CP violation in b-baryon decays to multibody final states at LHCb

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On behalf of the LHCb collaboration

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CPV in b-baryons

- b-baryon sector, relatively unexplored territory to search for CPV,

  sizeable amount of CPV predicted in CKM mechanism

- Complementary fields to test CKM mechanism and search for new sources of CPV w.r.t. B-meson

- Rich structures in multibody decays could enhance CPV sensitivities

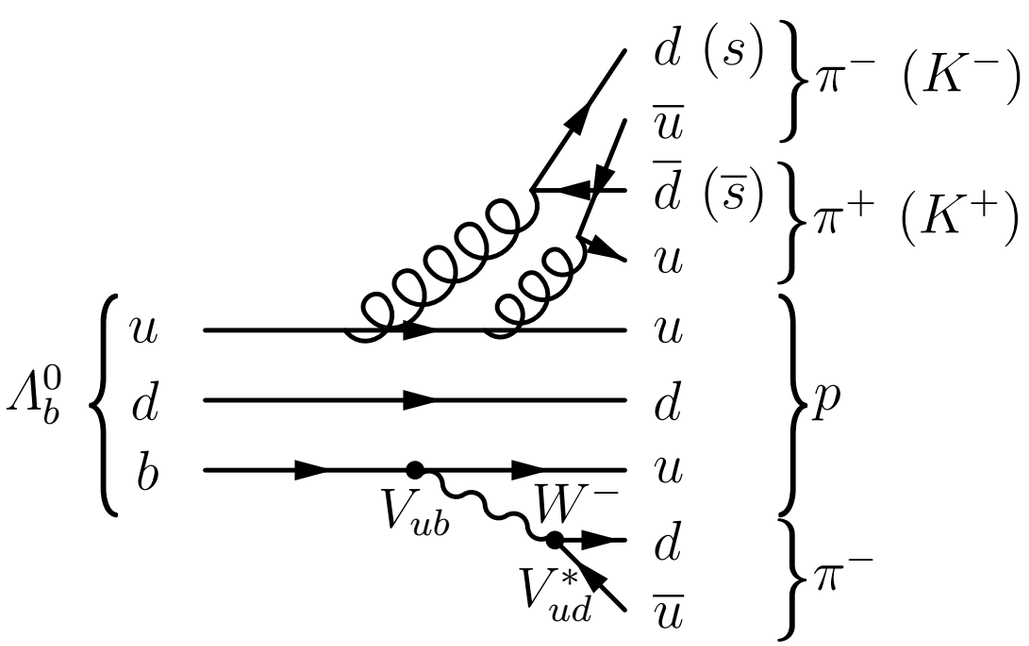
- LHCb is a b-baryon factory, one Λ^0_b for every two B^0 :

  opens a new field for precision measurements in flavour physics

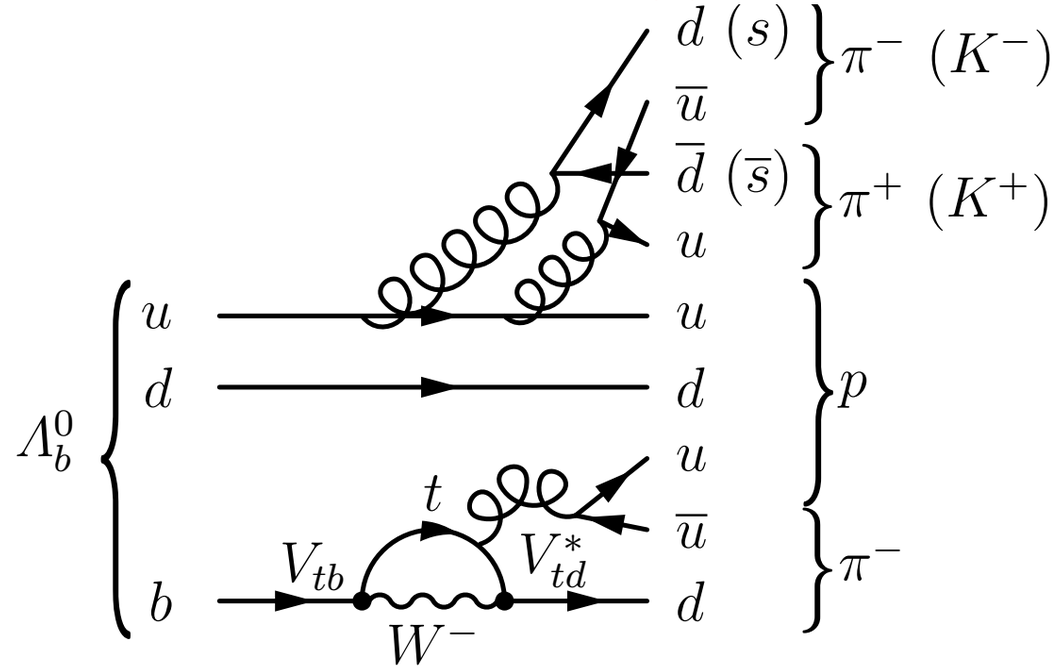
Search for CPV in $\Lambda^0_b, \Xi^0_b \to$ p3h decays

- Potential non negligible CPV effects in SM

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



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



large relative weak phase from CKM elements, $\arg(V_{tb}V_{td}^*/V_{ub}V_{ud}^*)=\alpha$

I.I. Bigi, arXiv:1608.06528

M. Gronau, J.Rosner, PLB749 (2015) 104-107

W. Bensalem et al., PLB538 (2002) 309-320

W. Bensalem et al., PRD66 (2002) 094004

- Triple product asymmetries (TPA) used in search for CPV in $\Lambda^0_b \to p\pi^-\pi^+\pi^-$, $\Lambda^0_b \to p\pi^-K^+K^-$, $\Lambda^0_b \to pK^-\pi^+\pi^-$, $\Lambda^0_b \to pK^-K^+K^-$, and $\Xi^0_b \to p\pi^+K^-K^-$ decays

TPA technique

- Triple products in Λ^0_b rest frame

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

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

- $\hat{T}$-odd asymmetries:

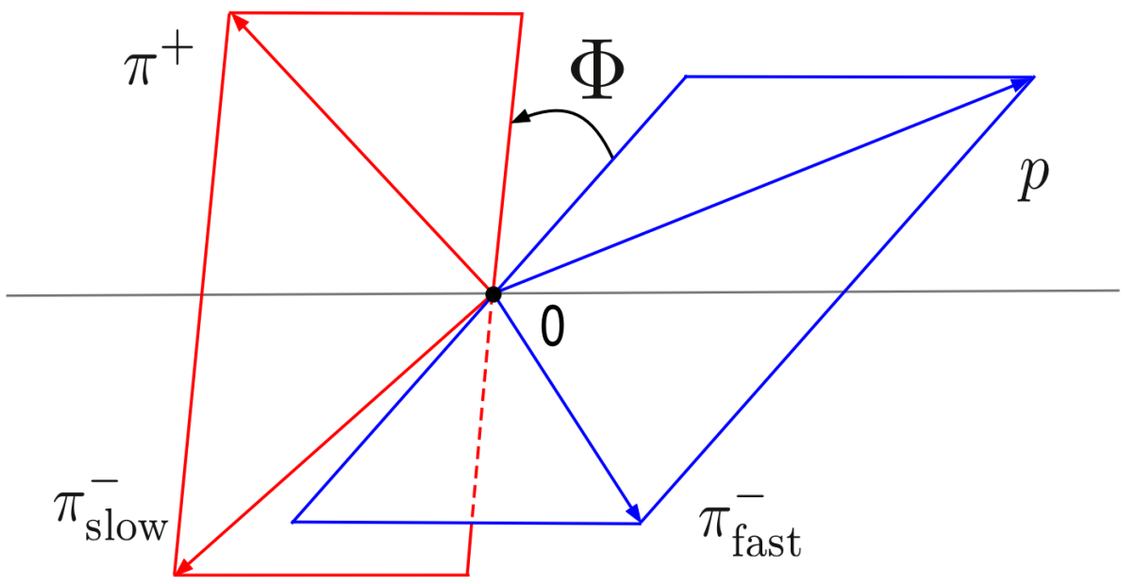
$$A_{\hat{T}} = \frac{N_{\Lambda_b^0}(C_{\hat{T}} > 0) - N_{\Lambda_b^0}(C_{\hat{T}} < 0)}{N_{\Lambda_b^0}(C_{\hat{T}} > 0) + N_{\Lambda_b^0}(C_{\hat{T}} < 0)},$$

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

- CP-violating observable:
- P-violating observable:

$\hat{T}$ = motion reversal operator

K or π choice ambiguity resolved by taking fast momentum in Λ^0_b rest frame.



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

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

Sensitivity to CPV

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

- Complementary approach to A_{CP} analysis $A_{CP} = \dfrac{N_{\Lambda_b} - N_{\bar{\Lambda}_b}}{N_{\Lambda_b} + N_{\bar{\Lambda}_b}}$

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

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

G.Durieux, Y.Grossman, PRD92 (2015) 076013

$$A_{CP} \propto \sin\left(\delta_1 - \delta_2\right) \sin\left(\varphi_1 - \varphi_2\right)$$

not sensitive if δ_1–δ_2 = 0 or π

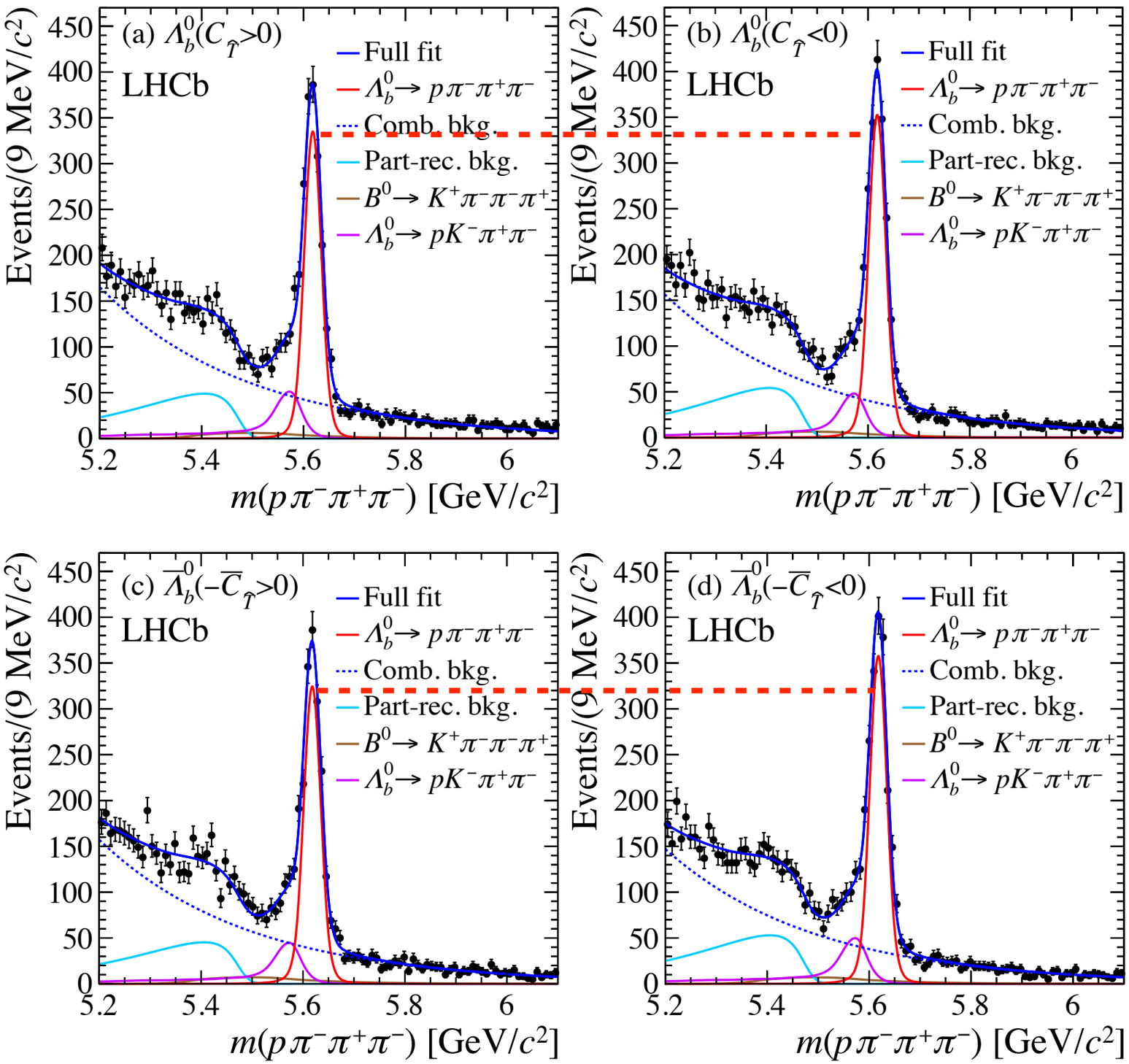
- Sensitive to potential new physics effects:

W. Bensalem, A. Datta, and D. London, New physics effects on triple product correlations in Λ^0_b decays, Phys. Rev. D66 (2002) 094004, arXiv:hep-ph/0208054

CPV measurements in $\Lambda^0_b \to p\pi^-\pi^+\pi^-, pK^-\pi^+\pi^-$

Nature Phys. 13 (2017) 391-396

Run1, 3fb^{-1}



reminder:

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

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

- For $\Lambda^0_b \to p\pi^-\pi^+\pi^-$:

$$a_P^{\hat{T}\text{-odd}} = (-3.71 \pm 1.45 \pm 0.32)\%$$

$$a_{CP}^{\hat{T}\text{-odd}} = (1.15 \pm 1.45 \pm 0.32)\%$$

- For $\Lambda^0_b \to pK^-K^+K^-$:

$$a_P^{\hat{T}\text{-odd}} = (3.62 \pm 4.54 \pm 0.42)\%$$

$$a_{CP}^{\hat{T}\text{-odd}} = (-0.93 \pm 4.54 \pm 0.42)\%$$

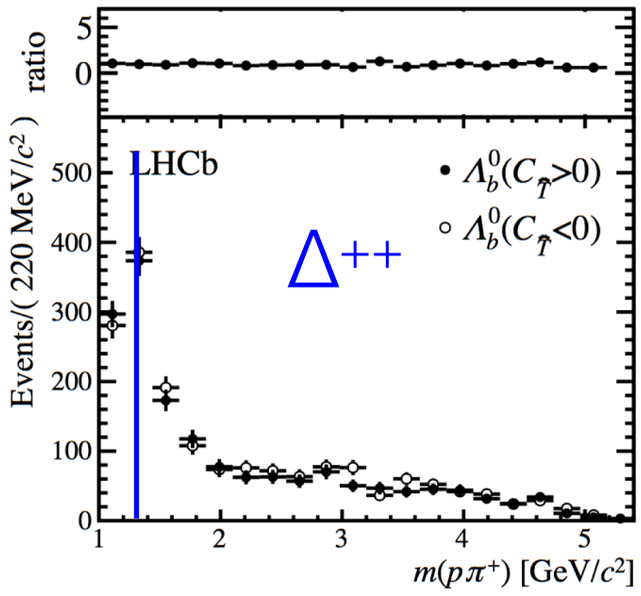
Phase space integrated results consistent with P or CP symmetry

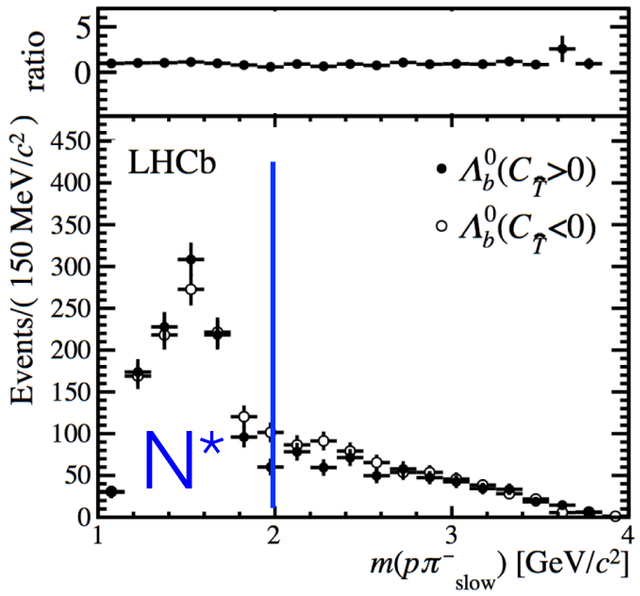
CPV measurements in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$, $p\pi^-K^+K^-$

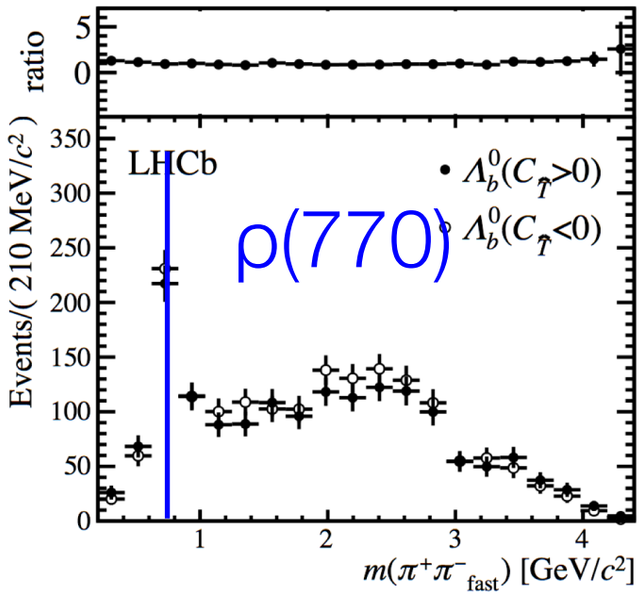
Nature Phys. 13 (2017) 391-396

- Measurements in different regions of phase space of $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ enhance sensitivity to localised CPV effects

  ✓ Scheme A: on dominant resonances, Δ^{++},N*,ρ(770)

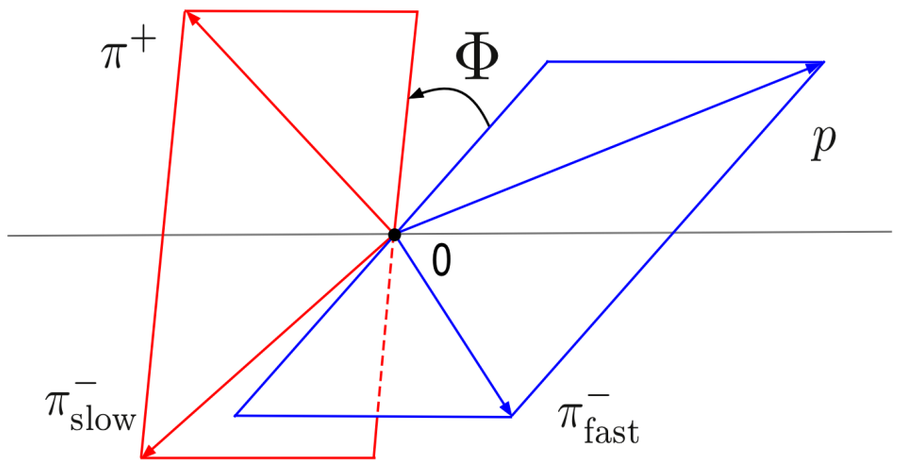






✓ Scheme B: on **Φ** angle between decay planes $\pi^+\pi^-_{\rm slow}$ and $p\pi^-_{\rm fast}$

exploits more the interference of P-even and P-odd contributions



CPV measurements in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-, pK^-K^+K^-$

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- Measurements in different regions of phase space of $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ enhance sensitivity to localised CPV effects
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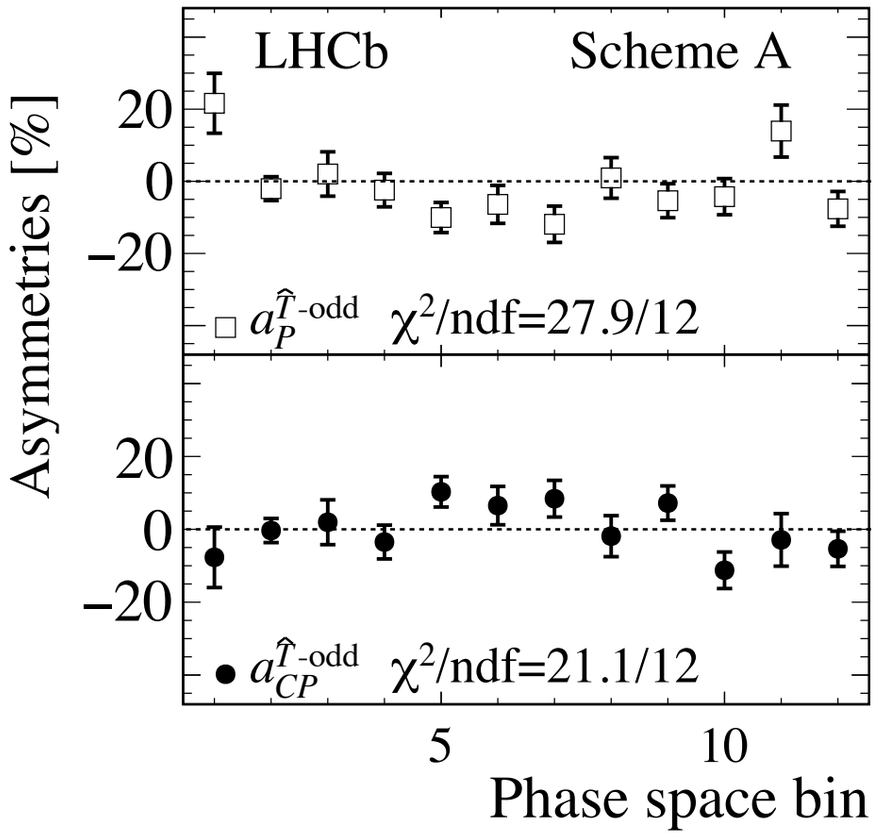
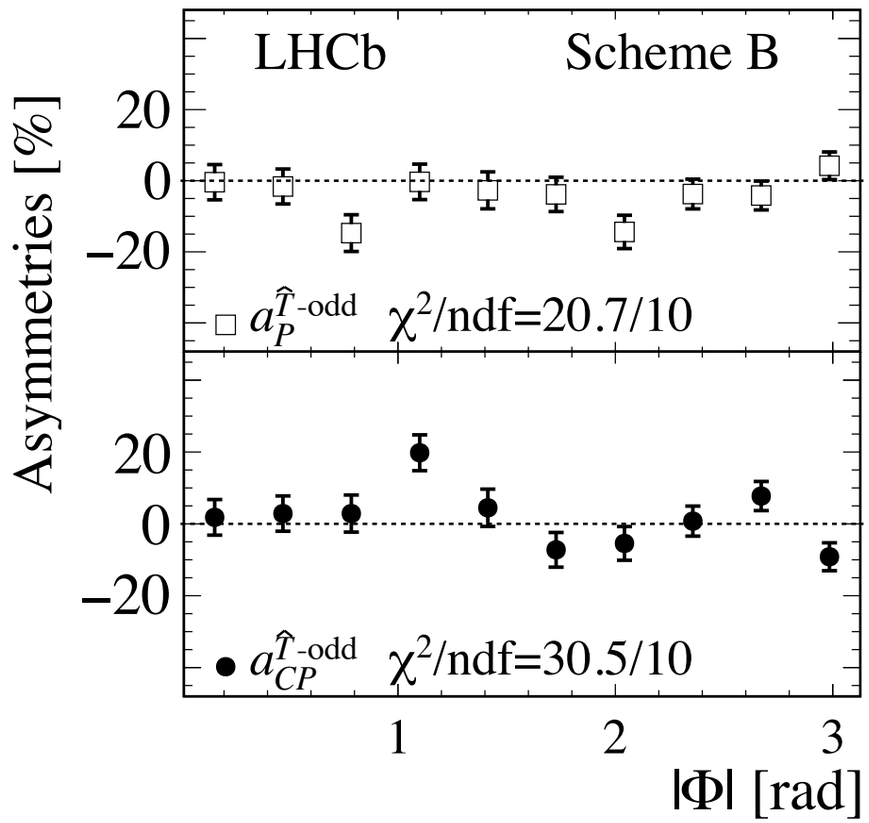




Run1, 3fb^{-1}

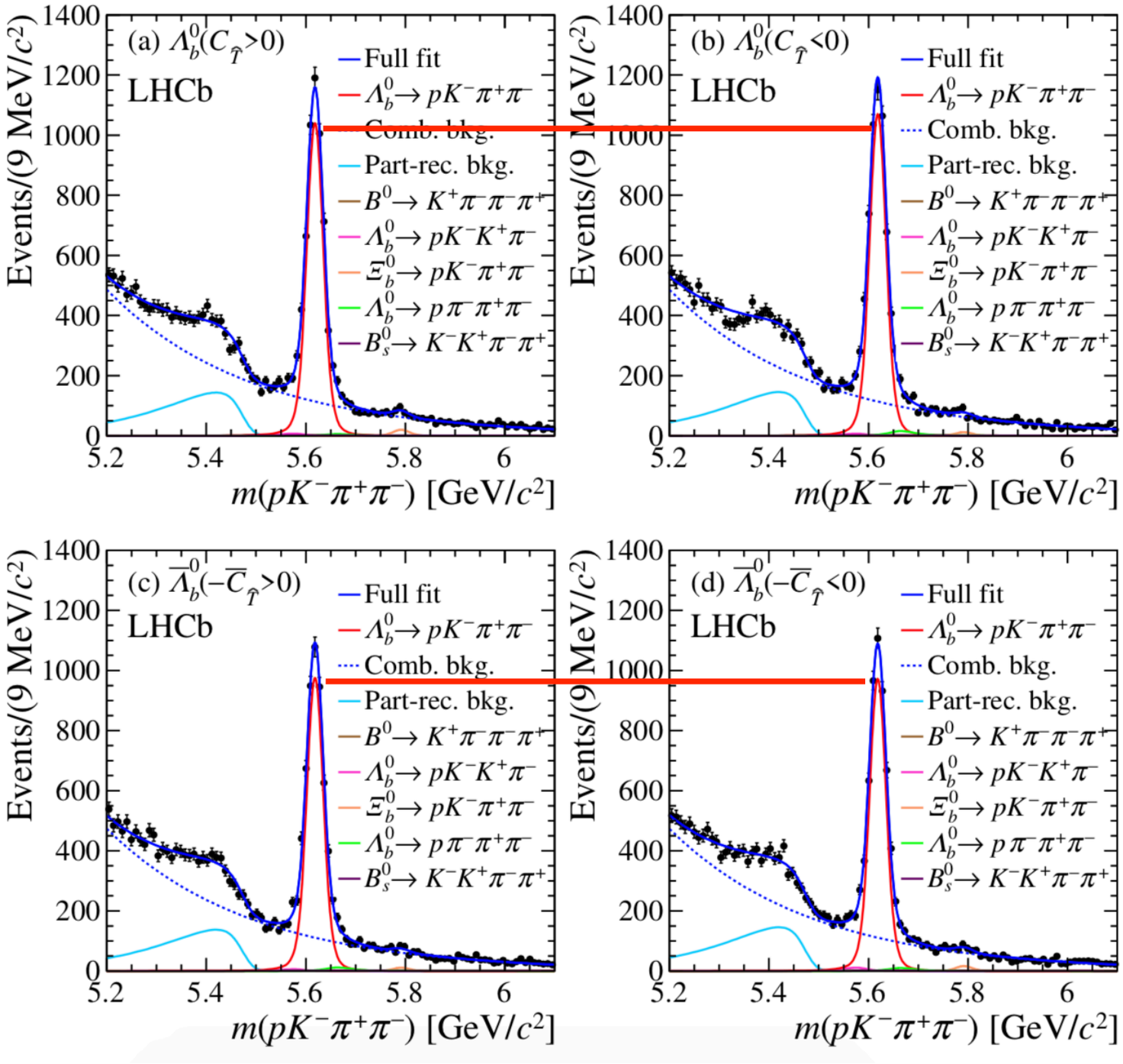
- Combined results of two schemes: 3.3σ deviation from CP symmetry

  The first evidence of CPV in the baryon sector

CPV in $\Lambda^0_b \to pK^-\pi^+\pi^-$, $pK^-K^+K^-$, $\Xi^0_b \to p\pi^+K^-K^-$

arXiv: 1805.03941, submitted to JHEP

Run1, 3fb^{-1}



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- For $\Lambda^0_b \to pK^-\pi^+\pi^-$:

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

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

- For $\Lambda^0_b \to pK^-K^+K^-$:

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

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

- For $\Xi^0_b \to p\pi^+K^-K^-$:

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

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

Phase space integrated results consistent with P or CP symmetry

CPV in $\Lambda^0_b \to pK^-\pi^+\pi^-$, $pK^-K^+K^-$, $\Xi^0_b \to p\pi^+K^-K^-$

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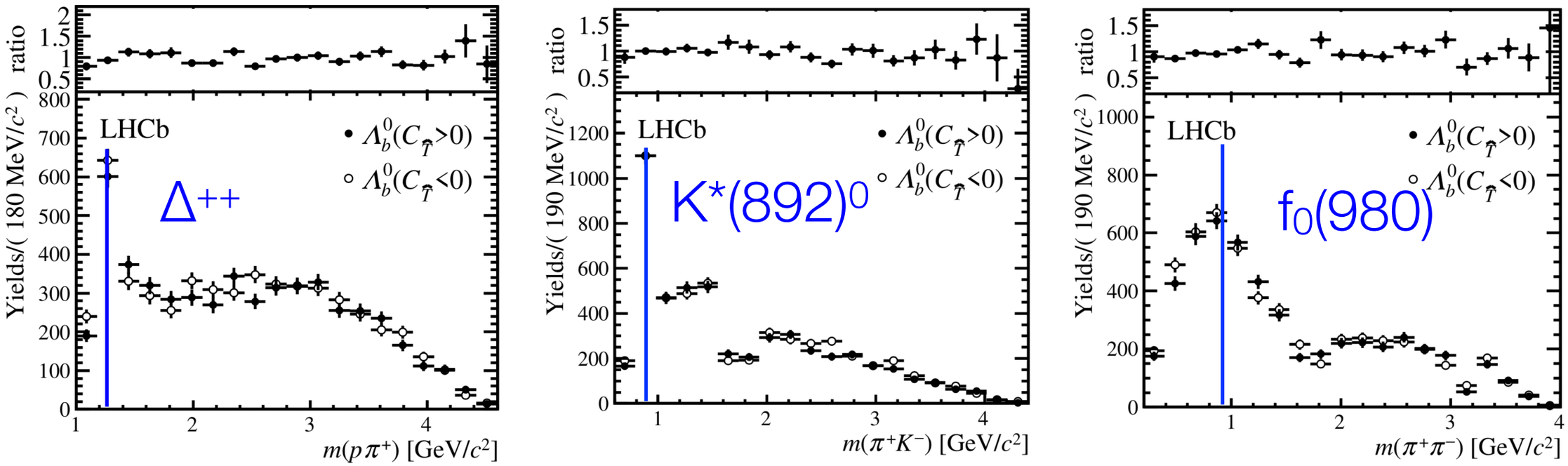
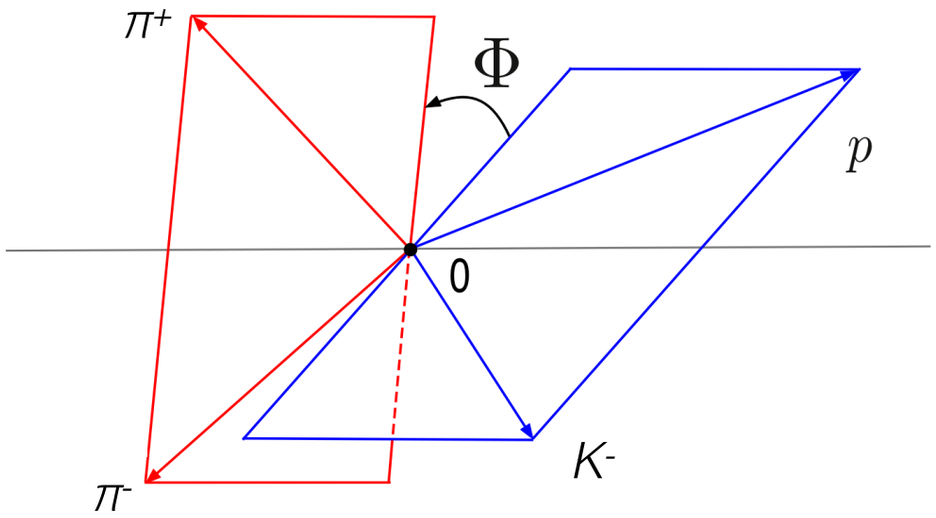
- Measurements in different regions of phase space of $\Lambda^0_b \to pK^-\pi^+\pi^-$

  ✓ Binning on dominant resonances, Δ^{++},$K^*(892)^0$,$f_0(980)$



✓ Binning on **Φ** angle between decay planes pK^- and $\pi^+\pi^-$

exploits more the interference of P-even and P-odd contributions



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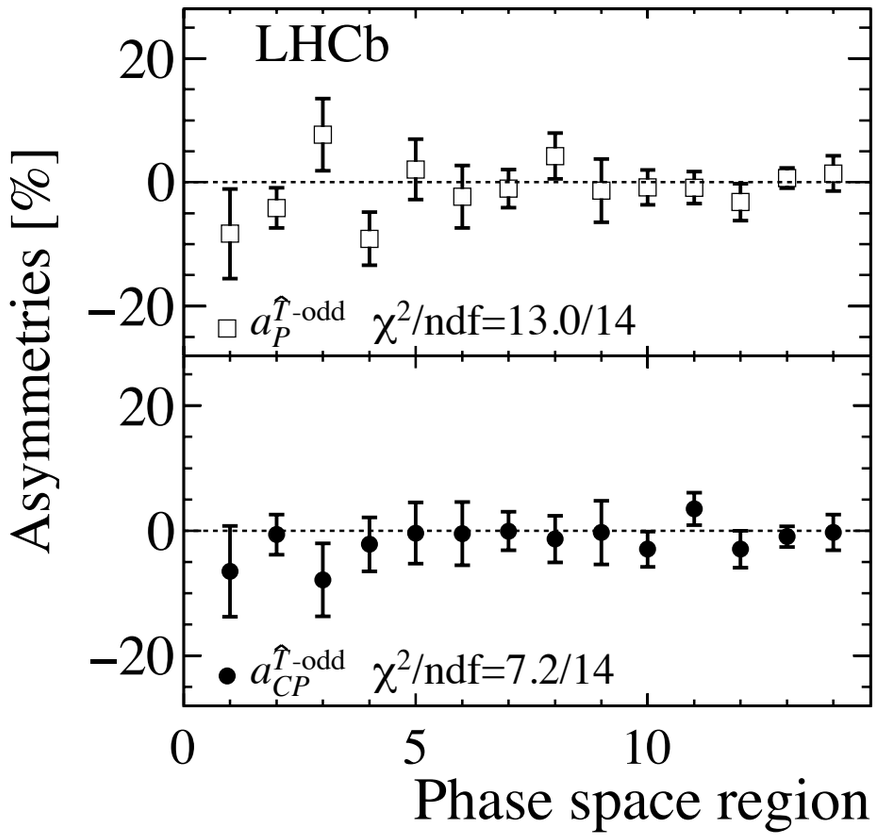
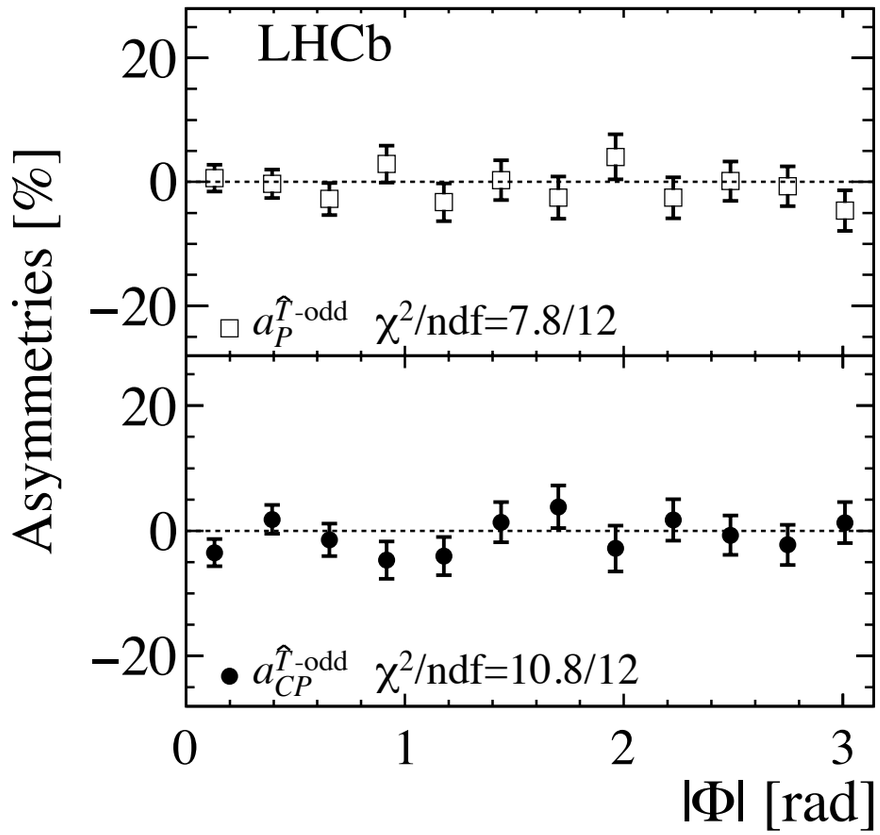


Binning on Φ angle between decay planes pK^- and $\pi^+\pi^-$



Run1, 3fb^{-1}

- Consistent with P or CP symmetry

CPV in $\Lambda^0_b \to pK^-\pi^+\pi^-$, $pK^-K^+K^-$, $\Xi^0_b \to p\pi^+K^-K^-$

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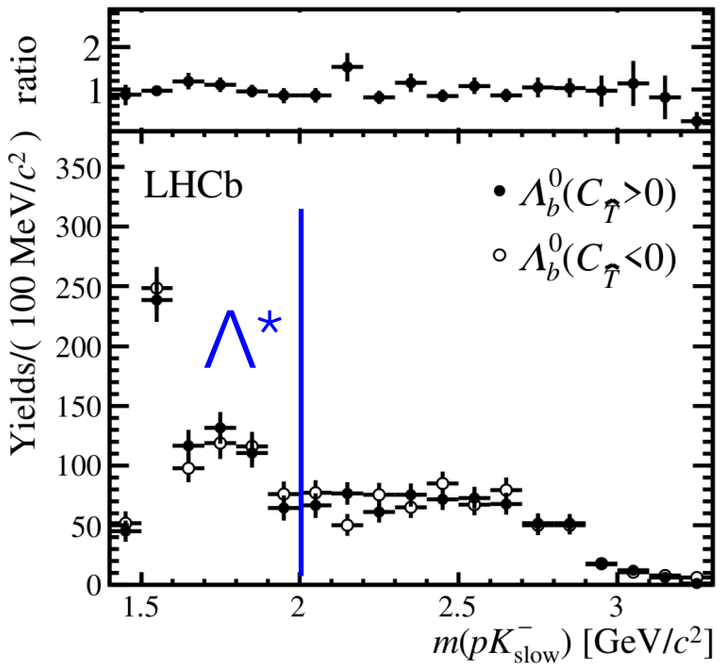
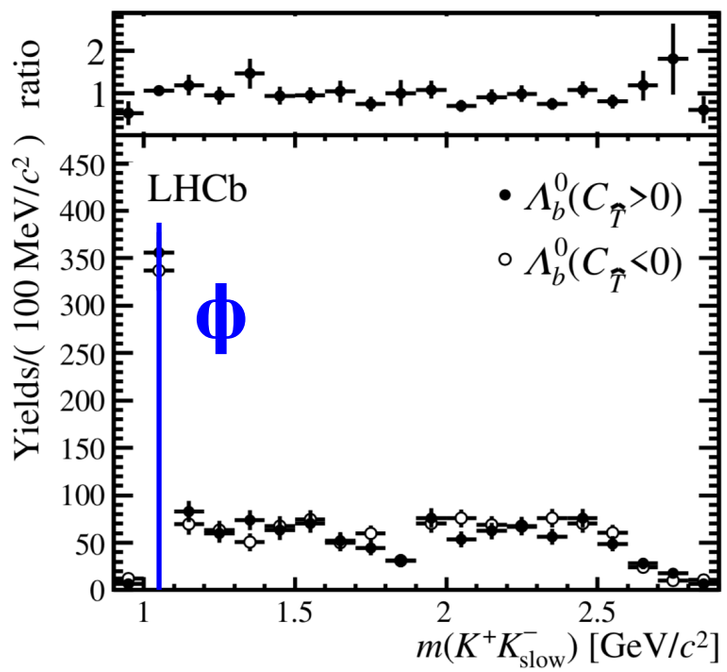
- Measurements in different regions of phase space of $\Lambda^0_b \to pK^-K^+K^-$

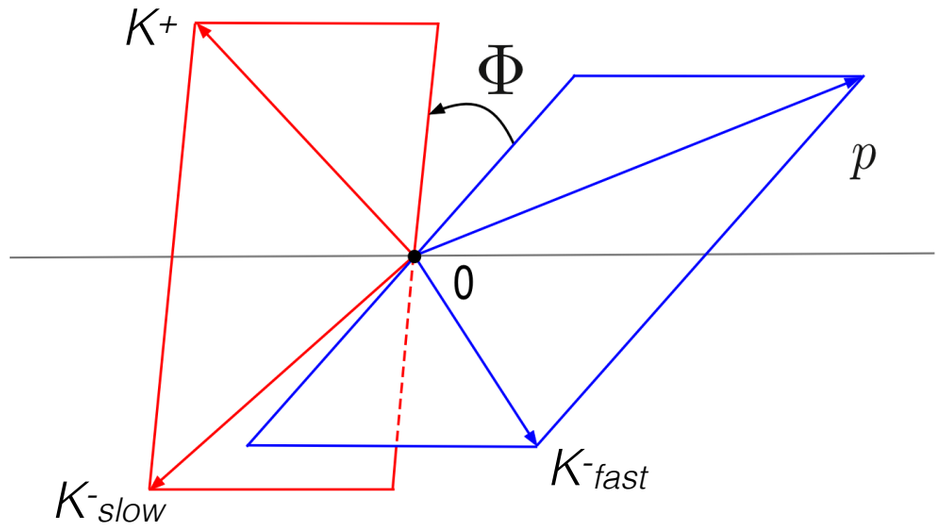
  ✓ Binning on dominant resonances, Λ^*, ϕ





✓ Binning on Φ angle between decay planes pK^-_{fast} and $K^+K^-_{slow}$

exploits more the interference of P-even and P-odd contributions



CPV in $\Lambda^0_b \to pK^-\pi^+\pi^-$, $pK^-K^+K^-$, $\Xi^0_b \to p\pi^+K^-K^-$

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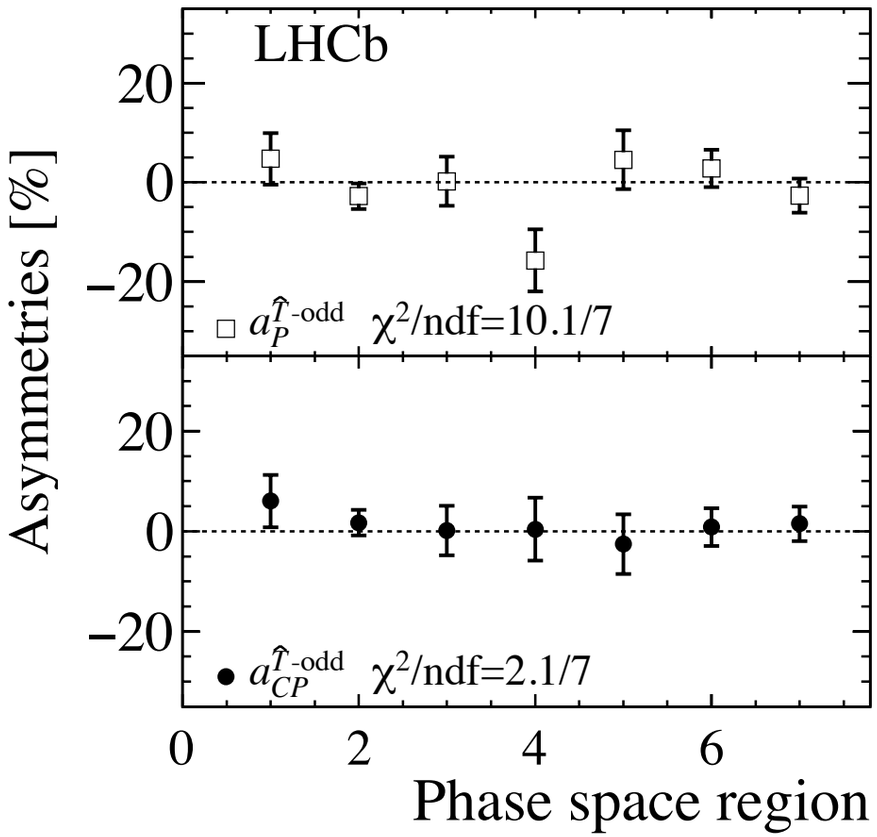
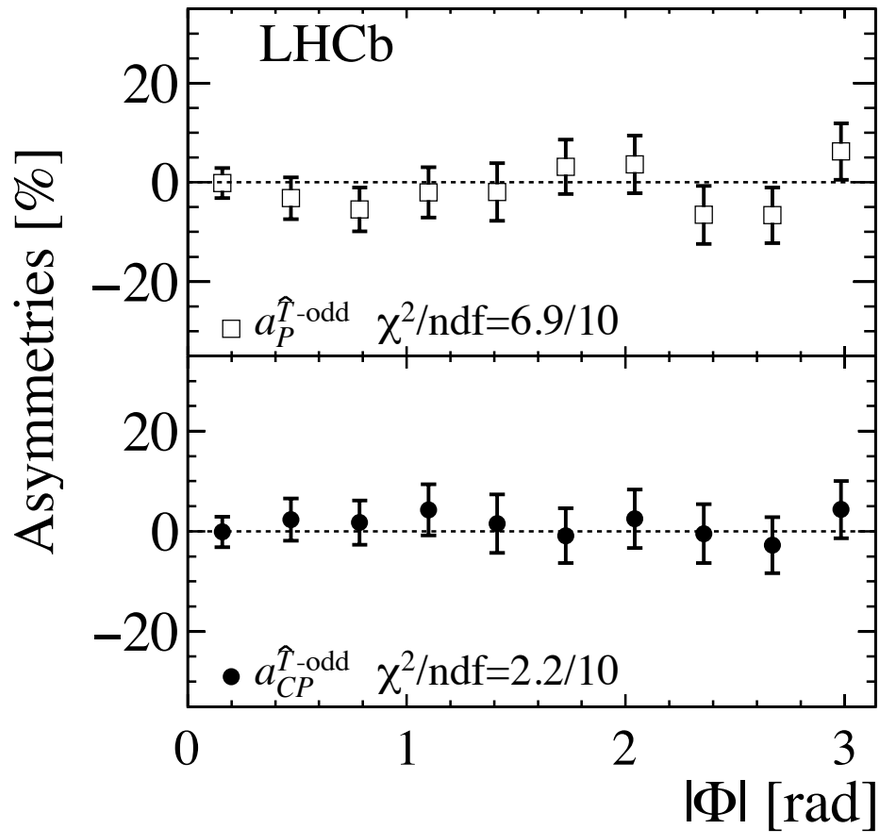
Binning on dominant resonances, Λ^*, $\boldsymbol{\phi}$



Binning on $\boldsymbol{\Phi}$ angle between decay planes pK^-_{fast} and $K^+K^-_{slow}$



Run1, 3fb^{-1}

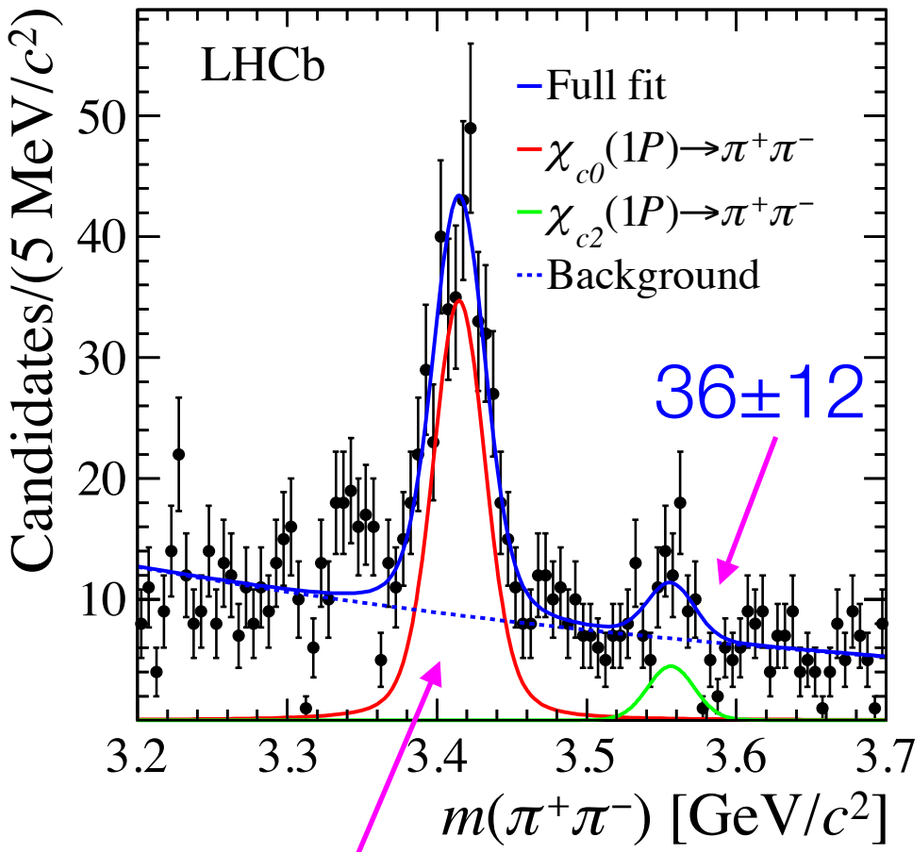
- Consistent with P or CP symmetry

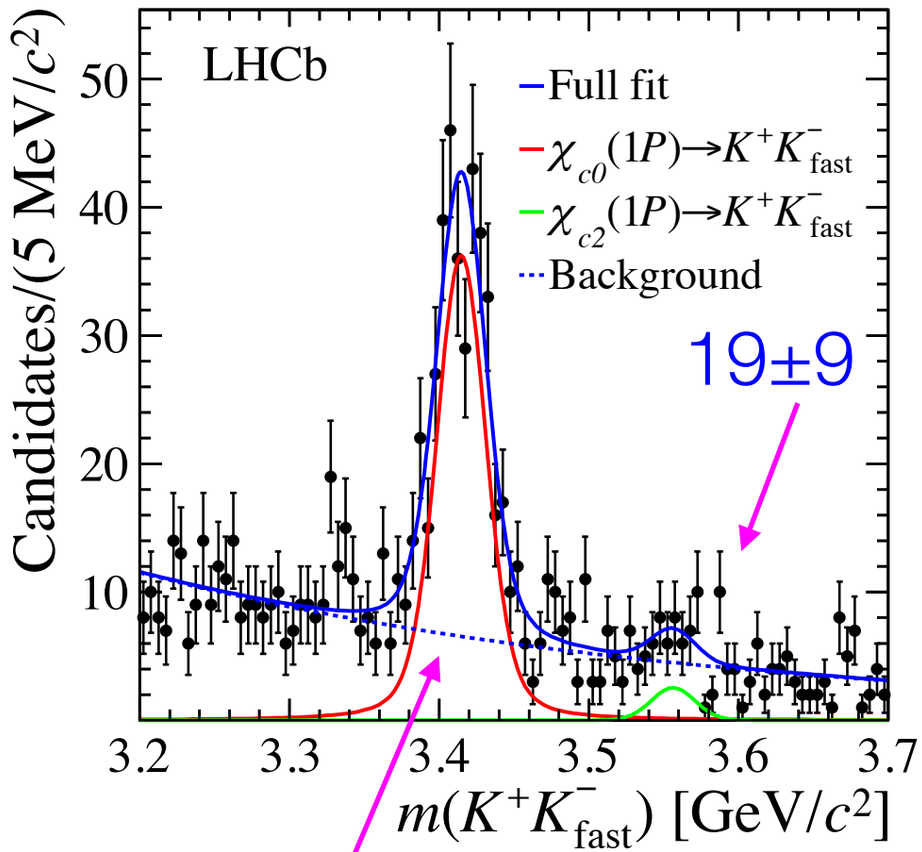
First observation of $\Lambda^0_b \to p\chi_{c0}(1P)K^-$

arXiv: 1805.03941, submitted to JHEP

- First observation of $\Lambda^0_b \to p\chi_{c0}(1P)K^-$, $\chi_{c0}(1P) \to \pi^+\pi^-$, K^+K^-

Run1, 3fb^{-1}





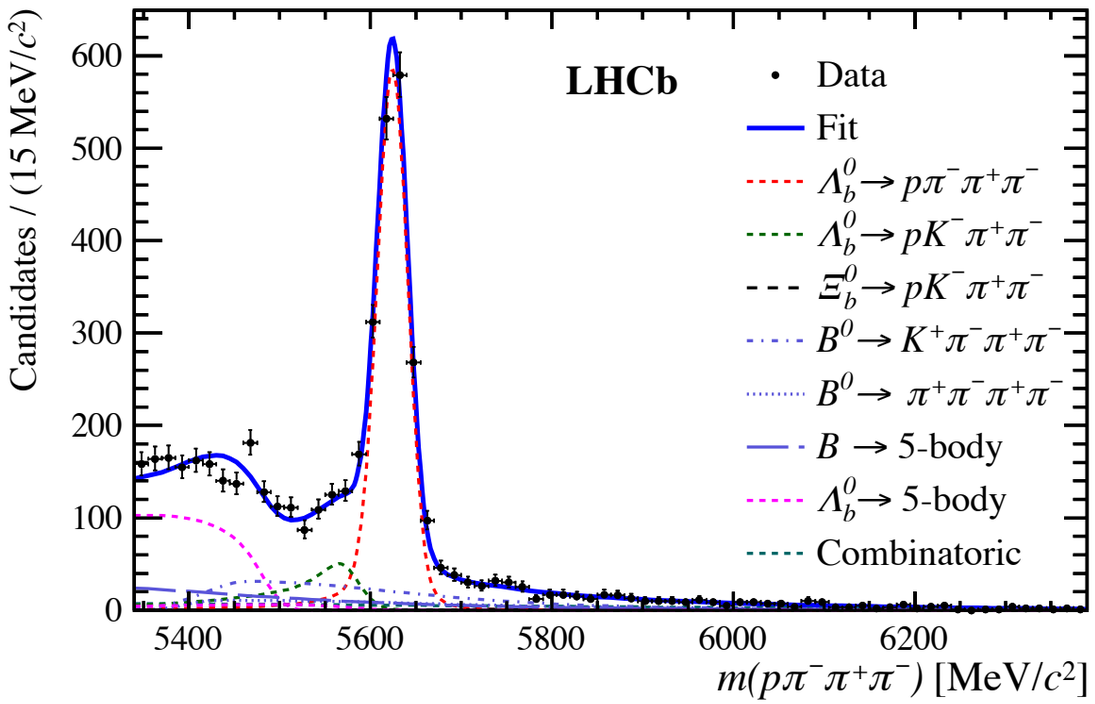
First BF measurements of $\Lambda^0_b, \Xi^0_b \to$ p3h

JHEP 1802(2018) 098

- $\Lambda^0_b \to \Lambda^+_c \pi^-$ normalisation channel. Simultaneous fit to signal and normalisation candidates.

$$R(X_b \to phh'h'') \equiv \frac{\mathcal{B}(X_b \to phh'h'')}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \pi^-)} \cdot \frac{f_{X_b}}{f_{\Lambda_b^0}},$$
$$= \frac{\epsilon^{\text{geo.}}_{\Lambda_b^0 \to \Lambda_c^+ \pi^-}}{\epsilon^{\text{geo.}}_{X_b \to phh'h''}} \cdot \frac{\epsilon^{\text{sel.}}_{\Lambda_b^0 \to \Lambda_c^+ \pi^-}}{\epsilon^{\text{sel.}}_{X_b \to phh'h''}} \cdot \frac{\epsilon^{\text{PID}}_{\Lambda_b^0 \to \Lambda_c^+ \pi^-}}{\epsilon^{\text{PID}}_{X_b \to phh'h''}} \cdot \frac{1}{\epsilon^{\text{veto}}_{X_b \to phh'h''}} \cdot \frac{\mathcal{N}_{X_b \to phh'h''}}{\mathcal{N}_{\Lambda_b^0 \to \Lambda_c^+ \pi^-}}$$

Run1, 3fb^{-1}



$$\mathcal{B}(\Lambda_b^0 \to p\pi^-\pi^+\pi^-) = (1.90 \pm 0.06 \pm 0.10 \pm 0.16 \pm 0.07) \cdot 10^{-5}$$
$$\mathcal{B}(\Lambda_b^0 \to pK^-\pi^+\pi^-) = (4.55 \pm 0.08 \pm 0.20 \pm 0.39 \pm 0.17) \cdot 10^{-5}$$
$$\mathcal{B}(\Lambda_b^0 \to pK^-K^+\pi^-) = (0.37 \pm 0.03 \pm 0.04 \pm 0.03 \pm 0.01) \cdot 10^{-5}$$
$$\mathcal{B}(\Lambda_b^0 \to pK^-K^+K^-) = (1.14 \pm 0.03 \pm 0.07 \pm 0.10 \pm 0.05) \cdot 10^{-5}$$
$$\mathcal{B}(\Xi_b^0 \to pK^-\pi^+\pi^-) \cdot f_{\Xi_b^0}/f_{\Lambda_b^0} = (1.72 \pm 0.21 \pm 0.25 \pm 0.15 \pm 0.07) \cdot 10^{-6}$$
$$\mathcal{B}(\Xi_b^0 \to pK^-\pi^+K^-) \cdot f_{\Xi_b^0}/f_{\Lambda_b^0} = (1.56 \pm 0.16 \pm 0.19 \pm 0.13 \pm 0.06) \cdot 10^{-6}$$

Br($\Lambda^0_b \to \Lambda^+_c \pi^-$)

Br($\Lambda^+_c \to pK^-\pi^+$)

Summary

- LHCb opens new window to search for CPV in baryon decays. Many b-baryon decays observed for the first time.

- Evidence of CPV found in $\Lambda^0_b \to p\pi^-\pi^+\pi^-$ decays with a statistical significance of 3.3σ. This represents the first evidence of CPV in baryon sector.

- Search for CPV using TPA has been performed in $\Lambda^0_b, \Xi^0_b \to$ p3h decays using Run 1 data. With the data collected in Run2, these analyses will be updated to increased sensitivity.

- Theoretical predictions for CPV in b-baryon decays needed to confront with precision measurements.

Thank you!

BACK UP

Significance of CPV using permutation tests

Nature Phys. 13 (2017) 391-396

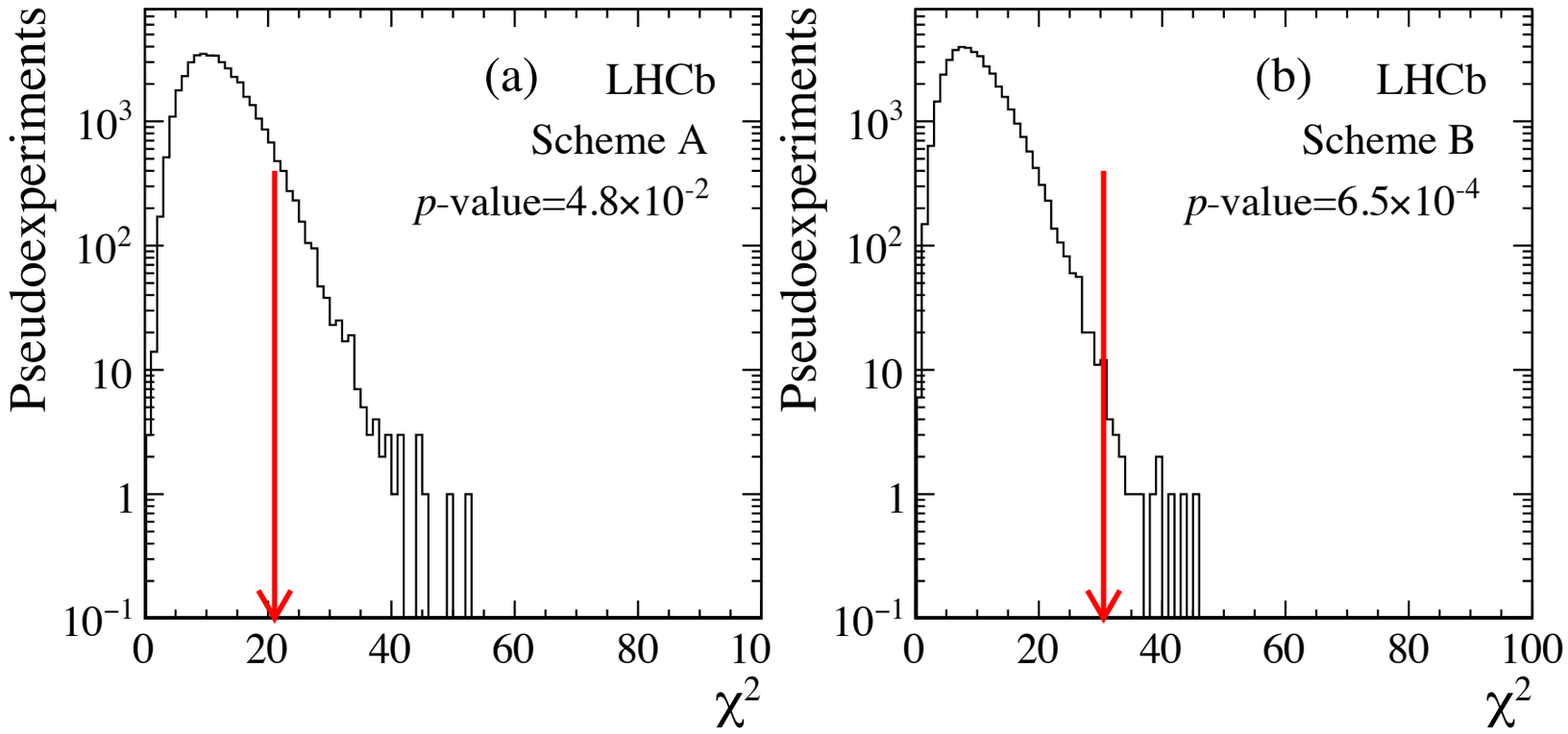
Permutation test based on resampling technique using signal sample: randomly assign Λ_b^0 flavour to each event, and define C_T sign only if a different flavour assigned, as follows:

$$\text{If} \quad \Lambda_b^0 \to \overline{\Lambda}_b^0 \quad \text{then} \quad C_T \to \overline{C}_T = -C_T$$
$$\text{If} \quad \overline{\Lambda}_b^0 \to \Lambda_b^0 \quad \text{then} \quad \overline{C}_T \to C_T = -\overline{C}_T$$

p-value of combination of scheme A and B results using Fisher method

$$p\text{-value} = \frac{N(p_A p_B < p_A^{obs} p_B^{obs})}{N_{total}}$$

Results consistent with χ^2 test



Significance=2.0σ

Significance=3.4σ

Significance=3.3σ