CP violation in charmed baryons at LHCb

5 March 2024

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Menu

- **The examples of the LHCb measurements**
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  - ✧ *CP* asymmetry difference between $\Lambda_c^+ \to pK^-K^+$ and $p\pi^-\pi^+$
  - ✧ Amplitude analysis of $\Lambda_c^+ \to pK^-\pi^+$
  - ✧ Polarization of $\Lambda_c^+ \to pK^-\pi^+$
  - ✧ Polarimeter vector field in $\Lambda_c^+ \to pK^-\pi^+$

- **Summary**

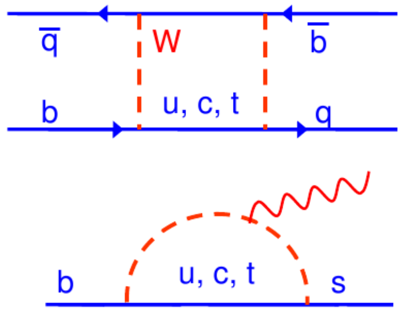
Why are we interested in charm physics?

- In the Standard Model (SM), the known value of *CP* violation (CPV) is too small to explain the observed size of matter domination over antimatter in the universe

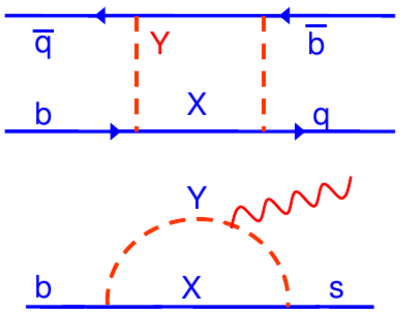
- At LHCb, we very precisely test known CPV in the SM
  → finding disagreement will be indirect indication of new phenomena existence

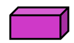
- The new particles can appear in the loops

Standard Model



New physics



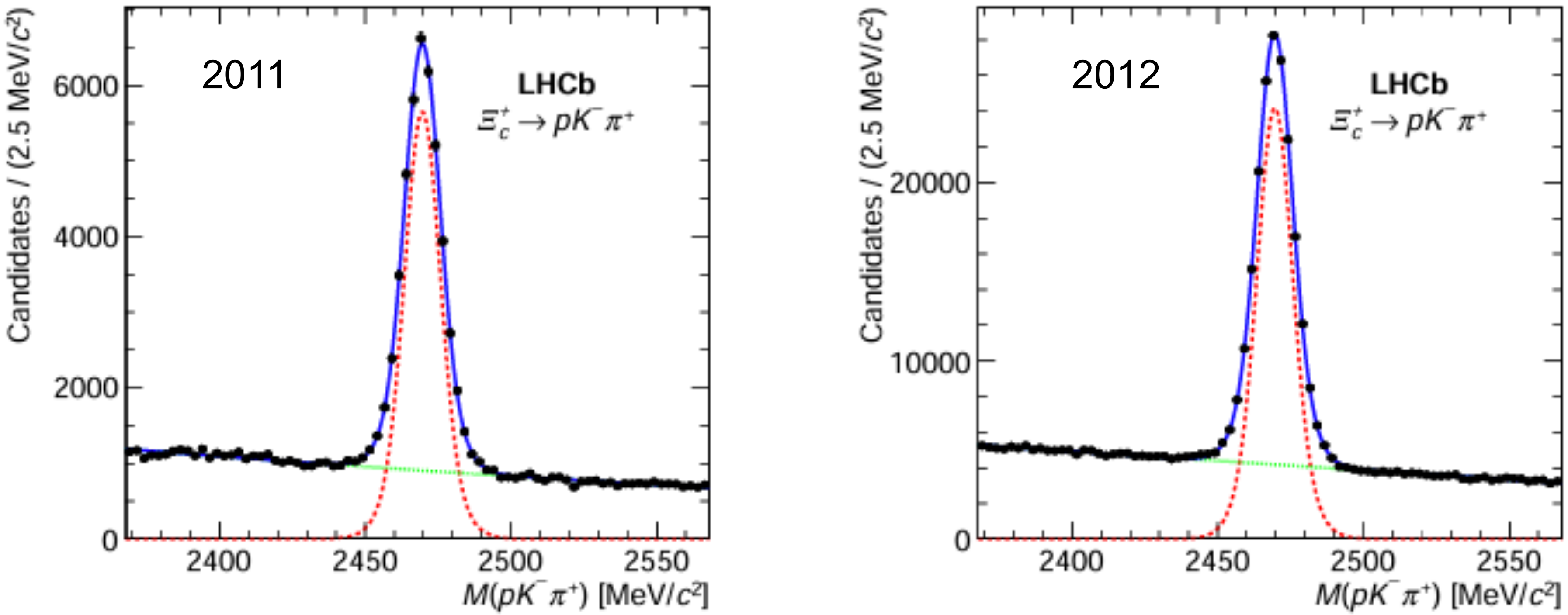
box diagrams 

penguin diagrams 

- Charm sector is very promising since the background from the SM is very small, expected CPV is only $\lesssim 10^{-4} - 10^{-3}$ (much smaller than we measure in beauty meson decays)

CP violation in $\Xi_c^+ \to pK^-\pi^+$

Eur. Phys. J. C80 (2020) 986



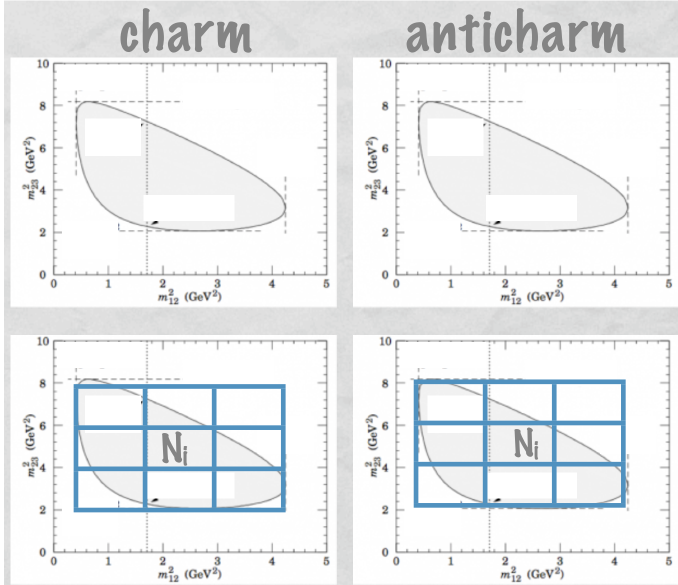
Ξ_c	2011	2012
Magnet Down	22701 ± 216	78688 ± 446
Magnet Up	15007 ± 181	77930 ± 484
Total	36410 ± 297	157420 ± 658

- In each bin a significance of a difference between Ξ_c^+ and Ξ_c^- is calculated

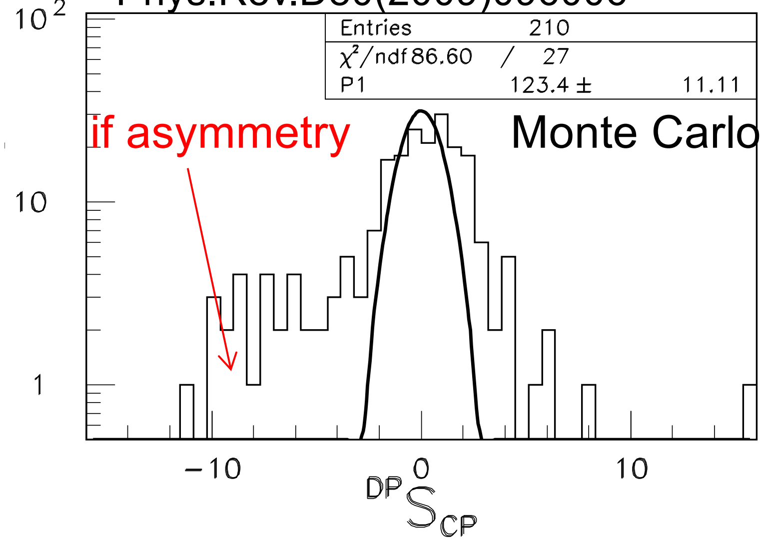
$$S^i_{CP} \equiv \frac{N^i_+ - \alpha N^i_-}{\sqrt{\alpha(N^i_+ + N^i_-)}} \qquad \alpha = \frac{N^+}{N^-}$$

- To cancel global asymmetries (production asymmetry etc.) the Dalitz plots are normalized
- If no CPV (only statistical fluctuations) then S_{CP} is Gaussian distribution (μ=0, σ=1)
- The $\chi^2 = \Sigma {S^i_{CP}}^2$ test is calculated to obtain p-value for the null hypothesis (no CPV) to test if Ξ_c^+ and Ξ_c^- distributions are statistically compatible

p-value $\ll$ 1 in case of CPV



Bediaga et al. Phys.Rev.D80(2009)096006



The results of local *CPV* search using binned S_{CP} method

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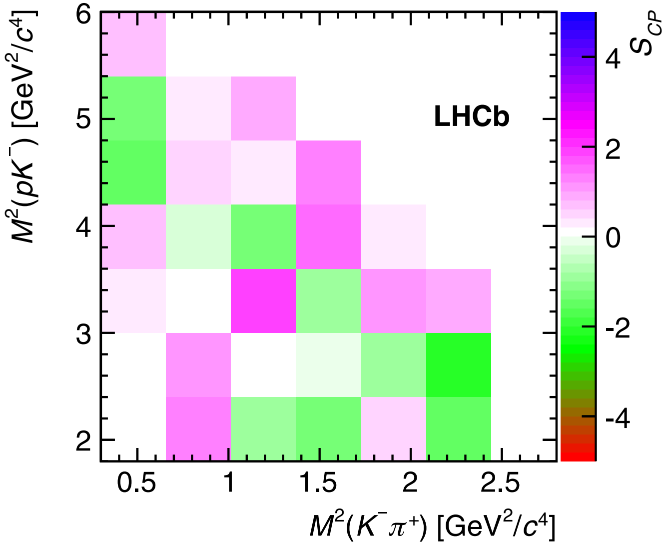
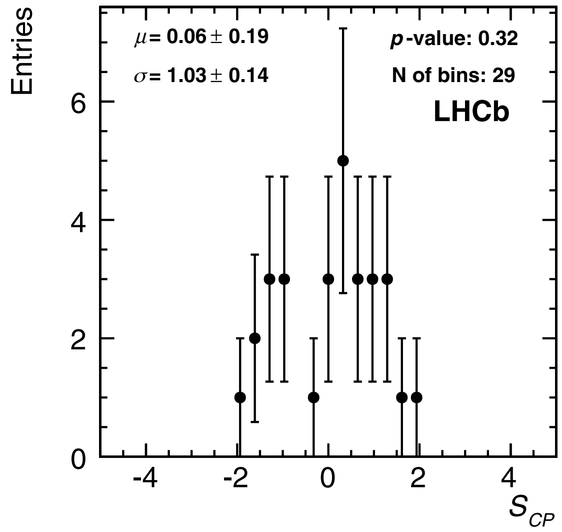
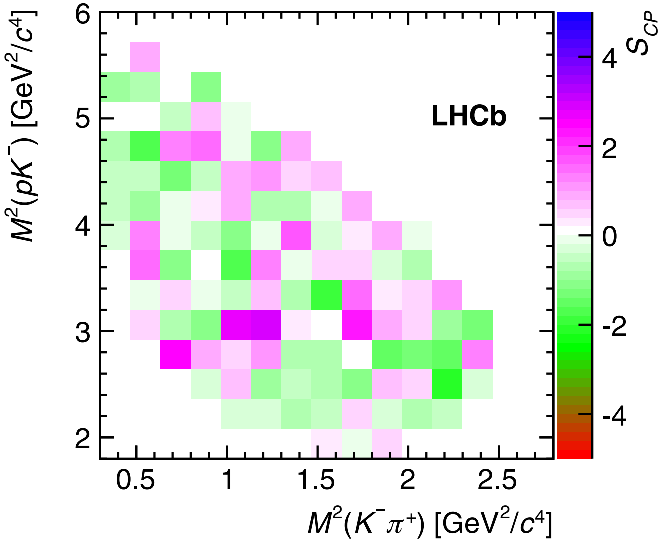
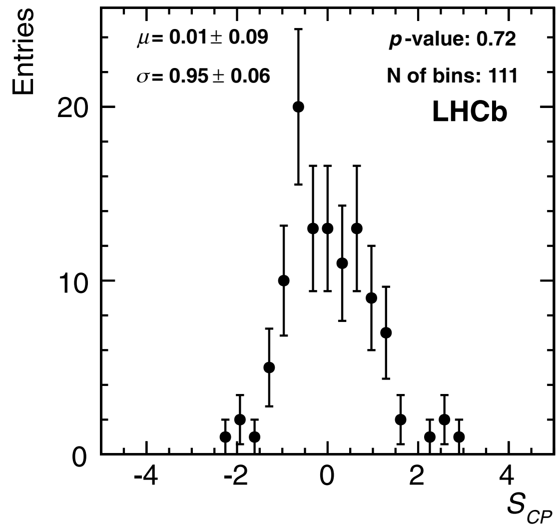


29 uniform bins





111 uniform bins

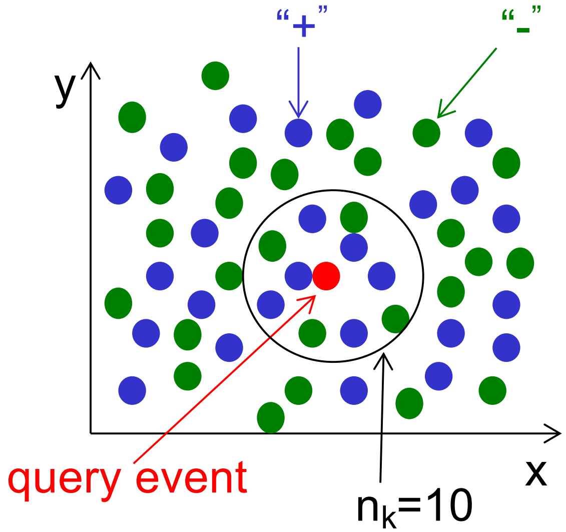


- Uniform and adaptive binning schemes with different bin numbers are tested
- The S_{CP} distributions agree with Gaussian
- The measured p-values are greater than 32%
- Results are consistent with no observation of *CP* asymmetry

The unbinned k-nearest neighbour method

- More difficult to use but can be more sensitive for small statistics

- To compare "+" and "–" a test statistic T is defined, which is based on the counting particles with the same sign to each event for a given number of the nearest neighbour events



$$T = \frac{1}{n_k(n_+ + n_-)} \sum_{i=1}^{n_+ + n_-} \sum_{k=1}^{n_k} I(i,k)$$

I(i,k) = 1 if i^{th} event and its k^{th} nearest neighbour have the same charge (+ + , – –)

I(i,k) = 0 if pair has opposite charge (+ –)

- T is the mean fraction of like pairs in the pooled sample of the two datasets

- The expected distribution can be calculated using mean μ_T and variance σ_T

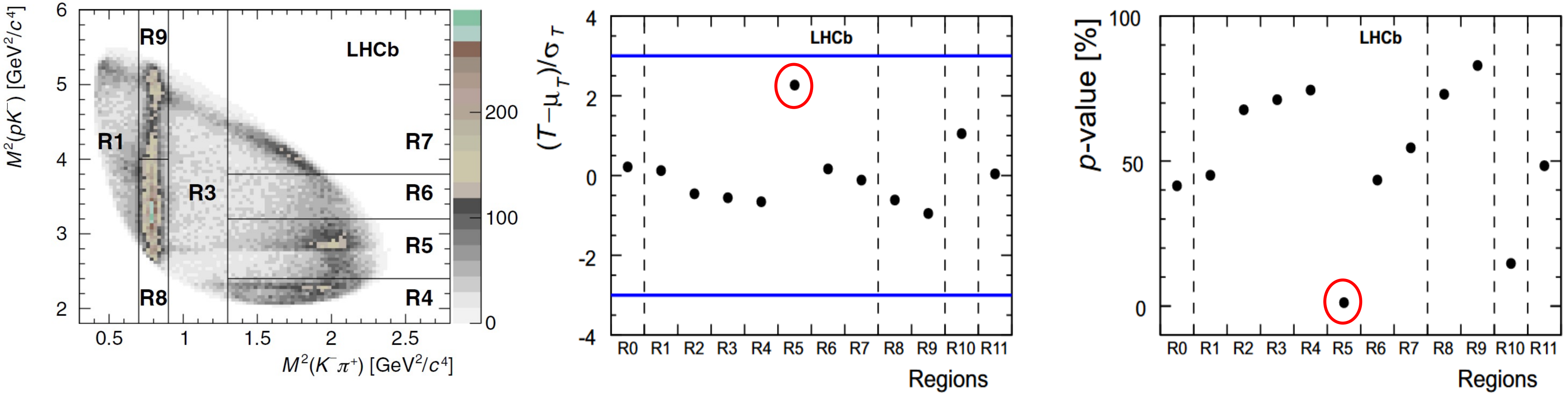
$$\mu_T = \frac{n_+(n_+ - 1) + n_-(n_- - 1)}{n(n-1)}$$

$$\lim_{n, n_k, D \to \infty} \sigma_T^2 = \frac{1}{n n_k} \left(\frac{n_+ n_-}{n^2} + 4 \frac{n_+^2 n_-^2}{n^4} \right)$$

The first searches for local *CPV* in $\Xi_c^+ \to pK^-\pi^+$

- Data collected in Run 1, $\sqrt{s}$ = 7 TeV and 8 TeV, L ~ 3 fb^{-1}
- The k-nearest neighbour method is used in regions of the Dalitz plot

Eur. Phys. J. C80 (2020) 986



- Results are consistent with *CP* symmetry but in one region of the Dalitz plot the local effect corresponds to 2.7σ
- To be continued with Run 2 data

CP asymmetry difference between $\Lambda_c^+ \to pK^-K^+$ and $p\pi^-\pi^+$

- The Λ_c^+ candidates are reconstructed from $\Lambda_b^0 \to \Lambda_c^+ \mu^- X$ decays

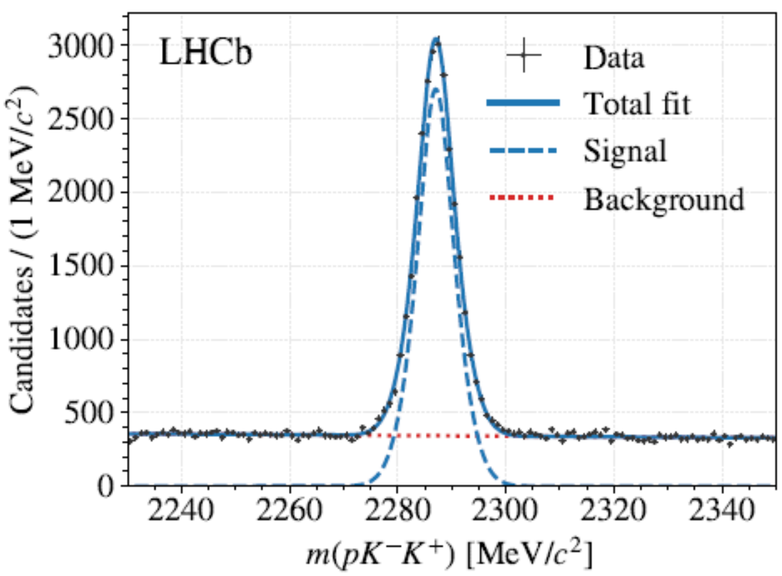
JHEP03 (2018) 182

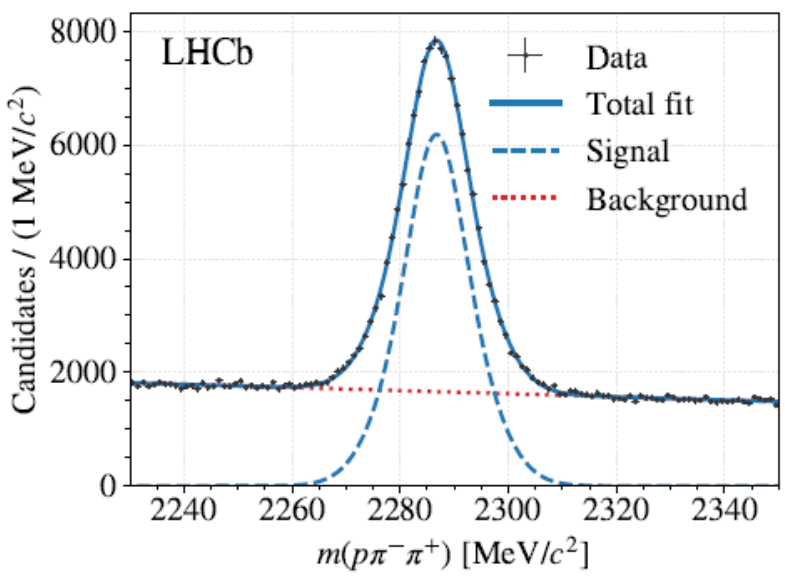
$$A_{CP} = \frac{\Gamma(f) - \Gamma(\bar{f})}{\Gamma(f) + \Gamma(\bar{f})}, \quad A_{raw} = \frac{N(f\mu^-) - N(\bar{f}\mu^+)}{N(f\mu^-) + N(\bar{f}\mu^+)}$$

$$A_{raw}(f) = A_{CP}(f) + A_P^{\Lambda_b^0}(f\mu) + A_D^{\mu}(\mu) + A_D^{f}(f)$$

- Kinematics of the pK^-K^+ and $p\pi^-\pi^+$ are and equal and data are weighted

$$\Delta A_{CP}^{wgt} = A_{CP}(pK^-K^+) - A_{CP}^{wgt}(p\pi^-\pi^+) \approx A_{raw}(pK^-K^+) - A_{raw}^{wgt}(p\pi^-\pi^+)$$





Run 1, 3 fb^{-1}

Total yields:
~25k pK^-K^+
~187k $p\pi^-\pi^+$

CP asymmetry difference between $\Lambda_c^+ \to pK^-K^+$ and $p\pi^-\pi^+$

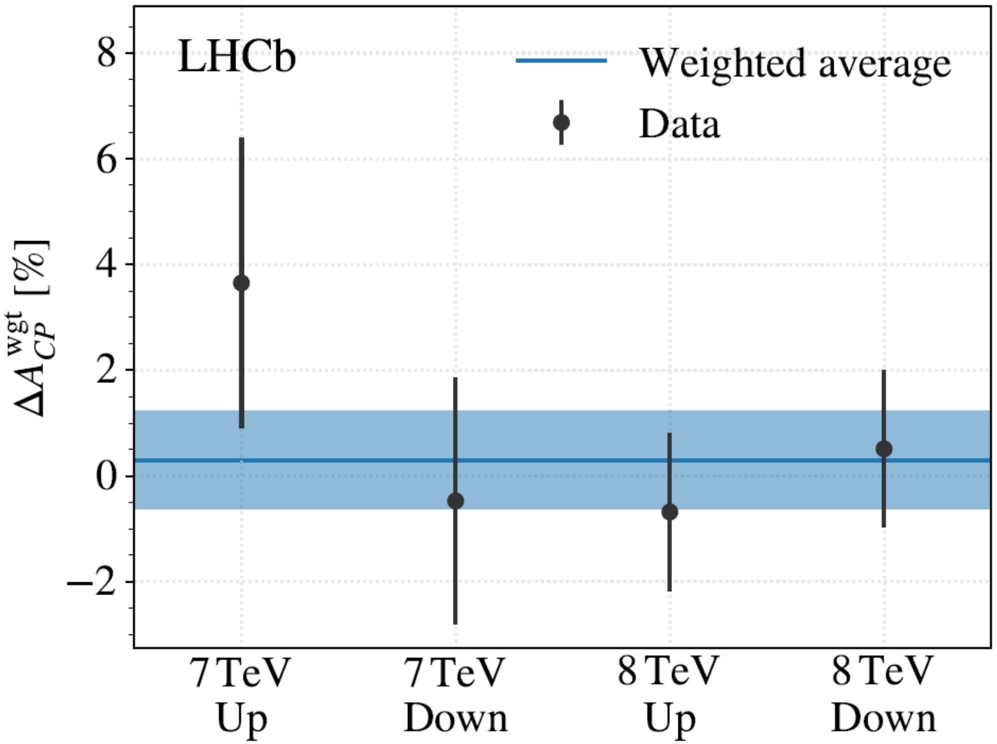
JHEP03 (2018) 182

$$A_{raw}(pK^-K^+) = (3.72 \pm 0.78)\%$$

$$A_{raw}^{wgt}(p\pi^-\pi^+) = (3.42 \pm 0.47)\%$$

$$\mathbf{\Delta A_{CP}^{wgt}} = \mathbf{(0.30 \pm 0.91 \pm 0.61)\%}$$

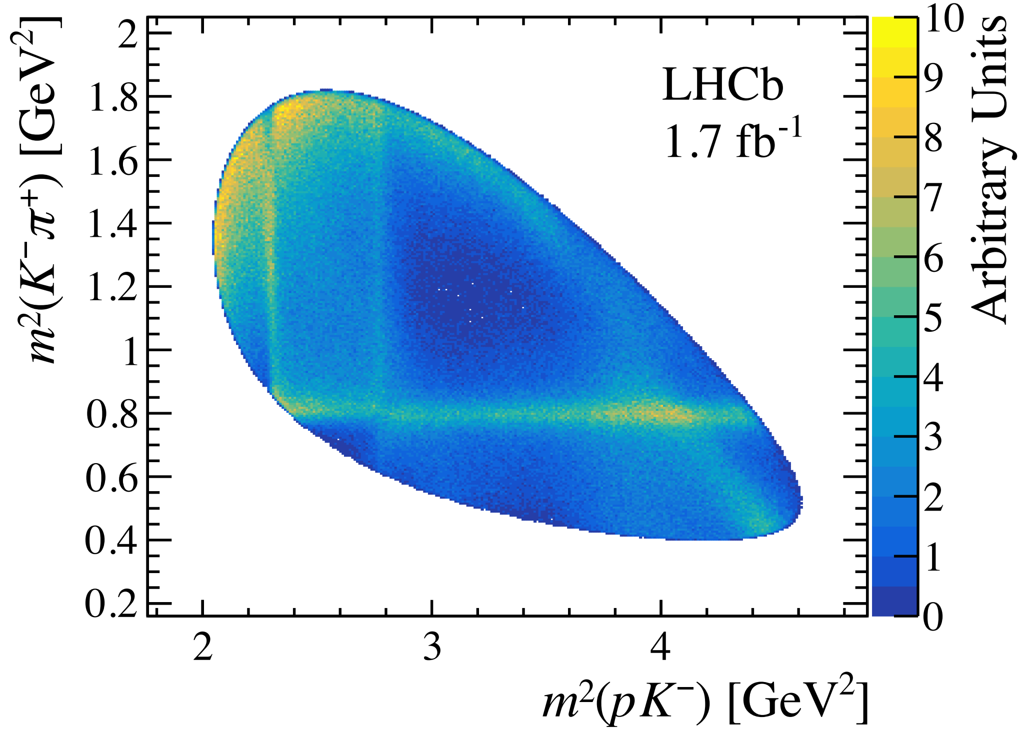
- Central value is measured to be consistent with zero
- The first measurement of the CP violation parameter in Λ_c^+ decays



Amplitude analysis of $\Lambda_c^+ \to pK^-\pi^+$

Phys.Rev. D108 (2023) 012023

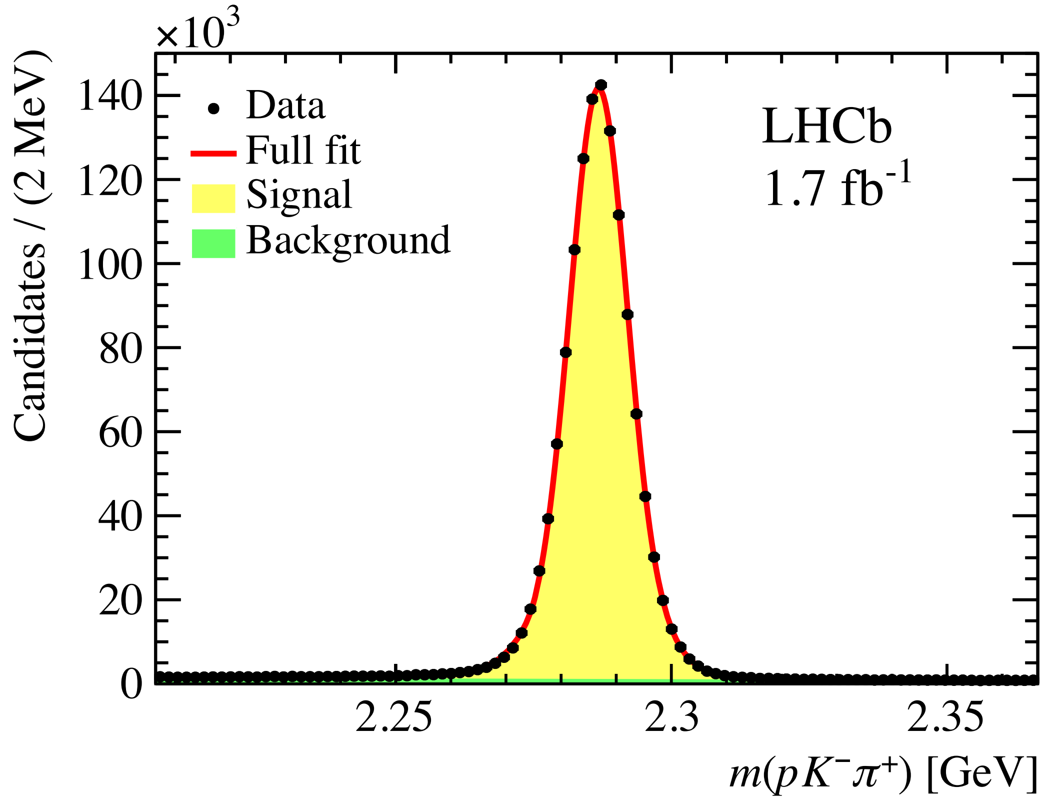
- Λ_c^+ from semileptonic beauty hadron decays $\Lambda_b^0 \to \Lambda_c^+ l^- \bar{\nu}$
- $\Lambda_c^+ \to pK^-\pi^+$ has a complex resonant structure with multiple overlapping states in the $K^-\pi^+$, pK^- and $p\pi^+$ systems
- A full amplitude analysis determines the composition of the decay amplitude
- The knowledge of the resonant structure is useful in searches for *CP* symmetry violation, which is still unobserved in baryon decays



Amplitude analysis of $\Lambda_c^+ \to pK^-\pi^+$

Phys.Rev. D108 (2023) 012023

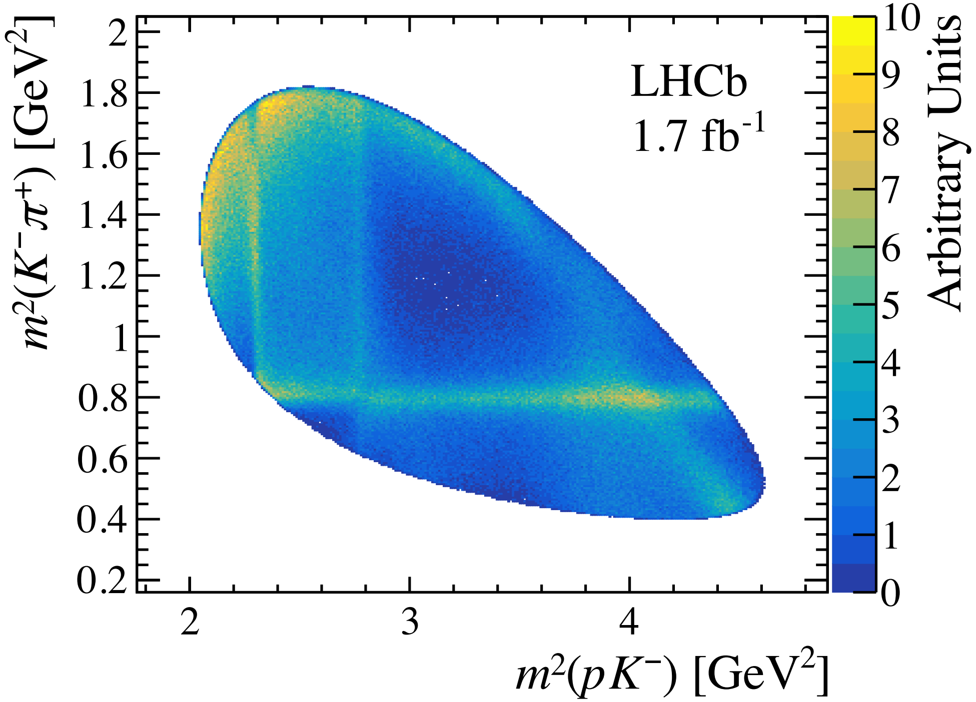
- LHCb 2016: ~1.7 fb^{-1}
- The signal region chosen within 15 MeV of the known Λ_c^+ mass, containing about 95% of the signal candidates
- ~400 000 candidates
- The fraction of background in the signal region is 1.69%



Amplitude analysis of $\Lambda_c^+ \to pK^-\pi^+$

Phys.Rev. D108 (2023) 012023

The Dalitz plot displays a rich structure with resonant contributions from all possible pairs of final state particles: $\Lambda \to pK^-$, $K^* \to K^-\pi^+$, $\Delta^{++} \to p\pi^+$



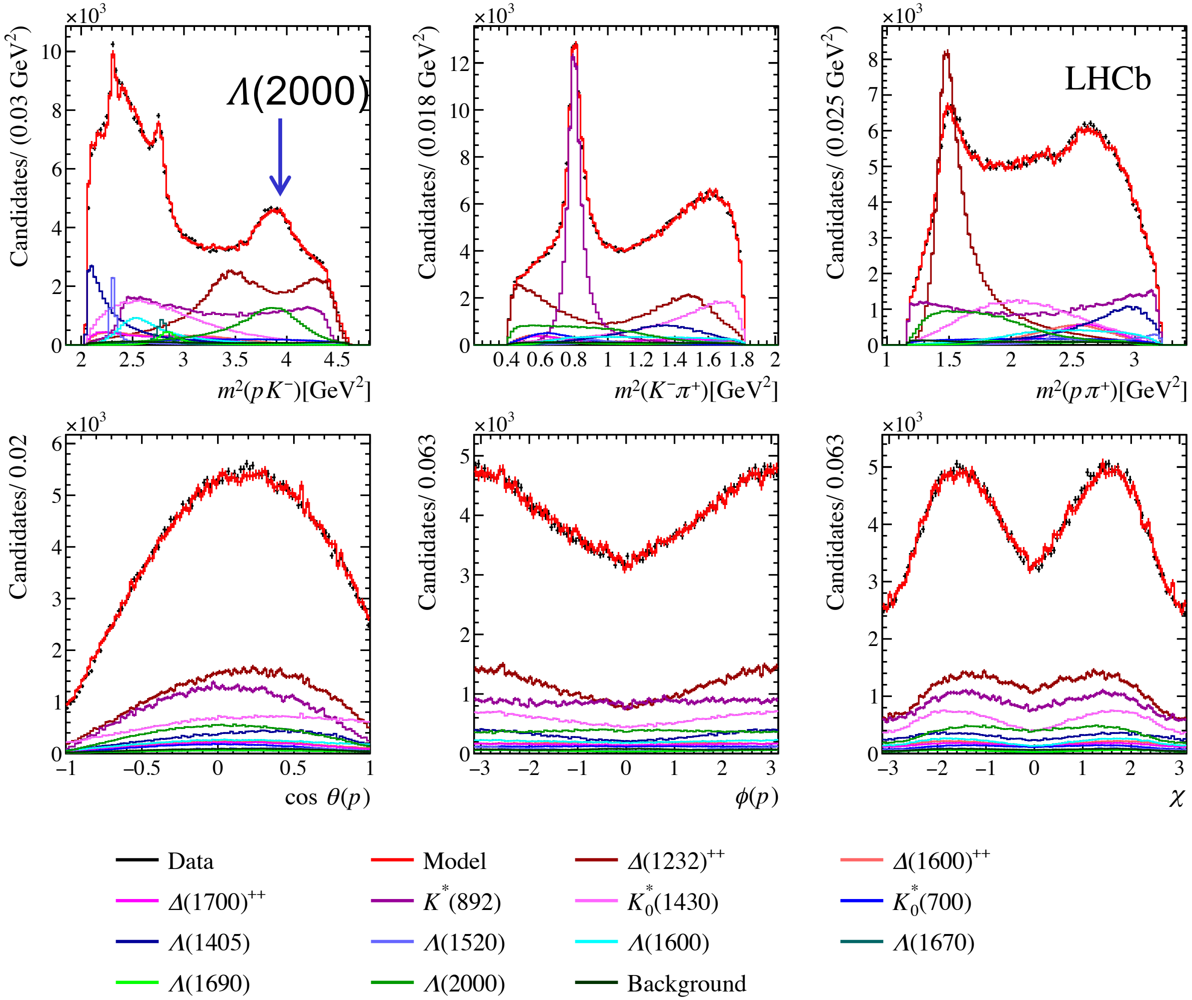
Resonance	J^P	Mass (MeV)	Width (MeV)
$\Lambda(1405)$	$1/2^-$	1405.1	50.5
$\Lambda(1520)$	$3/2^-$	1515 – 1523	10 – 20
$\Lambda(1600)$	$1/2^+$	1630	250
$\Lambda(1670)$	$1/2^-$	1670	30
$\Lambda(1690)$	$3/2^-$	1690	70
$\Lambda(2000)$	$1/2^-$	1900 – 2100	20 – 400
$\Delta(1232)^{++}$	$3/2^+$	1232	117
$\Delta(1600)^{++}$	$3/2^+$	1640	300
$\Delta(1700)^{++}$	$3/2^-$	1690	380
$K_0^*(700)$	0^+	824	478
$K^*(892)$	1^-	895.5	47.3
$K_0^*(1430)$	0^+	1375	190

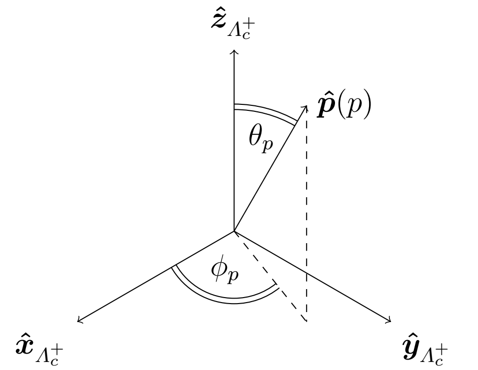
12 resonances

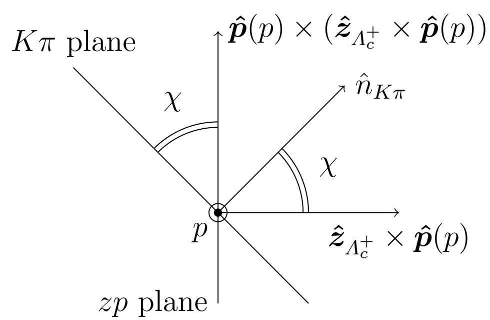
Amplitude analysis of $\Lambda_c^+ \to pK^-\pi^+$

Phys.Rev. D108 (2023) 012023

The amplitude model is written in the helicity formalism



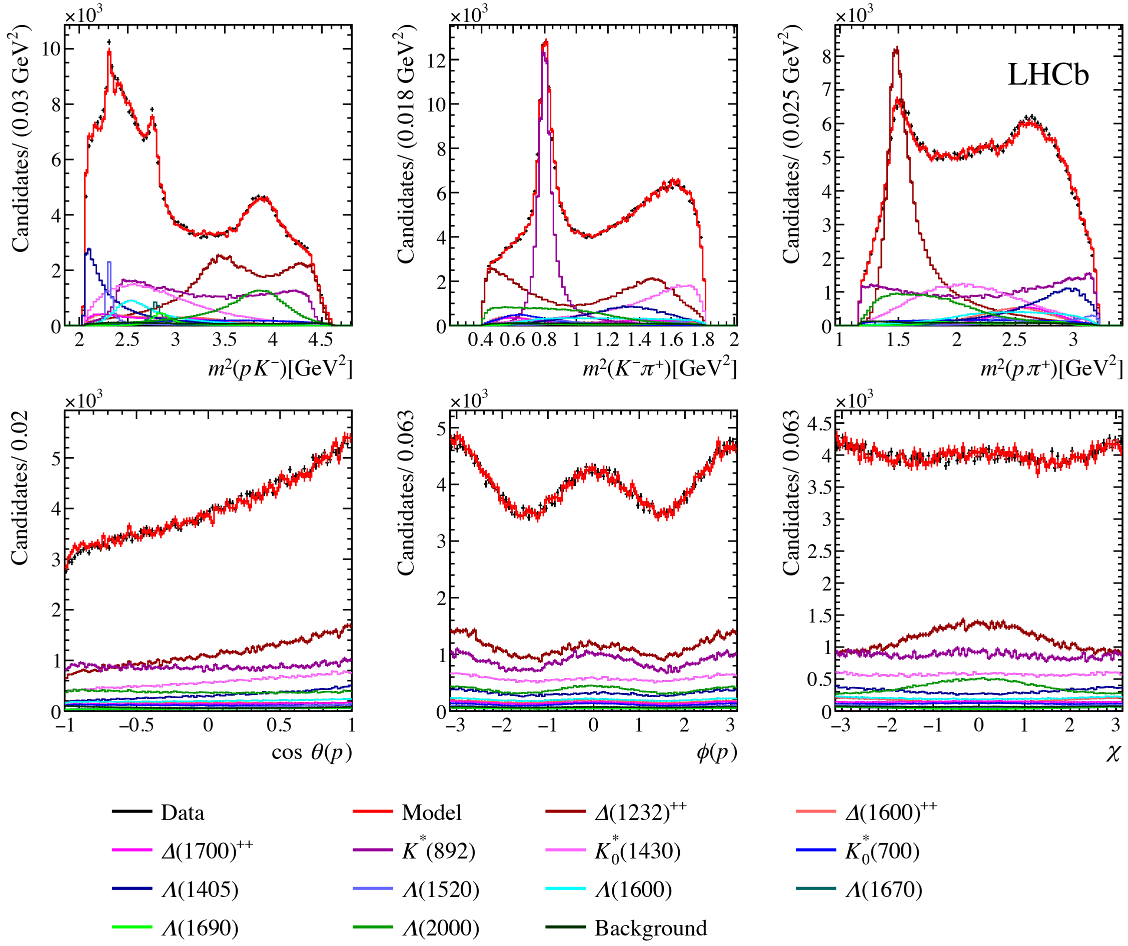




A significant contribution from a resonant in *m*(*pK*)~2GeV region (*Λ*(2000)), where clear resonances have not been previously been reported

Phys.Rev. D108 (2023) 012023

The $\Lambda_c^+ \to pK^-\pi^+$ amplitude model can be employed to measure the polarization of the Λ_c^+ baryon



A large averaged polarization is measured 65% with absolute uncertainty of order 1% with dominating transverse component 60% and a smaller longitudinal component -25%

Including polarization component in the laboratory

Measuring polarimeter vector field in $\Lambda_c^+ \to pK^-\pi^+$ decays

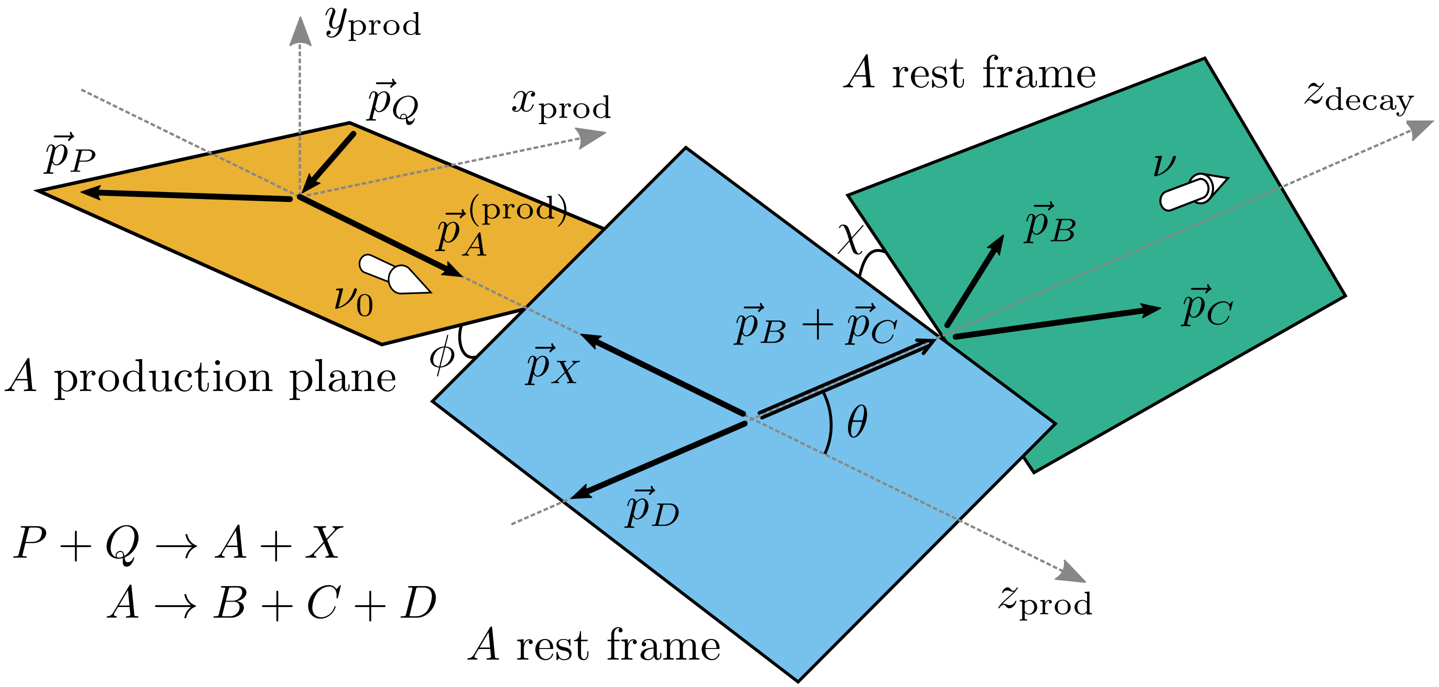
The averaged squared matrix element: LHCb-PAPER-2022-044, JHEP 2023(2023) 228

$$|\mathcal{M}(\phi,\theta,\chi,\kappa)|^2 = I_0(\kappa)\left(1+\sum_{i,j} P_i R_{ij}(\phi,\theta,\chi)\alpha_j(\kappa)\right)$$

$I_0(\kappa)$ – the unpolarized intensity

κ denotes the kinematic variables which the aligned reaction amplitude depends on

P – polarization



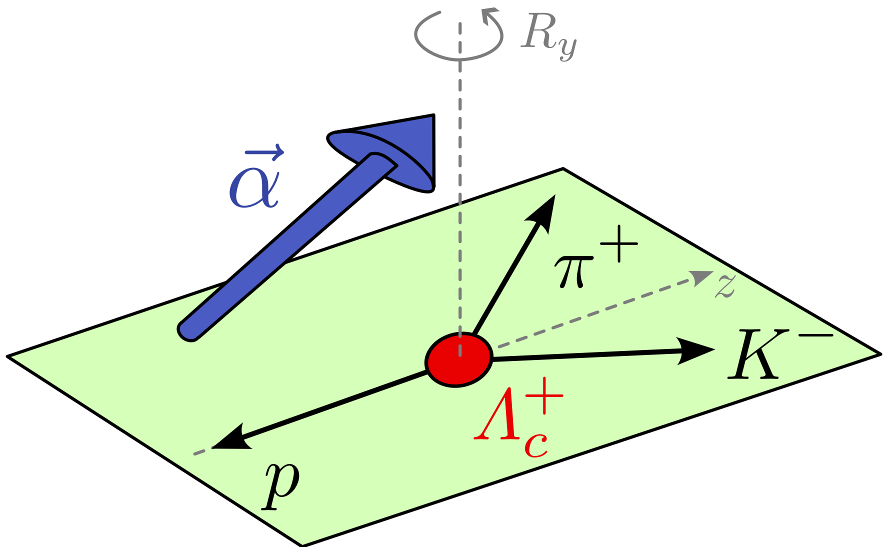
$R_{ij}(\phi,\theta,\chi)$ – three-dimensional rotation matrix implementing the Euler transformation to a physical vector that describe the orientation of the decay products in space

$\alpha_j(\kappa)$ polarimeter vector

Measuring polarimeter vector field in $\Lambda_c^+ \to pK^-\pi^+$ decays

LHCb-PAPER-2022-044, JHEP 2023(2023) 228

$\vec{\alpha}$ – polarimeter vector with respect to the decay plane
it gives a model-agnostic representation for polarization dependence of the decay rate

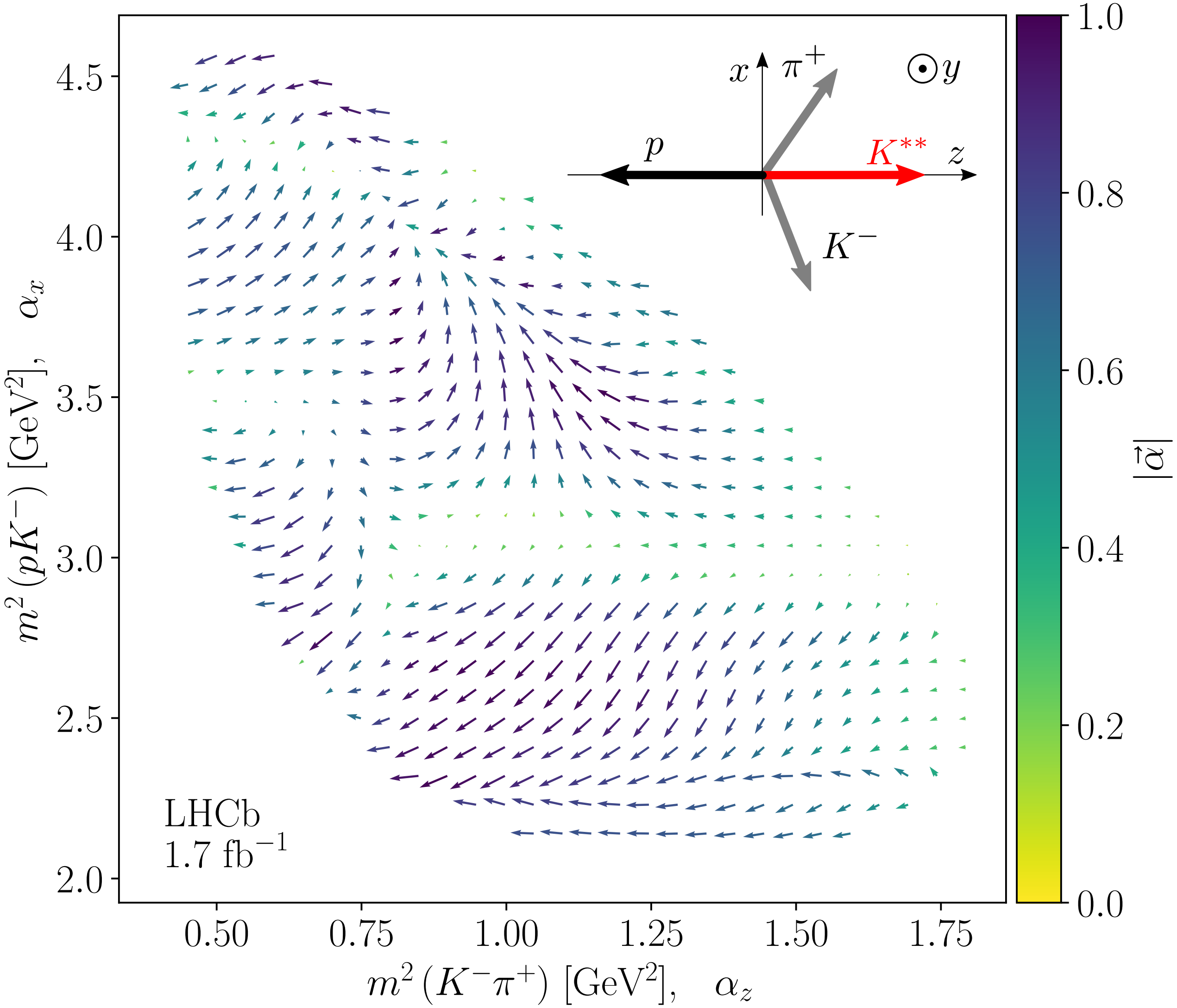


R_y is alignment ratio: who is z axis (the sum of the pion and kaon momenta defines the positive z direction)

The polarimeter vector field in Dalitz plot in $\Lambda_c^+ \to pK^-\pi^+$ decays

LHCb-PAPER-2022-044, JHEP 2023(2023) 228

- The length of the polarimeter vector (shown by the colour) changes from point to point
- It is greater than 0.5 for most of the kinematic domain
- The structures are driven by resonances in different subsystems and their interferences
- The $\bar{\alpha}$ field gives information needed to determine the Λ_c^+ polarization in future analyses



Summary

- Charm physics measurements are providing a wealth of interesting results over the last few years

- So far, *CP* violation in the charm sector is confirmed in mesons only

- In all other charm decays, results are consistent with *CP* symmetry
  - statistical uncertainties dominate
  - increasing data statistics will allow to test the SM in more details

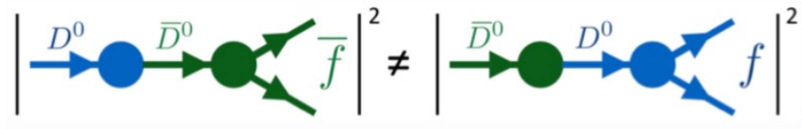
- We are running Run 3

- The goal is to reach ~23 fb^{-1} (Run 3) and ~50 fb^{-1} (Run 4) (Run 1+2: ~9 fb^{-1})

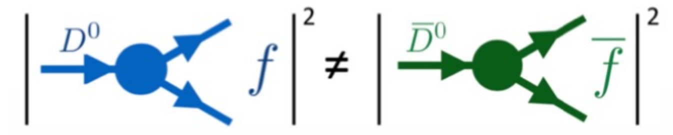
Back up

Three ways of *CP* violation in the Standard Model

1. In the mixing (only neutral particles)
   $P^0 \rightarrow$ anti-P^0 $\neq$ anti-$P^0 \rightarrow P^0$



2. In the amplitudes of direct decays
   (neutral and charge particles)
   $P^{\pm} \rightarrow f$ $\neq$ anti-$P^{\pm} \rightarrow$ anti-f



3. In the interference between
   direct decays and decays via
   mixing (only neutral particles)

Federico's & Jolanta's talks

P^0 = K^0, B^0, B^0_s, D^0, D^0_s

$P^{\pm}$ = $K^{\pm}$, $B^{\pm}$, $B^{\pm}_s$, $D^{\pm}$, $D^{\pm}_s$, $\Lambda^{\pm}_b$, $\Lambda^{\pm}_c$, $\Xi^{\pm}_c$ …

This talk

Charm-ing and beauti-ful experiment (LHCb)

The single-arm forward spectrometer (a new concept for HEP experiments)

$$\sigma(b\bar{b}) = 75.3 \pm 5.4 \pm 13.0\ \mu b$$

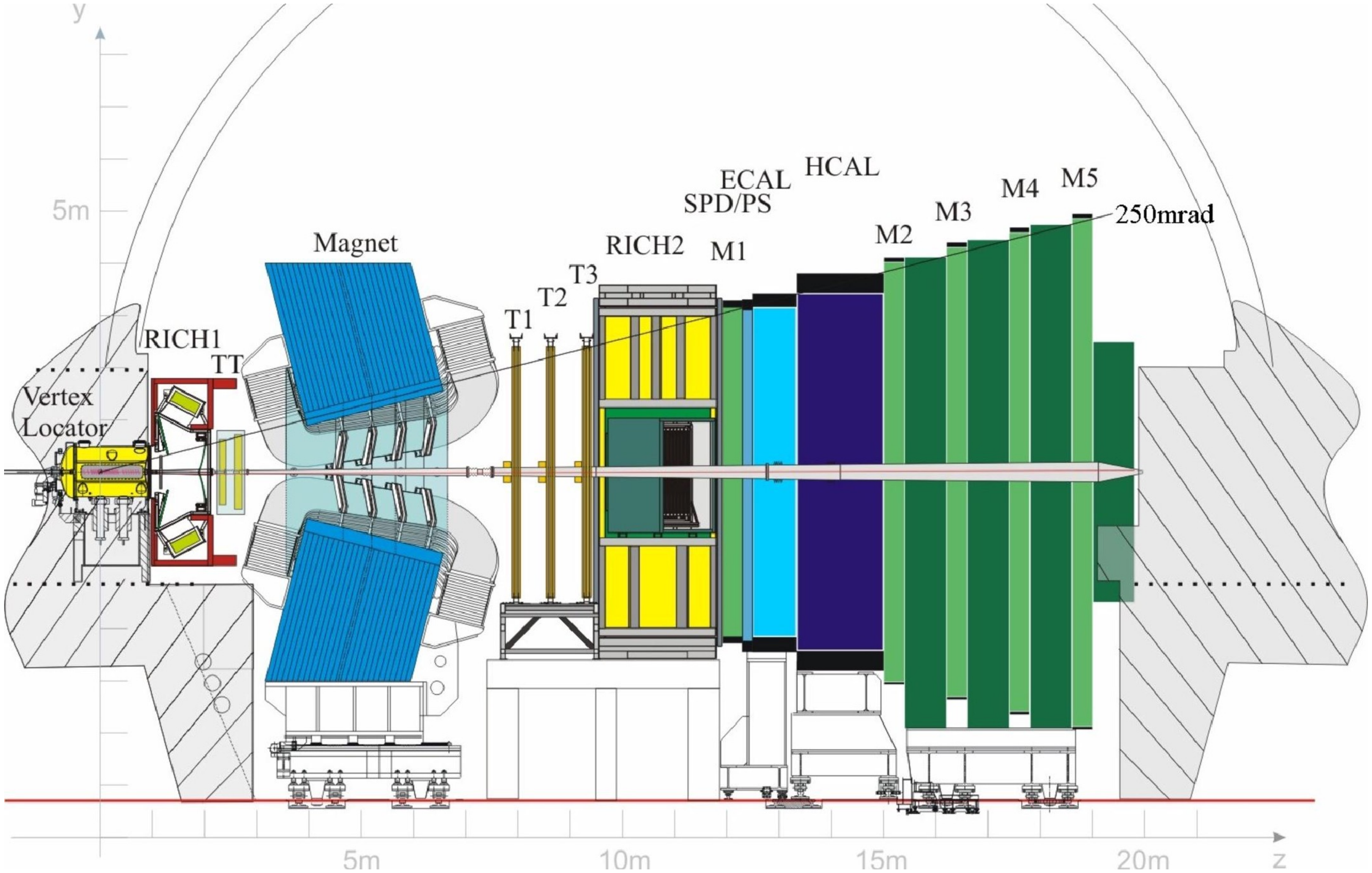
Phys.Lett.B694 (2010) 209-216

10 < θ < 300 mrad (2<η<5)

$$\sigma(c\bar{c}) = 1419 \pm 12 \pm 116\ \mu b \sim 20 \times \sigma(b\bar{b})$$

Nucl.Phys.B871 (2013) 1

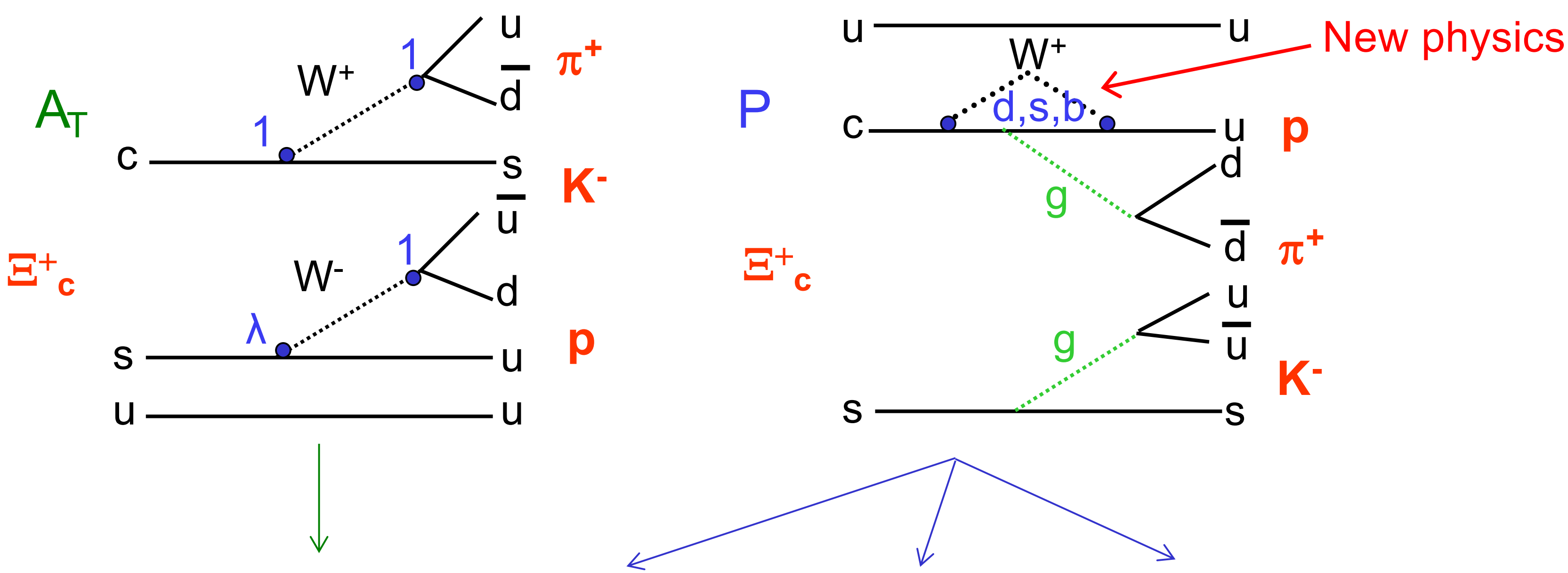
Int. J. Mod. Phys. A 30 (2015) 1530022



Singly Cabibbo−suppressed decays (SCS):

- the only place for *CP* violation in the Standard Model
- both: tree and penguin diagrams

$\lambda = 0.22$



$$A = V_{us}V^*_{cs}\,A_T + V_{ud}V^*_{cd}\,P_d + V_{us}V^*_{cs}\,P_s + V_{ub}V^*_{cb}\,P_b$$

$\sim\lambda$ $\quad\sim\lambda$ $\quad\sim\lambda$ $\quad\sim\lambda^6$

$$Asym_{CP} \sim |A_1||A_2| sin(\phi_1 - \phi_2) sin(\delta_1 - \delta_2)$$

$=A_T$ $\quad =P$ $\quad$ weak phases $\quad$ strong phases !!!

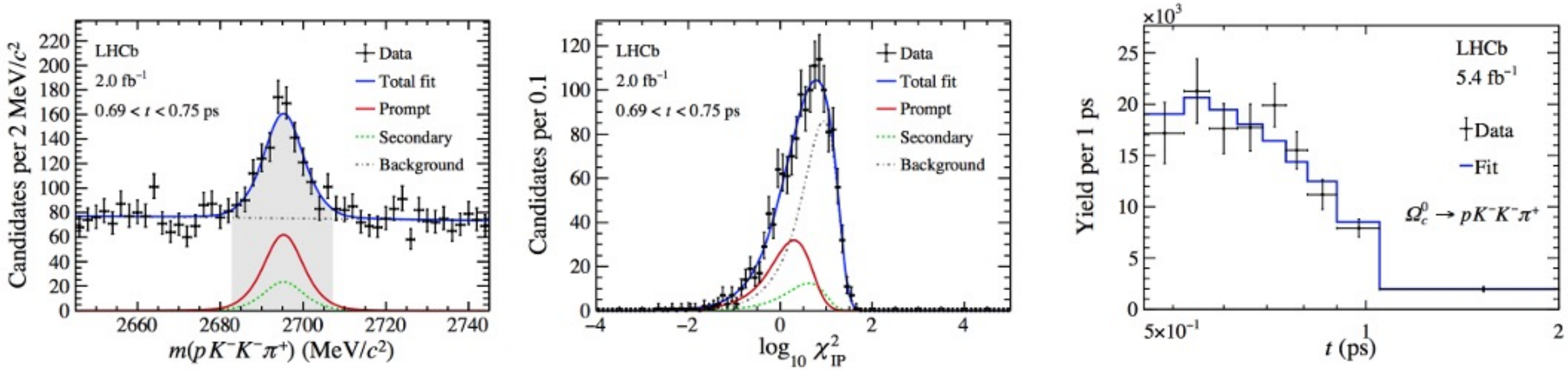
To observe *CP* violation, at least two amplitudes must interfere with different weak phases AND DIFFERENT STRONG PHASES

Lifetime measurement of Ω_c^0 and Ξ_c^0

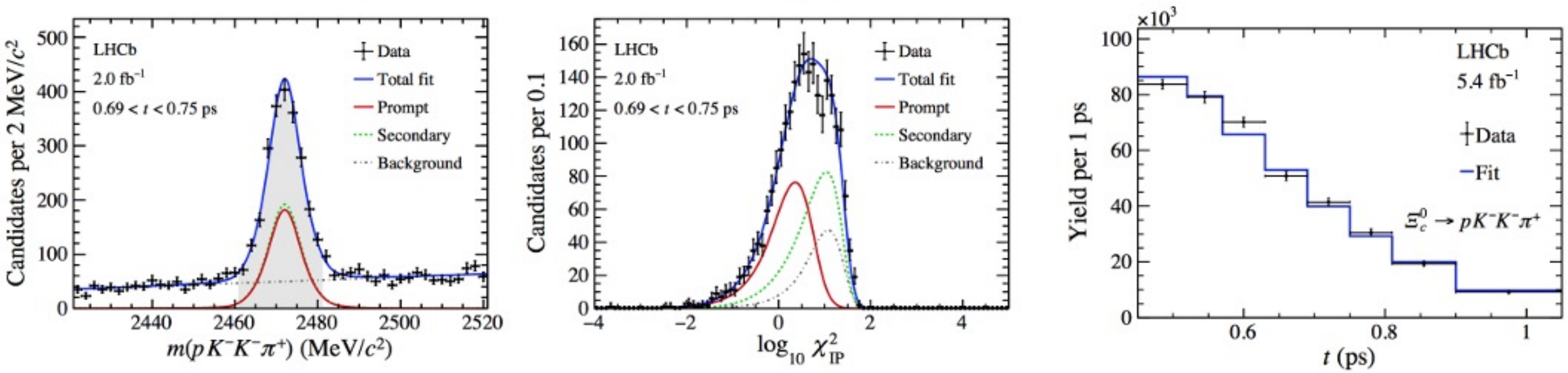
LHCb 2016-2018 dataset at 13TeV and 5.4 fb^{-1} (Prompt production)
Two-dimensional unbinned extended maximum likelihood fits are performed to the mass and log χ^2 distributions

Sci.Bull.67 (2022) 479

Ω_c^0:



Ξ_c^0:



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

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

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

The results confirm the charmed-hadron lifetime hierarchy, improve the precision of the previous Ω_c lifetime by a factor of two