Searches for CP violation in multi body baryon decays at LHCb

Andrea Merli[1]
on behalf of the LHCb collaboration

[1]INFN Milano

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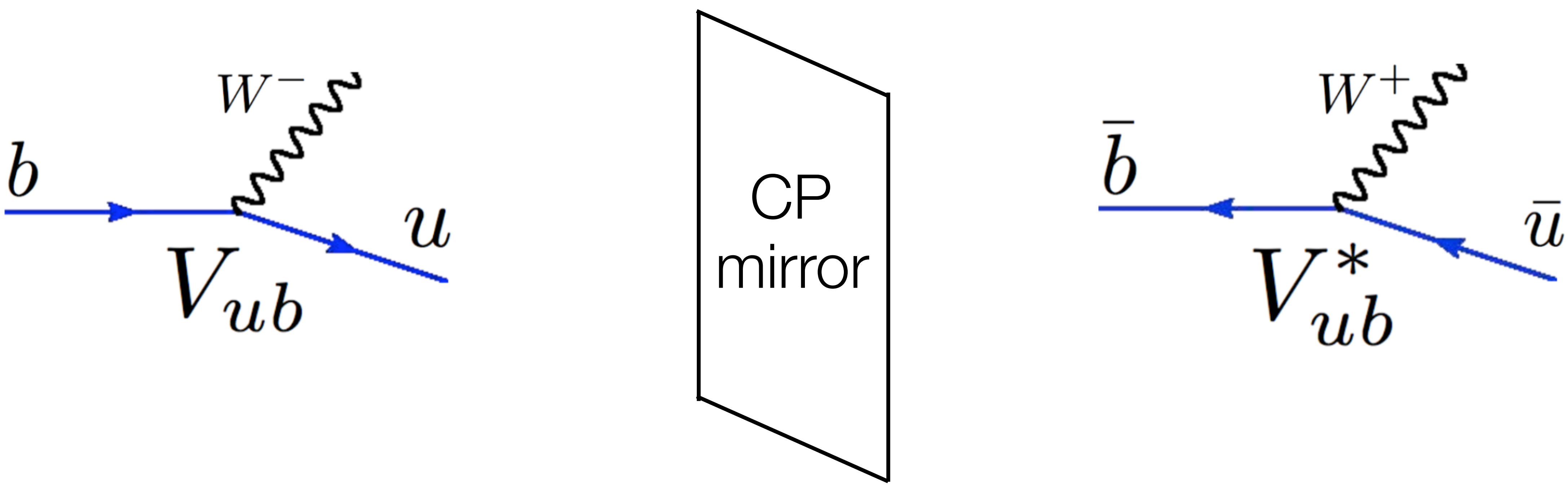
CP violation

- C = charge conjugation: $A \to \bar{A}$
- P = parity, spatial inversion: $x \to -x, y \to -y, z \to -z$
- CP transformation: $(A \to f) \to (\bar{A} \to \bar{f})$

A difference between decays of particles and antiparticles breaks CP symmetry



Why study CP violation?

Violation of CP (CPV) symmetry is a necessary condition for the Baryon Asymmetry of the Universe

The predicted amount of CPV in the Standard Model (SM) is far too small to explain the absence of antimatter in the universe

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

CP violation in Standard Model

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

$$\frac{g}{\sqrt{2}}\overline{U}_L\gamma^\mu V_{CKM} D_L W_\mu^- + \overline{D}_L\gamma^\mu V_{CKM}^\dagger U_L W_\mu^+$$

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

- Wolfestein parametrisation: CKM described by 4 parameters λ, A, ρ, η
- η is the only source of CPV in the SM

CP violation: a long path

1956
Parity violation:
T. D. Lee, C. N. Yang, and C. S. Wu et al.

1963
Cabibbo mixing:
N. Cabibbo

1964
Strange particles: CP violation in K meson decays:
J. W. Cronin
V. L. Fitch et al.

1973
The CKM matrix:
M. Kobayashi and T. Maskawa

1999
Strange particles: Direct CP violation in K meson decays:
NA31, NA48 and KTeV Collaborations

2001
Beauty particles: CP violation in B^0 meson decays:
BaBar and Belle Collaborations

2013
Beauty-strange particles: CP violation in B_s^0 meson decays:
LHCb collaboration

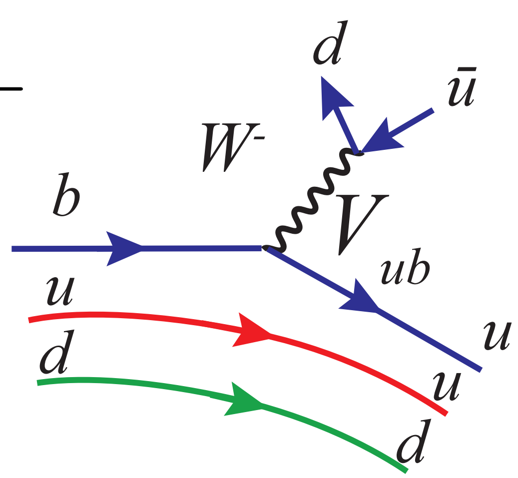
2019
Charm particles: CP violation in D^0 meson decays:
LHCb collaboration

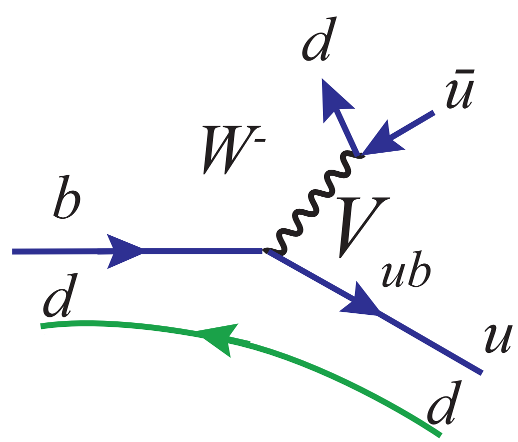
Where are baryons?
CPV not yet discovered in this system

Physics motivation to search for CPV in baryons

- CKM mechanism predicts sizeable amount of CPV in b-baryons that can be precisely measured Phys. Rev. D 91 (2015) 116007
- Test in c-baryons the transitions $c \to ud\bar{d}(s\bar{s})$ that led to the first CPV observation in charm

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





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

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

Status for CPV in baryon decays prior to LHC era

Experiment	Decay	Measurement	
HyperCP	$\Xi^- \to \Lambda\pi^- \to p\pi^-\pi^-$	$(0.0 \pm 5.1 \pm 4.4) \times 10^{-4}$	[1]
HyperCP	$\Omega^- \to \Xi^-\pi^+\pi^-$	0.12 ± 0.20	[2]
FOCUS	$\Lambda_c^+ \to \Lambda\pi^+$	$-0.07 \pm 0.19 \pm 0.12$	[3]
CLEO	$\Lambda_c^+ \to \Lambda e^+\nu_e$	$0.00 \pm 0.03 \pm 0.01 \pm 0.02$	[4]
CDF	$\Lambda_b^0 \to pK^-$	$-0.10 \pm 0.08 \pm 0.04$	[5]
CDF	$\Lambda_b^0 \to p\pi^-$	$0.06 \pm 0.07 \pm 0.03$	[5]

[1] Phys. Rev. Lett. 93 (2004) 262001
[2] Phys. Lett. B 693 (2010) 236
[3] Phys. Lett. B 634 (2006) 165
[4] Phys. Rev. Lett. 94 (2005) 191801
[5] Phys. Rev. Lett. 113 (2014) 242001

Consistent with CP symmetry

Status of CPV searches in Λ_b^0

$\mathcal{O}(10\%)$

- CDF (prior to LHC era):
  - $A_{CP}(\Lambda_b^0 \to p\pi^-) = (6 \pm 7 \pm 3)\,\%$ Phys. Rev. Lett. 113 (2014) 242001
  - $A_{CP}(\Lambda_b^0 \to pK^-) = (10 \pm 8 \pm 4)\,\%$ Phys. Rev. Lett. 113 (2014) 242001

up to $\mathcal{O}(1\%)$

- LHCb:
  - $A_{CP}(\Lambda_b^0 \to K_S^0 p\pi^-) = (22 \pm 13 \pm 3)\,\%$ JHEP 04 (2014) 087
  - $\Delta A_{CP}(\Lambda_b^0 \to J/\psi p\pi^-/K^-) = A_{CP}(\Lambda_b^0 \to J/\psi p\pi^-) - A_{CP}(\Lambda_b^0 \to J/\psi pK^-) = (5.7 \pm 2.4 \pm 1.2)\,\%$ JHEP 07 (2014) 103
  - $A_{CP}(\Lambda_b^0 \to \Lambda K^+\pi^-) = (53 \pm 23 \pm 11)\,\%$ JHEP 05 (2016) 081
  - $A_{CP}(\Lambda_b^0 \to \Lambda K^+K^-) = (28 \pm 10 \pm 7)\,\%$ JHEP 05 (2016) 081
  - $A_{CP}(\Lambda_b^0 \to pK^-) = (-2.0 \pm 1.3 \pm 1.9)\,\%$ Phys. Lett. B787 (2018) 124
  - $A_{CP}(\Lambda_b^0 \to p\pi^-) = (-3.5 \pm 1.7 \pm 2.0)\,\%$ Phys. Lett. B787 (2018) 124
  - $a_{CP}^{\hat{T}-odd}(\Lambda_b^0 \to pK^-\pi^+\pi^-) = (-0.81 \pm 0.84 \pm 0.31)\,\%$ JHEP 39 (2018) 1808
  - $a_{CP}^{\hat{T}-odd}(\Lambda_b^0 \to pK^-K^+K^-) = (1.12 \pm 1.51 \pm 0.32)\,\%$ JHEP 39 (2018) 1808
  - $a_{CP}^{\hat{T}-odd}(\Lambda_b^0 \to p\pi^-\pi^+\pi^-) = (1.15 \pm 1.45 \pm 0.32)\,\%$ Nature Phys. 13 (2017) 391
  - $a_{CP}^{\hat{T}-odd}(\Lambda_b^0 \to pK^-K^+\pi^-) = (-0.93 \pm 4.54 \pm 0.42)\,\%$ Nature Phys. 13 (2017) 391

b-baryon production

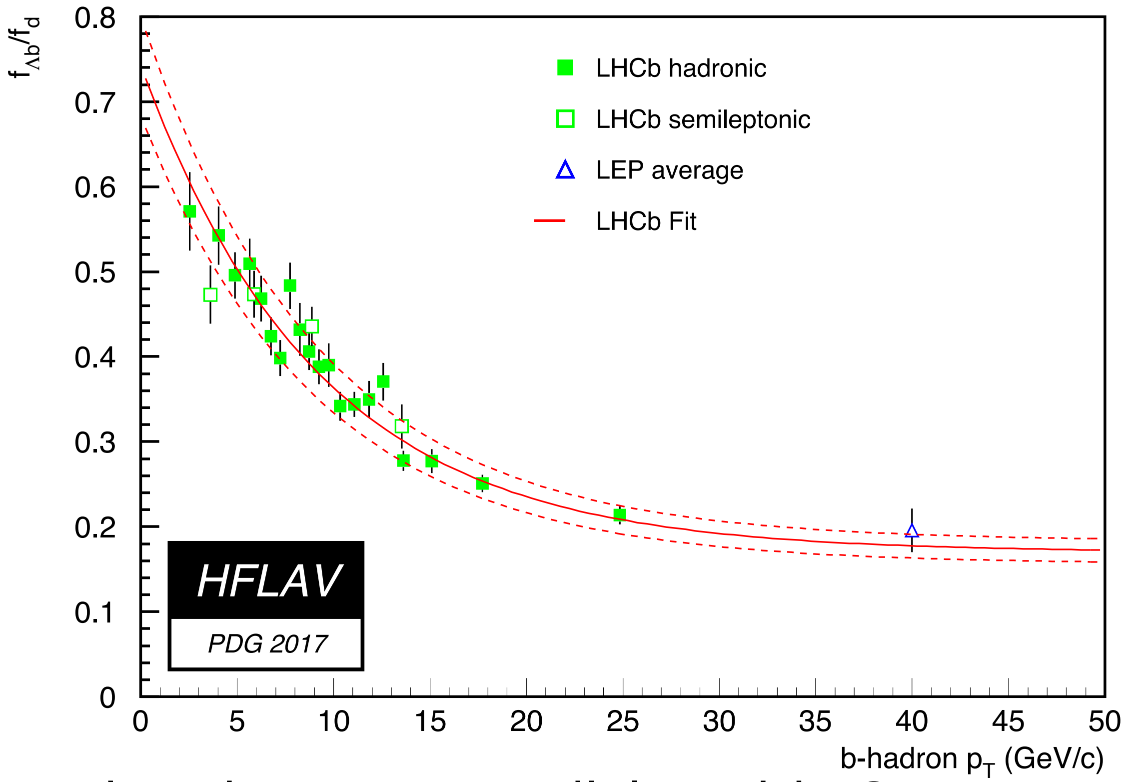
- Production cross-section strongly depends on p_T of the hadron:
- Large production of Λ_b^0

$$\sigma(b\bar{b})[LHCb] = 144 \pm 1 \pm 21 \mu b$$ Phys. Rev. Lett. 118 052002

$$\sigma(b\bar{b})[CDF] = 2.39 \pm 0.32 \pm 0.44 \mu b$$ Phys. Rev. Lett. **75**, 1451

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

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



- Λ_b^0 polarization measured to be compatible with 0:
  - $P_{\Lambda_b^0} = (-2.0 \pm 2.3)\,\%$ PRL 7 (2015), 115
  - $P_{\Lambda_b^0} = (6 \pm 7 \pm 2)\,\%$ Phys. Lett. B 724 (2013), 27

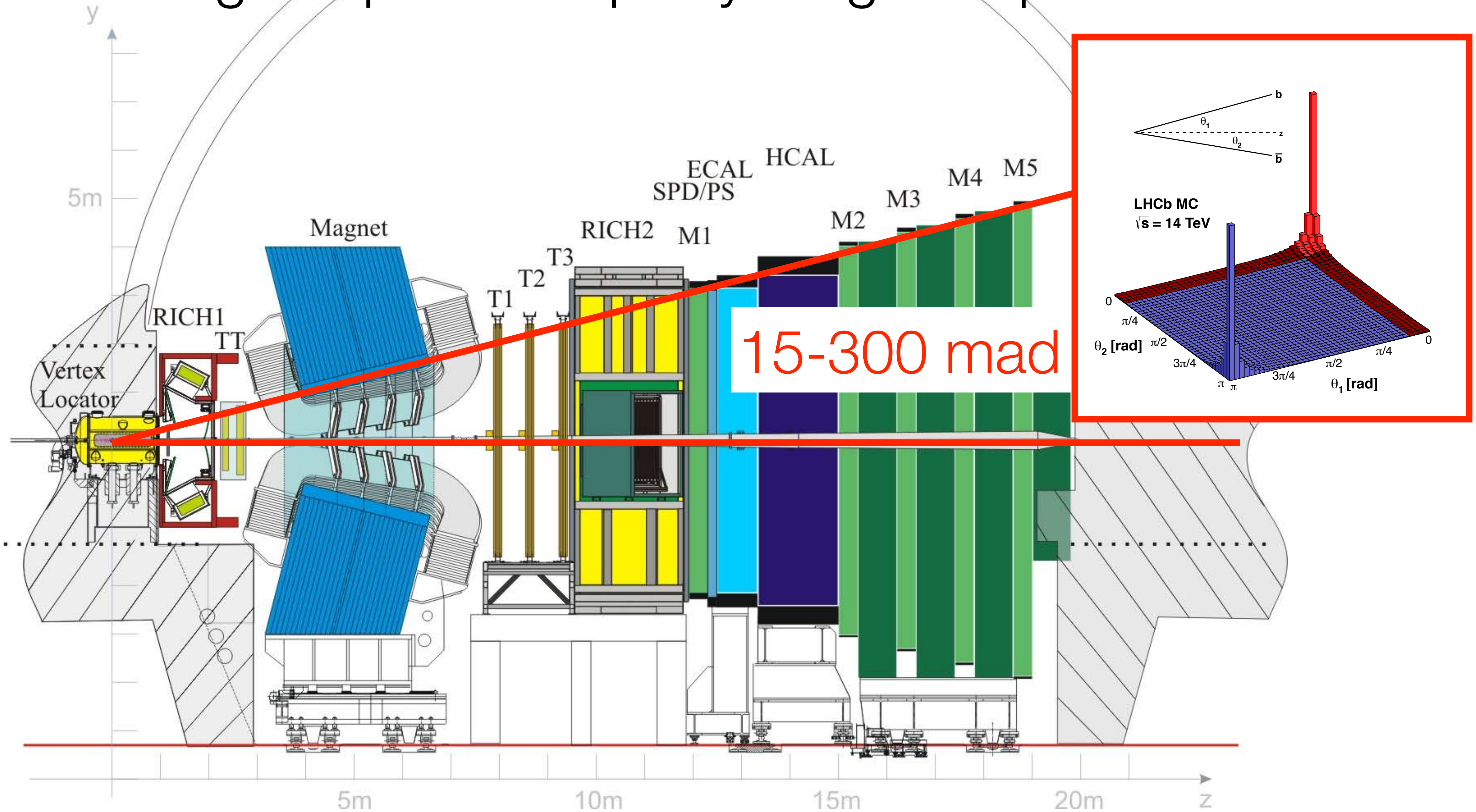
Beauty baryons at LHCb

- Most precise measurement of $|V_{ub}|$ using $\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu$ decays
  Nature Physics 10 (2015) 1038
- First observation of pentaquark using $\Lambda_b^0 \to J/\psi p K^-$decays
  Phys. Rev. Lett. 115 (2015) 072001
- Observation of excited $\Lambda_b^0, \Xi_b, \Sigma_b$
  Phys. Rev. Lett. 122 (2018) 012001
  Phys. Rev. Lett. 114 (2015) 062004
  Phys. Rev. Lett. 109 (2012) 172003
- Mass, lifetime and branching ratio measurements
  Phys. Rev. Lett. 119 (2017) 062001
  Phys.Lett. B734 (2014) 122-130
  Phys.Rev.Lett. 113 (2014) 242002
  Phys.Rev.Lett. 113 (2014) 032001
  Phys.Rev. D93 (2016) 092007
- Search for CPV
- Searches for baryon oscillations
  Phys. Rev. Lett. 119 (2017) 181807
- At LHCb b-baryons are produced in unprecedented quantities
  - Opens a new field in flavour physics for precision measurements

The LHCb detector

FORWARD PEAKED PRODUCTION of b-hadrons

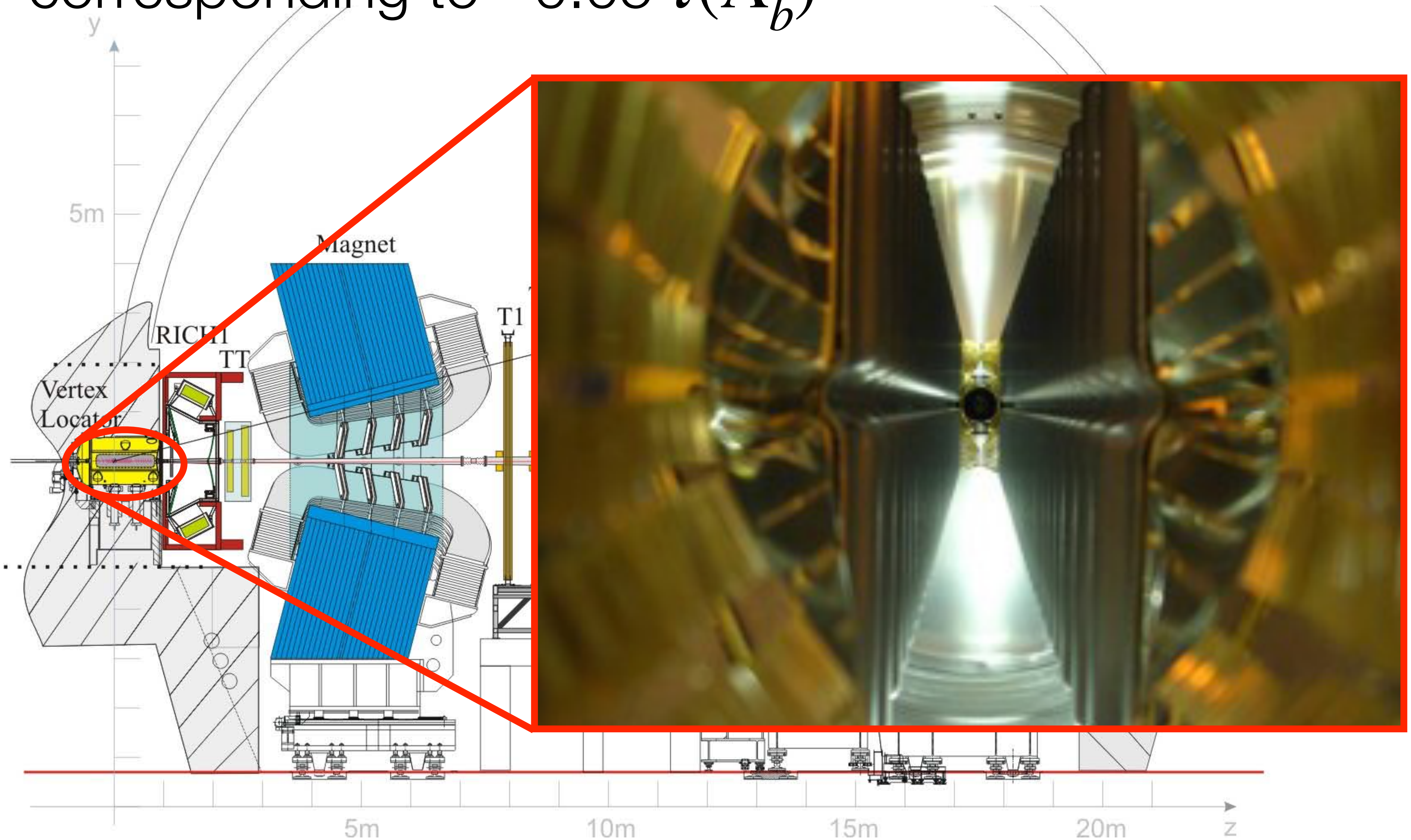
- LHCb designed as forward spectrometer covering the pseudorapidity range $2<\eta<5$



The LHCb detector

VErtex LOcator for precision vertexing

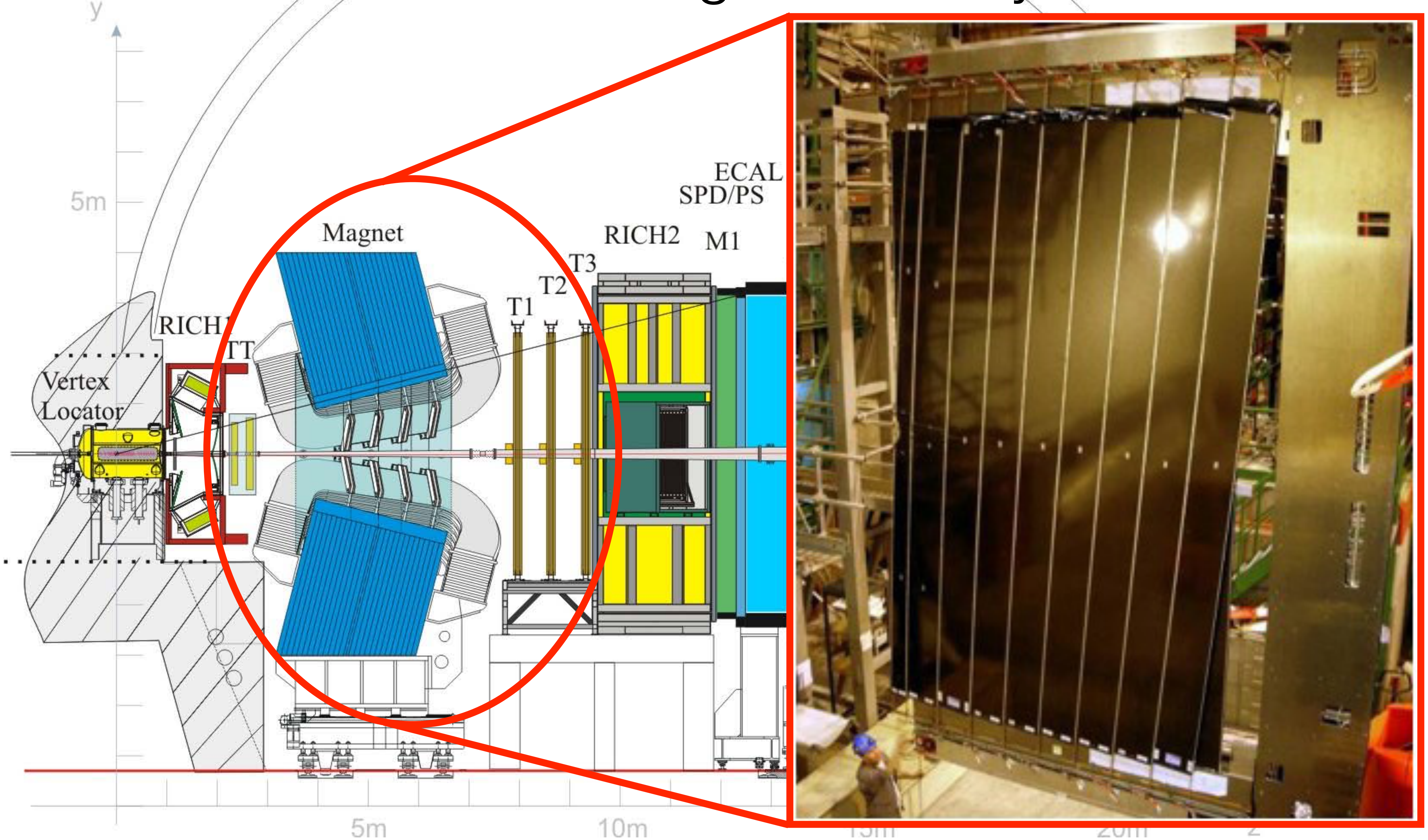
- 20 μm impact parameter resolution, corresponding to ~0.05 $\tau(\Lambda_b^0)$



The LHCb detector

TRACKING SYSTEM

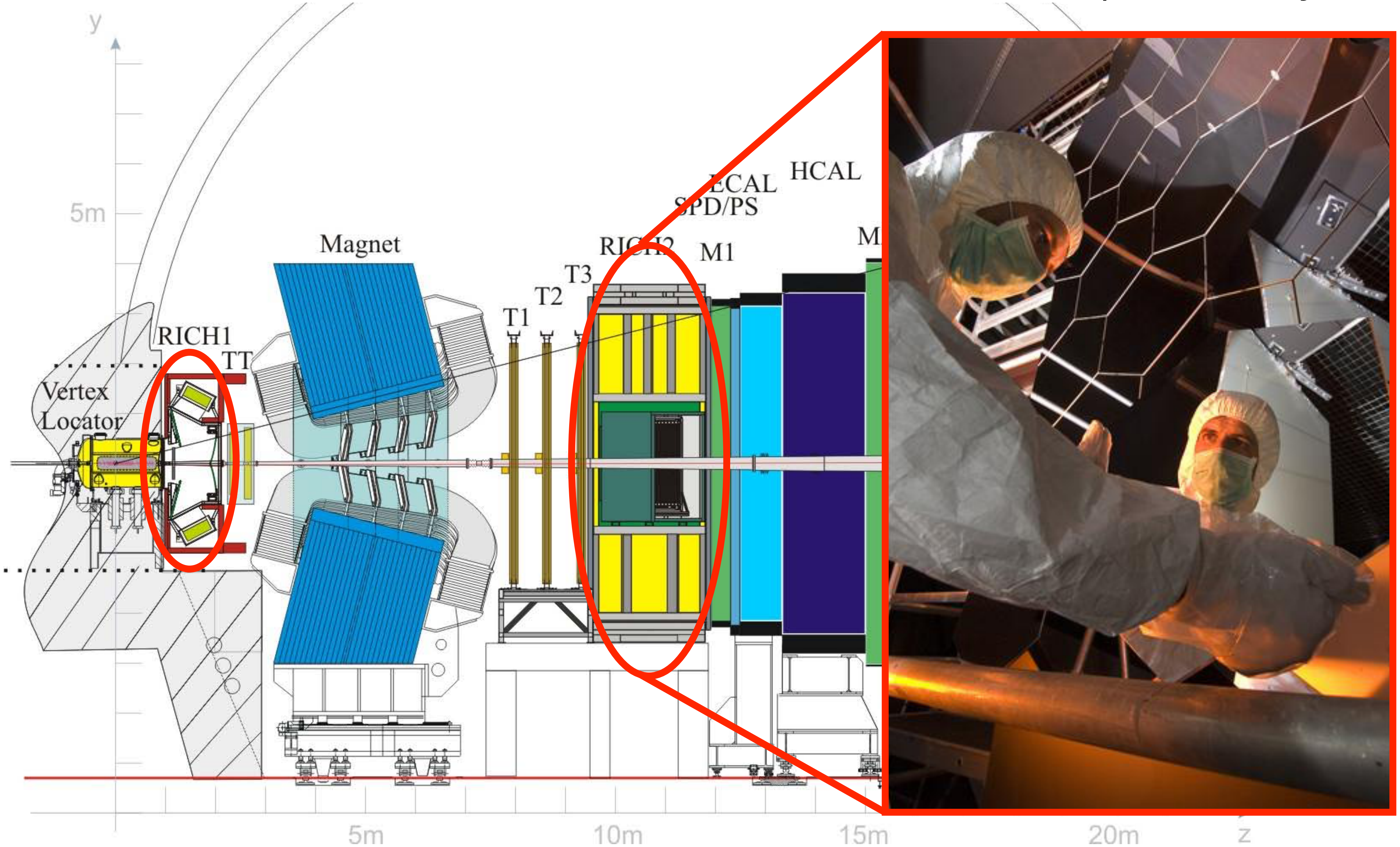
- Δp/p=0.4-0.6% in 5-100 GeV/c, corresponding to ~20 MeV/c^2 for a charged B decay



The LHCb detector

RICH DETECTORS

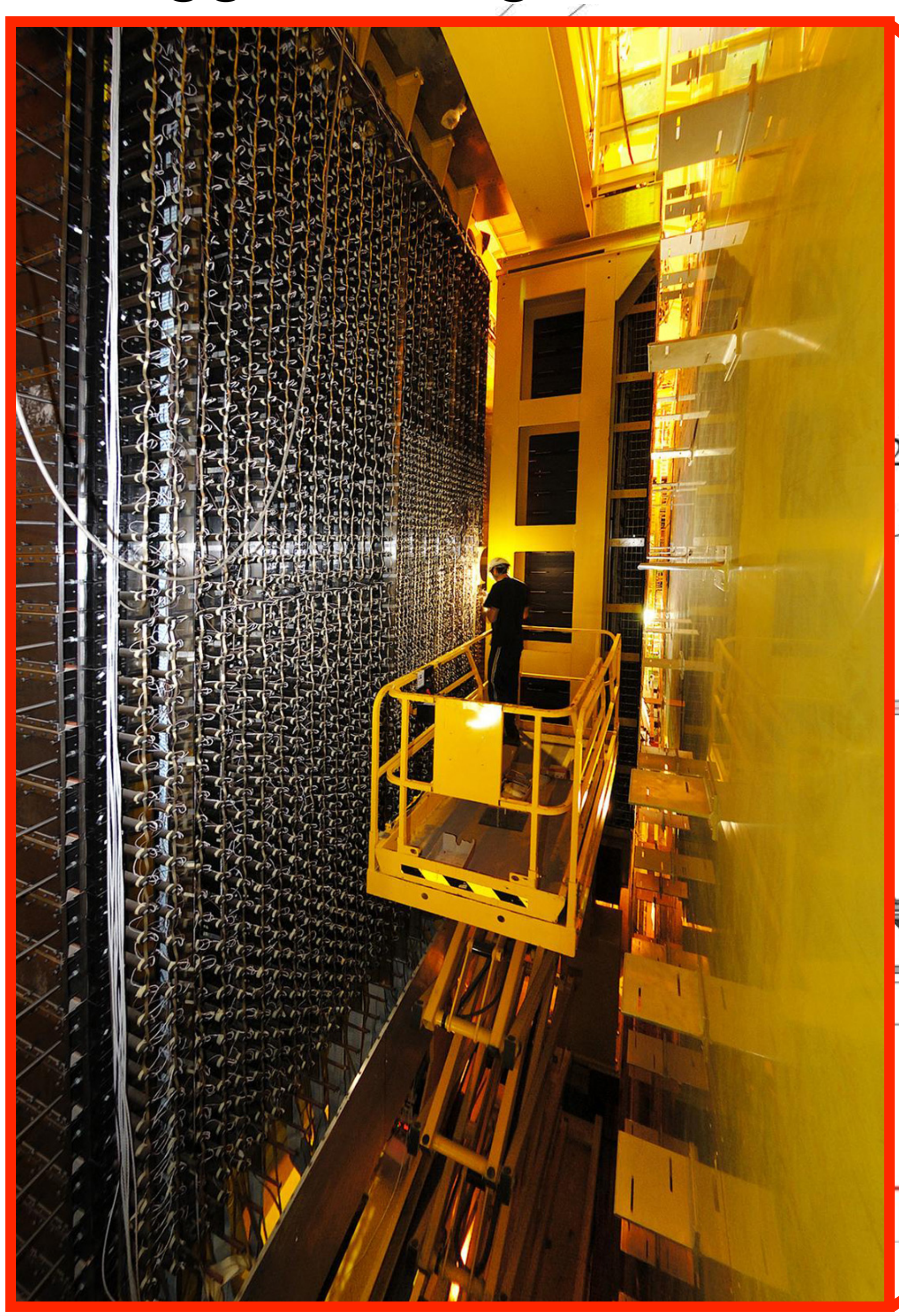
- Provide discrimination between kaons, pions and protons in 5-100 GeV/c. Kaon ID~95% for ~5% π->K misID probability

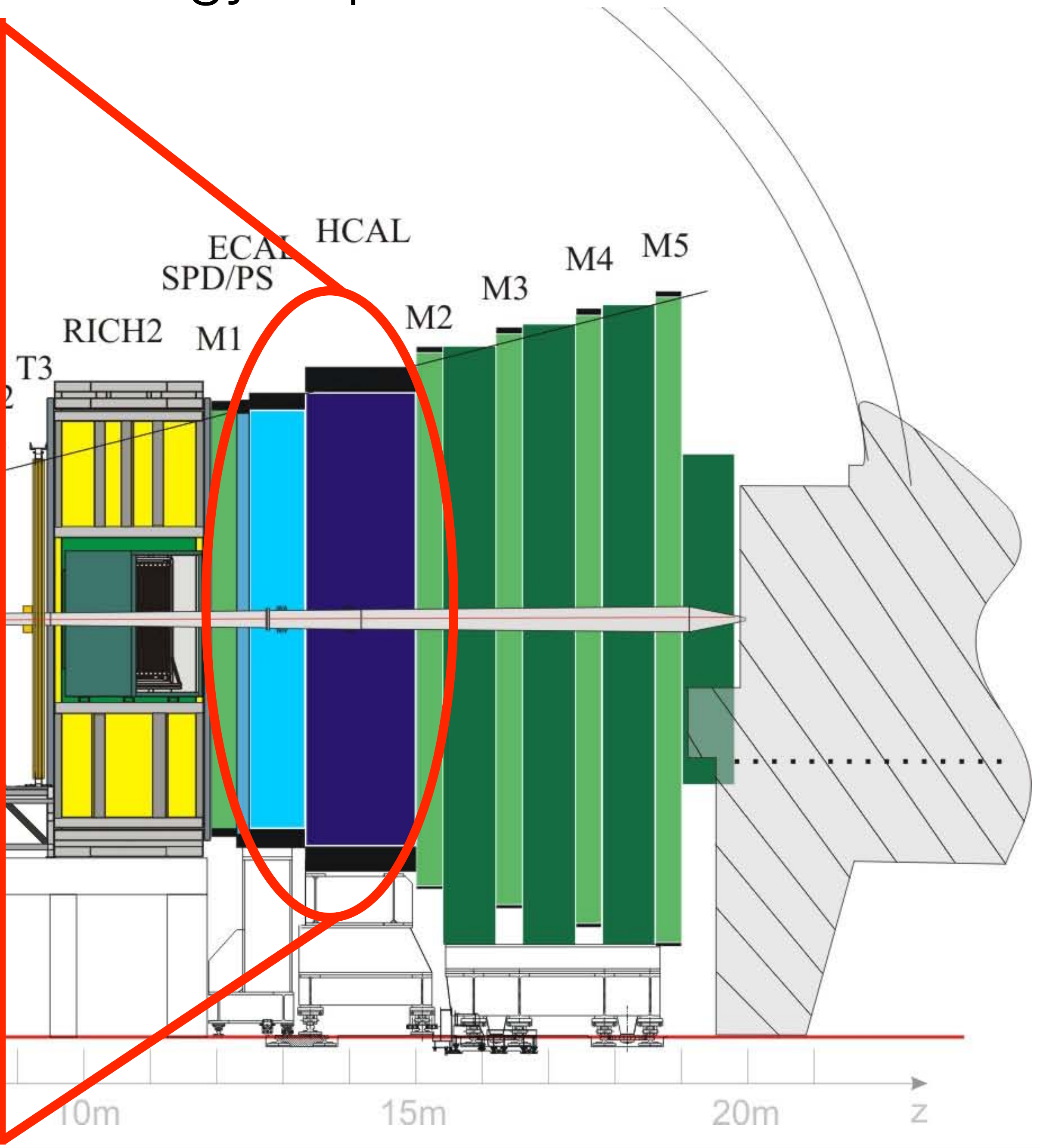


The LHCb detector

CALORIMETERS

- Preshower+SPD+electromagnetic+hadronic calorimeters
- Trigger on high transverse energy deposit

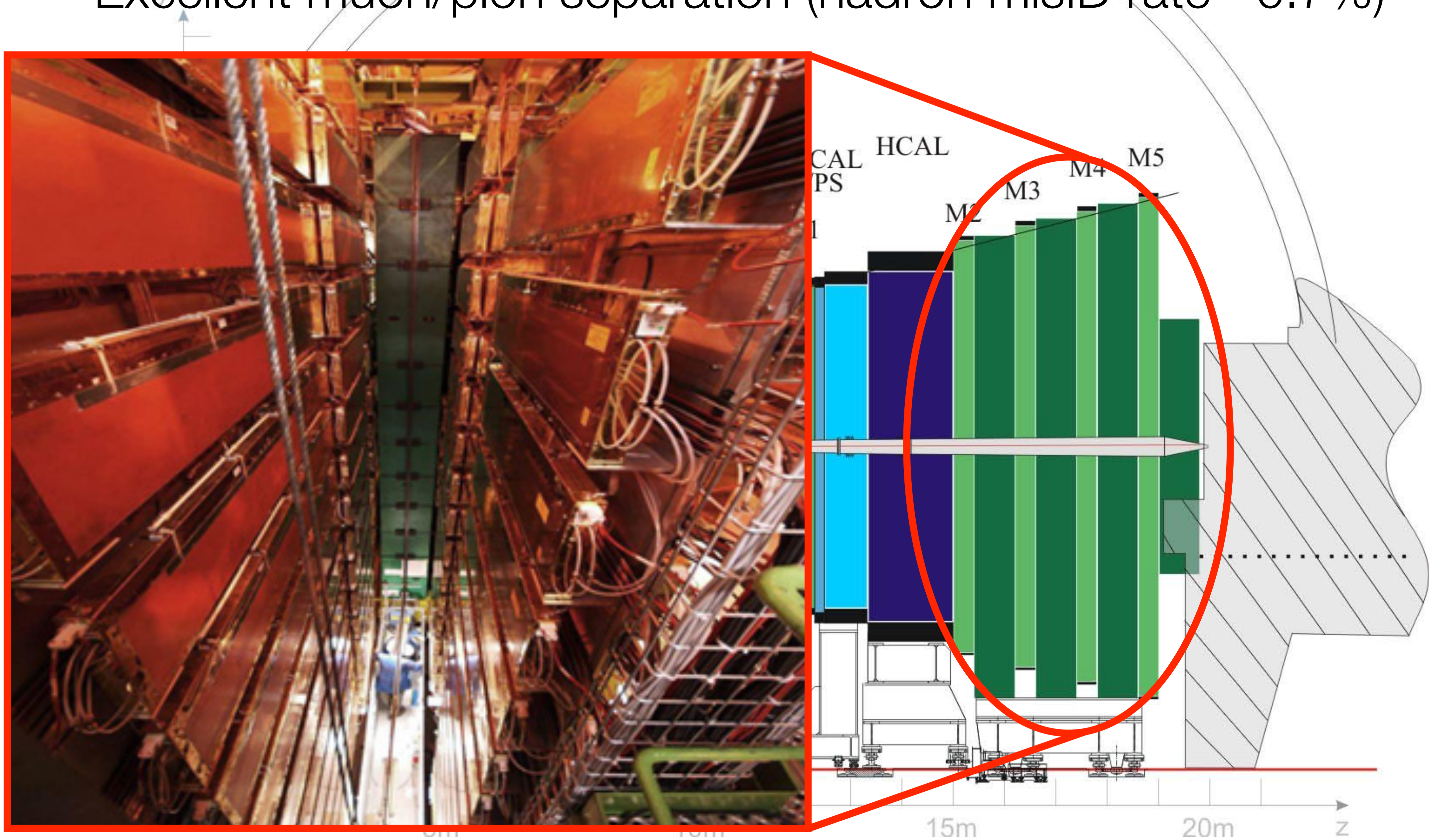




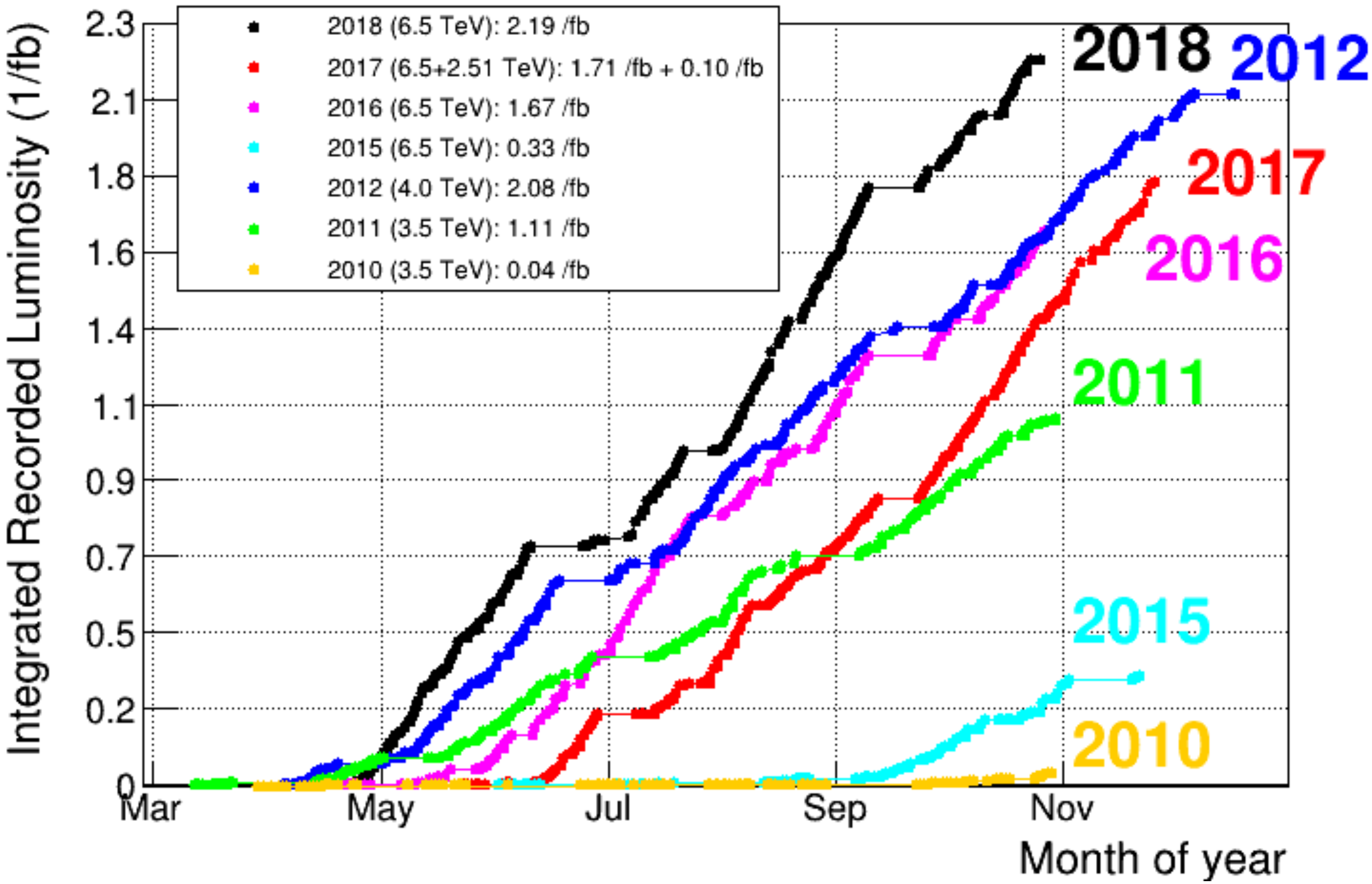
The LHCb detector

MUON STATIONS

- Five stations, hardware trigger on muons with high transverse energy
- Excellent muon/pion separation (hadron misID rate ~0.7%)



Integrated recorded luminosity



The full LHCb dataset is about ~9fb^{-1}

Theory side

What are the predictions of the SM in baryon decays?

- Few theoretical predictions: strong phases not known
- Multibody decays could help:
  - Several quasi two-body amplitudes —> access to strong and weak phases
- Searches for CPV in regions of phase space would be easier to interpret in terms of resonant contributions and decay amplitudes
- Possibility to exploit polarisation of initial and final state to build CPV asymmetries, although experimentally complicated
- New observables proposed by theorists can be measured

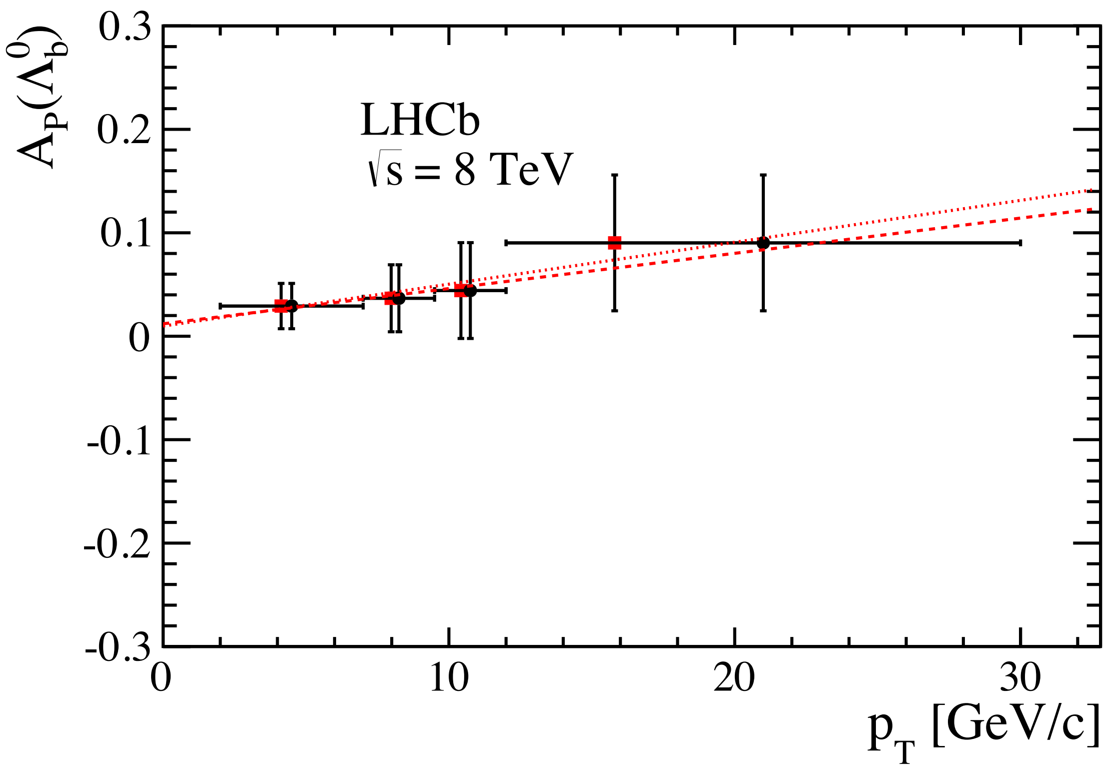
Experimental challenges

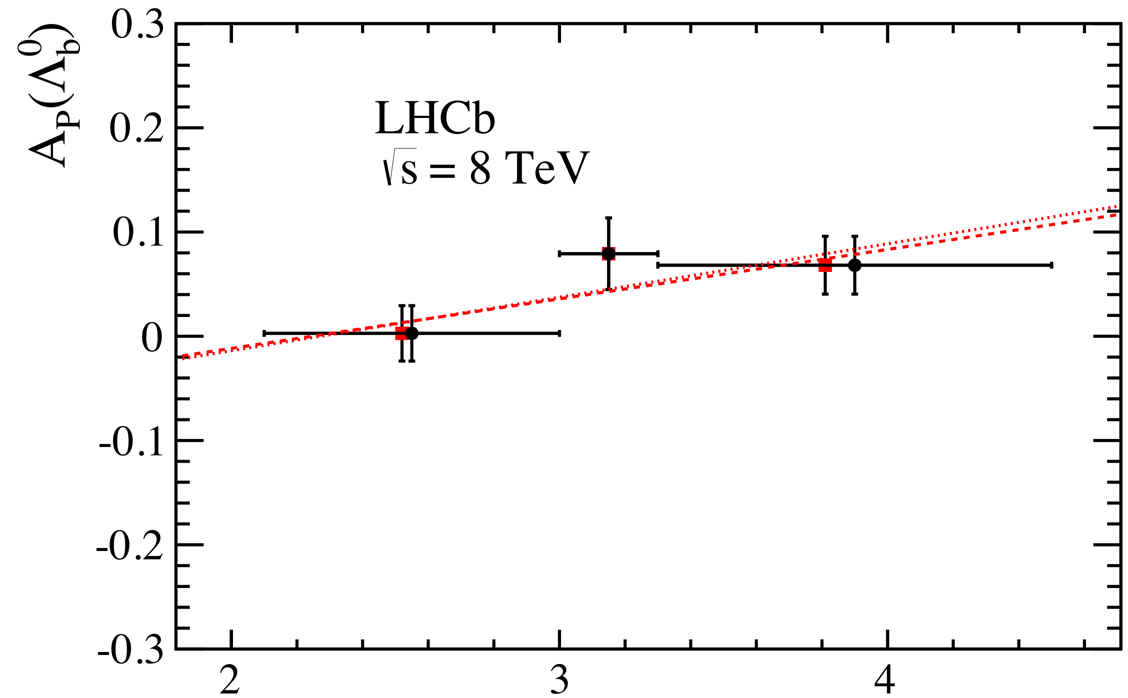
Particle-antiparticle production asymmetries

Phys. Lett. B 774 (2017) 139

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

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





Pseudorapidity

- By means of the unitary relation:

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

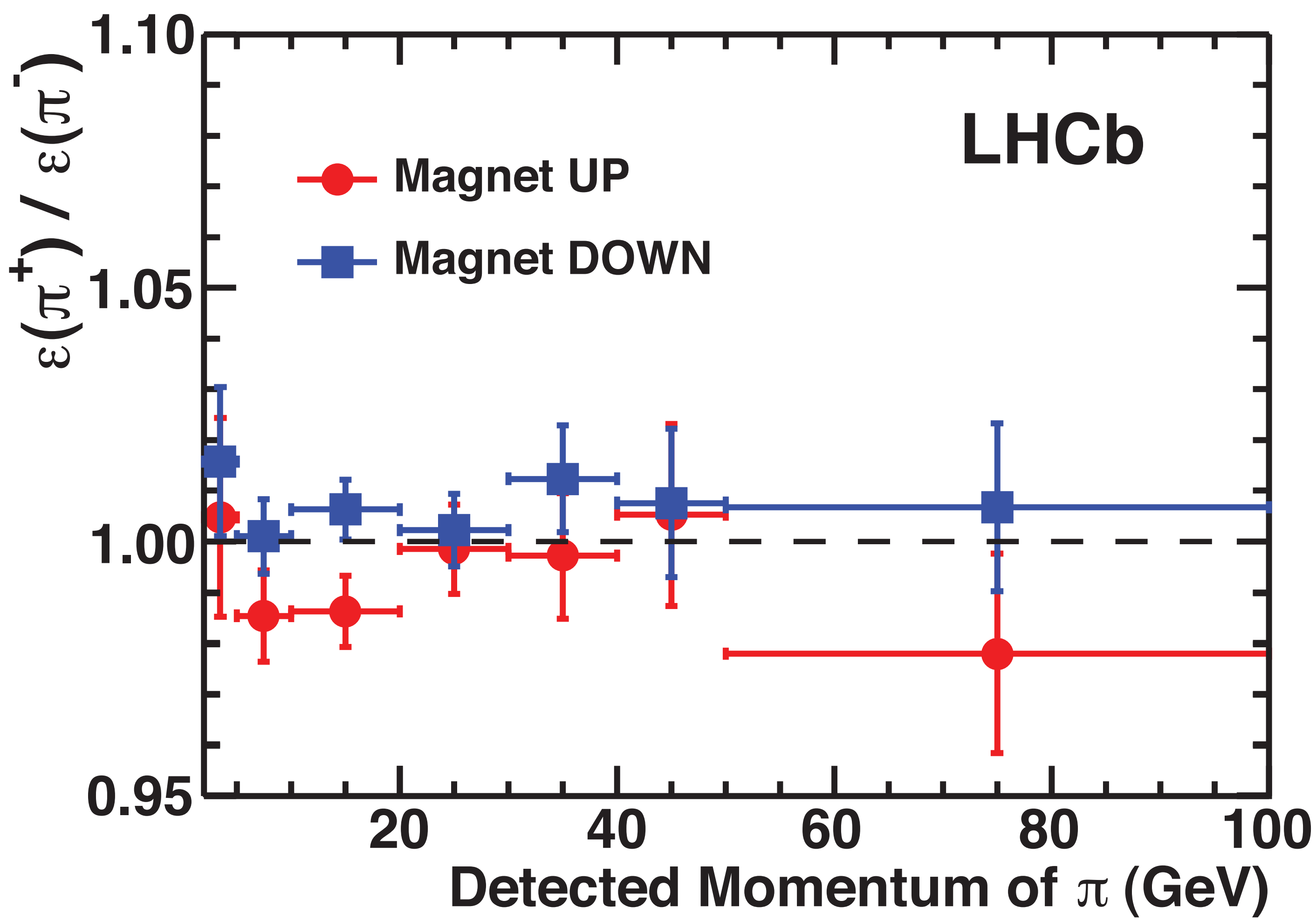
Experimental challenges

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



Phys. Lett. B 713 (2012)

Experimental approach

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

δ: strong phase

θ: weak phase

$$A_{CP} = \frac{N(B \to f) - N(\overline{B} \to \bar{f})}{N(B \to f) + N(\overline{B} \to \bar{f})} \propto \sin(\delta_1 - \delta_2)\sin(\theta_1 - \theta_2)$$

✓ The decay receives contributions from at least two amplitudes

✓ Sensitive to baryon-antibaryon production asymmetries $A_P(B)$

✓ Sensitive to charged particle reconstruction asymmetries $A_D(f)$

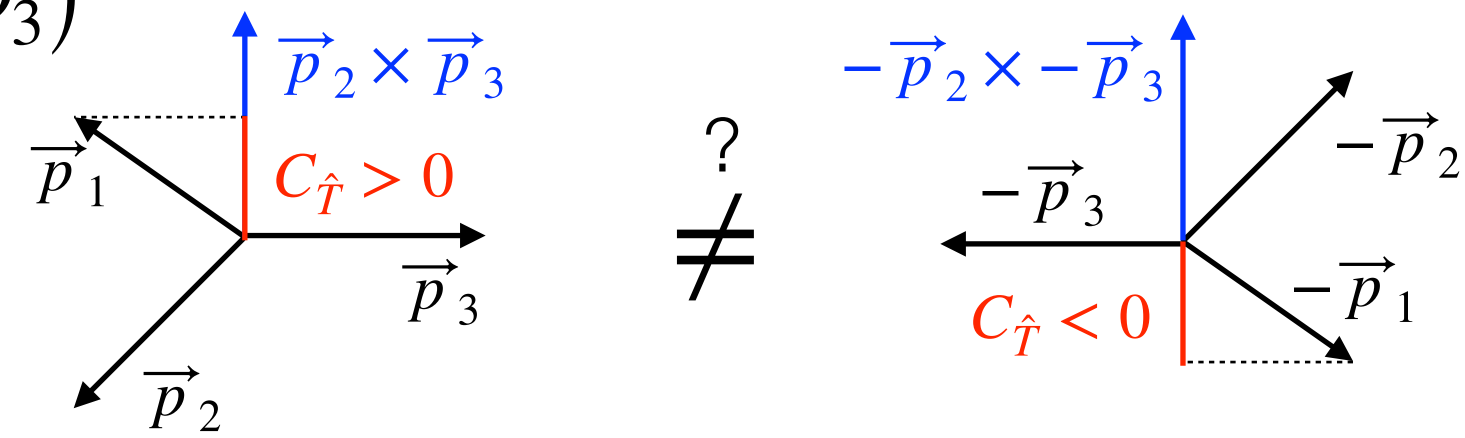
- Measure $\Delta A_{CP} = A_{CP}(B \to f) - A_{CP}(B \to f')$ to mitigate the effect of the experimental effects
- P-even CPV test

Experimental approach

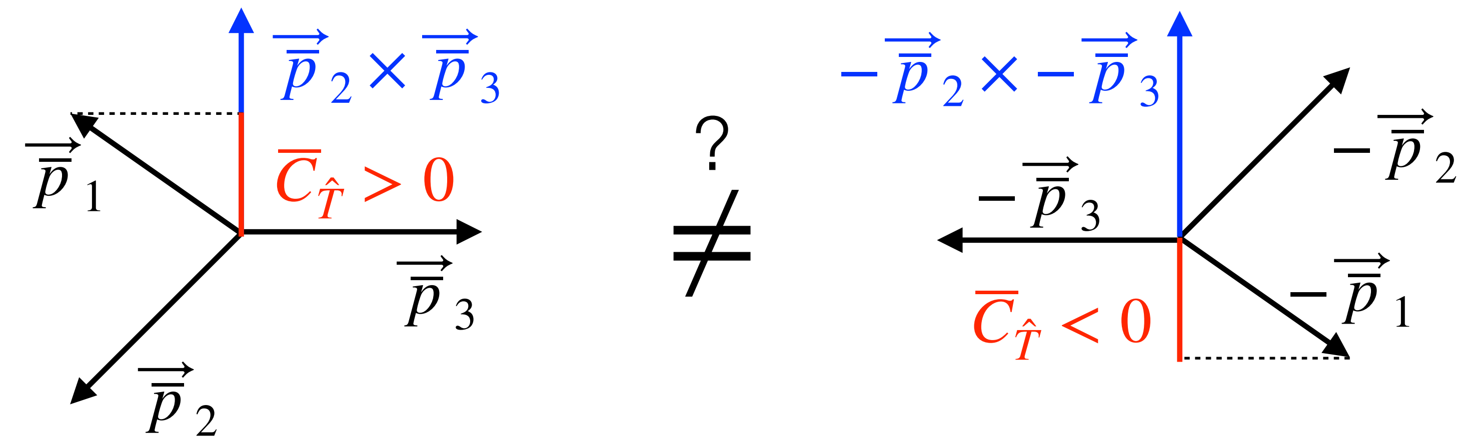
Measure *CPV* via $\hat{T}$-(P-)violating aymmetries in $\Lambda_b^0 \to p h^- h^+ h^-$:

- $C_{\hat{T}} = p_1 \cdot (p_2 \times p_3)$

For Λ_b^0 particle:



For $\overline{\Lambda}_b^0$ antiparticle:



- Is the P violation different between particle and antiparticle?
- P-odd CPV test

Experimental approach

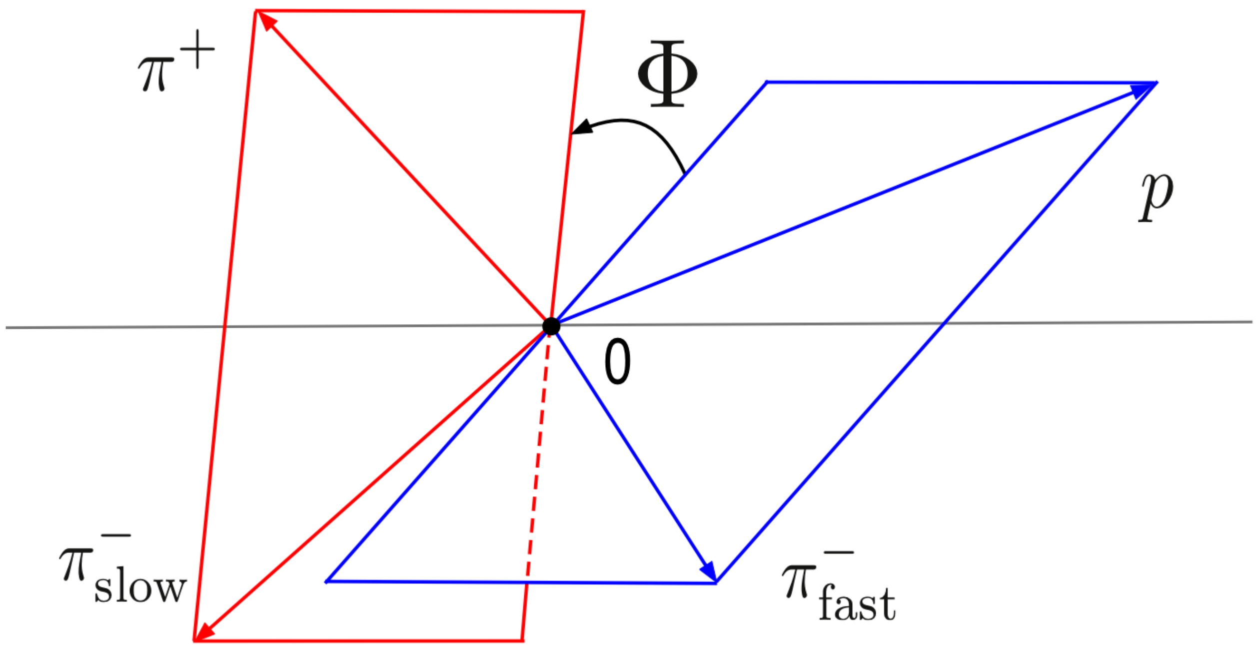
Measure *CPV* via $\hat{T}$-(P-)violating aymmetries in $\Lambda_b^0 \to p h^- h^+ h^-$:

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

- Triple products in Λ_b rest frame

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

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



- $\hat{T}$(*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:

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

- *P*-violating observable:

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

Sensitivity to CPV

- Complementary approach to other measurements

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

not sensitive if $\delta_{\text{even}}-\delta_{\text{odd}} = \pi/2$ or $3\pi/2$

Phys. Rev. D 92 (2015) 076013

δ: strong phase

θ: weak phase

$\hat{T}$-even, $\hat{T}$-odd amplitudes

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

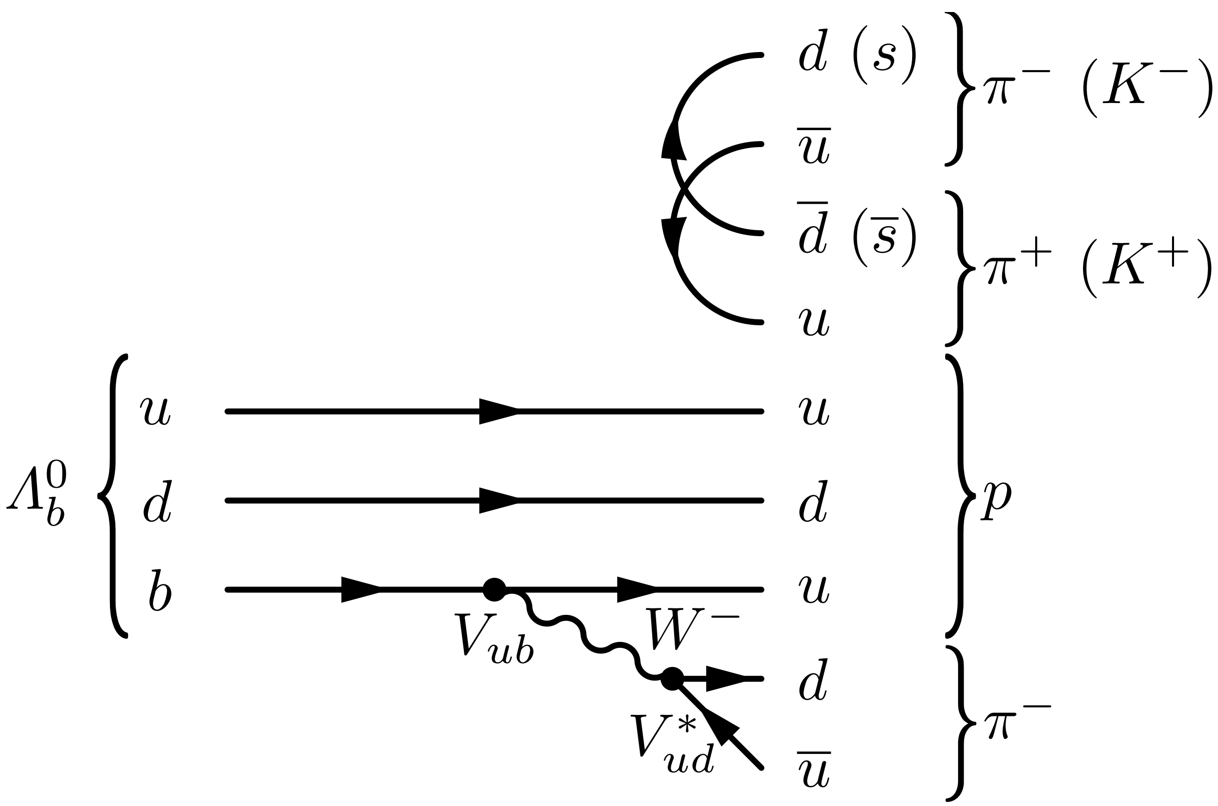
- Sensitive to potential new physics effects

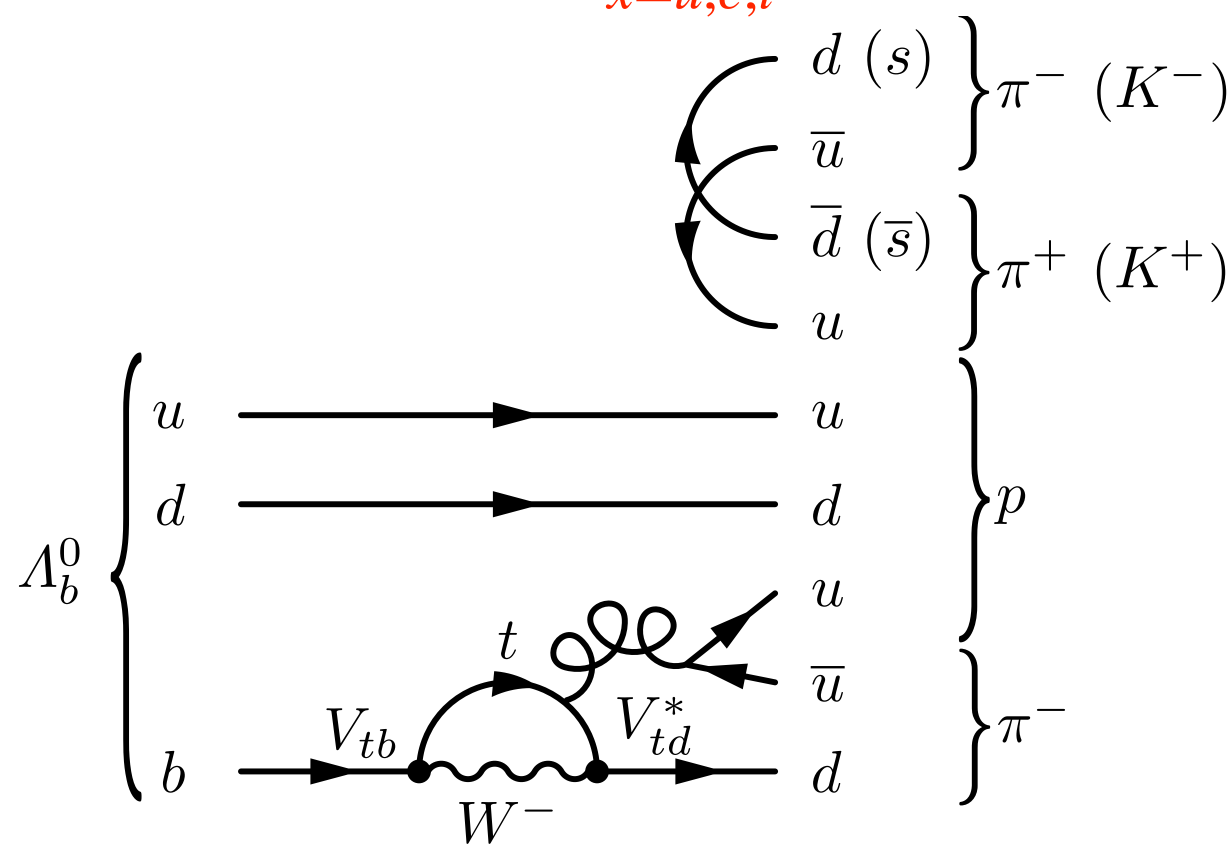
W. Bensalem, A. Datta, and D. London, New physics effects on triple product correlations in Λ_b decays, Phys. Rev. D66 (2002) 094004, arXiv:hep-ph/0208054

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

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

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





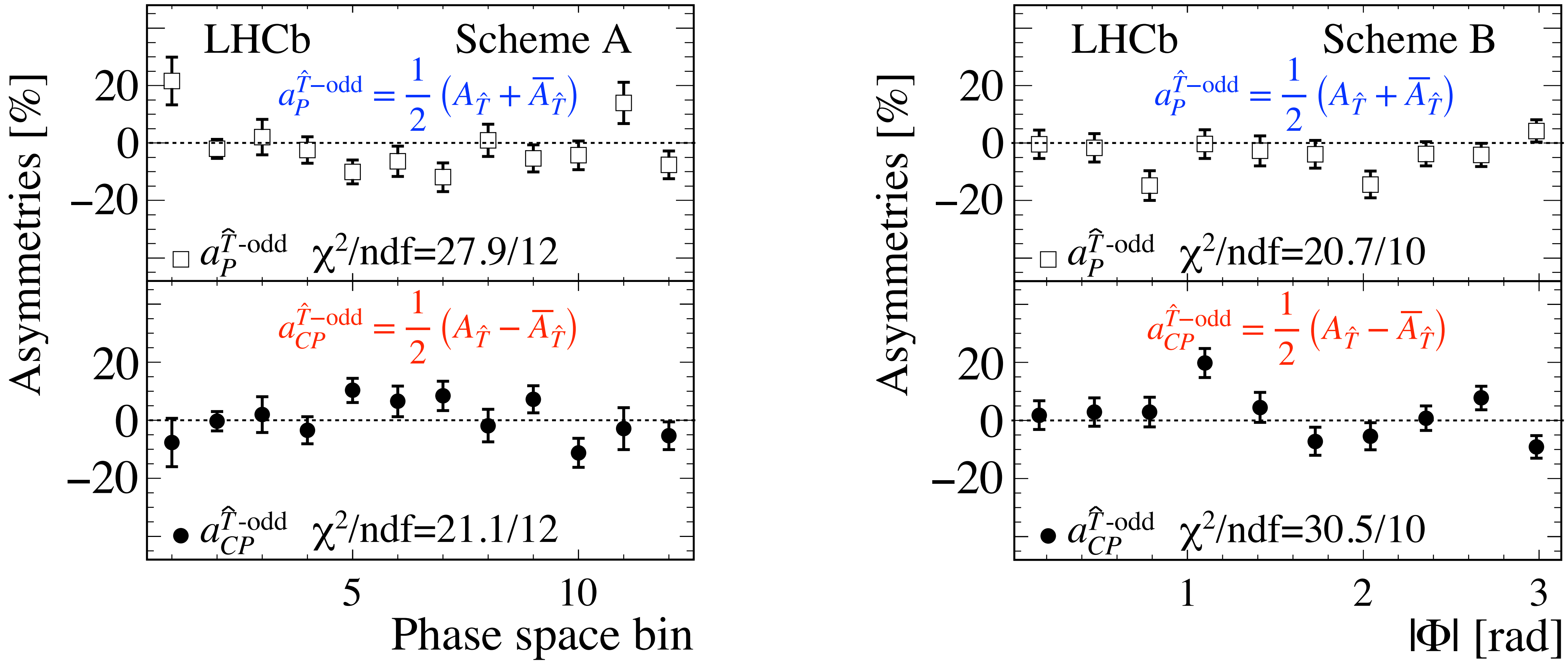
- Transitions governed by $b \to u d \overline{u}$ tree and $b \to d u \overline{u}$ penguin amplitudes of similar magnitude
- Large relative weak phase $\alpha = Arg\left(\frac{V_{tb}^* V_{td}}{V_{ub}^* V_{ud}}\right)$ in SM from the CKM elements
- Potential non negligible CPV effects in the SM

First evidence of CPV in baryons in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$

Nature Physics 13, 391-396 (2017)

Scheme on dominant resonances

Scheme on Φ angle intervals



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

CP symmetry p-value = 9.8×10^{-4}

3.3 σ deviation

P symmetry compatible at 2.2 σ

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

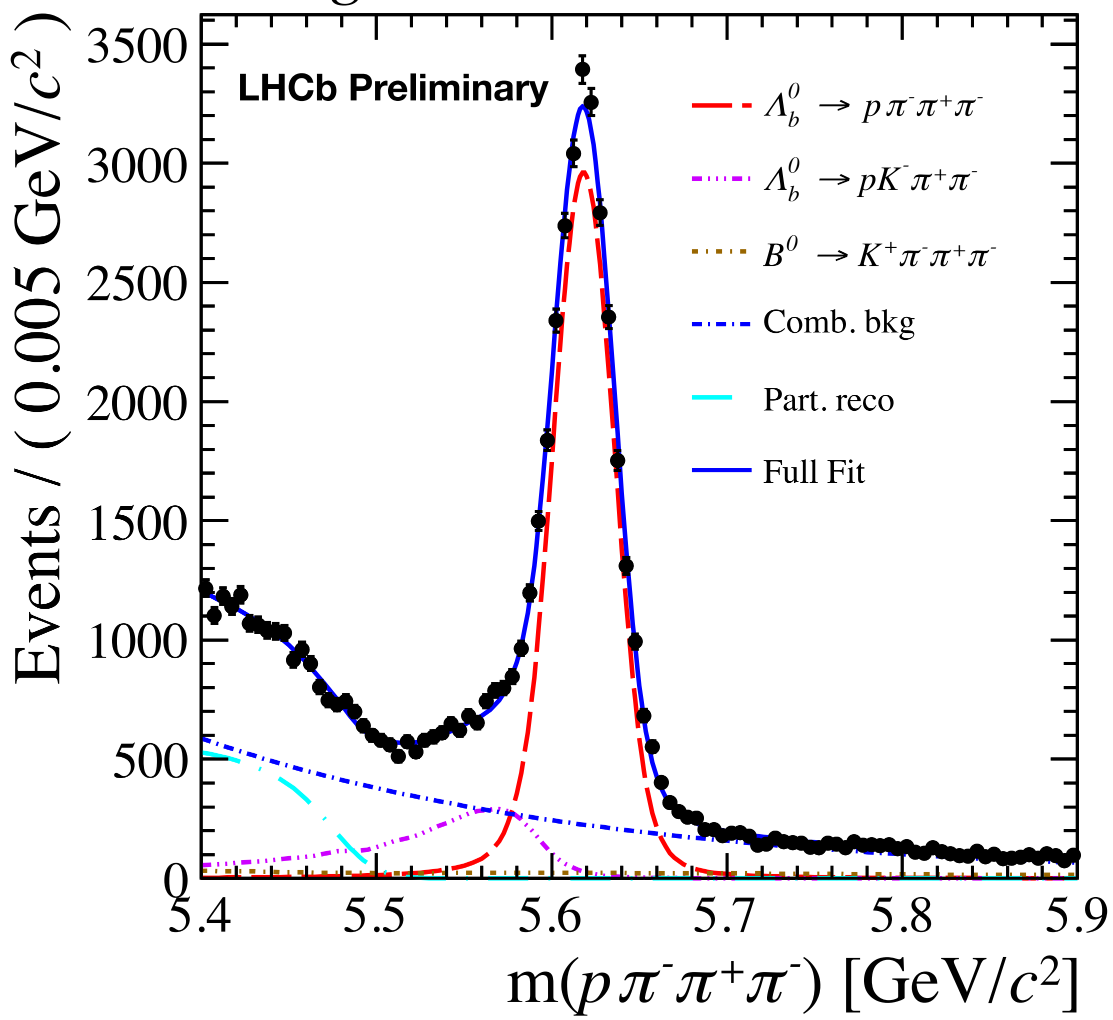
JHEP 10 (2016) 005, Nature Phys. 13 (2017) 322, PoS ICHEP (2016) 531, Phys.Rev. D95 (2017) 093001

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

LHCb-PAPER-2019-028

- 6.6 fb^{-1} data analysed
- Signal yield = x4 signal yield Run1
- Applied 2 methods to search for CPV:
  - Triple Product Asymmetries (TPA), new optimization
  - Energy Test, applied here for the first time

$$N_{sig} = 27600 \pm 200$$

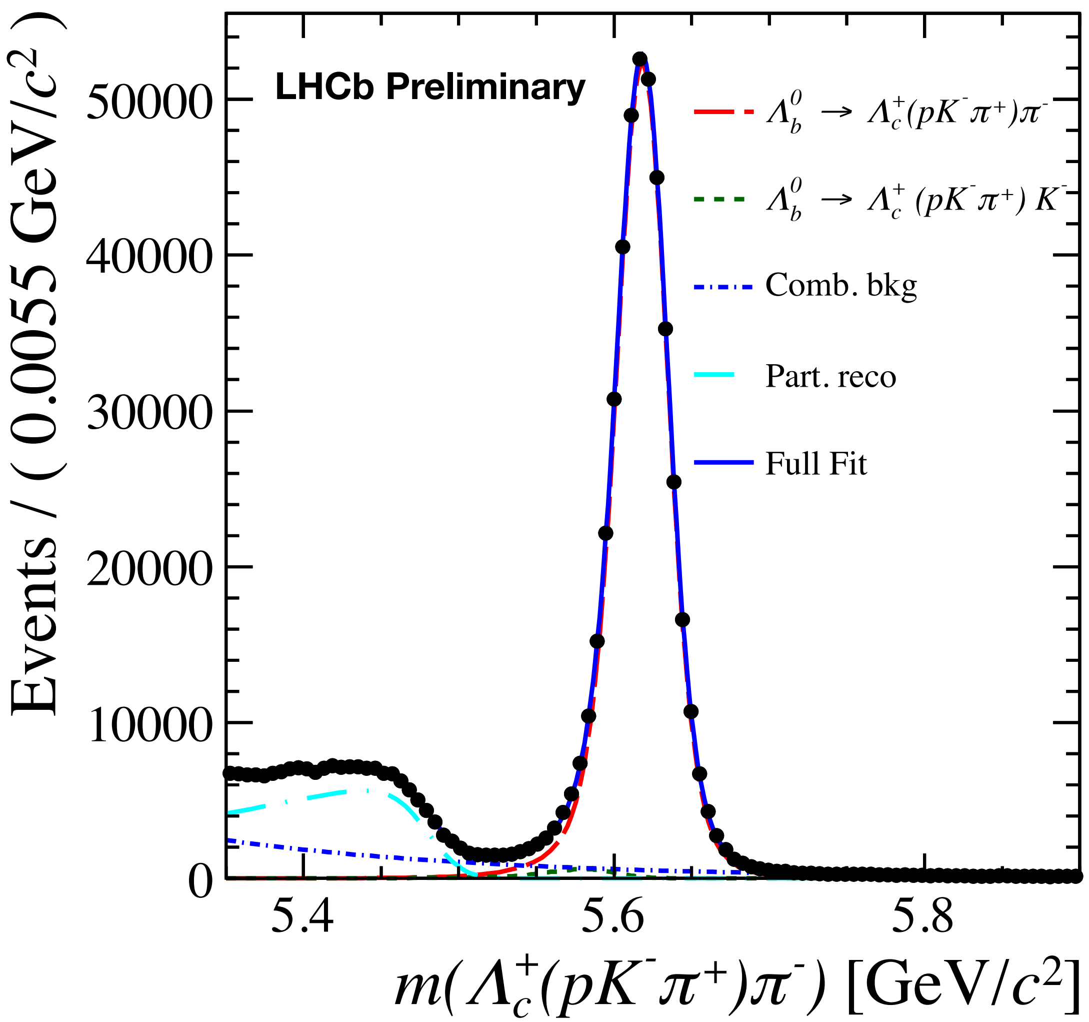


$\Lambda_b^0 \rightarrow \Lambda_c^+(pK^-\pi^+)\pi^-$ control sample

- Technique validated on control sample
- No CPV expected ($b \rightarrow c$ transition)
- Measured CP asymmetry: $a_{CP}^{\hat{T}-odd} = (+0.04 \pm 0.16)\,\%$

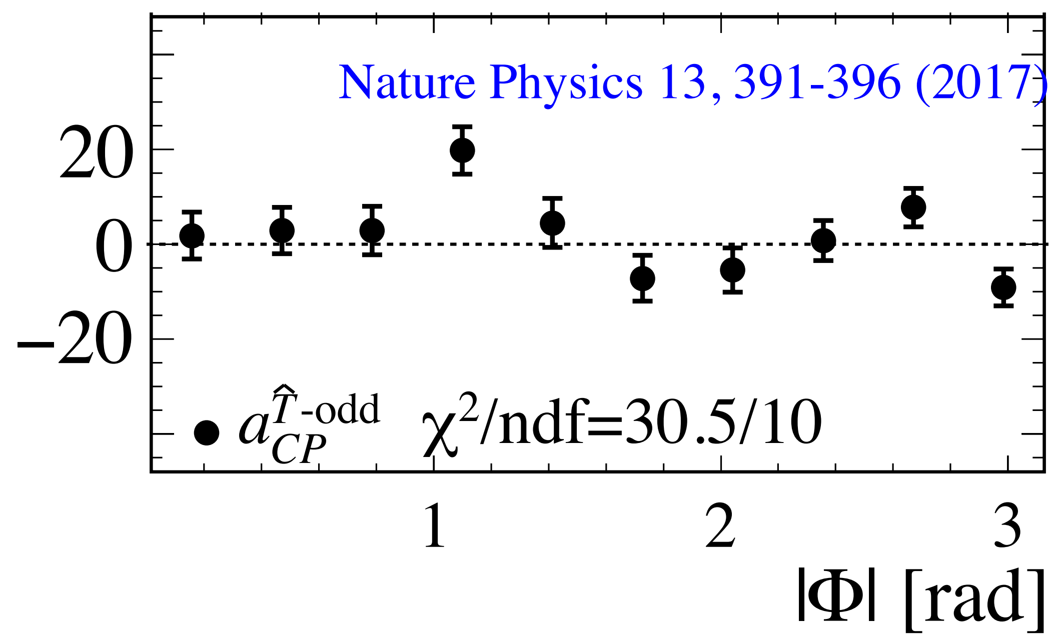
$$N_{sig} = 434500 \pm 800$$

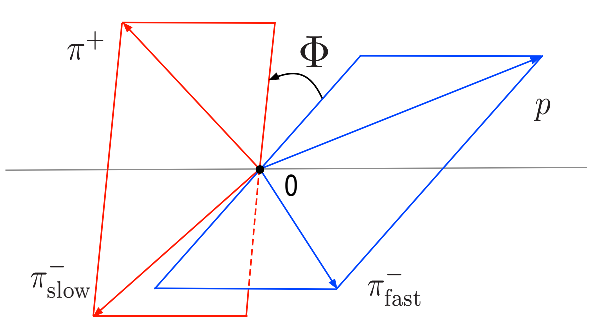
- The statistical error is conservatively assigned as systematic error
- No CPV in regions of the phase space both with TPA and Energy test



Sensitivity optimisation

- Improved understanding of decay dynamics
- Main contributions $\Lambda_b^0 \to N^{*+}\pi^-, pa_1^-$ $m(p\pi^+\pi^-_{slow}) < (>)2.8$ GeV/c^2
- Expected negligible CPV, separate it to avoid dilution
- Inject CPV effects in N^{*+} region (many interfering resonances would allow for interference of amplitudes with different parity, i.e. S and P waves)
- Reproduce the same effect as observed with Run1 data





- Binning schemes:
  - New binning scheme in terms of the helicity angles of the decay chain $\Lambda_b^0 \to N^{*+}(\to \Delta^{++}(\to p\pi^+)\pi^-)\pi^-$: scheme A
  - Binning scheme in Φ as Run1 analysis: scheme B
  - A1, B1 dominated by $\Lambda_b^0 \to pa_1^-$; A2, B2 dominated by $\Lambda_b^0 \to N^{*+}\pi^-$

Systematic uncertainties

Negligible wrt to statistical error — TPA method

Experimental Bias

- Estimated from the large statistics control sample:
  - Integrated: $\Delta a_{CP}^{\hat{T}-odd}, \Delta a_{P}^{\hat{T}-odd} \sim 0.16\,\%$
  - In bins of the phase space: $\Delta a_{CP}^{\hat{T}-odd}, \Delta a_{P}^{\hat{T}-odd} \sim 0.5/1.8\,\%$

$C_{\hat{T}}$ resolution

- The finite resolution on $C_{\hat{T}}$ might induce a migration of events between the categories $C_{\hat{T}}>0, C_{\hat{T}}<0$
- Estimated on MC events $\Delta a_{CP}^{\hat{T}-odd}, \Delta a_{P}^{\hat{T}-odd} < 0.1\,\%$

Fit Model

- Estimated with pseudo experiments generated with an alternative model

$$\Delta a_{CP}^{\hat{T}-odd}, \Delta a_{P}^{\hat{T}-odd} \sim 0.1\,\%$$

Phase-space integrated results

TPA method

- First observation of P violation at 5.5σ in a b-baryon decay
- No sign of CPV integrated over phase space

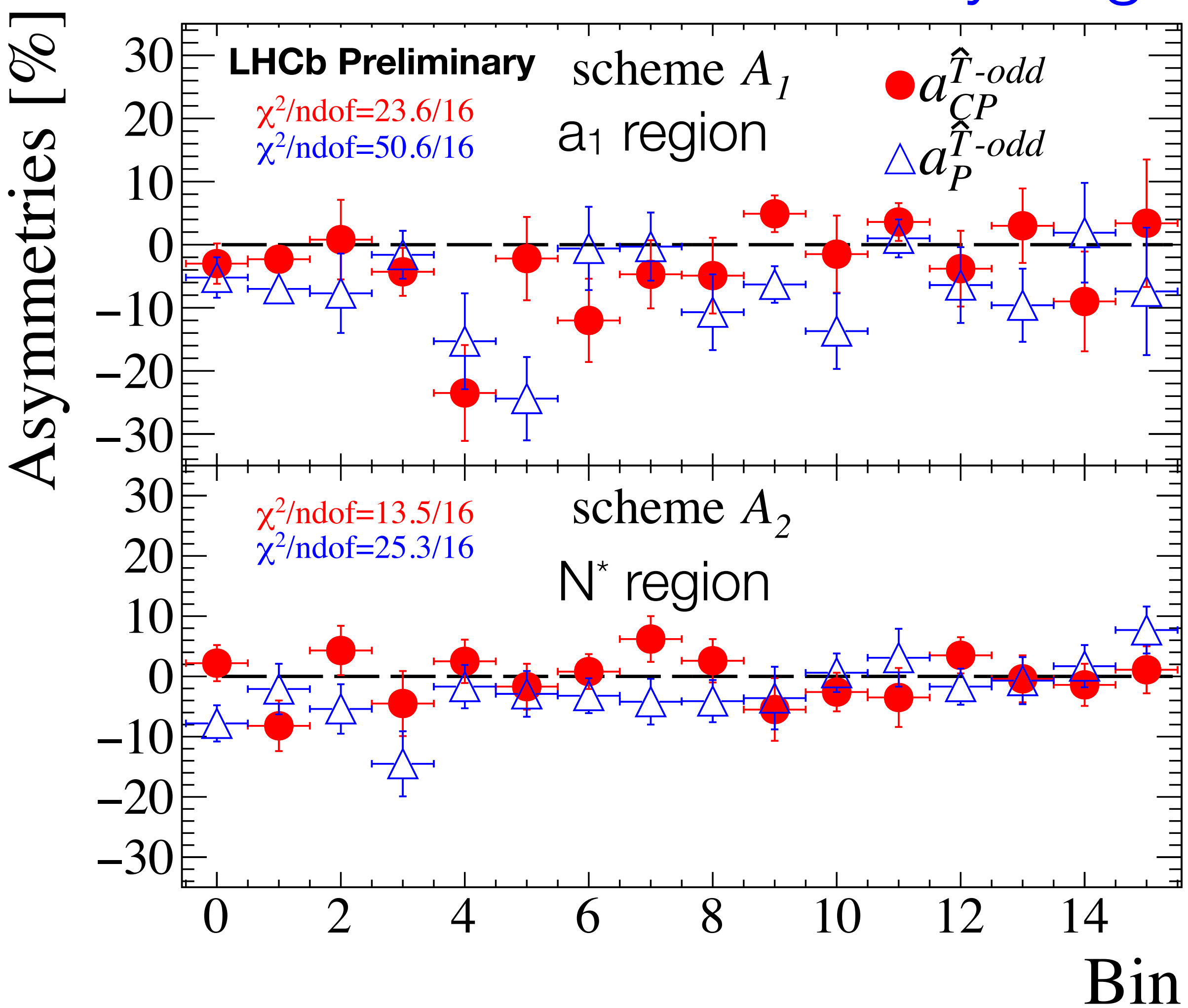
Asymmetry	Dataset: **Run1+Run2** (2011-2017)	Dataset: Run 1 (2011-2012)
$A_{\widehat{T}}$ (%)	$-4.68 \pm 0.99 \pm 0.24$	$-2.56 \pm 2.05 \pm 0.44$
$\overline{A}_{\widehat{T}}$ (%)	$-3.29 \pm 0.99 \pm 0.24$	$-4.86 \pm 2.05 \pm 0.44$
$a_P^{\widehat{T}\text{-odd}}$ (%)	$-3.98 \pm 0.70 \pm 0.17$	$-3.71 \pm 1.45 \pm 0.32$
$a_{CP}^{\widehat{T}\text{-odd}}$ (%)	$-0.70 \pm 0.70 \pm 0.17$	$1.15 \pm 1.45 \pm 0.32$

Results in bins of phase space

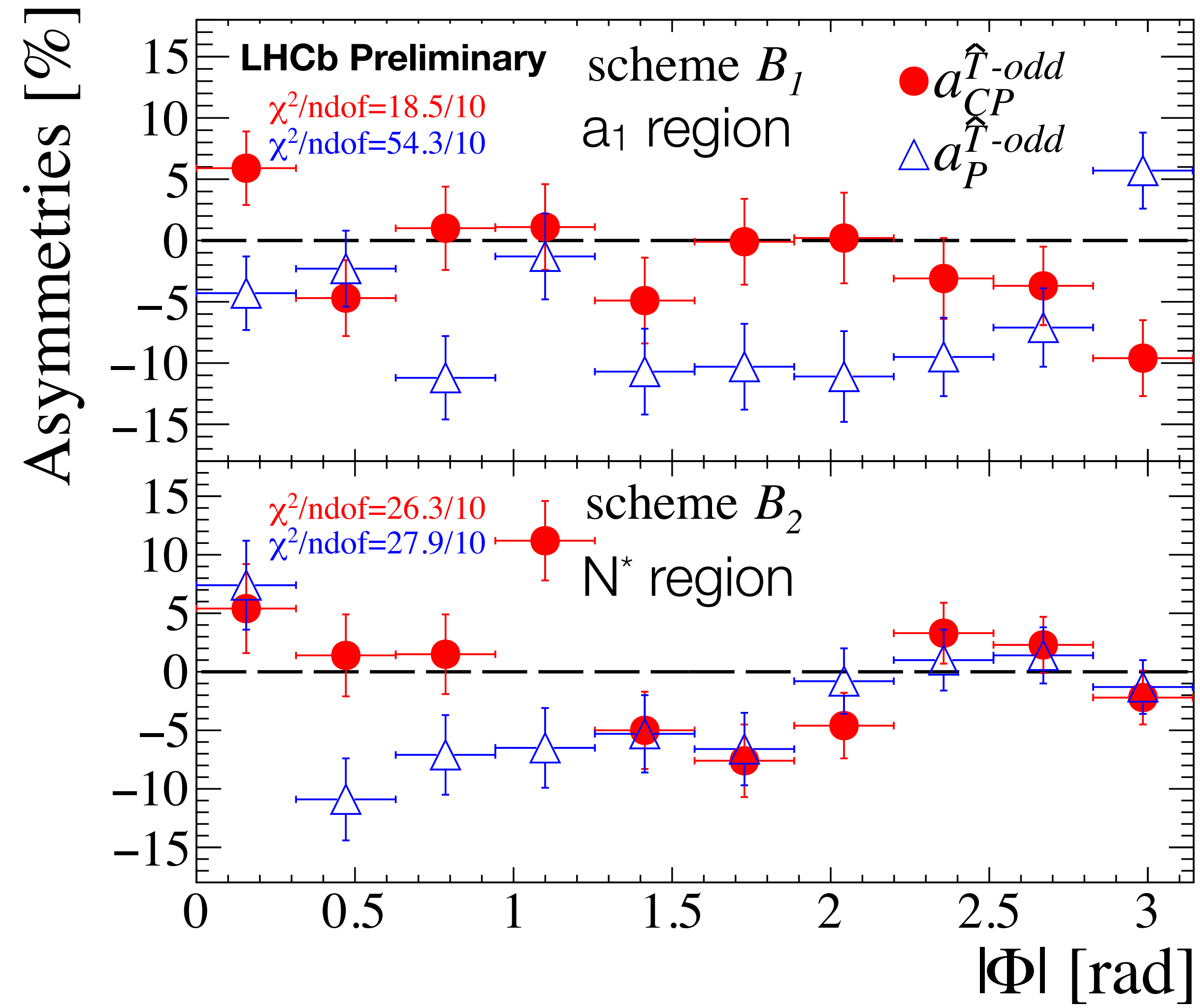
TPA method

LHCb-PAPER-2019-028

Scheme A: based on helicity angles



Scheme B: on Φ angle intervals



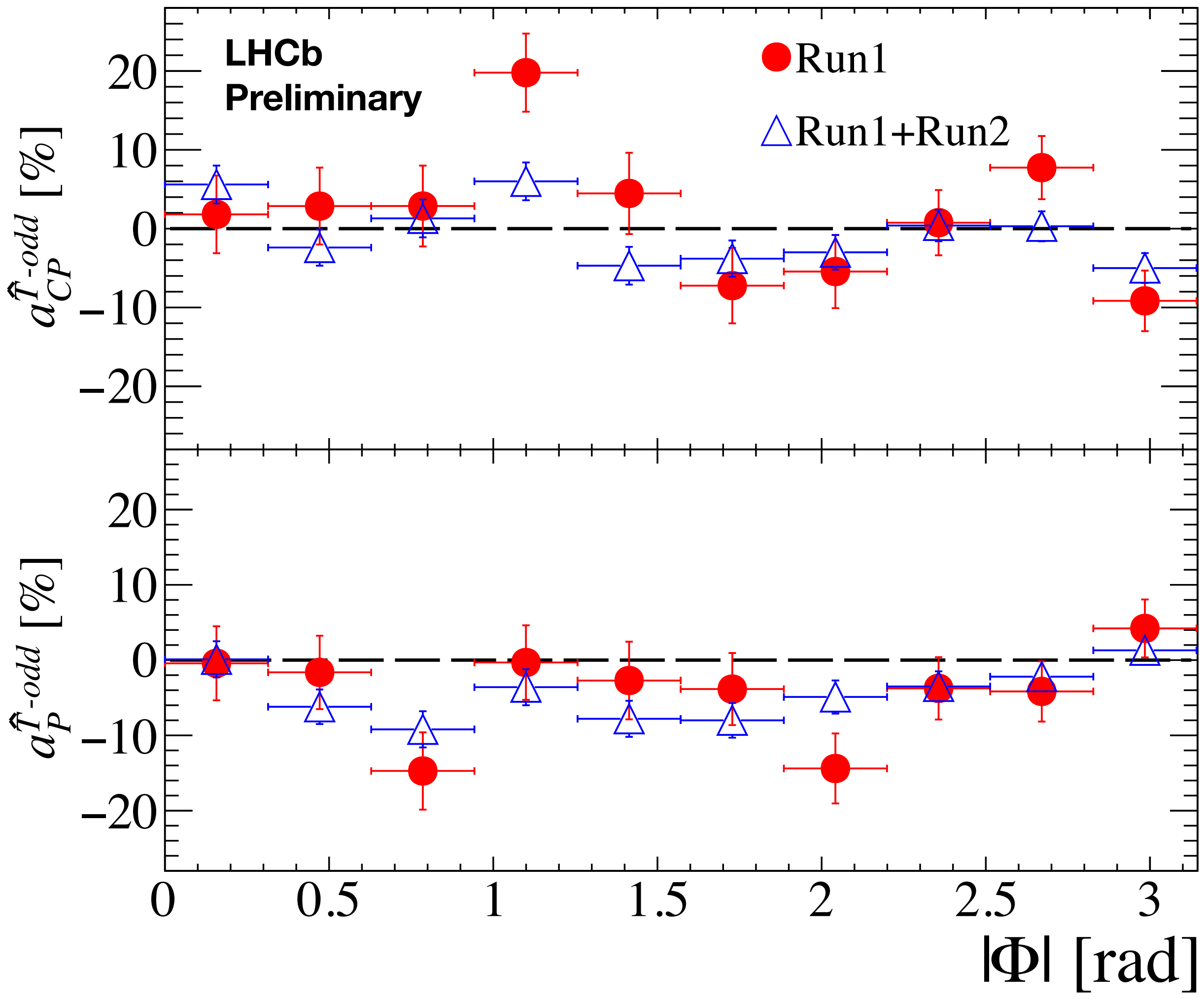
- CPV at the level of 2.9σ in scheme B_2
- Observation of P violation at the level of 5.5σ in scheme B_1

Results in bins of phase space

TPA method

LHCb-PAPER-2019-028

- Comparison wrt the previous result



- Compatibility at the level of 2.6σ checked with pseudo experiments

Results in bins of phase space

TPA method

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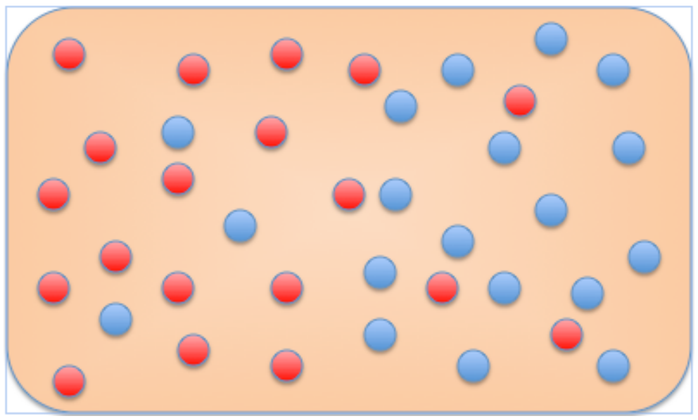
Binning scheme	Dominant contribution	Hypothesis	p-value	
A_1 (helicity angles)	$\Lambda_b^0 \to p a_1^-$	CP-conserving	9.8×10^{-2}	
		P-conserving	1.8×10^{-5}	
A_2 (helicity angles)	$\Lambda_b^0 \to N^{*+}\pi^-$	CP-conserving	6.4×10^{-1}	
		P-conserving	6.4×10^{-2}	
B (in $\|\Phi\|$)	Entire sample	CP-conserving	5.0×10^{-3}	
		P-conserving	3.5×10^{-7}	
B_1 (in $\|\Phi\|$)	$\Lambda_b^0 \to p a_1^-$	CP-conserving	4.7×10^{-2}	
		P-conserving	4.3×10^{-8}	5.5σ
B_2 (in $\|\Phi\|$)	$\Lambda_b^0 \to N^{*+}\pi^-$	CP-conserving	3.4×10^{-3}	2.9σ
		P-conserving	1.9×10^{-3}	

Experimental approach

LHCb-PAPER-2019-028

Energy Test

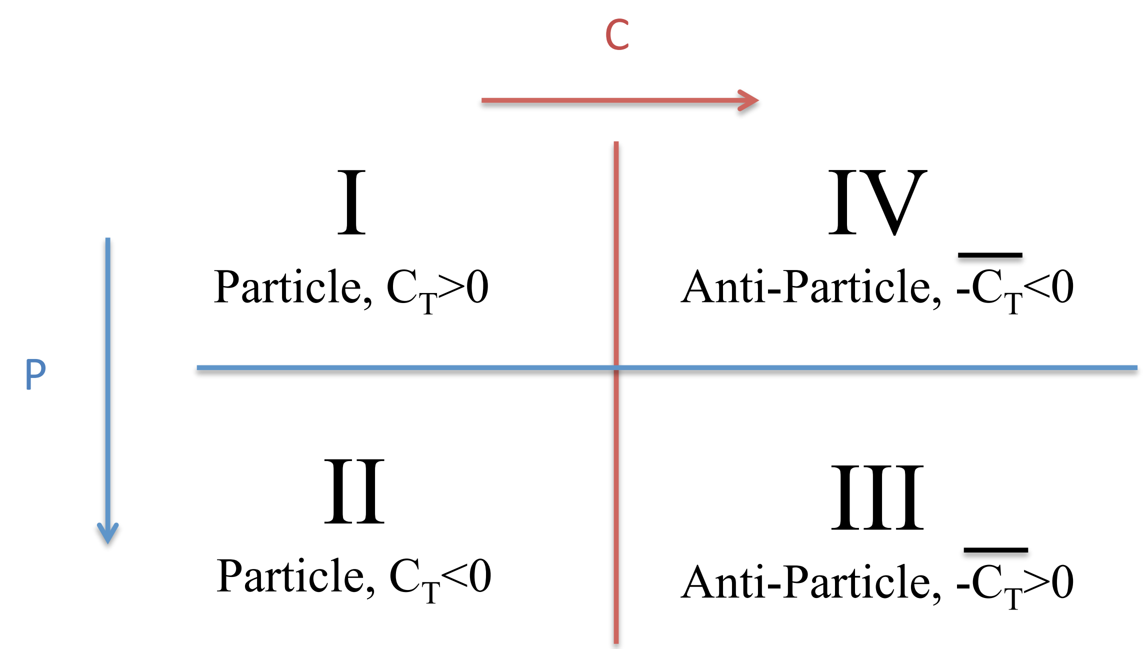


Test Statistic:

$$T = \underbrace{\frac{1}{n(n-1)}\sum_{i,j>1}^{n}\psi(d_{ij})}_{\Lambda_b^0 - \Lambda_b^0} + \underbrace{\frac{1}{\overline{n}(\overline{n}-1)}\sum_{i,j>1}^{\overline{n}}\psi(d_{i,j})}_{\overline{\Lambda}_b^0 - \overline{\Lambda}_b^0} - \underbrace{\frac{1}{n\overline{n}}\sum_{i,j}^{n,\overline{n}}\psi(d_{ij})}_{\Lambda_b^0 - \overline{\Lambda}_b^0}$$

- $\psi(d_{ij}) = e^{-d_{ij}^2/\delta^2}$: distance function
- $n, \overline{n}$: number of particle (antiparticle) candidates
- d_{ij} : distance in phase space
- δ : parameter to optimize

- **P violation**:
  - CP-even P-odd: [I]+[III] vs [II]+[IV]
- **CP violation**:
  - CP-odd P-even test: [I+II] vs [III+IV]
  - CP-odd P-odd test: [I+IV] vs [II+III]



Energy Test optimisation

- Many ways how CPV could manifest in the complicated 4-body phase space
- Identified 3 different value for metric parameter δ:
  - 1.6 GeV^2 – mean distance between 600 nearest neighbours in N^{*+}/Δ^{++} resonances mass peak
  - 2.7 GeV^2 – mean distance between 600 nearest neighbours in full phase space
  - 13 GeV^2 – median distance between events in phase space

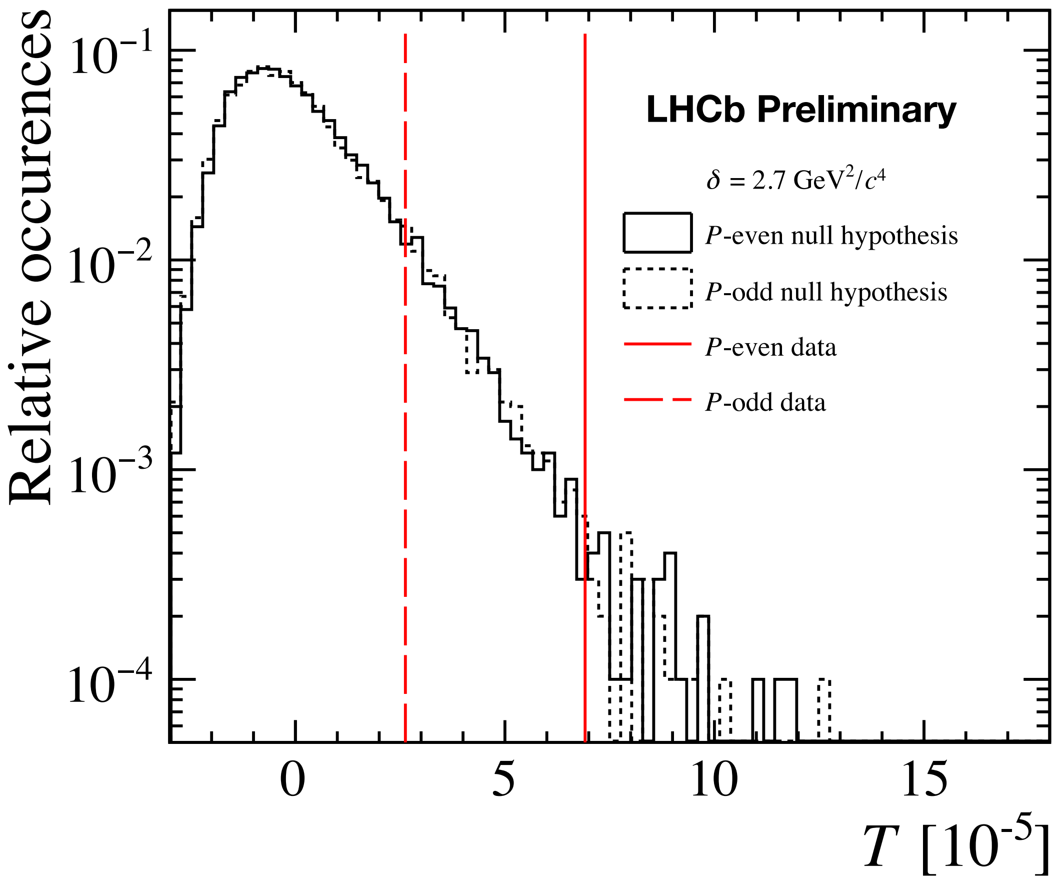
Energy Test results

LHCb-PAPER-2019-028

- CP(P)-symmetry hypothesis (with permutation test)

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}

- Permutation test to take into account LEE



- Overall P-even CPV significance is at 2.8σ (taking into account LEE)

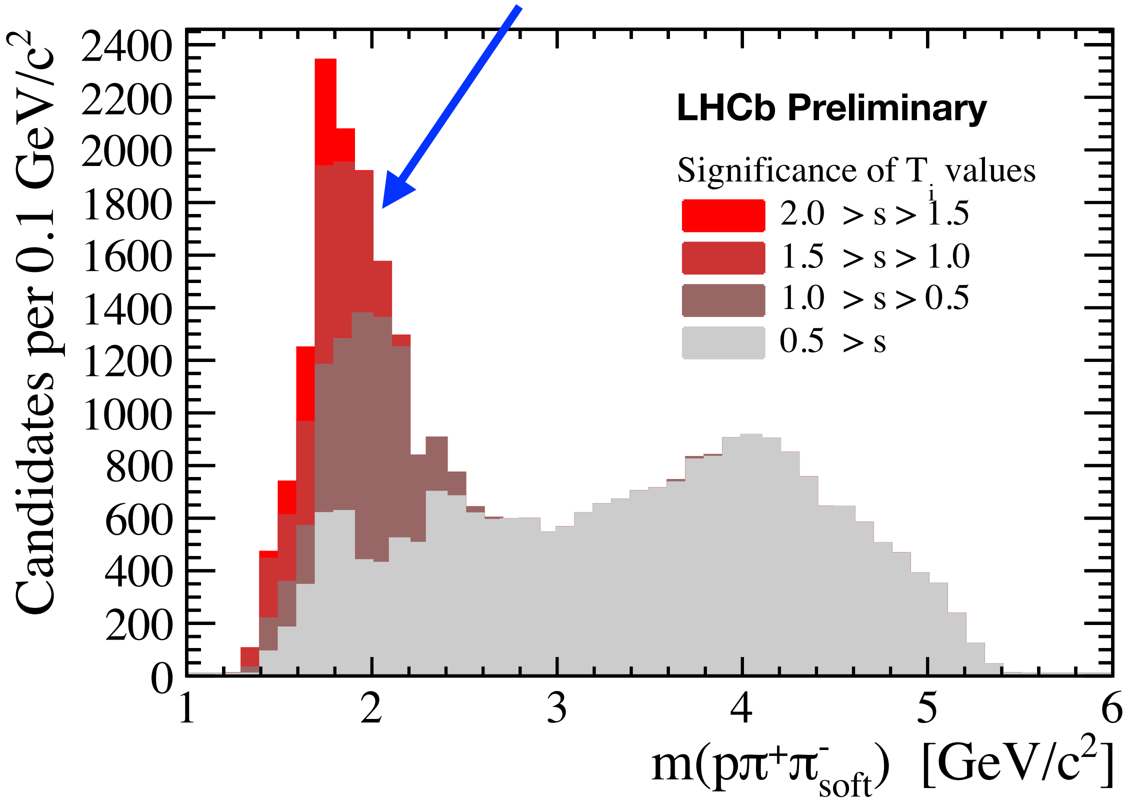
- P violation exceeds 5σ

Energy Test results

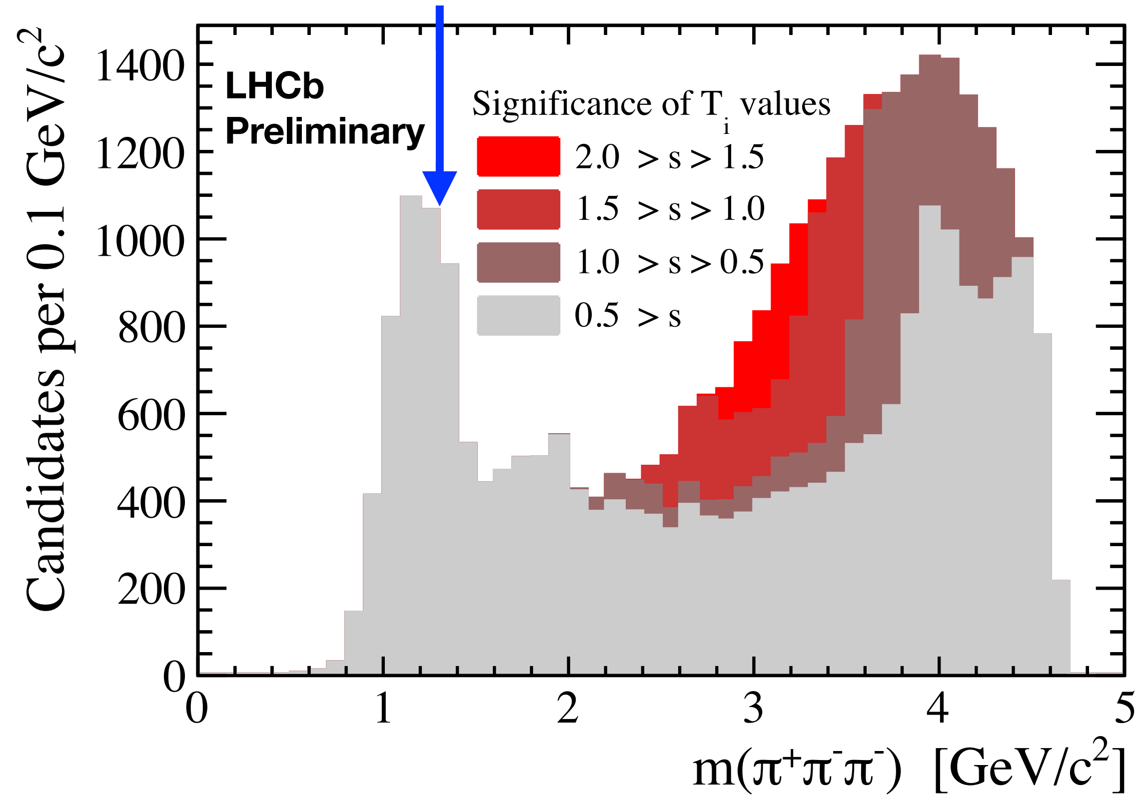
LHCb-PAPER-2019-028

- Visualise the regions where CPV is concentrated
- Select events that contribute mostly to the Test Statistic

N* contribution



a_1 contribution



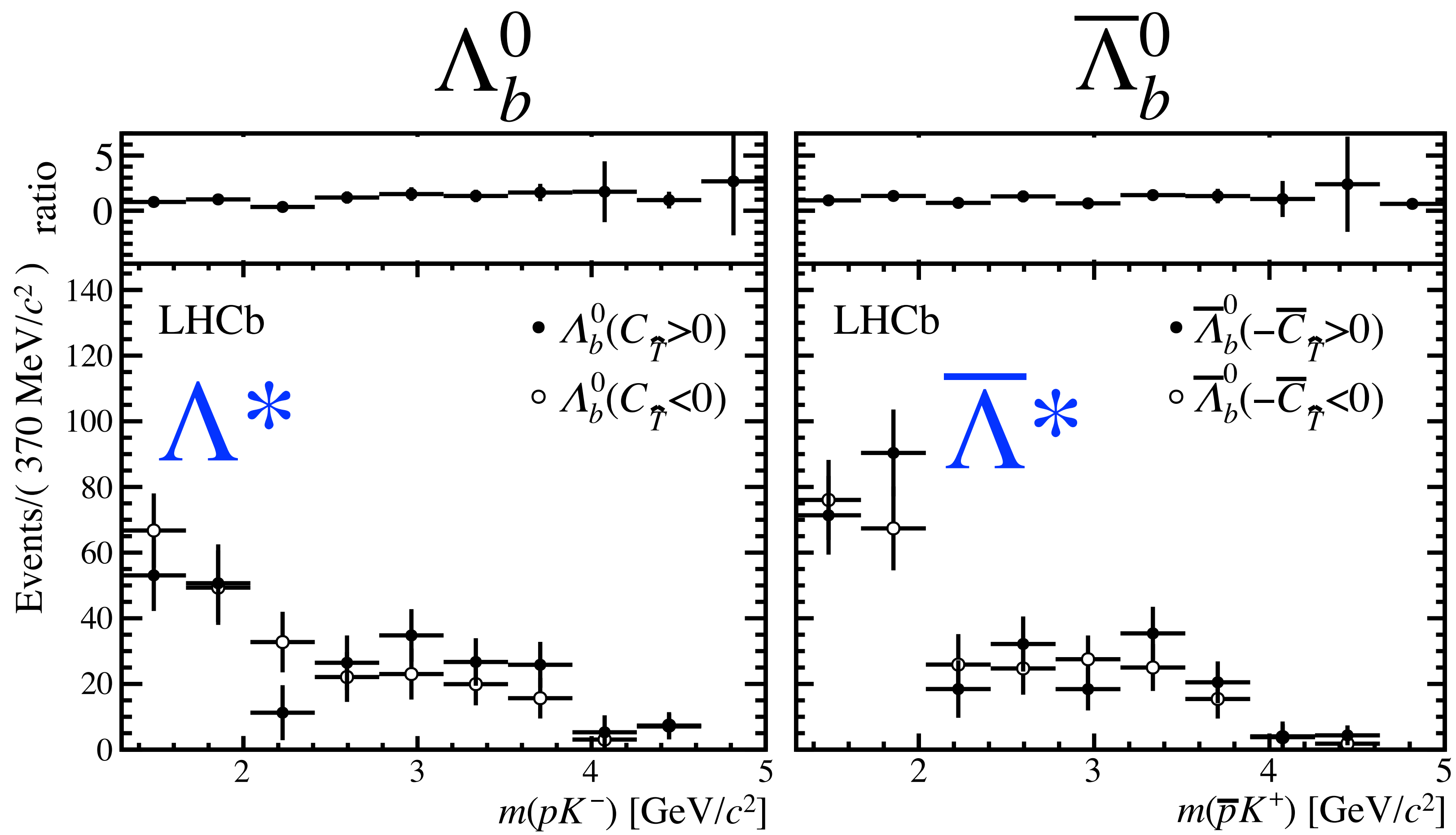
P-even CP-odd configuration

Other CPV searches in heavy baryon decays

- Search for CPV in $\Lambda_b^0 \to p\pi^- K^+ K^-$ (TPA method)
- Search for CPV in $\Lambda_b^0(\Xi_b^0) \to ph^- h^+ h^-$, both with ΔA_{CP} and TPA methods
- Search for CPV in $\Lambda_b^0 \to K_S^0 p\pi^-$ (ΔA_{CP} method)
- Search for CPV in charmed decay $\Lambda_c^+ \to ph^- h^+$ (ΔA_{CP} method)

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

Nature Physics 13 (2017) 391



Background subtracted using sPlot method

Divide phase space with/without Λ^* resonances

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

Result consistent with P and CP symmetry

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

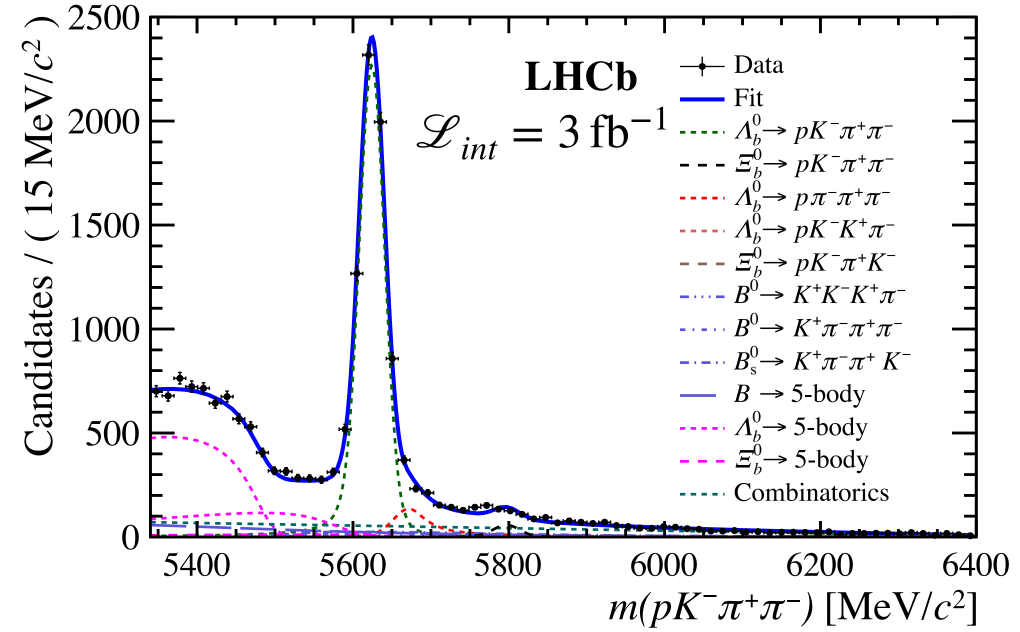
Eur. Phys. J. C79 (2019) 745

Measure ΔA_{CP} difference of *CP* asymmetries

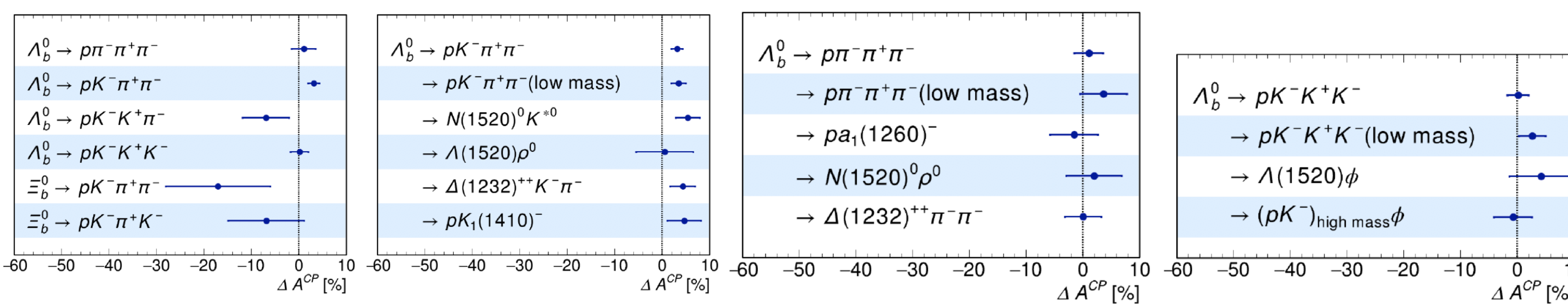
$$A_{raw}(\Lambda_b^0 \to p3h) = A_{CP}(\Lambda_b^0 \to p3h) + \boxed{A_{prod}(\Lambda_b^0)} + \boxed{A_{reco}(p)} + \ldots$$

$$\Delta A_{CP} = A_{raw}(\Lambda_b^0 \to p3h) - A_{raw}(\Lambda_b^0 \to \Lambda_c^+ \pi)$$
$$= A_{CP}(\Lambda_b^0 \to p3h) - A_{CP}(\Lambda_b^0 \to \Lambda_c^+ \pi^-)$$

Cancel A_P and A_D



- Results consistent with no CPV
- Asymmetries measured wrt control channels $\Lambda_b^0 \to \Lambda_c^+\pi^-, \Xi_b^0 \to \Xi_c^+\pi^-$

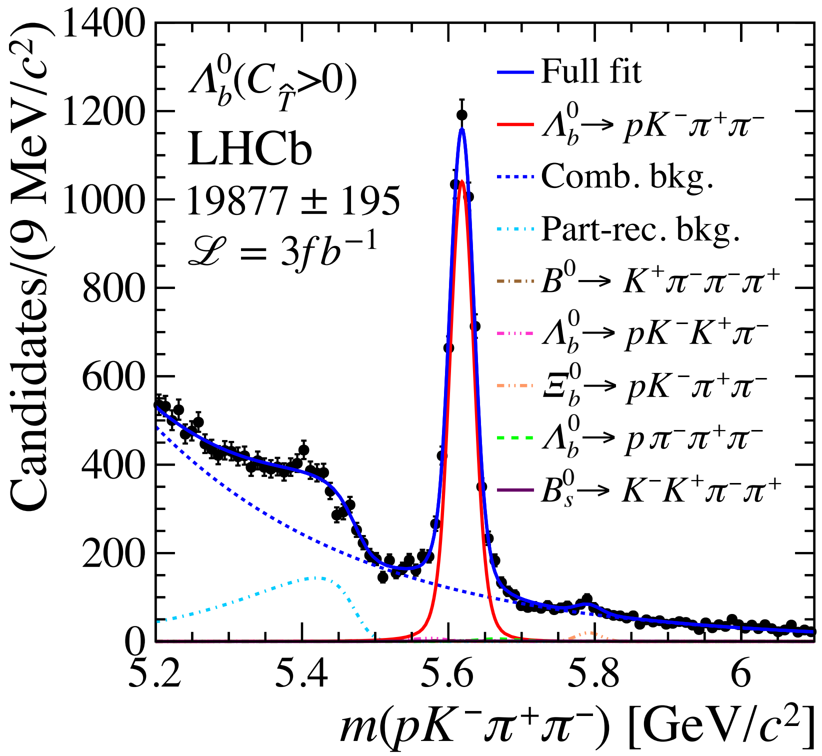


Search for CPV in $\Lambda_b^0(\Xi_b^0) \to p h^- h^+ h^-$

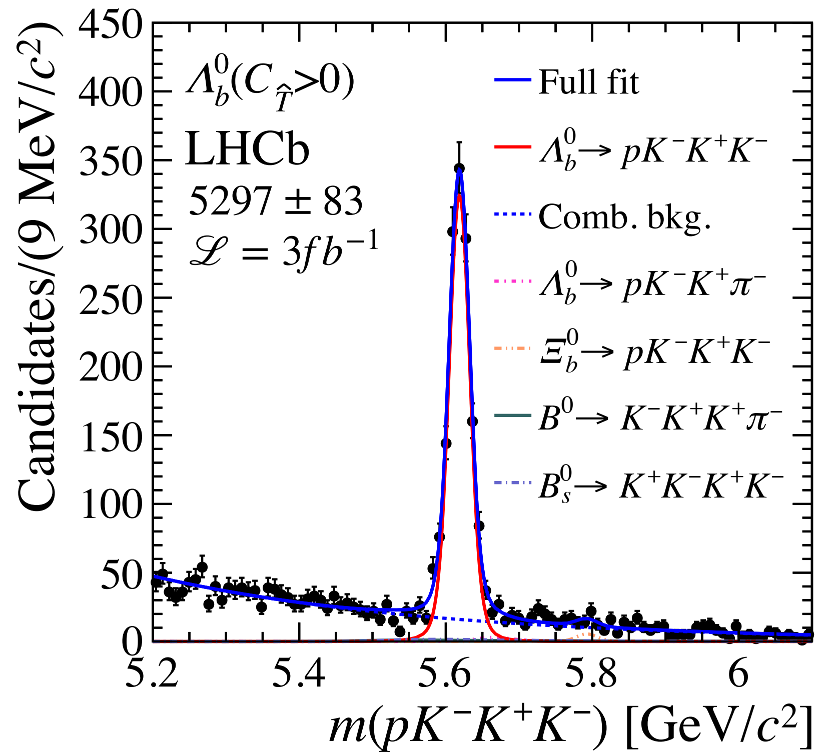
JHEP 08 (2018) 039

Measurement of Triple Product Asymmetries

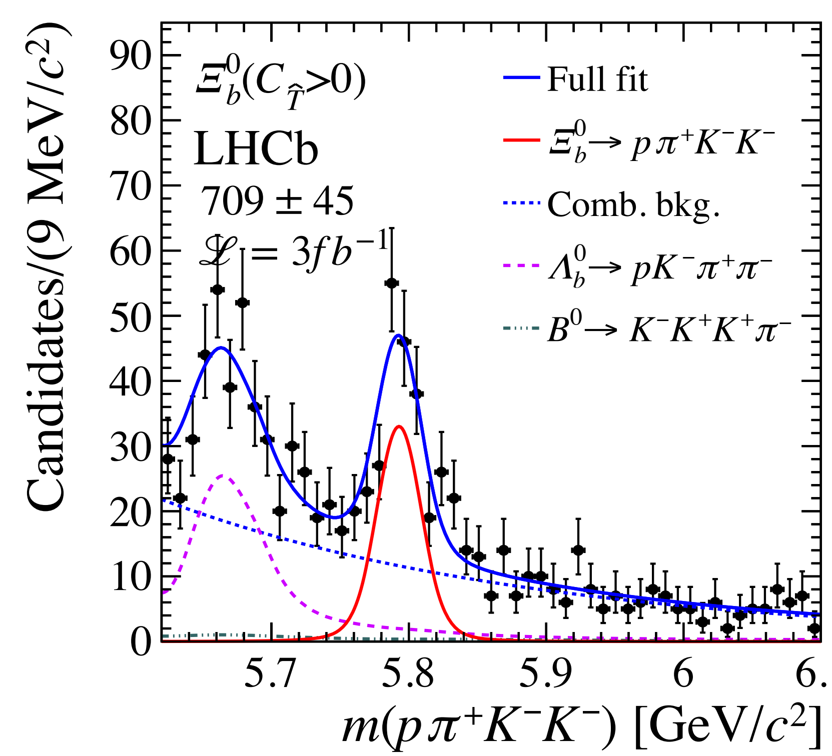
$\Lambda_b^0 \to p K^- \pi^+ \pi^-$



$\Lambda_b^0 \to p K^- K^+ K^-$



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

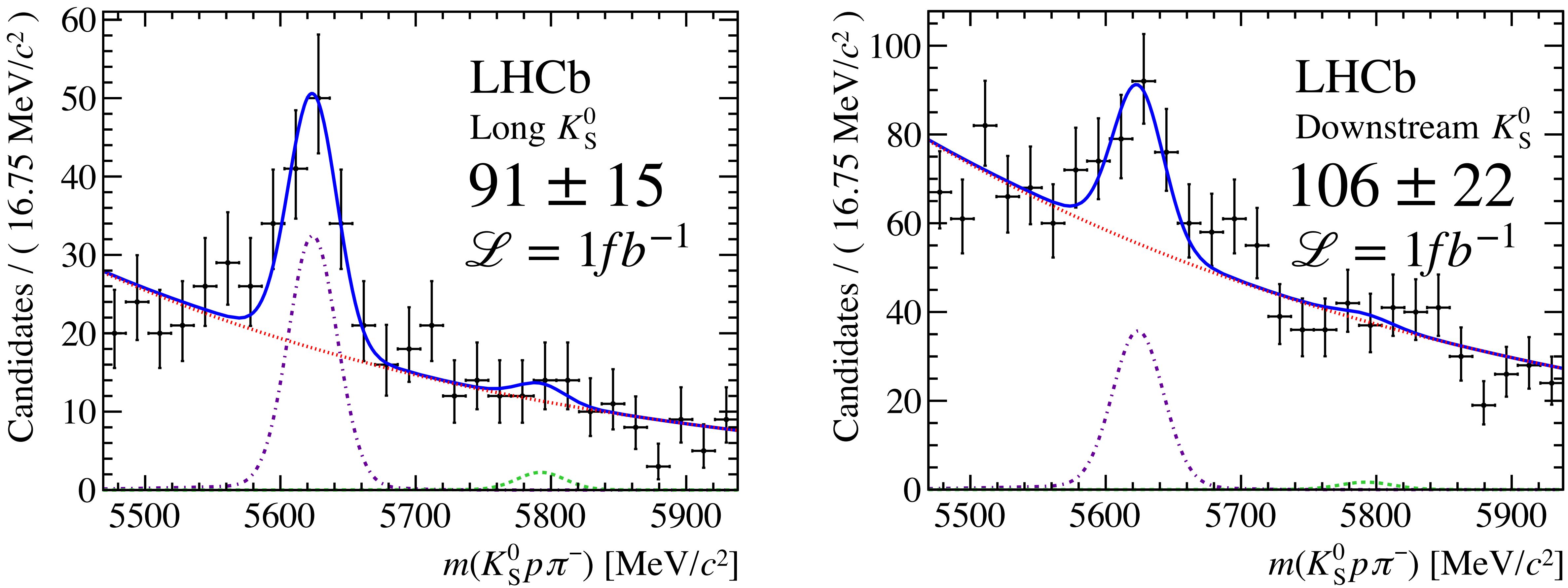


	$\Lambda_b^0 \to pK^-\pi^+\pi^-$	$\Lambda_b^0 \to pK^-K^+K^-$	$\Xi_b^0 \to pK^-K^-\pi^+$
$a_P^{\hat{T}\text{-odd}}$ (%)	$-0.60 \pm 0.84 \pm 0.31$	$-1.56 \pm 1.51 \pm 0.32$	$-3.04 \pm 5.19 \pm 0.36$
$a_{CP}^{\hat{T}\text{-odd}}$ (%)	$-0.81 \pm 0.84 \pm 0.31$	$1.12 \pm 1.51 \pm 0.32$	$-3.58 \pm 5.19 \pm 0.36$

Result consistent with P and CP symmetry both integrated and in bins of phase space

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

JHEP 04 (2014) 087



- Theory prediction: $A_{CP}(\Lambda_b^0 \to pK^*) = (19.6 \pm 1.6)\,\%$ Phys. Rev. D 91 (2015) 116007
- $\Delta A_{CP} = 0.22 \pm 0.13 \pm 0.03$ control channel: $\Lambda_b^0 \to \Lambda_c^+(\to pK_S^0)\pi^-$
- Consistent with CP symmetry
- We plan to update with Run2 data

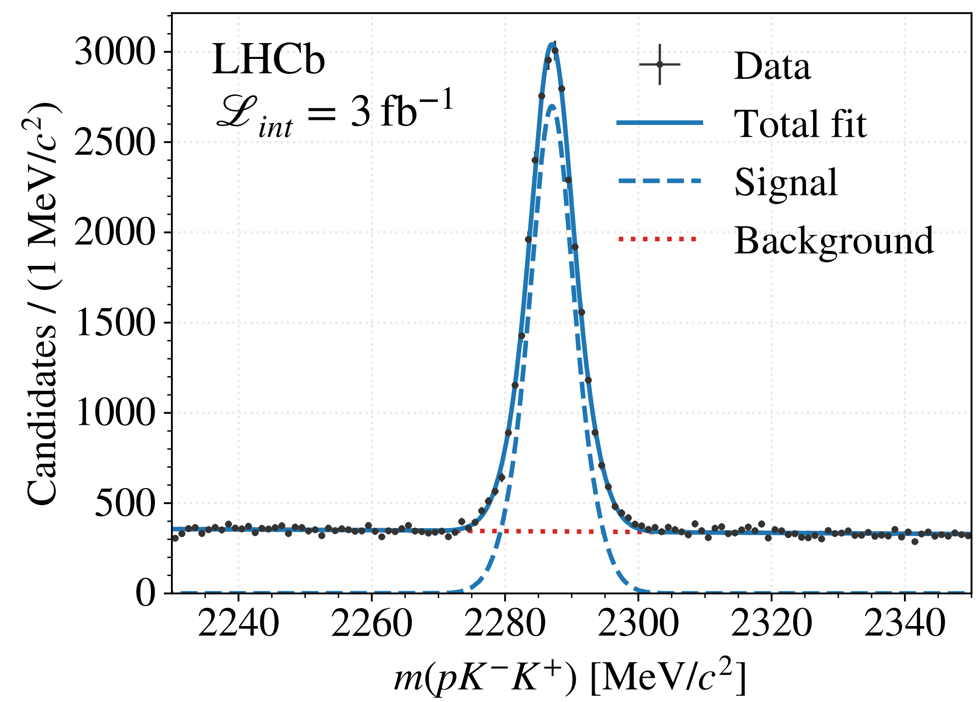
Search for CPV in $\Lambda_c^+ \to ph^-h^+$

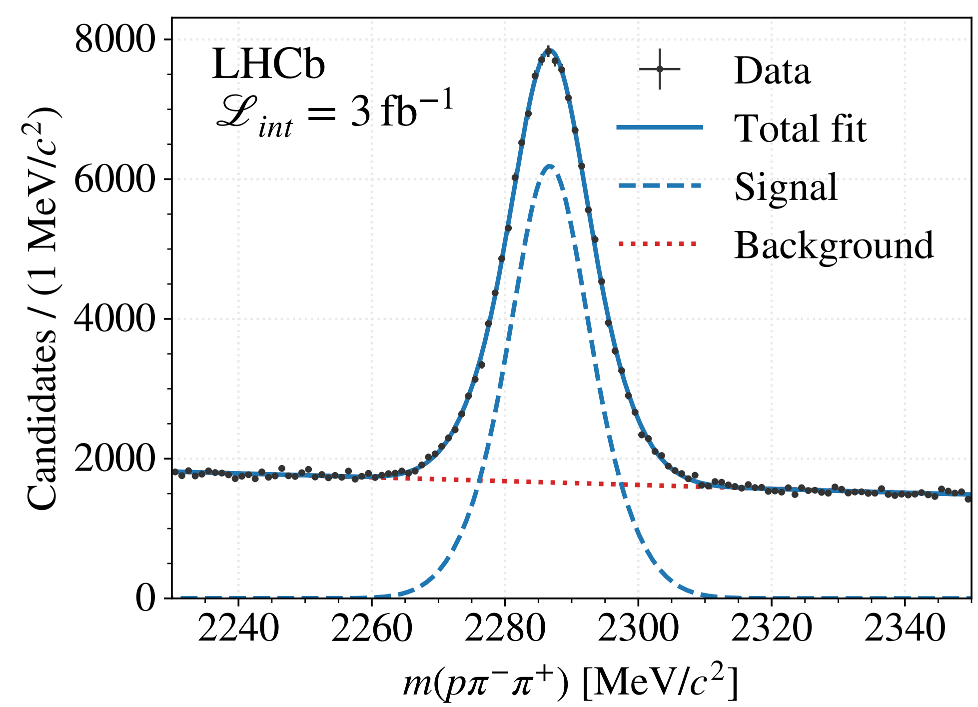
JHEP 03(2018) 182

- Test the same transitions $c \to ud\bar{d}(s\bar{s})$ that led to the first observation of CPV in charm
- Integrated over the phase space search for global CP-violating effects
- Selected $\Lambda_b^0 \to \Lambda_c^+\mu^-X$ to reduce bkg
- Measure ΔA_{CP}

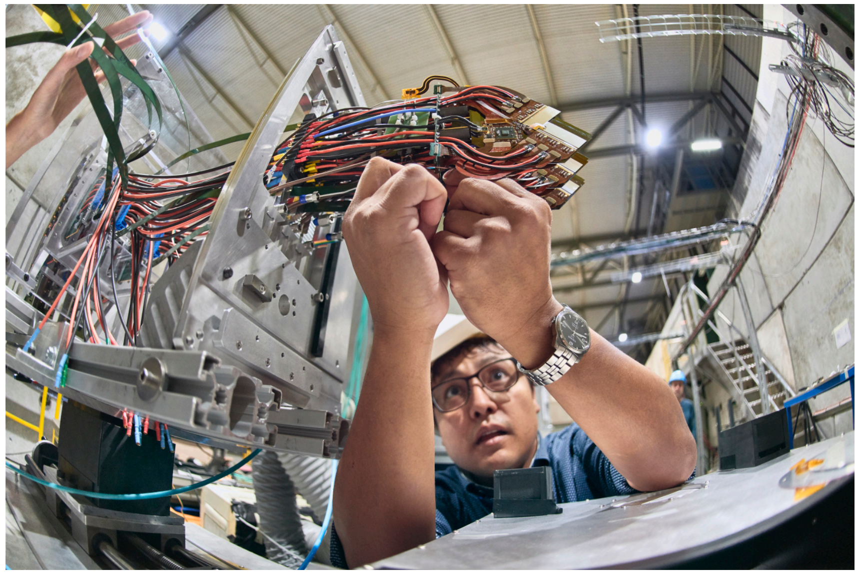
$$\Delta A_{CP} = A_{CP}(\Lambda_c^+ \to pK^+K^-) - A_{CP}^{wgt}(\Lambda_c^+ \to p\pi^+\pi^-)$$
$$= (0.30 \pm 0.91 \pm 0.61)\,\%$$

- Reweighted to match the Λ_b, μ and p kinematics to cancel $A_P(\Lambda_b^0)$ and in the difference $A_D(f)$
- Result compatible with no CPV





Perspectives for the Upgrade



LHCb will collect $\mathscr{L} = 50fb^{-1}$

It will be the biggest baryon data sample ever collected

New opportunities:

- Discovery of new baryon decays
- Reach <1% precision for integrated measurements
- Search for CPV in Ξ_b^0, Ω_b^-
- Search for CPV in regions of the phase space: could be enhanced wrt integrated measurements

Conclusions

- LHCb opens a new window to search for CPV in heavy baryon decays. Many b-baryon decays are observed for the first time
- Updated measurement for $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$: first observation of P violation at 5.5σ integrated and in bins of phase space and CP violation at 2.9σ in regions of phase space
- CPV not yet observed in baryons. Good hope to discover it with the LHCb upgrade dataset
- CPV searches ongoing in several b-baryon decays. With additional dataset new b-baryons and new decays will be studied
- Not only b-baryons: effort to find CPV also in charm baryon decays
    - Work ongoing on Λ_c^+, Ξ_c^+ decays

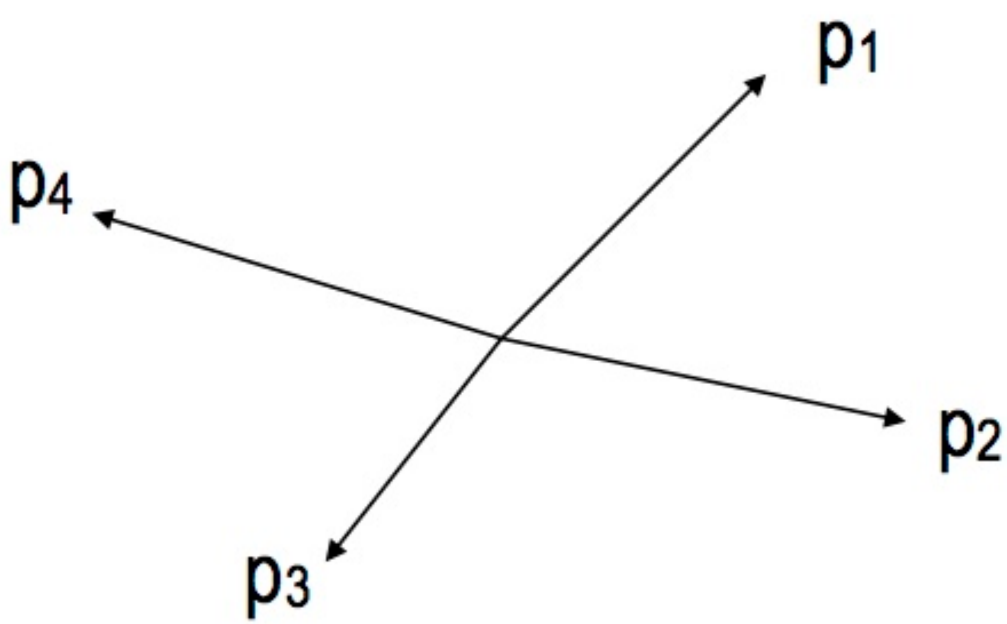
Backup

Experimental approach

Definition of a $\hat{T}$-odd observable

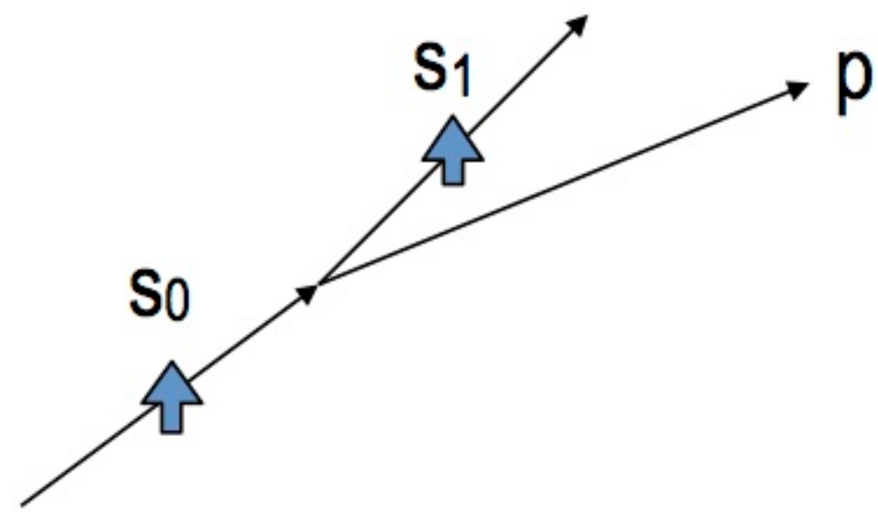
$\hat{T}$ = spin and momentum reversal operator

- Using the momenta



$$C_{\hat{T}} = p_1 \cdot (p_2 \times p_3)$$
$$\overline{C}_{\hat{T}} = \overline{p}_1 \cdot (\overline{p}_2 \times \overline{p}_3)$$

- Using spin and momenta



$$C_{\hat{T}} = s_0 \cdot (s_1 \times p)$$
$$\overline{C}_{\hat{T}} = \overline{s}_0 \cdot (\overline{s}_1 \times \overline{p})$$

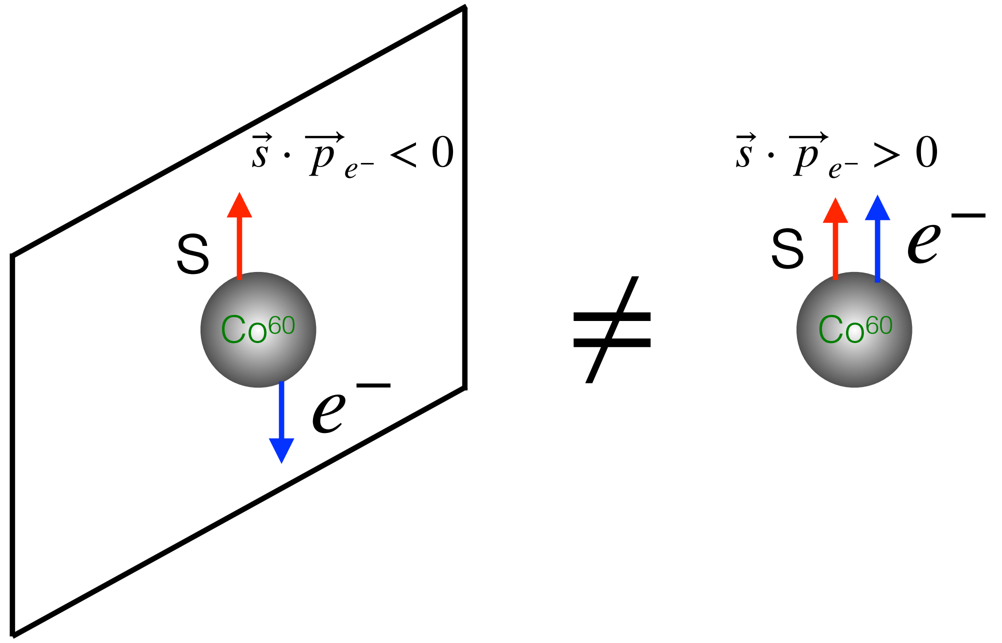
Test the symmetries

- P violation

  Madame Wu et al., Phys. Rev. 105 (1957) 1413

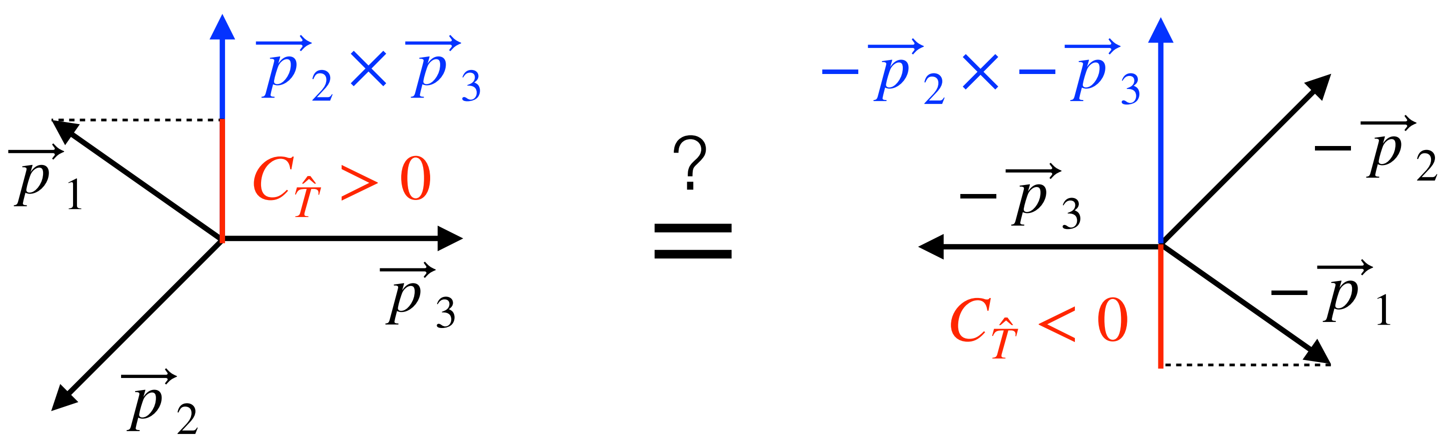
  Compare P-odd quantities of the same decay

  In particular: $< \vec{s} \cdot \vec{p}_{e^-} > \neq 0$

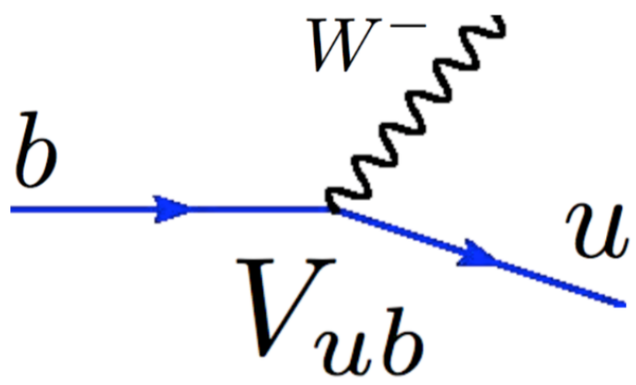


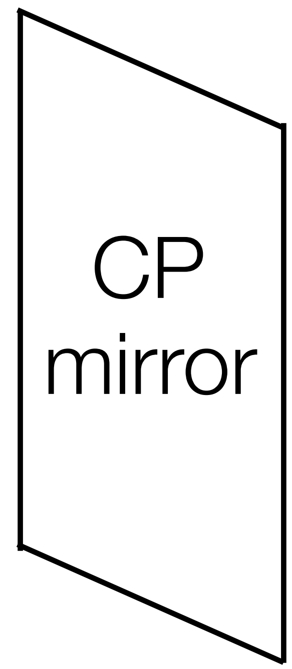
- P violation in our case

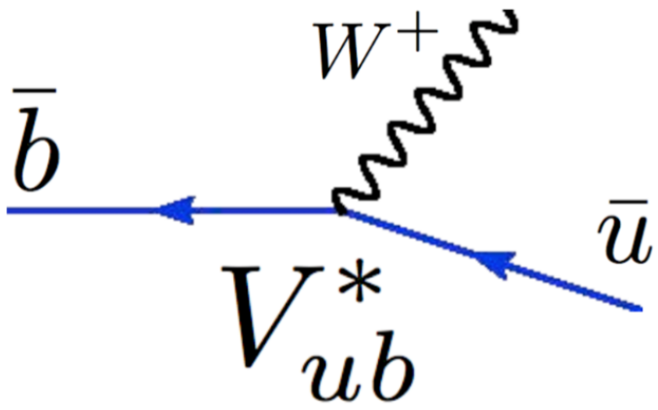
  $C_{\hat{T}}$ is our P-odd quantity



CP violation





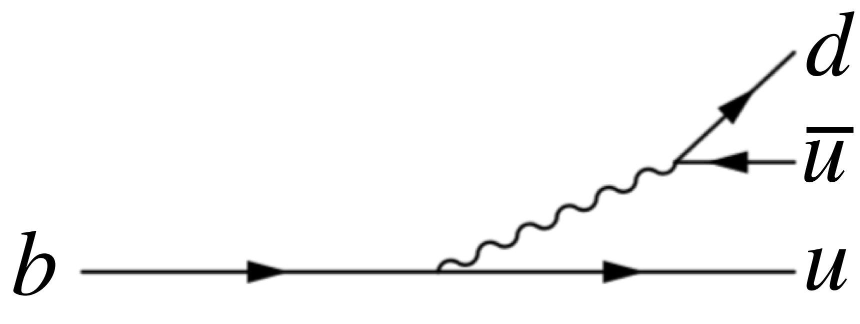


$$A = \rho\, e^{i\delta} e^{i\theta} \qquad \bar{A} = \rho\, e^{i\delta} e^{-i\theta}$$

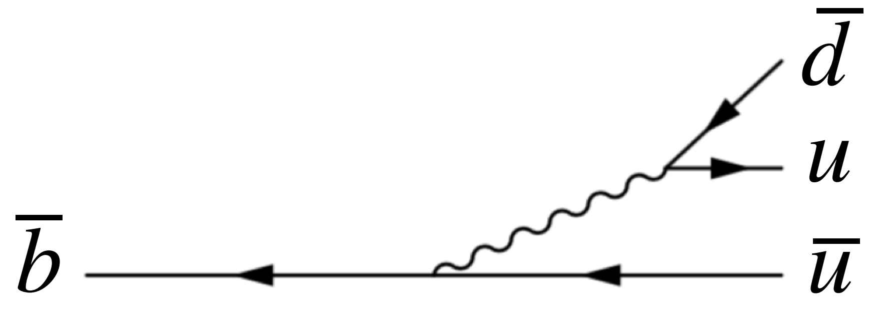
A CP transformation has the effect of:

- Changing the sign of phase due to weak interactions (θ)
- Leaving unchanged the phase due to strong interactions (ρ)

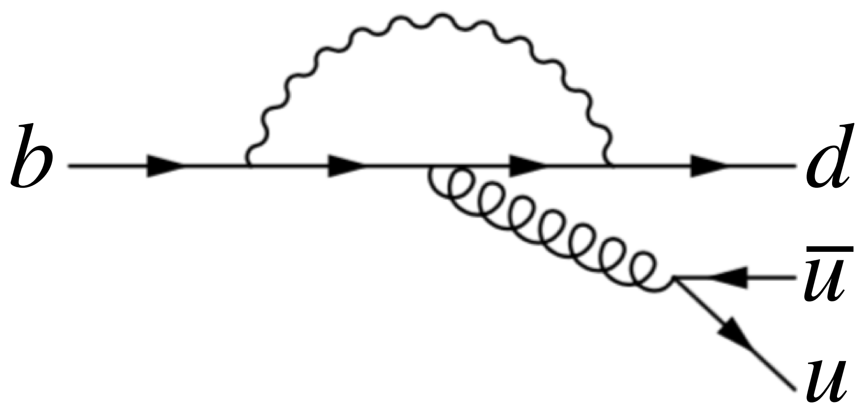
CP violation



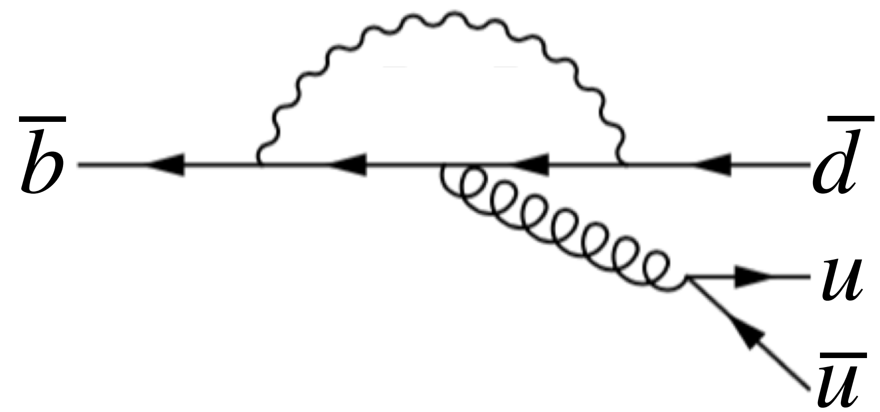
$$A_1 = \rho_1 e^{i\delta_1} e^{i\theta_1}$$



$$\bar{A}_1 = \rho_1 e^{i\delta_1} e^{-i\theta_1}$$



$$A_2 = \rho_2 e^{i\delta_2} e^{i\theta_2}$$



$$\bar{A}_2 = \rho_2 e^{i\delta_2} e^{-i\theta_2}$$

$$|\bar{A}_1 + \bar{A}_2|^2 - |A_1 + A_2|^2 = 4\rho_1\rho_2 \sin(\delta_1 - \delta_2) \sin(\theta_1 - \theta_2)$$

CP violation

$$|\bar{A}_1 + \bar{A}_2|^2 - |A_1 + A_2|^2 = 4\rho_1\rho_2 \sin(\delta_1 - \delta_2)\sin(\theta_1 - \theta_2)$$

It differs from 0 if $\delta_1 - \delta_2 \neq 0$ and $\theta_1 - \theta_2 \neq 0$

To observe CP violation in the decay it is necessary to have two distinct paths with amplitudes of different weak phases

The Unitary Triangle

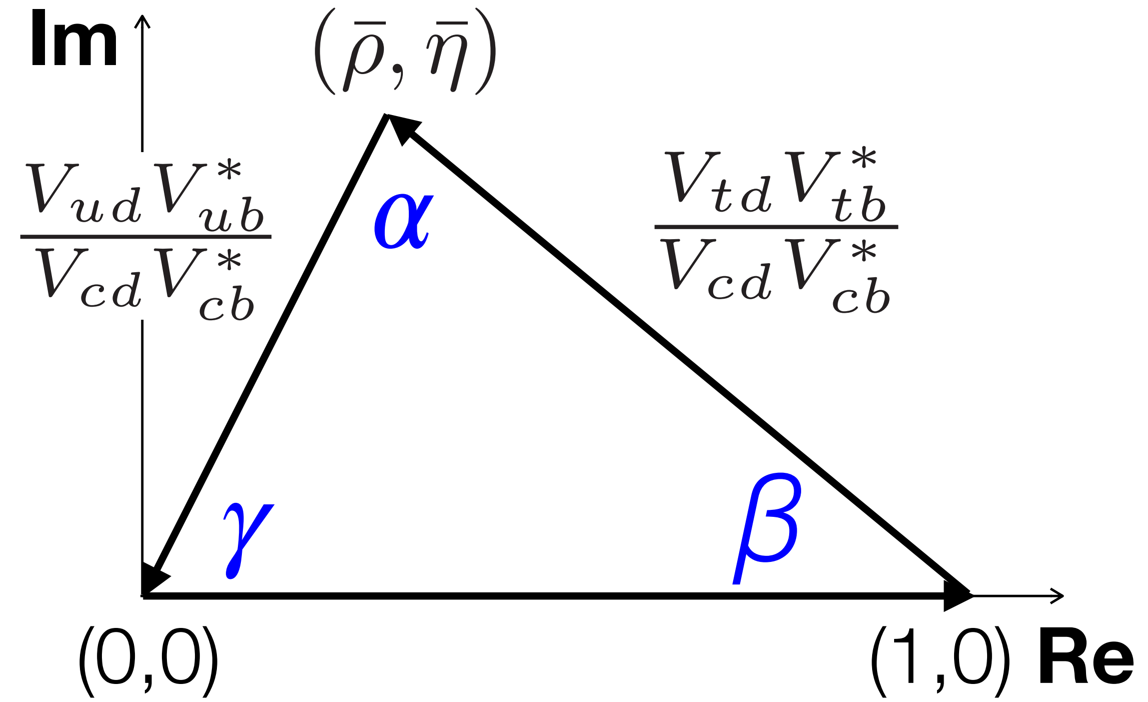
$$V_{CKM} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

Unitary condition from 1st and 3rd columns:

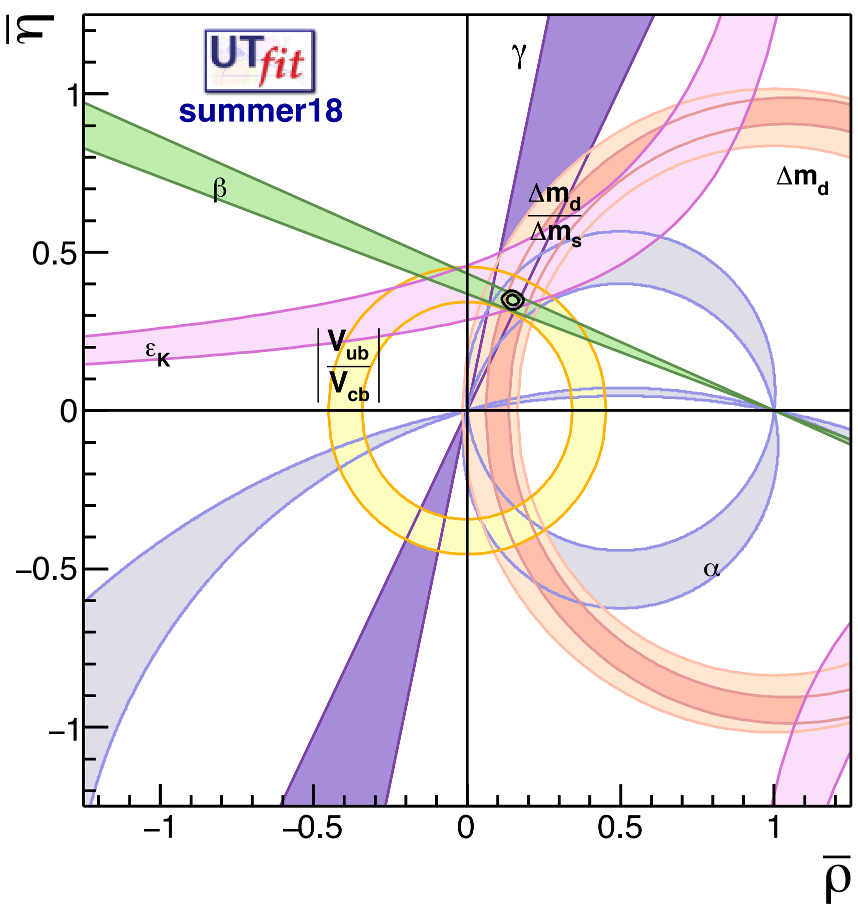
$$V_{ud}V^*_{ub} + V_{cd}V^*_{cb} + V_{td}V^*_{tb} = 0$$

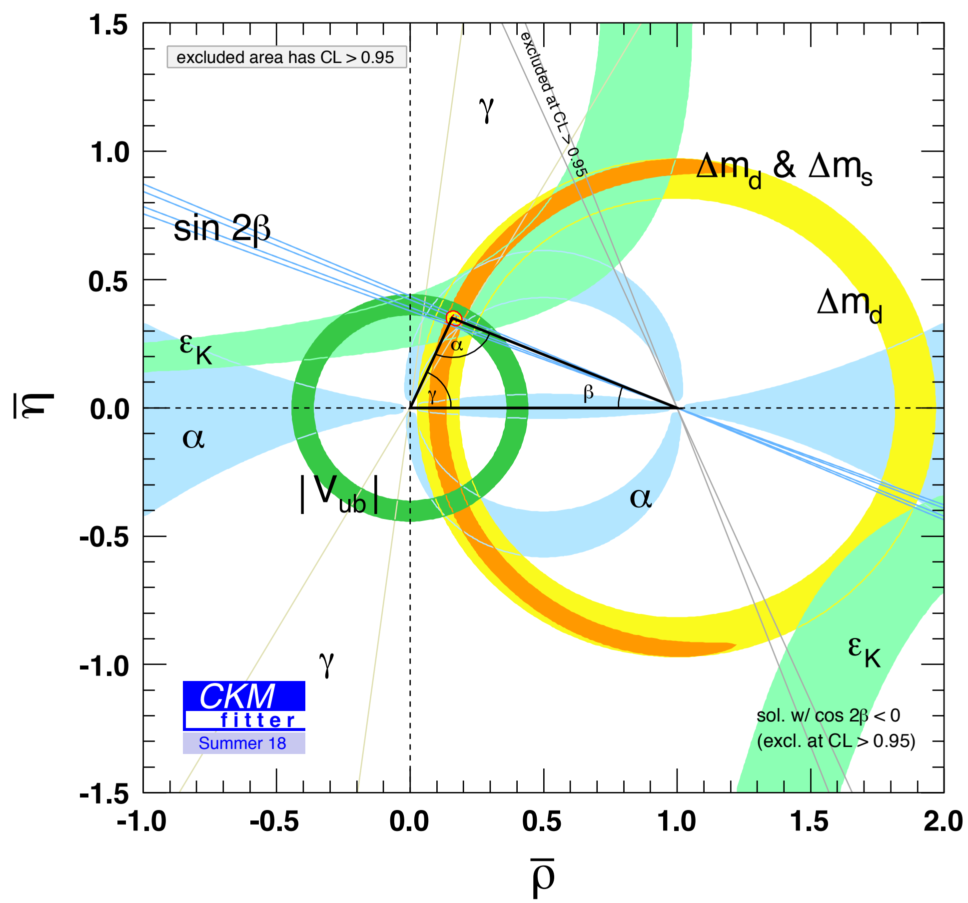
Over-constrain apex coordinates for a stringent test of SM:

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



The Unitary Triangle





$$\bar{\rho} = 0.148 \pm 0.013$$

$$\bar{\eta} = 0.348 \pm 0.010$$

$$\bar{\rho} = 0.1577^{+0.0096}_{-0.0074}$$

$$\bar{\eta} = 0.3493^{+0.0095}_{-0.0071}$$

Overall picture is consistent with SM, agreement at 9/6% and at 3% level, but still room for new physics

CP violation: a long path

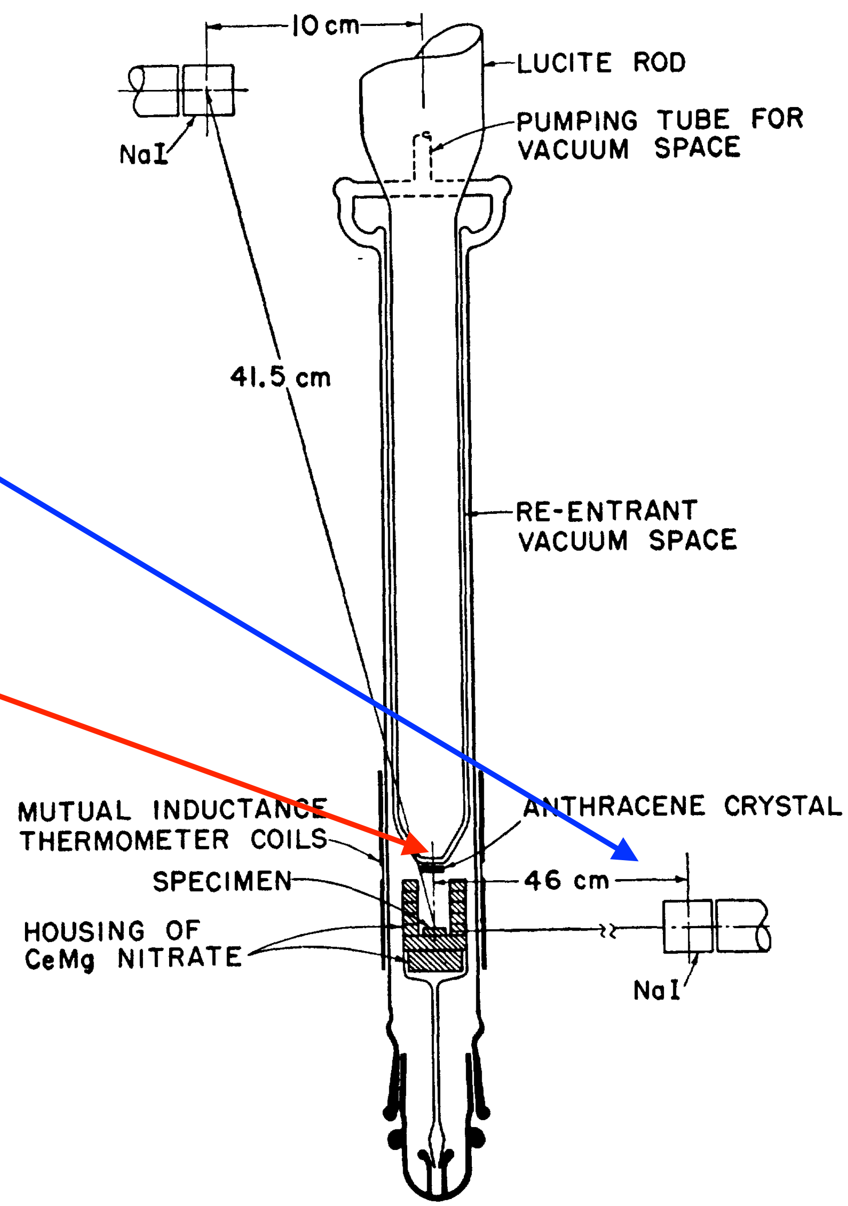
1956
Parity violation:
T. D. Lee, C. N. Yang, and C. S. Wu et al.

CP violation: a long path

The spin of Co^{60} is aligned with the external magnetic field B

Photon detector

Electron detector



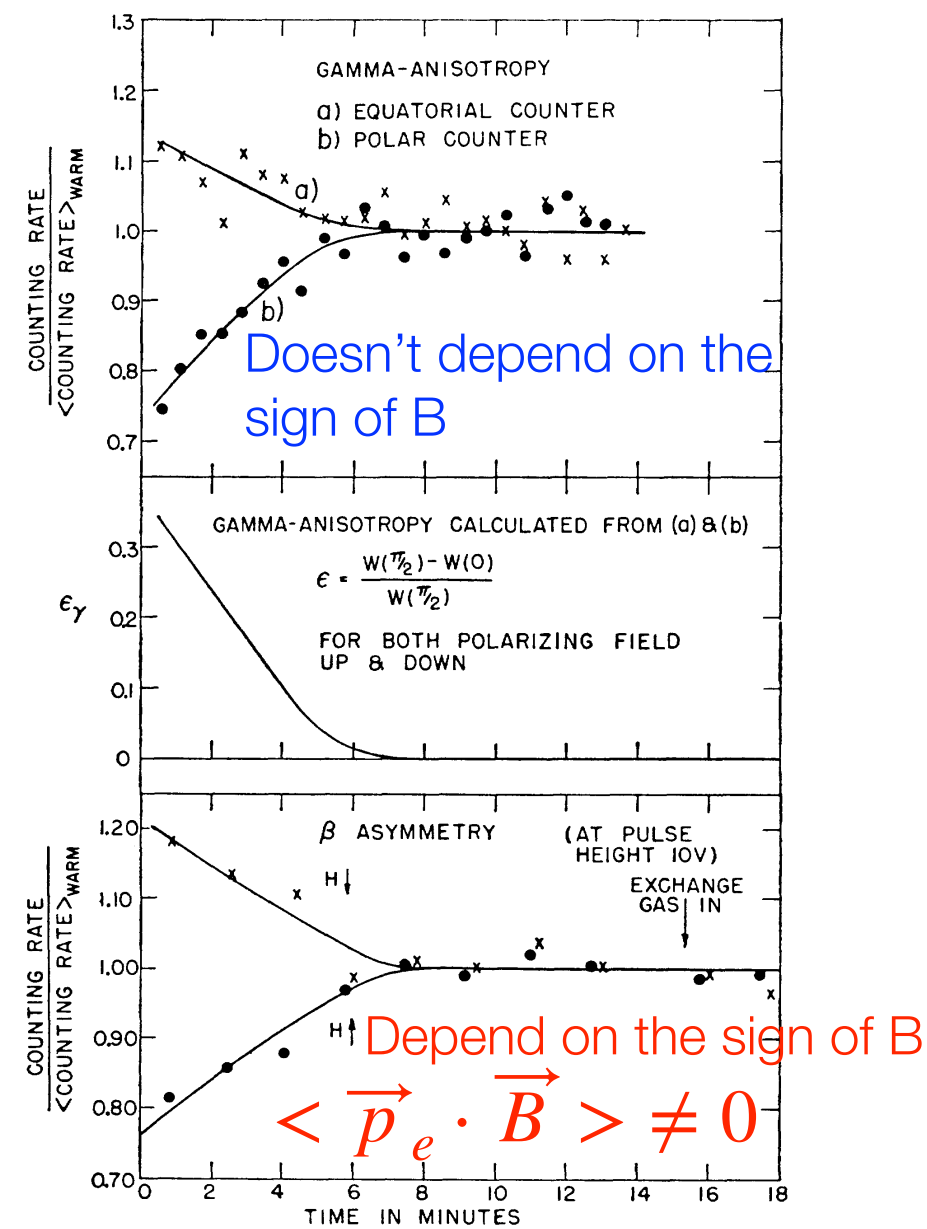


FIG. 2. Gamma anisotropy and beta asymmetry for polarizing field pointing up and pointing down.

CP violation: a long path

1956
Parity violation:
T. D. Lee, C. N. Yang, and C. S. Wu et al.

1963
Cabibbo mixing:
N. Cabibbo

CP violation: a long path

Recover the universality of weak interaction in hadron currents introducing the Cabibbo angle θ_C

$$|d'\rangle = \cos\theta_c\,|d\rangle + \sin\theta_c\,|s\rangle$$

1956
Parity violation:
T. D. Lee, (
Yang, and C
et al.

UNITARY SYMMETRY AND LEPTONIC DECAYS

Nicola Cabibbo
CERN, Geneva, Switzerland
(Received 29 April 1963)

We present here an analysis of leptonic decays based on the unitary symmetry for strong interactions, in the version known as "eightfold way,"[1] and the V-A theory for weak interactions.[2,3] Our basic assumptions on J_μ, the weak current of strong interacting particles, are as follows:

(1) J_μ transforms according to the eightfold representation of SU_3. This means that we neglect currents with $\Delta S = -\Delta Q$, or $\Delta I = 3/2$, which should belong to other representations. This limits the scope of the analysis, and we are not able to treat the complex of K^0 leptonic decays, or $\Sigma^+ \to n + e^+ + \nu$ in which $\Delta S = -\Delta Q$ currents play a role. For the other processes we make the hypothesis that the main contributions come from that part of J_μ which is in the eightfold representation.

(2) The vector part of J_μ is in the same octet as the electromagnetic current. The vector contribution can then be deduced from the electromagnetic properties of strong interacting particles. For $\Delta S = 0$, this assumption is equivalent to vector-

CP violation: a long path

<u>1956</u>
Parity violation:
T. D. Lee, C. N. Yang, and C. S. Wu et al.

<u>1964</u>
Strange particles: CP violation in K meson decays:
J. W. Cronin
V. L. Fitch et al.

<u>1963</u>
Cabibbo mixing:
N. Cabibbo

CP violation: a long path

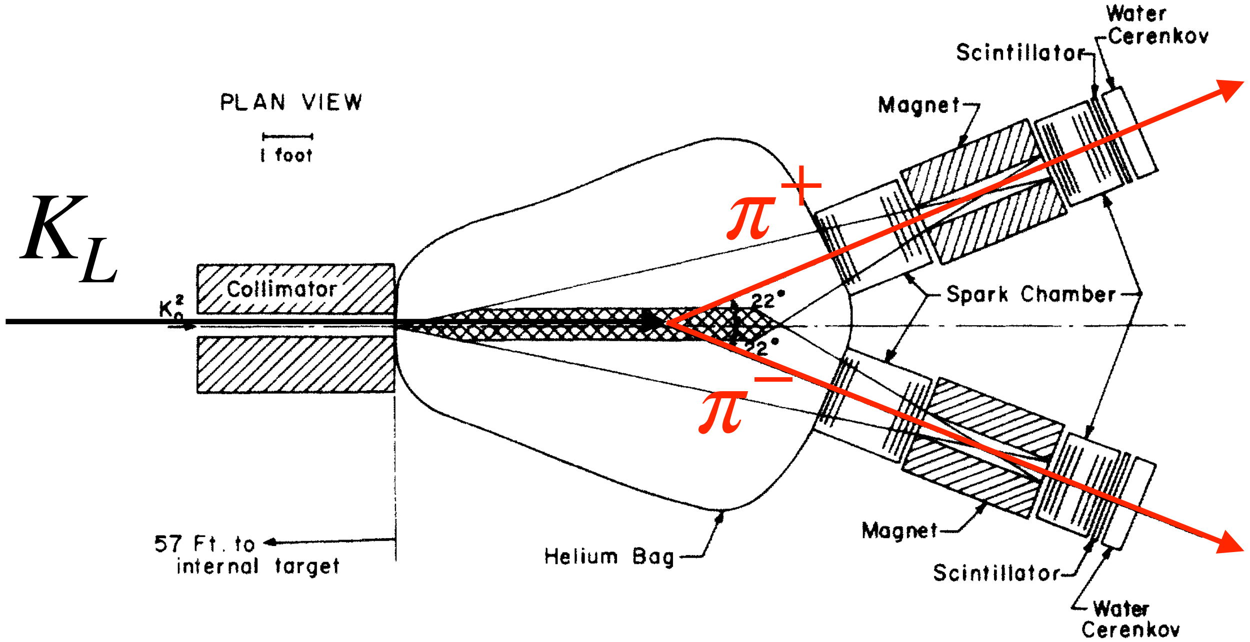
Phys. Rev. Lett. 13 (1964) 138

Look for CP-violating decays:

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

$CP(\pi^+\pi^-) = +1$
$CP(K_L) \approx -1$

K_L must contain a CP=+1 component



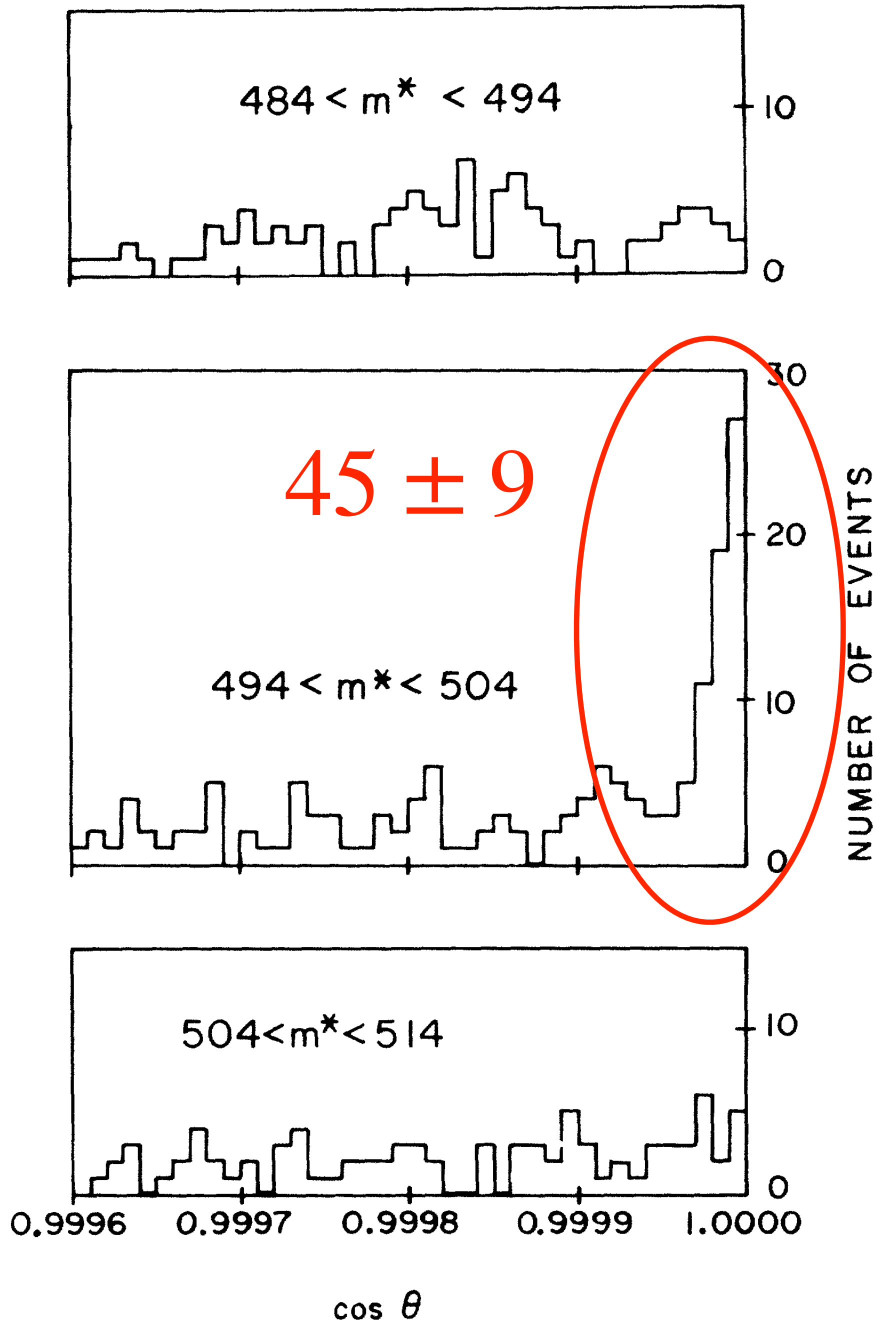


FIG. 3. Angular distribution in three mass range for events with $\cos\theta > 0.9995$.

CP violation: a long path

1956
Parity violation:
T. D. Lee, C. N. Yang, and C. S. Wu et al.

1963
Cabibbo mixing:
N. Cabibbo

1964
Strange particles: CP violation in K meson decays:
J. W. Cronin
V. L. Fitch et al.

1973
The CKM matrix:
M. Kobayashi and T. Maskawa

CP violation: a long path

Apply the mixing for the case of three quark generations
CPV feasible and described by one weak phase

1964
Strange particles:

1956
Parity vi
T. D. Lee
Yang, and
et a

Progress of Theoretical Physics, Vol. 49, No. 2, February 1973

CP-Violation in the Renormalizable Theory of Weak Interaction

Makoto KOBAYASHI and Toshihide MASKAWA

Department of Physics, Kyoto University, Kyoto

(Received September 1, 1972)

In a framework of the renormalizable theory of weak interaction, problems of *CP*-violation are studied. It is concluded that no realistic models of *CP*-violation exist in the quartet scheme without introducing any other new fields. Some possible models of *CP*-violation are also discussed.

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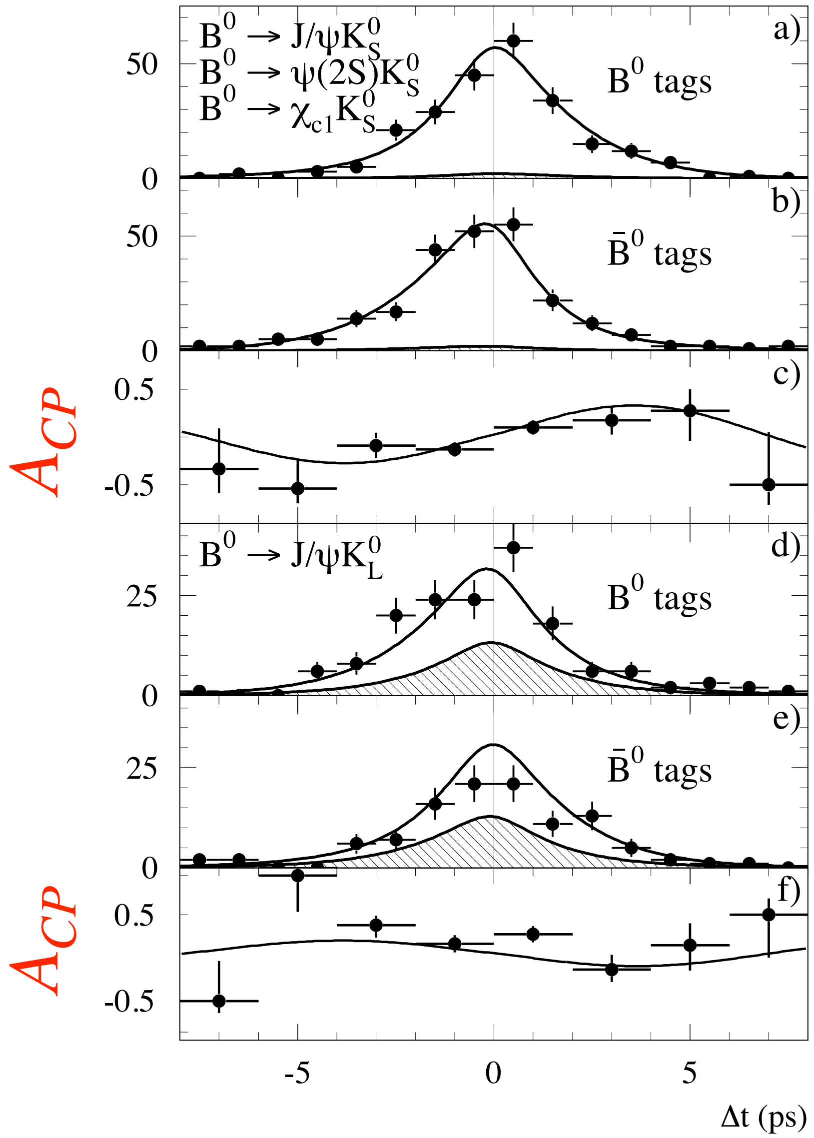
2001
Beauty particles: CP violation in B^0 meson decays:
BaBar and Belle Collaborations

CP violation: a long path

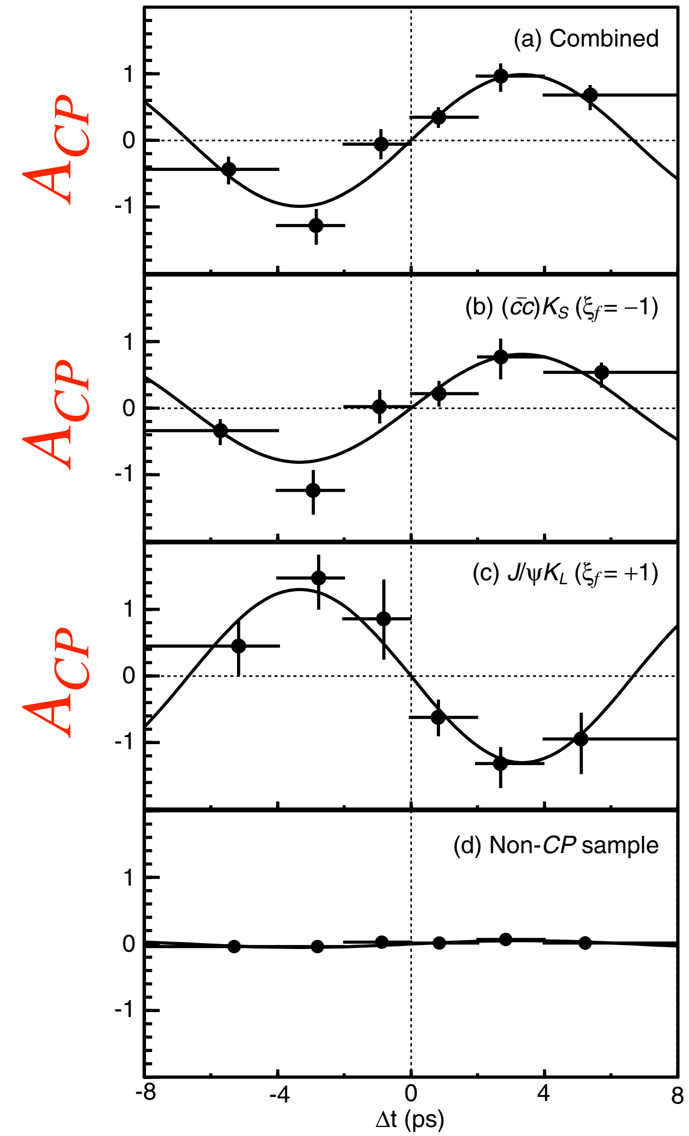
Amplitude of CP-violating asymmetry proportional to $\sin(2\beta)$, derived from the decay time distribution

$$A_{CP}(\Delta t) = \frac{\Gamma(\overline{B}^0 \to f_{CP}) - \Gamma(B^0 \to f_{CP})}{\Gamma(\overline{B}^0 \to f_{CP}) + \Gamma(B^0 \to f_{CP})} = -\eta_f \sin(2\beta)\sin(\Delta m_{B^0}\Delta t)$$

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



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



CP violation: a long path

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BaBar and Belle Collaborations

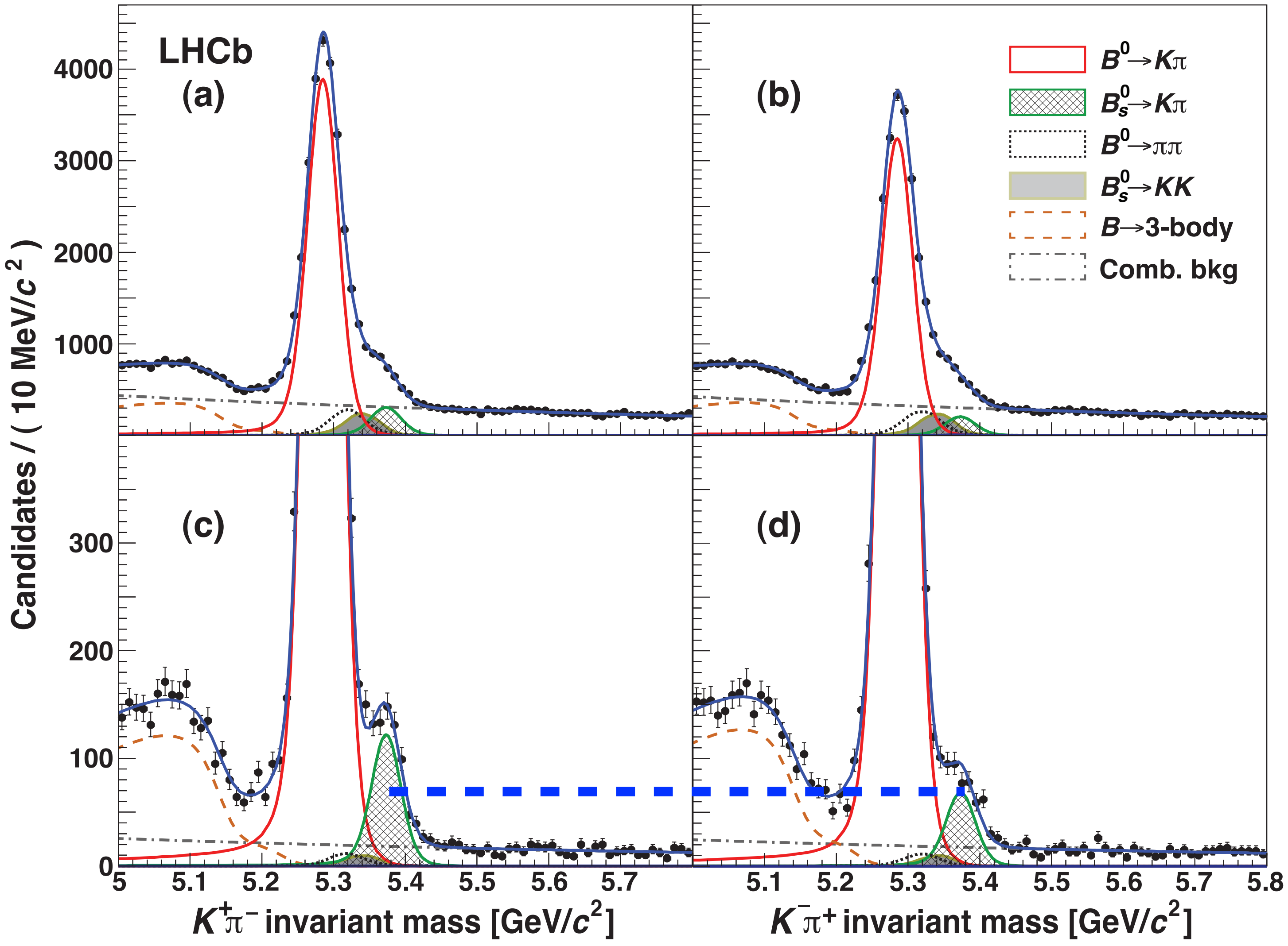
2013
Beauty-strange particles: CP violation in B_s^0 meson decays:
LHCb collaboration

CP violation: a long path

Phys. Rev. Lett. 110 (2013) 221601

CP-violating asymmetry for time integrated measurement

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



$$A_{CP} = 0.27 \pm 0.04 \pm 0.01$$

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2013
Beauty-strange particles: CP violation in B_s^0 meson decays:
LHCb collaboration

2019
Charm particles: CP violation in D^0 meson decays:
LHCb collaboration

CP violation: a long path

Phys. Rev. Lett. 122 (2019) 211803

CP-violating asymmetry for time integrated measurement

$$\Delta A_{CP} = A_{CP}(D^0 \to K^- K^+) - A_{CP}(D^0 \to \pi^- \pi^+) = (-15.4 \pm 2.9) \times 10^{-4}$$