CHARM 2016

Bologna, 07 Sep 2016

Mixing and indirect CP violation using 2-body decays at LHCb

Pietro Marino on behalf of LHCb collaboration

SNS & INFN-Pi

INFN Istituto Nazionale di Fisica Nucleare

SCUOLA NORMALE SUPERIORE

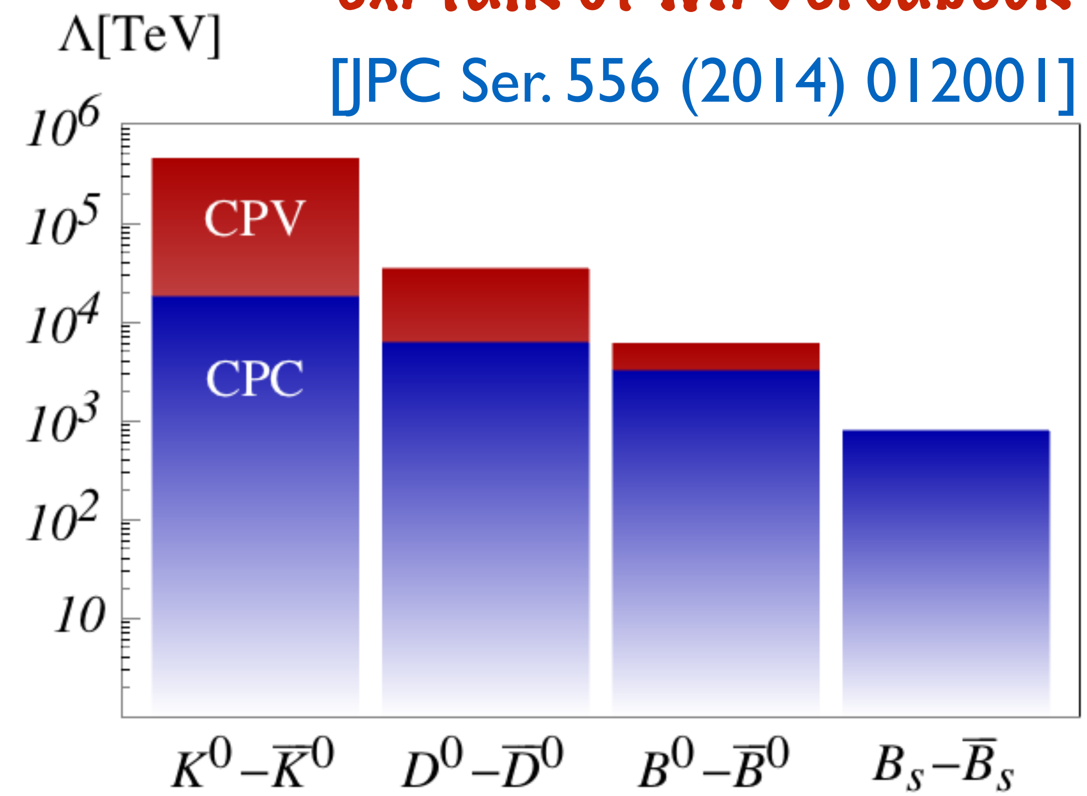
LHCb

Why is charm charming?

th: talk of A. Lenz
ex: talk of M. Gersabeck

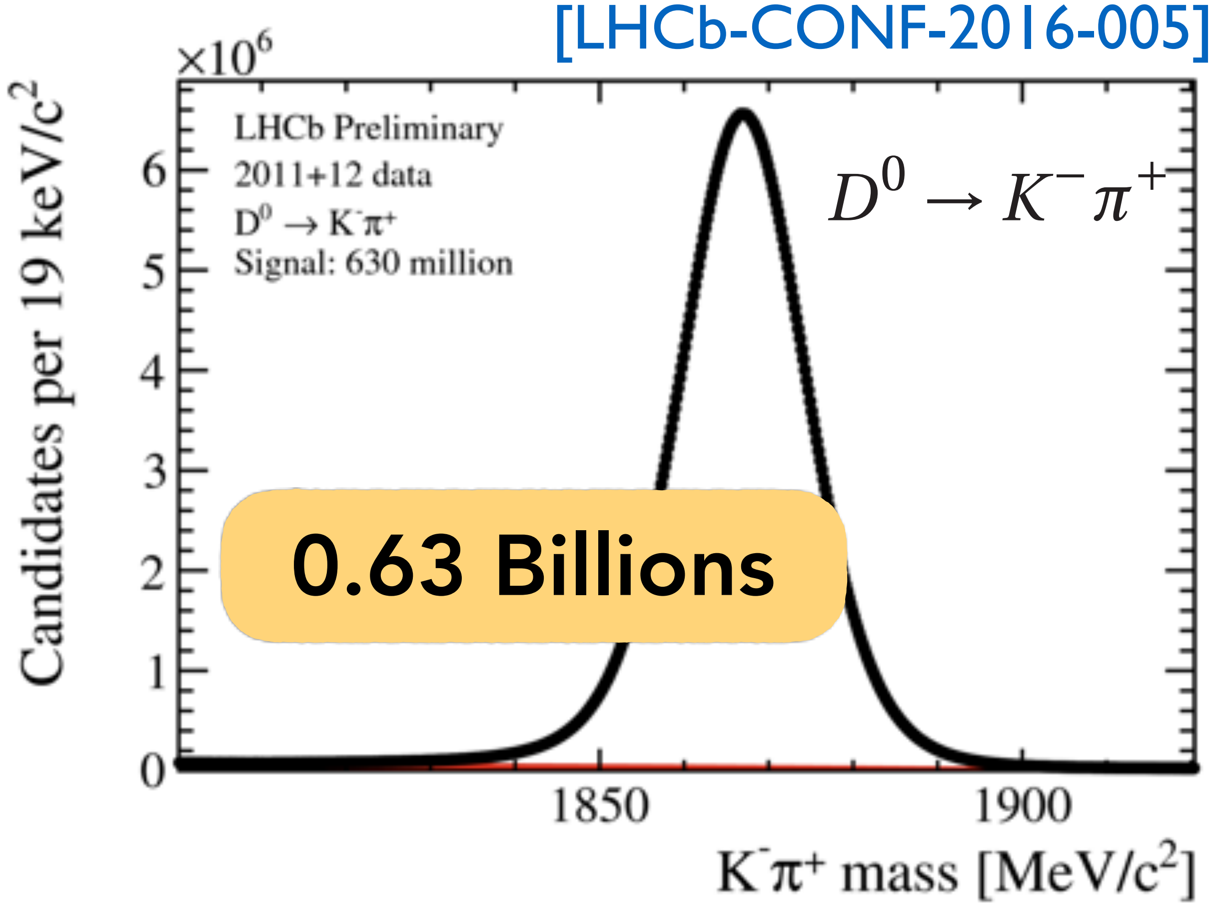
- Unique and powerful probe of BSM flavour effects.
- Charm is an up-type quark:
  - complementary to *B* and *K* meson system;
  - best bounds on a generic new physics model after the kaon mixing.

[JPC Ser. 556 (2014) 012001]



- **Huge data samples,**
  - LHCb has the opportunity to exploit fully the charm sector as a probe for new physics.
- SM predictions are **difficult** on D-meson sector:
  - D^0 mass ≈ 1864 MeV/c^2
  - QCD perturbative only at energies ≫ 1GeV

[LHCb-CONF-2016-005]

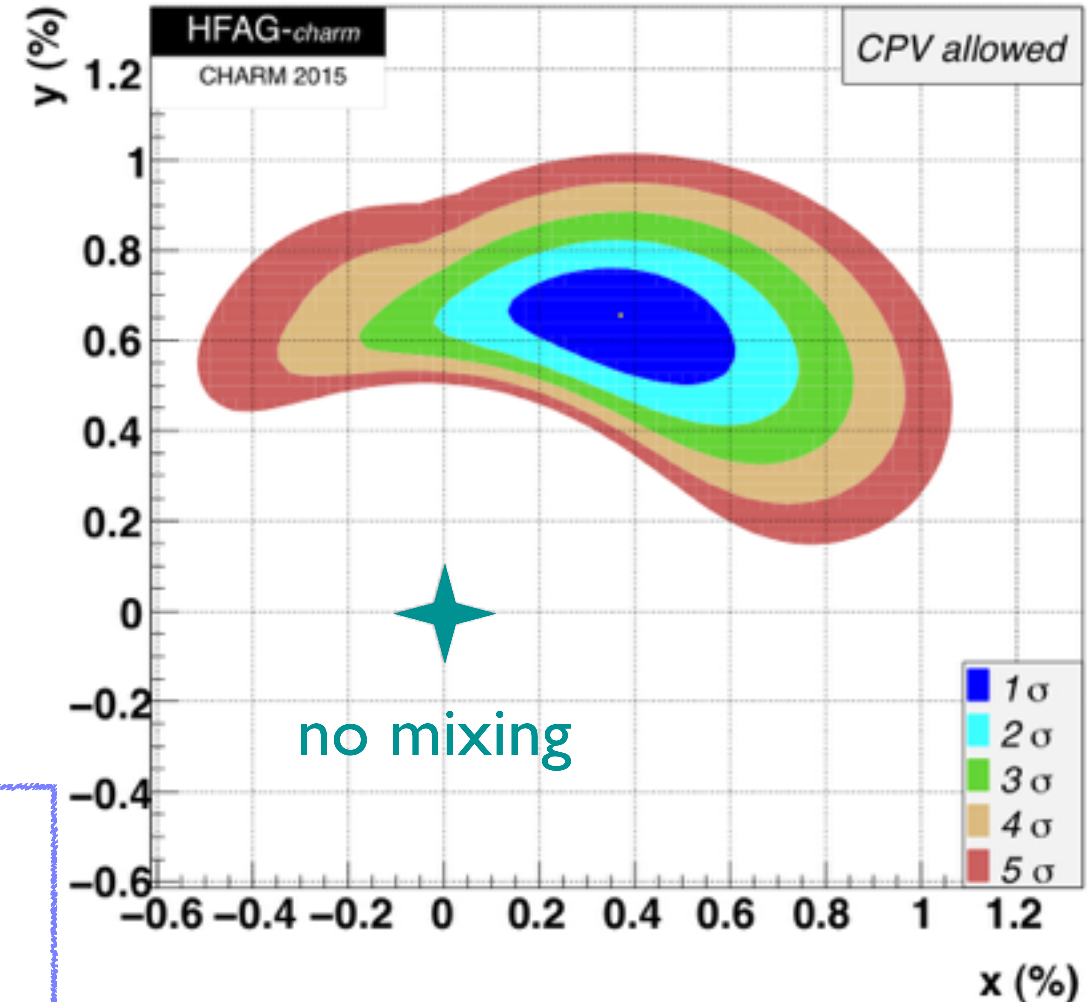


Charm mixing and CP violation

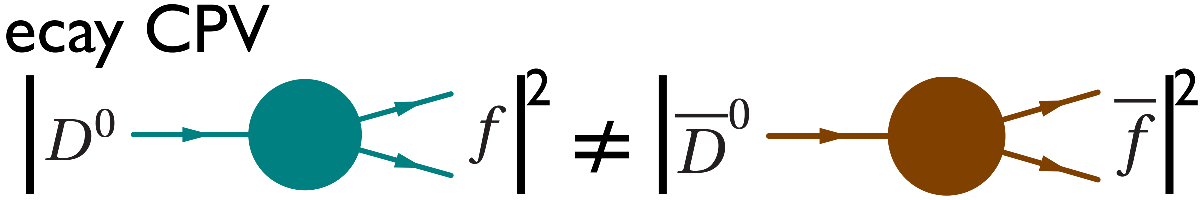
th: talk of A. Lenz
ex: talk of M. Gersabeck

- D^0 mixing is established.
- CP violation yet unobserved!
  - Small value expected from SM $\mathcal{O}(V_{ub}V_{cb}^*/V_{us}V_{cs}^*) \sim \mathcal{O}(10^{-3})$
  - Present sensitivity close to possible BSM contribution (yields ~ $\mathcal{O}(10^6)$)

[HFAG, arXiv:1412.7515]

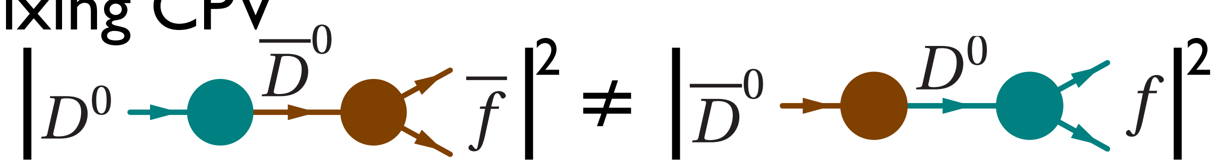


Decay CPV



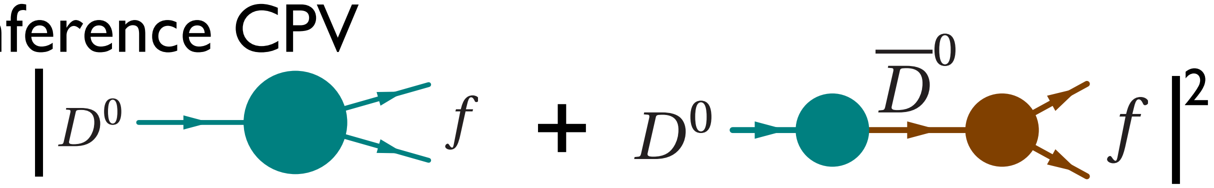
$$\leftrightarrow \left|\frac{A_f}{\bar{A}_{\bar{f}}}\right| \neq 1$$

Mixing CPV



$$\leftrightarrow \left|\frac{q}{p}\right| \neq 1 \; (\phi \neq 0)$$

Inference CPV



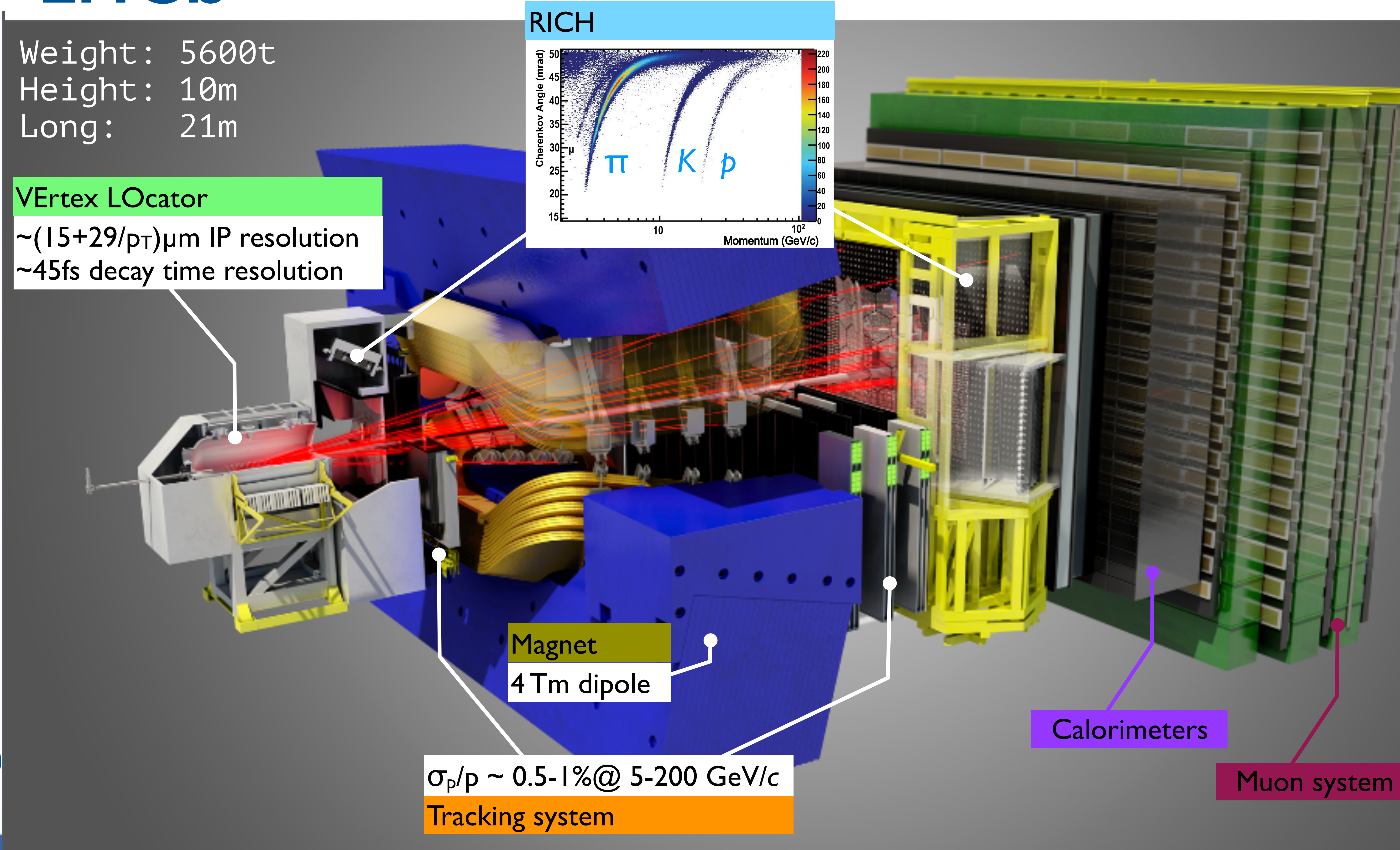
$$\leftrightarrow \arg\left(\frac{q A_f}{p \bar{A}_{\bar{f}}}\right) \neq 0$$

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

$$x \equiv \frac{m_1 - m_2}{\Gamma}, \quad y \equiv \frac{\Gamma_1 - \Gamma_2}{2\Gamma}$$

$$\phi = \arg(q/p)$$

LHCb



Weight: 5600t
Height: 10m
Long: 21m
VErtex LOcator
~(15+29/p_T)μm IP resolution
~45fs decay time resolution
RICH
Cherenkov Angle (mrad)
Momentum (GeV/c)
π
K
p
Magnet
4 Tm dipole
σ_p/p ~ 0.5-1%@ 5-200 GeV/c
Tracking system
Calorimeters
Muon system

Mixing with $D^0 \to K\pi$ decays

WS mixing with double tagged D^0

[LHCb-PAPER-2016-033] (in prep.)

- Measure time-dependent ratio

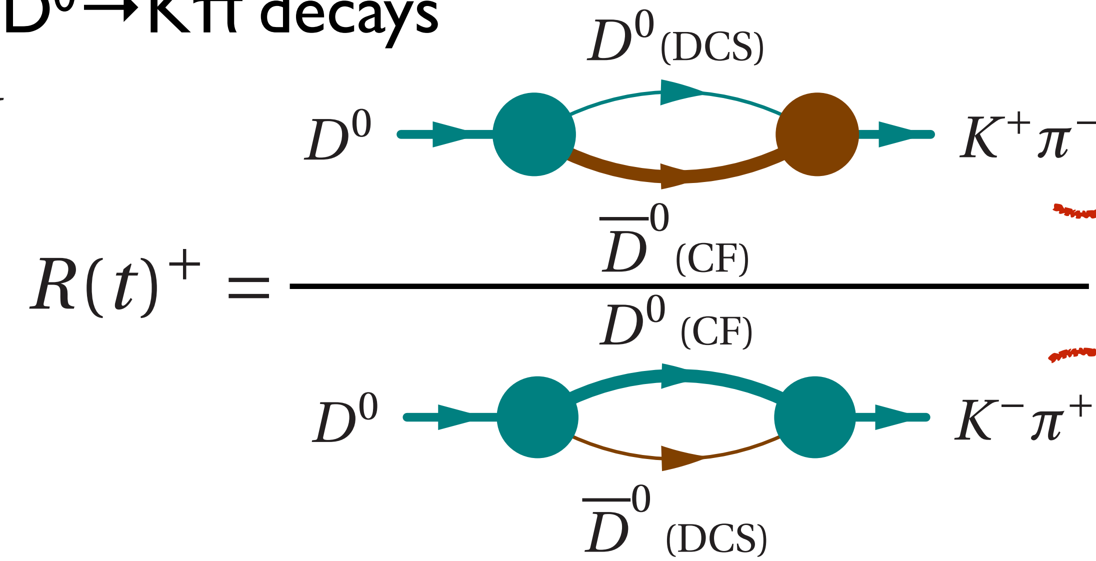
$$R(t)^{\pm} = \frac{\mathrm{WS}(t)^{\pm}}{\mathrm{RS}(t)^{\pm}} \approx R_D^{\pm} + \sqrt{R_D^{\pm}}\, y'^{\pm} \frac{t}{\tau} + \frac{(x'^{\pm})^2 + (y'^{\pm})^2}{4} \left(\frac{t}{\tau}\right)^2$$

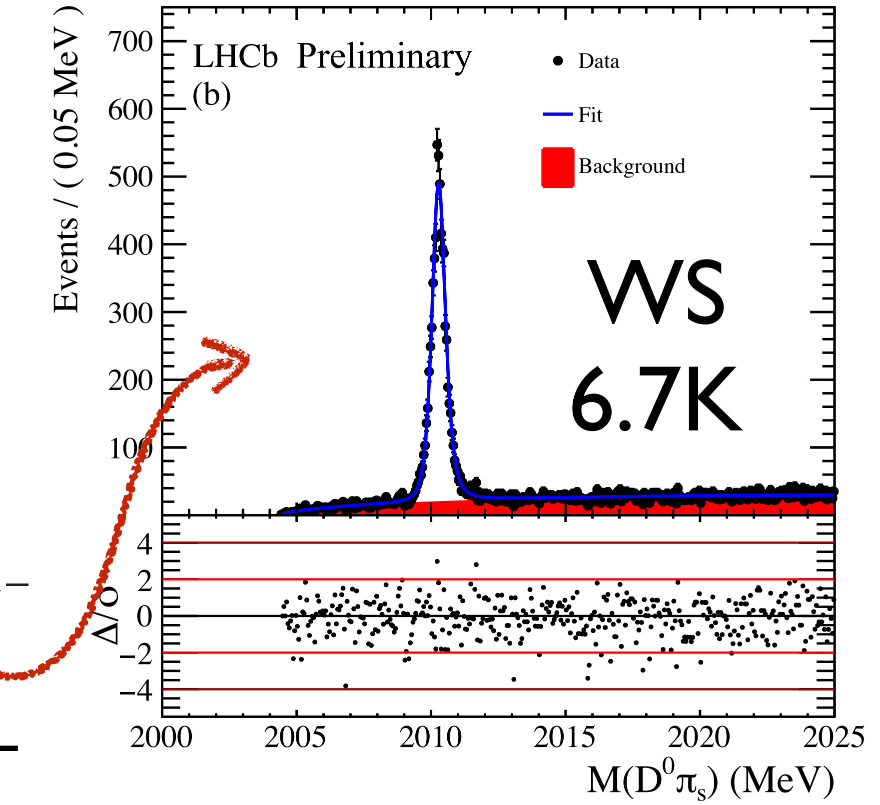
$$x' = \; x\cos\delta + y\sin\delta,\; y' = -x\sin\delta + y\cos\delta$$

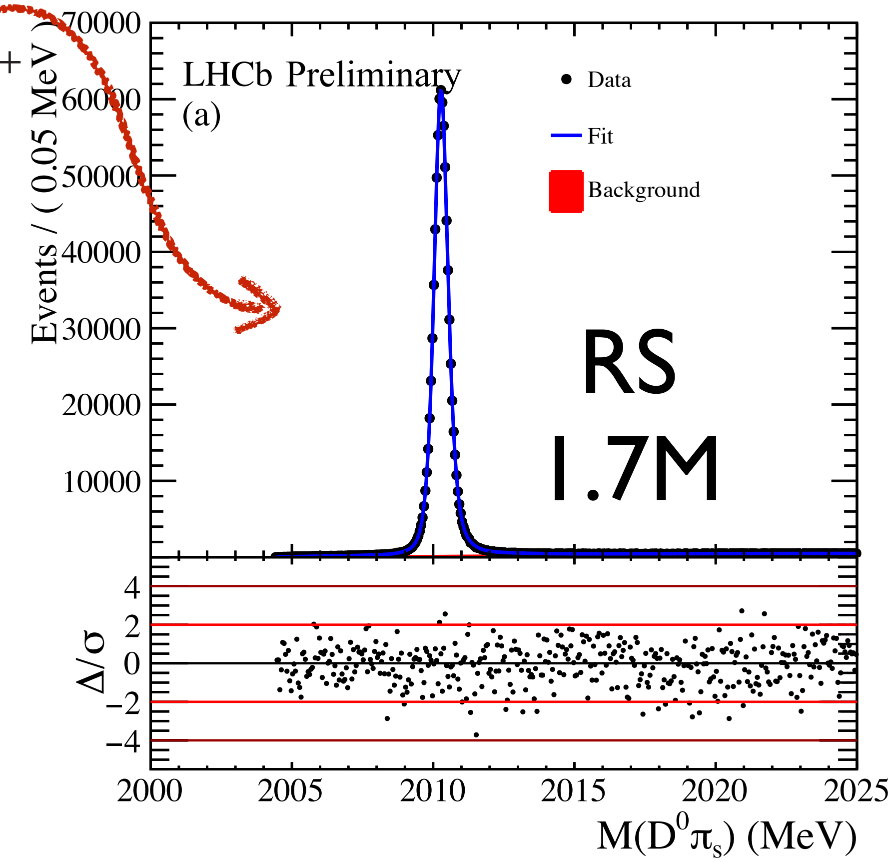
- Use double-tagged (π and μ) $D^0 \to K\pi$ decays

$$\overline{B} \to \mu^- D^{*+}(\to D^0 \pi_s^+) X$$

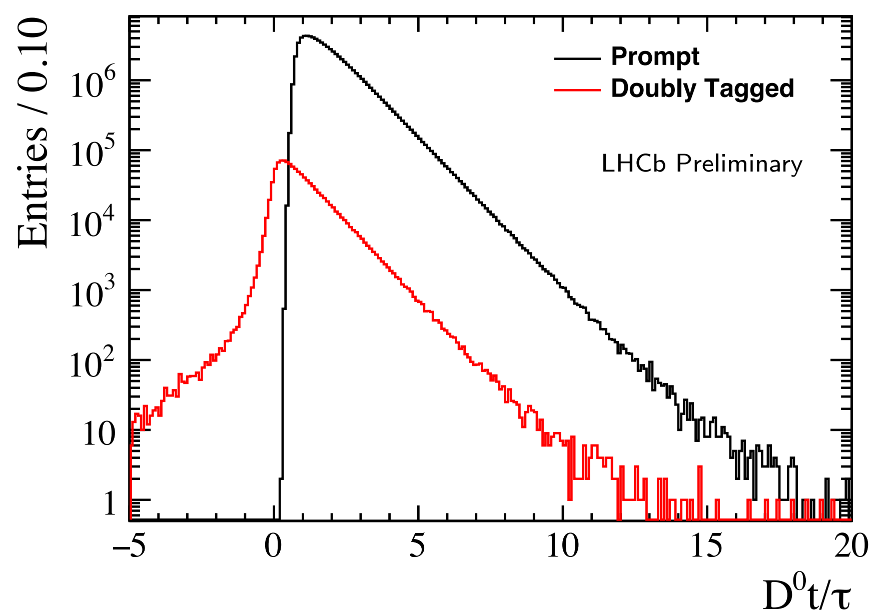
- Very clean.







- Complements previous measurement using prompt $D^{*+} \to D^0 \pi_s^+$ [PRL 11, 251801 (2013)]



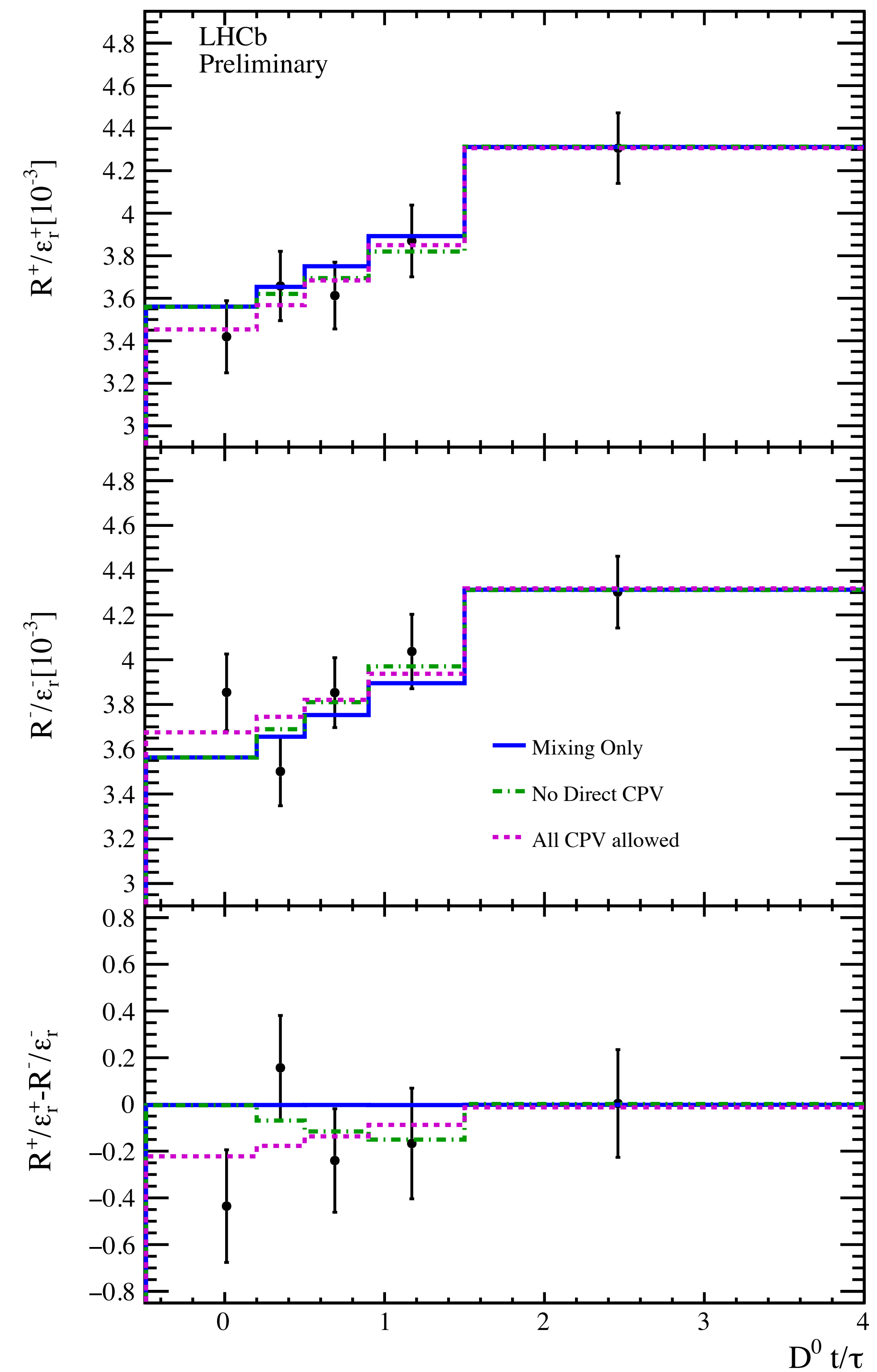
- Candidates in both datasets are vetoed.

DT mixing results

- Mixing only: $R^+_D = R^-_D$, $x'^+ = x'^-$ and $y'^+ = y'^-$
- No direct CPV: $R^+_D = R^-_D$
- All CPV allowed: all +/- free
- Kπ detection asymmetry accounted for in the fit.
- Consistent with mixing only fit.

Parameter	Value
No CPV	
$R_D[10^{-3}]$	$3.48 \pm 0.10 \pm 0.01$
$x'^2[10^{-4}]$	$0.28 \pm 3.10 \pm 0.11$
$y'[10^{-3}]$	$4.60 \pm 3.70 \pm 0.18$
χ^2/NDF	6.293/7
No Direct CPV	
$R_D[10^{-3}]$	$3.48 \pm 0.10 \pm 0.01$
$x'^{2+}[10^{-4}]$	$1.94 \pm 3.67 \pm 1.17$
$y'^+[10^{-3}]$	$2.79 \pm 4.27 \pm 0.98$
$x'^{2-}[10^{-4}]$	$-1.53 \pm 4.04 \pm 1.68$
$y'^-[10^{-3}]$	$6.51 \pm 4.38 \pm 1.66$
χ^2/NDF	5.589/5
All CPV Allowed	
$R_D^+[10^{-3}]$	$3.38 \pm 0.15 \pm 0.06$
$x'^{2+}[10^{-4}]$	$-0.19 \pm 4.46 \pm 0.32$
$y'^+[10^{-3}]$	$5.81 \pm 5.25 \pm 0.31$
$R_D^-[10^{-3}]$	$3.60 \pm 0.15 \pm 0.07$
$x'^{2-}[10^{-4}]$	$0.79 \pm 4.31 \pm 0.38$
$y'^-[10^{-3}]$	$3.32 \pm 5.21 \pm 0.40$
χ^2/NDF	4.473/4

Dominant systematic uncertainties from combinatorial μ background, prompt veto, fit model and time-dependent asymmetry.

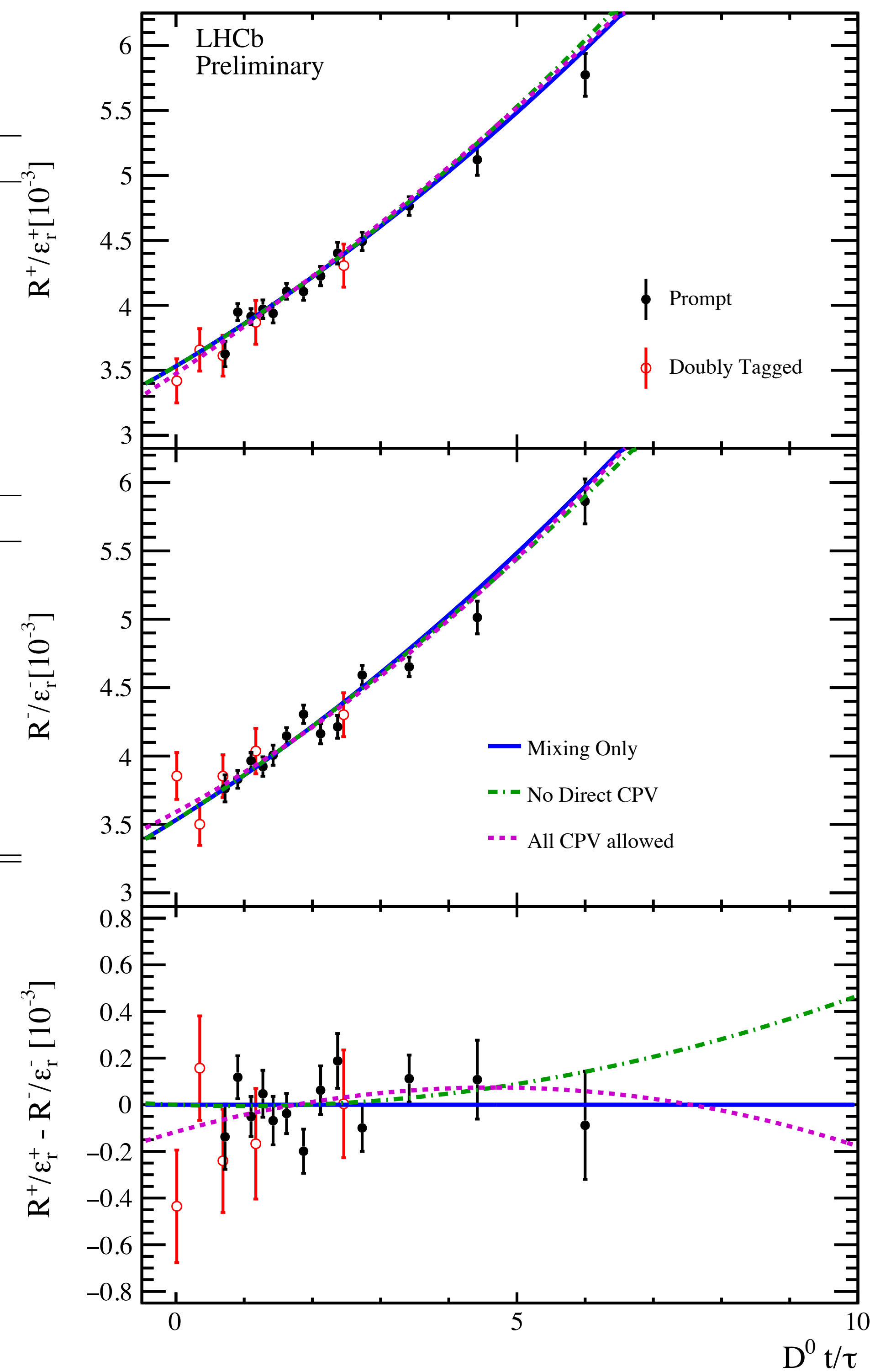


DT + prompt mixing results

Parameter	DT+prompt combination	Prompt alone
	No CPV	
$R_D[10^{-3}]$	3.533 ± 0.054	3.568 ± 0.067
$x'^2[10^{-5}]$	3.6 ± 4.3	5.5 ± 4.9
$y'[10^{-3}]$	5.23 ± 0.84	4.80 ± 0.94
χ^2/NDF	$96.594/111$	
	No Direct CPV	
$R_D[10^{-3}]$	3.533 ± 0.054	3.568 ± 0.067
$x'^{2+}[10^{-5}]$	4.9 ± 5.0	6.4 ± 5.6
$y'^{+}[10^{-3}]$	5.14 ± 0.91	4.80 ± 1.08
$x'^{2-}[10^{-5}]$	2.4 ± 5.0	4.6 ± 5.5
$y'^{-}[10^{-3}]$	5.32 ± 0.91	4.8 ± 1.08
χ^2/NDF	$96.147/109$	
	All CPV Allowed	
$R_D^+[10^{-3}]$	3.474 ± 0.081	3.545 ± 0.095
$x'^{2+}[10^{-5}]$	1.1 ± 6.5	4.9 ± 7.0
$y'^{+}[10^{-3}]$	5.97 ± 1.25	5.10 ± 1.38
$R_D^-[10^{-3}]$	3.591 ± 0.081	3.591 ± 0.090
$x'^{2-}[10^{-5}]$	6.1 ± 6.1	6.0 ± 6.8
$y'^{-}[10^{-3}]$	4.50 ± 1.21	4.50 ± 1.39
χ^2/NDF	$94.960/108$	

- Mixing only: $R^+_D = R^-_D$, $x'^+=x'^-$ and $y'^+=y'^-$
- No direct CPV: $R^+_D = R^-_D$
- All CPV allowed: all +/- free
- Kπ detection asymmetry accounted for in the fit.
- Consistent with mixing only fit.
- 10-20% of improvements in sensitivity when combining with prompt measurement.

Dominant systematic uncertainties from combinatorial μ background, prompt veto, fit model and time-dependent asymmetry.



Indirect CP asymmetry in $D^0 \to h^+ h^-$ decays

A_Γ observable

- Time-dependent *CP* asymmetry, at the first order in t/τ_D,

$$A_{CP}(t) = \frac{\Gamma(D^0(t)\to f) - \Gamma(\overline{D}^0(t)\to f)}{\Gamma(D^0(t)\to f) + \Gamma(\overline{D}^0(t)\to f)} \approx a_{CP}^{\text{dir}} + \frac{t}{\tau_D} a_{CP}^{\text{ind}}$$

- The indirect *CP* violation is equal to $-A_\Gamma$, defined as [Phys. Rev. D 75, 036008]

$$A_\Gamma = \frac{\hat{\Gamma}(D^0\to f) - \hat{\Gamma}(\overline{D}^0\to f)}{\hat{\Gamma}(D^0\to f) + \hat{\Gamma}(\overline{D}^0\to f)} = \frac{1}{2}\left[\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) y\cos\phi - \left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) x\sin\phi\right]$$

CPV in the mixing CPV in the inference

$\hat{\Gamma}$ is the effective decay with, $f = K^+K^-$ or $\pi^+\pi^-$

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

$$x \equiv \frac{m_1 - m_2}{\Gamma}, \quad y \equiv \frac{\Gamma_1 - \Gamma_2}{2\Gamma}$$

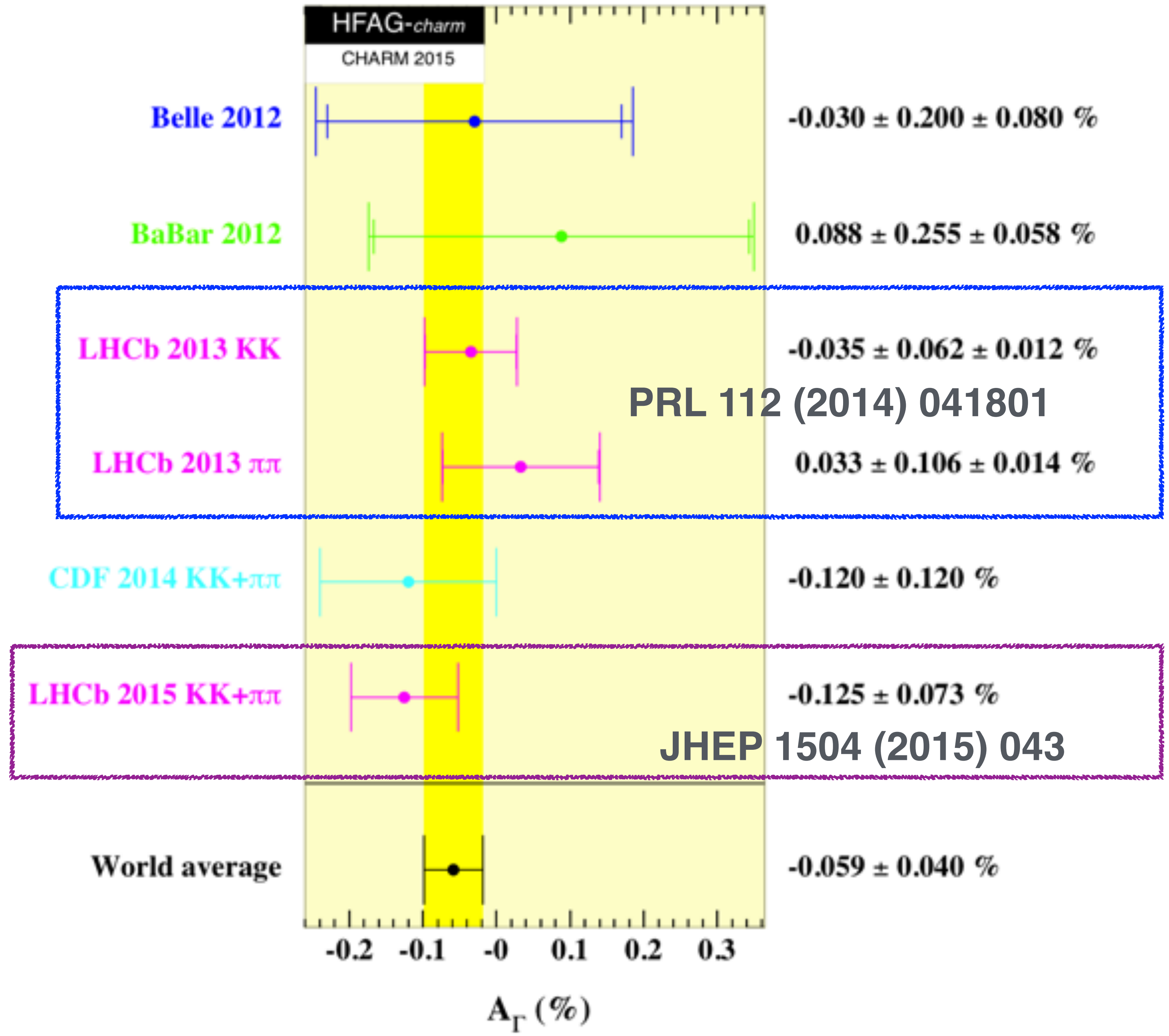
$$\phi = \arg(q/p)$$

A_Γ state-of-the-art

- Two measurement from LHCb
  - semi-leptonic tagged D^0 on the full Run I data sample of 3 fb^{-1},
  - D*-tagged D^0 with only 1fb^{-1}, the 2011 data sample.

- D*-tagged is already the **world best measurement** with **only 1fb^{-1}**.

[HFAG, arXiv:1412.7515]



A_Γ state-of-the-art

- Two measurement from LHCb
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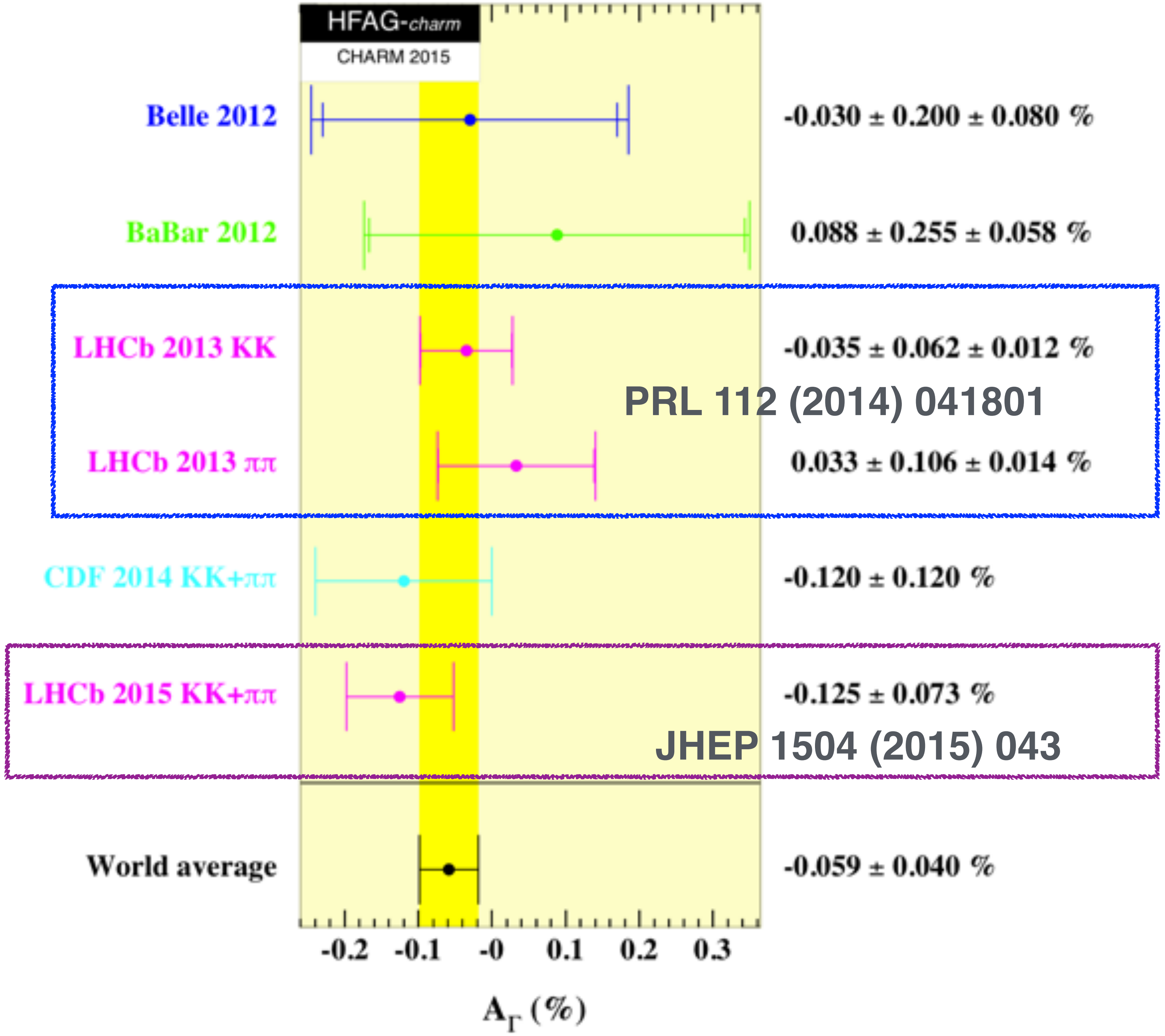
[HFAG, arXiv:1412.7515]



- D*-tagged is already the **world best measurement** with **only 1fb^{-1}**.

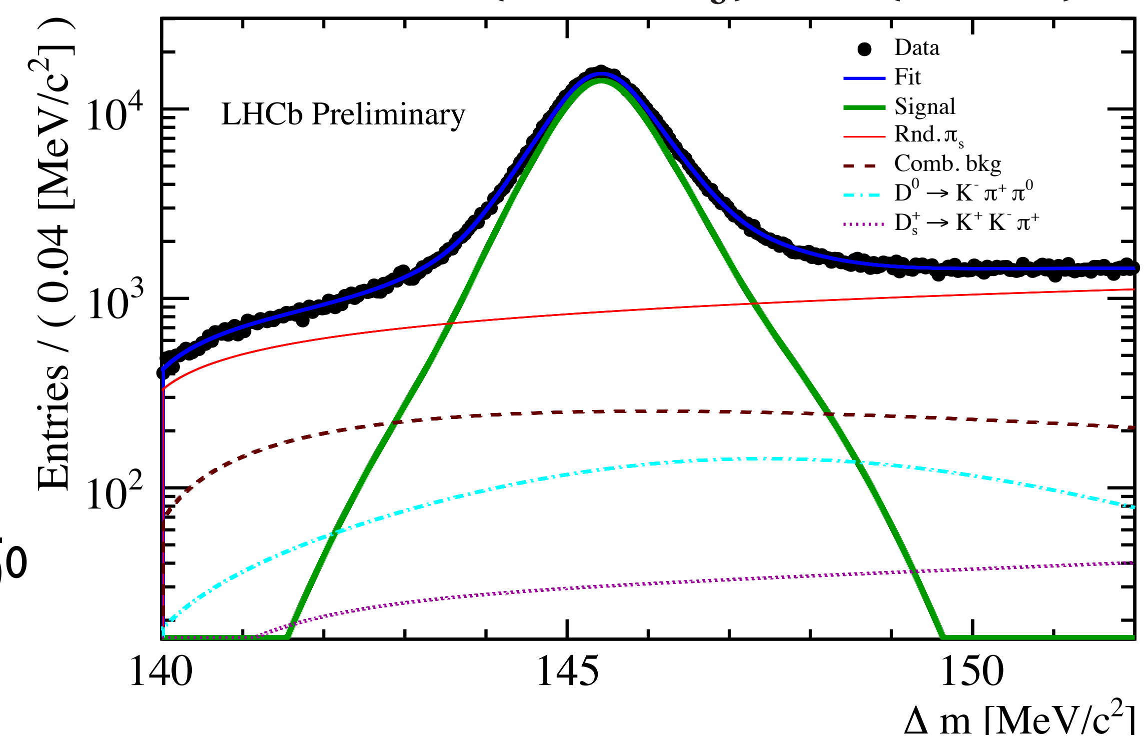
In this talk, for the fist time,
A_Γ measurement
with the full LHCb Run I (3fb^{-1})

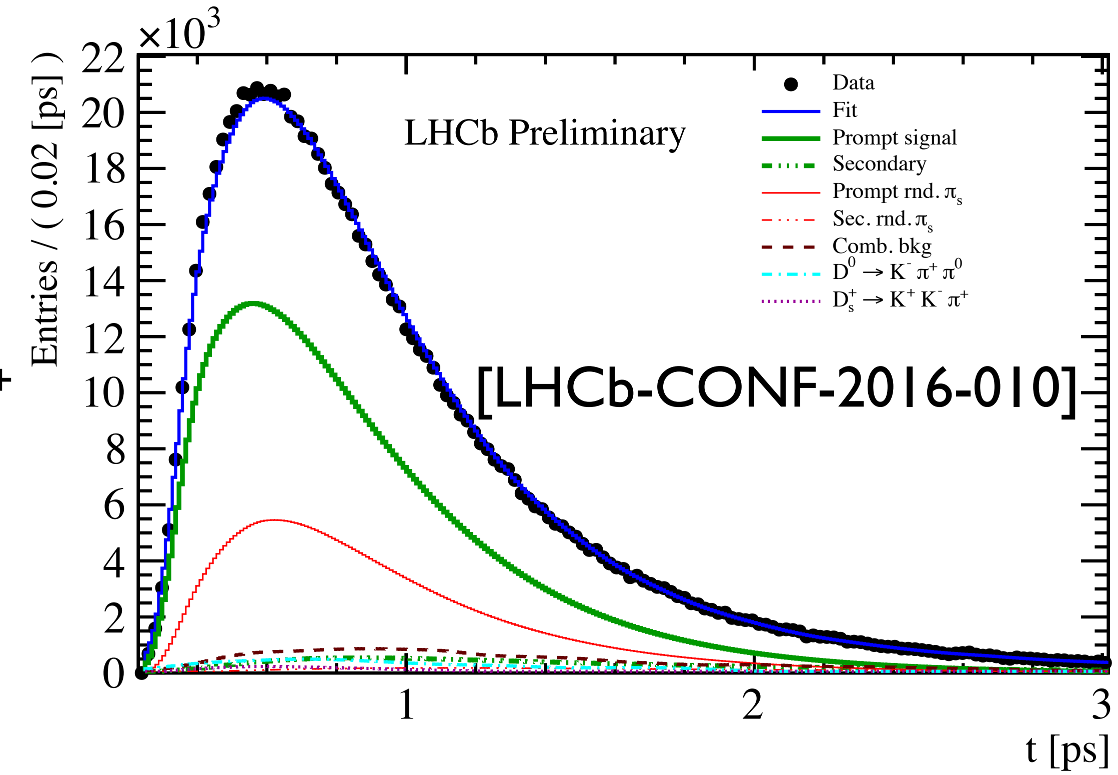
Effective-lifetime asymmetry [LHCb-CONF-2016-010]

- A_Γ already measured with $1 fb^{-1}$ (at 7TeV) [PRL 112 (2014) 041801],
- Today extension to the full Run I data adding to $2 fb^{-1}$ at 8TeV.
- Adopted the same strategy by measuring effective lifetimes (single exponential-model) of SCS D*-tagged $D^0 \rightarrow KK$ (~11M) and $D^0 \rightarrow \pi\pi$ (~4M) decays;
  - ✦ Unbinned maximum likelihood fits, in two stages
    - 2D fit of m(hh) and Δm → extract D^0 signal
    - 2D fit of $t(D^0)$ and $\ln(\chi^2_{IP}(D^0))$ → extract D^0 and $\overline{D}^0$ lifetime and compute A_Γ
  - ✦ evaluate per-event acceptance function, moving the D^0 along its momentum direction and re-running the trigger and the reconstruction for each event [Phys. Conf. Ser. 396 (2012) 022016];
  - ✦ validate the analysis on larger sample of CF $D^0 \rightarrow K^- \pi^+$ (~77M) decays, where pseudo-A_Γ is expected to be undetectable with current sensitivity

$$A_\Gamma(K\pi) = (-0.07 \pm 0.15) \times 10^{-3}$$

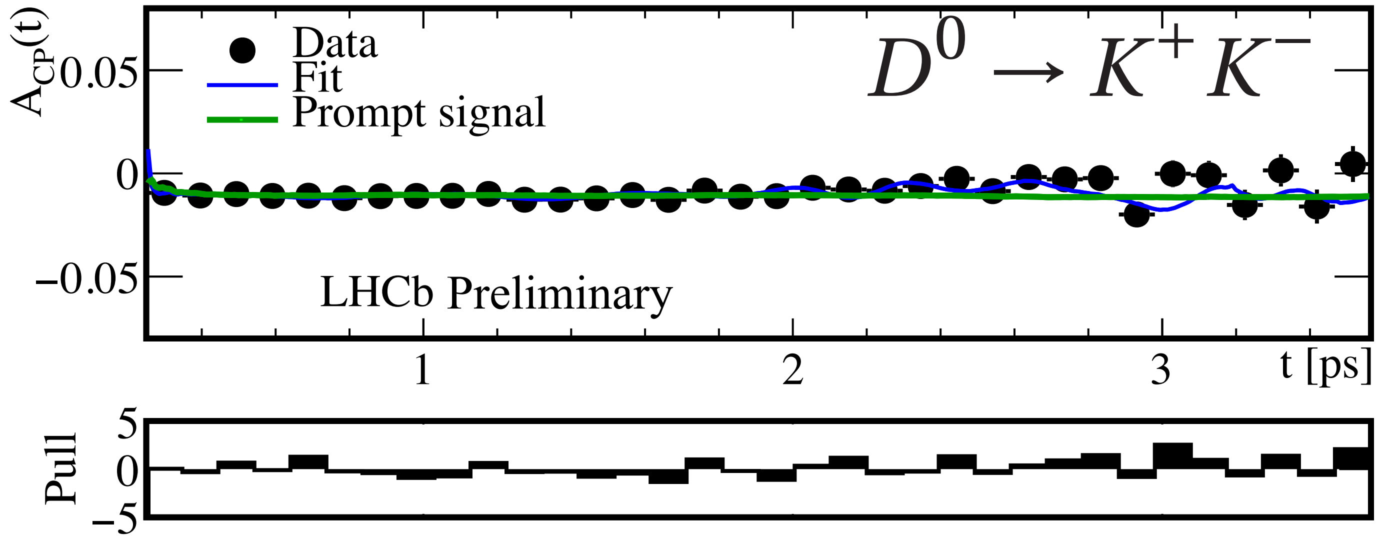
$$\Delta m = m(h^+ h^- \pi_s) - m(h^+ h^-)$$



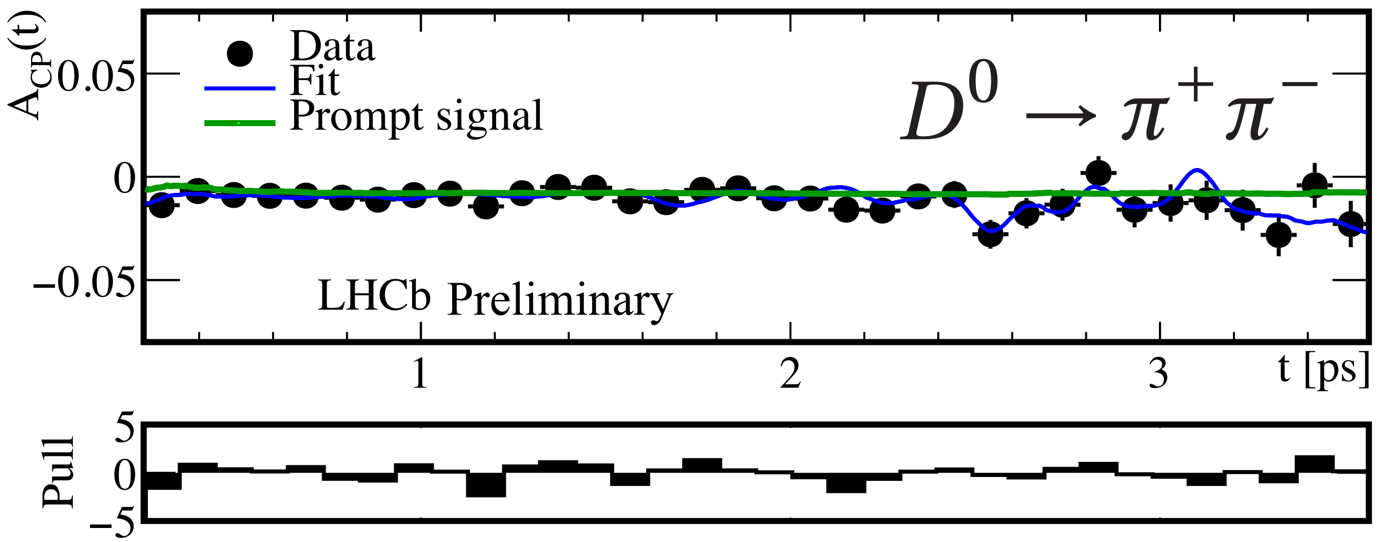


Effective-lifetime asymmetry – results

[LHCb-CONF-2016-010]   2012 data, 2fb^{-1}



$$A_\Gamma(KK) = (-0.03 \pm 0.46 \pm 0.10) \times 10^{-3}$$



$$A_\Gamma(\pi\pi) = (\ \ 0.03 \pm 0.79 \pm 0.16) \times 10^{-3}$$

- **No signs of indirect CP violation.**

Dominant systematic uncertainties from charm from *b* decays, partially reconstructed background, decay-time acceptance and fit model.

- Combining results with previous 1fb^{-1} analysis:

$$A_\Gamma(KK, 2011-2012) = (-0.14 \pm 0.37 \pm 0.10) \times 10^{-3}$$
$$A_\Gamma(\pi\pi, 2011-2012) = (\ \ 0.14 \pm 0.63 \pm 0.15) \times 10^{-3}$$

Towards future high precision measurements

- Computation of per-candidate acceptance function vs. D^0 proper decay time is an essential ingredient of this measurement (and others at hadron colliders),
  - this is done rerunning the trigger and reconstruction algorithm around a hundred times on each event [Phys. Conf. Ser. 396 (2012) 022016] (for 50M of $D^0 \to K^- \pi^+$ the total CPU needed is 2.5×10^9 HS06.s)

- While this technique has been successful, it will be demanding to continue to use it in the Run II and in the LHCb-Upgrade, where much higher statistics is expected.
- An alternative analysis of A_Γ has therefore been performed with a different technique, that can be 'easily' performed even with much larger samples.

A_Γ: measuring yield asymmetries in bins of decay time

P. Marino (SNS & INFN-Pi)

- Measure yield asymmetries in various bin of D^0 proper decay time,
  - from sideband subtracted yields in each time bin

$$A^i_{\rm raw} = \frac{n_i(D^0 \to f) - n_i(\overline{D}^0 \to f)}{n_i(D^0 \to f) + n_i(\overline{D}^0 \to f)}; \qquad i = 1, \ldots, m$$

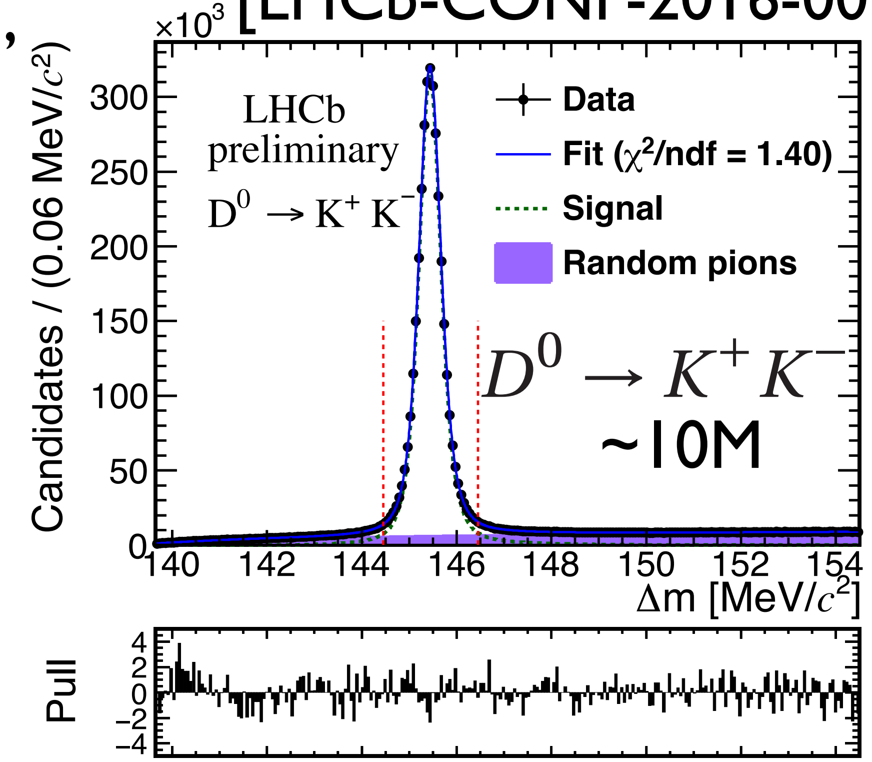
- Straight line fit to the asymmetry as function of decay time

$$A_{\rm raw}(t) = A_0 - \frac{t}{\tau_{D^0}} A_\Gamma;$$

- Sample splits in 4 subsample by year (2011 @ 7TeV and 2012 @ 8TeV) and magnet polarity (Up and Down)
- control sample: CF $D^0 \to K^-\pi^+$, where pseudo-$A_\Gamma(D^0 \to K\pi) = 0$.

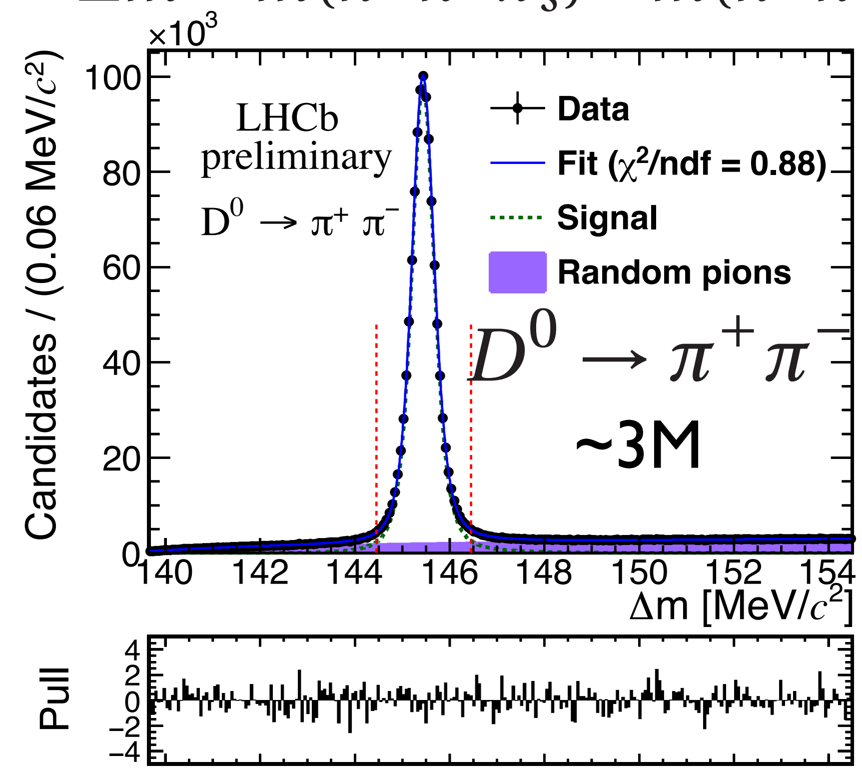
- This type of approach has already been used in the 1fb^{-1} publication. It has now been enhanced with new techniques, to significantly reduce the systematic uncertainties.

[LHCb-CONF-2016-009]



$D^0 \to K^+K^-$ ~10M

$$\Delta m = m(h^+h^-\pi_s) - m(h^+h^-)$$



$D^0 \to \pi^+\pi^-$ ~3M

Detection asymmetries correction

- Momentum-dependent detection charge-asymmetries (through a correlation between the momentum of D^0 candidate and its reconstructed proper decay time) generate a **time-dependent detection asymmetry**.

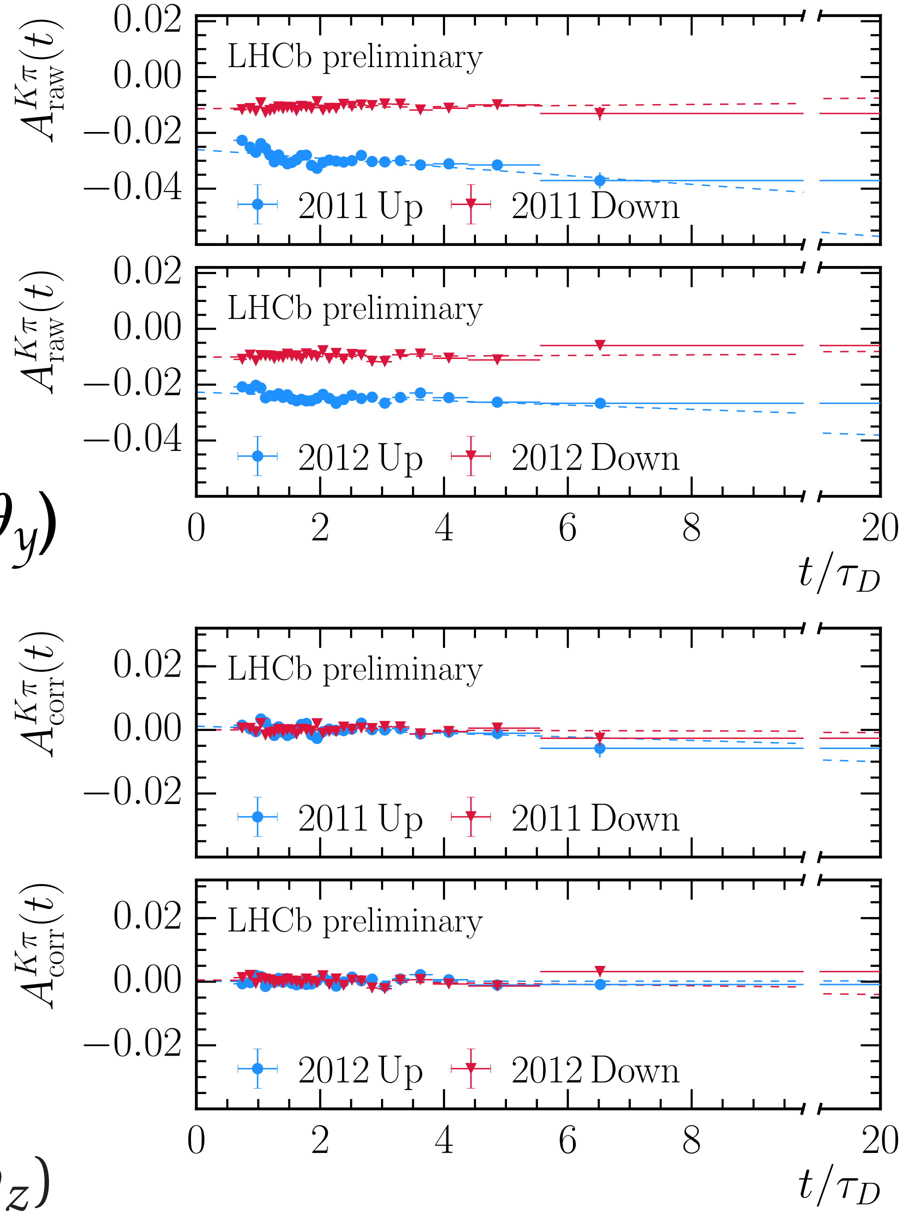
- Detection asymmetries cancelled equalising soft pions kinematic between positive and negative charges.

- In particular, (k, θ_x, θ_y) of positive soft pions are reweigh to $(k, -\theta_x, \theta_y)$ of negative soft pions,
  - restoring CP-symmetric detector acceptance:

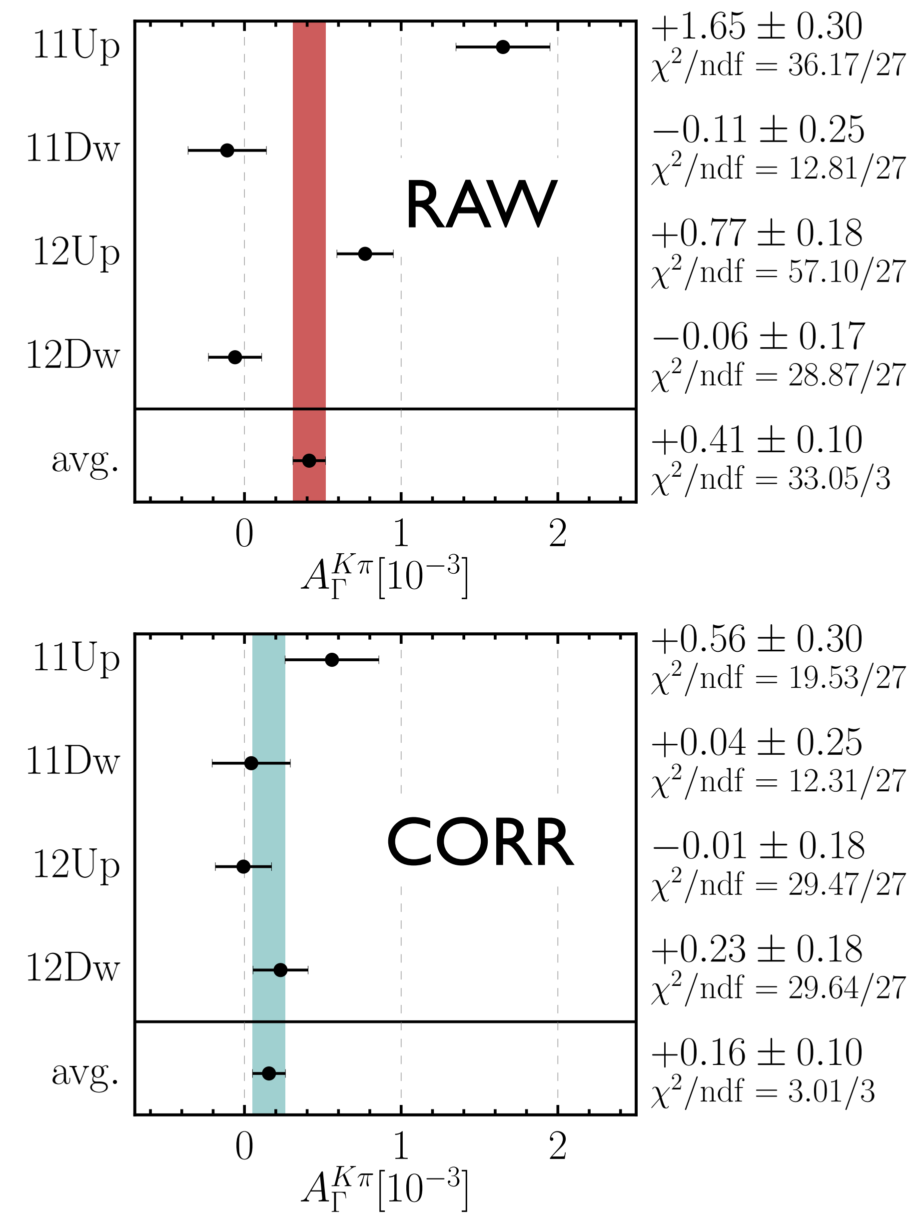
$$n^+(k, \theta_x, \theta_y) = n^-(k, -\theta_x, \theta_y)$$

$$k = \frac{1}{\sqrt{p_x^2 + p_y^2}} \qquad \theta_x = \arctan(p_x/p_z) \qquad \theta_y = \arctan(p_y/p_z)$$

[LHCb-CONF-2016-009]



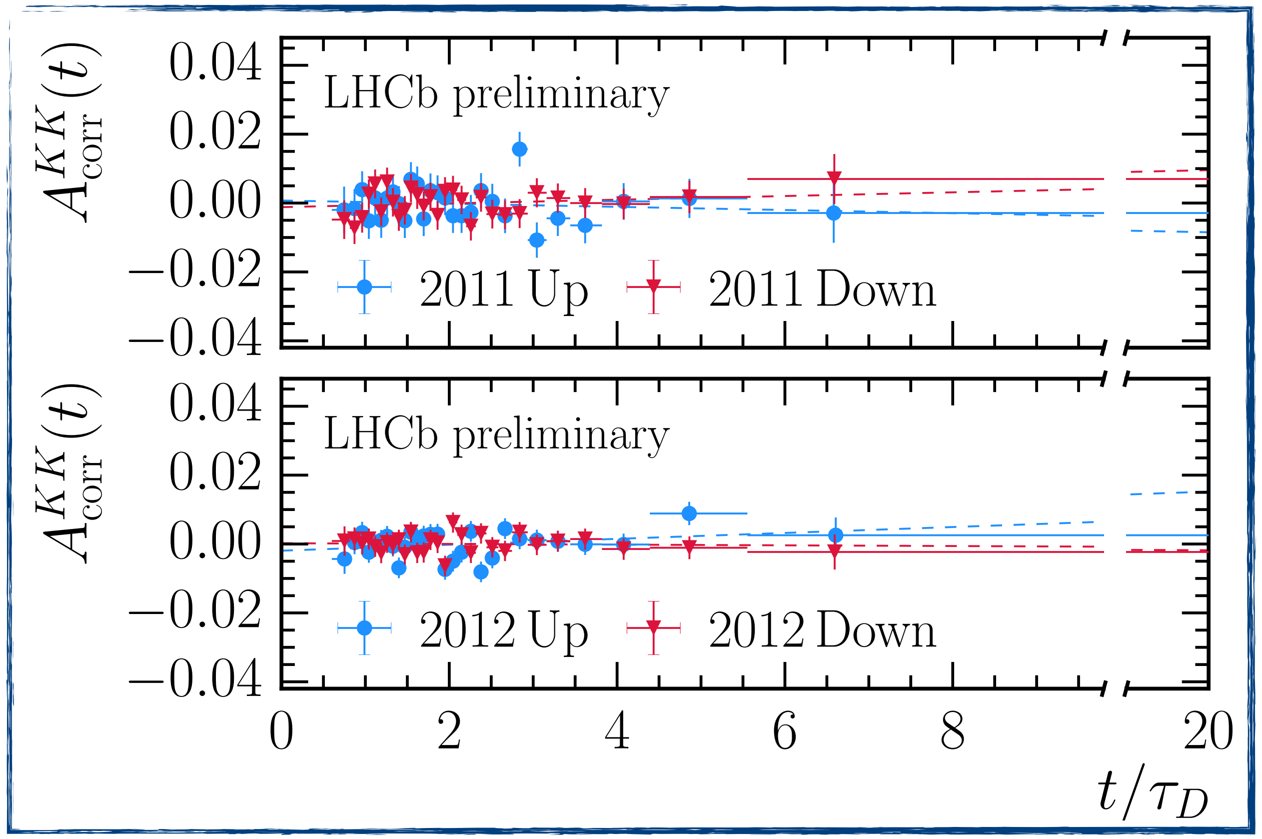
$D^0 \to K^-\pi^+$

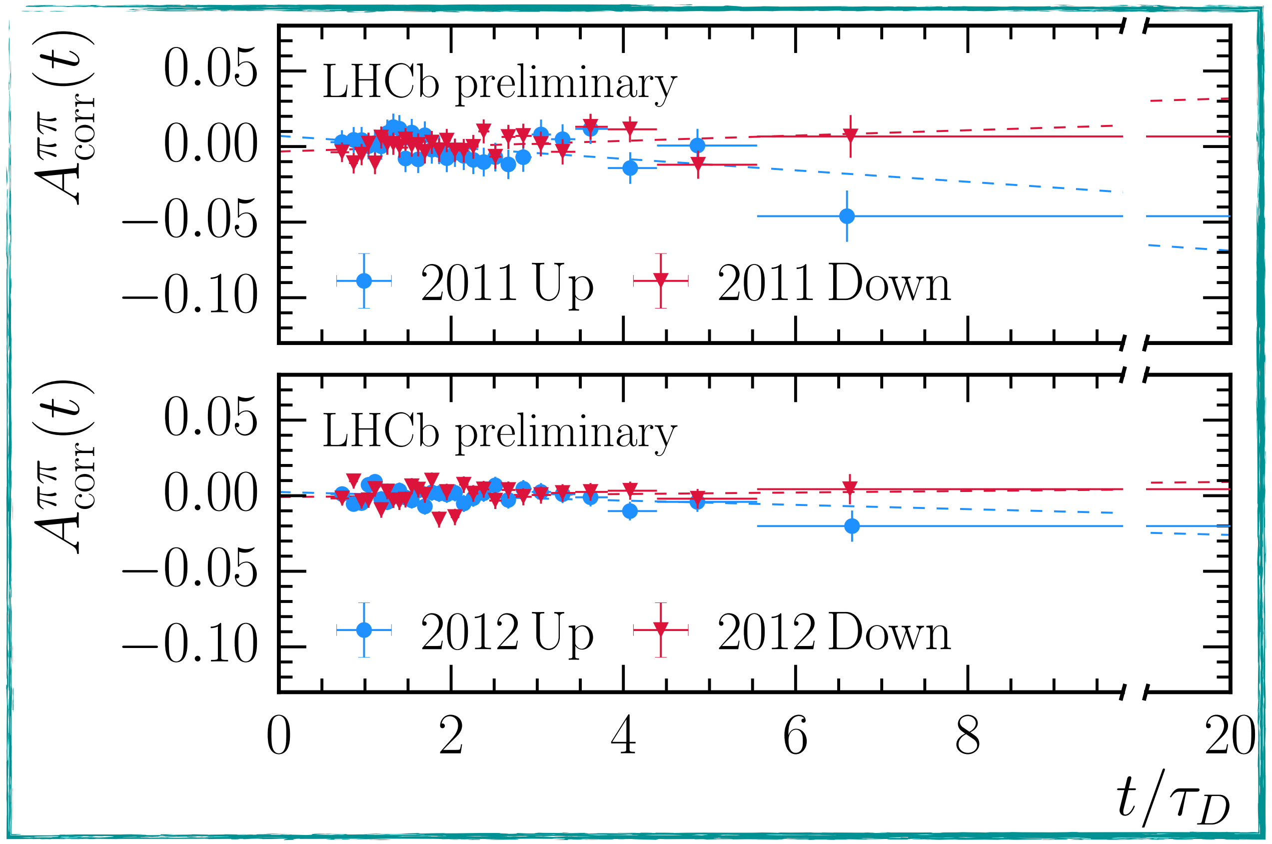


control mode: $A_\Gamma(K\pi) = (0.16 \pm 0.10) \times 10^{-3}$

Results

[LHCb-CONF-2016-009] Run I data, 3fb^{-1}





- Results averaging the four subsamples:

$$A_\Gamma(KK) = (-0.30 \pm 0.32 \pm 0.14) \times 10^{-3}$$

$$A_\Gamma(\pi\pi) = (\ \ 0.46 \pm 0.58 \pm 0.16) \times 10^{-3}$$

- **No signs of indirect CP violation.**

Dominant systematic uncertainties from charm from *b* decays, partially reconstructed background and random pions background subtraction.

Conclusion

- Search for mixing and CPV in DCS $D^0 \to K\pi$ with double tagged D^0. [LHCb-PAPER-2016-33]

- Two measurements of A_Γ with two different method presented:

$$A_\Gamma(KK, 1\text{fb}^{-1} + 2\text{fb}^{-1}) = (-0.14 \pm 0.37 \pm 0.10) \times 10^{-3}$$
$$A_\Gamma(\pi\pi, 1\text{fb}^{-1} + 2\text{fb}^{-1}) = (\ \ 0.14 \pm 0.63 \pm 0.15) \times 10^{-3}$$

Measured *CP* asymmetries of effective lifetimes (traditional method)
[LHCb-CONF-2016-010]

$$A_\Gamma(KK; 3\text{fb}^{-1}) = (-0.30 \pm 0.32 \pm 0.14) \times 10^{-3}$$
$$A_\Gamma(\pi\pi; 3\text{fb}^{-1}) = (\ \ 0.46 \pm 0.58 \pm 0.16) \times 10^{-3}$$

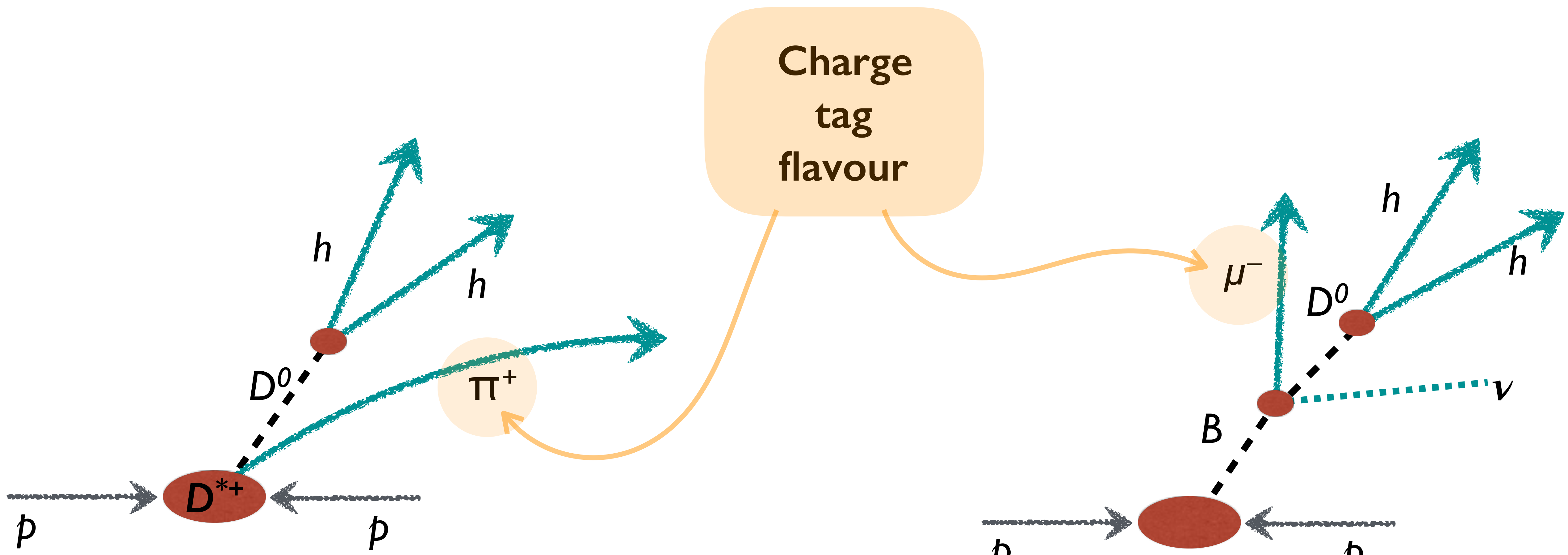
Measured using yield asymmetries in bins of decay time (new method)
[LHCb-CONF-2016-009]

- **World best measurements!**
- **Indirect CP violation still compatible with zero at a level of about 0.3 per mille**.
- Two independent methods compatible with each other, confirming the robustness of the two analyses.
- Run I measurement of A_Γ completed. Now prepare to new exciting data from Run II.

Spare slides

Charm flavour tagging

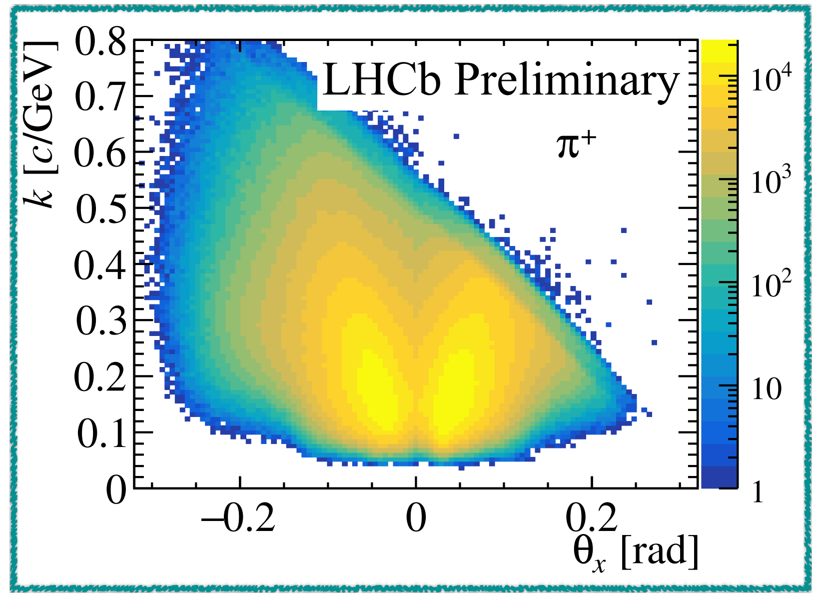
- In order to measure mixing and CPV, it is necessary to identify the flavour of the D^0 meson.
- LHCb exploits two decays:
  - $D^{*+} \to D^0 \pi^+$ decays
  - semi-leptonic *B*-decays

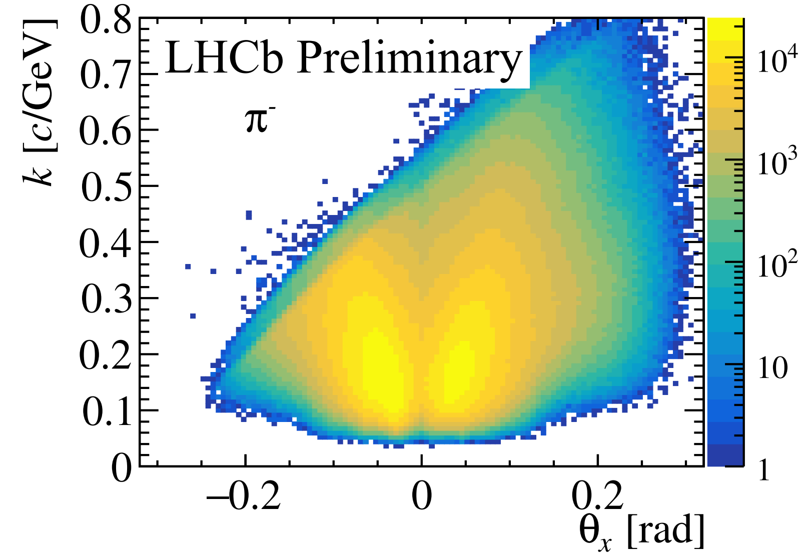


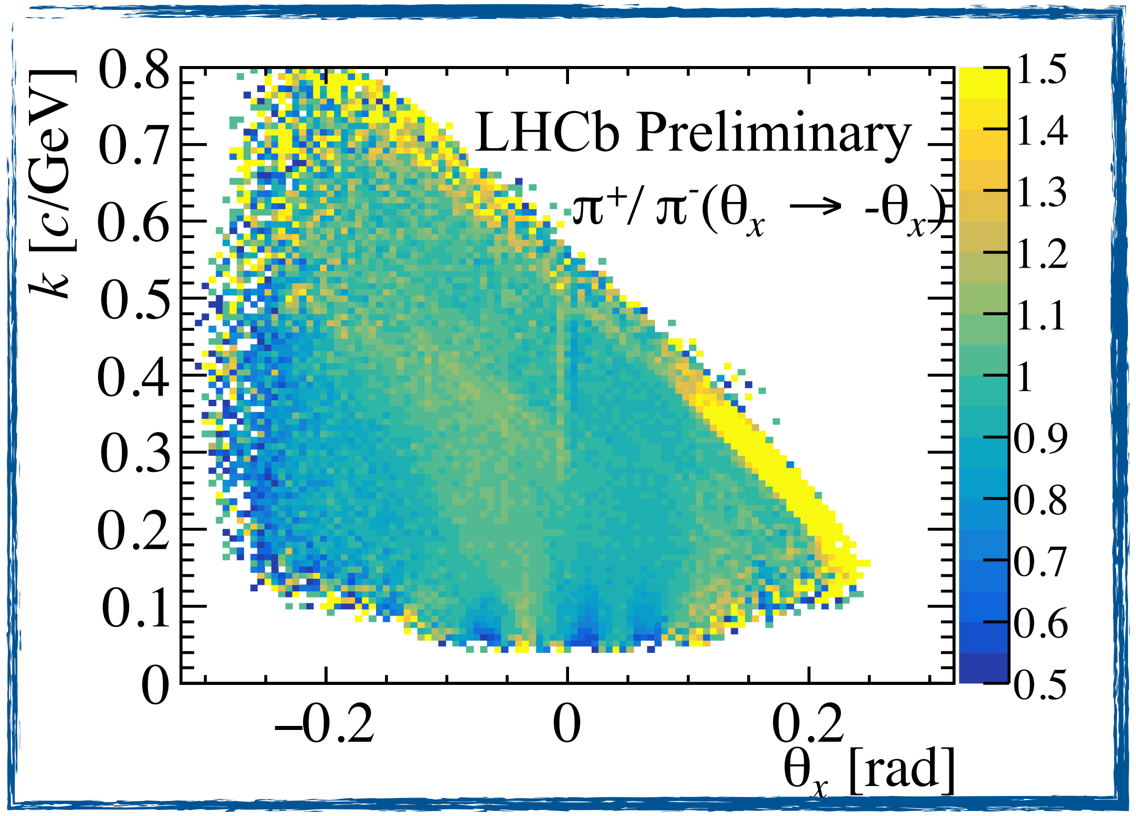
CP-symmetrisation

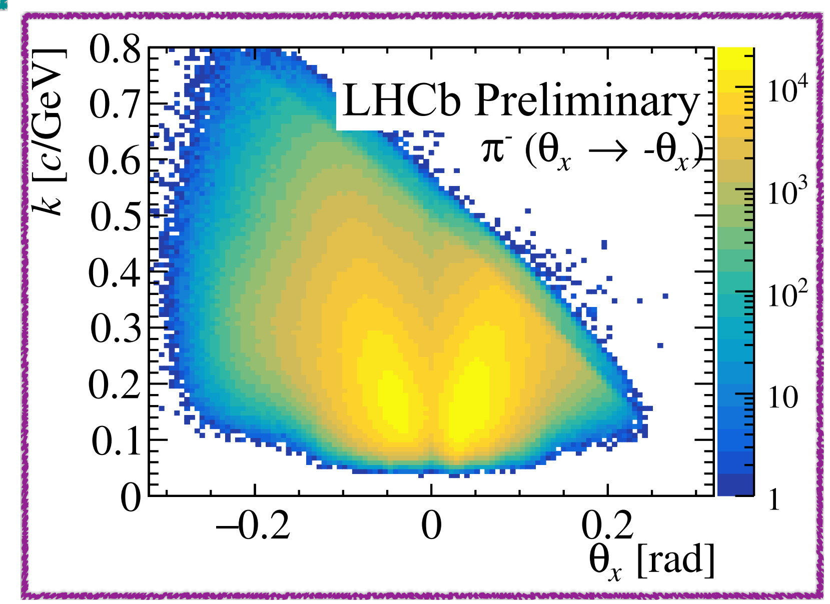
- In order to cancel momentum-dependent asymmetries, a **new method** has been devised, the soft pions kinematic is equalised between the two charges:
  - ✦ (k, θ_x, θ_y) **of positive soft pions** are reweigh to $(k, -\theta_x, \theta_y)$ **of negative soft pions**.

$$k = \frac{1}{\sqrt{p_x^2 + p_y^2}} \qquad \theta_x = \arctan(p_x / p_z) \qquad \theta_y = \arctan(p_y / p_z)$$









The ratio $(k, \theta_x, \theta_y)/(k, -\theta_x, \theta_y)$ should be a constant if no detection asymmetries are present, but large variations are clearly visible. The CP-symmetrisation makes this flat and equal to one.

Reweigh details

- In each proper decay time, the reweigh asymmetry is

$$a^{\alpha}_{\text{corr}} = \frac{\sum_{l,i,j} \sqrt{v_{l,i,j}} n^{\alpha+}_{l,i,j} - \sum_{l,i,j} \sqrt{w_{l,i,j}} n^{\alpha-}_{l,i,j}}{\sum_{l,i,j} \sqrt{v_{l,i,j}} n^{\alpha+}_{l,i,j} + \sum_{l,i,j} \sqrt{w_{l,i,j}} n^{\alpha-}_{l,i,j}},$$

$$w_{l,i,j} = \frac{\sum_{\alpha} n^{\alpha+}_{l,i,j}}{\sum_{\alpha} n^{\alpha-}_{l,-i,j}}, \qquad v_{l,i,j} = \frac{\sum_{\alpha} n^{\alpha-}_{l,i,j}}{\sum_{\alpha} n^{\alpha+}_{l,-i,j}}$$