

First evidence for CP  
violation in charm decays  
at LHCb

Angelo Carbone  
(INFN-Bologna)  
on behalf of the LHCb  
Collaboration

Reference: [arXiv:1112.0938](https://arxiv.org/abs/1112.0938) [hep-ex]

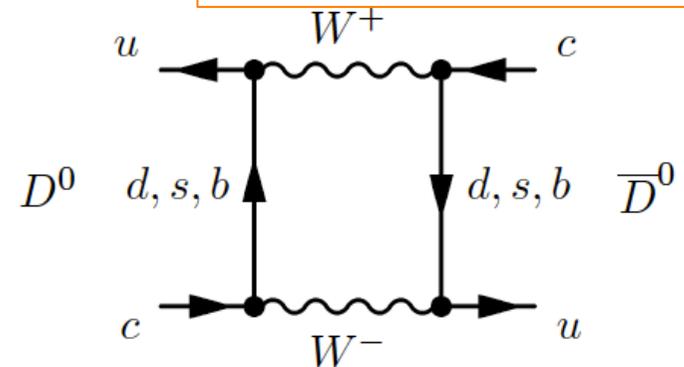
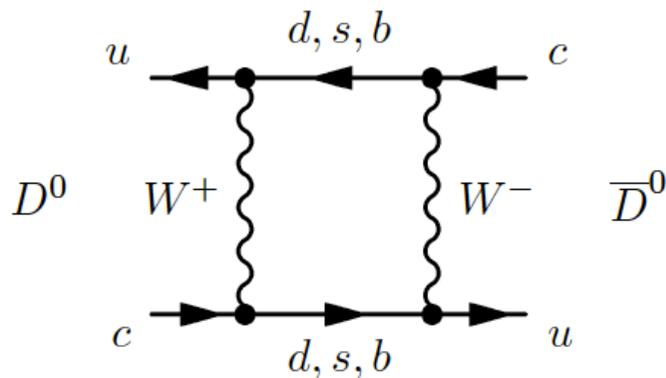
# Preamble

# Why search for CP violation in charm ?

CP-violating asymmetries in the charm sector provide a unique probe for physics beyond the Standard Model (SM)

Interest increased in the past few years since evidence for  $D^0$  mixing was first seen

BaBar, Belle,  
[arXiv:hep-ex/0703020](https://arxiv.org/abs/hep-ex/0703020)  
[arXiv:hep-ex/0703036](https://arxiv.org/abs/hep-ex/0703036)

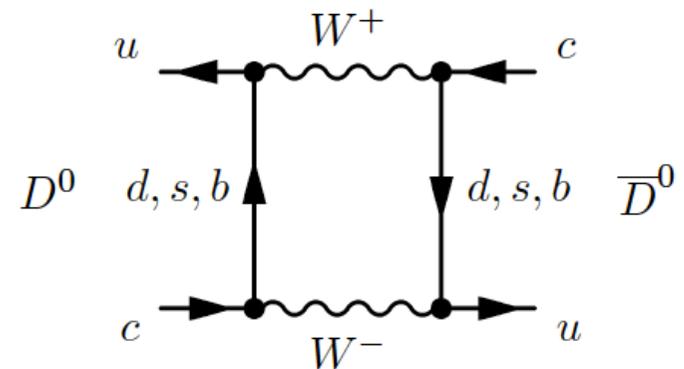
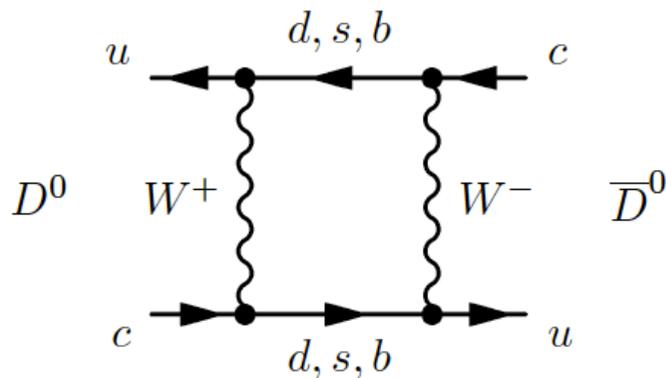


# Why search for CP violation in charm ?

$D^0$  mixing is well established at a level which is consistent with, but at the upper end of SM expectations

HFAG arXiv:1010.1589

No evidence for CP violation in charm decays has yet been found



# Why search for CP violation in charm ?

SM charm physics is CP conserving to first approximation  
(dominance of 2 generation)

New Physics (NP) can enhance CP-violating observables

Unitary triangle for charm

$$V_{ud}V_{cd}^* + V_{us}V_{cs}^* + V_{ub}V_{cb}^* = 0$$

$\sim \lambda$        $\sim \lambda$        $\sim \lambda^5$

With b-quark contribution neglected: only 2 generations contribute  
→ **real 2x2 Cabibbo matrix**

# CP violation in charm

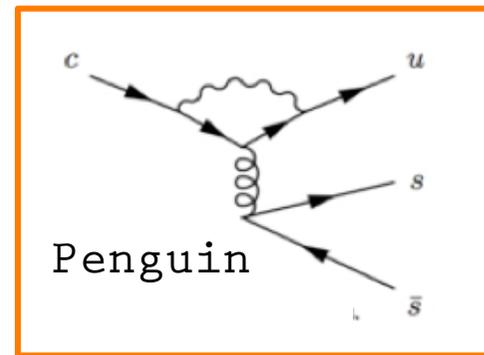
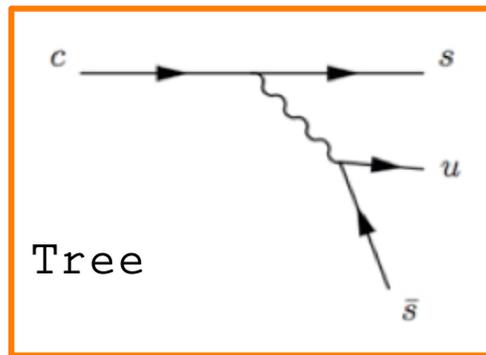
- 3 modes of observing CP violation:
  - in mixing: rates of  $D^0 \rightarrow \bar{D}^0$  and  $\bar{D}^0 \rightarrow D^0$  differ  $\rightarrow$  indirect
  - in decay: amplitudes for a process and its conjugate differ  $\rightarrow$  direct
  - in interference between mixing and decay diagrams  $\rightarrow$  indirect
- In the SM indirect CP violation expected to be very small and universal for CP eigenstates  $\rightarrow O(10^{-3})$
- Direct CP violation expected small as well
  - Negligible in Cabibbo-favoured modes (SM tree dominates everything)
  - In singly-Cabibbo-suppressed modes: up to  $O(10^{-4} - 10^{-3})$  plausible
- Both can be enhanced by NP, in principle up to  $O(\%)$

[Bianco, Fabbri, Benson & Bigi, Riv. Nuovo. Cim 26N7 \(2003\)](#)  
[Grossman, Kagan & Nir, PRD 75, 036008 \(2007\)](#)  
[Bigi, arXiv:0907.2950](#)

[Bobrowski, Lenz, Riedl & Rorhwild, JHEP 03 009 \(2010\)](#)  
[Bigi, Blanke, Buras & Recksiegel, JHEP 0907 097 \(2009\)](#)

# Where to look for CP violation?

- Singly Cabibbo Suppressed (SCS) decays are an interesting sector for **direct** CPV searches
- Interference between **Tree** and **Penguin** can generate direct CP asymmetries
  - Several classes of NP can contribute
  - ... but also non-negligible SM contribution



Today special guest

Time-integrated asymmetries in  $D^0 \rightarrow hh$

# Introduction to LHCb

# LHC as a charm and beauty factory

Large production of charm and beauty  
Cross sections at  $\sqrt{s}=7$  TeV measured by LHCb:  
 $\sigma_{b\bar{b}}(pp\rightarrow b\bar{b}X) = (284 \pm 20 \pm 49)\mu\text{b}$   
 $\sigma_{c\bar{c}}(pp\rightarrow c\bar{c}X) = (6.10 \pm 0.93)\text{mb}$   
charm is  $\sim 20$  times more abundant than beauty

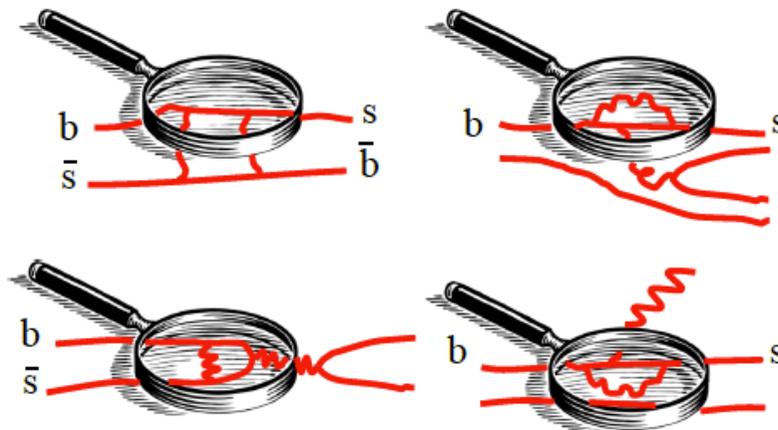


# The LHCb experiment

LHCb is the dedicated flavour physics experiment at the LHC

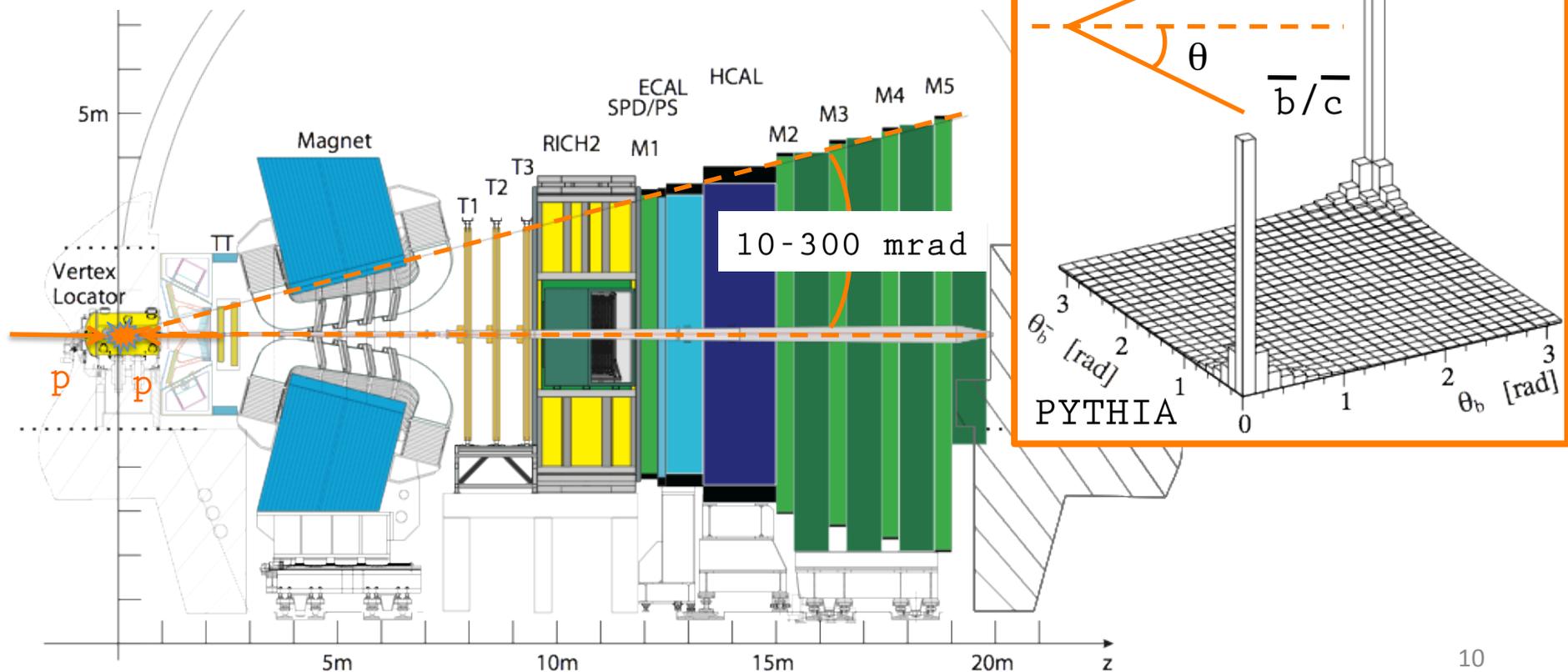
ATLAS and CMS search for the direct production of new states

LHCb is designed to search for the indirect effect of such states on **charm** and **beauty** decays via virtual production



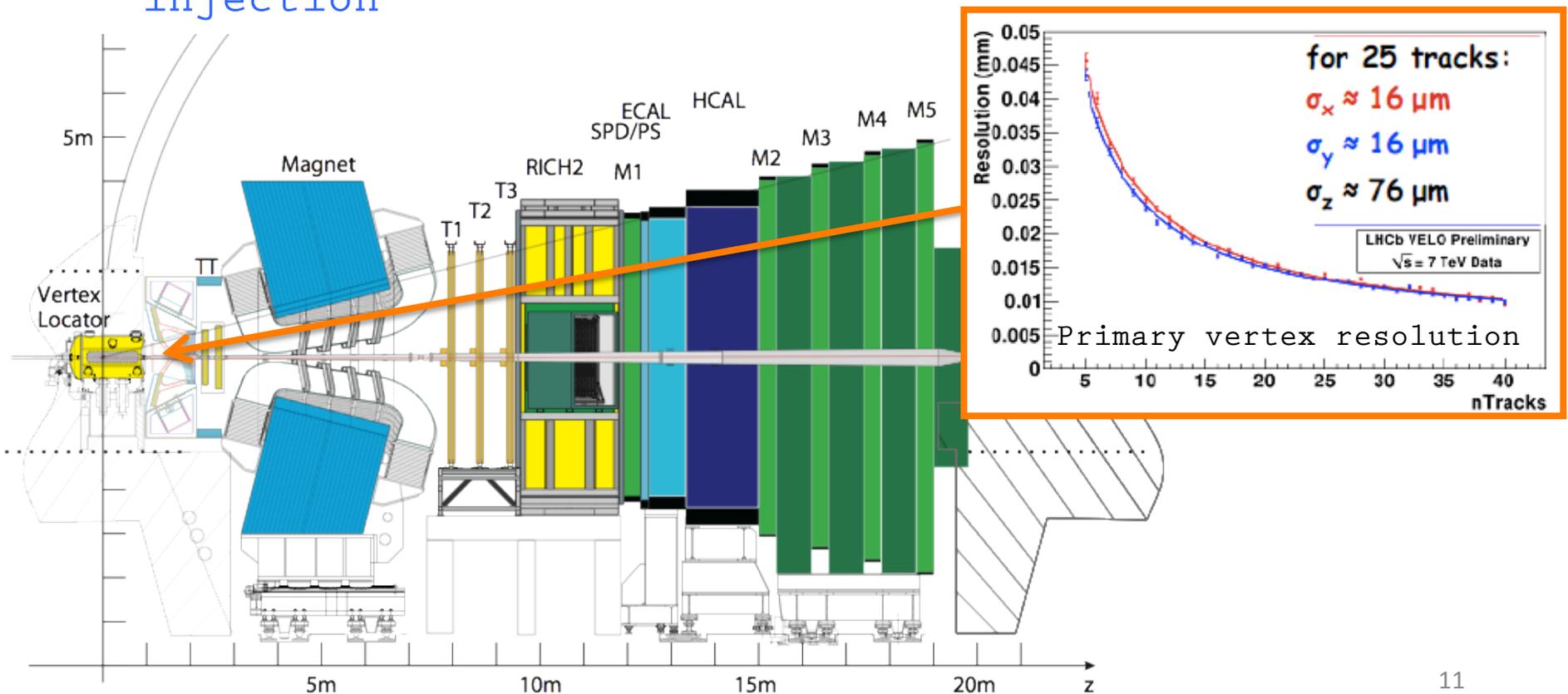
# The LHCb detector

- Forward-peaked production of heavy quarks  $\rightarrow$  LHCb designed as forward spectrometer (operating in collider mode)



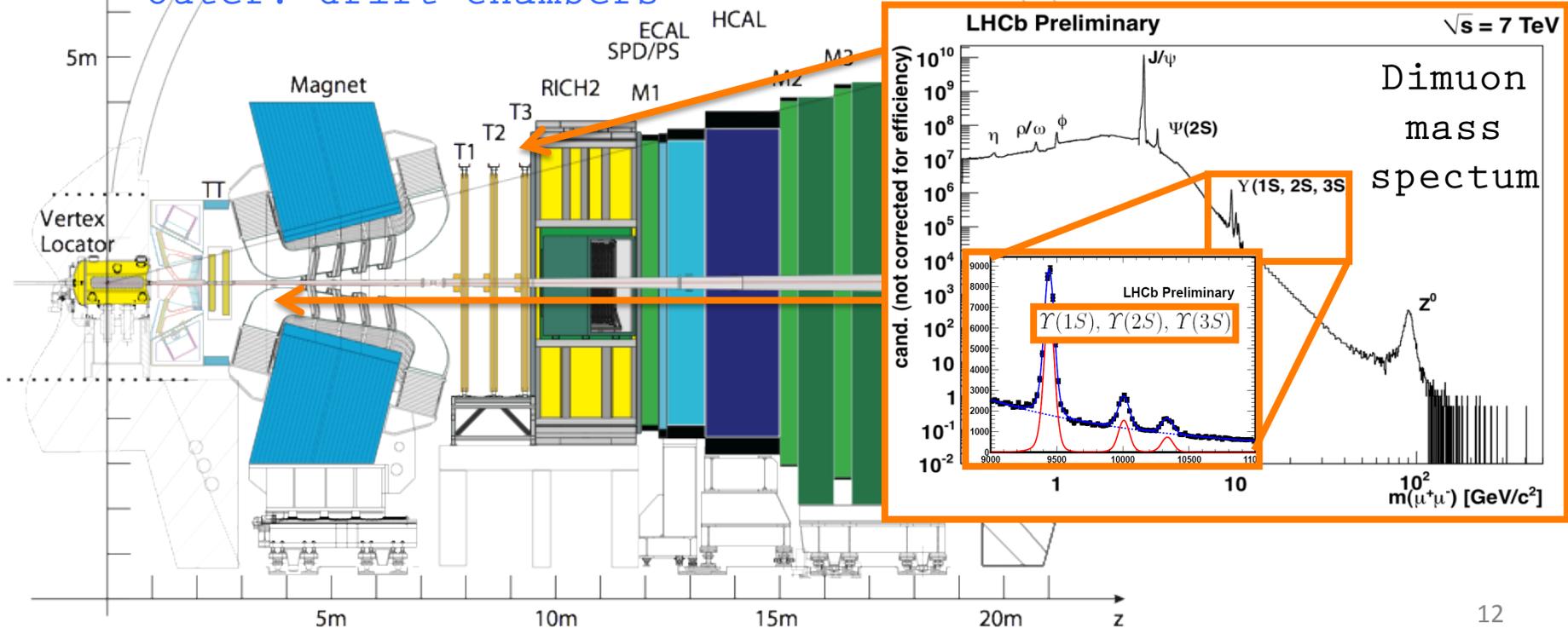
# The LHCb detector

- VELO: precision vertexing
  - 42x2 silicon planes, strip pitch 40-100  $\mu\text{m}$
  - 7mm from beam during data-taking retracted during injection



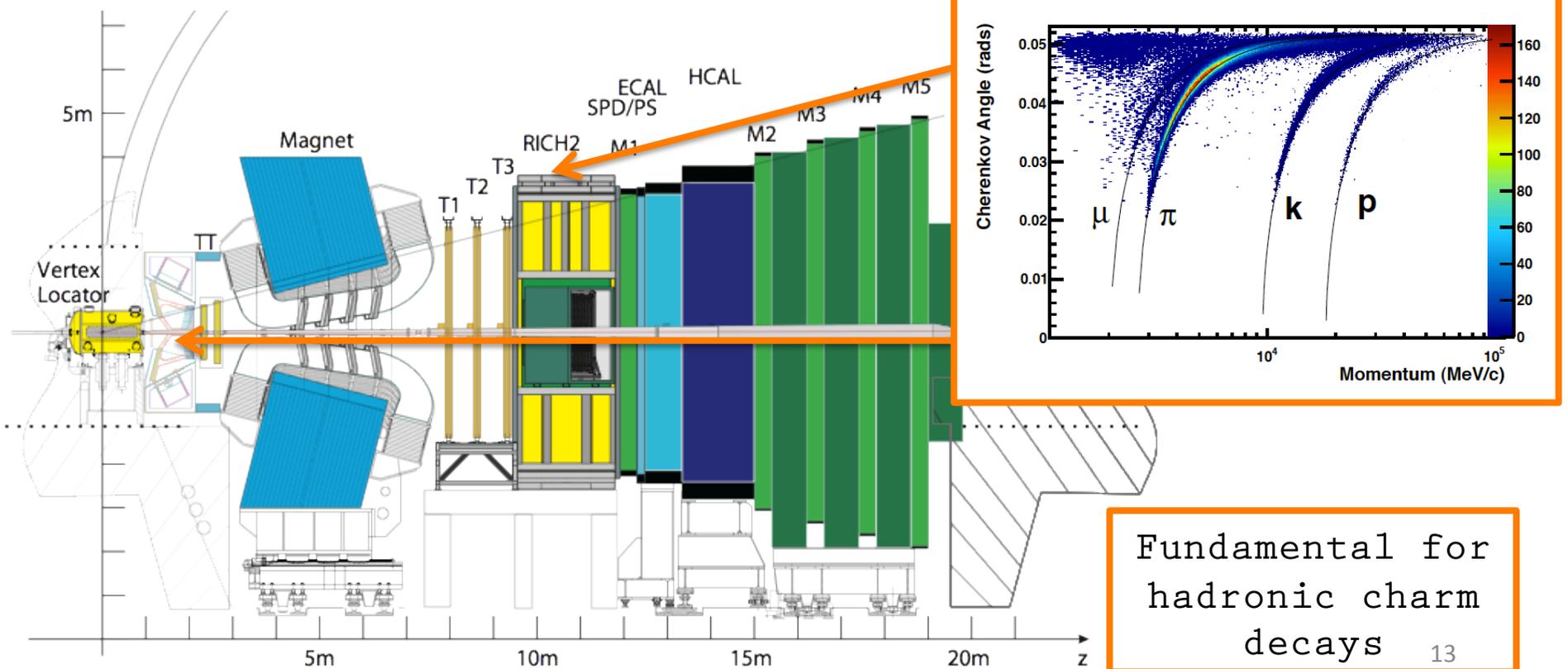
# The LHCb detector

- TRACKER systems
  - Magnetic field reverse during data taking, integrated B field 4 Tm. Momentum resolution 0.4-0.6%
  - Stations upstream and downstream of magnet
  - Upstream & inner: silicon microstrips
  - Outer: drift chambers



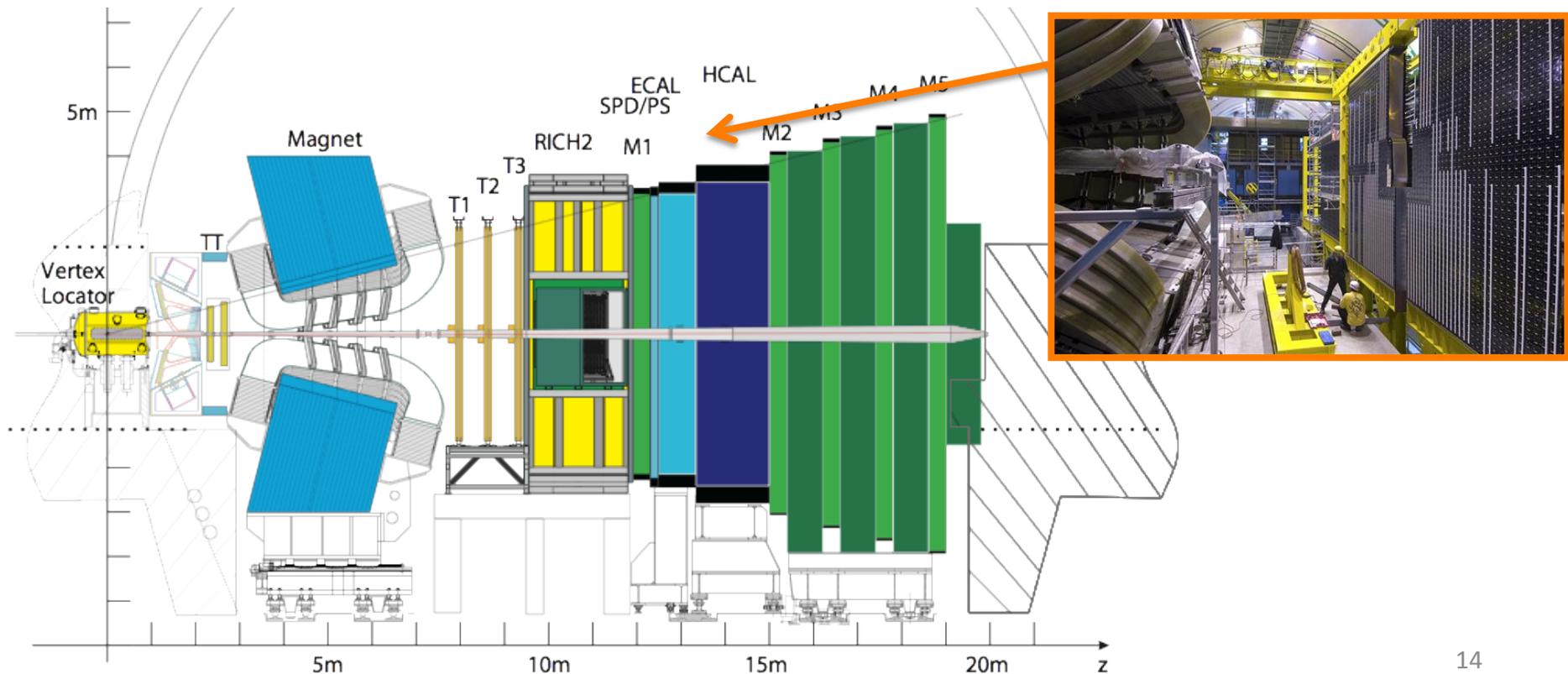
# The LHCb detector

- RICH detectors: hadron ID
  - RICH1 uses aerogel and  $C_4F_{10}$  to cover 2-60 GeV/c
  - RICH2 uses  $CF_4$  to cover 20-100 GeV/c
  - Excellent  $\pi/K/p$  separation up to 100 GeV/c



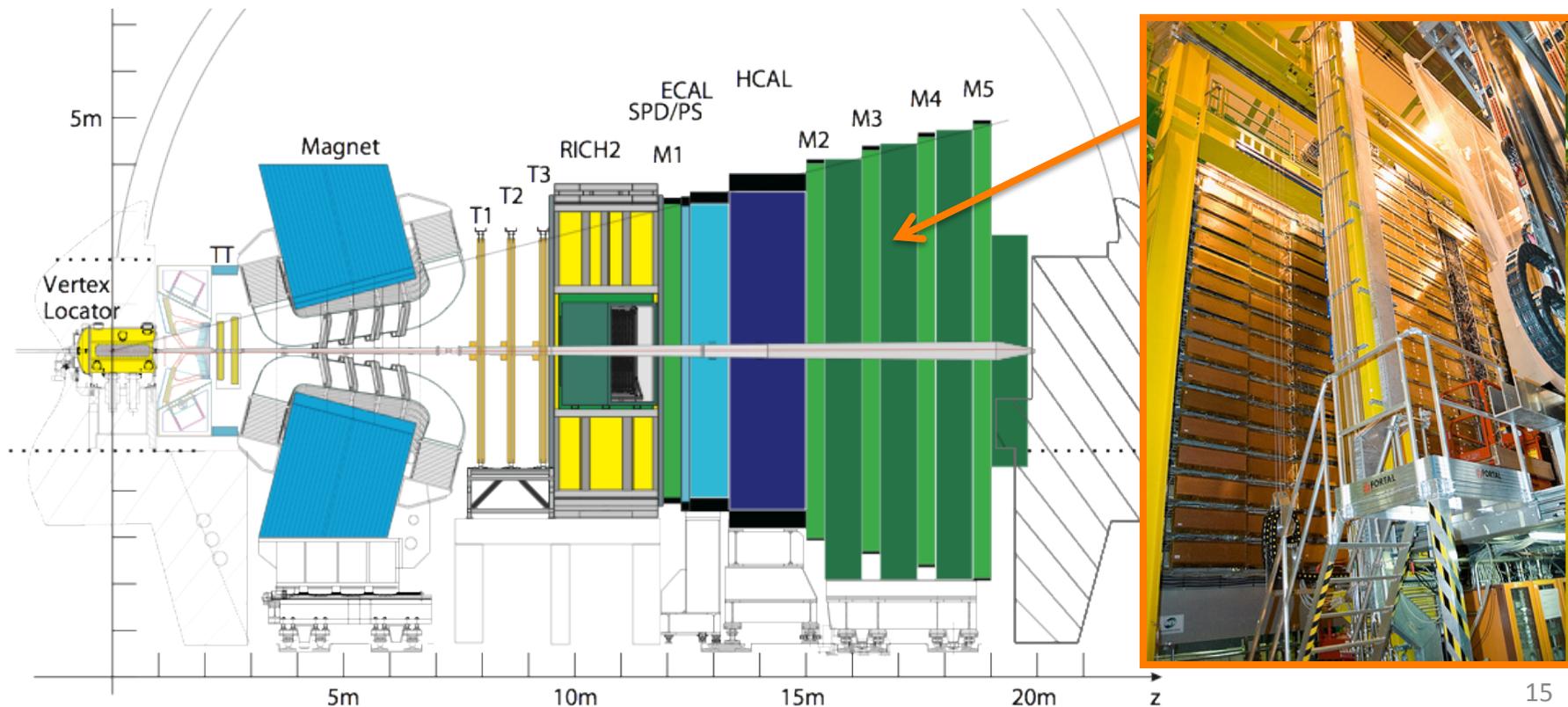
# The LHCb detector

- CALORIMETERS: trigger, photon/electron ID
  - Preshower + SPD + electromagnetic + hadronic calorimeters
  - Vital for hardware-level hadron triggering



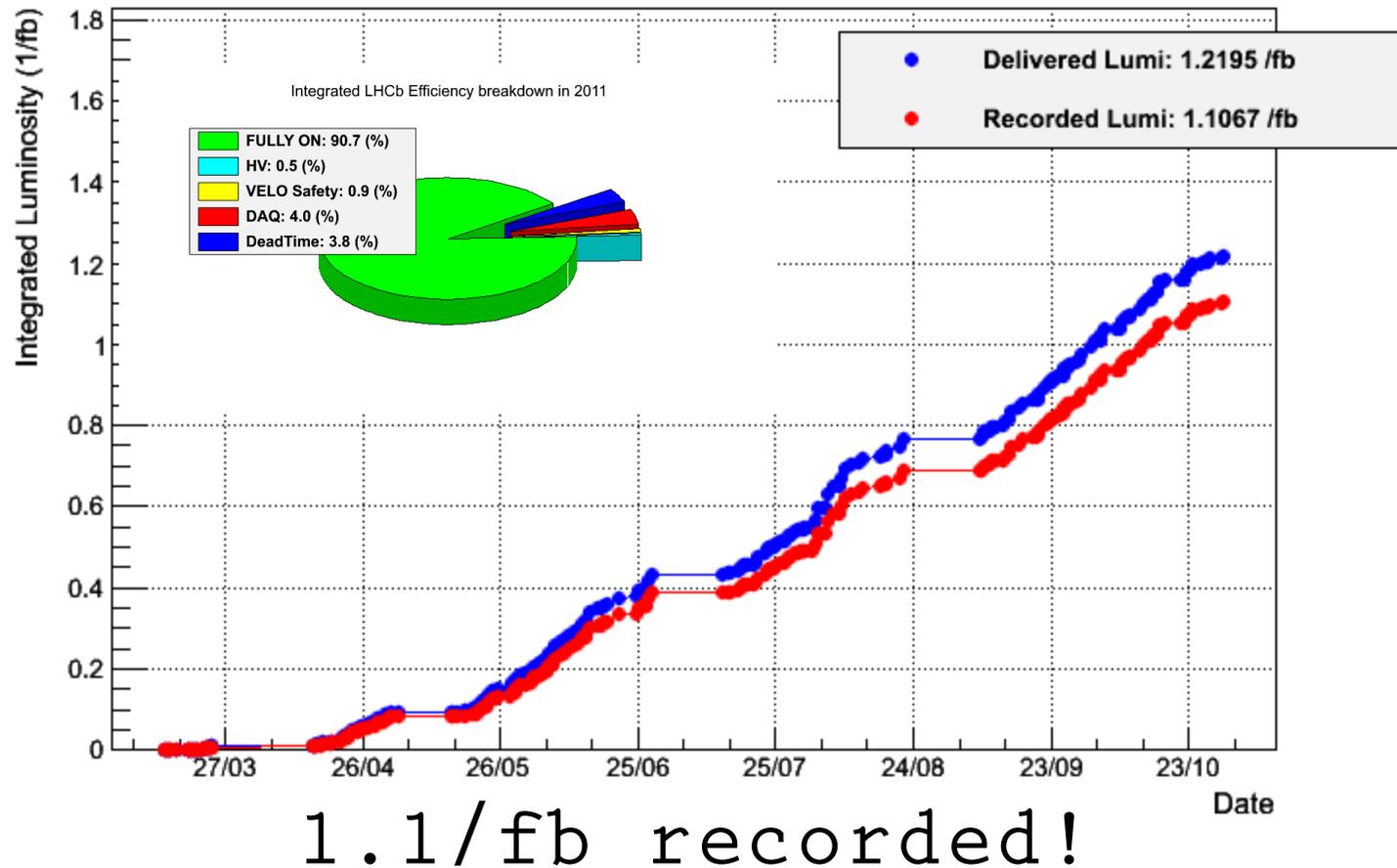
# The LHCb detector

- MUON STATIONS: muon ID
  - Five stations, used also in hardware trigger.
  - Excellent muon/pion separation (single hadron mis-ID rate 0.7% Phys. Lett. B699 (2011) 330)



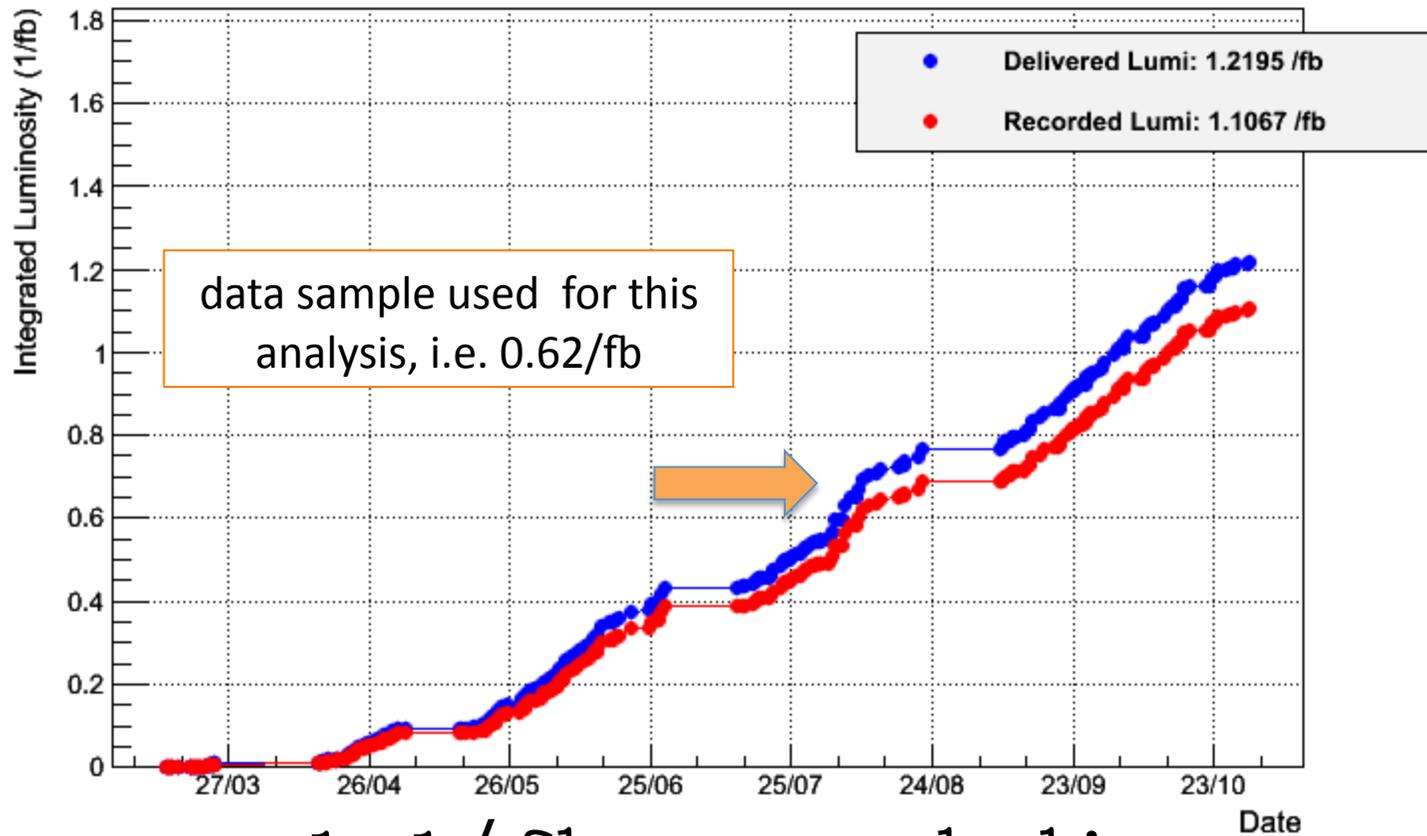
# Data-taking

LHCb integrated Luminosity at 7 TeV in 2011



# Data-taking

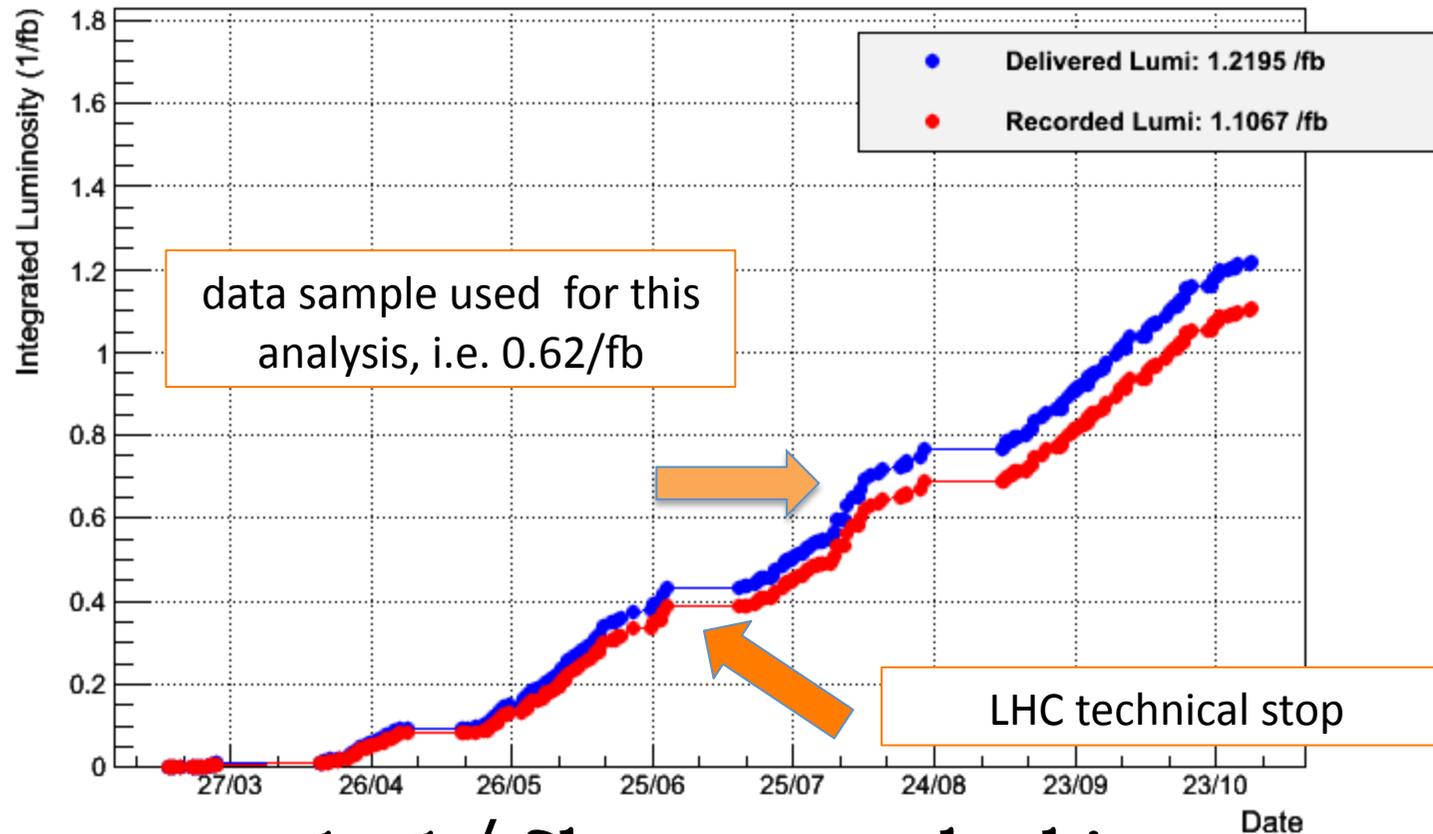
LHCb integrated Luminosity at 7 TeV in 2011



1.1/fb recorded!

# Data-taking

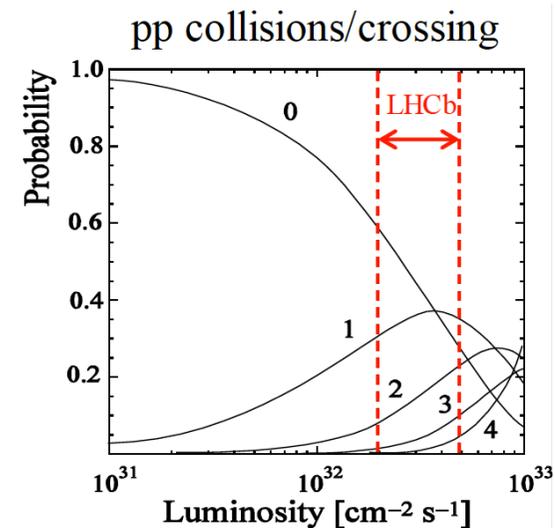
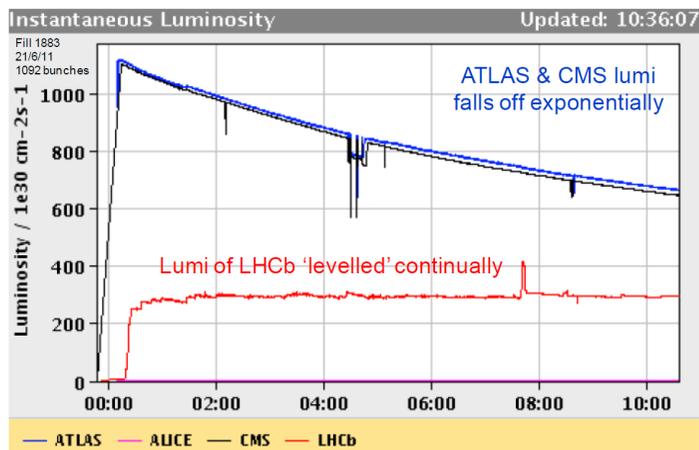
LHCb integrated Luminosity at 7 TeV in 2011



1.1/fb recorded!

# Running strategy

- LHCb has different runnings condition with respect to ATLAS and CMS
  - lower luminosity at the interaction point
- LHCb ran above its design luminosity
  - Average  $L \sim 3 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$  (nominal  $2 \times 10^{32}$ )
  - less bunches than nominal (50 ns bunch spacing)
- Need to cope with higher occupancies
  - More pile-up: average  $\mu \sim 1.5$  (nominal 0.5)
  - Continuous, automatic adjustment of offset of colliding beams.



# The trigger

(from charm point of view)

LHC bunch-crossing frequency  
Max possible 40 MHz  
Visible collision 10 MHz



10 MHz

L0: hardware trigger  
Hadrons: require cluster with high  $E_T$   
Also muon, electron triggers



1 MHz

HLT1: inclusive software trigger  
Hadrons: require track with high IP,  $p_T$   
Also muon, electron and other triggers



50 kHz

HLT2: exclusive software trigger  
Require fully reconstructed  $D^0, D^+, D_s^+$

3 kHz



After hardware trigger we already have 50%  $c\bar{c}$  events (500 kHz).

No possibility of an inclusive charm trigger!

Instead, we select useful/reconstructable events from the most sensitive modes.

Storage  
About 3kHz total rate  
**1kHz charm<sup>20</sup>**

Time-integrated search for  
CPV in  $D^0 \rightarrow KK$  and  $D^0 \rightarrow \pi\pi$

# Time-integrated CP asymmetry

(what we measure at LHCb)

- We are looking for CP asymmetry defined as

$$A_{CP}(f) = \frac{\Gamma(D^0 \rightarrow f) - \Gamma(\bar{D}^0 \rightarrow f)}{\Gamma(D^0 \rightarrow f) + \Gamma(\bar{D}^0 \rightarrow f)}$$

with  $f=KK$  and  $f=\pi\pi$  and

- The flavor of the initial state ( $D^0$  or  $\bar{D}^0$ ) is tagged by requiring a  $D^{*+} \rightarrow D^0 \pi_s^+$  decay, with the flavour determined by the charge of the slow pion ( $\pi_s^+$ )
- “slow” because of its lower average momentum ( $\sim 5$  GeV/c) with respect to the  $D^0$  daughters ( $\sim 30$  GeV/c)

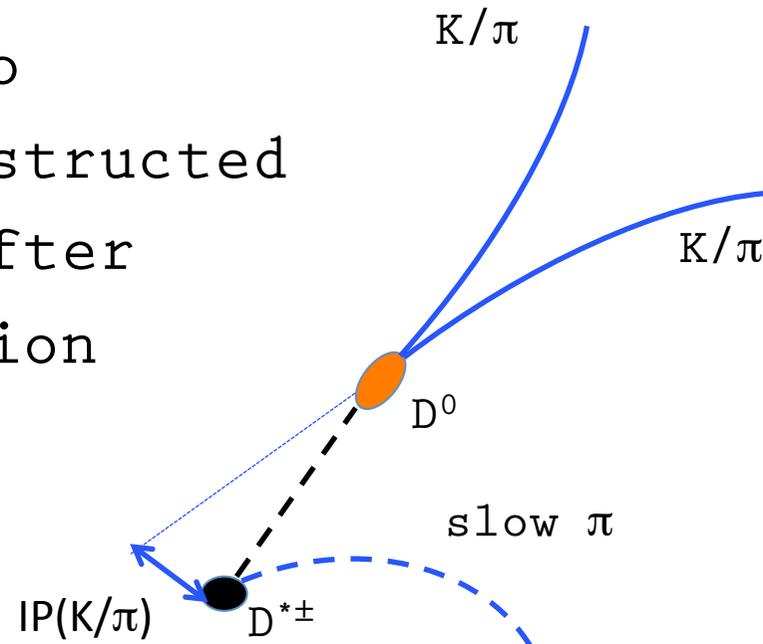
# Time-integrated CP asymmetry

(what we measure at LHCb)

- The raw asymmetry for tagged  $D^0$  decays to a final state  $f$  is given by

$$A_{raw}(f) = \frac{N(D^{*+} \rightarrow D^0(f)\pi_s^+) - N(D^{*-} \rightarrow \bar{D}^0(\bar{f})\pi_s^-)}{N(D^{*+} \rightarrow D^0(f)\pi_s^+) + N(D^{*-} \rightarrow \bar{D}^0(\bar{f})\pi_s^-)}$$

- where  $N(X)$  refers to the number of reconstructed events of decay  $X$  after background subtraction



# Time-integrated CP asymmetry (what we measure at LHCb)

- What we measure is the physical asymmetry plus asymmetries due both to production and detector effects

$$A_{\text{raw}}(f) = A_{CP}(f) + A_D(f) + A_D(\pi_s) + A_P(D^{*+})$$

# Time-integrated CP asymmetry (what we measure at LHCb)

- What we measure is the physical asymmetry plus asymmetries due both to production and detector effects

$$A_{\text{raw}}(f) = A_{CP}(f) + A_D(f) + A_D(\pi_s) + A_P(D^{*+})$$

- First order expansion assumes raw asymmetry not large
  - ... which is true: 0(%)

# Time-integrated CP asymmetry (what we measure at LHCb)

- What we measure is the physical asymmetry plus asymmetries due both to production and detector effects

$$A_{\text{raw}}(f) = A_{CP}(f) + A_D(f) + A_D(\pi_s) + A_P(D^{*+})$$



Physics CP asymmetry

# Time-integrated CP asymmetry (what we measure at LHCb)

- What we measure is the physical asymmetry plus asymmetries due both to production and detector effects

$$A_{\text{raw}}(f) = A_{CP}(f) + A_D(f) + A_D(\pi_s) + A_P(D^{*+})$$

The diagram illustrates the decomposition of the raw CP asymmetry into its constituent parts. The equation  $A_{\text{raw}}(f) = A_{CP}(f) + A_D(f) + A_D(\pi_s) + A_P(D^{*+})$  is shown. The term  $A_{CP}(f)$  is enclosed in a red box, and a red arrow points from a red box labeled "Physics CP asymmetry" below to it. The term  $A_D(f)$  is enclosed in a black box, and a black arrow points from a black box labeled "Detection asymmetry of  $D^0$ " below to it.

# Time-integrated CP asymmetry (what we measure at LHCb)

- What we measure is the physical asymmetry plus asymmetries due both to production and detector effects

$$A_{\text{raw}}(f) = A_{CP}(f) + A_D(f) + A_D(\pi_s) + A_P(D^{*+})$$

The diagram illustrates the decomposition of the raw CP asymmetry  $A_{\text{raw}}(f)$  into four components, each enclosed in a colored box:

- $A_{CP}(f)$  is enclosed in a red box. A red arrow points from a red box labeled "Physics CP asymmetry" below to this term.
- $A_D(f)$  is enclosed in a black box. A black arrow points from a black box labeled "Detection asymmetry of  $D^0$ " below to this term.
- $A_D(\pi_s)$  is enclosed in a blue box. A blue arrow points from a blue box labeled "Detection asymmetry of 'slow' pions" below to this term.
- $A_P(D^{*+})$  is not enclosed in a box.

# Time-integrated CP asymmetry (what we measure at LHCb)

- What we measure is the physical asymmetry plus asymmetries due both to production and detector effects

$$A_{\text{raw}}(f) = A_{CP}(f) + A_D(f) + A_D(\pi_s) + A_P(D^{*+})$$

The diagram illustrates the decomposition of the raw asymmetry  $A_{\text{raw}}(f)$  into four components, each enclosed in a colored box:

- $A_{CP}(f)$  (red box): Labeled "Physics CP asymmetry" (red box) with a red arrow pointing to it.
- $A_D(f)$  (black box): Labeled "Detection asymmetry of  $D^0$ " (black box) with a black arrow pointing to it.
- $A_D(\pi_s)$  (blue box): Labeled "Detection asymmetry of 'slow' pions" (blue box) with a blue arrow pointing to it.
- $A_P(D^{*+})$  (green box): Labeled "Production asymmetry" (green box) with a green arrow pointing to it.

- $D/\bar{D}$  (as well as  $B/\bar{B}$ ) production asymmetries need to be taken into account in proton-proton interactions at LHC

# Time-integrated CP asymmetry (what we measure at LHCb)

- What we measure is the physical asymmetry plus asymmetries due both to production and detector effects

$$A_{\text{raw}}(f) = A_{CP}(f) + \cancel{A_D(f)} + A_D(\pi_s) + A_P(D^{*+})$$

The diagram illustrates the components of the raw asymmetry  $A_{\text{raw}}(f)$ . The equation is  $A_{\text{raw}}(f) = A_{CP}(f) + \cancel{A_D(f)} + A_D(\pi_s) + A_P(D^{*+})$ . The term  $A_{CP}(f)$  is enclosed in a red box, with a red arrow pointing to a red box labeled "Physics CP asymmetry". The term  $\cancel{A_D(f)}$  is enclosed in a black box with a large black 'X' over it, and a black arrow points from a black box labeled "Detection asymmetry of  $D^0$ " to it. The term  $A_D(\pi_s)$  is enclosed in a blue box, with a blue arrow pointing from a blue box labeled "Detection asymmetry of 'slow' pions" to it. The term  $A_P(D^{*+})$  is enclosed in a green box, with a green arrow pointing from a green box labeled "Production asymmetry" to it.

- No detection asymmetry for  $D^0$  decays to  $K^-K^+$  or  $\pi^-\pi^+$

# Time-integrated CP asymmetry (what we measure at LHCb)

- ... if we take the raw asymmetry difference

$$\Delta A_{CP} \equiv A_{raw}(KK) - A_{raw}(\pi\pi) = A_{CP}(KK) - A_{CP}(\pi\pi)$$

- the production and the “slow” pion detection asymmetries will cancel

# Experimental status (individual $A_{CP}$ )

Year	Experiment	CP Asymmetry in the decay mode $D^0$ to $\pi^+\pi^-$	$[\Gamma(D^0)-\Gamma(D^0\text{bar})]/[\Gamma(D^0)+\Gamma(D^0\text{bar})]$
2010	CDF	<a href="#">M.J. Morello (CDF Collab.), Preprint (CHARM 2010).</a>	$+0.0022 \pm 0.0024 \pm 0.0011$
2008	BELLE	<a href="#">M. Staric et al. (BELLE Collab.), Phys. Lett. B 670, 190 (2008).</a>	$+0.0043 \pm 0.0052 \pm 0.0012$
2008	BABAR	<a href="#">B. Aubert et al. (BABAR Collab.), Phys. Rev. Lett. 100, 061803 (2008).</a>	$-0.0024 \pm 0.0052 \pm 0.0022$
2002	CLEO	<a href="#">S.E. Csorna et al. (CLEO Collab.), Phys. Rev. D 65, 092001 (2002).</a>	$+0.019 \pm 0.032 \pm 0.008$
2000	FOCUS	<a href="#">J.M. Link et al. (FOCUS Collab.), Phys. Lett. B 491, 232 (2000).</a>	$+0.048 \pm 0.039 \pm 0.025$
1998	E791	<a href="#">E.M. Aitala et al. (E791 Collab.), Phys. Lett. B 421, 405 (1998).</a>	$-0.049 \pm 0.078 \pm 0.030$
.	.	COMBOS average	$+0.0020 \pm 0.0022$

Year	Experiment	CP Asymmetry in the decay mode $D^0$ to $K^+K^-$	$[\Gamma(D^0)-\Gamma(D^0\text{bar})]/[\Gamma(D^0)+\Gamma(D^0\text{bar})]$
2011	CDF	<a href="#">A. Di Canto (CDF Collab.), Preprint (BEAUTY 2011).</a>	$-0.0024 \pm 0.0022 \pm 0.0010$
2008	BELLE	<a href="#">M. Staric et al. (BELLE Collab.), Phys. Lett. B 670, 190 (2008).</a>	$-0.0043 \pm 0.0030 \pm 0.0011$
2008	BABAR	<a href="#">B. Aubert et al. (BABAR Collab.), Phys. Rev. Lett. 100, 061803 (2008).</a>	$+0.0000 \pm 0.0034 \pm 0.0013$
2002	CLEO	<a href="#">S.E. Csorna et al. (CLEO Collab.), Phys. Rev. D 65, 092001 (2002).</a>	$+0.000 \pm 0.022 \pm 0.008$
2000	FOCUS	<a href="#">J.M. Link et al. (FOCUS Collab.), Phys. Lett. B 491, 232 (2000).</a>	$-0.001 \pm 0.022 \pm 0.015$
1998	E791	<a href="#">E.M. Aitala et al. (E791 Collab.), Phys. Lett. B 421, 405 (1998).</a>	$-0.010 \pm 0.049 \pm 0.012$
1995	CLEO	<a href="#">J.E. Bartelt et al. (CLEO Collab.), Phys. Rev. D 52, 4860 (1995).</a>	$+0.080 \pm 0.061$
1994	E687	<a href="#">P.L. Frabetti et al. (E687 Collab.), Phys. Rev. D 50, 2953 (1994).</a>	$+0.024 \pm 0.084$
.	.	COMBOS average	$-0.0023 \pm 0.0017$

Dominated by CDF, especially for  $D^0 \rightarrow \pi^+\pi^-$

$K^+K^-$  and  $\pi^+\pi^-$  values consistent with zero but have opposite sign.

# $\Delta A_{CP}$ interpretation

- The physics asymmetry of each final state may be written at first order as [arXiv:1103.5785]

$$A_{CP}(f) \approx a_{CP}^{\text{dir}}(f) + \frac{\langle t \rangle}{\tau} a_{CP}^{\text{ind}}$$

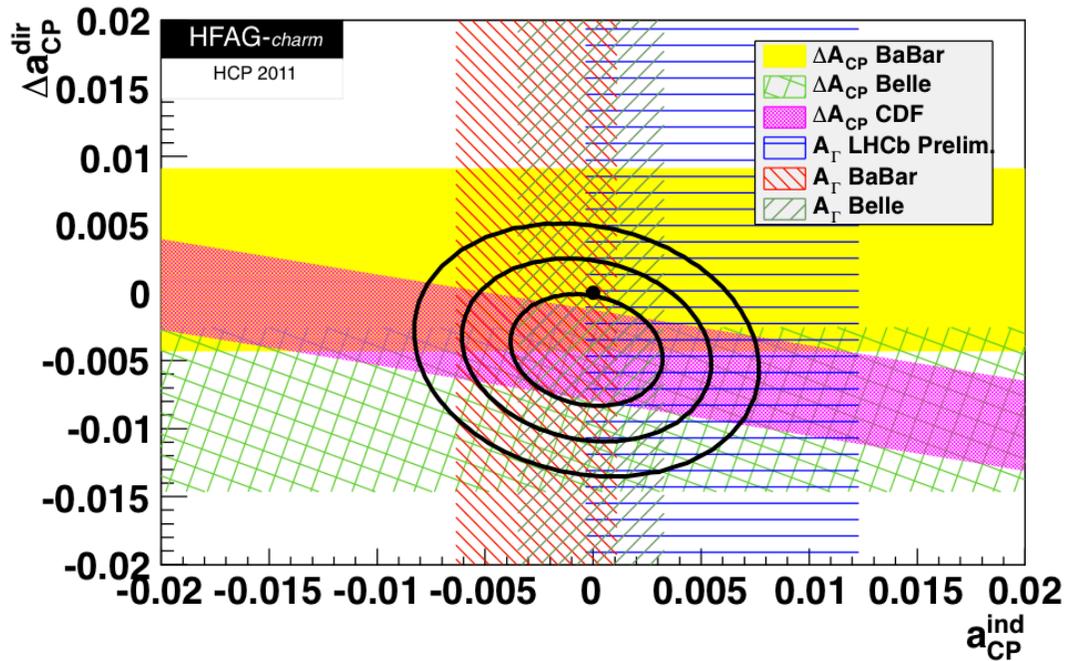
- $a_{CP}^{\text{dir}}(f)$  is the direct CP asymmetry in the decay
  - $\langle t \rangle$  is the average decay time  $\rightarrow$  experiment dependent
  - $\tau$  is the  $D^0$  lifetime
  - $a_{CP}^{\text{ind}}(f)$  is the CP asymmetry due to the the mixing and/or the interference between mixing and decay
- To a good approximation  $a_{CP}^{\text{ind}}(f)$  does not depend on the final state [arXiv:0609178], and so:

$$\Delta A_{CP} = [a_{CP}^{\text{dir}}(K^- K^+) - a_{CP}^{\text{dir}}(\pi^- \pi^+)] + \frac{\Delta \langle t \rangle}{\tau} a_{CP}^{\text{ind}}$$

- In the limit of U-spin symmetry,  $a_{CP}^{\text{dir}}(f)$  is equal in magnitude and opposite in sign for  $K^+ K^-$  and  $\pi^+ \pi^-$
- Interpretation of  $\Delta A_{CP}$  depends on experiment

# Experimental status

## ( $\Delta A_{CP}$ )



World average  $\Delta a_{CP}^{dir}$   
 $1.6\sigma$  from zero

HFAG combination

$$a_{CP}^{ind} = (-0.03 \pm 0.23)\%$$

$$\Delta a_{CP}^{dir} = (-0.42 \pm 0.27)\%$$

Consistency with NO  
 CPV hypothesis: 28%

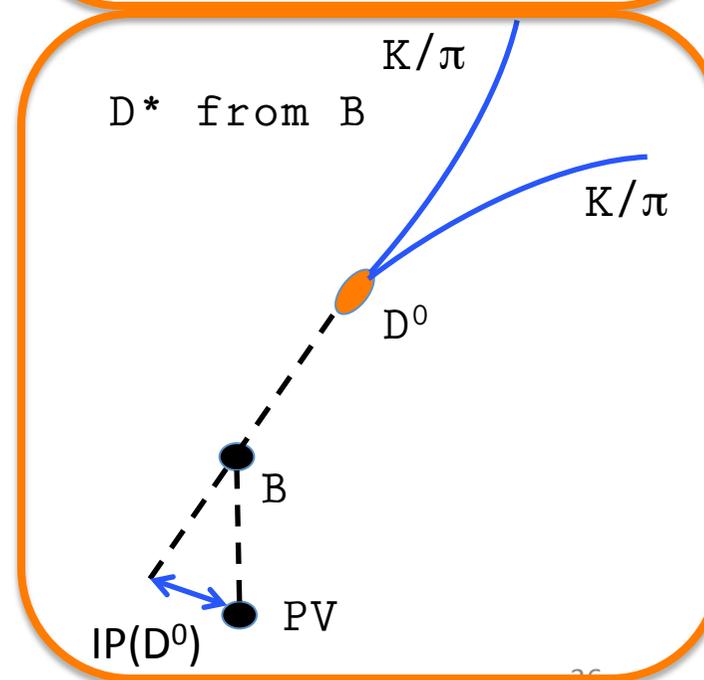
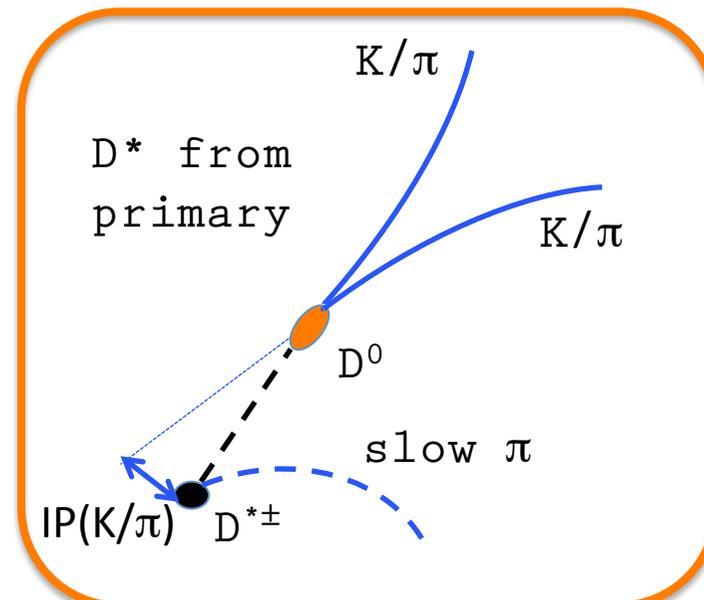
Recent CDF measurement  
 $\Delta A_{CP} = [-0.46 \pm 0.31 \pm 0.12]\%$   
 arXiv:1111.5023

# $\Delta A_{CP}$ extraction strategy

- $\Delta A_{CP}$  robust against systematics, however detector effect can induce different fake asymmetries for KK and  $\pi\pi$ :
  - Dependence of  $A_p(f)$  and  $A_D(f)$  with respect to KK/ $\pi\pi$  efficiency ratio
- Solution: divide data into bins of the variable (such that no correlation within bin) and treat each bin independently.
  - Divide data into kinematic bins of  $p_T$  of  $D^{*+}$ ,  $\eta$  of  $D^{*+}$ ,  $p$  of slow pion.
- Along similar lines:
  - split by magnet polarity (B field up/down)
  - split into left/right hemisphere (slow pion momentum points left/right of the bending plane)
  - split into two run groups (before & after technical stop)
- 216 independent measurements of  $\Delta A_{CP}$

# Event selection

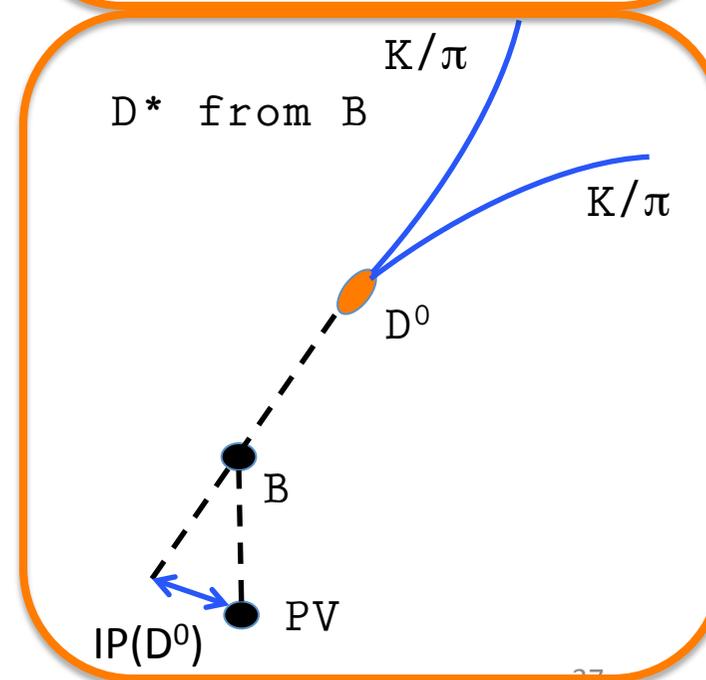
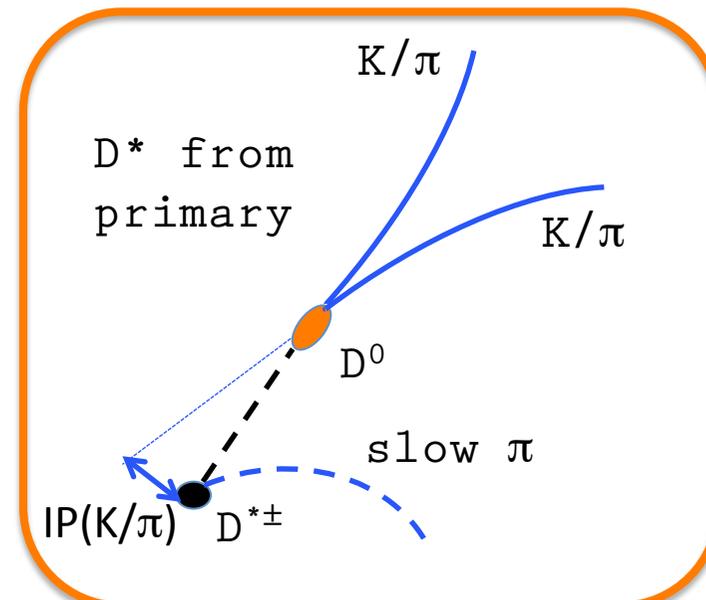
The following offline selection cuts have been applied on events which fired the software trigger explicitly on  $D^0$  candidate:



# Event selection

The following offline selection cuts have been applied on events which fired the software trigger explicitly on  $D^0$  candidate:

Track fit quality for all the tracks  
 $D^0$  and  $D^{*\pm}$  vertex fit quality



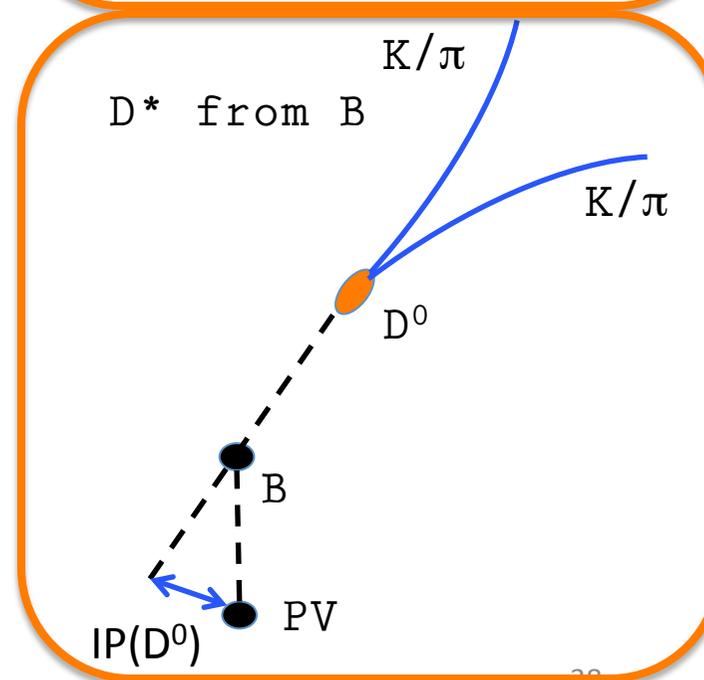
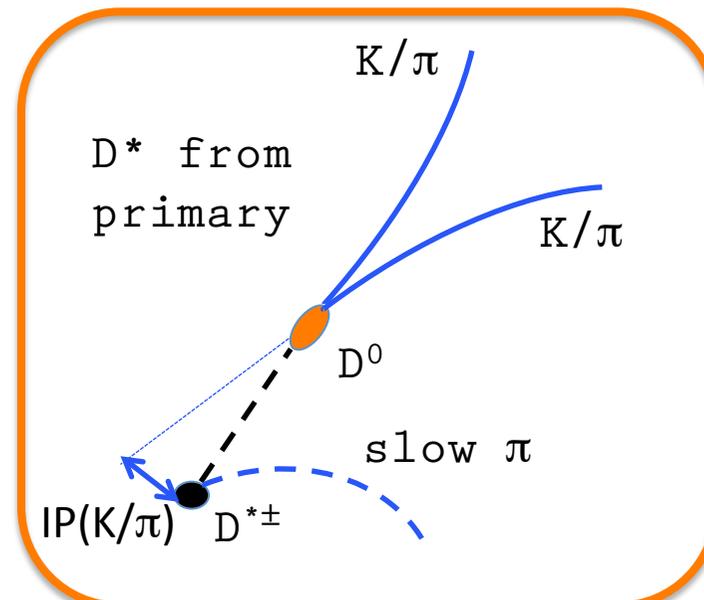
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Track fit quality for all the tracks

$D^0$  and  $D^{*\pm}$  vertex fit quality

Transverse momentum of  $D^0$  ( $p_T > 2$  GeV)



# Event selection

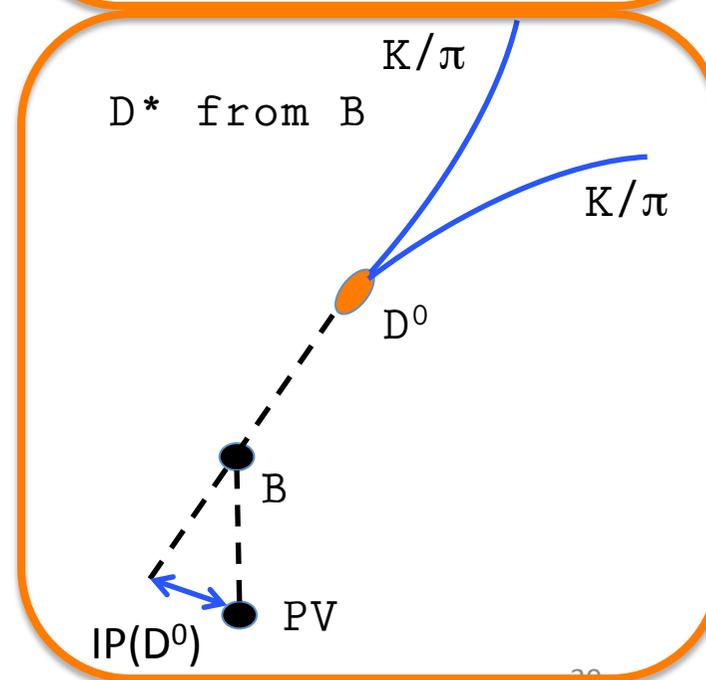
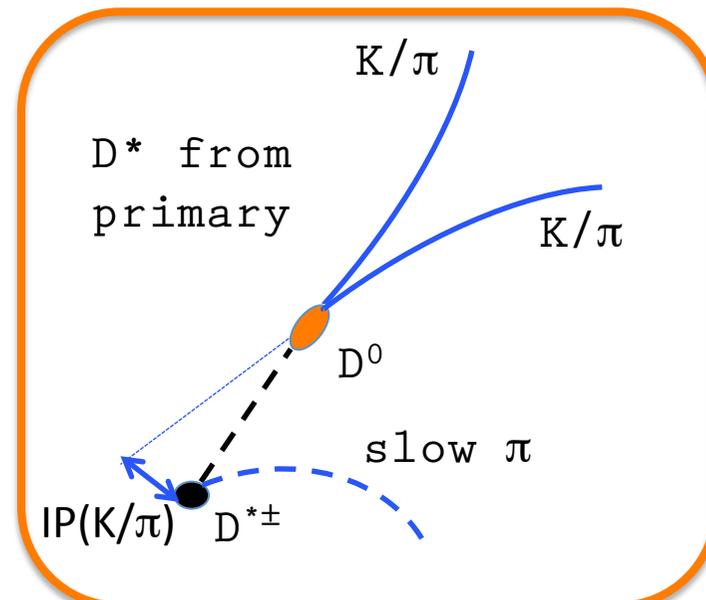
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$D^0$  and  $D^{*\pm}$  vertex fit quality

Transverse momentum of  $D^0$  ( $p_T > 2$  GeV)

Proper lifetime of  $D^0$  ( $ct > 100\mu\text{m}$ )



# Event selection

The following offline selection cuts have been applied on events which fired the software trigger explicitly on  $D^0$  candidate:

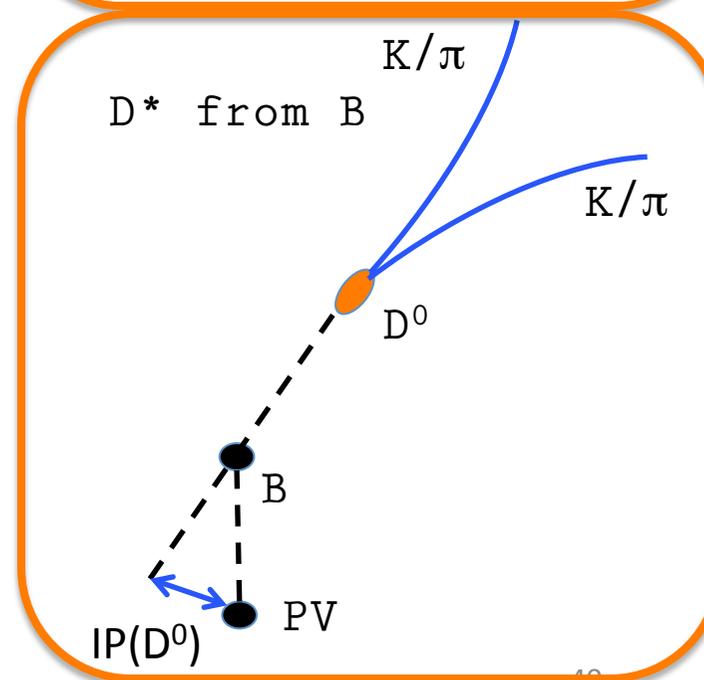
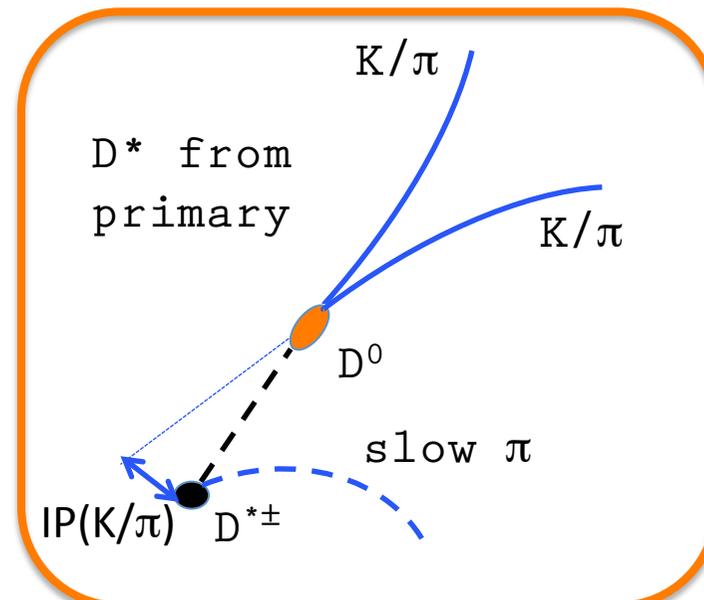
Track fit quality for all the tracks

$D^0$  and  $D^{*\pm}$  vertex fit quality

Transverse momentum of  $D^0$  ( $p_T > 2$  GeV)

Proper lifetime of  $D^0$  ( $ct > 100\mu\text{m}$ )

Angle between the  $D^0$  momentum in the lab frame and its daughter momenta in the  $D^0$  rest frame ( $|\cos \theta| < 0.9$ )



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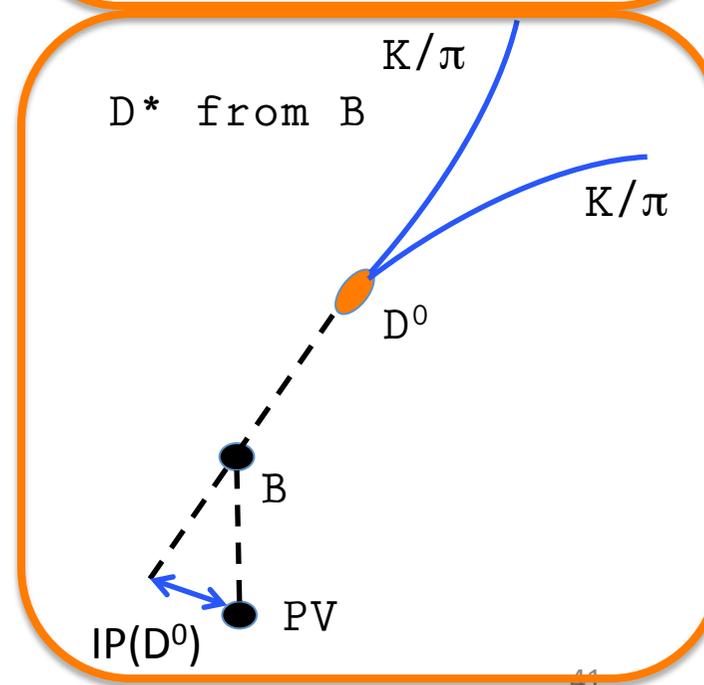
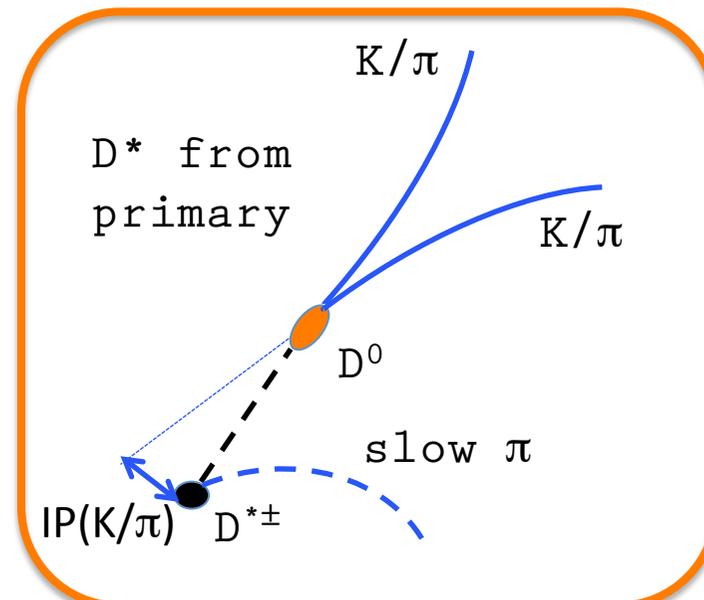
Proper lifetime of  $D^0$  ( $ct > 100 \mu\text{m}$ )

Angle between the  $D^0$  momentum in the lab frame and its daughter momenta in the  $D^0$  rest frame ( $|\cos \theta| < 0.9$ )

$D^0$  must point back to primary vertex (reject  $D^0$  coming B)

→ 3% of B contamination after this cut

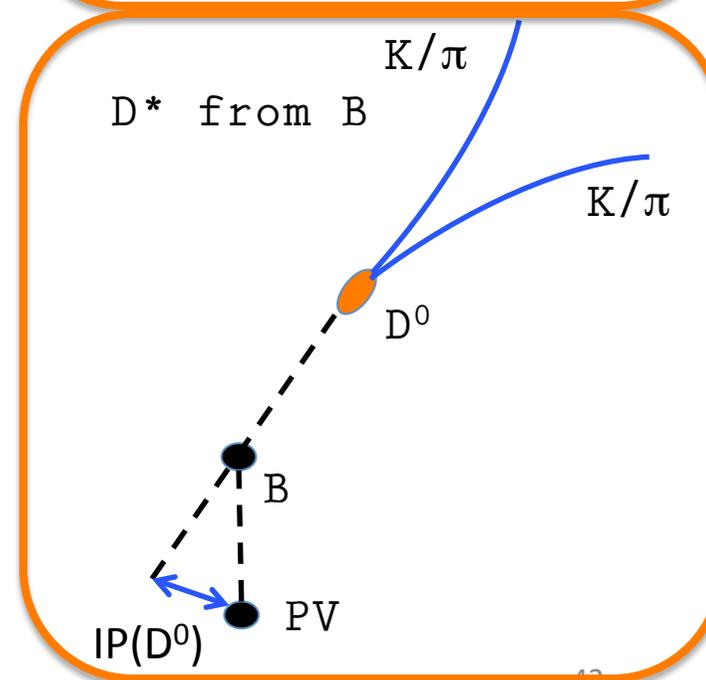
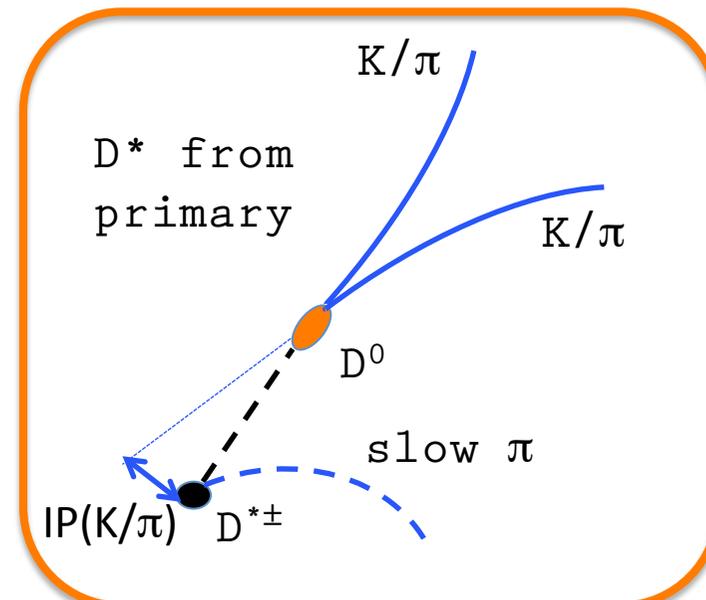
→ only lifetime measurements effected  
not  $\Delta A_{CP}$



# Event selection

The following offline selection cuts have been applied on events which fired the software trigger explicitly on  $D^0$  candidate:

$D^0$  daughter tracks must not point back to the primary

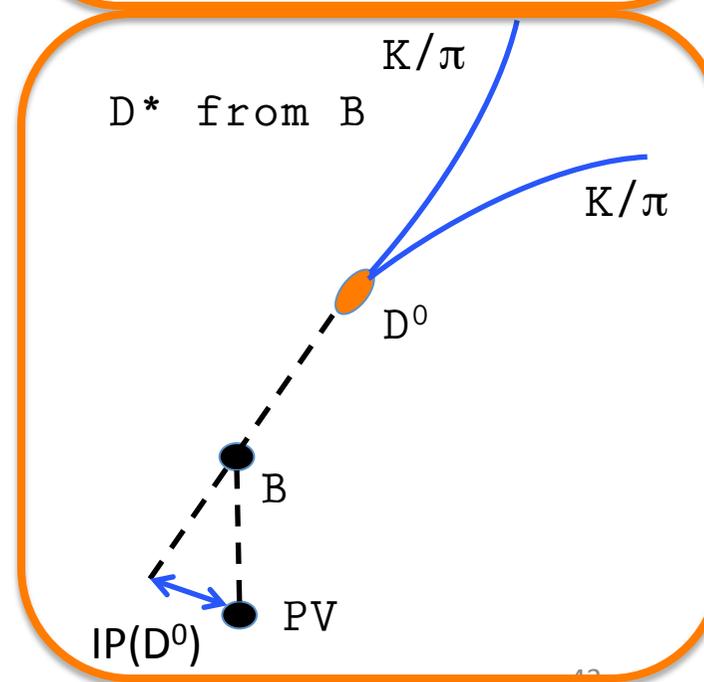
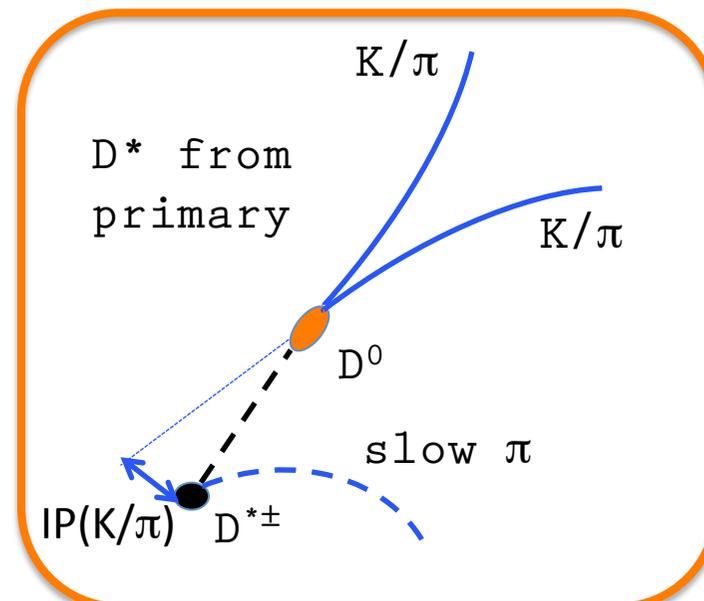


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Kaon/pion hadron ID cuts imposed with RICH information



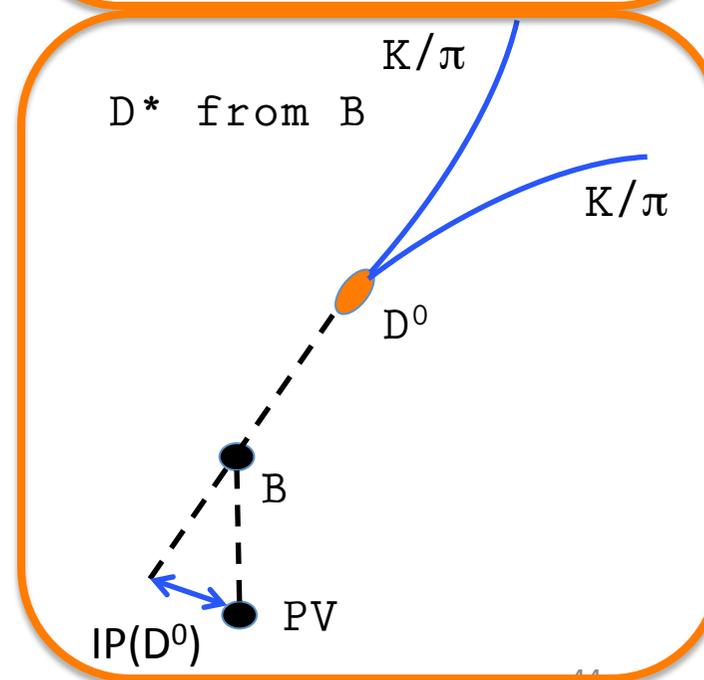
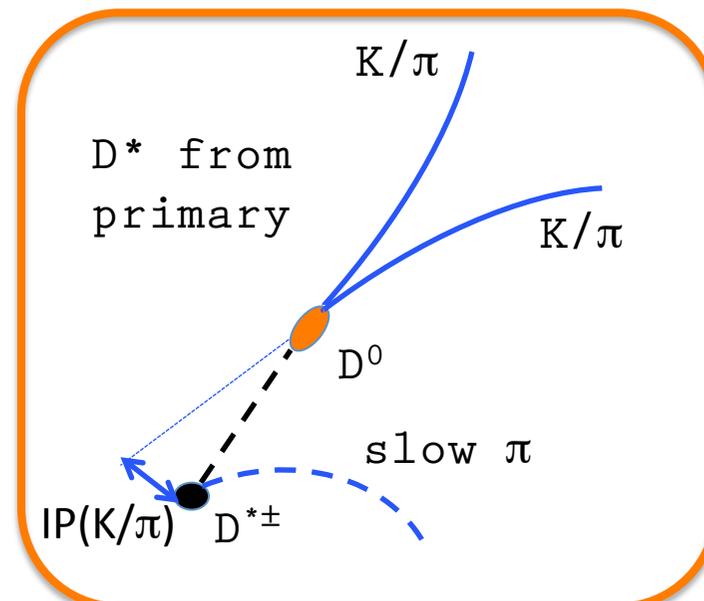
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Fiducial cuts to exclude edges where the B-field caused large  $D^{*+}/D^{*-}$  acceptance asymmetry



# Event selection

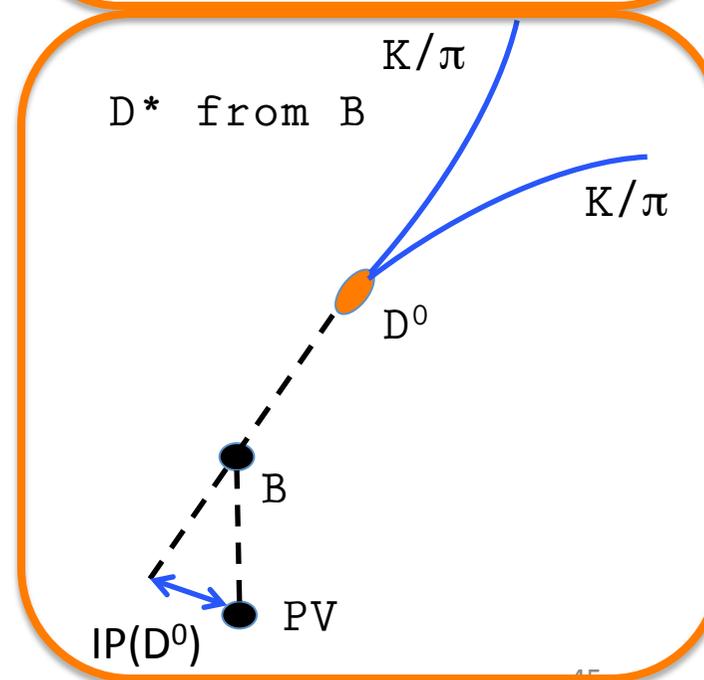
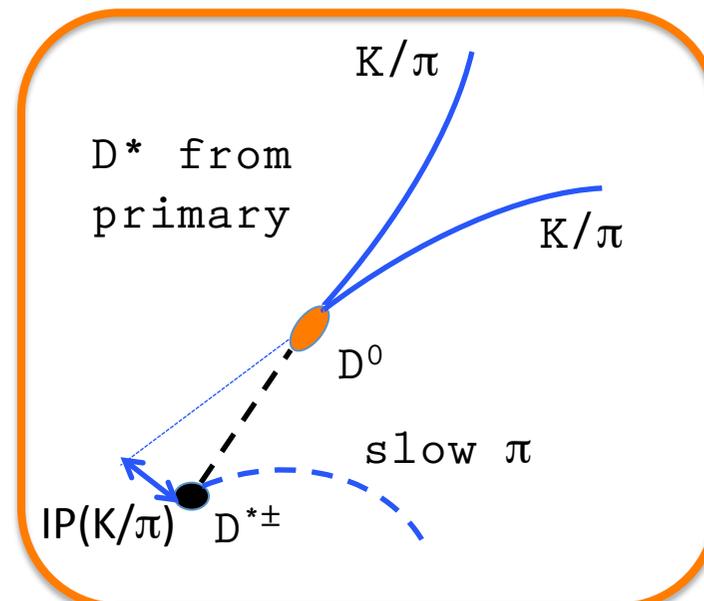
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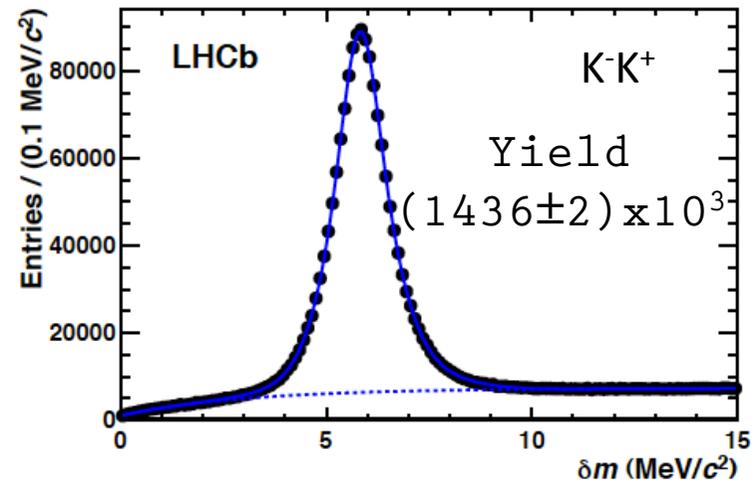
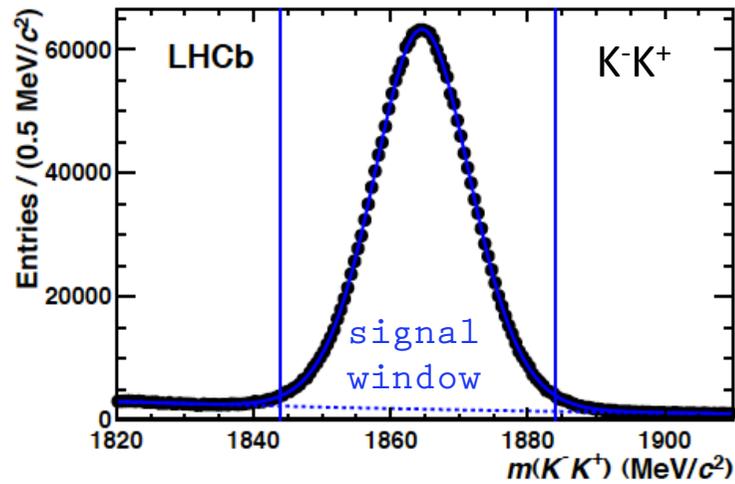
Fiducial cuts to exclude edges where the B-field caused large  $D^{*+}/D^{*-}$  acceptance asymmetry

$D^0$  mass window ( $1844 < m(D^0) < 1884$  MeV/ $c^2$ )



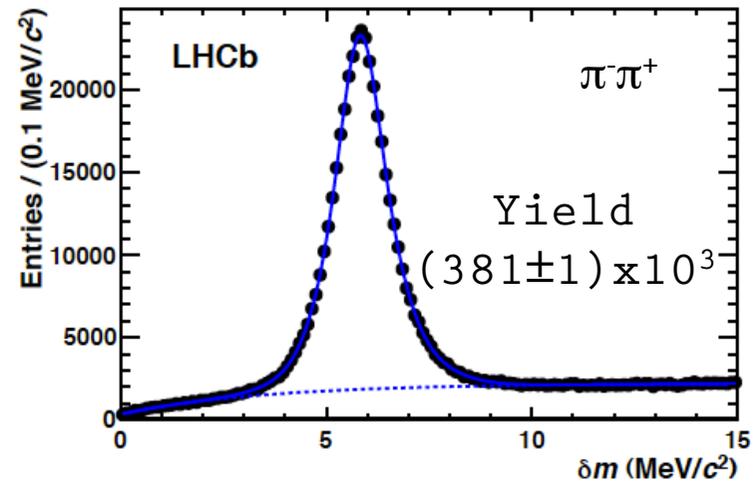
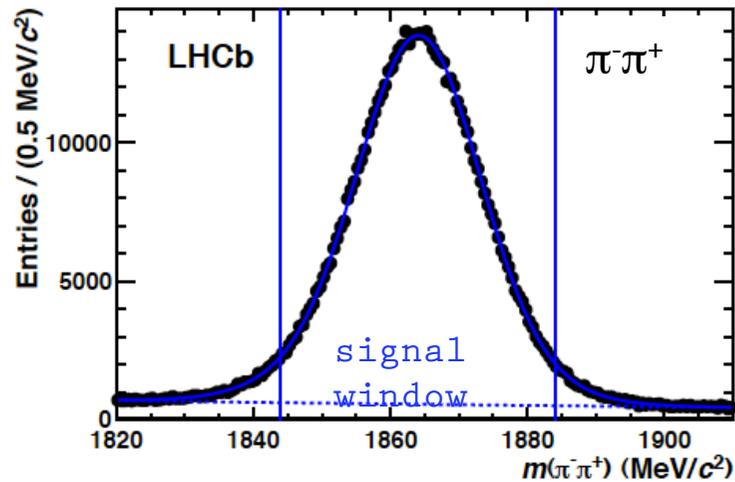
# Mass spectra

$$\delta m = m(h^+h^-\pi^+) - m(h^+h) - m(\pi^+)$$



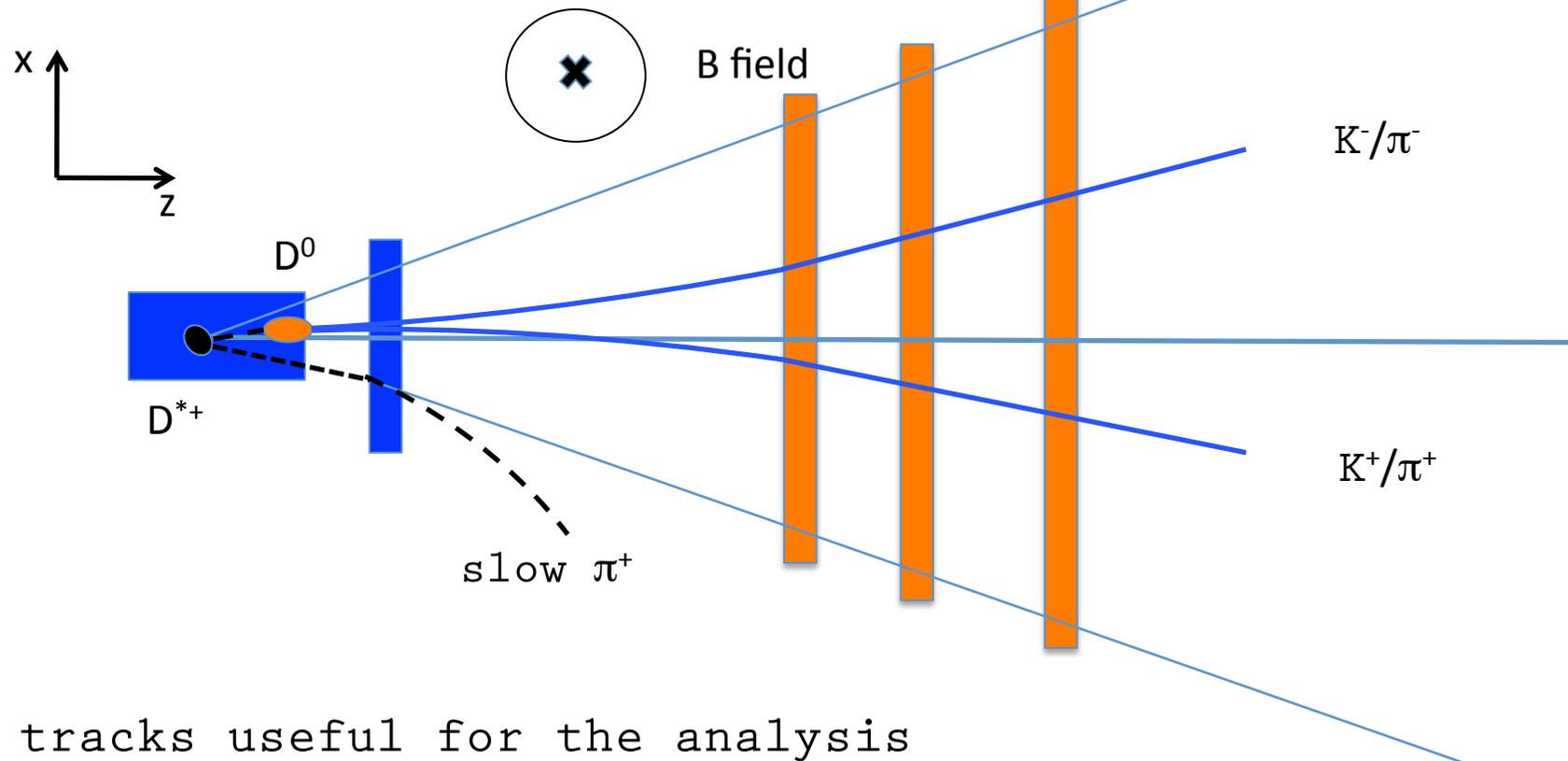
$$1844 < m(D^0) < 1884 \text{ MeV}/c^2$$

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# $D^{*+}/D^{*-}$ reconstruction efficiency

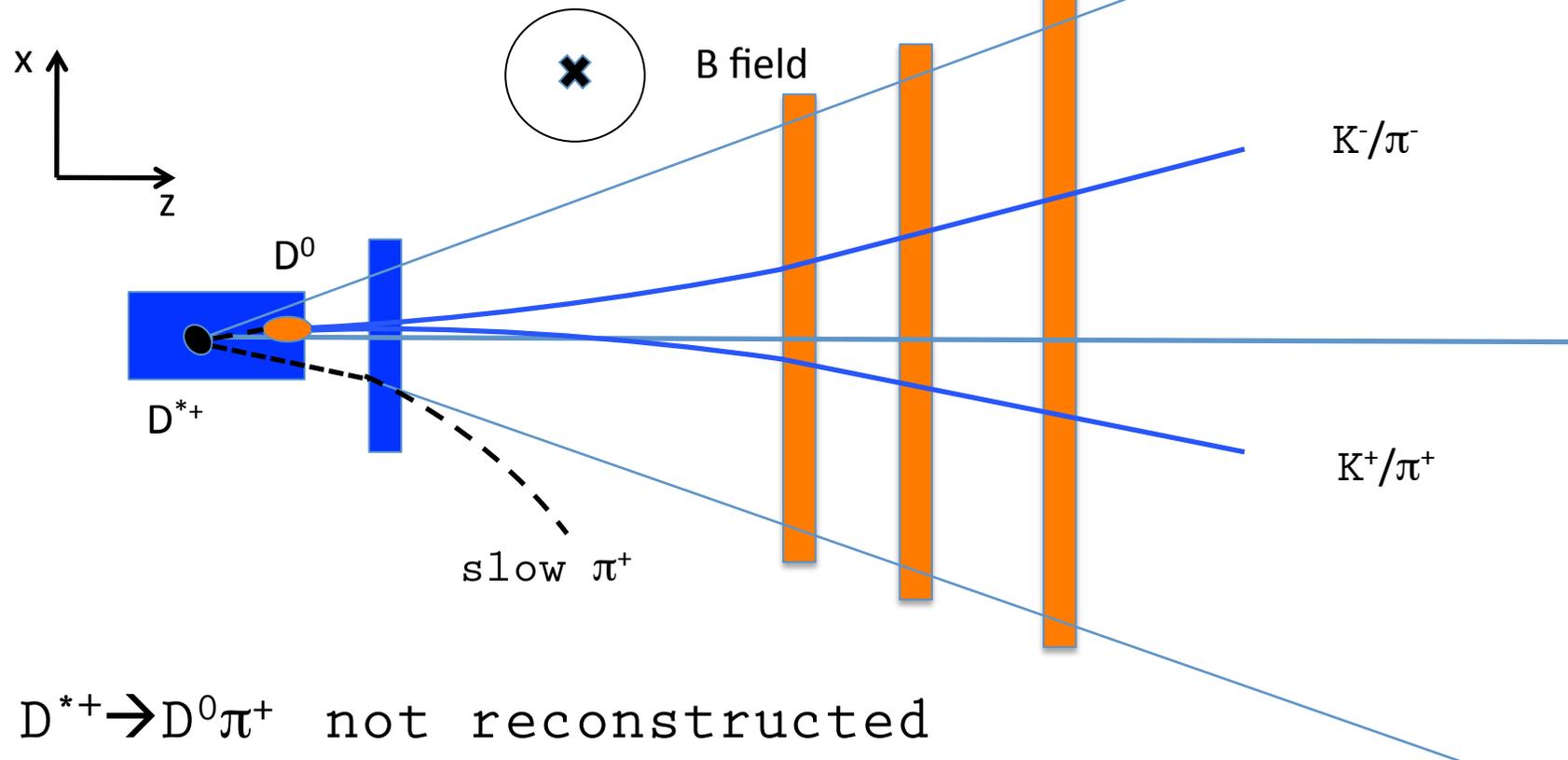
LHCb simplified bending plane view  
Only tracking systems shown  
Arbitrary scale used



tracks useful for the analysis  
must cross all the tracking  
station

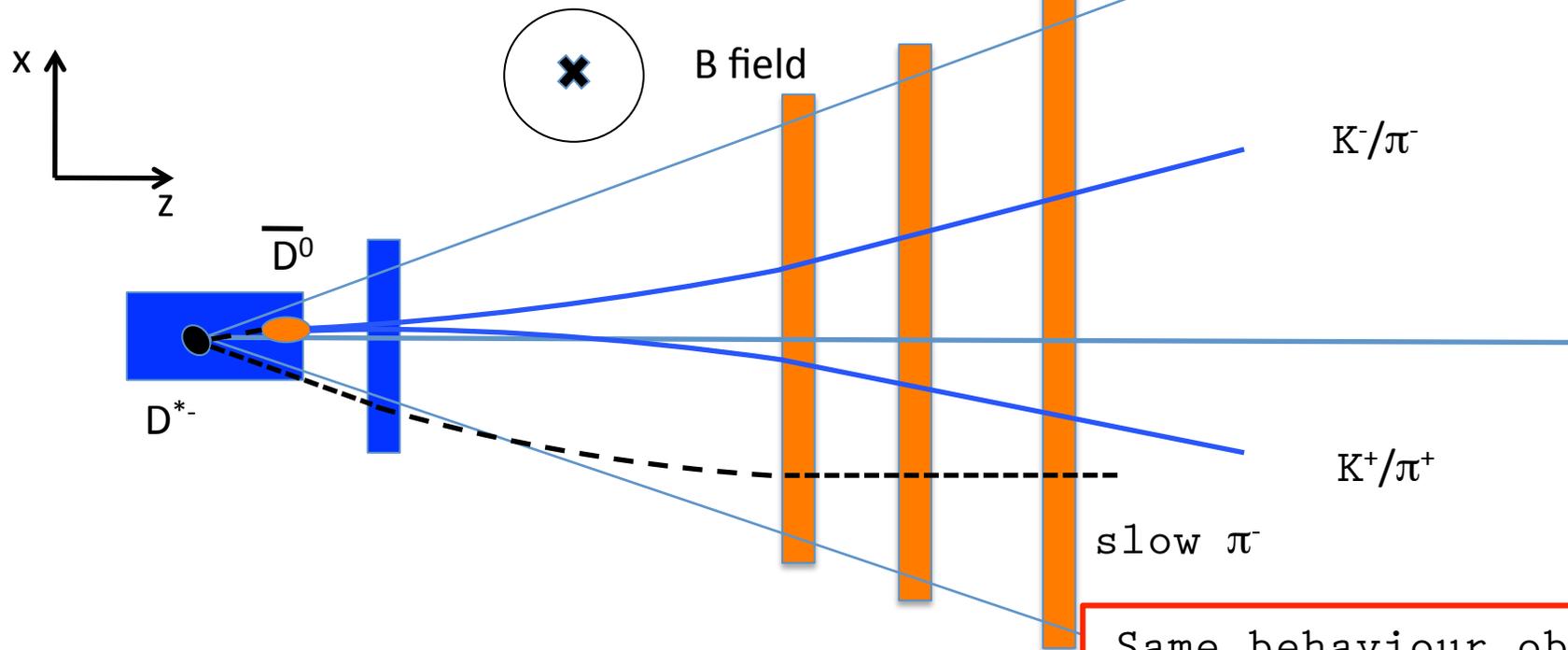
# $D^{*+}/D^{*-}$ reconstruction efficiency

LHCb simplified bending plane view  
Only tracking systems shown  
Arbitrary scale used



# $D^{*+}/D^{*-}$ reconstruction efficiency

LHCb simplified bending plane view  
Only tracking systems shown  
Arbitrary scale used



$D^{*+} \rightarrow D^0 \pi^+$  not reconstructed  
 $D^{*-} \rightarrow D^0 \pi^-$  reconstructed



Same behaviour observed also for tracks which cross the beam-pipe, ( i.e. small  $|P_y/P_z|$  of slow  $\pi$ )

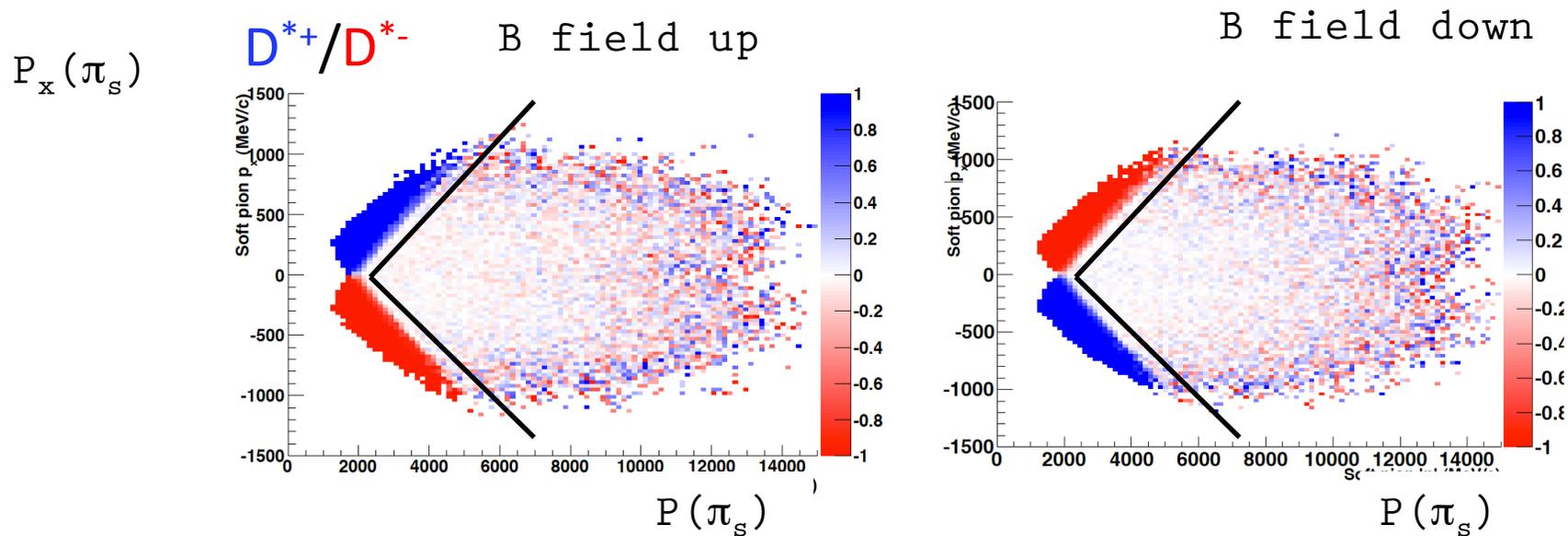
# Fiducial cuts

- There are regions of phase space where only  $D^{*+}$  or only  $D^{*-}$  is kinematically possible.
  - this causes large value of  $A_{CP}^{Raw}$  up to 100% in the edges regions where only  $D^{*+}$  or  $D^{*-}$  is reconstructed
- This asymmetry is independent of the  $D^0$  decay modes but it breaks the assumption that the raw asymmetries are small
- and it carries a risk of second-order systematic effects if the ratio of efficiencies of  $D^0 \rightarrow K^- K^+$  and  $D^0 \rightarrow \pi^- \pi^+$  varies in the affected region.

# Fiducial cuts

- The edge regions are therefore excluded with cuts in the slow pion( $P_x, P$ ) plane.

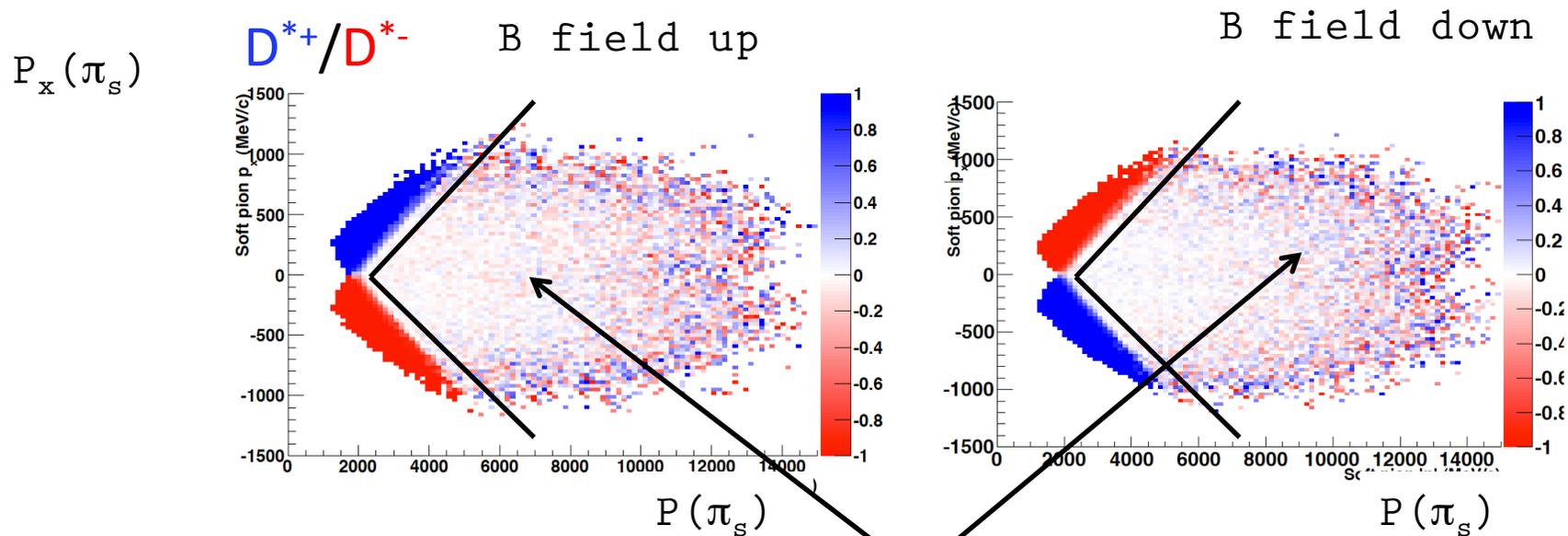
Raw asymmetry of  $D^{*+} \rightarrow D^0(KK)\pi^+$  and  $cc$  in the  $(P_x, P)$  plane of slow pion



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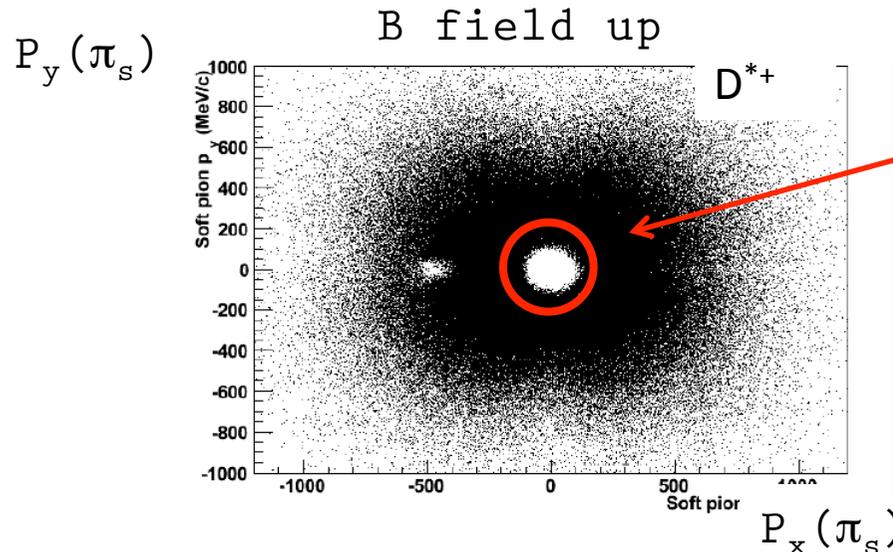
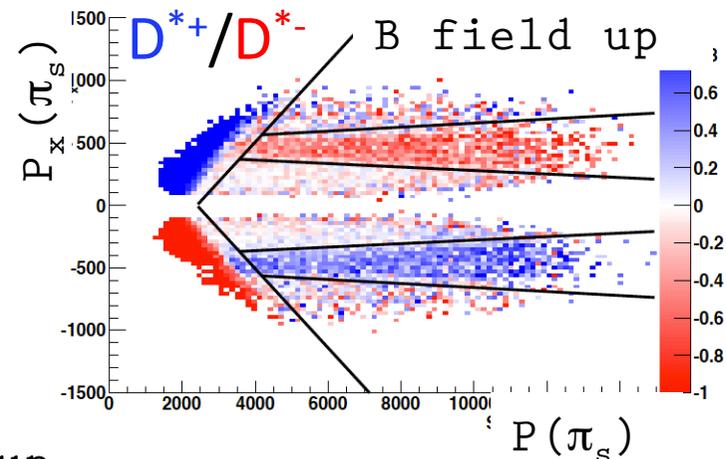
Accepted region  
reject 25% of events

# Fiducial cuts

- The edge regions are therefore excluded with cuts in the slow pion ( $P_x, P_y$ ) plane.

Raw asymmetry of  
 $D^{*+} \rightarrow D^0(KK)\pi^+ + cc$  in the  
 $(P_x, P_y)$  plane of slow pion

$|P_y/P_x| (\text{slow } \pi) < 0.2$   
 beam pipe region



Soft pions go  
 directly into the  
 beam pipe  
 (low  $P_x$  and  $P_y$ )  
 These events are  
 lost  
 No charge dependents

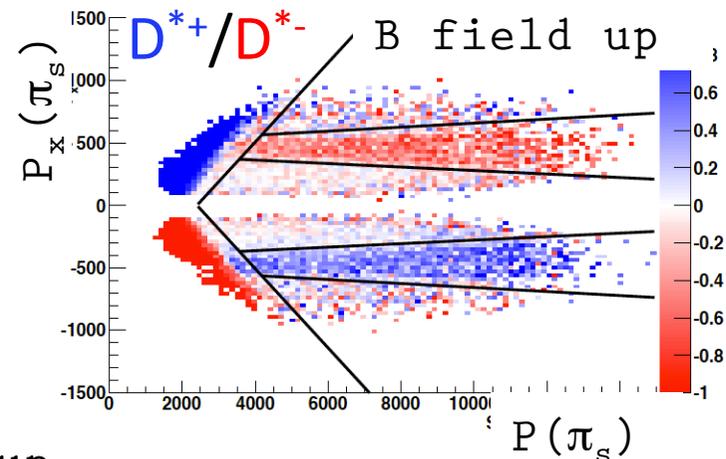
# Fiducial cuts

- The edge regions are therefore excluded with cuts in the slow pion ( $P_x, P_y$ ) plane. Further 5% events rejected

Raw asymmetry of  $D^{*+} \rightarrow D^0(KK)\pi^+ + cc$  in the ( $P_x, P_y$ ) plane of slow pion

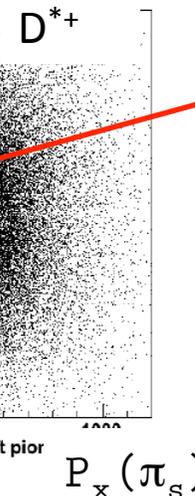
$$|P_y/P_x| (\text{slow } \pi) < 0.2$$

beam pipe region



$P_y (\pi_s)$

B field up



Soft pions swept through the beam pipe where there is no tracking station. These events are lost. Charged dependent

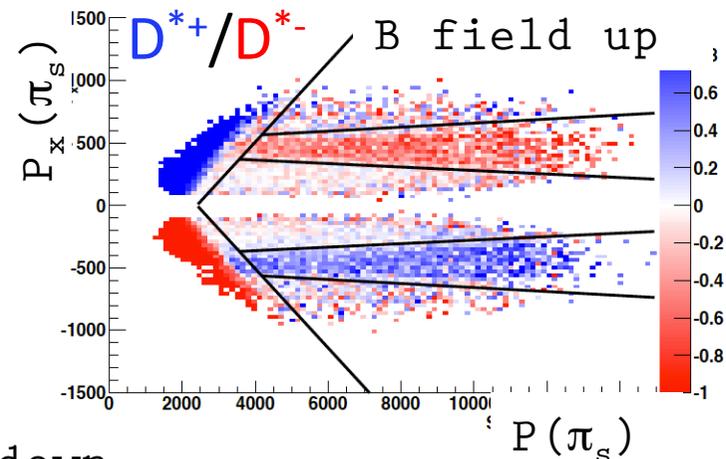
Soft pions go directly into the beam pipe (low  $P_x$  and  $P_y$ ). These events are lost. No charge dependents

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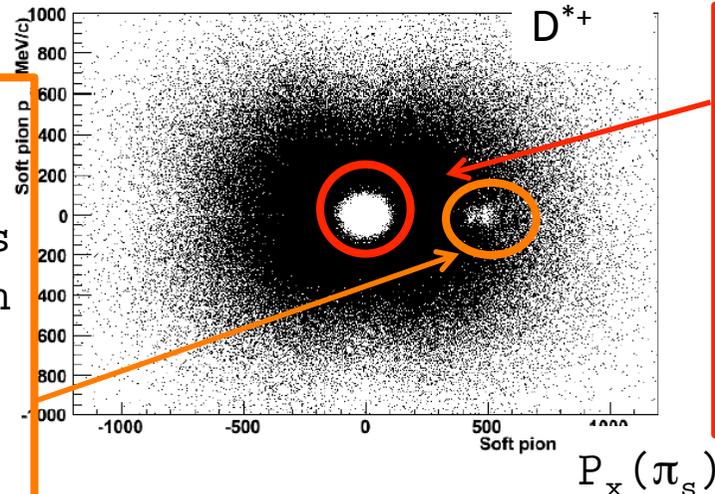
$|P_y/P_x| (\text{slow } \pi) < 0.2$   
beam pipe region



$P_y (\pi_s)$

B field down

Soft pions swept through the beam pipe where there is no tracking station. These events are lost. Charged dependent



Soft pions go directly into the beam pipe (low  $P_x$  and  $P_y$ ). These events are lost. No charge dependents

# Fit procedure

- Use 1D fits to mass difference

$$\delta m = m(h^+h^-\pi^+) - m(h^+h) - m(\pi^+)$$

- Signal model: double-Gaussian convolved with a function accounting for the asymmetric tail:

$$B(\delta m; s) = \Theta(\delta m) \delta m^s$$

- Background model:

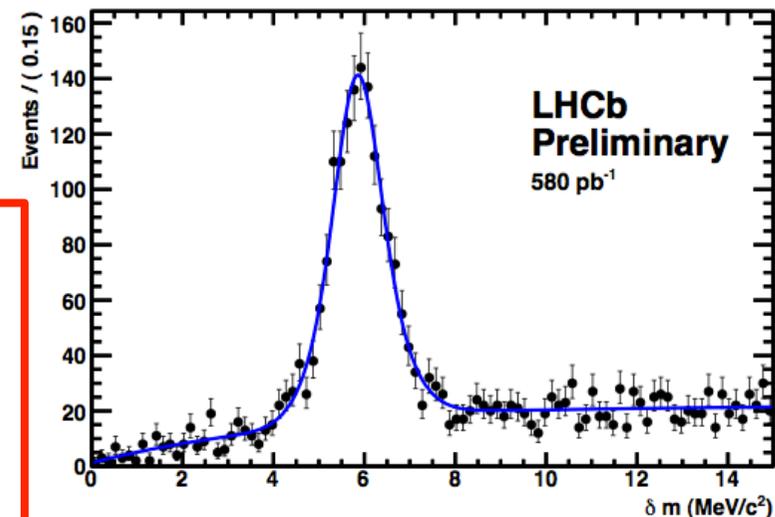
$$h(\delta m) = B \left[ 1 - \exp\left(-\frac{\delta m - \delta m_0}{c}\right) \right]$$

Consistency for  $\Delta A_{CP}$  among  
216 kinematic bins:

$$\chi^2/\text{NDF} = 211/215$$

( $\chi^2$  prob. 56%)

Example fit  $D^* \rightarrow D^0(KK)\pi$  in  
one kinematic bin



A weighted average of the kinematic bins yields the result

$$\Delta A_{CP} = [-0.82 \pm 0.21(\text{stat.})]\%$$

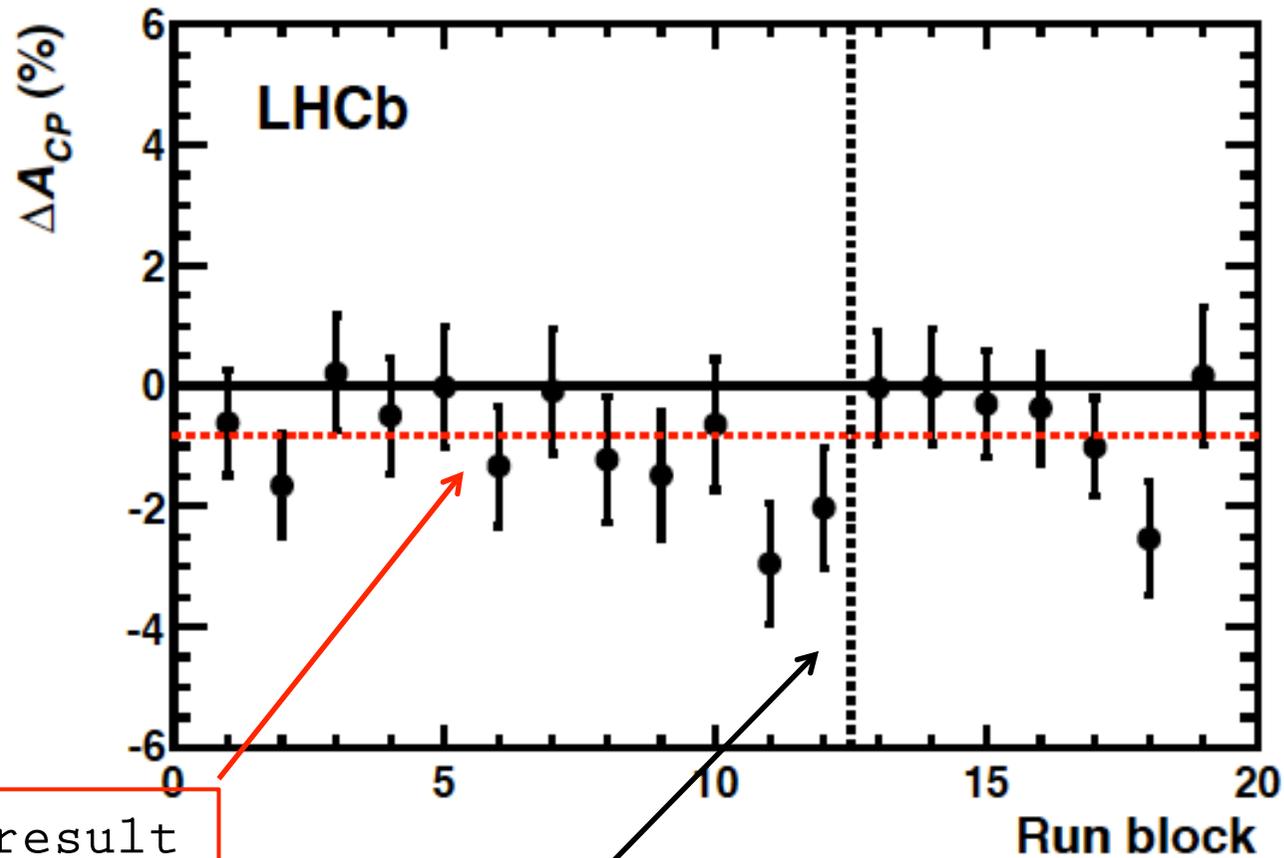
# Further cross checks

- Numerous crosschecks carried out, including:
  - Electron and muon vetoes on the soft pion and on the  $D^0$  daughters
  - Different kinematic binnings
  - Stability of result vs data taking-runs
  - Stability vs kinematic variables
  - Toy MC studies of fit procedure, statistical errors
  - Tightening of PID cuts on  $D^0$  daughters
  - Tightening of kinematic cuts
  - Variation with event track multiplicity
  - Use of other signal, background line-shapes in the fit
  - Use of alternative offline processing (skimming/ stripping)
  - Internal consistency between subsamples (splitting left/right, field up/ field down, etc)

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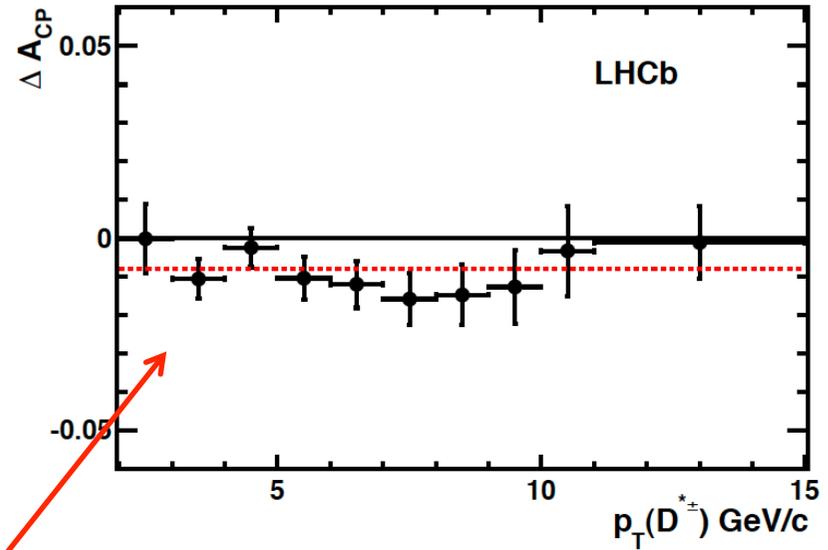
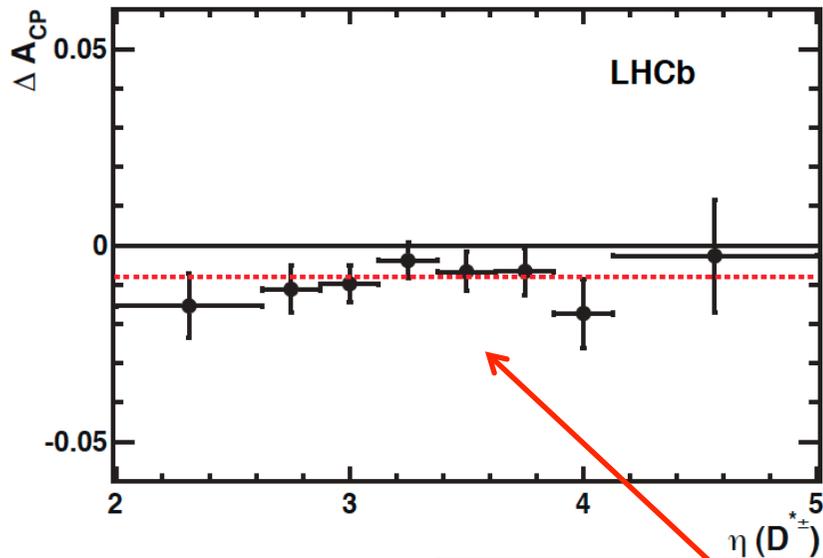
# Stability of result vs data-taking runs



Final result  
(dashed line)

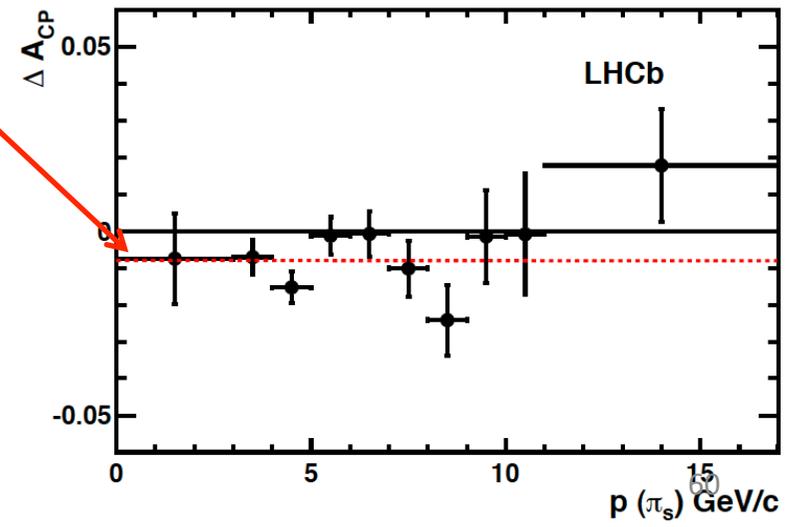
Before and after a technical stop

# Stability of result on relevant kinematic variables



Final result  
(dashed line)

No evidence of dependence on relevant kinematic variables



# Tightening of PID cuts on $D^0$ daughters

- The measurement is repeated with progressively more restrictive RICH particle identification requirements, finding values

tight PID cut

$$(-0.88 \pm 0.26)\%$$

tight++ PID cut

$$(-1.03 \pm 0.31)\%$$

- consistent with the baseline result

# Internal consistency between subsamples

- Disjoint subsamples of data split according
  - to magnet polarity
  - the sign of  $P_x$  of the tagging slow pion
  - whether the data were taken before or after the technical stop.
- The  $\chi^2$  probability for consistency among the subsamples is 45% ( $\chi^2/\text{ndf}=6.7/7$ ).

Subsample	$\Delta A_{CP}$	$\chi^2/\text{ndf}$
Pre-TS, field up, left	$(-1.22 \pm 0.59)\%$	13/26(98%)
Pre-TS, field up, right	$(-1.43 \pm 0.59)\%$	27/26(39%)
Pre-TS, field down, left	$(-0.59 \pm 0.52)\%$	19/26(84%)
Pre-TS, field down, right	$(-0.51 \pm 0.52)\%$	29/26(30%)
Post-TS, field up, left	$(-0.79 \pm 0.90)\%$	26/26(44%)
Post-TS, field up, right	$(+0.42 \pm 0.93)\%$	21/26(77%)
Post-TS, field down, left	$(-0.24 \pm 0.56)\%$	34/26(15%)
Post-TS, field down, right	$(-1.59 \pm 0.57)\%$	35/26(12%)
All data	$(-0.82 \pm 0.21)\%$	211/215(56%)

# Systematic uncertainties

- Kinematic binning: 0.02%
  - Evaluated as change in  $\Delta A_{CP}$  between full 216-bin kinematic binning and “global” analysis with just one giant bin.
- Fit procedure: 0.08%
  - Evaluated as change in  $\Delta A_{CP}$  between baseline and not using any fitting at all (just sideband subtraction in  $\delta m$  for KK and  $\pi\pi$  modes)
- Peaking background: 0.04%
  - Evaluated with toy studies injecting peaking background with a level and asymmetry set according to  $D^0$  mass sidebands (removing signal tails).
- Multiple candidates: 0.06%
  - Evaluated as mean change in  $\Delta A_{CP}$  when removing multiple candidates, keeping only one per event chosen at random.
- Fiducial cuts: 0.01%
  - Evaluated as change in  $\Delta A_{CP}$  when cuts are significantly loosened.
- Sum in quadrature: 0.11%

# Result

$$\Delta A_{CP} = [-0.82 \pm 0.21(\text{stat.}) \pm 0.11(\text{sys.})] \%$$

Significance:  $3.5\sigma$

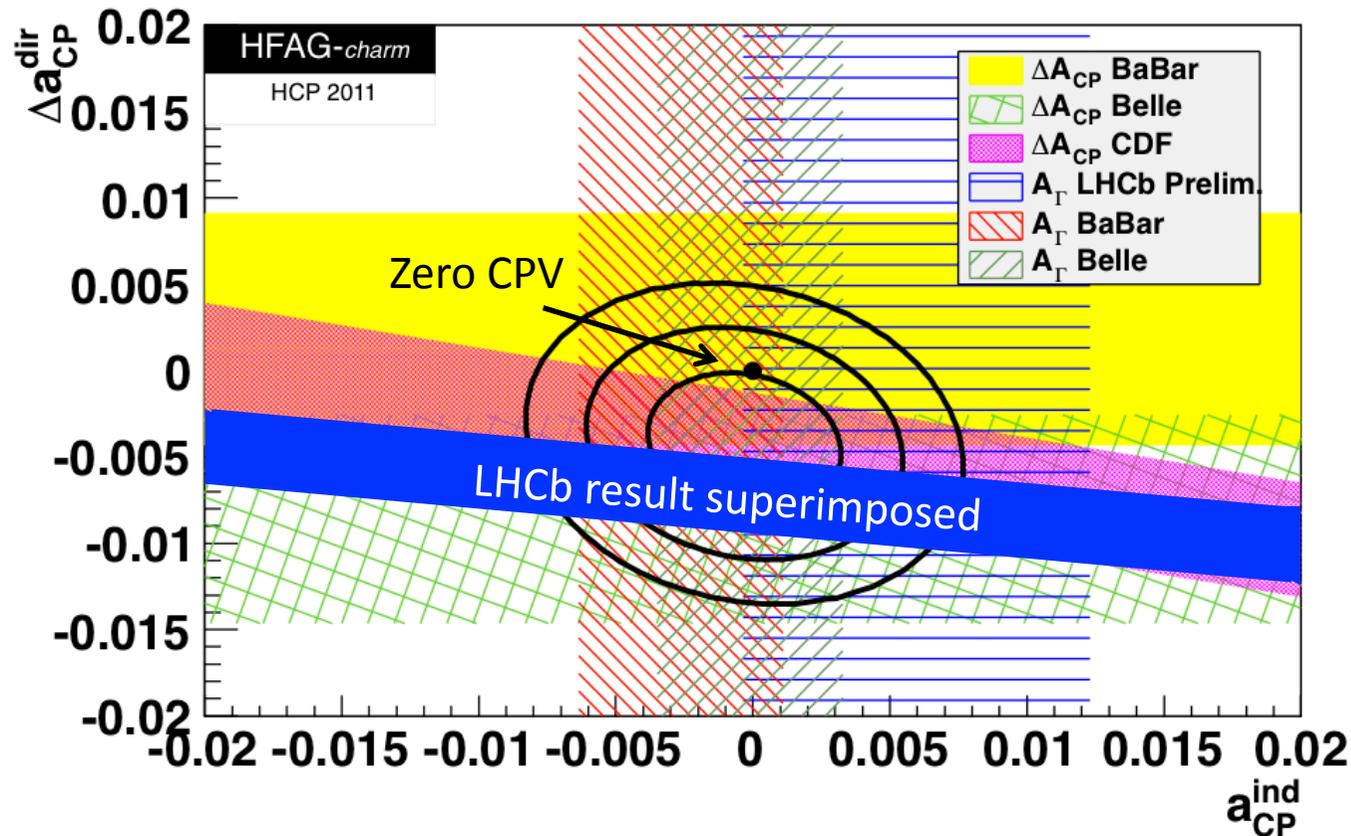
# Interpretation: lifetime acceptance

- Lifetime acceptance differs between  $D^0 \rightarrow K^+K^-$  and  $D^0 \rightarrow \pi^+\pi^-$ 
  - e.g. smaller opening angle  $\Rightarrow$  short-lived  $D^0 \rightarrow K^+K^-$  more likely to fail cut requiring daughters not to point to PV than  $D^0 \rightarrow \pi^+\pi^-$
- Need this to compute how much indirect CPV could contribute.
- Background-subtracted average decay time of  $D^0$  candidates passing the selection is measured for each final state, and the fractional difference with respect to world average  $D^0$  lifetime is obtained:

$$\Delta\langle t \rangle / \tau = [9.83 \pm 0.22(\text{stat.}) \pm 0.19(\text{syst.})] \%$$

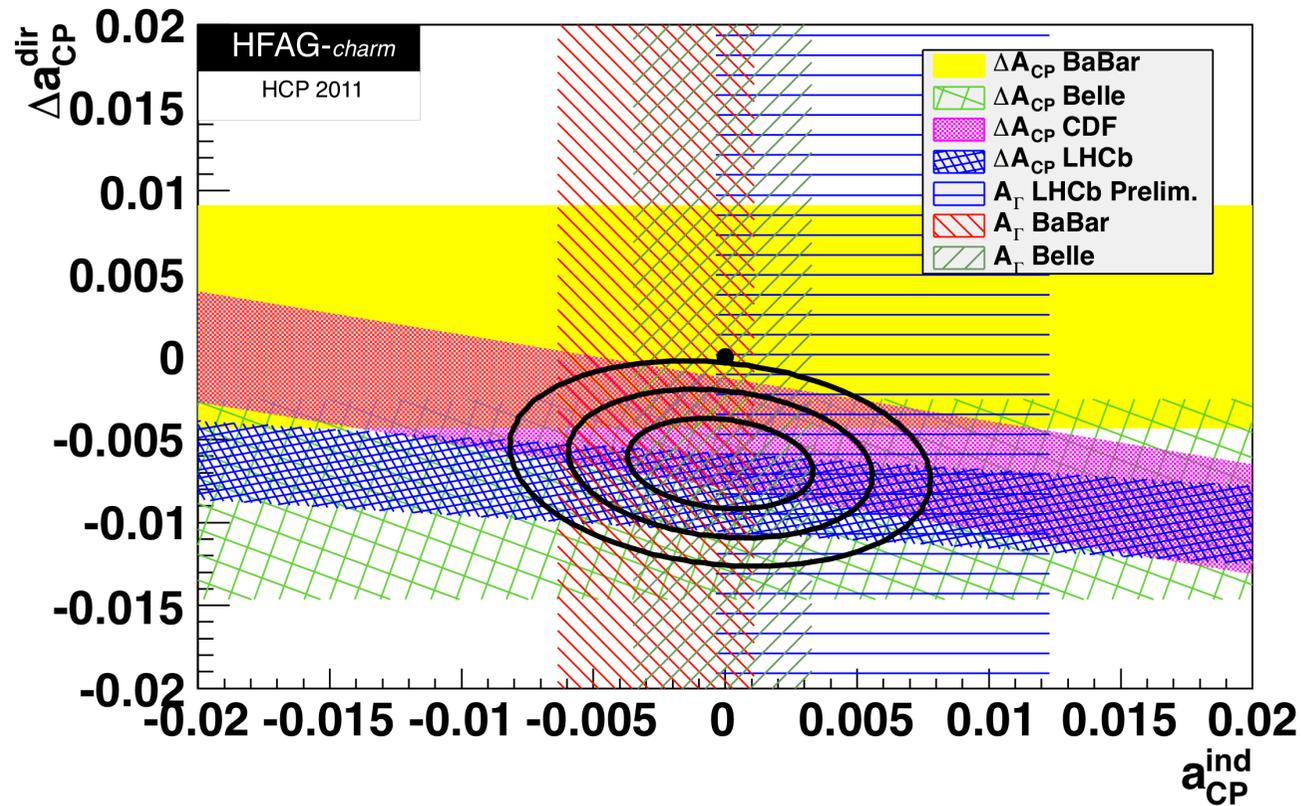
- Systematics:
  - world-average  $D^0$  lifetime 0.04%
  - fraction of charm from B-hadron decays 0.18%
  - background-subtraction procedure 0.04%
- Remind:  $\Delta A_{CP} = [a_{CP}^{\text{dir}}(K^-K^+) - a_{CP}^{\text{dir}}(\pi^-\pi^+)] + \frac{\Delta\langle t \rangle}{\tau} a_{CP}^{\text{ind}}$
- ... so indirect CP violation mostly cancel

# Comparison with the world average



LHCb measurement, interpreted assuming no  $a_{CP}^{ind}$ , is consistent with HFAG averages based on previous results (1.1 sigma)

# New HFAG combination (with LHCb result)



$$a_{CP}^{ind} = (-0.02 \pm 0.23)\% \quad \Delta a_{CP}^{dir} = (-0.65 \pm 0.18)\%$$

Consistency with NO CP violation: 0.15%

# Prospects

- Current measurement of  $\Delta A_{CP}$  performed with 60% of 2011 recorded sample
  - To establish whether this result is consistent with the SM will require the analysis of more data (work in progress, as well as improved theoretical understanding)
- Measure  $\Delta A_{CP}$  with  $D^0$  from B semileptonic decays
- Look for direct CPV in other SCS modes, especially 3 body ones
- In addition to direct CPV search, perform time dependent measurements to look for indirect CPV, i.e.  $A_\Gamma$  and studies of  $D^0 \rightarrow K_S hh$

# Summary

First evidence of CP violation in charm sector

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Significance  $3.5\sigma$  (incl. statistical and systematic uncertainties)

Our value is consistent with HFAG average ( $1\sigma$ )

Magnitude of central value larger than current SM expectation ... but charm is notoriously difficult to pin down theoretically

Looking forward to more data and many new charming results!

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Thanks!

# Backup

# Search for direct CPV in $D^+ \rightarrow K^- K^+ \pi^-$

Results of fit with a Gaussian to  $S_{CP}^i$  distribution

arXiv 1110.3970

Binning	Fitted mean	Fitted width	$\chi^2/\text{ndf}$	p-value (%)
Adaptive I	$0.01 \pm 0.23$	$1.13 \pm 0.16$	32.0/24	12.7
Adaptive II	$-0.024 \pm 0.010$	$1.078 \pm 0.074$	123.4/105	10.6
Uniform I	$-0.043 \pm 0.073$	$0.929 \pm 0.051$	191.3/198	82.1
Uniform II	$-0.039 \pm 0.045$	$1.011 \pm 0.034$	519.5/529	60.5

No evidence for CP violation in the 2010 dataset of  $38 \text{ pb}^{-1}$

Preliminary:  
2010 data,  $38 \text{ pb}^{-1}$

Strategy:  
for each bin in the Dalitz plot, a local CP asymmetry variable is defined

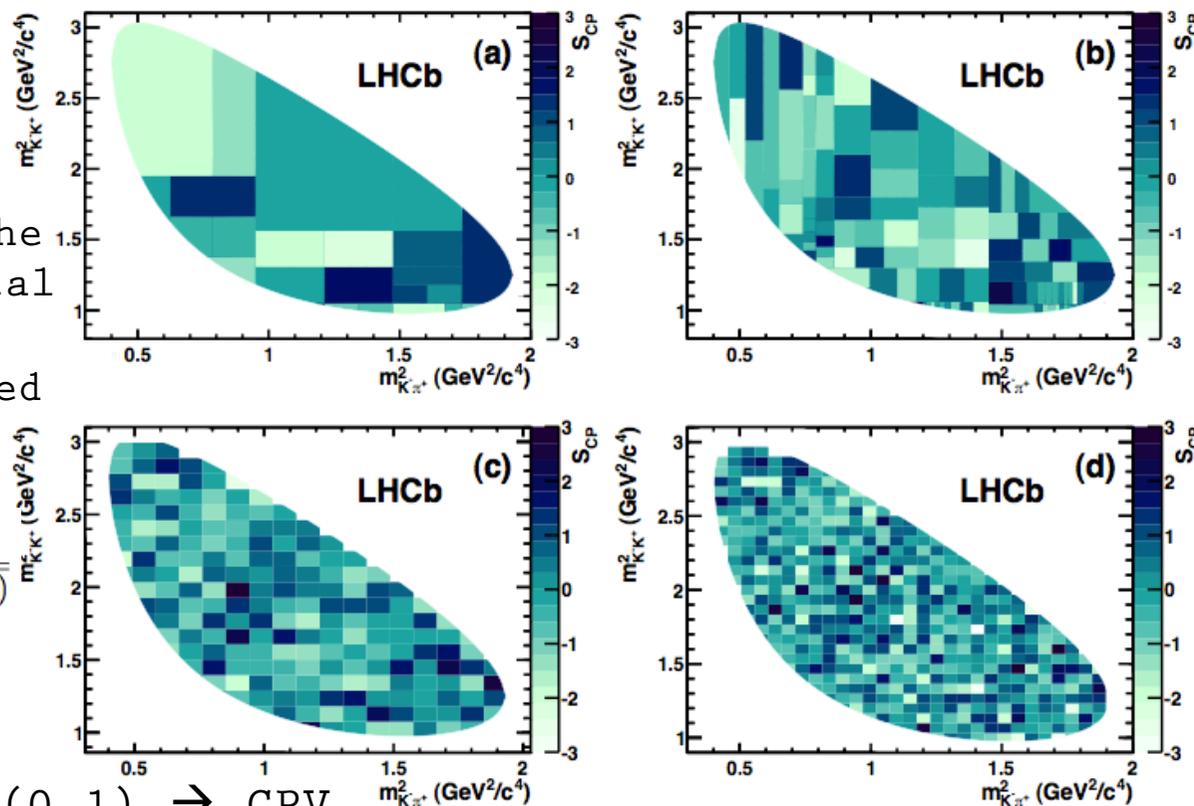
arXiv:

0905.4233,0802.4035

$$S_{CP}^i = \frac{N^i(D^+) - \alpha N^i(D^-)}{\sqrt{N^i(D^+) + \alpha^2 N^i(D^-)}}$$

$$\alpha = \frac{N_{\text{tot}}(D^+)}{N_{\text{tot}}(D^-)}$$

If  $S_{CP}^i$  is not  $G(0,1) \rightarrow \text{CPV}$



# Search for time-dependent CPV

LHCb-CONF-2011-54  
LHCb-CONF-2011-46

- Search CP violation in mixing involves two observables

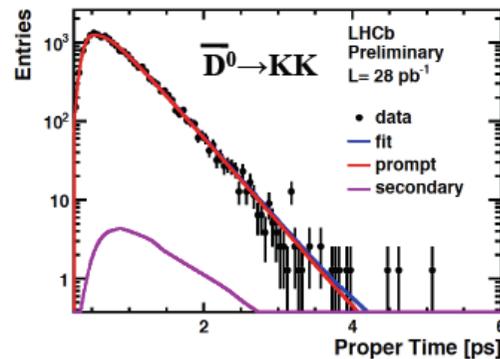
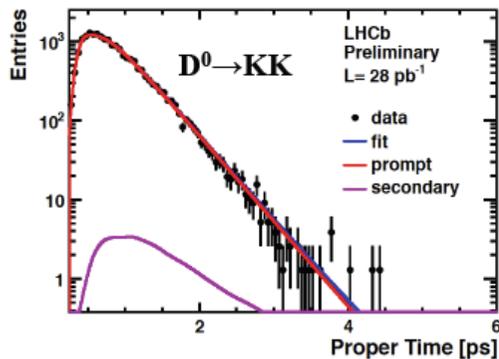
$$y_{CP} \equiv \frac{\hat{\Gamma}(D^0 \rightarrow K^+K^-)}{\hat{\Gamma}(D^0 \rightarrow K^-\pi^+)} - 1 \quad \longrightarrow$$

$D^0$  mixing well established,  $y_{CP} \neq y$   
 $\rightarrow$  indirect CP violation  
 $y = (7.5 \pm 1.2) \times 10^{-3}$  HFAG

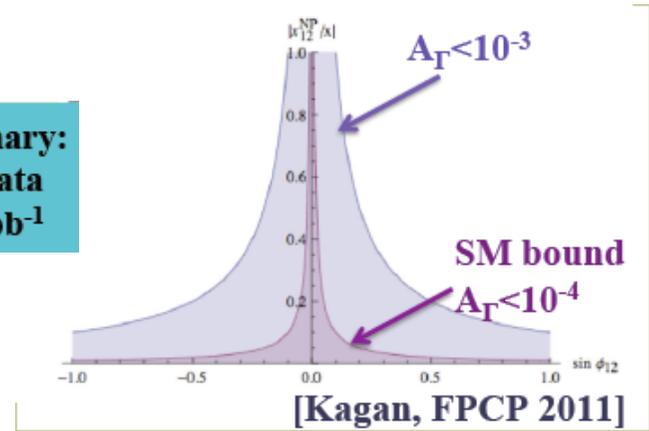
$$A_\Gamma = \frac{\tau(\bar{D}^0 \rightarrow K^-K^+) - \tau(D^0 \rightarrow K^-K^+)}{\tau(\bar{D}^0 \rightarrow K^-K^+) + \tau(D^0 \rightarrow K^-K^+)} \quad \longrightarrow$$

non-zero value of  $A_\Gamma \rightarrow$   
 indirect CP violation

- where the flavour of  $D^0 \rightarrow K^-K^+$  is determined from the sign of  $D^{*\pm}$



Preliminary:  
2010 data  
L=28 pb<sup>-1</sup>



$$A_\Gamma = (-5.9 \pm 5.9_{\text{stat}} \pm 2.1_{\text{syst}}) \times 10^{-3}$$

$$y_{CP} = (5.5 \pm 6.3_{\text{stat}} \pm 4.1_{\text{syst}}) \times 10^{-3}$$

# Peaking background

- Mis-reconstructed  $D^{*+}$  decays that peaks in  $\delta m$  but not  $m(D^0)$ , i.e.:
  - $D^{*+} \rightarrow D^0 (K^- \pi^+ \pi^0) \pi^+$ , where the  $\pi^0$  is missing and the  $\pi^-$  is mis-reconstructed as K or proton
  - Semi-leptonic  $D^0$  decays
- Background studied on  $\delta m$  from the  $D^0$  sidebands, upper and lower, after signal-subtraction, leaving the component that does not peak in  $m(D^0)$ .
- Estimated to be 1% both for KK and  $\pi\pi$ .
- Systematic evaluated with toy studies injecting peaking background with a level and asymmetry from this study.