Physics at LHC 2010

June 11th, 2010

Charm Physics Results and Prospects at LHCb

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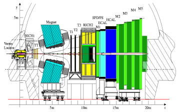
for the
LHCb
Collaboration

Outline

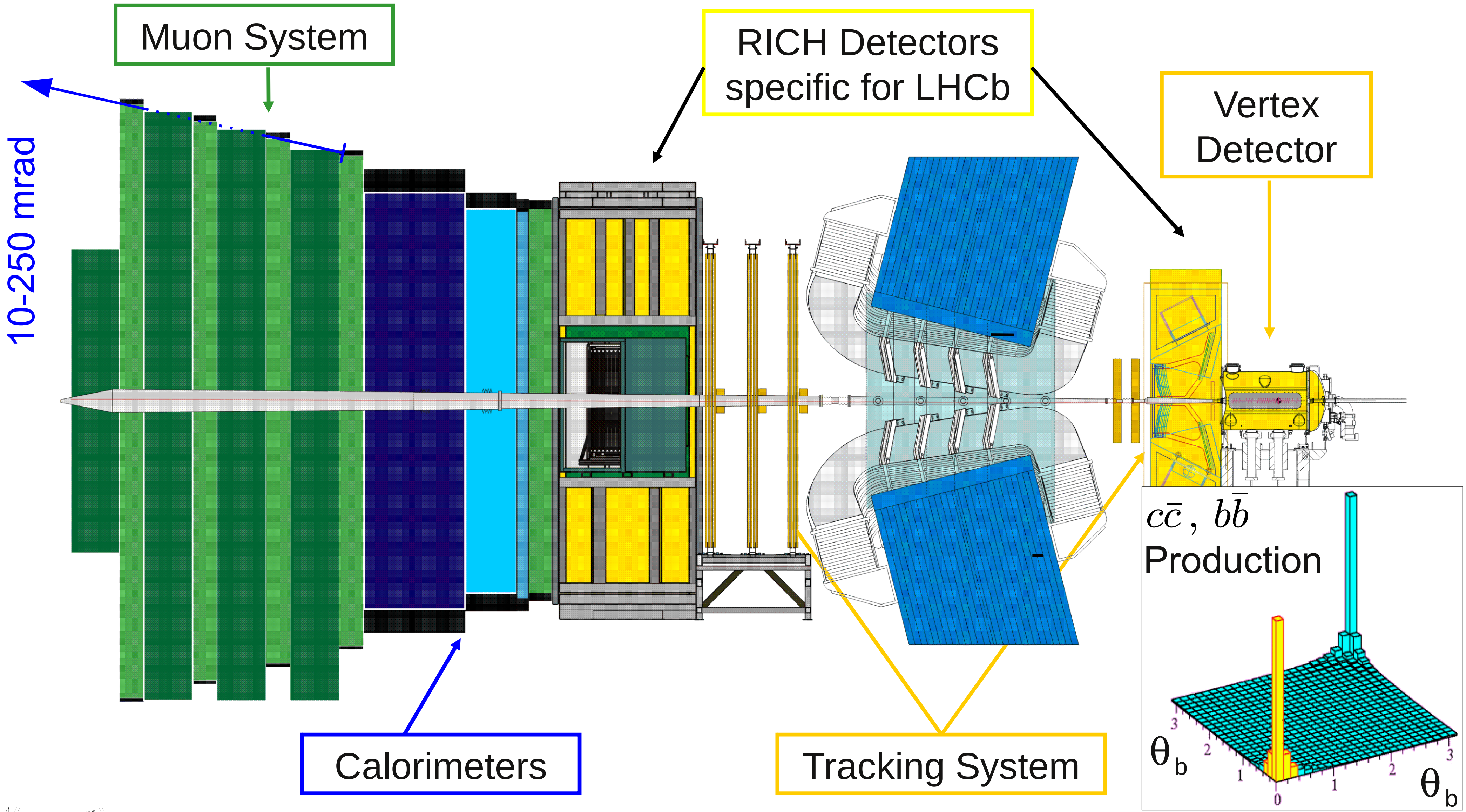
After a successful startup, LHC is constantly improving its "performance" with the aim to reach $\mathcal{L} \approx 10^{31}\, cm^{-2} s^{-1}$ by end of the year.

The road to design luminosity values implies a big opportunity for charm physics at LHCb.

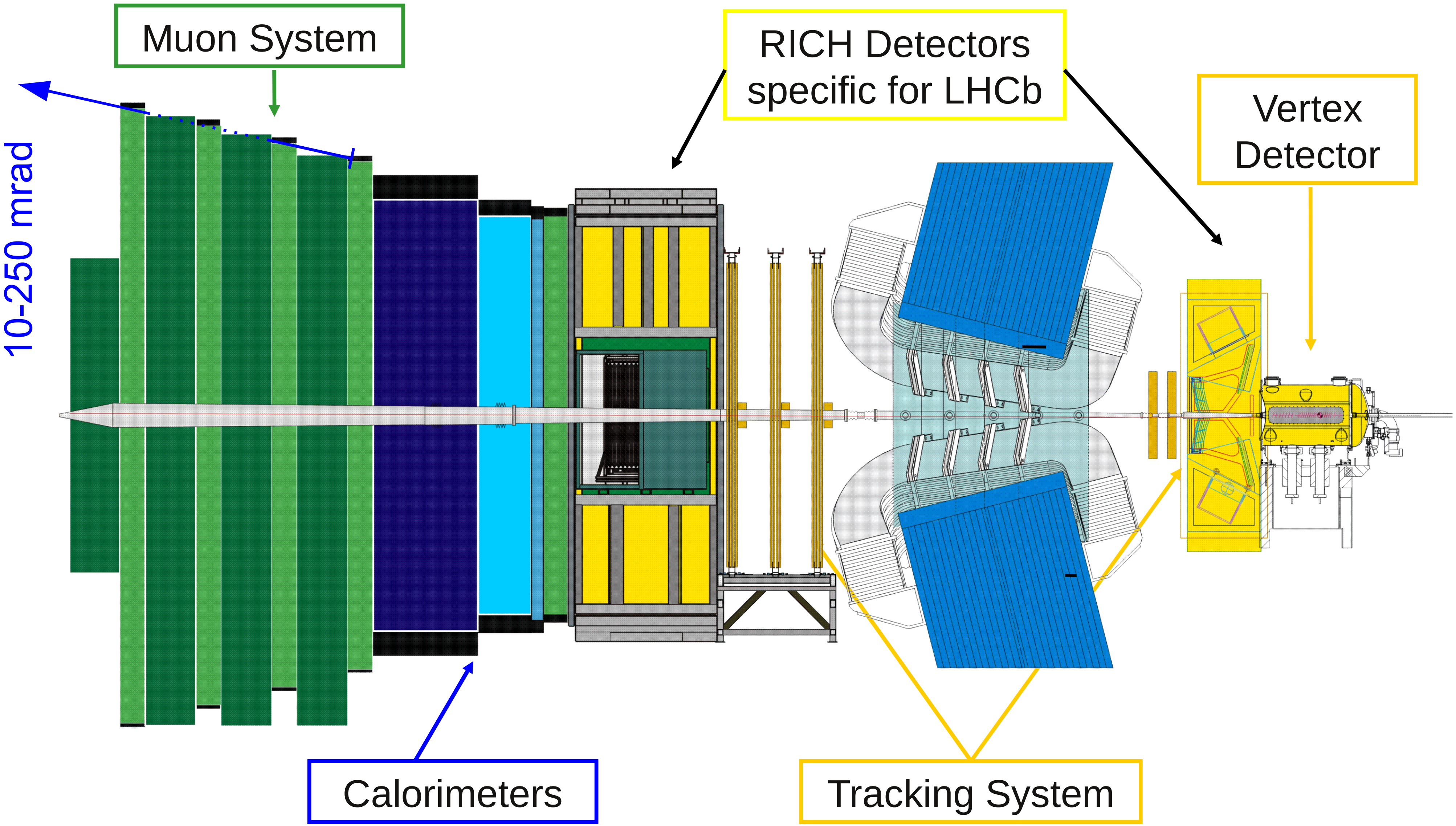
- LHCb experiment
- Run 2010/11 and LHCb trigger in view of charm physics
- Open charm signals
- LHCb prospects in charm mixing and CP violation
  - Time dependent mixing measurements in tagged $D^{\cdot} \rightarrow K\pi$
  - y_{CP} measurement from lifetime differences
  - Direct CP violation SCS 3-body decays
  - Rare decays: $D^{\cdot} \rightarrow \mu\mu$ see talk by Justine Serrano
- Summary



LHCb Experiment



LHCb Experiment



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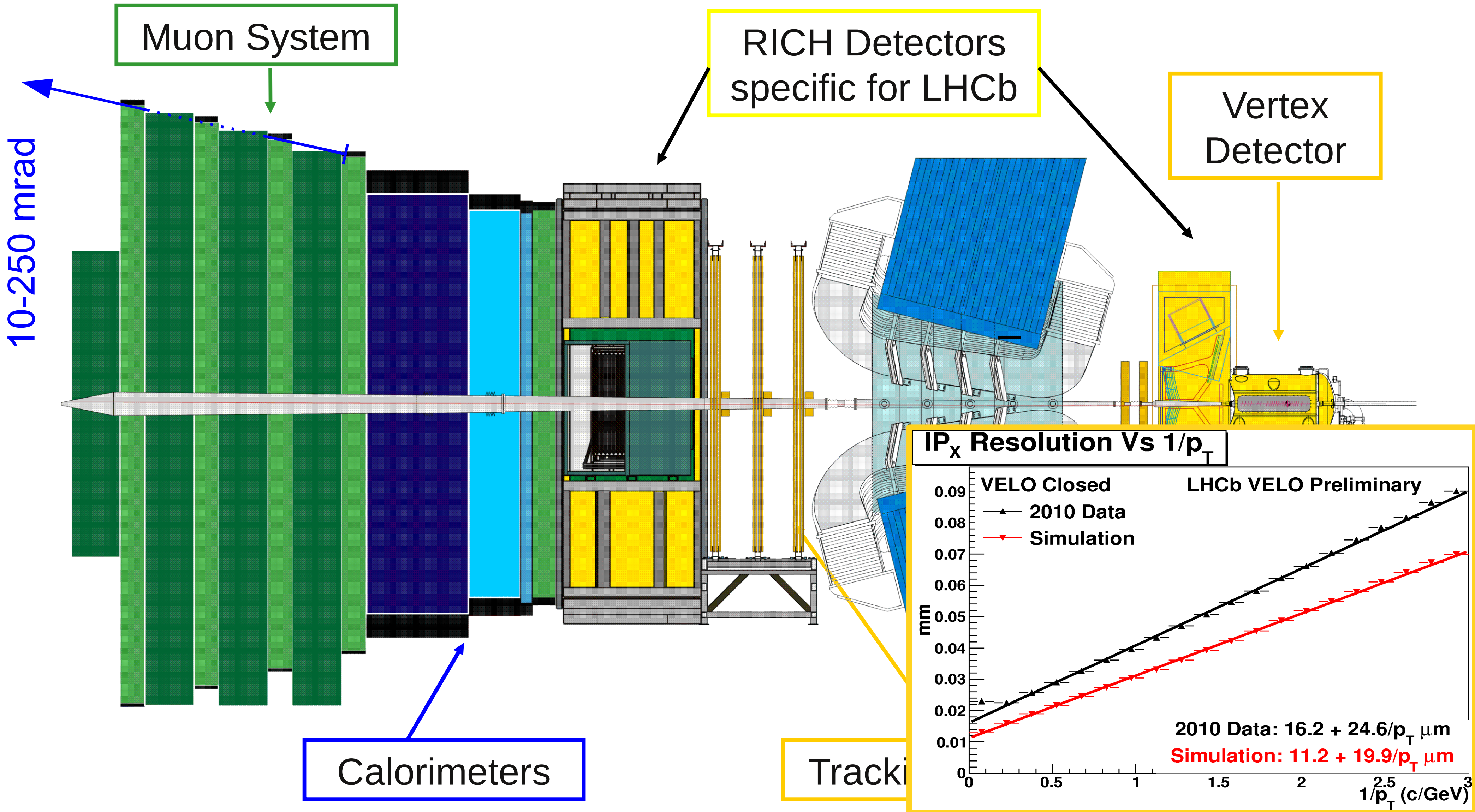
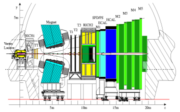
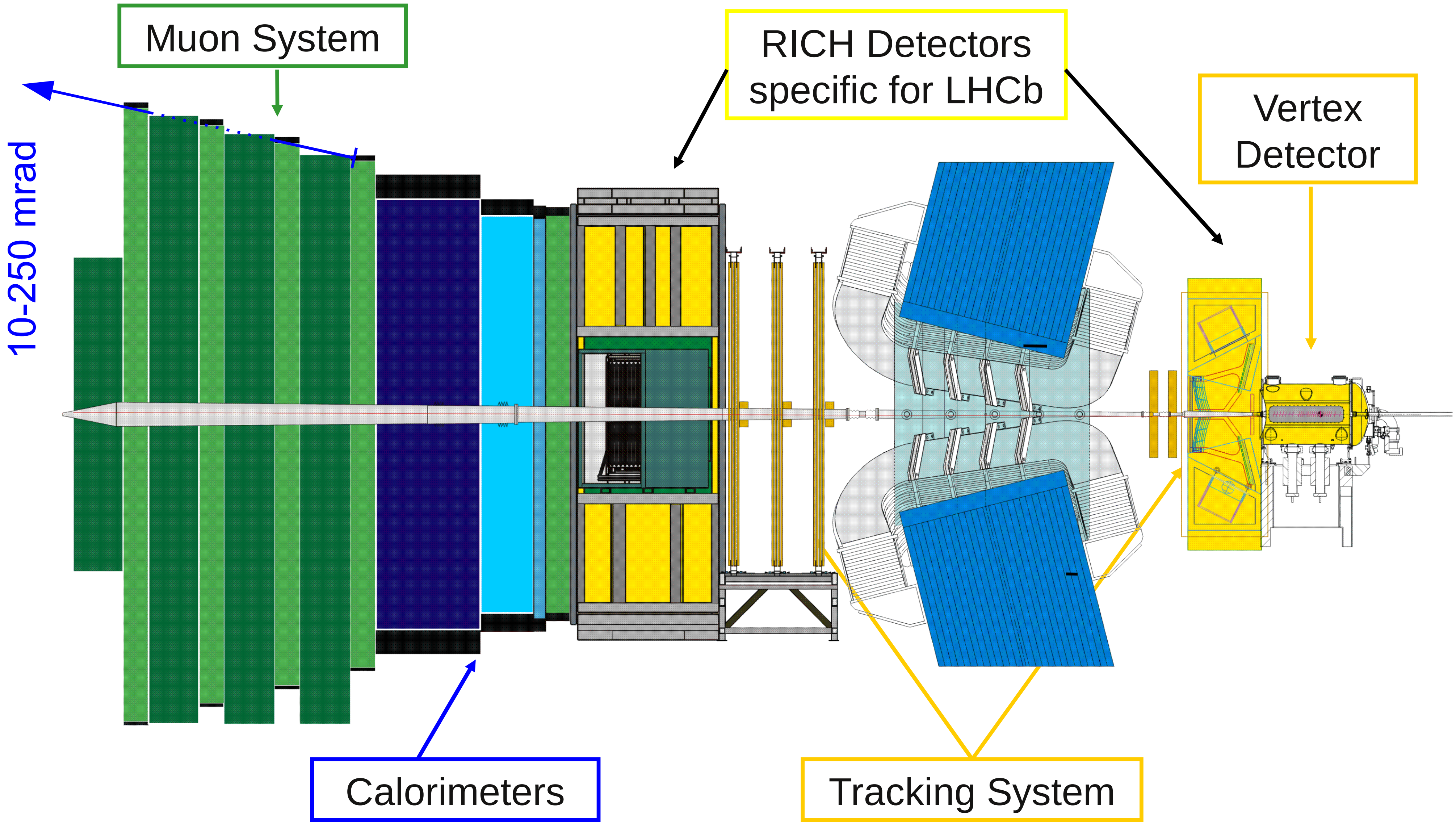
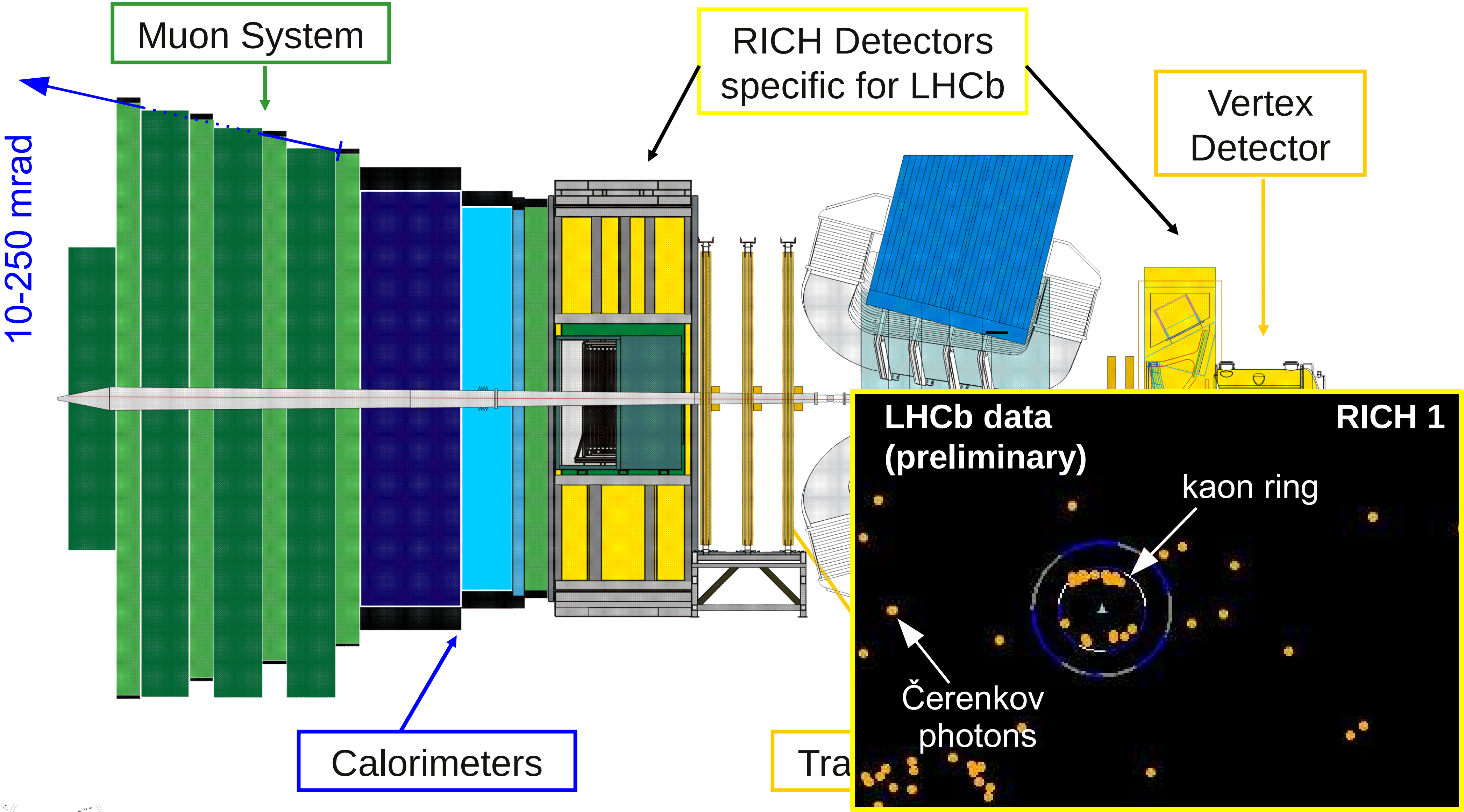


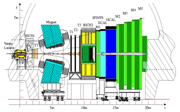


LHCb Experiment

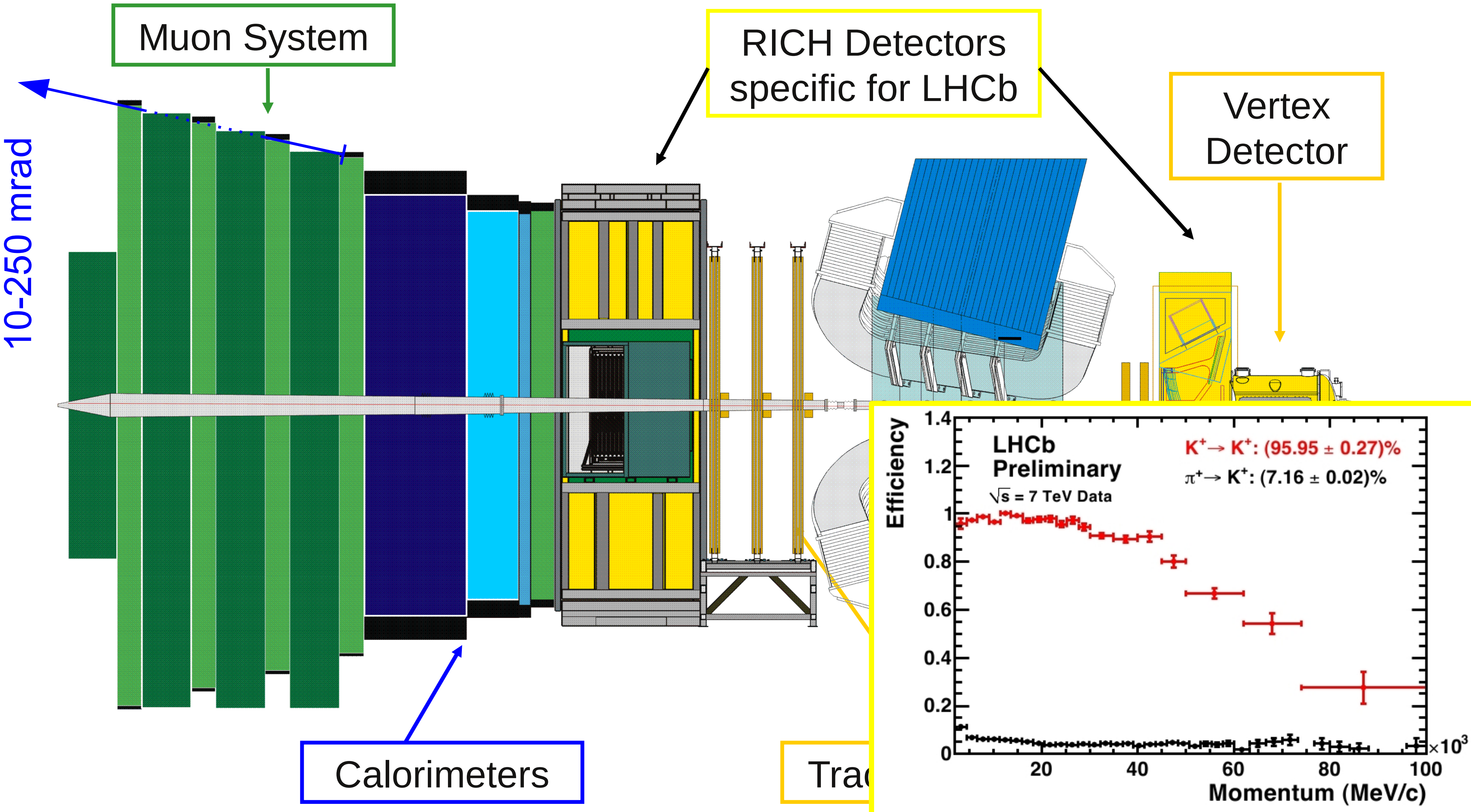


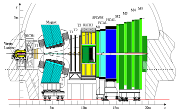
LHCb Experiment





LHCb Experiment

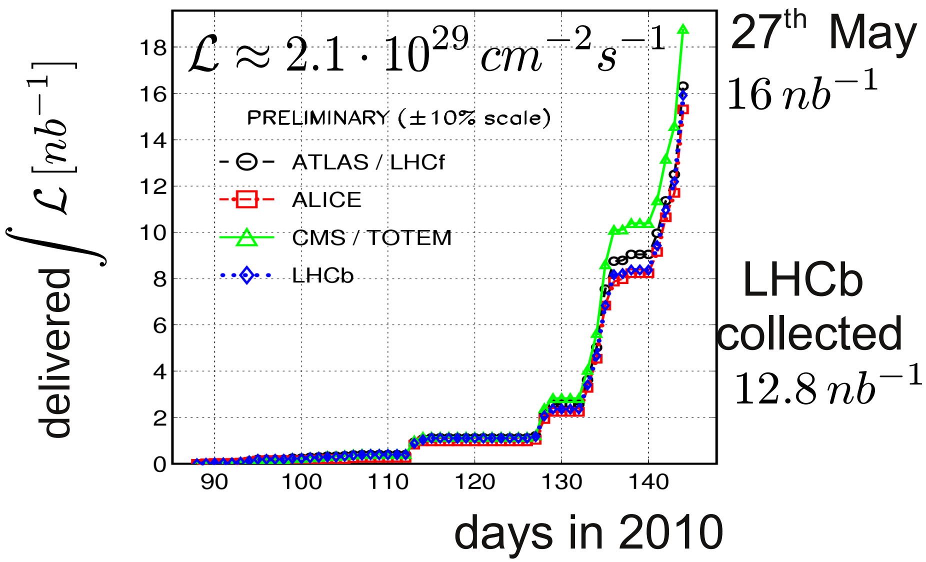




Run 2010 / 2011

➢ LHC startup in 2010

- E_{CM} = 14 TeV → E_{CM} = 7 TeV



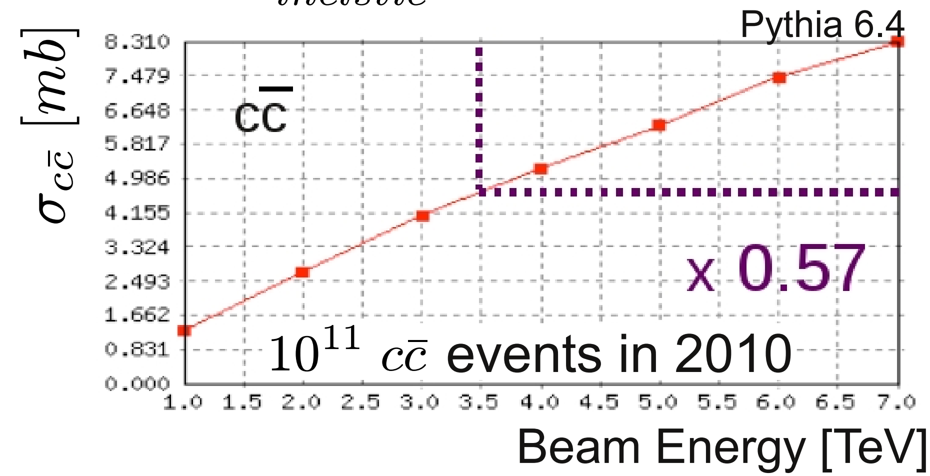
- 2010 up to $\mathcal{L} \approx 10^{31}\, cm^{-2} s^{-1}$
- $\int \mathcal{L} \approx 1\, pb^{-1}$ ICHEP 2010

  $\approx 100\, pb^{-1}$ end of 2010

➢ Expectations for 2011

- Cross section

14 TeV: $\sigma_{inelstic} \approx 100\, mb$

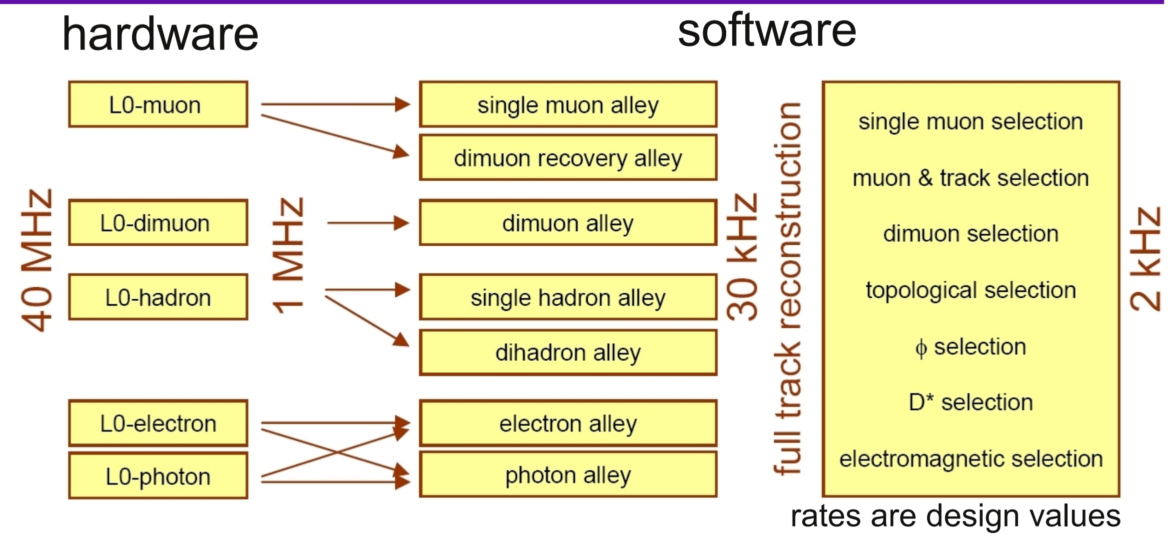


- In 2011 $\mathcal{L}_{LHCb} \approx 2 \cdot 10^{32}\, cm^{-2} s^{-1}$
- $\int_{2011} \mathcal{L} \approx 1\, fb^{-1}$ small reduction in statistical precision
- LHCb should reach nominal physics performance in 2011

Trigger Overview

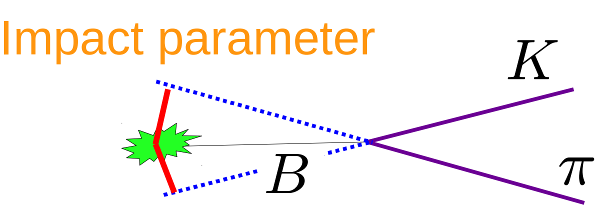
➢ Hardware Trigger (L0) based on VELO, Calorimeter and Muonsystem

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

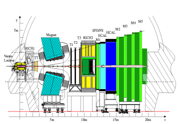


➢ Two level software trigger based on partly / fully reconstructed objects fully reconstructed objects with all detector information

- 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 signiture



➢ All thresholds are optimized for B selection prompt D production: $\epsilon_{prompt\ D} \approx 10\%$ $\rightarrow$ still a large sample of D



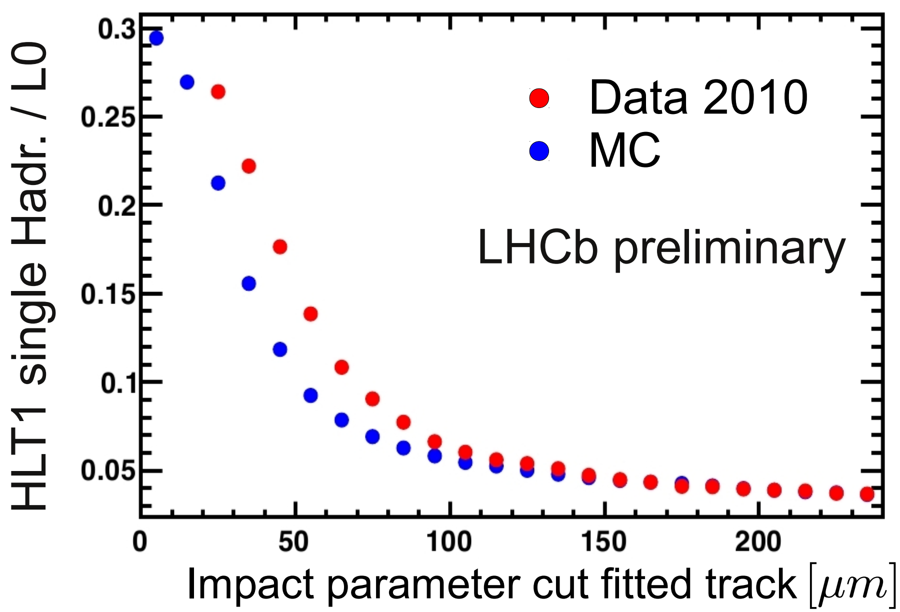
Trigger - Run 2010 / 2011

➢ Trigger schemes

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

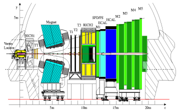
Software single hadron trigger fraction

Max. L0 rate reached: $L0^{max}_{beam} \approx 13kHz$



The initally lower rate allows for lower trigger thresholds

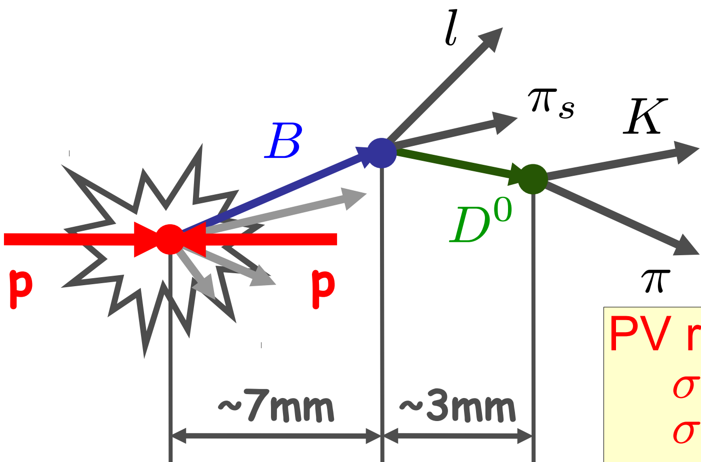
$\rightarrow$ big opportunity for c-physics

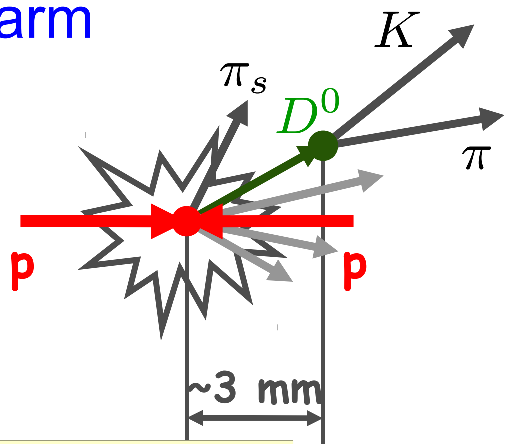


Charm Production at LHCb

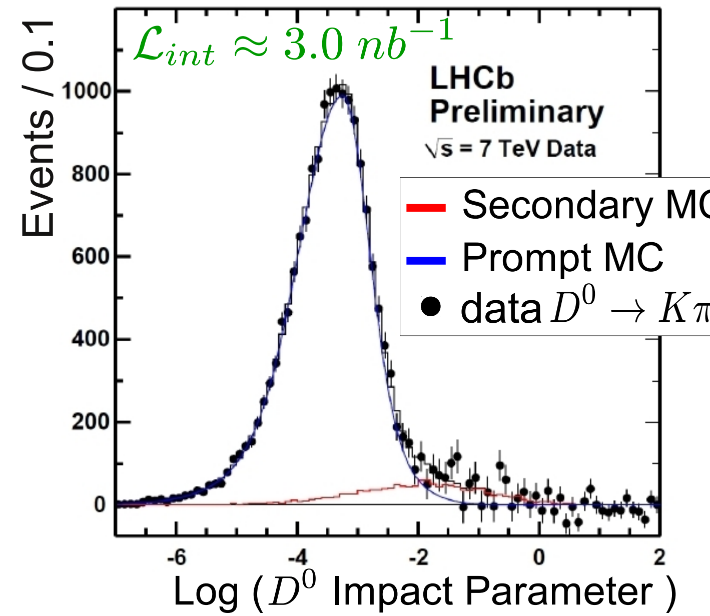
- Prompt and secondary charm

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

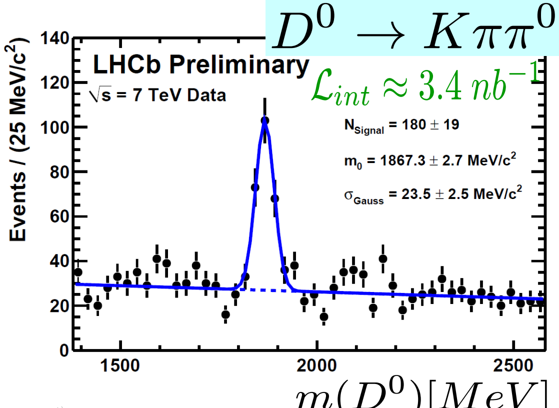


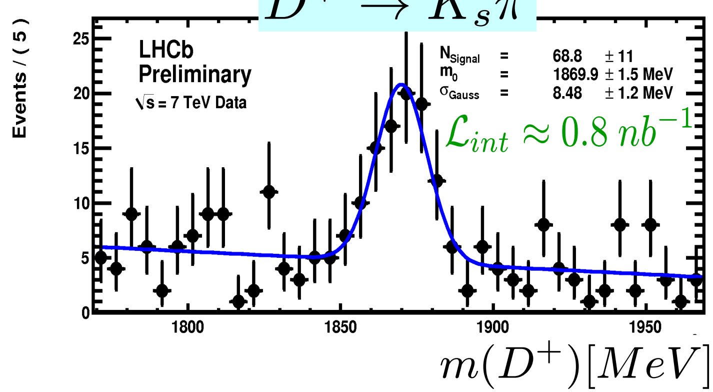


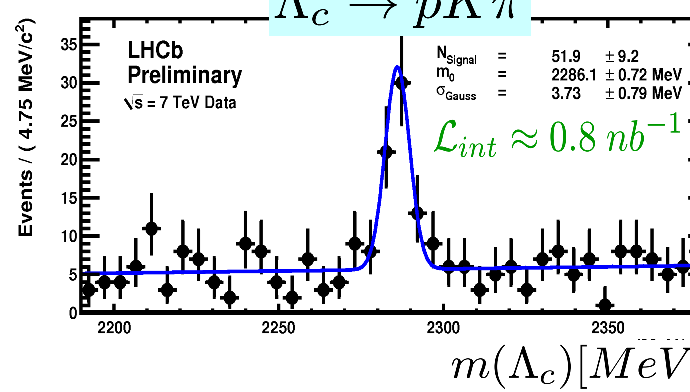
PV resolution data (MC)
$\sigma_x = 16\ \ (12)\ \mu m$
$\sigma_y = 15\ \ (11)\ \mu m$
$\sigma_z = 91\ \ (57)\ \mu m$



- Open charm signals in minimum bias data 2010

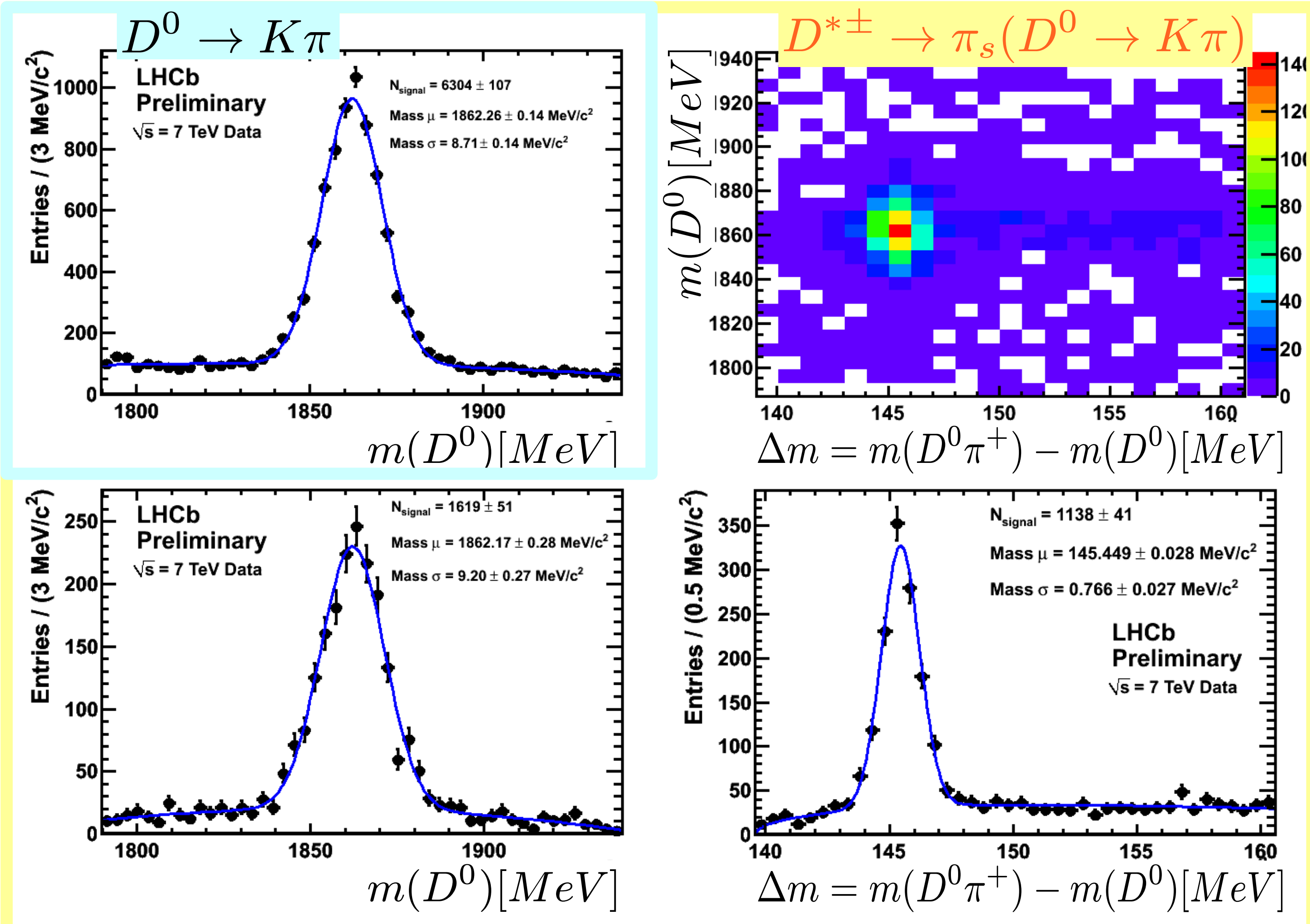






$D^0 \to K\pi$ Decays

- Untagged and tagged D^0 mass spectra



- $\int \mathcal{L} \approx 2.7\ nb^{-1}$
- $m_{D^0}, \Delta m$ compatible with PDG
- Expected events in $\int \mathcal{L} \approx 100\ pb^{-1}$:

$$N_{100\ pb^{-1}} \approx N_{signal} \cdot f_{trigger}$$
$$f_{trigger} \approx 0.4$$

tagged: $\approx 17 \cdot 10^6$

untagged: $\approx 93 \cdot 10^6$

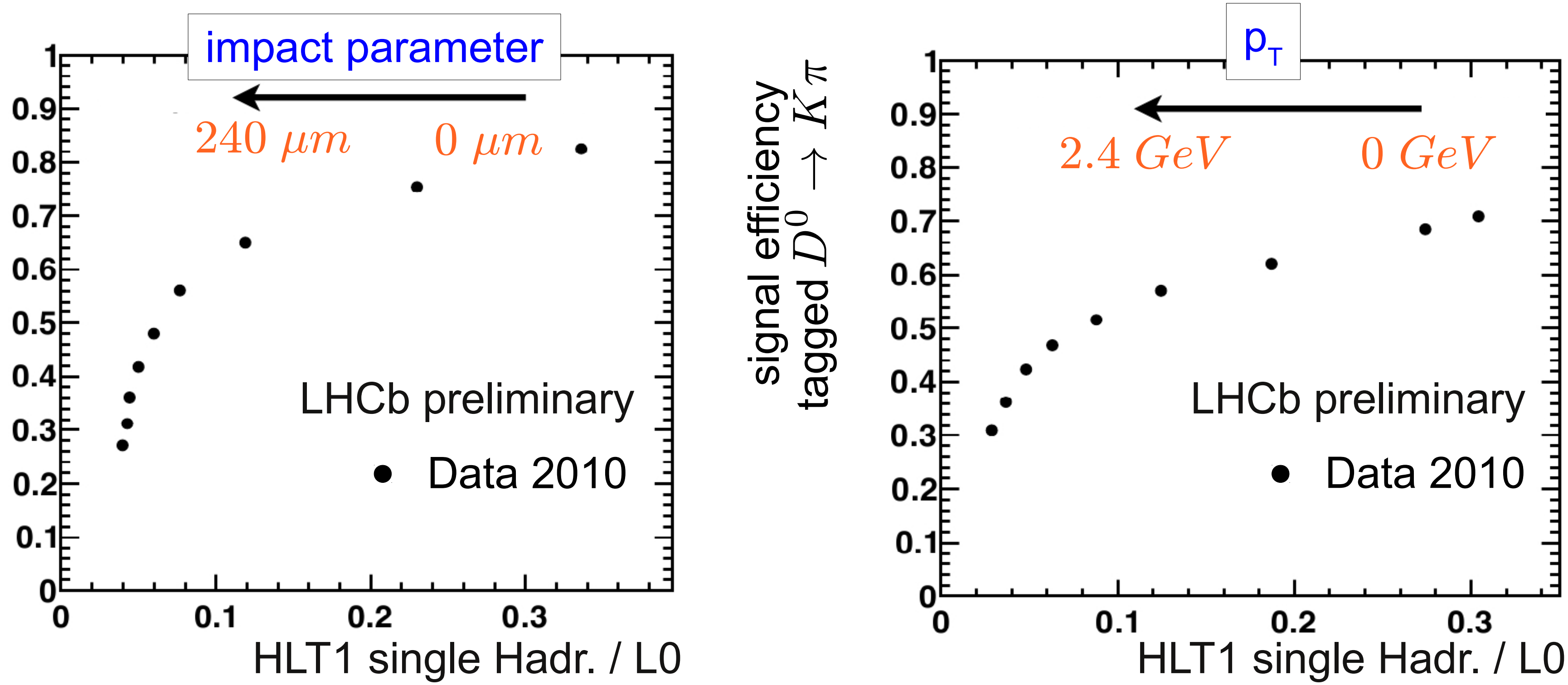
Trigger $- D^0 \rightarrow K\pi$

- 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

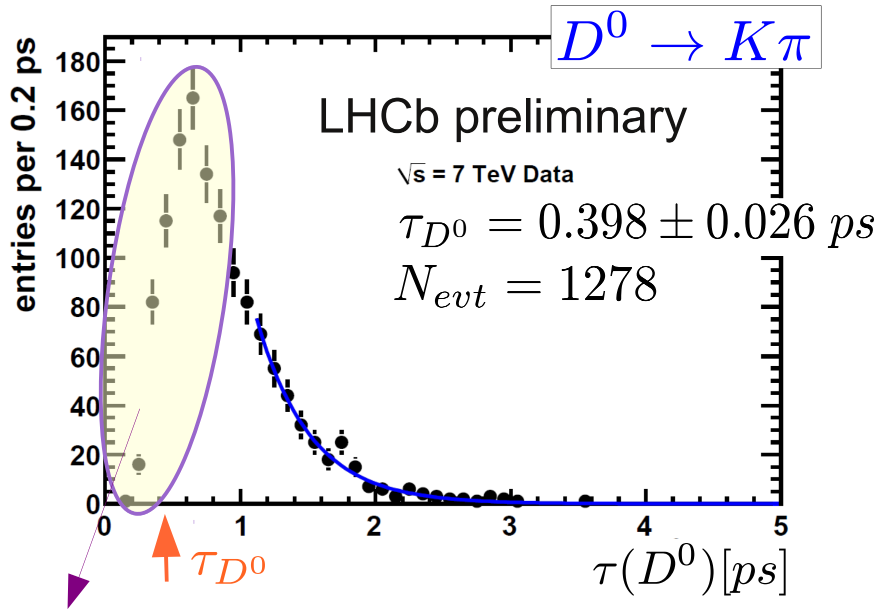
  $$\epsilon^{data}_{L0*HLT1} = 60 \pm 4\%$$

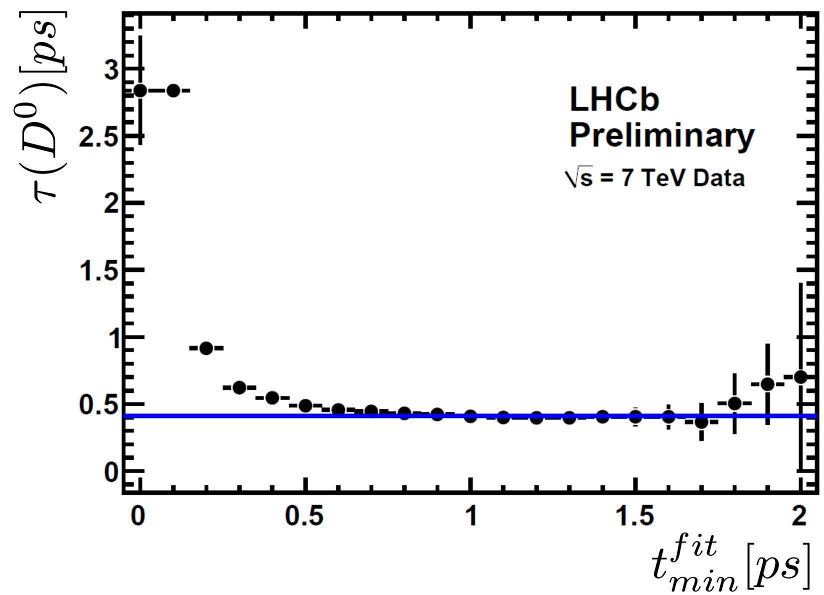
- p_T and impact parameter dependence of the software Trigger



D^0 Lifetime

- Estimate of the D^0 lifetime in untagged decays





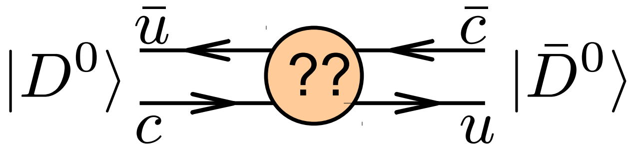
lifetime acceptance due to selection and software trigger

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

$\sigma_t \approx 0.040\, ps$ LHCb: $\frac{\sigma_t}{\tau_{D^0}} \approx 1/10$ *BABAR:* $\frac{\sigma_t}{\tau_{D^0}} \approx 1/2$

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:

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

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

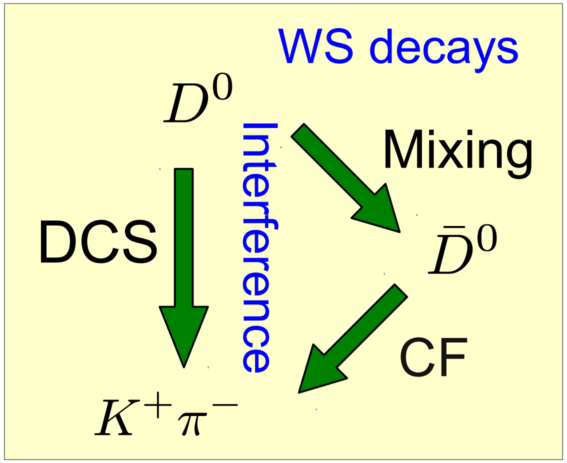
Time Evolution in $D^0 \to K\pi$ Decays

- Event classes - flavour tagging at production and decay time

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

Mixing: $D^{*+} \to \pi_s^+ D^0 \to \bar{D}^0 \to \pi^- K^+$ — 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 ($D^0 \to K\pi$)

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

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

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

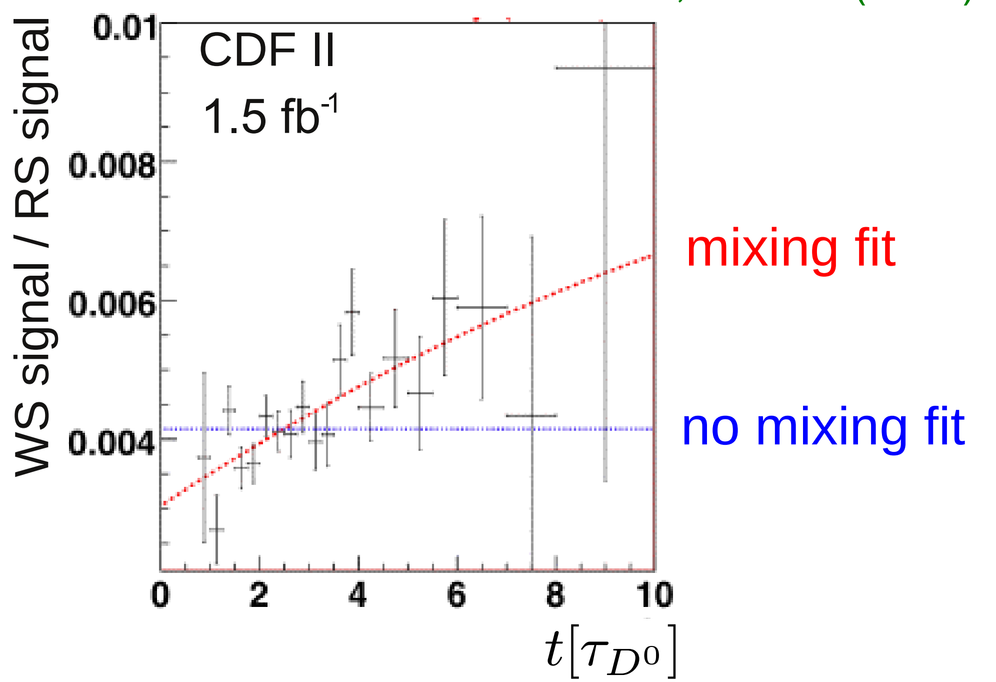
CDF approach

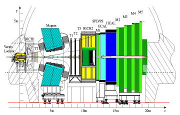
- Measure the Number of WS and RS D^0 decays in bins of the decay time

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

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

PRL100, 121802 (2008)





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

PRL 98, 211802 (2007) — 3.9 σ

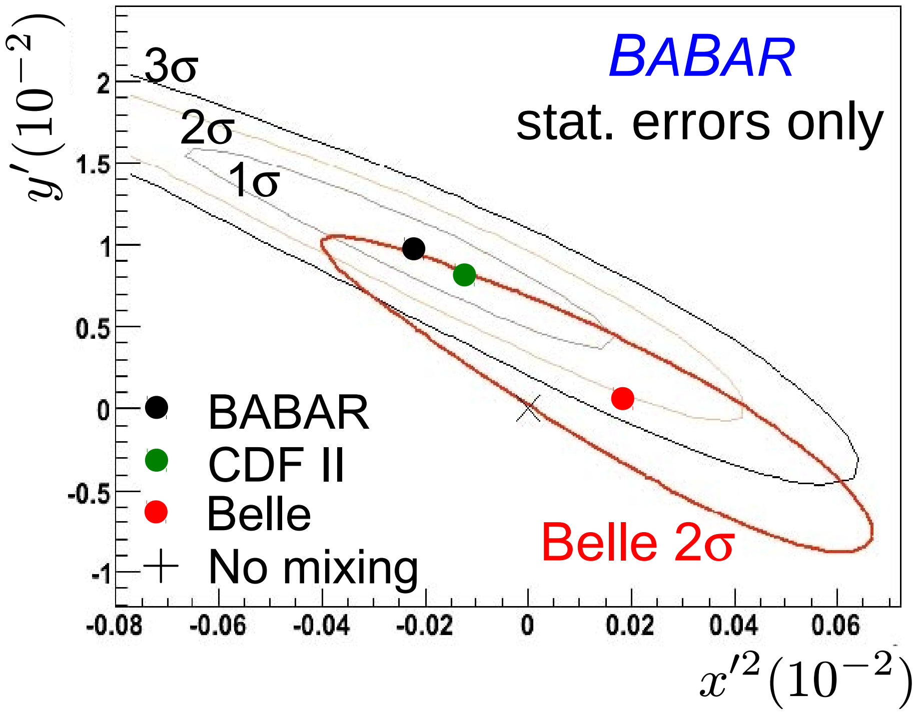
$$R_D = (0.303 \pm 0.016 \pm 0.01)\%$$
$$y' = (0.97 \pm 0.44 \pm 0.31)\%$$
$$x'^2 = (-0.022 \pm 0.03 \pm 0.021)\%$$

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

$$N_{RS} \approx 17 \cdot 10^6$$
$$N_{WS} \approx 60 \cdot 10^3$$

factor 10 more than *BABAR*

Measurement of y_{CP} - Introduction

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

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

$\tau^{\pm}$: 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

$$\Delta Y = \frac{\tau^0 A_\tau}{\tau}$$

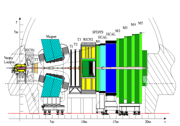
with

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

$\Delta Y \neq 0 \;\Rightarrow$ CP violation in D^0-$\bar{D}^0$ mixing

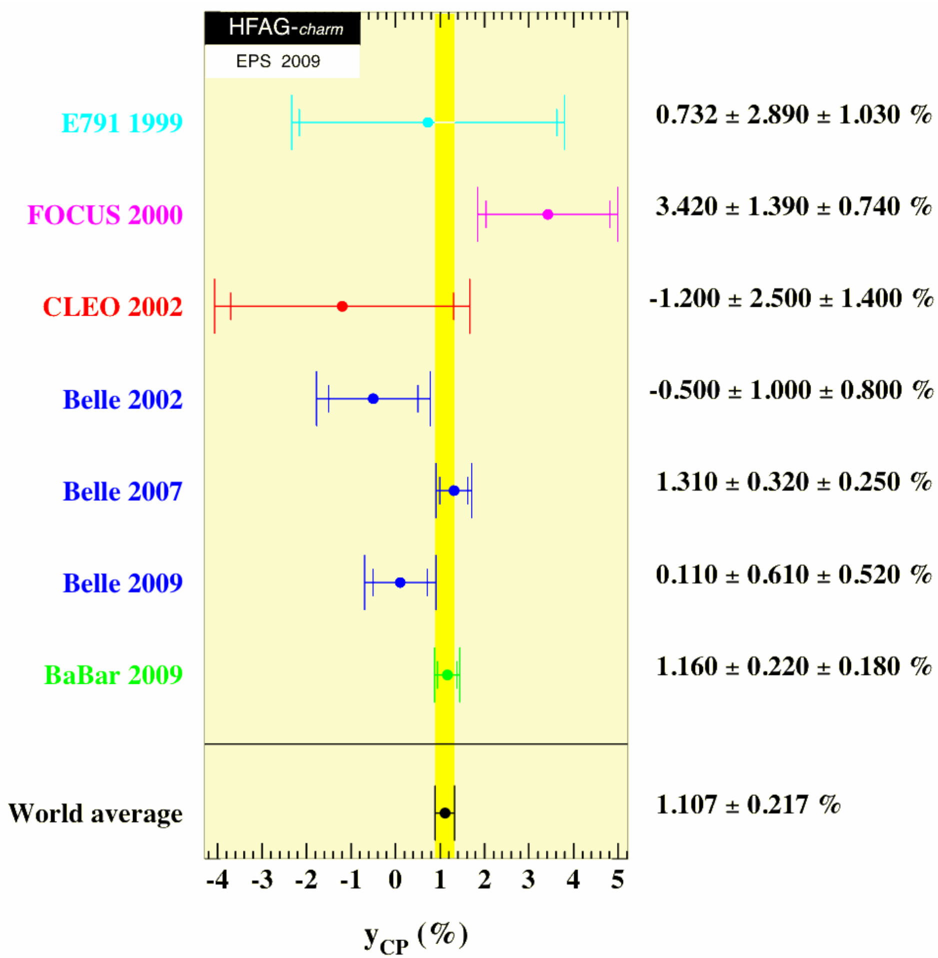
CP violation in interf. between mixing and decay

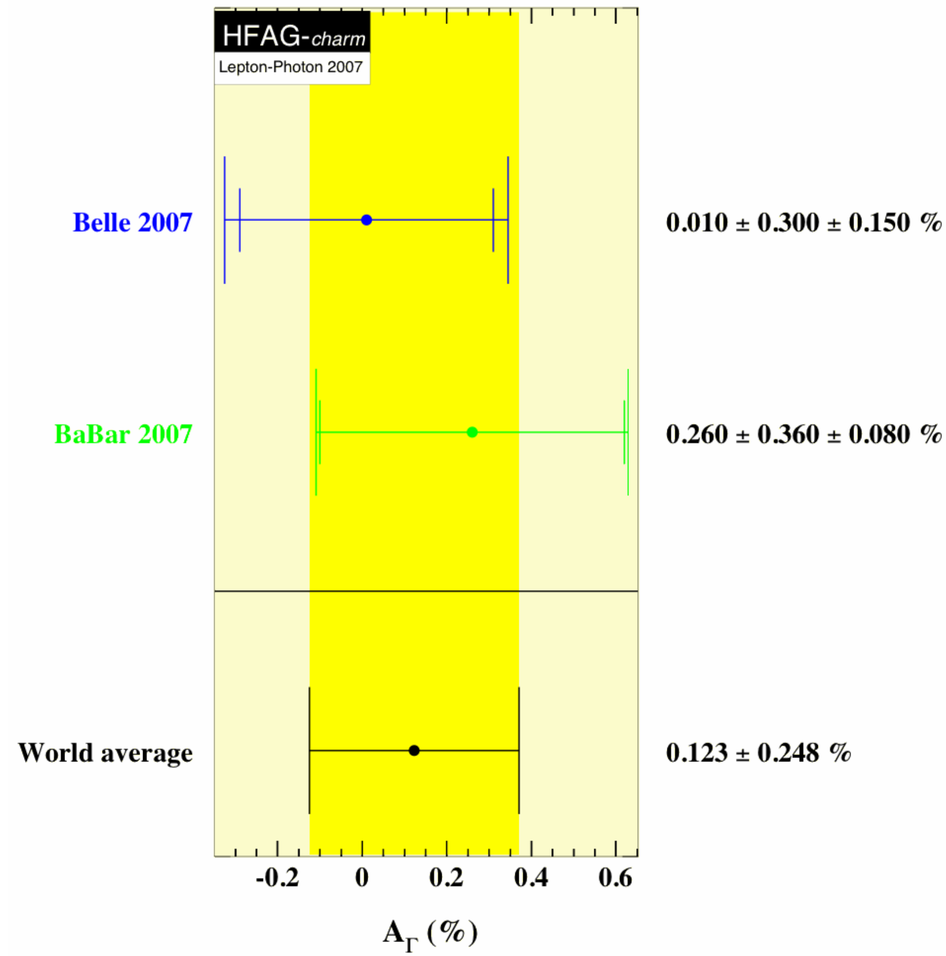
$y_{CP} = y \;\Leftarrow$ CP conservation



Experimental Results – y_{CP}

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



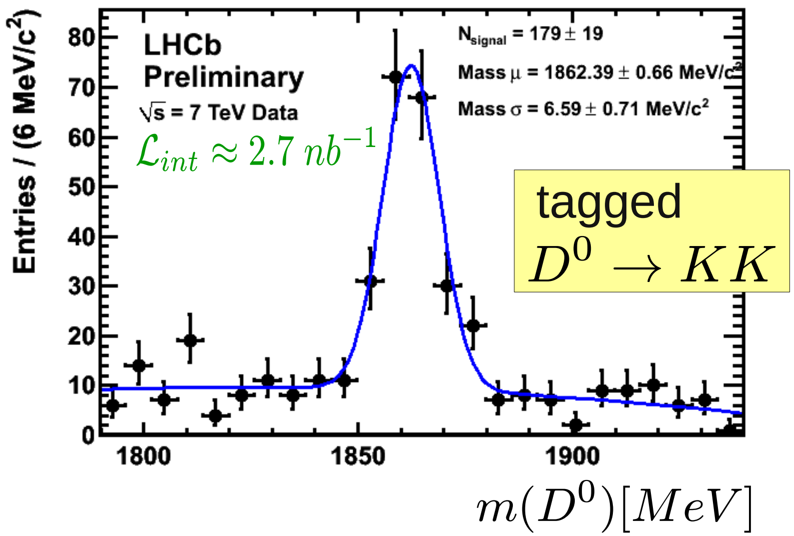


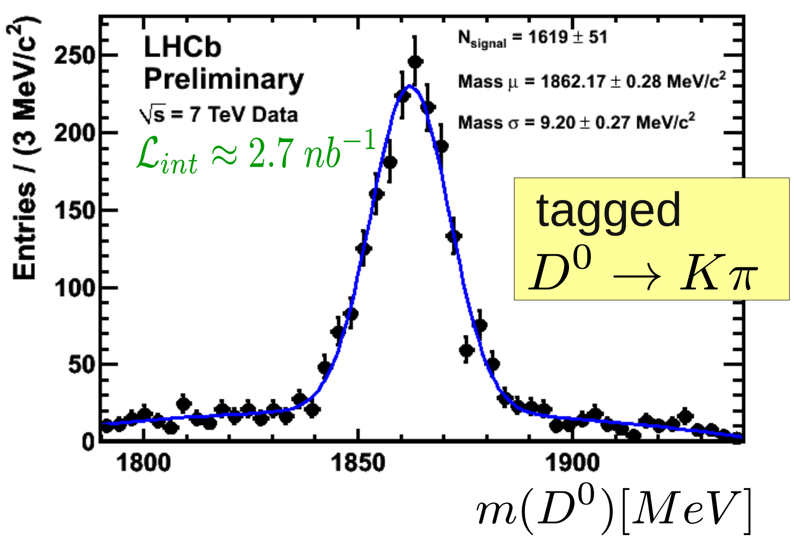
$$y_{CP} = (1.107 \pm 0.217)\%$$

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

LHCb – Towards y_{CP} and A_Γ

➢ Compare $D^0 \to KK$, $D^0 \to \pi\pi$ and $D^0 \to K\pi$ 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 $\int \mathcal{L} \approx 100\ pb^{-1}$:

$$N_{100\ pb^{-1}}(D^0 \to K\pi) \approx 17 \cdot 10^6$$

$$N_{100\ pb^{-1}}(D^0 \to KK) \approx 1.3 \cdot 10^6$$

factor 10 more data than the *BABAR* analysis

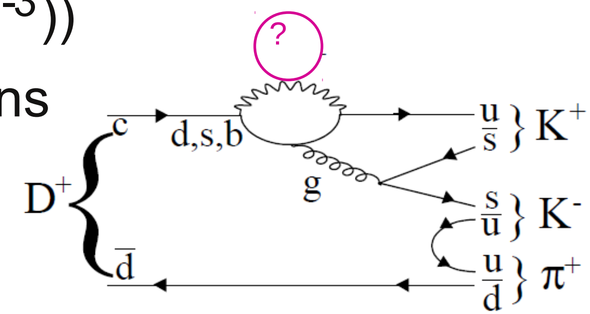
B. Aubert et al., Phys. Rev. D80 071103 (2009)

Direct CP Violation in SCS Decays

- Single Cabbibo suppressed charm decays (SCS)

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

- CPV in SM is CKM and loop suppressed (CPV < O (10^{-3}))
- SCS decays are sensitive to CPV in $c \to uq\bar{q}$ transitions
  Contributions due to supersymmetric $\Delta C = 1$ QCD penguins could enter.
  - $\to$ measurement of large CPV would be a sign of NP



- Search for CPV in SCS tagged $D^0 \to \pi^+\pi^-\pi^0$, $D^0 \to K^+K^-\pi^0$ by *BABAR*
  - $\to$ results are in accord with SM predictions (few %)

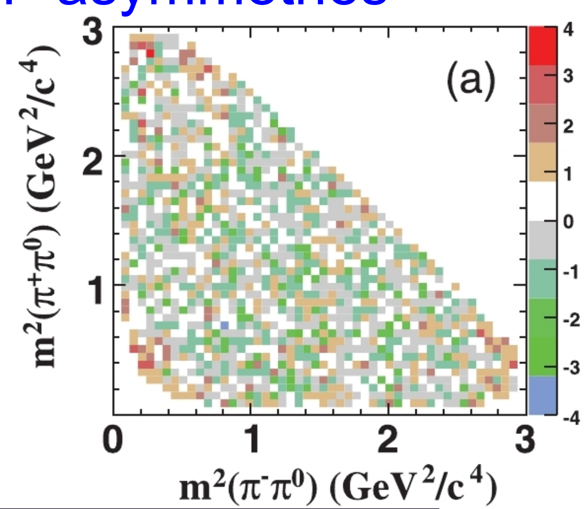
B. Aubert et al.
Phys. Rev. D78 051102 (2008)

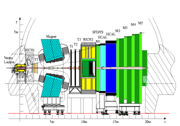
- Model independent Dalitz Plot analysis to look for CP asymmetries

Miranda procedure arXiv 0905.4233
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





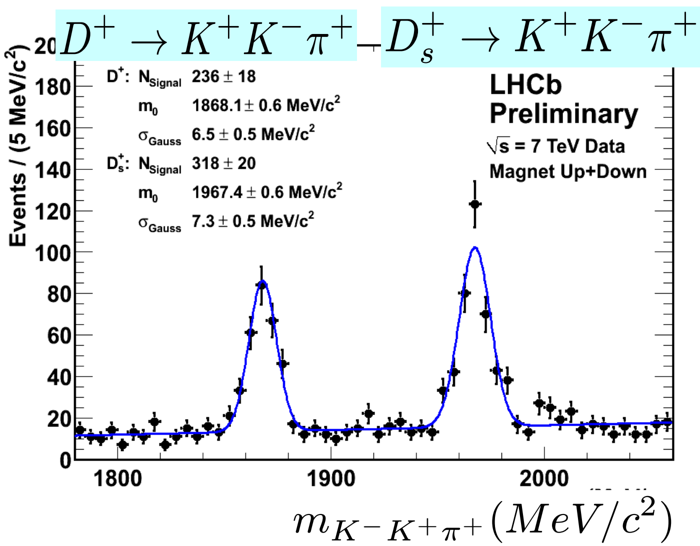
LHCb - Direct CP Violation Search

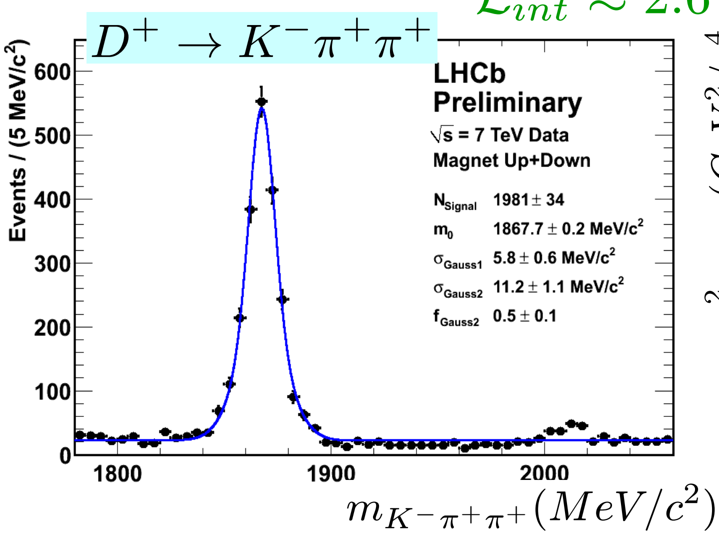
➤ Dalitz analysis of the SCS decay $D^+ \to K^+K^-\pi^+$

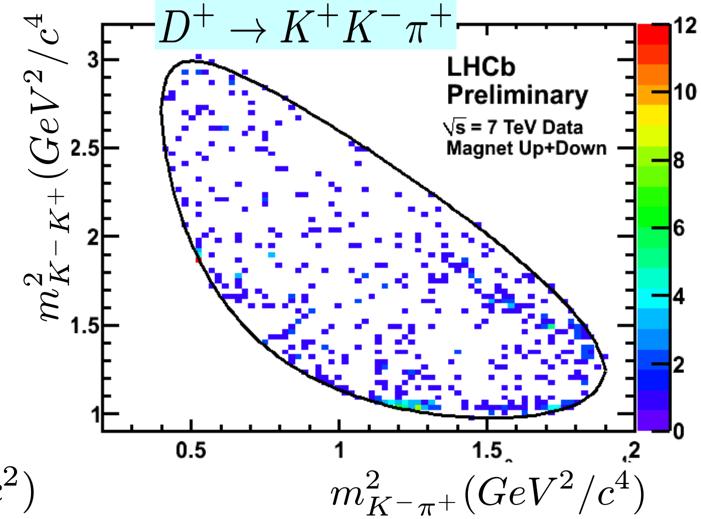
Time integrated and model independent search for local CP asymmetries in bins of the Dalitz plane.

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

$\mathcal{L}_{int} \approx 2.6\ nb^{-1}$



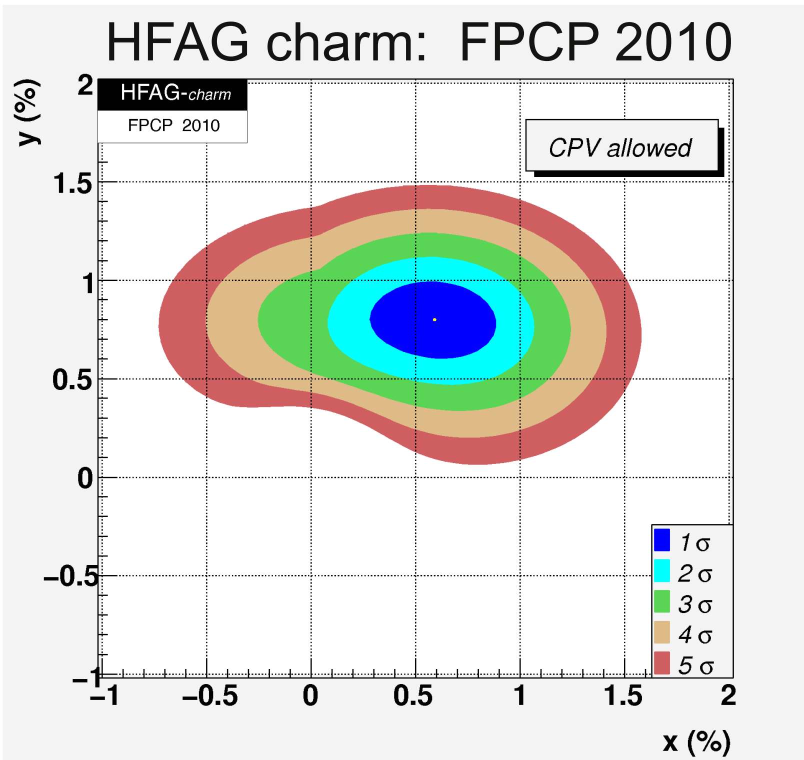


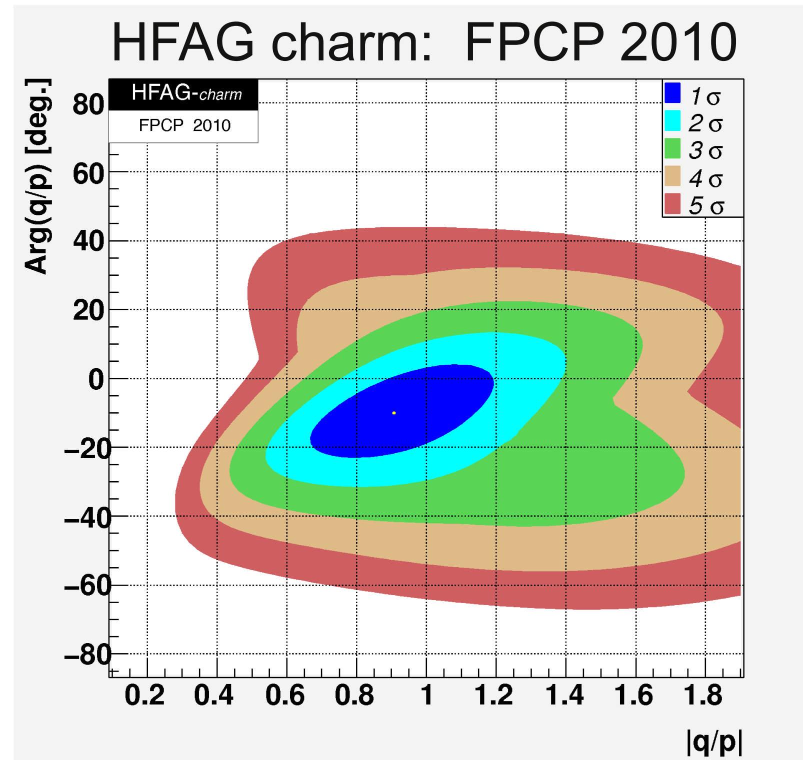


- Expect in $\int \mathcal{L} \approx 100\ pb^{-1}$ (end of 2010) a sample of several million events

Averaged Mixing Parameters

- Mixing parameter as combined by the HFAG charm group





$$y = (0.80 \pm 0.13)\%$$
$$x = (0.59 \pm 0.20)\%$$

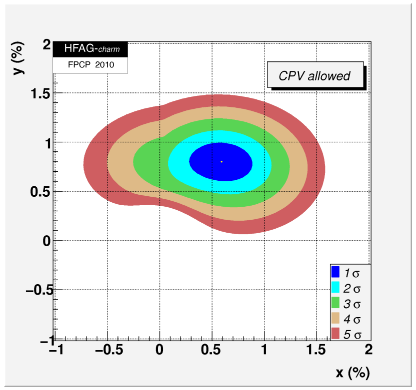
$$|q/p| = (0.91^{+0.19}_{-0.16})\%$$
$$\phi = (-10.0^{+9.3}_{-8.7})^o$$

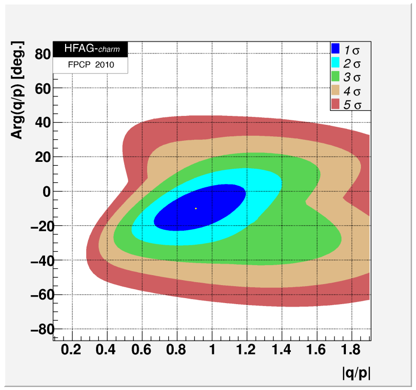
Exclude no mixing case at 10.2 σ

Fully compatible with the CP conservation

Summary

- LHCb has a large potential for charm physics and profits here from the LHC 2010 run conditions
- LHCb will soon be able to contribute to the charm sector of flavour physics, especially in



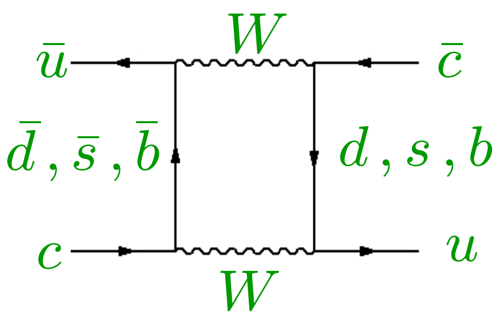


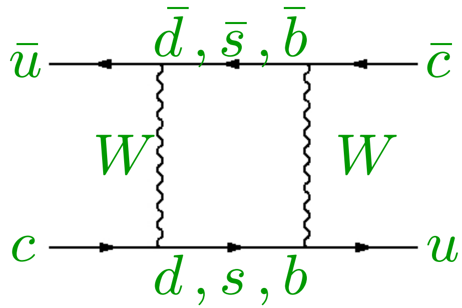
- Ongoing analyses which were not covered in this presentation
  - t-dependent Dalitz analysis in $D^0 \rightarrow K_s\pi^+\pi^-$, $K_sK^+K^-$
  - T violation in $D^0 \rightarrow K^+K^-\pi^+\pi^-$

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





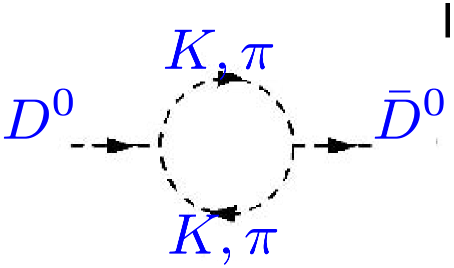
  - ❖ Suppression by
    - GIM mechanism (d,s)

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

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

- Long distance contributions dominate

Numerical predictions lack in precision



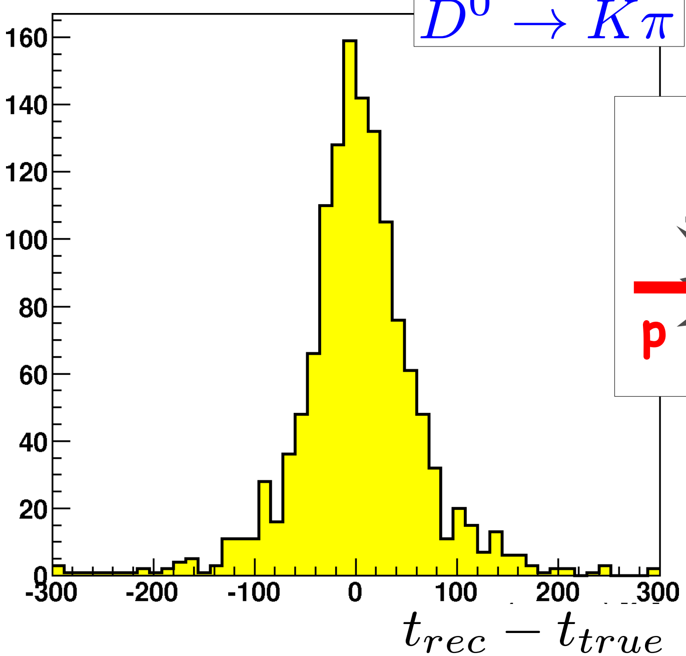
$x \approxeq O(10^{-2})$

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

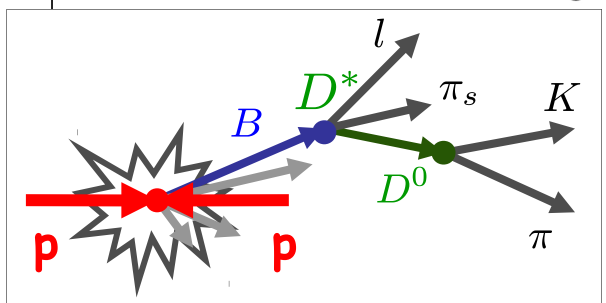
- New Physics
  - ❖ E.Golowich et al.: arXiv:0705.3650
    Which new physics model can yield sizeable values for x and y
  - ❖ CP violation in charm is small in SM
    Measurement of CPV: New Physics

LHCb - D^0 Lifetime Resolution in MC

- Time resolution
  For prompt charm
  use primary vertex for D^*

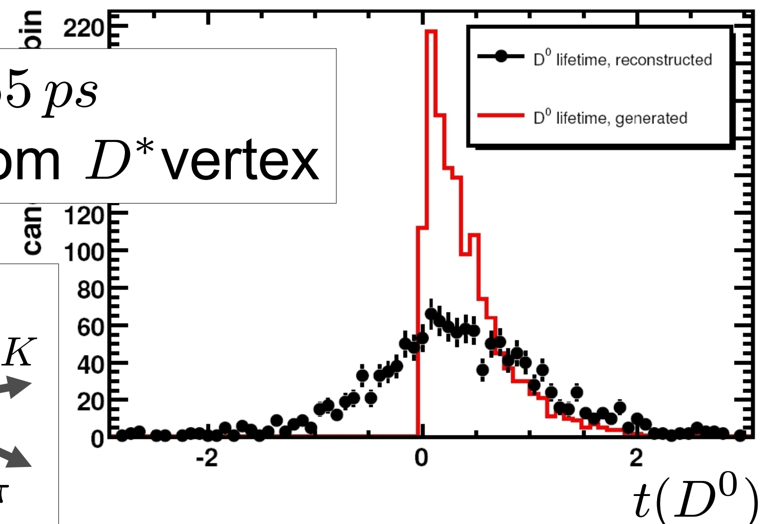


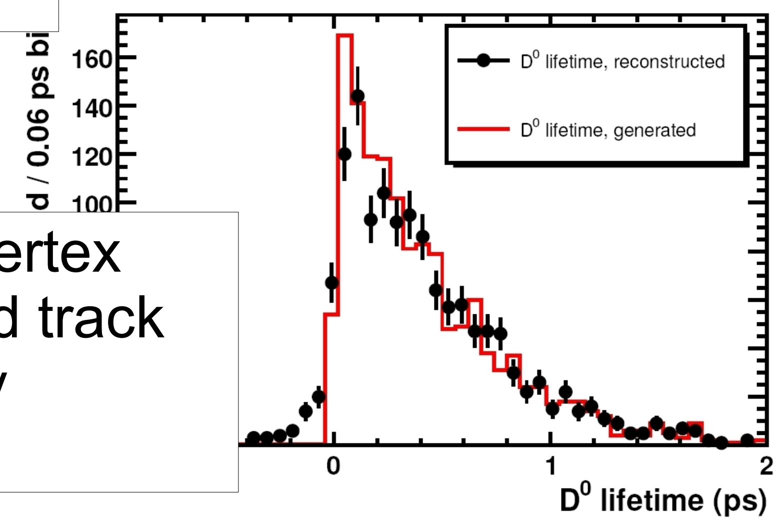
$\sigma_t \approx 0.040\, ps$



secondary charm

$\sigma_t \approx 0.465\, ps$
mainly from D^* vertex





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

Toy Simulation – WS $D^0 \to K\pi$

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

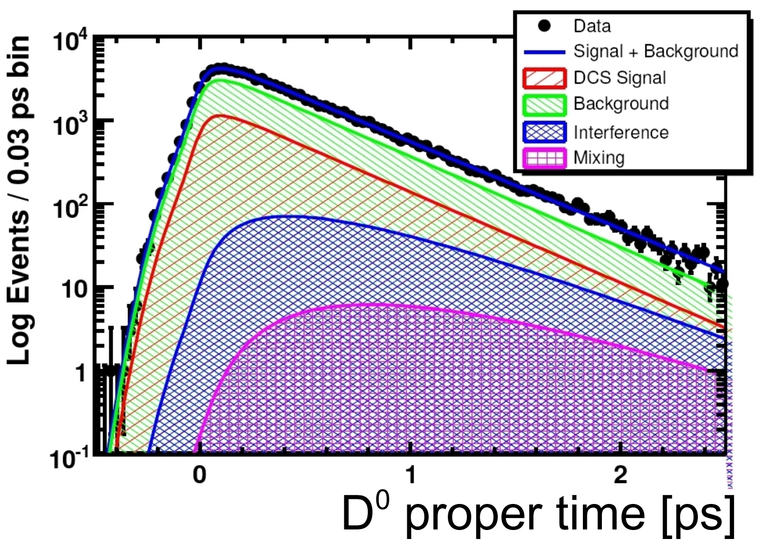
➢ ML fit of mixing parameters in the lifetime distribution of the WS data

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

$$+PDF_{bckgr.}(t;\tau_{bck},t0,\sigma)$$

- Decay time distribution

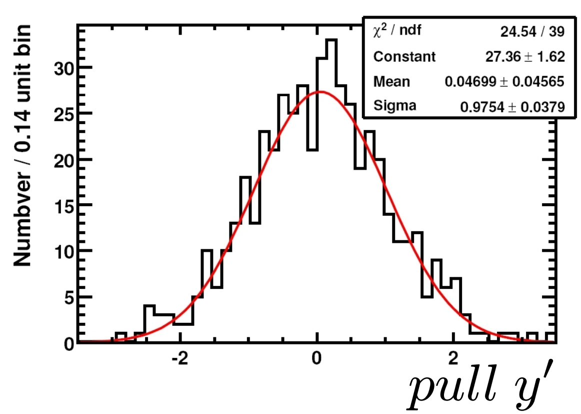
$Bckgr/Signal = 2.56$

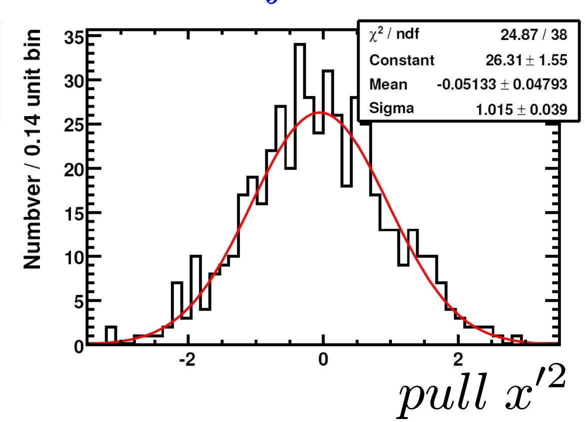


- Mixing parameter

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

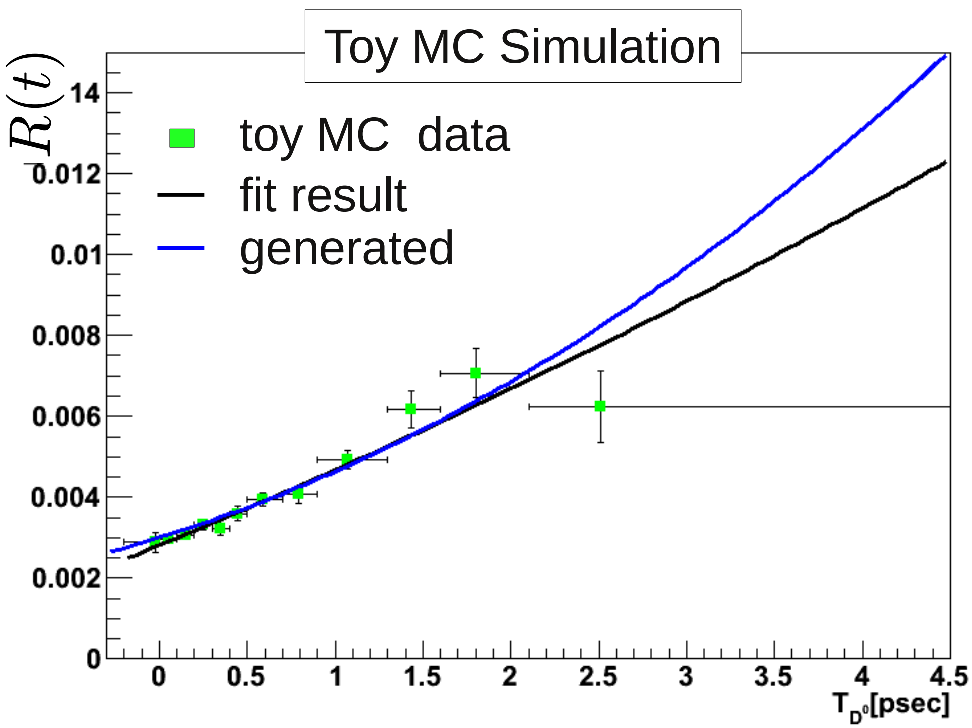
- Pull distributions 500 toy sets, each $\int \mathcal{L} \approx 10\, fb^{-1}$





Mixing Parameter Determination

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



- Simulate decay time distributions of of WS and RS decays

  $\sigma_t = ٠.٠٤٠\ ps \quad \tau_{D^\cdot} = ٠.٤١\ ps$

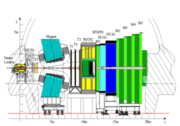
  $x = ٠.٠١ \quad y = ٠.٠١ \quad R_D = ٠.٠٠٣$

- 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

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

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



Sensitivity – D^0 Mixing Parameters

LHCb-2007- 049

- Summary from selection

$$Bckgr/Signal = 2.56$$

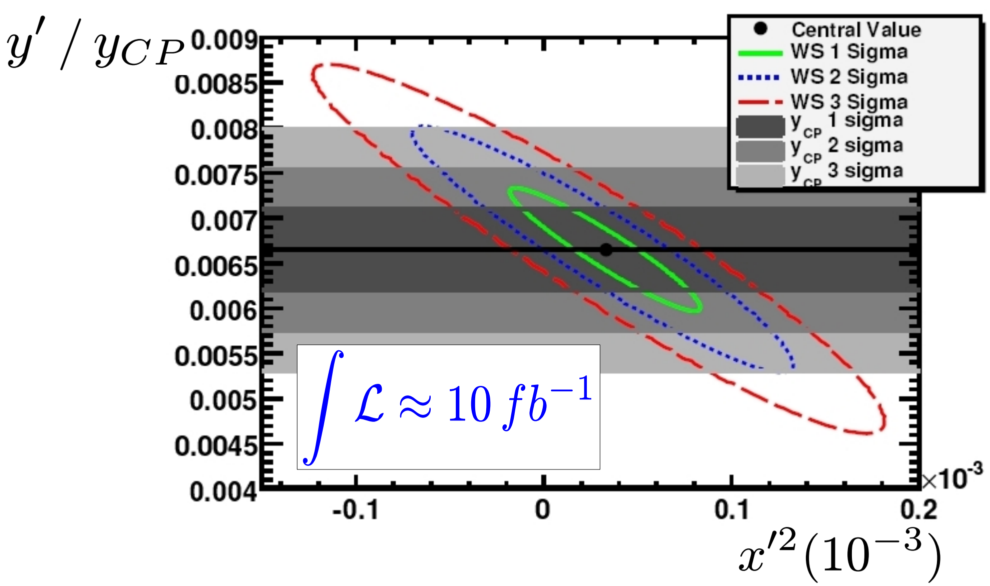
$$N^{WS}_{Signal} = 46500 \pm 2200/fb^{-1}$$

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

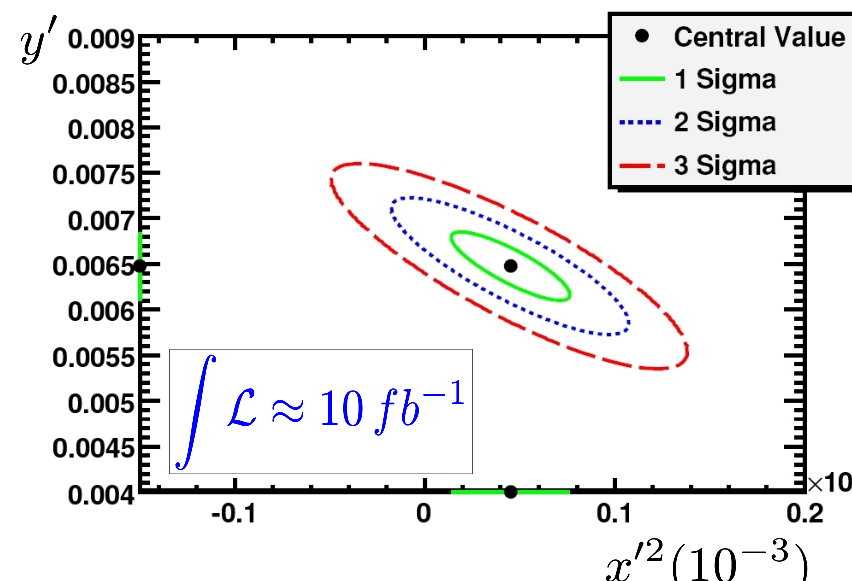
- Statistical errors

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

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



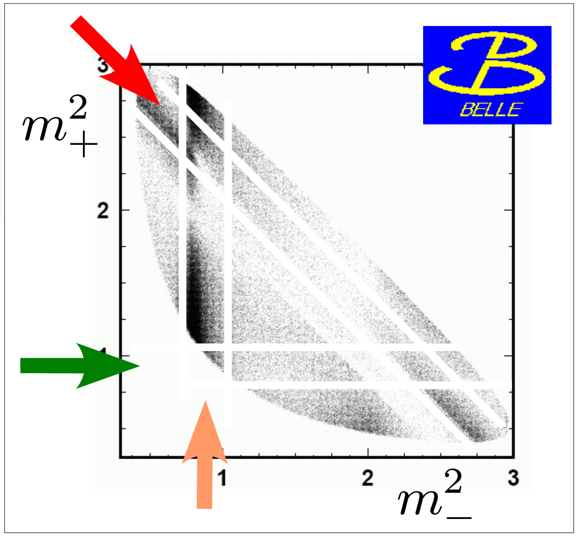
- Sensitivity - combining likelihoods



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: $D^0 \to K_s^0\rho^0$



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

- Time dependence

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

decay amplitude

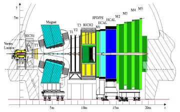
$\lambda_{1,2} = f(x, y)$

- ❖ The decay rates contain functions of x and y

- Perform unbinned max. likelihood fit in the signal region to (m_+^2, m_-^2, t)

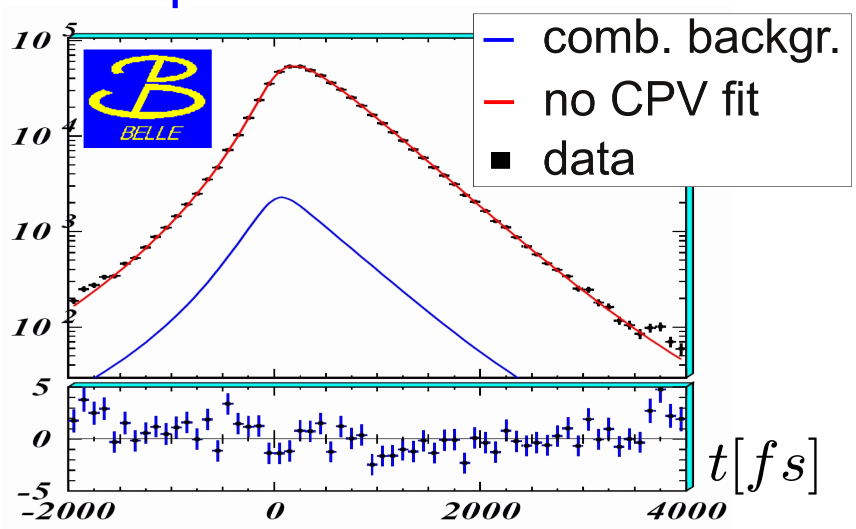
  $\Rightarrow$ extract relative amplitudes and relative phases

  $\Rightarrow$ x, y and τ_{D^0}



Belle – t Dep. Dalitz Analysis Results

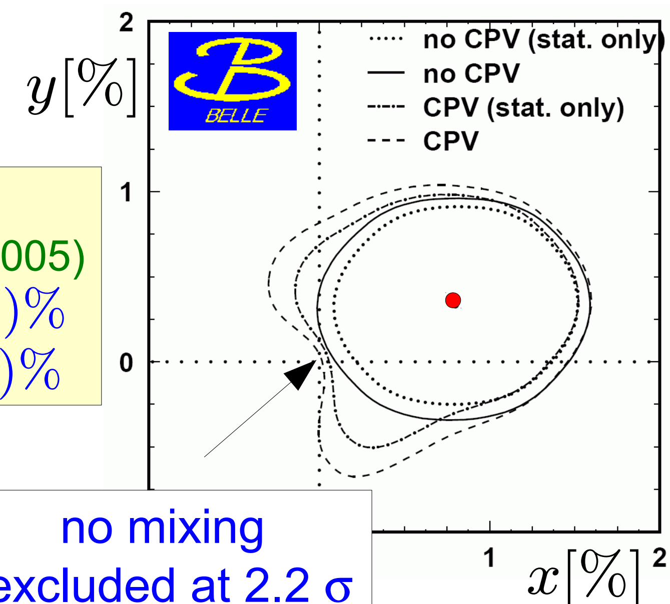
- Proper time fit results



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

- Mixing parameter fit results

CLEO 9 fb^{-1} :
PRD 72, 012001 (2005)
$(-4.7 < x < 8.6)\%$
$(-6.1 < y < 3.5)\%$



no mixing
excluded at 2.2 σ

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

$$x = (0.80 \pm 0.29^{+0.09+0.10}_{-0.07-0.14})\%$$
$$y = (0.33 \pm 0.24^{+0.08+0.06}_{-0.12-0.08})\%$$

- 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 :

$$|q/p| = 0.86^{+0.30+0.06}_{-0.29-0.03} \pm 0.08$$
$$arg\,(q/p)[^\circ] = -14^{+16+5+2}_{-18-3-4}$$

no CP violation