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CP violation in *b*-baryons at LHCb

Rafael Silva Coutinho

University of Zurich

On behalf of the LHCb experiment

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Outline

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This talk covers some recent results in *b*-baryon decays at LHCb

- Introduction, techniques and experimental constraints

  [*e.g.* production and detection asymmetries]

  [$3\,\text{fb}^{-1}$ Run-I (2011/12) at 7/8 TeV]

- Searches for *CP* violation in *b*-baryons, including first evidence in $\Lambda^0_b \to p\pi^-\pi^+\pi^-$

  [Local phase-space asymmetry]

- Searches for baryon number violation in Ξ^0_b

  [**NEW!** LHCb-PAPER-2017-023]

CP violation in the baryonic sector

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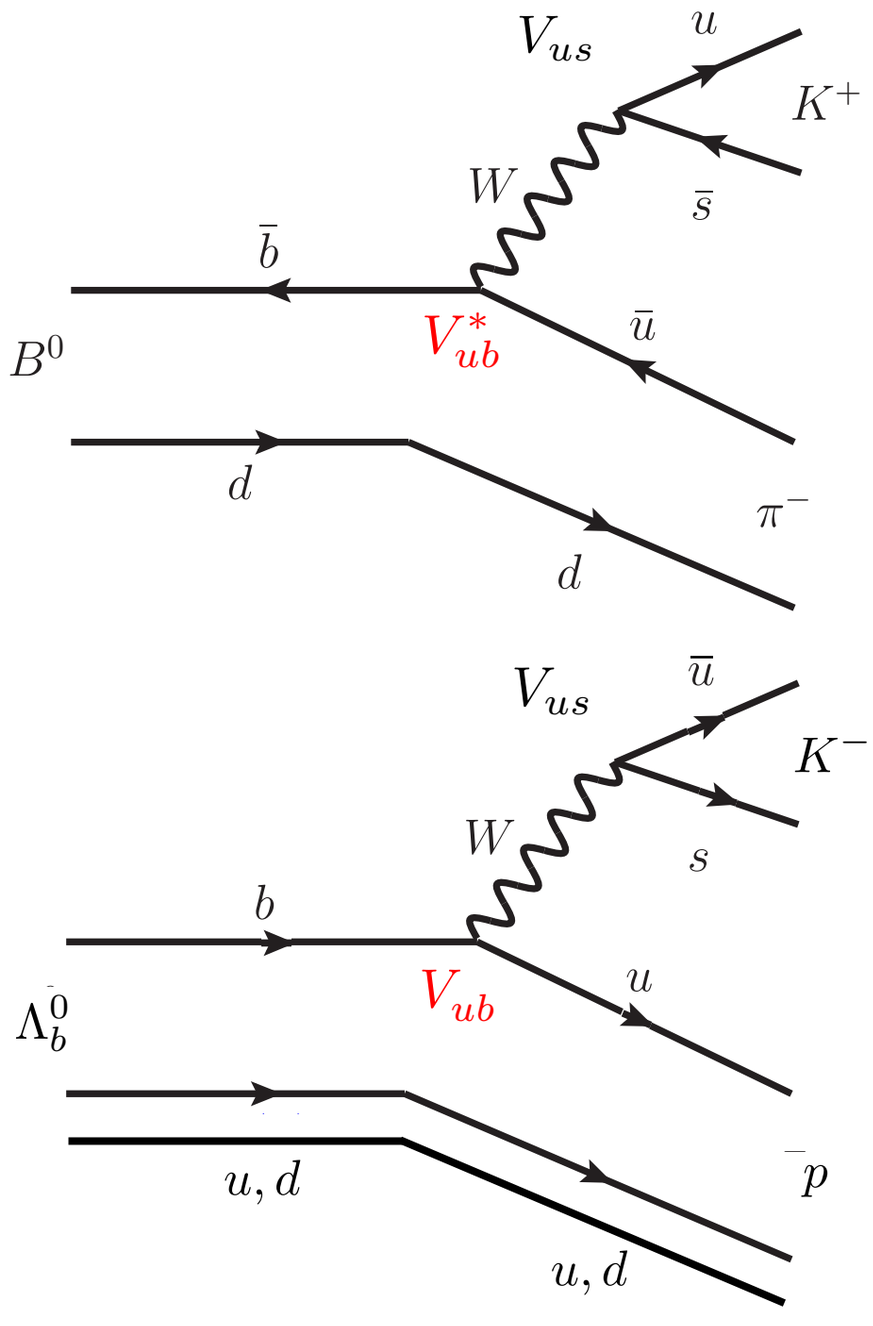
Phenomenon well stablished in the meson sector, *i.e.* Kaon and $B^{\pm,0}_{(s)}$ decays: no deviation from the SM has been seen

As-of-yet no CP violation in *b*-baryons has been observed, though the CKM mechanism predicts sizeable amount of violation

At LHCb *b*-baryons are collected in unprecedented quantities → opens a new field in flavour physics for precision measurements

Same underlying short distance physics for *b*-baryons and *B* mesons but with different spin and QCD structure



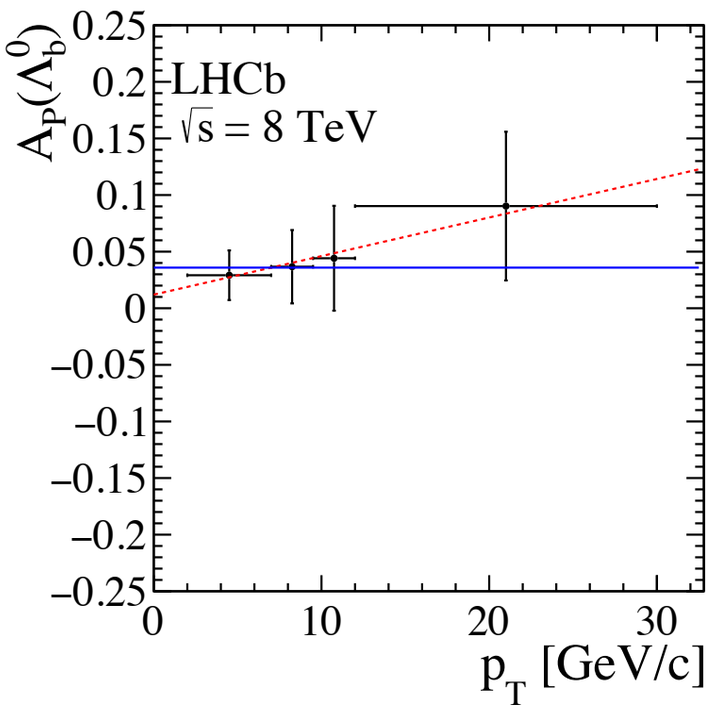
Experimental issues

- Initial *pp* state is not *CP* symmetric

[i] Particle-antiparticle production asymmetries (A_P)

- Asymmetry could mimic CPV and needs to be disentangled or measured

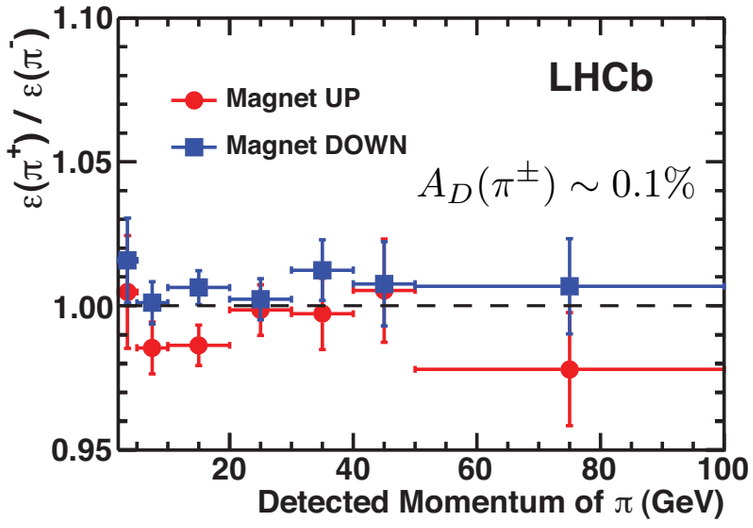
[LHCb-PAPER-2016-062, Submitted to PLB]



- Detector is made of matter

[ii] particle/antiparticle detection asymmetries (A_D)

[LHCb, PLB 713 (2012), PRL 110 (2013) 221601]



$$A_D(p/\bar{p}) \sim 1 - 2\%$$

- B field inversion is crucial to keep charged particle tracking asymmetries under control (10^{-4})

Experimental techniques

CP violation **in decay**: only type available in the baryonic sector (no mixing due to baryon number conservation)

This observable can be measured by comparing yields between baryon/anti-baryon:

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

strong phase — CP conserving

weak phase — *CP* violating

- Contributions from at least two amplitudes: *e.g.* $A_1 e^{i\delta_1} e^{i\phi_1}, A_2 e^{i\delta_2} e^{i\phi_2}$
- Need non-vanishing strong and weak phase difference
- Sensitive to baryon-antibaryon production asymmetries
- Sensitive to charged particle reconstruction asymmetries

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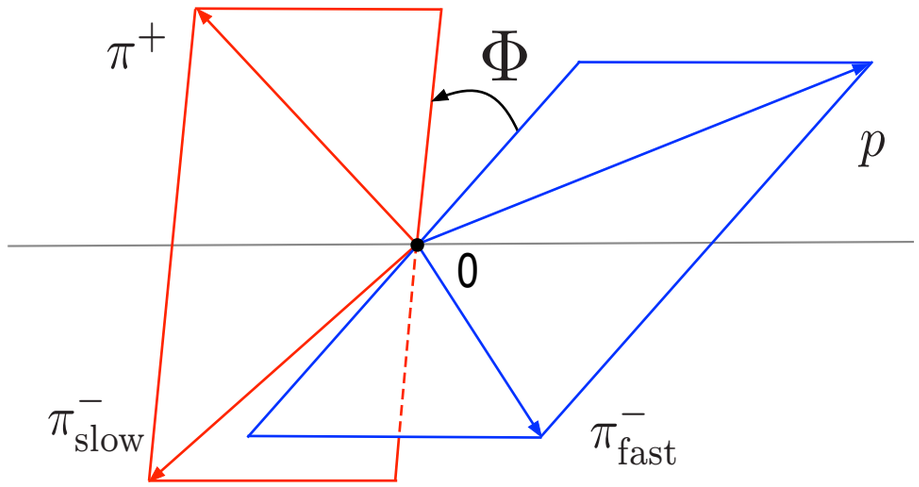
Triple product asymmetry: use momenta of any 3 final particles in 4-body decays

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



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

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

P-odd asymmetries:

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

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

CP violation observable

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

P-violating observable

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

The $A_{\hat{T}}, \bar{A}_{\hat{T}}, a_P^{\hat{T}-\text{odd}}$ and $a_{CP}^{\hat{T}-\text{odd}}$ observables are largely unaffected by A_D and A_P

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Searches for *CP* violation in *b*-baryon decays

LHCb results : $\mathcal{L} = 3\,\text{fb}^{-1}$ – 2011 + 2012 dataset

Searches for CP in multi-body decays

[LHCb, JHEP **04** (2014) 087, JHEP 05 (2016) 08]

First evidence for CP violation in $\Lambda^0_b \to p\pi^-\pi^+\pi^-$ decays

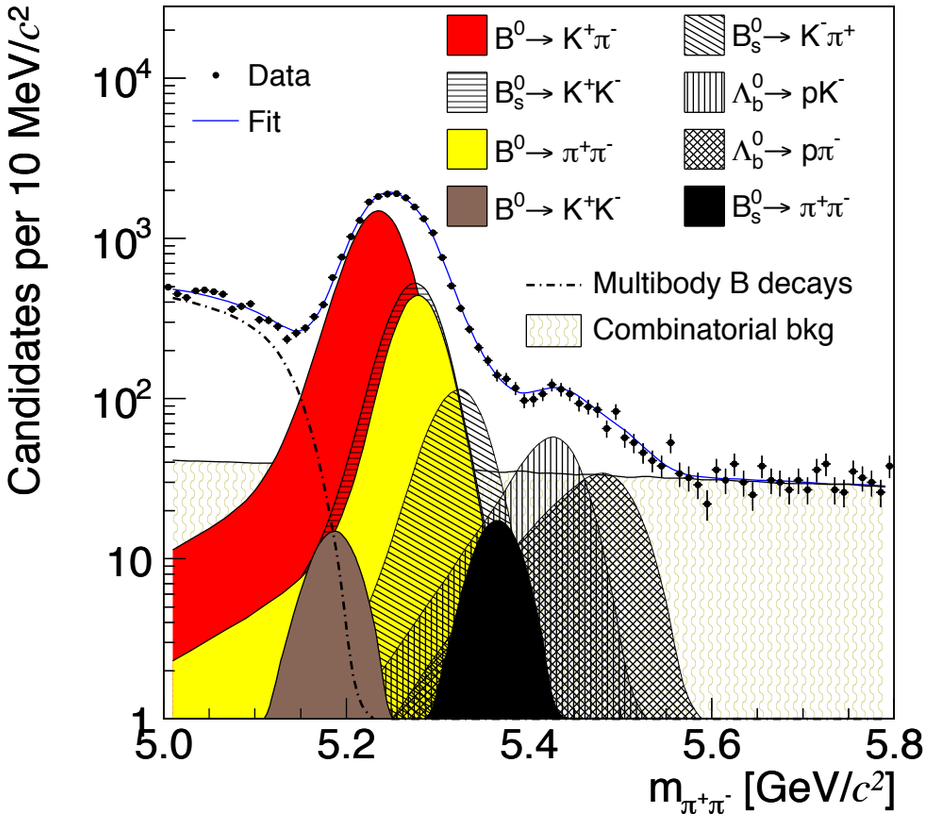
[LHCb, arXiv:1609.05216, submitted to Nature Physics]

LHCb

Beauty baryon: two-body case

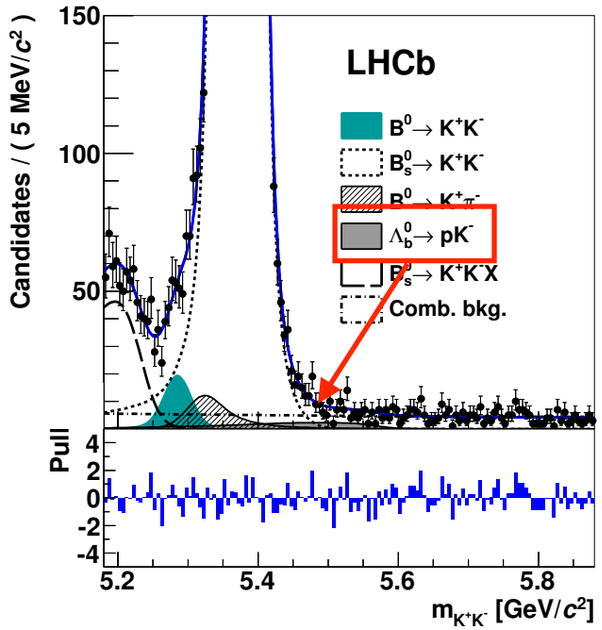
Simplest decay modes: $\Lambda^0_b \to pK^-$, $p\pi^-$

[CDF, PRL 113, 242001 (2014)]



Decay	$\mathcal{A}(b \to f)$
$\Lambda^0_b \to p\pi^-$	$+0.06 \pm 0.07 \pm 0.03$
$\Lambda^0_b \to pK^-$	$-0.10 \pm 0.08 \pm 0.04$

[LHCb, PRL 118, 081801 (2017)]



Ongoing analysis - expected approximately 10x CDF statistics

Potentially large CPV effects in charmless decays

[Phys. Rev. D 91, 116007 (2015)]

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

Beauty baryon: multi-body decays

Limited information available in two-body decays: i.e. BF and A_{CP}

Additional information can be obtained via multi-body decays (n >2)

- CPV in $\Lambda^0_b \to pK^0\pi^-$ decays [LHCb, JHEP **04** (2014) 087]

  [Note that amplitude analysis (Dalitz plot) of this mode can access the intermediate channel pK* - SM CP violation expected to be ~20%]

- CPV in $\Lambda^0_b \to \Lambda h^+h^-$ decays [LHCb, JHEP **05** (2016) 08]

- Triple-product asymmetry in $\Lambda^0_b \to \Lambda\varphi$ decays [LHCb, PLB 759 (2016) 282]

- CPV in $\Lambda^0_b \to J/\psi p\pi^-$ and $J/\psi pK^-$ decays [LHCb, JHEP **07** (2014) 103]

- CPV in $\Lambda^0_b \to pK^-\mu^+\mu^-$ decays [LHCb, JHEP **06** (2017) 108]

Search for *CP* violation in 4-body decays

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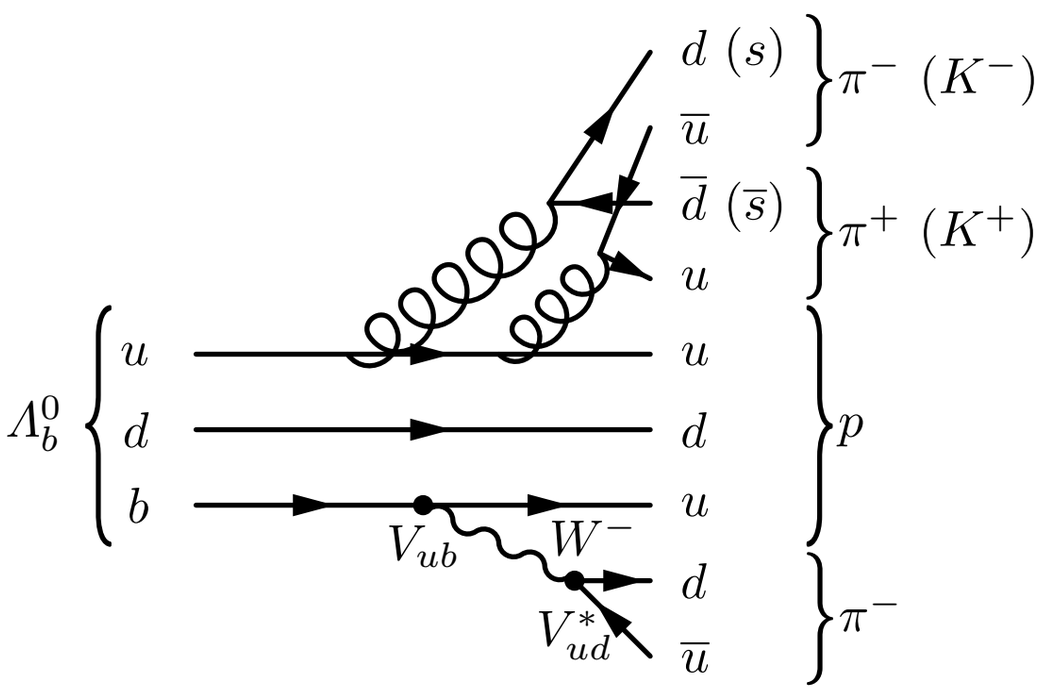
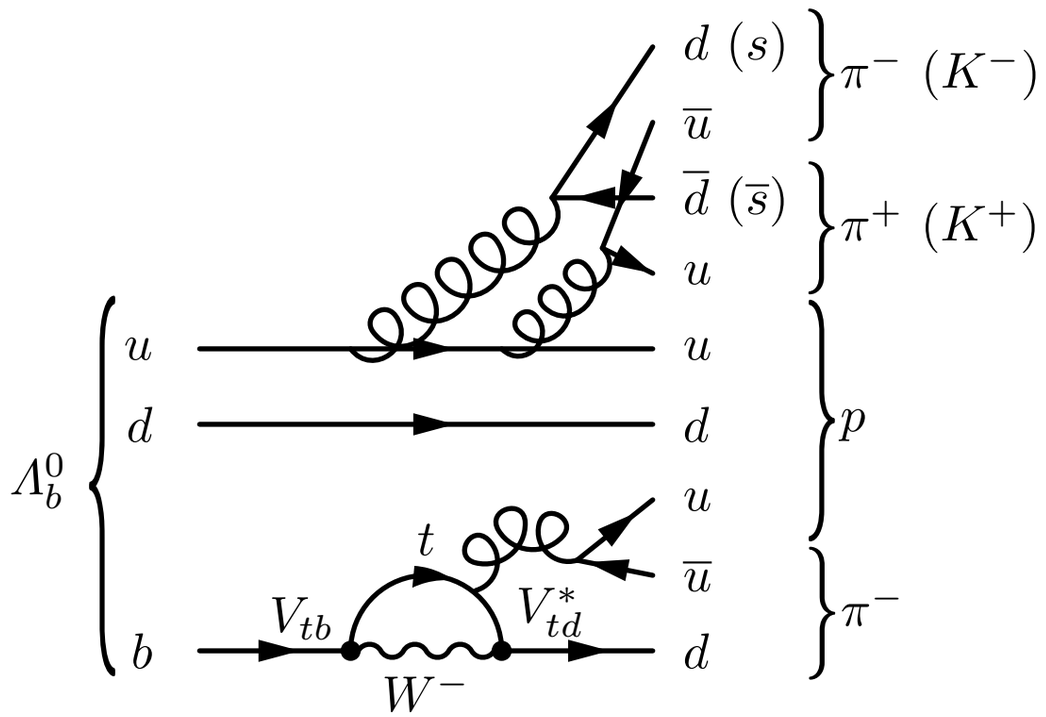
[LHCb, Nature Physics **13** (2017) 391]

Integrated and triple-product asymmetry measurements in $\Lambda^0_b \to p\pi^-[\pi^+\pi^-,K^+K^-]$

Transitions with both tree and penguin amplitudes at comparable magnitude

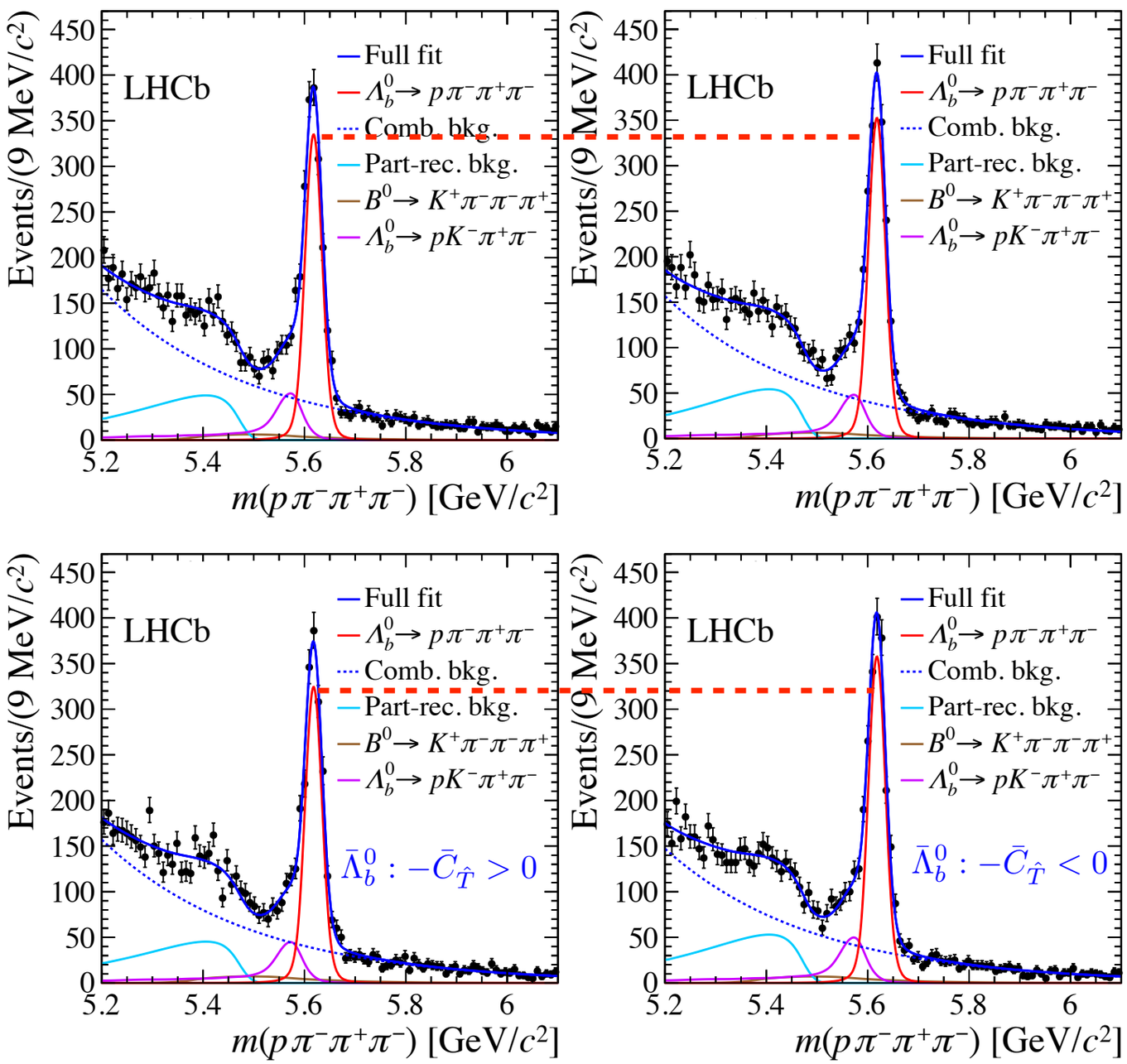


Tree diagram $\propto V_{ub} \sim \lambda^3$



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

CP violation measurements in $\Lambda^0_b \to p\pi^-[\pi^+\pi^-, K^+K^-]$



[LHCb, Nature Physics **13** (2017) 391]

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

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

Phase space integrated asymmetries for $\Lambda^0_b \to p\pi^-\pi^+\pi^-$

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

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

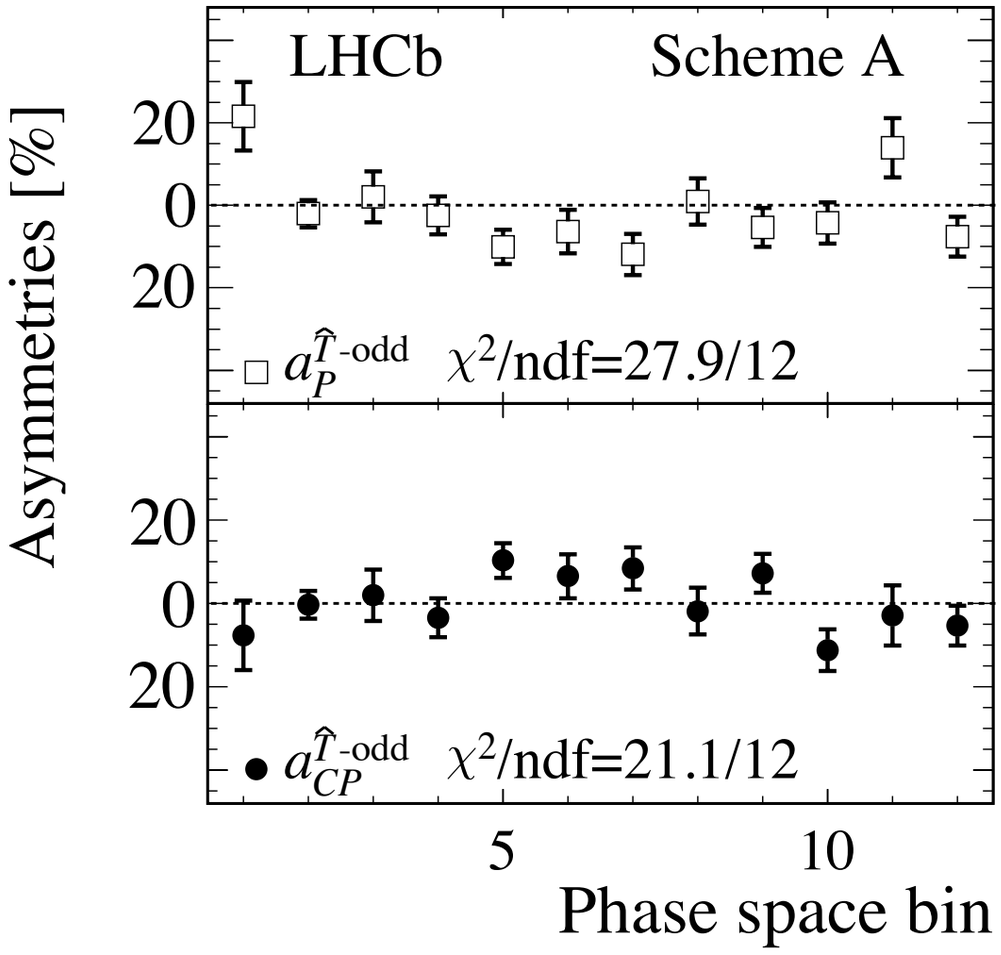
Consistent with hypothesis of P and CP symmetry

Similar results are found for the less sensitive mode $p\pi^-K^+K^-$

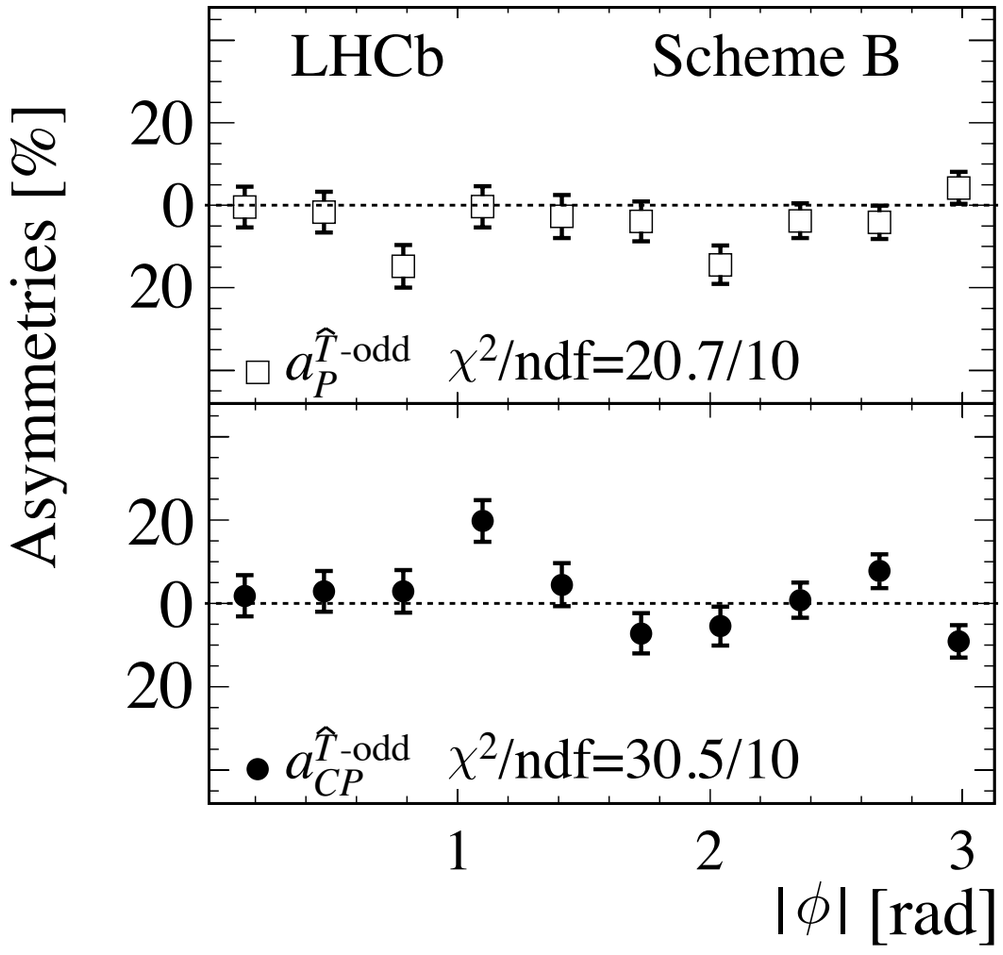
Phase-space *CP* violation in $\Lambda^0_b \to p\pi^-\pi^+\pi^-$

[LHCb, Nature Physics **13** (2017) 391]

Binning A: based on dominant resonant structures, *e.g.* Δ^{++}, N* and $\rho(770)$



Binning B: function of the angle between the decay planes $\pi^+\pi^-_{slow}$ and $p\pi^-_{fast}$



First evidence for *CP* violation with 3.3 standard deviations!

Search for baryon number violation (BNV) in Ξ^0_b decays

LHCb results : $\mathcal{L} = 3\,\mathrm{fb}^{-1}$ – 2011 + 2012 dataset

BNV oscillations in decays of $\Xi^{*-}_b \to \Xi^0\pi^-$ or $\Xi'^-_b \to \Xi^0\pi^-$

[**NEW!** Preliminary - to be submitted to PRL]

Baryon number violation measurements

- BNV has never been seen experimentally, and there are very strong constraints on the proton lifetime

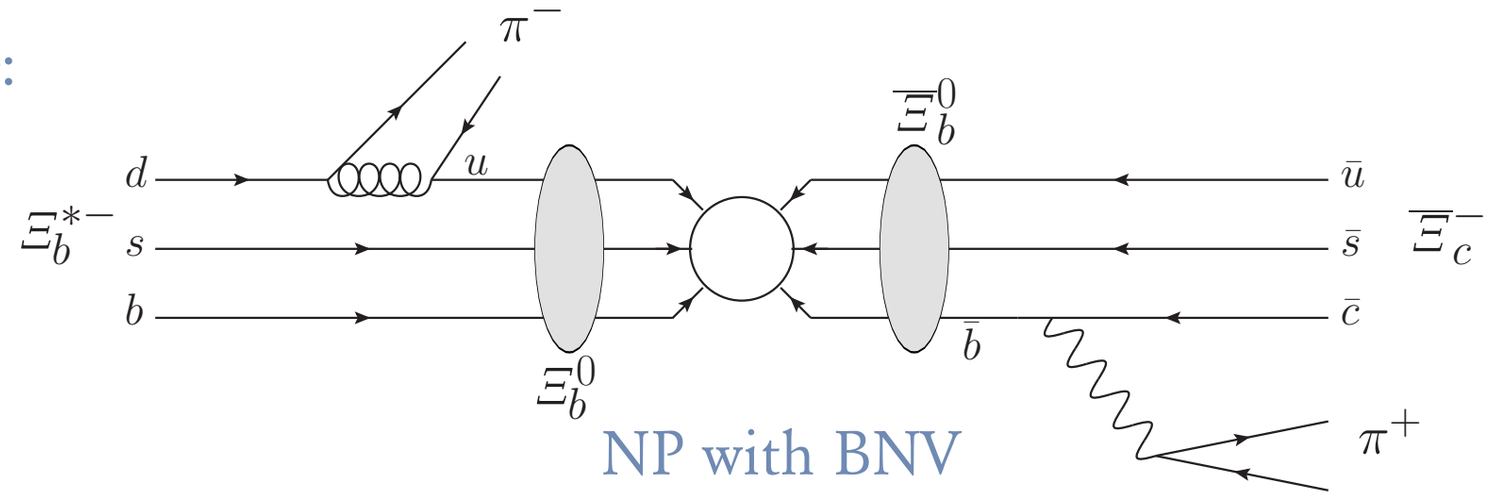
- In models of flavour-diagonal six fermions BSM vertices allow such BNV without excessive proton decay

[PRD **85**, 036005 (2012), PLB **721** 82-85 (2013)]

- Signatures of BNV are experimentally challenge (*e.g.* same-sign di-lepton + top jets)

- Unambiguous experimental evidence: baryon-antibaryon oscillations of hadrons that contain quarks of all three generations.

For instance:



NP with BNV

Baryon number violation measurements

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- Analysis strategy: search for time-dependent oscillations of Ξ^0_b (bsu), tagged by resonances Ξ^{*-}_b and $\Xi^{'-}_b$ (right-sign [RS] $\Xi^0_b \to \Xi^+_c\pi^-$ and wrong-sign [WS])

- Oscillation similar to meson mixing [B-field effects negligible for Ξ^0_b at LHCb]

Ξ_b^0 mixing

$$\frac{\Gamma(\Xi_b^0 \to \bar{f})}{\Gamma(\Xi_b^0 \to f)} \simeq \left|\frac{q}{p}\right|^2 \left[(\Delta\Gamma/4)^2 + (\Delta m/2)^2\right] t^2 = \alpha t^2$$

α describes the mixing rate and has units of ps^{-2}

D^0 mixing

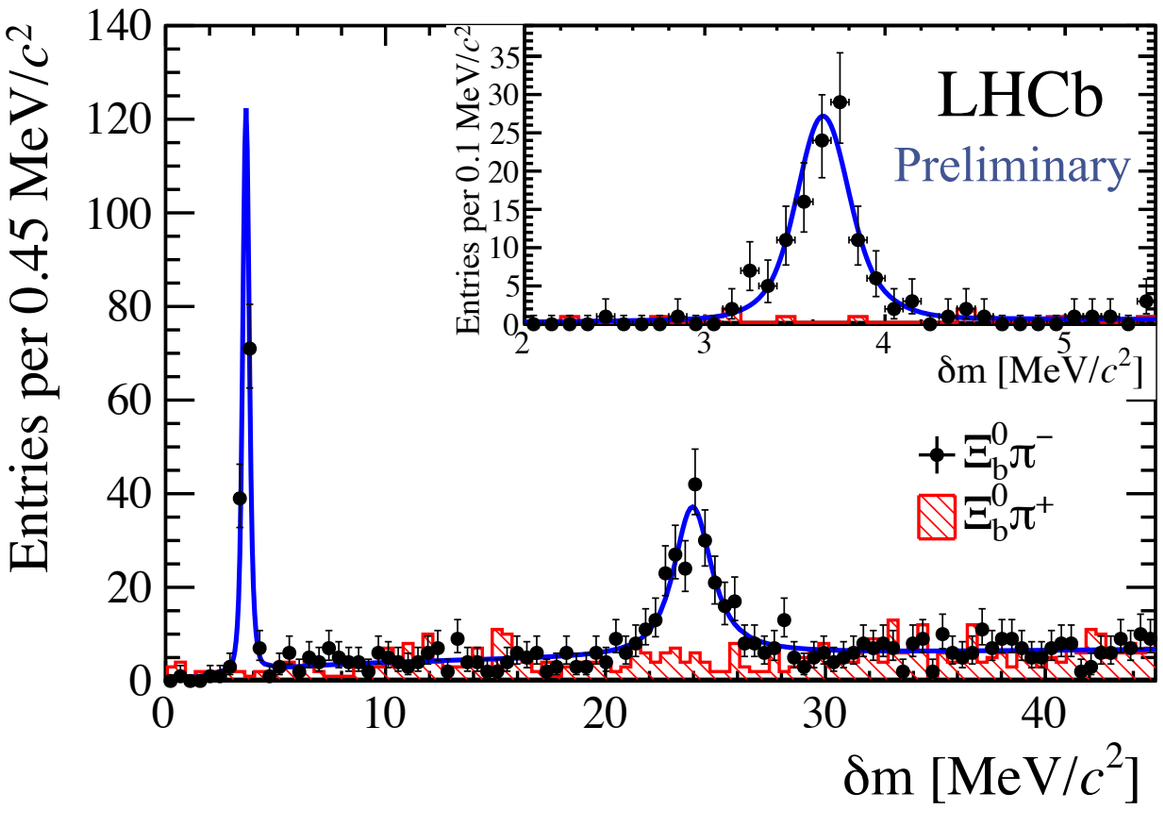
$$\frac{\Gamma(D^0 \to K^+\pi^-)}{\Gamma(D^0 \to K^-\pi^+)} \simeq R_D + \sqrt{R_D}\, y'\, \Gamma t + (x'^2 + y'^2)\Gamma^2 t^2$$

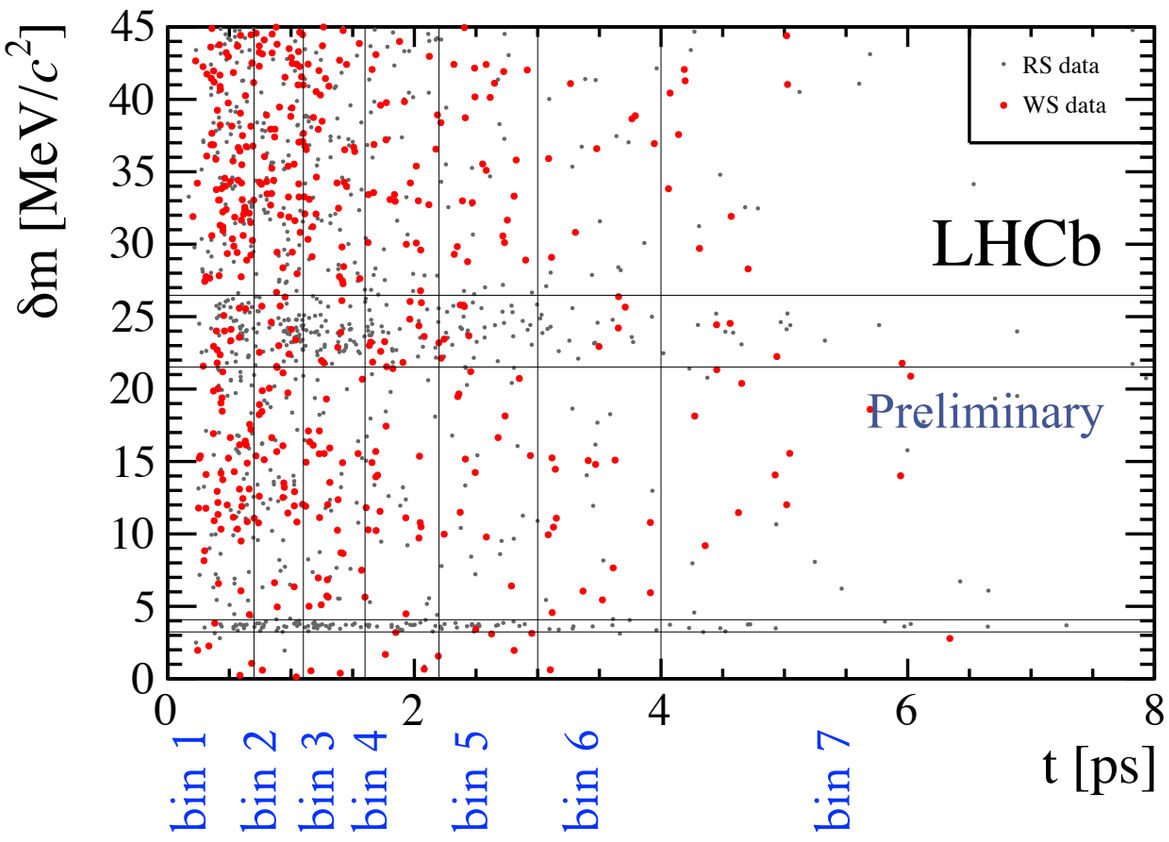
Measurement: fit the time-dependent WS/RS yield ratio as a function of αt^2

- Likelihood scan for various values of α and use toys to set significance/limits
- Test statistics: $\Delta = 2\,\Delta\, lnL = 2\, ln\, L(\alpha = \alpha_{\mathrm{best-fit}}) - 2\, ln\,(\alpha = 0) \geq 0$

Analysis data sample

[LHCb-PAPER-2017-023, to be submitted to PRL]





- Data sample is obtained with almost identical to spectroscopy paper

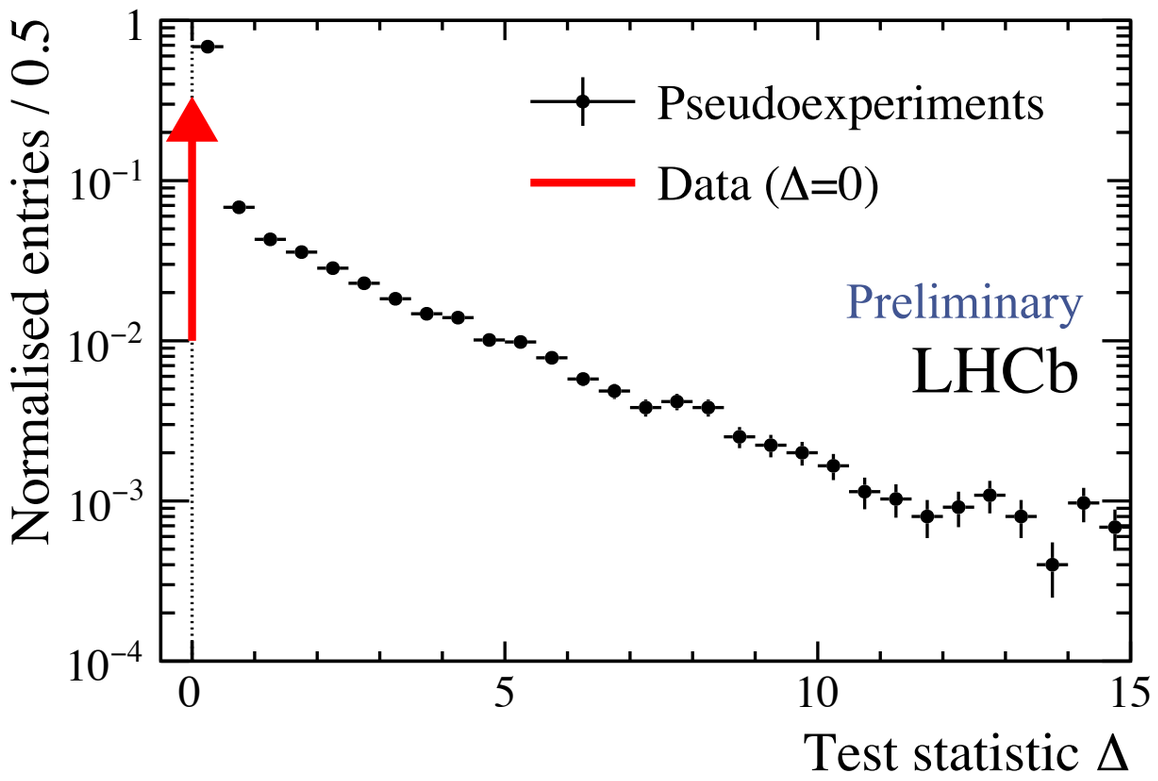
  [LHCb, PRL114, 062004 (2015)]

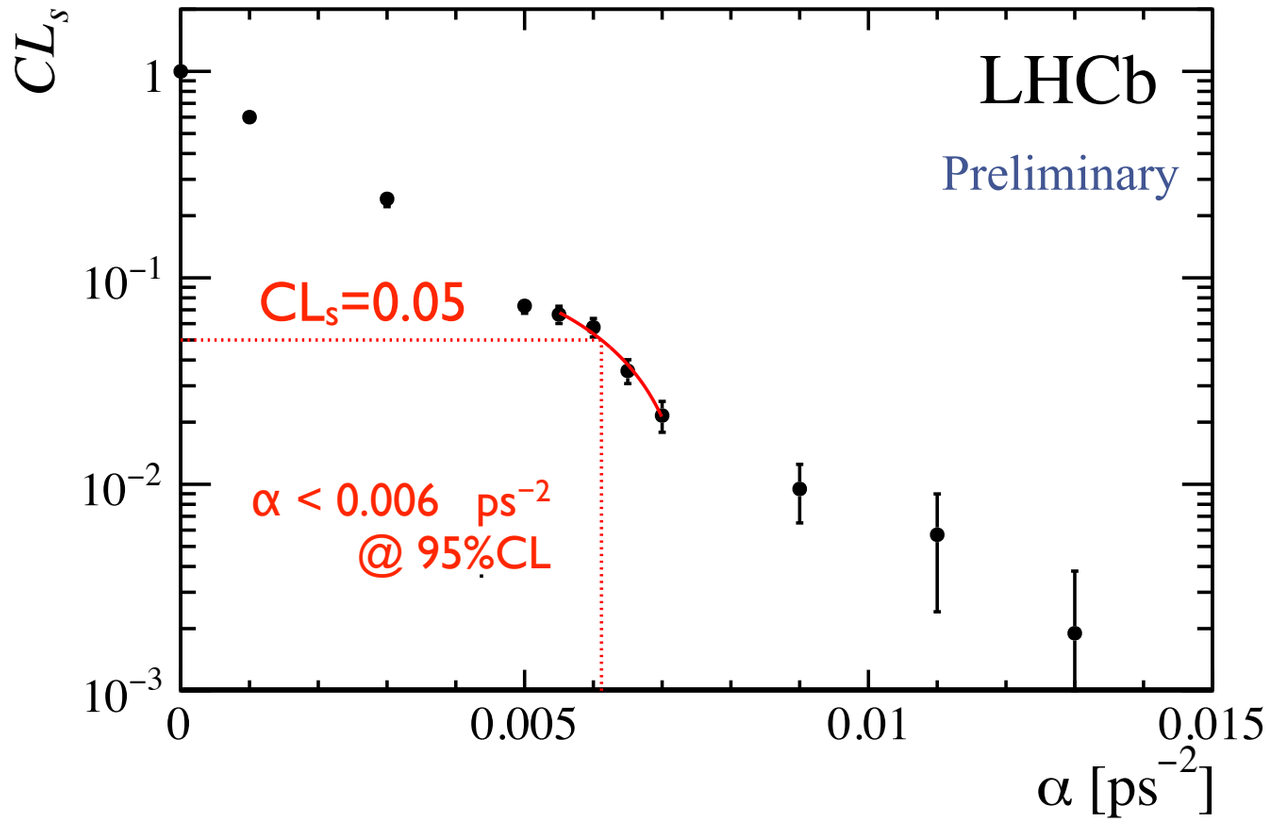
- Improved signal to noise ratio in comparison to previous paper

BNV results

[LHCb-PAPER-2017-023, to be submitted to PRL]

- The best-fit value of the oscillation parameter in data is $\alpha = 0$, and the test statistic is found to be $\Delta_{data} = 0$





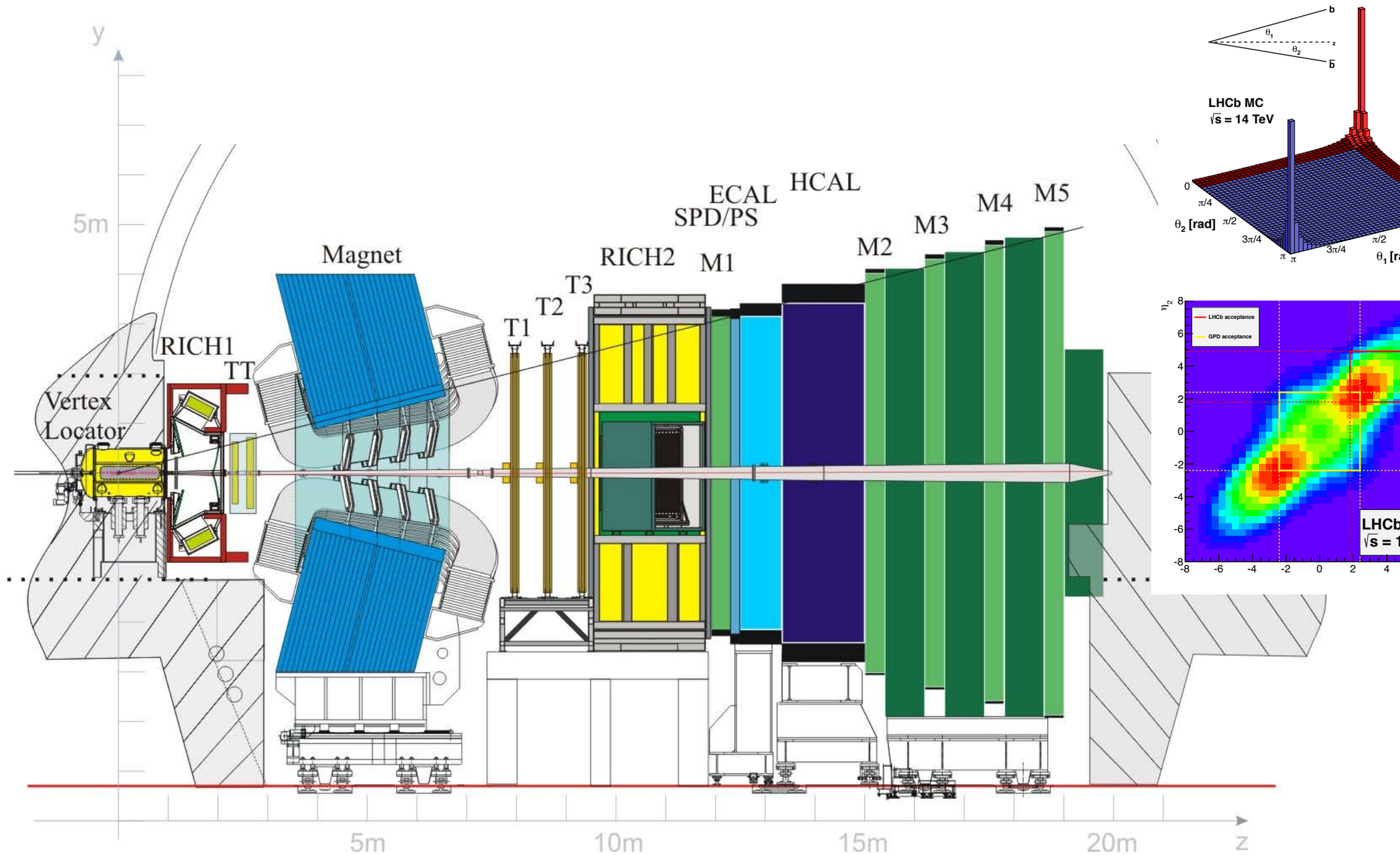
α	$<$	0.006 ps^{-2}	**at the 95% CL**
τ_{mix}	$>$	13 ps	**for** $\alpha = 1/\tau^2_{\text{mix}}$

No evidence of baryon-number-violating oscillations is found

General conclusions

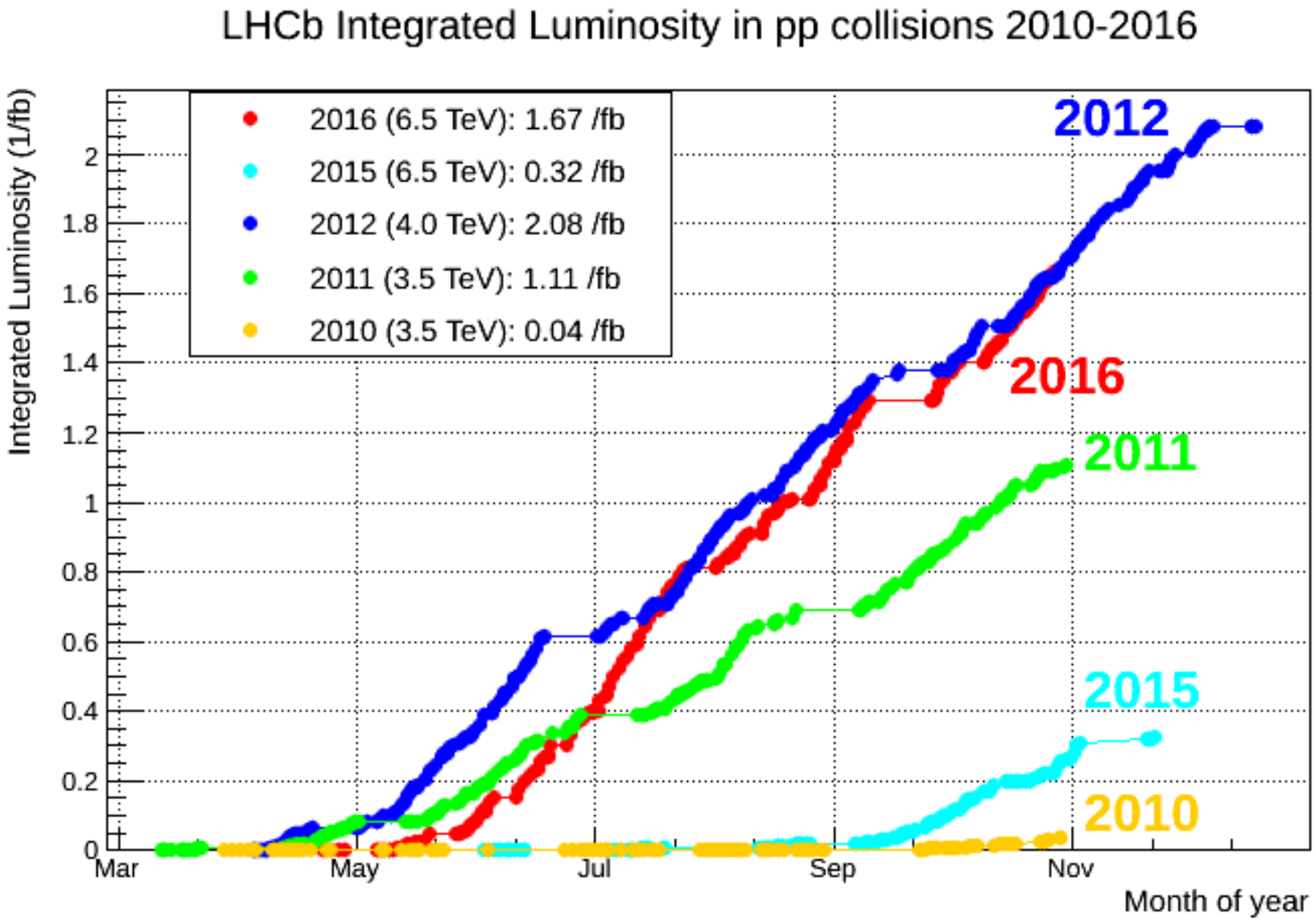
- Searches for CPV *b*-baryons are still in the early stages but with increased data from the LHC this area is becoming more of interest
- *CP* violation is expected in the baryon sector and first evidence in $\Lambda^0_b \to p\pi^-\pi^+\pi^-$ decays has been seen by LHCb
- First search for oscillation of heavy baryon has been performed
- Many interesting results are foreseen with the LHCb Run-II data
  - Precise measurement two body decays, *e.g.* $\Lambda^0_b \to pK^-$, $p\pi^-$
  - Local phase-space A_{CP} measurements can further reveal the presence of CPV in multi-body decays
  - Semi-leptonic decays of Ξ^0_b are also a possibility [larger signal]

The LHCb experiment



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

The LHCb experiment



$3\,\text{fb}^{-1}$ in 2011 and 2012 (Run 1, $\sqrt{s} = 7, 8\,\text{TeV}$)
$2\,\text{fb}^{-1}$ in 2015 and 2016 (Run 2, $\sqrt{s} = 13\,\text{TeV}$, higher b cross section)

Search for $\Lambda^0_b(\Xi^0_b) \to \Lambda h^{\pm} h'^{\mp}$ decays

JHEP 05 (2016) 08

Studies of *b*-baryon decays is still at an early stage, although LHCb interesting has been significantly increasing

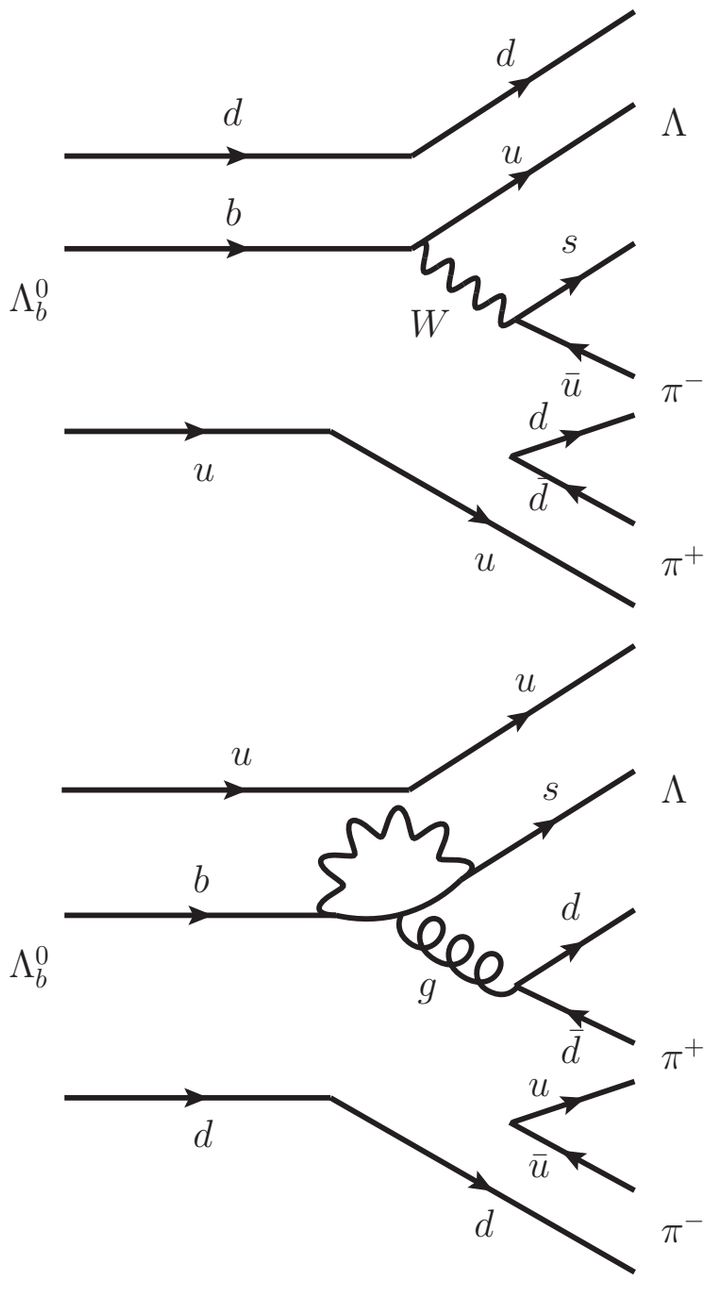
- Among possible ground states with $J^P = 1/2^+$, only a single mode ($\Lambda^0_b \to K^0 p\pi^-$) had been observed
- No *b*-baryon mixing lead to a clean measurement of *CP* violation in the decay (self-tagging)
- CP violation is yet to be observed in *b*-baryon

$[e.g.\ \mathcal{A}_{CP}(\Lambda_b^0 \to K^0 p\pi^-) = -0.22 \pm 0.13 \pm 0.03]$

[JHEP **04** (2014) 087]

Predictions vary in the range of 10^{-7} to 10^{-9} and are in general limited by the uncertainties

[PRD **69** 017901 (2004), PRD **58** 096013 (1998)]



Fit results for $\Lambda^0_b(\Xi^0_b) \to \Lambda h^+h^-$ decays

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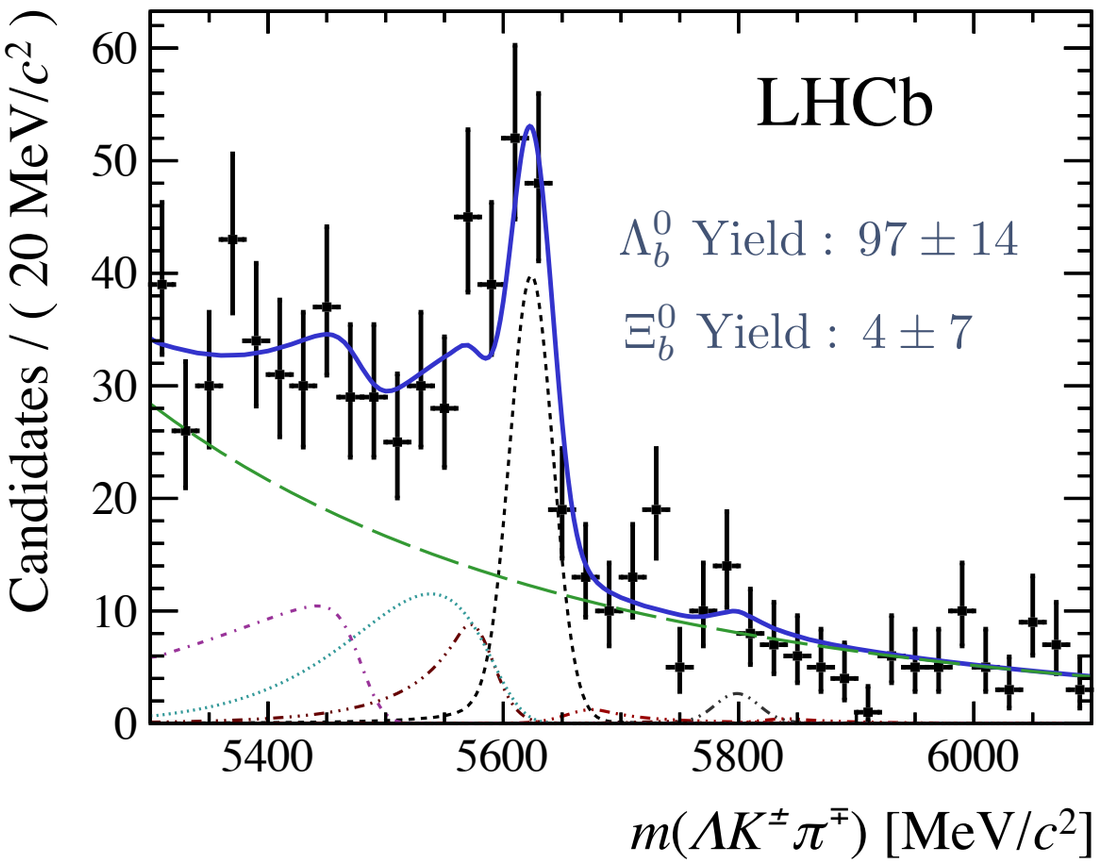
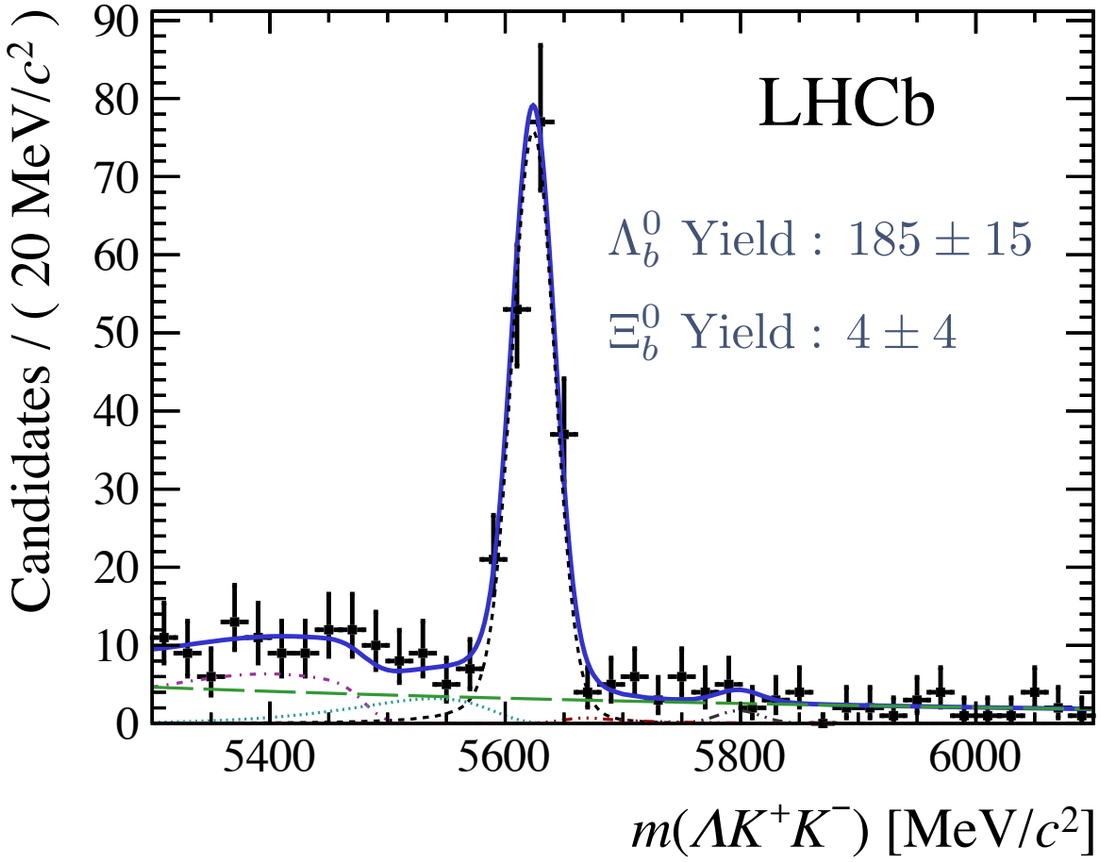
First observation of the decays $\Lambda^0_b \to \Lambda K^+\pi^-$ (8.1σ) and $\Lambda^0_b \to \Lambda K^+K^-$ (15.8σ) with 3 fb^{-1}





Decays involving an un-reconstructed π^0 or photon are shown with the magenta and cyan lines, respectively

Fit results for $\Lambda^0_b(\Xi^0_b) \to \Lambda h^+h^-$ decays

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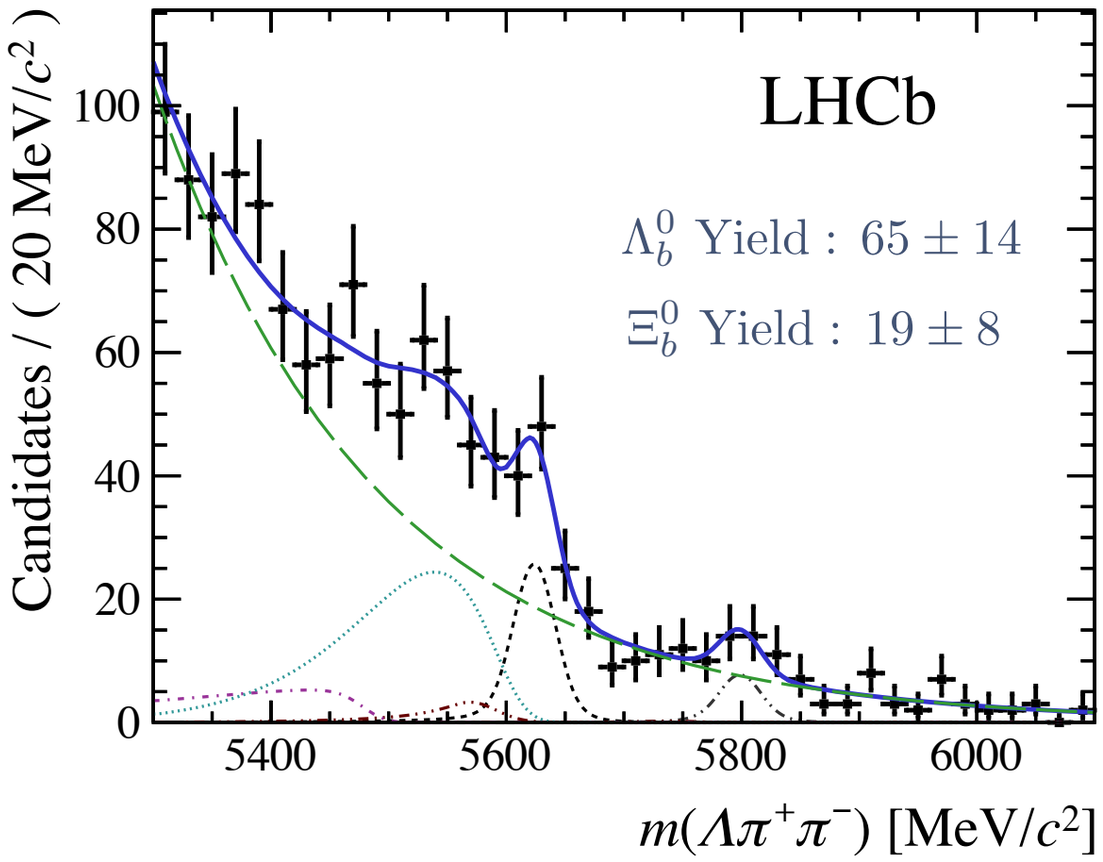
JHEP 05 (2016) 08

BF measured using as normalisation mode $\Lambda^0_b \to \Lambda^+_c\pi^-$ (471± 22)

Evidence for $\Lambda^0_b \to \Lambda\pi^+\pi^-$ (4.7σ)



First observations:

$$\mathcal{B}(\Lambda_b^0 \to \Lambda K^+K^-) = (15.9 \pm 1.2 \pm 1.2 \pm 2.0) \times 10^{-6}$$

$$\mathcal{B}(\Lambda_b^0 \to \Lambda K^+\pi^-) = (5.6 \pm 0.8 \pm 0.8 \pm 0.7) \times 10^{-6}$$

Evidence:

$$\mathcal{B}(\Lambda_b^0 \to \Lambda\pi^+\pi^-) = (4.6 \pm 1.2 \pm 1.4 \pm 0.6) \times 10^{-6}$$

Limits (No hints for any Ξ^0_b mode):

$$f_{\Xi_b^0}/f_{\Lambda_b^0} \times \mathcal{B}(\Xi_b^0 \to \Lambda\pi^+\pi^-) < 1.7\,(2.1) \times 10^{-6} \text{ at } 90\ (95)\,\%\ \text{CL}$$

$$f_{\Xi_b^0}/f_{\Lambda_b^0} \times \mathcal{B}(\Xi_b^0 \to \Lambda K^+\pi^-) < 0.8\,(1.0) \times 10^{-6} \text{ at } 90\ (95)\,\%\ \text{CL}$$

$$f_{\Xi_b^0}/f_{\Lambda_b^0} \times \mathcal{B}(\Xi_b^0 \to \Lambda K^+K^-) < 0.3\,(0.4) \times 10^{-6} \text{ at } 90\ (95)\,\%\ \text{CL}$$

Systematic are either dominated by the fit model/efficiency/$\Lambda^+_c\pi^-$ yield (observed modes) or by the phase-space limited knowledge

CP asymmetry measurements

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JHEP 05 (2016) 08

Significant signal observed allow measurements of phase-space integrated *CP* asymmetry

- Corrected raw asymmetry: $\mathcal{A}_{CP} = \mathcal{A}_{CP}^{\text{raw}} - (\mathcal{A}_P + \mathcal{A}_D)$
- $\Lambda^0_b \to \Lambda^+_c \pi^-$ control mode: negligible CP asymmetry

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

- Phase-space signal-corrected distribution of events

CP asymmetry is measured to be:

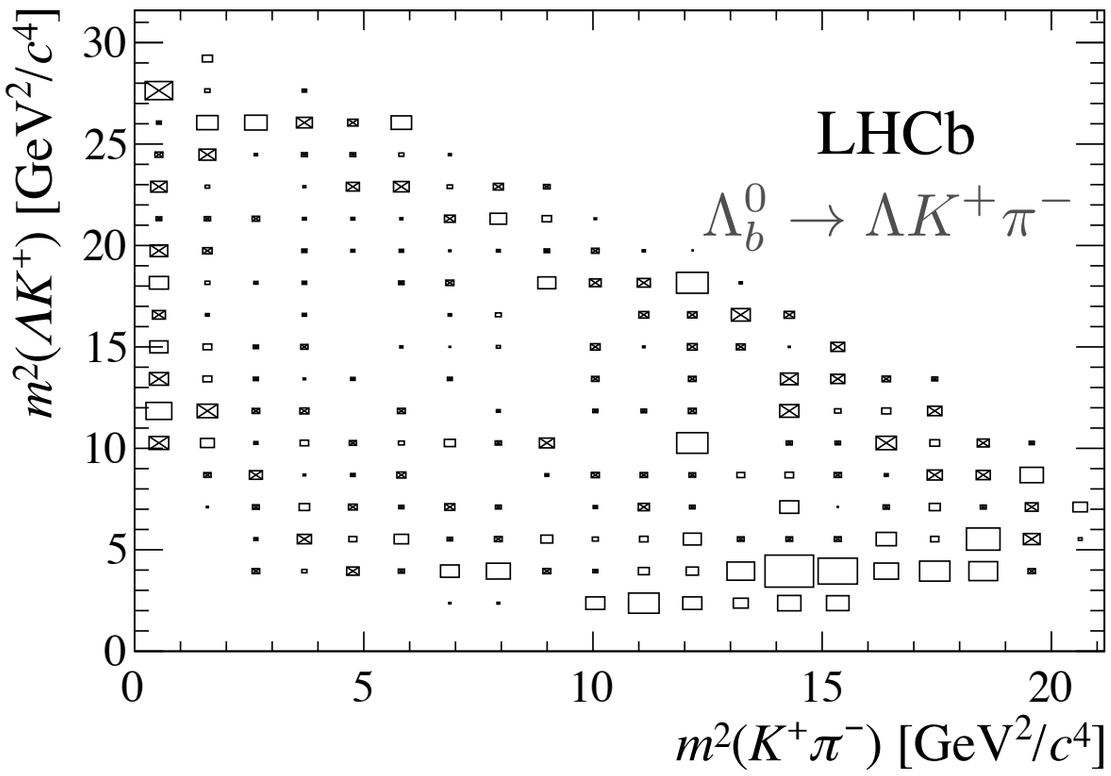
$$\mathcal{A}_{CP}(\Lambda_b^0 \to \Lambda K^+ \pi^-) = -0.53 \pm 0.23\,(\text{stat}) \pm 0.11\,(\text{syst})$$

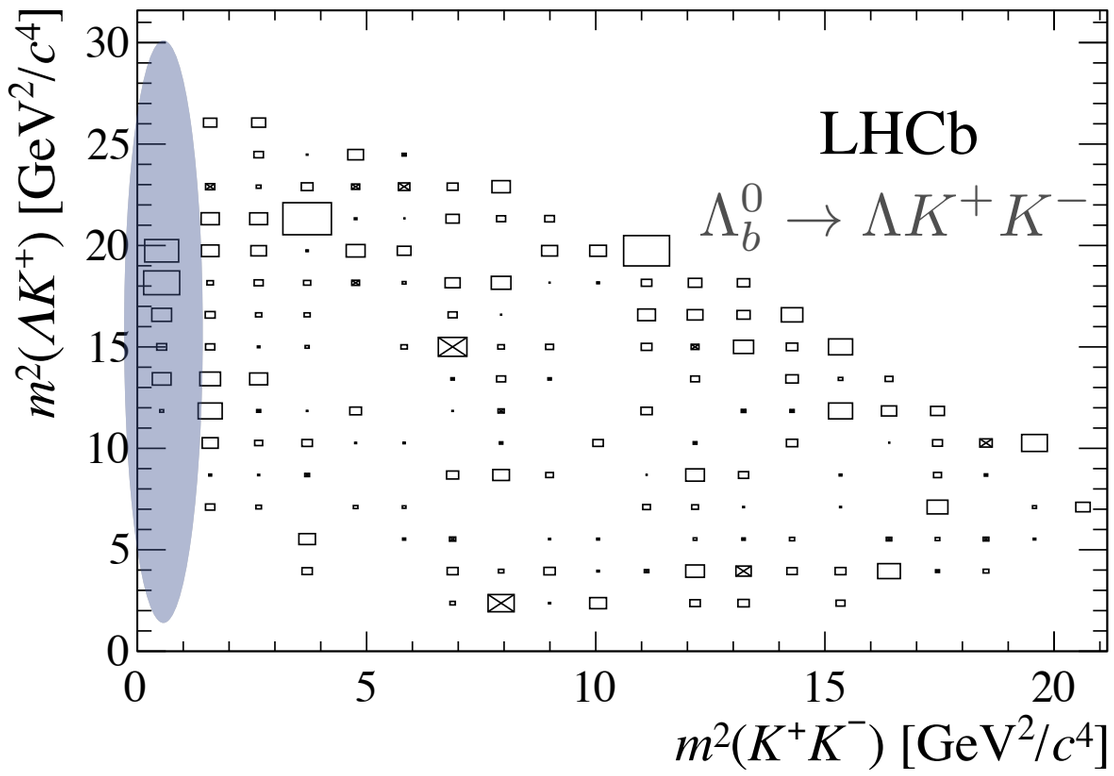
$$\mathcal{A}_{CP}(\Lambda_b^0 \to \Lambda K^+ K^-) = -0.28 \pm 0.10\,(\text{stat}) \pm 0.07\,(\text{syst})$$

Results are consistent with CP symmetry and an update with Run 2 data is appealing!

Dalitz-plot distributions

JHEP 05 (2016) 08





Interesting structures over the phase space, in particular the excess at low m(K^+K^-) consistent with a φ resonance (dedicated analysis at LHCb):

$$\mathcal{B}(\Lambda_b^0 \to \Lambda\phi) = 5.18 \pm 1.04\,(\text{stat}) \pm 0.35\,(\text{syst})^{+0.50}_{-0.43}\,(\text{norm}) \pm 0.44(f_d/f_{\Lambda_b^0}) \times 10^{-6}$$

First observation (5.9σ) of the baryonic version of $B^0_s \to \varphi\varphi$ [arXiv:1603.02870]