Mixing and indirect CP violation in two-body Charm decays at LHCb

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on behalf of the LHCb collaboration

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Overview

1) **A_Γ** with Run 1 prompt data (3 fb^{-1})
   [PRL 118, 261803 (2017)]

2) **Mixing and CP violation in D^0 —> $K^\pm\pi^\mp$** decays
   with 2011–2016 prompt data (5 fb^{-1})
   [PRD 97, 031101 (2018)]

3) **y_{CP}** with Run 1 semileptonic-tagged data (3 fb^{-1})
   [PRL 122, 011802 (2018)]

New!

Mixing and CPV in charm

Mixing is established.

- Mixing parameters: $x = \frac{m_2 - m_1}{\Gamma}$ $\quad y = \frac{\Gamma_2 - \Gamma_1}{2\Gamma}$ $\quad \Gamma = \frac{\Gamma_1 + \Gamma_2}{2}$
- Mass eigenstates: $|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$

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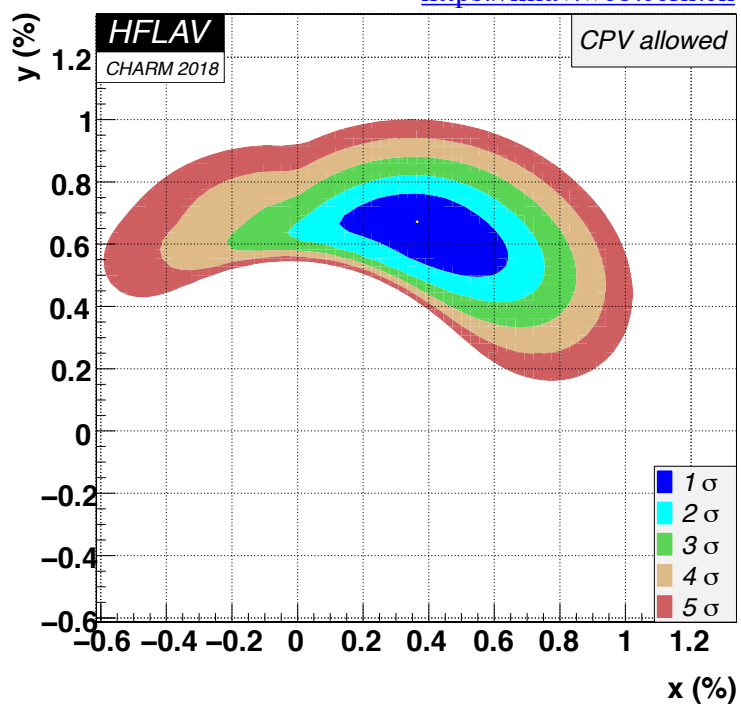


CPV still not observed.

- Charm is the only up-type quark where CPV can be fully investigated;
- CPV < $\mathcal{O}(10^{-3})$ in the SM, BSM contributions could enhance it.

A_Γ with Run 1 data

A_Γ definition

- Measure of indirect CPV in D^0 singly-Cabibbo-suppressed decays to CP eigenstates:

$$A_{CP}(t) = \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to f)} \approx A_{CP}^{dir} - A_\Gamma \left(\frac{t}{\tau}\right), \qquad f = K^+K^-, \pi^+\pi^-$$

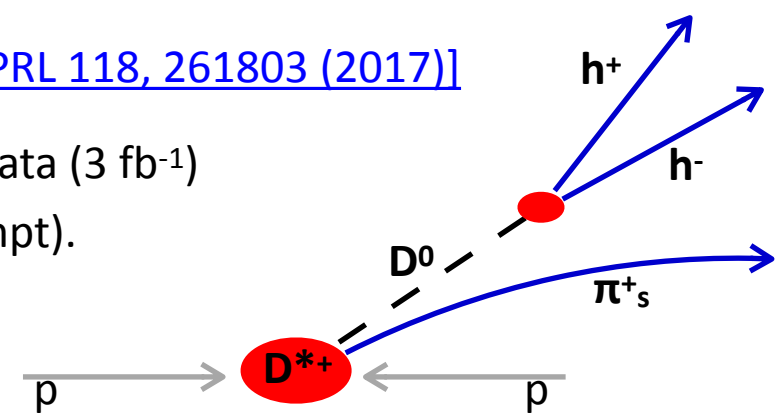
$$A_\Gamma = \frac{1}{2}\left[\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) y \cos\phi + \left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) x \sin\phi\right] \approx y\left(\left|\frac{q}{p}\right| - 1\right) - x\phi$$

with $\phi = \arg\left(-\frac{q}{p}\frac{\bar{A}_f}{A_f}\right)$

- If $A_\Gamma \neq 0$ —> indirect CPV.

[PRL 118, 261803 (2017)]

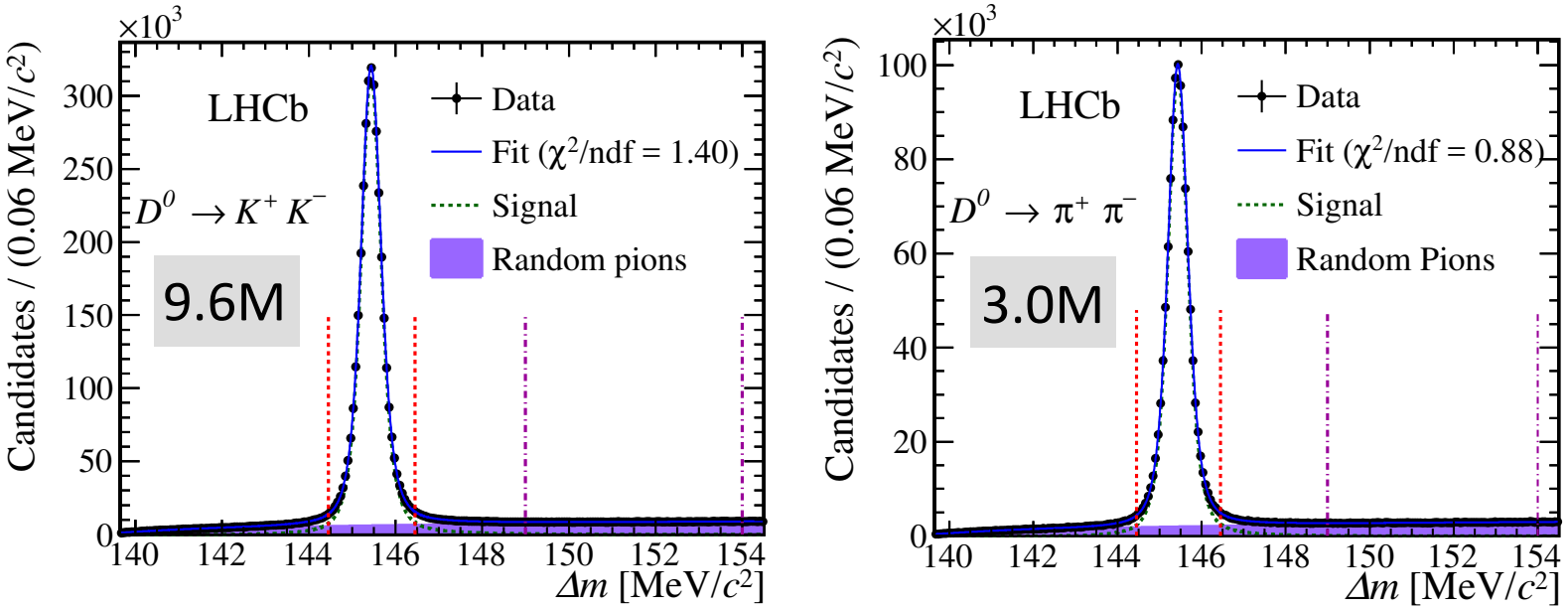
- At LHCb: measurement performed with Run 1 data (3 fb^{-1})
- D^0 flavour from strong decay $D^{*+} \to D^0 \pi^+_s$ (prompt).



Data sample

[PRL 118, 261803 (2017)]

$$\Delta m = m(h^+h^-\pi_S^\pm) - m(h^+h^-)$$



- Cuts on $m(h^+h^-)$, PID, IP of D^0 daughters.

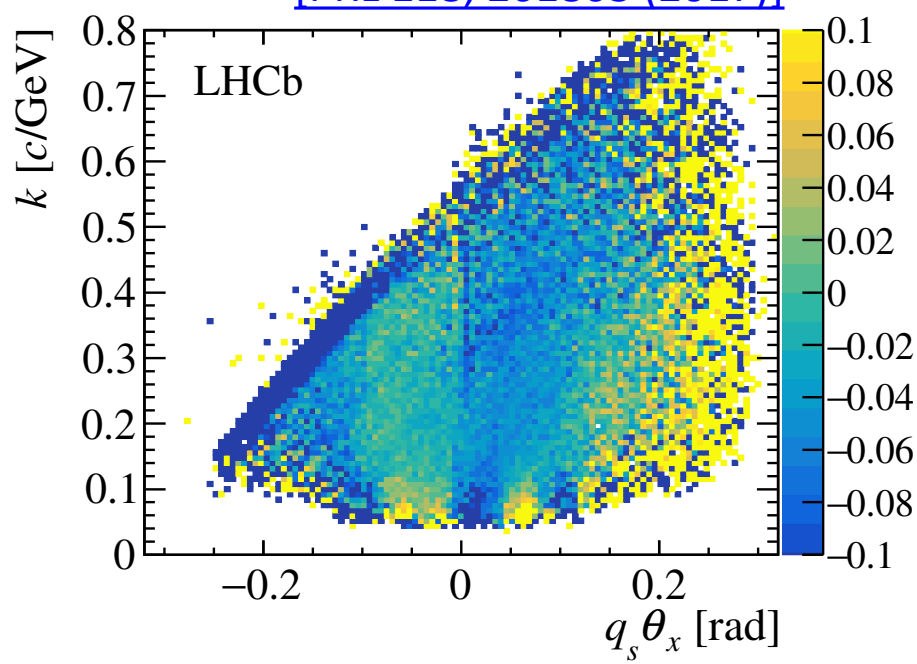
Detection charge asymmetries

$$D^{*+} \to [h^+h^-]_{D^0}\pi_s^+$$

CP-symmetric,
no asymmetries

large detection
asymmetries

[PRL 118, 261803 (2017)]



Charge asymmetry of the π_s

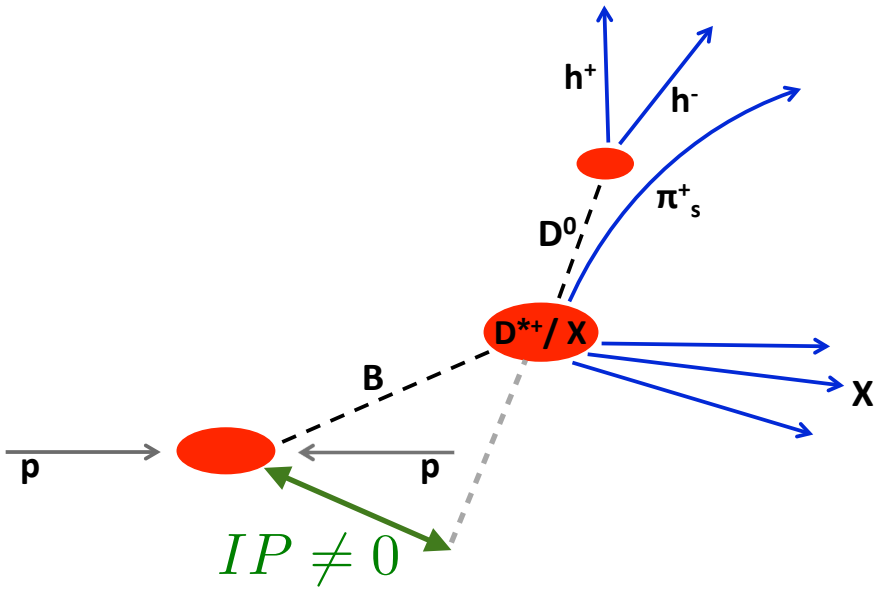
$$k = \frac{1}{\sqrt{p_x^2 + p_z^2}}, \quad \theta_x = \arctan\left(\frac{p_x}{p_z}\right)$$

- Trigger introduces correlations between the measured decay time of the D^0 and the momentum of the π^+_s;
- momentum-dependent detection asymmetries reflect in time-dependent asymmetries mimicking a fake A_Γ value as large as 10^{-3} ($3\sigma(A_\Gamma)$).

- Reweigh the 3D momentum distribution of the π^-_s to match that of π^+_s.
- Validated on $D^0 \to K^-\pi^+$ (no CPV expected).

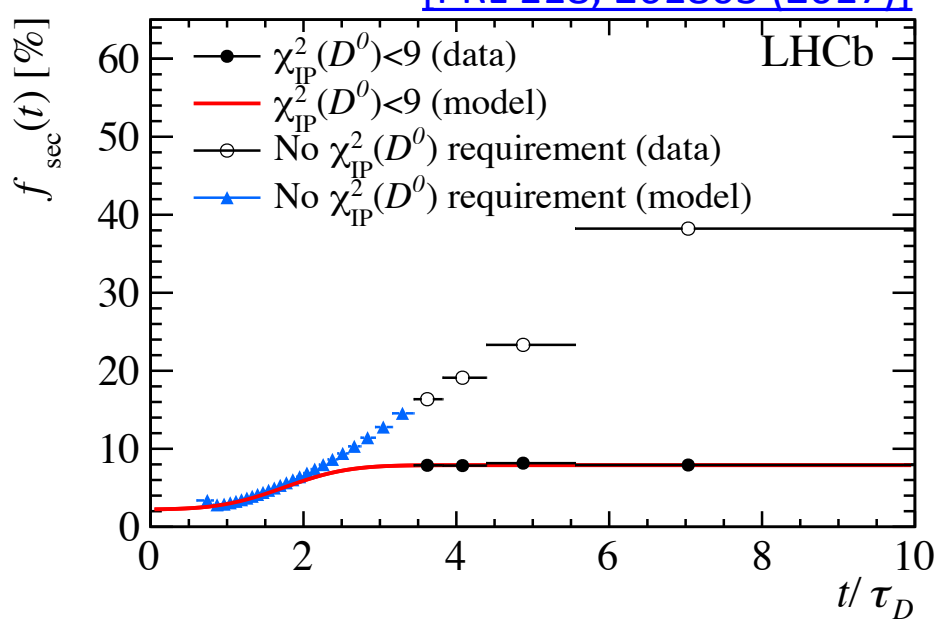
Secondary decays

- Measured decay-time of D^0 from *b*-hadrons biased to higher values -> their fraction increases as a function of time;
- B production asymmetry different from D^{*+};
- secondary decays induce time-dependent asymmetries.



- Suppressed requiring the D^0 to come from the PV ($\chi^2_{IP} < 9$);
- residual fraction estimated through a model whose normalization is fixed using the yields at high decay times.

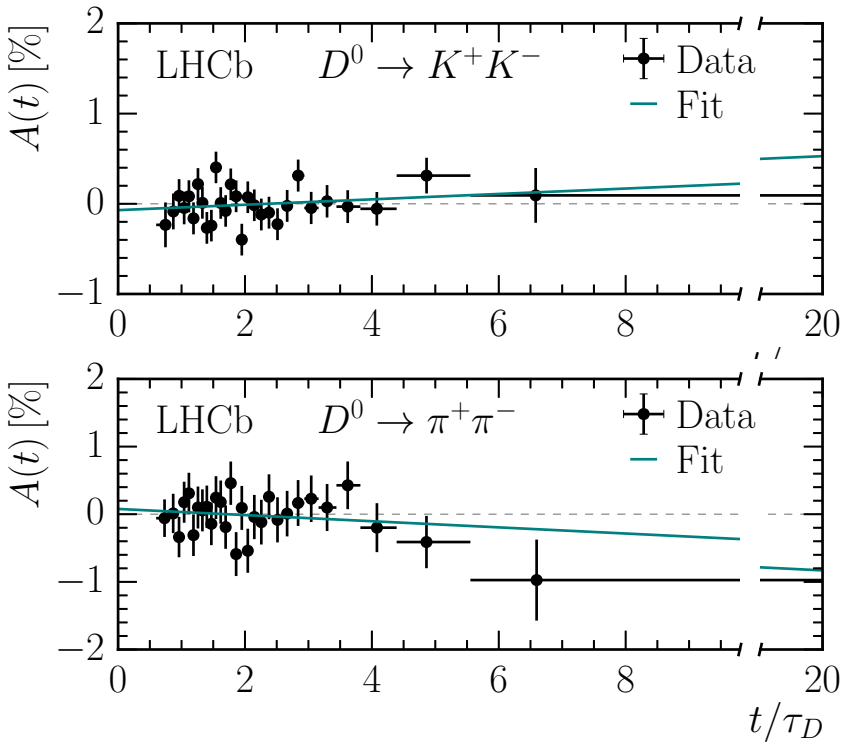
[PRL 118, 261803 (2017)]



χ^2_{IP} = difference in *pp* vertex-fit χ^2 reconstructed with and without the particle

Results

[PRL 118, 261803 (2017)]



$$A_\Gamma^{KK} = (-3.0 \pm 3.2 \pm 1.0) \cdot 10^{-4}$$

$$A_\Gamma^{\pi\pi} = (\ \ 4.6 \pm 5.8 \pm 1.2) \cdot 10^{-4}$$

- Sys. unc. dominated by secondary decays and multi-body partially and misreconstructed D-meson decays.

- Combination with the smaller, independent muon-tagged sample $\bar{B} \to D^0\mu^-X$ [JHEP 04 (2015) 043]:

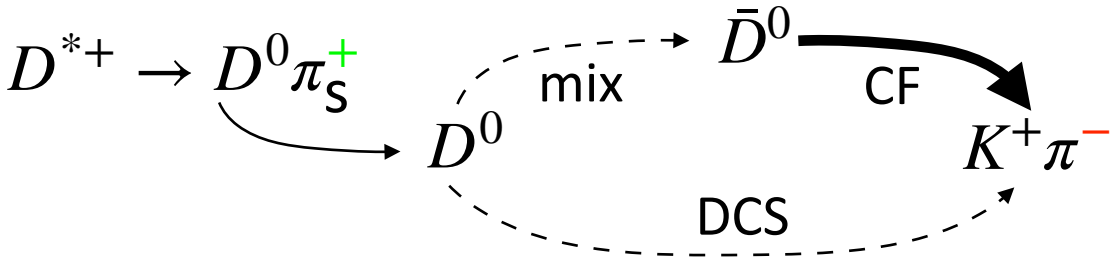
$$A_\Gamma = (-2.9 \pm 2.8) \cdot 10^{-4}$$

- dominates the world average
- compatible with zero within $3 \cdot 10^{-4}$

Mixing and CPV with $D^0 \longrightarrow K^{\pm}\pi^{\mp}$ decays

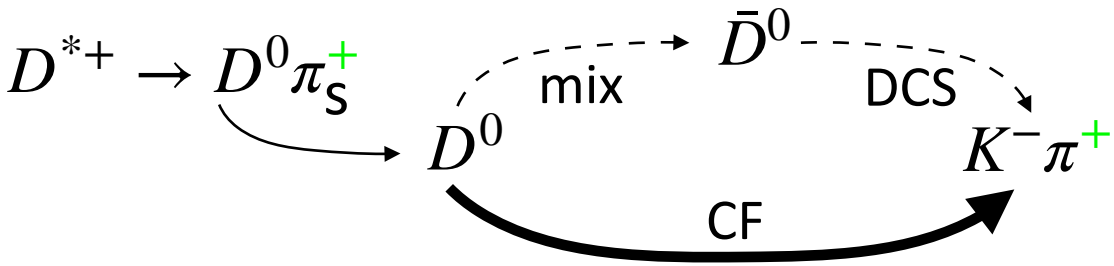
Mixing in $D^0 \to K^\pm\pi^\mp$

- Wrong sign (WS) decays:



a time-dependent WS decay rate implies mixing

- Right sign (RS) decays:



decay rate nearly independent of time

Assuming negligible CPV:

$$R(t) = \frac{\Gamma_{\mathrm{WS}}(t)}{\Gamma_{\mathrm{RS}}(t)} = \underbrace{R_{\mathrm{D}}}_{\text{DCS decay}} + \underbrace{\sqrt{R_{\mathrm{D}}}\, y' \left(\frac{t}{\tau}\right)}_{\text{interference}} + \underbrace{\frac{(x')^2 + (y')^2}{4}\left(\frac{t}{\tau}\right)^2}_{\text{mixing + CF decay}}$$

$$x' = x\cos\delta + y\sin\delta$$

$$y' = y\cos\delta - x\sin\delta$$

$$\frac{A(D^0 \to K^+\pi^-)}{A(\bar{D}^0 \to K^+\pi^-)} = -\sqrt{R_{\mathrm{D}}}\, e^{-i\delta}$$

CP violation in $D^0 \longrightarrow K^{\pm}\pi^{\mp}$

- Measure WS/RS(t) separately for D^{*+} and D^{*-} decays:

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

direct CPV
$R^{+}_{\mathrm{D}} \neq R^{-}_{\mathrm{D}}$

CPV in the mixing or interference

$$x'^{\pm} = \left|\frac{q}{p}\right|^{\pm 1}\left[x\cos(\delta \pm \phi) + y\sin(\delta \pm \phi)\right]$$

$$y'^{\pm} = \left|\frac{q}{p}\right|^{\pm 1}\left[y\cos(\delta \pm \phi) - x\sin(\delta \pm \phi)\right]$$

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

- D^{*+} production cross section and π^{+}_{s} detection asymmetry cancel out in the ratio; need to account only for Kπ detection asymmetry:

$$\frac{N^{\pm}_{\mathrm{WS}}}{N^{\pm}_{\mathrm{RS}}} = \frac{N(D^{*\pm} \to [K^{\pm}\pi^{\mp}]_{D^0}\,\pi^{\pm}_{\mathrm{S}})}{N(D^{*\pm} \to [K^{\mp}\pi^{\pm}]_{D^0}\,\pi^{\pm}_{\mathrm{S}})} = R^{\pm}\boxed{\frac{\epsilon(K^{\pm}\pi^{\mp})}{\epsilon(K^{\mp}\pi^{\pm})}}$$

Data sample

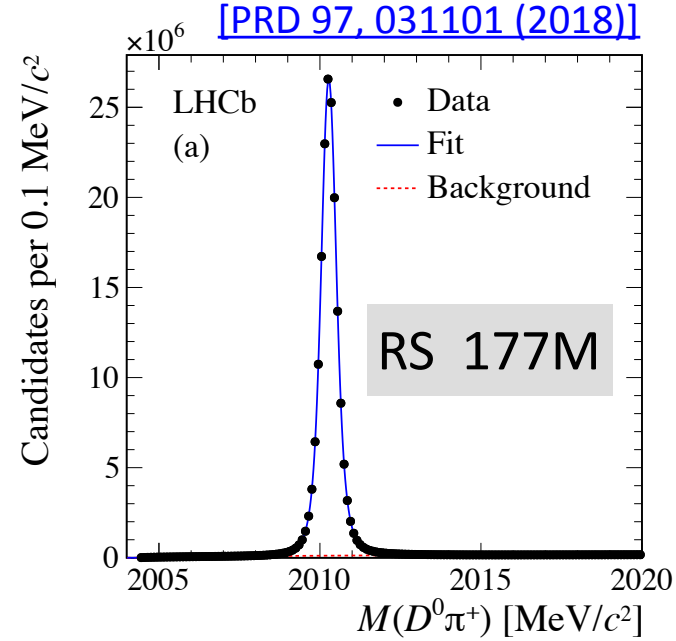
- 5 fb^{-1} (2011–2016);
- prompt decays, sample selection ≈ that of A_Γ.

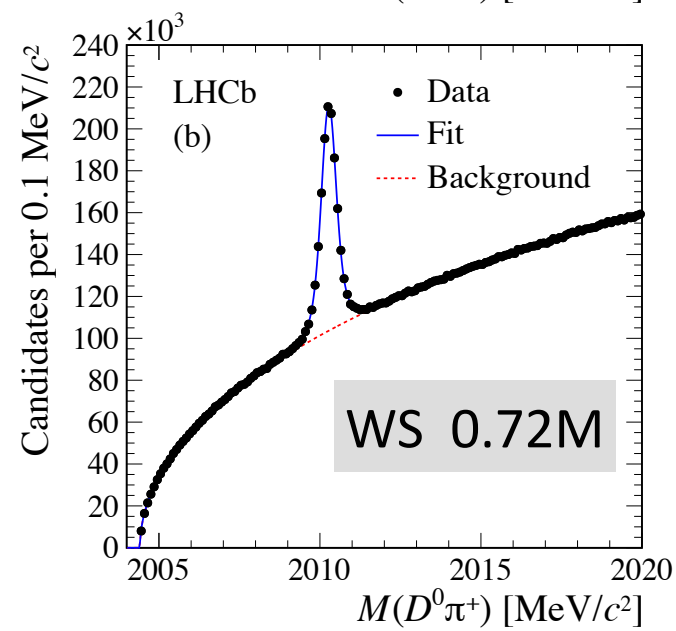
- $A(K^-\pi^+)$ accounted for employing measured asymmetries of $D^+ \to K^-\pi^+\pi^+$ and $D^+ \to \bar{K}^0\pi^+$ decays, reweighed to make their kinematic distributions coincide with that of $D^0 \to K^-\pi^+$

estimated at LHCb
in [JHEP 07 (2013) 041]

$$
\begin{aligned}
A_{\mathrm{D}}(K^-\pi^+) &= A_{\mathrm{raw}}(K^-\pi^+\pi^+) - A_{\mathrm{raw}}(\bar{K}^0\pi^+) + A_{\mathrm{D}}(\bar{K}^0) \\
&= \cancel{A_{\mathrm{P}}(D^+)} + A_{\mathrm{D}}(K^-\pi^+) + \cancel{A_{\mathrm{D}}(\pi^+)} \\
&\quad - \cancel{A_{\mathrm{P}}(D^+)} - \cancel{A_{\mathrm{D}}(\bar{K}^0)} - \cancel{A_{\mathrm{D}}(\pi^+)} \\
&\quad + \cancel{A_{\mathrm{D}}(\bar{K}^0)}
\end{aligned}
$$

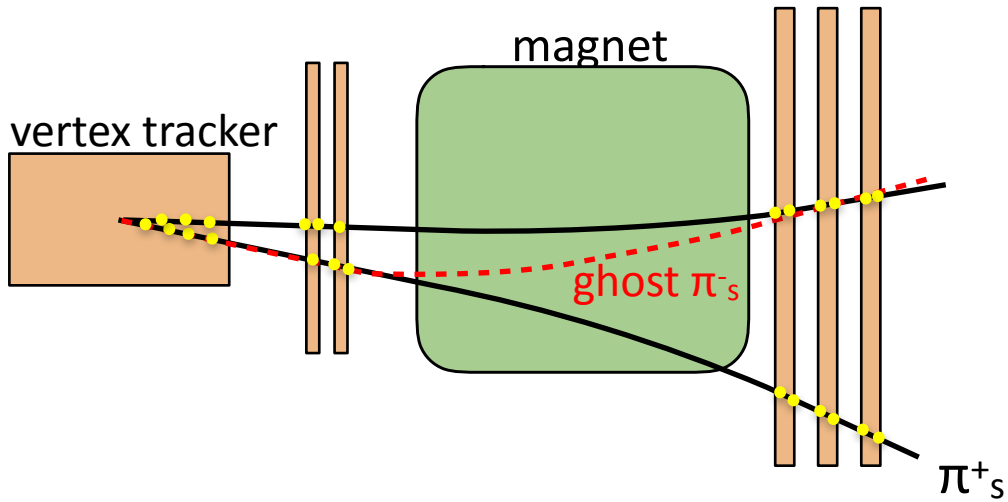
[PRD 97, 031101 (2018)]





Ghost tagging π^+_s

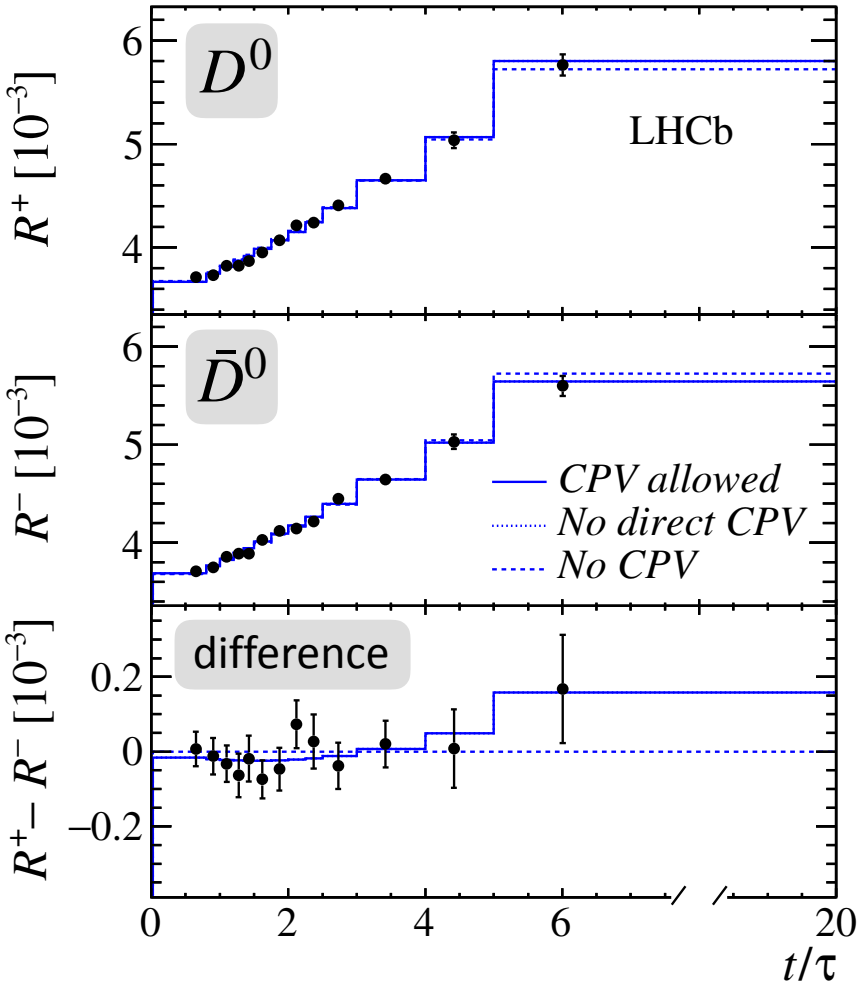
- It may happen that clusters belonging to the π_s track in the tracking stations upstream the magnet are matched to wrong clusters downstream it;
  - measured direction between D^0 and π_s is correct—> bkg. peaks in $m(D^{*+})$ even if reconstructed $p(\pi_s)$ is wrong;
  - RS decay is tagged as much rarer WS ≈ half of the times.



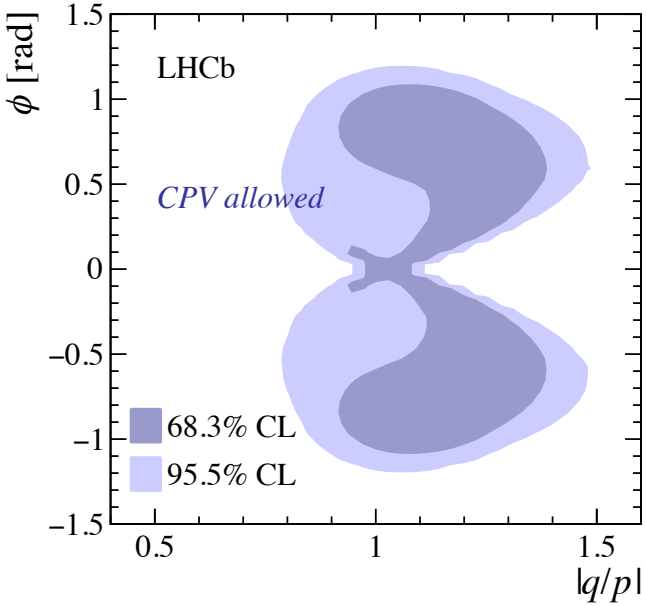
- Misreconstruction probability must be kept well under $BR(D^0 \to K^+\pi^-)/BR(D^0 \to K^-\pi^+) \approx 3\times10^{-3}$
  - neural-network-based algorithm (occupancies & hit multiplicities in each subdetector, momentum of the track) [LHCb-PUB-2017-011]
  - accounts for 30—50% of sys. uncertainty.

Results

[PRD 97, 031101 (2018)]



- No evidence for CPV



- If no CPV is assumed:

$$x'^2 = (0.039 \pm 0.023 \pm 0.014) \cdot 10^{-3}$$
$$y' = (5.28 \pm 0.45 \pm 0.27) \cdot 10^{-3}$$

- Twice as precise as previous superseded LHCb measurement [PRL 111 251801 (2013)]

y_{CP} with $\bar{B} \to D^0 \mu^- X$ tagging

y_{CP} definition

$$y_{CP} = \frac{\hat{\Gamma}(D^0 \to h^+h^-) + \hat{\Gamma}(\bar{D}^0 \to h^+h^-)}{2\Gamma} - 1$$

$f = K^+K^-,\ \pi^+\pi^-$ (CP-even)

$$= \frac{1}{2}\left[\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) y\cos\phi - \left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) x\sin\phi\right] \approx y + y\left[\frac{1}{2}\left(\left|\frac{q}{p}\right| - 1\right)^2 - \frac{\phi^2}{2}\right] - x\phi\left(\left|\frac{q}{p}\right| - 1\right)$$

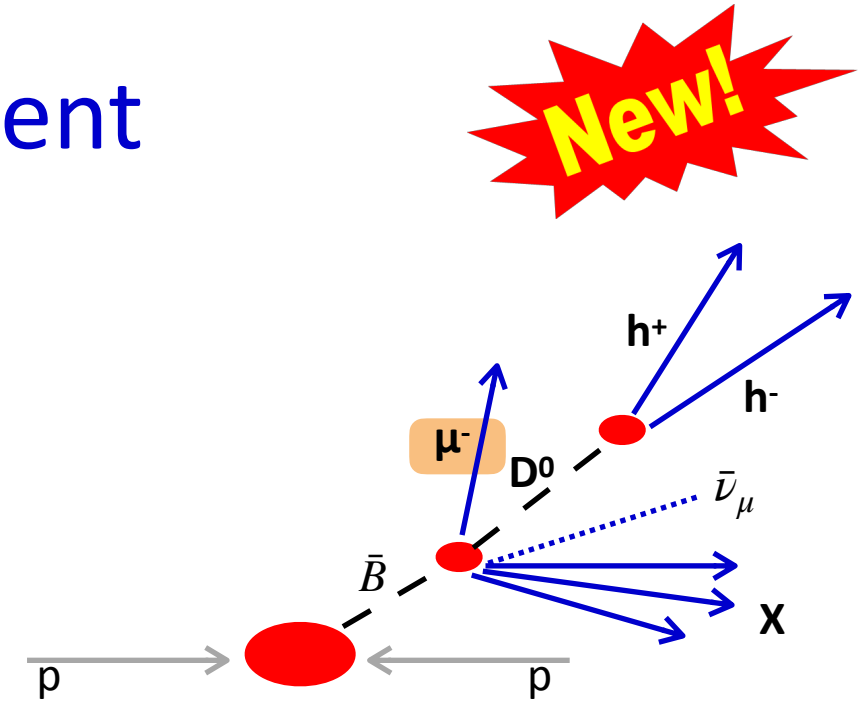
- equal to y in the limit of no CPV;
- differences are
  - linear in mixing parameters
  - quadratic in ϕ, |q/p|-1

  } 5% of y or less

- current precision (≈ 20%) not as competitive as A_Γ for CPV searches;
- it is a measurement of y independent of R(t) = WS/RS.

- First measurement at LHCb [JHEP 04 (2012) 129] with prompt decays but very limited data sample (2010, 29 pb^{-1}), not competitive with world average.

New LHCb measurement



- 3 fb^{-1} (Run 1);
- tagging with $\bar{B} \to D^0 \mu^- X$
- lower yield w.r.t. prompt decays;
- hardware and first level software trigger on the muon;
  - smaller trigger-induced decay-time biases.

- Extract y_{CP} from the time-dependent ratio between h^+h^- and $K^-\pi^+$ yields (same strategy as B_s, D_s lifetimes measurements at LHCb [PRL 119, 101801]).

$\bar{B} \to D^0\mu^- X$ selection

New!

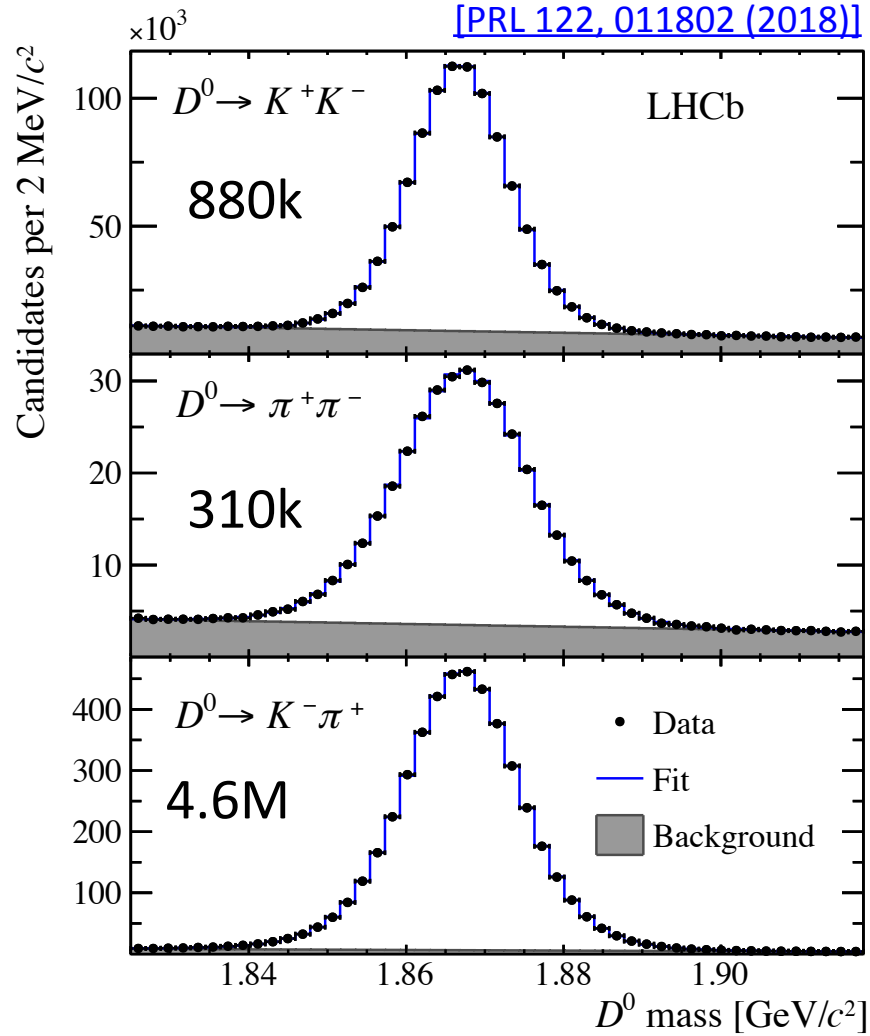
- Mainly inherited from muon-tagged ΔA_{CP} and B_s, D_s lifetimes measurements [JHEP 07 (2014) 041], [PRL 119, 101801]
- loose cuts on all tracks χ^2_{IP};
- cut in the $p_T(D^0)$ — $m_{corr}(B)$ plane to reduce contamination from combinatorial bkg., double-charmed B decays, $\bar{B} \to D^0\tau^- X$

- Final contamination in $m(D^0)$ peak:
  - < 1.5% from these bkgs.
  - < 1% from prompt D^0.

$$m_{\text{corr}}(B) = \sqrt{m^2(D\mu) + p_\perp^2(D\mu)} + p_\perp^2(D\mu)$$

χ^2_{IP} = difference in *pp* vertex-fit χ^2 reconstructed with and without the particle

[PRL 122, 011802 (2018)]



Experimental strategy

New!

- Inspired by [PRL 119, 101801]:
  - determine the yields of h^+h^- and $K^-\pi^+$ through a fit to $m(D^0)$, separately for 19 bins of decay time;
  - minimise the χ^2 from the difference of $N_i(h^+h^-)$ / $N_i(K^-\pi^+)$ with the expected value:

$$R_i = \boxed{N} \cdot \boxed{A_i} \cdot \boxed{\frac{\int_{t_i}^{t_{i+1}} e^{-(\Gamma+\Delta_\Gamma)t}\,\mathrm{d}t}{\int_{t_i}^{t_{i+1}} e^{-\Gamma t}\,\mathrm{d}t}}$$

$$\Delta_\Gamma = \Gamma_{h^+h^-} - \Gamma$$

$$y_{CP} = \frac{\Delta_\Gamma}{\Gamma}$$

normalisation factor common to all time bins

acceptance ratio in time bin i (from MC)

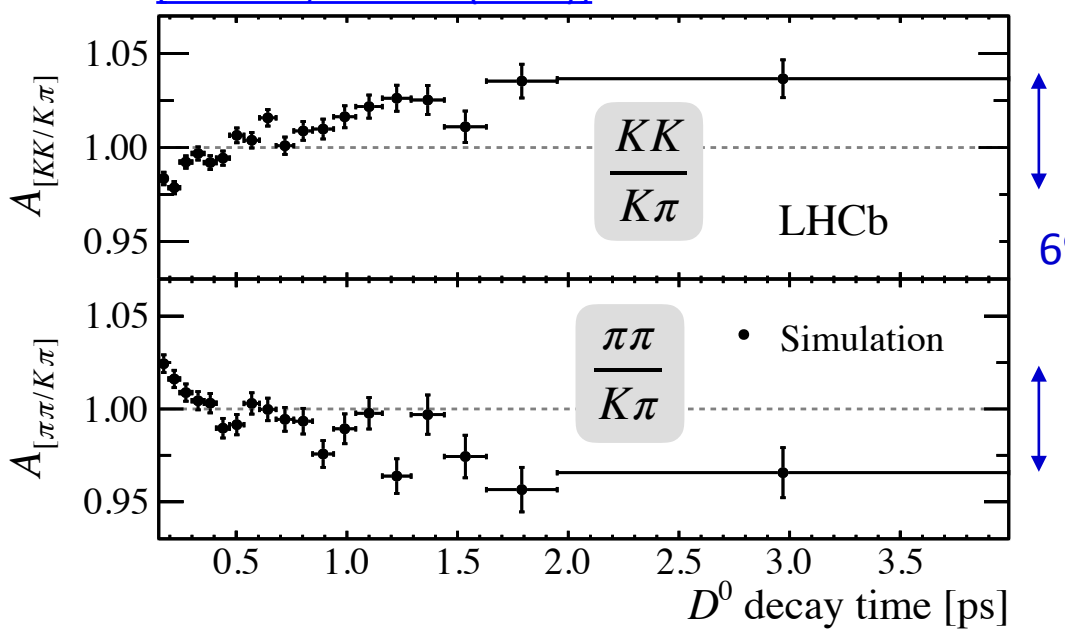
ratio of the PDFs of h^+h^- and $K^-\pi^+$ decays (nearly independent of the value of Γ)

Acceptance ratio

New!

- Acceptances calculated from MC simulation of inclusive B^0, B^- semi-muonic decays into D^0;
- main MC mismodellings of detector *etc*. expected to cancel in the ratio.

[PRL 122, 011802 (2018)]



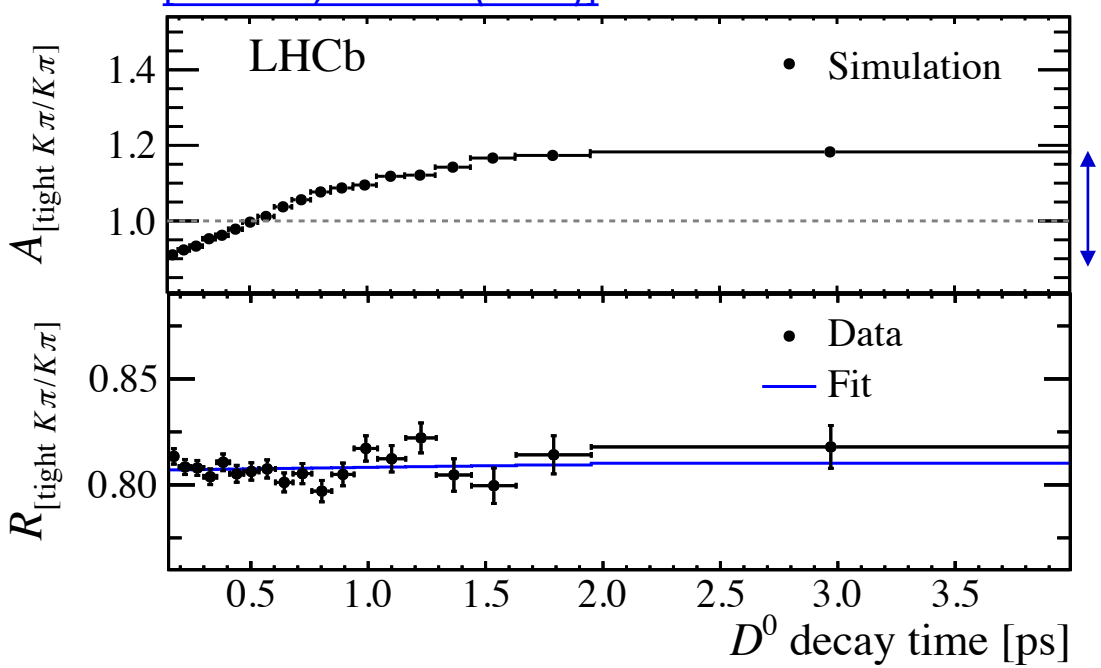
6% variations mainly due to χ^2_{IP} cuts

Null test (1): $\frac{\Gamma(D^0 \to K^-\pi^+), \chi^2_{\text{IP}} > 60}{\Gamma(D^0 \to K^-\pi^+), \chi^2_{\text{IP}} > 8}$

New!

- Test the MC description of the time-dependence of the acceptance:
  - split the $K^-\pi^+$ sample in two;
  - apply a tighter cut $\chi^2_{IP} > 60$ to the μ^-, K^-, π^+ of the numerator sample (std. is $\chi^2_{IP} > 8$);
  - measure Δ_Γ between the two samples (should be 0).

[PRL 122, 011802 (2018)]



nearly 30% variations of acceptance ratio

$$\Delta_\Gamma^{K\pi/K\pi} = (-1.8 \pm 3.3) \cdot 10^{-3}\ \text{ps}^{-1}$$

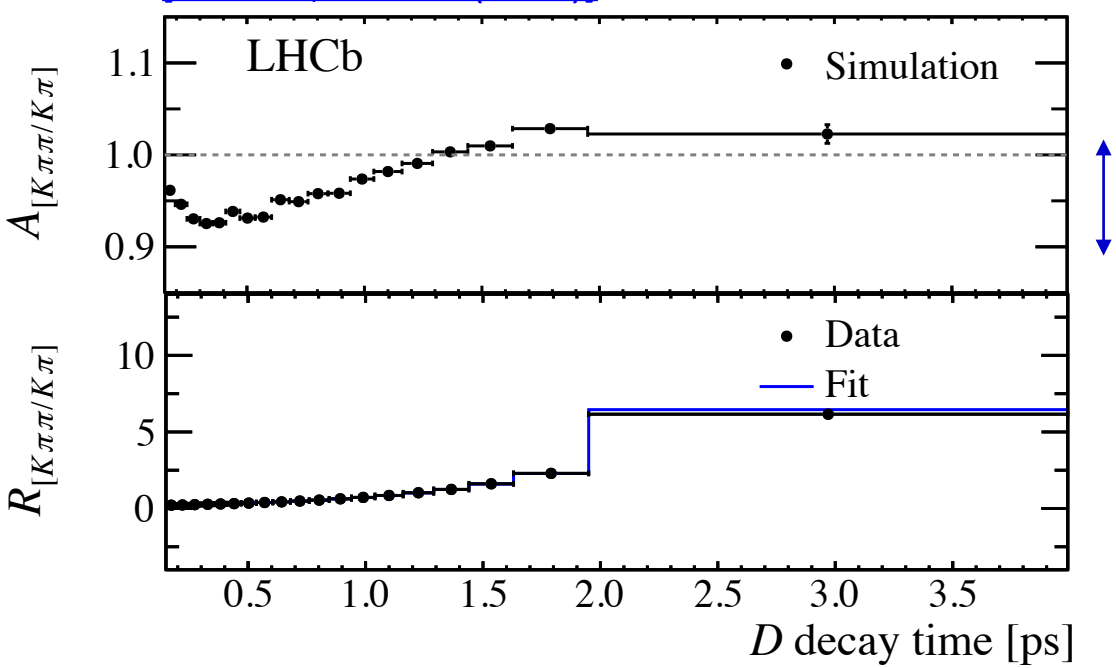
uncertainty corresponds to $\sigma(y_{CP}) = 0.14\,\%$

Null test (2): $\frac{\Gamma(D^+ \to K^-\pi^+\pi^+)}{\Gamma(D^0 \to K^-\pi^+)}$

New!

- 3-body vs. 2-body decays —> different topology, kinematics, acceptance;
- (B^0 : B^-) very different for D^0 and D^+ —> check impact of B-mixture uncertainty in MC;
- $\tau(D^+) / \tau(D^0) \approx 2.5$ —> sensitive to biases linear in Δ_Γ.

[PRL 122, 011802 (2018)]



~ 10% variations

$\tau(D^+) / \tau(D^0) = 2.5141 \pm 0.0082$ compatible with PDG within 1σ (test limited by PDG precision 2.536 ± 0.019).

Biases linear in Δ_Γ are < 0.8% Δ_Γ.

Other checks and systematics

New!

[PRL 122, 011802 (2018)]

- Further checks:
  - $\dfrac{\Gamma(D^+ \to K^-\pi^+\pi^+),\ \chi^2_{IP} > 60}{\Gamma(D^+ \to K^-\pi^+\pi^+),\ \chi^2_{IP} > 8}$
  - $\dfrac{\Gamma(D^+ \to K^-K^+\pi^+)}{\Gamma(D^+ \to K^-\pi^+\pi^+)}$

  } Δ_Γ consistent with 0 within stat. uncertainty

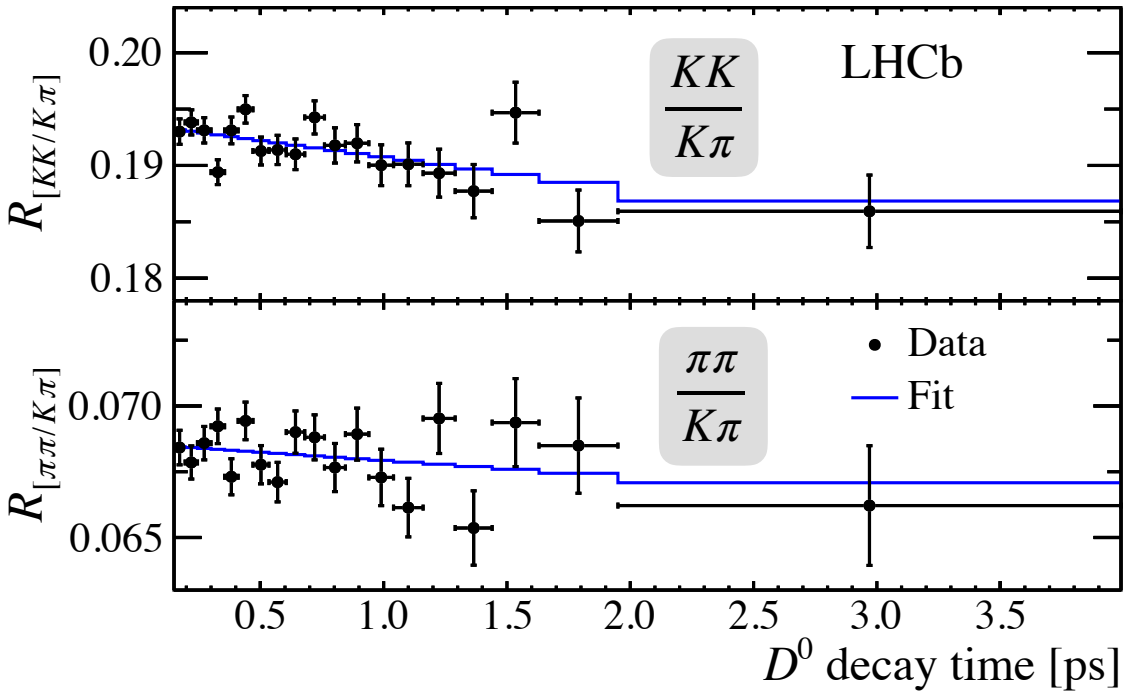
- Systematic uncertainties:

Source	KK (%)	ππ (%)	
Finite size of MC sample (acceptance ratio)	0.11	0.15	uncorrelated
Fit bias	0.02	0.02	fully correlated
B^0:B^- ratio and decay model	0.02	0.02	fully correlated
Decay-time resolution	0.01	0.01	fully correlated
B - Bbar production asymm.	< 0.01	< 0.01	fully correlated
Total sys.	0.11	0.15	
Statistical	0.15	0.28	

Fit result

New!

[PRL 122, 011802 (2018)]



$$y_{CP}^{KK} = (0.63 \pm 0.15 \pm 0.11)\,\%$$

$$y_{CP}^{\pi\pi} = (0.38 \pm 0.28 \pm 0.15)\,\%$$

$$\boxed{y_{CP} = (0.57 \pm 0.13 \pm 0.09)\,\%}$$

- Compatible and with same precision of world average (0.835 ± 0.155)%;
- compatible with $y = \left(0.67^{+0.06}_{-0.13}\right)\,\%$ within 1σ.

Summary

- LHCb leads the world averages of all indirect CPV parameters thanks to huge c-cbar prompt production at LHC;
  - now eventually entering the region allowed by the SM, $\mathcal{O}(10^{-4})$;
- uncertainty on mixing parameters steadily decreasing, other 4 fb^{-1} of data taken in 2017—2018;
- analyses still limited by the statistical uncertainty.

Thank you for your attention.
Any questions?

Backup

A_Γ: systematics

[PRL 118, 261803 (2017)]

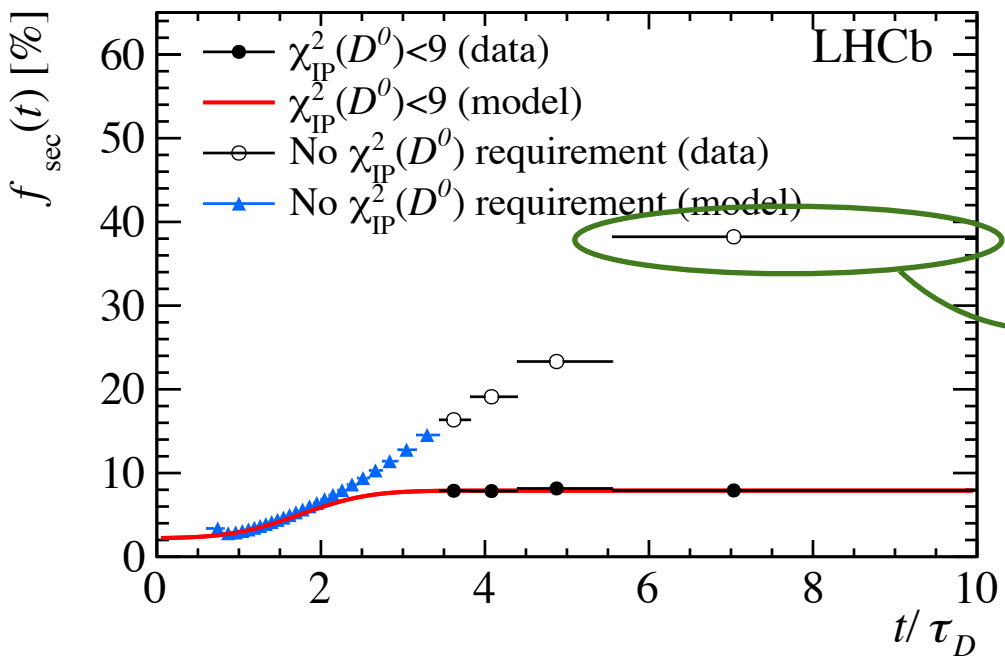
Source	KK (10^{-4})	ππ (10^{-4})
Secondary decays	0.8	1.2
Discretisation of weighing procedure	0.2	0.2
Subtraction of Δm bkg. from random π^+_s	0.1	0.1
Bkg. from partially-reconstructed and misidentified D-meson multi-body decays	0.5	-
Total sys.	1.0	1.2
Statistical	3.2	5.8

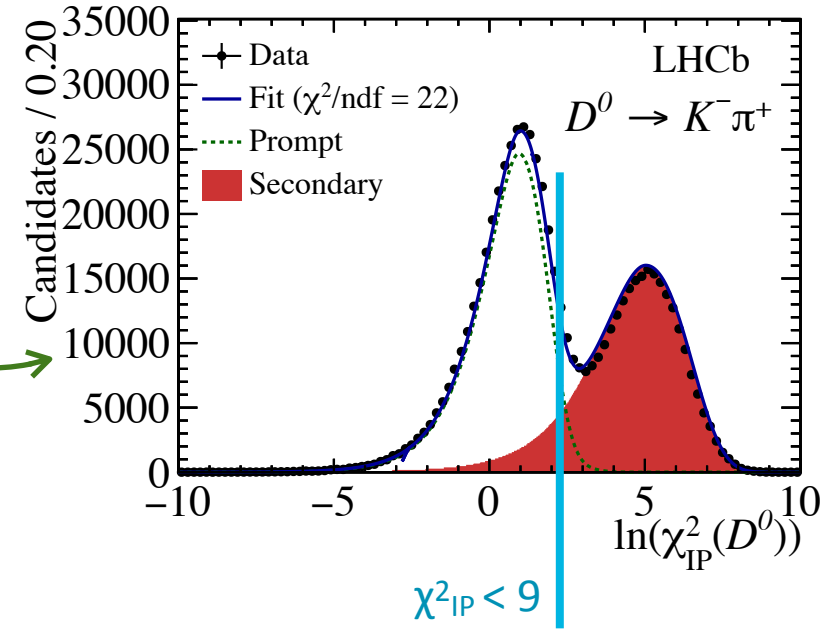
A_Γ: contribution from secondary decays

$$A_{\text{raw}} = A_{\text{prim}}(t) + f_{\text{sec}}(t) \cdot [A_{\text{sec}}(t) - A_{\text{prim}}(t)]$$

[PRL 118, 261803 (2017)]

≈ $A_{\text{production}}(B) - A_{\text{production}}(D^{*+})$





f_{sec} extracted from $\ln(\chi^2_{IP})$ fit in last four time bins and extrapolated with physically-motivated empiric model to lower bins where the distributions of prompt and secondary decays can't be easily disentangled. Uncertainty on the empiric model is the main source of systematic uncertainty.

A_Γ and y_{CP} world averages

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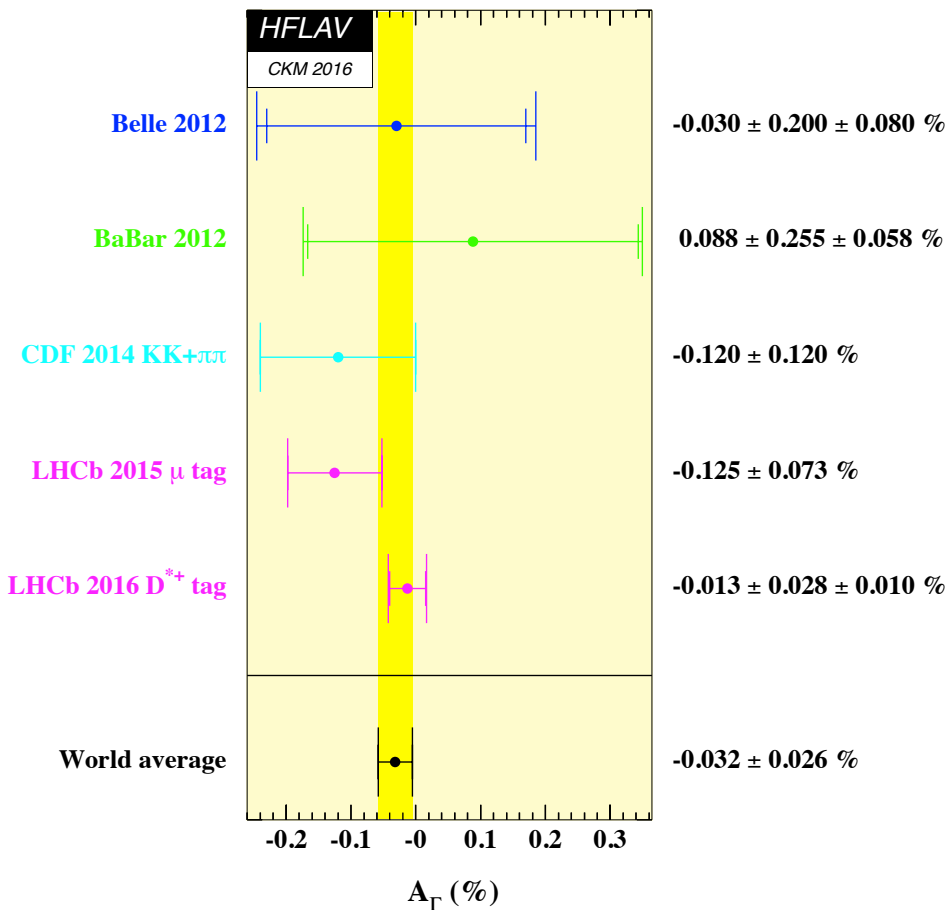
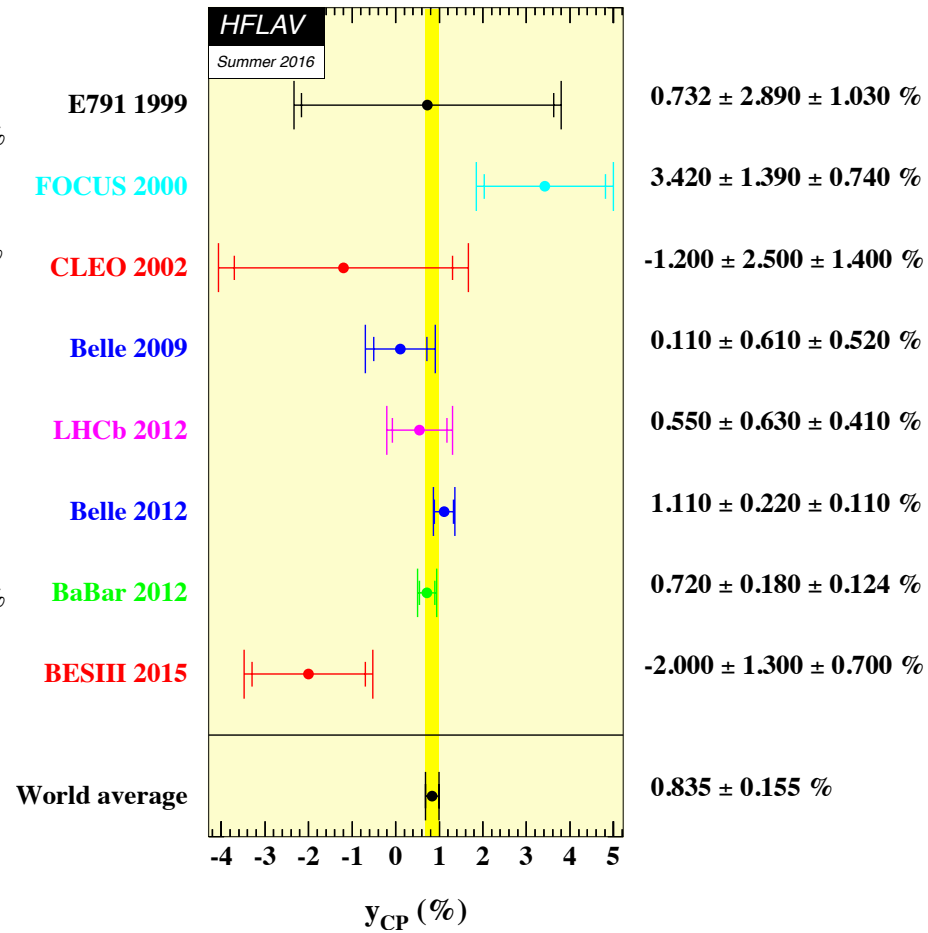
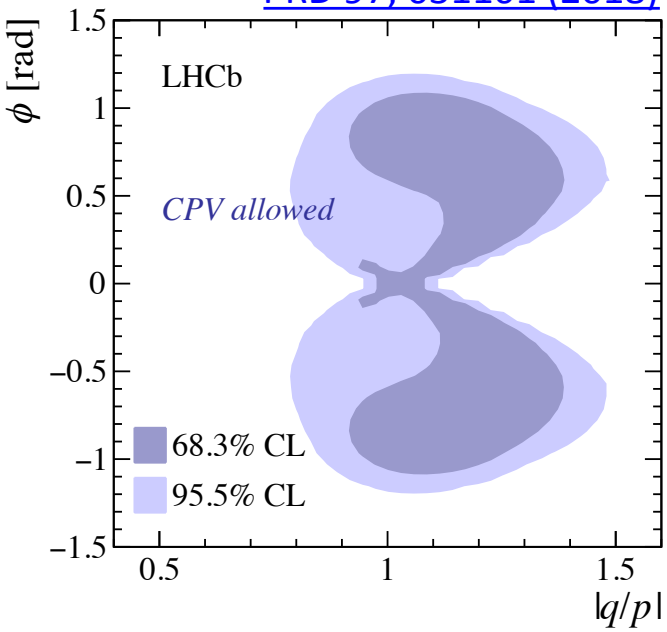




Indirect CPV: $D^0 \to K^{\pm}\pi^{\mp}$ *vs* A_Γ

$D^0 \to K^{\pm}\pi^{\mp}$: determines the 8-like shape of allowed (ϕ, $|q/p|$) region; nearly full degeneracy $\phi \to -\phi$

PRD 97, 031101 (2018)



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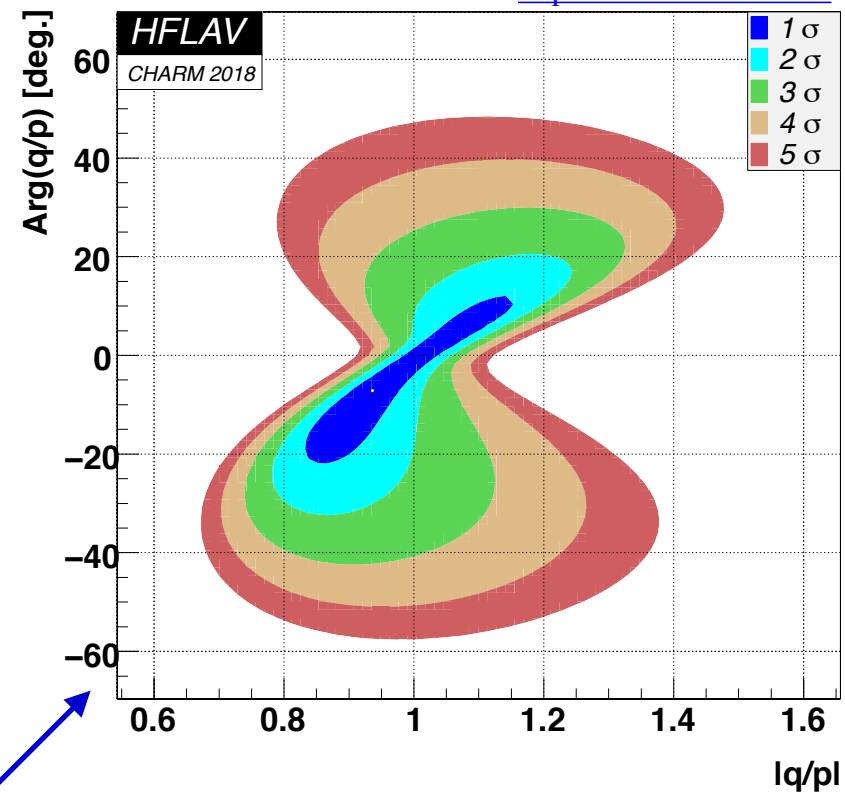


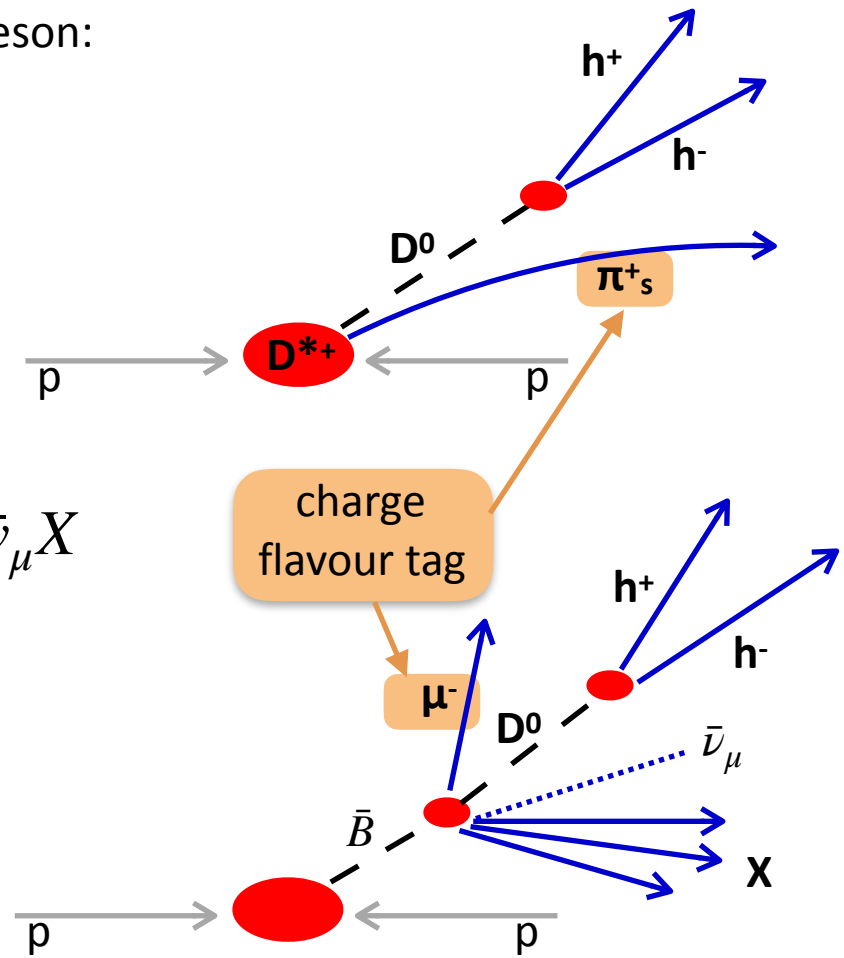
$$A_\Gamma \approx y\left(\left|\frac{q}{p}\right| - 1\right) - x\phi$$

— it's a line in the plane
— responsible for the tilt (and significant reduction of CPV-allowed region w.r.t. $D^0 \to K^{\pm}\pi^{\mp}$ constraints only)

Tagging strategies at LHCb

To identify the flavour at production of the D^0 meson:

- **Prompt tag**: strong decay $D^{*+} \to D^0 \pi_s^+$
  - larger production cross section;
  - tight trigger cut on D^0 flight distance and h^+, h^- impact parameters to improve S/B;
  - low trigger efficiency at low decay times;
  - D^0 points at the primary vertex (PV).
- **Semileptonic tag**: weak decay $\bar{B} \to D^0 \mu^- \bar{\nu}_\mu X$
  - lower production cross section;
  - no need to cut on D^0 flight distance;
  - all D^0 decay times collected by the trigger;
  - total yield ≈ 25% of prompt one;
  - D^0 does not necessarily point at PV.
- **Double-tag**: $\bar{B} \to [D^0 \pi_s^+]_{D^{*+}} \mu^- \bar{\nu}_\mu X$
  - highest purity;
  - lowest yield.



Indirect CPV prospects at LHCb Upgrade II

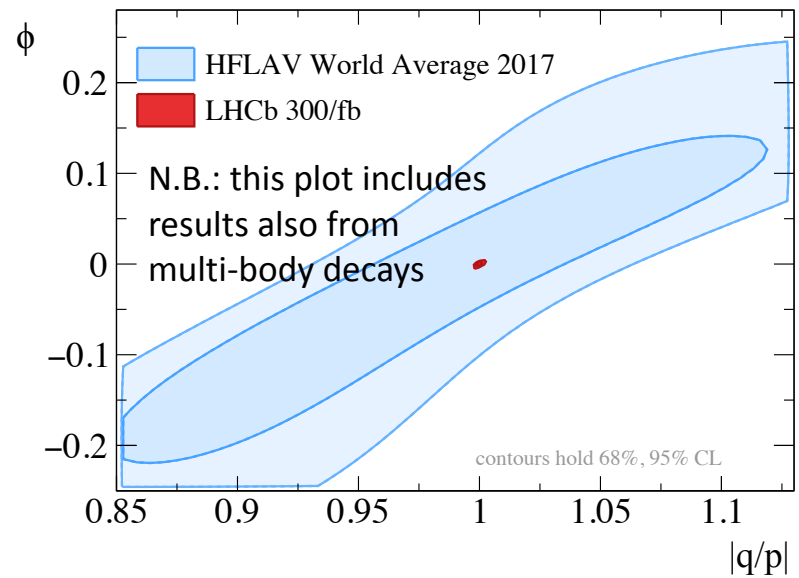
Sample ($\mathcal{L}$)	Yield ($\times 10^6$)	$\sigma(x'^2_{K\pi})$	$\sigma(y'_{K\pi})$	$\sigma(A_D)$	$\sigma(\lvert q/p\rvert)$	$\sigma(\phi)$
Run 1–2 ($9\,\mathrm{fb}^{-1}$)	1.8	1.5×10^{-5}	2.9×10^{-4}	0.51%	0.12	10°
Run 1–3 ($23\,\mathrm{fb}^{-1}$)	10	6.4×10^{-6}	1.2×10^{-4}	0.22%	0.05	4°
Run 1–4 ($50\,\mathrm{fb}^{-1}$)	25	3.9×10^{-6}	7.6×10^{-5}	0.14%	0.03	3°
Run 1–5 ($300\,\mathrm{fb}^{-1}$)	170	1.5×10^{-6}	2.9×10^{-5}	0.05%	0.01	1°

Sample ($\mathcal{L}$)	Tag	Yield K^+K^-	$\sigma(A_\Gamma)$	Yield $\pi^+\pi^-$	$\sigma(A_\Gamma)$
Run 1–2 ($9\ \mathrm{fb}^{-1}$)	Prompt	60M	0.013%	18M	0.024%
Run 1–3 ($23\ \mathrm{fb}^{-1}$)	Prompt	310M	0.0056%	92M	0.0104 %
Run 1–4 ($50\ \mathrm{fb}^{-1}$)	Prompt	793M	0.0035%	236M	0.0065 %
Run 1–5 ($300\ \mathrm{fb}^{-1}$)	Prompt	5.3G	0.0014%	1.6G	0.0025 %

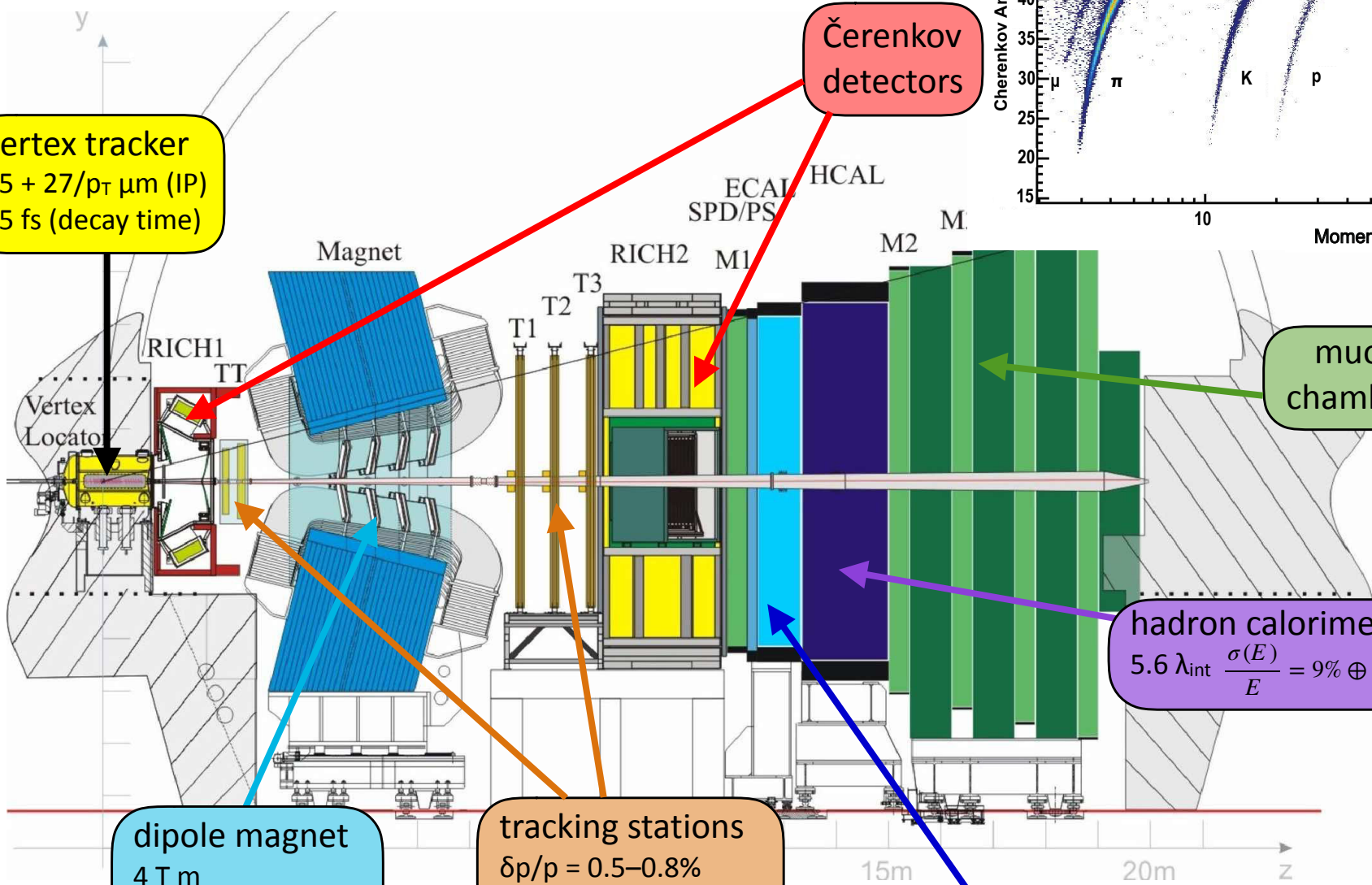
Physics case for an LHCb Upgrade II [arXiv:1808.08865]

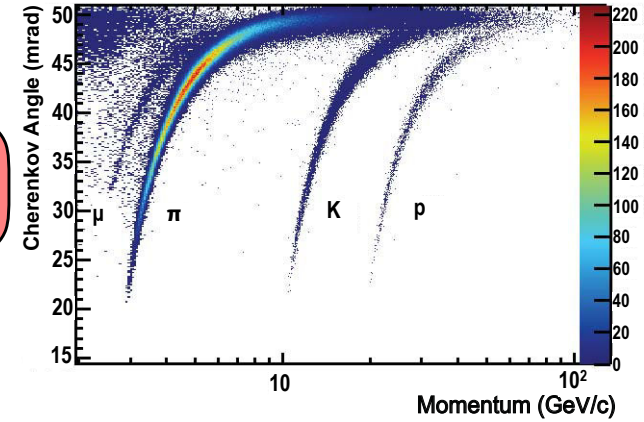
Assumptions:

- x2 of hadron trigger efficiency (no hardware trigger + new magnet stations);
- current LHCb performance is maintained in Upgrade II conditions;
- statistical uncertainty only (with 1/√N scaling).



LHCb detector





vertex tracker
15 + 27/p_T μm (IP)
45 fs (decay time)

Čerenkov detectors

muon chambers

hadron calorimeter
5.6 λ_{int} $\frac{\sigma(E)}{E} = 9\% \oplus \frac{69\%}{\sqrt{E/GeV}}$

dipole magnet
4 T m
along y direction

tracking stations
δp/p = 0.5–0.8%
for p = 20–200 GeV/*c*

electromagnetic calorimeter
25 X_0, 1.2 λ_{int} $\frac{\sigma(E)}{E} = 1\% \oplus \frac{10\%}{\sqrt{E/GeV}}$

The LHCb detector at the LHC, JINST 3 S08005 (2008)