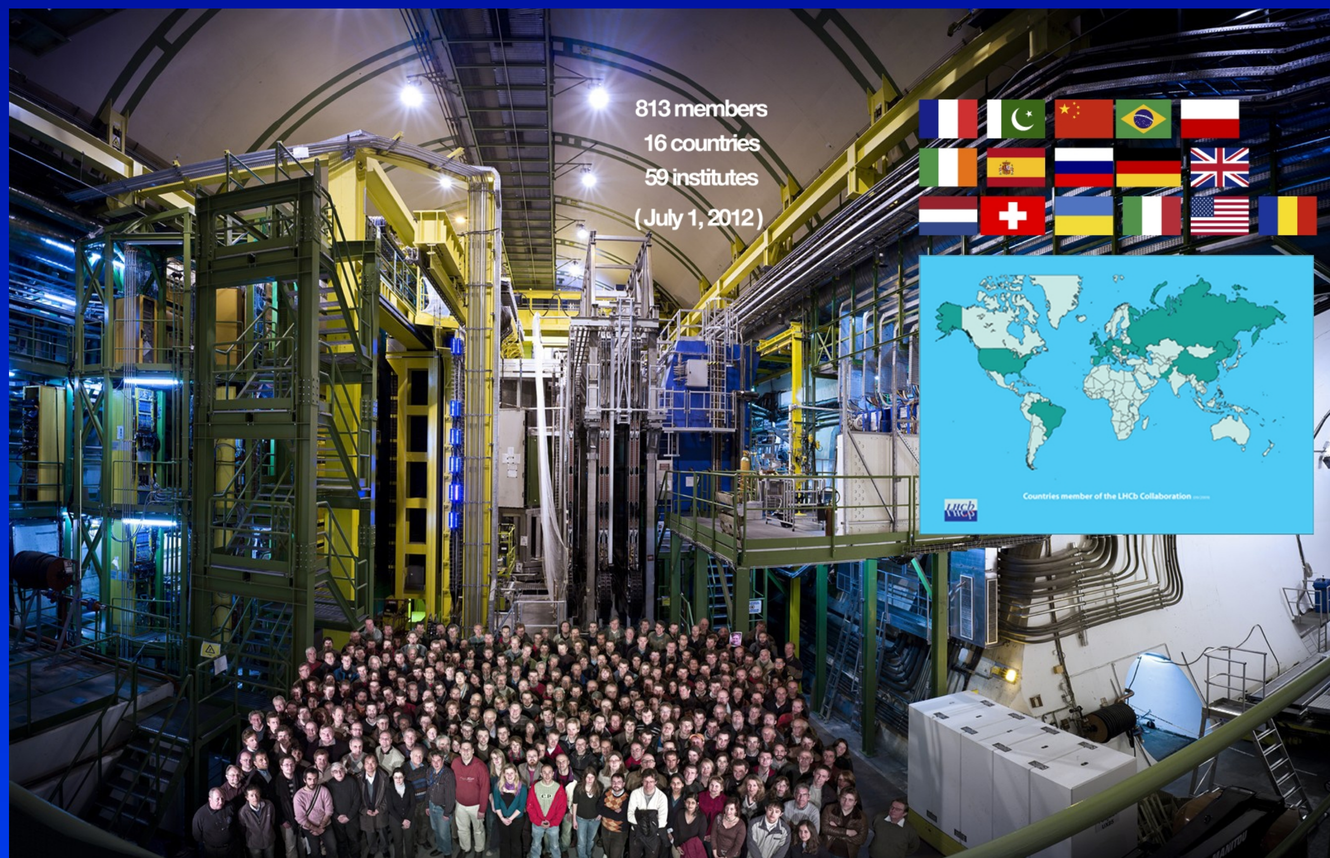
Physics in Collision 2019, Taipei

September 17th, 2019

Mixing and CP Violation in Charm Decays

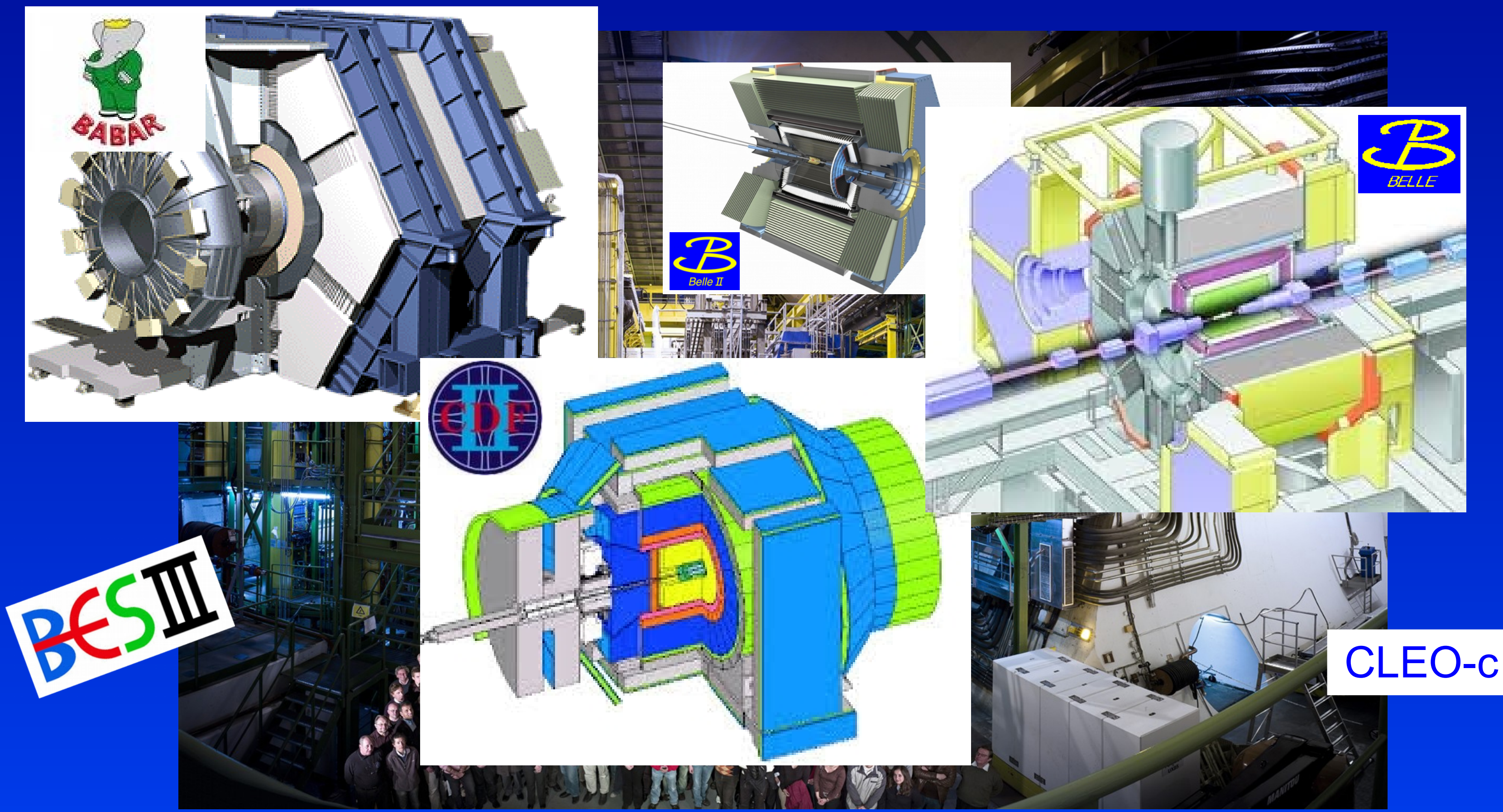


Jörg Marks, Heidelberg University
on behalf of the LHCb collaboration

Physics in Collision 2019, Taipei

September 17th, 2019

Mixing and CP Violation in Charm Decays



Jörg Marks, Heidelberg University
on behalf of the LHCb collaboration

Introduction

Photo: Sandbox Studio

- Search for evidence of physics beyond the Standard Model in CP violation and rare decays of charm and beauty hadrons
  - Indirect search, probe large mass scales via the study of virtual quantum loops of new particles
- Charm sector
  - SM predicts small effects in mixing and CP violation due to suppression by GIM mechanism (d,s) and CKM matrix (b)

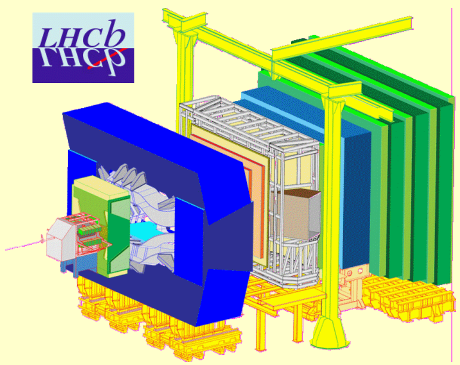
    → deviations can be attributed to new physics
  - Complement K and B systems, access to new physics coupling to up-type sector
  - Calculations are difficult due to the intermediate mass range

    → need for high precision measurements
- Survey of recent results in D mixing and CP violation

Charm Physics – Contributors

B physics experiments are well suited for charm physics

hadron collider



LHCb at LHC

$\int_{run1} \mathcal{L} \approx 3 fb^{-1}$ $\quad 3.6 \cdot 10^{12}\ c\bar{c}$

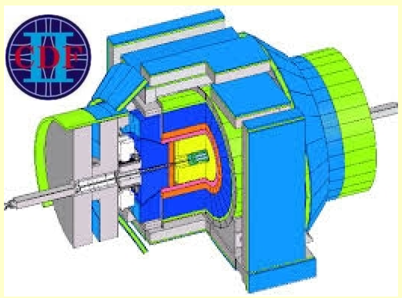
$\int_{run2} \mathcal{L} \approx 5.5 fb^{-1}$ $\quad 9.6 \cdot 10^{12}\ c\bar{c}$

world's largest c sample

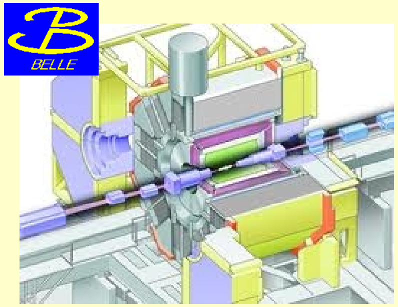
CDF at TEVATRON

$\int \mathcal{L} \approx 9.6 fb^{-1}$

$2.3 \cdot 10^{11}\ c\bar{c}$



e^+e^- collider



Belle at KEKB

$\int \mathcal{L} \approx 1 ab^{-1}$

$1.3 \cdot 10^{9}\ c\bar{c}$

Belle II

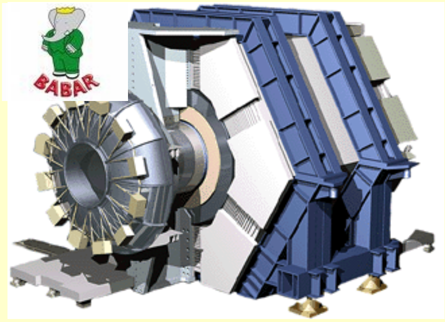
$\int \mathcal{L} \approx 6.5 fb^{-1}$

$8.5 \cdot 10^{6}\ c\bar{c}$

BABAR at PEPII

$\int \mathcal{L} \approx 550 fb^{-1}$

$7 \cdot 10^{8}\ c\bar{c}$

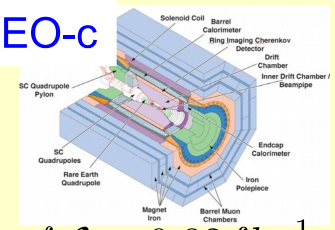


Charm Facilities

$\psi(3770)$

$\int \mathcal{L} \approx 2.9 fb^{-1}$

CLEO-c



$\int \mathcal{L} \approx 0.82 fb^{-1}$

BESIII		CLEO-c
$10.6 \cdot 10^{6}$	$D^0/\bar{D}^0$	$3.0 \cdot 10^{6}$
$8.4 \cdot 10^{6}$	D^+/D^-	$2.4 \cdot 10^{6}$

Charm Physics – Contributors

B physics experiments are well suited for charm physics

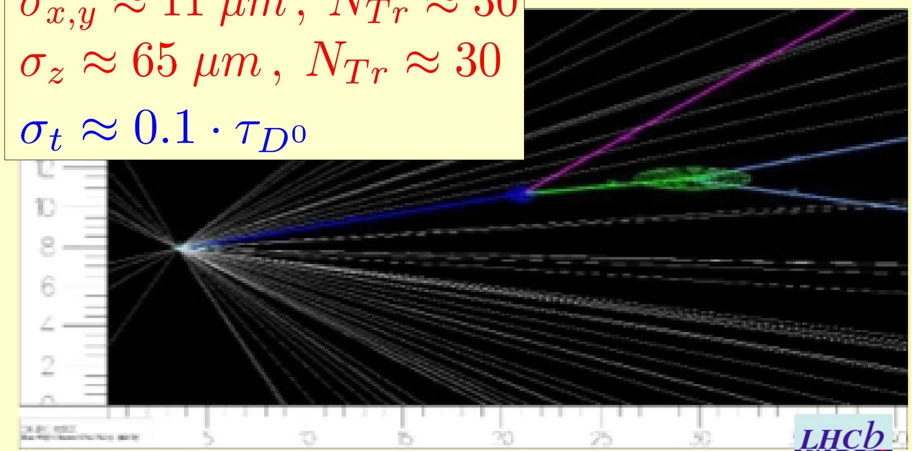
hadron collider

PV resolution

$\sigma_{x,y} \approx 11\ \mu m\,,\ N_{Tr} \approx 30$

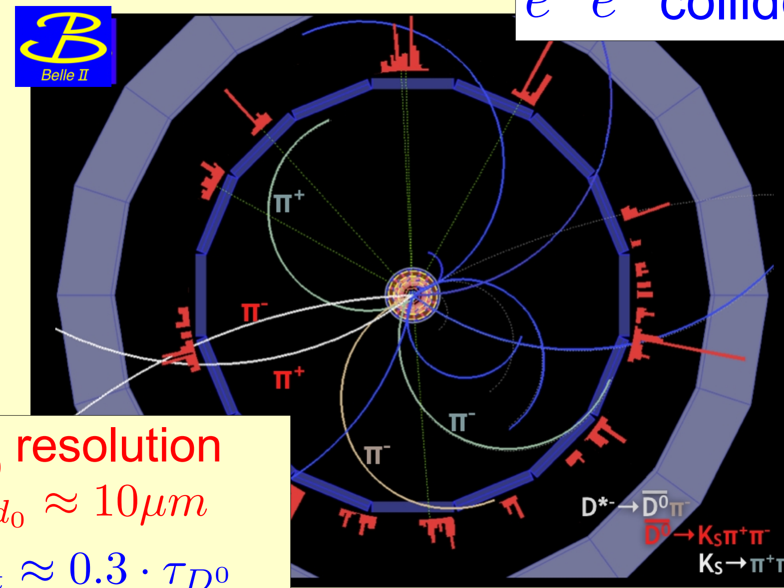
$\sigma_z \approx 65\ \mu m\,,\ N_{Tr} \approx 30$

$\sigma_t \approx 0.1 \cdot \tau_{D^0}$



$\sim 1\ MHz\ c\bar{c}$ pairs

e^+e^- collider



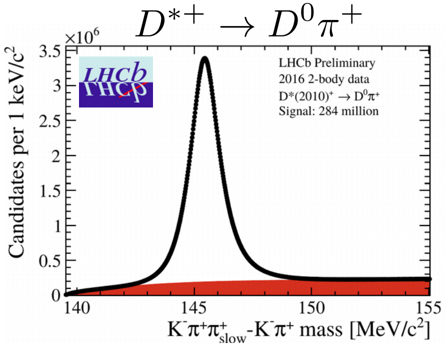
d0 resolution

$\sigma_{d_0} \approx 10\mu m$

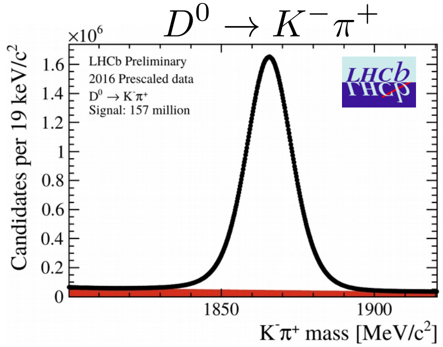
$\sigma_t \approx 0.3 \cdot \tau_{D^0}$

triggered, selected, reconstructed online

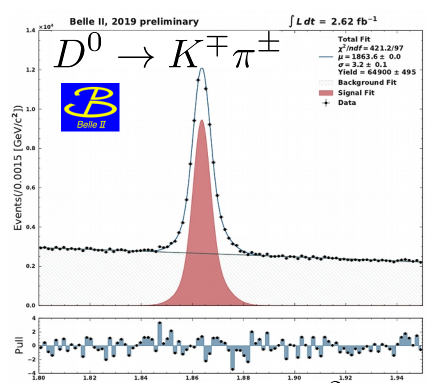
$D^{*+} \to D^0\pi^+$



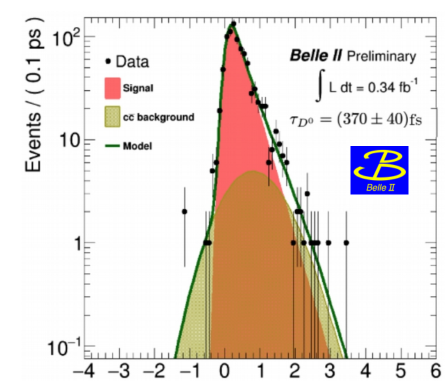
$D^0 \to K^-\pi^+$



$D^0 \to K^\mp\pi^\pm$



$m_{D^0}(GeV/c^2)$

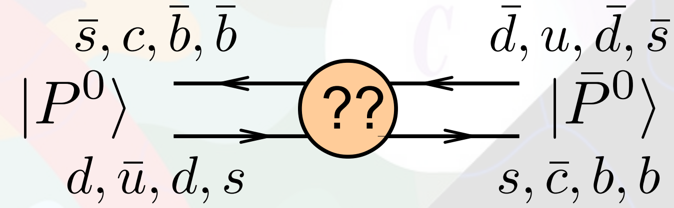


$t_{D^0}(ps)$

BELLE2-TALK-CONF-2019-101

Mixing in Neutral Mesons

Neutral mesons (K, D, B, B_s) are created as flavour eigenstates of the strong interaction. They can mix through weak interactions.



- The time evolution is obtained by

$$i\frac{\partial}{\partial t}\begin{pmatrix} P^0(t) \\ \bar{P}^0(t) \end{pmatrix} = \left[\begin{pmatrix} M_{11} & M_{12} \\ M_{12}^* & M_{22} \end{pmatrix} - \frac{i}{2}\begin{pmatrix} \Gamma_{11} & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma_{22} \end{pmatrix}\right]\begin{pmatrix} P^0(t) \\ \bar{P}^0(t) \end{pmatrix}$$

- The physical eigenstates are P_L and P_H:

$$|P_{L,H}\rangle = p|P^0\rangle \mp q|\bar{P}^0\rangle$$

$$|P_{L,H}(t)\rangle = e^{-i(m_{L,H} - i\Gamma_{L,H}/2)t}|P_{L,H}(t=0)\rangle$$

- Define mass and lifetime differences of P_L and P_H:

$$\boxed{x = \frac{\Delta m}{\Gamma} = \frac{m_H - m_L}{\Gamma} \qquad y = \frac{\Delta\Gamma}{2\Gamma} = \frac{\Gamma_H - \Gamma_L}{2\Gamma}} \qquad \Gamma = \frac{\Gamma_L + \Gamma_H}{2}$$

Charm Physics – CP Violation

Modified: Photo by Reidar Hahn, Fermilab with Sandbox Studio, Chicago

The CKM phase is the only source of SM CPV in the quark sector

- CPV is well established in Kaon and B meson systems
- In spring 2019 LHCb discovered direct CPV in charm decays
- CP violation measurements
  - needs 2 interfering amplitudes with strong δ and weak ϕ phase
  - CP violation in decay (direct CPV)

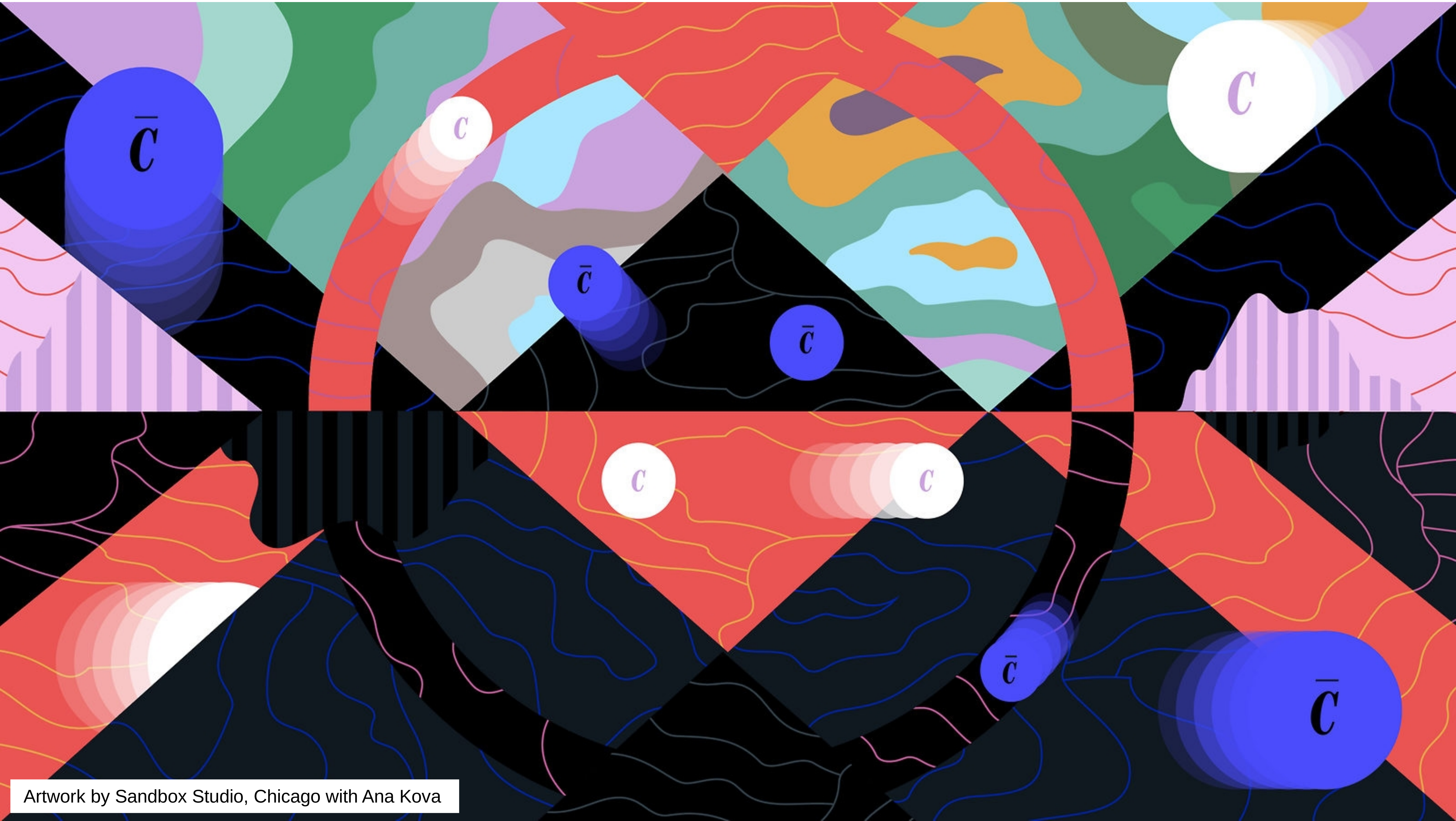
    $\Gamma(P \to f) \neq \Gamma(\bar{P} \to \bar{f}) \qquad |\mathcal{A}_f| \neq |\bar{\mathcal{A}}_{\bar{f}}|$
  - CP violation in mixing (indirect CPV)

    $|q/p| \neq 1$
  - CP violation in interence of mixing and decay (indirect CPV)

    $arg(\lambda_f) \neq arg(\lambda_{\bar{f}})\ , \quad \lambda_f \equiv q\bar{\mathcal{A}}_f/p\mathcal{A}_f$
  - CP violating effects are predicted to be small $(\sim 10^{-3} - 10^{-4})$

Selected results

D^0 Mixing and indirect CP Violation



Artwork by Sandbox Studio, Chicago with Ana Kova

Mixing in $D^0 \to K\pi$ Decays

- Flavour tagging at production and decay

$D^{*+} \to \pi_s^+ D^0$

$\bar{B} \to X \mu^- D^0$

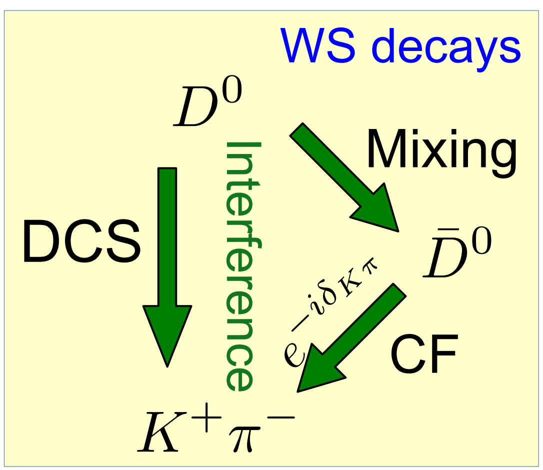
No Mixing: $D^0 \to \pi^+ K^-$ — right sign decay (RS), no D^0 Mixing

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

Mixing: $\bar{D}^0 \to \pi^- K^+$

wrong sign decay (WS): D^0 Mixing + DCS

- Time evolution of the WS decay rate determines mixing parameters



- assume CP conservation and $|x| \ll 1$; $|y| \ll 1$

$$R_{WS}(t) \propto e^{-\Gamma t} \left(\underbrace{R_D}_{\text{DCS}} + \underbrace{\sqrt{R_D}\, y'\, \Gamma t}_{\text{Interference}} + \underbrace{\frac{x'^2 + y'^2}{4} (\Gamma t)^2}_{\text{Mixing}} \right)$$

up to a strong phase difference between CF and DCS decays

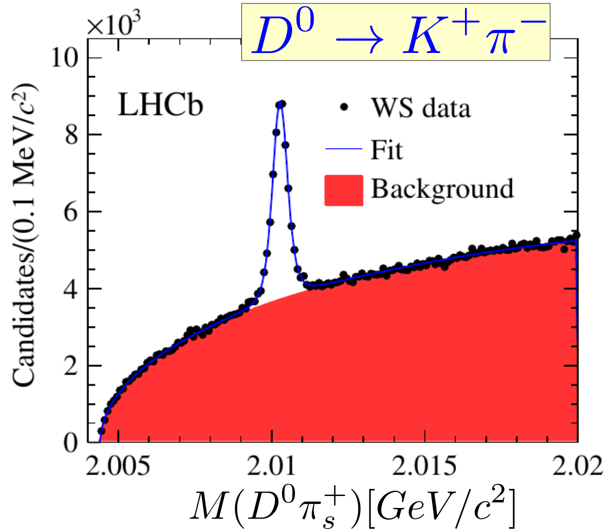
$$x' = \quad x \cos\delta_{K\pi} + y \sin\delta_{K\pi}$$
$$y' = -x \sin\delta_{K\pi} + y \cos\delta_{K\pi}$$

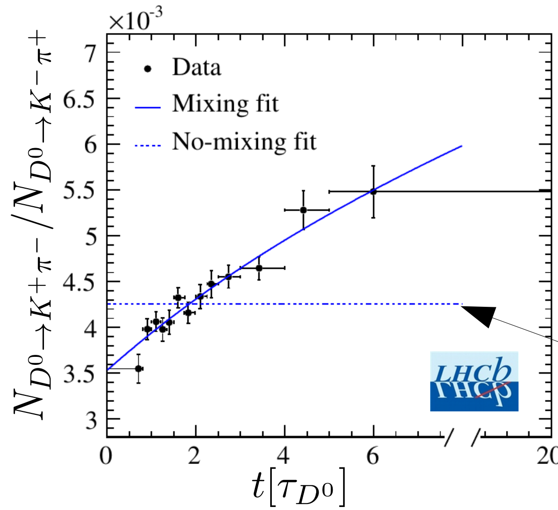
$$y'^2 + x'^2 = x^2 + y^2$$

Mixing in $D^0 \to K\pi$ Decays

- D^0 mixing was discovered in 2013 by LHCb in $D^0 \to K^+\pi^-$ decays
  - Established earlier by combining many B factory results

PRL 110 (2013) 101802





$\mathcal{L}_{int} = 1.0\, fb^{-1}$

$N_{WS} = 3.6 \cdot 10^4$

$N_{RS} = 8.4 \cdot 10^6$

no mixing excluded at $9.1\ \sigma$

- D^0 mixing parameters measured in a decay t-dependent fit to $\dfrac{N_{D^0\to K^+\pi^-}}{N_{D^0\to K^-\pi^+}}$

y' [%]	x'^{2} [10^{-3}]	
0.53 ± 0.052	0.039 ± 0.027	PRD 97 (2018) 031101
0.48 ± 0.10	0.055 ± 0.049	PRL 111 (2013) 251801
043 ± 0.43	0.08 ± 0.18	PRL 111 (2013) 231802
0.72 ± 0.24	-0.09 ± 0.13	PRL 110 (2013) 101802
0.85 ± 0.76	-0.12 ± 0.35	PRL 100 (2008) 121802

y' [%]	x'^{2} [10^{-3}]	
0.46 ± 0.34	0.09 ± 0.22	PRL 112 (2014) 111801
$0.97 \pm 0.44 \pm 0.31$	$-0.22 \pm 0.30 \pm 0.21$	PRL 98 (2007) 111802
$-2.8 <$ y' < 2.1	< 0.72 (95% C.L.)	PRL 96 (2006) 151801

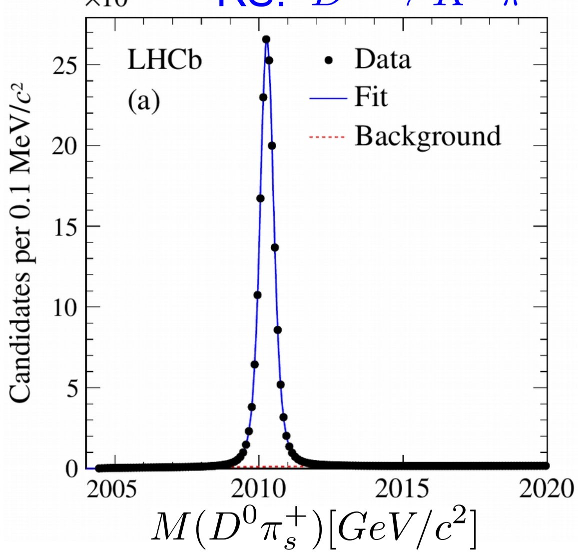
CP Violation in $D^0 \to K\pi$ Decays

PRD 97 (2018) 031101

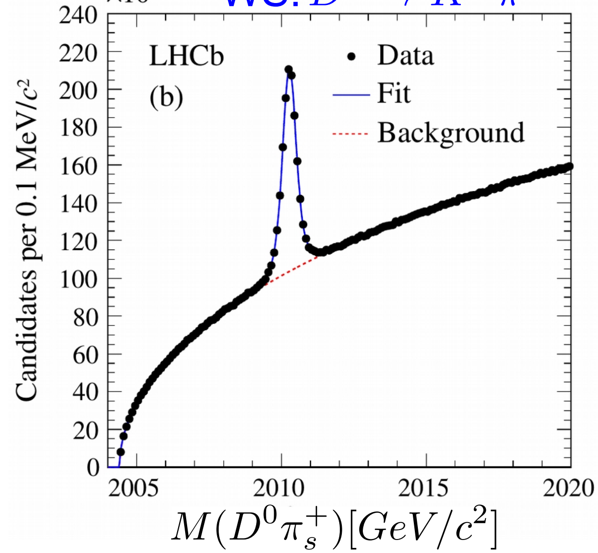
- CP violating mixing parameters in $D^0 - \bar{D}^0$ oscillation based on the t-dependent WS to RS ratio $R^{\pm}(t)$ of tagged D^0 and $\bar{D}^0 \to K\pi$ decays

PRD 97 (2018) 031101

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



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



data of 2011 – 2016

$\mathcal{L}_{int} = 5.0\, fb^{-1}$

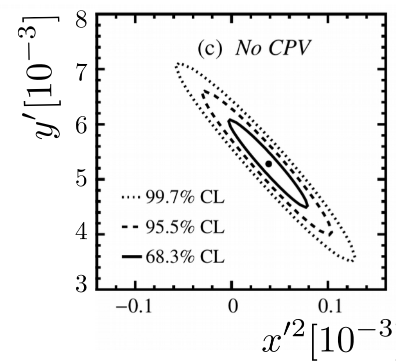
$N_{WS} = 7.22 \cdot 10^5$

$N_{RS} = 1.77 \cdot 10^8$

- Mixing parameters using CP conservation hypothesis

$$y' = (0.528 \pm 0.052) \cdot 10^{-2}$$
$$x'^2 = (0.39 \pm 0.27) \cdot 10^{-4}$$
$$R_D = (3.454 \pm 0.031) \cdot 10^{-3}$$

- Superseds previous LHCb measurements
- $x'^2 = 0$ within 1σ



CP Violation in $D^0 \to K\pi$ Decays

LHCb PRD 97 (2018) 031101

- CP violating mixing parameters in $D^0 - \bar{D}^0$ oscillation based on the t-dependent WS to RS ratio $R^{\pm}(t)$ of tagged D^0 and $\bar{D}^0 \to K\pi$ decays

$$R^{\pm}(t) = R_D^{\pm} + \sqrt{R_D^{\pm}}\, y'^{\pm}\,\Gamma t + \frac{(x'^{\pm})^2 + (y'^{\pm})^2}{4}(\Gamma t)^2$$

- Results
  - CPV in mixing

$$1.00 < |q/p| < 1.35 \;\; @\, 68.3\,\%\, CL$$

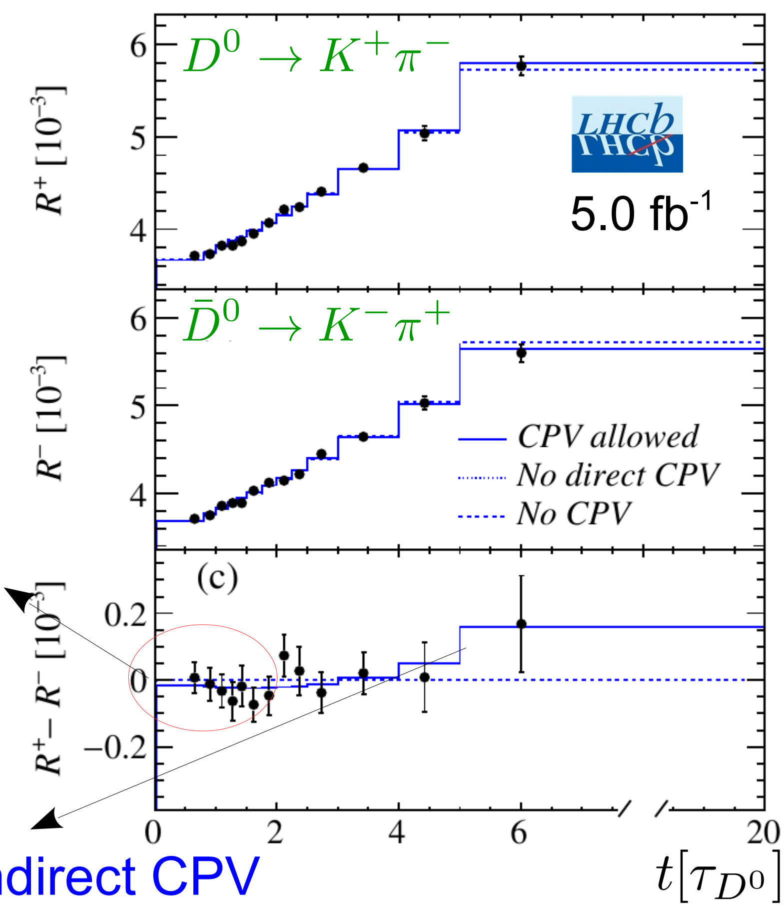
  - Direct CPV

$$A_D = \frac{R_D^+ - R_D^-}{R_D^+ + R_D^-} = (-0.1 \pm 9.1)\cdot 10^{-3}$$

$\neq 0 \to$ direct CPV

No indication for direct or indirect CPV

  - Ongoing analysis with all LHCb data



$\neq 0 \to$ indirect CPV

$\delta_{K\pi}$ Measurement in $\psi(3770) \to D^0\bar{D}^0$

BESIII PLB 734 (2014) 227

Using quantum correlated $D^0\bar{D}^0$ pairs in e^+e^- collisions at $\sqrt{S} = 3.773\,GeV$ the asymmetry in CP-odd and CP-even $D^0 \to K\pi$ decay rates allows to determine the strong phase difference $\delta_{K\pi}$ between the CF and DCS mode.

$$\bar{D}_{CP+} \longleftarrow \overset{\psi(3770)}{\star} \longrightarrow D_{CP-}$$

- Use various CP tagging decay modes to obtain

$$\mathcal{A}^{CP}_{K\pi} = \frac{\mathcal{B}^{CP-}_{D\to K^-\pi^+} - \mathcal{B}^{CP+}_{D\to K^-\pi^+}}{\mathcal{B}^{CP-}_{D\to K^-\pi^+} + \mathcal{B}^{CP-}_{D\to K^-\pi^+}} = (12.7 \pm 1.3 \pm 0.7) \cdot 10^{-2}$$

to derive with external measurements from the most precise $\delta_{K\pi}$ to date ($\mathcal{L}_{int} \approx 2.92\ fb^{-1}$)

$$2\underbrace{r}_{\frac{\langle K^+\pi^-|D^0\rangle}{\langle K^+\pi^-|\bar{D}^0\rangle}} cos(\delta_{K\pi}) + y = (1 + \underbrace{R_{WS}}_{\frac{N(D^0\to K^+\pi^-)}{N(D^0\to K^-\pi^+)}}) \cdot \mathcal{A}^{CP}_{K\pi}$$

$$\boxed{cos(\delta_{K\pi}) = 1.02 \pm 0.11 \pm 0.06 \pm 0.01}$$

BESIII Phys. Lett. B 734 (2014) 227

- Compare to results by CLEO-c ($\mathcal{L}_{int} \approx 818\ pb^{-1}$) using external input

$$\boxed{cos(\delta_{K\pi}) = 1.15^{+0.19+0.00}_{-0.17-0.08}}$$

CLEO-c Phys. Rev. D 86 (2012) 112001

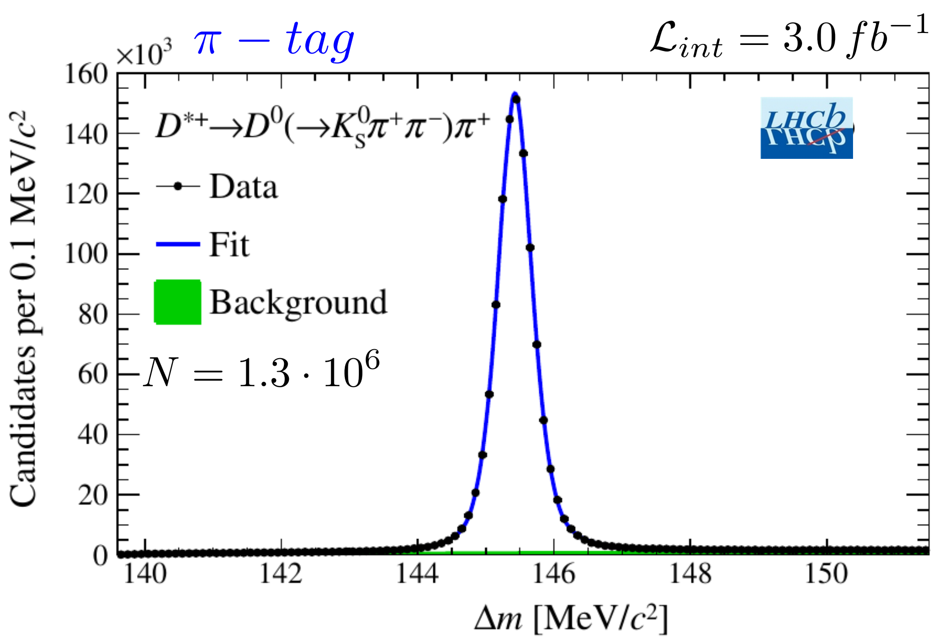
$\to$ Important contribution to the charm mixing and CKM angle γ measurements

LHCb - Mass Difference Measurement

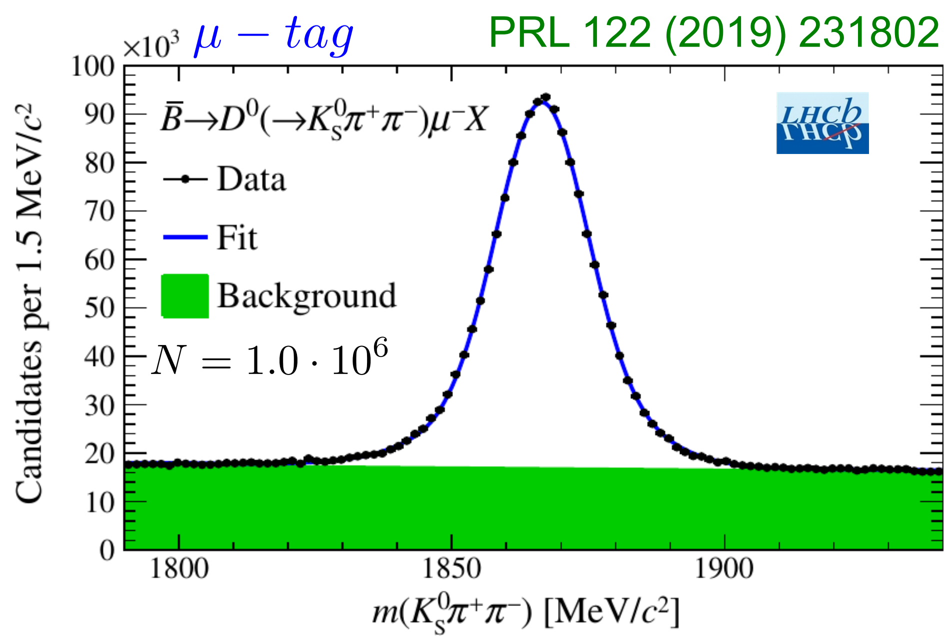
PRL 122 (2019) 231802

LHCb applied a novel, model independent approach of time dependent Dalitz analysis to $D^0 \to K_s^0\pi^+\pi^-$ decays to measure the mass difference between the neutral D^0 meson mass eigenstates and indirect CP violation

- CLEO pioneered method of t-dependent amplitude analyses PRD 72 (2005) 012001
- Run 1 prompt (π-tagged) and semileptonic (μ-tagged) data



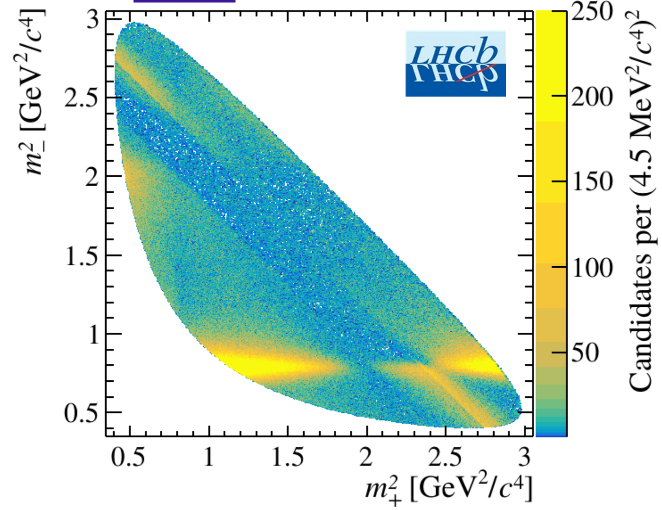
PRL 122 (2019) 231802



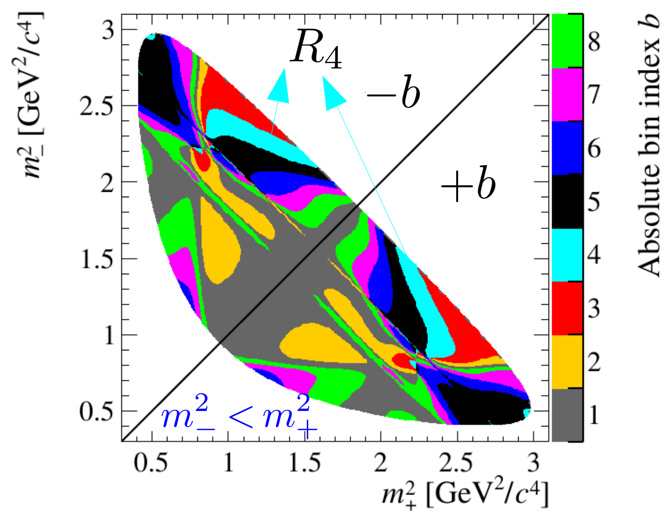
LHCb - Mass Difference Measurement

PRL 122 (2019) 231802

- ➢ "bin-flip" method PRD 99 (2019) 012007
  - Partion data in D^0 decay time and Dalitz plot regions symmetric to the bisector line
  - Measure the ratio of the decay yields R_b in corresponding bins b and in decay time bins
  - R_b depends on
    - mixing and CPV parameters
    - known hadronic decay parameters determined in external CLEO measurements PRD 82 (2010) 112006
  - Small strong phase variation across each bin
  - Perform a fit which compares the decay time evolution of signal yields in the Dalitz plot bins -b and +b



$$m_\pm^2 \equiv \begin{cases} m^2(K_s^0\pi^\pm) \text{ for } D^0 \to K_s^0\pi^+\pi^- \\ m^2(K_s^0\pi^\mp) \text{ for } \bar{D}^0 \to K_s^0\pi^+\pi^- \end{cases}$$

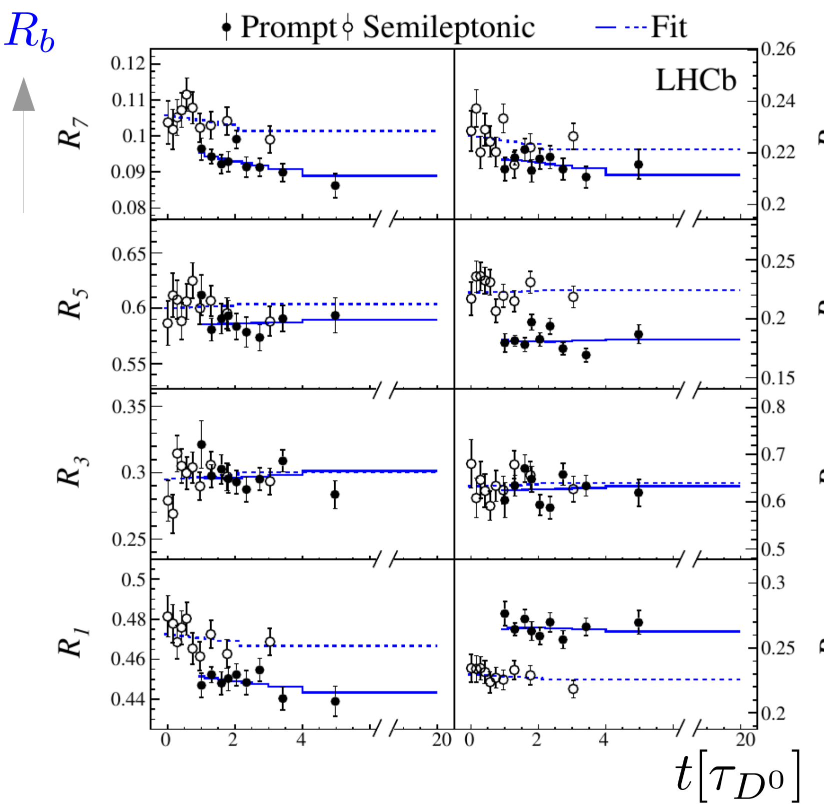


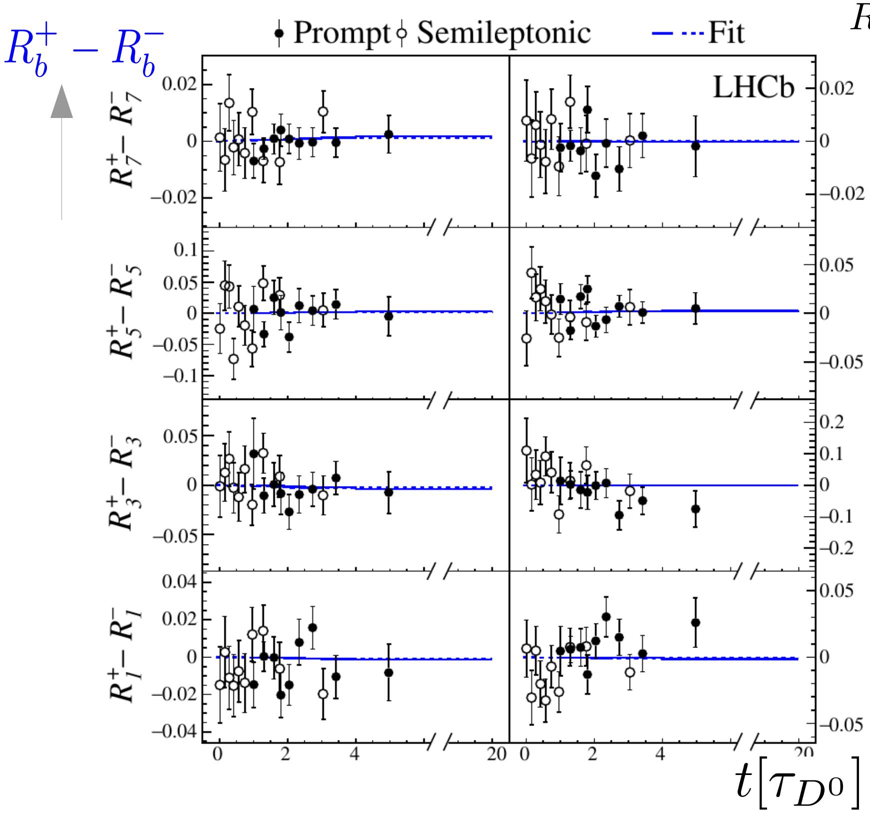
LHCb - Mass Difference Measurement

PRL 122 (2019) 231802

- t dependence of R_b determines the mixing parameters and the difference of R_b^+ and R_b^- indirect CP violation

$R_b^+ \equiv R_b(D^0)$
$R_b^- \equiv R_b(\bar{D}^0)$





Difference in prompt and semileptonic data due to efficiency variations across Dalitz plane

LHCb - Mass Difference Measurement

PRL 122 (2019) 231802

- t dependence of R_b determines the mixing parameters and the difference of R_b^+ and R_b^- indirect CP violation

LHCb	95 % C.L.
$x = (0.27^{+0.17}_{-0.15}) \cdot 10^{-2}$	$[-0.05, 0.6] \cdot 10^{-2}$
$y = (0.74 \pm 0.37) \cdot 10^{-2}$	$[0.00, 1.50] \cdot 10^{-2}$

LHCb	95 % C.L.
$\lvert q/p \rvert = (1.05^{+0.22}_{-0.17})$	$[0.55, 2.15]$
$\phi = (-0.09^{+0.11}_{-0.16})$	$[-0.73, 0.29]$

- Most precise measurement of the mass difference, but $x = 0$ within 2σ
- No indirect CP violation

- t-dependent Dalitz Plot analyses of $D^0 \to K_s^0 \pi^+ \pi^-$ decays using an amplitude model approach

CLEO-c PRD 72 (2005) 012001

PRD 89, 091103(R) (2014)

PRL 105, 081803 (2010)

LHCb - Mass Difference Measurement

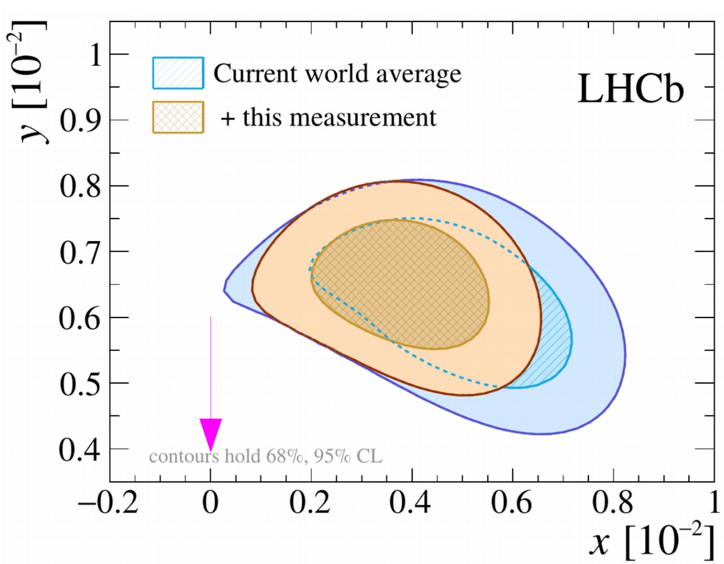
PRL 122 (2019) 231802

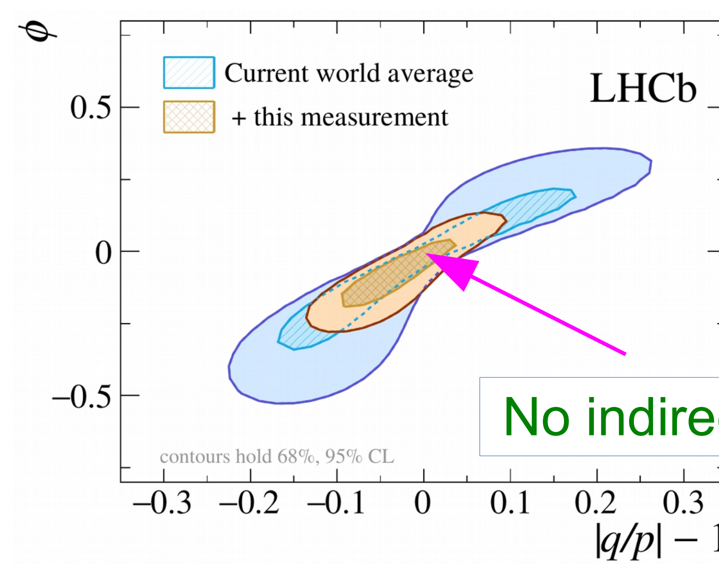
- t dependence of R_b determines the mixing parameters and the difference of R_b^+ and R_b^- indirect CP violation

	95 % C.L.
$x = (0.27^{+0.17}_{-0.15}) \cdot 10^{-2}$	$[-0.05, 0.6] \cdot 10^{-2}$
$y = (0.74 \pm 0.37) \cdot 10^{-2}$	$[0.00, 1.50] \cdot 10^{-2}$

	95 % C.L.
$\lvert q/p \rvert = (1.05^{+0.22}_{-0.17})$	$[0.55, 2.15]$
$\phi = (-0.09^{+0.11}_{-0.16})$	$[-0.73, 0.29]$

- Updated world averages indicate evidence for $x > 0$: $x = (0.39^{+0.11}_{-0.12}) \cdot 10^{-2}$





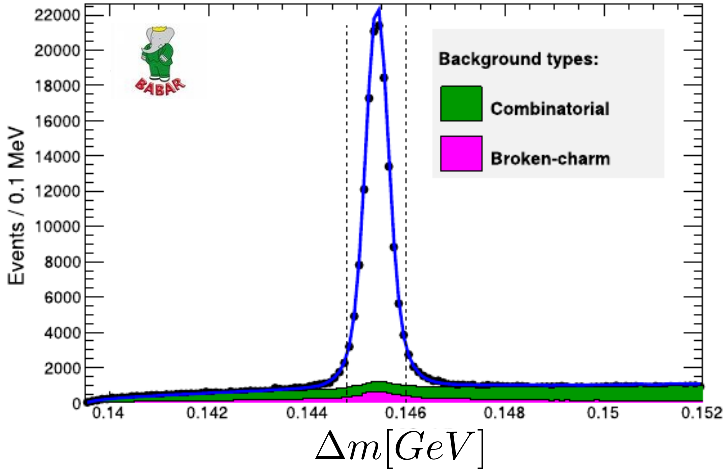
No indirect CPV

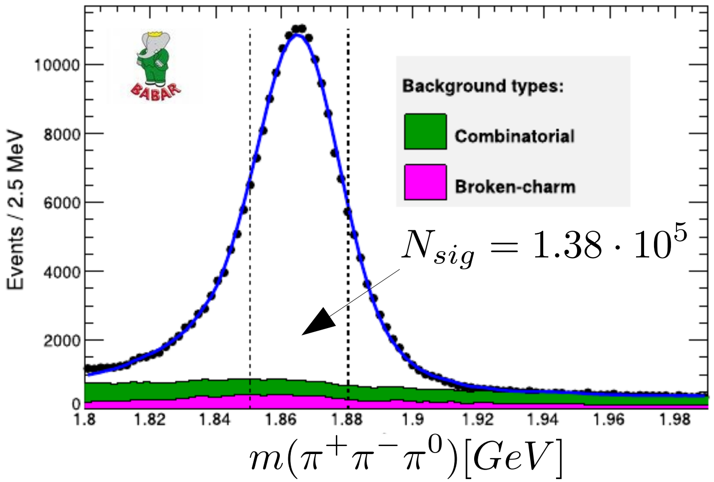
BABAR – Mixing in $D^0 \to \pi^+\pi^-\pi^0$

PRD 93 (2016) 112014

In a t-dependent amplitude analysis of the Dalitz Plot of SCS self-conjugated decays $D^0 \to \pi^+\pi^-\pi^0$ mixing parameters were measured for the first time.

- *BABAR* used 468 fb^{-1} of data to tag D^0 in D^{*+} decays



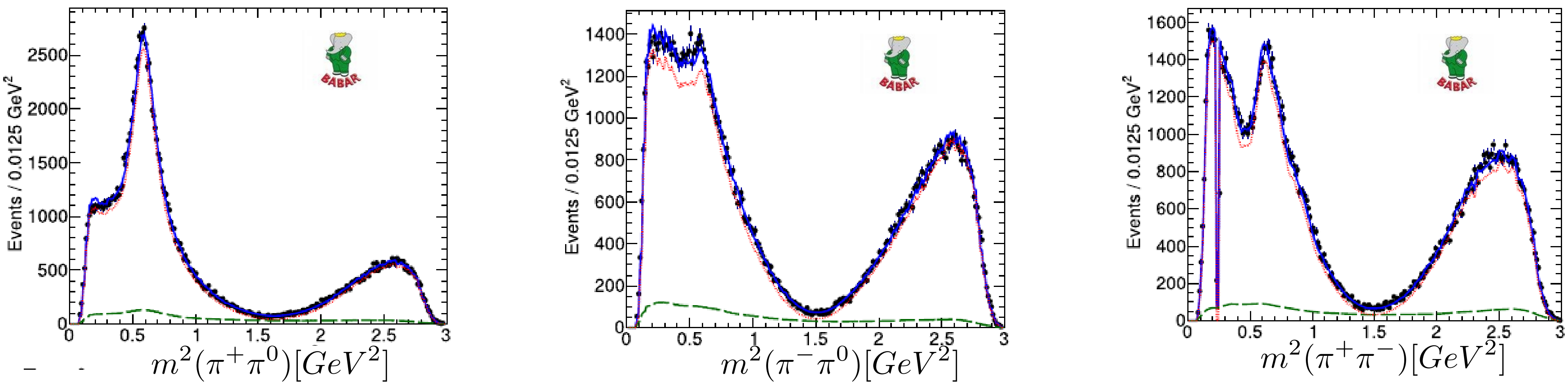


BABAR – Mixing in $D^0 \to \pi^+\pi^-\pi^0$

PRD 93 (2016) 112014

In a t-dependent amplitude analysis of the Dalitz Plot of SCS self-conjugated decays $D^0 \to \pi^+\pi^-\pi^0$ mixing parameters were measured for the first time.

- *BABAR* used 468 fb^{-1} of data to tag D^0 in D^{*+} decays



- In a fit to the decay time in the Dalitz Plot x, y, τ_{D^0} and the parameters of the isobar model were determined assuming CP conservation

$$x = (1.5 \pm 1.2 \pm 0.6) \cdot 10^{-2}$$
$$y = (0.2 \pm 0.9 \pm 0.5) \cdot 10^{-2}$$

uncertainties dominated by statistics

LHCb – y_{CP} Measurement

PRL 122 (2019) 011802

Effective decay width between CP+ and CP mixed states gives access to the decay time difference of the D⁰ mass eigenstates

$$y_{CP} = \frac{\Gamma(D^0 \to K^+K^-, \pi^+\pi^-)}{\Gamma(D^0 \to K^-\pi^+)} - 1 \approx \frac{1}{2}\left[\left(\frac{q}{p}+\frac{p}{q}\right) y\, cos\phi_f \;-\; \left(\frac{q}{p}-\frac{p}{q}\right) x\, sin\phi_f\right]$$

assuming $\phi_f^{K^+K^-} \approx \phi_f^{\pi^+\pi^-}$

$y_{CP} \neq 0 \;\Rightarrow\;$ D^0-$\overline{D}^0$ mixing $\qquad y_{CP} = y \;\Leftarrow\;$ CP conservation

- LHCb determines y_{CP} in a decay time dependent fit to $R = \frac{N_{D^0 \to K^+K^-, \pi^+\pi^-}}{N_{D^0 \to K^-\pi^+}}$ using $\mathcal{L}_{int} \approx 3.0\ fb^{-1}$ of μ-tagged data

$$\boxed{y_{CP}(K^+K^-, \pi^-\pi^+) = (0.57 \pm 0.13 \pm 0.09) \cdot 10^{-2}}$$

- LHCb measurements for $y_{CP}(K^+K^-)$ and $y_{CP}(\pi^+\pi^-)$ are consistent with each other and as precise as the current world average dominated by B factory results
- No deviation from the world averaged y measurements

$$y = (0.62 \pm 0.07) \cdot 10^{-2}$$

→ No indirect CPV in D^0 mixing

CPV in t-dependent $D^0 \to K^+K^- / \pi^+\pi^-$

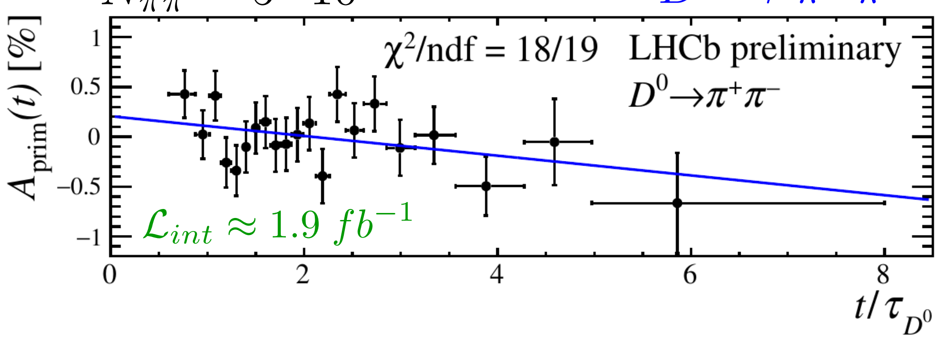
LHCb-CONF-2019-001

- Access A_Γ through decay time dependent asymmetry measurements

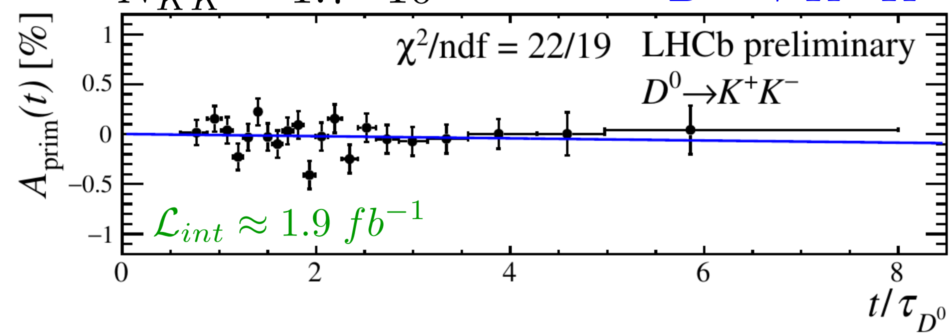
$$A_{CP}(f;t) \equiv \frac{\Gamma(D^0(t)\to f) - \Gamma(\bar{D}^0(t)\to f)}{\Gamma(D^0(t)\to f) + \Gamma(\bar{D}^0(t)\to f)} \approx \underbrace{a_{CP}^{dir}(f)}_{\text{CPV in decay}} - \underbrace{\frac{t}{\tau_{D^0}} A_\Gamma}_{\text{CPV in mixing + interfer.}}$$

CP eigenstate

$N_{\pi\pi} = 5 \cdot 10^6$ $D^0 \to \pi^+\pi^-$



$N_{KK} = 1.7 \cdot 10^7$ $D^0 \to K^+K^-$



- LHCb measurement with run 2 data $\mathcal{L}_{int} \approx 1.9\ fb^{-1}$: LHCb-CONF-2019-001

$A_\Gamma(\pi^-\pi^+) = (11.3 \pm 6.9 \pm 0.8)\cdot 10^{-4}$ $\quad$ $A_\Gamma(K^-K^+) = (1.3 \pm 3.5 \pm 0.7)\cdot 10^{-4}$

$A_\Gamma(K^+K^- + \pi^-\pi^+) = (3.4 \pm 3.1 \pm 0.6)\cdot 10^{-4}$ $\quad$ $\Delta A_\Gamma(KK - \pi\pi) = (-10.1 \pm 7.8 \pm 0.5)\cdot 10^{-4}$

- Combined LHCb measurement for $\mathcal{L}_{int} \approx 4.9\ fb^{-1}$: LHCb-CONF-2019-001, PRL 118 (2017) 261803

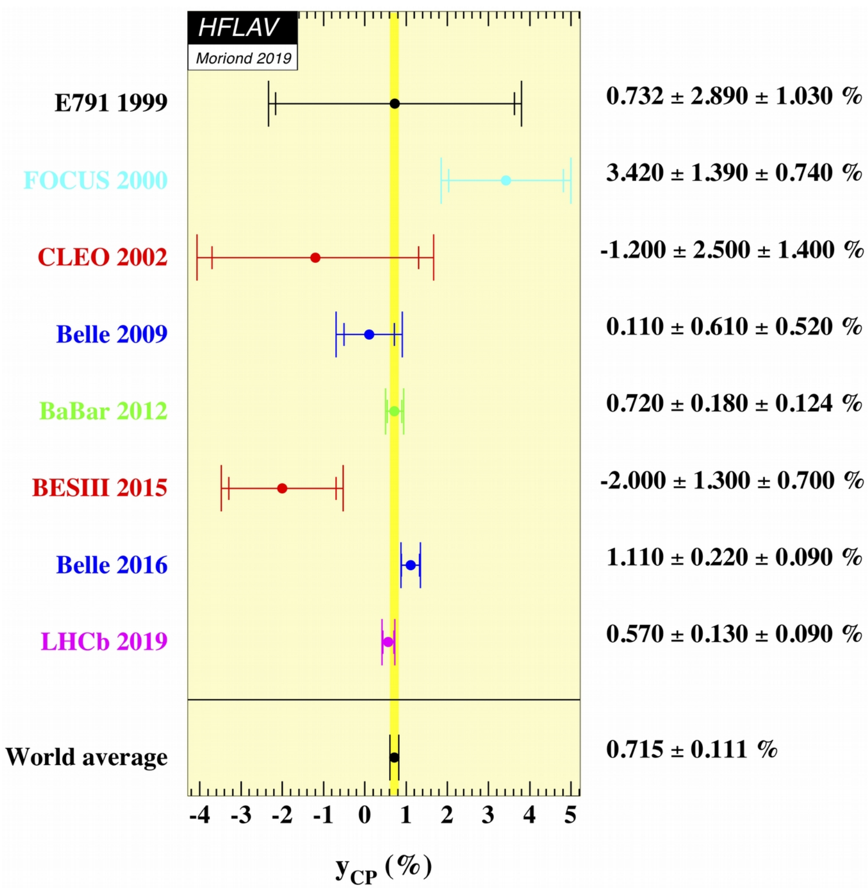
$\boxed{A_\Gamma(K^+K^- + \pi^-\pi^+) = (0.9 \pm 2.1 \pm 0.7)\cdot 10^{-4}}$ $\quad$ $\boxed{\Delta A_\Gamma = (-8.6 \pm 5.0 \pm 0.5)\cdot 10^{-4}}$

No indirect CPV, level of precision $2\cdot 10^{-4}$

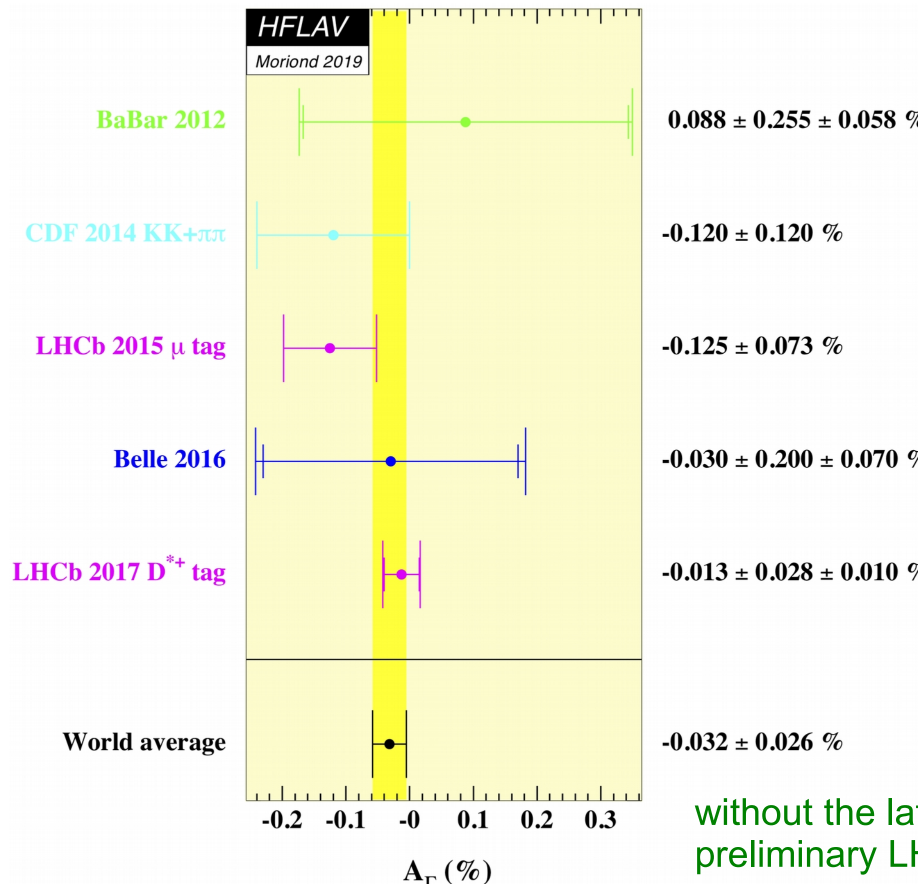
Experimental Results – y_{CP} and A_Γ

- Combined y_{CP} and A_Γ as averaged by HFLAV indicate D^0 mixing but no indirect CP violation

HFLAV https://hflav.web.cern.ch



$$y_{CP} = (0.715 \pm 0.111)\%$$



without the latest preliminary LHCb result

$$A_\Gamma = (-0.032 \pm 0.026)\%$$

Direct CP Violation in Two-body D Decays

CP Violation in Decay

Photo by Reidar Hahn, Fermilab with Sandbox Studio, Chicago

CPV in t-integrated $D^0 \to K^+K^-/\pi^+\pi^-$

Use single Cabibbo suppressed (SCS) 2-body D^0 decays to measure time integrated CP violating effects

- Access CP violation through asymmetry measurements

$$A_{CP}(f) \equiv \frac{N(D^0 \to f) - N(\bar{D}^0 \to f)}{N(D^0 \to f) + N(\bar{D}^0 \to f)} \approx \underbrace{a_{CP}^{dir}(f)}_{\text{CPV in decay}} + \underbrace{\frac{\langle t(f)\rangle}{\tau(D^0)} A_\Gamma(f)}_{\text{CPV in mixing + interfer.}}$$

CP eigenstate

- Measure time integrated A_{CP} difference for $f = K^+K^-$ and $f = \pi^+\pi^-$

J.Phys.G 39 045005

$$\Delta A_{CP} = A_{CP}^{raw}(K^+K^-) - A_{CP}^{raw}(\pi^+\pi^-)$$
$$\approx [a_{CP}^{dir}(K^+K^-) - a_{CP}^{dir}(\pi^+\pi^-)] - \frac{<t>_{K^+K^-} - <t>_{\pi^+\pi^-}}{\tau_{D^0}} A_\Gamma$$

- Measurement of ΔA_{CP} with 2 independent data samples at hadron colliders

$B \to D^0\mu^-\nu_\mu X$ CDF PRL 109 (2012) 111801 LHCb PLB 723 (2013) 33, JHEP 07 (2014) 041

$D^{*+} \to D^0\pi^+$ LHCb PRL 108 (2012) 111602, PRL 116 (2016) 191601

- Measurements at e^+e^- colliders BABAR PRL 100 (2008) 061803 BELLE PLB 670 (2008) 190

CPV in t-integrated $D^0 \to K^+K^-/\pi^+\pi^-$

Use single Cabibbo suppressed (SCS) 2-body D^0 decays to measure time integrated CP violating effects

➢ Access CP violation through asymmetry measurements

$$A_{CP}(f) \equiv \frac{N(D^0 \to f) - N(\bar{D}^0 \to f)}{N(D^0 \to f) + N(\bar{D}^0 \to f)} \approx \underbrace{a_{CP}^{dir}(f)}_{\text{CPV in decay}} + \underbrace{\frac{\langle t(f)\rangle}{\tau(D^0)} A_\Gamma(f)}_{\text{CPV in mixing + interfer.}}$$

CP eigenstate

➢ Measure time integrated A_{CP} difference for $f = K^+K^-$ and $f = \pi^+\pi^-$

J.Phys.G 39 045005

$$\Delta A_{CP} = A_{CP}^{raw}(K^+K^-) - A_{CP}^{raw}(\pi^+\pi^-)$$
$$\approx [a_{CP}^{dir}(K^+K^-) - a_{CP}^{dir}(\pi^+\pi^-)] - \frac{<t>_{K^+K^-} - <t>_{\pi^+\pi^-}}{\tau_{D^0}} A_\Gamma$$

- Measurement of ΔA_{CP} with 2 independent data samples at hadron colliders

$B \to D^0\mu^-\nu_\mu X$ — PRL 109 (2012) 111801 — PLB 723 (2013) 33, JHEP 07 (2014) 041 — Run 1

$D^{*+} \to D^0\pi^+$ — PRL 108 (2012) 111602, PRL 116 (2016) 191601 — Run 1

Run 2 — PRL 122 (2019) 211803

- Measurements at e^+e^- colliders — PRL 100 (2008) 061803 — PLB 670 (2008) 190

LHCb – CPV in $D^0 \to h^+h^-$

PRL 122 (2019) 2113803

- Perform new measurement with the Run 2 dataset (5.9 fb^{-1})

- Measured asymmetries contain detection and production asymmetries

$$A_{meas}^{h^+h^-} = A_{CP}^{h^+h^-} + A_D + A_P$$

$$\frac{N(D^0 \to h^+h^-) - N(\bar{D}^0 \to h^+h^-)}{N(D^0 \to h^+h^-) + N(\bar{D}^0 \to h^+h^-)}$$

CP asymmetry of h$^+$ h$^-$

Production asymmetry between D^{*+} and D^{*-} / B and $\bar{\mathrm{B}}$

Detection asymmetry of the positive and negative tagging π / μ

  - A_D and A_P are $< \mathcal{O}(10^{-2})$ and independent of the final state

- Difference $\Delta A_{CP} = A_{meas}^{KK} - A_{meas}^{\pi\pi} = A_{CP}^{KK} - A_{CP}^{\pi\pi}$ cancels detection and production asymmetries

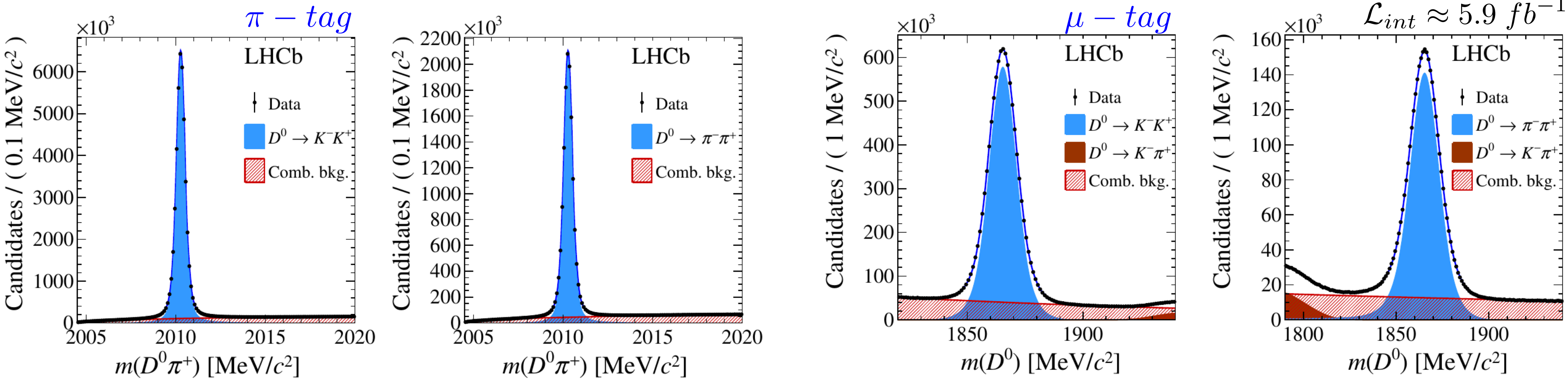
  - Due to sign flip in CKM structure $(V_{us} \sim -V_{cd})$ $\quad A_{CP}^{KK} = -A_{CP}^{\pi\pi}$
  - ΔA_{CP} is largely insensitive to systematic effects

LHCb – Observation of CPV in Charm

PRL 122 (2019) 2113803

➢ A_{meas} is determined from fits to $m(D^0\pi^+)$ and $m(D^0)$

$\pi - tag$ $\mu - tag$ $\mathcal{L}_{int} \approx 5.9\ fb^{-1}$



$N_{KK} \approx 4.4 \cdot 10^7$ $N_{\pi\pi} \approx 1.4 \cdot 10^7$ $N_{KK} \approx 9 \cdot 10^6$ $N_{\pi\pi} \approx 3 \cdot 10^6$

$\Delta A_{CP}^{\pi-tag} = (-18.9 \pm 3.2\,(stat) \pm 0.9\,(sys)) \cdot 10^{-4}$

$\Delta A_{CP}^{\mu-tag} = (-9 \pm 8\,(stat) \pm 5\,(sys)) \cdot 10^{-4}$

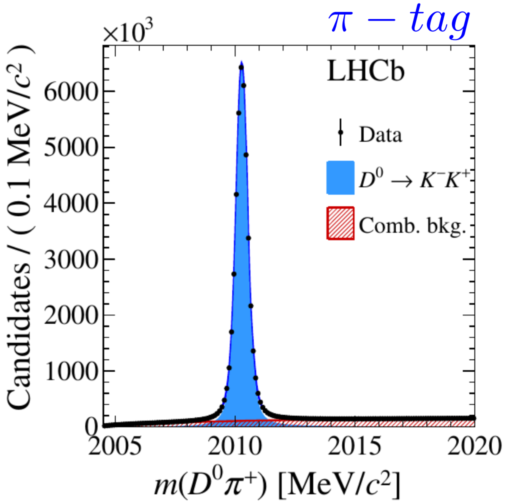
- Good agreement with world averages and previous LHCb results
- Numerous robustness checks → no dependency of ΔA_{CP} on run range, magnet polarity, $\eta(\pi^+)$, $\phi(\pi^+)$, $p_T(\pi^+)$, $\chi^2_{IP}(\pi^+)$, ………

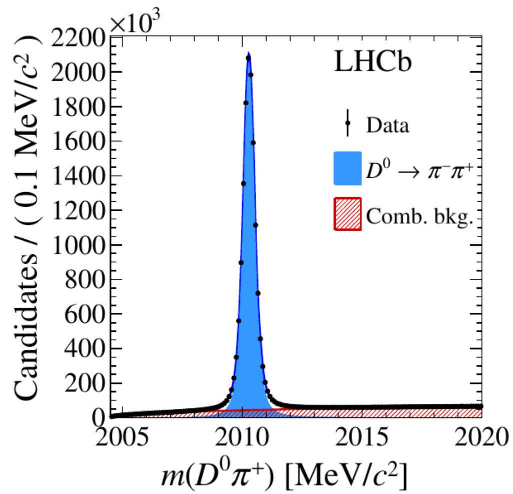
LHCb – Observation of CPV in Charm

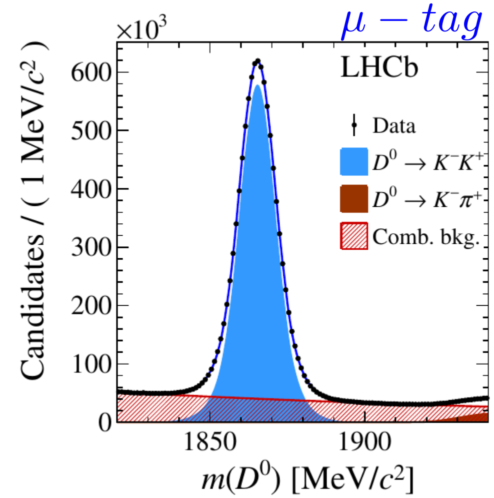
PRL 122 (2019) 2113803

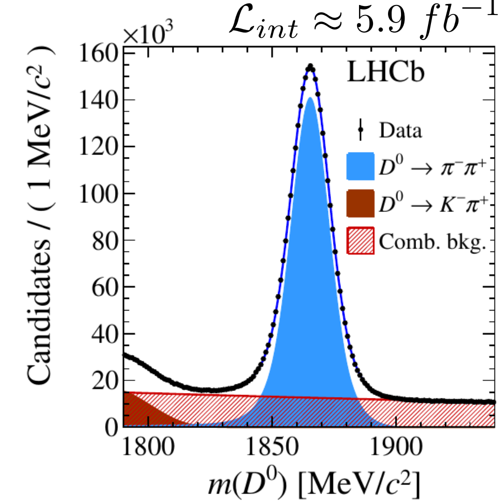
- A_{meas} is determined from fits to $m(D^0\pi^+)$ and $m(D^0)$

$\pi - tag$ $\qquad$ $\mu - tag$ $\qquad$ $\mathcal{L}_{int} \approx 5.9\ fb^{-1}$









$N_{KK} \approx 4.4 \cdot 10^7$ $\qquad$ $N_{\pi\pi} \approx 1.4 \cdot 10^7$ $\qquad$ $N_{KK} \approx 9 \cdot 10^6$ $\qquad$ $N_{\pi\pi} \approx 3 \cdot 10^6$

$$\Delta A_{CP}^{\pi-tag} = (-18.9 \pm 3.2\,(stat) \pm 0.9\,(sys)) \cdot 10^{-4}$$

$$\Delta A_{CP}^{\mu-tag} = (-9 \pm 8\,(stat) \pm 5\,(sys)) \cdot 10^{-4}$$

- Combination of LHCb Run 1 with new Run 2 results

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

First observation of CPV in charm decays at 5.3 σ

LHCb – Direct CPV in $D^0 \to h^+h^-$

PRL 122 (2019) 2113803

➢ Determine direct CP violation combining with LHCb measurements of A_Γ and y_{CP}

$$\Delta A_{CP} \simeq \Delta a_{CP}^{dir}\left(1 + \frac{\langle \bar{t}\rangle}{\tau_{D^0}} y_{CP}\right) + \frac{\Delta\langle t\rangle}{\tau_{D^0}} \underbrace{a_{CP}^{ind}}_{\simeq -A_\Gamma}$$

with

$$\langle \bar{t}\rangle = \frac{\langle t\rangle_{KK} + \langle t\rangle_{\pi\pi}}{2}$$

$$\Delta\langle t\rangle = \langle t\rangle_{KK} - \langle t\rangle_{\pi\pi}$$

$$\left.\begin{aligned} \Delta\langle t\rangle/\tau_{D^0} &= 0.115 \pm 0.002 \\ \langle \bar{t}\rangle/\tau_{D^0} &= 1.71 \pm 0.10 \end{aligned}\right\}$$ using the full dataset

- Using LHCb measurements

$y_{CP} = (5.7 \pm 1.5) \cdot 10^{-3}$ JHEP 04 (2012) 129, PRL 122 (2019) 011802

$A_\Gamma \simeq (-2.8 \pm 2.8) \cdot 10^{-4}$ JHEP 04 (2015) 043, PRL 118 (2017) 261803

determines the direct CPV contribution

$$\Delta a_{CP}^{dir} = (-15.7 \pm 2.9) \cdot 10^{-4}$$

→ ΔA_{CP} is mainly sensitive to direct CPV

HFLAV – Direct CPV in $D^0 \to h^+h^-$

PRL 122 (2019) 2113803

➢ Determine direct CP violation combining with LHCb measurements of A_Γ and y_{CP}

$$\Delta A_{CP} \simeq \Delta a_{CP}^{dir}\left(1 + \frac{\langle \bar{t}\rangle}{\tau_{D^0}} y_{CP}\right) + \frac{\Delta\langle t\rangle}{\tau_{D^0}} \underbrace{a_{CP}^{ind}}_{\simeq -A_\Gamma}$$

with

$$\langle \bar{t}\rangle = \frac{\langle t\rangle_{KK} + \langle t\rangle_{\pi\pi}}{2}$$

$$\Delta\langle t\rangle = \langle t\rangle_{KK} - \langle t\rangle_{\pi\pi}$$

$$\left.\begin{aligned}\Delta\langle t\rangle/\tau_{D^0} &= 0.115 \pm 0.002 \\ \langle \bar{t}\rangle/\tau_{D^0} &= 1.71 \pm 0.10\end{aligned}\right\}$$ using the full dataset

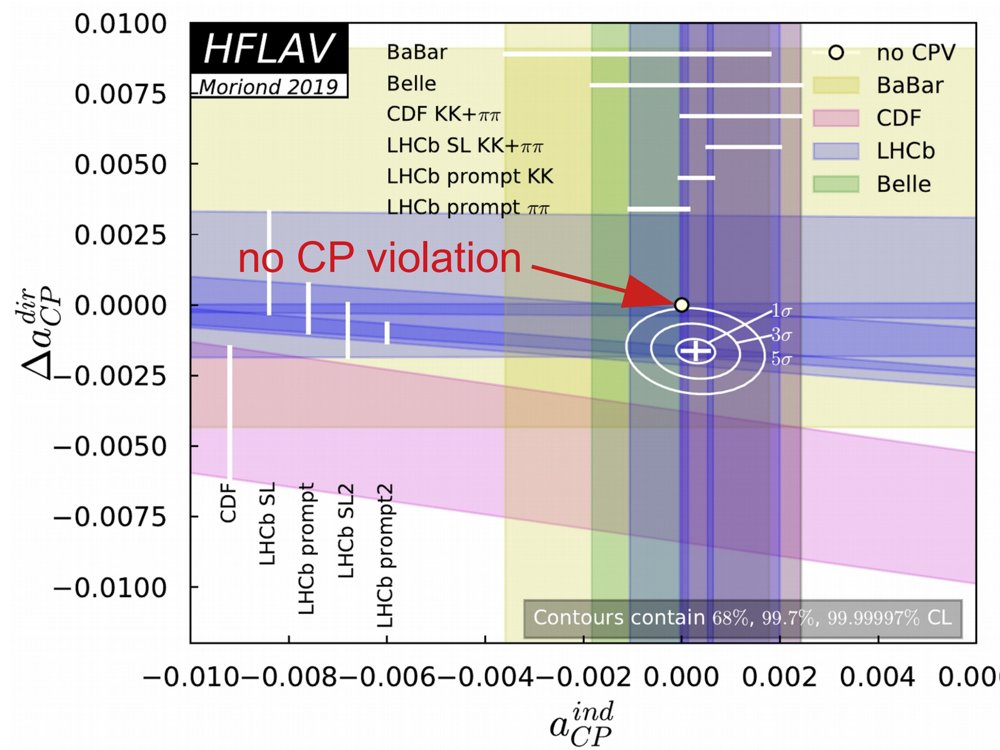
- Using LHCb measurements

$$\Delta a_{CP}^{dir} = (-15.7 \pm 2.9)\cdot 10^{-4}$$

- HFLAV combination

No CP violation excluded at 5.4σ

$$\Delta a_{CP}^{dir} = (-16.4 \pm 2.8)\cdot 10^{-4}$$
$$a_{CP}^{ind} = (2.8 \pm 2.6)\cdot 10^{-4}$$



Direct CPV in $D^+_{(s)} \to K^0_s h^+$, $D^+ \to \phi\pi^+$

PRL 122 (2019) 191803

- Search for direct CP asymmetry in SCS decays $D^\pm_{(s)} \to K^0_s h^\pm$, $D^+ \to \phi\pi^+$ $(h = K, \pi)$

$$A_{CP}^{D^+_{(s)}\to K^0_s h^+} \equiv \frac{\Gamma(D^+_{(s)} \to K^0_s h^+) - \Gamma(D^-_{(s)} \to K^0_s h^-)}{\Gamma(D^+_{(s)} \to K^0_s h^+) + \Gamma(D^-_{(s)} \to K^0_s h^-)} = \frac{N_{D^+_{(s)}\to K^0_s h^+} - N_{D^-_{(s)}\to K^0_s h^-}}{N_{D^+_{(s)}\to K^0_s h^+} + N_{D^-_{(s)}\to K^0_s h^-}}$$

- Measured raw asymmetries contain pollution asymmetries

$$A_{CP}^{raw} \approx A_{CP} + A_D(h) + A_P(D^+_{(s)}) + A_{K^0}$$

mixing / CPV of K^0 and detection asymmetry K^0 : $A_{K^0} = (+0.07 \pm 0.02)\%$

JHEP 07(2014) 041

use CF modes $D^+ \to K^0_s \pi^+$, $D^+_s \to K^0_s K^+$

- Construct CP asymmetries combining signal and CF modes to cancel detection and production asymmetries

$$\mathcal{A}_{CP}(D^+_s \to K^0_s \pi^+) \approx \mathcal{A}_{CP}(D^+_s \to K^0_s \pi^+) - \mathcal{A}_{CP}(D^+_s \to \phi\pi^+)$$

$$\mathcal{A}_{CP}(D^+ \to K^0_s K^+) \approx \mathcal{A}_{CP}(D^+ \to K^0_s K^+) - \mathcal{A}_{CP}(D^+ \to K^0_s \pi^+) - \mathcal{A}_{CP}(D^+_s \to K^0_s K^+) + \mathcal{A}_{CP}(D^+_s \to \phi\pi^+)$$

$$\mathcal{A}_{CP}(D^+ \to \phi\pi^+) \approx \mathcal{A}_{CP}(D^+ \to \phi\pi^+) - \mathcal{A}_{CP}(D^+ \to K^0_s \pi^+)$$

Direct CPV in $D^+_{(s)} \to K^0_s h^+$, $D^+ \to \phi\pi^+$

PRL 122 (2019) 191803

➤ Search for direct CP asymmetry in SCS decays $D^{\pm}_{(s)} \to K^0_s h^{\pm}$, $D^+ \to \phi\pi^+$ $(h = K, \pi)$

$$A_{CP}^{D^+_{(s)} \to K^0_s h^+} \equiv \frac{\Gamma(D^+_{(s)} \to K^0_s h^+) - \Gamma(D^-_{(s)} \to K^0_s h^-)}{\Gamma(D^+_{(s)} \to K^0_s h^+) + \Gamma(D^-_{(s)} \to K^0_s h^-)} = \frac{N_{D^+_{(s)} \to K^0_s h^+} - N_{D^-_{(s)} \to K^0_s h^-}}{N_{D^+_{(s)} \to K^0_s h^+} + N_{D^-_{(s)} \to K^0_s h^-}}$$

- LHCb measurement with run 2 data $\mathcal{L}_{int} = 3.8 fb^{-1}$ most precise to date

PRL 122 (2019) 191803

$$\begin{aligned}
\mathcal{A}_{CP}(D^+_s \to K^0_s \pi^+) &= (1.3 \pm 1.9 \pm 0.5) \cdot 10^{-3} \\
\mathcal{A}_{CP}(D^+ \to K^0_s K^+) &= (-0.09 \pm 0.65 \pm 0.48) \cdot 10^{-3} \\
\mathcal{A}_{CP}(D^+ \to \phi\pi^+) &= (0.05 \pm 0.42 \pm 0.29) \cdot 10^{-3}
\end{aligned}$$

effects of K^0 system are subtracted

- Combined LHCb measurement for $\mathcal{L}_{int} = 6.8 fb^{-1}$

PRL 122 (2019) 191803, JHEP 06 (2013) 112, JHEP 10 (2014) 025

$$\begin{aligned}
\mathcal{A}_{CP}(D^+_s \to K^0_s \pi^+) &= (1.6 \pm 1.7 \pm 0.5) \cdot 10^{-3} \\
\mathcal{A}_{CP}(D^+ \to K^0_s K^+) &= (-0.04 \pm 0.61 \pm 0.45) \cdot 10^{-3} \\
\mathcal{A}_{CP}(D^+ \to \phi\pi^+) &= (0.03 \pm 0.40 \pm 0.29) \cdot 10^{-3}
\end{aligned}$$

$\rightarrow$ No direct CPV

Direct CPV in $D^+_{(s)} \to K^0_s h^+$, $D^+ \to \phi\pi^+$

PRL 122 (2019) 191803

- Search for direct CP asymmetry in SCS decays $D^\pm_{(s)} \to K^0_s h^\pm$, $D^+ \to \phi\pi^+$ $(h = K, \pi)$

$$A_{CP}^{D^+_{(s)}\to K^0_s h^+} \equiv \frac{\Gamma(D^+_{(s)} \to K^0_s h^+) - \Gamma(D^-_{(s)} \to K^0_s h^-)}{\Gamma(D^+_{(s)} \to K^0_s h^+) + \Gamma(D^-_{(s)} \to K^0_s h^-)} = \frac{N_{D^+_{(s)}\to K^0_s h^+} - N_{D^-_{(s)}\to K^0_s h^-}}{N_{D^+_{(s)}\to K^0_s h^+} + N_{D^-_{(s)}\to K^0_s h^-}}$$

- Combined LHCb measurement for $\mathcal{L}_{int} = 6.8 fb^{-1}$

PRL 122 (2019) 191803, JHEP 06 (2013) 112, JHEP 10 (2014) 025

$$\mathcal{A}_{CP}(D^+_s \to K^0_s \pi^+) = (1.6 \pm 1.7 \pm 0.5) \cdot 10^{-3}$$
$$\mathcal{A}_{CP}(D^+ \to K^0_s K^+) = (-0.04 \pm 0.61 \pm 0.45) \cdot 10^{-3}$$
$$\mathcal{A}_{CP}(D^+ \to \phi\pi^+) = (0.03 \pm 0.40 \pm 0.29) \cdot 10^{-3}$$

$\to$ No direct CPV

- Comparison to other results shows huge improvement in precision, eg

$\mathcal{A}_{CP}(D^+ \to K^0_s K^+)[10^{-3}]$

t

$-0.04 \pm 0.61 \pm 0.45$	LHCb	PRL 122 (2019) 191803
$2.5 \pm 2.8 \pm 1.4$	Belle	JHEP 02 (2013) 98
$4.6 \pm 3.6 \pm 2.5$	BaBar	PRD 87 (2013) 052012
$-2.0 \pm 15 \pm 9$	CLEO-c	PRD 81 (2010) 052013
$71 \pm 61 \pm 12$	FOCUS	PRL 88 (2002) 041602

- Results of the other modes are available by Belle BaBar

CP Violation in Multi-body D Decays

CPV with Kinematic Asymmetries

PRD 99 (2019) 011104

Search for CPV in the SCS decay $D^0 \to K^+K^-\pi^+\pi^-$ with the asymmetry of kinematic variables using the full Belle dataset, $\mathcal{L}_{int} \approx 988 fb^{-1}$

➢ Construct a CP violating asymmetry $a_X^{CP} = \frac{1}{2}(\mathcal{A}_X - \eta_X^{CP}\bar{\mathcal{A}}_X)$

- Amplitudes are derived from the decay width asymmetries $\mathcal{A}_X$ using kinematic variable X

$$\mathcal{A}_X = \frac{\Gamma_D(X>0) - \Gamma_D(X<0)}{\Gamma_D(X>0) + \Gamma_D(X<0)}$$

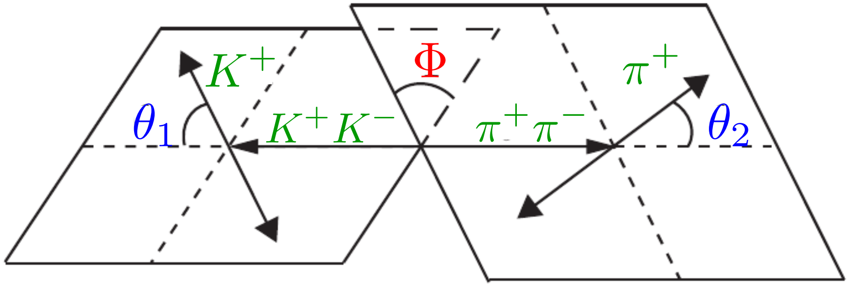
$$D^{*+} \to \pi^+ D^0 : \ \mathcal{A}_X$$
$$D^{*-} \to \pi^- \bar{D}^0 : \ \bar{\mathcal{A}}_{\bar{X}}$$

- Set of 5 kinematic variables X

$\eta_X^{CP} = +1 :$ $cos\,\Phi$, $cos\,\theta_1 \cdot cos\,\theta_2 \cdot cos\,\Phi$

$\eta_X^{CP} = -1 :$ $sin\,\Phi$ ~ triple product, $sin\,2\Phi$, $cos\,\theta_1 \cdot cos\,\theta_2 \cdot sin\,\Phi$

LHCb: JHEP 10 (2014) 005



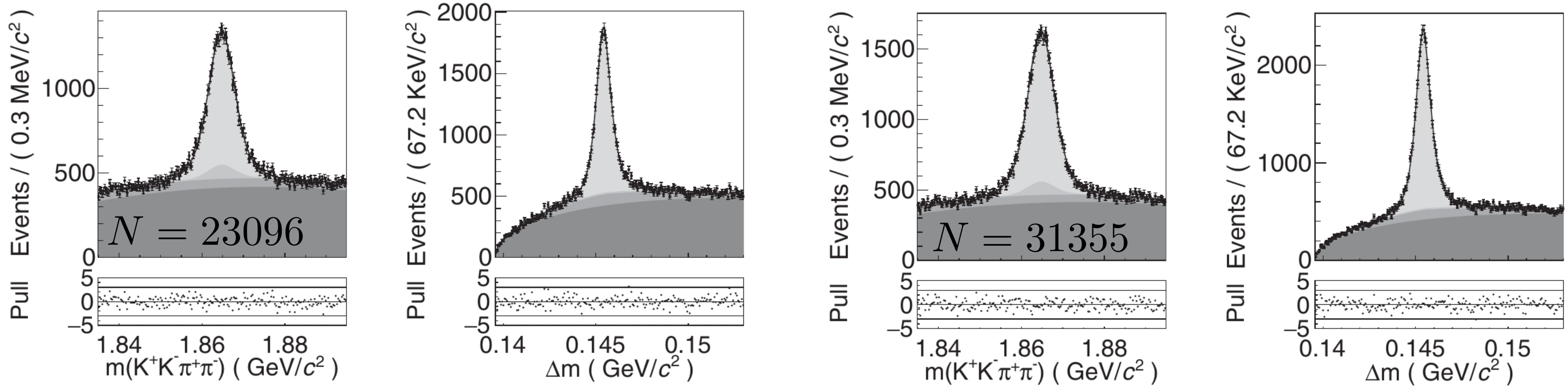
- Interfering amplitudes can be sensitive to non-SM CP-violating phases

CPV with Kinematic Asymmetries

PRD 99 (2019) 011104

- In a 2D fit to $(\Delta m\,,\, m(K^+K^-\pi^+\pi^-))$ yields for the 5 different kinematic variables X and asymmetries $\mathcal{A}_X$ are determined

$D^0(sin\,2\Phi > 0)$ $D^0(sin\,2\Phi < 0)$ $\mathcal{L}_{int} \approx 988 fb^{-1}$



- CP-violating asymmetries - results

$$a^{CP}_{sin\Phi} = (5.2 \pm 3.7 \pm 0.7)\cdot 10^{-3}$$
$$a^{CP}_{sin2\Phi} = (3.9 \pm 3.6 \pm 0.7)\cdot 10^{-3}$$
$$a^{CP}_{cos_1 cos\theta_2 sin\Phi} = (0.2 \pm 3.7 \pm 0.7)\cdot 10^{-3}$$

$$a^{CP}_{cos_1 cos\theta_2 cos\Phi} = (-0.2 \pm 3.6 \pm 0.7)\cdot 10^{-3}$$
$$a^{CP}_{cos\Phi} = (3.4 \pm 3.6 \pm 0.6)\cdot 10^{-3}$$

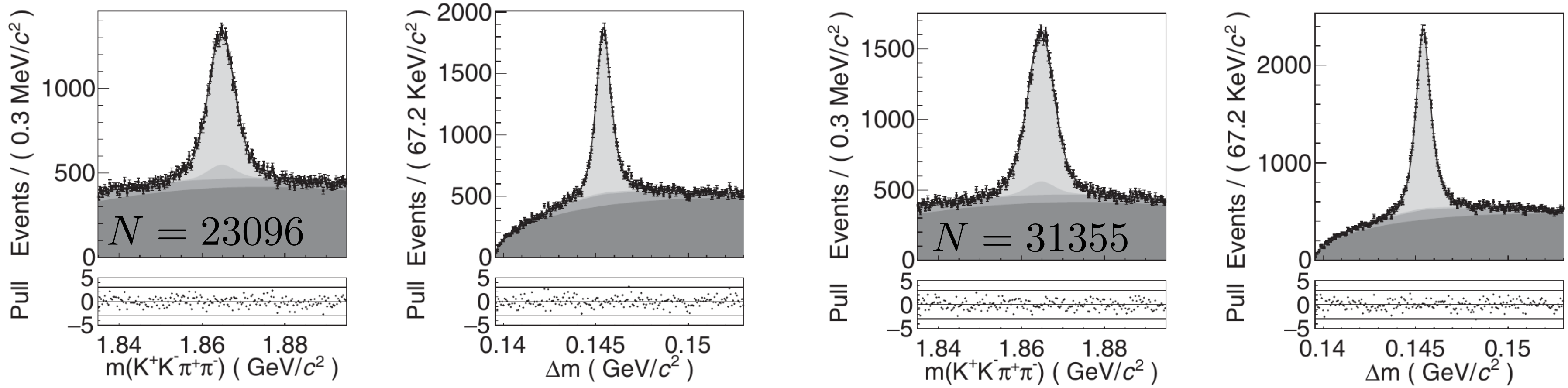
→ no evidence for CP violation

CPV with Kinematic Asymmetries

PRD 99 (2019) 011104

- In a 2D fit to $(\Delta m\,,\, m(K^+K^-\pi^+\pi^-))$ yields for the 5 different kinematic variables X and asymmetries A_X are determined

$D^0(sin\,2\Phi > 0)$ $\qquad$ $D^0(sin\,2\Phi < 0)$ $\qquad$ $\mathcal{L}_{int} \approx 988 fb^{-1}$



- CP-violating asymmetries - results
  - measurement within the precision consistent with CP conservation
  - $a^{CP}_{sin\Phi}$ is similar to the triple product based T-odd observable a^{T-odd}_{CP} as measured by LHCb with Run 1 data $\quad a^{T-odd}_{CP} = (1.8 \pm 2.9 \pm 0.4) \cdot 10^{-3}$

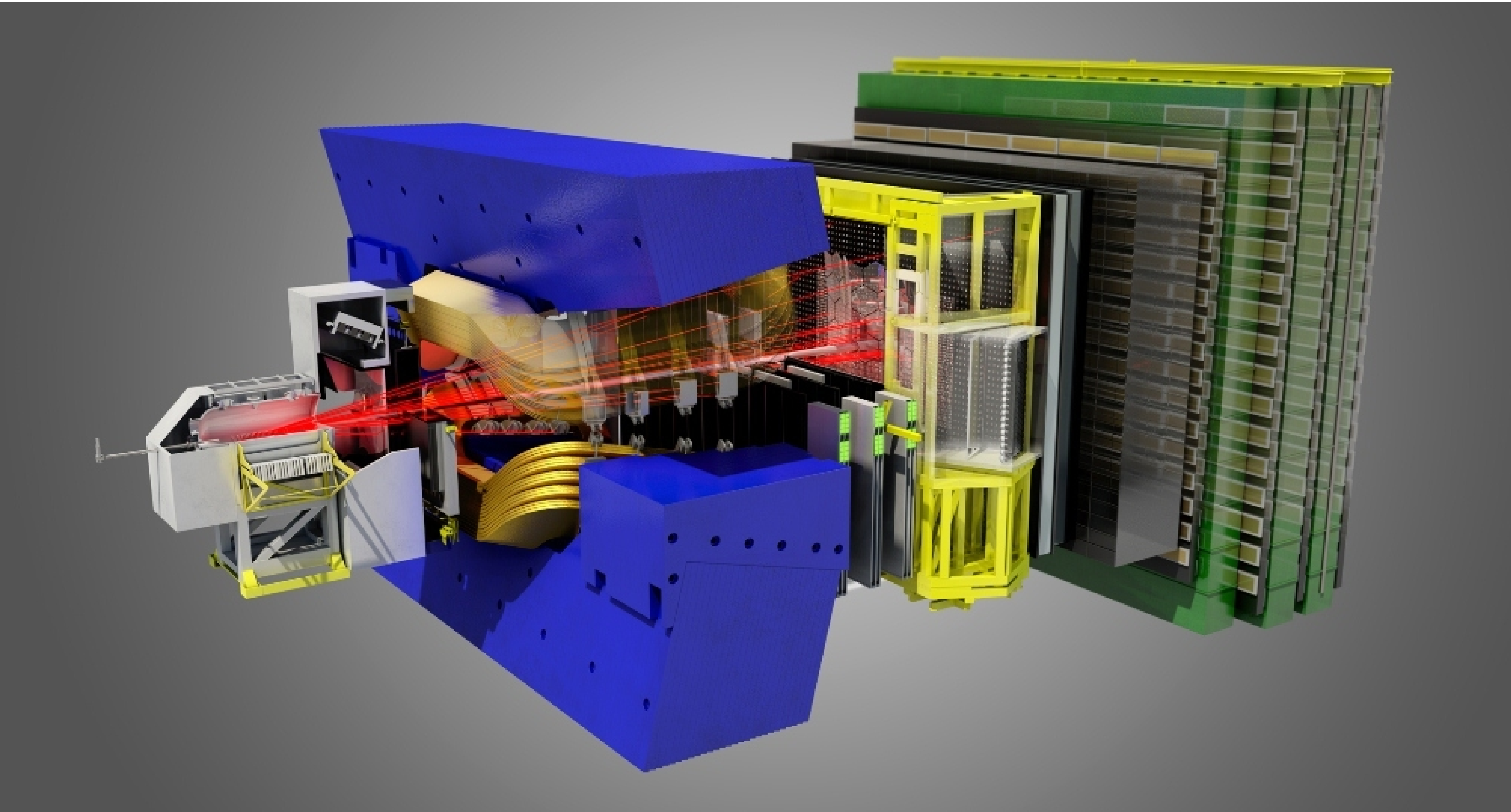
JHEP 10 (2014) 005

Summary

Artwork by Sandbox Studio, Chicago with Ana Kova

- LHCb observed direct CP violation in charm decays
  - An experimental precision at the sub-permille level in the measurement of CP asymmetries was achieved
  - Result is compatible with SM expectations
- LHCb's new results in charm mixing and CP violation improved the world averages in the past year significantly.
  - Evidence for the world average mass difference x larger than zero
- Future measurements at LHC and SuperKEKB of mixing and CPV in charm decays along with possible theoretical improvements will clarify if there is new dynamics in the up-quark sector

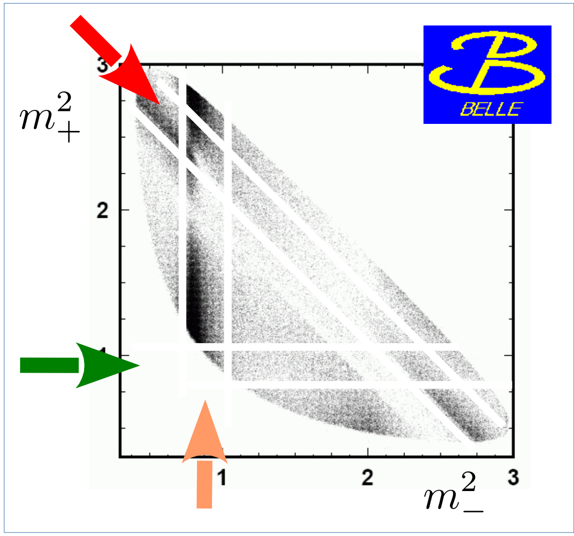
Backup



Introduction – t Dep. Dalitz Analysis

- Dalitz plot of $D^0 \to K_s^0\pi^+\pi^-$
  CLEO, PRD 72, 012001 (2005)
  - Different quasi 2 body amplitudes contribute and interfere
  - Dalitz analyses allows to determine amplitude and relative phases of interfering modes

CF: $D^0 \to K^{*-}\pi^+$
DCS: $D^0 \to K^{*+}\pi^-$
CP: $D^0 \to K_s^0\rho^0$



PRL 99, 131803 (2007)

$D^0 : m_+^2(K_s^0\pi^+)$
$\bar{D}^0 : m_+^2(K_s^0\pi^-)$

- Time dependence

$$\langle K_s^0\pi^+\pi^-|D^0(t)\rangle = \overbrace{\frac{1}{2}A(m_-^2, m_+^2)}^{\langle f|D^0\rangle}[e^{-i\lambda_1 t} + e^{-i\lambda_2 t}]$$

decay amplitude

$$+\frac{1}{2}\frac{q}{p}\underbrace{\bar{A}(m_-^2, m_+^2)}_{\langle f|\bar{D}^0\rangle}[e^{-i\lambda_1 t} + e^{-i\lambda_2 t}]$$

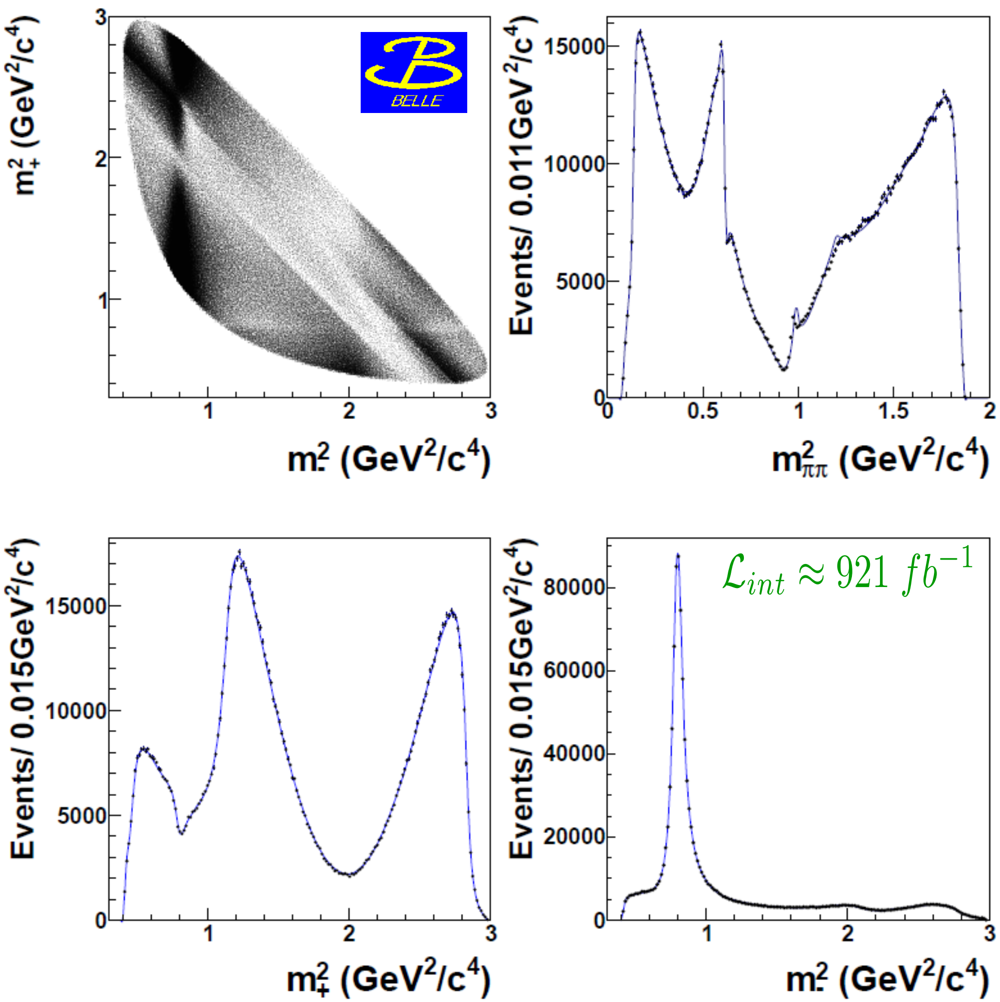
$$\lambda_{1,2} = f(x, y)$$

- Perform unbinned max. likelihood fit in the signal region to (m_+^2, m_-^2, t)
  $\Rightarrow$ extract relative amplitudes and relative phases
  $\Rightarrow$ x, y and τ_{D^0}
  $\Rightarrow$ CP violation parameter q/p and $arg(q/p)$

t Dep. Dalitz Analysis in $D^0 \rightarrow K_s\pi^+\pi^-$

PRD 89 (2014) 091103R

- $1.2 \cdot 10^6$ signal candidates with a purity of 96 %.



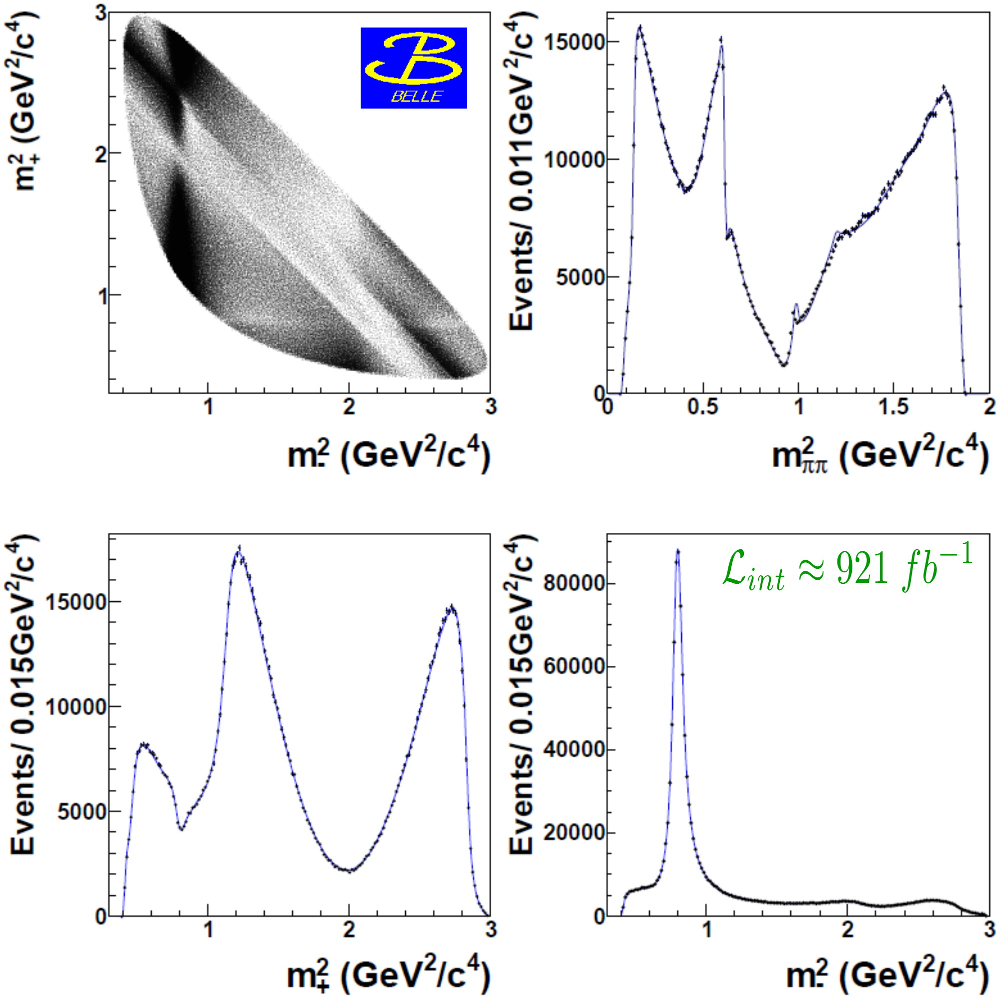
Fit contributions of the amplitude model:

Resonance	Amplitude	Phase (deg)	Fit fraction
$K^*(892)^-$	1.590 ± 0.003	131.8 ± 0.2	0.6045
$K_0^*(1430)^-$	2.059 ± 0.010	-194.6 ± 1.7	0.0702
$K_2^*(1430)^-$	1.150 ± 0.009	-41.5 ± 0.4	0.0221
$K^*(1410)^-$	0.496 ± 0.011	83.4 ± 0.9	0.0026
$K^*(1680)^-$	1.556 ± 0.097	-83.2 ± 1.2	0.0016
$K^*(892)^+$	0.139 ± 0.002	-42.1 ± 0.7	0.0046
$K_0^*(1430)^+$	0.176 ± 0.007	-102.3 ± 2.1	0.0005
$K_2^*(1430)^+$	0.077 ± 0.007	-32.2 ± 4.7	0.0001
$K^*(1410)^+$	0.248 ± 0.010	-145.7 ± 2.9	0.0007
$K^*(1680)^+$	1.407 ± 0.053	86.1 ± 2.7	0.0013
$\rho(770)$	1 (fixed)	0 (fixed)	0.2000
$\omega(782)$	0.0370 ± 0.0004	114.9 ± 0.6	0.0057
$f_2(1270)$	1.300 ± 0.013	-31.6 ± 0.5	0.0141
$\rho(1450)$	0.532 ± 0.027	80.8 ± 2.1	0.0012
$\pi\pi$ S-wave			0.1288

t Dep. Dalitz Analysis in $D^0 \to K_s\pi^+\pi^-$

PRD 89 (2014) 091103R

- $1.2 \cdot 10^6$ signal candidates with a purity of 96 %.



Fit contributions of the amplitude model:

Resonance	Amplitude	Phase (deg)	Fit fraction
$K^*(892)^-$	1.590 ± 0.003	131.8 ± 0.2	0.6045
$K_0^*(1430)^-$	2.059 ± 0.010	-194.6 ± 1.7	0.0702

Belle 921 fb⁻¹ : PRD 89, 091103(R) (2014)

$$x = (0.56 \pm 0.19^{+0.03+0.06}_{-0.09-0.09}) \cdot 10^{-2}$$

$$y = (0.30 \pm 0.15^{+0.04+0.03}_{-0.05-0.06}) \cdot 10^{-2}$$

no indirect CPV

$$|q/p| = (0.90^{+0.16+0.05+0.06}_{-0.15-0.04-0.05})$$

$$arg(q/p) = (-6 \pm 11 \pm 3^{+3}_{-4})^\circ$$

BABAR 469 fb⁻¹ : PRL 105, 081803 (2010)

$$x = (0.16 \pm 0.23 \pm 0.12 \pm 0.08) \cdot 10^{-2}$$

$$y = (0.57 \pm 0.20 \pm 0.13 \pm 0.07) \cdot 10^{-2}$$

CPV with T-odd Correlations

Search for CPV using T-odd correlations assuming CPT invariance

- Triple Products in $D \to VV$ are odd under T reversal

A. Datta and D. London
Int.J.Mod.Phys. A19 2505 (2004)

$$A_T = \frac{\Gamma_D(\vec{v}_1 \cdot (\vec{v}_2 \times \vec{v}_3 > 0) - \Gamma_D(\vec{v}_1 \cdot (\vec{v}_2 \times \vec{v}_3 < 0)}{\Gamma_D(\vec{v}_1 \cdot (\vec{v}_2 \times \vec{v}_3 > 0) + \Gamma_D(\vec{v}_1 \cdot (\vec{v}_2 \times \vec{v}_3 < 0)} \qquad \vec{v}_i = \{\vec{s}\,,\, \vec{p}\}$$

  - But FSI can produce $A_T \neq 0$

BABAR: PRD-RC 81 111103 (2010)

- Measure CPV observable $a_{CP}^{T-odd} = 1/2(A_T - \bar{A}_T)$ using triple products of final state particle momenta in $D^0 \to K^+K^-\pi^+\pi^-$ decays in D^0 $c.m.s.$

$$D^0 :\ C_T \equiv \vec{p}_{K^+} \cdot (\vec{p}_{\pi^+} \times \vec{p}_{\pi^-}) \qquad A_T \equiv \frac{\Gamma_{D^0}(C_T > 0) - \Gamma_{D^0}(C_T < 0)}{\Gamma_{D^0}(C_T > 0) + \Gamma_{D^0}(C_T < 0)}$$

$$\bar{D}^0 :\ \bar{C}_T \equiv \vec{p}_{K^-} \cdot (\vec{p}_{\pi^-} \times \vec{p}_{\pi^+}) \qquad \bar{A}_T \equiv \frac{\Gamma_{\bar{D}^0}(-\bar{C}_T > 0) - \Gamma_{\bar{D}^0}(-\bar{C}_T < 0)}{\Gamma_{\bar{D}^0}(-\bar{C}_T > 0) + \Gamma_{\bar{D}^0}(-\bar{C}_T < 0)}$$

  - Effective CPV differs depending on strong phase difference of the two interfering amplitudes $(\delta_1 - \delta_2)$

weak phases   strong phases

$$\mathcal{A}_{CP} \propto sin(\phi_1 - \phi_2) \cdot sin(\delta_1 - \delta_2) \qquad a_{CP}^{T-odd} \propto sin(\phi_1 - \phi_2) \cdot cos(\delta_1 - \delta_2)$$

a_{CP}^{T-odd} maximal for small $(\delta_1 - \delta_2)$

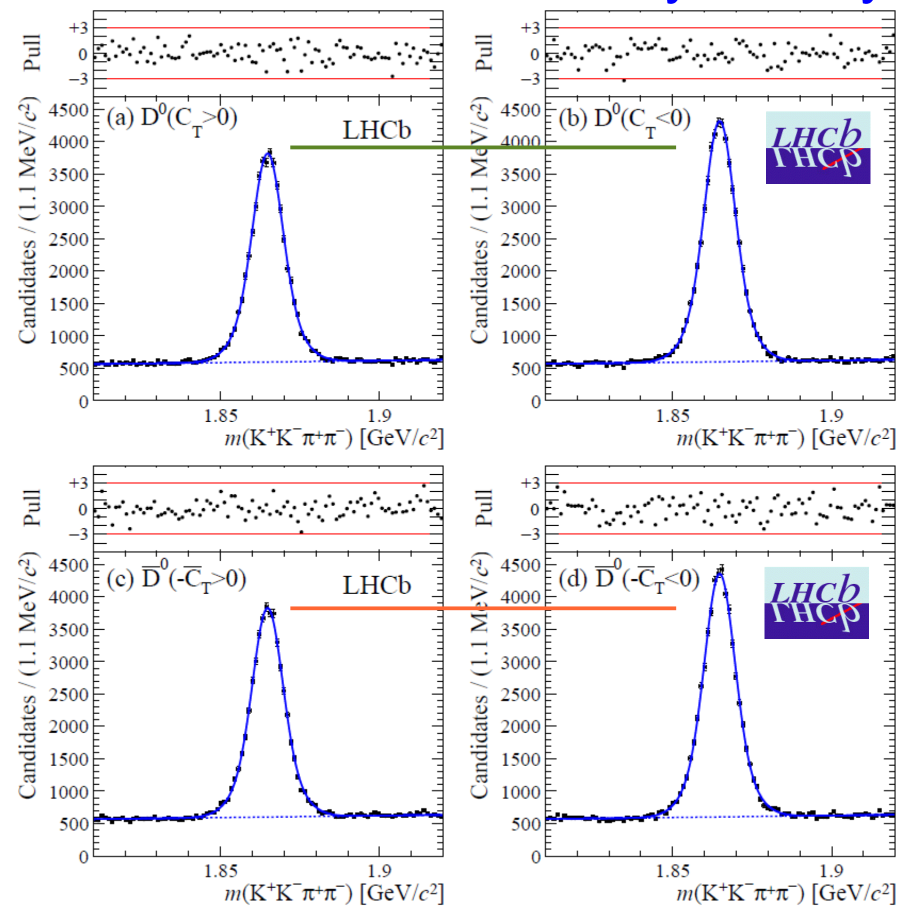
CPV - T-odd Cor. in $D^0 \to K^+K^-\pi^+\pi^-$

LHCb searches for CPV in 171 k secondary $D^0 \to K^+K^-\pi^+\pi^-$ decays using T-odd correlations with $3fb^{-1}$ of data

arXiv:1408.1299
accepted by JHEP

- Measure phase space integrated T-odd observables and CP asymmetry

$$D^0 \; : \; A_T = (-7.18 \pm 0.41 \pm 0.13)\%$$
$$\bar{D}^0 \; : \; \bar{A}_T = (-7.55 \pm 0.41 \pm 0.12)\%$$



CPV - T-odd Cor. in $D^0 \to K^+K^-\pi^+\pi^-$

LHCb searches for CPV in 171 k secondary $D^0 \to K^+K^-\pi^+\pi^-$ decays using T-odd correlations with $3fb^{-1}$ of data

arXiv:1408.1299
accepted by JHEP

- Measure phase space integrated T-odd observables and CP asymmetry

$$D^0 \ : \ A_T = (-7.18 \pm 0.41 \pm 0.13)\%$$
$$\bar{D}^0 \ : \ \bar{A}_T = (-7.55 \pm 0.41 \pm 0.12)\%$$

$$a_{CP}^{T-odd} = (0.18 \pm 0.29 \pm 0.04)\%$$

CPV - T-odd Cor. in $D^0 \to K^+K^-\pi^+\pi^-$

LHCb searches for CPV in 171 k secondary $D^0 \to K^+K^-\pi^+\pi^-$ decays using T-odd correlations with $3fb^{-1}$ of data

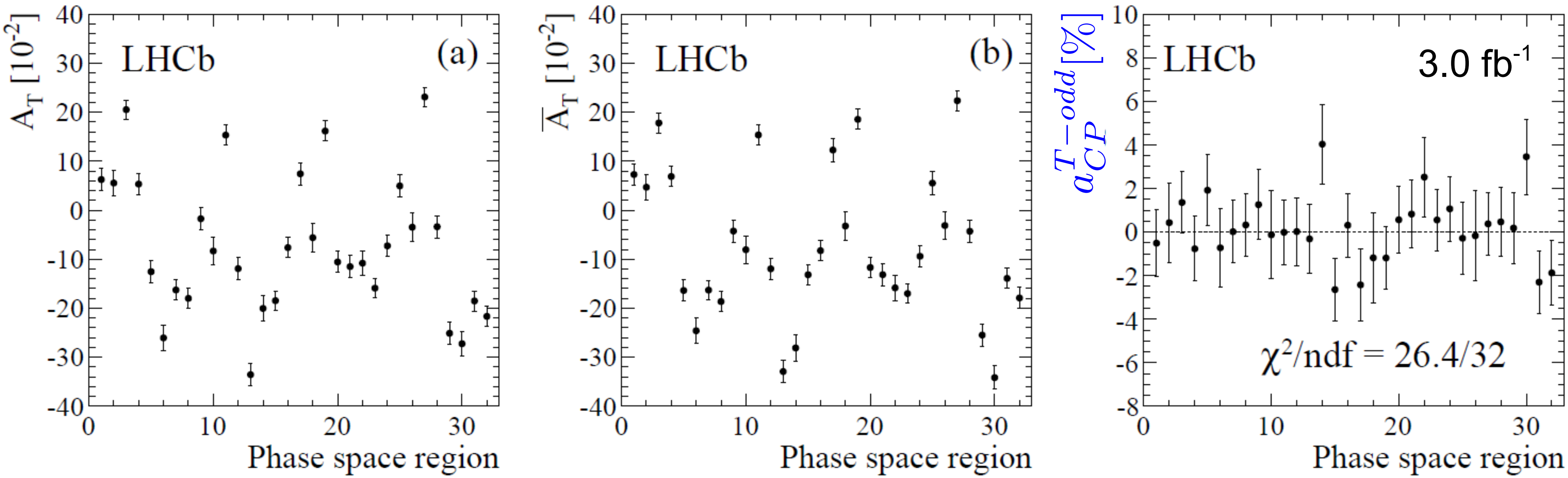
arXiv:1408.1299
accepted by JHEP

- Measure phase space integrated T-odd observables and CP asymmetry

$$D^0 \;:\; A_T = (-7.18 \pm 0.41 \pm 0.13)\%$$
$$\bar{D}^0 \;:\; \bar{A}_T = (-7.55 \pm 0.41 \pm 0.12)\%$$

$$a_{CP}^{T-odd} = (0.18 \pm 0.29 \pm 0.04)\%$$

- Variations of T-odd variable with 5D phase space cancelling in a_{CP}^{T-odd}



CPV - T-odd Cor. in $D^0 \to K^+K^-\pi^+\pi^-$

LHCb searches for CPV in 171 k secondary $D^0 \to K^+K^-\pi^+\pi^-$ decays using T-odd correlations with $3fb^{-1}$ of data

arXiv:1408.1299
accepted by JHEP

- Measure phase space integrated T-odd observables and CP asymmetry

$$D^0 \; : \; A_T = (-7.18 \pm 0.41 \pm 0.13)\%$$
$$\bar{D}^0 \; : \; \bar{A}_T = (-7.55 \pm 0.41 \pm 0.12)\%$$

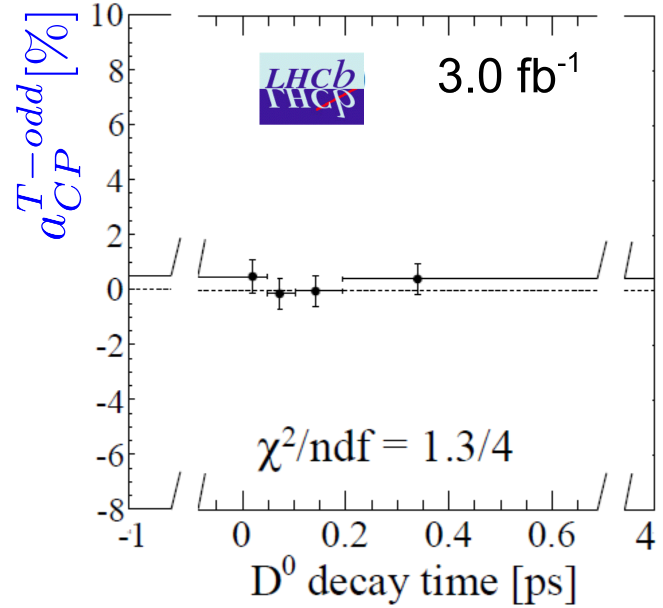
$$a_{CP}^{T-odd} = (0.18 \pm 0.29 \pm 0.04)\%$$

- Variations of T-odd variable with 5D phase space cancelling in a_{CP}^{T-odd}

- No variations with τ_{D^0} which excludes effects of indirect CPV

- Precision on a_{CP}^{T-odd} significantly improved

No evidence of CP asymmetry

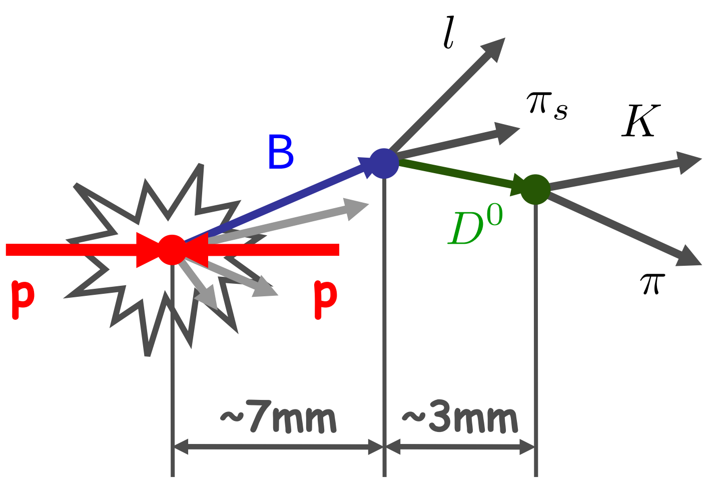


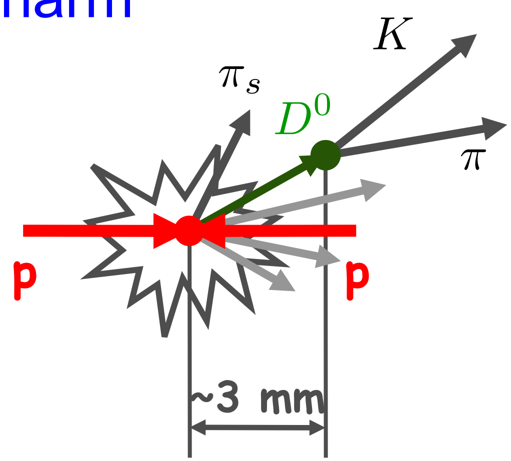
Charm Production at Hadron Colliders

The large cross section for charm production at hadron colliders leads to
$10^{12} c\bar{c}/fb^{-1}$ events within LHCb acceptance $\rightarrow$ world's largest c sample

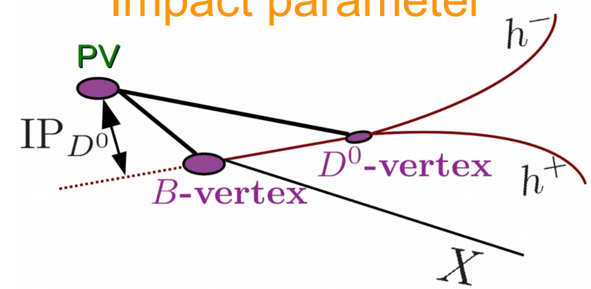
- Prompt and secondary charm

$BR(B \rightarrow D^{*\pm}X) \approx 0.23$

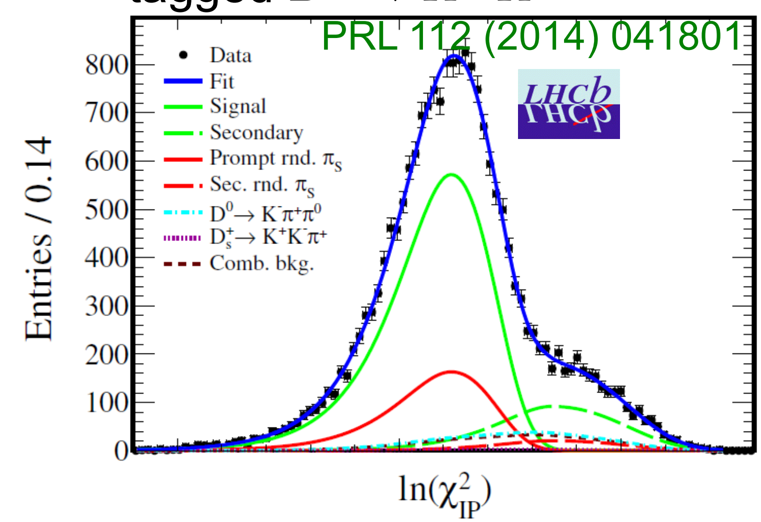




Impact parameter



tagged $D^0 \rightarrow K^+K^-$



PV resolution
$\sigma_{x,y} \approx 11\ \mu m\,,\ N_{Tr} \approx 30$
$\sigma_z \approx 65\ \mu m\,,\ N_{Tr} \approx 30$

IP resolution, p_t > 2 GeV
$\sigma_{IP} \approx 22\ \mu m$

LHCb uses both charm samples

Asymmetry Measurements

Measure CP asymmetries at $10^{-3} \rightarrow$ control systematic uncertainties at a similar level

- Determine raw asymmetries A_{raw} by comparing partial decay rates of a process and its CP conjugate

$$A_{raw} = \frac{N(x) - N(\bar{x})}{N(x) + N(\bar{x})}$$

- Systematic uncertainties cancel, 2 contributions in case of LHCb
  - production rate asymmetries, A_P (measurements for $B^0, B^0_s, B^+, \Lambda^0_b$)
  - asymmetries due to particle / anti-particle detection, A_D

Phys. Lett. B774 (2017) 139

- For LHCb A_P and A_D are determined by
  - use of control samples
  - regularly reverse magnet polarity
  - remove fiducial volumes contributing to asymmetries

- CP asymmetry: $A_{CP} = A_{raw} - A_P - A_D$