CP Violation in Charmed and Bottom Baryons

John Yelton
U. of Florida

CP violation well studied in mesons (strange, charmed and bottom)

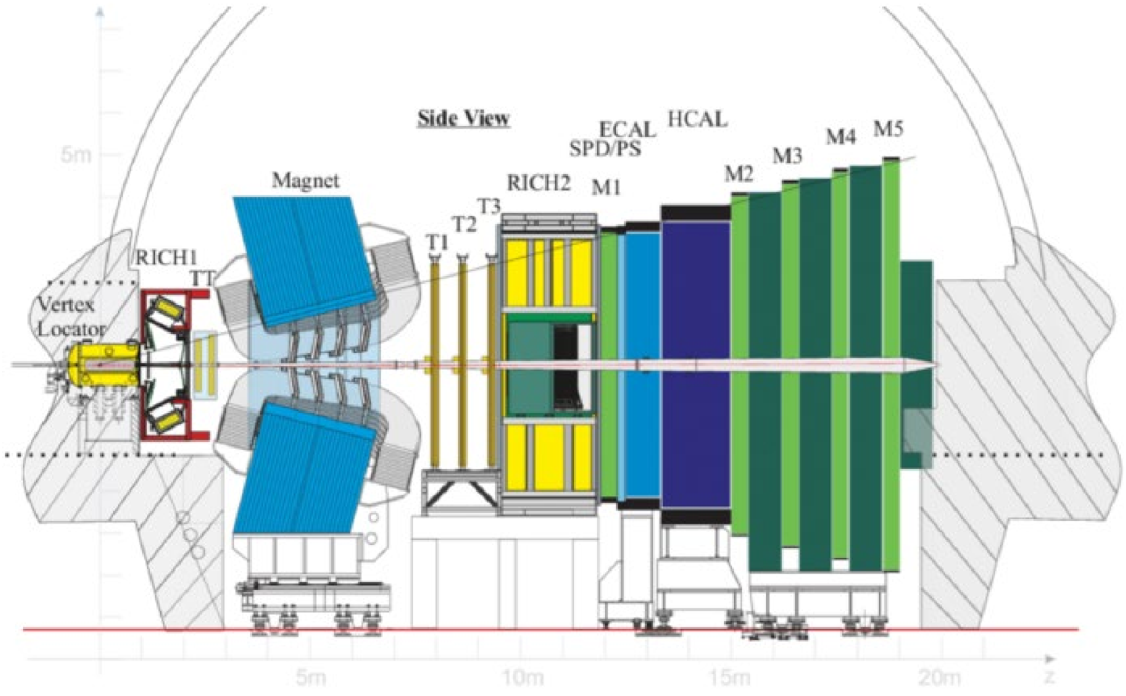
Baryons are always harder to study than mesons!

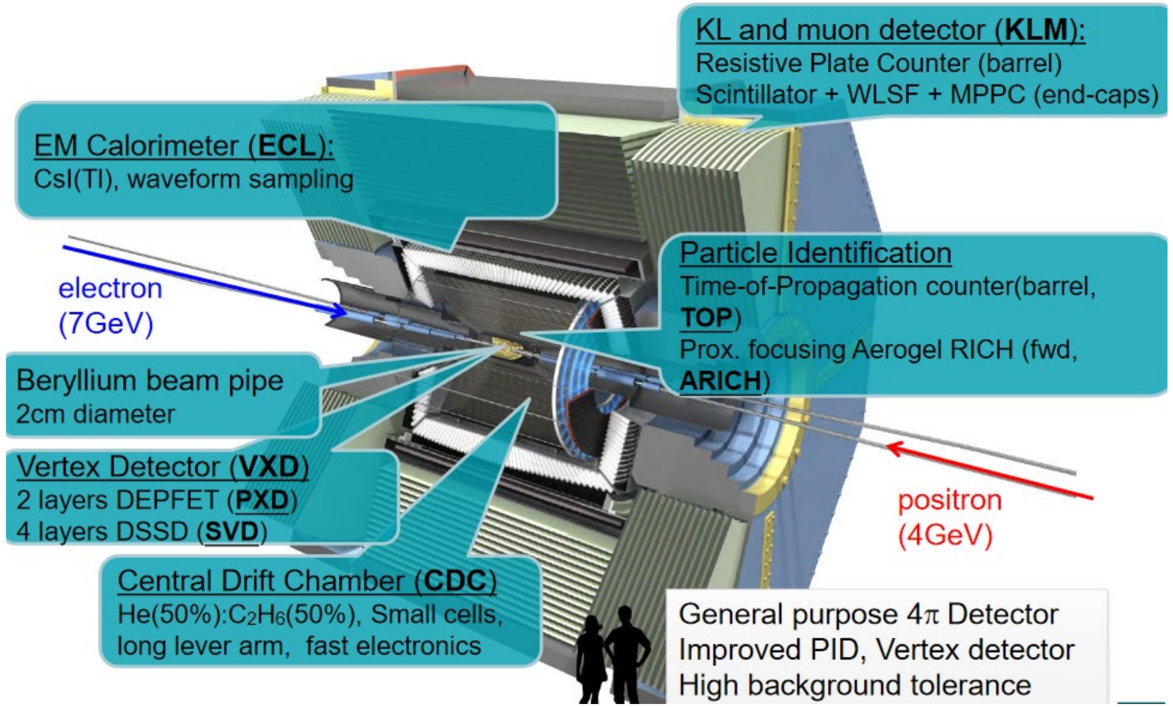
In addition to the usual difficulties, CPV in baryons has a distinct disadvantage. Whereas in neutral mesons there can be mixing between particle and anti-particle and two distinct interfering amplitudes which can produce time-dependent CP violation.

Baryon number conservation is a very strong constraint!

But – if we want to understand why we are here today (and made out of matter), we need to understand CP violation in baryons.

This is an experimentalist's review of recent results on, and prospects for, CP violation studies in c and b baryons





Energy frontier experiments

e.g. LHCb

Intensity frontier experiments

e.g. Belle II

Comparing LHCb and Belle (II)

Property	LHCb at LHC	Belle II at KEK
$\sigma\,(b+\bar{b})$nb	~150,000	~1
$\int Ldt$ (fb^{-1}) goal	~50 (phase 1)	~50,000 (eventually……)
Background Level	Higher	Lower
Typical Efficiency	Lower	Higher
Neutral efficiency	Lower	Higher
Decay time resolution	Great	Good
Production Ratios	Baryons produced preferentially	Baryons/Antibaryons produced equally
Hyperon efficiency	Lower	Higher
Collision spot size	Bigger	Tiny
Particles produced	Includes B	Only c and s

LHCb Search for CP Violation in $\Xi_b^- \to pK^-K^-$

Why this mode?

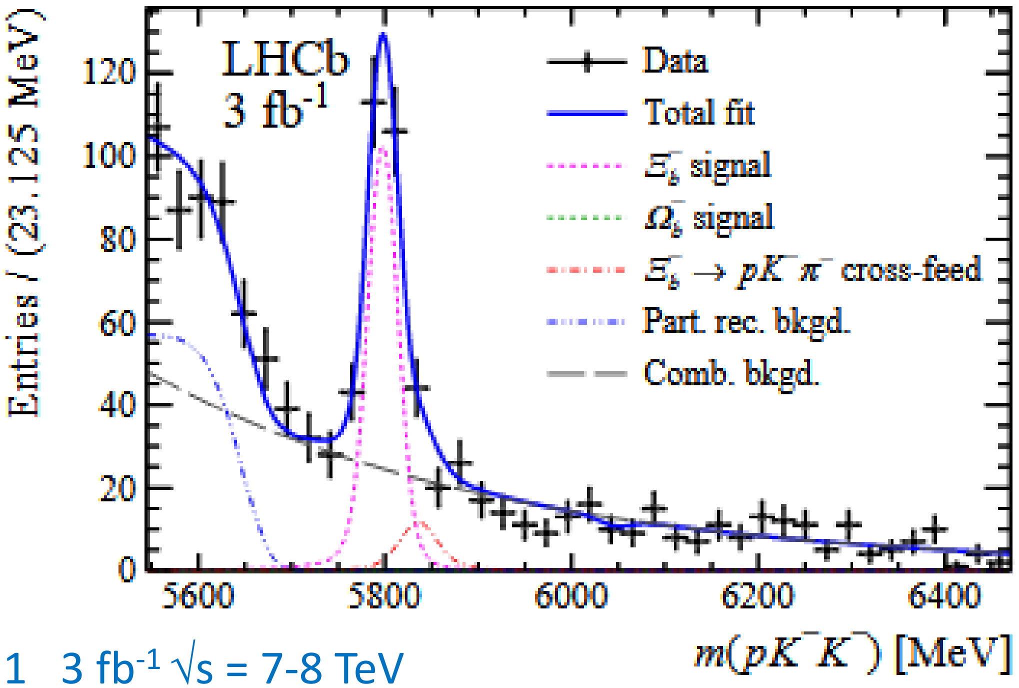
Interference between two amplitudes with different weak and strong phases leads to CP violation in decay

Weak phases are associated with the complex elements of the CKM matrix

Strong phases associated with hadronic final-state effects.

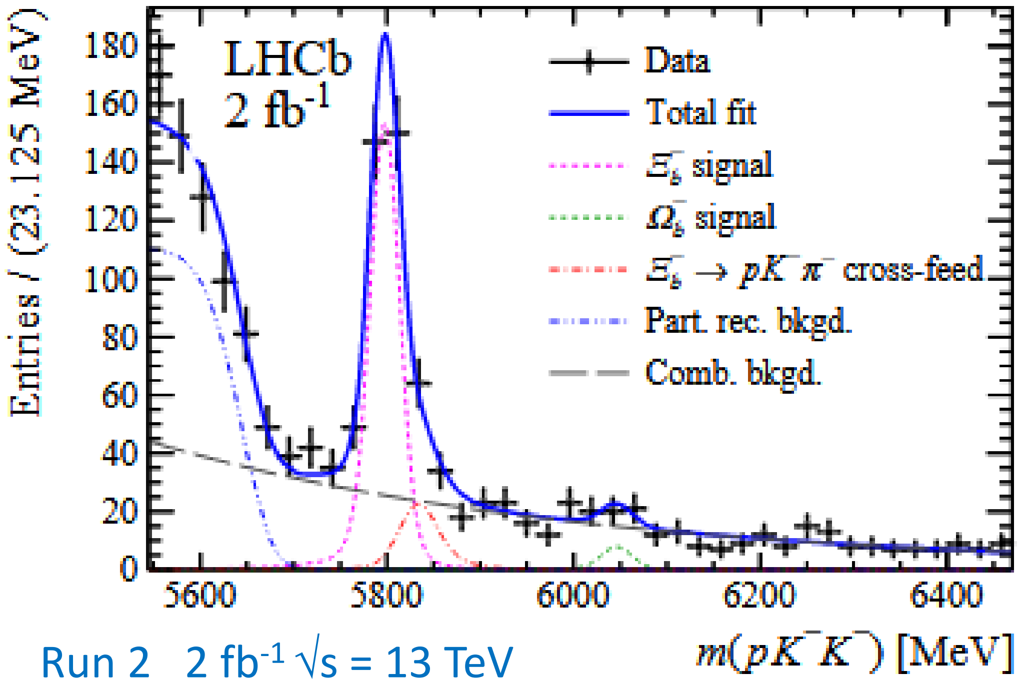
Decays of b hadrons *without charm quarks* have good potential for CP violation – in both baryons and mesons

193 ± 21 events



Run 1 3 fb^{-1} $\sqrt{s}$ = 7-8 TeV

297 ± 23 events

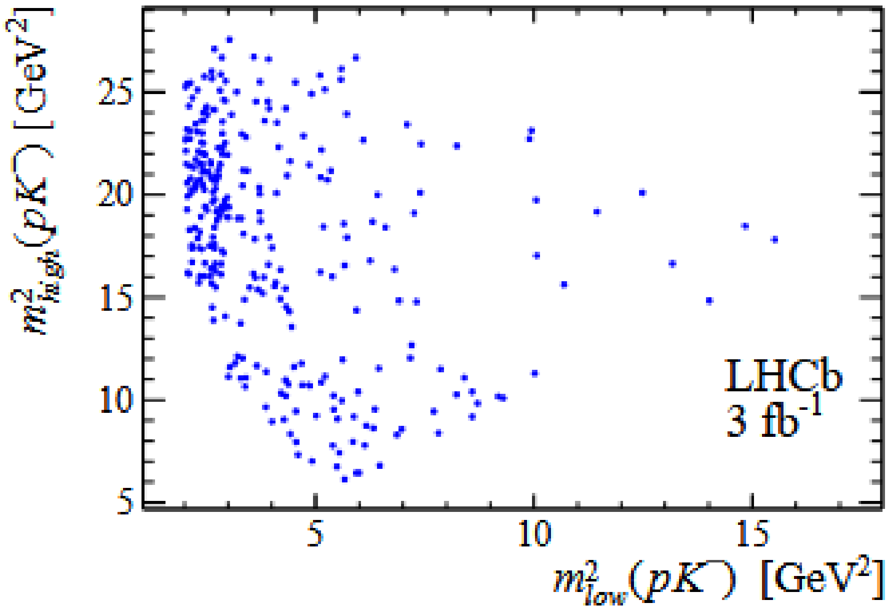


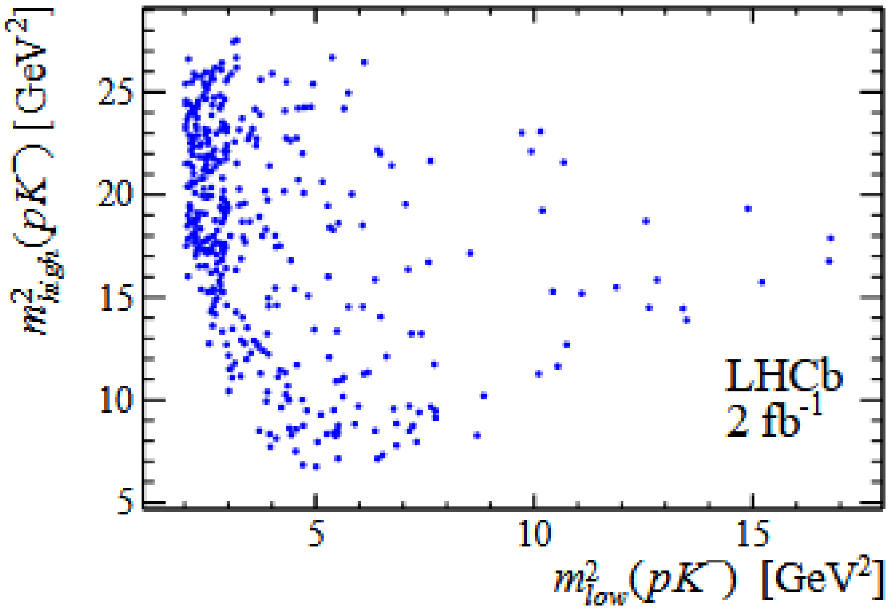
Run 2 2 fb^{-1} $\sqrt{s}$ = 13 TeV

R. Aaij et al, Phys. Rev. D 104 (2021) 5, 052010

LHCb Search for CP Violation in $\Xi_b^- \to pK^-K^-$, continued

Ξ_b^- taken to be unpolarized. Make the Dalitz plots according to the mass of the pK^-

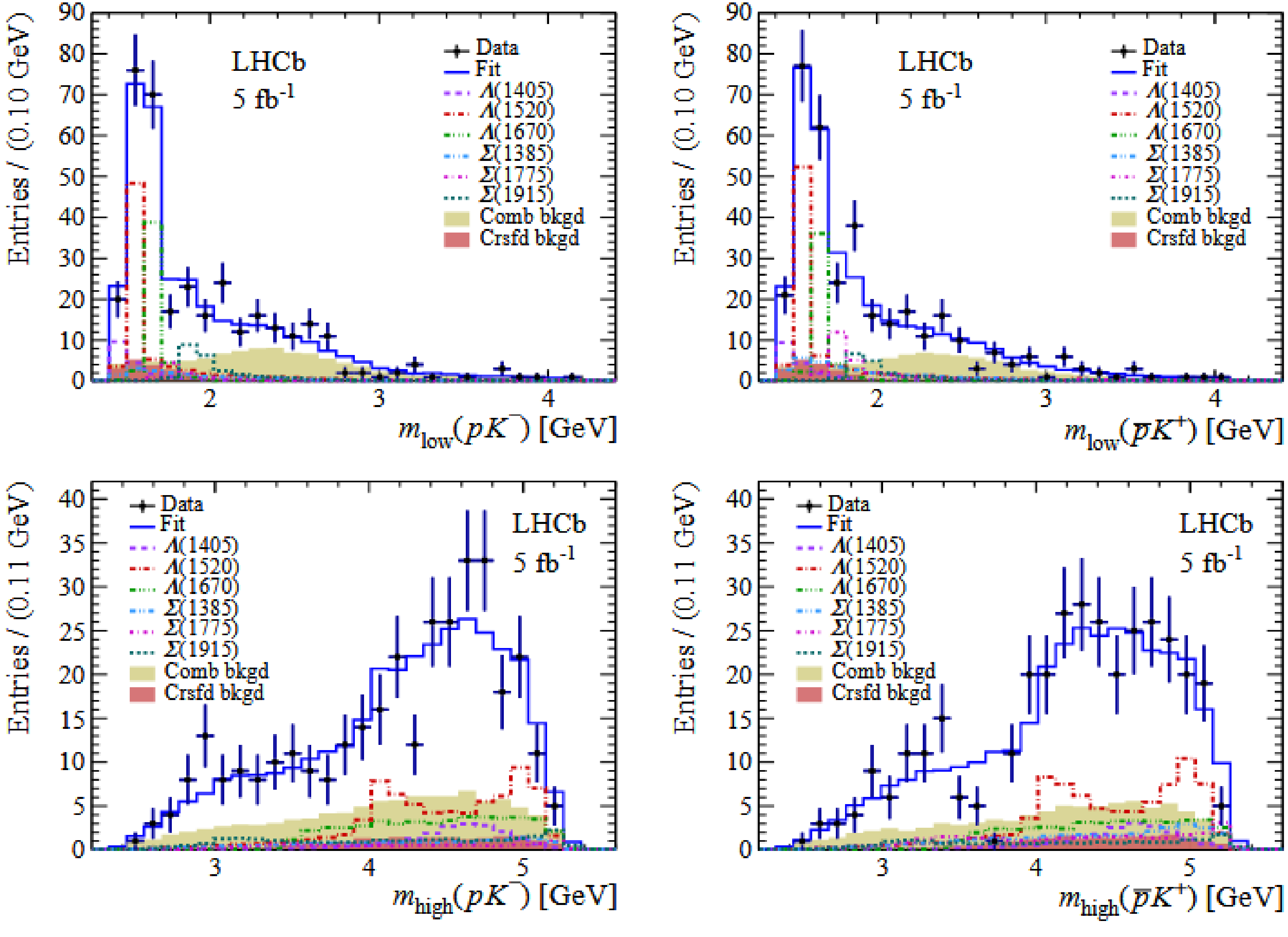




Many intermediate resonances possible: the fit considered the following six well-established intermediate states

State	Mass (MeV/c^2)	Width (MeV/c^2)	J^P
Λ(1405)	1405.1 ± 1.3	50.5 ± 2.0	$\frac{1}{2}^-$
Λ(1520)	1518 to 1520	15 to 17	$\frac{3}{2}^-$
Λ(1670)	1660 to 1680	25 to 50	$\frac{1}{2}^-$
Σ(1385)	1383.7 ± 1	36 ± 5	$\frac{3}{2}^+$
Σ(1775)	1770 to 1780	105 to 135	$\frac{5}{2}^-$
Σ(1915)	1900 to 1935	80 to 160	$\frac{5}{2}^+$

LHCb Search for CP Violation in $\Xi_b^- \rightarrow pK^-K^-$, continued



Baryons

Anti-Baryons

$$A_i^{CP} = \frac{\int_\Omega (d\Gamma_i^+/d\Omega - d\Gamma_i^-/d\Omega)d\Omega}{\int_\Omega (d\Gamma_i^+/d\Omega + d\Gamma_i^-/d\Omega)d\Omega}$$

Note units

Component	$A_{CP}(10^{-2})$
Λ(1405)	-27 ± 34 (stat) ± 73 (syst)
Λ(1520)	-1 ± 24 (stat) ± 32 (syst)
Λ(1670)	-5 ± 9 (stat) ± 8 (syst)
Σ(1385)	3 ± 14 (stat) ± 10 (syst)
Σ(1775)	-47 ± 26 (stat) ± 14 (syst)
Σ(1915)	11 ± 26 (stat) ± 22 (syst)

No evidence of CP violation

Note large statistical uncertainties – systematic uncertainties from many sources some of which will decrease with more statistics

Branching fractions of the six quasi-two-body decays are found, but most are of marginal significance

LHCb Search for CP Violation in $\Lambda_b^0 \rightarrow DpK^-$

Why this mode?
Actually there are more than one final state possible:

1. $\Lambda_b^0 \rightarrow [K^-\pi^+]_D\, p\, K^-$ Kaons have same charge - comparatively favored

2. $\Lambda_b^0 \rightarrow [K^+\pi^-]_D\, p\, K^-$ Kaons have opposite charge - comparatively suppressed

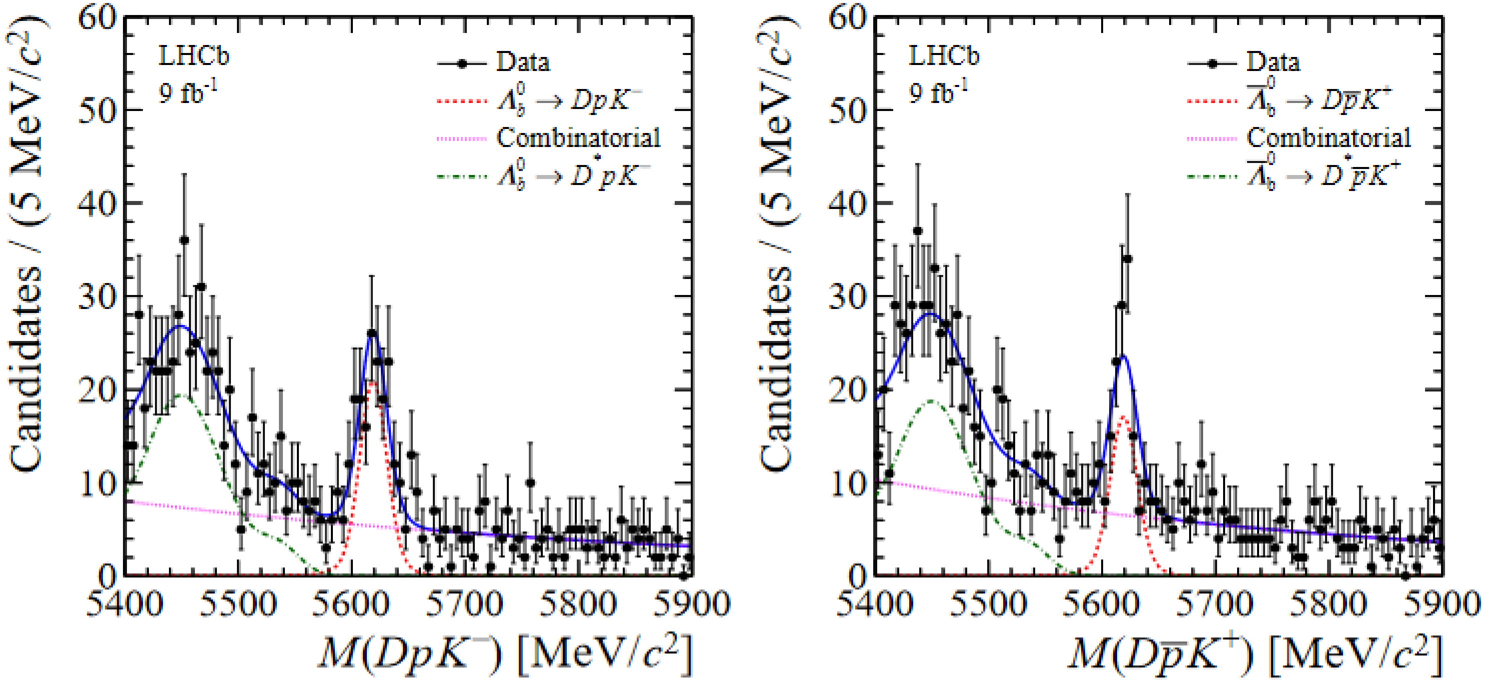
The ratio between the two is approximately: $R \approx \left|\frac{V_{cb}V_{us}^*}{V_{ub}V_{cs}^*}\right|^2 = 6.0.$

The suppressed decay has an amplitude with contributions from $b \rightarrow c$ and $b \rightarrow u$ of similar size, and these have an interference that depend on the CKM angle γ

$$A = \frac{\mathcal{B}(\Lambda_b^0 \rightarrow [K^+\pi^-]_D pK^-) - \mathcal{B}(\bar{\Lambda}_b^0 \rightarrow [K^-\pi^+]_D \bar{p}K^+)}{\mathcal{B}(\Lambda_b^0 \rightarrow [K^+\pi^-]_D pK^-) + \mathcal{B}(\bar{\Lambda}_b^0 \rightarrow [K^-\pi^+]_D \bar{p}K^+)}$$

Note that the asymmetry is anticipated to be amplified in regions of the phase space involving excited Λ states

LHCb Search for CP Violation in $\Lambda_b^0 \rightarrow DpK^-$, continued



Baryons

Anti-Baryons

The interesting "suppressed" mode

Asymmetry integrated over all phase space:

$$A_{CP} = 0.12 \pm 0.09(stat)^{+0.02}_{-0.03}(syst.)$$

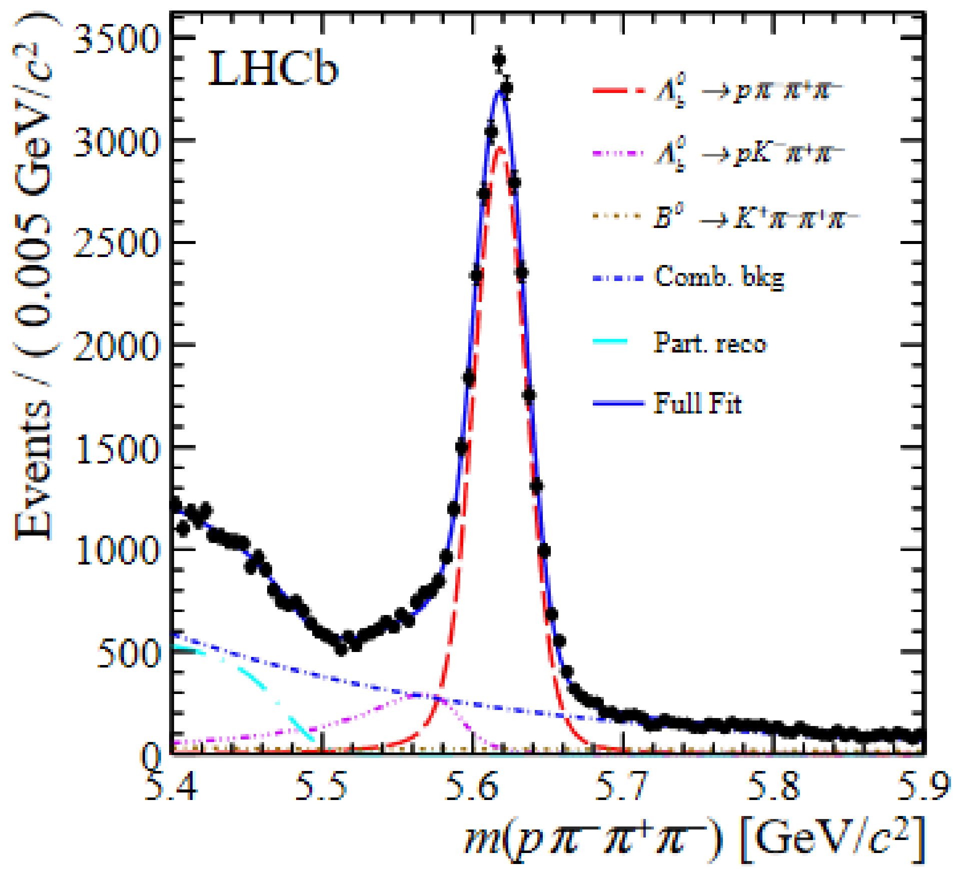
No evidence of CP violation

In the low M(pK-) region:

$$A_{CP} = 0.01 \pm 0.16(stat)^{+0.03}_{-0.02}(syst.)$$

R. Aaij et al, Phys. Rev. D 104 (2021) 11, 112008

LHCb Search for CP Violation in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$



Signal Yield: 27,600 ± 200
6.6 fb^{-1}

CP asymmetry measured using two different approaches:
Method 1: Triple product correlations uses scalar triple products*

$$C_{\hat{T}} \equiv \vec{p}_p \cdot \left(\vec{p}_{\pi^-_{\text{fast}}} \times \vec{p}_{\pi^+}\right) \qquad \overline{C}_{\hat{T}} \equiv \vec{p}_{\overline{p}} \cdot \left(\vec{p}_{\pi^+_{\text{fast}}} \times \vec{p}_{\pi^-}\right)$$

Data then divided into 4 pieces, with yields N, (i.e. divide by 2 by whether it is a particle or antiparticle an again by 2 according to the sign of the scalar triple product)
The Triple Product Asymmetry is then defined as:

$$A_{\hat{T}} = \frac{N(C_{\hat{T}}>0) - N(C_{\hat{T}}<0)}{N(C_{\hat{T}}>0) + N(C_{\hat{T}}<0)}, \quad \overline{A}_{\hat{T}} = \frac{\overline{N}(-\overline{C}_{\hat{T}}>0) - \overline{N}(-\overline{C}_{\hat{T}}<0)}{\overline{N}(-\overline{C}_{\hat{T}}>0) + \overline{N}(-\overline{C}_{\hat{T}}<0)}$$

$$a_{CP}^{\hat{T}\text{-odd}} = \frac{1}{2}\left(A_{\hat{T}} - \bar{A}_{\hat{T}}\right) \qquad a_{P}^{\hat{T}\text{-odd}} = \frac{1}{2}\left(A_{\hat{T}} + \bar{A}_{\hat{T}}\right)$$

CP violating piece

*variables explained in G. Durieux, JHEP 10 (2016) 005
R. Aaij et al., Phys. Rev. D 102 (2020) 051101

LHCb Search for CP Violation in $\Lambda_b^0 \rightarrow p\pi^-\pi^+\pi^-$ continued

If we integrate over all phase-space:

$$a_{CP}^{\hat{T}\text{-odd}} = (-0.7 \pm 0.7 \pm 0.2)\%$$

No evidence of CP violation!

$$a_P^{\hat{T}\text{-odd}} = (-4.0 \pm 0.7 \pm 0.2)\%$$

There is a very rich resonant substructure in the decay, e.g.

$\Lambda_b^0 \rightarrow N^{*+}\pi^-$, $N^{*+} \rightarrow \Delta^{++}(1234)\,\pi^-$, $\Delta^{++} \rightarrow p\,\pi^+$

$\Lambda_b^0 \rightarrow p a_1^-(1260)$, $a_1^-(1260) \rightarrow \rho^0(770)\,\pi^-$, $\rho^0(770) \rightarrow \pi^+\pi^-$

Therefore divide into different bins of phase space according to two schemes

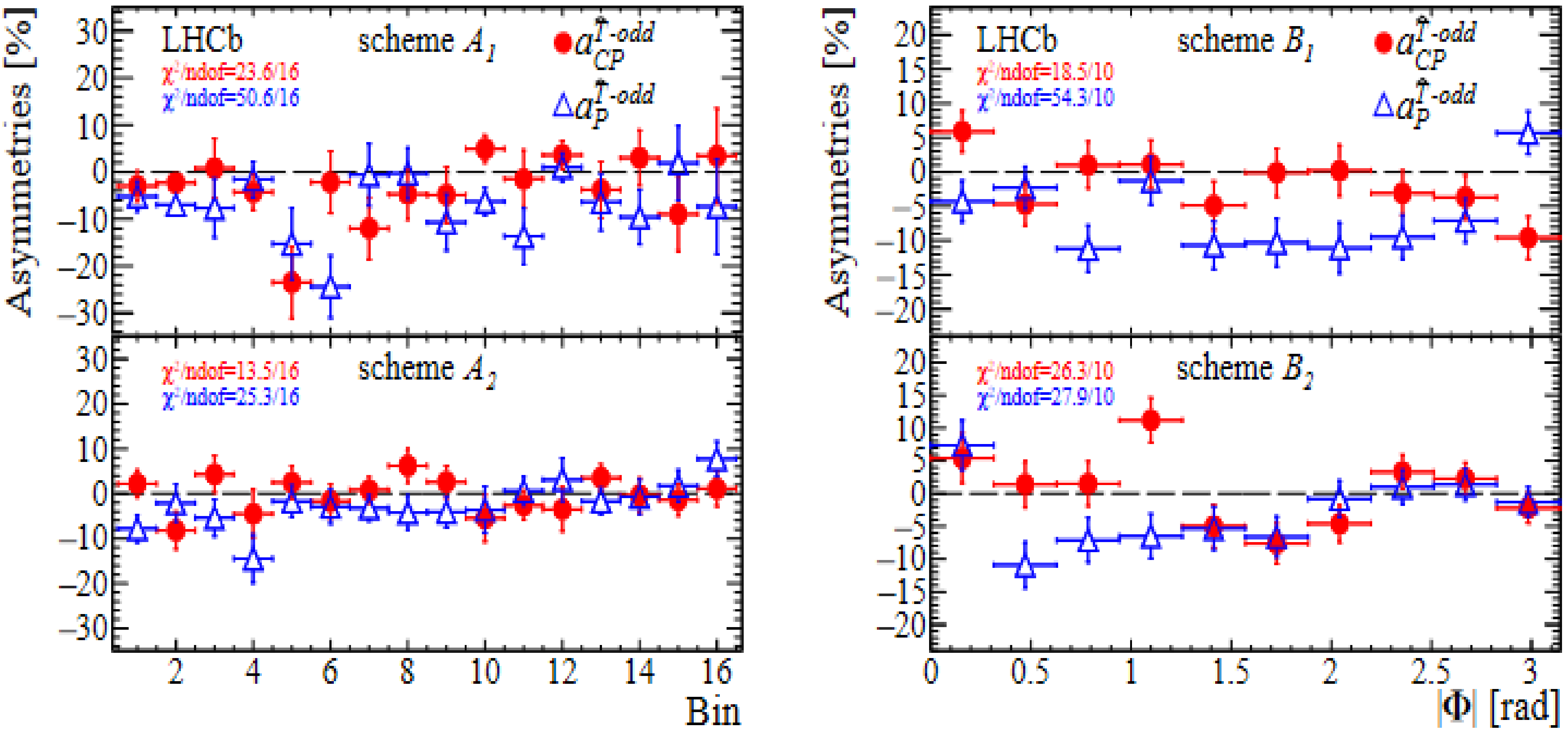
Scheme A: 16 bins of polar and azimuthal angles of the p in the Δ^{++} frame

Scheme B: 10 bins of ϕ angle between decay planes $\pi^+\pi^-_{slow}$ and $p\pi^-_{fast}$

For each scheme divide into:

sample 1 (A_1 and B_1) for $m(p\pi^+\pi^-_{slow}) > 2.8$ GeV dominated by a_1

sample 2 (A_2 and B_2) for $m(p\pi^+\pi^-_{slow}) < 2.8$ GeV dominated by N*



Highest significance for CP violation is in B_2 and is 2.9 σ

Note a similar analysis on a 25% of this dataset and found 3.3 σ

The present analysis supercedes that previous result

LHCb Search for CP Violation in $\Lambda_b^0 \rightarrow p\pi^-\pi^+\pi^-$ continued

A new method uses model independent unbinned tests.*
Defines a distance scale (δ) which is a free parameter
Calculates p-values for 3 different values of δ

Distance scale δ	1.6 GeV^2/c^4	2.7 GeV^2/c^4	13 GeV^2/c^4
p-value (CP conservation, P even)	3.1×10^{-2}	2.7×10^{-3}	1.3×10^{-2}
p-value (CP conservation, P odd)	1.5×10^{-1}	6.9×10^{-2}	6.5×10^{-2}
p-value (P conservation)	1.3×10^{-7}	4.0×10^{-7}	1.6×10^{-1}

Combined significance for CP violation < 3 σ in CP test
(note that for P test, 5.3 σ significance observation)

*M. Williams, Phys. Rev. D 84, 054015 (2011)

CP violation searches using charmed baryons

Some clear experimental advantages over B physics:

e^+e^- machines can get good signals for many charmed baryon modes

comparatively low multiplicity makes for final states that are easier to analyze

Looking for CPV in charmed baryon decays is a several step process:

1. Choose a suitable decay mode and measure the branching fraction
2. Measure the asymmetry parameter, α
3. Measure the difference in asymmetry parameters for particles/anti-particles

Note, once again, no measurable CPV is expected in 2-body Cabibbo-favored decays, whereas for Cabibbo-suppressed modes $\sim 10^{-3}$ can be expected.

Numbers for specific channels are difficult to predict

CP violation searches using charmed baryons continued

What sort of modes should we look for?

Two-body decays are the easiest.

$\Xi_c^0 \rightarrow \Xi^- \pi^+$ has been investigated, but is Cabibbo allowed

$\Lambda_c^+ \rightarrow \Lambda K^+$ and $\Sigma^0 K^+$

Branching Fractions: $(6.1 \pm 1.2) \times 10^{-4}$ and $(5.2 \pm 0.8) \times 10^{-4}$

(dominated by statistical uncertainty)

At e^+e^- machines:

Λ and Ξ^- efficiency and purity are good.

$\Sigma^0 \rightarrow \Lambda\gamma$ efficiency and purity OK

For 1 ab^{-1} (Belle integrated luminosity, but small fraction of what Belle II WILL take)

$\Xi_c^0 \rightarrow \Xi^- \pi^+$ has around 35,000 events and statistical uncertainty $\sim$ 1%

ΛK^+ will have around 10,000 events and statistical uncertainty $\sim$ 3%

$\Sigma^0 K^+$ will have around 3,000 events and statistical uncertainty $\sim$ 6%

CP violation searches using charmed baryons continued

For a decay such as $\Lambda_c^+ \rightarrow$ BP (baryon + pseudoscalar meson), the α parameter is defined to be:

$$\alpha = \frac{2Re(s.p)}{|s|^2+|p|^2}$$

(where s and p are the parity-violating s-wave and the parity-conserving p-wave amplitudes in the decay)

Operationally, for a decay such as $\Lambda_c^+ \rightarrow \Lambda K^+$ we define an angle θ_Λ, which is the angle between the proton momentum in the Λ frame and the Λ in the Λ_c^+ frame. We divide the data into bins of cos(θ_Λ) and then use the equation:

$$dN/d\cos\theta_\Lambda \propto 1 + \alpha(\Lambda_c^+ \rightarrow \Lambda K^+)\, \alpha(\Lambda \rightarrow p\pi^-)\cos\theta_\Lambda$$

In other words, split the data into bins of $\cos\theta_\Lambda$, fit the peak in each one, make a plot, find the slope and extract the product of the α parameters
(α for a Λ is well known)

Luckily for these analyses, the efficiency tends to be rather flat over varying $\cos\theta_\Lambda$

These asymmetries "α" are interesting in their own right, as they may be predicted (along with partial widths) and so give a check on the understanding of weak decays of baryons.

α (PDG etc.)		
-0.84 ± 0.09	$\Lambda_c^+ \to \Lambda\pi^+$	BESIII /Focus/CLEO/Argus
-0.55 ± 0.11	$\Lambda_c^+ \to \Sigma^+\pi^0$	BESIII/CLEO
-0.73 ± 0.18*	$\Lambda_c^+ \to \Sigma^0\pi^+$	CLEO/Argus
-0.86 ± 0.04	$\Lambda_c^+ \to \Lambda l\nu$	CLEO/Argus (more complicated analysis….)
0.2 ± 0.5	$\Lambda_c^+ \to pK^0_s$	BESIII
-0.63 ± 0.03	$\Xi_c^0 \to \Xi_c^-\pi^+$	CLEO2/Belle
-0.15 ± 0.22	$\Xi_c^0 \to \Lambda K^{*0}$	Belle
-0.52 ± 0.30	$\Xi_c^0 \to \Sigma^+K^{*-}$	Belle

**when there is a Σ^0 electromagnetic decay involved, the analysis becomes more complicated*

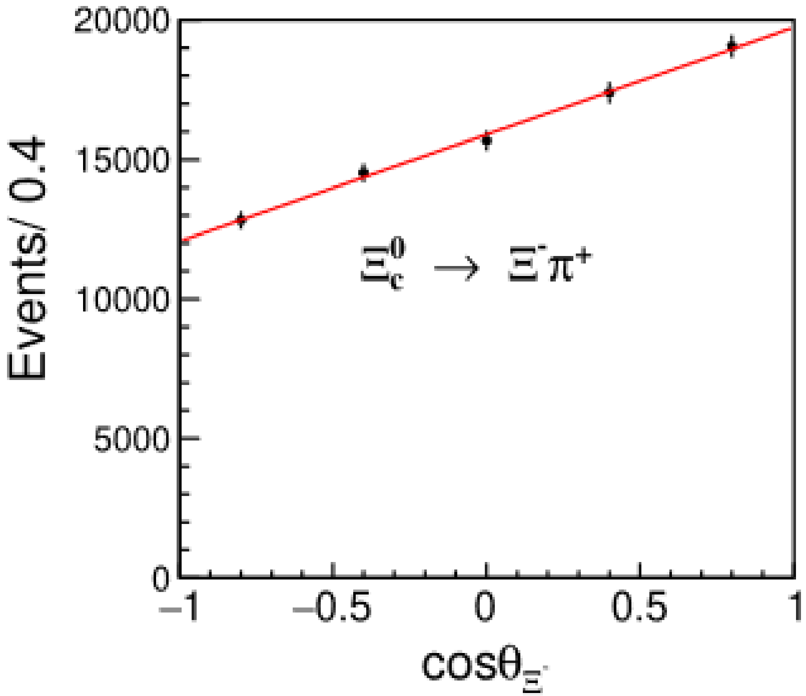
Once an α parameter is measured for a particular decay, then we can look for the CP violating parameter:

$$A^{\alpha}_{CP} = \frac{\alpha(\Lambda_c^+) + \alpha(\Lambda_c^-)}{\alpha(\Lambda_c^+) - \alpha(\Lambda_c^-)}$$

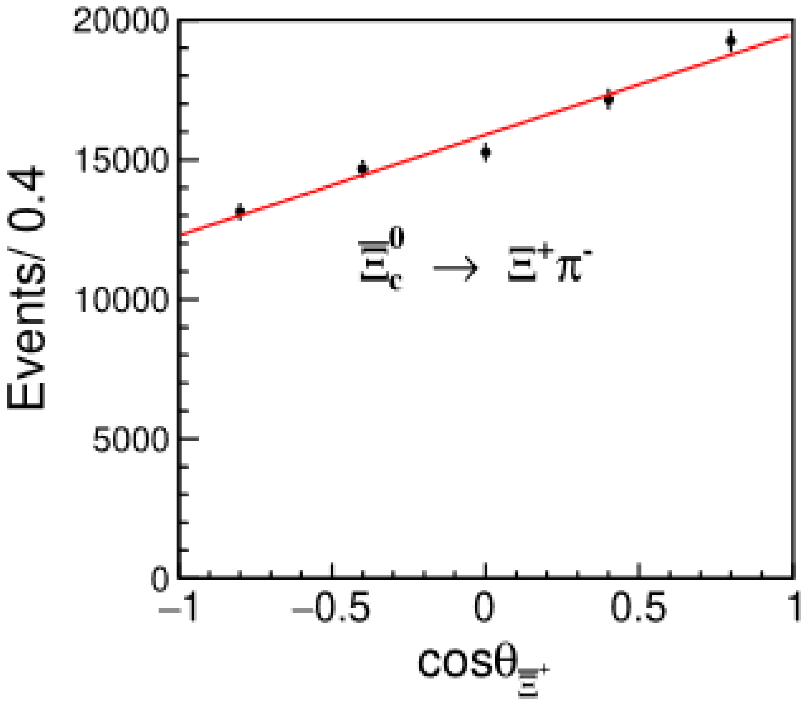
In other words, it depends on the difference in the α parameters for particles and anti-particles

Search for CP Violation in Charmed Baryons - BELLE

Asymmetry measurement of the (Cabibbo-allowed) decay $\Xi_c^0 \to \Xi^- \pi^+$



Baryons



Anti-Baryons

$$\alpha^+ = -0.64 \pm 0.05$$

$$\alpha^- = 0.61 \pm 0.05$$

$$\mathcal{A}_{CP} = 0.024 \pm 0.052 \pm 0.014$$

No Evidence of CP Violation

Y.B. Li et al, PRL 127, 121803 (2021)

A_{CP} measurements in Charmed Baryons

Channel	Experiment	A_{CP}^{α}
$\Lambda_c^+ \to \Lambda l \nu$	CLEO	$0.00 \pm 0.03 \pm 0.01 \pm 0.02$
$\Lambda_c^+ \to \Lambda \pi^+$	FOCUS	$-0.07 \pm 0.19 \pm 0.12$
$\Xi_c^0 \to \Xi_c^- \pi^+$	Belle	$0.024 \pm 0.052 \pm 0.017$
$\Lambda_c^+ \to \Lambda X$	BES III	$0.021 \pm 0.068 \pm 0.014$

For each 1 ab^{-1} data expected A_{CP}^{α} precision for the Cabibbo-suppressed modes $\Lambda_c^+ \to \Lambda K^+$ and $\Sigma^0 K^+$ are $\sim$0.1 and $\sim$0.3

Not very precise, but who knows?

Charmed baryons LHCb measurements: $\Lambda_c^+ \to ph^+h^-$

The big challenge is that measurements require a complete knowledge of the relative detection efficiency of protons and anti-protons

One way of avoiding this is to use two related decays and compare them. That's why they look at $\Lambda_c^+ \to ph^+h^-$ decays with h being either a π or a K (and so Cabibbo-suppressed)

Instead of:

$$A_{CP}(f) = \frac{\Gamma(f) - \Gamma(\bar{f})}{\Gamma(f) + \Gamma(\bar{f})}$$

stick with

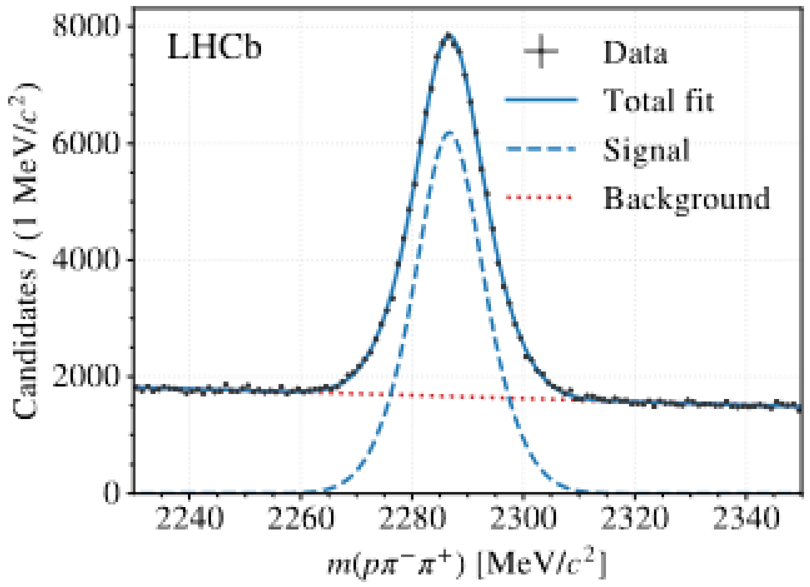
$$A_{\mathrm{Raw}} = \frac{N(f) - N(\bar{f})}{N(f) + N(\bar{f})}$$

(*f* refers to the final state)

$$\begin{aligned}\Delta A_{CP} &= A_{\mathrm{Raw}}(pK^-K^+) - A_{\mathrm{Raw}}(p\pi^-\pi^+) \\ &\approx A_{CP}(pK^-K^+) - A_{CP}(p\pi^-\pi^+)\end{aligned}$$

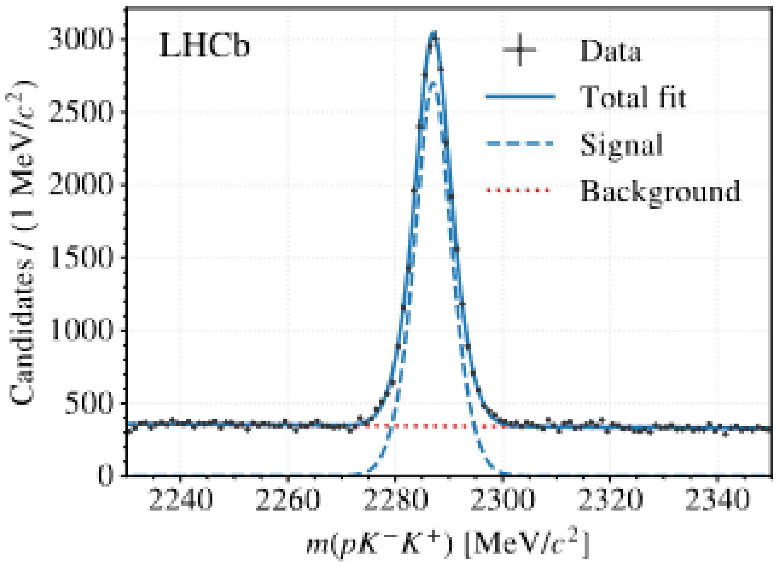
Aaij et al, JHEP 03(2018) 182

Charmed baryons LHCb measurements: $\Lambda_c^+ \rightarrow ph^+h^-$, continued



$$A_{\text{Raw}}(pK^-K^+) = (3.72 \pm 0.78)\,\%$$
$$A_{\text{Raw}}^{\text{wgt}}(p\pi^-\pi^+) = (3.42 \pm 0.47)\,\%$$
$$\Delta A_{CP}^{\text{wgt}} = (0.30 \pm 0.91 \pm 0.61)\,\%$$

Note that the raw asymmetries are non-zero but are probably not due to CP Violation



The two modes have the same asymmetry within uncertainties.

Therefore no evidence of CPV

Aaij et al, JHEP 03(2018) 182

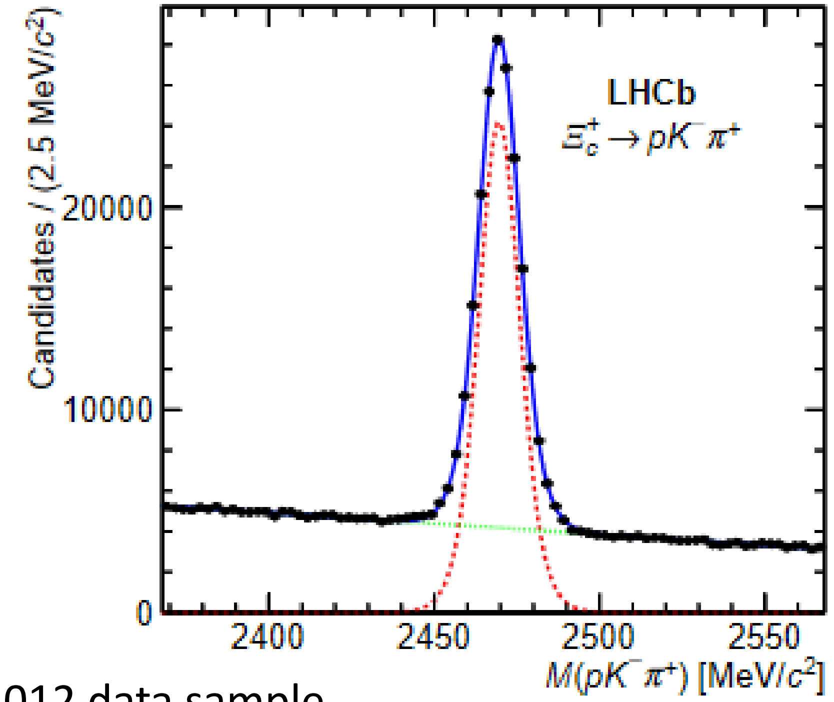
Use the decay $\Lambda_b^0 \rightarrow \Lambda_c^+\mu^-X$ for a clean sample

Search for CP violation in $\Xi_c^+ \to pK^-\pi^+$ (LHCb)

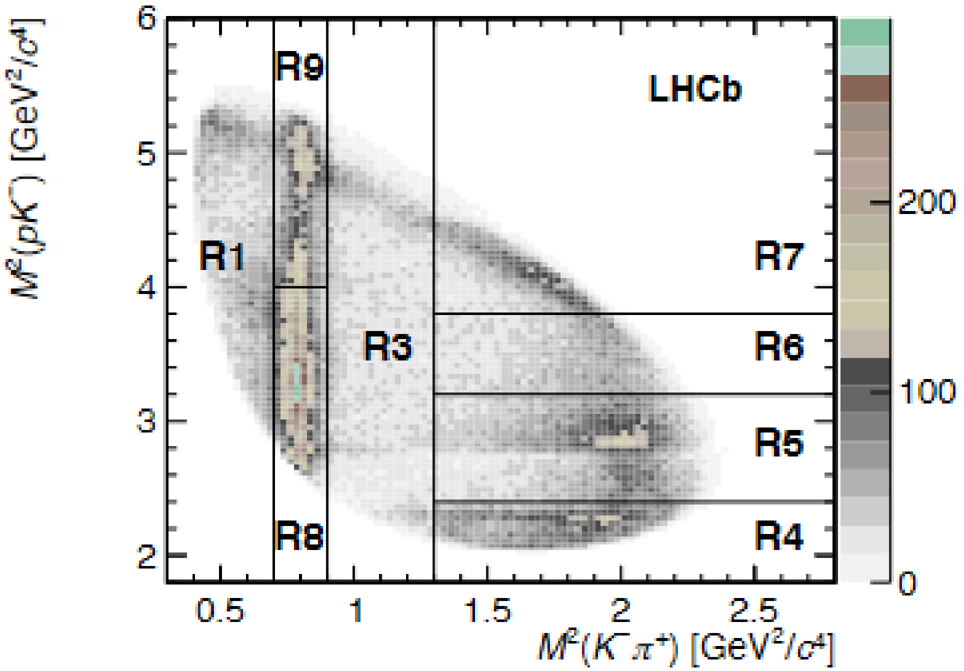
Why this mode:

Singly Cabibbo suppressed mode where we might get a finite value of A_{CP}
Good efficiency and signal:noise
The decay $\Lambda_c^+ \to pK^-\pi^+$ can be used as a control

Look in different regions of the Dalitz plot



2012 data sample



R. Aaij et al, Eur. Phys. J. C80 (2020) 10

Search for CP violation in $\Xi_c^+ \to pK^-\pi^+$ (LHCb) continued

Two different analysis techniques:

- Binned (searches for localized asymmetries in the phasespace of the decay based on the bin-by-bin comparison of the Dalitz plots of baryons and anti-baryons)
- Unbinned (test statistics based on the Euclidean distance between closest points in the Dalitz plot)

Both methods are sensitive to CP asymmetry larger than 5% in the regions around the K*(892) or Δ^{++}(1232)

Bottom line according to LHCb:

"results are consistent with the hypothesis of no CP Violation"

R. Aaij et al, Eur. Phys. J. C80 (2020) 10

Conclusions

I have reviewed a number of searches, and projected searches for CP violation in charmed and bottom baryons

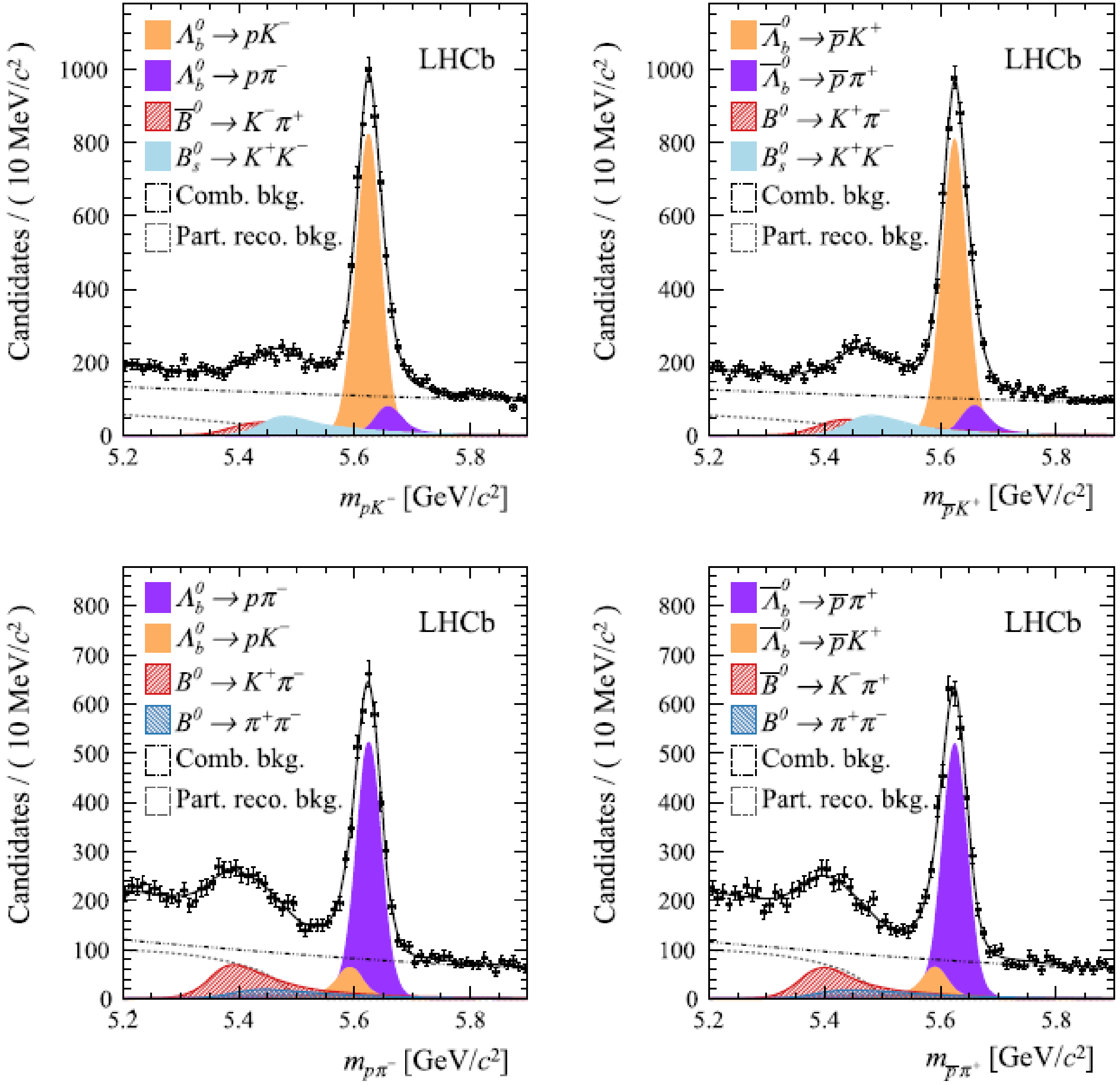
No significant violation has been observed. However, the sensitivity is not at the level where this is a surprise.

For the one mode with reported "evidence", the evidence has not increased with more data analyzed.

Some places where work needs to be done:

1. More predictions for specific decay modes for CPV
2. More measurements of the asymmetry parameters, α, which are interesting in themselves
3. More knowledge of excited hyperons, to disentangle the resonant substructure of heavy baryon decays
4. MORE DATA

LHCb Search for CP Violation in $\Lambda_b^0 \rightarrow$ pK and pπ



$$A_{CP}^{pK^-} = -0.020 \pm 0.013 \pm 0.019$$
$$A_{CP}^{p\pi^-} = -0.035 \pm 0.017 \pm 0.020$$

$$\Delta A_{CP} = 0.014 \pm 0.022 \pm 0.010$$

(some systematics cancel in the difference)

R. Aaij et al, Phys. Lett. B 787 (2018)