Mixing and indirect CPV in multibody charm decays at LHCb

Eva Gersabeck
on behalf of the LHCb collaboration

CKM 2018, 17-21 September 2018, Heidelberg

Mixing formalism

Mass eigenstates   Flavour eigenstates

Assuming *CPT* symmetry, the physical eigenstates can be expressed as a superposition of the flavour eigenstates

$$|M_{1,2}\rangle = p|M^0\rangle \pm q|\overline{M}^0\rangle$$

with complex coefficients p,q satisfying $|p|^2 + |q|^2 = 1$

The transition probability

$$P(M^0 \rightarrow \overline{M}^0, t) = \frac{1}{2}\left|\frac{q}{p}\right|^2 e^{-\Gamma t}(\cosh(y\Gamma t) - \cos(x\Gamma t))$$

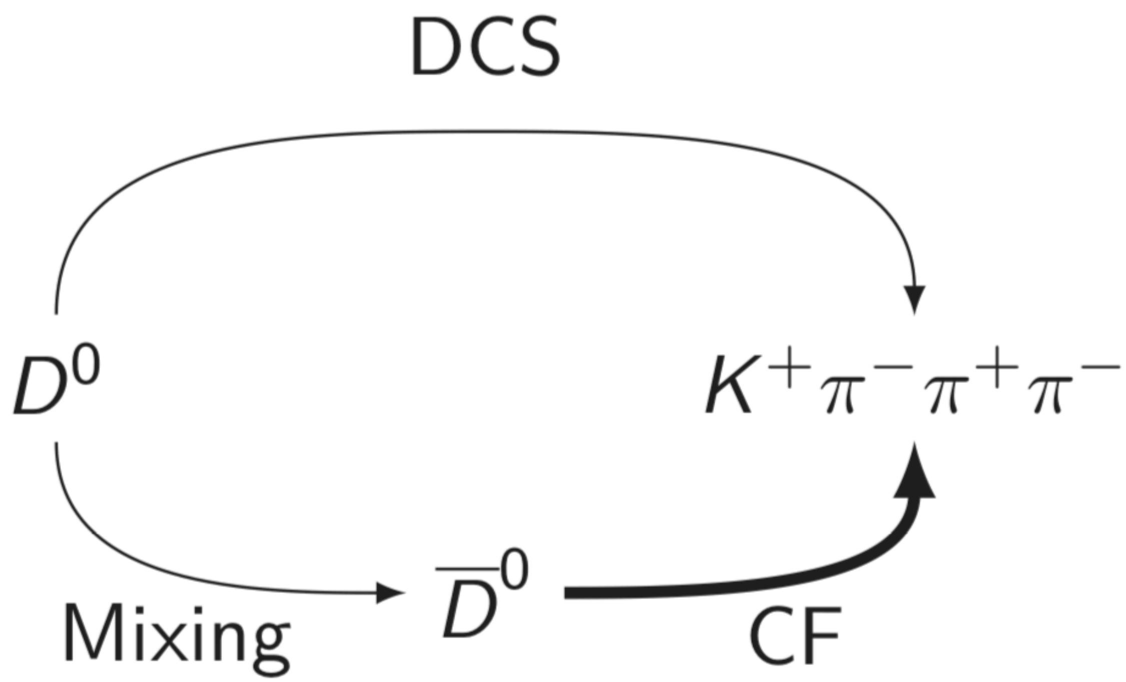
dimensionless $y \equiv \Delta\Gamma/(2\Gamma)$ $x \equiv \Delta m/\Gamma$

$\Delta\Gamma \equiv \Gamma_2 - \Gamma_1$ $\Delta m \equiv m_2 - m_1$

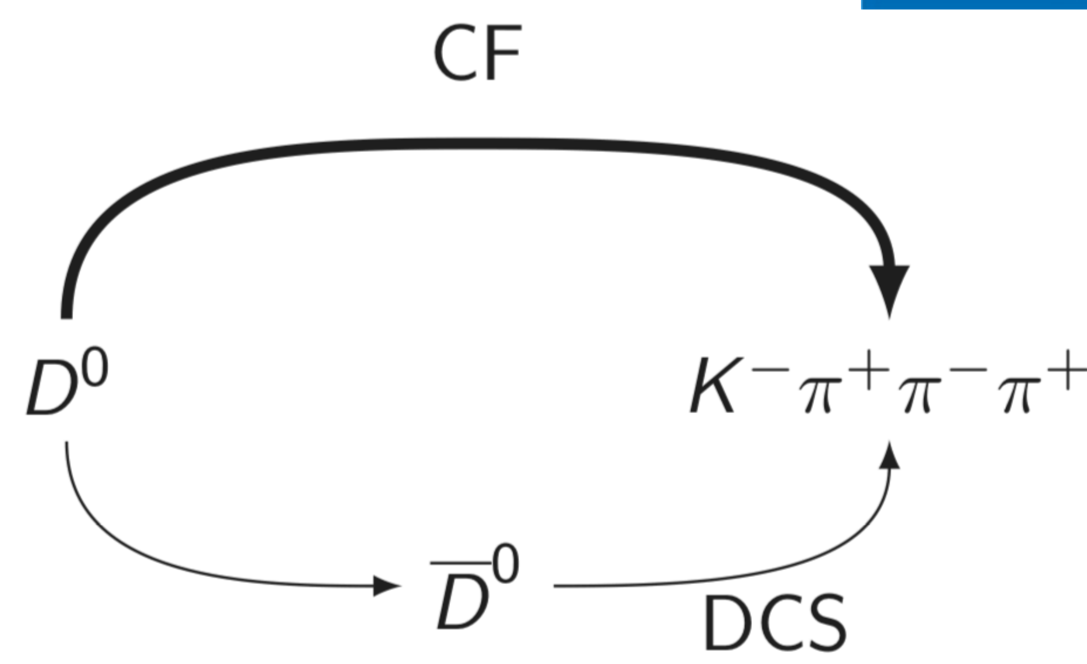
Width difference
→ Lifetime difference

Mass difference
→ Oscillation

D^0-$\bar{D}^0$ oscillations in $K^+\pi^-\pi^+\pi^-$



Right sign amplitude



Wrong sign amplitude

$$R(t) \approx (r_D^{K3\pi})^2 - r_D^{K3\pi} R_D^{K3\pi} y'_{K3\pi} \frac{t}{\tau} + \frac{x^2 + y^2}{4} \left(\frac{t}{\tau}\right)^2$$

$r_D^{K3\pi}$ phase space averaged ratio of DCS/CF amplitudes

coherence factor $R_D^{K3\pi} e^{-i\delta_D^{K3\pi}} \equiv \langle \cos\delta \rangle + i \langle \sin\delta \rangle$

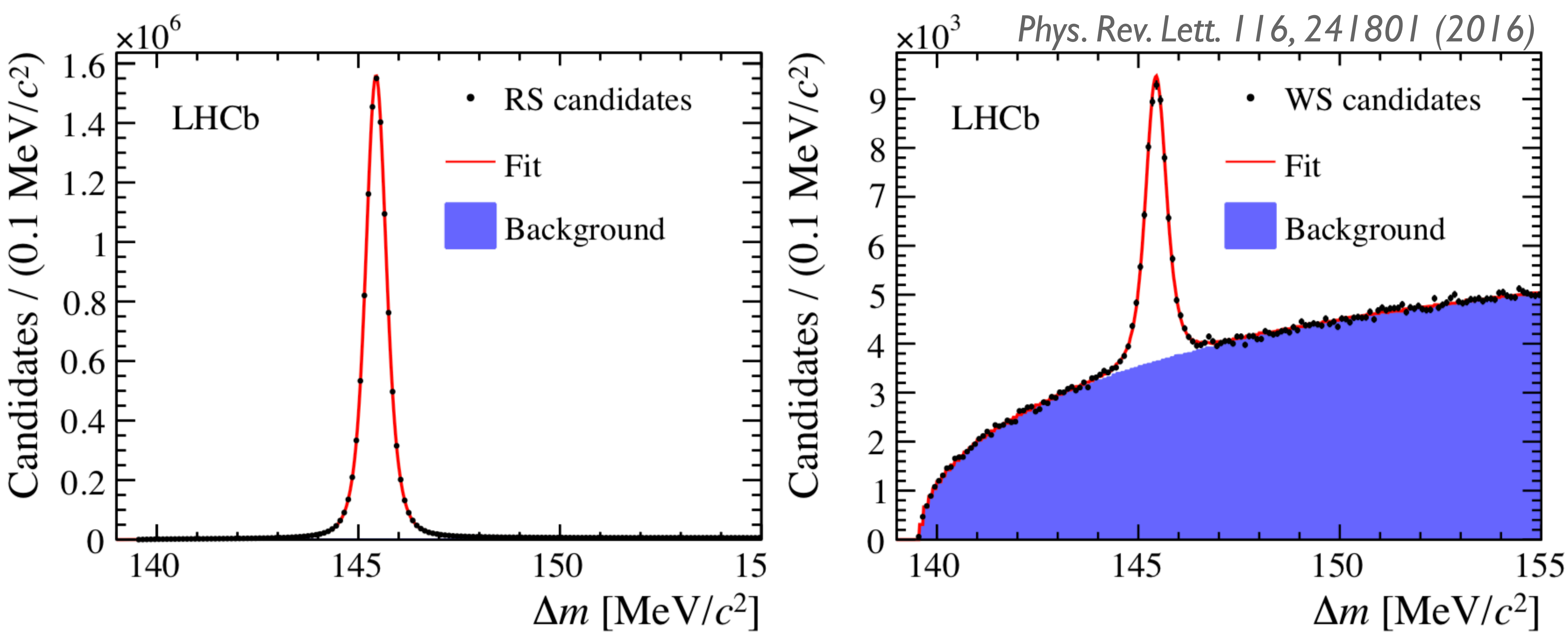
$$y'_{K3\pi} \equiv y \cos\delta_D^{K3\pi} - x \sin\delta_D^{K3\pi}$$

averaged strong phase difference

Dataset

- Using 3 fb^{-1} of luminosity collected in Run 1 (prompt charm)
  - Experimentally challenging
    - Lower reconstruction efficiency
    - Five-dimensional phase space to parameterise the efficiency
- 11×10^6 RS and 42×10^3 WS signal candidates

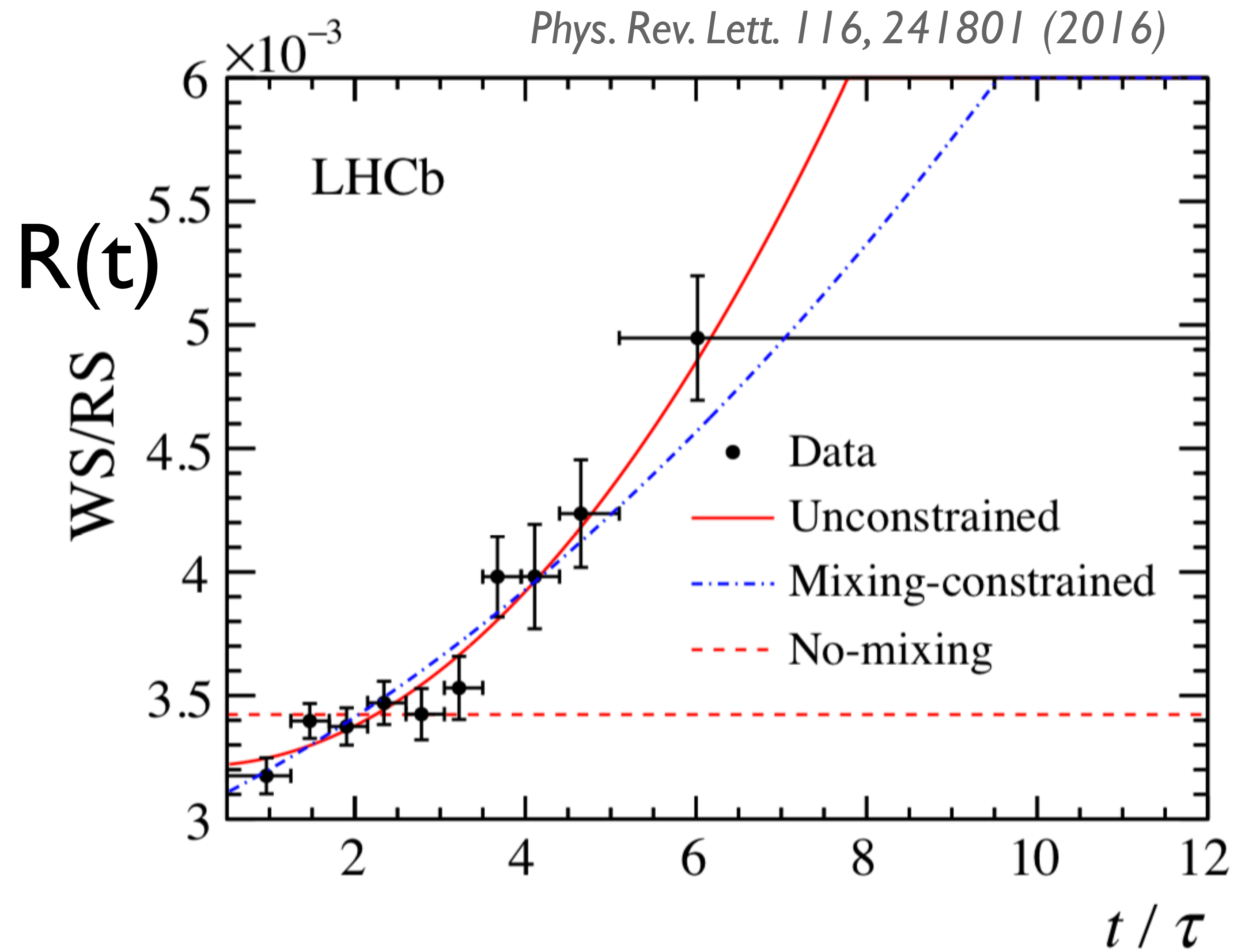
Phys. Rev. Lett. 116, 241801 (2016)



The mixing fit

- The WS/RS ratio measured in 10 decay time bins
- Systematic uncertainties included
- Detection asymmetries cancel

Phys. Rev. Lett. 116, 241801 (2016)



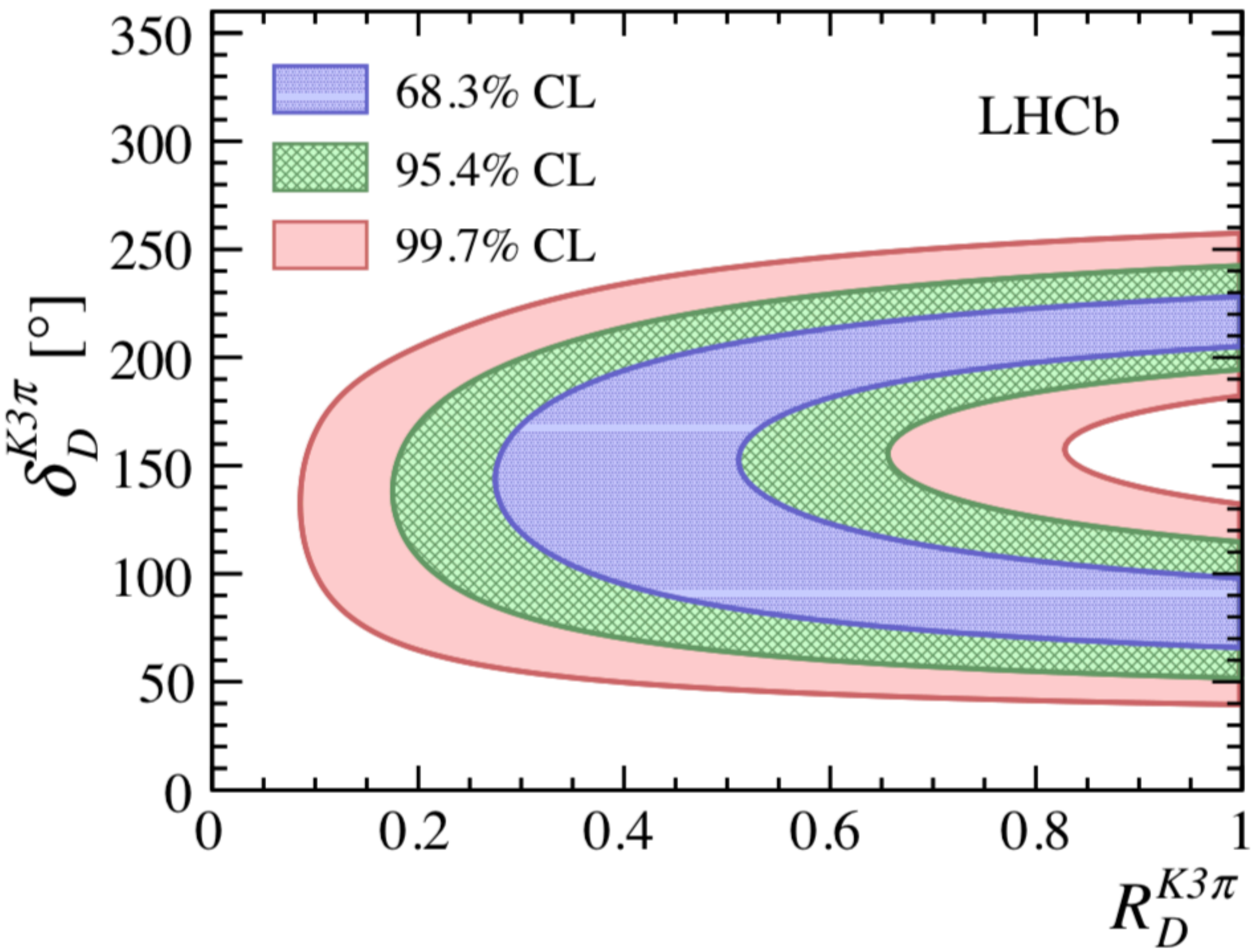
No-mixing hypothesis rejected at 8.2 σ

Fit Type χ^2/ndf (p-value)	Parameter	Fit result	Correlation coefficient $r_D^{K3\pi}$	$R_D^{K3\pi} \cdot y'_{K3\pi}$	$\frac{1}{4}(x^2+y^2)$
Unconstrained	$r_D^{K3\pi}$	$(5.67 \pm 0.12) \times 10^{-2}$	1	0.91	0.80
7.8/7 (0.35)	$R_D^{K3\pi} \cdot y'_{K3\pi}$	$(0.3 \pm 1.8) \times 10^{-3}$		1	0.94
	$\frac{1}{4}(x^2+y^2)$	$(4.8 \pm 1.8) \times 10^{-5}$			1

Strong phase and coherence factor

- Constrained fit: x and y constrained to the WA values
- The constrained fit allows to determine a line of solutions in the ($\delta_D^{K3\pi}$,$R_D^{K3\pi}$) plane
- Uncertainties on $r_D^{K3\pi}$ and $R_D^{K3\pi} y'^{K3\pi}$ are greatly reduced
- Useful input to the CKM angle γ (see my talk on Monday about γ inputs)
- A combination with CLEO-c data significantly improves the precision Phys Lett B 757 (2016) 520–527

Phys. Rev. Lett. 116, 241801 (2016)



			$r_D^{K3\pi}$	$R_D^{K3\pi} \cdot y'_{K3\pi}$	x	y
Mixing-constrained	$r_D^{K3\pi}$	$(5.50 \pm 0.07) \times 10^{-2}$	1	0.83	0.17	0.10
11.2/8 (0.19)	$R_D^{K3\pi} \cdot y'_{K3\pi}$	$(-3.0 \pm 0.7) \times 10^{-3}$		1	0.34	0.20
	x	$(4.1 \pm 1.7) \times 10^{-3}$			1	-0.40
	y	$(6.7 \pm 0.8) \times 10^{-3}$				1

Strong phase and coherence factor

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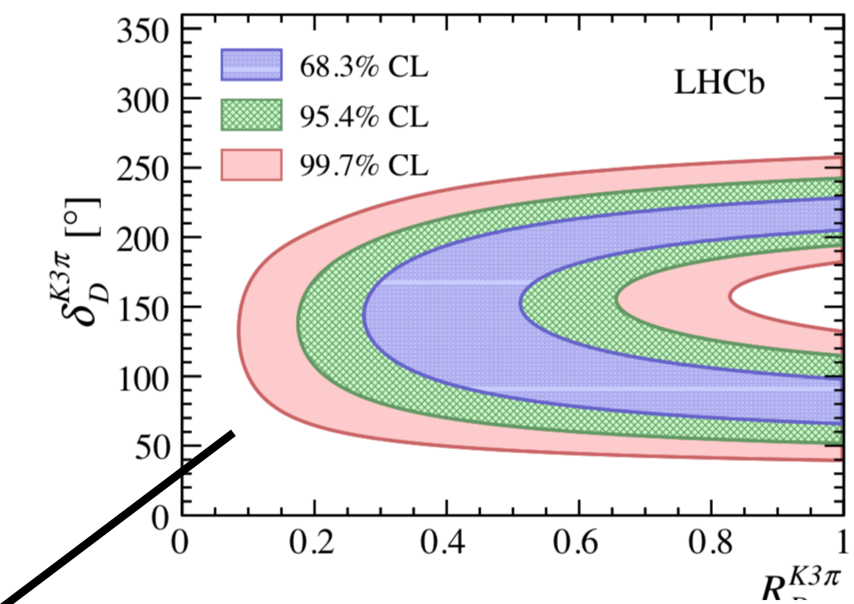
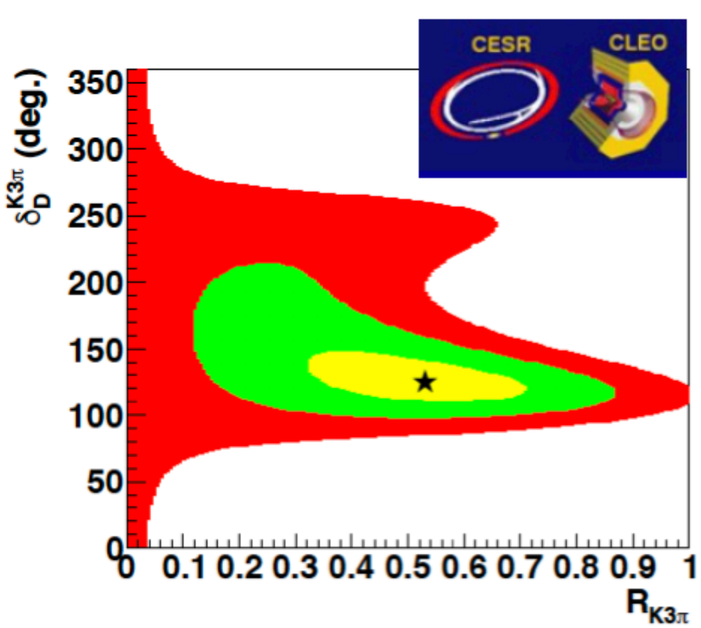


Scan from D-D̄ superpositions at CLEO-c



Phys.Lett. B757 (2016) 520-527

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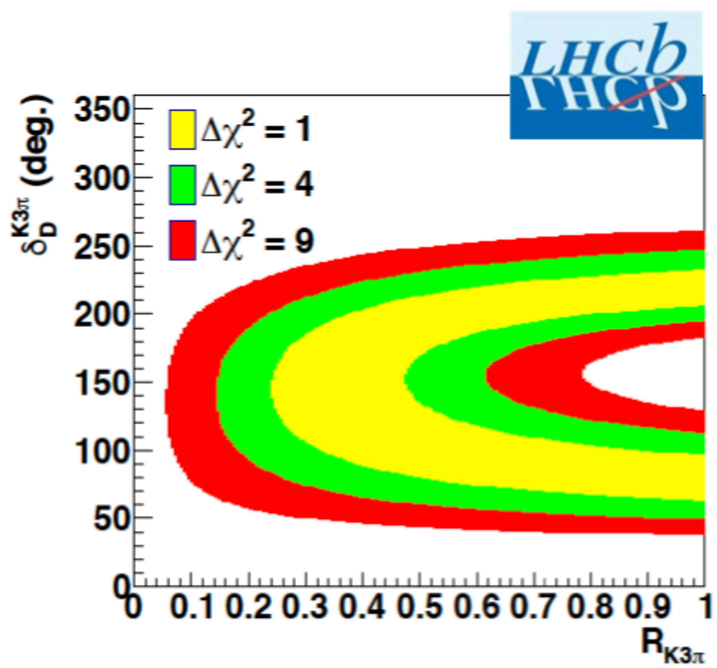
Input from charm mixing (LHCb)



PRL 116 (2016) no.24, 241801

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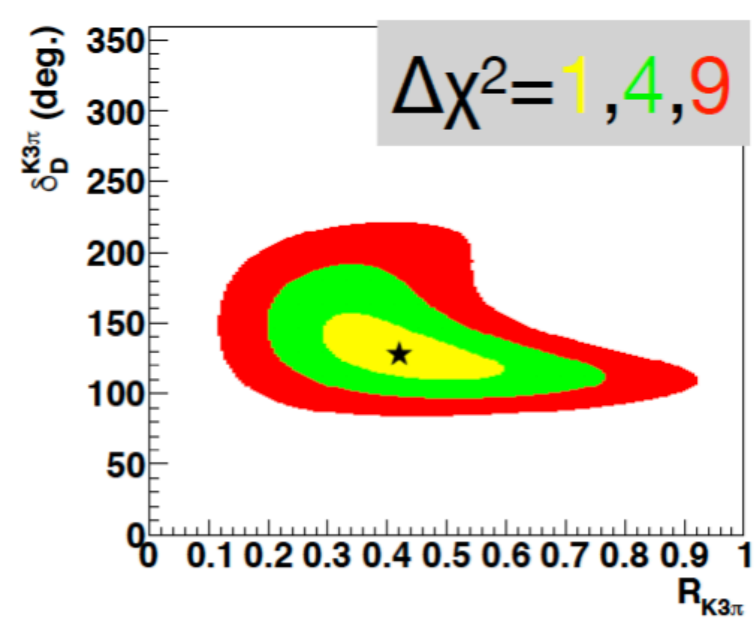
Combination:CLEO-c and mixing.



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Status of mixing and indirect CPV in charm

- Mixing by now well established ($D^0 \to K\pi$, $D^0 \to K\pi\pi\pi$ decays) by excluding the no-mixing hypothesis

- Mixing parameters: difficult to measure due to slow oscillation of D^0

  $x = (0.32 \pm 0.14)\%$
  $y = (0.69^{+0.06}_{-0.07})\%$

  HFLAV averages*
  CPV allowed

  *Eur. Phys. J. C77 (2017) 895 and online update at http://www.slac.stanford.edu/xorg/hflav

  - $y > 0$: CP-even eigenstate is shorter lived than CP-odd
  - $x > 0$?: mass splitting not yet clear

- CP violation in charm: expected to be small in the SM
  - Powerful constraints without hints for CPV: precision of A_Γ and ΔA_{CP} at sub per mille level

$$\lambda_f \equiv \frac{q\bar{A}_{\bar{f}}}{pA_f} = -\eta_{CP}\left|\frac{q}{p}\right|\left|\frac{\bar{A}_f}{A_f}\right| e^{i\phi}$$

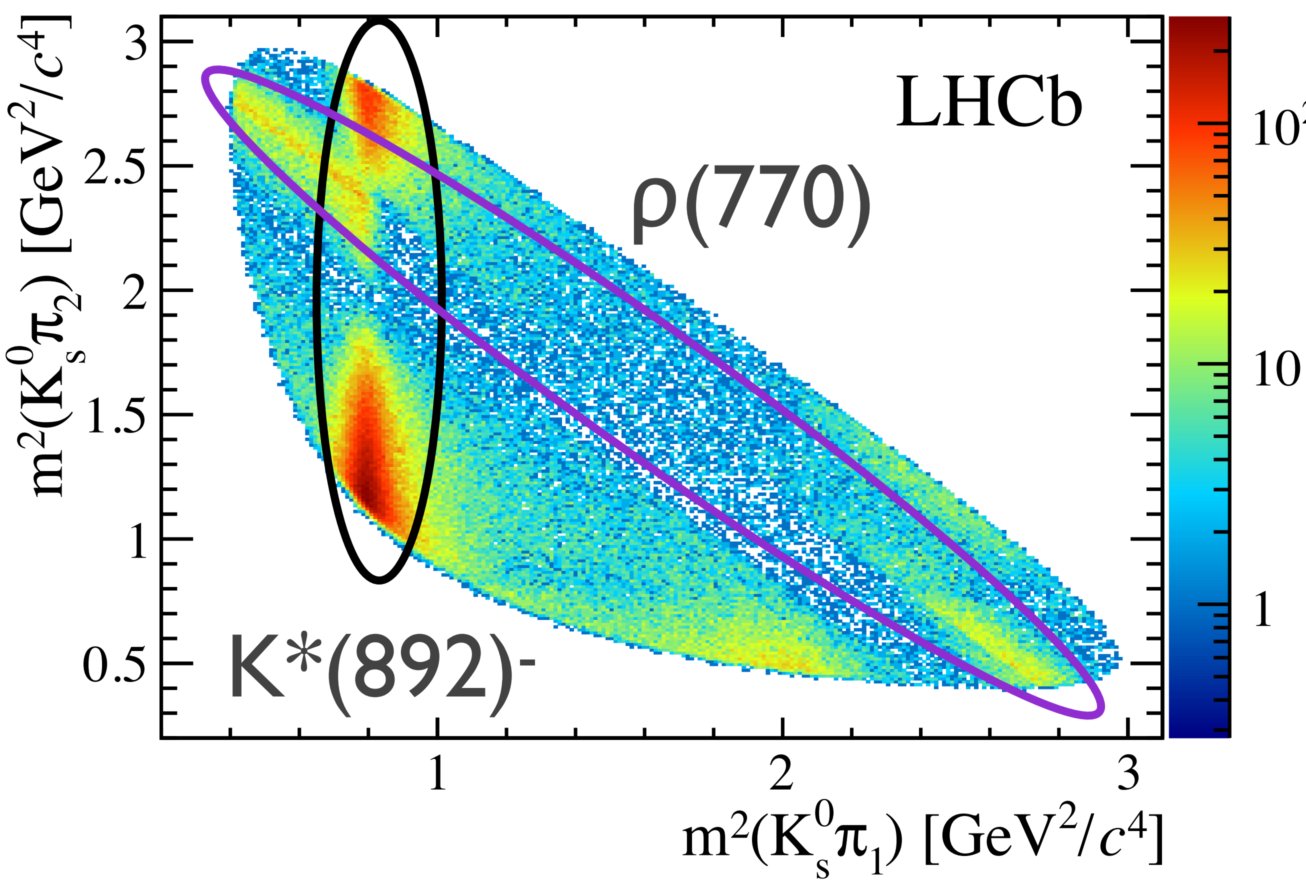
$|q/p| \neq 1$ CPV in mixing

or $\phi \neq 0$ CPV in the interference

Mixing in the golden mode $D^0 \to K_S hh$

JHEP 04 (2016) 033

- $K_S K^- K^+$ and $K_S \pi^- \pi^+$
  - Complex assembly of different resonances including flavour and CP eigenstates
  - Different superposition of amplitudes at each point in phase-space
  - Strong phase δ_D varies continuously across phase-space
  - Multiple interfering amplitudes enhance sensitivity to mixing

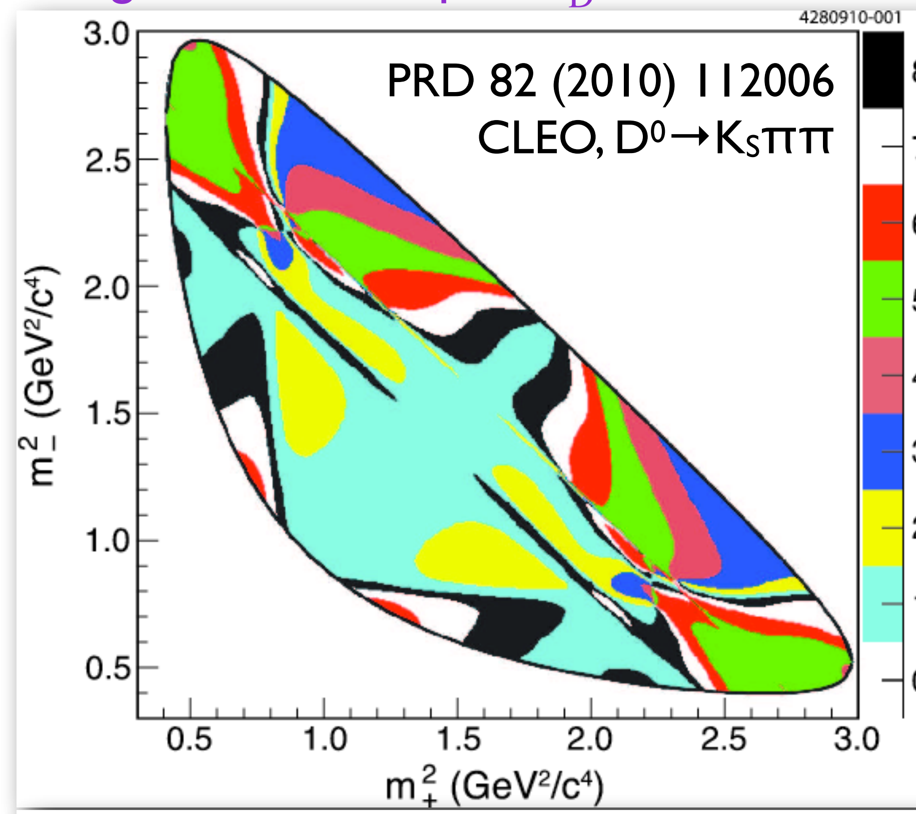


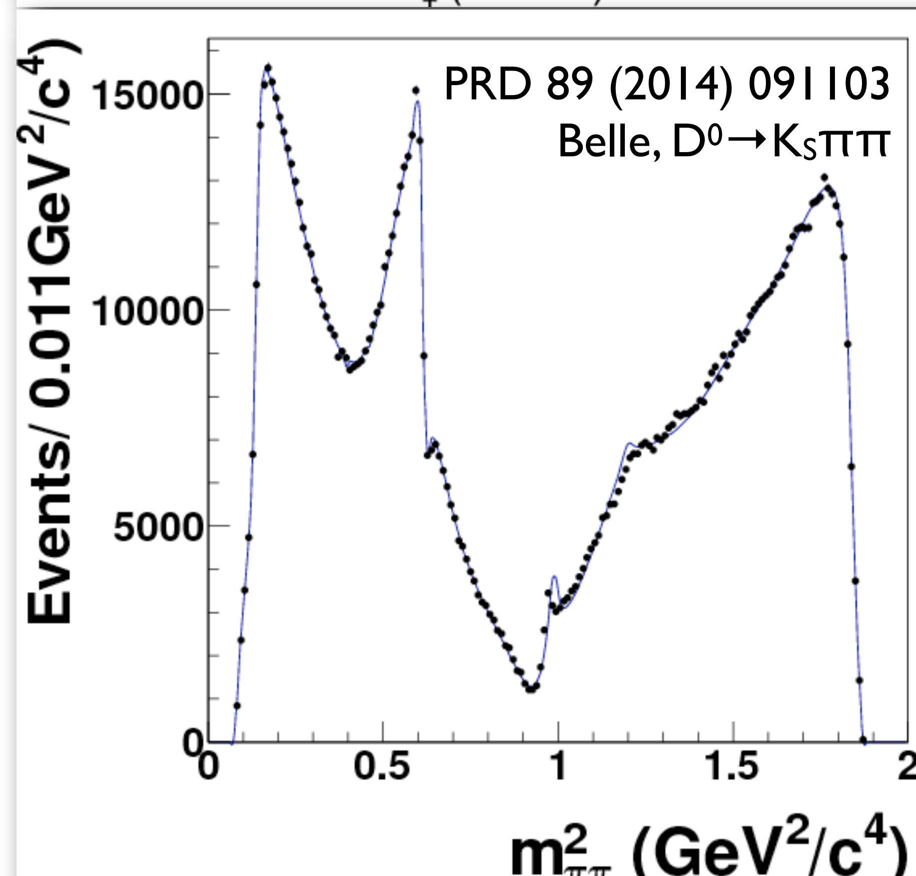
- Access to charm mixing parameters x_D and y_D
- Measure indirect CP violation via parameters $|q/p|$ and $\phi = \arg(p, q)$

Techniques

- Model-independent
  - Study decay-time evolution in bins of similar strong phase difference
  - Systematics from external input (CLEO-c, BESIII)
- Model-dependent
  - Measure effective lifetime of individual resonances
  - Difficulty at LHCb: Efficiencies varying as function of position in phase space and decay time
  - The choice of the model adds irreducible systematics
- New (model independent, unbinned): Fourier analysis of the complex phase difference between D^0 and $\bar{D}^0$ decay amplitudes (initially proposed and the sensitivity was tested for the CKM angle γ)
  Eur. Phys. J. C (2018) 78: 121

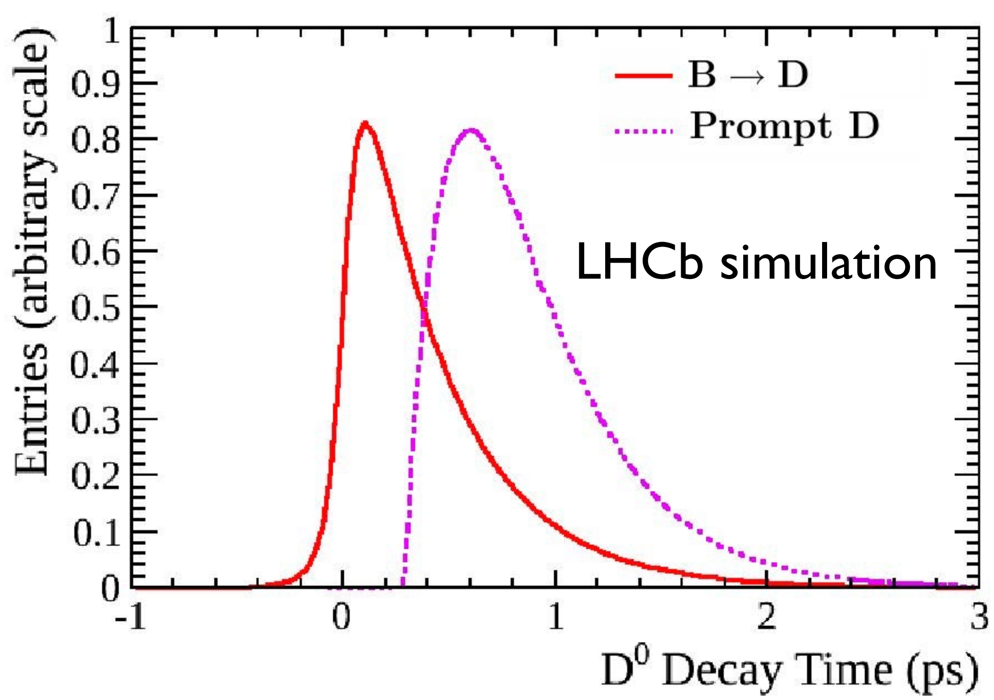
Babar 2008 optimal binning: bins with equal δ_D





Prompt vs secondary decays

- prompt charm: (from $D^{*\pm}\to D^0\pi^\pm$ decays) high yield, access only to high D^0 decay times
- secondary charm: (from $B\to D^0\mu^\mp\nu X$ decays) high trigger efficiency, access to all D^0 decay times
- doubly-tagged secondary events: ($B\to D^{*\pm}(\to D^0\pi^\pm)\mu^\mp\nu$ decays) high trigger efficiency, clean signature, access to all D^0 decay times, low yield



Convolution of (decay time x time resolution) and acceptance

Formalism of the unbinned technique

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- Phase-space dependent amplitudes for
  - $D^0 \to K_S^0\pi^+\pi^-$ decays: $\mathcal{A}$
  - $\overline{D}^0 \to K_S^0\pi^-\pi^+$ decays: $\mathcal{B}$
- Fraction of D^0 events in bin i → $T_i = \int_i |\mathcal{A}|^2 dm_+^2 dm_-^2$
- Interference terms between amplitudes $\mathcal{A}$ and $\mathcal{B}$

$$c_i \equiv \frac{1}{\sqrt{T_i T_{-i}}} \int_i |\mathcal{A}^*||\mathcal{B}| \cos(\Delta\delta_D) dm_+^2 dm_-^2$$

strong phase difference

$$s_i \equiv \frac{1}{\sqrt{T_i T_{-i}}} \int_i |\mathcal{A}^*||\mathcal{B}| \sin(\Delta\delta_D) dm_+^2 dm_-^2$$

Method

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- Time-dependent decay rates expressed as

$$\mathcal{P}(D^0) \approx e^{\Gamma t}\left(T_{-i} - \Gamma t\sqrt{T_i T_{-i}}\{y c_i + x s_i\}\right)$$
$$\mathcal{P}(\overline{D}^0) \approx e^{\Gamma t}\left(T_{-i} - \Gamma t\sqrt{T_i T_{-i}}\{y c_i - x s_i\}\right)$$

assuming CP symmetry

- T_i, c_i and s_i provided by CLEO

→ allows model-independent measurement of mixing parameters x and y

Model independent measurement

- Using prompt charm, collected at 7 TeV in 2011
- Separate D^0 signal and combinatorial background by fit to D^0 mass m_D
- Difference in χ^2 between PV reconstructed with and without D^0 to discriminate prompt against secondary decays ($\ln \chi^2_{IP}$)

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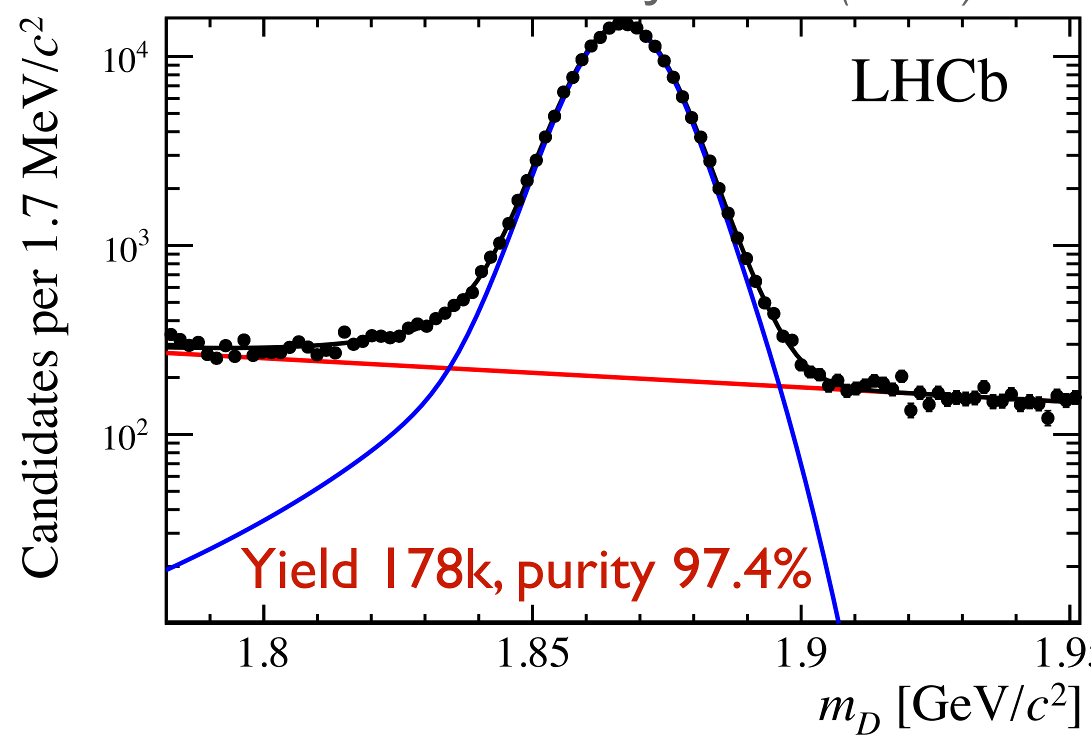

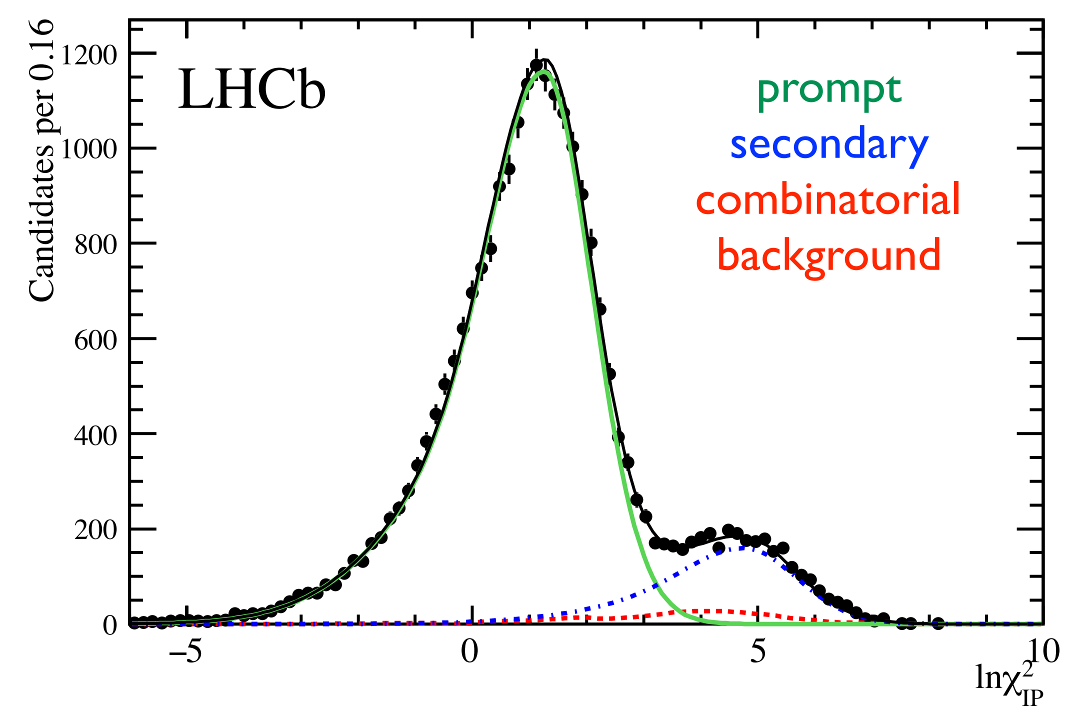

The results ($1 fb^{-1}$)

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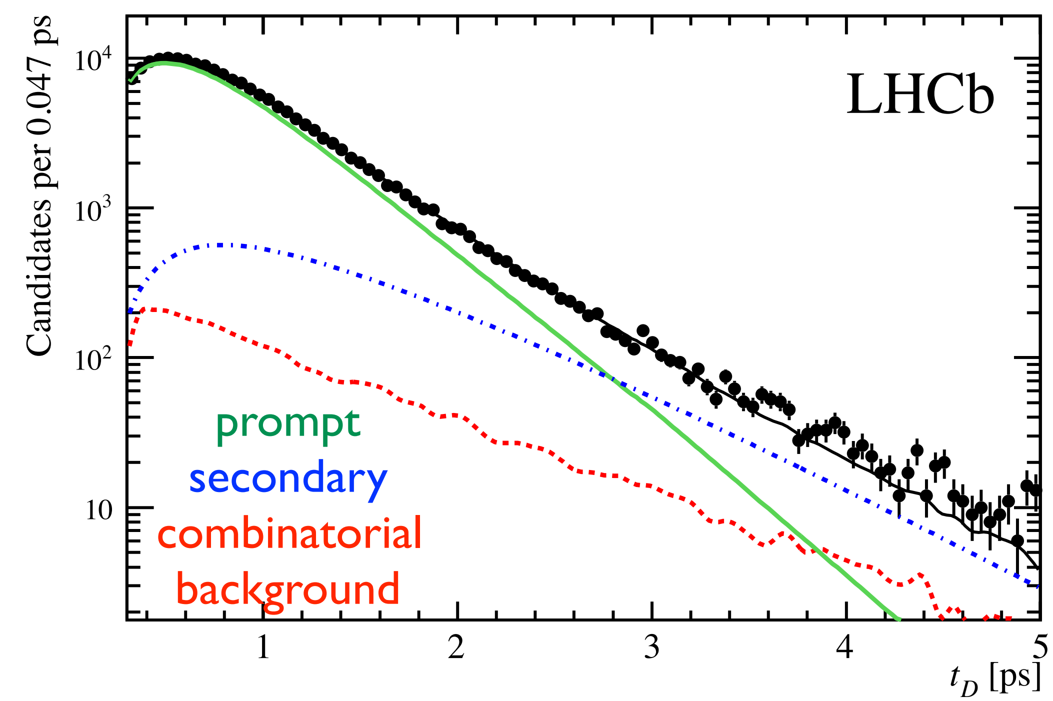
- Two-dimensional fits to D^0 decay time and ln χ^2_{IP} samples in each Dalitz bin to extract mixing parameters



x = (-0.86 ± 0.53 ± 0.17)%

y = (0.03 ± 0.46 ± 0.13)%

- Dominant sources of systematic uncertainties from resolution, efficiency variation over phase-space, uncertainty on T_i (CLEO-c input)

- The systematics can be reduced by using more precise input measurements - BESIII

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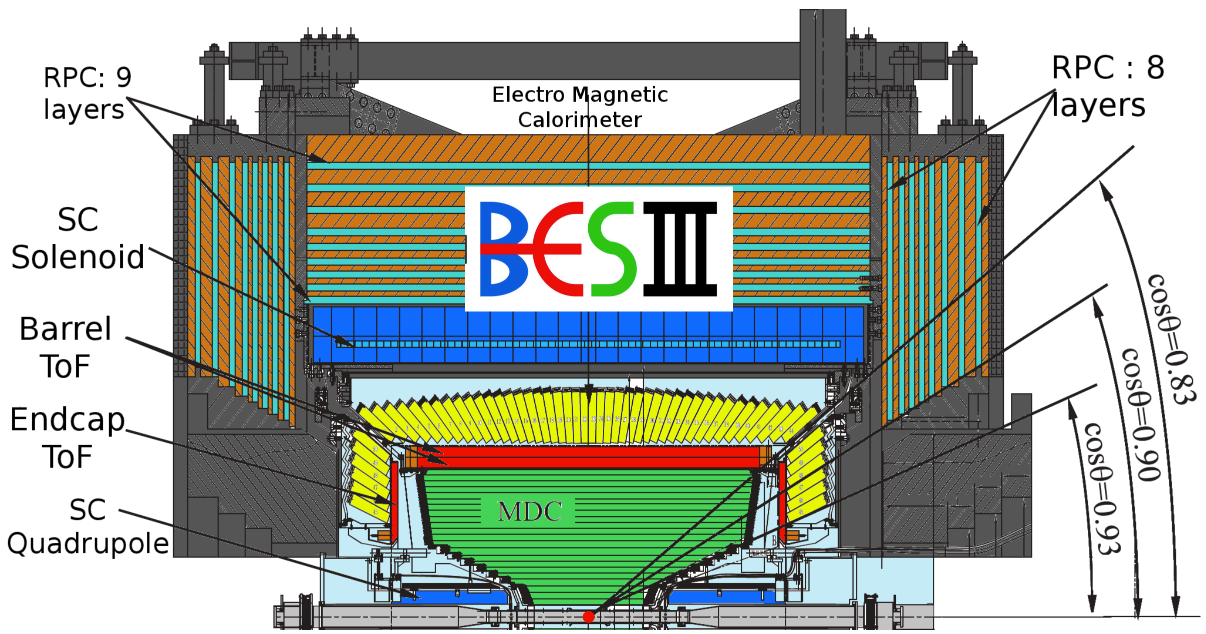
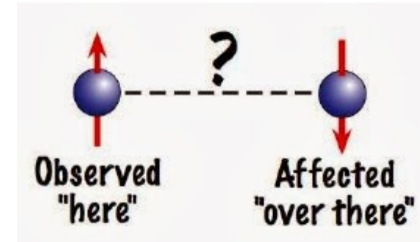
BESIII experiment, Beijing





Threshold production of charm with $e^+e^- \rightarrow \psi(3770)$

The $\psi(3770)$ decays to *coherent* pair of D mesons

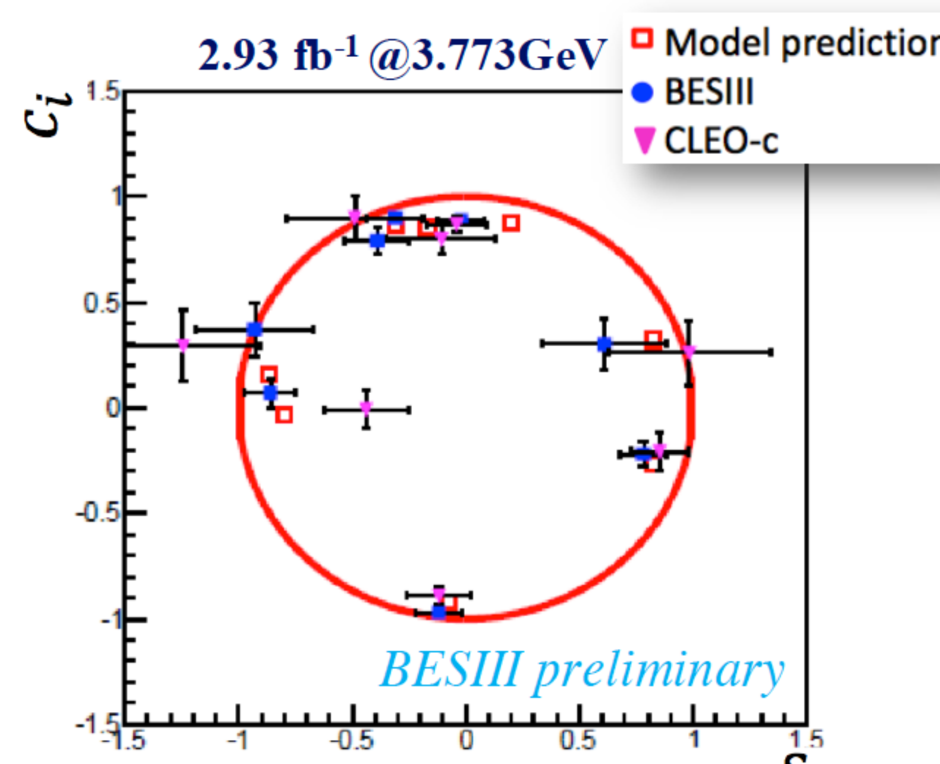
$$\psi(3770) \rightarrow \frac{1}{\sqrt{2}}\left[D^0(+z)\overline{D}^0(-z) - \overline{D}^0(+z)D^0(-z) \right]$$

$$\psi(3770) \rightarrow \frac{1}{\sqrt{2}}\left[D_{CP-}(+z)D_{CP+}(-z) - D_{CP+}(+z)D_{CP-}(-z) \right]$$

CP eigen-states: $D_{CP\pm} = [D^0 \pm \overline{D}^0]/\sqrt{2}$

- Unique access to relative strong phases, CP content & ability to extract model-independent results with charm at threshold
  - Use CP tags: reconstruct one meson as a CP eigenstate
  - Project the other meson as a superposition of D^0 and $\bar{D}^0$
  - D^0 and $\bar{D}^0$ amplitudes to a common final state interfere; Interference can change sign depending on the CP tag
- More about the synergy of LHCb and BESIII physics in LHCb-PUB-2016-025

4x Cleo-c statistics



Dan Ambrose, APS 2014

Summary

- Mixing studies with $D^0 \to K3\pi$ bring out important information about the mixing parameters and the coherence factor (useful input for the CKM angle γ)
- First model-independent measurement of x and y with LHCb 1 fb^{-1} @7TeV data sample $D^0 \to K_S hh$ as a proof of principle
  - statistically dominated
  - systematics can be reduced by using more precise input information from BESIII (BESIII results on c_i and s_i are preliminary)
- LHCb has several ongoing measurements of the charm mixing parameters, with Run 2 data (factor 5 more data)
  - Run 2: dedicated TURBO triggers
  - expecting higher yields therefore improved precision

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BACKUP

Types of CP violation

The symmetry under CP transformation can be violated in different ways: Present if λ_f is not equal to 1

$$\lambda_f \equiv \frac{q\bar{A}_{\bar{f}}}{pA_f} = -\eta_{CP}\left|\frac{q}{p}\right|\left|\frac{\bar{A}_f}{A_f}\right|e^{i\phi}$$

$$|\bar{A}_{\bar{f}}/A_f| \neq 1$$

direct CPV
depends on the decay mode

$$|q/p| \neq 1$$

CPV in mixing
The transition probability of particles to anti-particles compared to the reverse process differs.

CPV in the interference
φ, the CP-violating relative phase between q/p and $\bar{A}_{\bar{f}}/A_f$, is non-zero

The indirect CP violation is independent of the decay mode.

It involves neutral particles

Charm

- Charm is unique: only bound up-type quark system where mixing and CP violation can occur

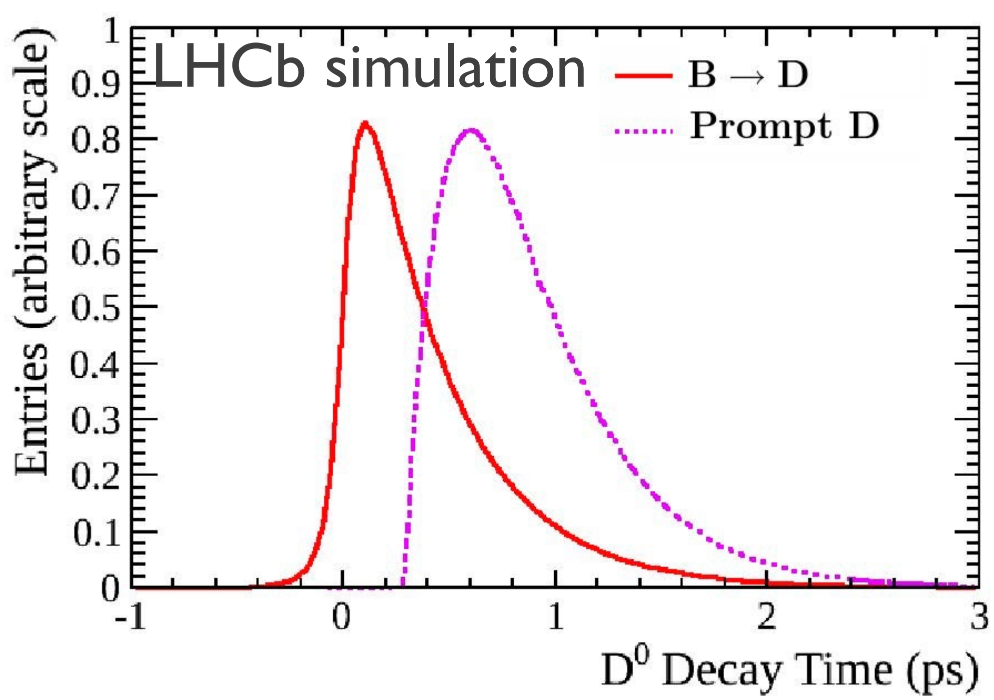
No CP violation at first order: imaginary part of V_{cd} very small

$$
\begin{array}{c} \\ \\ V_{CKM} \approx \end{array}
\begin{array}{c}
\begin{array}{ccc} \quad d \quad & \quad s \quad & \quad b \quad \end{array} \\
\begin{pmatrix}
1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\
-\lambda - iA^2\lambda^5\eta & 1-\frac{\lambda^2}{2} & A\lambda^2 \\
A\lambda^3(1-\hat{\rho}-i\hat{\eta}) & -A\lambda^2 - iA\lambda^4\eta & 1
\end{pmatrix}
\end{array}
\begin{array}{c} \\ u \\ c \\ t \end{array}
$$

- Making precise SM predictions in the D-meson sector is difficult
  - Perturbative QCD valid at energies >> 1 GeV
  - Chiral perturbation theory valid between 0.1 GeV and 1 GeV

Prompt vs secondary decays

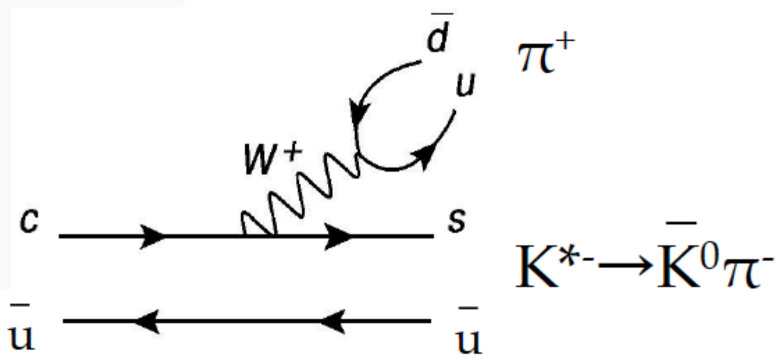
- Reconstructed prompt D^0 decays ≈ 3x muon -tagged D^0 decays
- More efficient triggering for secondary decays
- Small IP parameter for prompt decays; larger for muon-tagged decays
- Smaller flight distance for prompt decays; larger for the muon-tagged decays
- Different decay-time acceptances

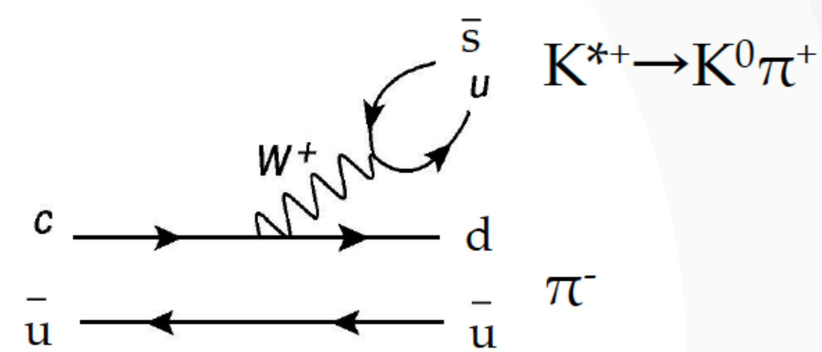


Convolution of (decay time x time resolution) and acceptance

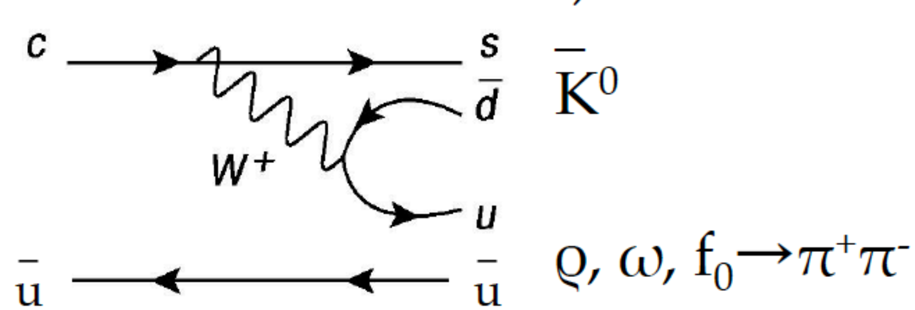
Quark diagrams for $D^0 \rightarrow K_S \pi^+ \pi^-$

- External W-emission
  - Cabibbo favoured $c \rightarrow s\underline{u}d$ doubly Cabibbo suppressed $c \rightarrow d\underline{u}s$

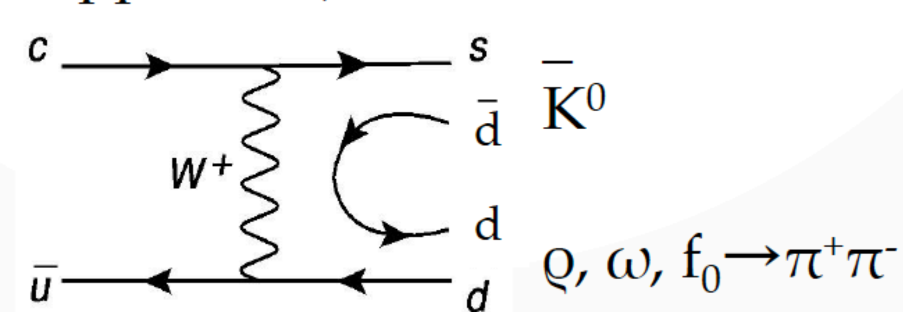




- Internal W-emission (colour suppressed)



- W-exchange (colour suppressed)



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analysis strategy

LHCb

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Extended ML fit to m_D
(signal and combinatorial background) → n(sig) and n(comb)

ML fit to (t_D, lnχ^2_{IP})
(background shapes from sidebands) → Shape of lnχ^2_{IP} for prompt and secondary

Extended ML fits to (m_D, δm)
(per bin for D^{*+} and D^{*-} separately) → n(sig) and n(bkg) per bin

Simultaneous ML fits to (t_D, lnχ^2_{IP})
(background shapes from sidebands) → x, y

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Systematic uncertainties, 1fb^{-1} result

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Source	$x\,(\times 10^{-2})$	$y\,(\times 10^{-2})$
Fit bias	0.021	0.020
Decay time resolution	0.065	0.039
Turning point (TP) resolution	0.020	0.022
Invariant mass resolution	0.073	0.028
Prompt/secondary TP distributions	0.051	0.023
Efficiency over phase space	0.057	0.071
Tracking efficiency parameterisation	0.015	0.025
Kinematic boundary	0.012	0.006
Combinatorial background	0.061	0.052
Treatment of secondary D decays	0.046	0.025
Uncertainty from T_i	0.079	0.056
Uncertainties from $(m_D, \Delta m)$ fits	0.000	0.000
Uncertainties from lifetime fit	0.020	0.043
D^0 background	0.001	0.006
Variation of signal components across the phase space	0.013	0.017
Total systematic uncertainty	0.171	0.134
Statistical uncertainty	0.527	0.463

Related measurements

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

PhysRevD 93 (2016) 112014

- Time-dependent Dalitz plot analysis: unbinned logL fit to $(t, s(\pi^-\pi^0), s(\pi^+\pi^0))$

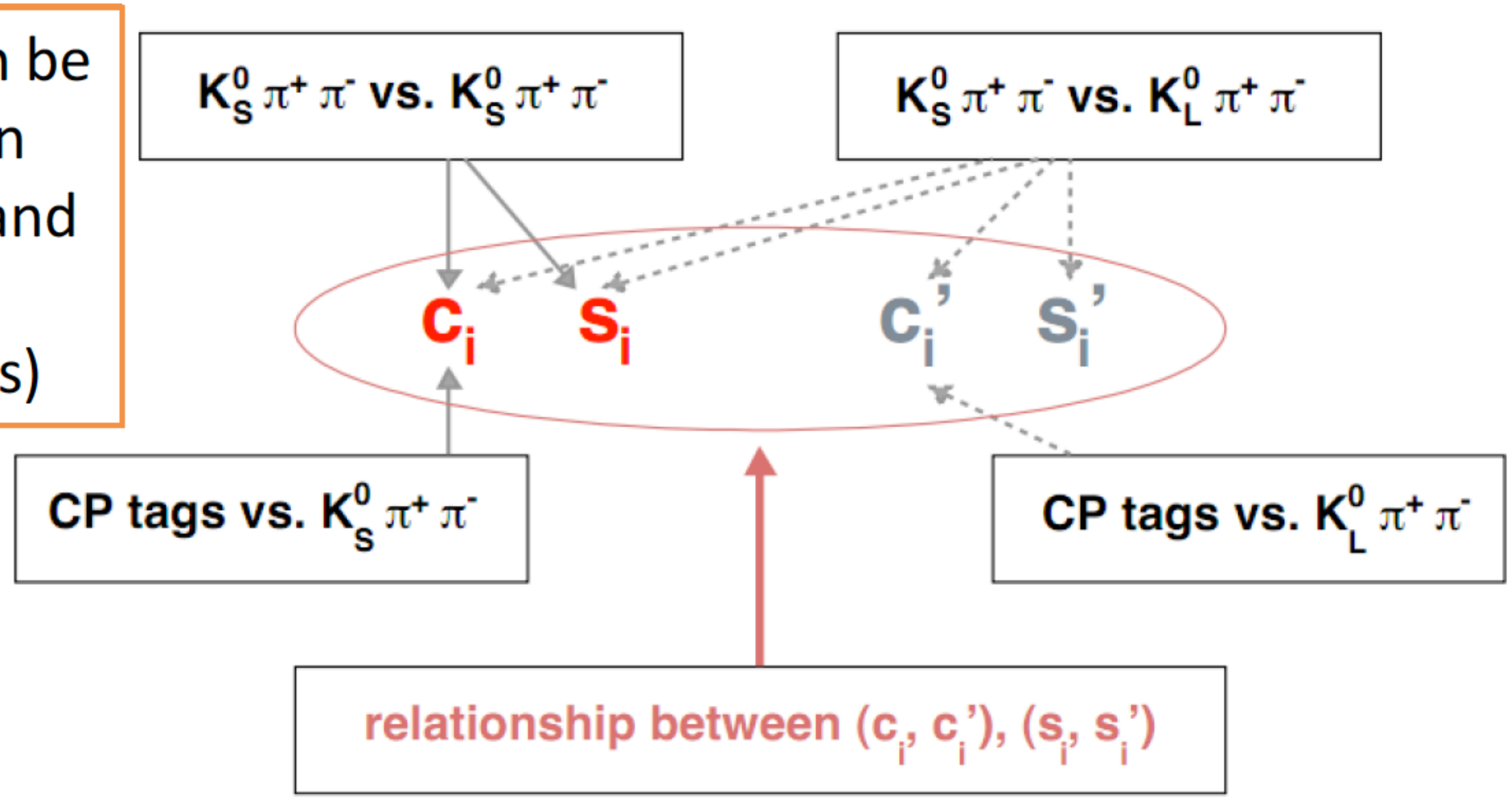
$x = (1.5 \pm 1.2 \pm 0.6)\%$

$y = (0.2 \pm 0.9 \pm 0.5)\%$

BESIII Preliminary $K_S\pi^+\pi^-$ Results

We can calculate c_i and s_i from double tags of
$D^0 \rightarrow K_S\pi^+\pi^-$ vs $D^0 \rightarrow (K_{S,L}\pi^+\pi^-$ or CP eigenstates)

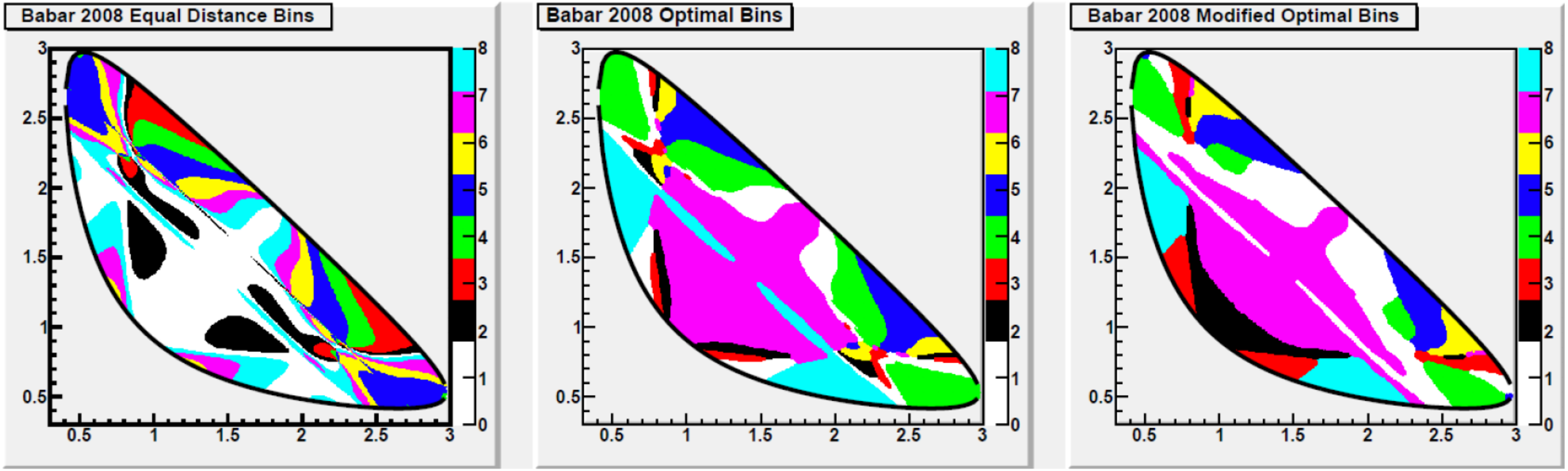
A relationship can be shown between Dalitz bin yields and c_i and s_i (in backup slides)



Only c_i, s_i from $K_S\pi^+\pi^-$ is used to calculate γ.
However adding in $D^0 \rightarrow K_L\pi^+\pi^-$ we can calculate c'_i, s'_i and use how they relate to c_i, s_i to further constrain our results in a Global fit.

Slide from Dan Ambrose, APS 2014

Preliminary $K_S\pi^+\pi^-$ Results



Result of splitting the Dalitz phase space into 8 equally spaced phase bins based on the BaBar 2008 Model.

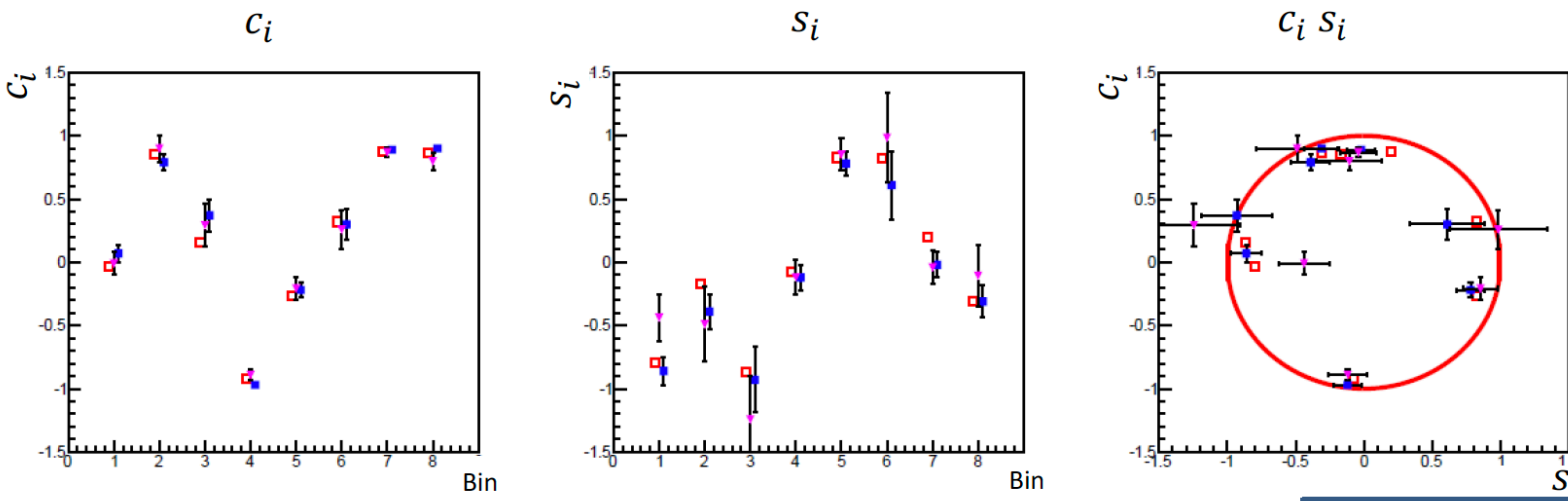
Starting with the equally spaced bins, bins are adjusted to optimize the sensitivity to γ. A secondary adjustment smooths binned areas smaller than detector resolution.

Similar to the "optimal binning" except the expected background is taken into account before optimizing for γ sensitivity.

Source: CLEO Collaboration, Physical Review D, vol 82., pp. 112006 - 112035

Slide from Dan Ambrose, APS 2014

Preliminary $K_S\pi^+\pi^-$ Results



Bins	c_i BES-III	c_i CLEO-c	s_i BES-III	s_i CLEO-c
1	0.066 ± 0.066	-0.009 ± 0.088	-0.843 ± 0.119	-0.438 ± 0.184
2	0.796 ± 0.061	0.900 ± 0.106	-0.357 ± 0.148	-0.490 ± 0.295
3	0.361 ± 0.125	0.292 ± 0.168	-0.962 ± 0.258	-1.243 ± 0.341
4	-0.985 ± 0.017	-0.890 ± 0.041	-0.090 ± 0.093	-0.119 ± 0.141
5	-0.278 ± 0.056	-0.208 ± 0.085	0.778 ± 0.092	0.853 ± 0.123
6	0.267 ± 0.119	0.258 ± 0.155	0.635 ± 0.293	0.984 ± 0.357
7	0.902 ± 0.017	0.869 ± 0.034	-0.018 ± 0.103	-0.041 ± 0.132
8	0.888 ± 0.036	0.798 ± 0.070	-0.301 ± 0.140	-0.107 ± 0.240

***Only statistical uncertainty is listed

□ Model prediction
● BESIII
▼ CLEO-c

BESIII Preliminary

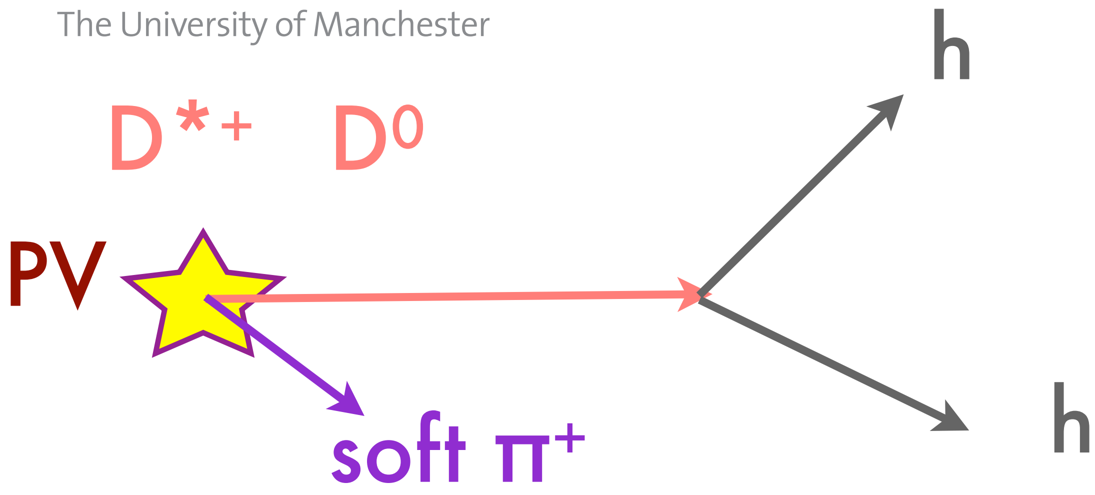
Consistent agreement with CLEO-c measurements.

Source: CLEO Collaboration, Physical Review D, vol 82., pp. 112006 - 112035

Improved errors w.r.t. CLEO-c

Slide from Dan Ambrose, APS 2014

Flavour tagging at LHCb



$h = \pi^\pm$ or $K^\pm$

Prompt charm:

D points to primary vertex

Daughters of D don't in general

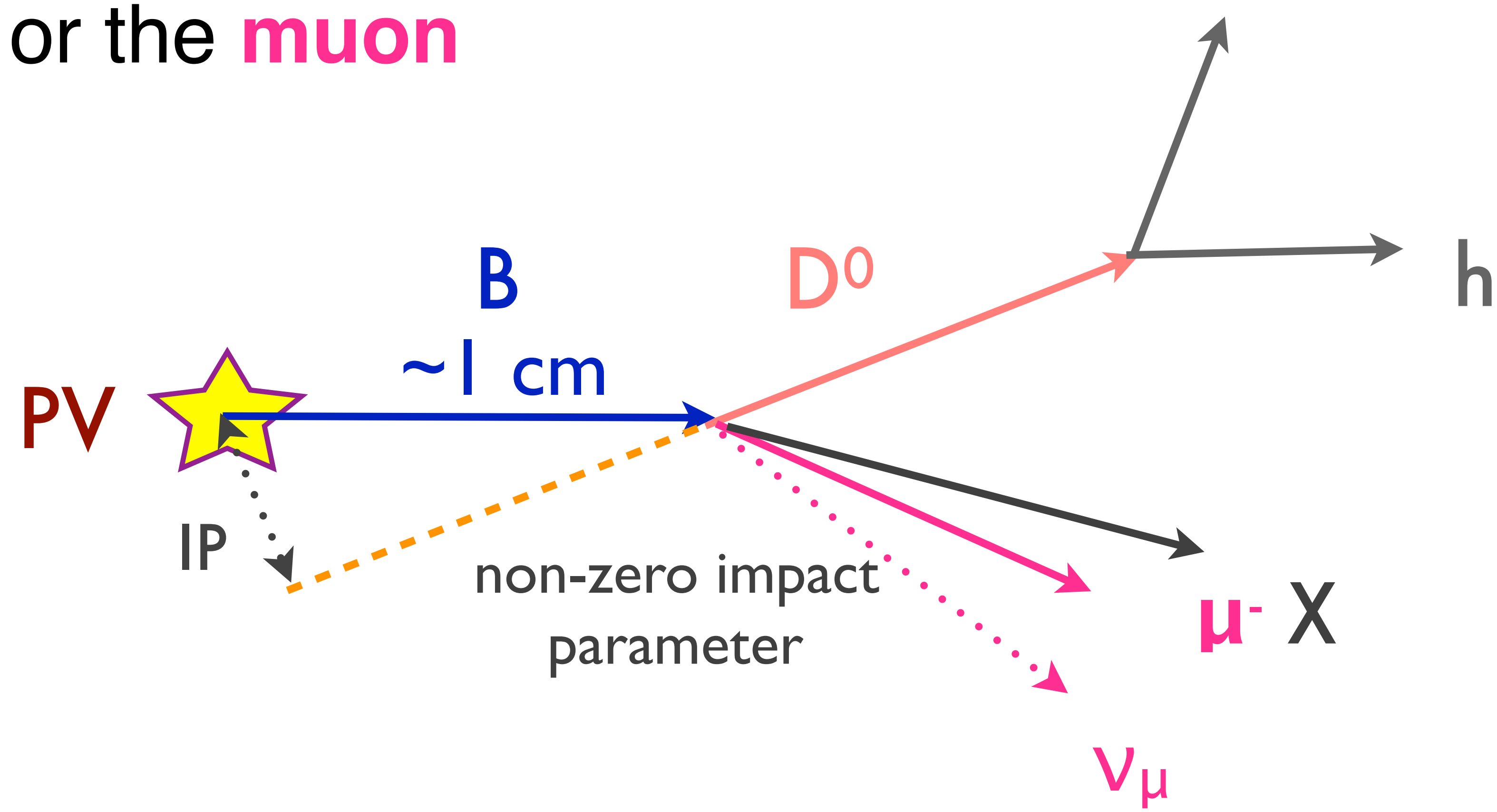
The flavour of the initial state $(D^0, \bar{D}^0)$ is tagged by the charge of the **soft pion** or the **muon**

Secondary charm:

D doesn't point to PV

If $B \rightarrow D^{*\pm}(\rightarrow D^0\pi^\pm)\mu^\mp\nu$:

doubly-tagged decays



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A new idea on the horizon

LHCb

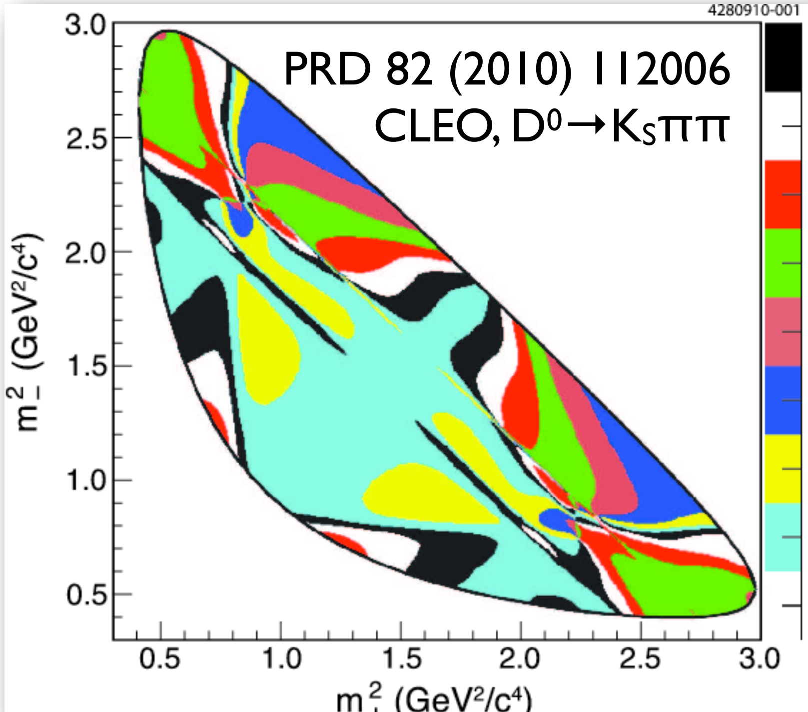
- Anton Poluektov arXiv:1712.08326v1
- A model-independent approach to perform a measurement of CKM angle γ with GGSZ method is proposed that has superior statistical sensitivity than the well-established method involving binning of the $D^0 \to K_S hh$ decay phase space.
- The technique employs Fourier analysis of the complex phase difference between D^0 and $\bar{D}^0$ decay amplitudes and can be easily generalised to other similar measurements, such as studies of charm mixing
- The method uses a construction inspired by a D^0 amplitude model, but provides an unbiased measurement even if the wrong model is used.

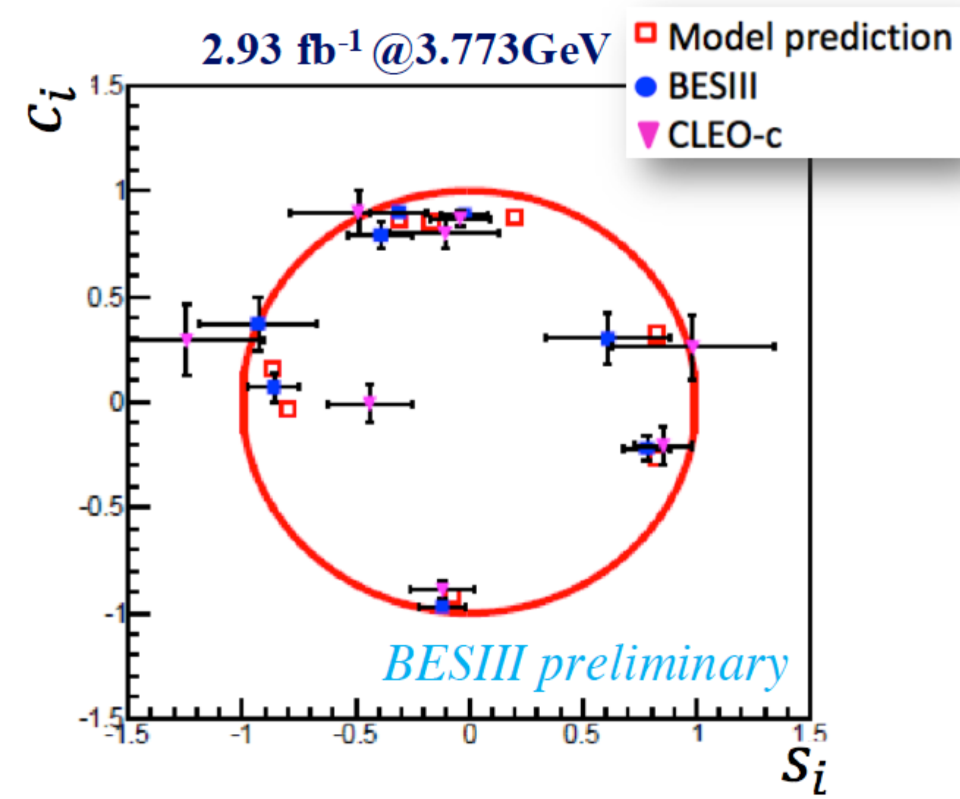
THE ROYAL SOCIETY

Mixing and indirect CPV

$D^0 \to K_S \pi^+ \pi^-$
preliminary since APS 2014

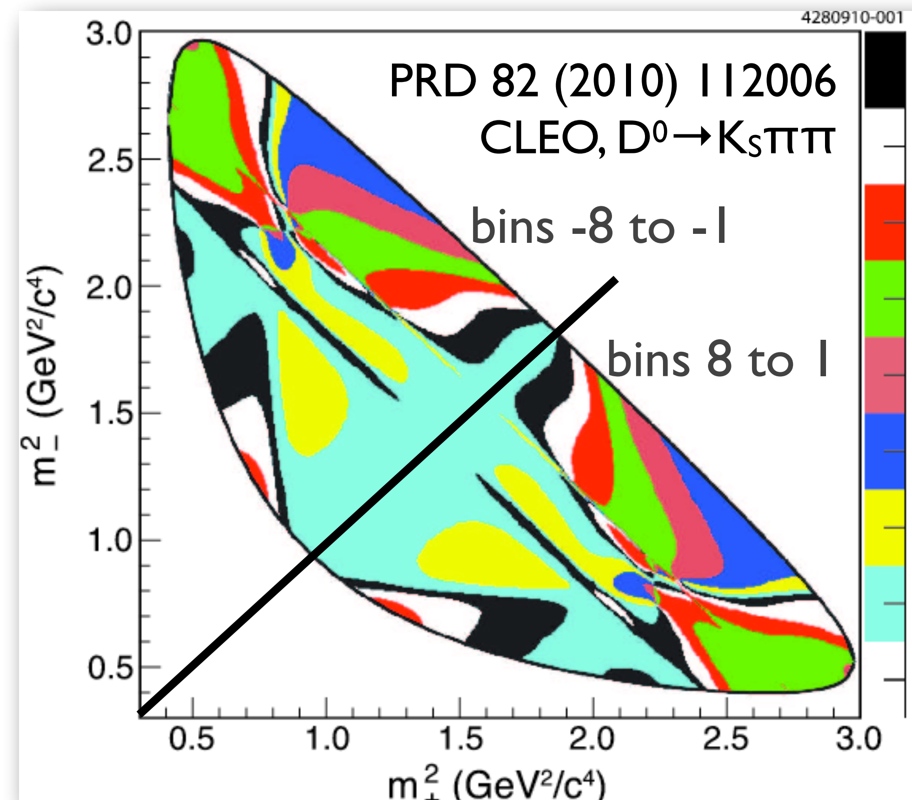
- Quantum correlations in ψ(3370) to tag D flavour and CP
- Obtain $c_i = \cos(\Delta\delta_{D,i})$ and $s_i = \sin(\Delta\delta_{D,i})$
- 4x Cleo-c statistics
- Important input for model independent measurements of charm mixing parameters
- Fundamental for the GGSZ method for γ ($B^+ \to D^0 K$ decays with $D^0 \to K_S hh$ decays) - uncertainty due to c_i, s_i can be halved with the existing statistics
- More about the synergy of LHCb and BESIII physics in LHCb-PUB-2016-025





Model independent technique

- Split the phase space in 16 bins with similar strong phase differences
- Bins symmetric around $m^2(\pi^-\pi^+)$ axis
- Binned measurements provided by Cleo-c for various amplitude models



Babar 2008 optimal binning: bins with equal δ_D