Search for CP violation in beauty baryons at LHCb

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on behalf of the LHCb collaboration

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WPI-next mini-workshop “Hint for New Physics in Heavy Flavor Physics”
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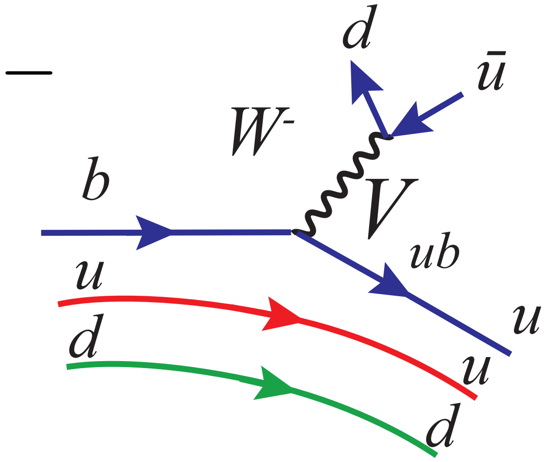
Beauty baryons at LHCb (a bit of history)

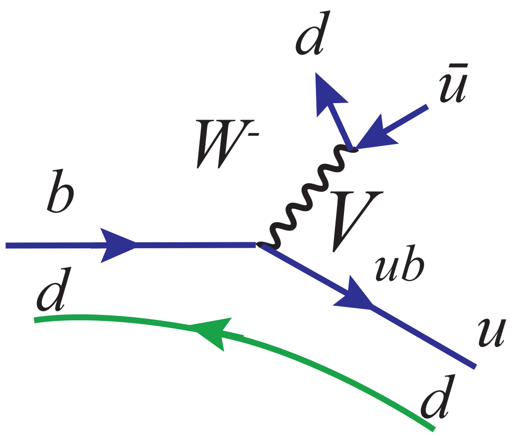
- Most precise measurement of $|V_{ub}|$ using $\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu$ decays
  LHCb: Nature Physics 10(2015) 1038
- First observation of pentaquark using $\Lambda_b^0 \to J/\psi pK^-$decays
  LHCb: Phys. Rev. Lett. 115, 072001 (2015)
- Observation of $\Xi_b^{\prime -}$ and $\Xi_b^{\prime *}$ in $\Xi_b^0\pi^-$ mode LHCb: Phys. Rev. Lett. 114, 062004 (2015)
- Observation of two orbitally excited Λ_b^{*0} states
  LHCb: Phys. Rev. Lett. 109, 172003 (2012)
- Mass, lifetimes and branching ratios measurements
- Search for CPV CDF: Phys. Rev. Lett. 113, 242001
  And other from LHCb presented here
- At LHCb b-baryons are produced in unprecedented quantities
  - Opens a new field in flavour physics for precision measurements

Physics motivation

- CP violation (CPV) in b-baryons:
  - CKM mechanism predicts sizeable amount of CPV in b-baryons that can be precisely measured
  - Complementary means to test Standard Model with respect to B mesons

$\Lambda_b^0 \to p\pi^-$





$B_d^0 \to \pi^+\pi^-$

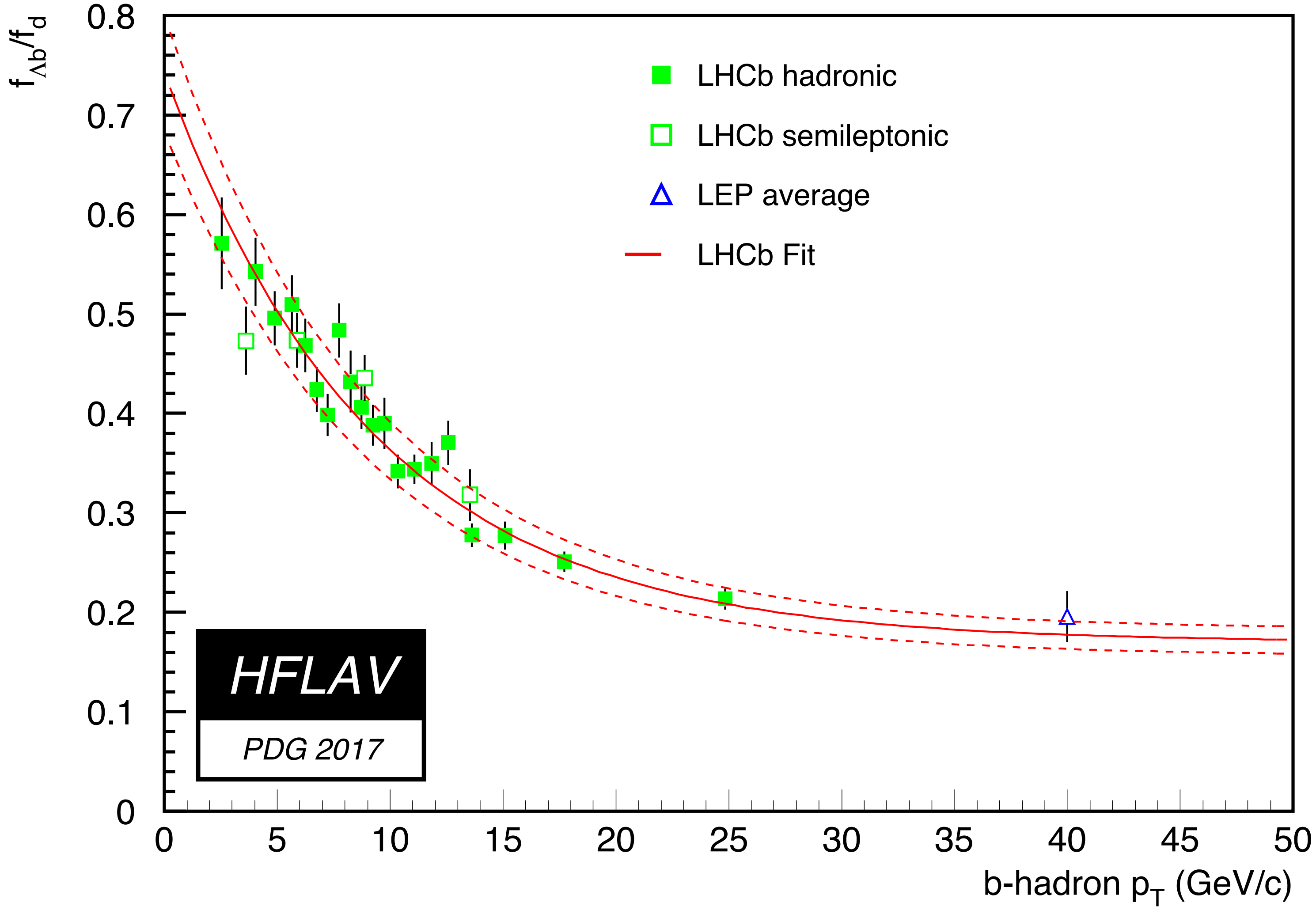
- Same underlying short distance physics as B mesons, with different spin and QCD structure
- New CPV sources

b-baryons production

- Production cross-section strongly depends on p_T of the hadron:
  - measurement of $f_{\Lambda_b^0}/f_d$ vs p_T of b-quark is cleaner to interpret, expected a slow dependence in this case arXiv: 1505.02771
- Large production of Λ_b^0

$$f_{\Lambda_b^0} = P(b \to \Lambda_b^0)$$

$$f_d = P(b \to B^0)$$



- Production of Ξ_b^0 is 1/5 the production of Λ_b^0 from a naive estimate

Phys. Rev. Lett. 113 (2014) 032001

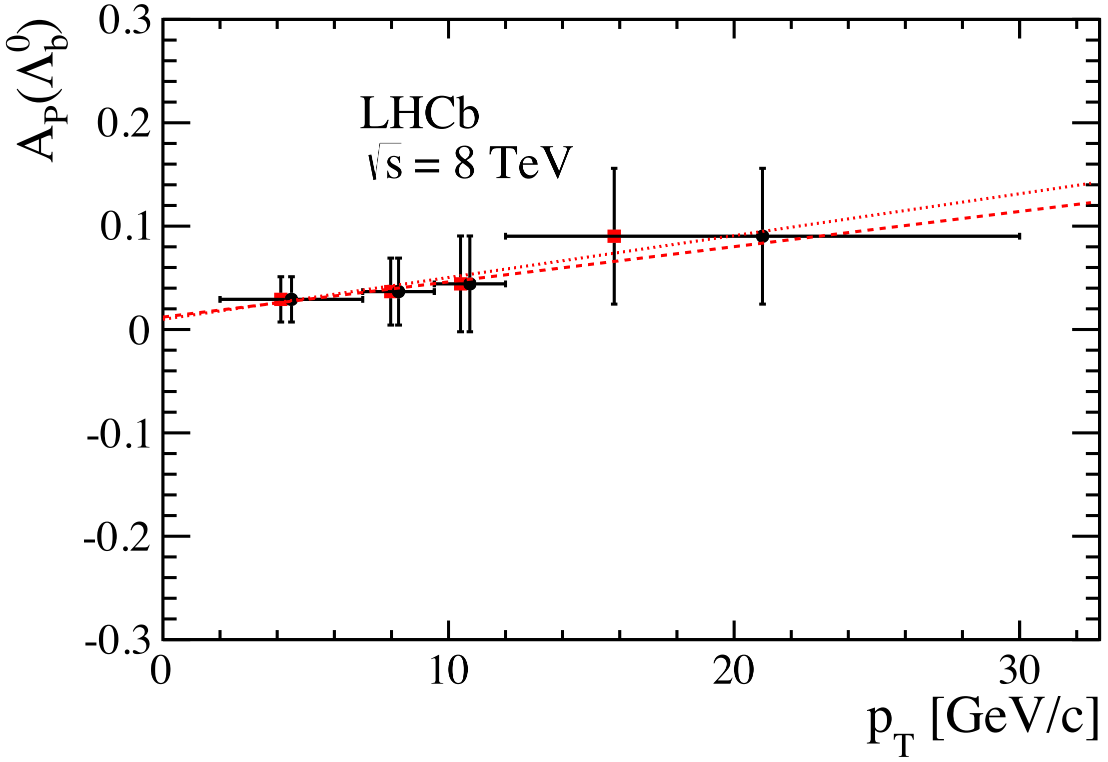
Experimental issue

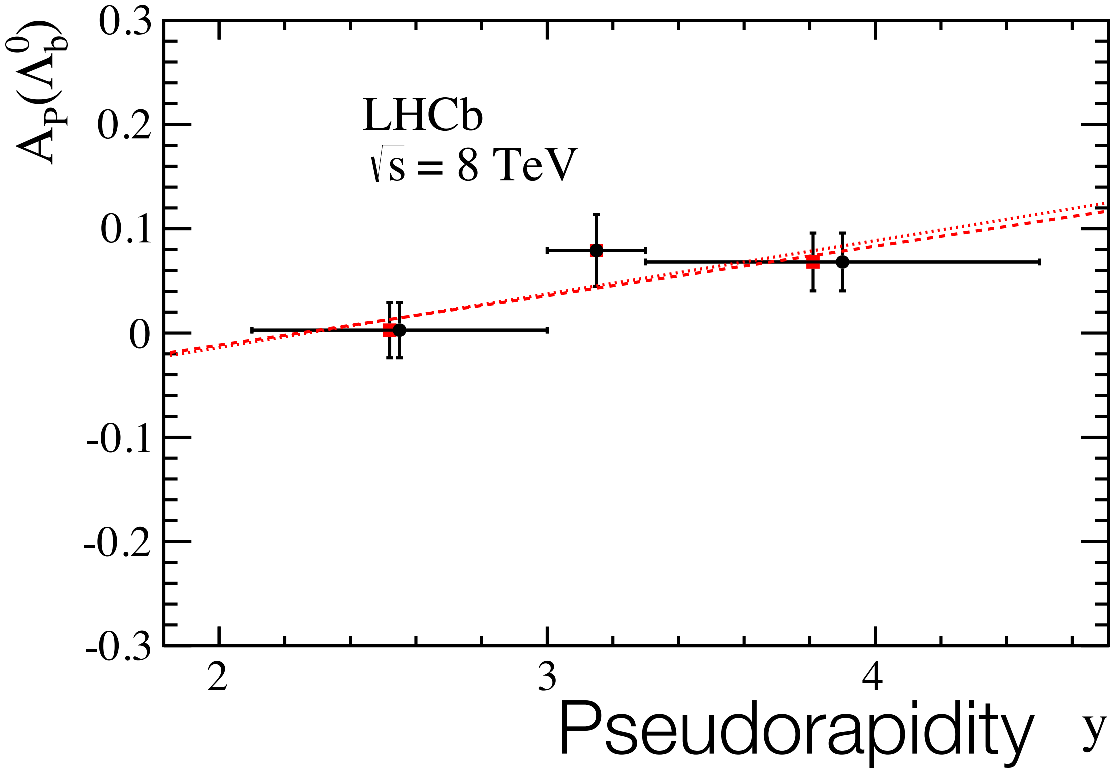
Particle-antiparticle production asymmetries

LHCb: Phys. Lett. B 774 (2017)

- Initial state pp
  - is not CP symmetric
- Initial asymmetry $\approx 1\%$ could mimic CPV

$$A_P = \frac{\sigma(P) - \sigma(\overline{P})}{\sigma(P) + \sigma(\overline{P})}$$





- By means of the unitary relation:

$$A_P(\Lambda_b^0) = -\left[\frac{f_d}{f_{\Lambda_b^0}} A_P(B^0) + \frac{f_u}{f_{\Lambda_b^0}} A_P(B^+) + \frac{f_s}{f_{\Lambda_b^0}} A_P(B_s^0)\right]$$

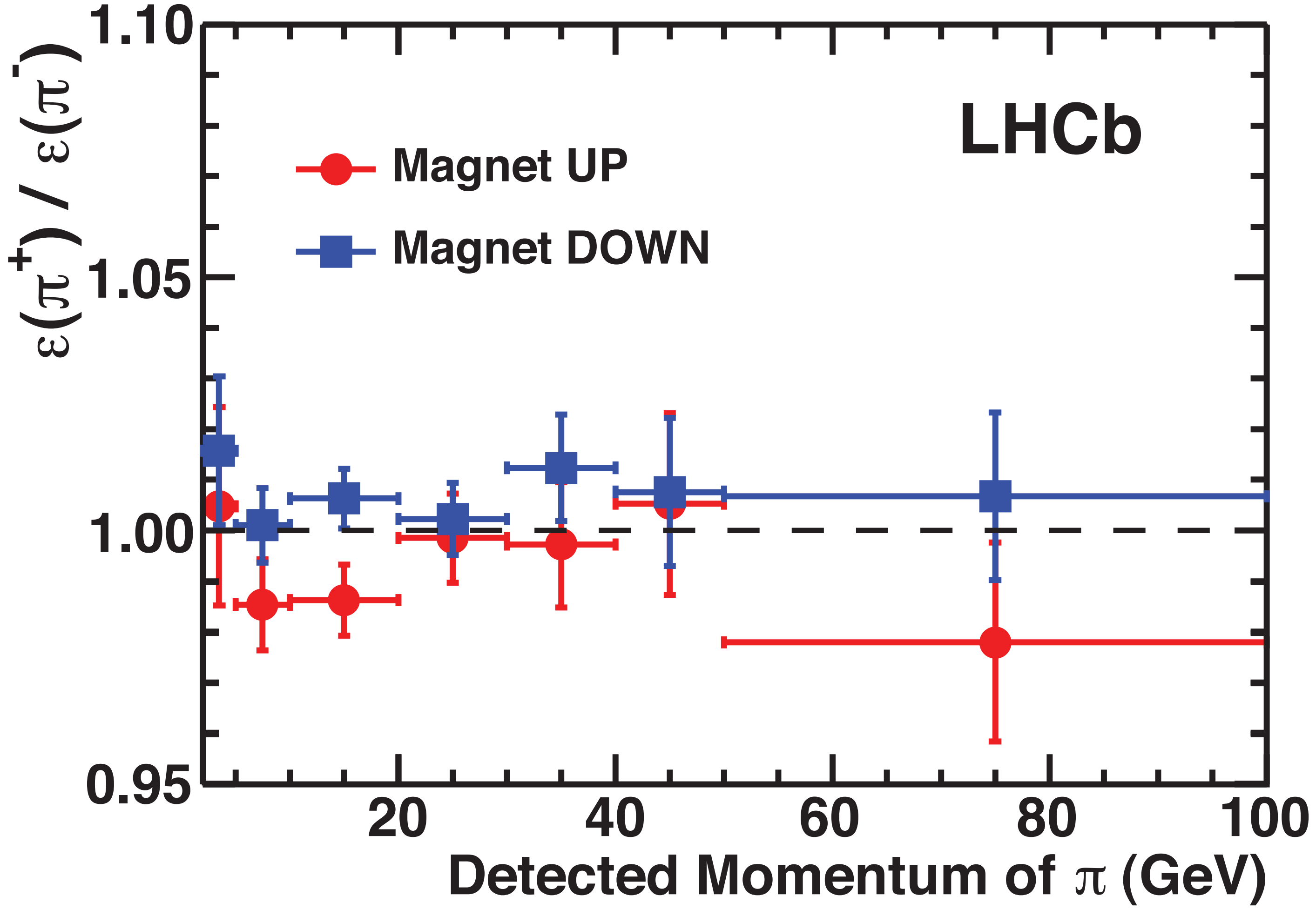
Experimental issue

Detector reconstruction asymmetries

- Detector is made of matter
  - is not CP symmetric

$$A_D(\pi^{\pm}) \approx 0.1\%, A_D(K^{\pm}) \approx 1\%, A_D(p/\overline{p}) \approx 1 - 2\%$$

- A_D can be measured using “ad hoc” abundant control sample



LHCb: Phys. Lett. B 713 (2012)

Experimental approaches

Measure ΔA_{CP} difference of *CP* asymmetries

$$A_{raw}(\Lambda_b^0 \to J/\psi p h^-) = A_{CP}(\Lambda_b^0 \to J/\psi p h^-) + \boxed{A_{prod}(\Lambda_b^0)} - A_{reco}(h^+) + \boxed{A_{reco}(p)}$$

$$\Delta A_{CP} = A_{raw}(\Lambda_b^0 \to J/\psi p\pi^-) - A_{raw}(\Lambda_b^0 \to J/\psi pK^-)$$

$$= A_{CP}(\Lambda_b^0 \to J/\psi p\pi^-) - A_{CP}(\Lambda_b^0 \to J/\psi pK^-) + \boxed{A_{reco}(K^+) - A_{reco}(\pi^+)}$$

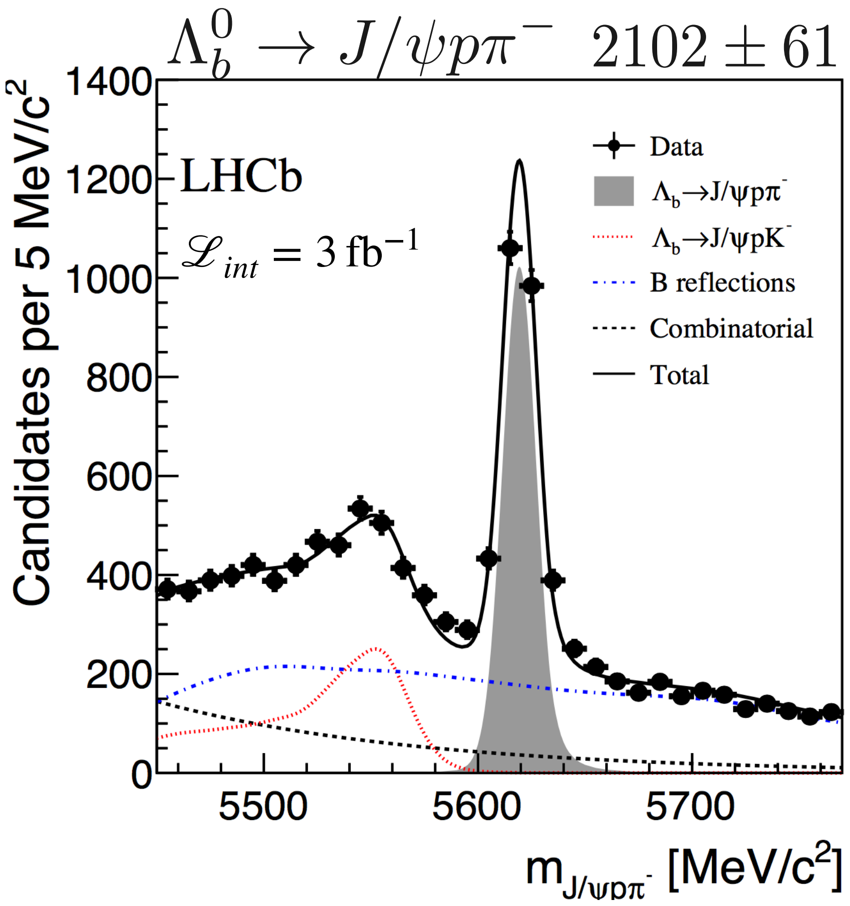
Cancel A_{prod} and $A_{reco}(p)$

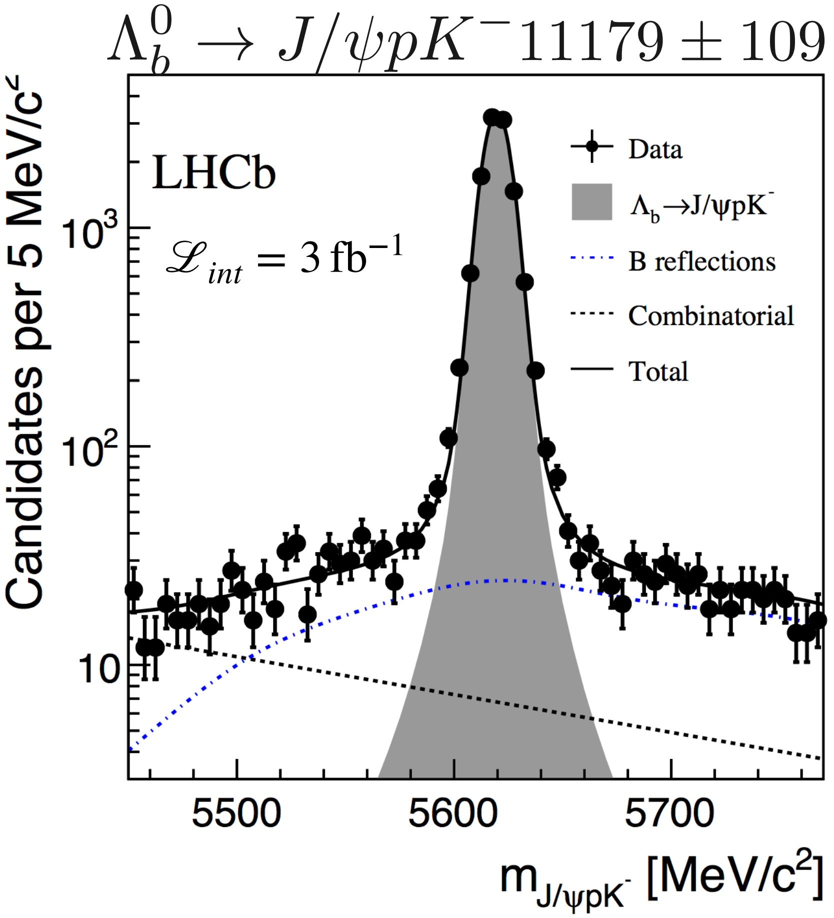
Measured on data

$$\Delta A_{CP} = (5.7 \pm 2.4 \pm 1.2)\,\%$$

2.2σ from zero

LHCb: JHEP 07 (2014) 103





Experimental approaches

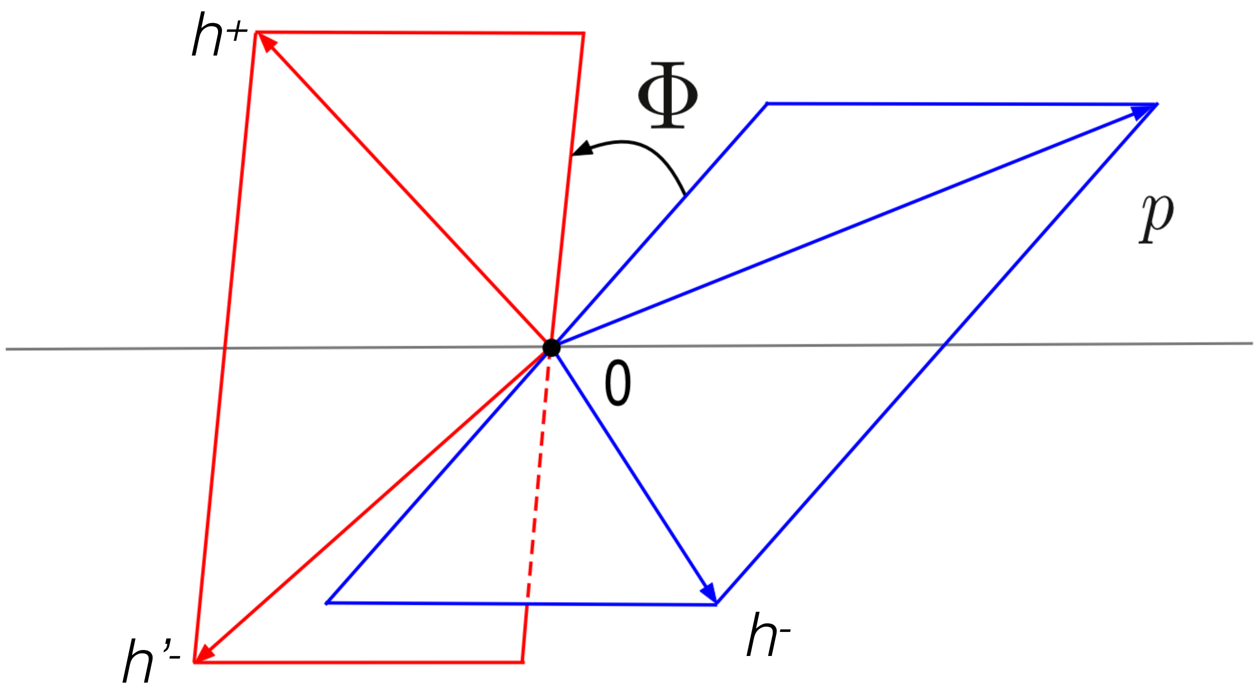
Measure *CPV* via $\hat{T}$-violating aymmetries:

$\hat{T}$ = spin and momentum reversal operator

- Triple products in Λb rest frame

$$C_{\hat{T}} = \vec{p}_p \cdot (\vec{p}_{h^-} \times \vec{p}_{h^+}) \propto \sin\Phi$$

$$\overline{C}_{\hat{T}} = \vec{p}_{\overline{p}} \cdot (\vec{p}_{h^+} \times \vec{p}_{h^-}) \propto \sin\overline{\Phi}$$



- $\hat{T}$(*P*)-odd asymmetries:

$$A_{\hat{T}} = \frac{N_{\Lambda_b^0}(C_{\hat{T}} > 0) - N_{\Lambda_b^0}(C_{\hat{T}} < 0)}{N_{\Lambda_b^0}(C_{\hat{T}} > 0) + N_{\Lambda_b^0}(C_{\hat{T}} < 0)}$$

$$\overline{A}_{\hat{T}} = \frac{N_{\overline{\Lambda}_b^0}(-\overline{C}_{\hat{T}} > 0) - N_{\overline{\Lambda}_b^0}(-\overline{C}_{\hat{T}} < 0)}{N_{\overline{\Lambda}_b^0}(-\overline{C}_{\hat{T}} > 0) + N_{\overline{\Lambda}_b^0}(-\overline{C}_{\hat{T}} < 0)}$$

- *CP*-violating observable:

$$\boxed{a_{CP}^{\hat{T}-\text{odd}} = \frac{1}{2}\left(A_{\hat{T}} - \overline{A}_{\hat{T}}\right)}$$

- *P*-violating observable:

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

Sensitivity to CPV

- By construction, $A_{\widehat{T}}$, $\overline{A}_{\widehat{T}}$, $a_{CP}^{\widehat{T}\text{-odd}}$ and $a_{P}^{\widehat{T}\text{-odd}}$ are insensitive to
  - ✓ particle/antiparticle production asymmetries
  - ✓ detector-induced charge asymmetries
  - $\Longrightarrow$ reduced systematic uncertainties

δ: strong phase

ϕ: weak phase

- Complementary approach to ΔA_{CP} analysis

$$a_{CP}^{\hat{T}\text{–odd}} \propto \cos\left(\delta_{even} - \delta_{odd}\right) \sin\left(\phi_{even} - \phi_{odd}\right)$$

not sensitive if δ_{even}–δ_{odd} = π/2 or 3π/2

$\hat{T}$-*even*

$\hat{T}$-*odd*

amplitudes

$$A_{CP} \propto \sin\left(\delta_1 - \delta_2\right) \sin\left(\phi_1 - \phi_2\right)$$

not sensitive if δ_1–δ_2 = 0 or π

A_1

A_2

amplitudes

- Sensitive to potential new physics effects

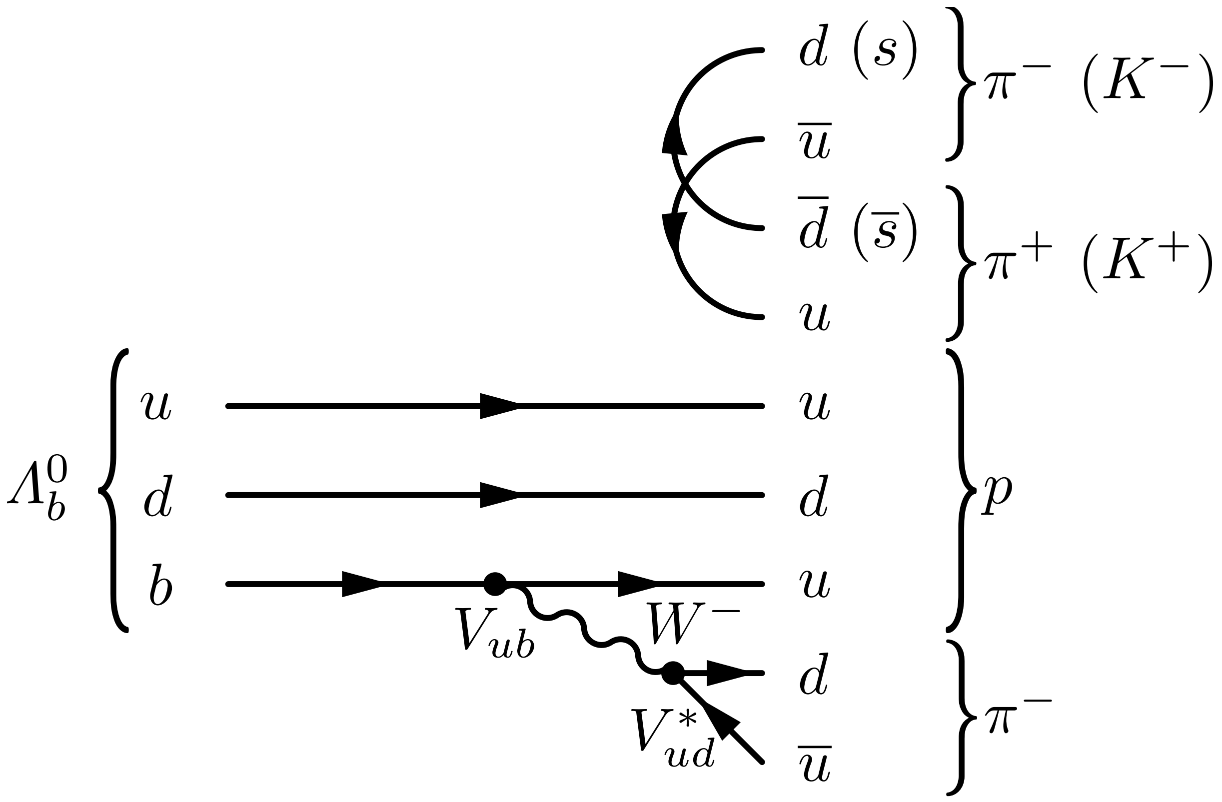
W. Bensalem, A. Datta, and D. London, New physics effects on triple product correlations in Λ_b decays, Phys. Rev. D66 (2002) 094004, arXiv:hep-ph/0208054

Search for CPV in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$

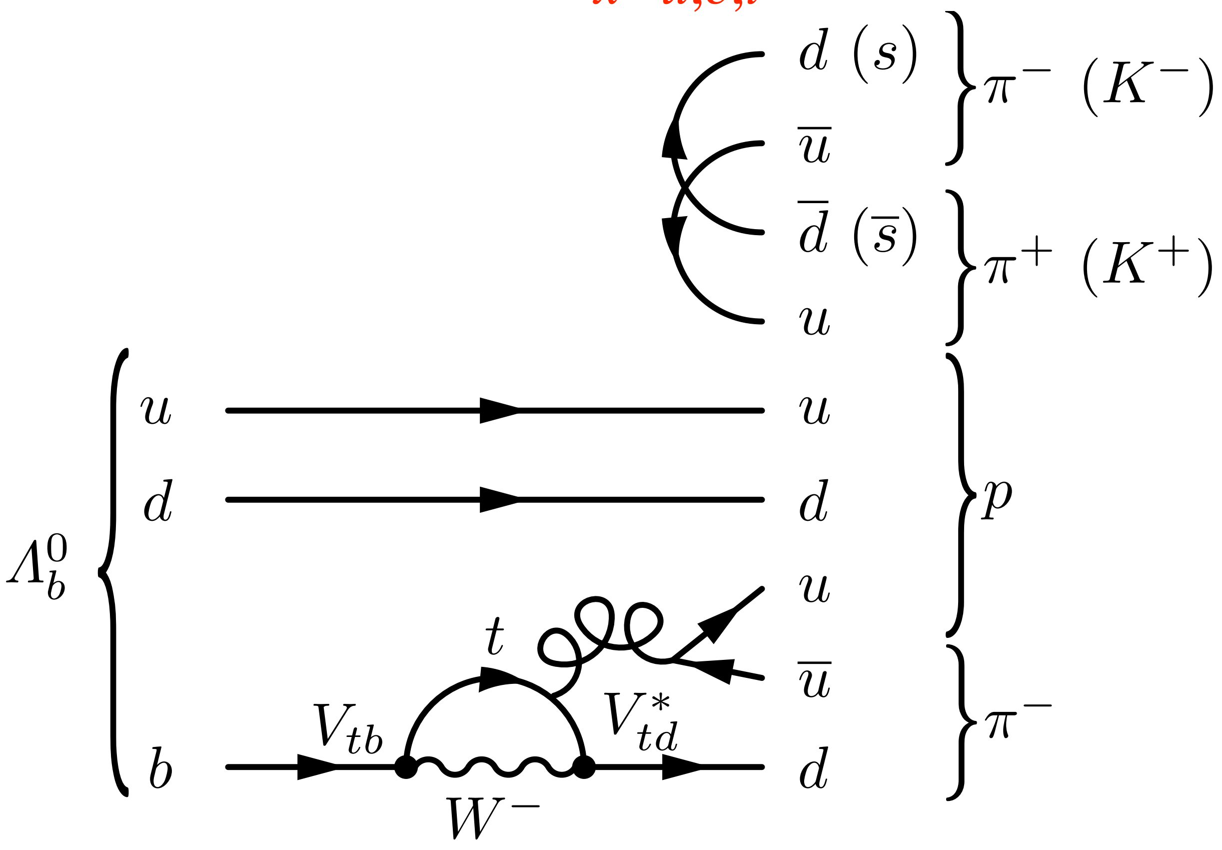
LHCb: Nature Physics 13, 391-396 (2017)

- Transitions governed by $b \to ud\bar{u}$ tree and $b \to du\bar{u}$ penguin amplitudes of similar magnitude
- Large relative weak phase $\alpha/\phi_2 = Arg\left(\frac{V_{tb}^* V_{td}}{V_{ub}^* V_{ud}}\right)$ in SM from the CKM elements
- Potential non negligible CPV effects in the SM

Tree $\propto V_{ub}^* V_{ud} \sim \lambda^3$



Penguin $\propto \sum_{x=u,c,t} V_{xb}^* V_{xd} \sim \lambda^3$

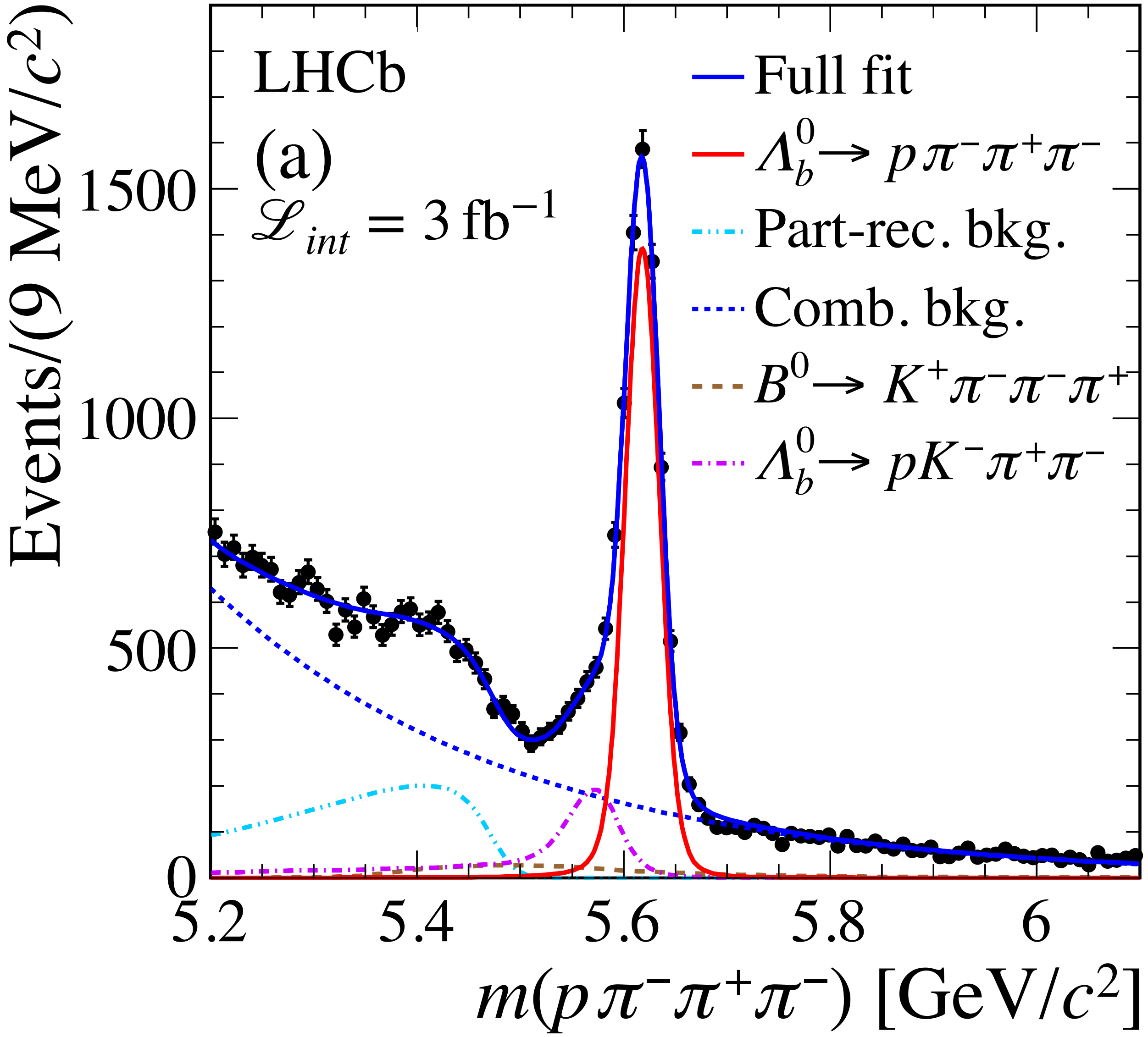


Search for CPV in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$

LHCb: Nature Physics 13, 391-396 (2017)

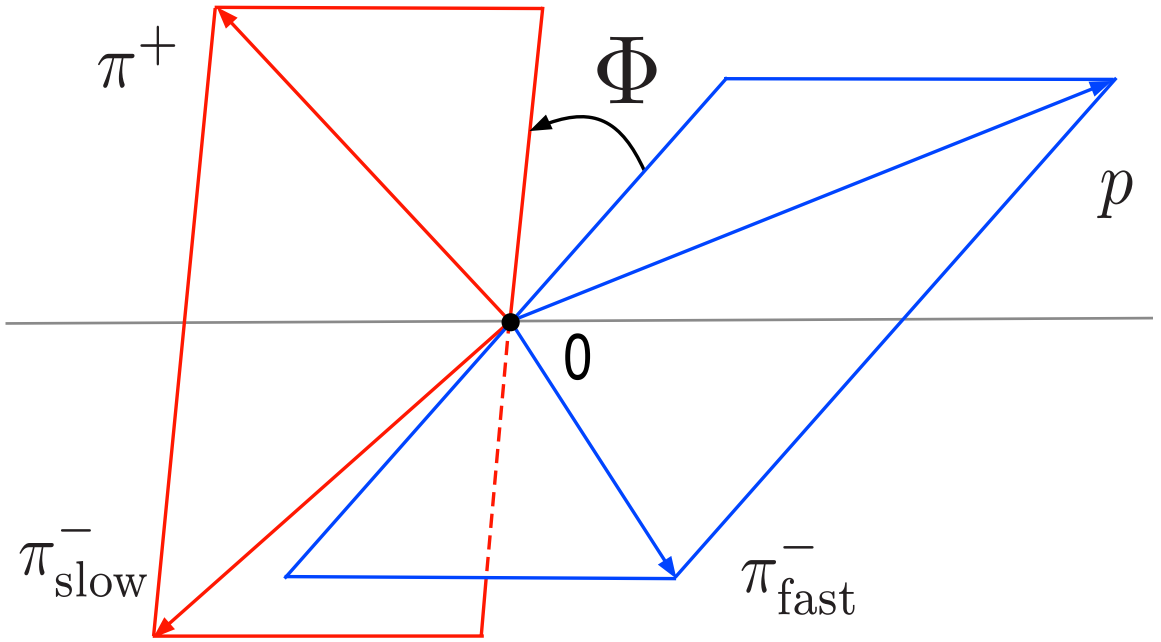
- Use 4-body topology to build P-violating asymmetries

$N_{sig}(\Lambda_b^0 \to p\pi^-\pi^+\pi^-) = 6646 \pm 105$



- *P*-odd, $\hat{T}$-odd triple products:

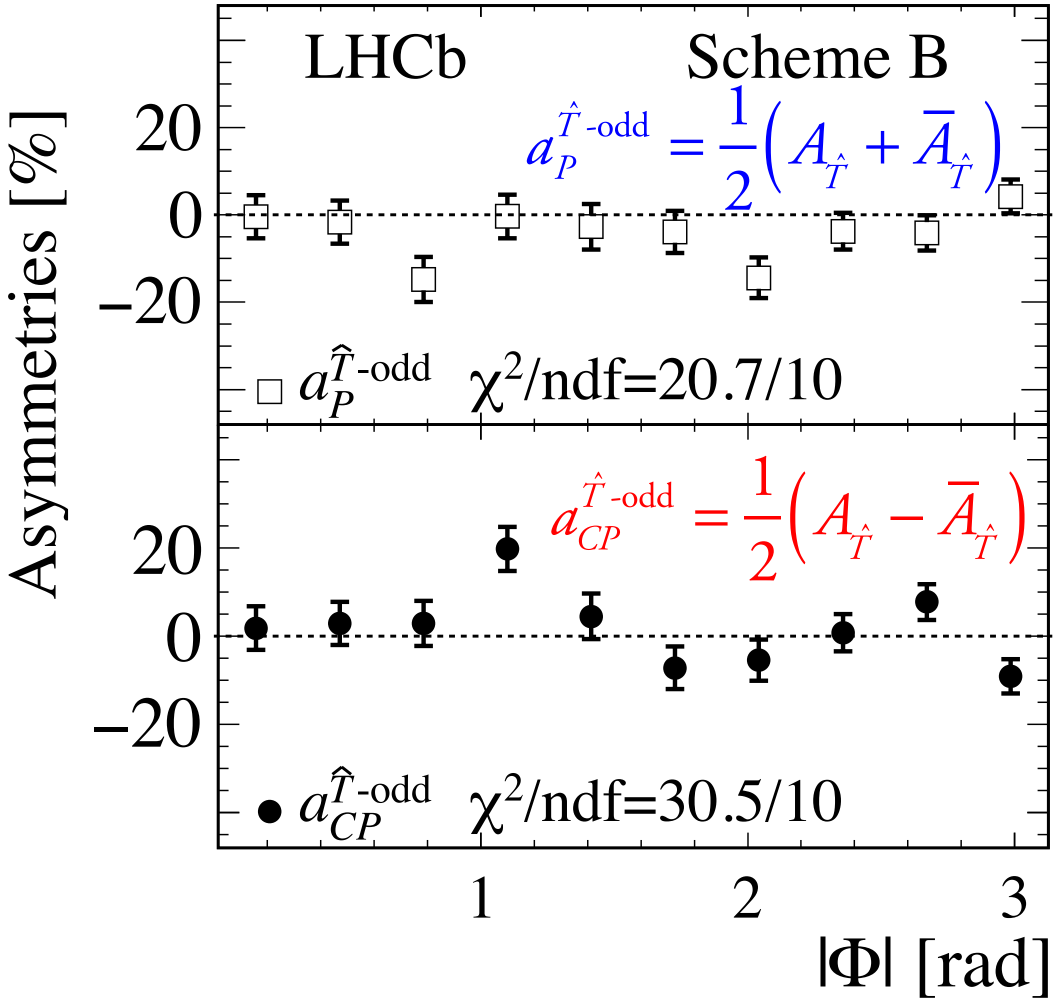
$$C_{\hat{T}} = \vec{p}_p \cdot \left(\vec{p}_{\pi^-_{fast}} \times \vec{p}_{\pi^+}\right) \propto \sin\Phi, \text{ for } \Lambda_b^0$$
$$\overline{C}_{\hat{T}} = \vec{p}_{\overline{p}} \cdot \left(\vec{p}_{\pi^+_{fast}} \times \vec{p}_{\pi^-}\right) \propto \sin\overline{\Phi}, \text{ for } \overline{\Lambda}_b^0$$



First evidence of CPV in baryons

LHCb: Nature Physics 13, 391-396 (2017)

Scheme B: on **Φ** angle intervals



Refer to backup slides for bins definition

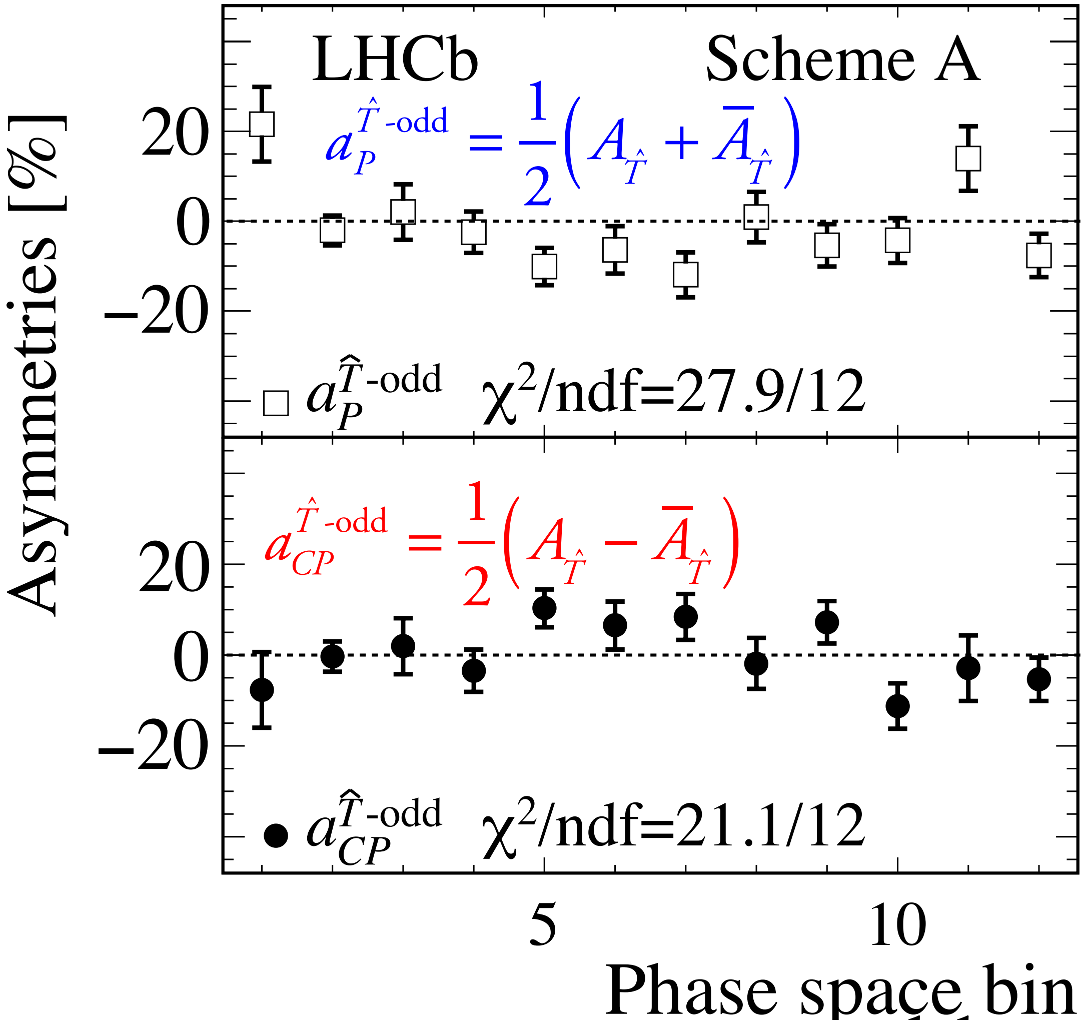
$\mathscr{L}_{int} = 3\ \text{fb}^{-1}$

CP symmetry p-value = 9.8x10^{-4}

3.3 σ deviation

P symmetry compatible at 2.2 σ

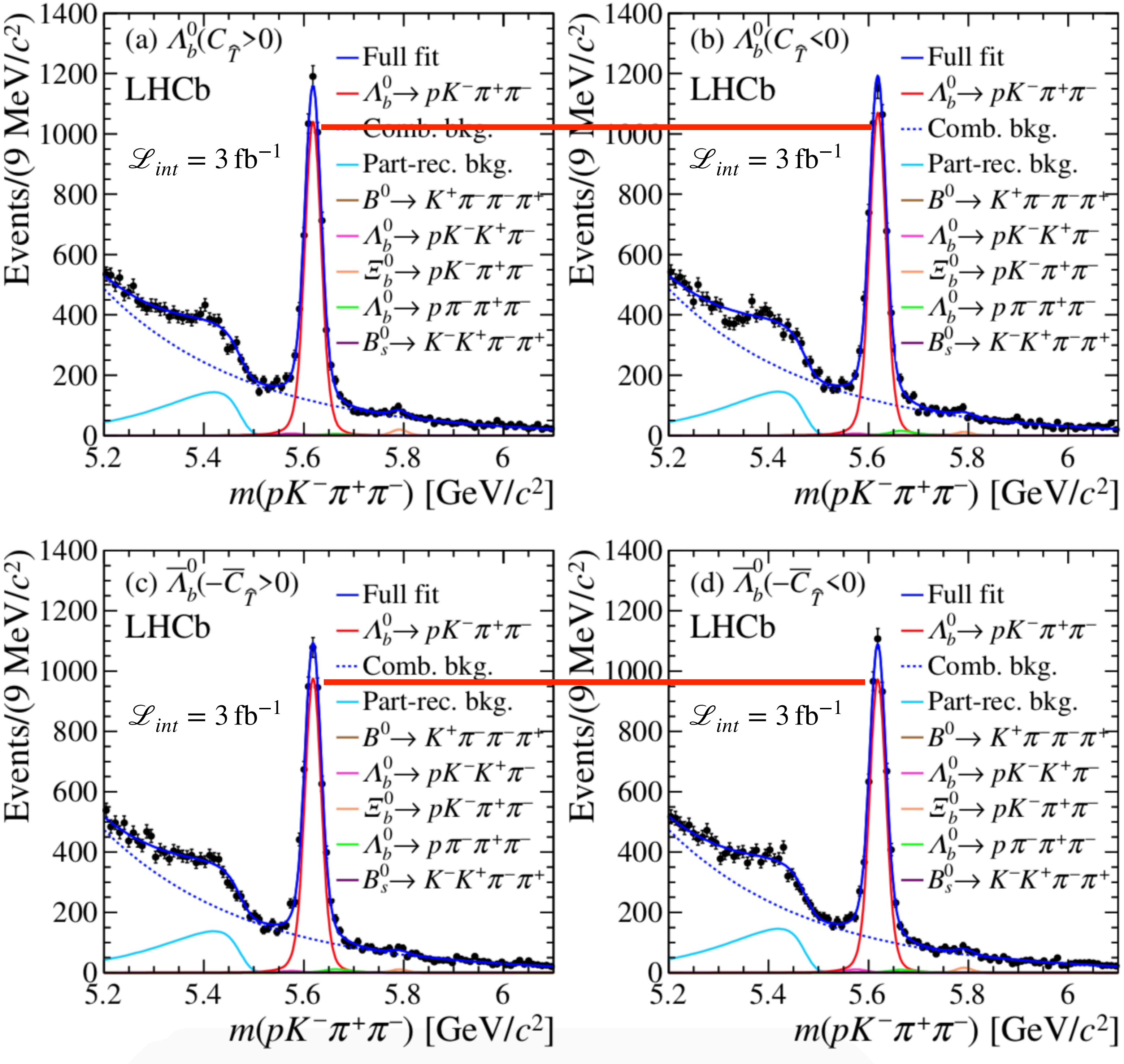
Scheme A: on dominant resonances



- Integrated results compatible with *CP* & *P* conservation
- Largely insensitive to A_P & A_D
- Low systematic uncertainties <1%
- Already triggered some theorists

$\Lambda_b^0 \rightarrow pK^-\pi^+\pi^-$ integrated asymmetries

LHCb: JHEP08(2018)039



$a_P^{\hat{T}-odd}$ =(-0.60±0.84±0.31)%

$a_{CP}^{\hat{T}-odd}$ =(-0.81±0.84±0.31)%

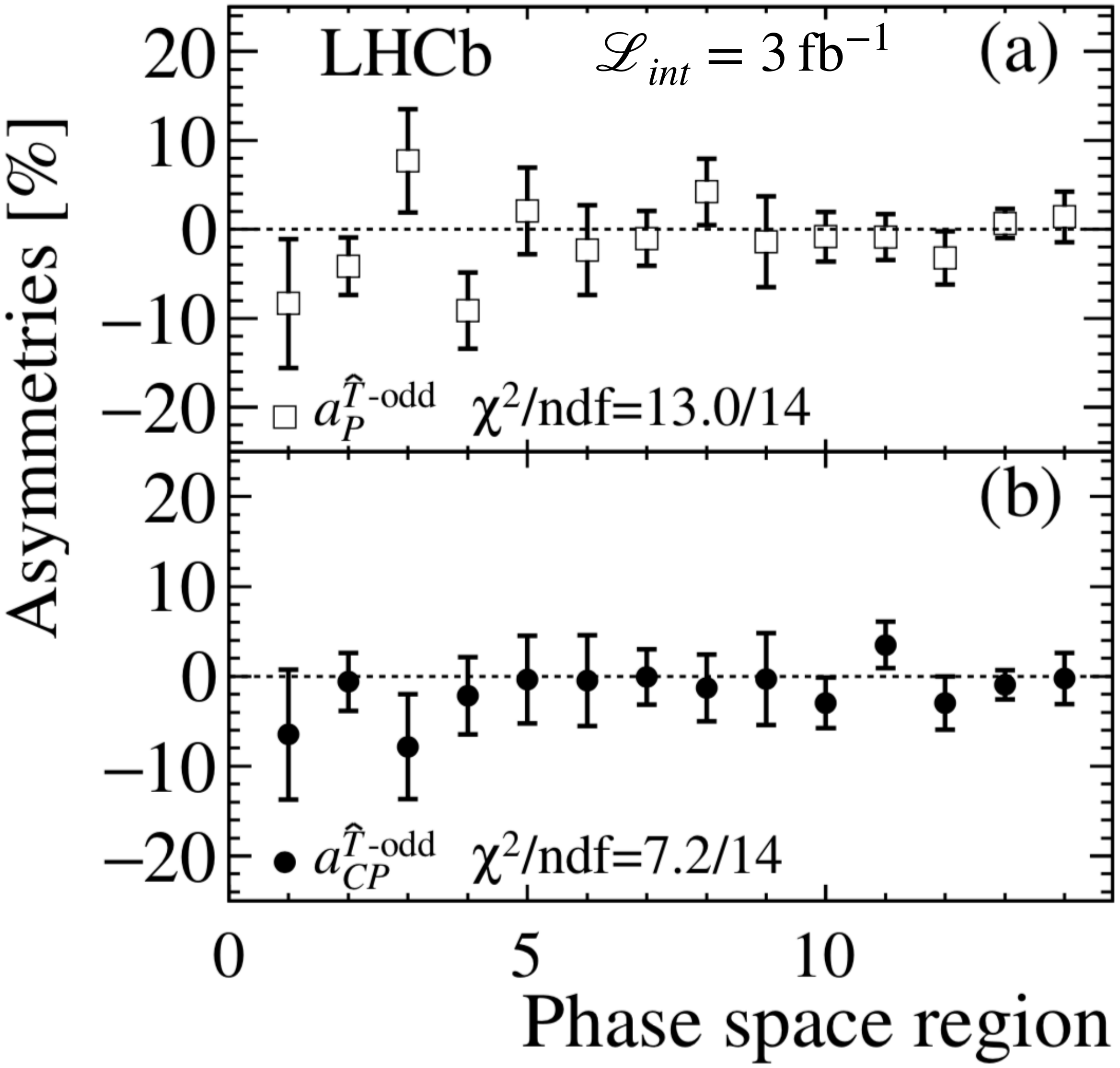
N_{sig}=19877±195

- Phase space integrated result consistent with P and CP symmetry

$\Lambda_b^0 \to pK^-\pi^+\pi^-$ phase space measurements

LHCb: JHEP08(2018)039

Scheme A: on dominant resonances



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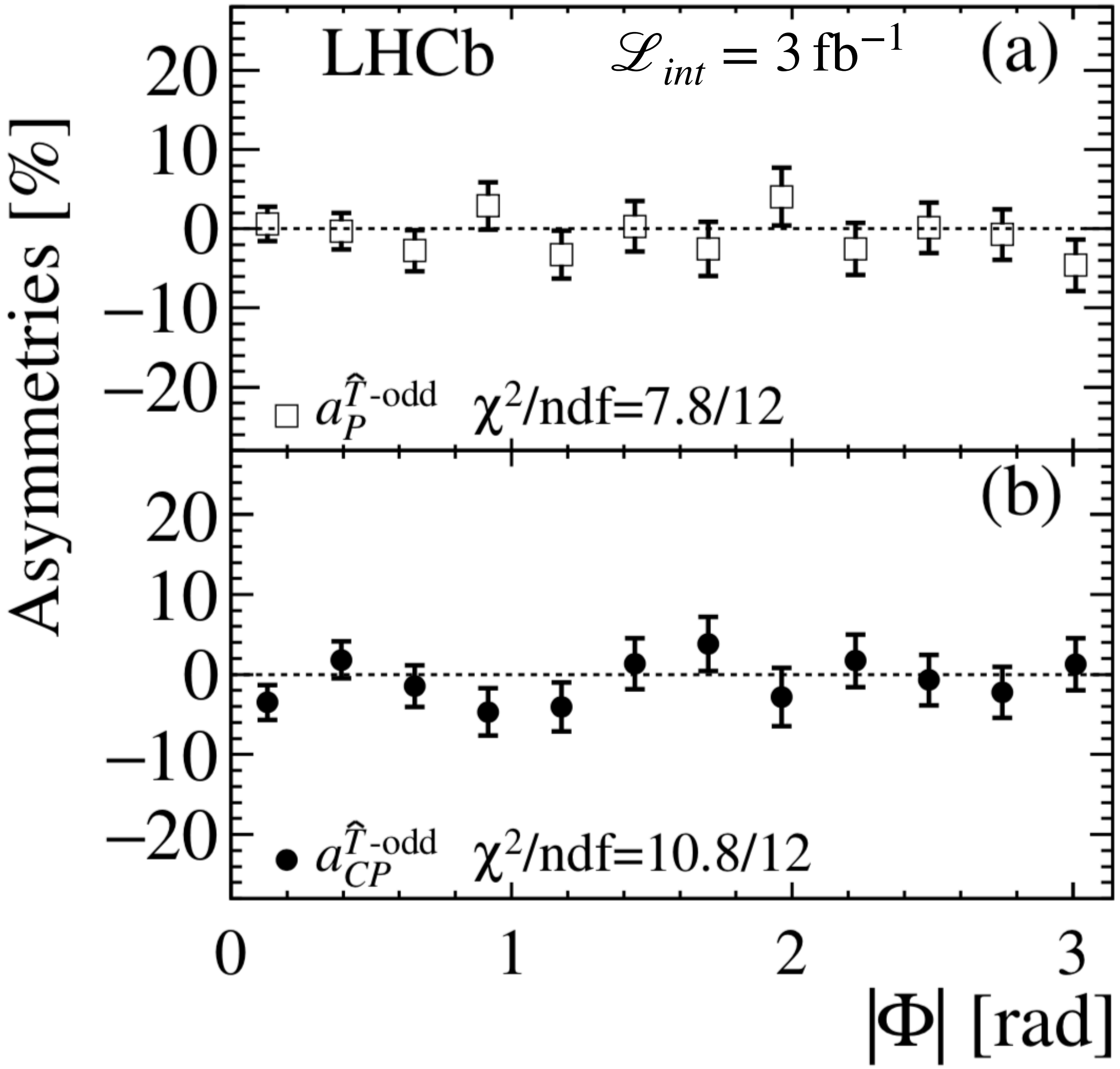
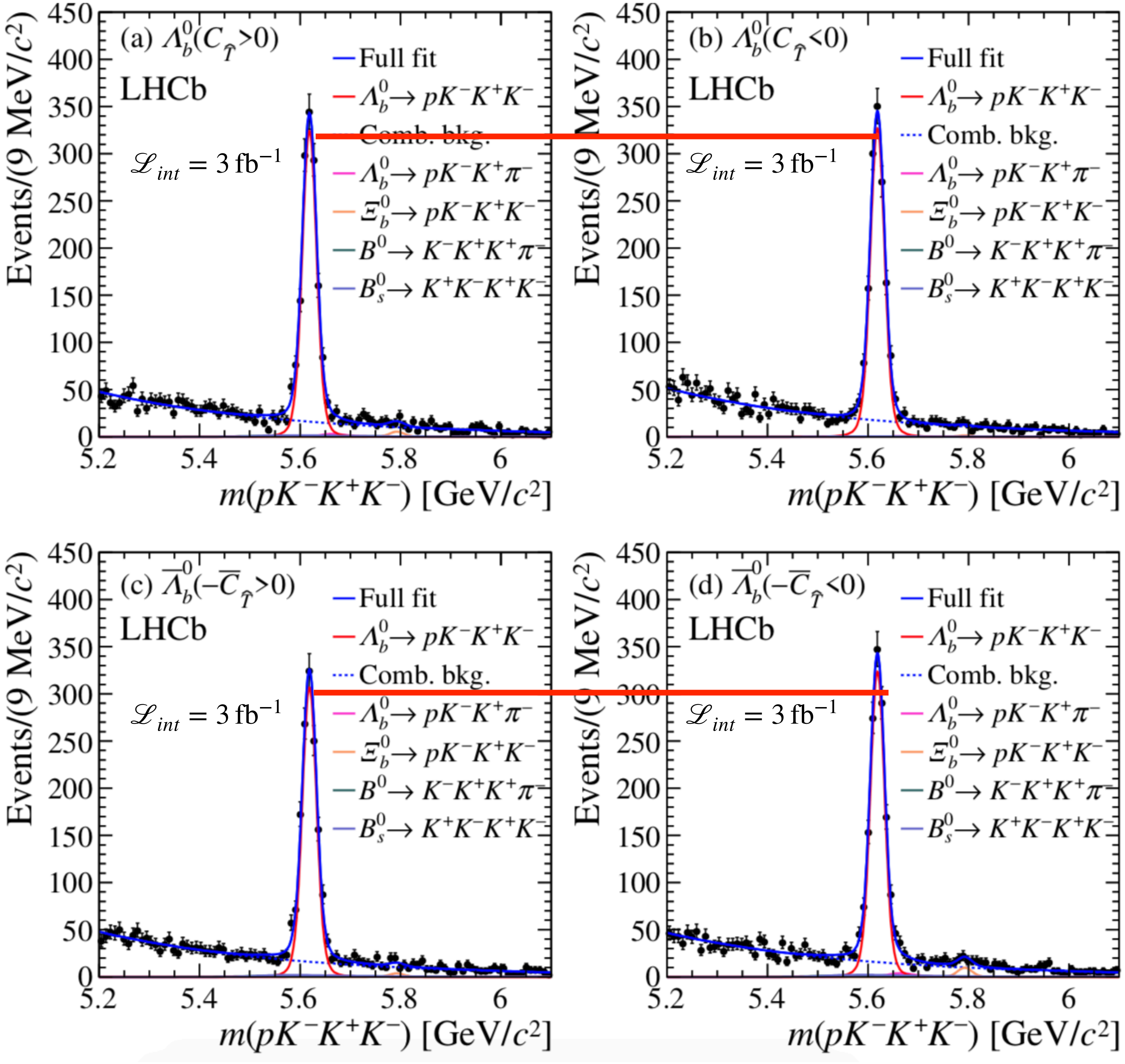
Scheme B: on **Φ** angle intervals



χ^2 test: consistent with P and CP symmetry

$\Lambda_b^0 \to pK^-K^+K^-$ integrated asymmetries

LHCb: JHEP08(2018)039



$a_P^{\hat{T}-odd}$=(-1.56±1.51±0.32)%

$a_{CP}^{\hat{T}-odd}$=(1.12±1.51±0.32)%

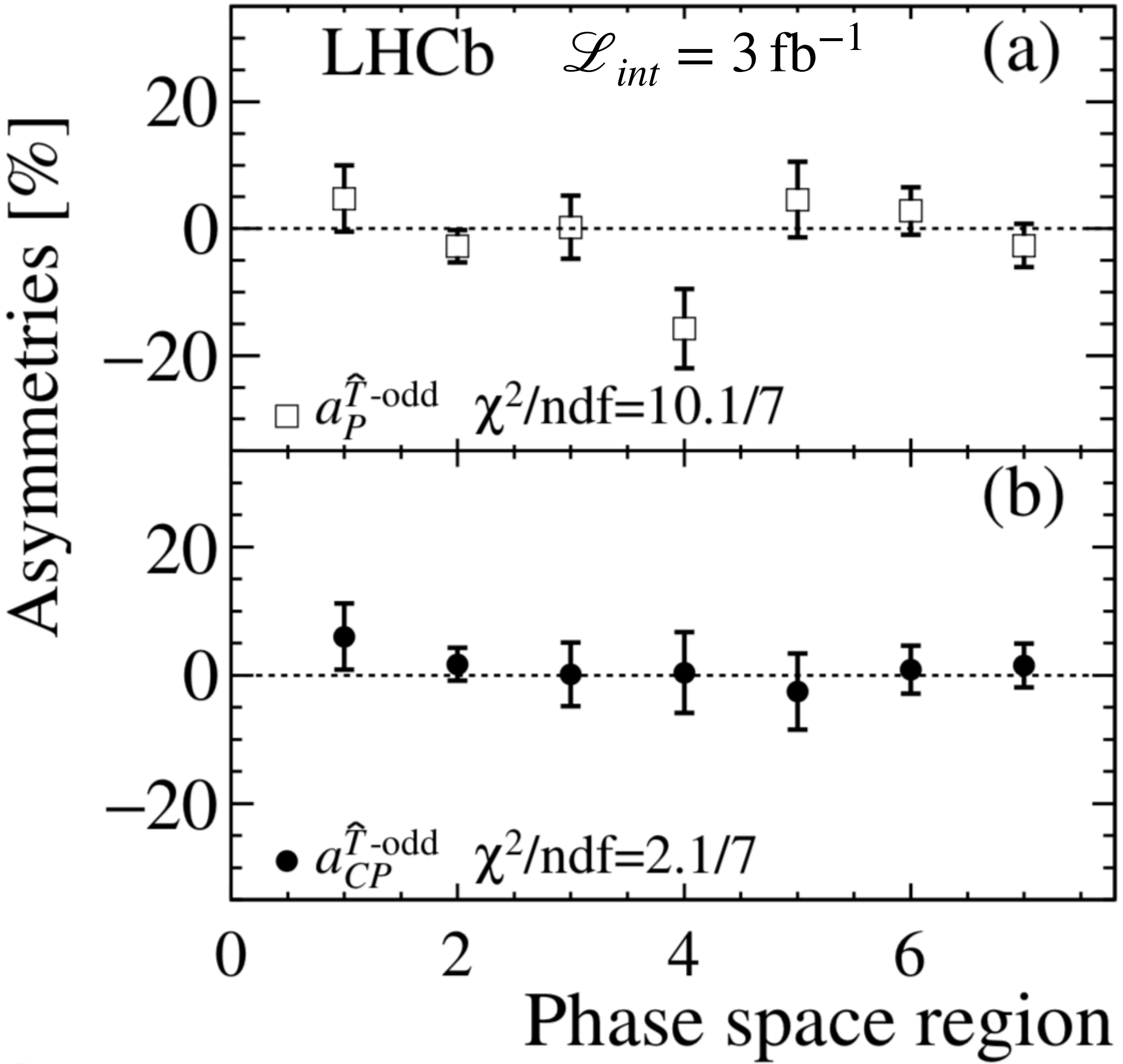
N_{sig}=5297±83

- Phase space integrated result consistent with P and CP symmetry

$\Lambda_b^0 \to pK^-K^+K^-$ phase space measurements

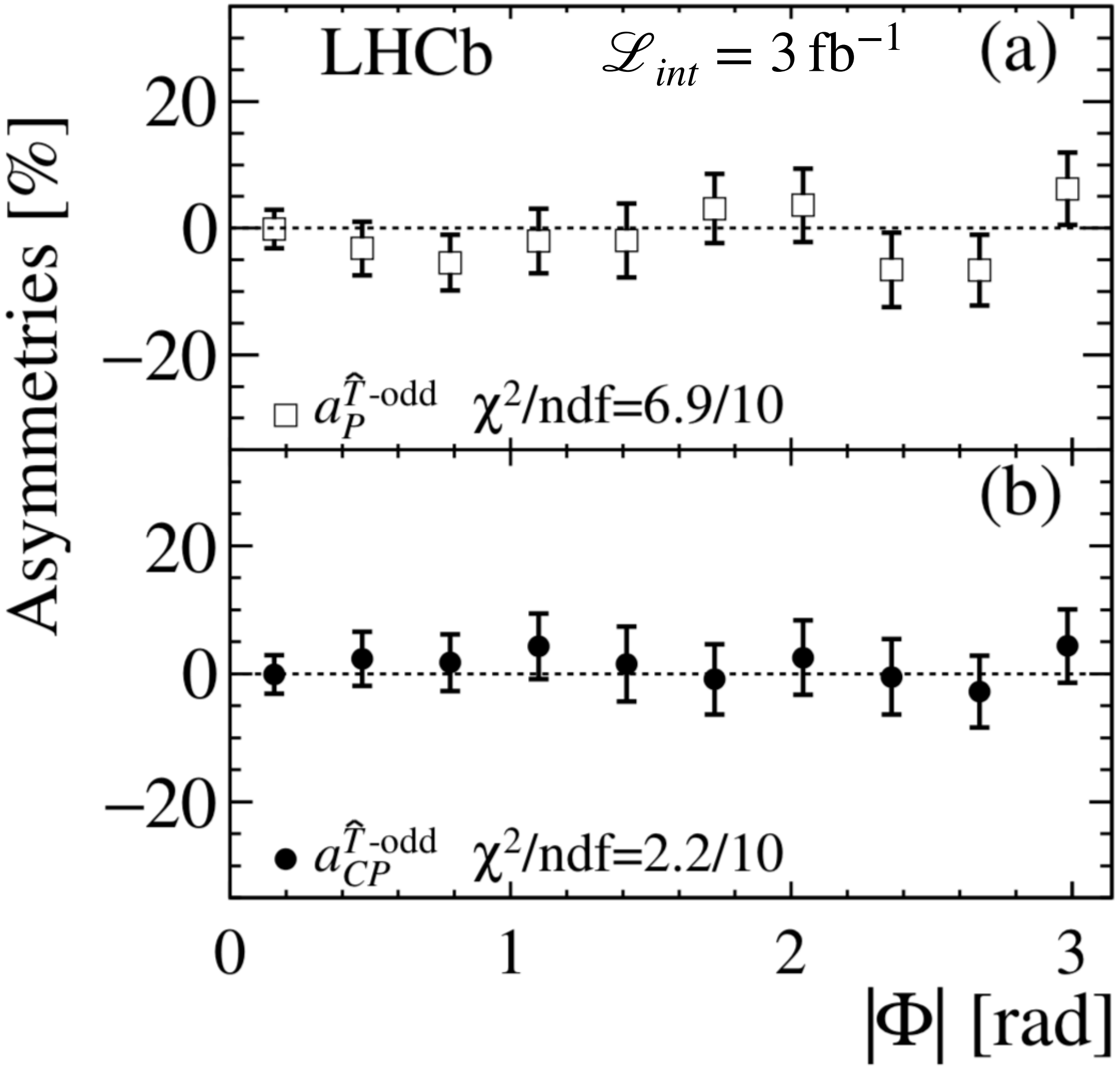
LHCb: JHEP08(2018)039

Scheme C: on dominant resonances



Refer to backup slides for bins definition

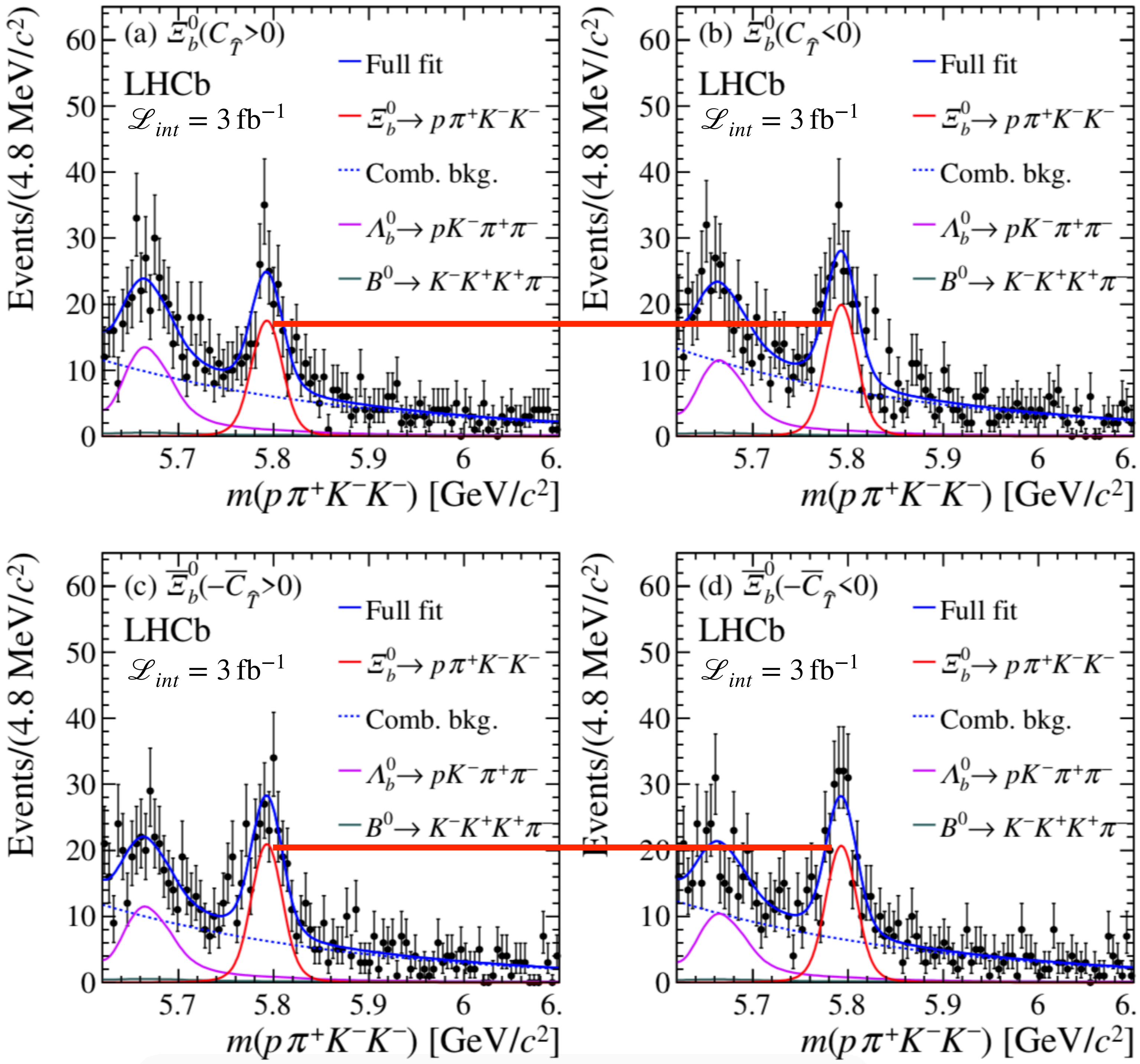
Scheme D: on $\mathbf{\Phi}$ angle intervals



χ^2 test: consistent with P and CP symmetry

$\Xi_b^0 \to p\pi^+K^-K^-$ integrated asymmetries

LHCb: JHEP08(2018)039



$a_P^{\hat{T}-odd}$ =(-3.04±5.19±0.36)%

$a_{CP}^{\hat{T}-odd}$ =(-3.58±5.19±0.36)%

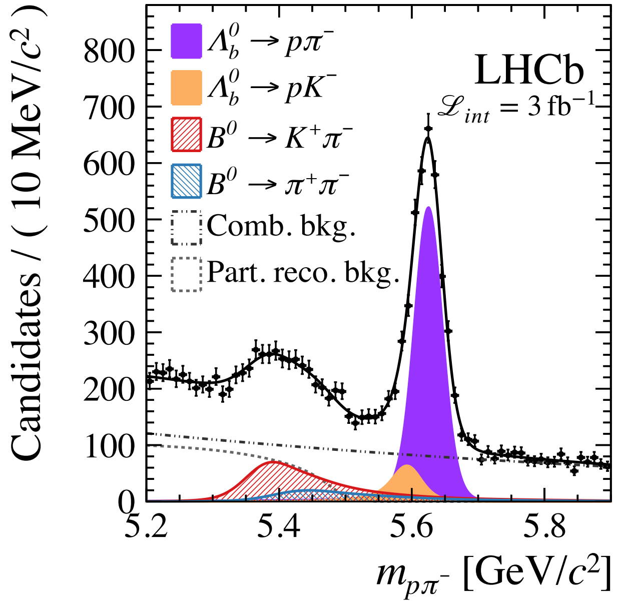
N_{sig}=709±45

- Phase space integrated result consistent with P and CP symmetry

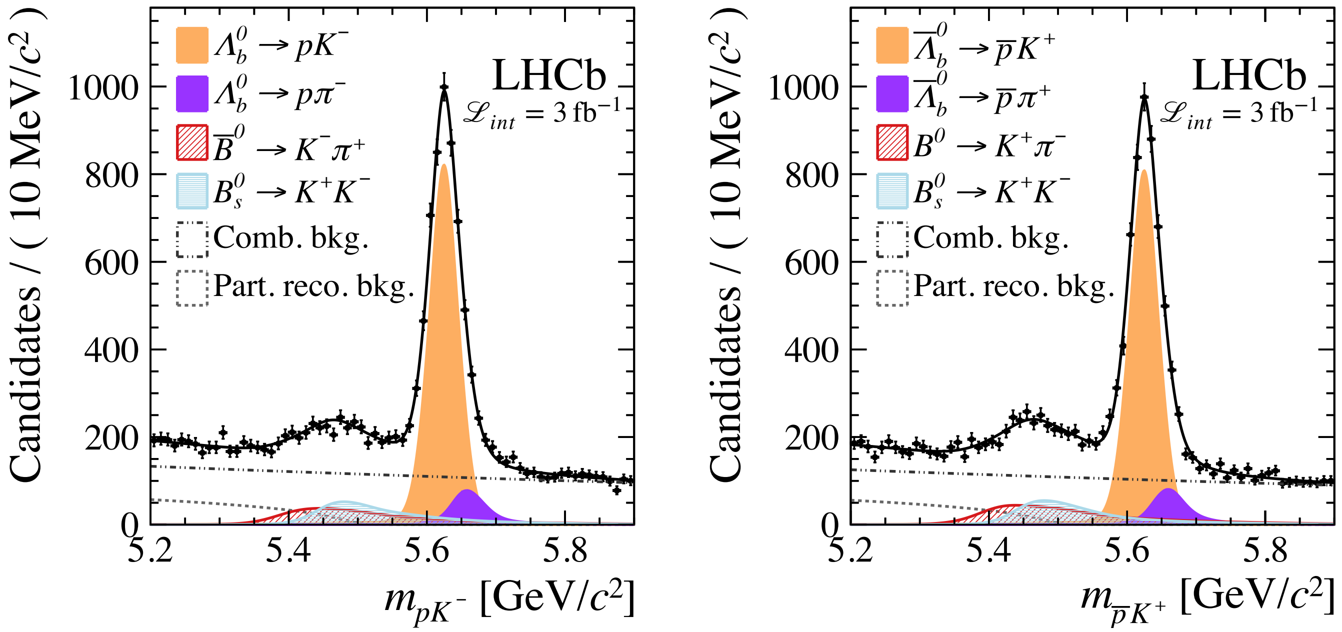
Search for CPV in $\Lambda_b^0 \to p\pi^-$ and $\Lambda_b^0 \to pK^-$

LHCb: Phys. Lett. B 787 (2018) 124-133

$\Lambda_b^0 \to pK^-$ 8800 signal events



$\Lambda_b^0 \to p\pi^-$ 6000 signal events



$$A_{CP}^{ph^-} = \boxed{A_{raw}^{ph^-}} - \boxed{A_D^p} - \boxed{A_D^{h^-} - A_{PID}^{ph^-}} - \boxed{A_P^{\Lambda_b^0}} - \boxed{A_{trigger}^{ph^-}}$$

Measured on data

From simulation

Estimated from control samples

External input

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

$$A_{CP}^{pK^-} = -0.020 \pm 0.013 \pm 0.019$$

$$\Delta A_{CP} = A_{CP}^{pK^-} - A_{CP}^{p\pi^-} = 0.014 \pm 0.022 \pm 0.013$$

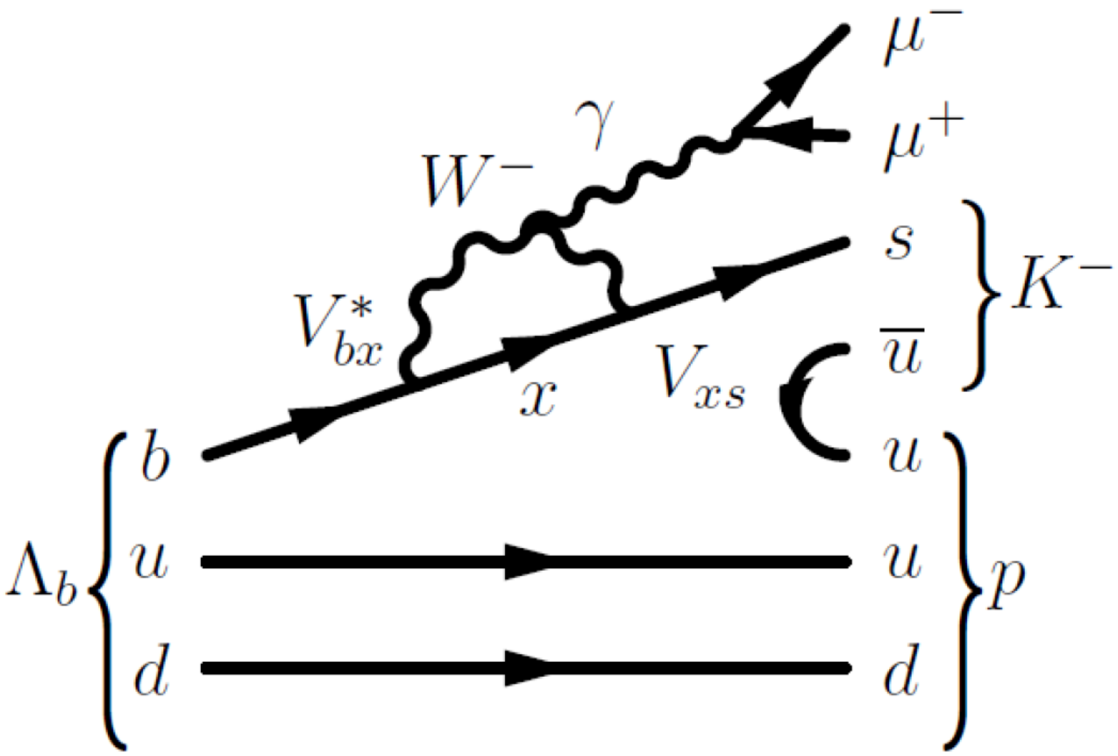
% level of precision

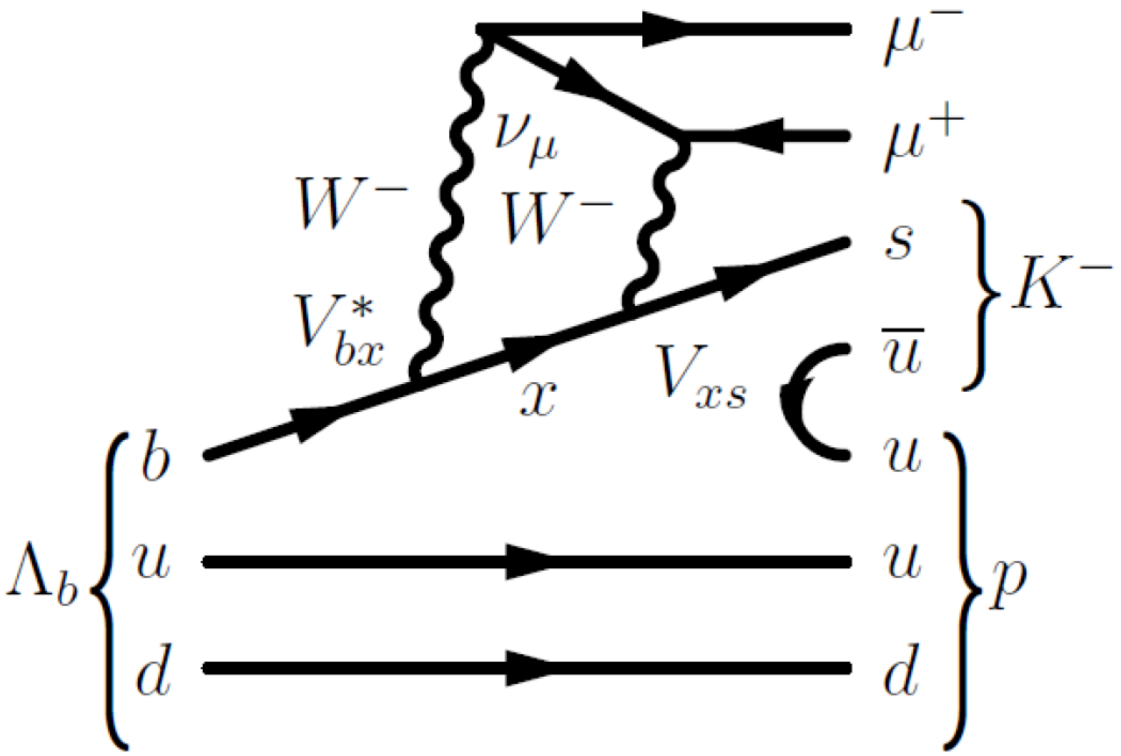
No sign of CPV

Search for CPV in $\Lambda_b^0 \to pK^-\mu^+\mu^-$

LHCb: JHEP 06(2017)108

- Rare transitions sensitive to new physics, with new particles contributing to loop diagrams or via new tree-level amplitudes
- Limited CPV in the SM~10^{-2} (simple estimate from CKM)
- Very high muon identification efficiency -> excellent bkg rejection
- Possibility to compare baryon and meson ($B^0 \to K^*\mu^+\mu^-$) decays



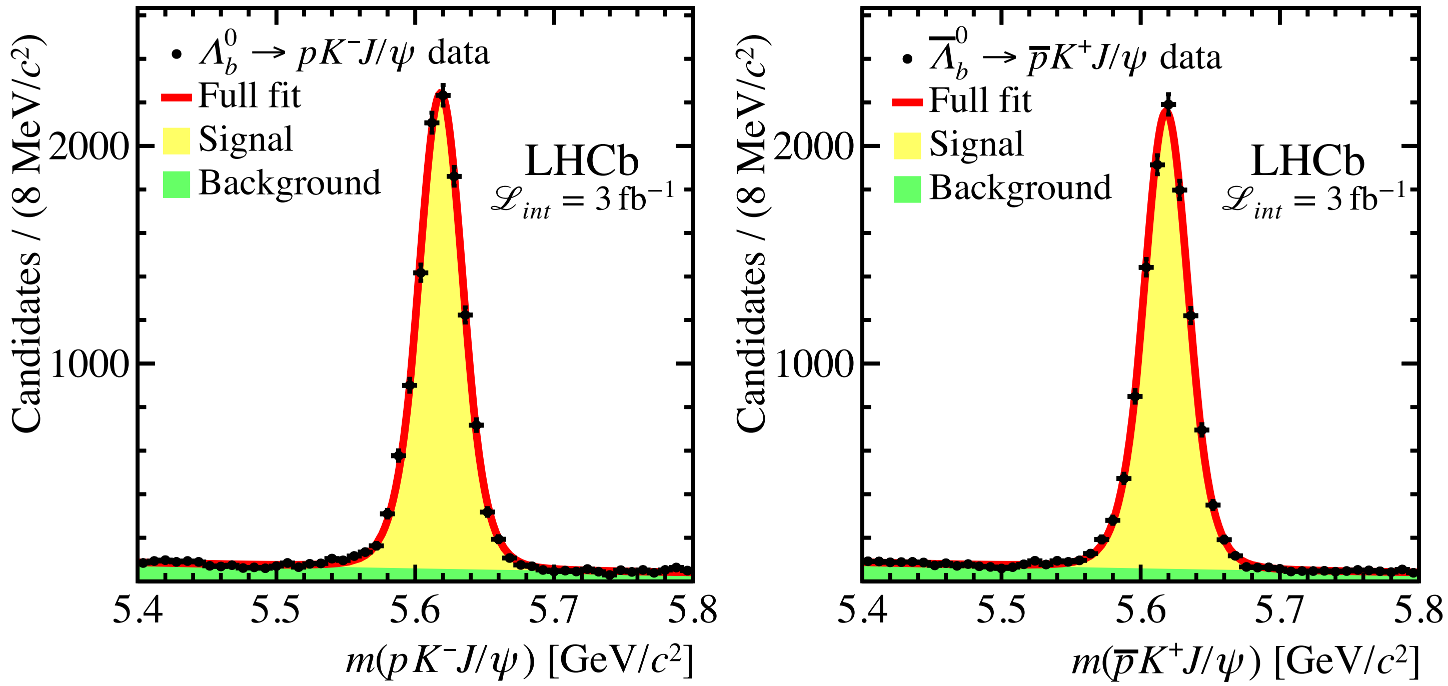


Search for CPV in $\Lambda_b^0 \to pK^-\mu^+\mu^-$

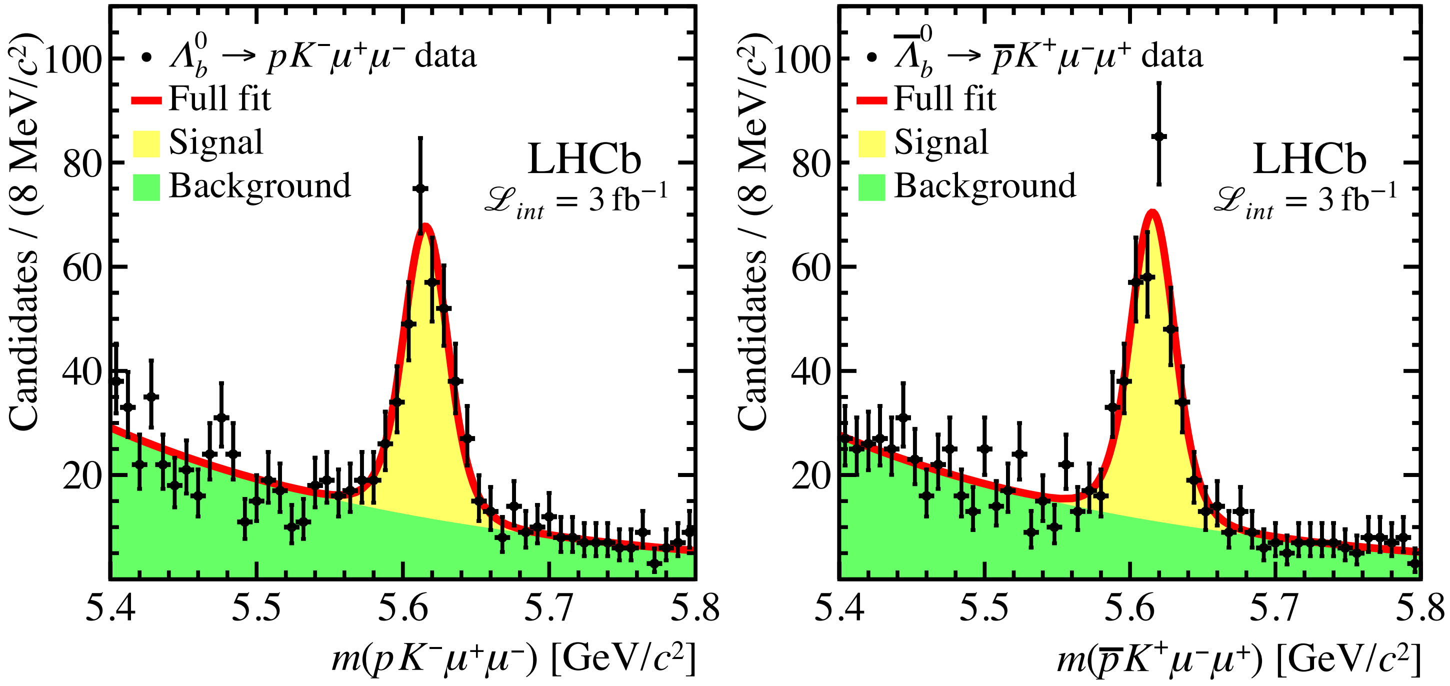
- Use the abundant $\Lambda_b^0 \to J/\psi pK^-$ control mode

LHCb: JHEP 06(2017)108

$$N_{sig}\left(\Lambda_b^0 \to J/\psi pK^-\right) = 22900 \pm 290$$



$$N_{sig}\left(\Lambda_b^0 \to pK^-\mu^+\mu^-\right) = 600 \pm 44$$



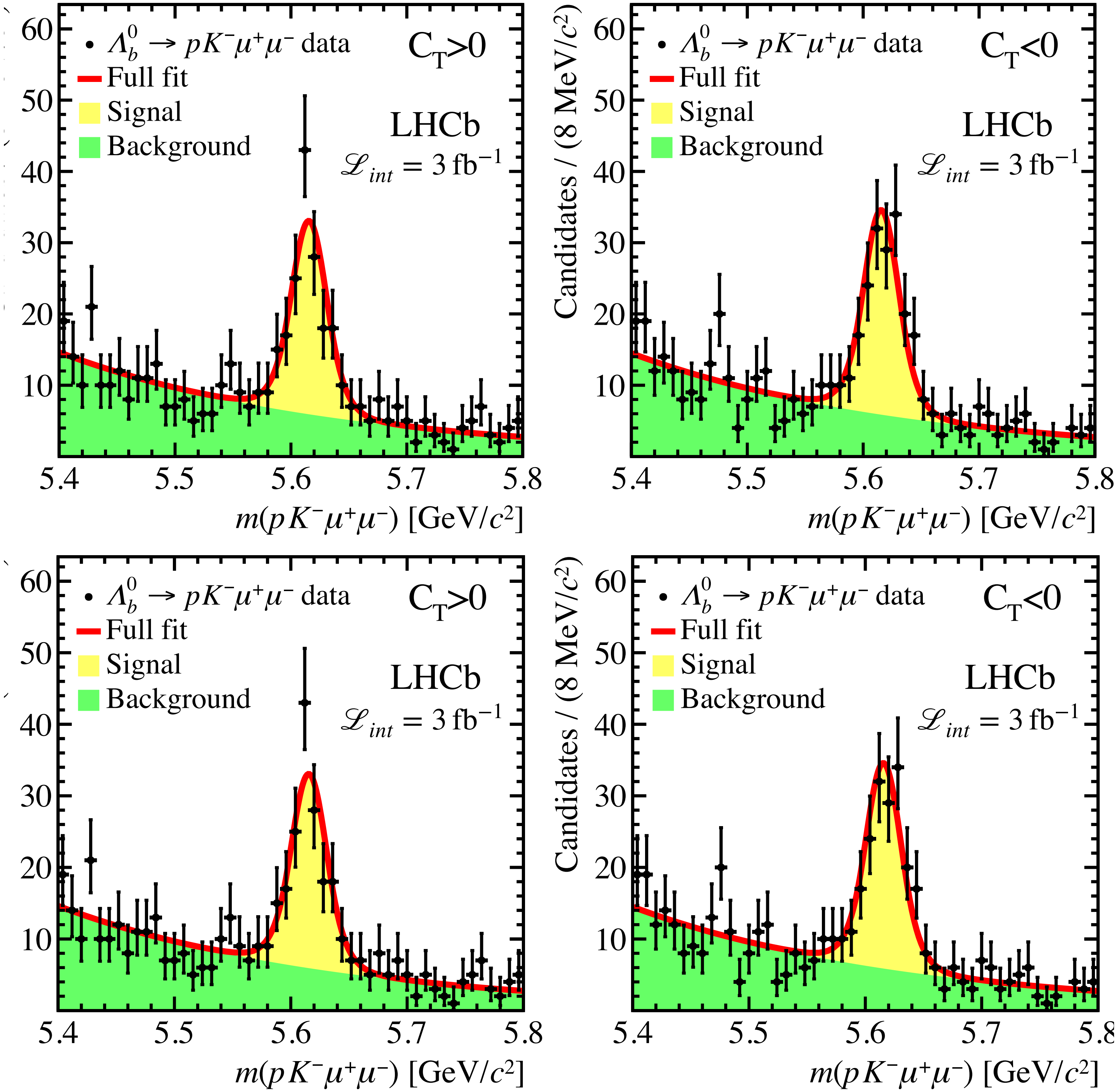
$$\boxed{\Delta A_{CP} = (-4.8 \pm 5.0 \pm 0.3)\,\%}$$

- Consistent with CP symmetry
- Difference in kinematics added as systematic error

Search for CPV in $\Lambda_b^0 \to pK^-\mu^+\mu^-$

- Use the abundant $\Lambda_b^0 \to J/\psi pK^-$ control mode

LHCb: JHEP 06(2017)108



$$\boxed{\begin{aligned} a_{CP}^{\hat{T}-\text{odd}} &= (0.6 \pm 5.0 \pm 0.7)\,\% \\ a_{P}^{\hat{T}-\text{odd}} &= (-3.4 \pm 5.0 \pm 0.7)\,\% \end{aligned}}$$

- Consistent with P and CP symmetry
- Main systematic uncertainty due to selection and detector acceptance:
  - Estimated on control sample

$$a_{CP}^{\hat{T}-\text{odd}}\left(\Lambda_b^0 \to J/\psi pK^-\right) = (0.48 \pm 0.70)\,\%$$

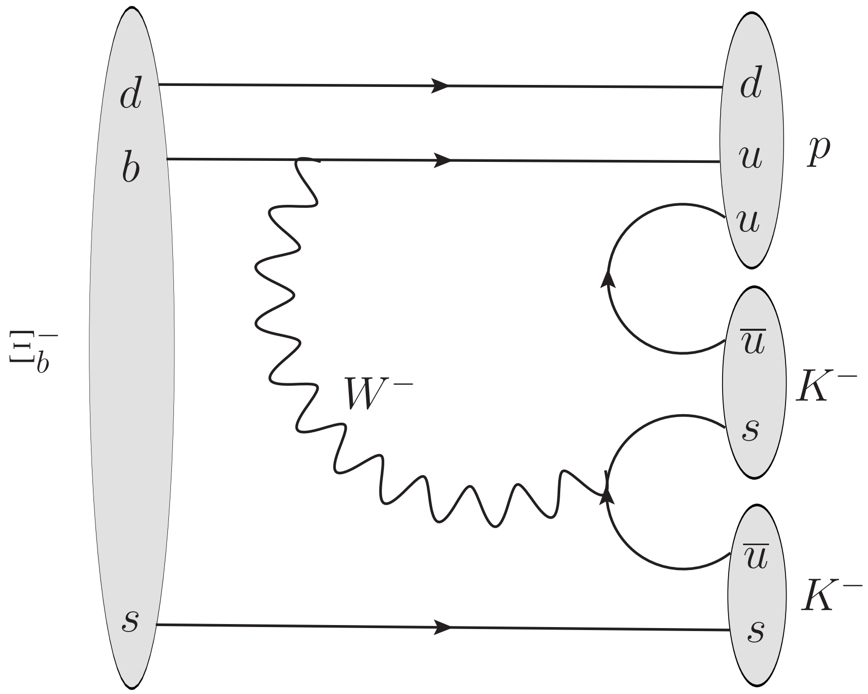
Study of $\Xi_b^- \to p h^- h'^-$

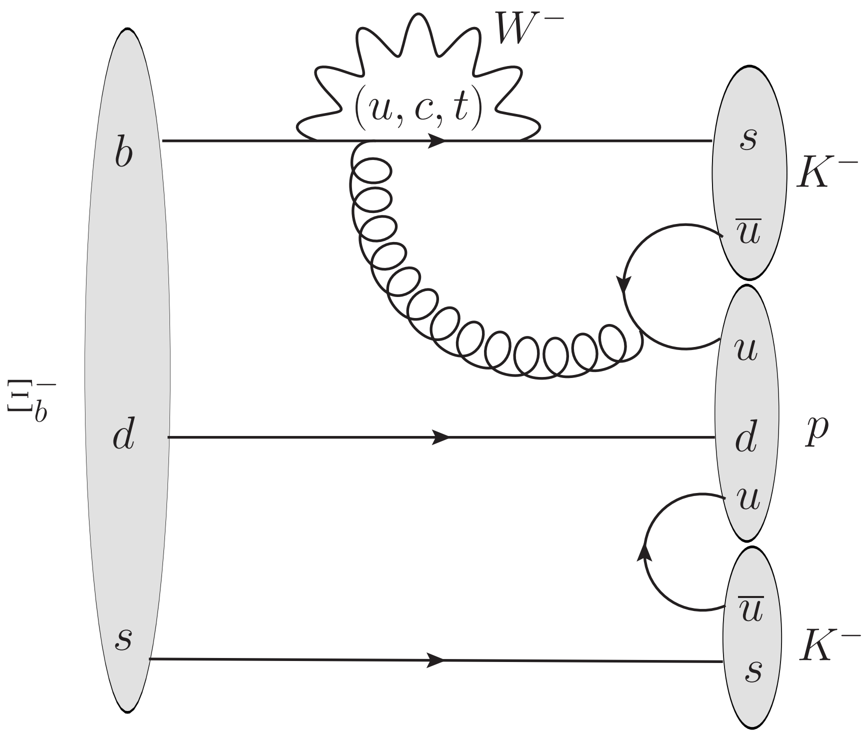
LHCb: Phys. Rev. Lett. 118 (2017) 071801

- Not only Λ_b^0
- Promising modes where to search for CPV with the additional statistics
- Significant CP asymmetries have been observed in regions of phase space of $B^- \to \pi^+\pi^-\pi^-, K^-\pi^+\pi^-, K^+K^-K^-, K^+K^-\pi^-$

LHCb: Phys. Rev. Lett. 111(2013)101801, Phys. Rev. Lett. 112(2014)011801, Phys. Rev. D D90(2014)112004

- Do the equivalent b-baryon decays exhibit similar behaviour?

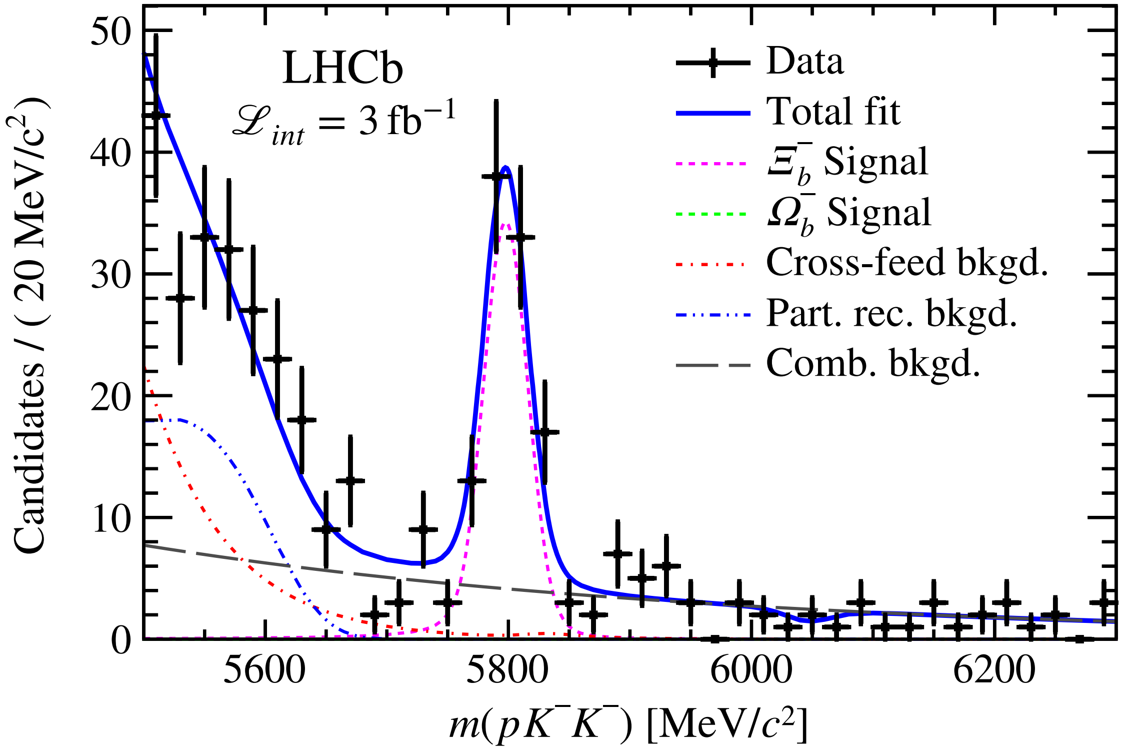




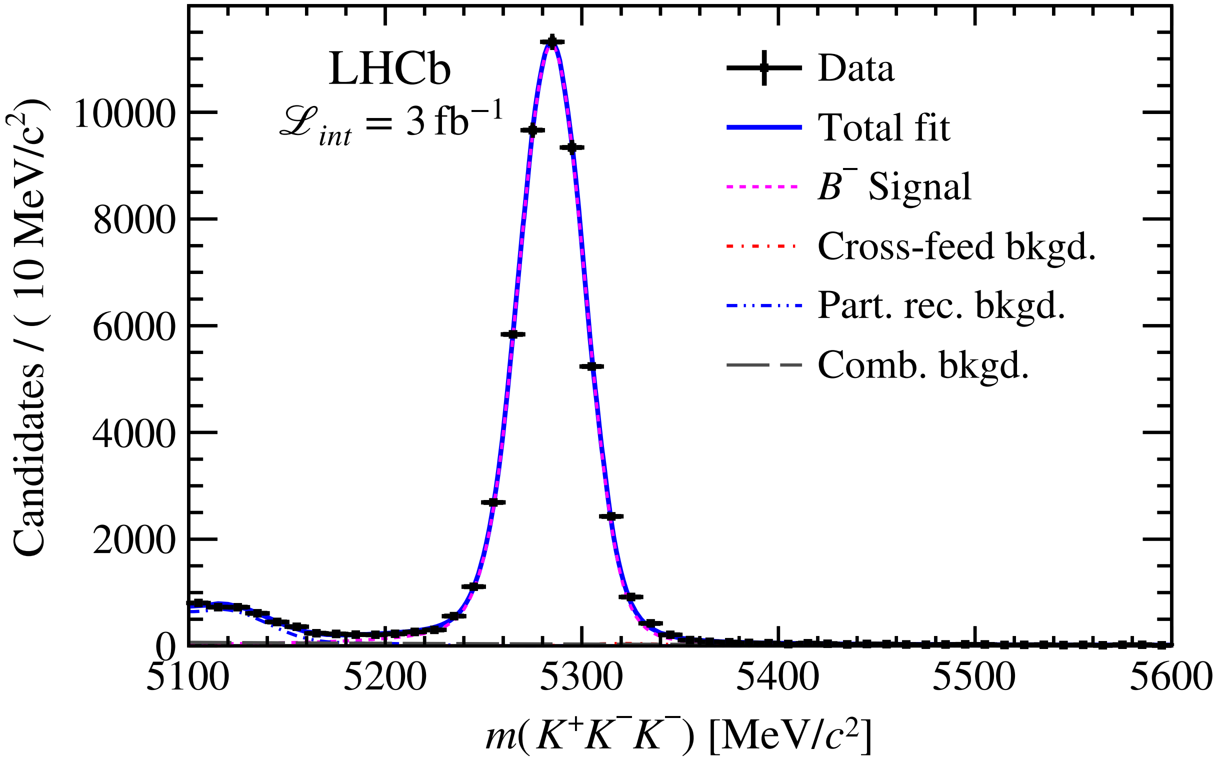
Study of $\Xi_b^- \to p h^- h'^-$

LHCb: Phys. Rev. Lett. 118 (2017) 071801

$N_{sig}(\Xi_b^- \to pK^-K^-) = 82.9 \pm 10.4, 8.7\sigma$



$N_{sig}(B^- \to K^+K^-K^-) = 50490 \pm 250$



$$\frac{f_{\Xi_b^-}}{f_u}\frac{\mathcal{B}\left(\Xi_b^- \to pK^-K^-\right)}{\mathcal{B}\left(B^- \to K^+K^-K^-\right)} = \boxed{\frac{N\left(\Xi_b^- \to pK^-K^-\right)}{N\left(B^- \to K^+K^-K^-\right)}}\,\boxed{\frac{\varepsilon\left(B^- \to K^+K^-K^-\right)}{\varepsilon\left(\Xi_b^- \to pK^-K^-\right)}} = (245 \pm 35 \pm 47) \times 10^{-5}$$

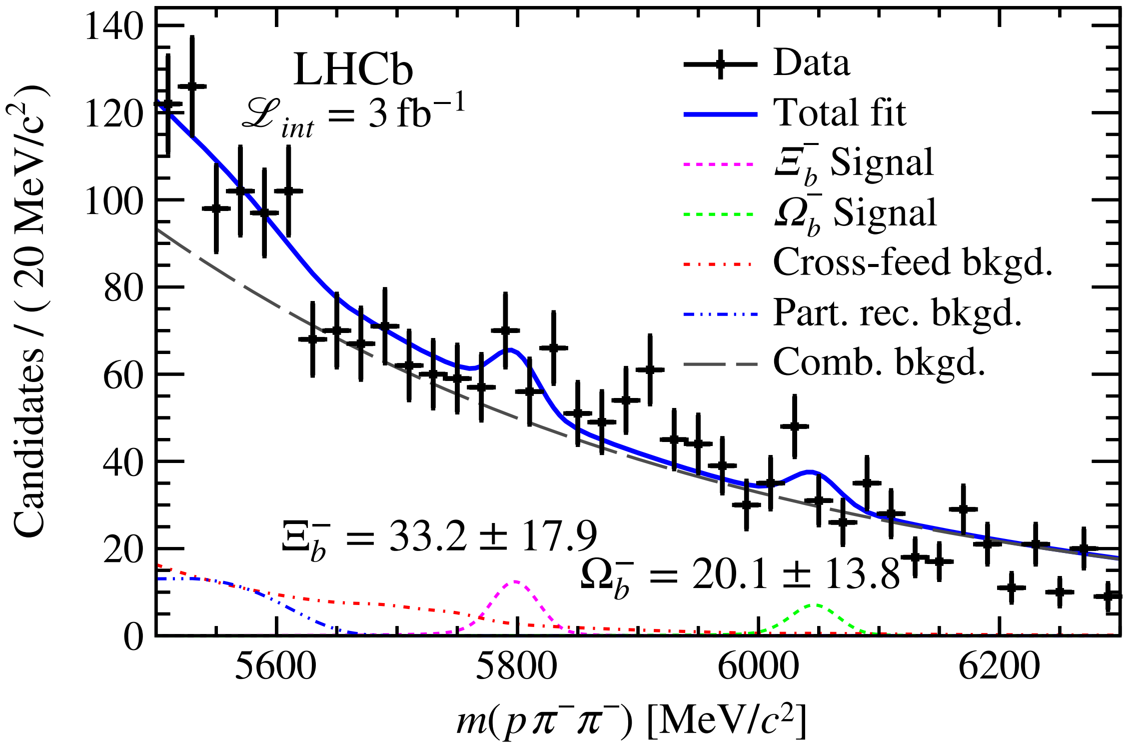
Estimated from fit

Estimated from MC +

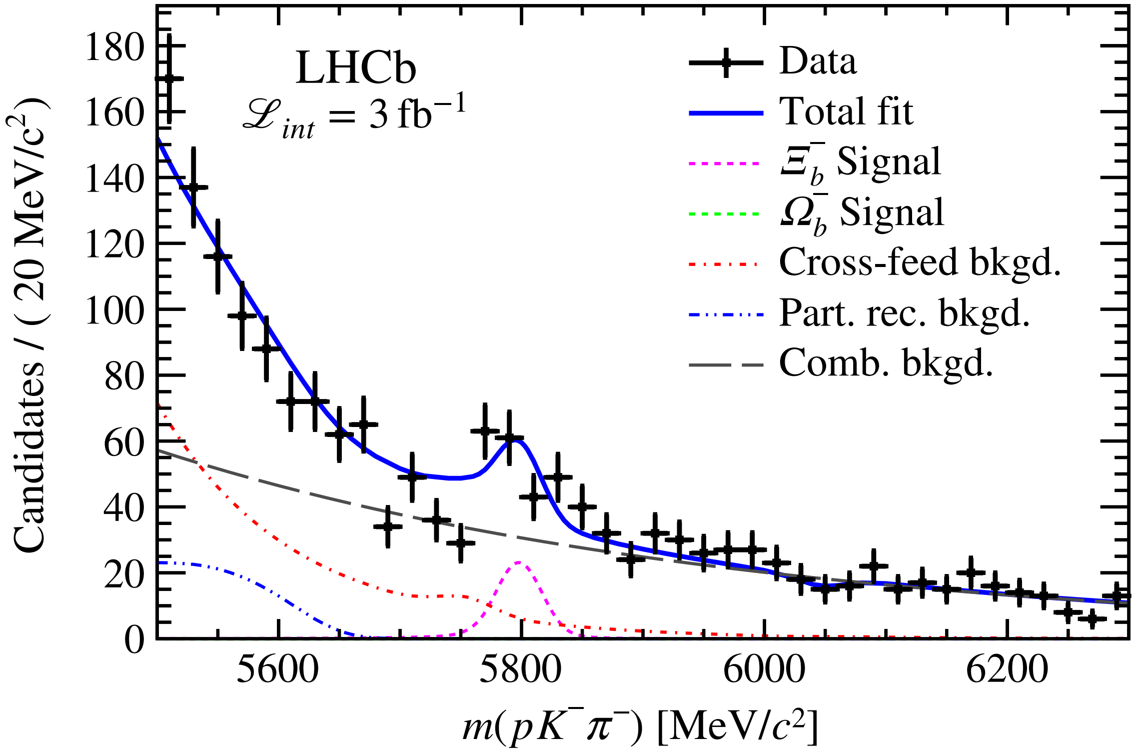
Data driven for PID cuts

Study of $\Xi_b^- \to p h^- h'^-$

LHCb: Phys. Rev. Lett. 118 (2017) 071801



$$N_{sig}(\Xi_b^- \to pK^-\pi^-) = 59.6 \pm 16.0, 3.4\sigma$$



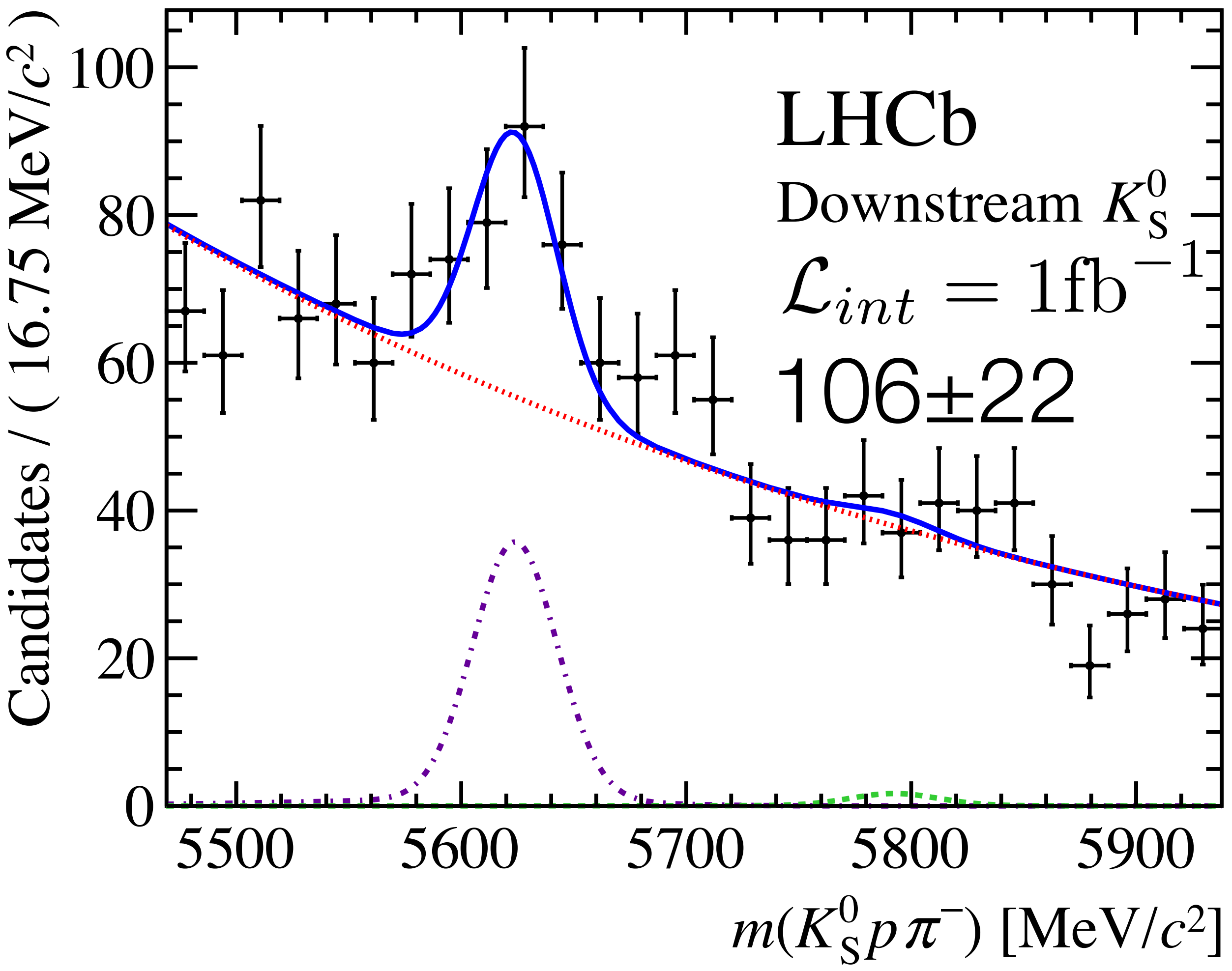
Evidence

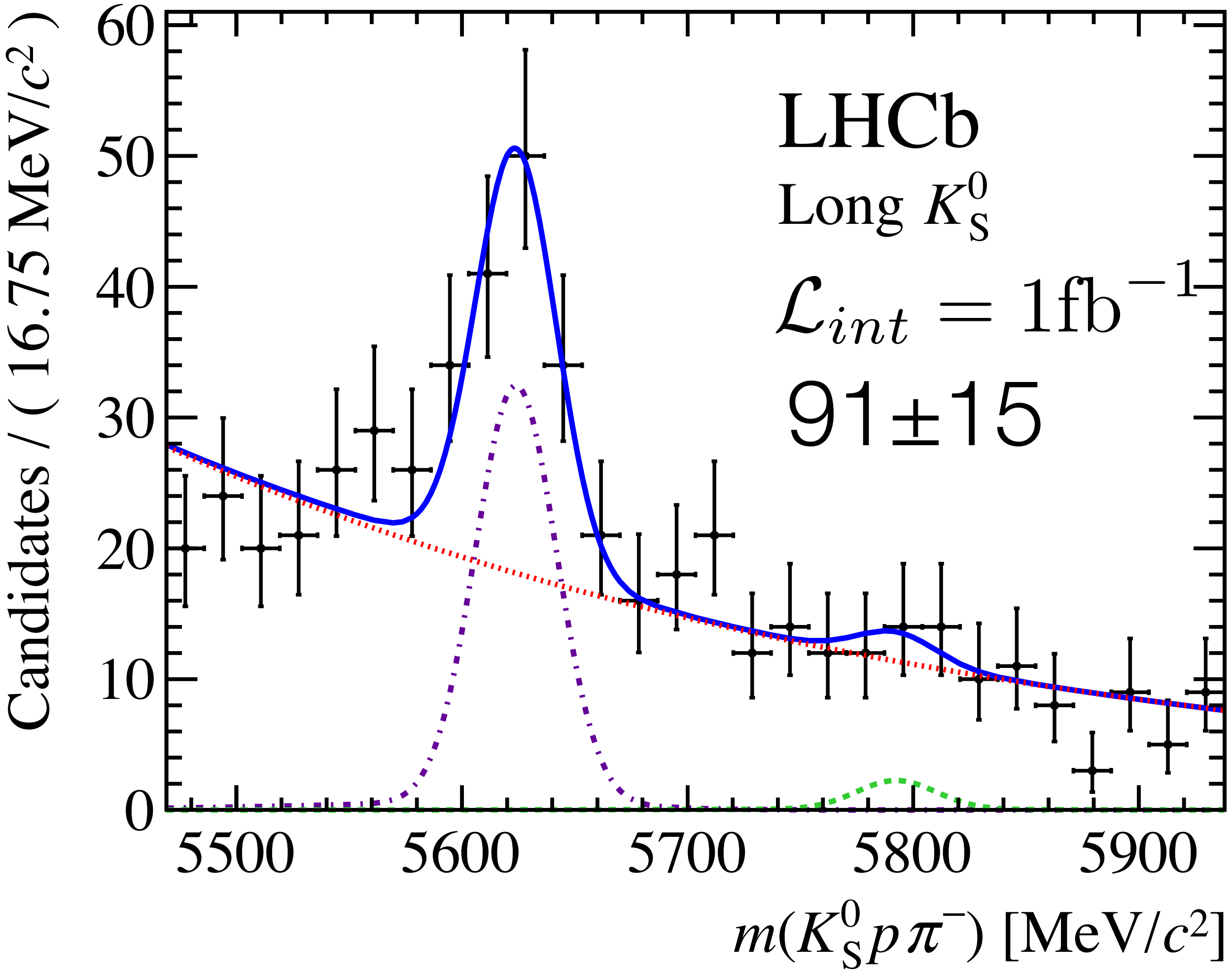
$$\frac{\mathscr{B}\left(\Xi_b^- \to pK^-\pi^-\right)}{\mathscr{B}\left(\Xi_b^- \to pK^-K^-\right)} = 0.98 \pm 0.27 \pm 0.09$$

Search for CPV in $\Lambda_b^0 \to K_s^0 p\pi^-$

LHCb: JHEP 04(2014)087

- Large A_{CP}(pK*-)~20% predicted in SM Phys. Rev. D91(2015)11, 116007





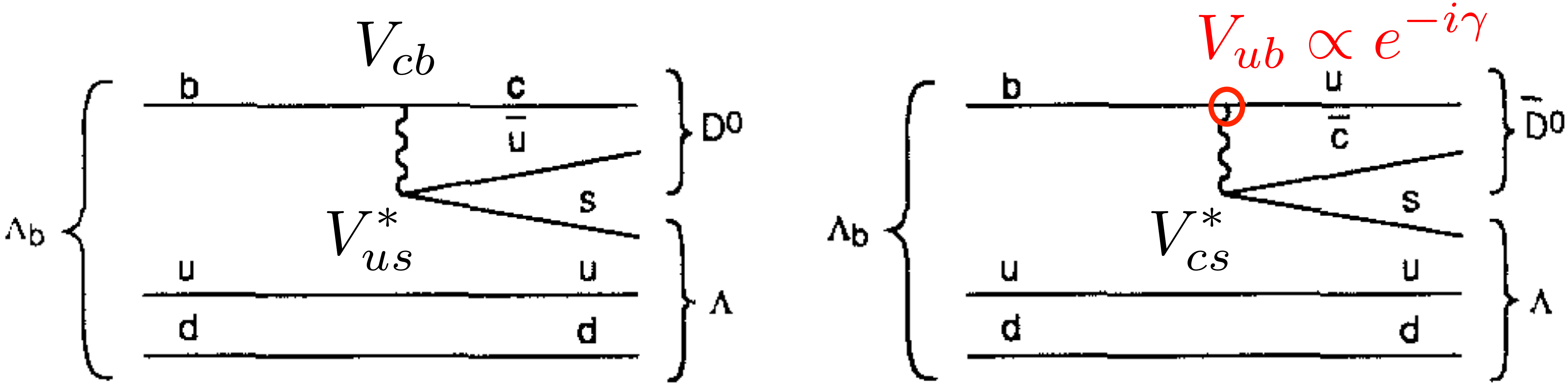
$A_{CP} = 0.22 \pm 0.13 \pm 0.03$ use $\Lambda_b^0 \to (K_s^0 p)_{\Lambda_c^+}\pi^-$ as control mode

- Precision at some % is already achievable with Run2 data

CKM angle γ using Λ_b^0 decays

Z. Phys. C - Particles and Fields (1992) 56: 129 Phys. Rev. D 65, 073029 (2002)

- Extract γ from BR of $\Lambda_b^0 \to \Lambda D^0$, $\Lambda_b^0 \to \Lambda \overline{D}^0$, $\Lambda_b^0 \to \Lambda D^0_{CP}$ and charge conjugate decays à la GLW



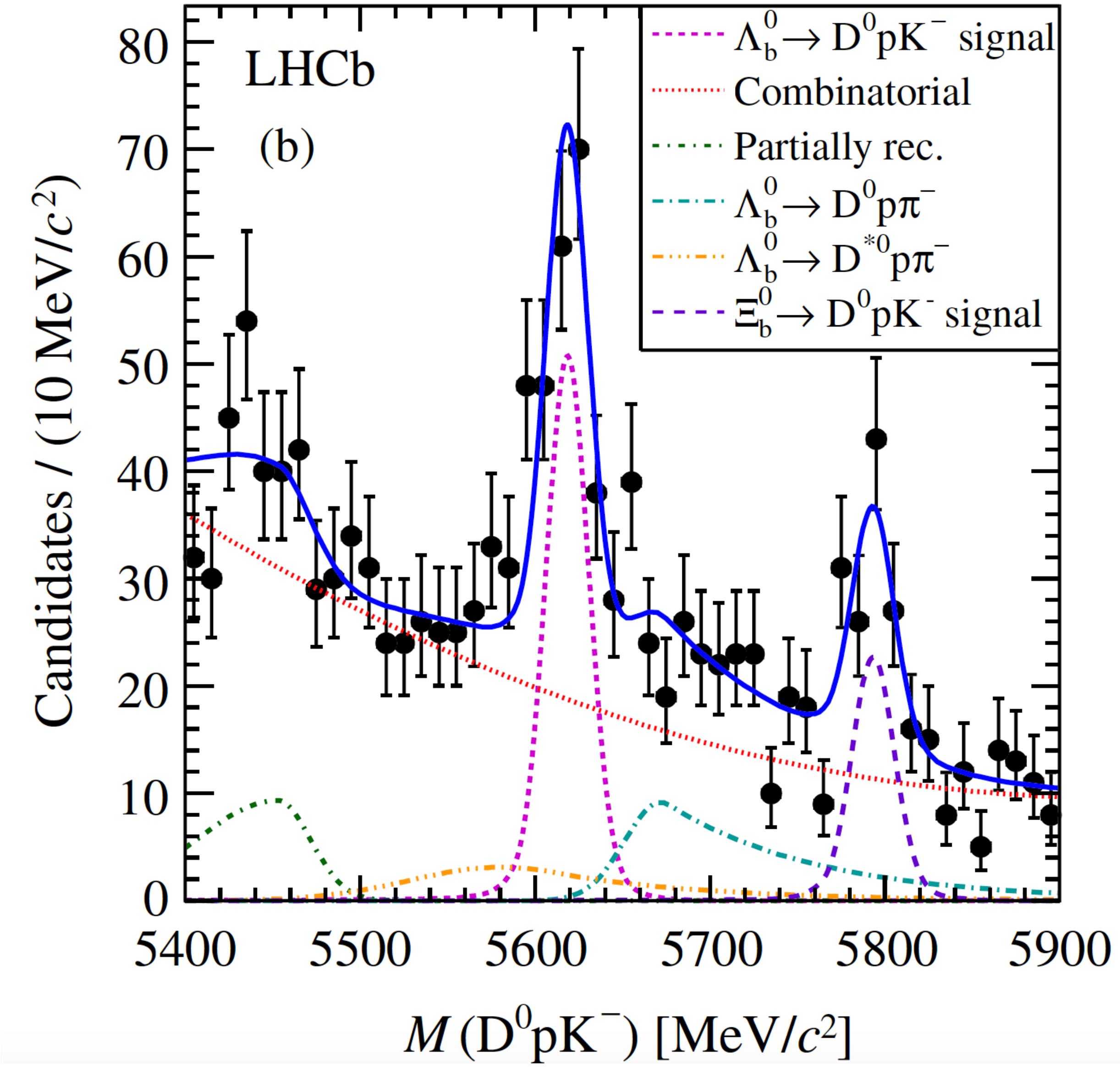
- Theory clean measurement of γ using baryons
- Small yields $BR\left(\Lambda_b^0 \to \Lambda D^0\right) \approx 4 \cdot 10^{-6}, BR\left(\Lambda_b^0 \to \Lambda \overline{D}^0\right) \approx 8 \cdot 10^{-7}$
- Use $\Lambda_b^0 \to D^0 p K^-$ for improved reco efficiency and higher BR

Towards the measurement of γ

Phys. Rev. D 89, 032001 (2014)

$$\Lambda_b^0 \rightarrow D^0 p K^- = 163 \pm 18$$

$$\mathscr{L}_{int} = 1\,\mathrm{fb}^{-1}$$



- Interesting decay mode for the future, $\mathrm{BR} = (4.8 \pm 0.9) \times 10^{-5}$
- Hard to estimate the impact on γ determination at present

Conclusions

- LHCb opens a new window to search CPV in baryon decays. Many b-baryon decays are observed for the first time
- First evidence for CPV in baryons is found in decays with a statistical significance of 3.3σ
- CPV searches ongoing in several b-baryon decays. With additional data new b-baryons and new decays will be studied
- Next step amplitude analysis to determine source of CPV. Systematic study of CPV in baryons, angle γ
- Interesting to compare the results with mesons
  - Theoretical predictions are needed and more than welcome

Back-up

$\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ phase space regions

LHCb: JHEP08(2018)039

Scheme A: division based on dominant resonant structures

Δ^{++}

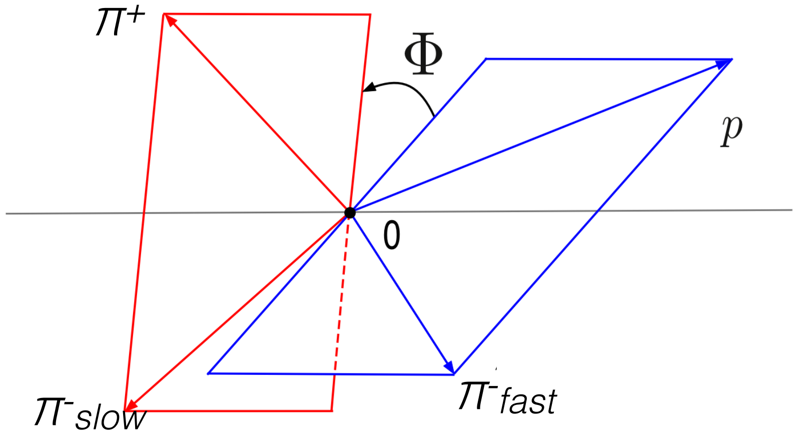
N*

ρ^0 peak

Phase space bin	$m(p\pi^+)$	$m(p\pi^-_{\text{slow}})$	$m(\pi^+\pi^-_{\text{slow}}),\ m(\pi^+\pi^-_{\text{fast}})$	$\lvert\Phi\rvert$
1	$(1.07, 1.23)$			$(0, \frac{\pi}{2})$
2	$(1.07, 1.23)$			$(\frac{\pi}{2}, \pi)$
3	$(1.23, 1.35)$			$(0, \frac{\pi}{2})$
4	$(1.23, 1.35)$			$(\frac{\pi}{2}, \pi)$
5	$(1.35, 5.34)$	$(1.07, 2.00)$	$m(\pi^+\pi^-_{\text{slow}}) < 0.78$ or $m(\pi^+\pi^-_{\text{fast}}) < 0.78$	$(0, \frac{\pi}{2})$
6	$(1.35, 5.34)$	$(1.07, 2.00)$	$m(\pi^+\pi^-_{\text{slow}}) < 0.78$ or $m(\pi^+\pi^-_{\text{fast}}) < 0.78$	$(\frac{\pi}{2}, \pi)$
7	$(1.35, 5.34)$	$(1.07, 2.00)$	$m(\pi^+\pi^-_{\text{slow}}) > 0.78$ and $m(\pi^+\pi^-_{\text{fast}}) > 0.78$	$(0, \frac{\pi}{2})$
8	$(1.35, 5.34)$	$(1.07, 2.00)$	$m(\pi^+\pi^-_{\text{slow}}) > 0.78$ and $m(\pi^+\pi^-_{\text{fast}}) > 0.78$	$(\frac{\pi}{2}, \pi)$
9	$(1.35, 5.34)$	$(2.00, 4.00)$	$m(\pi^+\pi^-_{\text{slow}}) < 0.78$ or $m(\pi^+\pi^-_{\text{fast}}) < 0.78$	$(0, \frac{\pi}{2})$
10	$(1.35, 5.34)$	$(2.00, 4.00)$	$m(\pi^+\pi^-_{\text{slow}}) < 0.78$ or $m(\pi^+\pi^-_{\text{fast}}) < 0.78$	$(\frac{\pi}{2}, \pi)$
11	$(1.35, 5.34)$	$(2.00, 4.00)$	$m(\pi^+\pi^-_{\text{slow}}) > 0.78$ and $m(\pi^+\pi^-_{\text{fast}}) > 0.78$	$(0, \frac{\pi}{2})$
12	$(1.35, 5.34)$	$(2.00, 4.00)$	$m(\pi^+\pi^-_{\text{slow}}) > 0.78$ and $m(\pi^+\pi^-_{\text{fast}}) > 0.78$	$(\frac{\pi}{2}, \pi)$

Scheme B: based on **Φ** angle intervals

i (i=1,2,…,12) $\quad (\frac{i-1}{12}\pi, \frac{i}{12}\pi)$



$\Lambda_b^0 \to pK^-\pi^+\pi^-$ phase space regions

LHCb: JHEP08(2018)039

Scheme A: division based on dominant resonant structures

Region	$m(p\pi^+)$	$m(pK^-)$	$m(\pi^+\pi^-)$	$m(K^-\pi^+)$	$\|\Phi\|$
1	$(1.00, 1.23)$				$(0, \frac{\pi}{2})$
2	$(1.00, 1.23)$				$(\frac{\pi}{2}, \pi)$
3	$(1.23, 1.35)$				$(0, \frac{\pi}{2})$
4	$(1.23, 1.35)$				$(\frac{\pi}{2}, \pi)$
5	$(1.35, 5.40)$	$(1.00, 2.00)$	$(0.27, 0.99)$		$(0, \frac{\pi}{2})$
6	$(1.35, 5.40)$	$(1.00, 2.00)$	$(0.27, 0.99)$		$(\frac{\pi}{2}, \pi)$
7	$(1.35, 5.40)$	$(1.00, 2.00)$	$(0.99, 4.50)$		$(0, \frac{\pi}{2})$
8	$(1.35, 5.40)$	$(1.00, 2.00)$	$(0.99, 4.50)$		$(\frac{\pi}{2}, \pi)$
9	$(1.35, 5.40)$	$(2.00, 5.00)$	$(0.27, 0.99)$	$(0.63, 0.89)$	$(0, \frac{\pi}{2})$
10	$(1.35, 5.40)$	$(2.00, 5.00)$	$(0.27, 0.99)$	$(0.89, 4.50)$	$(0, \frac{\pi}{2})$
11	$(1.35, 5.40)$	$(2.00, 5.00)$	$(0.27, 0.99)$		$(\frac{\pi}{2}, \pi)$
12	$(1.35, 5.40)$	$(2.00, 5.00)$	$(0.99, 4.50)$	$(0.63, 0.89)$	$(0, \frac{\pi}{2})$
13	$(1.35, 5.40)$	$(2.00, 5.00)$	$(0.99, 4.50)$	$(0.89, 4.50)$	$(0, \frac{\pi}{2})$
14	$(1.35, 5.40)$	$(2.00, 5.00)$	$(0.99, 4.50)$		$(\frac{\pi}{2}, \pi)$

Δ^{++}

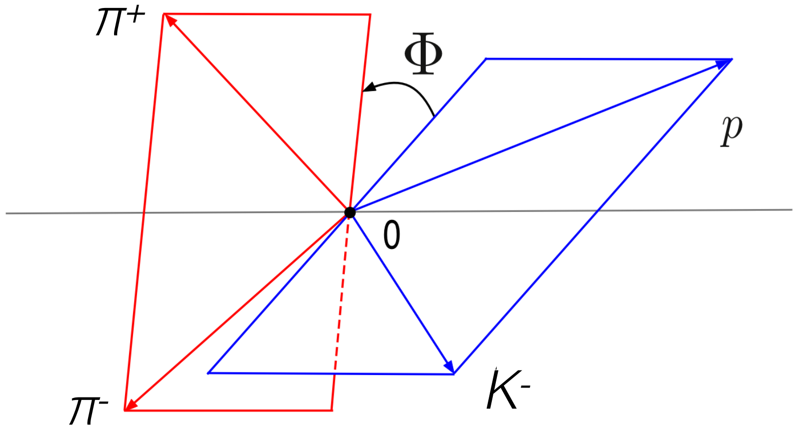
Λ^*

$f_0(980)$ peak

K^{*0} peak

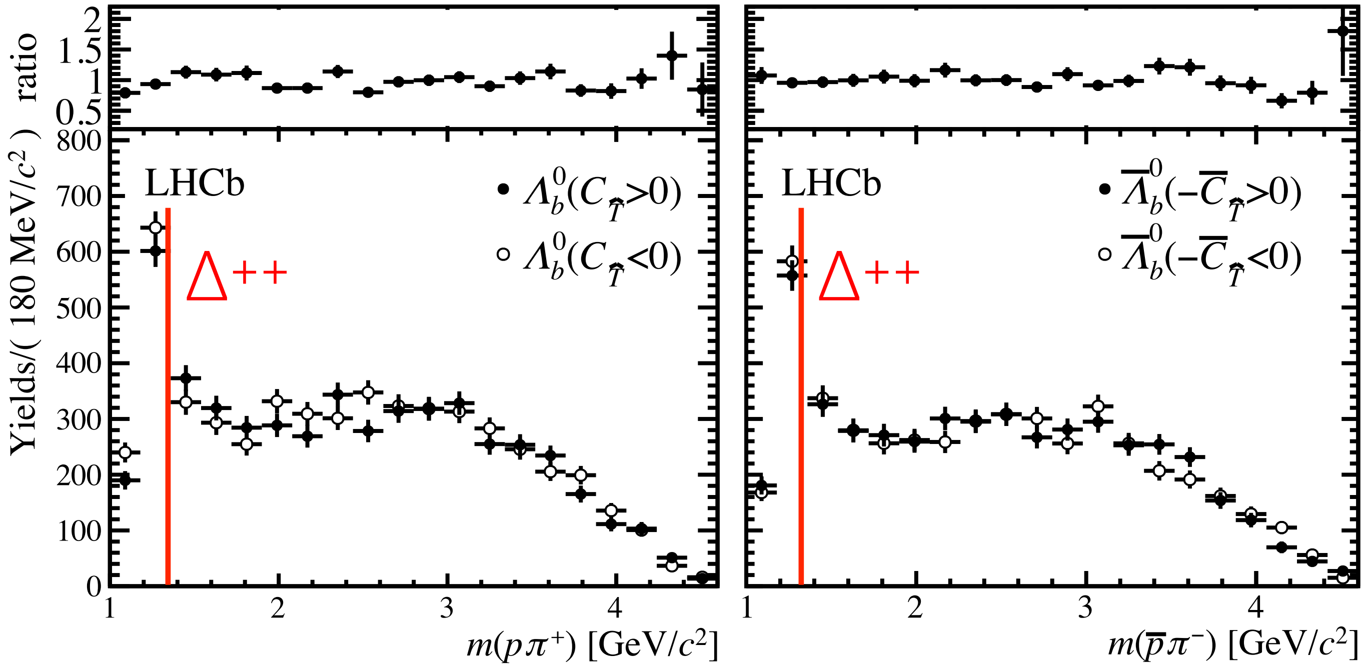
Scheme B: based on $\mathbf{\Phi}$ angle intervals

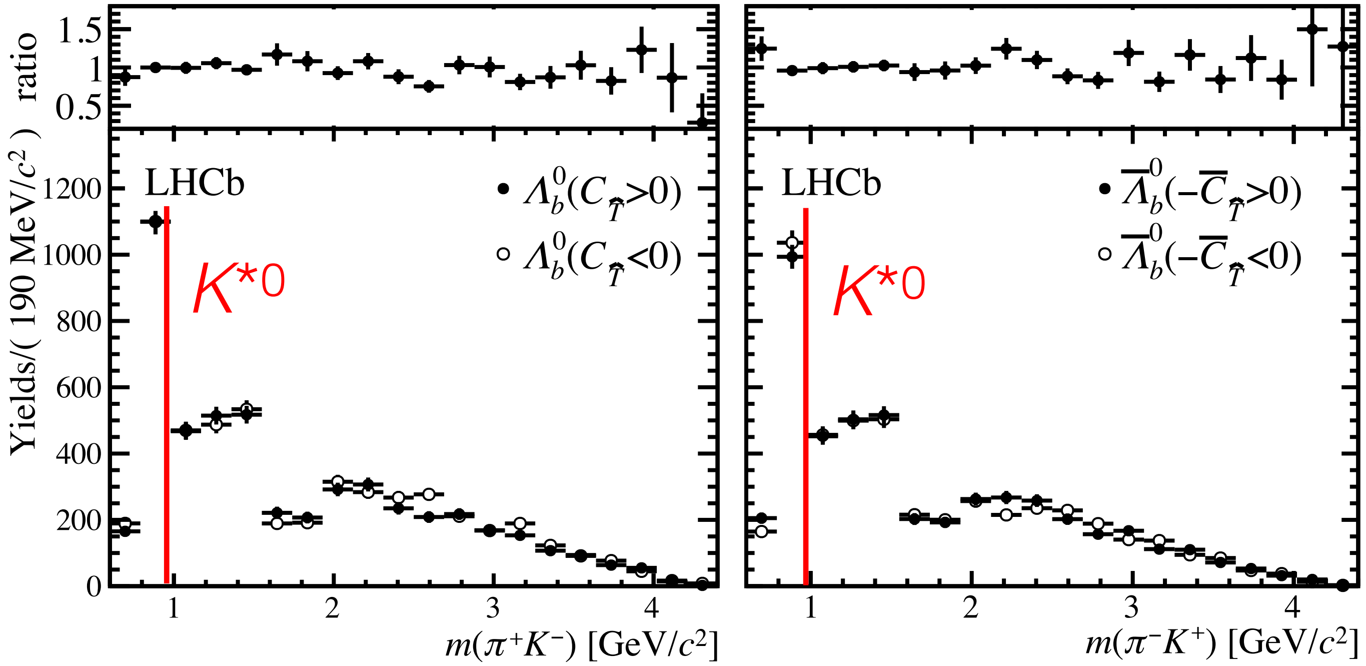
i (i=1,2,…,12) $\quad (\frac{i-1}{12}\pi, \frac{i}{12}\pi)$



$\Lambda_b^0 \to pK^-\pi^+\pi^-$ phase space regions

LHCb: JHEP08(2018)039





$\Lambda_b^0 \to pK^-K^+K^-$ phase space regions

LHCb: JHEP08(2018)039

Scheme C: division based on dominant resonant structures

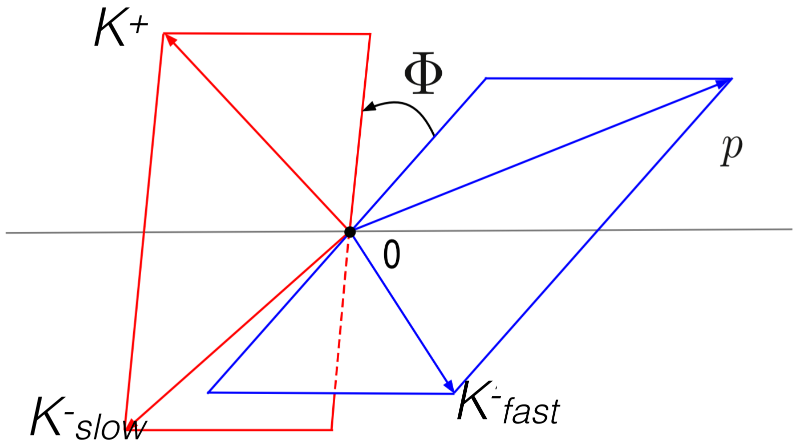
ϕ peak

Λ^*

Region	$m(pK^-_{\text{slow}})$	$m(K^+K^-_{\text{slow}}), m(K^+K^-_{\text{fast}})$	$\lvert\Phi\rvert$
1	$(0.9, 2.0)$	$m(K^+K^-_{\text{slow}}) < 1.02$ or $m(K^+K^-_{\text{fast}}) < 1.02$	
2	$(0.9, 2.0)$	$m(K^+K^-_{\text{slow}}) > 1.02$ and $m(K^+K^-_{\text{fast}}) > 1.02$	$(0, \frac{\pi}{2})$
3	$(0.9, 2.0)$	$m(K^+K^-_{\text{slow}}) > 1.02$ and $m(K^+K^-_{\text{fast}}) > 1.02$	$(\frac{\pi}{2}, \pi)$
4	$(2.0, 4.0)$	$m(K^+K^-_{\text{slow}}) < 1.02$ or $m(K^+K^-_{\text{fast}}) < 1.02$	$(0, \frac{\pi}{2})$
5	$(2.0, 4.0)$	$m(K^+K^-_{\text{slow}}) < 1.02$ or $m(K^+K^-_{\text{fast}}) < 1.02$	$(\frac{\pi}{2}, \pi)$
6	$(2.0, 4.0)$	$m(K^+K^-_{\text{slow}}) > 1.02$ and $m(K^+K^-_{\text{fast}}) > 1.02$	$(0, \frac{\pi}{2})$
7	$(2.0, 4.0)$	$m(K^+K^-_{\text{slow}}) > 1.02$ and $m(K^+K^-_{\text{fast}}) > 1.02$	$(\frac{\pi}{2}, \pi)$

Scheme D: based on Φ angle intervals

i (i=1,2,…,10) $\left(\frac{i-1}{10}\pi, \frac{i}{10}\pi\right)$



$\Lambda_b^0 \to pK^-K^+K^-$ phase space regions

LHCb: JHEP08(2018)039