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Hadronic charm decays and direct CP-violation at LHCb

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on behalf of the LHCb collaboration

11th International workshop on Charm physics (CHARM 2023),
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LHCb

Outline

- Direct CP violation
- Searches in two body decays at LHCb
  - Brief recap of ΔA_{CP}
  - Individual asymmetries in $D^0 \to hh$ decays
  - CP violation in $D^+_{(s)} \to \eta^{(')}\pi^+$
- Searches in multibody decays at LHCb
  - Energy test results with $D^0 \to \pi^+\pi^-\pi^0$ and $D^0 \to K^0_S K^\mp \pi^\pm$ decays
  - CP violation searches with $D^+_{(s)} \to KKK$ decays with model-independent binned methods

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Direct CP violation

- Condition for direct CP violation: $|A/\bar{A}| \neq 1$
- Need A and $\bar{A}$ to consist of (at least) two parts: with different weak (ϕ) and strong (δ) phases
- Divide amplitudes into leading and sub-leading parts:

$$A(D \to f) = C(1 + re^{i(\delta+\phi)})$$
$$\bar{A}(\bar{D} \to \bar{f}) = C(1 + re^{i(\delta-\phi)})$$

- C is the leading amplitude
- r is the ratio of sub-leading over leading amplitude

- CP violation requires difference in strong (δ) and weak phase (ϕ):

$$a_{CP} \equiv \frac{|A|^2 - |\bar{A}|^2}{|A|^2 + |\bar{A}|^2} = 2r\sin(\delta)\sin(\phi)$$

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CP violation in decay: example $D^0 \to h^+h^-$

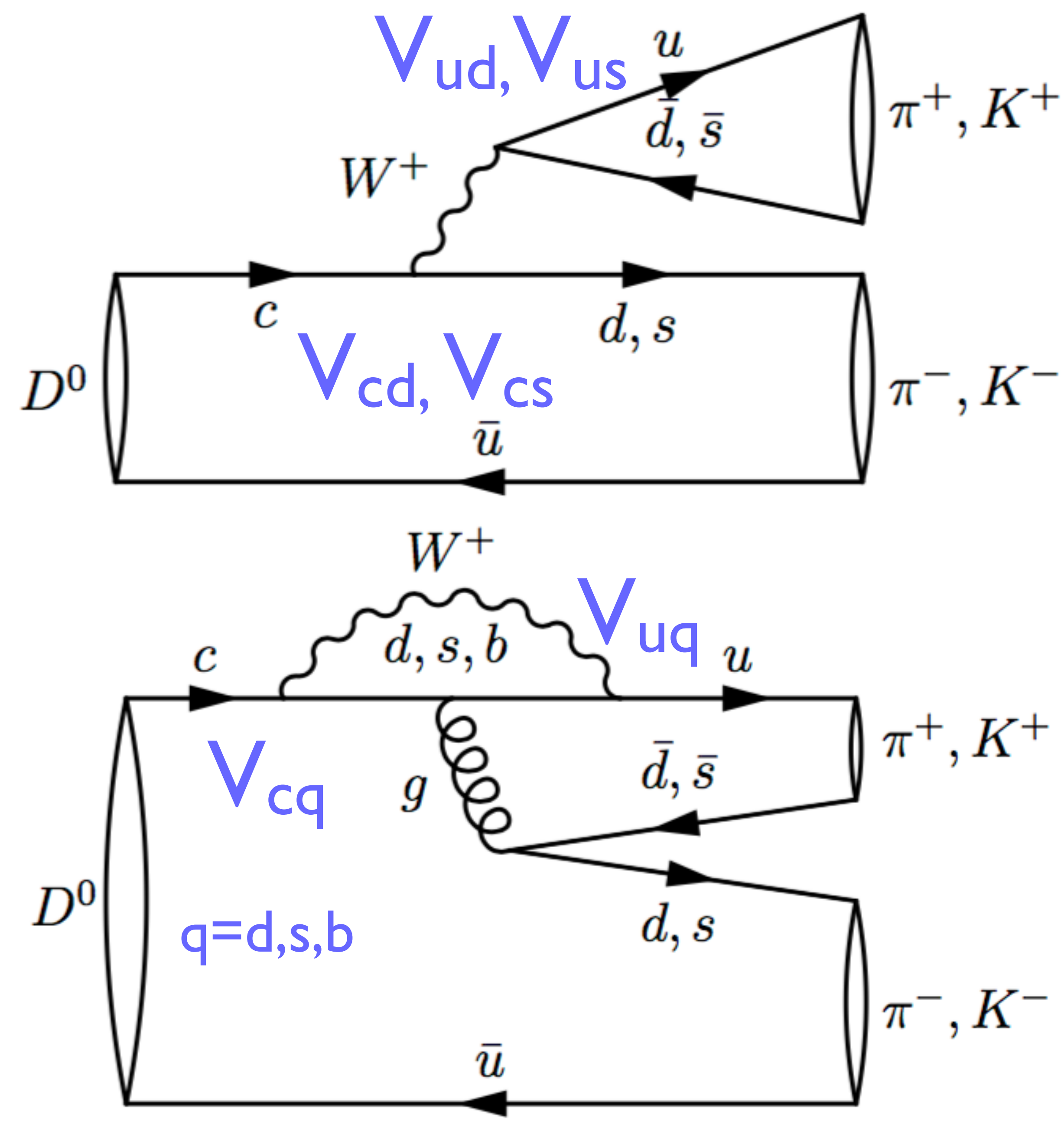
Often realised by "tree" and "penguin" diagrams

Tree-level weak decay amplitude.

- involves the CKM matrix elements
  - V_{us} and V_{cs} for $D^0 \to K^+K^-$
  - V_{ud} and V_{cd} for $D^0 \to \pi^+\pi^-$

One-loop amplitude ("penguin")

- b-loop involves $V_{ub} V_{cb}^*$: tiny
- s and d loops: similar magnitude, opposite sign



$V_{us} \approx -V_{cd} \approx 0.22$ gives the Cabbibo suppression

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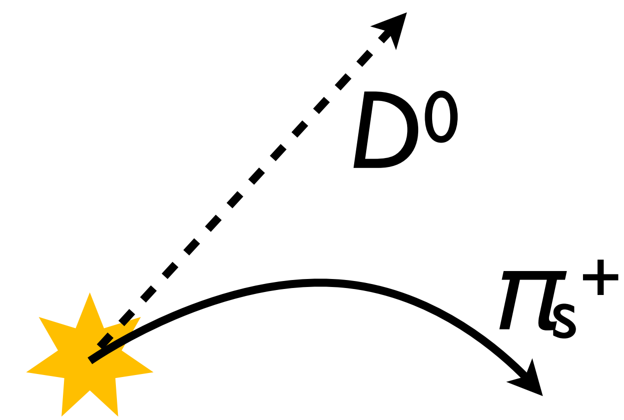
Flavour tagging at LHCb

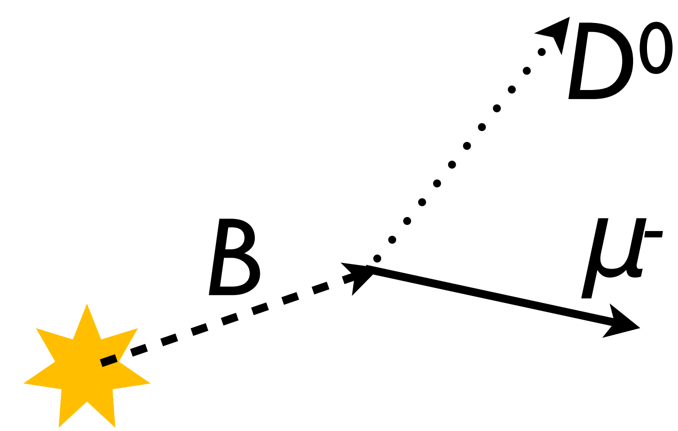
- Need to know flavour at production

- Prompt D*-tagged
  - Larger yields
  - Background from D-from-B

$D^{*\pm} \to D^0\pi^\pm$



- Muon-tagged
  - Lower BF but efficient trigger
  - Larger level of combinatorial background



$B \to D^0\mu^\mp\nu X$

- Doubly-tagged $B \to D^{*\pm}(\to D^0\pi^\pm)\mu^\mp\nu$
  - Very clean signature
  - Smallest samples

Independent complementary samples with independent systematics

Example of yields with $D^0 \to KK$ decays:

44×10^6 π tagged vs 3×10^6 μ tagged samples

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The CP asymmetries

Measure the time integrated asymmetry in the SCS decays $D^0 \to hh$

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

$f = \bar{f} = K^+K^-$
or
$f = \bar{f} = \pi^+\pi^-$

But A_{CP} is not what we measure. We measure

$$A_{\mathrm{raw}}(f) = \frac{N\left(D^{*+} \to D^0(f)\pi_s^+\right) - N\left(D^{*-} \to \bar{D}^0(\bar{f})\pi_s^-\right)}{N\left(D^{*+} \to D^0(f)\pi_s^+\right) + N\left(D^{*-} \to \bar{D}^0(\bar{f})\pi_s^-\right)}$$

where N(X) refers to the number of reconstructed events of decay X after background subtraction

We measure the physical CP asymmetry plus asymmetries due to detection effects and production

$$A_{\mathrm{raw}} = A_{CP} + A_{\mathrm{production}} + A_{\mathrm{detection}}$$

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Nuisance asymmetries ~1%

- Production asymmetry: production rates of D^0 and $\bar{D}^0$ (or B and $\bar{B}$ for secondary charm) are not the same
  - gluon fusion, quarks combine with valence quark from the beam protons, valence quark scattering, etc.

$$A_P = \frac{\sigma(pp \to D) - \sigma(pp \to \bar{D})}{\sigma(pp \to D) + \sigma(pp \to \bar{D})}$$

- Detection asymmetries
  - Detector asymmetries: left-right asymmetries can be cancelled by swapping dipole magnet field
  - Interaction asymmetries: e.g. K^+ cross-section for interaction with matter differs from K^- cross-section

$$A_D = \frac{\epsilon(f) - \epsilon(\bar{f})}{\epsilon(f) + \epsilon(\bar{f})}$$

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ΔA_{CP} cancellations

Main experimental challenge: separate the asymmetries

$$A_{\text{raw}} = A_{CP} + A_{\text{production}} + A_{\text{detection}}$$

Take the raw asymmetry difference:
experimentally more robust

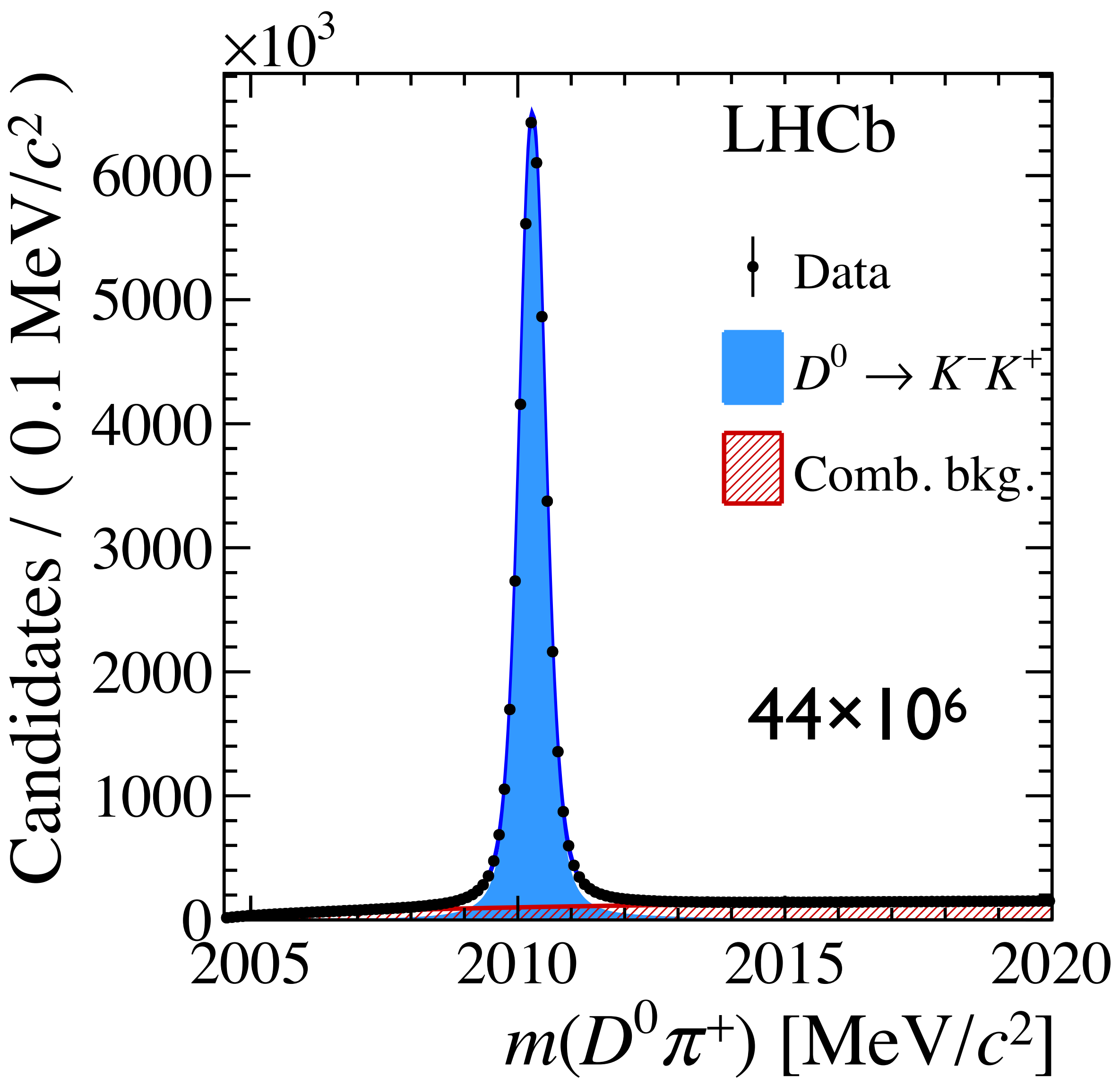
1st order

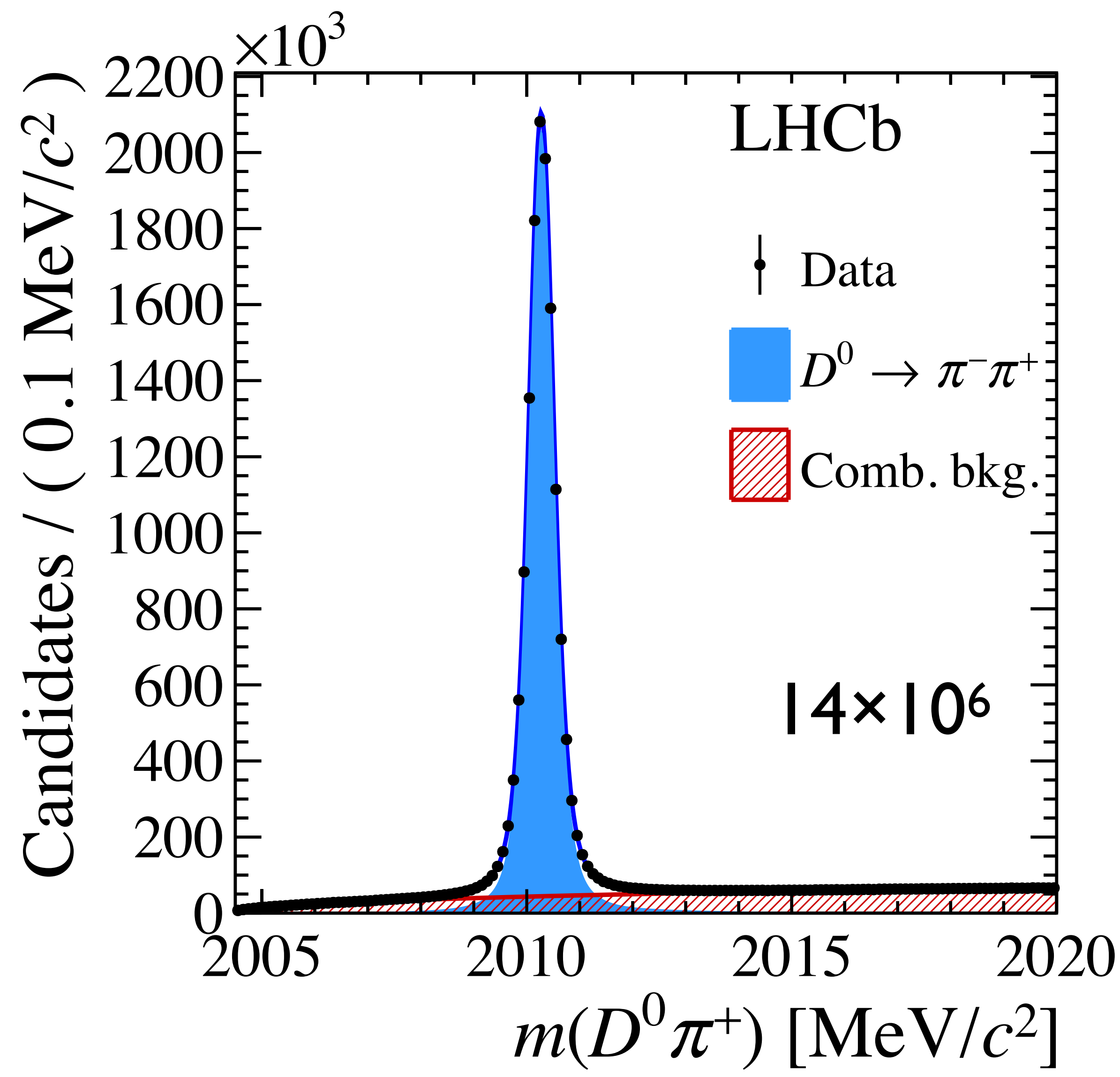
$$\Delta A_{CP} \equiv A_{\text{raw}}(K^+K^-) - A_{\text{raw}}(\pi^+\pi^-) \approx A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-)$$

Second order effects reduced by kinematic weighting:
the nuisance asymmetries depend on the kinematics,
A_{CP} does not

Signal $D^0 \to hh$ decays

LHCb, Phys. Rev. Lett. 122 (2019) 211803

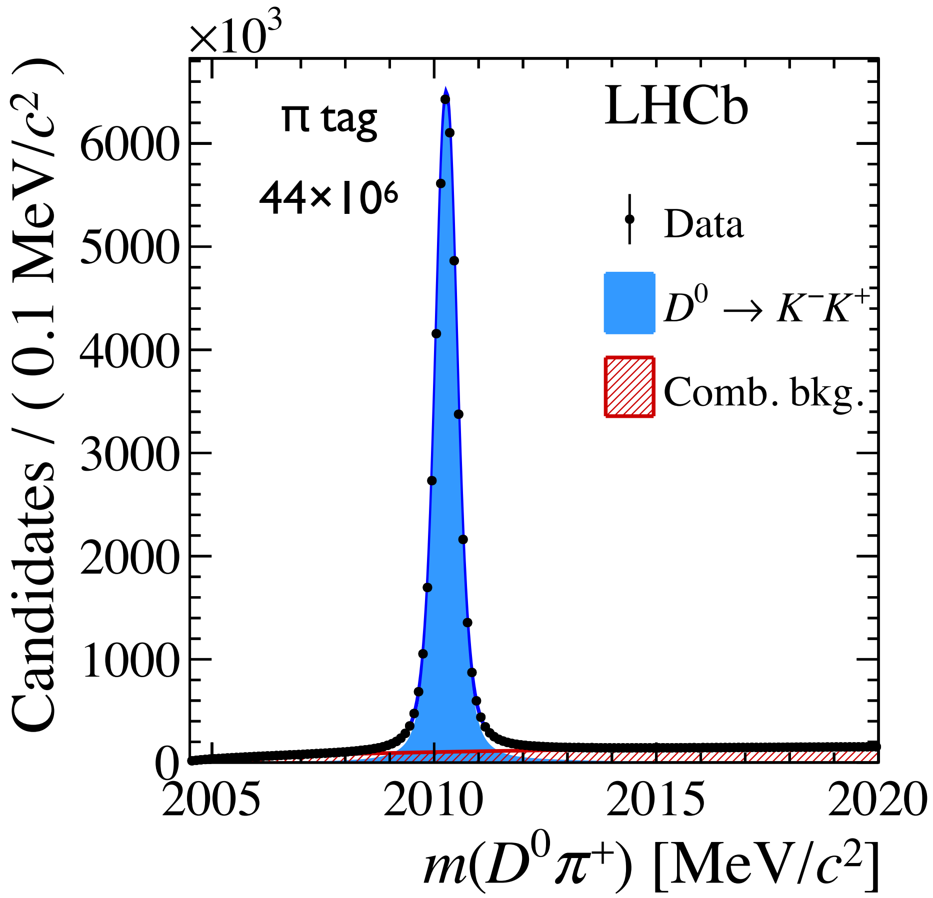


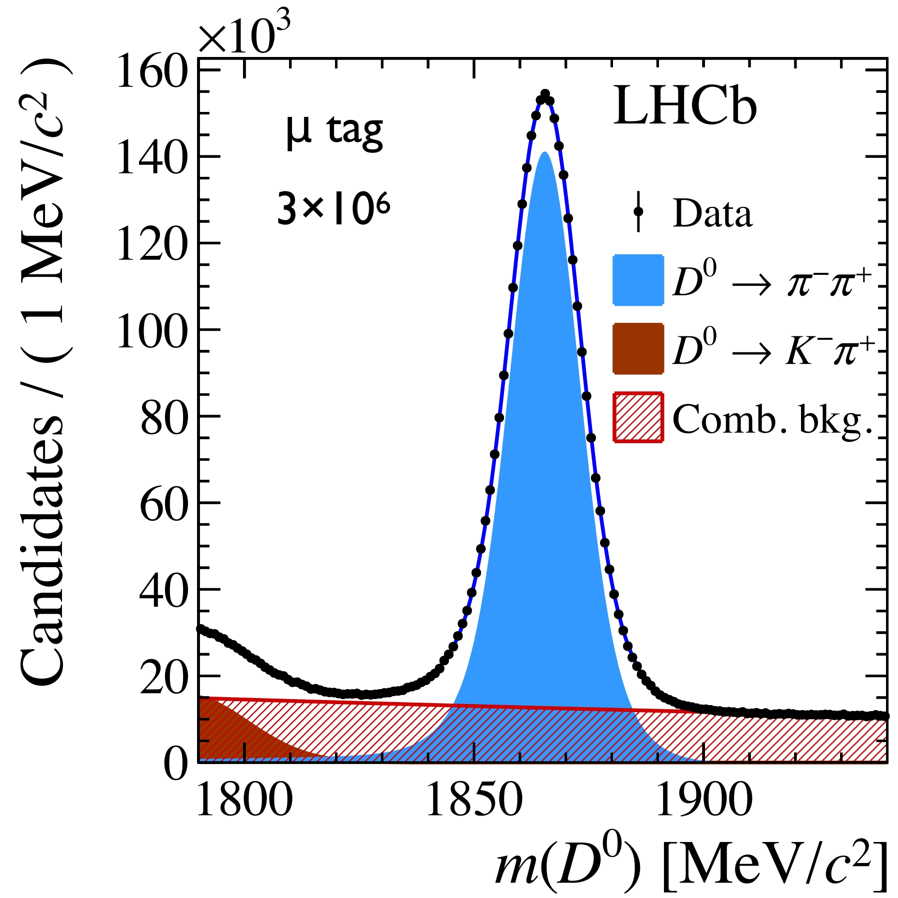


ΔA_{CP} combined results

- Full Run 1+2 result (9 fb^{-1}) determined from prompt charm (π tag) and charm from B decays (μ tag)

LHCb, Phys. Rev. Lett. 122 (2019) 211803





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

- First observation of CPV in charm decays

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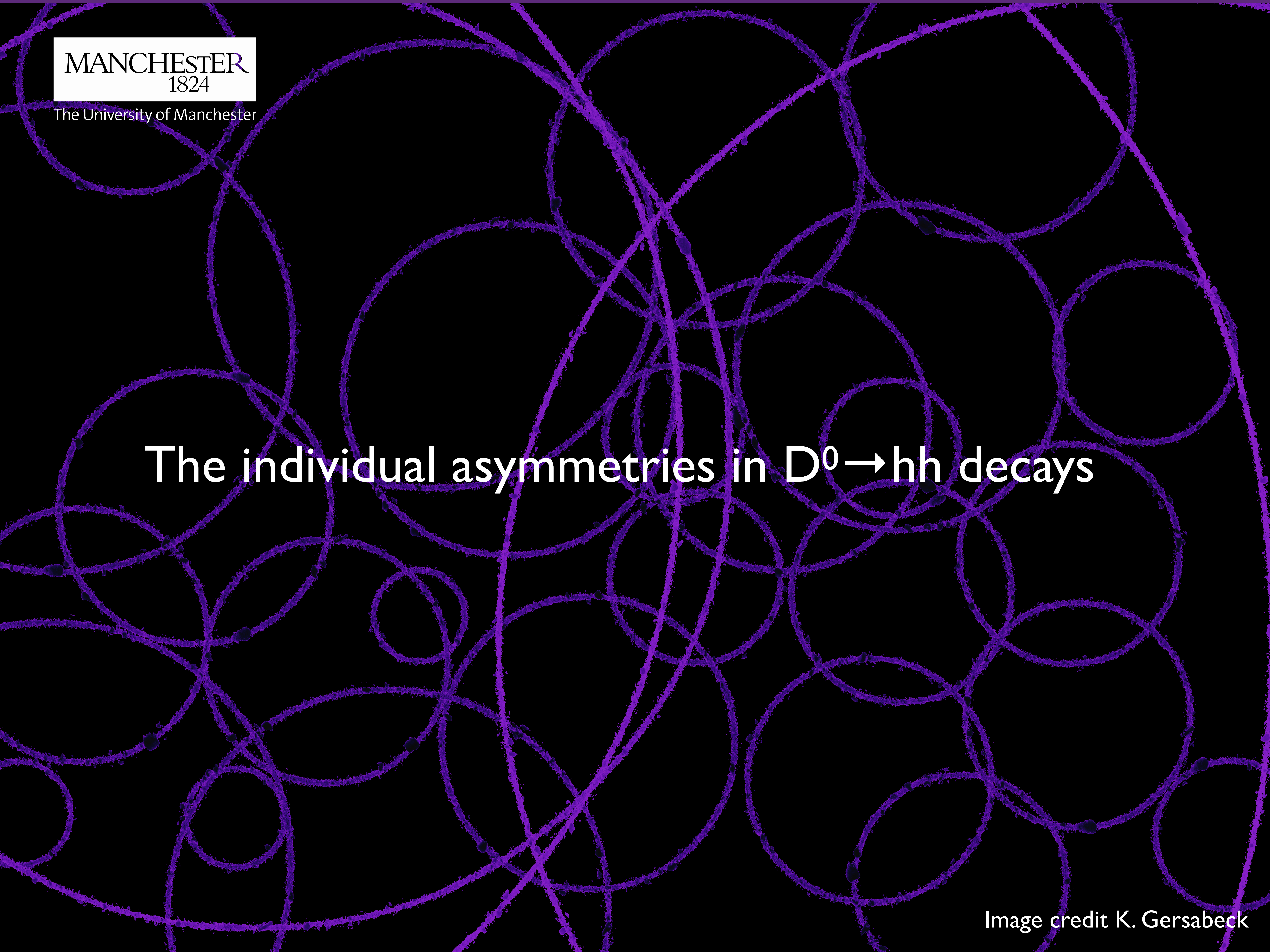


The individual asymmetries in $D^0 \to hh$ decays

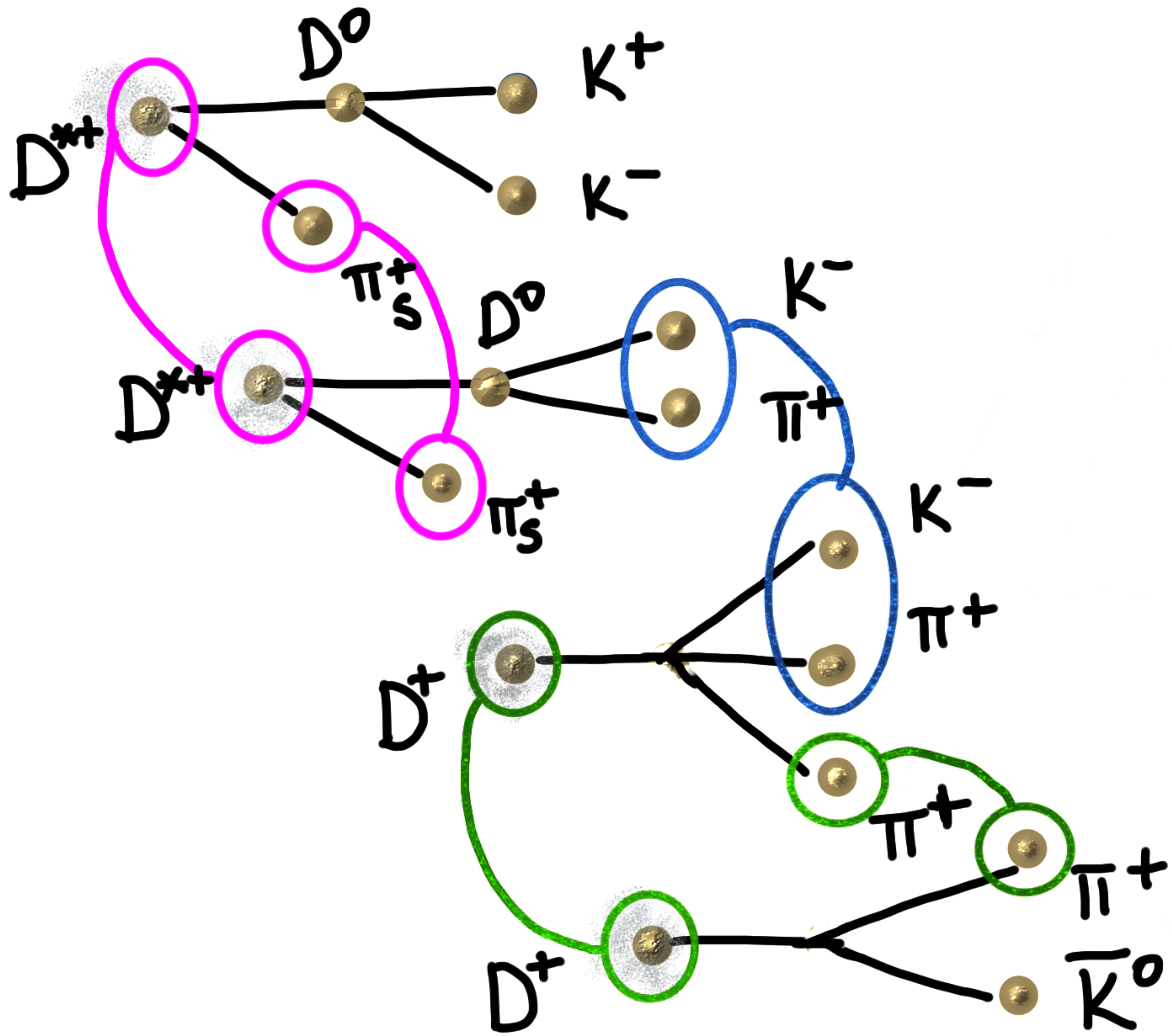
Image credit K. Gersabeck

Strategy

- Use control samples, Cabibbo favoured decays, where no CP violation is expected
- Two different sets of control samples (statistically independent):
  - D^+ decays
  - D_s^+ decays
- Reweight the relevant kinematic distribution so second order effects cancel

Cancelation of detection and production asymmetries

arXiv:2209.03179



*similar scheme exists for D_s^+ decays

Signal and control samples (D+ modes)

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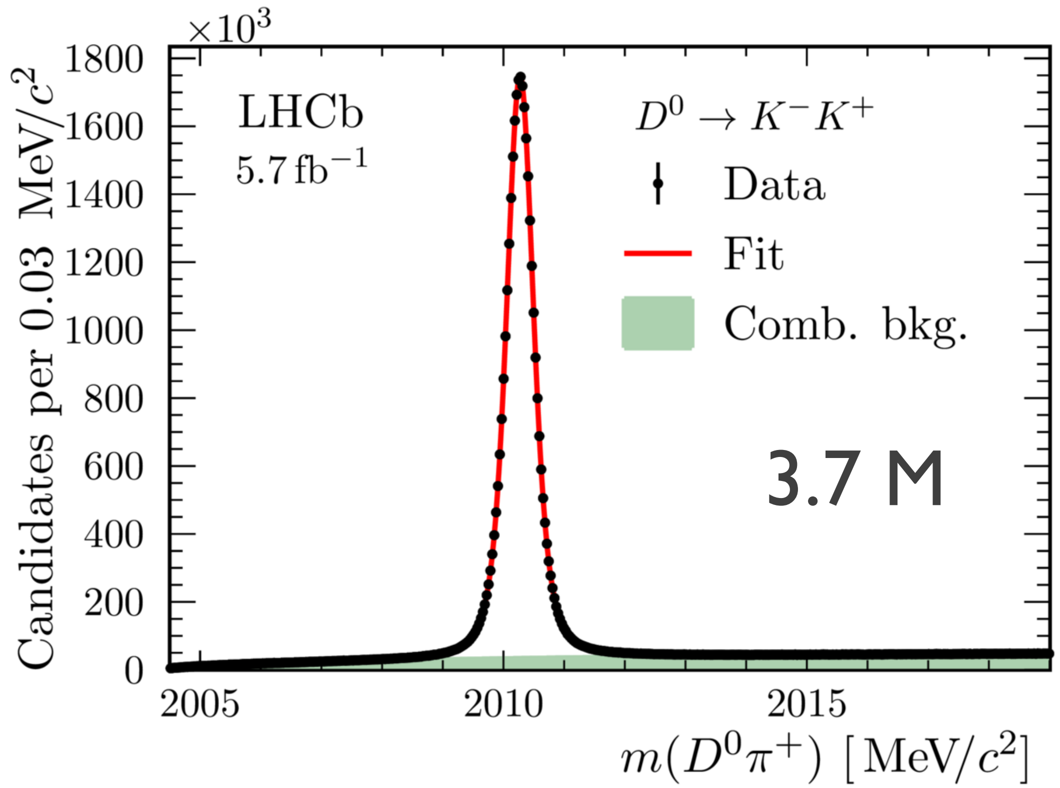
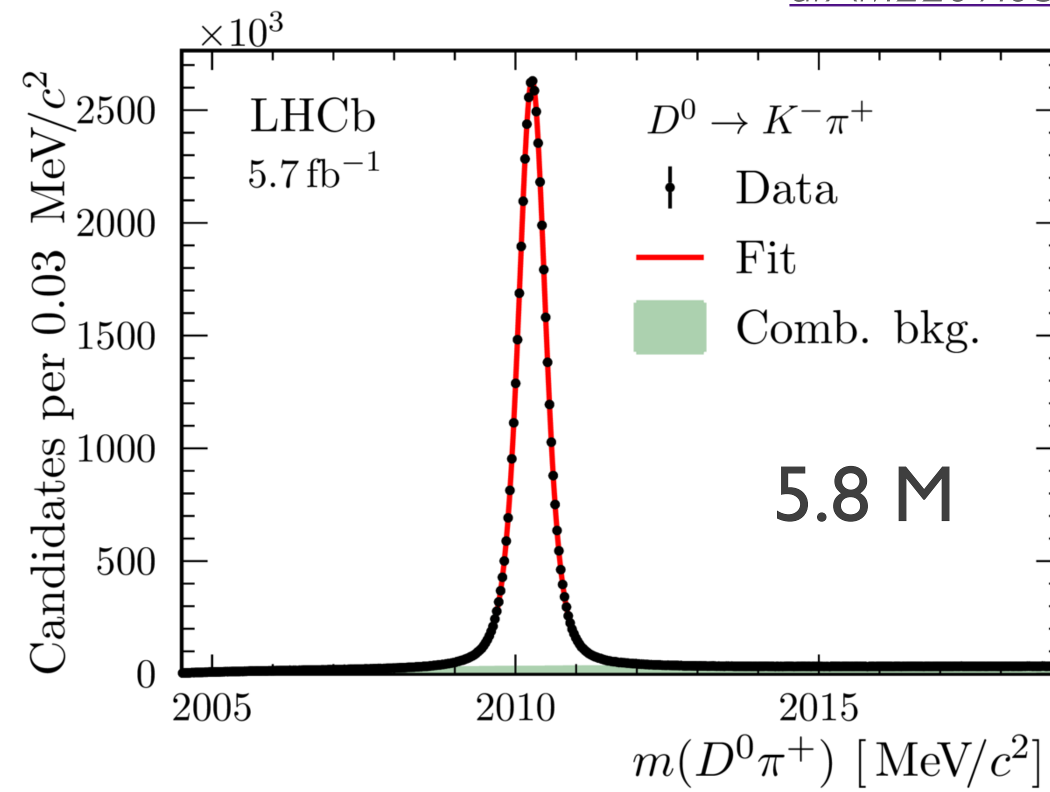
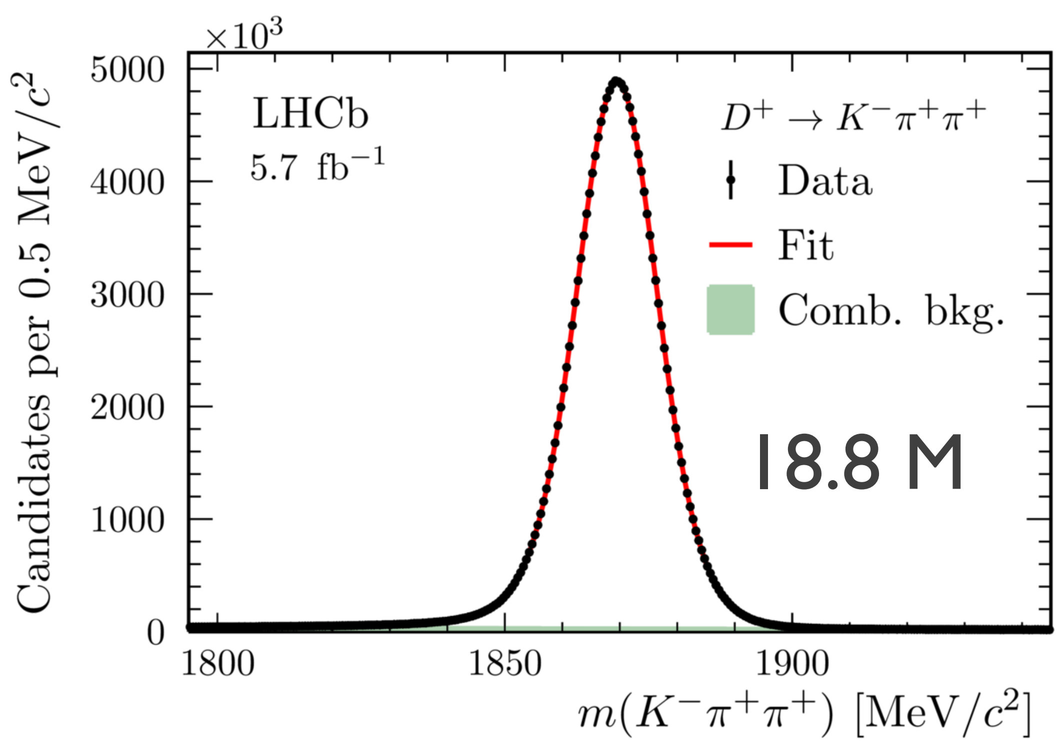
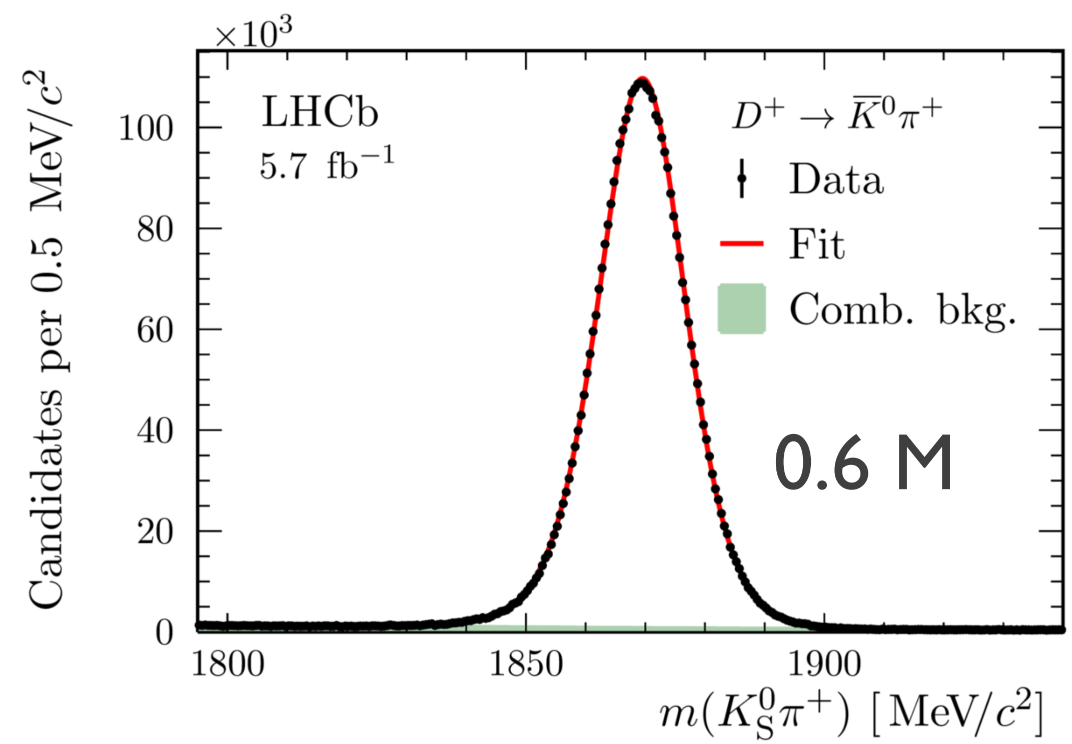
arXiv:2209.03179









*similar plots for D_s^+ decays

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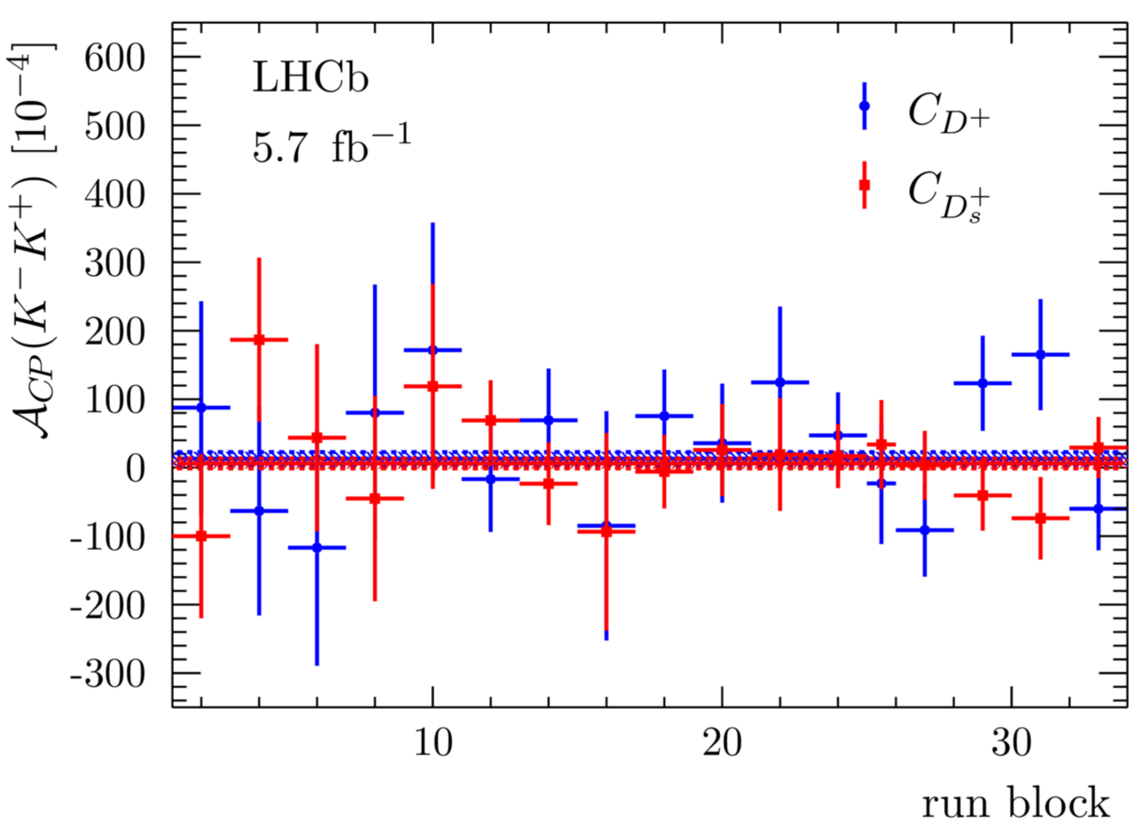
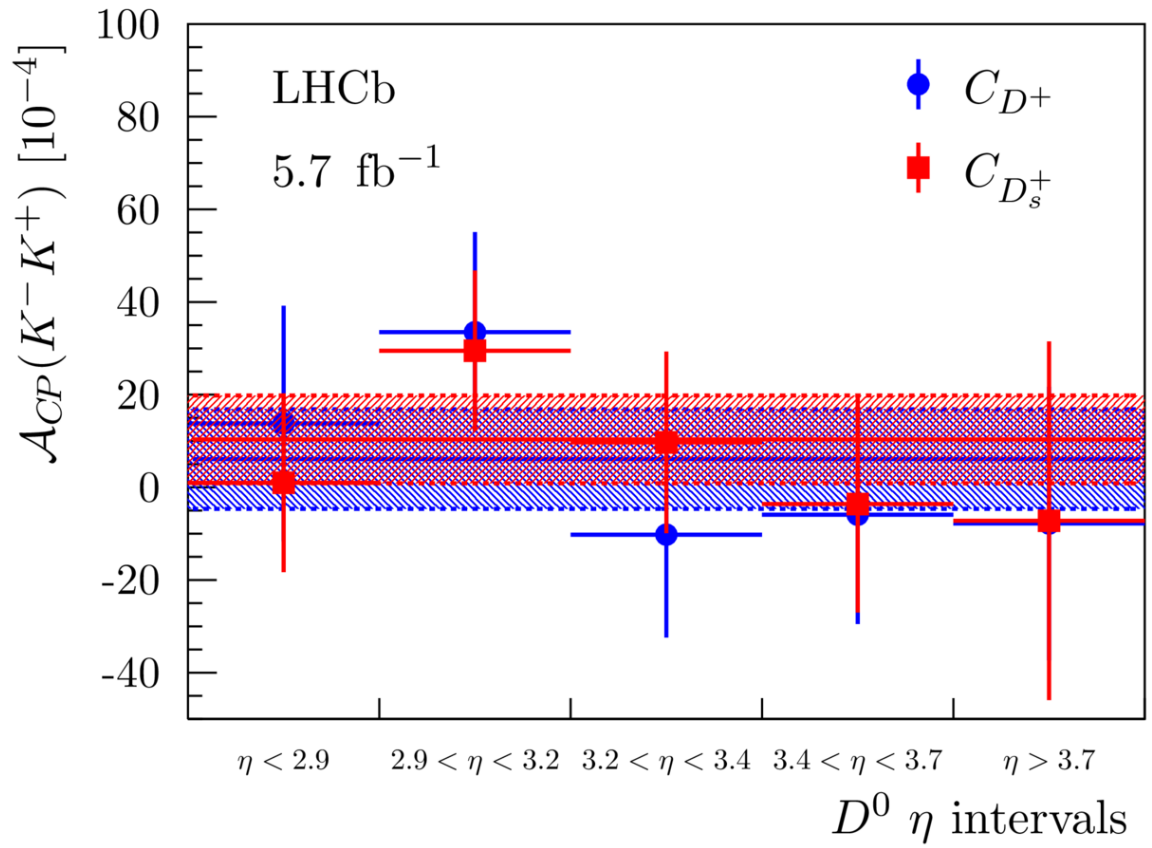
Cross checks

arXiv:2209.03179

- Various stability and cross checks performed
  - As a function of run number block
  - Year and magnet polarity split
  - Kinematics
  - Decay time





First evidence for CP violation in $D^0 \to \pi\pi$

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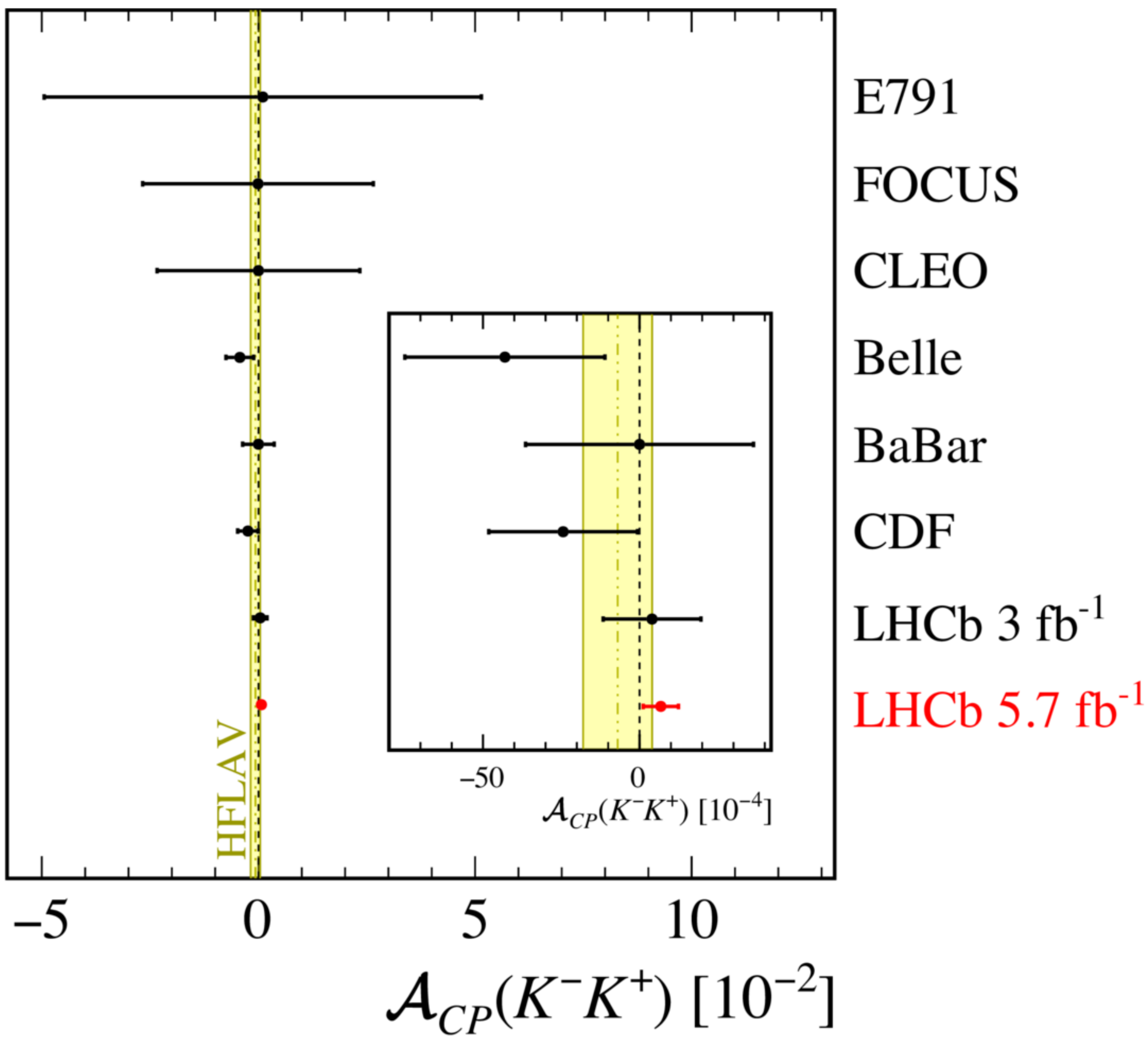
$$A_{CP}(K^-K^+) = (6.8 \pm 5.4 \pm 1.6) \times 10^{-4}$$



arXiv:2209.03179

ΔA_{CP} mostly a measure of direct CP violation

$$\Delta A_{CP} \equiv A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) \approx a^{\rm d}_{CP}\left(1 + \frac{\langle t \rangle}{\tau}\Delta Y_f\right)$$

$$a^d_{K^-K^+} = (7.7 \pm 5.7) \times 10^{-4}$$

$$a^d_{\pi^-\pi^+} = (23.2 \pm 6.1) \times 10^{-4}$$

Inconsistent with the CP symmetry hypothesis (3.8σ)

First evidence for direct CP violation in a specific charm decay, $D^0 \to \pi^-\pi^+$

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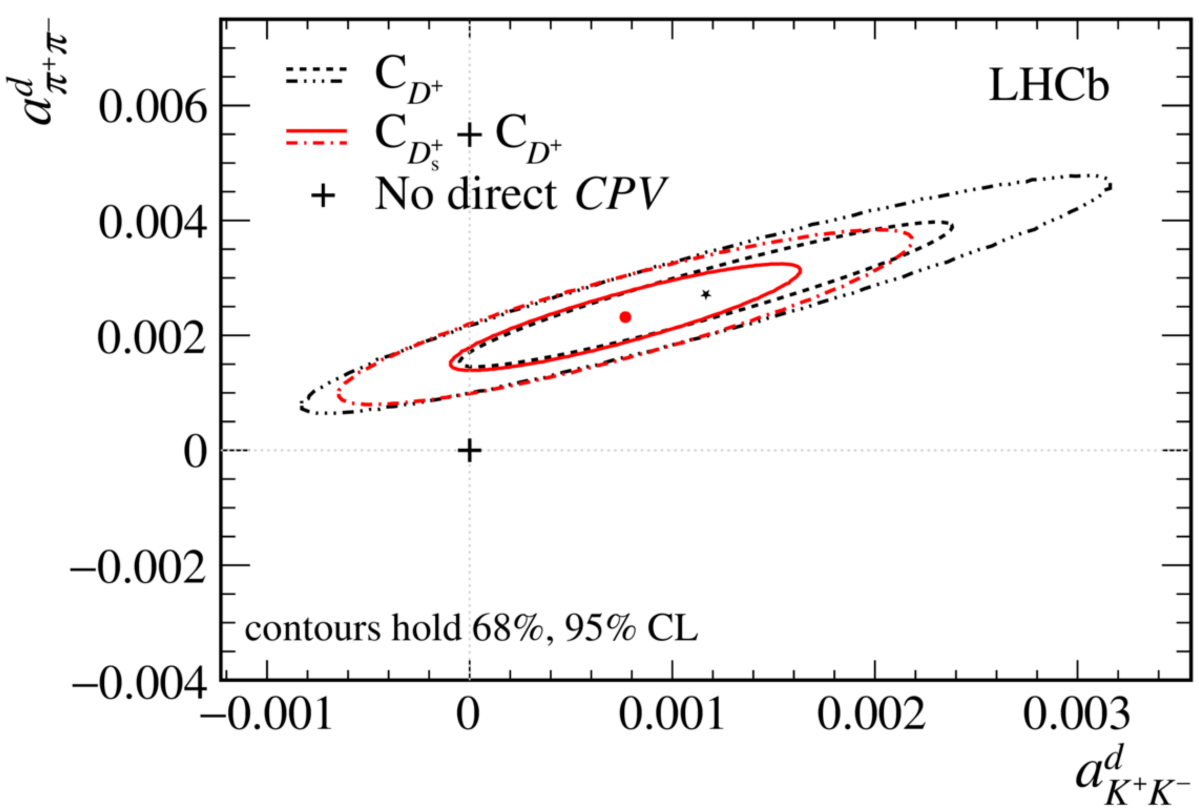
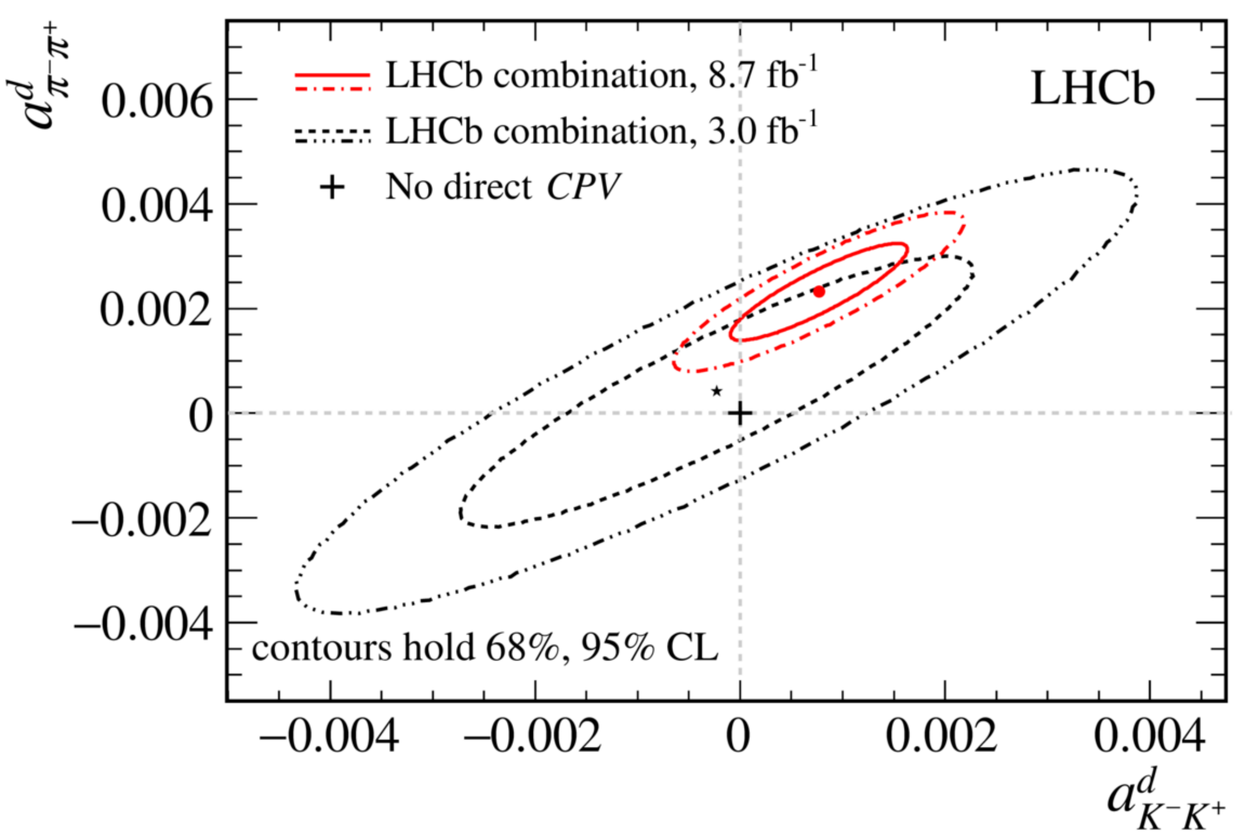
Combined results

arXiv:2209.03179

Improved precision thanks to the inclusion of D^+_s modes

Combination of Run 1 and Run 2 results





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Other two-body decays

Image credit K. Gersabeck

Search for CP violation in $D_{(s)}^+ \to \eta\pi^+$ and $D_{(s)}^+ \to \eta'\pi^+$ decays

JHEP 04 (2023) 081

- Cabibbo favoured $D_s^+ \to \eta^{(')}\pi^+$
- Singly Cabibbo suppressed $D^+ \to \eta^{(')}\pi^+$
- Run 2 data, 6 fb^{-1}
- Follow a similar strategy:
  - Measure raw asymmetry $$A_{\mathrm{raw}} = A_{CP} + A_{\mathrm{production}} + A_{\mathrm{detection}}$$
  - Cancelation of detection and production asymmetries with control samples $D_{(s)}^+ \to \phi\pi^+$

$$A_{\mathrm{raw}}(D^+ \to \eta^{(')}\pi^+) - A_{\mathrm{raw}}(D^+ \to \phi\pi^+) = A_{CP}(D^+ \to \eta^{(')}\pi^+) - A_{CP}(D^+ \to \phi\pi^+)$$

known

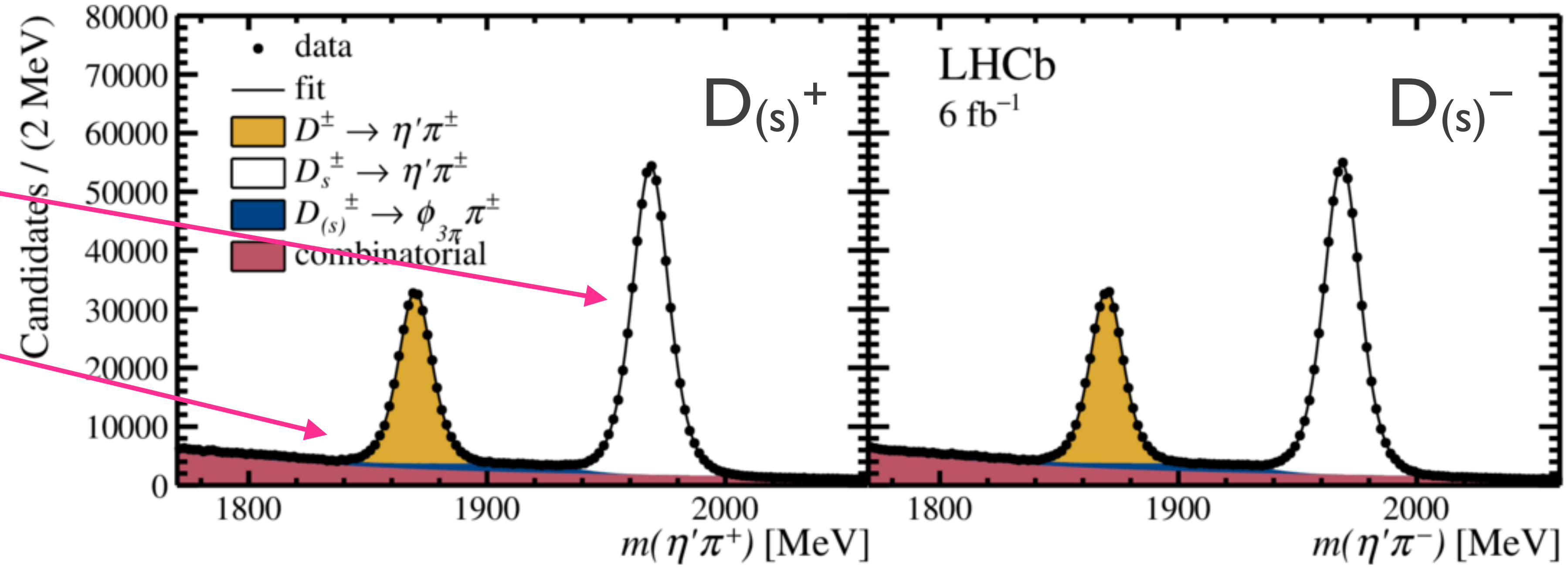
$$A_{\mathrm{raw}}(D_s^+ \to \eta^{(')}\pi^+) - A_{\mathrm{raw}}(D_s^+ \to \phi\pi^+) = A_{CP}(D^+ \to \eta^{(')}\pi^+)$$

Signal samples

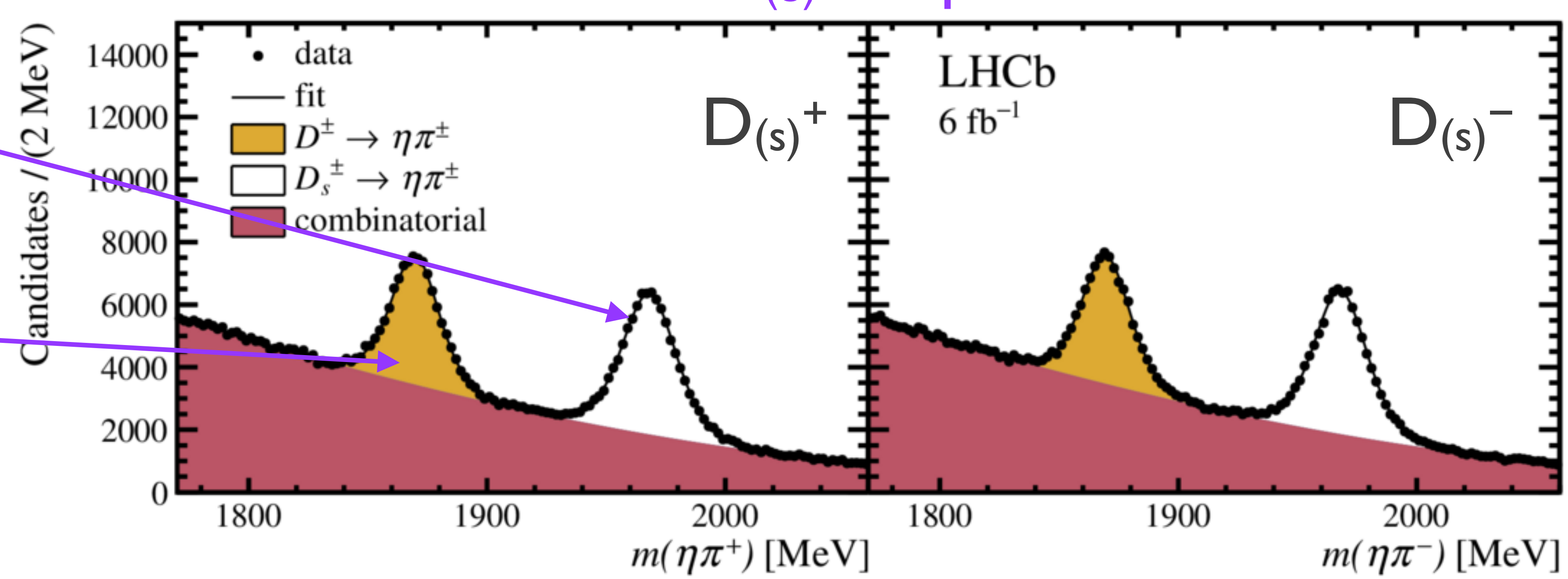
- Yields for
- $D_s^+ \rightarrow \eta'\pi^+$ 1.1 M
- $D^+ \rightarrow \eta'\pi^+$ 0.6 M
- $D_s^+ \rightarrow \eta\pi^+$ 0.1 M
- $D^+ \rightarrow \eta\pi^+$ 0.1 M

$D_{(s)}^+ \rightarrow \eta'\pi^+$

JHEP 04 (2023) 081



$D_{(s)}^+ \rightarrow \eta\pi^+$



Results

- Combination of Run 1 and Run 2 results

JHEP 04 (2023) 081

$$\mathcal{A}^{CP}(D^+ \to \eta\pi^+) = (0.13 \pm 0.50 \pm 0.18)\%,$$
$$\mathcal{A}^{CP}(D_s^+ \to \eta\pi^+) = (0.48 \pm 0.42 \pm 0.17)\%,$$
$$\mathcal{A}^{CP}(D^+ \to \eta'\pi^+) = (0.43 \pm 0.17 \pm 0.10)\%,$$
$$\mathcal{A}^{CP}(D_s^+ \to \eta'\pi^+) = (-0.04 \pm 0.11 \pm 0.09)\%,$$

- Statistically dominated
- Compatible with CP symmetry

Multibody decays

Image credit K. Gersabeck

Multibody decays

- Multibody decays: final states are reached mainly through resonances
- Unique sensitivity to phases
- Excellent environment for CP violation: strong-phase differences varying across the Dalitz plot enhance the sensitivity

$$a_{CP} \equiv \frac{|A|^2 - |\bar{A}|^2}{|A|^2 + |\bar{A}|^2} = 2r\sin(\delta)\sin(\phi)$$

- Can use model-dependent (amplitude analyses) and model independent methods (binned, unbinned)
- Huge samples: a bless and a curse for model-dependent methods

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Why go model independent?

- Fast discovery tools
- Binned or unbinned methods
- Can be used for direct and indirect CP violation tests
  - Will cover direct CP violation today
  - By design sensitive to local asymmetries rather than to global asymmetries

More details in the talk "Model-independent searches for direct CP violation in charm decays" by M. Gersabeck

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The Energy test

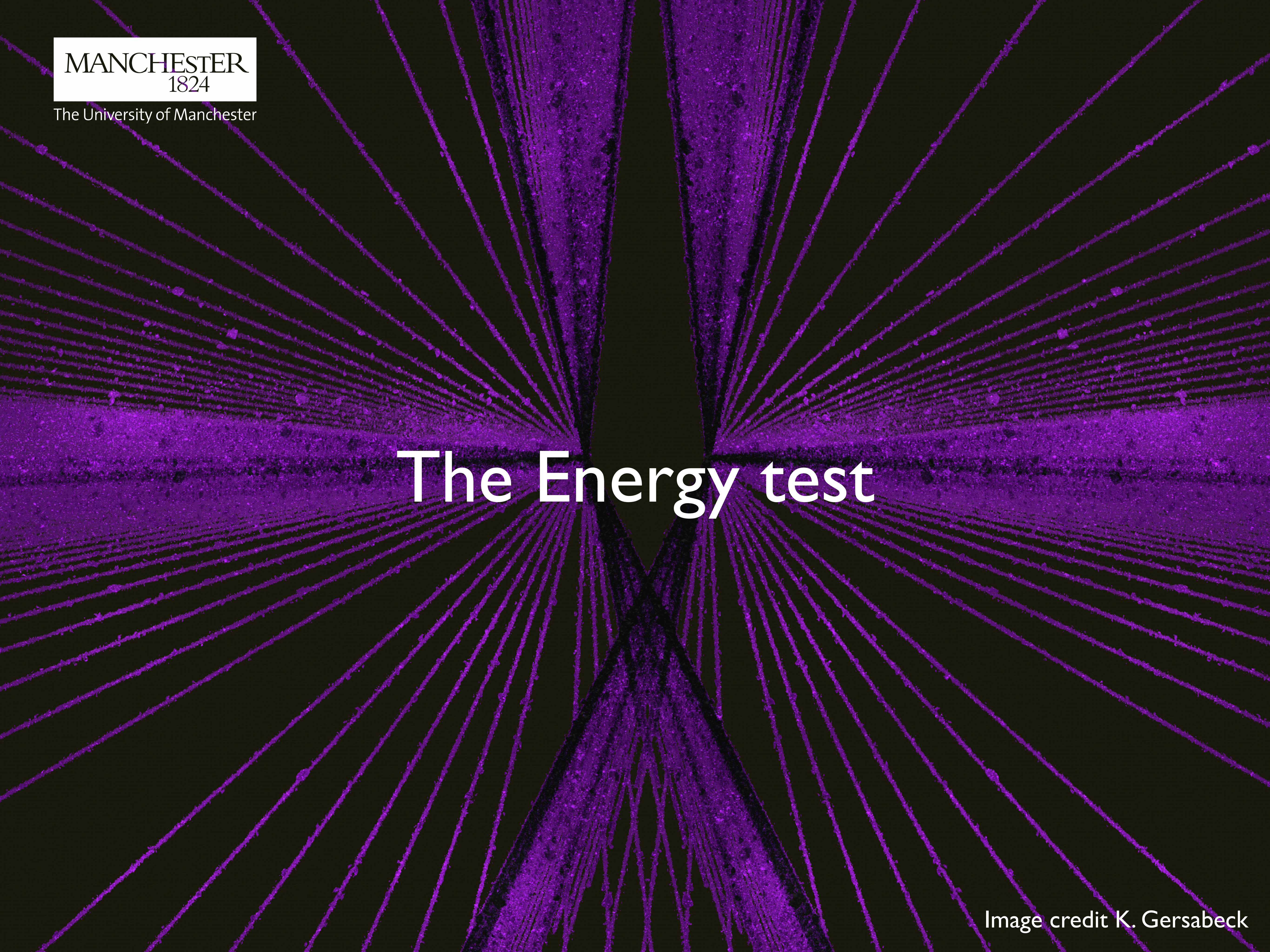

Image credit K. Gersabeck

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Energy test

- The Energy test uses a distance function ψ_{ij} to compute a T value
- T compares the average distance between pairs of events in the phase space

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

Average distance in the first sample

Average distance in the second sample

Average distance between the two samples

- The distance function

$$\psi(d_{ij}) = e^{-d_{ij}^2/2\delta}$$

Phase space distance

$$d_{ij}^2 = \sum_{k=1}^{D} (x_{k,i} - x_{k,j})^2$$

Our case

$$x_{k,i} = m_{k,i}^2$$

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Optimising the sensitivity

- δ is a tunable distance parameter describing the effective phase-space radius where a local asymmetry is measured
- δ is analogous to the bin size in a binned approach
- It must be:
  - Larger than the resolution of d_{ij}
  - Small enough not to dilute local asymmetries
  - Optimised value from sensitivity studies

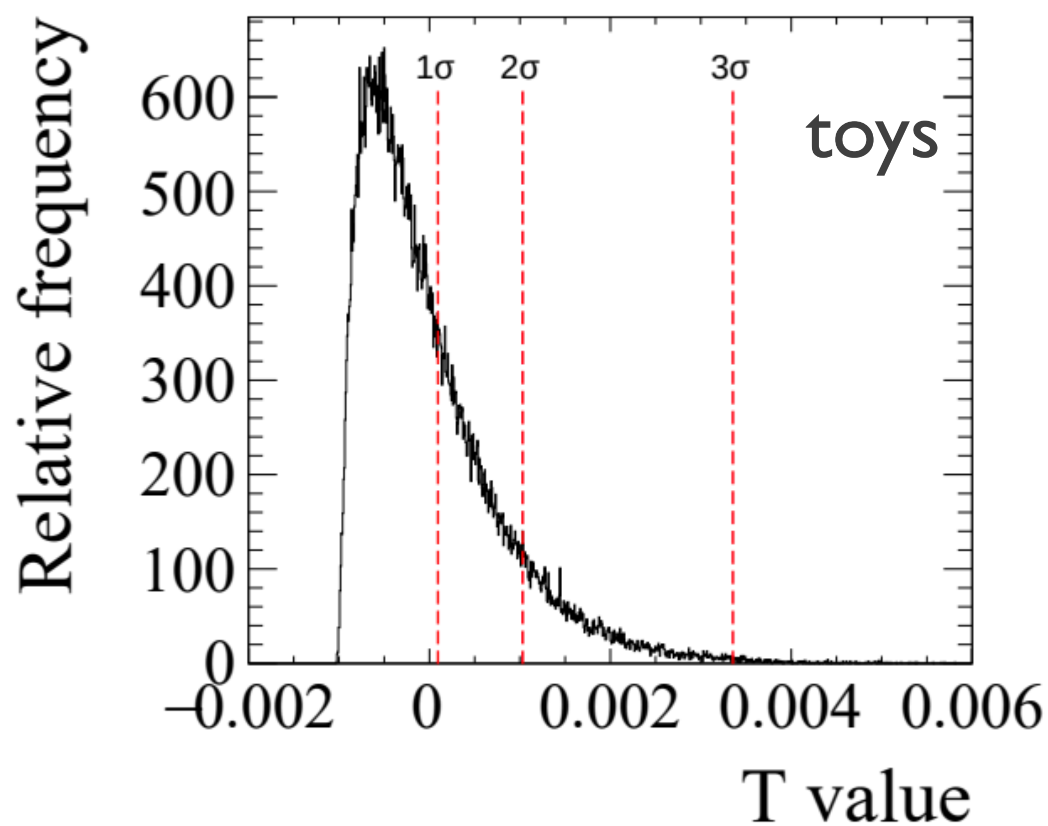
The Energy test in a nutshell

Used in: Phys. Rev. D102 (2020) 051101

Phys. Lett. B740 (2015) 158

Phys. Lett. B769 (2017) 345

- Split sample is D^0 and $\bar{D}^0$ decays
- Compute reference T value
- Compute T values from permuted samples using random flavour tags (null hypothesis)
- Compute P-value = fraction of permuted T values > reference T value



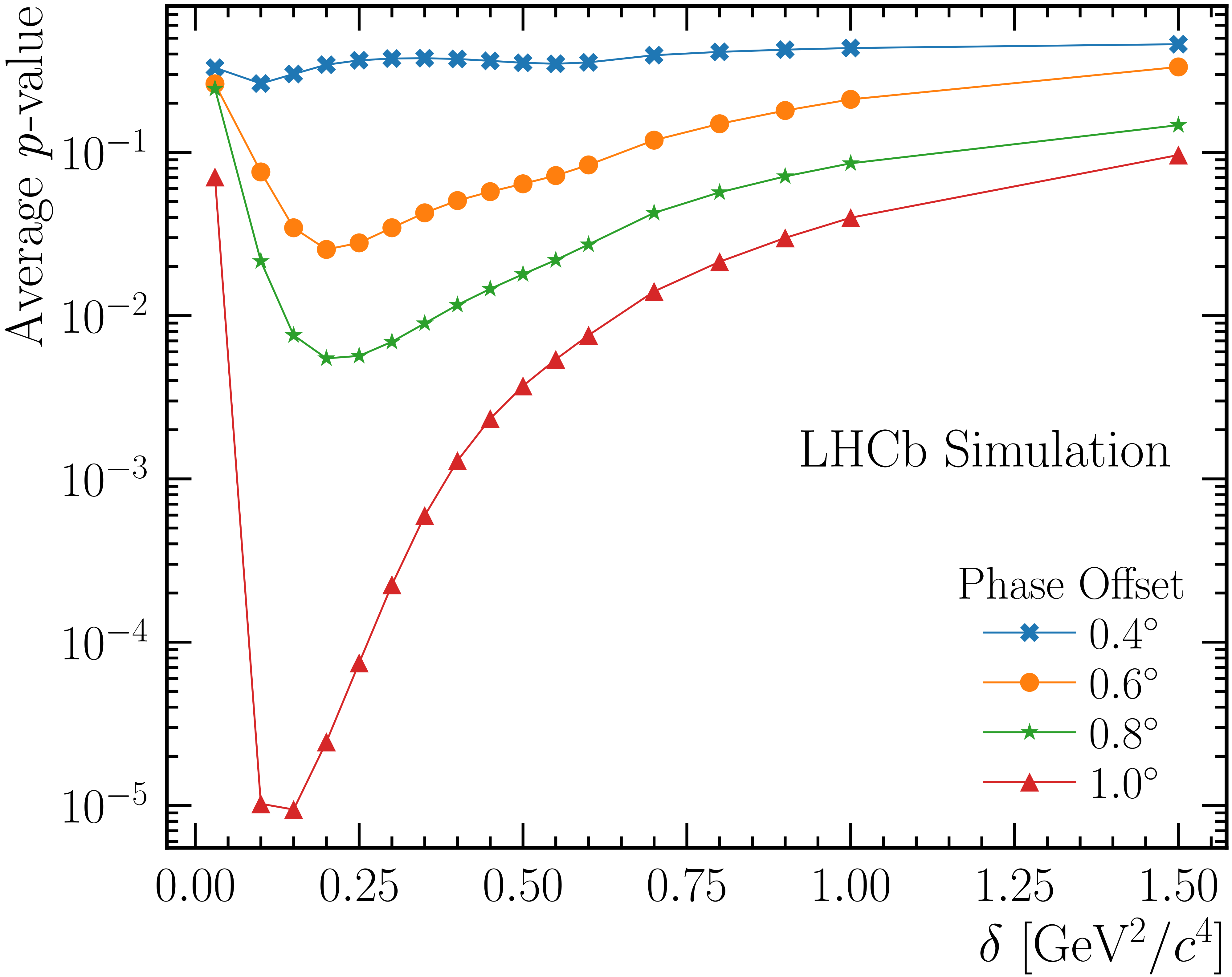
*plot credit Gianluca Zunica

Sensitivity studies

- To verify that and how sensitive the Energy test is to CP violation:
  - Simulate samples with comparable size to the Run 2 data samples
  - Simulation inspired by model
  - Input different amplitude and phase asymmetries in different resonances (e.g. 1%, 2%, 5%, 10% or 1°,2°,5°, ….)
  - Run the Energy test
  - Reset and repeat for a a set of δ values (i.e. perform a so called "δ-scan")
  - Plot the P-value distributions
  - Choose the δ value (or values) that ensures the lowest P-values (i.e. the best sensitivity)

Sensitivity studies

[arXiv:2306.12746]

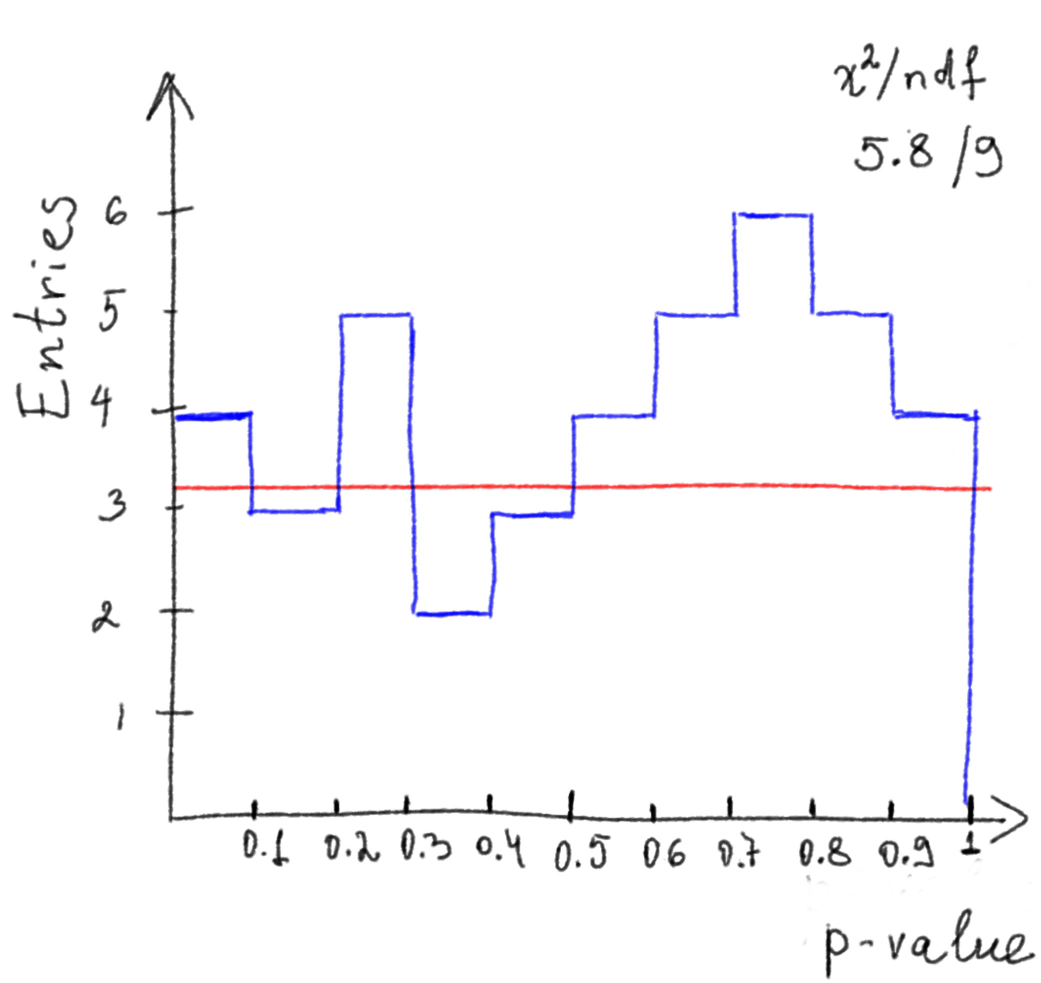


Validation of the Energy test

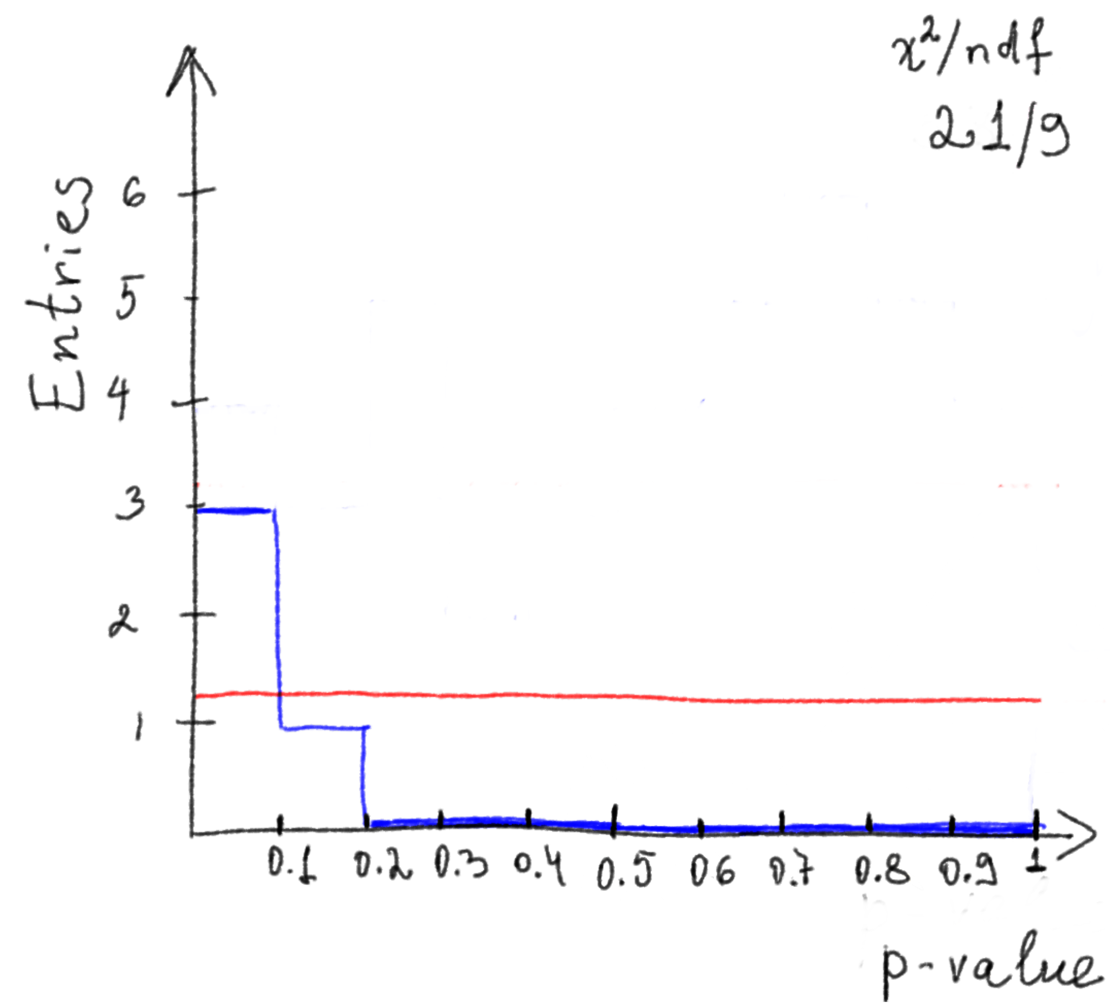
- To validate the Energy test is insensitive to instrumentation asymmetries a control channel is needed:
  - Same/ similar final state particles
  - No CP violation expected: Cabibbo favoured decays are great control samples
  - High statistics
- Apply signal requirement to control channels
  - Split into n subsamples with signal sample statistics
  - Run Energy test with optimised δ value
  - Compute and plot the P-values

Symmetric or not?

- For visualisation only:



Symmetric: flat distribution of the p-values



Asymmetric: p-values accumulate in the first bin

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

- Singly Cabibbo suppressed D^0 decays
- Prompt sample tagged by $D^{*+} \to D^0\pi^+$
- Run 1 result [PLB 740 (2015) 158]: p-value = 2.6%
- LHCb Run 2 data (6 fb^{-1}): four times larger than the Run 1 sample
- Control sample: $D^0 \to K^-\pi^+\pi^0$
- π^0 reconstructed from two photons: merged or resolved

[arXiv:2306.12746]

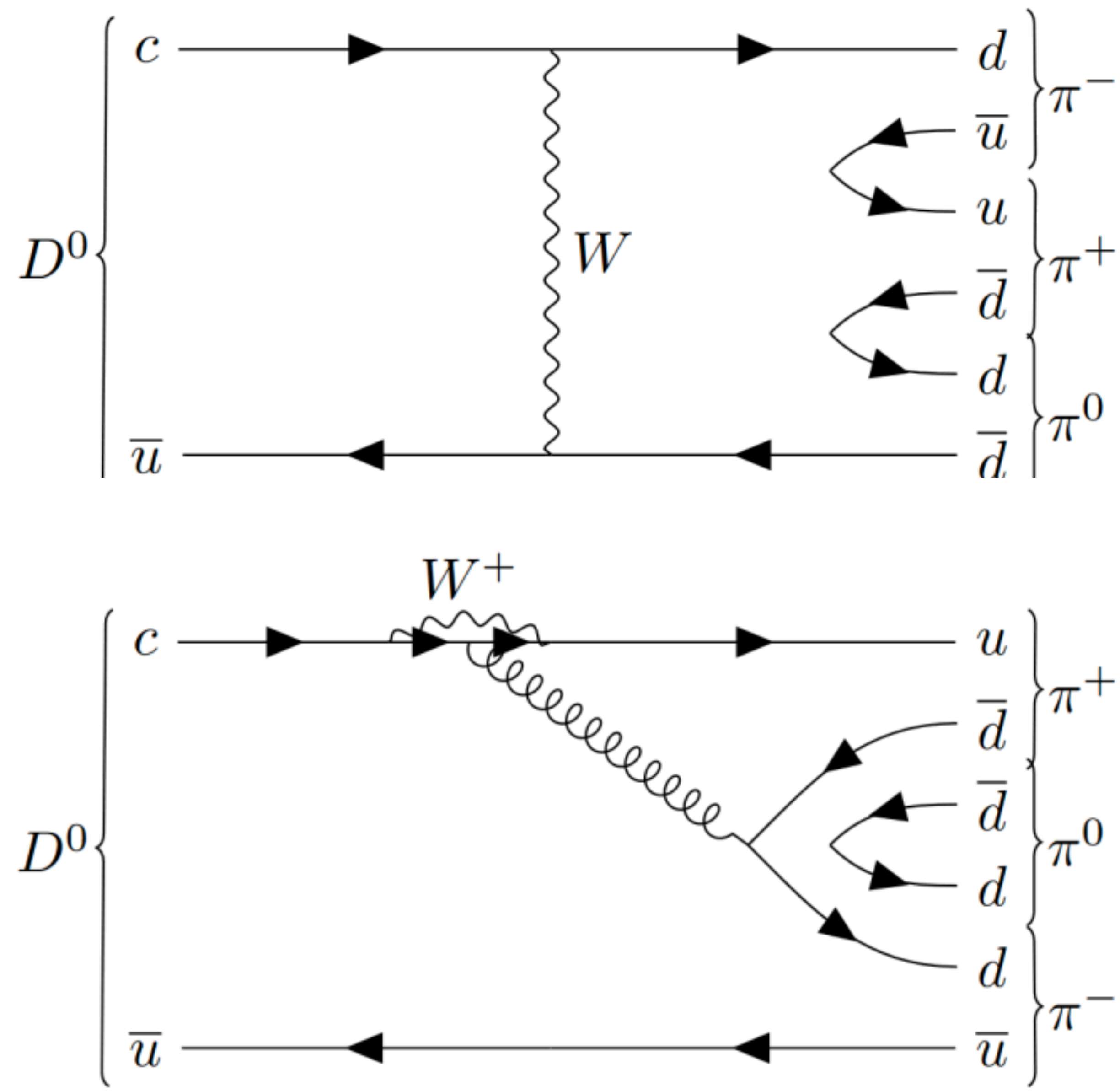
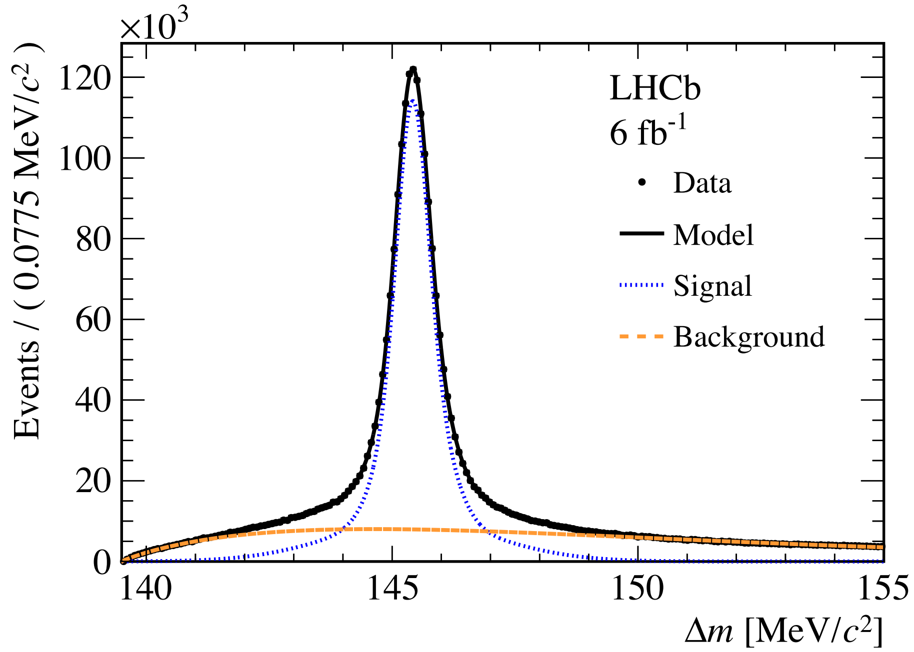


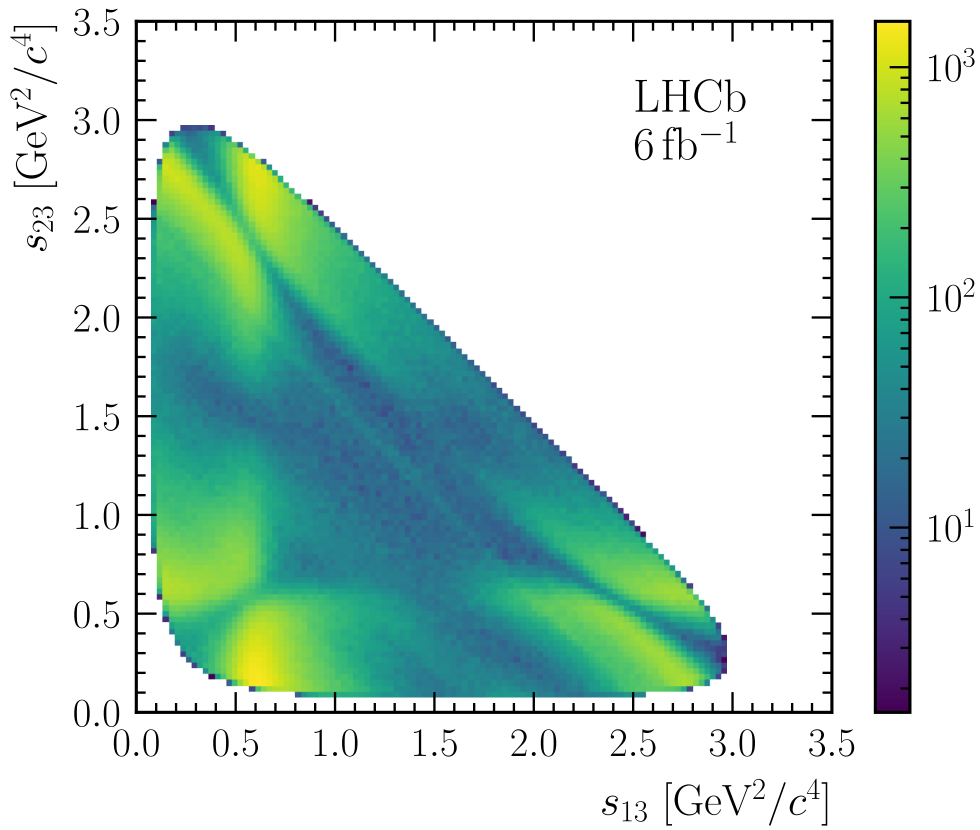
*image credit Lanxing Li

Signal distributions

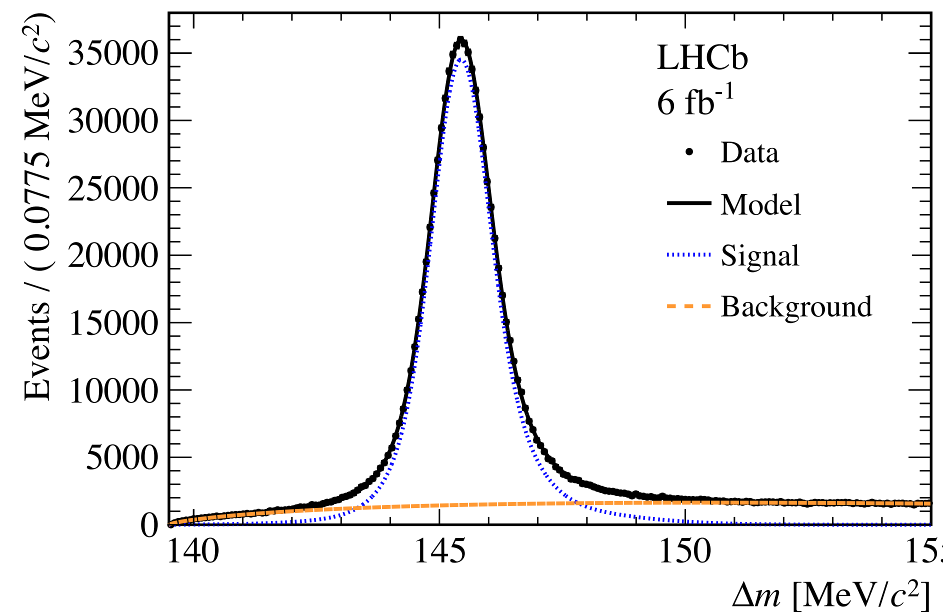
[arXiv:2306.12746]

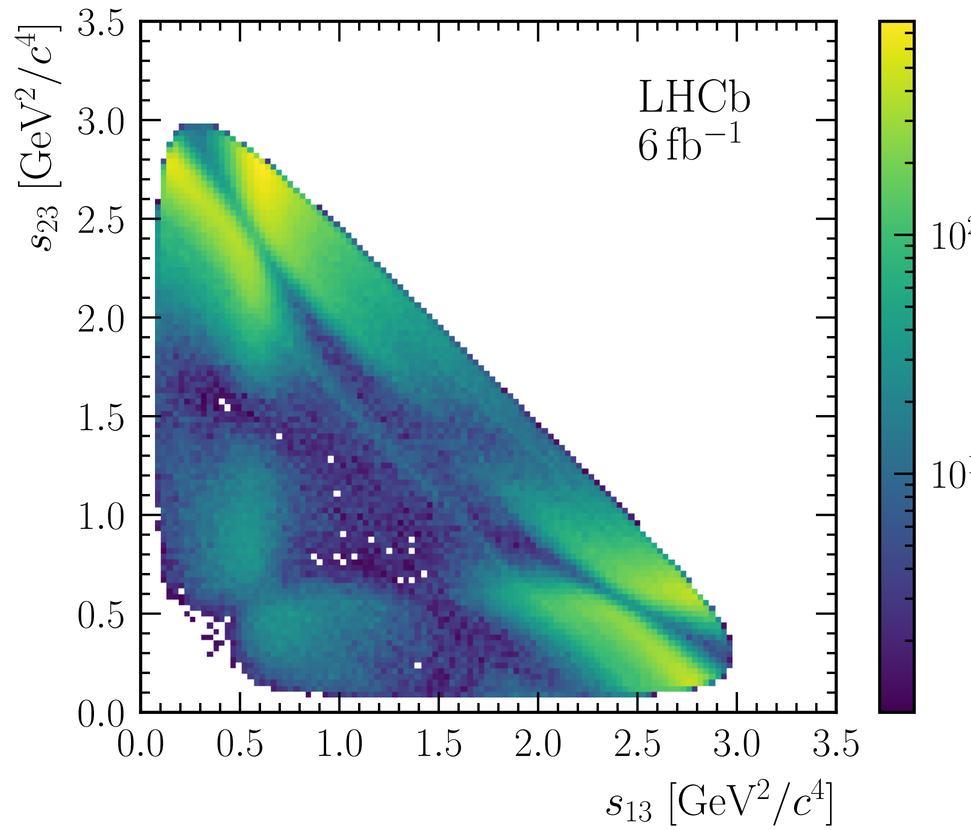
Resolved π^0:1.7 M, Purity 81%





Merged π^0:0.8 M, Purity 91%

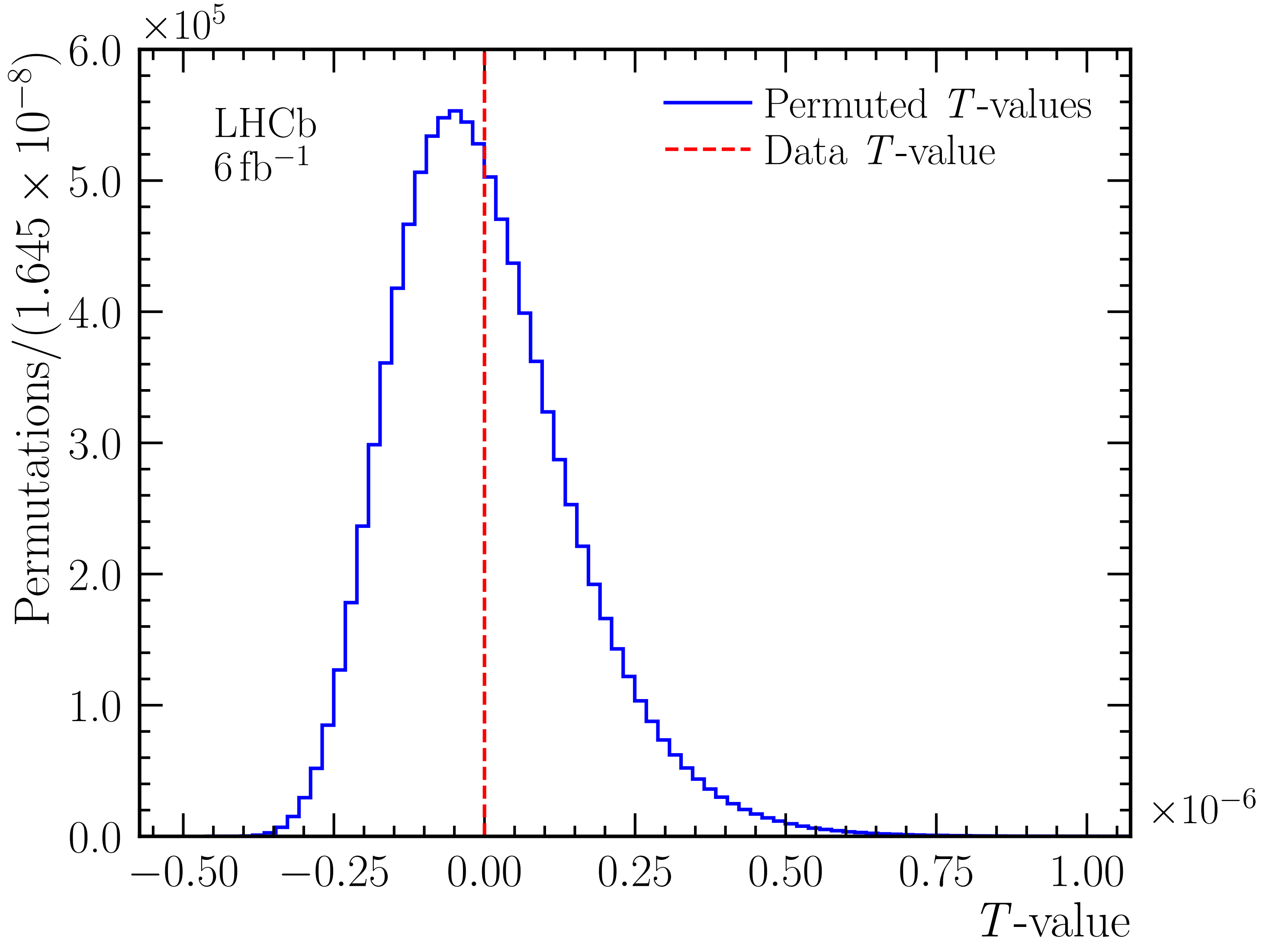




CP violation results in $D^0 \to \pi^+\pi^-\pi^0$

[arXiv:2306.12746]

- No evidence for local CP violation
- p-value = 61%



Search for CP violation in $D^0 \rightarrow K^0_S K^{\mp}\pi^{\pm}$

- Prompt sample tagged by $D^{*+} \rightarrow D^0\pi^+$
- LHCb Run 2 data (5.4 fb^{-1})
- Amplitude analysis with Run 1 data, including model dependent search for CP violation

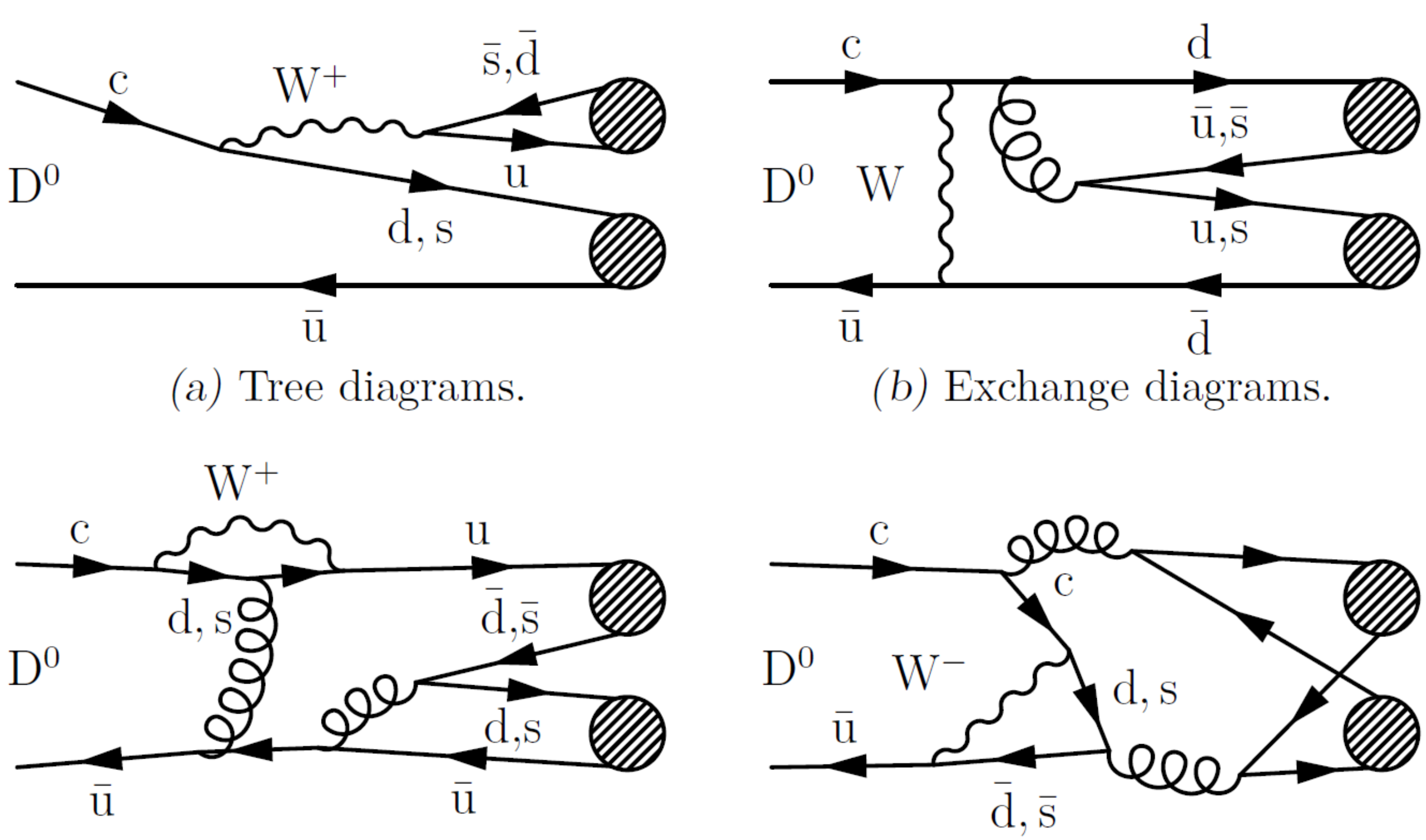
  Phys. Rev. D 93 (2016) 052018,

- Control samples $D^0 \rightarrow K^0_S\pi^+\pi^-$ and $D^0 \rightarrow K^-\pi^+\pi^-\pi^+$

Singly Cabibbo suppressed decays

$D^0 \rightarrow K^0_S K^-\pi^+$, $D^0 \rightarrow K^0_S K^+\pi^-$,

$\bar{D}^0 \rightarrow K^0_S K^-\pi^+$, $\bar{D}^0 \rightarrow K^0_S K^+\pi^-$



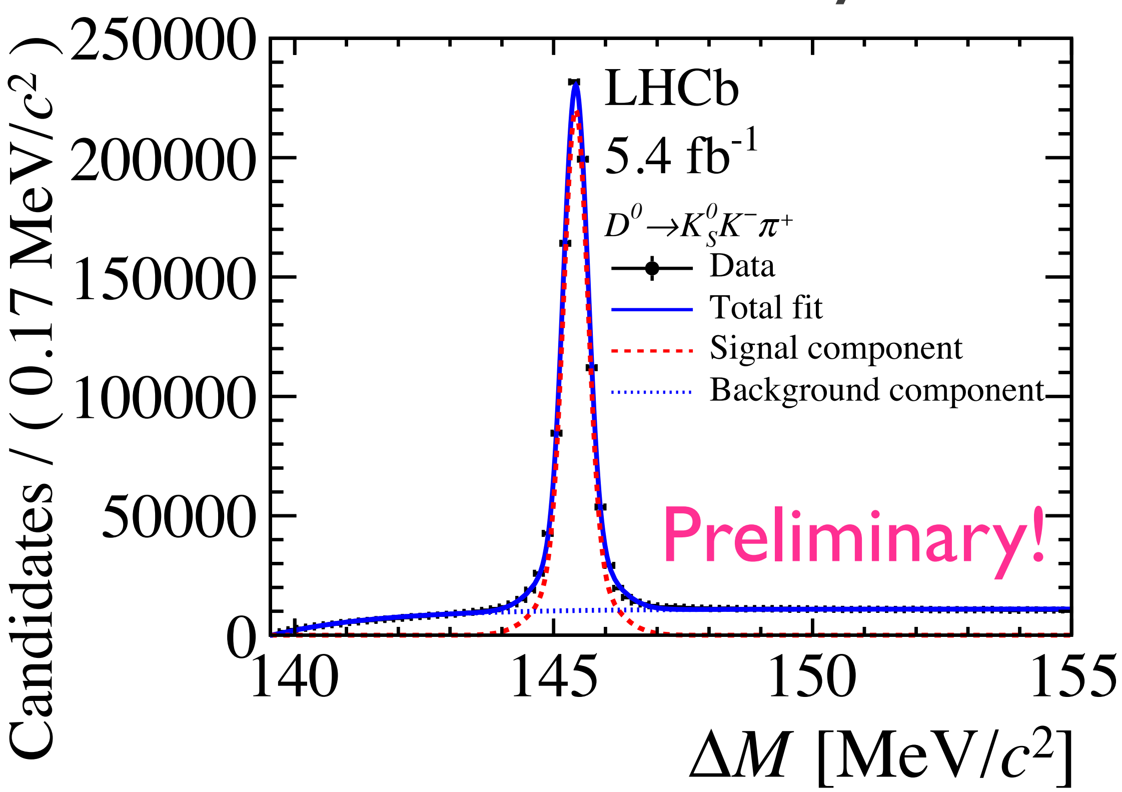
(a) Tree diagrams. (b) Exchange diagrams. (c) Penguin diagrams. (d) OZI-suppressed diagrams.

Signal samples

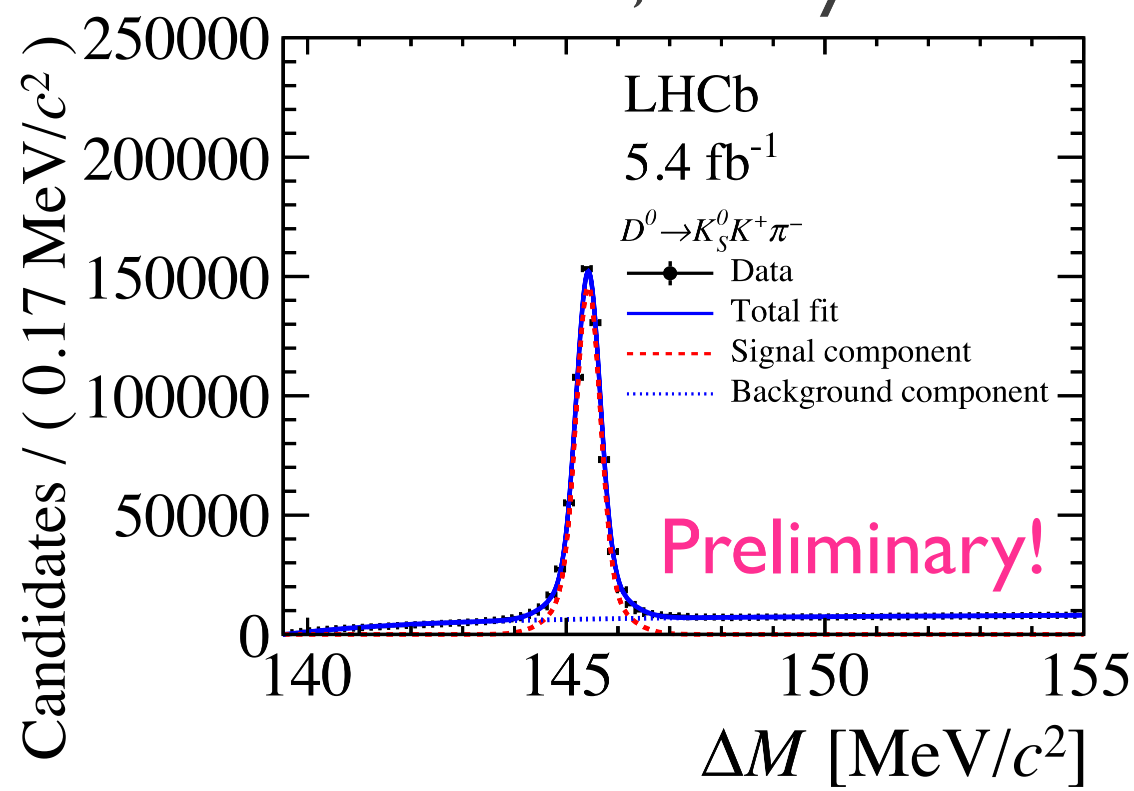
LHCb-PAPER-2023-019

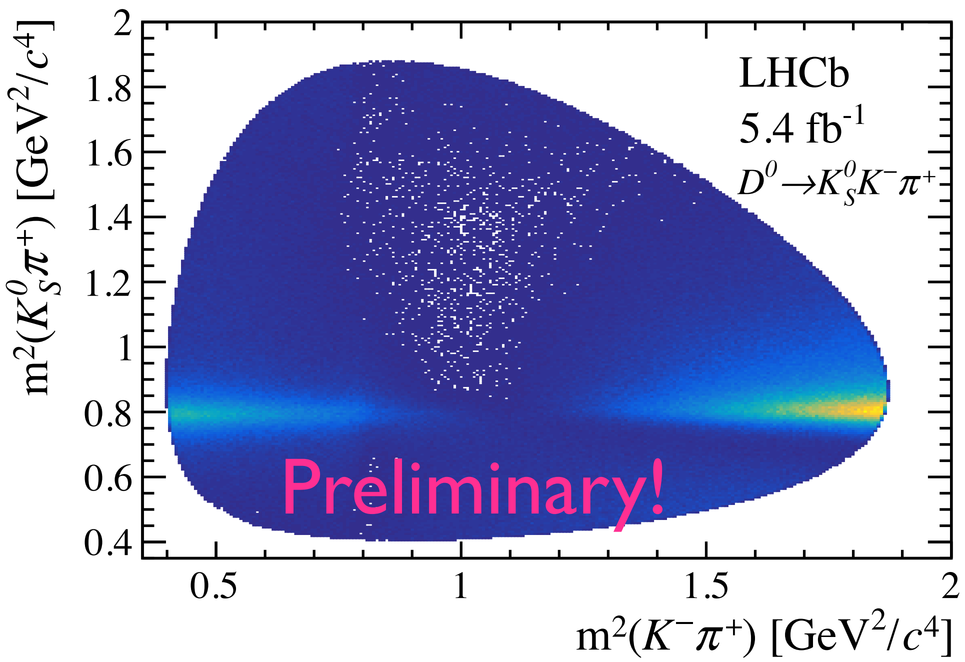
Preliminary!

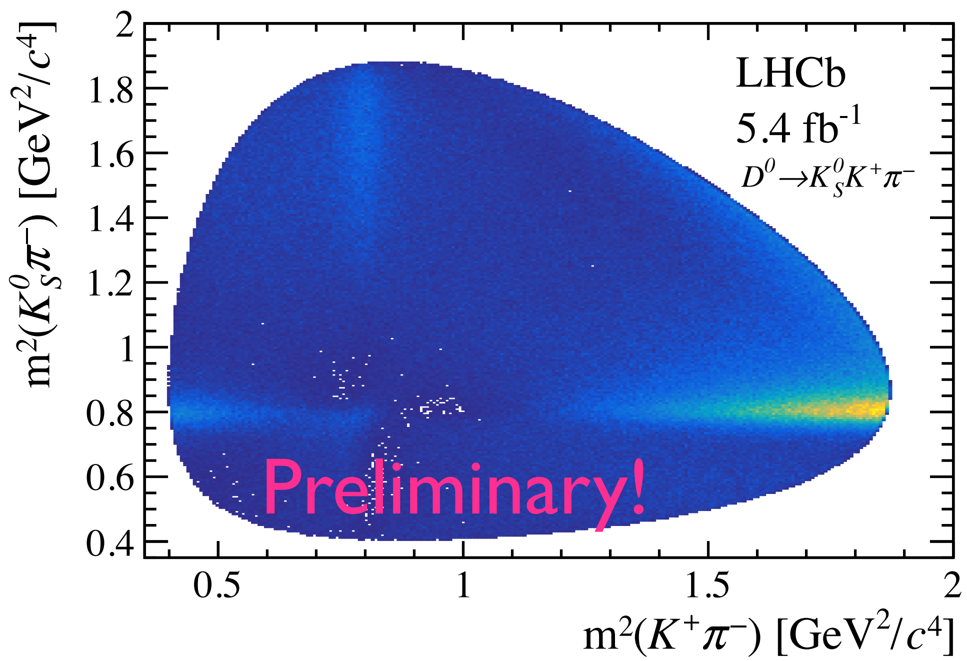
950k, Purity 90.9%



620k, Purity 91.4%





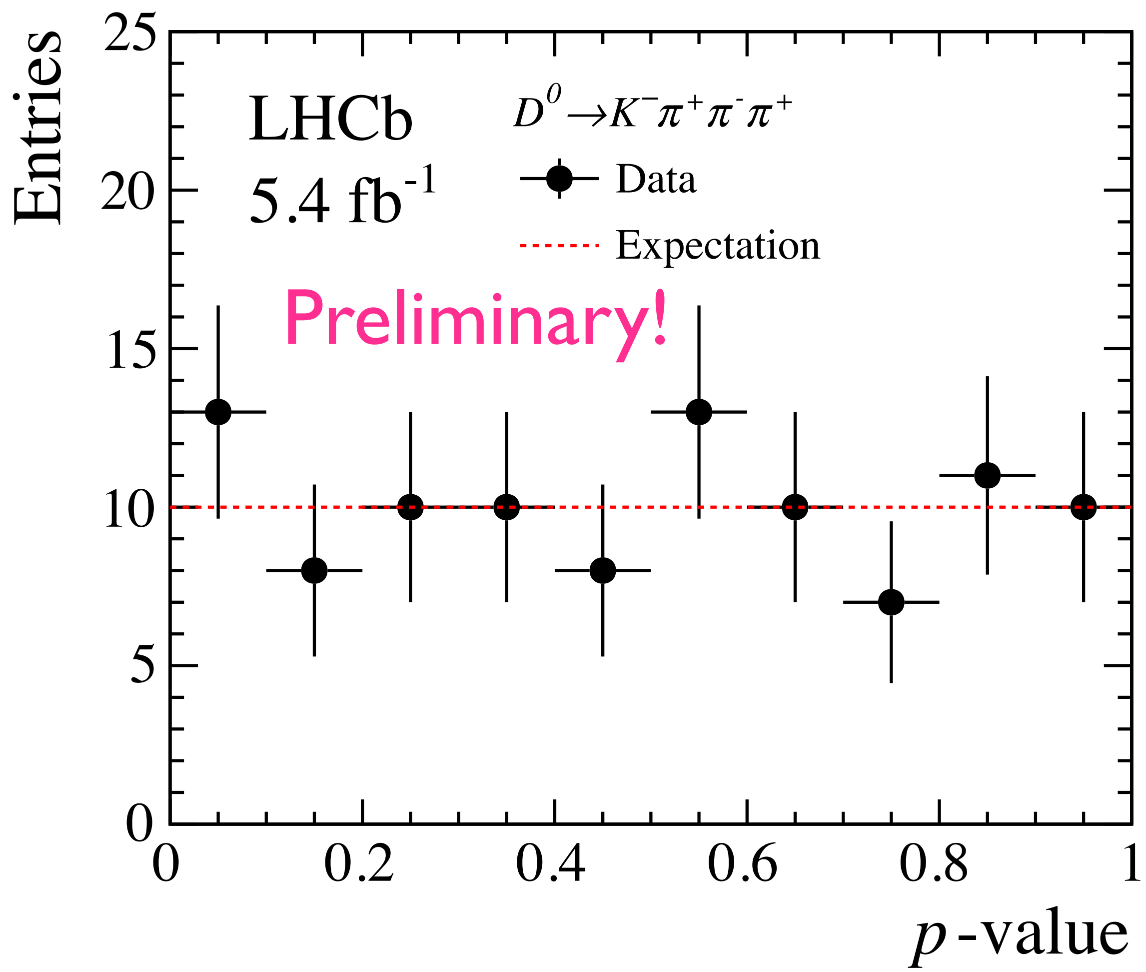


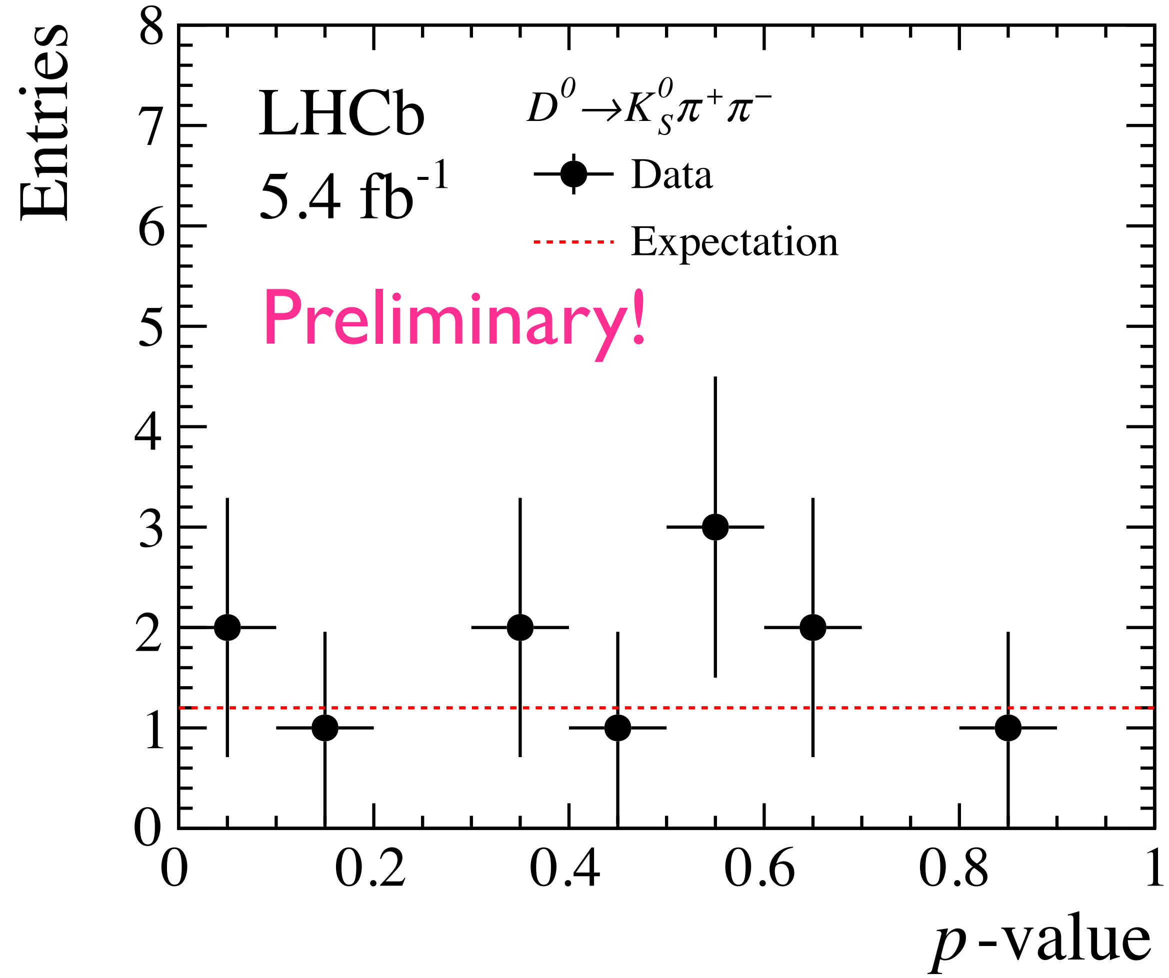
No nuisance asymmetries

LHCb-PAPER-2023-019

Preliminary!

- Control samples: symmetric distributions



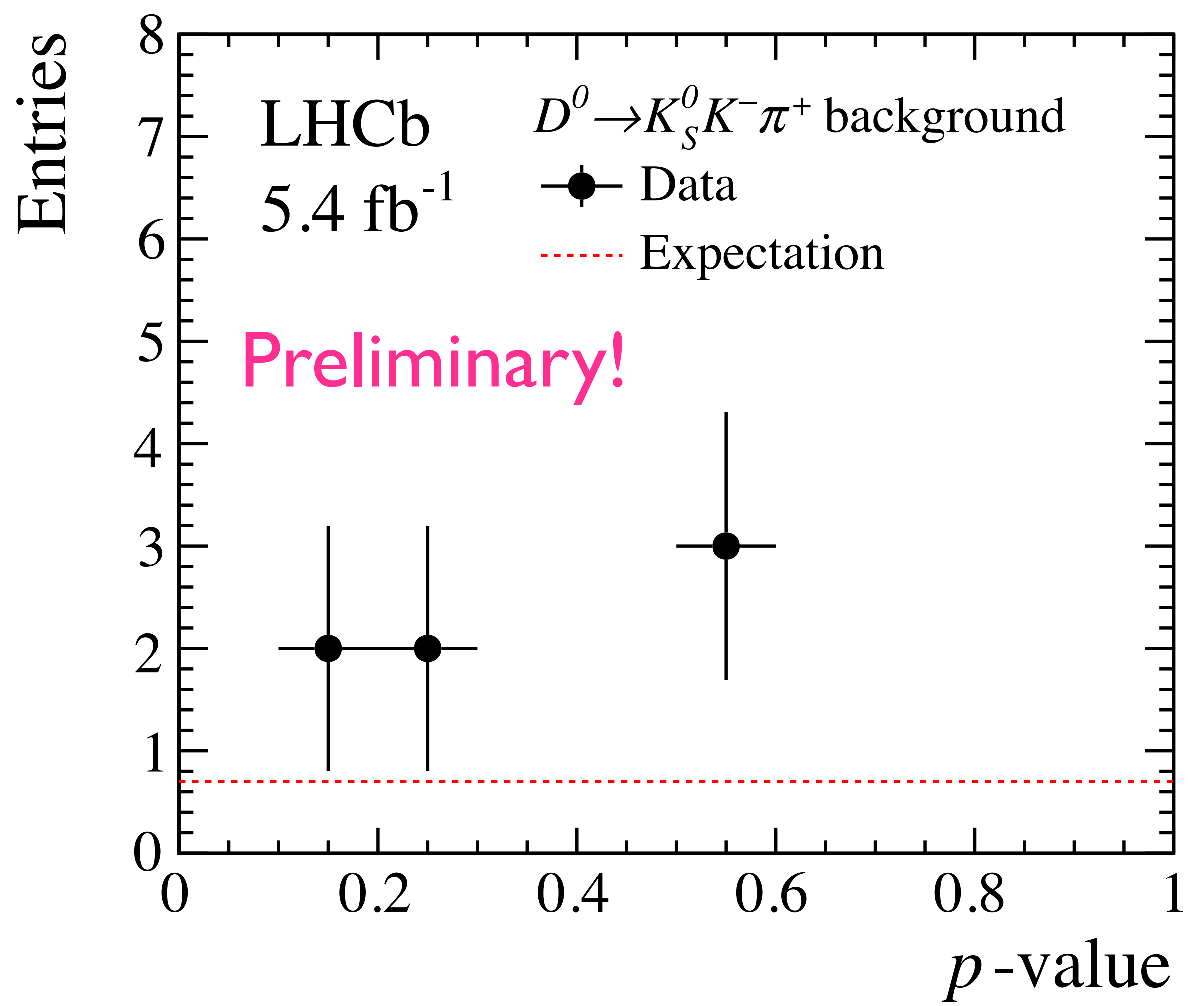


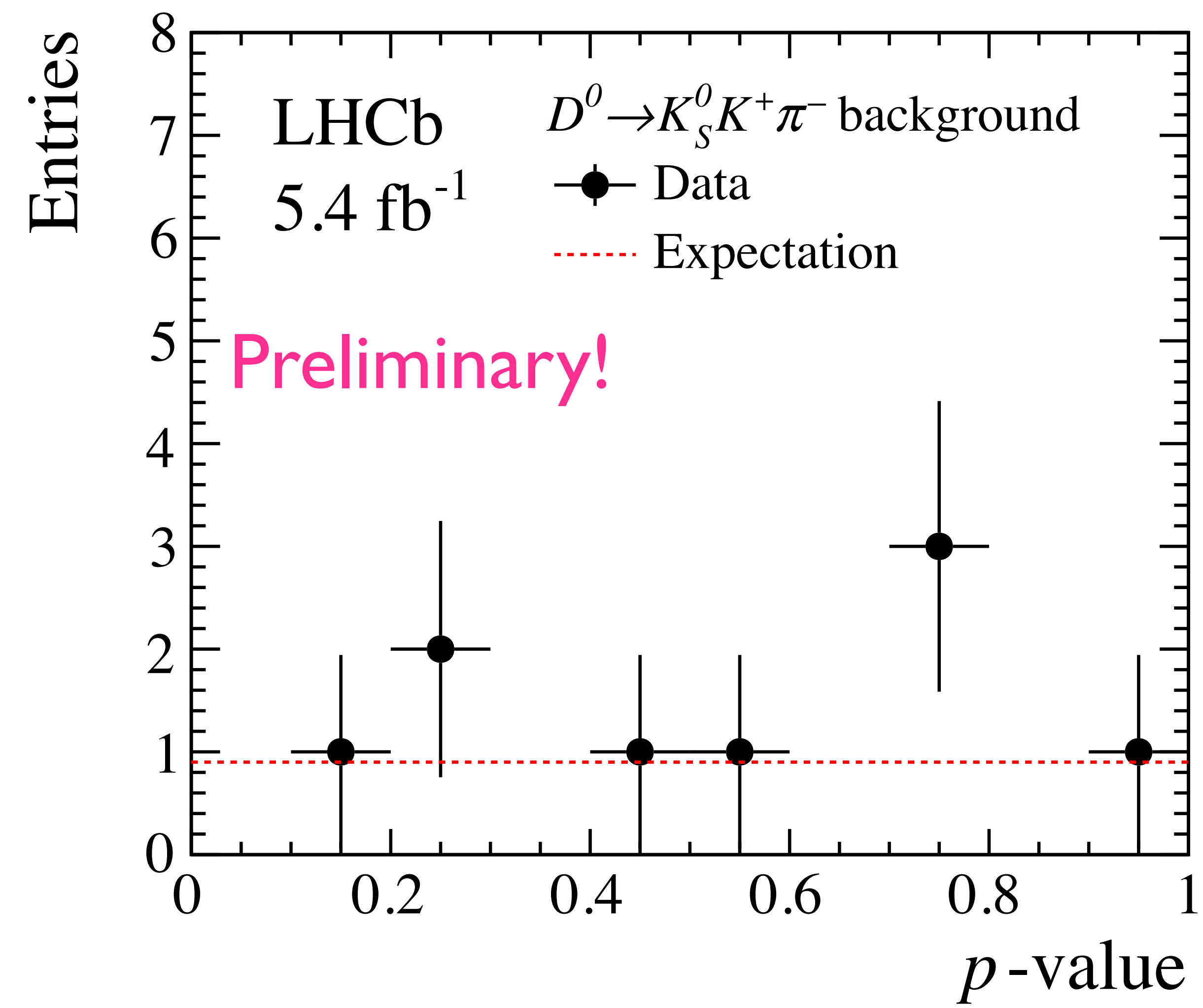
No background asymmetries

LHCb-PAPER-2023-019

Preliminary!

- No background asymmetries





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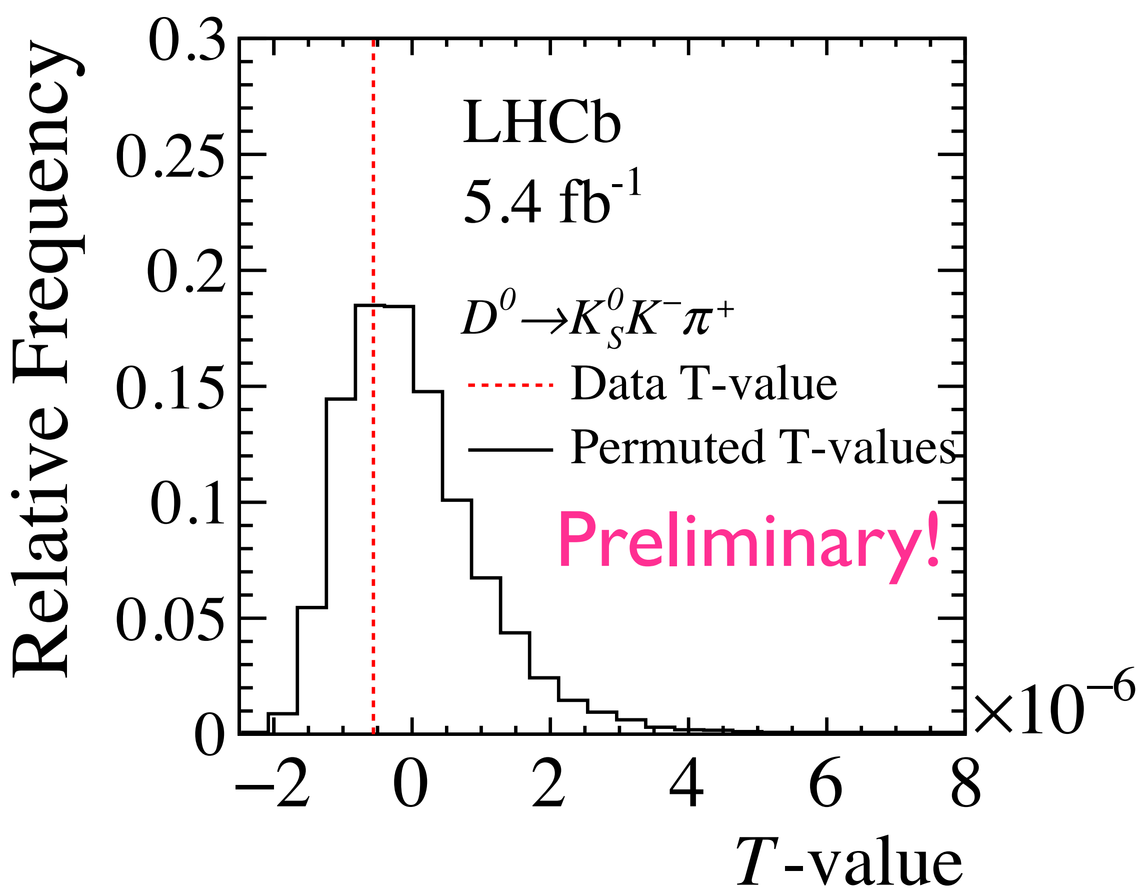
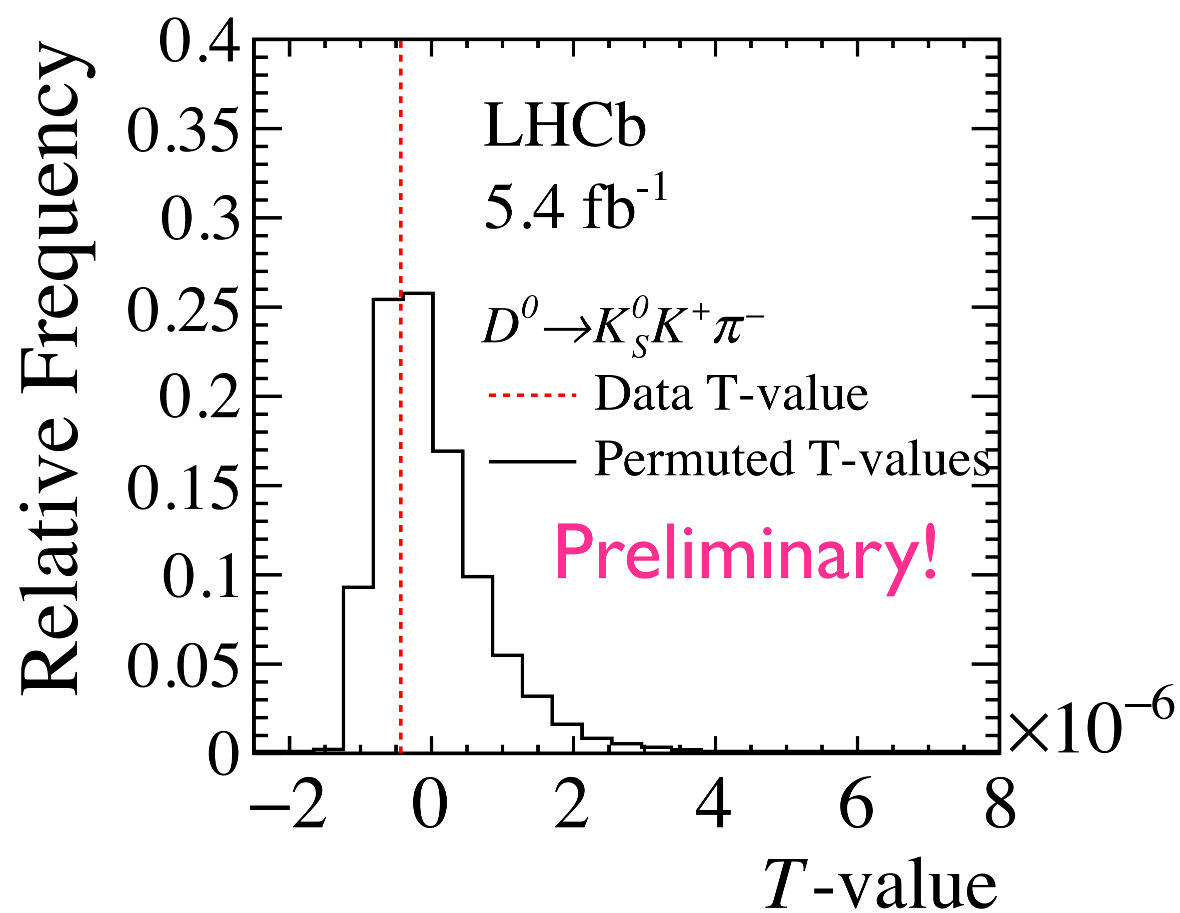
Results

LHCb-PAPER-2023-019

Preliminary!

- Results consistent with CP symmetry





p-value 70%

p-value 66%

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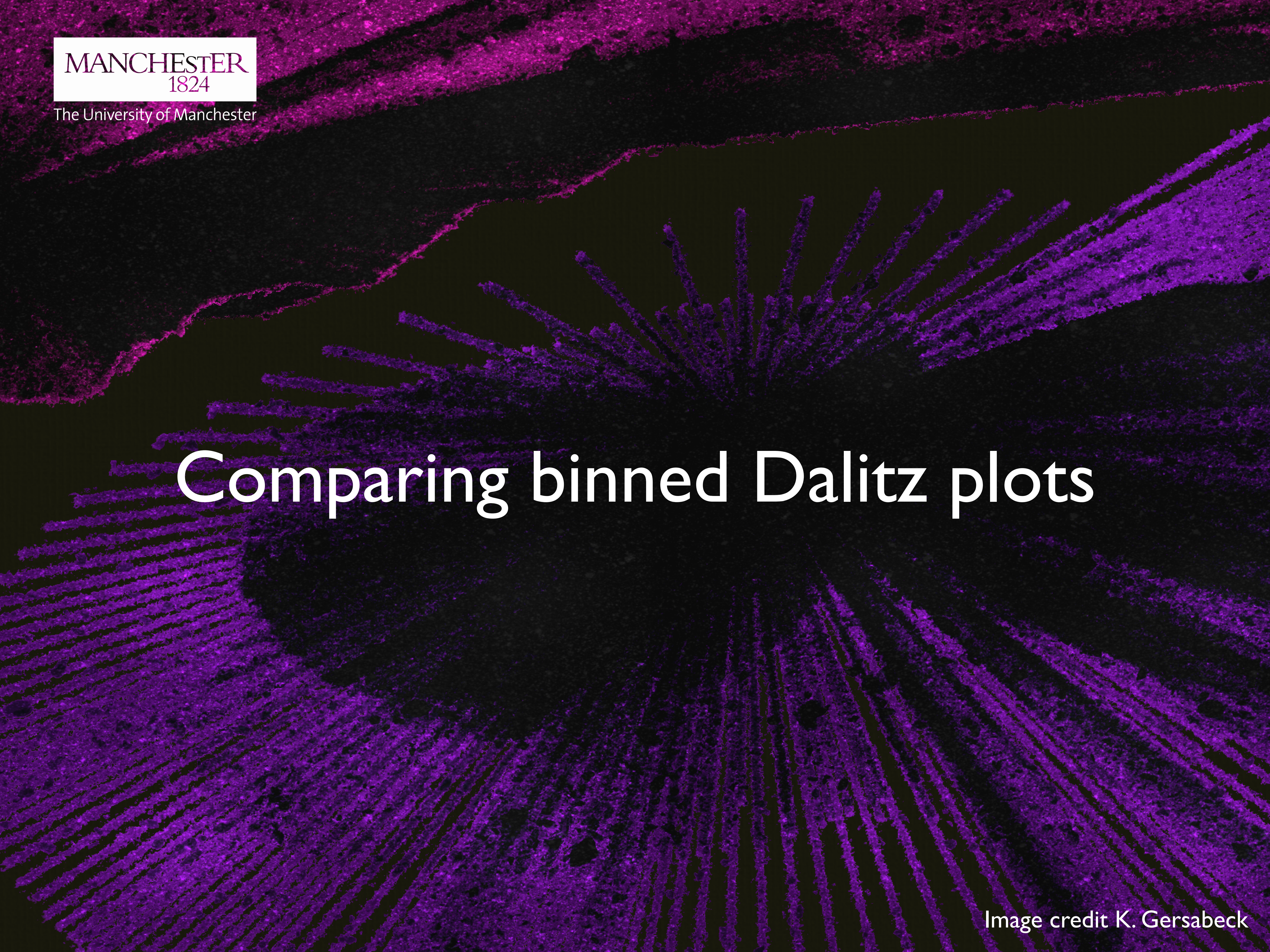


Comparing binned Dalitz plots

Image credit K. Gersabeck

The Miranda method

Introduced by BaBar: PRD78, 051102 (2008). Developed further in PRD 80, 096006 (2009), PRD86, 036005 (2012)

- Divide the Dalitz plot in two-dimensional bins

- Compute, for each bin, the significance of the difference in the numbers of $D^+_{(s)}$ candidates and $D^-_{(s)}$ candidates, where the latter is corrected for global charge asymmetry (e.g. from production and detection).

JHEP 2023, 67 (2023)

Modified: Fit in each bin, no background (fit per bin)

$$S^i_{CP} = \frac{N^i(D^+_{(s)}) - \alpha N^i(D^-_{(s)})}{\sqrt{\alpha(\delta^2_{N^i(D^+_{(s)})} + \delta^2_{N^i(D^-_{(s)})})}} \qquad \alpha = \frac{\sum_i N^i(D^+_{(s)})}{\sum_i N^i(D^-_{(s)})}$$

- Two-sample χ^2 test: calculate p-value for no-CPV hypothesis based on $\chi^2(\mathcal{S}_{CP}) = \sum (\mathcal{S}_{CP})^2$

Applied also to:

LHCb D→KKπ PRD 84.112008 (2011)

LHCb D→3π PLB 728 (2014) 585-595

CDF D→KSππ PRD 86, 032007 (2012)

LHCb D→φπ, D→KSπ JHEP 1306 (2013) 112

BaBar D→KKπ: PRD 87 (2013) 052010 (check)

LHCb D°→πππ° PLB 740, 158 (2015).

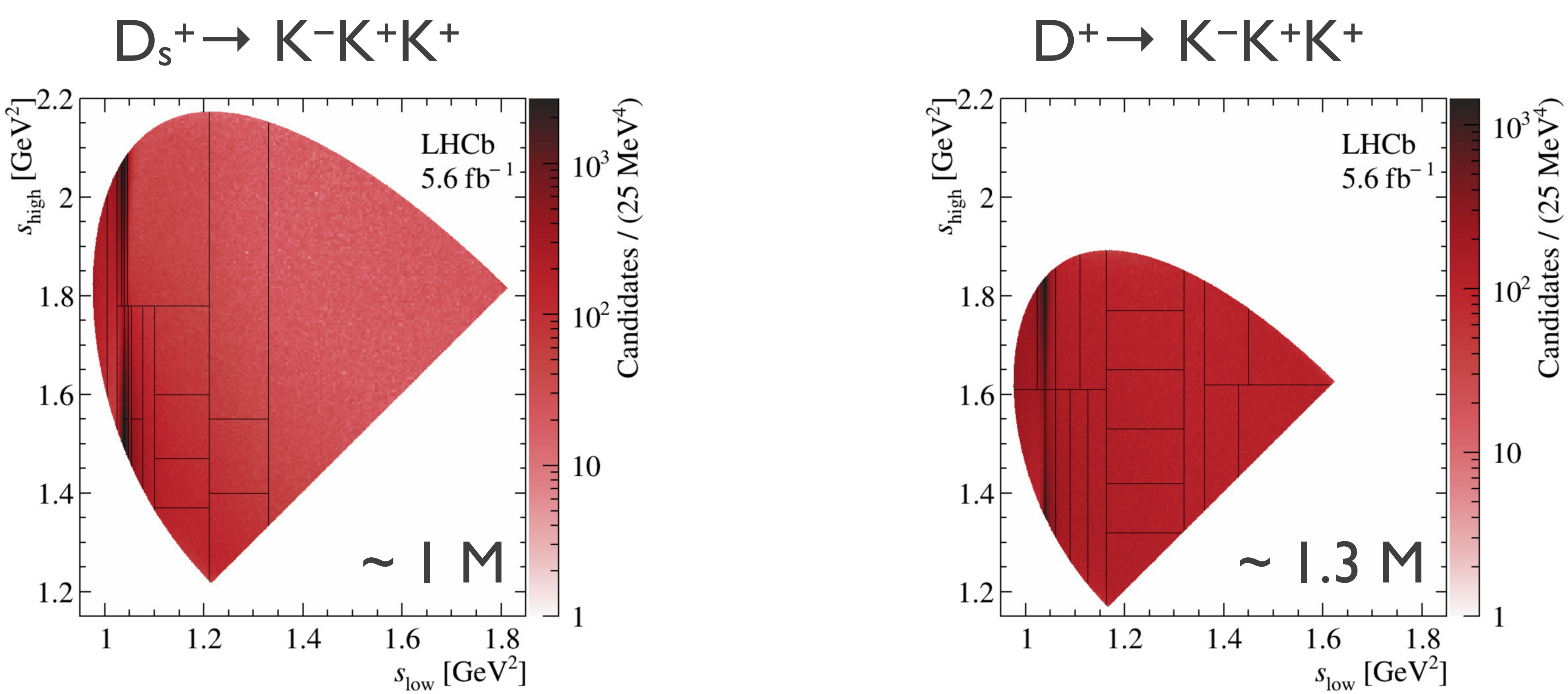
LHCb D→KKππ, D→4π PLB 726 (2013) 623-633 (5D bins)

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

JHEP 2023, 67 (2023)

- Singly Cabibbo suppressed $D_s^+ \to K^-K^+K^+$; doubly Cabibbo suppressed $D^+ \to K^-K^+K^+$
- Signal purity 64% (D_s^+) and 78% (D^+)
- LHCb Run 2 data (5.6 fb^{-1})
-

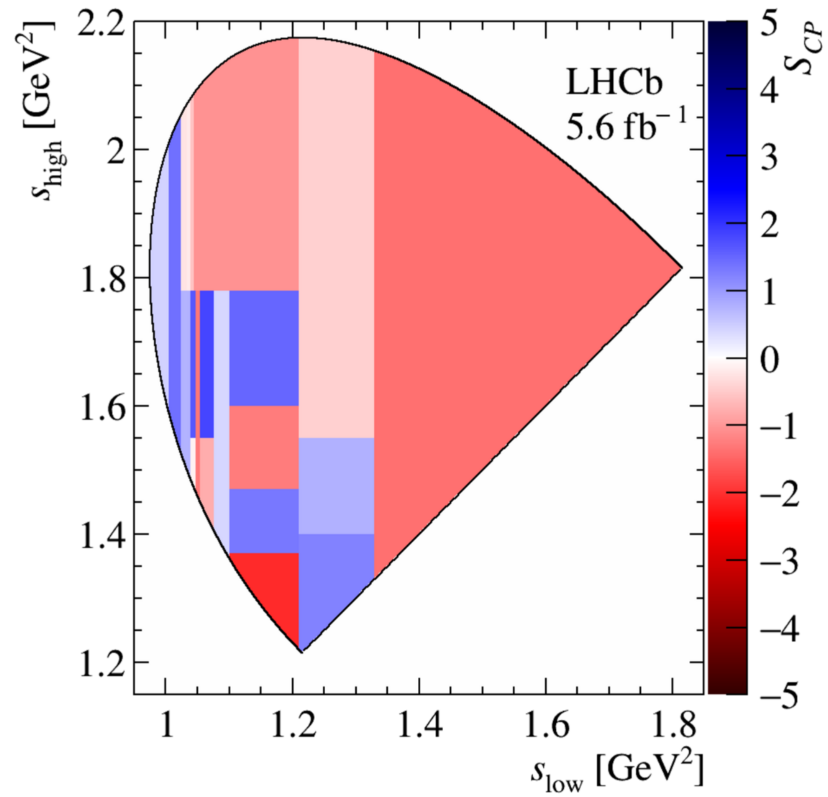
21 bins in total overlaid



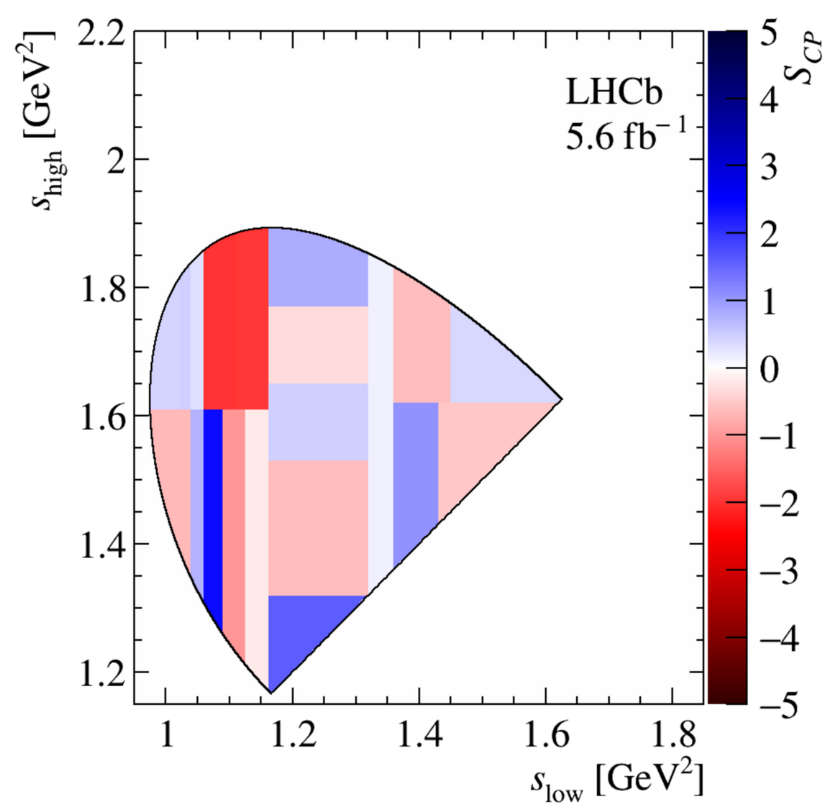
Modified Miranda: Fit in each bin, no background (fit per bin)

Results

JHEP 2023, 67 (2023)



- Control samples:
  - Phase space simulation
  - Background samples
  - $D_s^+ \to K^- K^+ \pi^+$ and $D^+ \to K^- \pi^+ \pi^+$ (CF)
- Stability checks:
  JHEP 2023, 67 (2023)
  - different invariant mass fit models
  - different binning schemes
- No evidence for CP violation
  - p-value ($D_s^+ \to K^- K^+ K^+$) = 13.3%
  - p-value ($D^+ \to K^- K^+ K^+$) = 31.6%



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The future

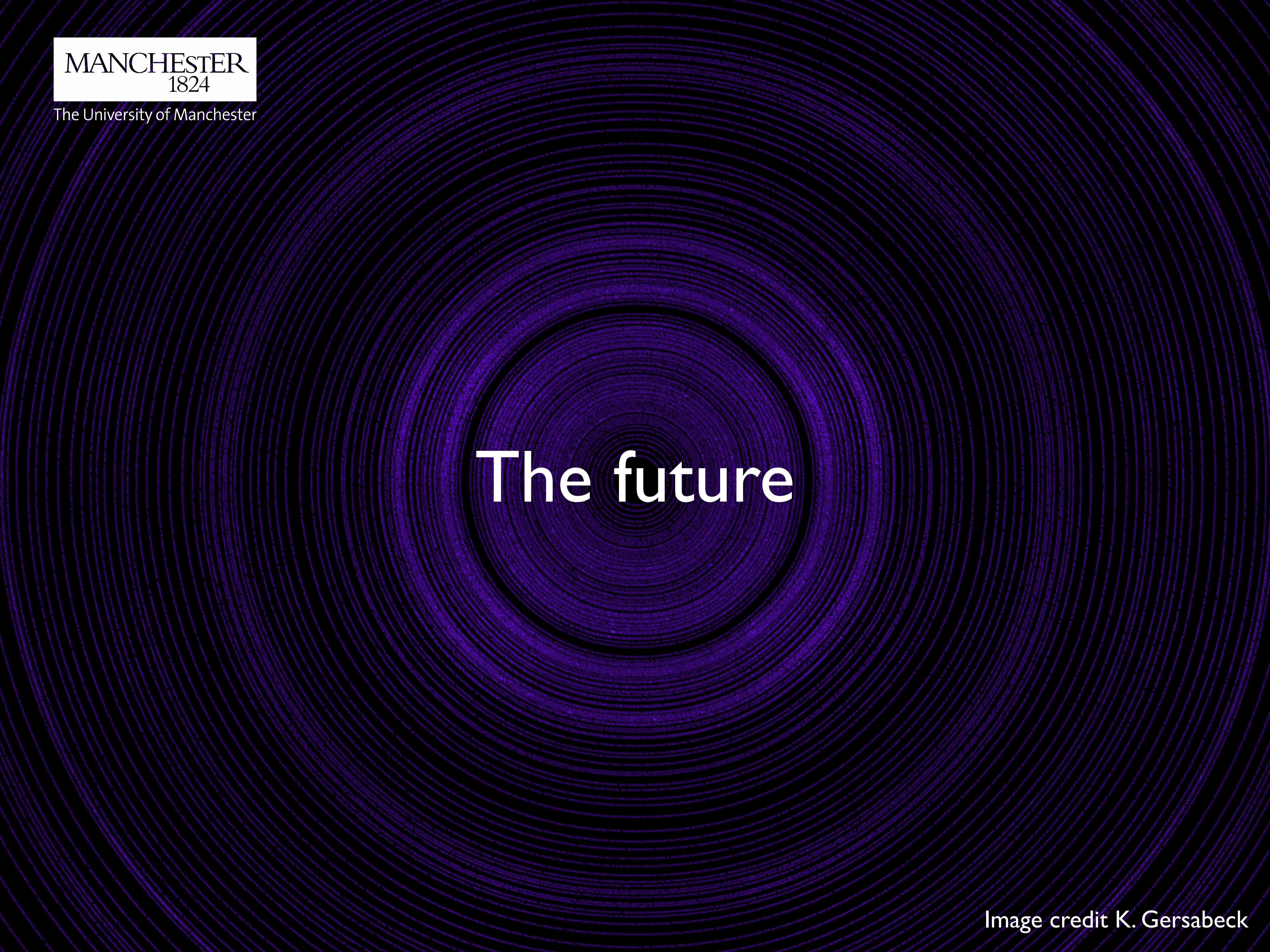

Image credit K. Gersabeck

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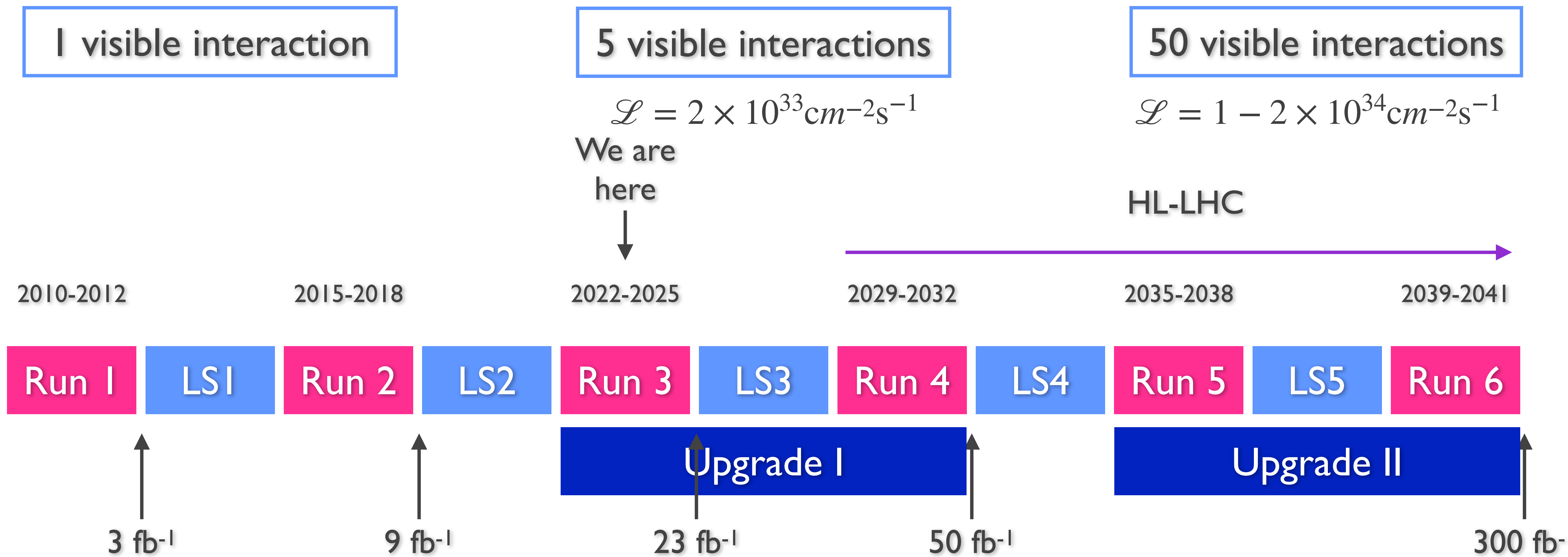
Timeline for the LHCb upgrades



Sensitivity and yields projections

ΔA_{CP} &co

Sample	σ (ΔA_{CP}) [%]	σ ($A_{CP}(hh)$) [%]
run 1-3 (23 / fb)	0.013	0.003
run 1-4 (50 / fb)	0.007	0.015
run 1-5 (300 / fb)	0.003	0.007

Multibody decays yields

$D^0 \to KKK$	Yields, 10^6
run 1-3 (23 / fb)	70
run 1-4 (50 / fb)	182
run 1-5 (300 / fb)	1,219

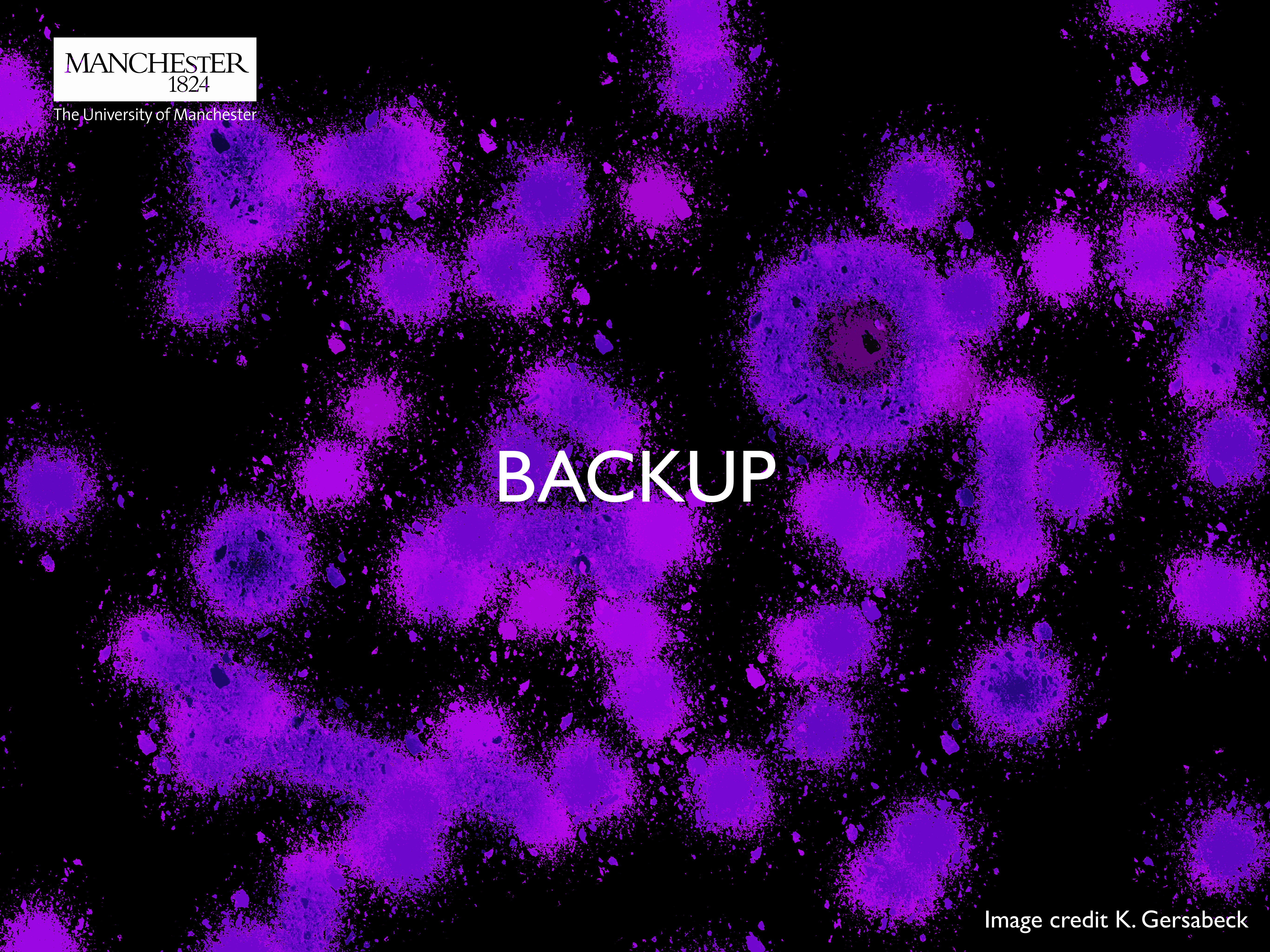
Other two-body decays

Mode	σ (A_{CP}) [%] for Upgrade II
$D^+_s \to K^0_S \pi$	0.032
$D^+ \to K^0_S K^+$	0.012
$D^+ \to \phi \pi$	0.006
$D^+ \to \eta' \pi$	0.0032
$D^+_s \to \eta' \pi$	0.032
$D^0 \to K^0_S K^0_S$	0.28
$D^0 \to K^0_S \overline{K}^{*0}$	0.006
$D^0 \to K^0_S K^{*0}$	0.008

More projections here: *arXiV:1808.08865* and in the backup slides

Summary

- LHCb has collected an unprecedented sample of hadronic charm decays: unique opportunities for CP violation searches
- Evidence for CP violation in $D^0 \to \pi\pi$ decays
- No CP violation in $D^0 \to KK$ or $D_{(s)}^+ \to \eta^{(\prime)}\pi^+$ decays
- Multibody decays:
  - unique sensitivity to local CP violation effects
  - various methods used
- No evidence for CP violation in multibody decays
  - $D^0 \to \pi^+\pi^-\pi^0$
  - $D^0 \to K^0_S K^\mp \pi^\pm$
  - $D_{(s)}^+ \to K^-K^+K^+$

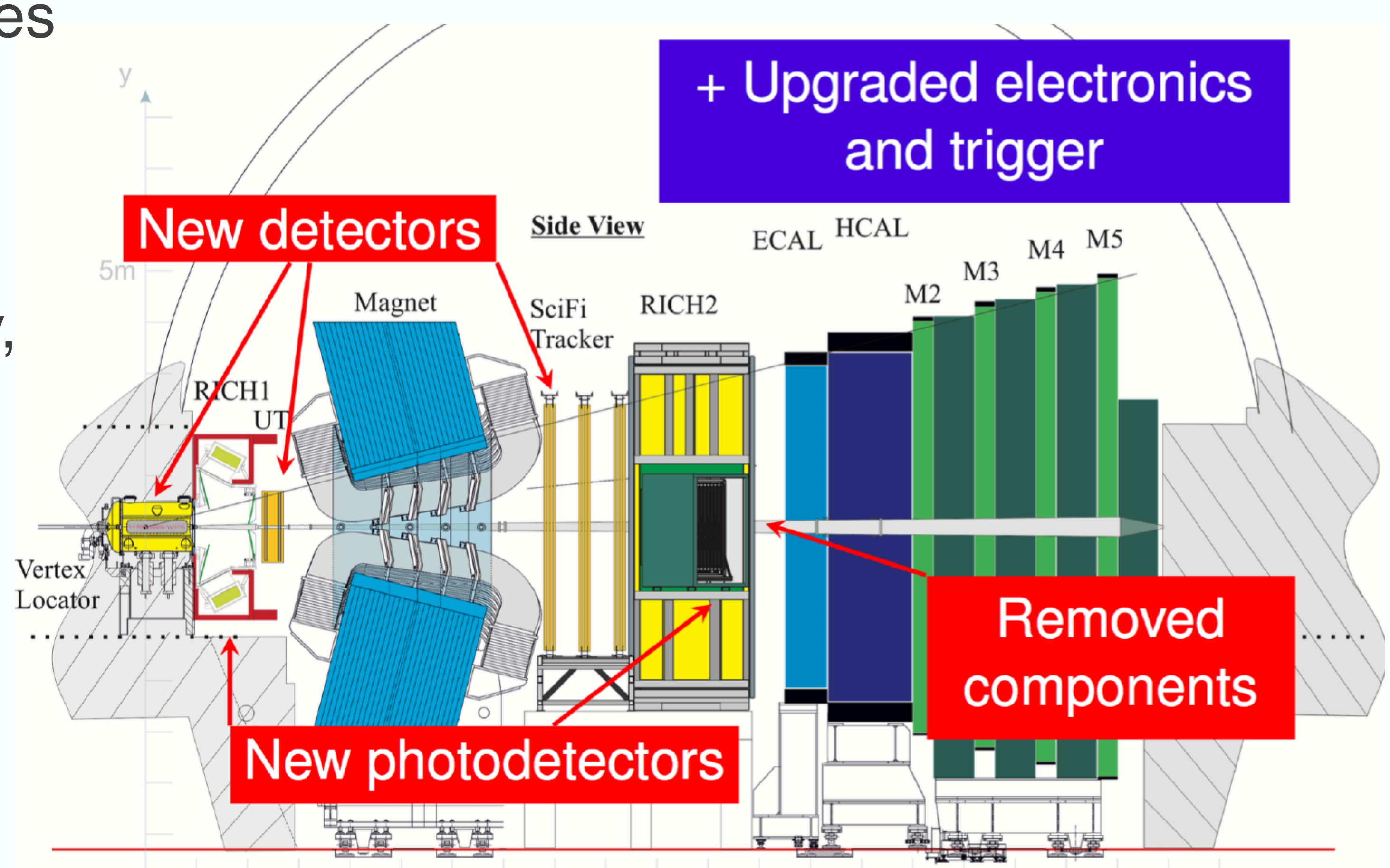


BACKUP

Image credit K. Gersabeck

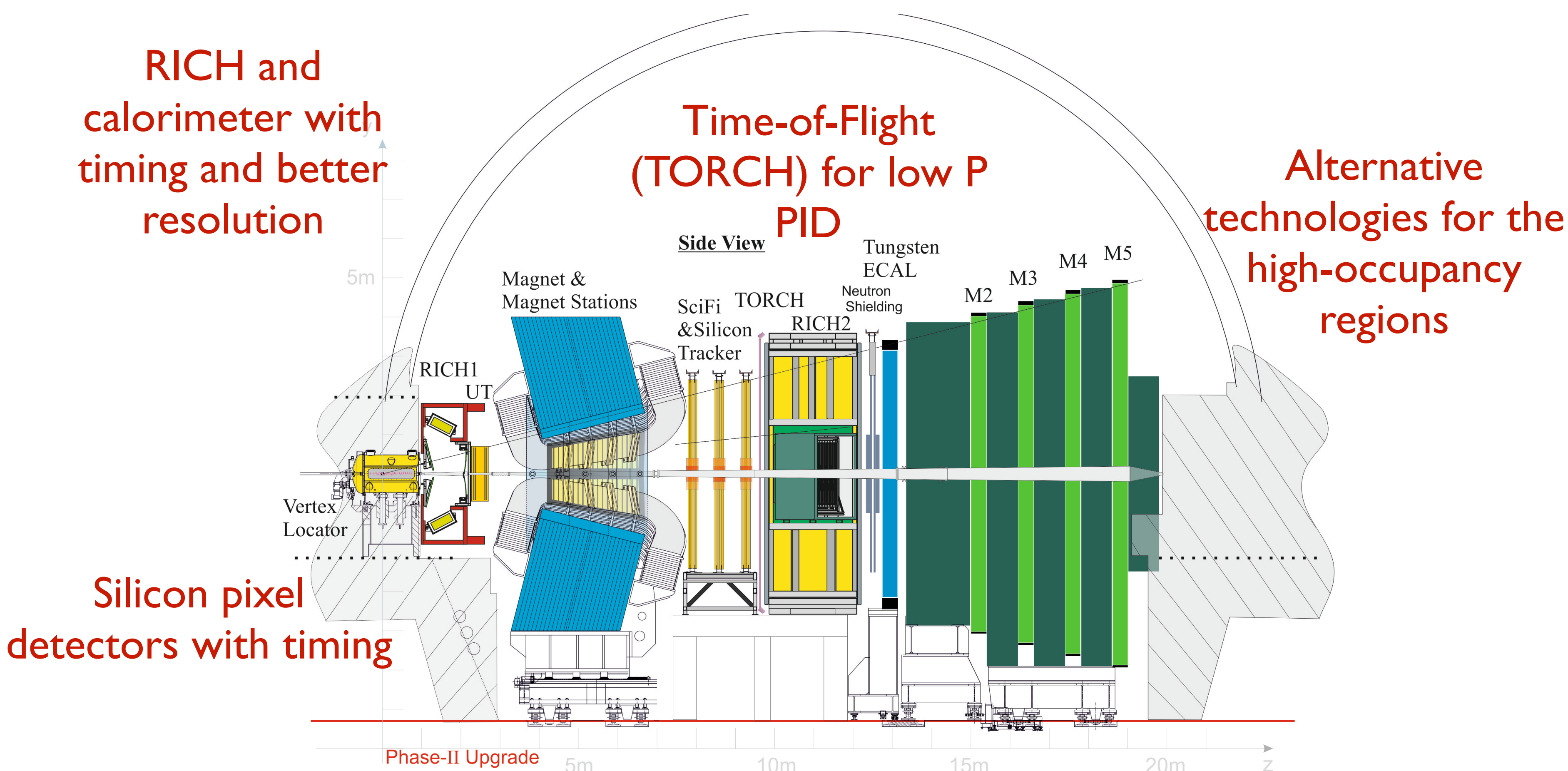
The LHCb upgrade I

- **LHCb upgrade I:** **50 fb^{-1}** in Runs-3,4 (2022-2024, 2027-2030).
- Strategy & challenges
  - Instantaneous Luminosity $\mathscr{L}$ increasing by factor 5 up to 2x10^{33}cm^{-2}s^{-1}
  - Increase readout rate to 40 MHz
  - Remove L0 hardware trigger
  - Full software trigger with first stage on GPUs
    - Huge boost to signal efficiencies
- Higher pile-up, occupancy and radiation levels
  - New detectors: higher granularity, radiation hardness,…
  - New front end electronics



The LHCb upgrade II

- **LHCb upgrade II**: **300 fb^{-1}** in Runs-5,6 (2032-2034, 2036→).
- Run at a 10x higher luminosity: major challenge
  - Retain the performance under much harsher conditions
  - Requirements: ~50 ps timing (VELO), radiation hardness, & high granularity
- Extensive R&D underway (hardware and software)



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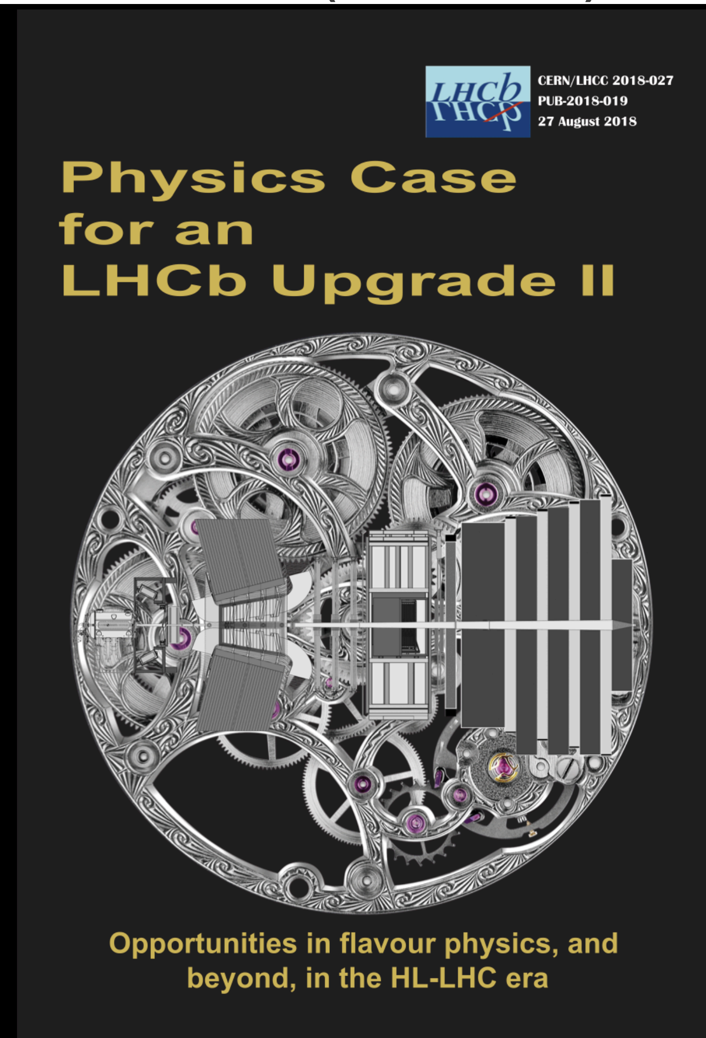
[LHCB-PUB-2018-009] arXiV:1808.08865

Strong flavour physics case but also covering EW physics, dark sector, spectroscopy, heavy ions, fixed-target mode (SMOG) etc.



* projections assume similar or better performance
* trigger efficiencies are expected to be higher but will vary from channel to channel

Projections

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 ($9\,\text{fb}^{-1}$)	200	100	14	8
Run 1–4 ($23\,\text{fb}^{-1}$)	1,000	500	70	40
Run 1–4 ($50\,\text{fb}^{-1}$)	2,600	1,300	182	104
Run 1–6 ($300\,\text{fb}^{-1}$)	17,420	8,710	1,219	697

resonant channel	$9\,\text{fb}^{-1}$	$23\,\text{fb}^{-1}$	$50\,\text{fb}^{-1}$	$300\,\text{fb}^{-1}$
$f_0(500)\pi$	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

	$D^0 \to \pi^+\pi^-\pi^+\pi^-$		$D^0 \to K^+K^-\pi^+\pi^-$	
Sample ($\mathcal{L}$)	Yield ($\times 10^6$)	$\sigma(a_{CP}^{\widehat{T}\text{-odd}})$	Yield ($\times 10^6$)	$\sigma(a_{CP}^{\widehat{T}\text{-odd}})$
Run 1–2 ($9\,\text{fb}^{-1}$)	13.5	2.4×10^{-4}	4.7	5.4×10^{-4}
Run 1–3 ($23\,\text{fb}^{-1}$)	69	1.1×10^{-4}	12	3.4×10^{-4}
Run 1–4 ($50\,\text{fb}^{-1}$)	150	7.5×10^{-5}	26	2.3×10^{-4}
Run 1–5 ($300\,\text{fb}^{-1}$)	900	2.9×10^{-5}	156	9.4×10^{-5}

Projections

Sample ($\mathcal{L}$)	Tag	Yield $D^0 \to K^- K^+$	Yield $D^0 \to \pi^- \pi^+$	$\sigma(\Delta A_{CP})$ [%]	$\sigma(A_{CP}(hh))$ [%]
Run 1–2 (9 fb^{-1})	Prompt	52M	17M	0.03	0.07
Run 1–3 (23 fb^{-1})	Prompt	280M	94M	0.013	0.03
Run 1–4 (50 fb^{-1})	Prompt	1G	305M	0.007	0.015
Run 1–5 (300 fb^{-1})	Prompt	4.9G	1.6G	0.003	0.007

Theory perspective*

$$\Delta A_{CP}^{\mathrm{Exp.}} = (-15.6 \pm 2.9) \times 10^{-4}$$

Physics Letters B 774 (2017) 235–242

$$\left|\Delta a_{CP}^{dir}\right| < 0.020 \pm 0.003\%$$

Direct CP asymmetry in $D \to \pi^-\pi^+$ and $D \to K^-K^+$ in QCD-based approach

Alexander Khodjamirian [a], Alexey A. Petrov [a,b,c,*]

[a] Theoretische Physik 1, Naturwissenschaftlich-Technische Fakultät, Universität Siegen, D-57068 Siegen, Germany
[b] Department of Physics and Astronomy, Wayne State University, Detroit, MI 48201, USA
[c] Michigan Center for Theoretical Physics, University of Michigan, Ann Arbor, MI 48196, USA

BSM!

ΔA_{CP} within the Standard Model and beyond

Mikael Chala, Alexander Lenz, Aleksey V. Rusov and Jakub Scholtz

BSM!

$$|\Delta A_{CP}^{\mathrm{SM}}| \leq 3 \times 10^{-4}$$

Z'?

The Emergence of the $\Delta U = 0$ Rule in Charm Physics

SM

Yuval Grossman* and Stefan Schacht†

D... of Physics, LEPP, Cornell University, Ithaca, NY 14853, USA

"in SM requires mild non-perturbative enhancement due to rescattering amplitudes"

Implications on the first observation of charm CPV at LHCb

Hsiang-nan Li[1*], Cai-Dian Lü[2†], Fu-Sheng Yu[3‡]

[1] Institute of Physics, Academia Sinica, Taipei, Taiwan 11529, Republic of China

Lanzhou 730000, People's Republic of China

SM

$$\Delta A_{CP}^{\mathrm{SM}} = (-0.57 \sim -1.87) \times 10^{-3}$$

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*a brief snapshot that cannot do justice to the amount of work done here

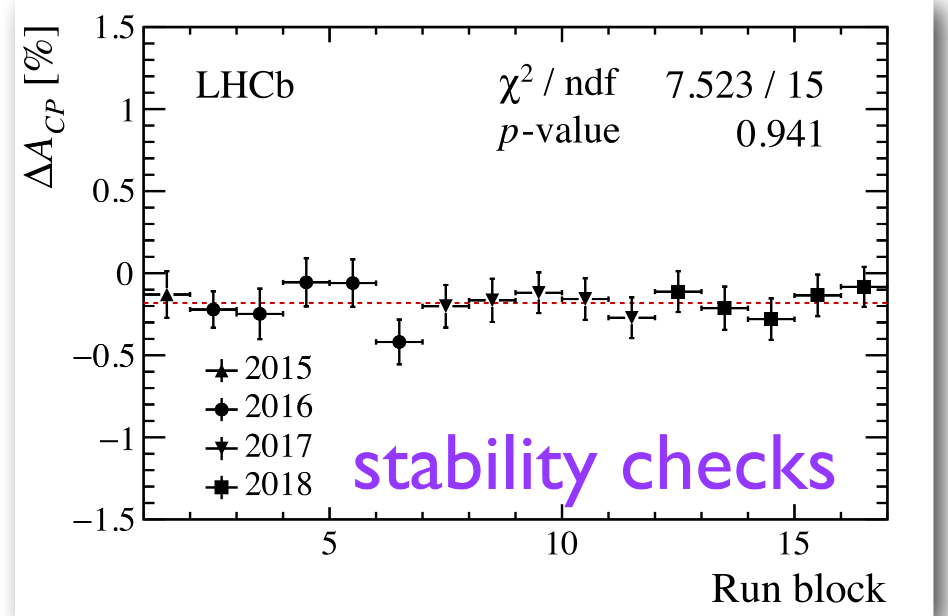
Stability checks and systematics

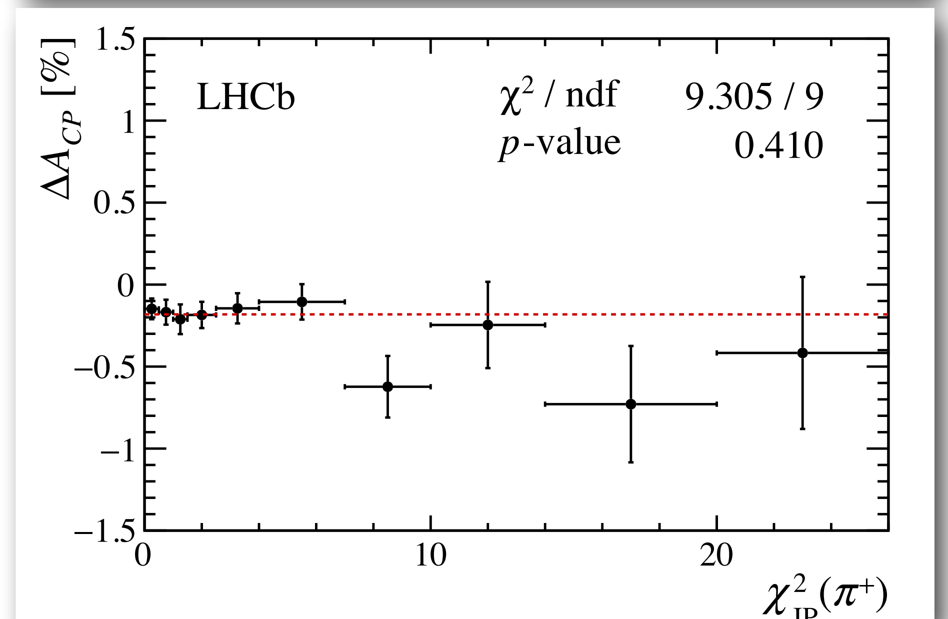
LHCb, Phys. Rev. Lett. 122 (2019) 211803

- New analysis based on Run 2 data, corresponds to 6 fb^{-1}
- Systematic uncertainties sub-dominant and determined by data-driven methods

Source	π-tagged	μ-tagged
Fit model	0.6	2
Mistag	–	4
Weighting	0.2	1
Secondary decays	0.3	–
B fractions	–	1
B reco. efficiency	–	2
Peaking background	0.5	–
Total	0.9	5

$$\Delta A_{CP}^{\pi\text{-tagged}} = [-18.2 \pm 3.2\,(\text{stat.}) \pm 0.9\,(\text{syst.})] \times 10^{-4},$$
$$\Delta A_{CP}^{\mu\text{-tagged}} = [-9 \pm 8\,(\text{stat.}) \pm 5\,(\text{syst.})] \times 10^{-4}.$$





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Results

- Run 2 results (statistically dominated)

JHEP 04 (2023) 081

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

- Combined with the Run 1 results

$$\mathcal{A}^{CP}(D^+ \to \eta\pi^+) = (0.13 \pm 0.50 \pm 0.18)\%,$$
$$\mathcal{A}^{CP}(D_s^+ \to \eta\pi^+) = (0.48 \pm 0.42 \pm 0.17)\%,$$
$$\mathcal{A}^{CP}(D^+ \to \eta'\pi^+) = (0.43 \pm 0.17 \pm 0.10)\%,$$
$$\mathcal{A}^{CP}(D_s^+ \to \eta'\pi^+) = (-0.04 \pm 0.11 \pm 0.09)\%,$$

Compatible with CP symmetry

ΔA_{CP}: mostly direct CPV

Individual asymmetries are expected to have opposite sign due to the CKM structure

$$\Delta A_{CP} \equiv A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-)$$

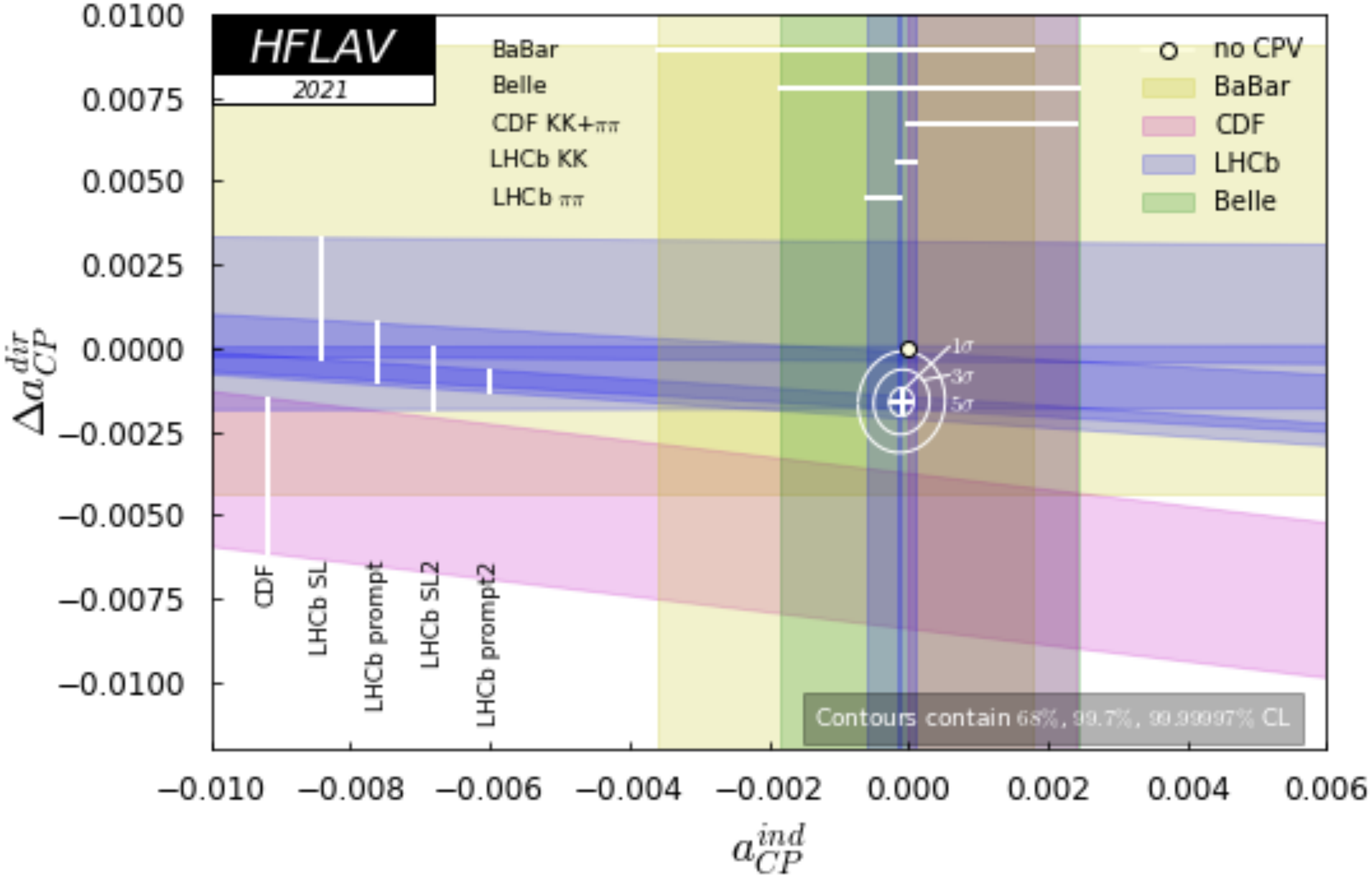
$$\approx \Delta a_{CP}^{\text{dir}}\left(1 + \frac{\overline{\langle t \rangle}}{\tau} y_{CP}\right) + \frac{\Delta\langle t \rangle}{\tau} a_{CP}^{\text{ind}}$$

where $y_{CP} \equiv \frac{\Gamma_{CP\pm}}{\Gamma} - 1$

Mostly a measure of direct CPV

The indirect CPV is expected to cancel but a small amount could be present due to the different decay time acceptance of the two decays

CP violated in charm



$a_{CP}^{ind} = (-0.010 \pm 0.012)\%$

$\Delta a_{CP}^{dir} = (-0.161 \pm 0.028)\%$

- Direct CPV in charm
- No hint for indirect CPV
- SM or BSM?
  - Open question for now
- Need theoretical advances and more measurements

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MODEL DEPENDENT METHODS

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Dalitz plot analysis features

- Interference plays a significant role in the phase space distributions and in the physics sensitivity
- Amplitude analysis can explore several features of multibody decays
  - Relative phases between states
  - Sensitivity to CP violating effects
  - Resolve ambiguities in weak phases
  - Hadron spectroscopy

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Amplitude analysis

- Amplitude: sum of contributions

- $$\mathscr{A}(m_{12}^2, m_{23}^2) = \sum_{j=1}^{N} A_j(m_{12}^2, m_{23}^2) = \sum_{j=1}^{N} c_j F_j(m_{12}^2, m_{23}^2)$$

c_l : complex coefficients describing the relative magnitude and phase of the different isobars

F_l : dynamical amplitudes that contain the lineshape and spin-dependence of the hadronic part

Resonance mass term (e.g. Breit–Wigner) | *Barrier factors - p, q: momenta of bachelor and resonance* | *Angular probability distribution*

- S-wave (non-resonant component) description difficult, increasingly turning to multiple approaches

- Isobar: Each contribution has clear physical meaning

- K-matrix: Experimental interface scattering results that enforce 2-body unitarity

- Quasi-model-independent: Binned amplitude determined directly from data