New Results in Charm Physics at LHCb

Maurizio Martinelli on behalf the LHCb Collaboration
University of Milano Bicocca and INFN

LISHEP
UERJ, 07.07.2021

Charm Physics @ LHCb

Charm Physics

Mixing
CPV

Production
Spectroscopy
Amplitude Analyses

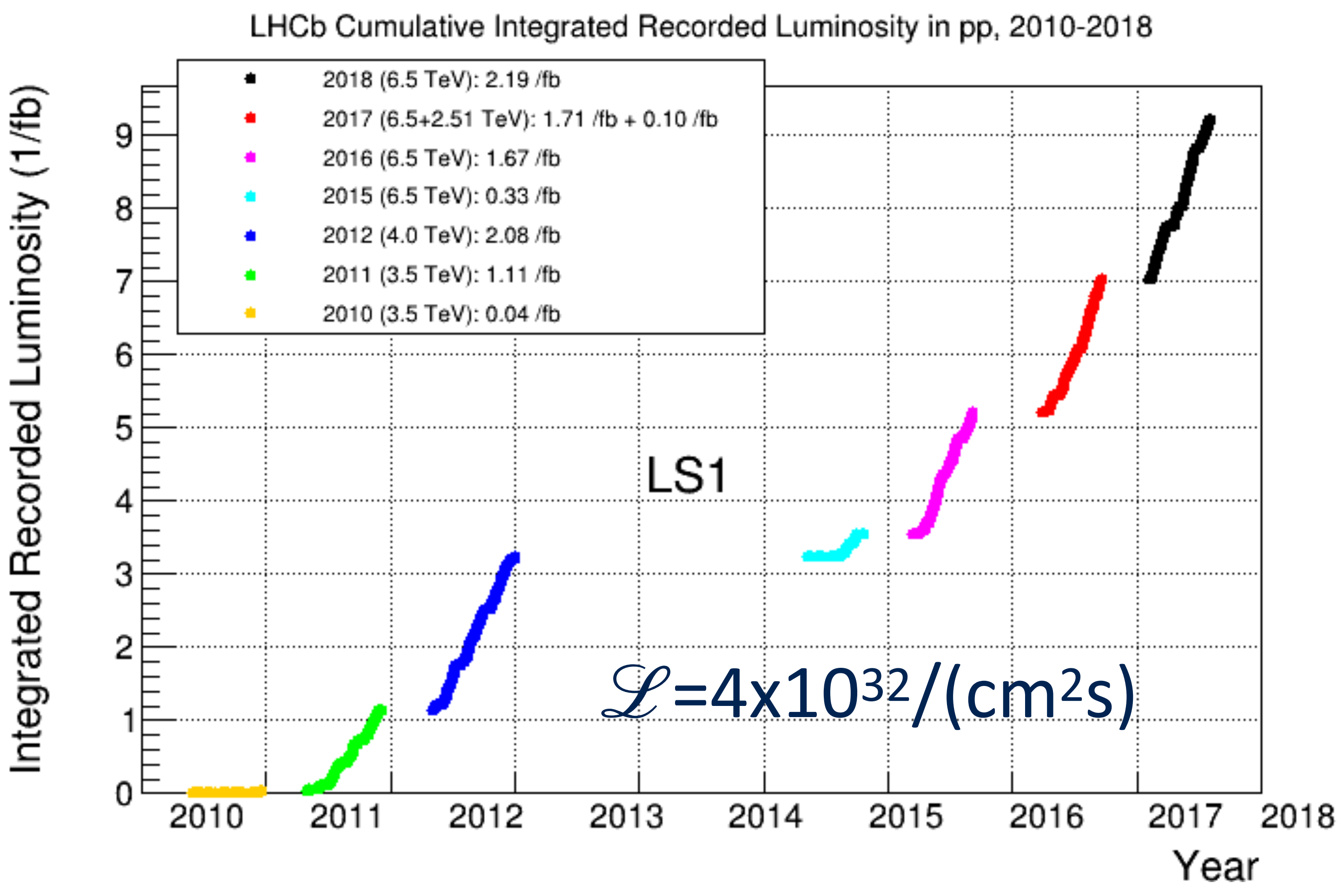
Rare
Decays

This talk

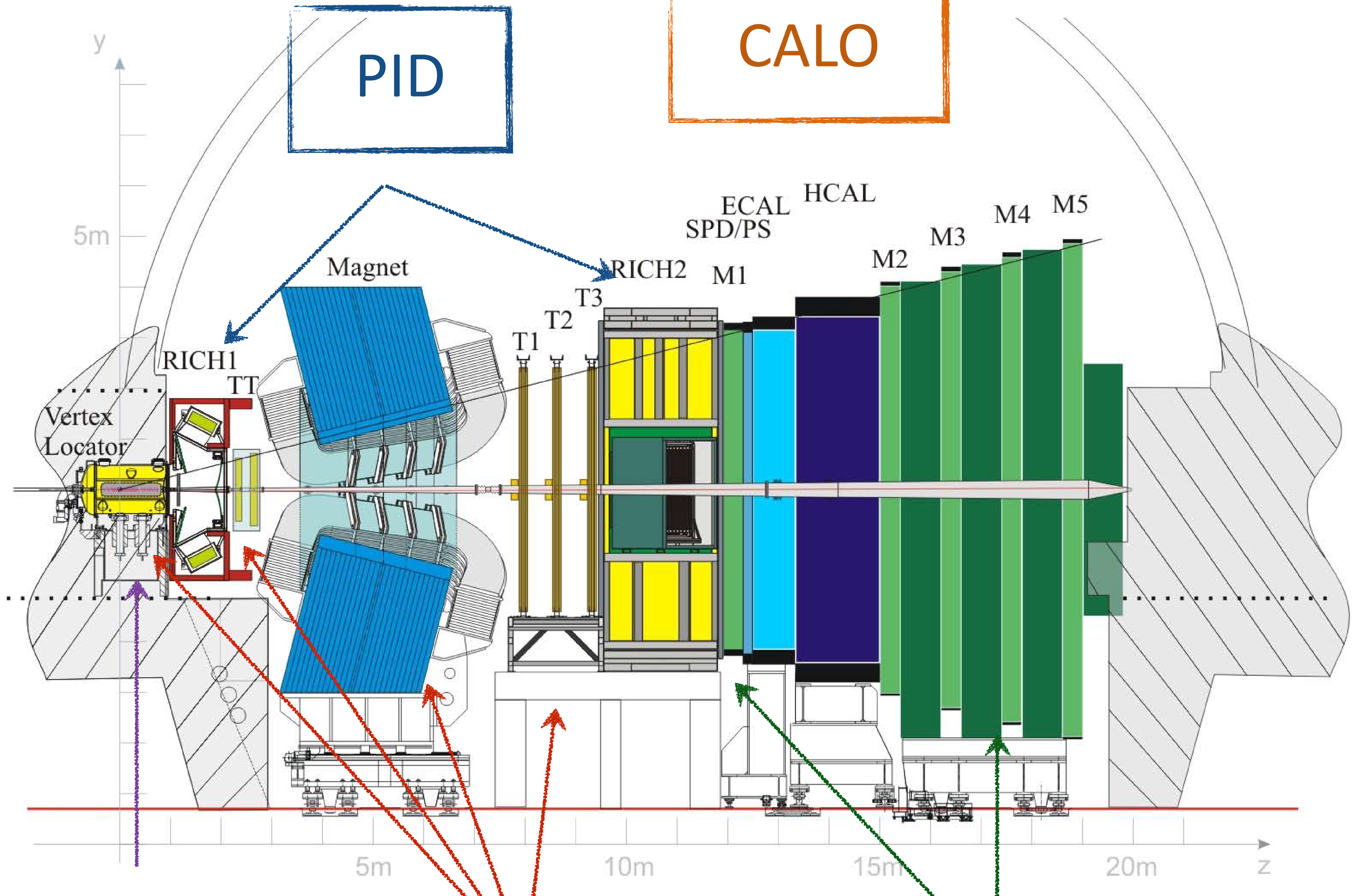
The LHCb Experiment

JINST 3 (2008) S08005

Charm quarks produced in high η at LHC
$\sigma(pp \to c\bar{c}) \sim 20\sigma(pp \to b\bar{b})$



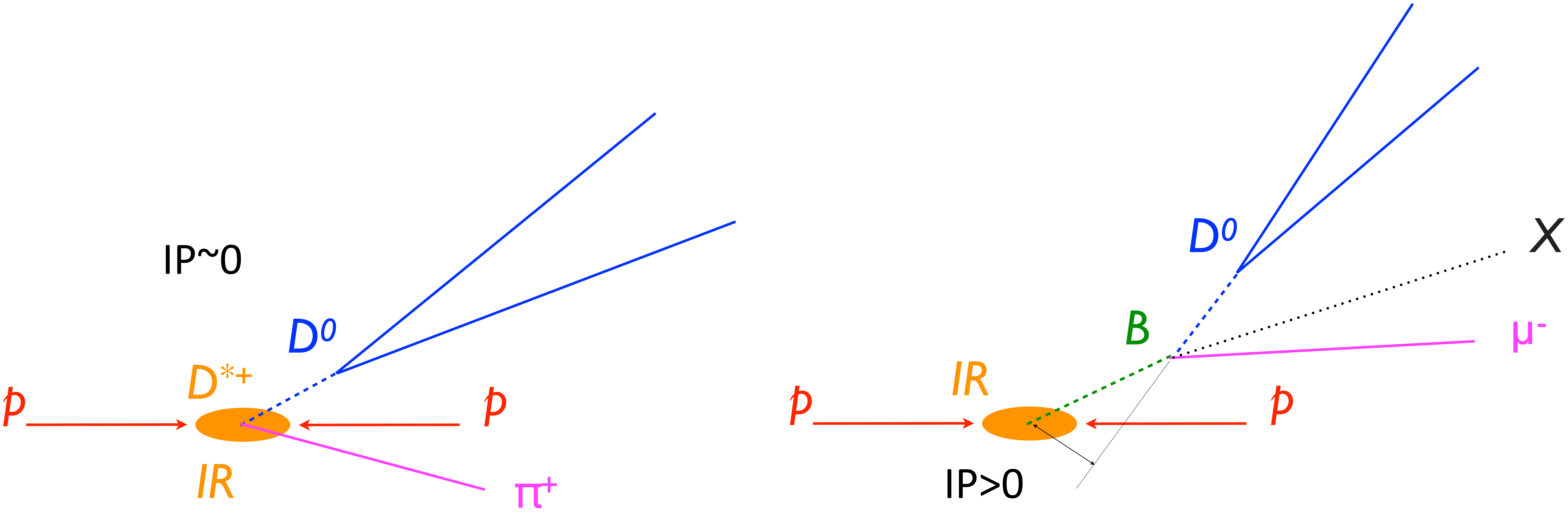
$\mathscr{L}$=4x10^{32}/(cm^{2}s)



$\varepsilon_{VELO} \approx 98\%$	$\varepsilon_{Track} \approx 95\%$
$\delta t/t = 45fs$	$\varepsilon_{PID}(K) \approx 95\%$
$\sigma(IP) \approx 20\mu m$	$\varepsilon_{PID}(\mu) \approx 97\%$
$\delta p/p \approx 0.5\%$	$\varepsilon_{PID}(e) \approx 90\%$

Int.J.Mod.Phys. A30 (2015) no.07, 1530022

Charm Production at LHCb



Prompt
(π-tagged)

Secondary
(μ-tagged)

Mixing and CP Violation Experimental Status

Why Studying Mixing and CPV in Charm Decays?

Unique

- Only up-type quark decay in which new physics couplings can be probed

Discovery Tool

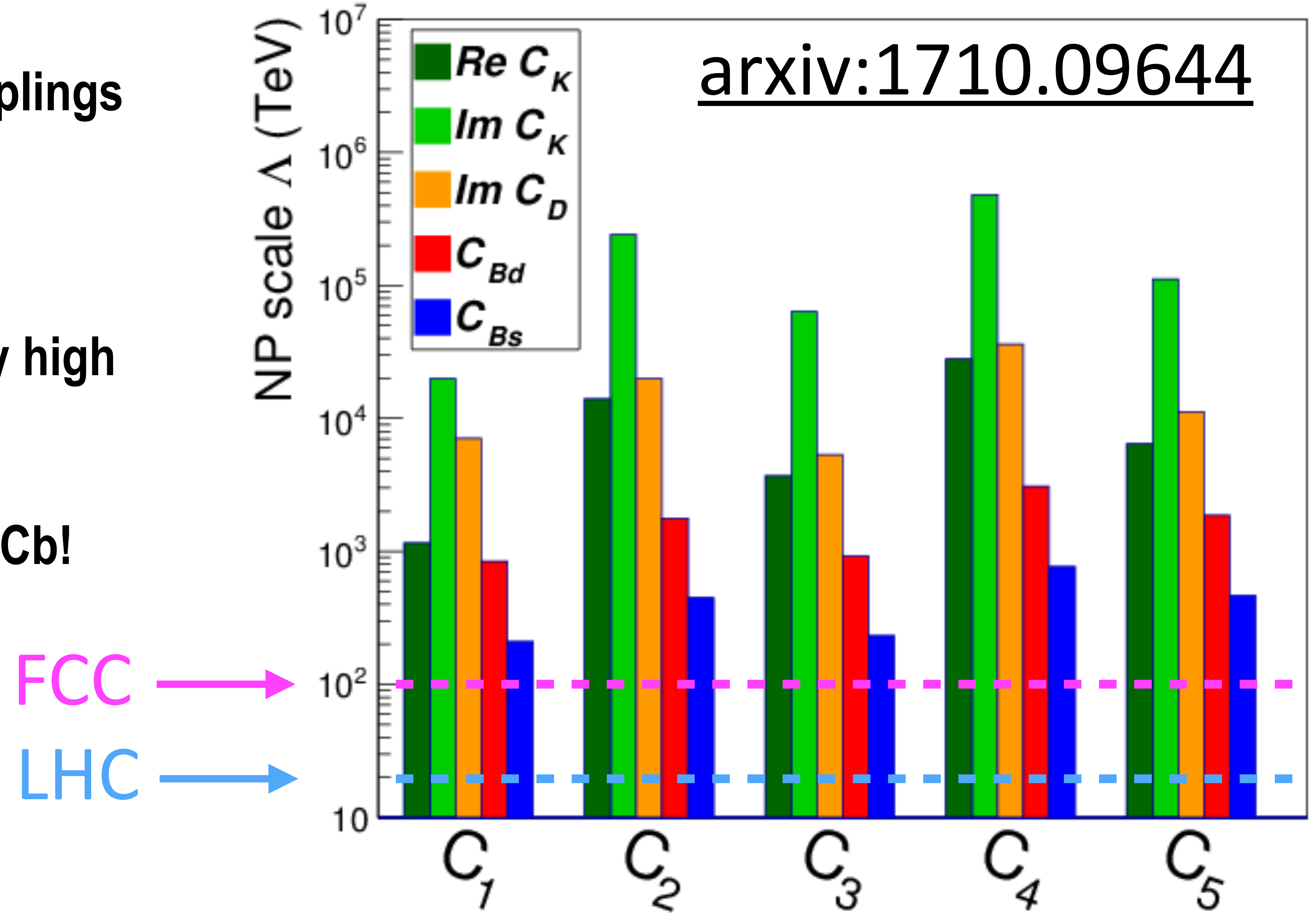
- Indirect CPV in Charm decays could probe extremely high BSM scales and are highly suppressed in the SM
- Complementary to direct searches for BSM particles
- We have billions of decays ready to be studied at LHCb!

Challenging

- Predictions are difficult (not a precision probe)
- Interesting laboratory for non-perturbative QCD and (exotic) hadron dynamics

Limits

arxiv:1710.09644



Wilson Coefficients

2019: First Observation of CP Violation in Charm

PRL122 (2019) 211803

symmetry
dimensions of particle physics

topics

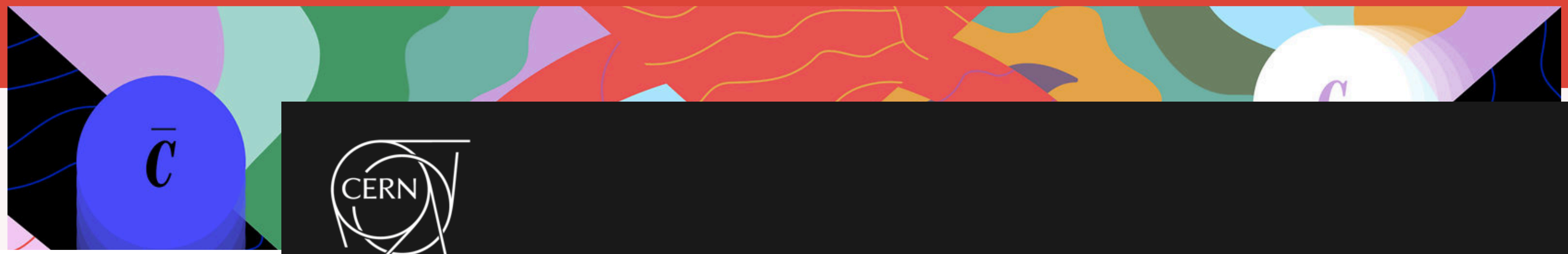
follow +

A joint Fermilab/SLAC publication

LHCb discovers matter-antimatter asymmetry in charm quarks

03/21/19 | By Sarah Charley

A new observation by the LHCb experiment finds that charm quarks behave differently than their antiparticle counterparts.



CERN

ABOUT

News › Press release › Topic: Physics

Voir en *français*

LHCb sees a new flavour of matter–antimatter asymmetry

The LHCb collaboration has observed a phenomenon known as CP violation in the decays of a particle known as a D0 meson for the first time

21 MARCH, 2019

INFN
Istituto Nazionale di Fisica Nucleare

Today: Observation of D^0 eigenstates mass difference!

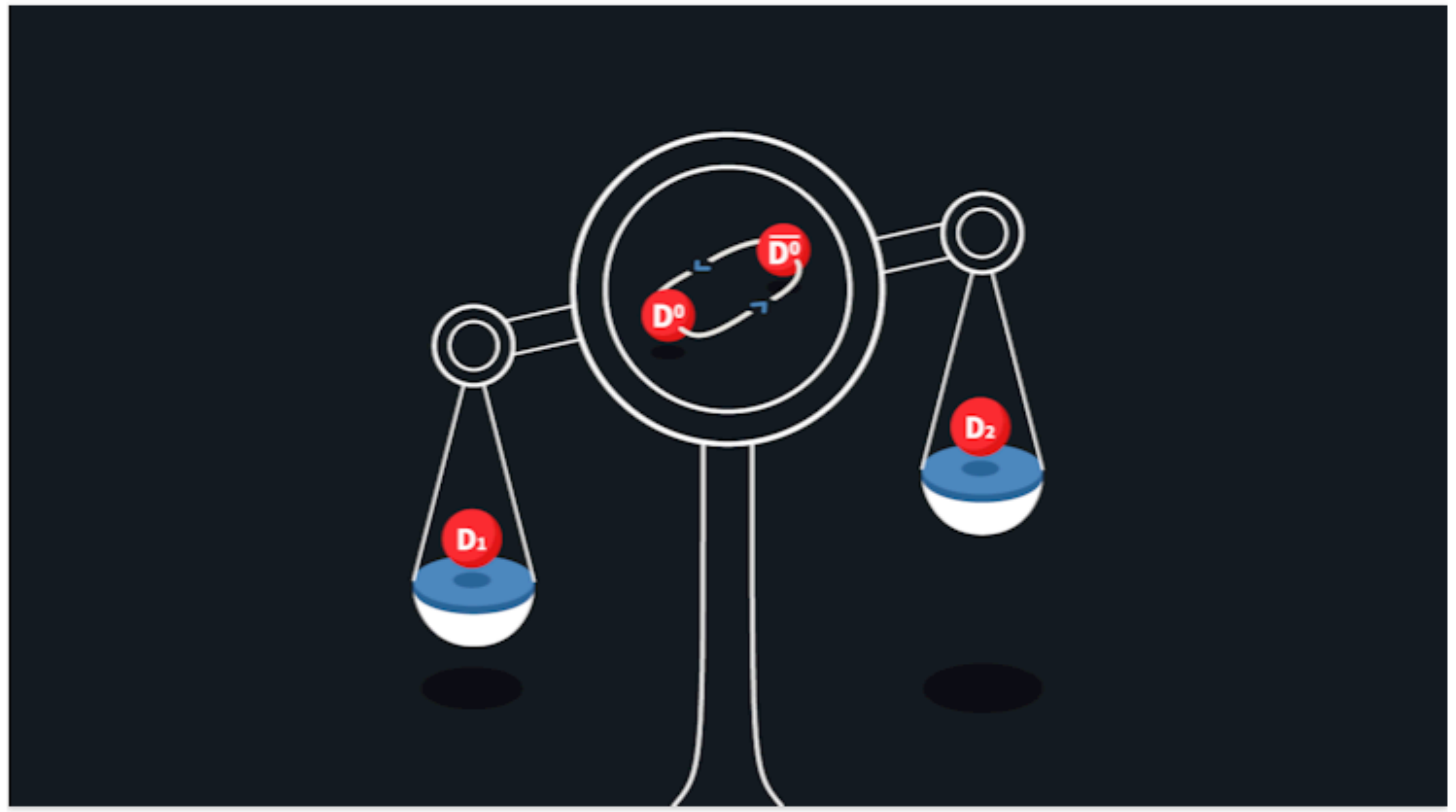
arXiv:2106.03744

CERN ABOUT NEWS S

LHCb measures tiny mass difference between particles

The result is a milestone in the study of how a particle known as a D0 meson changes from matter into antimatter and back

8 JUNE, 2021 | By Ana Lopes



The LHCb collaboration has measured the tiny mass difference between the D1 and D2 mesons, which are a manifestation of the quantum superposition of the D0 particle and its antiparticle. This mass difference controls the speed of the D0 oscillation into its antiparticle and back. (Image: CERN)

The LHCb collaboration has measured a difference in mass between two particles of 0.00000000000000000000000000000000000001 grams – or, in scientific notation, 10^{-38} g. The result, reported in a paper just submitted for publication in the journal *Physical Review Letters* and presented today at a CERN seminar, marks a milestone in the study of how a particle known as a D^0 meson changes from matter into antimatter and back.

INFN Istituto Nazionale di Fisica Nucleare

UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA

Mixing and CP Violation

Neutral Mesons Mixing

$$|D_1\rangle = p|D^0\rangle + q|\overline{D}^0\rangle$$

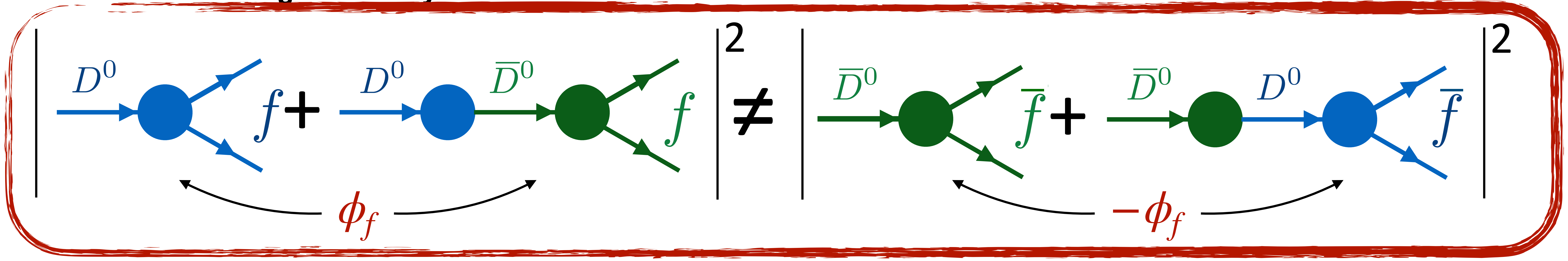
$$|D_2\rangle = p|D^0\rangle - q|\overline{D}^0\rangle$$

With $x = \frac{m_2 - m_1}{\Gamma}$ and $y = \frac{\Gamma_2 - \Gamma_1}{2\Gamma}$ $\left(\text{with } \Gamma = \frac{\Gamma_2 + \Gamma_1}{2}\right)$

CP Asymmetry

$$\phi_f = \arg \frac{q}{p}\frac{\overline{A}_f}{A_f} \neq 0 \Longrightarrow CPV$$

- Interference between mixing and decay



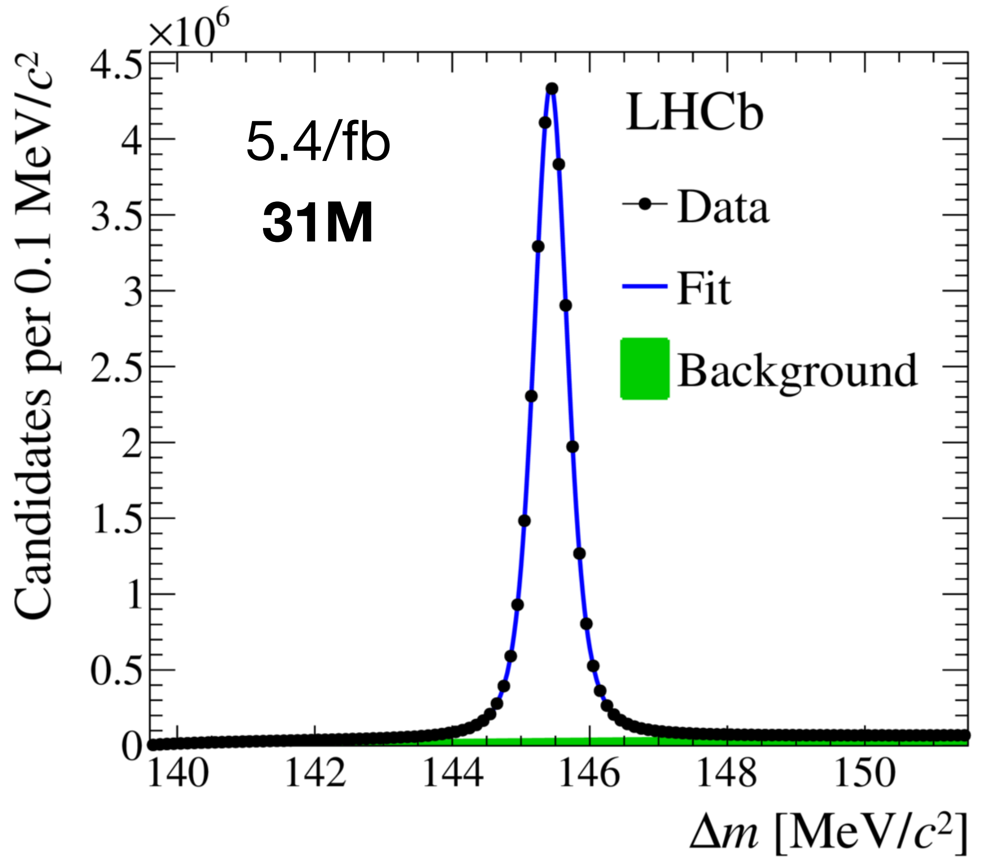
$$\textbf{i.e.: } A \propto x \sin\phi_f \left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) + y\cos\phi_f\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right)$$

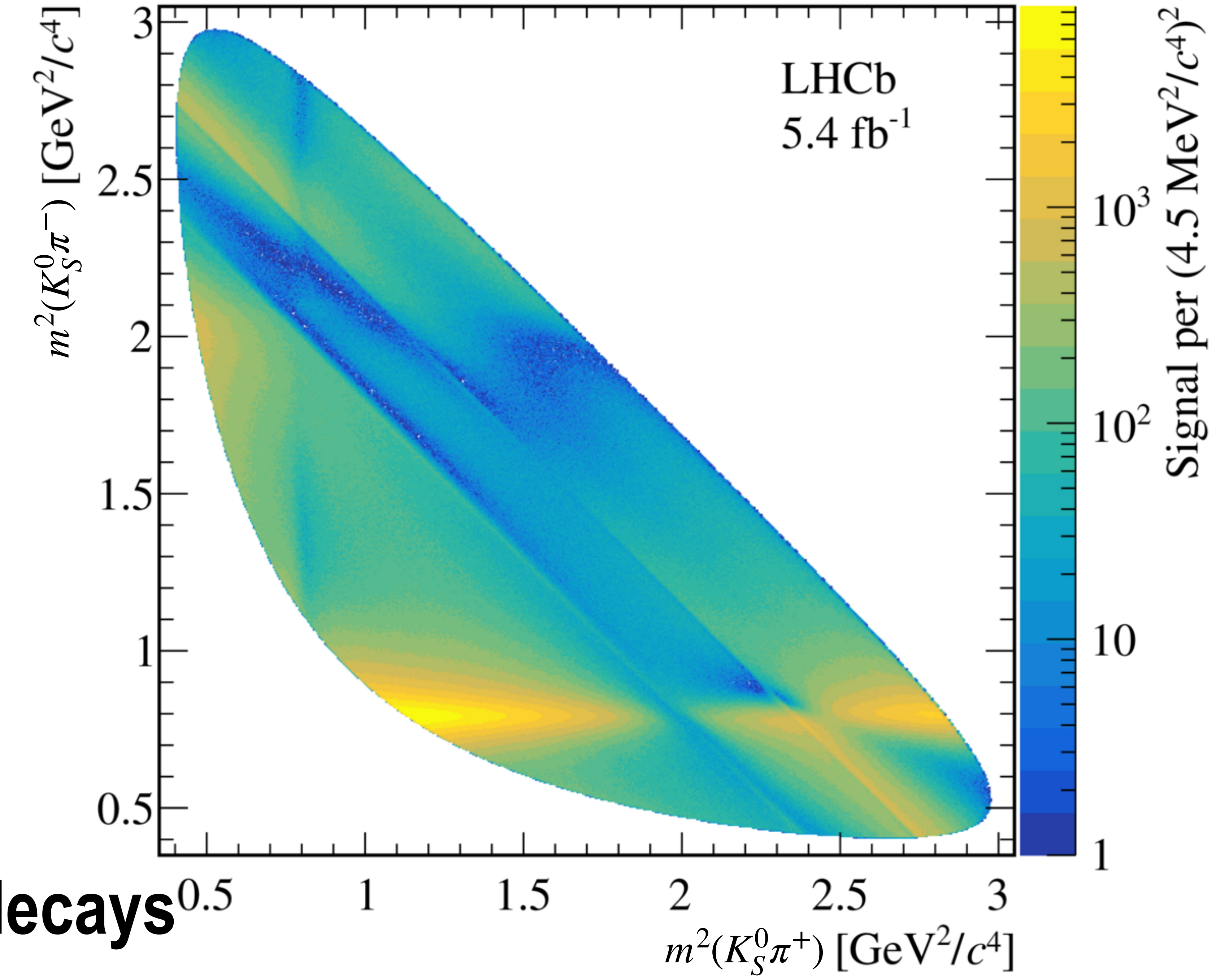
The Golden Channel: $D^0 \to K^0_S\pi^+\pi^-$

arXiv:2106.03744

Mixing and indirect CPV

- Allows to measure directly x, y
- Indirect CPV from measurement of q/p





Analysis Approaches

- Time-dependent amplitude analysis
- Bin-flip

Bin-flip PRD 99, 012007 (2019)

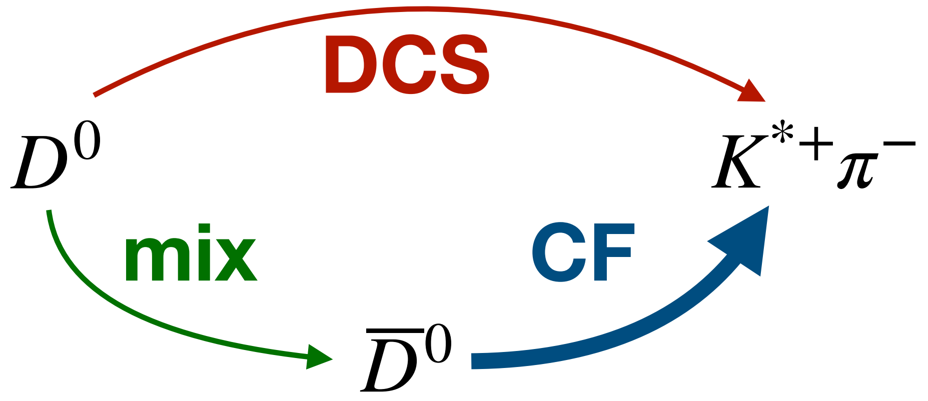
- An extension of the WS mixing measurement concept to multi body decays

$$R_b \approx r_b - \sqrt{r_b}\left[(1-r_b)c_b y - (1+r_b)s_b x\right]\Gamma t$$

- Hadronic parameters (c_b,s_b) constrained by external input

  From measurement of quantum-correlated D^0-$\overline{D}^0$ pairs (e.g. CLEO, BESIII)
- Slightly degraded precision with respect to amplitude analysis approach

  At the advantage of significantly simplified analysis



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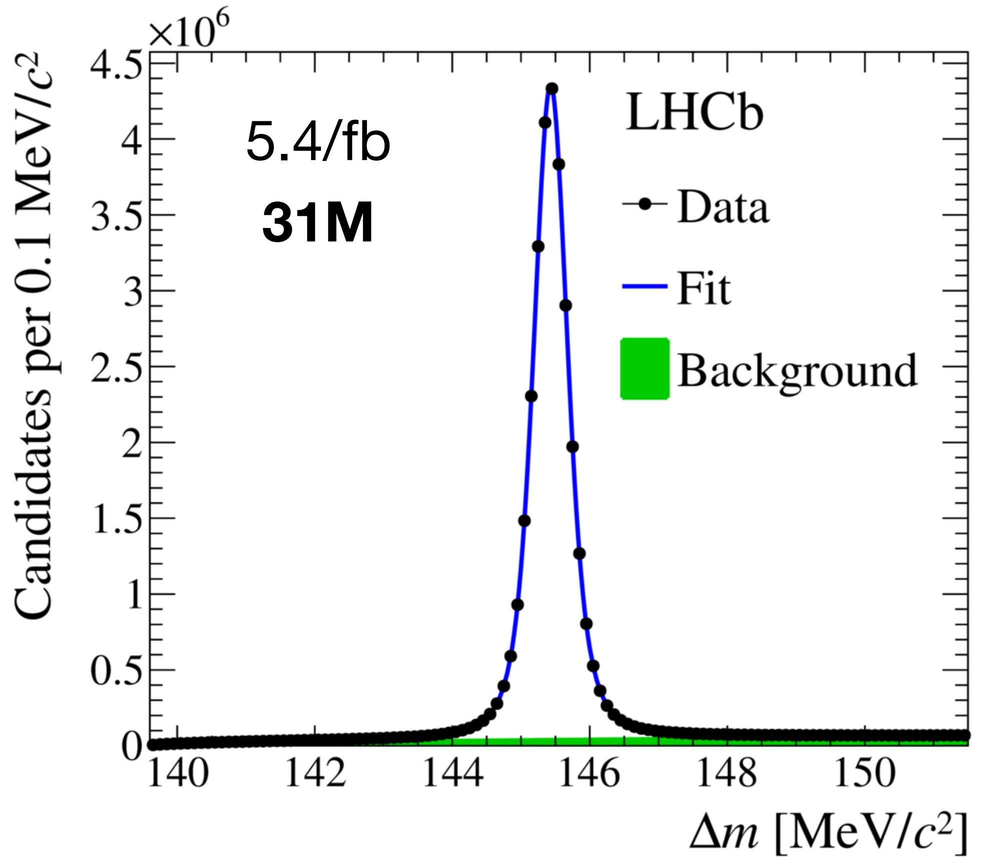

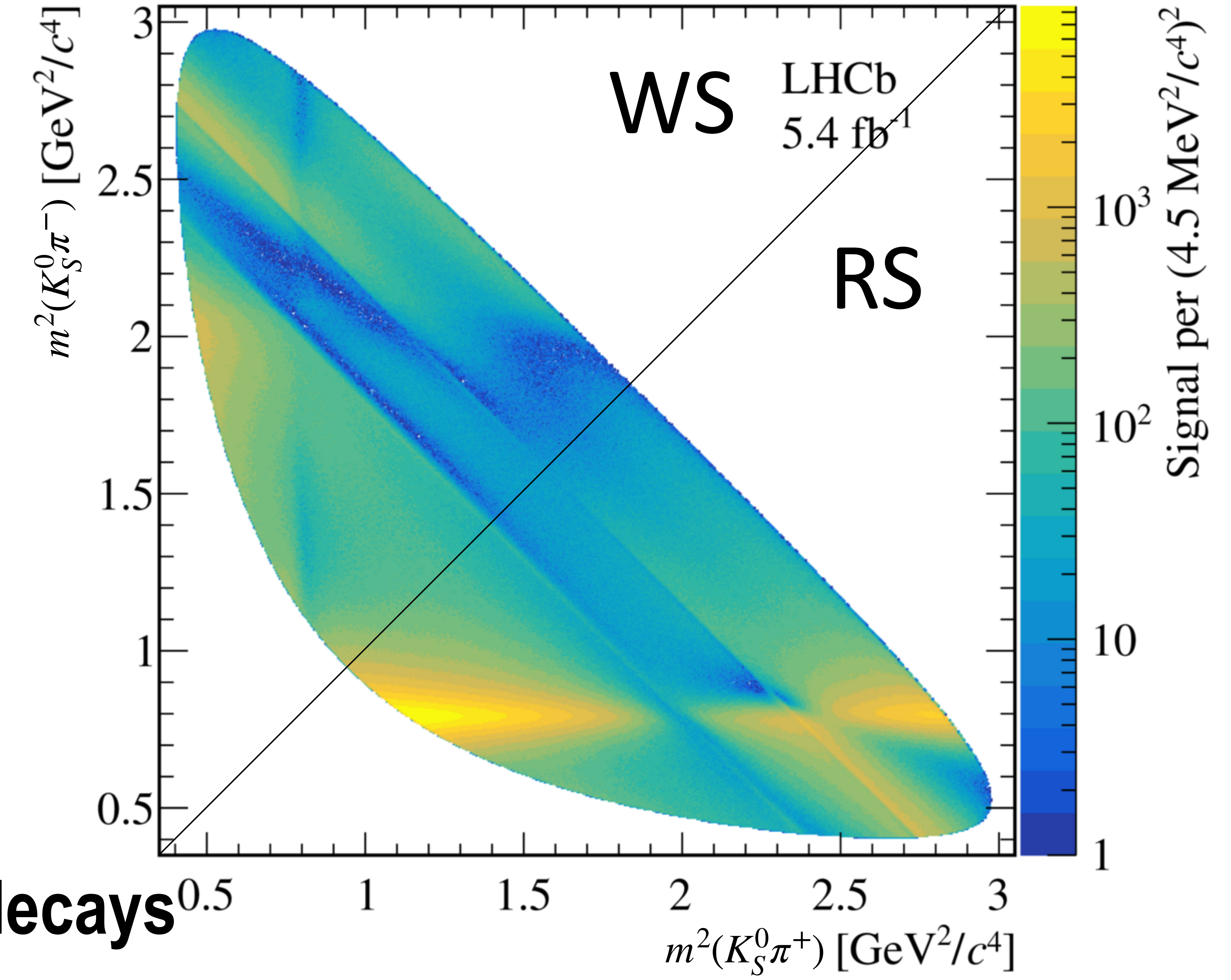

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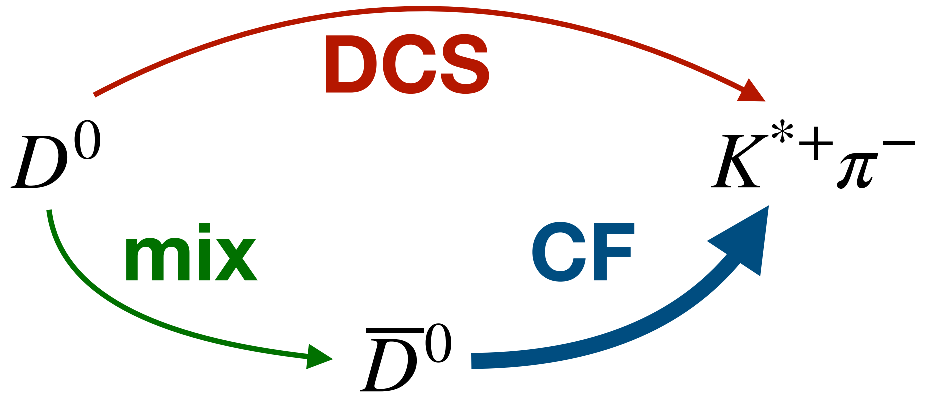

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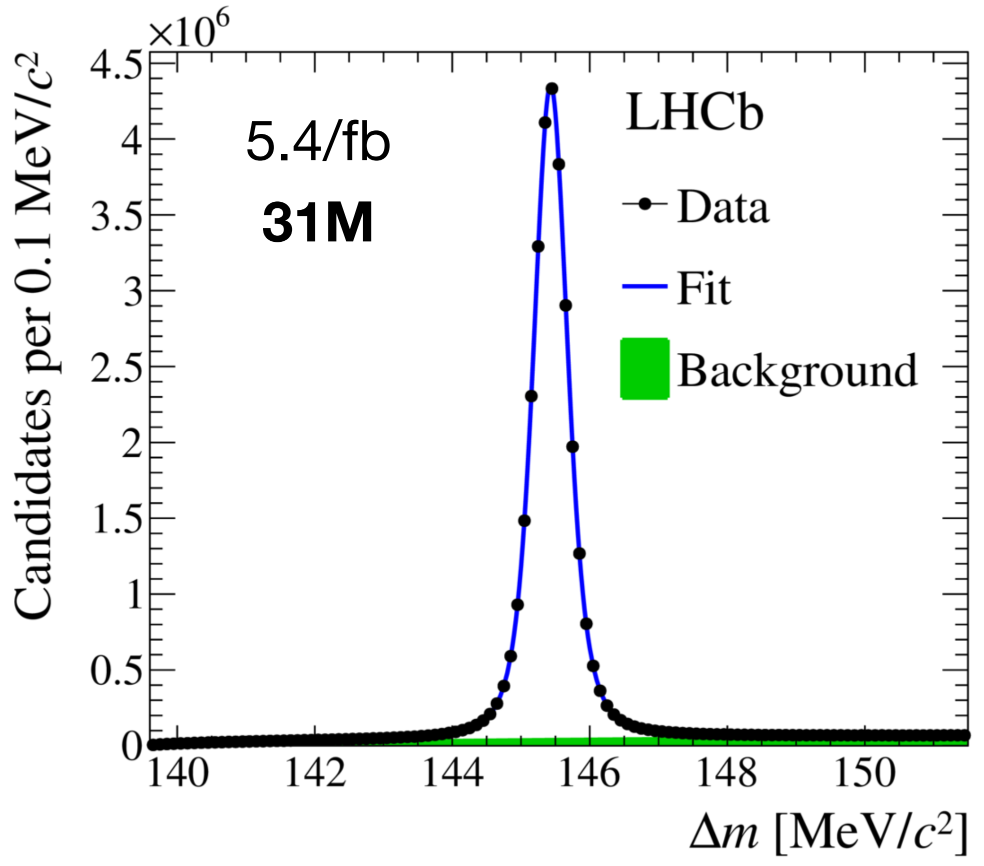

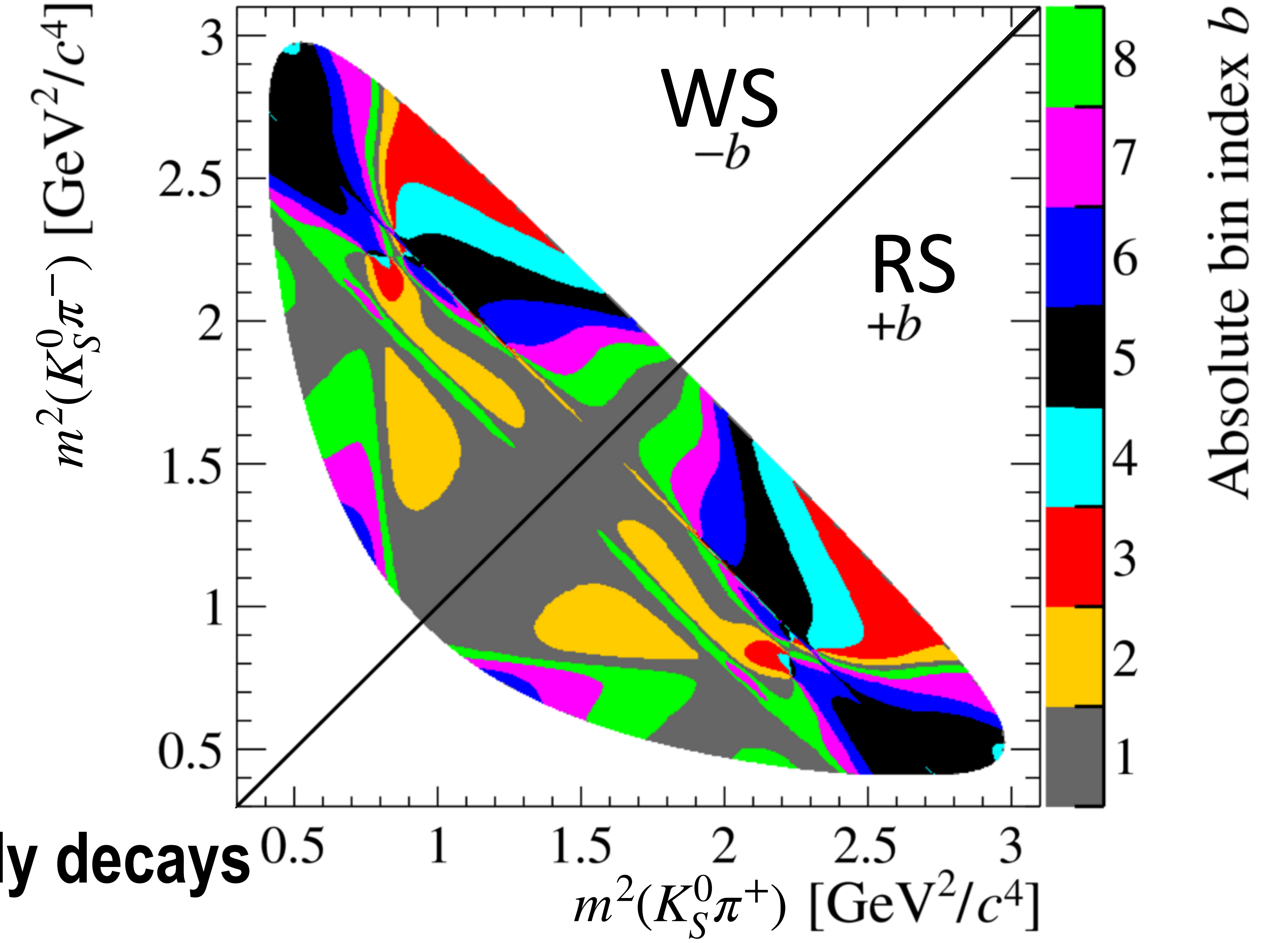

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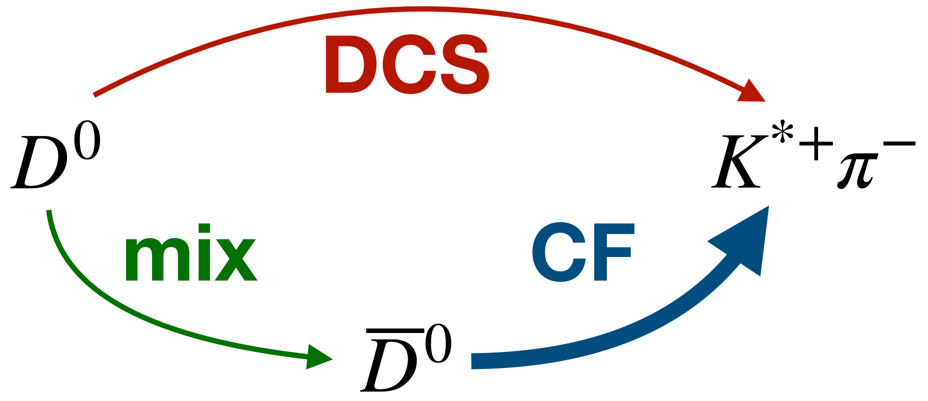

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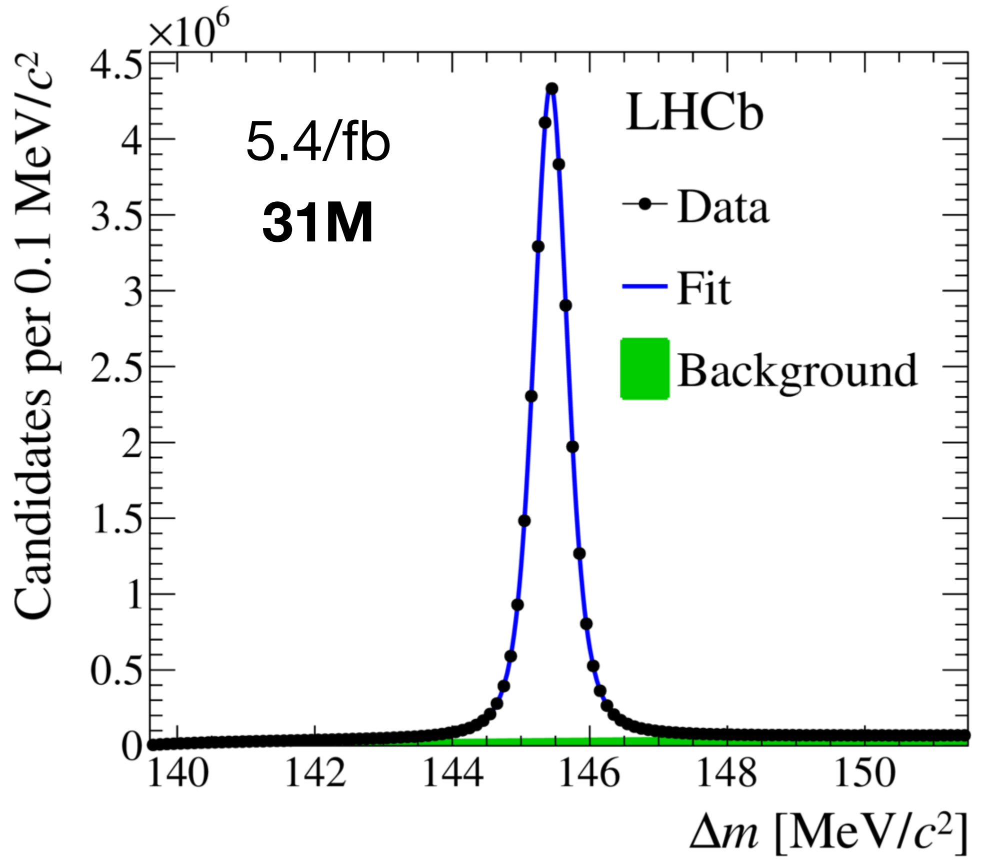

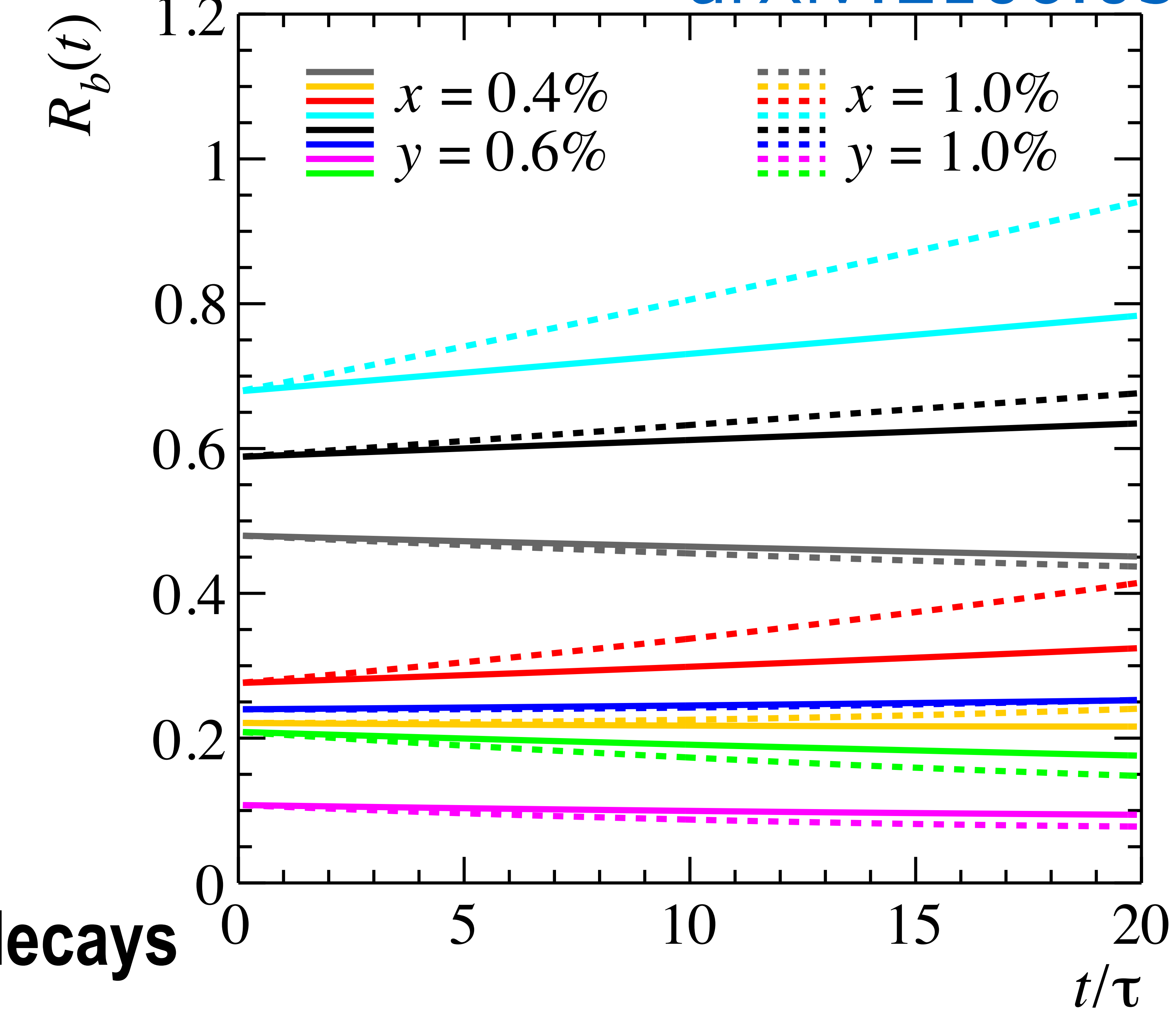

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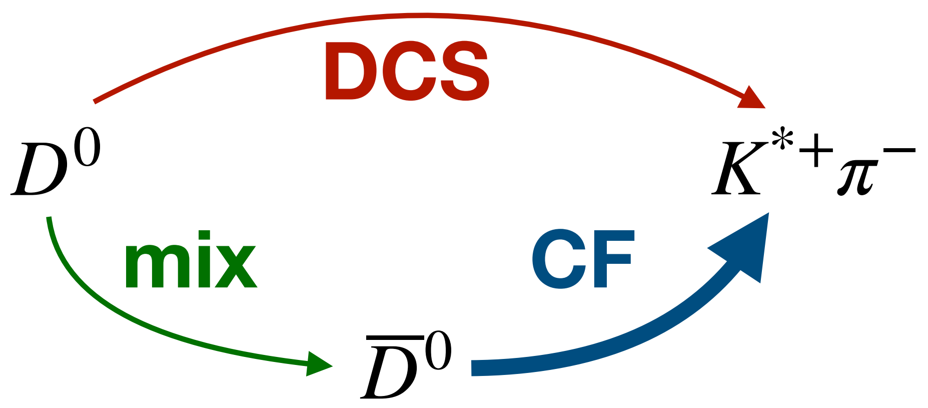
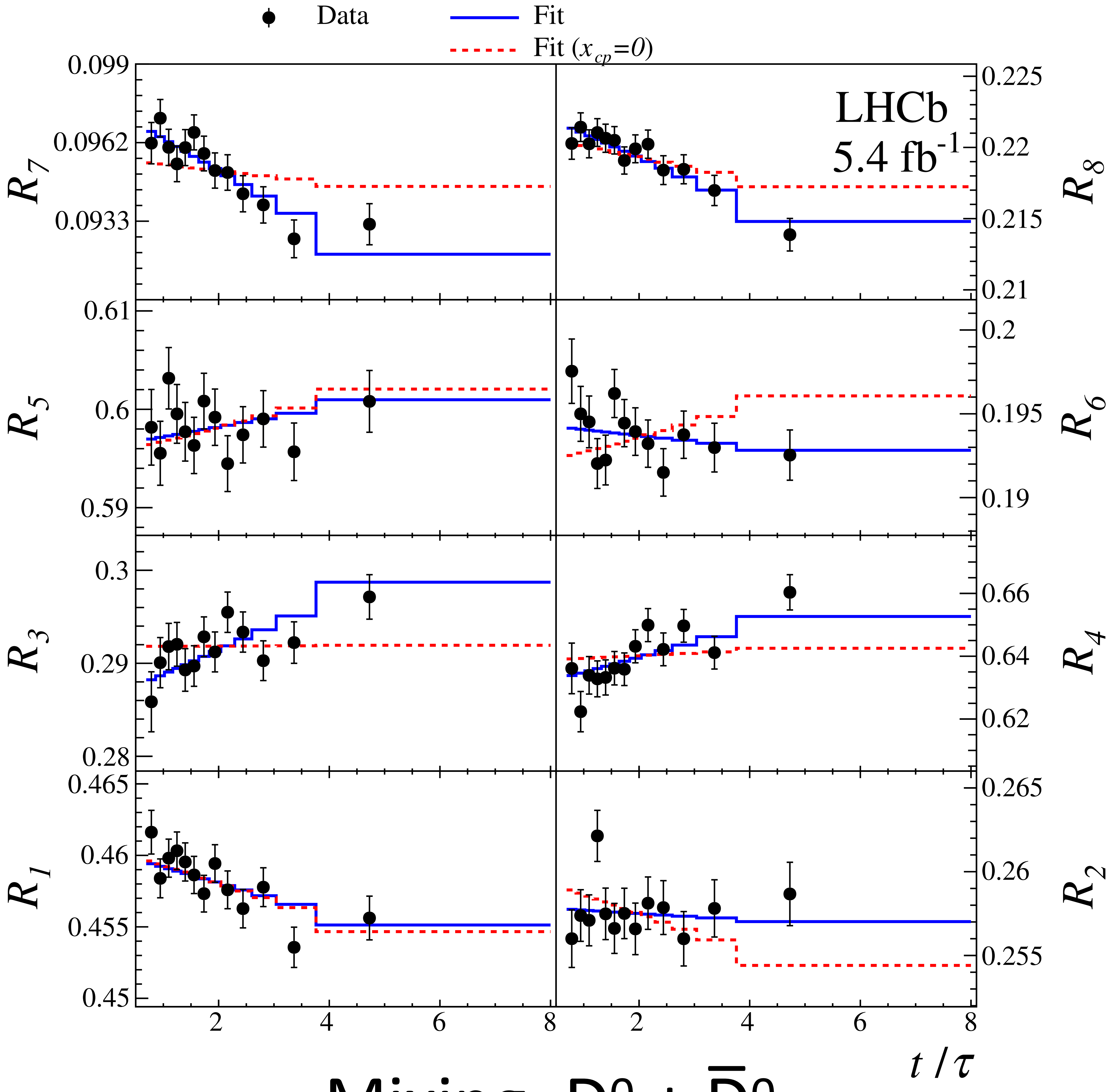
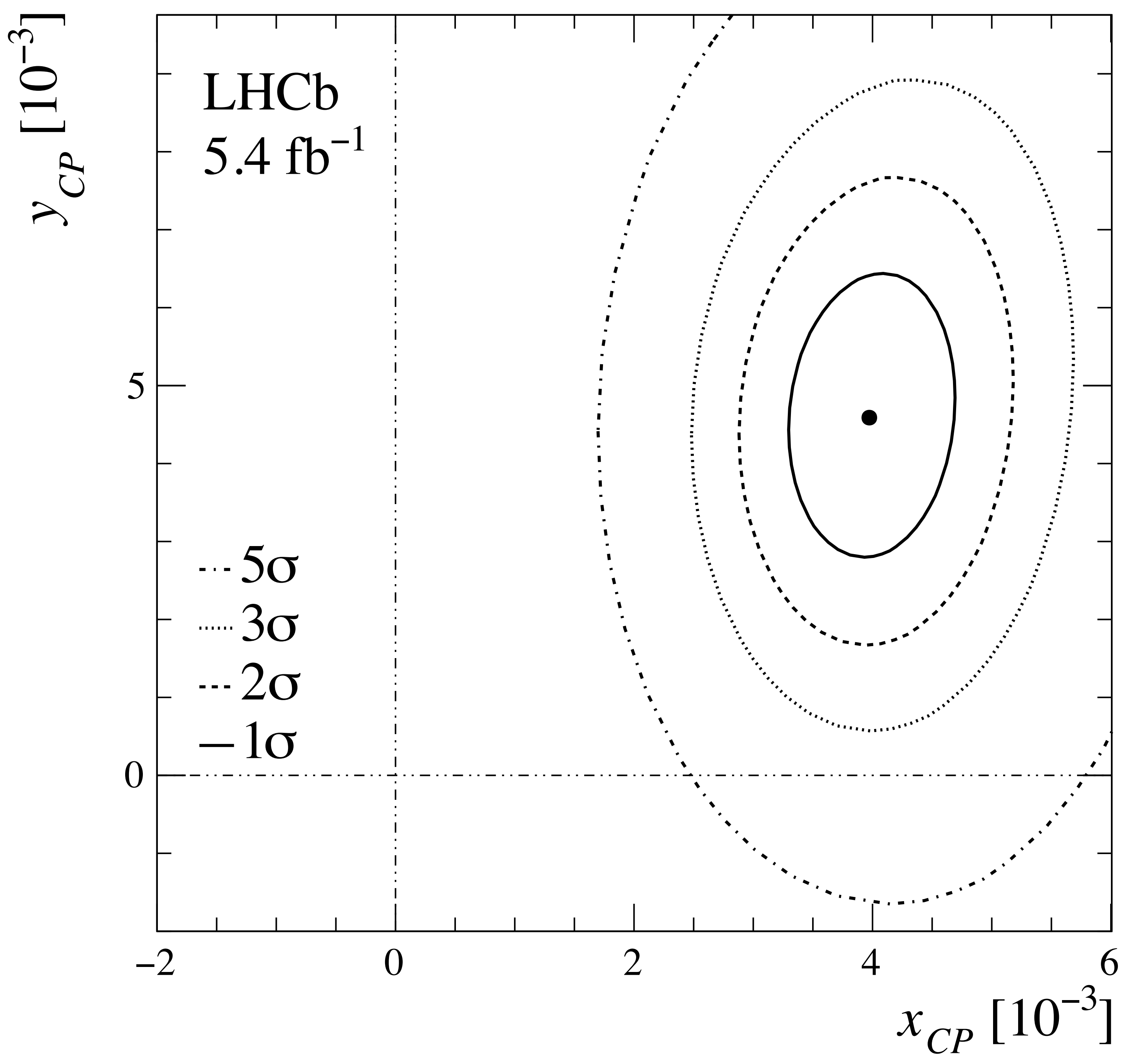


$D^0 \to K^0_S \pi^+ \pi^-$ Bin-Flip Results



Mixing: $D^0 + \overline{D}^0$

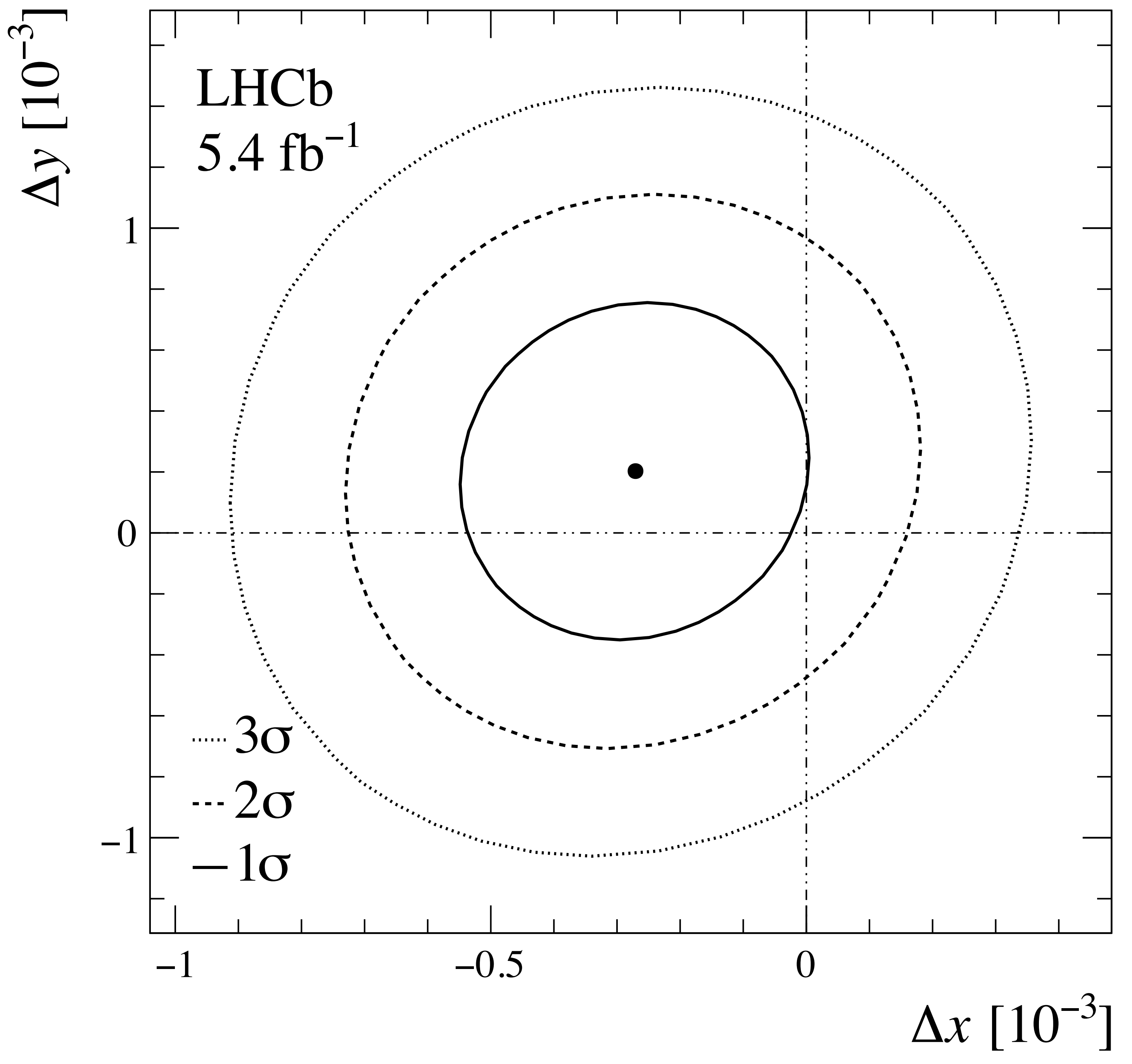
arXiv:2106.03744

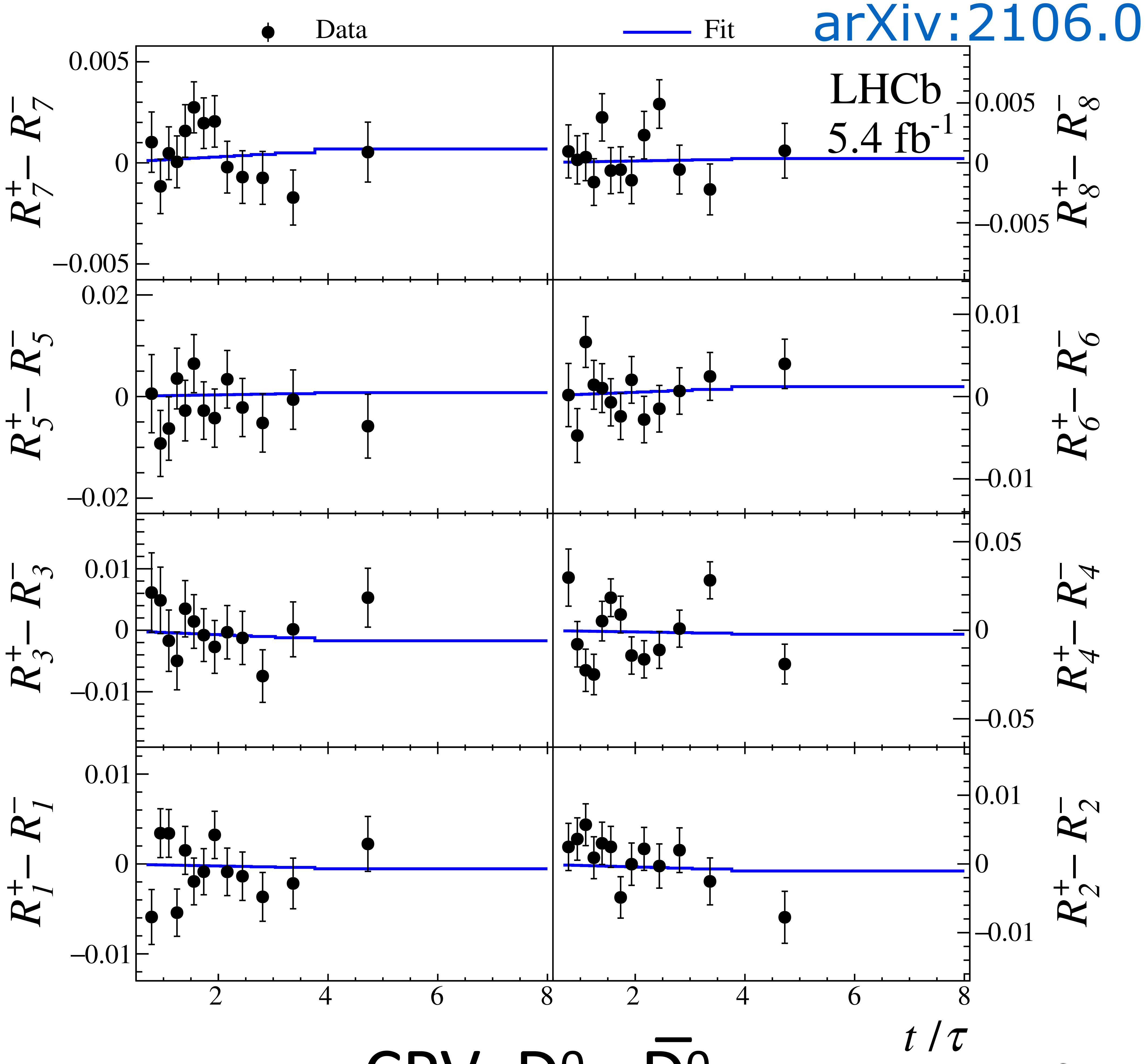


$$x_{CP} = (3.97 \pm 0.46 \pm 0.29) \times 10^{-3}$$

$$y_{CP} = (4.59 \pm 1.20 \pm 0.85) \times 10^{-3}$$

$D^0 \to K^0_S \pi^+ \pi^-$ Bin-Flip Results





$$\Delta x = (-0.27 \pm 0.18 \pm 0.01) \times 10^{-3}$$

$$\Delta y = (\ \ 0.20 \pm 0.36 \pm 0.13) \times 10^{-3}$$

CPV: D^0 - $\overline{D}^0$

$D^0 \to K^0_S \pi^+ \pi^-$ Bin-Flip Results

arXiv:2106.03744

Statistical and Systematic Uncertainties

- Largest systematic uncertainties evaluated on pseudoexperiments

Trigger-induced efficiency correlations → Reconstruction and selection

Wrong measurement of decay time for secondary charm from B-hadrons → Secondary charm decays

Time-dependent detection asymmetry → Detection asymmetry

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 uncertainties → Strong phase inputs

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

Time-dependent CP Violation in $D^0 \to h^+h^-$ (h=K,π)

arXiv:2105.09889

CP Violation in Two-body final states

Final state dependent CPV

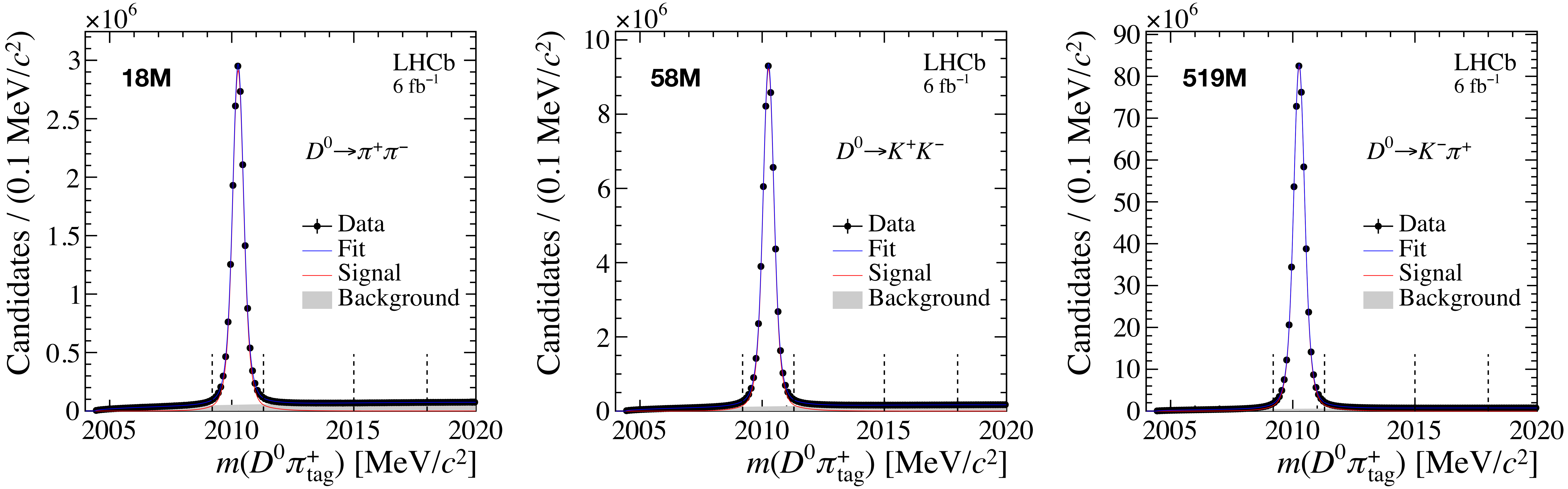
$$A_{CP}(t) = \frac{\Gamma(D^0(t) \to f) - \Gamma(\overline{D}^0(t) \to f)}{\Gamma(D^0(t) \to f) + \Gamma(\overline{D}^0(t) \to f)} \approx a_f^d + \Delta Y_f \frac{t}{\tau_D}$$

(aka $-A_\Gamma$)

$$-\Delta y \approx \Delta Y_f \approx x\phi - y\left(\left|\frac{q}{p}\right| - 1\right)$$

SM expectations ~ 10^{-5} Kagan & Silvestrini, 2020 Li et al, 2020

- **Studied at LHCb with Run2 dataset (2015-2018)**



Time-dependent CP Violation in $D^0 \to h^+h^-$ (h=K,π)

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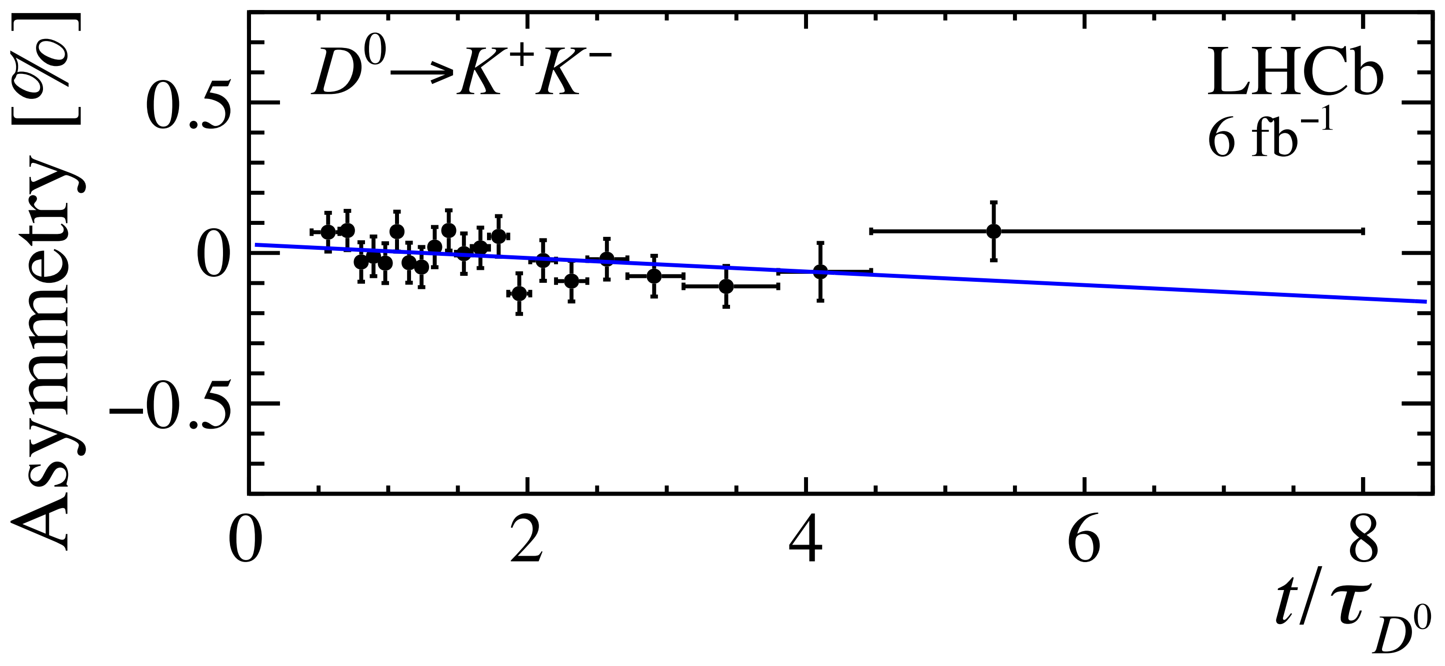
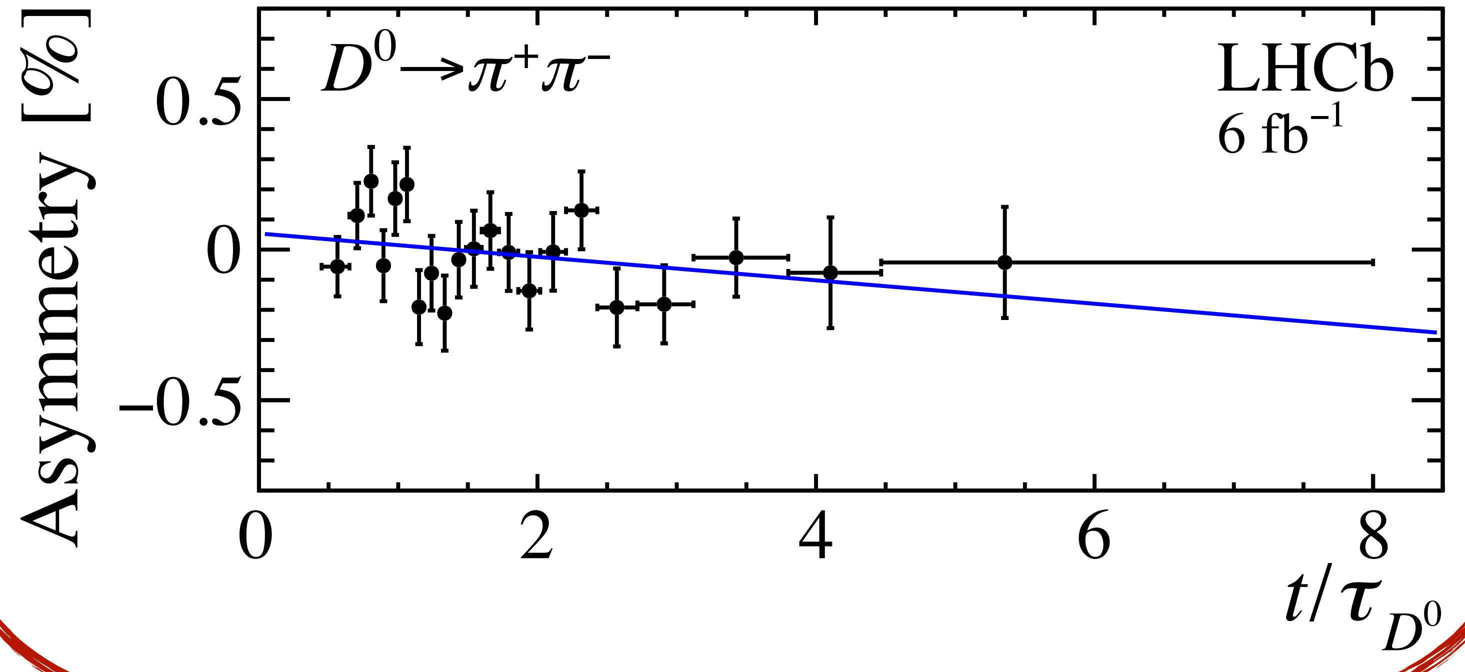
Results

$\Delta Y_{K^+K^-} = (-2.3 \pm 1.5 \pm 0.3) \times 10^{-4}$



$\Delta Y_{\pi^+\pi^-} = (-4.0 \pm 2.8 \pm 0.4) \times 10^{-4}$



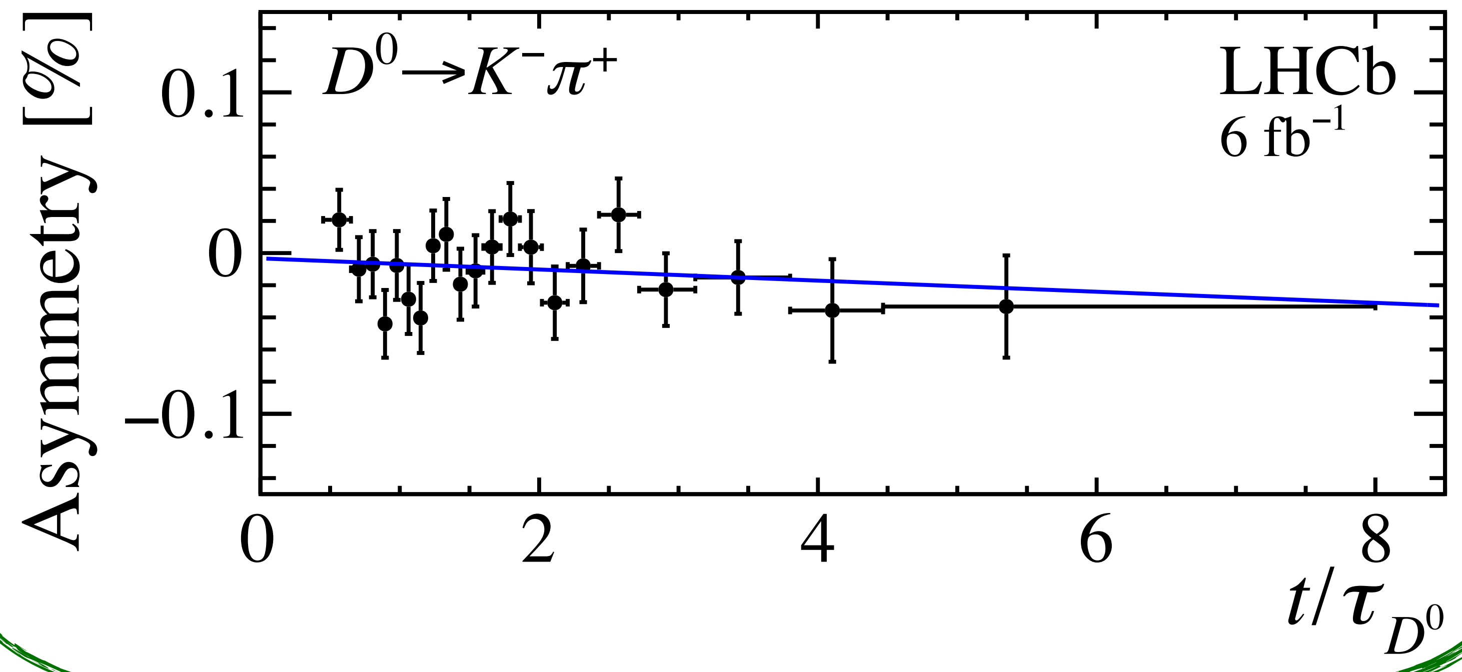
$\Delta Y = (-2.7 \pm 1.3 \pm 0.3) \times 10^{-4}$

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

Control Sample

$\Delta Y_{K^-\pi^+} = (-0.4 \pm 0.5 \pm 0.2) \times 10^{-4}$



$D^0 \to K^-\pi^+$

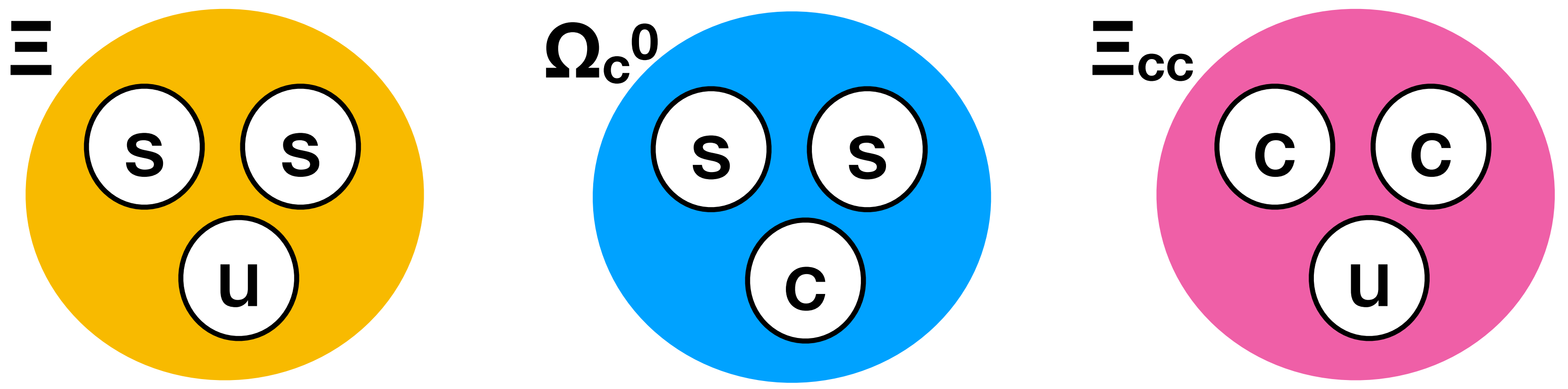
No CPV Expected

Latest Results in Spectroscopy

Baryon Spectroscopy

Charm Baryons

- **Measured by LHCb with unprecedented precision (lifetime, mass)**
- **Allow to test various hypotheses such as the quark-diquark picture in different scenarios**

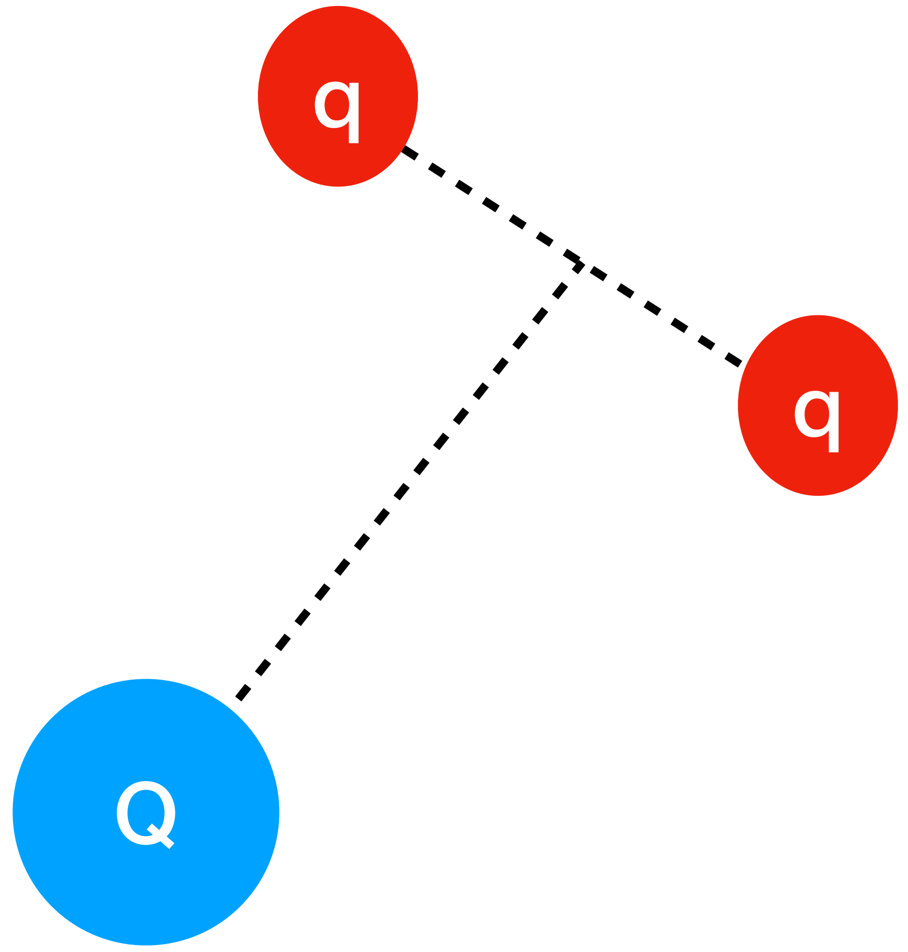


- **Quark-diquark picture**

  Heavy quark static and spineless in the limit $m_Q \rightarrow \infty$

  Excitations governed by the light diquark

  Different excitation patterns have effects on the number of states and their spin



Lifetime of the Ω_c^0 Baryon

LHCB-PAPER-2021-021

Charm Hadron Lifetime Hierarchy

- **Until 2018, the most accepted hierarchy was**

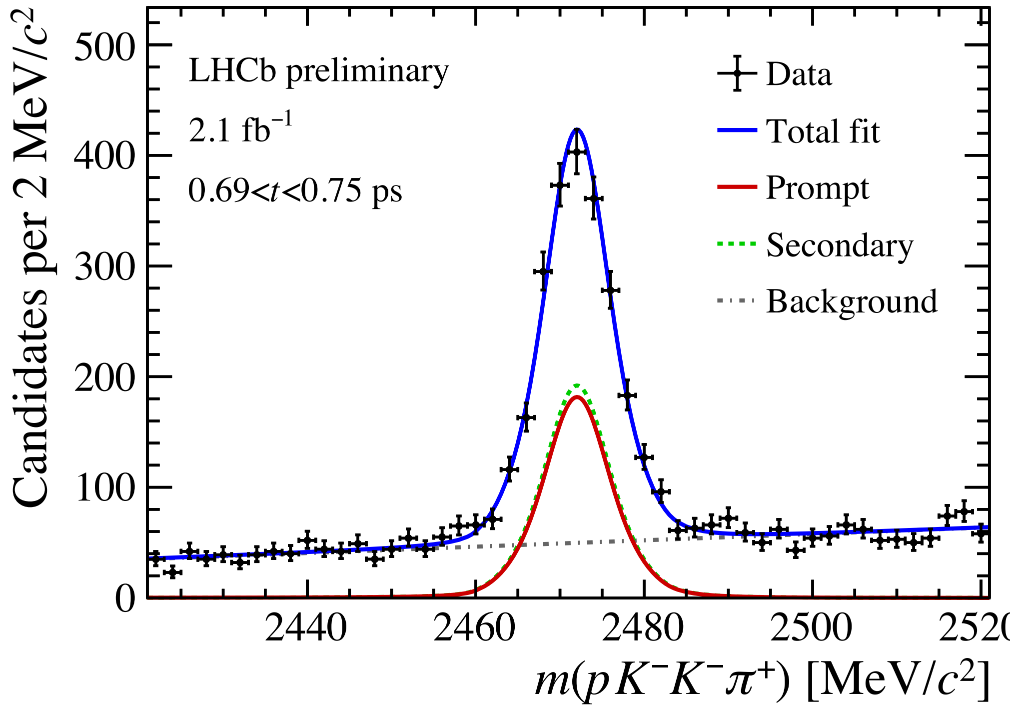
  $\tau_{\Xi_c^+} > \tau_{\Lambda_c+} > \tau_{\Xi_c^0} > \tau_{\Omega_c^0}$

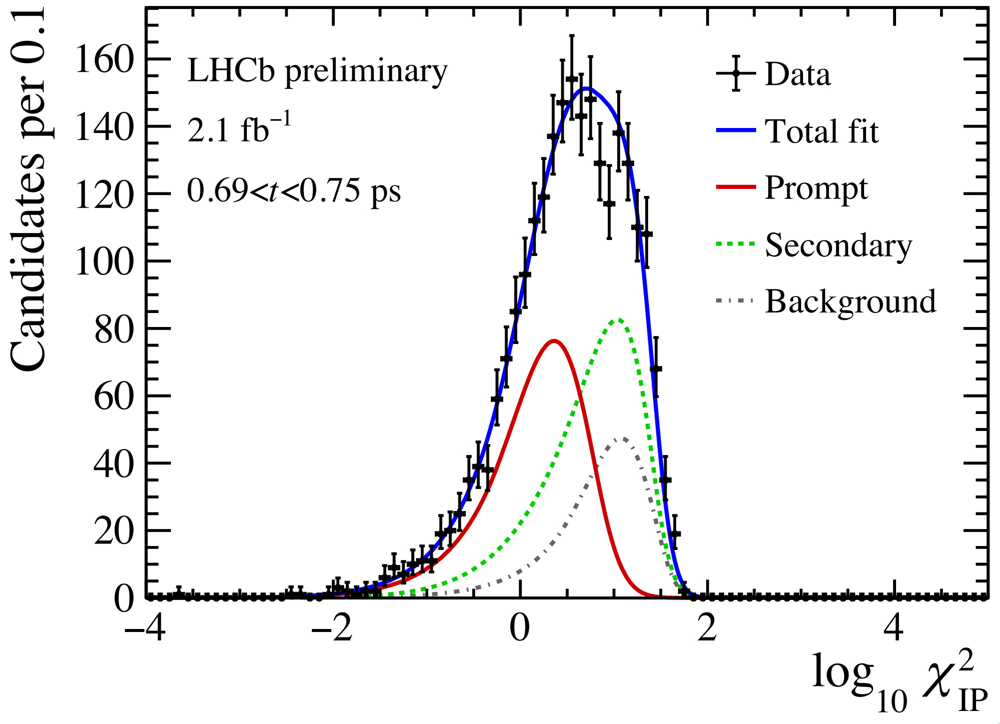
- **Then LHCb presented the most precise measurement of Ω_c^0 and Ξ_c^0 lifetimes that subverted the scenario using baryons from b-baryons decays**

  $\tau_{\Xi_c^+} > \tau_{\Omega_c^0} > \tau_{\Lambda_c+} > \tau_{\Xi_c^0}$ PRL121(2018)092003

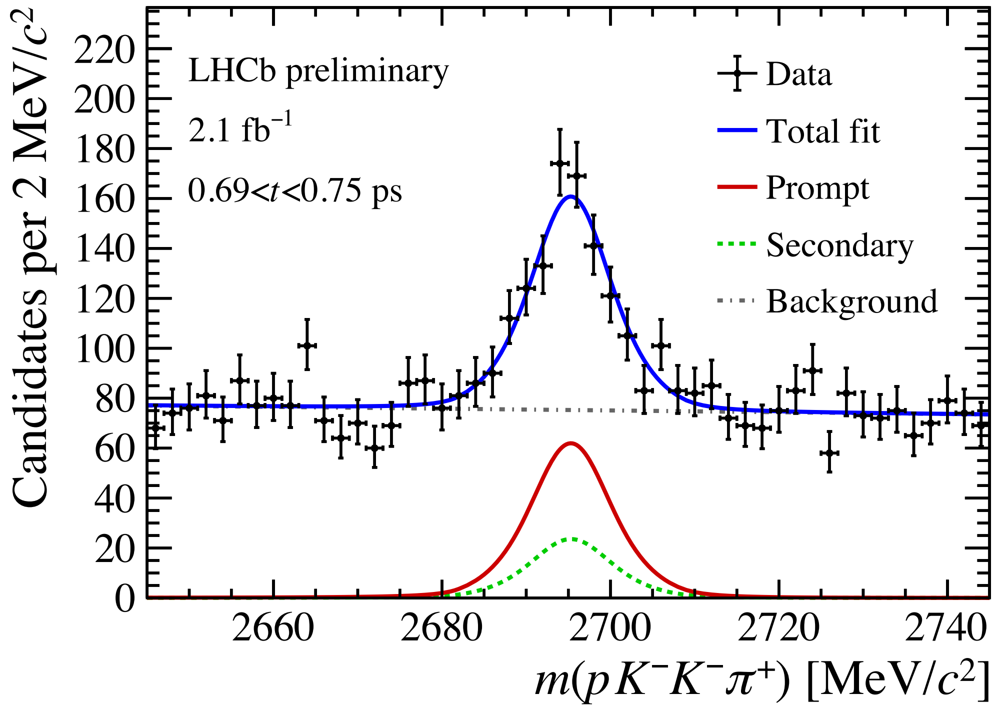
- **It was necessary to cross-check the result with an independent sample**

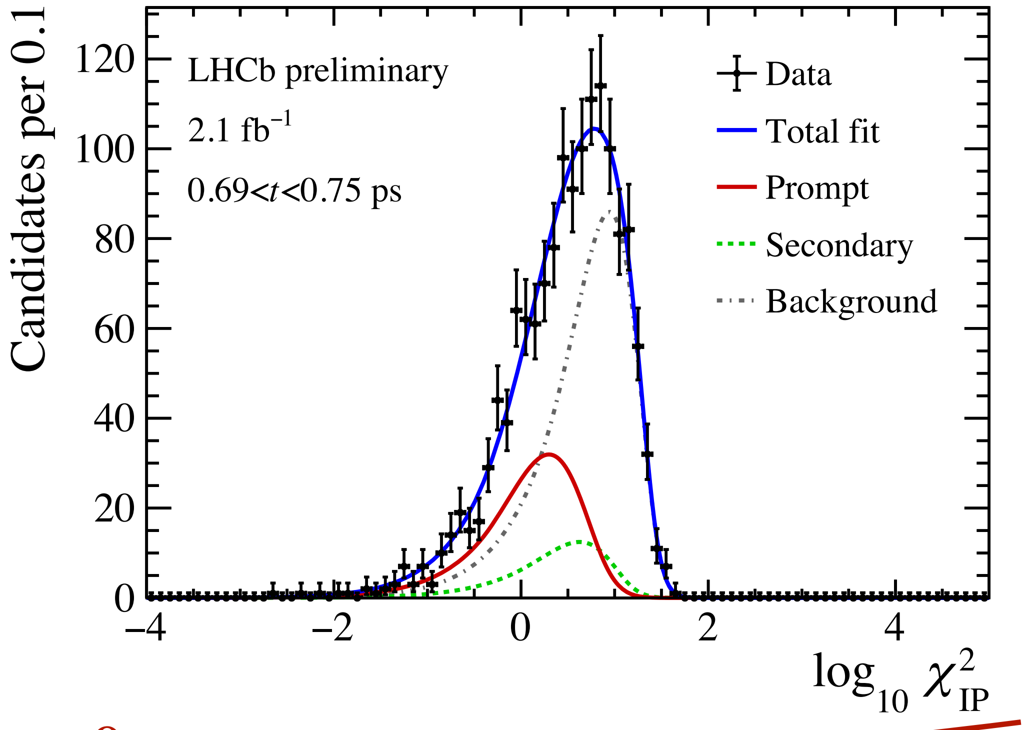
  Analysed Run2 data (5.4/fb) and measured promptly produced charm baryons (+$D^0 \to K^+K^-\pi^+\pi^-$ control sample)





Ξ_c^0





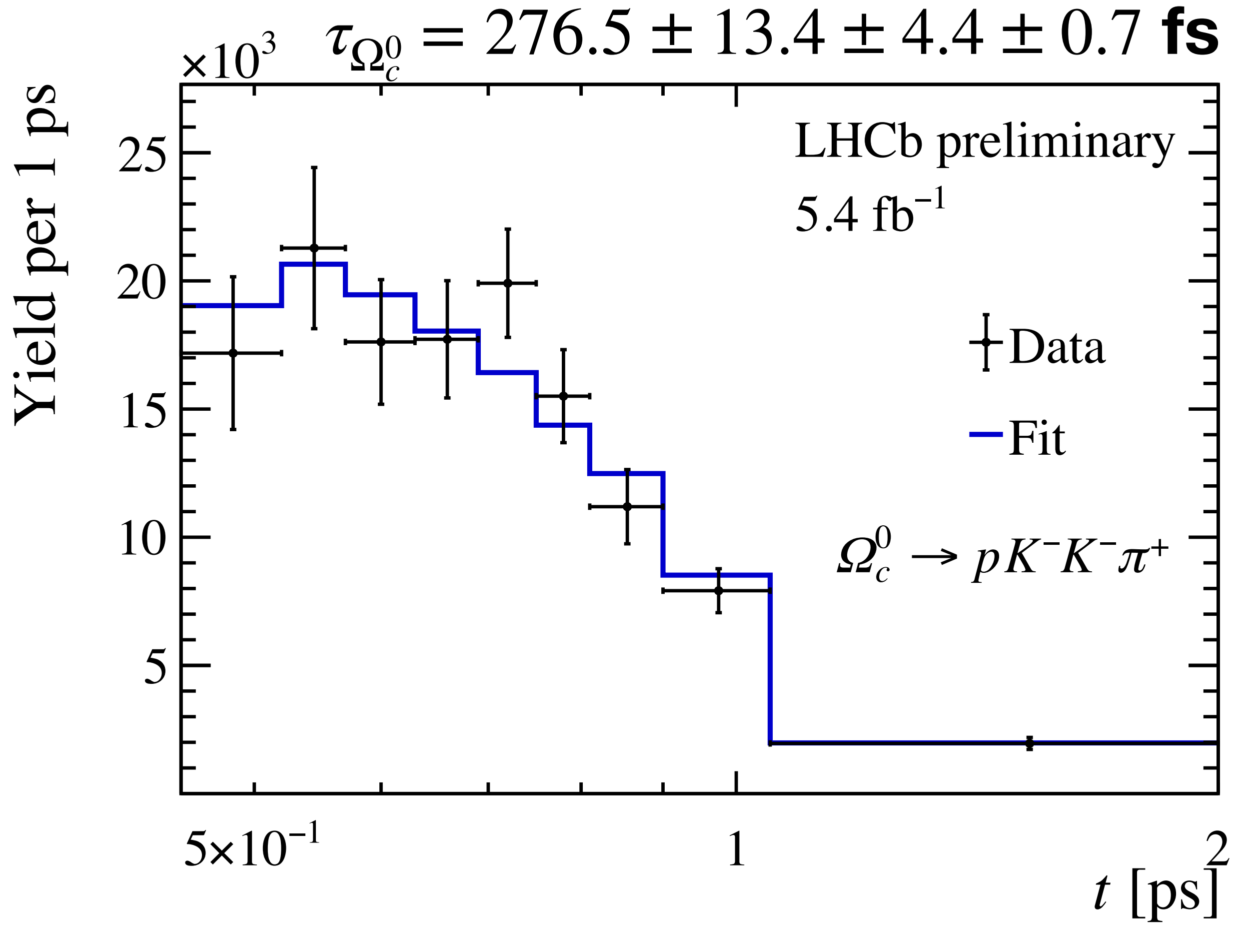
Ω_c^0

Lifetime of the Ω_c^0 Baryon

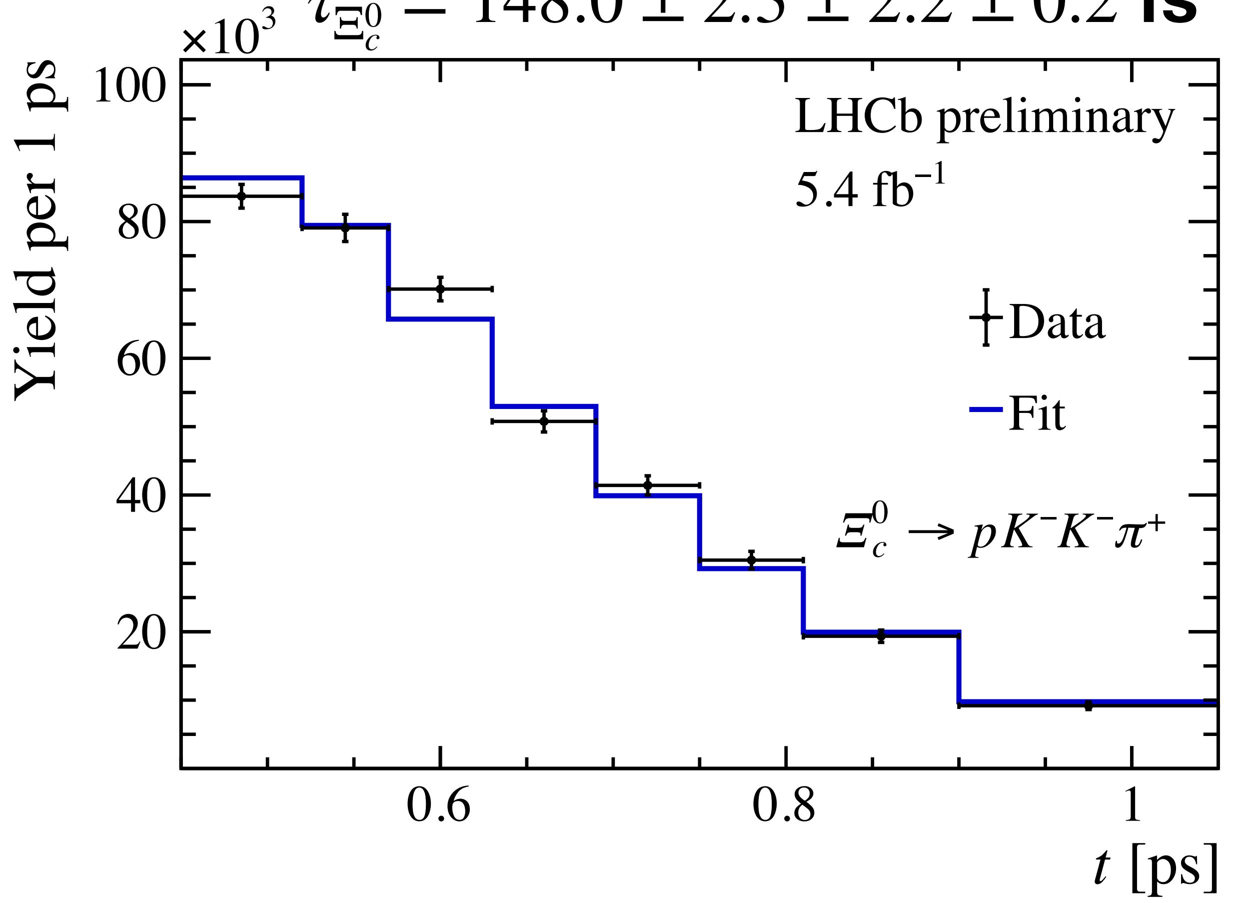
LHCB-PAPER-2021-021

Results

$\tau_{\Omega_c^0} = 276.5 \pm 13.4 \pm 4.4 \pm 0.7$ **fs**



$\tau_{\Xi_c^0} = 148.0 \pm 2.3 \pm 2.2 \pm 0.2$ **fs**



Systematic Uncertainties

Sources	$\tau_{\Omega_c^0}$ [fs]	$\tau_{\Xi_c^0}$ [fs]
Fit model	2.2	1.0
Calibration sample size	0.1	0.1
Kinematic correction	3.4	0.4
Decay-time resolution	1.3	1.8
χ^2_{IP} scaling	1.1	0.5
Decay-length scale	0.1	0.1
D^0 mixing	0.8	0.6
Total systematic uncertainty	4.4	2.2
D^0 lifetime	0.7	0.2
Statistical uncertainty	13.4	2.3

Control Sample (Fit model, Calibration sample size)

Data/MC differences (Kinematic correction, Decay-time resolution, χ^2_{IP} scaling)

External Input (Decay-length scale, D^0 mixing)

$\tau_{\Xi_c^+} > \tau_{\Omega_c^0} > \tau_{\Lambda_c^+} > \tau_{\Xi_c^0}$ **confirmed!**

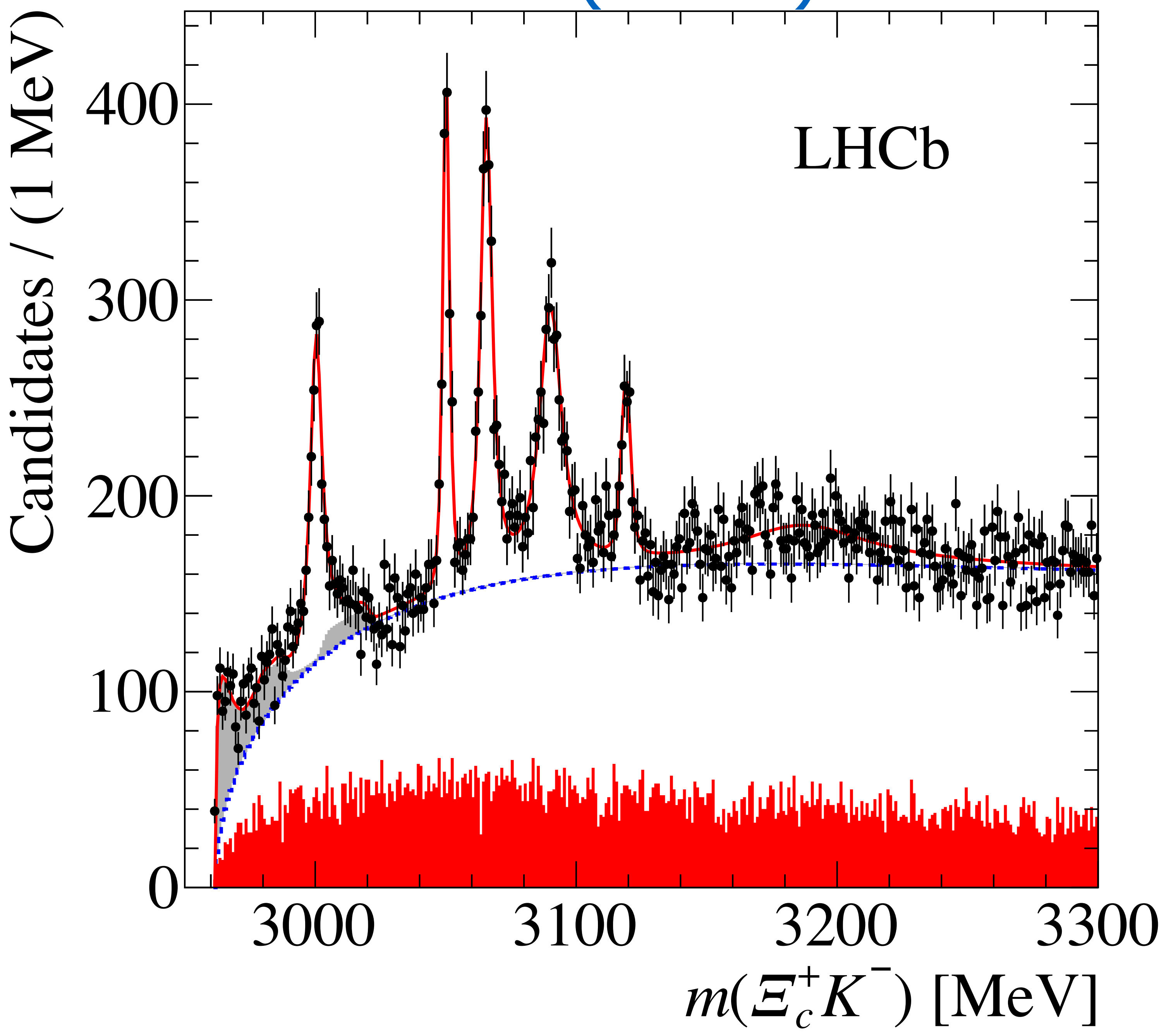
Excited Ω_c^0 Baryons

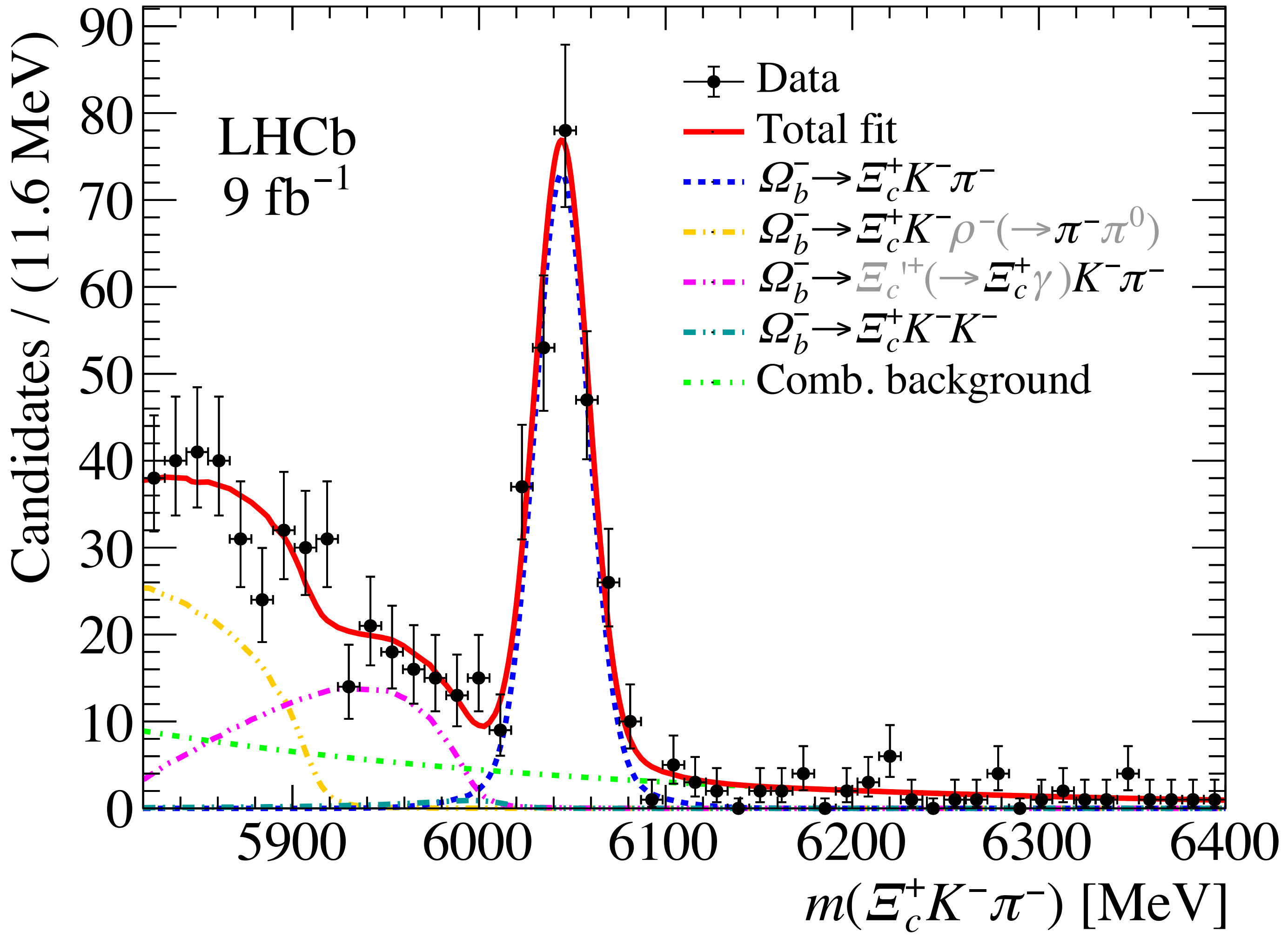
LHCB-PAPER-2021-012

Strikingly Narrow Structures

- LHCb observed in 2018 5 strikingly narrow structures in $m(\Xi_c^+K^-)$
- Considered as Ω_c^0 excitations, a natural spin structure (J^P) was proposed
  $\frac{1}{2}^-$ $\frac{1}{2}^-$ $\frac{3}{2}^-$ $\frac{3}{2}^-$ $\frac{5}{2}^-$
- Cannot be tested in promptly produced decays, but needs exclusive decays: $\Omega_b^- \rightarrow \Xi_c^+ K^- \pi^-$

PRL118(2017)182001





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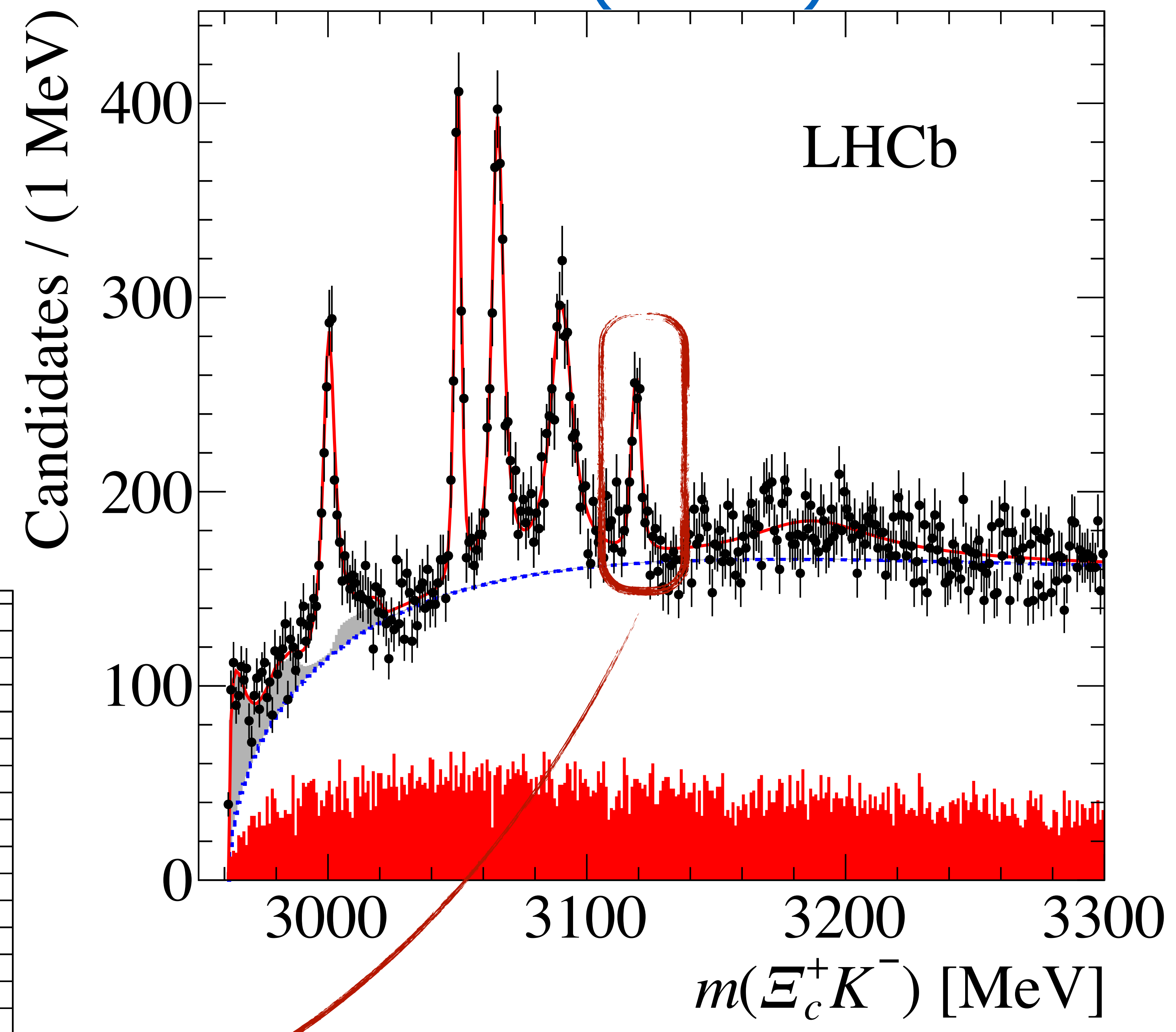
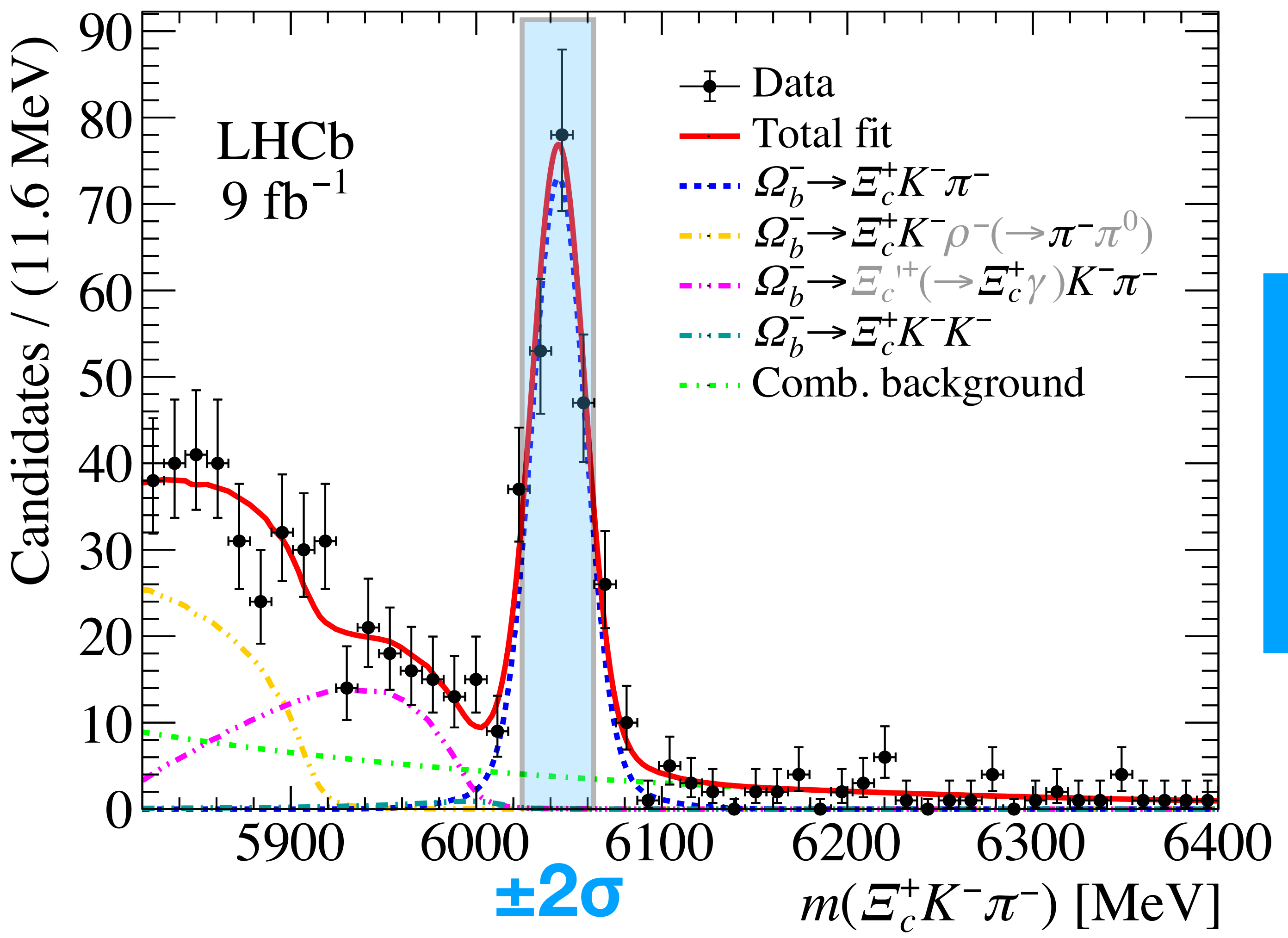
Strikingly Narrow Structures

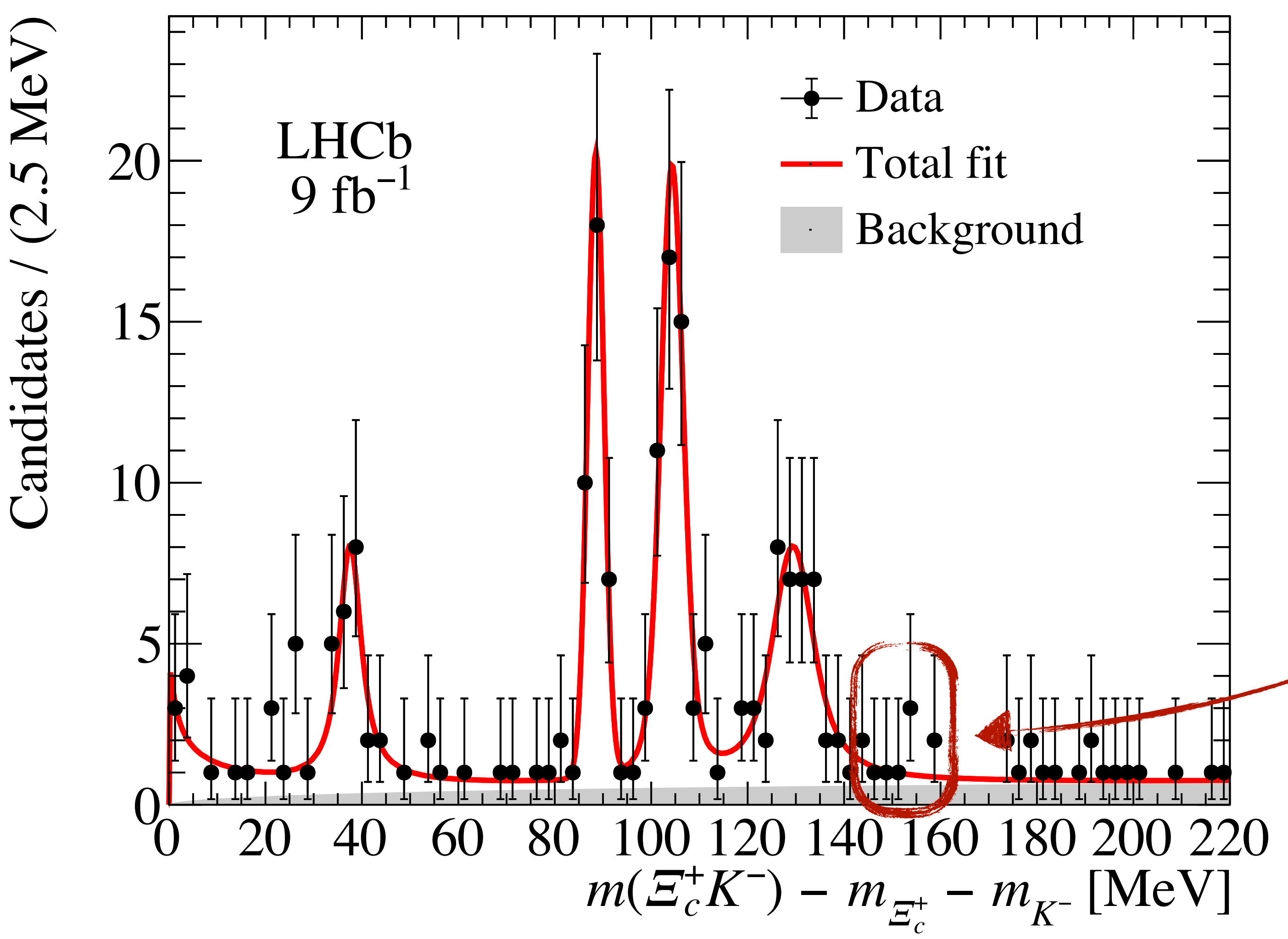
- **LHCb observed in 2018 5 strikingly narrow structures in $m(\Xi_c^+K^-)$**
- **Considered as Ω_c^0 excitations, a natural spin structure (J^P) was proposed**
  $\frac{1}{2}^-$ $\frac{1}{2}^-$ $\frac{3}{2}^-$ $\frac{3}{2}^-$ $\frac{5}{2}^-$
- **Cannot be tested in promptly produced decays, but needs exclusive decays: $\Omega_b^- \to \Xi_c^+ K^- \pi^-$**

PRL118(2017)182001





Specific Selection



Missing?

Excited Ω_c^0 Baryons

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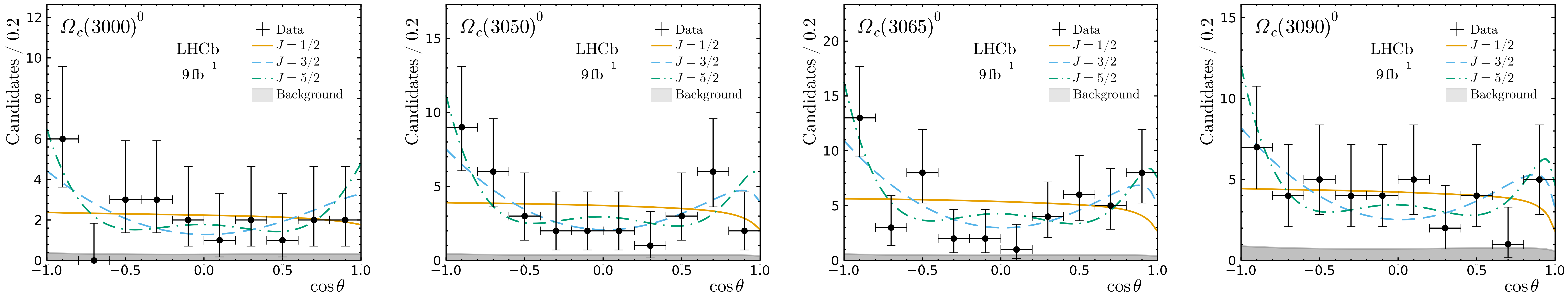
Angular Analysis

- **Distribution of the helicity angle θ between K⁻ and π⁻ in Ξ_c^+ rest frame**
- **Boundaries:**
  - spin of Ω_b^- is 1/2 $\Longrightarrow$ spin projection of Ω_c^{**0} is 1/2 on π direction
  - spin projection of Ω_c^{**0} cannot exceed 1/2 in the direction of either decay products
- **Angular distribution**

$$I_J(\cos\theta) = \frac{(2J+1)}{2}\left(\left|d^J_{1/2,-1/2}(\cos\theta)\right|^2 + \left|d^J_{1/2,+1/2}(\cos\theta)\right|^2\right)$$



Excited Ω_c^0 Baryons

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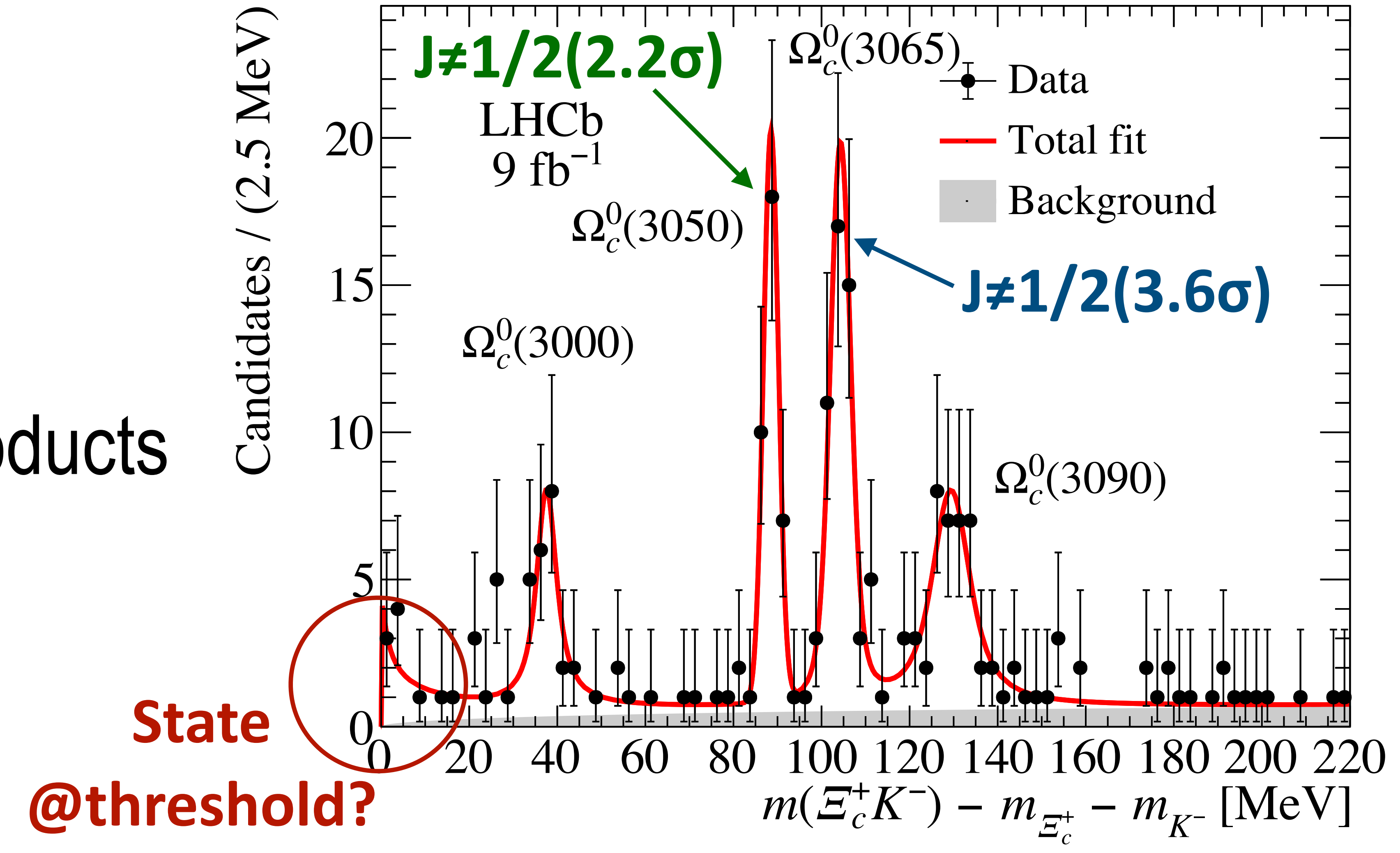
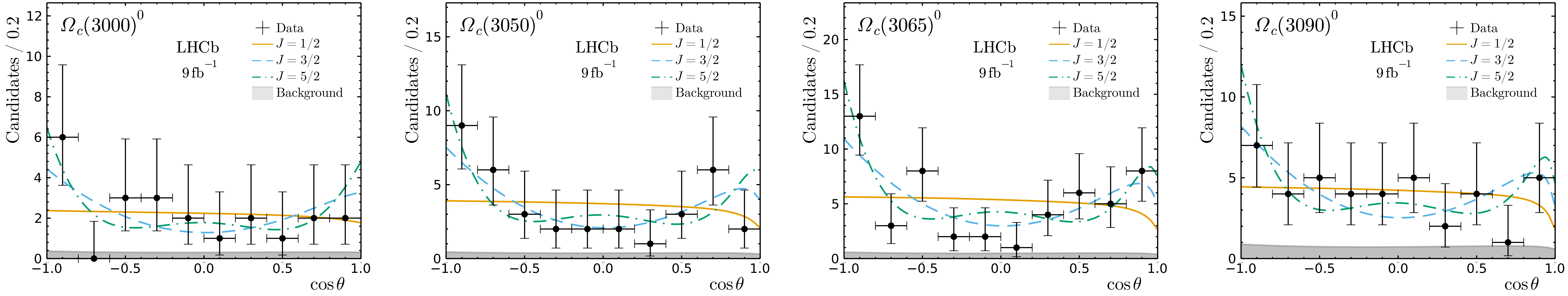
Angular Analysis

- **Distribution of the helicity angle θ between K^- and π^- in Ξ_c^+ rest frame**
- **Boundaries:**
  - spin of Ω_b^- is 1/2 $\Longrightarrow$ spin projection of Ω_c^{**0} is 1/2 on π direction
  - spin projection of Ω_c^{**0} cannot exceed 1/2 in the direction of either decay products
- **Angular distribution**

$$I_J(\cos\theta) = \frac{(2J+1)}{2}\left(\left|d^J_{1/2,-1/2}(\cos\theta)\right|^2 + \left|d^J_{1/2,+1/2}(\cos\theta)\right|^2\right)$$





Summary

Very Active Field

- Charm is providing a lot of new and interesting results at LHCb
- Historical results achieved in the mixing and CPV
- Deepening our understanding of QCD

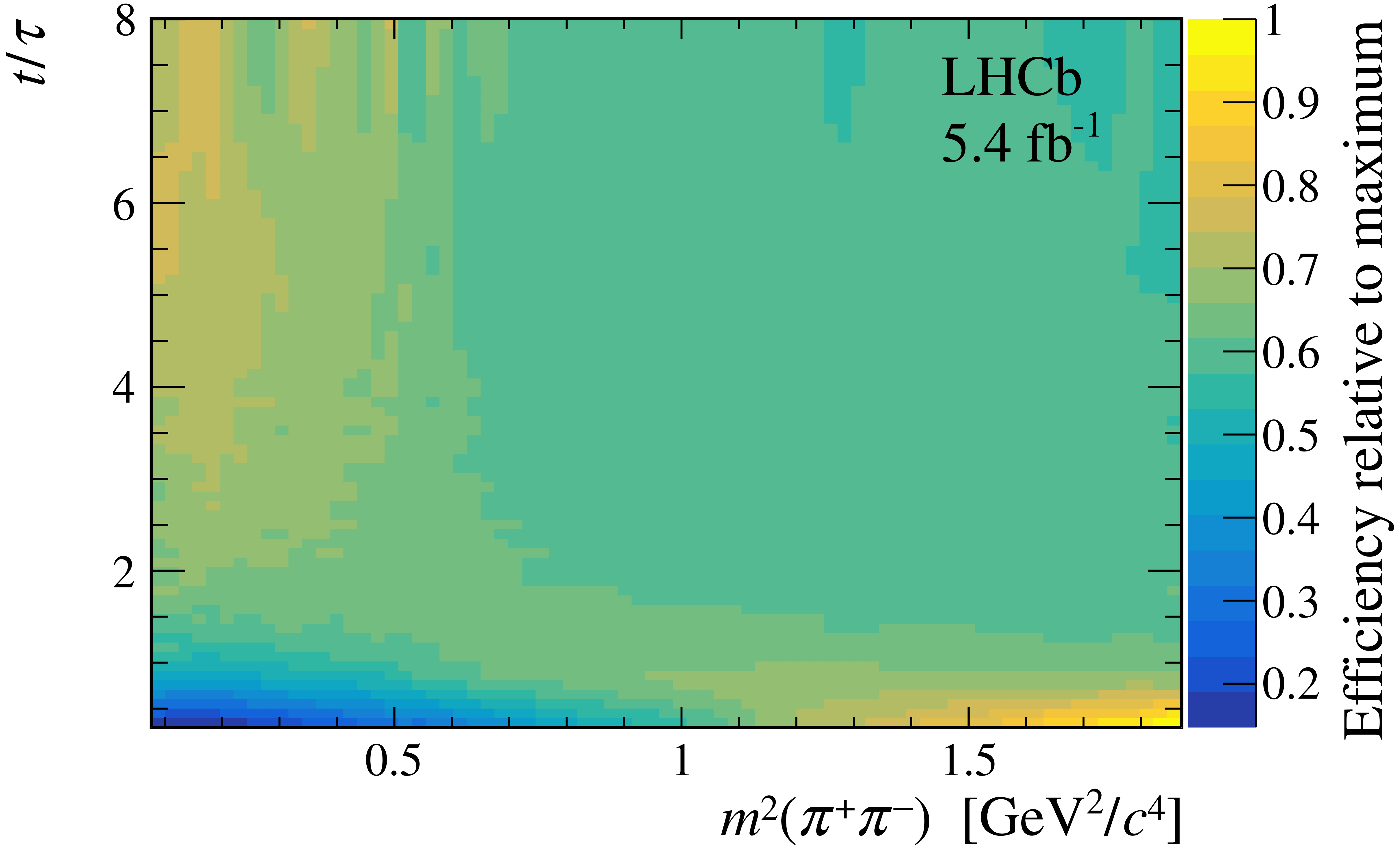
Future

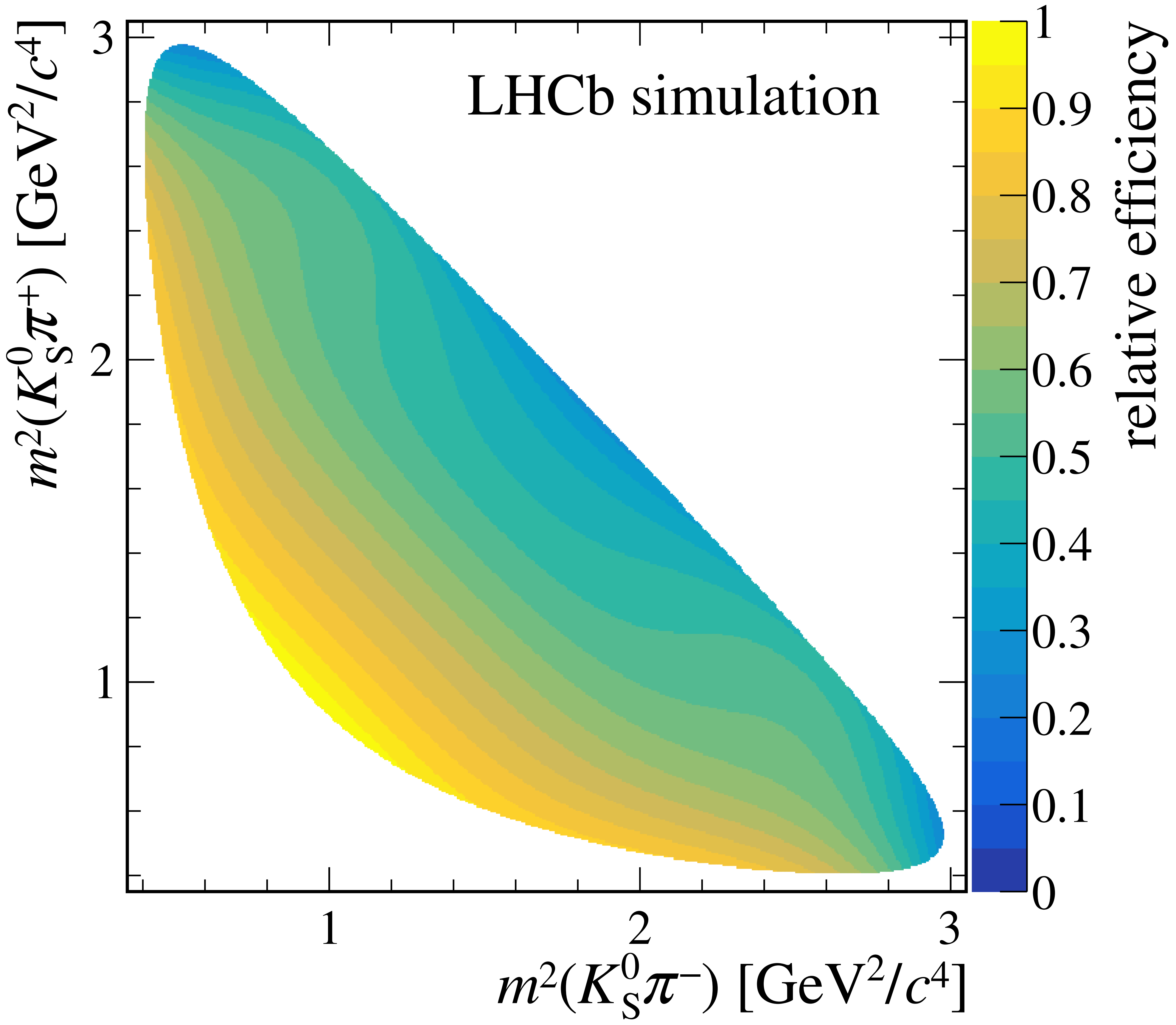
- LHCb Upgrade upcoming in 2022 (50/fb by 2030)
- We are working to prepare our new detector and push forward our limits

Spares

$D^0 \to K^0_S \pi^+ \pi^-$ Acceptance

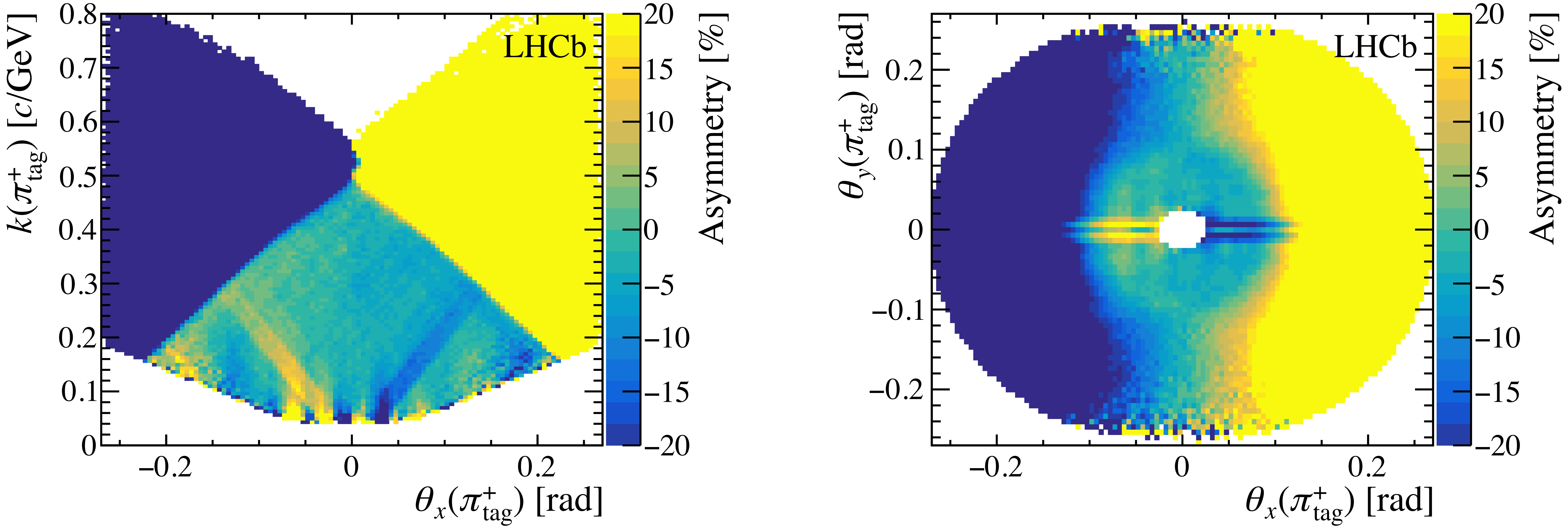
arXiv:2106.03744





Soft Pion Asymmetry Correction in $D^0 \rightarrow h^+h^-$

arXiv:2105.09889

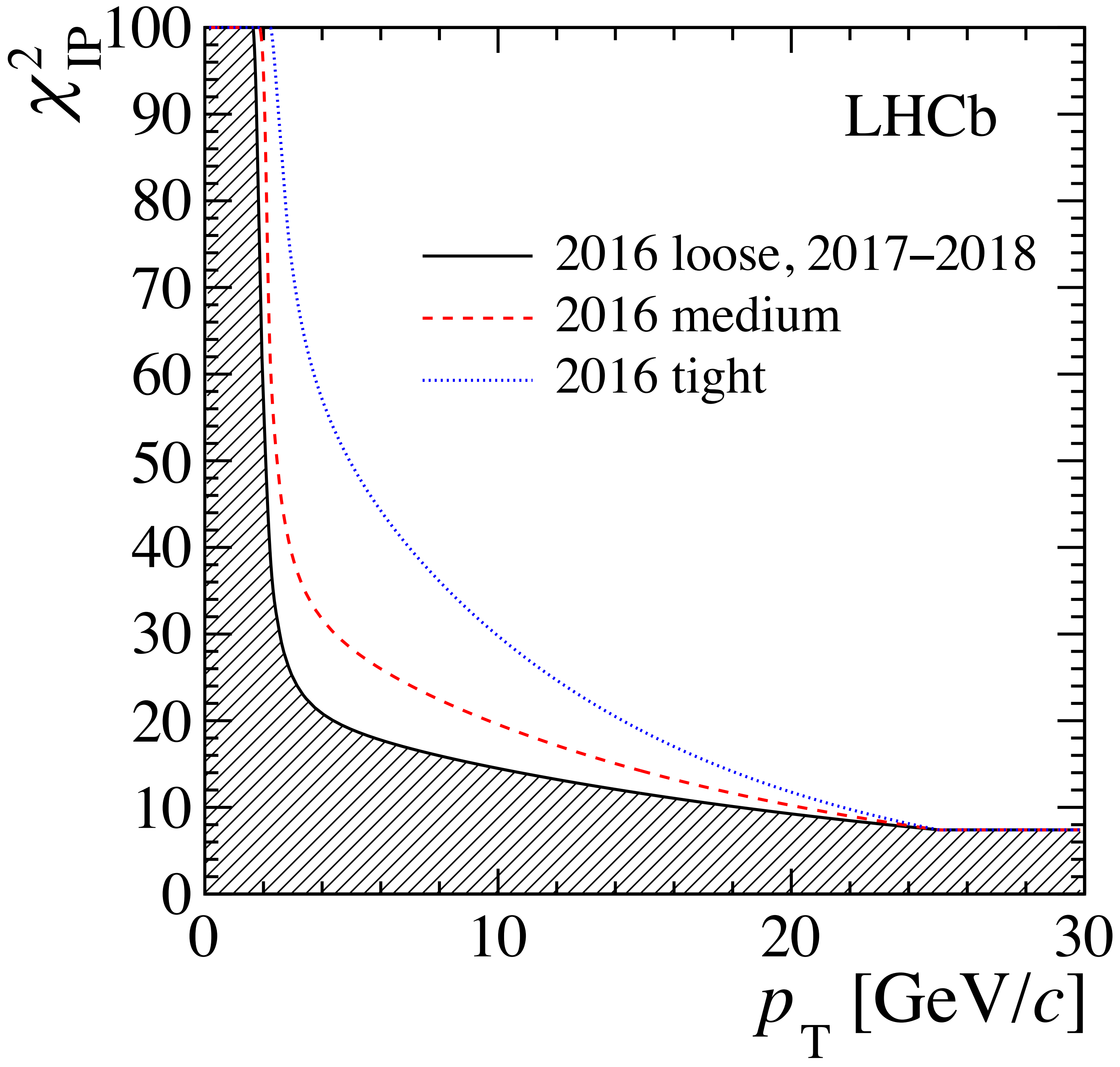


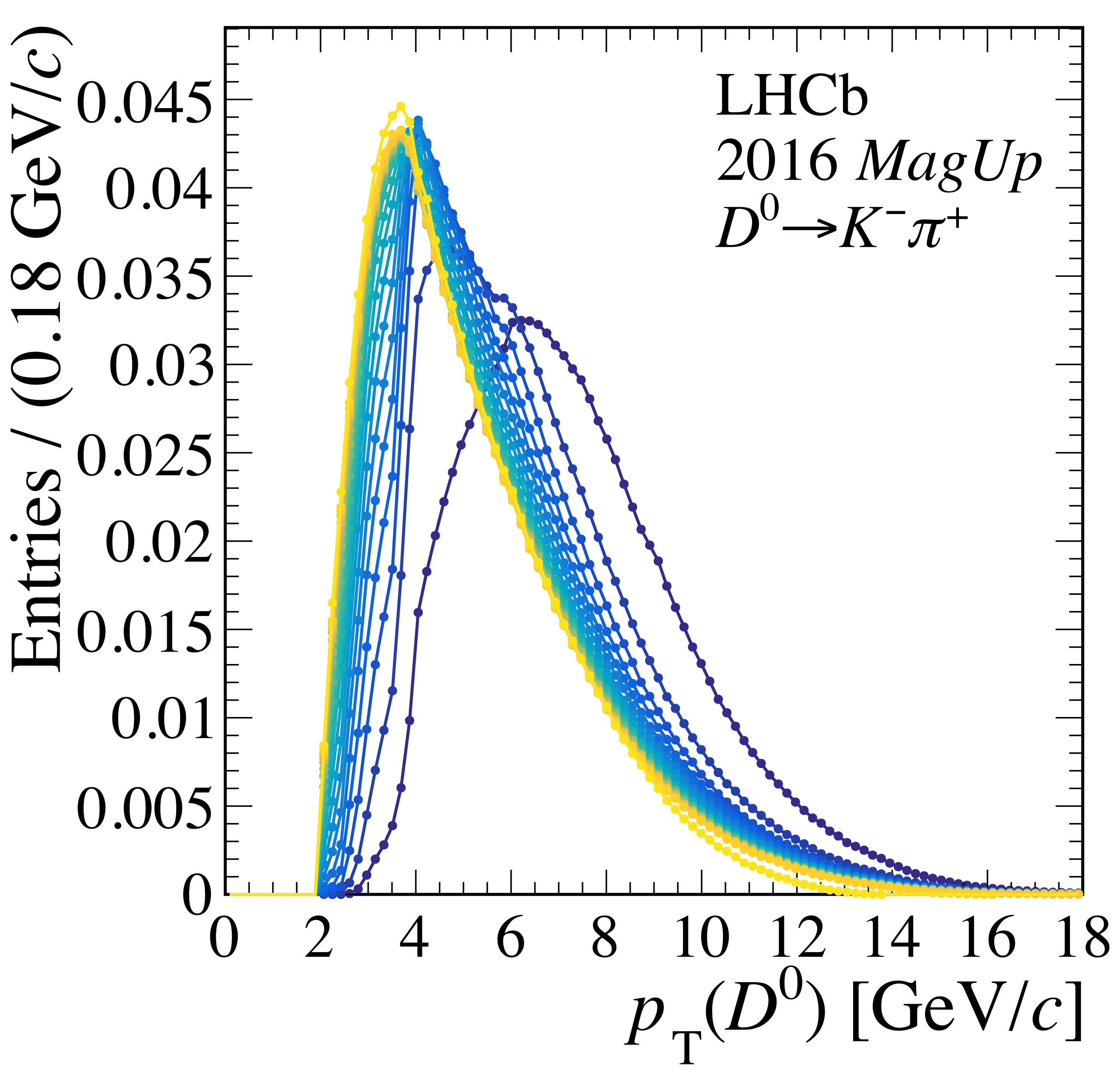
- Regions with |asymmetry| ≥ 20% are removed
- Kinematics of $\pi^+_{\mathbf{tag}}$ and $\pi^-_{\mathbf{tag}}$ are equalised by reweighing in k, θ_x, θ_y

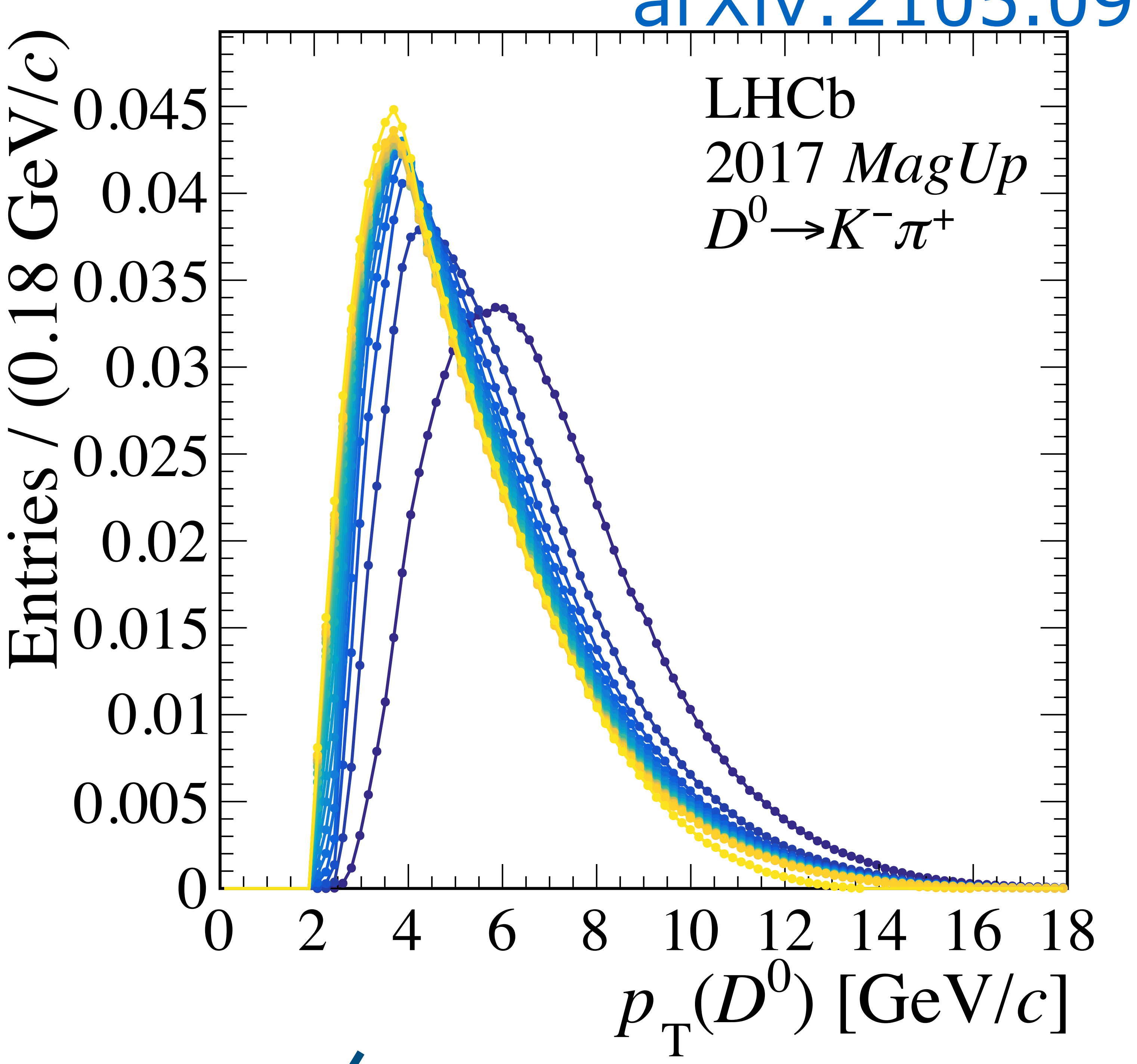
$$\theta_{x(y)} \equiv \arctan\left(\frac{p_{x(y)}}{p_z}\right) \qquad k \equiv \frac{1}{\sqrt{p_x^2 + p_z^2}}$$

$D^0 \rightarrow h^+h^-$ Acceptance

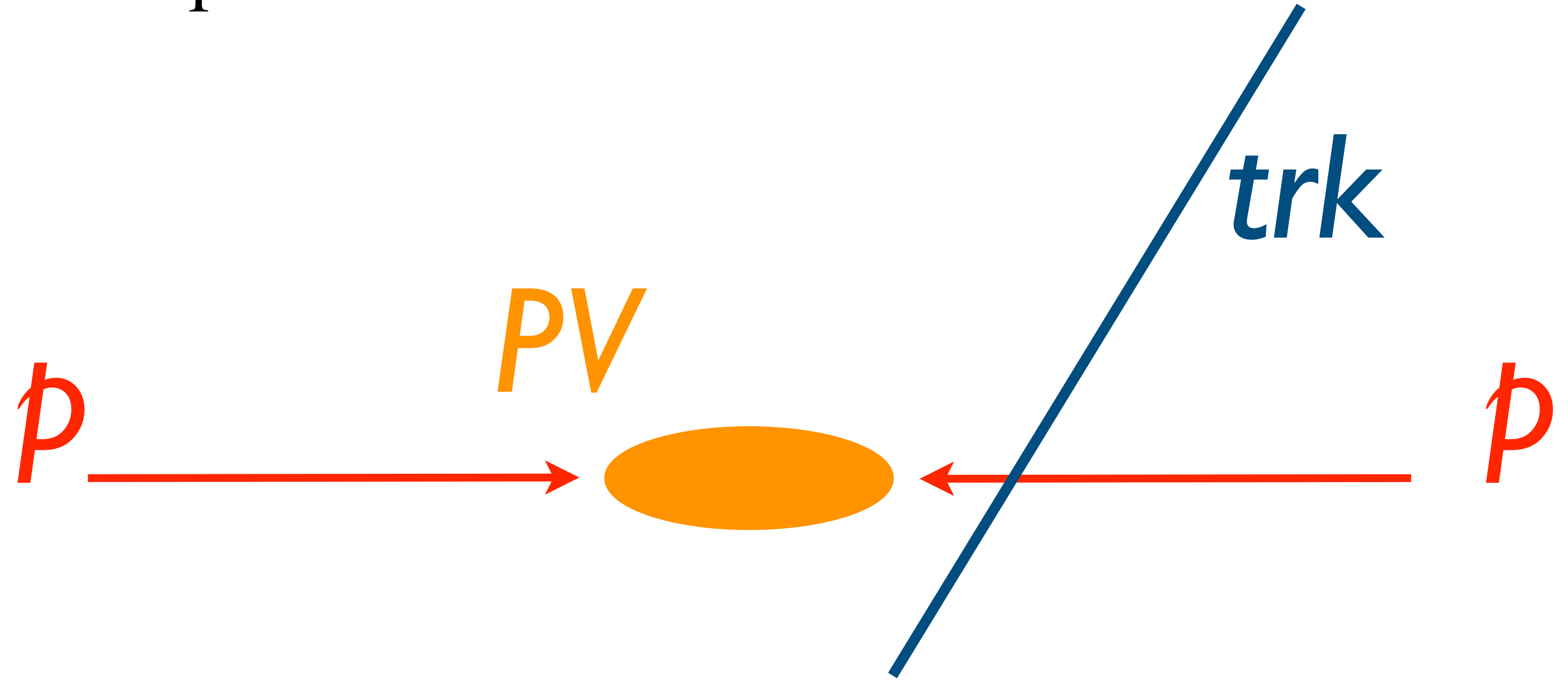
arXiv:2105.09889





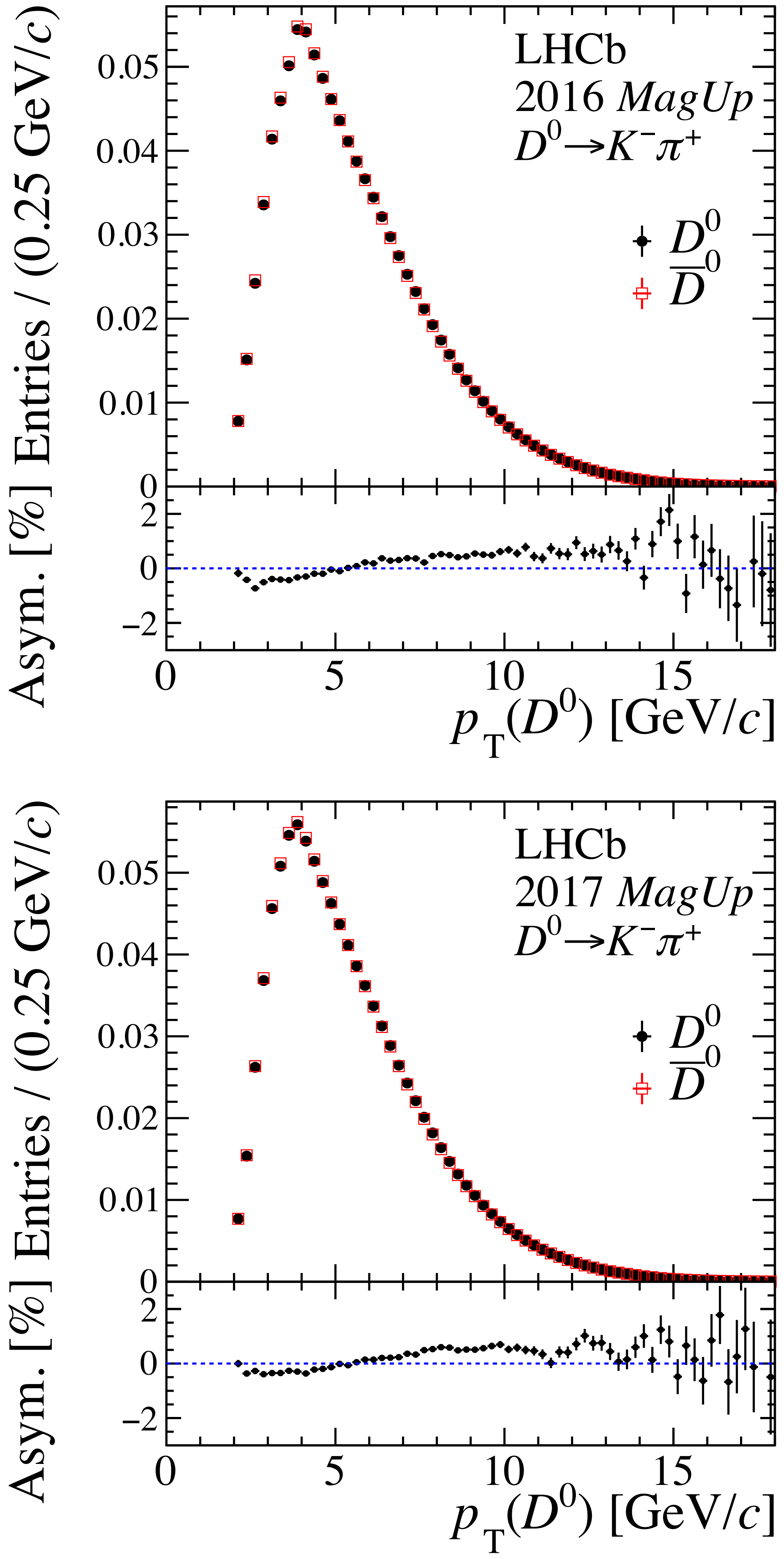


$$\chi^2_{IP} = \chi^2(\textbf{PV} + \textbf{trk}) - \chi^2(\textbf{PV})$$

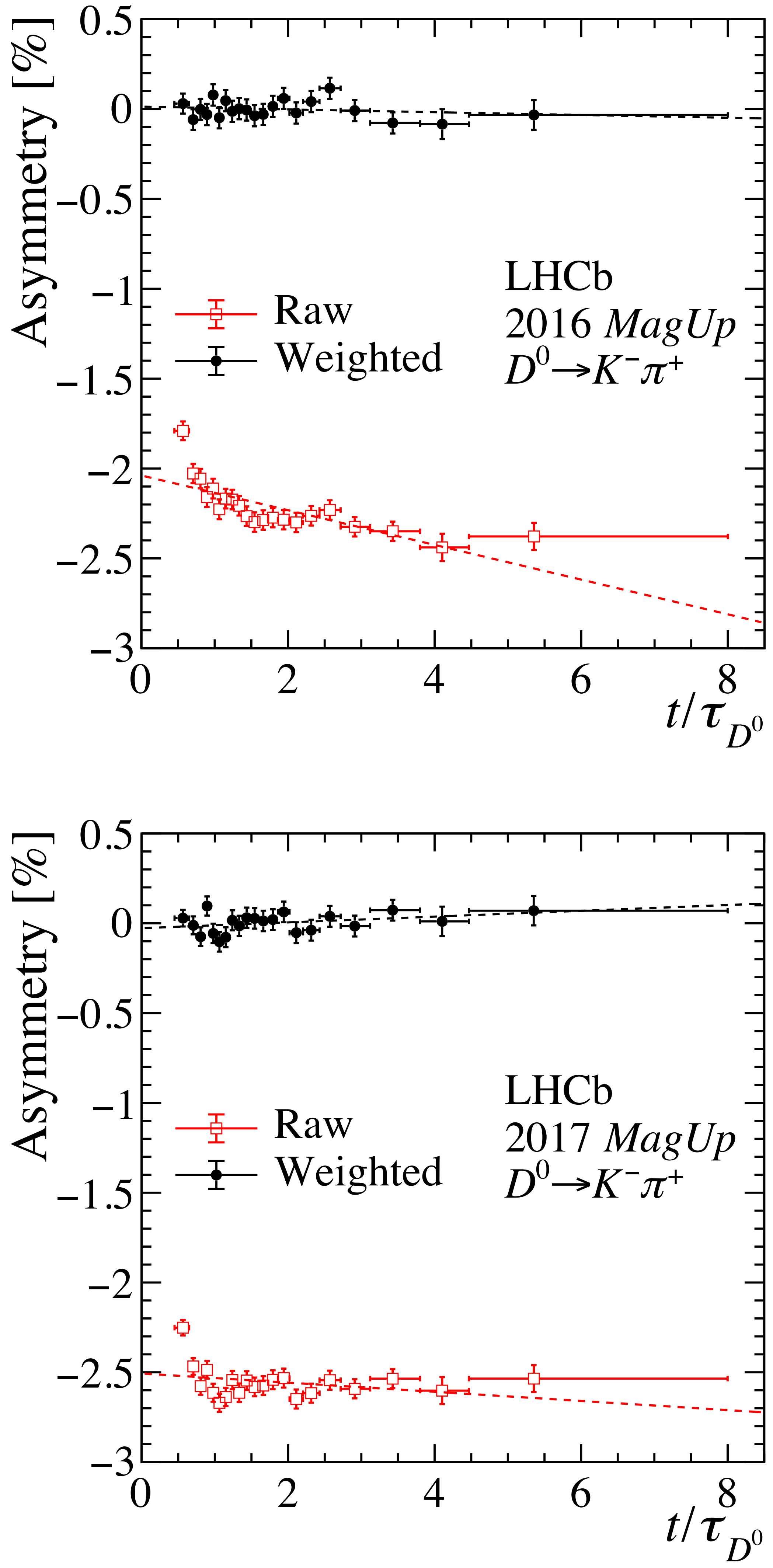


Residual Asymmetry in $D^0 \to h^+h^-$

arXiv:2105.09889



- After π^+_{tag} reweighing residual asymmetry in $p_T(D^0)$ due to trigger acceptance
- Further reweighing in $p_T(D^0)$, $\eta(D^0)$, $\eta(\pi^+_{tag})$



Excited Ω_c^0 Baryons

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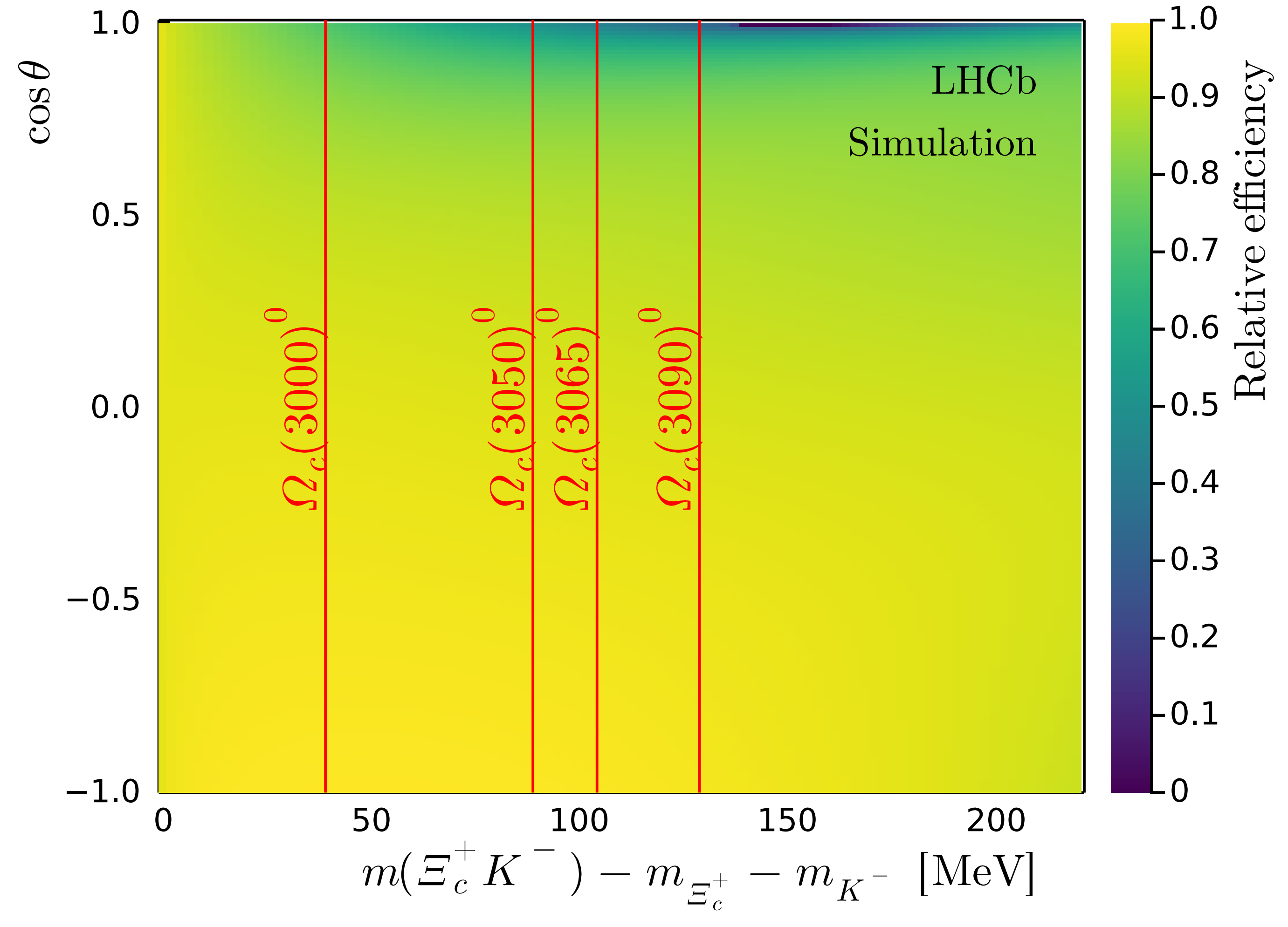
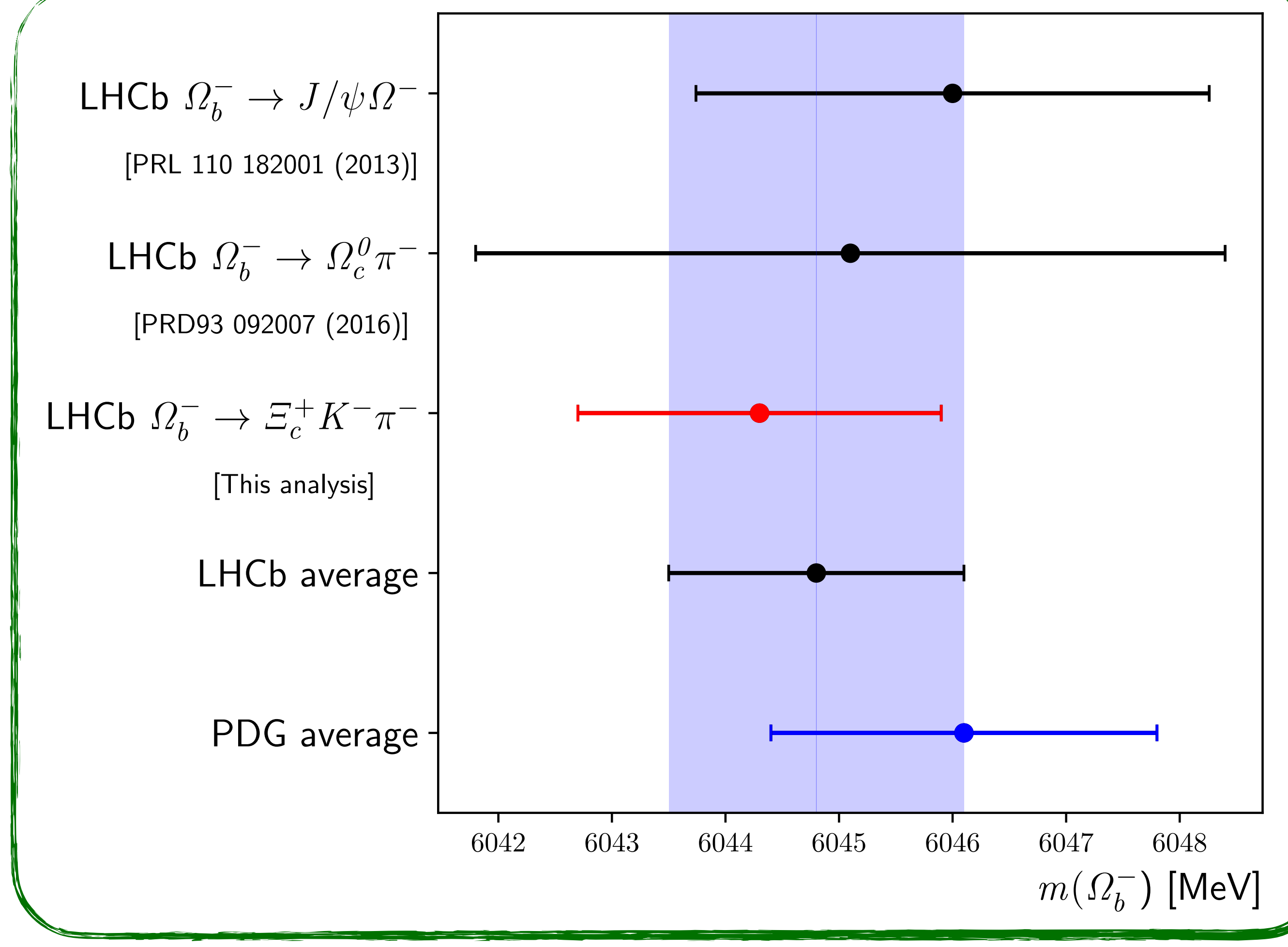
Efficiency



Ω_b^- Mass measurement



Spin Assignments