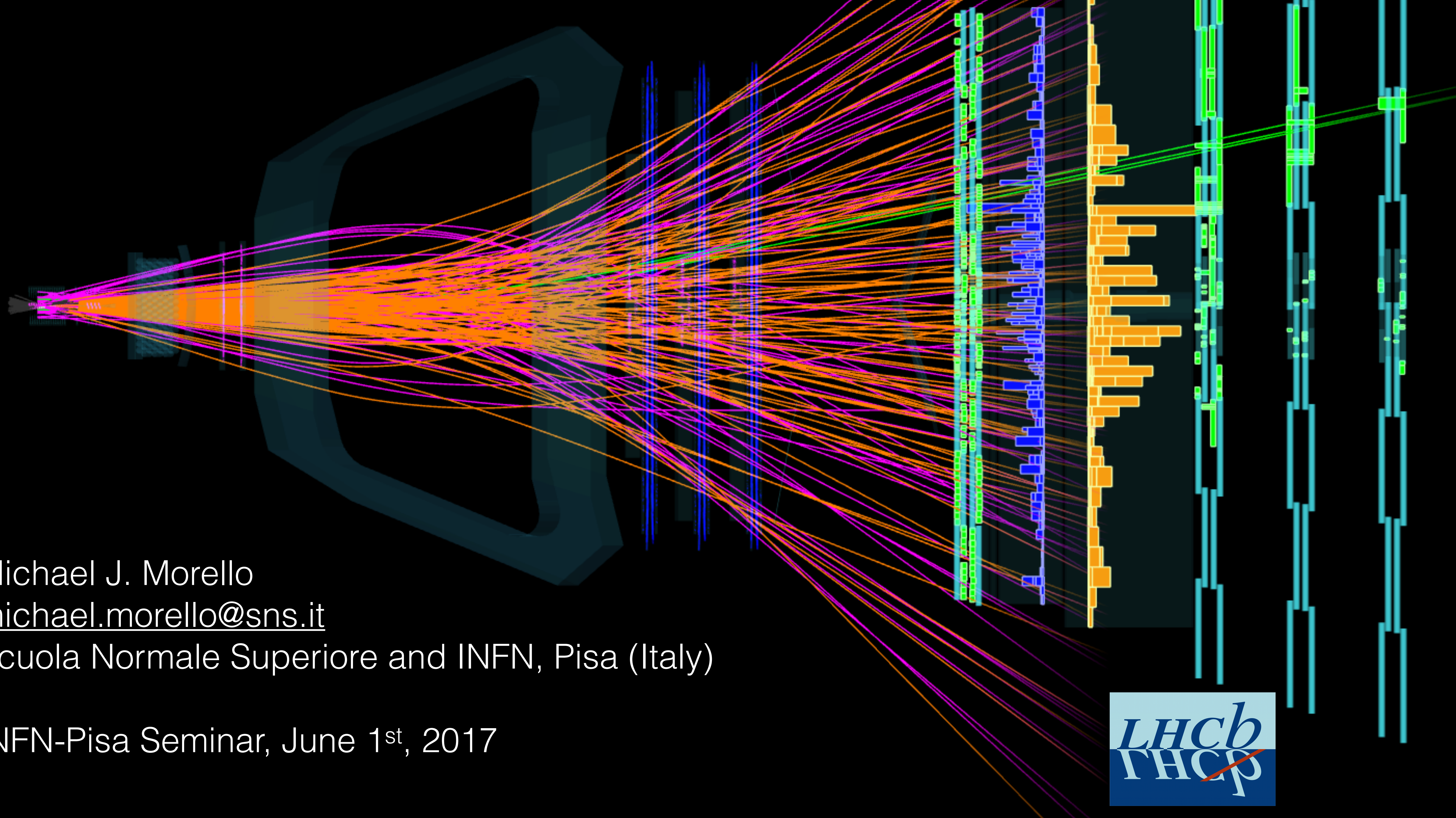
Precision measurement of indirect CP violation in charm hadrons



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INFN-Pisa Seminar, June 1st, 2017

CP Violation

- The non-invariance of the weak interactions with respect to the combined charge-conjugation (C) and parity (P) dates back to year 1964
  - discovered through the observation of $K_L \to \pi^+\pi^-$ decays, which exhibit a branching ratio at 10^{-3} level (the famous ε_K parameter),
  - it was the first manifestation of (indirect) CP violation.
- Ever since the understanding of CPV has become a crucial goal in HEP:
  - to study and test reliability and robustness of the SM,
  - to probe physics beyond the SM,
  - to shed light on cosmology issues. CPV present in the SM not sufficient to explain the observed baryonic asymmetry $O(10^{-10})$.

The CKM mechanism

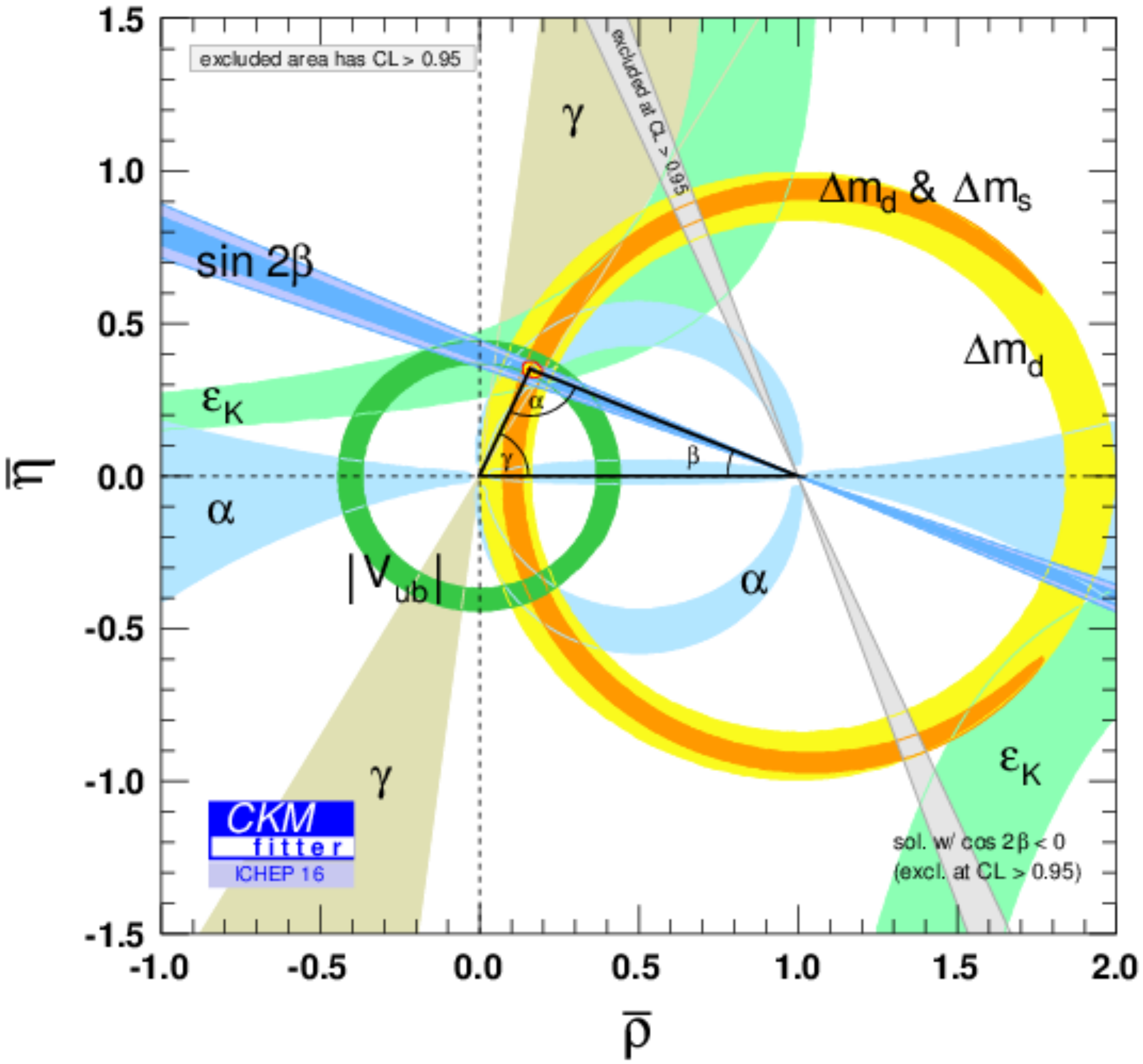
- CP-violating effects originate in the SM from the charged-current interactions of quarks

$$\frac{-g}{\sqrt{2}}(\overline{u_L},\, \overline{c_L},\, \overline{t_L})\gamma^\mu W_\mu^+ V_{\rm CKM} \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} + \text{h.c.}$$

- V_{CKM} matrix connects the electroweak states (d',s',b') of the down, strange and bottom quarks with their mass eigenstates (d,s,b) through an unitary transformation.

- This feature ensures the absence of flavour-changing neutral-current (FCNC) processes at the tree level in the SM, and is hence at the basis of the famous Glashow–Iliopoulos–Maiani (GIM) mechanism.

CPV accommodated in the SM through a single complex phase in the CKM matrix.



- All direct measurements of elementary particle phenomena to date support the CKM phase, within the current theoretical and experimental uncertainties, being the dominant source of CP violation observed in quark transitions.

- However, widely accepted theoretical arguments and cosmological observations suggest that the SM might be a lower-energy approximation of more fundamental theories which are likely to possess a different CP structure and therefore should manifest themselves as deviations from the CKM scheme.

- Essential to measure CP-violating asymmetries in Nature.

The role of charm physics

- Charm transitions are a unique portal (complementarity wrt B and K mesons) for obtaining a novel access to flavor dynamics with the experimental situation being a priori favorable (“low SM background”).

- Charm is the only up-type quark allowing full range of probes for mixing and CPV:

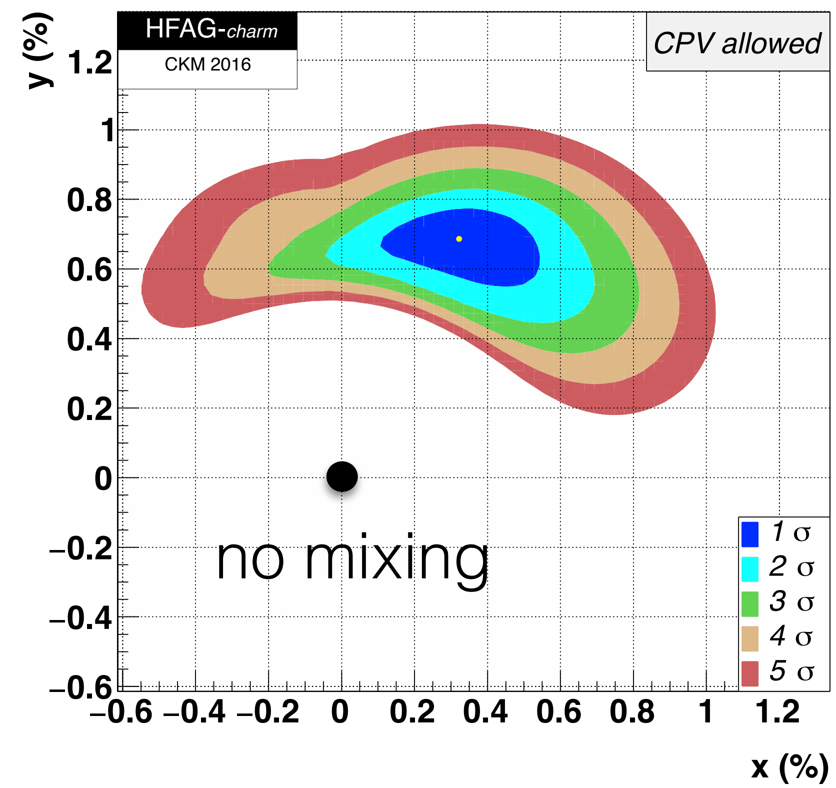
  - top quark decays too fast (no hadronization),

  - π^0-π^0 oscillations not possible (particle and anti-particle are identical).

- CPV not yet observed in charm and predicted to be “small” within SM.

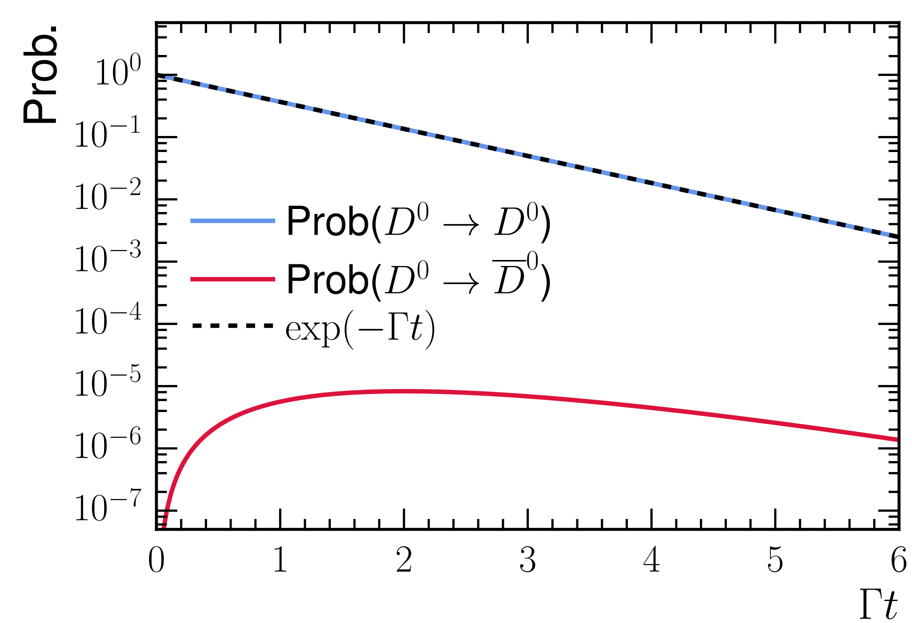
Charm Mixing

$$|D_{1,2}\rangle = q\,|D^0\rangle \pm q\,|\overline{D}^0\rangle \qquad x \equiv 2(m_2 - m_1)/(\Gamma_1 + \Gamma_2)$$
$$(|q|^2 + |p|^2 = 1, \phi = \arg(q/p)) \qquad y \equiv (\Gamma_2 - \Gamma_1)/(\Gamma_1 + \Gamma_2)$$



D^0 mixing experimentally well established, only recently.
First hints from Babar/Belle in 2007.
Very slow rate $x \lesssim 10^{-2}$ and $y \simeq 10^{-2}$.

$$\mathrm{Prob}(D^0 \to \overline{D}^0; t) = |\langle D^0(t)|\overline{D}^0\rangle|^2 = \left|\frac{q}{p}\right|^2 \cdot |g_-(t)|^2$$
$$\mathrm{Prob}(\overline{D}^0 \to D^0; t) = |\langle \overline{D}^0(t)|D^0\rangle|^2 = \left|\frac{p}{q}\right|^2 \cdot |g_-(t)|^2$$
$$|g_\pm(t)|^2 = \frac{1}{2}e^{-\Gamma t}\left[\cosh\frac{\Delta\Gamma t}{2} \pm \cos\Delta M t\right].$$



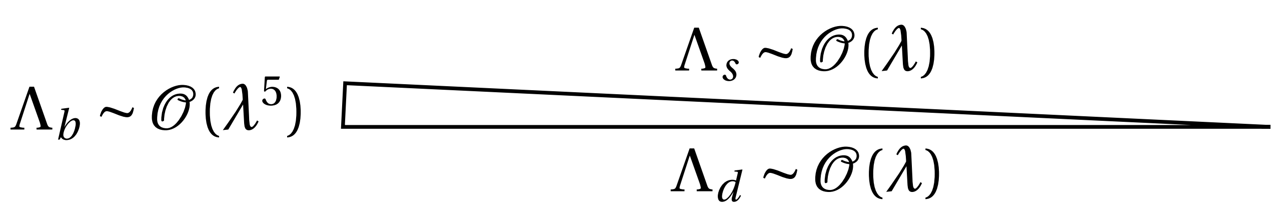
Prob(D^0 → anti-D^0) ≠ Prob(anti-D^0→D^0) if |q/p| ≠ 1.

CPV in the charm sector

Only transitions of *c* quark to lighter quarks involved in charm meson decays, mixing and relevant amplitudes are therefore described, to an excellent approximation, by the physics of the first two generations only.

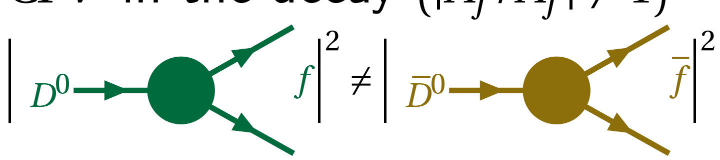
"charm unitary triangle" $\Lambda_q = V_{cq}^* V_{uq} \; (q \in d, s, b)$

$$\Lambda_d = -\lambda + \frac{\lambda^3}{2} + \frac{\lambda^5}{8}(1+4A^2) - \lambda^5 A^2(\rho + i\eta) + \mathcal{O}(\lambda^7),$$
$$\Lambda_s = \lambda - \frac{\lambda^3}{2} - \frac{\lambda^5}{8}(1+4A^2) + \mathcal{O}(\lambda^7),$$
$$\Lambda_b = \lambda^5 A^2(\rho - i\eta) + \mathcal{O}(\lambda^{11}),$$



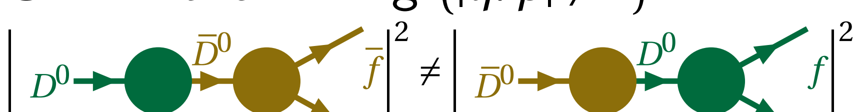
SM expectations are of the order of $(V_{ub}V^*_{cb}/V_{us}V^*_{cs}) \sim 10^{-3}$ (or less). CPV not yet observed in the charm sector.

CPV in the decay $(|\bar{A}_f/A_f| \neq 1)$

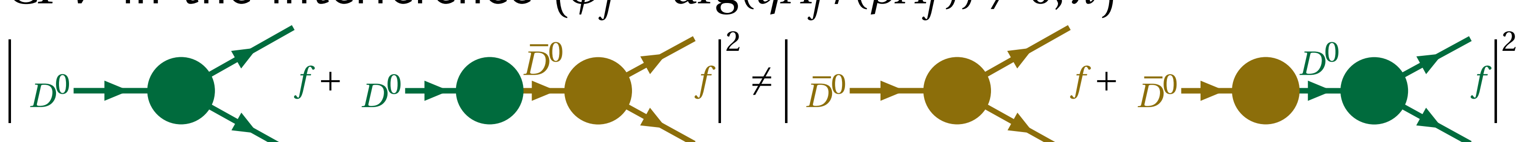


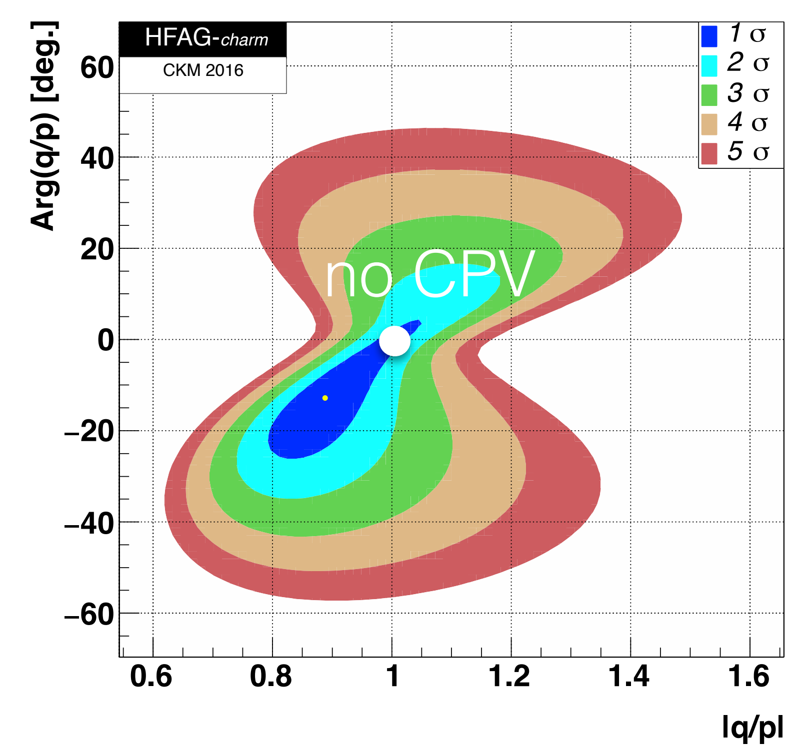
$$A_f = \langle f | \mathcal{H} | D^0 \rangle$$
$$\bar{A}_f = \langle f | \mathcal{H} | \bar{D}^0 \rangle$$

CPV in the mixing $(|q/p| \neq 1)$



CPV in the interference $(\phi_f = \arg(q\bar{A}_f/(pA_f)) \neq 0, \pi)$





Experiments and theory

- Predictions affected by “large uncertainties” due to the difficulties in the computation of the long-distance contributions.
    - non perturbative calculation (approximations holding in the B and K cases do not apply for charm)
    - the available computational power is not yet enough for lattice QCD.
- Only very recently experiments able to collect large samples of charm decays. High precision measurements already have been impacting theory and vice-versa.
    - The widely accepted statement *“measuring CPV with the current experimental sensitivity is a clear sign of NP”* has been disavowed and, as a consequence, accuracy on calculations tremendously increased to account for experimental inputs.
- Predictive power of the theory is (and will be) strictly related to the precision and the variety of the inputs that experiments will be able to provide in the near and far future.
- An extensive and precise study of the charm decays, and in general of the heavy flavour physics, at much higher precision than today is fundamental to over-constrain the theory parameters, and in particular the CKM scheme, that is a crucial ingredient for the SM and for any new exotic theory, which must include the flavour structure.

The intensity frontier

- Unprecedented huge and pure samples of charm decays are therefore needed for probing CPV and mixing.

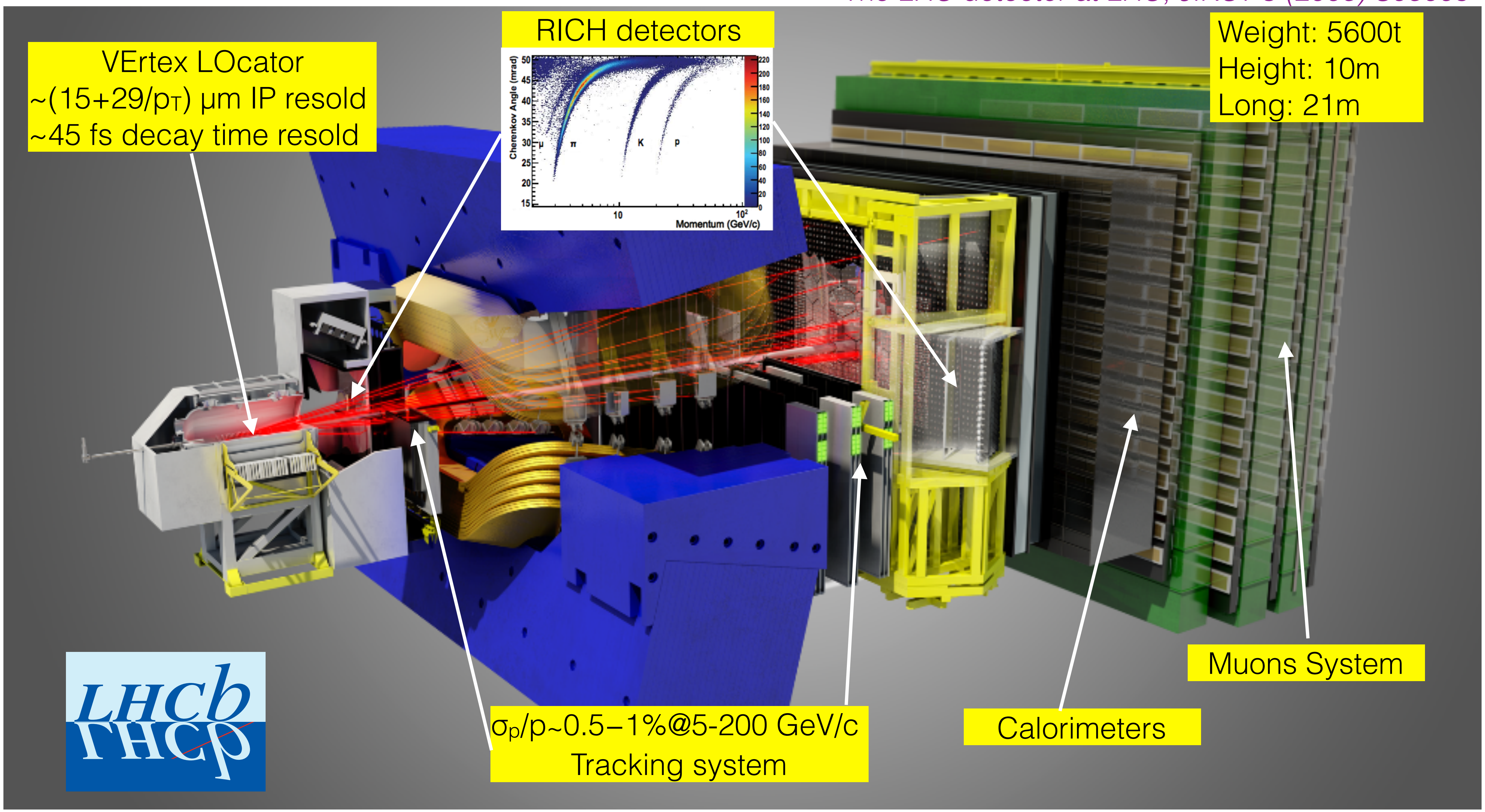
- Slow mixing rate ask for large samples enriched at higher lifetime values.

- Measuring CP-violating asymmetries below the level of 10^{-3} (10^{-4}) requires samples with $>10^6$ (10^8) charm decays.

  - note, in absence of background: $\sigma(A_{CP}) \approx 1/\mathrm{sqrt}(N)$

The ‘charming’ beauty experiment

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



Excellent trigger capabilities (Level-0 of custom electronics + HLT of commercial CPUs) to handle 11MHz of visible physics collisions. Events written on tape extremely fast at 5KHz, where typical event size is 60KBytes in Run 1 (2011-2012). In Run 2 (2015-2016) performances are even better. [LHCb-PROC-2015-011].

Charm Physics with LHCb

- All c-hadrons produced in pp collisions.

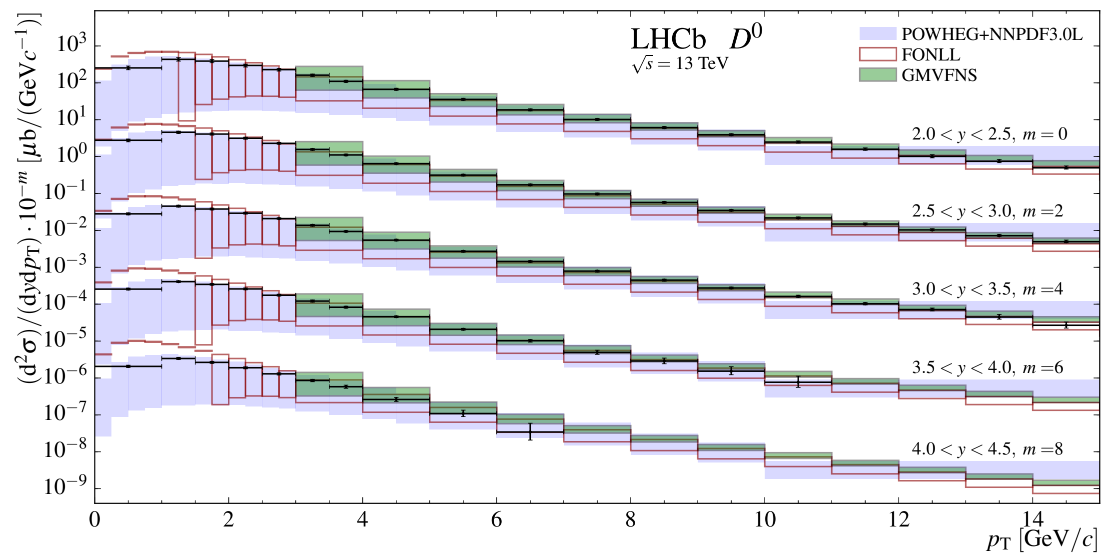
- Copious production of prompt (and secondary) charm at 13 TeV:

$$
\begin{aligned}
\sigma(pp \to D^0 X) &= 2072 \pm 2 \pm 124\,\mu\mathrm{b} \\
\sigma(pp \to D^+ X) &= 834 \pm 2 \pm 78\,\mu\mathrm{b} \\
\sigma(pp \to D_s^+ X) &= 353 \pm 9 \pm 76\,\mu\mathrm{b} \\
\sigma(pp \to D^{*+} X) &= 784 \pm 4 \pm 87\,\mu\mathrm{b}
\end{aligned}
$$

- Produced ~5×10^{12} D^0 and ~2×10^{12} D^{*+} mesons in only $3\,\mathrm{fb}^{-1}$ (Run 1) of data at $L_{inst} = 4\times10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$.

- Final Run 1 (2011-2012) sample about factor of 30 larger than samples collected by past experiments.

JHEP03(2016)159, Erratum: JHEP 1609 (2016) 013



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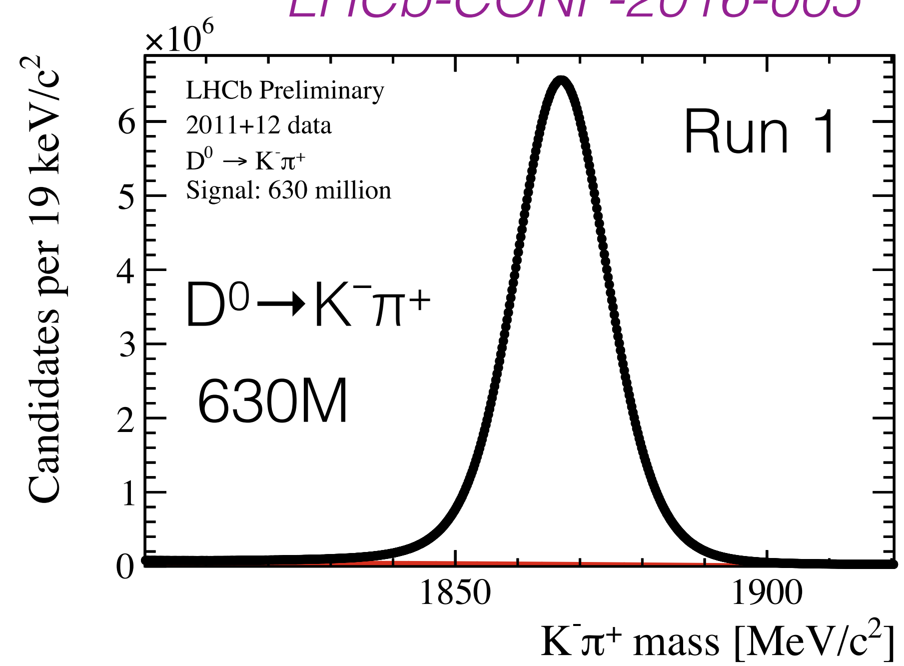
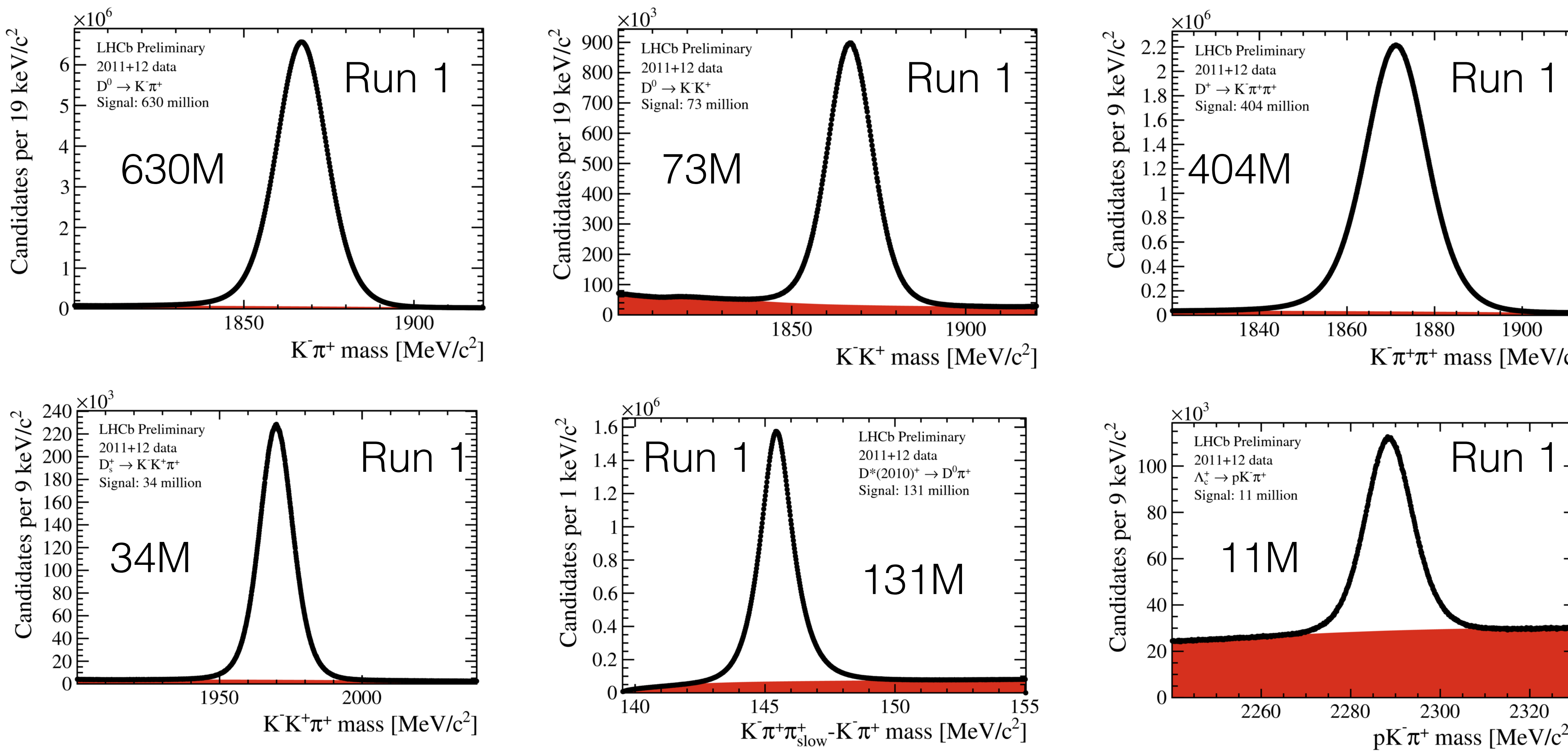


A plenty of charm



LHCb-CONF-2016-005

Today N_{sig}(Run 1 + Run 2) ~ 3 x N_{sig}(Run 1), and LHCb is taking data until the end of 2018, collecting about a total of 8fb^{-1} of data with the same efficiency and purity (yield per luminosity in 2015-16 increased by a factor of ~4 wrt Run 1).

Two-body $D^0 \to h^+h^-$ decays

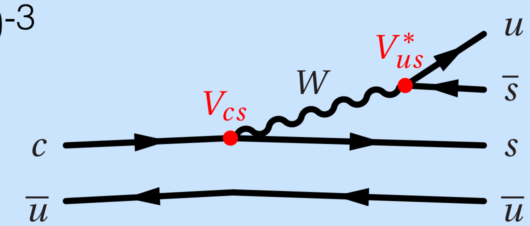
- $D^0 \to h^+h^-$ decays, where h=K,π, are experimentally clean channels allowing the study of the CP violation in the charm system.

- $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ Singly-Cabibbo-Suppressed decays. Final states are CP-eigenstates and allow a full probe of all types of CP-violation.

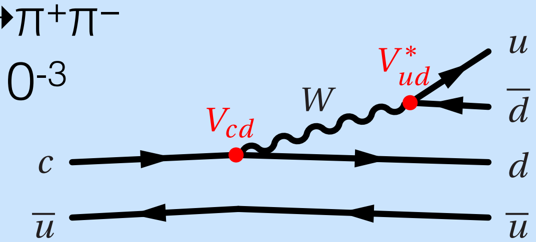
- $D^0 \to K^-\pi^+$ Cabibbo-Favored decays. They are flavour-specific and are used as a formidable control channel, being much more abundant than the SCS modes.

- $D^0 \to K^+\pi^-$ Doubly-Cabibbo-Suppressed decays. Essential to measure mixing parameters.

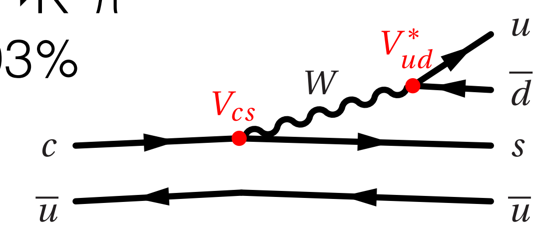
SCS: $D^0 \to K^+K^-$
BR≈4×10^{-3}



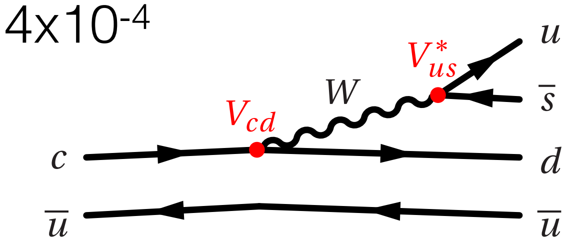
SCS: $D^0 \to \pi^+\pi^-$
BR≈1.4×10^{-3}



CF: $D^0 \to K^-\pi^+$
BR≈3.93%



DCS: $D^0 \to K^+\pi^-$
BR≈1.4×10^{-4}



Time-dependent CPV in $D^0 \to h^+h^-$

Because of the slow mixing rate of charm mesons ($x,y \sim 10^{-2}$) the time-dependent asymmetry is approximated at first order as the sum of two terms:

$$A_{CP}(f;t) = \frac{\Gamma_{D^0\to f}(t) - \Gamma_{\bar{D}^0\to f}(t)}{\Gamma_{D^0\to f}(t) - \Gamma_{\bar{D}^0\to f}(t)} \approx A^{\mathrm{dir}}_{CP}(f) + A^{\mathrm{ind}}_{CP}(f)\frac{t}{\tau_D}$$

$$A^{\mathrm{ind}}_{CP}(f) = \frac{\eta_{CP}}{2}\left[y\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right)\cos\varphi_f - x\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right)\sin\varphi_f\right]$$

CPV in the mixing $|q/p| \neq 1$ CPV in the interference $\varphi_f \neq 0,\pi$

In the limit of small CP violation in the decay:

$$A_\Gamma \equiv \frac{\hat{\Gamma}(D^0 \to f) - \hat{\Gamma}(\bar{D}^0 \to f)}{\hat{\Gamma}(D^0 \to f) + \hat{\Gamma}(\bar{D}^0 \to f)} \approx -A^{\mathrm{ind}}_{CP}(f)$$

$$1/\hat{\Gamma} = \hat{\tau} = \frac{\int t\Gamma(t)dt}{\int \Gamma(t)dt}$$

where A_Γ defined as the asymmetry between D^0 and antiD^0 effective lifetimes

$A_\Gamma \neq 0$ clearly indicates CPV in the charm sector. Sensitive to CPV in both mixing and interference.

A golden observable: A_Γ

- The coefficient $-A_{CP}^{ind}$ can potentially be measured with greater precision than the constant term A_{CP}^{dir} because it is less affected by instrumental asymmetries that are to a large extent time-independent.

- The current experimental precision on A_{CP}^{ind} is at the level of $\sim 0.5\text{x}10^{-3}$, i.e. it has reached sensitivity where it becomes possible to test SM predictions, and where further improvements are expected to be particularly valuable.

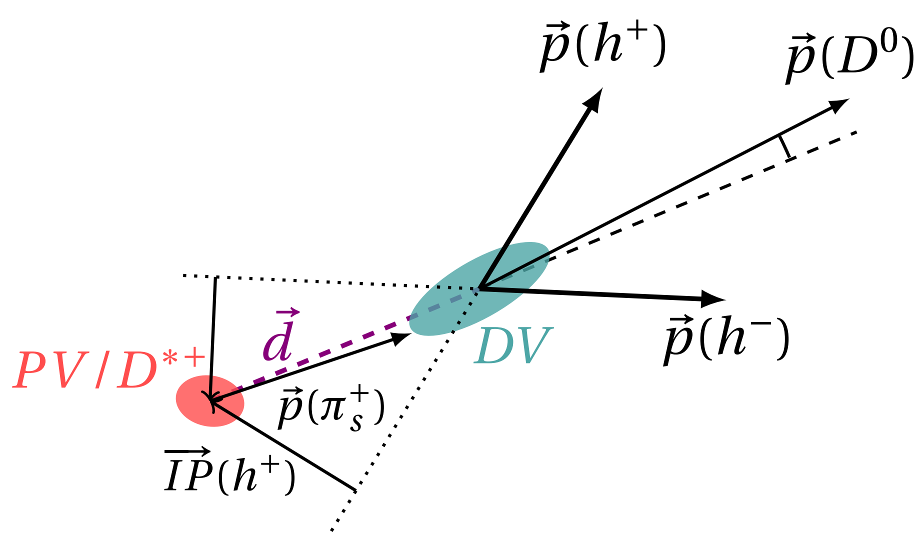
  - Neglecting subleading amplitudes A_Γ is independent of the final state f. Furthermore, in the absence of CP violation in mixing, it can be found that $A_\Gamma = -x \sin\varphi \longrightarrow |A_\Gamma| \leq |x| < 5\text{x}10^{-3}$.

  - Latest SM prediction: $A_\Gamma \simeq 10^{-4}$ [Bobrowski et al. JHEP 03 (2010) 009].

Flavour identification

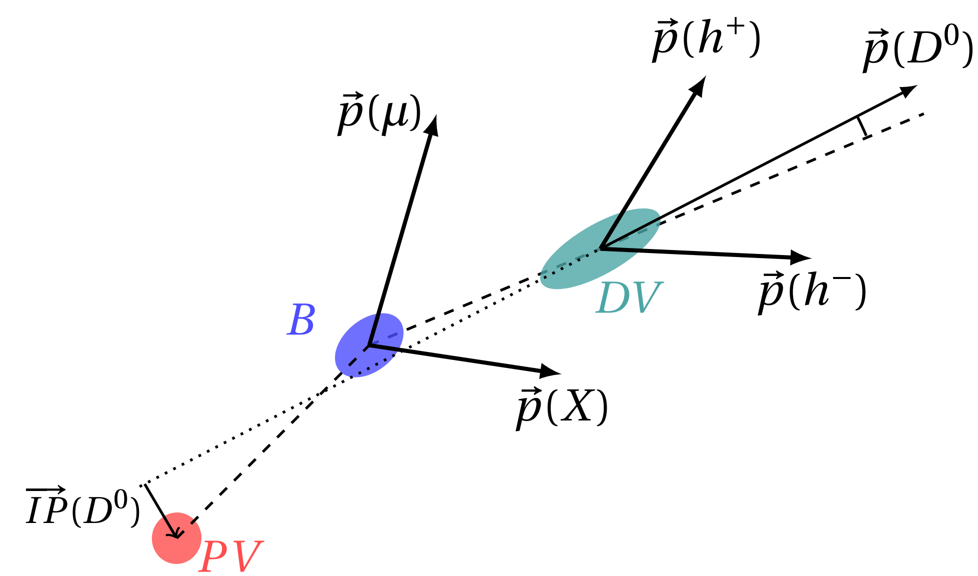
K^+K^- and $\pi^+\pi^-$ are CP-eigenstates —> D^0 flavour cannot be inferred from its decay products. Production mechanism is exploited.

D*-tag (or prompt) tag



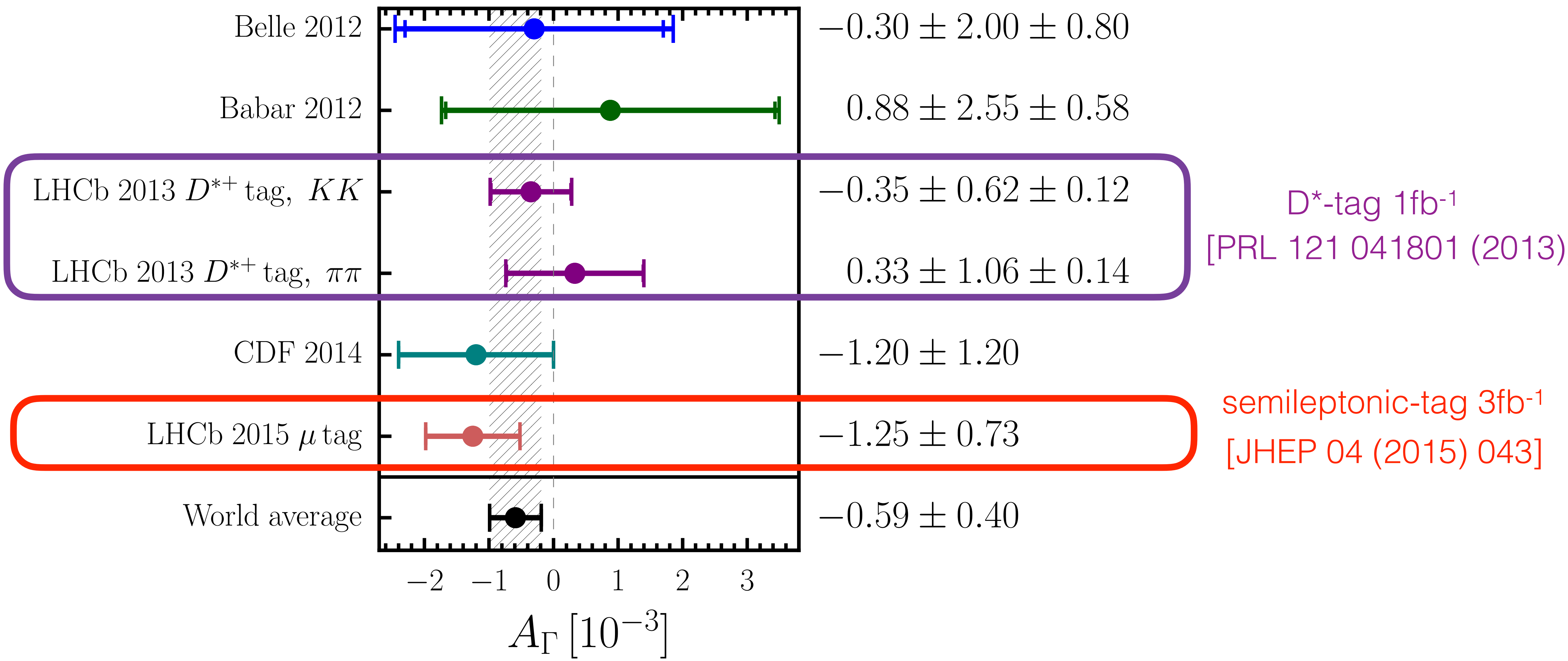
$$D^{*+} \to D^0[\to h^+ h'^-]\pi^+$$

Semileptonic tag



$$\bar{B} \to D^0[\to h^+ h'^-]\ell^-\overline{\nu}_\ell X$$

A_Γ state-of-the-art



LHCb already dominates the world average, but more precision is needed…
Beyond the intrinsic goal of looking for first hints of CPV in the charm sector, the aim is an unprecedented reduction of systematic uncertainties to demonstrate the feasibility of the measurement at much higher precision.

LHCb D^{*+}-tagged A_Γ measurement Full Run 1 data sample

- Sample: $1fb^{-1}$ at 7TeV + $2fb^{-1}$ at 8TeV.
- D*-tag used to infer the flavor of the D^0 meson at production
- A_Γ measured through a linear fit to the $A_{CP}(t)$.
- High statistics CF decay $D^0 \rightarrow K^-\pi^+$ used as control channel
  - $|A_\Gamma(D^0 \rightarrow K^-\pi^+)| < 5 \times 10^{-5}$, undetectable with current experimental sensitivity.
  - Analysis strategy, checks, and systematic uncertainties entirely developed and accurately studied using the high statistics control channel. $A_\Gamma(D^0 \rightarrow K^+K^-)$ and $A_\Gamma(D^0 \rightarrow \pi^+\pi^-)$ blinded until the approval.

Trigger (and stripping) selection

- Logical OR of all Level-0 (energy deposit in the calorimeter system) triggers accepted.
- Two body D^0 HLT lines (plus stripping preselection) apply mainly requirements on momentum and lifetime-related quantities.
- Moderate PID requirements (DLL).
- Signals already very pure and abundant at the trigger level, but not for free (see later).

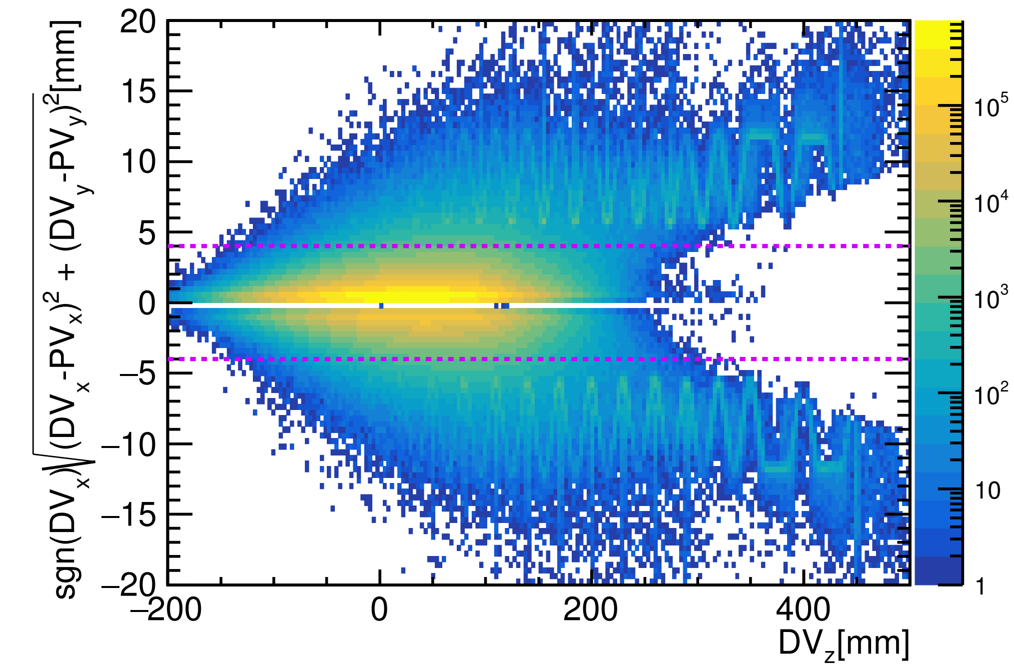
Selection details on P. Marino, CERN-THESIS-2017-007

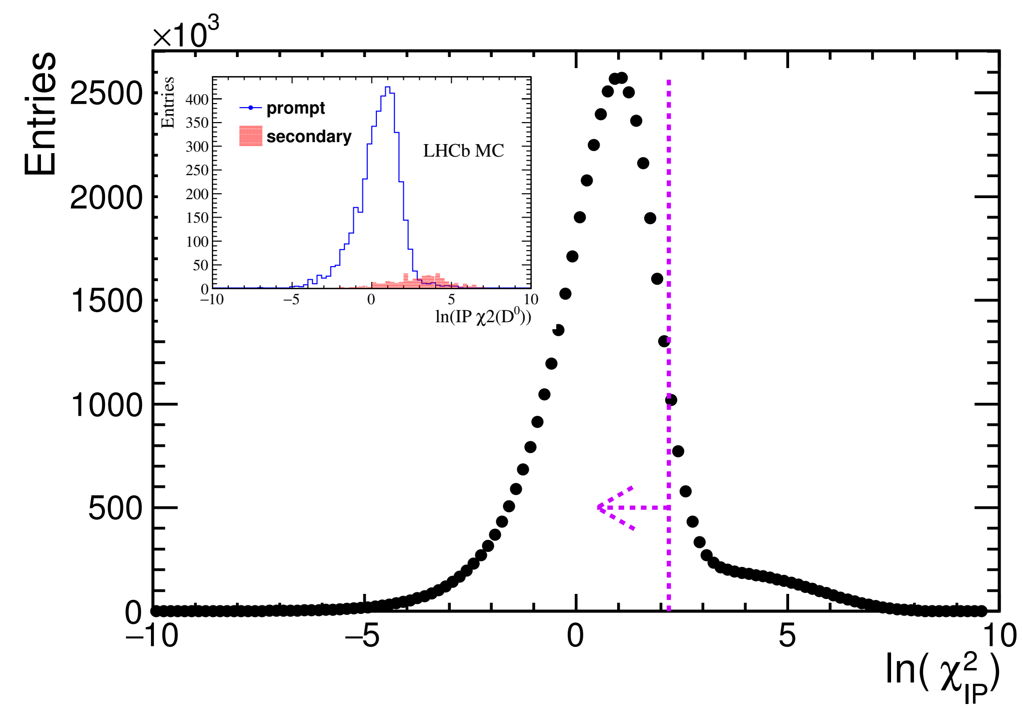
Candidate	Quantity	Requirement	Unit
h	$D_{KL}(h)$	> 5000	-
	$p_{\mathrm{T}}(h)$	> 800	MeV/c
	$p(h)$	> 5	GeV/c
	track χ^2/ndf(h)	< 3	-
	$\chi^2_{\mathrm{IP}}(h)$	> 9	-
	$(D^0 \to K^-\pi^+)$ $\mathrm{DLL}_{K\pi}(\pi)$, $\mathrm{DLL}_{K\pi}(K)$	$< 0, > 5$	-
	$(D^0 \to K^+K^-)$ $\mathrm{DLL}_{K\pi}(K)$	> 0	-
	$(D^0 \to \pi^+\pi^-)$ $\mathrm{DLL}_{K\pi}(\pi)$	< 0	-
D^0	$p_{\mathrm{T}}(D^0)$	> 2	GeV/c
	$p(D^0)$	> 5	GeV/c
	DV χ^2-distance from PV	> 40	-
	DIRA	> 0.9999	-
	DOCA	< 0.07	mm
	p_{T} of at least one daughters	> 1.5	GeV/c
	fit vertex $\chi^2(D^0)$/ndf	< 10	-
	$m(D^0)$	$\in [1765, 2065]$	MeV/c^2
D^{*+}	π_s track χ^2/ndf	< 5	-
	fit vertex $\chi^2(D^*)$/ndf	< 100	-
	$\Delta m = m(D^0\pi^+) - m(D^0)$	< 160	MeV/c^2

Further offline requirements

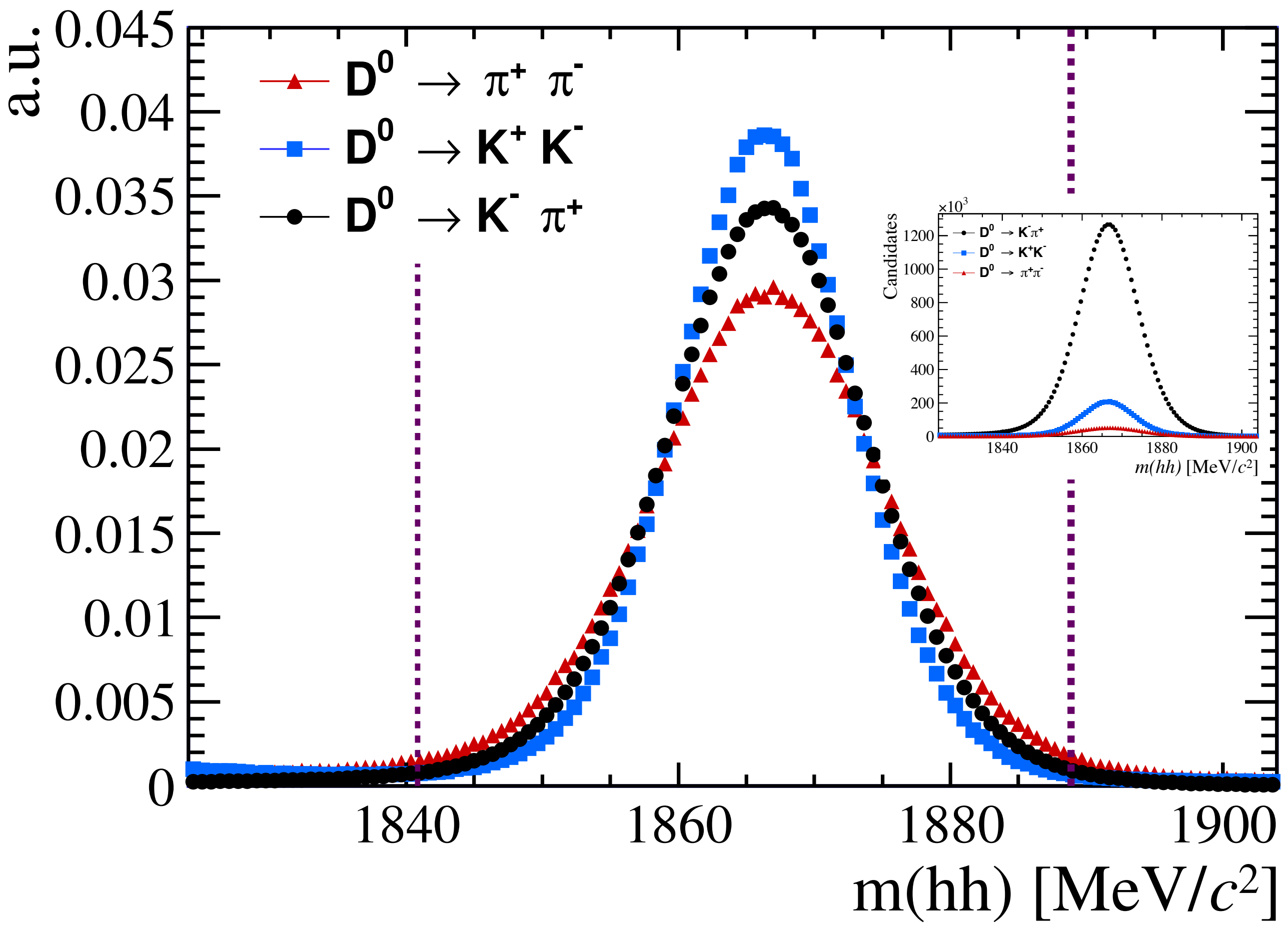
- PID of D^0 daughters to further improve purity and reduce physics backgrounds (DLL).
- VELO fiducial cut to remove D^0 produced from interactions with detector material (R_{xy}).
- Suppression of secondary decays (χ^2_{IP} of D^0).
- D^0 mass window (3σ around the peak);

Quantity	Requirement	Unit
$\mathrm{DLL}_{K\pi}(K)$	>5	-
$\mathrm{DLL}_{K\pi}(\pi)$	<-5	-
$\chi^2_{\mathrm{IP}}(D^0)$	<9	-
R_{xy}	<4	mm
$m(D^0)$	$\in[1840.84, 1888.84]$	MeV/c^2

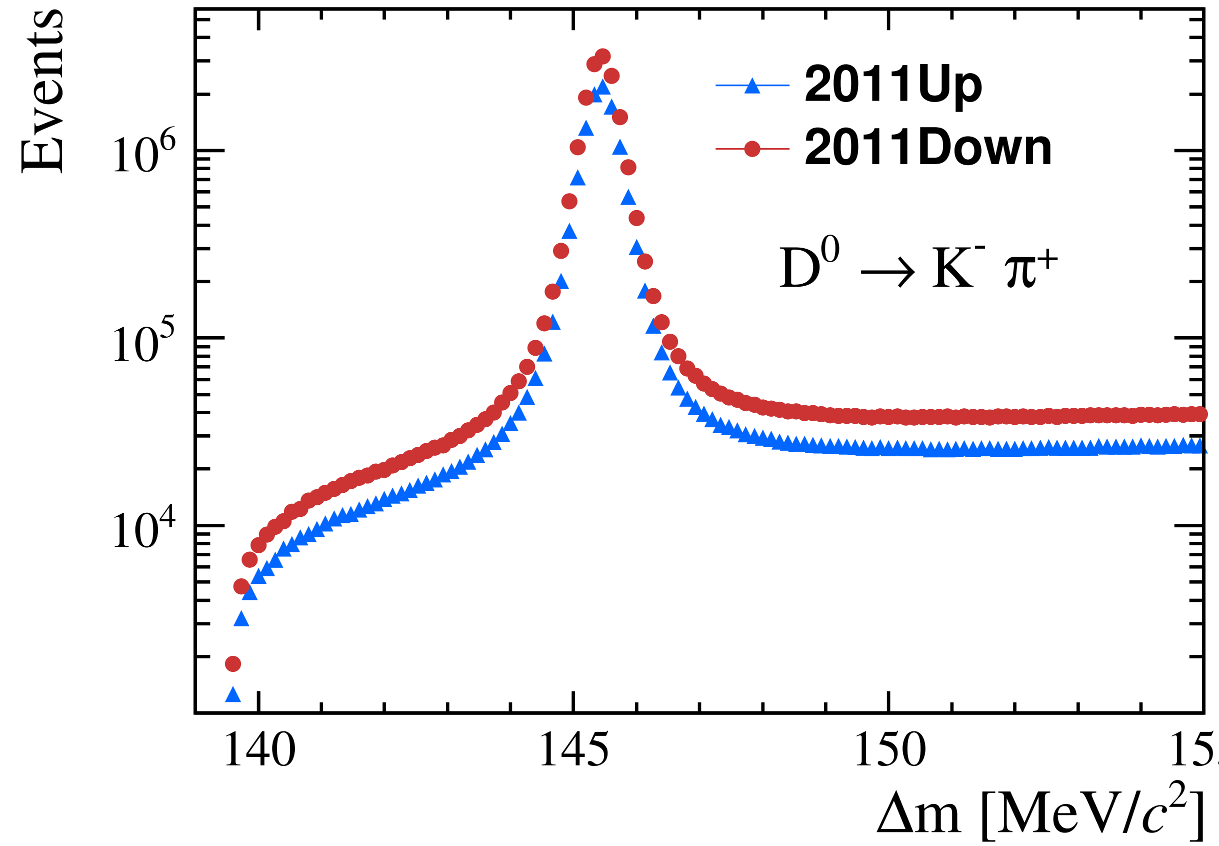


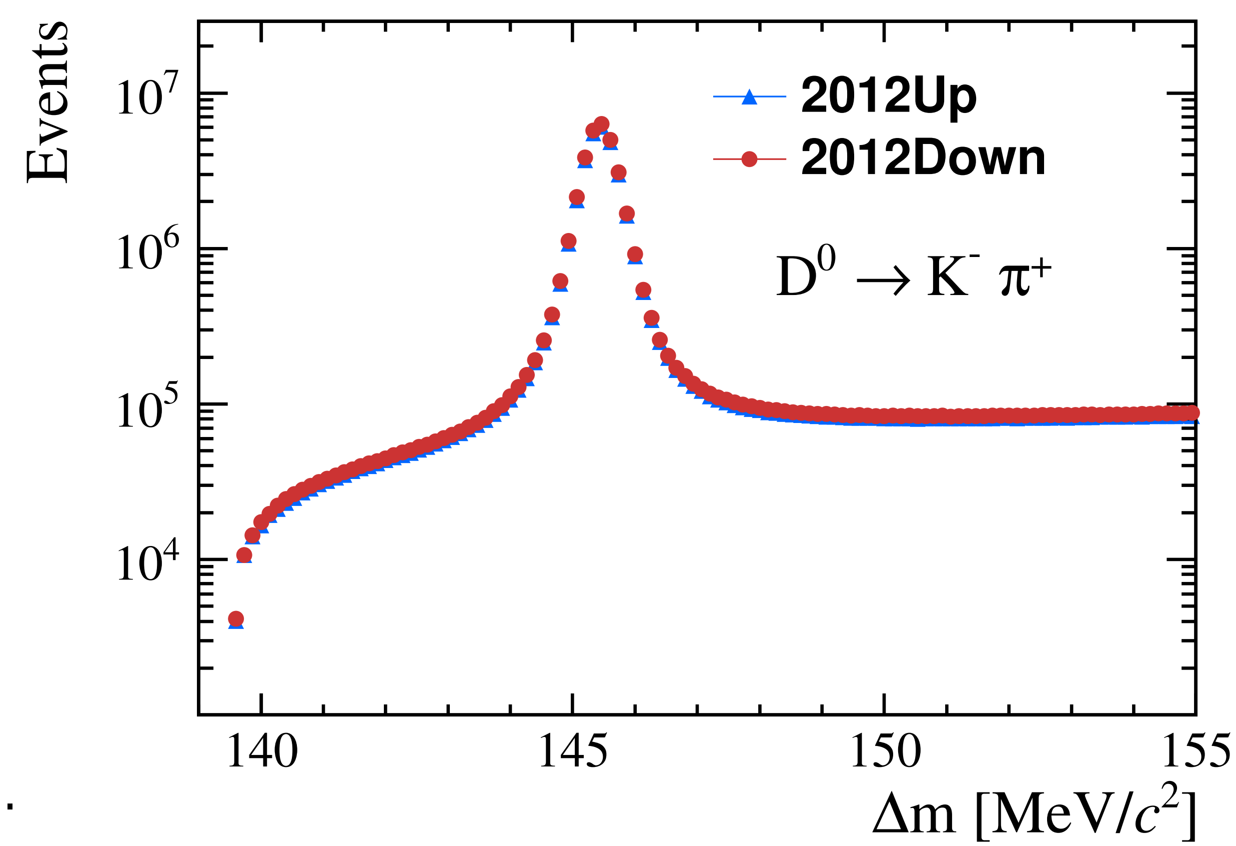


Signals



The data sample is split into four independent subsamples by the magnet polarity (Up, Down) and by the center-of-mass energy (2011 at 7TeV, 2012 at 8TeV).





Analysis approach

- Approaching a unprecedented level of precision ($<10^{-3}$) by handling huge data samples requires new methodologies. Analysis choices must be driven by “simplicity” criteria.
  - Time needed to make plots and numbers, once data are ready for users, greatly impacts the game.
  - For a fruitful review each requested check should be run in a human time scale with finite resources.
  - Systematic uncertainties and subtle effects are difficult to keep under control, if analysis is not transparent and rapidly reproducible.

Analysis strategy (A_Γ)

- Sideband subtraction of the random pions background using $\Delta m = m(hh\pi) - m(hh)$.
- Split sample in 30 approximately equally populated bins of D^0 decay time.
- Determination of the raw asymmetry in each bin of decay time.
- Correct for detection-induced charge asymmetries.
- Extract A_Γ through a linear fit to raw asymmetry as function of D^0 decay time.
- Determination of systematic uncertainties on assumptions and approximations done, in previous steps.

Raw yields extraction

Signal PDF

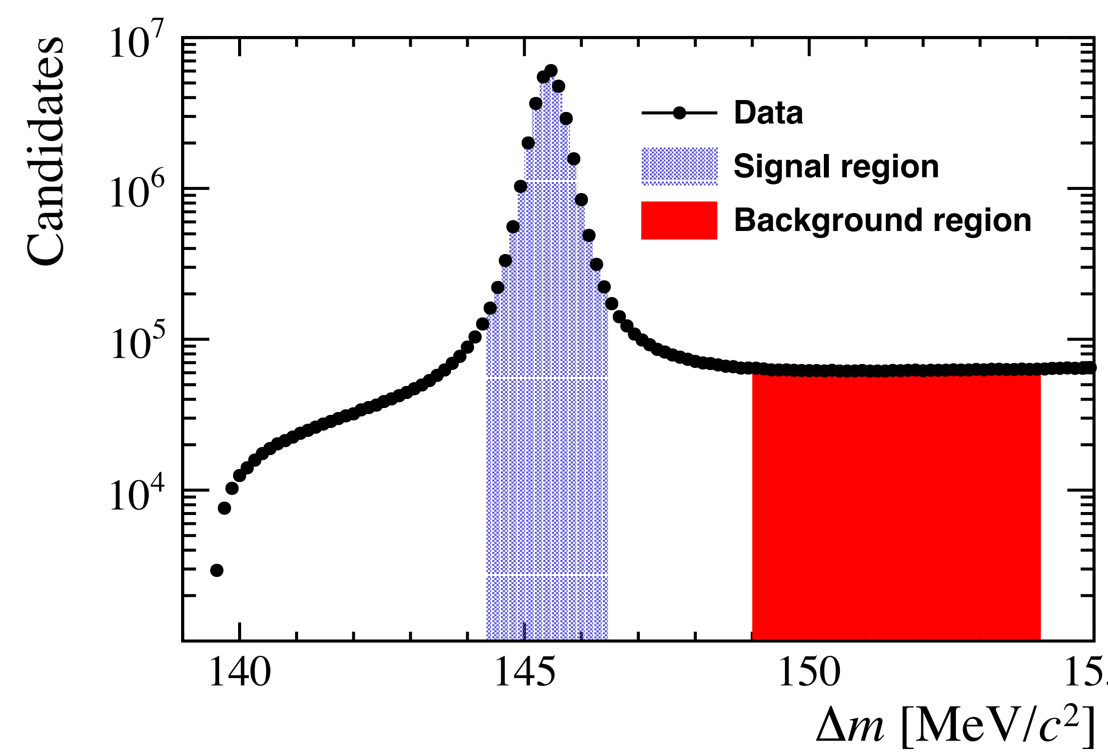
$$\mathcal{P}_{\rm sgn}(\Delta m|\boldsymbol{\theta}_{\rm sgn}) = f_J \mathcal{J}(\Delta m|\mu_J,\sigma_J,\delta_J,\gamma_J) + f_1\mathcal{G}(\Delta m|\mu_1,\sigma_1) + \\ + f_2\mathcal{G}(\Delta m|\mu_2,\sigma_2) + (1-f_J-f_1-f_2)\mathcal{G}(\Delta m|\mu_3,\sigma_3),$$

$$\mathcal{J}(x|\mu,\sigma,\delta,\gamma) = \frac{1}{I_J}\frac{\exp\left[-\frac{1}{2}\left(\gamma+\delta\sinh^{-1}\left(\frac{x-\mu}{\sigma}\right)\right)^2\right]}{\sqrt{1+\left(\frac{x-\mu}{\sigma}\right)^2}},$$

$$\mathcal{G}(x|\mu,\sigma) = \frac{1}{I_G}\exp\left[-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2\right],$$

Background PDF

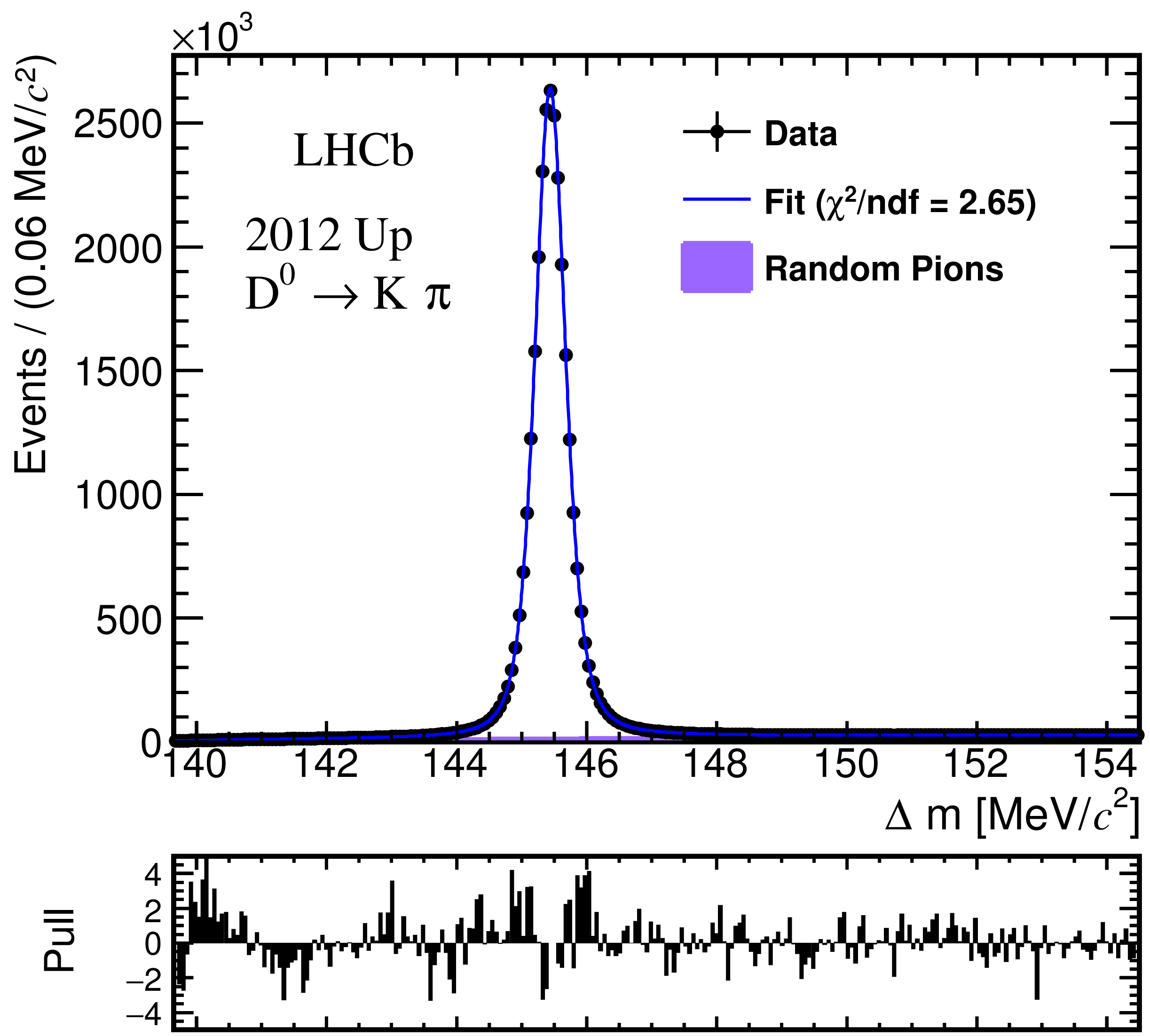
$$\mathcal{P}_{\rm bkg}(\Delta m|\boldsymbol{\theta}_{\rm bkg}) = \frac{1}{I_B}\left(1-\exp\left[-\frac{\Delta m - m_0}{c}\right] + b\left(\frac{\Delta m}{m_0}-1\right)\right),$$

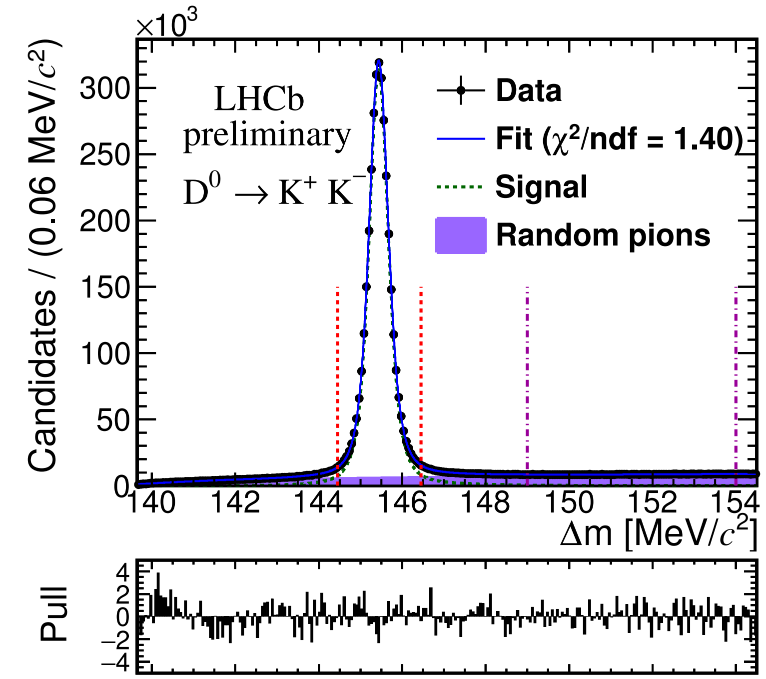


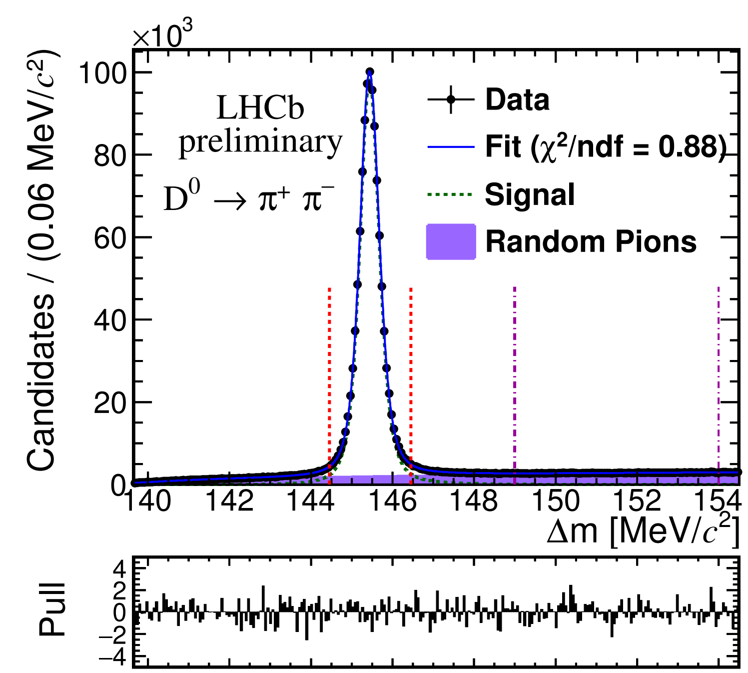
Mass fit only to extract time-integrated signal-over-background normalization factor for sideband subtraction.

Small residual random pions background subtracted using the sideband [149,154]MeV/c². Signal region [144.45,146.45] MeV/c² about 5σ around the peak

2012 Down sample







Signal yields (in millions)

sample	$D^0 \to K^-\pi^+$	$D^0 \to K^+K^-$	$D^0 \to \pi^+\pi^-$
2011 Up	10.7	1.2	0.36
2011 Down	15.5	1.7	0.53
2012 Up	30.0	3.3	1.02
2012 Down	31.3	3.4	1.07
Total	87.5	9.6	2.98

The data sample is split into four independent subsamples by the magnet polarity (Up, Down) and by the center-of-mass energy (2011 at 7TeV, 2012 at 8TeV).

A_Γ independently measured in the four subsamples. The convergence of all values to a common value provides a cross-check of the validity and robustness of the measurement.

Raw asymmetry

$$A_{\text{raw}}(t) = \frac{N(t, D^{*+} \to D^0\pi^+) - N(t, D^{*-} \to \bar{D}^0\pi^-)}{N(t, D^{*+} \to D^0\pi^+) - N(t, D^{*-} \to \bar{D}^0\pi^-)} \approx A_P + A_D + A_{CP}(t)$$

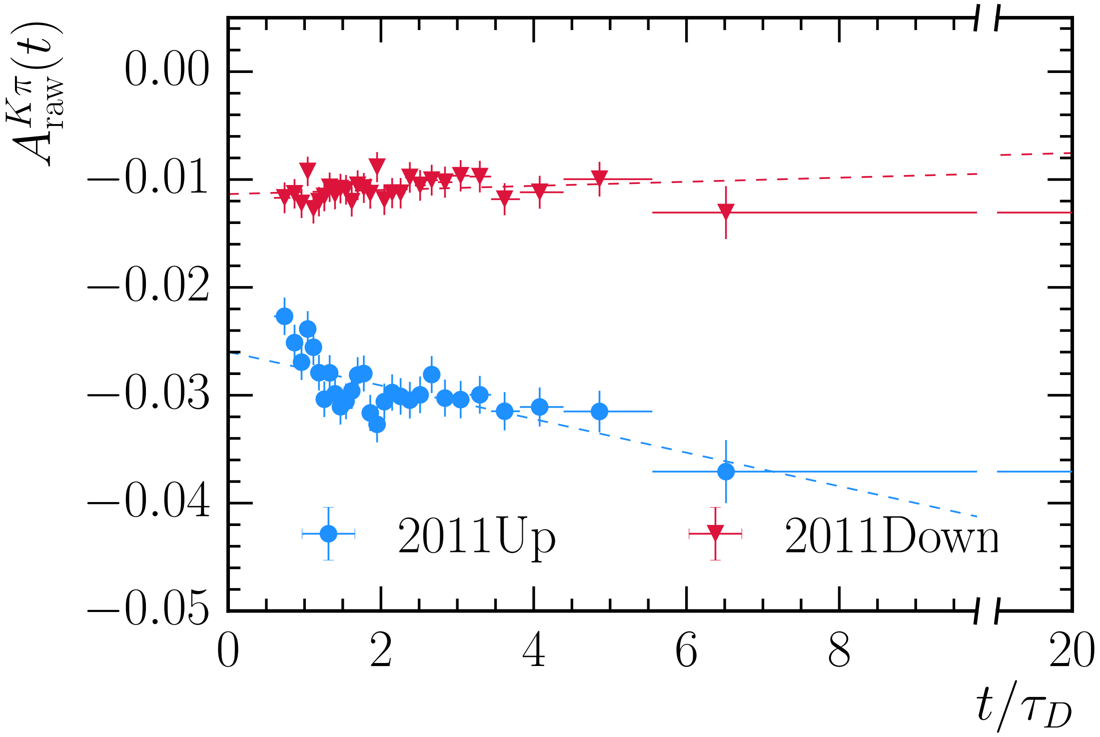
Production asymmetry, time-independent by definition.

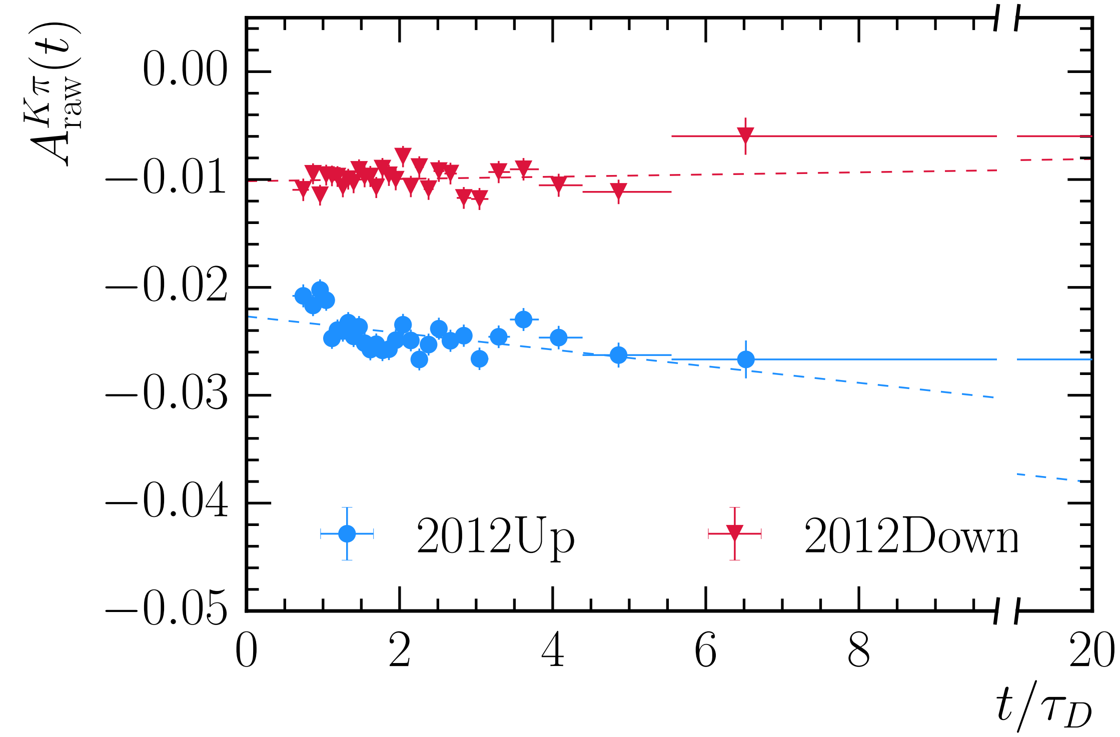
Detector induced charge asymmetry. It can be time-dependent mimicking a fake slope. Very dangerous.

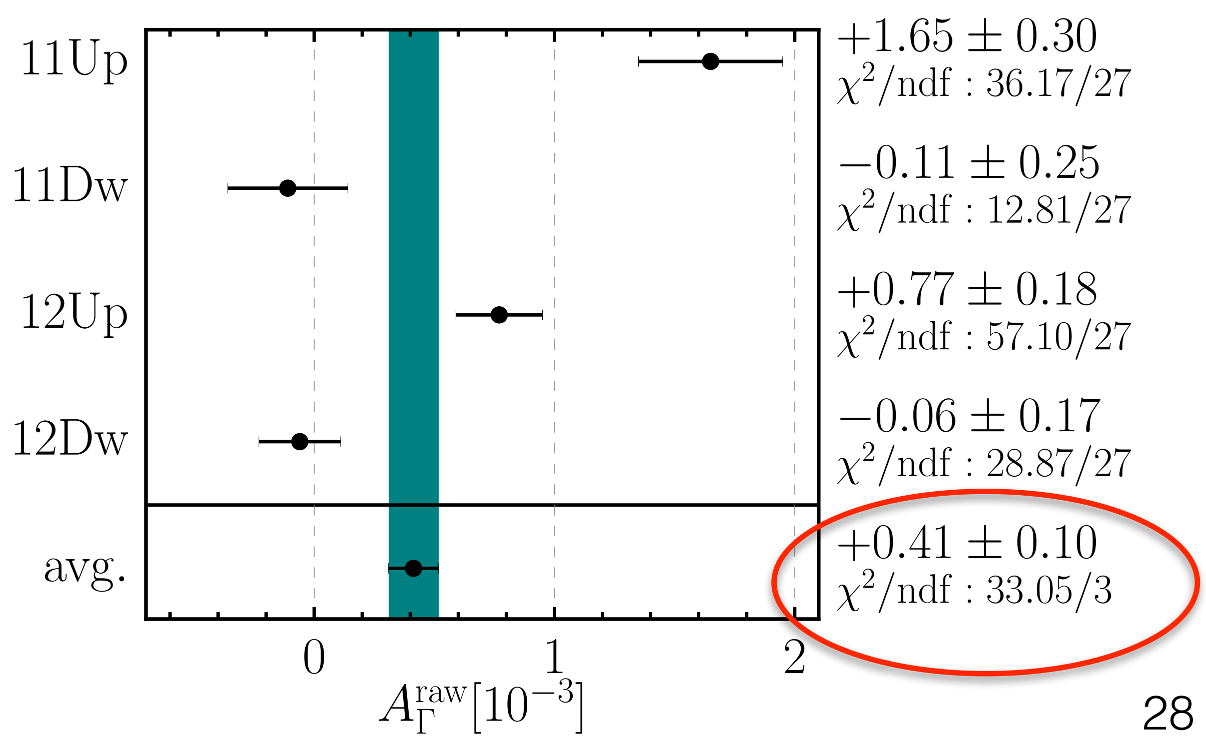
$$A_{CP}^{\text{dir}} - A_\Gamma \frac{t}{\tau_D}$$

A_Γ slope is our physics observable

“raw” $A_\Gamma(D^0 \to K^-\pi^+)$







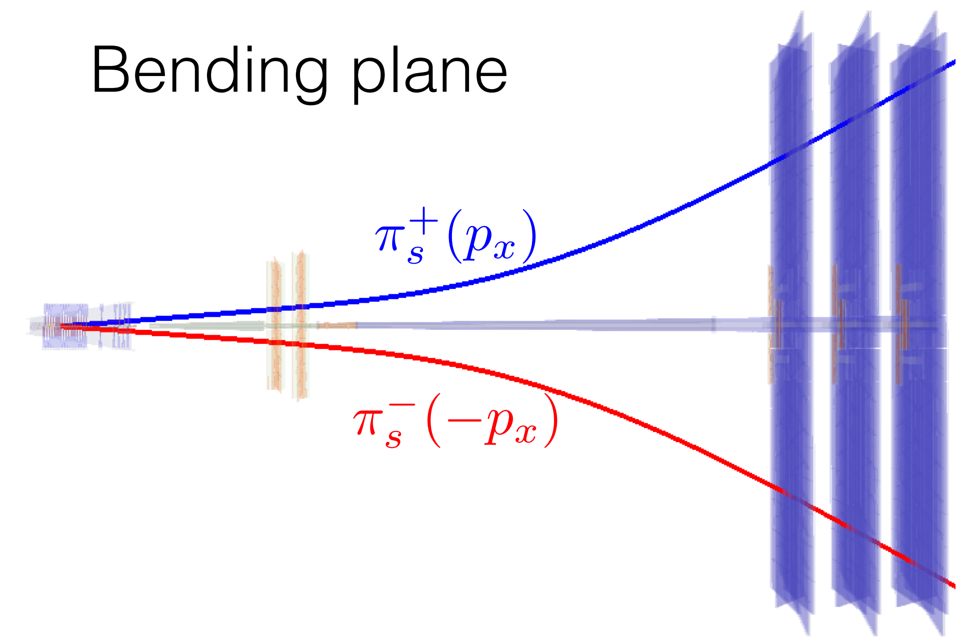
All values should be compatible with each other and compatible with zero, however, results are incompatible with hypothesis of no slope, and are significantly different depending on the subsample. Not even straight lines.

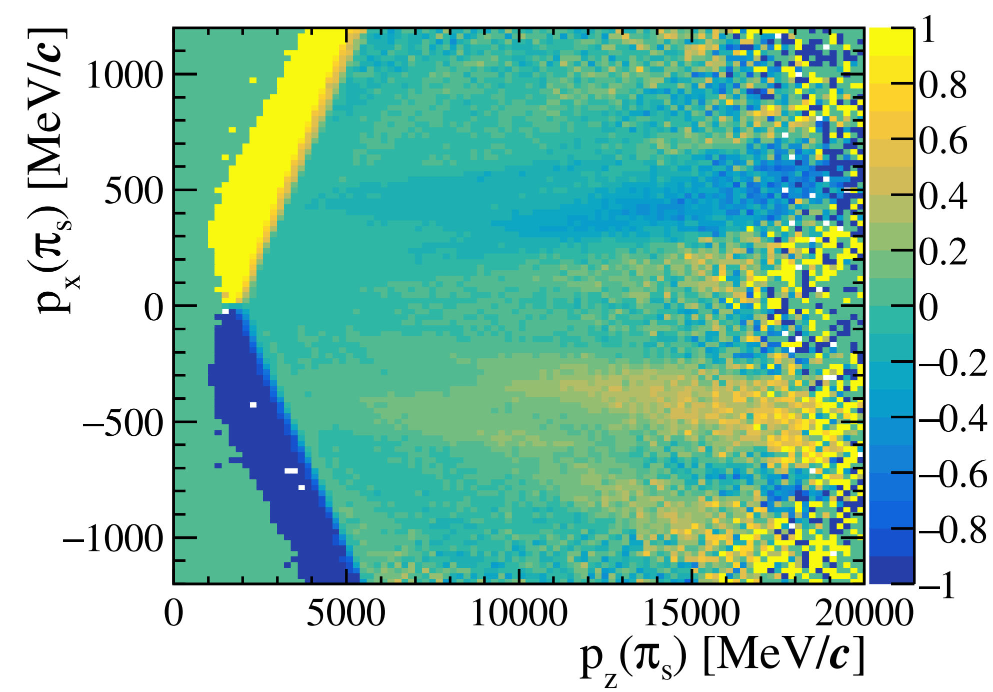
Time-dependent detector charge asymmetries

- The presence of significant deviations from zero for the control channel indicates the existence of non-negligible time-dependent residual detector asymmetries.
- They partially cancel in the combination of the MagUp and MagDown samples, but not completely, yielding an overall average that is incompatible with zero.
- These residual biases arise due to correlations between the decay time and other kinematic variables that affect the efficiency, most notably the momentum of the soft pion.

Momentum charge asymmetries

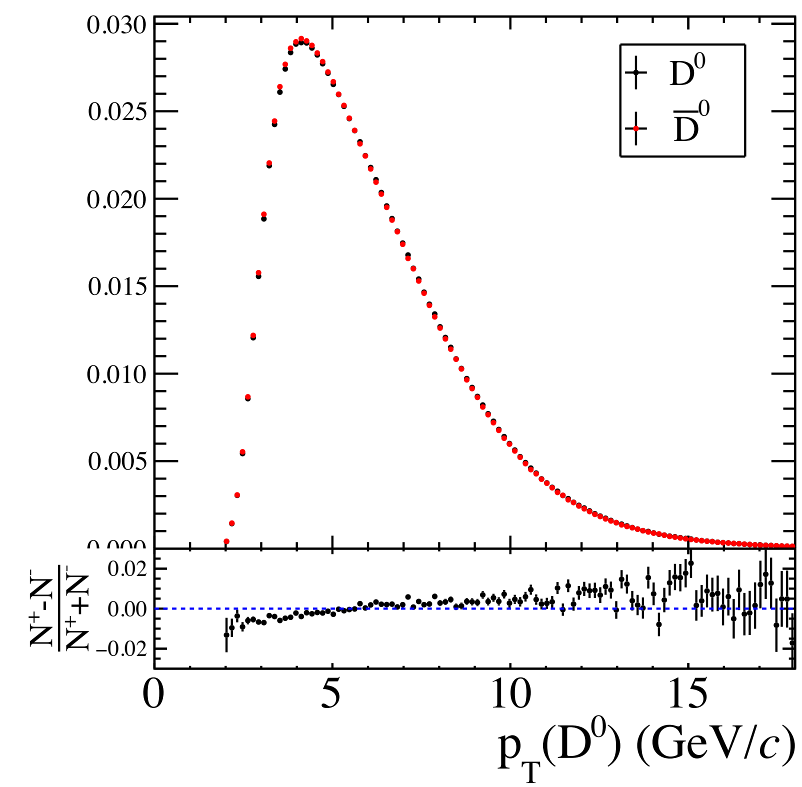
- Soft pions charge asymmetries are notoriously sizeable and strongly momentum-dependent.
- A pion with a $p_z \simeq 5$ GeV/c and $p_x \sim 100 \div 200$ MeV/c changes its direction, due to the magnetic field, of a quantity of ≈ 250 mrad, which is comparable to the entire LHCb acceptance of 300 mrad; this generates large differences in acceptance for positively and negatively charged pions,
- Even particles hitting the same location on a given detector layer, will intersect different sub-detectors with different trajectories according to their charge and momentum.
- Averaging the two magnet polarities does not necessarily eliminated the effect with the degree of precision needed, because of variation of run and detector conditions over time.

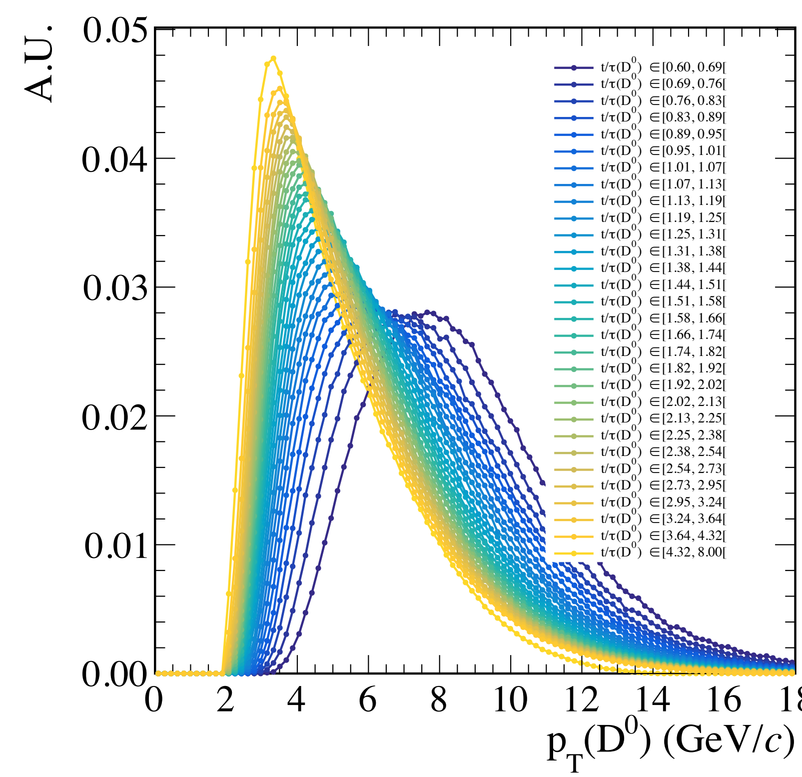




Momentum-time correlation

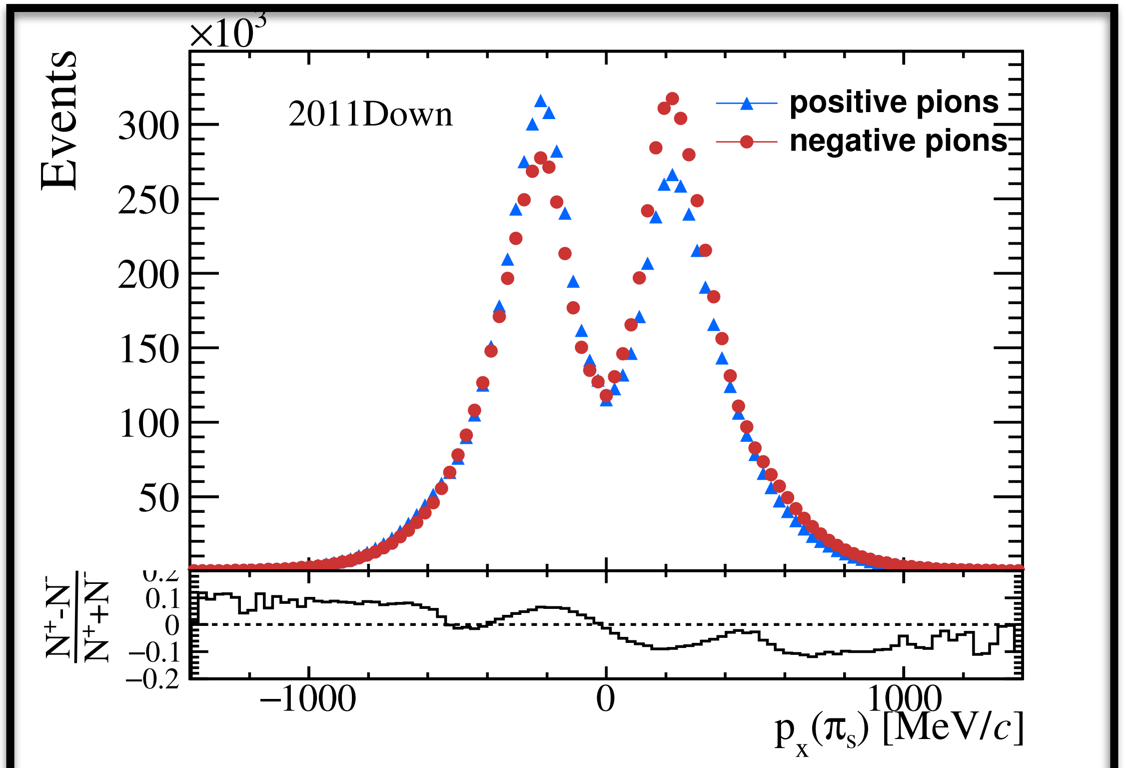
- Momentum and proper decay time should be independent by definition, however,
- capability of collecting unprecedented pure and huge samples of charm (and beauty) decays at hadron collisions has a price. It is not for free!
- Requirements on track impact parameter of D^0 decays products, on D^0 flight distance, on transverse momentum, and in general on kinematics of the decay do introduce correlations.
    - Note, this is unavoidable. Extremely important to keep this correlation as much as possible "small" and "simple", in order to correct for the effect.

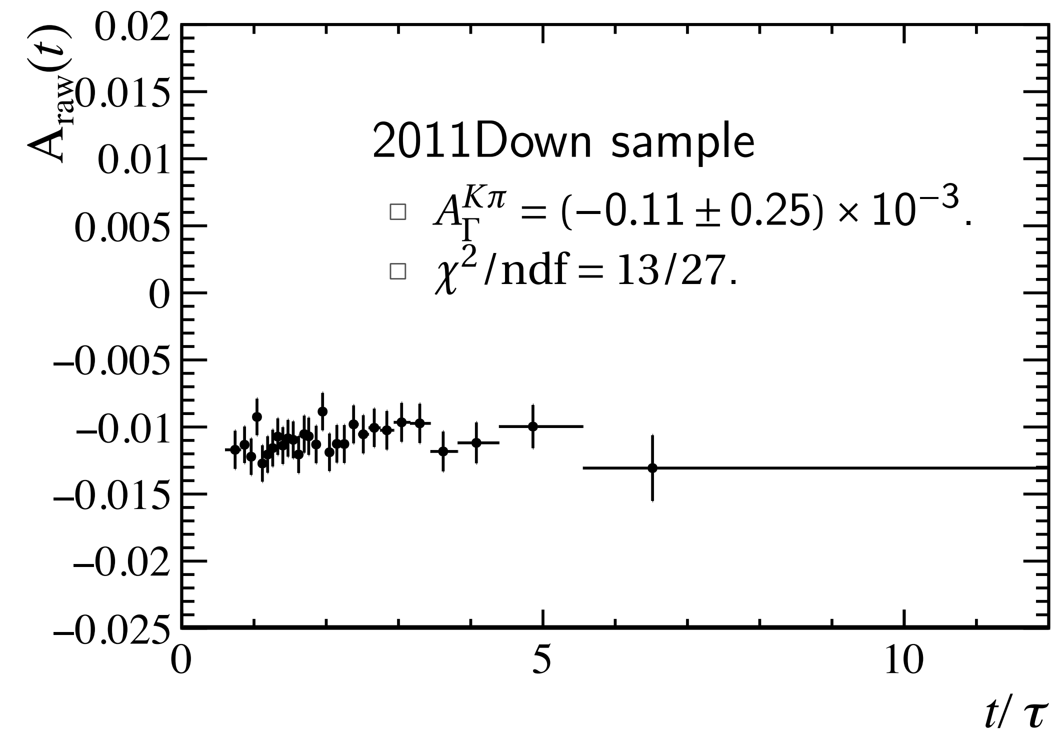


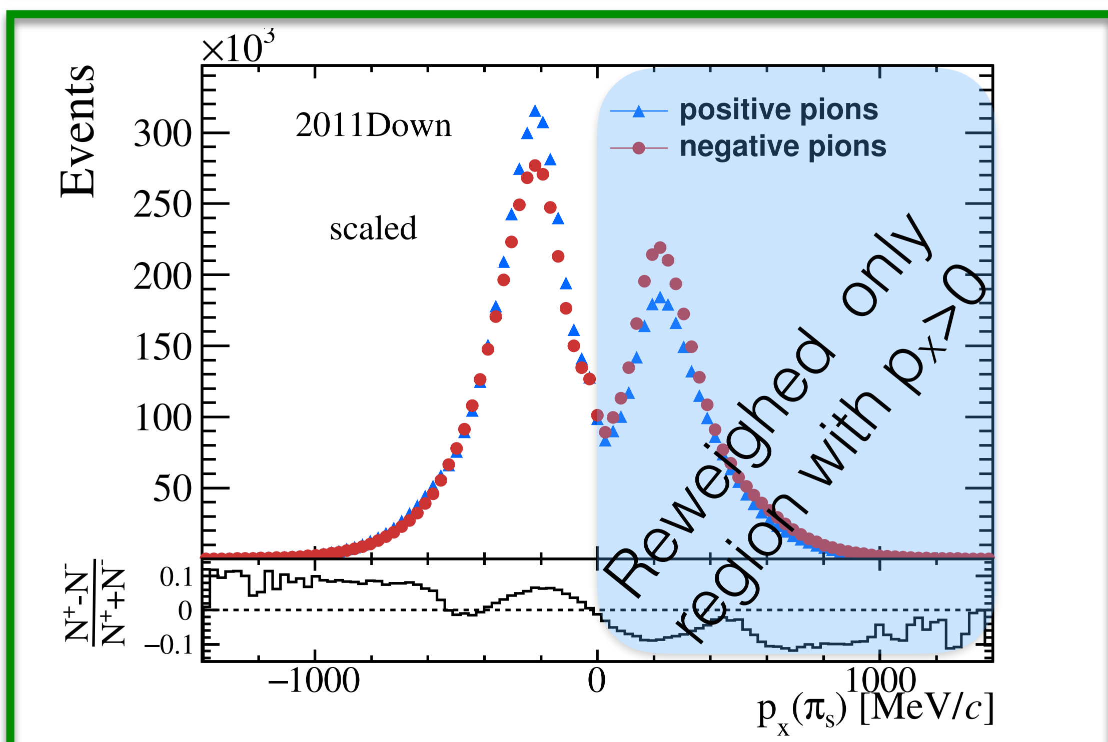


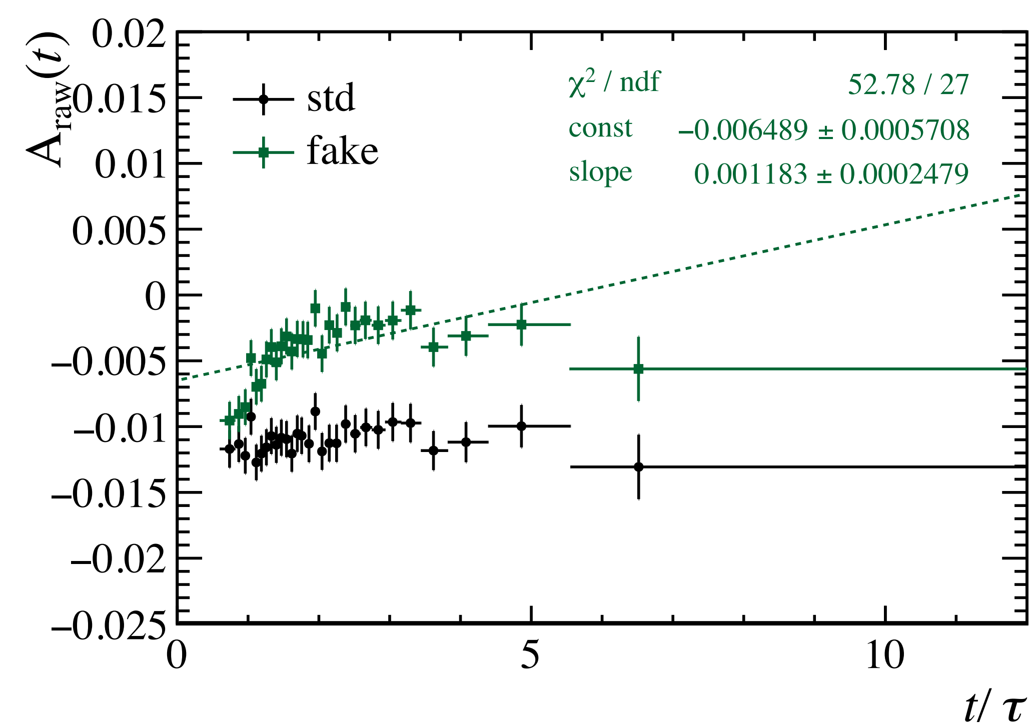
low $p_T(D^0)$: higher decay time —> lower asymmetry
high $p_T(D^0)$: lower decay time —> higher asymmetry

How does it work?









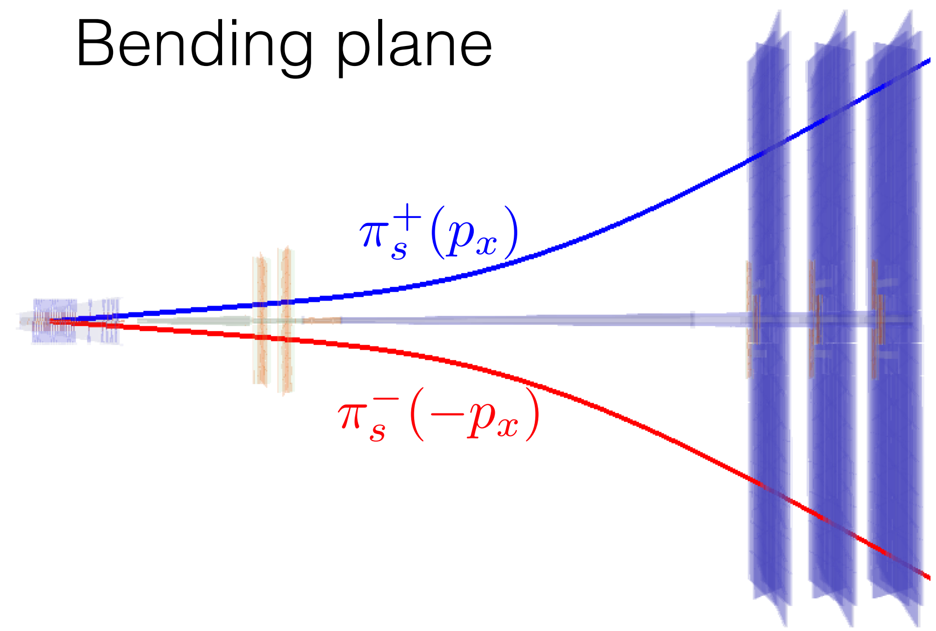
Remove the source

- LHCb detector nearly L/R symmetric by design.

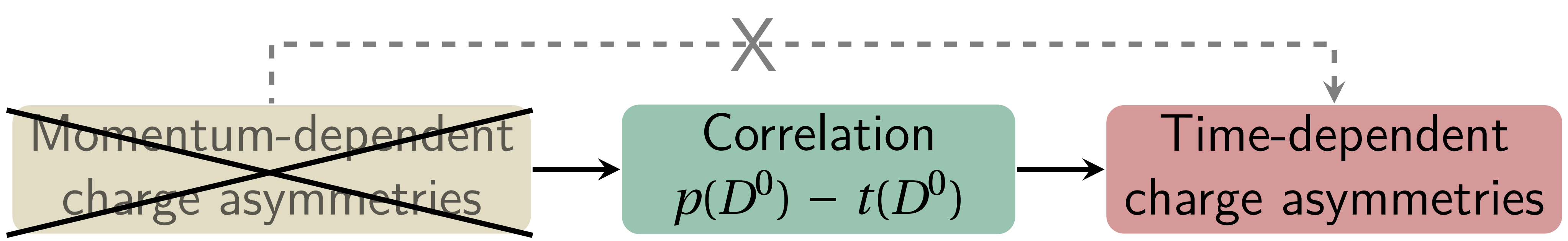
- Departures from the nominal geometry and variations of the efficiency produce small residual deviations from an ideally symmetric detector acceptance ($\pi^{+}_{s} = \pi^{-}_{s}$).

  - Variations of detector efficiency over the space, mis-alignments, matter effects, non homogeneous magnetic field, …

Bending plane



- Need to correct these residual asymmetries is actually desirable.



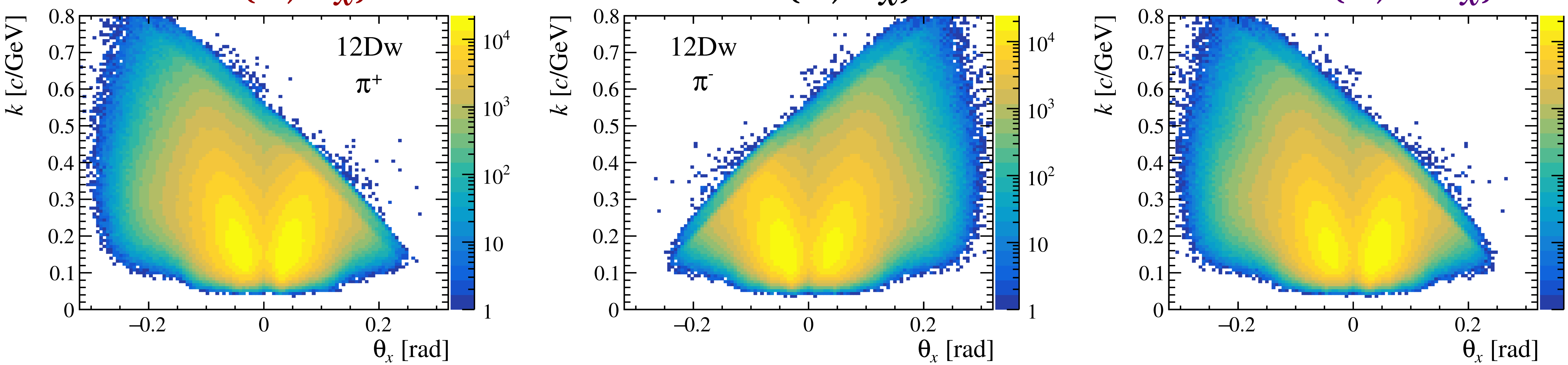
How do we correct?

Using more natural variables to parametrize soft pion kinematics

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

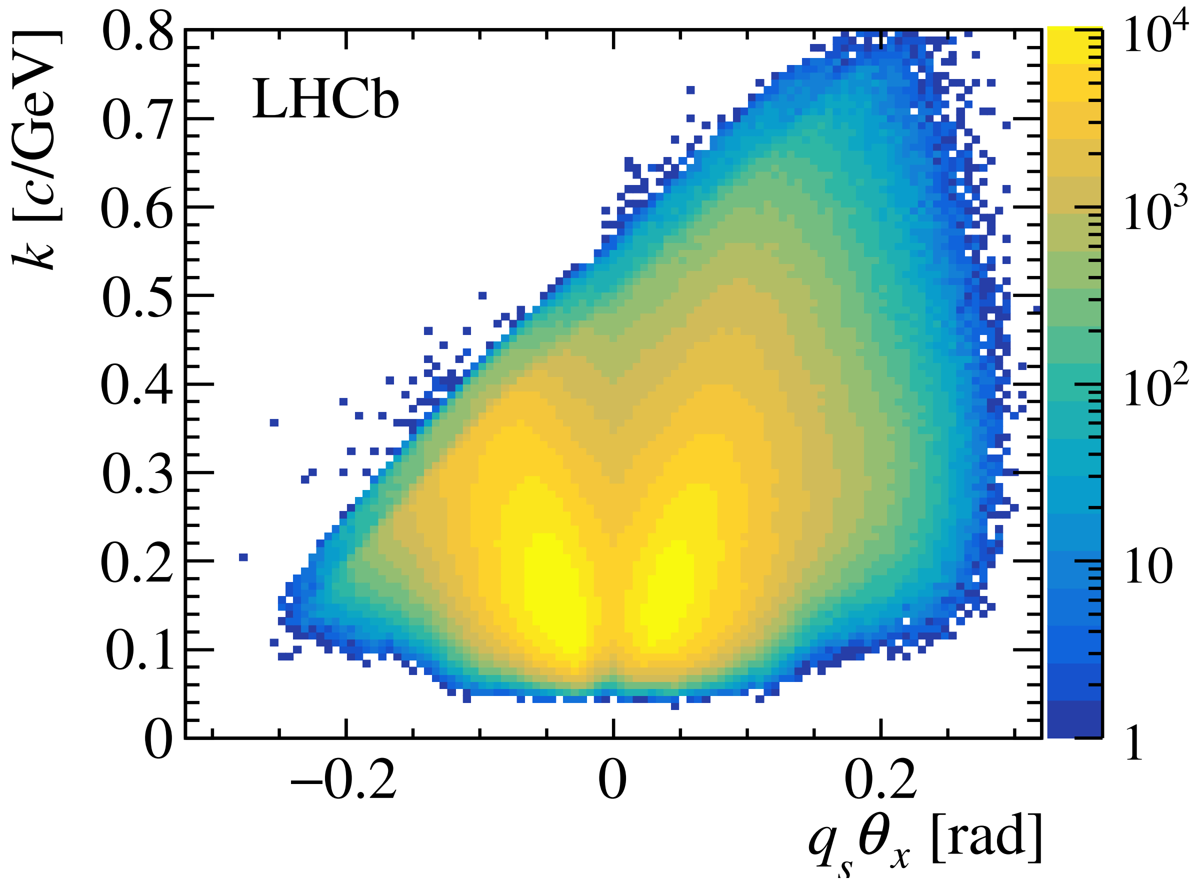
$$\begin{aligned} k &= 1/\sqrt{p_x^2+p_y^2} \\ \theta_x &= \arctan(p_x/p_z) \\ \theta_y &= \arctan(p_y/p_z) \end{aligned}$$

$n^{+}(k,\theta_x)$ $\quad$ $n^{-}(k,\theta_x)$ $\quad$ $n^{-}(k,-\theta_x)$

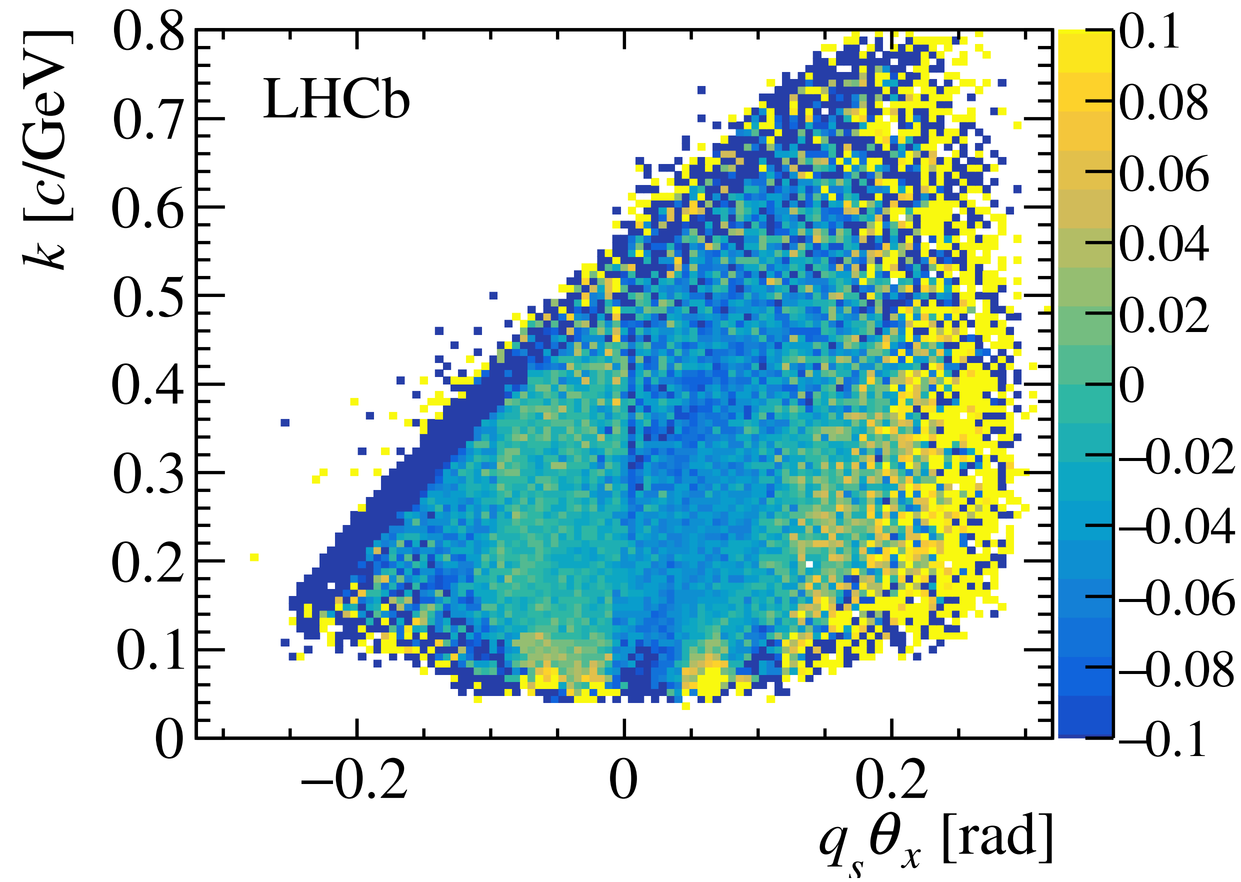


Reweigh of soft pion kinematics in the time-integrated $(k,q_s\theta_x,\theta_y)$ distribution in order to have $n^{+}(k,\theta_x,\theta_y) = n^{-}(k,-\theta_x,\theta_y)$.

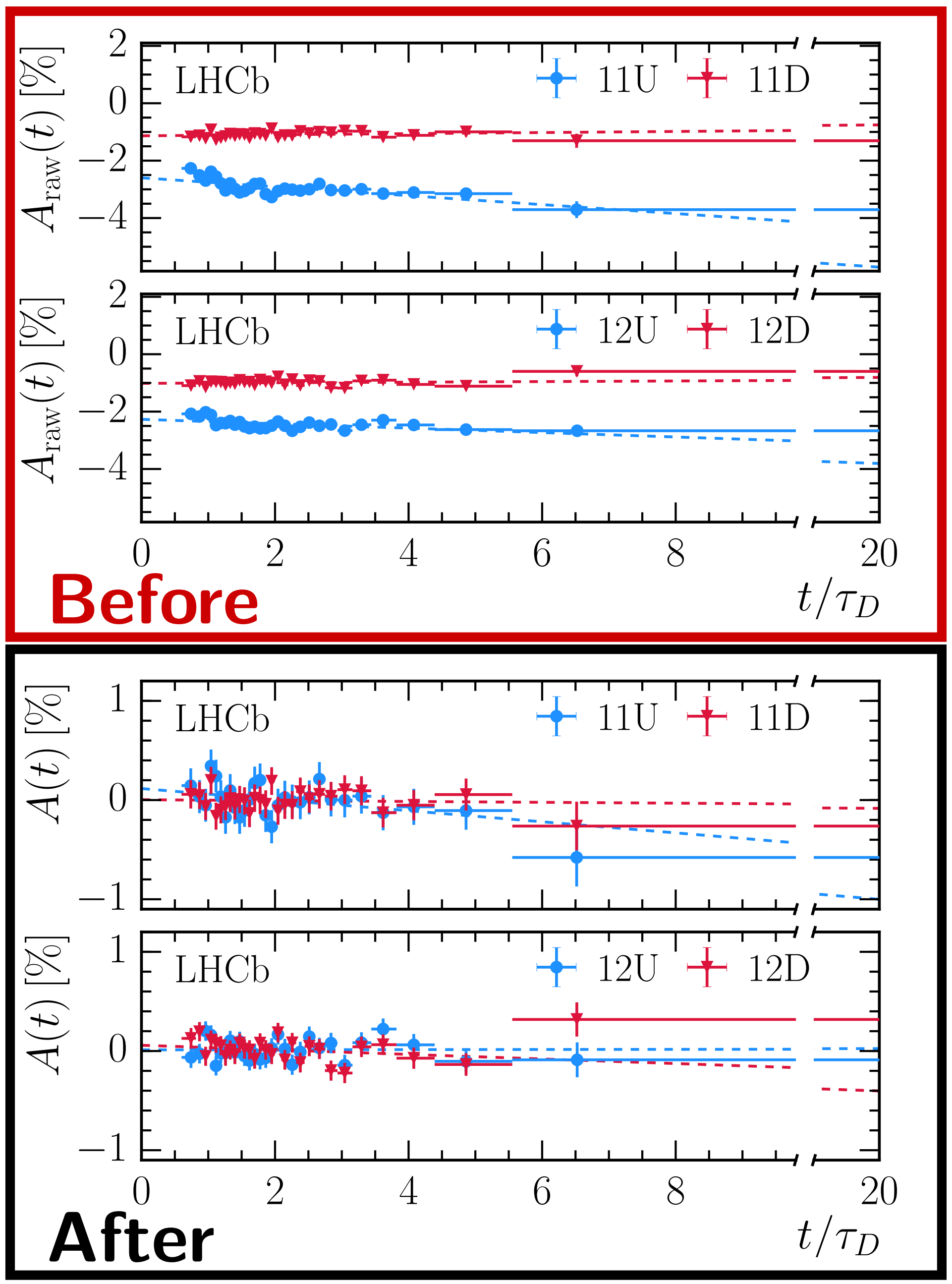
Asymmetry in (k,$q_s\theta_x$,θ_y) space

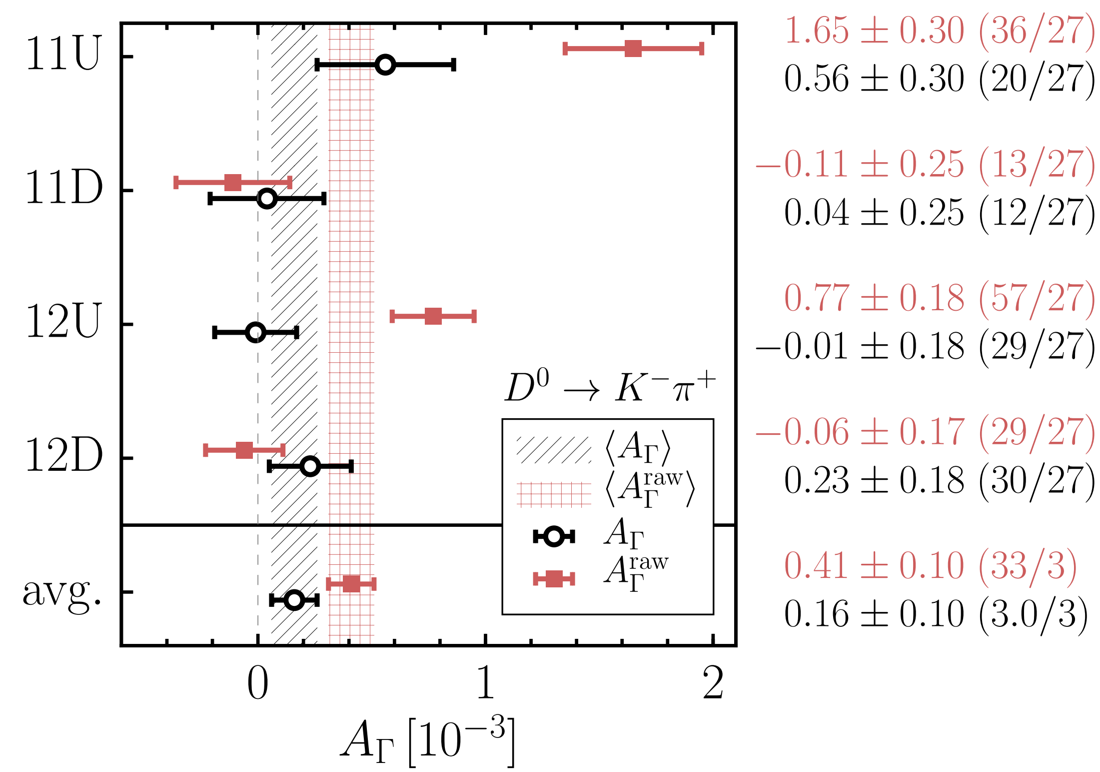


Raw asymmetry



$A_\Gamma(D^0 \to K^-\pi^+)$ results





Results now compatible with zero.

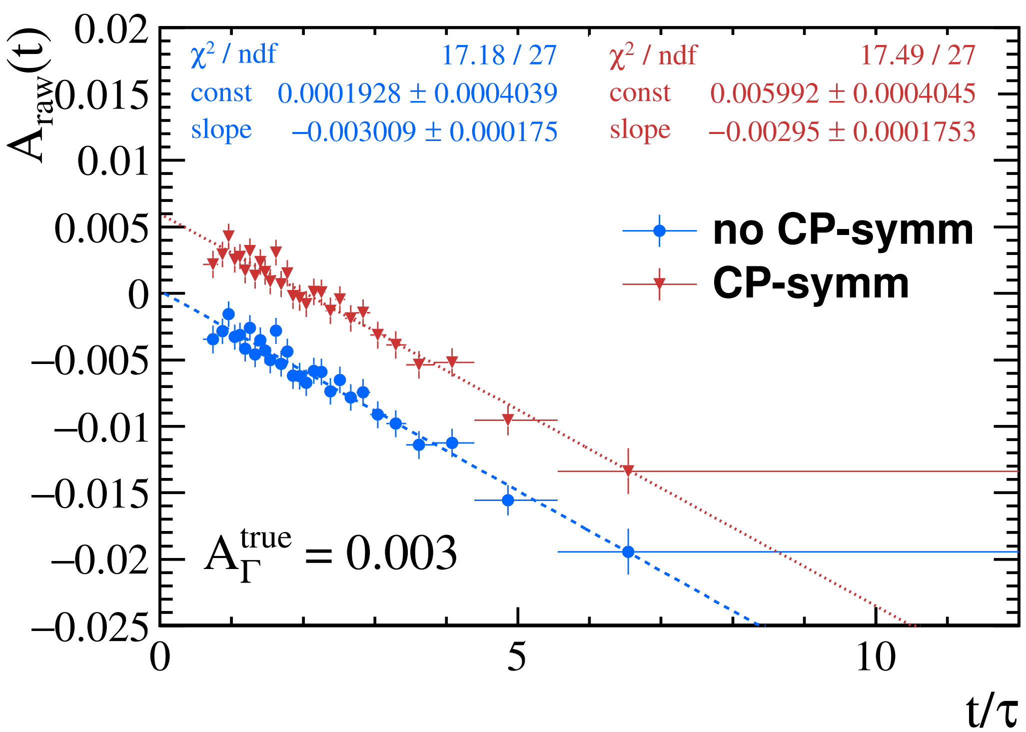
$\Delta\chi^2$ improves by 30 units.

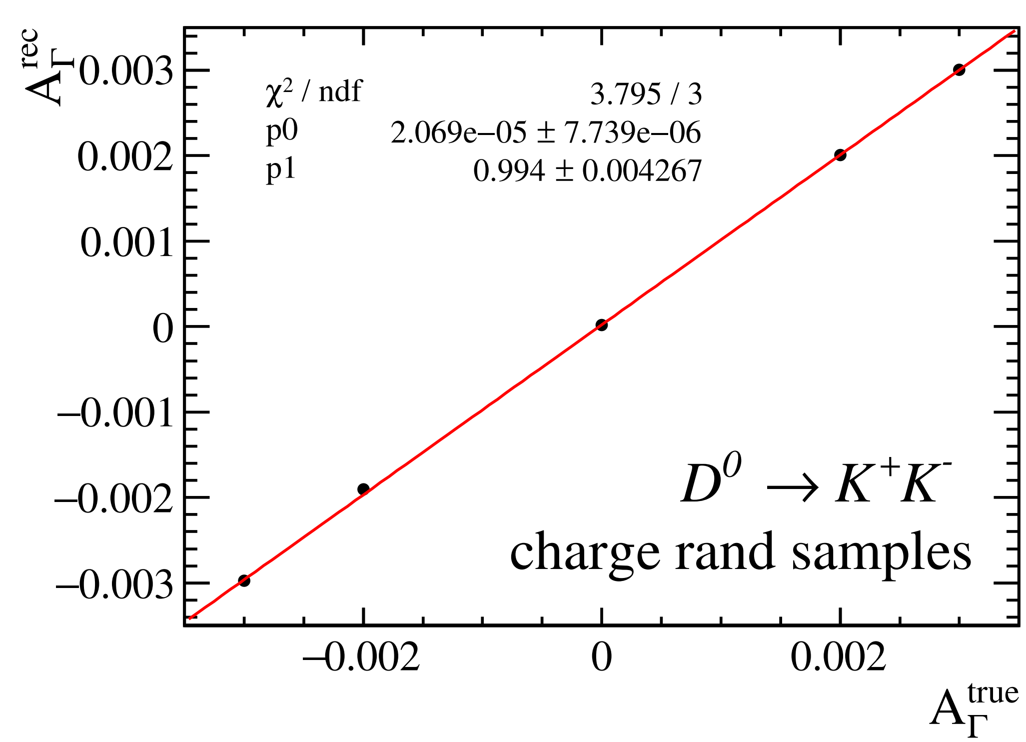
Individual fits are now compatible with the hypothesis of straight line.

Is A_Γ affected by the correction?

- The correction directly impacts the momentum charge asymmetry, and it may affect also physical asymmetry, as A_Γ. However, it can be demonstrated that neglecting third-order asymmetry terms ($A_{CP}\delta^2$, δ^3), A_Γ remains unchanged.

- Pseudo-experiments produced by injecting different fake values for A_Γ.





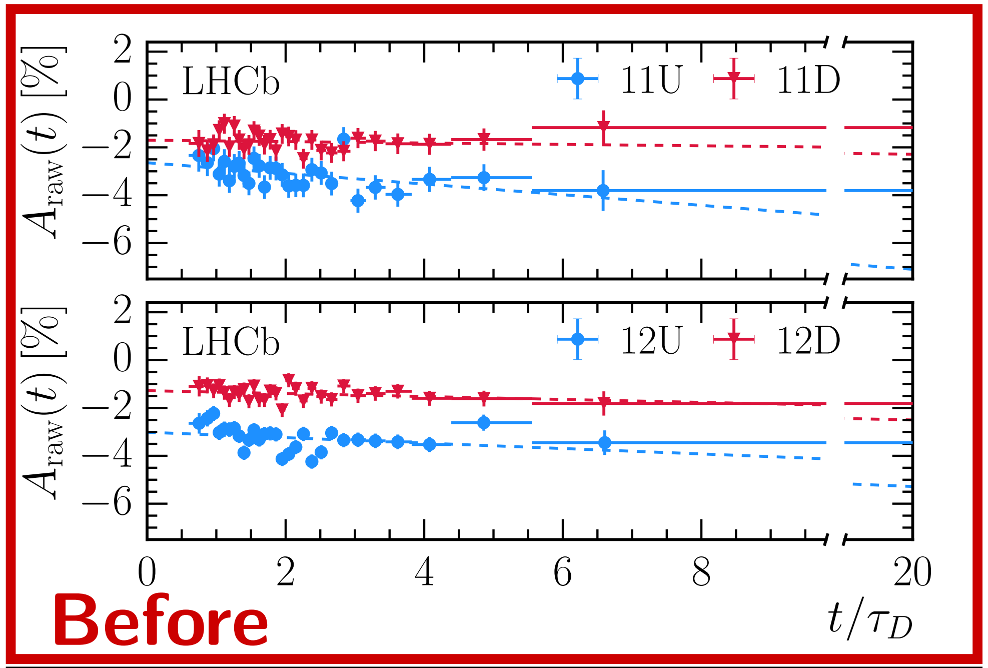
The measured value accurately tracks the input, and no bias is present in the procedure (checked up to a level of precision of 3% of the quoted statistical uncertainty).

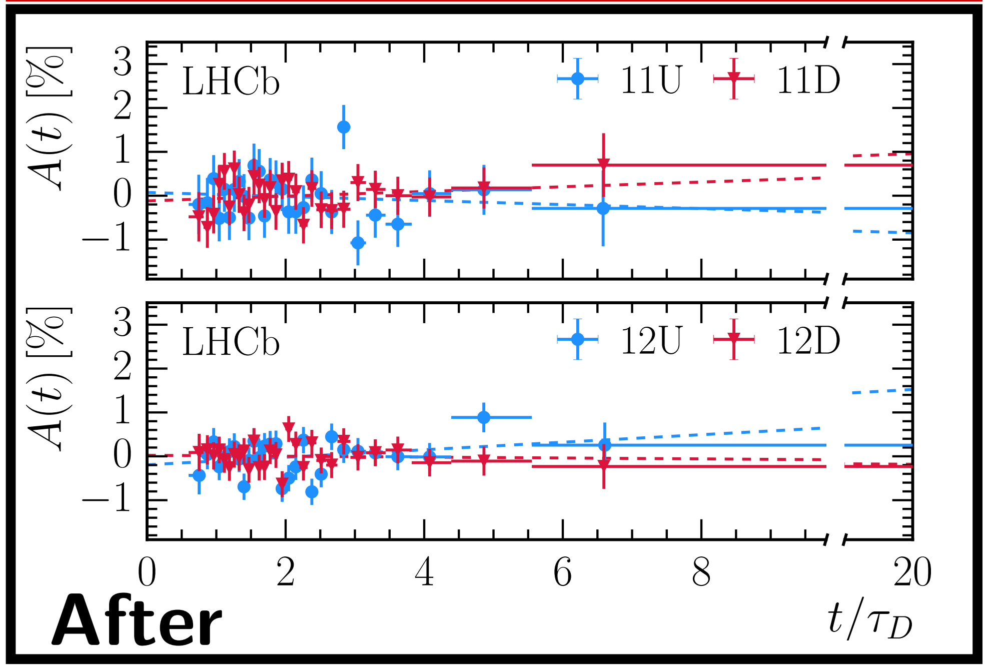
Results on A_Γ in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays

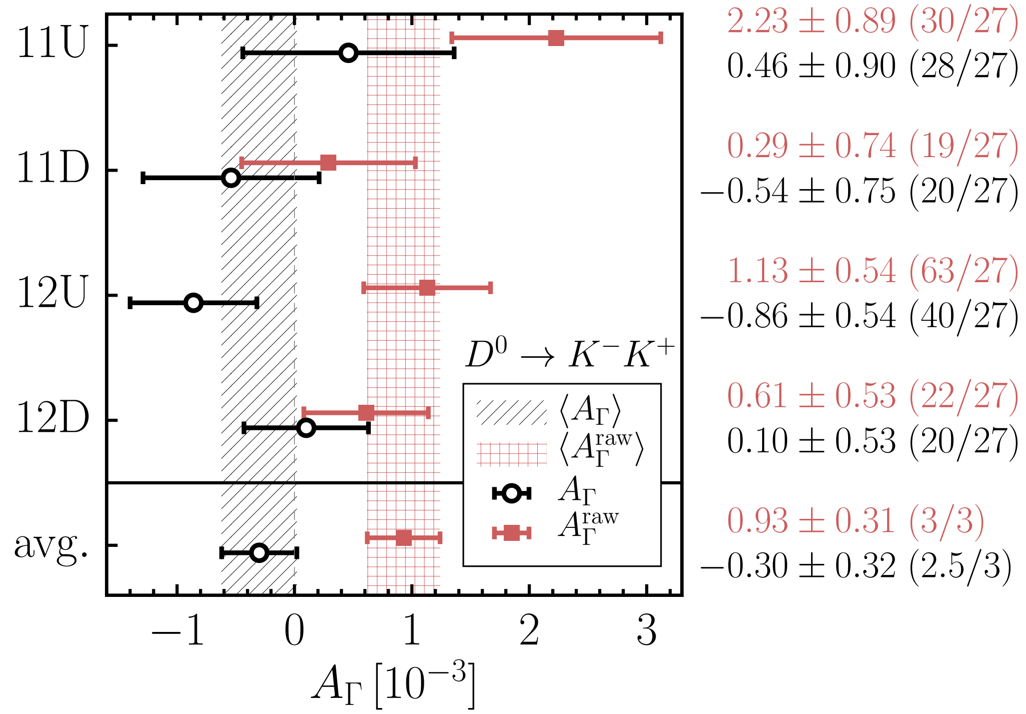
Same procedure used for the high statistics CF $D^0 \to K^-\pi^+$ control sample. Correction weights are independently extracted from its own data sample.

$A_\Gamma(D^0 \to K^+K^-)$ and $A_\Gamma(D^0 \to \pi^+\pi^-)$ blinded until the approval.

Results: $A_\Gamma(D^0 \to K^+K^-)$



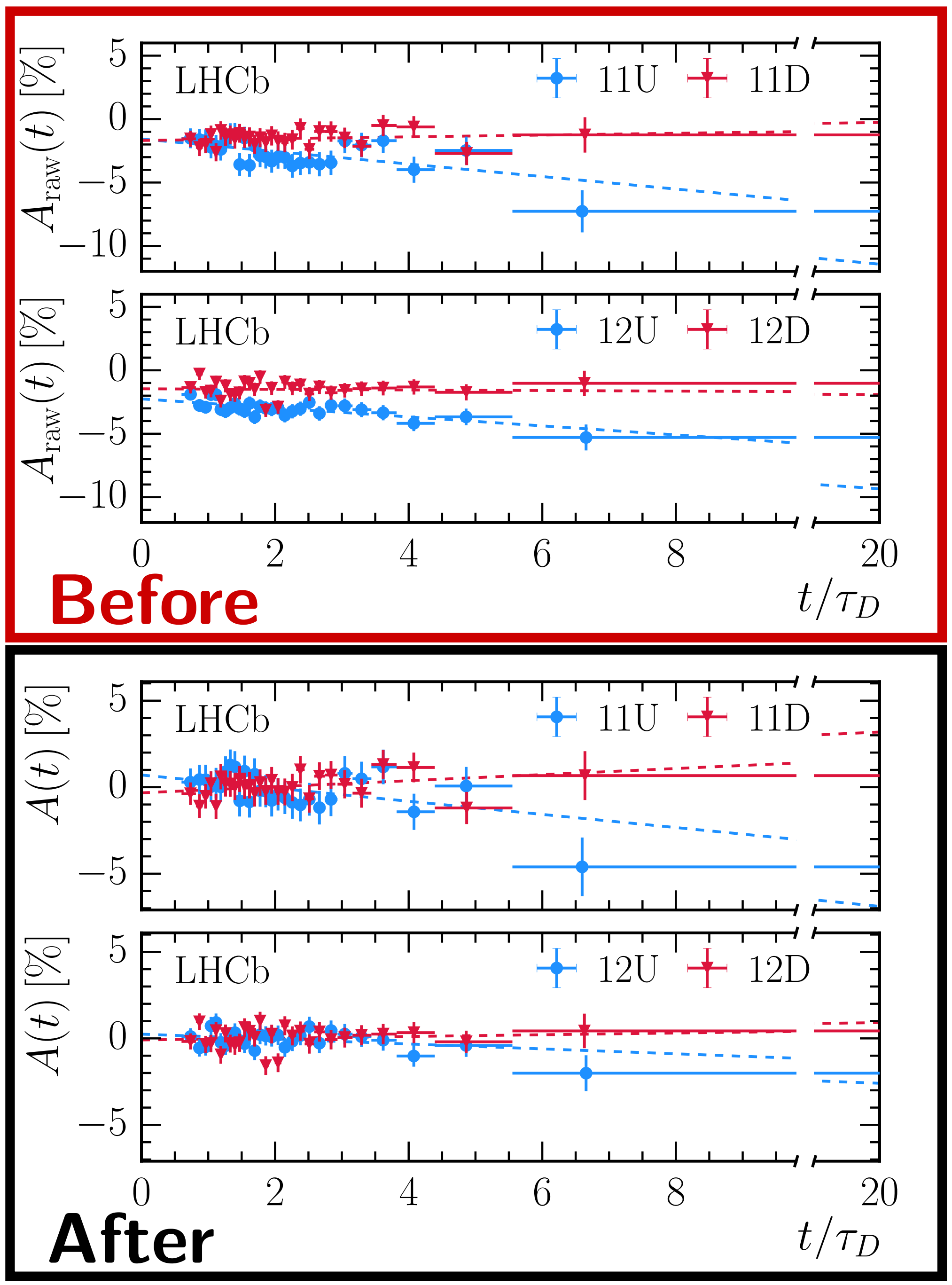


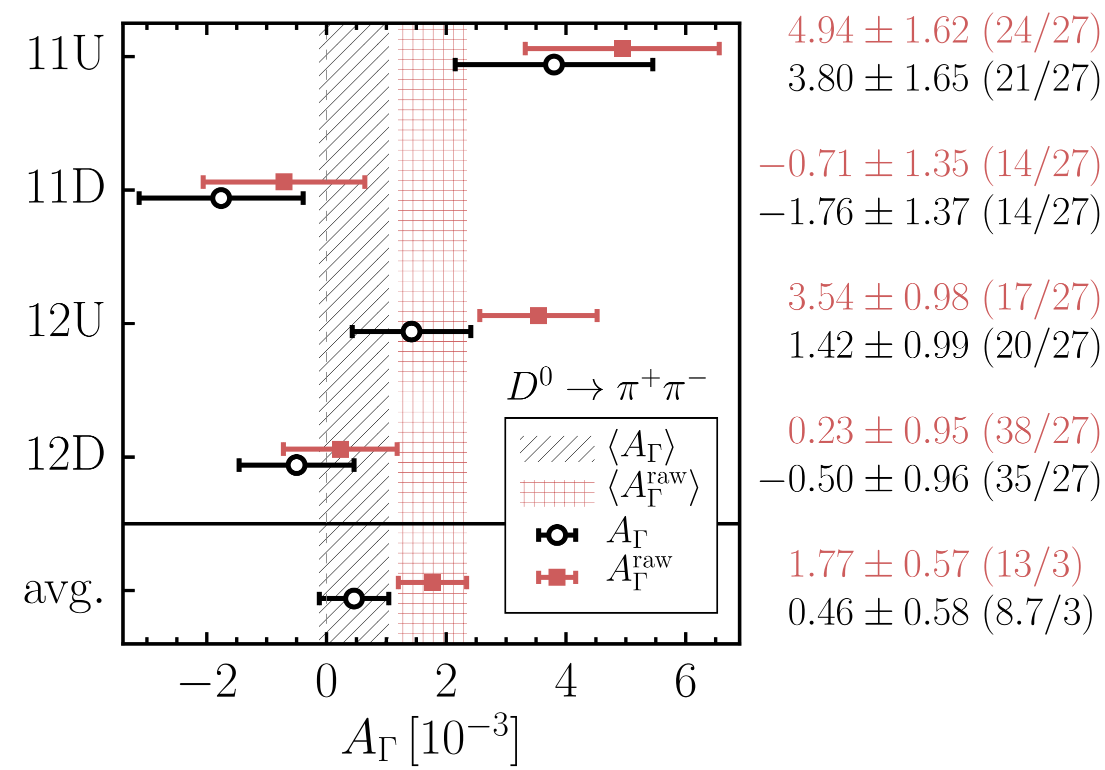


$$A_\Gamma(D^0 \to K^+K^-) = (-0.30 \pm 0.32) \times 10^{-3}$$

(stat. only)

Results: $A_\Gamma(D^0 \to \pi^+\pi^-)$



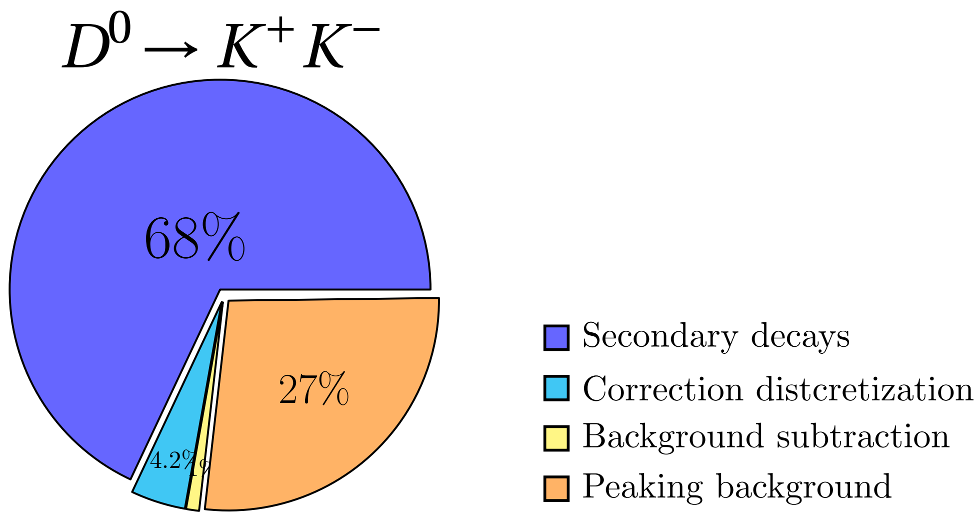


$$A_\Gamma(D^0 \to \pi^+\pi^-) = (\ \ 0.46 \pm 0.58) \times 10^{-3}$$

(stat. only)

Systematic uncertainties (in 10^{-3} units)

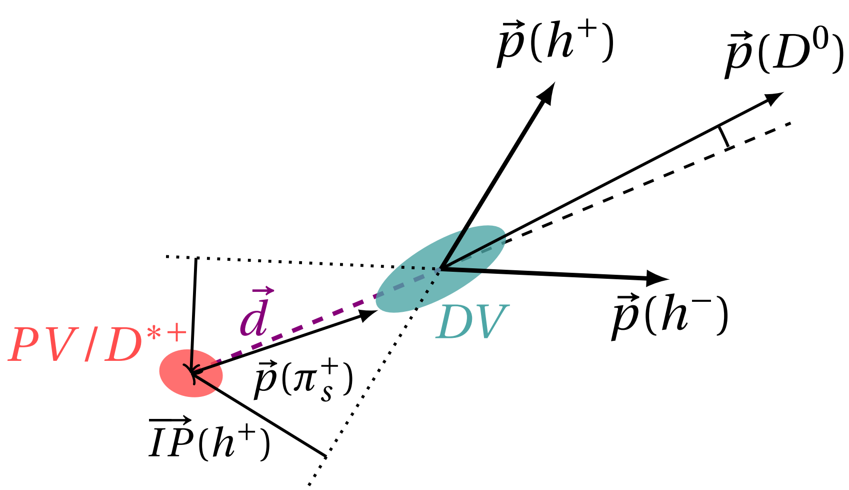
source	$D^0 \to K^+K^-$	$D^0 \to \pi^+\pi^-$
Secondary decays	0.08	0.12
Correction discretization	0.02	0.02
Background subtraction	0.01	0.01
Peaking background	0.05	-
Total	0.10	0.12



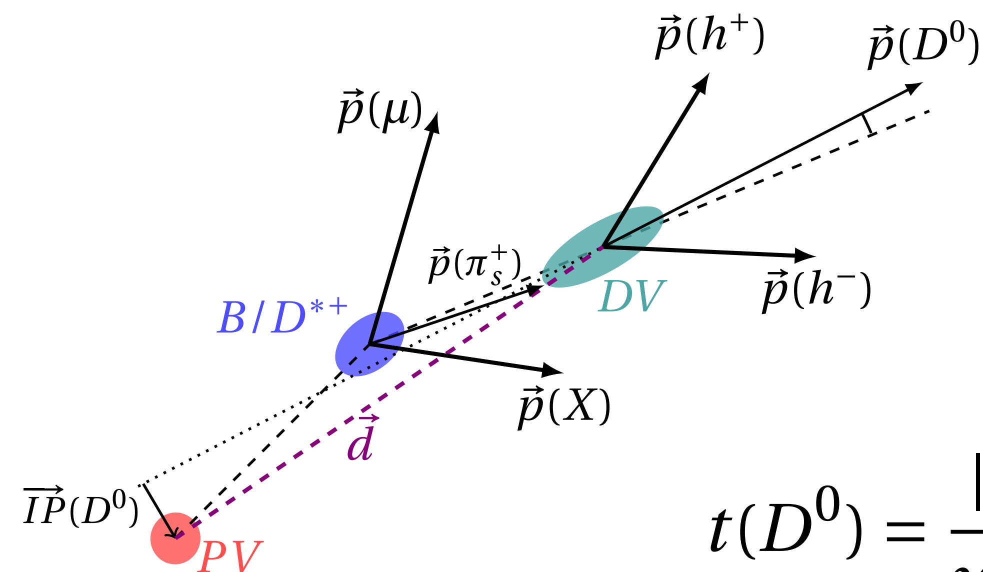
- **Secondary decays**: Bias due to the residual contamination of secondary decays.
- **Correction discretization**: A_Γ variations as a function of the number of bins of the correction (assumed to be constant over the bin).
- **Background subtraction**: uncertainty on Δm sideband subtraction procedure.
- **Peaking background**: impact of residual contaminations of partial- and mis-reconstructed D^0 decays peaking in Δm. Assessed using D^0 mass sideband.

Secondary decays

Prompt decays: signal



Secondary decays: backg.



$$t(D^0) = \frac{|\vec{d}|}{\gamma\beta c} = |\vec{d}|\frac{m_{D^0}}{p_{D^0}},$$

what we measure | prompt decays asym. | relative fraction of sec. | sec. decays asym.

$$A_{\mathrm{raw}}(t) = (1 - f_{\mathrm{sec}}(t))A_{\mathrm{ppt}}(t) + f_{\mathrm{sec}}(t)A_{\mathrm{sec}}(t)$$

Reconstructed decay times of charm mesons that originate from weak decays of b hadrons (secondary decays) are biased towards positive values.

The challenge of secondaries

- Bias due to the presence of D^{*+} decays generated in secondary decay vertices of bottom hadrons needs to be accurately accounted for.
    - even if the contamination is reduced to a few percent by requiring the reconstructed D^0 momentum to point back to the PV and $\chi^2_{IP}(D^0) < 9$.
- The relative contribution of secondary component grows with the observed decay time of the charm meson, and it may have an intrinsic production asymmetry different from promptly produced D^* particles, leading to a potential bias on the A_Γ measurement.
- The complexity and tightness of the data selection makes it difficult to obtain absolute estimates of $f_{sec}(t)$ and $A_{sec}(t)$ purely from Monte Carlo simulations with the required precision, while a purely data-driven extraction is also subject to significant uncertainties. Therefore, a mixed approach was adopted.

Model of secondary decays

- The absolute number of secondary decays $n_{sec}(t)$, as a function of proper decay time, can be determined with a good level of approximation just using a simple analytical approach, with some reasonable assumptions:
  - $B \to D^{*}X \to [D^{0}\pi]X$ decay occurs linearly along the z-direction (b-hadrons decays have a large boost in the z);
  - "same" acceptance function on proper decay time both for prompt and secondary decays, that can be extracted from data sculpting at lower values of proper time;
- Absolute normalizations come from $\chi^{2}_{IP}(D^{0})$ fit of the last four higher time bins, removing the analysis requirement $\log[\chi^{2}_{IP}(D^{0})] < 2.2$ cut.
- $A_{sec}(t)$ extracted from an almost pure sample of secondary decays, obtained by inverting the cut on $\chi^{2}_{IP}(D^{0})$, requiring $\log[\chi^{2}_{IP}(D^{0})] > 4$.

Analytical model for $f_{sec}(t)$

Prompt model:

$$\mathscr{P}_{\rm ppt}(t) = \mathscr{P}_{D^0}(t) = \frac{1}{\tau_{D^0}} \exp\left[-\frac{t}{\tau_{D^0}}\right] \quad (t \geq 0).$$

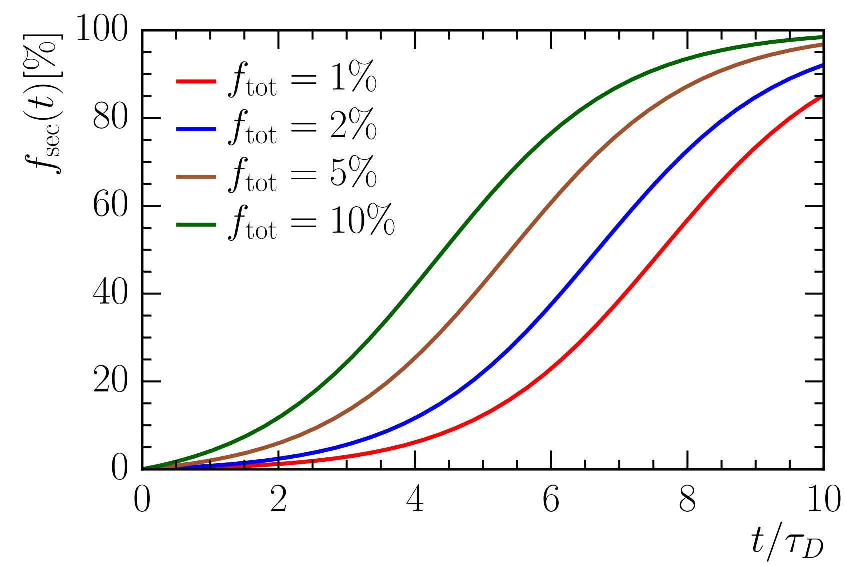
Secondary model:

$$\mathscr{P}_{\rm sec}(t) = (\mathscr{P}_B * \mathscr{P}_{D^0})(t) =$$
$$= \int_0^\infty \frac{1}{\tau_B} \exp\left[-\frac{t-t'}{\tau_B}\right] \cdot \frac{1}{\tau_{D^0}} \exp\left[-\frac{t'}{\tau_{D^0}}\right] \mathrm{d}t'$$
$$= \frac{\exp\left[-\frac{t}{\tau_B}\right] - \exp\left[-\frac{t}{\tau_{D^0}}\right]}{\tau_B - \tau_{D^0}} \quad (t \geq 0);$$

Absolute normalizations from data, using bins at higher proper time

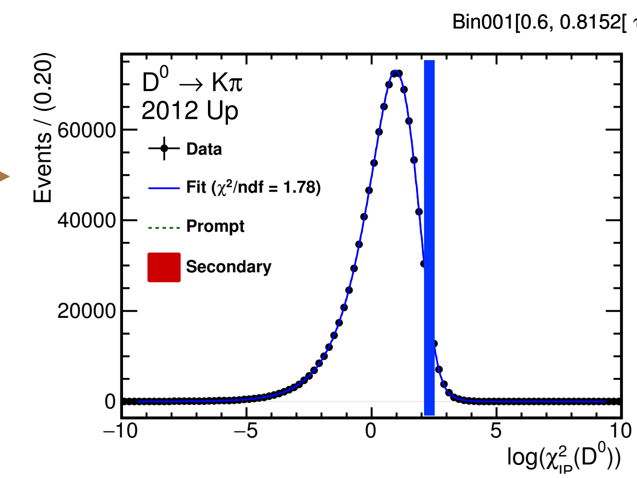
Acceptance from data, assuming to be the same for prompt and secondaries.

$$f_{\rm sec}(t) = \frac{n_{\rm sec} \cdot A(t)\mathscr{P}_{\rm sec}(t)}{n_{\rm ppt} \cdot A(t)\mathscr{P}_{\rm ppt}(t) + n_{\rm sec} \cdot A(t)\mathscr{P}_{\rm sec}(t)}$$



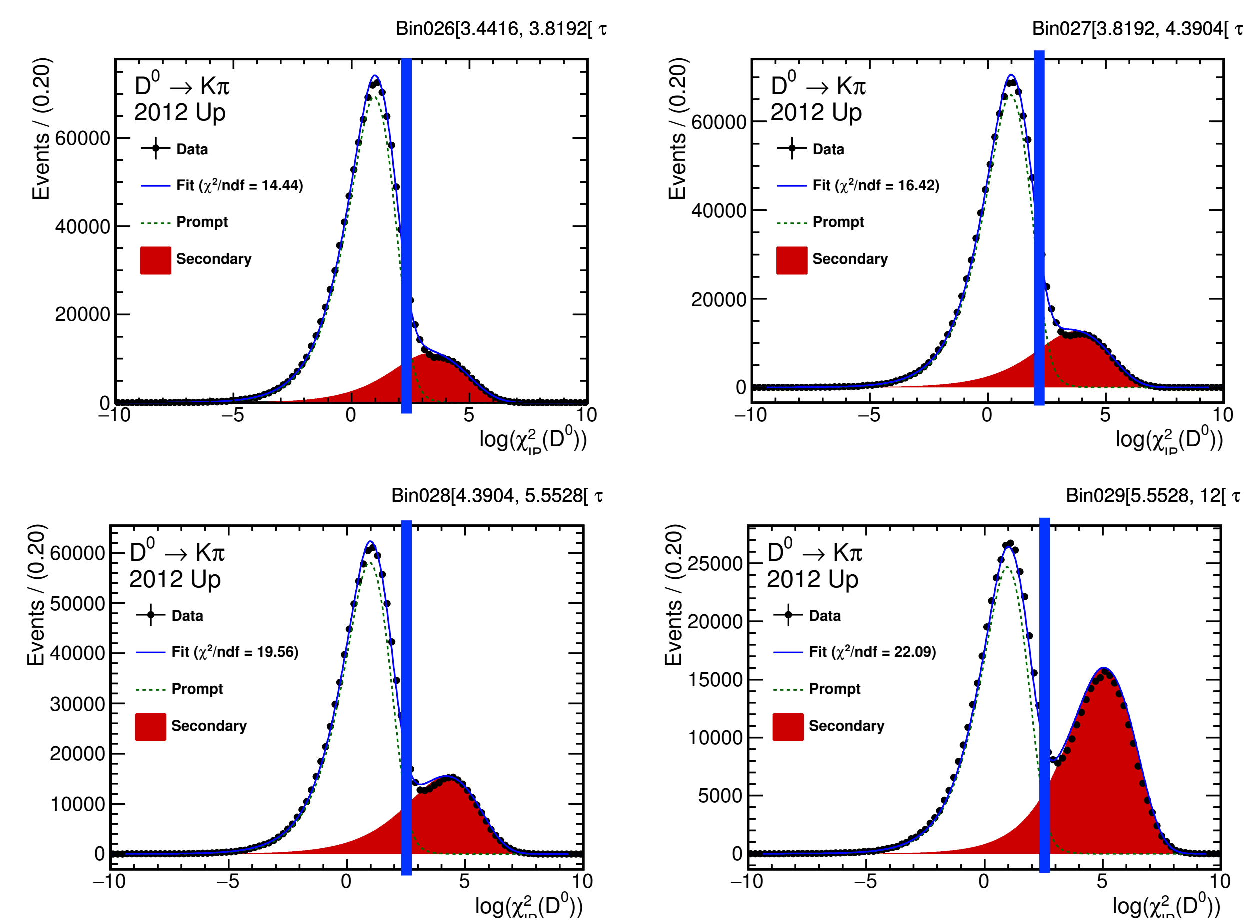
Absolute normalization $f_{sec}(t)$

Model of prompt component determined from the first bin of the proper decay time distribution. Expected negligible contamination there. Assumed to be the same in each time bin.

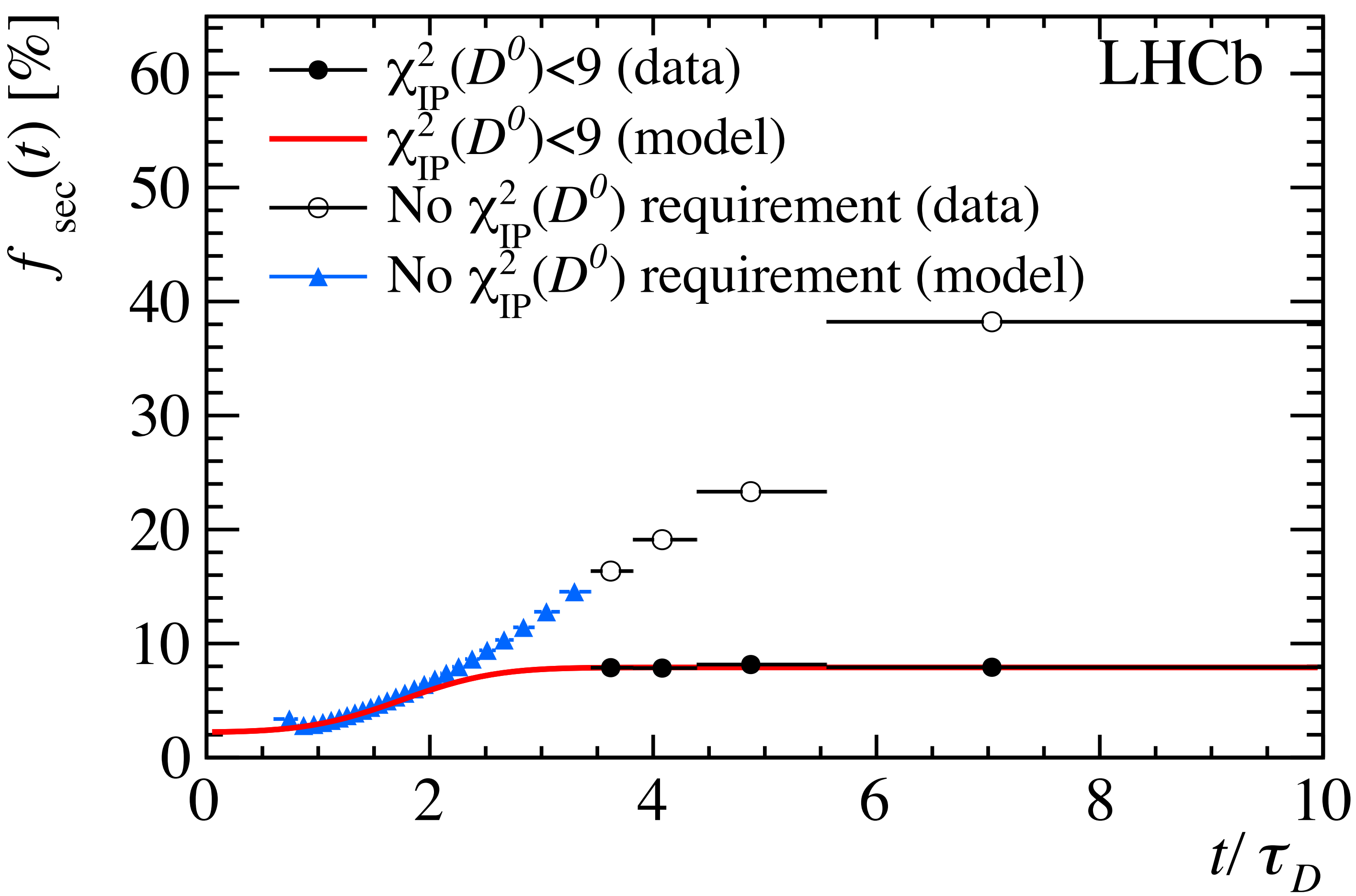


Fit to the last four bins (higher decay time), where the measurement of $f_{sec}(t)=n_{sec}(t)/n_{tot}(t)$ is much more reliable, being the relative fraction of secondary decays large and the two separate peaks are clearly visible (red bumps).

While quality of the fits is not excellent, it is totally satisfactory for the purpose of assessing a systematic uncertainty.



$f_{sec}(t)$ model



Empirical approximation of $f_{sec}(t)$ (red curve). It does intersect black dots (data) at higher decay time values and tends to the normalized analytical model (blue triangles) at lower decay time, where sculpting due to $\chi^2_{IP}(D^0)$ cut disappears.

Secondary decays syst.

1000 pseudo-experiments by varying $A_{raw}(t_i)$ within their Gaussian statistical uncertainties, in order to determine prompt asymmetry in each time bins. Account for uncertainties on $f_{sec}(t)$ model, $A_{sec}(t)$ determination, and contribution for a nonzero A_Γ.

$$A_{\mathrm{ppt}}(t_i) = \frac{1}{1 - f_{\mathrm{sec}}(t_i)} \left(A_{\mathrm{raw}}(t_i) - f_{\mathrm{sec}}(t_i) A_{\mathrm{sec}}(t_i)\right)$$

in unit of 10^{-3}

sample	Δ	σ_{A_Γ}	$\sigma_{A_{\mathrm{sec}}}$	$\sigma_{f_{\mathrm{sec}}}$	$\sqrt{\Delta^2 + \sigma^2_{A_\Gamma} + \sigma^2_{A_{\mathrm{sec}}} + \sigma^2_{f_{\mathrm{sec}}}}$
$D^0 \to K^-\pi^+$	0.094	0.008	0.012	0.035	0.101
$D^0 \to K^+K^-$	0.065	0.022	0.012	0.041	0.081
$D^0 \to \pi^+\pi^-$	0.113	0.041	0.012	0.026	0.123

Assessed the full size of the effect (~10^{-4}) as systematic uncertainty (syst. << stat.).

It may be reduced (already today) by a factor greater than 2, applying the correction instead of taking the full size of the effect. A factor of 10 of reduction is clearly achievable by increasing the statistics (see $D^0 \to K^-\pi^+$ line).

Final results

Final *word* of LHCb on A_Γ with Run 1 data sample ($3\,\mathrm{fb}^{-1}$):

$$A_\Gamma(D^0 \to K^+K^-) = (-0.30 \pm 0.32 \pm 0.10) \times 10^{-3},$$
$$A_\Gamma(D^0 \to \pi^+\pi^-) = (\;\;0.46 \pm 0.58 \pm 0.12) \times 10^{-3},$$
$$A_\Gamma(KK + \pi\pi) = (-0.13 \pm 0.28 \pm 0.10) \times 10^{-3}.$$

Most precise measurement of CPV in the charm sector.
Most precise measurement of the LHCb experiment.

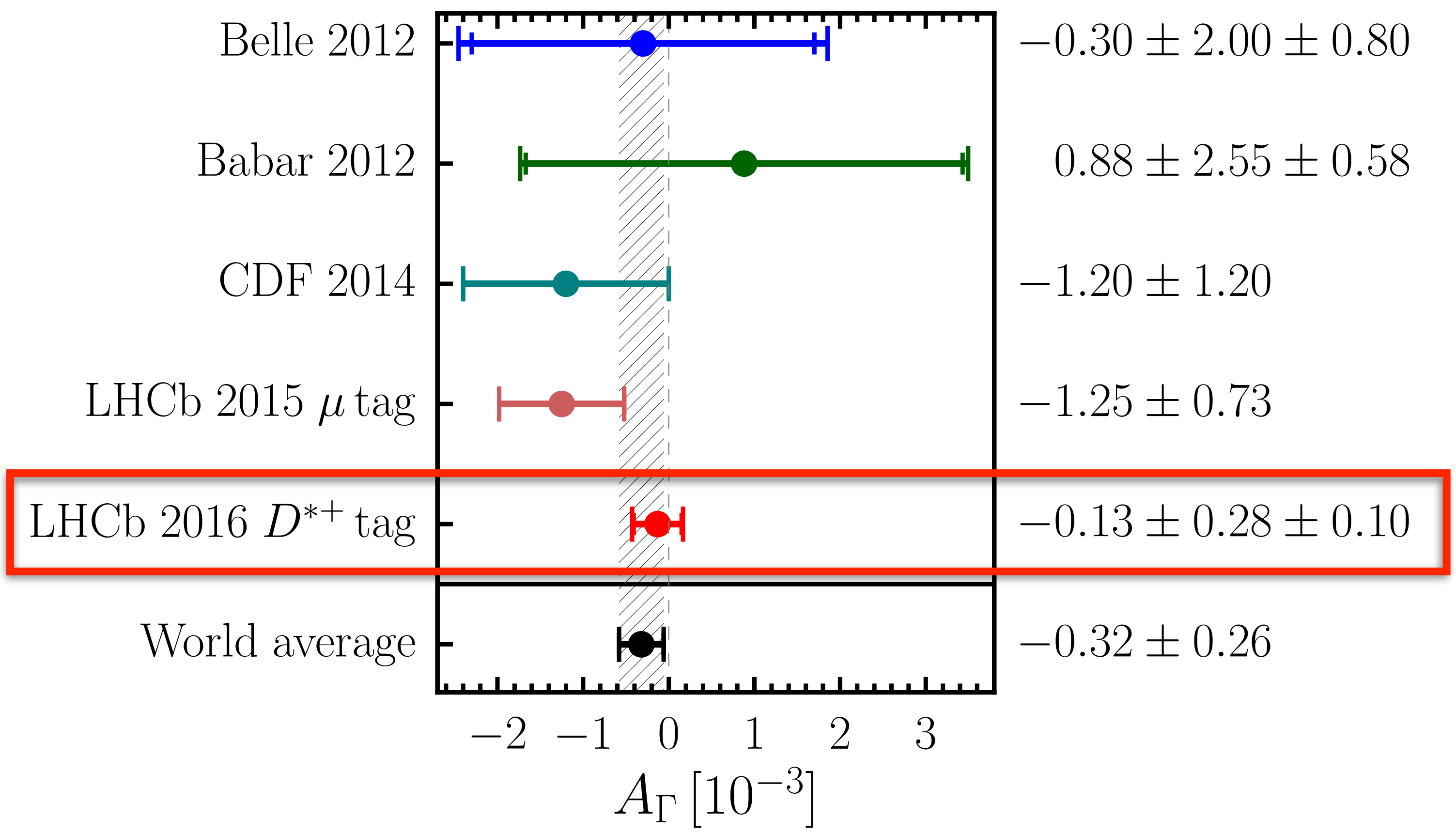
Measurement of the CP violation parameter A_Γ in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays

LHCb collaboration
Authors are listed at the end of this Letter.
(Dated: April 21, 2017)

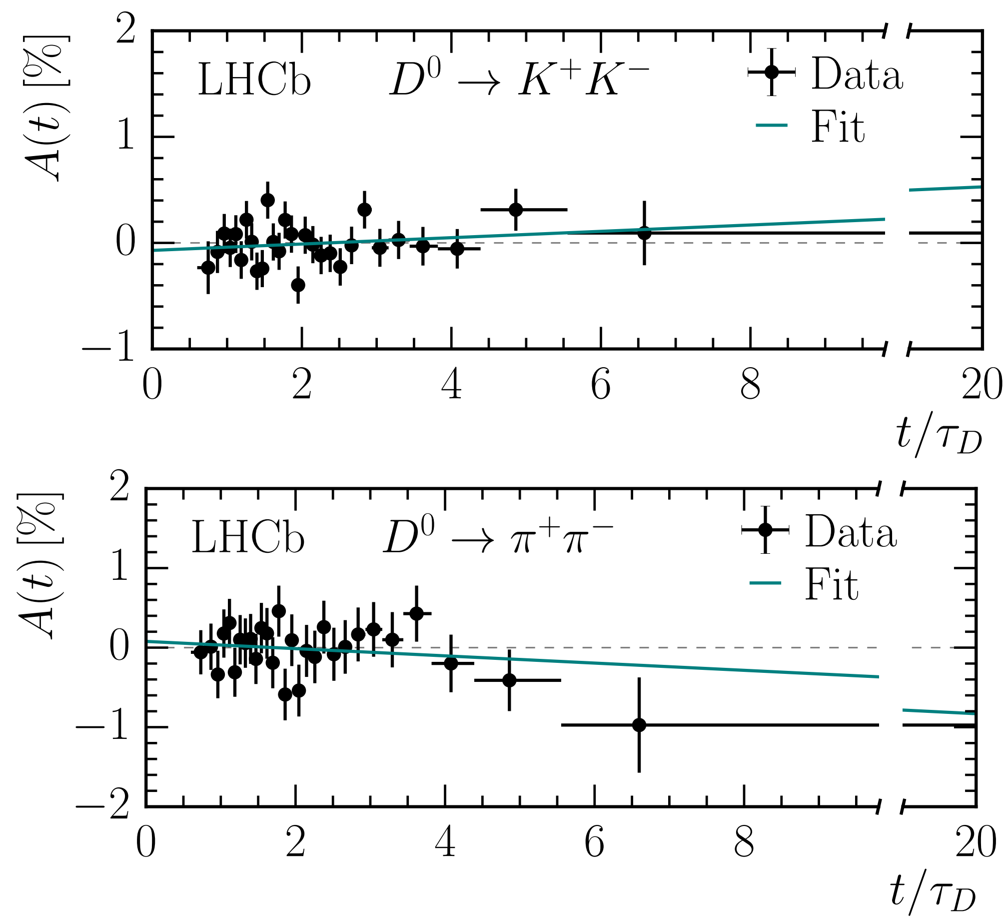
Asymmetries in the time-dependent rates of $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays are measured in a pp collision data sample collected with the LHCb detector during LHC Run 1, corresponding to an integrated luminosity of $3\,\mathrm{fb}^{-1}$. The asymmetries in effective decay widths between D^0 and $\overline{D}^0$ decays, sensitive to indirect CP violation, are measured to be $A_\Gamma(K^+K^-) = (-0.30 \pm 0.32 \pm 0.10) \times 10^{-3}$ and $A_\Gamma(\pi^+\pi^-) = (0.46 \pm 0.58 \pm 0.12) \times 10^{-3}$, where the first uncertainty is statistical and the second systematic. These measurements show no evidence for CP violation and improve on the precision of the previous best measurements by nearly a factor of two.

Accepted for publication to PRL arXiv:1702.06490 [hep-ex]

Final results



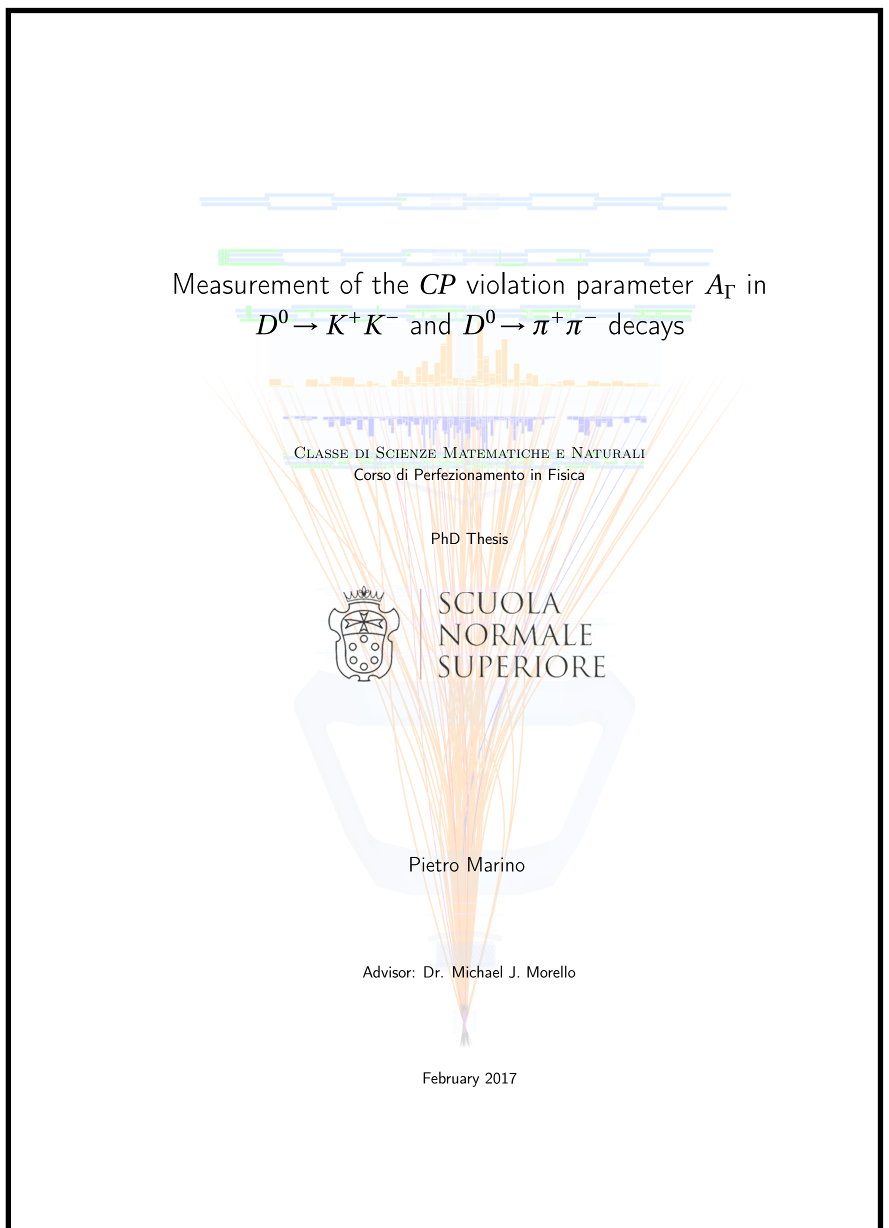
arXiv:1702.06490 [hep-ex].



No sign of indirect CP violation at the level of 2.6×10^{-4}.

The LHCb-Pisa role

CERN-THESIS-2017-007



Measurement of the CP violation parameter A_Γ in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays

Classe di Scienze Matematiche e Naturali
Corso di Perfezionamento in Fisica

PhD Thesis

SCUOLA NORMALE SUPERIORE

Pietro Marino

Advisor: Dr. Michael J. Morello

February 2017

Main authors:
P. Marino, MJM, and G. Punzi

Direct CPV: $\Delta A_{CP}(D^0 \to h^+h^-)$

- Effects of "direct" CP violation can be isolated by taking the difference between the time-integrated CP asymmetries in the K^+K^- and $\pi^+\pi^-$ modes:

$$\begin{aligned} \Delta A_{\mathrm{CP}} &\equiv A_{\mathrm{CP}}(D^0 \to K^+K^-) - A_{\mathrm{CP}}(D^0 \to \pi^+\pi^-) \\ &\approx \Delta A_{\mathrm{CP}}^{\mathrm{dir}} \left(1 + y_{\mathrm{CP}} \frac{\overline{\langle t \rangle}}{\tau}\right) + A_{\mathrm{CP}}^{\mathrm{ind}} \frac{\Delta \langle t \rangle}{\tau} \end{aligned}$$

- where a residual experiment-dependent contribution from indirect CP violation can be present, due to the fact that there may be a decay time dependent acceptance function that can be different for the K^+K^- and $\pi^+\pi^-$ channels.

- Well suited for LHCb because of cancellation of instrumental and production asymmetries. Measurement performed using both D*-tag *[PRL 116, 191601 (2016)]* and semi-leptonic $B \to D^0 \mu X$ *[JHEP 07 (2014) 041]* decays.

D*-tag: $\Delta A_{CP} = (-0.10 \pm 0.08\ (\mathrm{stat}) \pm 0.03\ (\mathrm{syst}))\ \%$

μ-tag: $\Delta A_{CP} = (+0.14 \pm 0.16\,(\mathrm{stat}) \pm 0.08\,(\mathrm{syst}))\%$

LHCb dominates the world average with systematics well below statistical uncertainty.

The impact on LHCb on CP Violation of $D^0 \rightarrow h^+h^-$ decays in Run 1

From HFAG 2016 the world average values are:

$$\begin{aligned} A_{\rm CP}^{\rm ind} &= (\ \ 0.30 \pm 0.26) \times 10^{-3} \\ \Delta A_{\rm CP}^{\rm dir} &= (-1.34 \pm 0.70) \times 10^{-3} \end{aligned}$$

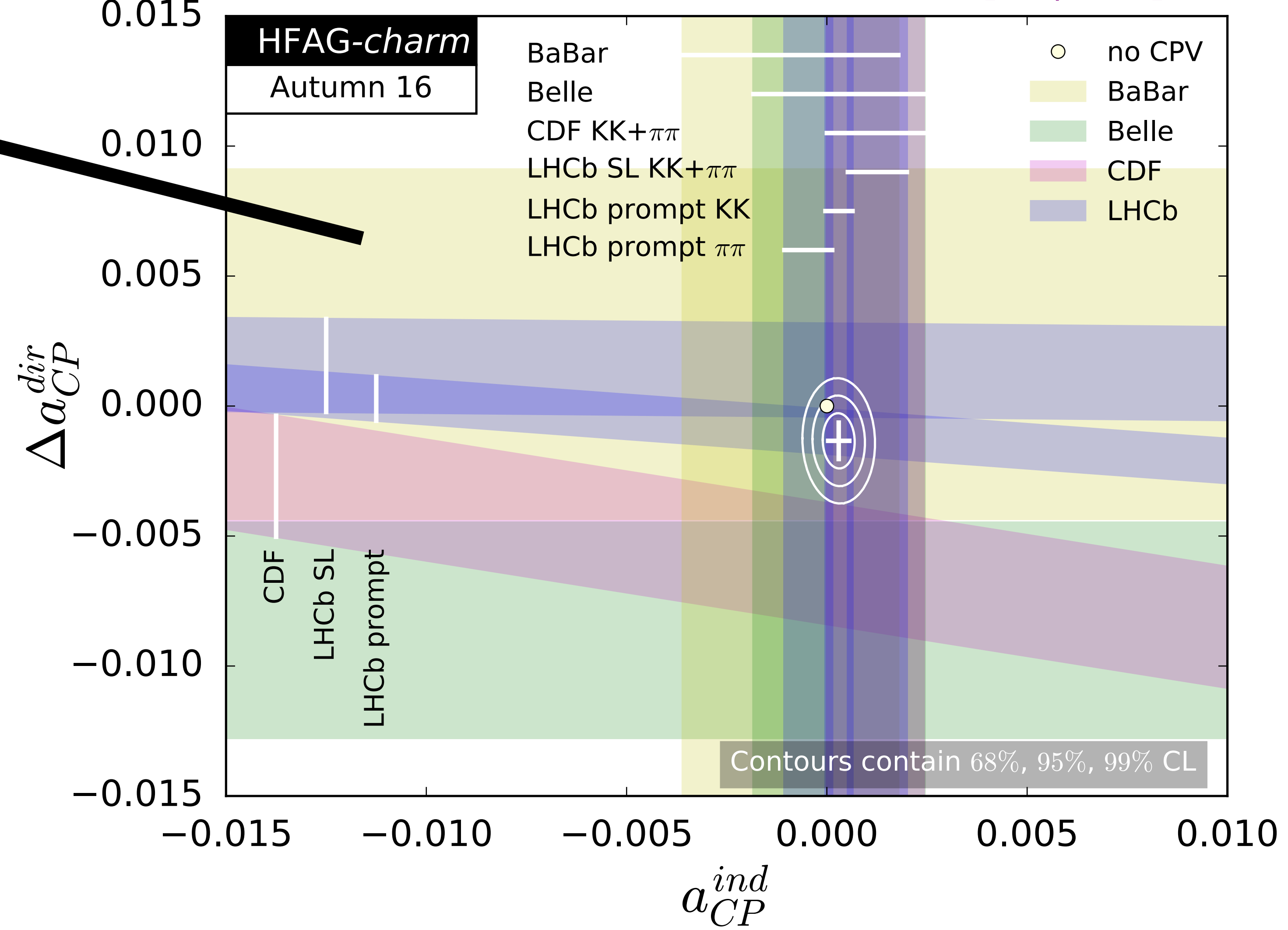
Consistent with the hypothesis of CP symmetry with a p-value of 9.3% (1.7$\boldsymbol{\sigma}$)

My “unofficial” LHCb-only average:

$$\begin{aligned} A_{\rm CP}^{\rm ind} &= (\ \ 0.29 \pm 0.28) \times 10^{-3} \\ \Delta A_{\rm CP}^{\rm dir} &= (-0.56 \pm 0.76) \times 10^{-3} \end{aligned}$$

Consistent with the hypothesis of CP symmetry with a p-value of 79%.

HFAG 2016 arXiv:1612.07233 [hep-ex]



LHCb dominates the world average and much more data are coming.

LHCb & Charm today

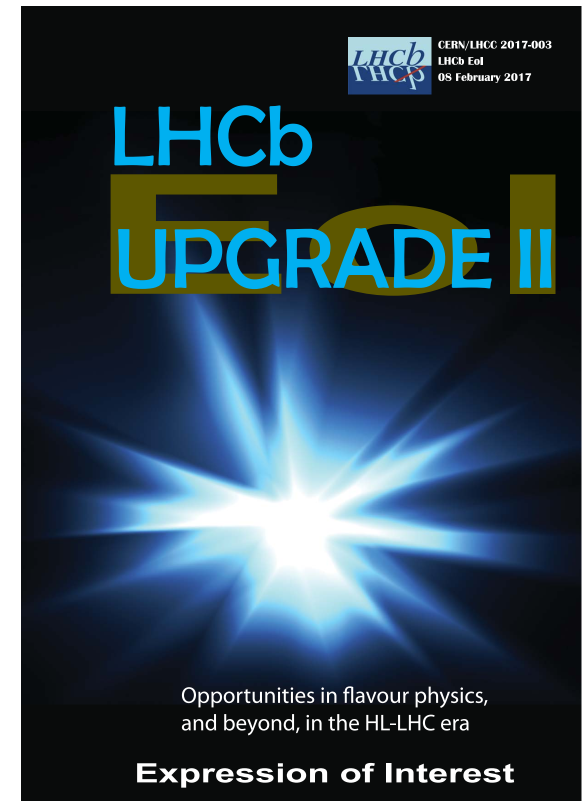
- LHC is a super-duper charm-factory, and LHCb is doing an excellent job collecting the largest ever charm samples.
- Already achieved statistical precision well below 10^{-3}, and systematic uncertainties better than 10^{-4} (especially for two-body golden modes)
- LHCb covers a broad program, with many world leading measurements
  - on multi-body charm decays where CPV can be studied through the phase space (local asymmetries larger than integrated ones),
  - and on rare decays ($D^0 \to \mu^+\mu^-$, $D^0 \to \pi^-\pi^+\mu^-\mu^+$, $D^+_{(s)} \to \pi^+\mu^+\mu^-$, $D^0 \to e\mu$, etc..) where limits from other experiments were already improved by orders of magnitude with only Run 1 data,
  - promising results with neutrals ($D^+_{(s)} \to \eta' \pi^+$) and with long-lived particles (K_s,K_L,Λ) in the final state.
- No hints of CP-violation found so far, just started to barely approach SM expectations.

Future perspectives

- The Run 2 (2015-2018, ~8fb^{-1}) is currently ongoing and the size of LHCb samples already increased more than proportionally to the integrated luminosity.

- Phase1 LHCb-Upgrade at L = 2x10^{33} cm^{-2}s^{-1}. (2020-29, ~50fb^{-1}) is behind the corner.

- A proposal of a Phase 2 LHCb-Upgrade at L >10^{34} cm^{-2}s^{-1} (2031-??, >300fb^{-1}) is currently under discussion.



CERN-LHCC-2017-003

http://agenda.infn.it/event/LHCb-FU

>300 fb^{-1} of data implies $\sigma_{stat}(A_\Gamma) < 3 \times 10^{-5}$.
I hope I convinced you that no systematic walls are in front of us to get such a precision.

thank you

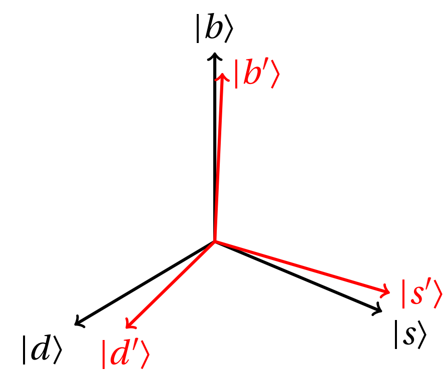
Backup

Abstract

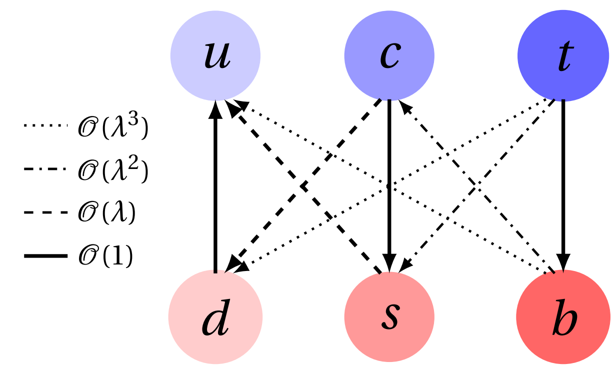
Charm hadrons provide the only sector involving up-type quarks where CP violation effects are expected to be observable. This uniqueness makes CP violation in charm particularly important to study, as it might be sensitive to effects beyond the Standard Model, which could leave other quarks unaffected. Asymmetry in the time-dependent rates of singly Cabibbo-suppressed $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays, the so called A_Γ parameter, is one of the most sensitive probe for indirect CP violation in the charm sector and can potentially be measured with great precision. The recent measurement of the A_Γ parameter with pp collision data collected by LHCb experiment in Run 1, corresponding to an integrated luminosity of 3 fb^{-1}, is presented here. This is the most precise measurement of a CP asymmetry in the charm sector, with a statistical uncertainty reaching the sub-permille level and systematic uncertainties below the unprecedented level of 10^{-4}. Innovative experimental methodologies and new data analysis techniques have been used to achieve such a result, with the aim of allowing measurements of CP violation at even better precision in the near and far future experiments. Perspectives for CP violation searches in the charm sector with Run 2 data and beyond are also discussed.

CKM Matrix

$$\boldsymbol{V}_{\text{CKM}} \equiv \boldsymbol{V}_{uL}\boldsymbol{V}_{dL}^{\dagger} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$



(a) Quark mass eigenstates interactions representation.



(b) Mass and interaction eigenstates decay scheme.

$$\boldsymbol{V}_{\text{CKM}} = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix}$$

$$\lambda = s_{12}, \quad A\lambda^2 = s_{23}, \quad A\lambda^3(\rho - i\eta) = s_{13}\mathrm{e}^{-i\delta}$$

$$\lambda = |V_{us}| \approx 0.22$$

$$\boldsymbol{V}_{\text{CKM}} = \begin{bmatrix} 1 - \frac{1}{2}\lambda^2 - \frac{1}{8}\lambda^4 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda + \frac{1}{2}\lambda^5 A^2(1 - 2(\rho + i\eta)) & 1 - \frac{1}{2}\lambda^2 - \frac{1}{8}\lambda^4(1 + 4A^2) & A\lambda^2 \\ A\lambda^3[1 - (\rho + i\eta)] + \frac{1}{2}\lambda^5 A(\rho + i\eta) & -A\lambda^2 + \frac{1}{2}\lambda^4 A(1 - 2(\rho + i\eta)) & 1 - \frac{1}{2}\lambda^4 A^2 \end{bmatrix} + \mathcal{O}(\lambda^6)$$

Mixing phenomenology

meson system	$\Delta M/\Gamma$	$\Delta\Gamma/(2\Gamma)$
K^0–$\overline{K}^0$	−0.95	0.99
D^0–$\overline{D}^0$	0.005	0.006
B^0–$\overline{B}^0$	0.77	−0.001
B_s^0–$\overline{B}_s^0$	26.7	0.06

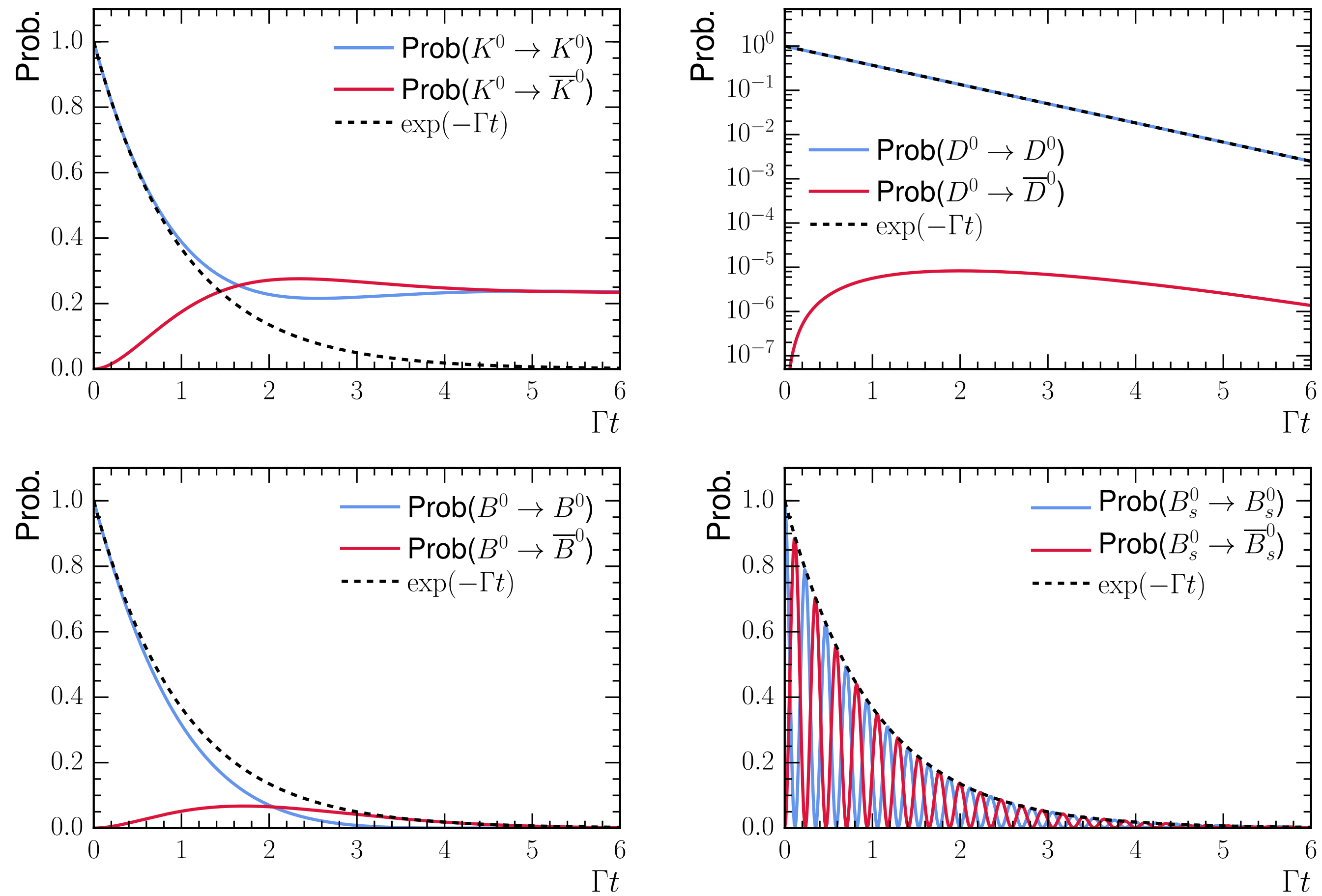
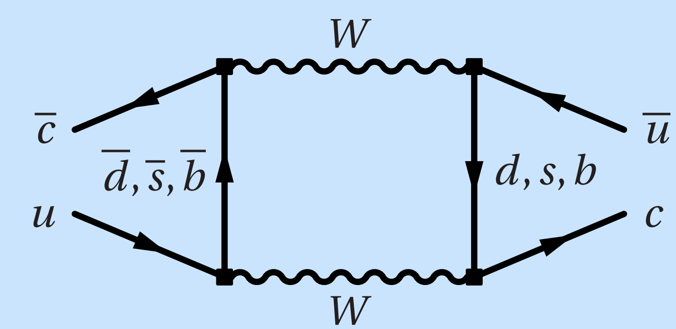


Figure 1.6 – Flavour-changing and flavour-unchanging PDFs for the four neutral meson systems (from left to right and from top to bottom): K^0–$\overline{K}^0$, D^0–$\overline{D}^0$ (note the logarithmic scale), B^0–$\overline{B}^0$, B_s^0–$\overline{B}_s^0$. The single exponential function, black-dashed line, it is also drawn.

SM predictions

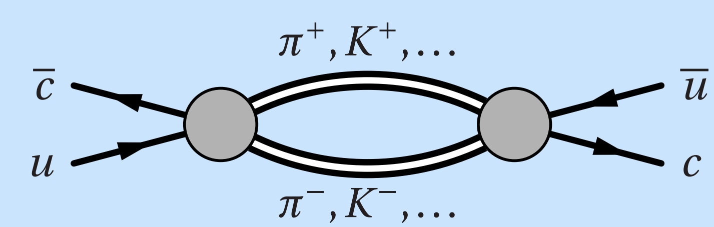
- Affected by "large uncertainties" due to the difficulties in the computation of the long-distance contributions:
  - non perturbative calculation (approximations holding in the B and K cases do not apply for charm)
  - the available computational power is not yet enough for lattice QCD.
- Inclusive approaches (i.e. Heavy Quark Effective Field Theory) rely on expansions in powers of $O(1/m_c)$, which are of limited validity because the intermediate value of the charm quark mass.
- Exclusive approaches rely on explicitly accounting for all possible intermediate states, which may be modeled or fitted directly to experimental data.
  - However, the D meson is not light enough to have few final states, and in absence of sufficiently precise measurements of amplitudes and strong phases of many decays, several assumptions are made limiting the predictions.

Short distance



intermediate state massive off-shell W
mainly contributing to $\Delta m = 2M_{12}$
strongly suppressed
x,y predicted to be ~10^{-6} (very far from %)

Long distance



intermediate state on–shell light quarks
can travel from interaction point
mainly contributing to $\Delta\Gamma = 2\Gamma_{12}$
precise calculations are difficult

Experiments and theory

- Only very recently experiments able to collect large and pure samples of charm decays. High precision measurements already have been impacting theory and vice-versa.
  - D^0-mixing rate is slow, but not so slow to be “unmeasurable” as believed in the recent past.
  - The widely accepted statement *“measuring CPV with the current experimental sensitivity is a clear sign of NP”* has been disavowed and, as a consequence, accuracy on calculations tremendously increased to account for experimental inputs.
- Predictive power of the theory is (and will be) strictly related to the precision and the variety of the inputs that experiments will be able to provide in the near and far future.
- An extensive and precise study of the charm decays, and in general of the heavy flavour physics, at much higher precision than today is fundamental to over-constrain the theory parameters, and in particular the CKM scheme, that is a crucial ingredient for the SM and for any new exotic theory, which must include the flavour structure.

$A_{CP}(t)(D^0 \rightarrow h^+h^-)$ $h=K,\pi$

Because of the slow mixing rate of charm mesons (x,y~10^{-2}) the time-dependent asymmetry is approximated at first order as the sum of two terms:

$$A_{CP}(h^+h^-;t) \approx A_{CP}^{\text{dir}}(h^+h^-) + \frac{t}{\tau} A_{CP}^{\text{ind}}(h^+h^-)$$

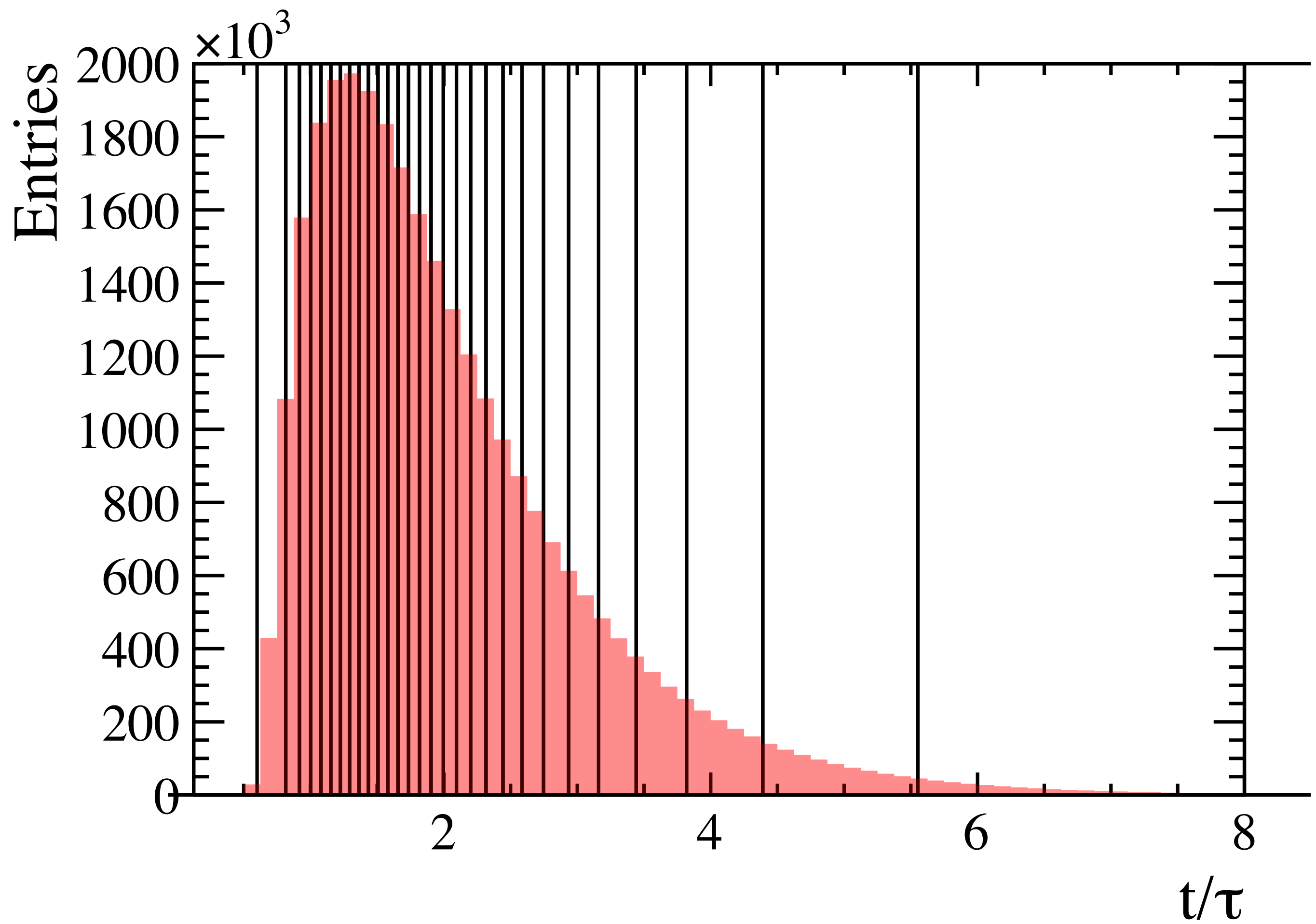
$$\begin{aligned} A_{CP}^{\text{dir}}(h^+h^-) &\equiv A_{CP}(t=0) \\ &= \frac{|\mathcal{A}(D^0 \to h^+h^-)|^2 - |\mathcal{A}(\bar{D}^0 \to h^+h^-)|^2}{|\mathcal{A}(D^0 \to h^+h^-)|^2 + |\mathcal{A}(\bar{D}^0 \to h^+h^-)|^2} \end{aligned}$$

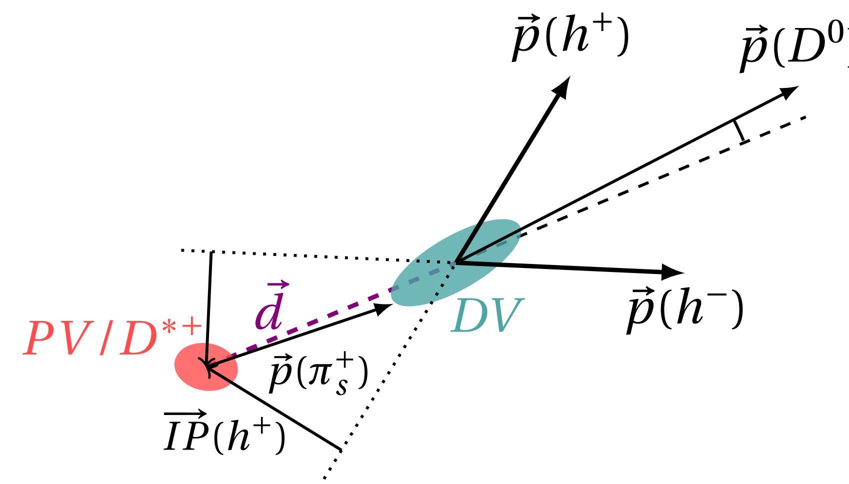
$$\begin{aligned} A_{CP}^{\text{ind}}(h^+h^-) = \frac{\eta_{CP}}{2}\Bigg[& y\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right)\cos\varphi \\ & - x\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right)\sin\varphi\Bigg], \end{aligned}$$

The time-integrated asymmetry is then the time integral of $A_{CP}(t)$ over the experimental observed distribution of proper decay time D(t):

$$\begin{aligned} A_{CP}(h^+h^-) &= A_{CP}^{\text{dir}}(h^+h^-) + A_{CP}^{\text{ind}}(h^+h^-) \int_0^\infty \frac{t}{\tau} D(t)dt \\ &= A_{CP}^{\text{dir}}(h^+h^-) + \frac{\langle t \rangle}{\tau} A_{CP}^{\text{ind}}(h^+h^-). \end{aligned}$$

Decay time bins





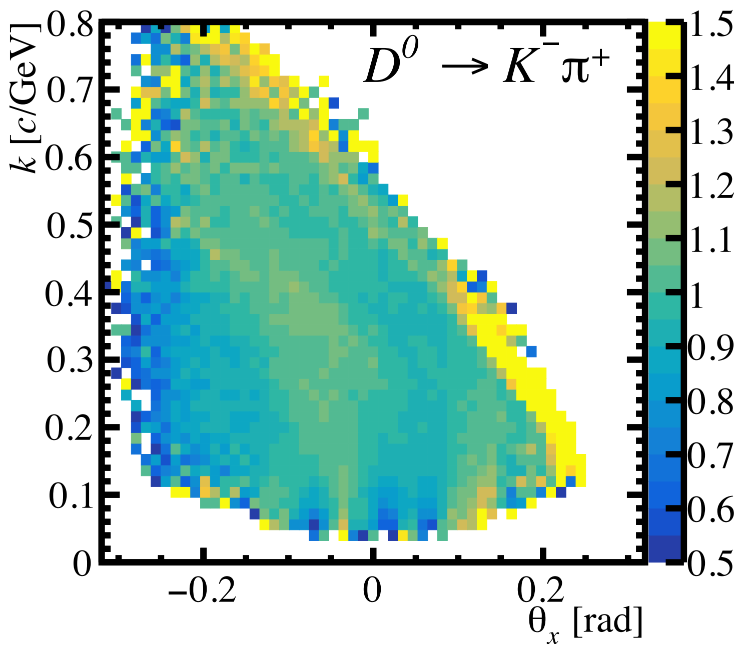
$$t(D^0) = \frac{|\vec{d}|}{\gamma\beta c} = |\vec{d}|\frac{m_{D^0}}{p_{D^0}},$$

30 approximately equally populated bins in the range [$0.6\tau_D$,$20\tau_D$]. Events in the region [0,$0.6\tau_D$] removed to avoid large asymmetries due to the very low efficiency.

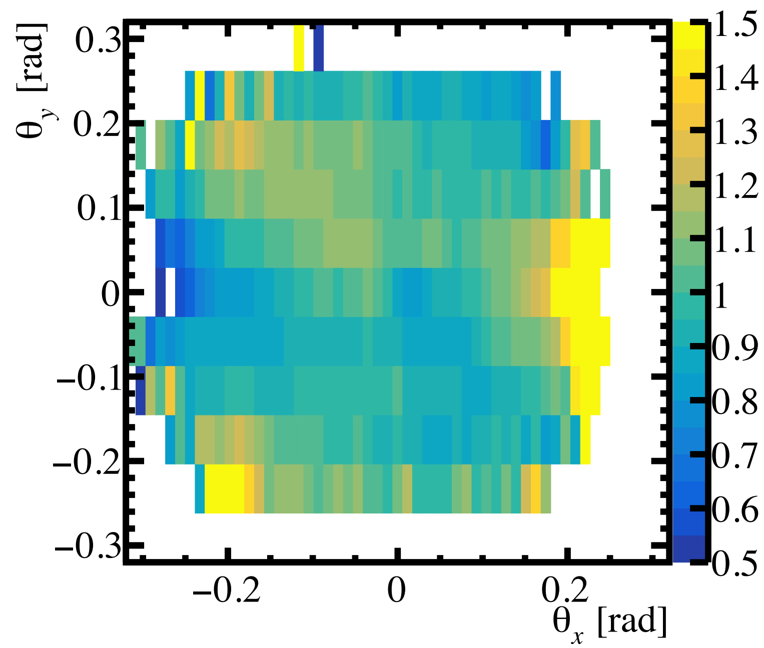
$D^0 \to K^- \pi^+$ correction weights

$$\frac{n^+(k, \theta_x, \theta_y)}{n^-(k, -\theta_x, \theta_y)}$$

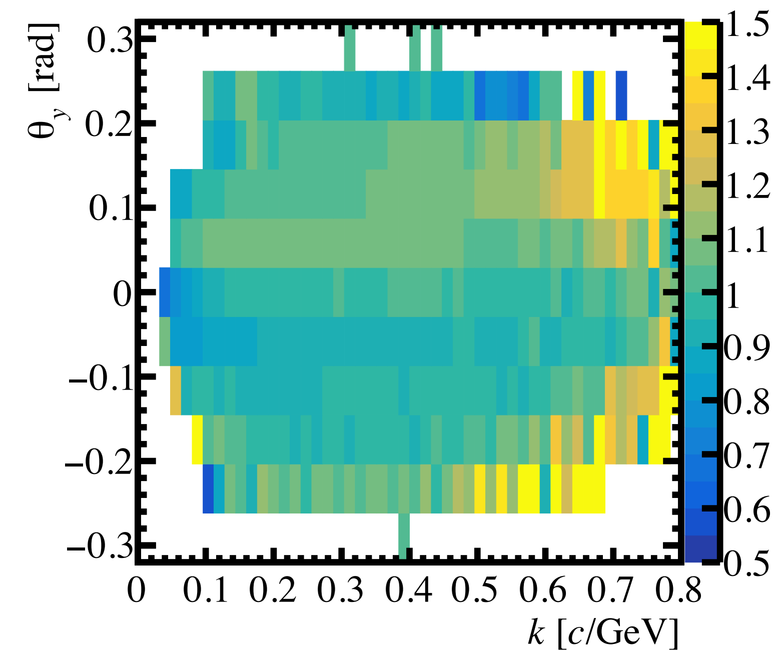
k vs. θ_x



θ_y vs. θ_x



θ_y vs. k

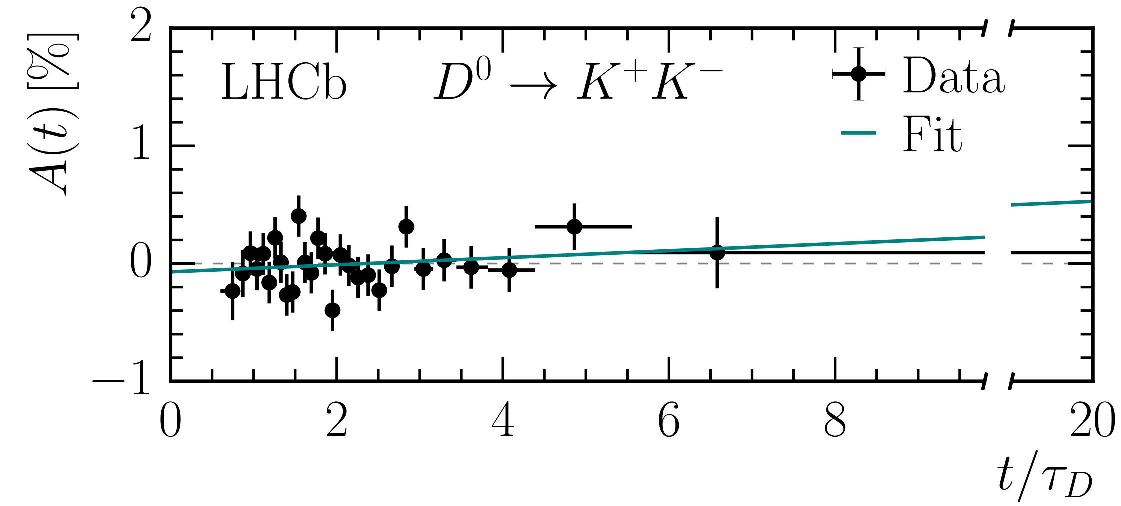


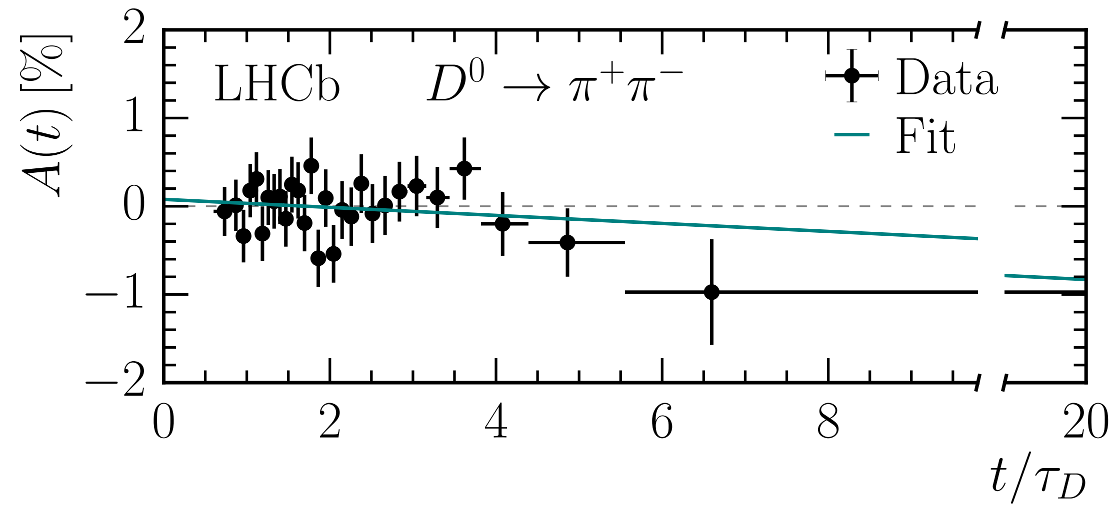
Weights of 2012 Down subsample.
Note: A_Γ independently measured in each subsample and weights are separately extracted by its own subsample.

Time-dependent CPV in $D^0 \to h^+h^-$

$$A_\Gamma(K^+K^-) = (-0.30 \pm 0.32 \pm 0.10) \times 10^{-3}$$
$$A_\Gamma(\pi^+\pi^-) = (0.46 \pm 0.58 \pm 0.12) \times 10^{-3}$$

arXiv:1702.06490 [hep-ex]. Submitted to PRL.





Precision approaches the level of 10^{-4}. No evidence for CP violation and improve on the precision of the previous best measurements by nearly a factor of 2.

Assuming that only indirect CP violation contributes to A_Γ, the two values, can be averaged to yield a single value:

$$A_\Gamma = (-0.13 \pm 0.28 \pm 0.10) \times 10^{-3}$$

Consistent with the result obtained by LHCb in a muon-tagged sample [*JHEP 1504 (2015) 043*], which is statistically independent. The two results are therefore combined to yield an overall LHCb Run 1 value:

$$A_\Gamma = (-0.29 \pm 0.28) \times 10^{-3}$$

Most precise measurement of CPV in the charm sector.

Time-integrated $A_{CP}(D^0 \to K^+K^-)$

Full Run 1 data sample (3fb-1).
D^0 flavor inferred with strong $D^{*+} \to D^0\pi^+$ decay chain.
CPV in calibration channels assumed negligible

$$\begin{aligned}
&A_{CP}(D^0 \to K^-K^+) \\
&\quad = A_{\text{raw}}(D^0 \to K^-K^+) - A_{\text{raw}}(D^0 \to K^-\pi^+) \\
&\qquad + A_{\text{raw}}(D^+ \to K^-\pi^+\pi^+) - A_{\text{raw}}(D^+ \to \overline{K}^0\pi^+) \\
&\qquad + A_D(\overline{K}^0).
\end{aligned}$$

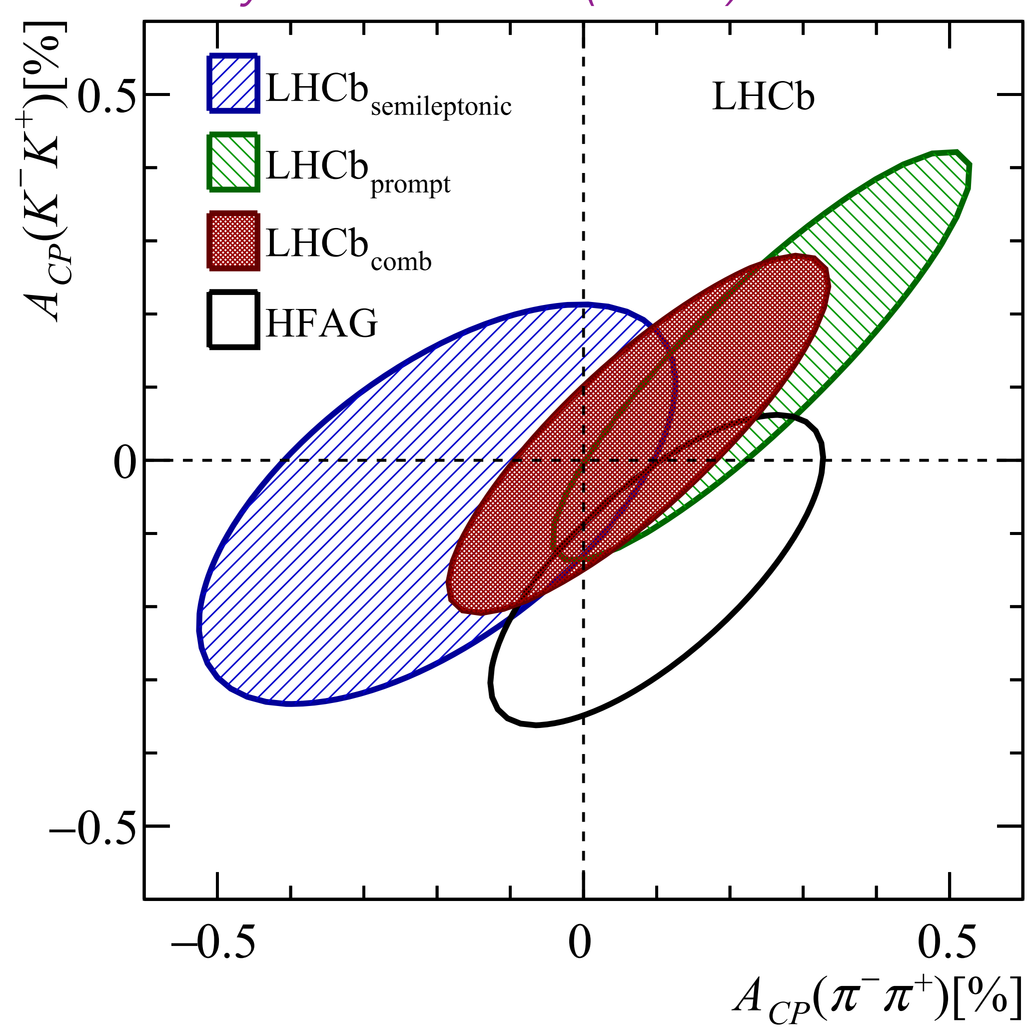
$$A_{CP}(K^-K^+) = (0.14 \pm 0.15\,(\text{stat}) \pm 0.10\,(\text{syst}))\%$$

A combination with other LHCb measurements yields

$$A_{CP}(K^-K^+) = (0.04 \pm 0.12\,(\text{stat}) \pm 0.10\,(\text{syst}))\%$$

$$A_{CP}(\pi^-\pi^+) = (0.07 \pm 0.14\,(\text{stat}) \pm 0.11\,(\text{syst}))\%$$

Phys.Lett. B767 (2017) 177-187



Most precise measurements from a single experiment. No evidence of CP asymmetry.

Time-dependent CPV in $D^0 \rightarrow h^+h^-$

Because of the slow mixing rate of charm mesons ($x,y \sim 10^{-2}$) the time-dependent asymmetry is approximated at first order as the sum of two terms:

$$A_{CP}(h^+h^-;t) \approx A_{CP}^{\text{dir}}(h^+h^-) + \frac{t}{\tau} A_{CP}^{\text{ind}}(h^+h^-)$$

$$A_{CP}^{\text{ind}}(h^+h^-) = \frac{\eta_{CP}}{2}\left[y\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right)\cos\varphi - x\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right)\sin\varphi \right],$$

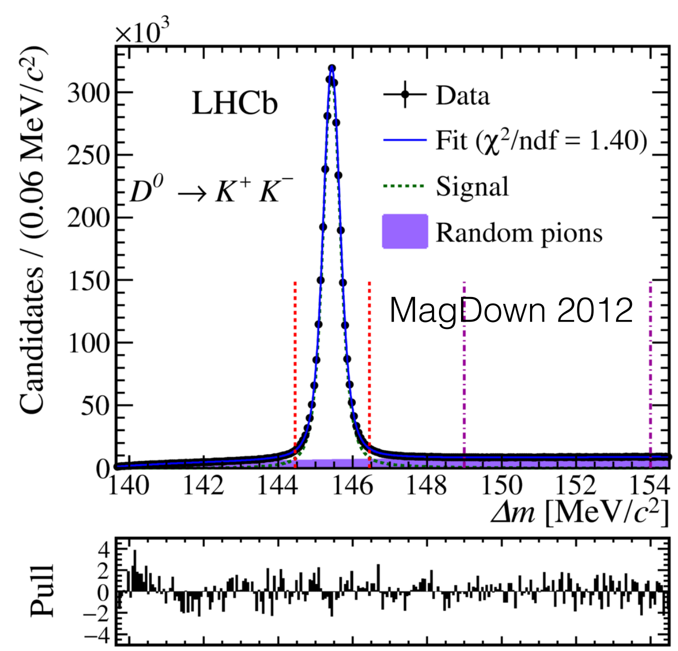
CPV in the mixing $|q/p| \neq 1$ CPV in the interference $\varphi_f \neq 0,\pi$

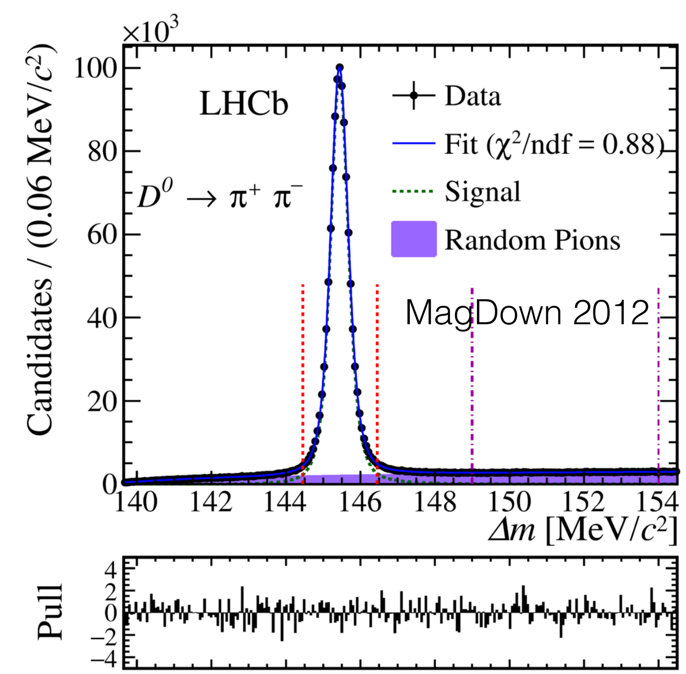
$$A_\Gamma \approx -A_{\text{CP}}^{\text{ind}}$$

defined as the asymmetry between D^0 and antiD^0 effective lifetimes

Neglecting subleading amplitudes A_Γ is independent of the final state f. Furthermore, in the absence of CP violation in mixing, it can be found that $A_\Gamma = -x \sin\varphi \longrightarrow |A_\Gamma| \leq |x| < 5\times10^{-3}$.

arXiv:1702.06490 [hep-ex]. Submitted to PRL.





Full Run 1 data sample (3fb-1).

D^0 flavor inferred with strong $D^{*+} \rightarrow D^0\pi^+$ decay.

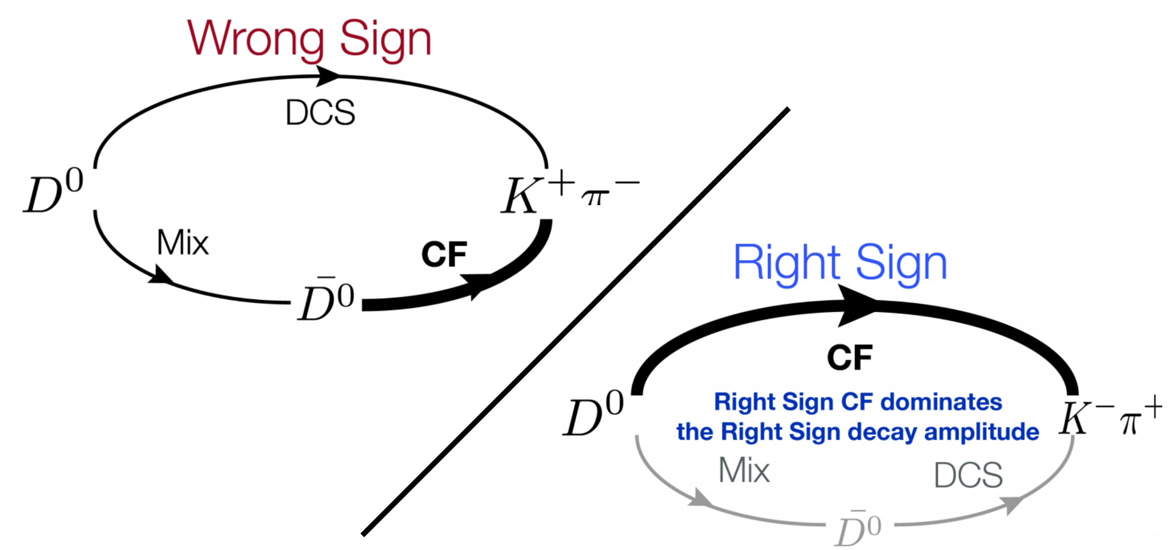
Subsample [10^6]	$D^0 \rightarrow K^-\pi^+$	$D^0 \rightarrow K^+K^-$	$D^0 \rightarrow \pi^+\pi^-$
2011 *MagUp*	10.7	1.2	0.4
2011 *MagDown*	15.5	1.7	0.5
2012 *MagUp*	30.0	3.3	1.0
2012 *MagDown*	31.3	3.4	1.1
Total	87.5	9.6	3.0

Charm mixing and CPV in $D^0 \to K^{\mp}\pi^{\pm}$(WS/RS)

Time-dependent measurement of the R(t)=WS/RS(t)

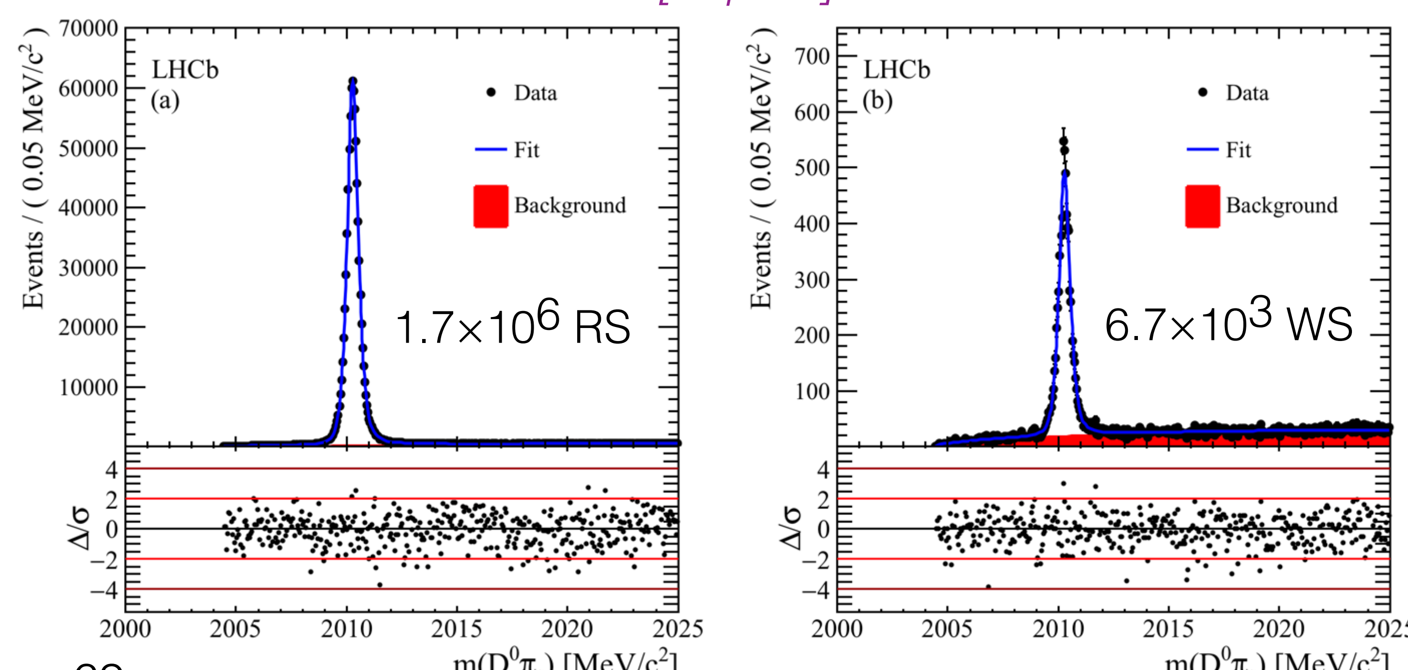
$$R(t)^{\pm} = \underbrace{R_D^{\pm}}_{DCS} + \underbrace{\sqrt{R_D^{\pm}}\,y'^{\pm}\left(\frac{t}{\tau}\right)}_{interference} + \underbrace{\frac{(x'^{\pm})^2 + (y'^{\pm})^2}{4}\left(\frac{t}{\tau}\right)^2}_{mixing}$$

$$x' = x\cos\delta_{K\pi} + y\sin\delta_{K\pi} \qquad y' = y\cos\delta_{K\pi} - x\sin\delta_{K\pi}$$



- Full Run 1 data sample ($3fb^{-1}$) .
- Use Doubly-Tagged (DT) D* decays ($B\to D^{*+}\mu^-X\to[D^0\pi^+]\mu^-X, D^0 \to K\pi$) resulting in a very pure sample.
- Much lower statistics than "prompt" decays ($D^{*+}\to D^0\pi^+, D^0 \to K\pi$), but it covers a complementary region in decay time.

arXiv:1611.06143v1 [hep-ex]. Submitted to PRD.

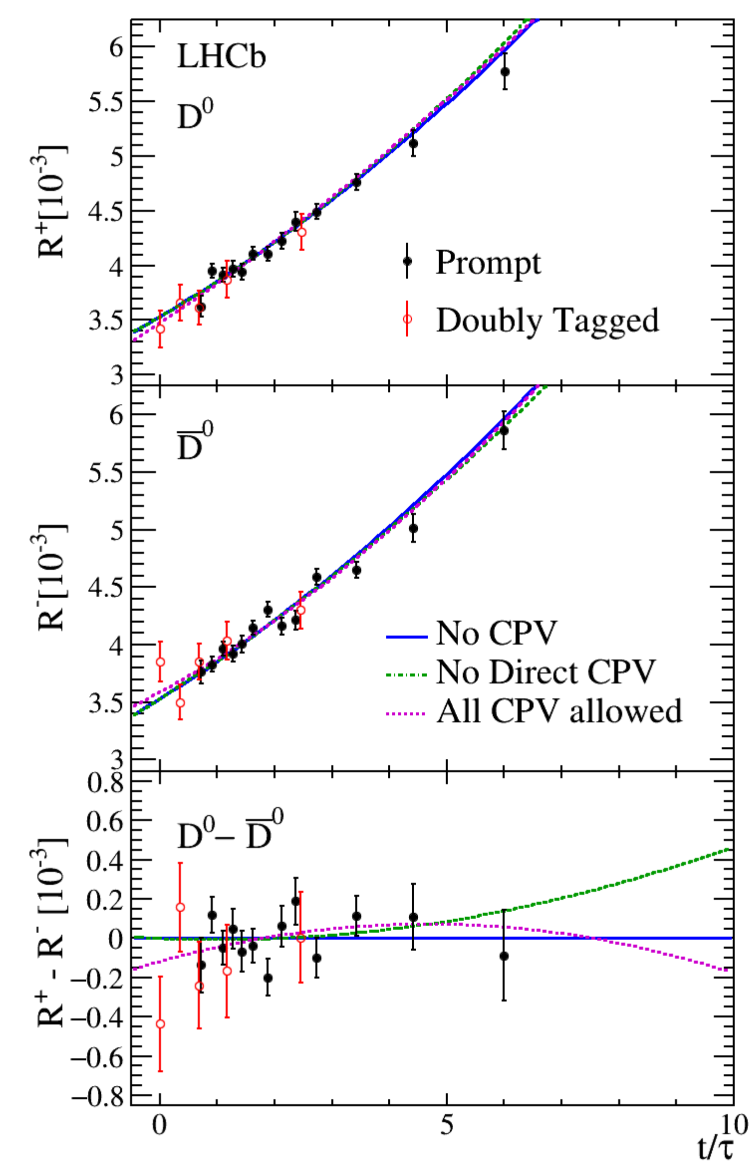


Charm mixing and CPV in $D^0 \to K^{\mp}\pi^{\pm}$(WS/RS)

- $R^+(t)$ and $R^-(t)$ for initially produced D^0 and antiD^0 mesons.
- Direct CPV occurs if $R_D^+ \neq R_D^-$.
- CPV in mixing and interference occurs if $x'^+ \neq x'^-$ and $y'^+ \neq y'^-$.

$$R(t)^{\pm} = \underbrace{R_D^{\pm}}_{DCS} + \underbrace{\sqrt{R_D^{\pm}}\,y'^{\pm}\left(\frac{t}{\tau}\right)}_{interference} + \underbrace{\frac{(x'^{\pm})^2 + (y'^{\pm})^2}{4}\left(\frac{t}{\tau}\right)^2}_{mixing}$$

Parameter	DT + Prompt	Prompt-only
All CPV allowed		
$R_D^+[10^{-3}]$	3.474 ± 0.081	3.545 ± 0.095
$(x'^+)^2\,[10^{-4}]$	0.11 ± 0.65	0.49 ± 0.70
$y'^+[10^{-3}]$	5.97 ± 1.25	5.1 ± 1.4
$R_D^-[10^{-3}]$	3.591 ± 0.081	3.591 ± 0.090
$(x'^-)^2\,[10^{-4}]$	0.61 ± 0.61	0.60 ± 0.68
$y'^-[10^{-3}]$	4.50 ± 1.21	4.5 ± 1.4
χ^2/ndf	95.0/108	85.9/98

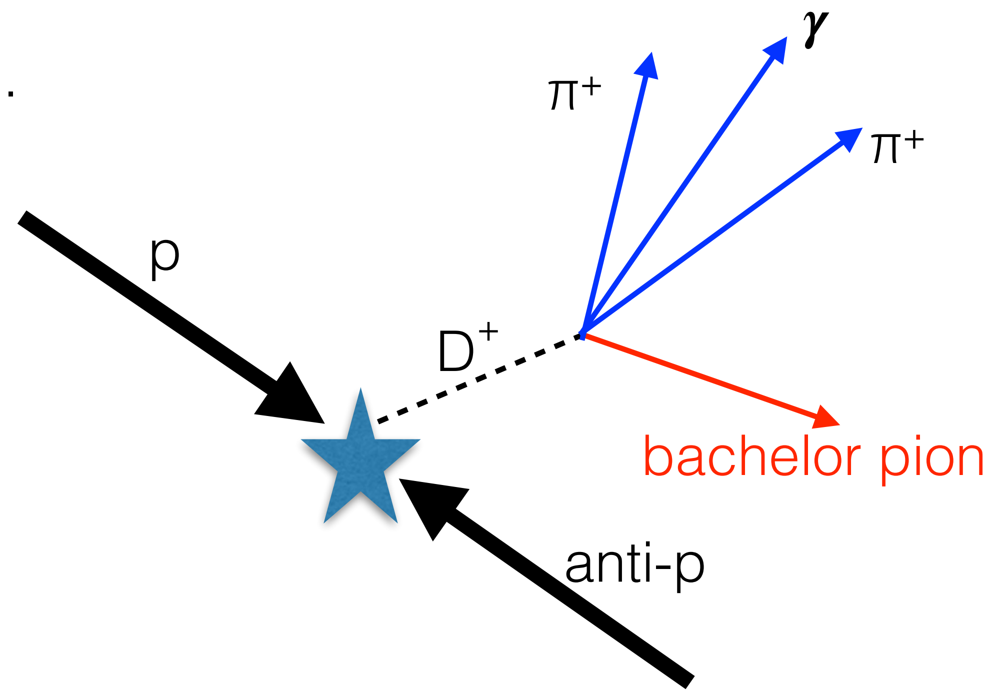


arXiv:1611.06143v1 [hep-ex]. Submitted to PRD.

World best measurement of charm mixing parameters. Results consistent with conservation of CP symmetry. Precision improves by 10-20% wrt prompt-only data sample.

Still on CPV hunting: $D^+_{(s)} \to \eta' \pi^+$

First time measurement of CPV in charm with neutrals at LHCb.

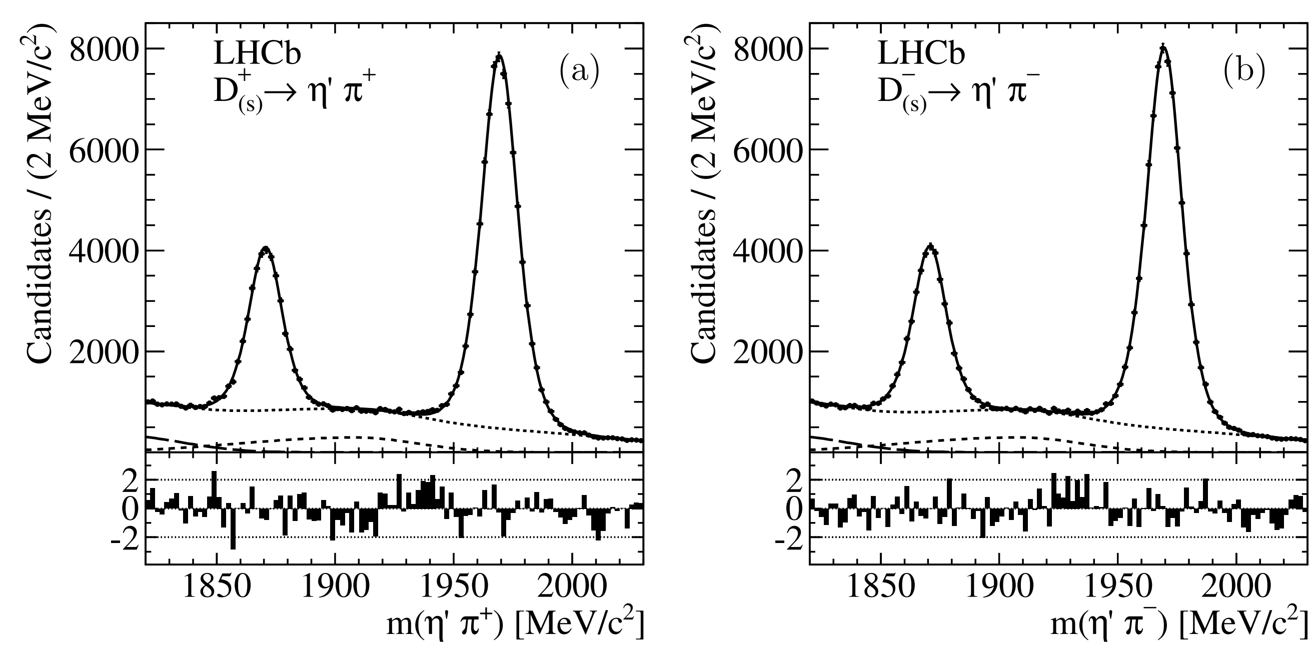


Full Run 1 data sample, $N(D^{\pm})$=63k and $N(D_s^{\pm})$=152k. Measurement with respect to reference channels in order to cancel production and detection asymmetries.

$$\mathcal{A}_{CP}(D^{\pm} \to \eta' \pi^{\pm}) \approx \Delta\mathcal{A}_{CP}(D^{\pm} \to \eta' \pi^{\pm}) + \mathcal{A}_{CP}(D^{\pm} \to K^0_S \pi^{\pm}).$$

$$\mathcal{A}_{CP}(D_s^{\pm} \to \eta' \pi^{\pm}) \approx \Delta\mathcal{A}_{CP}(D_s^{\pm} \to \eta' \pi^{\pm}) + \mathcal{A}_{CP}(D_s^{\pm} \to \phi \pi^{\pm}).$$

arXiv:1701.01871v1 [hep-ex]



$$\mathcal{A}_{CP}(D^{\pm} \to \eta' \pi^{\pm}) = (-0.61 \pm 0.72 \pm 0.55 \pm 0.12)\%,$$
$$\mathcal{A}_{CP}(D_s^{\pm} \to \eta' \pi^{\pm}) = (-0.82 \pm 0.36 \pm 0.24 \pm 0.27)\%,$$

Most precise measurement of CP asymmetries in $D^+_{(s)} \to \eta' \pi^+$ decays to date. Previous measurements at e^+e^- machines error>1%.

LHCb Trigger (Run 1)