Time Dependent Measurements of D^0 Decays at LHCb

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on behalf of the LHCb Collaboration

Workshop on Charm physics at threshold
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Content

Motivation

Charm@LHCb

Measurements using 2010 data:
  - y_{CP} and A_Γ
  - wrong sign $D^0 \to K\pi$ decays

Prospects for 2011

Motivation

Measurements of mixing and (possible) $\cancel{CP}$ parameters in the charm sector provide a complementary way to search for New Physics, as

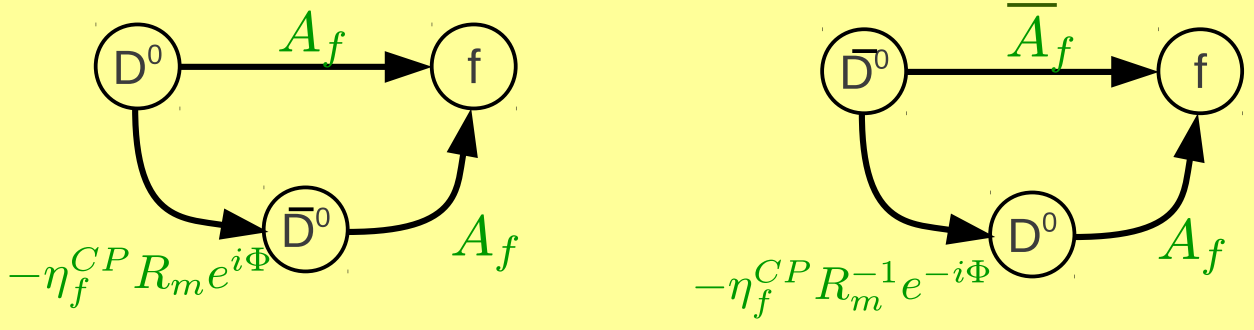
- they are sensitive to the up sector.
- due to the dominance of the first 2 generations in the SM CP is conserved to first order.

Contributions to CP violation may come from:

- **Mixing:** different rates for $D^0 \rightarrow \overline{D}{}^0$ and $\overline{D}{}^0 \rightarrow D^0$
- **Decay:** different amplitudes for a process and its charge conjugate
- **Interference between mixing and decay**

Time dependent measurements give valuable information to identify the sources for CPV in the charm sector

The $D^0 - \overline{D}^0$ system



Φ : Weak phase between mixing and decay

η_f^{CP} : $+(-)$for CP-even (odd) final states

Some definitons:

$$x = \frac{\Delta m_D}{\Gamma_D}, \quad y = \frac{\Delta\Gamma_D}{2\Gamma_D}$$

$$\lambda_f = \frac{q}{p}\frac{\overline{A}_f}{A_f}, \quad R_m = \left|\frac{q}{p}\right|$$

$$r_f = \frac{\overline{A}_f}{A_f}$$

Parametrization of CPV sources:

Direct CPV : $a_f^d = 2r_f \sin\Phi_f \sin\delta_f$

CPV from interference: $a^i = \eta_f^{CP}\frac{x}{2}(R_m + R_m^{-1})\sin\Phi$

CP violation in mixing: $a^m = -\eta_f^{CP}\frac{y}{2}(R_m - R_m^{-1})\cos\Phi$

(assuming $x, y, r_f \ll 1$)

Experimental access to mixing parameters

Measure time evolution of D^0 decay rates for different final states :

1. DCS $D^0 \to K^+\pi^-$ with respect to CF $D^0 \to K^-\pi^+$ allows to extract

$$\begin{aligned} x' &= x\cos\delta_{K\pi} + y\sin\delta_{K\pi} \\ y' &= -x\sin\delta_{K\pi} + y\cos\delta_{K\pi} \end{aligned}$$

$\delta_{K\pi}$: Strong phase for $D^0 \to K\pi$.

To extract x and y we need a precise measurement of $\delta_{K\pi}$.
This can be extracted from quantum correlations in the $D^0 - \overline{D}^0$ system.

Valuable input from BES III possible.

2. Time dependent Dalitz plot analysis of $D^0 \to K_s h^+ h^-$ gives direct access to x and y.

Experimental access to CPV parameters

1. Compare decay time of CP eigenstates f_{CP} relative to CP non-eigenstates f_{non-CP}:

$$y_{CP} = \frac{\Gamma(D^0 \to f_{CP})}{\Gamma(D^0 \to f_{non-CP})} - 1 = y \cos\Phi - \frac{1}{2} y R_M \sin\Phi$$

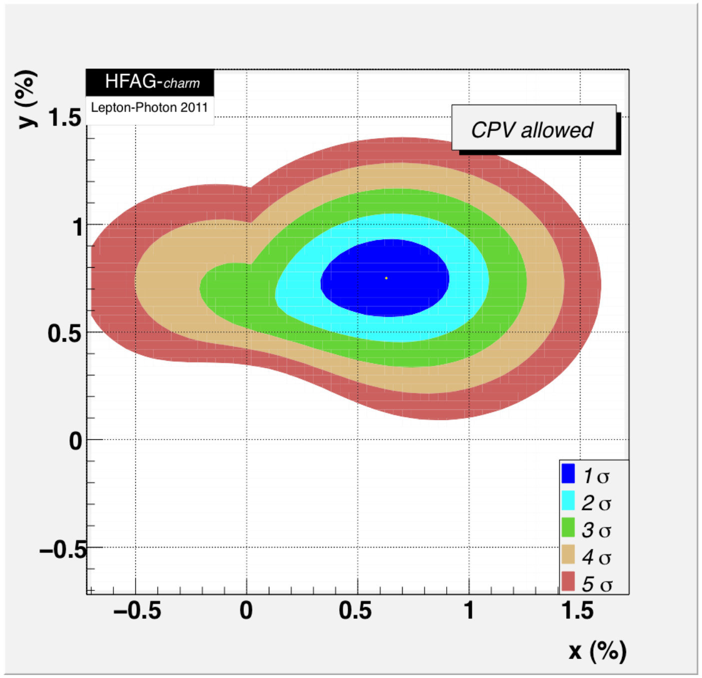
A measurement of $y_{CP} \neq y$ signals CP violation!

Possible for $D^0 \to KK/\pi\pi$ wrt. $D^0 \to K\pi$ and in time dependent Dalitz analysis of $D^0 \to K_s KK$

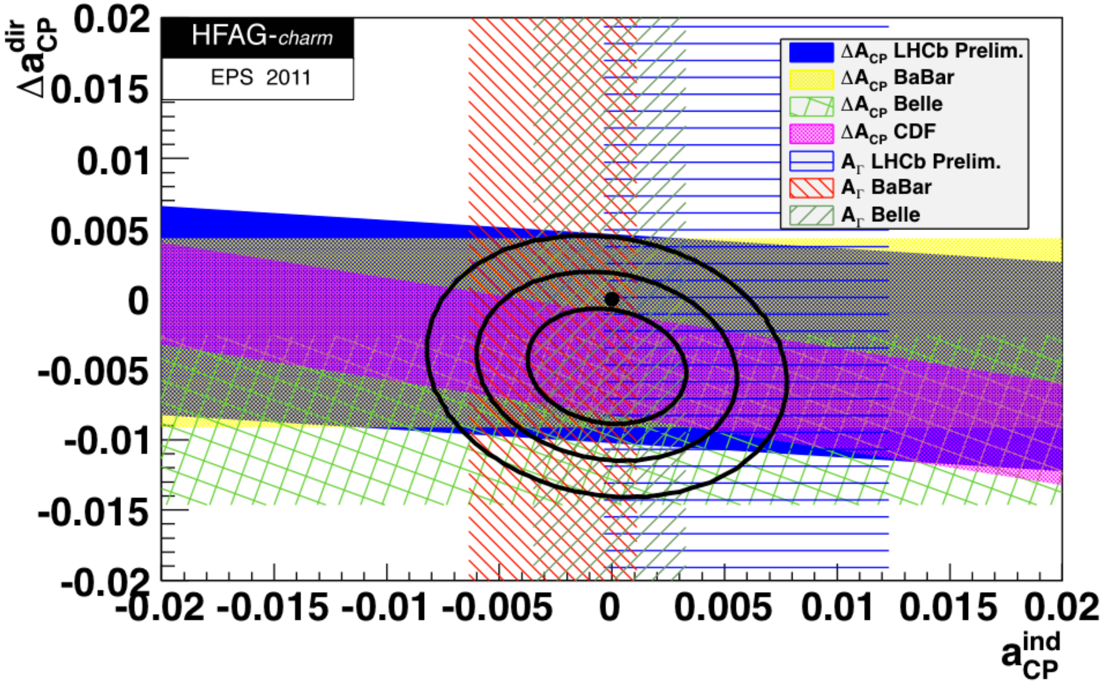
2. Compare decay rate evolution of D^0 and $\overline{D}^0$, e.g.

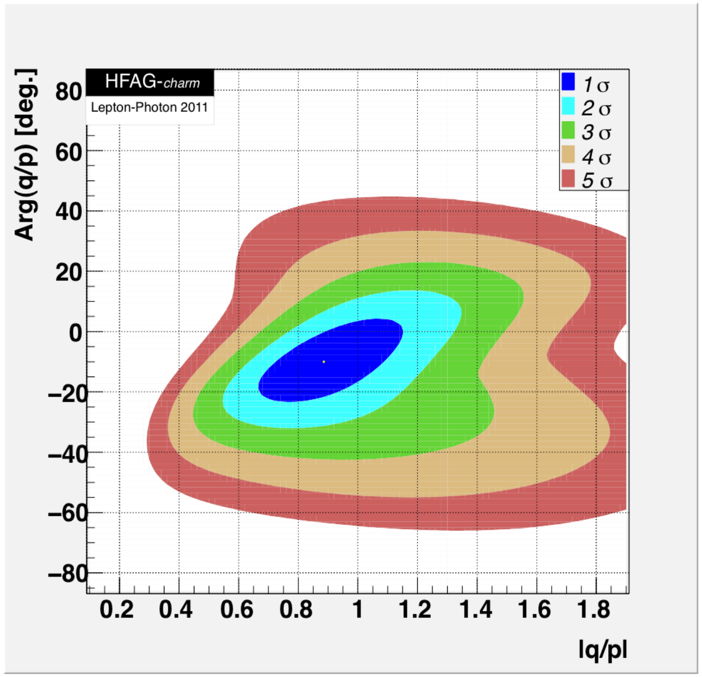
- $A_\Gamma = \frac{\Gamma_{D^0 \to f_{CP}} - \Gamma_{\overline{D}^0 \to f_{CP}}}{\Gamma_{D^0 \to f_{CP}} + \Gamma_{\overline{D}^0 \to f_{CP}}} = a_m + a_i$
- DCS $D^0 \to K^+\pi^-$ wrt. to the cc mode $\overline{D}^0 \to K^-\pi^+$

Experimental status



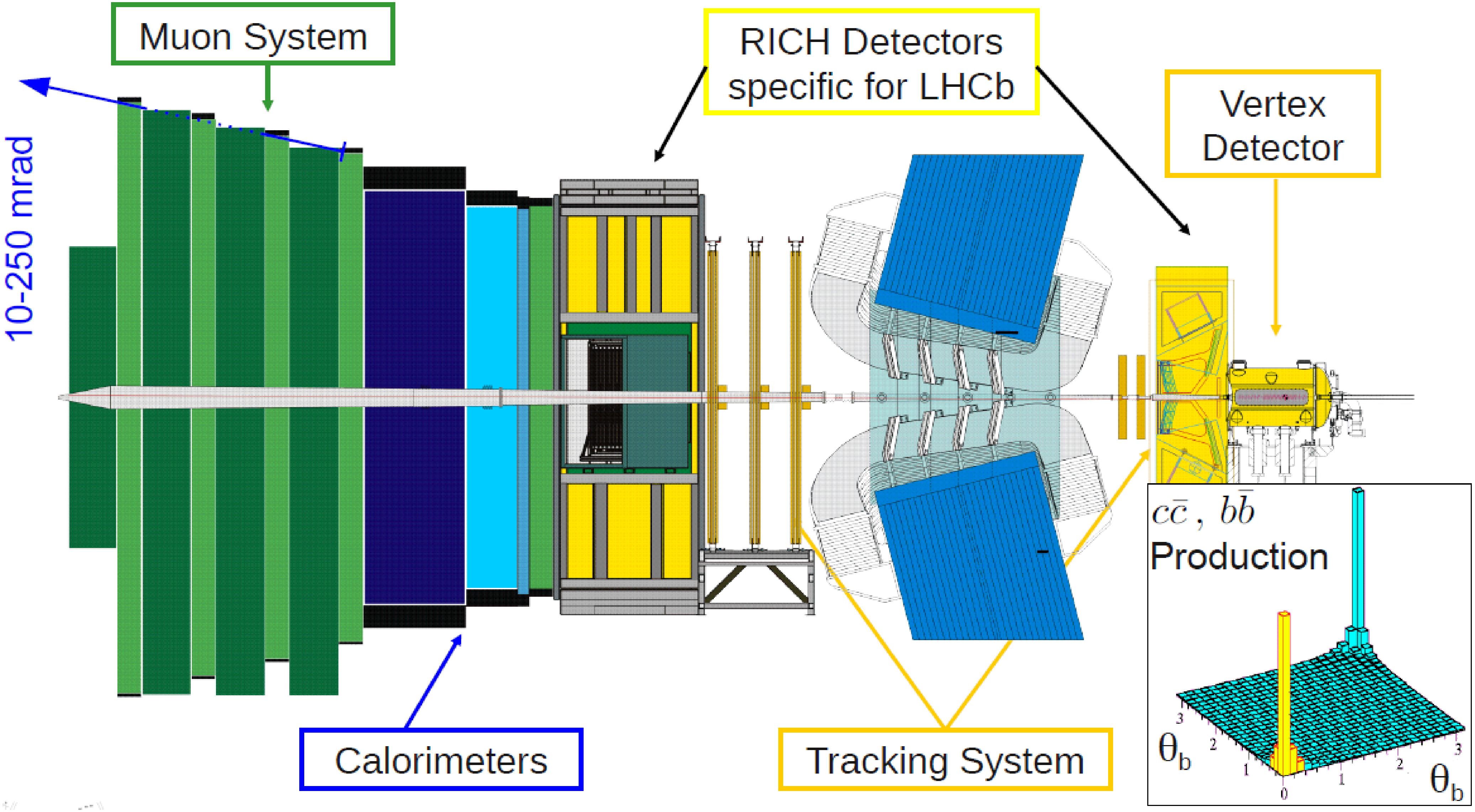
$$\Delta a_{CP}^{dir} = a_{CP}(D^0 \to KK) - a_{CP}(D^0 \to \pi\pi)$$
$$a_{CP}^{ind} = A_\Gamma(D^0 \to KK)$$





Within the sensitivity of LHCb there is still a lot of room for both, direct and indirect CPV...

The LHCb experiment



Muon System

10-250 mrad

RICH Detectors specific for LHCb

Vertex Detector

Calorimeters

Tracking System

$c\bar{c}\,,\ b\bar{b}$

Production

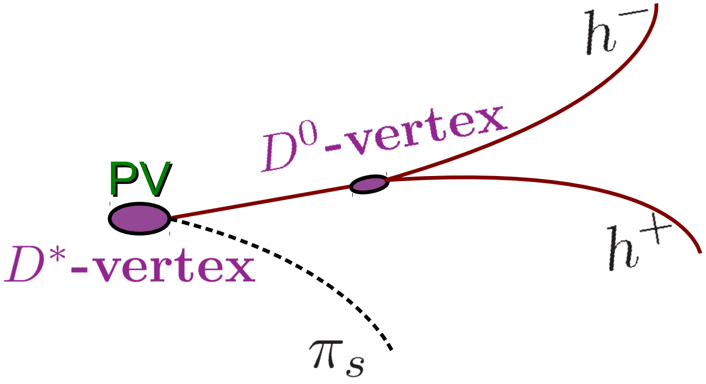
The LHCb collaboration

760 members
15 countries
54 institutes

Charm at LHCb

Charm is produced copiously at LHCb:

- few times 10^8 $D^0 \rightarrow K\pi$ decays on tape
- use slow pion in $D^* \rightarrow D^0\pi_s$ for tagging



LHCb key features for charm measurements:

- **Excellent vertex resolution and proper time resolution**
  - IP resolution: 38µm@1GeV
  - decay time resolution: ~50fs (12% of D^0 decay time)
- **Very good particle identification via two RICH detectors**
  - clean separation of π & K over broad momentum range
- **Dedicated exclusive trigger lines for charm**
  - 1kHz of charm events written to tape

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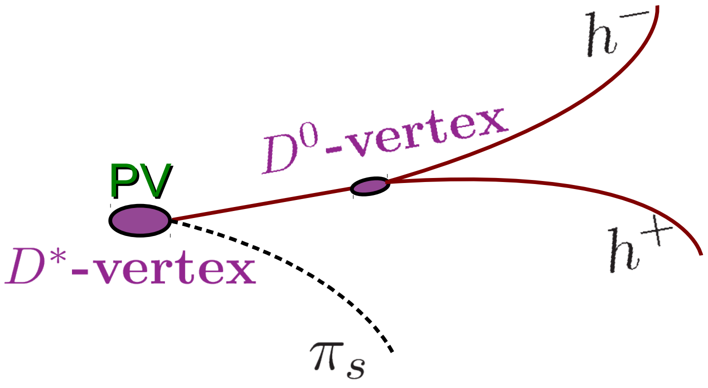

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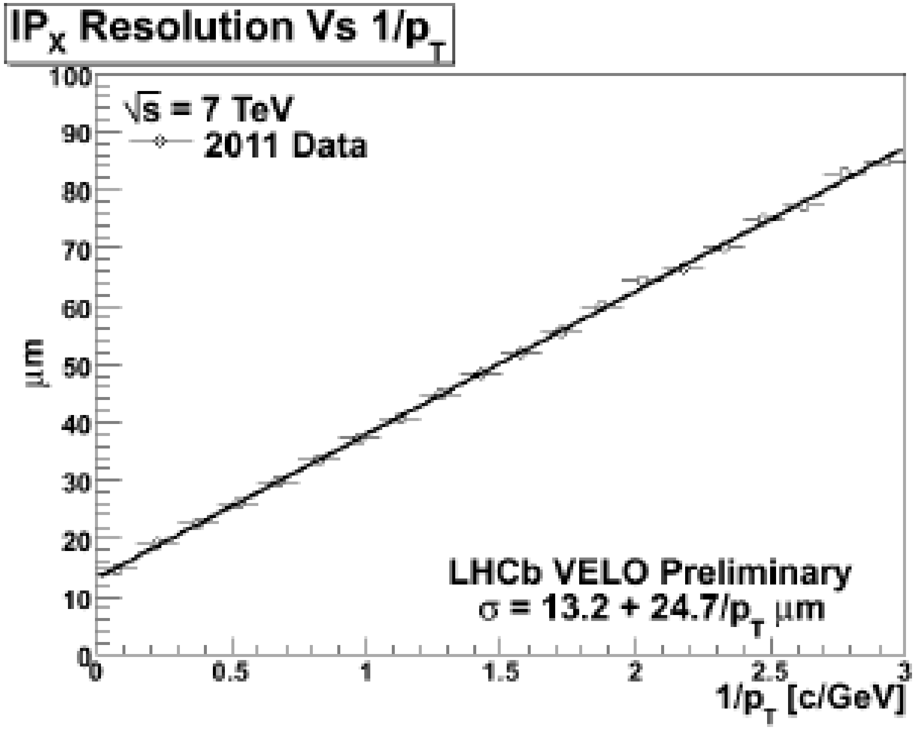

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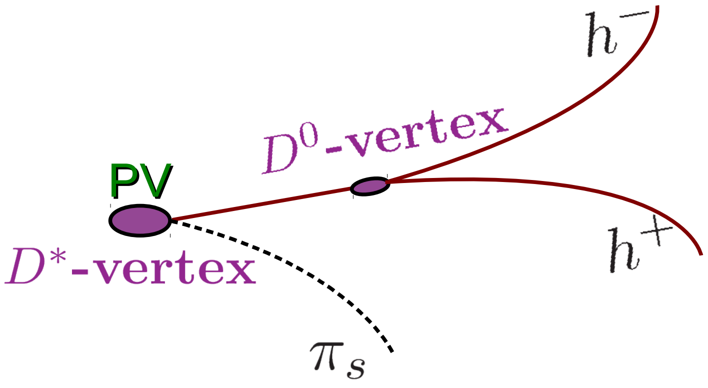

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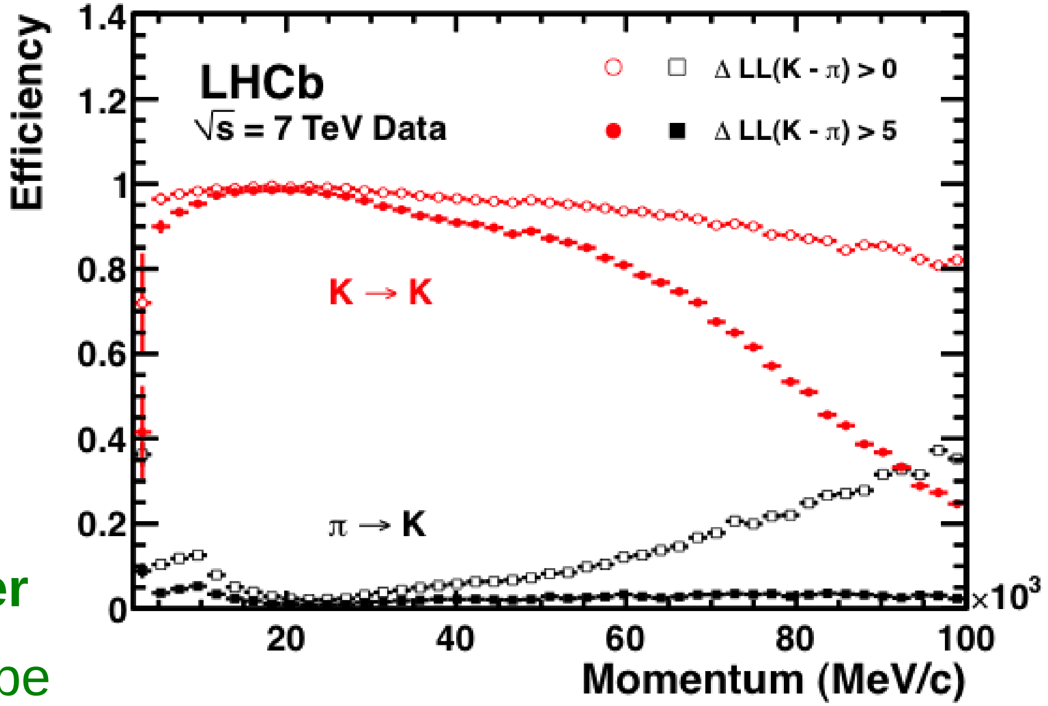
2010 data



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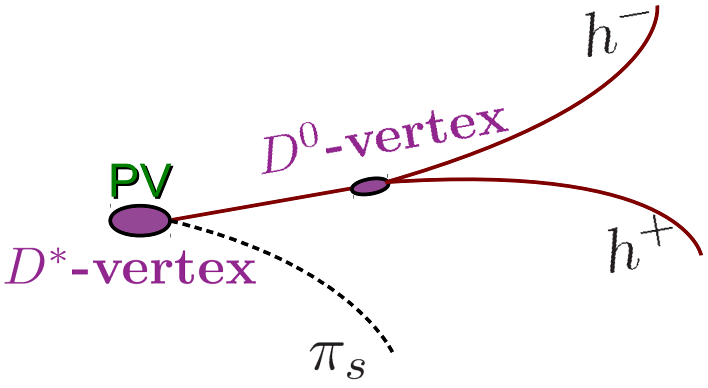

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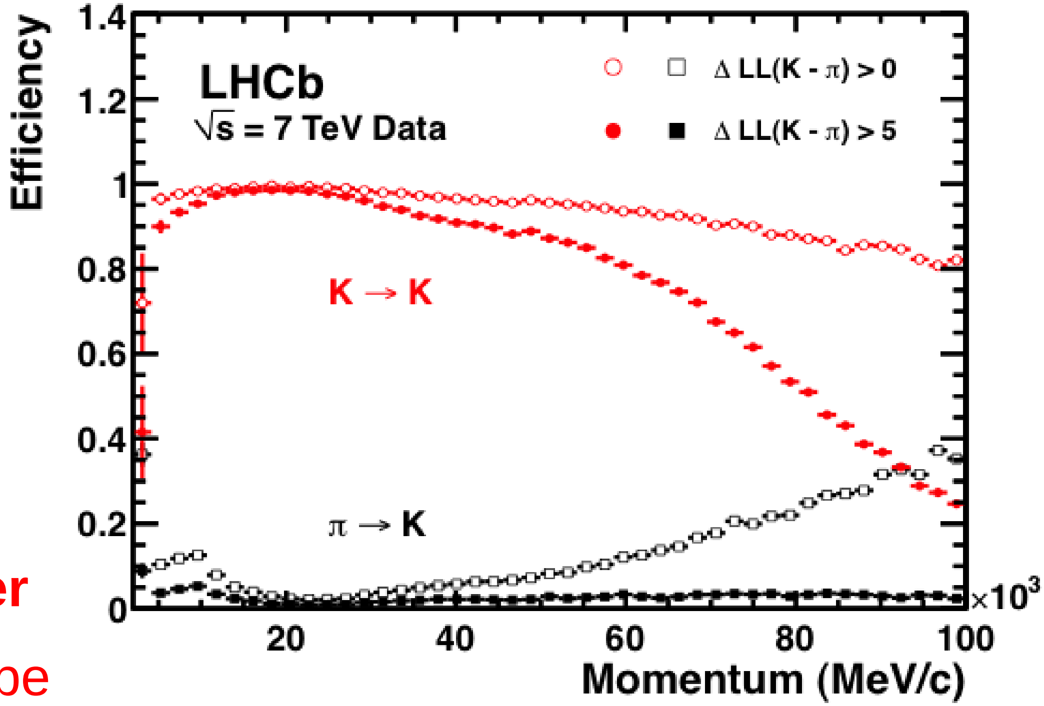
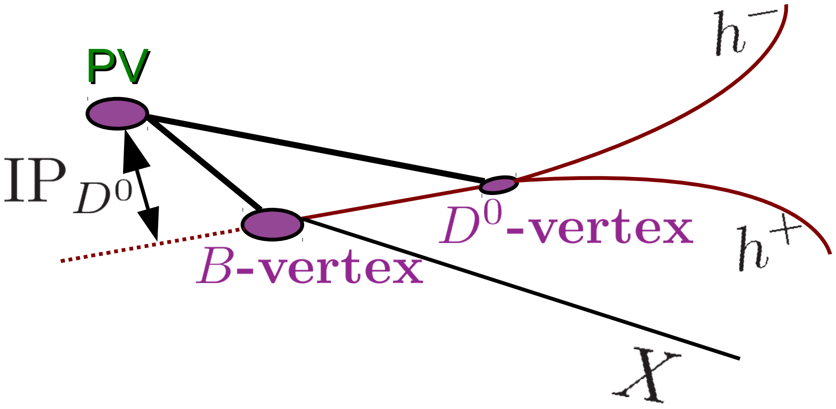


Charm from B-decays

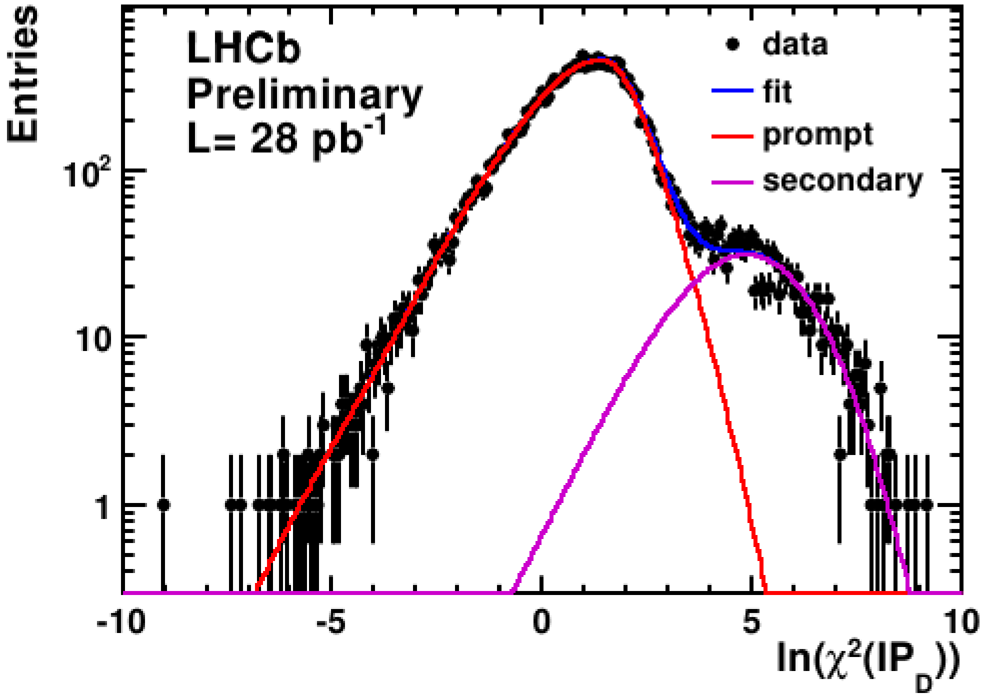
We use Charm produced at the proton-proton primary vertex for our analysis.

But: ~50% of B-hadrons decay into charm
(so called secondary charm)

- misidentification of charm from B-decays as prompt charm results in a significant bias of the lifetime measurement.
- physical BG: Can not be distinguished from invariant mass distribution



Use simultanoues fit of lifetime and Impact Parameter (IP_{D0}) to discriminate prompt charm and charm from B-decays:



Lifetime acceptance

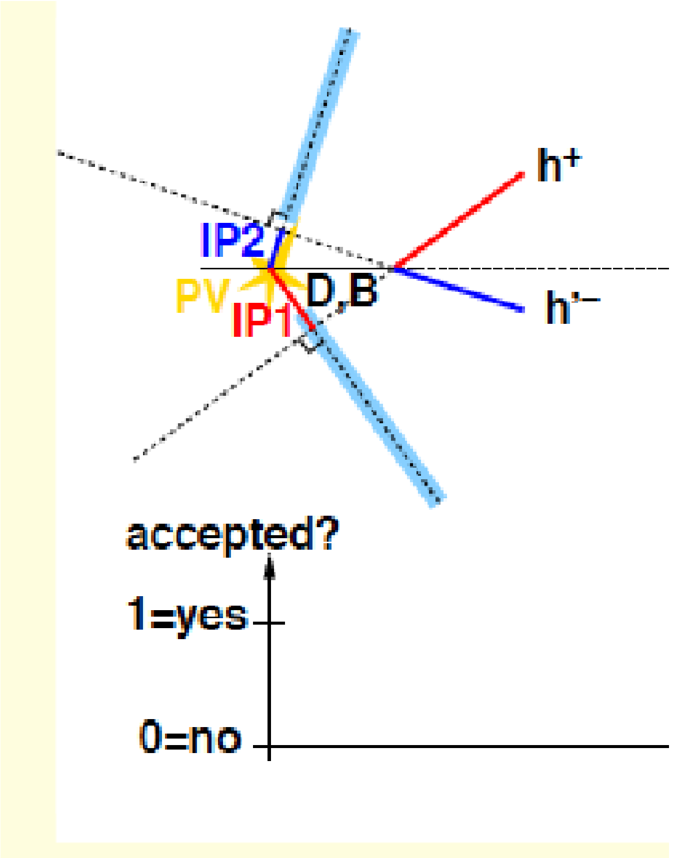
Knowledge of trigger & selection acceptance is crucial for all lifetime-dependent measurements:

- **can be determined on an event-per-event basis by the so called swimming method** (initially developed by CDF*)
- **LHCb offline software allows to rerun the trigger for different configurations**

Elegant implementation of 'swimming' with improved performance possible

Measure acceptance as a function of lifetime by iterative procedure:

1. Moving PV along D0 momentum
2. Evaluation of trigger & selection decision



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* J. Rademacker, Nucl. Instrum. Meth. A 570 (2007) 525,
T. Aaltonen et al. [CDF Collaboration],
Phys.Rev.D 83(2011)032008

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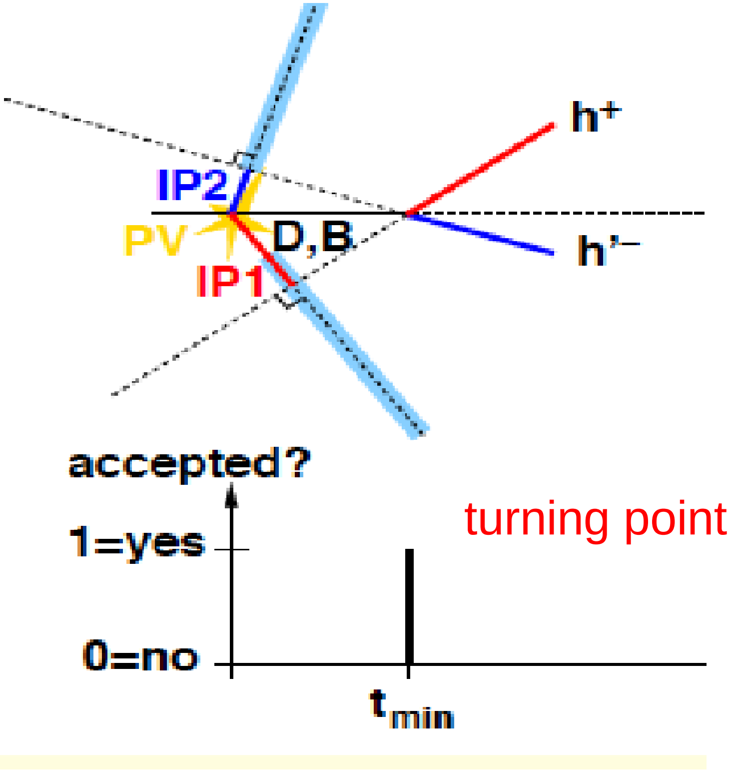

turning point

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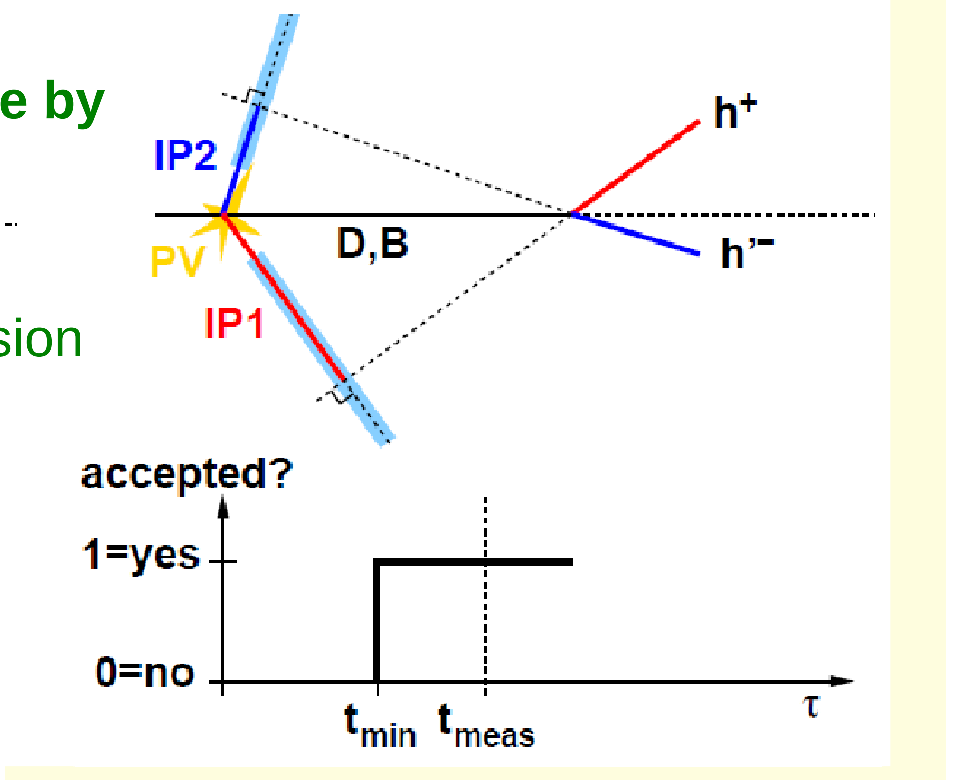

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Lifetime acceptance cross-check: Determination of lifetime for $D^0 \rightarrow K\pi$

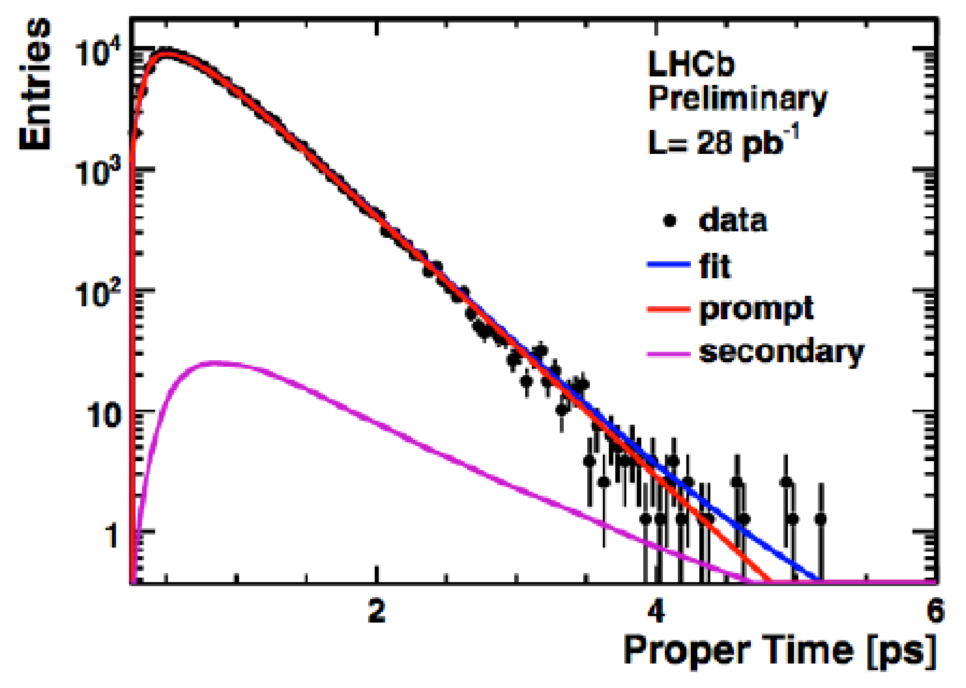
Determine D^0 lifetime as proof of principle:

- Acceptance well modelled by swimming method.
- 220k $D^0 \rightarrow K\pi$ events.
- Mean value consistent with PDG!
- Error is statistical only.

2010 data

$\tau = 410.3 \pm 0.9$ fs

($\tau_{PDG} = 410.1 \pm 1.5$ fs)



Time dependent observables for $D^0 \to hh$

1. Ratio of DCS (wrong sign, WS) over CF (right sign, RS) decays in $D^0 \to K\pi$

$$r(t) = \frac{\Gamma(D^0 \to K^+\pi^-)}{\Gamma(D^0 \to K^-\pi^+)} = R_D + \sqrt{R_D}\,y'\Gamma t + \frac{x'^2+y'^2}{4}t^2$$

R_D : DCS decay rate relative to CF

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

2. $y_{CP} = \frac{\Gamma(D^0 \to KK)}{\Gamma(D^0 \to K\pi)} - 1 = y\cos\Phi - \frac{1}{2}yR_M\sin\Phi$

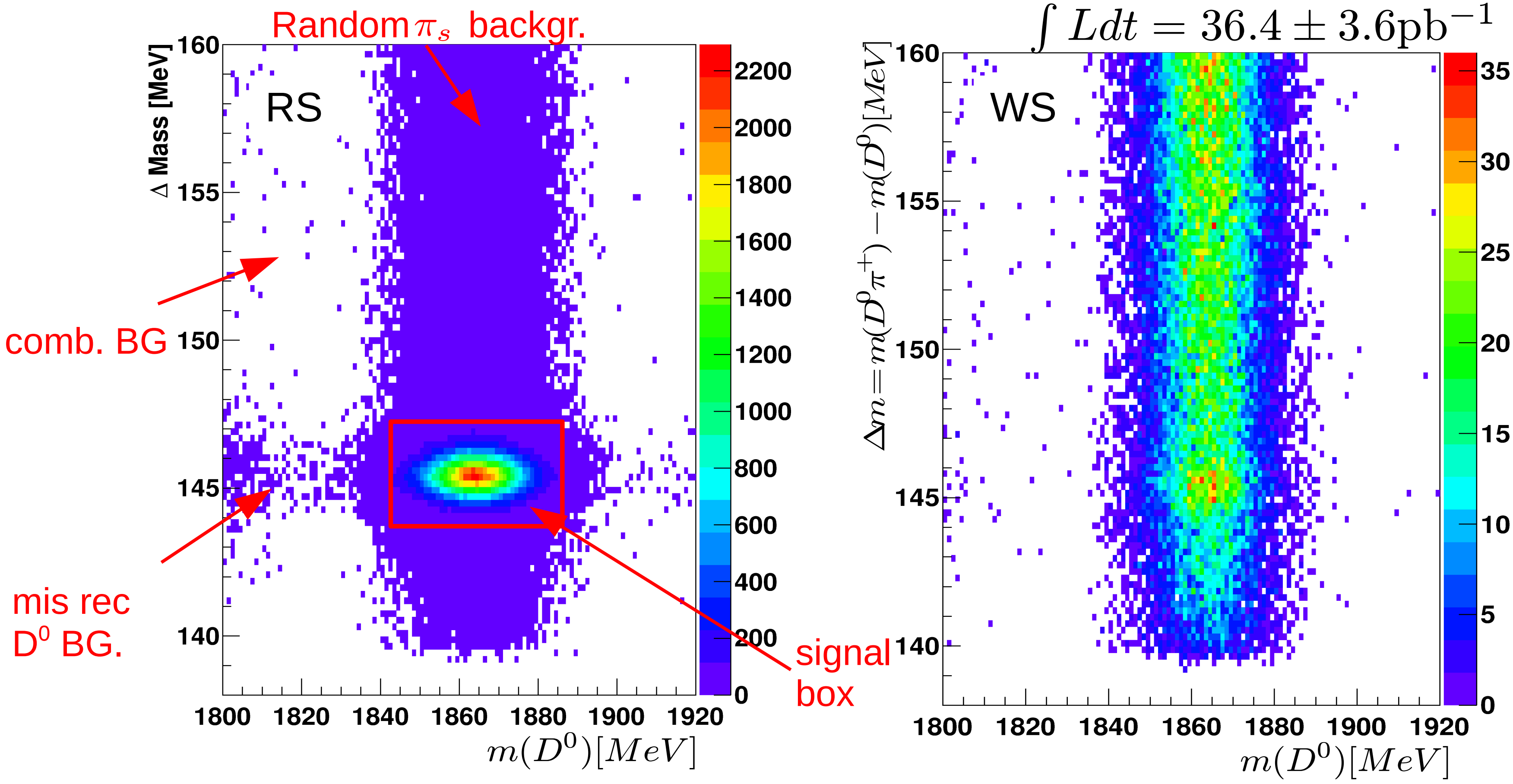
3. $A_\Gamma = \frac{\Gamma(D^0 \to KK) - \Gamma(\overline{D^0} \to KK)}{\Gamma(D^0 \to KK) + \Gamma(\overline{D^0} \to KK)} = \frac{1}{2}R_M y\cos\Phi - x\sin\Phi$

Nota bene:

All equations assume $|x| << 1$, $|y| << 1$ and absence of direct CP-violation

Signal yield for $D^0 \to K\pi$

- Signal yield is extracted from an unbinned maximum likelihood fit. in the $(m_{D^0}, \Delta m)$-plane
- WS decays need due to higher BG stronger selection criteria.
- Identical selection for WS and RS decays.



$S_{raw}(RS) = 214523 \pm 494$

$S_{raw}(WS) = 948 \pm 70$

The time integrated WS/RS ratio from 2010 data

Due to limited statistics in 2010 data we measure only time integrated WS/RS ratio:

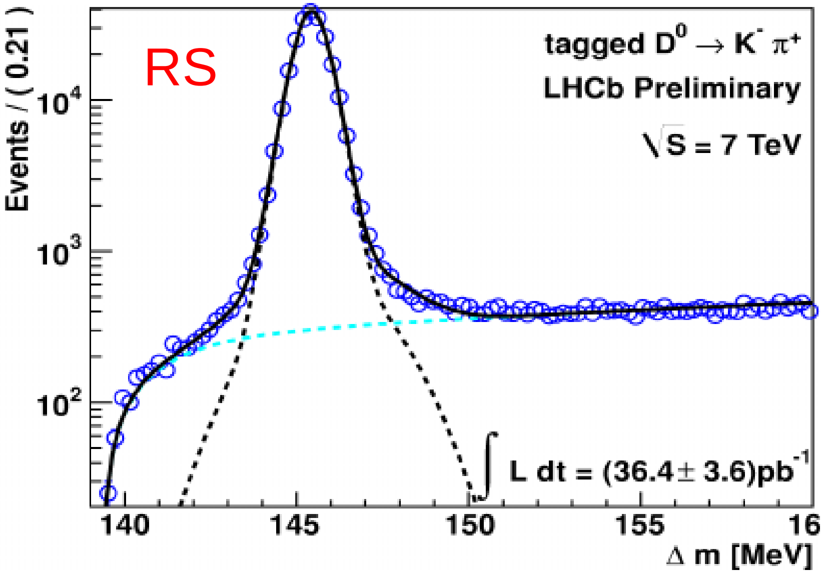
$$R = \int_0^\infty r(t)dt = R_D + \sqrt{R_D}y' + \frac{x'^2 + y'^2}{4}$$

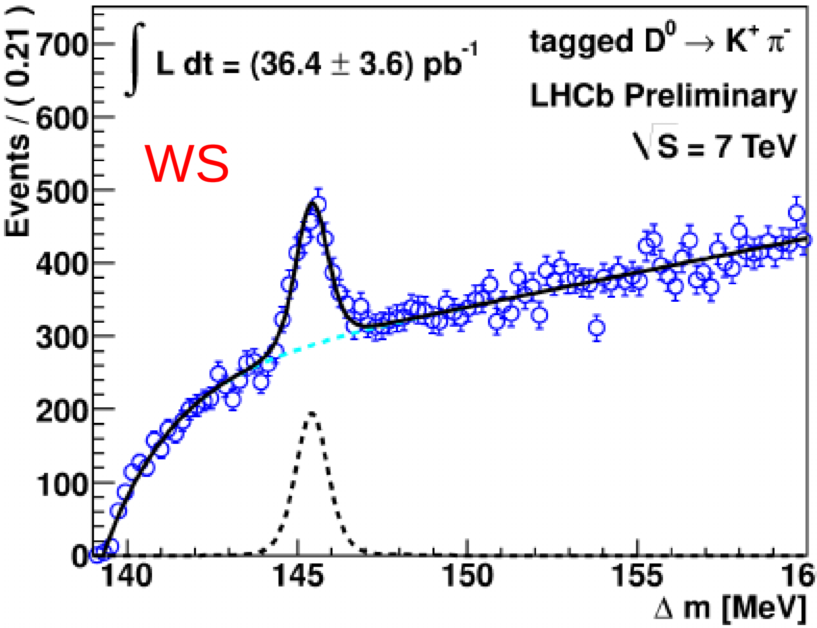
	WS/RS of $D \to K\pi$ decays (%)
R_{meas}	0.442 ± 0.033 (stat.) ± 0.042 (sys.)
R^{*}_{corr}	0.409 ± 0.031 (stat.) ± 0.039 (sys.)
$R(PDG)$	0.380 ± 0.018

*A correction for the non-flat lifetime acceptance has been applied.

Systematic error sources:

1. fit model: $0,035\%$
2. size of signal box: $0,023\%$
3. double mis-id of K and π: negligible



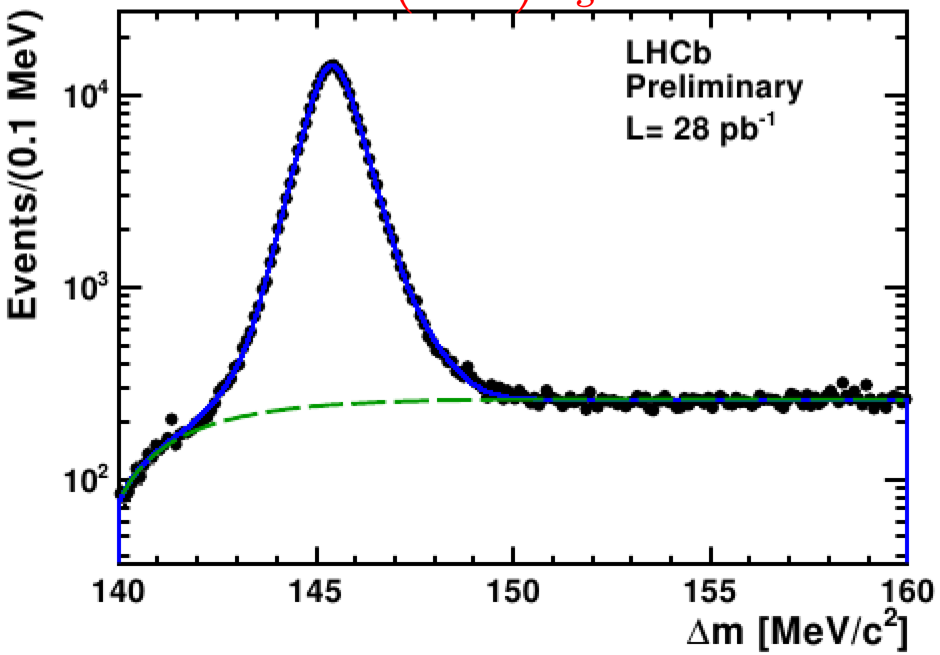


y_{CP} and A_Γ

Analysis for y_{CP} and A_Γ very similar, based on direct lifetime measurements:

- Selection of events in signal region of two-dimensional $(m_{D0}, \Delta m)$ plane.
- Combinatorial BG is estimated from side bands to $\mathcal{O}(\ 1\%)$ for $D^0 \to K\pi$ and $\mathcal{O}(3\ \%)$ for $D^0 \to KK$.
- We use a maximum likelihood fit for extraction of lifetime.

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



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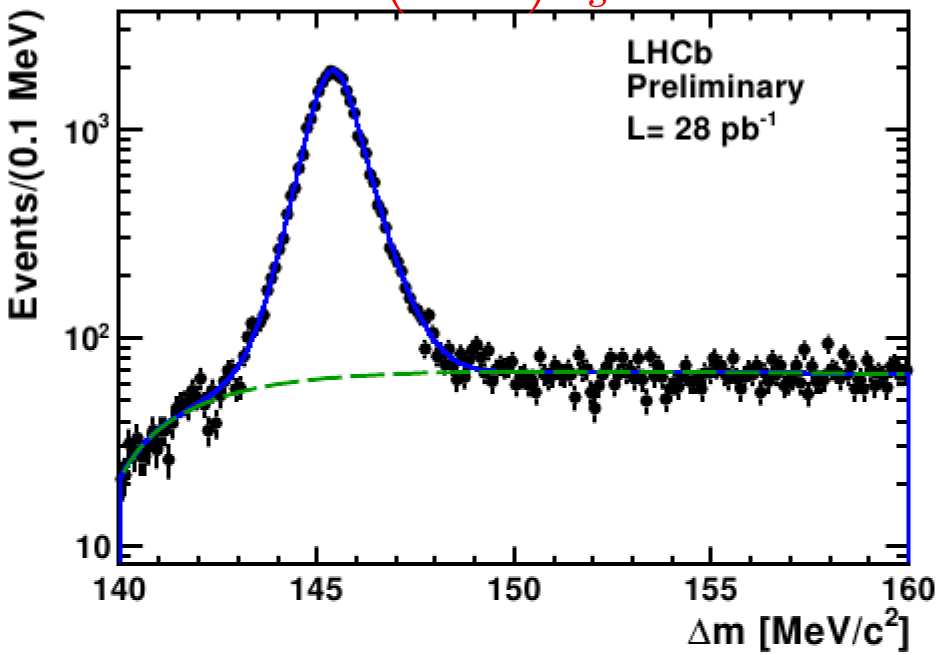
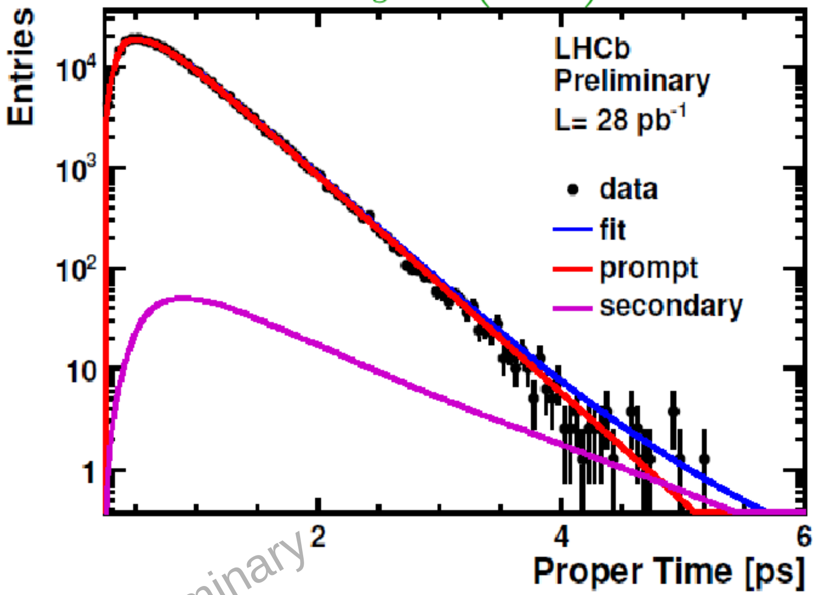


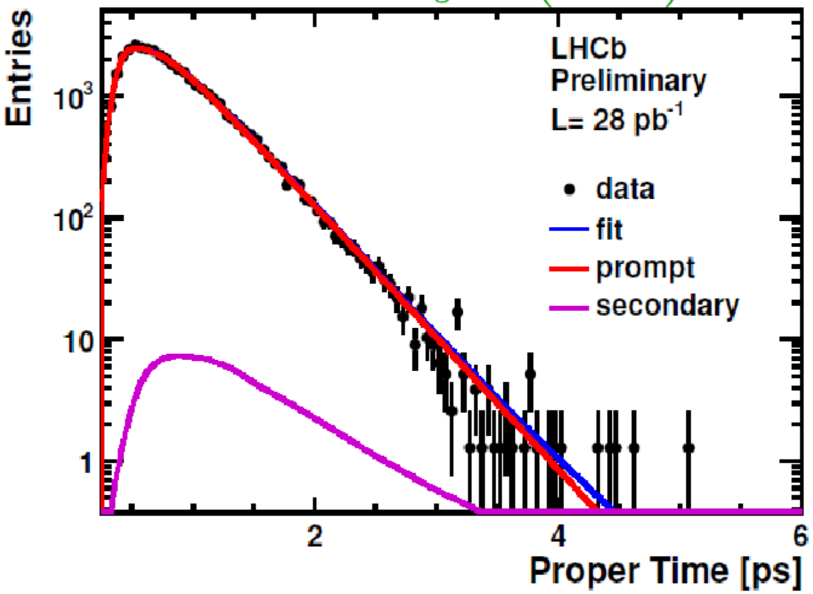
Result for y_{CP} with 2010 data

y_{CP} measures the ratio of lifetimes between CP eigenstates $D^0 \to K\pi$ and CP-mixed states $D^0 \to \pi\pi$.

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



$D^* \to \pi_s D^0(KK)$



preliminary result

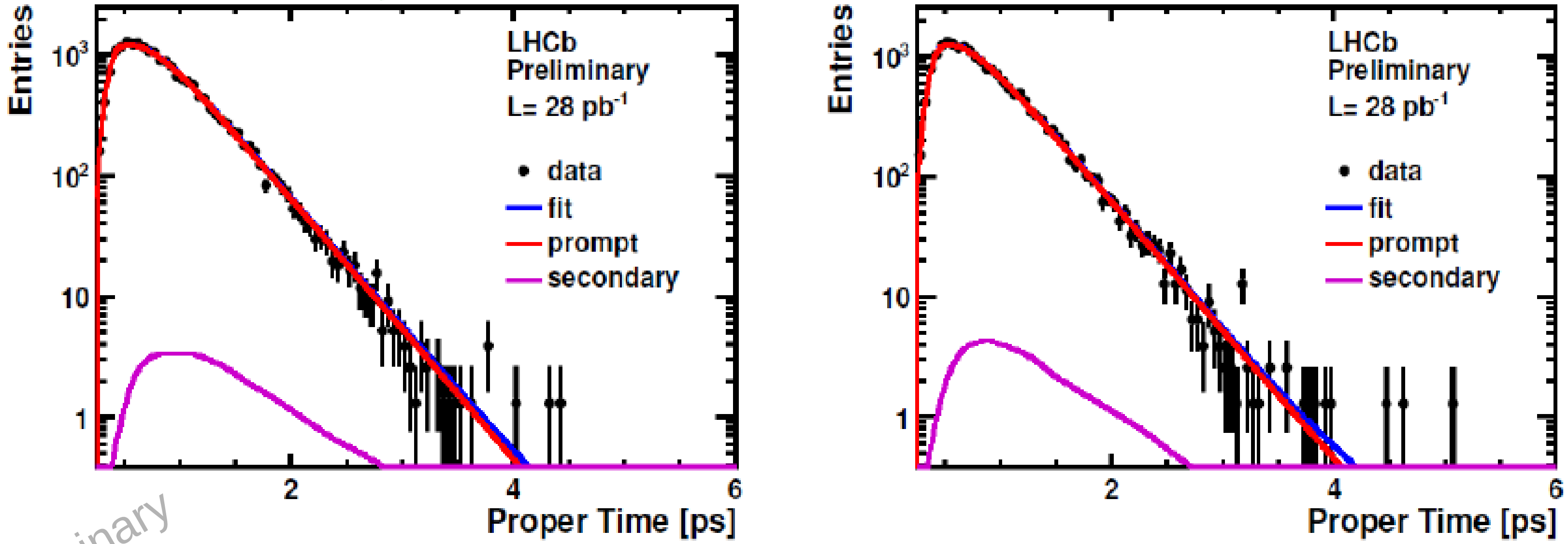
$$y_{CP} = (0.55 \pm 0.63\,(stat)\ \pm 0.41\,(syst)\ )\%$$

- **Budget for systematic error:**
  - Contribution from Combinatorical BG: ± 0.08%
  - Fit model: ± 0.08%
  - Impact of secondary charm: ± 0.39%

Measurement of A_Γ with 2010 data

A_Γ measures the lifetime difference between
D^0 and $\overline{D^0}$ into CP-eigenstates K^+K^-

- Mistag rate determined from sidebands in $\Delta m(D^* - D^0(hh))$
- Systematic error mainly from combinatorical and secondary charm BG


$D^{*+} \rightarrow \pi_s^+ D^0(K^-K^+)$ $\qquad$ $D^{*-} \rightarrow \pi_s^- D^0(K^-K^+)$

preliminary
result

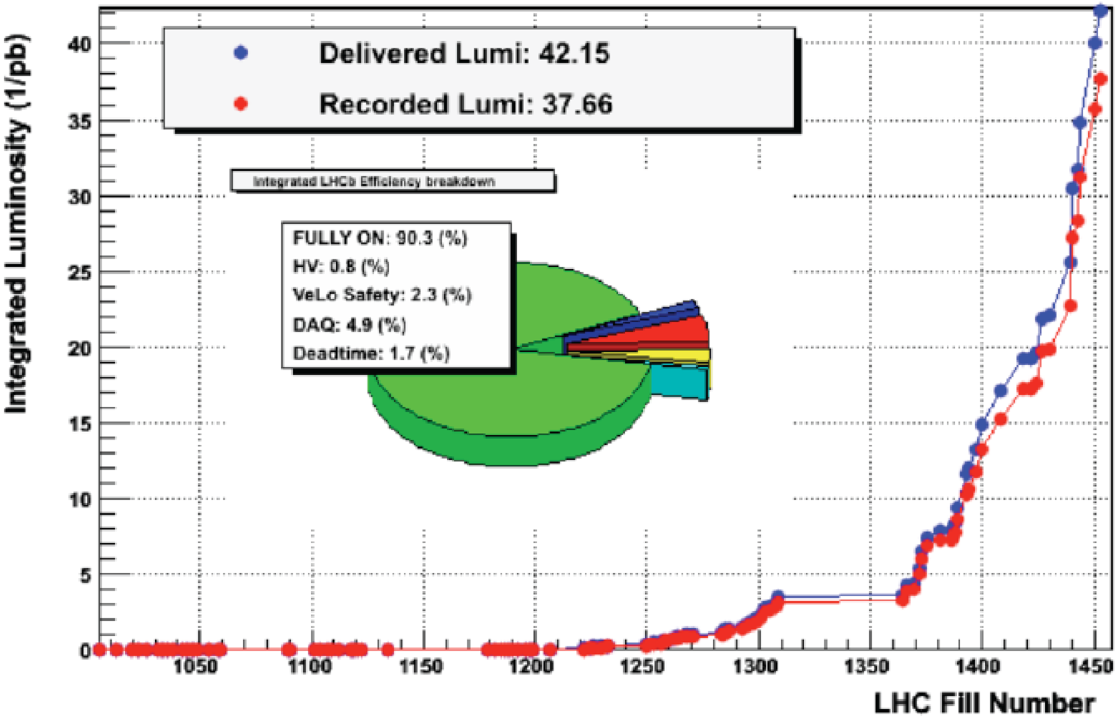
$$A_\Gamma = (-0.59 \pm 0.59(stat) \pm 0.21(syst))\%$$

Error budget for A_Γ

Effect	A_Γ (10^{-3})
VELO length scale	negligible
Turning point bias	negligible
Turning point scaling	±0.1
Combinatorial background	±1.3
Proper time resolution	±0.1
Minimum proper-time cut	±0.1
Maximum proper-time cut	±0.2
Secondary charm background	±1.6
Total	±2.1

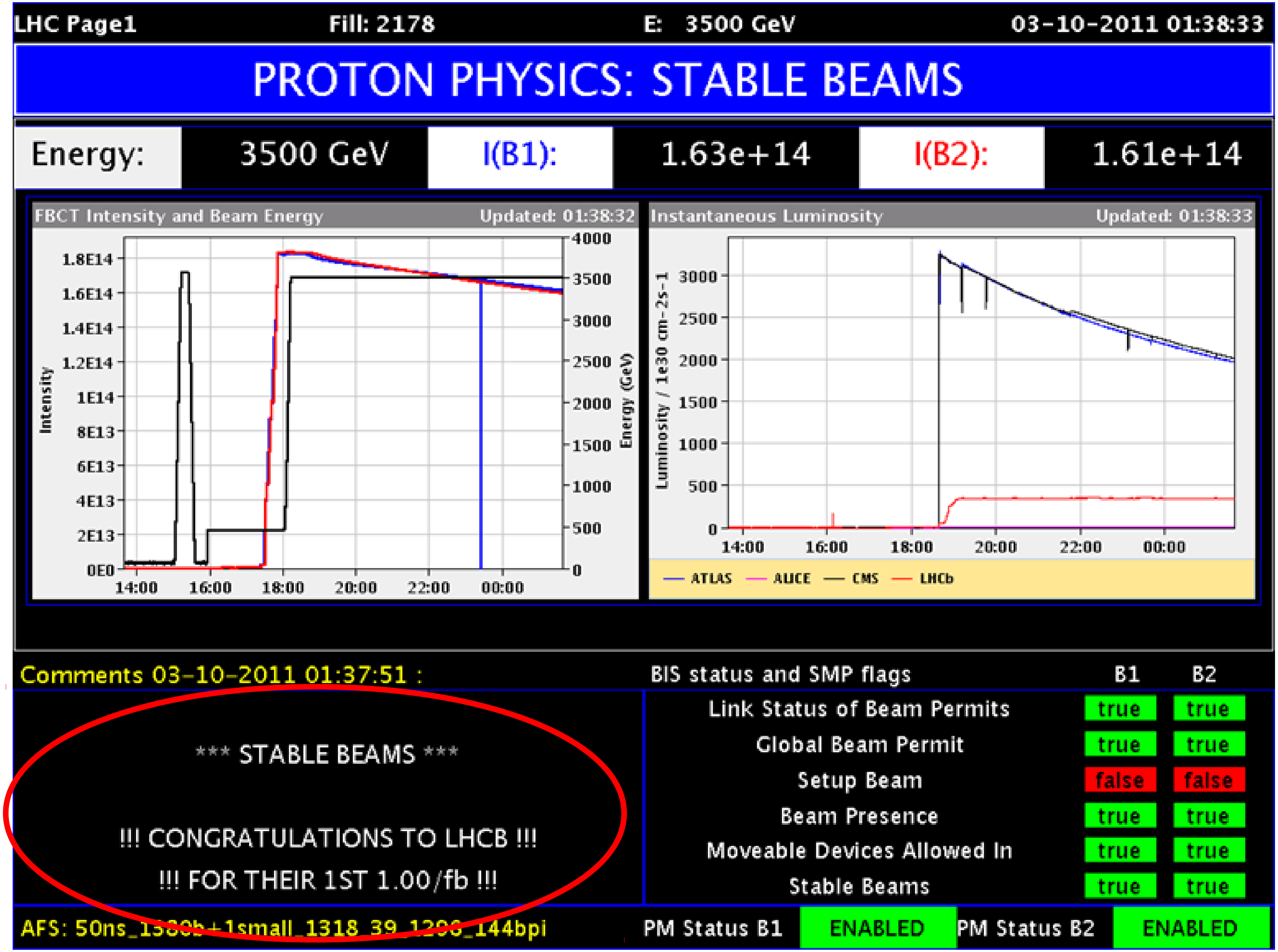
Summary of 2010 results

Measurements have been performed on a data sample corresponding to an integrated luminosity of $\int \mathcal{L} = 38\ \mathrm{pb}^{-1}$.



	LHCb 2010	PDG / HFAG charm
R	$(0.409 \pm 0.031(stat.) \pm 0.039(syst.))\%$	$(0.380 \pm 0.018)\%$
y_{CP}	$(0.55 \pm 0.63(stat.) \pm 0.41(syst))\%$	$(1.107 \pm 0.217)\%$
A_{Γ}	$(0.59 \pm 0.59(stat.) \pm 0.21(syst.))\%$	$(0.123 \pm 0.248)\%$

October 3rd 2011



LHC Page1 Fill: 2178 E: 3500 GeV 03-10-2011 01:38:33

PROTON PHYSICS: STABLE BEAMS

Energy: 3500 GeV I(B1): 1.63e+14 I(B2): 1.61e+14

Comments 03-10-2011 01:37:51 :

*** STABLE BEAMS ***

!!! CONGRATULATIONS TO LHCB !!!

!!! FOR THEIR 1ST 1.00/fb !!!

BIS status and SMP flags	B1	B2
Link Status of Beam Permits	true	true
Global Beam Permit	true	true
Setup Beam	false	false
Beam Presence	true	true
Moveable Devices Allowed In	true	true
Stable Beams	true	true

AFS: 50ns_1380b+1small_1318_39_1296_144bpi

PM Status B1 ENABLED PM Status B2 ENABLED

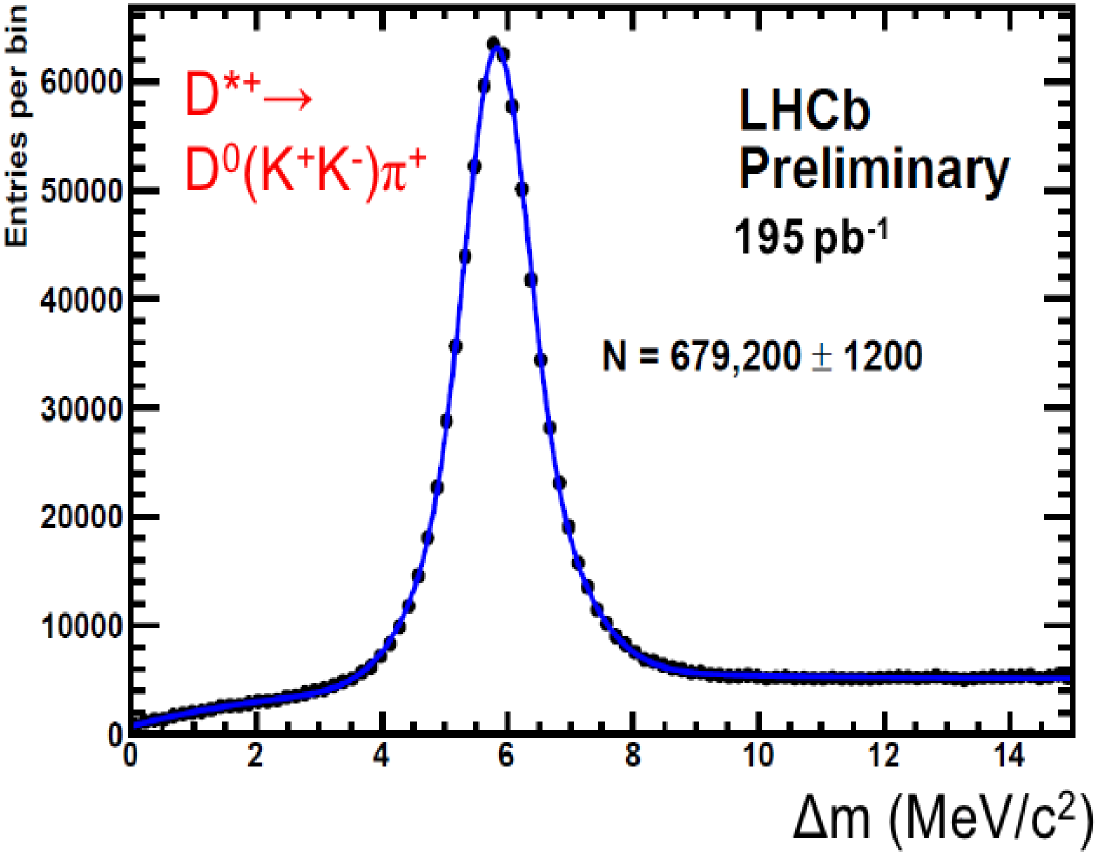
Prospects for 2011

In 2011 we increased already now the amount of data by a factor 30! (i.e. already now the world highest statistics for many channels)

Signal yield per pb^{-1} approximately the same or even improved (e.g. $3x10^5$ untagged $D0 \to K\pi$ decays per pb^{-1})

Trigger settings have been improved And more channels have been added To the trigger..

Modelling of combinatorical BG and BG from B-decays will be improved.



→ Larger data sample + improved trigger allow to reduce systematic error significantly.

But there is much more to come

Higher statistics also allows to tackle new channels and new analysis techniques with high sensitivity to seek for new physics.

Studies are going on to

- exploit more channels to measure mixing parameters

  $D^* \to D^0(K\pi\pi\pi)\pi_s$ ¬ needs 2011 data for sensitive measurement

  $D^* \to D^0(K^+\mu^-\overline{\nu}_\mu)\pi_s$ ¬ needs 2011&2012 data for sensitive measurement

- search for CPV using T-odd correlations in $D^0 \to K^+K^-\pi^+\pi^-$

  construct T-odd observables like $C_T^{\pm} = \vec{p}_{K^\pm} \cdot (\vec{p}_{\pi^+} \times \vec{p}_{\pi^-})$

  these observables allow to construct T-violating asymmetries between C_T^+ and C_T^-.

  I.I.Bigi hep/ph-0107102 (2001)

- perform a time dependent Dalitz Plot analysis of $D^0 \to K_S hh$

  see next slides

Time dependent Dalitz analysis of $D^0 \rightarrow K_s hh$

- Presence of many resonant modes result in a rich Dalitz structure for $D^0 \rightarrow K_s hh$.
- Decay amplitudes for $|\mathcal{D}^0>$ and $|\overline{\mathcal{D}}^0>$ are given by:

$m_\pm^2 = m^2(K_s^0 h^\pm)$

$$\begin{aligned}\mathcal{M}(m_-^2, m_+^2, t) &= \mathcal{A}(m_-^2, m_+^2)\frac{e_H(t)+e_L(t)}{2} + \frac{q}{p}\overline{\mathcal{A}}(m_-^2, m_+^2)\frac{e_H(t)-e_L(t)}{2}\\ \overline{\mathcal{M}}(m_-^2, m_+^2, t) &= \overline{\mathcal{A}}(m_-^2, m_+^2)\frac{e_H(t)+e_L(t)}{2} + \frac{p}{q}\mathcal{A}(m_-^2, m_+^2)\frac{e_H(t)-e_L(t)}{2}\end{aligned}$$

sum over resonant and n.r. decay amplitudes

$e_{H,L}(t) = \exp[-i(m_{H,L} - i\Gamma_{H,L}/2)t]$

- Squaring of $\mathcal{M}$ and $\overline{\mathcal{M}}$ give decay rates $\exp(-\Gamma t)\cos(x\Gamma t)$, $\exp(-\Gamma t)\sin(x\Gamma t)$ and $\exp(-(1 \pm y)\Gamma t)$

time dependent Dalitz analysis gives direct access to x and y and CPV parameters! ... contrary to WS decays in $D^0 \rightarrow K\pi$ (see there)

- Sensitivity stems mostly from regions in Dalitz plots where CF and DCS amplitudes from CP eigenstates interfere.

Prospects for $D^0 \rightarrow K_s hh$

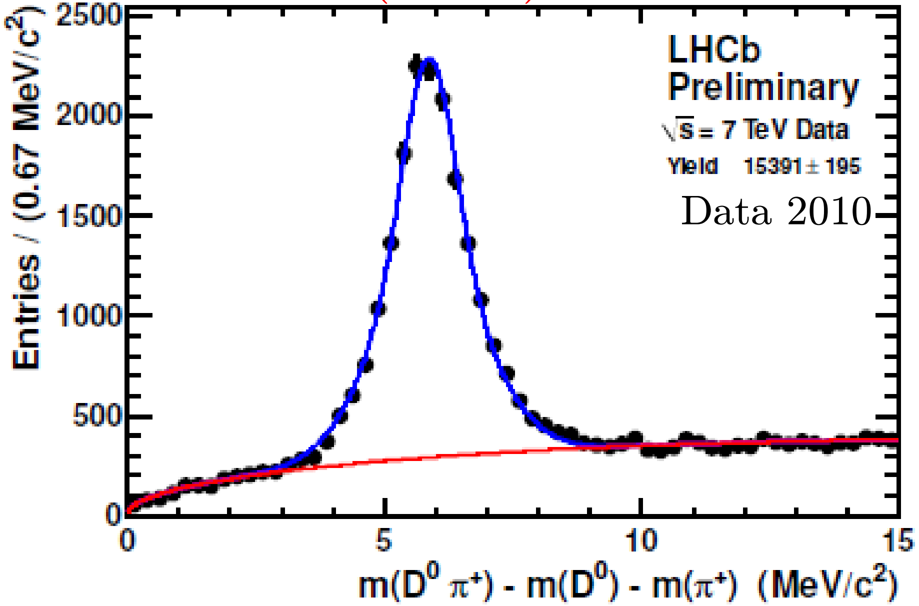
- LHCb was running in 2010 without a dedicated trigger for D^0->$K_s$hh

  → despite that a nice signal in 35pb^{-1} is seen!

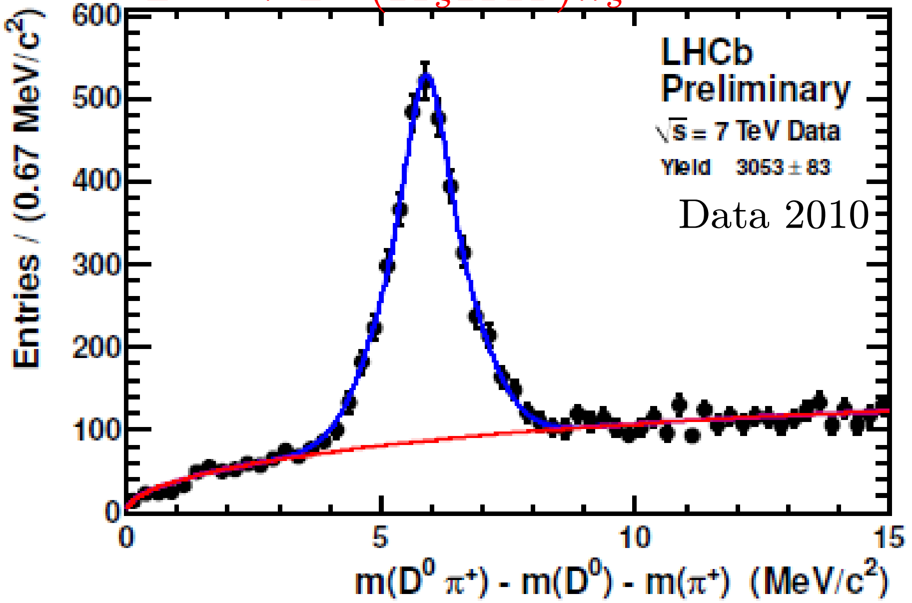
- In 2011 LHCb is running with a dedicated trigger for that channel.

This offers LHCb a method to measure x, y and CPV parameters complementary to the decay channel $D^0 \rightarrow hh$!

$D^* \rightarrow D^0(K_s\pi\pi)\pi_s$



$D^* \rightarrow D^0(K_sKK)\pi_s$



Summary

- With the analysis of data from 2010 LHCb has proven to be able to perform 38pb^{-1} competitive measurements in the field of mixing CPV in the charm sector.
- Already now, LHCb has collected ~30 x more data than in 2010.
- Trigger settings have been improved, new channels have been added in the high level trigger.
- High statistics available and the very good performance of LHCb allows us to improve the sensitivity for our existing measurements and to exploit new channels.

→ **We expect many charming results from the 2011 data with unprecedented sensitivity to New Physics in the charm sector.**