Measurement of the charm-mixing and CP violation parameter y_{CP} at LHCb

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On the behalf of LHCb collaboration

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Neutral meson mixing

A quantum mechanical phenomenon in which neutral mesons can oscillate between their particle and anti-particle state

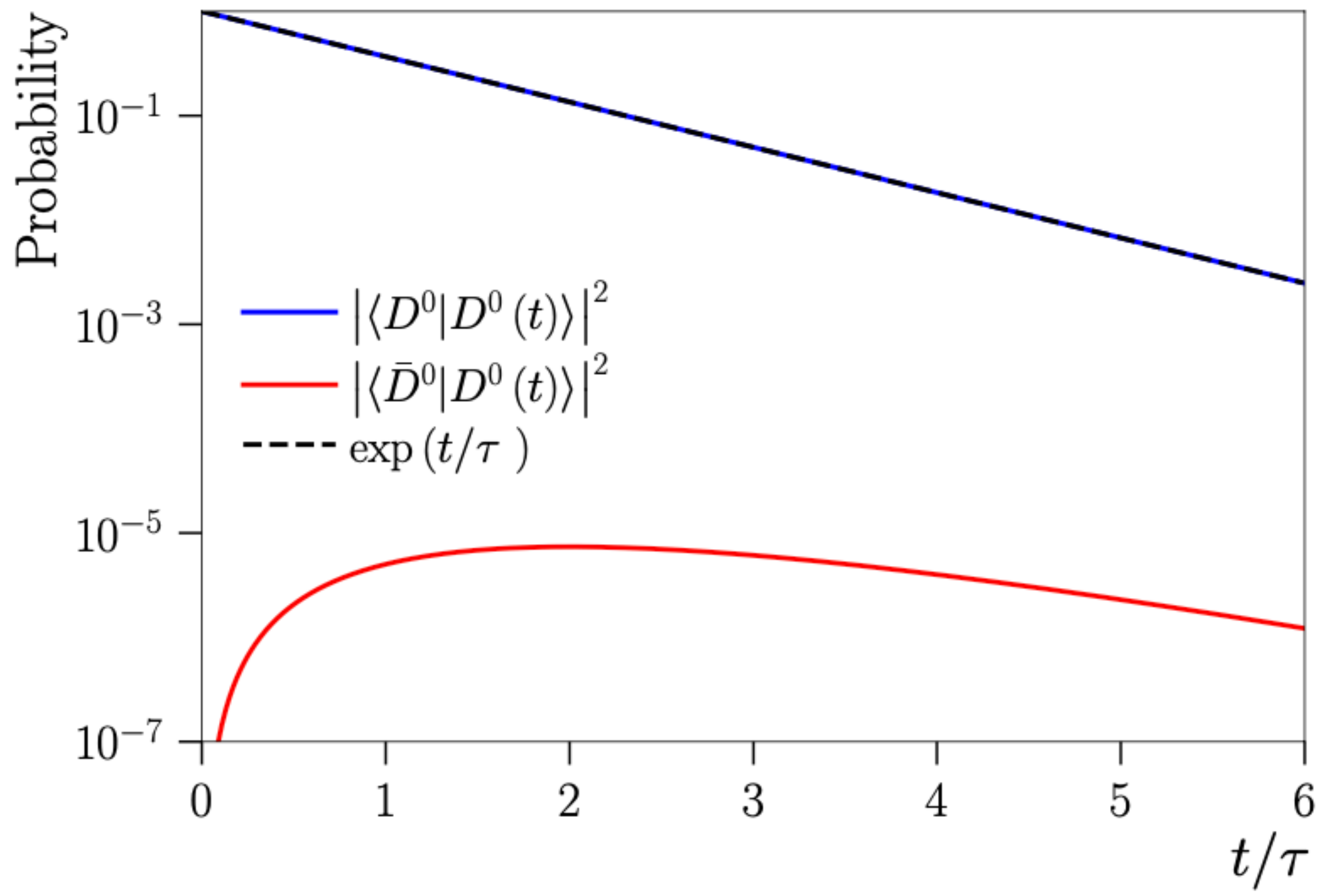
Their mass eigenstates, related to the flavour eigenstates, are:

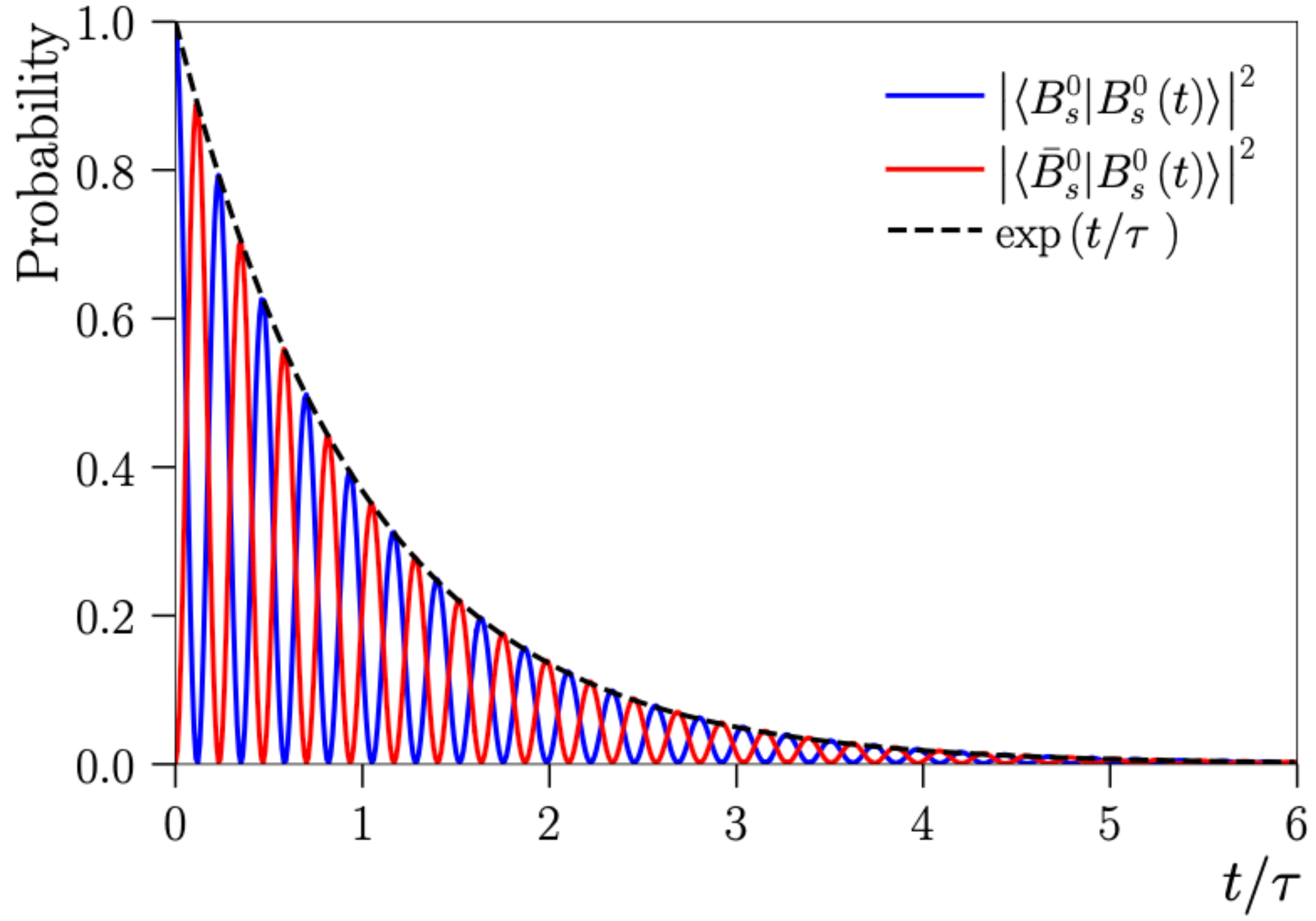
$$|D_{1,2}> = p|D^0> \pm q|\bar{D}^0> \quad \text{with } |p|^2 + |q|^2 = 1$$

In the limit of CP symmetry, $q = p$ and the oscillations characterised by two dimensionless parameters

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

where $m_{1,2}$ and $\Gamma_{1,2}$ are the mass and decay width of the CP-even/odd eigenstate $D_{1,2}$ and Γ is the average decay width





$\cancel{CP}$ in mixing

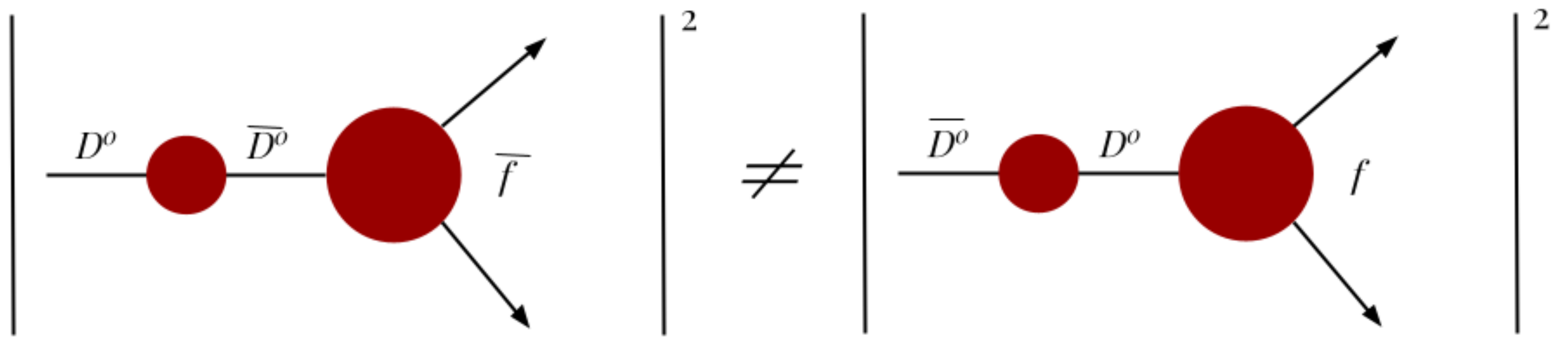
The probabilities of an initially produced D^0 evolving into a given state at the time t are:

$$P(D^0 \to D^0, t) = \left|\langle D^0 | D^0(t) \rangle\right|^2 = \frac{e^{-\Gamma t}}{2}\left[cosh(y\Gamma t) + cos(x\Gamma t)\right]$$

$$P(D^0 \to \bar{D}^0, t) = \left|\langle \bar{D}^0 | D^0(t) \rangle\right|^2 = \left|\frac{q}{p}\right|^2 \frac{e^{-\Gamma t}}{2}\left[cosh(y\Gamma t) - cos(x\Gamma t)\right]$$

For $\left|\frac{q}{p}\right|^2 \neq 1$ the $D^0 \to \bar{D}^0$ and the $\bar{D}^0 \to D^0$ processes do not have the same probability

This is CP violation in mixing



The values of x and y are of the order of 1 %

$\cancel{CP}$ in the decay

Defined the decay amplitude of a D^0 or $\bar{D}^0$ meson to a final state f or $\bar{f}$ as

$A_f = < f \,|\, \mathscr{H} \,|\, D^0 >$ $\quad$ $A_{\bar{f}} = < \bar{f} \,|\, \mathscr{H} \,|\, D^0 >$

$\bar{A}_f = < f \,|\, \mathscr{H} \,|\, \bar{D}^0 >$ $\quad$ $\bar{A}_{\bar{f}} = < \bar{f} \,|\, \mathscr{H} \,|\, \bar{D}^0 >$

If $|A_f| \neq |\bar{A}_f|$ CP violation can proceed through the decay

For charm decays, CP violation in the decay was observed by the LHCb collaboration in 2019 [Phys. Rev. Lett. 122, 211803 (2019)]:

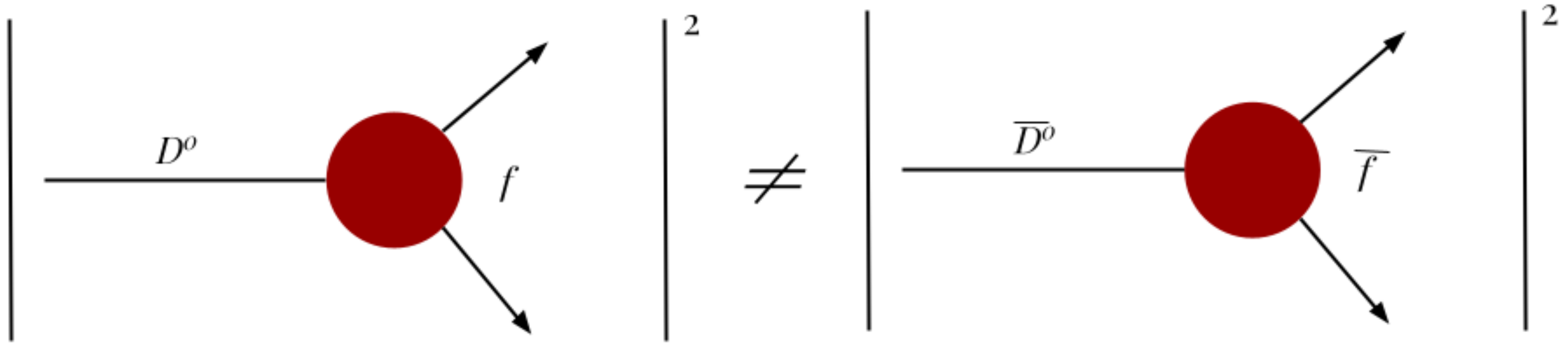
$\Delta A_{CP} = A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-)$

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

corresponding to a $\Delta A_{CP} \neq 0$ in 5.3σ

Experimentally, CP violation in the decay is measured by the asymmetry

$$A_{CP}(f) = \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to \bar{f})}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to \bar{f})} = \frac{|A_f|^2 - |\bar{A}_{\bar{f}}|^2}{|A_f|^2 + |\bar{A}_{\bar{f}}|^2}$$



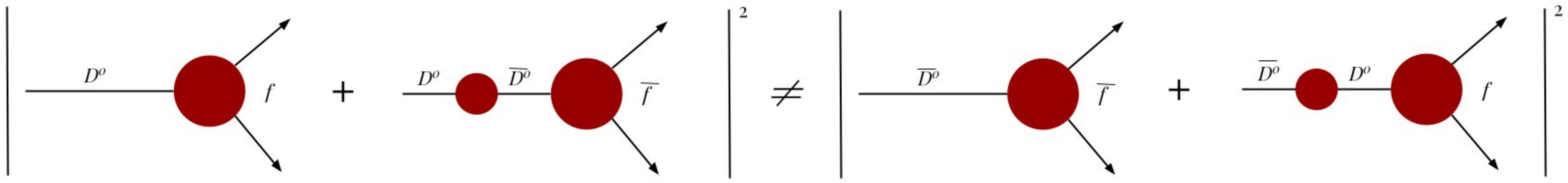
$\cancel{CP}$ in the interference between mixing and decay

The D^0 and the $\bar{D}^0$ meson must share the final state $(f = \bar{f})$

This occurs when the decay amplitude for the $D^0 \to f$ process interferes with the decay amplitude for the $D^0 \to \bar{D}^0 \to f$ process and induces a CP violation

Mathematically it is expressed as:

$$\phi_{\lambda_f} = arg\left(\frac{q}{p}\frac{\bar{A}_f}{A_f}\right) = arg(\lambda_f) \neq 0$$



The parameter y_{CP}

Because of $D^0 - \bar{D}^0$ mixing, the effective decay width $\hat{\Gamma}_{CP}$ of decays to CP-even final states differs from the average width Γ

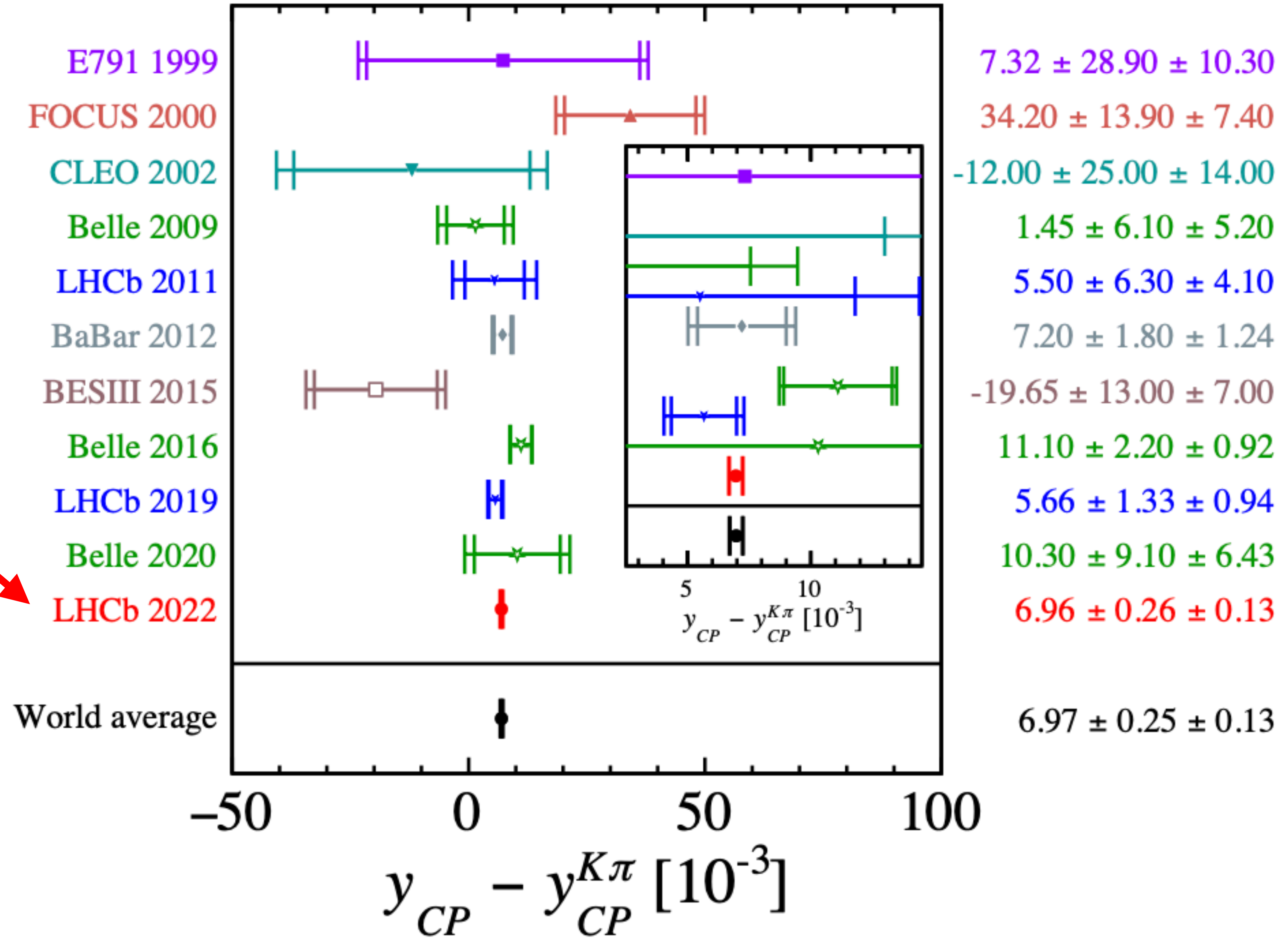
$$y^f_{CP} = \frac{\hat{\Gamma}(D^0 \to f) + \hat{\Gamma}(\bar{D}^0 \to f)}{2\Gamma} - 1 \sim |y|\, cos\phi_{\lambda_f}$$

- No CP violation if $\phi_{\lambda_f} = 0 \Rightarrow y = y_{CP}$
- Any significant departure in the measurement of y_{CP} from y would indicate the CP violation through mixing and in the interference between mixing and decay

Status of the art

- $y_{CP} - y_{CP}^{K\pi} = (6.96 \pm 0.26 \pm 0.13) \times 10^{-3}$
- Four times more precise than the previous world average

Supplementary Material Phys.Rev.D 105 (2022) 9, 092013



Measurement of the charm mixing parameter $y_{CP} - y_{CP}^{K\pi}$ using two-body D^0 meson decays

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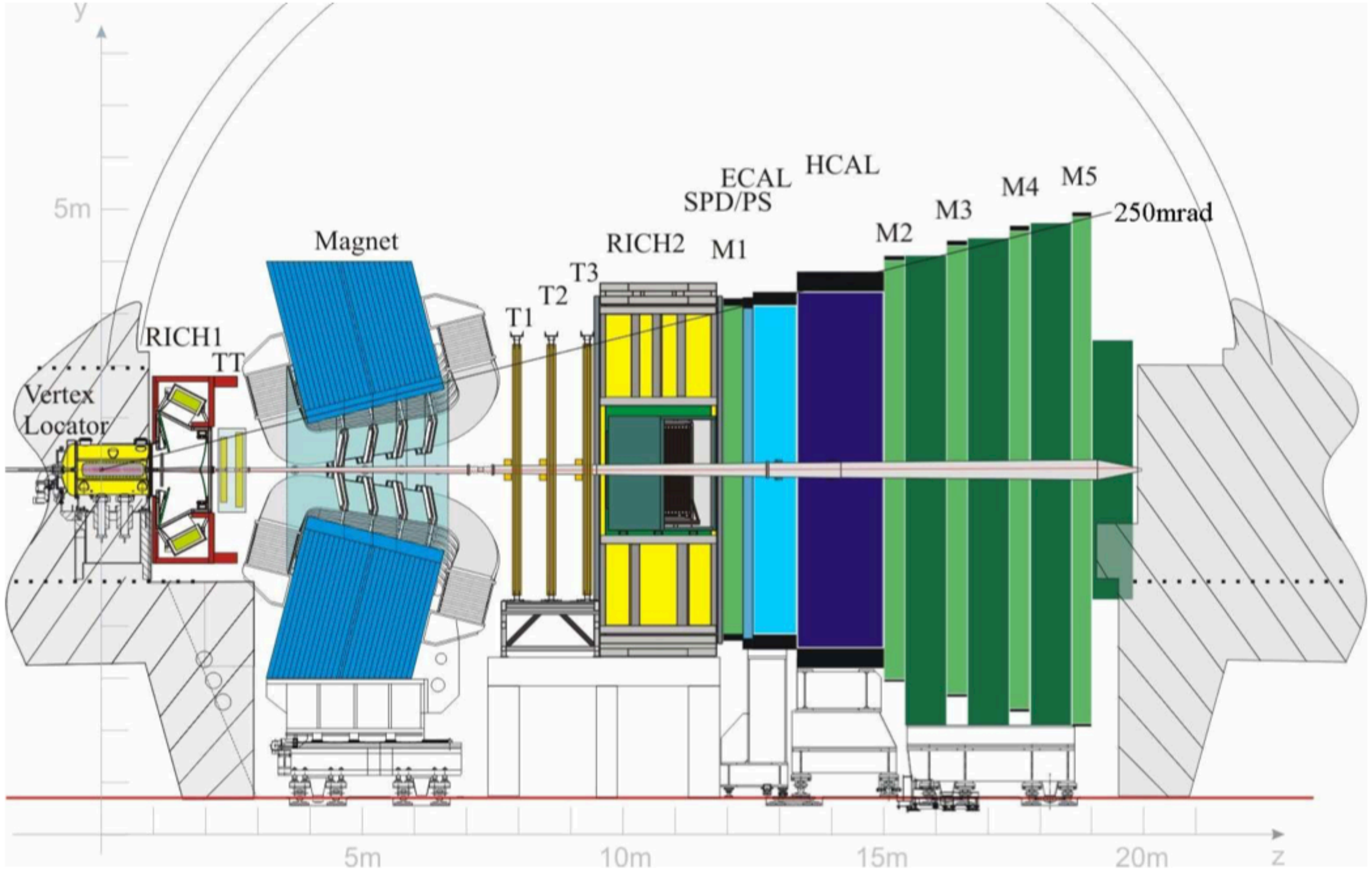
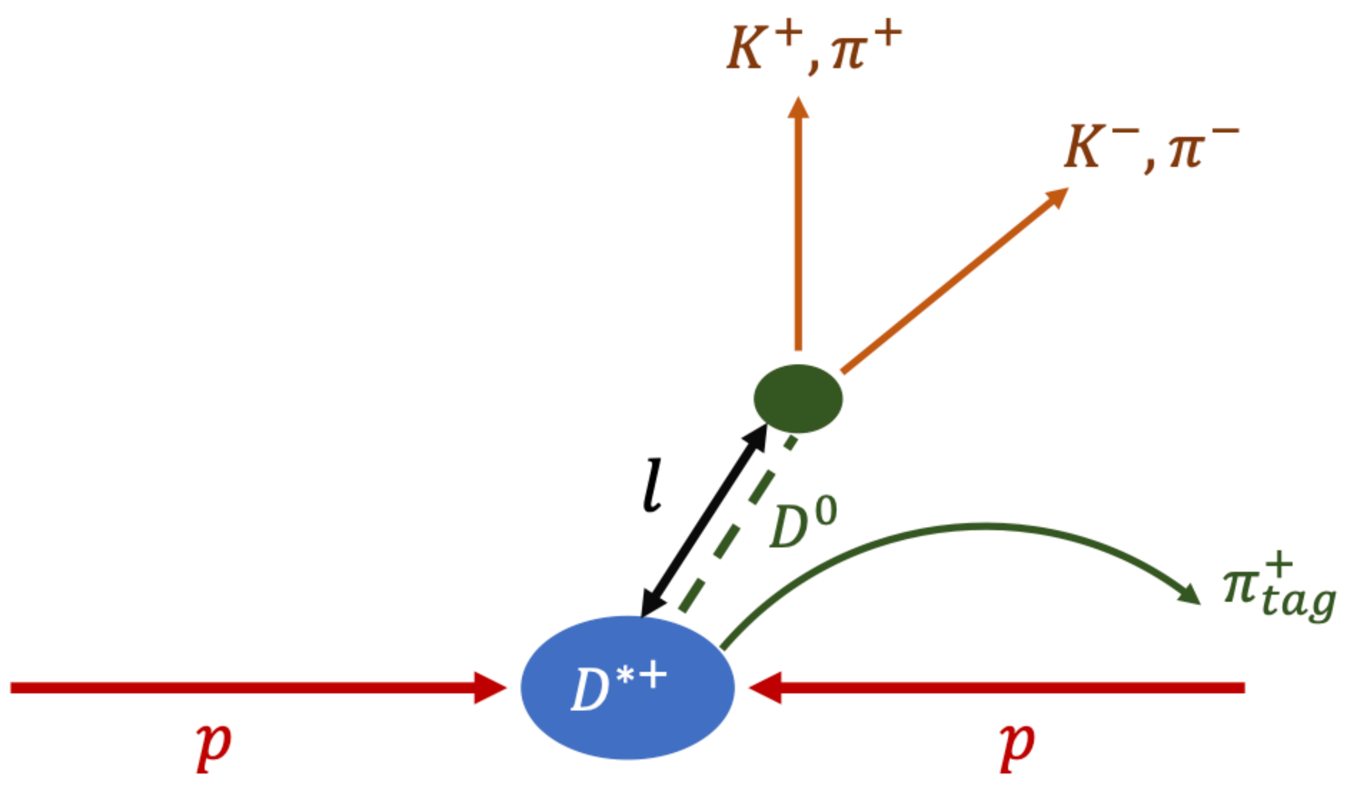
LHCb

- A single-arm forward spectrometer designed for the study of particles containing *b* or *c* quarks
- Pseudorapidity range: $2 < \eta < 5$
- IP resolution: $(15 + 29/p_T)$ µm
- Relative uncertainties on momentum:
  - 0.5 % for low *p*
  - 1 % at 200 GeV/c



Analysis strategy (I)



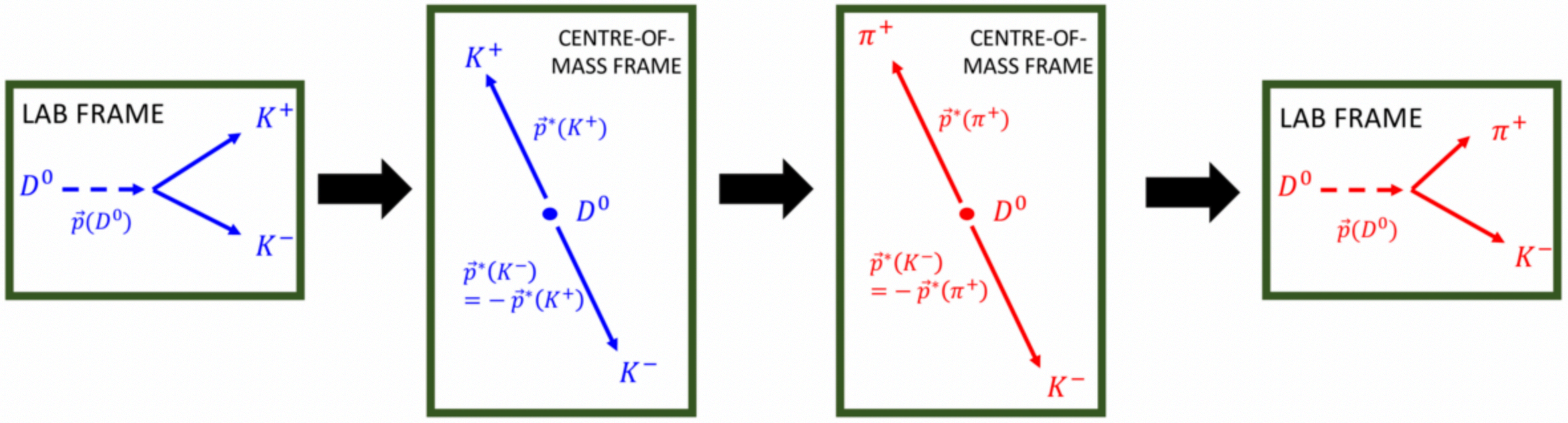
- Measurement of y_{CP} using $D^0 \to K^+K^-$, $D^0 \to \pi^+\pi^-$ and $D^0 \to K^-\pi^+$ decays
- The D^0 mesons are required to originate from $D^*(2010)^+ \to D^0\pi^+$
- Reconstructed in a LHCb dataset in pp collisions at $\sqrt{s} = 13$ TeV in the Run2 data taking period corresponding to an integrated luminosity of 6 fb^{-1}
- The parameters $y_{CP} - y_{CP}^{K\pi}$ are measured from the decay-time ratios $R^f(t)$ of $D^0 \to f$ over $D^0 \to K^-\pi^+$ signal yields as a function of the reconstructed D^0 decay time, t

$$R^f(t) = \frac{N(D^0 \to f, t)}{N(D^0 \to K^-\pi^+, t)} = e^{-(y_{CP}^f - y_{CP}^{K\pi})\frac{t}{\tau_{D^0}}} \frac{\epsilon(f, t)}{\epsilon(K^-\pi^+, t)} \quad (f = K^+K^-, \pi^+\pi^-)$$

with $\tau_{D^0} = (410.1 \pm 1.5)$ fs and $\epsilon(K^{\pm}\pi^{\pm}, t)$ is the time-dependent efficiency for the considered final state

Analysis strategy (II)

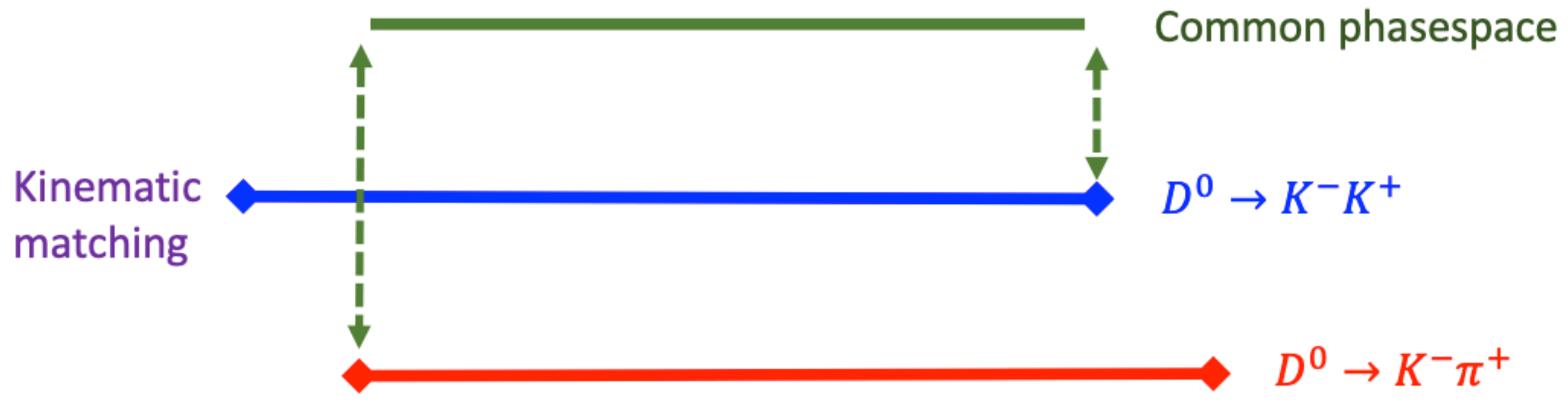
- The selection efficiencies of $D^0 \to f$ and $D^0 \to K^-\pi^+$ decays differ because of the different masses of their final-state particles $\Rightarrow$ distinct kinematic distributions of the final state particles of the D^0 candidate in the LAB
- To obtain equal acceptance for both decays each D^0 candidate selected in one final state would also pass the selection requirements for the other final state with the same D^0 kinematic properties $\Rightarrow$ a kinematic matching procedure



Kinematic matching procedure

- Event-by-event analytical transformation: matches the final-state kinematic variables of one decay to the other
- To match the kinematics of a $D^0 \rightarrow K^-K^+$ decay to a $D^0 \rightarrow K^-\pi^+$ decay, a boost to the CoM frame of the D^0 candidate is performed, such that both final-state particle momenta have equal magnitude

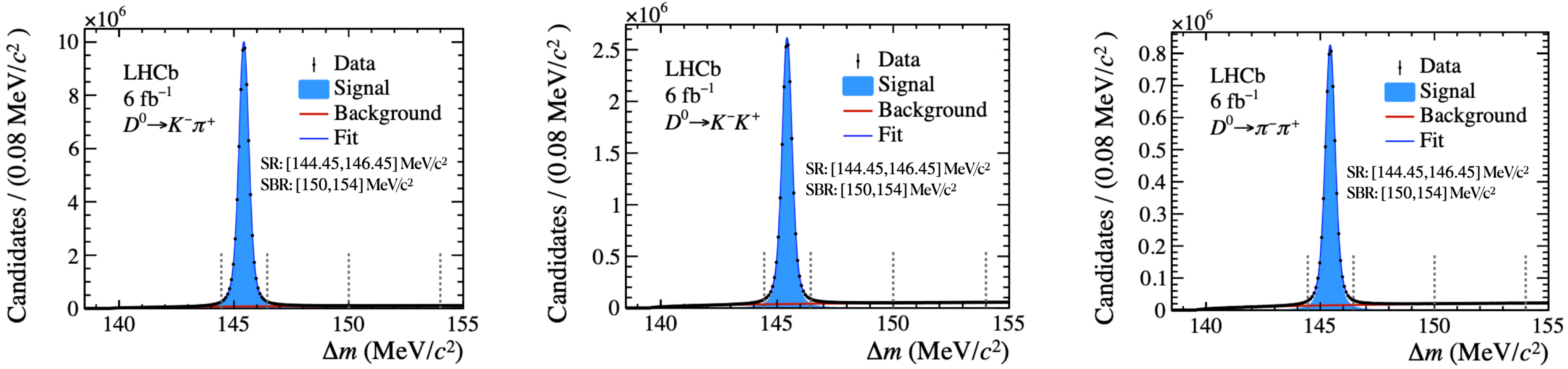
$$|\vec{p}^*| = \frac{\sqrt{\left(m_{D^0}^2 - (m_{K^+} - m_{K^-})^2\right)\left(m_{D^0}^2 - (m_{K^+} + m_{K^-})^2\right)}}{2m_{D^0}}$$



- By substituting m_{K^+} with m_{π^+}, a $D^0 \rightarrow K^-\pi^+$ state with identical kinematic properties is generated
- The use of the $K^-\pi^+$ kinematics in the LAB ensures that both the D^0 decays cover the same kinematic phase space
- Then a kinematic weighting procedure is performed to treat the difference of detection efficiencies

Mass distribution

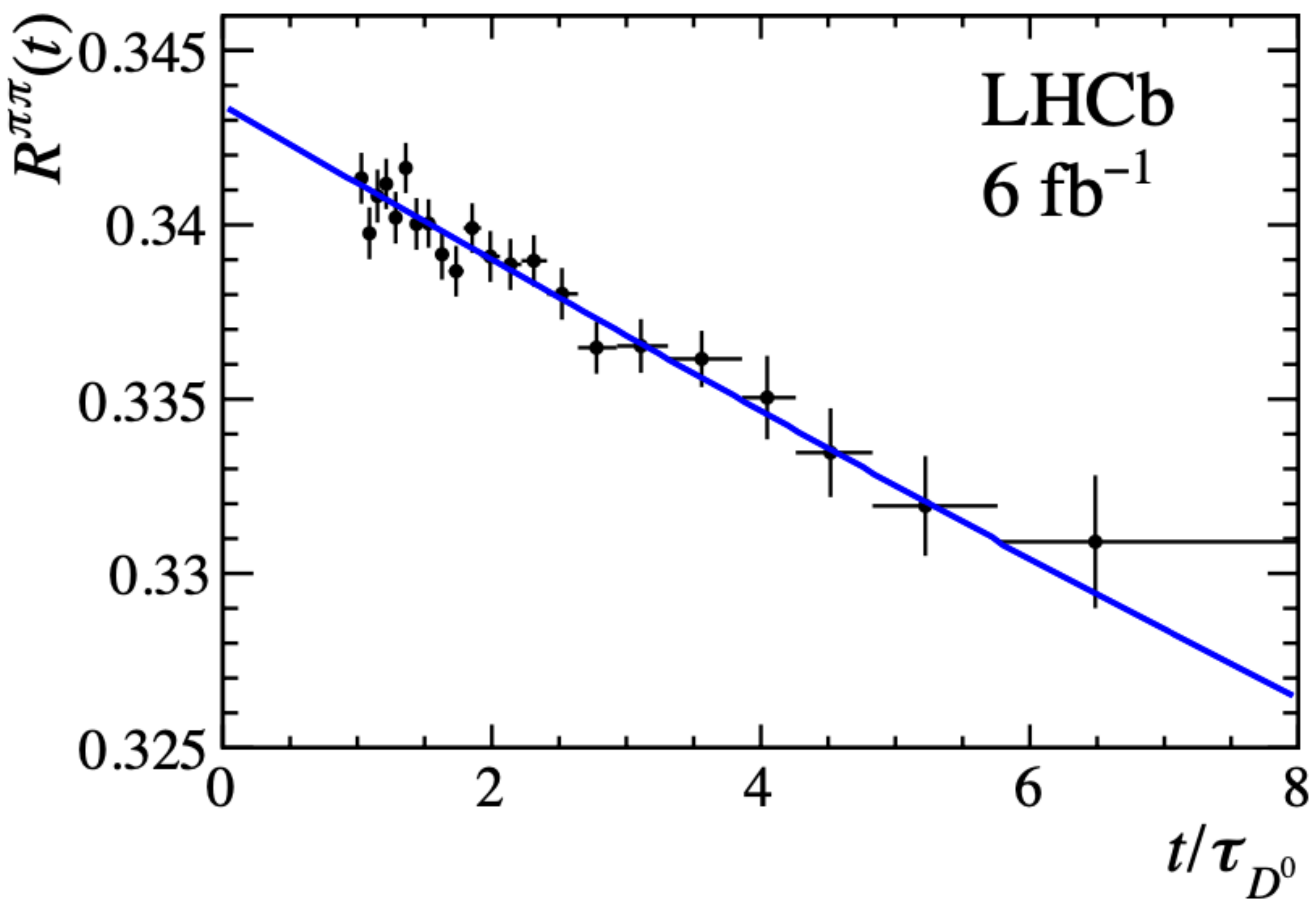
- Defined $\Delta m = m(D^0\pi^+) - m(D^0)$, fits:
  - a Johnson S_U and three Gaussian functions
  - the combinatorial background is fitted with an empirical model
- The fitting performed independently for each D^0 flavour, year, magnet polarity and in each of the 22 intervals τ_{D^0}
- Time integrated signal yields amount to 70 million $(K^-\pi^+)$, 18 million (K^-K^+), and 6 million decays $(\pi^-\pi^+)$



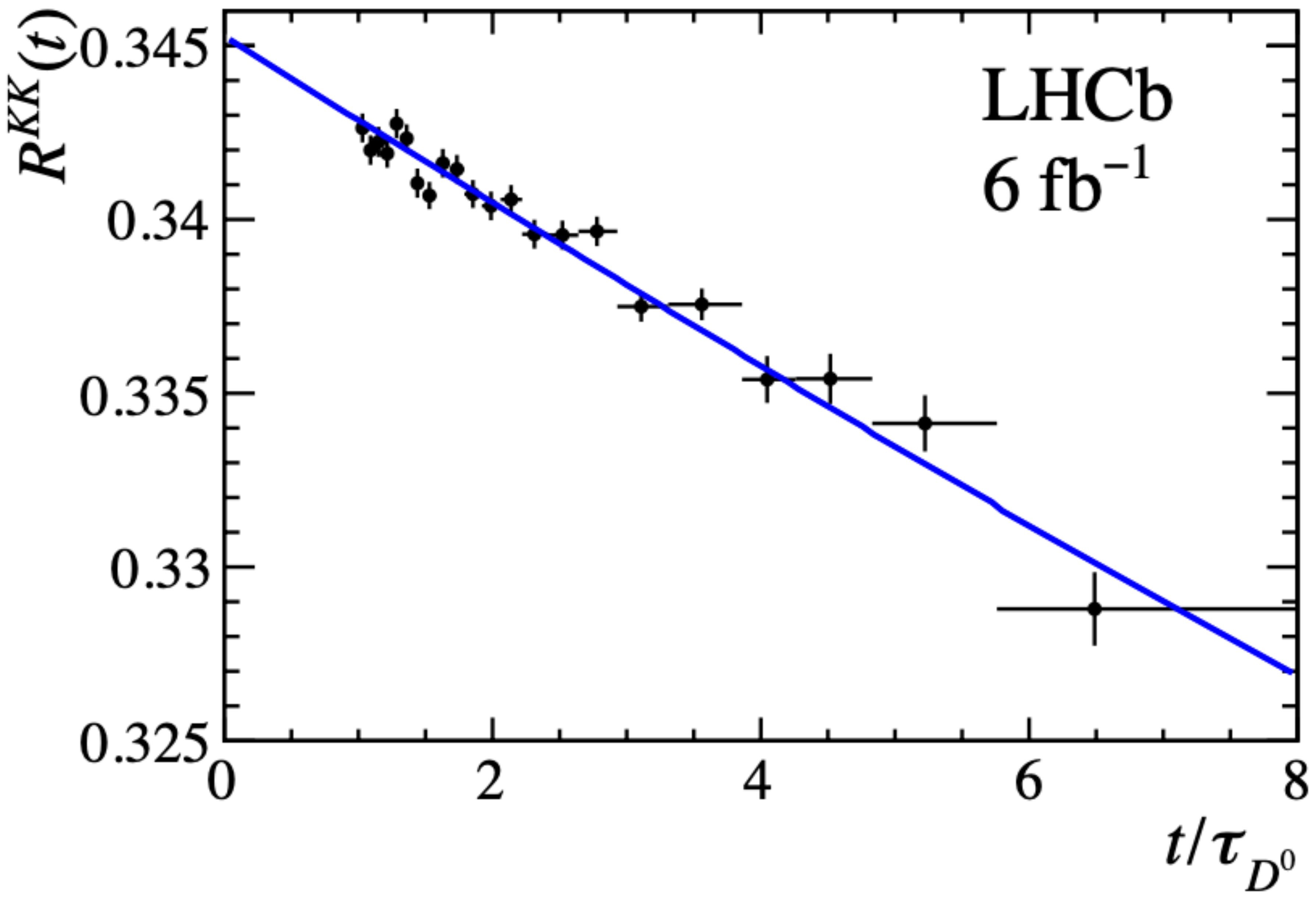
Results

- The parameters are determined from a χ^2 fit to the corresponding time-dependent $R^f(t)$ ratios

$$y_{CP}^{\pi\pi} - y_{CP}^{K\pi} = (6.57 \pm 0.53 \pm 0.16) \times 10^{-3}$$



$$y_{CP}^{KK} - y_{CP}^{K\pi} = (7.08 \pm 0.30 \pm 0.14) \times 10^{-3}$$



$$y_{CP} - y_{CP}^{K\pi} = (6.96 \pm 0.26 \pm 0.13) \times 10^{-3}$$

Systematic uncertainties

	$\sigma(y_{CP}^{\pi\pi} - y_{CP}^{K\pi})$ $[10^{-3}]$	$\sigma(y_{CP}^{KK} - y_{CP}^{K\pi})$ $[10^{-3}]$
Combinatorial background	0.12	0.07
Peaking background	0.02	0.11
Treatment of secondary decays	0.03	0.03
Kinematic weighting procedure	0.08	0.02
Input D^0 lifetime	0.03	0.03
Residual nuisance asymmetries	0.03	< 0.01
Fit bias	0.03	0.03
Total	0.16	0.14

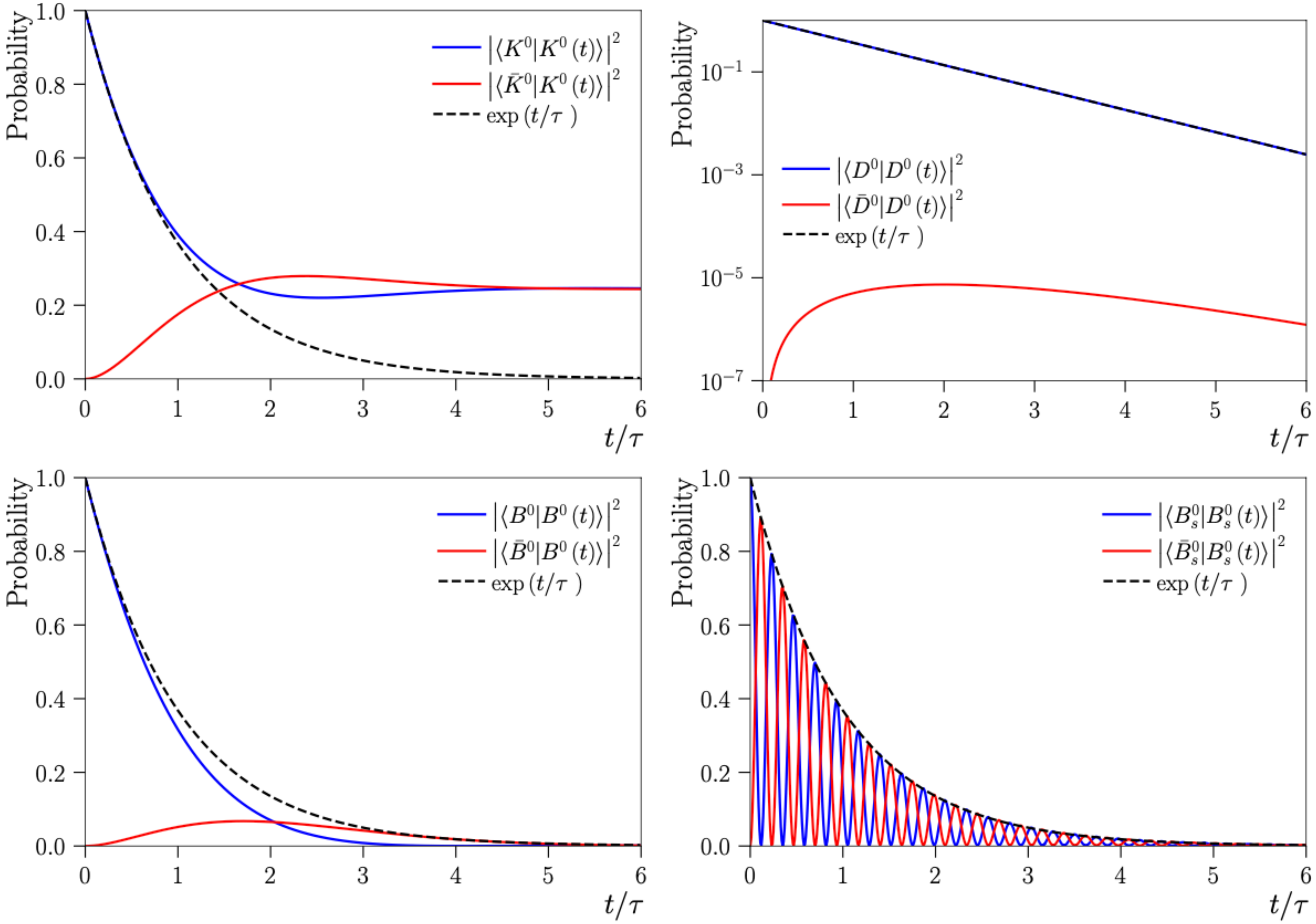
Future perspective

- The goal for Runs 3 & 4, planned for 2022-2025 and 2029-2032 respectively, is to accumulate an additional 50 fb^{-1} of *pp* data at $\sqrt{s} \approx 13.6$ TeV
- Run 3:
  - Removal of hardware trigger $\Rightarrow$ no detection asymmetry and greater flexibility in design of the selections
  - Introduction of exclusive HLT1 lines to reduce time-momentum correlations and reduce related systematic uncertainties
- These data should provide more precise measurements of $D^0 - \bar{D}^0$ mixing and significantly greater sensitivity to direct and indirect CP violation in D^0 decays

Thank you for your attention

Backup

Neutral meson mixing



Measured quantity

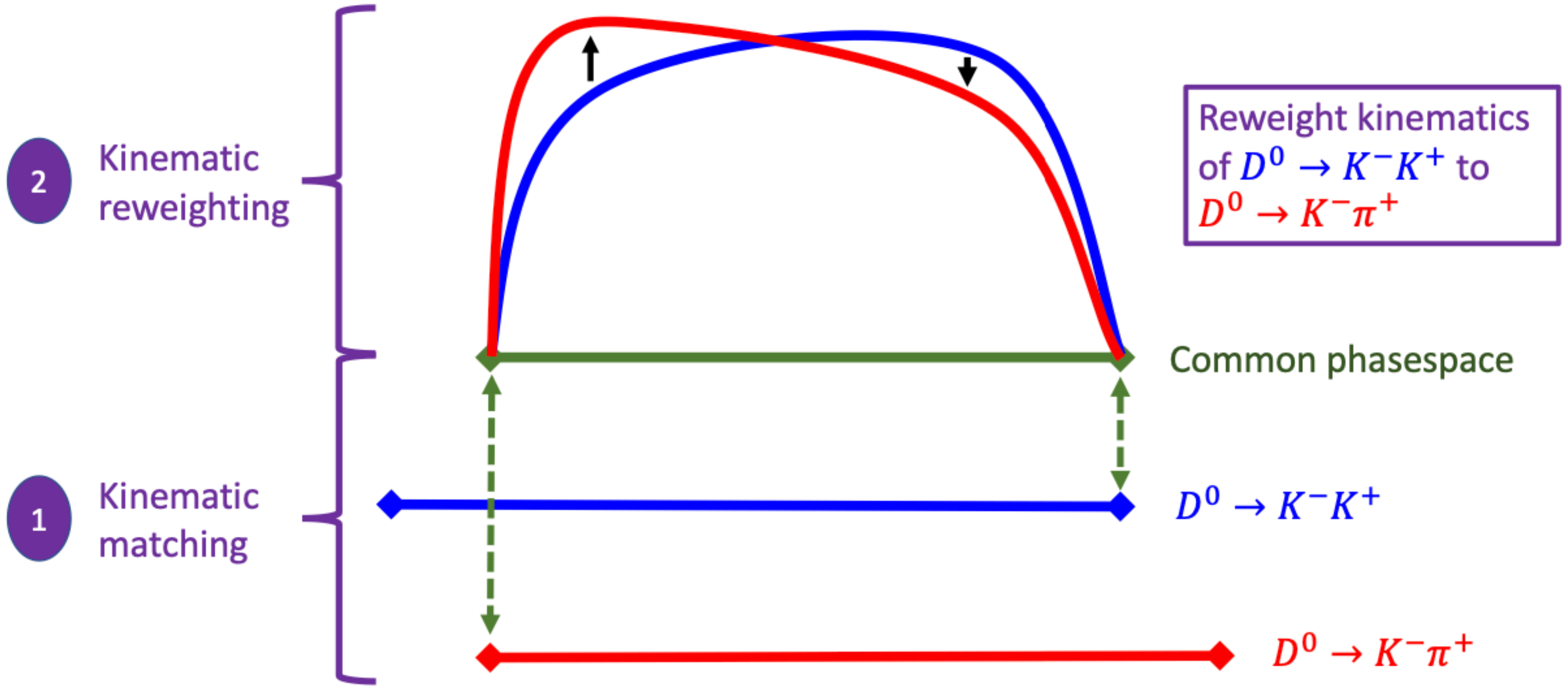
- The previous measurements use the average decay width of $D^0 \to K^-\pi^+$ and $D^0 \to K^+\pi^-$ decays as a proxy to Γ
- This does not give direct access to y_{CP}^{f} but corresponds to

$$\frac{\hat{\Gamma}(D^0 \to f) + \hat{\Gamma}(\bar{D}^0 \to f)}{\hat{\Gamma}(D^0 \to K^-\pi^+) + \hat{\Gamma}(\bar{D}^0 \to K^+\pi^-)} - 1 \approx y_{CP}^{f} - y_{CP}^{K\pi}$$

- $y_{CP}^{K\pi} \approx -0.4 \times 10^{-3}$

Kinematic weighting procedure

- The correction of the difference of detection efficiencies is treated with the kinematic weighting procedure, which is performed after the kinematic matching
- The procedure consists of weighting the p, p_T and η distributions of the D^{*+} meson and both matched final-state particles of one of the decays to the distributions of the other decay
- The procedure is performed using a gradient-boosted-reweighting algorithm from the `hep_ml` library



Johnson S_U-distribution

The Johnson S_U distribution is defined as:

$$S_U(x \mid \mu, \sigma, \delta, \gamma) = \frac{\delta}{\sigma\sqrt{2\pi}} \frac{1}{\sqrt{1 + \left(\frac{x-\mu}{\sigma}\right)^2}} e^{-\frac{1}{2}\left(\gamma + \delta sinh^{-1}\left(\frac{x-\mu}{\sigma}\right)\right)^2}$$

where δ and γ are tail parameters

Empirical function

The combinatorial background is fitted with the empirical model :

$$P_{BKG}(\Delta m \,|\, m_0, \alpha) = \frac{1}{I_B} \Delta m \sqrt{\frac{\Delta m^2}{m_0^2} - 1} \cdot e^{-\alpha\left(\frac{\Delta m^2}{m_0^2} - 1\right)}$$

where m_0 and α are free parameters and I_B is a normalisation constant

Time-dependent efficiency

- It can be written as the product of two distinct components
  - The **selection efficiency** is related to requirements applied at various stages of the LHCb data acquisition system
  - The **detection efficiency** arises from the interaction of the charged kaons and pions with the LHCb detector
- The time dependence of the efficiencies of the numerator and denominator decays differs because of their different final states, and could bias the measurement if not accounted for
- The analysis strategy consists of equalising the selection efficiencies and then the detection efficiencies of the numerator and denominator decays
- Their combined effects cancel out in the decay time ratio, such that $y_{CP}^{f} - y_{CP}^{K\pi}$ can be measured without additional corrections
- Both steps are performed using data-driven methods

Validation procedure through cross-check

- The procedure is validated with LHCb data through a study of a cross-check observable, $R^{CC}(t)$, built from the time-dependent ratio of the yields of $D^0 \to h^- h^+$ decays

$$R^{CC}(t) = \frac{N(D^0 \to \pi^+\pi^-, t)}{N(D^0 \to K^-K^+, t)} \propto e^{-y_{CP}^{CC}\frac{t}{\tau_{D^0}}} \frac{\epsilon(\pi^+\pi^-, t)}{\epsilon(K^-K^+, t)}$$

where the parameter y_{CP}^{CC} is expected to be compatible with zero, since the final-state dependent part of y_{CP} is negligible

- $R^{CC}(t)$ benefits from the fact that both final state tracks are different for numerator and denominator decays, increasing the biasing effects from their corresponding efficiencies
- The data samples are contaminated by the presence of three noticeable background contributions:
  - the combinatorial background, which is subtracted by means of a fit to the distribution of $\Delta m = m(h^-h^+\pi^+) - m(h^-h^+)$ where $m(h^-h^+\pi^+)$ is the mass of the D^{*+} candidate and $m(h^-h^+)$ that of the D^0 candidate
  - the second background contribution comes from D^{*+} mesons that are not produced at the PV but from the decay of B mesons: the effect of such secondary decays on the measurement is accounted by including their presence in the fit model
  - a third background contribution is related to the presence of partially reconstructed or misreconstructed $D^{*+} \to D^0\pi^+$ decays

Validation procedure with RapidSim

- Signal candidates of prompt $D^{*+} \to (D^0 \to K^-K^+)\pi^+$ and $D^{*+} \to (D^0 \to K^-\pi^+)\pi^+$ decays are generated without $D^0 - \bar{D}^0$ mixing
- Selection criteria representative of the trigger $\Rightarrow$ requirements on momentum and IP-related quantities, which are strongly correlated with the D^0 decay time and induce substantial differences between the selection efficiency profiles of $D^0 \to K^-K^+$ and $D^0 \to K^-\pi^+$ decays at low τ_{D^0}
- The kinematic matching procedure is then applied to equalise the selection efficiencies of $D^0 \to K^-K^+$ and $D^0 \to K^-\pi^+$ decays
- A fit to the decay time ratio $R^{KK}(t)$ gives $y_{CP}^{KK} - y_{CP}^{K\pi} = (0.17 \pm 0.19) \times 10^{-3}$, compatible with the expected value of zero
- The kinematic matching procedure corrects effectively for the kinematic differences between the two decays

Validation procedure with full simulation

- Large signal yields of $D^0 \to K^-\pi^+$, $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays are obtained by generating the particles of the decay chain without the full underlying event
- The analysis procedure is applied to all three decay channels independently for each year and magnet polarity to account for potential differences between the data taking conditions, and the results are combined as a final step
- Following the application of the kinematic matching and weighting procedures, the parameters are

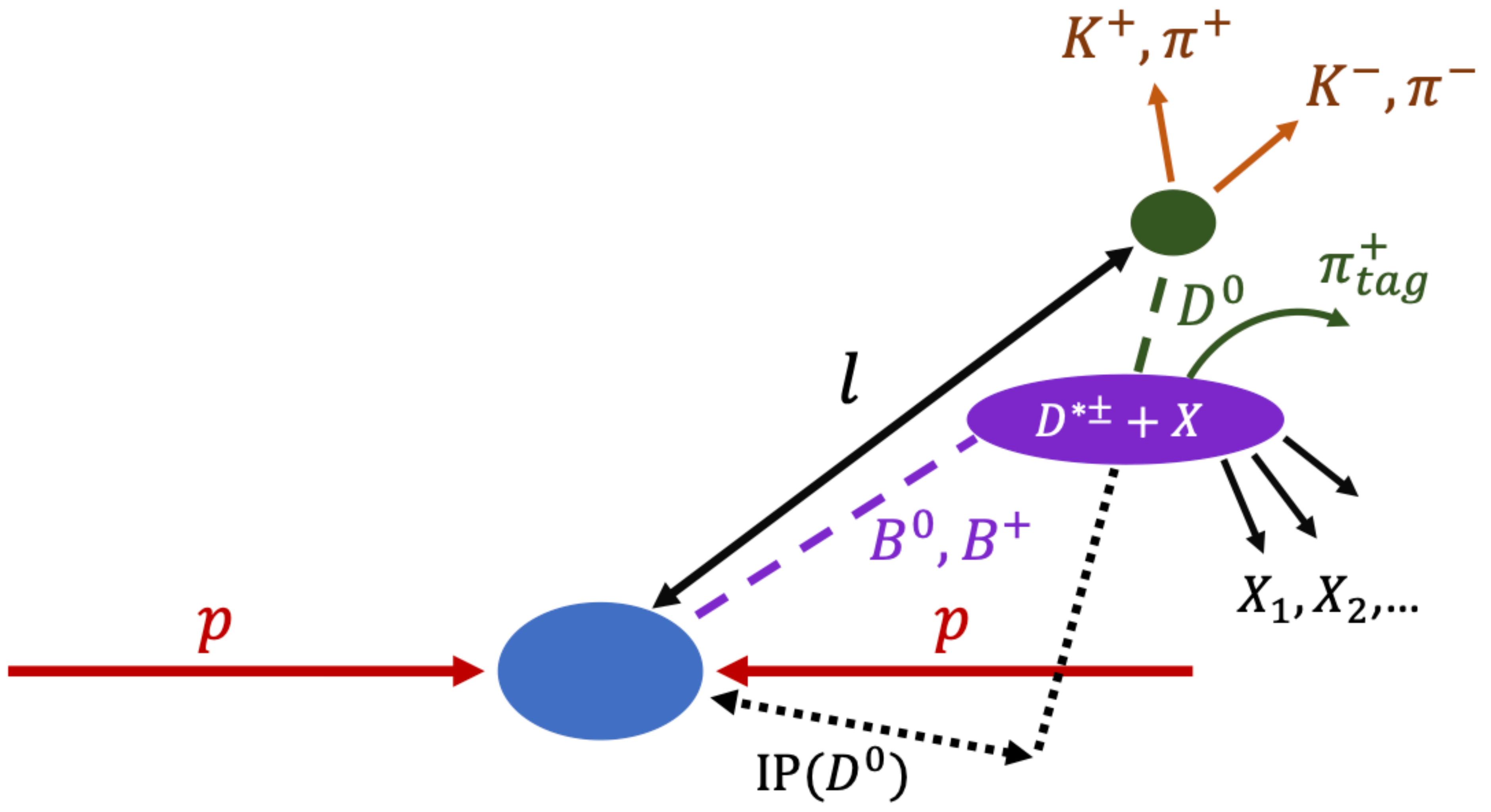
$$
\begin{aligned}
y_{\mathrm{CP}}^{\mathrm{CC}} &= (0.15 \pm 0.36) \times 10^{-3}, \\
y_{\mathrm{CP}}^{\pi\pi} - y_{\mathrm{CP}}^{K\pi} &= (0.17 \pm 0.43) \times 10^{-3}, \\
y_{\mathrm{CP}}^{KK} - y_{\mathrm{CP}}^{K\pi} &= (0.10 \pm 0.24) \times 10^{-3}
\end{aligned}
$$

- All three results are compatible with zero $\Rightarrow$ expected since $D^0 - \bar{D}^0$ mixing has not been simulated
- This result validates the analysis procedure with simulation

Secondaries contamination (I)

- The data samples are also contaminated by the presence of secondary D^{*+} mesons, which are not produced at the PV but from B meson decays
- $f_{sec}(t)$ is the time-dependent ratio of the number of D^0 mesons from secondary decays over the total
- To account for the residual contamination of secondary D^{*+} candidates, the ratio $R^f(t)$ is separated according to its prompt and secondary components, $R^f_{prompt}(t)$ and $R^f_{sec}(t)$, as

$$R^f(t) \approx \left(1 - f_{sec}(t)\right) R^f_{prompt(t)} + f_{sec}(t) R^f_{sec(t)}$$



Secondaries contamination (II)

- The decay time ratio of D^0 mesons from secondary D^{*+} decays is expressed as

$$R^f_{sec}(t) \propto e^{-(y^f_{CP}-y^{K\pi}_{CP})\frac{\langle t_D(t)\rangle}{\tau_{D^0}}}$$

where $\langle t_D(t)\rangle$ is the average true D^0 decay time $\langle t_D\rangle$ as a function of the reconstructed D^0 decay time t

- $f_{sec}(t)$ is obtained by fitting the distribution of IP(D^0) in data in each interval of t using simulation-based templates of IP(D^0) from prompt and secondary decays
- $\langle t_D(t)\rangle$ is determined from the simulated sample of secondary decays