Mixing and CP violation in charm at LHCb

Mark Williams
on behalf of the LHCb collaboration

THE UNIVERSITY of EDINBURGH

THE ROYAL SOCIETY

LHCb

Conference on Flavor Physics and CP Violation (FPCP 2021)

Fudan University, Shanghai, China

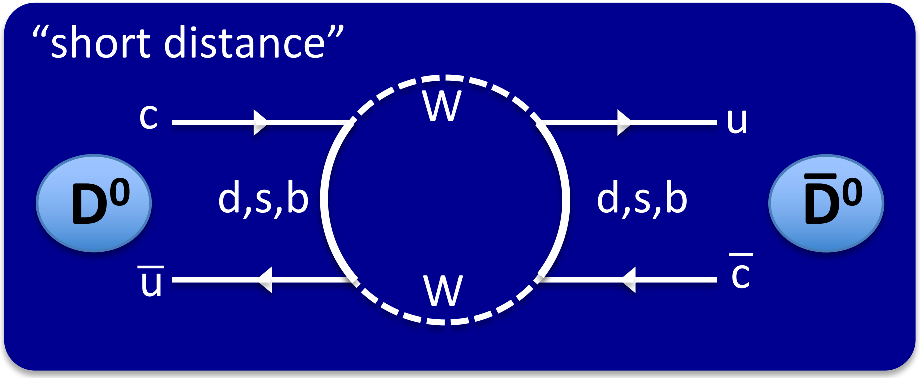
7 – 11 June 2021

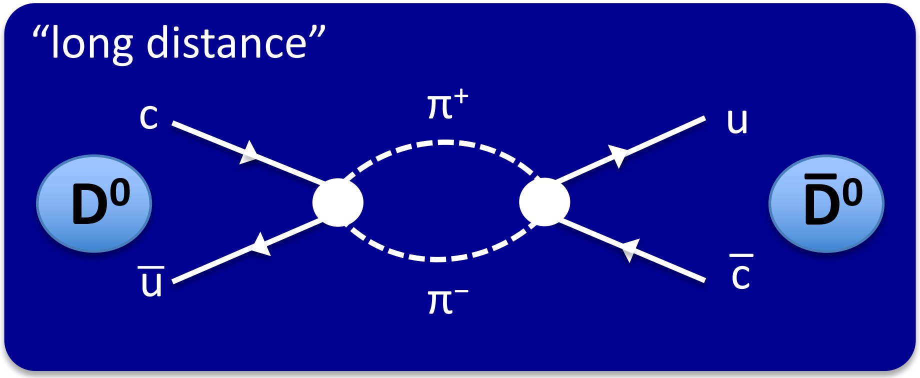
Outline

- **What, why?** – background and motivation
- **Where, how?** – charm physics at LHCb
- **What now?** – The post-discovery era
- **CPV in decay**:
  - $D_{(s)}^+ \rightarrow h^+h^0$ decays (https://arxiv.org/abs/2103.11058)
  - $D^0 \rightarrow K_S^0 K_S^0$ decays (https://arxiv.org/abs/2105.01565)
- **Mixing and mixing-induced CPV**:
  - ΔY in $D^0 \rightarrow h^+h^-$ (https://arxiv.org/abs/2105.09889)
  - $D^0 \rightarrow K_S^0 \pi^+\pi^-$ with 'bin flip' approach (https://arxiv.org/abs/2106.03744)
- **Summary and Outlook**

NEW TODAY

Neutral charm meson mixing





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:

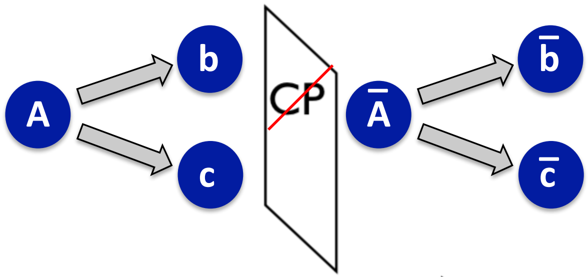
$|q/p|$
$\phi = \arg(q/p)$
CP violation
or Δx, Δy

- **Unique** - up-type quarks
- **NP-sensitive** – CPV very small (~10^{-4}) in SM
- **Poorly experimentally-constrained** – x=0 not yet ruled out

CP violation

CP violation in decay:

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

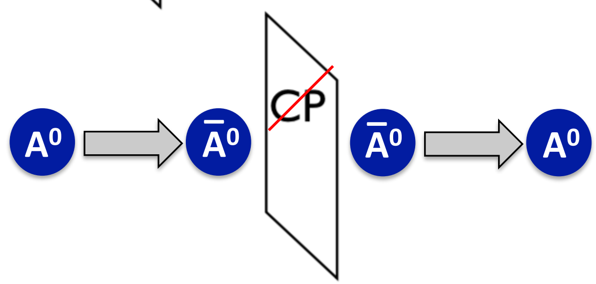


$$A_{CP}(D^0 \rightarrow f) = \frac{\Gamma(D^0 \rightarrow f) - \Gamma(\bar{D}^0 \rightarrow \bar{f})}{\Gamma(D^0 \rightarrow f) + \Gamma(\bar{D}^0 \rightarrow \bar{f})}$$

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

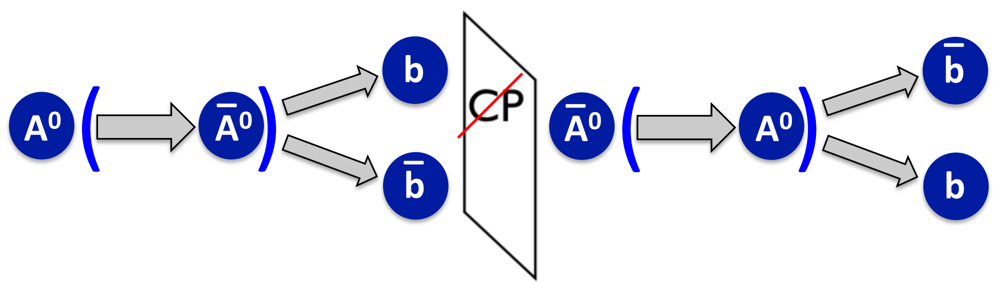
CP violation in mixing:

$|q/p| \neq 1$

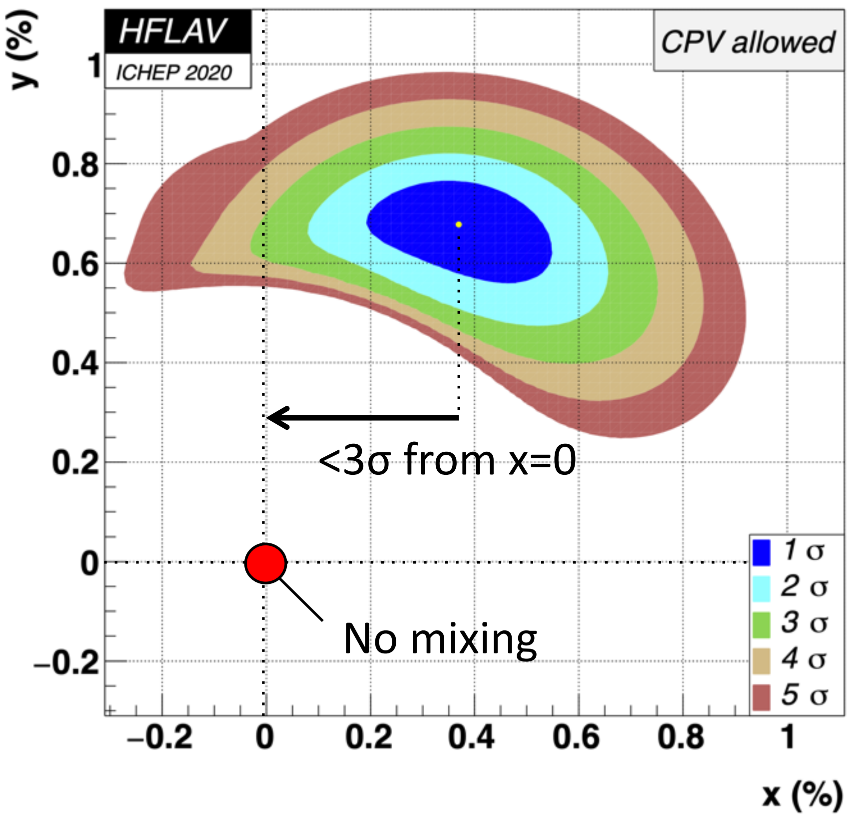


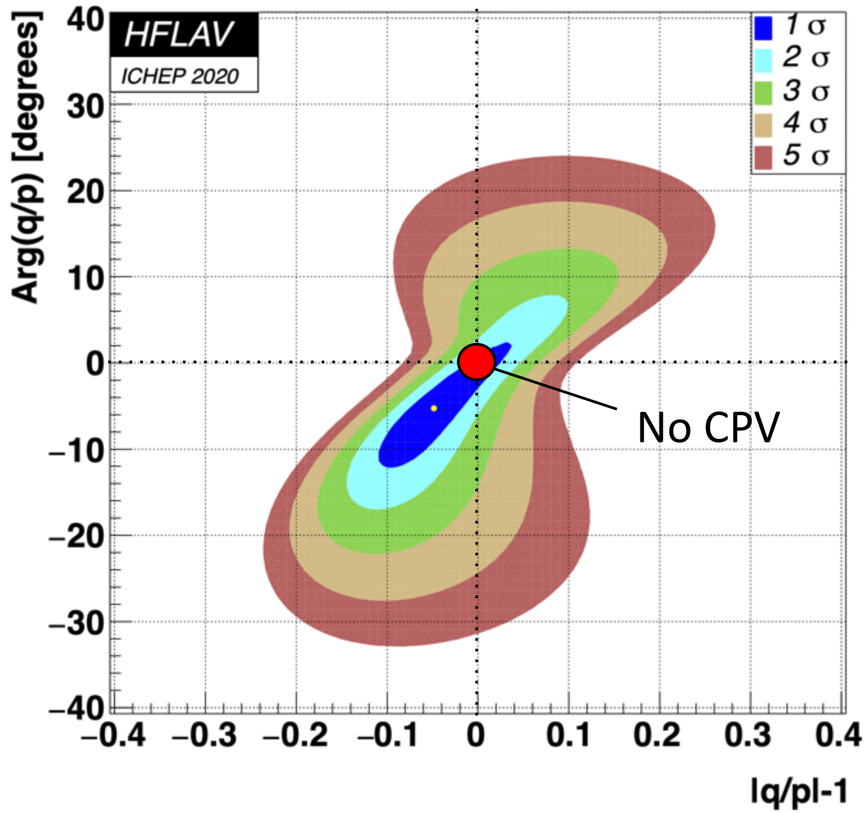
CP violation in interference between mixing and decay:

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



State-of-the-art: Mixing

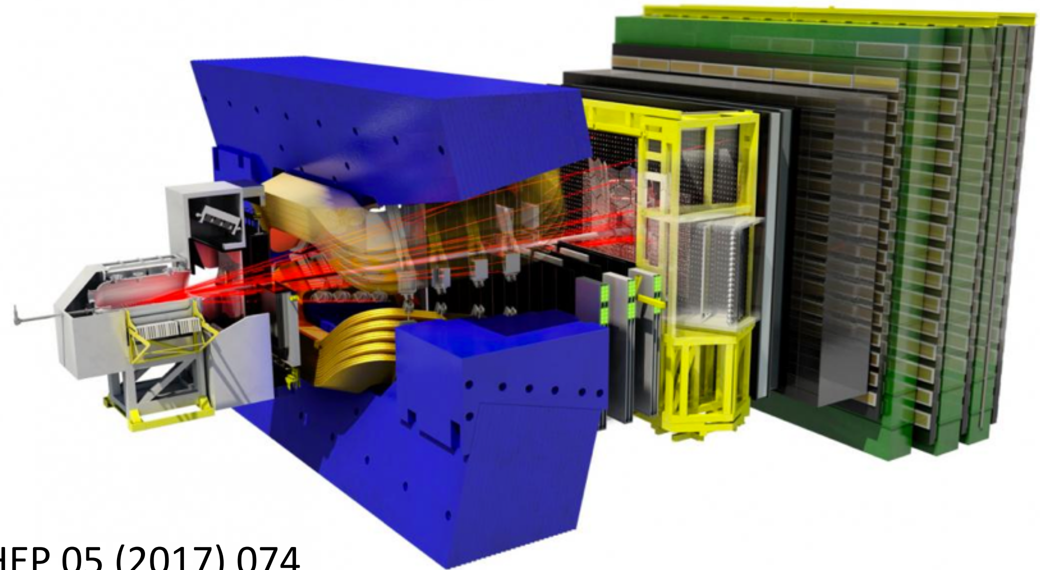




Charm physics at LHCb

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, …)

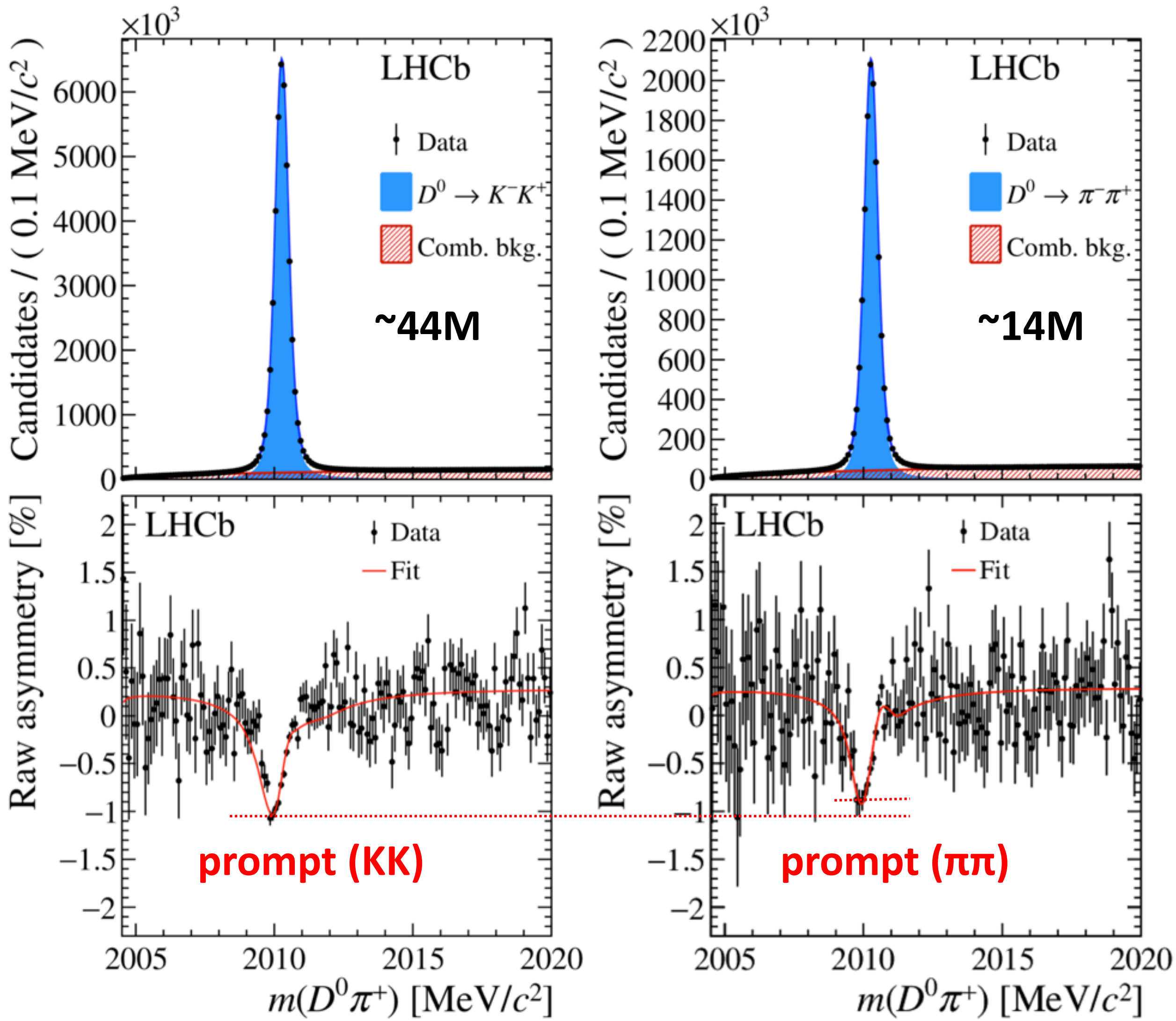
The 2019 discovery: ΔA_{CP}

PRL 122 (2019) 211803

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

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

5.3σ from zero ⇒ Discovery of CPV in charm



What next?

- **More (and more precise) measurements of CPV in decay**
  ⇒ add new channels, including those previously unexplored at LHCb

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

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

$A_{CP}(D_{(s)}^{+} \to h^{+}h^{0})$

arXiv:2103.11058
Accepted by JHEP

Measure A_{CP} in 7 modes with $h^{\pm} = \{K^{\pm},\pi^{\pm}\}$, $h^{0} = \{\pi^{0}, \eta\}$

Use all available data

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

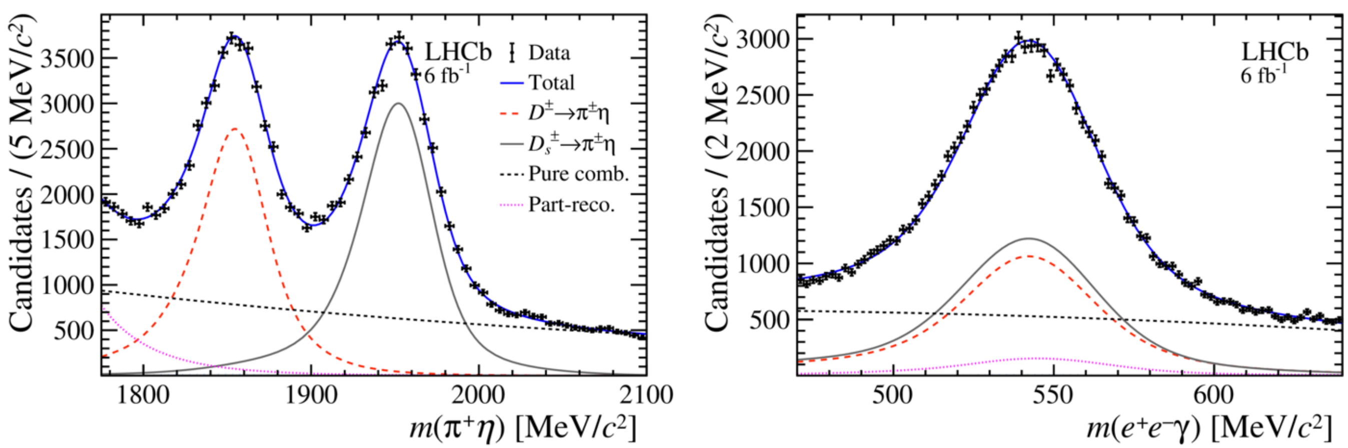
$$\mathcal{A}_{CP}(D_{s}^{+} \to K^{+}\eta) = (0.9 \pm 3.7 \pm 1.1)\%$$ **SCS**

Probe a range of processes, with strong constraints from SM

No evidence for CPV

Several world-leading measurements (*)

Example 2D fits



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

arXiv:2105.01565

Full Run 2 analysis of "Discovery mode" ⇒ Upgrade (data + tools) of previous analysis

Most precise single measurement (as precise as WA):

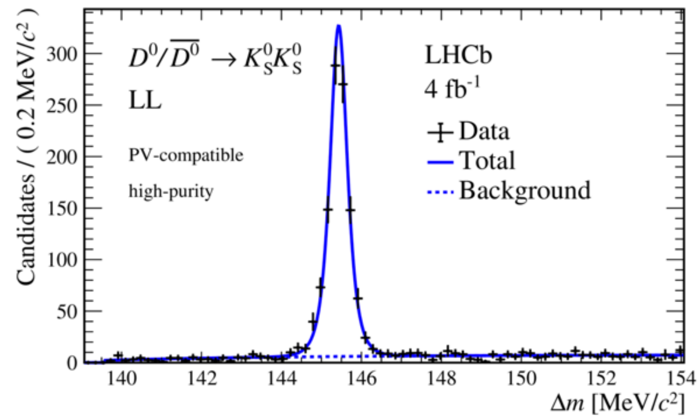
$$\mathcal{A}^{CP}(D^0 \to K_S^0 K_S^0) = (-3.1 \pm 1.2 \pm 0.4 \pm 0.2)\%$$

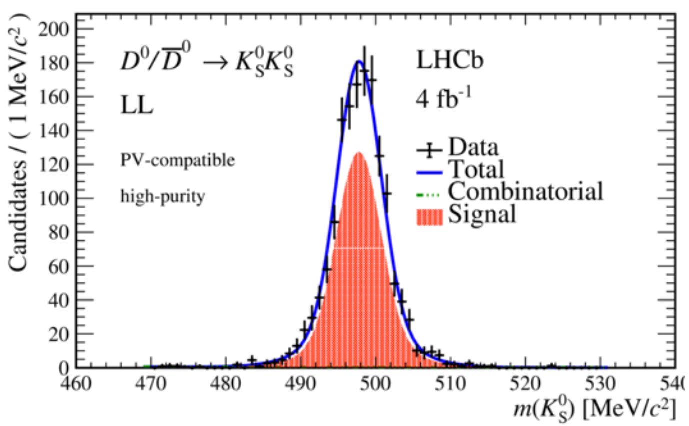
stat syst control mode

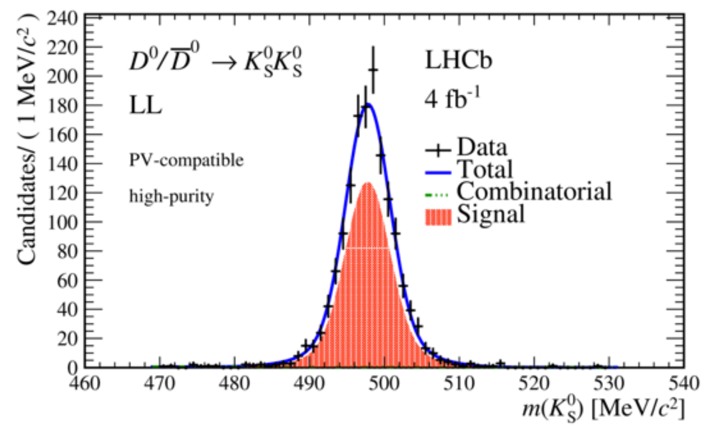
30% more precise per fb^{-1} than previous LHCb measurement

⇒ equivalent to doubling the data

Example 3D fits







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

Time-dep. CPV: ΔY (≈−A_Γ)

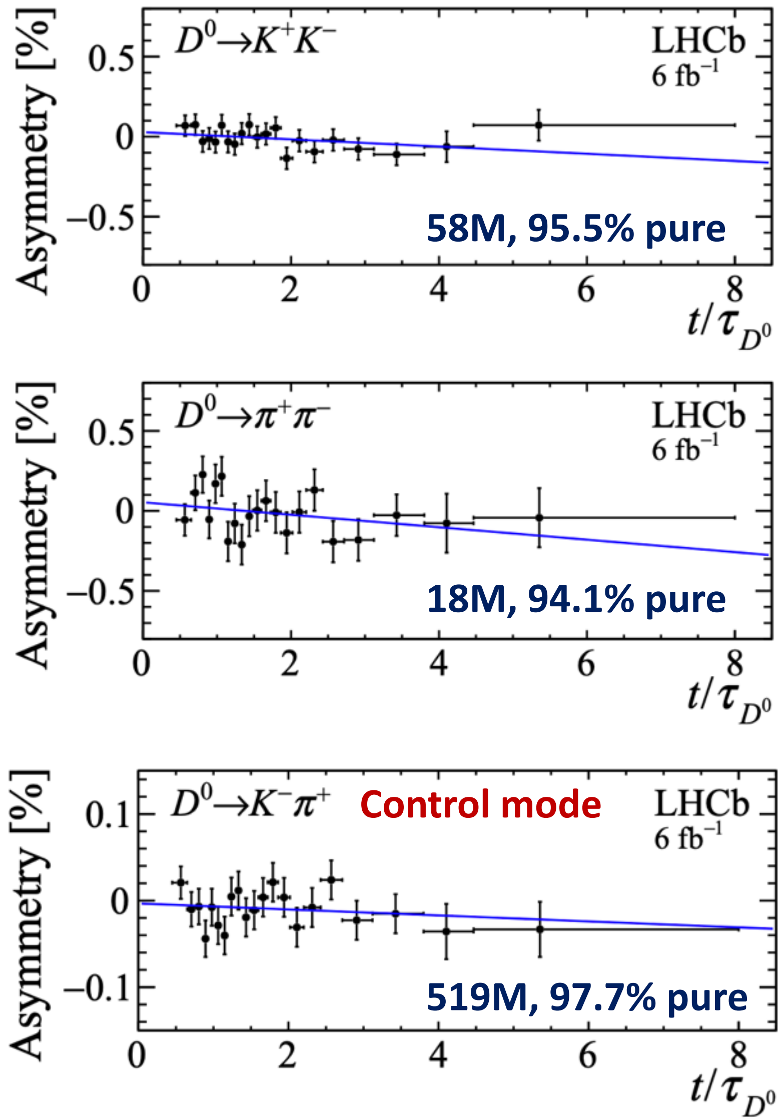
arXiv:2105.09889

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

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

Full Run 2 sample

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

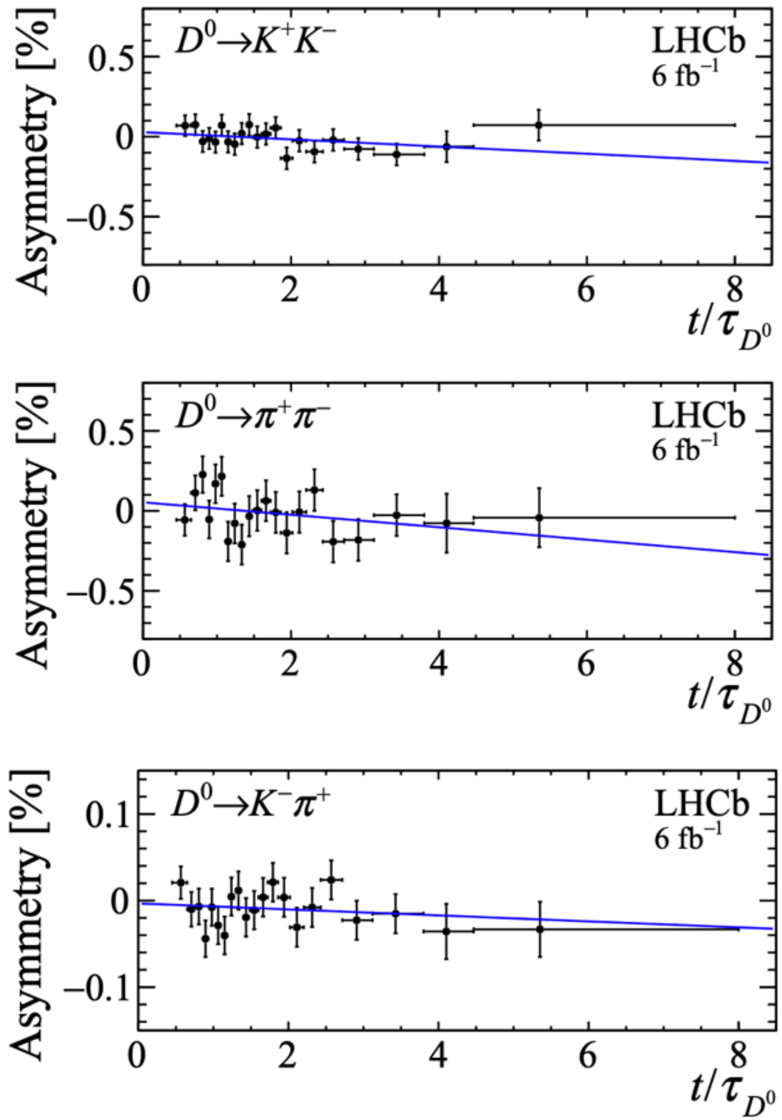
Data-driven validation with CF $D^0 \to K^- \pi^+$

>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



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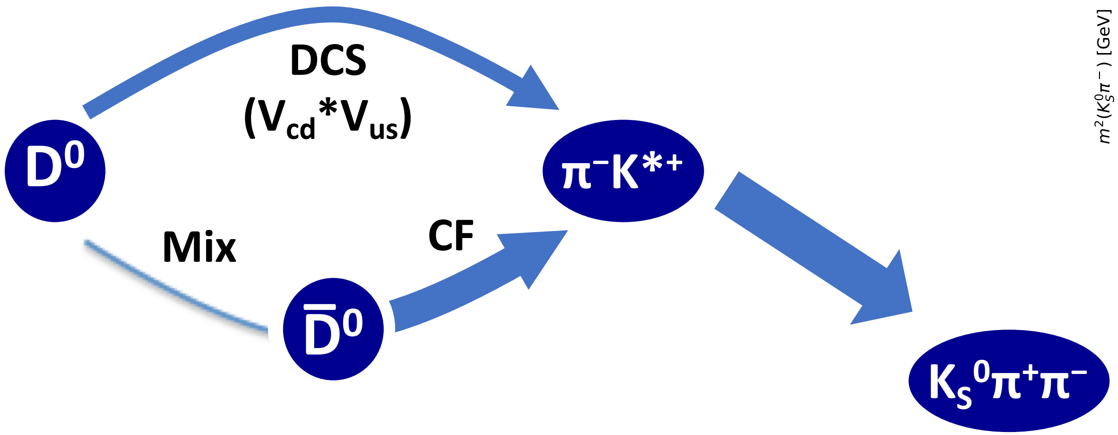
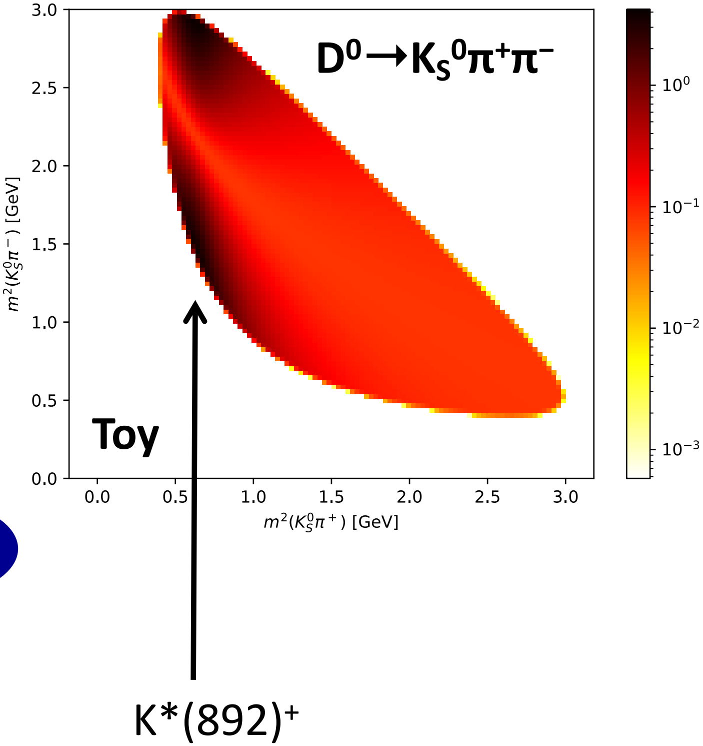
The Golden Mode: $D^0 \rightarrow K_S^0\pi^+\pi^-$

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





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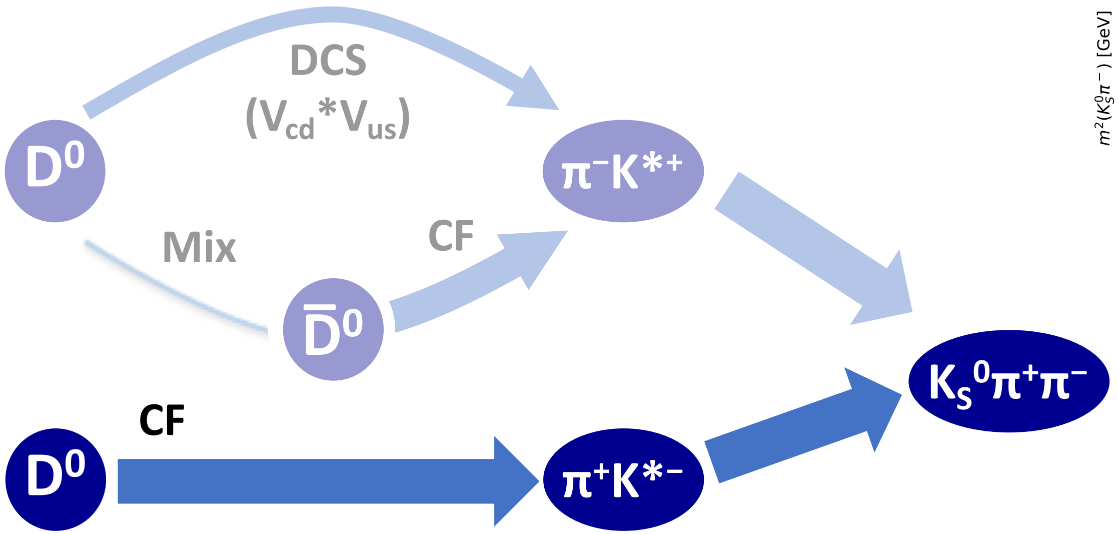

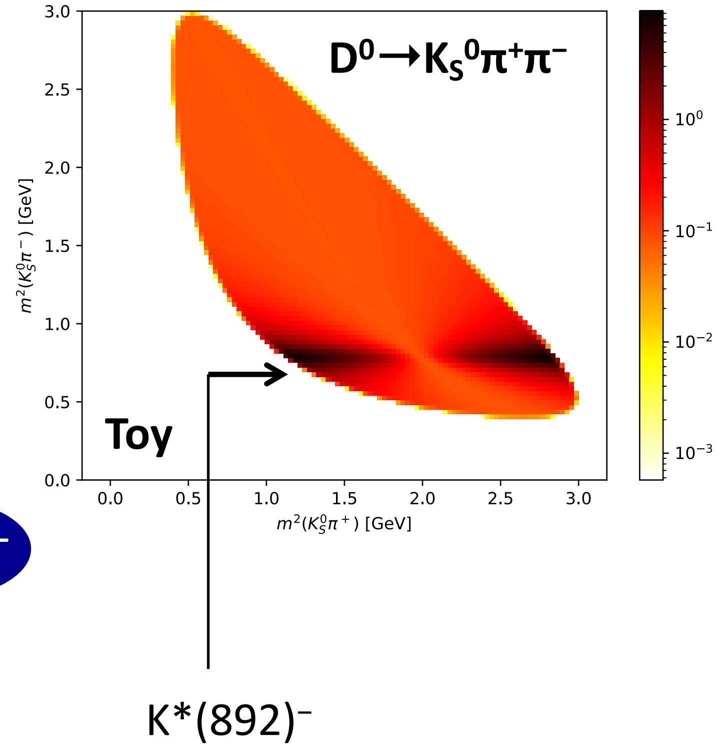

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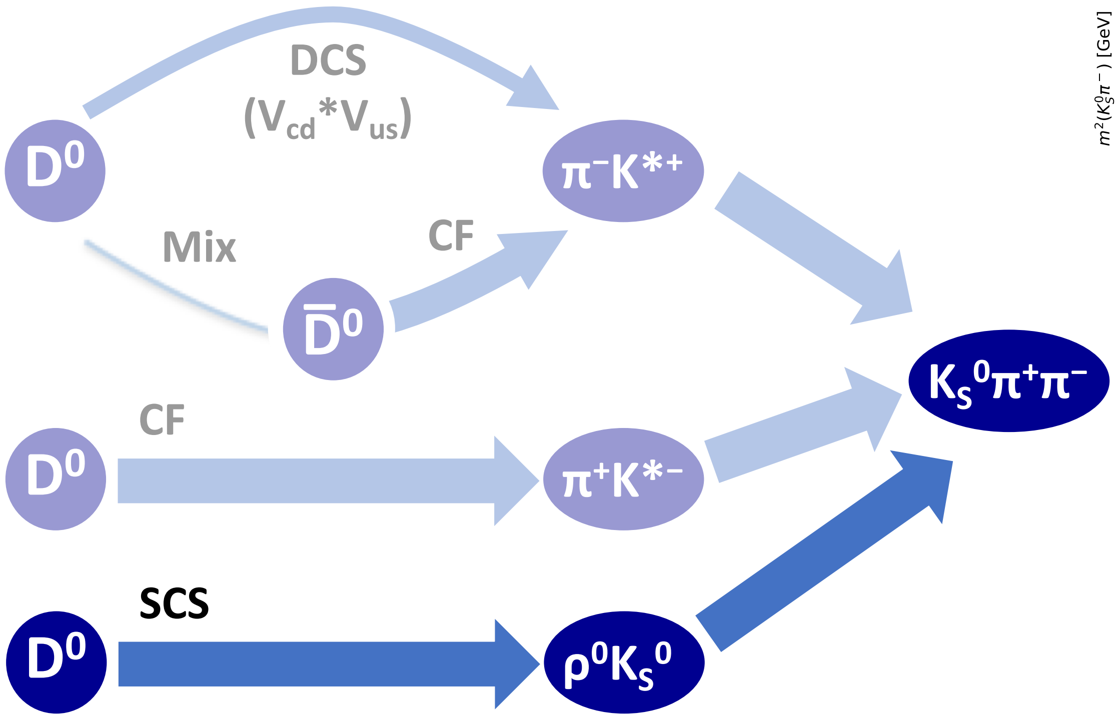

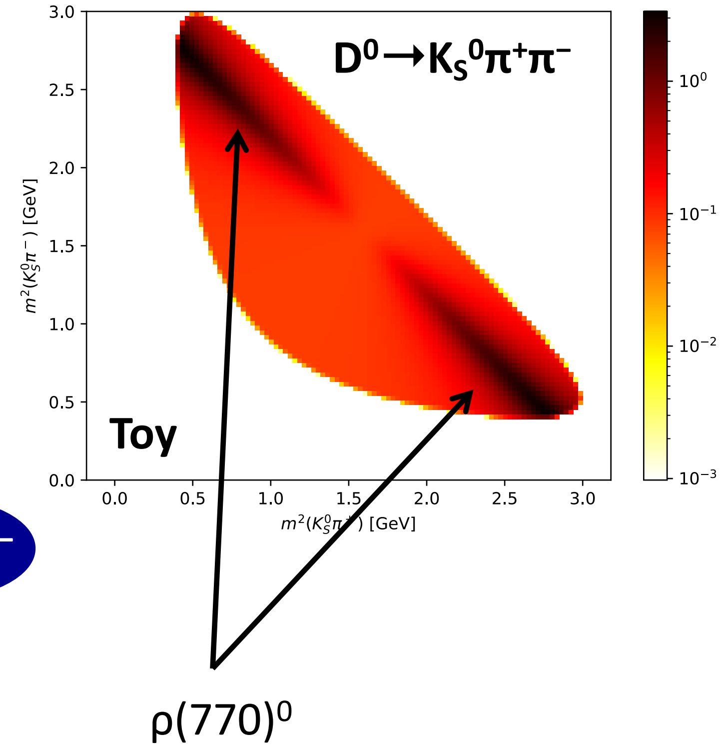

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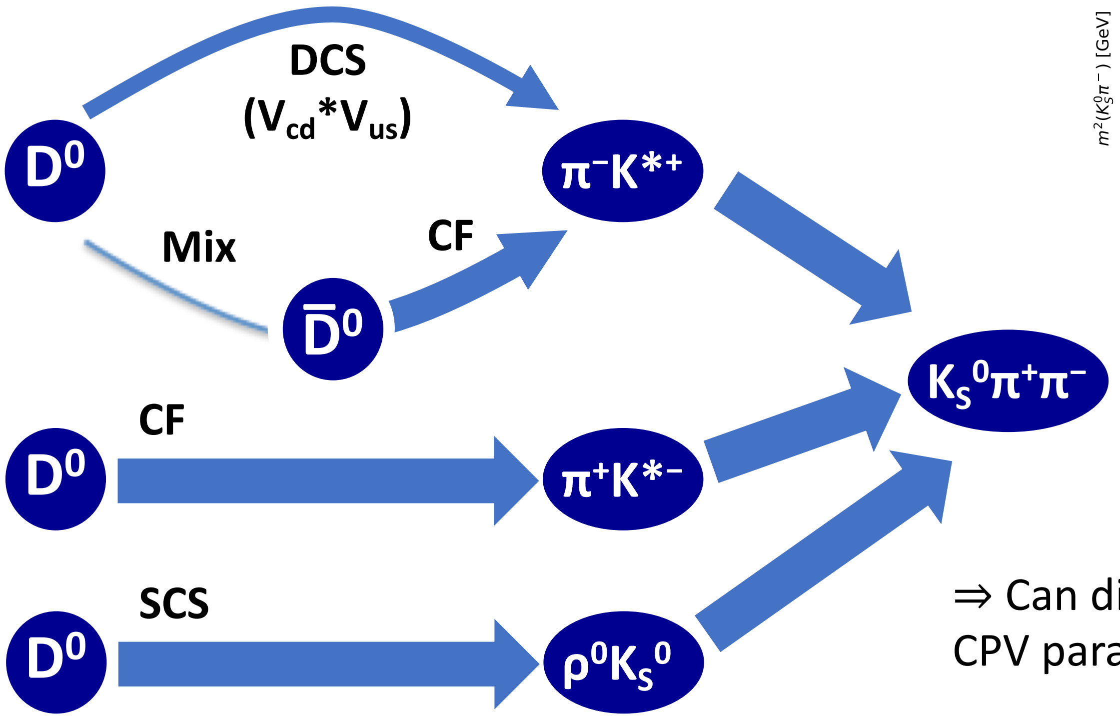
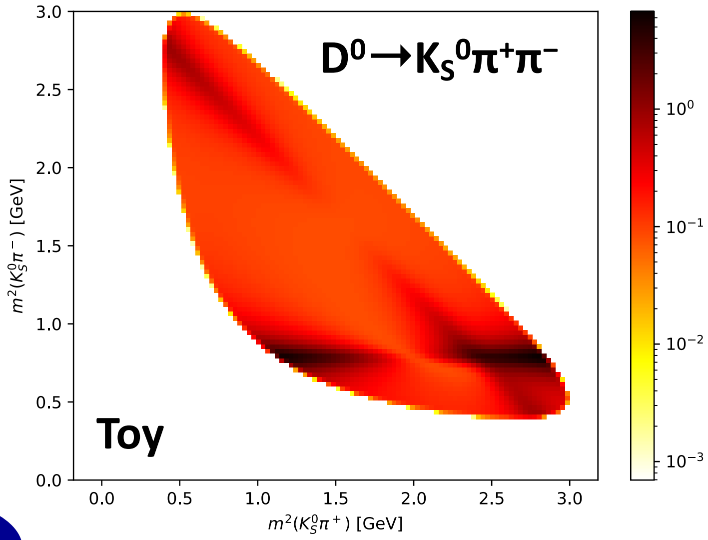




K*(892)+ + K*(892)− + ρ(770)0

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

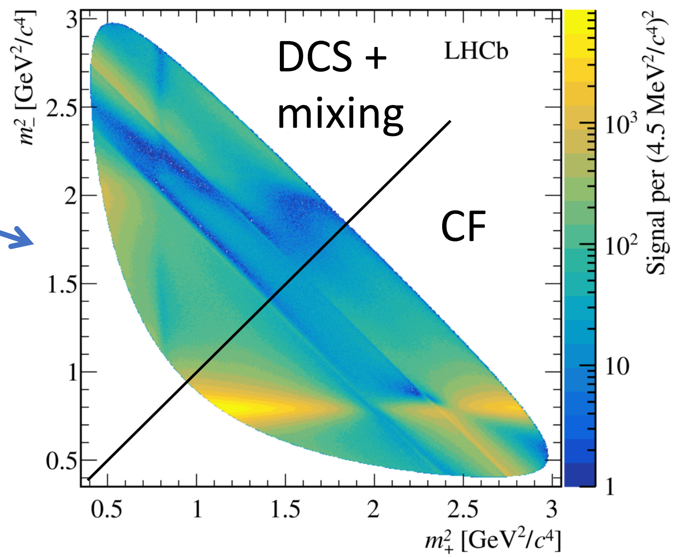
Requires **time and phase-space dependent analysis**

‘Bin-flip’ analysis

arXiv:2106.03744

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



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Exploit symmetry in final state:

(1) Oscillated contributions mainly in upper half
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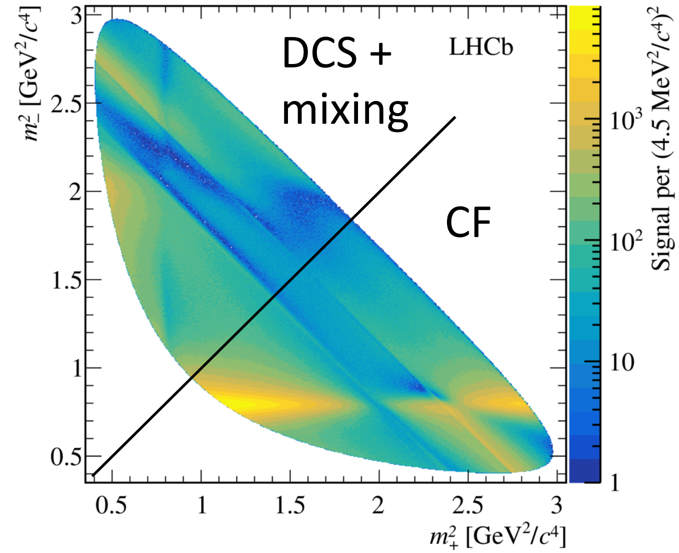
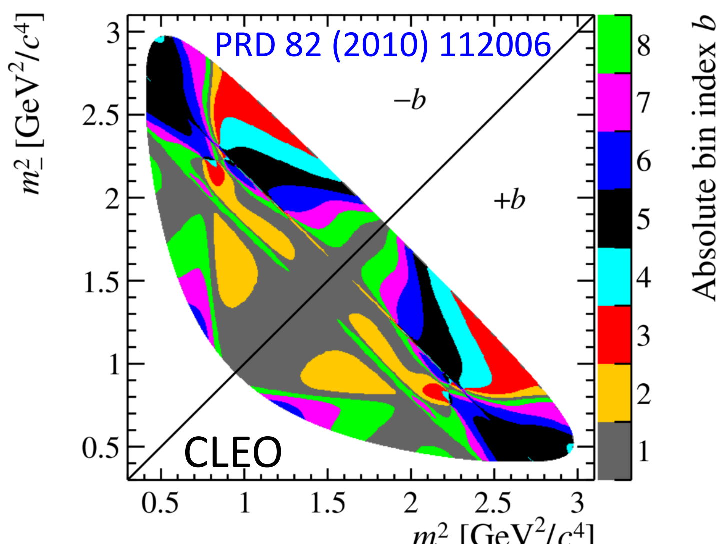
(2) Divide into 8 bins per half
⇒ boosts sensitivity, reducing dilution from strong phase variation

Strong phases constrained from CLEO & BESIII





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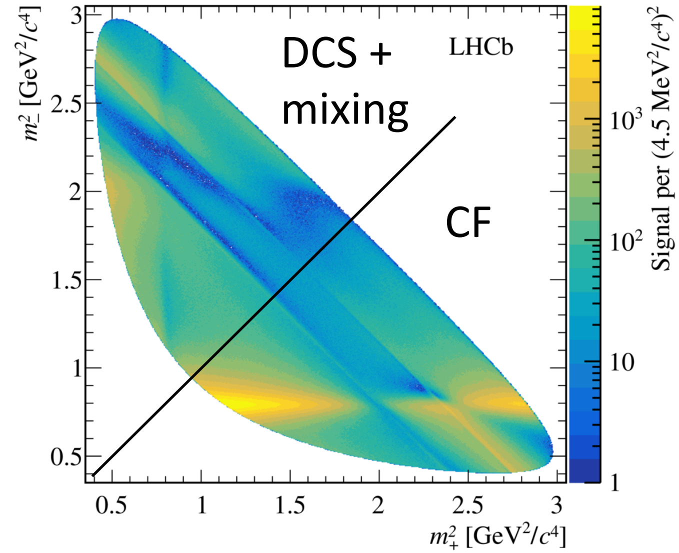
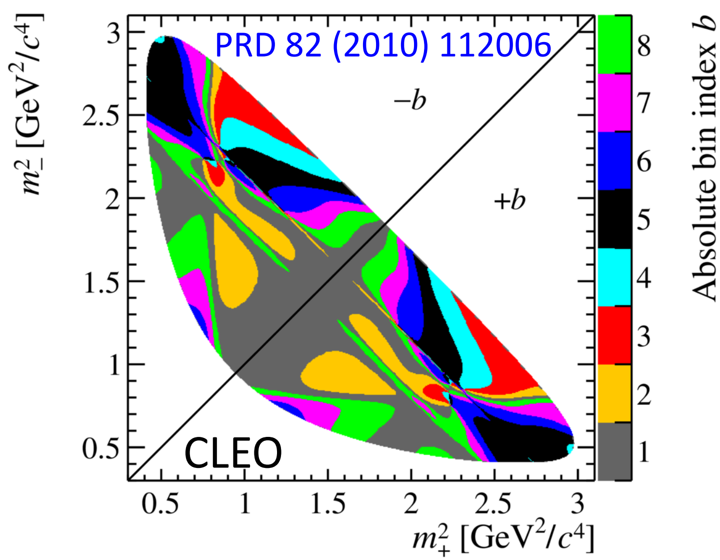
Analysis overview:

⇒ Measure 8 time-dependent ratios $R_i(t)$
⇒ Fit these ratios for D^0 and $\overline{D}^0$ separately, and averaged
⇒ Fit parameters include x, y, Δx, Δy
⇒ Can then translate to |q/p| and ϕ





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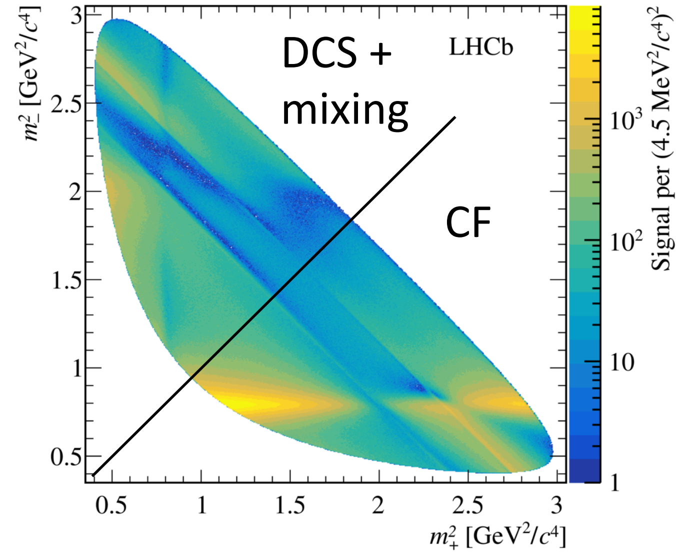
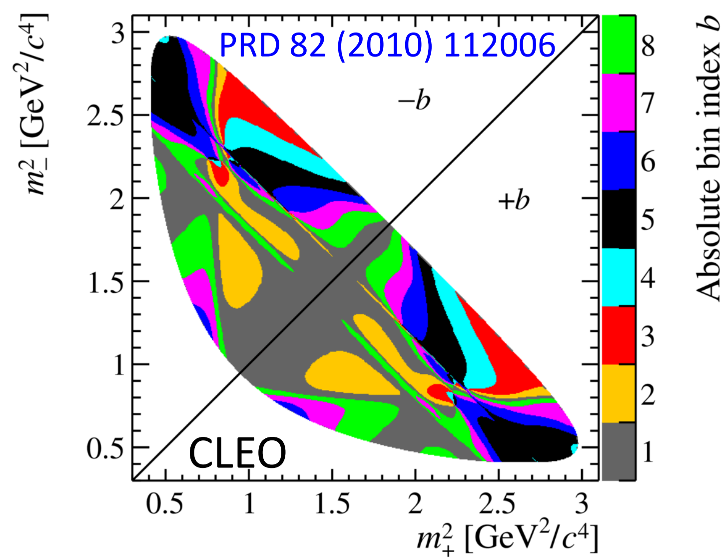
Strong phases constrained from CLEO & BESIII

(3) Most detector effects ~cancel in the ratio

Careful data-driven reweighting to remove residual nuisance effects





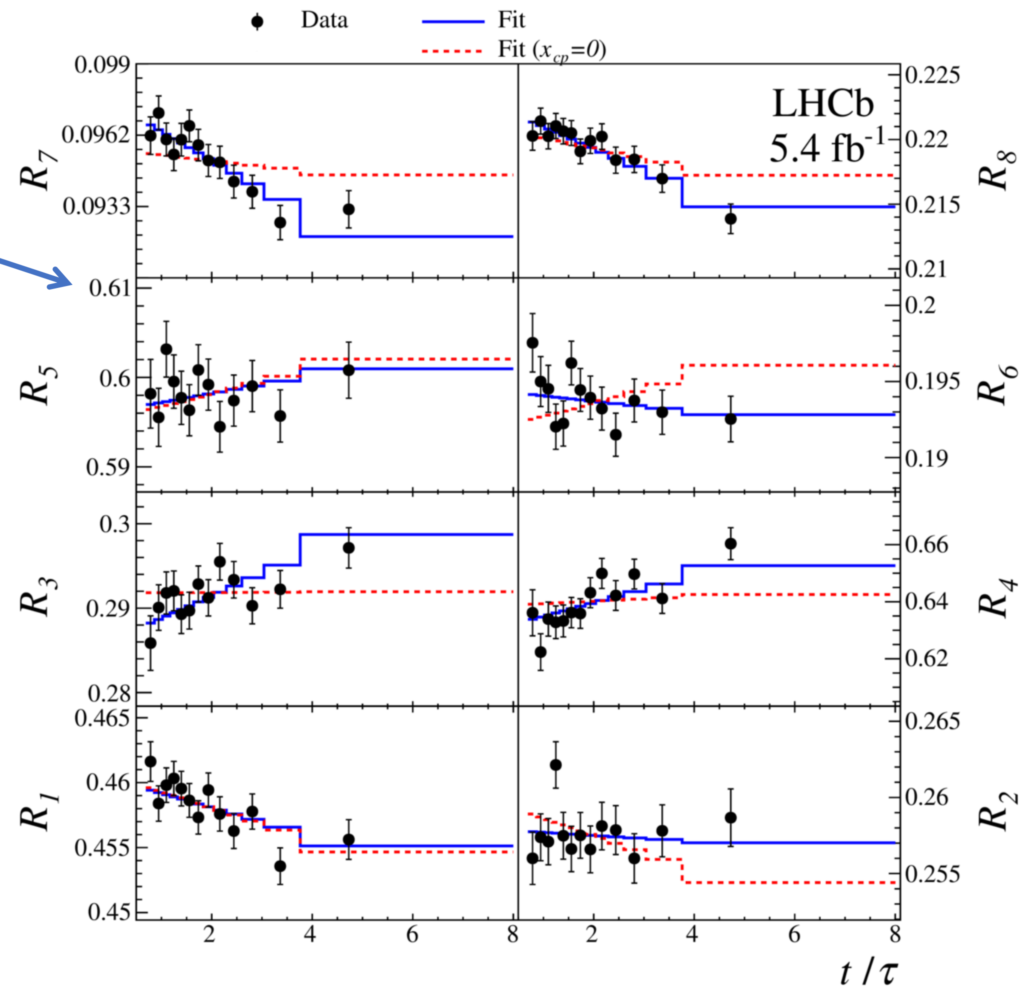
'Bin-flip' analysis: results

arXiv:2106.03744

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]%



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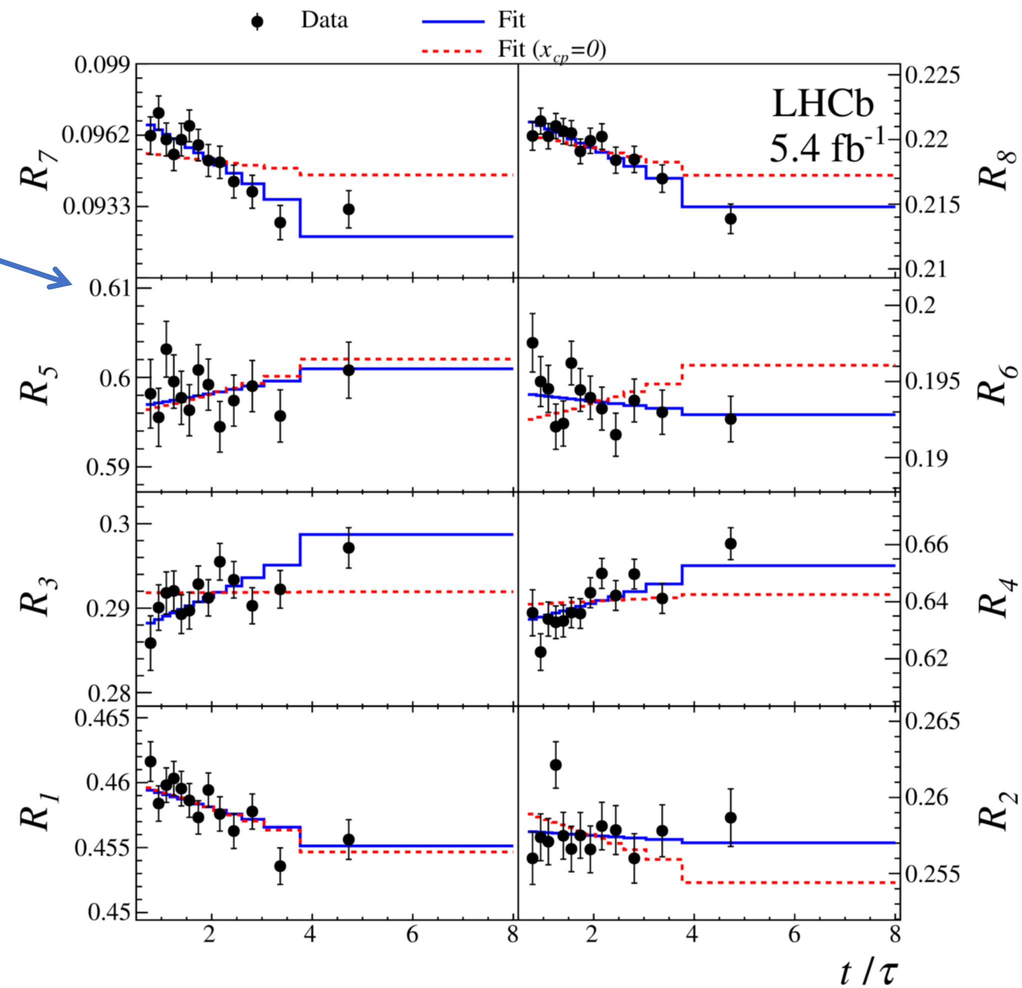


First measurement of non-zero x (>7σ significance)

Oscillation period ~630ps (D^0 lifetime 0.4ps)

'Bin-flip' analysis: results

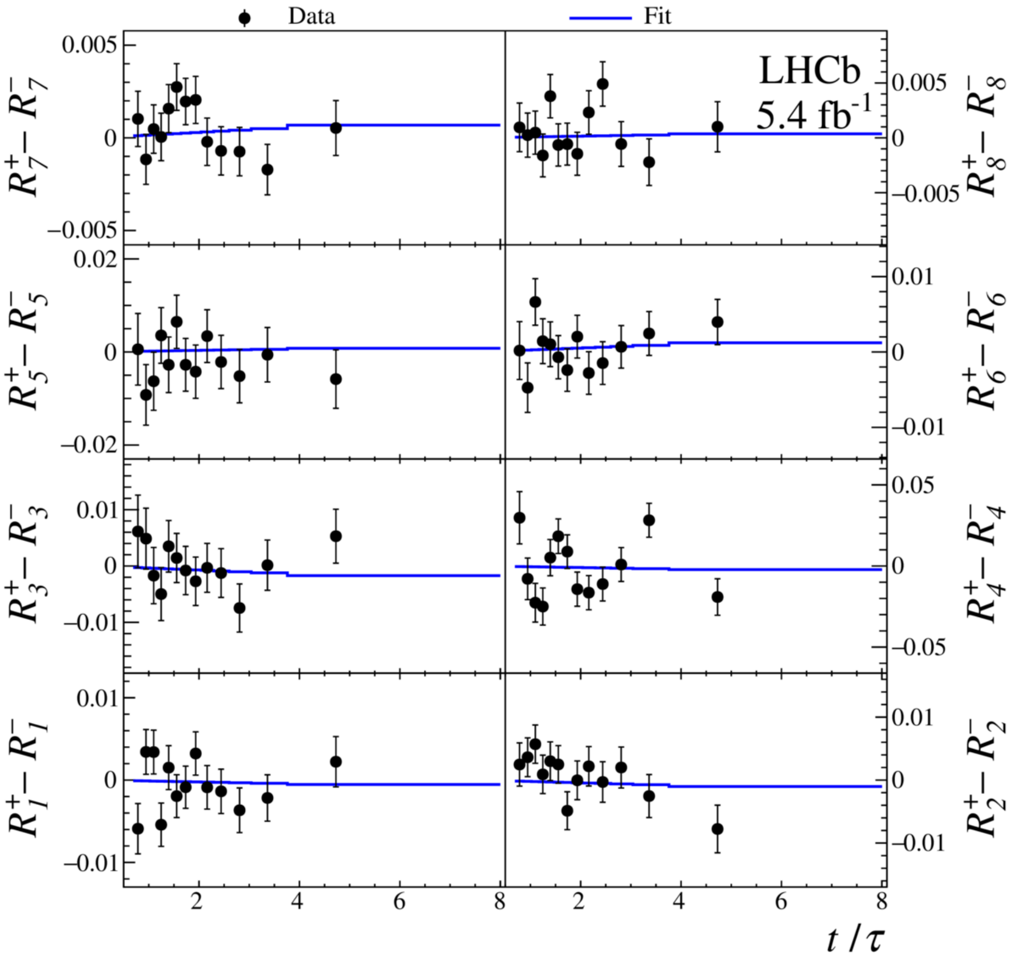
arXiv:2106.03744

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

Clear time dependence from mixing (Dalitz bin specific)

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

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



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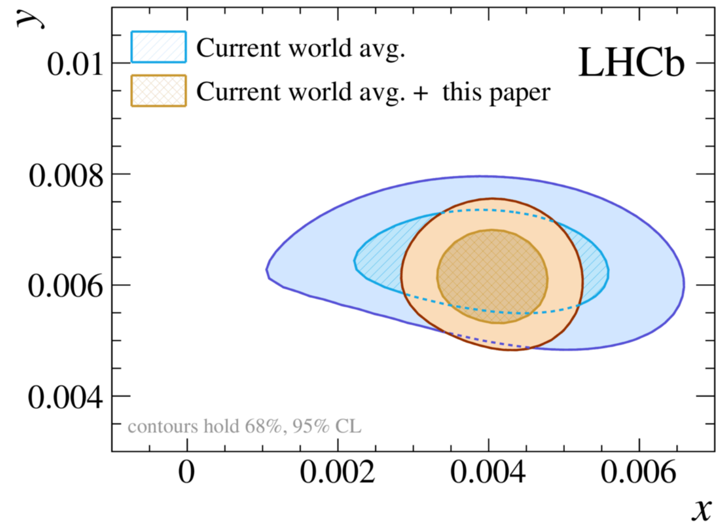
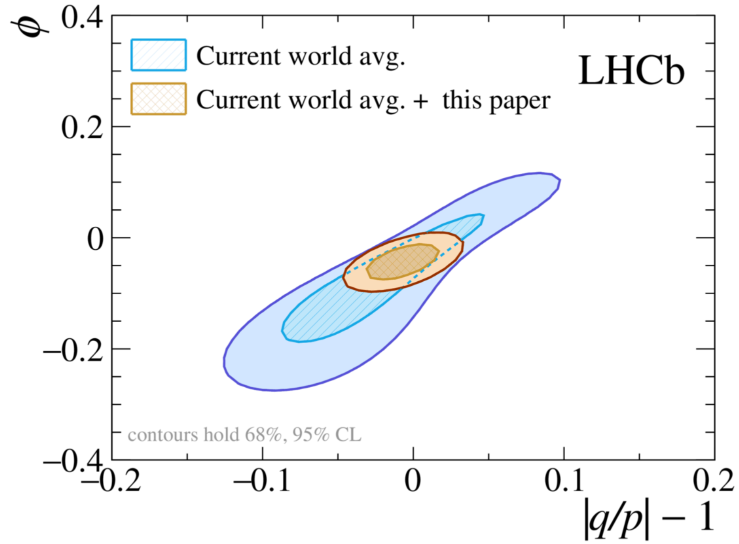
Significant improvements in WA for both mixing and CPV parameters

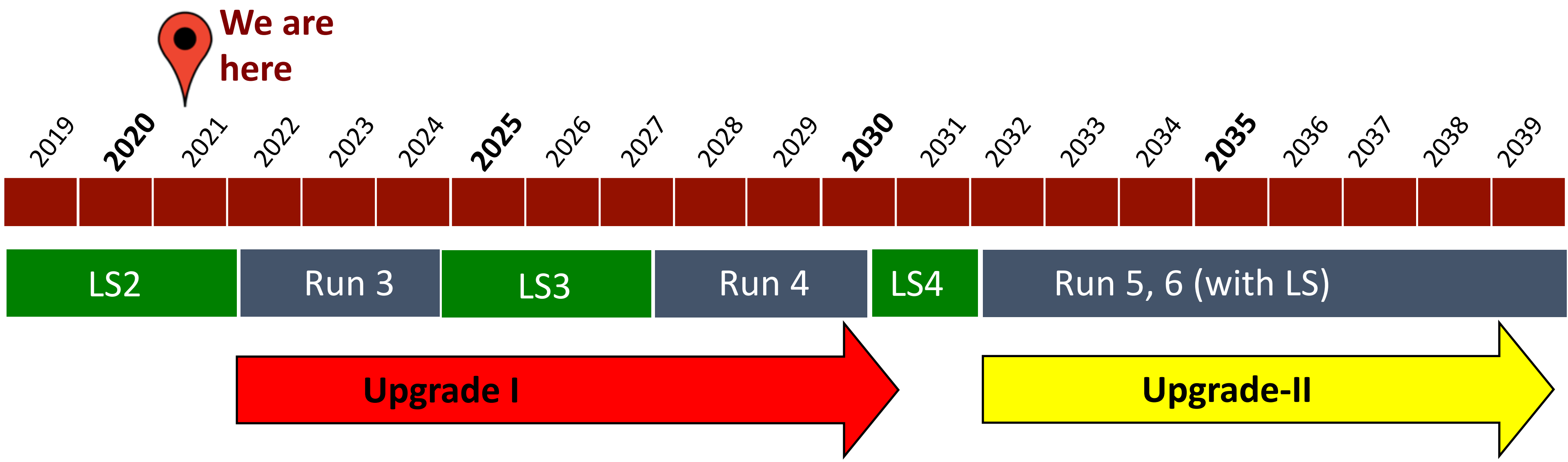




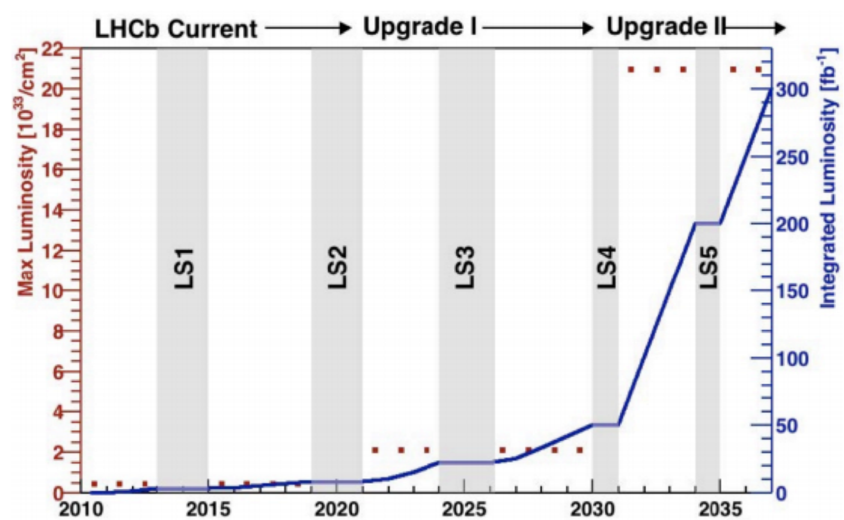
Summary & Outlook

- CPV discovery the **start** of a new adventure in charm
- Squeezing the most out of LHCb Run 1-2 data
  ⇒ New channels, new techniques
- Large gains in precision on CPV and mixing parameters
  ⇒ reaching 10^{-4} level
- First measurement of charm mixing frequency ($x \propto \Delta m$)
  ⇒ important step to discovering mixing-induced CPV
- Many other measurements in progress, e.g.
  ⇒ In decay: $A_{CP}(D^0 \to K^+K^-)$, $A_{CP}(D_{(s)}^+ \to \eta' h^+)$,
  ⇒ In mixing: $D^0 \to K^+\pi^-$ 'WS' mixing, y_{CP}
  ⇒ Local CPV in multibody D decays
  ⇒ Baryon CPV
  ⇒ Asymmetries in rare decays: $D^0 \to h^+h^-\mu^+\mu^-$

Run 3 and beyond



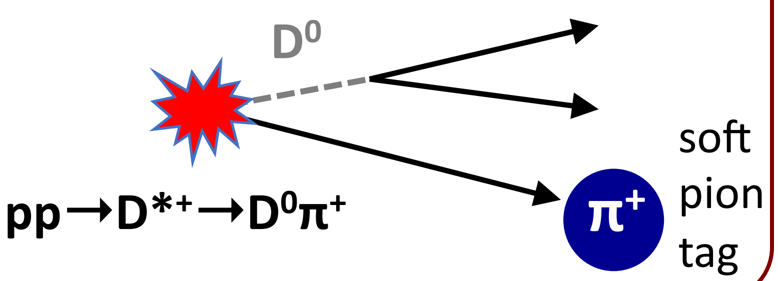
- LHCb has ambitious long-term upgrade plans
- All charm mixing/CPV analyses statistically limited
- The future is bright



Extra Slides

Charm flavour tagging

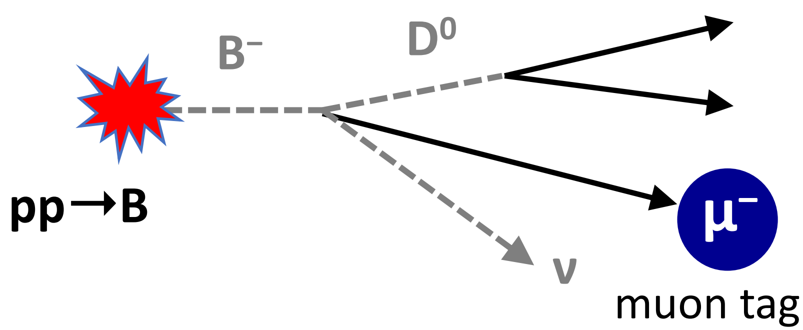
π-tagged (“prompt charm”)



Lifetime-biasing trigger

High signal yield & purity

μ-tagged (“secondary charm”)



Lifetime unbiased trigger

Higher backgrounds, lower yields

Contributes important background to prompt analyses!

$A_{CP}(D_{(s)}^{+} \to h^{+}h^{0})$

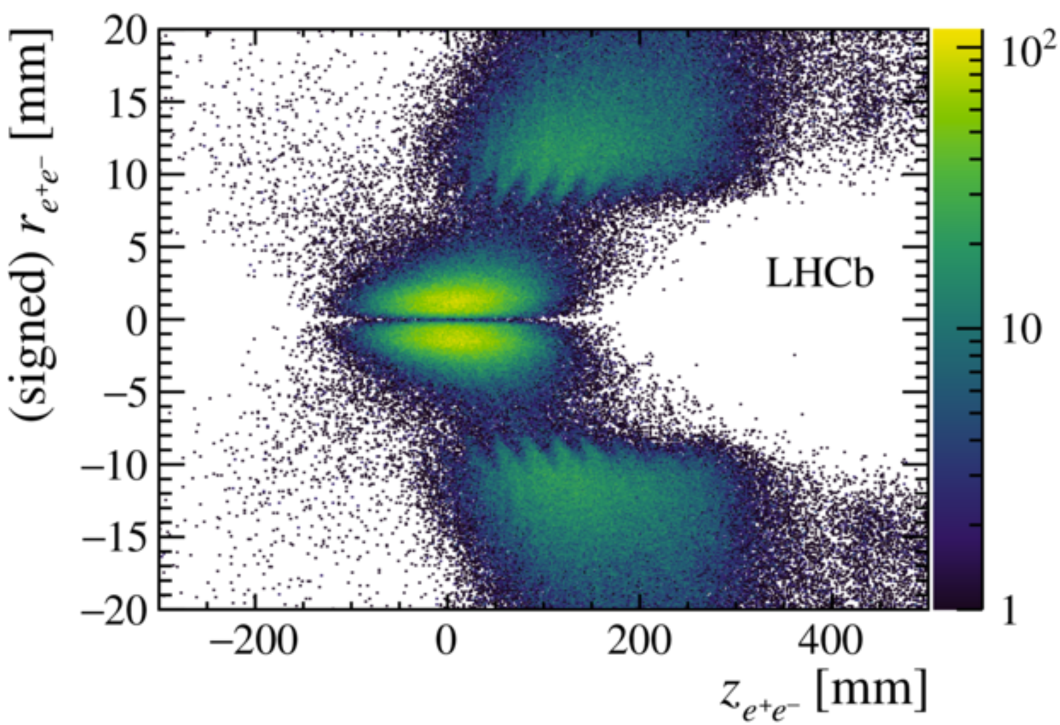
arXiv:2103.11058
Accepted by JHEP

Full Run 2 (η) or Run 1+2 (π^0) samples

$\pi^0,\eta \to e^+e^-\gamma$ (3-body – BR ~1%)

$\pi^0,\eta \to \gamma(\to e^+e^-)\gamma$ (conversion – BR ~40-99%)

⇒ first time at LHCb



$A_{CP}(D_{(s)}^+ \to h^+h^0)$

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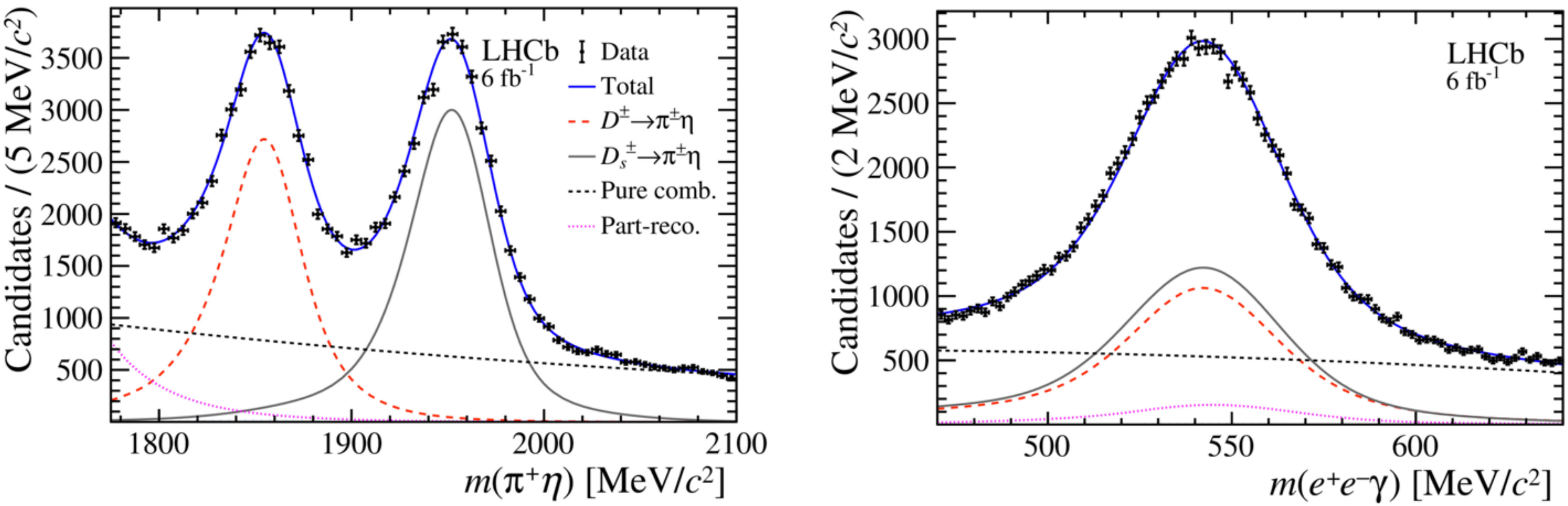
Accepted by JHEP

Yields and raw asymmetries from 2D UML fits to $\mathbf{m(e^+e^-\gamma)}$ and $\mathbf{m(h^+h^0)}$
where $m(h^+h^0) \equiv m(h^+e^+e^-\gamma) - m(e^+e^-\gamma) + m_{PDG}(h^0)$



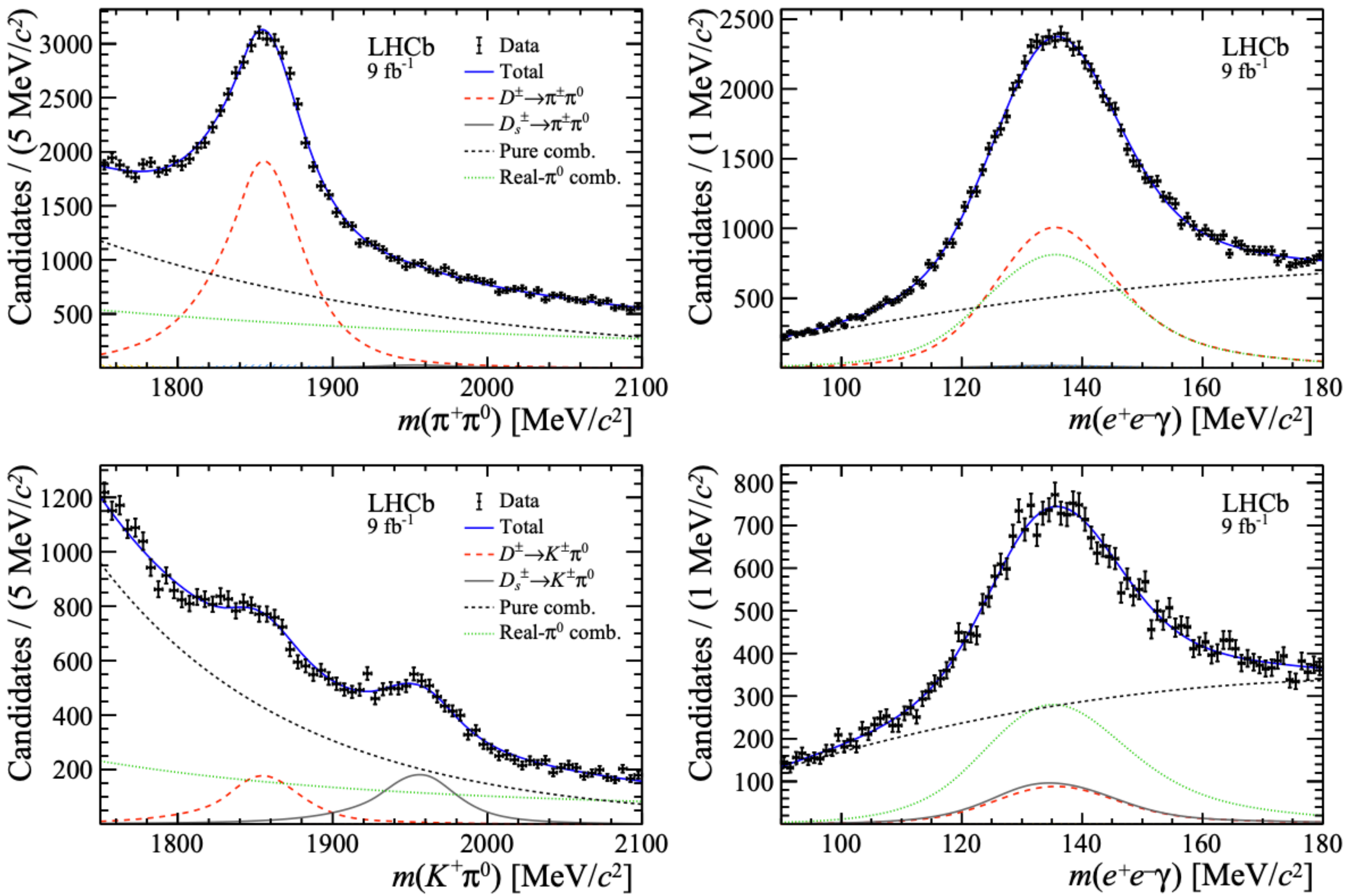
Use $D_{(s)}^+ \to K_S^0 h^+$ as control mode to correct nuisance asymmetries

Main systematic uncertainties from fit model (primary), control mode (secondary)

$A_{CP}(D_{(s)}^+ \rightarrow h^+h^0)$

arXiv:2103.11058
Accepted by JHEP

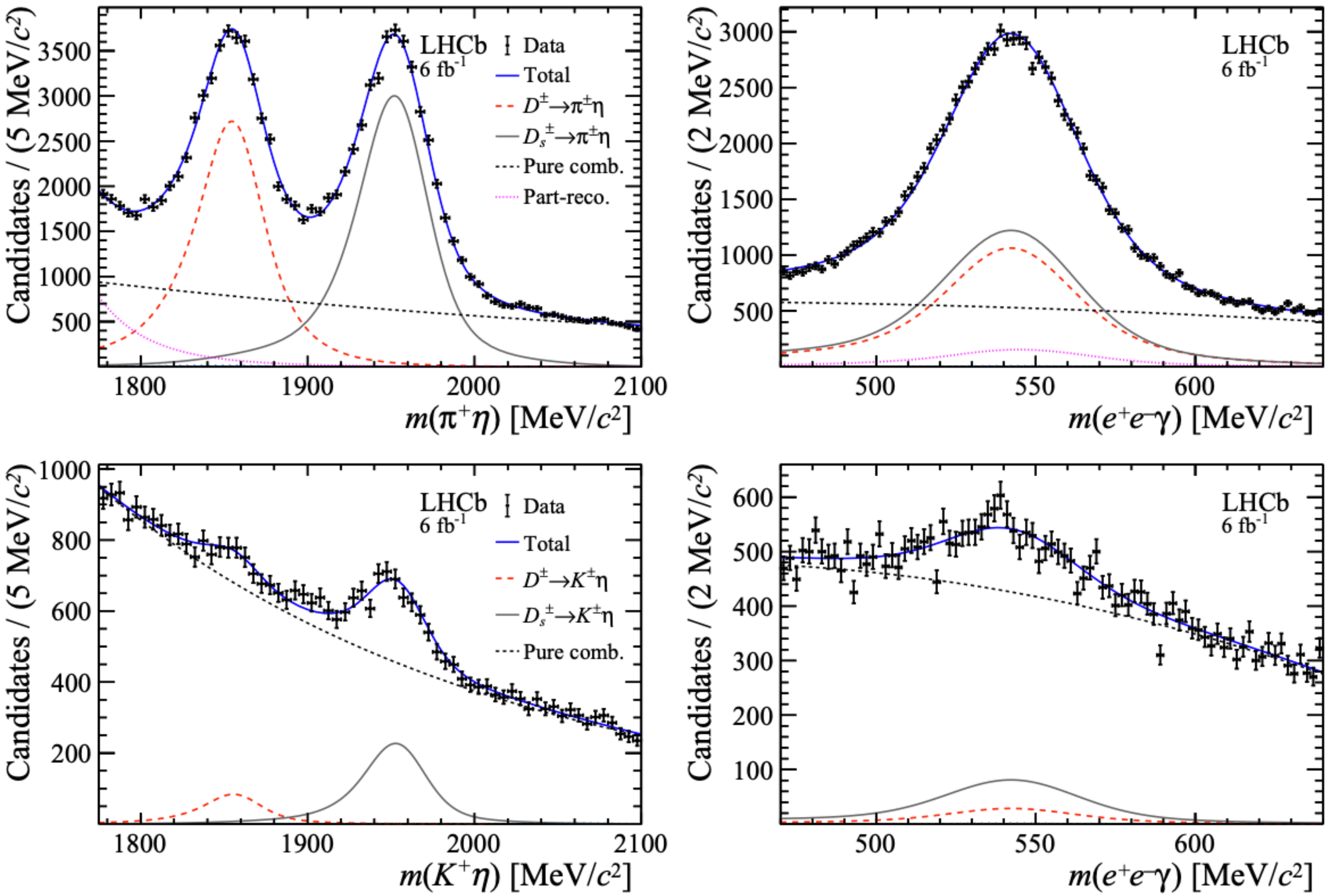
Fit projections (π^0 modes)



$A_{CP}(D_{(s)}^+ \to h^+h^0)$

arXiv:2103.11058
Accepted by JHEP

Fit projections (η modes)



$A_{CP}(D_{(s)}^{+} \rightarrow h^{+}h^{0})$

arXiv:2103.11058
Accepted by JHEP

Yields & raw asymmetries:

Mode	Yield 2011	Yield 2012	Yield Run 2	A_{Raw} (%)
$D^{+} \rightarrow \pi^{+}\pi^{0}$	740 ± 60	$2\,240 \pm 120$	$25\,750 \pm 430$	-1.64 ± 0.93
$D_s^{+} \rightarrow \pi^{+}\pi^{0}$	20 ± 30	-50 ± 50	450 ± 120	-
$D^{+} \rightarrow K^{+}\pi^{0}$	10 ± 13	90 ± 30	$2\,440 \pm 110$	-2.53 ± 4.75
$D_s^{+} \rightarrow K^{+}\pi^{0}$	54 ± 13	150 ± 30	$2\,580 \pm 90$	-0.25 ± 3.87
$D^{+} \rightarrow \pi^{+}\eta$	-	-	$32\,760 \pm 380$	-0.55 ± 0.76
$D_s^{+} \rightarrow \pi^{+}\eta$	-	-	$37\,950 \pm 340$	0.75 ± 0.65
$D^{+} \rightarrow K^{+}\eta$	-	-	880 ± 70	-5.39 ± 10.40
$D_s^{+} \rightarrow K^{+}\eta$	-	-	$2\,520 \pm 70$	1.28 ± 3.67

$A_{CP}(D_{(s)}^+ \to h^+h^0)$

arXiv:2103.11058
Accepted by JHEP

Signal asymmetry:

$$A_{\mathrm{Raw}}(D_{(s)}^+ \to h^+h^0) \approx \mathcal{A}_{CP}(D_{(s)}^+ \to h^+h^0) + A_{\mathrm{Prod}}(D_{(s)}^+) + A_{\mathrm{Det}}(h^+),$$

Control mode asymmetry:

$$A_{\mathrm{Raw}}(D_{(s)}^+ \to K_{\mathrm{S}}^0h^+) \approx \mathcal{A}_{CP}(D_{(s)}^+ \to K_{\mathrm{S}}^0h^+) + A_{\mathrm{Prod}}(D_{(s)}^+) + A_{\mathrm{Det}}(h^+) + A_{\mathrm{Mix}}(K^0),$$

Correction procedure:

$$\begin{aligned}\mathcal{A}_{CP}(D_{(s)}^+ \to h^+h^0) = A_{\mathrm{Raw}}(D_{(s)}^+ \to h^+h^0) - A_{\mathrm{Raw}}^{\mathrm{w}}(D_{(s)}^+ \to K_{\mathrm{S}}^0h^+) \\ + \mathcal{A}_{CP}(D_{(s)}^+ \to K_{\mathrm{S}}^0h^+) + A_{\mathrm{Mix}}(K^0),\end{aligned}$$

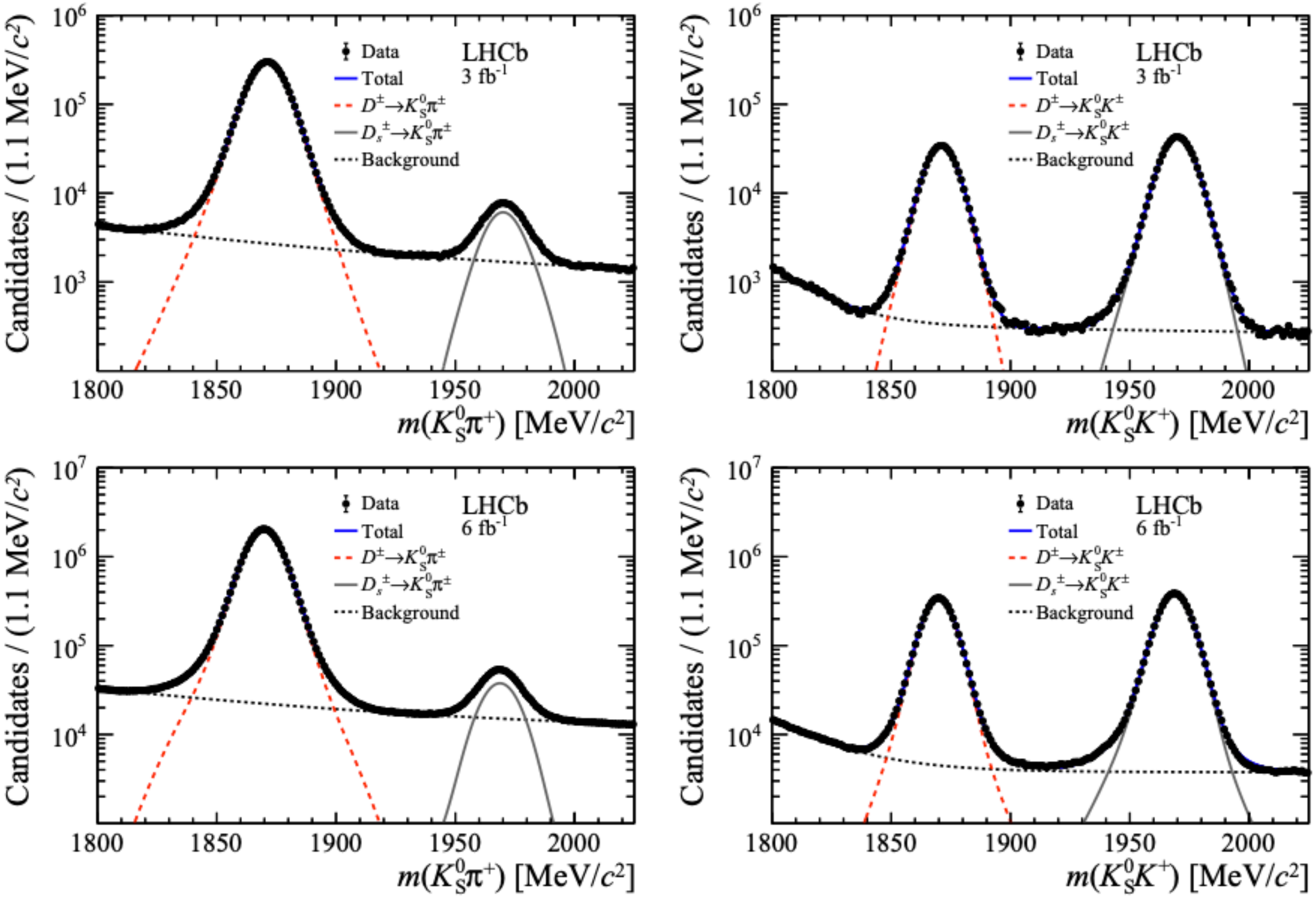
$A_{CP}(D_{(s)}^+ \to h^+h^0)$

arXiv:2103.11058
Accepted by JHEP

Control mode

Run 1

Run 2



$A_{CP}(D_{(s)}^{+} \rightarrow h^{+}h^{0})$

arXiv:2103.11058
Accepted by JHEP

Systematic uncertainties:

π^0 modes

Source	$D^+ \to \pi^+\pi^0$	$D^+ \to K^+\pi^0$	$D_s^+ \to K^+\pi^0$
Fit model	0.59	1.55	1.01
PID asymmetry	0.06	0.27	0.15
Secondary decays	< 0.01	0.01	0.02
Combined A_{Raw} Run 1 and Run 2	0.23	0.65	0.30
Control modes	0.03	1.18	0.59
$A_{\text{Mix}}(K^0)$	< 0.01	< 0.01	< 0.01
$\mathcal{A}_{CP}(D_{(s)}^+ \to K_S^0 h^+)$	0.12	0.08	0.26
Total	0.65	2.07	1.24

η modes

Source	$D^+ \to \pi^+\eta$	$D_s^+ \to \pi^+\eta$	$D^+ \to K^+\eta$	$D_s^+ \to K^+\eta$
Fit model	0.35	0.15	4.04	1.08
PID asymmetry	0.06	0.01	0.87	0.16
Secondary decays	< 0.01	0.02	0.01	0.04
Control modes	0.05	0.39	0.14	0.12
$A_{\text{Mix}}(K^0)$	< 0.01	< 0.01	< 0.01	< 0.01
$\mathcal{A}_{CP}(D_{(s)}^+ \to K_S^0 h^+)$	0.12	0.20	0.08	0.26
Total	0.38	0.46	4.13	1.13

$A_{CP}(D_{(s)}^+ \to h^+h^0)$

arXiv:2103.11058
Accepted by JHEP

Input asymmetries:

	$D^+ \to \pi^+\pi^0$	$D^+ \to K^+\pi^0$	$D_s^+ \to K^+\pi^0$
$A_{\mathrm{Raw}}(D_{(s)}^+ \to h^+\pi^0)$	-1.64 ± 0.93	-2.53 ± 4.75	-0.25 ± 3.87
$A_{\mathrm{Raw}}^{\mathrm{w}}(D_{(s)}^+ \to K_S^0 h^+)$	-0.45 ± 0.02	0.58 ± 0.08	0.60 ± 0.07
$\mathcal{A}_{CP}(D_{(s)}^+ \to K_S^0 h^+)$	-0.02 ± 0.12	-0.01 ± 0.08	0.09 ± 0.26
$A_{\mathrm{Mix}}(K^0)$	-0.070 ± 0.004	-0.072 ± 0.004	-0.072 ± 0.004
$\mathcal{A}_{CP}(D_{(s)}^+ \to h^+\pi^0)$	$-1.3 \pm 0.9 \pm 0.6$	$-3.2 \pm 4.7 \pm 2.1$	$-0.8 \pm 3.9 \pm 1.2$

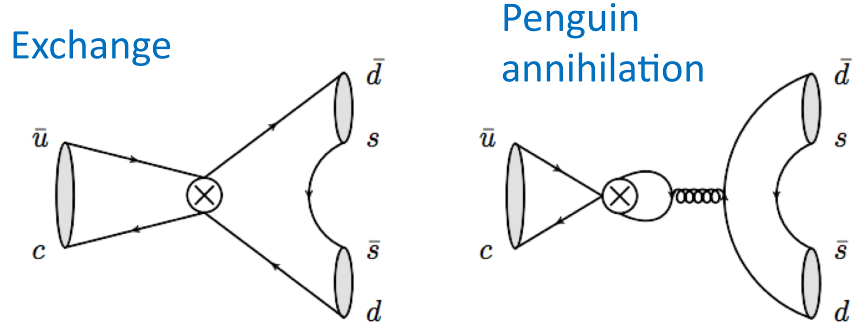
	$D^+ \to \pi^+\eta$	$D_s^+ \to \pi^+\eta$
$A_{\mathrm{Raw}}(D_{(s)}^+ \to h^+\eta)$	-0.55 ± 0.76	0.75 ± 0.65
$A_{\mathrm{Raw}}^{\mathrm{w}}(D_{(s)}^+ \to K_S^0 h^+)$	-0.46 ± 0.04	-0.02 ± 0.37
$\mathcal{A}_{CP}(D_{(s)}^+ \to K_S^0 h^+)$	-0.02 ± 0.12	0.13 ± 0.20
$A_{\mathrm{Mix}}(K^0)$	-0.070 ± 0.004	-0.070 ± 0.004
$\mathcal{A}_{CP}(D_{(s)}^+ \to h^+\eta)$	$-0.2 \pm 0.8 \pm 0.4$	$0.8 \pm 0.7 \pm 0.5$

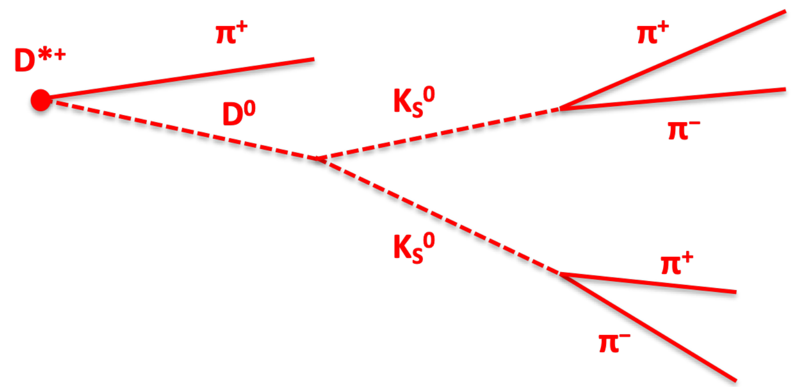
	$D^+ \to K^+\eta$	$D_s^+ \to K^+\eta$
$A_{\mathrm{Raw}}(D_{(s)}^+ \to h^+\eta)$	-5.39 ± 10.40	1.28 ± 3.67
$A_{\mathrm{Raw}}^{\mathrm{w}}(D_{(s)}^+ \to K_S^0 h^+)$	0.33 ± 0.10	0.36 ± 0.10
$\mathcal{A}_{CP}(D_{(s)}^+ \to K_S^0 h^+)$	-0.01 ± 0.08	0.09 ± 0.26
$A_{\mathrm{Mix}}(K^0)$	-0.073 ± 0.004	-0.073 ± 0.004
$\mathcal{A}_{CP}(D_{(s)}^+ \to h^+\eta)$	$-6 \pm 10 \pm 4$	$0.9 \pm 3.7 \pm 1.1$

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

arXiv:2105.01565

Full Run 2 analysis of "Discovery mode" (D*-tagged)





CP-conserving component suppressed by SU(3) symmetry
⇒ CPV can be large even if solely due to CKM phase

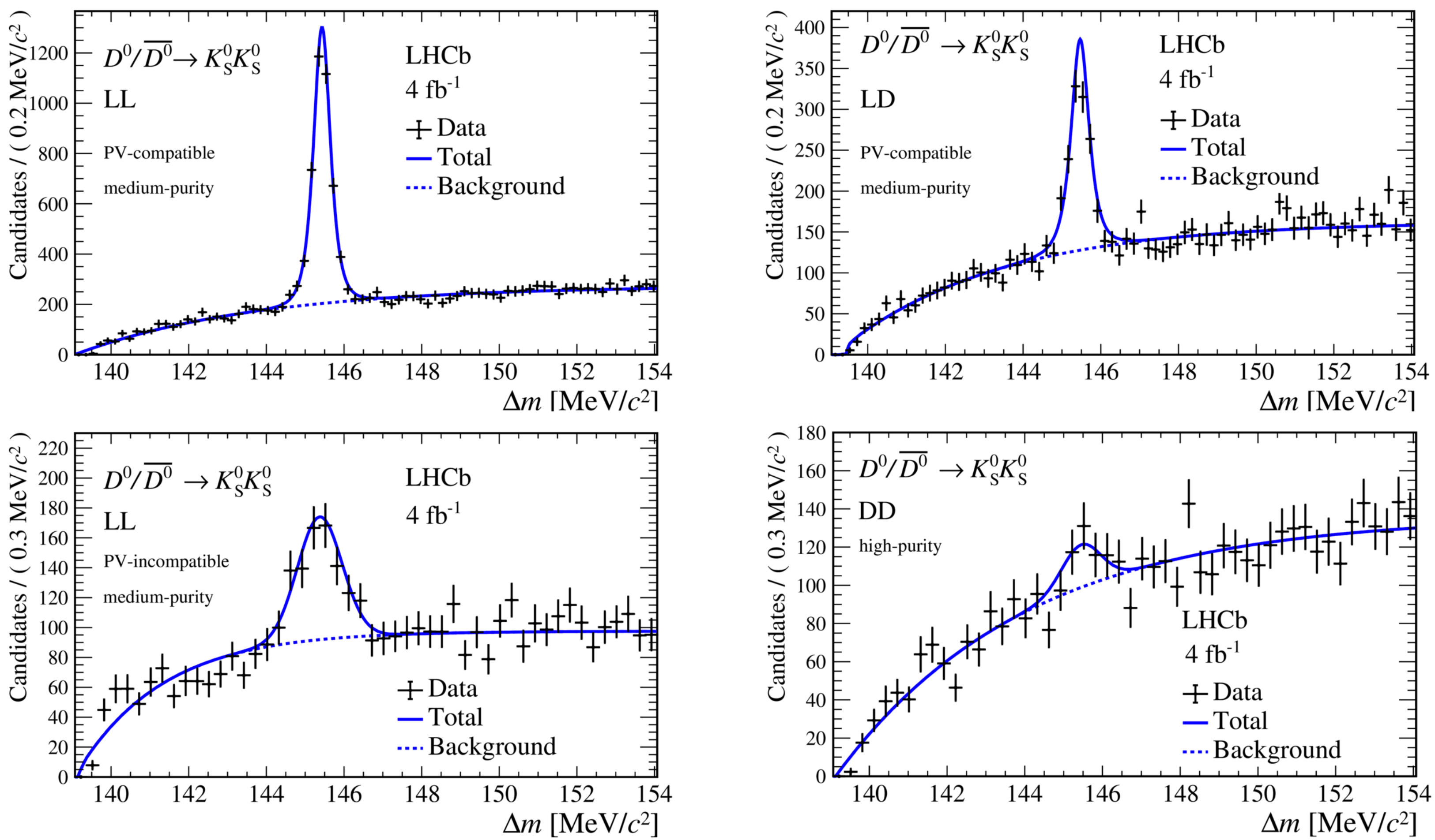
Sophisticated analysis – the power of marginal gains

- Cuts → categories (split by K_S^0 signature, run period, purity, PV consistency)
- Nuisance asymmetries corrected through MVA classifier and $D^0 \to K^+K^-$ control mode
- 3D fit to $\Delta M \equiv [M(D^{*+}) - M(D^0)]$, $M_1(K_S^0)$, $M_2(K_S^0)$ to separate signal & backgrounds

$A_{CP}(D^0 \rightarrow K_S^0 K_S^0)$

arXiv:2105.01565

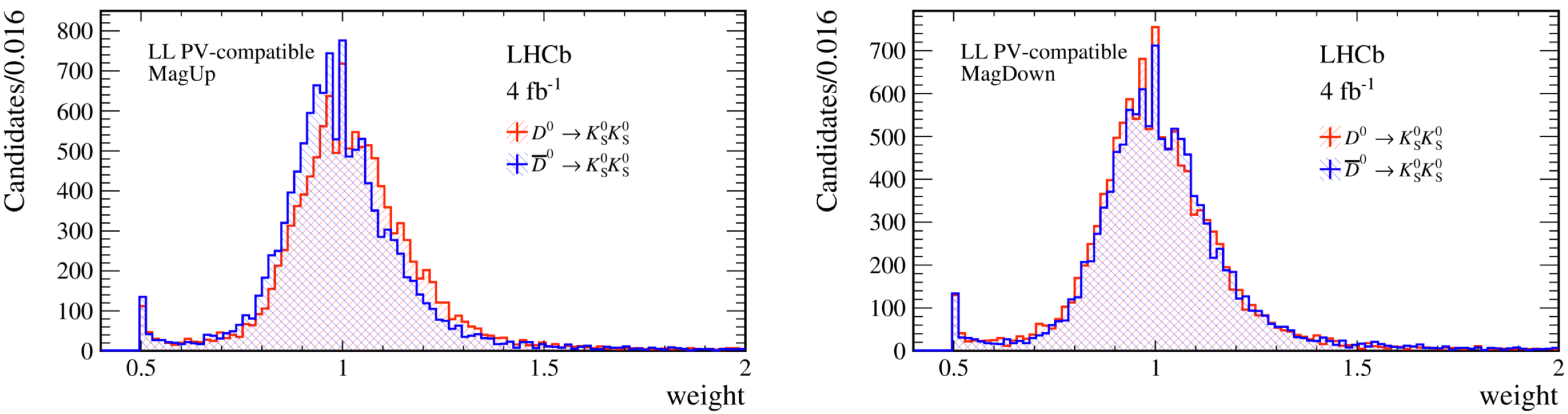
ΔM fit projections for different categories:



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

arXiv:2105.01565

Reweighting procedure to equalize nuisance asymmetries between signal and control mode ($D^0 \to K^+K^-$)



Weight applied to signal →

$$w^{\pm}(\vec{p}_0) = \frac{n_C^+(\vec{p}_0) + n_C^-(\vec{p}_0)}{2n_C^{\pm}(\vec{p}_0)} \left[1 \pm \mathcal{A}^{CP}(K^+K^-)\right]$$

kinematic parameters

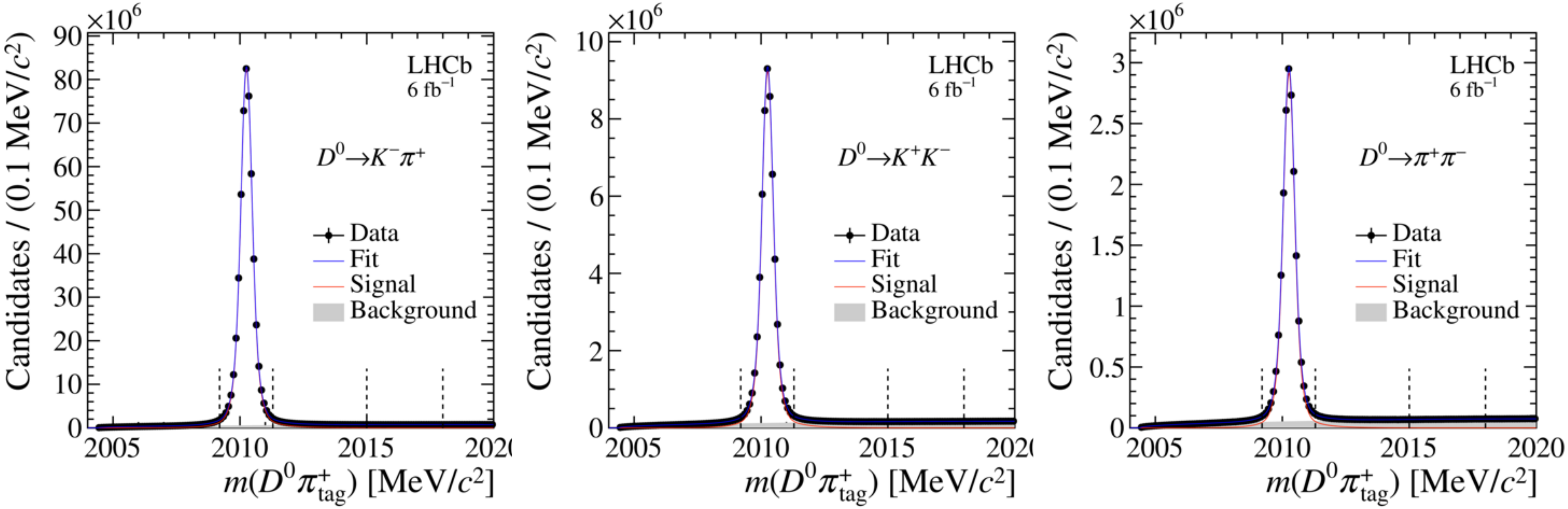
Density of calibration sample for $D^{*\pm}$

Control mode asymmetry

Time-dep. CPV: Δy (≈A_Γ)

arXiv:2105.09889

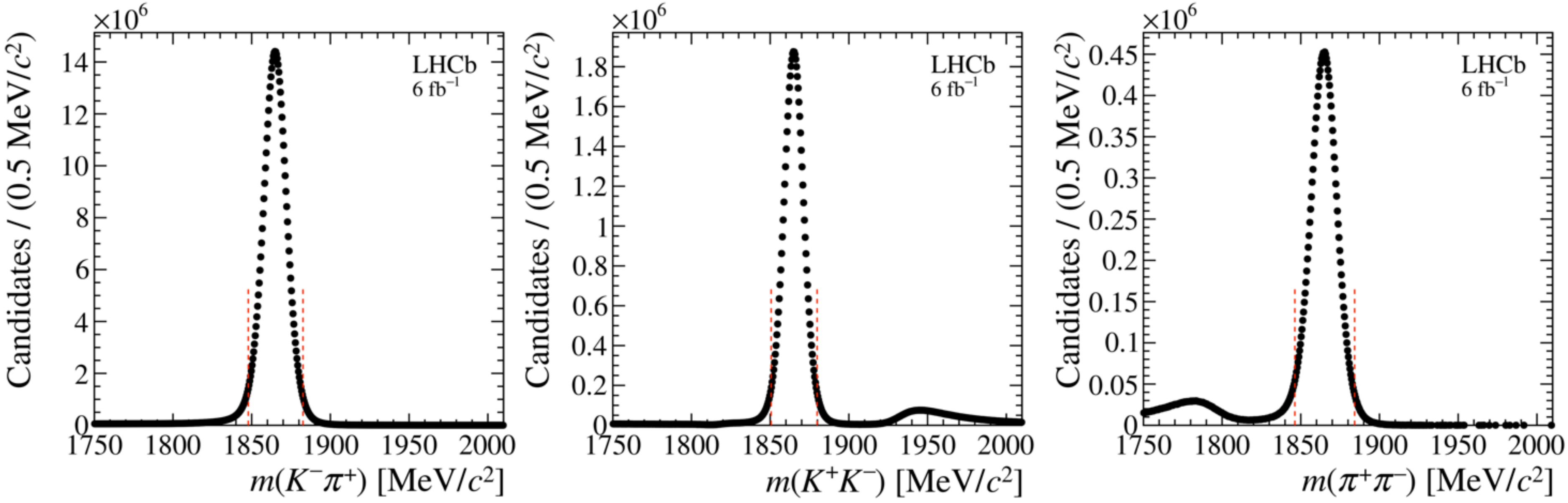
Time-integrated mass fits (D^{*+})



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

arXiv:2105.09889

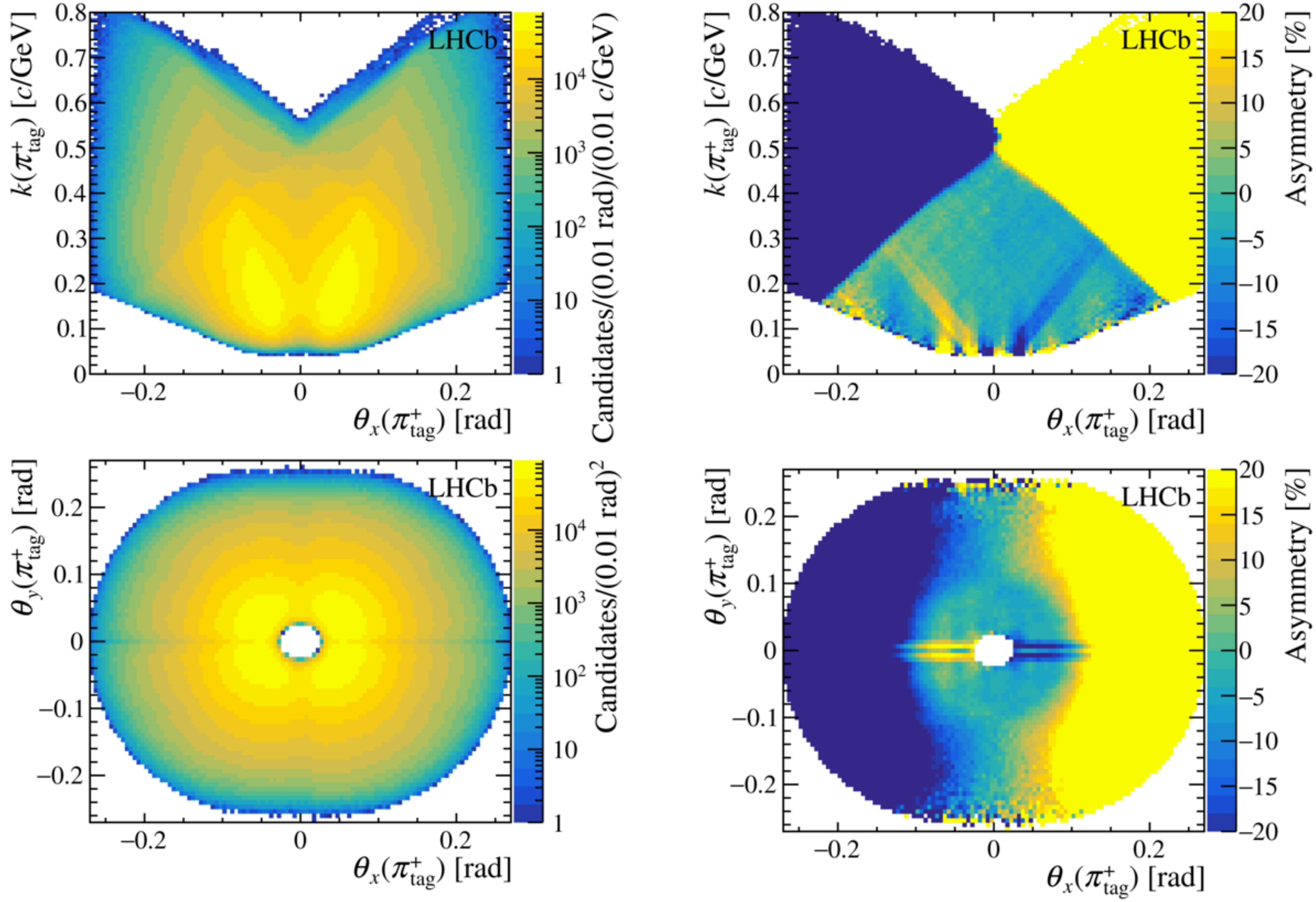
Time-integrated mass distributions (D^0)



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

arXiv:2105.09889

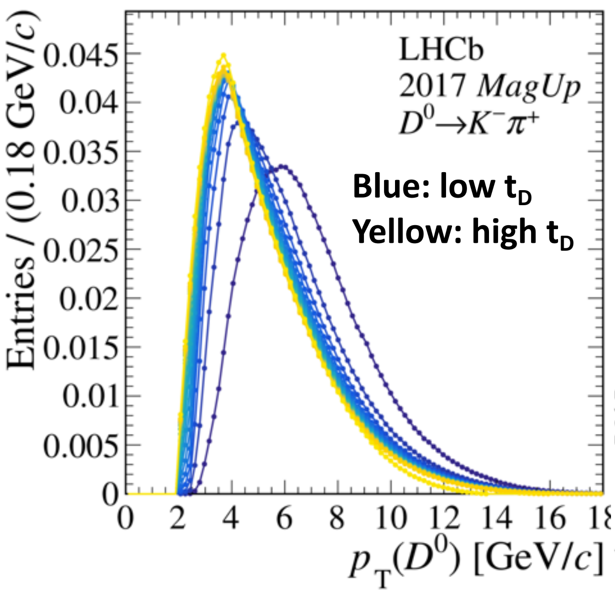
Nuisance asymmetries (tagging pion)



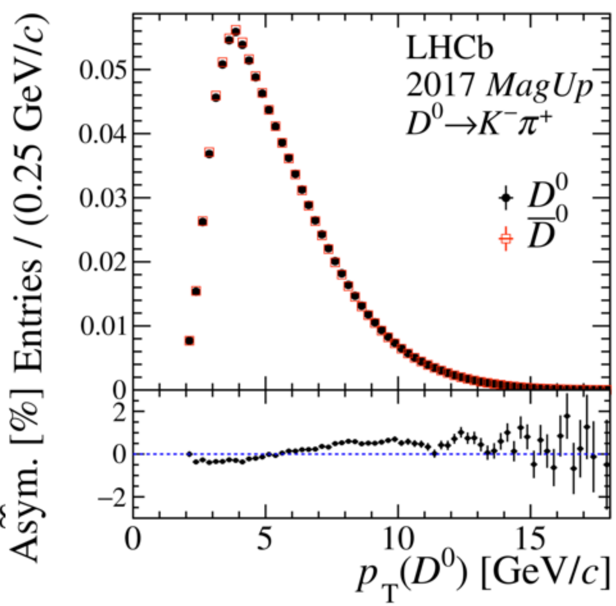
Time-dep. CPV: Δy ($\approx A_{\Gamma}$)

arXiv:2105.09889

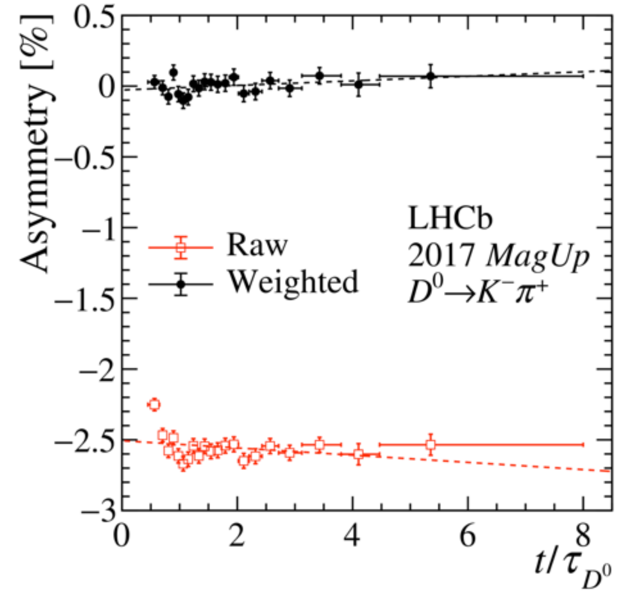
Correlation between kinematics & decay time



+ kinematically-dependent asymmetry



= time-dependent asymmetry (red)



⇒ **Removed with correction (black)**

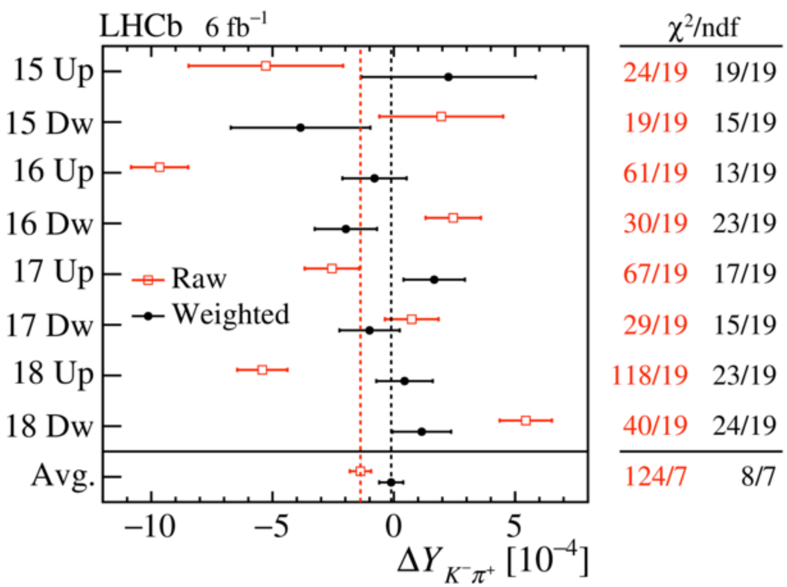
Time-dep. CPV: Δy (≈A_Γ)

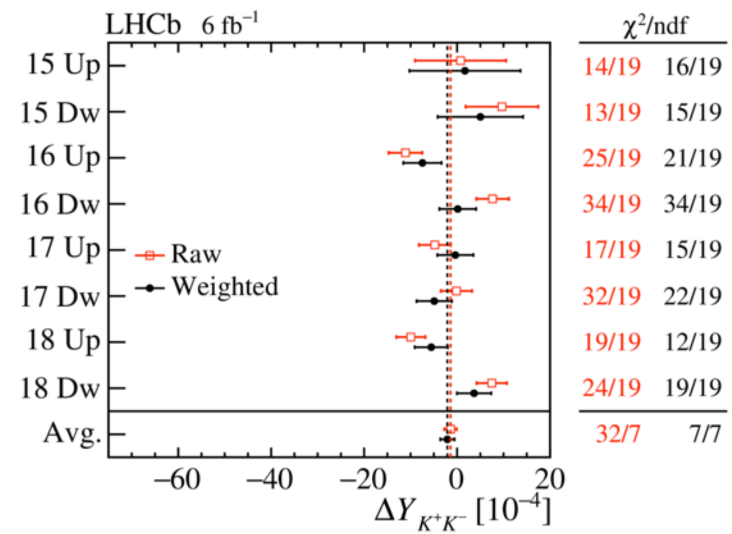
arXiv:2105.09889

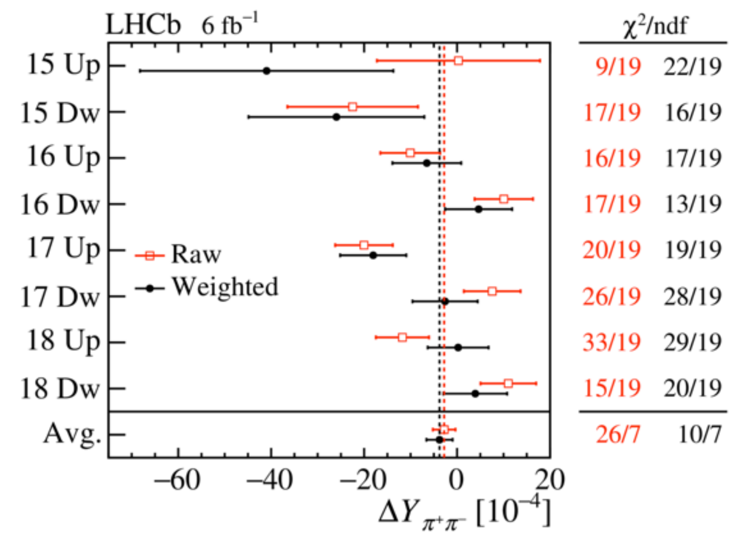
Results per subsample

Red: before weighting

Black: after weighting



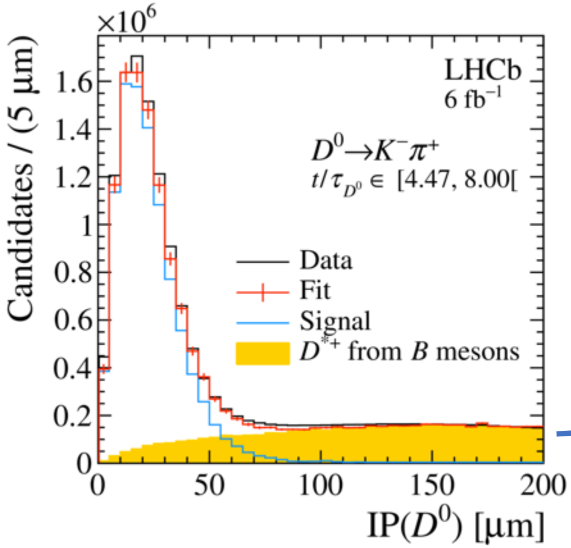


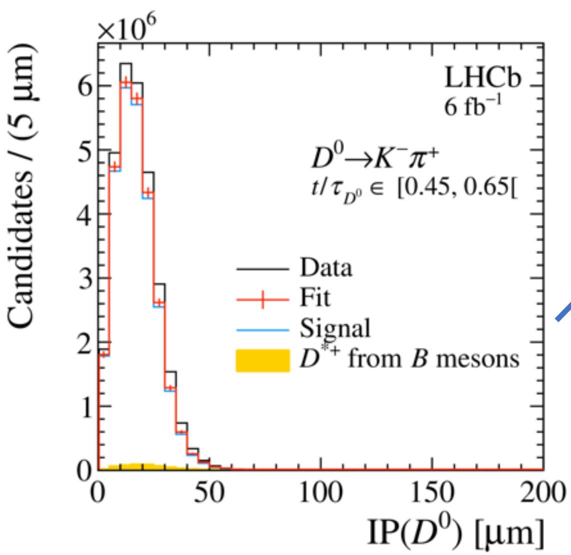


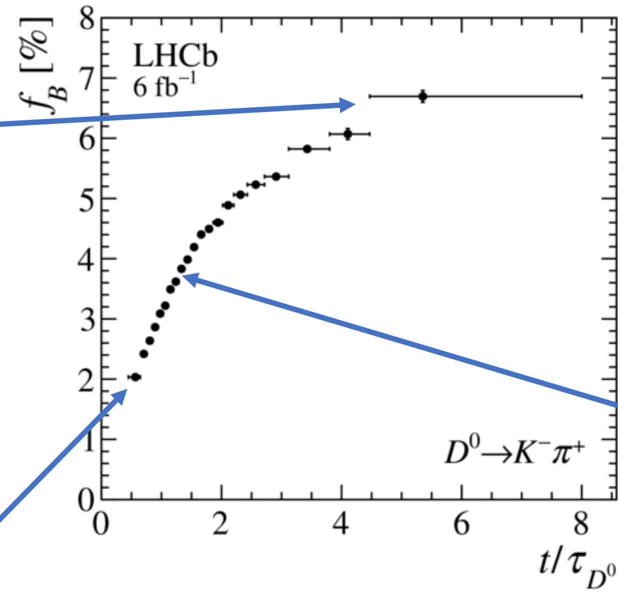
Time-dep. CPV: Δy (≈A_Γ)

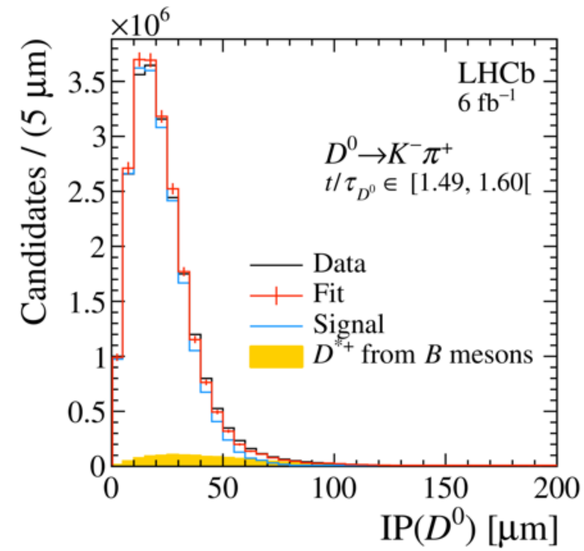
arXiv:2105.09889

Secondary charm contamination









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

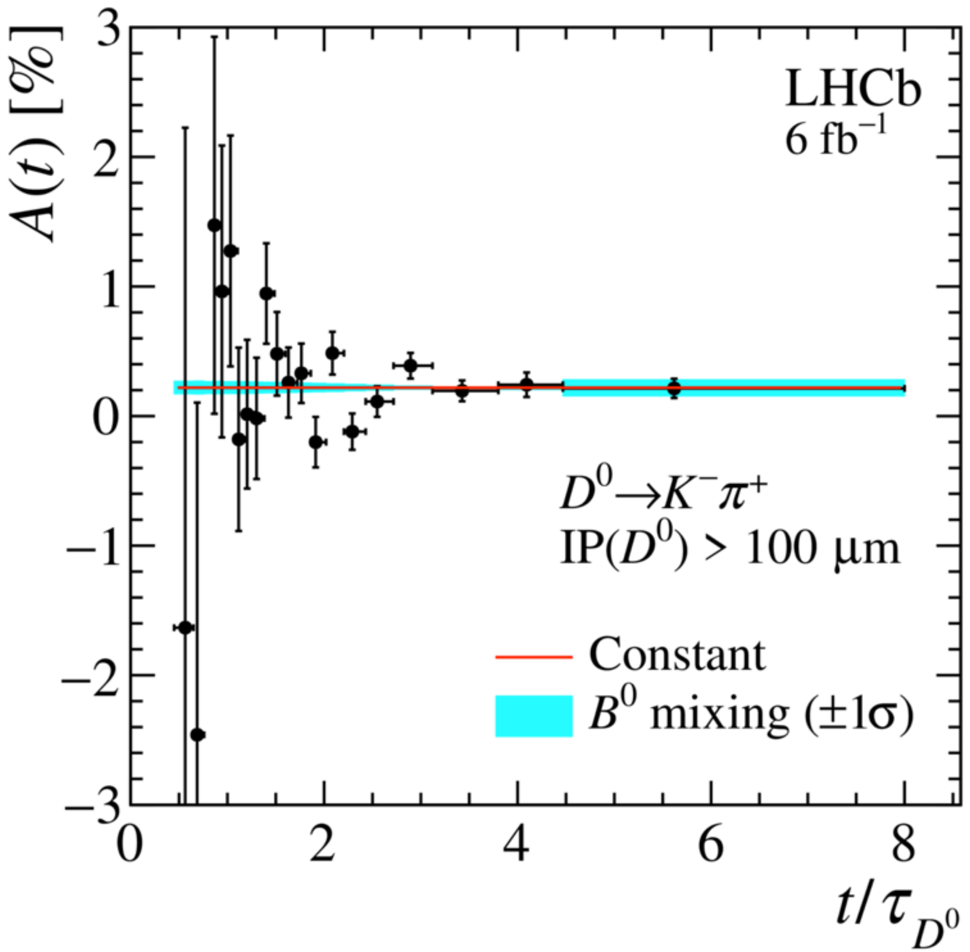
arXiv:2105.09889

Asymmetry from secondaries

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

Measured in pure secondary sample:

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



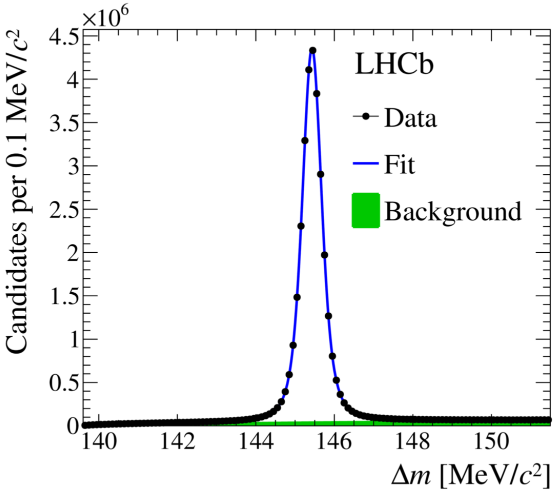
Time-dep. CPV: Δy (≈A_Γ)

arXiv:2105.09889

Systematic uncertainties

Source	$\Delta Y_{K^+K^-}$ $[10^{-4}]$	$\Delta Y_{\pi^+\pi^-}$ $[10^{-4}]$
Subtraction of the $m(D^0\pi^+_{\rm tag})$ 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

‘Bin-flip’ analysis: details

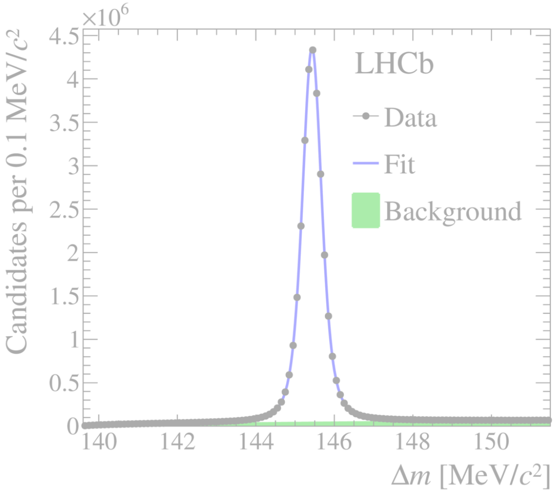


~31M signal candidates (>10x larger than LHCb Run 1 sample)

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

Main systematics from:

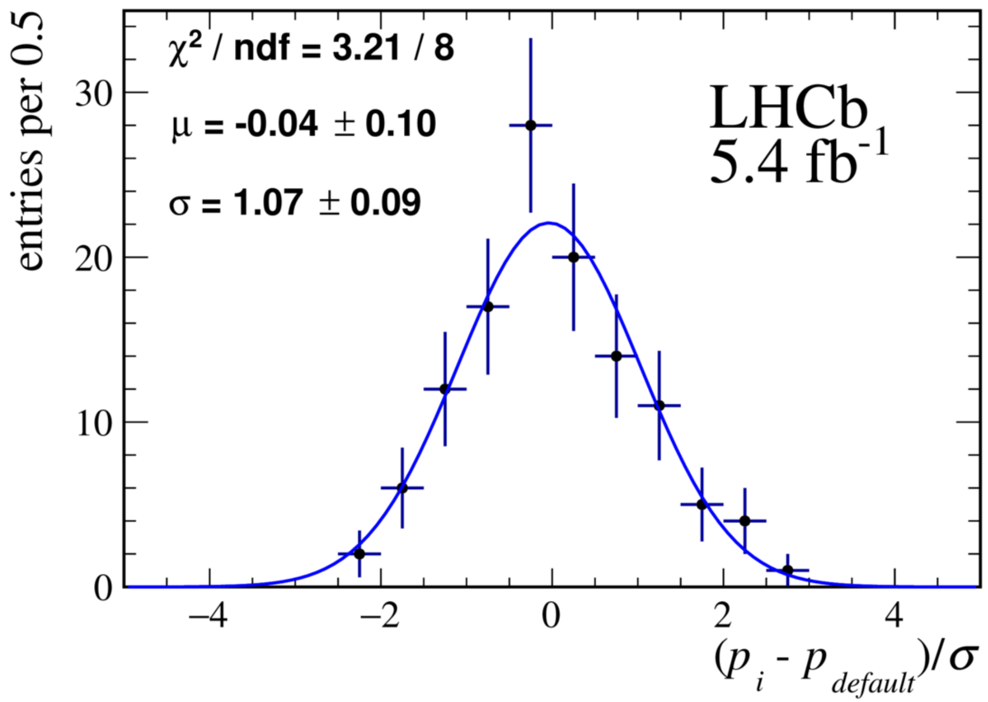
- Treatment of experimental effects
- 'Secondary' charm background
- Mass fit procedure, …

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

‘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:

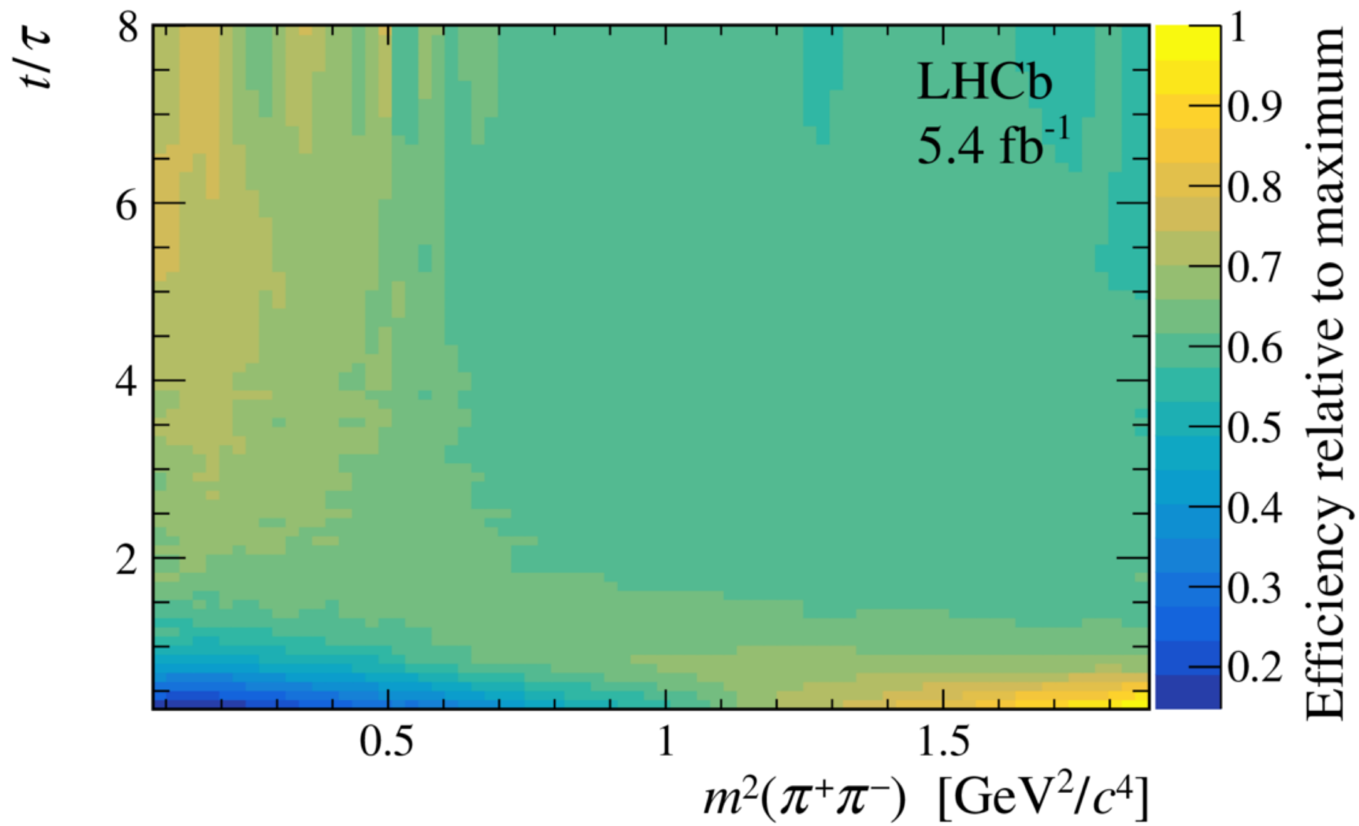
$$R_{bj}^{\pm} \approx \frac{r_b + \frac{1}{4} r_b \langle t^2 \rangle_j \mathrm{Re}(z_{CP}^2 - \Delta z^2) + \frac{1}{4} \langle t^2 \rangle_j \left| z_{CP} \pm \Delta z \right|^2 + \sqrt{r_b} \langle t \rangle_j \mathrm{Re}[X_b^* (z_{CP} \pm \Delta z)]}{1 + \frac{1}{4} \langle t^2 \rangle_j \mathrm{Re}(z_{CP}^2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

Where:

- $\pm$ denotes the case for D^0 (+) and $\bar{D}^0$ (−)
- 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: Correlations

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



‘Bin-flip’ analysis: Corrections

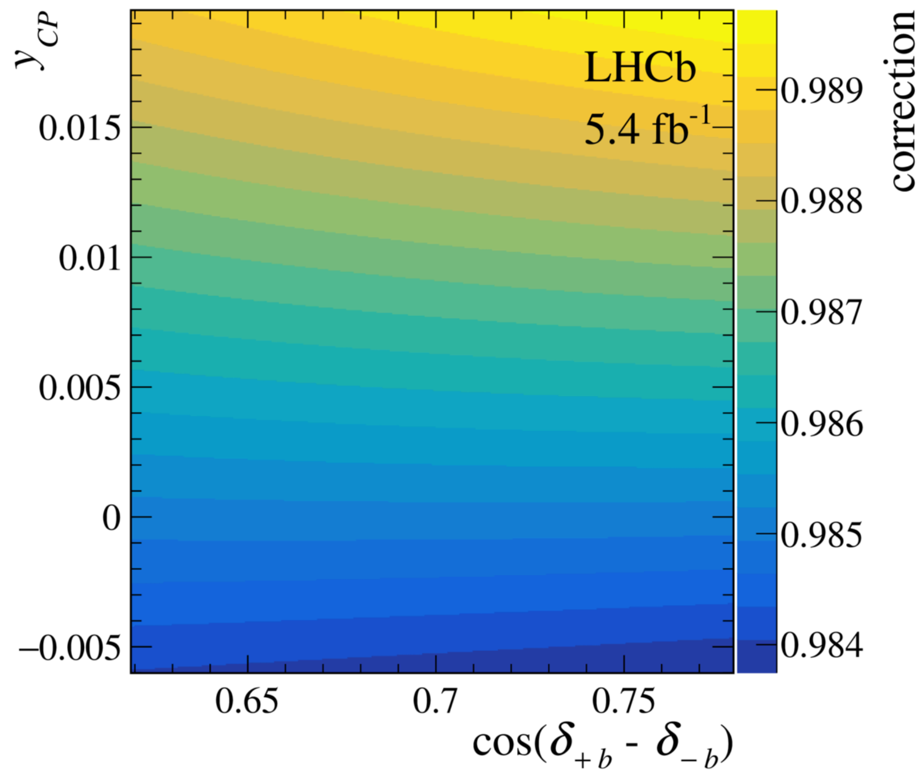
Example of correction map (for Dalitz bin b=1, decay time bin j=1)

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)

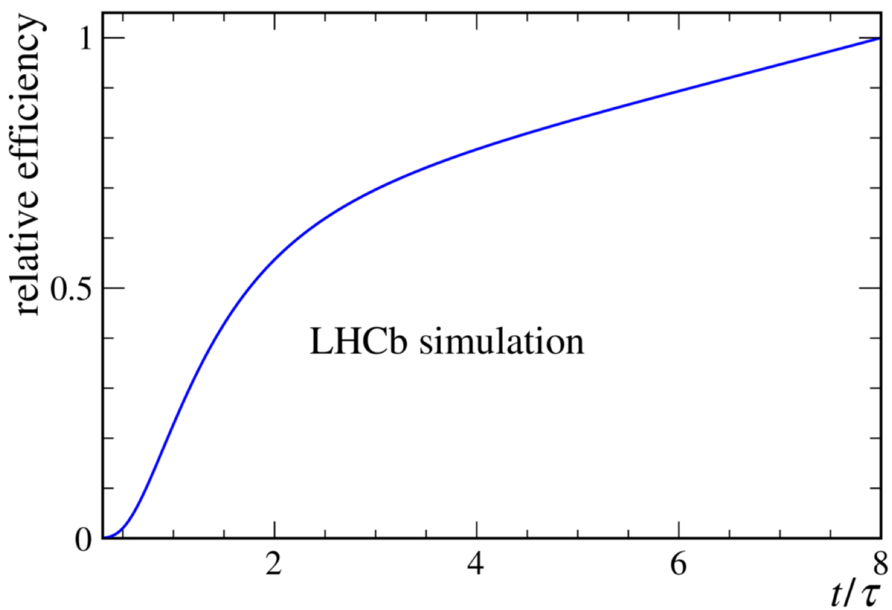
⇒ Small impact on y and strong phases, so correction depends on these values

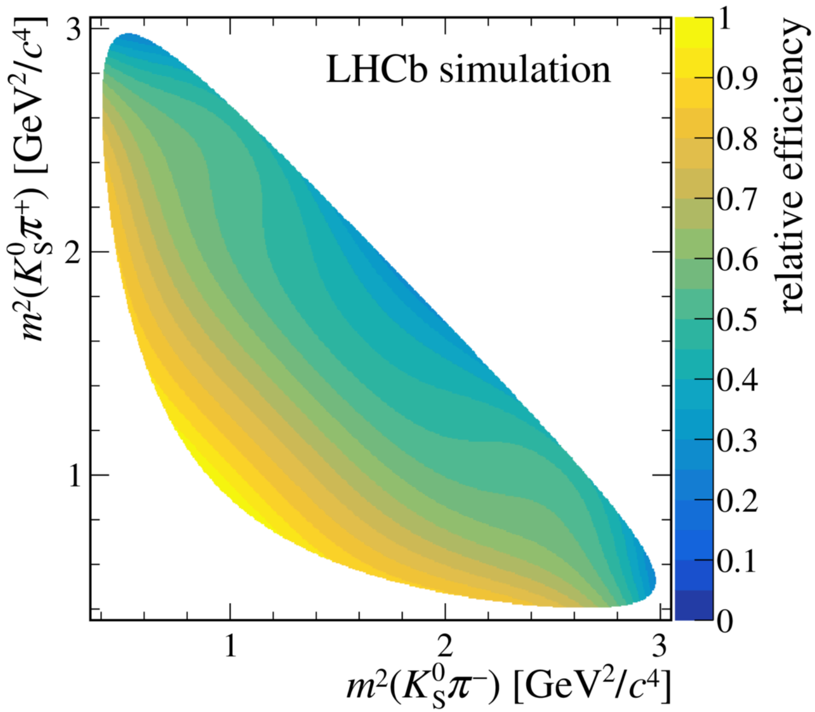
⇒ So, correction depends on values of y and c_b in fit



‘Bin-flip’ analysis: Efficiencies

Efficiency vs decay time and Dalitz plane





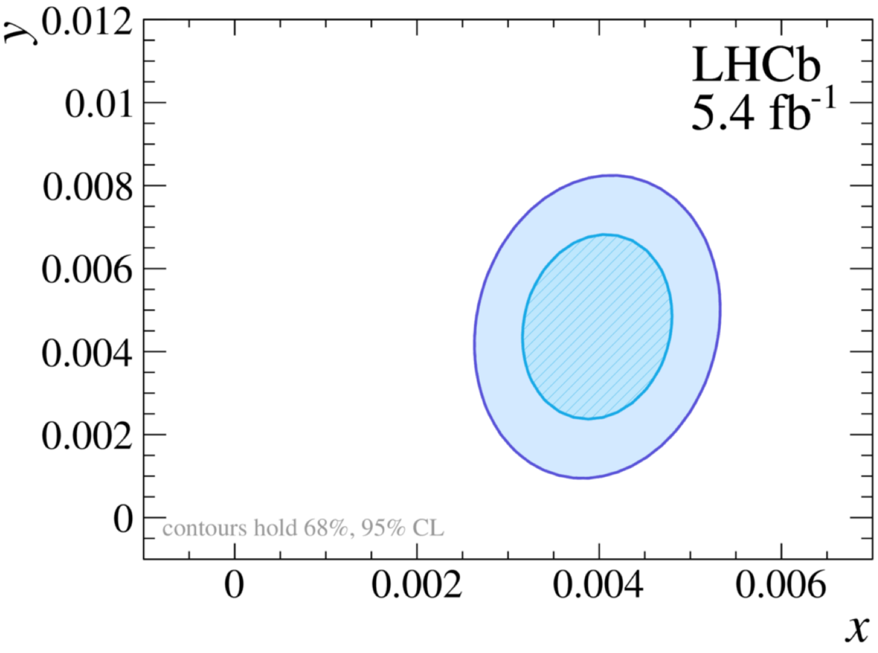
'Bin-flip' analysis: Strong phases

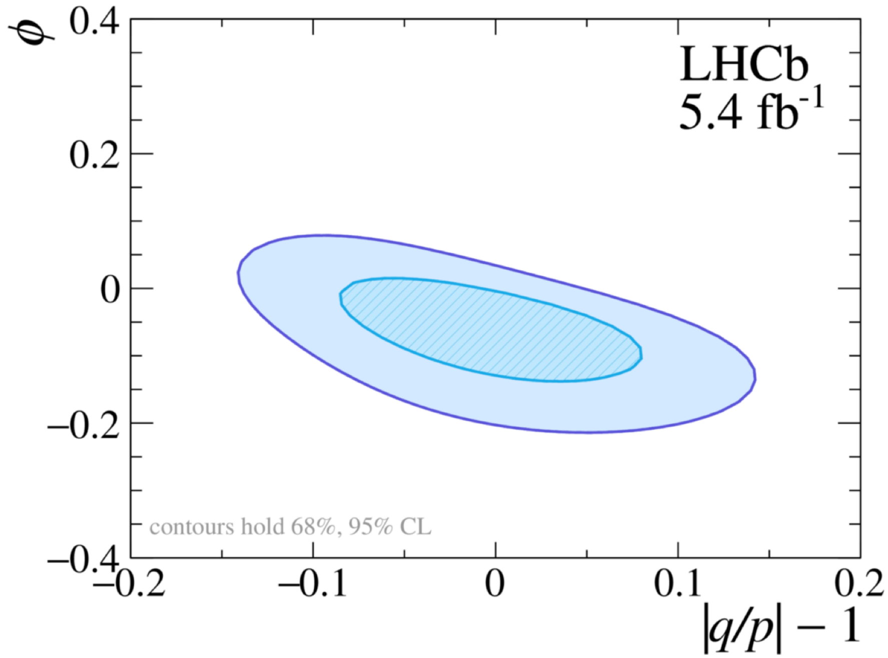
Initial and final values of strong phase inputs (Gaussian constrained in fit)

	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

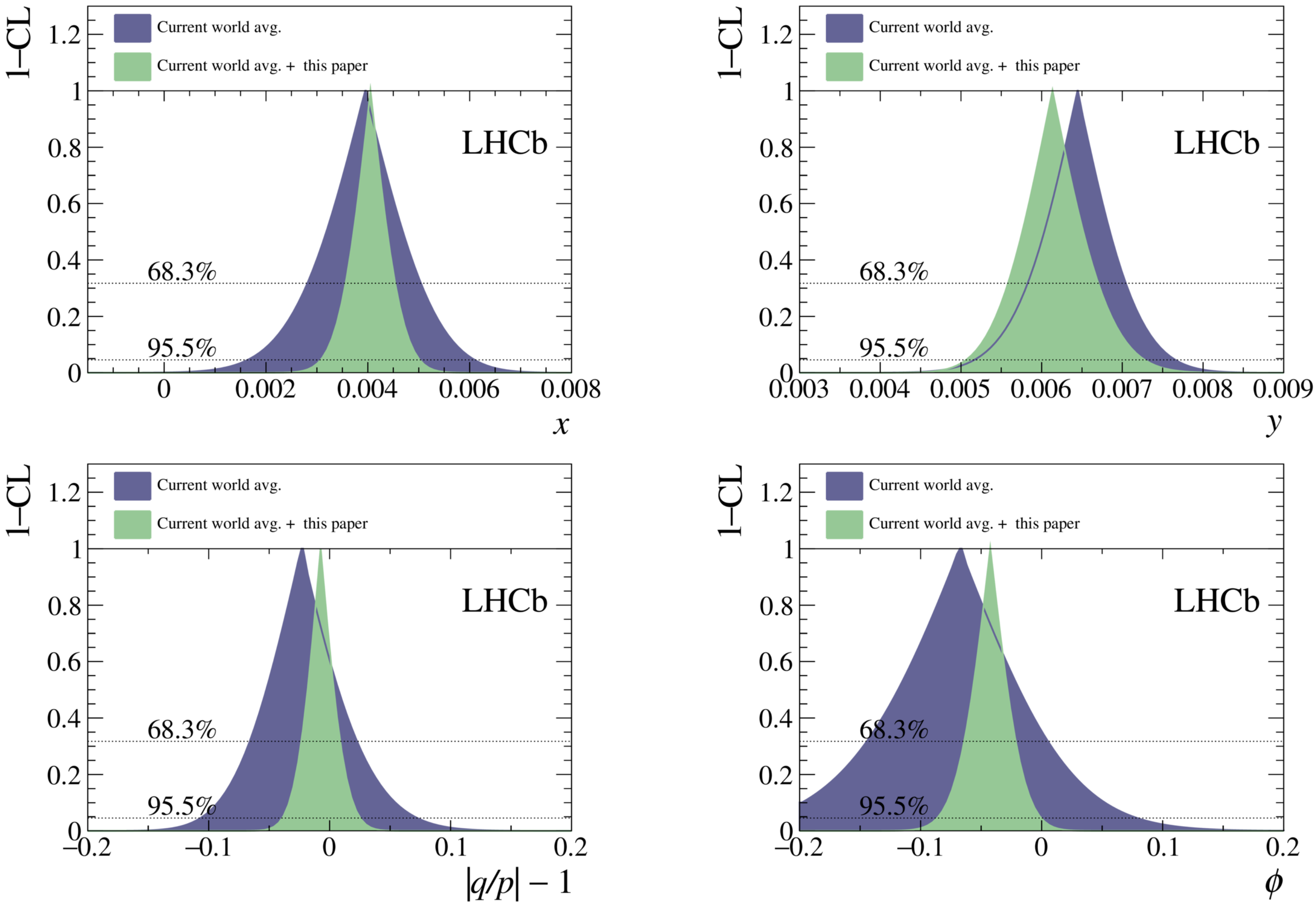
‘Bin-flip’ analysis: Contours

2D contours

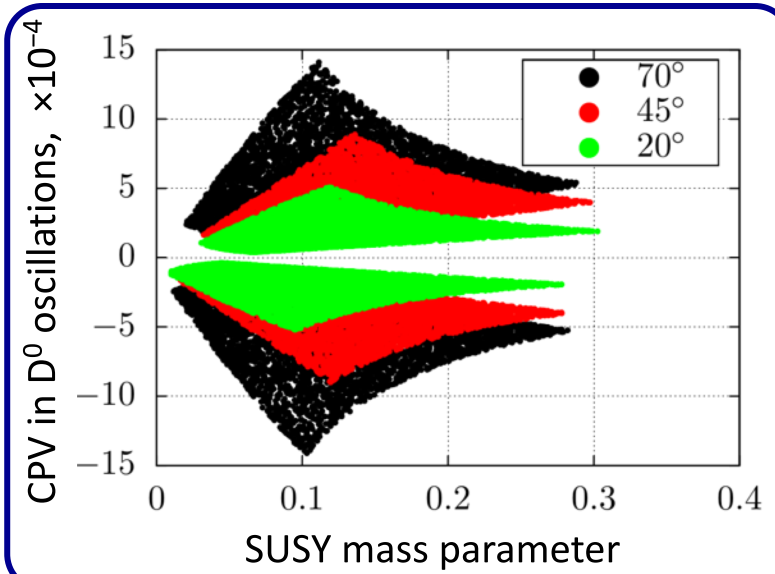




‘Bin-flip’ analysis: New WA Combo



So, why Charm?



Supersymmetry

"…any experimental signal of CP violation in D^0 mixing above the per mill level would probably point towards a NP effect"

"the LHCb experiment … is starting now to probe the natural predictions of alignment models" (Ghosh *et al*, arXiv:1512.03962)

Warped extra dimensions

"the bounds from D^0 mixing play a crucial role"

"The flavor constraints are then stronger than those from the electroweak precision measurements for a large portion of the parameter space." (Gedalia *et al*, arXiv:0906.1879)

Little-Higgs models

"an observation of large mixing induced CP asymmetries in D decays … would be a clear signal of New Physics"

"we have just entered a regime where one can realistically hope for an effect to emerge" (Bigi *et al*, arXiv:0904.1545)

+ Flavoured dark matter, 4^{th} generation, …

ΔA_{CP} interpretation

$\Delta A_{CP} = (-15.4 \pm 2.9)\times10^{-4}$

5.3σ from zero ⇒
Discovery of CPV in charm

Is this asymmetry from the standard model alone?
⇒ no clear consensus!

BSM corner:

JHEP 1907 (2019) 161
Chala, Lenz, Rusov, Scholtz
$|\Delta A_{CP}|_{SM} \leq 3.6\times10^{-4}$
Propose flavour violating Z'

arXiv:1909.11242
Dery, Nir
Need O(10) enhancements to explain result (e.g. 2HDM, MSSM, vector-like quarks)

SM corner:

JHEP 1907 (2019) 020
Grossman, Schacht

PRD 99 (2019) 113001
Buccella, Paul, Santorelli

arXiv:1903.10638
Li, Lu, Yu

arXiv:1905.00907
Soni

arXiv:1909.03063
Cheng, Chiang