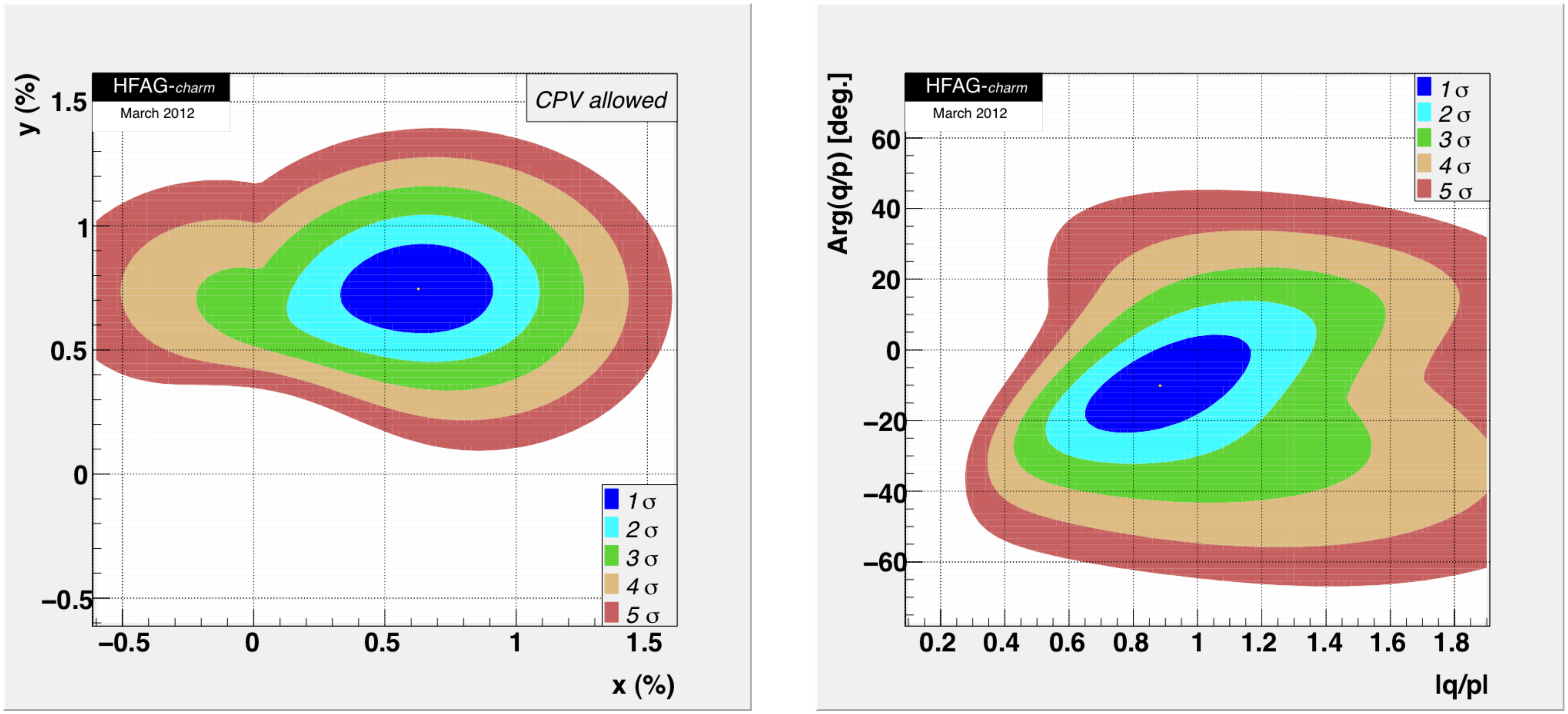
Charm mixing and CPV @ LHCb

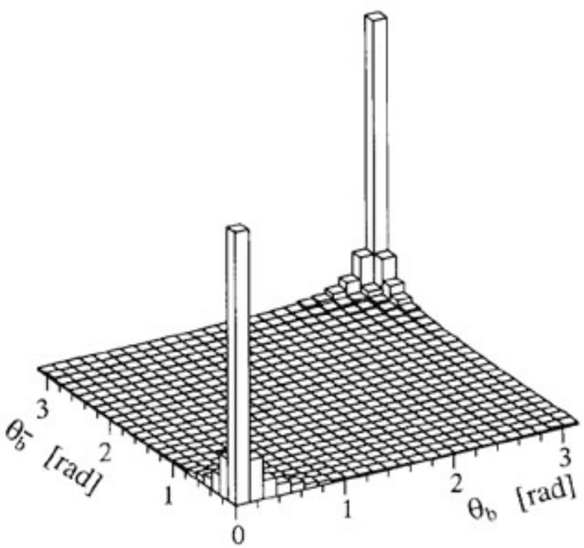


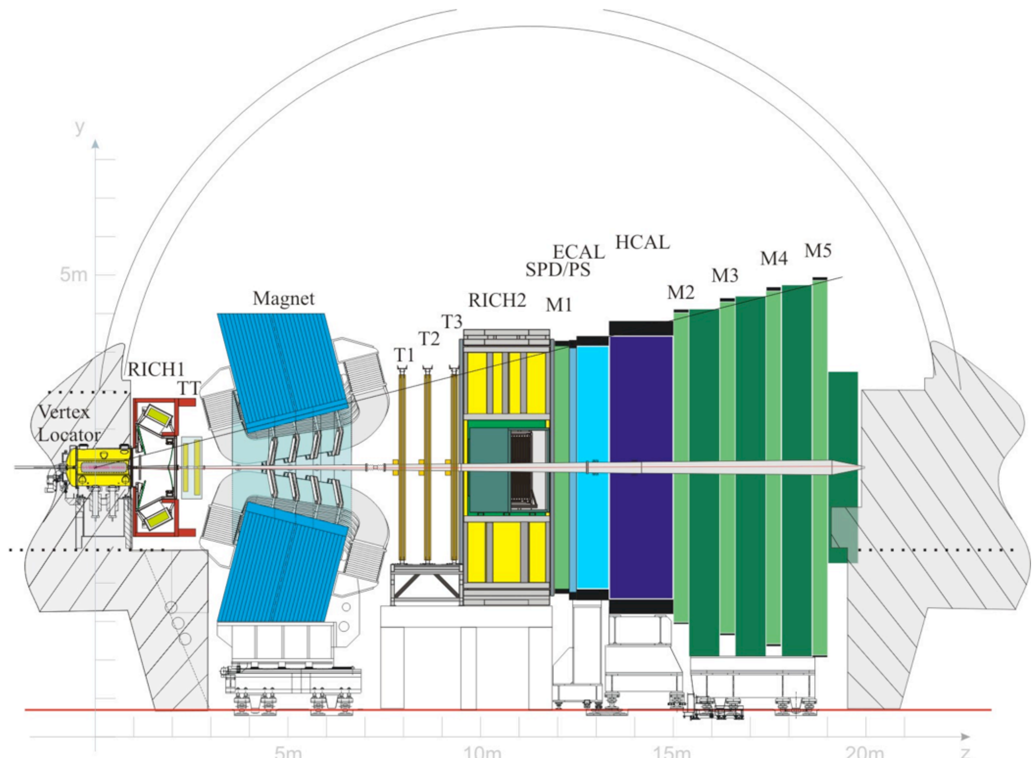
V. Gligorov, CERN

11th HQL conference, Prague, June 2012

On behalf of the LHCb collaboration

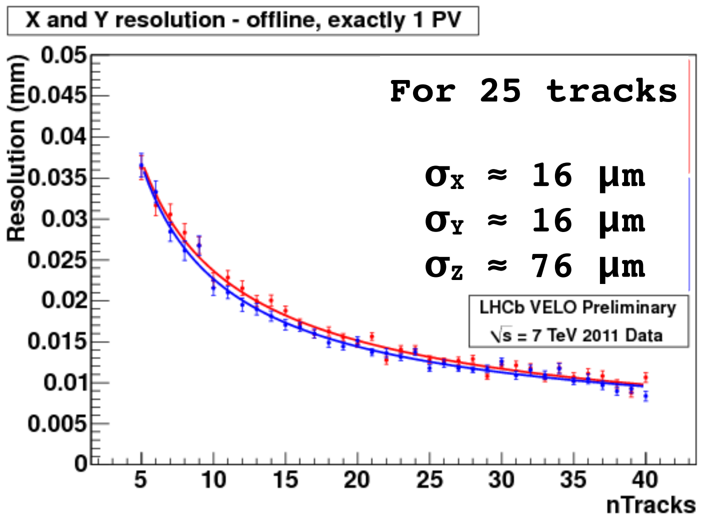
LHCb design

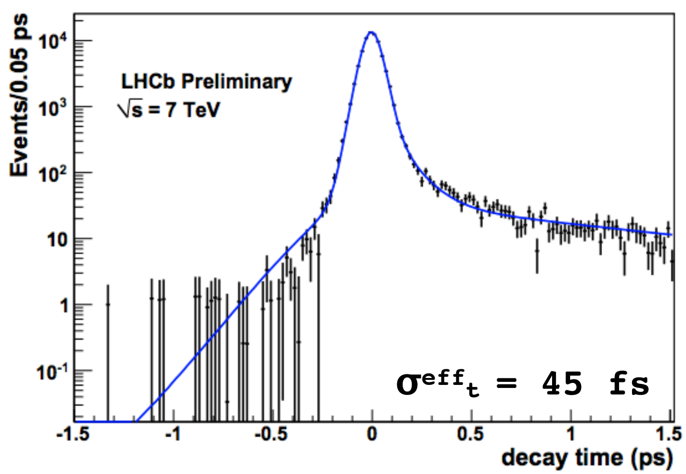


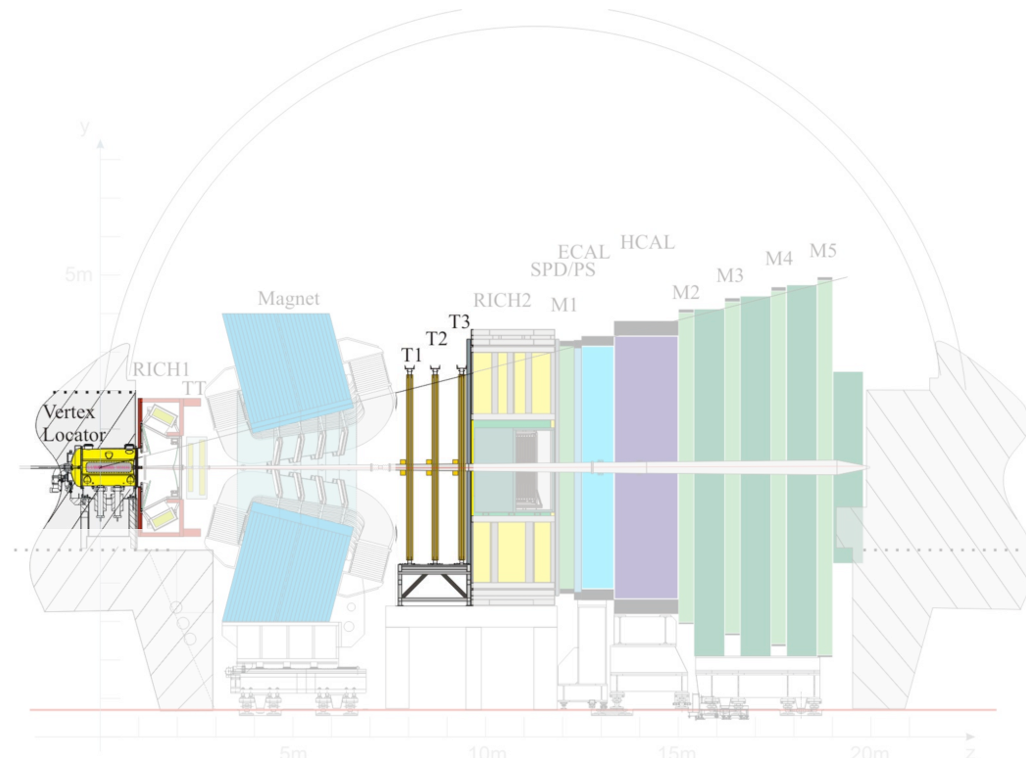


Production of heavy flavour particles correlated in the forward direction

LHCb tracking

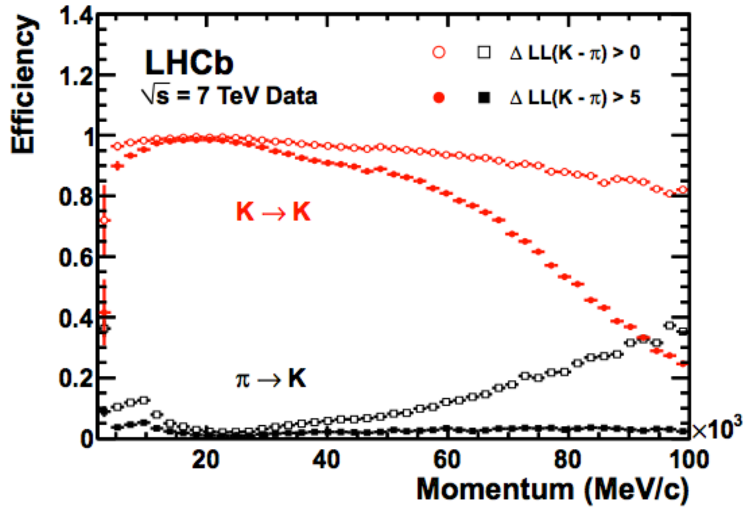


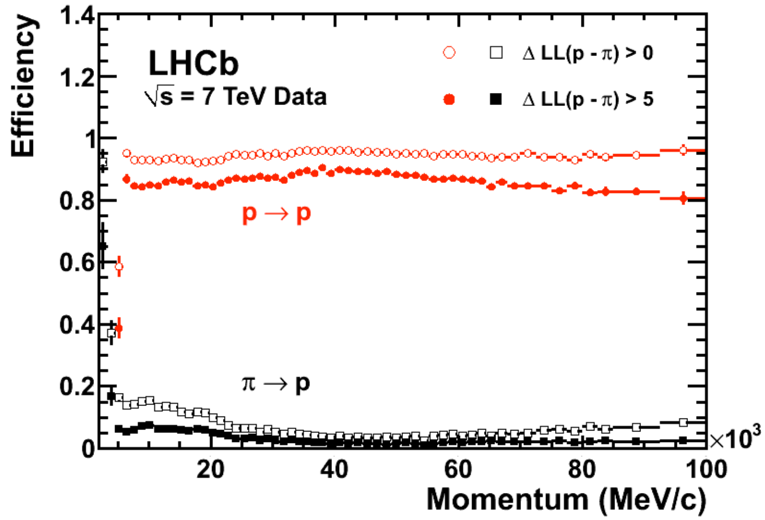


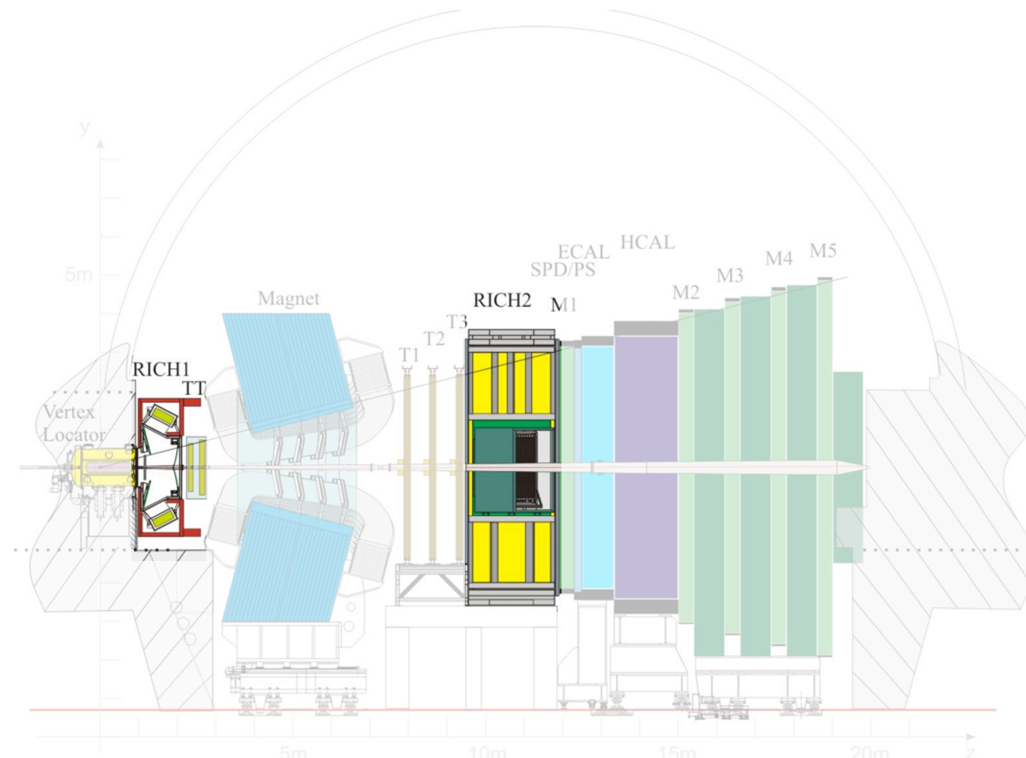


Excellent vertexing and decay time resolution

LHCb Particle identification

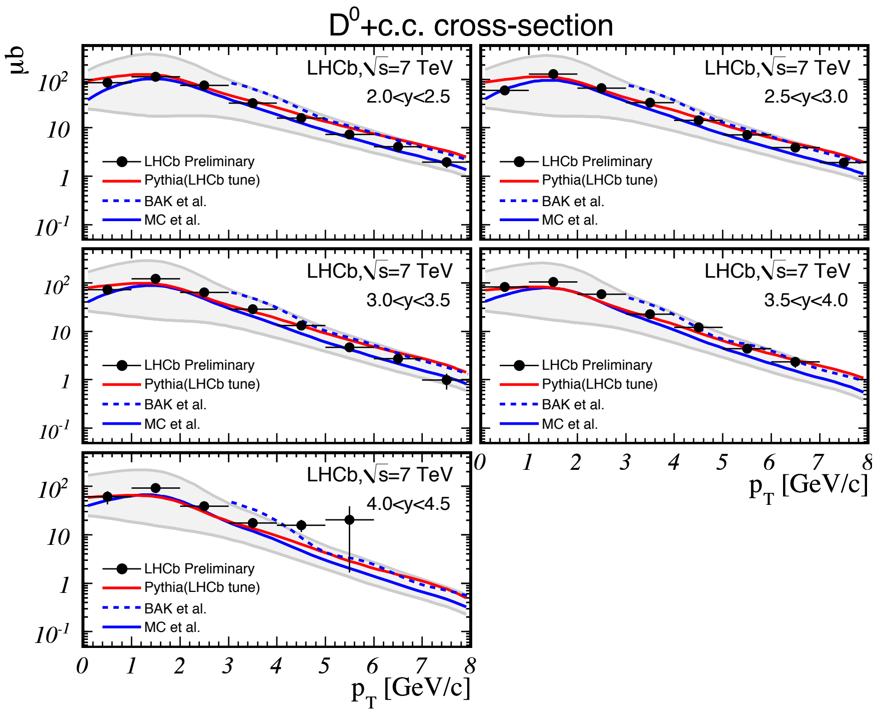


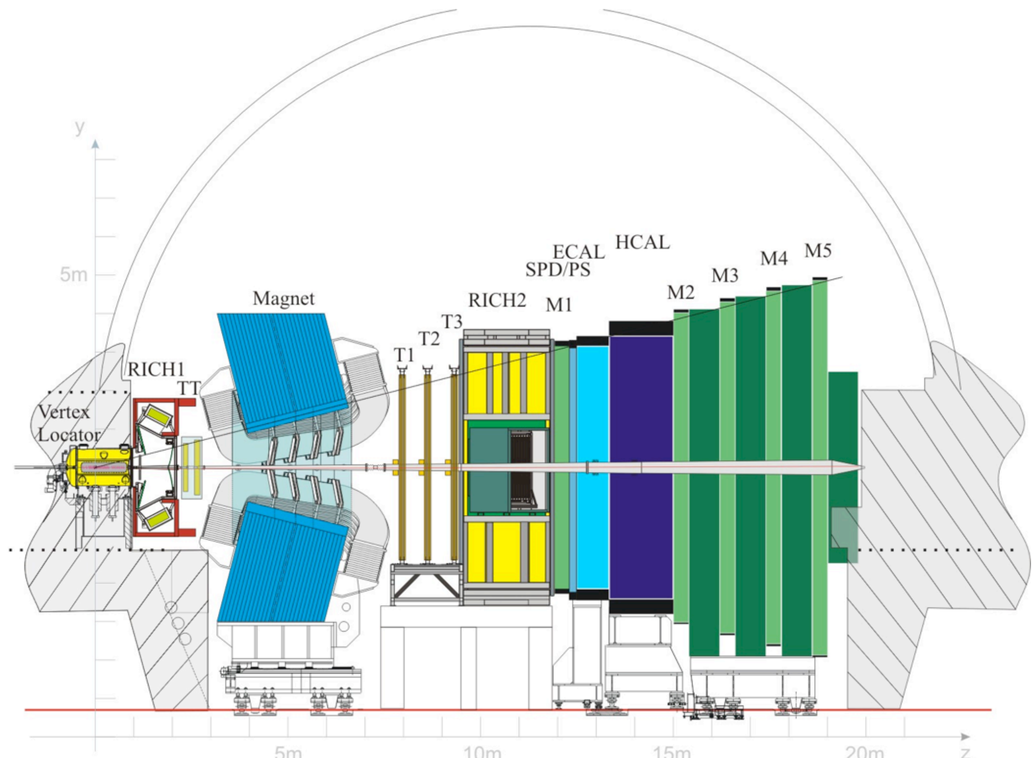




Excellent pion-kaon-proton separation between 2 and 100 GeV/c of momentum

LHCb charm cross section





Large prompt charm cross section of σ = 6.10 ± 0.93 mb

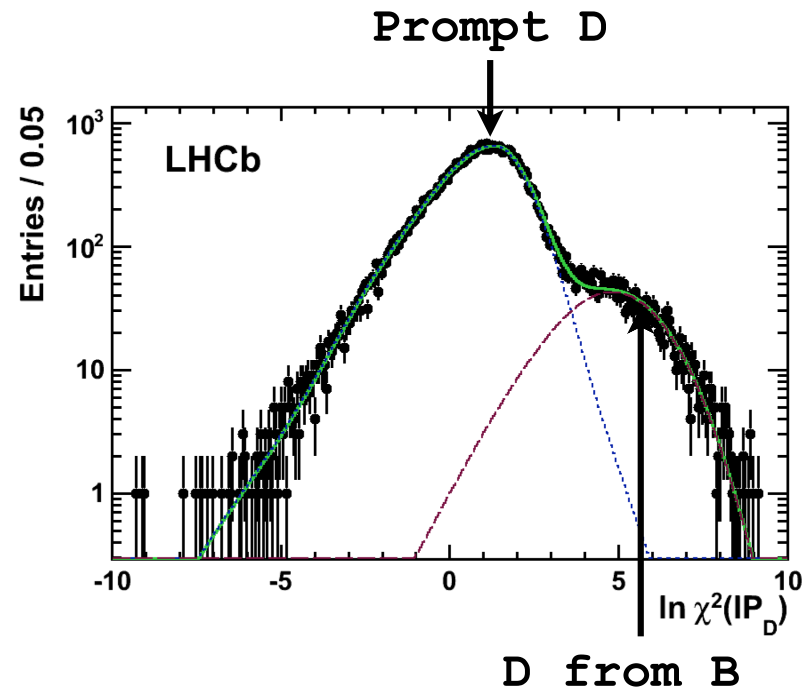
[See LHCb-CONF-2010-013]

Charm @ LHC

Two types of charm production:

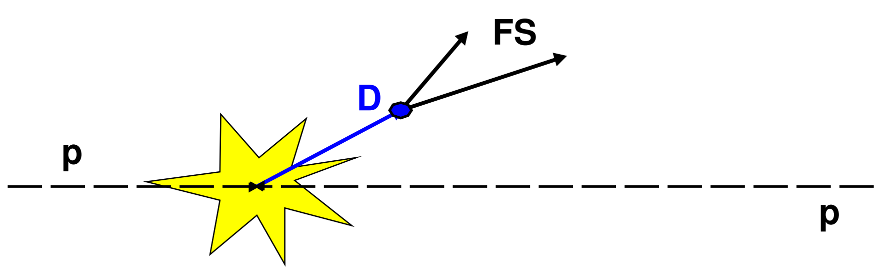
Prompt : Charm produced directly in the primary interaction

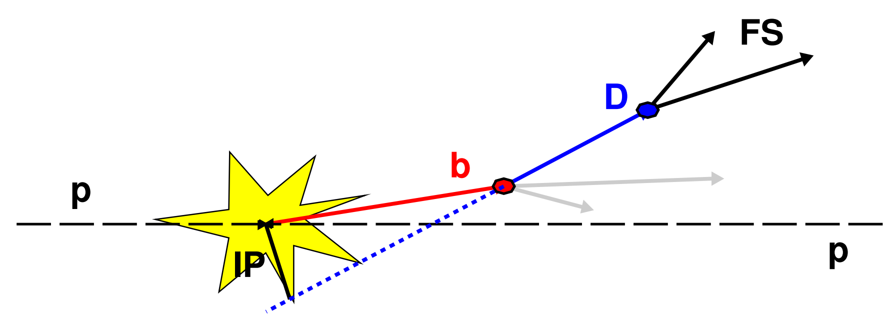
Secondary : Charm produced in B decays [$\mathcal{B}$(B->DX) > 50%]



Prompt charm is much more abundant because the LHC charm cross-section is ~20x higher than the B cross-section

Must discriminate between the two for analyses : use the D impact parameter χ^2





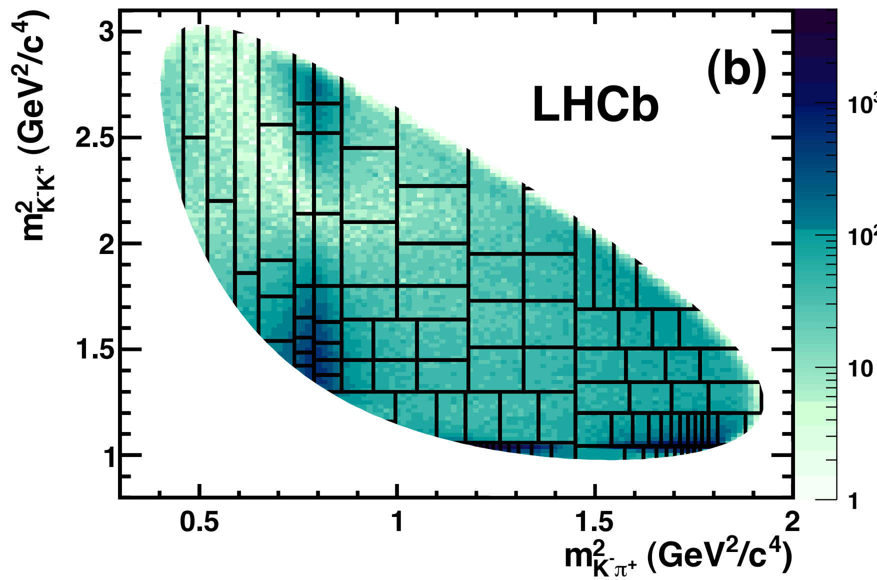
Time Integrated CPV studies

$D^+ \to K^+K^-\pi^+$ — method

Search for direct CPV across Dalitz plot using a global χ^2 test of the consistency of the data with the no-CPV hypothesis

Measure CPV in bins of the Dalitz plot according to :

$$\mathcal{S}^{i}_{CP} = \frac{N^i(D^+) - \alpha N^i(D^-)}{\sqrt{N^i(D^+) + \alpha^2 N^i(D^-)}}, \quad \alpha = \frac{N_{\rm tot}(D^+)}{N_{\rm tot}(D^-)}$$



See LHCb-PAPER-2011-017

See Bediaga et al. PRD 80 096006 (2009)

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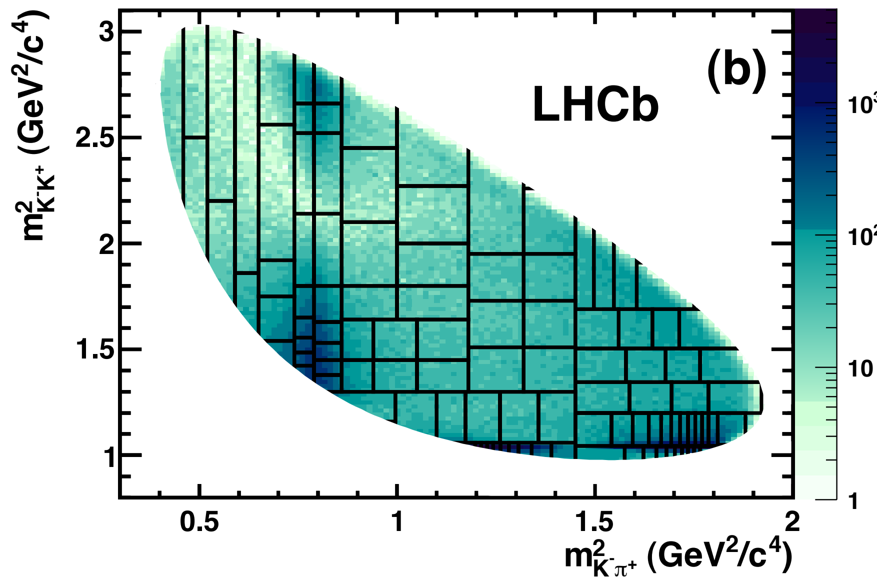
Production asymmetry effects removed by global asymmetry correction term



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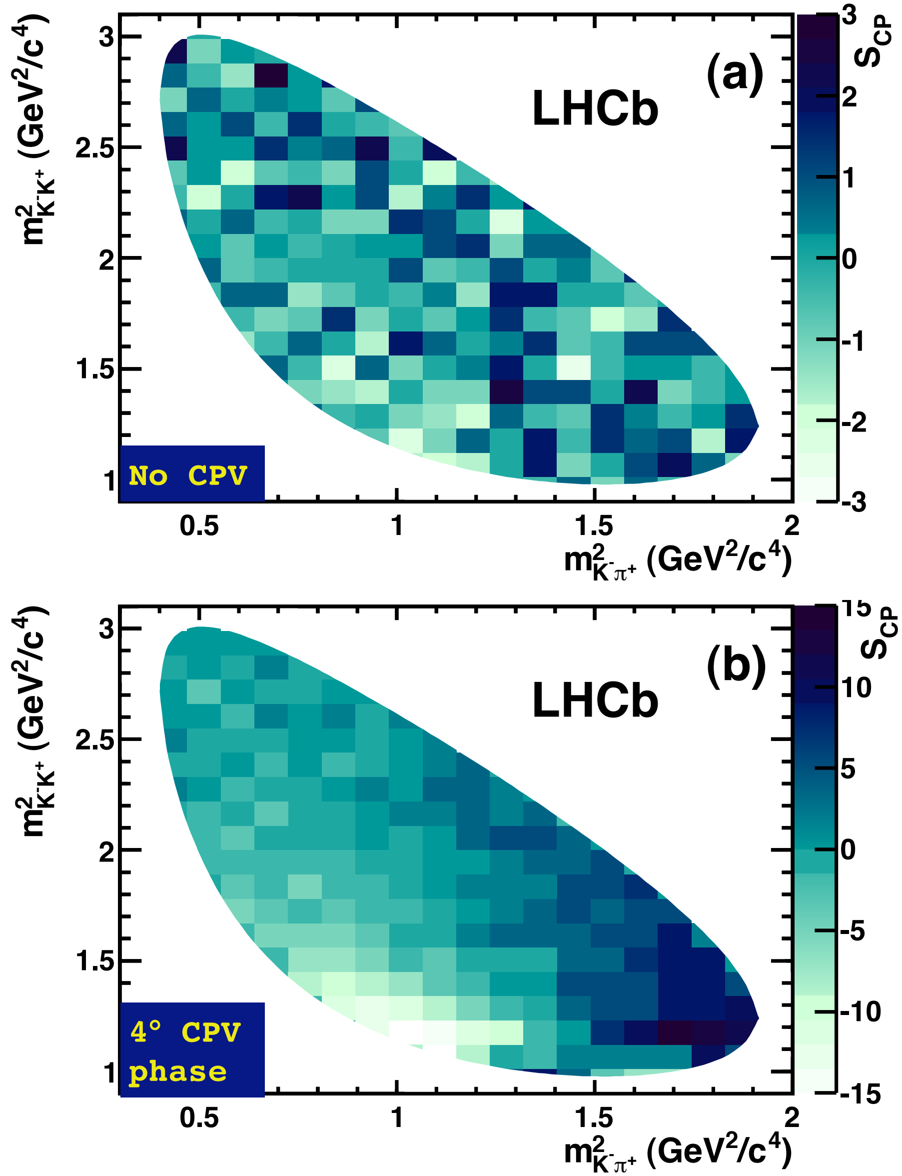
Production asymmetry effects removed by global asymmetry correction term

In absence of CPV the S^i_{CP} values are Gaussian distributed with mean zero and unit width

Ability of the method to resolve CPV validated with toy MC studies, different binnings developed



See LHCb-PAPER-2011-017

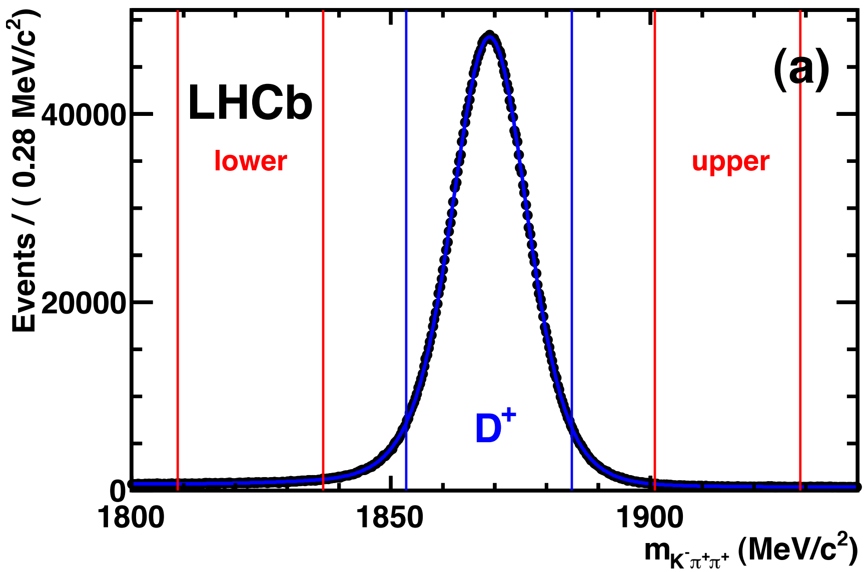
See Bediaga et al. PRD 80 096006 (2009)

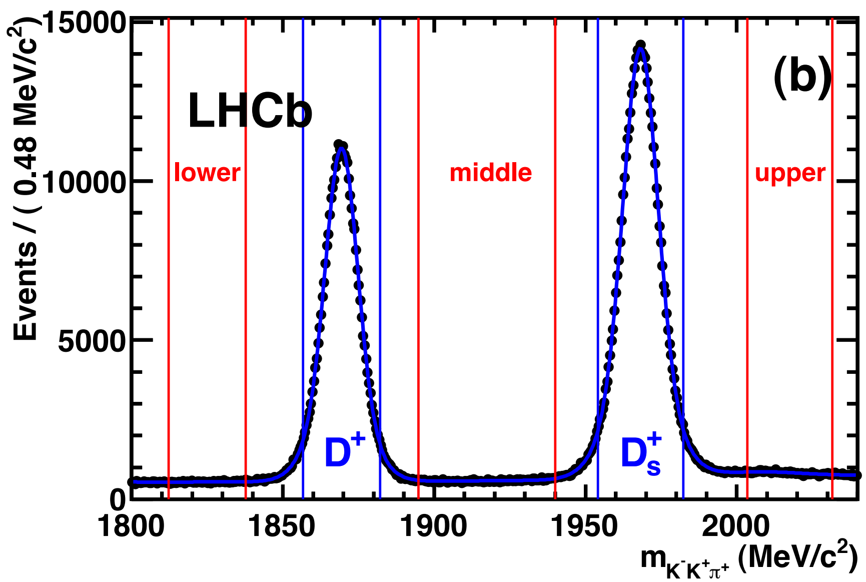
$D^+ \to K^+K^-\pi^+$ — signals

Use sample of ~370,000 $D^+ \to K^+K^-\pi^+$ decays collected during 2010 data taking, corresponding to ~35 pb^{-1}

Selection designed for as uniform an efficiency as possible across the Dalitz plot

Use $D^+ \to K^-\pi^+\pi^+$ and $D_s^+ \to K^+K^-\pi^+$ decays as control modes, which are Cabbibo Favoured so no CPV expected





See LHCb-PAPER-2011-017

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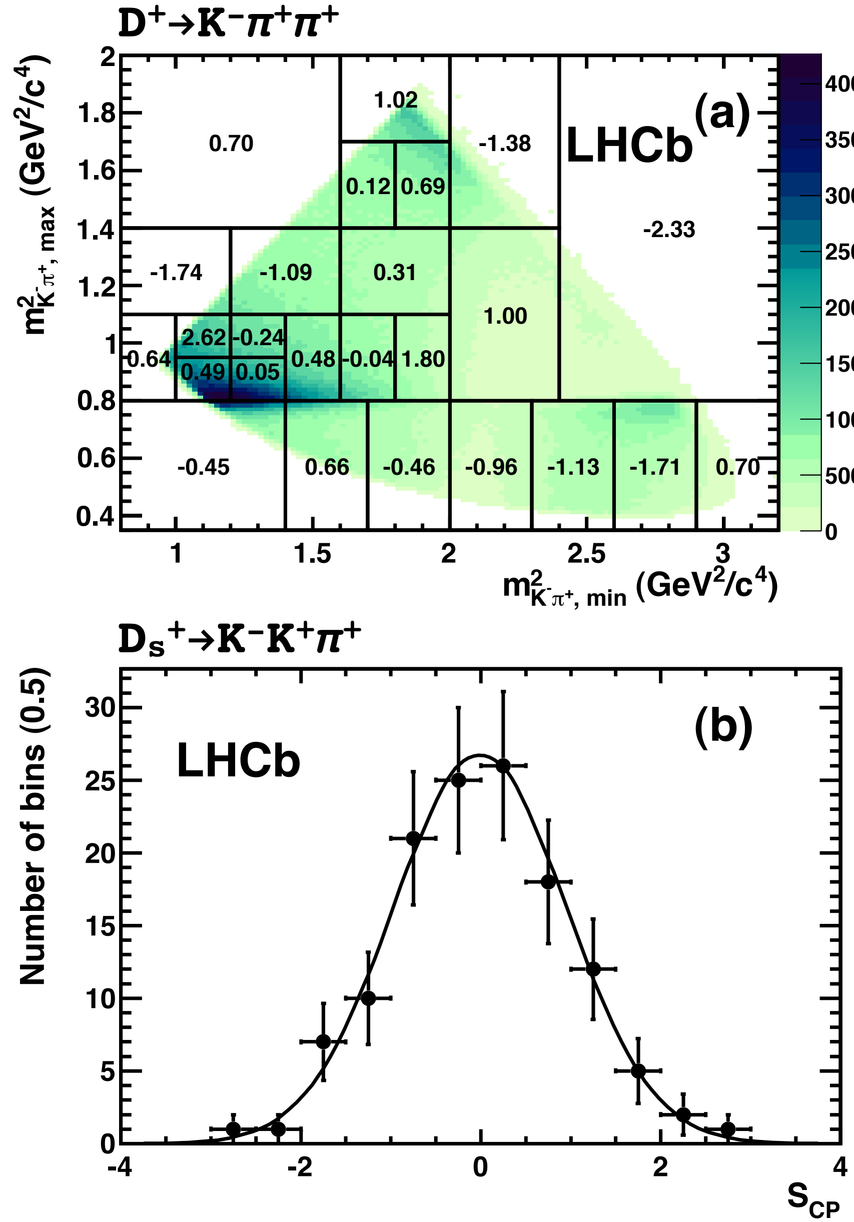
=> And none observed



See LHCb-PAPER-2011-017
See Bediaga et al. PRD 80 096006 (2009)

$D^+ \to K^+K^-\pi^+$ — results

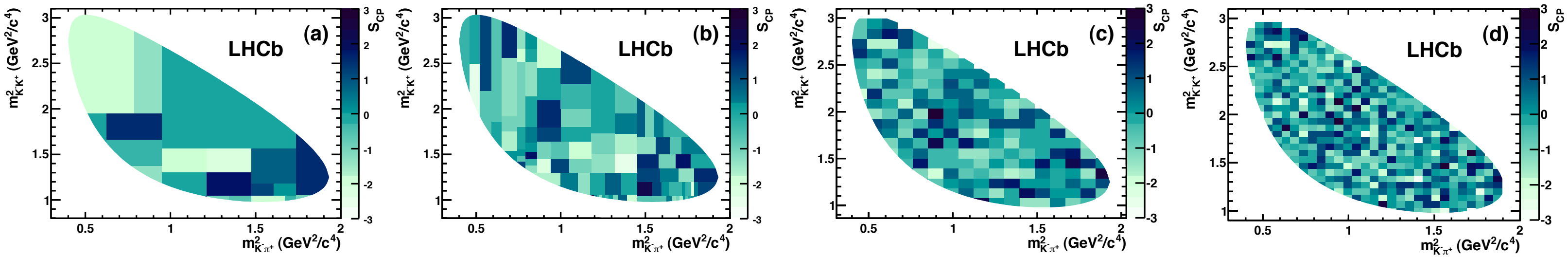


TABLE IX. Fitted means and widths, χ^2/ndf and p-values for consistency with no CPV for the $D^+ \to K^-K^+\pi^+$ decay mode with four different binnings.

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

No CPV observed in this mode with 2010 data (35 pb^{-1})

Similar measurements (including 4-body)are ongoing with 2011 data, and a ~30x larger sample

See LHCb-PAPER-2011-017

See Bediaga et al. PRD 80 096006 (2009)

$D^0 \to K^+K^-/\pi^+\pi^-$ — motivation

Search for CP asymmetry defined as

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

Requires flavour tagging : use D^{*+} decays to determine the flavour of the D0 meson at production

$$A_{\text{raw}}(f) \equiv \frac{N(D^{*+} \to D^0(f)\pi_s^+) - N(D^{*-} \to \bar{D}^0(f)\pi_s^-)}{N(D^{*+} \to D^0(f)\pi_s^+) + N(D^{*-} \to \bar{D}^0(f)\pi_s^-)}$$

Note that D^{*+} decays are right at the threshold to decay into $D^0\pi^+$, hence the pion is “slow” => low momentum and transverse momentum

See LHCb-PAPER-2011-023

$D^0 \to K^+K^- / \pi^+\pi^-$ — observables

What is actually measured is a mixture of different effects, of which we are primarily interested in one

$$A_{\rm raw}(f) = A_{CP}(f) + A_{\rm D}(f) + A_{\rm D}(\pi_{\rm s}) + A_{\rm P}(D^{*+})$$

See LHCb-PAPER-2011-023

$D^0 \to K^+K^-/\pi^+\pi^-$ — observables

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$$A_{\text{raw}}(f) = \boxed{A_{CP}(f)} + A_{\text{D}}(f) + A_{\text{D}}(\pi_{\text{s}}) + A_{\text{P}}(D^{*+})$$

Physical asymmetry we want to measure

See LHCb-PAPER-2011-023

$D^0 \to K^+K^-/\pi^+\pi^-$ — observables

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Physical asymmetry we want to measure

Detection asymmetry of D^0

See LHCb-PAPER-2011-023

$D^0 \to K^+K^-/\pi^+\pi^-$ — observables

What is actually measured is a mixture of different effects, of which we are primarily interested in one

$$A_{\mathrm{raw}}(f) = A_{CP}(f) + A_{\mathrm{D}}(f) + A_{\mathrm{D}}(\pi_{\mathrm{s}}) + A_{\mathrm{P}}(D^{*+})$$

- $A_{CP}(f)$: **Physical asymmetry we want to measure**
- $A_{\mathrm{D}}(f)$: **Detection asymmetry of D^0**
- $A_{\mathrm{D}}(\pi_{\mathrm{s}})$: **Detection asymmetry of slow pion**

See LHCb-PAPER-2011-023

$D^0 \to K^+K^- / \pi^+\pi^-$ — observables

What is actually measured is a mixture of different effects, of which we are primarily interested in one

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- $A_{\rm P}(D^{*+})$: **Production asymmetry of D^{*+}**

See LHCb-PAPER-2011-023

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- $A_{\rm D}(f)$: **Detection asymmetry of D^0**
- $A_{\rm D}(\pi_{\rm s})$: **Detection asymmetry of slow pion**
- $A_{\rm P}(D^{*+})$: **Production asymmetry of D^{*+}**

Therefore measure the difference in raw asymmetries between the KK and $\pi\pi$ modes

-- Detection asymmetry of D0 does not exist due to charge symmetric final state

-- D^{*+} production and π_s detection asymmetries cancel

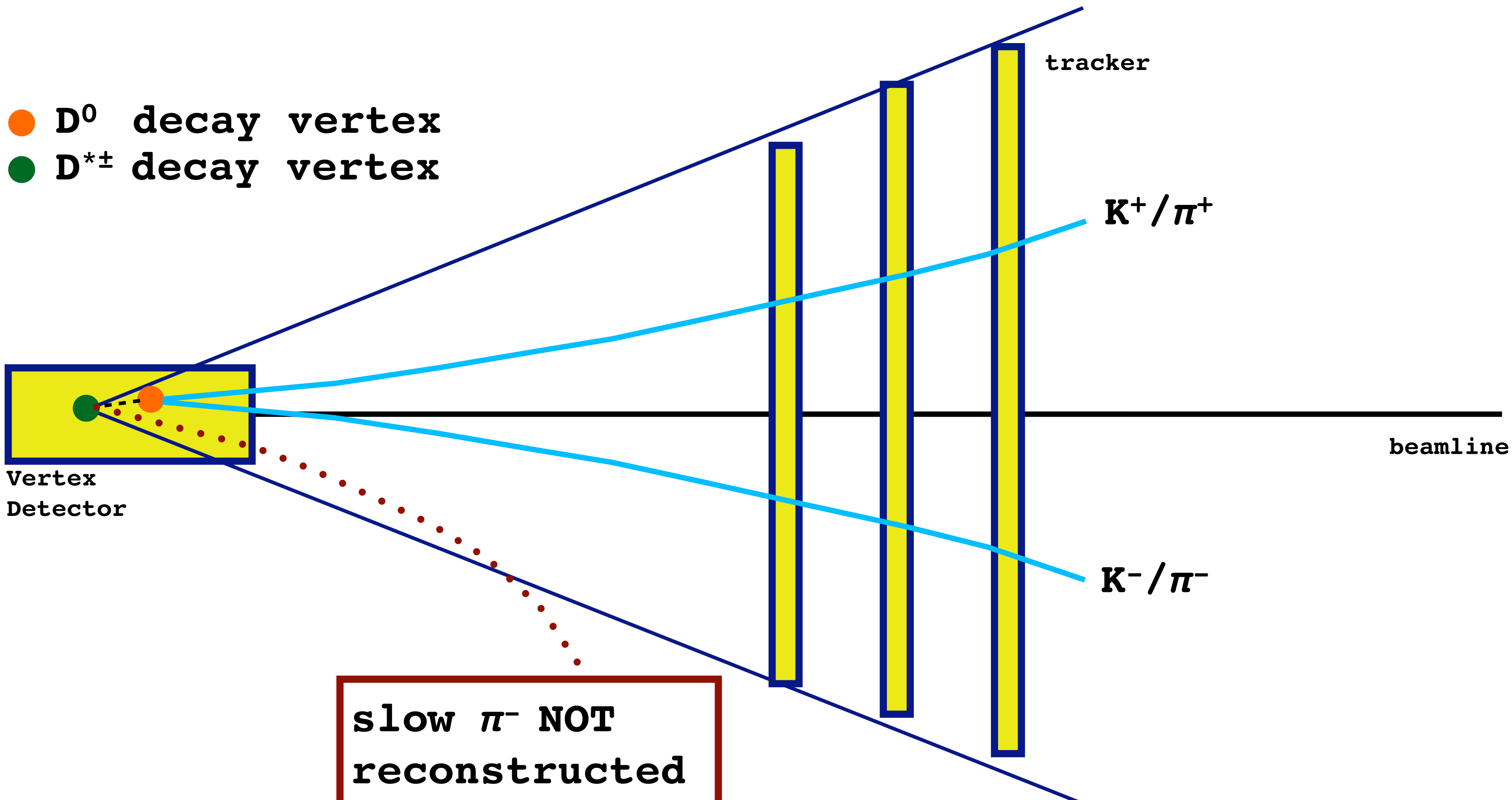
$$\Delta A_{CP} \equiv A_{raw}(KK) - A_{raw}(\pi\pi) = A_{CP}(KK) - A_{CP}(\pi\pi)$$

See LHCb-PAPER-2011-023

$D^0 \to K^+K^-/\pi^+\pi^-$ — fitting

Measurement is inherently robust against biases at first order, but subtle effects can spoil this

In particular there are regions of phase space where only a D^{*+} or a D^{*-} can be reconstructed due to the LHCb geometry



See LHCb-PAPER-2011-023

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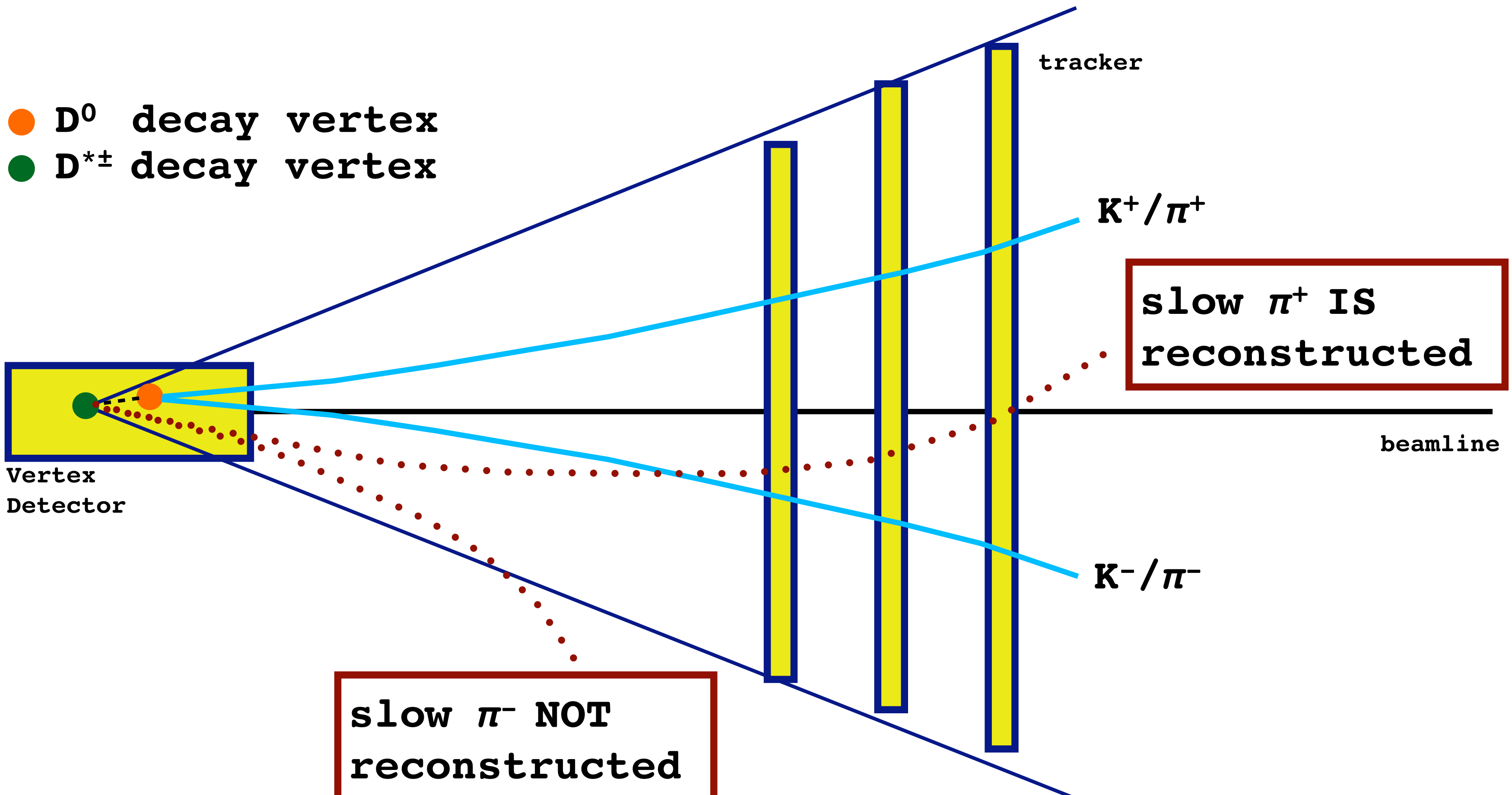


See LHCb-PAPER-2011-023

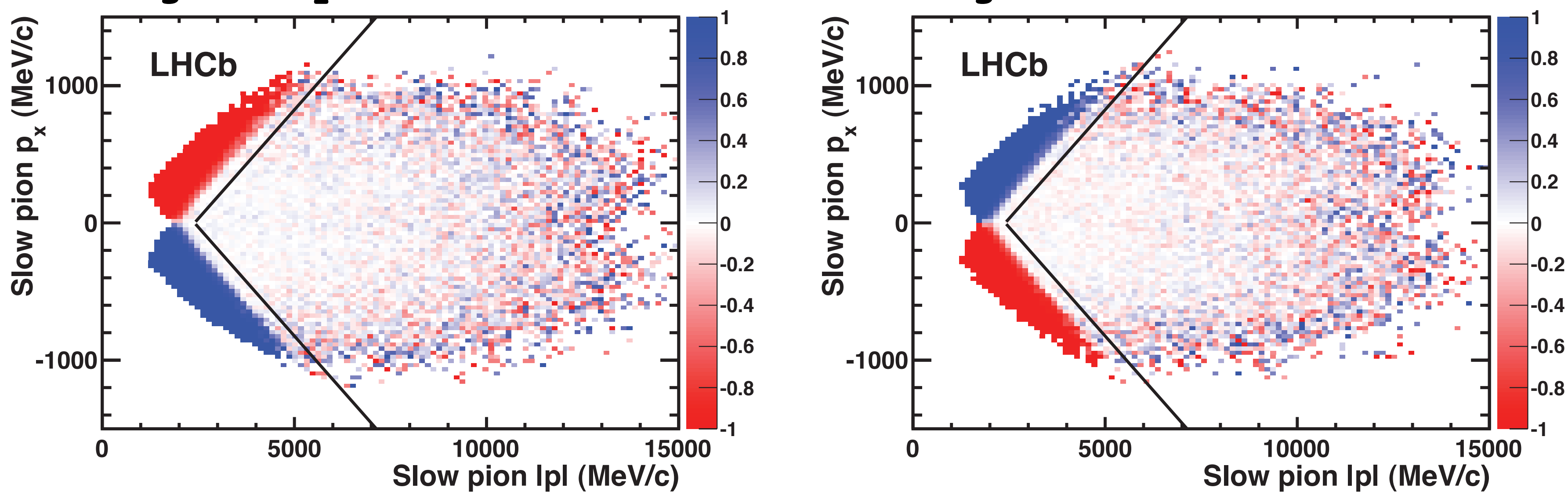
$D^0 \to K^+K^- / \pi^+\pi^-$ — fitting

Measurement is inherently robust against biases at first order, but subtle effects can spoil this

In particular there are regions of phase space where only a D^{*+} or a D^{*-} can be reconstructed due to the LHCb geometry

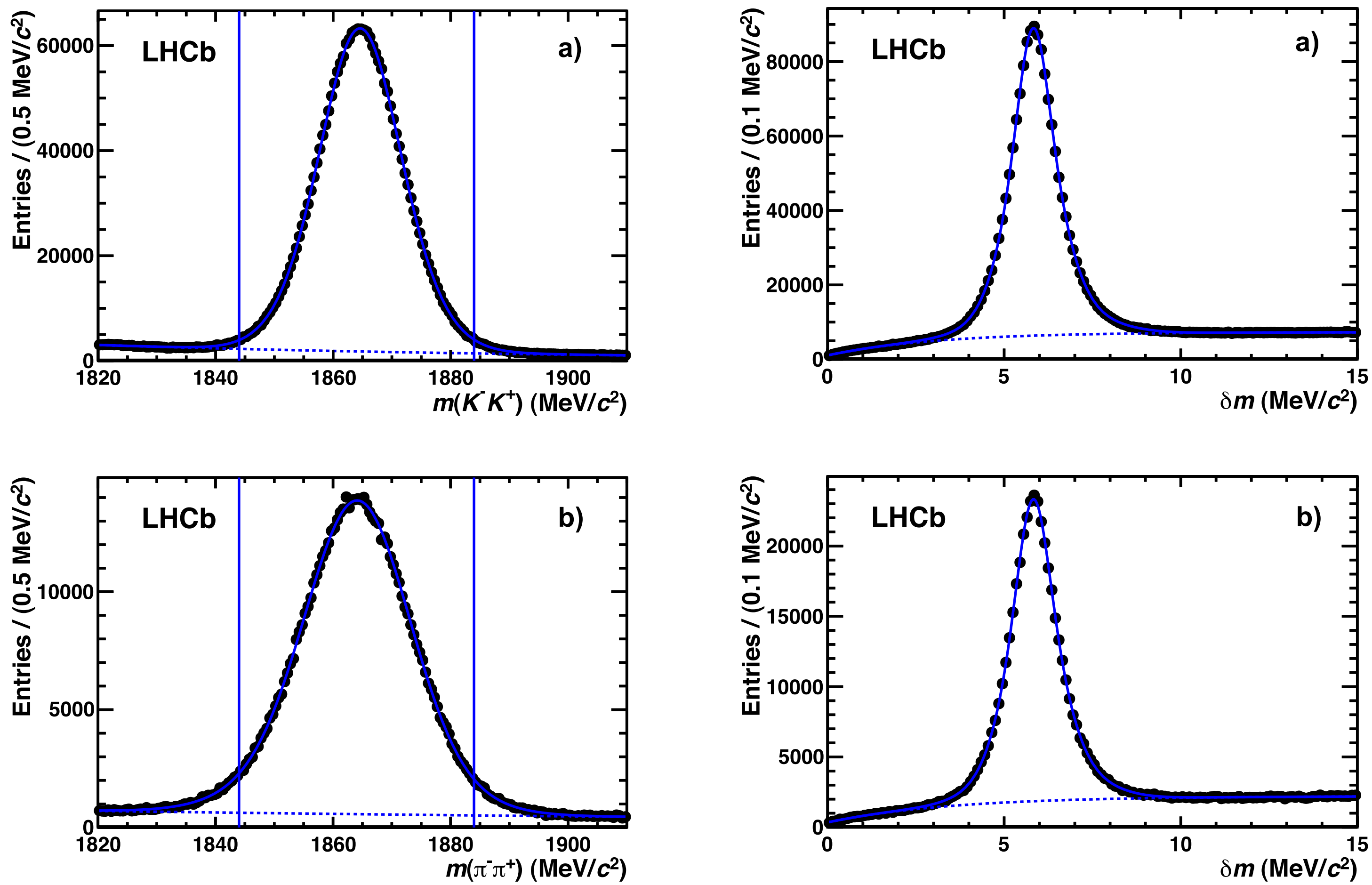
These regions of 100% A^{raw}_{CP} break the underlying assumption in the expansion on the previous pages that the raw asymmetries are small => they are removed using fiducial cuts

Magnet Up **Magnet Down**



See LHCb-PAPER-2011-023

$D^0 \to K^+K^- / \pi^+\pi^-$ — signals



Total signal yields with 0.6 fb^{-1} are ~1.4 M KK and ~0.4 M $\pi\pi$

Signal split into 216 subsamples according to decay kinematics, magnet polarity, and left/right detector hemisphere. Weighted average of DACP across all 216 independent measurements reduces possibility of second order detector effects inducing fake asymmetries.

See LHCb-PAPER-2011-023

$D^0 \to K^+K^- / \pi^+\pi^-$ — result

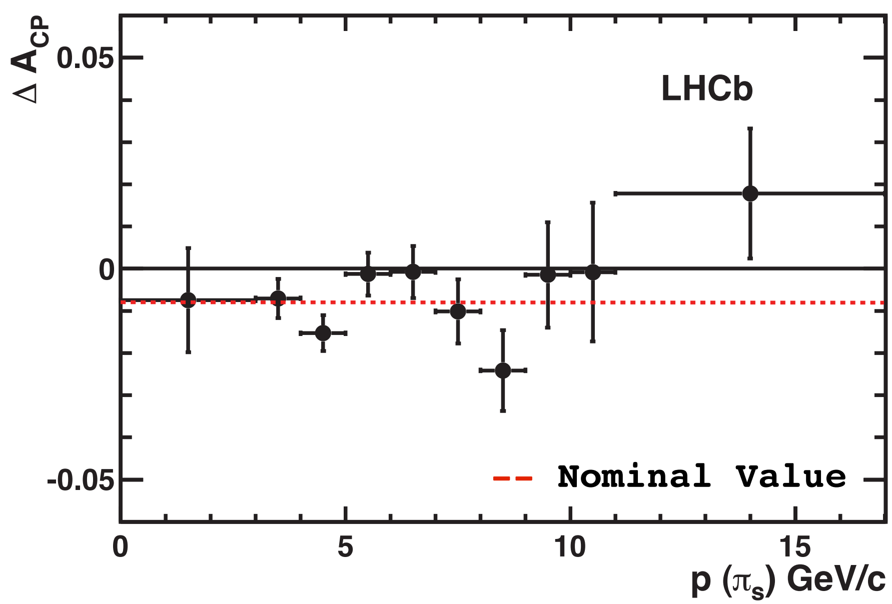
Result is first evidence of CPV in charm hadron decays with 3.5σ significance

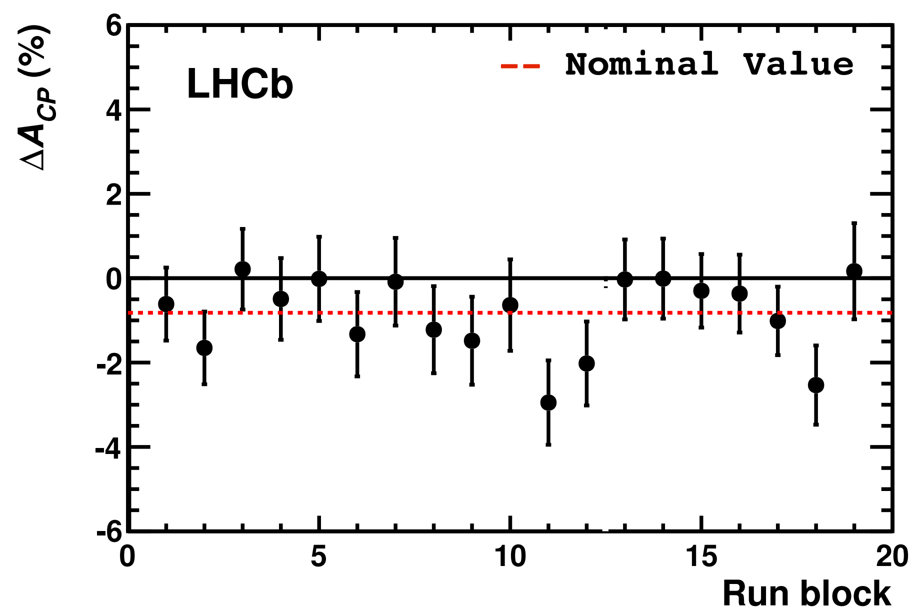
$$\Delta A_{CP} = [-0.82 \pm 0.21(\text{stat}) \pm 0.11(\text{syst})]\%$$

Many other cross-checks performed and all results are consistent with the baseline number

TABLE II. Summary of absolute systematic uncertainties for ΔA_{CP}.

Source	Uncertainty
Fiducial requirement	0.01%
Peaking background asymmetry	0.04%
Fit procedure	0.08%
Multiple candidates	0.06%
Kinematic binning	0.02%
Total	0.11%





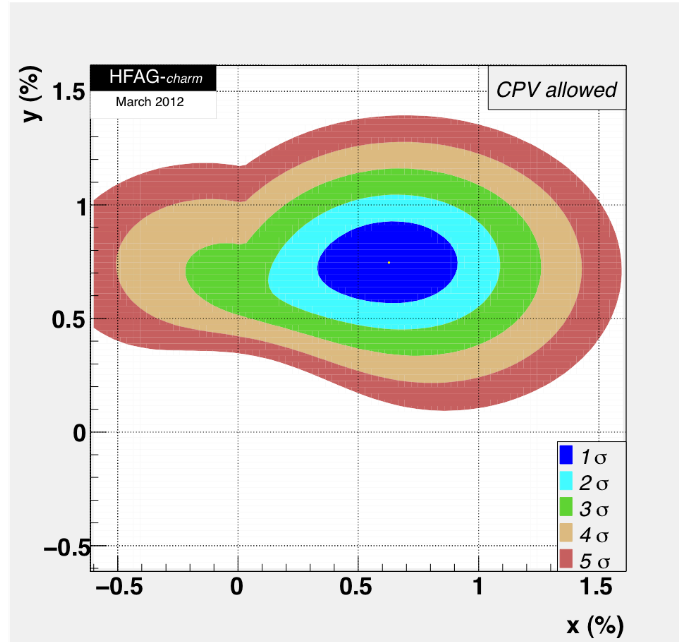
See LHCb-PAPER-2011-023

Mixing and time dependent CPV studies

Motivation

$$y_{CP} \equiv \frac{\tau(D^0 \to K^-\pi^+)}{\tau(D^0 \to K^-K^+)} - 1$$

$$\approx \left(1 - \frac{1}{8}A_m{}^2\right) y\cos\phi - \frac{1}{2}A_m x \sin\phi$$



$$A_\Gamma \equiv \frac{\tau(\overline{D}^0 \to K^+K^-) - \tau(D^0 \to K^+K^-)}{\tau(\overline{D}^0 \to K^+K^-) + \tau(D^0 \to K^+K^-)}$$

$$\approx \frac{1}{2}(A_m + A_d) y\cos\phi - x\sin\phi$$

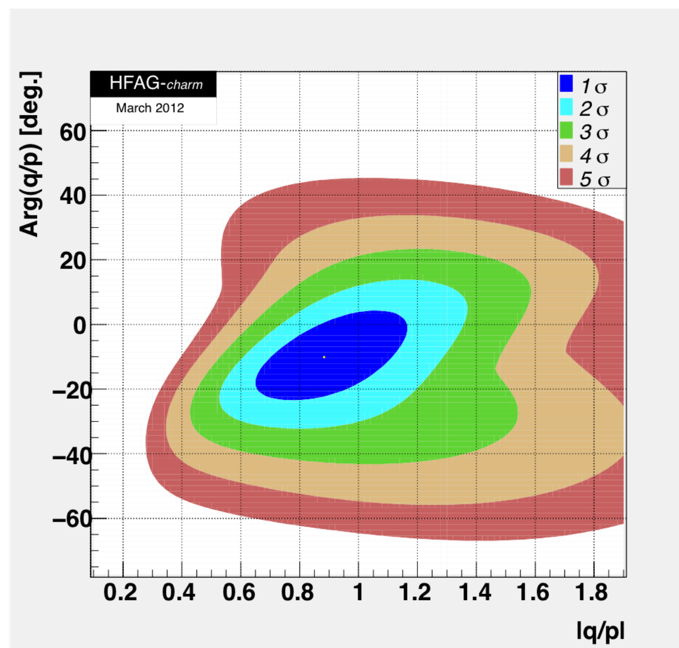
In the above A_m represents CPV in mixing and A_d in decay.

Probe mixing and CPV through tagged lifetime measurements

- **Use prompt $D^{*+} \to D^0(K^+K^-, K^-\pi^+)\pi^+$ decays**

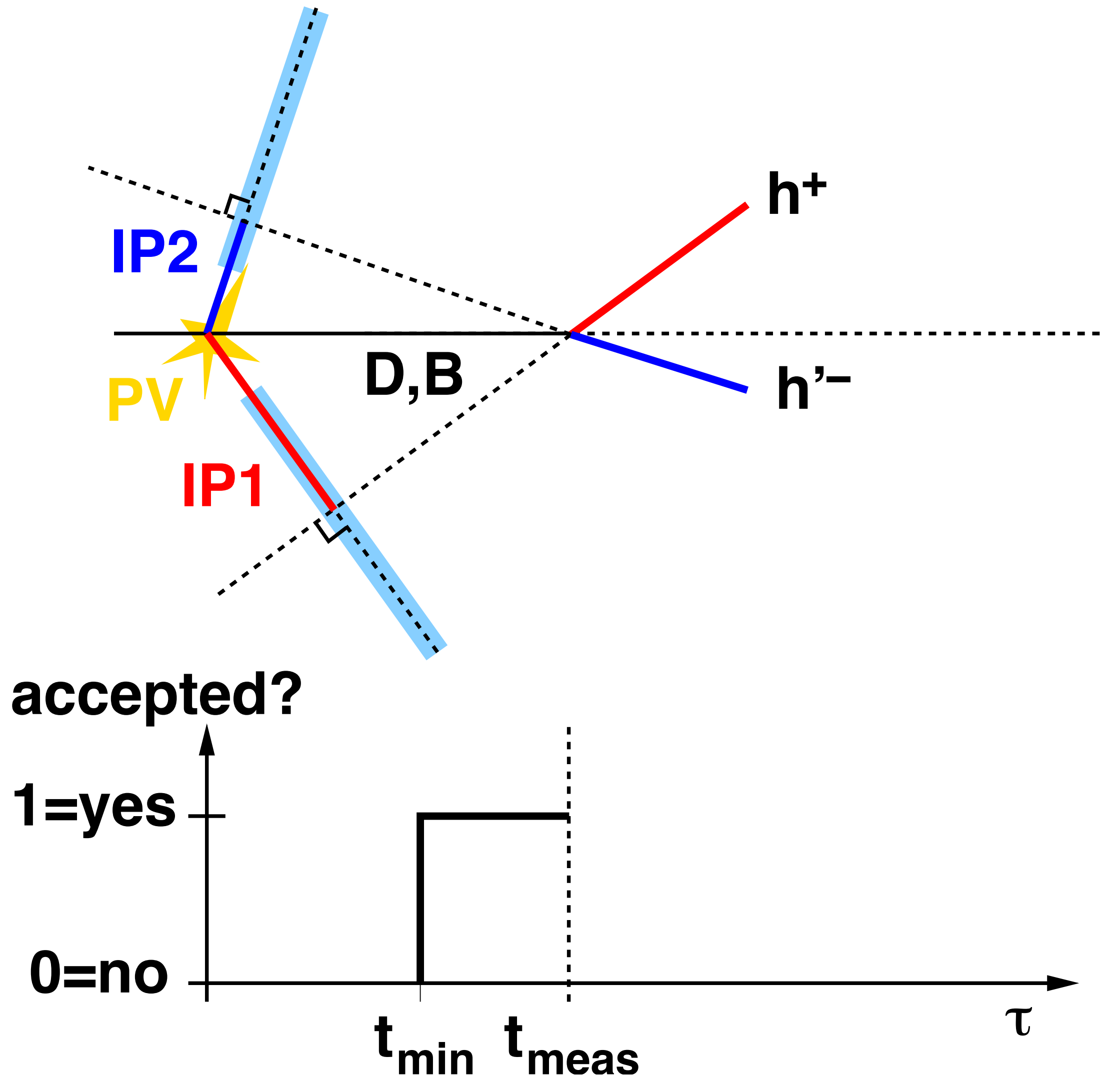
Key challenges :

- **Obtain the selection propertime acceptance event by event**
- **Separate prompt from secondary charm**



See LHCb-PAPER-2011-032

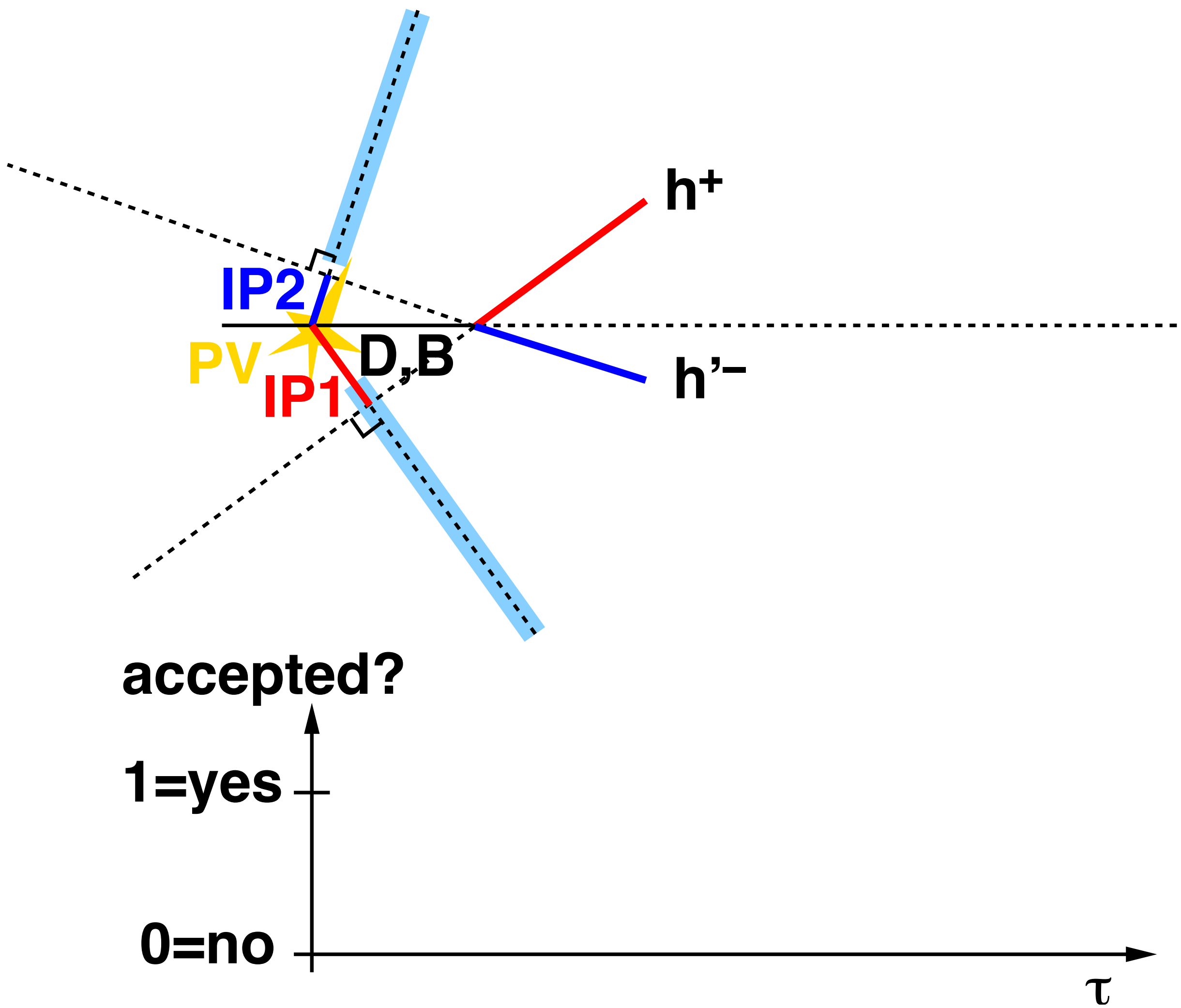
Measuring propertime acceptances



Each event fully describes its own propertime acceptance: can be measured by moving the B vertex and reapplying the selection

See LHCb-PAPER-2011-032

Measuring propertime acceptances



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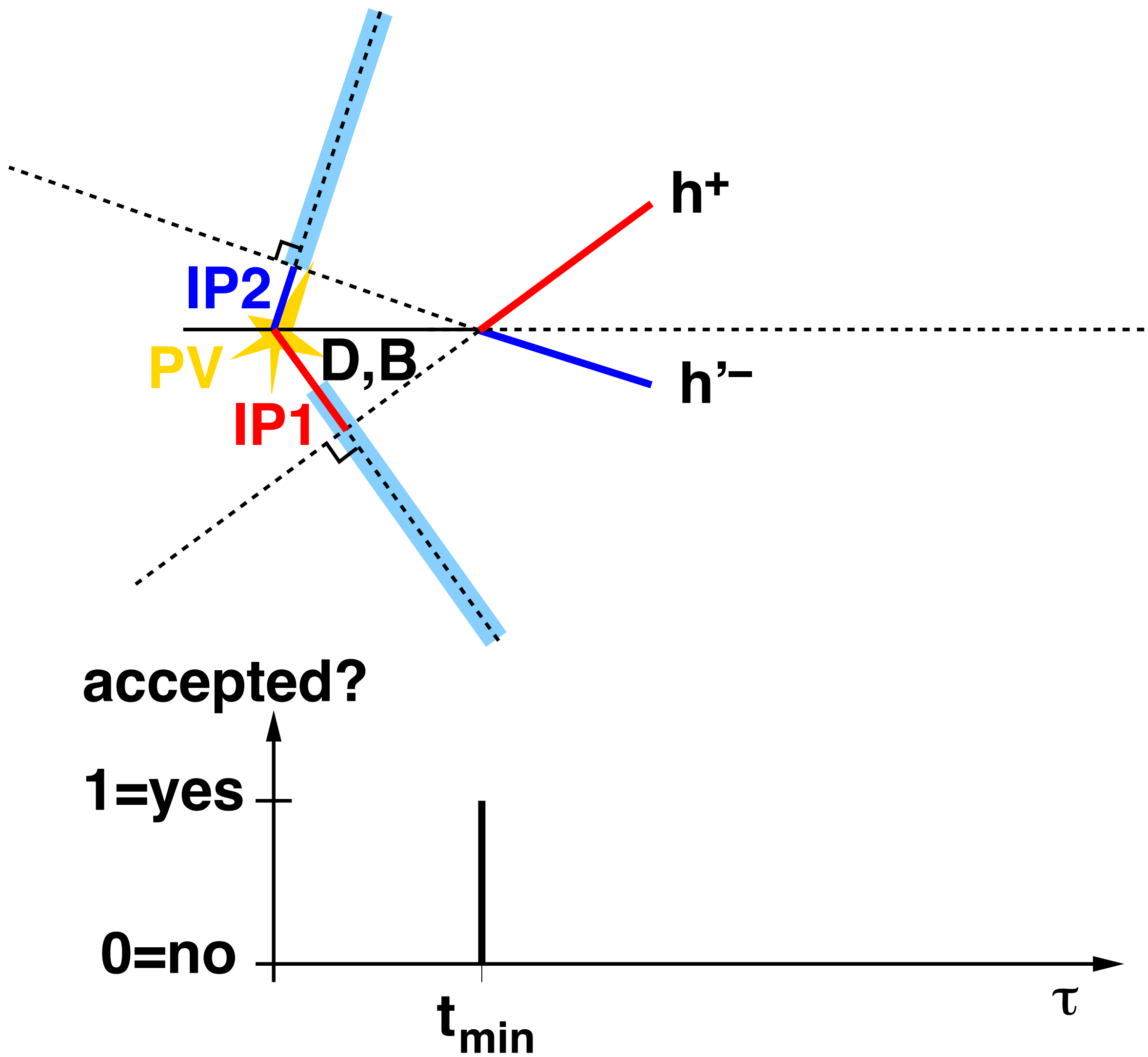
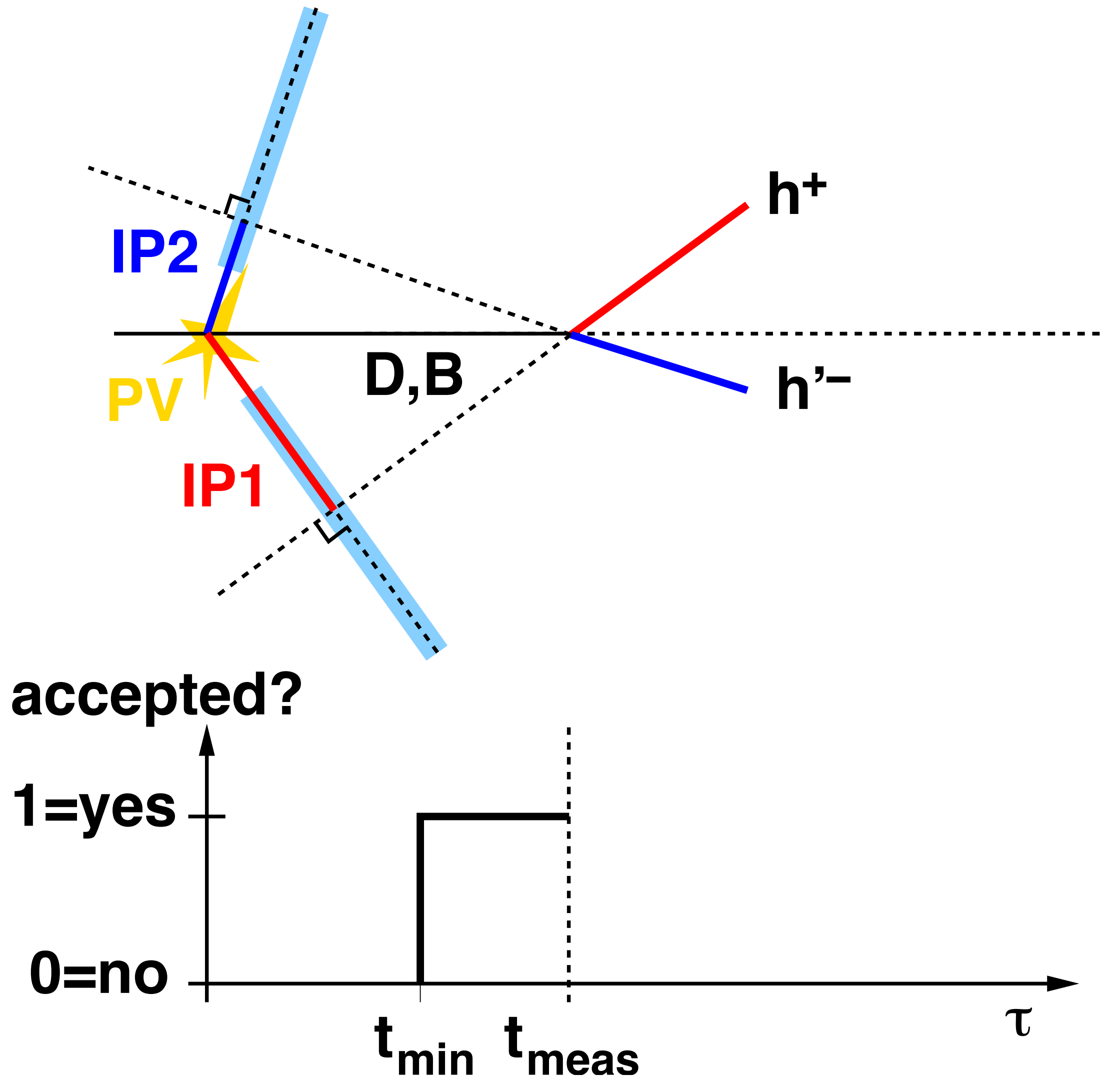


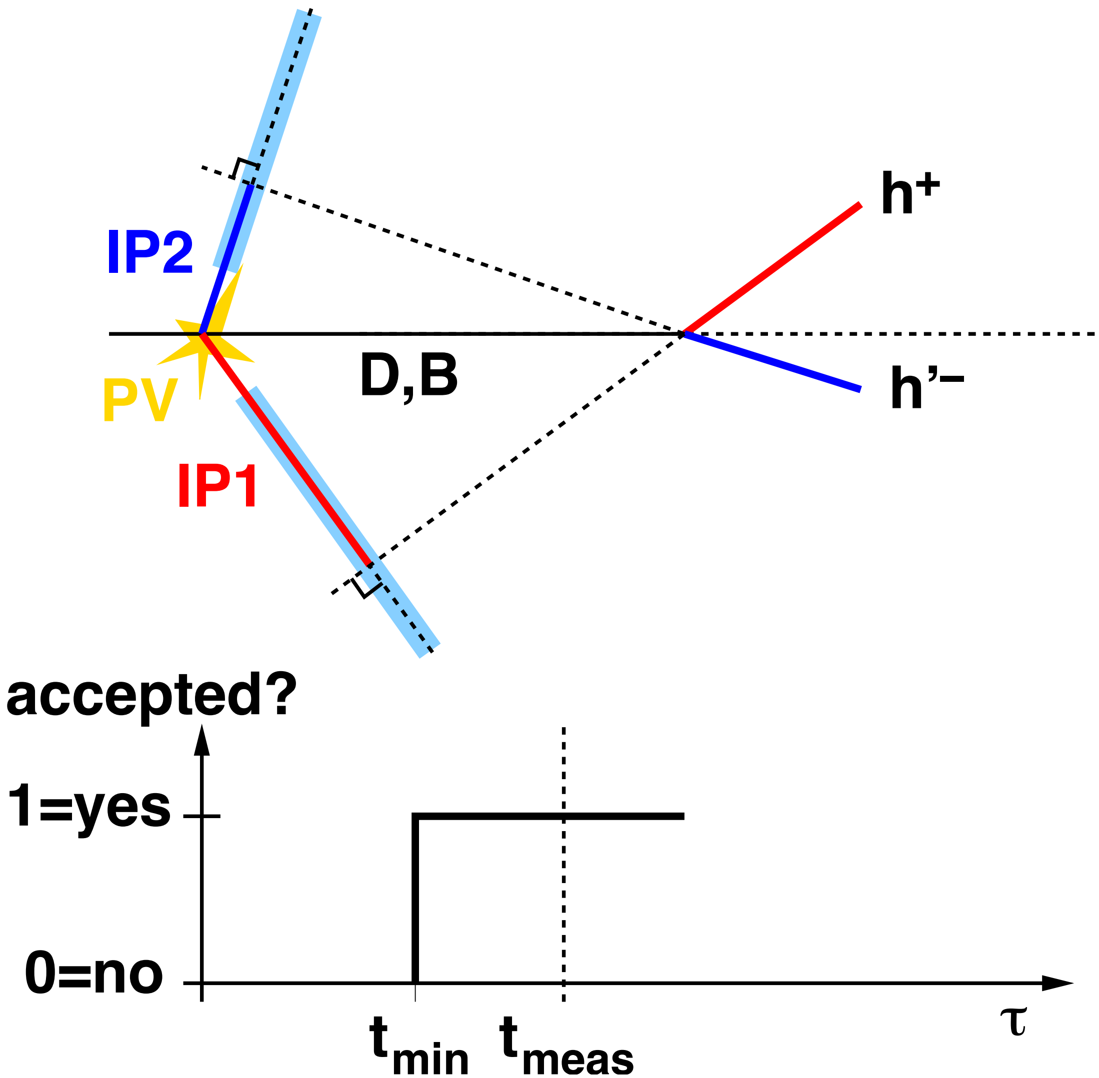
See LHCb-PAPER-2011-032

Measuring propertime acceptances



See LHCb-PAPER-2011-032

Measuring propertime acceptances



See LHCb-PAPER-2011-032

Results

Separate prompt and secondary charm on a statistical basis through their distribution in $\ln(\chi^2 IP_D)$

Fit lifetime distributions using event-by-event acceptance functions obtained on data

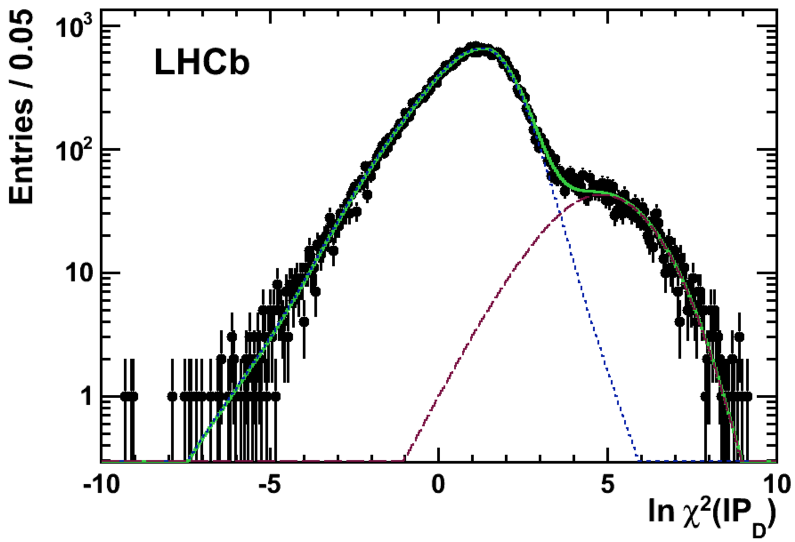
Results based on 29 pb^{-1} of data taken in 2010 are

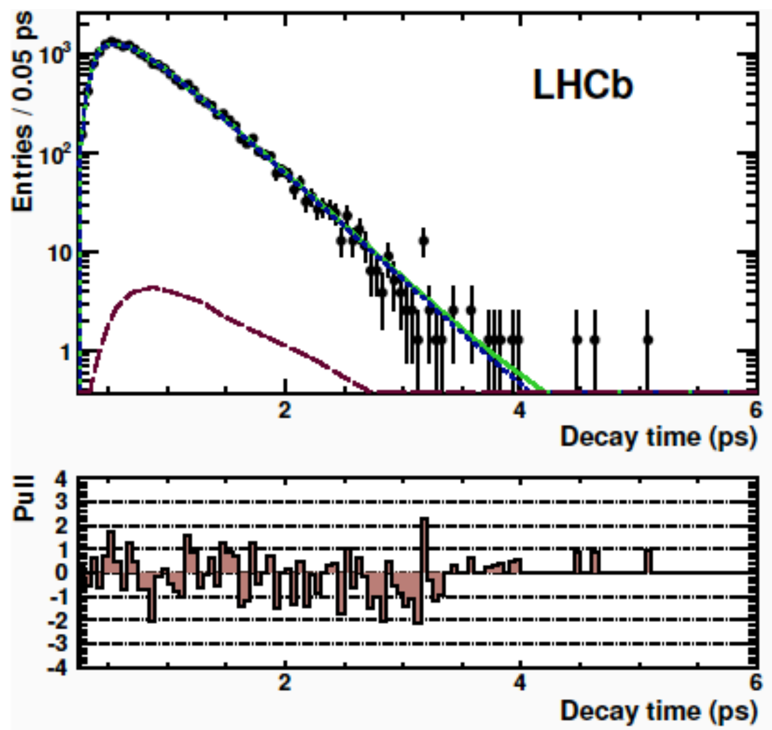
$$y_{CP} = (5.5 \pm 6.3_{stat} \pm 4.1_{syst}) \times 10^{-3}$$

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

Effect	A_Γ (10^{-3})	y_{CP} (10^{-3})
Decay-time acceptance correction	0.1	0.1
Decay-time resolution	0.1	0.1
Minimum decay-time cut	0.1	0.8
Maximum decay-time cut	0.2	0.2
Combinatorial background	1.3	0.8
Secondary-like background	1.6	3.9
Total	2.1	4.1

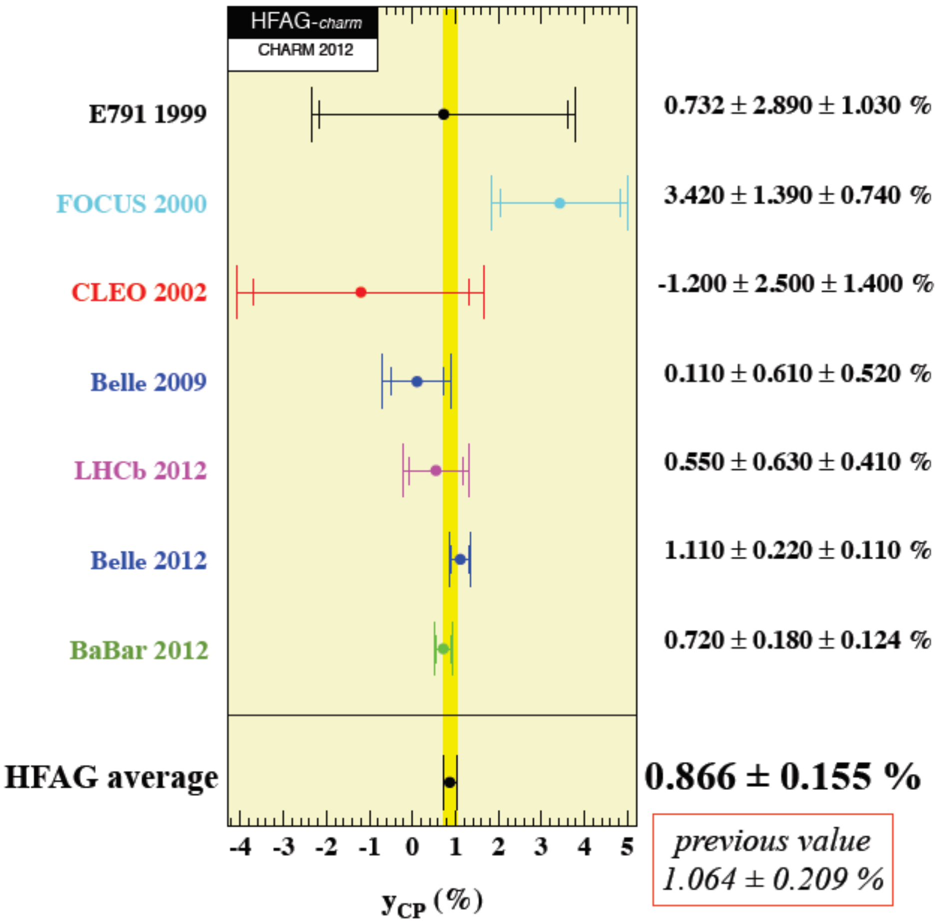
Table 1. Summary of systematic uncertainties.

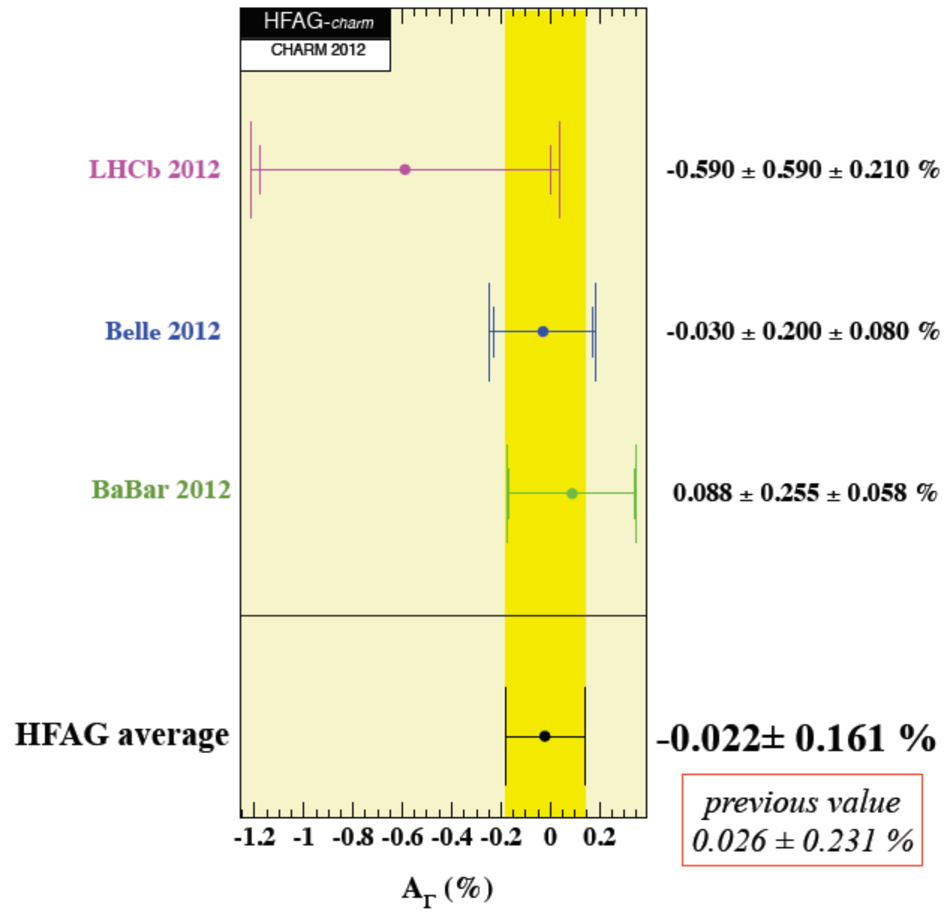




See LHCb-PAPER-2011-032

LHCb and the world





Including new BaBar and Belle results: significant improvement in the uncertainty and lower value for y_{CP}.

See N. Neri, Charm 2012

Interplay of dir. and ind. CPV

At the present level of precision A_Γ is a measurement of indirect CPV, although note that direct CPV around 10^{-2} would induce A_Γ at 10^{-4} from the equation

$$A_\Gamma \approx \frac{1}{2}(\mathrm{A_m} + \mathrm{A_d}) y \cos\phi - x \sin\phi.$$

Experiment is not yet there, but will be soon(ish)

On the other hand, DACP contains both direct and indirect CPV contributions due to the lifetime acceptance of the selection criteria. For each state

$$A_{CP}(f) = a_{CP}^{dir}(f)\left(1 + y\cos\phi\frac{\langle t\rangle}{\tau}\right) + a_{CP}^{ind}(f)\frac{\langle t\rangle}{\tau}$$

where <t> is the average decay time and is experiment dependent! Since a^{ind}_{CP} is universal

$$\Delta A_{CP}(f) = \Delta a_{CP}^{dir}(f)\left(1 + y\cos\phi\frac{\overline{\langle t\rangle}}{\tau}\right) + \left(a_{CP}^{ind}(f) + \overline{a_{CP}^{dir}}(f) y\cos\phi\right)\frac{\Delta\langle t\rangle}{\tau}$$

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

See Grossman et al. Phys. Rev. D 75 (2007) 036008

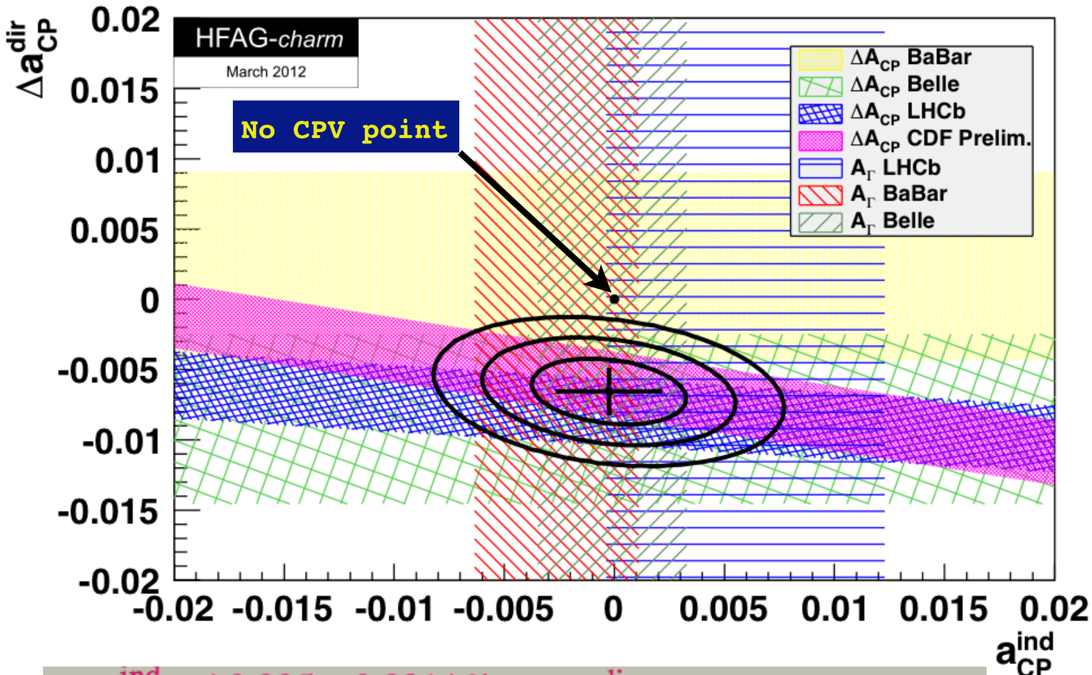
Interplay of dir. and ind. CPV

Uses the following relations

$$A_\Gamma = -a_{CP}^{ind} - y_{CP}a_{CP}^{dir}$$

$$\Delta A_{CP} = \Delta a_{CP}^{dir}\left(1 + y_{CP}\frac{\overline{\langle t\rangle}}{\tau}\right) + a_{CP}^{ind}\frac{\Delta\langle t\rangle}{\tau}$$

The data is consistent with no CPV at 0.006% CL

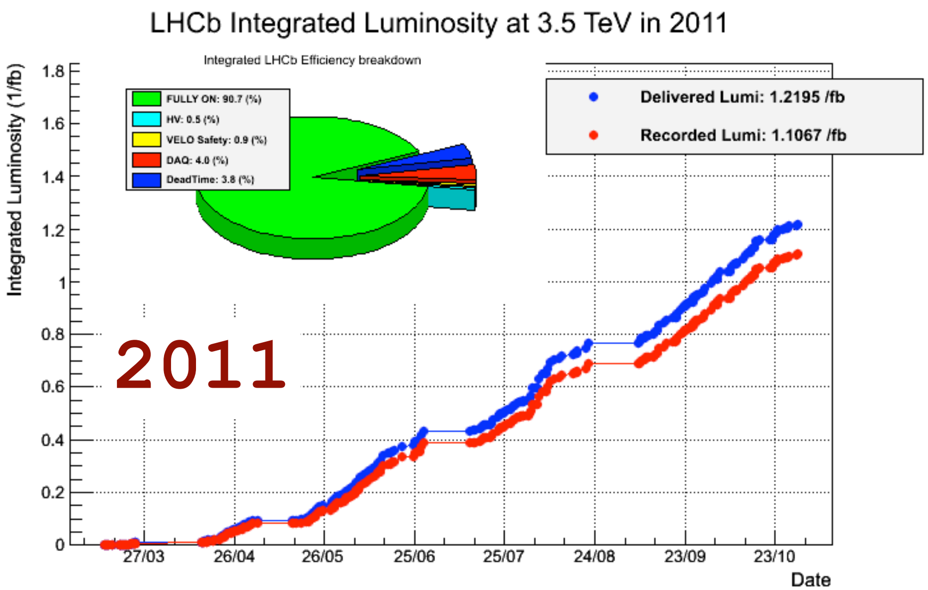


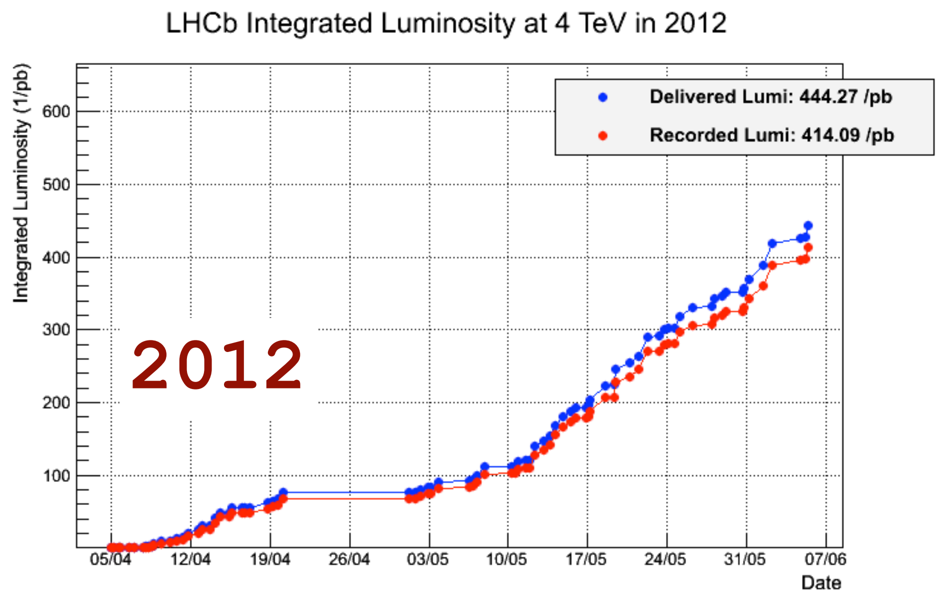
$a_{CP}^{ind} = (-0.025 \pm 0.231)\%$ $\Delta a_{CP}^{dir} = (-0.656 \pm 0.154)\%$

Year	Experiment	Results	$\Delta\langle t\rangle/\tau$	$\overline{\langle t\rangle}/\tau$
2007	Belle	$A_\Gamma = (0.01 \pm 0.30 \text{ (stat.)} \pm 0.15 \text{ (syst.)})\%$	-	-
2008	BaBar	$A_\Gamma = (0.26 \pm 0.36 \text{ (stat.)} \pm 0.08 \text{ (syst.)})\%$	-	-
2011	LHCb	$A_\Gamma = (-0.59 \pm 0.59 \text{ (stat.)} \pm 0.21 \text{ (syst.)})\%$	-	-
2008	BaBar	$A_{CP}(KK) = (0.00 \pm 0.34 \text{ (stat.)} \pm 0.13 \text{ (syst.)})\%$ $A_{CP}(\pi\pi) = (-0.24 \pm 0.52 \text{ (stat.)} \pm 0.22 \text{ (syst.)})\%$	0.00	1.00
2008	Belle	$\Delta A_{CP} = (-0.86 \pm 0.60 \text{ (stat.)} \pm 0.07 \text{ (syst.)})\%$	0.00	1.00
2011	LHCb	$\Delta A_{CP} = (-0.82 \pm 0.21 \text{ (stat.)} \pm 0.11 \text{ (syst.)})\%$	0.10	2.08
2012	CDF Prelim.	$\Delta A_{CP} = (-0.62 \pm 0.21 \text{ (stat.)} \pm 0.10 \text{ (syst.)})\%$	0.25	2.58
	Fit Result	**Agreement with no CP violation** **CL = 6.1×10^{-5}**		

See Gersabeck et al. J.Phys.G G39 (2012) 045005

Prospects in 2011/2012





>1 fb^{-1} of data on tape in 2011, and 2012 datataking well underway. World's largest samples of two/three body $D^0/D^+/D_s$ decays available for analysis!

Analyses ongoing across a range of key CPV modes : $D^0 \to hh$, $D^+ \to hhh$, $D^0 \to hhhh$, $D^+ \to K_S h$, $D^0 \to K_S hh$...

...stay tuned!

BACKUPS

Why charm?

Only up-type quark where we can look for mixing/CPV : top doesn't hadronize, while π^0 is its own antiparticle and CPV is tightly limited by CPT constraints

Large branching fractions ($>10^{-3}$) for many CPV sensitive modes, very low SM backgrounds, hence potentially

$$\left[\frac{\text{experim. NP signal}}{\text{SM }\mathbf{CP}\text{ ``background''}}\right]_{\mathbf{D}\text{ decays}} > \left[\frac{\text{experim. NP signal}}{\text{SM }\mathbf{CP}\text{ ``background''}}\right]_{\mathbf{B}\text{ decays}}$$

Very broad range of modes which one can study

$$\begin{aligned}
D^0(t) &\to K_S\phi,\ K_SK^+K^-,\ K_S\rho,\ K_S\pi^+\pi^-,\ K_S\eta^{(\prime)},\ K_S\omega \\
D^0(t) &\to l^-\bar{\nu}K^+ \\
D^0(t) &\to K^+K^-,\ \pi^+\pi^-,\ K^+\pi^- \\
D^0(t) &\to 3\pi,\ K\bar{K}\pi \\
D^0(t) &\to K^+K^-\pi^+\pi^-,\ K^+K^-\mu^+\mu^-,\ K^+\pi^-\pi^+\pi^-,\ K^+K^-K^+\pi^- \\
D^\pm &\to K_S\pi^\pm,\ K_SK^\pm \\
D^\pm &\to 3\pi,\ K\bar{K}\pi,\ K^\pm K^+K^-,\ K^\pm\pi^+\pi^- \\
D^0 &\to \mu^+\mu^-\ [,\ \gamma\gamma]
\end{aligned}$$

See Bigi ArXiv:0902.3048

Why charm?

Only up-type quark where we can look for mixing/CPV : top doesn't hadronize, while π^0 is its own antiparticle and CPV is tightly limited by CPT constraints

Large branching fractions (>10^{-3}) for many CPV sensitive modes, very low SM backgrounds, hence potentially

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Very broad range of modes which one can study

Concentrate here on studies at LHCb in 2010/2011 data

$$\begin{array}{rcl}
D^0(t) & \to & K_S\phi,\ K_SK^+K^-,\ K_S\rho,\ K_S\pi^+\pi^-,\ K_S\eta^{(\prime)},\ K_S\omega \\
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D^0(t) & \to & 3\pi,\ K\bar{K}\pi \\
D^0(t) & \to & K^+K^-\pi^+\pi^-,\ K^+K^-\mu^+\mu^-,\ K^+\pi^-\pi^+\pi^-,\ K^+K^-K^+\pi^- \\
D^\pm & \to & K_S\pi^\pm,\ K_SK^\pm \\
D^\pm & \to & 3\pi,\ K\bar{K}\pi,\ K^\pm K^+K^-,\ K^\pm\pi^+\pi^- \\
D^0 & \to & \mu^+\mu^-\ [,\ \gamma\gamma]
\end{array}$$

See Bigi ArXiv:0902.3048

Trigger and DAQ

LHC rate ~ 15 MHz	cc fraction ~ 10%
↓	↓
L0 E_T trigger ~ 1 MHz	cc fraction ~ 50%

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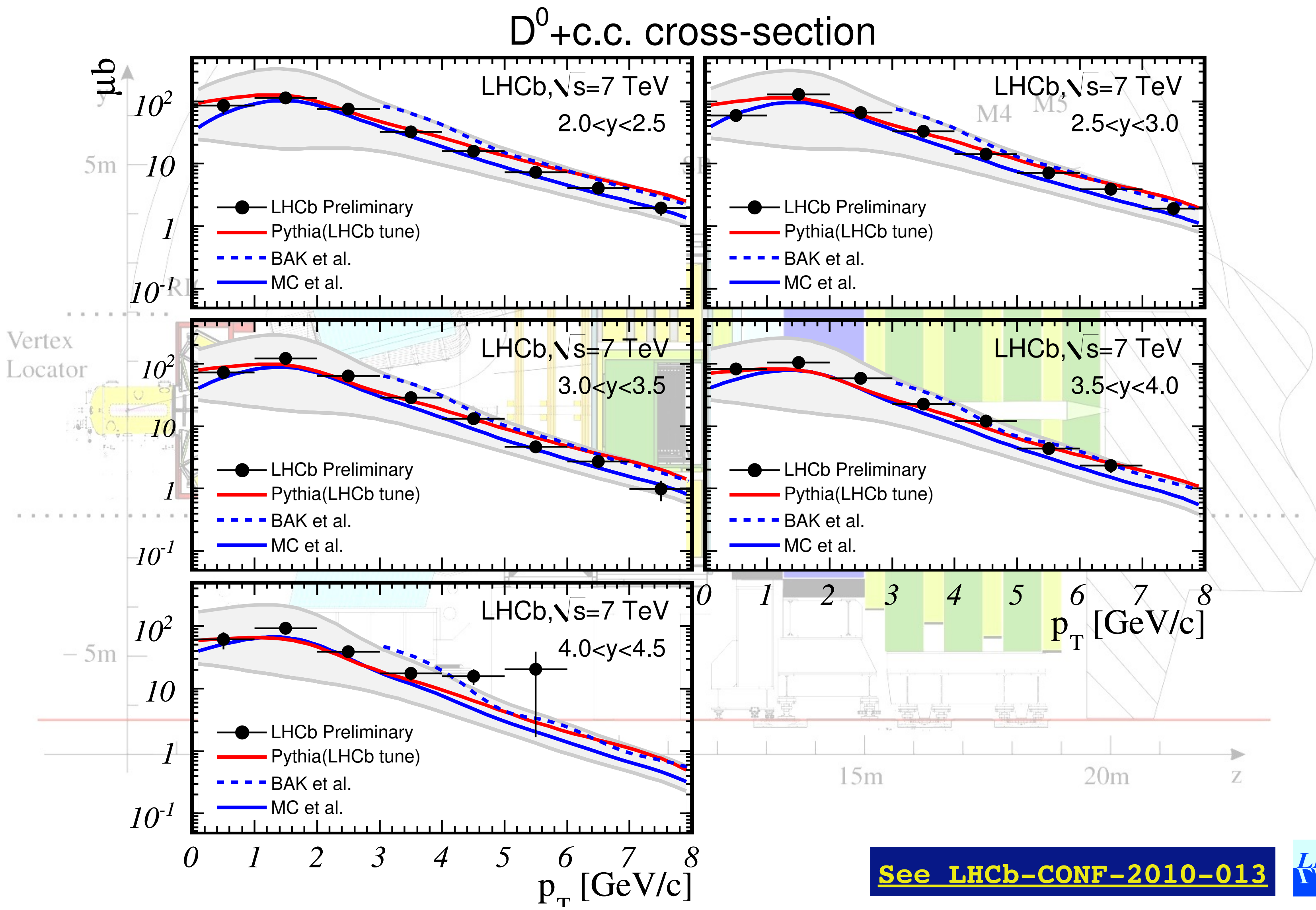
High P_T,IP track ~ 80 kHz (50% eff.)

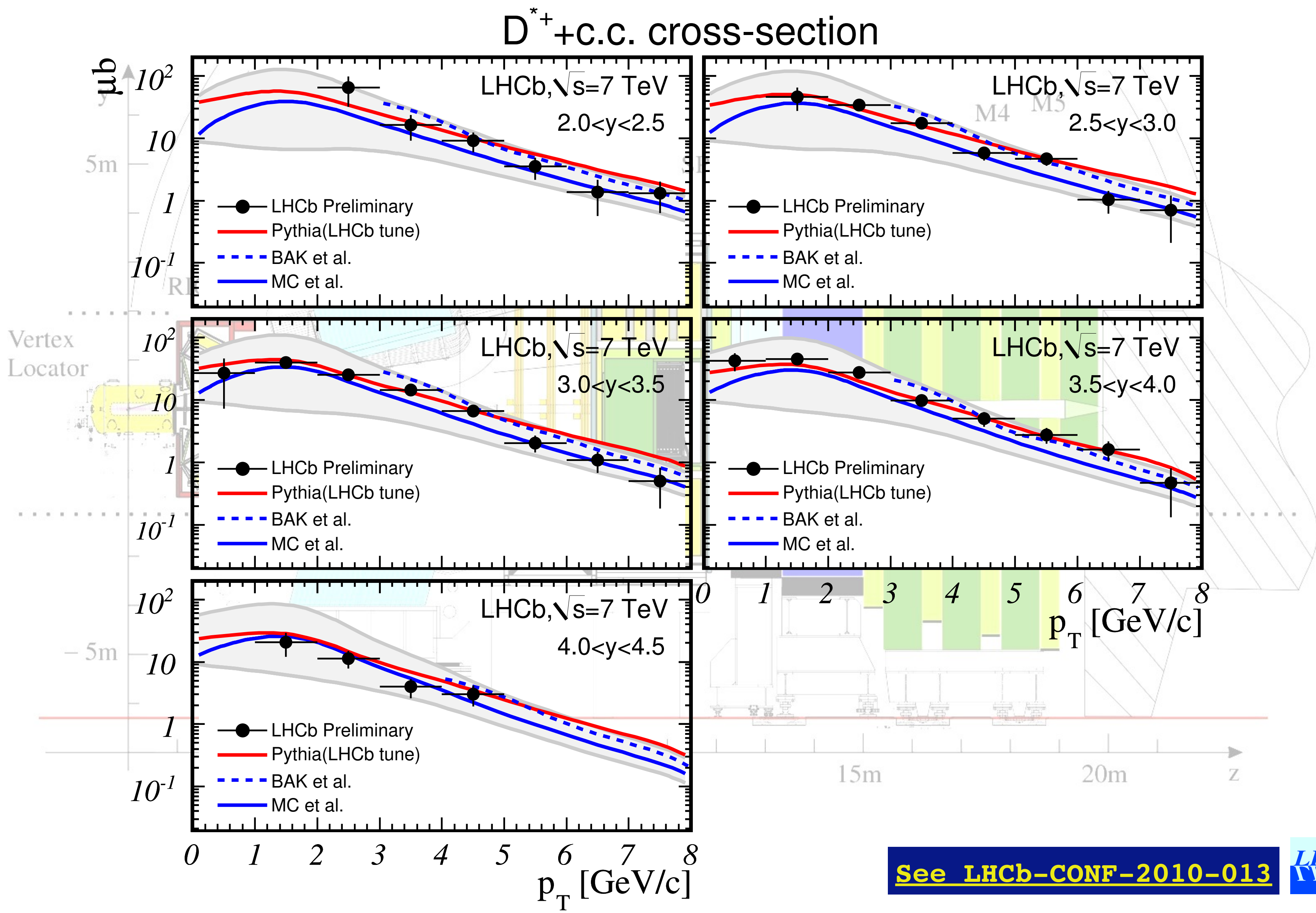
Exclusive D->hh/3h/4h ~ 2 kHz (50-90% eff.)

Cross sections



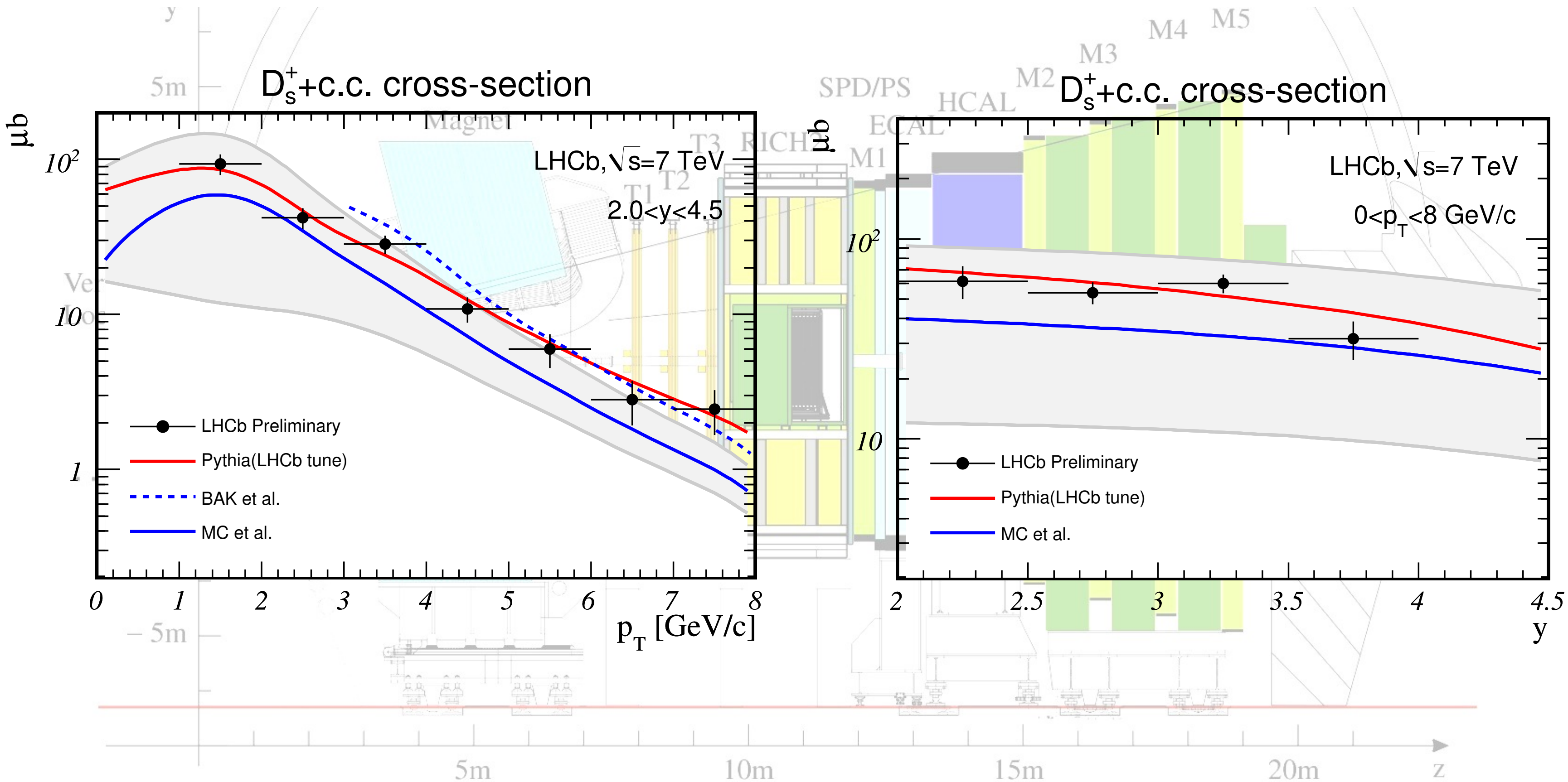
See LHCb-CONF-2010-013

Cross sections



See LHCb-CONF-2010-013

Cross sections



See LHCb-CONF-2010-013