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On behalf of the LHCb collaboration

MONASH University

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Melbourne
18th July 2023

Mixing and CPV in charm decays

Introduction

Charge-Parity violation as been well established in the **B** and **K** systems

Much **more elusive** in the charm sector → ***Standard Model:*** *GIM cancellation and CKM suppression* $A_{CP} \sim \mathcal{O}(10^{-3})$

CP violation in charm **observed** for the first time in 2019

$$\Delta A_{CP} \equiv A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-)$$ [PRL 122 08726]

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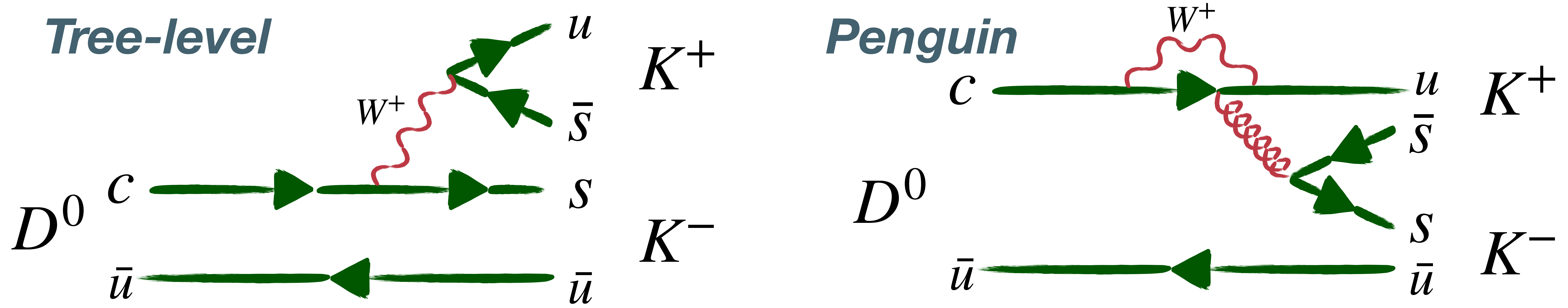
Standard Model predictions are ***hard***; there is still some debate as to whether the measured CPV is consistent with SM or not

More experimental measurements will help add clarity

Singly-Cabbibo suppressed decays offer a good avenue to look for CP violation in charm decays



Types of CP violation

Direct CP violation requires **interference** between **two different** decay processes

*Difference in both **weak phase** and **strong phase***

$$|A|^2 - |\overline{A}|^2 \propto \sin(\delta_1 - \delta_2)\sin(\phi_1 - \phi_2)$$

Neutral D mesons can also **mix** between particle and antiparticle states

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

$\left|\frac{q}{p}\right| \neq 1$ → CPV in mixing

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This results in **more mechanisms** for CP violation:

Charged D mesons		Neutral D mesons
✓	Direct CPV between $D \rightarrow f$ and $\bar{D} \rightarrow \bar{f}$	✓
✕	CPV in mixing between D and $\bar{D}$	✓
✕	Interference between mixing and decay	✓

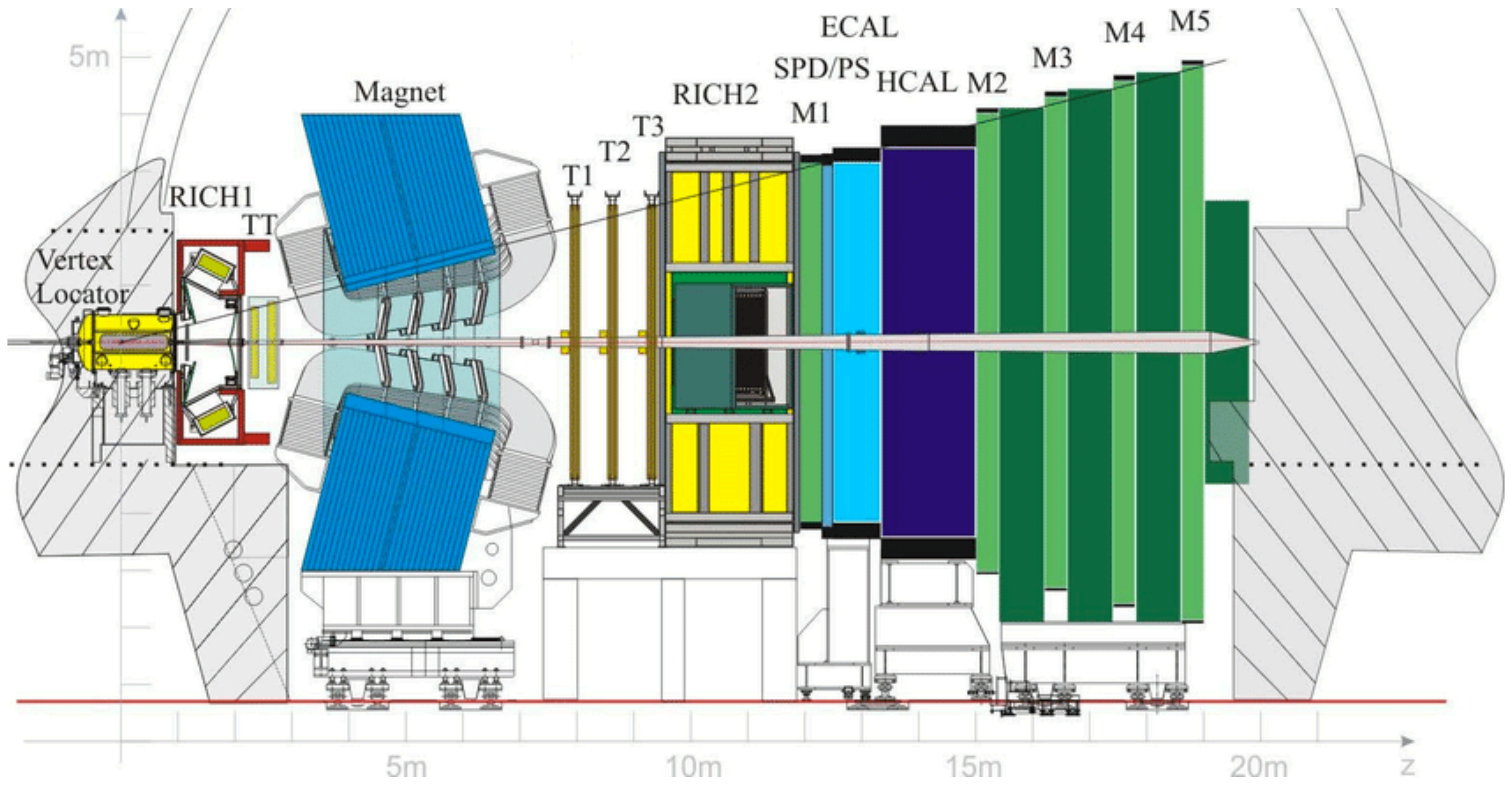
Charm at LHCb

LHCb has collected huge samples of ***charm decays***

- ✓ Displaced vertex resolution *Crucial for mixing*
- ✓ Efficient hadron PID

Turbo trigger configuration allows exclusive reconstruction of many final states in real-time

Run 2: 1MHz $c\bar{c}$



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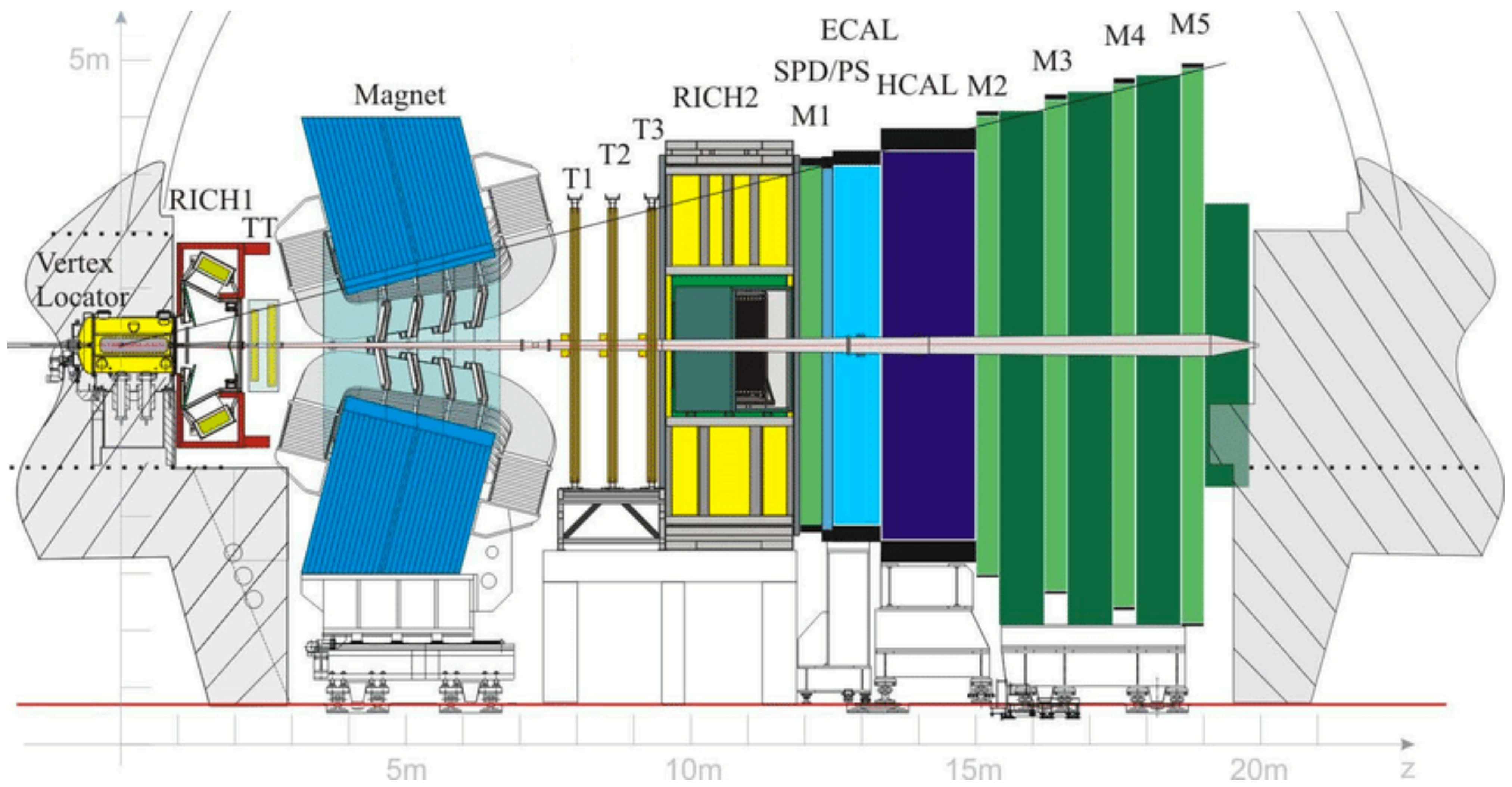
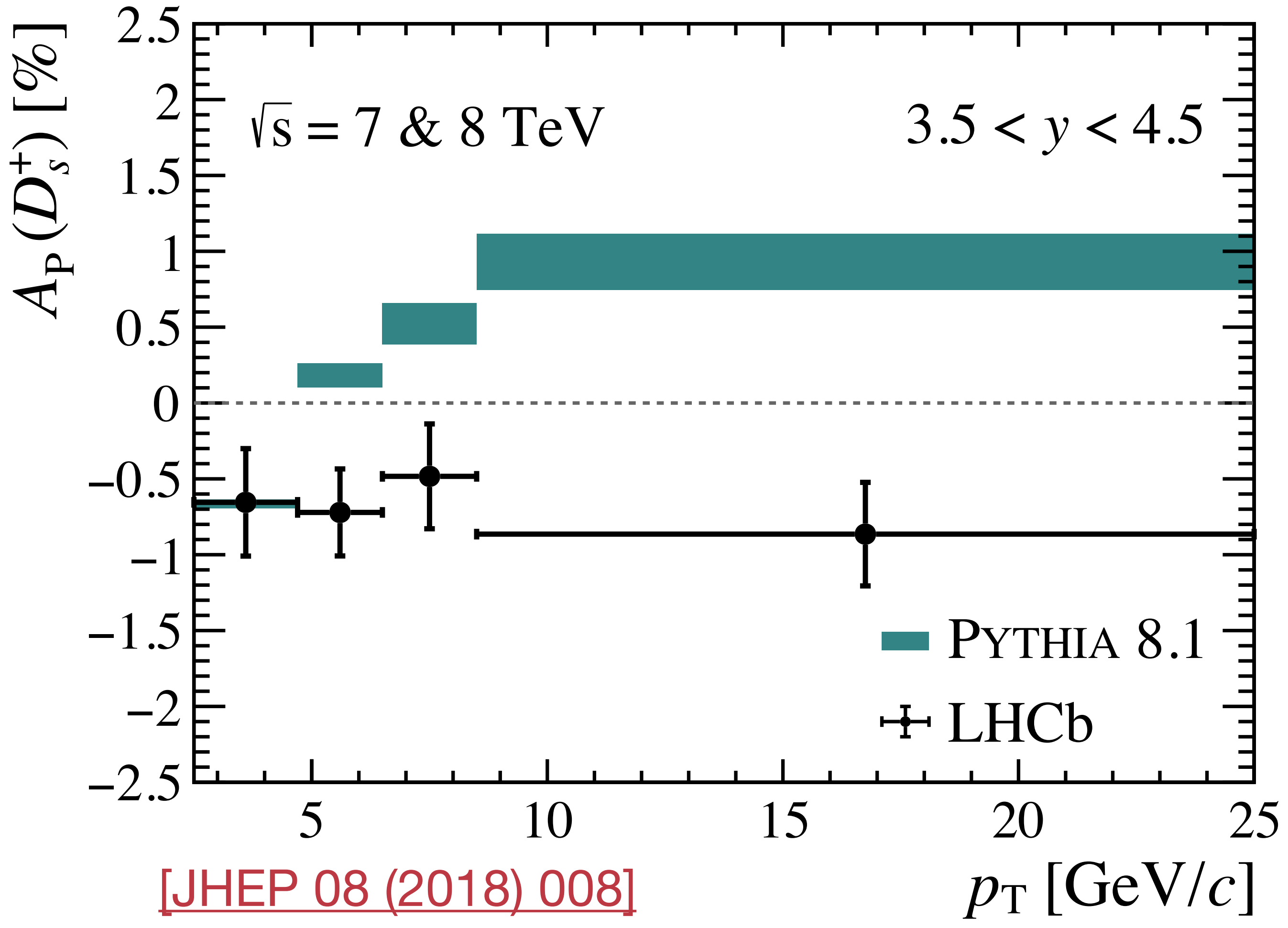


Measuring CP violation in charm decays requires precise control of **nuisance asymmetries**



[JHEP 08 (2018) 008]

Production asymmetries

Do we make as many c as $\bar{c}$?

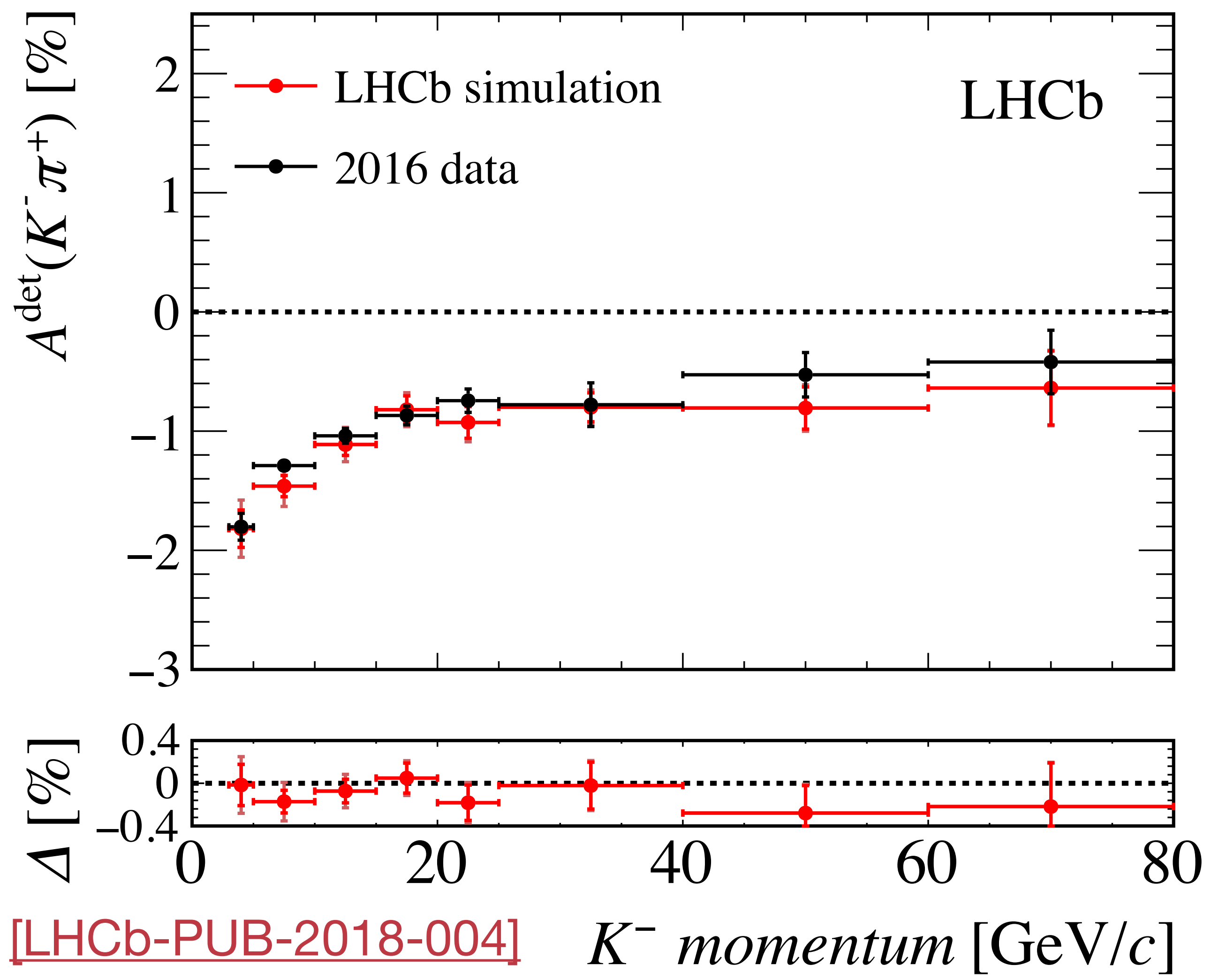
Detection asymmetries

Do we reconstruct antiparticles as well as particles?

Both are $\mathcal{O}(\%)$ effects

$\times 10$ larger than A_{CP}

Not perfect in simulations



[LHCb-PUB-2018-004]

Today's menu

LHCb-PAPER-2022-024 arXiv:2209.03179
Measurement of the time-integrated CP asymmetry in $D^0 \to K^-K^+$ decays

LHCb-PAPER-2022-042 J. High Energ. Phys. 2023, 67 (2023)
Search for CP violation in $D^+_{(s)} \to K^+K^-K^+$ decays

LHCb-PAPER-2023-005 arXiv:2306.12746
Search for CP violation in the phase space of $D^0 \to \pi^-\pi^+\pi^0$ decays with the energy test

All performed with the **Run 2** data samples

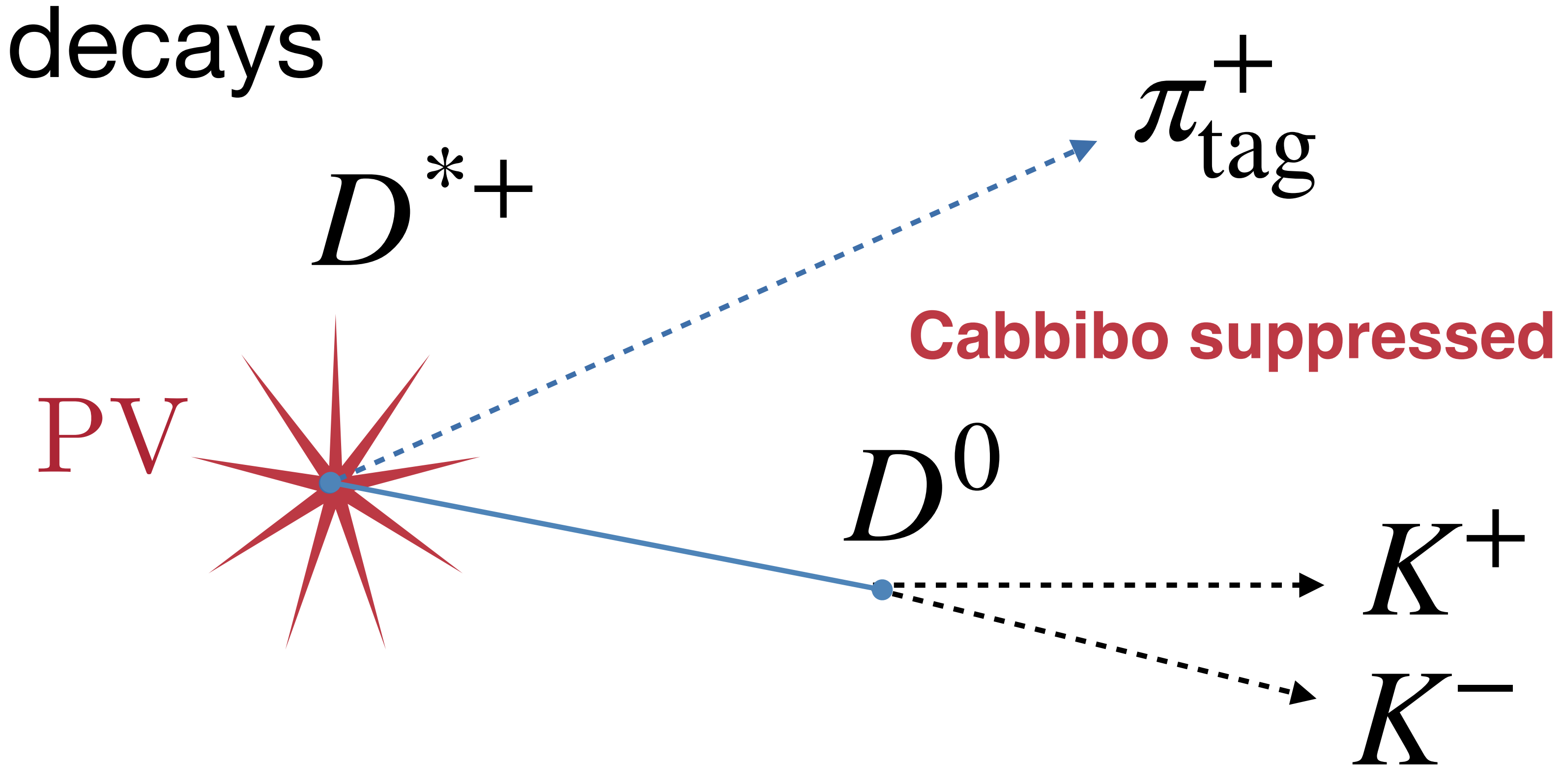
CP asymmetry in $D^0 \to K^- K^+$

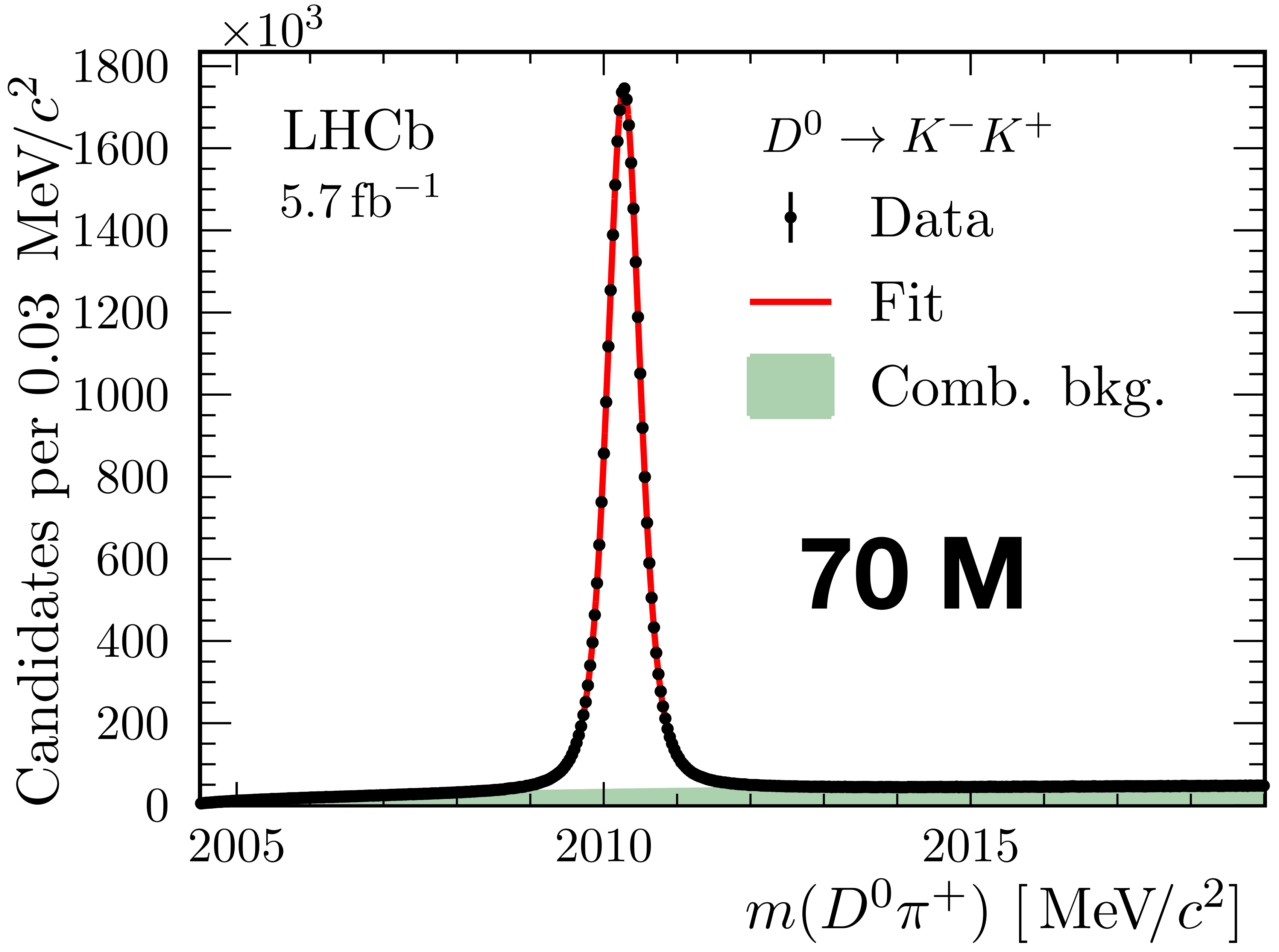
Time-integrated CP asymmetry has been measured in $D^0 \to K^+ K^-$ decays

Direct — Mixing

$$A_{CP}(f) \approx a_f^d + \frac{\langle t \rangle_f}{\tau_D} \Delta Y_f$$

Contributions from both direct CP and mixing





CP asymmetry in $D^0 \to K^-K^+$

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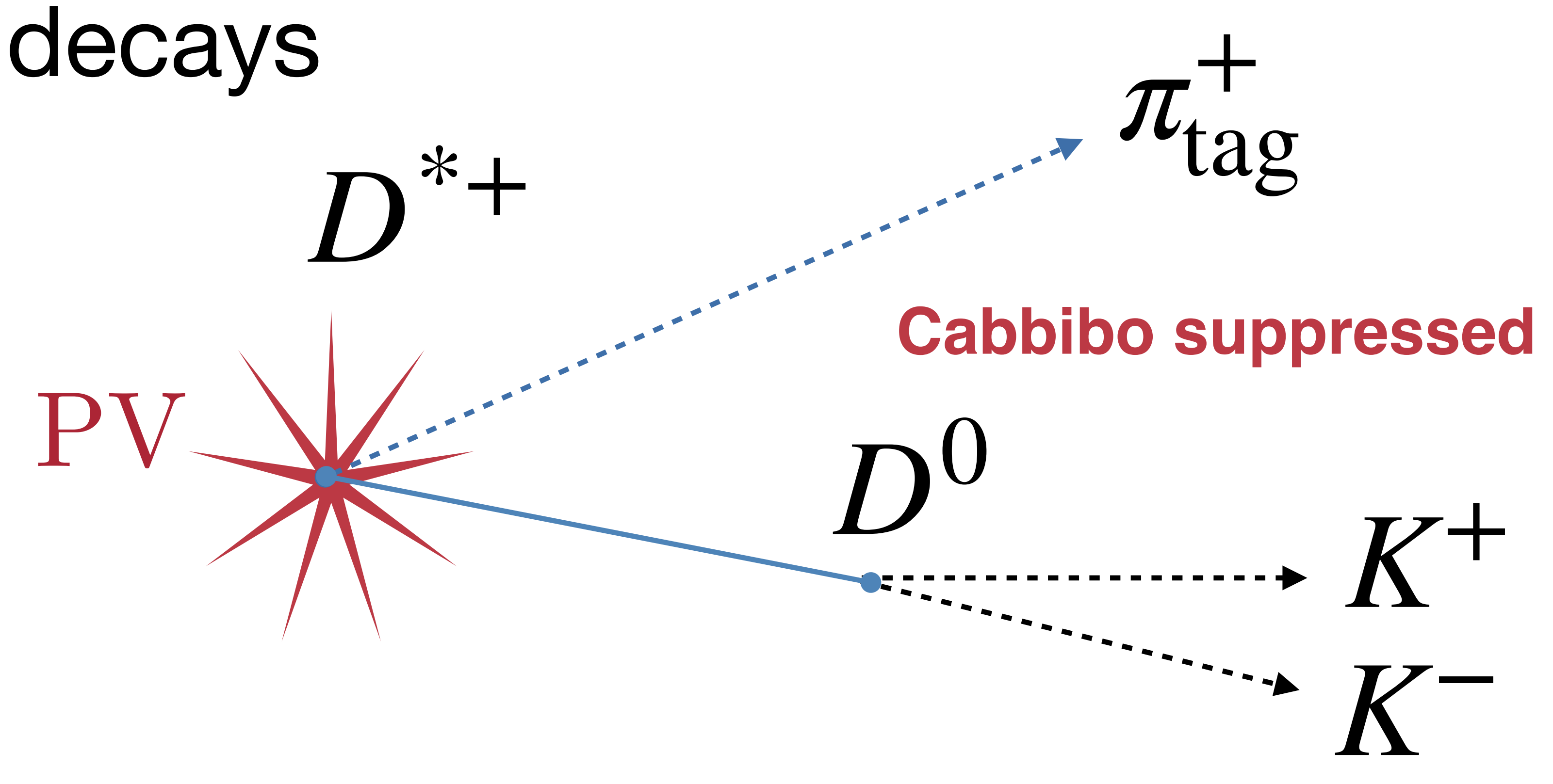

Two methods are used to cancel the nuisance asymmetries using **Cabbibo favoured** decays

Data-driven corrections

C_{D^+}

$$\begin{aligned}A_{CP}(D^0 \to K^+K^-) = \\ &+A(D^{*+} \to (D^0 \to K^+K^-)\pi^+_{tag}) \\ &-A(D^{*+} \to (D^0 \to K^-\pi^+)\pi^+_{tag}) \\ &+A(D^+ \to K^-\pi^+\pi^+) \\ &-A(D^+ \to K^0_S\pi^+) \\ &+A(K^0_S)\end{aligned}$$

$C_{D_s^+}$

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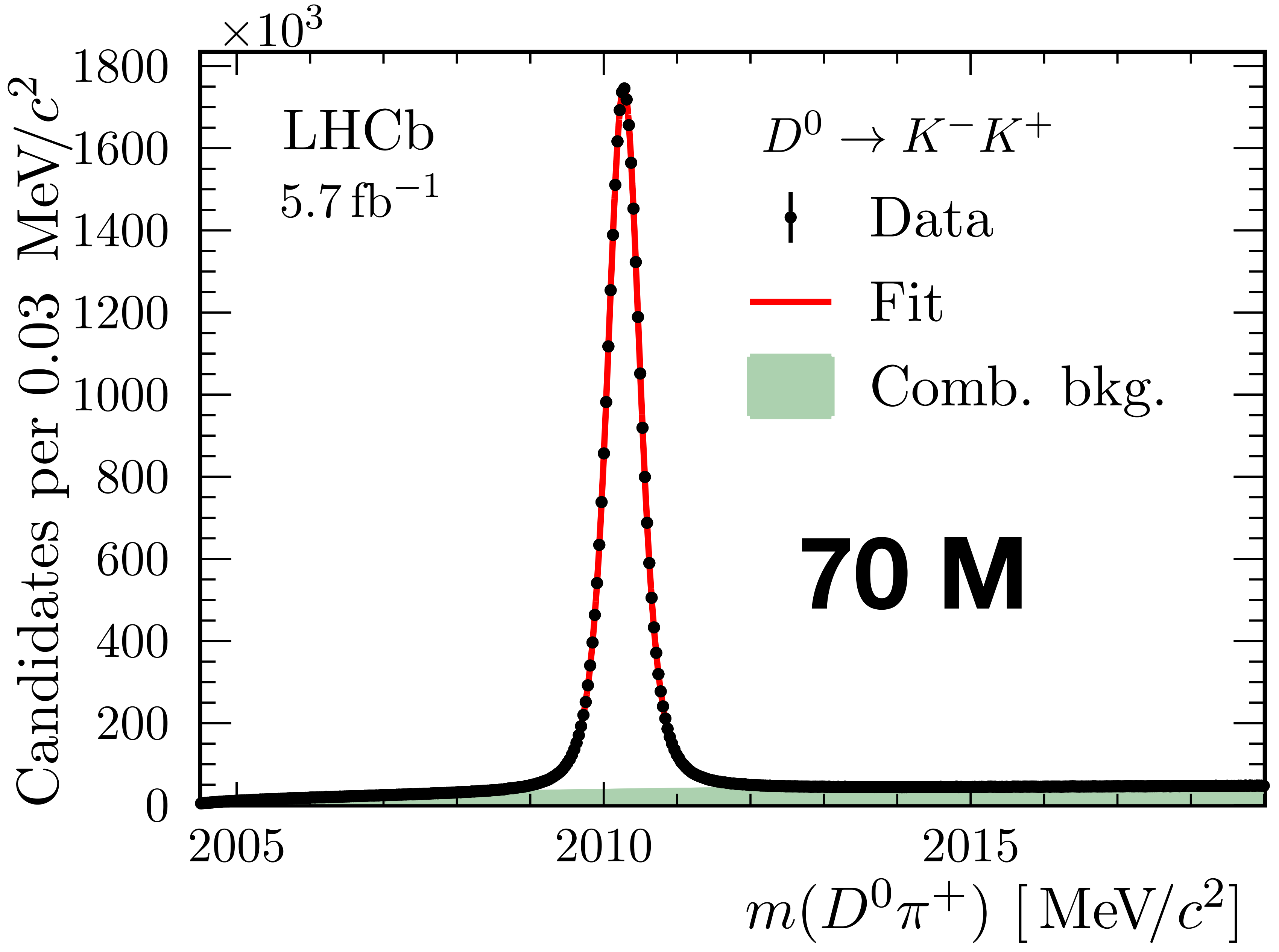

Control modes are reweighted to ensure complete cancellation

CP asymmetry in $D^0 \to K^- K^+$

LHCb-PAPER-2022-024
arXiv:2209.03179

Fits performed separately by year, magnet polarity and control method are combined:

$$\mathcal{A}_{CP}(K^- K^+) = [6.8 \pm 5.4\,(\text{stat}) \pm 1.6\,(\text{syst})] \times 10^{-4}$$

Combination is performed with other LHCb measurements

$$\Delta A_{CP} = A_{CP}(D^0 \to K^+ K^-) - A_{CP}(D^0 \to \pi^+ \pi^-) = (-15.4 \pm 2.9) \times 10^{-4}$$ [PRL 122 08726]

$$\Delta Y = (-1.0 \pm 1.1 \pm 0.4) \times 10^{-4}$$ [PRD 104 072010]

Mixing contribution is small

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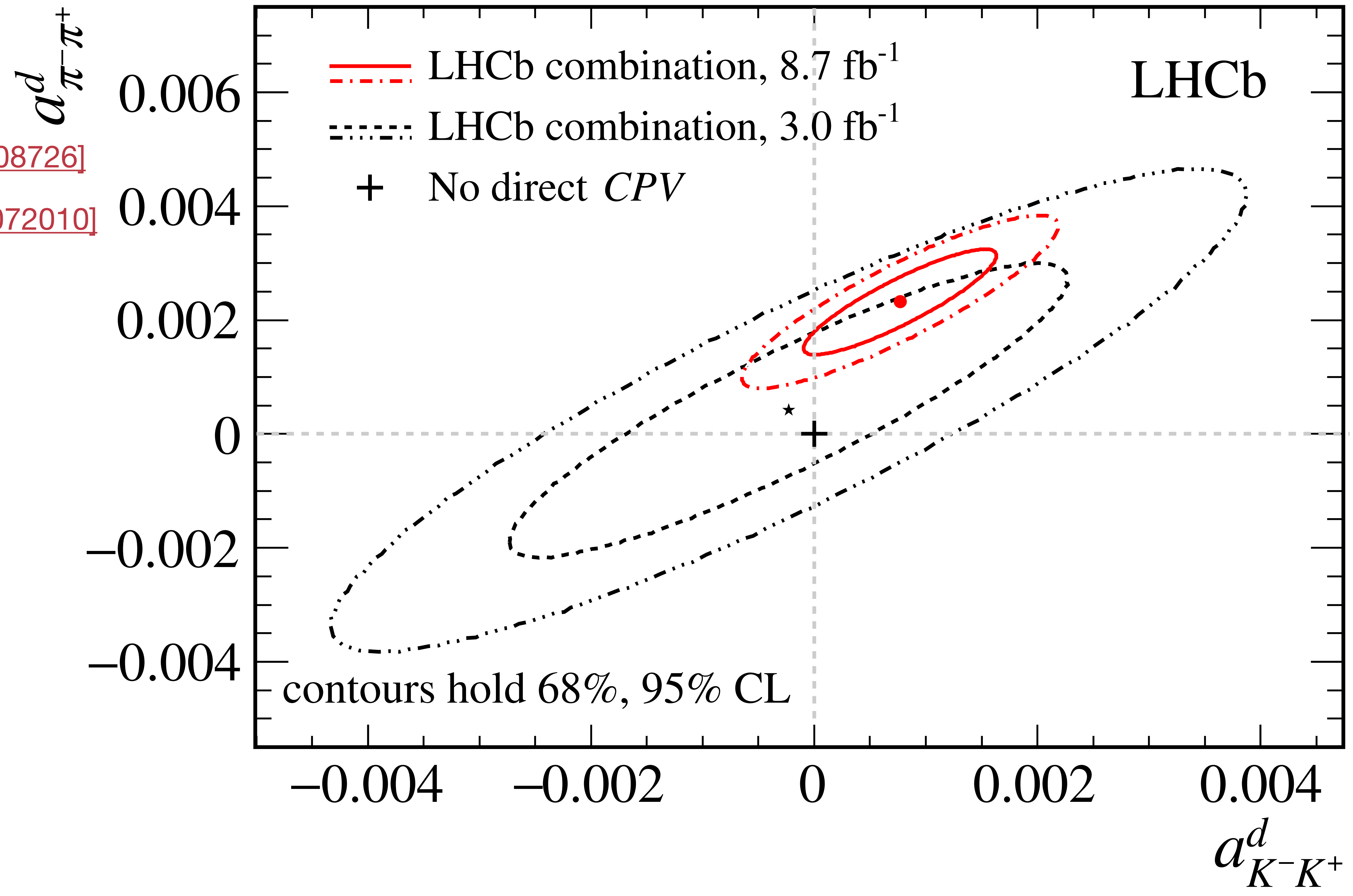
This allows the **direct asymmetries** to be extracted:

$$a^d_{K^-K^+} = (7.7 \pm 5.7) \times 10^{-4} \quad 1.4\sigma$$
$$a^d_{\pi^-\pi^+} = (23.2 \pm 6.1) \times 10^{-4} \quad 3.8\sigma$$



First evidence of direct CP violation in a single charm decay mode!

Search for CP violation in $D^+_{(s)} \to K^+K^-K^+$

LHCb-PAPER-2022-042
J. High Energ. Phys. 2023, 67 (2023)

The rich **resonant structure** in multi-body decays can provide a source of **strong-phase variation** due to the many different contributing processes

*CP violation can be **locally enhanced** within multi-body decays*

This analysis uses a method that is constructed to only be sensitive to local CP violation

*Insensitive to **global** nuisance and CP asymmetries*

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Large samples of **Cabibbo suppressed** $D_s^+ \to K^+K^-K^+$ and **doubly-cabbibo suppressed** $D^+ \to K^+K^-K^+$ decays are collected

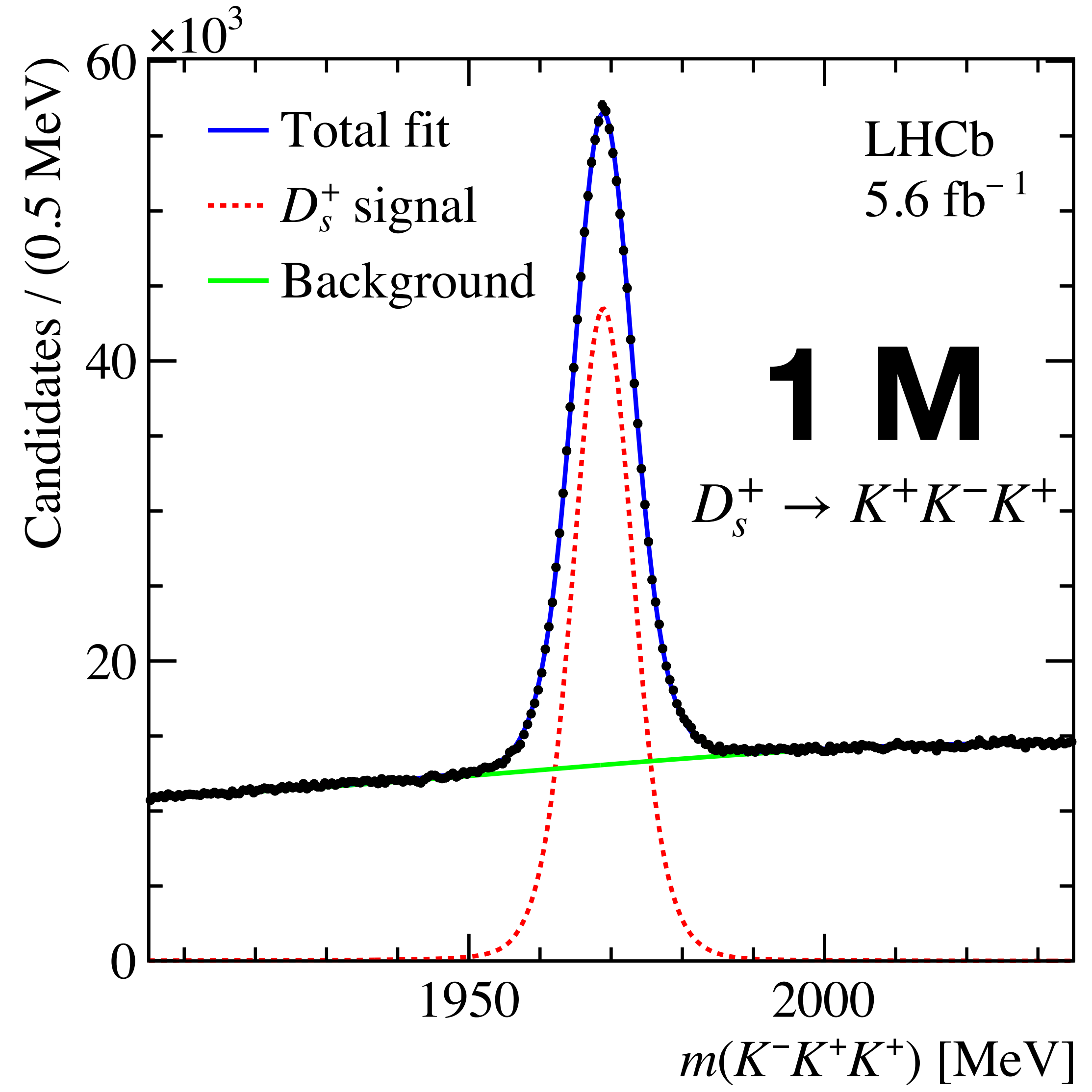
*This analysis uses a **binned method** previously used for B meson decays*

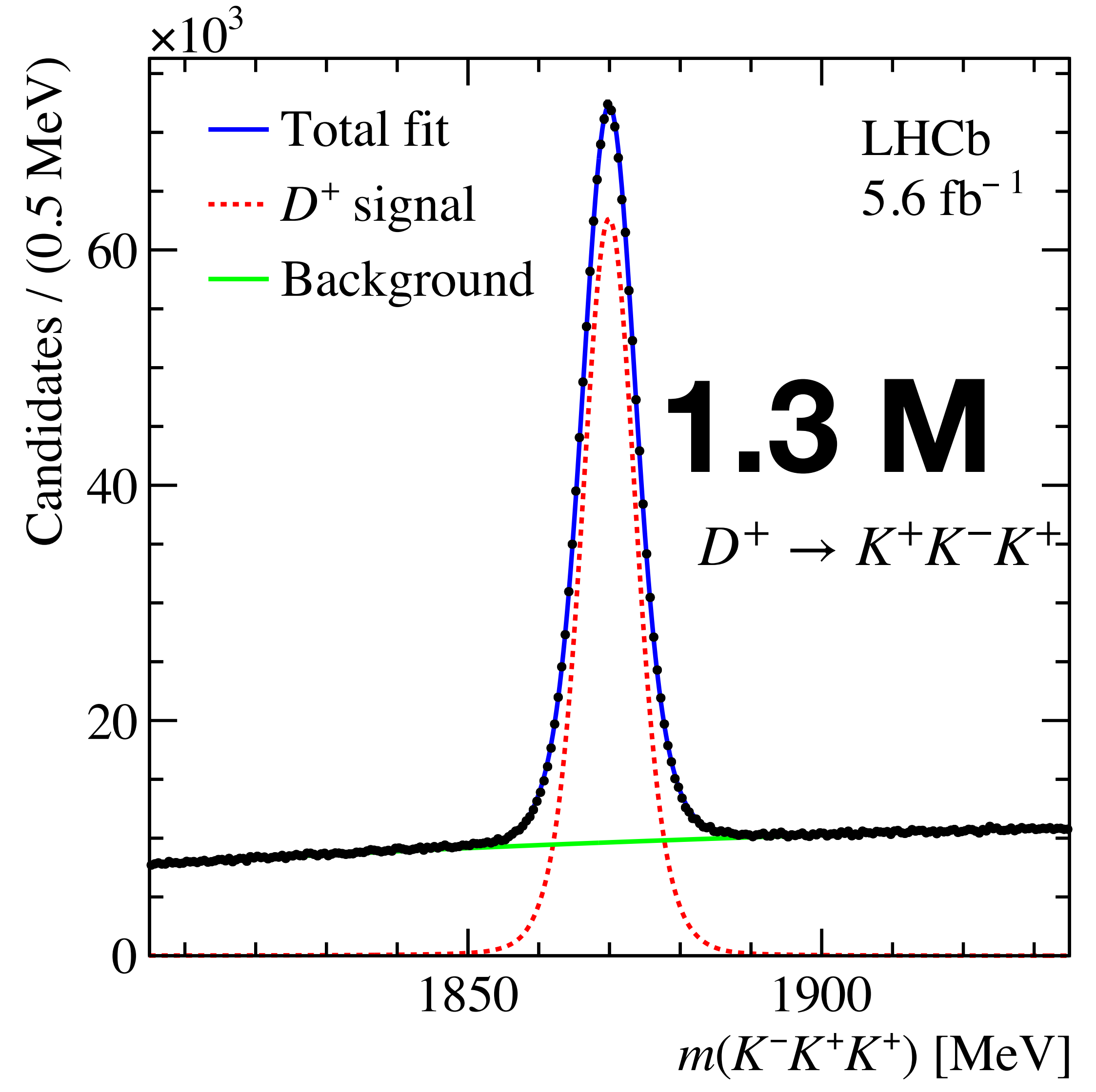
[Phys.Rev.D 80 (2009) 096006]

e.g. [arXiv:2206.07622]

Significance of normalised yield difference is calculated

$$S^i_{CP} = \frac{N^i_+ - \alpha N^i_-}{\alpha^2 \sqrt{[\sigma^i_+]^2 + [\sigma^i_-]^2)}} \qquad \alpha = \frac{\sum_i N^i_+}{\sum_i N^i_-}$$



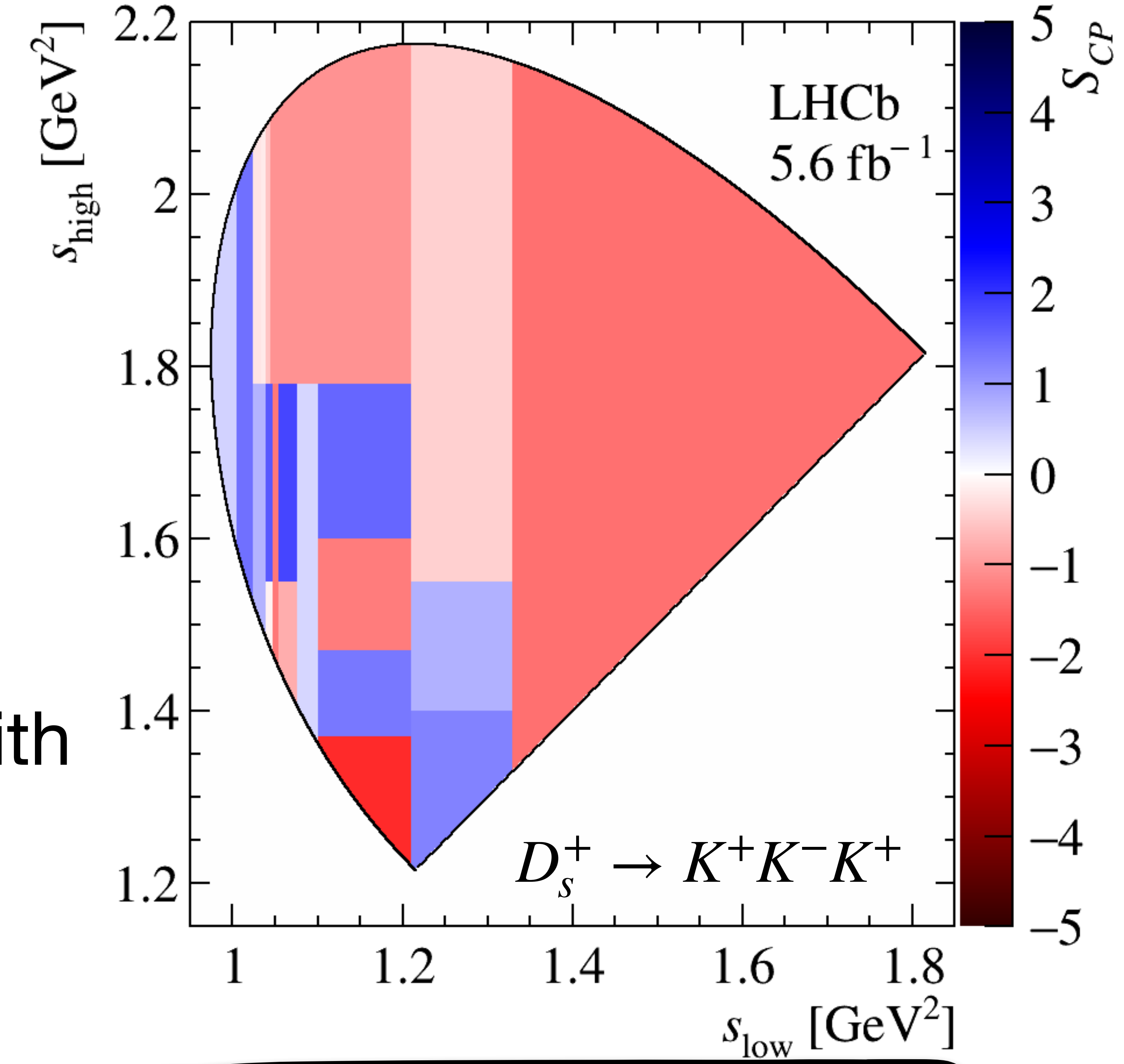


Search for CP violation in $D^+_{(s)} \to K^+K^-K^+$

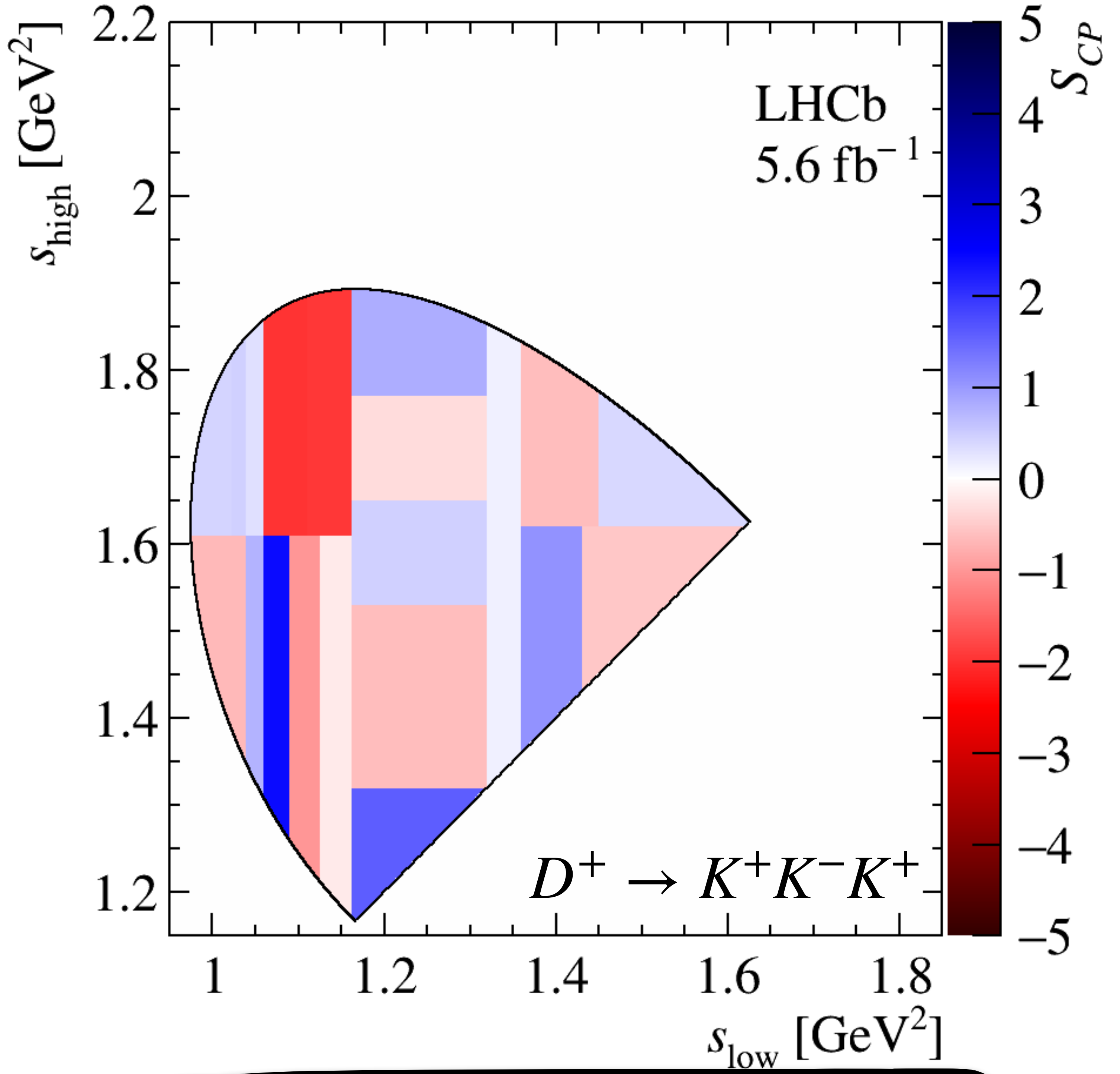
The significance of $D^+_{(s)}$ vs. $D^-_{(s)}$ yield differences is studied in bins of the **Dalitz** plot

*Binning scheme **optimised** to use many bins where strong phases vary **quickly***

e.g. around $D_s^+ \to \phi K^+$



p-value$(D_s^+) = 13.3\,\%$



p-value$(D^+) = 31.6\,\%$

χ^2 **test** is performed to determine **significance of local asymmetries** with respect to CP conserving hypothesis

Cabbibo favoured decay $D_s^+ \to K^+K^-\pi^+$ used to validate method

No evidence for CP violation in these decays

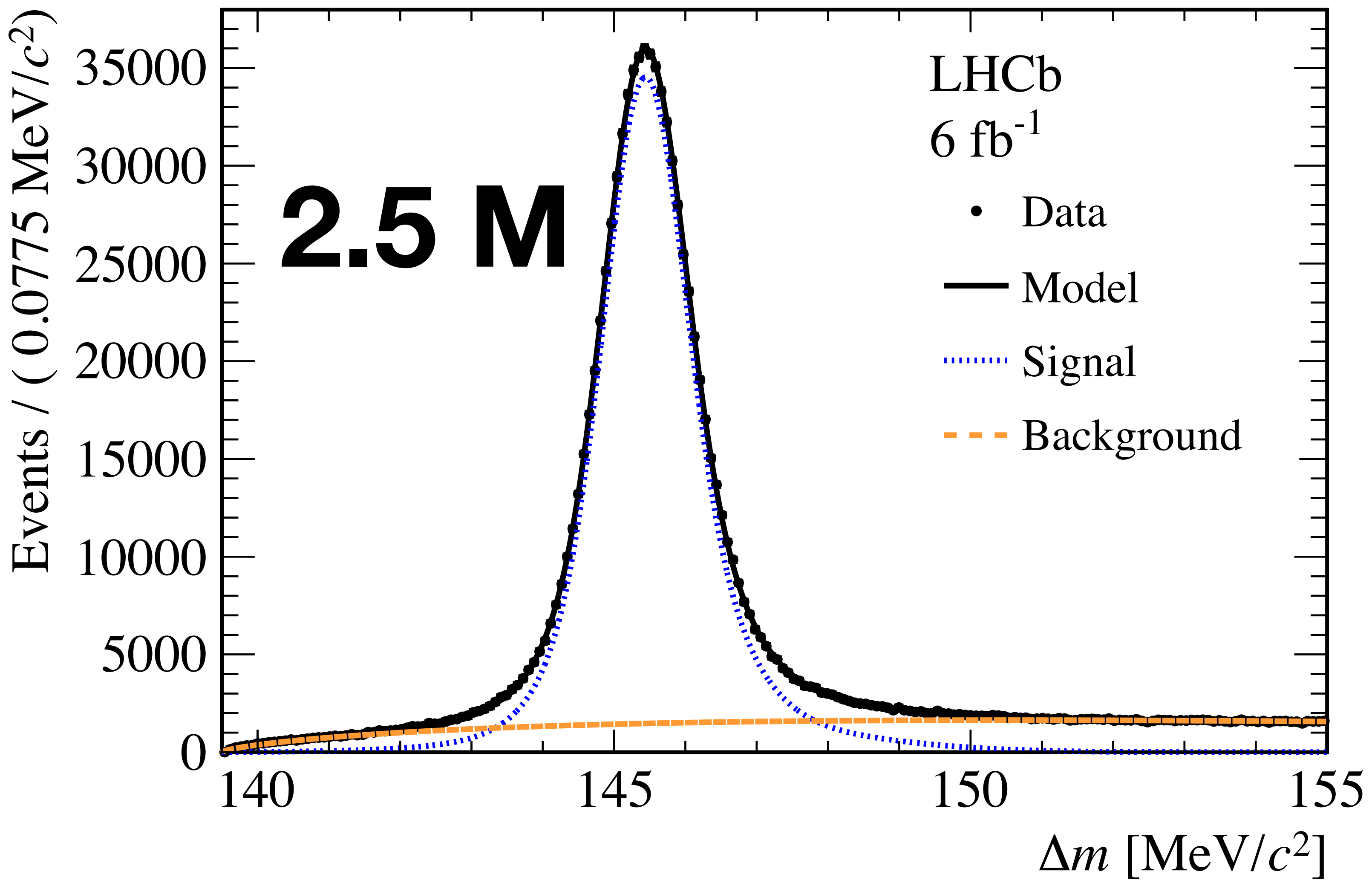
Search for CP violation in $D^0 \to \pi^-\pi^+\pi^0$ decays

LHCb-PAPER-2023-005
arXiv:2306.12746

$D^0 \to \pi^-\pi^+\pi^0$ decays via similar quark-level processes to $D^0 \to \pi^-\pi^+$

***Promising** area to search for CP violation*

This analysis uses an **unbinned** method to search for localised CP asymmetries called **the energy test** [Phys. Rev. D 84, 054015 (2011)]



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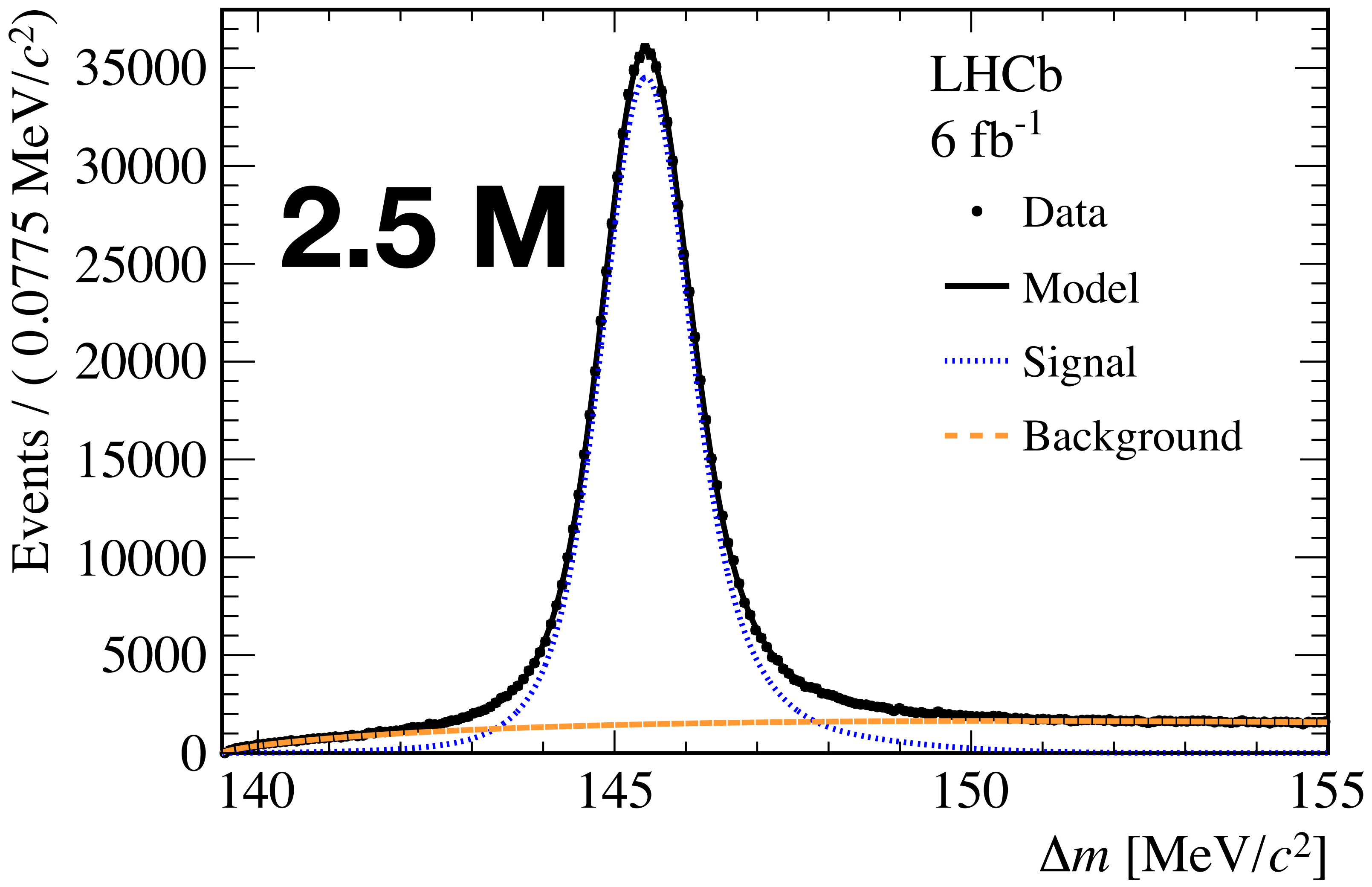
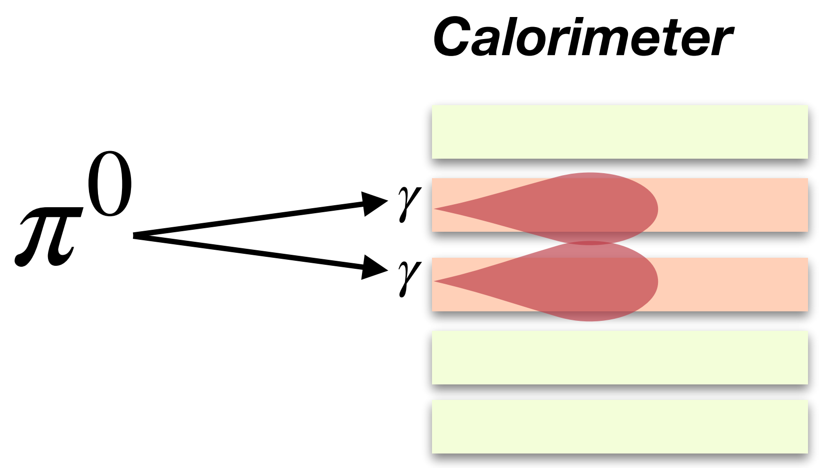
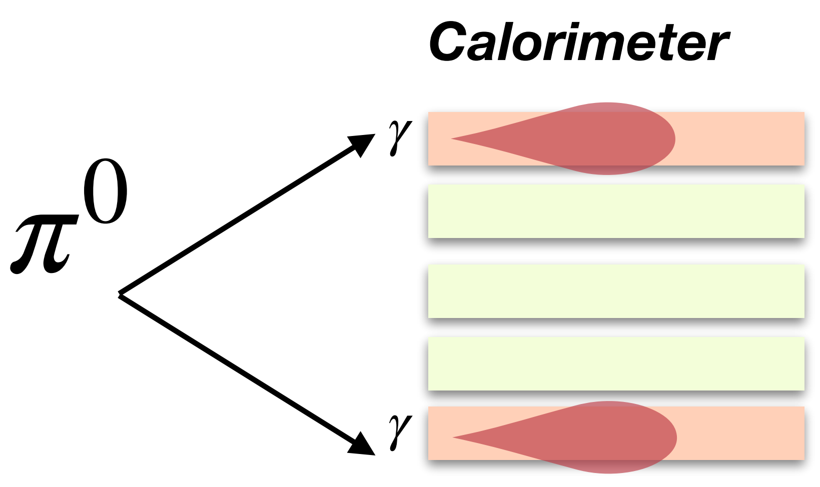


This analysis makes use of $\pi^0 \to \gamma\gamma$ decays

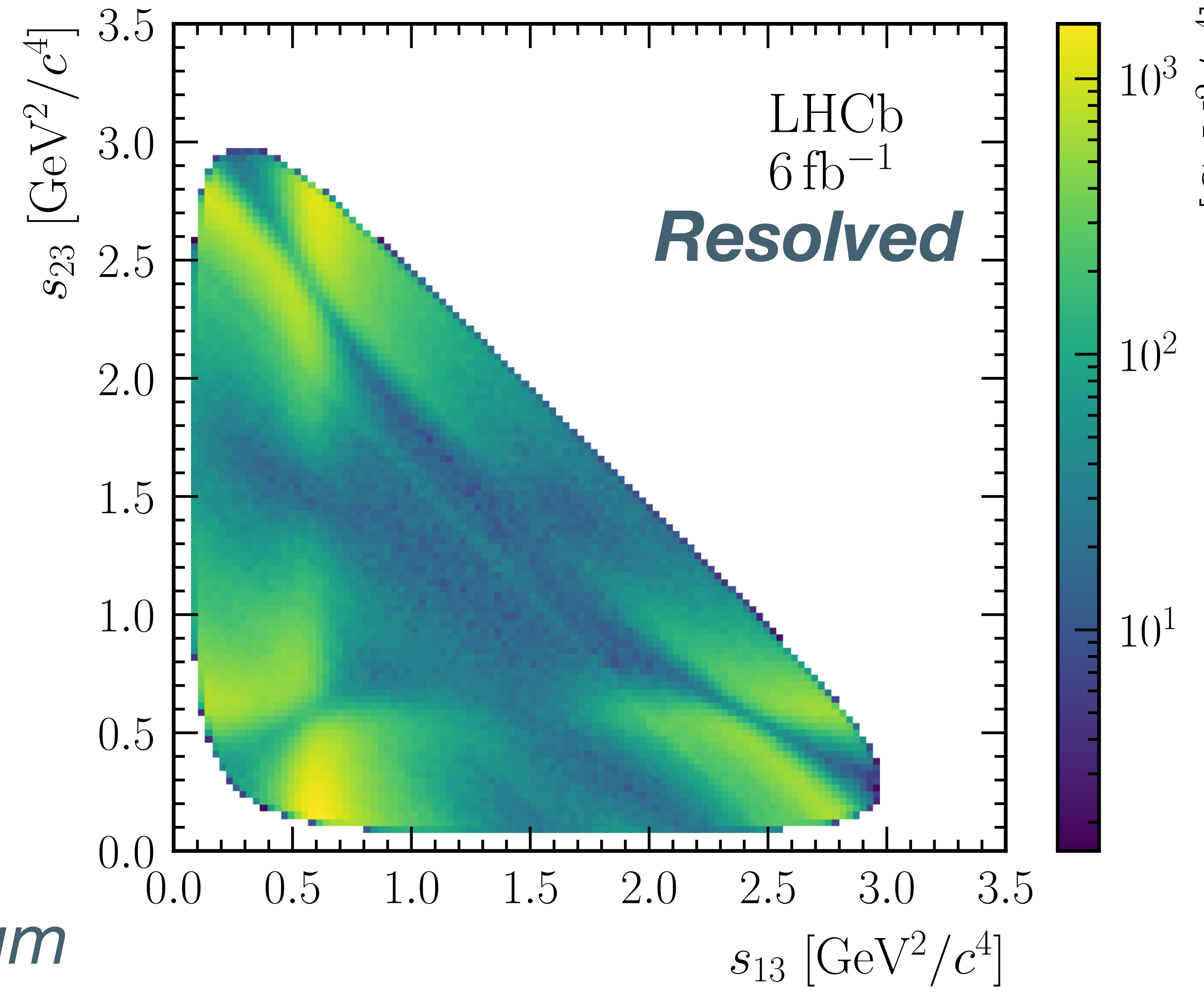
Depending on the energy, these are reconstructed as **one** or **two deposits** in the electromagnetic calorimeter

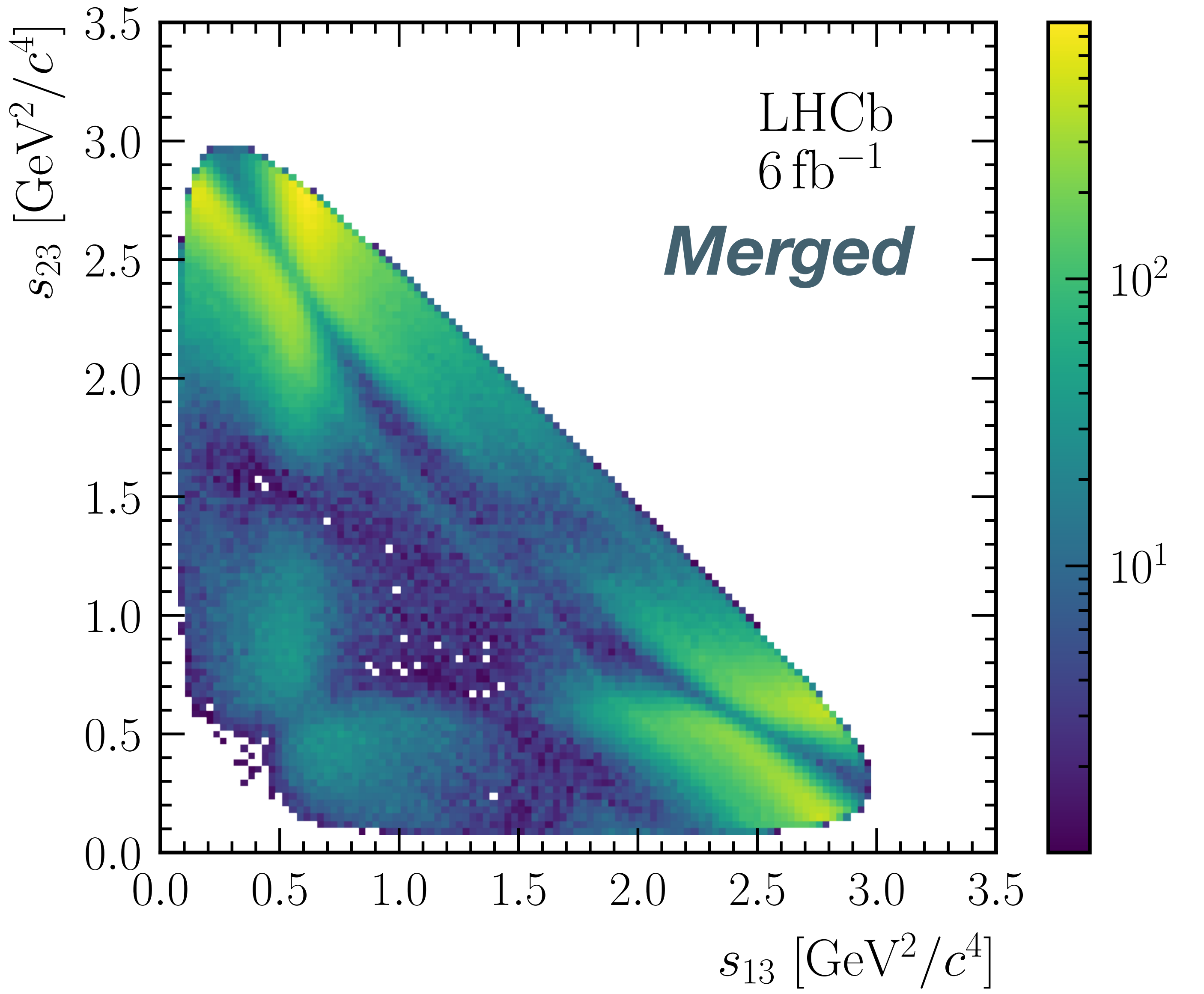


***Merged:** high momentum*



***Resolved:** low momentum*





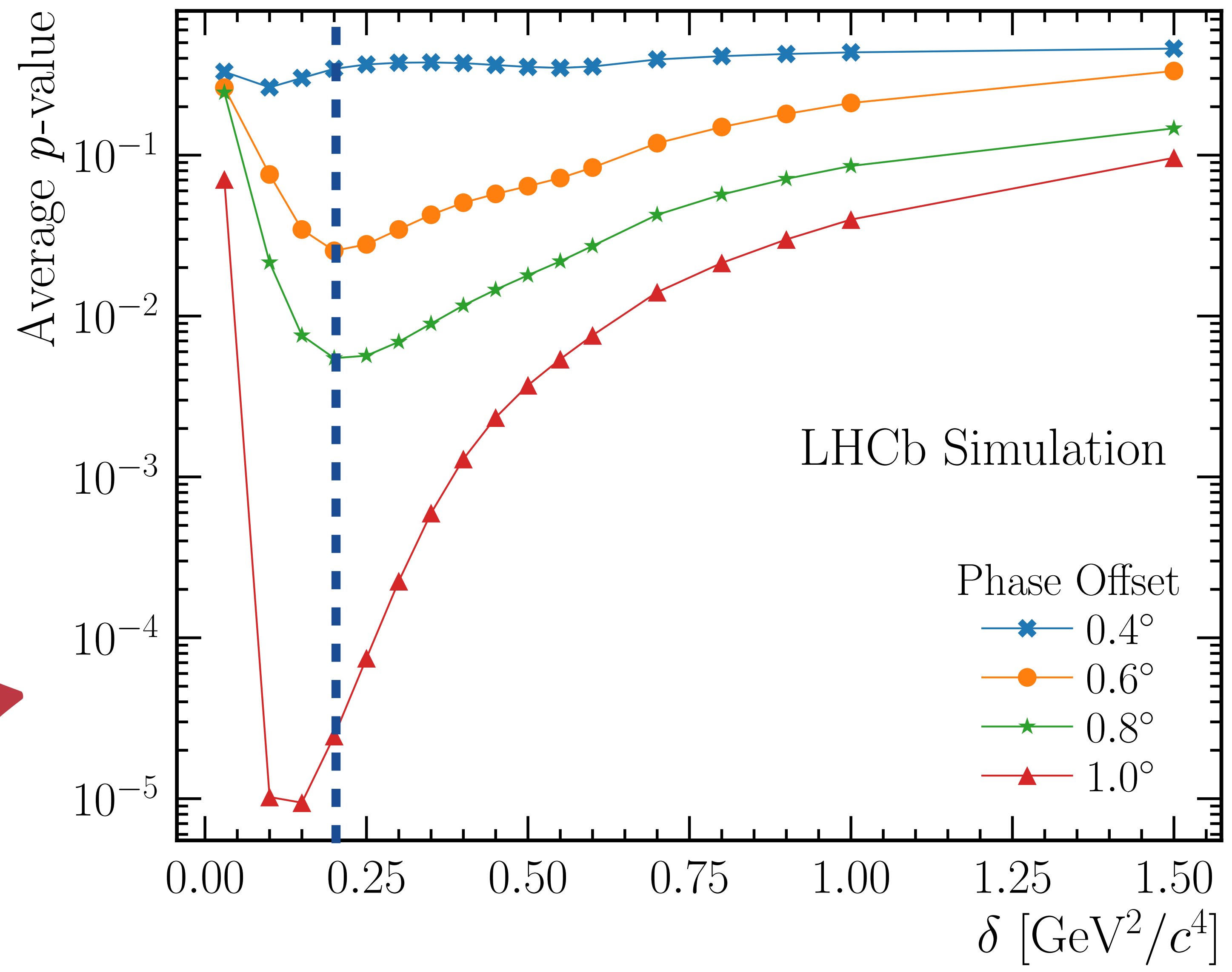
***Distance between points** in the phase space used to build the test statistic*

$$T \equiv \frac{1}{2n(n-1)}\sum_{i,j}\psi_{ij} + \frac{1}{2\bar{n}(\bar{n}-1)}\sum_{i,j}\psi_{ij} - \frac{1}{n\bar{n}}\sum_{i,j}\psi_{ij}$$

D^0-D^0 **distances** $\quad \bar{D}^0$-$\bar{D}^0$ **distances** $\quad D^0$-$\bar{D}^0$ **distances**

Function ψ_{ij} is a Gaussian with width δ

δ controls the local radius that is probed and is optimised to maximise sensitivity



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D^0-D^0 **distances** | $\overline{D}{}^0$-$\overline{D}{}^0$ **distances** | D^0-$\overline{D}{}^0$ **distances**

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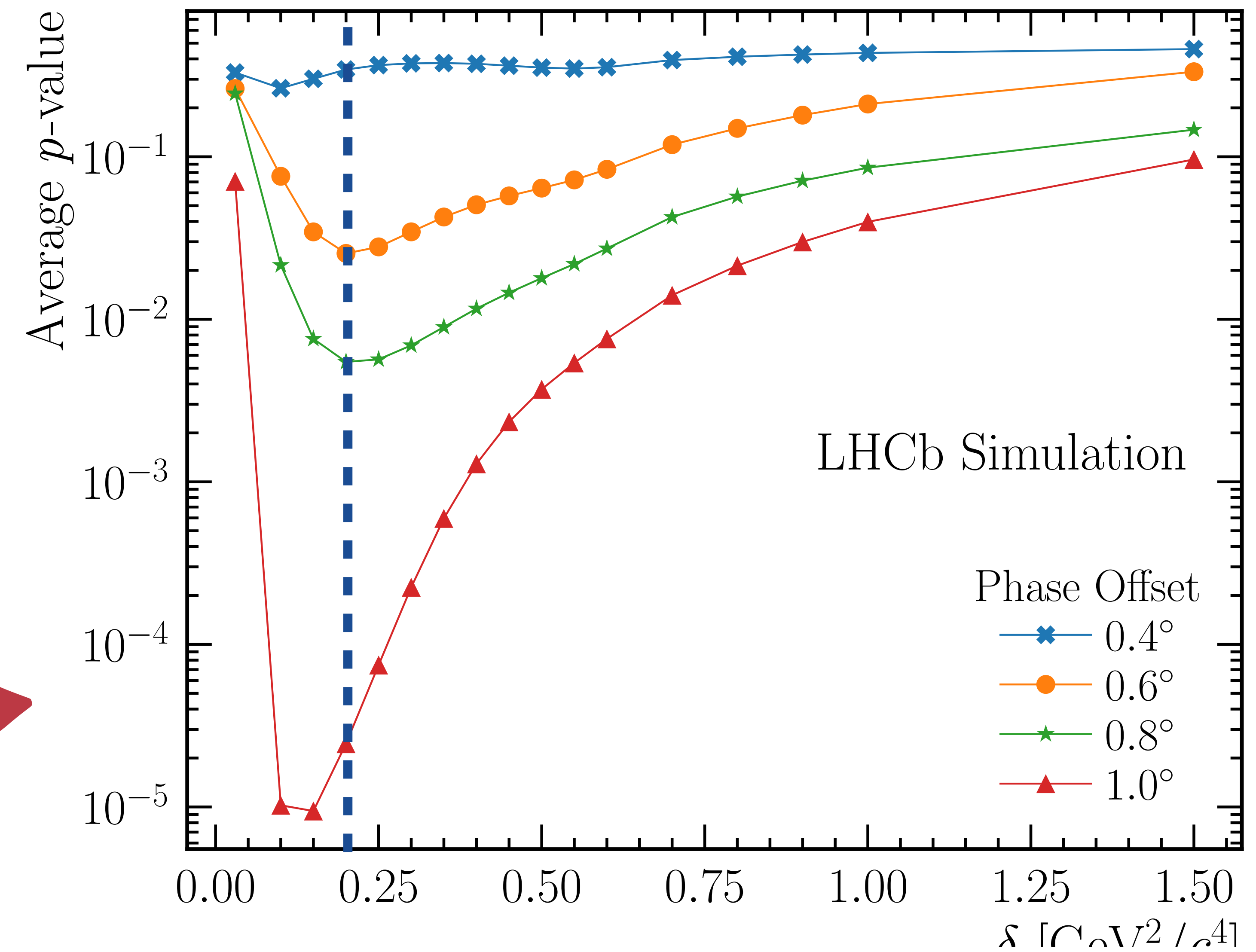
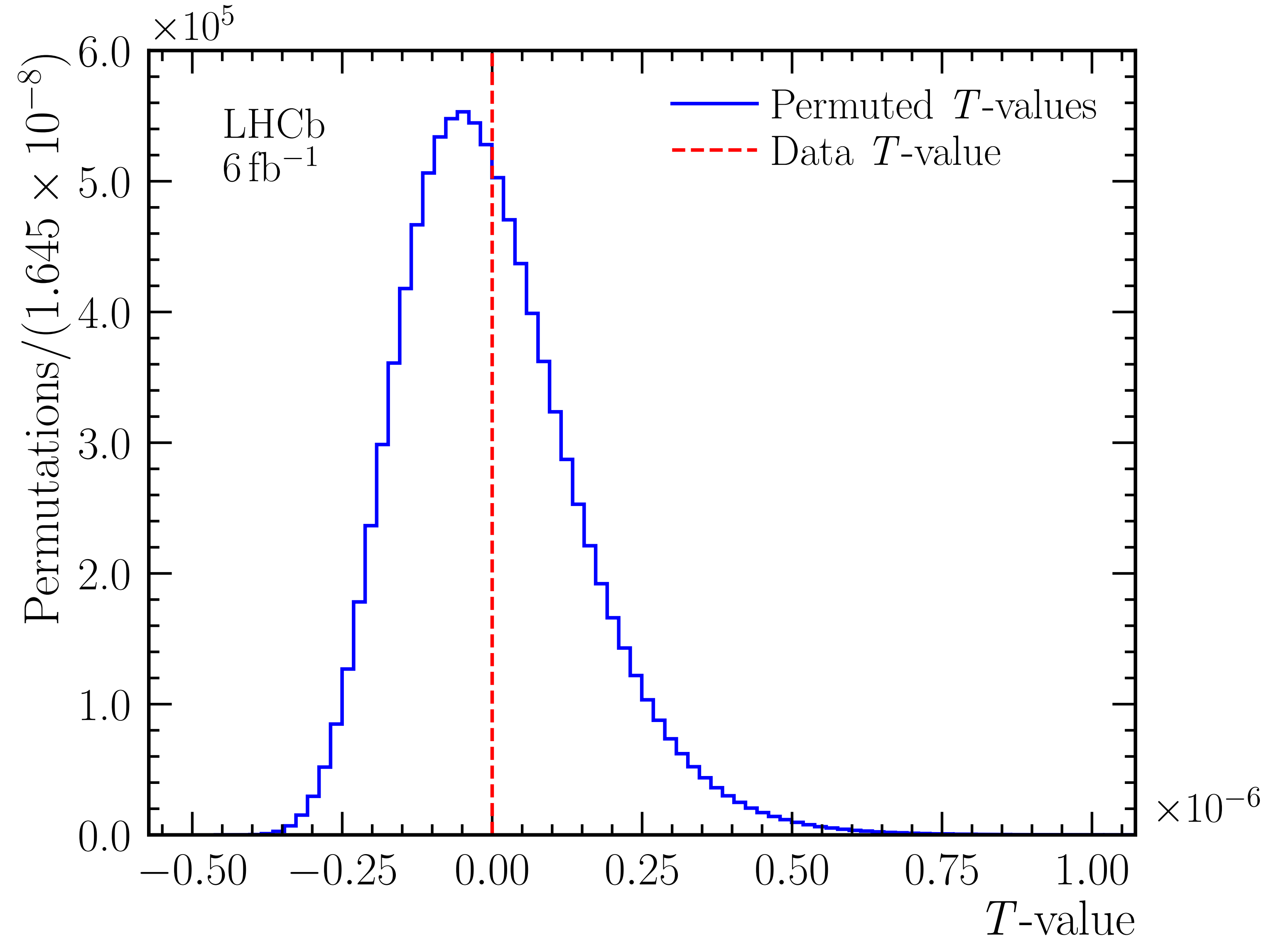


The **p-value** is computed by comparing T to a distribution of samples created by **randomly-permuting** the flavour assignment

Low p-value → sign of CP violation



Previous Run 1 analysis measured a p-value of 2.6%
[Phys. Lett. B740 (2015) 158]

p-value = 62 %

No evidence for CP violation in this decay

Conclusions and outlook

LHCb has performed new measurements and searches for CP violation in charm decays

First evidence of direct CP violation in a single charm decay mode

No evidence of localised CP asymmetries in $D^+_{(s)} \to K^+K^-K^+$ and $D^0 \to \pi^+\pi^-\pi^0$ decays

More analyses planned with the Run 2 data set

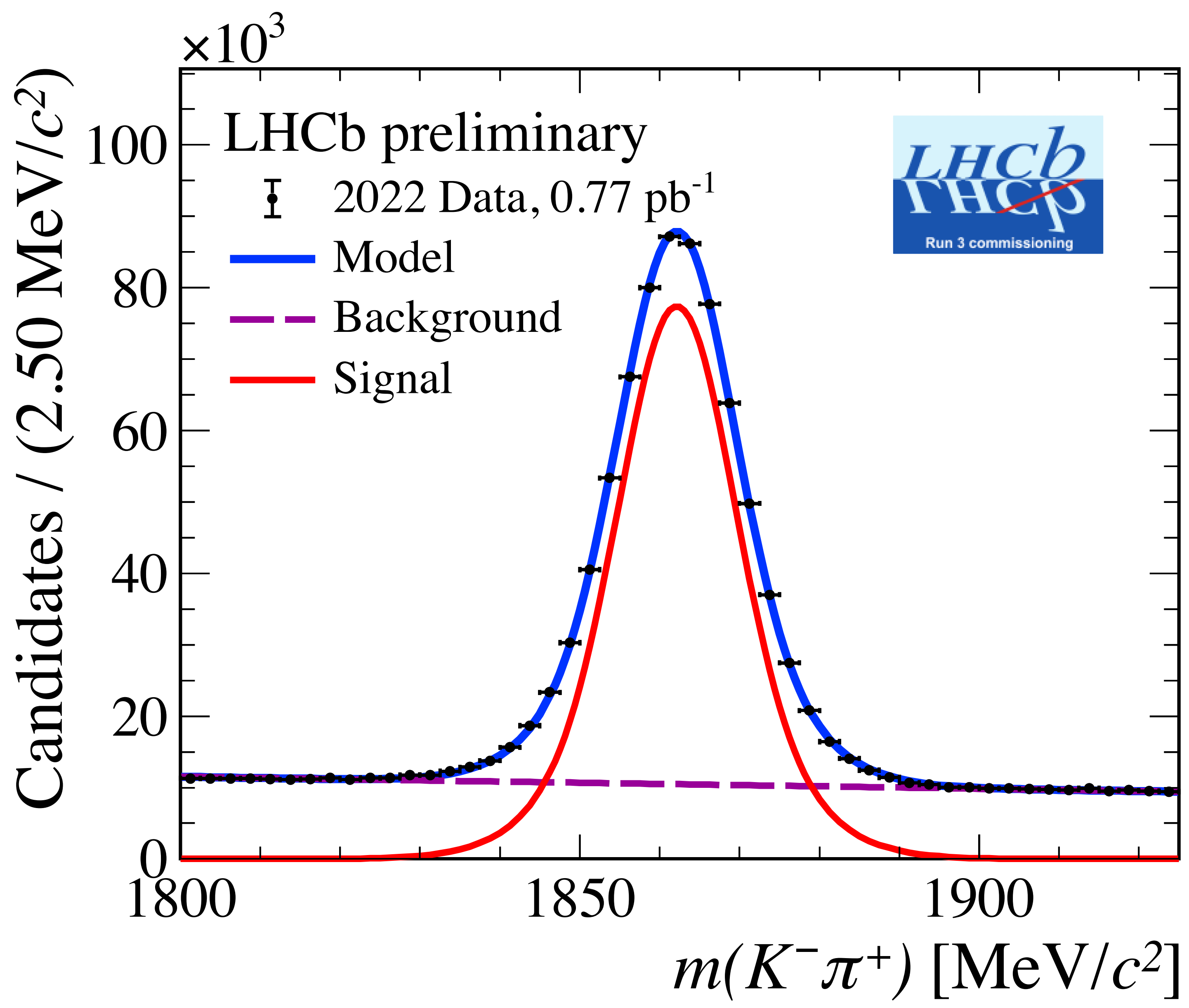
Run 3 has begun: expect larger samples with an upgraded detector!

Larger samples will help understand CP violation in charm

Sample ($\mathscr{L}$)	Forecast $D^0 \to K^+K^-$ Yield	Actual Yield	Predicted sensitivity (%)	Actual sensitivity (%)
Run 1-2 (9 fb^{-1})	52 M	70 M	0.07	0.056 ✓
Run 1-3 (23 fb^{-1})	280 M		0.03	
Run 1-4 (50 fb^{-1})	1 B		0.015	
Run 1-5 (300 fb^{-1})	4.9 B		0.007	

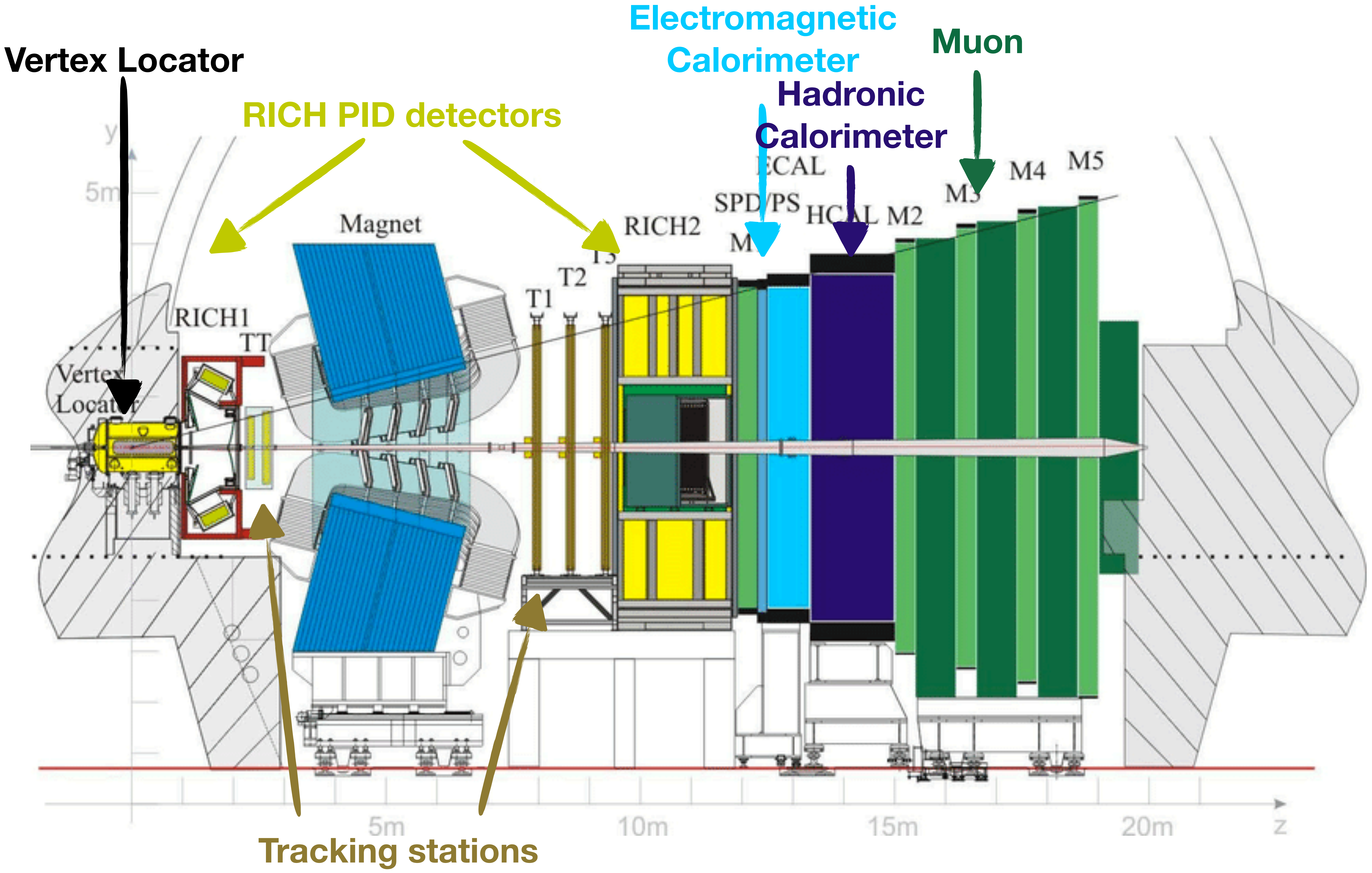
[LHCb-PUB-2018-009]

[LHCb-FIGURE-2023-011]



Back up

LHCb detector



Future prospects

[LHCb-PUB-2018-009]

Table 6.6: Extrapolated signal yields, in units of 10^6, of the Cabibbo-suppressed decays $D^+ \to K^- K^+ \pi^+$, $D^+ \to \pi^- \pi^+ \pi^+$, and of the doubly Cabibbo-suppressed decays $D^+ \to K^- K^+ K^+$, $D^+ \to \pi^- K^+ \pi^+$.

Sample ($\mathcal{L}$)	$D^+ \to K^- K^+ \pi^+$	$D^+ \to \pi^- \pi^+ \pi^+$	$D^+ \to K^- K^+ K^+$	$D^+ \to \pi^- K^+ \pi^+$
Run 1–2 ($9\,\mathrm{fb}^{-1}$)	200	100	14	8
Run 1–4 ($23\,\mathrm{fb}^{-1}$)	1,000	500	70	40
Run 1–4 ($50\,\mathrm{fb}^{-1}$)	2,600	1,300	182	104
Run 1–6 ($300\,\mathrm{fb}^{-1}$)	17,420	8,710	1,219	697

Table 6.7: Sensitivities to *CP*-violation scenarios for $D^+ \to \pi^- \pi^+ \pi^+$ decays. Simulated D^+ and D^- Dalitz plots are generated with relative changes in the phase of the $R\pi^\pm$ amplitude, $R = \rho^0(770)$, $f_0(500)$ or $f_2(1270)$. The values of the phase differences are given in degrees and correspond to a 5σ *CP*-violation effect. Simulations are performed with $3\,\mathrm{fb}^{-1}$ and extrapolated to the expected integrated luminosities.

resonant channel	$9\,\mathrm{fb}^{-1}$	$23\,\mathrm{fb}^{-1}$	$50\,\mathrm{fb}^{-1}$	$300\,\mathrm{fb}^{-1}$
$f_0(500)\pi$	0.30	0.13	0.083	0.032
$\rho^0(770\pi$	0.50	0.22	0.14	0.054
$f_2(1270)\pi$	1.0	0.45	0.28	0.11