

Charm Mixing and CPV

Prospects at LHCb

Jörg Marks

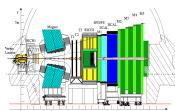
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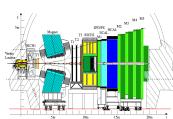
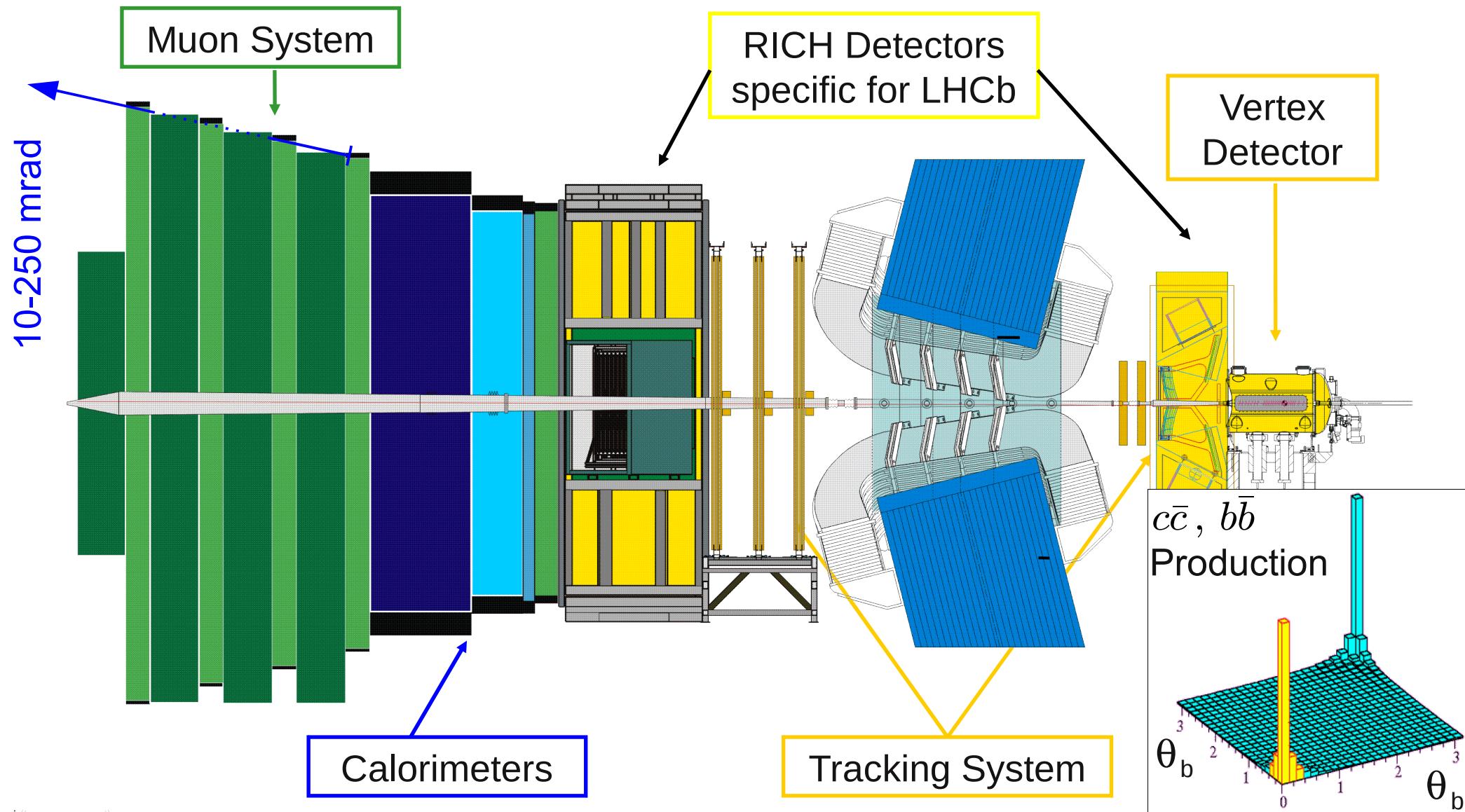


Outline

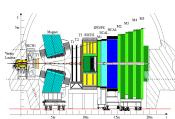
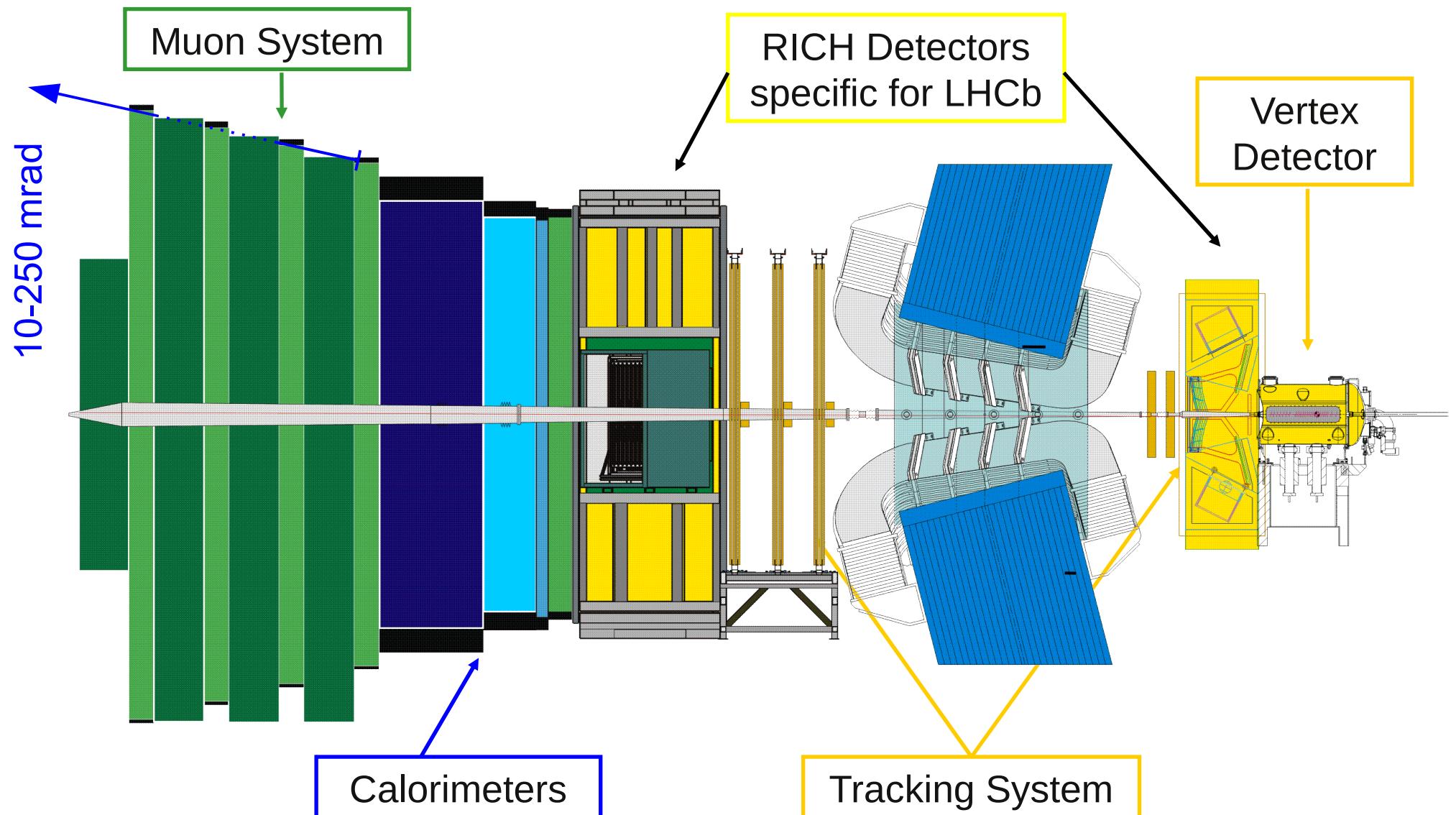
- LHCb experiment
- Run 2010 and LHCb trigger in view of charm physics
- Open charm signals
- LHCb prospects in charm mixing and CP violation
 - ❖ Time dependent mixing measurements in tagged $D^0 \rightarrow K\pi$
 - ❖ y_{CP} measurement from lifetime differences
 - ❖ Time dependent Dalitz Analysis
 - ❖ CP violation SCS 3- and 4-body decays
- Summary



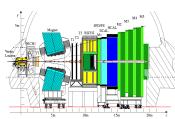
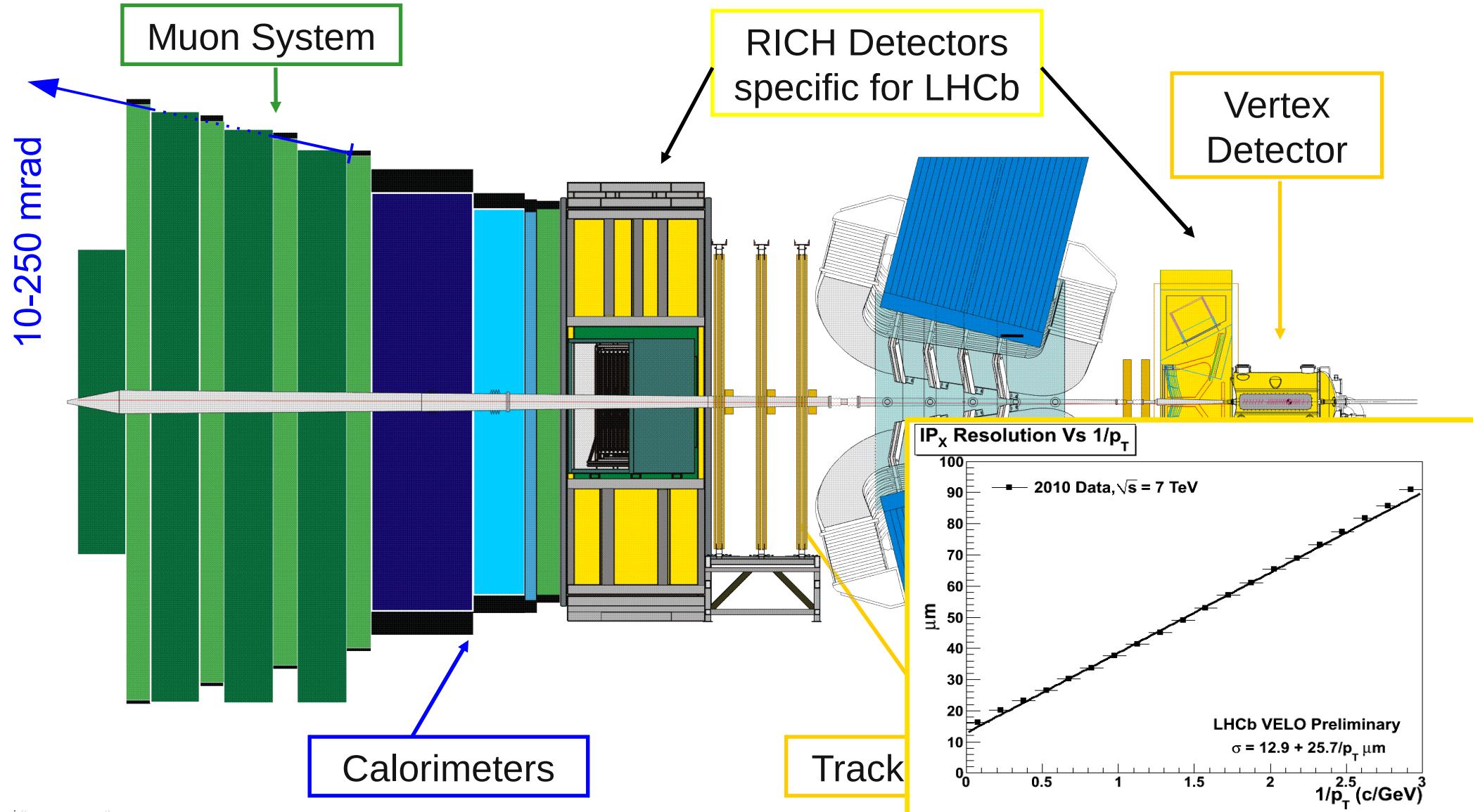
LHCb Experiment



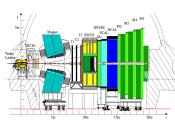
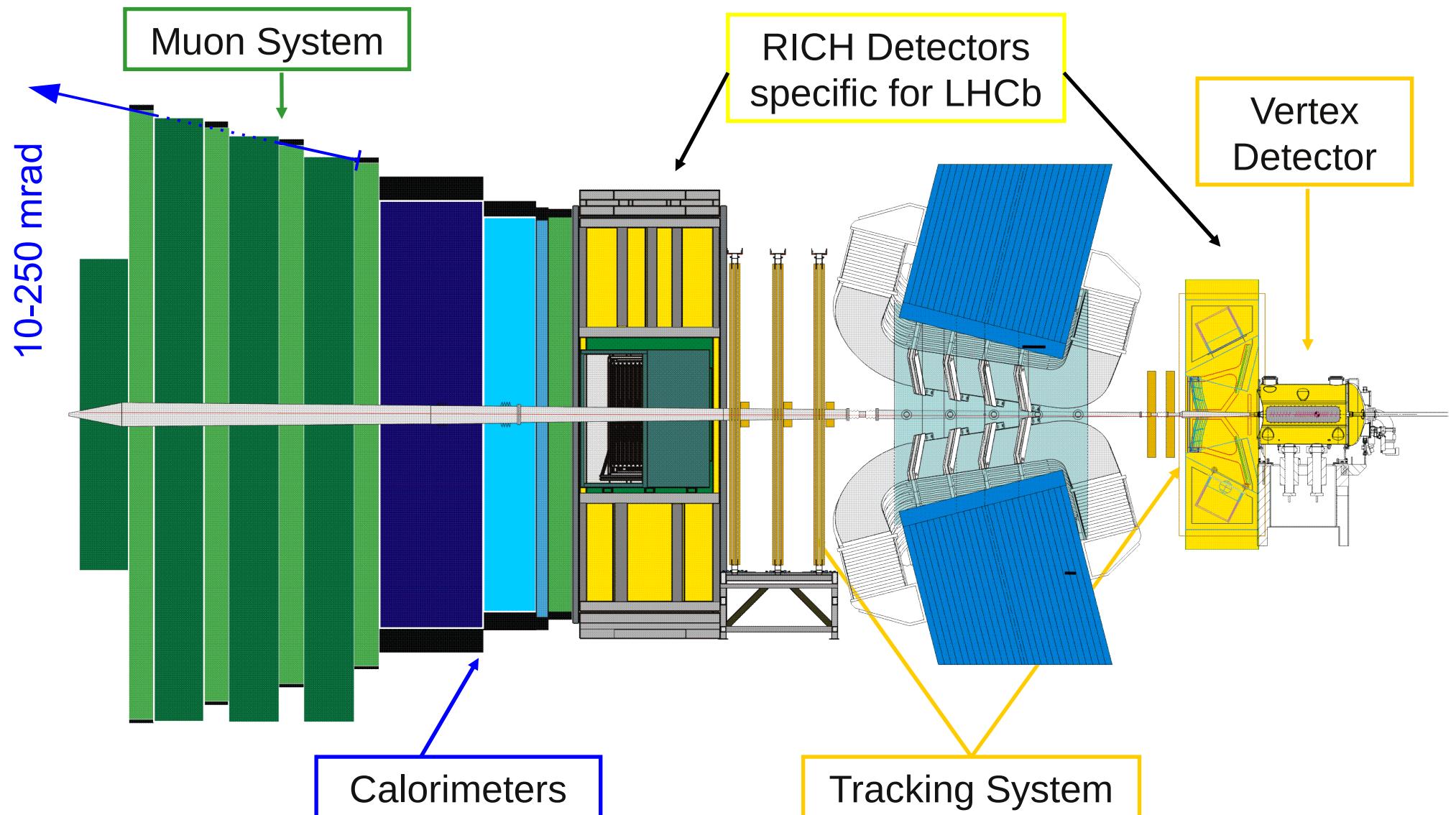
LHCb Experiment



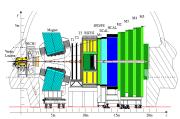
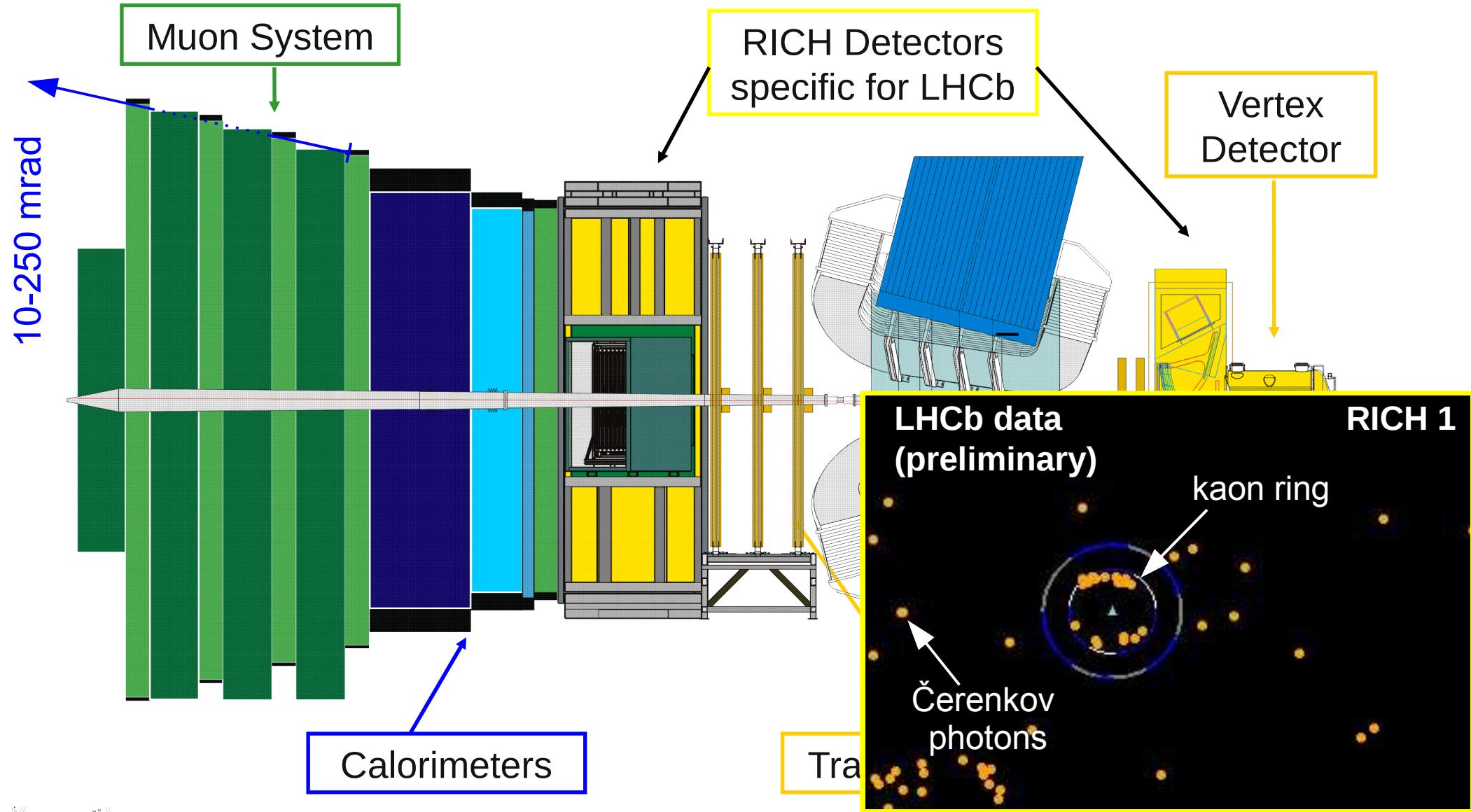
LHCb Experiment



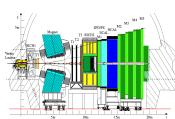
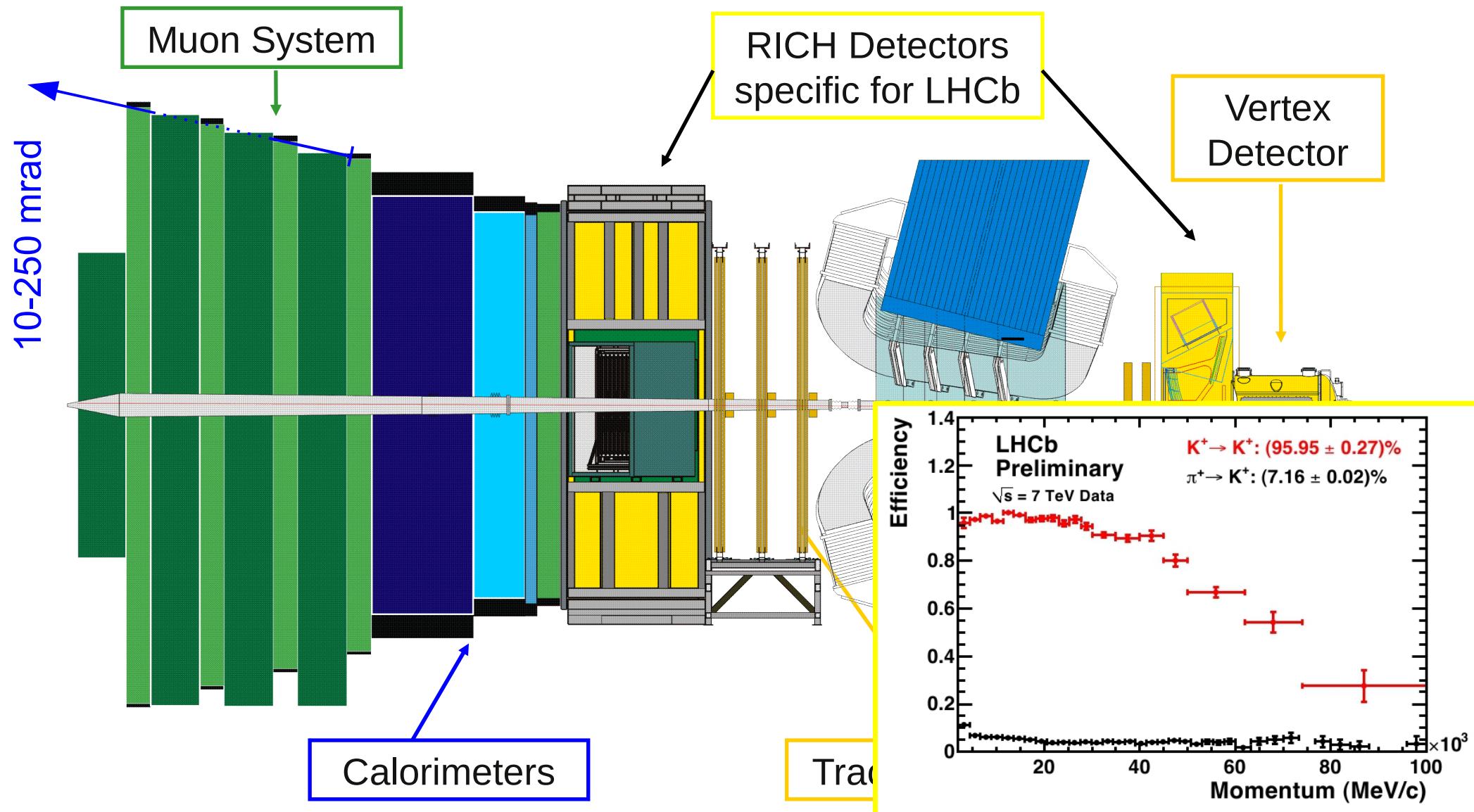
LHCb Experiment



LHCb Experiment



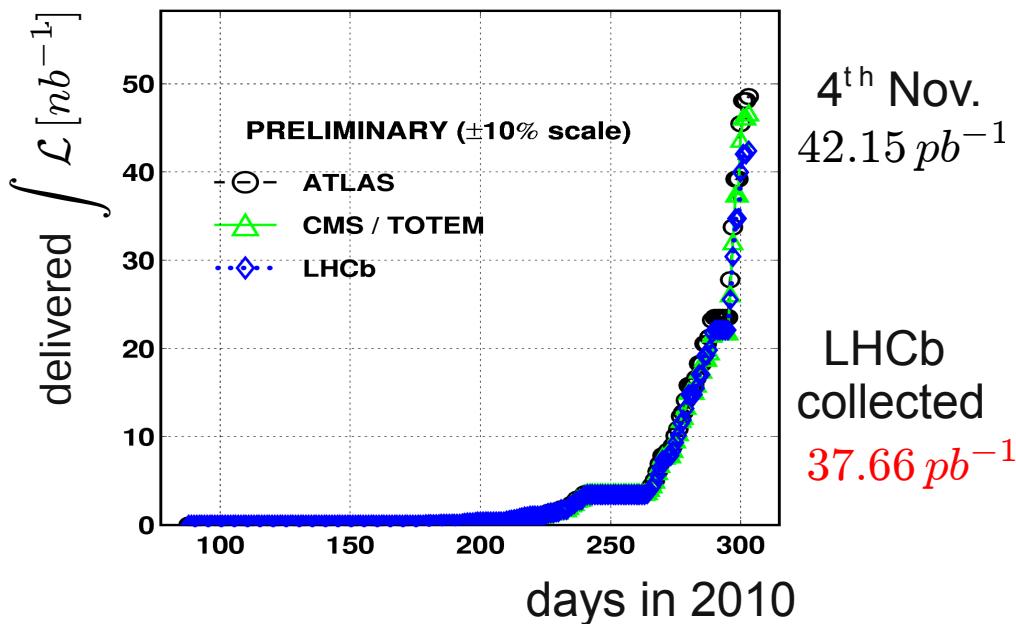
LHCb Experiment



Run 2010

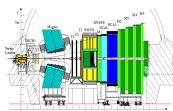
➤ LHC in 2010

- $E_{CM} = 7 \text{ TeV}$
- Luminosity



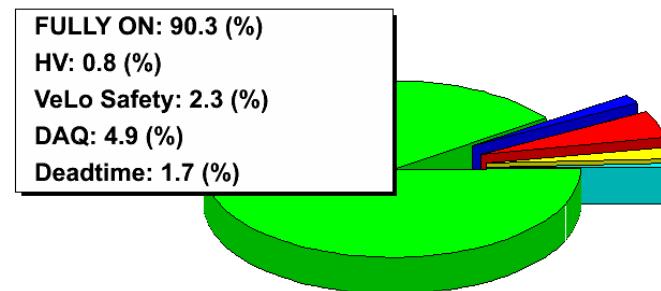
$$\mathcal{L}_{peak} \approx 2 \cdot 10^{32} \text{ cm}^{-2} \text{s}^{-1}$$

$$\int \mathcal{L} \approx 6.2 \text{ pb}^{-1}/\text{day}$$



➤ LHCb in 2010

- $10^{11} c\bar{c}$ events in 2010
- LHCb efficiency



- Luminosity / beam crossing exceeds design values

Mean visible p-p interactions / crossing
 $\mu = 0.4 \rightarrow 2.5$

With the beam conditions also the LHCb trigger evolved rapidly in 2010

Trigger Overview

- Hardware Trigger (L0) 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

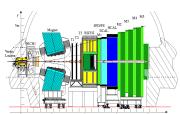
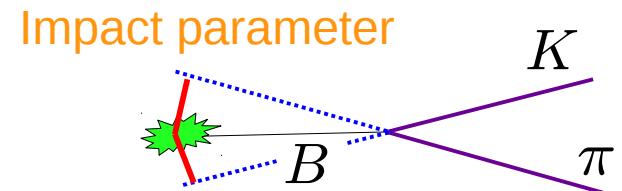
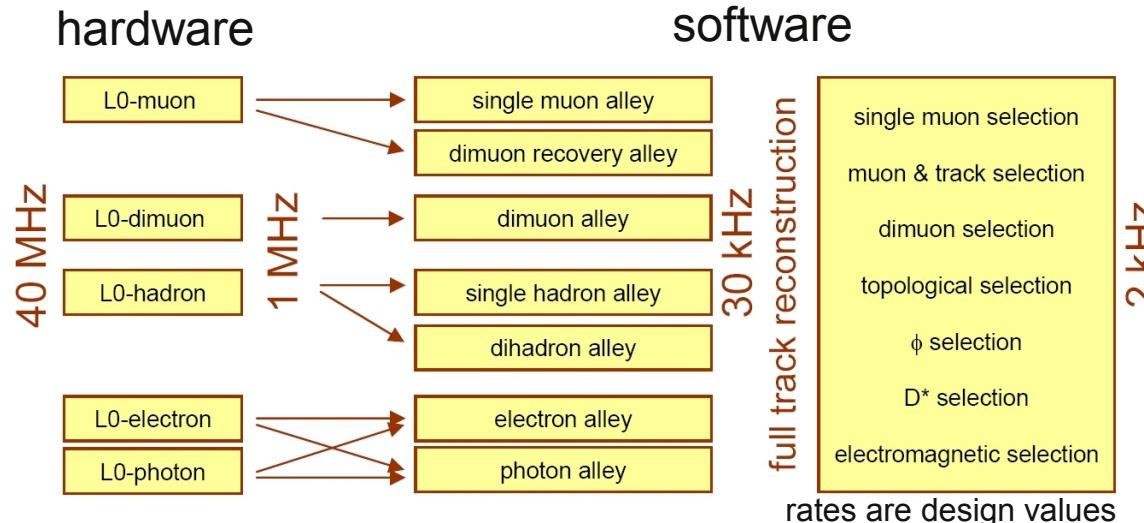
- Two level software trigger based on partly / fully reconstructed objects fully reconstructed objects with all detector information

- Confirm L0 trigger objects using reconstr. and combined detector information
- Select on displaced vertices using VELO
- Use reconstructed objects for exclusive selections and inclusive streams with clear signature

- All thresholds are optimized for B selection

prompt D production: $\epsilon_{prompt\ D} \approx 10\%$

→ still a large sample of D

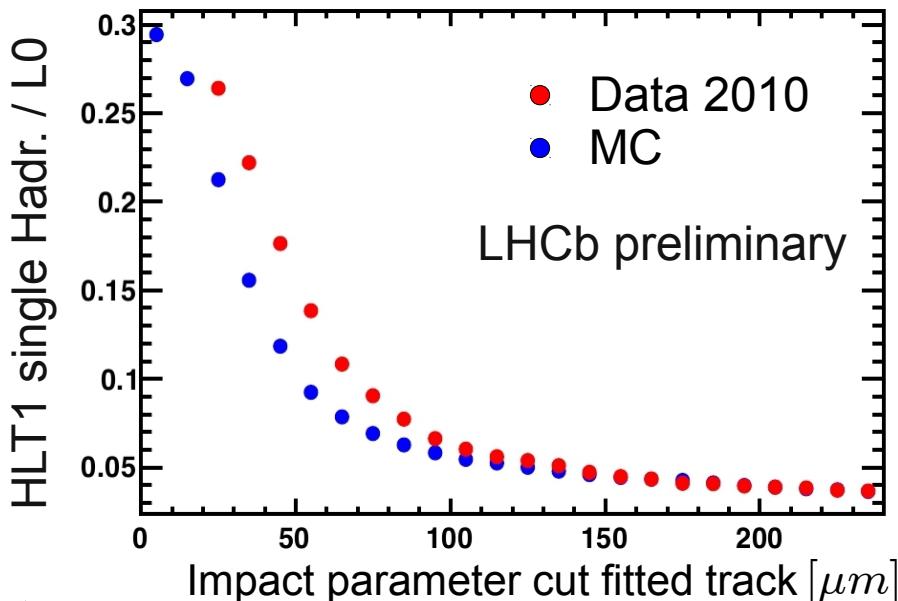


Trigger - Run 2010

➤ Rapidly evolving trigger

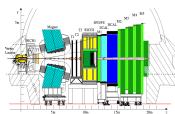
	collision rate	L0	HLT1	HLT2	$\epsilon_{prompt\ D}$	
2010	< 2 kHz		minimum bias trigger		> 90%	p_T , IP thresholds increasing
	< 25 kHz	< 25 kHz	2 kHz			
	< 300 kHz	< 300 kHz	10 kHz	2 kHz		
2011	nominal	1 MHz	20 kHz	2 kHz	10%	

Software single hadron trigger fraction



- The sample size of the data collected in 2010 depends on the trigger analysis

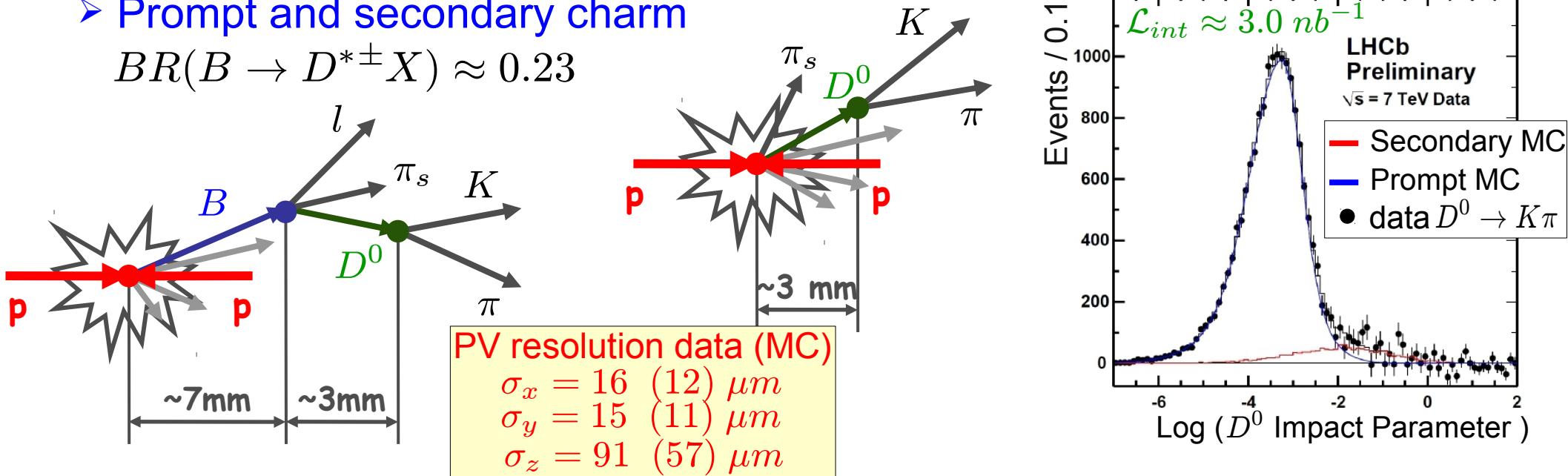
The initially lower rate allowed for lower trigger thresholds
→ **larger fraction of c events**



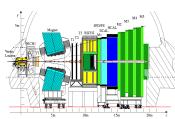
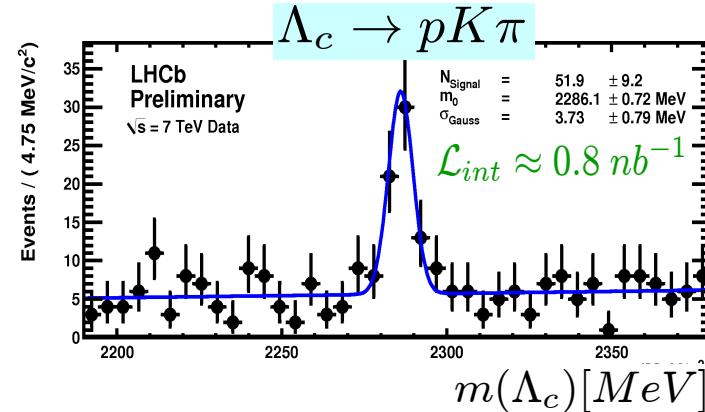
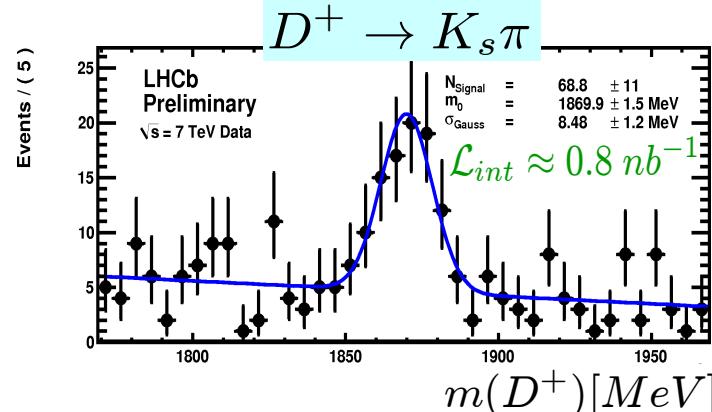
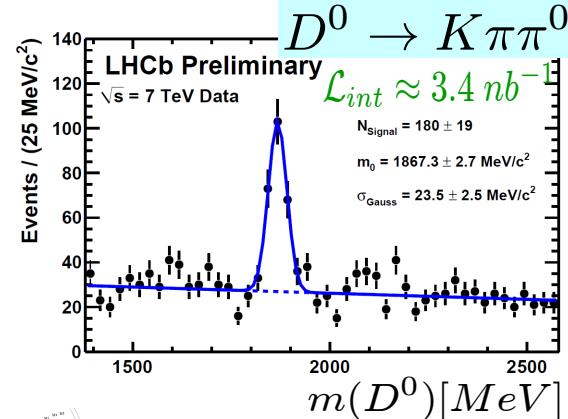
Charm Production at LHCb

- Prompt and secondary charm

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

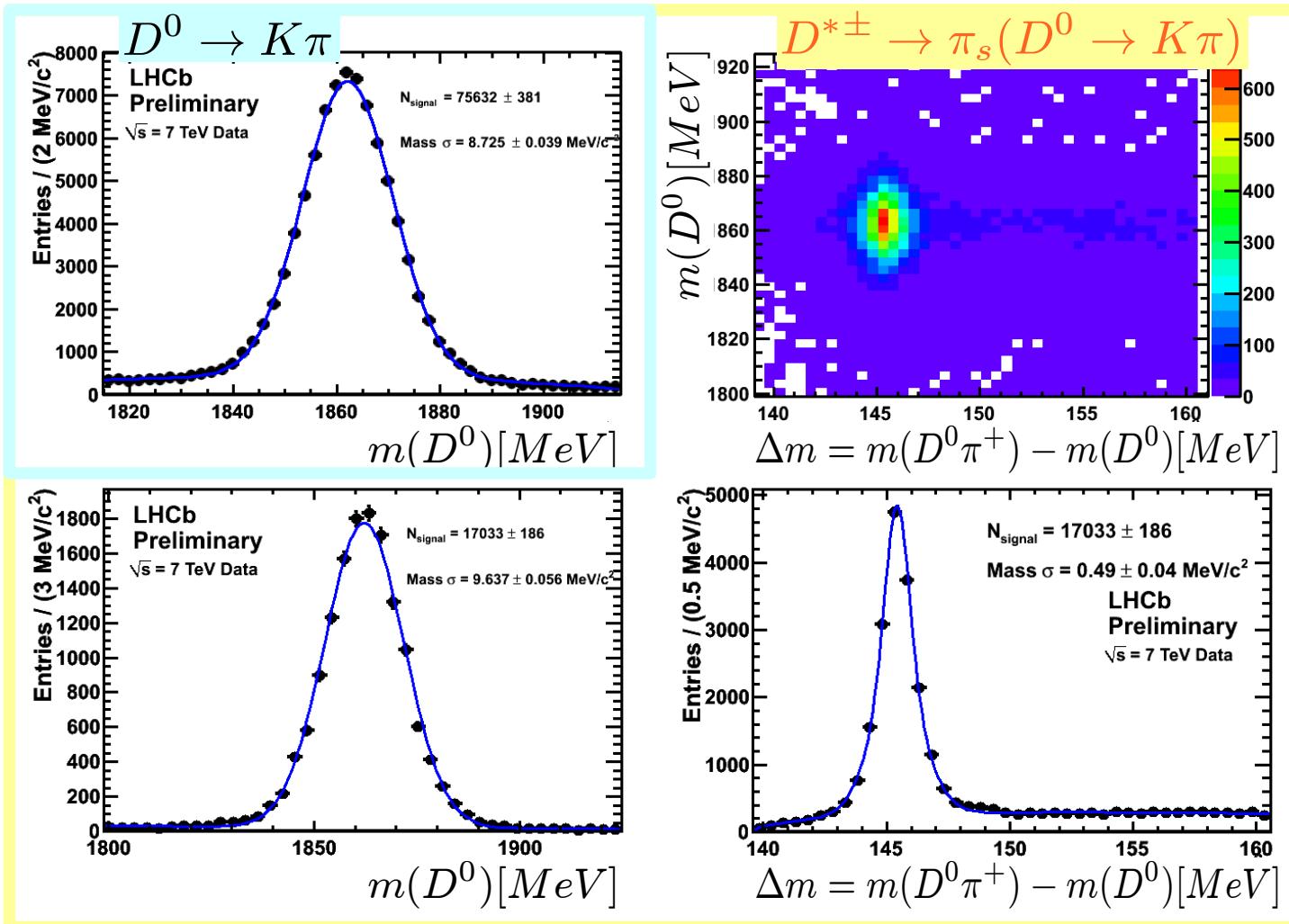


- Open charm signals in the first minimum bias data 2010

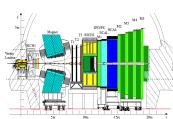


$D^0 \rightarrow K\pi$ Decays

➤ Untagged and tagged D^0 mass spectra



- $\int \mathcal{L} \approx 124 \text{ nb}^{-1}$
- $m_{D^0}, \Delta m$ compatible with PDG
- Expected events in $\int \mathcal{L} \approx 100 \text{ pb}^{-1}$:
 - tagged: $\approx 14 \cdot 10^6$
 - untagged: $\approx 61 \cdot 10^6$



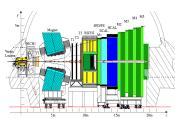
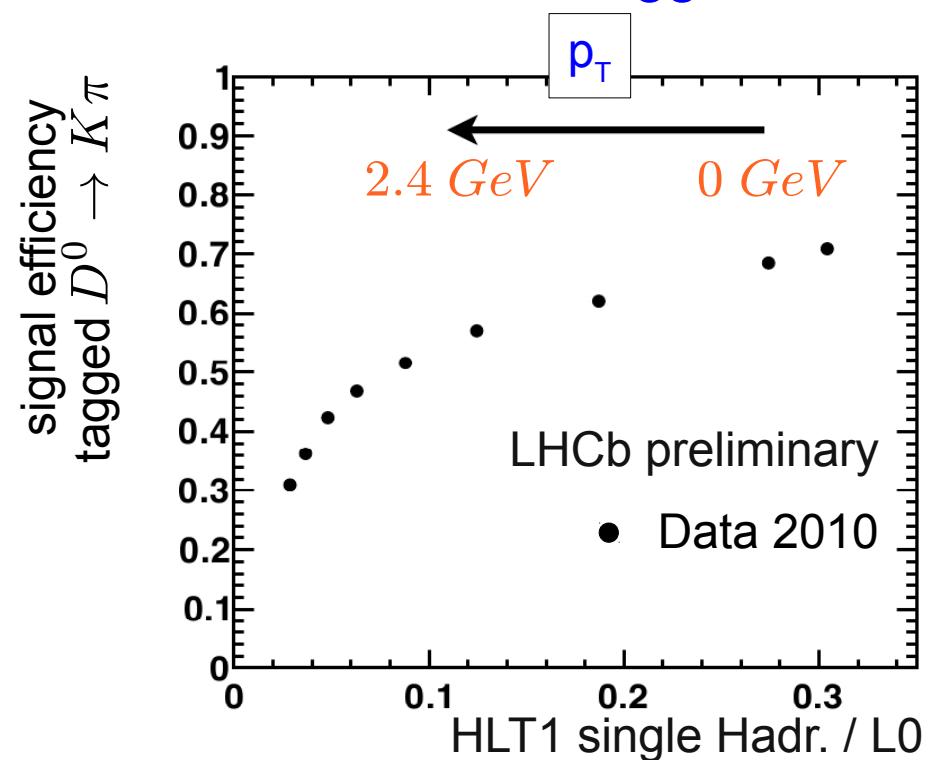
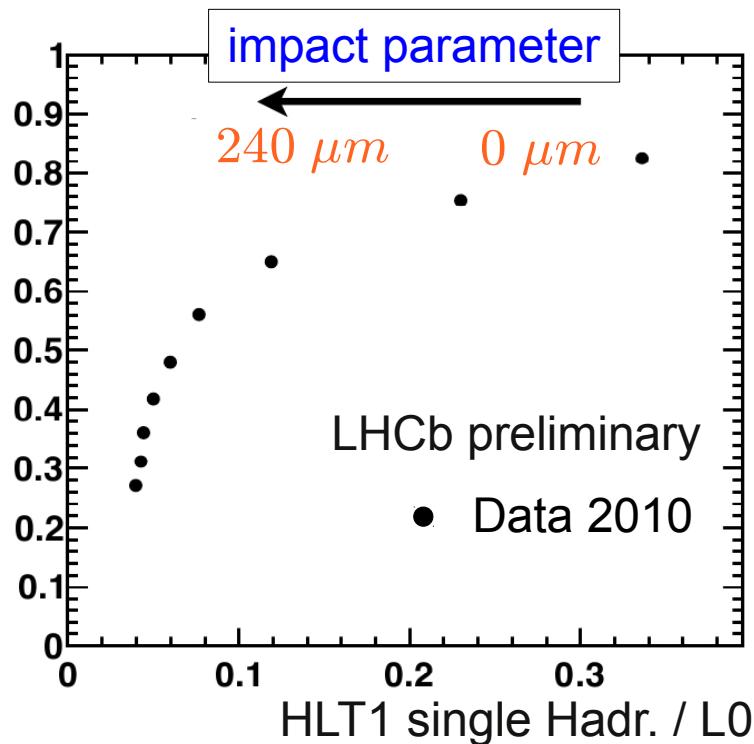
Trigger – $D^0 \rightarrow K\pi$

- Trigger performance on tagged $D^0 \rightarrow K\pi$ minimum bias data

Hardware and first stage software trigger efficiency of selected $D^* \rightarrow \pi_s (D^0 \rightarrow K\pi)$ data in the low luminosity setup

$$\epsilon_{L0*HLT1}^{data} = 60 \pm 4\%$$

- p_T and impact parameter dependence of the software Trigger



Mixing Formalism

Neutral D⁰ 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 D₁ and D₂:

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

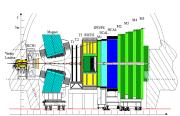
$$|D_{1,2}(t)\rangle = e^{-i(M_{1,2}-i\Gamma_{1,2}/2)t} |D_{1,2}(t=0)\rangle$$

D₁ : CP even
D₂ : CP odd

- Define mass and lifetime differences of D₁ and D₂:

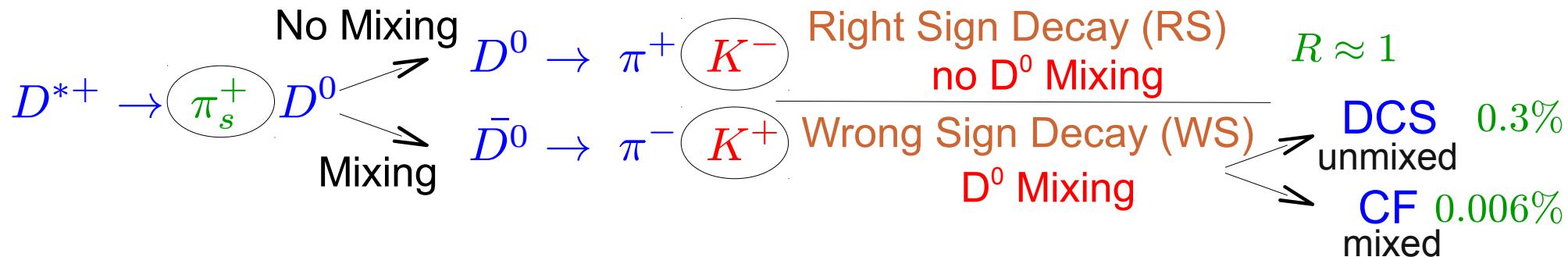
$$x = \frac{\Delta M}{\Gamma} = \frac{M_1 - M_2}{\Gamma} \quad y = \frac{\Delta\Gamma}{2\Gamma} = \frac{\Gamma_1 - \Gamma_2}{2\Gamma}$$

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

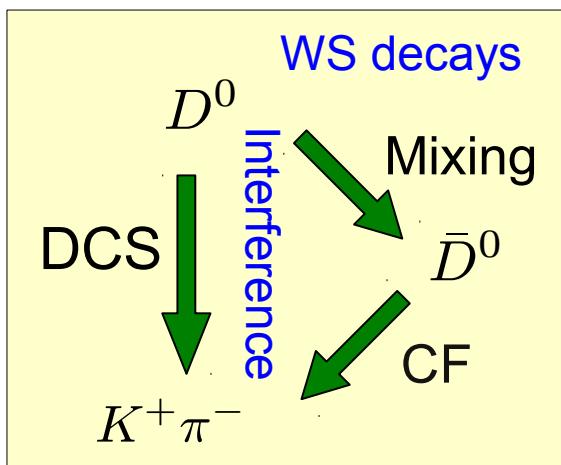


Time Evolution in $D^0 \rightarrow K\pi$ Decays

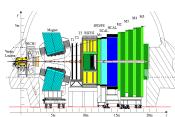
- Event classes - flavour tagging at production and decay time



- Time evolution of the WS decay rate



- assume CP conservation and $|x| \ll 1 ; |y| \ll 1$
 - $T_{WS}(t) \propto e^{-\Gamma t} \left(\underbrace{R_D}_{DCS} + \underbrace{\sqrt{R_D} y' \Gamma t}_{\text{Interference}} + \underbrace{\frac{x'^2 + y'^2}{4} (\Gamma t)^2}_{\text{Mixing}} \right)$
 - $\delta_{K\pi}$ is the strong phase between CF and DCS amplitudes ($D^0 \rightarrow K\pi$)
- $$x' = x \cos \delta_{K\pi} + y \sin \delta_{K\pi}$$
- $$y' = -x \sin \delta_{K\pi} + y \cos \delta_{K\pi}$$
- $$y'^2 + x'^2 = x^2 + y^2$$



Analysis Strategy

BABAR approach

- Determine signal and background PDF's by unbinned max. likelihood fit
- Unbinned maximum likelihood fit of the wrong sign D^0 decay time distribution

BABAR (384 fb⁻¹)
PRL 98, 211802 (2007)

Use the fit results of RS decay time and the resolution function

no mixing fit

$$\frac{\Gamma_{WS}(t)}{e^{-\Gamma t}} = R_D + y' \sqrt{R_D} \Gamma t + \frac{x'^2 + y'^2}{4} (\Gamma t)^2$$

mixing fit

CDF approach

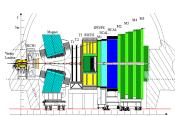
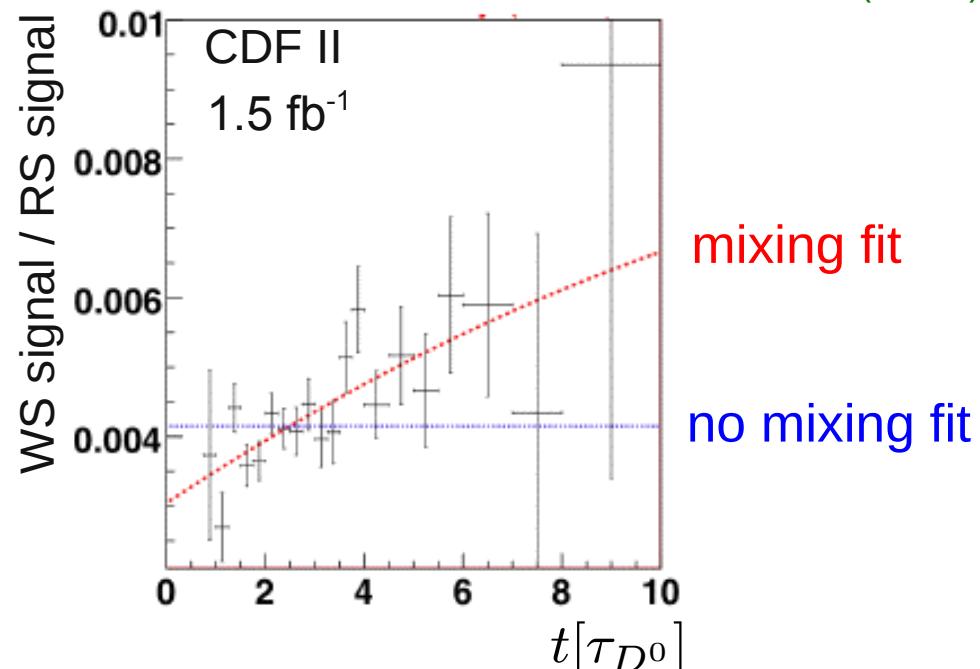
- Measure the Number of WS and RS D^0 decays in bins of the decay time

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

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

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

PRL 100, 121802 (2008)



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



PRL 98, 211802 (2007)

3.9 σ

$$R_D = (0.303 \pm 0.016 \pm 0.01)\%$$

$$y' = (0.97 \pm 0.44 \pm 0.31)\%$$

$$x'^2 = (-0.022 \pm 0.03 \pm 0.021)\%$$



PRL 100, 121802 (2008)

3.8 σ

$$R_D = (0.304 \pm 0.055)\%$$

$$y' = (0.85 \pm 0.76)\%$$

$$x'^2 = (-0.012 \pm 0.035)\%$$



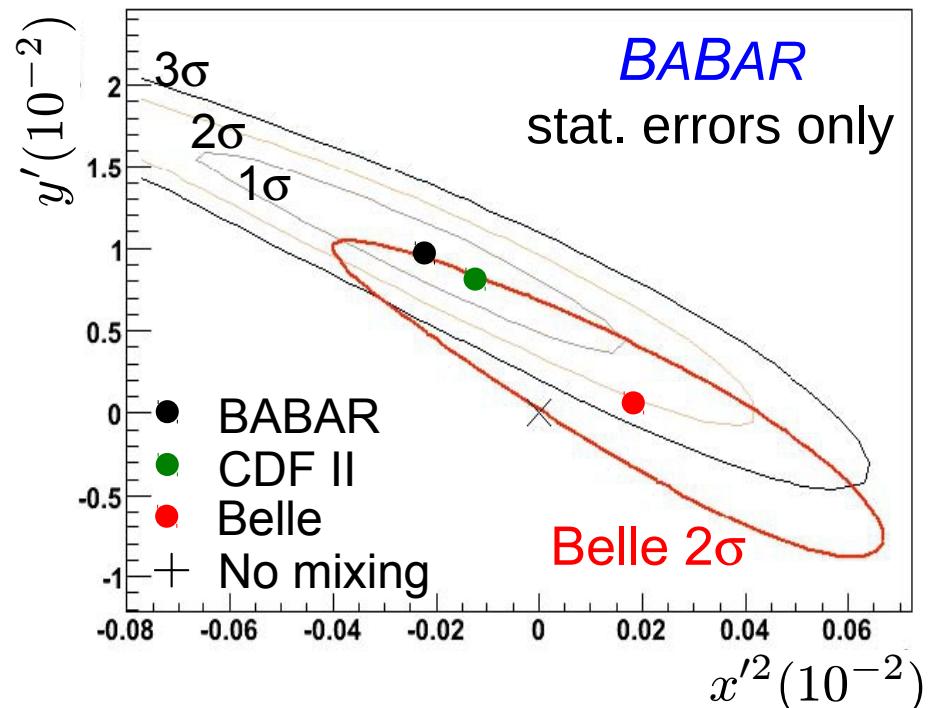
PRL 96, 151801

2 σ

$$R_D = (0.364 \pm 0.017)\%$$

$$y' = (0.06^{+0.40}_{-0.39})\%$$

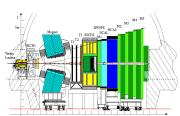
$$x'^2 = (0.018^{+0.021}_{-0.23})\%$$



➤ LHCb prospects

- Expected events in $\int \mathcal{L} \approx 100 \text{ pb}^{-1}$:
stronger selection criteria to improve S/B
for WS $N_{RS} \approx 1.4 \cdot 10^6$
 $N_{WS} \approx 5.3 \cdot 10^3$

same order of magnitude as *BABAR*



Measurement of y_{CP} - Introduction

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

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

τ^\pm : lifetime of D^0 (\bar{D}^0) \rightarrow CP+ eigenstates
 τ^0 : lifetime of D^0 \rightarrow CP mixed (CF)

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

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

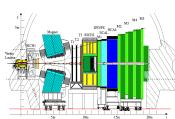
$$y_{CP} = \frac{\tau(K^- \pi^+)}{\tau(K^- K^+)} - 1 = \frac{\tau(K^- \pi^+)}{\tau(\pi^- \pi^+)} - 1 = |q/p|(y \cos\phi_f - x \sin\phi_f)$$

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

- Test of CP violation

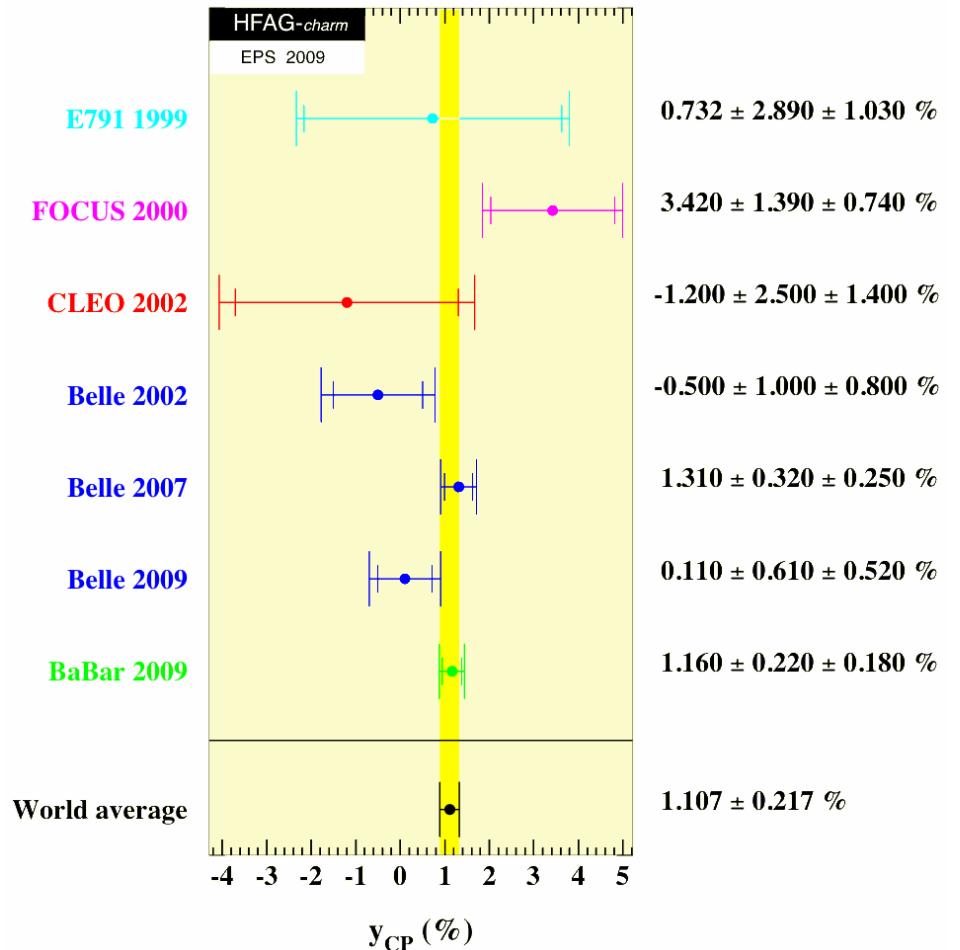
$$\Delta Y = \frac{\tau^0 A_\tau}{\tau} \quad \text{with} \quad A_\tau = \frac{\tau^+ - \tau^-}{\tau^+ + \tau^-} = -A_\Gamma$$

$$\Delta Y \neq 0 \Rightarrow \begin{aligned} &\text{CP violation in } D^0\text{-}\bar{D}^0 \text{ mixing} \\ &\text{CP violation in interf. between mixing and decay} \\ y_{CP} = y &\Leftarrow \text{CP conservation} \end{aligned}$$

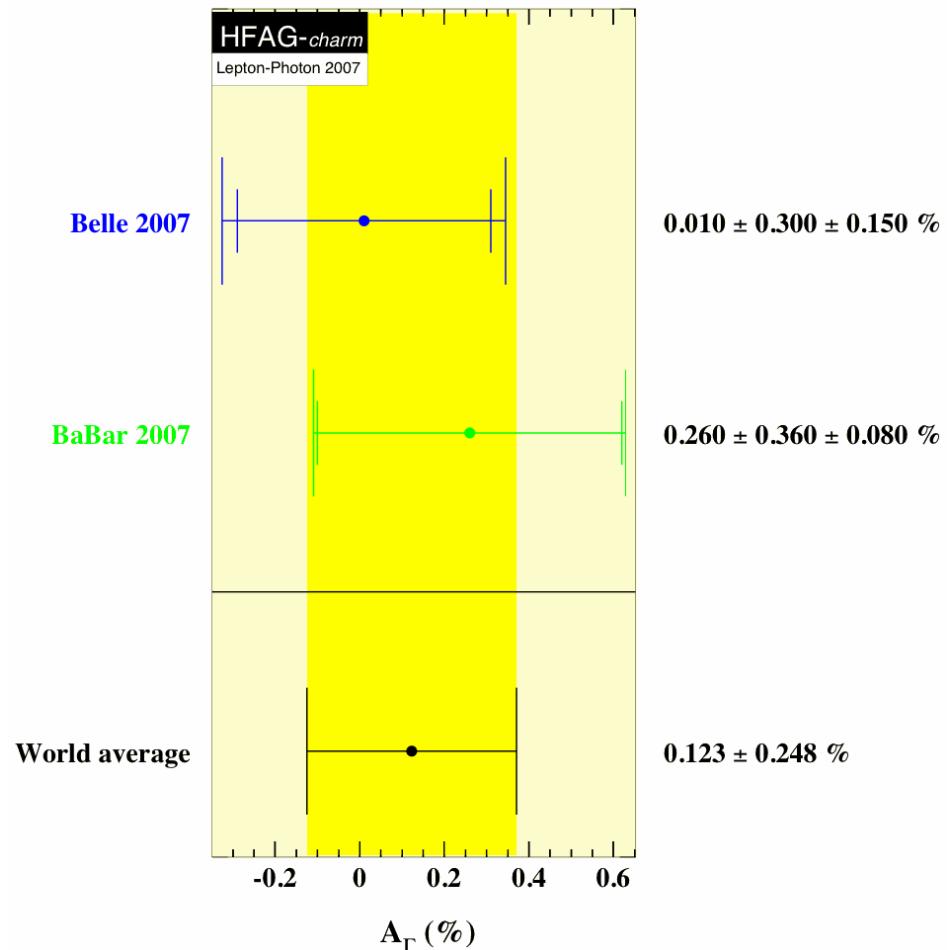


Experimental Results – y_{CP}

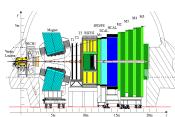
➤ Combined y_{CP} and A_Γ as averaged by the charm subgroup of HFAG



$$y_{CP} = (1.107 \pm 0.217)\%$$

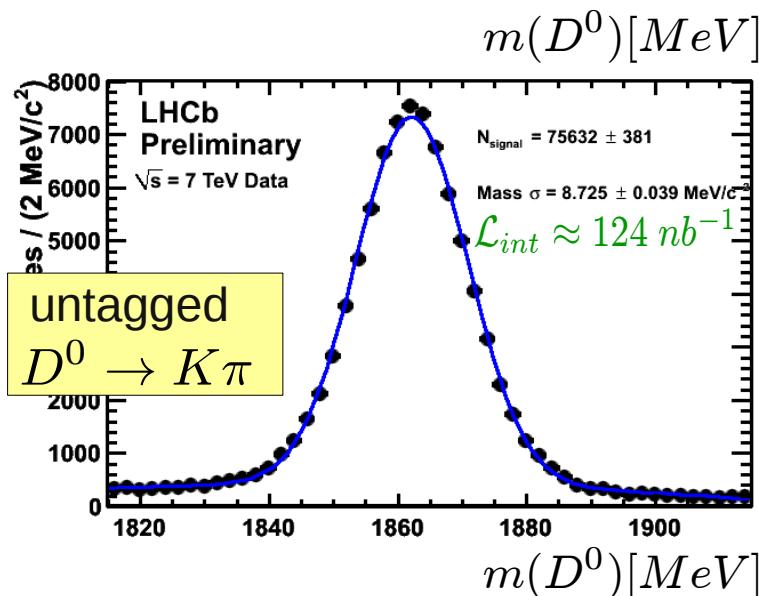
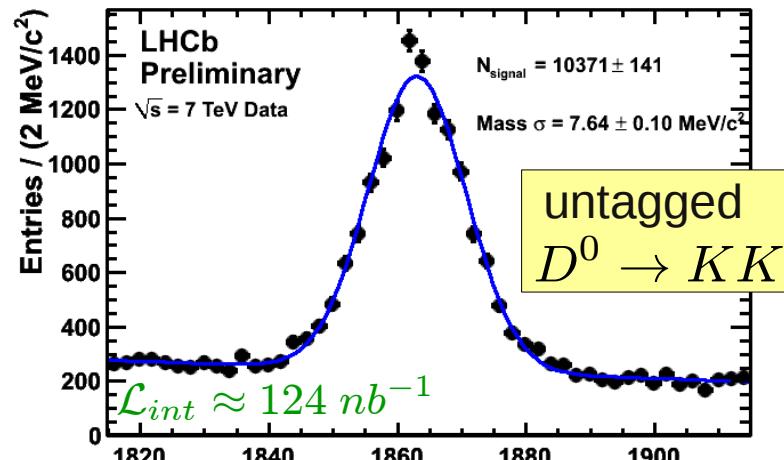


$$A_\Gamma = (0.123 \pm 0.248)\%$$



LHCb – Towards y_{CP} and A_Γ

➤ Compare $D^0 \rightarrow KK$, $D^0 \rightarrow \pi\pi$ and $D^0 \rightarrow K\pi$ to extract y_{CP} and A_Γ



- Analyse the D^0 decay time distributions
 - Determine $\langle N_{KK} \rangle_i / \langle N_{K\pi} \rangle_i$ in bins i of the lifetime distribution
 - Determine $\tau_{K\pi}$, τ_{KK}^+ , τ_{KK}^- from unbinned max. likelihood fits to the lifetime distributions

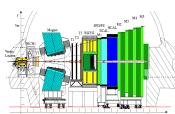
- Expected events in $\int \mathcal{L} \approx 100$ pb⁻¹ :

$$N_{100 \text{ pb}^{-1}}(D^0 \rightarrow K\pi) \approx 61 \cdot 10^6$$

$$N_{100 \text{ pb}^{-1}}(D^0 \rightarrow KK) \approx 8.3 \cdot 10^6$$

factor 10 more data than the *BABAR* analysis

B. Aubert et al., Phys. Rev. D80 071103 (2009)



Introduction - t Dep. Dalitz Analysis

➤ Dalitz plot of $D^0 \rightarrow K_s^0 \pi^+ \pi^-$

- ❖ Different quasi 2 body amplitudes contribute and interfere
- ❖ Dalitz analysis allows to determine amplitude and relative phases of 18 modes

➤ Time dependence

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

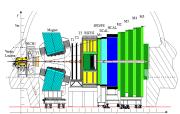
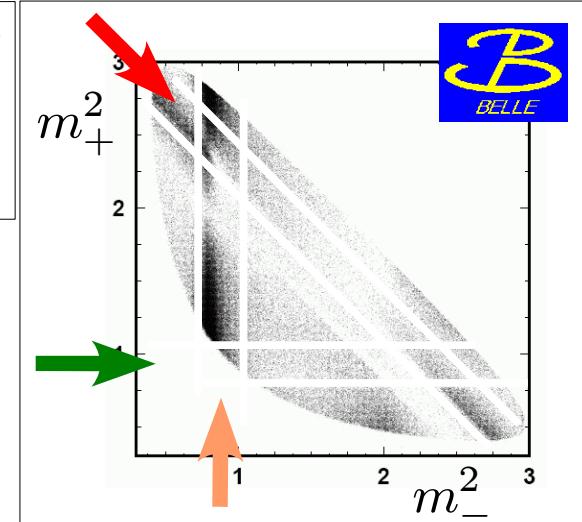
decay amplitude

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

- ❖ The decay rates contain functions of x and y

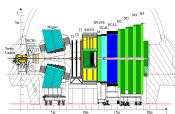
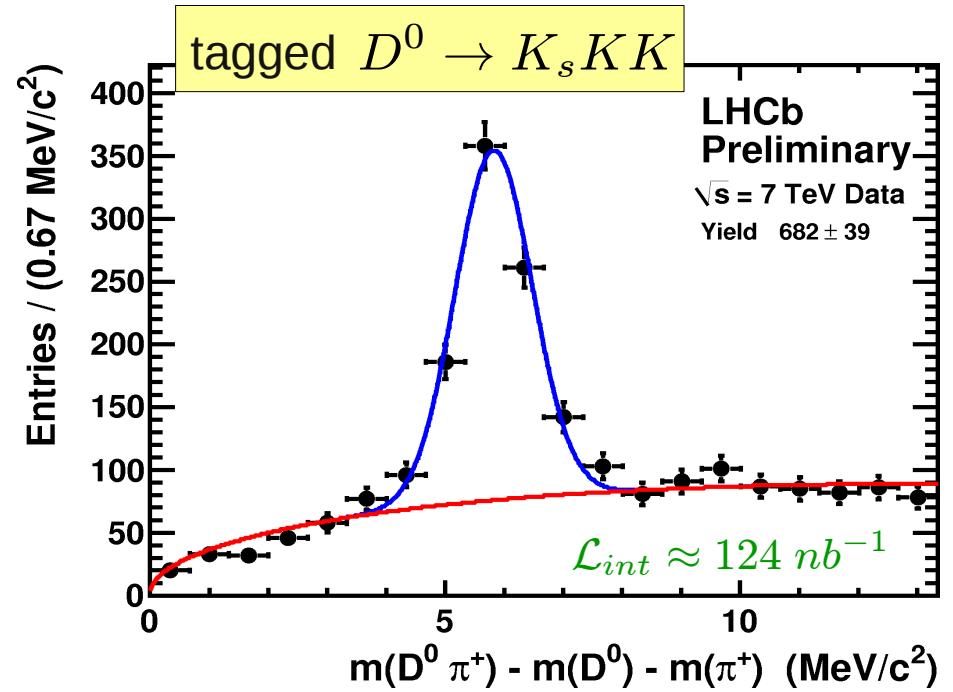
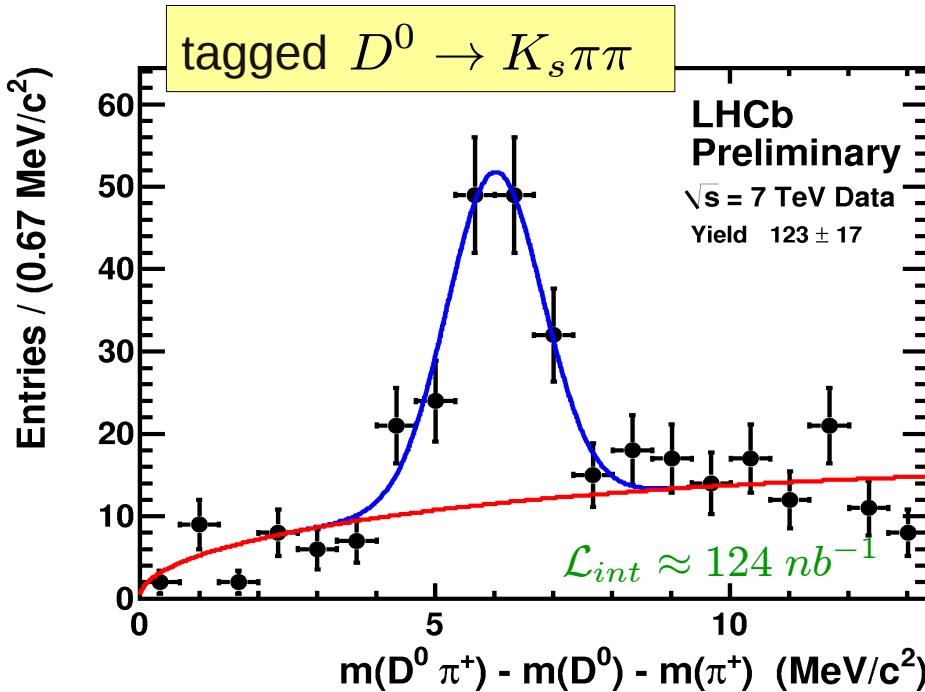
- ## ➤ Perform unbinned max. likelihood fit in the signal region to (m_+^2, m_-^2, t)
- ⇒ extract relative amplitudes and relative phases
 - ⇒ x, y and τ_{D^0}

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



LHCb – Signal Samples

- Selected tagged $D^0 \rightarrow K_s \pi\pi$ and $D^0 \rightarrow K_s KK$ decays

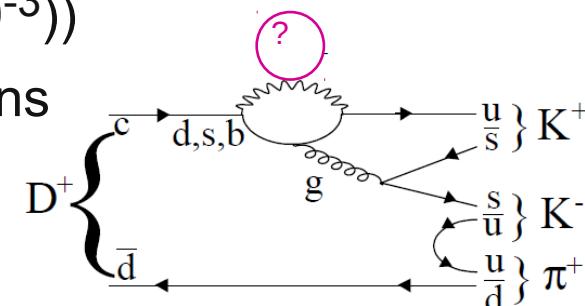


Direct CP Violation in SCS Decays

➤ Single Cabibbo suppressed charm decays (SCS)

- CPV in SM is CKM and loop suppressed ($\text{CPV} < \mathcal{O}(10^{-3})$)
- SCS decays are sensitive to CPV in $c \rightarrow uq\bar{q}$ transitions
Contributions due to supersymmetric $\Delta C = 1$ QCD penguins could enter.
→ measurement of large CPV would be a sign of NP
- Search for CPV in SCS tagged $D^0 \rightarrow \pi^+\pi^-\pi^0$, $D^0 \rightarrow K^+K^-\pi^0$ by *BABAR*
→ results are in accord with SM predictions (few %)

Y. Grossman et al.
Phys. Rev. D75 036008 (2007)



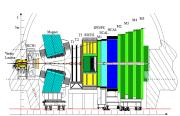
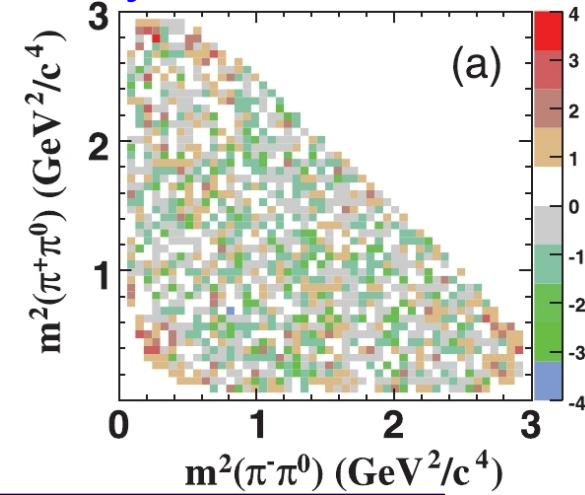
➤ Model independent Dalitz Plot analysis to look for CP asymmetries

Miranda procedure Phys. Rev. D80 096006 (2009)

Consider the significance in the difference between corresponding Dalitz plot bins.

$$D_p S_{CP} = \frac{N(i) - \bar{N}(i)}{\sqrt{N(i) + \bar{N}(i)}}$$

- Provides better filtering between real asymmetries and statistical fluctuations
- Not sensitive to production asymmetries

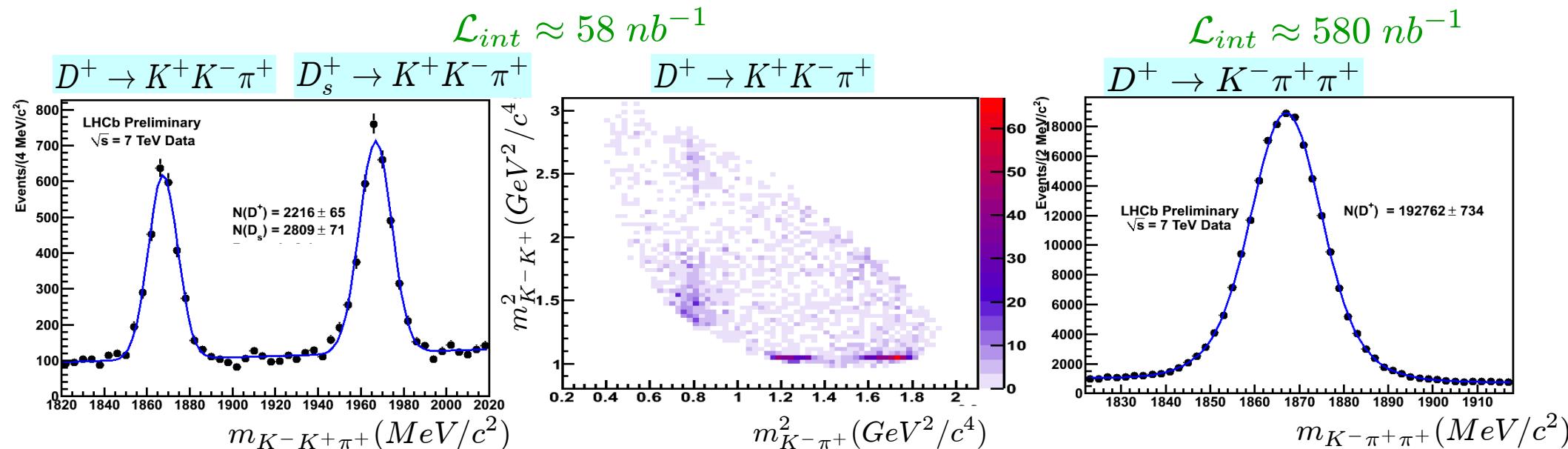


LHCb - Direct CP Violation Search

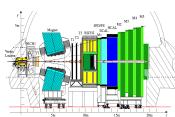
➤ Dalitz analysis of the SCS decay $D^+ \rightarrow K^+ K^- \pi^+$

Time integrated and model independent search for **local** CP asymmetries in bins of the Dalitz plane.

- Two suitable control channels: $D_s^+ \rightarrow K^+ K^- \pi^+$ and $D^+ \rightarrow K^- \pi^+ \pi^+$



- Expect in $\int \mathcal{L} \approx 100 \text{ pb}^{-1}$ a sample of several million events

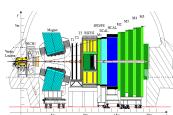
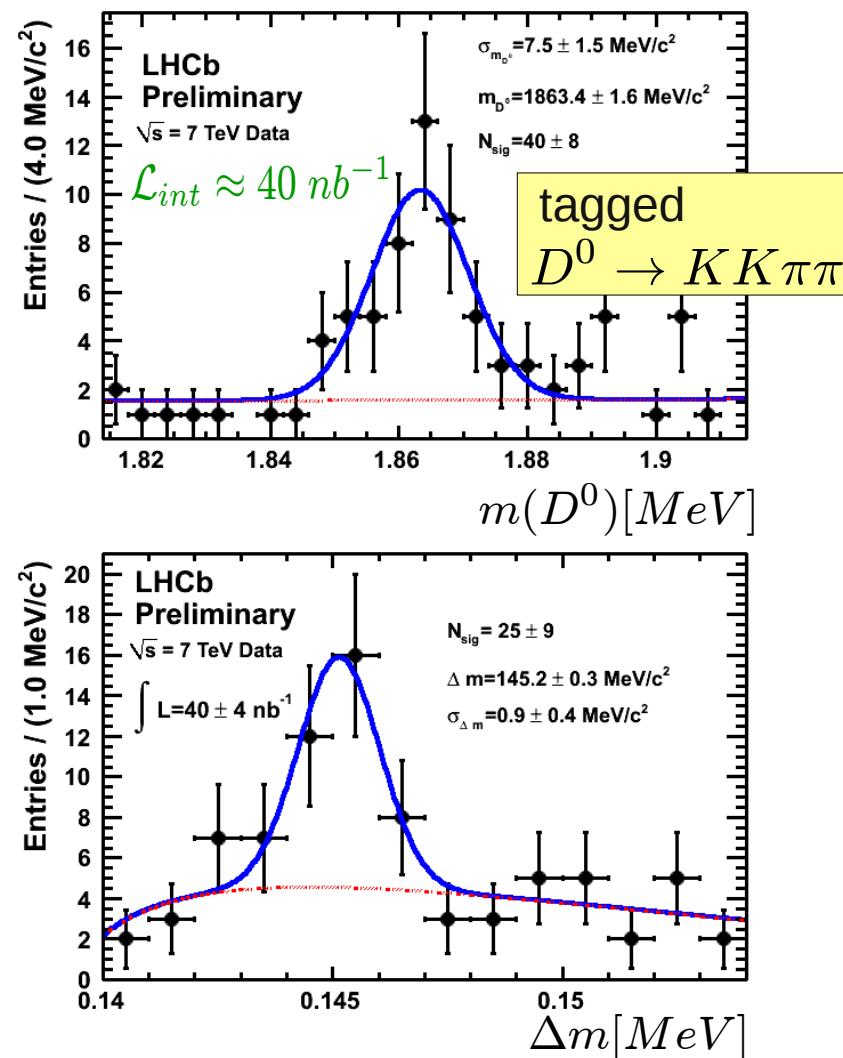


CPV in $D^0 \rightarrow KK\pi\pi$ Decays

- Measure T violation and CPV (assuming CPT) in time integrated 4 body SCS D^0 decays, like $D^0 \rightarrow KK\pi\pi$

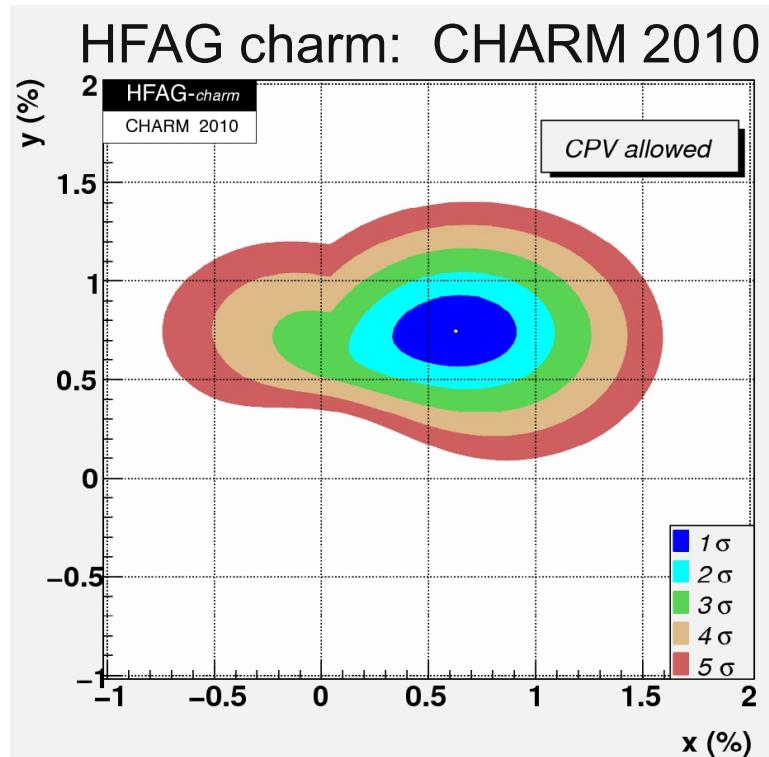
I.I. Biggi hep-ph-0107102 (2001)

- Analyse T odd moments
 - Construct an observable which is odd under time reversal, eg a scalar triple product of kinematic variables or the $KK - \pi\pi$ decay plane angle
 - Construct a T-violating asymmetry from this observable on the conjugate decays
- Expect in $\int \mathcal{L} \approx 100 pb^{-1}$
a sample of several 10k events

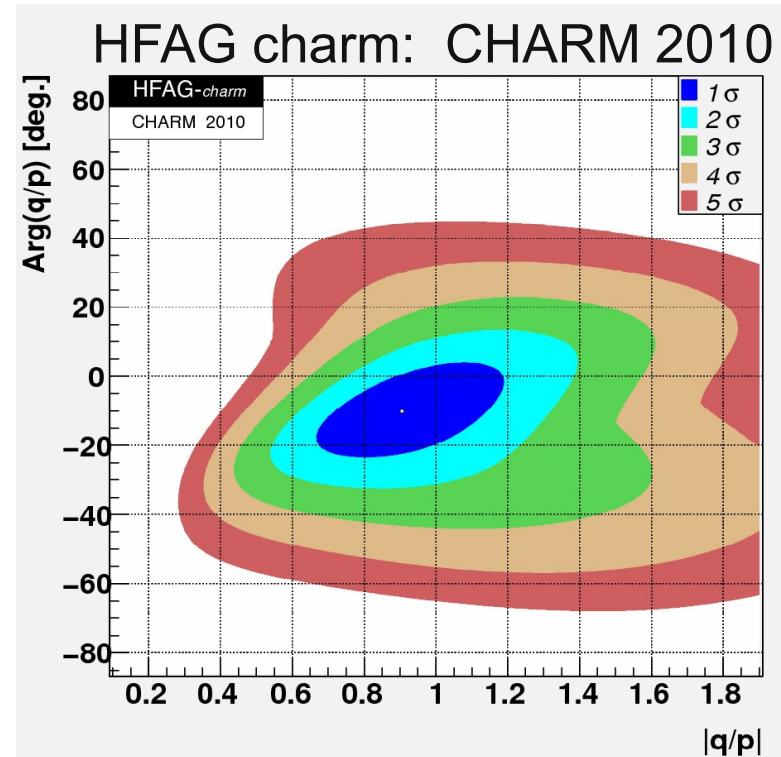


Averaged Mixing and CPV Parameters

- Mixing parameter as combined by the HFAG charm group



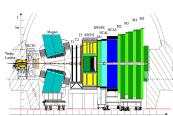
$$y = (0.75 \pm 0.12)\%$$
$$x = (0.63^{+0.19}_{-0.20})\%$$



$$|q/p| = (0.91^{+0.18}_{-0.16})\%$$
$$\phi = (-10.2^{+9.4}_{-8.9})^\circ$$

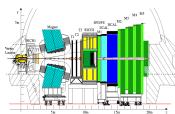
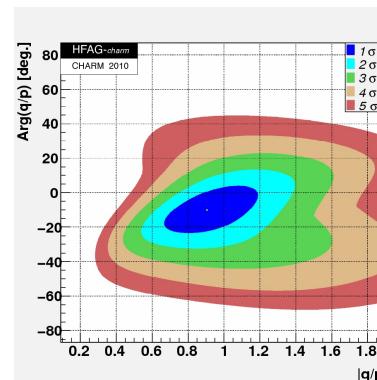
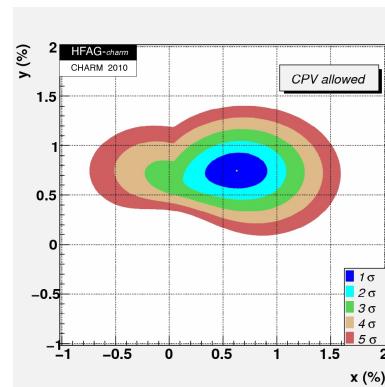
Exclude no mixing case at 10.2σ

Fully compatible with the CP conservation



Summary

- LHCb has a large potential for charm physics and is producing beautiful charm samples
- Raw sample sizes are in some modes already approaching those of existing measurements
- In 2011 LHCb expects to produce charm samples capable of significant improvements in sensitivity
- LHCb looks forward to making significant contributions to the charm sector of flavor physics, especially in

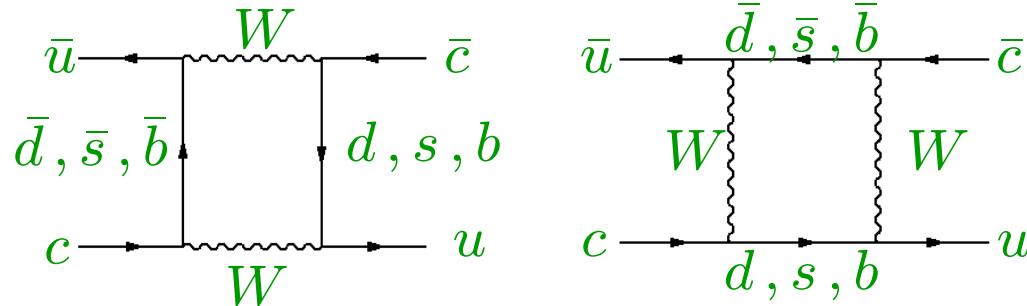


back up slides

Charm Mixing Processes

- The box diagram contributions to charm mixing in the Standard Model are expected to be very small

- ❖ d-type quarks enter the mixing loop



- ❖ Suppression by

- GIM mechanism (d,s)

$$x \sim \frac{m_s^2 - m_d^2}{m_c^2}$$

- CKM matrix (b)

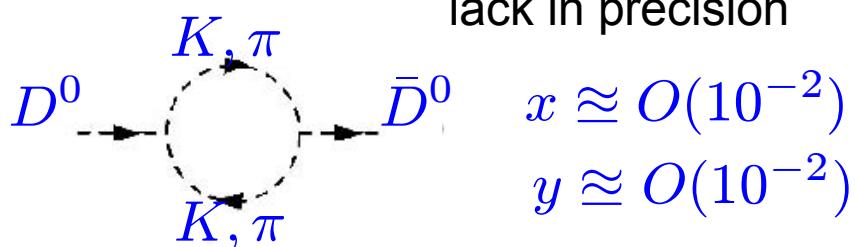
- ❖ Lowest order short distance calculation: $x_{box} \approx O(10^{-5})$ $y_{box} \approx O(10^{-7})$
- ❖ x and y enhancement due to higher orders in OPE: $x \sim y \approx O(10^{-3})$

- Long distance contributions

dominate

Numerical predictions

lack in precision



$$x \approx O(10^{-2})$$

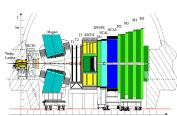
$$y \approx O(10^{-2})$$

- New Physics

- ❖ E.Golowich et al.: [arXiv:0705.3650](https://arxiv.org/abs/0705.3650)

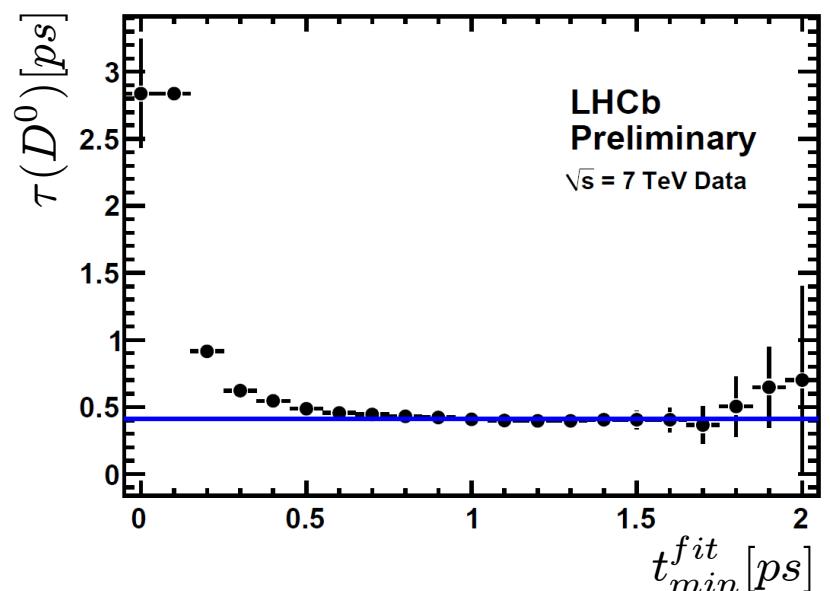
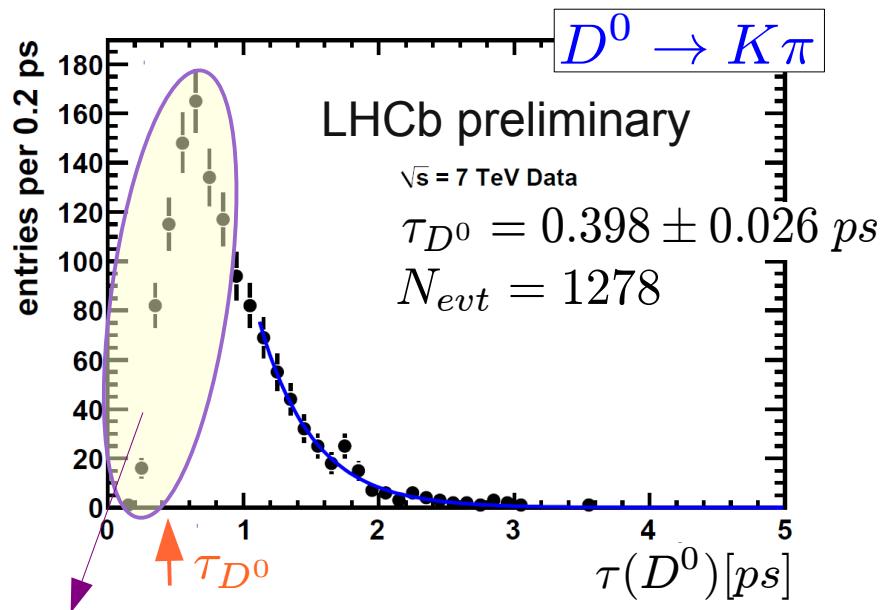
Which new physics model can yield sizeable values for x and y

- ❖ CP violation in charm is small in SM
Measurement of CPV: New Physics



D^0 Lifetime

- Estimate of the D^0 lifetime in untagged decays



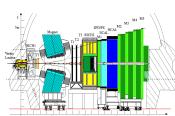
lifetime acceptance due to selection and software trigger

- Estimated lifetime is compatible with the PDG value
- In MC we obtain in prompt and secondary charm tagged $D^0 \rightarrow K\pi$ decays

$$\sigma_t \approx 0.040 \text{ } ps$$

$$\text{LHCb: } \frac{\sigma_t}{\tau_{D^0}} \approx 1/10$$

$$\text{BABAR: } \frac{\sigma_t}{\tau_{D^0}} \approx 1/2$$

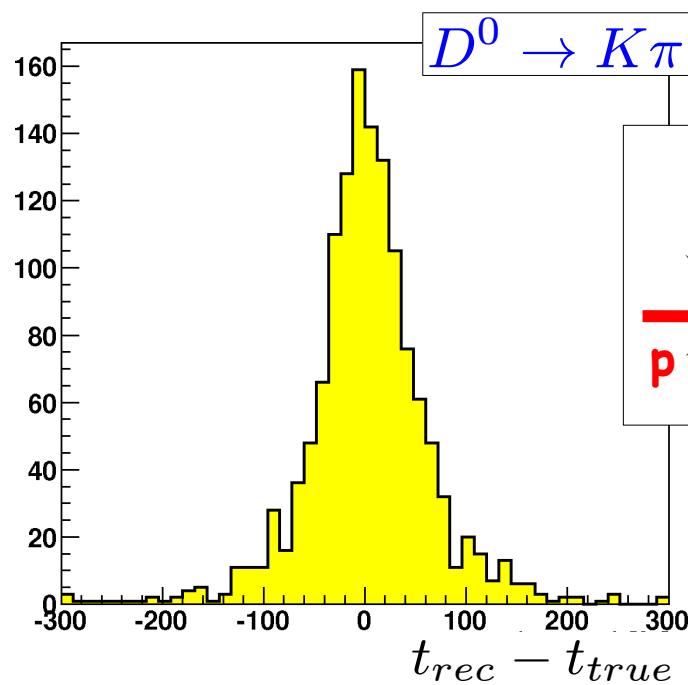


LHCb - D^0 Lifetime Resolution in MC

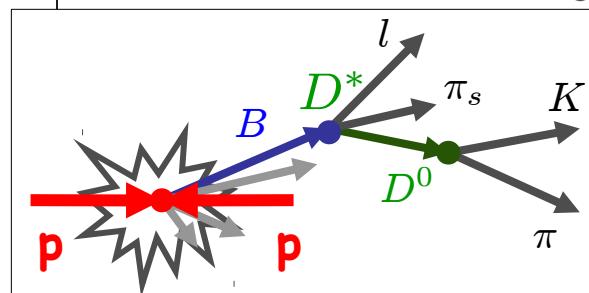
➤ Time resolution

For prompt charm

use primary vertex for D^*

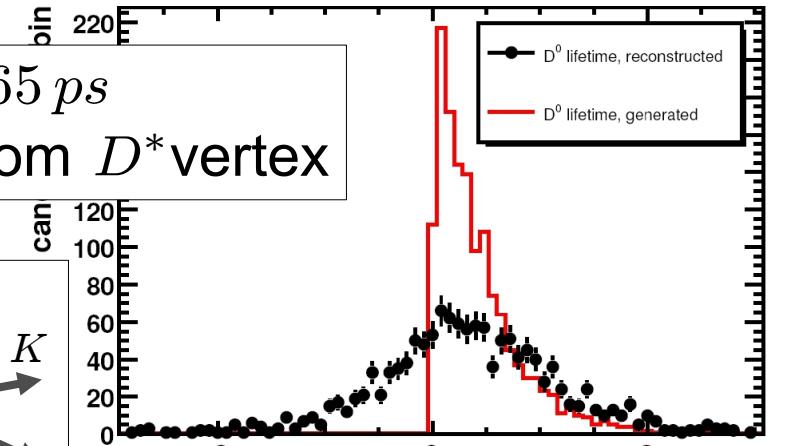


$$\sigma_t \approx 0.040 \text{ ps}$$

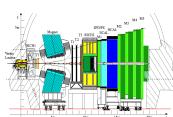
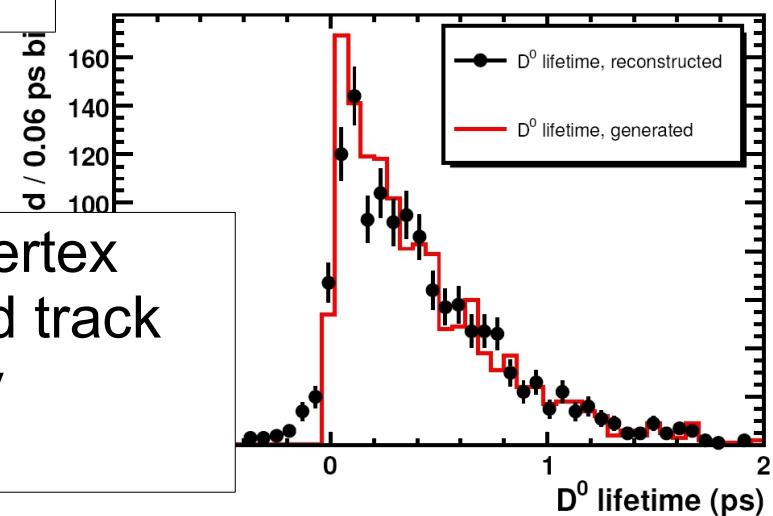


$\sigma_t \approx 0.465 \text{ ps}$
mainly from D^* vertex

secondary charm



Improve D^* vertex
using charged track
from B decay
 $\sigma_t \approx 0.045 \text{ ps}$



Toy Simulation – WS $D^0 \rightarrow K\pi$

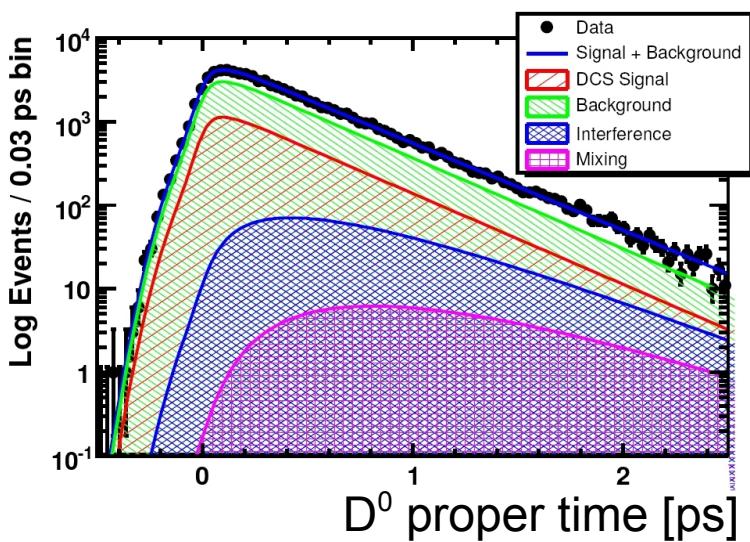
Use toy Monte Carlo simulations to understand mixing parameter extraction and statistical significance of the results. Use selection information and decay time acceptance.

- ML fit of mixing parameters in the lifetime distribution of the WS data

$$PDF(t; \tau, t_0, \sigma, b_1, b_2, b_3) = \frac{\theta(t)}{N} \int_{-\infty}^{+\infty} e^{\frac{t'}{\tau}} (b_1 + b_1 b_2 (\frac{t'}{\tau}) + \frac{b_3}{2} (\frac{t'}{\tau})^2) e^{-\frac{(t_0 - t' - t)^2}{2\sigma^2}} dt' + PDF_{bckgr.}(t; \tau_{bck}, t_0, \sigma)$$

- Decay time distribution

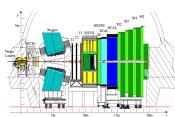
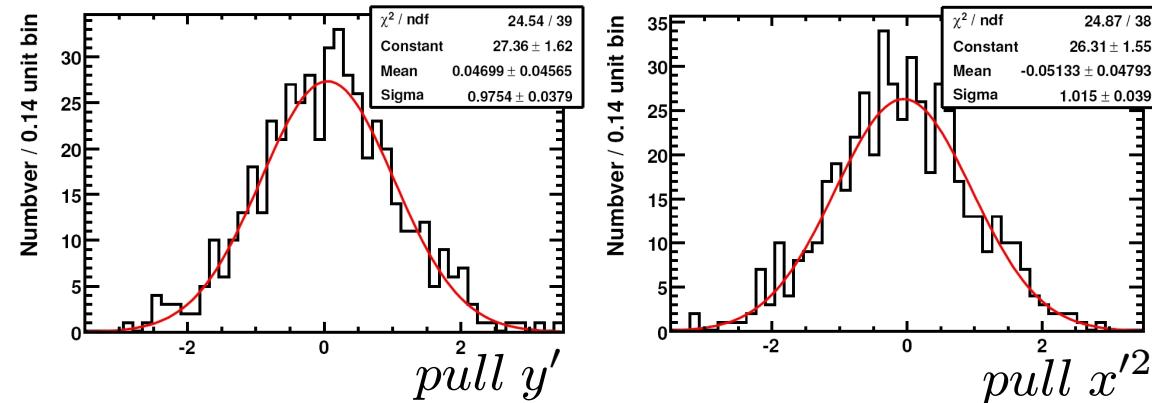
$$Bckgr/Signal = 2.56$$



- Mixing parameter

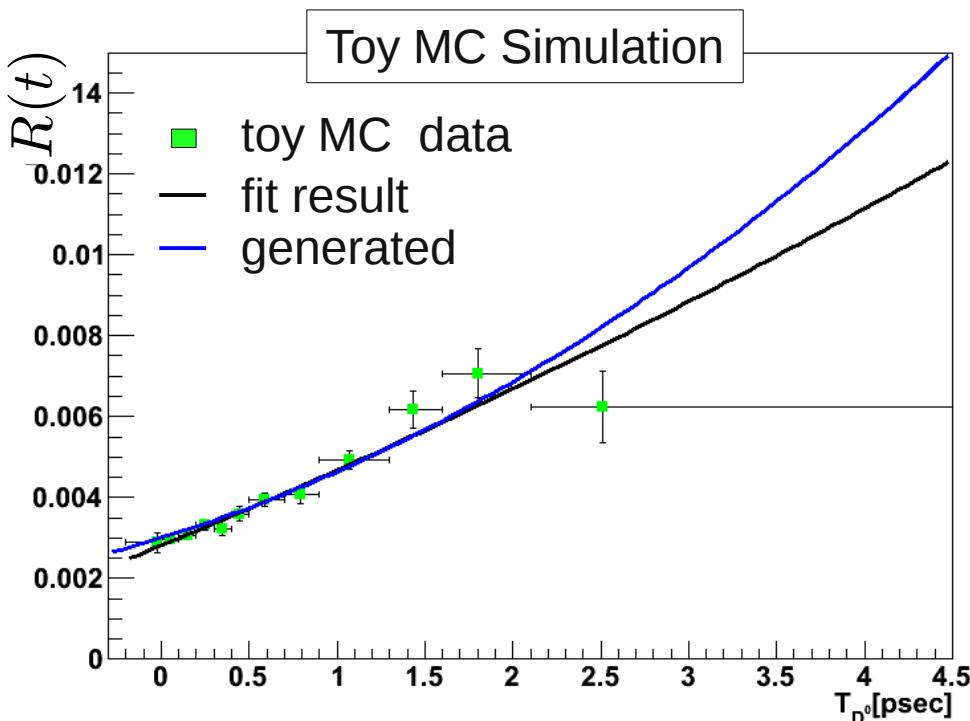
$$b_1 = \sqrt{R_D} \quad b_2 = y' \quad b_3 = (x'^2 + y'^2)/2$$

- Pull distributions 500 toy sets, each $\int \mathcal{L} \approx 10 fb^{-1}$



Mixing Parameter Determination

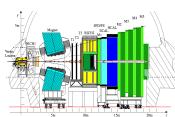
- Measure the number of WS and RS $D^0 \rightarrow K\pi$ decays in bins of of the decay time t and determine $R(t) = N_{WS}/N_{RS}(t)$ as CDF arXiv: 0712.1567 (2007)



$$R(t) = R_D + y' \sqrt{R_D} \frac{t}{\tau_{D^0}} + \frac{x'^2 + y'^2}{4} \left(\frac{t}{\tau_{D^0}} \right)^2$$

- Simulate decay time distributions of WS and RS decays
 $\sigma_t = 0.040 \text{ ps}$ $\tau_{D^0} = 0.41 \text{ ps}$
 $x = 0.01$ $y = 0.01$ $R_D = 0.003$
- Obtain N_{RS} and N_{WS} for a given binning in the decay time
- Fit $R = N_{WS}/N_{RS}$ as function of the average decay time in each bin

$$\rightarrow \sqrt{R_D}, y', x'^2$$



Sensitivity – D^0 Mixing Parameters

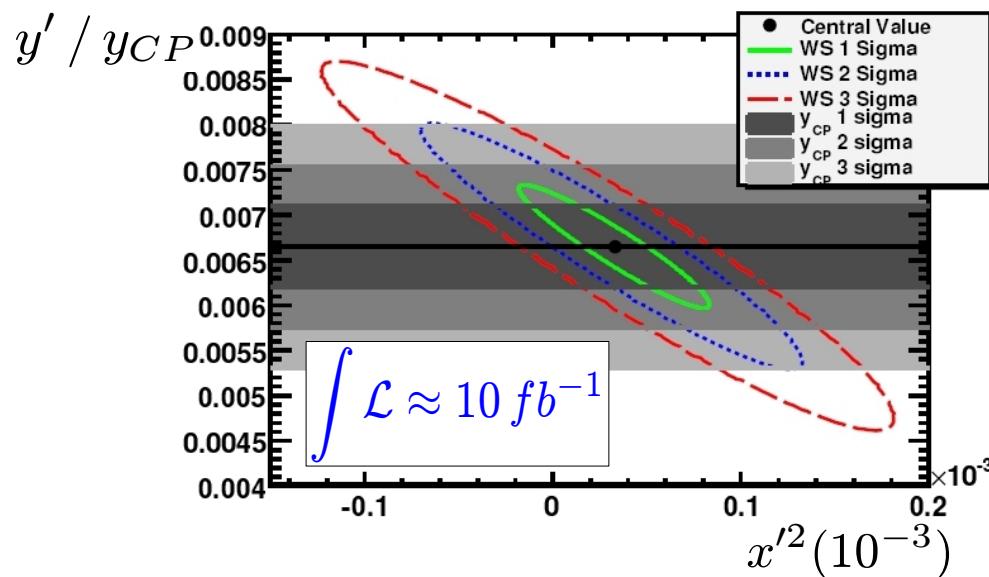
➤ Summary from selection

$$Bckgr/Signal = 2.56$$

$$N_{Signal}^{WS} = 46500 \pm 2200/fb^{-1}$$

$$\epsilon_{Signal}^{RS/WS} = (1.39 \pm 0.17) \cdot 10^{-3}$$

➤ Extract y_{CP} and (x'^2, y') from toy MC

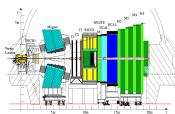
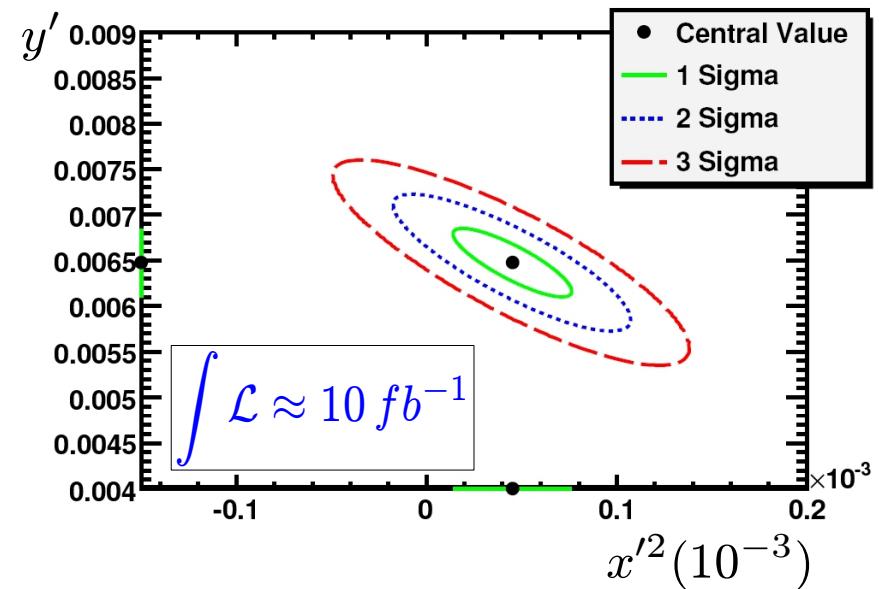


➤ Statistical errors

LHCb-2007- 049

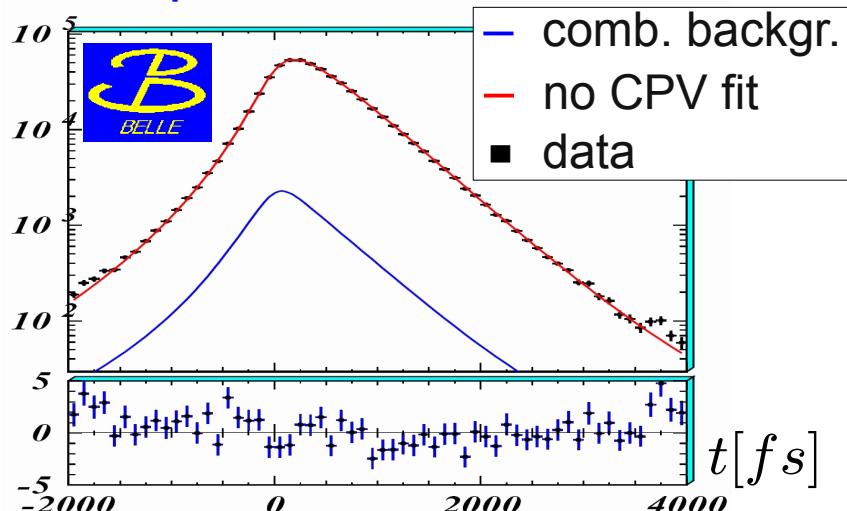
	$\sigma(x'^2) \cdot 10^{-3}$	$\sigma(y') \cdot 10^{-3}$
LHCb[2fb ⁻¹]	±0.064	±0.87
BABAR	±0.37	±5.4
Belle	+0.21 -0.23	+4.0 -3.9

➤ Sensitivity - combining likelihoods



Belle – t Dep. Dalitz Analysis Results

➤ Proper time fit results



$$\tau_{K_s^0 \pi^+ \pi^-} = 409.9 \pm 0.9 \text{ fs}$$

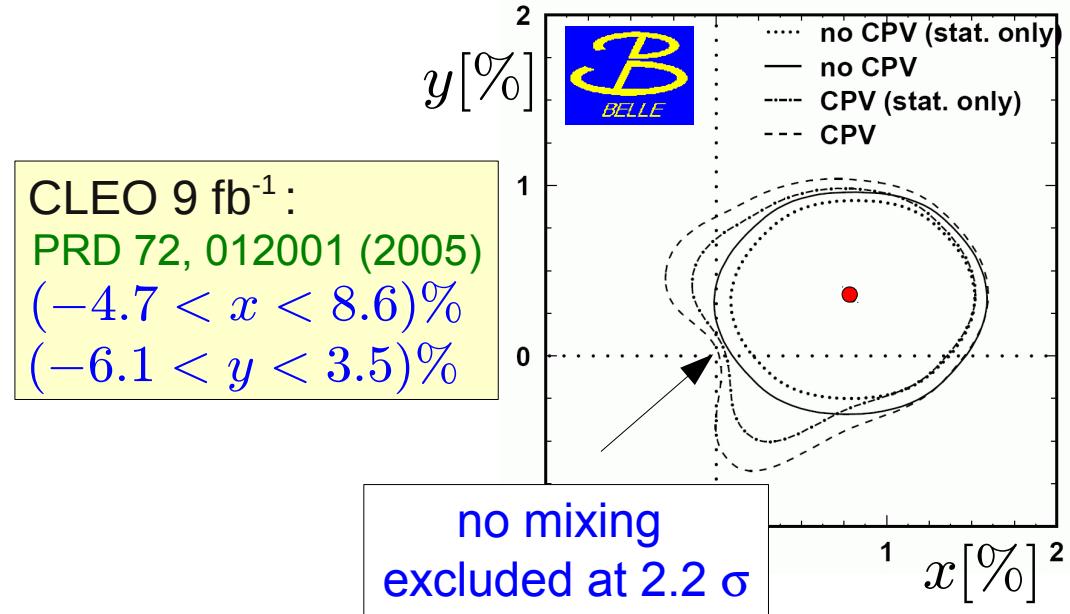
➤ Allow for CP violation

- ❖ Dalitz plot parameters from fit are similar for D^0 and \bar{D}^0 **no direct CP violation**
- ❖ CP violation results :

$$|q/p| = 0.86^{+0.30+0.06}_{-0.29-0.03} \pm 0.08$$

$$\arg(q/p)[^\circ] = -14^{+16+5+2}_{-18-3-4}$$

➤ Mixing parameter fit results



no mixing
excluded at 2.2σ

Belle 540 fb⁻¹: PRL 99, 131803 (2007)
 $x = (0.80 \pm 0.29^{+0.09+0.10}_{-0.07-0.14})\%$
 $y = (0.33 \pm 0.24^{+0.08+0.06}_{-0.12-0.08})\%$

no CP violation

