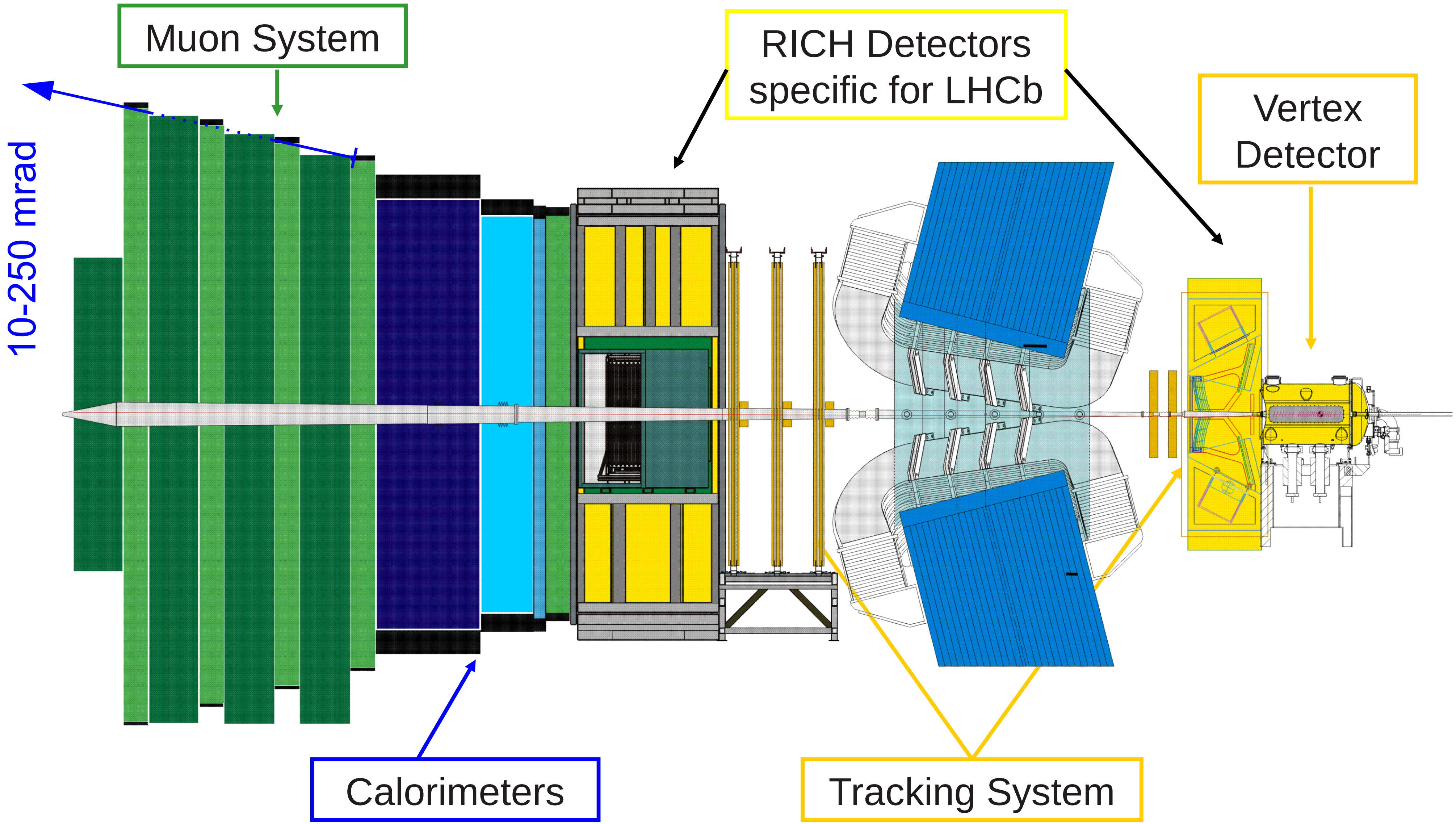
Charm 2012

May 16th, 2012

LHC and Tevatron Charm Mixing Results

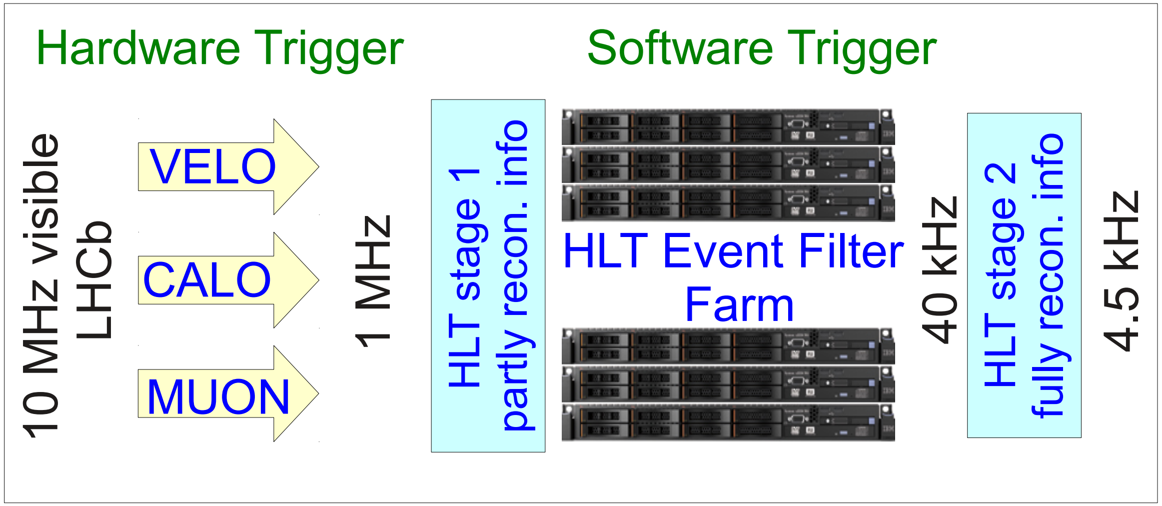
Jörg Marks
Heidelberg University
(LHCb Collaboration)

LHCb Experiment



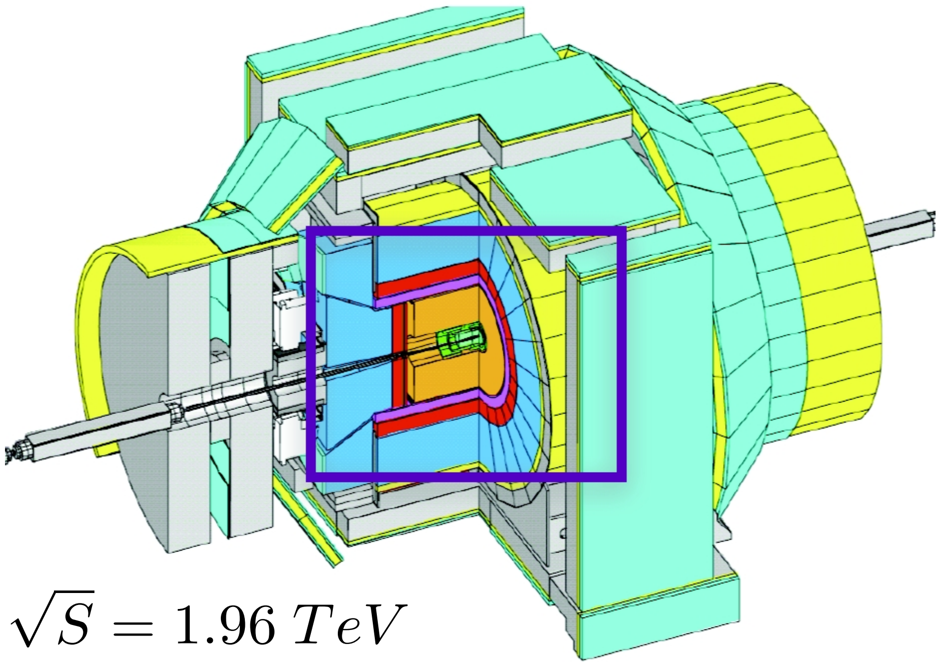
LHCb - Trigger Overview

- Hardware Trigger based on VELO, Calorimeter and Muonsystem
  - Select on p_T objects: $h, \mu, \mu\mu, e^{\pm}, \gamma, \pi^0$
  - Obtain p-p interaction and multiplicity information



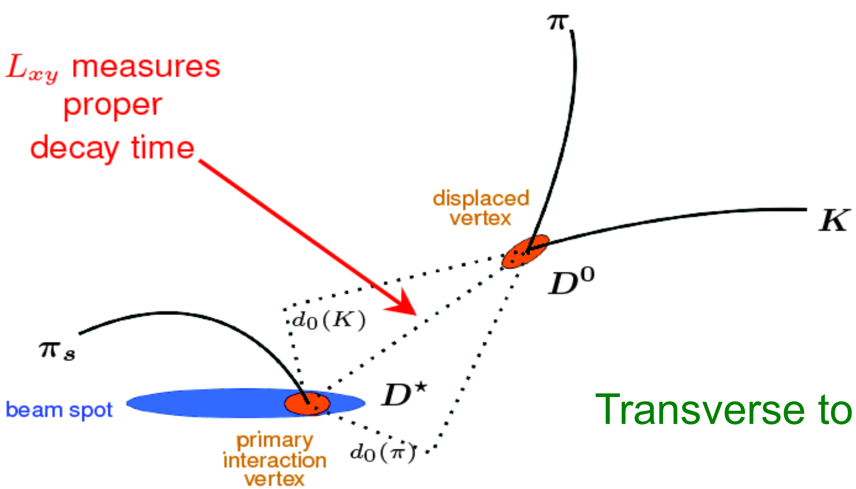
- Two level software trigger based on partly / fully reconstructed objects fully reconstructed objects with all detector information
  - Confirm L0 trigger objects using reconstr. and combined detector information
  - Select on a single track with high p_T and displaced vertices using VELO
  - Use reconstructed objects for exclusive selections and inclusive streams with clear signiture
- In 2012 write 4.5 kHz to storage with 2 kHz charm data

CDF II – Setup for Charm



$\sqrt{S} = 1.96\ TeV$

- Find fully reconstr. $D^* \rightarrow \pi_s(D^0 \rightarrow K\pi)$
  - Si vertex detector
  - Wire chamber COT in 1.4 T B field
  - PID via $\frac{dE}{dx}$ in COT
- Trigger on 2 oppositely charged tracks with detached vertex
  - $p_T^{track} > 2\ GeV/c$
  - $|d_0(K\pi)| > 100\ \mu m$
  - $L_{xy} > 200\ \mu m$



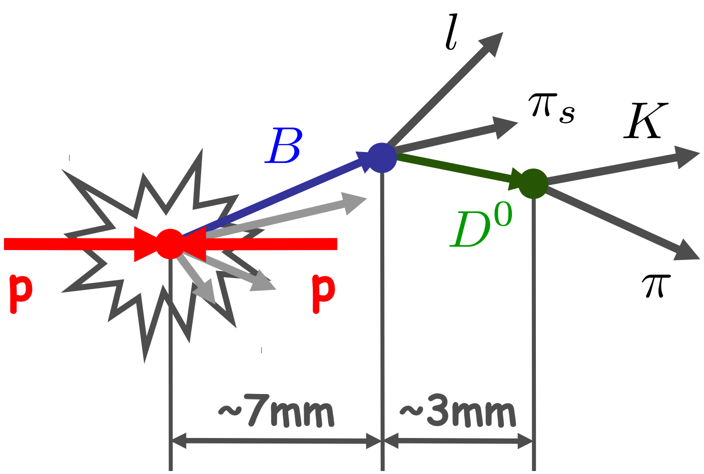
Transverse to Beam

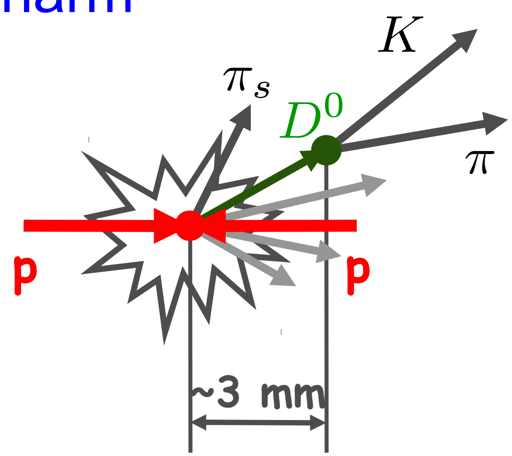
Charm Production

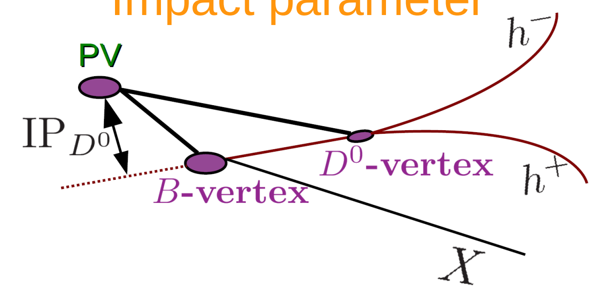
Huge cross section for heavy quark production at hadron colliders, e.g. events within LHCb acceptance: $10^{12} c\bar{c}/fb^{-1}$ and $10^{11} b\bar{b}/fb^{-1}$

- Prompt and secondary charm

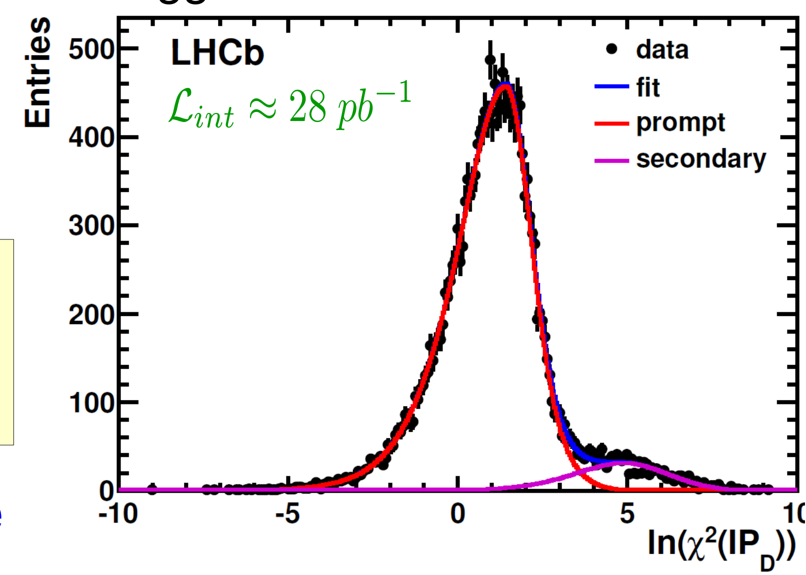
$BR(B \rightarrow D^{*\pm} X) \approx 0.23$







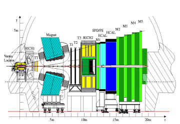
tagged $D^0 \rightarrow K\pi$



PV resolution data (MC)
$\sigma_{x,y} \approx 11\ \ (10)\ \mu m$
$\sigma_z \approx 60\ \ (50)\ \mu m$

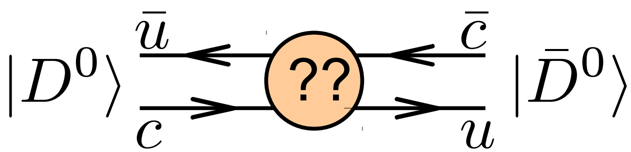
IP resolution, p_t > 2 GeV	
CDF II	$35\ \mu m$
LHCb	$22\ \mu m$

LHCb and CDF II use prompt charm sample



Mixing Formalism

Neutral D^0 mesons are created as flavor eigenstates of the strong interaction. They can mix through weak interactions.



- The time evolution is obtained by

$$i\frac{\partial}{\partial t}\begin{pmatrix} D^0(t) \\ \bar{D}^0(t) \end{pmatrix} = (M - \frac{i}{2}\Gamma)\begin{pmatrix} D^0(t) \\ \bar{D}^0(t) \end{pmatrix}$$

- The physical eigenstates are D_1 and D_2:

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

$$|D_{1,2}(t)\rangle = e^{-i(M_{1,2}-i\Gamma_{1,2}/2)t}|D_{1,2}(t=0)\rangle$$

D_1 : CP even

D_2 : CP odd

- Define mass and lifetime differences of D_1 and D_2:

$$x = \frac{\Delta M}{\Gamma} = \frac{M_1 - M_2}{\Gamma} \qquad y = \frac{\Delta\Gamma}{2\Gamma} = \frac{\Gamma_1 - \Gamma_2}{2\Gamma}$$

$$\Gamma = \frac{\Gamma_1 + \Gamma_2}{2}$$

Time Evolution in $D^0 \to K\pi$ Decays

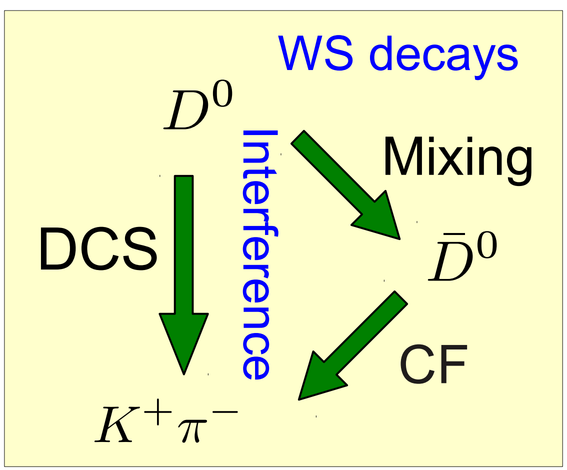
- Event classes - flavour tagging at production and decay time

No Mixing: $D^{*+} \to \pi_s^+ D^0$, $D^0 \to \pi^+ K^-$ — Right Sign Decay (RS), no D^0 Mixing, $R \approx 1$

Mixing: $\bar{D}^0 \to \pi^- K^+$ — Wrong Sign Decay (WS), D^0 Mixing

- DCS 0.3% unmixed
- CF 0.006% mixed

- Time evolution of the WS decay rate



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

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

- $\delta_{K\pi}$ is the strong phase between CF and DCS amplitudes ($D^0 \to K\pi$)

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

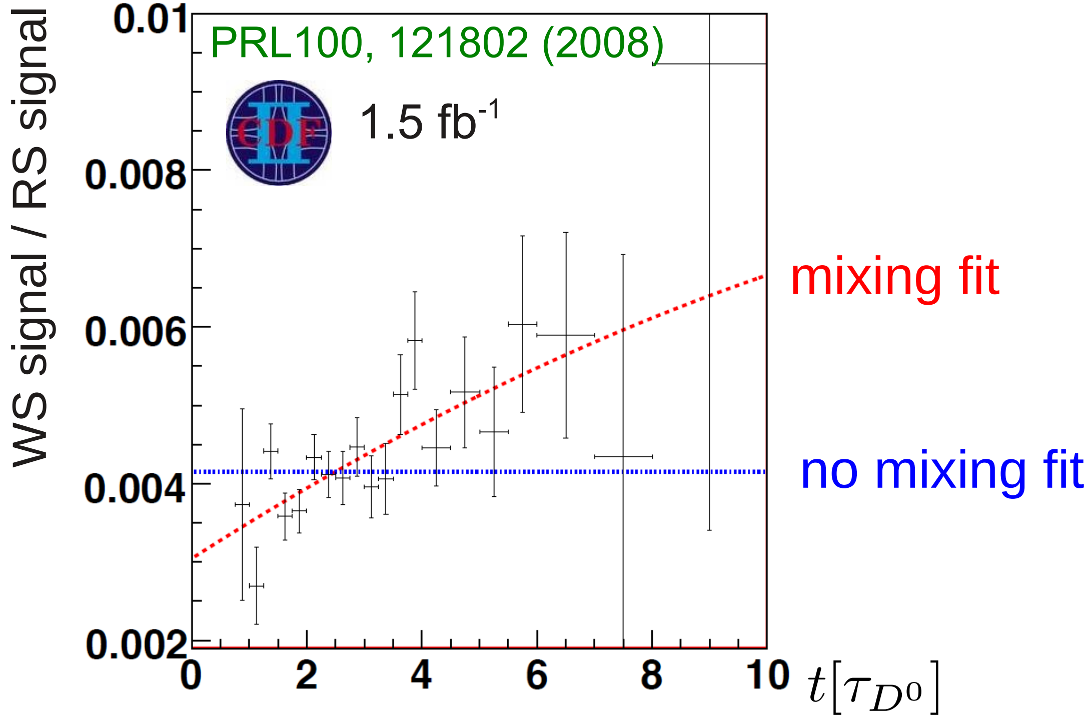
$$y'^2 + x'^2 = x^2 + y^2$$

CDF II – Mixing in $D^0 \to K\pi$

- Measure the Number of WS and RS D^0 decays in bins of the decay time

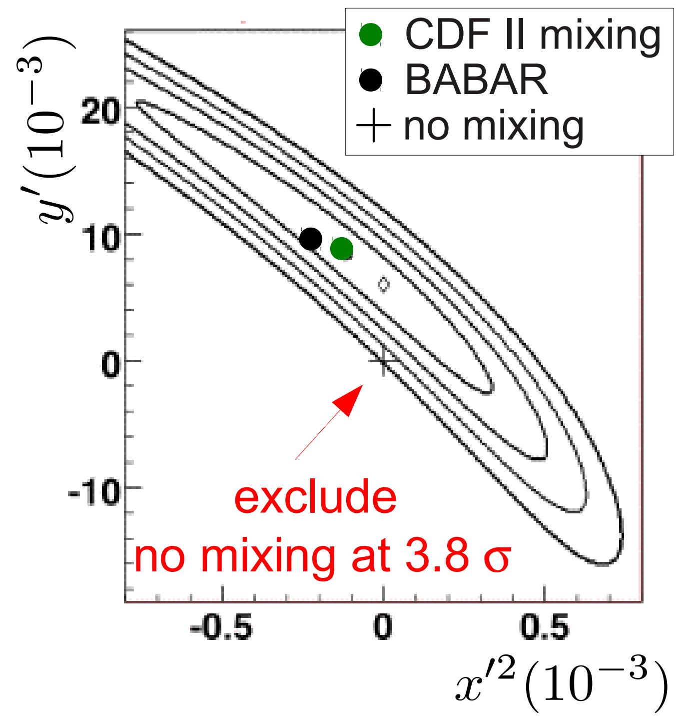
$$N_{RS}^{tot} = (3.044 \pm 0.0023) \cdot 10^6$$
$$N_{WS}^{tot} = (12.7 \pm 0.3) \cdot 10^3$$

- Fit the $N_{WS}^{tot}/N_{RS}^{tot}$ vs the D^0 decay time



- Mixing Parameter

$$R_D = (0.304 \pm 0.055)\%$$
$$y' = (0.85 \pm 0.76)\%$$
$$x'^2 = (-0.012 \pm 0.035)\%$$



Very good agreement with *BABAR*

Projection to the Full CDF Dataset

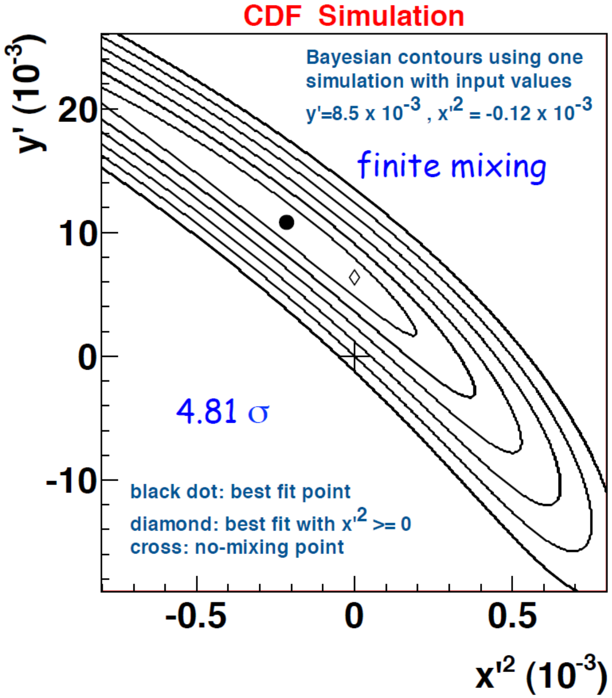
CDF dataset is $9.7\ fb^{-1}$, but charm trigger is prescaled at higher luminosities. Number of D^*s does not scale linearly.

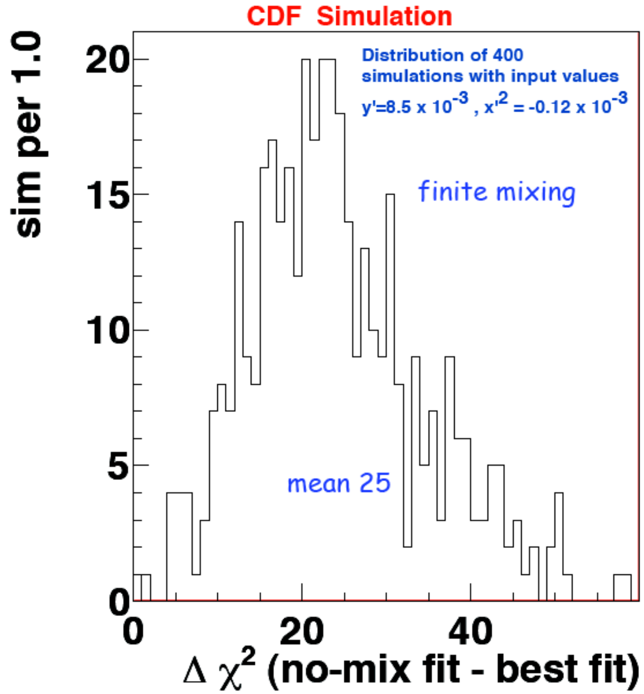
Plots: E Karchin, APS 2012

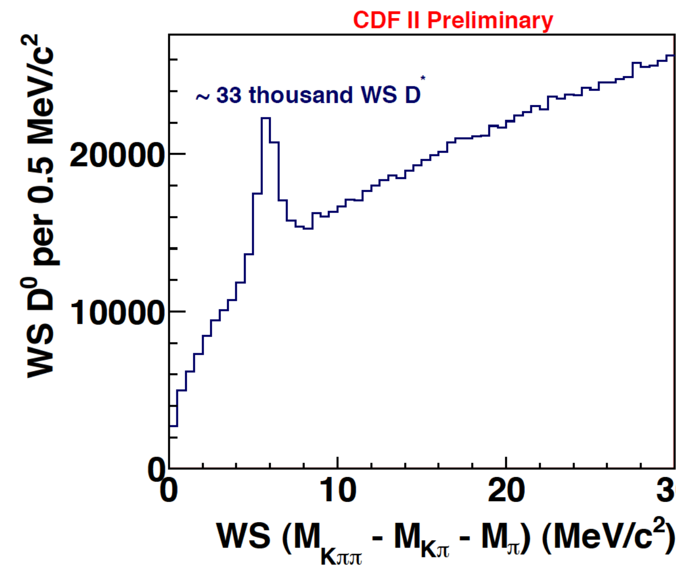
- Yields $D^* \to \pi_s (D^0 \to K\pi)$

  $$N_{RS} \approx 7.5 \cdot 10^6 \qquad N_{WS} \approx 3.3 \cdot 10^4$$

- Expected significance from simulations







$3\sigma \equiv 11.8 \quad 5\sigma \equiv 28.8$

CDF II could reach $5\ \sigma$ significance with the full dataset.

Experimental Results - $D^0 \to K\pi$

PRL 98, 211802 (2007) — 3.9 σ

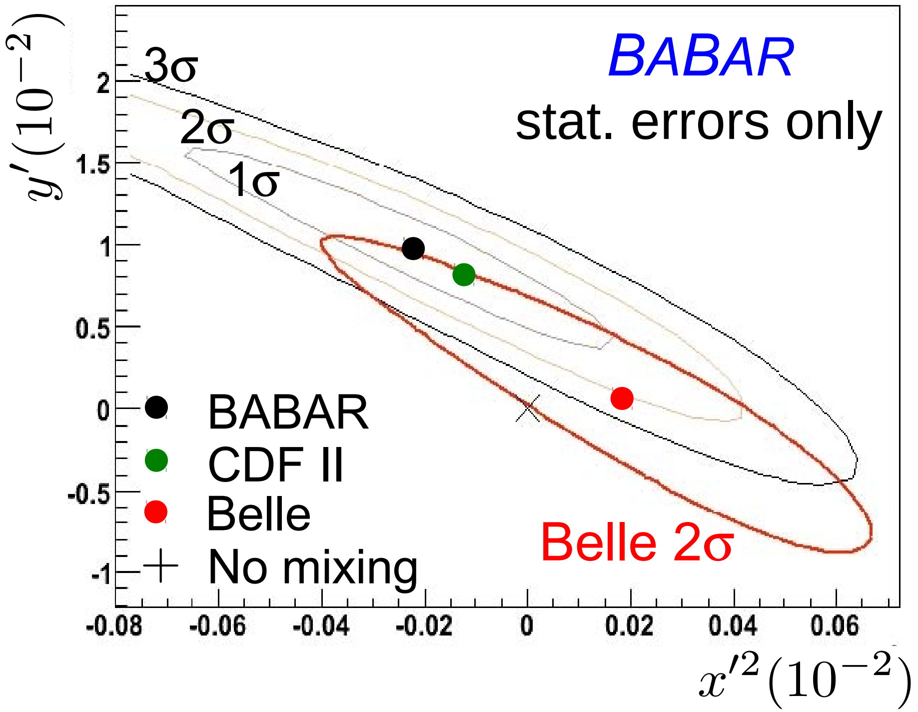
$$R_D = (0.303 \pm 0.016 \pm 0.01)\%$$
$$y' = (0.97 \pm 0.44 \pm 0.31)\%$$
$$x'^2 = (-0.022 \pm 0.03 \pm 0.021)\%$$

PRL100, 121802 (2008) — 3.8 σ

$$R_D = (0.304 \pm 0.055)\%$$
$$y' = (0.85 \pm 0.76)\%$$
$$x'^2 = (-0.012 \pm 0.035)\%$$

PRL 96,151801 — 2 σ

$$R_D = (0.364 \pm 0.017)\%$$
$$y' = (0.06^{+0.40}_{-0.39})\%$$
$$x'^2 = (0.018^{+0.021}_{-0.23})\%$$

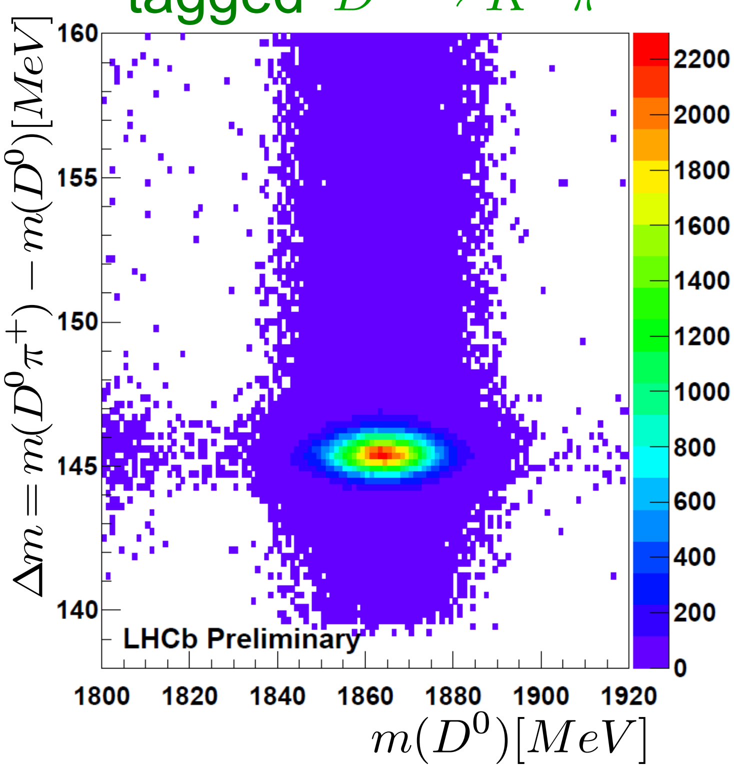


LHCb – t integrated WS/RS Ratio

- tagged D^0 mass spectra

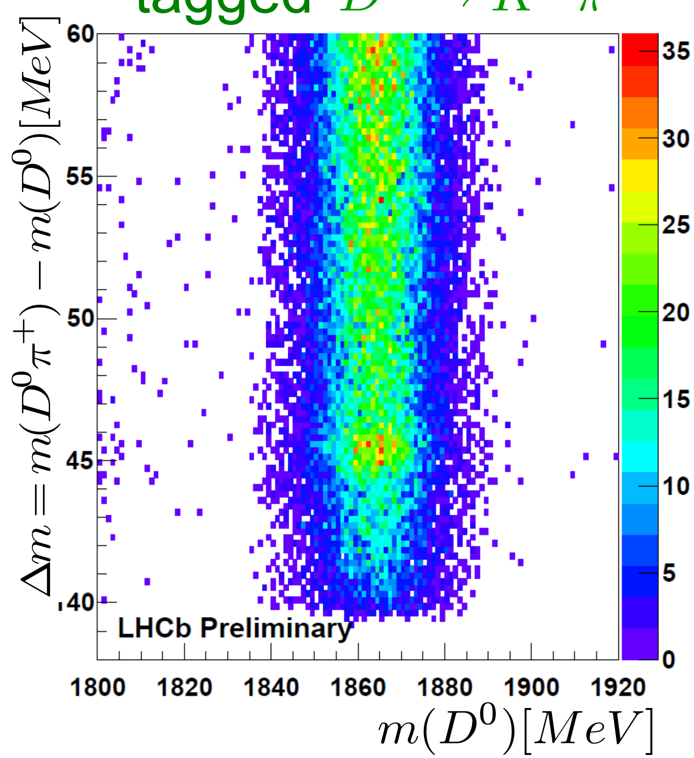
$\mathcal{L}_{int} \approx 34.6 \pm 0.34\ pb^{-1}$

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



$N_{RS}^{cand} \approx 287038$

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



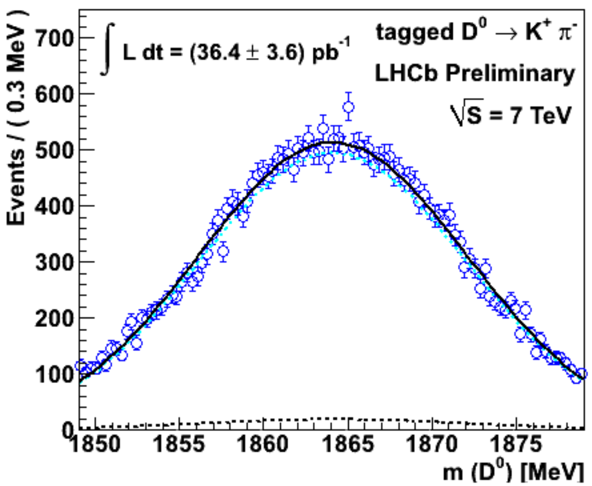
$N_{WS}^{cand} \approx 34997$

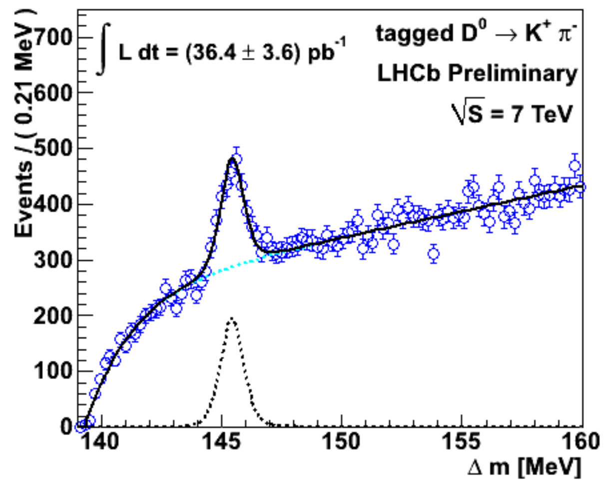
Signal yield is extracted from an unbinned max. likelihood fit in the $(m_{D^0}, \Delta m)$ plane

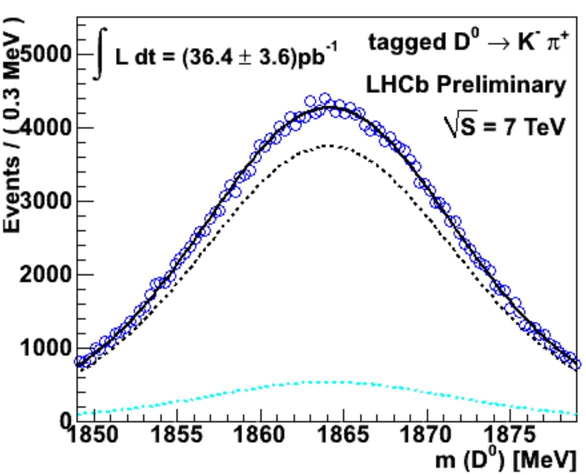
LHCb – t integrated WS/RS Ratio

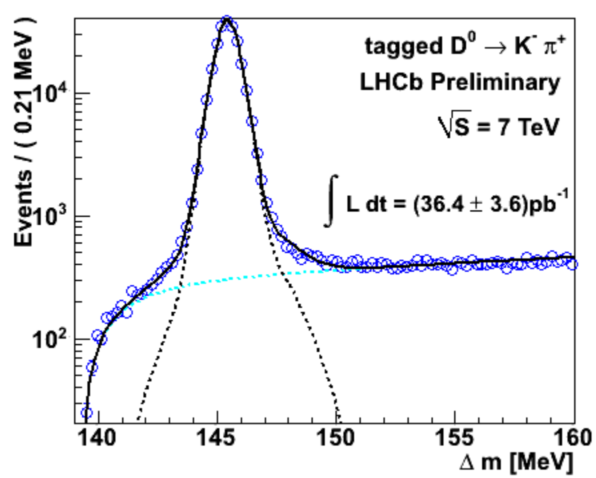
➢ Results

LHCb-CONF-2011-029









❖ WS/RS ratio

	WS/RS of $D \to K\pi$ decays (%)
R_{meas}	0.442 ± 0.033 (stat.) ± 0.042 (sys.)
R_{corr}	0.409 ± 0.031 (stat.) ± 0.039 (sys.)
$R(PDG)$	0.380 ± 0.018

❖ Systematic errors

fit model : 0.0035 %

size of the signal box: 0.0023 %

double mis-id : negligible

❖ Outlook

Time dependent measurement with $\mathcal{L}_{int} \approx 1\ fb^{-1}$ in progress.

$N_{RS} \approx 10$ Million

Measurement of y_{CP} - Introduction

- Decay time of D^0's is exponential with modifications due to mixing

$$\tau^{\pm} = \frac{\tau^0}{1 + |q/p|(y\, cos\phi_f \mp x\, sin\phi_f)}$$

$\tau^{\pm}$: lifetime of D^0 ($\bar{D}^0$) → CP+ eigenstates

τ^0: lifetime of D^0 → CP mixed (CF)

- A lifetime difference between CP+ and CP mixed states gives access to mixing

$$y_{CP} = \frac{\tau^0}{\tau} - 1$$

or

$$y_{CP} = \frac{\tau(K^-\pi^+)}{\tau(K^-K^+)} - 1 = \frac{\tau(K^-\pi^+)}{\tau(\pi^-\pi^+)} - 1 = |q/p|(y\, cos\,\phi_f - x\, sin\,\phi_f)$$

$y_{CP} \neq 0 \;\Rightarrow$ D^0-$\bar{D}^0$ mixing

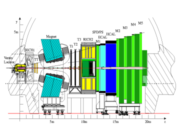
- Test of CP violation

$$A_\Gamma = \frac{\tau^- - \tau^+}{\tau^- + \tau^+}$$

$q/p \neq 1 \;\Rightarrow$ CP violation in D^0-$\bar{D}^0$ mixing

$cos\,\phi_f \neq 1 \;\Rightarrow$ CP violation in interf. between mixing and decay

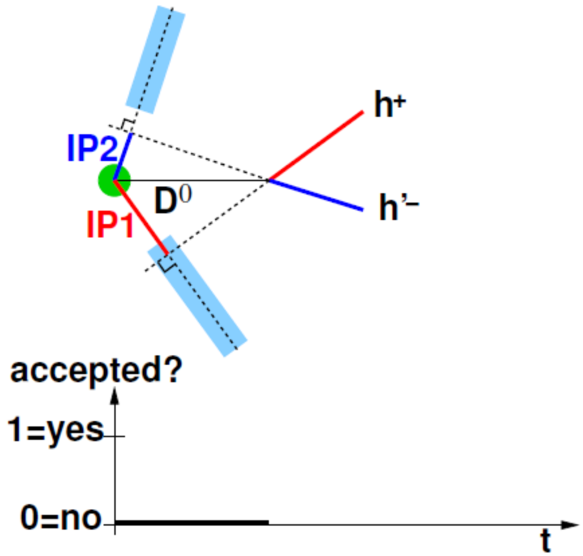
$y_{CP} = y \;\Leftarrow$ CP conservation



LHCb - Lifetime Acceptance

Knowledge of the proper time acceptance dependence on the trigger and selection is needed.

- Is determined on an event by event basis by the swimming method developed by NA11 and used by DELPHI and CDF.
- Recreate trigger decision while moving the PV along the D^0 momentum. Well suited for the LHCb software trigger.

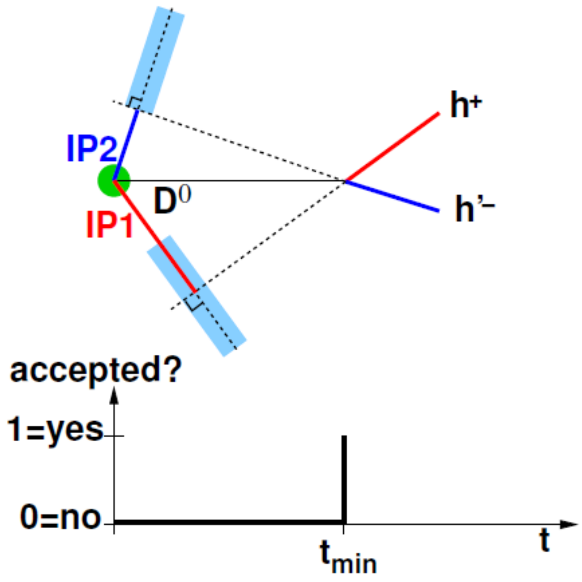


Initially the IP for this D^0 lifetime is still below trigger threshold.

LHCb - Lifetime Acceptance

Knowledge of the proper time acceptance dependence on the trigger and selection is needed.

- Is determined on an event by event basis by the swimming method developed by NA11 and used by DELPHI and CDF.
- Recreate trigger decision while moving the PV along the D^0 momentum. Well suited for the LHCb software trigger.



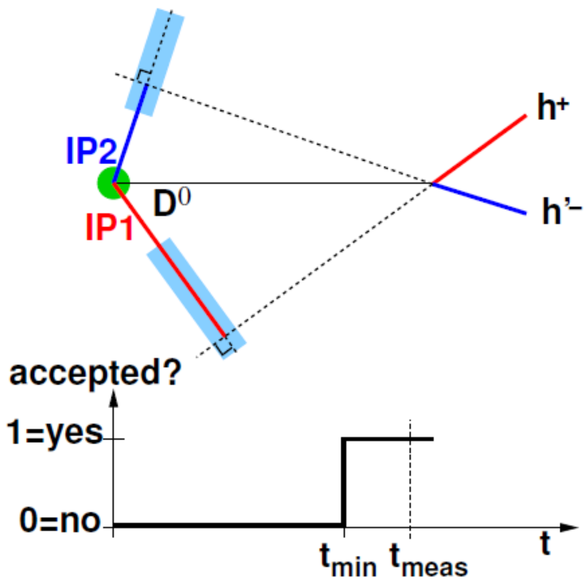
Initially the IP for this D^0 lifetime is still below trigger threshold.

Moving the PV and recreating the IP info yields a D^0 lifetime t_{min} which creates a trigger.

LHCb - Lifetime Acceptance

Knowledge of the proper time acceptance dependence on the trigger and selection is needed.

- Is determined on an event by event basis by the swimming method developed by NA11 and used by DELPHI and CDF.
- Recreate trigger decision while moving the PV along the D^0 momentum. Well suited for the LHCb software trigger.



Initially the IP for this D^0 lifetime is still below trigger threshold.

Moving the PV and recreating the IP info yields a D^0 lifetime t_{min} which creates a trigger.

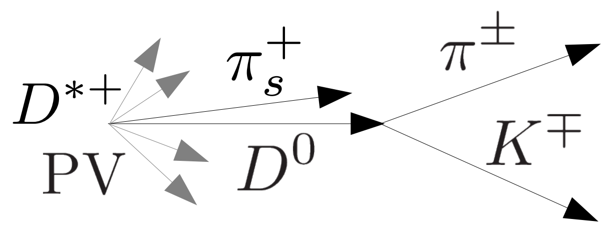
t_{meas} is reached.

Similar procedure can be applied for other selection criteria.

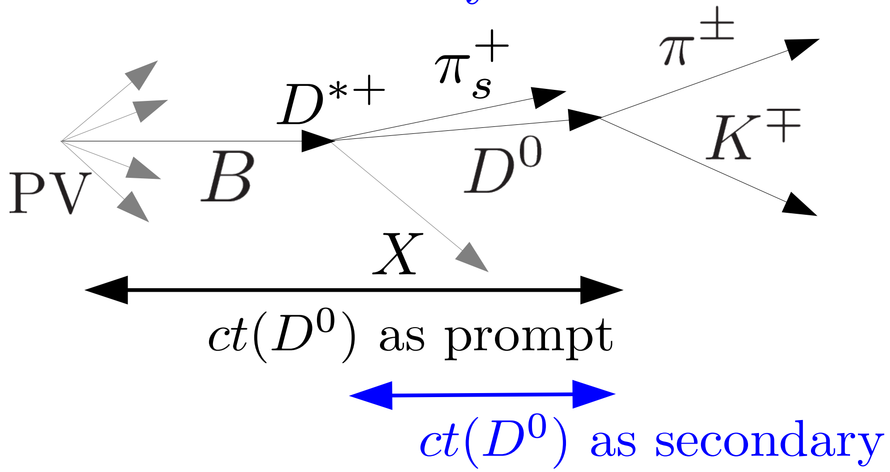
LHCb - $D^0 \to K\pi$ Decay Time

➢ Another important input for the lifetime measurement is the separation of

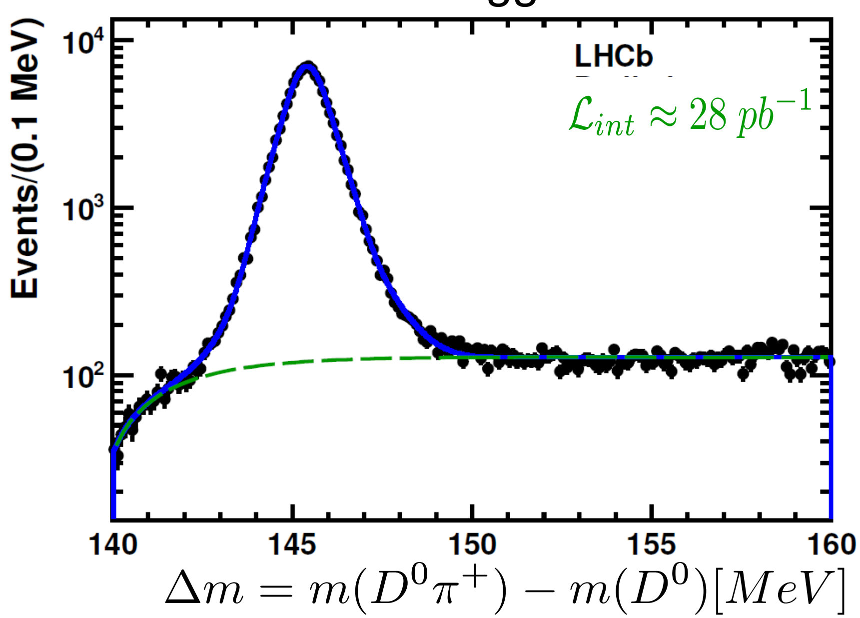
Prompt D



Secondary D

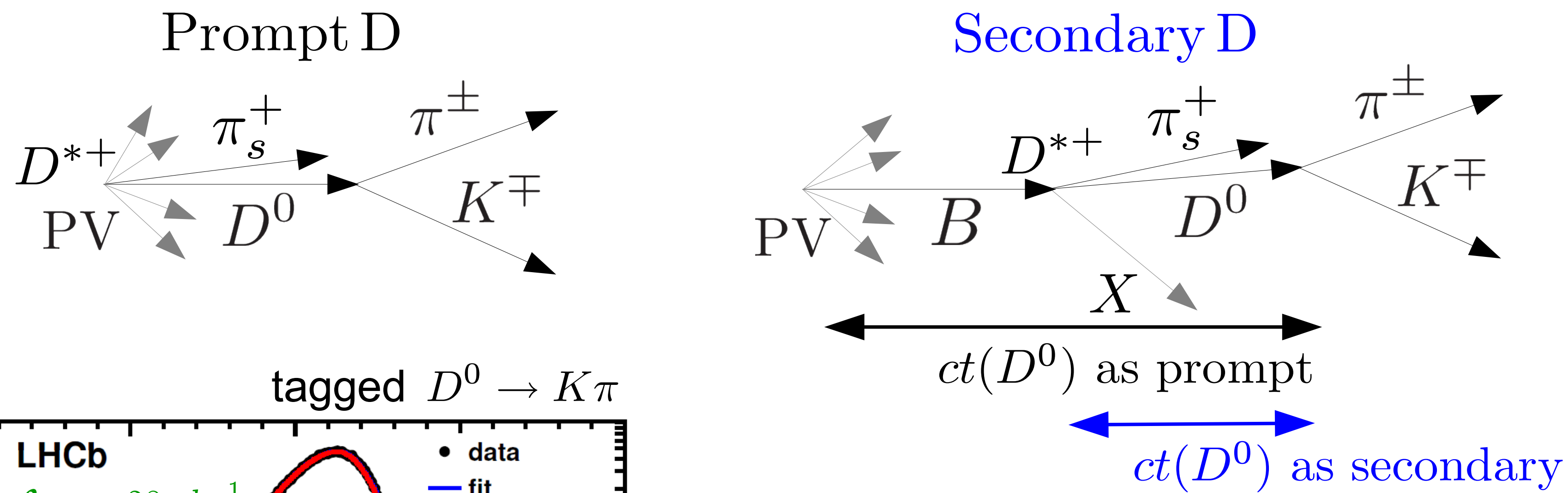


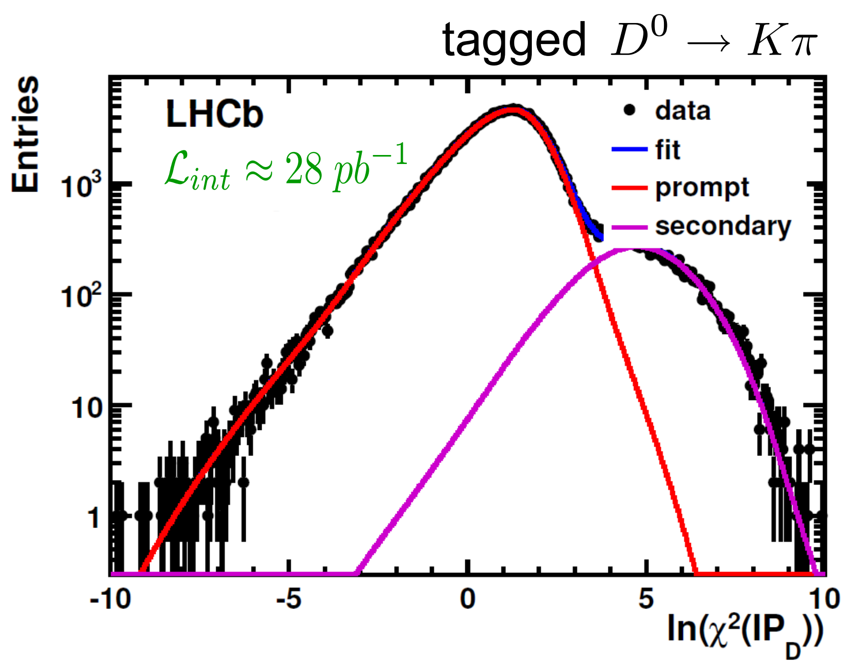
tagged $D^0 \to K\pi$



LHCb - $D^0 \to K\pi$ Decay Time

➢ Another important input for the lifetime measurement is the separation of

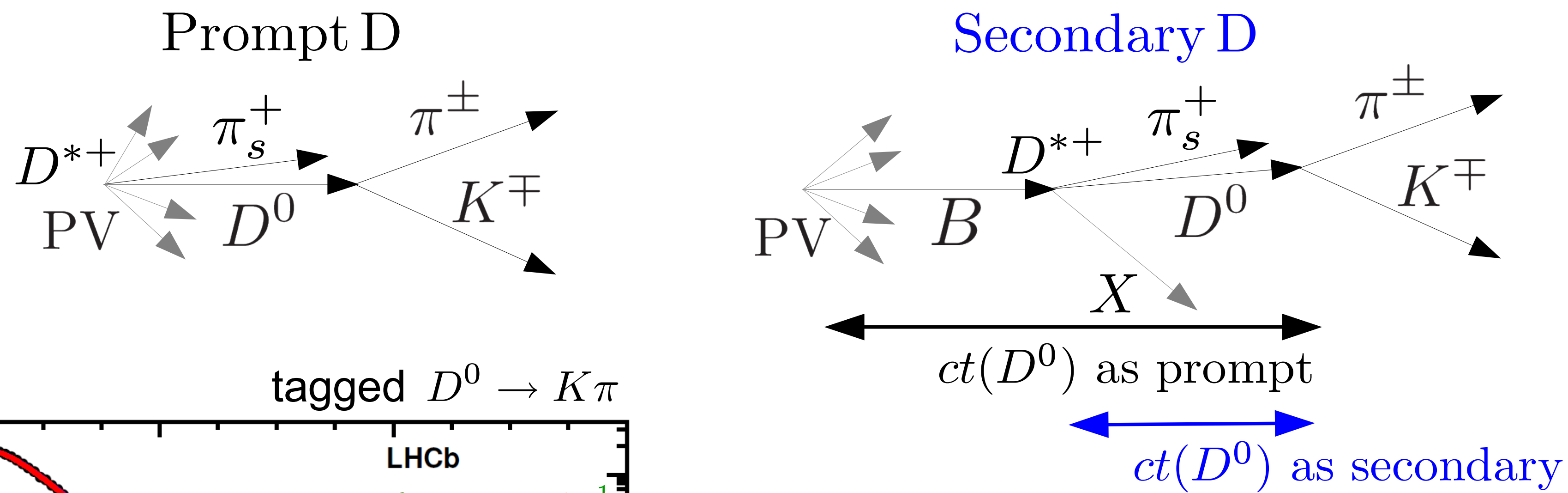




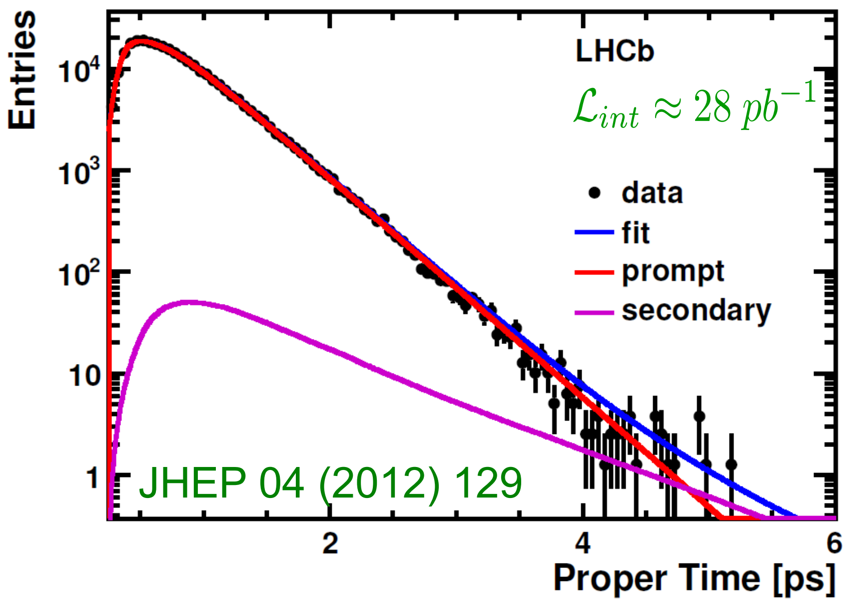
Separation in $\chi^2(IP_D)$

LHCb - $D^0 \to K\pi$ Decay Time

➤ Another important input for the lifetime measurement is the separation of



tagged $D^0 \to K\pi$



Separation in $\chi^2(IP_D)$

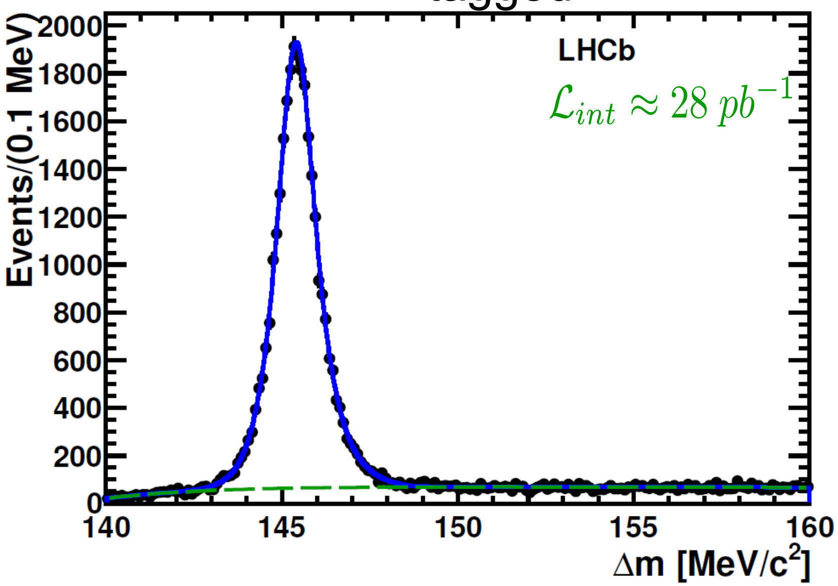
decay time measurement using an unbinned max. likelihood fit:

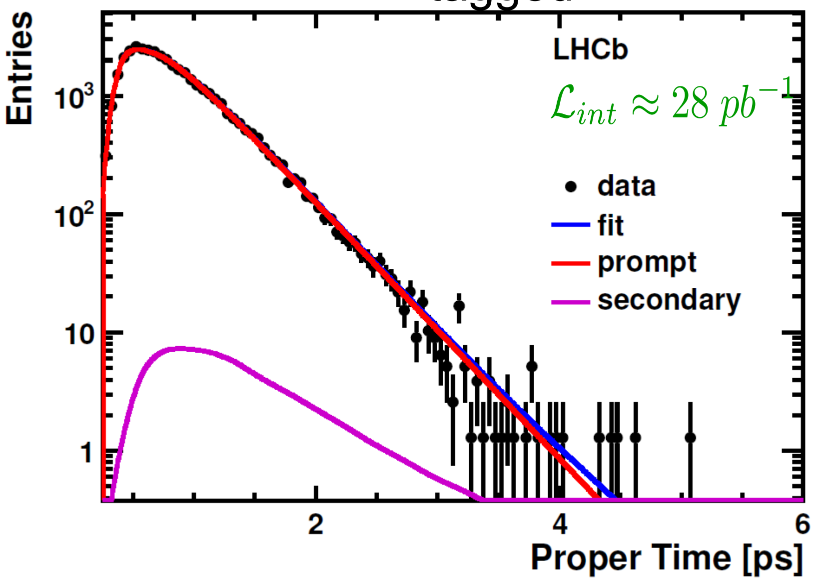
- lifetime is compatible with the PDG value

$$\tau(D^0 \to K\pi) = 410.3 \pm 0.9\ (stat.)\ fs$$

LHCb - y_{CP} Measurement

➢ Considering tagged $D^0 \to KK$ decays allows to measure y_{CP} and A_Γ





JHEP 04 (2012) 129

$$y_{cp} = (5.5 \pm 6.3\ (stat)\ \pm 4.1\ (sys)) \cdot 10^{-3}$$

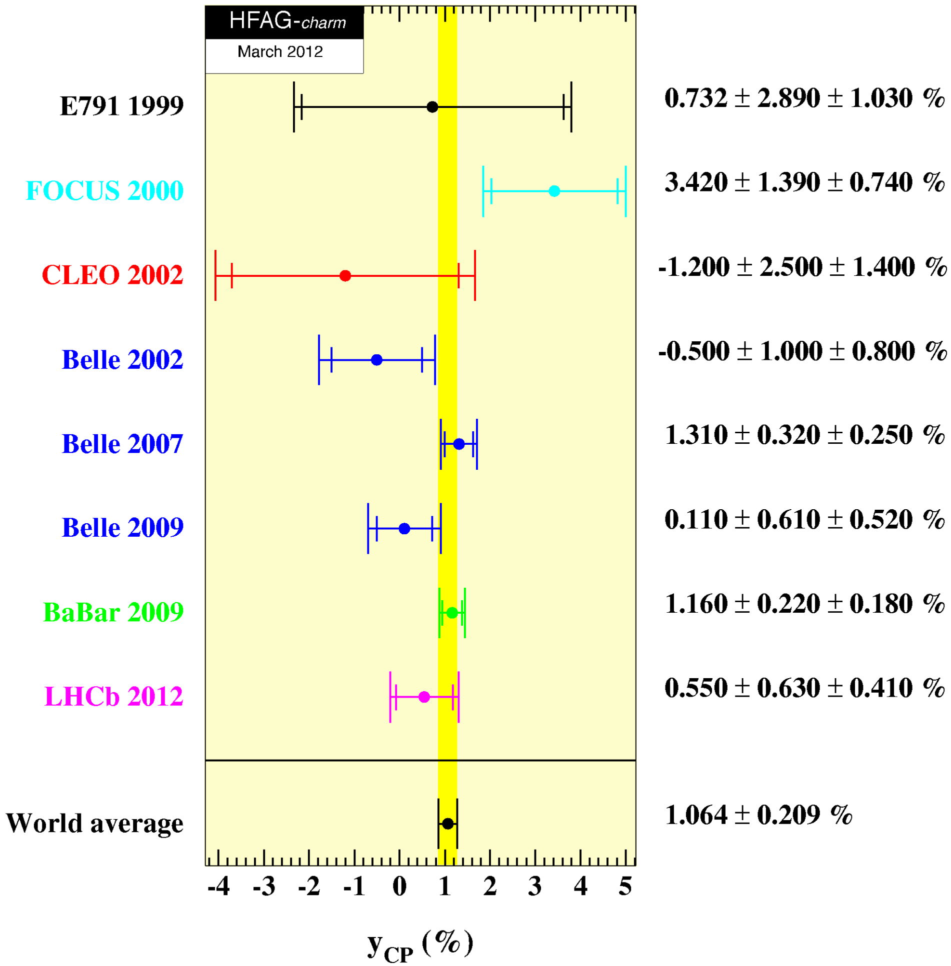
$$A_\Gamma = (-5.9 \pm 5.9\ (stat)\ \pm 2.1\ (sys)) \cdot 10^{-3}$$

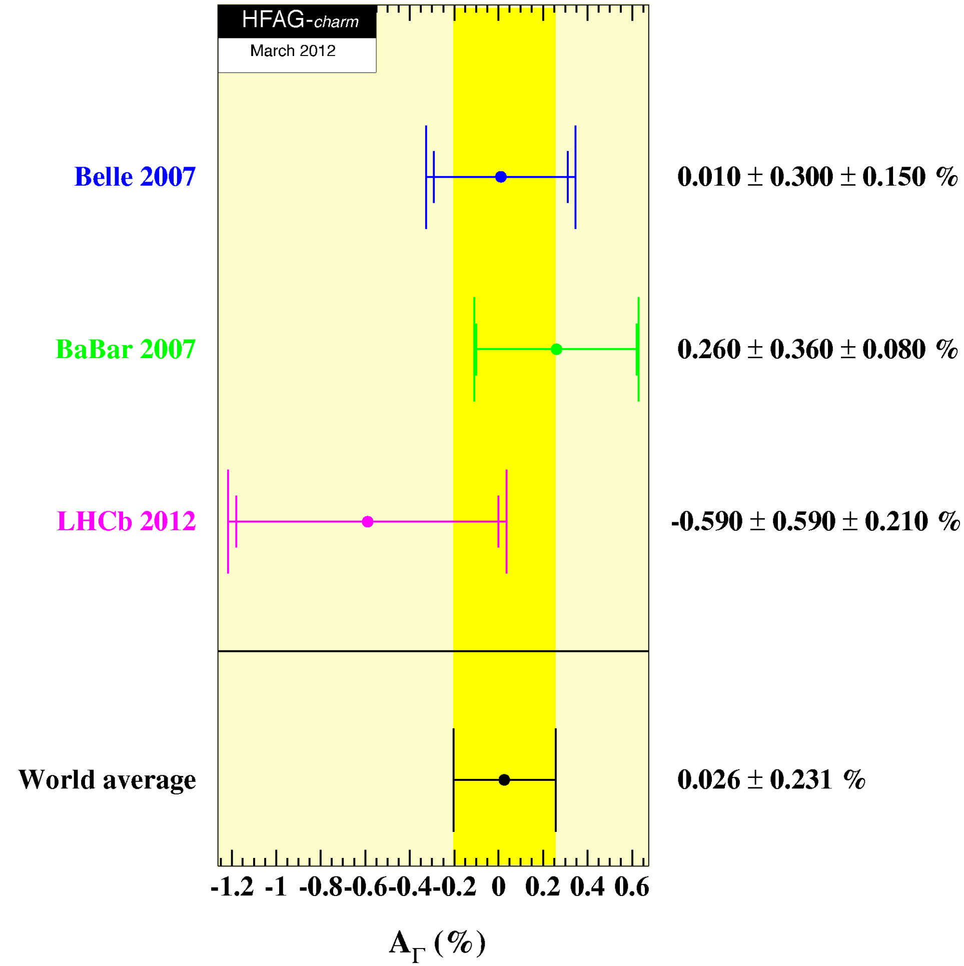
see talk by Angelo Carbone

Systematic uncertainties	y_{CP} (10^{-3})
Decay-time acceptance correction	0.1
Decay-time resolution	0.1
Minimum decay-time cut	0.8
Maximum decay-time cut	0.2
Combinatorial background	0.8
Secondary-like background	3.9
Total	4.1

Experimental Results – y_{CP}

- Combined y_{CP} and A_Γ as averaged by the charm subgroup of HFAG





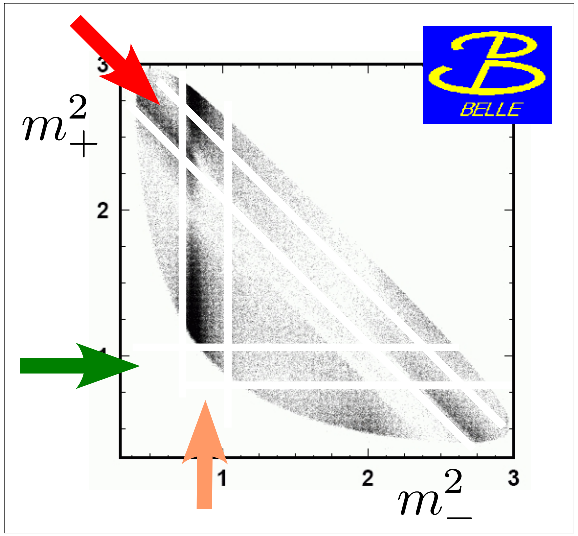
$$y_{CP} = (1.064 \pm 0.209)\%$$

$$A_\Gamma = (0.026 \pm 0.231)\%$$

Introduction - t Dep. Dalitz Analysis

- Dalitz plot of $D^0 \to K_s^0 \pi^+ \pi^-$
  - Different quasi 2 body amplitudes contribute and interfere
  - Dalitz analysis allows to determine amplitude and relative phases of 18 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

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

decay amplitude

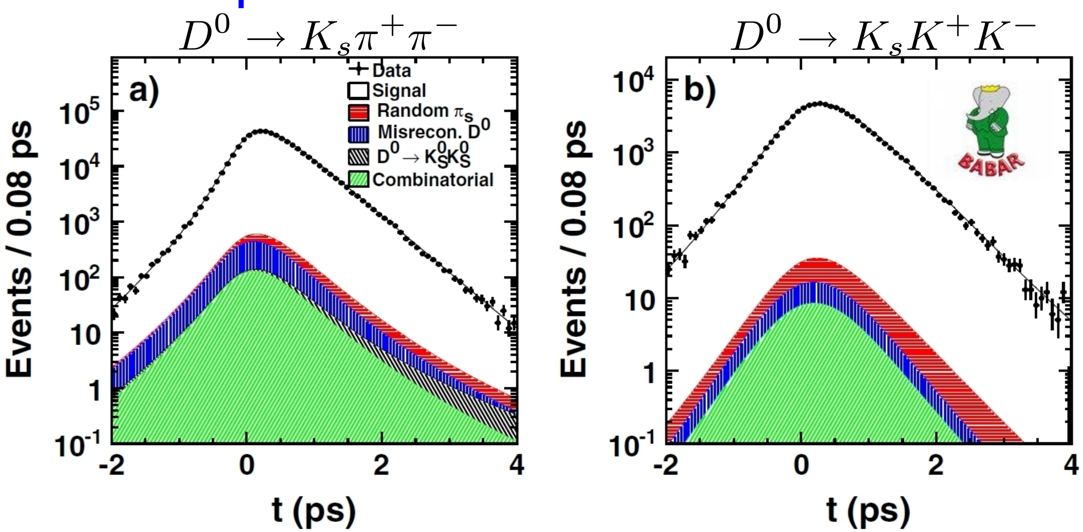
$$\lambda_{1,2} = f(x,y)$$

  - The decay rates contain functions of x and 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}

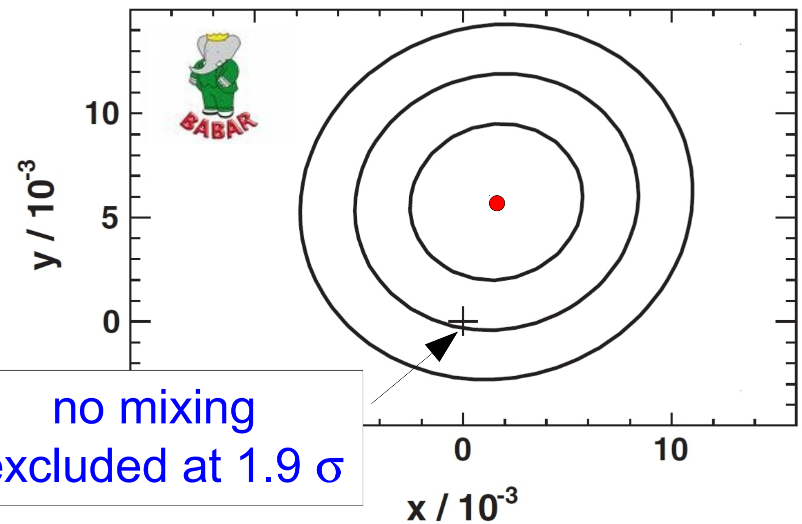
Mixing Parameter in $D^0 \to K_s h^+ h^-$

- Proper time fit results



  - τ_{D^0} compatible with PDG values

- Mixing parameter fit results



BABAR 469 fb^{-1} : PRL 105, 081803 (2010)

$$x = (0.16 \pm 0.23 \pm 0.12 \pm 0.08)\%$$

$$y = (0.57 \pm 0.20 \pm 0.13 \pm 0.07)\%$$

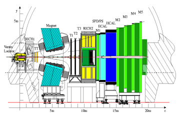
- Allow for CP violation
  - Dalitz plot parameters from fit are similar for D^0 and $\bar{D}^0$ no direct CP violation

	$x(\%)$	$y(\%)$
D^0	0.0 ± 0.33	0.55 ± 0.28
$\bar{D}^0$	0.33 ± 0.33	0.58 ± 0.28

Belle 540 fb^{-1} : PRL 99, 131803 (2007)

$$x = (0.80 \pm 0.29^{+0.09+0.10}_{-0.07-0.14})\%$$

$$y = (0.33 \pm 0.24^{+0.08+0.06}_{-0.12-0.08})\%$$



LHCb - Mixing in $D^0 \rightarrow K_s h^+ h^-$

Measure D^0 mixing parameter x and y without influence of a strong phase.

- $D^0 \rightarrow K_s^0 h^+ h^-$ is challenging to measure with LHCb.
  - ❖ Average momentum of the K_s is about 35 GeV. With a lifetime of 90 ps the flight distance in LHCb is about 2 m.

    $\longrightarrow$ Most of the K_s daughter tracks don't have VELO tracks.

- 2011: tagged $D^0 \rightarrow K_s^0 \pi^+ \pi^-$ decay yields provide sample sizes in the order of the ones for the B factories.

- 2012 data taking has an improved trigger scheme for this sample.

Mixing – t-dependent $D^0 \to K_S^0 K^{\mp}\pi^{\pm}$

- Determine y in a time dependent inclusive analysis of $D^0 \to K_S^0 K^{\mp}\pi^{\pm}$ using a CLEO-c measurement of the coherence factor and strong phase difference

S. Malde, G.Wilkinson
PLB 701 (2011) 353

Treat the SCS decays $D^0 \to K_S^0 K^{\mp}\pi^{\pm}$ similar as WS and RS $D^0 \to K\pi$

SCS D⁰ decays: $r_D^{K_S^0 K\pi} \approx 1$

Time dependence:

$$\Gamma[D^0 \to K_S^0 K^{\mp}\pi^{\pm}] = e^{-\Gamma t}[\kappa_1 + r_D^{K_S^0 K\pi} R_D^{K_S^0 K\pi} y'_{K_S^0 K\pi}\Gamma t + \frac{(1+(r_D^{K_S^0 K\pi})^2)y'^2 + \kappa_2(1-(r_D^{K_S^0 K\pi})^2)x'^2}{4}\Gamma t^2$$

$$D^0 \to K_S^0 K^-\pi^+ \; : \; \kappa_1 \equiv 1 \; ; \; \kappa_2 \equiv -1$$

$$D^0 \to K_S^0 K^+\pi^- \; : \; \kappa_1 \equiv (r_D^{K_S^0 K\pi})^2 \; ; \; \kappa_2 \equiv +1$$

coherence factor
strong phase difference
} CLEO-c

Fit $y'_{K_S^0 K\pi}$ and extract y by using the strong phase $\delta_D^{K_S^0 K\pi}$ with a precision similar to the time dependent WS $D^0 \to K\pi$ results.

- Tagged event sample for LHCb in 2011 similar as for the B factories

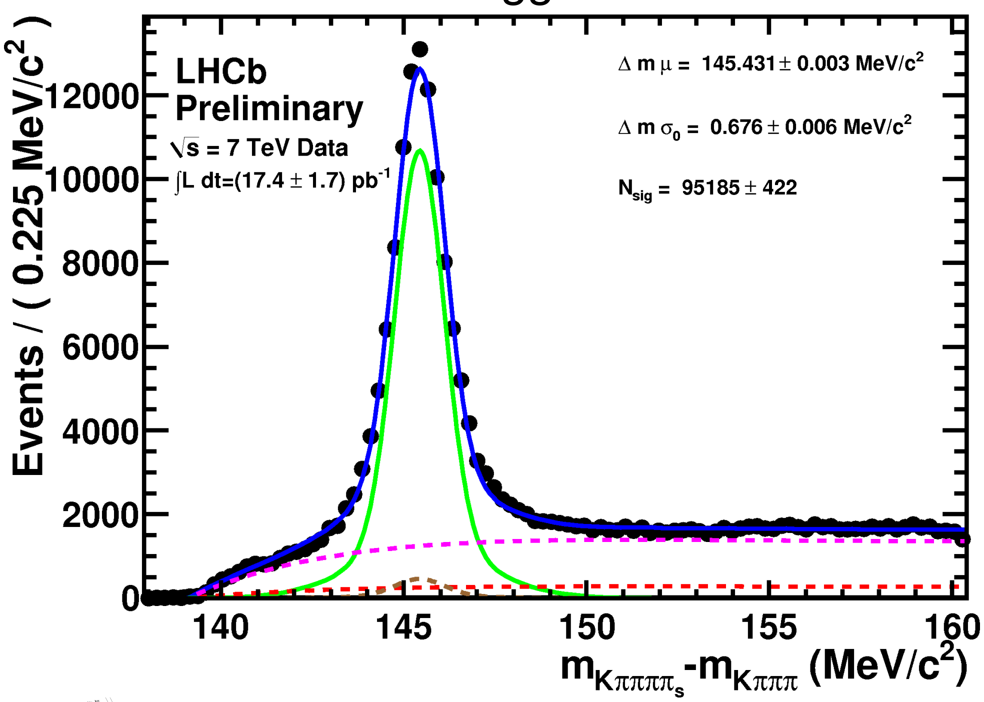
LHCb – t-dependent $D^0 \to K\pi\pi\pi$

WS rate of tagged $D^0 \to K\pi\pi\pi$ decays: $R_{WS} = (0.320 \pm 0.018^{+0.018}_{-0.013})\%$

BELLE PRL 95, 231801 (2005)

- LHCb: mixing measurement by analysing the time dependent WS rate
  - Determine $\langle N_{WS}\rangle_i / \langle N_{RS}\rangle_i$ in bins of the lifetime distribution

Tagged RS $D^0 \to K\pi\pi\pi$



- Measure $r_D^{K\pi\pi\pi}$
- Measure mixing parameter y' , x'^2 (rotated by a strong phase)
- In the 2011 dataset ($\mathcal{L}_{int} \approx 1 fb^{-1}$) several million RS events will be available

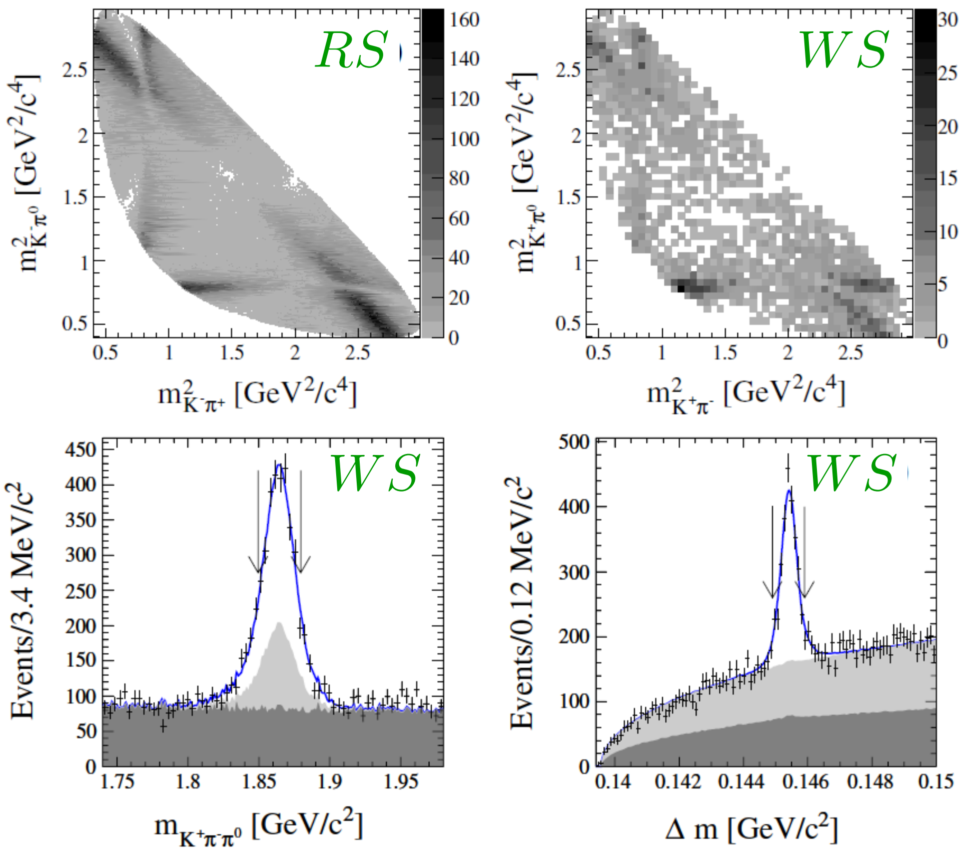
LHCb – t-dependent $D^0 \to K\pi\pi^0$

- WS rate of tagged $D^0 \to K\pi\pi^0$ decays: $R_{WS} = (0.229 \pm 0.015^{+0.013}_{-0.009})\%$

  PRL 95, 231801 (2005)

- Mixing measurement (y'', x'') by a time-dependent amplitude analysis in the Dalitz Plot of $D^0 \to K^+\pi^-\pi^0$

  PRL 103, 211801 (2009)



$\to$ exclude no mixing at 3.2 σ

- π^0's in a dense hadronic environm. are difficult to handle in LHCb

- 2012 data taking has a now a trigger and selection scheme for charm with π^0's.

Summary

- The full CDFII dataset has the potential of a 5 σ D mixing parameter measurement in the time dependent WS $D^0 \to K\pi$ decays.
- LHCb started with a y_{CP} measurement to contribute to the current world average.
- LHCb has good prospects for mixing measurements in multibody decays.
- Charm physics at hadron colliders will soon play a leading role in D mixing measurements and take the fine results of the B factories to an even higher precision.
- Measurements at the charm threshold as pioneered by CLEO-c are needed to determine strong phases and coherence factors.