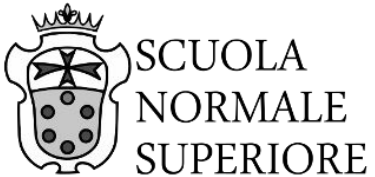
20th Conference on Flavour Physics and CP violation
Oxford, Mississippi, 23-27 May 2022

Mixing and CP violation in Charm decays at LHCb

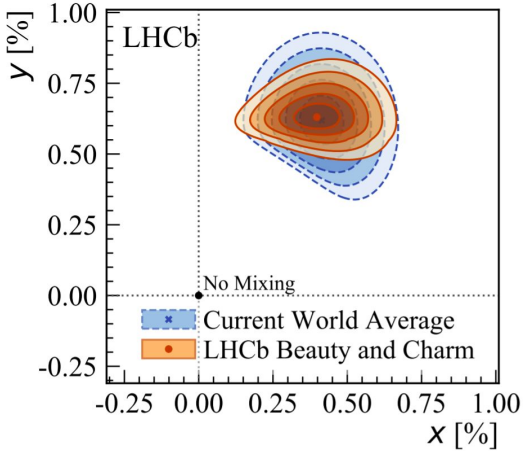
Roberto Ribatti
(Scuola Normale Superiore & INFN-Pisa)
roberto.ribatti@cern.ch
on behalf of the LHCb collaboration



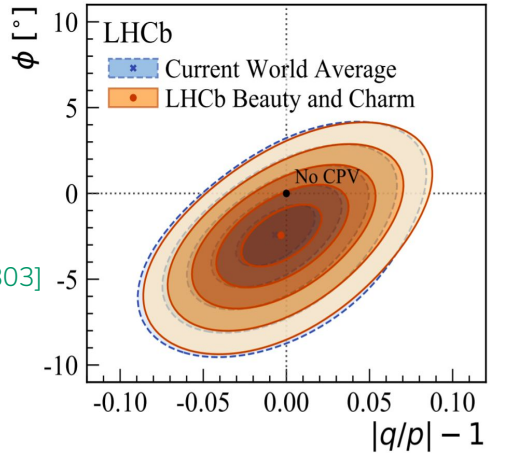
Mixing and CPV in charm

$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\overline{D^0}\rangle \qquad \phi = \arg\left(\frac{q}{p}\right)$$

$$x = \frac{M_2 - M_1}{\Gamma} \qquad y = \frac{\Gamma_2 - \Gamma_2}{2\Gamma}$$



- Charmed mesons are the only ones with up-type quarks where *CPV* can be measured
- In SM, mixing and CPV in charm are suppressed, $O(<10^{-3})$
- Simultaneous fit to beauty+charm observables, [JHEP12(2021)141] **leads to 3.5% relative precision on *y***, dominated by LHCb
- First observation of $x \neq 0$ in 2021 [PRL127(2021)111801]
- First observation of *CPV* in the decay in charm in 2019 [PRL122(2019)211803]
- Still no evidence of *CPV* in mixing and interference



Outline

- Measurement of the charm mixing parameter y_{CP}- $y_{CP}^{K\pi}$ using two-body D^0 meson decays [arXiv:2202.09106]

- Measurement of CP asymmetries in $D^+_{(s)} \to \eta\, \pi^+$ and $D^+_{(s)} \to \eta'\, \pi^+$ decays [arXiv:2204.12228]

[arXiv:2202.09106]

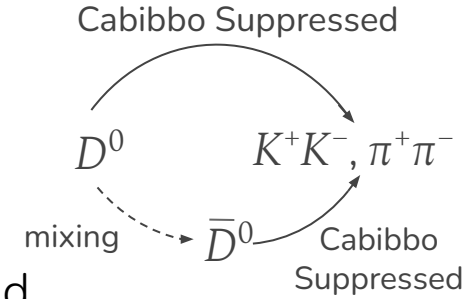
Measurement of charm mixing parameter y_{CP} with $D^0 \to h^+h^-$ decays at LHCb

y_{CP}- $y_{CP}^{K\pi}$ in $D^0 \to h^+h^-$: experimental observable

[arXiv:2202.09106]

- The experimental observable is: ($f = K^+K^-$ and $\pi^+\pi^-$)

$$\frac{\Gamma(D^0 \to f\,,\, t\,)}{\Gamma(D^0 \to K^-\pi^+,\, t\,)} - 1 = y_{CP}^{f}\text{-}\, y_{CP}^{K\pi} \approx y\,(\,1 + \sqrt{R_D}\,) \to \sqrt{\frac{B(D^0 \to K^+\pi^-)}{B(D^0 \to K^-\pi^+)}} \approx 6\,\%$$

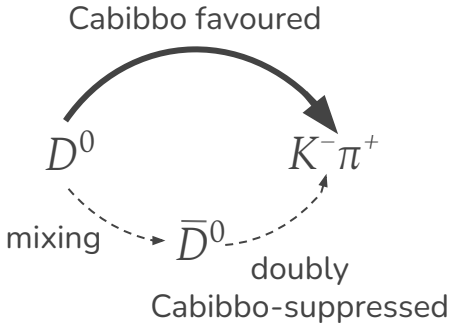


- The parameter y_{CP}- $y_{CP}^{K\pi}$ is the average of y_{CP}^{KK}- $y_{CP}^{K\pi}$ and $y_{CP}^{\pi\pi}$- $y_{CP}^{K\pi}$ and it's measurement directly constraint the mixing parameter y

- y_{CP}^{f}- $y_{CP}^{K\pi}$ is obtained with an exponential fit to R^f

$$R^f = \frac{N(D^0 \to f\,,\, t\,)}{N(D^0 \to K^-\pi^+,\, t\,)} \propto \exp[\,-(\,y_{CP}^{f} - y_{CP}^{K\pi}\,)\,t\,/\,\tau_{D^0}\,] \times \frac{\varepsilon(\,f\,,\,t\,)}{\varepsilon(\,K^-\pi^+,\,t\,)}$$

where ε are the time-dependent efficiencies

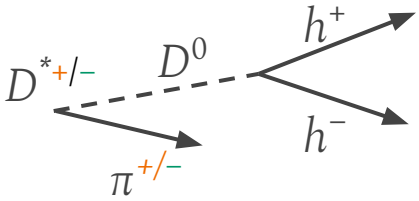


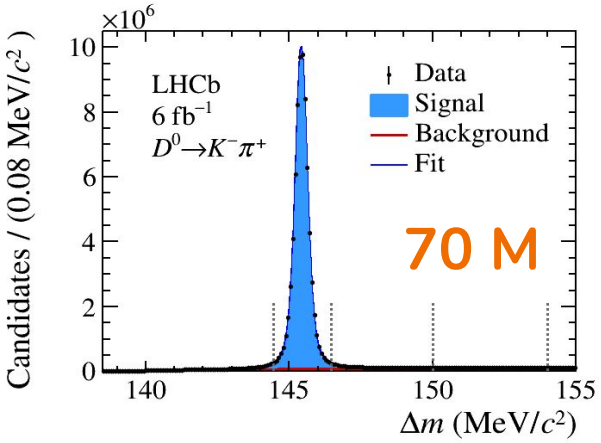
- Biggest challenge: equalize efficiencies so they cancel in the ratio

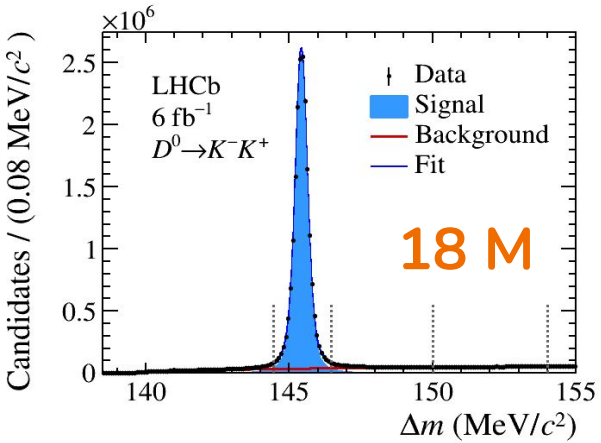
[arXiv:2202.09106]

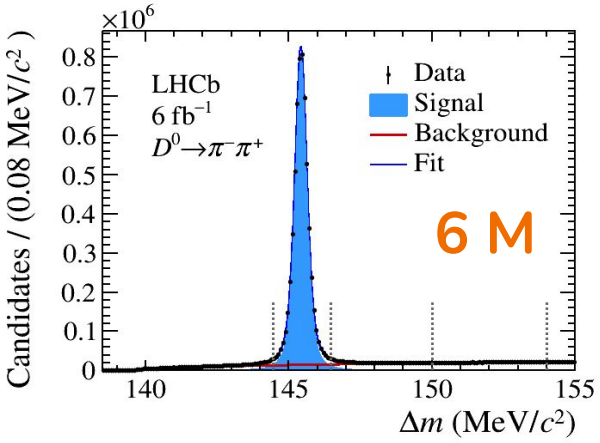
y_{CP} - $y_{CP}^{K\pi}$ in $D^0 \to h^+h^-$: dataset

- Run 2 dataset: 6 fb^{-1} of pp collision @ $\sqrt{s}$ = 13 TeV
- D^0 from $D^{*+} \to D^0\pi^+$ produced at the pp interaction point.
- Pion charge determines the D^0 flavour
- Fit to $\Delta m = m(h^-h^+\pi_{tag}) - m(h^-h^+)$ to subtract the combinatorial background





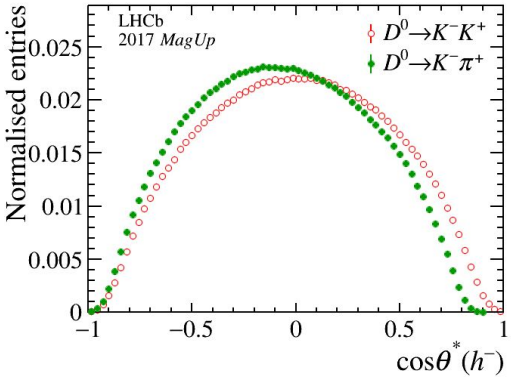




[arXiv:2202.09106]

y_{CP} - $y_{CP}^{K\pi}$ in $D^0 \to h^+h^-$: efficiency equalization

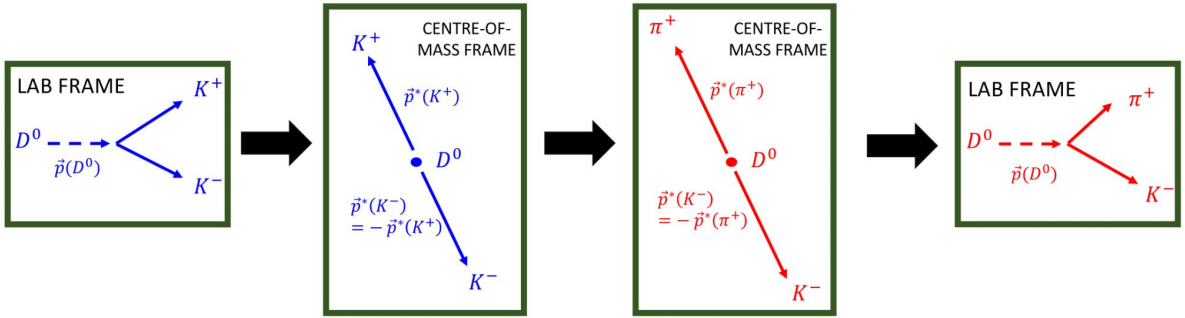
- Trigger requirement on D^0 daughters tracks (p, p_T, η, IP) are applied to two different final states
  → time-dependent efficiency discrepancies appear

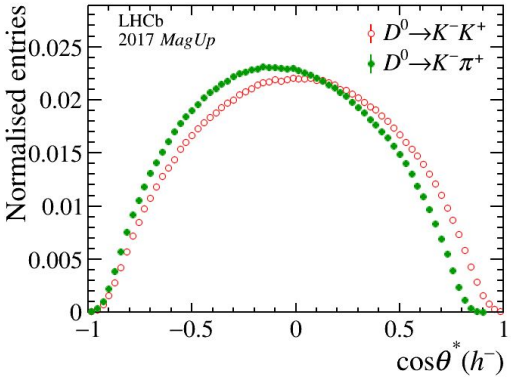


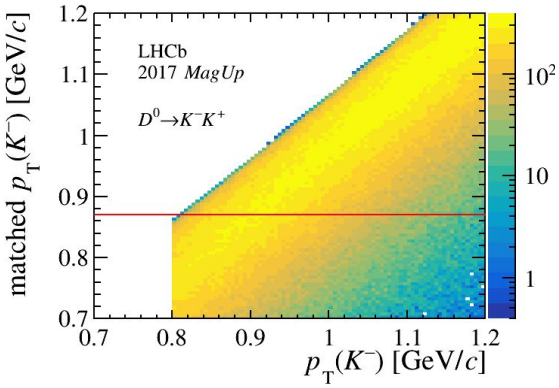
[arXiv:2202.09106]

y_{CP} - $y_{CP}^{K\pi}$ in $D^0 \to h^+h^-$: efficiency equalization

- Trigger requirement on D^0 daughters tracks (p, p_T, η, IP) are applied to two different final states
  → time-dependent efficiency discrepancies appear
- New *"matched"* variables are computed imposing |p| of D^0 daughters in the D^0 center of mass to be equal between the final states and then tighter selection on new variables is applied



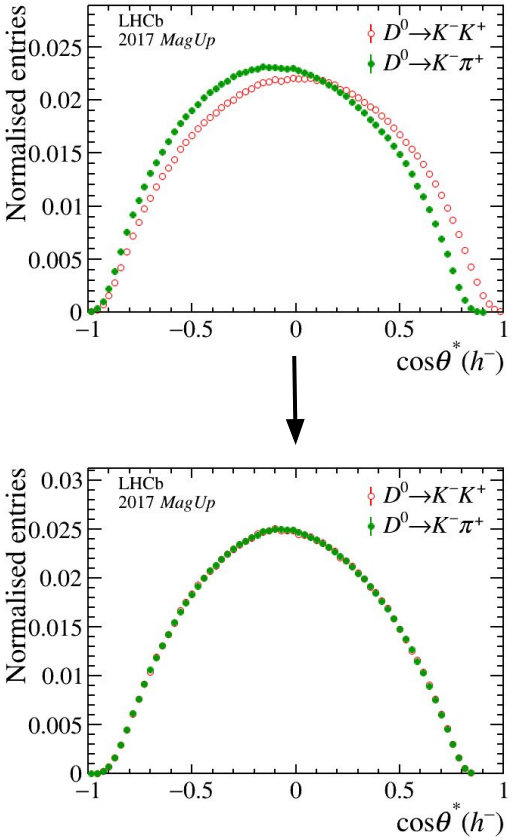




[arXiv:2202.09106]

y_{CP} - $y_{CP}^{K\pi}$ in $D^0 \to h^+h^-$: efficiency equalization

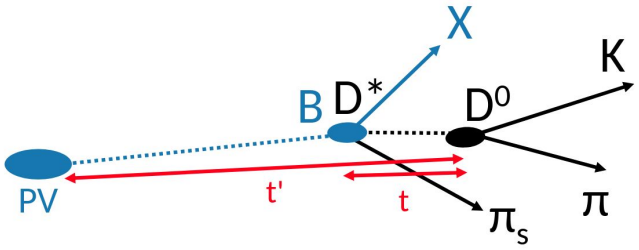
- Trigger requirement on D^0 daughters tracks (p, p_T, η, IP) are applied to two different final states
  → **time-dependent efficiency discrepancies appear**
- New *"matched"* variables are computed imposing |p| of D^0 daughters in the D^0 center of mass to be equal between the final states and then tighter selection on new variables is applied
- This efficiency equalization procedure is then validated both on full simulation and data

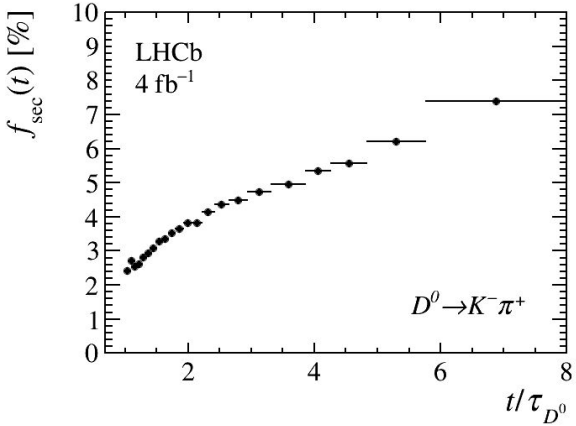


y_{CP} - $y_{CP}^{K\pi}$ in $D^0 \to h^+h^-$: secondary decays

[arXiv:2202.09106]

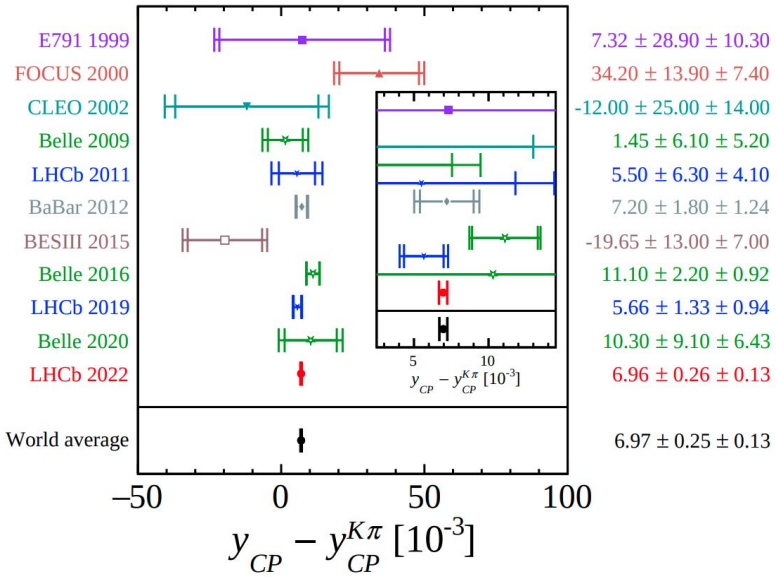
- D^0 decay time measured from pp interaction vertex
- Sample is contaminated by secondary $B^{0/+} \to D^{*+} X$ decays → reconstructed decay-times are biased towards larger values, **diluting mixing effect**
- Selection on $IP(D^0)$ reduce this background to few %
- Residual fraction is fitted to the 2D [$IP(D^0)$ - $t(D^0)$] distribution and the bias is subtracted with MC simulation

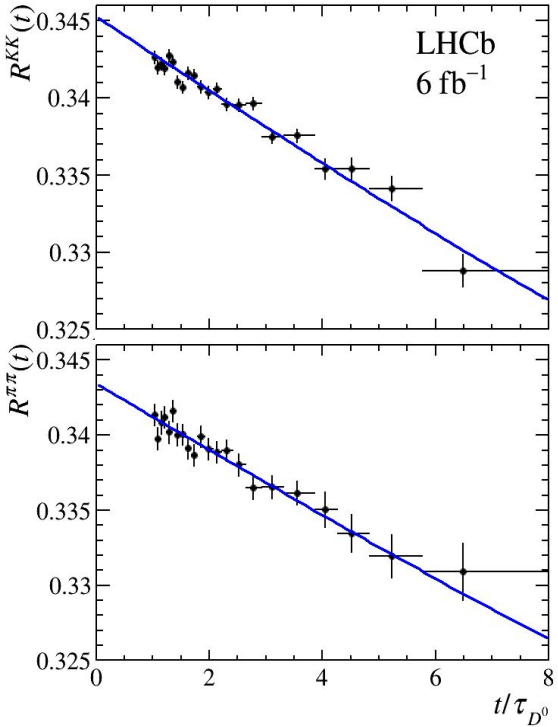




y_{CP} - $y_{CP}^{K\pi}$ in $D^0 \to h^+h^-$: results

- The measured values in each decay channel:
  - $y_{CP}^{KK} - y_{CP}^{K\pi} = (7.08 \pm 0.30_{stat} \pm 0.14_{sys}) \times 10^{-3}$
  - $y_{CP}^{\pi\pi} - y_{CP}^{K\pi} = (6.57 \pm 0.53_{stat} \pm 0.16_{sys}) \times 10^{-3}$





- Final average:

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

- World average improved by a factor 4!

[arXiv:2204.12228]

Measurement of CP asymmetries in $D^+_{(s)} \to \eta^{(\prime)}\pi^+$ decays at LHCb

[arXiv:2204.12228]

$A_{CP}(D^+_{(s)} \to \eta^{(\prime)}\pi^+)$: the experimental observable

- The CP asymmetry is defined as: (with $f = \eta^{(\prime)}(\to \gamma\,\pi^+\pi^-)\,\pi^+$)

$$A^{CP}(D^+_{(s)} \to f^+) \equiv \frac{\Gamma(D^+_{(s)} \to f^+) - \Gamma(D^-_{(s)} \to f^-)}{\Gamma(D^+_{(s)} \to f^+) + \Gamma(D^-_{(s)} \to f^-)}$$

- Experimentally the raw asymmetry is measured as:

$$A^{\text{raw}}(D^+_{(s)} \to f^+) \equiv \frac{N(D^+_{(s)} \to f^+) - N(D^-_{(s)} \to f^-)}{N(D^+_{(s)} \to f^+) + N(D^-_{(s)} \to f^-)}$$

- For small asymmetry:

$$A^{\text{raw}}(D^+_{(s)} \to f^+) \approx A^{CP}(D^+_{(s)} \to f^+) + A^{\text{prod}}(D^+_{(s)}) + A^{\text{det}}(f^+)$$

$$A^{\text{prod}}(D^+_{(s)}) \equiv \frac{\sigma(D^+_{(s)}) - \sigma(D^-_{(s)})}{\sigma(D^+_{(s)}) + \sigma(D^-_{(s)})}$$

$$A^{\text{det}}(f^+) \equiv \frac{\varepsilon(f^+) - \varepsilon(f^-)}{\varepsilon(f^+) + \varepsilon(f^-)}$$

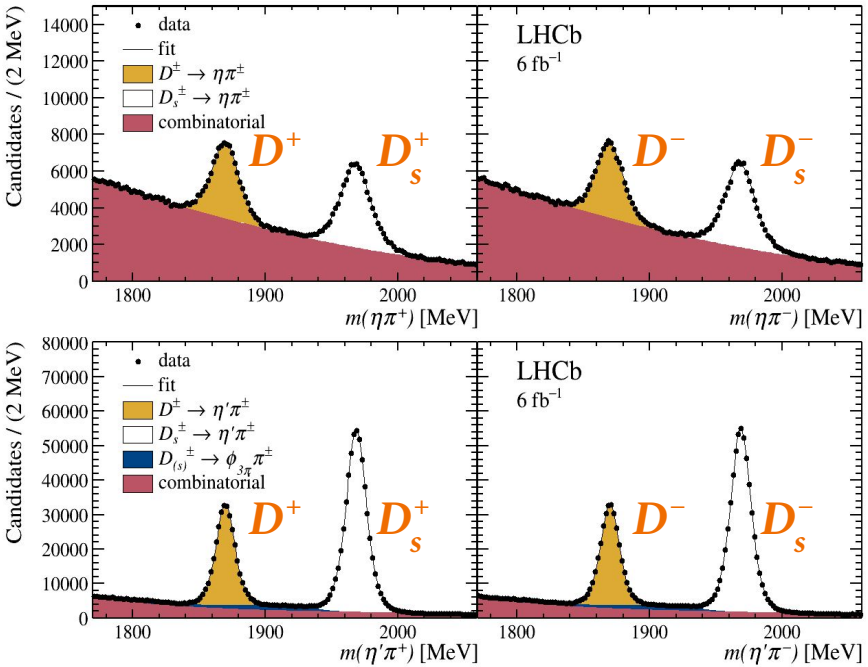
- Production and detection asymmetries are subtracted using control channels:
  - $A^{\text{raw}}(D^+ \to \eta^{(\prime)}\pi^+) - A^{\text{raw}}(D^+ \to \phi\pi^+) = A^{CP}(D^+ \to \eta^{(\prime)}\pi^+) - A^{CP}(D^+ \to \phi\pi^+)$
  - $A^{\text{raw}}(D_s^+ \to \eta^{(\prime)}\pi^+) - A^{\text{raw}}(D_s^+ \to \phi\pi^+) = A^{CP}(D_s^+ \to \eta^{(\prime)}\pi^+)$

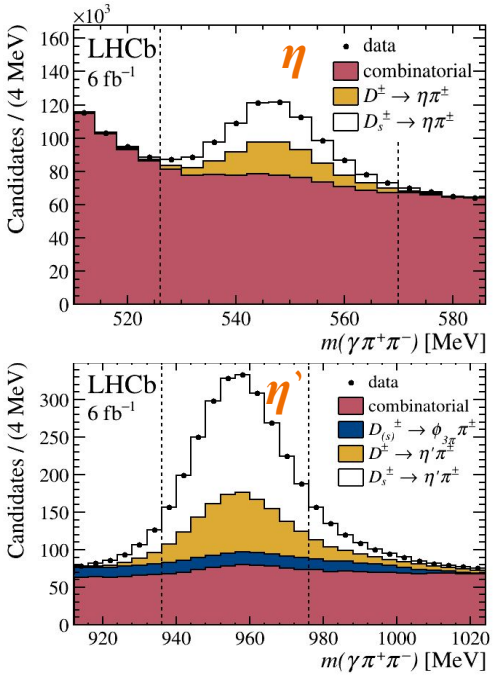
external input
$(0.005 \pm 0.051)\%$
[PRL122(2019)191803]

[arXiv:2204.12228]

$A_{CP}(D^+_{(s)} \to \eta^{(\prime)}\pi^+)$: analysis workflow

- Run 2 dataset: 6 fb^{-1} of pp collision @ $\sqrt{s}$ = 13 TeV
- CP asymmetry from simultaneous, binned ML fit to $m(\eta^{(\prime)}\pi^\pm)$ and $m(\gamma\,\pi^+\pi^-)$





[arXiv:2204.12228]

$A_{CP}(D^+_{(s)} \to \eta^{(\prime)}\pi^+)$: results

- The measured values in each decay channel:
  - $A^{CP}(D^+ \to \eta\,\pi^+) = (0.34 \pm 0.66_{\text{stat}} \pm 0.16_{\text{sys}} \pm 0.05_{\text{ctrl}})\,\%$ *
  - $A^{CP}(D_s^+ \to \eta\,\pi^+) = (0.32 \pm 0.51_{\text{stat}} \pm 0.12_{\text{sys}})\,\%$
  - $A^{CP}(D^+ \to \eta'\,\pi^+) = (0.49 \pm 0.18_{\text{stat}} \pm 0.06_{\text{sys}} \pm 0.05_{\text{ctrl}})\,\%$ *
  - $A^{CP}(D_s^+ \to \eta'\,\pi^+) = (0.01 \pm 0.12_{\text{stat}} \pm 0.08_{\text{sys}})\,\%$ *

- * Most precise measurement up to date!
- Statistically limited, no CP violation effect observed

Future prospect and conclusions

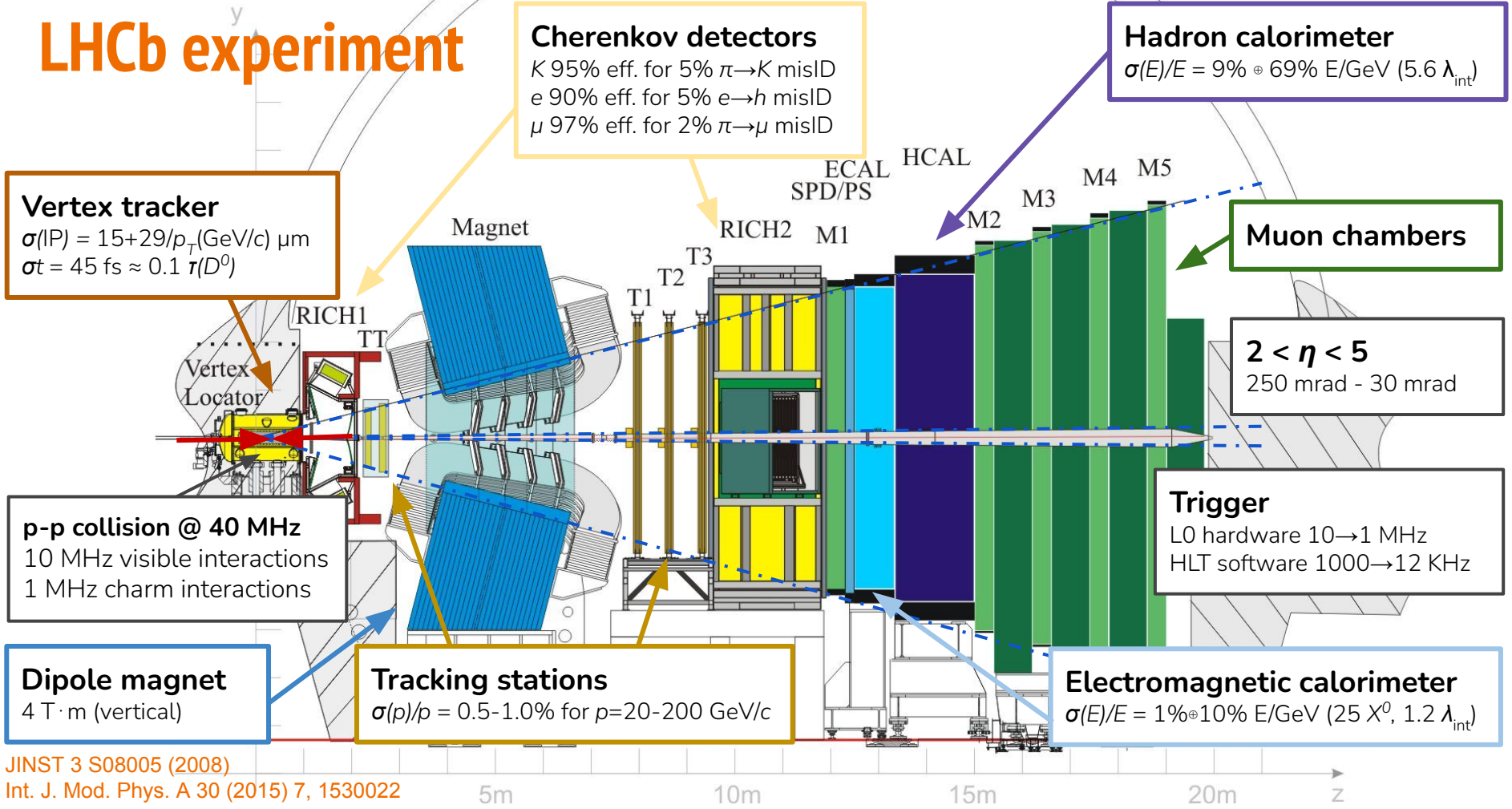
- Exciting results with Run 2 data and new one are on the way, however we have just barely started to approach SM upper limits for CPV

- LHCb Upgrade I is starting now. Expect to collect 23 fb^{-1} of integrated luminosity by the end of Run 3 and 50 fb^{-1} by the end of Run 4
  [CERN-PUB-LHCC-2018-027]

- The new LHCb DAQ&trigger system will grant a further gain w.r.t. Run 2 (about a factor of 2 in efficiency / fb^{-1}) for charm hadronic modes

Backup

LHCb experiment



Cherenkov detectors
K 95% eff. for 5% $\pi \to K$ misID
e 90% eff. for 5% $e \to h$ misID
μ 97% eff. for 2% $\pi \to \mu$ misID

Hadron calorimeter
$\sigma(E)/E$ = 9% ⊕ 69% E/GeV (5.6 λ_{int})

Vertex tracker
σ(IP) = 15+29/p_T(GeV/c) μm
σt = 45 fs ≈ 0.1 $\tau(D^0)$

Muon chambers

$2 < \eta < 5$
250 mrad - 30 mrad

p-p collision @ 40 MHz
10 MHz visible interactions
1 MHz charm interactions

Trigger
L0 hardware 10⟶1 MHz
HLT software 1000⟶12 KHz

Dipole magnet
4 T·m (vertical)

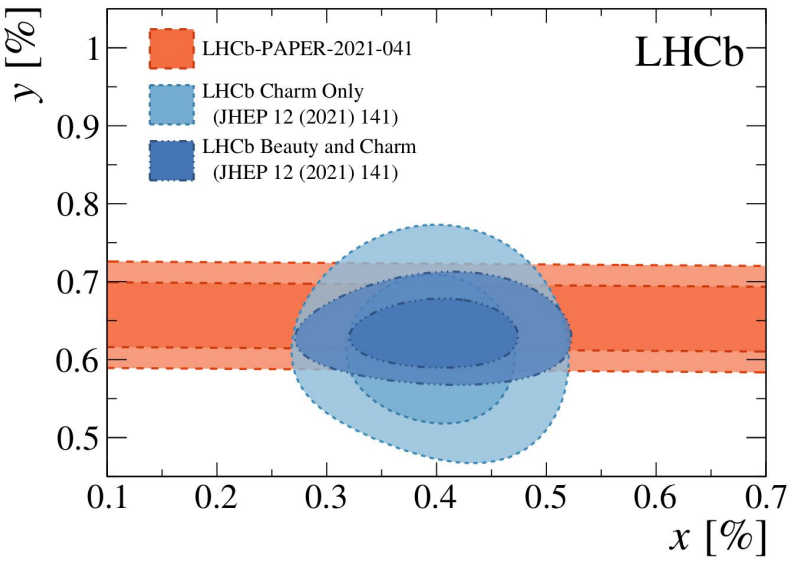
Tracking stations
$\sigma(p)/p$ = 0.5-1.0% for p=20-200 GeV/c

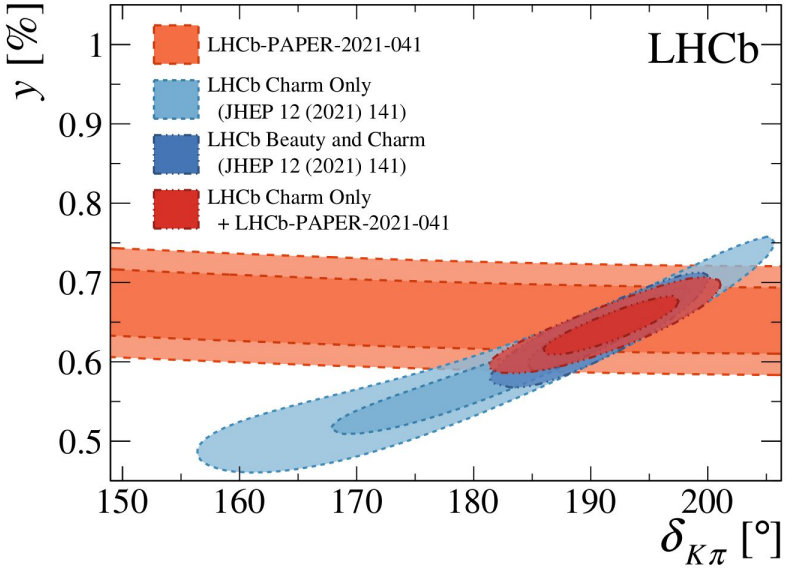
Electromagnetic calorimeter
$\sigma(E)/E$ = 1%⊕10% E/GeV (25 X^0, 1.2 λ_{int})

JINST 3 S08005 (2008)
Int. J. Mod. Phys. A 30 (2015) 7, 1530022

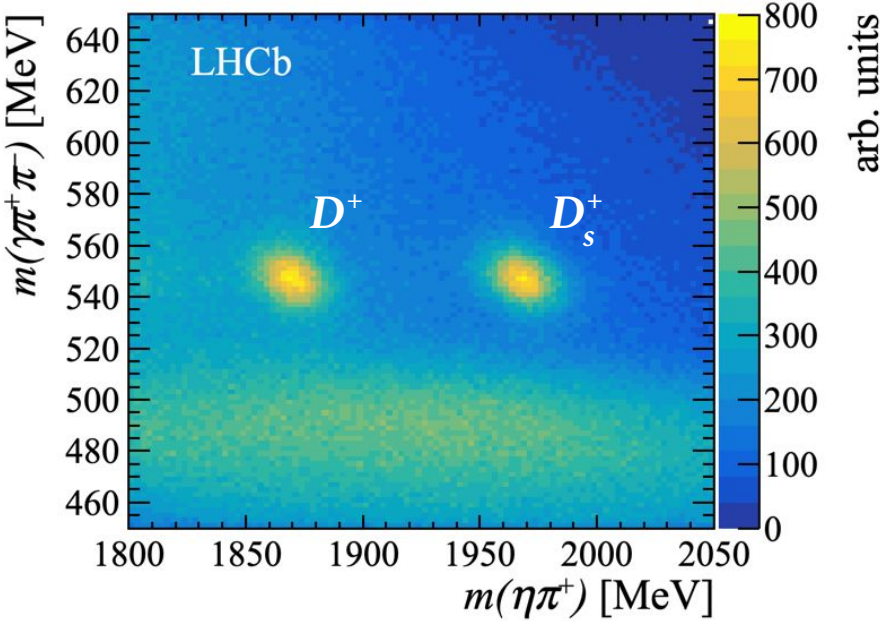
[arXiv:2202.09106]

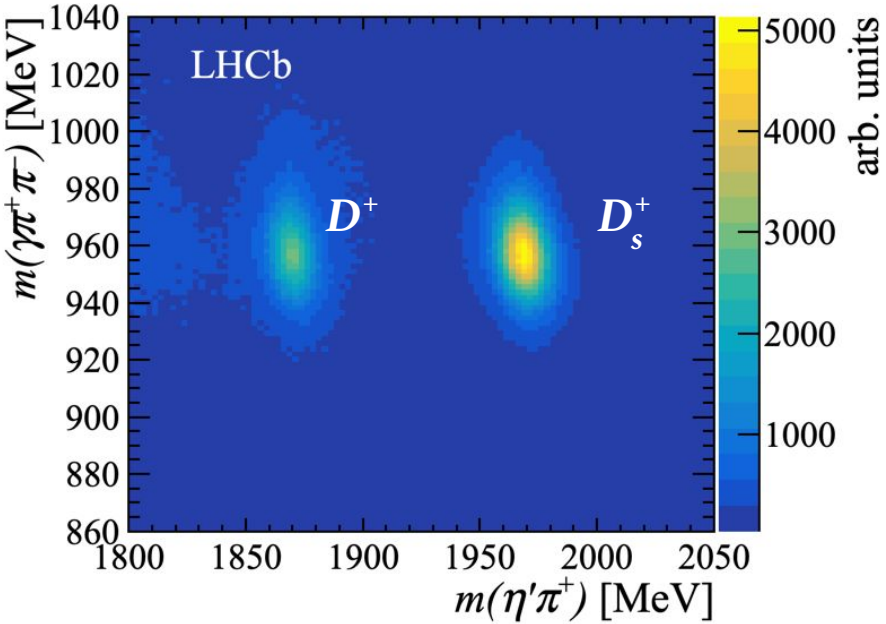
y_{CP} - $y_{CP}^{K\pi}$ in $D^0 \to h^+h^-$: impact on charm average





$A_{CP}(D^+_{(s)} \to \eta^{(\prime)}\pi^+)$: dataset





$A_{CP}(D^+_{(s)} \to \eta^{(\prime)}\pi^+)$: control sample