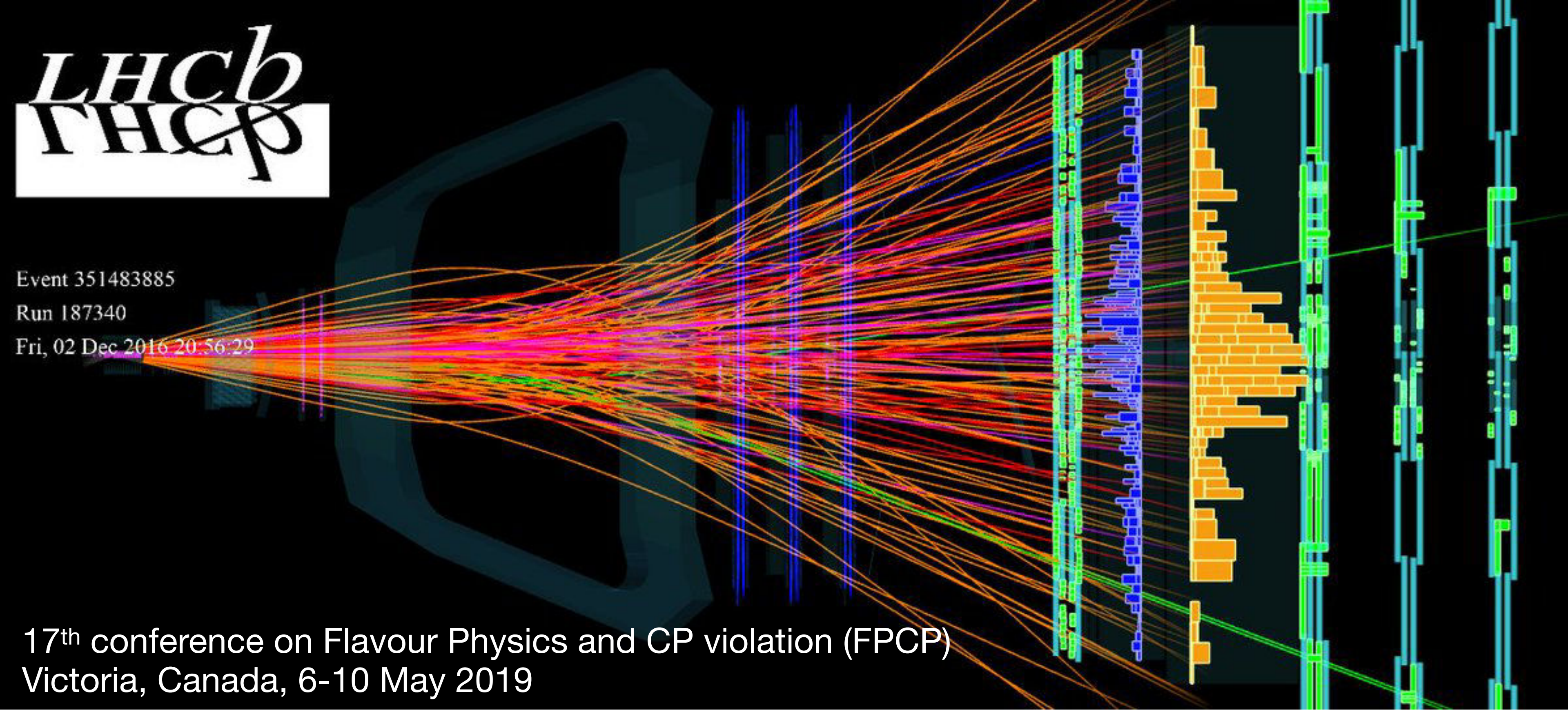

17th conference on Flavour Physics and CP violation (FPCP)
Victoria, Canada, 6-10 May 2019

Mixing and CP violation in charm at LHCb

Tommaso Pajero - Scuola Normale Superiore & INFN, Pisa
on behalf of the LHCb collaboration

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Why charm physics?

- It is the only up-type quark forming mesons where CP violation (CPV) can be observed;
  - **complementary to K and B mesons.**

- In the SM, CPV is expected to be typically **≤ 10^{-3}**;
  - CKM+GIM suppression;
  - large theory uncertainties owing to low-energy strong interactions.

- **First observation of CPV** on 21st March 2019; arXiv:1903.08726

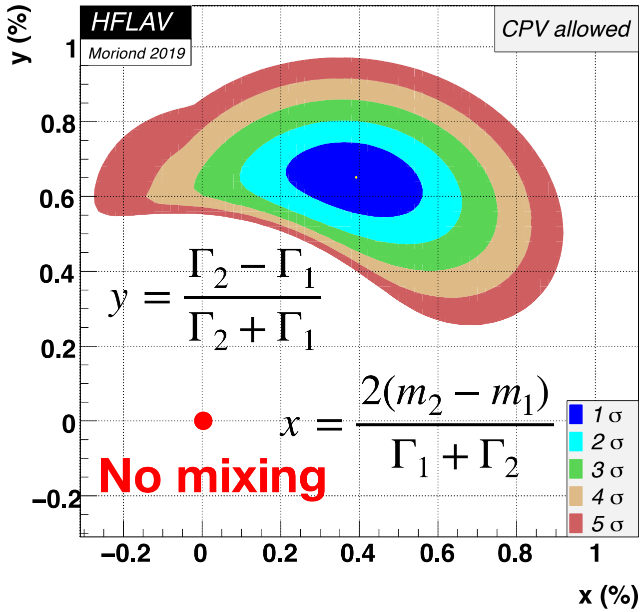
$$\Delta A_{CP} = (-15.4 \pm 2.9) \cdot 10^{-4}$$

Mainly a measurement of *CPV in the decay*.

see talk by Fabio Ferrari

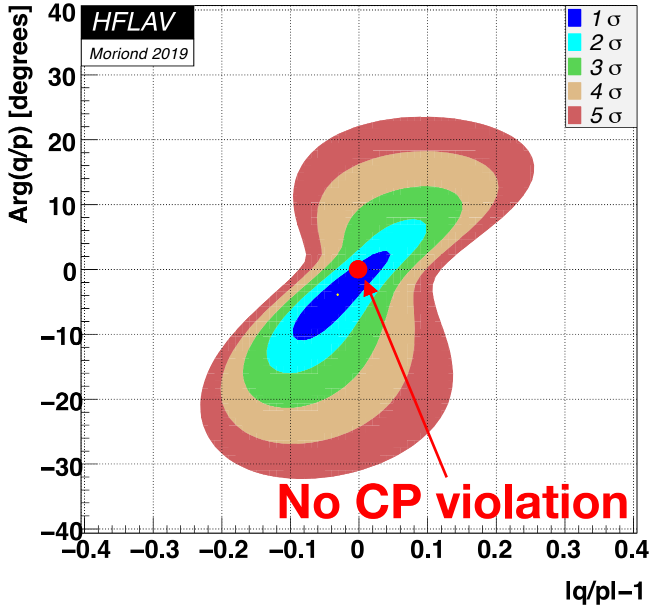
- More work is needed to clarify the physics picture;
- **still missing observation of time-dependent CPV.**

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



$$y = \frac{\Gamma_2 - \Gamma_1}{\Gamma_2 + \Gamma_1}$$

$$x = \frac{2(m_2 - m_1)}{\Gamma_1 + \Gamma_2}$$



Outline

1) Measurement of Δm of D^0 eigenstates in $\mathbf{D^0 \to K^0_S\, \pi^+\pi^-}$ with 2011—2012 data (3 fb^{-1});
   arXiv:1903.03074

2) Measurement of time-dependent CP violation (**A_Γ parameter**) with 2015—2016 prompt data (2 fb^{-1}).
   LHCb-CONF-2019-001

NEW

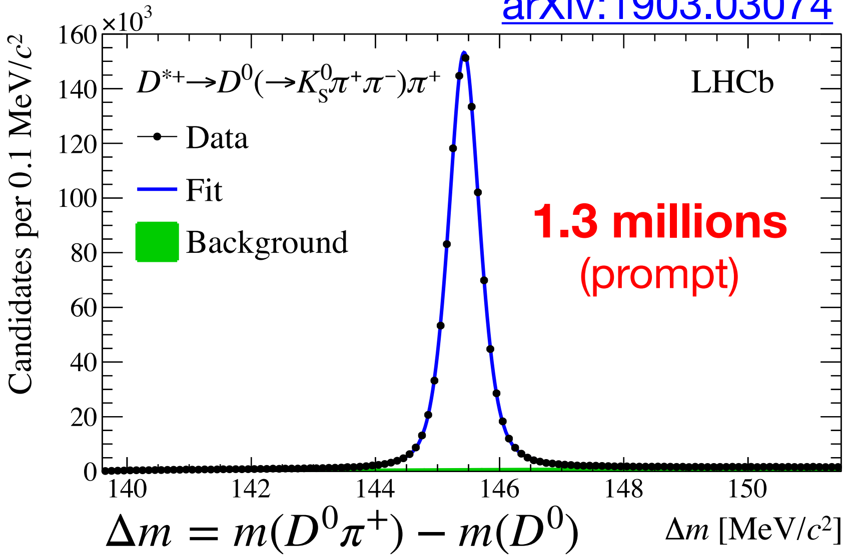
Measurement of Δm of D^0 mass eigenstates

arXiv:1903.03074

Mixing and CPV with $D^0 \rightarrow K^0_S \pi^+\pi^-$ decays

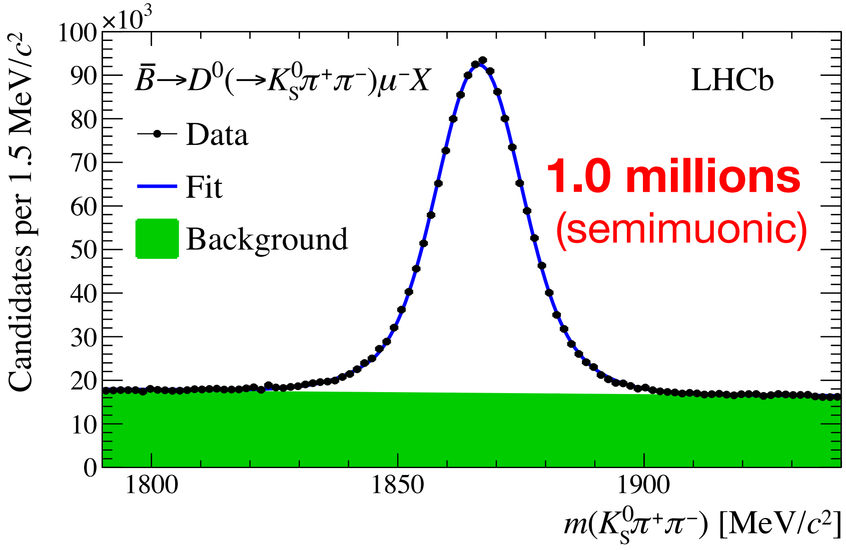
- LHCb Run 1 sample (2011–2012, 3 fb^{-1});
- $D^0 \rightarrow K^0_S \pi^+\pi^-$ decays feature a **rich resonance spectrum**.
  - good sensitivity to mixing and time-dependent CPV parameters thanks to varying strong phases;
  - difficult to model the decay dynamics and acceptance effects.

arXiv:1903.03074



1.3 millions
(prompt)

$\Delta m = m(D^0\pi^+) - m(D^0)$



1.0 millions
(semimuonic)

The “bin flip” method

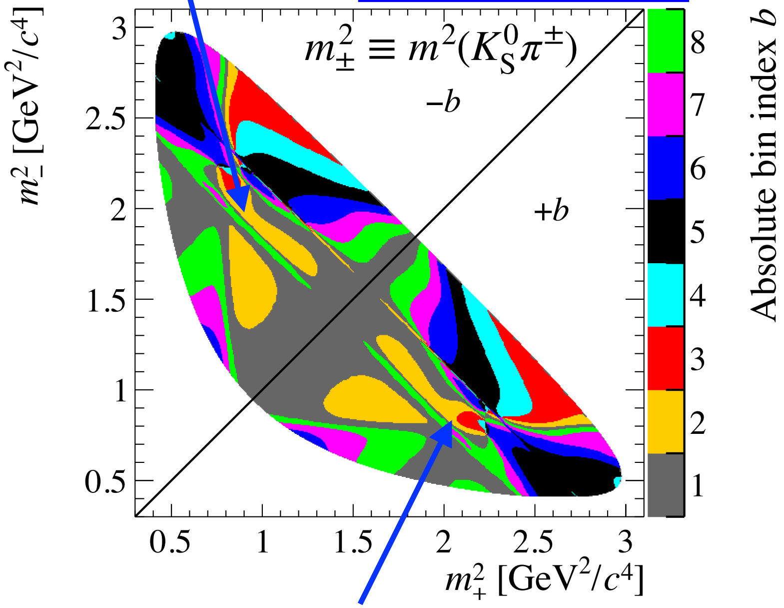
- New approach (arXiv:1811.01032) to minimise dependence on:
    - amplitude model;
    - detector acceptance.

- Data are **binned in Dalitz plane to keep strong phases approximately constant**;
- external measurements of strong-phases from CLEO arXiv:1010.2817 used as constraints;
- no modelling of dynamics of D^0 decay is needed.

- Data binned also in decay time;
- measure **ratio of yields in opposite bins across the bisector** of the Dalitz plot;
    - acceptance effects cancel;
    - good sensitivity to x.

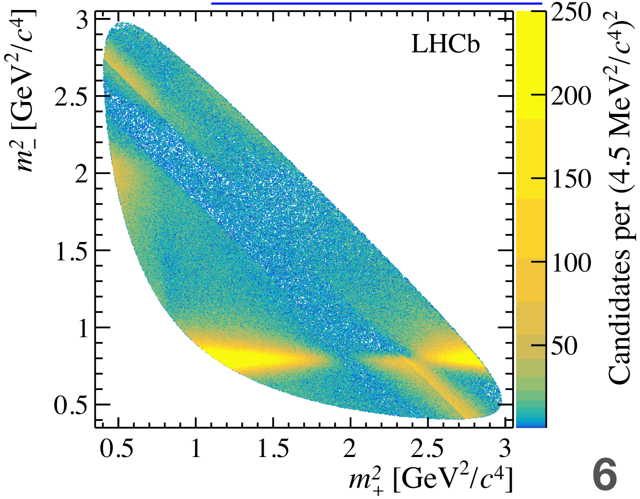
$m^2_+ < m^2_-$ region: mixed decays are more important.

arXiv:1811.01032



$m^2_+ > m^2_-$ region: dominated by unmixed Cabibbo-favoured $D^0 \to K^*(892)^-\pi^+$ decays.

arXiv:1903.03074



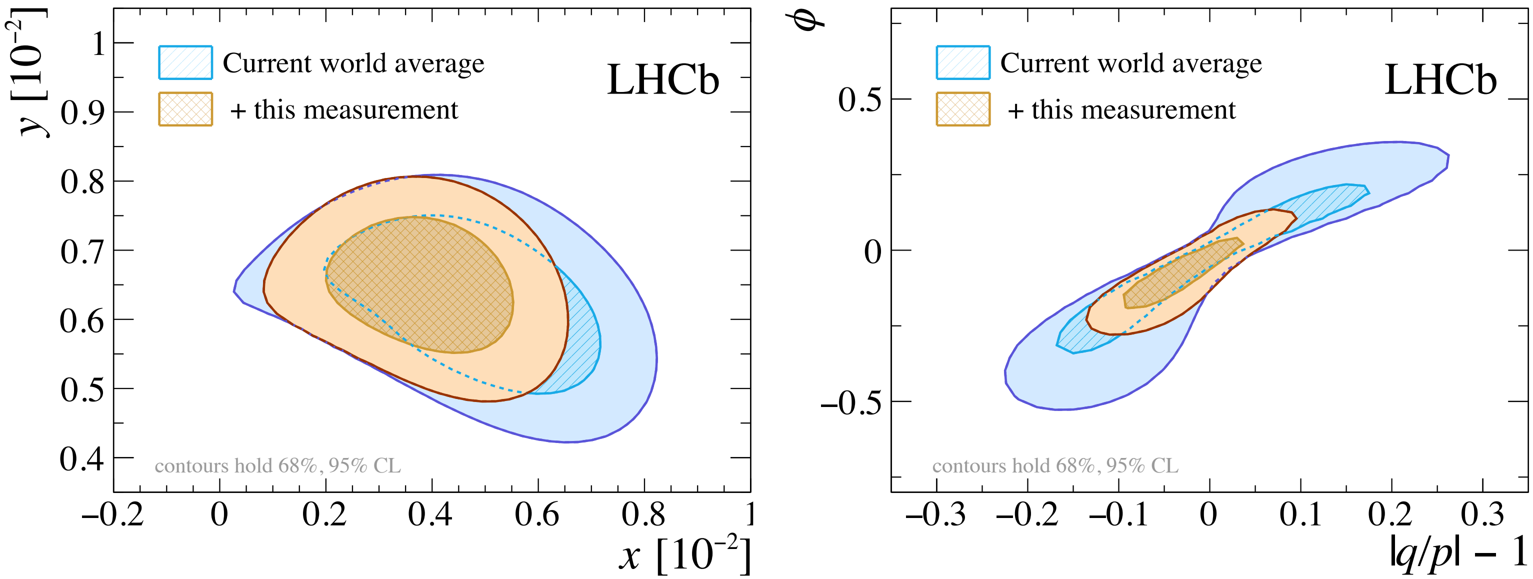
Results

arXiv:1903.03074

- Consistent with CP symmetry;
- **most precise measurement of x by a single experiment.**

Parameter	Value	95.5% CL interval
$x\ [10^{-2}]$	$0.27\,^{+0.17}_{-0.15}$	$[-0.05, 0.60]$
$y\ [10^{-2}]$	0.74 ± 0.37	$[\ \ 0.00, 1.50]$
$\lvert q/p \rvert$	$1.05\,^{+0.22}_{-0.17}$	$[\ \ 0.55, 2.15]$
ϕ	$-0.09\,^{+0.11}_{-0.16}$	$[-0.73, 0.29]$

- When added to the world average of the mixing parameters, gives first evidence that **x > 0 at > 3σ level** (the “CP-even eigenstate” is heavier);
  - sensitivity to ϕ mainly relies on observables ∝ *x sinϕ*.



- Around 30 times more data has already been collected during Run 2 (2015—2018).

Measurement of CPV parameter A_Γ in D^0 two-body decays

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NEW

Presented in this talk
for the first time

Today → brief review.
More details at tomorrow poster session.

Definition of A_Γ

- Measure of time-dependent CPV in the D^0 singly Cabibbo-suppressed decays into CP eigenstates:

$$A_{CP}(t) = \frac{\Gamma(D^0 \to f, t) - \Gamma(\bar{D}^0 \to f, t)}{\Gamma(D^0 \to f, t) + \Gamma(\bar{D}^0 \to f, t)} \overset{\overset{x, y < 10^{-2}}{\downarrow}}{\approx} A_{CP}^{\text{decay}}(f) - A_\Gamma \left(\frac{t}{\tau_{D^0}} \right), \quad f = K^+K^-, \pi^+\pi^-$$

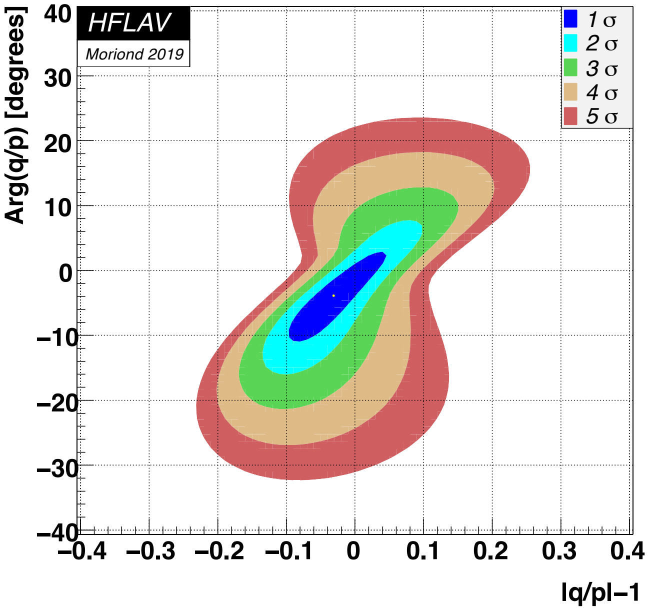
$$A_\Gamma \approx \underbrace{y\left(\left| \frac{q}{p} \right| - 1 \right)}_{\text{CPV in the mixing}} \overbrace{- x\phi_f}^{\text{CPV in the interference}} \underbrace{- yA_{CP}^{\text{decay}}(f)}$$

≈ 1 x 10^{-5} → negligible at the current exp. precision (3 x 10^{-4}), arXiv:1903.08726, arXiv:1610.09476

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

$$\phi_f = \arg\left(\frac{q\bar{A}_f}{pA_f} \right) \underset{\uparrow}{\approx} \arg\left(\frac{q}{p} \right)$$

Du 2006, Grossman, Kagan, Nir 2007



Motivation and experimental status

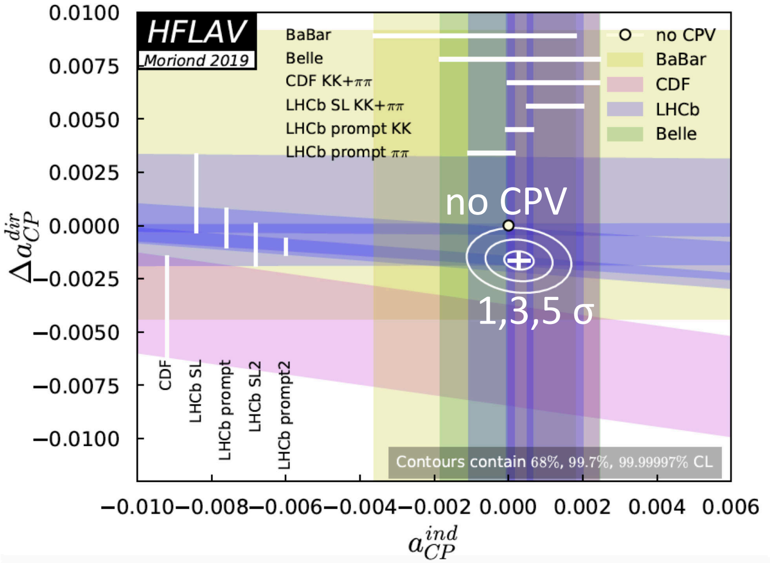
1. **Test of the SM**;
   - SM predictions: ≈ **3 x 10^{-5}** arXiv:1812.07638
   - independent of the measurement of CPV in the decay (ΔA_{CP});

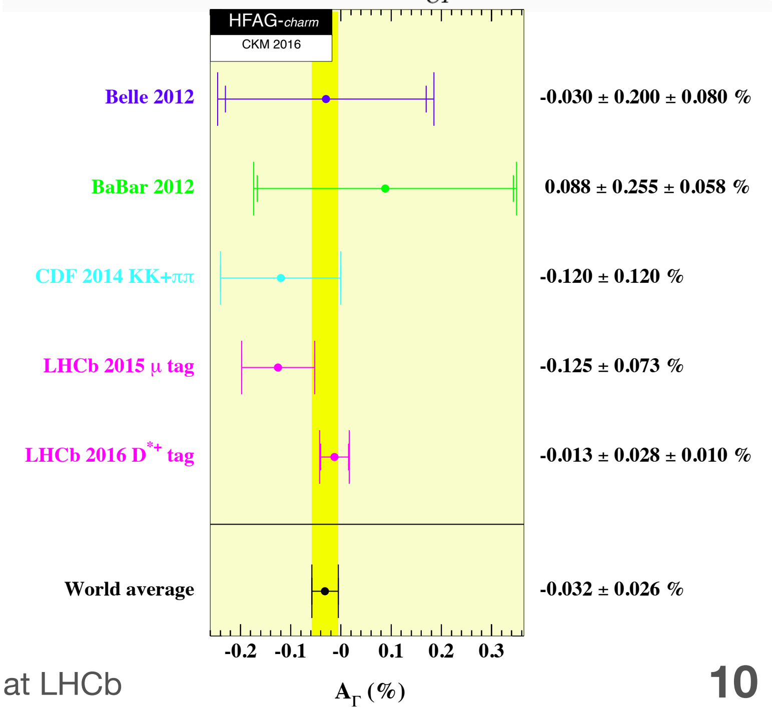
2. **required input to measure CPV in the decay** from time-integrated $A_{CP}(K^+K^-)$ and $A_{CP}(\pi^+\pi^-)$;

$$A_{CP}(h^+h^-) = A_{CP}^{\text{decay}}(h^+h^-) - A_\Gamma \frac{\langle t\rangle_{h^+h^-}}{\tau_{D^0}}$$

≈ 2 at LHCb

- World average **(-3.2 ± 2.6) x 10^{-4}** dominated by LHCb measurement with Run 1 (2011–2012) prompt data arXiv:1702.06490.





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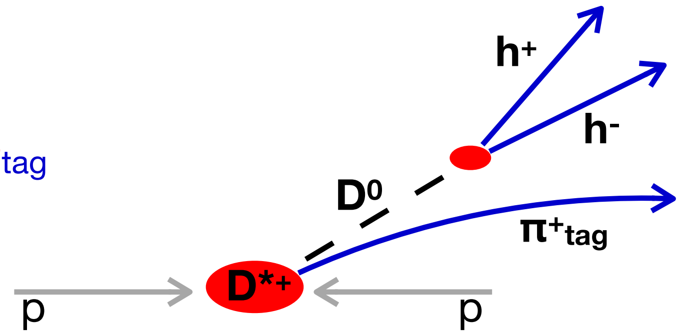
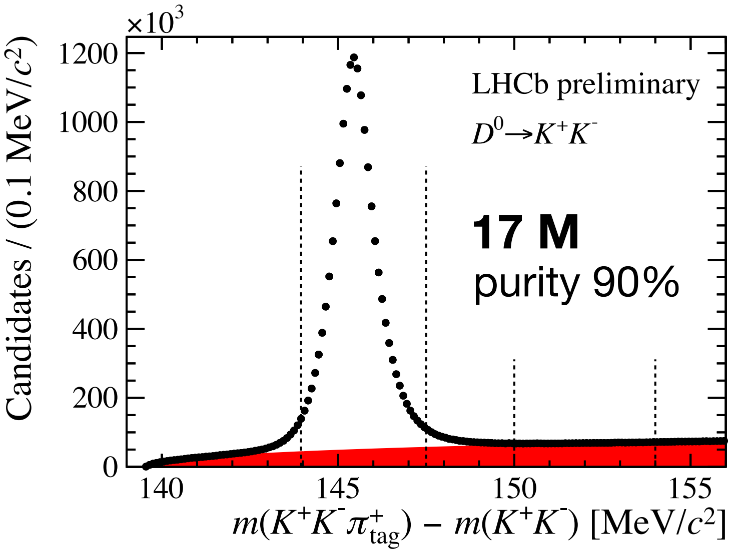
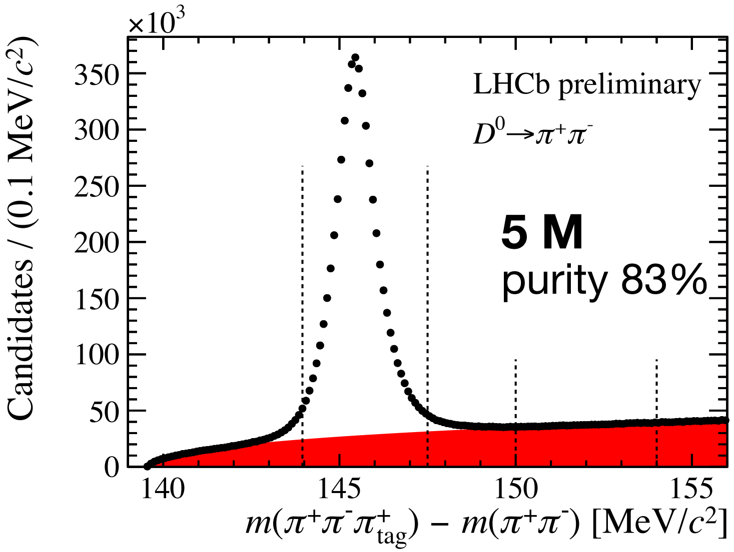
Data sample

- LHCb 2015—2016 data (2 fb^{-1});
- D^0 flavour at production inferred from $D^{*+} \rightarrow D^0 \pi^+_{\text{tag}}$ strong decay;
- asymmetry measured in 21 bins of decay time.







- Precision of the measurement is at the level of 3×10^{-4}. Analysis method validated on Cabibbo-favoured $D^0 \rightarrow K^- \pi^+$ decays (**146 M**);
  - $\boldsymbol{A_\Gamma^{K\pi} = 0}$ within experimental uncertainty.

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Detector-induced asymmetries

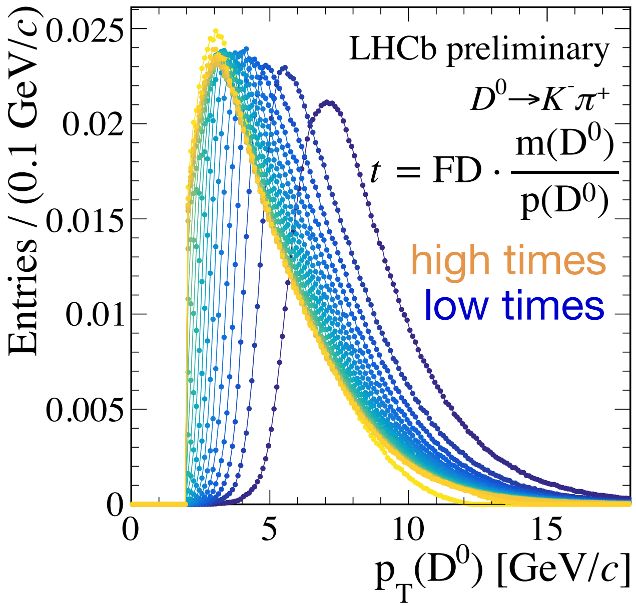
- **Time-dependent asymmetries** arise due to:
    - correlation between the measured decay time and the momentum of the D^0 induced by trigger requirements;
    - momentum-dependent detection asymmetries of the π^+_{tag}.

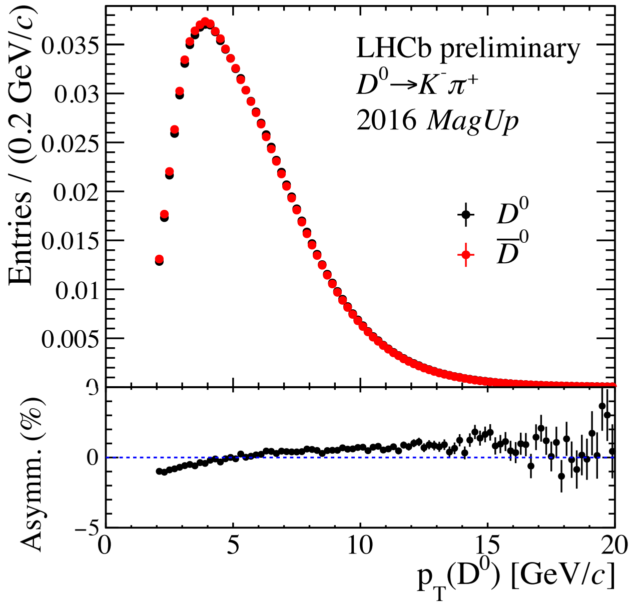
$$D^{*+} \rightarrow [h^+h^-]_{D^0}\,\pi^+_{\rm tag}$$

self-conjugate, no asymmetries

large detection asymmetries

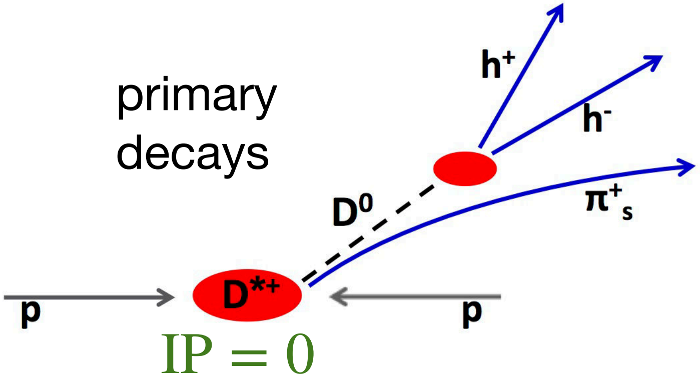
- Effect removed by weighting the events to equalise the 3D momentum distributions of D^0 and anti-D^0 candidates;
    - weighting performed separately for different data-taking years and dipole-magnet polarities (different detector conditions lead to different asymmetries).

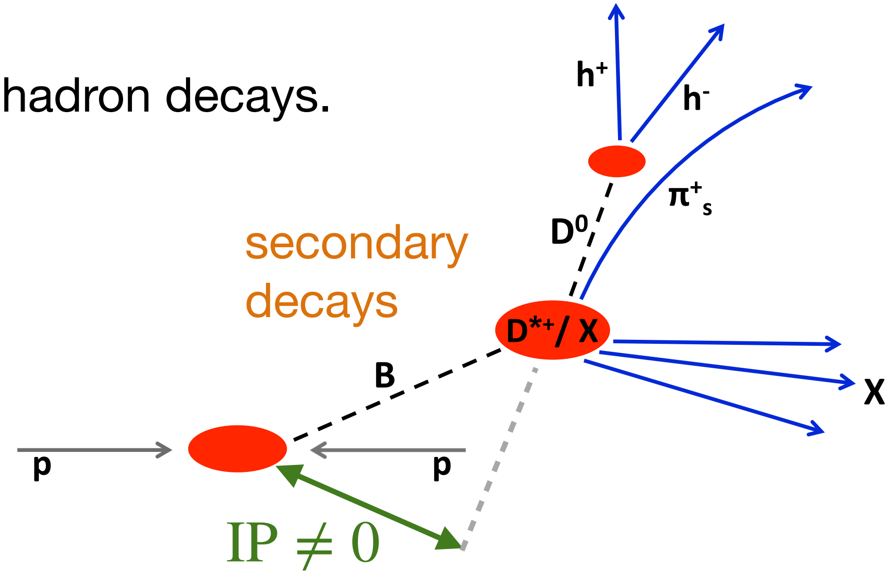




Secondary decays

- Contamination of D^{*+} coming from *b* hadron decays.





- Measured decay time of secondary decays biased to longer decay times:
  - $\tau(B^0) \approx 4\tau(D^0)$;
  - D^0 flight distance is measured from the *pp* vertex.
- Fraction of secondary decays in the sample increases as a function of time.

$$A_{\text{tot}}(t) = A_{\text{prim}}(t) + f_{\text{sec}}(t) \cdot \underbrace{[A_{\text{sec}}(t) - A_{\text{prim}}(t)]}_{\neq 0 \text{ because of different } D^{*+} \text{ and } b \text{ hadron production asymmetries}}$$

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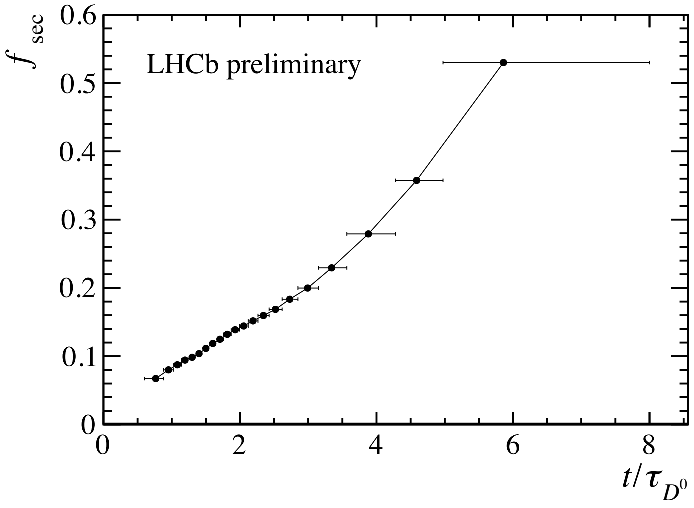
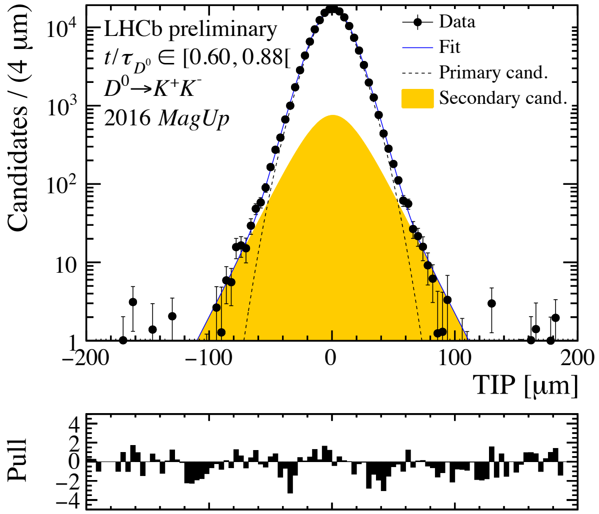
Fit to the TIP distribution

- **TIP** = IP in the plane transverse to the beam.
  - equal to zero for primary decays;
  - increasing as a function of time for secondary decays.

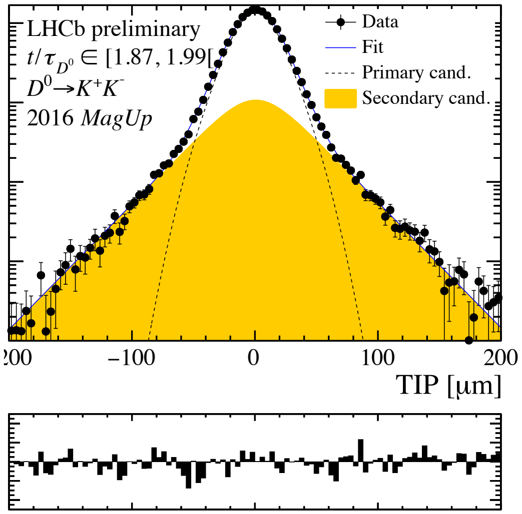
- Fraction of secondary decays and asymmetries from simultaneous fit of D⁰ and anti-D⁰ decays in all time bins.



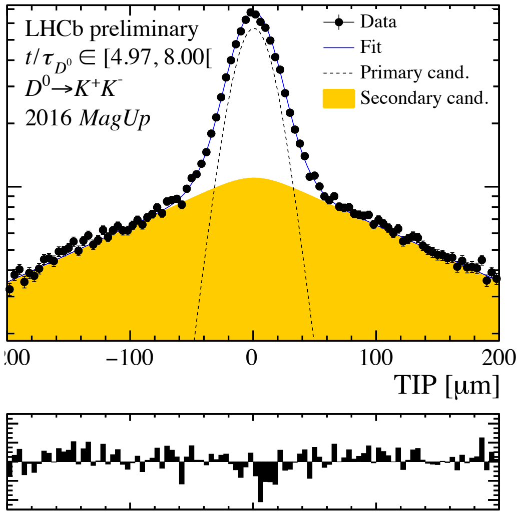
first time bin



central time bin



last time bin



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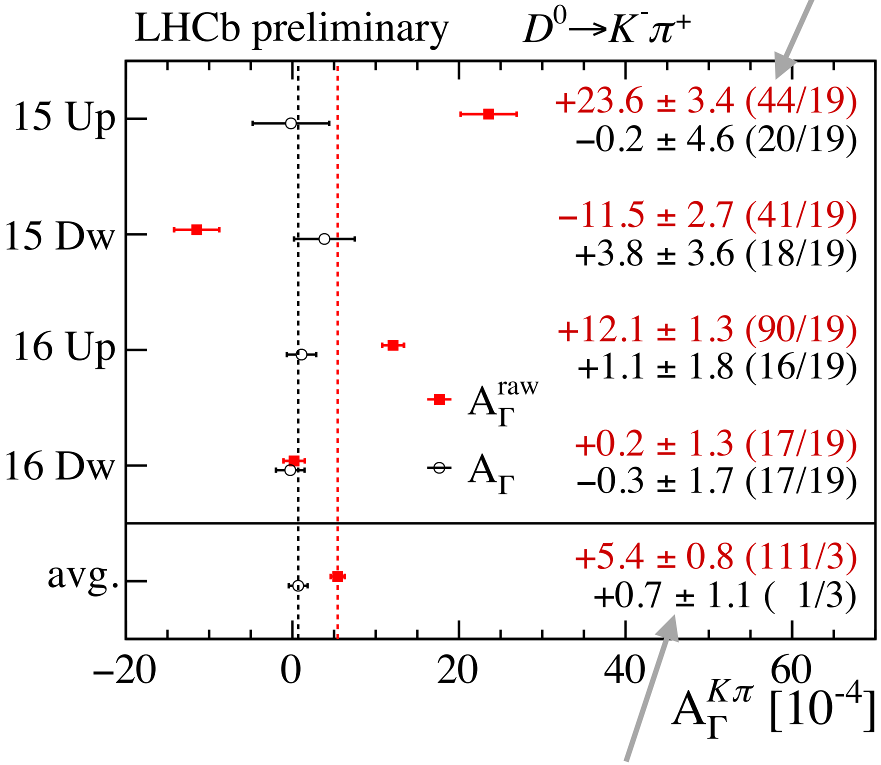
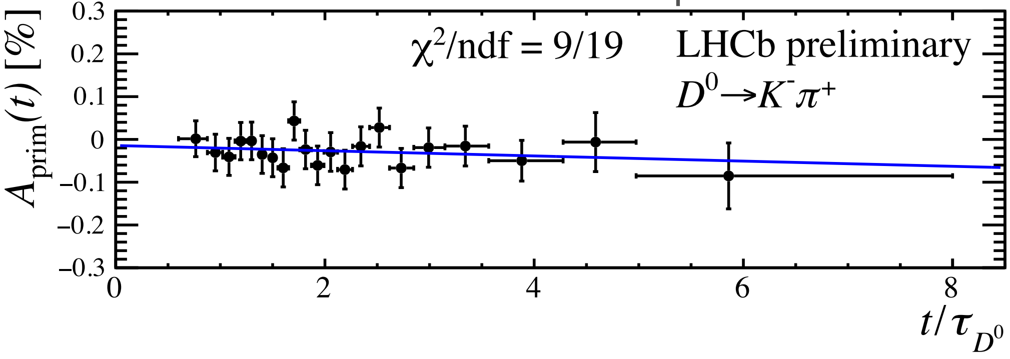
Results for the control sample

- Results divided according to year and magnet polarity.
- Red: raw results before kinematic weighting and subtraction of secondary decays (just |TIP| < 40 μm requirement to reduce their number);
- Black: final results after kinematic weighting and subtraction of secondary decays.

χ² / ndf



Whole data sample



Average compatible with zero within 1.1 x 10^{-4}.

$$A_\Gamma(K^-\pi^+) = (0.7 \pm 1.1) \times 10^{-4}$$

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Systematic uncertainties

knowledge of TIP resolution and PDF of secondary decays

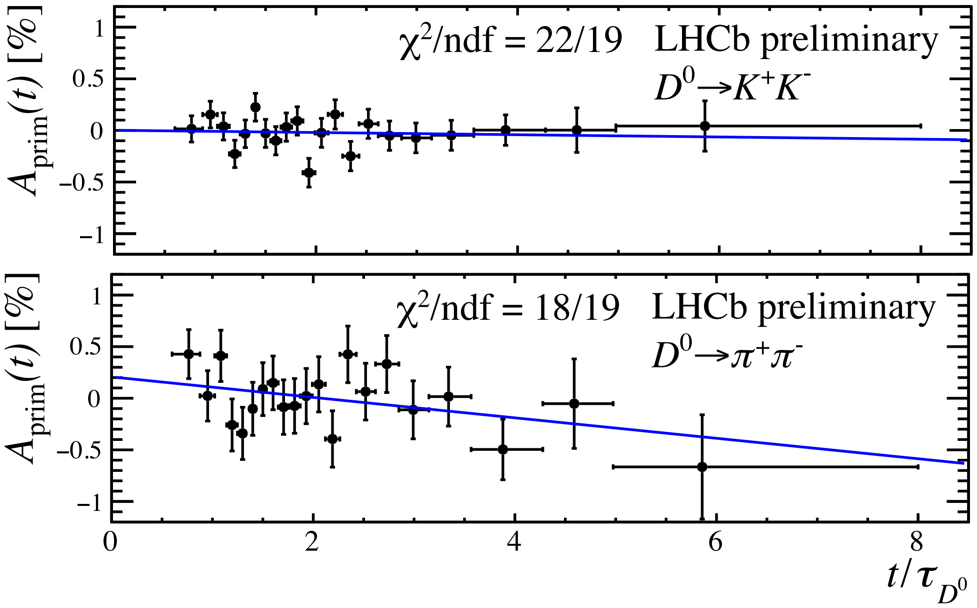
Source	**KK (10^{-4})**	**ππ (10^{-4})**
Subtraction of **secondary decays**	0.4	0.4
Binning of the **kinematic weighing**	0.3	0.3
$m(h^+h^-)$ bkg. from partially-reconstructed and misidentified D-meson multi-body decays	0.3	0.2
Subtraction of **Δm bkg.** from random π^+_{tag}	0.3	0.5
Total sys.	0.7	0.8
Statistical	3.5	6.9

dominated by stat. fluctuations

- Systematic uncertainty:
  - **reduced by 30%** with respect to previous LHCb result arXiv:1702.06490;
  - a factor of 3 under the stat. unc. of the world average.

Results

LHCb-CONF-2019-001, 2015–2016



$$A_\Gamma(K^+K^-) = (\ \ 1.3 \pm 3.5 \pm 0.7) \times 10^{-4}$$

$$A_\Gamma(\pi^+\pi^-) = (11.3 \pm 6.9 \pm 0.8) \times 10^{-4}$$

- Average between the two decay channels and with LHCb Run 1 results (2011—2012) with D*+ tagging arXiv:1702.06490:

$$\boxed{A_\Gamma(KK + \pi\pi) = (0.9 \pm 2.1 \pm 0.7) \times 10^{-4}}$$

- **Consistent with CP symmetry;**
- **dominated by statistical uncertainty.**

Conclusions

- LHCb measurements of CPV in charm still limited by statistical uncertainty:
  - even in $D^0 \rightarrow K^0_S \pi^+\pi^-$ three-body decays (**first 3σ evidence of x>0**);
- **Presented for the first time the measurement of the CPV parameter A_Γ with LHCb 2015—2016 data**:
  - compatible with zero within **2.2 x 10^{-4}** (improves by 22% the world average);
  - still need to improve to compare with SM expectations (≈ 3 x 10^{-5});
  - other 4 fb^{-1} of data collected in 2017—2018.
- LHCb upgrade II will be fundamental if we want to reach the SM predictions for CPV (talk by Silvia Gambetta).

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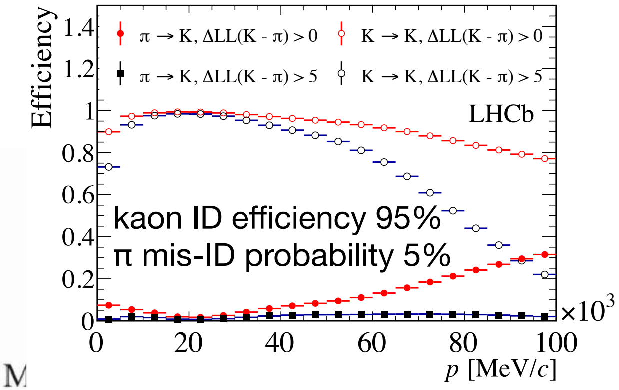
Thanks for you attention.
Any questions?

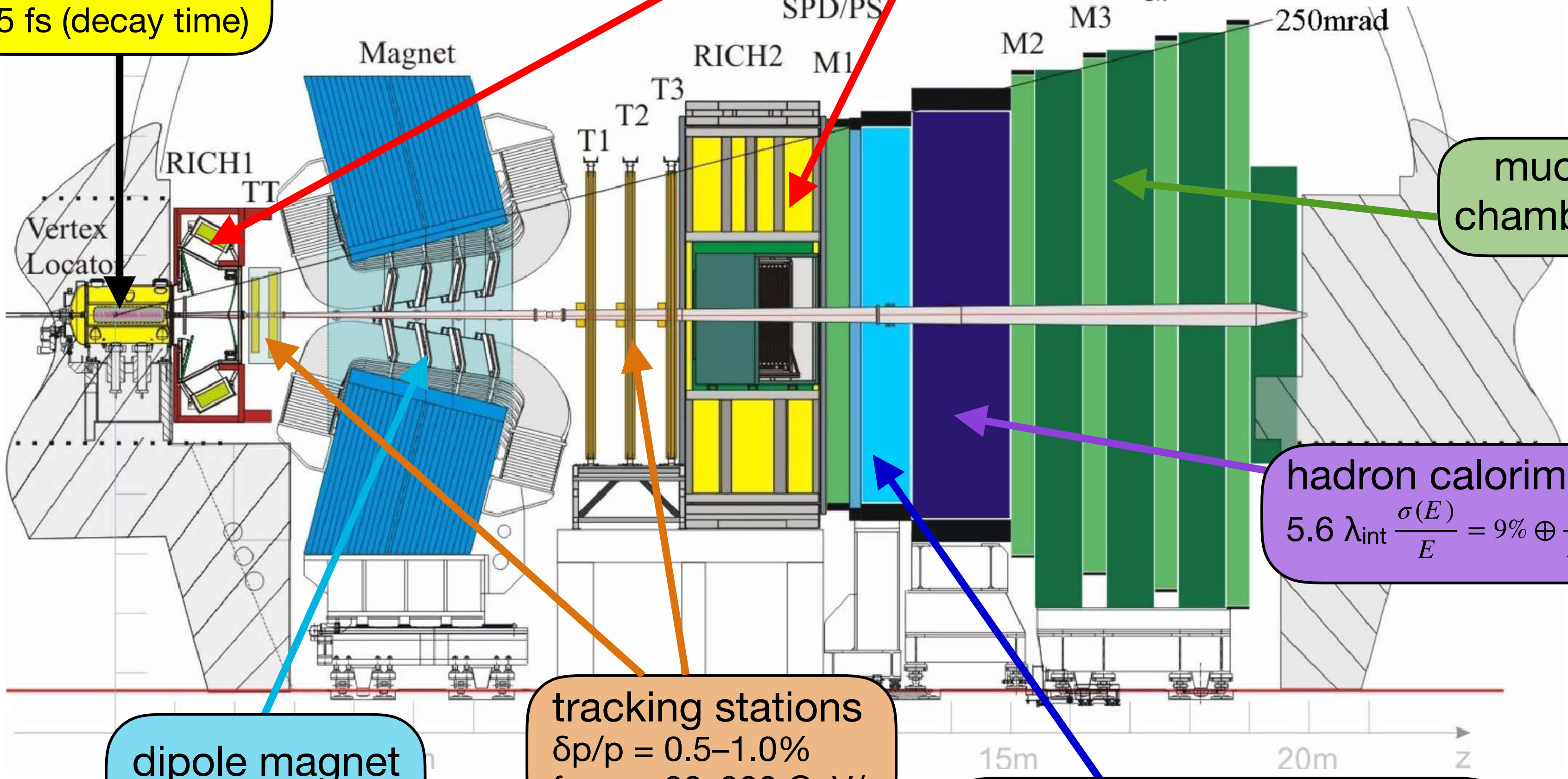
Backup slides

LHCb detector



kaon ID efficiency 95%

π mis-ID probability 5%



Čerenkov detectors

vertex tracker
15 + 29/p_T μm (IP)
45 fs (decay time)

muon chambers

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

dipole magnet
4 T·m (vertical)

tracking stations
δp/p = 0.5–1.0%
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)

Time-dependent CPV in Charm at LHCb upgrade II

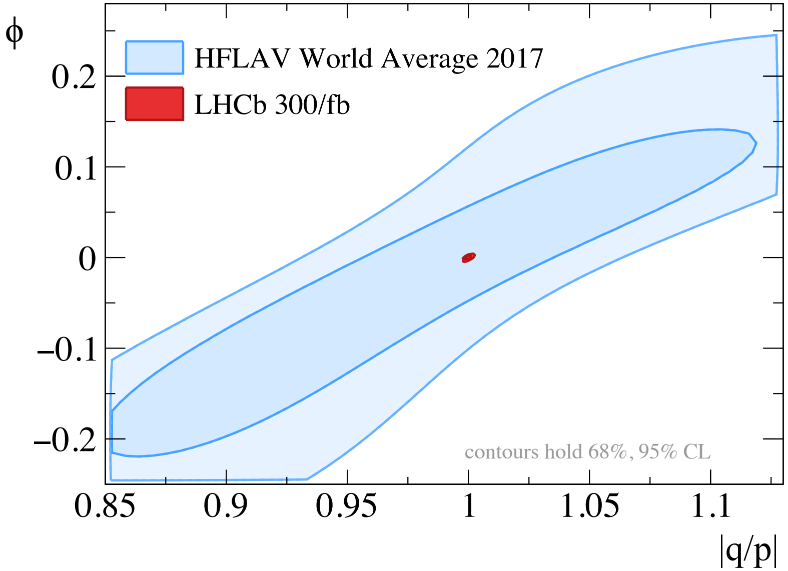
Physics case for an LHCb Upgrade II, arXiv:1808.08865

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 fb^{-1})	Prompt	60M	0.013%	18M	0.024%
Run 1–3 (23 fb^{-1})	Prompt	310M	0.0056%	92M	0.0104 %
Run 1–4 (50 fb^{-1})	Prompt	793M	0.0035%	236M	0.0065 %
Run 1–5 (300 fb^{-1})	Prompt	5.3G	0.0014%	1.6G	0.0025 %

Assumptions:

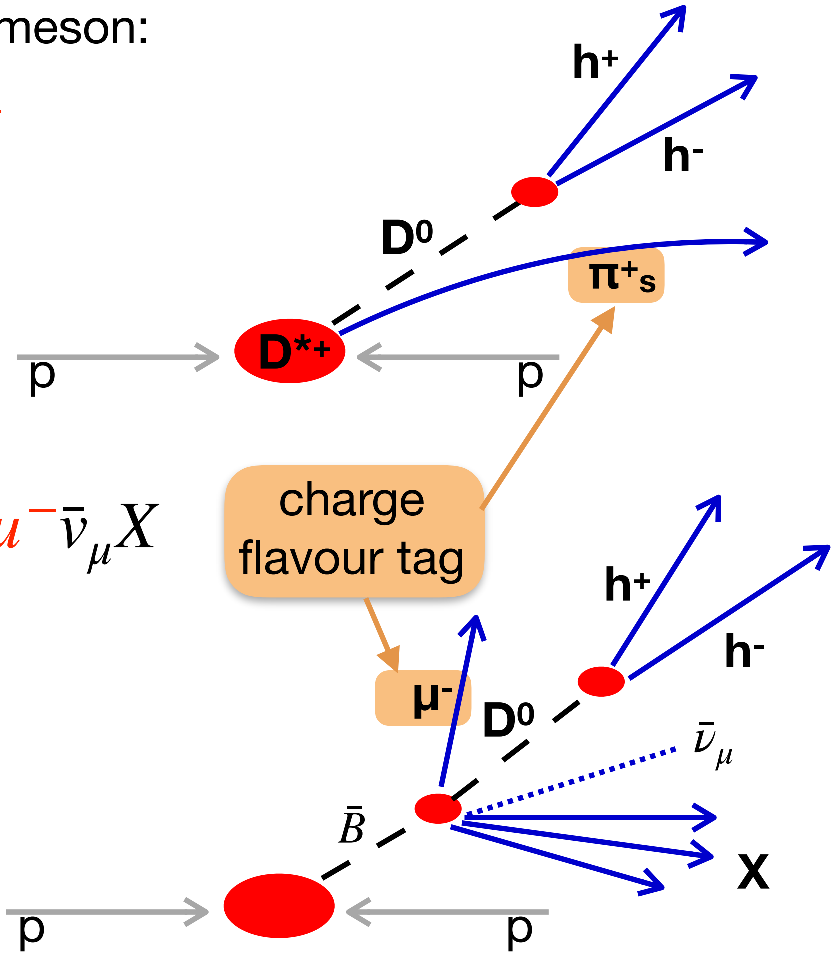
- x2 of hadron trigger efficiency (no hardware trigger + new magnet stations);
- current LHCb performance is maintained in Upgrade II conditions;
- statistical uncertainty only (with 1/√N scaling).



Tagging strategies

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

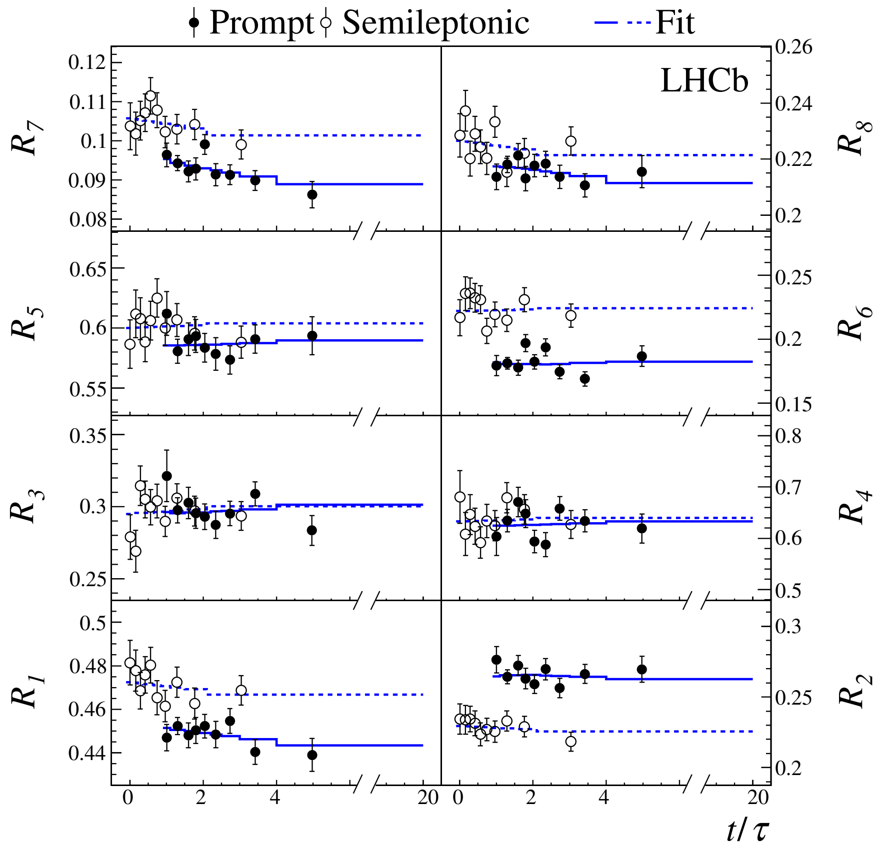
- **Prompt tag**: strong decay $D^{*+} \to D^0\pi_S^+$
  - larger production cross section;
  - tight trigger cut on D^0 flight distance and h^+, h^- impact parameters to improve S/B;
  - low trigger efficiency at low decay times;
  - D^0 points at the primary vertex (PV).
- **Semileptonic tag**: weak 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.



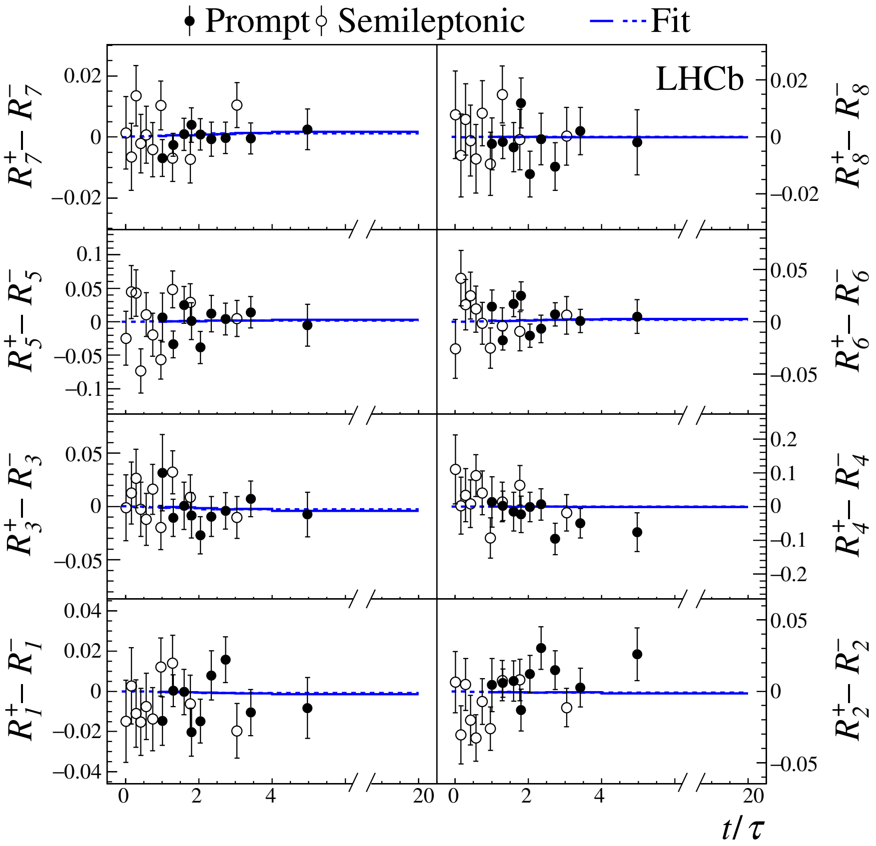
Fit to ratios

arXiv:1903.03074

CP-averaged yield ratios
$R_b \equiv N(-b)/N(+b)$



difference of D⁰—anti-D⁰ yield ratios



Offset between prompt and semileptonic data due to efficiency variations along the Dalitz plot.
Slopes are sensitive to mixing and CPV.

$D^0 \rightarrow K^0_S \pi^+\pi^-$ results

arXiv:1903.03074

Parameter	Value $[10^{-3}]$	Stat. correlations y_{CP}	Stat. correlations Δx	Stat. correlations Δy	Syst. correlations y_{CP}	Syst. correlations Δx	Syst. correlations Δy
x_{CP}	$2.7 \pm 1.6 \pm 0.4$	-0.17	0.04	-0.02	0.15	0.01	-0.02
y_{CP}	$7.4 \pm 3.6 \pm 1.1$		-0.03	0.01		-0.05	-0.03
Δx	$-0.53 \pm 0.70 \pm 0.22$			-0.13			0.14
Δy	$0.6 \pm 1.6 \pm 0.3$						

- Dominant sys. uncertainties from: secondary decays and combinatorial bkg. (x_{CP}), neglecting decay time and $m_{\pm}^2$ resolution (y_{CP}); non-symmetric efficiencies across the symmetry line of the Dalitz plot (Δx, Δy).

$$z \equiv -(y + ix)$$

$$z_{CP} \pm \Delta z \equiv (q/p)^{\pm 1} z$$

arXiv:1811.01032

$$x_{CP} = -\operatorname{Im}(z_{CP}) = \frac{1}{2}\left[x\cos\phi\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) + y\sin\phi\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right)\right]$$

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

$$y_{CP} = -\operatorname{Re}(z_{CP}) = \frac{1}{2}\left[y\cos\phi\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) - x\sin\phi\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right)\right]$$

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

AΓ definition

$$|D_{1,2}\rangle \equiv p|D^0\rangle \pm q|\bar{D}^0\rangle \qquad R_m \equiv \left|\frac{q}{p}\right|$$

$$R_f \equiv \left|\frac{\mathscr{A}(\bar{D}^0 \to f)}{\mathscr{A}(D^0 \to f)}\right| \qquad \phi_f \equiv \arg\left(\frac{q\bar{A}_f}{pA_f}\right) \underset{\uparrow}{\approx} \arg\left(\frac{q}{p}\right)$$

$$A_{CP}^{\text{decay}} \equiv \frac{1-R_f^2}{1+R_f^2}$$

Du 2006, Grossman, Kagan, Nir 2007

$$A_{CP}(t) = \frac{\Gamma(D^0 \to f, t) - \Gamma(\bar{D}^0 \to f, t)}{\Gamma(D^0 \to f, t) + \Gamma(\bar{D}^0 \to f, t)} \overset{\overset{x,\,y\,<\,10^{-2}}{\downarrow}}{\approx} A_{CP}^{\text{decay}}(f) - A_\Gamma(f)\left(\frac{t}{\tau_{D^0}}\right), \quad f = K^+K^-, \pi^+\pi^-$$

$$A_\Gamma(f) = -\frac{2R_f^2}{(1+R_f^2)^2}\left[(R_mR_f + R_m^{-1}R_f^{-1})x\sin\phi_f - (R_mR_f - R_m^{-1}R_f^{-1})y\cos\phi_f\right]$$

Expanding AΓ up to first order in CPV parameters gives:

$$A_\Gamma(f) \approx \underbrace{y\left(\left|\frac{q}{p}\right| - 1\right)}_{\text{CPV in the mixing}} \overbrace{-\,x\phi_f}^{\text{CPV in the interference}} \underbrace{-\,yA_{CP}^{\text{decay}}(f)}_{\approx 1 \times 10^{-5} \,\to\, \text{negligible at the current exp. precision } (3 \times 10^{-4})}$$

arXiv:1903.08726, arXiv:1610.09476

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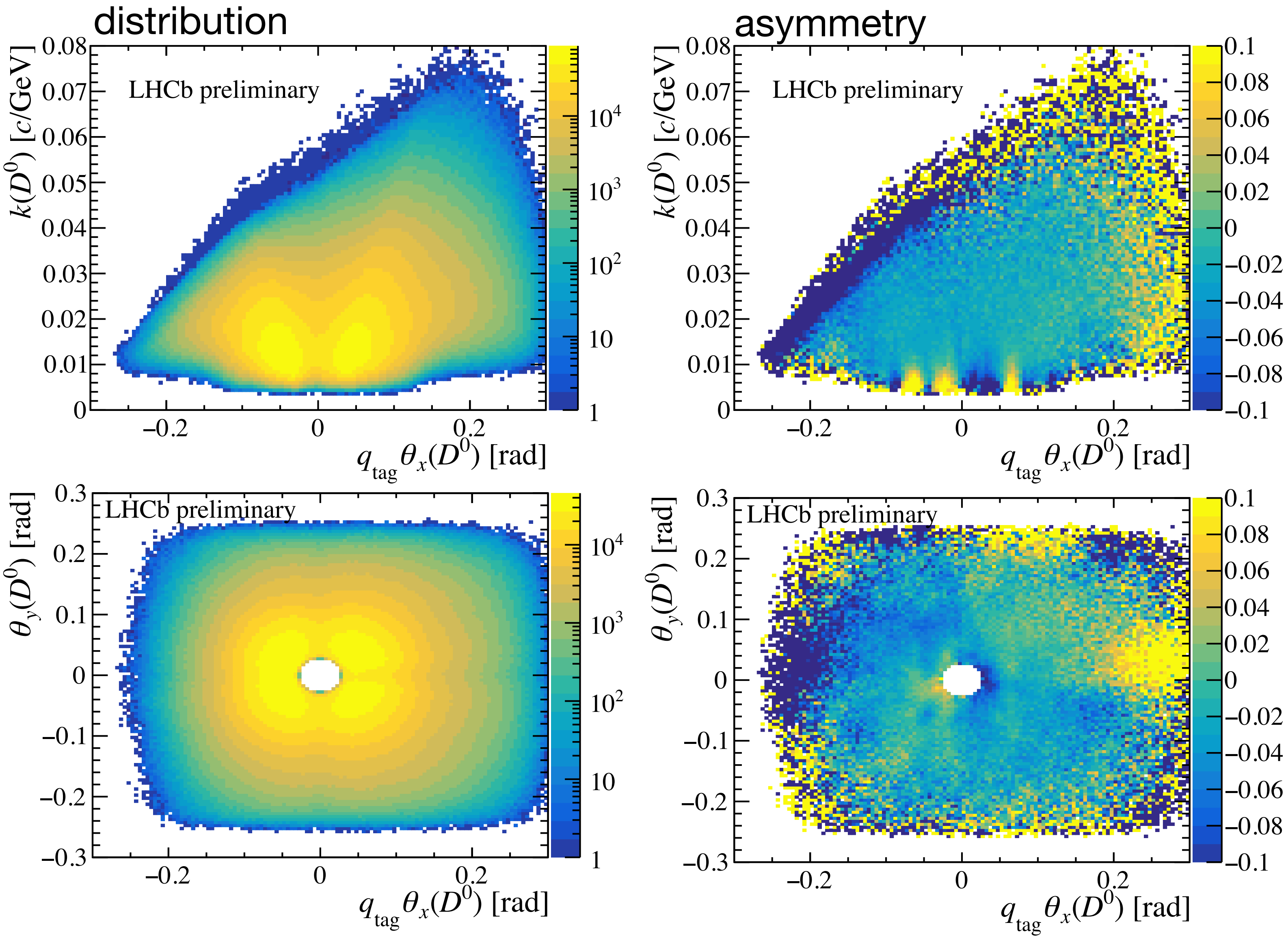
Detector-induced asymmetries

$$\theta_{x(y)} \equiv \arctan\left(\frac{p_{x(y)}}{p_z}\right)$$

$$k \equiv \frac{1}{\sqrt{p_x^2 + p_z^2}}$$



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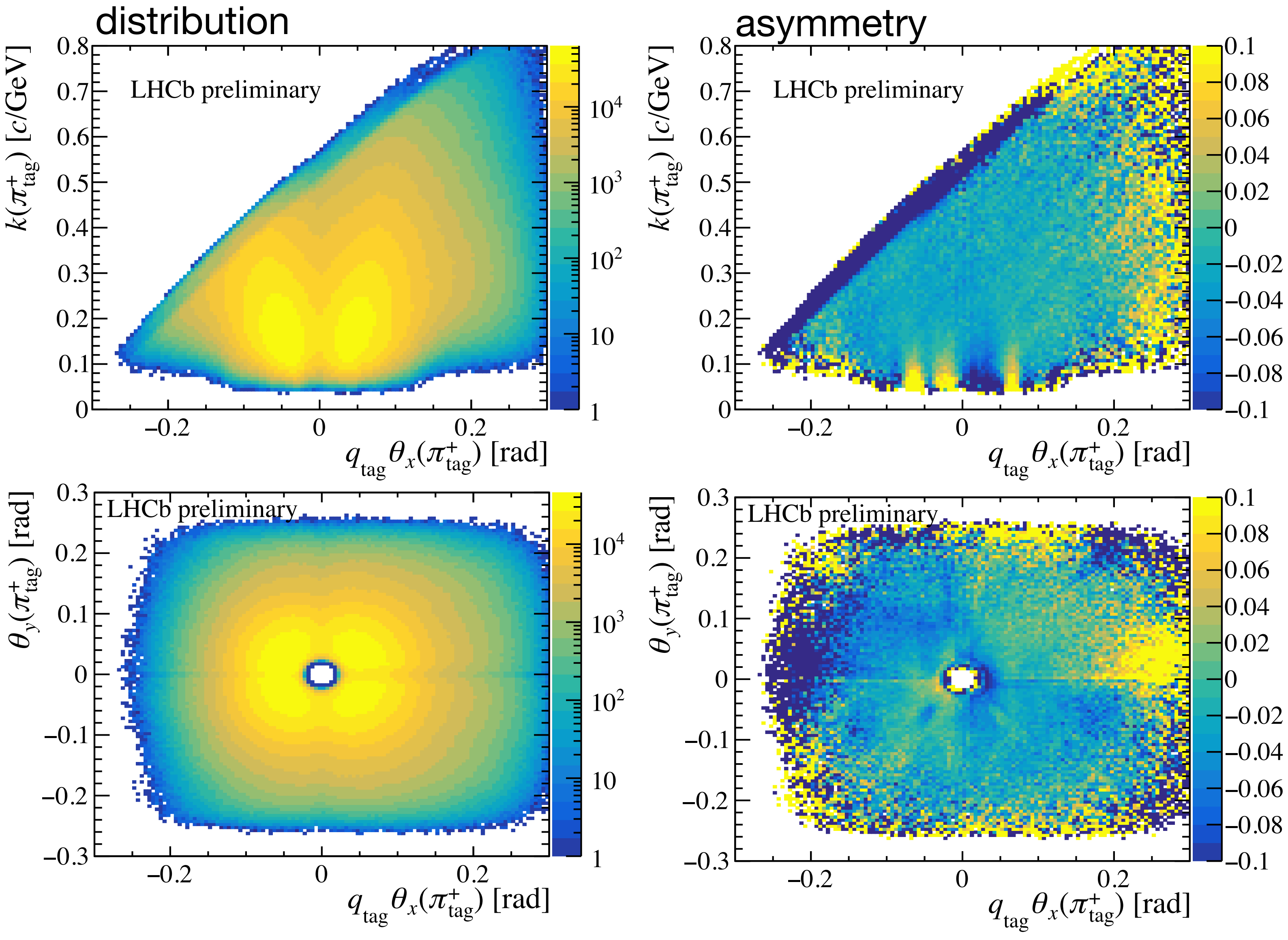

Time-dependent asymmetries

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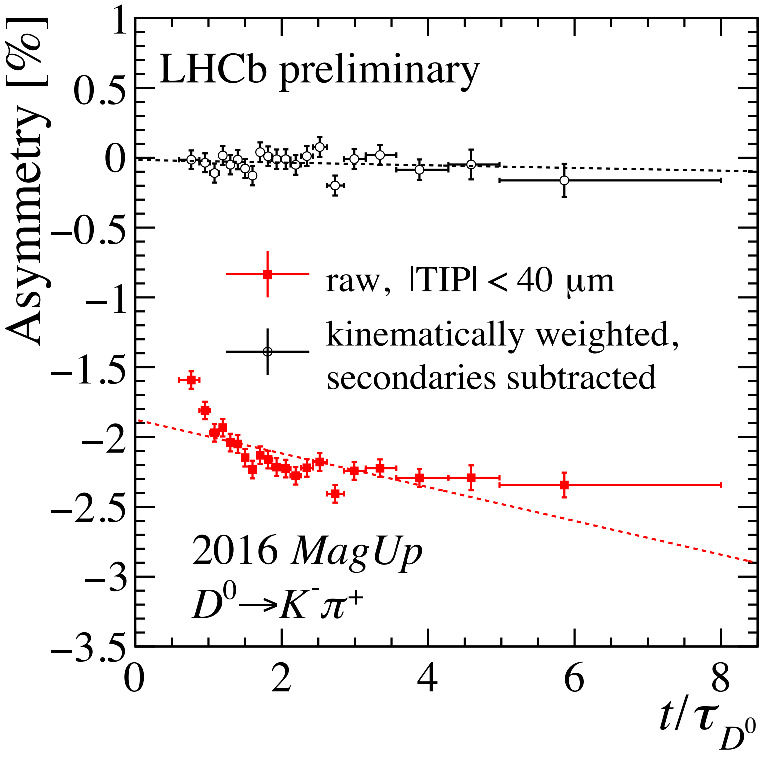

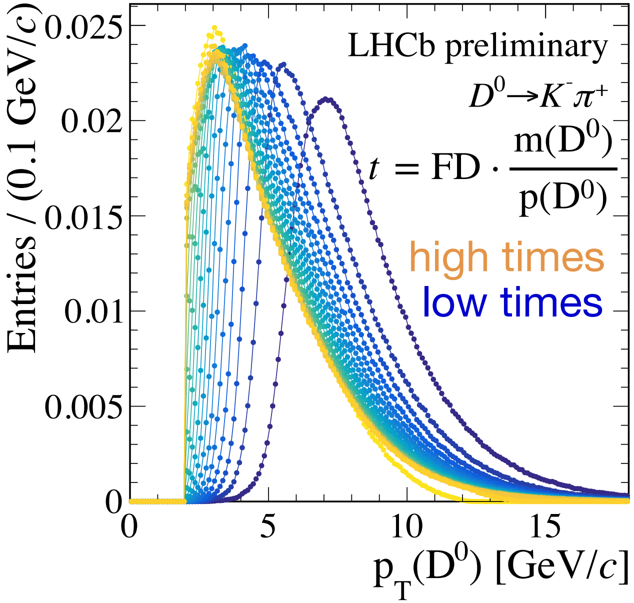

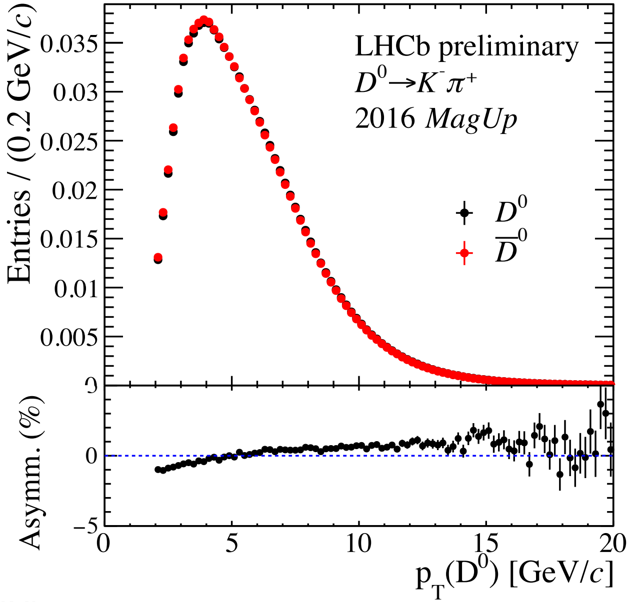

Kinematic weighting: dilution of measured A_Γ

- The correction comes at a price:
  - owing to the correlations between the measured t(D^0) and **p**(D^0), a physical time-dependent asymmetry would reflect in a momentum-dependent asymmetry;
  - it would be partially cancelled by the kinematic weighting.

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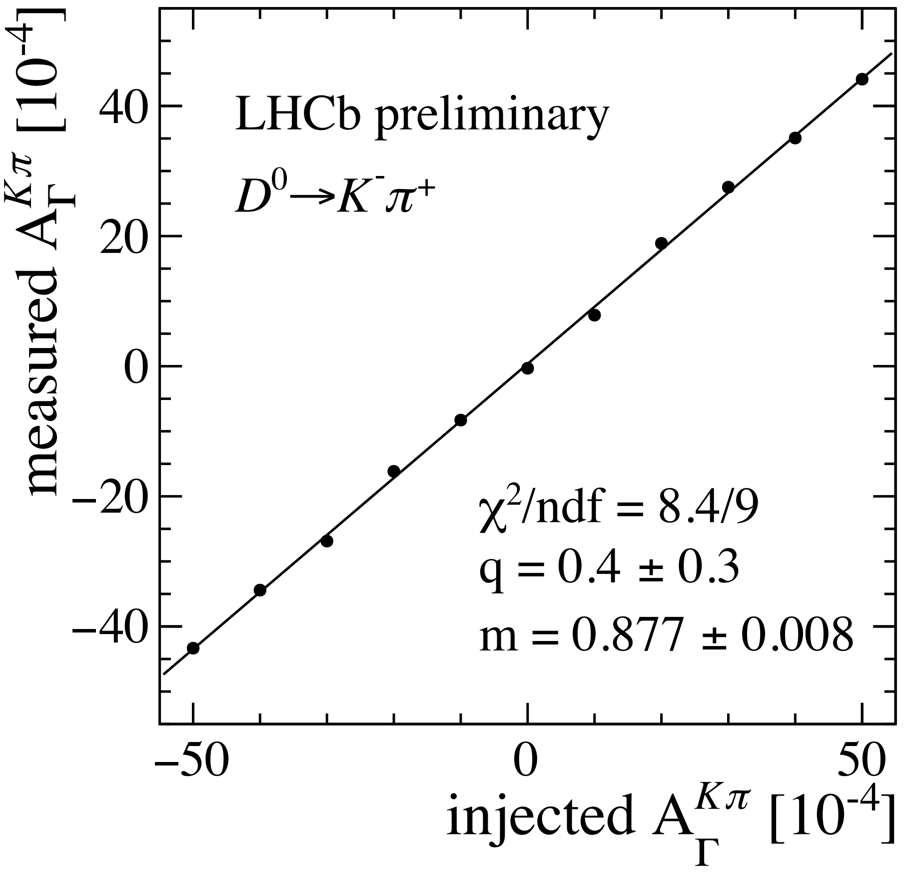
Size of dilution evaluated as follows:

1. assign randomly the flavour of the D^0 for each event (→ no initial asymmetries);
2. inject an artificial A_Γ by selecting the events with a time-dependent efficiency (opposite slope for D^0 and anti-D^0);
3. apply the kinematic weighing and measure A_Γ.

Dilution: **(87.7 ± 0.8)%**



Kπ sample

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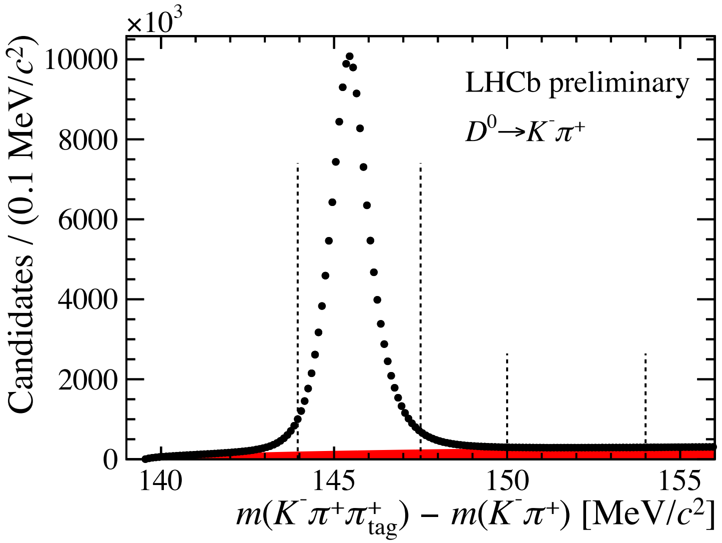

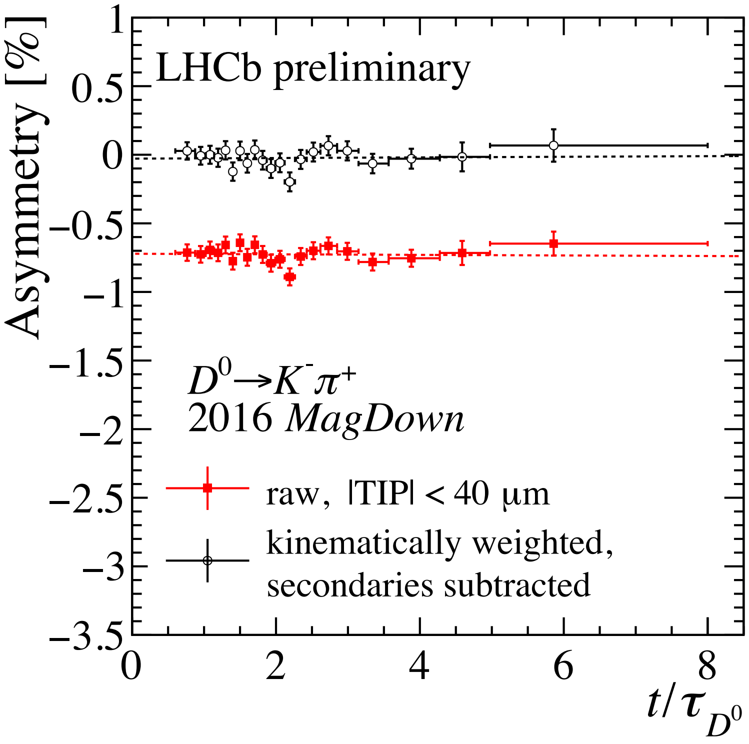

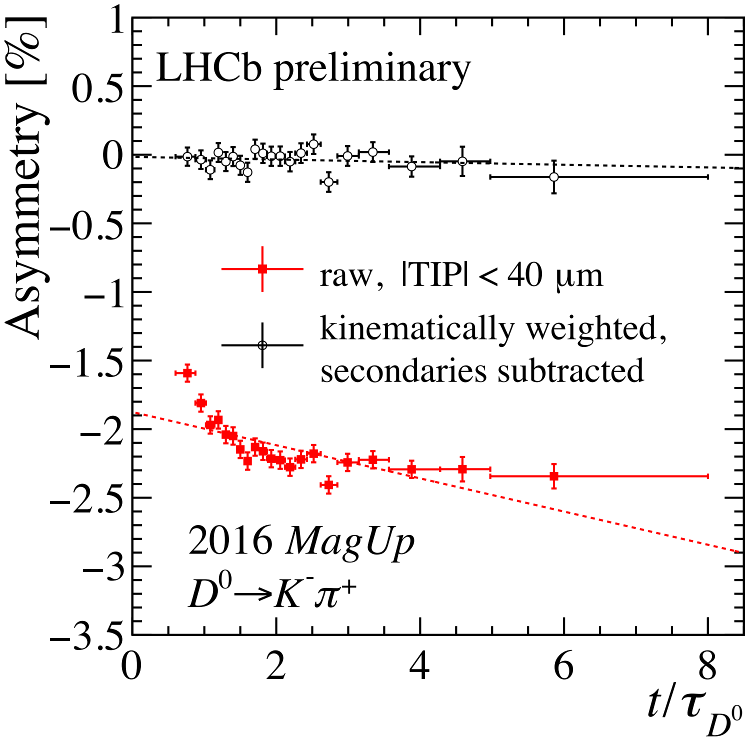

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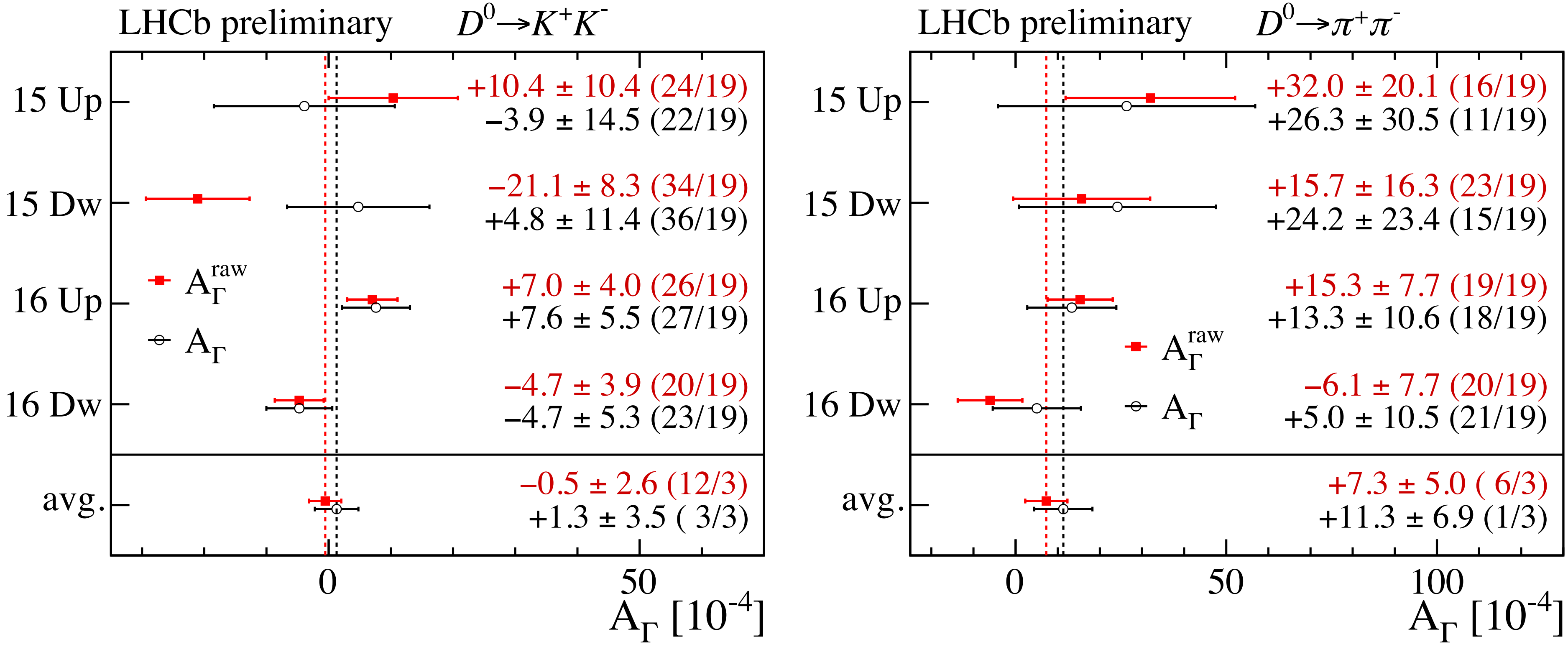
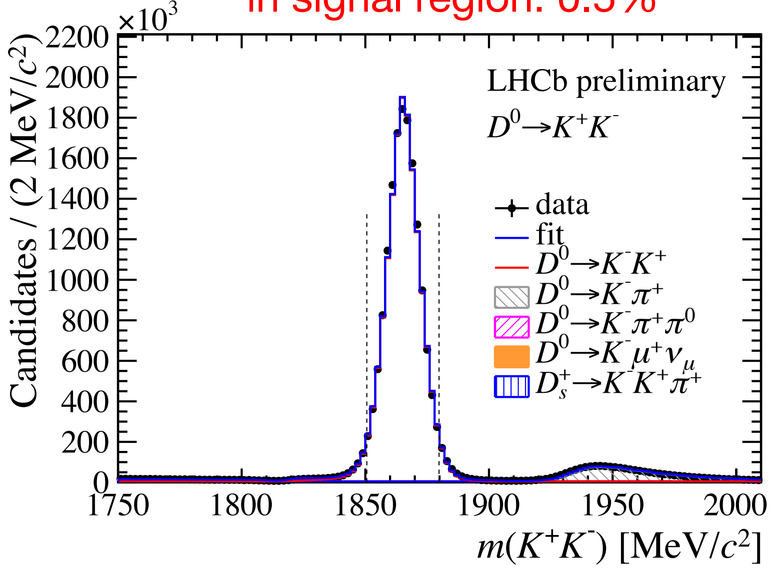
Results by year/magnet polarity



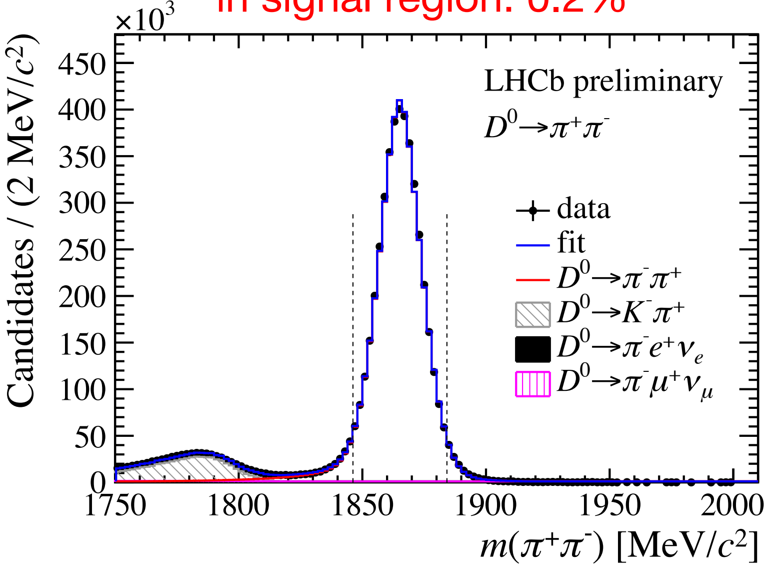
Backgrounds under m(D^0) peak

- Small contamination under the D^0 mass peak from multi-body partially and misreconstructed D-meson decays.
    - estimated from template fits to m(h^+h^-) distributions;
    - systematic uncertainties equal to 0.3 x 10^{-4} (0.2 x 10^{-4}) for the K^+K^- ($\pi^+\pi^-$) sample.

bkg. contamination in signal region: 0.5%



bkg. contamination in signal region: 0.2%



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Backgrounds under m(D^0) peak

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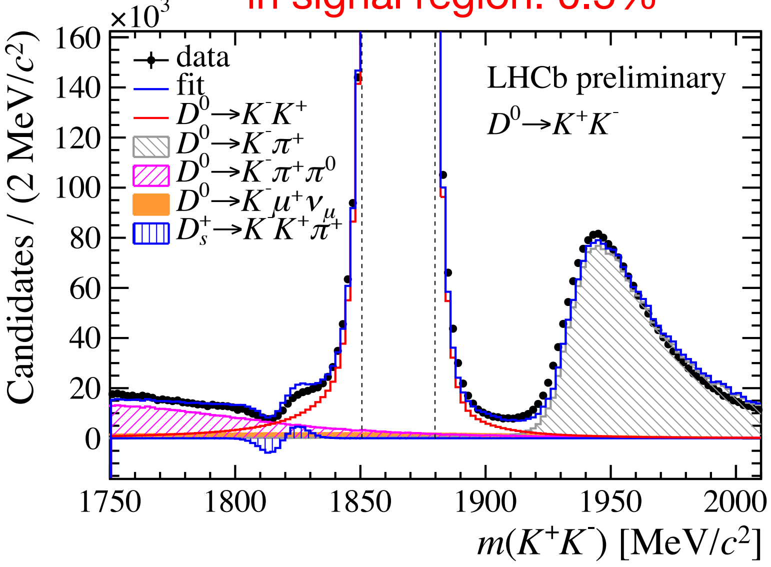
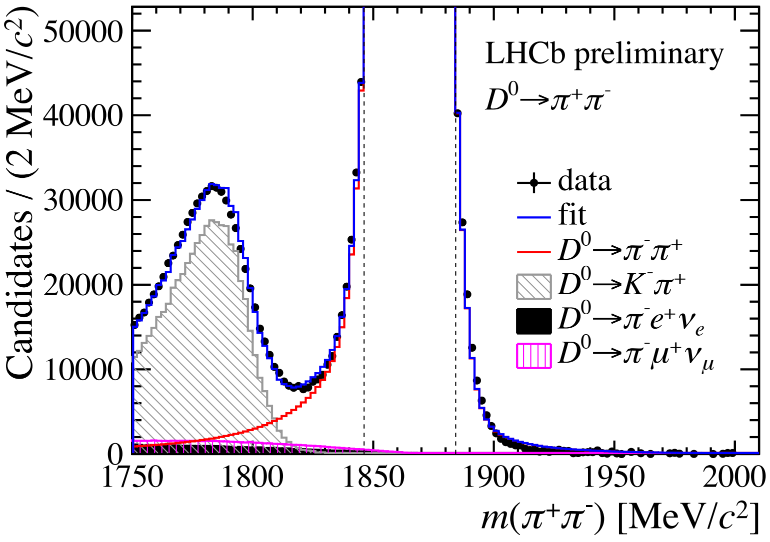
bkg. contamination
in signal region: 0.5%

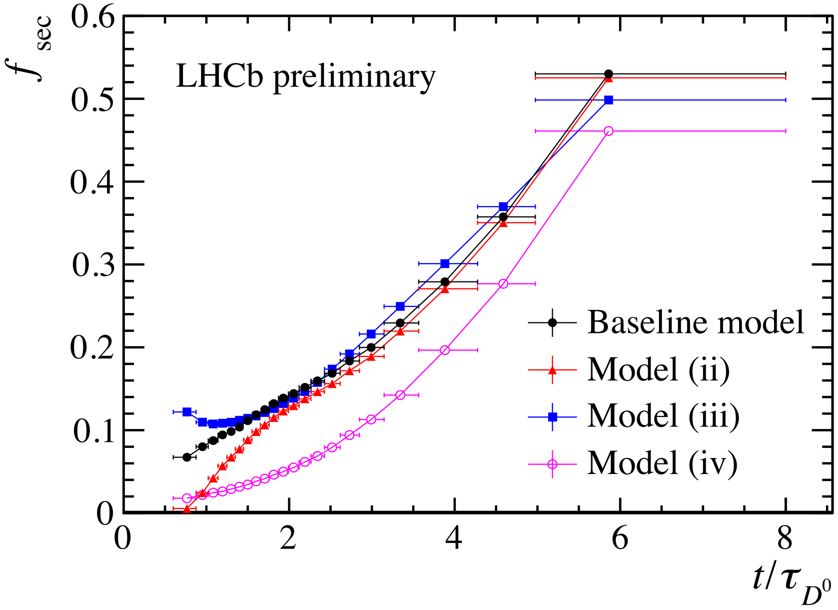


bkg. contamination
in signal region: 0.2%



Secondary decays: systematics

- At low decay times it is difficult to distinguish secondary decays from the resolution tails of primary decays in the fit to the TIP distributions;
  - fix the TIP resolution to the results of simulation, in each bin of decay time (model (ii));
- uncertainty on the choice of the PDF of secondary decays (*exponential*);
  - fix the fraction of secondary decays to that obtained in simulation (model (iii));
  - take the PDF of secondary decays from a sample that combines D^{*-} candidates with μ^+, used as a proxy for secondary $B^0 \longrightarrow D^{*-} \mu^+ X$ decays (model (iv)).



Sys. unc. 0.4×10^{-4}
(sum in quadrature of the two uncertainties)