Mixing and CP violation in charm: Experimental overview

10th Edition of Large Hadron Collider Physics Conference (LHCP 2022)

This talk LIVE from Edinburgh

Mark Williams

16th May 2022

THE UNIVERSITY of EDINBURGH

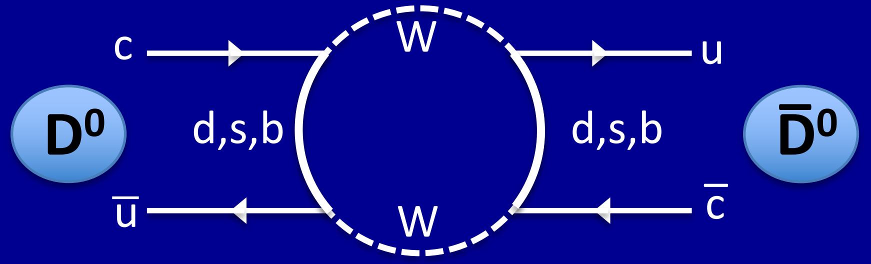
THE ROYAL SOCIETY

Outline

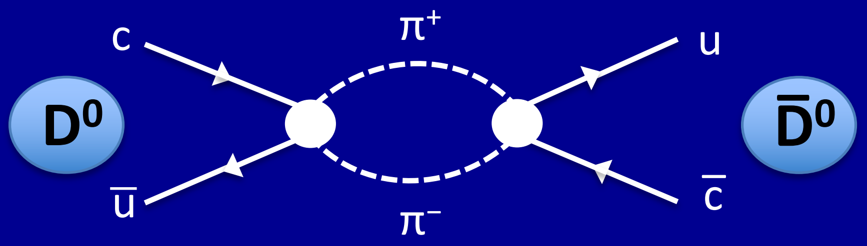
- **What, why, where, how?**
  - Background, motivation, state-of-the-art
- **CPV in decay**:
  - $D_{(s)}^+ \to \eta^{(\prime)}\pi^+$ decays (https://arxiv.org/abs/2204.12228)
- **CPV in rare charm decays:**
  - $D^0 \to \pi^+\pi^-\mu^+\mu^-$ and $K^+K^-\mu^+\mu^-$ (https://arxiv.org/abs/2111.03327)
- **Mixing and mixing-induced CPV**:
  - y_{CP} parameter (https://arxiv.org/abs/2202.09106)
  - ΔY in $D^0 \to h^+h^-$ (https://arxiv.org/abs/2105.09889)
  - $D^0 \to K_S{}^0 \pi^+\pi^-$ with 'bin flip' approach (https://arxiv.org/abs/2106.03744)
- **Summary and Outlook**

Neutral charm meson mixing

"short distance"



"long distance"



Mass states are superposition of flavor states:

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

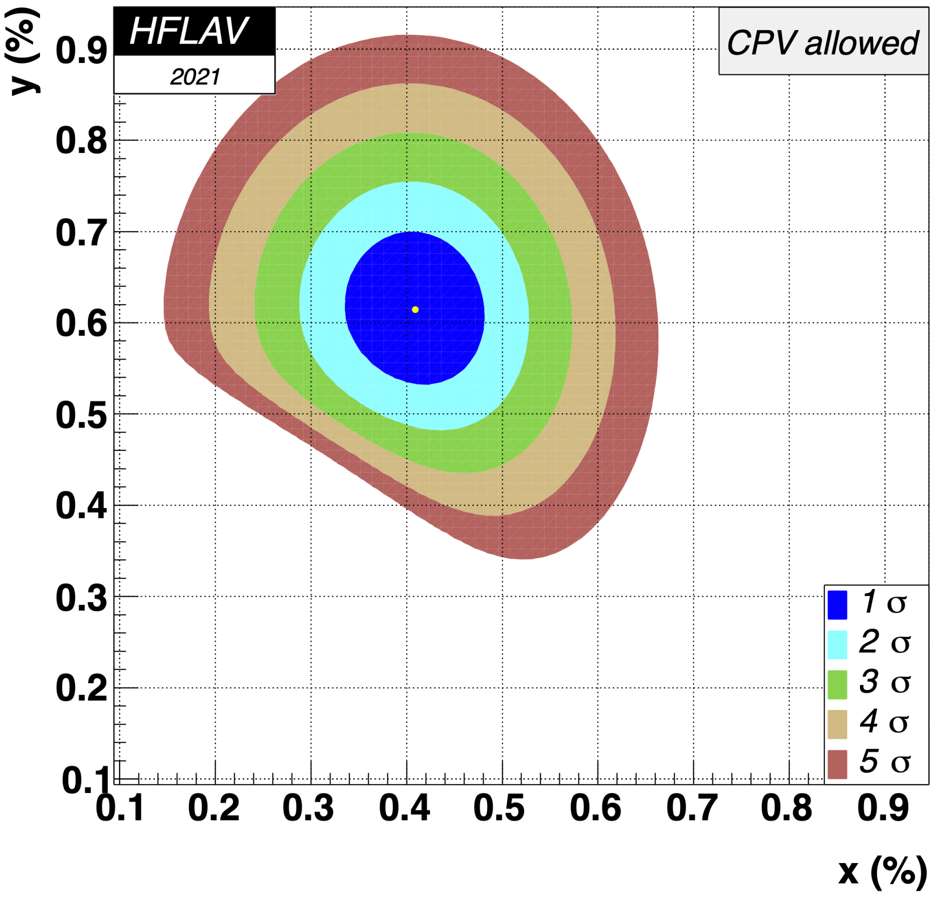
$x = (m_1 - m_2)/\Gamma$
$y = (\Gamma_1 - \Gamma_2)/2\Gamma$ } meson mixing

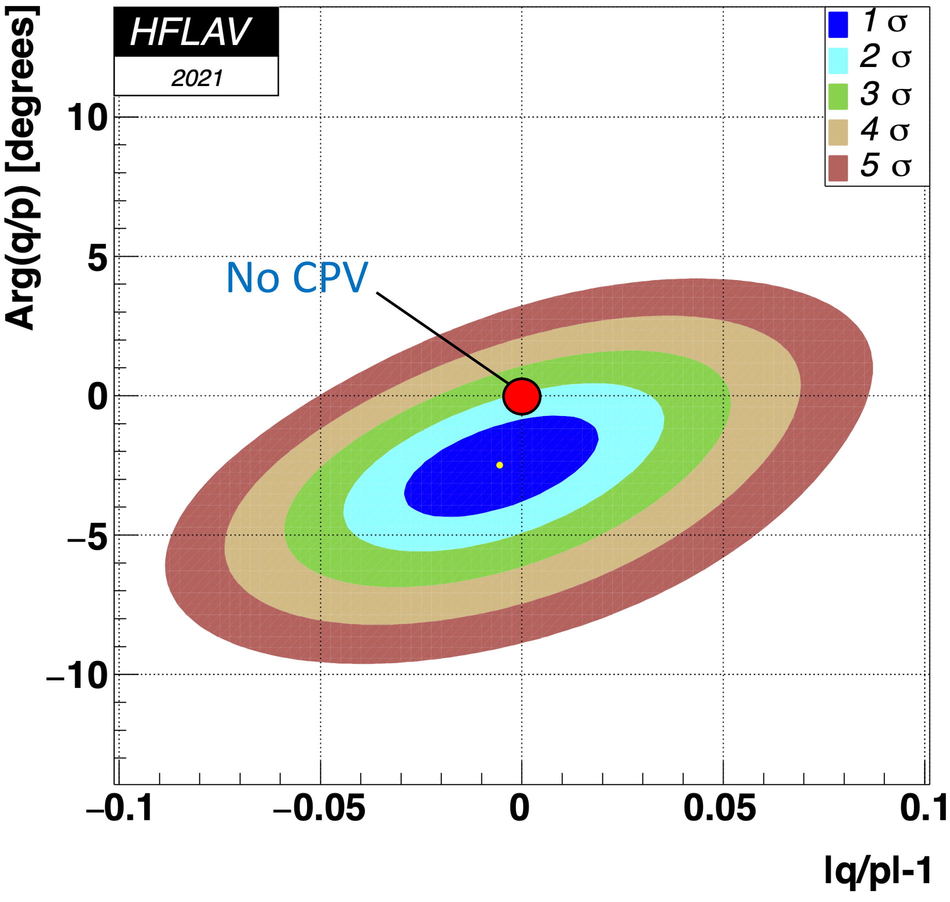
Oscillations characterized by four parameters:

$|q/p|$
$\phi = \arg(q/p)$ } CP violation

- **Unique** - up-type quarks
- **NP-sensitive** – CPV very small (~10^{-4}) in SM
- **Poorly experimentally-constrained** (until recently!)

State-of-the-art: mixing





Includes impact of final LHCb result covered today – see later!

Snapshot of charm mixing + CPV results

CPV in decay

Two-body

ΔA_{CP}($D^0 \to hh$) and A_{CP}(hh):
PRL 108 (2012) 111602
PLB 723 (2013) 33
JHEP 07 (2014) 041
PRL 116 (2016) 191601
PLB 767 (2017) 177
PRL 122 (2019) 211803

$D_{(s)}^+ \to \eta' \pi^+$
PLB 771 (2017) 21
arXiv:2204.12228

$D_{(s)}^+ \to h^+\pi^0$, $h^+\eta$
JHEP 06 (2021) 019

$D^0 \to K_S^0 K_S^0$
JHEP 10 (2015) 055
JHEP 11 (2018) 048
PRD 104 (2021) L031102

$D_{(s)}^+ \to K_S^0 h^+$
JHEP 06 (2013) 112
JHEP 10 (2014) 025
PRL 122 (2019) 191803

Multi-body

$D^0 \to K^-K^+\pi^-\pi^+$, $\pi^-\pi^+\pi^-\pi^+$:
PLB 726 (2013) 623 (S_{CP})
JHEP 10 (2014) 005 (T-odd)
PLB 769 (2017) 345 (energy test)
JHEP 02 (2019) 126 (AmAn)

$\Xi_c^+ \to pK^-\pi^+$ (SCP, KNN)
PRD 102 (2020) 071101(R)

$D^+ \to K^-K^+\pi^+$
PRD 84 (2011) 112008
JHEP 06 (2013) 112

$D^+ \to \pi^+\pi^-\pi^+$:
PLB 728 (2014) 585

$D^0 \to \pi^+\pi^-\pi^0$
PLB 740 (2015) 158

Rare

$D^0 \to h^+h^-\mu^+\mu^-$
arXiv:2111.03327

$\Lambda_c^+ \to ph^+h^-$
JHEP 03 (2018) 182

Mixing + mixing-induced CPV

A_Γ($D^0 \to hh$)
JHEP 1204 (2012) 129 (KK), **+y_{CP}**
PRL 112 (2014) 041801
JHEP 04 (2015) 043
PRL 118 (2017) 261803
PRD 101 (2020) 012005
PRD 104 (2021) 072010

y_{CP}(hh)
PRL 122 (2019) 011802
arXiv:2202.09106

WS $D^0 \to K^+\pi^-$
PRL 110 (2013) 101802
PRL 111 (2013) 251801
PRD 95 (2017) 052004
PRD 97 (2018) 031101

$D^0 \to K_S^0\pi^+\pi^-$
JHEP 04 (2016) 033
PRL 122 (2019) 231802
PRL 127 (2021) 111801

$D^0 \to K^-\pi^+\pi^-\pi^+$
PRL 116 (2016) 241801

https://lhcbproject.web.cern.ch/lhcbproject/Publications/p/Summary_Charm.html

The discovery of CPV in charm: in *decay*

PRL 122 (2019) 211803

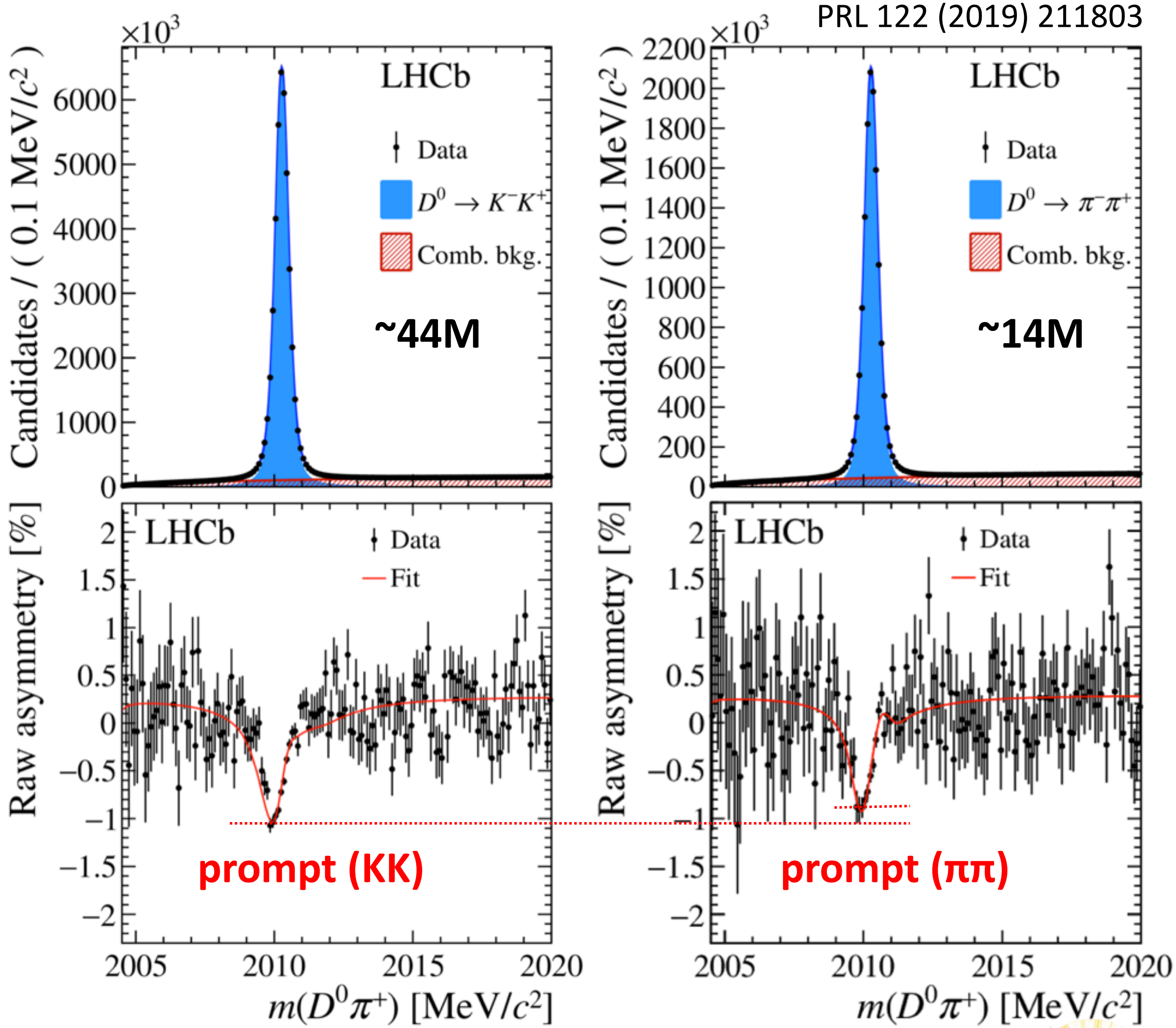
Difference in CP asymmetries A_{CP} between $D^0 \to \pi^+\pi^-$ and $D^0 \to K^+K^-$

$$A_{CP}(D^0 \to f) = \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to \bar{f})}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to \bar{f})}$$

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

5.3σ from zero

SM or BSM?



What next?

- **More (and more precise) measurements of CPV in decay**
  ⇒ add new channels, including ones more challenging to reconstruct
- More (and more precise) time-dependent analyses to search for mixing-induced CPV
- Exploit multibody final states sensitive to 'local' CPV through interference effects

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

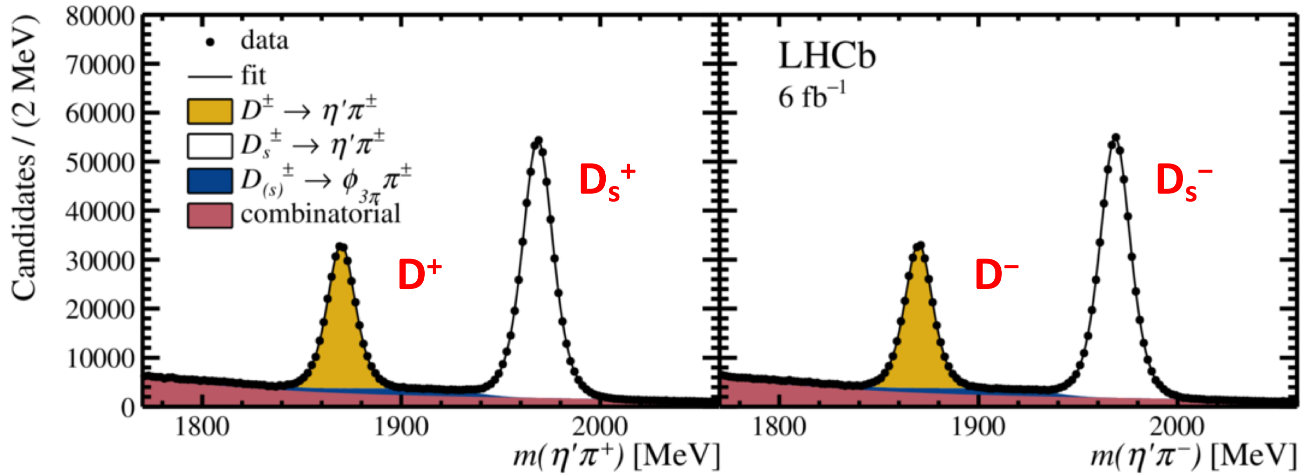
arXiv:2204.12228
(submitted to JHEP)

Signal

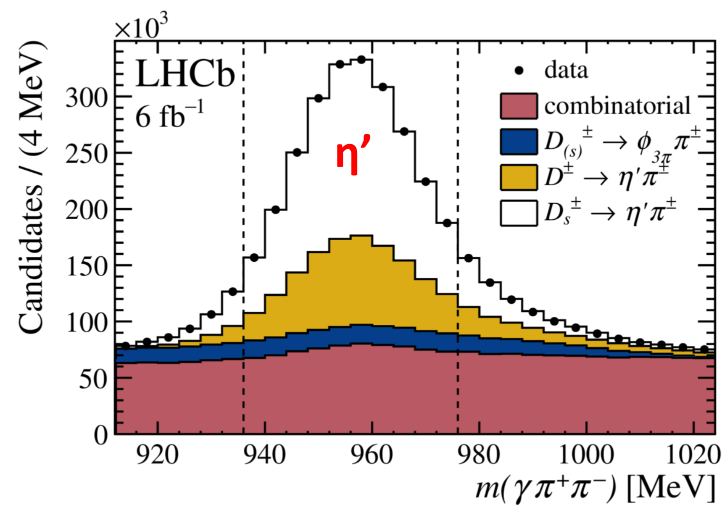
$D_{(s)}^{\pm} \to \eta^{(\prime)}\pi^{\pm}$
$\hookrightarrow \pi^+\pi^-\gamma$

Control

$D_{(s)}^{\pm} \to \phi\pi^{\pm}$
$\hookrightarrow K^+K^-$



Simultaneous fit of **m(π⁺π⁻γ)** and **m(η⁽′⁾π^±)**
⇒ separate $D_{(s)}^{\pm}$ signals from different backgrounds



$$\mathcal{A}^{CP}(D^+ \to \eta\pi^+) = (0.34 \pm 0.66 \pm 0.16 \pm 0.05)\%,$$
$$\mathcal{A}^{CP}(D_s^+ \to \eta\pi^+) = (0.32 \pm 0.51 \pm 0.12)\%,$$
$$\mathcal{A}^{CP}(D^+ \to \eta'\pi^+) = (0.49 \pm 0.18 \pm 0.06 \pm 0.05)\%,$$
$$\mathcal{A}^{CP}(D_s^+ \to \eta'\pi^+) = (0.01 \pm 0.12 \pm 0.08)\%,$$

Consistent with CP symmetry, statistically limited, world's best for 3/4 channels

+ Other recent studies

$A_{CP}(D^+_{(s)} \to h^+h^0)$ with $h^0 \to e^+e^-\gamma$

arXiv:2103.11058
JHEP 06 (2021) 019

$$\mathcal{A}_{CP}(D^+ \to \pi^+\pi^0) = (-1.3 \pm 0.9 \pm 0.6)\%$$ SCS *

$$\mathcal{A}_{CP}(D^+ \to K^+\pi^0) = (-3.2 \pm 4.7 \pm 2.1)\%$$ DCS *

$$\mathcal{A}_{CP}(D^+ \to \pi^+\eta) = (-0.2 \pm 0.8 \pm 0.4)\%$$ SCS *

$$\mathcal{A}_{CP}(D^+ \to K^+\eta) = (-6 \pm 10 \pm 4)\%$$ DCS *

$$\mathcal{A}_{CP}(D_s^+ \to K^+\pi^0) = (-0.8 \pm 3.9 \pm 1.2)\%$$ SCS *

$$\mathcal{A}_{CP}(D_s^+ \to \pi^+\eta) = (0.8 \pm 0.7 \pm 0.5)\%$$ CF

$$\mathcal{A}_{CP}(D_s^+ \to K^+\eta) = (0.9 \pm 3.7 \pm 1.1)\%$$ SCS

Probe range of processes

No evidence for CPV

Several world-leading measurements (*)

$A_{CP}(D^0 \to K^0_S K^0_S)$

arXiv:2105.01565
PRD 104 L031102

$$\mathcal{A}^{CP}(D^0 \to K^0_S K^0_S) = (-3.1 \pm 1.2 \pm 0.4 \pm 0.2)\%$$

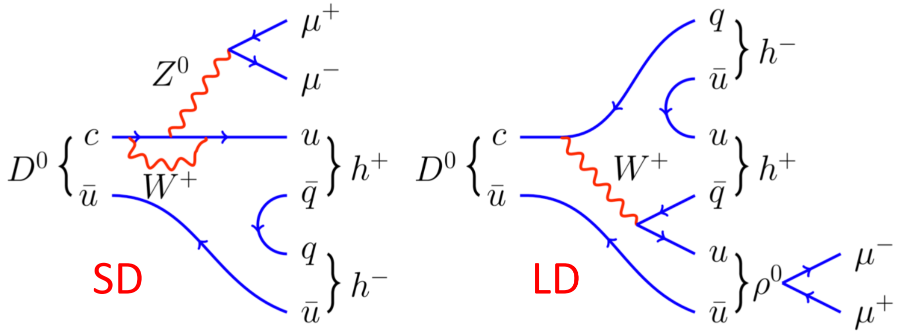
stat — syst — control mode

Most precise measurement (as precise as WA)

$D^0 \to h^+h^-\mu^+\mu^-$ angular analysis

arXiv:2111.03327
(submitted to PRL)

$D^0 \to K^+K^-\mu^+\mu^-$ and $D^0 \to \pi^+\pi^-\mu^+\mu^-$ proceed via $c \to u\,\mu^+\mu^-$ FCNC processes

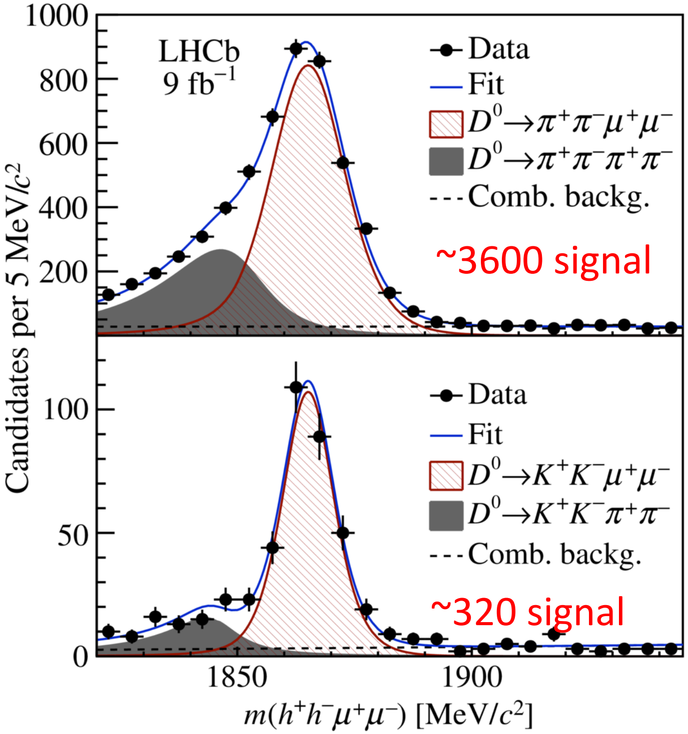


$\Rightarrow$ Sensitive to BSM physics through interference of short- (SD) and long-distance (LD) contributions

First full angular analysis of rare charm decay
(see talk from C. Agapopoulou tomorrow)

Measure overall CP asymmetry A_{CP}, in bins of q^2, and also CP asymmetries in angular observables

LHCb Run 1-2 data sample (9fb^{-1})



$D^0 \to h^+h^-\mu^+\mu^-$ angular analysis

arXiv:2111.03327
(submitted to PRL)

Nuisance asymmetries corrected with $D^0 \to K^+K^-$ control mode

Validated with $D^0 \to \pi^+K^-\mu^+\mu^-$ channel
$\Rightarrow$ dominated by SM decay $\rho^0/\omega \to \mu\mu$

No evidence of CPV from angular asymmetries, or integrated A_{CP}

Statistically dominated

Largest systematic uncertainty from angular efficiency

$m(\mu^+\mu^-)$ [MeV/c^2]	A_{CP} [%]
$D^0 \to \pi^+\pi^-\mu^+\mu^-$	
< 525	$28 \pm 13 \pm 1$
525–565	–
565–780	$-2.7 \pm 4.1 \pm 0.4$
780–950	$-1.9 \pm 5.8 \pm 0.4$
950–1020	$0.5 \pm 3.7 \pm 0.4$
1020–1100	$4.2 \pm 3.4 \pm 0.4$
> 1100	–
Full range	$2.9 \pm 2.1 \pm 0.4$
$D^0 \to K^+K^-\mu^+\mu^-$	
< 525	$4 \pm 15 \pm 1$
525–565	–
> 565	$-2.5 \pm 6.8 \pm 0.6$
Full range	$-2.3 \pm 6.3 \pm 0.6$

What next?

- More (and more precise) measurements of CPV in decay
  $\Rightarrow$ add new channels, including ones more challenging to reconstruct

- **More (and more precise) time-dependent analyses to precisely measure mixing and search for mixing-induced CPV**

- Exploit multibody final states sensitive to ‘local’ CPV through interference effects

y_{CP} in $D^0 \to h^+h^-$ decays

arXiv:2202.09106 (accepted by PRD)

What? Why?

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

In absence of CP violation

$y_{CP} = y$

Important input for global fits of charm mixing and CPV parameters
Main challenge – requires precise knowledge of time-acceptance for different final states

Use average of flavor eigenstates Kπ in denominator ⇒ introduces small shift ≈ −0.04%

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

(≈0.7 ± 0.1)%
HFLAV average

Measure separately for $f = K^+K^-, \pi^+\pi^-$ final states.

Flavour-tag D^0 at production using $D^{*\pm} \to D^0\pi^\pm$ decays

y_{CP} in $D^0 \to h^+h^-$ decays

arXiv:2202.09106
(accepted by PRD)

$$R^f(t) = \frac{N(D^0 \to f, t)}{N(D^0 \to K^-\pi^+, t)} \propto e^{-\left(y_{CP}^f - y_{CP}^{K\pi}\right)t/\tau_{D^0}} \frac{\varepsilon(f,t)}{\varepsilon(K^-\pi^+,t)}$$

What we want

Measure this ratio by fitting yields in bins of D^0 decay time

Ratio of time-dependent efficiencies
⇒ subject to tricky systematics

Account for backgrounds:

- Combinatorial
- Secondary charm ($b \to c$)
- Partially reconstructed decays and misID

Control by:

- Careful event selection criteria
- Kinematic matching and reweighting procedure
- Validate with fastMC, full MC, and real data

y_{CP} in $D^0 \to h^+h^-$ decays

arXiv:2202.09106
(accepted by PRD)

Results

$$y_{CP}^{\pi\pi} - y_{CP}^{K\pi} = (6.57 \pm 0.53 \pm 0.16) \times 10^{-3}$$
$$y_{CP}^{KK} - y_{CP}^{K\pi} = (7.08 \pm 0.30 \pm 0.14) \times 10^{-3}$$

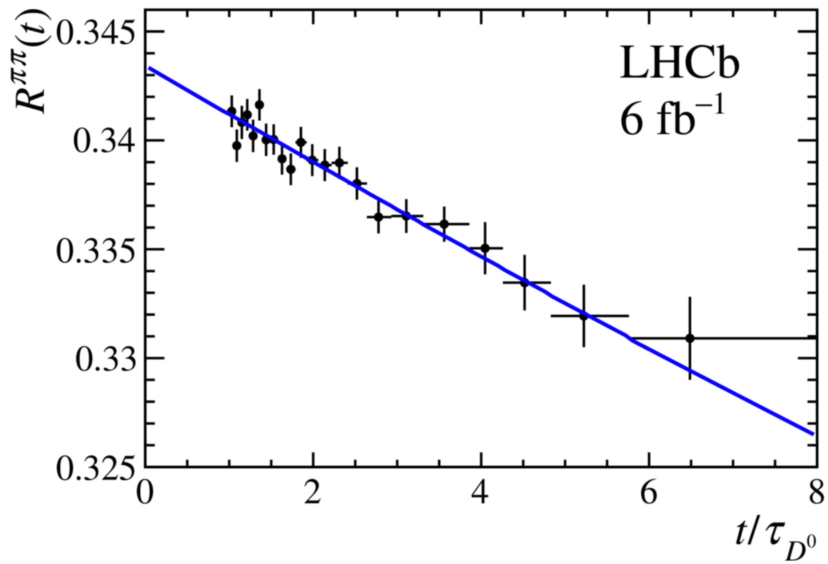
Statistically limited. Main systematic uncertainties from background treatment.

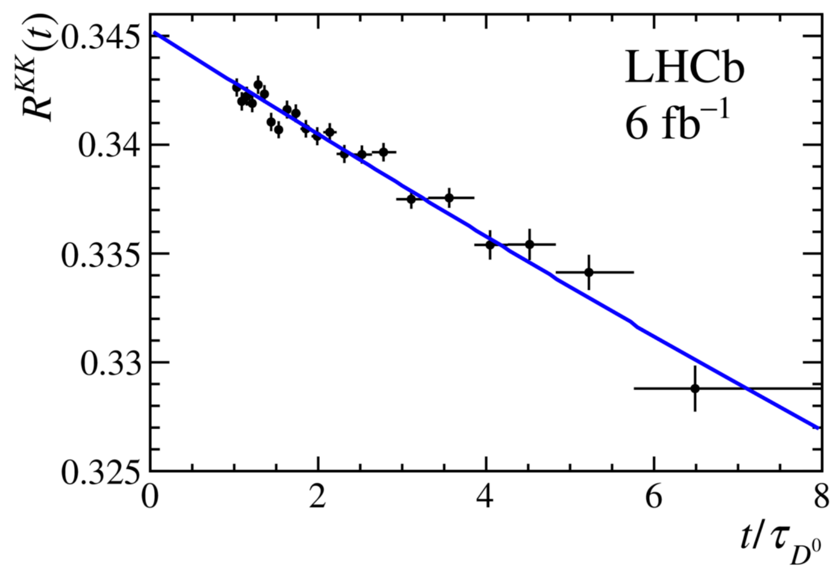
Combining channels:

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

4x more precise than existing world-average.

Consistent between data-taking years and magnet polarities





Time-dep. CPV: ΔY (≈−A_Γ)

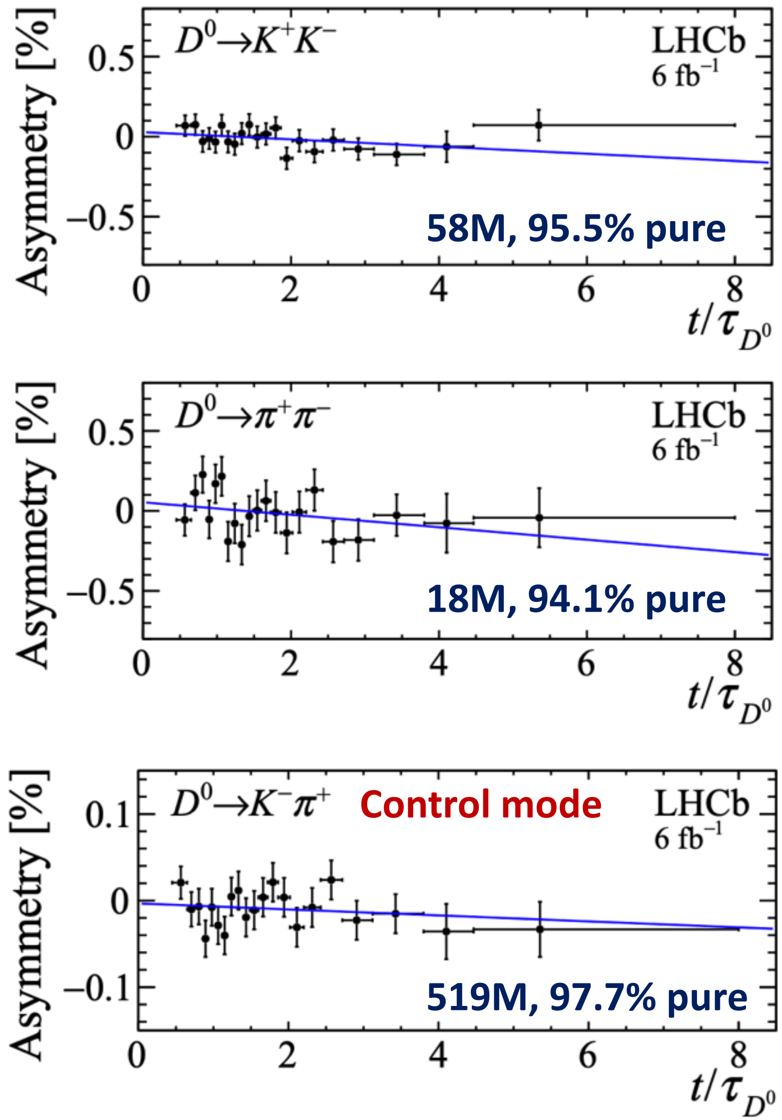
arXiv:2105.09889
PRD 104 072010

Same channels as ΔA_{CP} discovery
⇒ **Time-dependent asymmetry**

Full Run 2 sample

Careful correction of detector effects
(e.g. trigger-induced correlations)

Data-driven validation with CF $D^0 \to K^- \pi^+$



Time-dep. CPV: ΔY ($\approx -A_\Gamma$)

arXiv:2105.09889
PRD 104 072010

Same channels as ΔA_{CP} discovery
⇒ **Time-dependent asymmetry**

Full Run 2 sample

Careful correction of detector effects
(e.g. trigger-induced correlations)

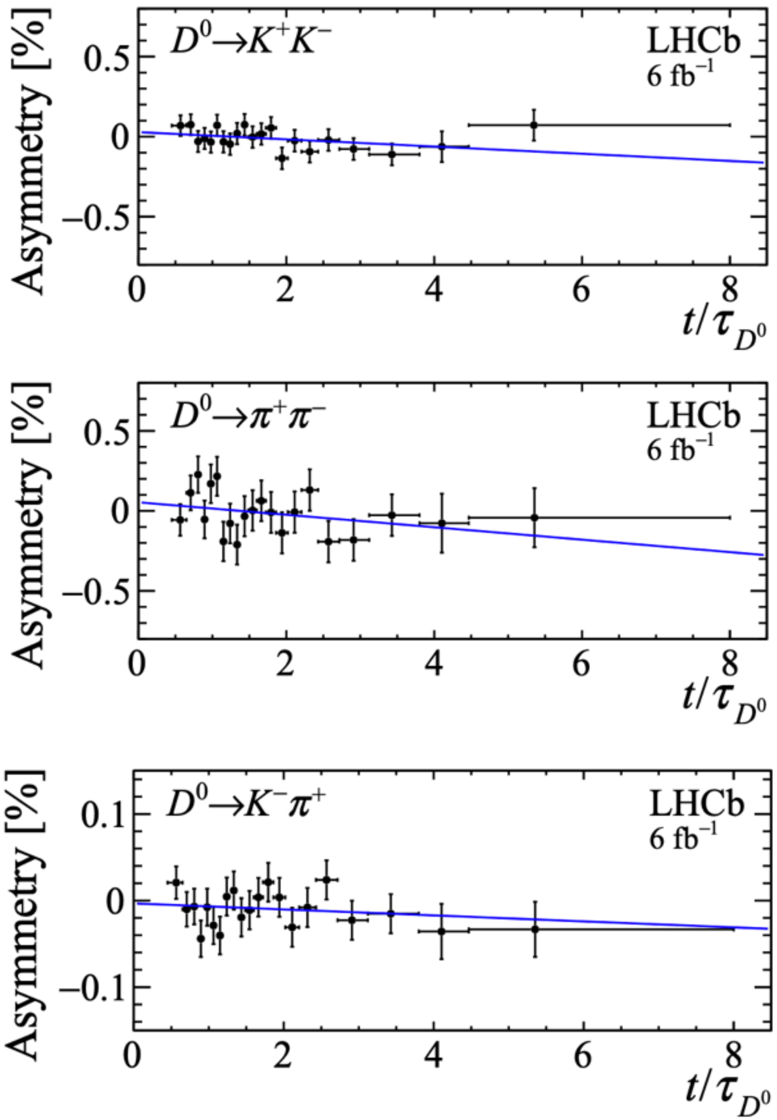
Data-driven validation with CF $D^0 \to K^- \pi^+$

>2x more precise than existing best measurement

Combine with previous LHCb results:

$$\Delta Y_{K^+K^-} = (-0.3 \pm 1.3 \pm 0.3) \times 10^{-4}$$
$$\Delta Y_{\pi^+\pi^-} = (-3.6 \pm 2.4 \pm 0.4) \times 10^{-4}$$
$$\Delta Y = (-1.0 \pm 1.1 \pm 0.3) \times 10^{-4}$$
$$\Delta Y_{K^+K^-} - \Delta Y_{\pi^+\pi^-} = (+3.3 \pm 2.7 \pm 0.2) \times 10^{-4}$$

No CPV observed, constrained at 10^{-4} level



What next?

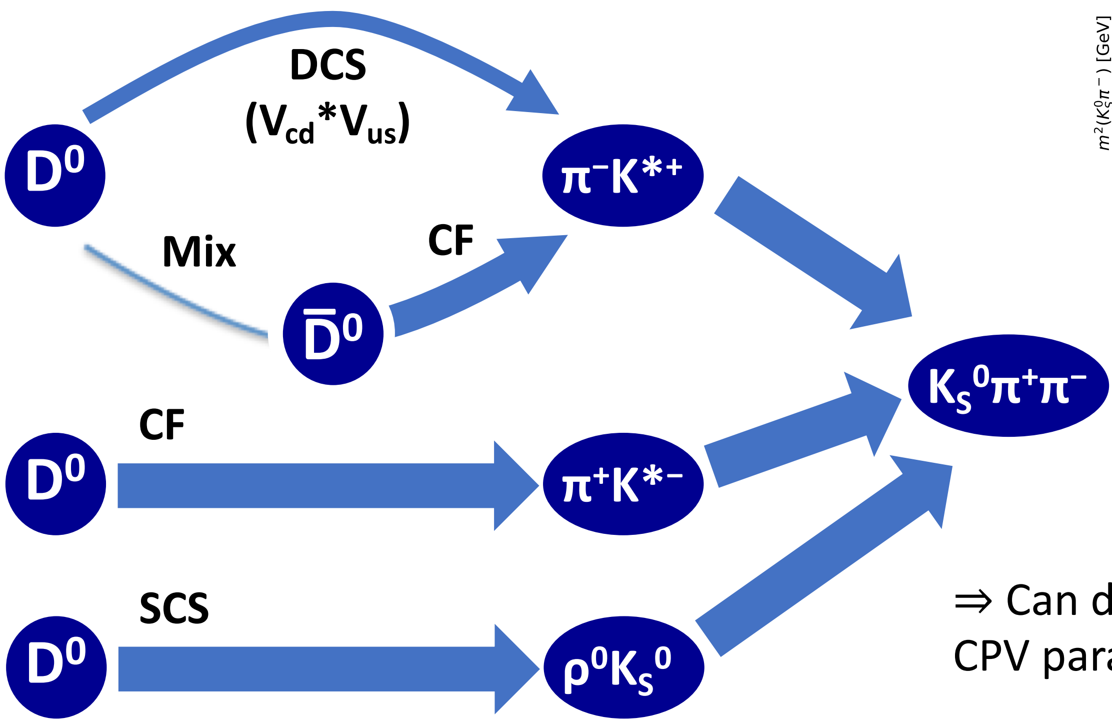
- More (and more precise) measurements of CPV in decay
  ⇒ add new channels, including ones more challenging to reconstruct

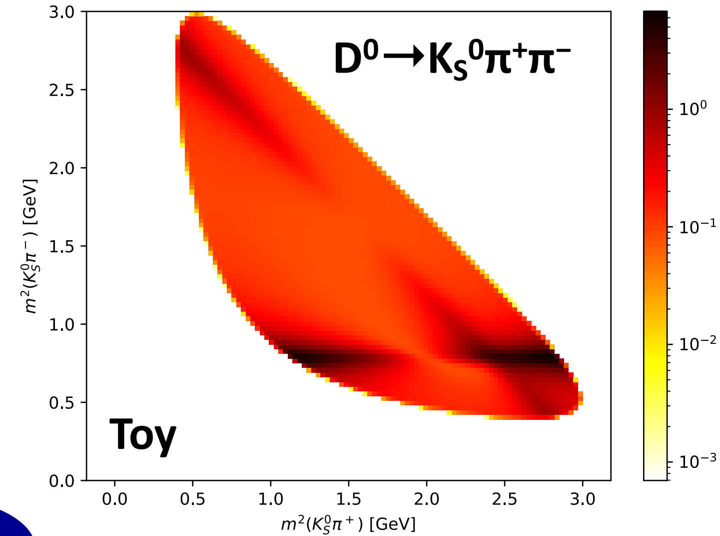
- **More (and more precise) time-dependent analyses to search for mixing-induced CPV**

- **Exploit multibody final states sensitive to ‘local’ CPV through interference effects**

The Golden Mode: $D^0 \rightarrow K_S^0 \pi^+ \pi^-$

Many possible interfering amplitudes, including via $D^0 \longleftrightarrow \bar{D}^0$ oscillation





$K^*(892)^+ + K^*(892)^- + \rho(770)^0$

$\Rightarrow$ Can directly measure all four mixing and CPV parameters x, y, $|q/p|$, $\arg(q/p)$

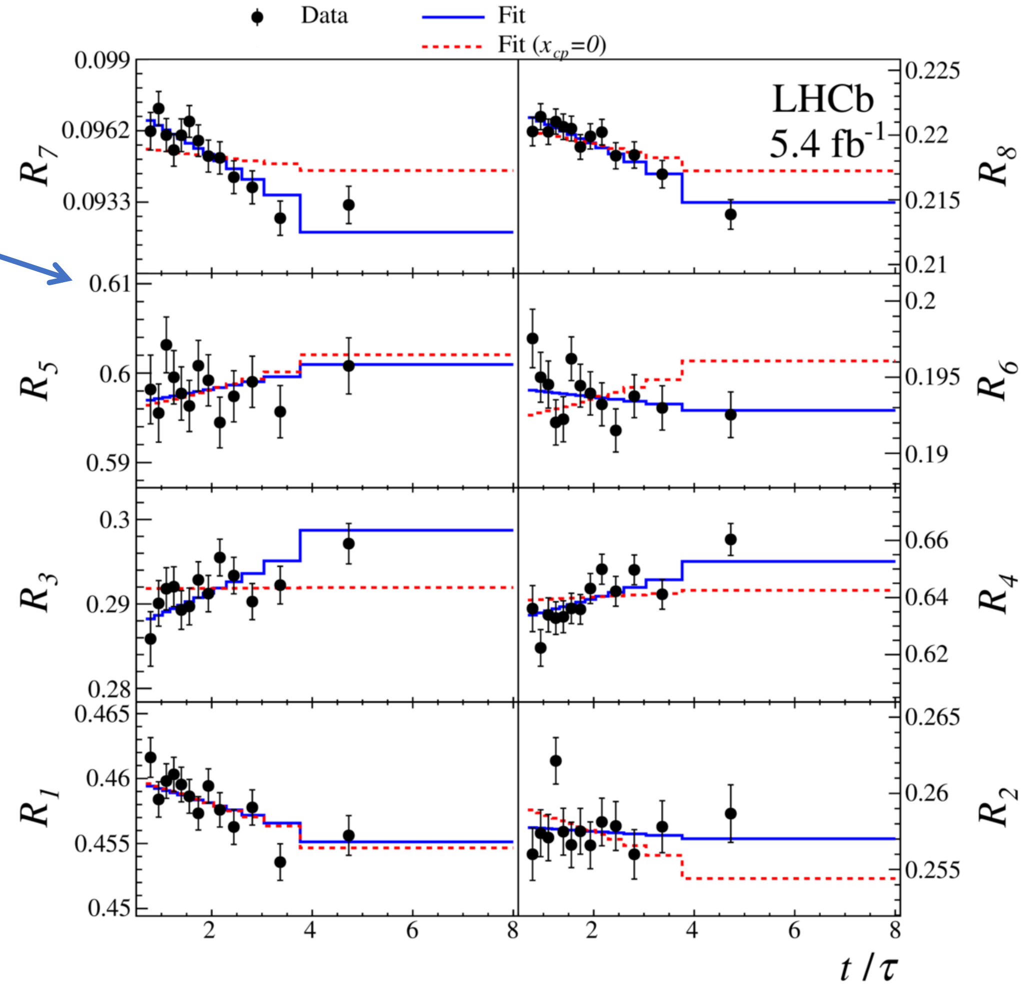
Requires **time and phase-space** dependent analysis

$D^0 \to K_S{}^0\pi^+\pi^-$ "bin-flip" analysis

arXiv:2106.03744
PRL 127 (2021) 111801

Full Run 2 sample (5.4 fb^{-1})

Clear time dependence from mixing (Dalitz bin specific)



x_{CP} = [0.397 ± 0.046 ± 0.029]%
y_{CP} = [0.459 ± 0.120 ± 0.085]%

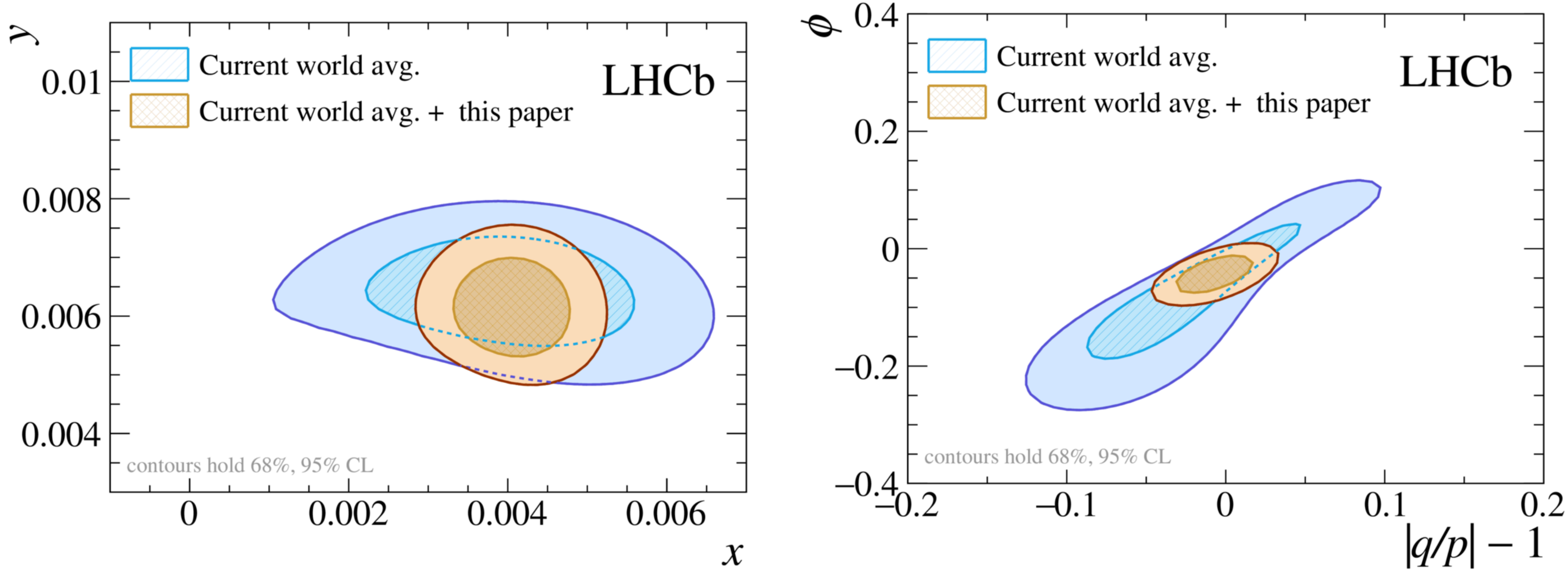
First measurement of non-zero x (>7σ significance)

D^0 and $\bar{D}^0$ samples consistent – no sign of CPV

$D^0 \to K_S^0 \pi^+ \pi^-$ "bin-flip" analysis

arXiv:2106.03744
PRL 127 (2021) 111801

Significant improvements in WA for both mixing and CPV parameters



Summary and outlook

- CPV discovery the **start** of a new adventure in charm
  ⇒ More experimental input essential to interpret this result
- Squeezing the most out of available data
  ⇒ New channels, new techniques
- Large gains in precision on CPV and mixing parameters
  ⇒ reaching 10^{-4} level – dominated by statistical precision
- Exciting times ahead with LHCb Run 3–4, Belle-II, BES-III, …

Belle-II ramping up physics programme in this area
e.g. most precise measurements of charm meson lifetimes:

https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.127.211801

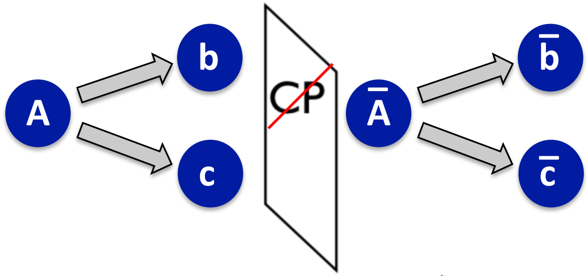
Extra Slides

CP Violation

$$A_{CP}(D^0 \to f) = \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to \bar{f})}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to \bar{f})}$$

CP violation in decay:

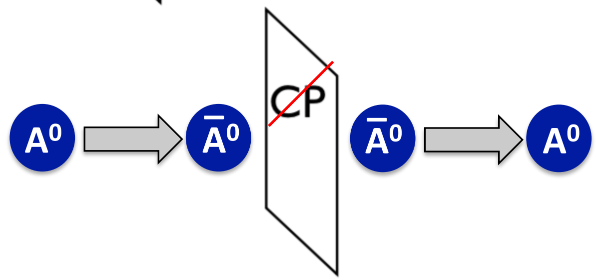
$|A_f| \neq |\bar{A}_f|$



Until 2019, no evidence of CPV in up-type quarks (u,c,t)

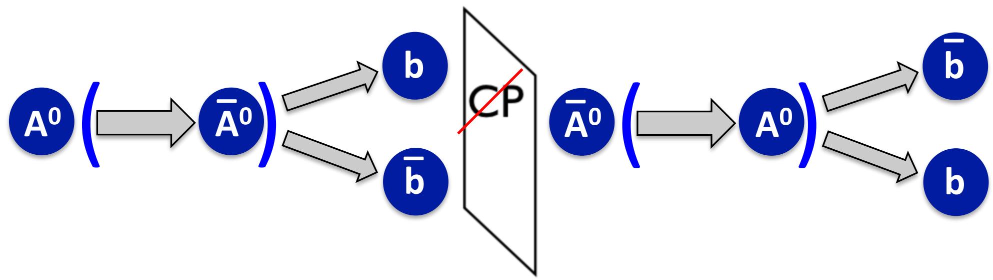
CP violation in mixing:

$|q/p| \neq 1$



CP violation in interference between mixing and decay:

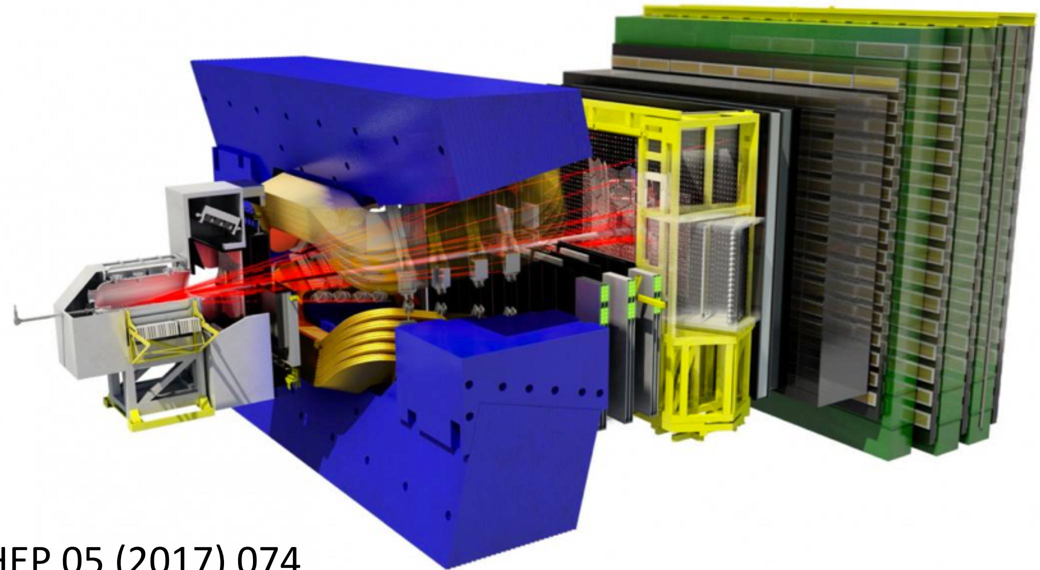
$\arg(q\bar{A}_f/pA_f) \neq 0$



Charm physics at LHCb

arXiv:1412.6352
Int. J. Mod. Phys. A 30 (2015) 07

Too charming?



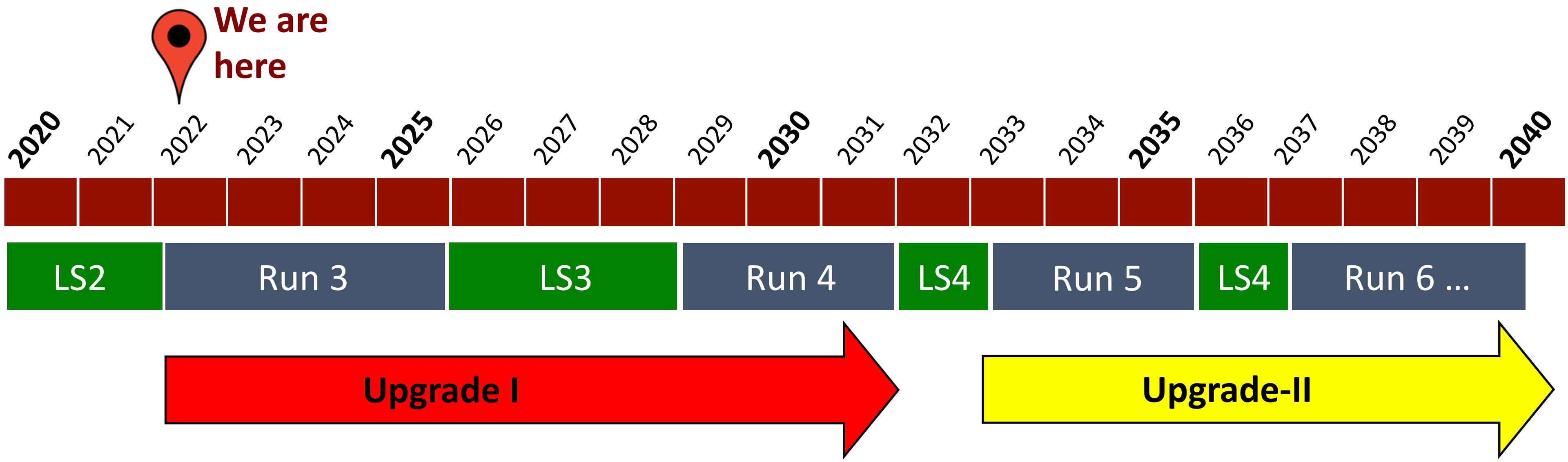
$$\sigma(pp \to D^0 X) = 2072 \pm 2 \pm 124\,\mu\text{b}$$
$$\sigma(pp \to D^+ X) = 834 \pm 2 \pm 78\,\mu\text{b}$$
$$\sigma(pp \to D_s^+ X) = 353 \pm 9 \pm 76\,\mu\text{b}$$
$$\sigma(pp \to D^{*+} X) = 784 \pm 4 \pm 87\,\mu\text{b}$$

JHEP 05 (2017) 074
(13 TeV, $2 < \eta < 4.5$, $0 < p_T < 8$ GeV/c)

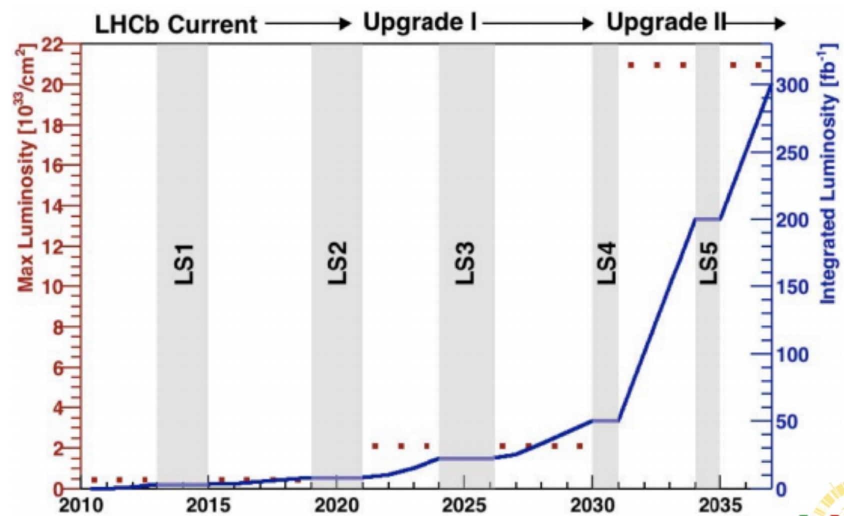
~2 MHz Charm mesons in acceptance → **~1 MHz** LHCb Hardware trigger limit → **~15 kHz** LHCb Event rate written to tape

Solution: Turbo triggers, fast (and accurate!) simulation, high-yield control modes (+ excellent vertexing, tracking, PID, magnet polarity reversal, …)

Run 3 and beyond

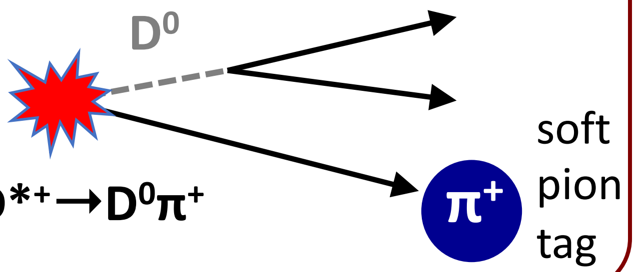


- LHCb has ambitious long-term upgrade plans
- All charm mixing/CPV analyses statistically limited
- The future is bright



Charm flavour tagging

π-tagged ("prompt charm")

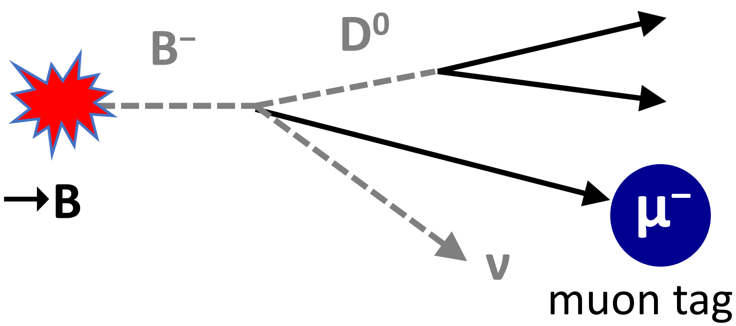


$pp \to D^{*+} \to D^0\pi^+$

Lifetime-biasing trigger

High signal yield & purity

μ-tagged ("secondary charm")



$pp \to B$

Lifetime unbiased trigger

Higher backgrounds, lower yields

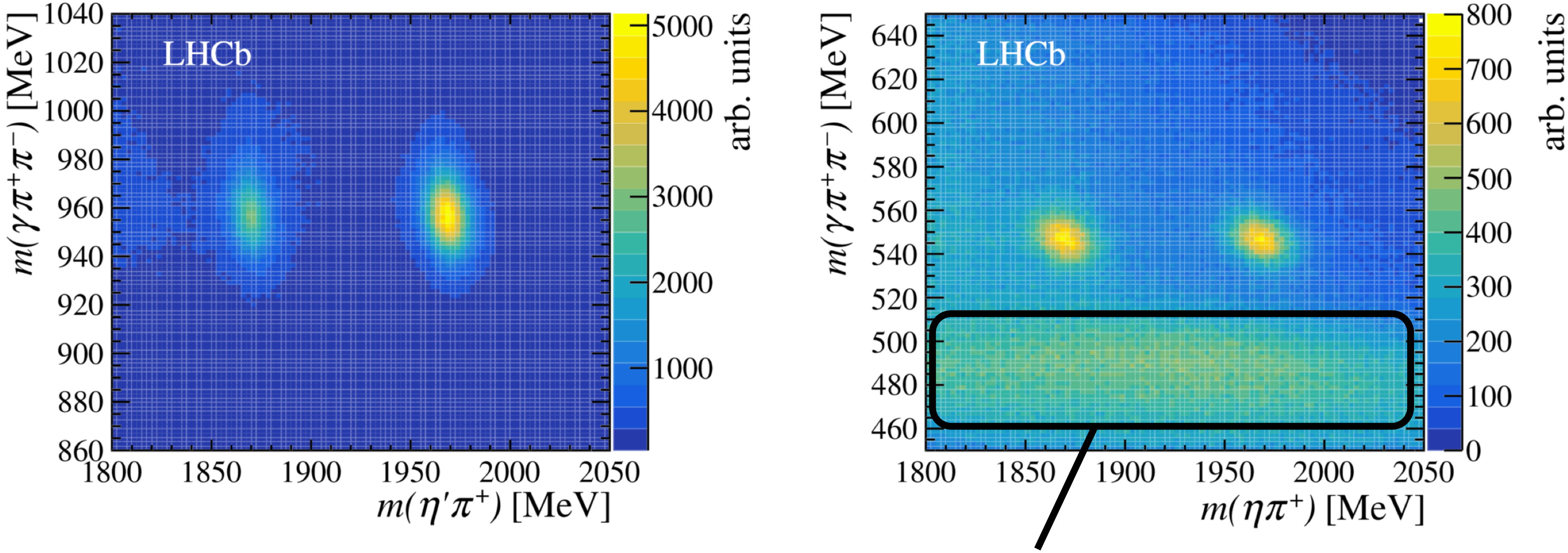
Contributes important background to prompt analyses!

arXiv:2204.12228
(submitted to JHEP)

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

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

2D plots for η' (left) and η (right) channels, showing signal and background contributions

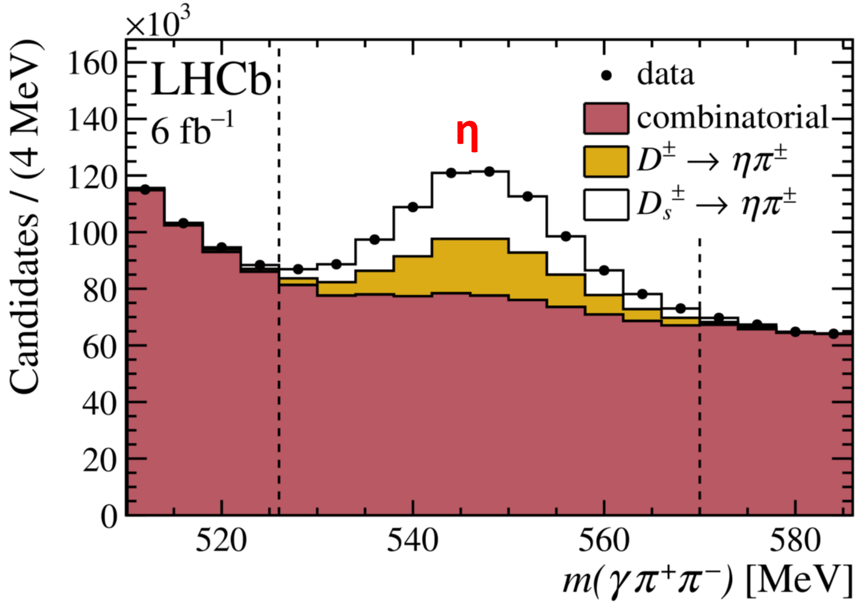


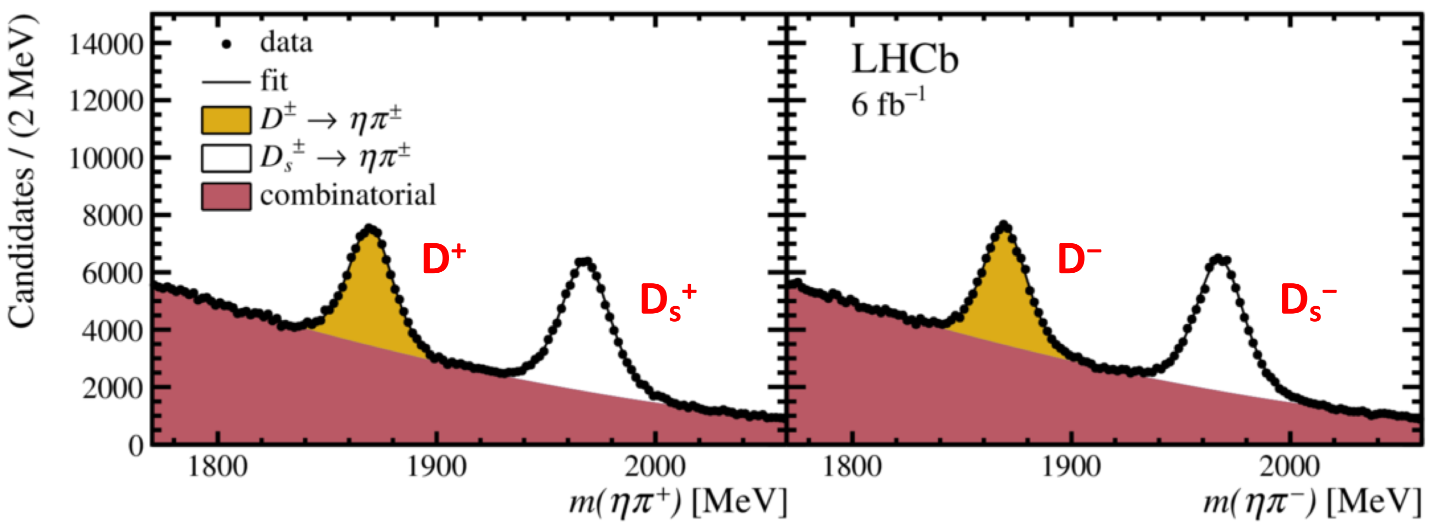
Background from $\eta \to \pi^+\pi^-\pi^0$

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

arXiv:2204.12228
(submitted to JHEP)

η channel mass fits

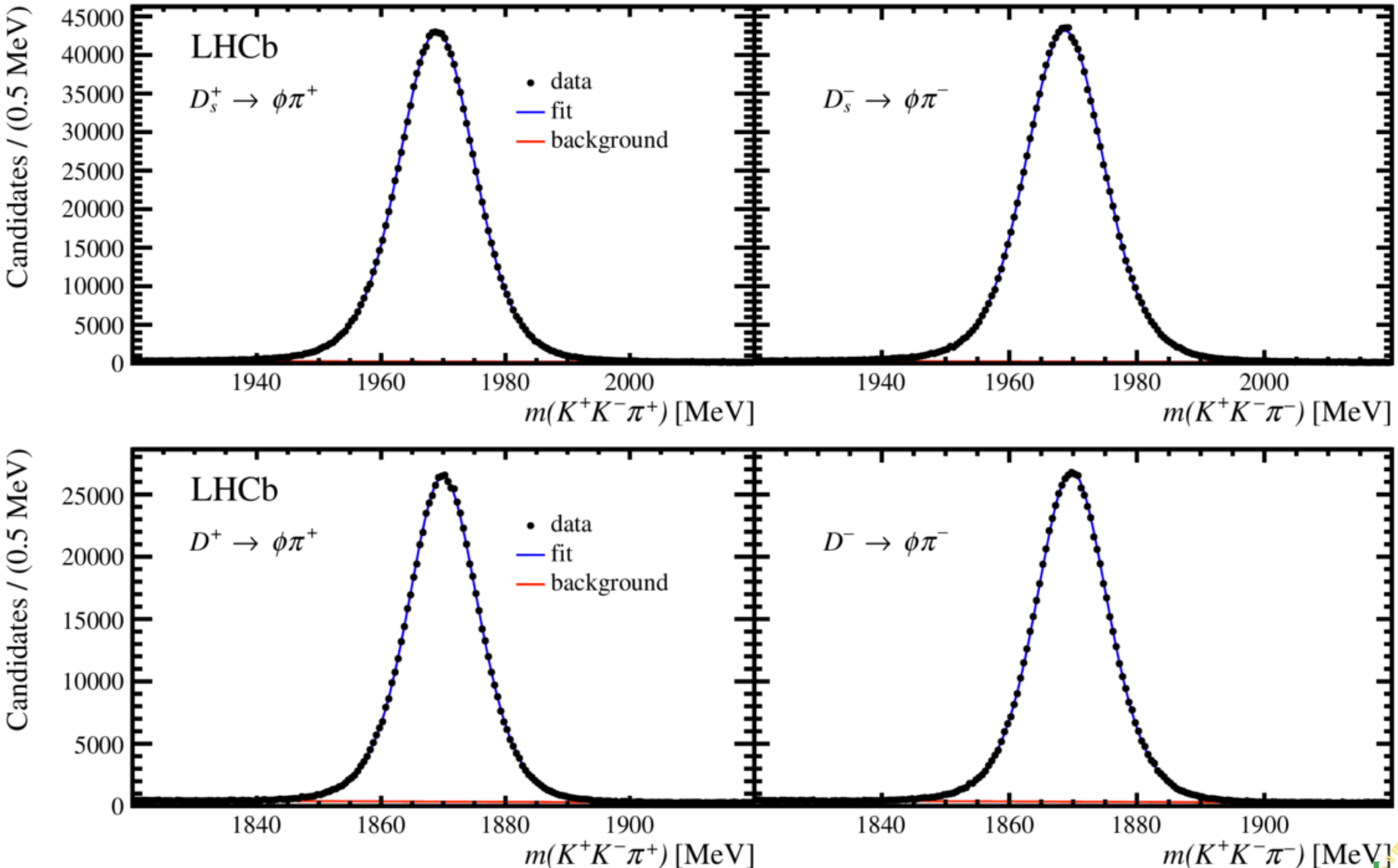




$A_{CP}(D^+_{(s)} \to \eta^{(\prime)}\pi^+)$

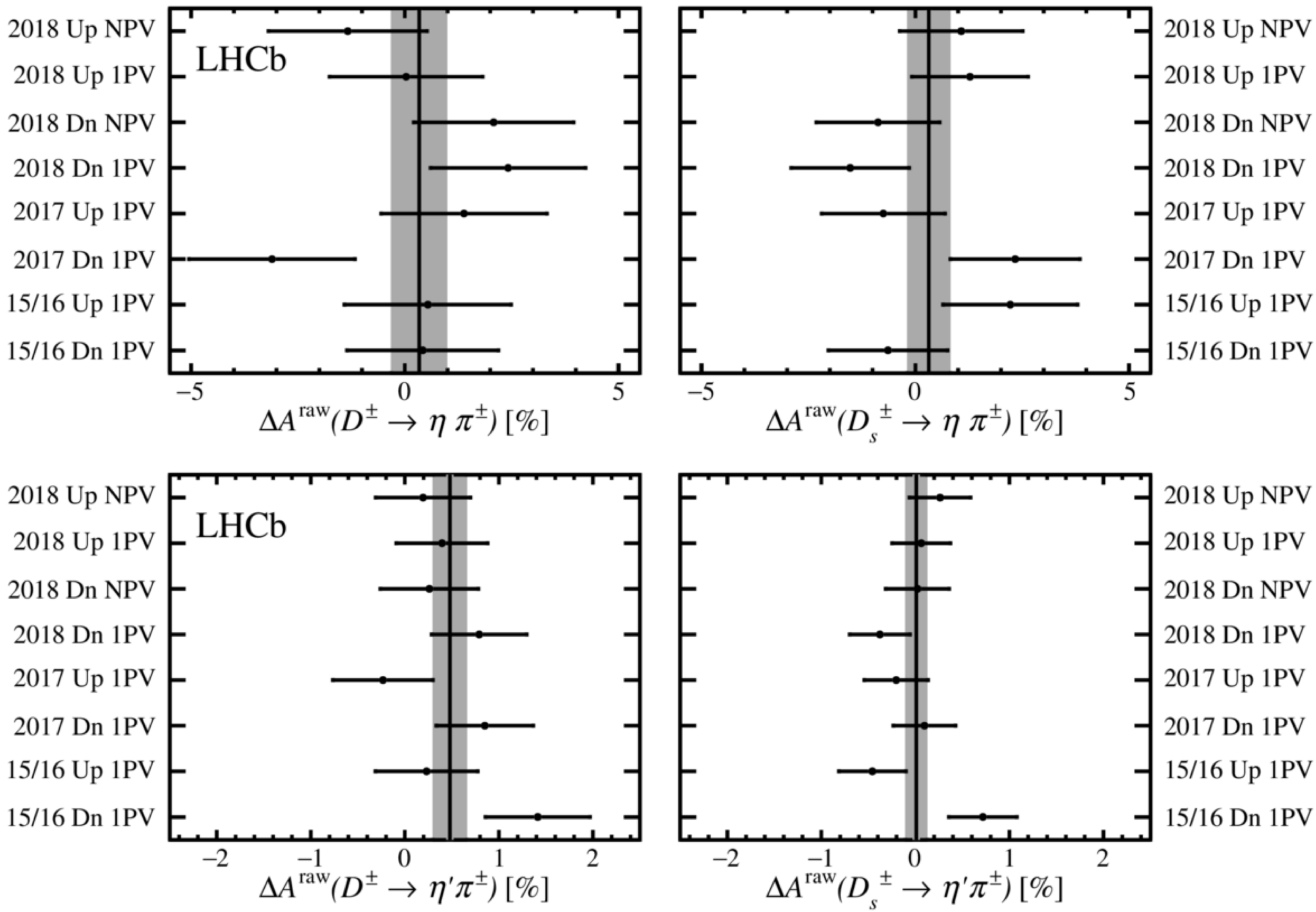
arXiv:2204.12228
(submitted to JHEP)

Control mode mass fits



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

arXiv:2204.12228
(submitted to JHEP)



arXiv:2202.09106
(accepted by PRD)

Extra material: y_{CP} in $D^0 \rightarrow h^+h^-$ decays

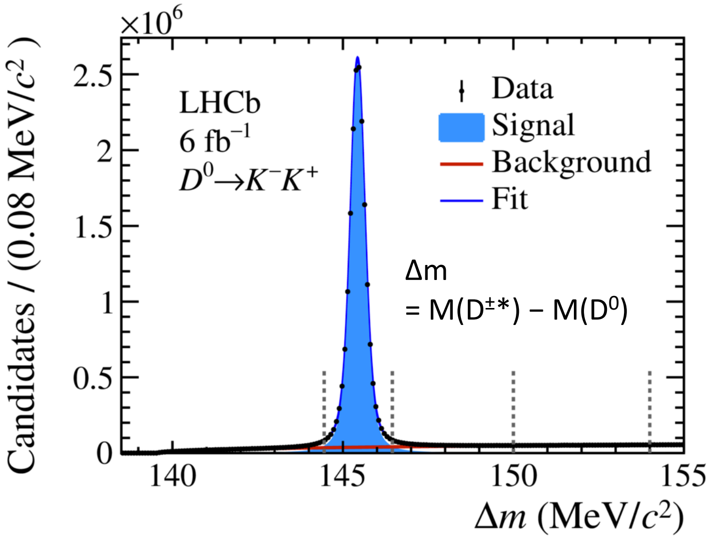
y_{CP} in $D^0 \to h^+h^-$ decays

Full LHCb Run 2 (6/fb)

- 95% – 98% purity
- 6M – 70M candidates

Fit D^0 and $\bar{D}^0$ samples separately, in 22 bins of decay time (+ split by year and polarity)

Subtract combinatorial BG

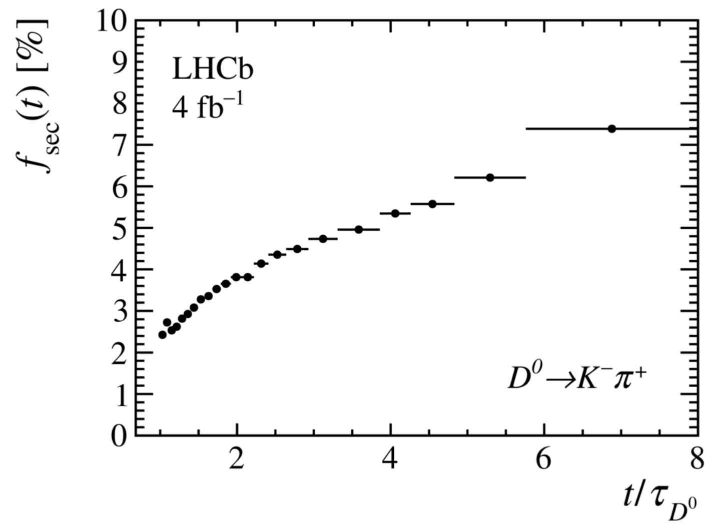


Correct for secondary contamination:

$$R^f(t) = (1 - f_{\rm sec}(t))R^f_{\rm prompt}(t) + f_{\rm sec}(t)R^f_{\rm sec}(t)$$

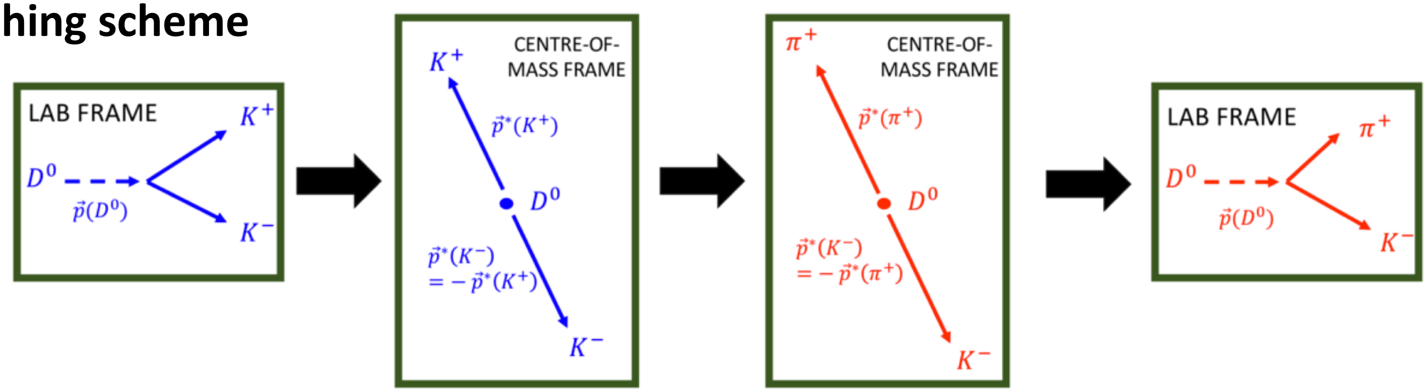
where $$R^f_{\rm sec}(t) \propto e^{-(y^f_{CP} - y^{K\pi}_{CP})\langle t_D(t)\rangle/\tau_{D^0}}$$

and $\langle t_D(t)\rangle$ reflects biased measurement of D^0 decay time from this source



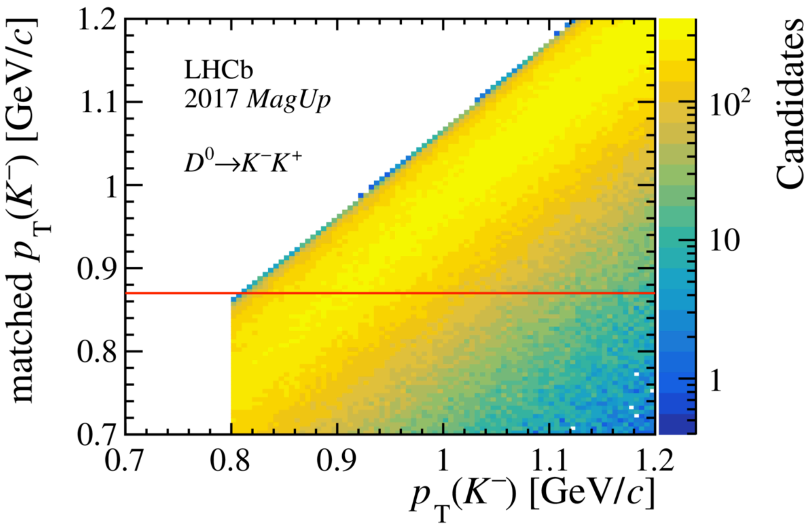
y_{CP} in $D^0 \to h^+h^-$ decays

Kinematic matching scheme



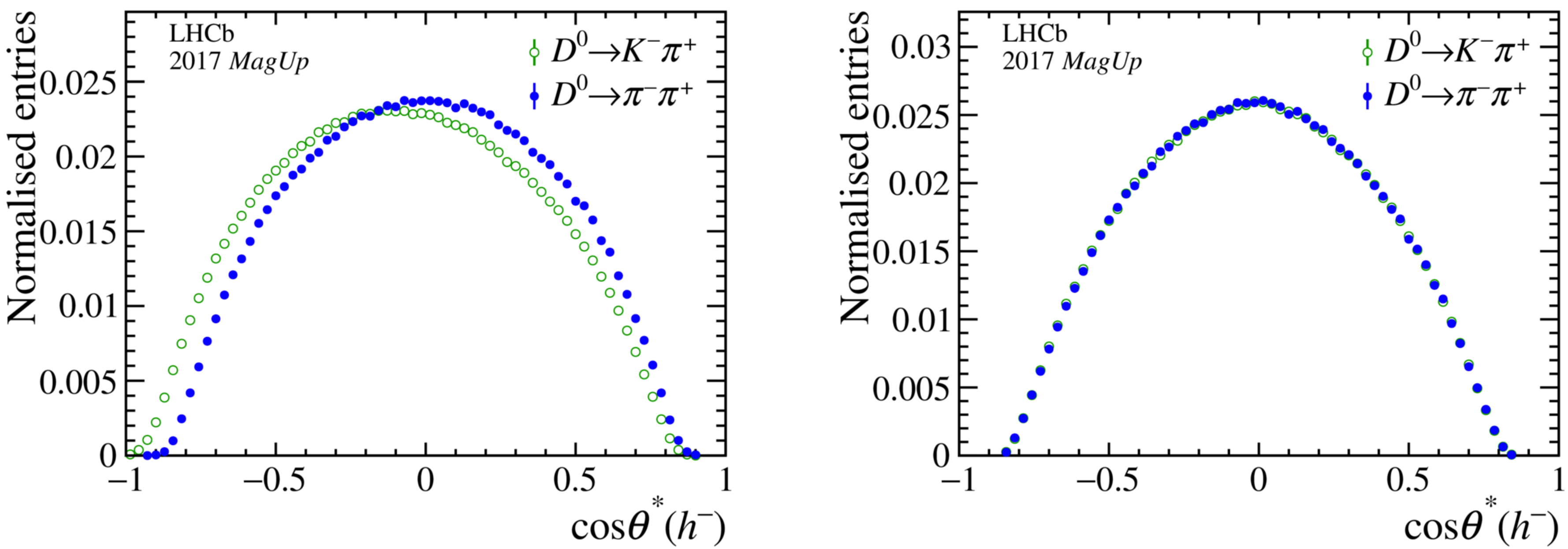
Example of kinematic matching requirement:

Red line shows cut on transformed pT(K⁻) which ensures all candidates would pass requirements for both channels in ratio measurement



y_{CP} in $D^0 \to h^+h^-$ decays

Kinematic matching & reweighting results



Example of D^0 decay angle for two channels before (left) and after (right) kinematic matching and reweighting

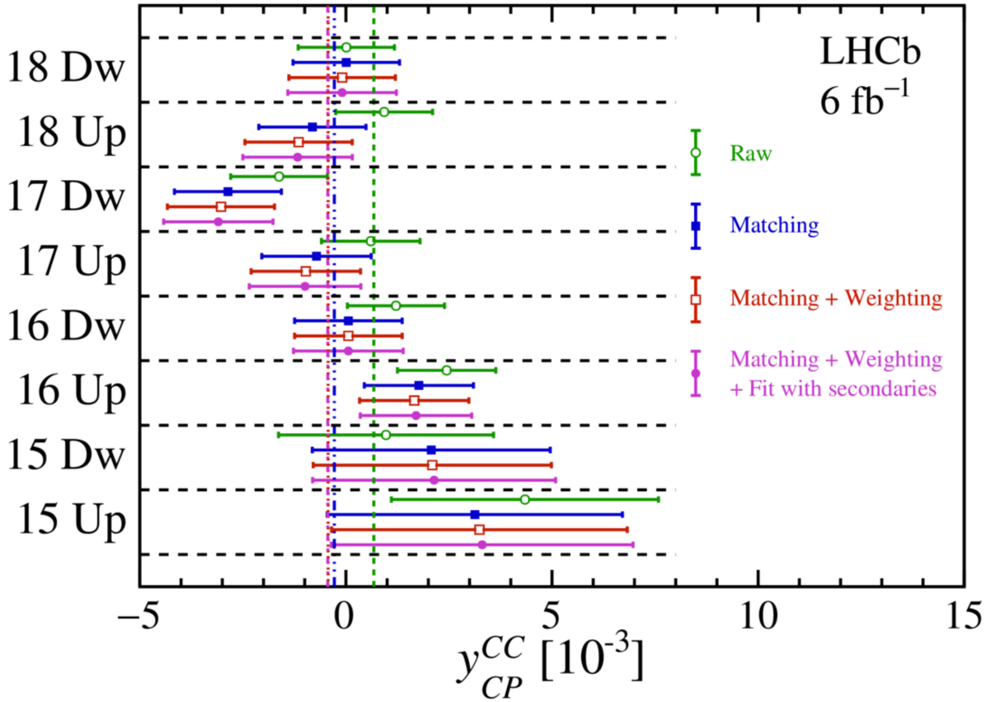
y_{CP} in $D^0 \to h^+h^-$ decays

Data-driven validation

Measure ratio for KK vs ππ final states – should give 'pseudo-y_{CP}' value consistent with zero:

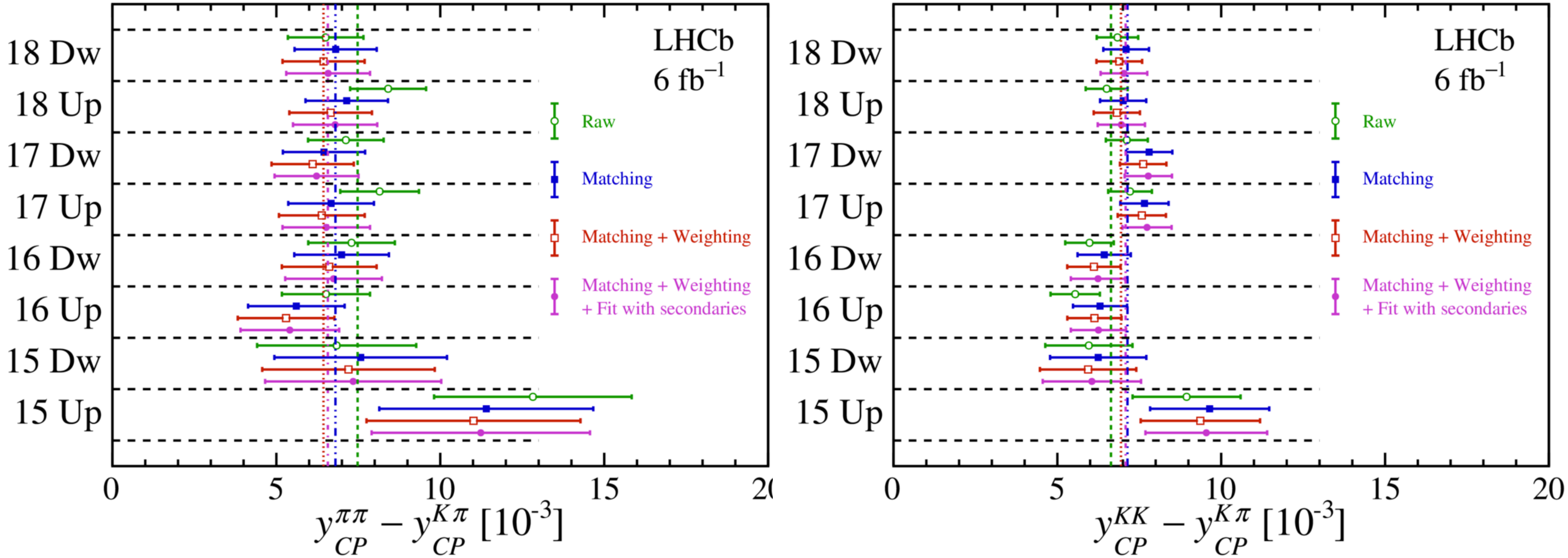
$$y_{CP}^{CC} = (-0.44 \pm 0.53) \times 10^{-3}$$

Consistent across data-taking years and between magnet polarities



y_{CP} in $D^0 \to h^+h^-$ decays

Comparison between disjoint sub-samples



y_{CP} in $D^0 \to h^+h^-$ decays

Breakdown of results and corrections

Table 1: Results of the χ^2 fits of Fig. 6 for each correction procedure. The results are shown in units of 10^{-3}, while the values in parenthesis correspond to the χ^2 of the fits, where the number of degrees of freedom is 7 for all measurements.

	y_{CP}^{CC}	$y_{CP}^{KK} - y_{CP}^{K\pi}$	$y_{CP}^{KK} - y_{CP}^{K\pi}$
Raw	$0.68 \pm 0.47\,(7.9)$	$7.48 \pm 0.48\,(5.5)$	$6.64 \pm 0.27\,(6.6)$
Matching	$-0.28 \pm 0.52\,(8.3)$	$6.80 \pm 0.52\,(2.9)$	$7.14 \pm 0.29\,(5.5)$
Matching + Weighting	$-0.43 \pm 0.52\,(9.0)$	$6.44 \pm 0.52\,(2.8)$	$6.94 \pm 0.29\,(5.9)$
Matching + Weighting + Fit with secondaries	$-0.44 \pm 0.53\,(9.0)$	$6.57 \pm 0.53\,(2.8)$	$7.08 \pm 0.30\,(5.9)$

y_{CP} in $D^0 \to h^+h^-$ decays

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
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
Peaking background	0.02	0.11
Fit bias	0.03	0.03
Total	0.16	0.14
(Stat uncertainty:	**0.53**	**0.30)**

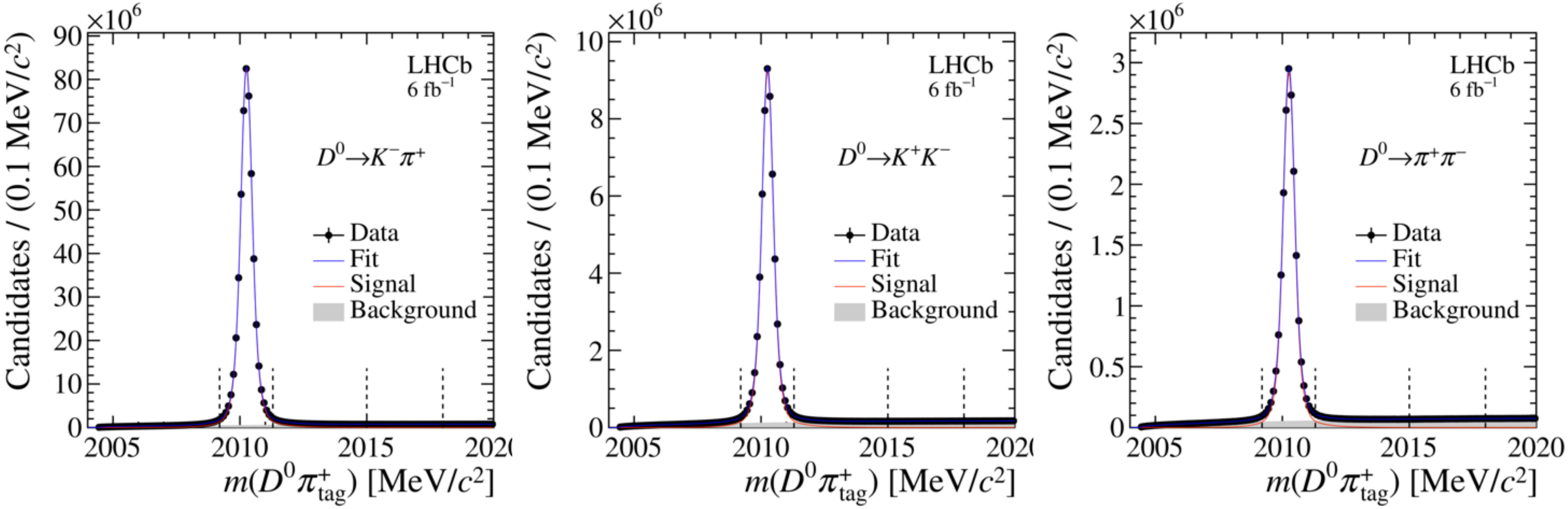
arXiv:2105.09889
PRD 104 072010

Extra material: Time-dep. CPV: ΔY ($\approx -A_\Gamma$)

Time-dep. CPV: ΔY ($\approx -A_\Gamma$)

arXiv:2105.09889
PRD 104 072010

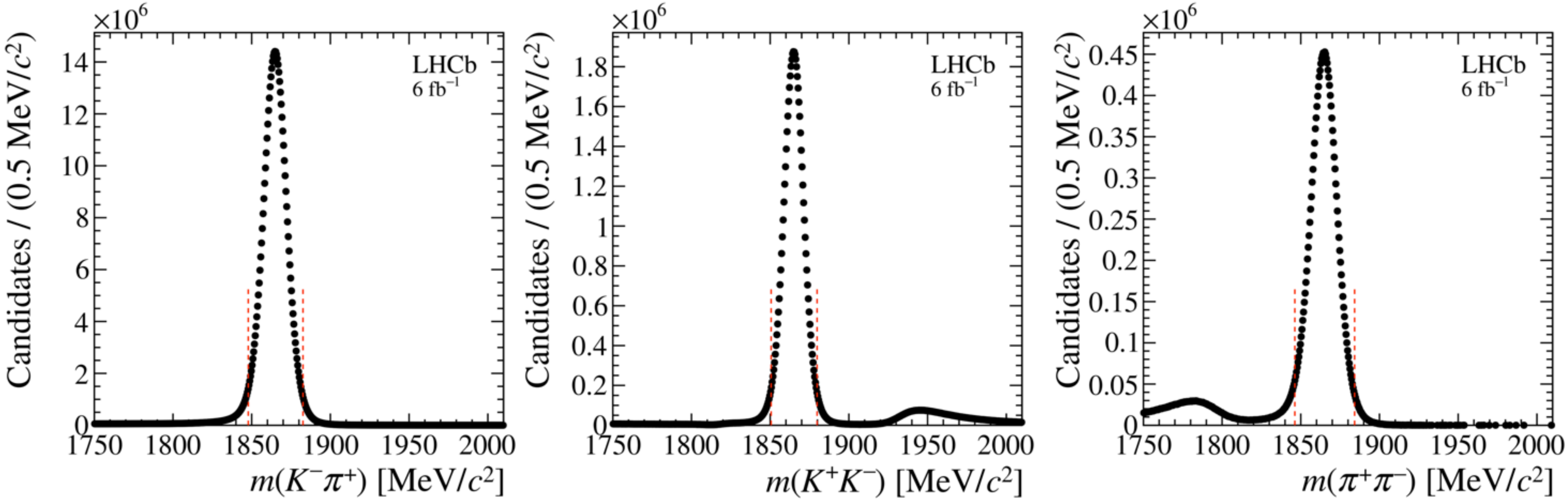
Time-integrated mass fits (D^{*+})



Time-dep. CPV: ΔY (≈$-A_\Gamma$)

arXiv:2105.09889
PRD 104 072010

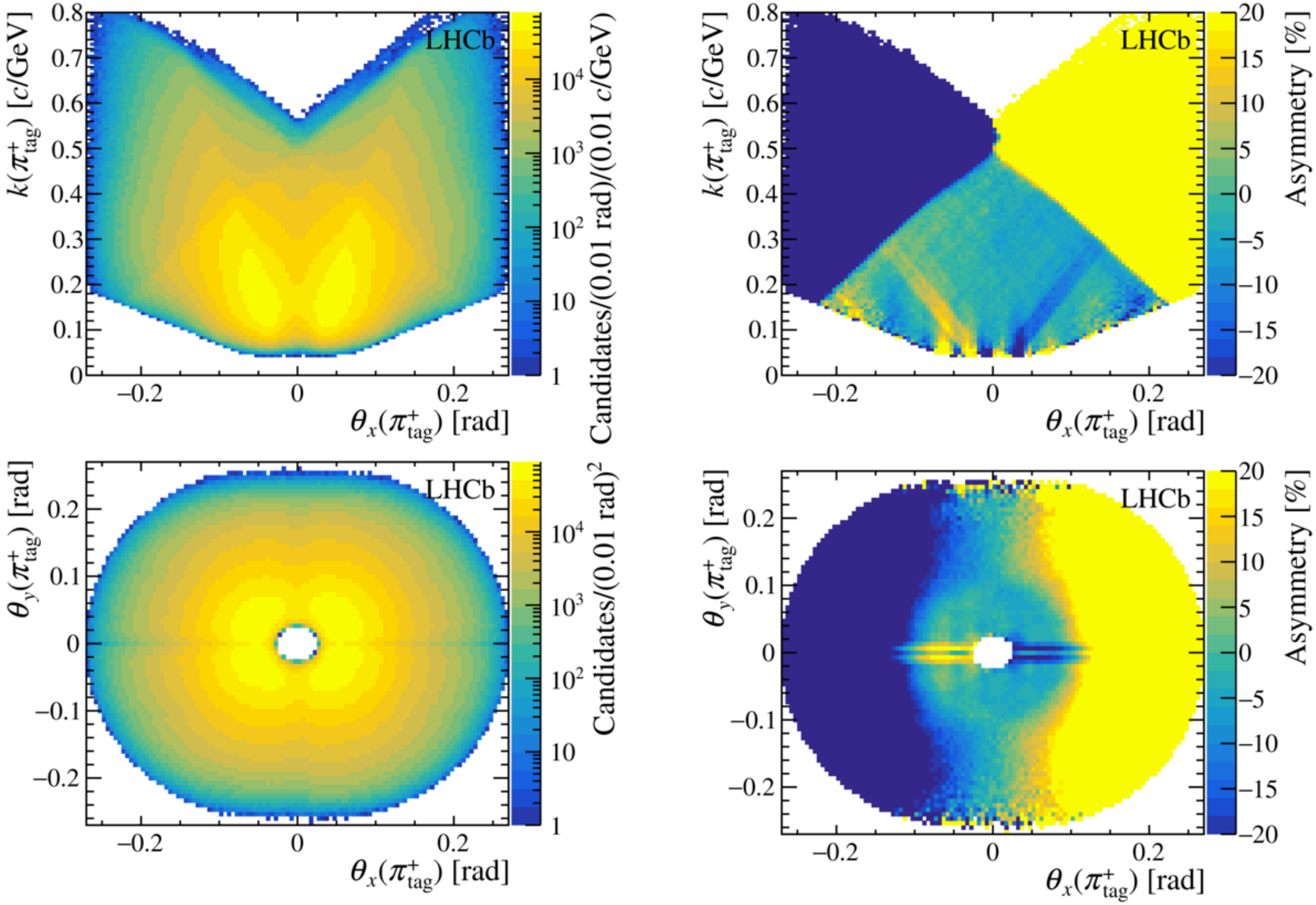
Time-integrated mass distributions (D^0)



Time-dep. CPV: ΔY ($\approx -A_\Gamma$)

arXiv:2105.09889
PRD 104 072010

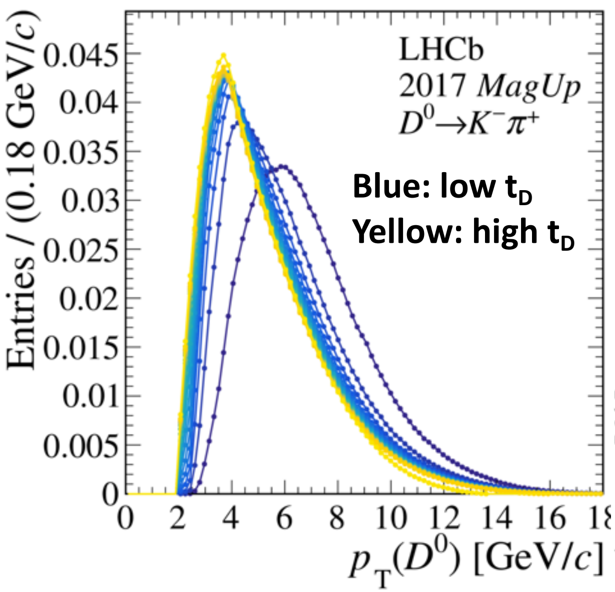
Nuisance asymmetries (tagging pion)



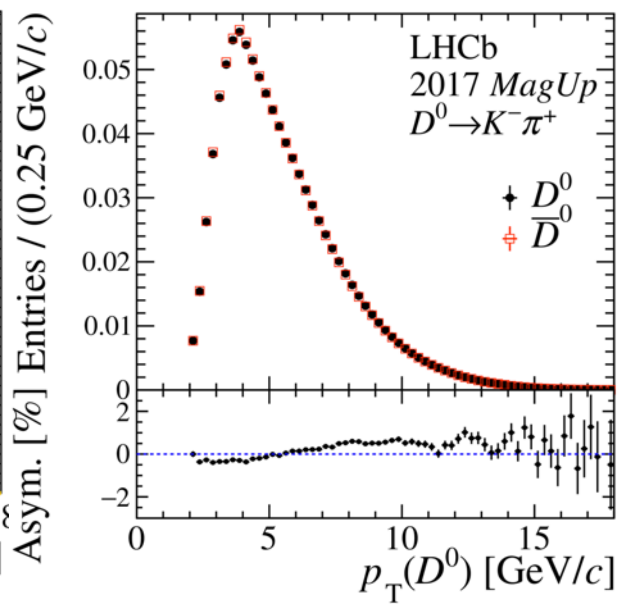
Time-dep. CPV: ΔY ($\approx -A_\Gamma$)

arXiv:2105.09889
PRD 104 072010

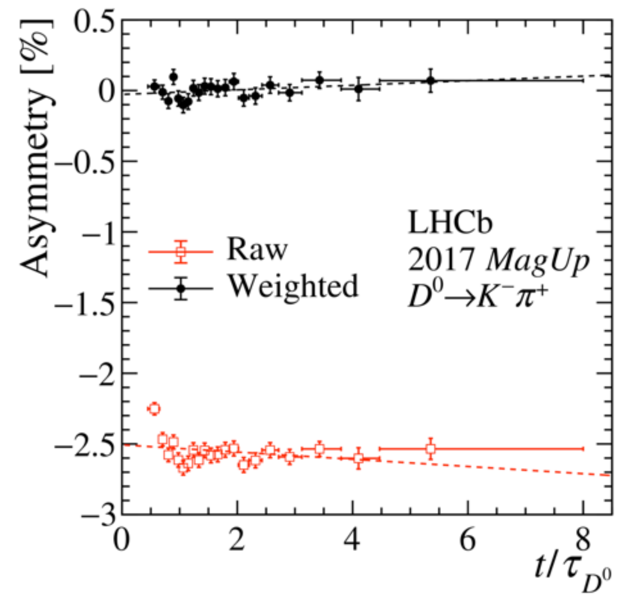
Correlation between kinematics & decay time



+ kinematically-dependent asymmetry



= time-dependent asymmetry (red)



⇒ Removed with correction (black)

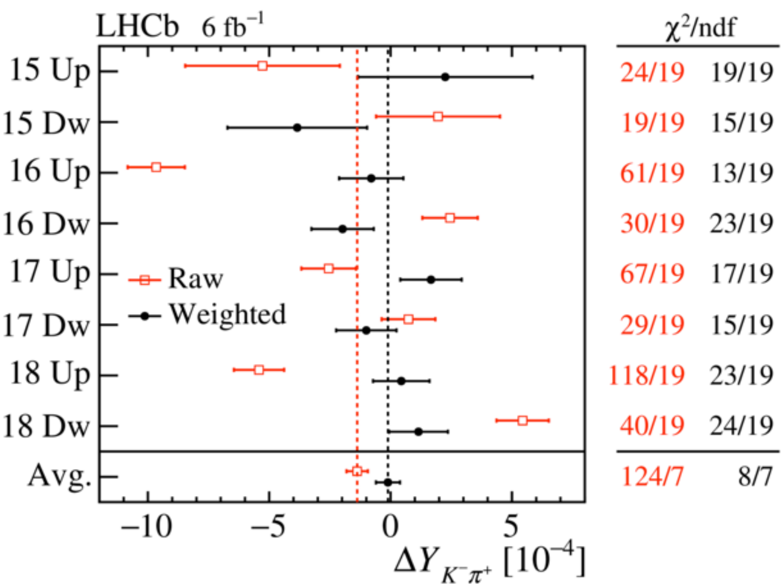
Time-dep. CPV: ΔY ($\approx -A_\Gamma$)

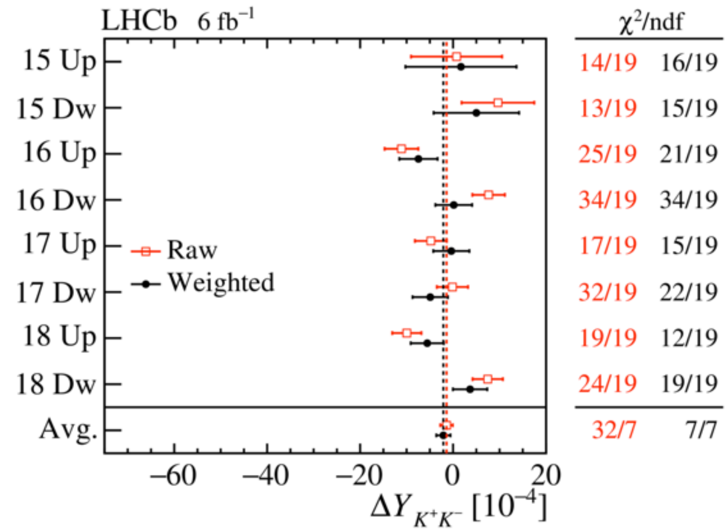
arXiv:2105.09889
PRD 104 072010

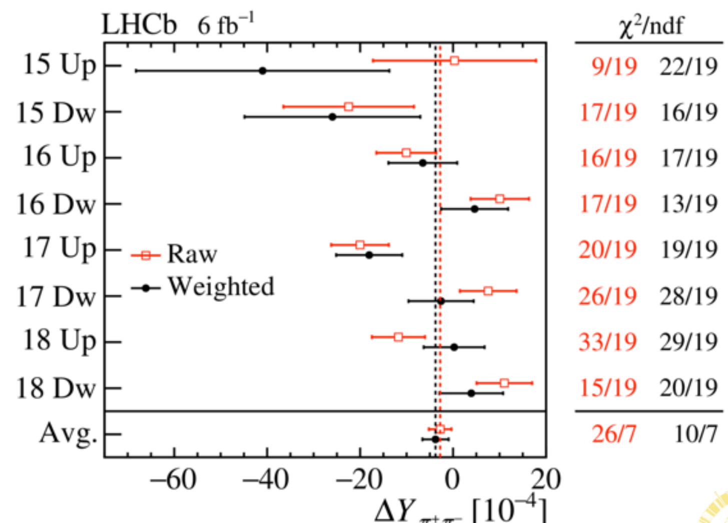
Results per subsample

Red: before weighting

Black: after weighting

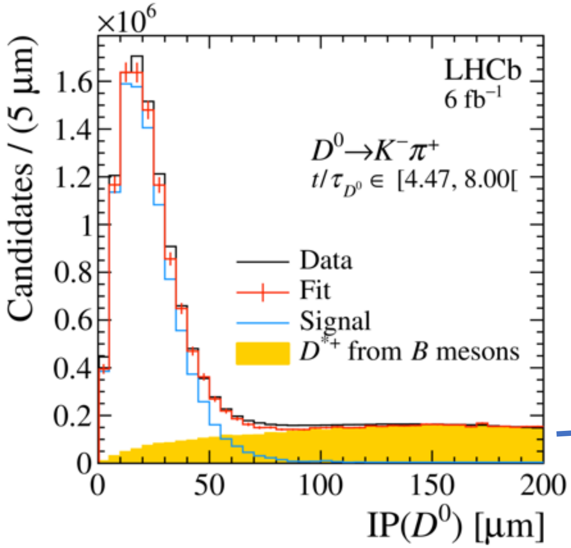




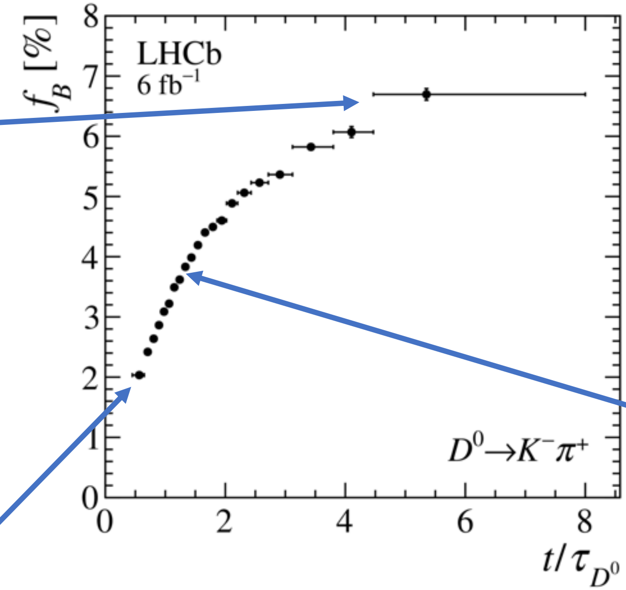


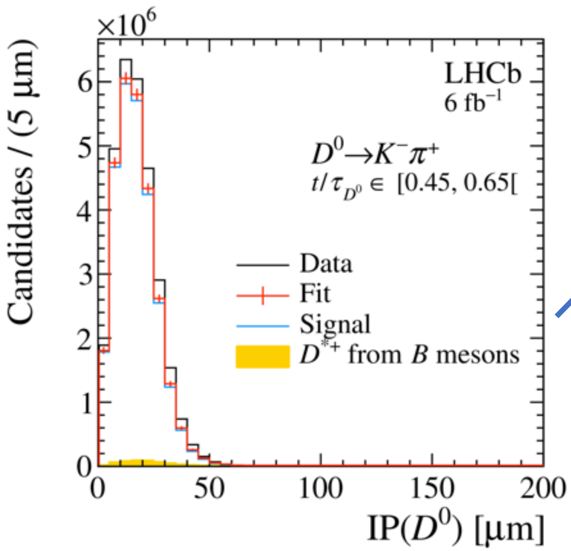
Time-dep. CPV: ΔY (≈−A_Γ)

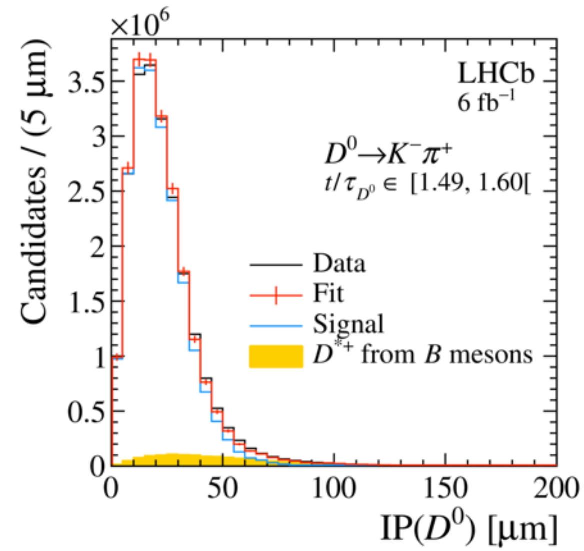
arXiv:2105.09889
PRD 104 072010



Secondary charm contamination







Time-dep. CPV: ΔY ($\approx -A_\Gamma$)

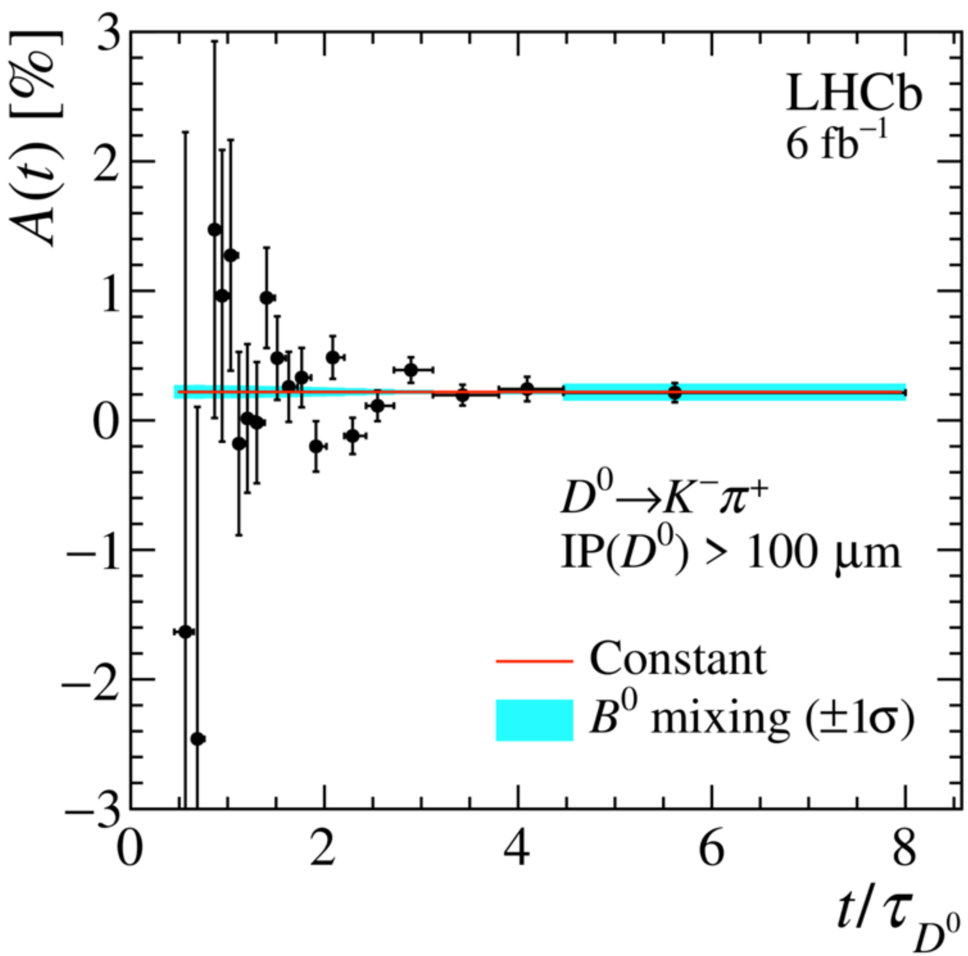
arXiv:2105.09889
PRD 104 072010

Asymmetry from secondaries

$$A(t) = A_{\text{sig}}(t) + f_B(t)[A_B(t) - A_{\text{sig}}(t)]$$

Measured in pure secondary sample:

$A_B - A_{sig} = (2.2 \pm 0.4) \times 10^{-3}$



Time-dep. CPV: ΔY ($\approx -A_\Gamma$)

arXiv:2105.09889
PRD 104 072010

Systematic uncertainties

Source	$\Delta Y_{K^+K^-}$ $[10^{-4}]$	$\Delta Y_{\pi^+\pi^-}$ $[10^{-4}]$
Subtraction of the $m(D^0\pi^+_{\text{tag}})$ background	0.2	0.3
Flavour-dependent shift of D^*-mass peak	0.1	0.1
D^{*+} from B-meson decays	0.1	0.1
$m(h^+h^-)$ background	0.1	0.1
Kinematic weighting	0.1	0.1
Total systematic uncertainty	0.3	0.4
Statistical uncertainty	1.5	2.8

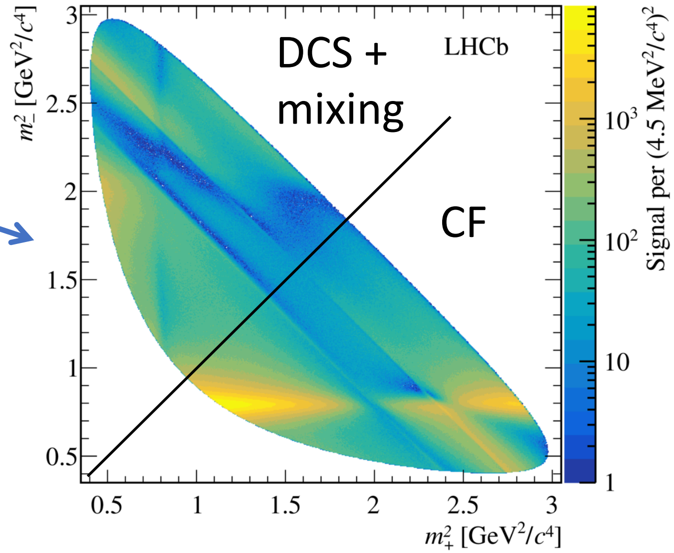
arXiv:2106.03744
PRL 127 (2021) 111801

Extra material:
$D^0 \rightarrow K_S{}^0\pi^+\pi^-$ “bin-flip” analysis

$D^0 \to K_S^0 \pi^+ \pi^-$ "bin-flip" analysis

Exploit **symmetry** in final state:

(1) Oscillated contributions mainly in upper half
⇒ Ratio of yields in upper/lower versus time is sensitive to mixing parameters



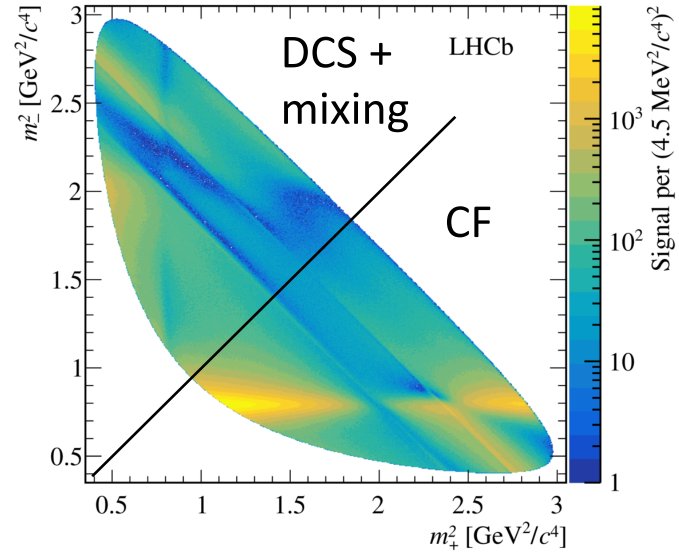
$D^0 \to K_S^0 \pi^+ \pi^-$ "bin-flip" analysis

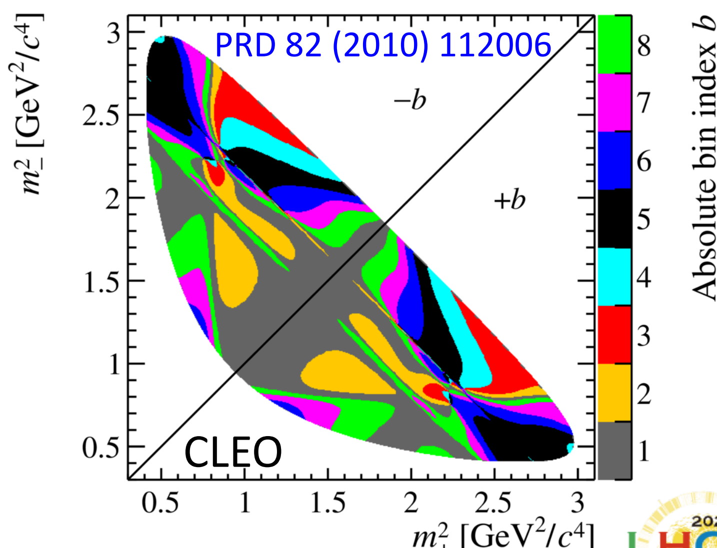
Exploit symmetry in final state:

(1) Oscillated contributions mainly in upper half
⇒ Ratio of yields in upper/lower versus time is sensitive to mixing parameters

(2) Divide into 8 bins per half
⇒ boosts sensitivity, reducing dilution from strong phase variation

Strong phases constrained from CLEO & BESIII





$D^0 \to K_S^0 \pi^+ \pi^-$ "bin-flip" analysis

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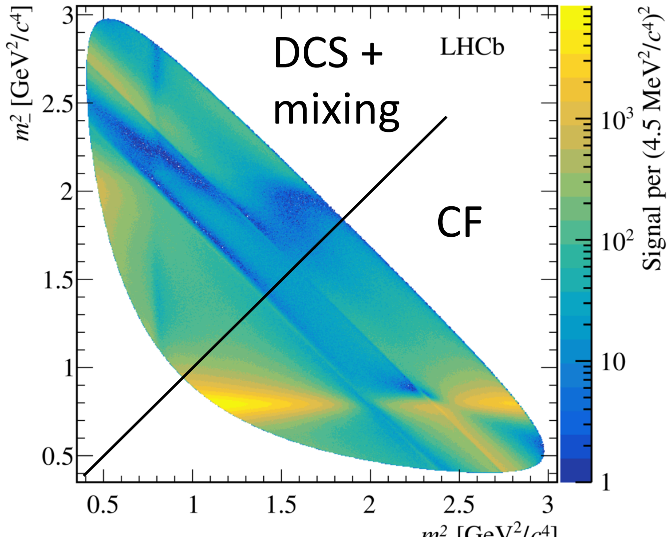
⇒ Ratio of yields in upper/lower versus time is sensitive to mixing parameters

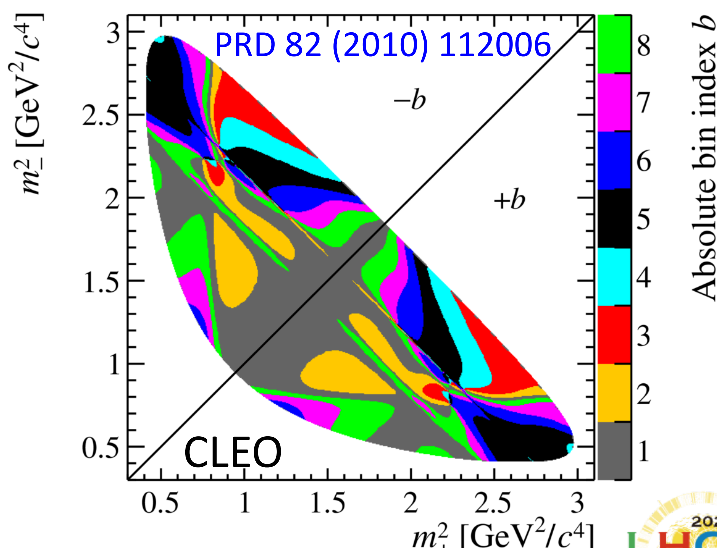
(2) Divide into 8 bins per half
⇒ boosts sensitivity, reducing dilution from strong phase variation

Strong phases constrained from CLEO & BESIII

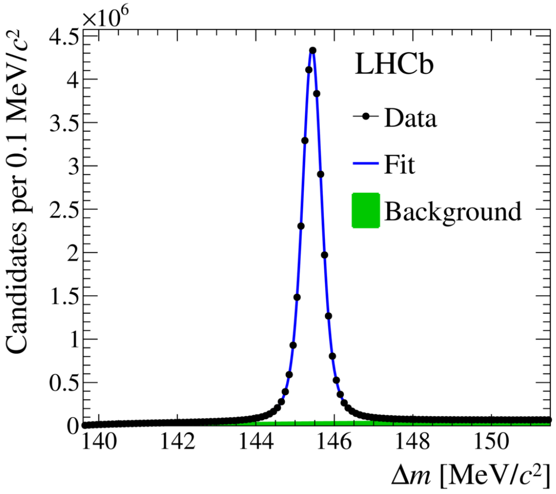
(3) Most detector effects ~cancel in the ratio

Careful data-driven reweighting to remove residual nuisance effects





‘Bin-flip’ analysis: details

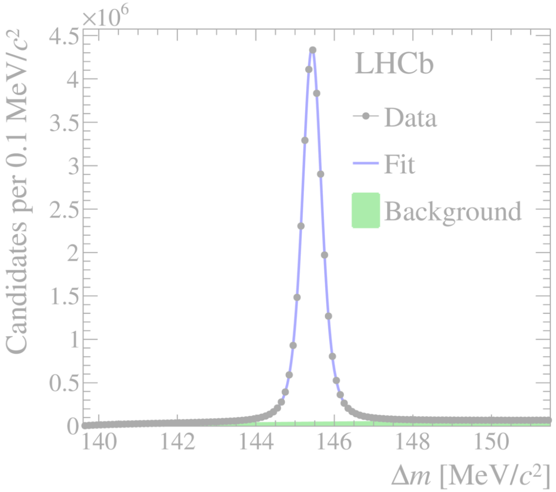


~31M signal candidates (>10x larger than LHCb Run 1 sample)

Fit Δm distribution in bins of Dalitz plane and decay time to get R_i values

⇒ Remains **statistically limited** (including strong-phase inputs)

‘Bin-flip’ analysis: details



~31M signal candidates (>10x larger than LHCb Run 1 sample)

Fit Δm distribution in bins of Dalitz plane and decay time to get R_i values

⇒ Remains **statistically limited** (including strong-phase inputs)

Correct for experimental effects:
(1) Correlations between time and PhSp
(2) Charge detection asymmetries

Source	x_{CP}	y_{CP}	Δx	Δy
Reconstruction and selection	0.199	0.757	0.009	0.044
Secondary charm decays	0.208	0.154	0.001	0.002
Detection asymmetry	0.000	0.001	0.004	0.102
Mass-fit model	0.045	0.361	0.003	0.009
Total systematic uncertainty	0.291	0.852	0.010	0.110
Strong phase inputs	0.23	0.66	0.02	0.04
Detection asymmetry inputs	0.00	0.00	0.04	0.08
Statistical (w/o inputs)	0.40	1.00	0.18	0.35
Total statistical uncertainty	0.46	1.20	0.18	0.36

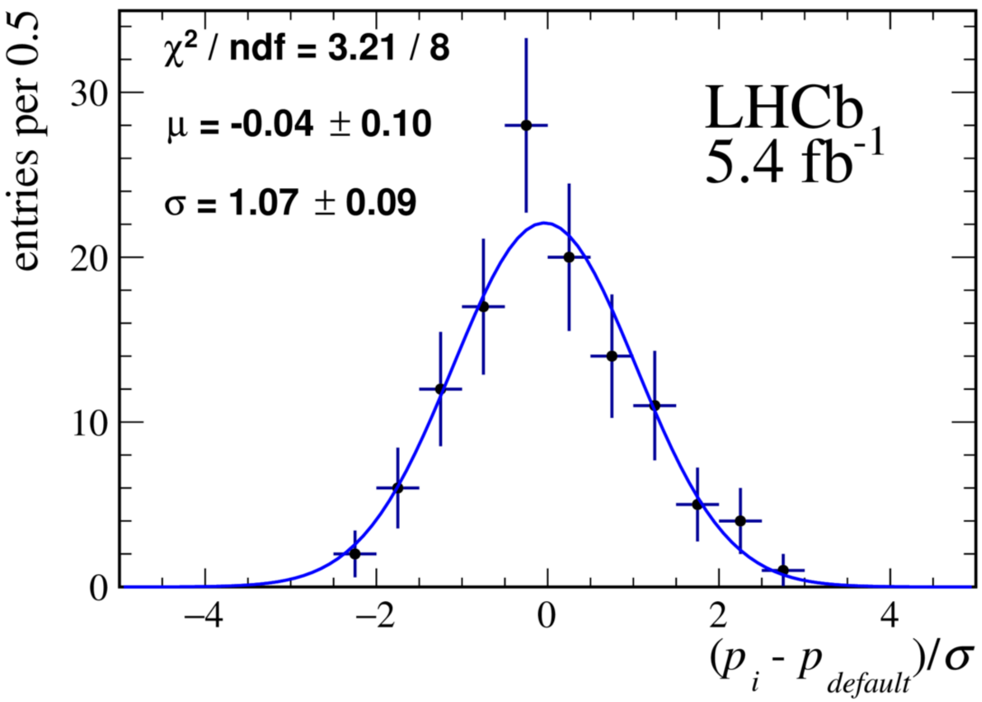
Main systematics from:

- Treatment of experimental effects
- ‘Secondary’ charm background
- Mass fit procedure, …

‘Bin-flip’ analysis: cross-checks

Repeat analysis in many disjoint samples (e.g. split by kinematics, magnet polarity, etc)

Pull distribution of measured parameters consistent with unit Gaussian



‘Bin-flip’ analysis: Formalism

Ratio of signal decays in upper/lower **Dalitz bin *b***, and **time bin *j***, given by:

$$R_{bj}^{\pm} \approx \frac{r_b + \frac{1}{4} r_b \langle t^2 \rangle_j \, \mathrm{Re}(z_{CP}^2 - \Delta z^2) + \frac{1}{4} \langle t^2 \rangle_j \left| z_{CP} \pm \Delta z \right|^2 + \sqrt{r_b} \langle t \rangle_j \, \mathrm{Re}[X_b^* (z_{CP} \pm \Delta z)]}{1 + \frac{1}{4} \langle t^2 \rangle_j \, \mathrm{Re}(z_{CP}^2 - \Delta z^2) + r_b \frac{1}{4} \langle t^2 \rangle_j \left| z_{CP} \pm \Delta z \right|^2 + \sqrt{r_b} \langle t \rangle_j \, \mathrm{Re}[X_b (z_{CP} \pm \Delta z)]}$$

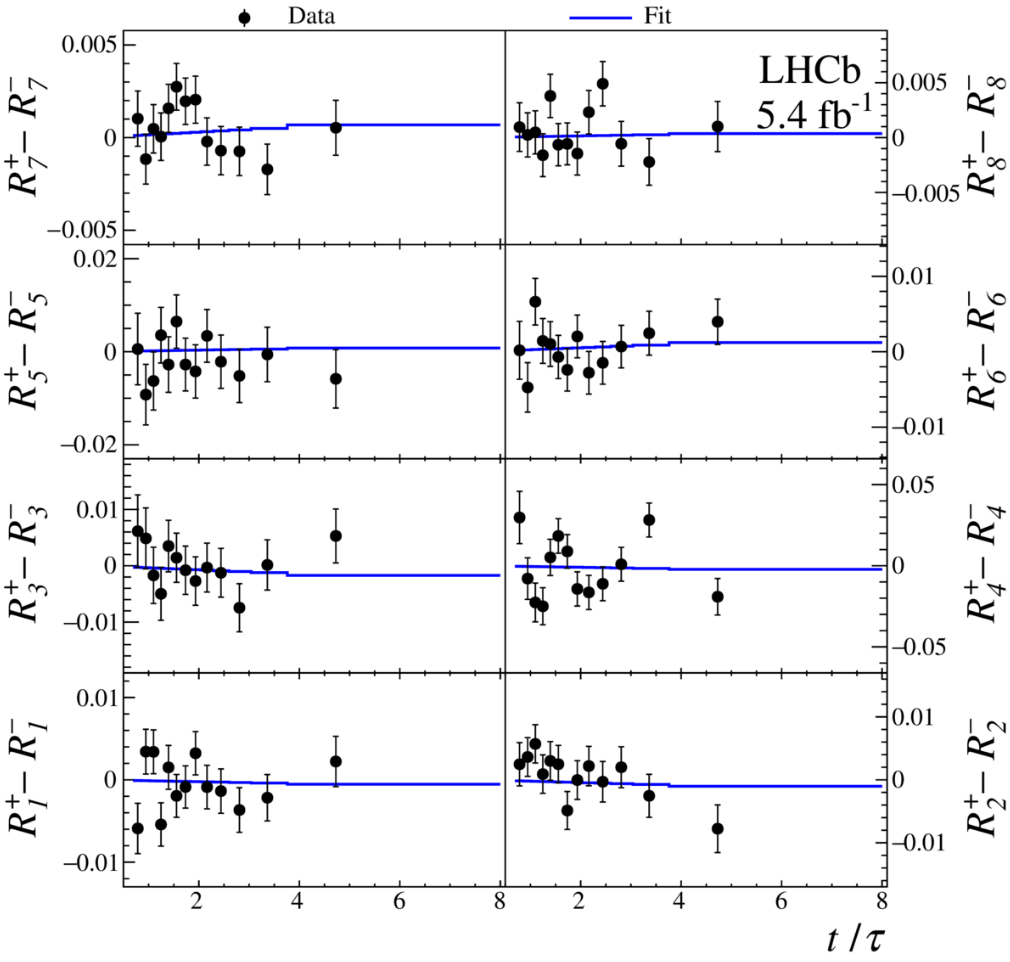
Where:

- ± denotes the case for D^0 (+) and $\overline{D}^0$ (−)
- r_b: value of ratio at t = 0
- X_b: amplitude-weighted average strong phase difference between ‘flipped’ bins
  ⇒ Use external constraints from quantum correlated charm production (CLEO, BESIII)
  ⇒ $c_b \equiv \mathrm{Re}(X_b)$, $s_b \equiv -\mathrm{Im}(X_b)$
- $z_{CP} \pm \Delta z = -(q/p)^{\pm 1} (y + ix)$
- $\langle t \rangle_j$ ($\langle t^2 \rangle_j$): average (squared) decay time of unmixed decays in each Dalitz plot bin, in units of D^0 lifetime $\tau \equiv 1/\Gamma$

‘Bin-flip’ analysis: CP violation results

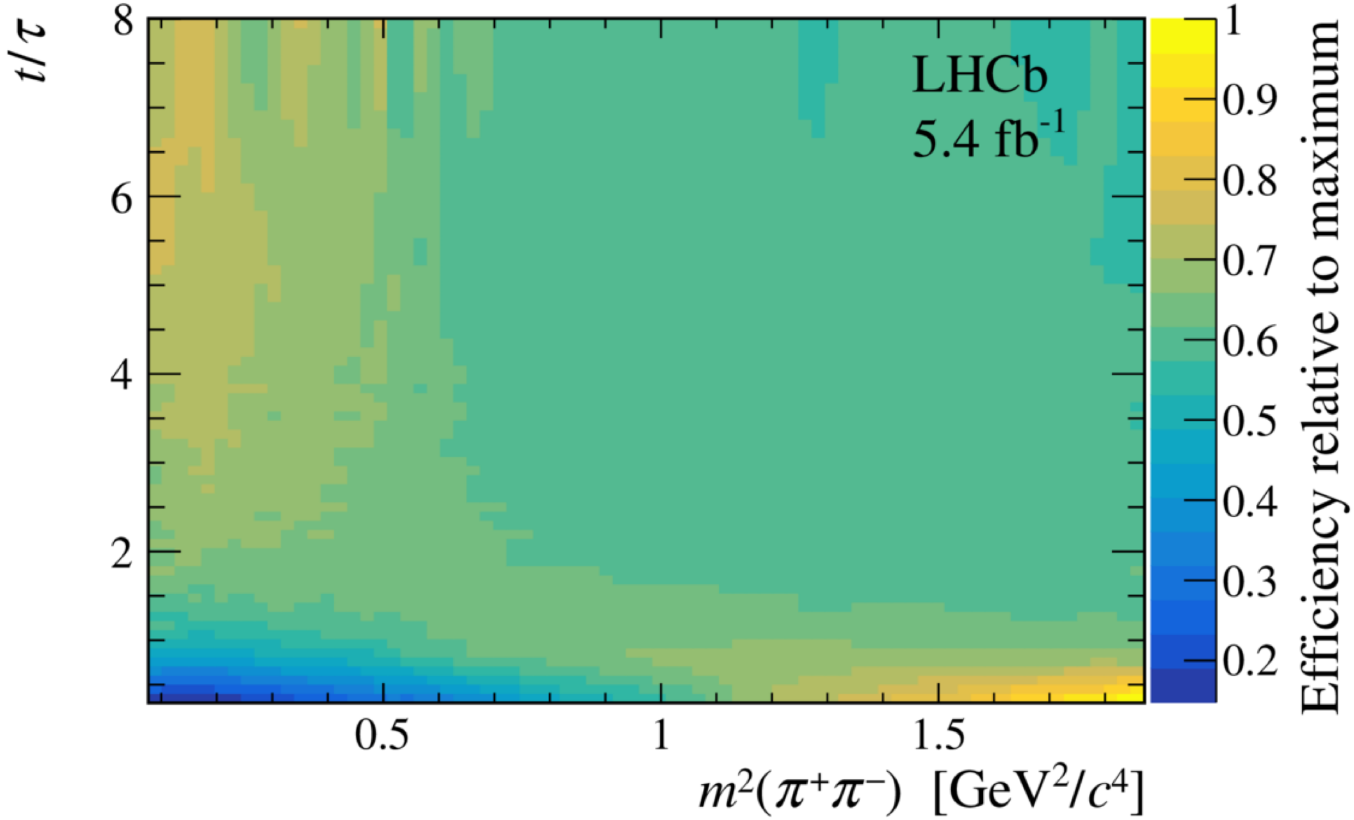
No significant differences D^0 vs $\overline{D}^0$

$\Delta x = [-0.027 \pm 0.018 \pm 0.001]\%$
$\Delta y = [+0.020 \pm 0.036 \pm 0.013]\%$



‘Bin-flip’ analysis: Correlations

Example of correlations between decay time and phase-space $m^2(\pi^+\pi^-)$



‘Bin-flip’ analysis: Corrections

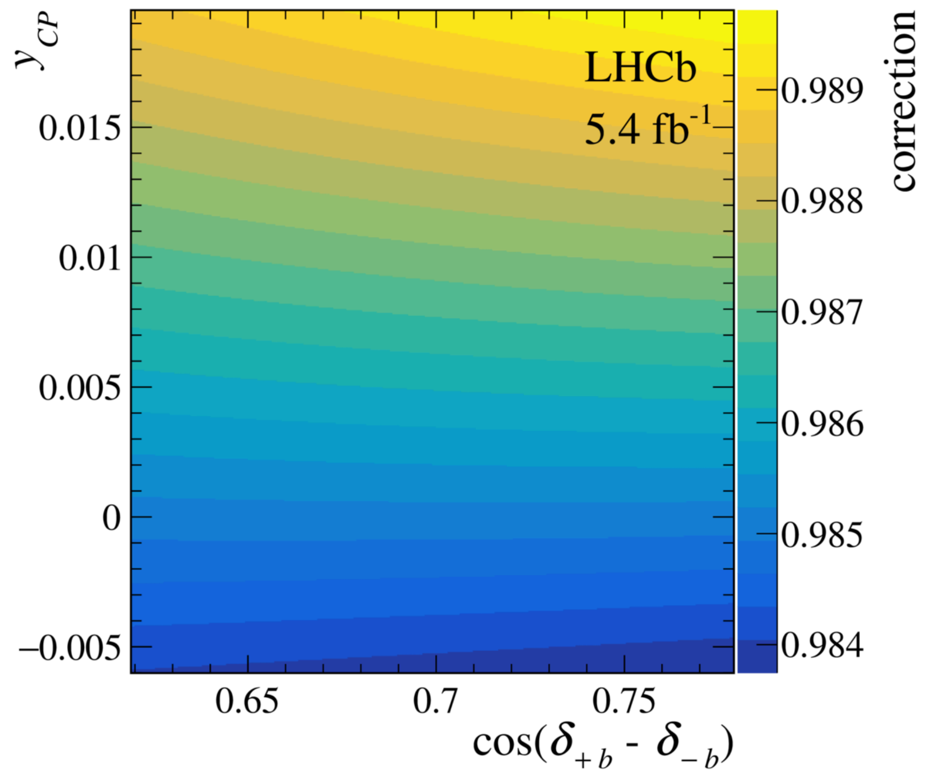
Example of correction map (for Dalitz bin b=1, decay time bin j=1)

Correction is applied to symmetrise the decay-time efficiency as a function of $m^2(\pi\pi)$

⇒ No impact on x (which preserves $m^2(\pi\pi)$ distribution)

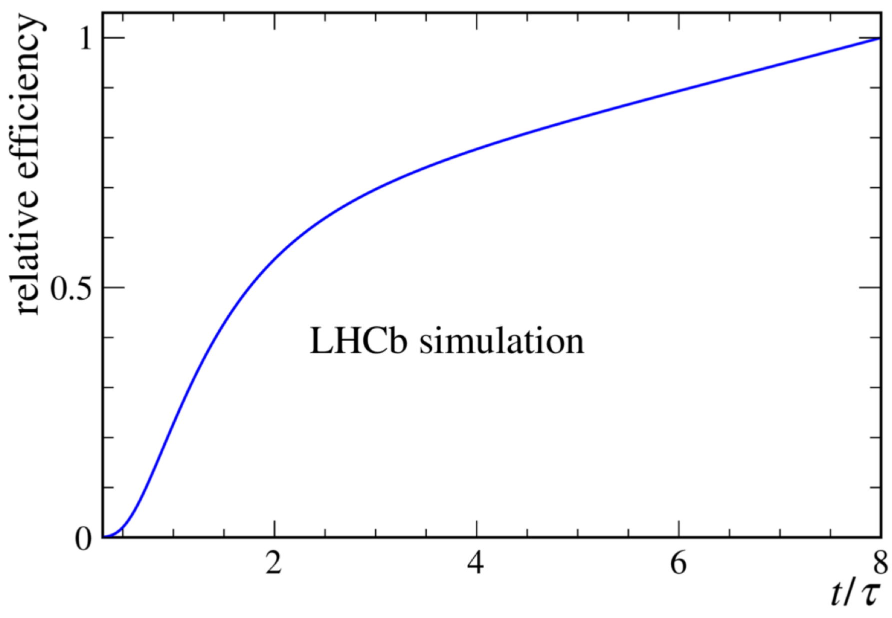
⇒ Small impact on y and strong phases, so correction depends on these values

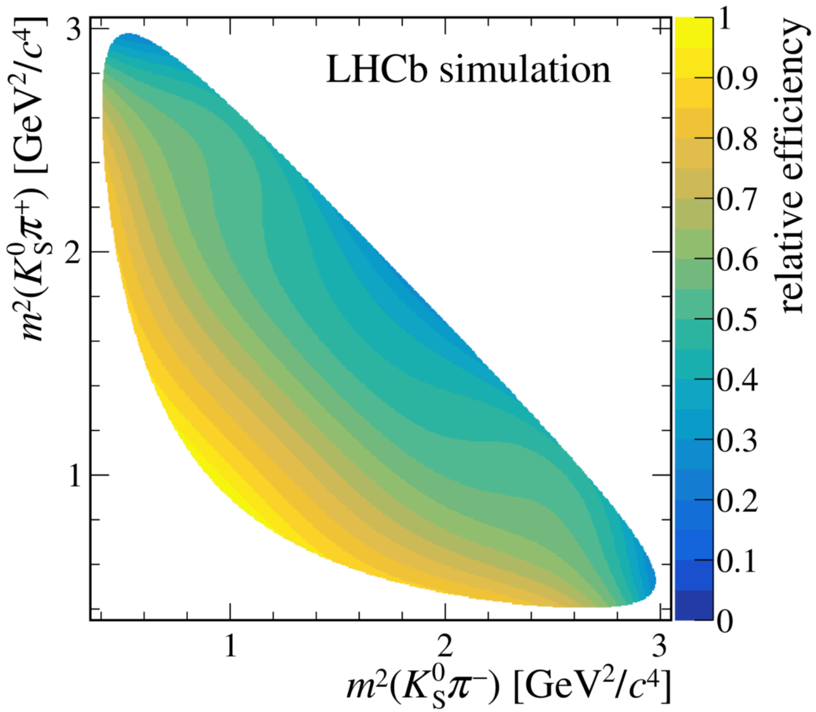
⇒ So, correction depends on values of y and c_b in fit



‘Bin-flip’ analysis: Efficiencies

Efficiency vs decay time and Dalitz plane





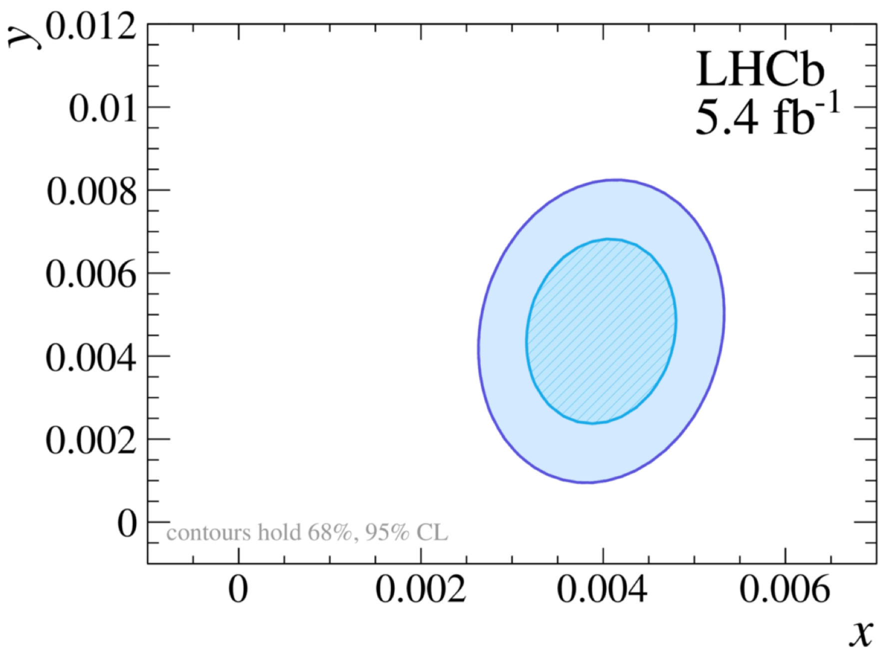
'Bin-flip' analysis: Strong phases

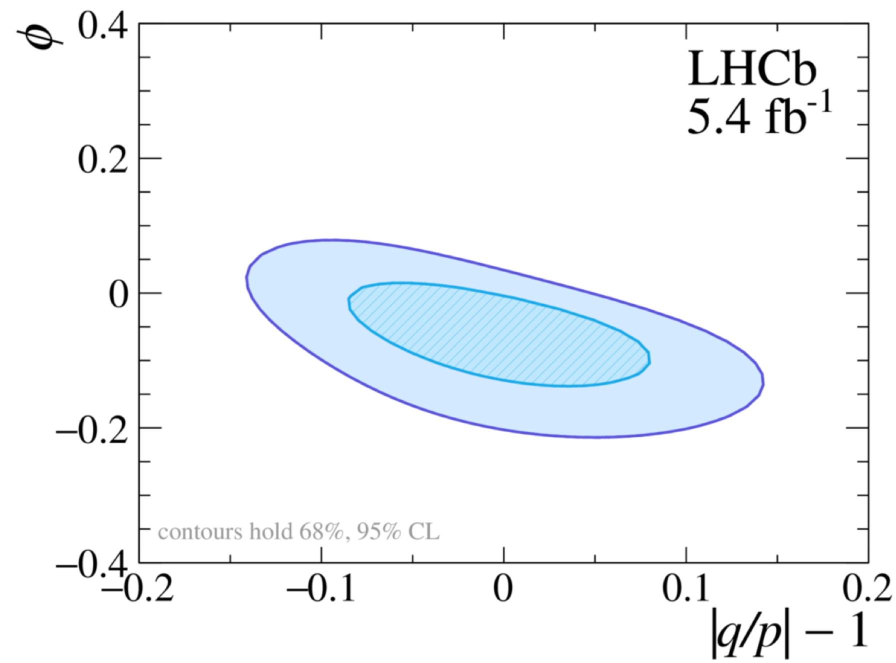
Initial and final values of strong phase inputs (Gaussian constrained in fit)

	Initial	Final
c_1	0.699 ± 0.020	0.702 ± 0.020
c_2	0.643 ± 0.036	0.641 ± 0.036
c_3	0.001 ± 0.047	0.006 ± 0.047
c_4	-0.608 ± 0.052	-0.613 ± 0.052
c_5	-0.955 ± 0.023	-0.955 ± 0.023
c_6	-0.578 ± 0.058	-0.568 ± 0.058
c_7	0.057 ± 0.057	0.047 ± 0.055
c_8	0.411 ± 0.036	0.413 ± 0.036
s_1	0.091 ± 0.063	0.014 ± 0.054
s_2	0.300 ± 0.110	0.341 ± 0.094
s_3	1.000 ± 0.075	0.956 ± 0.069
s_4	0.660 ± 0.123	0.767 ± 0.112
s_5	-0.032 ± 0.069	-0.073 ± 0.063
s_6	-0.545 ± 0.122	-0.627 ± 0.106
s_7	-0.854 ± 0.095	-0.828 ± 0.081
s_8	-0.433 ± 0.083	-0.449 ± 0.072

‘Bin-flip’ analysis: Contours

2D contours





‘Bin-flip’ analysis: New WA Combo