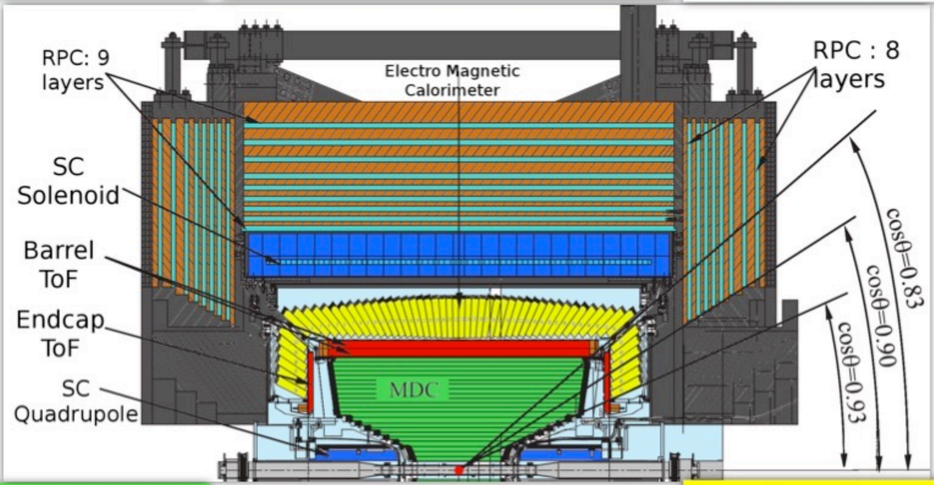
BES III (2008-) [16b]

- Study $e^+e^- \to \psi(3770) \to D^0\overline{D}^0$ 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)**

PID: Time Of Flight
2 layer plastic scintillators
time resolution σ_t (barrel) ~ 90 ps
σ_t (endcap) ~ 110 ps, (65 ps after the 2015 upgrade)

Superconducting magnet 1 T

Muon ID: Muon counters
9 layers of RPC
Spatial resolution $\delta_{r\phi}$ = 1.4 cm -1.7 cm

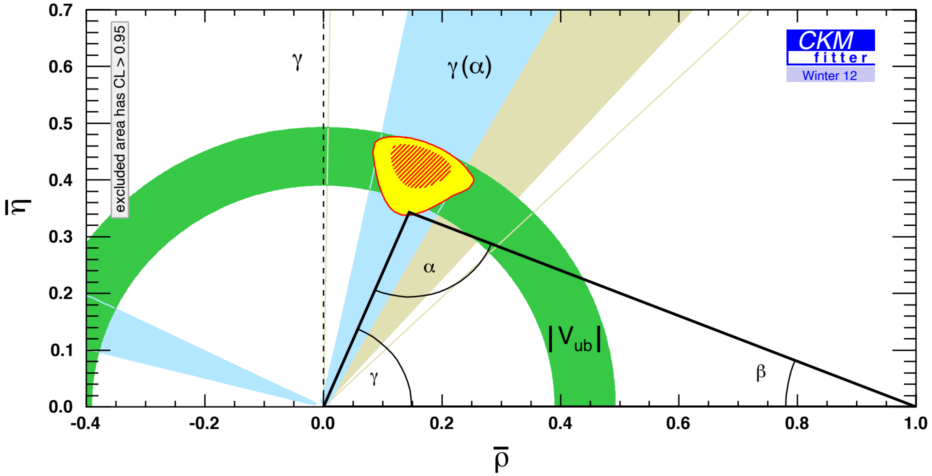


Main Drift Chamber
gas: He/ C_3H_8 60/40
43 layers
spatial resolution σ_x (1GeV/c) ~ 130 µm
momentum resolution dp/p (1GeV/c) = 0.5%

hermetic
barrel $|\cos\theta| < 0.83$
endcap $0.85 < |\cos\theta| < 0.93$

Electromagnetic Calorimeter
CsI (Tl) scintillating crystals 6240
energy resolution $dE/\sqrt{E}$ (1 GeV) = 2.5%
Spatial resolution σ_x (1 GeV) = 6 mm

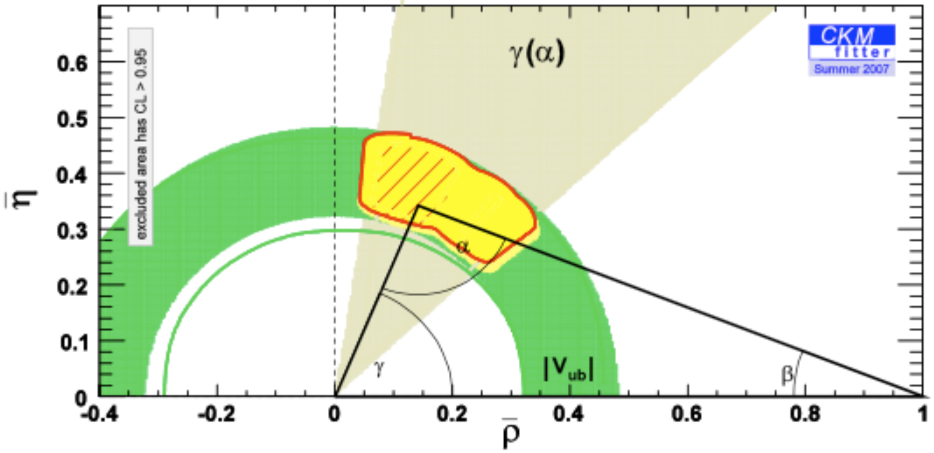
The CKM phase γ [18a]



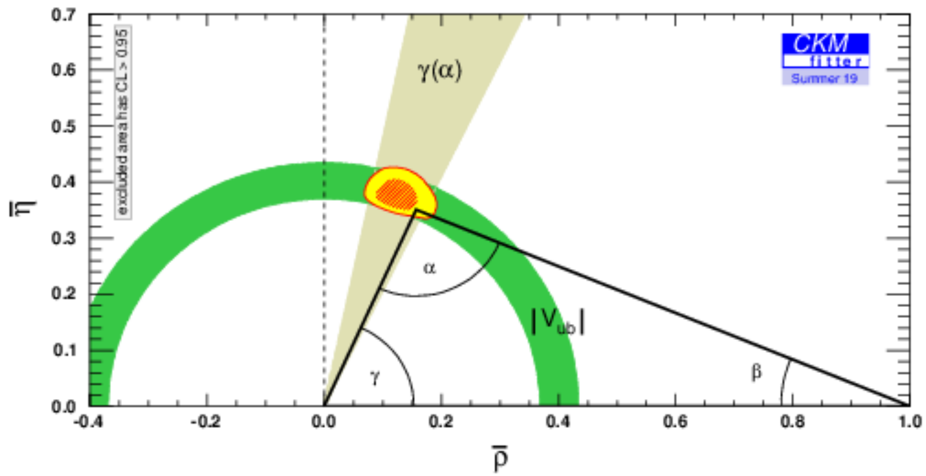
Constraints from “tree” quantities

- Of the three CKM phases, γ is the least constrained.
- A precision measurement of γ is essential in order to test the internal consistency of the CKM triangle.
- **The precision measurement of γ is one of the most important measurements of LHCb and e^+e^- flavor factories.**

Status of the Measurement of the CKM phase γ [18b]



Constraints from tree quantities



Constraints from tree quantities

$$\gamma : (76.8^{+30.4}_{-31.5})^{\circ}$$

Fit from direct measurements only (CKM Fitter, Summer 2007)

D decay strong-phase information from CLEO-c and BES III
+
B-factories / LHCb

$$\gamma : (72.1^{+5.4}_{-5.8})^{\circ}$$

Fit from direct measurements only (CKM Fitter, December 2019) [Latest LHCb gamma combination has uncertainty of 4 degrees]

CKMfitter Group (J. Charles et al.), Eur. Phys. J. C41, 1-131 (2005) [hep-ph/0406184], updated results and plots available at: http://ckmfitter.in2p3.fr

Coherence Factor definition [20]

Generalising for the decay $D \to S$, where S denotes a $K^- n\pi$ final state, these parameters are the coherence factor R_S, and the amplitude ratio r_D^S and CP-conserving strong-phase difference δ_D^S between the CF and DCS amplitudes averaged over phase space [5]:

$$R_S e^{-i\delta_D^S} = \frac{\int \mathcal{A}_S^\star(\mathbf{x})\mathcal{A}_{\bar{S}}(\mathbf{x})\mathrm{d}\mathbf{x}}{A_S A_{\bar{S}}} \quad \text{and} \quad r_D^S = A_{\bar{S}}/A_S. \tag{1.1}$$

Here $\mathcal{A}_S(\mathbf{x})$ is the decay amplitude of $D^0 \to S$ at a point in multi-body phase space described by parameters $\mathbf{x}$ and $A_S^2 = \int |\mathcal{A}_S(\mathbf{x})|^2 \mathrm{d}\mathbf{x}$, with equivalent definitions for the $D^0 \to \bar{S}$ amplitude. (The amplitudes are normalised such that, in the absence of oscillations, A_S^2 corresponds to the branching ratio of the D^0 meson into mode S.) Maximum (zero) interference in the term sensitive to γ occurs in the limiting case $R_S = 1$ (0). The parameter r_D^S is of the order $\lambda^2 \approx 0.06$ for $D \to K^- n\pi$ decays.

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	$\mathcal{N}^{C-} = 3\times10^6$	$\mathcal{N}^{C+} = 3\times10^6$	$\mathcal{N}^{C-} = 10\cdot\mathcal{N}^{C+} = 3\times10^6$
y	0	$\pm0.015\pm0.008$	$\pm0.007\pm0.003$	$\pm0.012\pm0.005$
x^2 (10^{-3})	0	$\pm0.6\pm0.6$	$\pm0.3\pm0.3$	$\pm0.6\pm0.6$
$\cos\delta_{K\pi}$	1	$\pm0.21\pm0.04$	$\pm0.27\pm0.05$	$\pm0.20\pm0.04$
$x\sin\delta_{K\pi}$	0	—	$\pm0.022\pm0.003$	$\pm0.027\pm0.005$
r^2 (10^{-3})	3.74	$\pm1.0\pm0.0$	$\pm1.7\pm0.1$	$\pm1.0\pm0.0$

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

Parameter	Standard Fit
$\mathcal{N}$ (10^6)	$3.092\pm0.050\pm0.040$
y (%)	$4.2\pm2.0\pm1.0$
r^2 (%)	$0.533\pm0.107\pm0.045$
$\cos\delta$	$0.81^{+0.22+0.07}_{-0.18-0.05}$
$\sin\delta$	$-0.01\pm0.41\pm0.04$
x^2 (%)	$0.06\pm0.23\pm0.11$

- 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)

Alternative sources of QC $D^0\bar{D}^0$ [23]

BES III, Belle II

$$e^+e^- \xrightarrow{\gamma^*} D^0\bar{D}^0 + m\gamma + n\pi^0$$

BES III is looking into this

$$C_{D^0\bar{D}^0} = (-1)^{m+1}$$

$$e^+e^- \xrightarrow{\Upsilon(1S)} D^0\bar{D}^0 + m\gamma + n\pi^0$$

This won't happen

At full Belle II luminosity
(@ Υ(1S), ~10^{36} cm^{-2}s^{-1})
expect ~4x yearly QC $D^0\bar{D}^0$ of BES III
(@ 3.77 GeV, 10^{33} cm^{-2}s^{-1})

Li & Yang, Phys. Rev. D 74 (2006) 094016 [hep-ph/0610073].

$$e^+e^- \xrightarrow{\psi(4230)} \chi_{c1}(3872)\gamma$$

Maybe, not a larger cross section

$$\sigma[e^+e^- \to \gamma\chi_{c1}(3872)] = (5.5^{+2.8}_{-3.6})\ \text{pb}$$

at sqrt(s) = 4.226 GeV

Li and Yuan Phys. Rev. D 100 (2019) 094003 [1907.09149]
using data from
BES III, Phys. Rev. Lett. 122 (2019) 232002 [1903.04695]

and many more
(Must be some [Υ(4S) → $D^0\bar{D}^0$ + C-definite] in Belle II 50/ab ?)

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

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

- Currently BES-III + CLEO-c is only source of C = -1 correlated $D^0\bar{D}^0$
  - ~ 12k (+1.7k) $[D^0 \to K\pi][\bar{D}^0 \to K\pi]$ in 2.9/fb (818/pb) BES-III (CLEO-c)
  - To date, no C = +1 correlated $D^0\bar{D}^0$ (guess: O(1k) in the BES-III data)

- 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:
  $B^0_{(s)} \to D^0\bar{D}^0K^+\pi^-$, $B^0_{(s)} \to D^0\bar{D}^0K_S$
  $B^+ \to D^0\bar{D}^0\pi^0/\gamma K^+$, $B^0_{(s)} \to D^0\bar{D}^0\pi^0/\gamma K^+\pi^-$, $B^0_{(s)} \to D^0\bar{D}^0\pi^0/\gamma K_S$
  $\Lambda_b \to D^0\bar{D}^0\Lambda$, $\Lambda_b \to D^0\bar{D}^0pK^-$, $\Lambda_b \to D^0\bar{D}^0\pi^0/\gamma\Lambda$, $\Lambda_b \to D^0\bar{D}^0\pi^0/\gamma pK^-$

- Could add up quickly, but of course backgrounds, interferences to deal with.
- Need to be creative to obtain equivalents to “single-tag” normalizations.

Quantum state evolution of $\chi_{c1}(3872)$ to $D\overline{D}^*$ [28]

$$D^*_{\pm} \to D_{\pm}\pi^0 \qquad D^*_{\pm} \to D_{\mp}\gamma$$

Bondar & Gershon, Phys.Rev.D 70:091503,2004 (hep-ph/0409281)

$$|\chi_{c1}(3872)\rangle \to \frac{|D^0\overline{D}^{*0}\rangle + |\overline{D}^0 D^{*0}\rangle}{\sqrt{2}} \to \frac{|D^0\overline{D}^0\rangle + |\overline{D}^0 D^0\rangle}{\sqrt{2}}|\pi^0\rangle$$

$$|\chi_{c1}(3872)\rangle \to \frac{|D^0\overline{D}^{*0}\rangle + |\overline{D}^0 D^{*0}\rangle}{\sqrt{2}} \to \frac{|D^0\overline{D}^0\rangle - |\overline{D}^0 D^0\rangle}{\sqrt{2}}|\gamma\rangle$$

Light neutral kinematics in X decays [30]

- $\chi_{c1}(3872)$ 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

- Note that in the X frame $\Delta E = m_{X(3872)} - E_{D^0\overline{D}^0}$ is the same as $E_{\pi^0/\gamma}$
  - Turns out that $\Delta m = m_{X(3872)} - m_{D^0\overline{D}^0}$ is almost the same, and invariant
  - Nice thing is these variables depend only on tracks.
- For off-shell, E_{π^0} still narrow, between the pion mass and threshold
- For off-shell, E_γ can fill a large phase space, very distinguishable.

Testing [31]

- Test with **RapidSim**

Some of the simulations also take account of momentum and impact parameter (IP) resolution representative of that of the LHCb detector [41, 42], and the effects of final state radiation (FSR). Such representative decays are generated with RapidSim [43], and FSR with PHOTOS++ v3.61 [44]. In RapidSim, we demand that the full decay chain occurs entirely within the acceptance of the LHCb detector (though it is possible to treat the neutral particle as invisible), and that the proton-proton collisions occur at a center-of-mass energy of 14 TeV/c^2. Momentum and IP smearing is performed at the level expected within the LHCb detector. Prompt $X(3872)$ decays are generated in RapidSim under the loose assumption that the low momentum release in the decay dictates, that in the lab frame, the particles in the $D^0\overline{D}^0$ system will move approximately colinearly; thus the included FONLL charmed meson transverse momentum and pseudorapidity distributions [45, 46] are extended to represent low-mass charmonium by simply doubling the transverse momenta generated, while maintaining the pseudorapidity. $X(3872)$ decays from B mesons are simulated with the B mesons having FONLL beauty meson transverse momentum and pseudorapidity distributions.

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

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

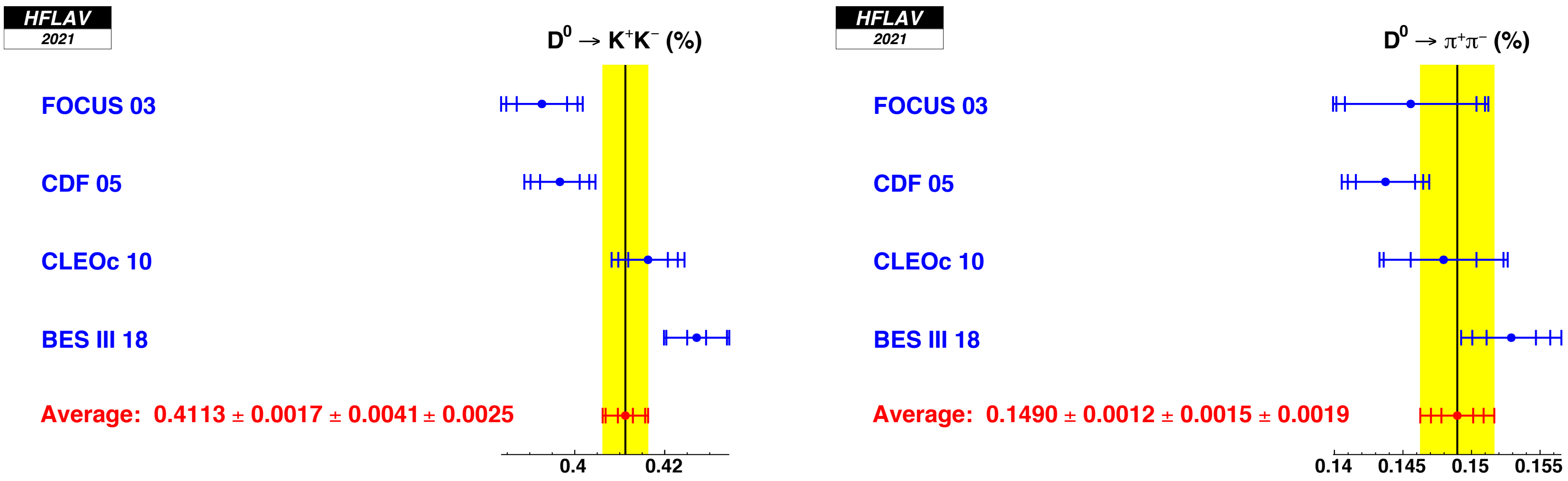
- For $\chi_{c1}(3872)$ decays, recall that it is possible to have C = +1 or C = –1 states.
  - Ideally we extract the C = +1 states cleanly, this should be fairly possible looking for a π^0 reflection peak or managing to fully reconstruct the decay.
  - However, if one thinks their sample is predominately 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…
  - Would have to think of a way to include another component for dilution from uncorrelated background.

HFLAV D0 branching fraction averages [34]



PRD 107, 052008 (2023)

How is this useful? [35]

P. Naik, JHEP 03 (2023) 038
Asner & Sun, Phys. Rev. D73:034024, 2006; Erratum-ibid. D77:019902, 2008

- Certainly would be interesting to extract quantum correlated $D^0\overline{D}^0$ systems for further study! I will come back to this point at the end of my talk.
- The fact that the two D mesons must exist in either CP-correlated or CP-anticorrelated states, has two very interesting consequences:
  - Reconstruction of both D mesons in states of the same CP eigenvalue suppresses C = –1 systems.
  - The product branching fraction of two D mesons reconstructed in the same CP eigenstate is (nearly) doubled in C = +1 systems.

$C = -1$

$$\psi(3770) \to D^0\overline{D}^0$$

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

$C = +1$

$$\chi_{c2}(3930) \to D^0\overline{D}^0$$

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

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

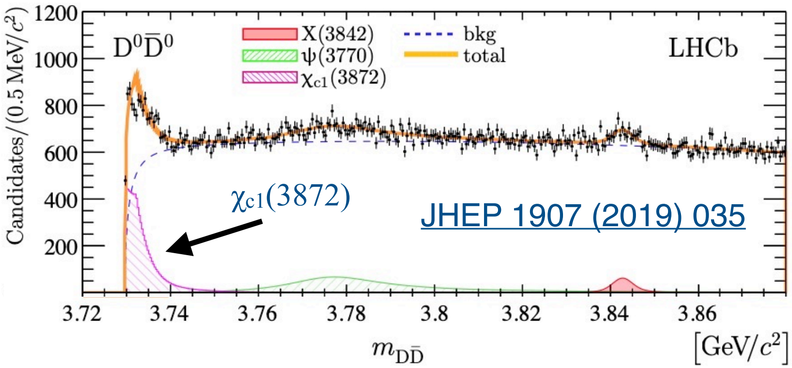
C = +1 correlated branching fractions

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

Homework...

$\chi_{c1}(3872)$ produces correlated $D^0\bar{D}^0$ [39]

JHEP 1907 (2019) 035
P. Naik, JHEP 03 (2023) 038



- Most copious: prompt $\chi_{c1}(3872) \to D^0\bar{D}^0\pi^0/\gamma$
  - Large backgrounds to be dealt with
  - My estimate: will be O(50k) $[D^0 \to K\pi][\bar{D}^0 \to K\pi]$ by the end of Run 3

- π^0/γ does not necessarily need to be reconstructed.

Sample size comparison [40a]

- Run 1 + Run 2 gives O(3.5x) the CLEO-c $D^0\overline{D}^0$ sample (in favored $K\pi$ vs favored $K\pi$) from $\chi_{c1}(3872)\rightarrow D^0\overline{D}^0\pi^0/\gamma$ in Run1+Run2.

- BES III has ~2 times LHCb Run1+2 in 2.9/fb. So ~14x LHCb in 20/fb.

- Getting the prompt statistics in current/future runs would be competitive with BES III, but will require
    - dealing w/ backgrounds
    - C = +/-1 sample separation

- Time-dependent measurements will already be worth pioneering with a few hundred events.

CLEO-c final sample

TABLE VI. Fully reconstructed DT yields and efficiencies including constituent branching fractions, for modes without $K_S^0\pi^+\pi^-$. Yield uncertainties are statistical and uncorrelated systematic, respectively, and efficiency uncertainties are statistical only.

Mode	Yield	Efficiency (%)
$K^-\pi^+$, $K^-\pi^+$	$5.6 \pm 2.5 \pm 0.4$	41.5 ± 2.8
$K^-\pi^+$, $K^+\pi^-$	$1731 \pm 42 \pm 11$	40.0 ± 0.2
$K^-\pi^+$, K^+K^-	$202 \pm 14 \pm 4$	35.2 ± 0.5
$K^-\pi^+$, $\pi^+\pi^-$	$82.6 \pm 9.1 \pm 0.4$	44.5 ± 0.9
$K^-\pi^+$, $K_S^0\pi^0\pi^0$	$132 \pm 12 \pm 1$	8.6 ± 0.2
$K^-\pi^+$, $K_S^0\pi^0$	$252 \pm 16 \pm 1$	19.4 ± 0.3
$K^-\pi^+$, $K_S^0\eta$	$36.7 \pm 6.2 \pm 1.3$	6.9 ± 0.3
$K^-\pi^+$, $K_S^0\omega$	$109 \pm 11 \pm 1$	8.5 ± 0.2
$K^+\pi^-$, $K^+\pi^-$	$4.0 \pm 2.0 \pm 0.0$	42.9 ± 2.9
$K^+\pi^-$, K^+K^-	$191 \pm 14 \pm 1$	35.3 ± 0.5
$K^+\pi^-$, $\pi^+\pi^-$	$77.3 \pm 8.9 \pm 0.7$	45.6 ± 0.9

Sample size comparison [40b]

- Run 1 + Run 2 gives O(36%) of CLEO-c $D^0\overline{D}^0$ sample (in favored Kπ vs favored Kπ) from $B^+ \to D^0\overline{D}^0K^+$ in Run1+Run2.

- Not a lot, compared to CLEO. BES III has ~7 times CLEO in 2.9/fb.

- Again, there are time dependent measurements that could be worth pioneering with a few hundred events.

CLEO-c final sample

TABLE VI. Fully reconstructed DT yields and efficiencies including constituent branching fractions, for modes without $K^0_S\pi^+\pi^-$. Yield uncertainties are statistical and uncorrelated systematic, respectively, and efficiency uncertainties are statistical only.

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In Amplitude Analysis [42]

P. Naik, JHEP 03 (2023) 038

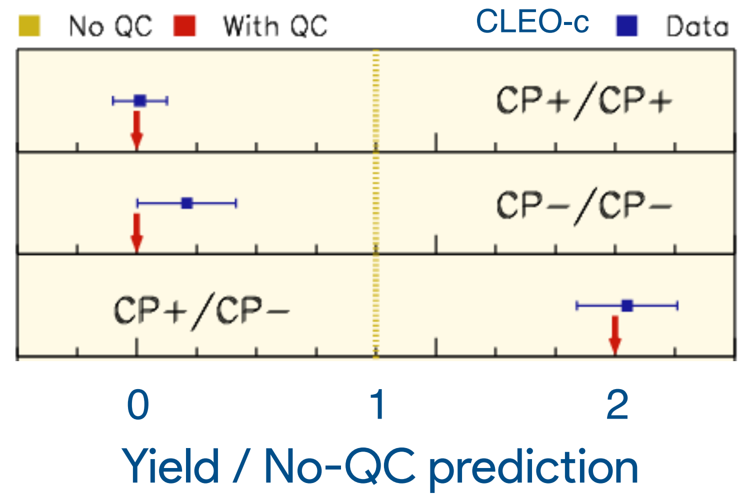
- Could envision a future $B \to D^0\bar{D}^0\pi^0 K$ amplitude analysis where:
  - Reconstructing D mesons with K^+K^-, $\pi^+\pi^-$ states only would mean:
    - All 1^{--} $D^0\bar{D}^0$ states [e.g. psi(3770)] **would not be observed**
    - Rate of $B \to (\chi_{c1}(3872) \to D^0\bar{D}^0\pi^0)\, K$ component doubled
    - Rate of $B \to (D^0\bar{D}^0)_{C=+1}\,\pi^0 K$ components [e.g. $\chi_{c2}(3930)$] doubled
- Could envision a future $B \to D^0\bar{D}^0\gamma K$ "amplitude" analysis where:
  - Reconstructing D mesons with K^+K^-, $\pi^+\pi^-$ states only would mean:
    - All 1^{--} $D^0\bar{D}^0$ states [e.g. psi(3770)] **would not be observed**
    - Rate of $B \to (\chi_{c1}(3872) \to D^0\bar{D}^0\gamma)\, K$ component is **zero**
    - Rate of $B \to (D^0\bar{D}^0)_{C=+1}\,\gamma K$ components [e.g. $\chi_{c2}(3930)$] doubled
- **Provides an alternative (albeit lower-statistics) environment to study DK resonances with fewer interfering charmonia components.**

A way to search for a CP-violating signal

$C = -1$

$e^+e^- \rightarrow \gamma^* \xrightarrow{\psi(3770)} D^0 \bar{D}^0$

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



Quantum correlations are seen in data!

*There is a second order effect where CPV *can* be seen

A. Petrov, hep-ph/0409130

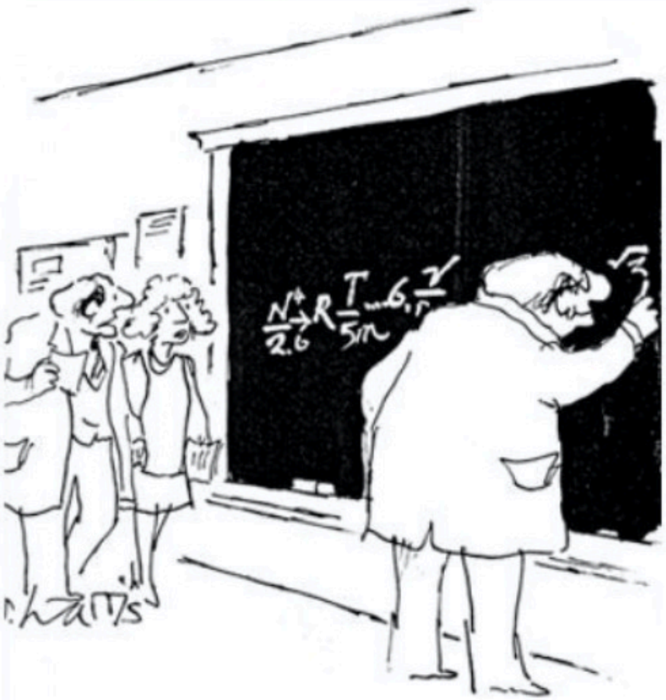
$$\Gamma_{f_1 f_2} = \frac{1}{2R_m^2}\left[\left(2+x^2-y^2\right)\left|\lambda_{f_1}-\lambda_{f_2}\right|^2 + \left(x^2+y^2\right)\left|1-\lambda_{f_1}\lambda_{f_2}\right|^2\right]\Gamma_{f_1}\Gamma_{f_2}$$

$$\lambda_f = \frac{q}{p}\frac{\overline{A}_f}{A_f} = R_m e^{i(\phi+\delta)}\left|\frac{\overline{A}_f}{A_f}\right| \qquad R_m^2 = |p/q|^2$$

f_1, f_2 are final states of the same CP

A way to search for unusual direct CP violation

The simplest CP-violating signal at LHCb

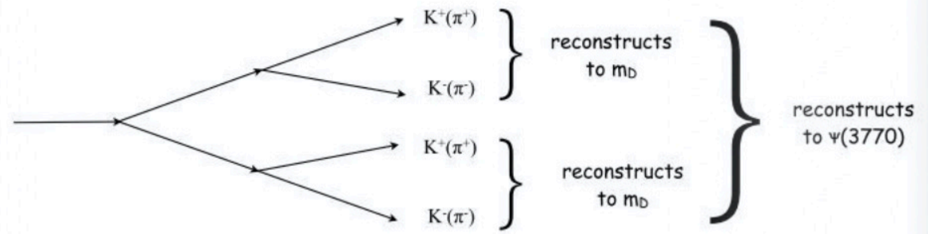


"I THINK HE'S CROSSED THAT THIN LINE FROM SPECULATIVE FICTION INTO OUTRIGHT FANTASY."

The simplest CP-violating signal at LHCb

★ Recall that CP of the states in $D^0\overline{D^0} \to (F_1)(F_2)$ are anti-correlated at ψ(3770):

★ a simple signal of CP violation: $\psi(3770) \to D^0\overline{D^0} \to (CP_\pm)(CP_\pm)$



$$\Gamma_{F_1F_2} = \frac{\Gamma_{F_1}\Gamma_{F_2}}{R_m^2}\left[\left(2+x^2+y^2\right)\left|\lambda_{F_1}-\lambda_{F_2}\right|^2 + \left(x^2+y^2\right)\left|1-\lambda_{F_1}\lambda_{F_2}\right|^2\right]$$

★ CP-violation in the **rate** → of the second order in CP-violating parameters.

★ No need to compensate for D/$\overline{\text{D}}$ production asymmetry

Alexey Petrov (WSU & MCTP) 10 Physics at LHCb, Apr 26-29, Bad Honnef

Abstract (Seminar)

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 earlier this year, 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.