Mixing & CP Violation in Charm

From LHCb perspective

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Flavour Physics with High-Luminosity Experiments

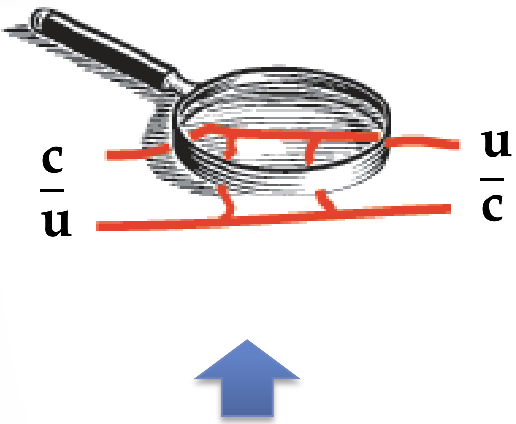
Munich, November 2016

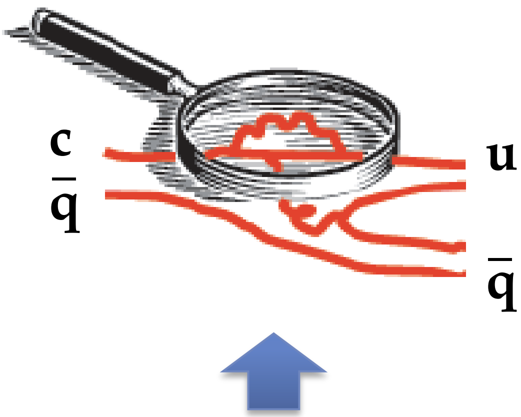
Outline

- Why is charm special?
- Where and how is charm studied?
- Introduction to mixing and CPV
- Recent results from LHCb
- Future opportunities and limitations
- Summary

Is there any New Physics?

- Loop processes are promising for NP searches





Underlies D^0-$\bar{D}^0$ mixing

Needed for CPV in charm decays

- Before we find NP it would be good
to measure mixing parameters and observe any CPV

Why is charm special?

- Complementary to strange and beauty sectors
- Unique access to system with up-type quarks
- Down-type quarks in loops: different New Particles?

- But…
- In SM rare charm processes are very suppressed
- QCD 'corrections' are large (usually disadvantageous)

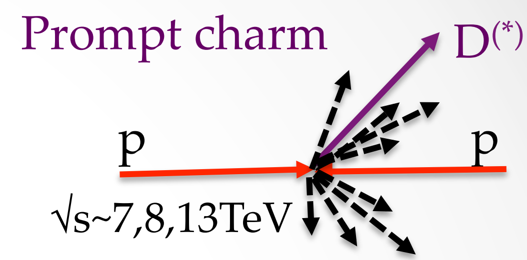
- Thus we need
- Large/clean data samples
- Precise estimation of SM contribution (penguin size)

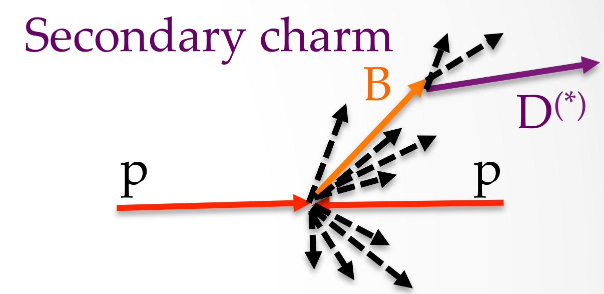
"Everything is smaller in charm"

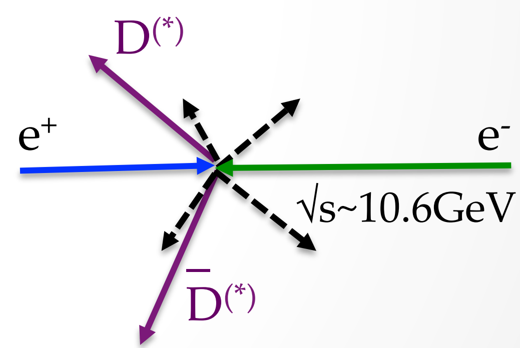
Mat Charles at CKM2014

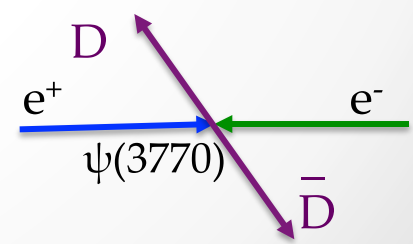
Charm samples

type	exp	$\sqrt{s}$	L_{int}	$\sigma(c\bar{c})$	$N(c\bar{c})$
hadron colliders					prompt charm
	LHCb	7, 8 TeV	3/fb	1.4 mb	3.6×10^{12}
		13 TeV	2/fb +	2.6 mb	4.5×10^{12}
	CDF	2 TeV	10/fb	0.1 mb	2.3×10^{11}
e^+e^- colliders	B-Factories			continuum charm	
	Belle	10.6 GeV	1000/fb	1.3 nb	1.3×10^{9}
	BaBar		550/fb		0.7×10^{9}
	Charm Factories @$D\bar{D}$ threshold				
	BESIII	3.7 GeV	3/fb	3 nb	20×10^{6}
	Cleo-c		0.8/fb		5×10^{6}



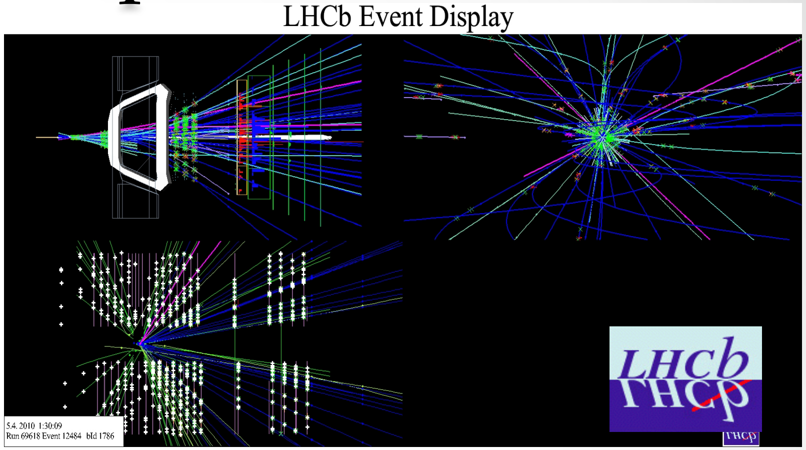






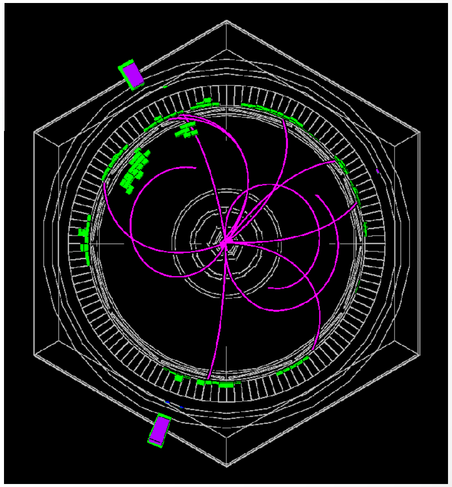
Pros & cons of charm experiments

- **LHCb**



☑ large x-section
☒ busy environment, nontrivial triggers
☒ decays with γ's and neutrinos difficult
☑ D flight distance~10mm, $\sigma(t)\sim0.1\times\tau_D$
☑ magnet polarity reversed periodically
☒ asymmetric production of charm/anti-charm

- **Belle/BaBar**



☑ clean environment
☑ good for neutrals & decays with neutrinos
☐ D flight distance~200μm, $\sigma(t)\sim0.5\times\tau_D$

- **BESIII/Cleo-c**

☑ background-free charm
☒ charm not boosted ⇨ no time measurement
☑ $\psi(3770)\rightarrow D\bar{D}$ quantum coherence ⇨ $CP(D)\times CP(\bar{D})=-1$

LHCb changes & will change more

- **LHCb Run-1** (2010-2012) Collected 3 fb^{-1}

  Finalizing charm analyses. Still more to come
- **LHCb Run-2** (2015-2018) Collect 5 fb^{-1} (2 fb^{-1} already collected)

  Improved triggers & computing. First results (charm x-section)

- **LHCb Run-3, Run-4** (2021-2023, 2026-2029)

  Major New Experiment: LHCb Upgrade Phase-I

  Collect >50 fb^{-1} data

  L ~2×10^{33} cm^{-2} s^{-1}

- **LHCb Run-5** (2031-)

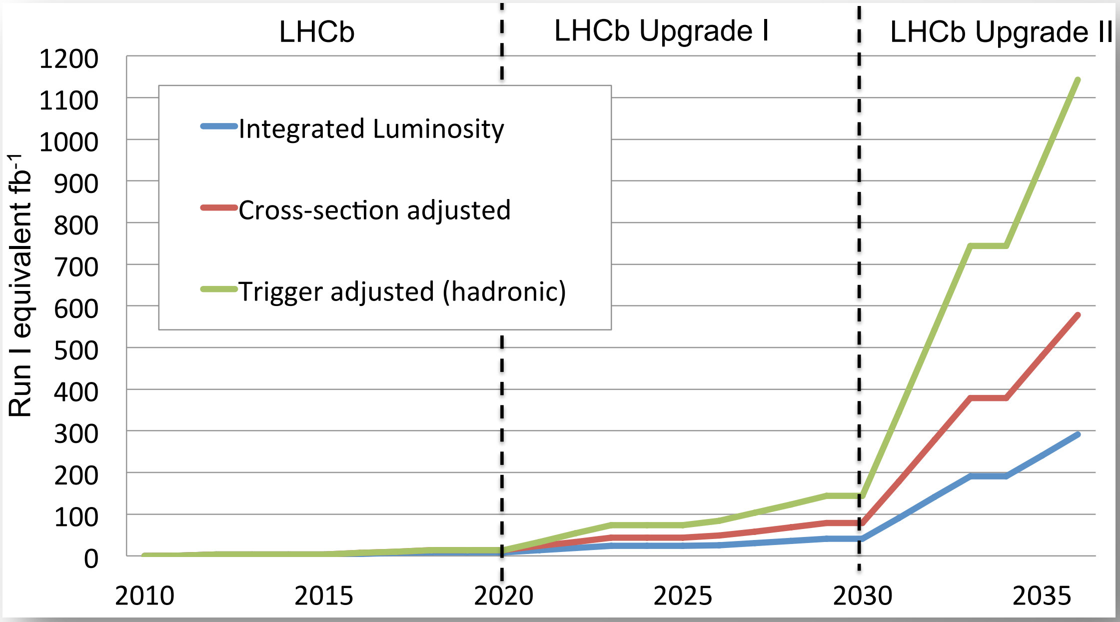
  LHCb Upgrade Phase-II

  Plans in discussion

  Collect ~300 fb^{-1} data

  L ~2×10^{34} cm^{-2} s^{-1}

C.Parkes@Charm2016

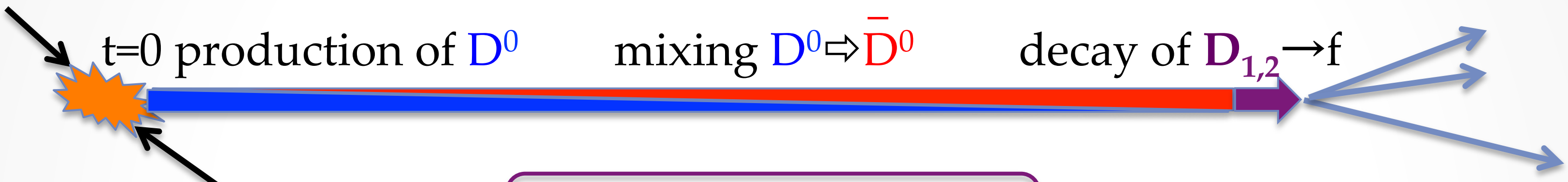


Quick Introduction
for non-charmers

Basics of mixing

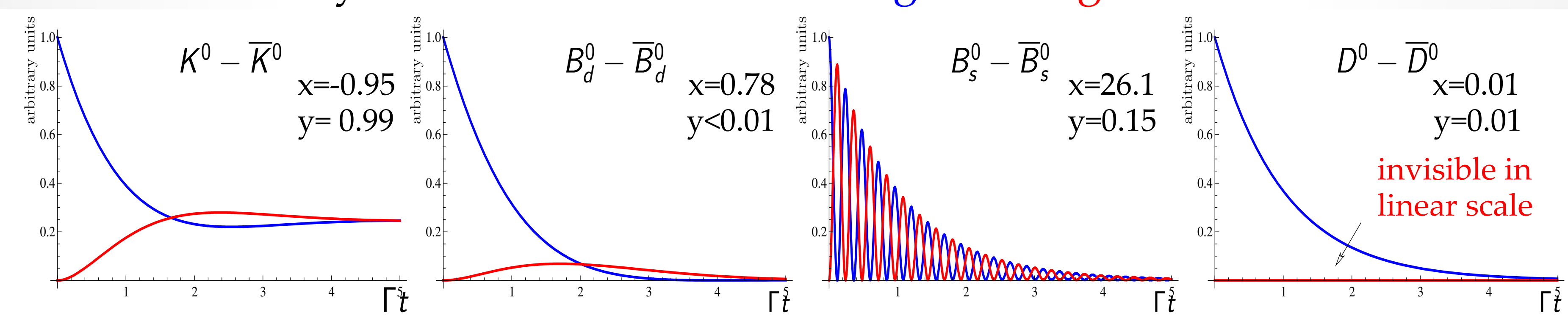
- Flavour eigenstates D^0 [$c\bar{u}$] $\bar{D}^0$ [$\bar{c}u$] ≠ mass eigenstates D_1 D_2 [$m_{1,2}$ $\Gamma_{1,2}$]

$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle \qquad |p|^2 + |q|^2 = 1$$



- Mixing frequencies $x = \dfrac{m_2 - m_1}{\Gamma}$ $\quad y = \dfrac{\Gamma_2 - \Gamma_1}{2\Gamma}$ $\quad \Gamma = \dfrac{\Gamma_1 + \Gamma_2}{2}$

- Probability that initial flavour unchanged/changed at time t



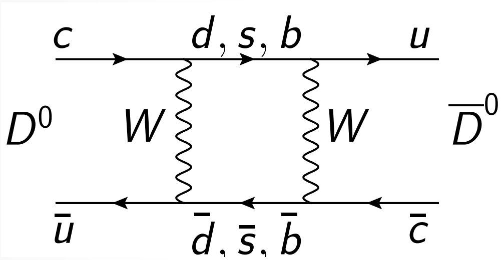
$$\mathcal{P}[D^0(t) \to D^0] \propto e^{-\Gamma t}\left[\cosh(\mathbf{y}\Gamma t) + \cos(\mathbf{x}\Gamma t)\right] \qquad \mathcal{P}[D^0(t) \to \overline{D}^0] \propto \left|\frac{q}{p}\right|^2 e^{-\Gamma t}\left[\cosh(\mathbf{y}\Gamma t) - \cos(\mathbf{x}\Gamma t)\right]$$

non-oscillating oscillating

What's behind x and y?

Short distance

mixing @ quark level

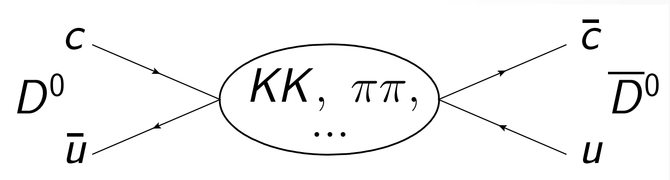


x~10^{-5}

- b loop ~$V_{ub}V_{cb}(m_b/m_W)^2$
- s & d cancel in SU(3) limit (m_s=m_d)

Long distance

mixing via final-state interactions



x, y ~ 1%

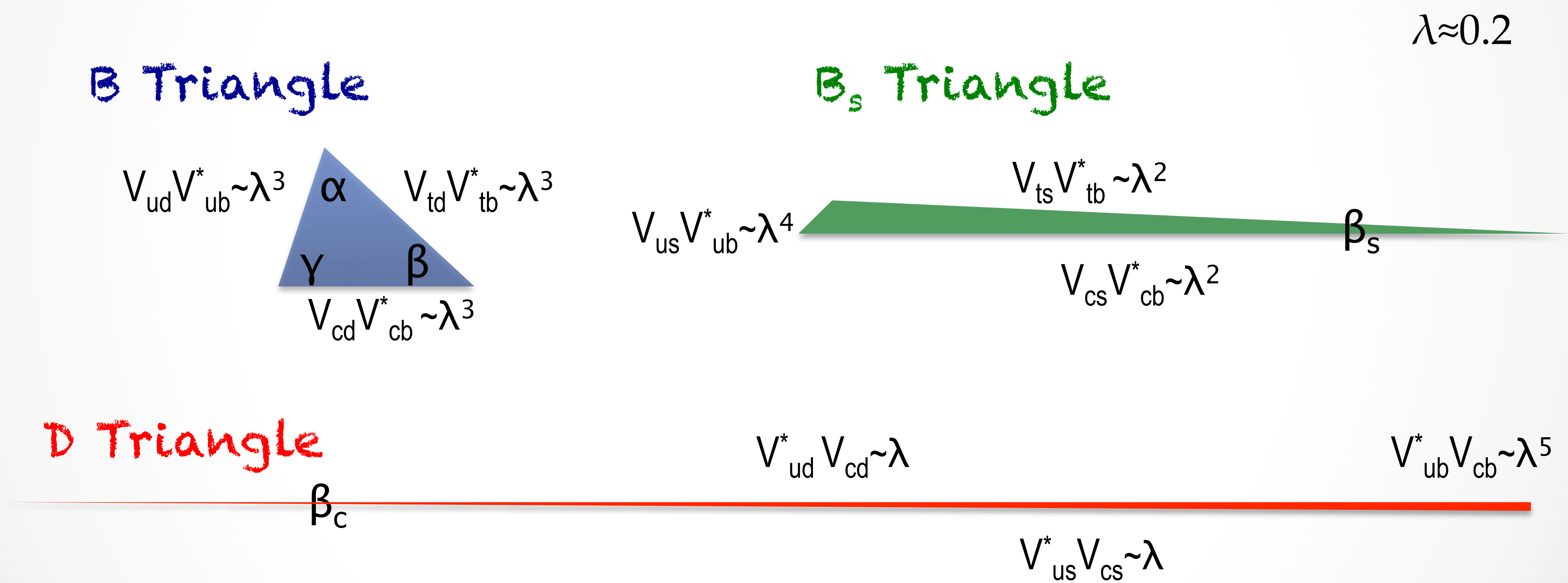
difficult to calculate

- No significant x measurement yet
- Large uncertainties in SM mixing rate ⇨ difficult to identify NP
- NP can increase x, does not affect y
- LQCD calculations finally happening (coupled channels with 2-body final states)

See M.Hansen talk @ 6th LHCb Implications Workshop

What charm UT tells us?

- If the CKM matrix elements complex ⇨ CPV exists ⇨ UT triangles
- Triangle openness indicates how large CPV expected



- D triangle ⇨ tiny CPV in preferred decays, larger CPV in rare decays

CP Violation: Types and Observables

direct CPV

In decays $|D \to f|^2 \neq |\bar{D} \to \bar{f}|^2 \Rightarrow |\bar{A}_{\bar{f}}/A_f|^2 \neq 1$

- Difference in rates for particles and antiparticles
- Depends on decay mode

indirect CPV

In mixing $|D^0 \to \bar{D}^0|^2 \neq |\bar{D}^0 \to D^0|^2 \Rightarrow |q/p| \neq 1$

In interference between mixing and decays $\left| D^0 \to \bar{D}^0 \to f + D^0 \to f \right|^2 \neq \left| \bar{D}^0 \to D^0 \to f + \bar{D}^0 \to f \right|^2$

$\Rightarrow \phi = \arg(q/p) \neq 0$

- Difference in rates as function of D^0 decay-time
- Independent of decay mode
- Final states accessible for both D^0 and $\bar{D}^0$

Mixing & indirect CPV

- Universal = don't depend on decay mode
- The way they are probed depends on decay mode
- Only in D^0

Recent results from LHCb + BaBar

- $D^0 \to K\pi$, LHCb
- $D^0 \to K\pi\pi\pi$, LHCb
- $D^0 \to \pi\pi\pi^0$, BaBar
- $D^0 \to K_S\pi\pi$, LHCb
- A_Γ , LHCb

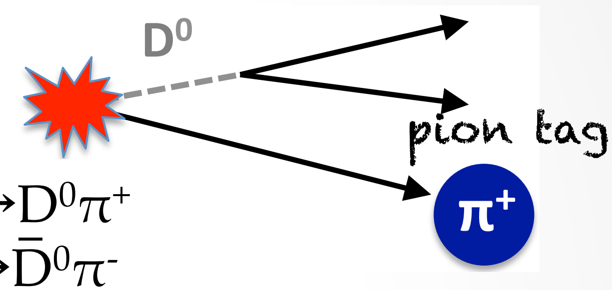
How to get flavour of D^0?

- Tag flavour at the production
  (then mixing changes flavour)

Prompt charm $pp \to D^{*\pm}$

- D tagged with soft-pion charge
- $D^{*\pm}$ reconstructed with high purity

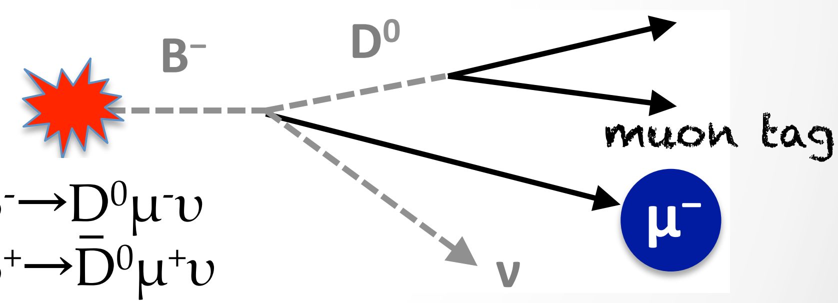
$D^{*+} \to D^0 \pi^+$
$D^{*-} \to \bar{D}^0 \pi^-$



Secondary charm $pp \to B \to D$

- D tagged with muon charge
- Not as pure, mis-tag ~few%

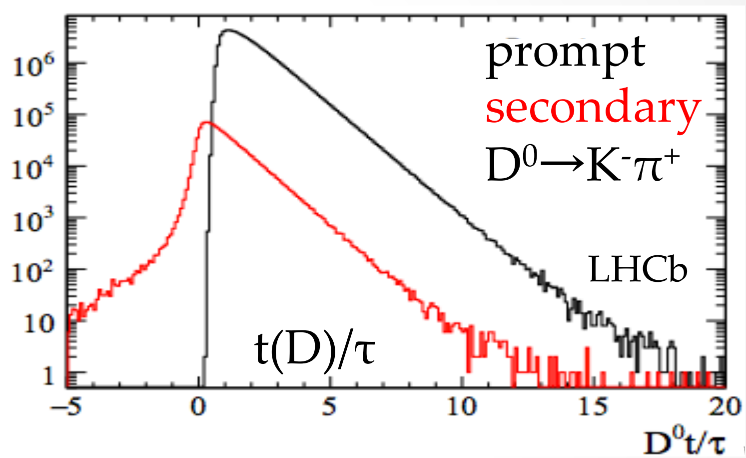
$B^- \to D^0 \mu^- \upsilon$
$B^+ \to \bar{D}^0 \mu^+ \upsilon$

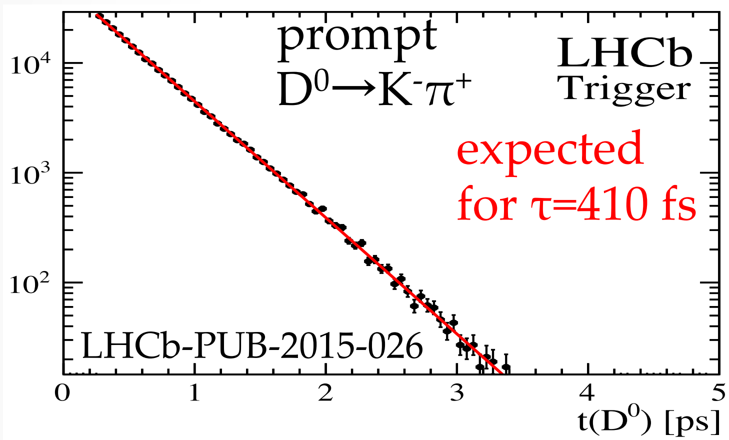


Doubly-tagged secondary charm $pp \to B \to D^{*\pm}$

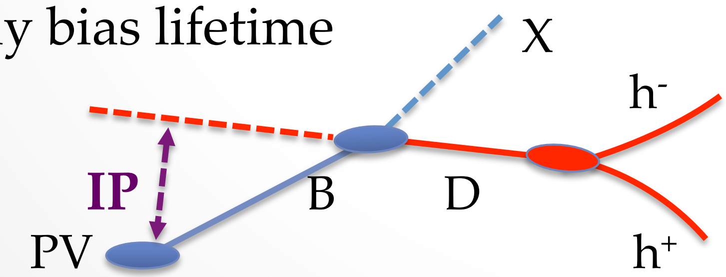
Prompt/secondary charm & related issues

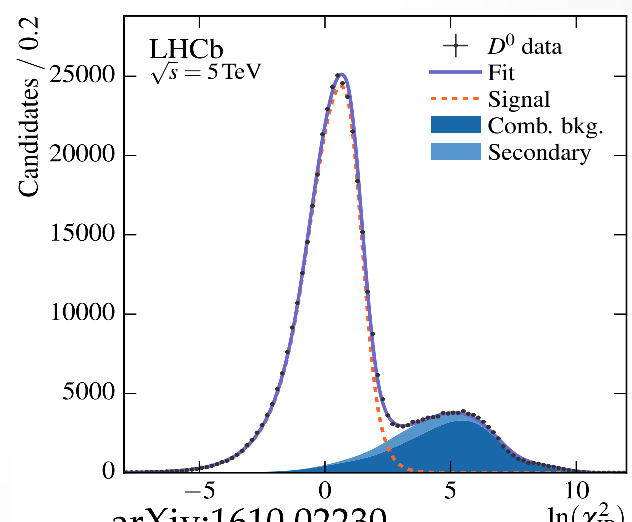
- Both samples used at LHCb ⇨ full coverage of D decay time
- Distorted decay time of prompt D
- Lifetime-unbiased triggers in Run-2





- Non-trivial prompt/sec separation
- May bias lifetime



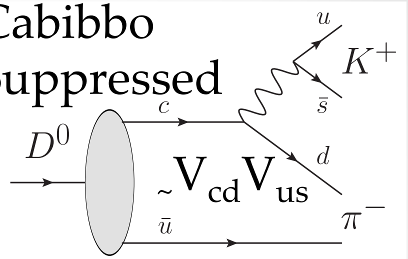


arXiv:1610.02230

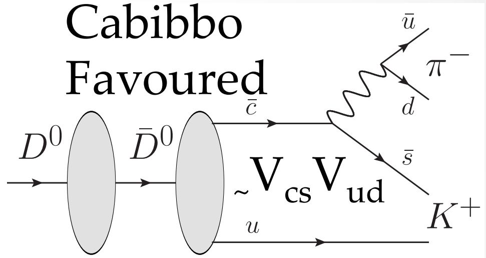
D^0 & $\bar{D}^0$ mix since 2013

- $D^0 \to K^+\pi^-$ = Wrong-Sign, $D^0 \to K^-\pi^+$ = Right-Sign

Cabibbo Suppressed



Cabibbo Favoured



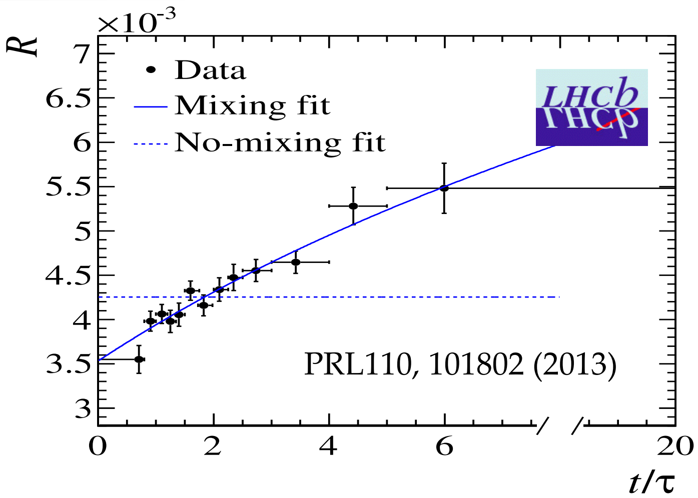
- WS/RS rate as a function of D^0 decay time

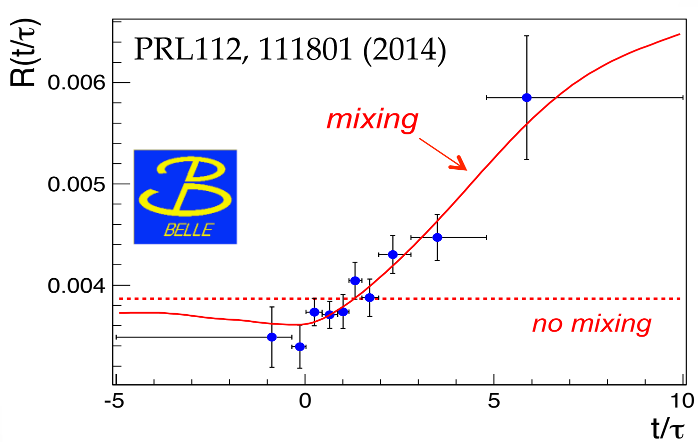
$$R(t) = \frac{N_{WS}}{N_{RS}}(t) \approx R_D + \sqrt{R_D}\, y' \frac{t}{\tau} + \frac{x'^2 + y'^2}{4}\left(\frac{t}{\tau}\right)^2$$

Decay CS/CF

Interference Mixing & Decay

Mixing





~1000×τ(D^0) needed to see full oscillation!

Mixing from WS/RS $D^0 \to K\pi$

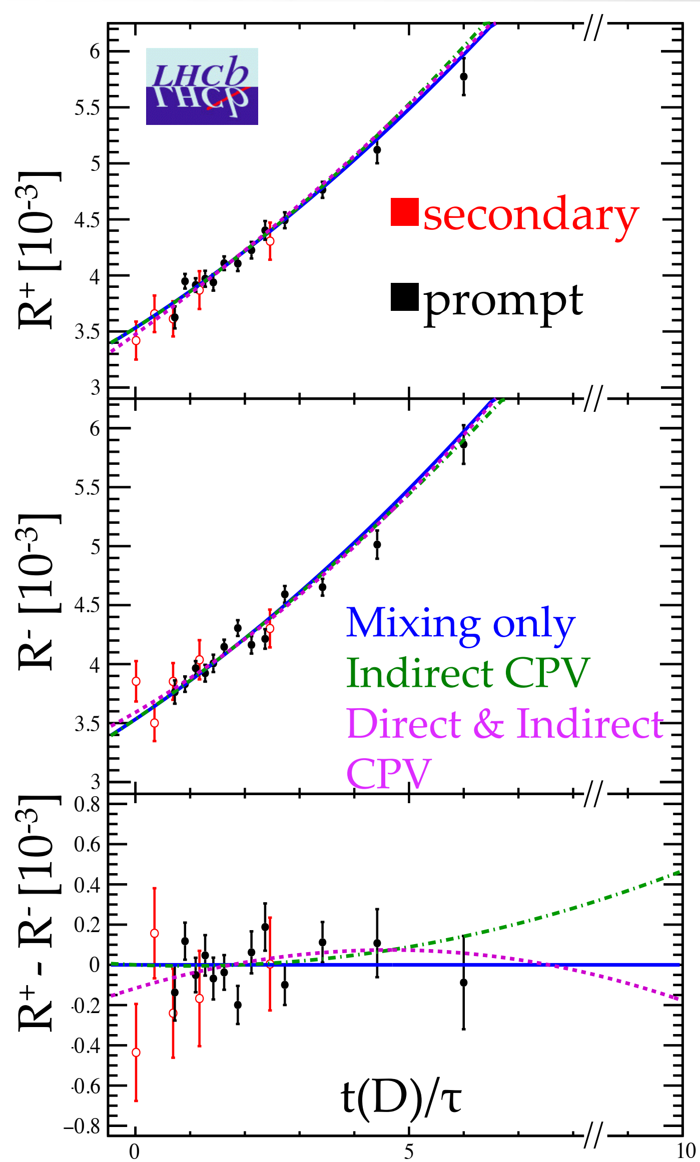
- With secondary charm, doubly tagged
- WS & RS signal yields in t bins ⇨

$$R(t) = \frac{N_{WS}}{N_{RS}}(t) \approx R_D + \sqrt{R_D}\, y' \frac{t}{\tau} + \frac{x'^2 + y'^2}{4}\left(\frac{t}{\tau}\right)^2$$

$$R_D = \frac{BR(CS\ \ D^0 \to K\pi)}{BR(CF\ \ D^0 \to K\pi)} \quad \begin{pmatrix} x' \\ y' \end{pmatrix} = \begin{pmatrix} \cos\delta_{K\pi} & \sin\delta_{K\pi} \\ -\sin\delta_{K\pi} & \cos\delta_{K\pi} \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix}$$

- $\delta_{K\pi}$: CF/CS strong phase; from Cleo-c/BESIII
- $R^{\pm}(t)$ for D produced as $D^0/\bar{D}^0$
- CPV if x, y, R_D differ for two flavours
- No evidence for CPV
- Prompt & secondary combination
- 20% improvement from sec charm

$$R_D = (3.53 \pm 0.05) \times 10^{-3}$$
$$y' = (5.2 \pm 0.8) \times 10^{-3}$$
$$x'^2 = (3.6 \pm 4.3) \times 10^{-5}$$



PRL116, 241801 (2016)

New mixing with $D^0 \to K\pi\pi\pi$

- WS: $D^0 \to K^+\pi^-\pi^+\pi^-$ RS: $D^0 \to K^-\pi^+\pi^+\pi^-$, pion-tagged

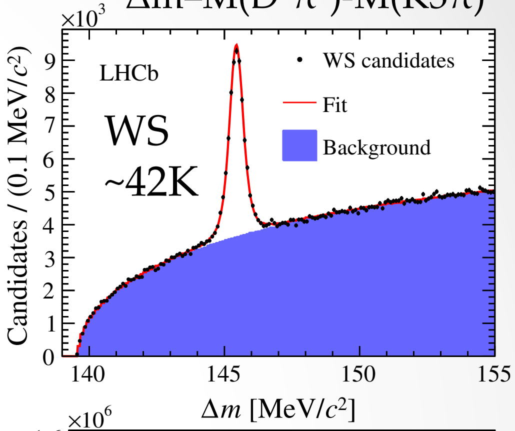
$$R(t) = \frac{N_{WS}}{N_{RS}}(t) \simeq R_D^{K3\pi} + \sqrt{R_D^{K3\pi}} R_{coh}\, y' \frac{t}{\tau} + \frac{x'^2 + y'^2}{4}\left(\frac{t}{\tau}\right)^2$$

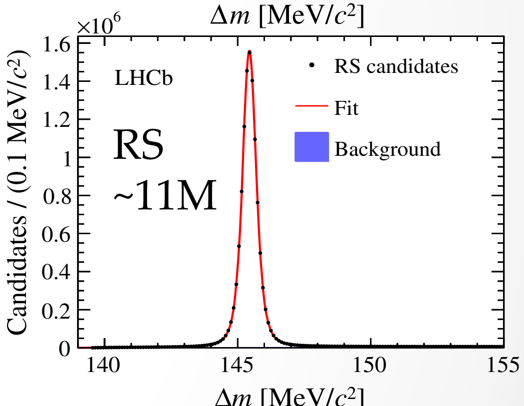
- Rates integrated over 5D Phase Space ⇨ dilution

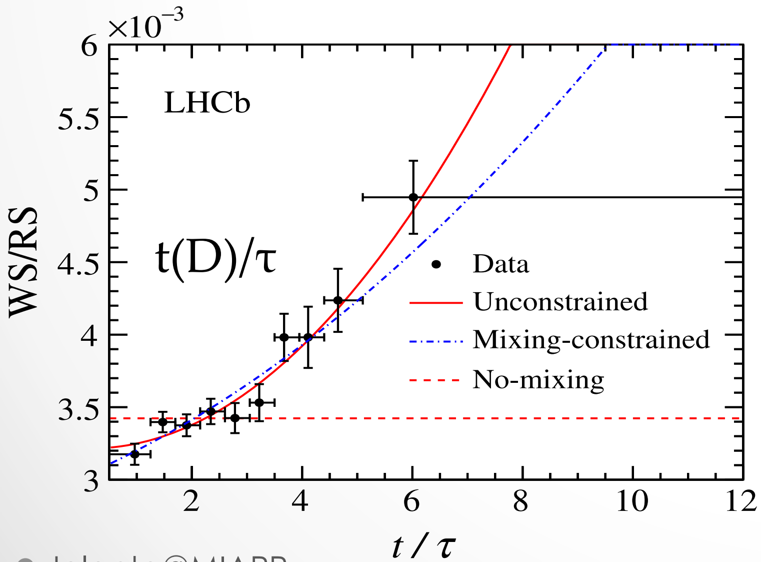
⇨ averaged strong phase and R_{coh} coherence factor

$$\int A_{K-3\pi}(\mathbf{r}) A_{K+3\pi}(\mathbf{r})\, d\mathbf{r} \Rightarrow R_{coh} e^{-i\delta_{K3\pi}}$$

- R_{coh}~0 phase variation; R_{coh}~1 resonances in phase







$$R_{coh} y' = (0.3 \pm 1.8) \times 10^{-3}$$

$$(x'^2 + y'^2)/4 = (4.8 \pm 1.8) \times 10^{-5}$$

- Measurement w/o PS integration expected to have large sensitivity

PRD93, 112014 (2016)

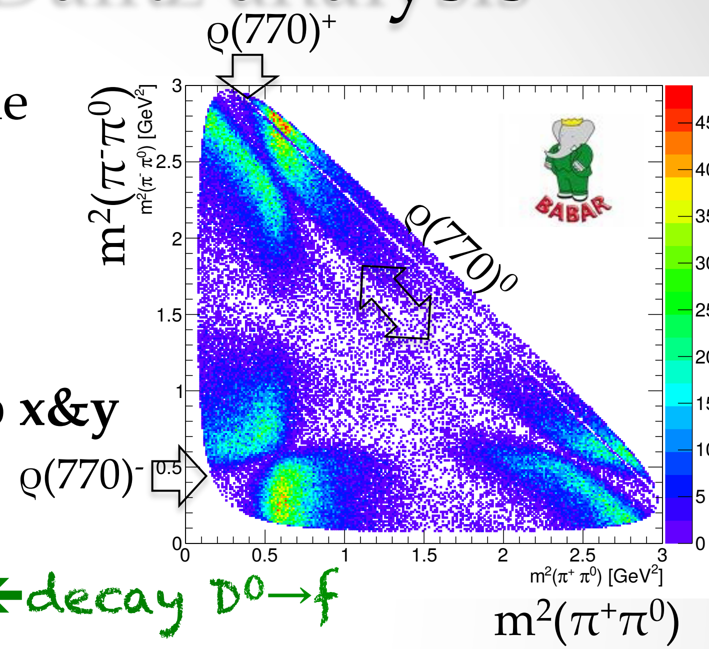
$D^0 \to \pi^+\pi^-\pi^0$, t-dependent Dalitz analysis

- Measure how Phase Space evolves with time

✗ Need model to describe resonances

ρ(770)→ππ dominate

✓ Access to interfering amplitudes and phases, no coherence factor dilution, **direct access to x&y**



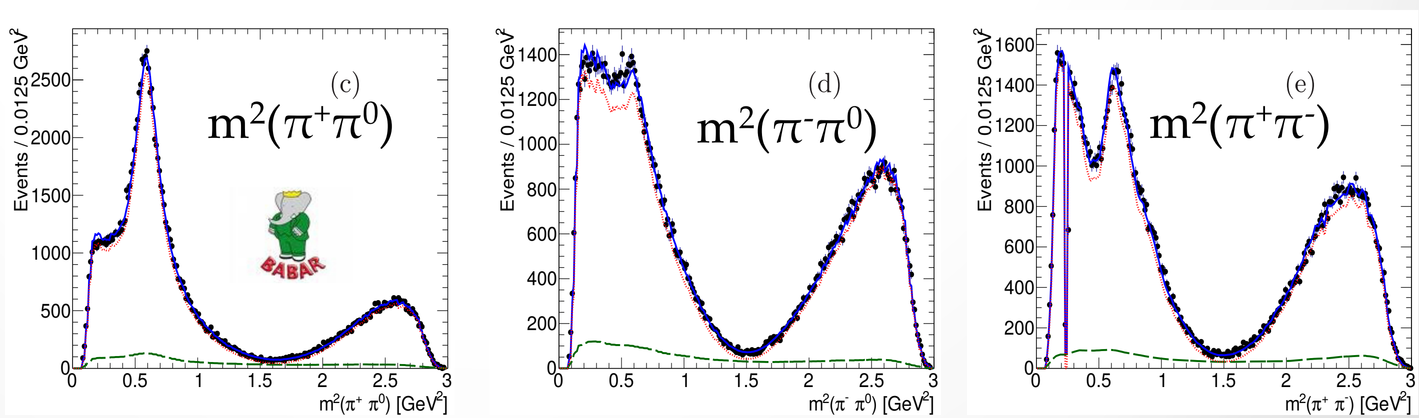
- Rate for D produced at t=0 as D^0

$$\mathcal{P}\left[D^0(Dalitz;t)\right] \propto e^{-\Gamma t}\Big\{|A_f|^2[\cosh(y\Gamma t)+\cos(x\Gamma t)]$$ ←decay $D^0 \to f$

$$+\left|\frac{q}{p}\overline{A}_f\right|^2[\cosh(y\Gamma t)-\cos(x\Gamma t)]$$ ←mixing $D^0 \to \bar{D}^0 \to f$

$$-2\Re\left(\frac{q}{p}A_f^*\overline{A}_f\right)\sinh(y\Gamma t)-2\Im\left(\frac{q}{p}A_f^*\overline{A}_f\right)\sin(x\Gamma t)\Big\}$$ ←interference of both

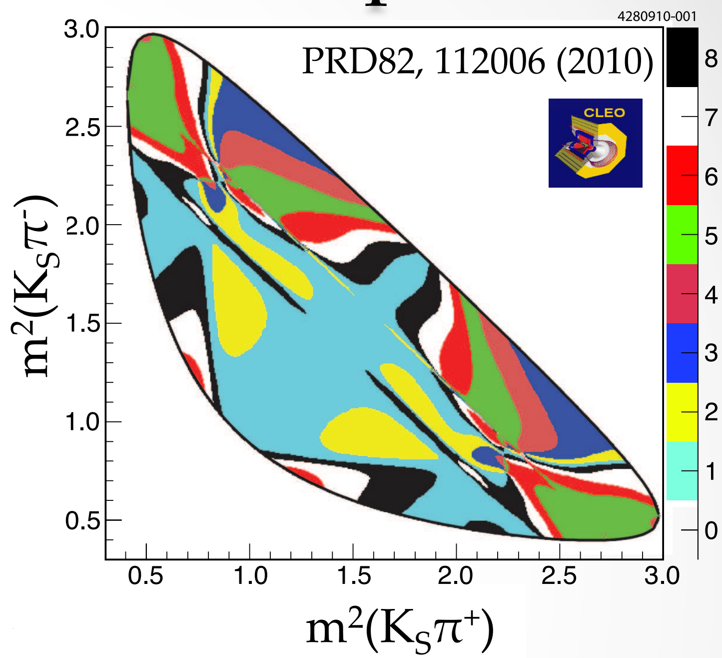
$$x = (1.5 \pm 1.2 \pm 0.6)\%$$
$$y = (0.2 \pm 0.9 \pm 0.5)\%$$
$$\tau_D = (410.2 \pm 3.8)\ \text{fs}$$

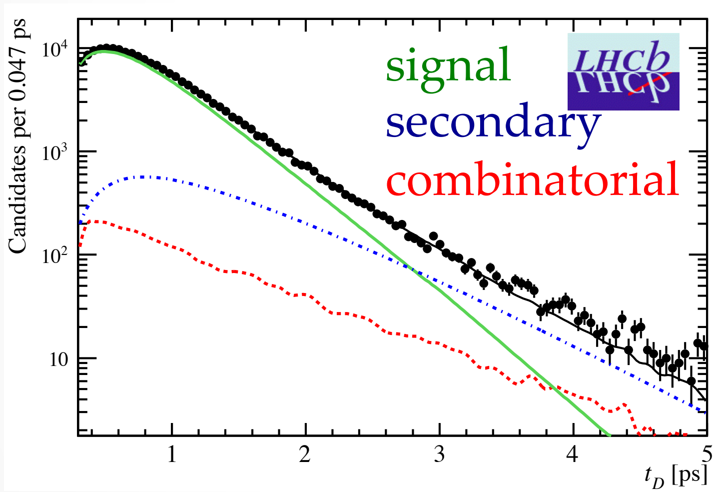


JHEP 04, 033 (2016)

$D^0 \to K_S\pi\pi$, t-dep. Dalitz, model independent

- $D^0 \to K_S\pi\pi$ is a golden mode for mixing
- Binned approach to Dalitz
- Strong phases & fractions from Cleo-c
- Fit t(D) with data driven acceptance





$$x = (-0.86 \pm 0.53 \pm 0.17)\%$$
$$y = (+0.03 \pm 0.46 \pm 0.13)\%$$
$$\tau_D = (410.9 \pm 1.1)\ \text{fs}$$

- This is with 2011 data: 180K signal

  K_S decayed inside vertex detector
- Ongoing for 2012 data: ~2M prompt+sec

  Also K_S decayed outside vertex detector

Belle: 1.2M signal

$$x = \left(0.56 \pm 0.19\,^{+0.04}_{-0.08}\,^{+0.06}_{-0.08}\right)\%$$
$$y = \left(0.30 \pm 0.15\,^{+0.04}_{-0.05}\,^{+0.03}_{-0.07}\right)\%$$

PRD89 091103 (2014)

LHCB-CONF-2016-009
LHCB-CONF-2016-010

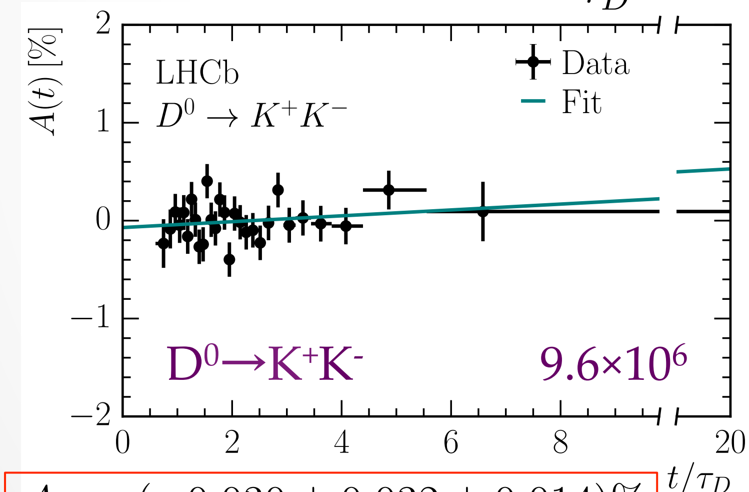
A_Γ: quest for indirect CPV

- Indirect CPV in SM is small: ~10^{-4}
- Easiest via A_Γ = asymmetry of 'effective' lifetimes of CP eigenstates

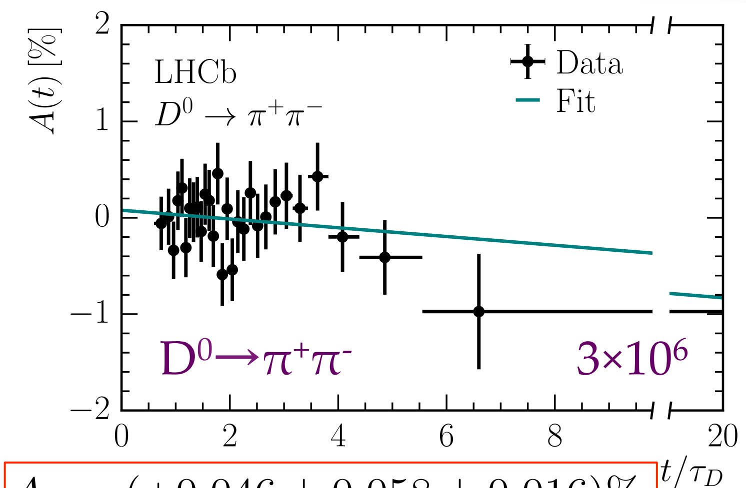
$$A_\Gamma = \frac{\tau(\overline{D}^0 \to h^+h^-) - \tau(D^0 \to h^+h^-)}{\tau(\overline{D}^0 \to h^+h^-) + \tau(D^0 \to h^+h^-)} \simeq -A_{CP}^{\text{indirect}}$$

- Binned approach: asymmetry of yields in t(D) bins

$$A_{CP}(t) \simeq A_{CP}^{\text{direct}} - \mathbf{A}_\Gamma \frac{t}{\tau_D}$$



$A_\Gamma = (-0.030 \pm 0.032 \pm 0.014)\%$



$A_\Gamma = (+0.046 \pm 0.058 \pm 0.016)\%$

- Unbinned approach (via effective lifetimes) gives similar results

A_Γ: status

As of 2015

- Run-1 (2011+2012)

$$A_\Gamma(KK) = (-0.030 \pm 0.032 \pm 0.014)\%$$

$$A_\Gamma(\pi\pi) = (+0.046 \pm 0.058 \pm 0.016)\%$$

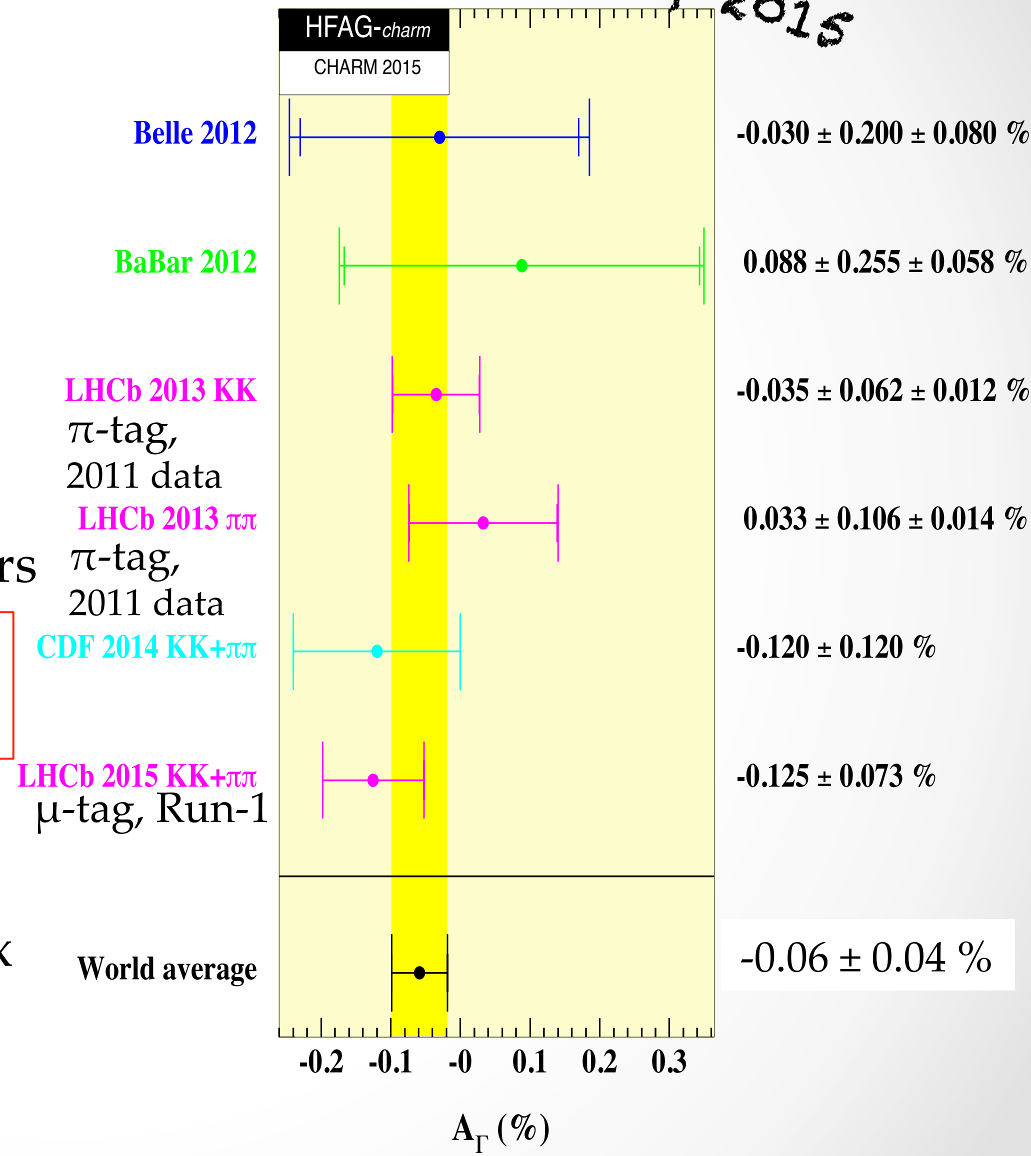
- Sensitivity O(10^{-4})
  Limited by statistics

- A_Γ in terms of basic parameters

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

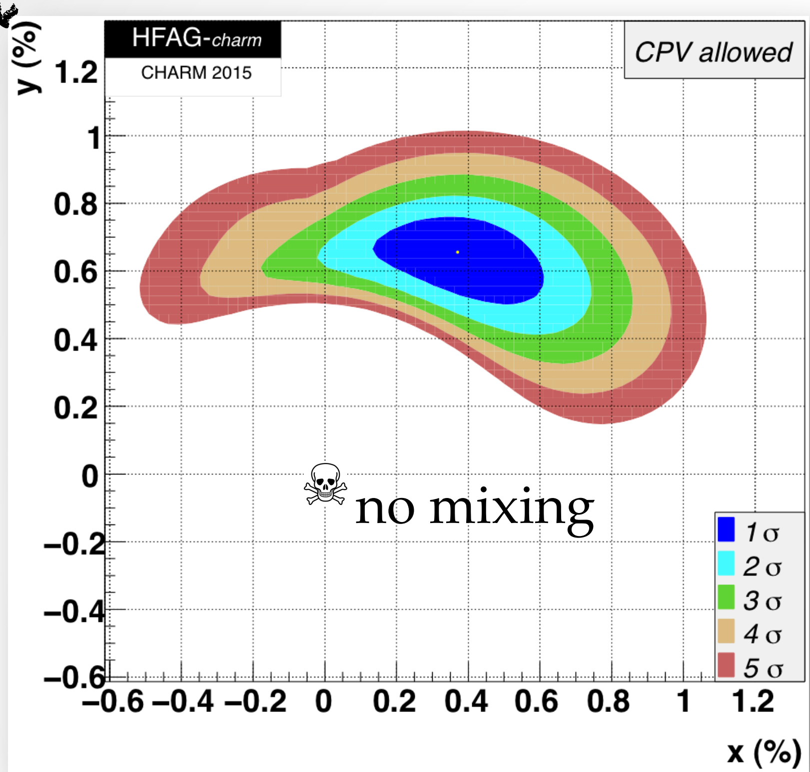
CPV in mixing — in mix-decay interference

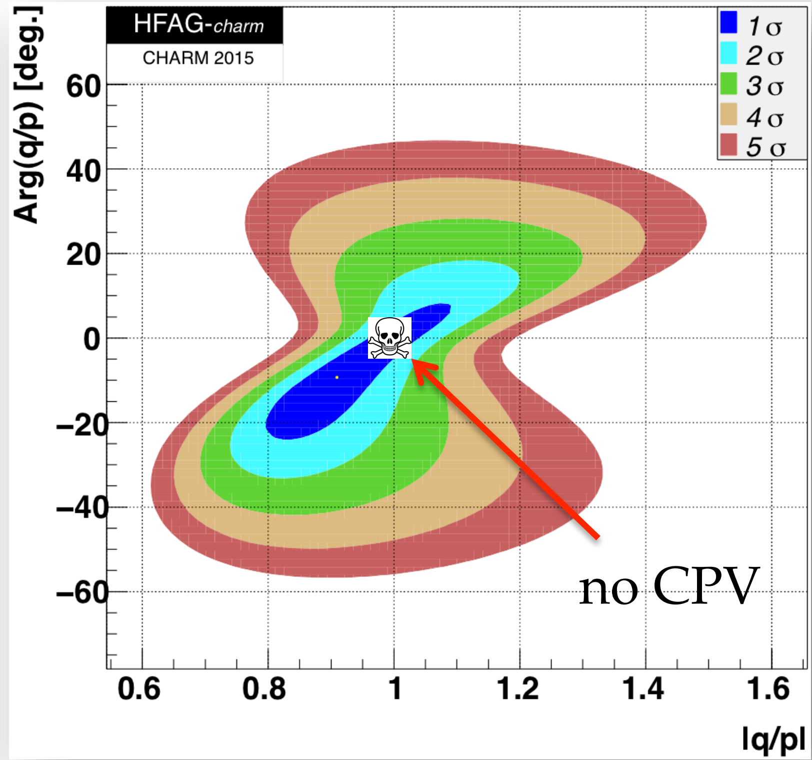
⇨ sensitivity to q/p depends on x



As of 2015

Mixing & indirect CPV from global fit





$x = (0.37 \pm 0.16)\%$ $\quad y = \left(0.66^{+0.07}_{-0.10}\right)\%$

$|q/p| = 0.91^{+0.12}_{-0.08}$

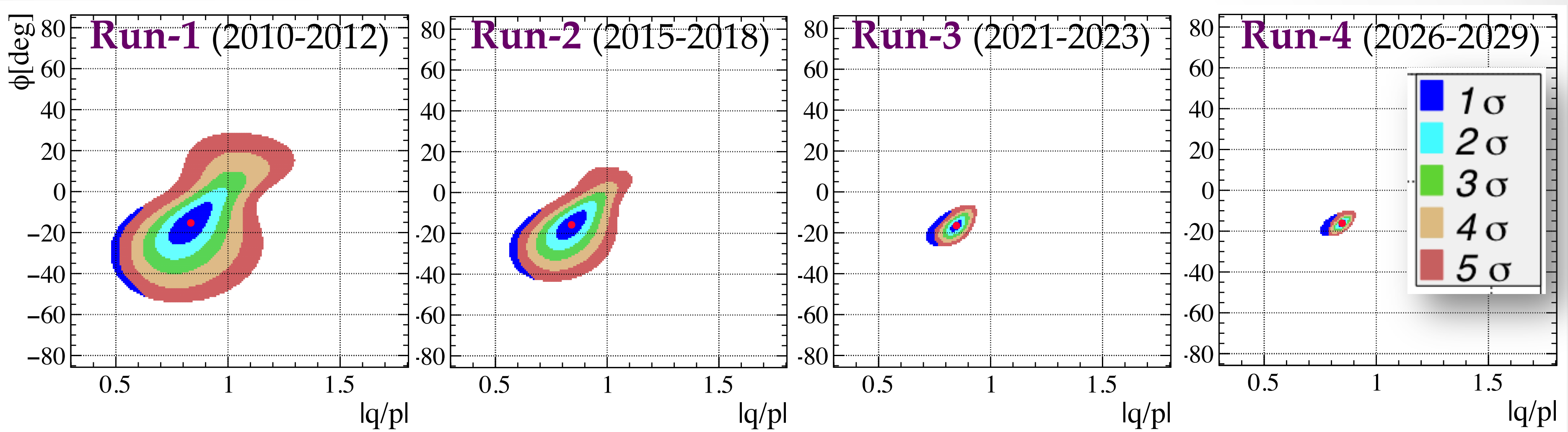
$\phi \equiv \arg(q/p) = -9.4^{+11.9}_{-9.8}$ deg

- Mixing established; x still not significant
- No evidence of indirect CPV
- Need data from BelleII and LHCb upgrade

Future sensitivities

A.Davis talk@ 6th LHCb Implications Workshop

- Current WA + Run-1 measurements as baseline
- Assume √N scaling of statistical and systematic errors



Run	$x[10^{-3}]$	$y[10^{-3}]$	$\left\|\frac{q}{p}\right\| [10^{-3}]$	ϕ[mrad]
Projected 2016 HFAG WA	1.39	0.90	80	156
1	1.10	0.78	65	119
2	0.81	0.58	47	83
3	0.32	0.24	17	32
4	0.20	0.14	11	19
5	0.07	0.05	5	7

200×Run-1 yields → (Run 5)

Opportunities & Limitations

- **Multi-body decays to exploit**
  $D^0 \to K3\pi$, 4π, $K_S\pi\pi\pi^0$,
- Phase Space modeling ⇨ model uncertainty
- Huge statistics ⇨ naïve approach to dynamics description fails
- Using external input on strong phases is a future?
- Must get more from c-Factories data

"Synergy of LHCb and BESIII physics programmes" LHCb-PUB-2016-025

- **Technicalities to control**
- Reliable and large MC (CPU consuming)
- t(D) acceptance, Phase Space acceptance and their correlations
- Prompt/secondary charm separation w/o biasing t(D)
- K and π detection asymmetries and their time dependence

Direct CPV

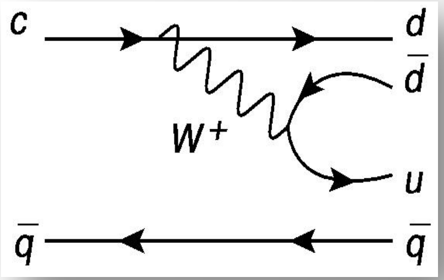
- Depends on decay mode
- Needs two amplitudes with different weak & strong phases

⇨ SCS decays with Tree + Penguin

- Penguin in charm is tiny (no t-quark in loop)

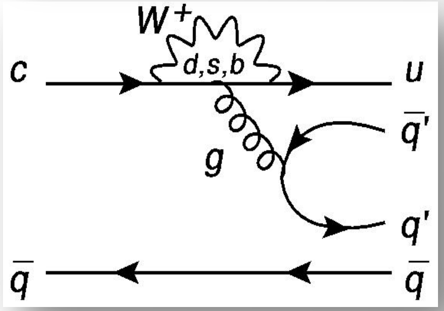
⇨ in SM direct CPV $\leq 10^{-3} \div 10^{-2}$

- Not observed yet



Recent LHCb results

- 2-body decays
  - ΔA_{CP}
  - $A_{CP}(D^0 \to K^+K^-)$
  - $A_{CP}(D_{(s)}^+ \to \eta' \pi^+)$
- Multibody decays
  - $D^0 \to \pi^+\pi^-\pi^+\pi^-$

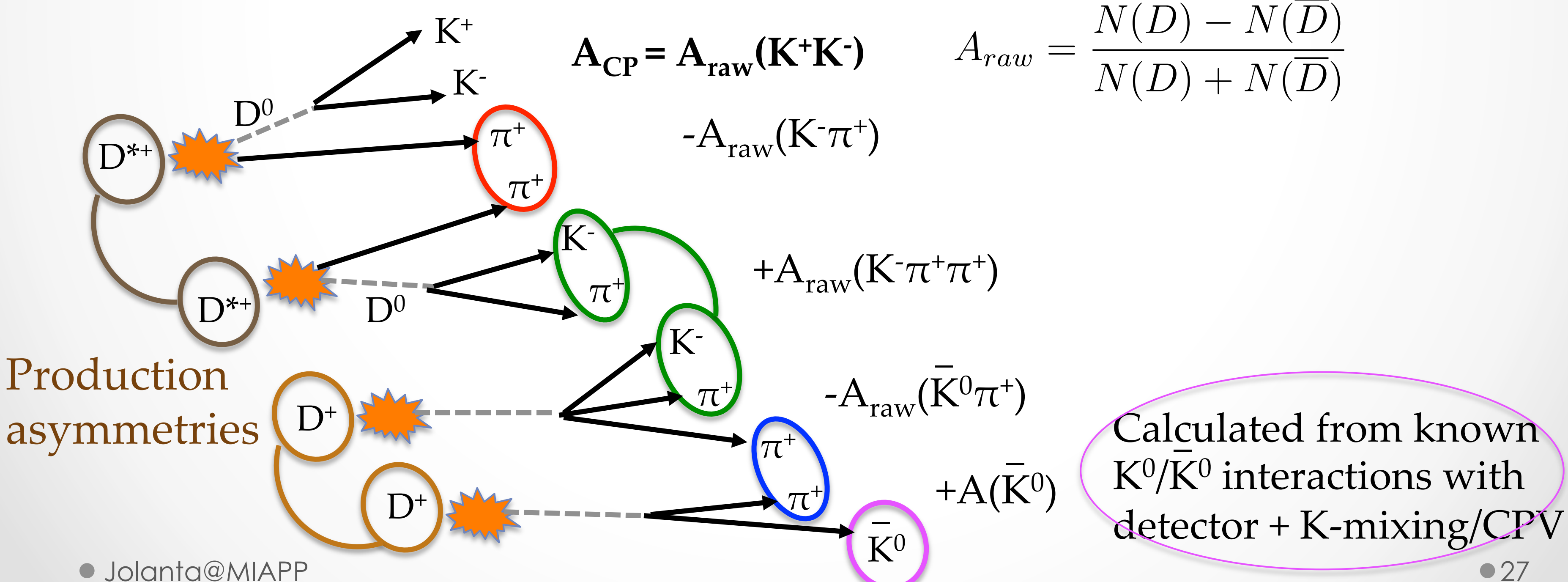


- b loop ~$V_{ub}V_{cb}(m_b/m_W)^2$
- s & d cancel in $SU(3)_f$ limit

'Extra' asymmetries to account for

- **Production asymmetry**
- pp: $\sigma(\Lambda_c^+) > \sigma(\Lambda_c^-)$ ⇨ $\sigma(D^+) < \sigma(D^-)$ to compensate (asym~1%)
- $e^+e^- \to \gamma/Z^*$ interference ⇨ FB asymmetry
- **Detection asymmetries** (K^+ vs K^-, π^+ vs π^-)
- different interactions with detector material: $\sigma(pK^-) > \sigma(pK^+)$
- **Correct with control modes** (CP symmetric)

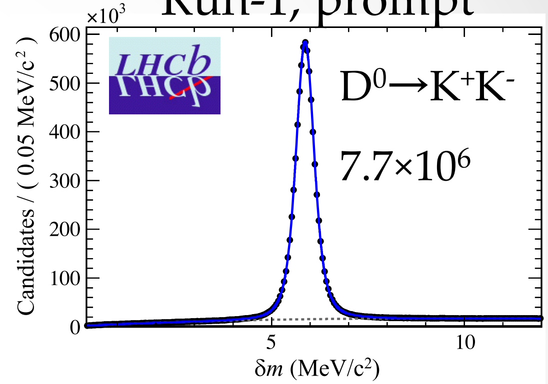
$$A_{raw} = \frac{N(D) - N(\overline{D})}{N(D) + N(\overline{D})}$$

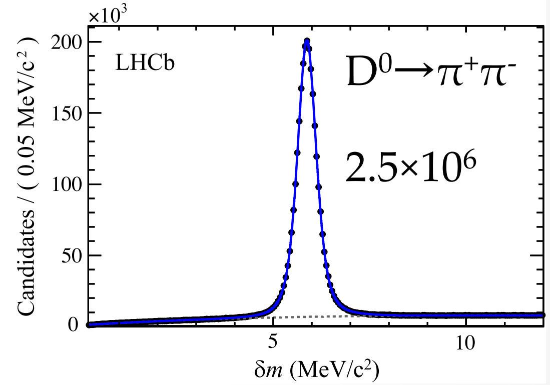


PRL 116, 191601 (2016)

$\Delta A_{CP} = A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-)$

Run-1, prompt

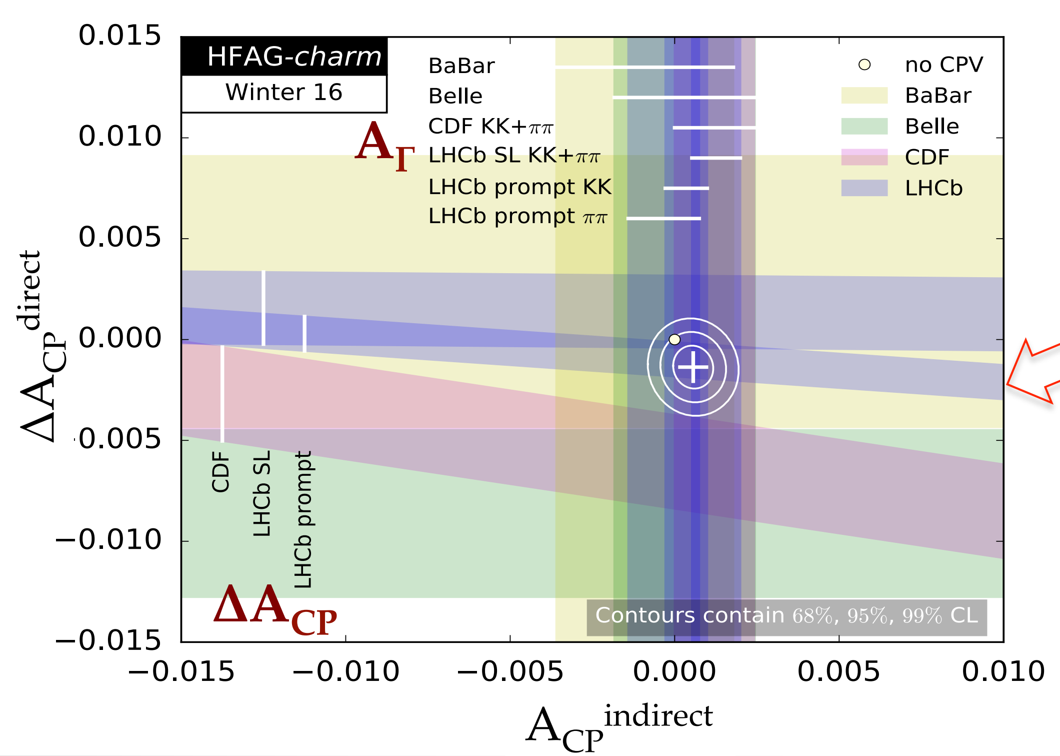




- Sensitive & simple

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

- 2012 evidence: $\Delta A_{CP} = (-0.8 \pm 0.2 \pm 0.1)\%$
- In SM $|\Delta A_{CP}^{\text{direct}}| \leq 0.6\%$
- ΔA_{CP} & A_Γ results ⇨ fit $\Delta A_{CP}^{\text{direct}}$ & A_{CP}^{indirect}



$$\Delta A_{CP} = (-0.10 \pm 0.08 \pm 0.03)\%$$

Most precise!

HFAG average:

$$\Delta A_{CP}^{direct} = (-0.14 \pm 0.07)\%$$

$$A_{CP}^{indirect} = (0.06 \pm 0.04)\%$$

arXiv:1610.09476

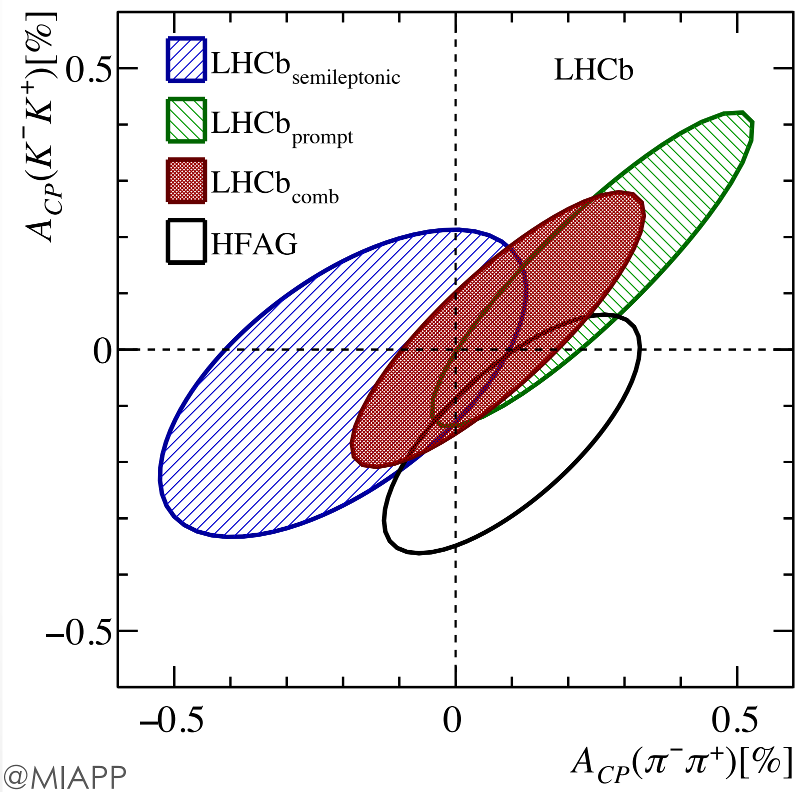
$A_{CP}(D^0 \to K^+K^-)$ & $A_{CP}(D^0 \to \pi^+\pi^-)$

- Individual A_{CP}(KK), pion-tagged sample

$$A_{CP}(K^+K^-) = (0.14 \pm 0.15 \pm 0.10)\%$$

- Combine with ΔA_{CP} ⇨

$$A_{CP}(\pi^+\pi^-) = A_{CP}(K^+K^-) - \Delta A_{CP} = (0.24 \pm 0.15 \pm 0.11)\%$$

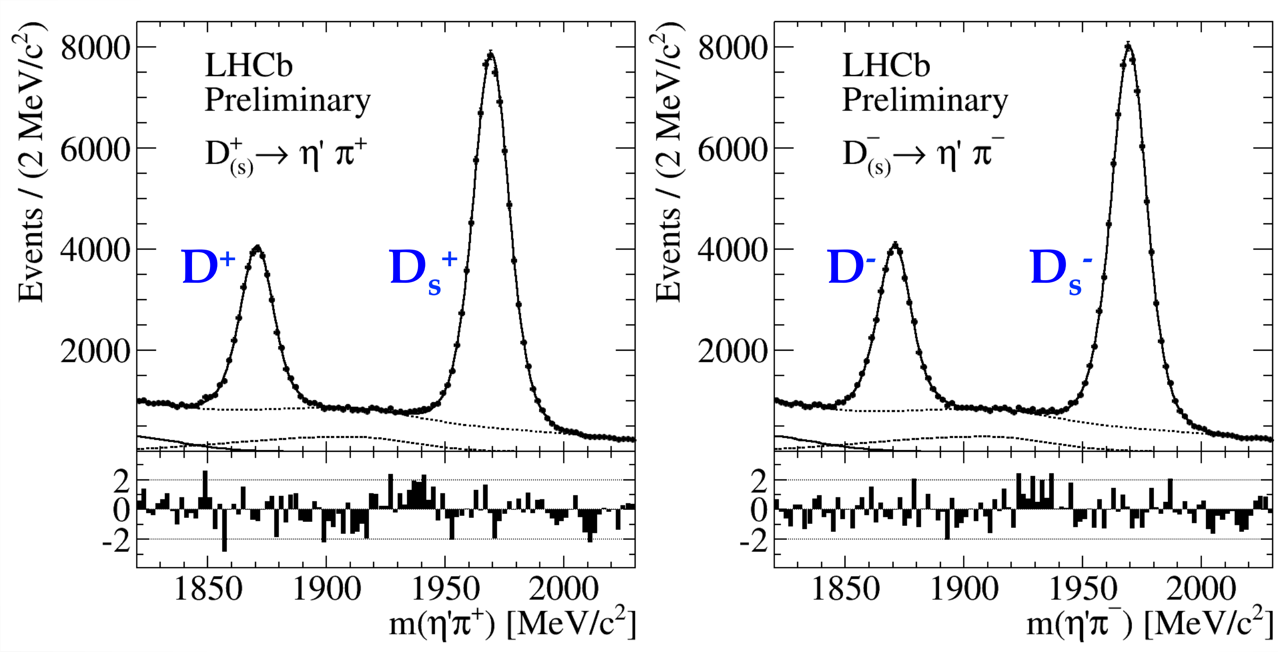


- Combine with results from muon-tagged sample
  JHEP07, 041 (2014)
  ⇨ LHCb combination

- Both A_{CP}'s consistent with zero

A_{CP} in $D_{(s)}^+ \to \eta' \pi^+$

- Charged $D_{(s)}$ = flavour 'self-tagged' by pion charge
- $\eta' \to \pi^+ \pi^- \gamma$ photon in final state ⇨ large background



$$\mathcal{A}_{CP}(D^{\pm} \to \eta' \pi^{\pm}) = (-0.61 \pm 0.72 \pm 0.55 \pm 0.12)\,\%$$ ← SCS

$$\mathcal{A}_{CP}(D_s^{\pm} \to \eta' \pi^{\pm}) = (-0.82 \pm 0.36 \pm 0.24 \pm 0.27)\,\%$$ ← CF

- 3rd uncertainty: Belle input on A_{CP} in control modes $D^+ \to K_S \pi^+$ & $D_s^+ \to \varphi \pi^+$

Most precise
Very important

A_{CP} in two-body SCS decays

	LHCb	Belle	BaBar	BESIII
Mode	A_{CP} [%]			
$D^0 \to K^+K^-$	+0.04 ± 0.12 ± 0.10 New	-0.32 ± 0.21 ± 0.09	+0.00 ± 0.34 ± 0.13	
$D^0 \to \pi^+\pi^-$	+0.07 ± 0.14 ± 0.11 New	+0.55 ± 0.36 ± 0.09	-0.24 ± 0.52 ± 0.22	
$D^0 \to K_s K_s$	-2.9 ± 5.2 ± 2.2	+0.00 ± 1.53 ± 0.17 New		
$D^0 \to \pi^0\pi^0$		-0.03 ± 0.64 ± 0.10		
$D^0 \to K_s\eta$		+0.54 ± 0.51 ± 0.16		
$D^0 \to K_s\eta'$		+0.98 ± 0.67 ± 0.14		
$D^+ \to K_s K^+$	+0.03 ± 0.17 ± 0.14	+0.08 ± 0.28 ± 0.14	+0.46 ± 0.36 ± 0.25	-1.5 ± 2.8 ± 1.6 New
$D^+ \to K_L K^+$				-3.0 ± 3.2 ± 1.2 New
$D^+ \to \phi\pi^+$	-0.04 ± 0.14 ± 0.14	+0.51 ± 0.28 ± 0.05		
$D^+ \to \eta\pi^+$		+1.74 ± 1.13 ± 0.19		
$D^+ \to \eta'\pi^+$	-0.61 ± 0.72 ± 0.55 ± 0.12 New	-0.12 ± 1.12 ± 0.17		
$D_s^+ \to K_s\pi^+$	+0.38 ± 0.46 ± 0.17	+5.45 ± 2.50 ± 0.33	+0.3 ± 2.0 ± 0.3	

http://www.slac.stanford.edu/xorg/hfag/charm

Comments on direct CPV searches

- **Precision down to O(10^{-3})**, still no evidence
  Will improve ~6 times with Run-4 data (by 2030)

- **Exploit correlations** between modes
  related through Isospin or U-spin
  ⇨ ~model independent test of SM, model dependent test of NP
  e.g. SM sum rules:
  $$A\left(D^{+}\to\pi^{+}\pi^{0}\right)-\overline{A}\left(D^{+}\to\pi^{+}\pi^{0}\right)=0$$
  $$\frac{1}{\sqrt{2}}A\left(\pi^{+}\pi^{-}\right)+A\left(\pi^{0}\pi^{0}\right)-\frac{1}{\sqrt{2}}\overline{A}\left(\pi^{+}\pi^{-}\right)-\overline{A}\left(\pi^{0}\pi^{0}\right)=0$$

- **Study charm baryons**
  1st evidence for CPV in baryons (in $\Lambda_b \to p3\pi$) arXiv:1609:05216

- **Rare decays**: CPV in SM at a few % level
  $D^0 \to \rho\gamma$, $\phi\gamma$, $K^*\gamma$ (BF~10^{-4}÷10^{-5}) Belle arXiv:1603.03257
  $D^0 \to \pi\pi l^+l^-$, KKl^+l^- (FCNC, BF~10^{-12})

PLB 728 (2014) 585
PLB 740 (2015) 158

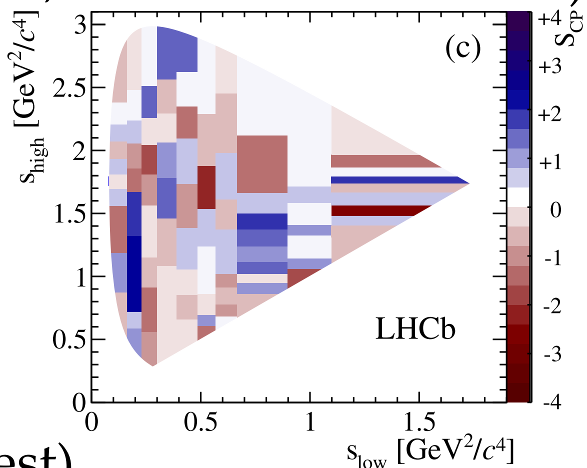
CPV in multi-body decays

- Strong phases vary in phase space ⇨ local asymmetries
- Model independent methods: test if data consistent with no-CPV

⇨ binned χ^2 (S_{CP} method, aka Miranda method)

$D^+ \rightarrow \pi^+\pi^+\pi^-$

p-value = 50÷100%



$$S_{CP}^i = \frac{N^i(D^+) - \alpha N^i(D^-)}{\sqrt{N^i(D^+) + \alpha^2 N^i(D^-)}} \qquad \alpha = \frac{N(D^+)}{N(D^-)}$$

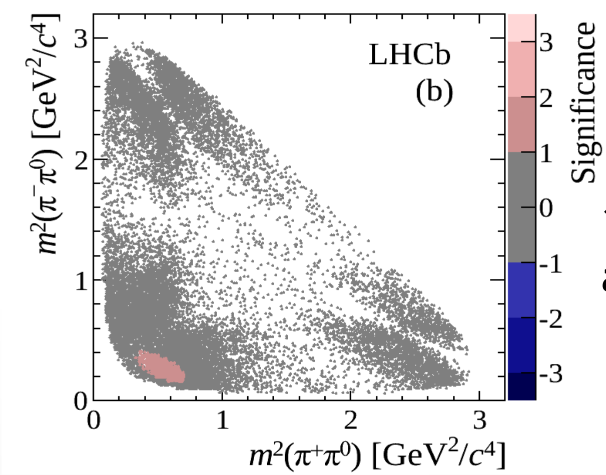
$$\chi^2 = \sum (S_{CP}^i)^2$$

🡐 Significance of asymmetry in Dalitz bins

⇨ unbinned (Energy Test)

$D^0 \rightarrow \pi^+\pi^-\pi^0$

p-value = 2÷5%

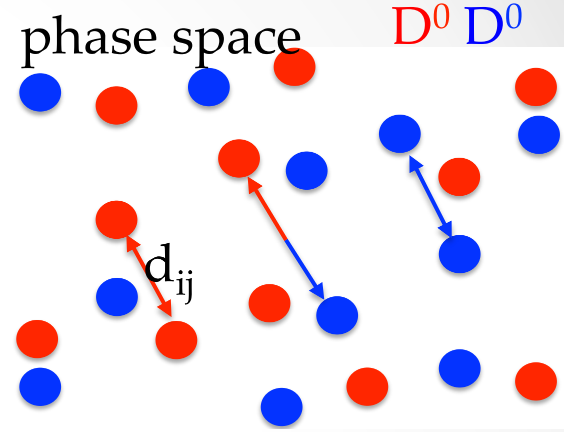


🡐 Significance of local asymmetry for each event

Search for CPV in $D^0 \to 4\pi$ with Energy Test

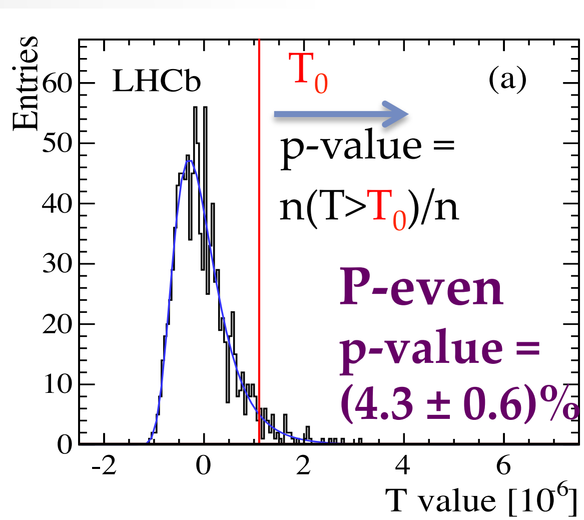
- Statistical comparison of two distributions
- Test statistics: based on distances of event pairs
- Compare with T distribution for no CPV case (randomize D flavour)

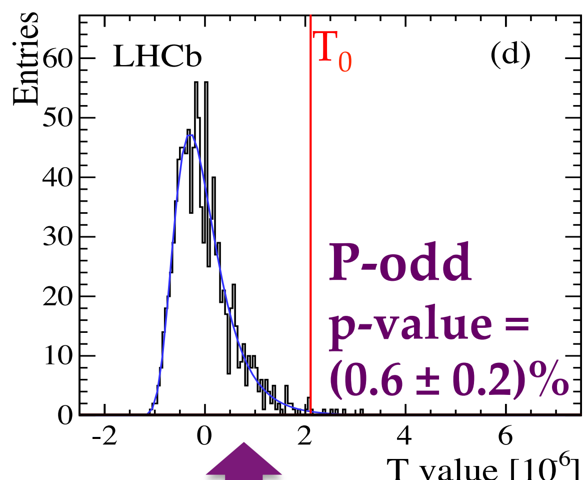
- 5-dim phase space: $m^2(\pi\pi)$, $m^2(\pi\pi\pi)$ ⇨ **P-even**
- Use triple-product sign to access **P-odd** CPV



$$T = \langle d_{ij} \rangle_{DD} + \langle d_{ij} \rangle_{\bar{D}\bar{D}} - \langle d_{ij} \rangle_{D\bar{D}}$$

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





Marginally consistent with no CPV (~2.7σ)

CP: I → III

I	III
D $C_T>0$	$\bar{D}$ $-\bar{C}_T>0$
II	**IV**
D $C_T<0$	$\bar{D}$ $-\bar{C}_T<0$

$$C_T \equiv \vec{p}\pi^+ \cdot \left(\vec{p}\pi^+ \times \vec{p}\pi^-\right)$$

Opportunities & Limitations

- **Measurement of CPV in multi-body decays**

  requires amplitude analysis ⇨ model dependent

  $D^0 \to K_S K\pi$: LHCb PRD93 052018 (2016)

- 4-body decays offer **access to P-odd amplitudes**
- CPV in P-even ampl.: $A_{CP} \sim \sin\Delta\phi_{weak}$ **$\sin\Delta\phi_{strong}$**

  CPV in P-odd ampl.: $A_{CP} \sim \sin\Delta\phi_{weak}$ **$\cos\Delta\phi_{strong}$** ← complementary

- Triple-product method (a.k.a T-odd) sensitive to P-odd CPV

  $D^0 \to KK\pi\pi$: LHCb JHEP10 (2014) 005, $D^+ \to K_S K\pi\pi$: BaBar PRD84 031103 (2011)

- **Technicalities to control**
- Reliable MC for Phase Space acceptance
- Detection asymmetries with CF decays as control modes

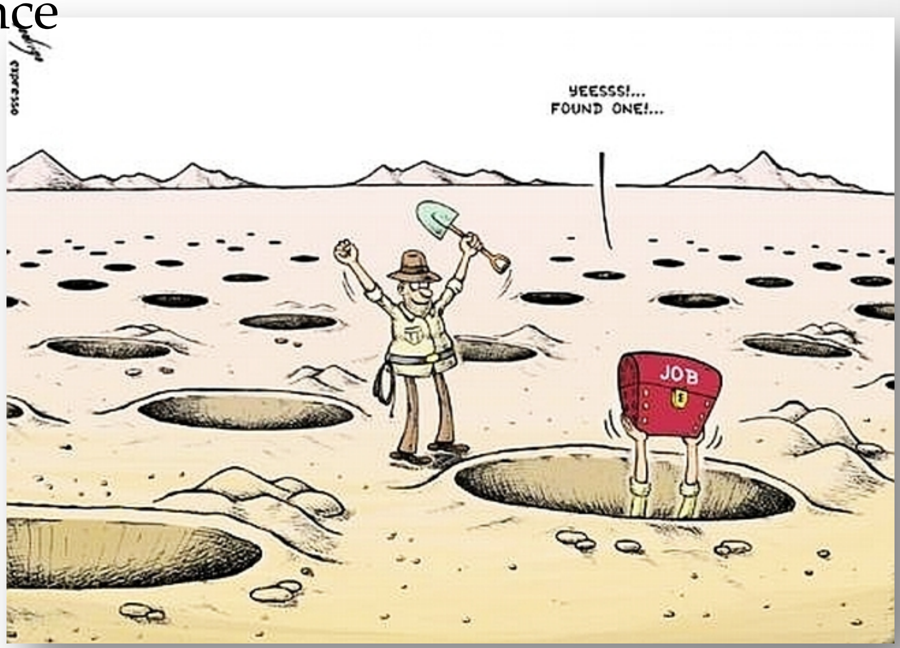
  (assume no CPV or include extra uncertainty)

Summary

- Still analyzing LHCb Run-1 data
- Increasing precision on x&y mixing parameters
- x still not measured well
- Indirect CPV searches with precision up to 10^{-4}

- Huge effort in searching for CPV in charm decays
- Sensitivity up to 10^{-3}, still no evidence
- How small can be CPV in SM?

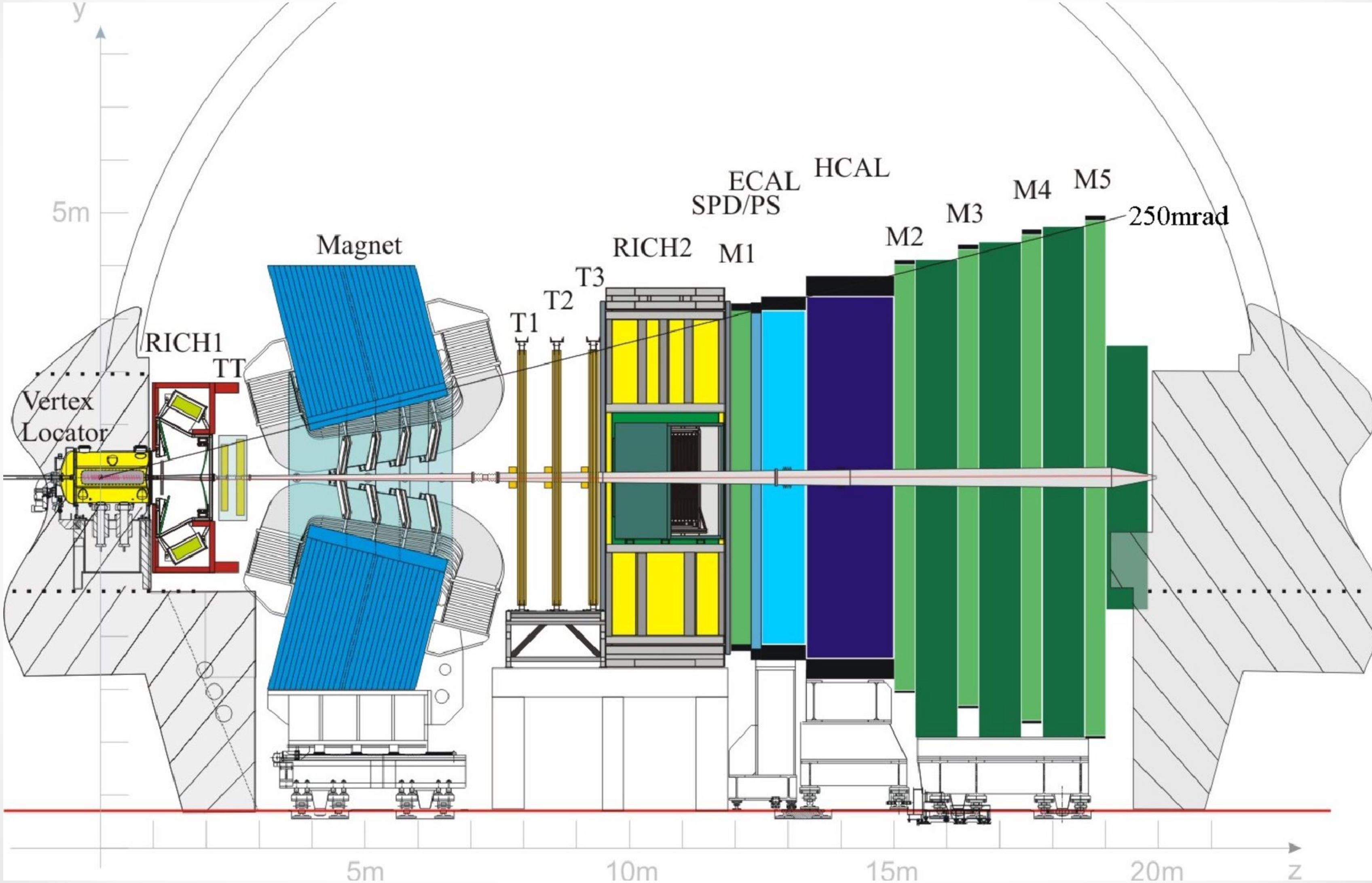
- Charm needs
  BelleII & LHCb upgrade



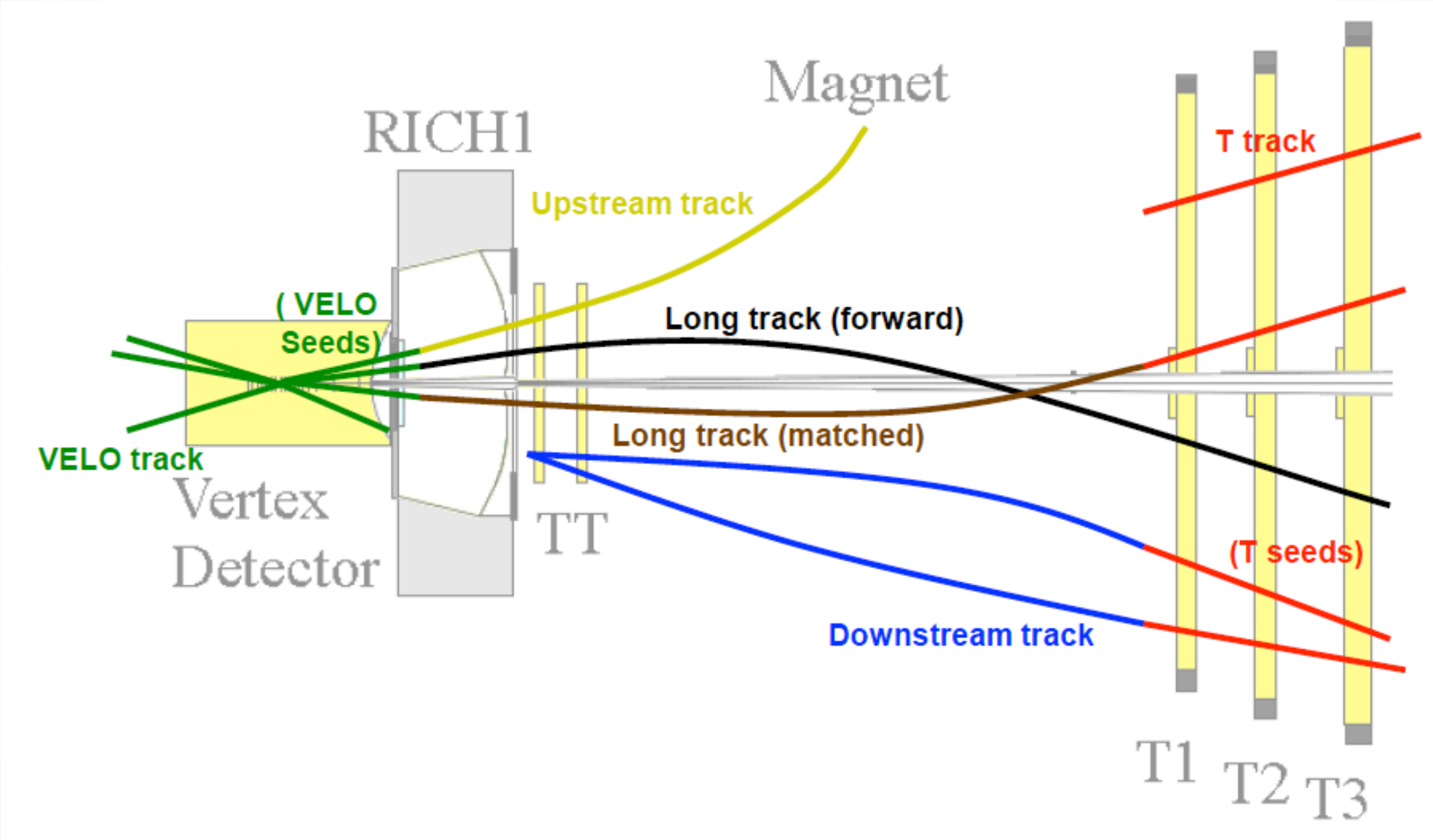
Backups

•

LHCb detector



Track types at LHCb



WS/RS $D^0 \to K\pi$. Various fits

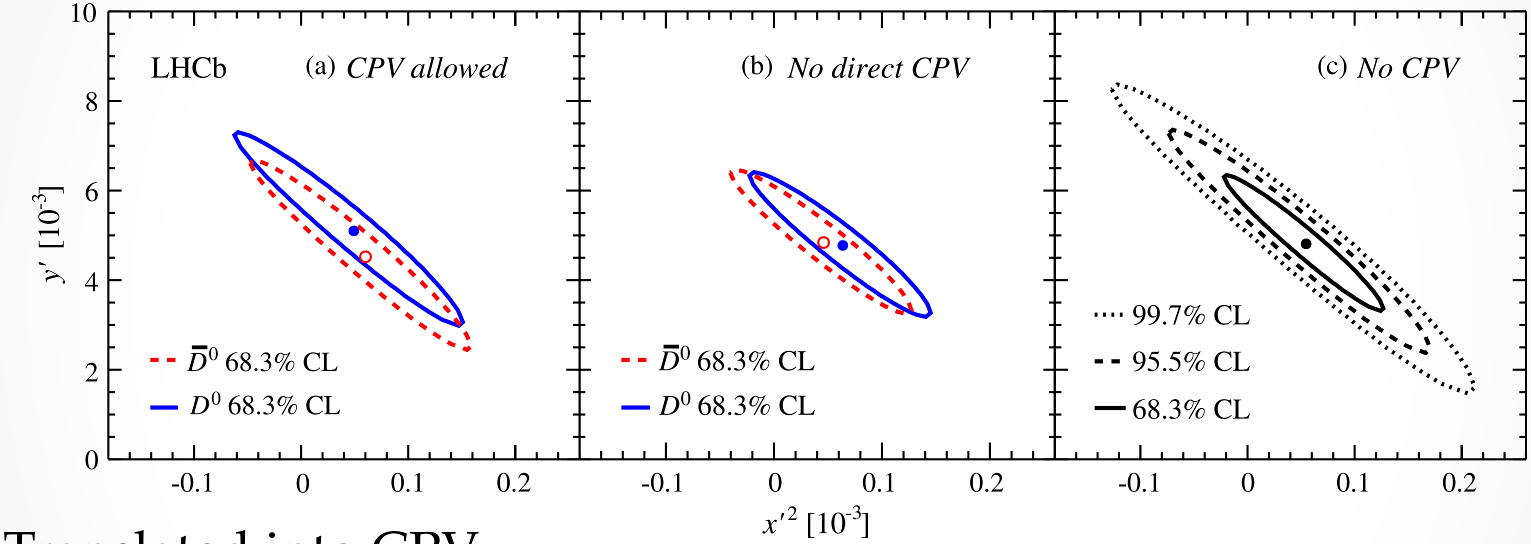
•

Parameter	DT+prompt combination	Prompt alone
	No CPV	
$R_D[10^{-3}]$	3.533 ± 0.054	3.568 ± 0.067
$x'^2[10^{-5}]$	3.6 ± 4.3	5.5 ± 4.9
$y'[10^{-3}]$	5.23 ± 0.84	4.80 ± 0.94
χ^2/NDF	96.594/111	
	No Direct CPV	
$R_D[10^{-3}]$	3.533 ± 0.054	3.568 ± 0.067
$x'^{2+}[10^{-5}]$	4.9 ± 5.0	6.4 ± 5.6
$y'^{+}[10^{-3}]$	5.14 ± 0.91	4.80 ± 1.08
$x'^{2-}[10^{-5}]$	2.4 ± 5.0	4.6 ± 5.5
$y'^{-}[10^{-3}]$	5.32 ± 0.91	4.8 ± 1.08
χ^2/NDF	96.147/109	
	All CPV Allowed	
$R_D^+[10^{-3}]$	3.474 ± 0.081	3.545 ± 0.095
$x'^{2+}[10^{-5}]$	1.1 ± 6.5	4.9 ± 7.0
$y'^{+}[10^{-3}]$	5.97 ± 1.25	5.10 ± 1.38
$R_D^-[10^{-3}]$	3.591 ± 0.081	3.591 ± 0.090
$x'^{2-}[10^{-5}]$	6.1 ± 6.1	6.0 ± 6.8
$y'^{-}[10^{-3}]$	4.50 ± 1.21	4.50 ± 1.39
χ^2/NDF	94.960/108	

PRL 111, 251801 (2013)

CPV from WS/RS $D^0 \to K\pi$

- Prompt sample, Run-1
- 2-dim confidence regions for measured x'^2 and y'



- Translated into CPV

$$A_{CP}^{direct} = \frac{R_D^+ - R_D^-}{R_D^+ + R_D^-} = (-0.7 \pm 1.9)\%$$

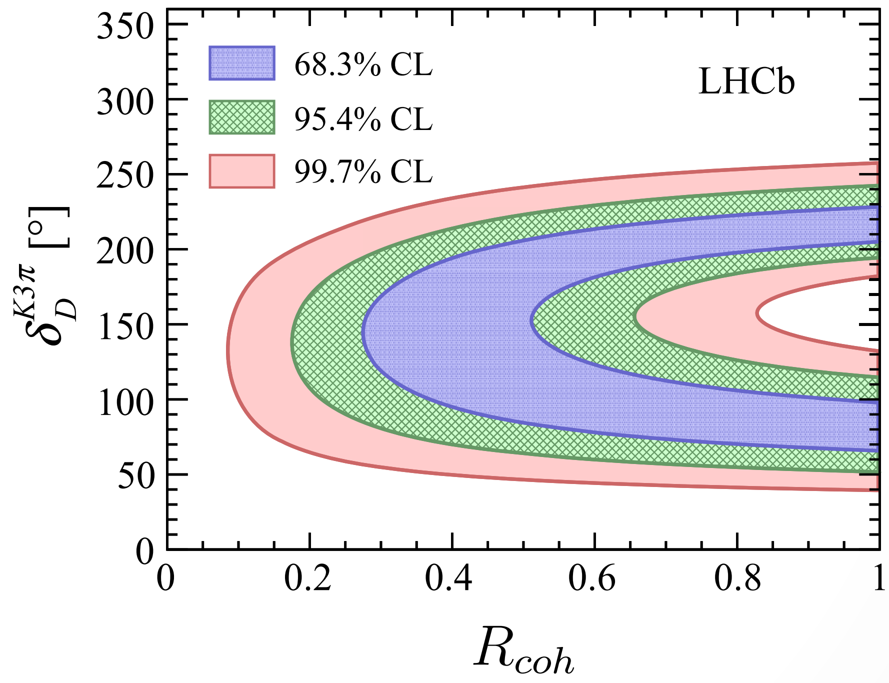
$$x^{\pm\prime} = \left|\frac{q}{p}\right|^{\pm 1} (x' \cos\phi \pm y' \sin\phi)$$

$$0.75 < |q/p| < 1.24 \text{ @68\% } CL$$

$$y^{\pm\prime} = \left|\frac{q}{p}\right|^{\pm 1} (y' \cos\phi \mp x' \sin\phi)$$

WS/RS $D^0 \to K3\pi$

- Constrain x&y from WA
- Get averaged strong phase & coherence factor



$D^0 \to Ks\pi\pi$

- Prob in i-bin

$$\mathcal{P}_{D^0}(i;t) = \int_i \mathcal{P}_{D^0}(m^2_{12}, m^2_{13}, t)\, \mathrm{d}m^2_{12}\, \mathrm{d}m^2_{13}$$
$$= \Gamma\, e^{-\Gamma t} \left[T_i - \Gamma t \sqrt{T_i T_{-i}} \{ y c_i + x s_i \} \right]$$

$$\mathcal{P}_{\bar{D}^0}(i;t) = \Gamma\, e^{-\Gamma t} \left[T_{-i} - \Gamma t \sqrt{T_i T_{-i}} \{ y c_i - x s_i \} \right]$$

- Integrals of rate and interference over i-bin

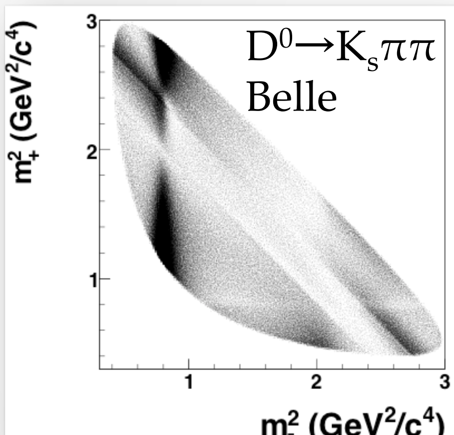
$$T_i \equiv \int_i |\mathcal{A}_{D^0}|^2\, \mathrm{d}m^2_{12}\, \mathrm{d}m^2_{13},$$
$$X_i \equiv \frac{1}{\sqrt{T_i T_{-i}}} \int_i \mathcal{A}^\star_{D^0}\, \mathcal{A}_{\bar{D}^0}\, \mathrm{d}m^2_{12}\, \mathrm{d}m^2_{13}$$

- strong phases

$$c_i \equiv \mathrm{Re}\,(X_i),$$
$$s_i \equiv -\,\mathrm{Im}\,(X_i)$$

To do: t-dependent Dalitz

- Access to amplitudes (CF, DCS and CP-eigenstates)
  ⇨ strong phases and interferences ⇨ direct access to x, y, q/p
- Rates for D^0 and $\underline{D}^0$ assuming no DCPV:



$m^2(K_s\pi^+)$ vs $m^2(K_s\pi^-)$

$$|\mathcal{M}(f,t)|^2 = \frac{e^{-\Gamma t}}{2}\{(|\mathcal{A}_f|^2 + |\tfrac{q}{p}|^2|\mathcal{A}_{\bar{f}}|^2)\cosh(\Gamma y t) + (|\mathcal{A}_f|^2 - |\tfrac{q}{p}|^2|\mathcal{A}_{\bar{f}}|^2)\cos(\Gamma x t) + 2\Re(\tfrac{q}{p}\mathcal{A}_{\bar{f}}\mathcal{A}_f{}^*)\sinh(\Gamma y t) - 2\Im(\tfrac{q}{p}\mathcal{A}_{\bar{f}}\mathcal{A}_f{}^*)\sin(\Gamma x t)\}$$

$$|\overline{\mathcal{M}}(f,t)|^2 = \frac{e^{-\Gamma t}}{2}\{(|\mathcal{A}_{\bar{f}}|^2 + |\tfrac{p}{q}|^2|\mathcal{A}_f|^2)\cosh(\Gamma y t) + (|\mathcal{A}_{\bar{f}}|^2 - |\tfrac{p}{q}|^2|\mathcal{A}_f|^2)\cos(\Gamma x t) + 2\Re(\tfrac{p}{q}\mathcal{A}_f\mathcal{A}_{\bar{f}}{}^*)\sinh(\Gamma y t) - 2\Im(\tfrac{p}{q}\mathcal{A}_f\mathcal{A}_{\bar{f}}{}^*)\sin(\Gamma x t)\}$$

Belle PRD89 091103 (2014)

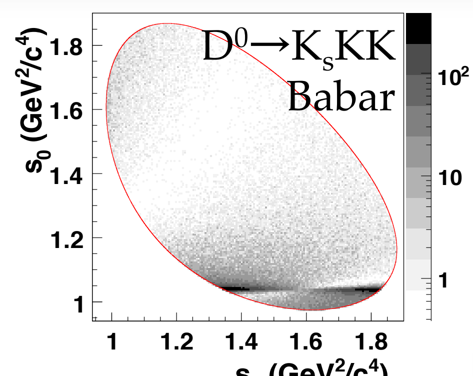
$$x = \left(5.6 \pm 1.9\,^{+0.4}_{-0.8}\,^{+0.6}_{-0.8}\right)\times 10^{-3}$$

$$y = \left(3.0 \pm 1.5\,^{+0.4}_{-0.5}\,^{+0.3}_{-0.7}\right)\times 10^{-3}$$

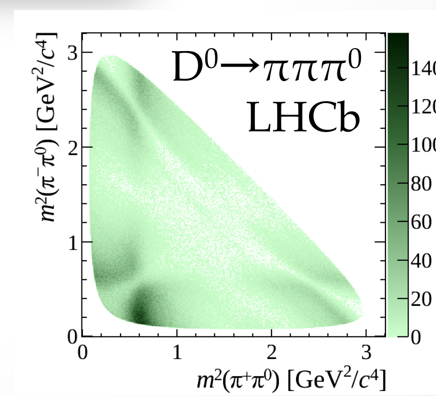
$$|q/p| = 0.90\,^{+0.16}_{-0.15}\,^{+0.05}_{-0.04}\,^{+0.06}_{-0.05}$$

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

- Belle $K_s\pi\pi$: 1.2M
  LHCb prompt + μ-tag: ~2M
- t-dep. Dalitz possible for
  $D^0 \to K_sKK$ $D^0 \to \pi\pi\pi^0$



$m^2(K^+K^-)$ vs $m^2(K_sK^+)$



$m^2(\pi^-\pi^0)$ vs $m^2(\pi^+\pi^0)$

$D^0 \to K_S \pi\pi$ phases from Cleo-c

TABLE X: Values of $F_{(-)i}$ (%) measured from the flavor-tagged $D^0 \to K^0_S \pi^+\pi^-$ data for the equal $\Delta\delta_D$ binning derived from the Belle model. Predicted values from the BABAR 2008 model of $D^0 \to K^0_S \pi^+\pi^-$ are also given.

i	F_i (%) Measured	F_i (%) Predicted	F_{-i} (%) Measured	F_{-i} (%) Predicted
1	16.5 ± 0.5	16.5	8.8 ± 0.4	8.0
2	7.7 ± 0.4	7.6	2.0 ± 0.2	1.6
3	9.8 ± 0.4	10.2	3.2 ± 0.2	2.8
4	3.0 ± 0.2	3.0	1.3 ± 0.1	1.2
5	8.0 ± 0.4	9.2	4.0 ± 0.3	4.6
6	7.1 ± 0.3	7.3	1.8 ± 0.2	1.7
7	9.9 ± 0.4	10.0	1.6 ± 0.2	1.3
8	12.4 ± 0.4	12.2	2.9 ± 0.2	2.6

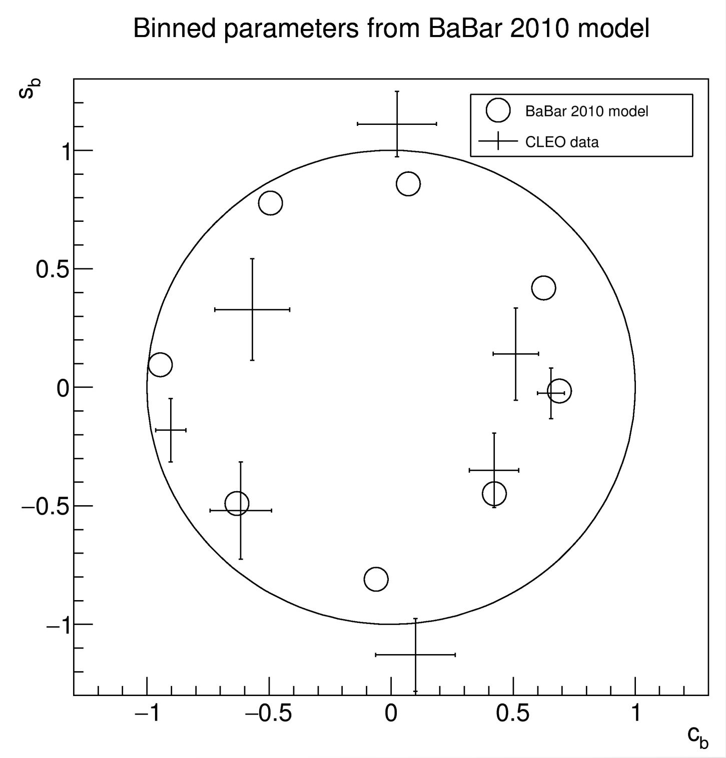


TABLE XVI: Measured values of c_i and s_i for the different $D^0 \to K^0_S \pi^+\pi^-$ binnings.

Equal $\Delta\delta_D$ Belle

c_i	s_i
$0.710 \pm 0.034 \pm 0.038$	$-0.013 \pm 0.097 \pm 0.031$
$0.481 \pm 0.080 \pm 0.070$	$-0.147 \pm 0.177 \pm 0.107$
$0.008 \pm 0.080 \pm 0.087$	$0.938 \pm 0.120 \pm 0.047$
$-0.757 \pm 0.099 \pm 0.065$	$0.386 \pm 0.208 \pm 0.067$
$-0.884 \pm 0.056 \pm 0.054$	$-0.162 \pm 0.130 \pm 0.041$
$-0.462 \pm 0.100 \pm 0.082$	$-0.616 \pm 0.188 \pm 0.052$
$0.106 \pm 0.105 \pm 0.100$	$-1.063 \pm 0.174 \pm 0.066$
$0.365 \pm 0.071 \pm 0.078$	$-0.179 \pm 0.166 \pm 0.048$

CPV in multibody decays (2)

- Model dependent: Dalitz analysis (still mainly from Cleo and BaBar)
  - ⇨ A_{CP} for contributing resonances
  - ⇨ test SM with sum rules e.g. for amplitudes in $D^0 \to \pi^+\pi^-\pi^0$

$$\left[A\left(\rho^+\pi^-\right)+A\left(\rho^-\pi^+\right)+2A\left(\rho^0\pi^0\right)\right]-\left[\overline{A}\left(\rho^+\pi^-\right)+\overline{A}\left(\rho^-\pi^+\right)+2\overline{A}\left(\rho^0\pi^0\right)\right]=0$$

- Triple-product asymmetries for 4-body; complementary to other methods
  - ⇨ Triple products for $D^0 \to K^+K^-\pi^+\pi^-$: $C_T \equiv \vec{p}_{K+} \cdot \left(\vec{p}_{\pi+} \times \vec{p}_{\pi-}\right)$ for D^0
  - ⇨ T-odd asymmetries $\overline{C}_T \equiv \vec{p}_{K-} \cdot \left(\vec{p}_{\pi-} \times \vec{p}_{\pi+}\right)$ for $\overline{D}^0$

$$A_T \equiv \frac{\Gamma_{D^0}(C_T > 0) - \Gamma_{D^0}(C_T < 0)}{\Gamma_{D^0}(C_T > 0) + \Gamma_{D^0}(C_T < 0)}$$

$$\overline{A}_T \equiv \frac{\Gamma_{\overline{D}^0}(-\overline{C}_T > 0) - \Gamma_{\overline{D}^0}(-\overline{C}_T < 0)}{\Gamma_{\overline{D}^0}(-\overline{C}_T > 0) + \Gamma_{\overline{D}^0}(-\overline{C}_T < 0)}$$

$$a_{CP}^{T-odd} \equiv \frac{1}{2}\left(A_T - \overline{A}_T\right)$$

$$a_{CP}^{T-odd}\left(D^0 \to KK\pi\pi\right) = \left(0.18 \pm 0.29 \pm 0.04\right)\%$$

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