Search for CP violation in baryon decays at LHCb

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On behalf of the LHCb collaboration

CERN–LHC Seminar
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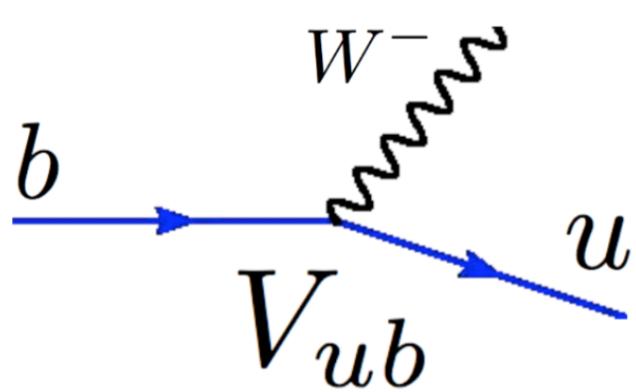
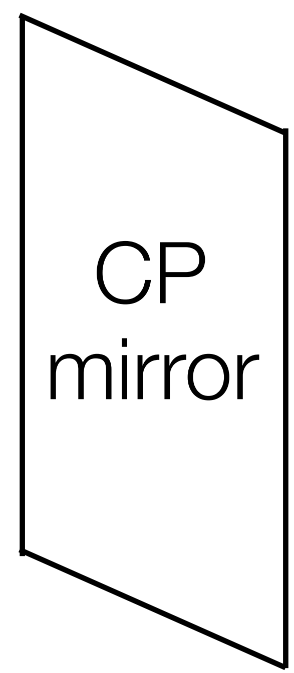
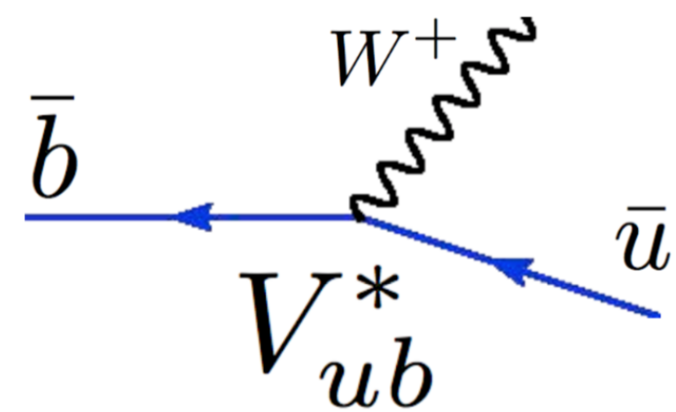
CP violation

- C = Charge conjugation: $A \rightarrow \bar{A}$
- P = Parity, spatial inversion: $x \rightarrow -x,\ y \rightarrow -y,\ z \rightarrow -z$
- CP transformation: $(A \rightarrow f) \rightarrow (\bar{A} \rightarrow \bar{f})$

CP violation (CPV):
A difference between decays of particles and anti-particles breaks CP symmetry







V_{ub}: coupling of b to u quark

CP violation in Standard Model

- In SM, CPV is accommodated in the weak quark current:

$$\frac{g}{\sqrt{2}}\left(\overline{U}_L\gamma^\mu V_{CKM} D_L W^-_\mu + \overline{D}_L\gamma^\mu V^\dagger_{CKM} U_L W^+_\mu\right)$$

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$$\cong \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

- Wolfenstein parametrisation: CKM matrix described by 4 parameters λ, A, ρ, η.

- η is the only source of CPV in the SM, and changes sign for quark and antiquark transitions.

The Unitarity Triangle

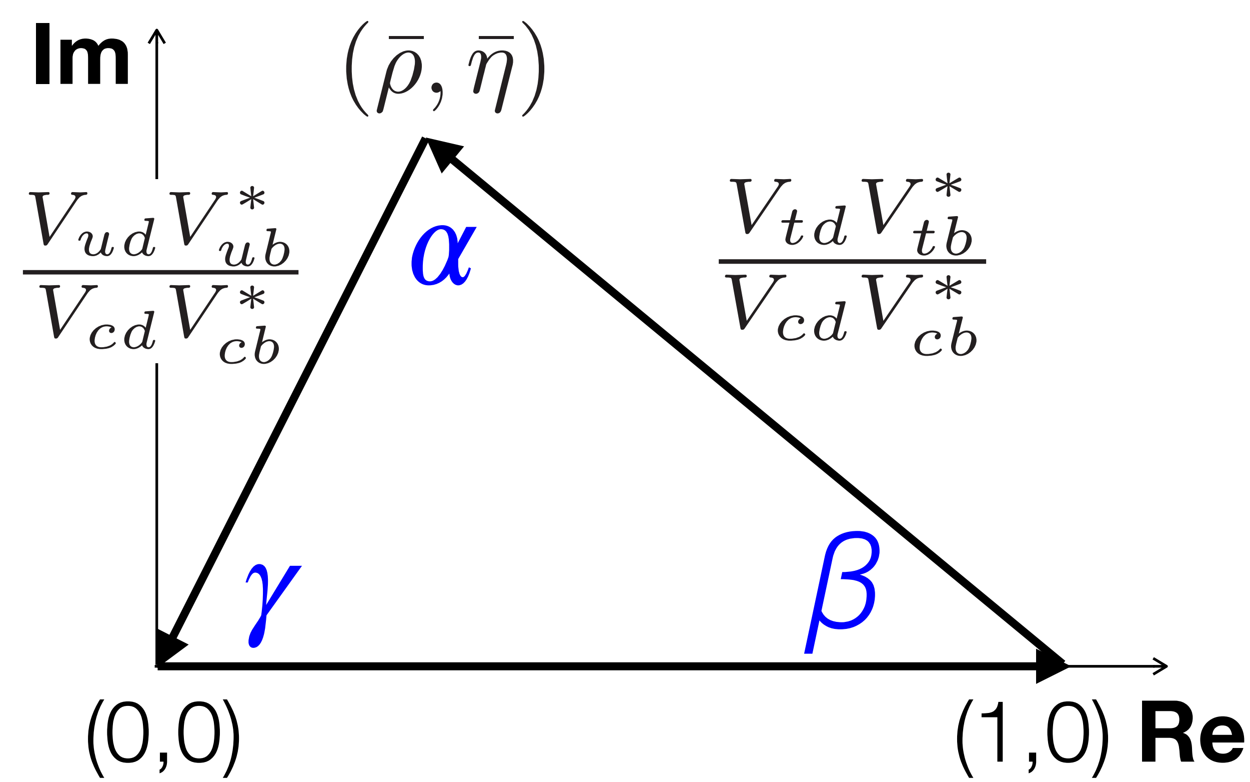
$$V_{CKM} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

Unitarity condition from 1st and 3rd columns:

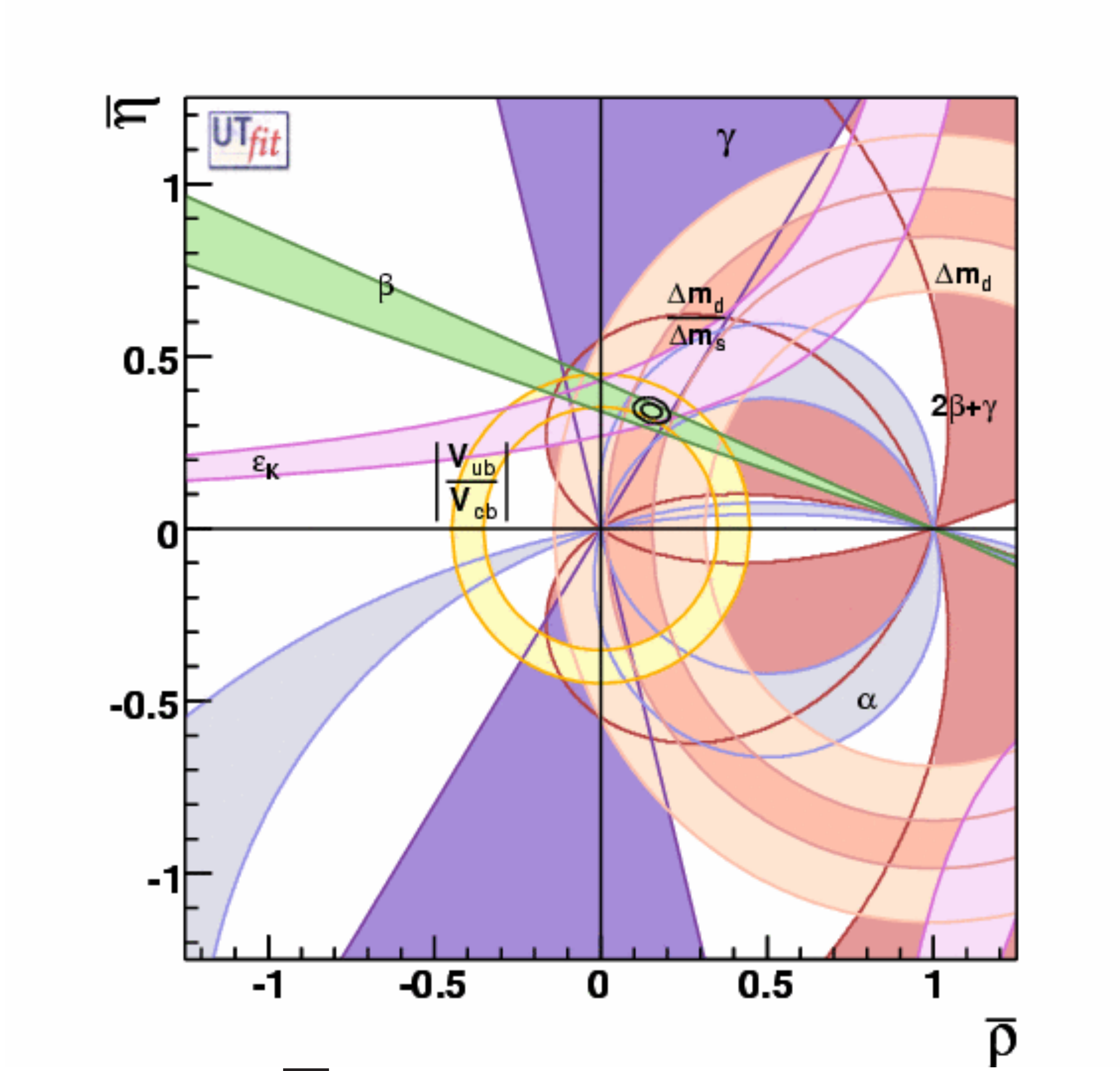
$$V_{ud}V_{ub}^* + V_{cd}V_{cd}^* + V_{td}V_{tb}^* = 0$$

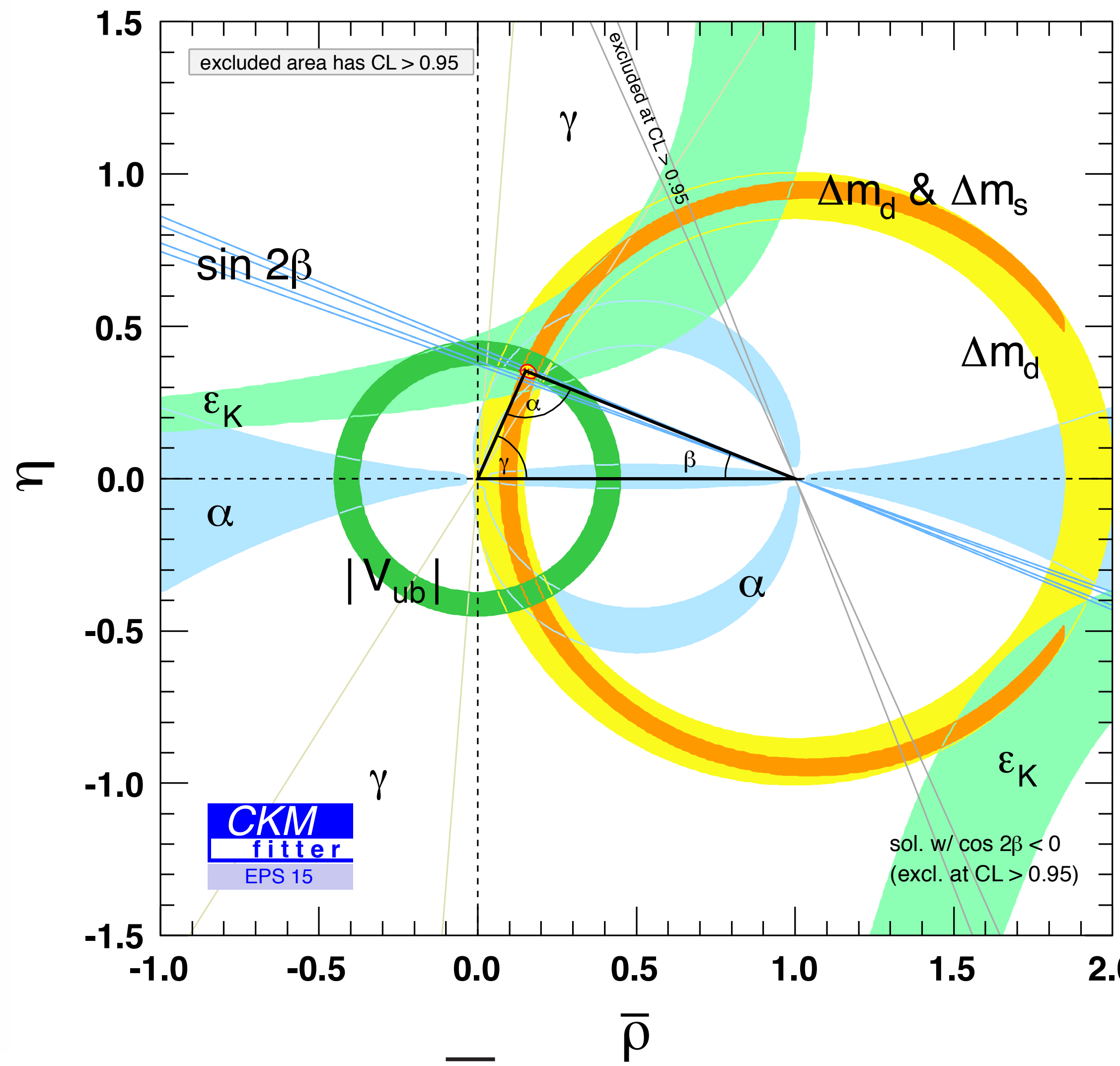
Over-constrain apex coordinates for a stringent test of SM:

- ✓ CP violation measurements give angles
- ✓ CP conserving measurements give sides



The Unitarity Triangle





$\bar{\rho}$ = 0.153±0.013

$\bar{\eta}$ = 0.343±0.011

$\bar{\rho}$ = 0.150±0.012

$\bar{\eta}$ = 0.354±0.007

overall picture is consistent with SM, $\bar{\rho}$ determined at 8% and $\bar{\eta}$ at 3% level, but still room for new physics.

Why study CPV ?

Violation of CP symmetry is a necessary condition for the Baryon Asymmetry of the Universe [1]

CPV is present only in the weak interactions via CKM mechanism in the SM, but is too small to explain the absence of antimatter in the universe

Possibly there are other sources of CPV beyond SM. Need to search for CPV effects extensively

[1] A. D. Sakharov, "Violation of *CP* invariance, *C* asymmetry, and baryon asymmetry of the universe," JETP Lett. 5, 24-27 (1967), Sov. Phys. Usp. 34, 392-393 (1991)

Some history of CPV in K- and B- meson system

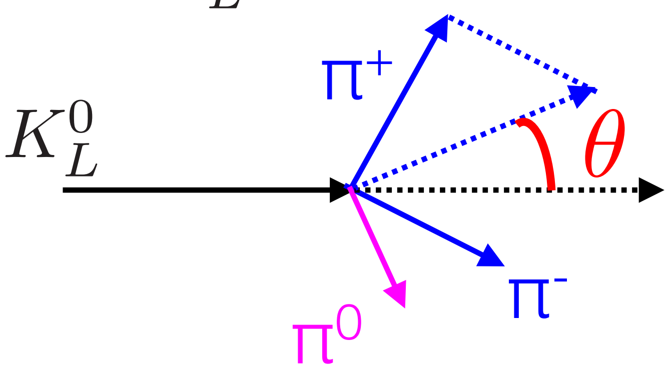
First evidence of CPV in $K_L^0 \to \pi^+\pi^-$

Phys.Rev.Lett. 13 (1964) 138

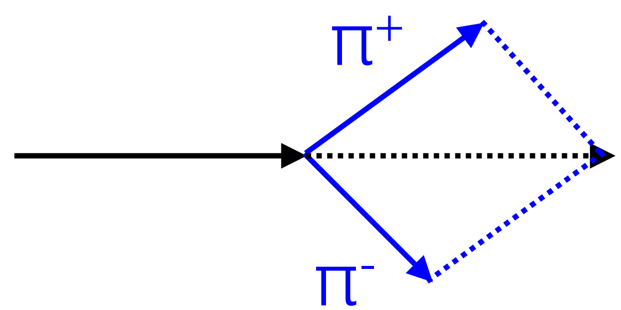
- Look for CP-violating decays:

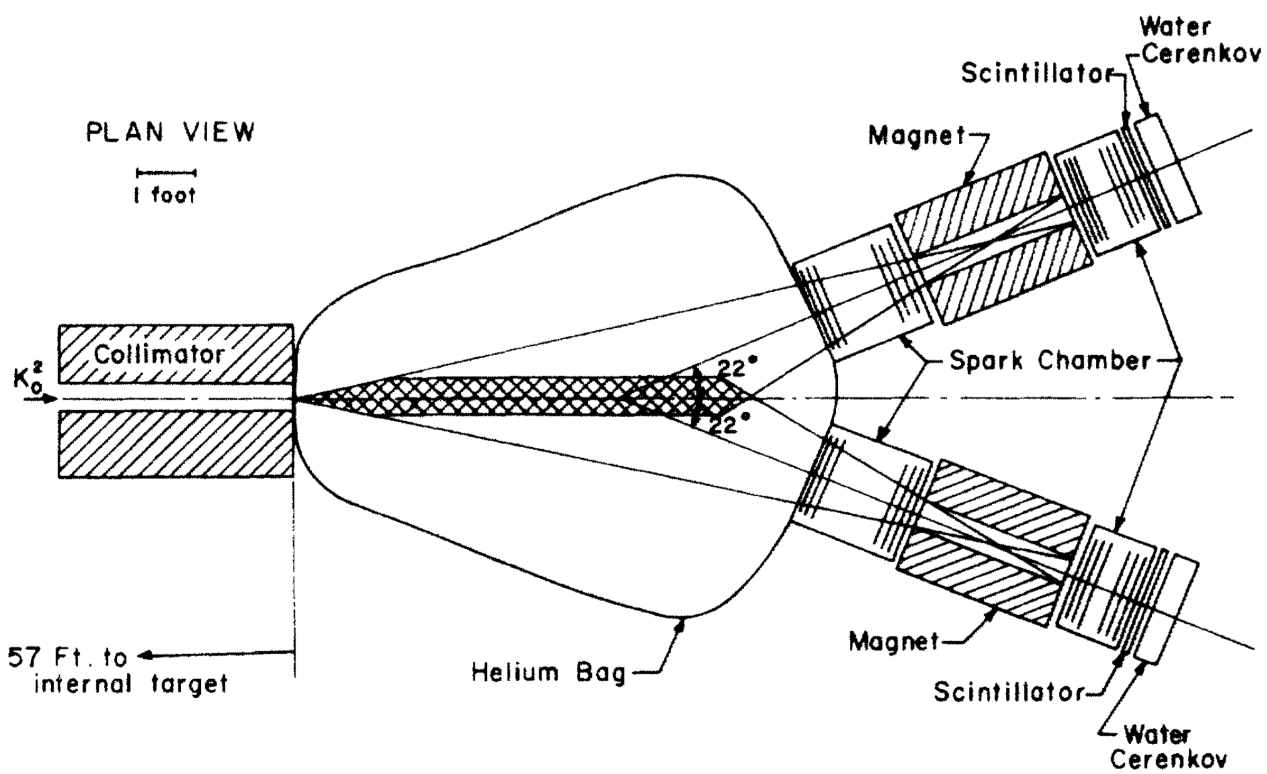
$$K_L^0 \to \pi^+\pi^-$$
$$CP(K_L^0) = -1 \qquad CP(\pi^+\pi^-) = +1$$

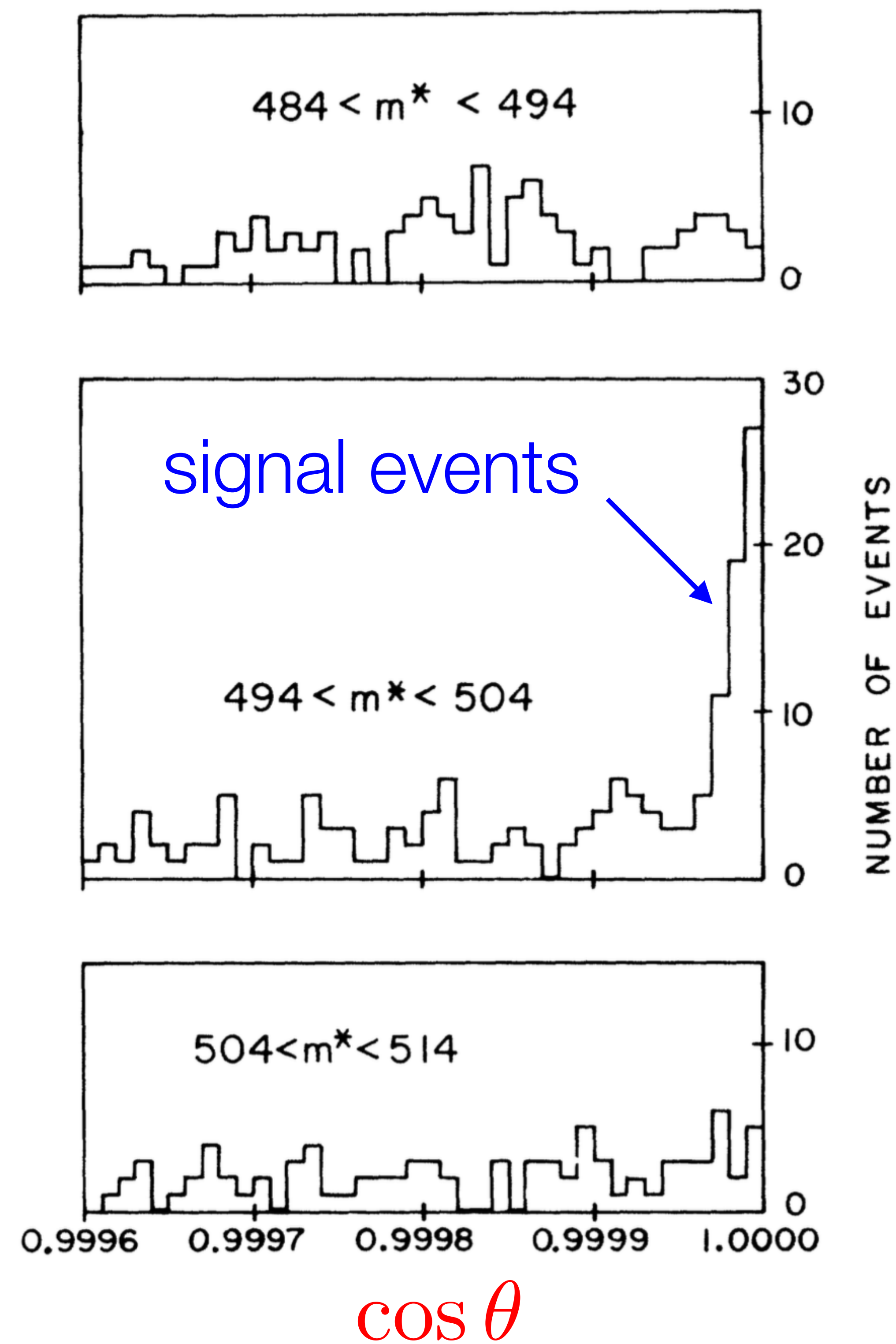
$K_L^0 \to \pi^+\pi^-\pi^0$



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







First observation of direct CPV in $K^0_{S,L} \to \pi\pi$

- Determine direct CP-violating parameter by measuring double ratio of decay rates.

$$R = \frac{\Gamma(K^0_L \to \pi^0\pi^0)/\Gamma(K^0_S \to \pi^0\pi^0)}{\Gamma(K^0_L \to \pi^+\pi^-)/\Gamma(K^0_S \to \pi^+\pi^-)}$$

$$= \left|\frac{\eta_{00}}{\eta_{+-}}\right|^2 = \left|\frac{\epsilon - 2\epsilon'}{\epsilon + \epsilon'}\right|^2$$

$$\approx 1 - 6 \cdot \mathrm{Re}\left(\frac{\epsilon'}{\epsilon}\right)$$

- The first evidence was obtained by NA31 **NA31: Phys. Lett. B317 (1993) 233**

$$\mathrm{Re}\left(\frac{\epsilon'}{\epsilon}\right) = (23.0 \pm 6.5) \times 10^{-4}$$

- The first observations followed few years later

$$\mathrm{Re}\left(\frac{\epsilon'}{\epsilon}\right) = (18.5 \pm 4.5 \pm 5.8) \times 10^{-4}$$ **NA48: Phys.Lett., B 465, 1999**

$$\mathrm{Re}\left(\frac{\epsilon'}{\epsilon}\right) = (28.0 \pm 3.0 \pm 2.8) \times 10^{-4}$$ **KTeV: Phys.Rev.Lett., 83, 22,1999**

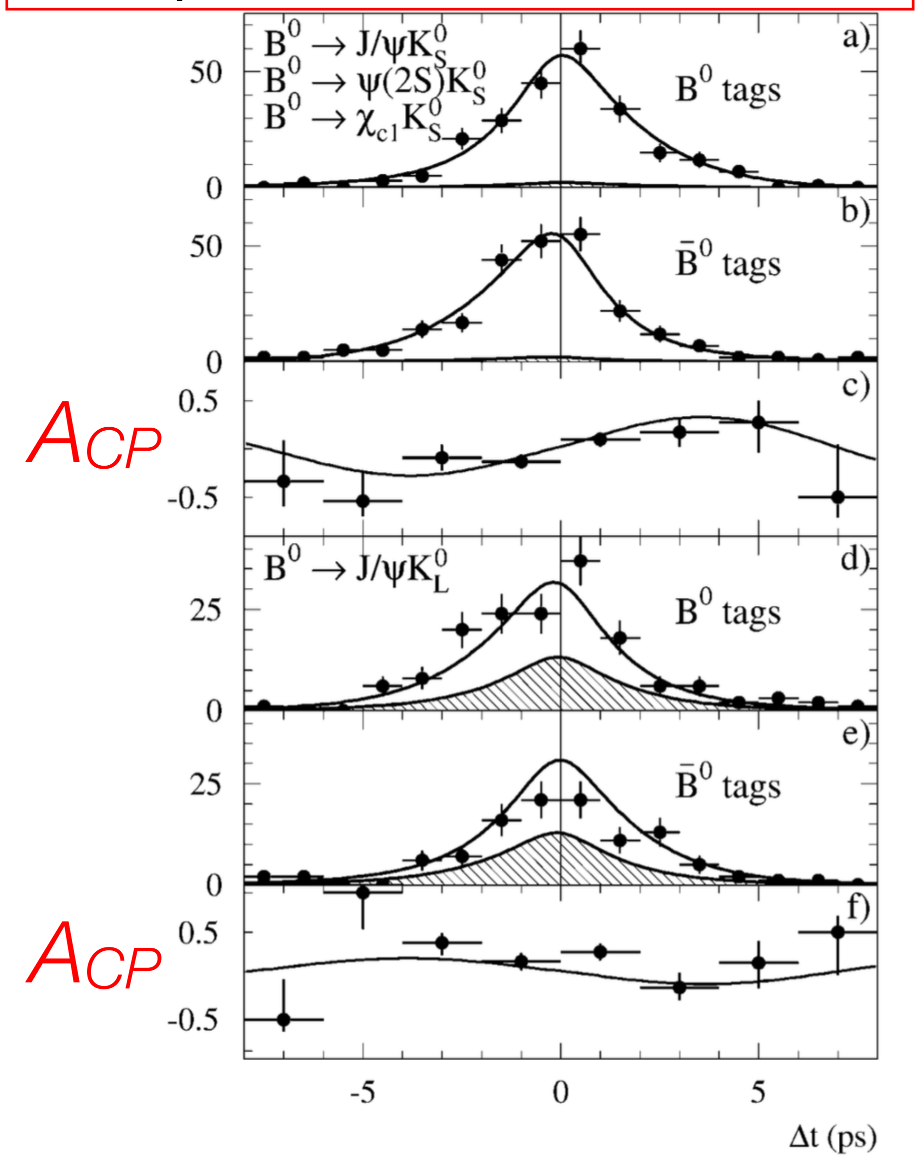
Observation of CPV in B_d^0 system

- The amplitude of CP-violating asymmetry, proportional to sin2β, derived from the decay time distribution

$$A_{CP}(\Delta t) = -\eta_f \sin(2\beta) \sin(\Delta m_{B^0} \Delta t)$$

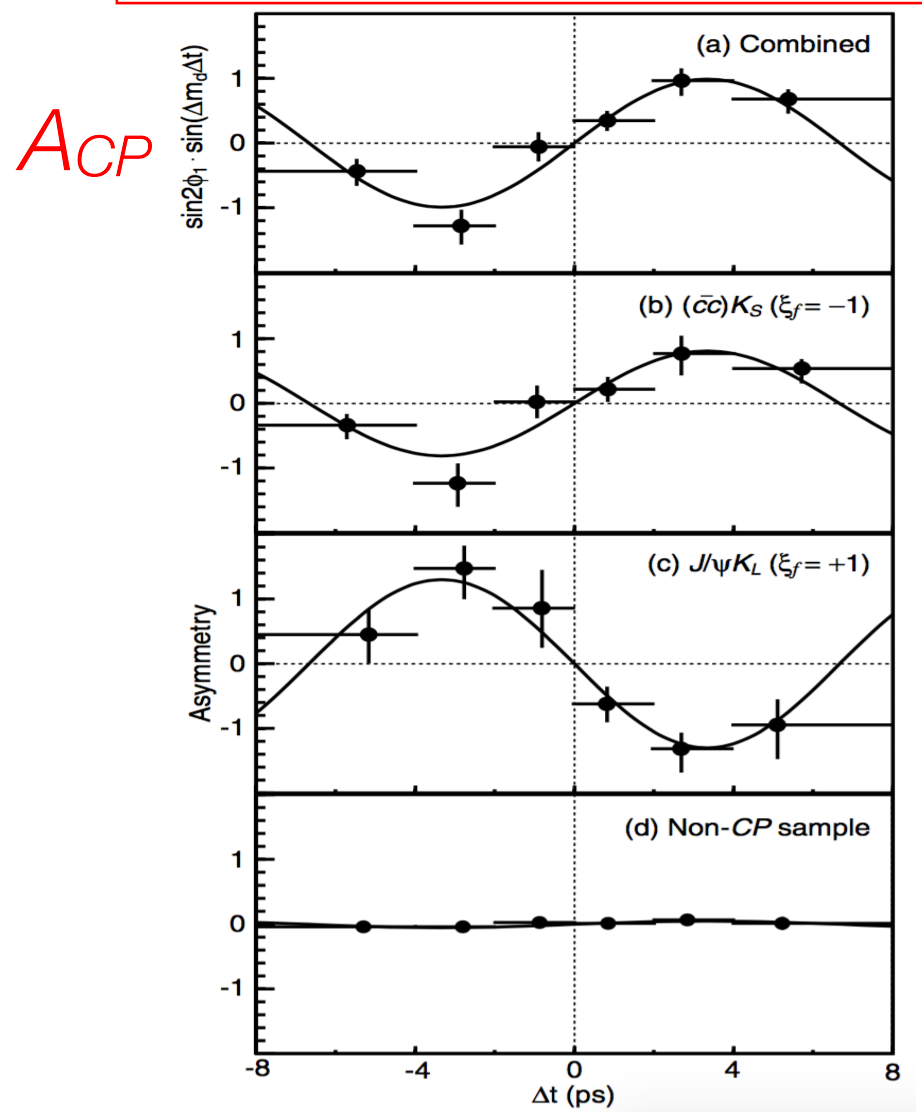
Babar: Phys.Rev.Lett. 87 (2001) 091801

sin2β=0.59±0.14±0.05



Belle: Phys. Rev. Lett. 87 (2001) 091802

sin2β=0.99±0.14±0.06



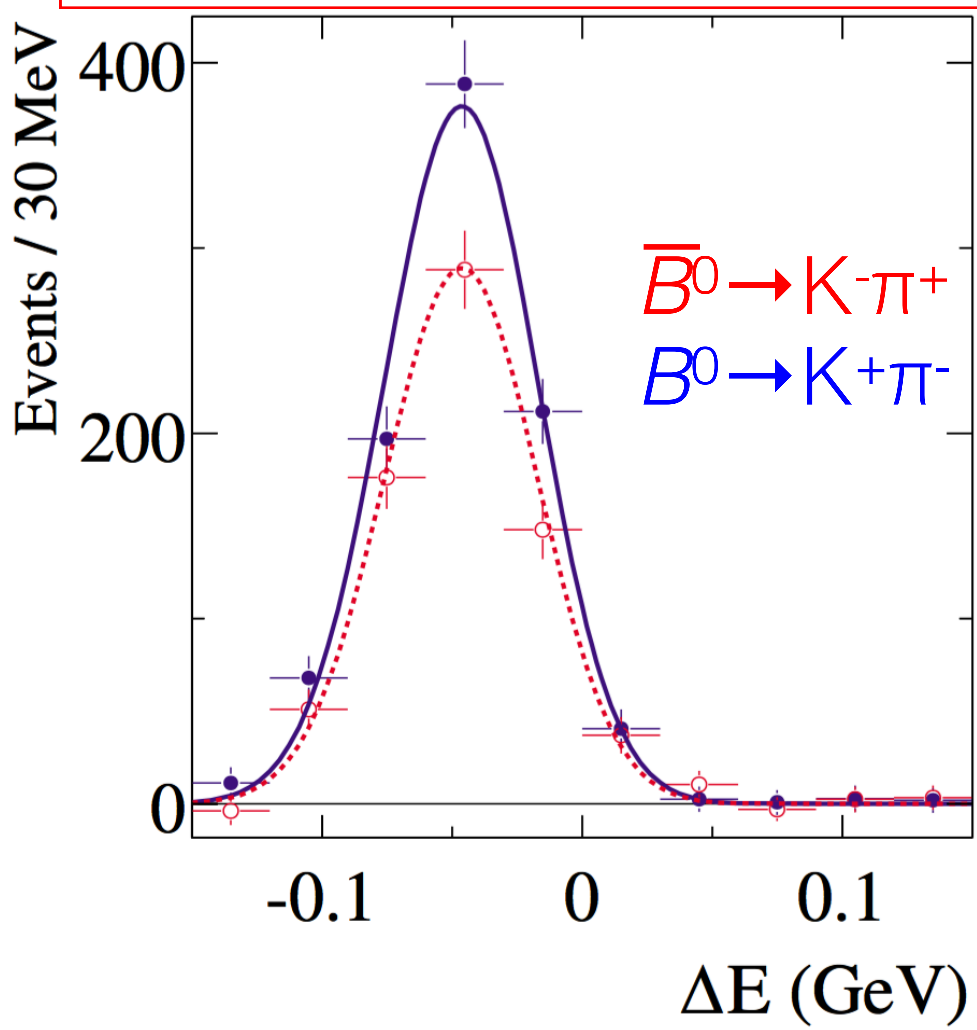
Observation of direct CPV in $B_d^0 \to K^+\pi^-$

- CP-violating asymmetry measured as:

$$A_{CP} = \frac{N(\overline{B}^0 \to K^-\pi^+) - N(B^0 \to K^+\pi^-)}{N(\overline{B}^0 \to K^-\pi^+) + N(B^0 \to K^+\pi^-)}$$

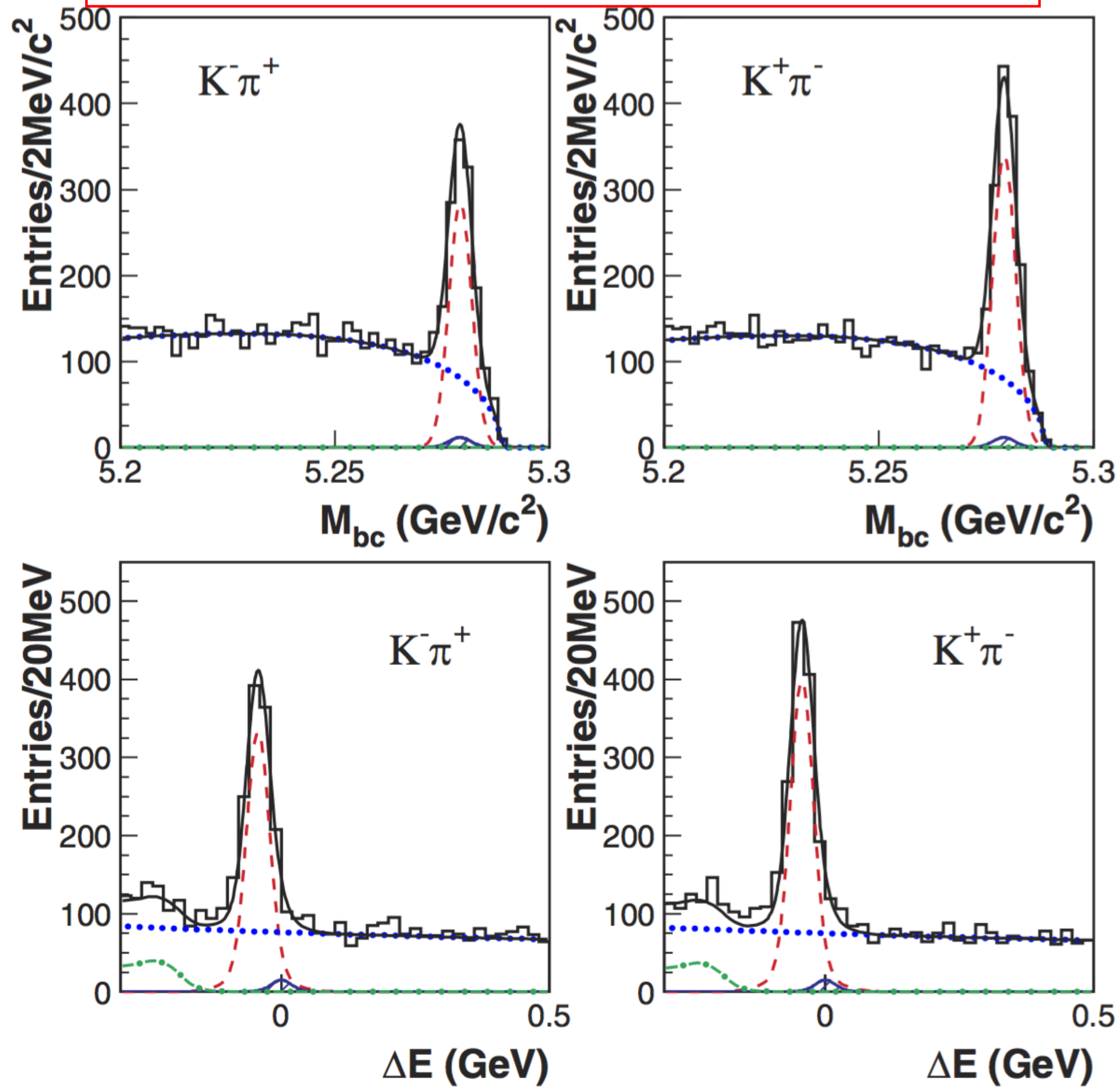
Babar: Phys.Rev.Lett., 93:131801, 2004

A_{CP}=−0.133±0.030±0.009



Belle: Phys.Rev.Lett., 93:191802, 2004

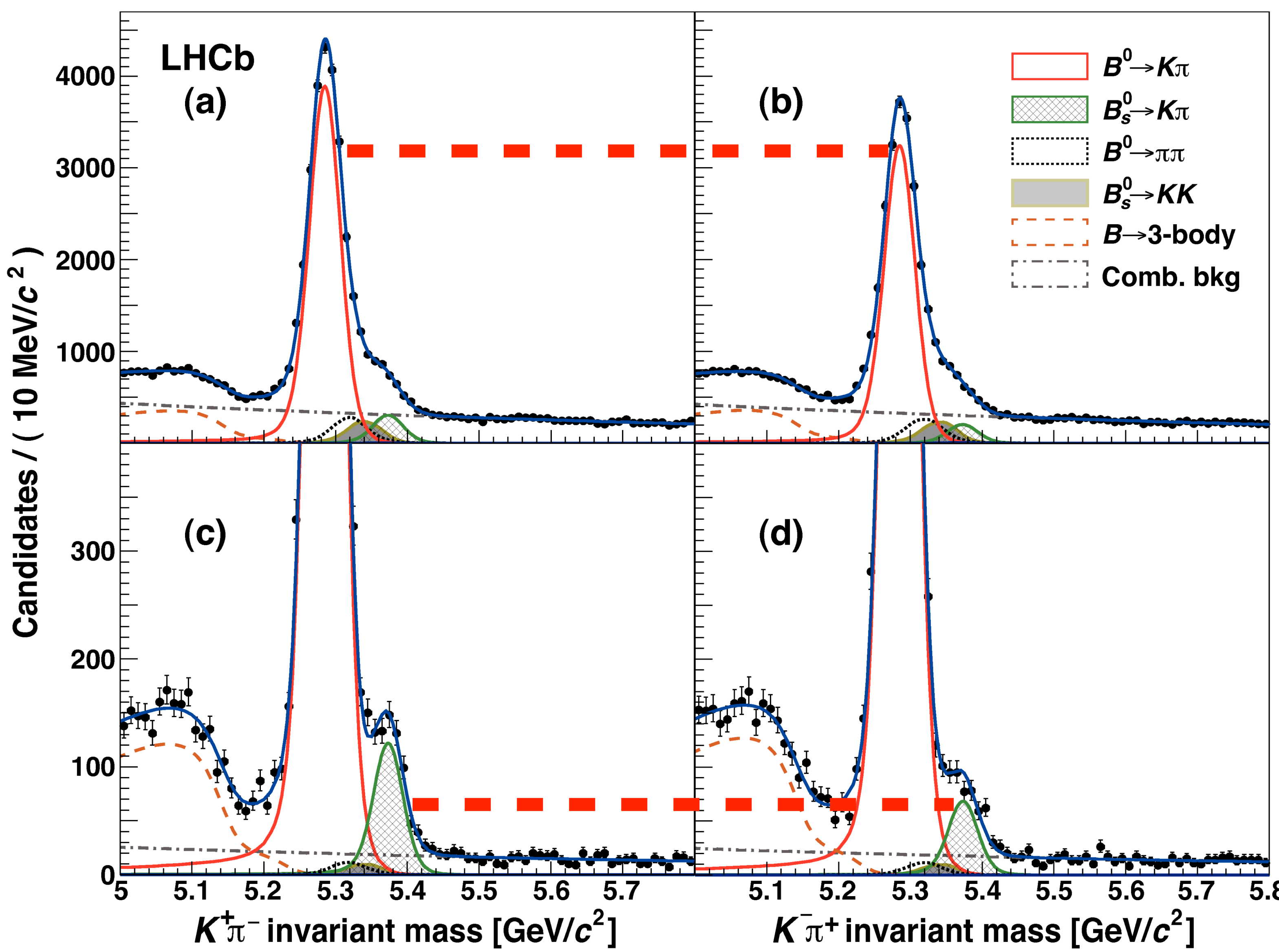
A_{CP}=−0.101±0.025±0.005



First observation of direct CPV in $B_s^0 \to K^- \pi^+$

- CP-violating asymmetry measured as:

$$A_{CP} = \frac{N(\overline{B}_s^0 \to K^+ \pi^-) - N(B_s^0 \to K^- \pi^+)}{N(\overline{B}_s^0 \to K^+ \pi^-) + N(B_s^0 \to K^- \pi^+)}$$



$B^0 \to K\pi$
$A_{CP} = -0.080 \pm 0.007 \pm 0.003$

$B_s^0 \to K\pi$
$A_{CP} = 0.27 \pm 0.04 \pm 0.01$

LHCb: Phys. Rev. Lett., 110:221601, 2013

Search for CPV in baryon decays

Exp.	Mode	Observable	
HyperCP	$\Xi^- \to \Lambda\pi^- \to p\pi^-\pi^-$	$A_{CP} = (0.0 \pm 5.1 \pm 4.4) \times 10^{-4}$	[1]
HyperCP	$\Omega^- \to \Xi^-\pi^+\pi^-$	$A_{CP} = 0.12 \pm 0.20$	[2]
FOCUS	$\Lambda_c^+ \to \Lambda\pi^+$	$A_{CP} = -0.07 \pm 0.19 \pm 0.12$	[3]
CLEO	$\Lambda_c^+ \to \Lambda e^+\nu_e$	$A_{CP} = 0.00 \pm 0.03 \pm 0.01 \pm 0.02$	[4]

CDF searched for CPV in Λ_b^0 baryons: [5]

$$\mathcal{A}_{CP}(\Lambda_b^0 \to pK^-) = +0.37 \pm 0.17(stat) \pm 0.03(syst)$$
$$\mathcal{A}_{CP}(\Lambda_b^0 \to p\pi^-) = +0.03 \pm 0.17(stat) \pm 0.05(syst)$$

[1]: Phys.Rev.Lett.93:262001,2004
[2]: Phys.Lett.B693:236-240,2010
[3]: Phys.Lett. B634 (2006) 165-172
[4]: Phys.Rev.Lett. 94 (2005) 191801
[5]: Phys.Rev.Lett. 106 (2011) 181802

Consistent with CP symmetry

Direct CPV in baryon sector

- Only direct CPV in baryon sector, because no baryon mixing due to baryon number conservation

- CPV can be measured by comparing yields between baryon and anti-baryon decays

δ: strong phase
φ: weak phase

$$A_{CP} = \frac{N(A \to f) - N(\overline{A} \to \overline{f})}{N(A \to f) + N(\overline{A} \to \overline{f})} \propto \sin(\delta_1 - \delta_2) \sin(\varphi_1 - \varphi_2)$$

- ✓ the decay receives contributions from at least two amplitudes: $A_1 e^{i\delta_1} e^{i\varphi_1}$, $A_2 e^{i\delta_2} e^{i\varphi_2}$
- ✓ need non-vanishing strong and weak phase difference
- ✓ sensitive to baryon-antibaryon production asymmetries
- ✓ sensitive to charged particle reconstruction asymmetries

Direct CPV in baryon sector

- CPV can be measured using difference of P-odd observables, between particle and antiparticles i.e. $a_{CP}^{P\text{-odd}}$ is a P-odd and CP-odd observable

- $a_{CP}^{P\text{-odd}}$ using triple products e.g $\vec{v}_1 \cdot (\vec{v}_2 \times \vec{v}_3)$, $v = p$. If v = spin then construct $a_{CP}^{\hat{T}\text{-odd}}$ observable

  $\hat{T}$: unitary operator, $\vec{p} \to -\vec{p}$ and $\vec{S} \to -\vec{S}$

- It can be demonstrated that:

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

Phys. Rev. D 92, 076013 (2015)

✓ sensitive to the interference of $\hat{T}$-even (P-even) and $\hat{T}$-odd (P-odd) amplitudes

✓ provides different sensitivity to CP violation (see next slides)

Beauty baryons at LHCb

- LHCb is a b-baryon factory, one Λ_b^0 for every two B^0 :
  opens a new field for precision measurements in flavour physics

- Some highlights from LHCb:

  ✓ Most precise measurement of $|V_{ub}|$ using $\Lambda_b^0 \to p\mu^-\bar{\nu}_\mu$ decays
  Nature Physics 10 (2015) 1038

  ✓ First observation of pentaquarks using $\Lambda_b^0 \to J/\psi p K^-$ decays
  Phys. Rev. Lett. 115, 072001 (2015)

  ✓ Observation of $\Xi_b^{\prime -}$ and $\Xi_b^{\prime *}$ in $\Xi_b^0\pi^-$ mode
  Phys. Rev. Lett 114, 062004 (2015)

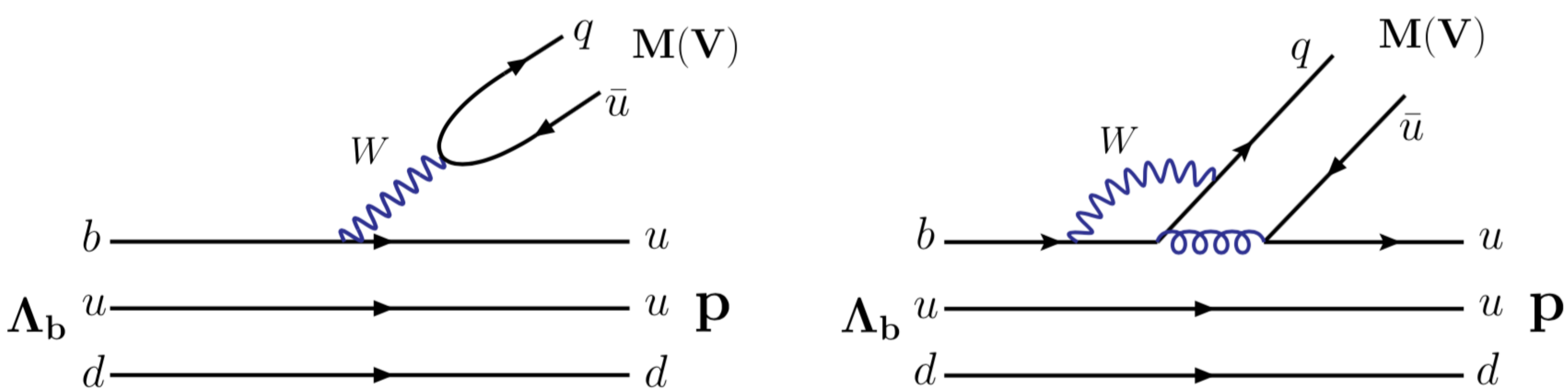
  ✓ Observation of two orbitally excited Λ_b^{*0} states
  Phys. Rev. Lett 109, 172003 (2012)

  ✓ Mass, lifetimes and branching ratios measurements

Beauty baryons at LHCb

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

possible large interference between tree and penguin diagrams



✓ Potentially large CPV effects in charmless Λ_b^0 decays, up to A_{CP}=20%

Phys. Rev. D 91, 116007 (2015)

	Our result	pQCD [4]	Data
$10^2 \mathcal{A}_{CP}(\Lambda_b \to pK^-)$	$5.8 \pm 0.2 \pm 0.1$	-5^{+26}_{-5}	$-10 \pm 8 \pm 4$ [7]
$10^2 \mathcal{A}_{CP}(\Lambda_b \to p\pi^-)$	$-3.9 \pm 0.2 \pm 0.0$	-31^{+43}_{-1}	$6 \pm 7 \pm 3$ [7]
$10^2 \mathcal{A}_{CP}(\Lambda_b \to pK^{*-})$	$19.6 \pm 1.3 \pm 1.0$	...	...
$10^2 \mathcal{A}_{CP}(\Lambda_b \to p\rho^-)$	$-3.7 \pm 0.3 \pm 0.0$	...	...

LHCb detector

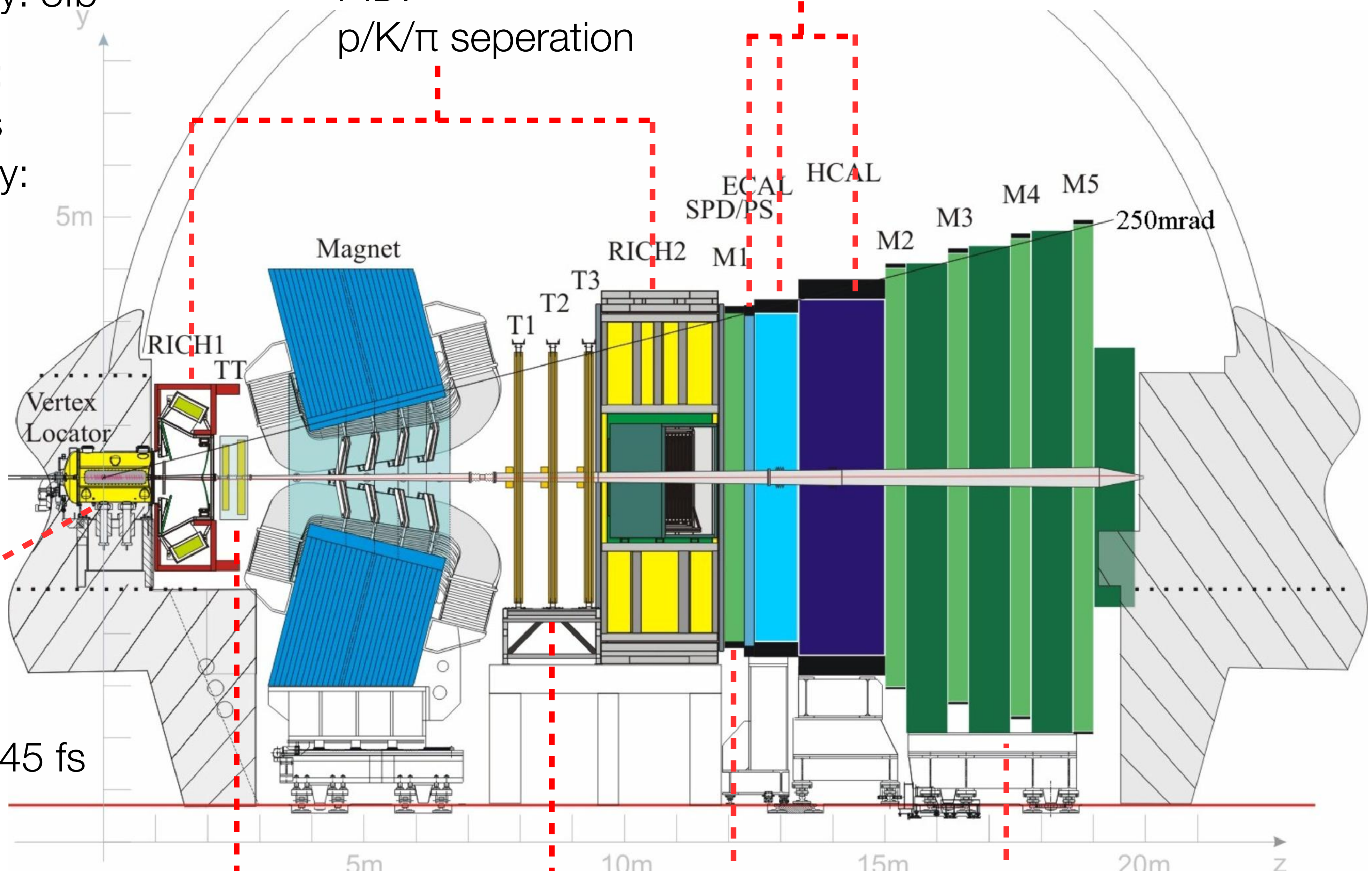
Int. J. Mod. Phys. A 30 (2015) 1530022

Run I (2010~2012):
7,8 TeV pp collisions
Integrated luminosity: 3fb^{-1}

Run II (2015~2018):
13 TeV pp collisions
Integrated luminosity:
(expected): 5fb^{-1}

PID:
p/K/π seperation

Calorimeter system:
trigger + γ/e energy and ID



Vertex detector:
precise vertexing,
decay time resolution: 45 fs
IP resolution: 20μm

Tracking system:
Δp/p 0.4%—0.6%

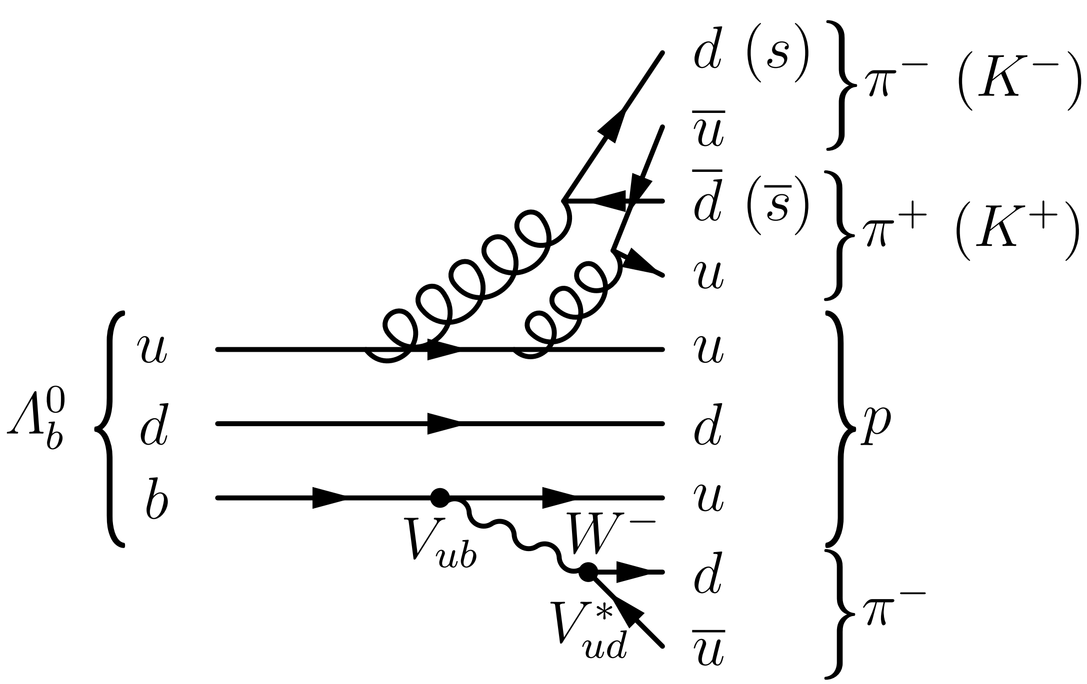
Muon system: trigger
+ μ ID

Search for CPV using triple-product asymmetries in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ and $\Lambda_b^0 \to p\pi^- K^+ K^-$ decays

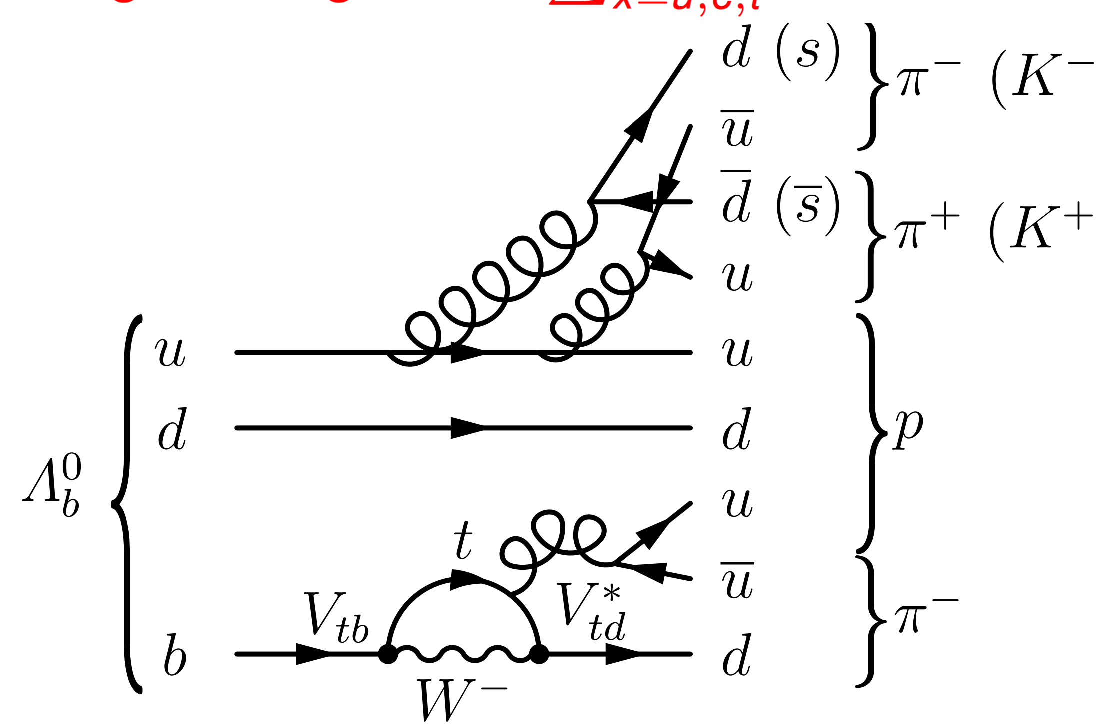
arXiv:1609.05216, submitted to Nature Physics

- Transitions governed by $b \to u d \bar{u}$ tree and $b \to d u \bar{u}$ penguin amplitudes of similar magnitude. Relative weak phase dominated by large CKM phases $-\arg(V_{ub})=\gamma$ and $-\arg(V_{td})=\beta$

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



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



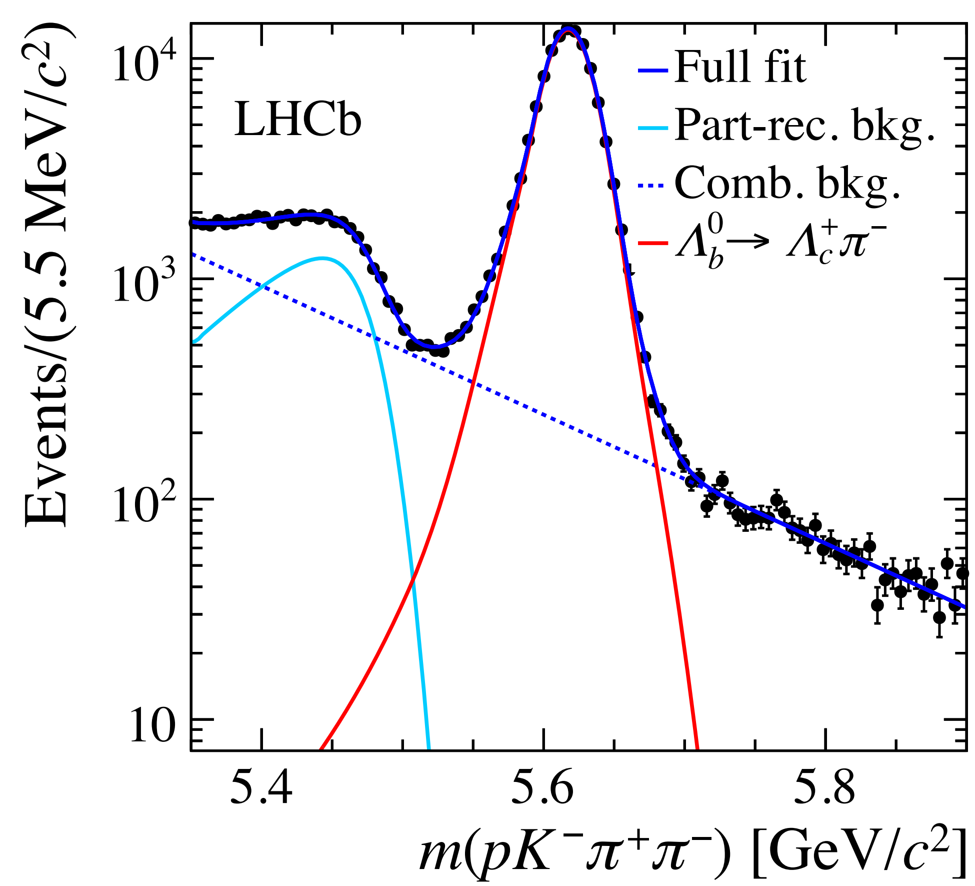
Event selection

arXiv:1609.05216, submitted to Nature Physics

- Veto intermediate charm hadrons
  $\Lambda_c^+, \Xi_c^+, D^0, D^\pm, D_s^\pm$
- Apply boosted decision tree to suppress combinatorial background, and particle identification criteria on charged hadrons

- Use $\Lambda_b^0 \to \Lambda_c^+(pK^-\pi^+)\pi^-$, a V_{cb} mediated decay with no CPV expected, as control sample to assess main source of systematic uncertainties

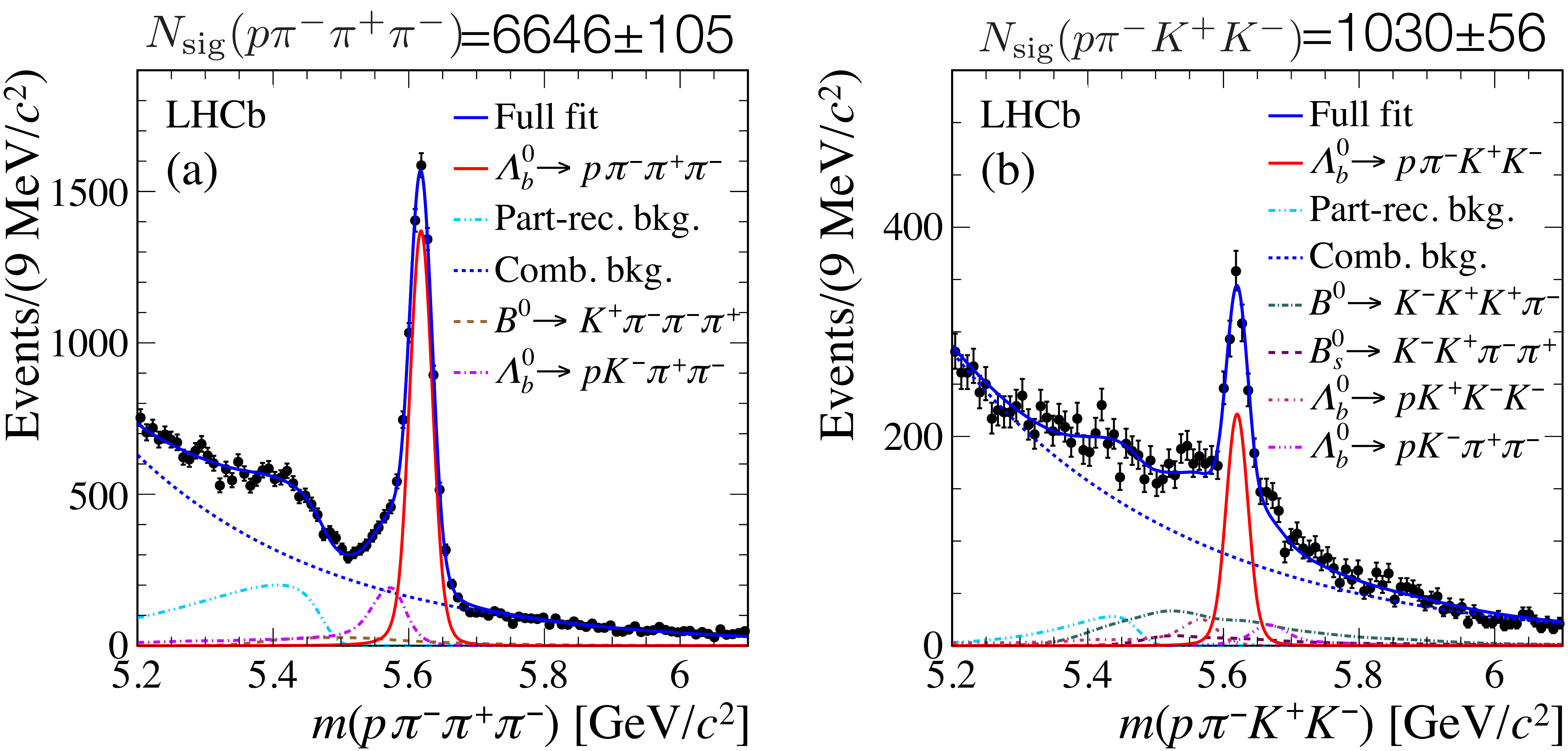
control sample



Signal yields

arXiv:1609.05216, submitted to Nature Physics

- First observation of two decay modes



Experimental technique

- Triple products:

  use momenta of any 3 final particles in Λ_b^0 4-body decays

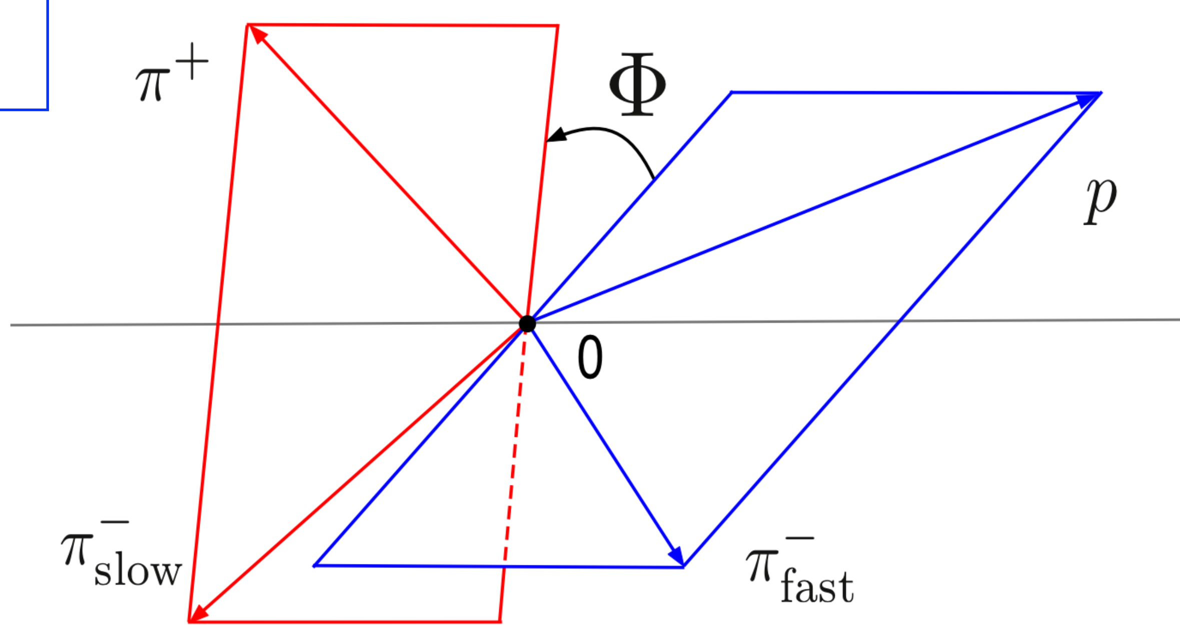
$$C_{\widehat{T}} = \vec{p}_p \cdot (\vec{p}_{h_1^-} \times \vec{p}_{h_2^+}) \quad \propto \sin\Phi \text{ , for } \Lambda_b^0$$
$$\overline{C}_{\widehat{T}} = \vec{p}_{\overline{p}} \cdot (\vec{p}_{h_1^+} \times \vec{p}_{h_2^-}) \quad \propto \sin\overline{\Phi} \text{ , for } \overline{\Lambda}_b^0$$

$h_1 = \pi, h_2 = K$ for $\Lambda_b^0 \to p\pi^- K^+ K^-$

$h_1 = \pi_{\text{fast}}, h_2 = \pi_{\text{slow}}$ for $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$

π choice ambiguity resolved by taking $\vec{p}_{\pi_{\text{fast}}} > \vec{p}_{\pi_{\text{slow}}}$ in Λ_b^0 rest frame.

Λ_b^0 rest frame



Experimental technique

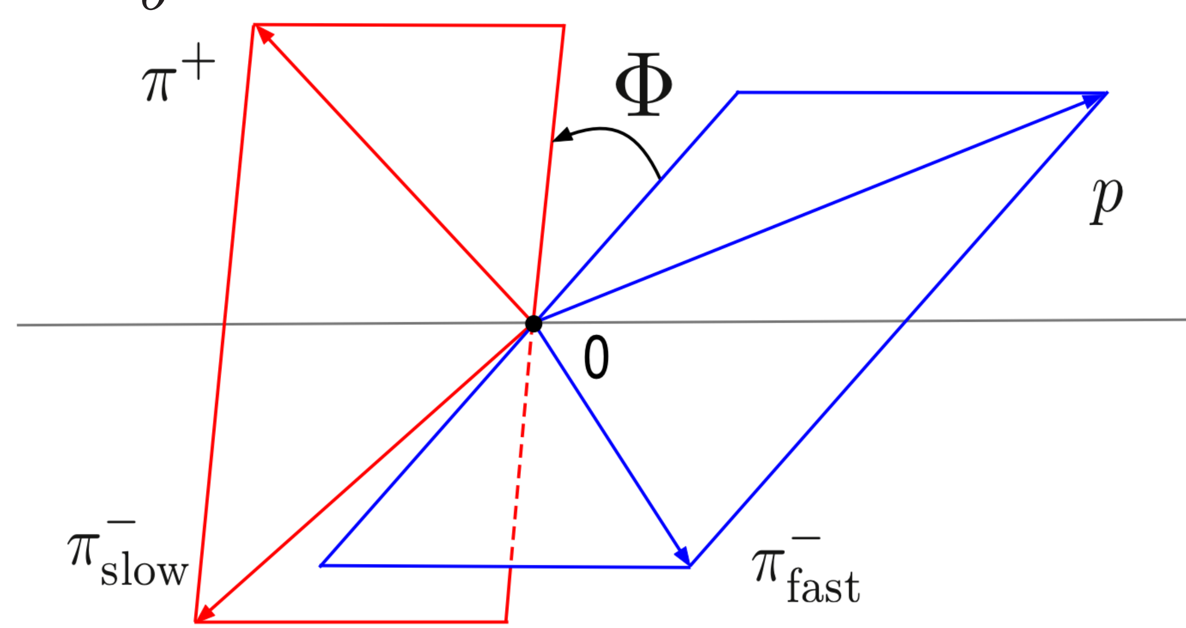
- P-odd ($\hat{T}$-odd) asymmetries:

$$A_{\hat{T}}(C_{\hat{T}}) = \frac{N(C_{\hat{T}}>0)-N(C_{\hat{T}}<0)}{N(C_{\hat{T}}>0)+N(C_{\hat{T}}<0)}$$, for Λ_b^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 $\overline{\Lambda}_b^0$

- $A_{\hat{T}}$ and $\overline{A}_{\hat{T}}$ indicate P violation, if non zero.

Gasiorowicz, S. (1966). *Elementary particle physics*. John Wiley & Sons, New York.



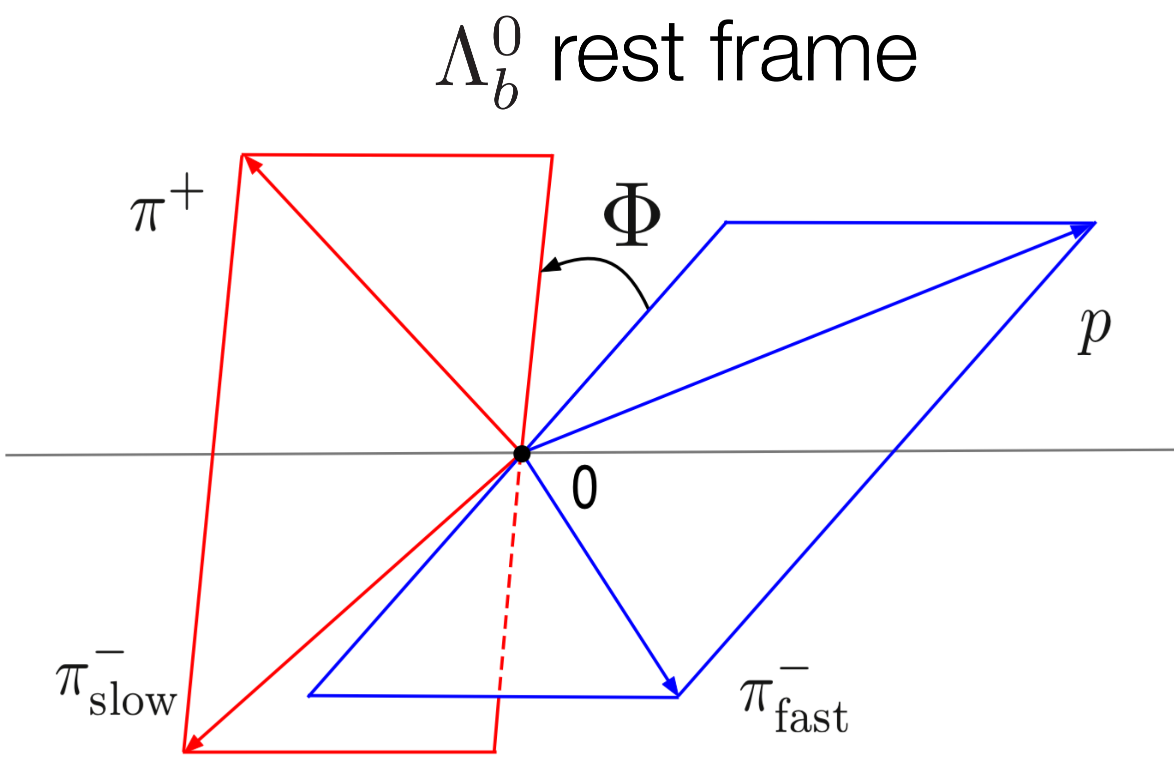
Experimental technique

- CP-violating observable:

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

- P-violating observable:

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



Sensitivity to CPV

- By construction, $A_{\hat{T}}$, $\overline{A}_{\hat{T}}$, $a_P^{\hat{T}\text{-odd}}$ and $a_{CP}^{\hat{T}\text{-odd}}$ are largely unaffected by
  - ✓ 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 $\delta_{\text{even}} - \delta_{\text{odd}} = \pi/2$ or $3\pi/2$

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

not sensitive if $\delta_1 - \delta_2 = 0$ or π

- Sensitive to potential new physics effects:

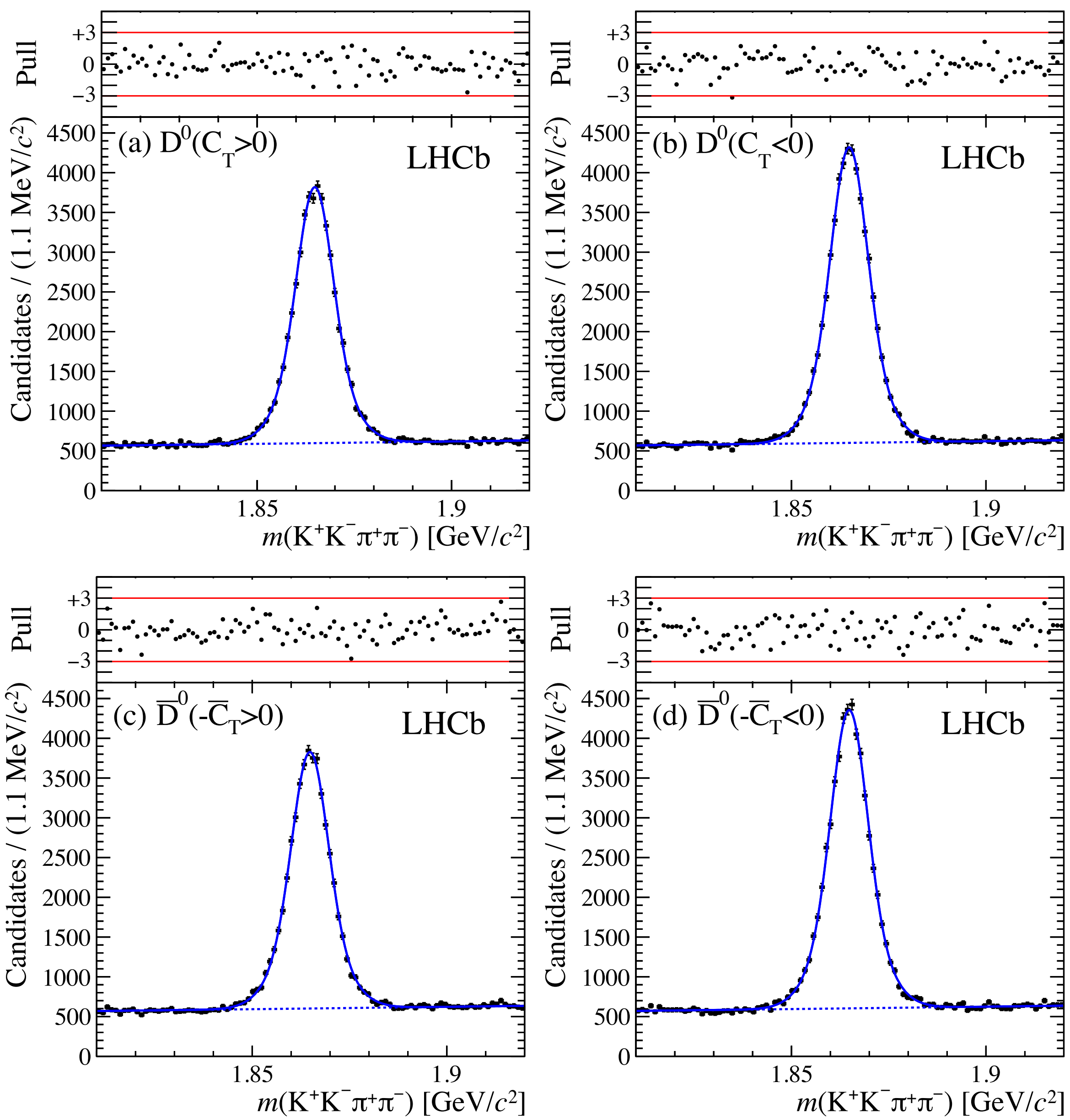
W. Bensalem, A. Datta, and D. London, New physics effects on triple product correlations in Λ_b decays, Phys. Rev. D66 (2002) 094004, arXiv:hep-ph/0208054

Experimental technique (continued)

This alternative approach for precision CPV searches established in $D^0 \to K^+K^-\pi^+\pi^-$ decays at LHCb **JHEP 10 (2014) 005**

Inspired theorists to study triple-product asymmetries systematically

Phys. Rev. D 92, 076013 (2015)
arXiv:1608.03288
Phys. Lett.B749 (2015) 104–107



$a_{CP}^{\hat{T}\text{-odd}}$=(0.18±0.29±0.04)%

statistical uncertainty is dominated, systematic uncertainty dominated by experimental bias, estimated using large control sample of Cabibbo favoured decay mode $D^0 \to K^-\pi^+\pi^-\pi^+$.

Measurement of asymmetries

- Asymmetries $A_{\hat{T}}$ and $\overline{A}_{\hat{T}}$ are extracted using a simultaneous unbinned maximum likelihood fit to the invariant mass distributions **m(p3h)** of different signal categories:

- Two measurements:
  - ✓ Measurements integrated in the phase space
  - ✓ Measurements in different regions of the phase space: enhance sensitivity to localised CPV effects

- Blind analysis:

  event selection, phase space division, systematic uncertainties and statistical procedures are determined before unblinding data.

Search for CPV in regions of phase space

- In order to improve sensitivity to CPV, measurements in bins of the phase space are performed.
- The compatibility with CP symmetry hypothesis is tested by means of a χ^2 test: $\chi^2 = R^T V^{-1} R$

✓ *R*: array of $a_{CP}^{\hat{T}\text{-odd}}$ measurements.

✓ *V*: sum of the statistical and systematic covariance matrices.

  - Systematic uncertainties assumed to be fully correlated among different bins.
  - An average systematic uncertainty assumed for the different bins.

Phase space division

- No priori knowledge of the best binning scheme due to the very complicated four-body decay dynamics.
- $a_{CP}^{\hat{T}\text{-odd}}$changes sign in one region would dilute sensitivity. Binning choice guided by decay topology, resonance structure, spin of particles, and location of the known resonances.**Phys. Rev. D 92, 076013 (2015)**

  ✓ divide phase space at peak of resonance

  ✓ divide phase space at π/2 in $|\mathbf{\Phi}|$

  ✓ interference might be largest in quasi-two body decays

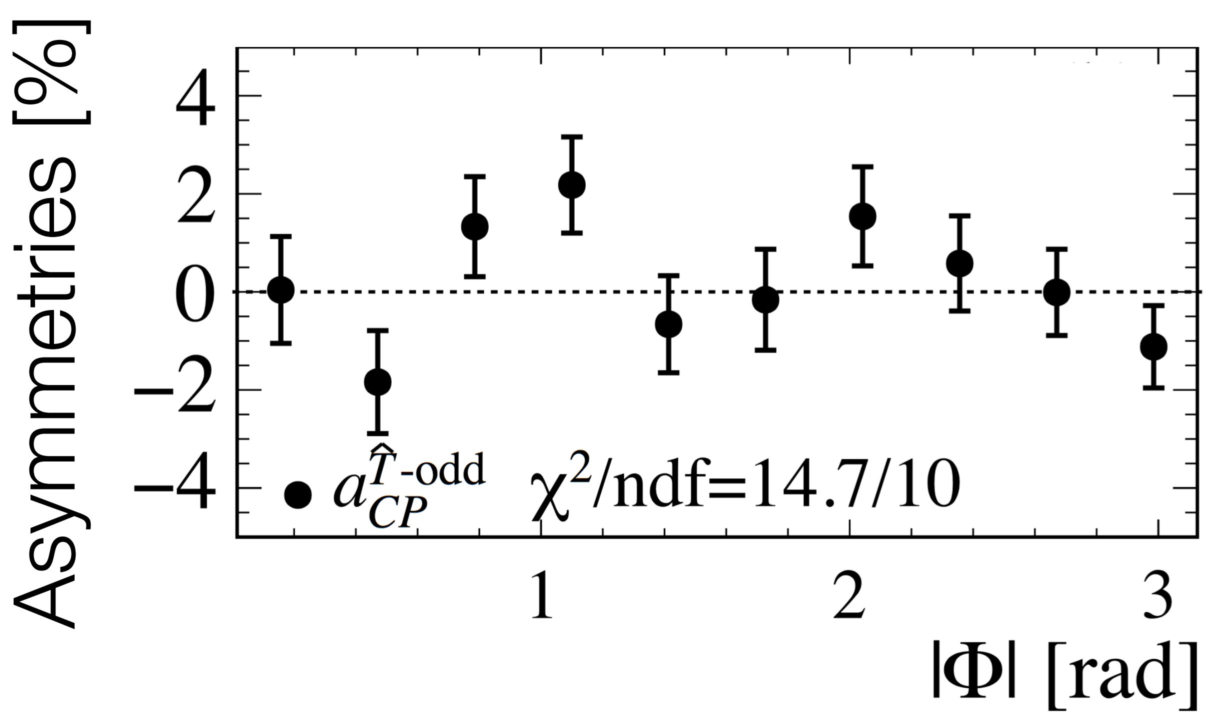
  ✓ compatible signal yields in each region

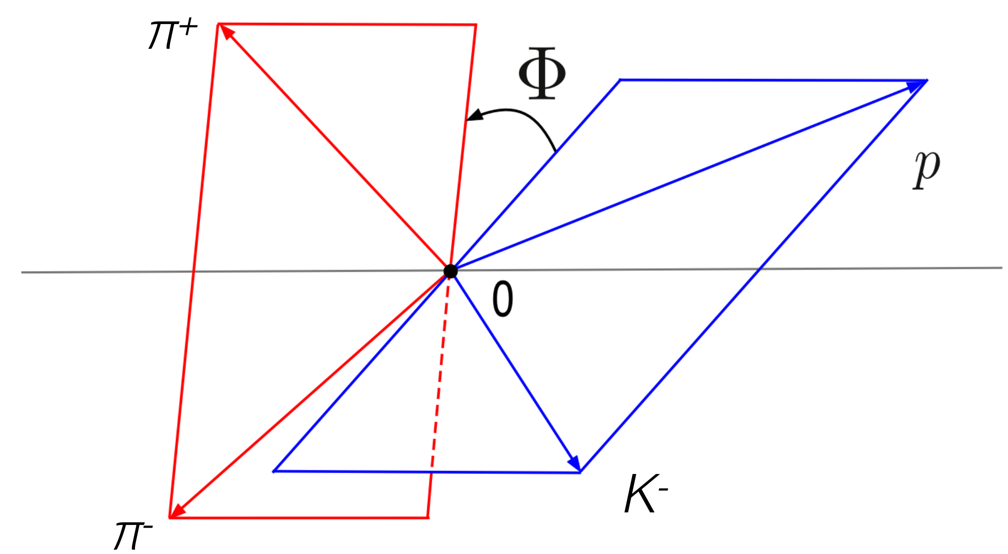
- Binning schemes fixed before unblind asymmetries. Consider look-else-where effect when multi-schemes applied.

Validation studies

arXiv:1609.05216, submitted to Nature Physics

- Analysis technique tested successfully in different regions of phase space using:
  - ✓ high statistics Monte Carlo samples (x30 data statistics)
  - ✓ abundant $\Lambda_b^0 \to \Lambda_c^+(pK^-\pi^+)\pi^-$ control sample, mediated by V_{cb} with no CPV expected, $a_{CP}^{\hat{T}\text{-odd}}$=(0.15±0.31)%
  - ✓ Measurements of $a_{CP}^{\hat{T}\text{-odd}}$ in bins of $|\boldsymbol{\Phi}|$ on control sample
    Result consistent with CP symmetry at 1.5σ level





Systematic uncertainties

- Main source of uncertainties is due to the experimental technique and detector reconstruction
  Estimated using control model $\Lambda_b^0 \to \Lambda_c^+ \pi^-$
- C_T resolution: estimated using signal MC
- Fit model: estimated by fitting 10,000 pseudo experiments with alternative models.

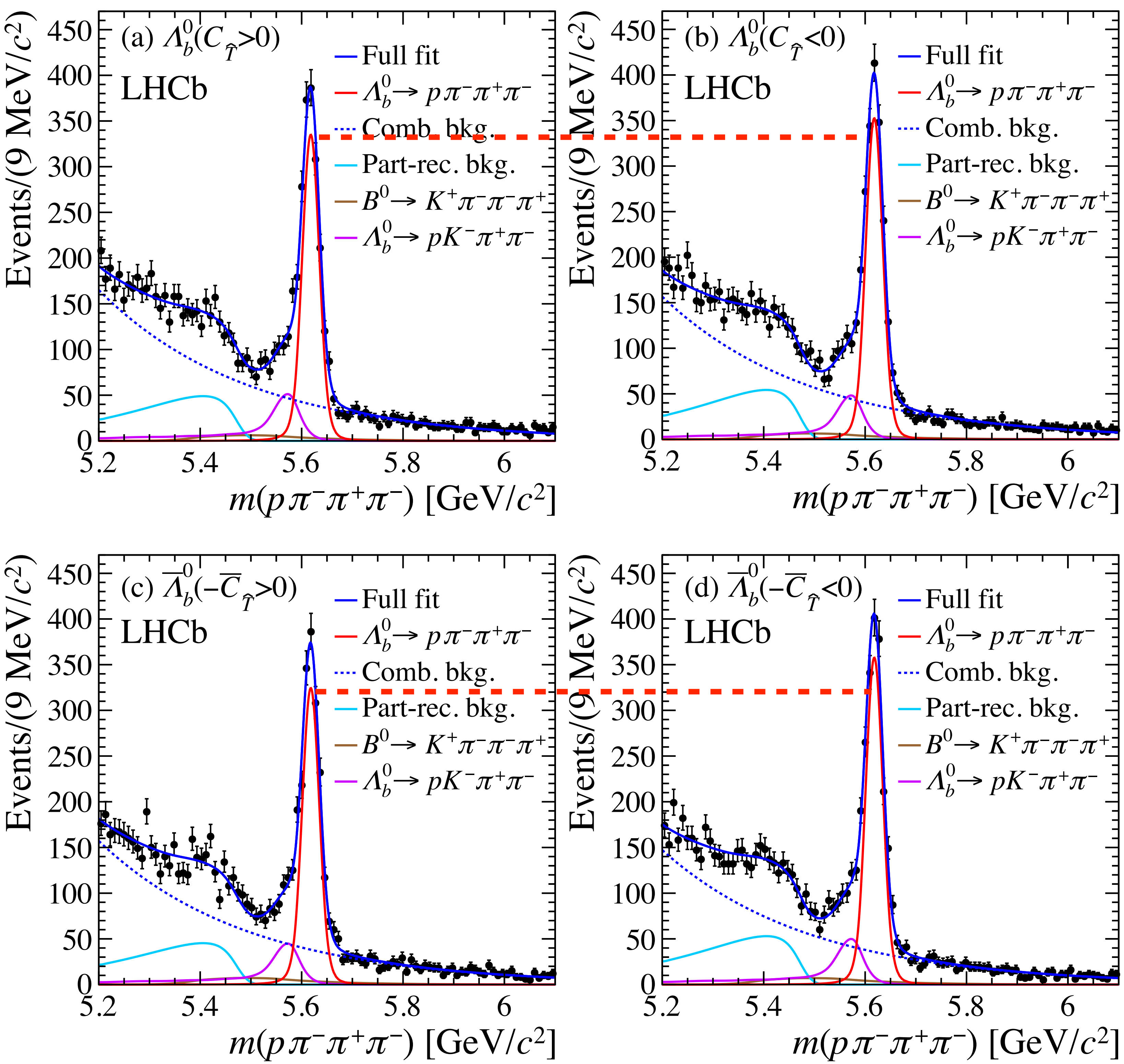
		$(\sigma_{a_{P,CP}^{\hat{T}\text{-odd}}})_{syst.}$ (%)
$\Lambda_b^0 \to p\pi^-\pi^+\pi^-$	Experimental bias	$\pm 0.31(\pm 0.60)$
	C_T resolution	± 0.05
	Fit model	± 0.03
	Total	$\pm 0.32(\pm 0.60)$
$\Lambda_b^0 \to pK^+K^-\pi^-$	Experimental bias	$\pm 0.31(\pm 0.60)$
	C_T resolution	± 0.06
	Fit model	± 0.28
	Total	$\pm 0.42(\pm 0.66)$

(*), bias systematic is evaluated separately for integrate and phase-space-dependent asymmetries

$(\sigma_{a_{P,CP}^{\hat{T}\text{-odd}}})_{stat.}$(%): 1.45 ($\Lambda_b^0 \to p\pi^-\pi^+\pi^-$), 4.54 ($\Lambda_b^0 \to pK^+K^-\pi^-$)

$\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ integrated asymmetries

arXiv:1609.05216, submitted to Nature Physics



reminder:

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

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

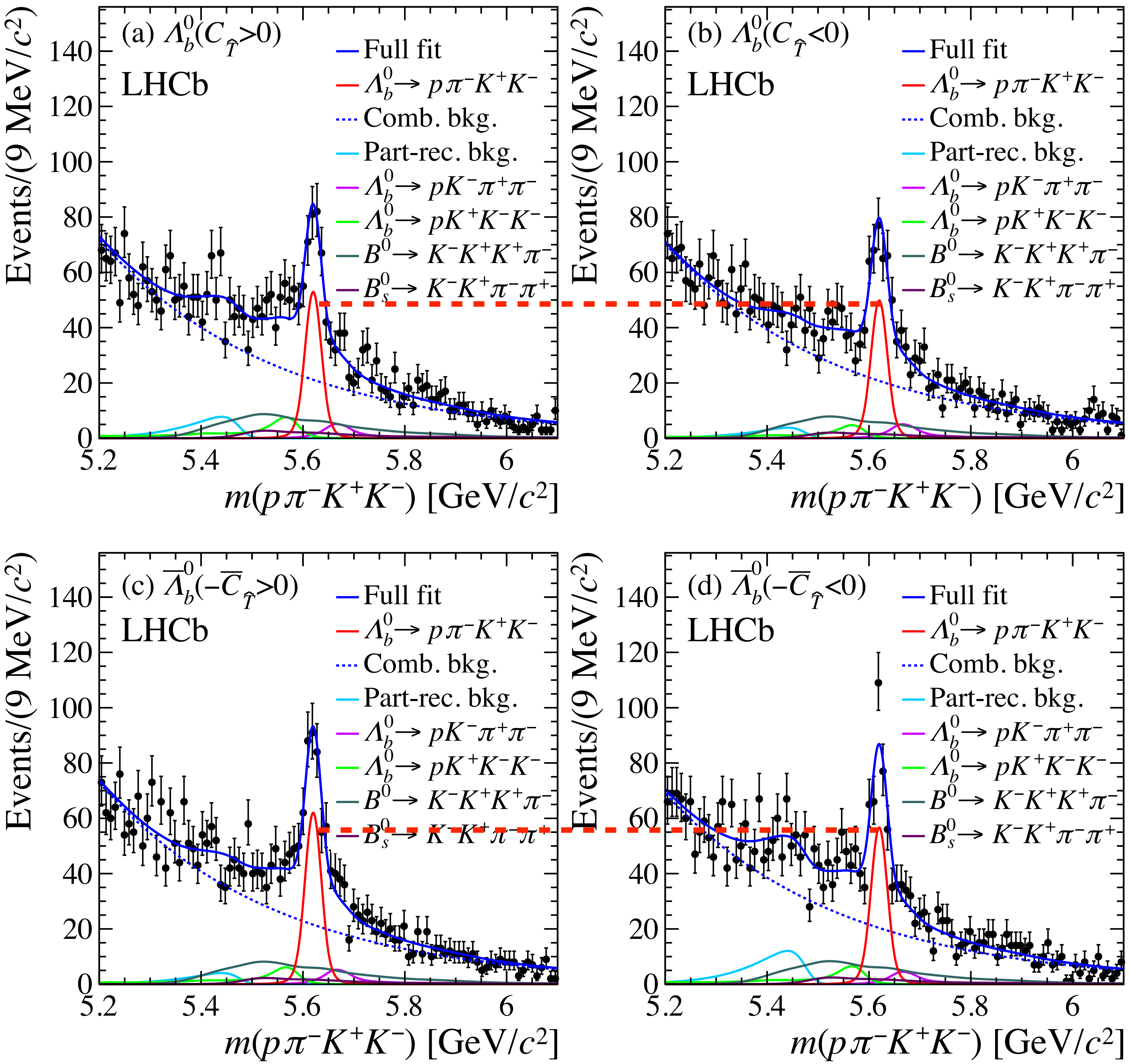
$a_P^{\hat{T}\text{-odd}}$=(–3.71±1.45±0.32)%

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

Phase space integrated result consistent with P and CP symmetry

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

arXiv:1609.05216, submitted to Nature Physics



reminder:

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

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

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

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

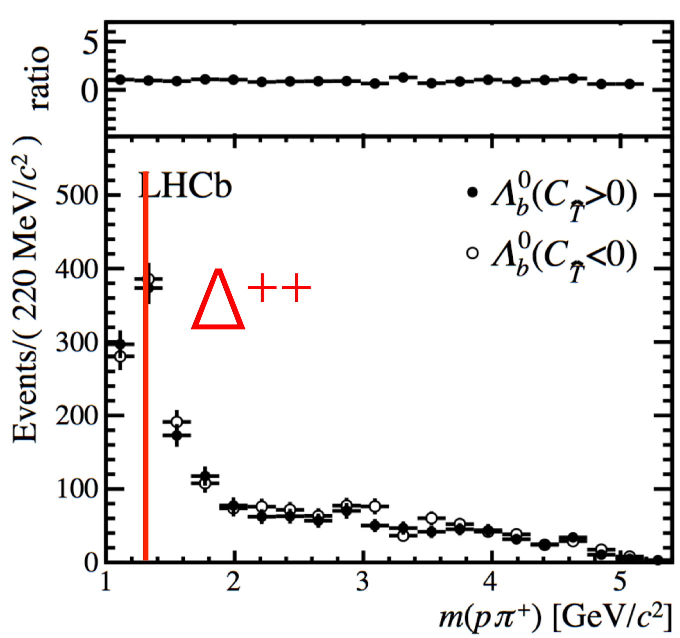
Phase space integrated result consistent with P and CP symmetry

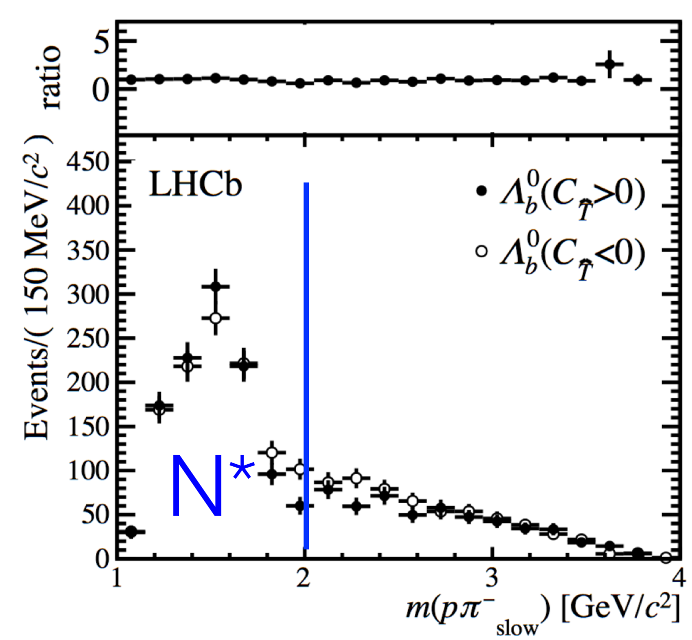
$\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ phase spase regions

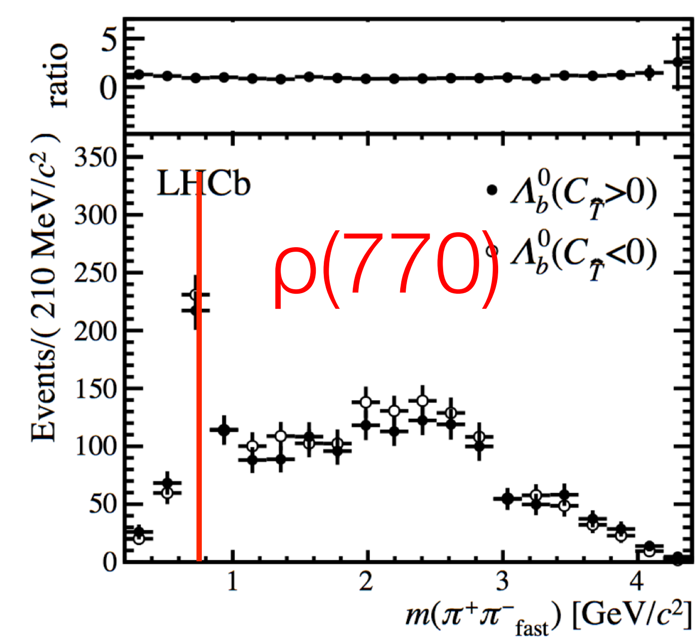
1) Scheme A: division based on dominant resonant structures

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

ρ(770) peak



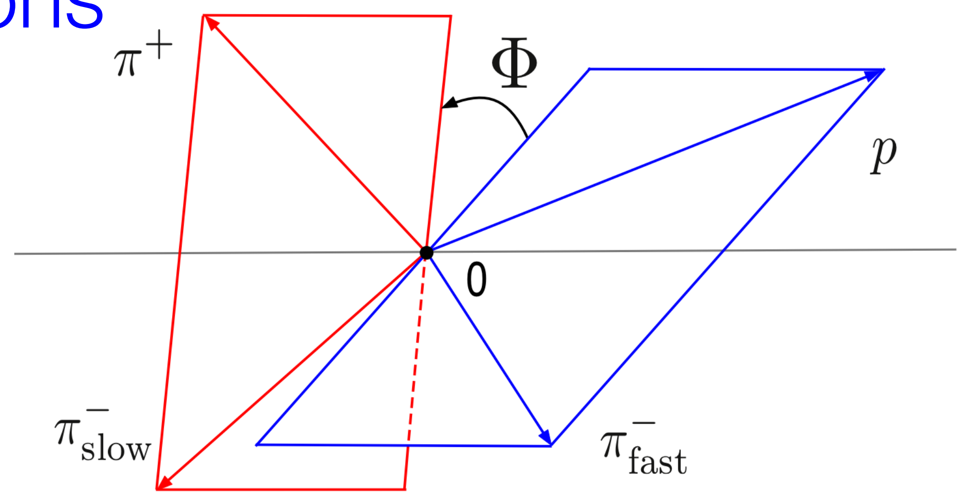




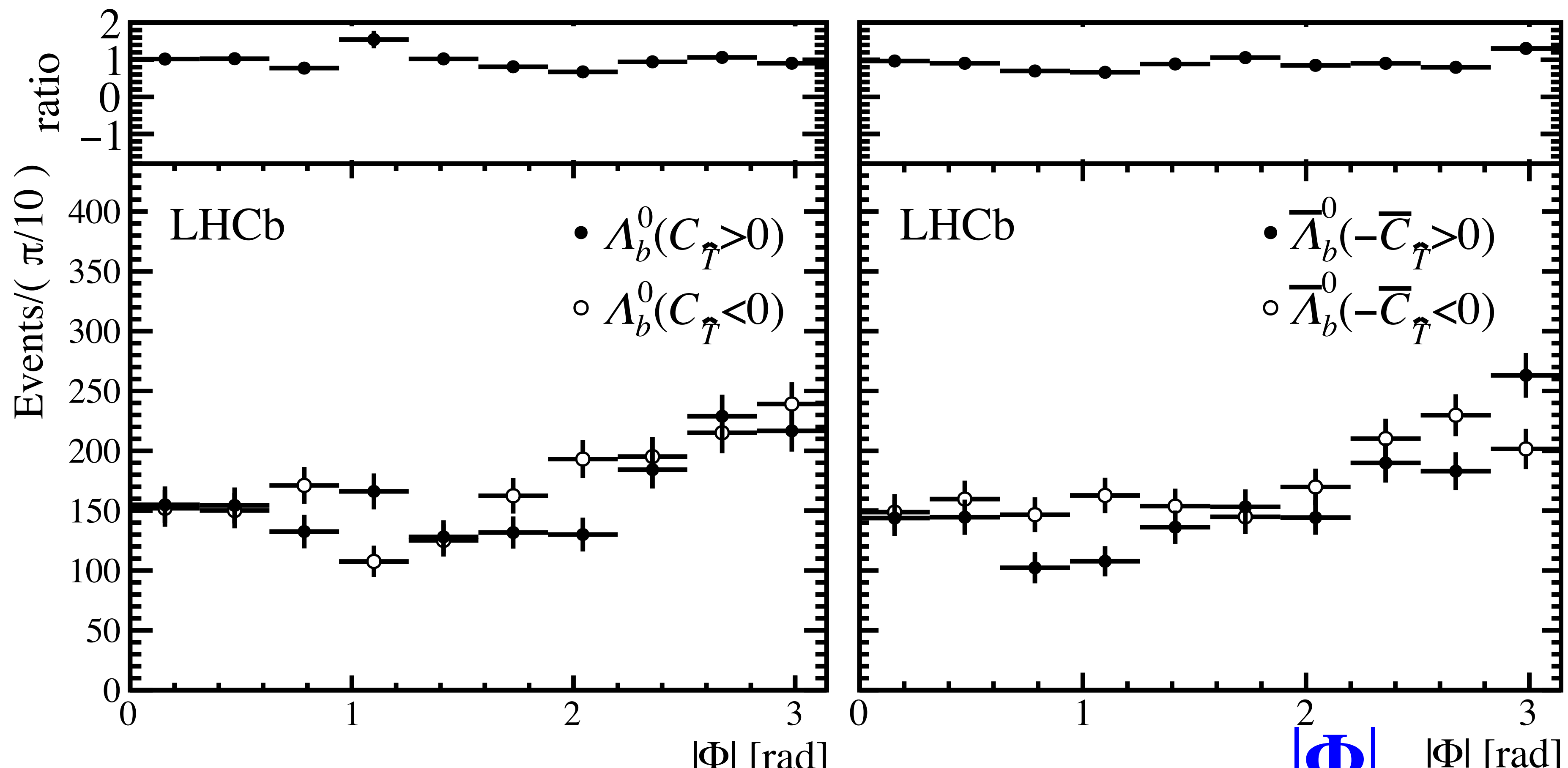
$\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ in bins of $\mathbf{\Phi}$

arXiv:1609.05216, submitted to Nature Physics

2) Scheme B: based on $|\mathbf{\Phi}|$ angle intervals, exploits more the interference of P-even and P-odd contributions



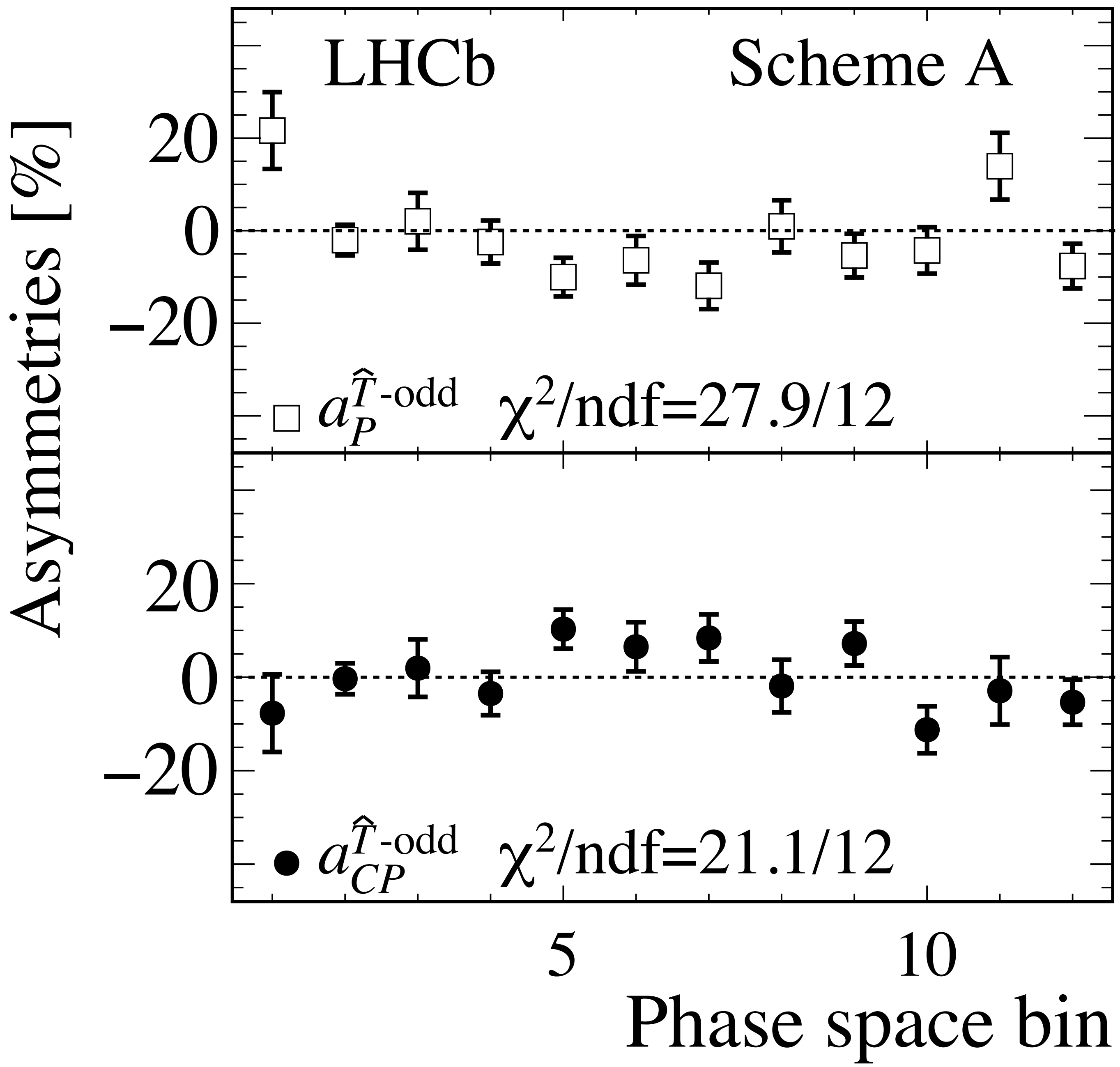
10 bins in $|\mathbf{\Phi}|$ $\left(\frac{i-1}{10}\pi, \frac{i}{10}\pi\right), (i = 1, 2, ..., 10)$



$|\mathbf{\Phi}|$

$\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ results in phase space in scheme A

arXiv:1609.05216, submitted to Nature Physics



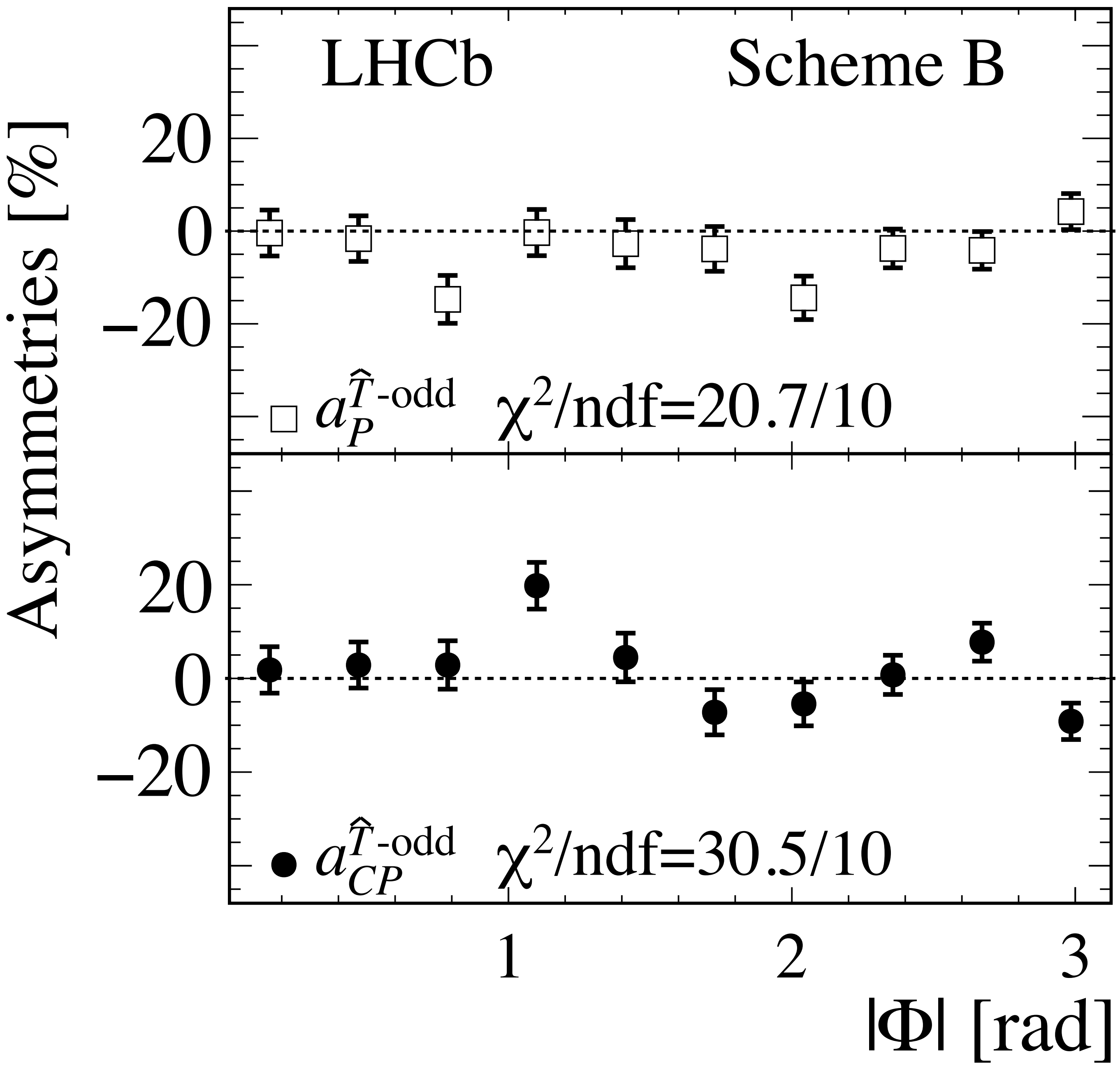
χ^2 test:

P symmetry *p*-value=5.8x10^{-3} (2.8σ deviation)

CP symmetry *p*-value=4.9x10^{-2} (2.0σ deviation)

First evidence of CP violation in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$

arXiv:1609.05216, submitted to Nature Physics



χ^2 test:

P symmetry p-value=2.4x10^{-2}
(2.3σ deviation)

CP symmetry p-value=7.1x10^{-4}
(3.4σ deviation)

Independent check after unblinding data

An independent analysis of the data based on alternative selection criteria reproduced the results

A similar number of events, of which 73.4% are in common with the baseline analysis

p-values for CP symmetry:

scheme A: $3.4\text{x}10^{-3}$ (2.9σ)

scheme B: $1.4\text{x}10^{-4}$ (3.8σ)

Significance of CPV using permutation tests

arXiv:1609.05216, submitted to Nature Physics

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:

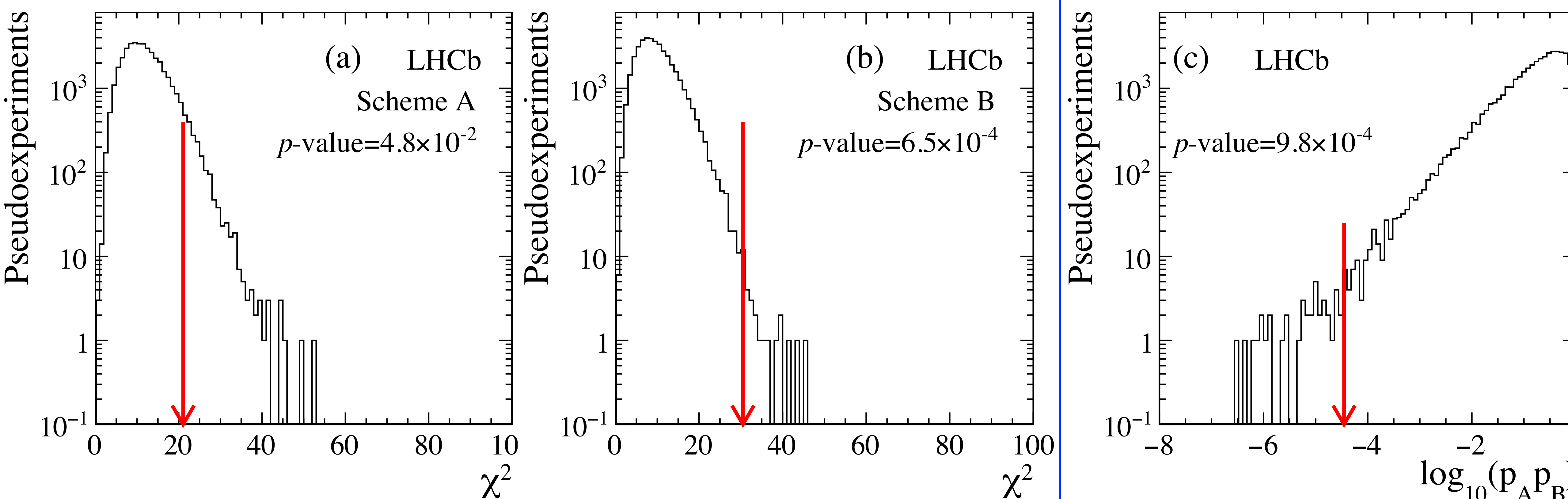
$$\text{If} \quad \Lambda_b^0 \to \overline{\Lambda}_b^0 \quad \text{then} \quad C_T \to \overline{C}_T = -C_T$$

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

Results consistent with χ^2 test

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

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



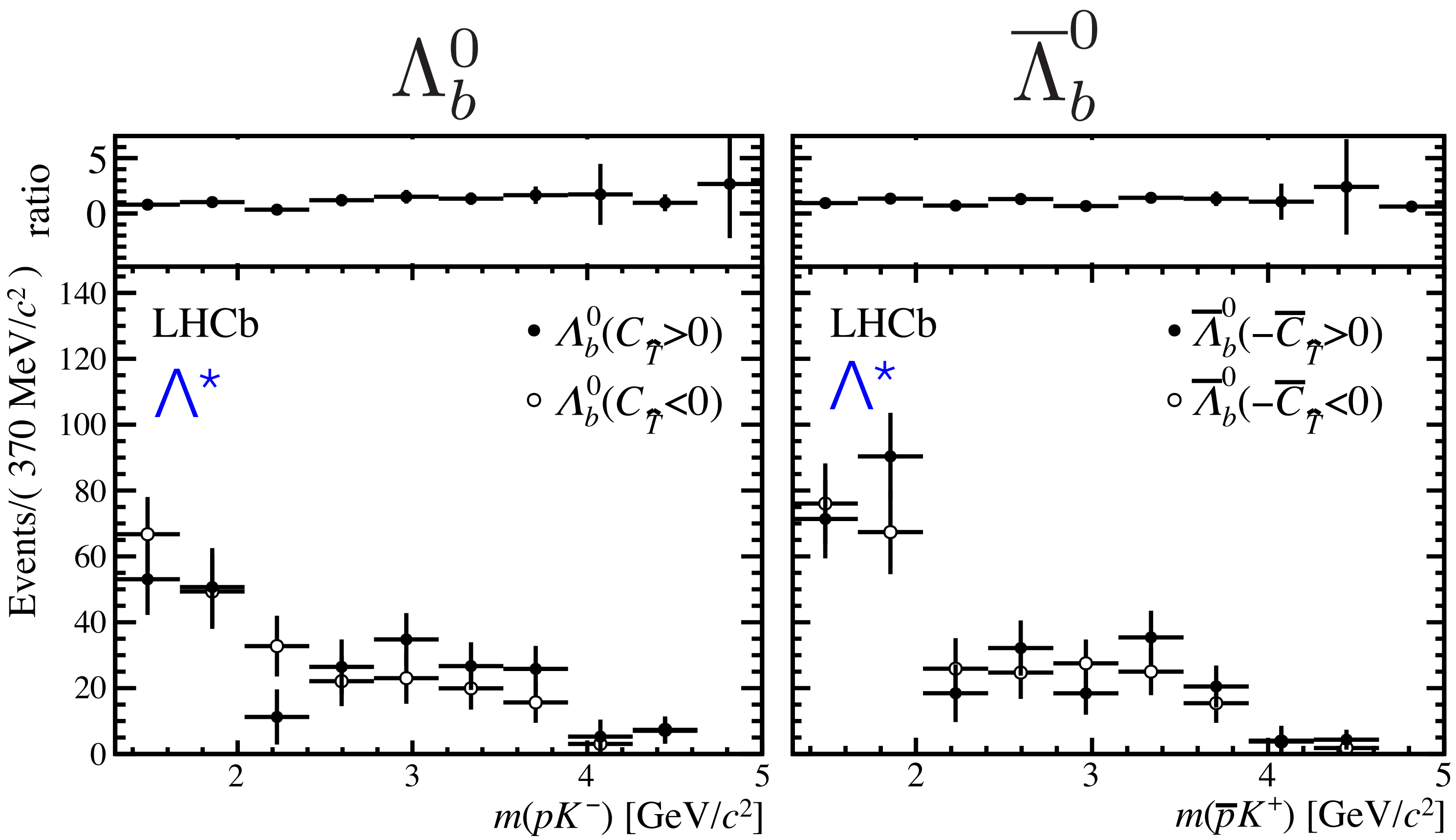
Significance=2.0σ

Significance=3.4σ

Significance=3.3σ

$\Lambda_b^0 \to p\pi^- K^+ K^-$ results in phase space

arXiv:1609.05216, submitted to Nature Physics



background-subtracted using the *sPlot* method

divide phase space with/ without Λ^* resonances

	$m(pK^-)$ GeV/c^2	$a_P^{\hat{T}\text{-odd}}$ [%]	$a_{CP}^{\hat{T}-\text{odd}}$ [%]
Λ^* →	(1.43, 2.00)	$3.27 \pm 6.07 \pm 0.66$	$-4.68 \pm 6.07 \pm 0.66$
	(2.00, 4.99)	$4.43 \pm 6.73 \pm 0.66$	$4.73 \pm 6.73 \pm 0.66$

Results consistent with P and CP symmetry

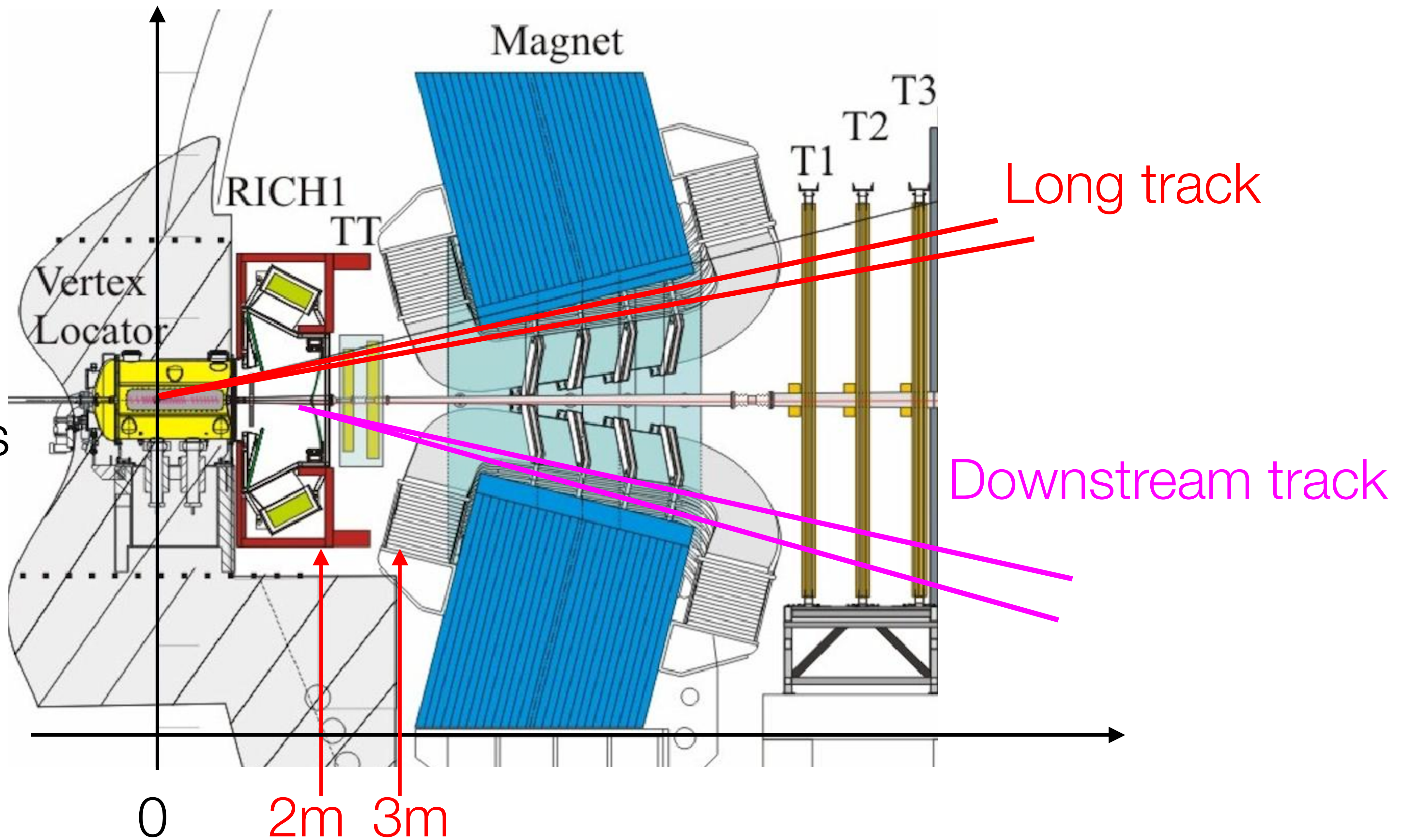
Other LHCb results on CPV searches in Beauty Baryons

- Search for CPV in $\Lambda_b^0 \to \Lambda\phi$ decays
- Search for CPV in $\Lambda_b^0 \to \Lambda h^+ h^{'-}$ decays
- Search for CPV in $\Lambda_b^0 \to K_s^0 p \pi^-$ decays
- Search for CPV in $\Lambda_b^0 \to J/\psi p \pi^-$ and $\Lambda_b^0 \to J/\psi p K^-$ decays

Reconstruction of Λ and K_s^0 from Λ_b^0 decays

$\tau(\Lambda_b^0)$: 1.5 ps

typical decay length: few millimetres



30GeV Λ decay length:~2.5m

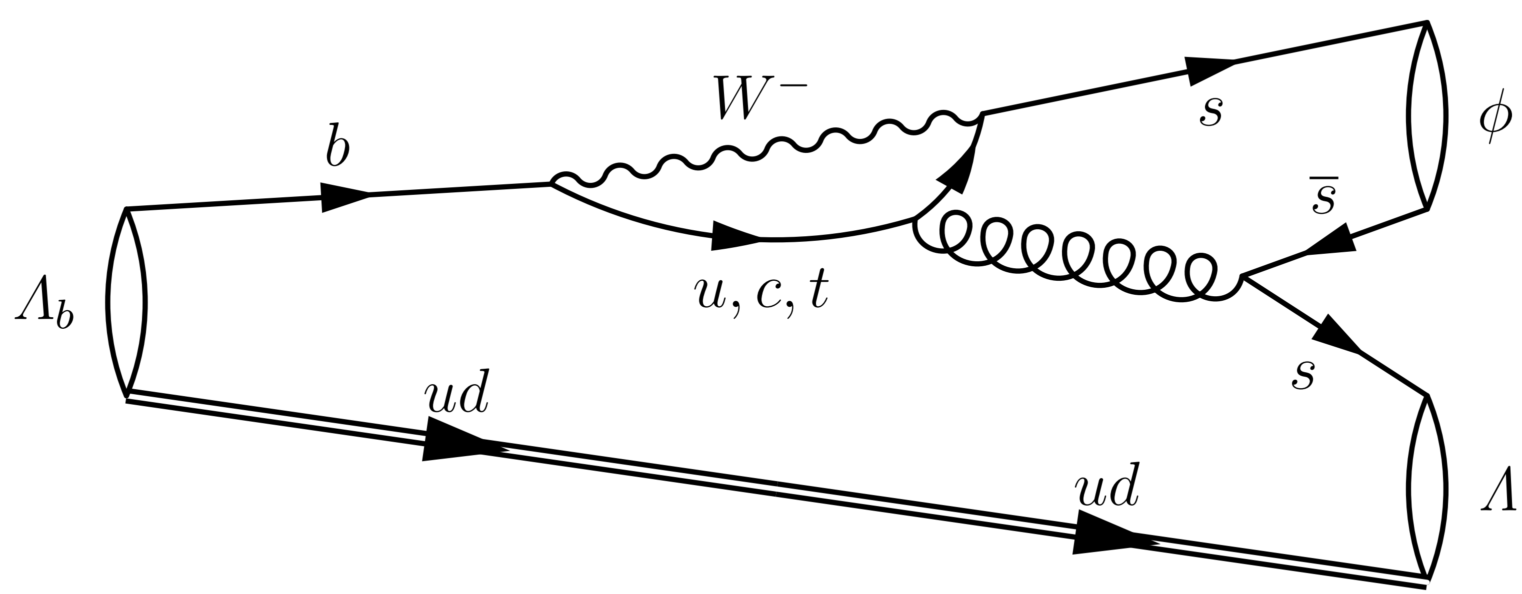
Λ and K_s^0 reconstructed using Long or Downstream tracks

Search for CPV using triple-product asymmetries in $\Lambda_b^0 \to \Lambda\phi$

Phys. Lett. B759 (2016) 282

b→s$\bar{s}$s transition has been the subject of theoretical and experimental interest in B^0, B_s decays, since new physics in the loop could induce non-SM CPV

Phys. Rev. D87 (2013) 056004
Phys. Lett. B671 (2009) 256
Phys. Lett. B493 (2000) 366

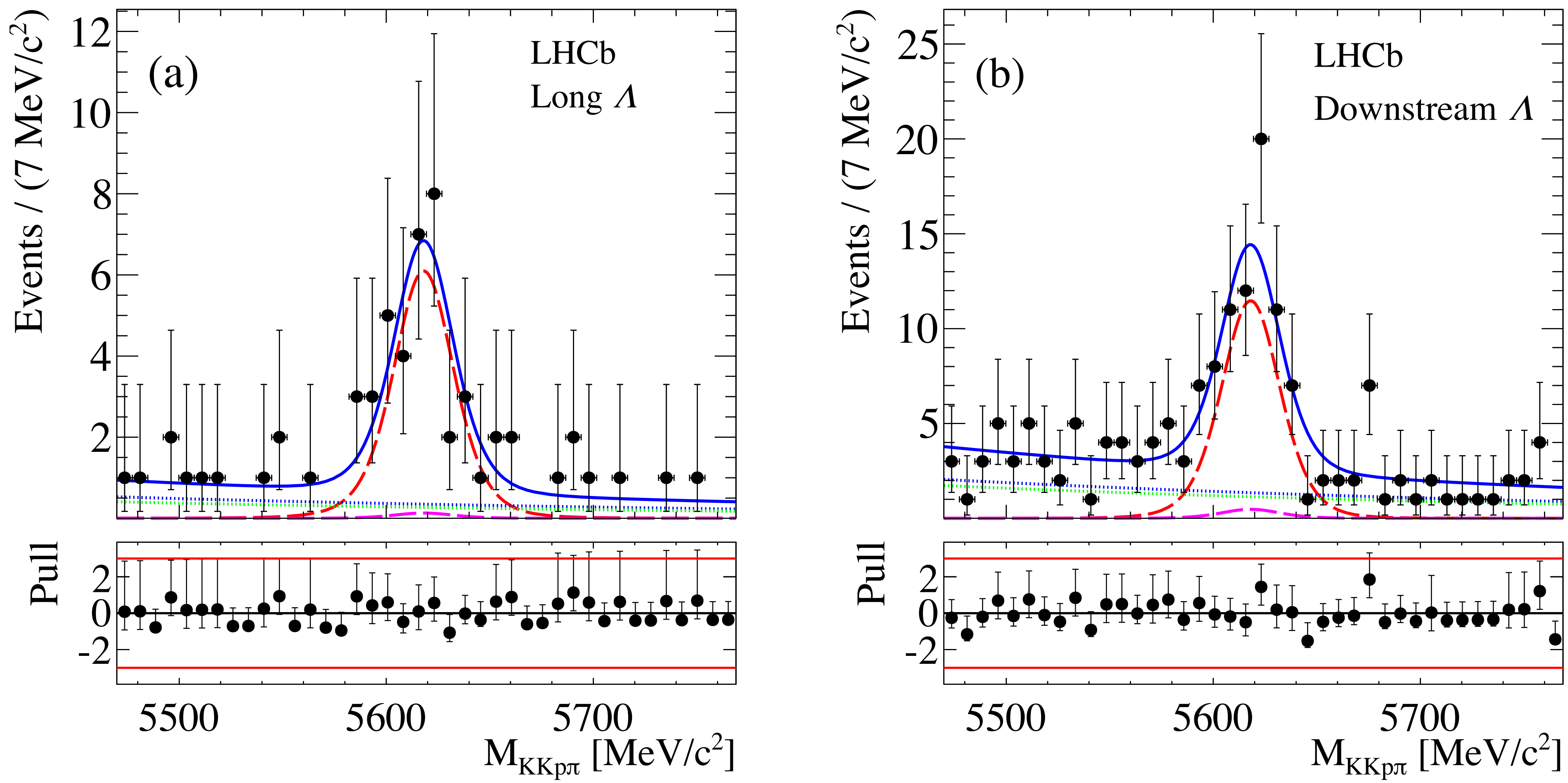


Signal yields

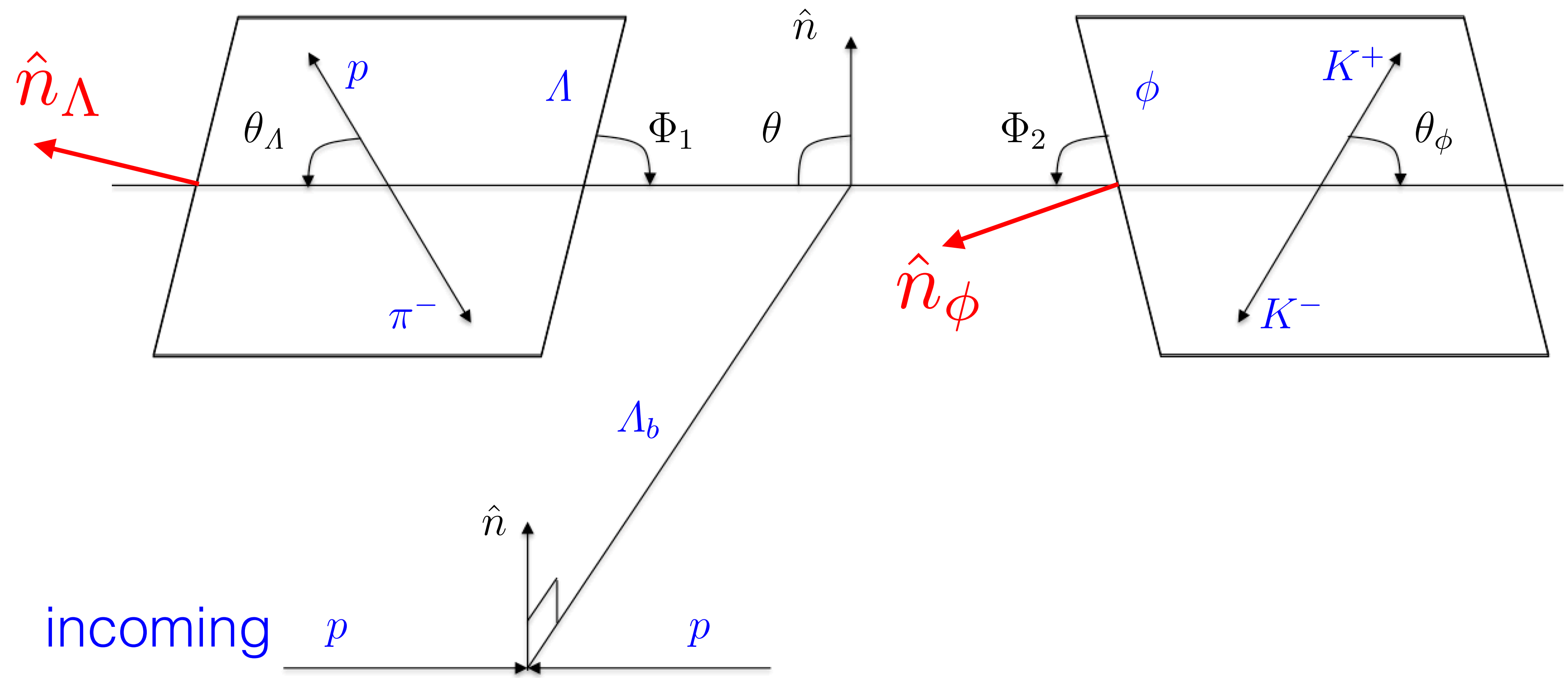
Phys. Lett. B759 (2016) 282

- First observation

$N_{\text{sig}}(\Lambda_b^0 \to \Lambda\phi)$=89±13, 5.9σ



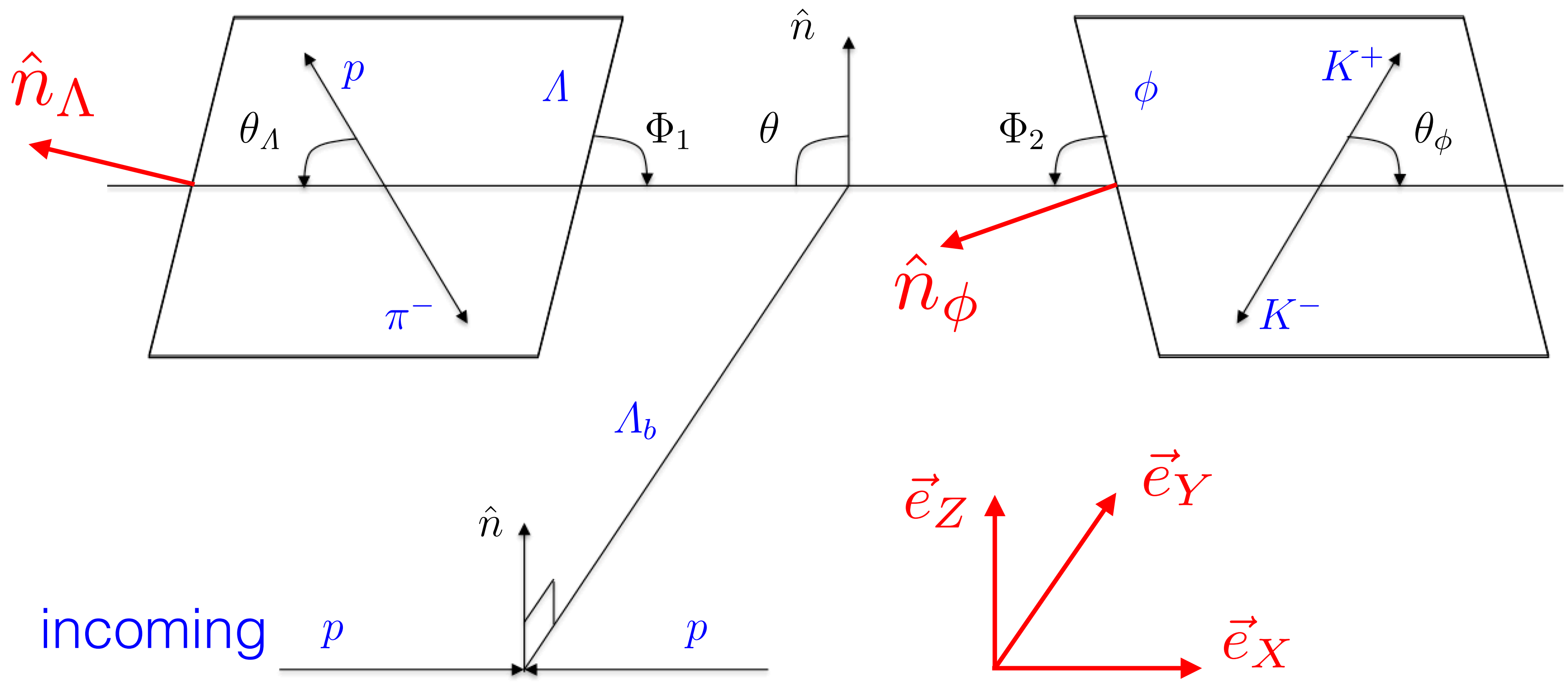
Triple-product asymmetries



5 angles describe decay, considering Λ_b^0 possibly produced with a transverse polarisation

- θ_Λ : polar angle of p in Λ rest frame
- θ_ϕ : polar angle of K^+ in ϕ rest frame
- Φ_1: angle between $\hat{n}$ and $\hat{n}_\Lambda$
- Φ_2: angle between $\hat{n}$ and $\hat{n}_\phi$
- θ : polar angle of Λ in Λ_b^0 rest frame w.r.t. $\hat{n}$

Triple-product asymmetries



$$\vec{u}_i = \frac{\vec{e}_Z \times \hat{n}_i}{|\vec{e}_Z \times \hat{n}_i|} \quad i \in \{\Lambda, \phi\}$$

triple products:

$$\cos\Phi_{n_i} = \vec{e}_Y \cdot \vec{u}_i$$

$$\sin\Phi_{n_i} = \vec{e}_Z \cdot (\vec{e}_Y \times \vec{u}_i)$$

Phys.Proc.Suppl.174:169-172,2007

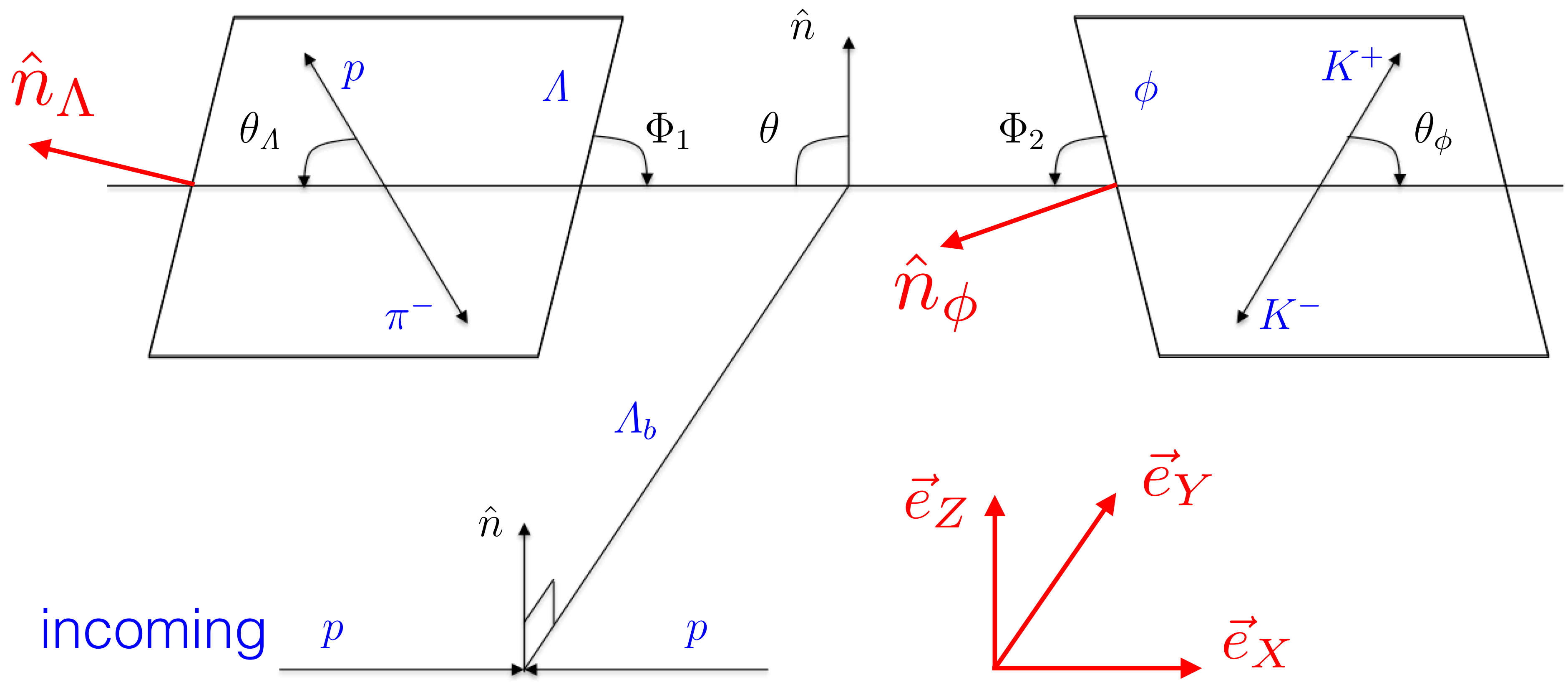
CPV observables, untagged sample:

$$A_i^c = \frac{N_i(\cos\Phi_{n_i} > 0) - N_i(\cos\Phi_{n_i} < 0)}{N_i(\cos\Phi_{n_i} > 0) + N_i(\cos\Phi_{n_i} < 0)}$$

$$A_i^s = \frac{N_i(\sin\Phi_{n_i} > 0) - N_i(\sin\Phi_{n_i} < 0)}{N_i(\sin\Phi_{n_i} > 0) + N_i(\sin\Phi_{n_i} < 0)}$$

Results

Phys. Lett. B759 (2016) 282



a simultaneous unbinned maximum likelihood fit to the datasets with positive or negative triple products

$$A^s_\Lambda = 0.13 \pm 0.12 \pm 0.05$$

$$A^c_\Lambda = -0.22 \pm 0.12 \pm 0.06$$

$$A^s_\phi = -0.07 \pm 0.12 \pm 0.01$$

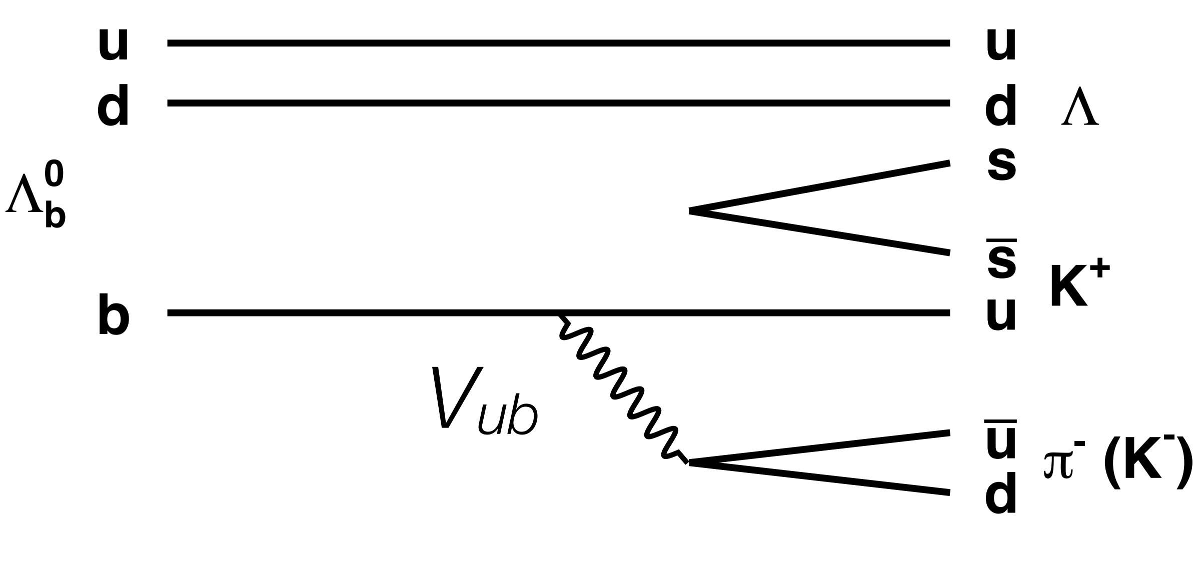
$$A^c_\phi = -0.01 \pm 0.12 \pm 0.03$$

Consistent with CP symmetry

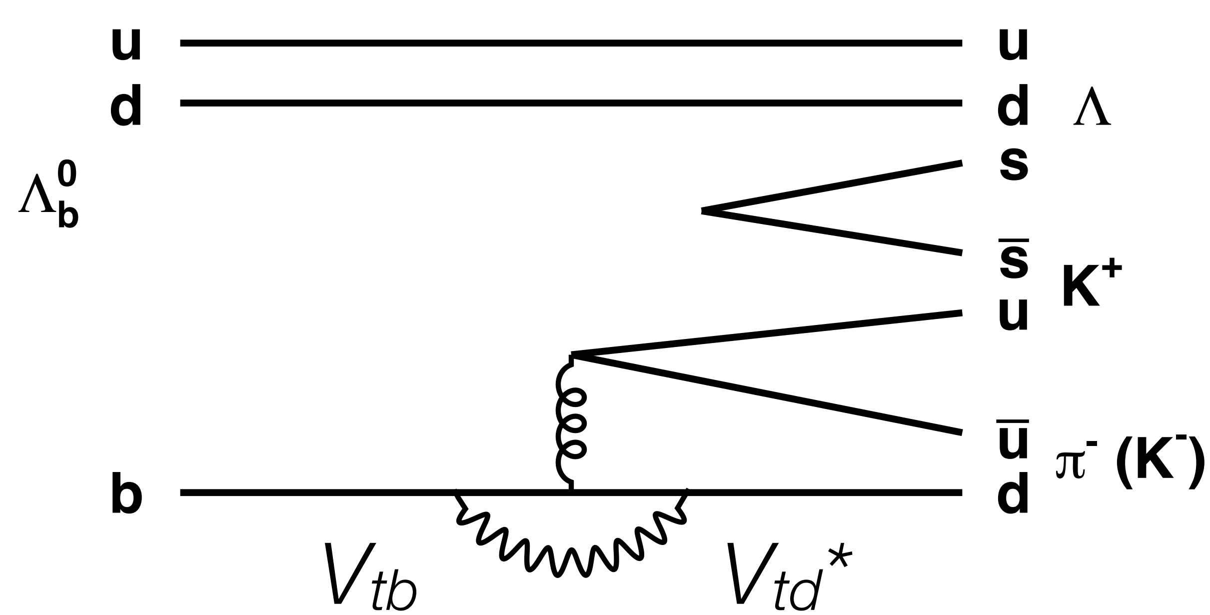
Search for CPV in $\Lambda_b^0 \to \Lambda h^+ h'^-$ decays

JHEP 05 (2016) 081

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



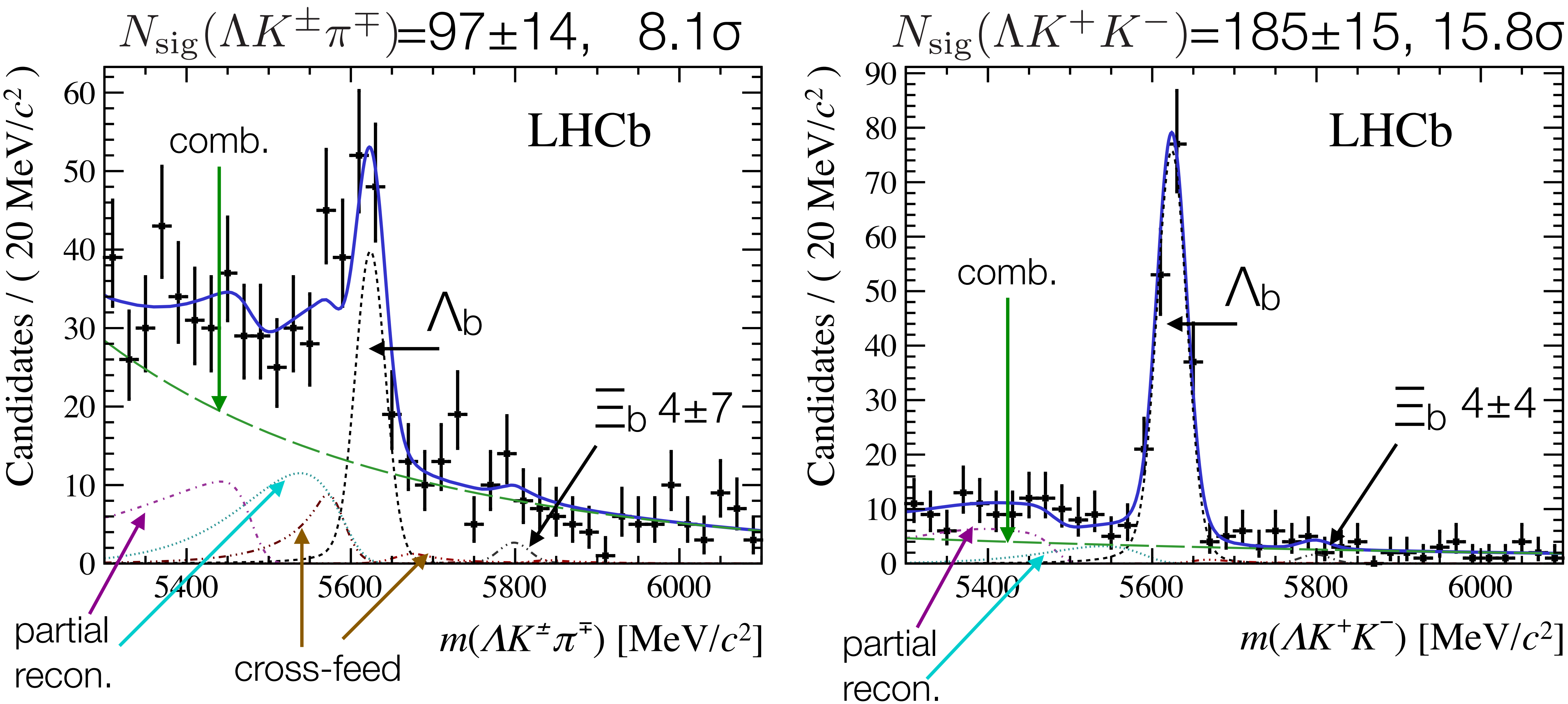
Penguin diagram $\propto \sum_{x=u,c,t} V_{bx} V_{xd} \sim \lambda^3$



Signal yields

JHEP 05 (2016) 081

- First observation of $\Lambda_b^0 \to \Lambda K^\pm \pi^\mp$ and $\Lambda_b^0 \to \Lambda K^+ K^-$

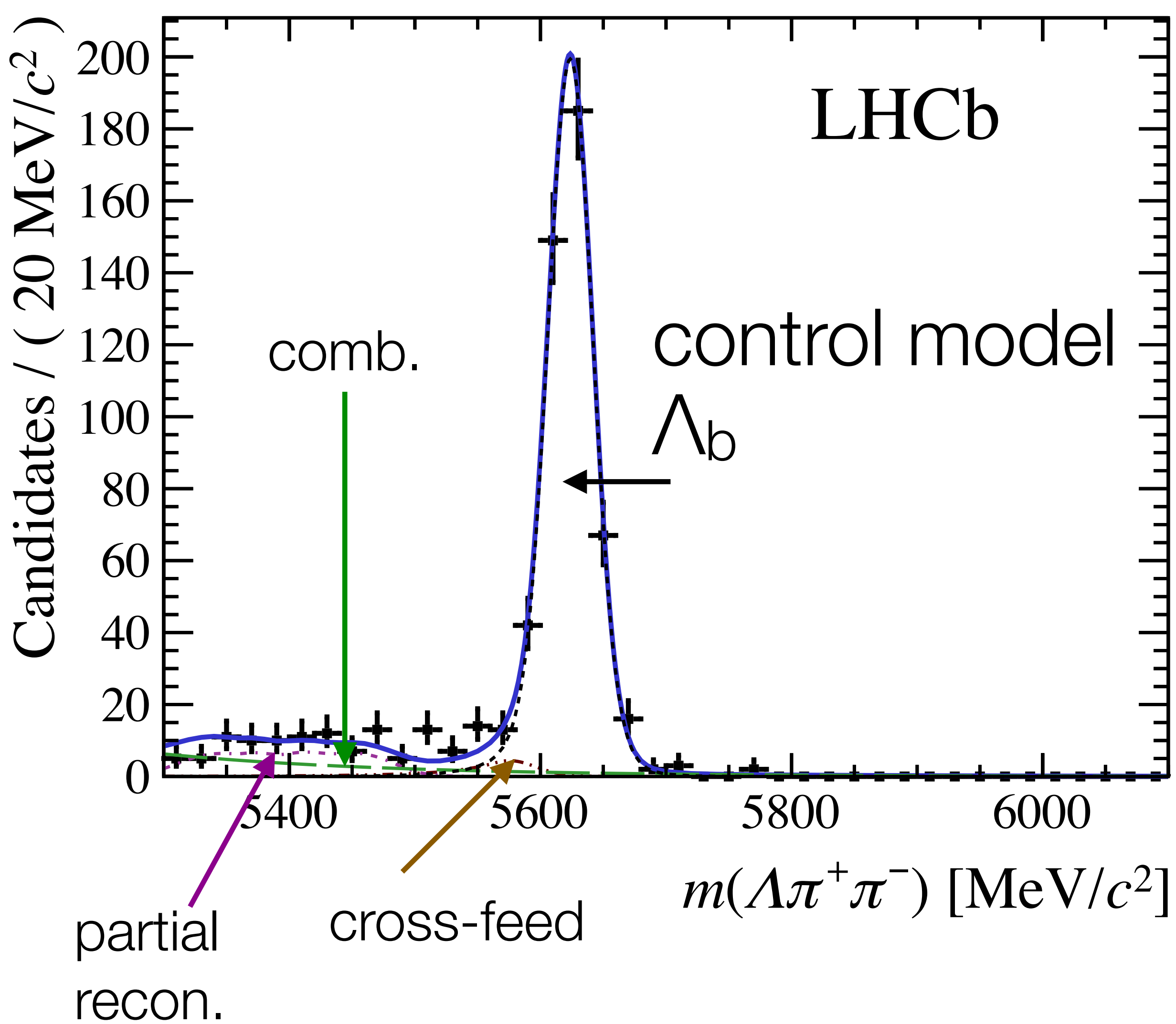


Signal yields

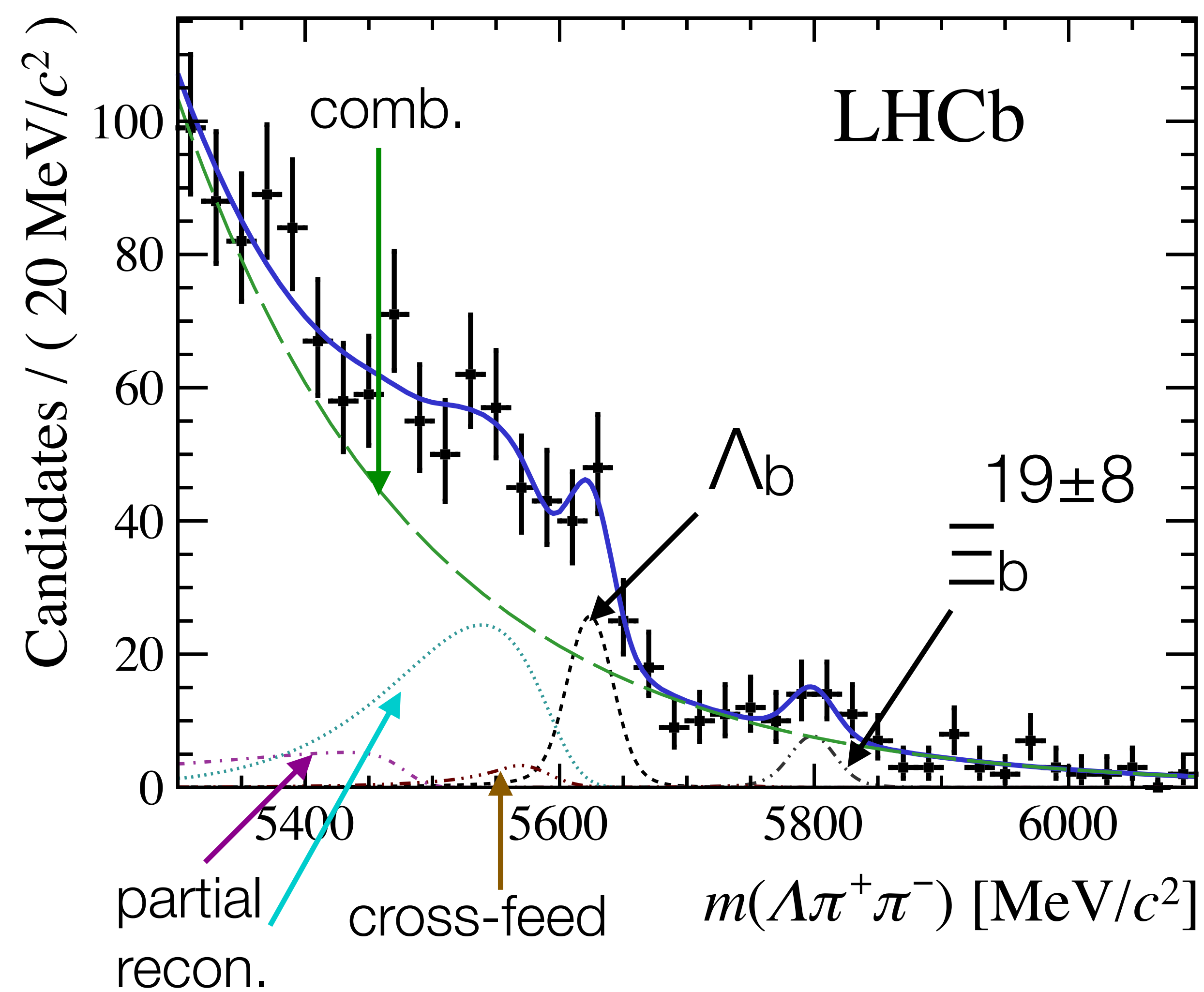
JHEP 05 (2016) 081

- Evidence of $\Lambda_b^0 \to \Lambda\pi^+\pi^-$, control model $\Lambda_b^0 \to (\Lambda\pi^+)_{\Lambda_c^+}\pi^-$ selected from $\Lambda_b^0 \to \Lambda\pi^+\pi^-$ phase space.
- No evidence of any $\Xi_b^0 \to \Lambda h^+ h'^-$

$N_{\rm control}(\Lambda_c^+\pi^-)$=471±22



$N_{\rm sig}(\Lambda\pi^+\pi^-)$=64±14, 4.7σ



Asymmetry measurements

$$\mathcal{A}_{CP}^{\text{raw}} = \frac{N_f^{\text{corr}} - N_{\bar{f}}^{\text{corr}}}{N_f^{\text{corr}} + N_{\bar{f}}^{\text{corr}}}$$

$N_f^{\text{corr}}(N_{\bar{f}}^{\text{corr}})$: efficiency-corrected yield for $\Lambda_b^0(\overline{\Lambda}_b^0)$ decays, since efficiencies various across phase space.

Phys. Rev. D90 (2014) 112004

$$\begin{aligned}\mathcal{A}_{CP} &= \mathcal{A}_{CP}^{\text{raw}} - (\mathcal{A}_{\text{P}} + \mathcal{A}_{\text{D}}) \\ &= \mathcal{A}_{CP}^{\text{raw}}(\Lambda_b^0 \to \Lambda h^+ h^{'-}) - \mathcal{A}_{CP}^{\text{raw}}(\Lambda_b^0 \to (\Lambda\pi^+)_{\Lambda_c^+}\pi^-)\end{aligned}$$

Use $\Lambda_b^0 \to (\Lambda\pi^+)_{\Lambda_c^+}\pi^-$ as control model:
negligible CPV effect, production asymmetry $\mathcal{A}_{\text{P}}$ and most detection asymmetry $\mathcal{A}_{\text{D}}$ cancel

$$\begin{aligned}\mathcal{A}_{CP}(\Lambda_b^0 \to \Lambda K^+\pi^-) &= -0.53 \pm 0.23 \pm 0.11 \\ \mathcal{A}_{CP}(\Lambda_b^0 \to \Lambda K^+K^-) &= -0.28 \pm 0.10 \pm 0.07\end{aligned}$$

Consistent with CP symmetry

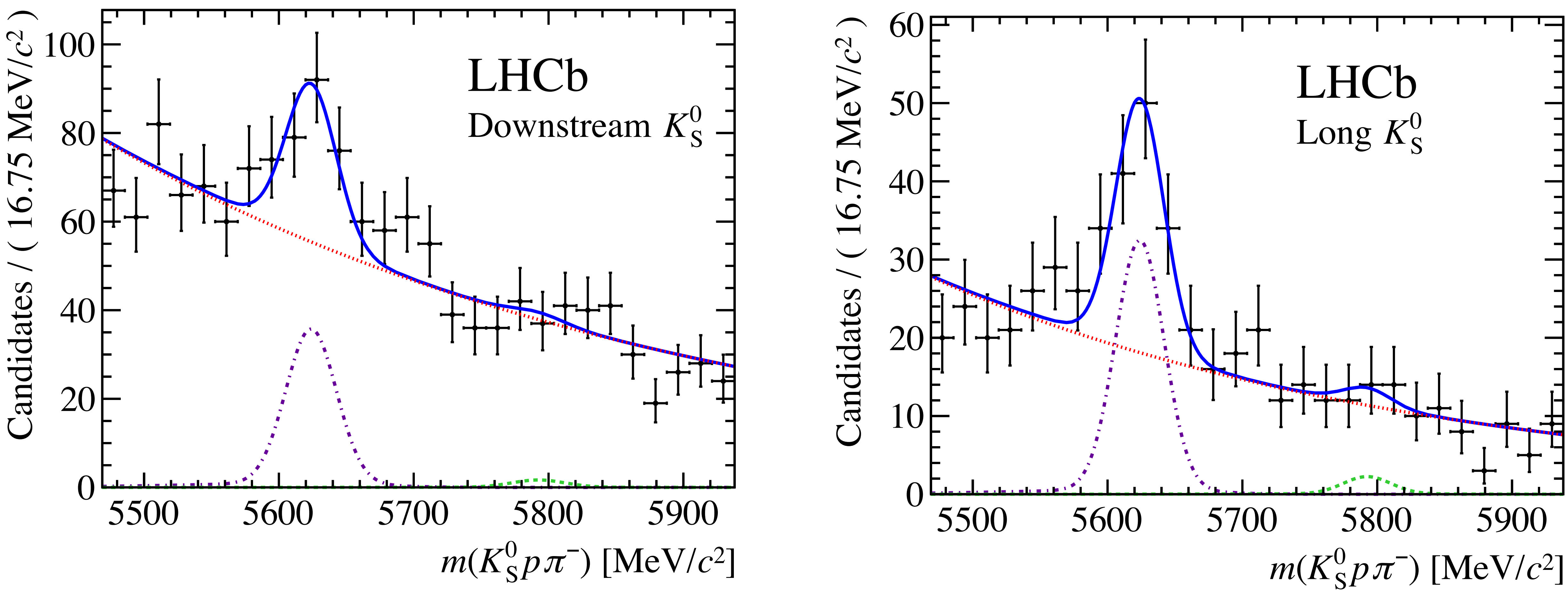
Search for CPV in $\Lambda_b^0 \to K_s^0 p \pi^-$

JHEP04(2014)087

- First observation

106±22

91±15



Asymmetry measurements

$$\mathcal{A}_{CP}^{\mathrm{RAW}} = \frac{N_{\bar{f}} - N_f}{N_{\bar{f}} + N_f}$$

$N_f(N_{\bar{f}})$: yield for $\Lambda_b^0(\overline{\Lambda}_b^0)$ decays

$$\begin{aligned}\mathcal{A}_{CP} &= \mathcal{A}_{CP}^{\mathrm{raw}} - (\mathcal{A}_{\mathrm{P}} + \mathcal{A}_{\mathrm{D}}) \\ &= \mathcal{A}_{CP}^{\mathrm{RAW}}(\Lambda_b^0 \to pK_s^0\pi^-) - \mathcal{A}_{CP}^{\mathrm{RAW}}(\Lambda_b^0 \to \Lambda_c^+(\to pK_s^0)\pi^-)\end{aligned}$$

Use $\Lambda_b^0 \to \Lambda_c^+(\to pK_s^0)\pi^-$ as control model:

negligible CPV effect, production asymmetry $\mathcal{A}_{\mathrm{P}}$ and most detection asymmetry $\mathcal{A}_{\mathrm{D}}$ cancel

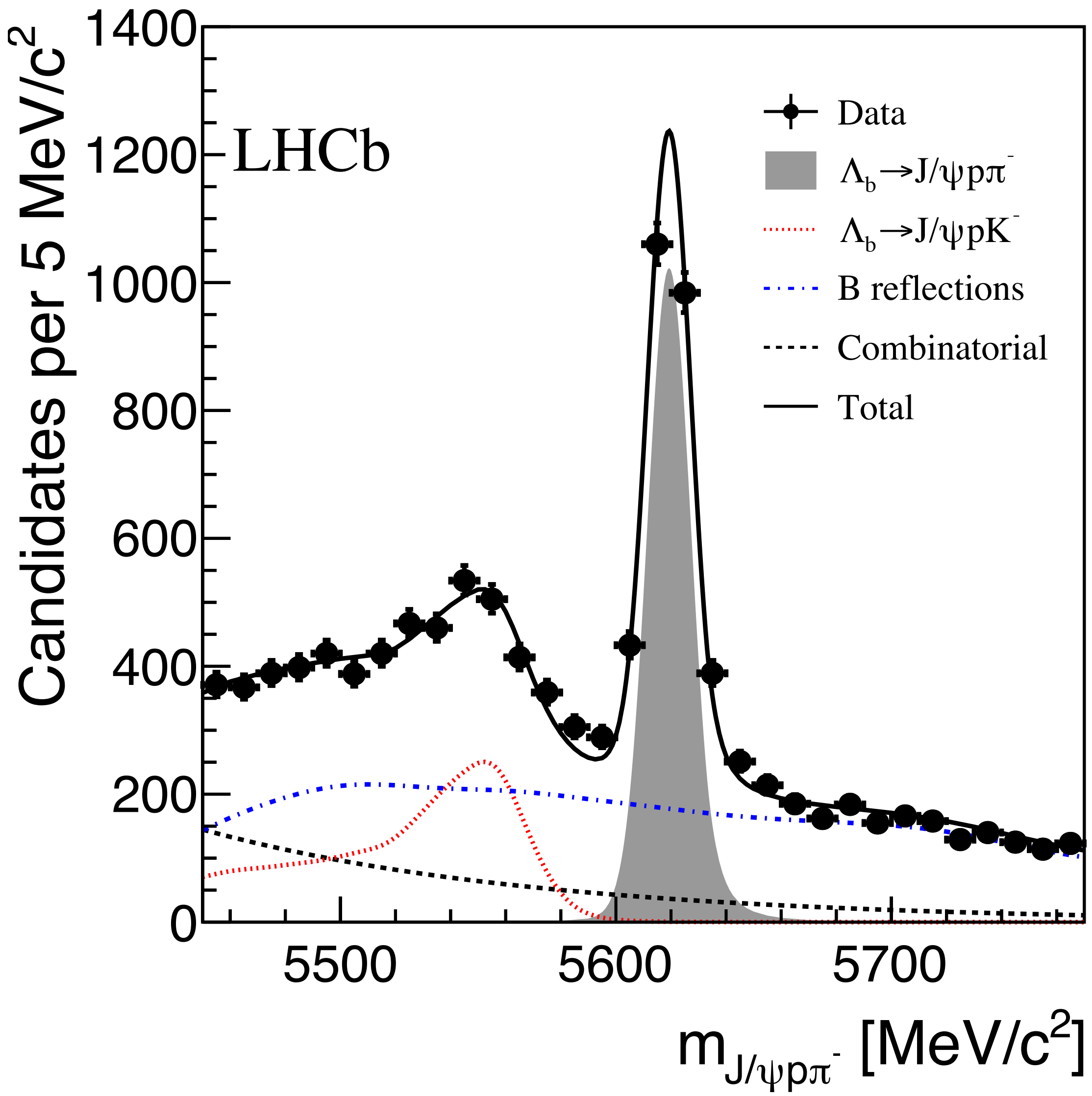
$$\mathcal{A}_{CP} = 0.22 \pm 0.13 \pm 0.03$$

Consistent with CP symmetry

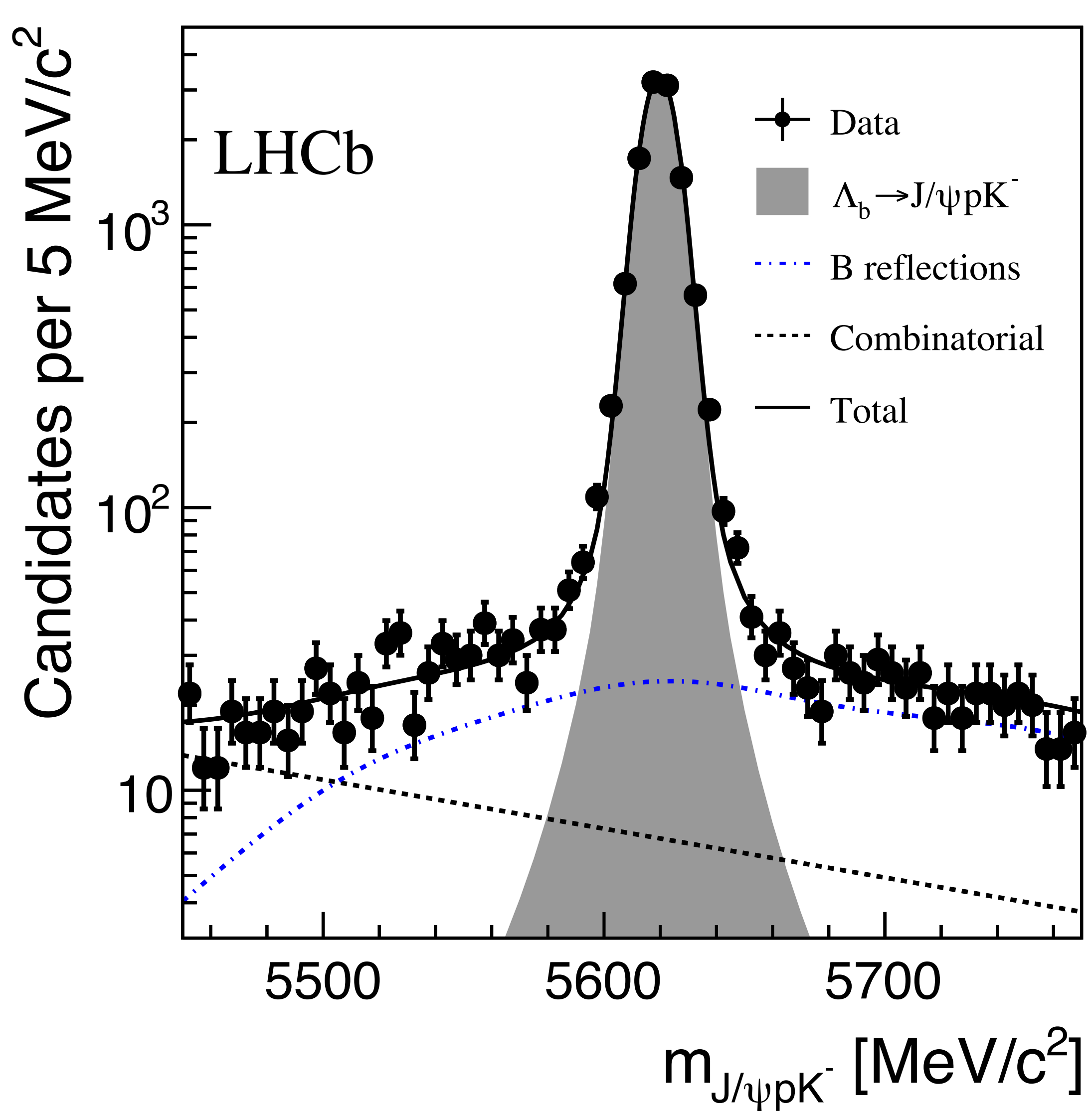
Search for CPV in $\Lambda_b^0 \to J/\psi p\pi^-$ and $\Lambda_b^0 \to J/\psi pK^-$

JHEP07(2014)103

2102±61



11179±109



Asymmetry measurements

$$\mathcal{A}_{\mathrm{raw}}(\Lambda_b^0 \to J/\psi p h^-) = \mathcal{A}_{CP}(\Lambda_b^0 \to J/\psi p h^-) + \mathcal{A}_{\mathrm{prod}}(\Lambda_b^0)$$
$$-\mathcal{A}_{\mathrm{reco}(h^+)} + \mathcal{A}_{\mathrm{reco}}(p)$$

$$\Delta A_{CP} \equiv \mathcal{A}_{CP}(\Lambda_b^0 \to J/\psi p\pi^-) - \mathcal{A}_{CP}(\Lambda_b^0 \to J/\psi pK^-)$$
$$= \mathcal{A}_{\mathrm{raw}}(\Lambda_b^0 \to J/\psi p\pi^-) - \mathcal{A}_{\mathrm{raw}}(\Lambda_b^0 \to J/\psi pK^-)$$
$$+\mathcal{A}_{\mathrm{reco}}(\pi^+) - \mathcal{A}_{\mathrm{reco}}(K^+)$$

production asymmetry $\mathcal{A}_{\mathrm{prod}}(\Lambda_b^0)$ and proton reconstruction asymmetry $\mathcal{A}_{\mathrm{reco}}(p)$ cancel in the difference of two asymmtries

$\mathcal{A}_{\mathrm{reco}}(\pi^+) - \mathcal{A}_{\mathrm{reco}}(K^+)$ to be determined

K^+, π^+ reconstruction asymmetry measurements

K^+ and π^+ reconstruction asymmetry can be determined using $\overline{B}^0 \to J/\psi \overline{K}^*(892)^0$ decay, with $\overline{K}^*(892)^0 \to K^-\pi^+$

$$\mathcal{A}_{\rm raw}(\overline{B}^0 \to J/\psi \overline{K}^*(892)^0) \equiv \frac{N(\overline{B}^0)-N(B^0)}{N(\overline{B}^0)+N(B^0)} = (-1.10\pm0.32\pm0.06)\%$$

$$\begin{aligned}\mathcal{A}_{\rm raw}(\overline{B}^0 \to J/\psi \overline{K}^*(892)^0) &= \mathcal{A}_{CP}(\overline{B}^0 \to J/\psi \overline{K}^*(892)^0) - \kappa \mathcal{A}_{\rm prod}(B^0) \\ &\quad + \mathcal{A}_{\rm reco}(\pi^+) - \mathcal{A}_{\rm reco}(K^+) \\ &\approx \mathcal{A}_{\rm reco}(\pi^+) - \mathcal{A}_{\rm reco}(K^+)\end{aligned}$$

κ: dilution factor due to B^0 mixing

Assumption:

no CP asymmetry and negligible production asymmetry

The combined Kπ reconstruction asymmetry consistent with measurement in the other decay modes. Phys.Rev.Lett. 110 (2013) 221601 JHEP 07 (2014) 041

Results

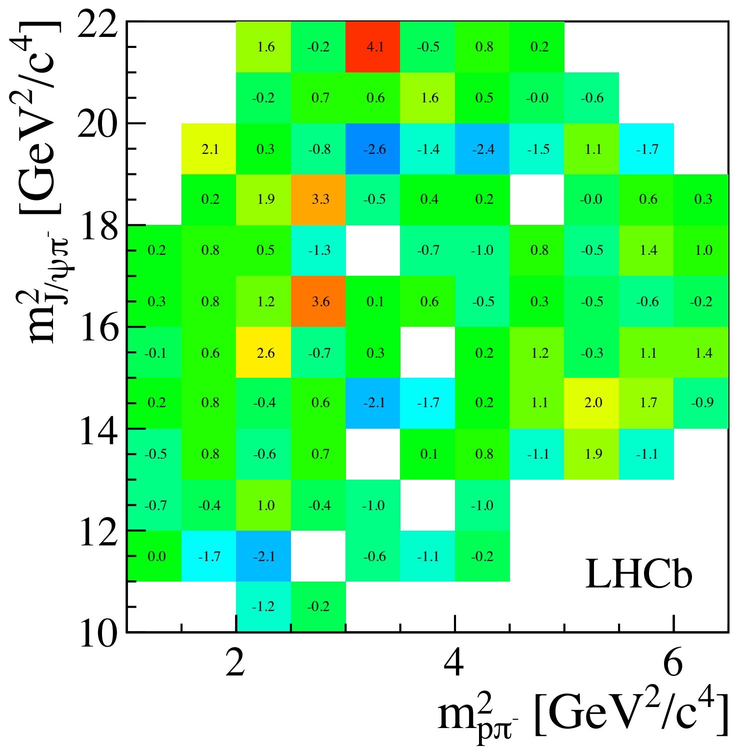
JHEP07(2014)103

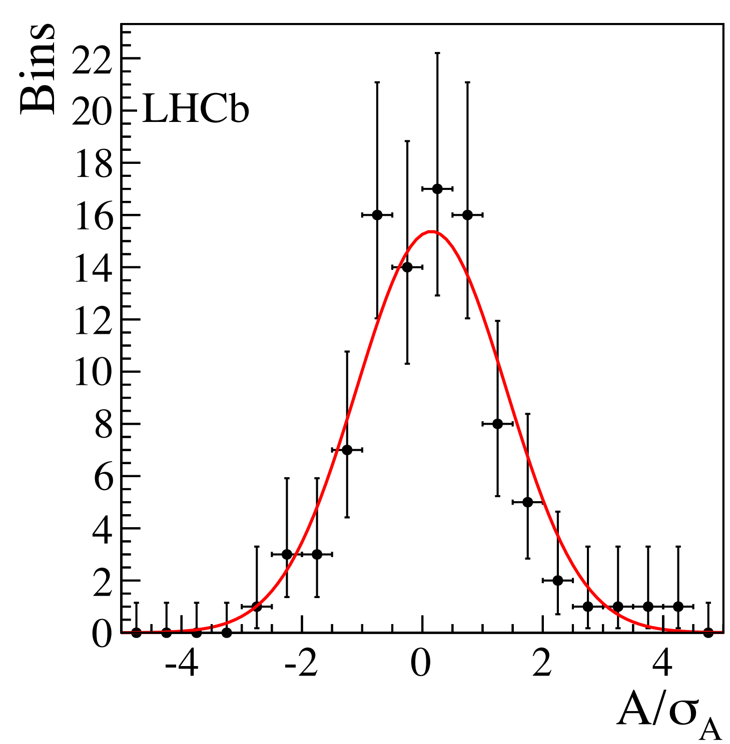
$$\Delta A_{CP} = \mathcal{A}_{\mathrm{raw}}(\Lambda_b^0 \to J/\psi p\pi^-) - \mathcal{A}_{\mathrm{raw}}(\Lambda_b^0 \to J/\psi pK^-)$$
$$+\mathcal{A}_{\mathrm{raw}}(\overline{B}^0 \to J/\psi \overline{K}^*(892)^0)$$
$$= (5.7 \pm 2.4 \pm 1.2)\%$$

Consistent with CP symmetry at the 2.2σ level

Local CP asymmetries in the Dalitz plane are also searched using Miranda procedure [1], no significant local asymmetries are found.

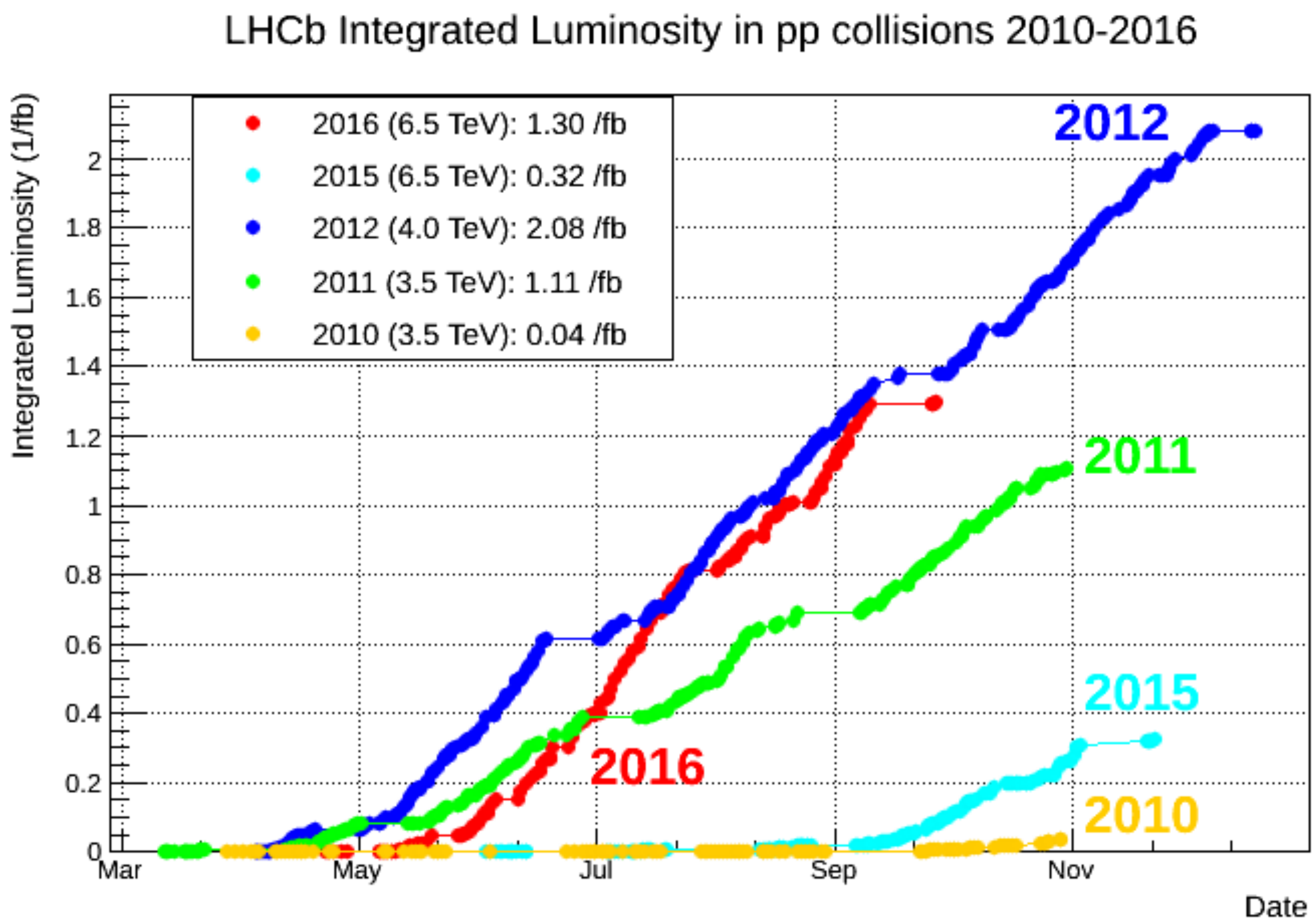
[1]: Phys. Rev. D86 (2012) 036005,Phys. Rev. D80 (2009) 096006





statistical significances of the CP asymmetry

Run 2 perspectives



For Run 2, $b\bar{b}$ production rate is approximately twice that of Run 1

Naive estimation for 2017, assume 3fb^{-1} at 7-8 TeV + 3fb^{-1}at 13-14 TeV

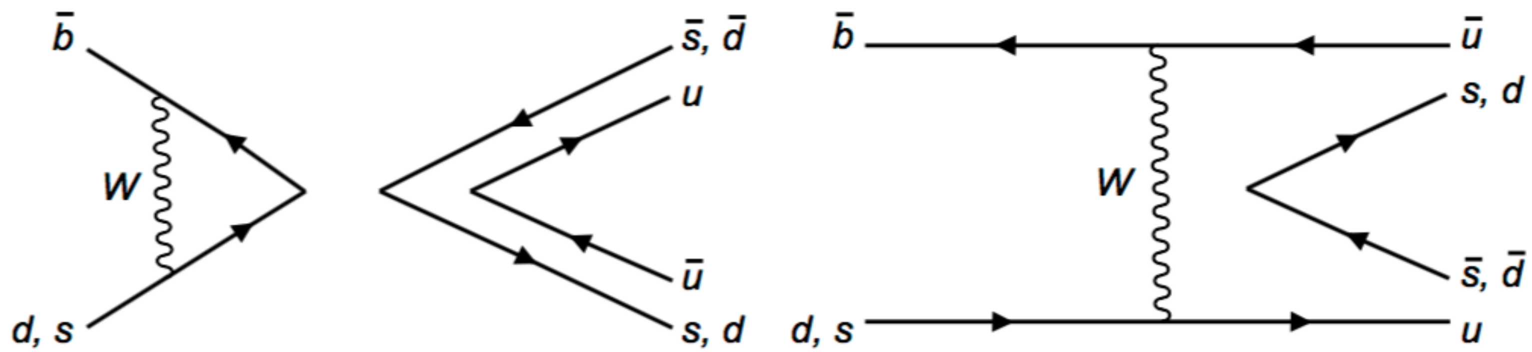
- ✓ uncertainty on CPV asymmetries <1% for several Λ_b^0 decays
- ✓ possibility to observe CPV in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ >5.0σ level

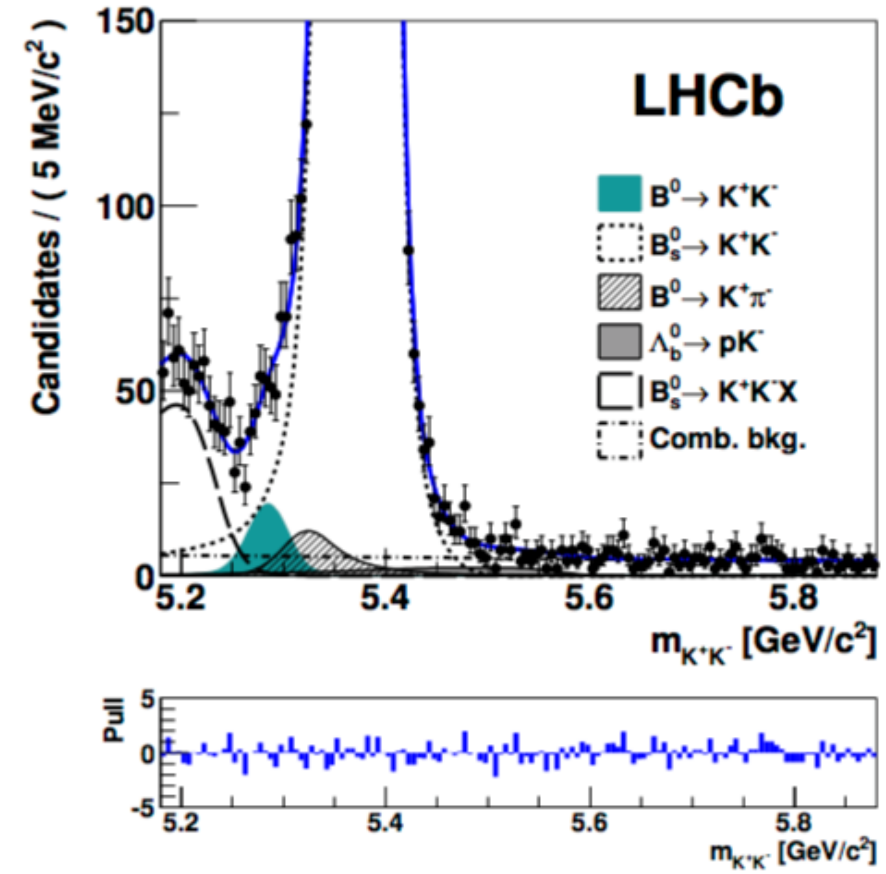
Summary

- LHCb opens a new window to search CP violation in baryon decays. Many b-baryon decays are observed for the first time.
- Evidence for CP violation is found in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ decays with a statistical significance of 3.3σ. This represents the first evidence for CP violation in baryon sector.
- CP violation is searched for in many Λ_b^0 decays using Run 1 data. With the data collected in Run 2, these analysis will be updated to increased sensitivity.
- Theoretical predictions for CPV in b-baryon decays are needed to confront with precision measurements.

BACK UP

Observation of the annihilation $B^0 \to K^+K^-$ decay





- Particular class of decays that can proceed only through so-called annihilation diagrams
  - Very useful to test QCD calculations
- $B^0 \to K^+K^-$ decay observed for the first time after many years of searches
  - Significance 5.8σ

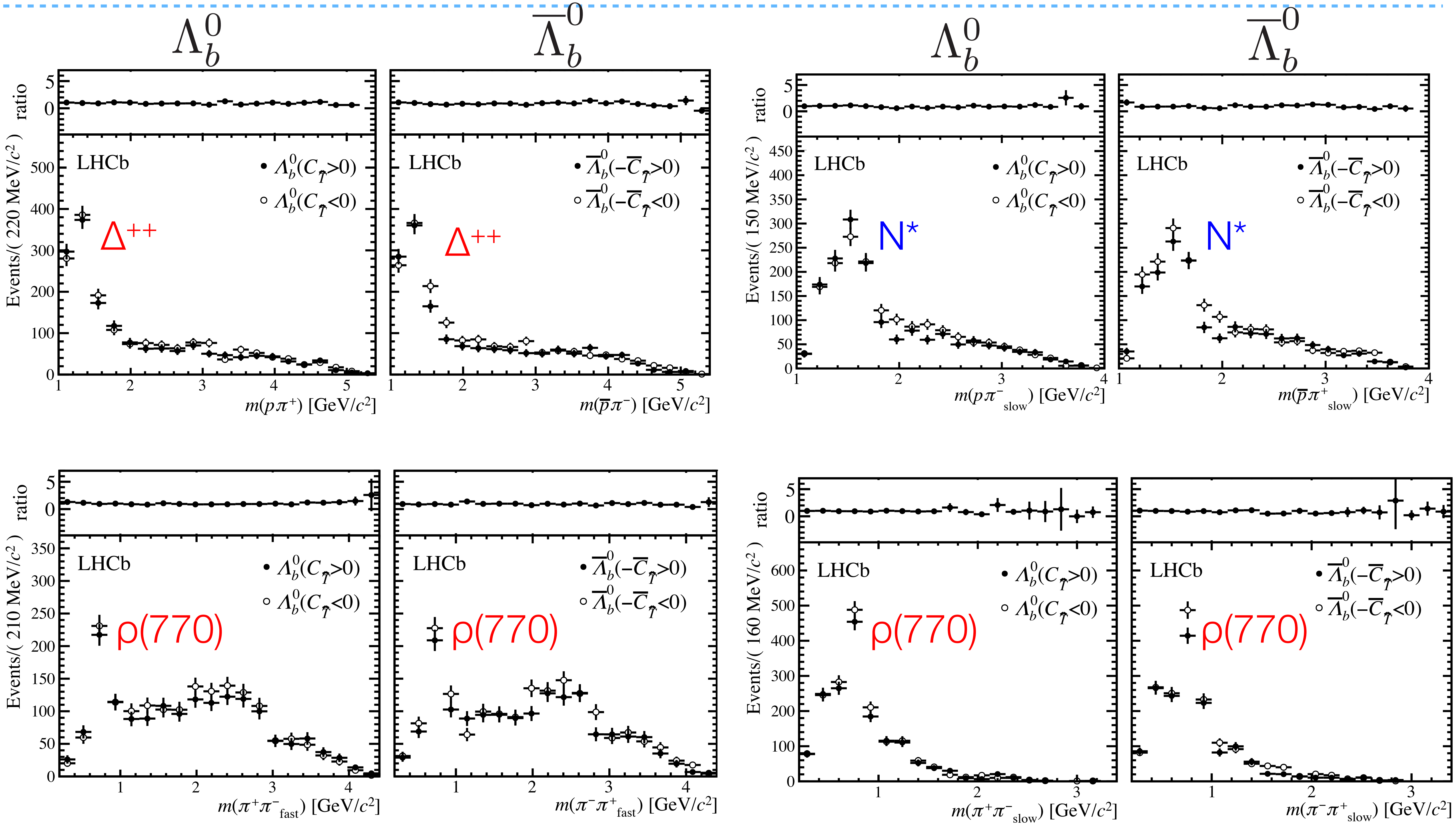
$$\mathcal{B}(B^0 \to K^+K^-) = (7.80 \pm 1.27 \pm 0.81 \pm 0.21) \times 10^{-8},$$
$$\mathcal{B}(B_s^0 \to \pi^+\pi^-) = (6.91 \pm 0.54 \pm 0.63 \pm 0.19 \pm 0.40) \times 10^{-7}$$

- The $B^0 \to K^+K^-$ is the rarest B-meson decay into a fully hadronic final state ever observed

LHCb-PAPER-2016-036 in preparation

$\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ phase spase distributions

arXiv:1609.05216, submitted to Nature Physics



background-subtracted using the *sPlot* method

Λ_b^0 polarisation

- Polarisation measurements from LHCb are consistent with zero:

$P(\Lambda_b^0) = 0.06 \pm 0.07 \pm 0.02$ **Phys.Lett.B 724 (2013) 27**

$P(\Lambda_b^0) = (-0.2 \pm 2.3)\ \%$ **Phys.Rev.Lett 115 (2015) 072001**

- Published measurements from LHCb estimated Λ_b^0 polarisation affect in CPV is negligible. **JHEP 04 (2014) 087** **JHEP 1407 (2014) 103**

- Checks using MC sample polarised at generation level.

- Do not expect any effect on triple product asymmetries due to polarisation.

Cross-checks

Cross-checks are made to investigate the stability of the results

- Different periods of recording data
- Different polarities of the spectrometer magnet
- The choice made in selection of multiple candidates
- The effect of the trigger and selection criteria.
- Alternative binning schemes are studied as a cross-check after unblinding

8 or 12 binning schemes in $|\mathbf{\Phi}|$ for $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ decays

significance of CPV measurements of the alternative binning schemes reduced to below 3.3σ

the overall significance of the combination of the these two additional schemes with scheme A and B remains 3.1σ, consistent with 3.3σ in the baseline analysis.

First observation of CPV using triple product asymmetries

Phys. Rev. Lett. 84, 408 (2000)

$K^0_L \to \pi^+\pi^-e^+e^-$

$\sin\phi\cos\phi$ given by $(\hat{n}_{ee} \times \hat{n}_{\pi\pi}) \cdot \hat{z}(\hat{n}_{ee} \cdot \hat{n}_{\pi\pi})$

ϕ angle between ($\pi^+\pi^-$) plane and (e^+e^-) plane in K_L rest frame

$\hat{n}'$ unit normals

$\hat{z}$ unit vector in the direction of the ($\pi^+\pi^-$) plane in K_L rest frame

CP-violating observable:

$$a_{CP}^{\widehat{T}\text{-odd}} = \frac{N(\sin\phi\cos\phi)>0 - N(\sin\phi\cos\phi)<0}{N(\sin\phi\cos\phi)>0 + N(\sin\phi\cos\phi)<0} = (13.6 \pm 2.5 \pm 1.2)\%$$