

30th International Symposium on Lepton Photon Interactions at High Energies. Manchester, 10-14 January 2022

LS LOWRY, Peel Park, Salford (1944)

- -
- -

Malcolm John - University of Oxford Lepton/Photon, January 2022

Topics and parallel sessions

- **•** Precision measurement of B_s meson oscillations
- \bigcirc Observation of D^0 meson mass difference
- Observation of direct *CP* violation with D^0 mesons
- **•** Time-dependent *CP* violation search with D^0 mesons
- \circ *CP* violation searches with $D_{(s)}^+$ mesons (*s*)
- \circ *CP* violation in charmless B^+ decays
- ๏ Unitarity Triangle: *β*
- ๏ Unitarity Triangle: *γ*
- **e** CP violating phase with B_s mesons

[Wed 10:40: Jordy Butter](https://indico.cern.ch/event/949705/contributions/4555596/)

"CPV and CKM measurements with beauty decays at LHCb"

[Wed 10:00: Markus Reif](https://indico.cern.ch/event/949705/contributions/4555574/)

"Hadronic B decays at Belle II"

Wed 12:00: Radek Zlebcik

["Charm and TDCPV in B decays at Belle II"](https://indico.cern.ch/event/949705/contributions/4555577/)

Malcolm John - University of Oxford Lepton/Photon, January 2022

$|B_{sL}\rangle = p |B_s\rangle + q |B_s\rangle$ $|B_{sH}\rangle = p |B_{s}\rangle - q |B_{s}\rangle$

$B_s \leftrightarrow B_s$ mixing frequency: Δm_s 0 *q ^p g*(*t*) *J*/ *K*⁰ S *A*¯*f* \overline{M} 1 h S $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$

k ing occurs if the eigenstates of the hamiltor are not aligned with the interactions eigenstates: ๏ Mixing occurs if the eigenstates of the hamiltonian

$B_s \leftrightarrow B_s$ mixing frequency: Δm_s \rightarrow *B*, mixing frequency: Δm *^p g*(*t*) *J*/ *K*⁰ S *A*¯*f* \overline{M} 1 h S $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$

igenstates of the hamiltor • Mixing occurs if the eigenstates of the hamiltonian $|B_{sH}\rangle = p |B_s\rangle - q |\bar{B}_s\rangle$ are not aligned with the interactions eigenstates: B_{sL} $=$ $p |B_s$ $+$ $q |B_s$ $>$

units, and is measured in the measured in inverse picoseconds. The inverse picoseconds. The inverse picoseconds. The inverse product of the inverse product of the inverse of the inverse of the inverse of the inverse of the

 $|B_{sL}\rangle = p |B_s\rangle + q |B_s\rangle$ $\langle B_{sH} \rangle = p |B_s \rangle - q | \overline{B}_s \rangle$ $P P S$. $P P S$. The prediction is consistent with but significant with but significant with significant with S . $|B|$. The prediction is consistent with but significant with but signific $\frac{1}{2}$ *^s* ! *D* $|B_{sL}\rangle = p |B_s\rangle + q |B_s\rangle$

existing experimental results. The control of the
The control of the c

written as de statisten.
Written as de statisten as de

centre-of-mass energy of 13 TeV. The second centre-of-mass energy of 13 TeV.

hadrons produced in *p* collisions at the produced in *p* collisions and the product in an around the proton around the proton are given by the proton and the proton are given by the proton are given by the proton are give b $\text{Constant } C = -1 (+1) \text{ for}$ mass difference $\overline{}$ $\text{Rstant } C = -\frac{1}{2}$ $\overline{1}$ $\mathbf{1}$ $\frac{1}{\sqrt{1-\frac{1}{2}}\left(1-\frac{1}{2}\right)}$ Constant $C = -1$ $(+1)$ for mixed (unmixed) *Bs* meson

Malcolm John - University of Oxford

$$
p^{3+1} s
$$
\n
$$
p^{3+1} s
$$
\n
$$
B_s
$$
\n
$$
\Gamma_s = (\Gamma_H + \Gamma_L)/2
$$
\n
$$
B_{+}(t)
$$
\n
$$
P(t) \sim e^{-\Gamma_s t} \left[\cosh\left(\frac{\Delta \Gamma_s t}{2}\right) + C \cdot \cos(\Delta m_s t) \right]
$$
\n
$$
\frac{q}{p}g_{-}(t)
$$
\nProbability to observe
\n
$$
[un] mixed B_s meson
$$
\n
$$
S_s = m_H - m_L
$$
\n
$$
= 2 \cdot 1 \cdot (1)
$$
\n
$$
= 2 \cdot 1 \cdot (1)
$$
\n
$$
= 2 \cdot 1 \cdot (1)
$$
\n
$$
= 2 \cdot 1 \cdot (1)
$$
\n
$$
= 2 \cdot 1 \cdot (1)
$$

mass difference

Δm_s with $B_s \to D_s^{\pm} \pi^{\mp}$

- ๏ Identify decay flavour with Cabibbo-favoured $b \rightarrow c\pi^-$ *vs.* $\overline{b} \rightarrow \overline{c}\pi^+$ transition
	- ๏ DCS contribution negligible
- ๏ Identify initial flavour with flavour tagging. c.f. \sim 31% at Belle(II)

- ๏ An initial mass fit identifies **379k** signal events
- **•** Result with $B_s \to D_s \pi$ combined with earlier result using $B_s \to D_s \pi \pi \pi$ (HEP 03 (2021) 137)
-

 $\frac{1}{\sqrt{1+\epsilon}}$ is exactly the criteria for a system to exhibit interference and we next show that $\frac{1}{\sqrt{1+\epsilon}}$ LIICD SHOWIL <u>FITYS. NEV. DEZ (ZOIO) OSIIOI</u> Pioneered by Babar [Phys. Rev. Lett. 98 \(2007\) 211802,](https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.98.211802) and Belle Phys. Rev. Lett. 98 (2007) 211803, LHCb shown [Phys. Rev. D97 \(2018\) 031101](https://cds.cern.ch/record/2293449)

On the other hand, charm mixing is slow are the other hand charm mixing is clays **OIT THE OTHET HATIA, CHATIH THEATILE IS SIOW**

- Probability of mixing too small to measure complete oscillations **ε** Though flavour tagging is near-perfect: $D^{*+} \to D^0 \pi^+$ or $B^- \to D^0 \mu^- \nu$ As the final state is accessible to both *D*⁰ and *D*⁰ **D** in the suppressed in the state $Pr(G)$ (*D*⁰ ! *^K*⁺ $\overline{\mathbf{u}}$ avo $\mathbf{1}$ $\overline{ }$ ir tagging is Γ $\overline{16}$
- ๏ Instead, look for a time-dependant change in the rate of DCS decays , we must consider the time-dependent rate of finding and $\frac{1}{2}$ **D**^o **l**n stead, look for a $\overline{\mathbf{u}}$ a time-dependant change in the ra

t

sin ✓ *^x*

2

^t iy

2

t

e

ⁱ^D cos ✓ *^x*

 \mathbf{I} f

2

^t iy

2

t

sin

2

^t ⁺ *iy*

2

t

e

$$
\Gamma(D^0 \to K^+ \pi^-) = |g_+(t) r_D e^{-i\delta_D} + g_-(t)|^2
$$

Malcolm John - University of Oxford Lepton/Photon, January 2022 Use of standard identities, remembering cos(*i*✓) = cosh ✓ and sin(*i*✓) = *i*sinh ✓ gives, \overline{M} *J*^o *L*₁ M_{α} laalus Ialus II μ imayaity af Ω $\frac{1}{1}$ is equivalently using that the signal shapes $\frac{1}{1}$. We assume that the signal shapes are signal shapes are the signal shapes are signal

cos *^D* sinh(*yt*) sin *^D* sin(*xt*)

 $\frac{1}{\sqrt{1+\epsilon}}$ is exactly the criteria for a system to exhibit interference and we next show that $\frac{1}{\sqrt{1+\epsilon}}$ LIICD SHOWIL <u>FITYS. NEV. DEZ (ZOIO) OSIIOI</u> Pioneered by Babar [Phys. Rev. Lett. 98 \(2007\) 211802,](https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.98.211802) and Belle Phys. Rev. Lett. 98 (2007) 211803, LHCb shown [Phys. Rev. D97 \(2018\) 031101](https://cds.cern.ch/record/2293449)

On the other hand, charm mixing is slow are the other hand charm mixing is clays the other's are of-order unity, *V*⇤ *csVud*. \blacksquare *iMtt*/2 ◯ ^DII LIIC ULICI HAIIU, CHAHIII HILAIII S IS SIUW

^{Probability of miving too small to measure complete oscillations} <u>*<i>r*</u>
 <i><u>rotate</u> assilla</u>

- ๏ Probability of mixing too small to measure complete oscillations **•** Though flavour tagging is near-perfect: $D^{*+} \to D^0 \pi^+$ or $B^- \to D^0 \mu^- \nu$ As the final state is accessible to both *D*⁰ and *D*⁰ \int_{0}^{∞} $\overline{ }$ \mathbf{I} leasure bability of mixing too small to measure complete oscillatio *t* .
11 *r* g is r ear-perf \overline{C} ◆ **D** in the suppressed in the state $Pr(G)$ (*D*⁰ ! *^K*⁺ $\overline{\mathbf{u}}$ avo $\mathbf{1}$ $\overline{ }$ ir tagging is Γ $\overline{16}$
- ๏ Instead, look for a time-dependant change in the rate of DCS decays , we must consider the time-dependent rate of finding and $\frac{1}{2}$ **D**^o **l**n stead, look for a til *t* \cdot *irD* pendant chang $\overline{\mathbf{u}}$ a time-dependant change in the ra

t

sin ✓ *^x*

2

^t iy

2

t

e

ⁱ^D cos ✓ *^x*

2

^t iy

2

t

sin

2

^t ⁺ *iy*

2

t

e

Use of standard identities, remembering cos(*i*✓) = cosh ✓ and sin(*i*✓) = *i*sinh ✓ gives,

t

" ¹ ⁺ *^y*

 D^{*+} $\rightarrow D^0 \pi^+$ 01 $\ddot{}$

e in the rate **c** $\frac{1}{\sqrt{1}}$ Γ *e* \overline{O} deca ✓ *x* \mathbf{I} f

² *^x*

2

2

y

² + *x*

#

^D(*x*

 $\begin{pmatrix} 2 & 60 \\ 40 & 20 \\ 20 & 6 \end{pmatrix}$

2

 $y \equiv \Delta\Gamma/2\Gamma$ $\Delta m/\Gamma$ $y \equiv \Delta \Gamma/2\Gamma$ *t*

The first evidence for *D*⁰–*D*⁰ oscillations was reported in 2007 [8, 9]. More recently,

 $+\frac{1}{2}$ (c) $\ddot{\ }$ \mathbf{S} $\frac{2}{3}$ 1 $\frac{1}{2} \left(\cosh(y\Gamma t) - \cos(x\Gamma t) \right) + r_D \left(\cos \delta_D \sinh(y\Gamma t) - \sin \delta_D \sin(x\Gamma t) \right)$ $\frac{1}{\rho}\exp\left(\frac{1}{2\pi\sigma^2}\right)$ = $\frac{1}{\rho}\left(\cosh(\sqrt{\Gamma}t) - \cos(\sqrt{\Gamma}t)\right) + r_D\left(\cos\delta_D\sinh(\sqrt{\Gamma}t) - \sin\delta_D\sin(\sqrt{\Gamma}t)\right)$ $r_{\text{D}}(v_{\text{D}}(v_{\text{D}})$ and $p_{\text{D}}(v_{\text{D}}(v_{\text{D}}))$ is the limit of sum of sum $p_{\text{D}}(v_{\text{D}})$ sum of sum *as before new term*

$$
R = \frac{D^0 \to K^+\pi^-}{\overline{D}^0 \to K^+\pi^-} \simeq r_D^2 + r_D \left(y \cos \delta_D - x \sin \delta_D \right) \left(\frac{t}{\tau} \right) + \frac{y^2 + x^2}{4} \left(\frac{t}{\tau} \right)^2
$$

where we reason $\frac{100}{60}$ $\frac{100}{60}$

$$
\Gamma(D^0 \to K^+\pi^-) = |g_+(t) r_D e^{-i\delta_D} + g_-(t)|^2
$$
\n
$$
= e^{-\Gamma t} \left[\frac{1}{2} r_D^2 (\cosh(y\Gamma t) + \cos(x\Gamma t)) + \frac{1}{2} (\cosh(y\Gamma t) - \cos(x\Gamma t)) + r_D (\cos \delta_D \sinh(y\Gamma t) - \sin \delta_D \sin(x\Gamma t))\right]
$$
\n
$$
= e^{-\Gamma t} \left[\frac{1}{2} r_D^2 (\cosh(y\Gamma t) + \cos(x\Gamma t)) + \frac{1}{2} (\cosh(y\Gamma t) - \cos(x\Gamma t)) + r_D (\cos \delta_D \sinh(y\Gamma t) - \sin \delta_D \sin(x\Gamma t))\right]
$$
\n
$$
x \equiv \Delta m/\Gamma \qquad y \equiv \Delta \Gamma/2\Gamma
$$

 n/Γ $\left(\begin{array}{c} \frac{1}{2} \left.\frac{1}{40}\right|_{\frac{1}{2005}} & \frac{1}{2010 \left(\frac{1}{2005}\right)^{2015}} \\ \frac{1}{2005} & \frac{1}{2010} \frac{1}{M(D^2\pi^4)\left[\text{MeV}/c^2\right]} \end{array}\right)$ dimensionless parameters $O(1\%)$

!

cos *^D* sinh(*yt*) sin *^D* sin(*xt*)

 $\frac{1}{2}$

Malcolm John - University of Oxford Lepton/Photon, January 2022 $\frac{M(D^2\pi^+)\left[\text{MeV}/c^2\right]}{2\rho r \sinh\left(\frac{1}{2} \right)}$ (*D*⁰ ! *^K*⁺ Malcolm John - University of Oxford *Explored 1. Iohn - University of Oxford J*^o *L*₁ \overline{M} *M*(D⁰π⁺) [MeV/c²]
alcolm Iohn - University of Oxford M_{α} laalus Ialus II μ imayaity af Ω $\frac{1}{1}$ is equivalently using that the signal shapes $\frac{1}{1}$. We assume that the signal shapes are signal shapes are the signal shapes are signal

sample contains approximately 1*.*77⇥10⁸ RS and 7*.*22⇥10⁵ WS signal decays. Each sample

 f_{H} f_{H} LITED SHOWH FITYS. KEV. DET (ZOIO) OSIIOI Pioneered by Babar Phys. Rev. Lett. 98 (2007) 211802, and Belle Phys. Rev. Lett. 98 (2007) 211803, Recent LHCb s Pioneered by Babar <u>Phys. Rev. Lett. 98 (2007) 211802,</u> and Belle <u>Phys. Rev. Lett. 98 (2007) 211803,</u> Recent LHCb shown <u>[Phys. Rev. D97 \(2018\) 031101](https://cds.cern.ch/record/2293449)</u>

On the other hand, charm mixing is slow are the other hand charm mixing is clays the other's are of-order unity, *V*⇤ *csVud*. \blacksquare *iMtt*/2 ◯ ^DII LIIC ULICI HAIIU, CHAHIII HILAIII S IS SIUW

^{Probability of miving too small to measure complete oscillations} <u>*<i>r*</u>
 <i><u>rotate</u> assilla</u>

- ๏ Probability of mixing too small to measure complete oscillations **•** Though flavour tagging is near-perfect: $D^{*+} \to D^0 \pi^+$ or $B^- \to D^0 \mu^- \nu$ As the final state is accessible to both *D*⁰ and *D*⁰ \int_{0}^{∞} $\overline{ }$ \mathbf{I} leasure bability of mixing too small to measure complete oscillatio *t* .
11 *r* g is r ear-perf \overline{C} ◆ **D** in the suppressed in the state $Pr(G)$ (*D*⁰ ! *^K*⁺ $\overline{\mathbf{u}}$ avo $\mathbf{1}$ $\overline{ }$ ir tagging is Γ $\overline{16}$
- ๏ Instead, look for a time-dependant change in the rate of DCS decays , we must consider the time-dependent rate of finding and $\frac{1}{2}$ **D**^o **l**n stead, look for a til *t* \cdot *irD* pendant chang $\overline{\mathbf{u}}$ a time-dependant change in the ra

 \sim $\frac{5}{1}$

r

 \overline{R}

2

22
22 March 2010
22 March 2010

 $\overline{\mathbf{r}}$

irD

t

sin ✓ *^x*

 $\ddot{\epsilon}$

2

^t iy

2

Malcolm John - University of Oxford Lepton/Photon, January 2022 $\frac{M(D^2\pi^+)\left[\text{MeV}/c^2\right]}{2\rho r \sinh\left(\frac{1}{2} \right)}$ (*D*⁰ ! *^K*⁺ Malcolm John - University of Oxford \overline{M} *M*(*D*°π⁺) [MeV/c²]
alcolm Iohn - University of Oxford *J*^o *L*₁ M_{α} laalus Ialus II μ imayaity af Ω $\frac{1}{1}$ is equivalently using that the signal shapes $\frac{1}{1}$. We assume that the signal shapes are signal shapes are the signal shapes are signal

2005 2010 2015

t

e

ⁱ^D cos ✓ *^x*

2

^t iy

2

!

t

sin

2

2

D $\frac{1}{\frac{1}{2}}$ sensitivity to non-standard-model phenomena [4–7].

2

t

" ¹ ⁺ *^y*

² *^x*

2

^D(*x*

The first evidence for *D*⁰–*D*⁰ oscillations was reported in 2007 [8, 9]. More recently,

 $0 \frac{1}{2005}$ 2010 $0 \frac{2015}{M(D^0 \pi^+)}$ $1 \frac{1}{2020}$

 $\frac{2}{3}$ $\frac{1}{2} \left(\cosh(y\Gamma t) - \cos(x\Gamma t) \right) + r_D \left(\cos \delta_D \sinh(y\Gamma t) - \sin \delta_D \sin(x\Gamma t) \right)$ $\frac{1}{\rho}\exp\left(\frac{1}{2\pi\sigma^2}\right)$ = $\frac{1}{\rho}\left(\cosh(\sqrt{\Gamma}t) - \cos(\sqrt{\Gamma}t)\right) + r_D\left(\cos\delta_D\sinh(\sqrt{\Gamma}t) - \sin\delta_D\sin(\sqrt{\Gamma}t)\right)$ $r_{\text{D}}(v_{\text{D}}(v_{\text{D}})$ and $p_{\text{D}}(v_{\text{D}}(v_{\text{D}}))$ is the limit of sum of sum $p_{\text{D}}(v_{\text{D}})$ sum of sum [10 *+ R as before new term*

$$
\Gamma(D^0 \to K^+\pi^-) = |g_+(t) r_{D}e^{-i\delta_D} + g_-(t)|^2
$$
\n
$$
= e^{-\Gamma t} \left[\frac{1}{2} r_D^2 (\cosh(\gamma \Gamma t) + \cos(\chi \Gamma t)) + \frac{1}{2} (\cosh(\gamma \Gamma t) - \cos(\chi \Gamma t)) + r_D (\cos \delta_D \sinh(\gamma \Gamma t) - \sin \delta_D \sin(\chi \Gamma t)) \right]
$$
\n
$$
x \equiv \Delta m/\Gamma \qquad y \equiv \Delta \Gamma/2\Gamma
$$
\ndimensions parameters O(1%)
\n
$$
R = \frac{D^0 \to K^+\pi^-}{\overline{D^0} \to K^+\pi^-} \simeq r_D^2 + r_D (\gamma \cos \delta_D - x \sin \delta_D) \left(\frac{t}{\tau}\right) + \frac{y^2 + x^2}{4} \left(\frac{t}{\tau}\right)^2
$$
\n
$$
\approx \frac{1}{2} \left[\frac{D^0}{\overline{D^0} \to K^+\pi^-} \right]
$$
\nProblem: need a precise δ_D for precision $x \& y$

1:

2

 \overline{a}

cos *^D* sinh(*yt*) sin *^D* sin(*xt*)

 $Lepto$ 2 $p_{\rm max}$ parameters, *x* $Lepton/Proton, January$ $Lepton/Photon, January 2022$

0

5

10

 $\begin{bmatrix} 5 \\ 0 \end{bmatrix}$ $\begin{bmatrix} 5 \\ 2005 \end{bmatrix}$ $\begin{bmatrix} 1 \\ 2010 \end{bmatrix}$ $\begin{bmatrix} 2015 & 2020 \\ M(D^0 \pi^+) [MeV/c^2] \end{bmatrix}$

 $0\frac{1}{2005}$ 2010 2015 2020

Figure 1: Distribution of *M*(*D*0⇡⁺

^s) distribution of *D*⁰

signal candidates. The decay-time-integrated *M*(*D*⁰⇡⁺

 $\sqrt{2}$

^s) distributions of the selected RS

 $\begin{array}{c|c}\n5 & 7 \\
0 & 2005 & 2010 \\
\hline\nM & 2\n\end{array}$

sample contains approximately 1*.*77⇥10⁸ RS and 7*.*22⇥10⁵ WS signal decays. Each sample

 D^{*+} $\rightarrow D^0 \pi^+$ 01 $\ddot{}$

e in the rate **c** $\frac{1}{\sqrt{1}}$ Γ *e* \overline{O} deca ✓ *x* \mathbf{I} f

Bin-flip method with $D \to K_S^0 \pi^+ \pi^-$

-
- *e*⁺*e*[−] → ψ (3770) dataset (\diamond). At LHCb, measure time-dependent "DCS" ratio R_b

Malcolm John - University of Oxford Lepton/Photon, January 2022

LHCb:<u>[Phys. Rev. Lett. 127, \(2021\) 111801](https://cds.cern.ch/record/2772062)</u> Method: [Phys. Rev. D99 \(2019\) 012007](https://journals.aps.org/prd/abstract/10.1103/PhysRevD.99.012007) BESIII: [Phys. Rev. D101 \(2020\) 112002](https://journals.aps.org/prd/abstract/10.1103/PhysRevD.101.112002)

• Use charge-conjugate multi-body decay. Subdivided into bins with a variety of δ_D (called X_b here) • Measure the relative phases between bin +*b* and $-b$, X_b using quantum-correlated D^0D^0 pairs in a dataset (\odot). At LHCb, measure time-dependent "DCS" ratio R_b in each bin-pair. X_b using quantum-correlated $D^0\overline{D}{}^0$

Observation of the neutral charm Δ*m* for *CPP-violating evaluation* and the contract of the contract of the change of t

• Formalism expanded and generalised to include the binning scheme and CP violation Formalism expanded and generalised to include the binning schem

. (1)

 $r_b = R_{bi}$ at $t = 0$

 $2 + \sqrt{r_b} \langle t \rangle_j \operatorname{Re}[X_b^*(z_{CP} \pm \Delta z)]$ $\langle t \rangle_i \text{Re}[X_h^*(z_{CP} \pm \Delta z)]$

 $2 + \sqrt{r_b} \langle t \rangle_j \operatorname{Re}[X_b(z_{CP} \pm \Delta z)]$ \mathcal{U}/j **Re**[$\Lambda b(\mathcal{Z}C P \pm \Delta \mathcal{Z})$] is the strong-phase difference between +b and -b

bj ratios, in which external information on *c^b* ⌘ Re(*Xb*) and *s^b* ⌘ Im(*Xb*) [22,

$$
R_{bj}^{\pm} \approx \frac{r_b + r_b \frac{\langle t^2 \rangle_j}{4} \operatorname{Re}(z_{CP}^2 - \Delta z^2) + \frac{\langle t^2 \rangle_j}{4} |z_{CP} \pm \Delta z|^2 + \sqrt{r_b} \langle t \rangle_j \operatorname{Re}[X_b^*(z_{CP} \pm \Delta z)]}{4}
$$

for Dalitz bin *b* and $1 + \frac{\langle t^2 \rangle_j}{4} \operatorname{Re}(z_{CP}^2 - \Delta z^2) + r_b \frac{\langle t^2 \rangle_j}{4} |z_{CP} \pm \Delta z|^2 + \sqrt{r_b} \langle t \rangle_j \operatorname{Re}[X_b(z_{CP} \pm \Delta z)]$
decay-time bin *j*

$$
X_b = \exp(i\delta_D(b))
$$
 where $\delta_D(b)$
is the strong-phase difference between *+* and *-b* between *+* and *-b*

$$
z_{CP} \pm \Delta z \equiv - (q/p)^{\pm 1} (y + ix) \qquad x \equiv \Delta m/\Gamma \qquad y \equiv \Delta \Gamma/2\Gamma
$$

LHCb:<u>[Phys. Rev. Lett. 127, \(2021\) 111801](https://cds.cern.ch/record/2772062)</u> <u> Method: [Phys. Rev. D99 \(2019\) 012007](https://journals.aps.org/prd/abstract/10.1103/PhysRevD.99.012007)</u> <u> BESIII:[Phys. Rev. D101 \(2020\) 112002](https://journals.aps.org/prd/abstract/10.1103/PhysRevD.101.112002)</u>

 $X_b = \exp(i\phi_D(b))$ where $\phi_D(b)$ $X_b = \exp(i\delta_D(b))$ where $\delta_D(b)$ is the strong-phase difference between +*b* and –*b*

 $f(x+ix)$. The $x \equiv \Delta m/\Gamma$ are $y \equiv \Delta \Gamma/2\Gamma$ $x \equiv \Delta m/\Gamma$ $y \equiv \Delta \Gamma/2\Gamma$ $\Delta m/\Gamma$ $y \equiv \Delta \Gamma/2\Gamma$

x Imensionless parameters $O(1\%)$ d imensionless parameters $O(1\%)$

govern the oscillations of neutral *D* mesons [1–3]. Long-distance amplitudes depend on the

detector \mathcal{Z}_2 is a single-arm forward spectrometer covering the pseudorapidity range \mathcal{Z}_2

13

$$
R_{bj}^{\pm} \approx \frac{r_b + r_b \frac{\langle t^2 \rangle_j}{4} \operatorname{Re}(z_{CP}^2 - \Delta z^2) + \frac{\langle t^2 \rangle_j}{4} \, | z_{CP} =
$$
alitz bin *b* and
$$
1 + \frac{\langle t^2 \rangle_j}{4} \operatorname{Re}(z_{CP}^2 - \Delta z^2) + r_b \frac{\langle t^2 \rangle_j}{4} \, | z_{CP} =
$$
ay-time bin *j*

 $\mathcal{L}(\mathcal{Y})$ $\overline{1}$

Malcolm John - University of Oxford Lepton/Photon, January 2022 parameters, *^x* = (4*.*6+1*.*⁴ 1*.*5)⇥10³ and *^y* = (6*.*2*±*0*.*8)⇥10³ [16], although neither a nonzero

Impact **0.8** \mathbf{r}

New global combination

0

 $\arg(q/p) = (-2.5 \pm 1.2)^{\circ}$ **20 30 Arg(q/p) [degrees]** $\sqrt{2}$ $\sqrt{2}$ **0 10 20 30 40** -|*q*/*p*| − 1 = − 0.005 ± 0.016

Arg(q/p) [degrees]

Summer 2021

Time dependant CPV in charm Cabibbo-suppressed *D*⁰ ! *f* decays, where the final state *f* = *K*⁺*K* or ⇡⁺⇡ is Common to *D* and *D* and *D D* and most sensitive tests of the most sensitive t *CP* violation through the measurement of the time-dependent asymmetry between the *D*⁰ and *D*⁰ decay rates, $A_{CP}(f,t) \equiv$ $\underline{\Gamma}(D^0 \to f, t) - \Gamma(\overline{D}^0 \to f, t)$ $\Gamma(D^0 \to f, t) + \Gamma(D^0 \to f, t)$ *,* (1) *^ACP* (*f, t*) ⇡ *^a^d ^f* + *Y^f* e↵ective Hamiltonian governing the time evolution of the *D*⁰–*D*⁰ system and is the aure dependant en van diami I ifetime asymmetry of D^0 and \overline{D}^0 to a CP eigenstate $f = K^+ K^- \pi^+ \pi^-$ expected to be 0.1 as has been used, and all terms have been expanded to first order in the *CP*-violation parameters *a^d ^f* , sin *^M ^f* and sin *^f* . Both phases *^M ^f* and corresponding of \overline{D}^0 and \overline{D}^0 to a CD significate $f = V^+ V^-$ states \overline{P}^+ standard to be \mathscr{O}^+ . $\frac{1}{2}$ \rightarrow $f, t)$ $\approx a_f^a$ *Y^f* ⇡ \overline{D}^0 to a \overline{D}^0 to a \overline{CD} constate $f = V^+V^-$ at \overline{F}^+ and \overline{F}^0 , to and \overline{D}^0 , \overline{F}^0 , \overline{F}^0 me asymmetry of D° and D° to a CP eigenvalue of P $\sum_{\alpha} \Gamma(D^0 \to f, t) - \Gamma(\overline{D}^0 \to f, t) \approx a^d + \Delta Y_t \frac{t}{\sqrt{D}}$ $\psi = \frac{\overline{\Gamma(D^0 \rightarrow f, t)} + \Gamma(\overline{D^0 \rightarrow f, t)}}{\sim}$

state *f* at time *t*. The dependence of the asymmetry on decay time is due to the oscillation and the slope measurement only 12 and 12 as the e $\frac{1}{2}$ shape measurement only

and *^y*12, defined as *^x*¹² ⌘ ²*|M*12*/[|]* and *^y*¹² ⌘ *[|]*12*/[|]* [22], where *^H* ⌘ *^M ⁱ*

 $\Delta Y_f \approx \approx$ $-$

² ⁺ *[|]A*¯*^f [|]*

• Lifetime asymmetry of D^0 and \overline{D}^0 to a *CP* eigenstate, $f = K^+K^-$, $\pi^+\pi^-$ expected to be $\mathcal{O}(10^{-5})$ ζ enstate, $j = K^*K^*$, $\pi^*\pi$ expected to be $\mathcal{O}(10^{-5})$

^f)*,* (16)

where \int \int $\text{slope measurement only}$ *t* τ_{D^0} $\begin{array}{cc} \cdot & \tau_D\circ \end{array}$ which has been used as alternative to $\frac{1}{2}$, $\frac{1}{2}$

is equal to unity for *D*⁰! *K*⇡⁺ decays. This method neglects the contributions to the

 $\hat{\Gamma}_{\text{D}0}$ $\hat{\Gamma}_{\text{D}0}$ $\hat{\Gamma}_{\text{D}0}$ $\Delta Y_f \approx -\frac{1}{\hat{n}} \frac{D^0 \rightarrow f}{\hat{n}} \frac{1}{\hat{n}}$ $\Gamma_{D^0\rightarrow f}+\Gamma_{\overline D^0\rightarrow f}$ $\ddot{}$ $\Gamma_{D^0 \rightarrow f}$ – ˆ $\frac{1}{D^0}$ $\sum_{i=1}^{n}$ $\ddot{}$ $D_{\rightarrow f} + 1$ ^{\cdot} $\gamma_f \approx -\frac{1}{\hat{\rho}} \frac{D^0 \rightarrow f}{\hat{\rho}}$ Γ $\hat{\Gamma}$ $D^0 \rightarrow f^ \Gamma$ $\hat{\Gamma}$ $\overline{D}{}^0 \rightarrow f$ Γ $\hat{\Gamma}$ $D^0 \rightarrow f$ + Γ $\hat{\Gamma}$ $\overline{D}{}^0 \rightarrow f$

⁼ *Y^f*

^f are measured to be approximately equal \overline{p} ˆ

*^D*0!*^f*

Asymmetry of the effective decay widths by and *Asymmetry* of the effective decay widths

*^D*0*/D*0!*^f* = 1 *c[±]*

a Using both $D^{*+} \to D^0 \pi^+$ (top) and $B^- \to D^0 \mu^- \nu$ self-tagging sources of D^0 decays, value of *ACP* is obtained

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

๏ *A*chieved using a difference method to cancel common systematics *pAf*

Observation of a direct *CP* violating effect in charm = *qAf*

5.3*σ* from zero

To be determined if KK or $\pi\pi$ or neither are consistent with zero

Malcolm John - University of Oxford

$$
\Delta A_{CP} \equiv A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-)
$$
\n
$$
\approx \Delta a_{CP}^{dir} + \frac{\Delta \langle t \rangle}{\tau_{D^0}} \Delta Y
$$
\ndominates\n
$$
\approx +3 \times 10^{-5}
$$
, with
\nearlier ΔY result

Other direct CPV searches with charm 8 Belle dataset (0.98 ab⁻¹) used to improve branching fractions and search for *CP* asymmetries ⁸²*Tokyo Metropolitan University, Tokyo 192-0397, Japan* ⁸³*Virginia Polytechnic Institute and State University, Blacksburg, VA 24061, U.S.A.* ⁸⁶*Yonsei University, Seoul 03722, South Korea* $D^0 \to \pi^+\pi^-\eta$ shown. ($Q \equiv \Delta m$) a
Belle: Phys. Rev. **B**OLICITIK tractions and search for CP asymmetrie *limit on its mesons,* With D^0 mesons,

Belle: [JHEP 2021, 75](https://link.springer.com/article/10.1007/JHEP09(2021)075) Belle: <u>[Phys. Rev. D 103, 112005](https://journals.aps.org/prd/abstract/10.1103/PhysRevD.103.112005)</u> P_{α} ll α , 111 \Box

 $D_s^+ \to \pi^+ \eta$ shown.

 $A_{CP}(D_s^+ \to \pi^+ \eta) = 0.002 \pm 0.003 \pm 0.003$. 223k events

 $A_{CP}(D^0 \to K^+K^-\eta) = [-1.4 \pm 3.3\,\text{(stat)} \pm 1.1\,\text{(syst)}]\%$, 1462 events $A_{CP}(D^0 \to \phi \eta) = [-1.9 \pm 4.4 \text{ (stat)} \pm 0.6 \text{ (syst)}]\%$. 728 events

The results for *^D*⁰ [→] *^π*+*π*−*^η* are a significant improvement over previous results. The branching fraction and *^ACP* results for *^D*⁰ [→] *^K*+*K*−*η*, and the *^ACP* result for *^D*⁰ [→] *φη*, These results are the most precise to date and representation \mathbf{r}_i significant improvement in precision over current world-

Malcolm John - University of Oxford

and the DCS modes *D*⁺ ! *K*⁺⇡⁰ and *D*⁺ ! *K*⁺⌘ receive contributions from only one *^W*⁺ ¯ *^W*⁺ ¯

is expected to be zero as a result of isospin constraints [3–6]. The *CP* asymmetries of the

CPV search with $D^+ \to \pi^+\pi^0$ CDV coard with D^+ $\rightarrow \pi^+ \pi^0$ CPV search with $+$ $+$ 0 *v dearch with* ⇡0 *,* ⌘ **V** coarch wit ⇡0 *,* ⌘ **c** ¯ *d, s*¯ *d, s* ¯ *d, s*¯ *PV* search with *I* (a) Colour-Supplement et de la distribution de la d $\rightarrow \pi^{2}$ L V DUCILUIL VVIUL $\longrightarrow \pi^* \pi$

(b) Chanch gulg Teconotraction for Brick. Then, and not $\sqrt{6}$ **Property u** ⇡0 *,* ⌘ **c** \overline{C} ⇡0 *,* ⌘ retrustion for LHCh Trick ⇡+*, K*⁺ ¯ *d, s*¯ very chanenging reconstruction *v* very chanenging reconstruct

[JHEP 06 \(2021\) 019](https://cds.cern.ch/record/2758622) *c d, s* Pelle: Dhys Rey D.07, 011101 LHCb:

le: 6.6k events (0.92 \cdot 6.6k events (0.92 a (*D*⁺ (*s*)! *h*⁺*h*⁰) + (*D* (*s*)! *hh*⁰) \bullet LHCb 26k events ($6fb^{-1}$) \bullet Belle: 6.6k events (0.92 ab⁻¹)

⇡+*, K*⁺

¯ *d, s*¯ Belle: [Phys. Rev. D 97, 011101 \(2018\)](https://arxiv.org/ct?url=https://dx.doi.org/10.1103/PhysRevD.97.011101&v=ecdbe888)

- Final state should symmetric in flavour.
- So must be a $I = 2$ as $I_3 = 1$.
- **a** Thus $\Delta I = \frac{3}{2}$. ($\Delta I = \frac{1}{2}$ in W^+ exchange) 3 $\frac{3}{2}$. ($\Delta I =$ $\frac{1}{2}$ in W^+
- *c* so socond discrem forhid. de set of CNW factors continue *d, s*¯ \overline{C} So one set of CKM factors contributes *c u c u u c u u u u u u u* $\Delta I = 1$ in gluon line would be a flavour *u*¯ change, so second diagram forbidden. ๏ So one set of CKM factors contributes.
- $l\hat{c}$ • Thus: zero *CP* violation.

h Cluding conversions $f(b)$. Trick: use $\pi^{\circ} \rightarrow$ $\frac{1}{2}$ $HCb.$ Irick: use π° ¯ *d, s*¯ e^+e^- (d) Penguin diagram 1 (d) Penguin diagram 1 **•** Very challenging reconstruction for LHCb. Trick: use π ⁰ → *γe*⁺*e*[−], including conversions

مسة 19 − Lepton/Photon, January 2022
يجمع السياسية 19 Depton/Photon, January 2022 $\frac{1}{\sqrt{d}}$ Malcolm John - University of Oxford 19

Down samples. The *CP* asymmetry for the decay *B*⁺ ! (*J/* ! *µ*⁺*µ*)*K*⁺ is taken to be

- $I_{K\pi} = A_{K^{+}\pi^{-}} + A_{K^{0}\pi}$ $+$ $\mathcal{B}(K^0\pi^+)$ $\mathcal{B}(K^+\pi^-)$ τ_{B^0} τB^+ $R(K^{0}\pi^{+})$ τ_{-0} $R(K^{+}\pi^{0})$ τ $I_{K\pi} = A_{K^+\pi^-} + A_{K^0\pi^+} \frac{\Sigma (11.6)}{R(K^+\pi^-)} \frac{\Sigma B^2}{\tau} - 2A_{K^+\pi^0} \frac{\Sigma (11.66)}{R(K^+\pi^-)} \frac{\Sigma (11.66)}{\tau}$ anding puzz with the time-integrated mixing parameter *^d* set to its known value *^d* = 0*.*1858 *±* $\mathbf{I} \mathbf{I} = \mathbf{A}$ decays to be flavor symmetry symmetry symmetry symmetry. $r_{K\pi}$ $\mathcal{L}_{K^+\pi}$ $\mathbf{r} \cdot \mathbf{r}$ $\mathcal{B}(K^{\circ}\pi^{\perp})$ $\tau_{\mathcal{D}}$ I_{max} in a systematic uncertainties are associated by variable by variable by variable by varying the parameters from B $K\pi$ \sim $K^{\pi}\pi$ \sim $K^{\sigma}\pi$ \approx $K^{\sigma}\pi$ $\mathcal{D}(\Lambda \pi)^T$ signal-to-background fractions constrained by the yield fit of S . The signal probability of S signal probability \mathcal{S}
	- $\mathcal{C}^{\text{max}}_{\text{max}}$ \pm $Y + 0$ $0.005 + 0.015 + 0.000 + 0.000$ $\overline{16}$ and the literature of the literature of the literature and **B**₂₅₀₀ ๏ LHCb now provide new information with 16.7k events. \bullet $A_{CP}(B^+ \to K^+\pi^0) = 0.025 \pm 0.015 \pm 0.006 \pm 0.003$ 10 \overline{a} M $^{\prime}$ **L** \cup $^{\prime}$ L'b n (*x provide new inform* n ation with $A_{CP}(B^+ \to K^+\pi^0) = 0.025 \pm 0.015 \pm 0.006$ 0*.*0011 [10]. We assume the background from charmless *B* decays to be flavor symmet-
	- **external inputs, external inputs, external inputs, and the precision of** $A_{K^0\pi^0}$ **by Belle II** *b* $\frac{0.4500 5000}{4500 5000}$ 5.24 5.25 5.26 5.27 5.28 5.29 5.3] 2 [GeV/*c M*bc rct moscuramont <u>L</u>_{Lι} First measurement of A_{res} a by Bell

ing fraction measurement, we test the analysis on the analysis on the data subset used in ℓ , corresponding ℓ $I. enton/Photon. I an uaru 2022$ asymmetry is found to be 0*.*009 *±* 0*.*002 for Magnet Up, and 0*.*012 *±* 0*.*002 for Magnet

K

e II predict $\sigma (A_{K^0\pi^0})$ reach 0.025 with 50 ab⁻¹ $\left[\begin{array}{c} \sim & -0.3 \\ \sim & -0.40 \pm 0.45 \end{array} \right]$ a⁻ 0*.*4 FIG. 3. Flavor-specific (*M*bc, *E*) projections on 2019-2020 Belle II data. The top panel shows δ *Belle II predict* σ *(A_{v0})* where *^B*tag is tagged as a *^B*⁰ (signal-side: *^B*⁰). The distribution and fit are integrated over *r*-bin $\overline{\Omega}$ 2 *c* tags ⁰ Data, *B* \blacksquare $\left| \begin{array}{c} \cdot \\ \cdot \end{array} \right|$ *Belle II* (preliminary) \prod predict O $(A_{K^0\pi^0})$ it $\mathbf r$ \cdot \cdot 1 $V\Gamma$ $\sqrt{11}$ $\overline{1}$ $\overline{0}$ $\overline{0}$ **ICIT O.** \circ Belle II predict σ ($A_{K^0\pi^0}$) reach 0.025 with 50 ab⁻¹

ress likely to be dominated by Belle II 0*.*2 ֦֧֦֧֦֧֦֧ׅ֦֘֘֘֝֘֘֘֘֘֝֘֝֘֘֘֘֘֜֘֘ . **** Candidates per 3 MeV/ 4 Progress likely to be dominated by Belle II

2

Lepton/Photon, January 2022

Unitarity triangle, *β*, *γ*

 $\overline{}$

ubVud

and Decompositions and QCD calculations *cbVcd* of semileptonic $b \to u$ decays and

$$
\begin{pmatrix}\nV_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}\n\end{pmatrix} = \begin{pmatrix}\n1 - \lambda^2/2 - \lambda^4/8 \\
-\lambda \\
A\lambda^3(1 - \rho - i\eta) & -A\lambda^2\n\end{pmatrix}
$$

$\mathcal{A}_{[c\overline{c}]K^0_{\mathrm{S}}}(t)\equiv$ \overline{z} $-C$ co $\mathcal{A}_{[c\overline{c}]}K^0_S(\iota) =$ =

where in the equation the symbols are as follows: $\frac{1}{\sqrt{2}}$ is the proper decay time; $\frac{1}{\sqrt{2}}$ is the mean of $\frac{1}{\sqrt{2}}$ is the m

Malcolm John - University of Oxford Lepton/Photon, January 2022 combined fracture controller tagging decision of α

sin 2*β* : world average

 $\phi_s = -2\beta_s$: the *CP*-violating phase of B_s^0 mixing *s* **•** β_s is analogous to β but is much smaller in the SM due to smallness of the complex phase in V_{ts} **a** LHCb/ATLAS/CMS use time-dependent analysis of $B_s \to J/\psi (K^+K^-)$ _φ (LHCb also $B_s \to J/\psi \pi^+ \pi^-$)

^a $m(K^+K^-) > 1.05$ GeV/ c^2 . ^b Run 2.

0

HFLAV: *ϕs* = − 0.050 ± 0.019

 $SM: -2\beta_s = -0.037 \pm 0.001$

Malcolm John - University of Oxford Lepton/Photon, January 2022

 χ) \propto $(r_D^f)^2 + (r_B^X)^2 + 2r_D^fr_B^X \cos(\delta_B^X + \delta_D^f \mp \gamma)$

Unitarity angle *γ* : ADS/GLW diagram. This means mixing is not needed and we can look for direct *CP* violation. Charged *B*[±] ! *DK*[±] decays do not

mix and the CP-violating phase in tree-level $b \to u \oplus b \to c^{-1}$ • The CP-violating phase in <u>tree-level</u> $b \to u \oplus b \to c$ transitions is γ . Negligible penguin/theory error several signal and background components in the same region of *Dh* invariant mass must $\rightarrow u \oplus v \rightarrow c$

24

• Gives rise to large, direct asymmetries $\Gamma(B^{\pm} \to [[f]_D h^{\mp}]_X) \propto$ (

 i **sance parameters**, r_p , δ_p , δ_p , r_p ↵*x*(1 (*r^X B*) 2)*r^K*⇡ *^D* sin *^K*⇡ *^D* ⁺ ↵*x*(1 (*r^K*⇡ • *γ* not measured directly, but must be inferred along with other nuisance parameters, r_B , δ_B , δ_D , r_D

Figure 2: Dalitz plot for *^D* decays of (left) *^B*⁺ ! *DK*⁺ and (right) *^B* ! *DK* candidates

Unitarity angle γ : $K_S^0 h^+ h^$ t arity angle $\gamma \cdot K_n h'$ fractional yield of pure *D*⁰ decays in bin *i* in the presence of this eciency profile is

denoted *Fi*, given by

and reconstruction e α non-uniform equation equation equation equation equation equation ℓ space, denoted by

2

 $\frac{1}{2}$

yDK

2

Malcolm John - University of Oxford Lepton/Photon, January 2022 or (*rDK ^B*)² *xDK* $=$ $\frac{1}{2}$ Malcolm John - University of Oxford 26

LHCb: <u>[JHEP 02 \(2021\) 169](https://cds.cern.ch/record/2742273)</u> BESIII: [Phys. Rev. D101 \(2020\) 112002](https://journals.aps.org/prd/abstract/10.1103/PhysRevD.101.112002)

• Recent work at BESIII (\bullet) has ensured c_i , s_i systematics remain 'small' for LHCb throughout 2020s

. A single value of *rDK*

$$
N_{+i}^{+} = h_{B^{+}} \left[F_{-i} + \left(\left(x_{+}^{DK} \right)^{2} + \left(y_{+}^{DK} \right)^{2} \right) F_{+i} + 2\sqrt{F_{i}F_{-i}} \left(x_{+}^{2} \right) F_{-i} + 2\sqrt{F_{i}F_{-i}} \left(x_{+}^{2} \right) F_{-
$$

Lepton/Photon, January 2022 $Lepton/I$ ◦ *,*

$$
x_{\pm}^{DK} \equiv r_B^{DK} \cos(\delta_B^{DK} \pm \gamma)
$$
 and
$$
y_{\pm}^{DK} \equiv r_B^{DK} s
$$

Malcolm John - University of Oxford Lepton/Photon, January 2022 $\frac{1}{2}$ rd

Figure 2: Dalitz plot for *^D* decays of (left) *^B*⁺ ! *DK*⁺ and (right) *^B* ! *DK* candidates

Lepton/Photon, January 2022 Figure 5: Confidence levels at 68.2 % and 95.5 % probability for (left, blue) (*xDK[±]* $Lepton/I$ ◦ *,*

Unitarity angle *γ* extracted in combination

• All $B \to DX$ results are combined with time-dependent charm results.

Malcolm John - University of Oxford

*B*⁰

 $\mathcal{A}(\mathcal{A})$, $\mathcal{A}(\mathcal{A})$ classics $\mathcal{A}(\mathcal{A})$ classics $\mathcal{A}(\mathcal{A})$ classics $\mathcal{A}(\mathcal{A})$ classics $\mathcal{A}(\mathcal{A})$

 $(0.3.6 \pm 2.2)$ CKMfitter expectation UTFit expectation $(65.7 \frac{+0.9}{-2.7})$ ∘ (65.8 ± 2.2) ∘

 $x = (0.400 \frac{+0.052}{-0.053})\%$ $y = (0.630 \frac{+0.033}{-0.030})\%$

$$
\gamma = (65.4^{+3.8}_{-4.2})
$$

CP violation and mixing in charm and beauty hadrons *Conclusion*

30th International Symposium on Lepton Photon Interactions at High Energies. Manchester, 10-14 January 2022

LS LOWRY, Peel Park, Salford (1944)

- ๏ LHCb is delivering a wealth of measurements on heavy-flavour *CP* violation and mixing
- ๏ All major results are compatible with the SM expectation
- ๏ But the search goes on. LHCb upgrade will provide a factor 5-10 more statistics
- And BelleII aims to improve B-factory statistics by a factor ~50
- ๏ No time to be playing football in the park.