CP violation in heavy baryons: experimental results and prospects

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on behalf of the LHCb collaboration

INFN - Sezione di Milano

Implications of LHCb measurements and future prospect
CERN, 12-14 October 2016

Outline

- CP violation in heavy baryon decays
- Experimental issues
- Experimental results
- Summary

CP violation in heavy baryon decays

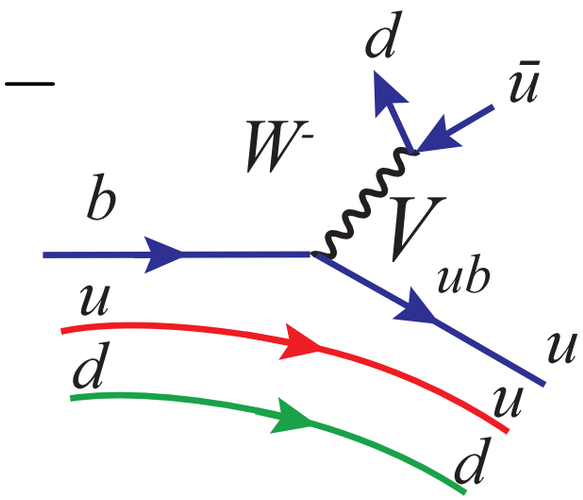
Physics motivations

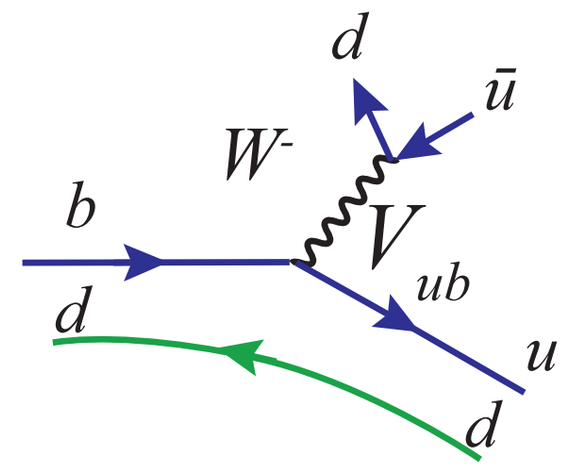
- At LHCb *b*-baryons are collected in unprecedented quantities → opens a new field in flavour physics for precision measurements
- CP violation (CPV) in *b*-baryons:
  - CKM mechanism predicts sizeable amount of CPV in *b*-baryons that can be precisely measured
  - complementary means to test Standard Model (SM) with respect to *B* mesons
  - opportunities to search for new sources of CPV
- CPV in *c*-baryons:
  - null test for SM

CPV in *b*-hadrons

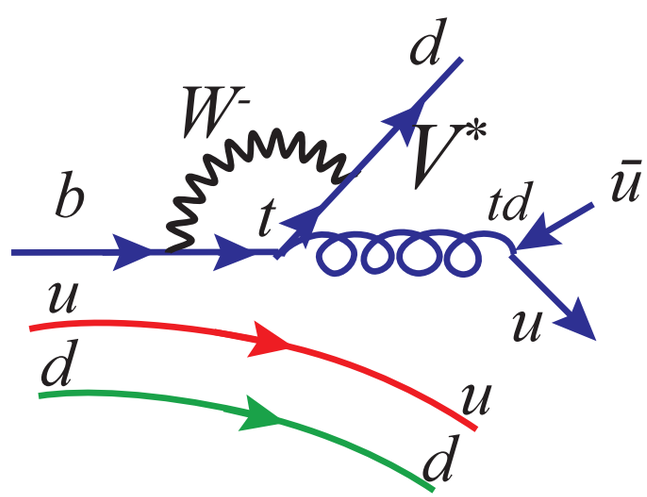
- Same underlying short distance physics for *b*-baryons and *B* mesons but with different spin and QCD structure

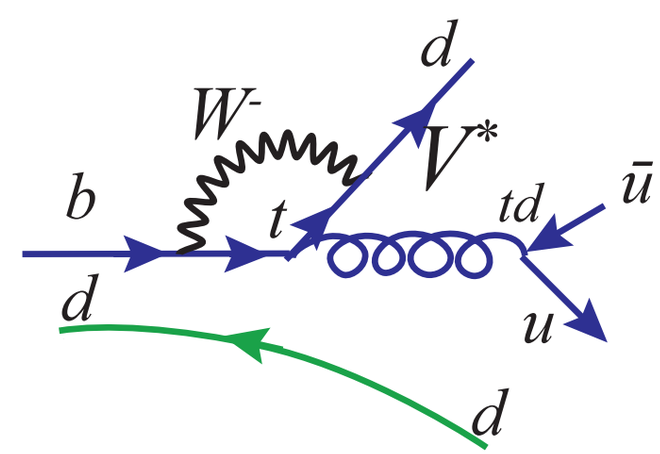
$\Lambda_b^0 \to p\pi^-$





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



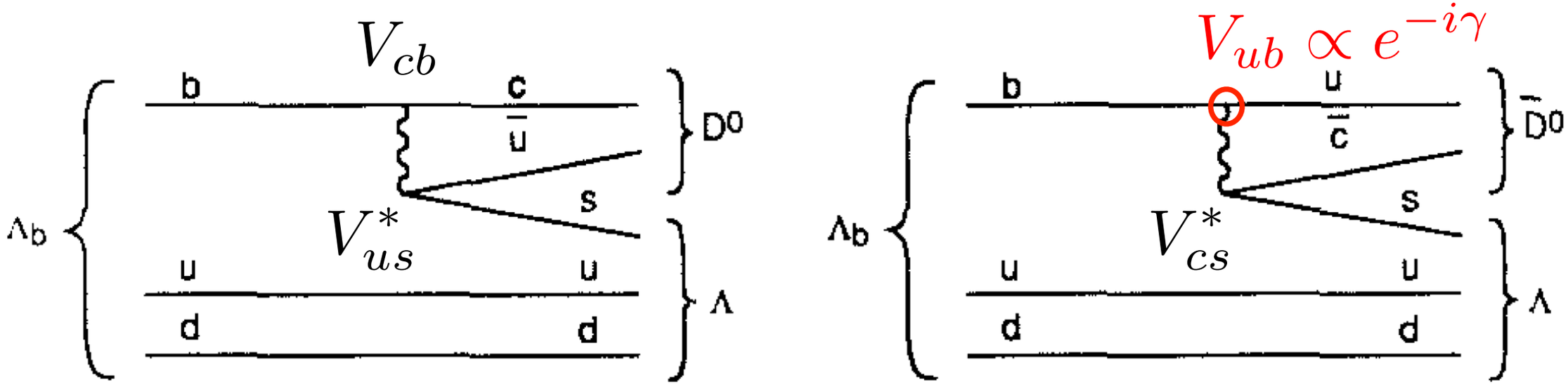


- Systematic study of CPV in *b*-baryons and in *B* mesons for a stringent test of CKM mechanism

CKM angle γ using Λ_b decays

I. Dunietz, Z. Phys. C - Particles and Fields (1992) 56: 129
A. K. Giri, R. Mohanta, and M. P. Khanna, Phys. Rev. D 65, 073029 (2002)

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



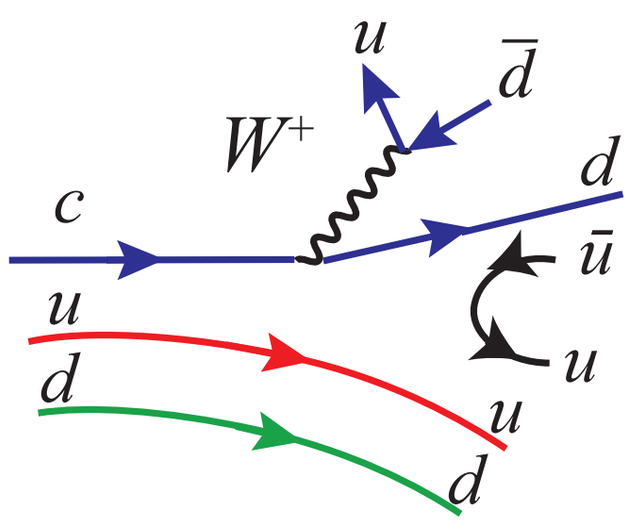
- Theory clean measurement of γ using baryons
- Small yields $BR = (\Lambda_b^0 \to \Lambda D^0) \sim 4 \cdot 10^{-6}$, $BR = (\Lambda_b^0 \to \Lambda \bar{D}^0) \sim 8 \cdot 10^{-7}$
- Use $\Lambda_b^0 \to D^0 p K^-$ for improved reco efficiency

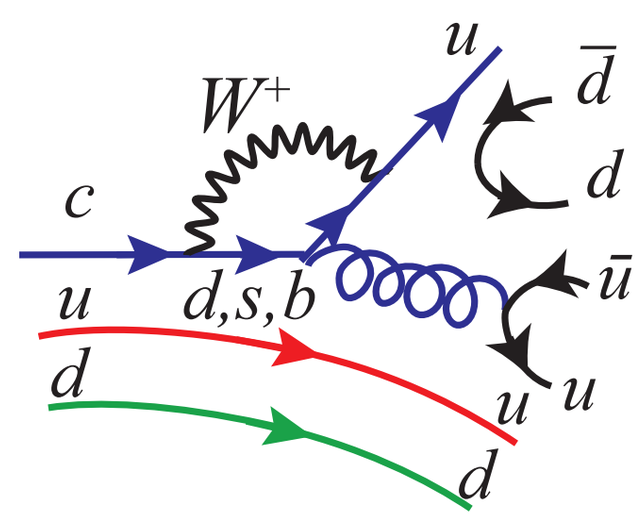
Search for CPV in charm baryons

I. I. Bigi, arXiv:1206.4554 X.W. Kang, et al. Int.J.Mod.Phys.A26:2523-2535,2011

- Null test for SM, sensitive to new physics effects
- CPV predictions for singly-Cabibbo suppressed (SCS) modes $\mathcal{O}(10^{-4})$ or less for doubly CS decays

$$\Lambda_c^+ \to p\pi^-\pi^+$$





- Large samples allow probe for localised CPV in differential distributions for enhanced sensitivity. Signal events for SCS modes ~10^5 in RunI ($3fb^{-1}$)

Experimental issues

Particle-antiparticle production asymmetry

- Initial *pp* state not *CP* symmetric → particle/antiparticle production asymmetries $A_P \sim 1\%$
- Initial asymmetry could mimic CPV and needs to be disentangled or measured

Phys. Lett. B739 (2014) 218

$$A_{\rm P}(B^0) = (-0.35 \pm 0.76 \pm 0.28)\%,$$

$$A_{\rm P}(B_s^0) = (\ \ 1.09 \pm 2.61 \pm 0.66)\%,$$

PLB 713 186 (2012), PLB 718 902 (2013)

$$A_{prod}(D_s^+) = (-0.33 \pm 0.13 \pm 0.18 \pm 0.10)\%$$

$$A_{prod}(D^+) = (-0.96 \pm 0.19 \pm 0.18 \pm 0.18)\%$$

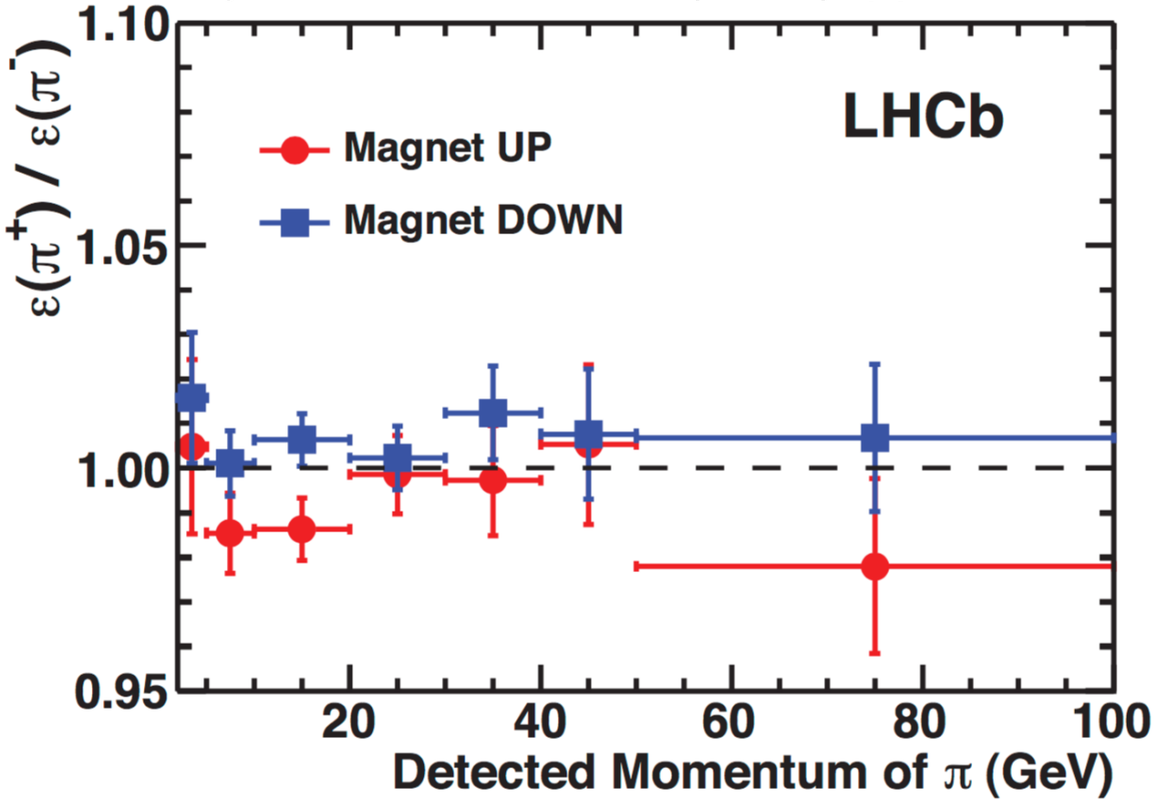
- Next step, measure $A_P(B^+)$ and obtain $A_P(\Lambda_b^0)$ by means of a unitary relation
- Similarly in charm for D^0 and Λ_c^+. A_P more relevant when probing small CPV asymmetries in charm

Detector reconstruction asymmetries

- Detector is made of matter, not CP symmetric
  → particle/antiparticle detection asymmetries
  $A_D(\pi^\pm) \sim 0.1\%$ $A_D(K^\pm) \sim 1\%$ $A_D(p/\bar{p}) \sim 1-2\%$

- A_D can be measured using "ad hoc" abundant control samples, see Phys. Rev. Lett. 110 (2013) 221601

Physics Letters B 713 (2012), pp. 186-195



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

Experimental approaches

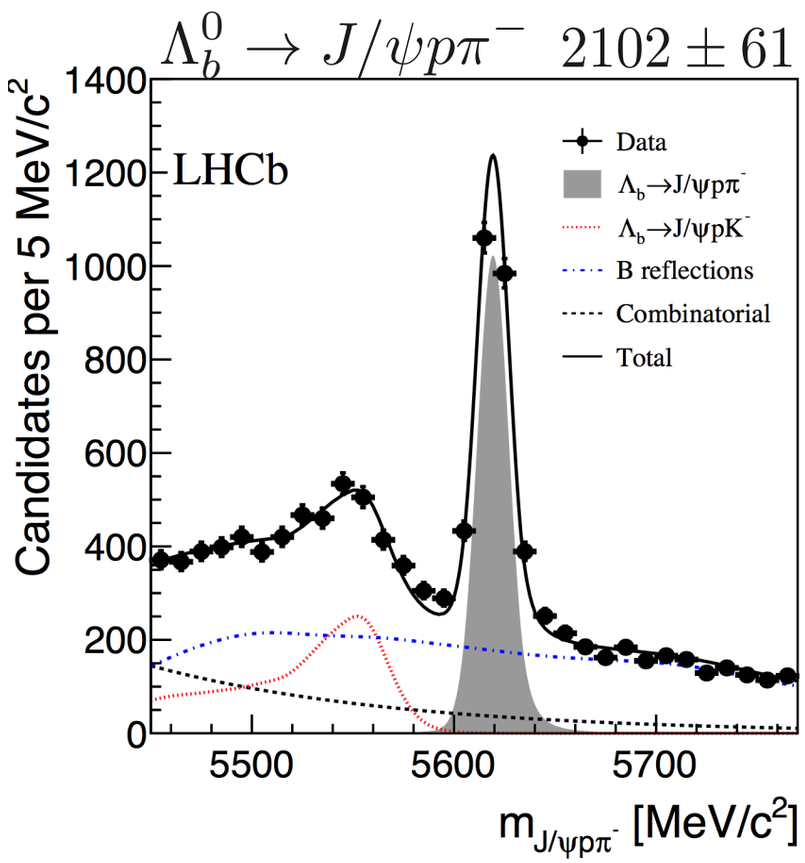
- Measure ΔA_{CP} difference of CP asymmetries:

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

$$\begin{aligned}\Delta A_{CP} =& \mathcal{A}_{\rm raw}(\Lambda_b^0 \to J/\psi p \pi^-) - \mathcal{A}_{\rm raw}(\Lambda_b^0 \to J/\psi p K^-) \\ =& \mathcal{A}_{CP}(\Lambda_b^0 \to J/\psi p \pi^-) - \mathcal{A}_{CP}(\Lambda_b^0 \to J/\psi p K^-) + \mathcal{A}_{\rm reco}(\pi^+) - \mathcal{A}_{\rm reco}(K^+)\end{aligned}$$

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

Measured on data

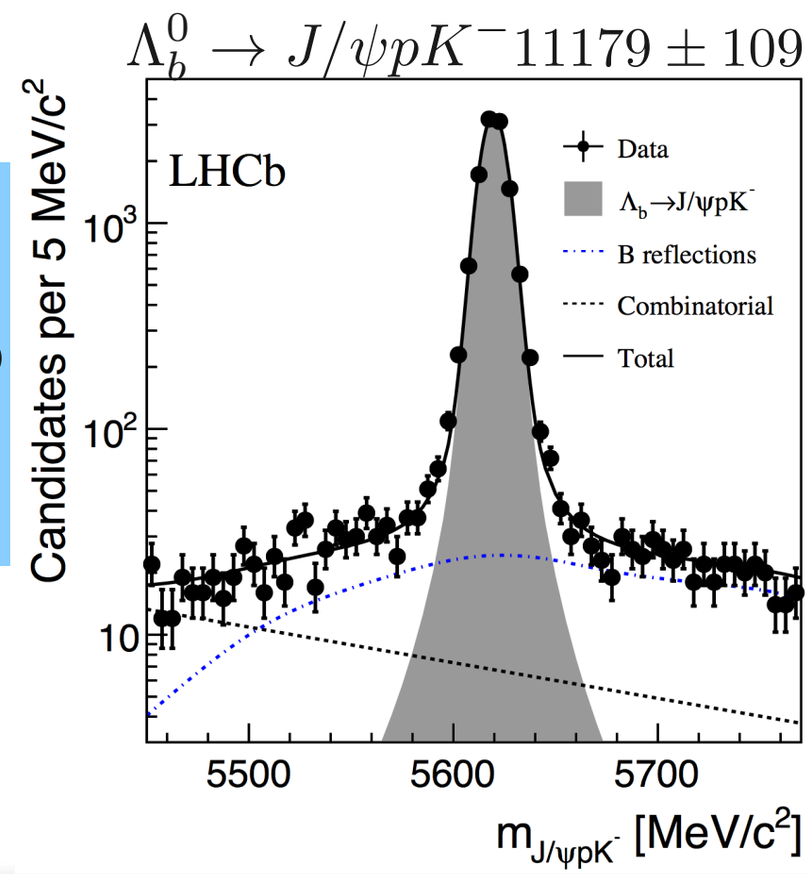


JHEP07(2014)103

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

2.2σ from zero

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



Experimental approaches

- Measure CPV via ($\hat{T}$-) P-violating asymmetries:

$$C_{\hat{T}} = \vec{p}_p \cdot (\vec{p}_{h_1^-} \times \vec{p}_{h_2^+}) \qquad \overline{C}_{\hat{T}} = \vec{p}_{\overline{p}} \cdot (\vec{p}_{h_1^+} \times \vec{p}_{h_2^-})$$

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

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

Largely insensitive to A_{prod} and A_{reco}

CP-violating observable:

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

$\hat{T}$ = motion reversal operator

- Complementary approach to A_{CP} analysis

δ: strong phase
φ: weak phase

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

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

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

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

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

A_1, A_2 amplitudes

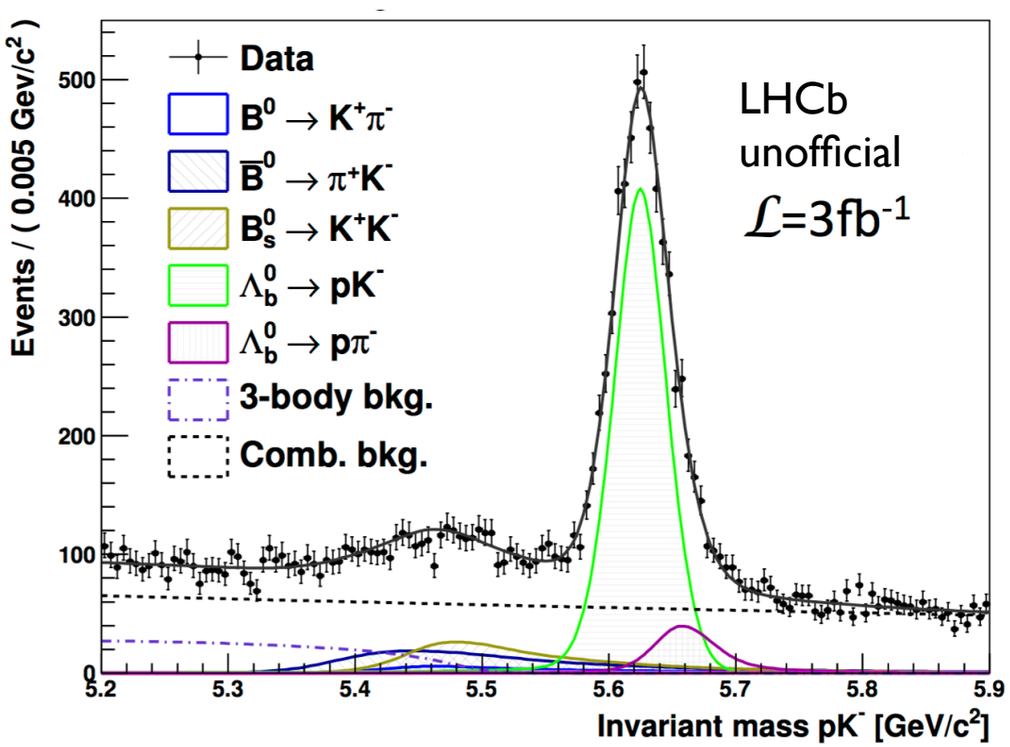
G. Durieux, Y. Grossman, Phys.Rev. D92 (2015) no.7, 076013

More in G. Durieux talk at this workshop

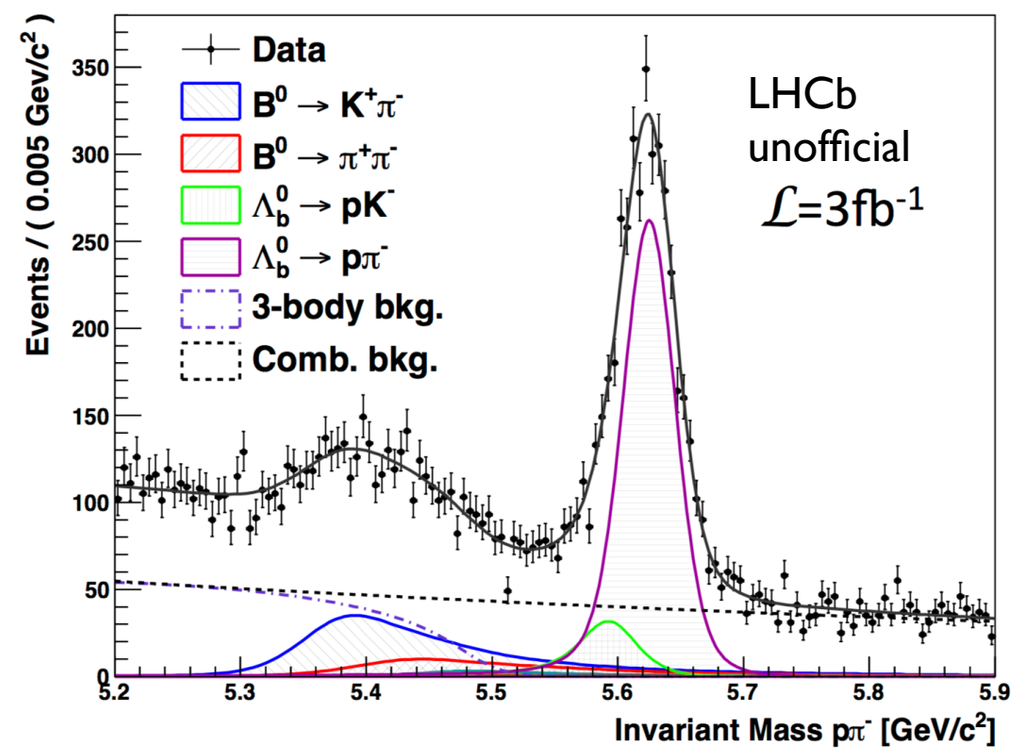
Experimental results

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

$\Lambda_b^0 \to pK^-$ 8,600 signal events



$\Lambda_b^0 \to p\pi^-$ 6,000 signal events



- Present sensitivity to CPV at $1 \cdot 10^{-2}$ level
- No irreducible systematic uncertainties identified so far
- Naive projections to 300 fb^{-1} (assume 200x signal): $1 \cdot 10^{-3}$ precision on CPV asymmetries

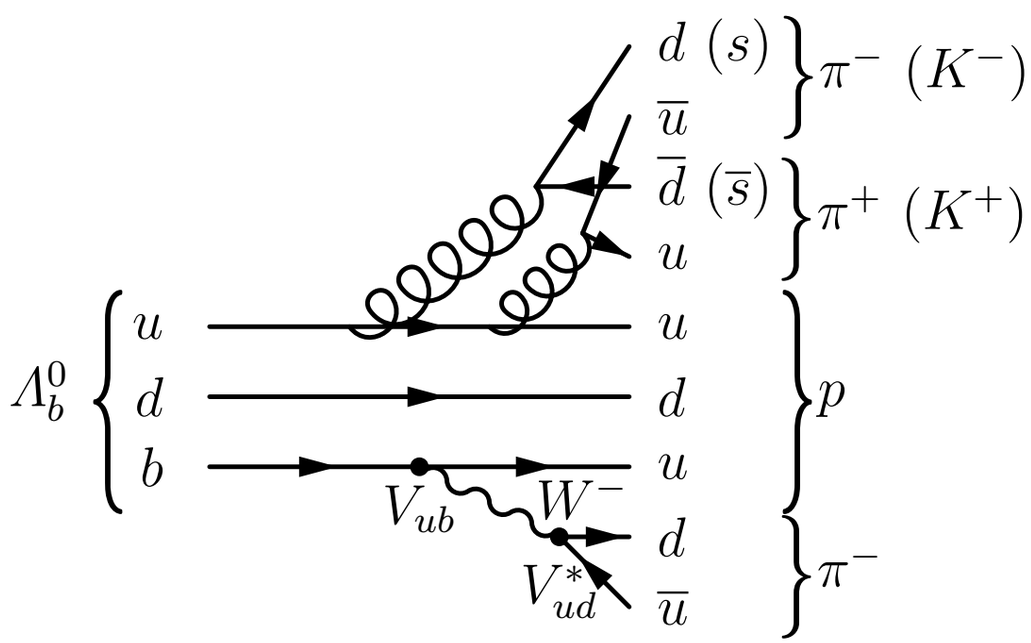
CPV in 4-body charmless decays

arXiv:1609.05216, submitted to Nature Physics

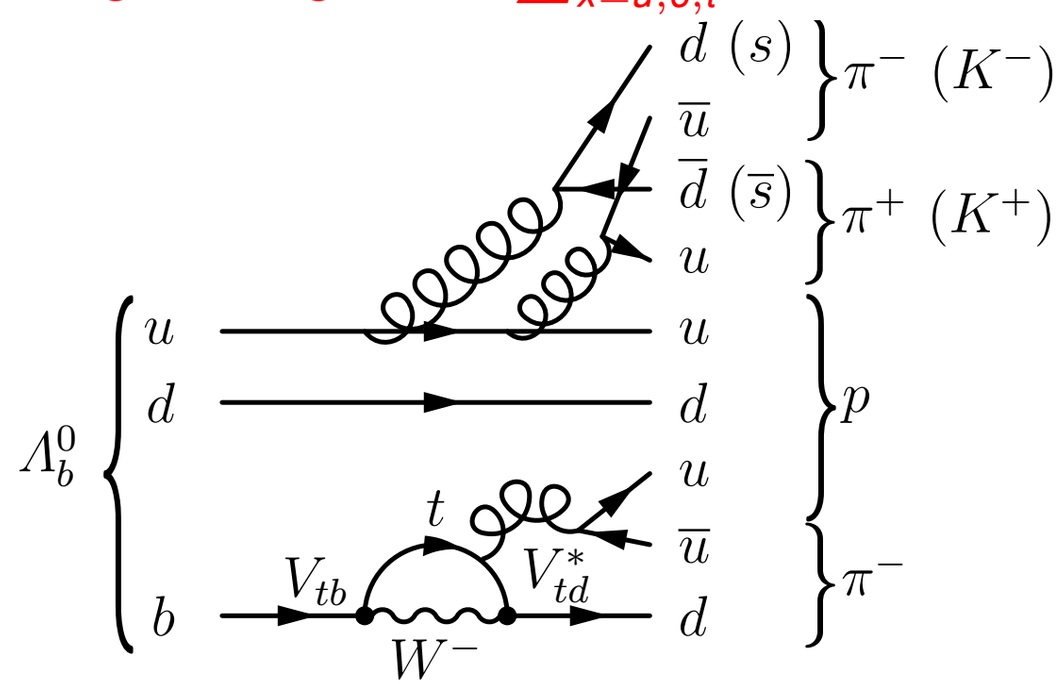
- Transitions governed by $b \to u d \bar{u}$ tree and $b \to d u \bar{u}$ penguin amplitudes of similar magnitude. Large relative weak phase in SM from CKM elements, $\arg(V_{tb}V_{td}^*/V_{ub}V_{ud}^*)=\alpha$

- Potential non negligible CPV effects in the SM

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



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



I.I. Bigi, arXiv:1608.06528

M. Gronau, J. Rosner, Phys.Lett. B749 (2015) 104-107

W. Bensalem et al.,Phys.Lett. B538 (2002) 309-320

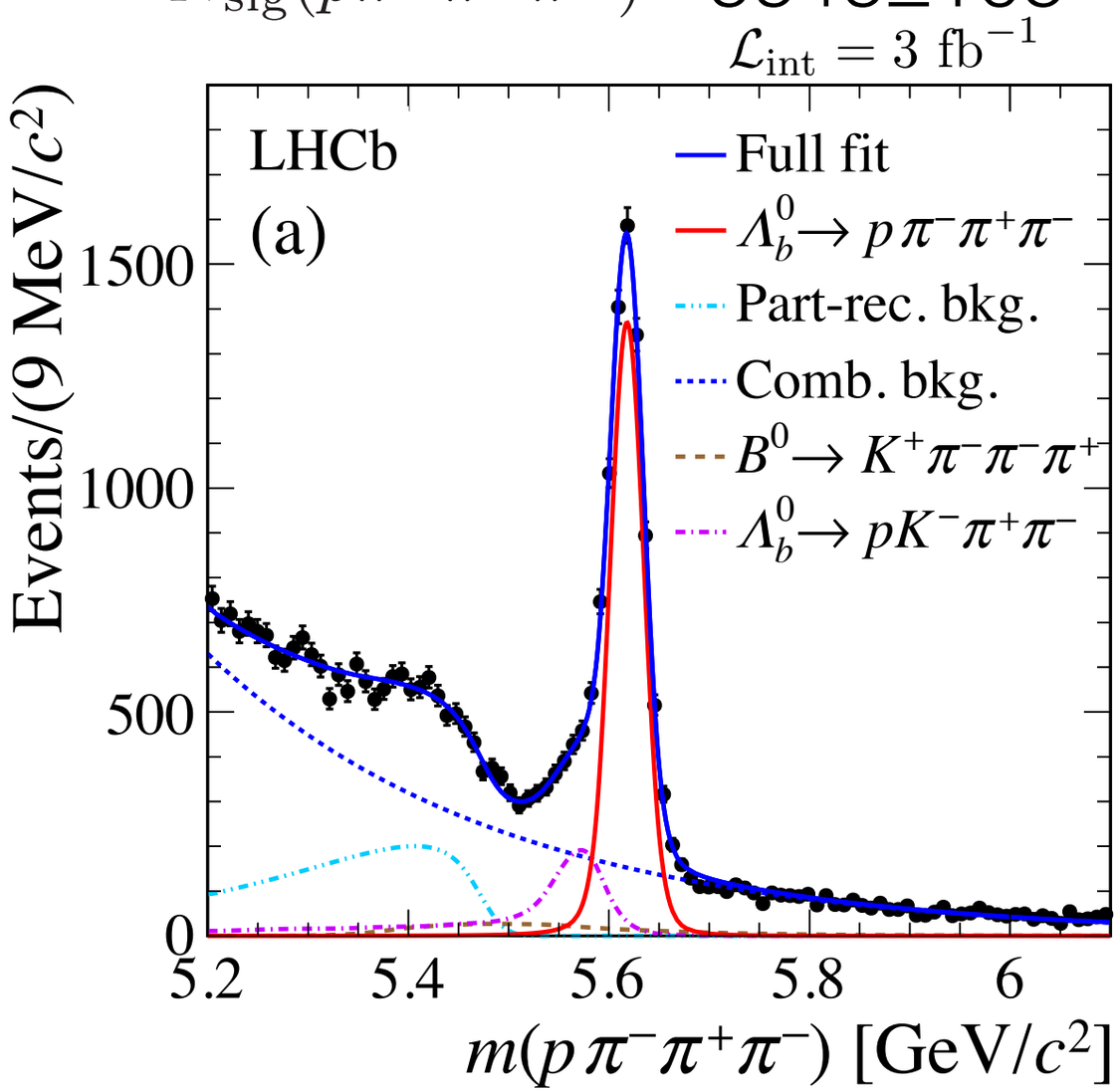
W. Bensalem et al., Phys. Rev. D66 (2002) 094004

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

arXiv:1609.05216, submitted to Nature Physics

- Search for localised CPV effects, enhanced sensitivity
- Use 4-body topology to build P-violating asymmetries

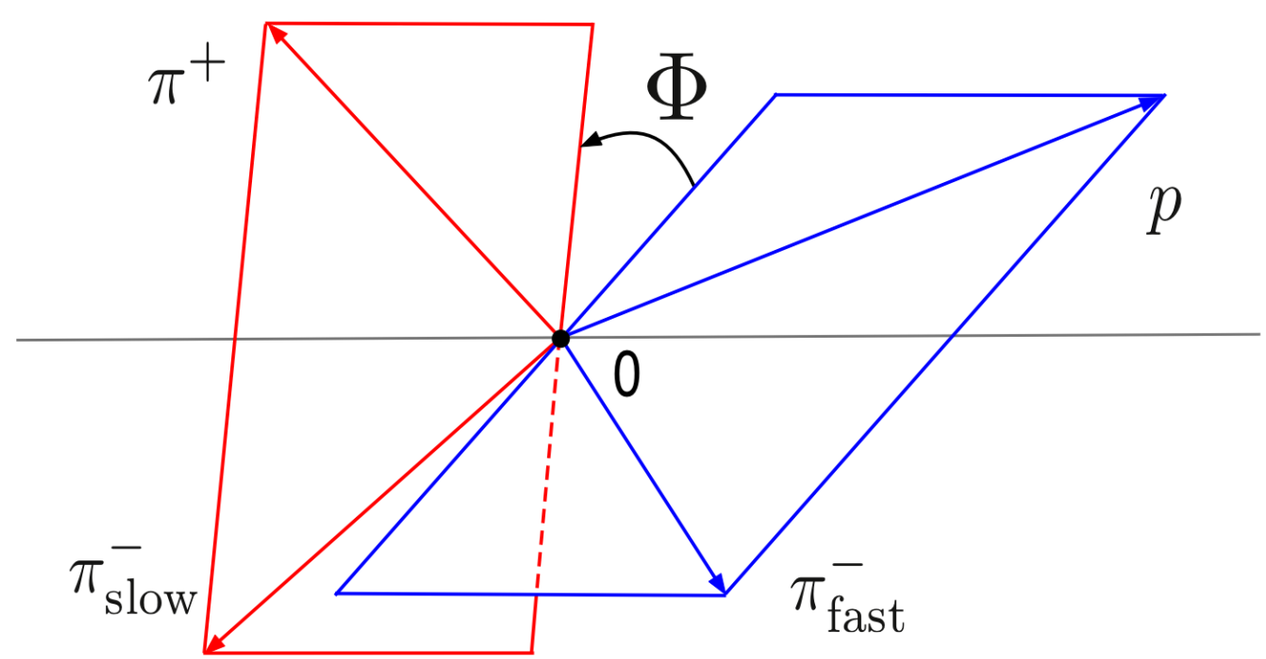
$N_{\rm sig}(p\pi^-\pi^+\pi^-)$ =6646±105



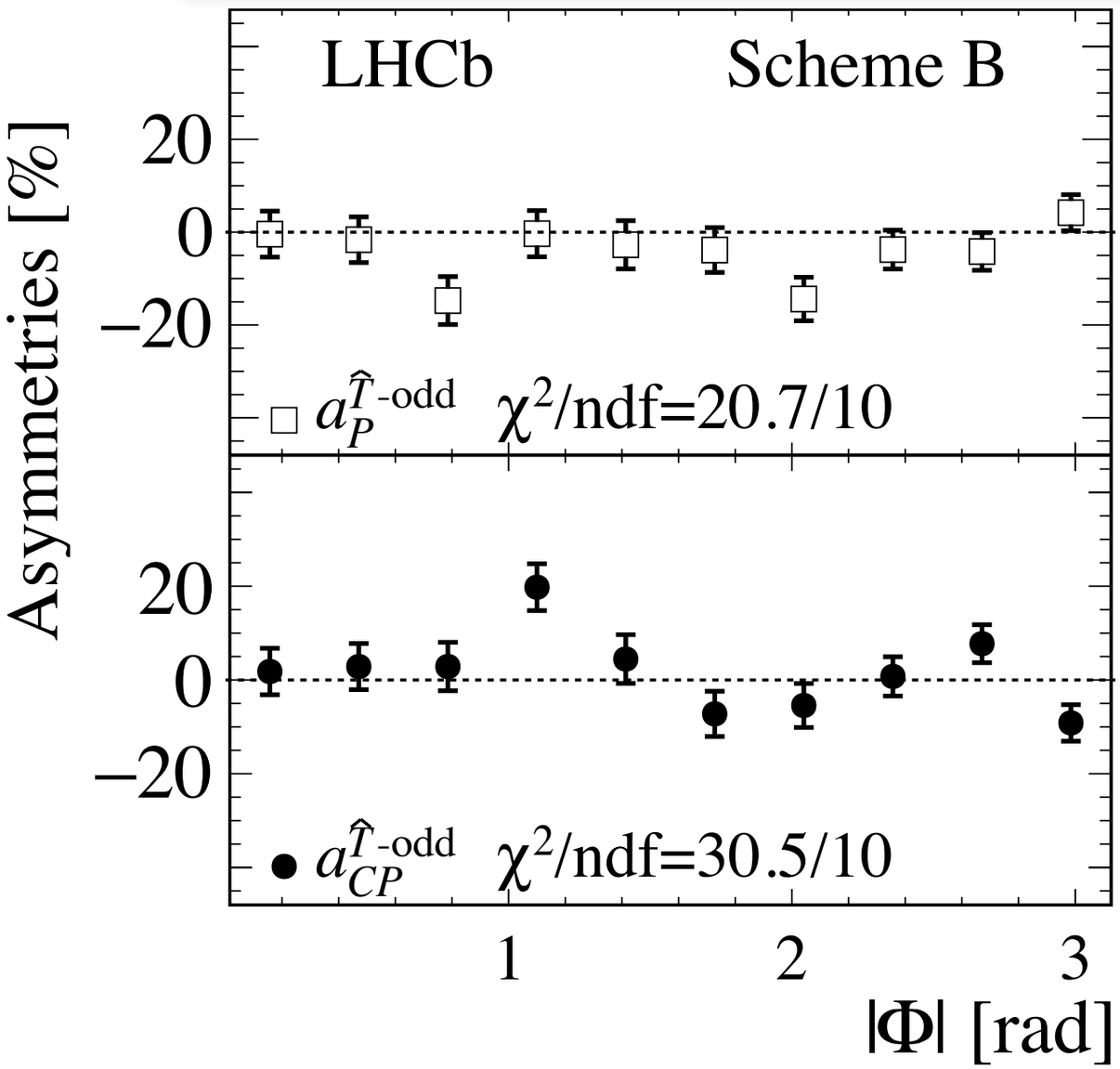
- P-odd, $\hat{T}$-odd triple products:

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

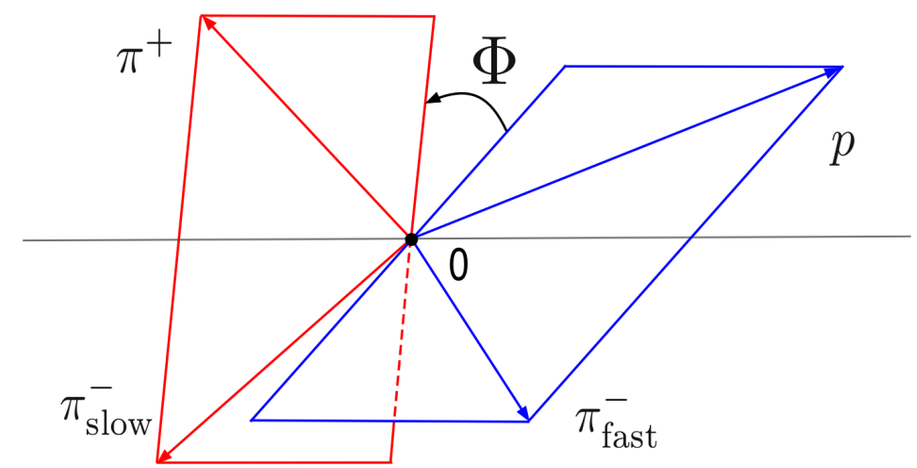
$$\overline{C}_{\hat{T}} = \vec{p}_{\overline{p}} \cdot (\vec{p}_{h_1^+} \times \vec{p}_{h_2^-}) \propto \sin\overline{\Phi} \text{ , for } \overline{\Lambda}_b^0$$



First evidence for CP violation in baryons



arXiv:1609.05216, submitted to Nature Physics



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

Combined results of 2 binning schemes:

CP symmetry *p*-value=9.8x10^{-4}
3.3σ deviation

- Very low systematic uncertainties. Sensitivity expected to scale with statistics i.e. 10^{-3} precision on CPV at 300 fb^{-1}
- CPV predictions, at least for some regions of phase space, very welcome

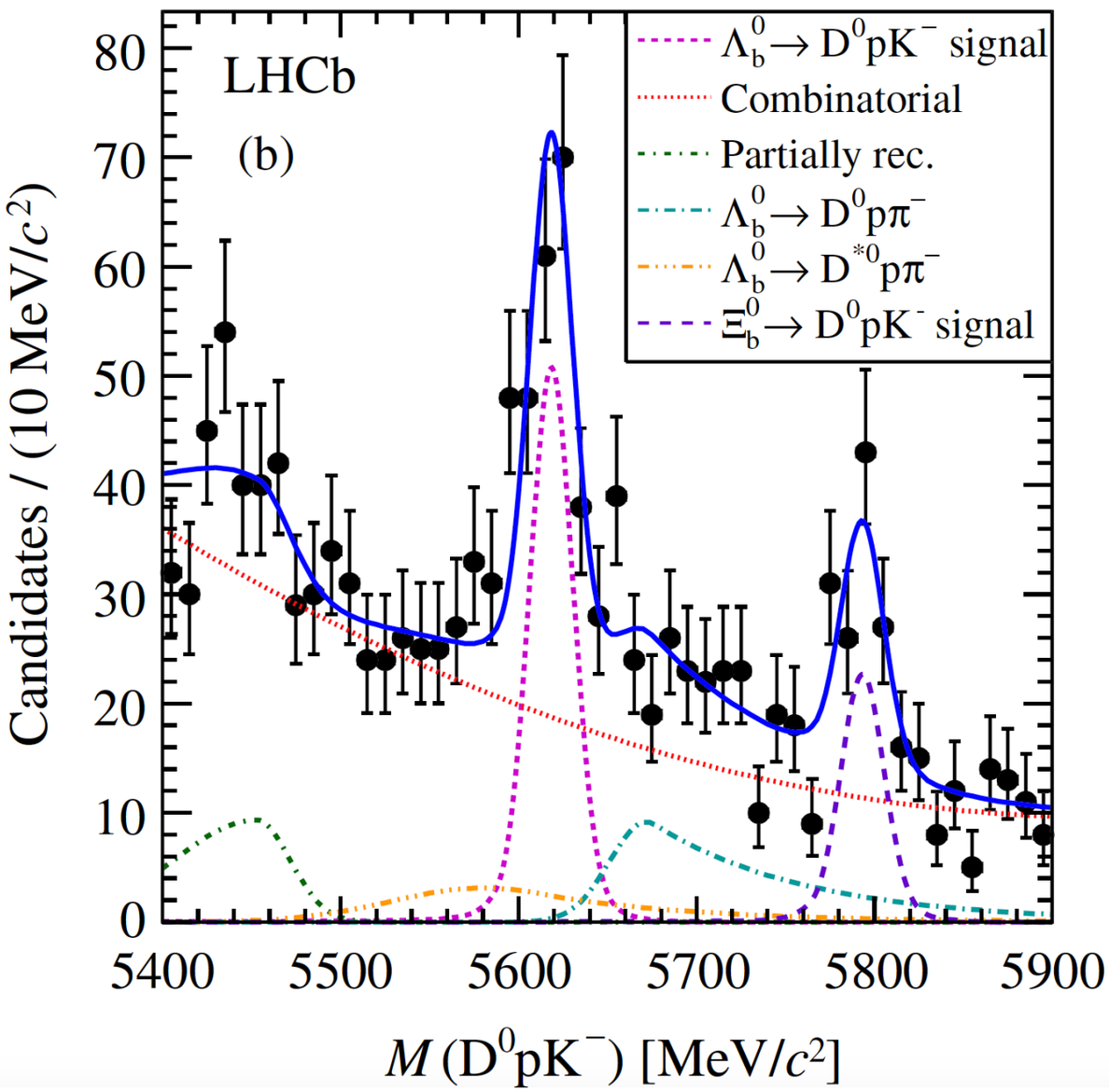
G. Durieux, arXiv:1608.03288

Towards the measurement of γ

Phys. Rev. D **89**, 032001 (2014)

$$\Lambda_b^0 \to D^0 p K^- \quad \text{sig} = 163 \pm 18$$

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

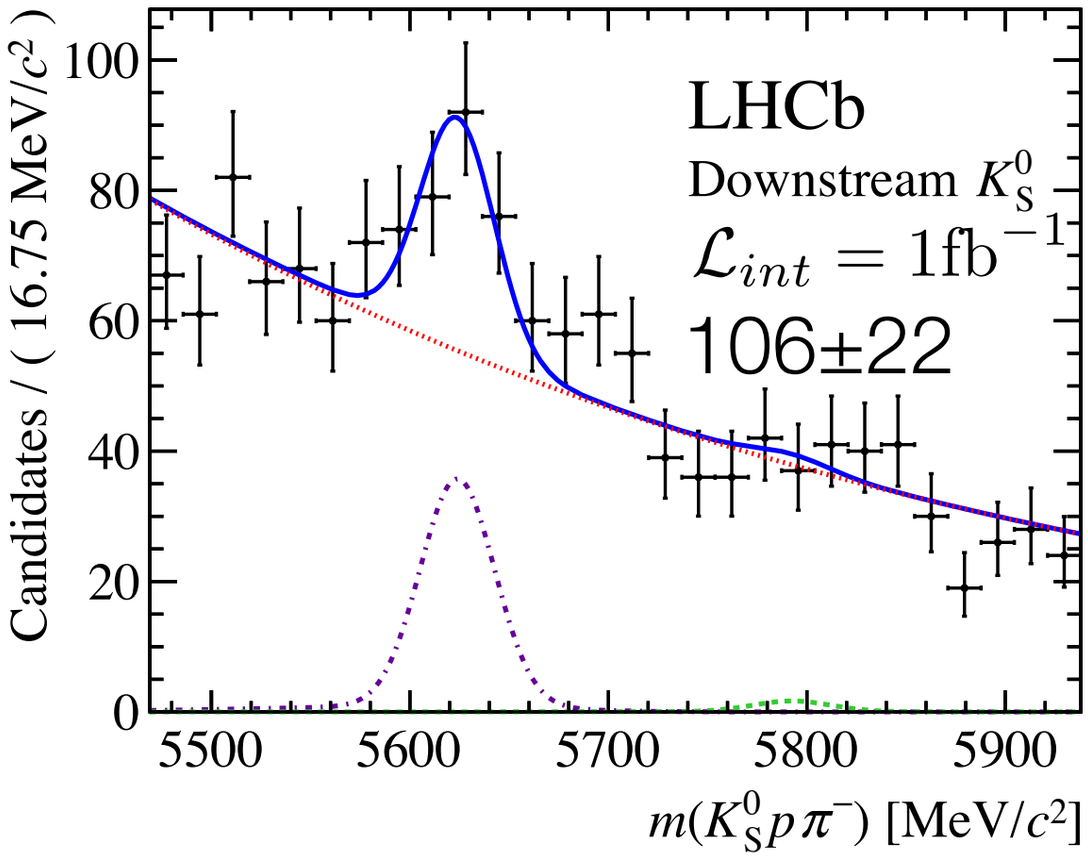


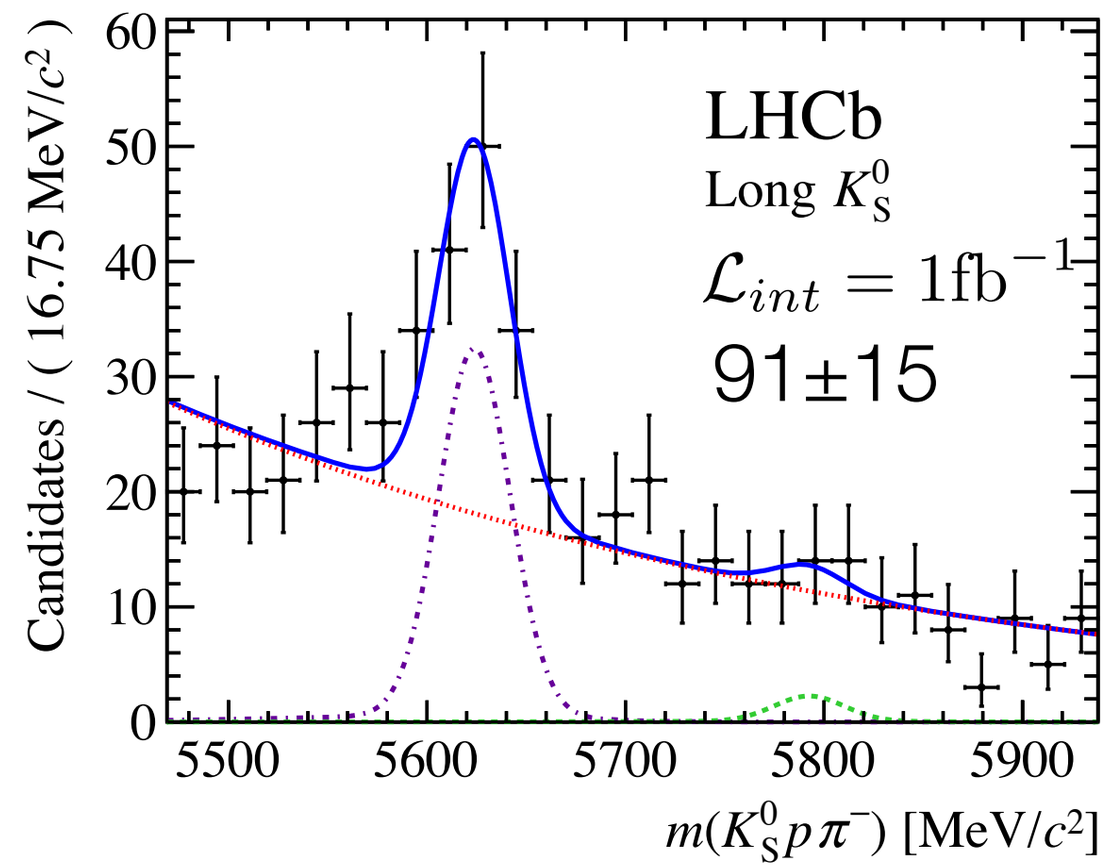
- Interesting decay modes for the future $\text{BR} = (4.8 \pm 0.9) \times 10^{-5}$
- Expect 100k D^0pK^-, 20k $\bar{D}^0pK^-$, 16k $D_{CP}pK^-$ signal events with 300 fb^{-1}
  $D^0 \to K^-\pi^+;\ D^0_{CP} \to \pi^+\pi^-, K^+K^-$
- Hard to estimate the impact on γ determination at present

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

JHEP04(2014)087

- Large $A_{CP}(pK^{*-})$~20% predicted in SM Hsiao Y.K., Phys.Rev. D91 (2015) no.11, 116007





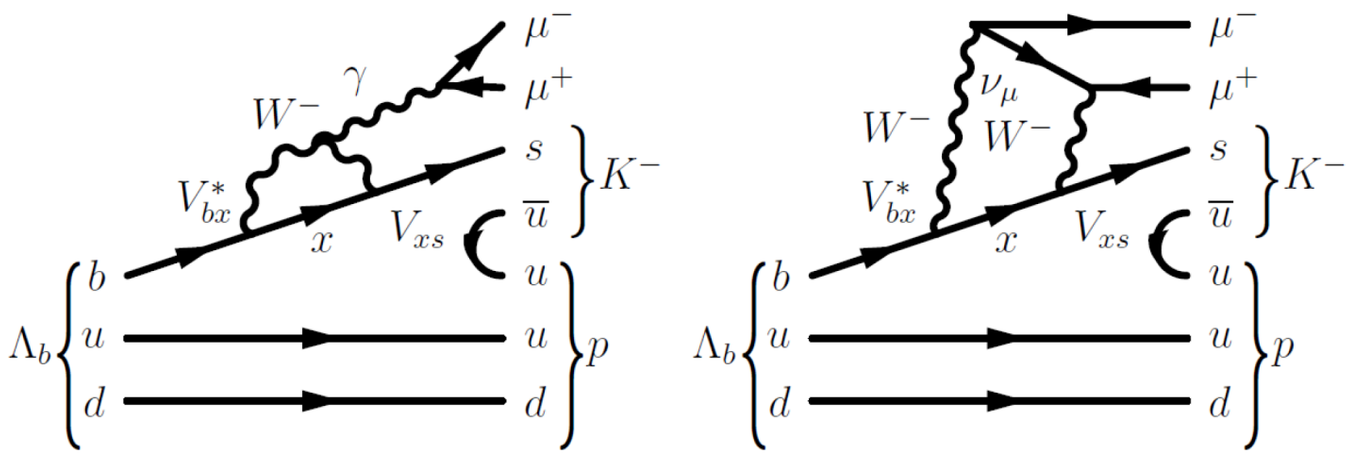
$\mathcal{A}_{CP} = 0.22 \pm 0.13 \pm 0.03$ use $\Lambda_b^0 \to (K_S^0 p)_{\Lambda_c^+} \pi^-$ as control mode

- Precision on CPV at $5 \cdot 10^{-3}$ is achievable with 300 fb^{-1}
- Other interesting results: $\Lambda_b^0 \to \Lambda h^+ h^-$, $\Lambda_b^0 \to \Lambda \phi$ decays

JHEP 05 (2016) 081 Phys. Lett. B759 (2016) 282

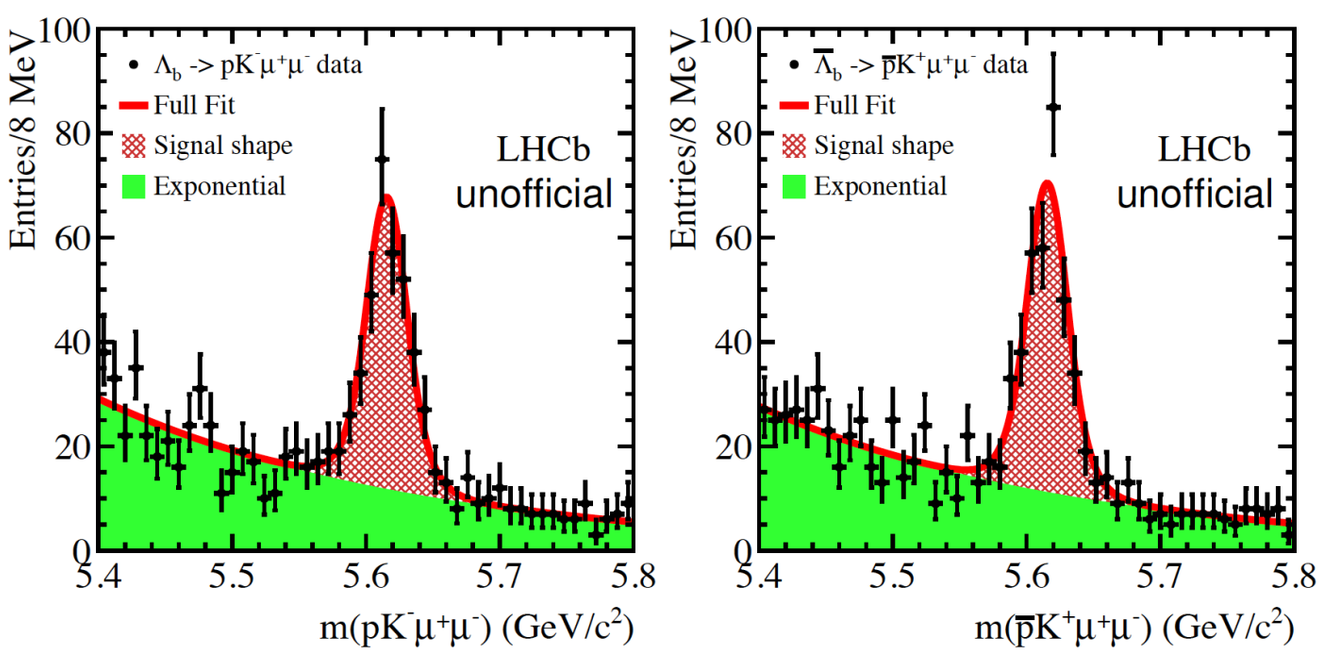
Search CPV in rare $\Lambda_b^0 \to pK^-\mu^+\mu^-$

- Rare FCNC decay with very small CPV in the SM, sensitive to new CPV sources via loop diagrams



LHCb-ANA-2015-055

$\Lambda_b^0 \to pK^-\mu^+\mu^- = 600 \pm 44 \quad \mathcal{L}_{\rm int} = 3\ {\rm fb}^{-1}$



- Measure ΔA_{CP} and $a_{CP}^{\hat{T}\text{-odd}}$
- Use abundant $J/\psi pK^-$ control mode
- Present precision on CPV is $5 \cdot 10^{-2}$
- Precision of $4 \cdot 10^{-3}$ is achievable with 300 fb^{-1}

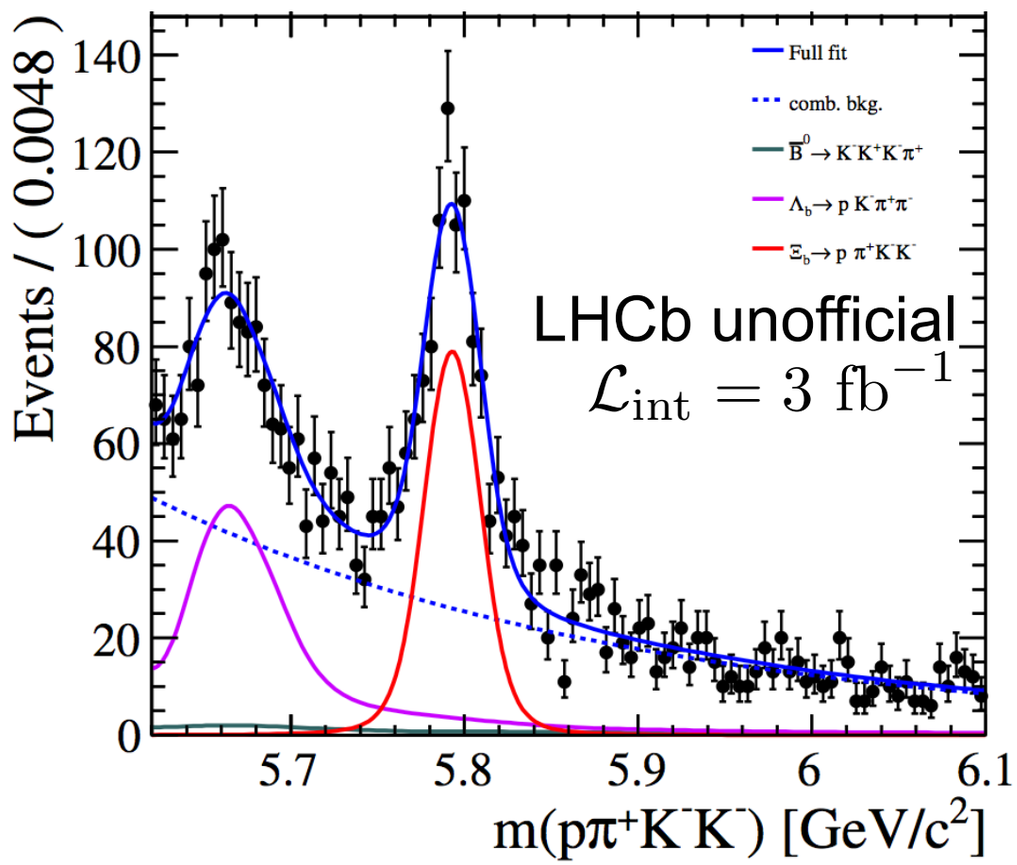
Ξ_b charmless decays

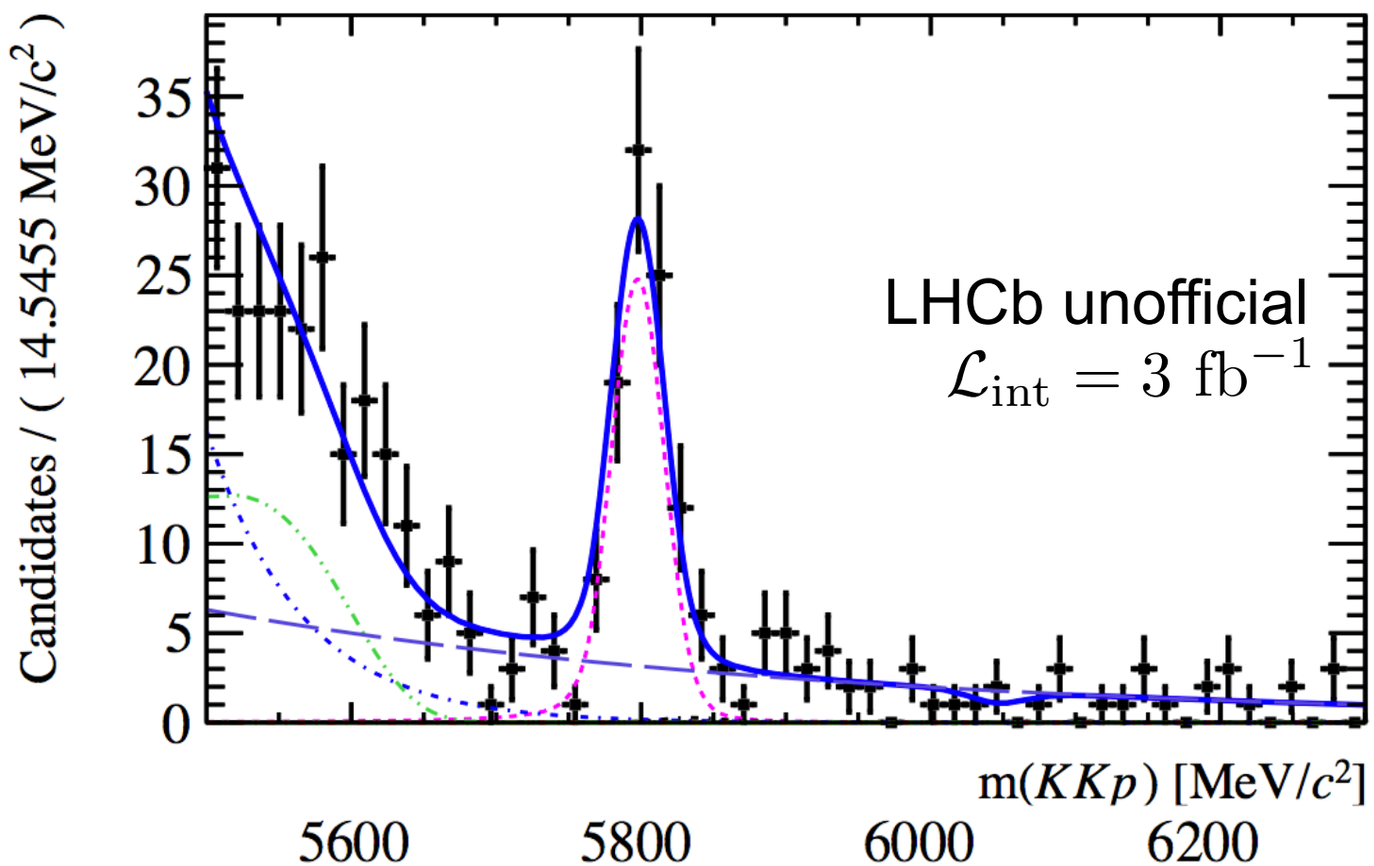
- First observation of several decay modes
- Search for CPV in Ξ_b decays is next step

$$\Xi_b^0 \to p\pi^+K^-K^-$$
$$\mathrm{N_{sig}} = 709 \pm 45$$

$$\Xi_b^- \to pK^-K^-$$
$$\mathrm{N_{sig}} = 83 \pm 10$$

not published yet



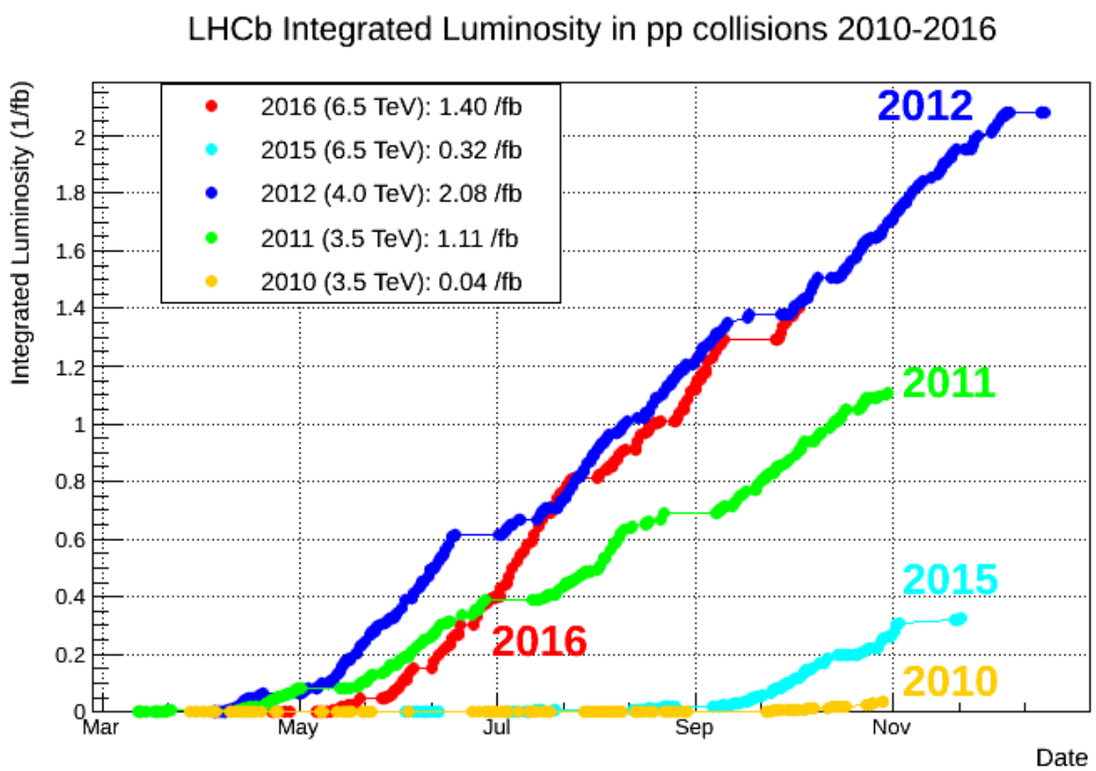


LHCb-ANA-2014-077

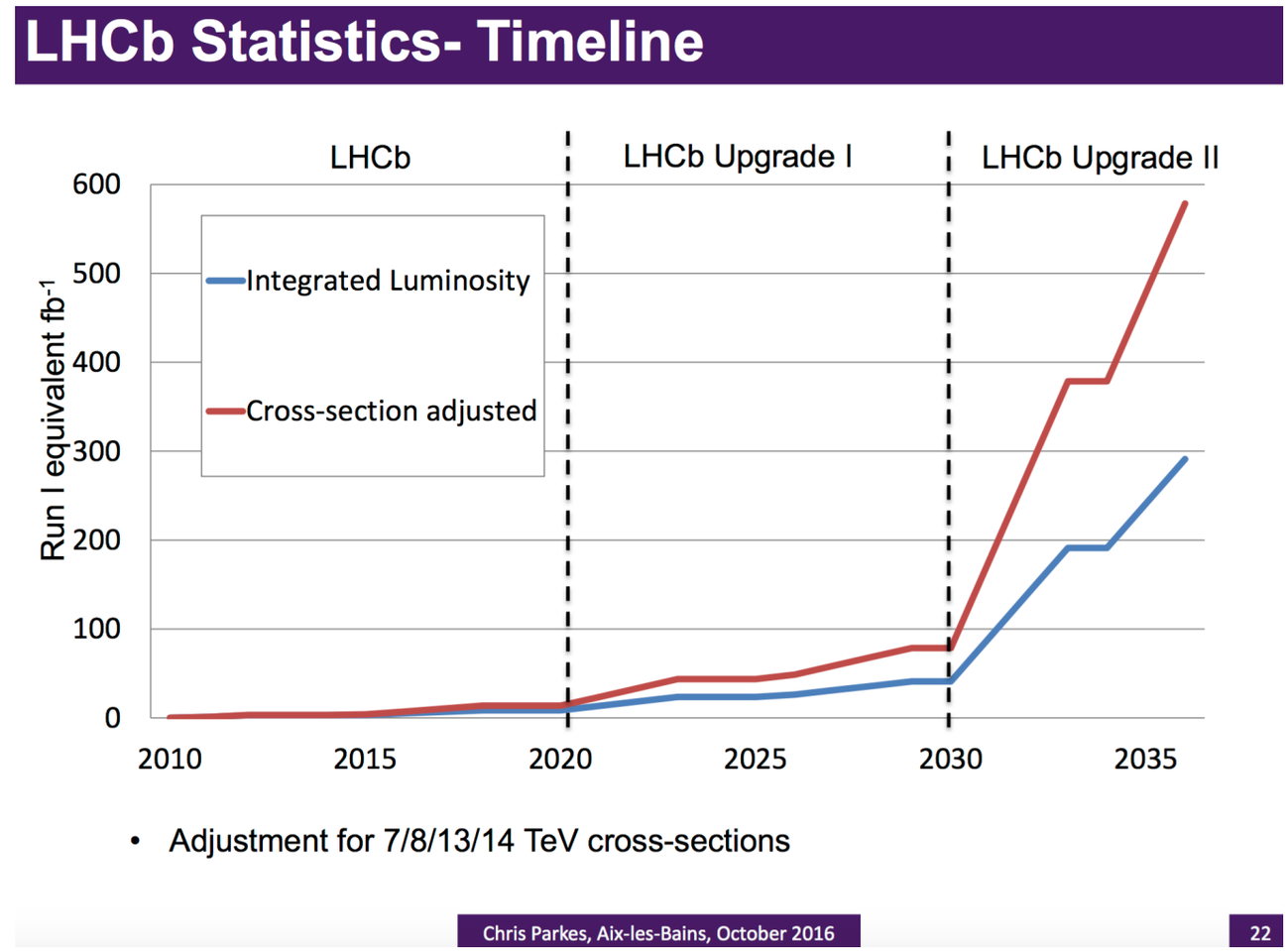
LHCb-ANA-2014-087

LHCb statistics and perspectives

LHCb data sample



From Chris Parkes at ECFA workshop, Oct16



- In 2016 collected almost twice *b*-baryon signal yields wrt Run1
- Possibility to increase yields x30 UpgradeI and x200 UpgradeII

Summary

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

- Evidence for CPV found in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ decays with a statistical significance of 3.3σ. This represents the first evidence for CPV in baryon sector. Eagerly looking for a 5σ observation.

- CPV searches ongoing in several *b*-baryon decays. Next step, amplitude analysis to determine source of CPV. Important effort needed for development of phenomenological models

- At high luminosity 300fb^{-1} reach 10^{-3} precision on CPV in several *b*-baryon decays. Systematic study of CPV in baryons, angle γ

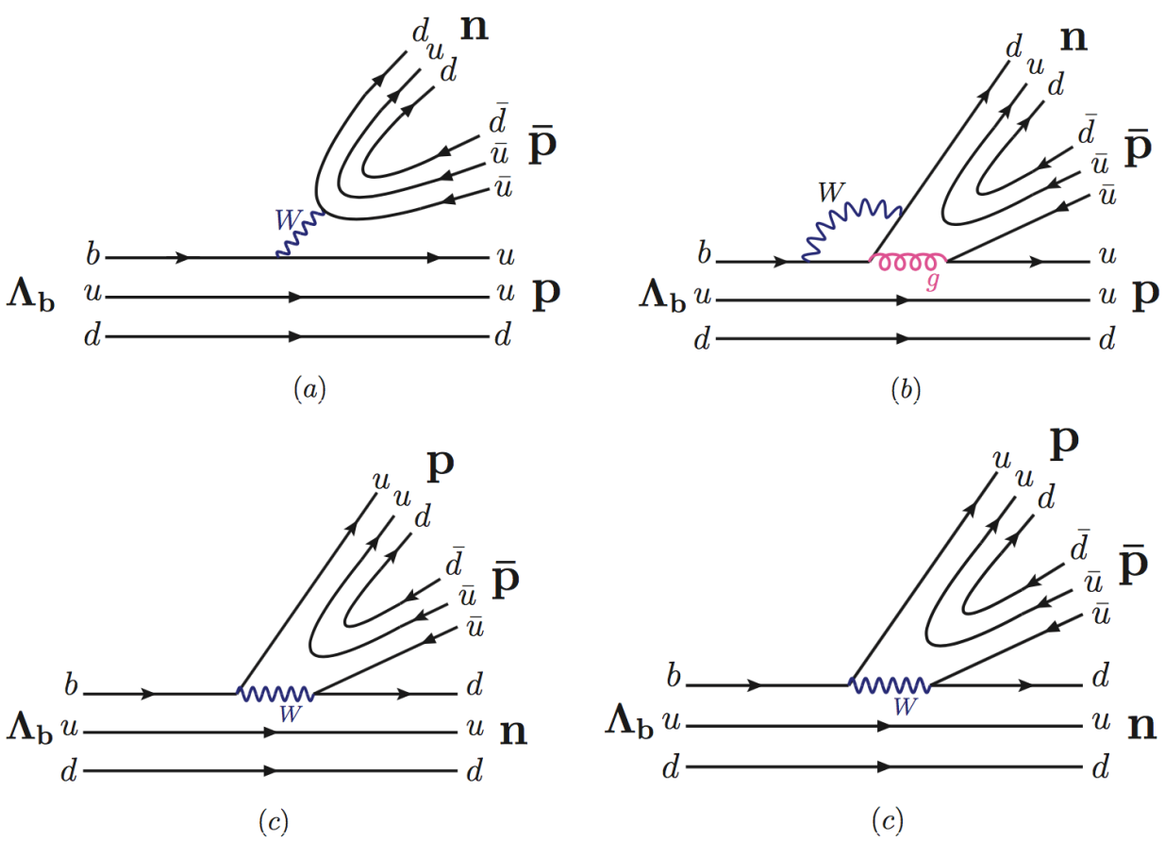
- Theoretical predictions for CPV in *b*-baryon decays are needed to confront with precision measurements

Backup slides

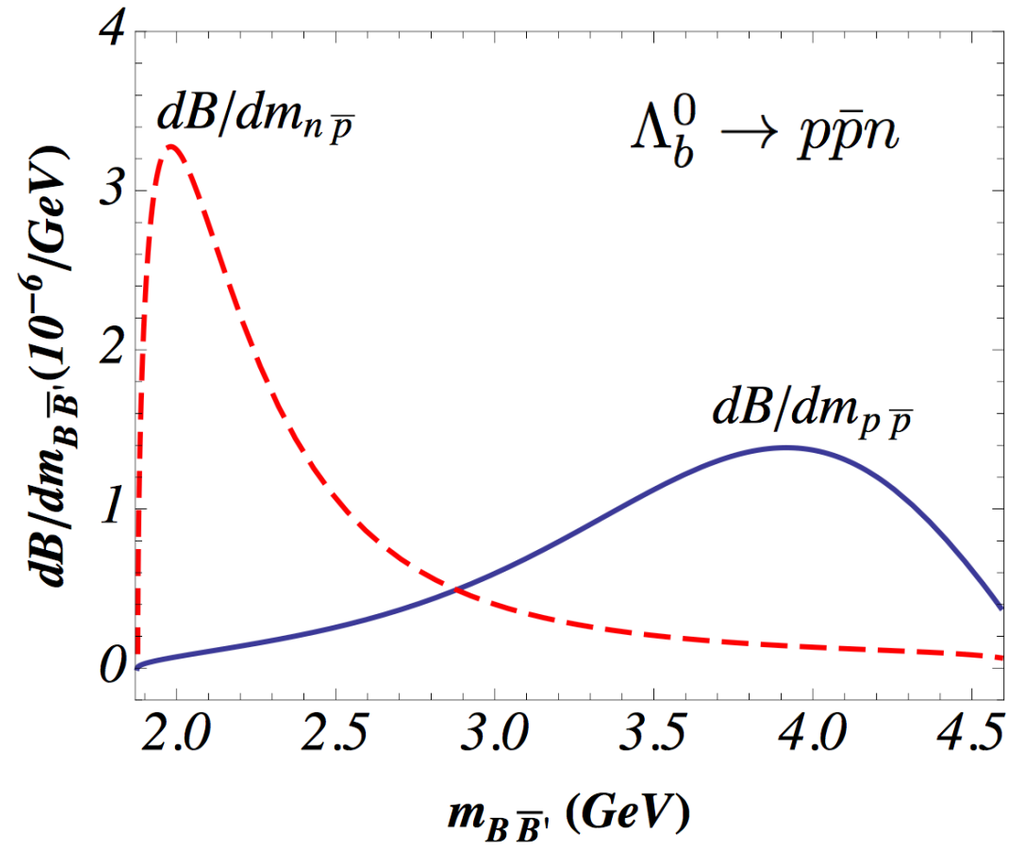
Explore purely baryonic decays

C.Q. Geng, Y.K. Hsiao, Eduardo Rodrigues, Phys. Rev. D 94, 014027 (2016)

- No such type of decay has ever been observed
- Prediction $\mathcal{B}(\Lambda_b^0 \to p\bar{p}n) = (2.0^{+0.3}_{-0.2}) \times 10^{-6}$
- Other modes $\Lambda_b^0 \to p\bar{p}\Lambda \quad \Lambda_b^0 \to \Lambda\bar{\Lambda}\Lambda$



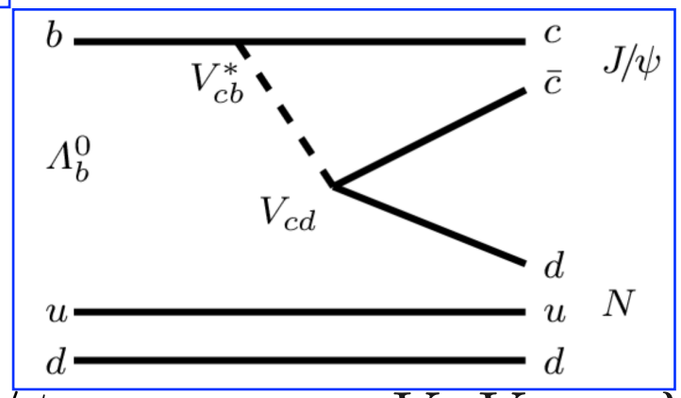
Dibaryon invariant mass spectra prediction

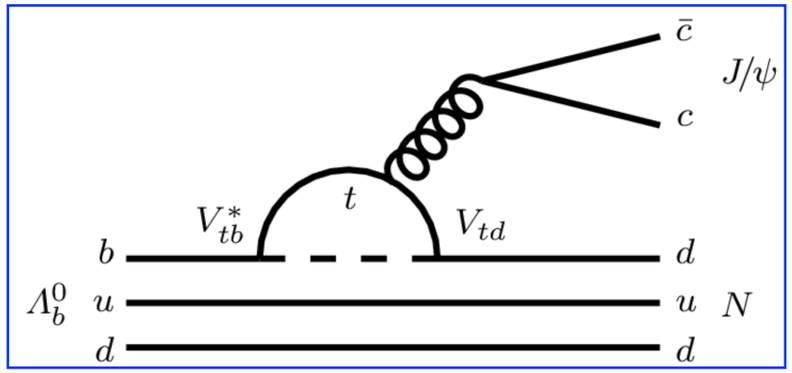


Observation of $\Lambda_b^0 \to J/\psi p \pi^-$ decay

JHEP07(2014)103

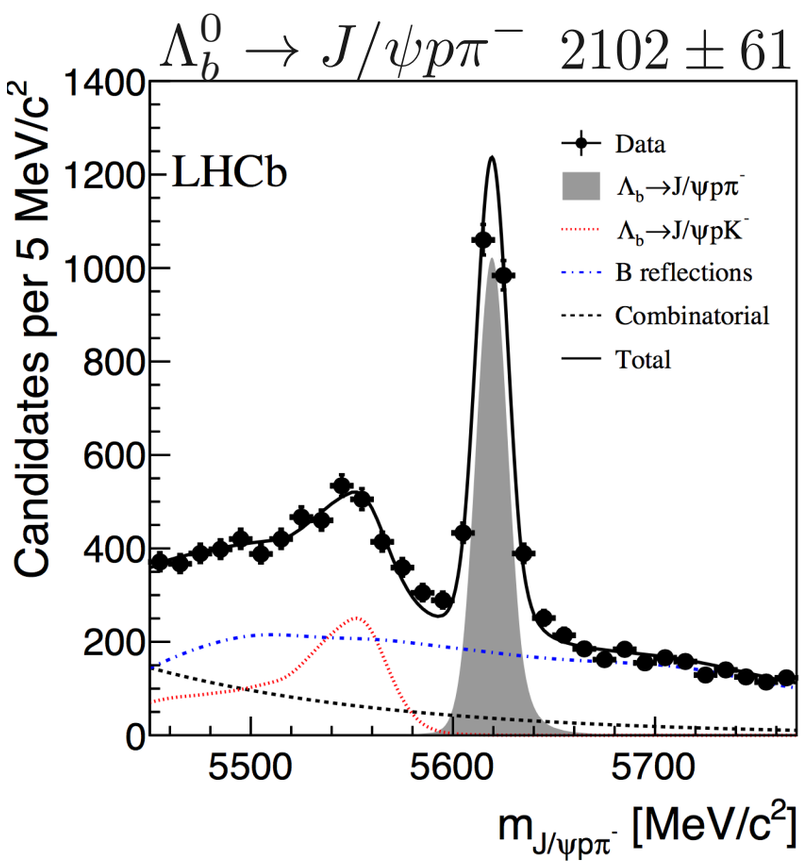
- Large interference between tree and penguin amplitudes. Measure relative BR wrt $\Lambda_b^0 \to J/\psi p K^-$ and search for CPV

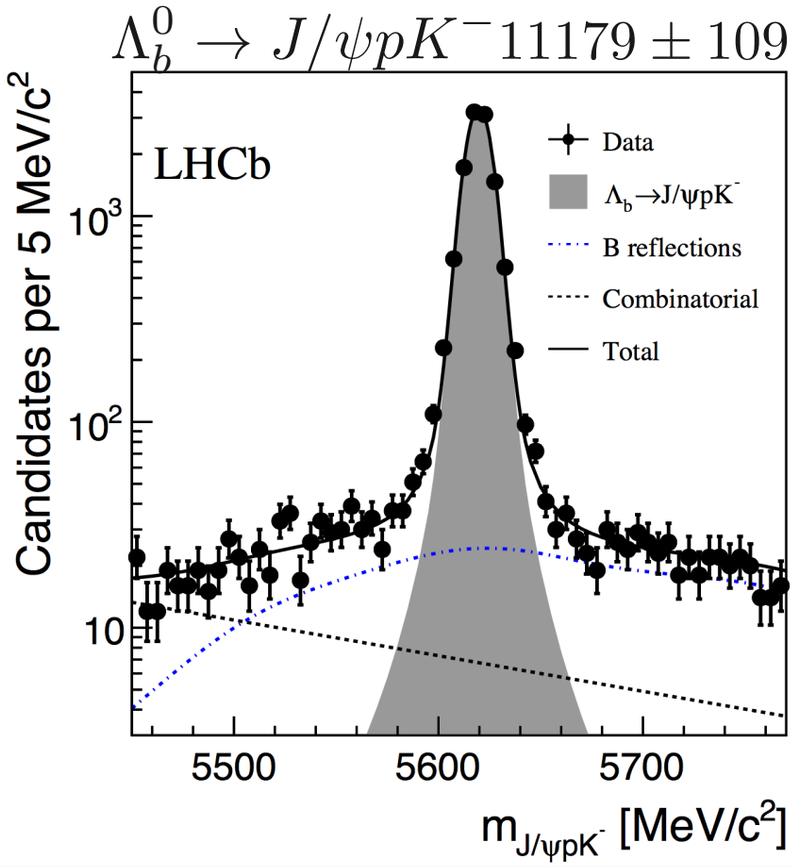




$\Lambda_b^0 \to J/\psi\, p\pi^-$ tree $\propto V_{cb}V_{cd} \sim \lambda^3$

$\Lambda_b^0 \to J/\psi\, p\pi^-$ penguin $\propto V_{tb}V_{td} \sim \lambda^3$ $(|V_{us}| = \lambda)$





Search for CP violation

3fb^{-1} data at 7-8 TeV
JHEP07(2014)103

- Measurement of ΔA_{CP} cancel production and proton reconstruction asymmetries

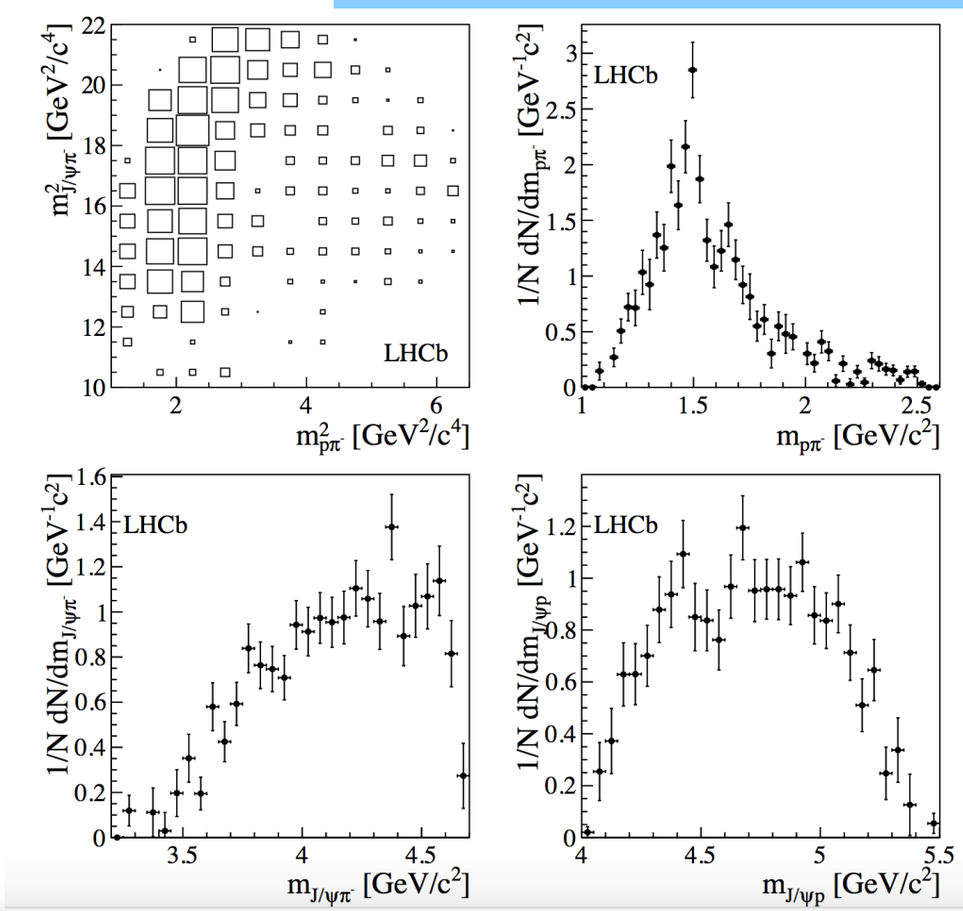
$$\mathcal{A}_{\rm raw}(\Lambda_b^0 \to J/\psi p h^-) = \mathcal{A}_{CP}(\Lambda_b^0 \to J/\psi p h^-) + \mathcal{A}_{\rm prod}(\Lambda_b^0) - \mathcal{A}_{\rm reco}(h^+) + \mathcal{A}_{\rm reco}(p)$$

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

$$= \mathcal{A}_{CP}(\Lambda_b^0 \to J/\psi p \pi^-) - \mathcal{A}_{CP}(\Lambda_b^0 \to J/\psi p K^-) + \mathcal{A}_{\rm reco}(\pi^+) - \mathcal{A}_{\rm reco}(K^+)$$

$(5.7 \pm 2.4 \pm 1.2)\%$ 2.2σ from zero

$\approx \mathcal{A}_{\rm raw}(\overline{B}^0 \to J/\psi \overline{K}^{*0}) = (-1.10 \pm 0.32 \pm 0.0.6)\%$



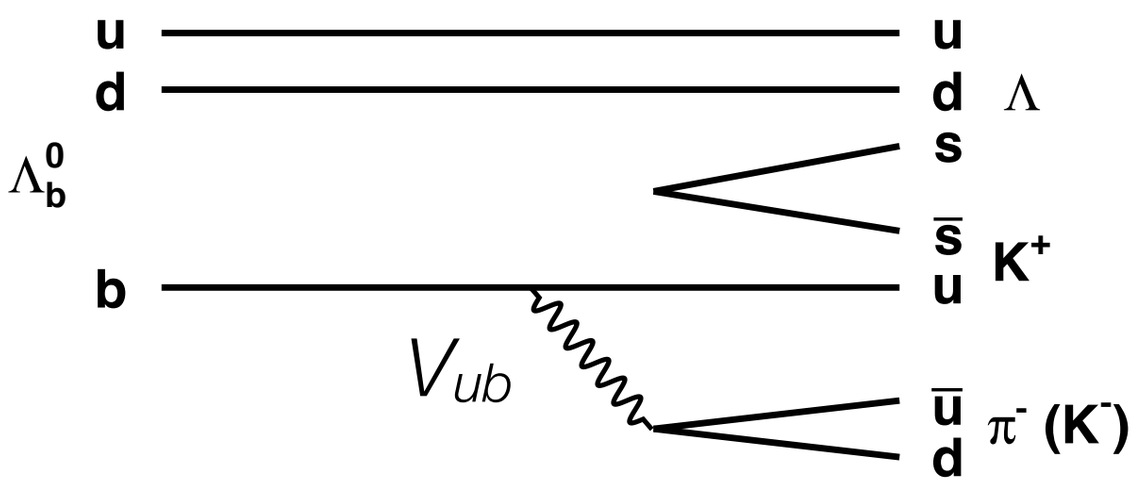
- No indications of large local CP asymmetries in Dalitz plane
- Rich resonant structure in $m(p\pi^-)$, and 2 pentaquark in $m(J/\psi p)$ distributions
- BR compatible with expected value 0.08: CKM x phase space factor

$$\frac{\mathcal{B}(\Lambda_b^0 \to J/\psi p \pi^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-)} = 0.0824 \pm 0.0025\,({\rm stat}) \pm 0.0042\,({\rm syst})$$

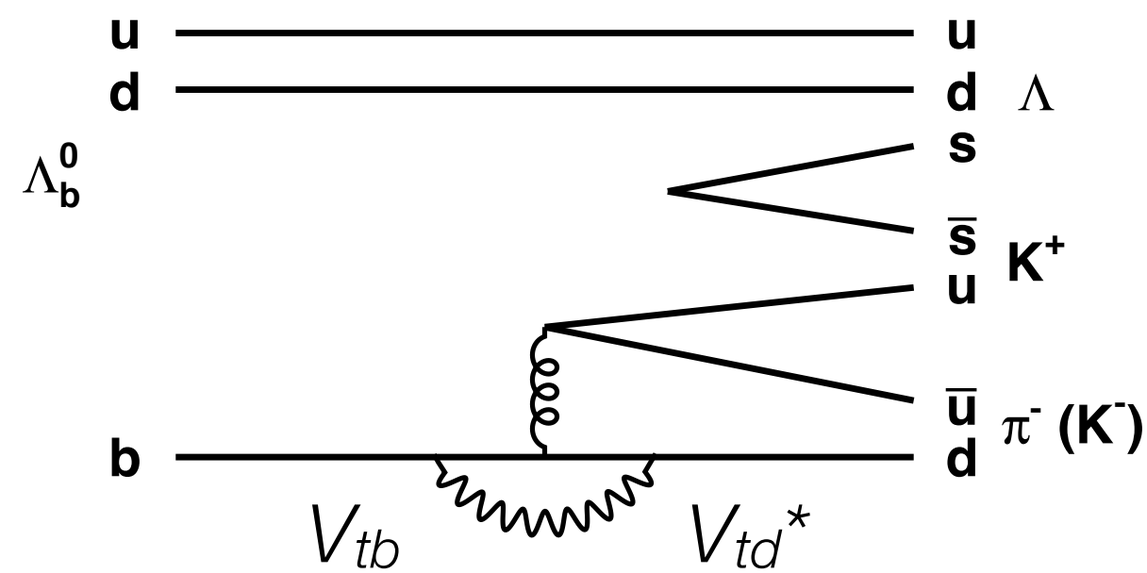
Search for CPV in $\Lambda_b^0 \to \Lambda h^+ h'^-$ decays

JHEP 05 (2016) 081

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



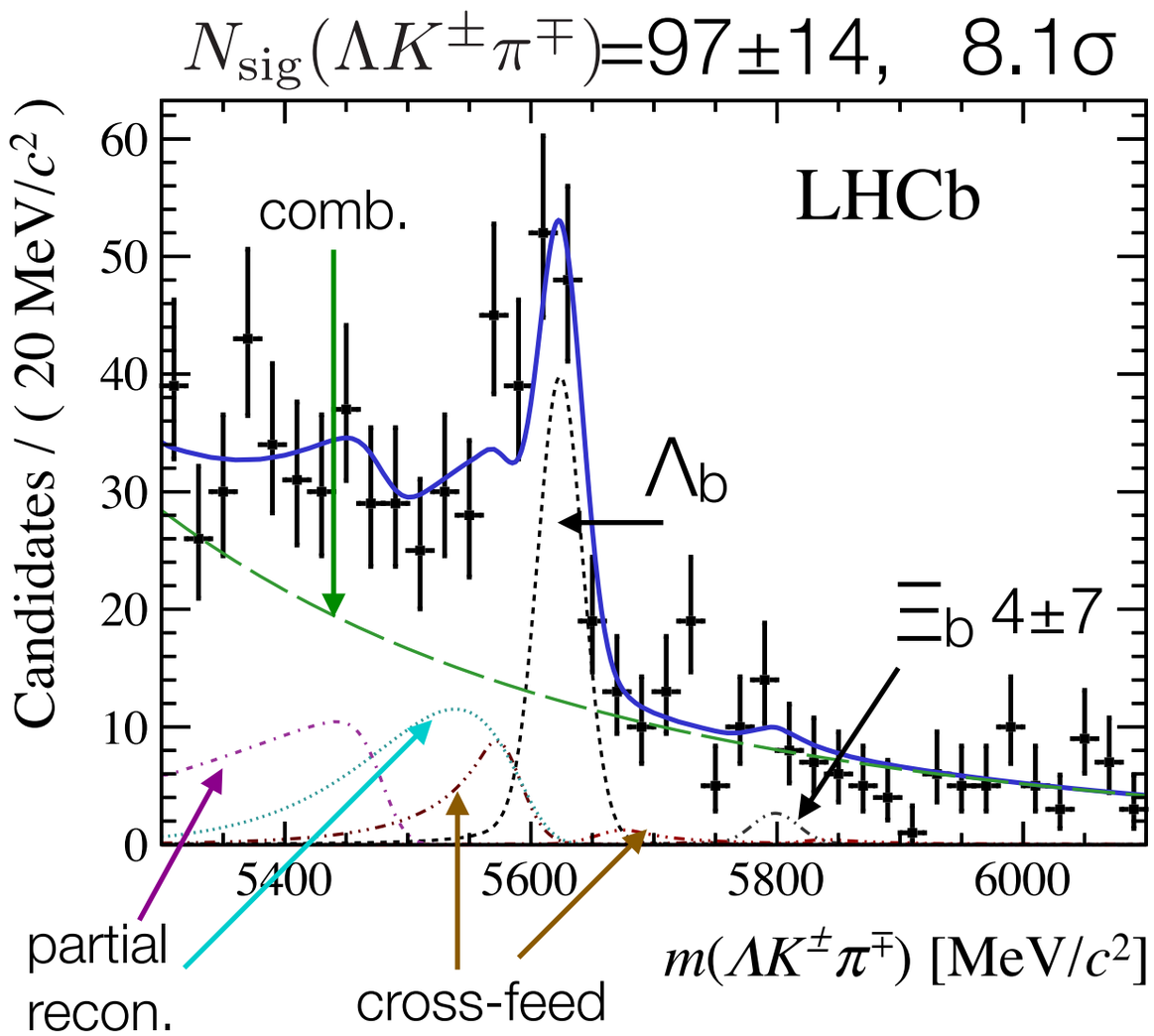
Penguin diagram $\propto \sum_{x=u,c,t} V_{bx} V_{xd} \sim \lambda^3$

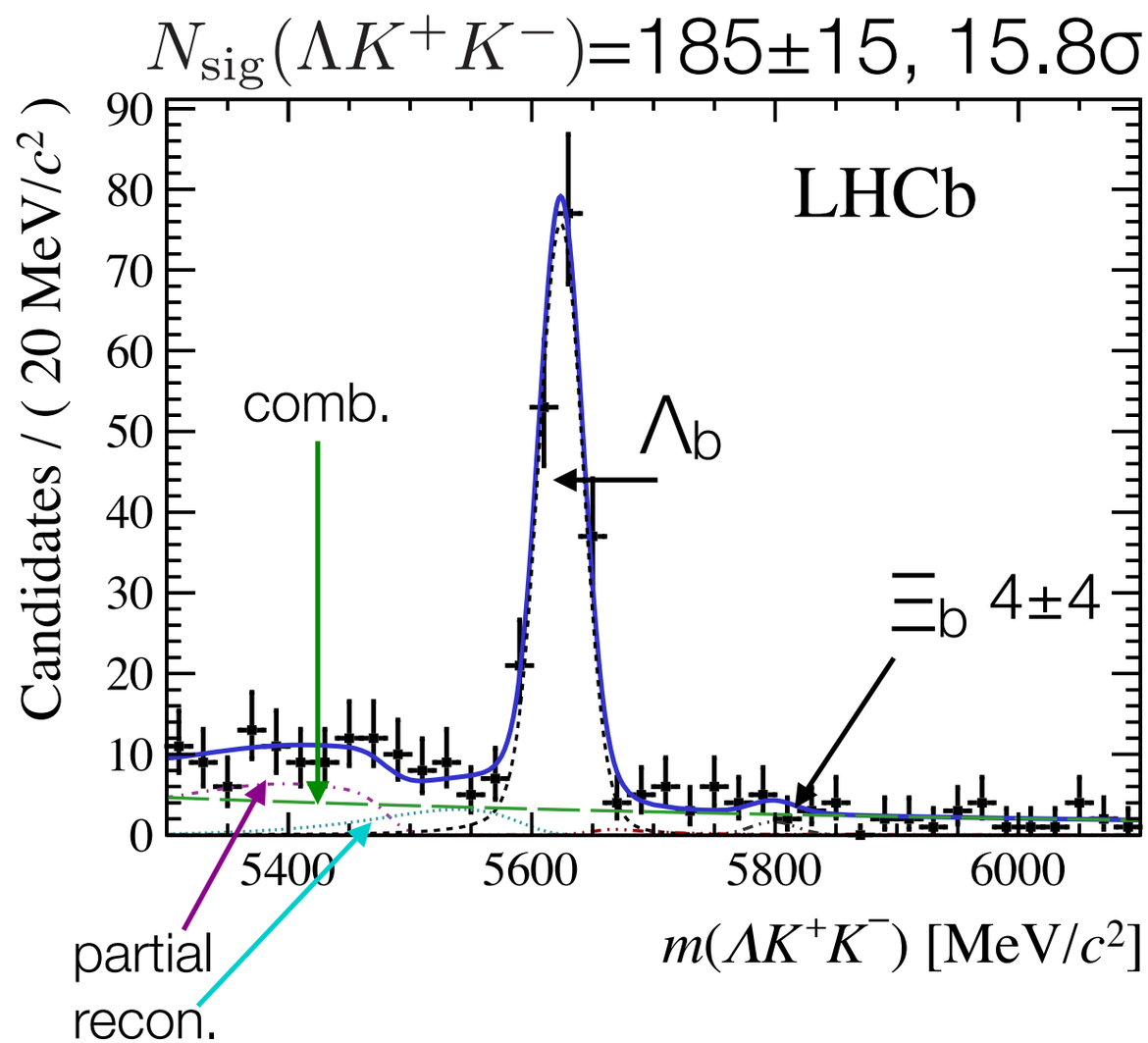


Signal yields

JHEP 05 (2016) 081

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

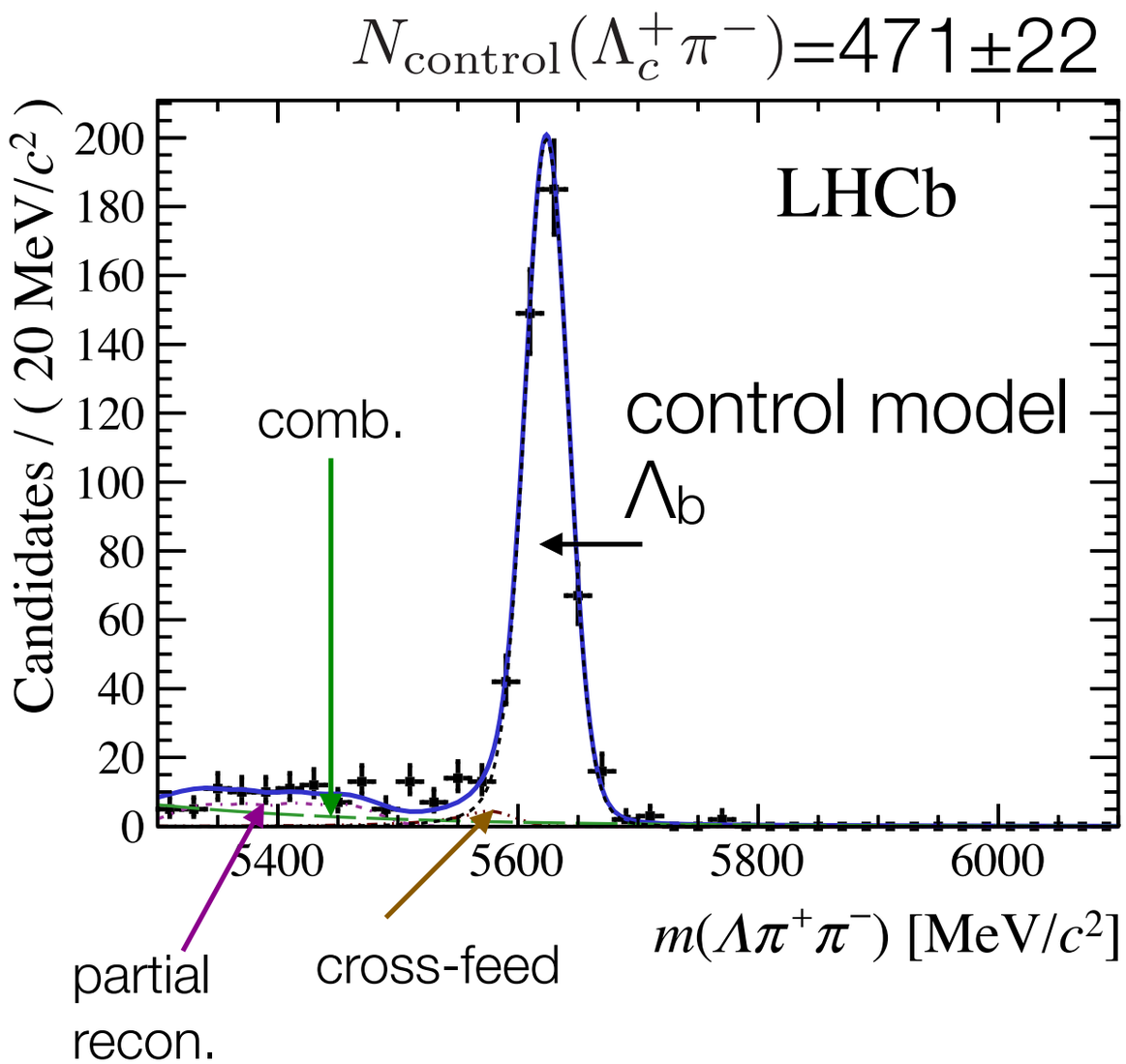


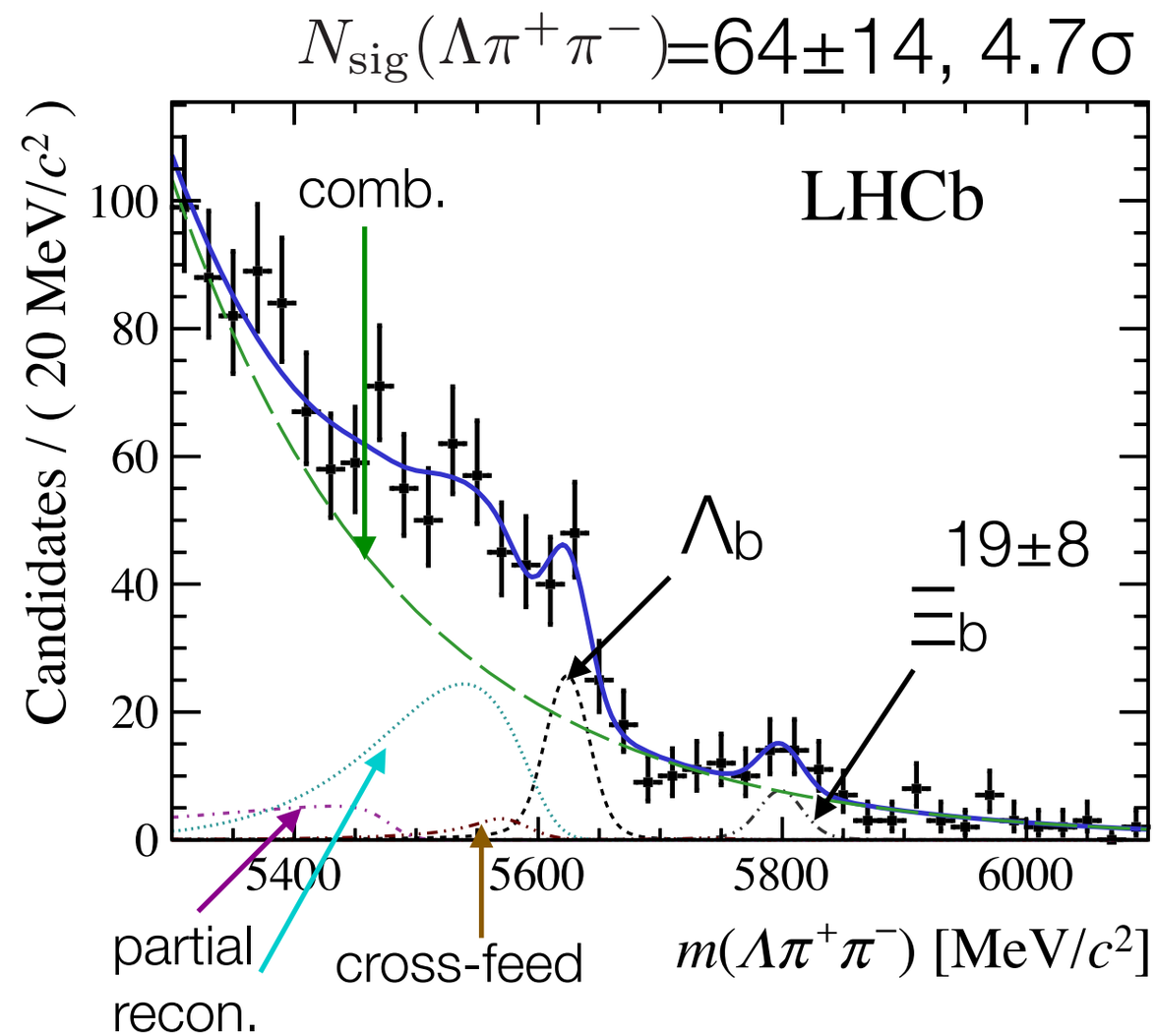


Signal yields

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 $\Xi_b^0 \to \Lambda h^+ h'^-$



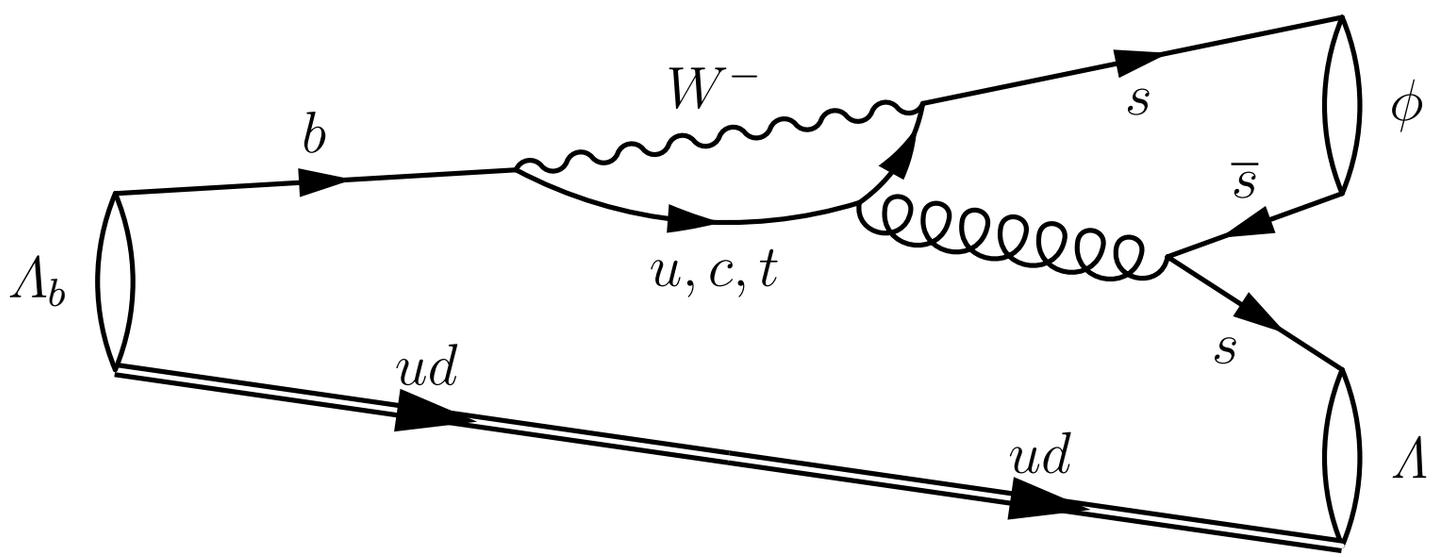


Search for CPV using triple-product asymmetries in $\Lambda_b^0 \to \Lambda\phi$

Phys. Lett. B759 (2016) 282

$b \to s\bar{s}s$ 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

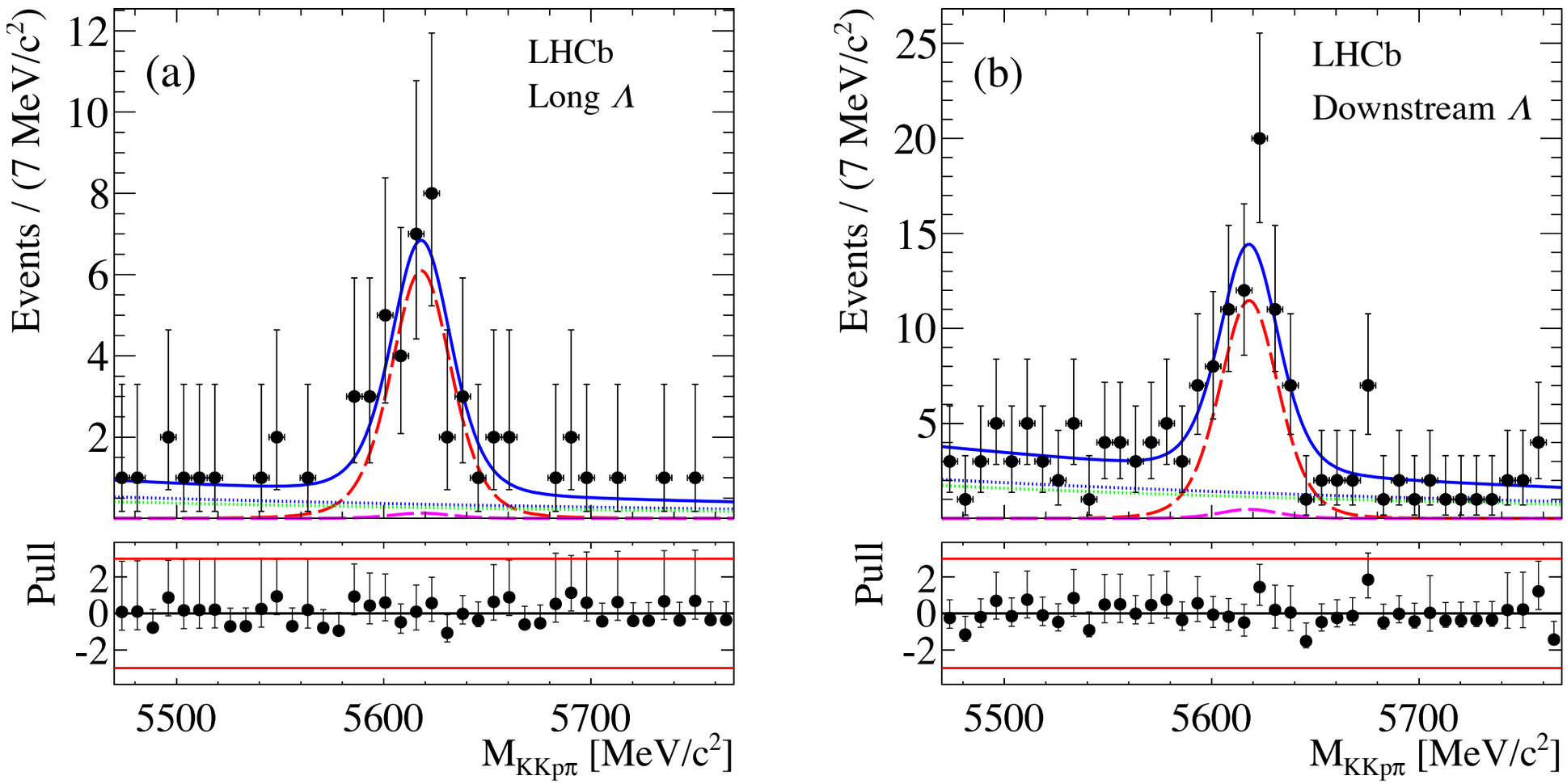


Signal yields

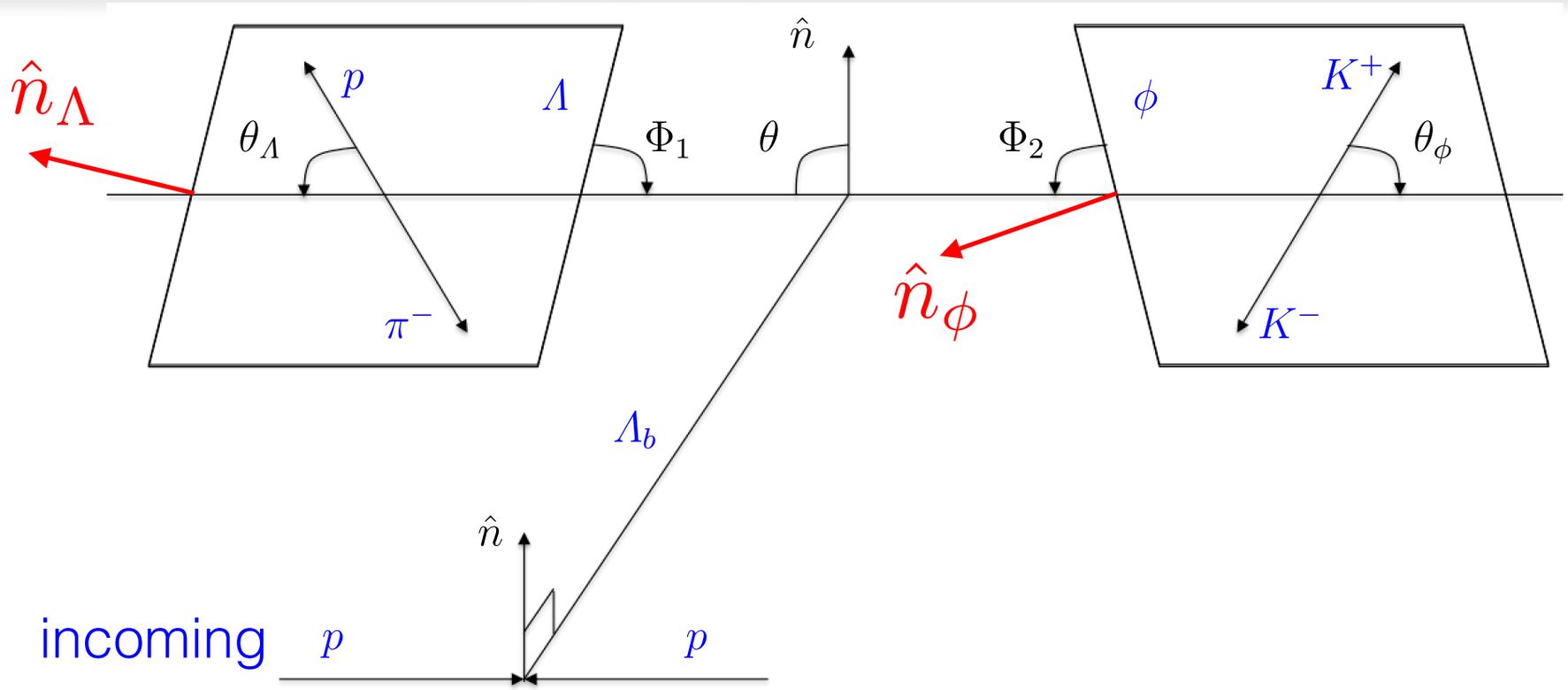
Phys. Lett. B759 (2016) 282

- First observation

$N_{\mathrm{sig}}(\Lambda_b^0 \to \Lambda\phi)$=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

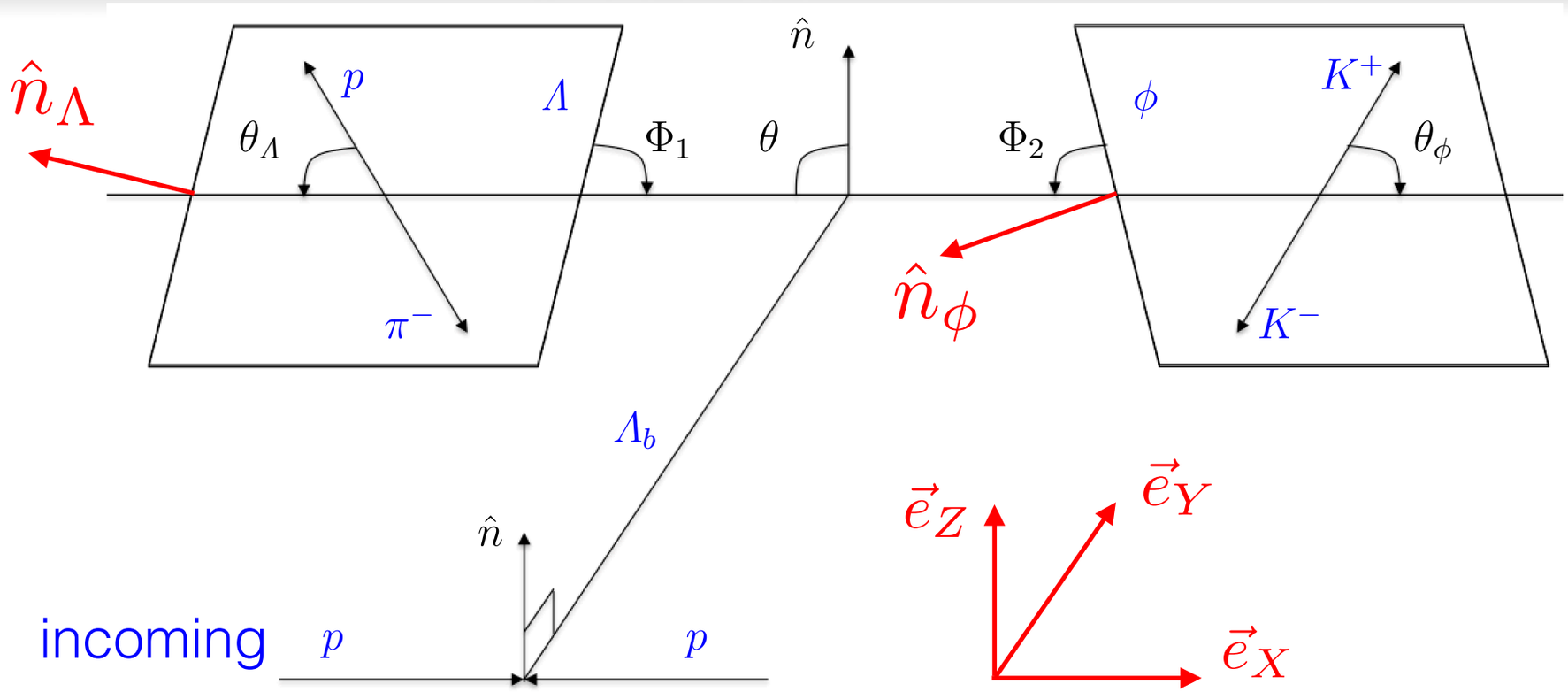
θ_ϕ : polar angle of K^+ in ϕ rest frame

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

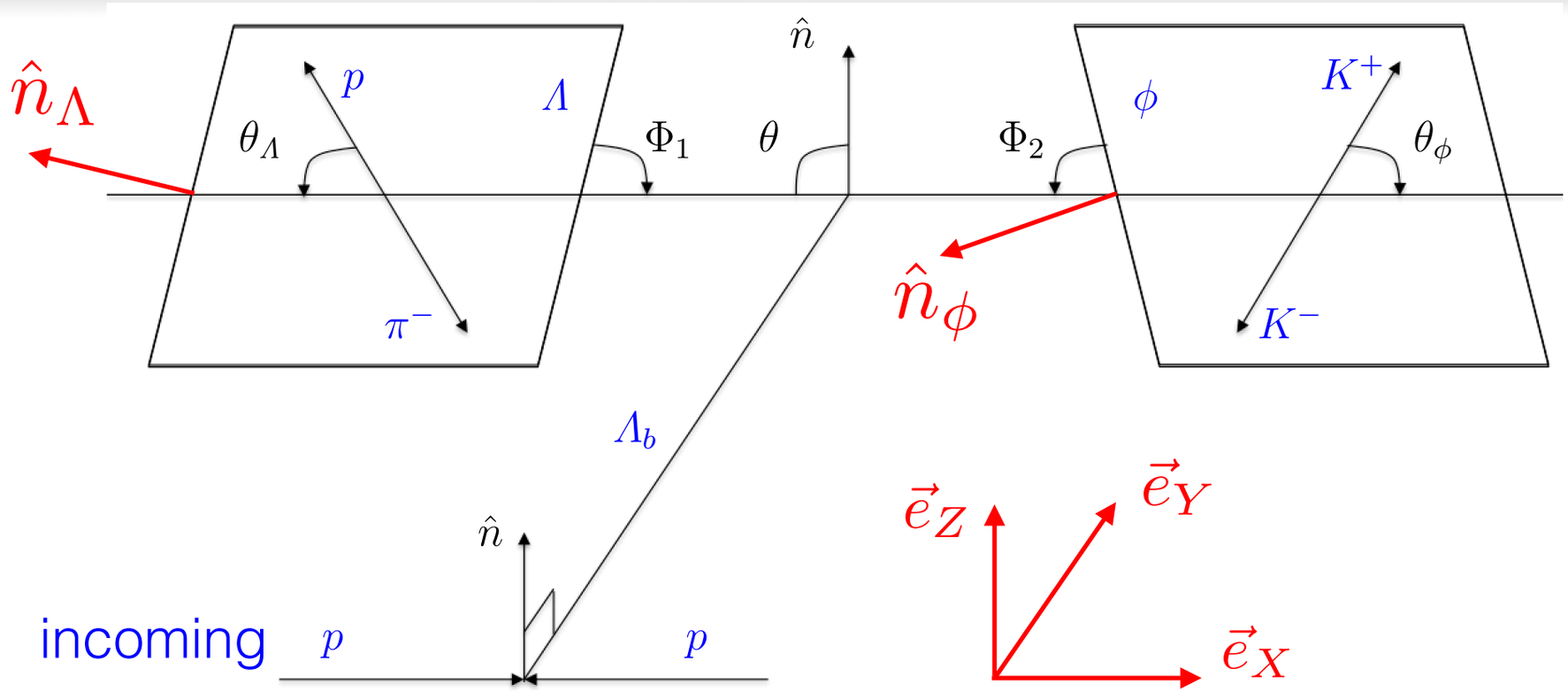
CPV observables, untagged sample:

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

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

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

See G. Durieux, arXiv:1608.03288

Asymmetry measurements

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

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

Phys. Rev. D90 (2014) 112004

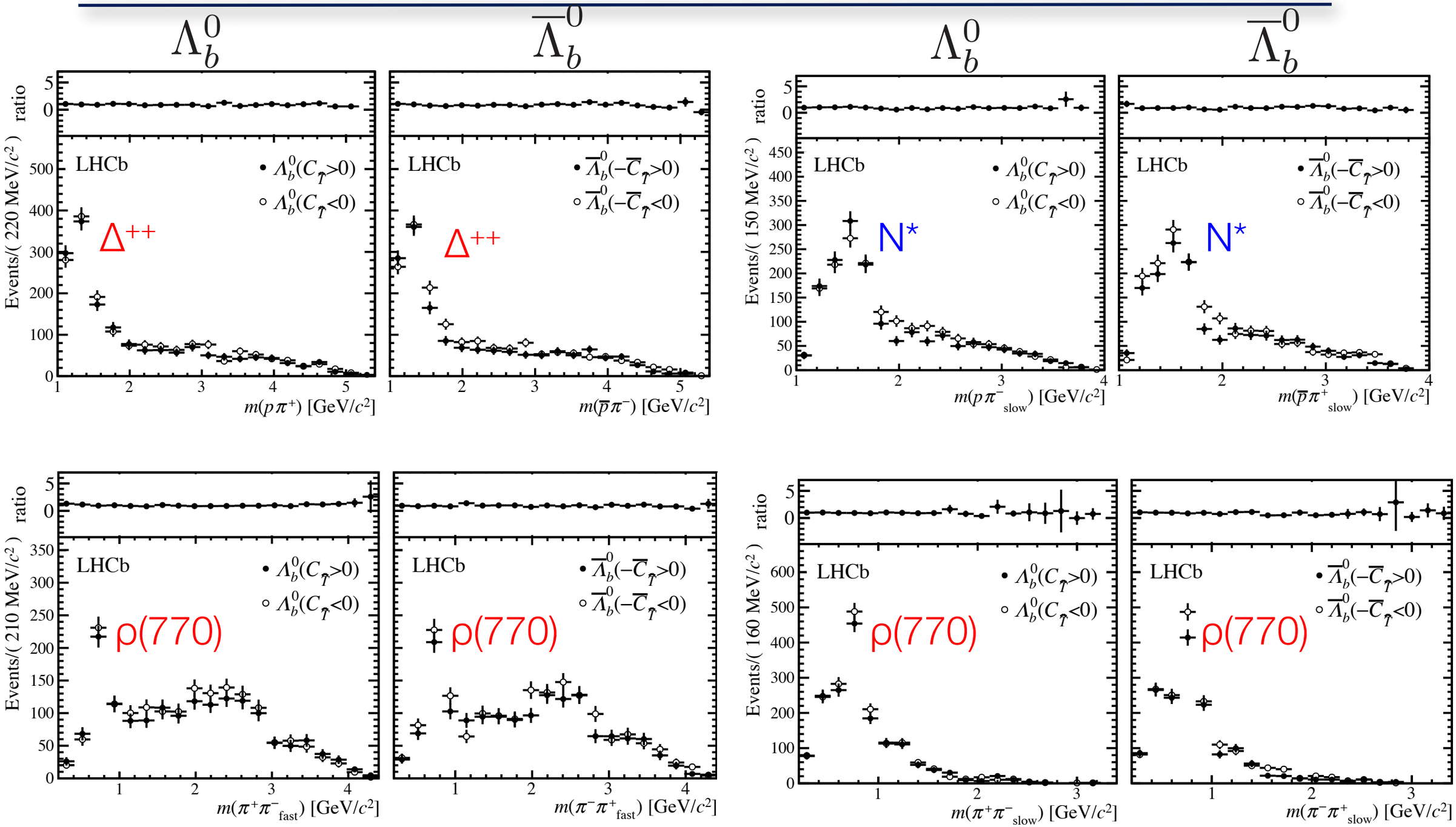
$$\begin{aligned}\mathcal{A}_{CP} &= \mathcal{A}_{CP}^{\rm raw} - (\mathcal{A}_{\rm P} + \mathcal{A}_{\rm D}) \\ &= \mathcal{A}_{CP}^{\rm raw}(\Lambda_b^0 \to \Lambda h^+ h'^-) - \mathcal{A}_{CP}^{\rm raw}(\Lambda_b^0 \to (\Lambda\pi^+)_{\Lambda_c^+}\pi^-)\end{aligned}$$

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

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

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

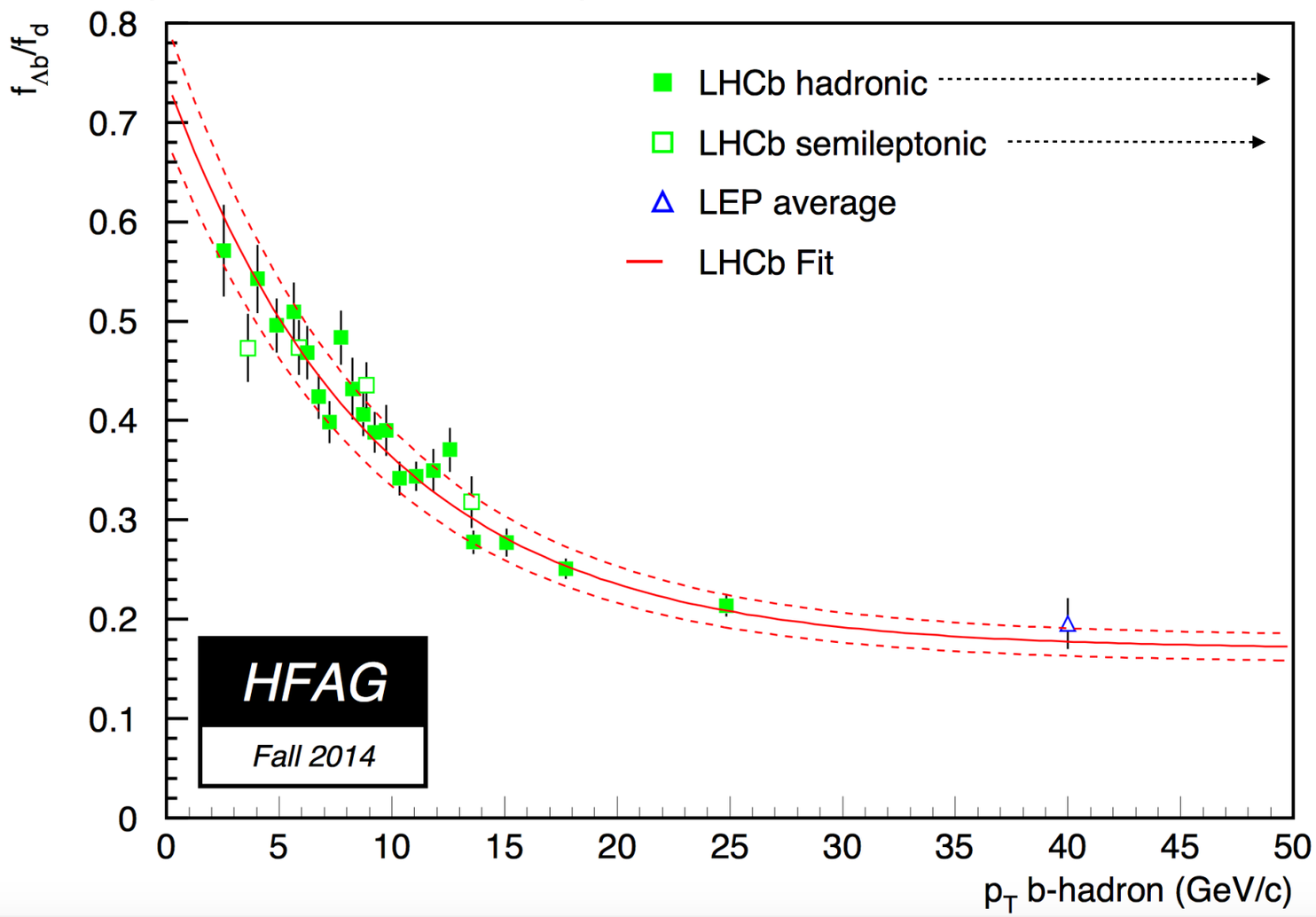
arXiv:1609.05216, submitted to Nature Physics



background-subtracted using the *sPlot* method

b-baryon production

- Production cross-section strongly depends on p_T of *b*-hadron :
  - different *b*-quark fragmentation function ratio $f_{\Lambda_b^0}/f_d$ measured at LEP and at LHC, where $f_{\Lambda_b^0} = P(b \to \Lambda_b^0)$ and $f_d = P(b \to B_d^0)$
  - measurement of $f_{\Lambda_b^0}/f_d$ vs p_T of *b*-quark is cleaner to interpret. Expected a slow dependence in that case arXiv:1505.02771



JHEP 08, 143 (2014)

PRD85, 032008 (2012)

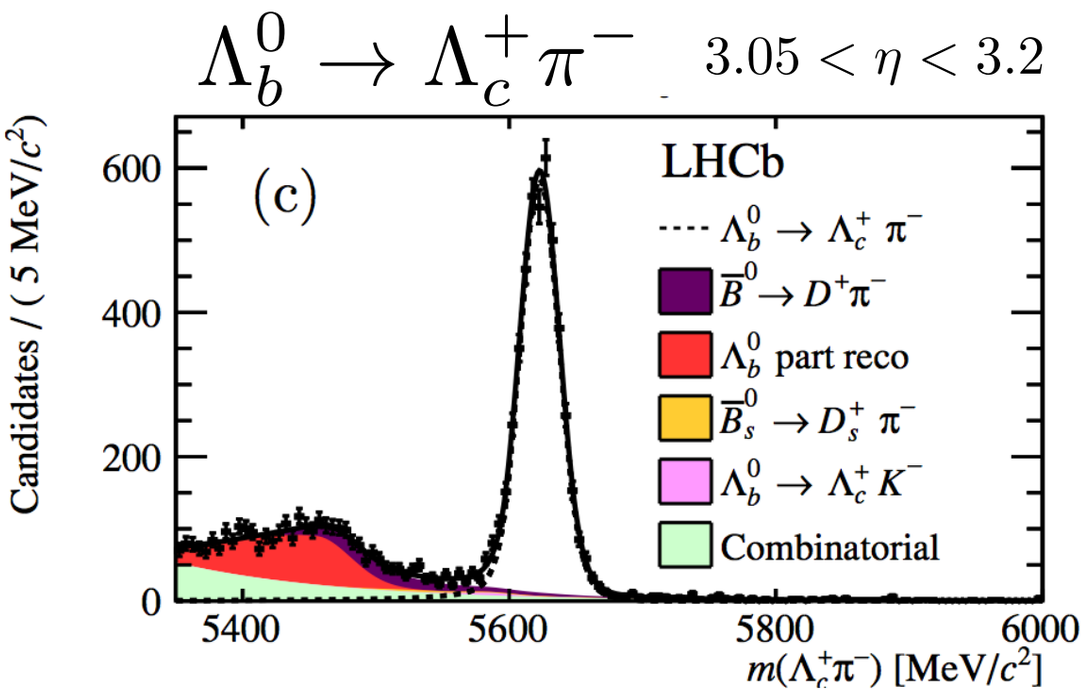
Note: LEP average not included in the fit. LHCb measurements are not independent

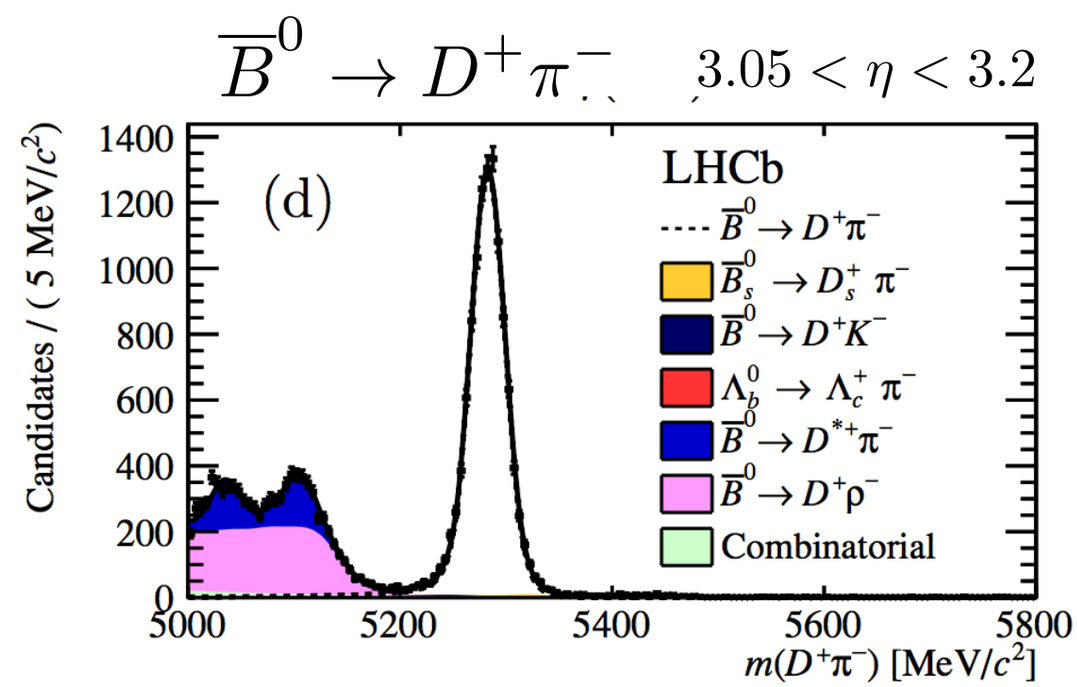
Production kinematic dependence

- Use clean $\Lambda_b^0 \to \Lambda_c^+ \pi^-$(45K) , $\overline{B}^0 \to D^+ \pi^-$ (106K) exclusive decays to measure dependance of $f_{\Lambda_b^0}/f_d$ on *b*-hadron kinematics, e.g. p_T, pseudorapidity η.
- Measure $$\frac{f_{\Lambda_b^0}}{f_d}(x) = \frac{\mathcal{B}\left(\overline{B}^0 \to D^+\pi^-\right)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\pi^-)} \times \frac{\mathcal{B}(D^+ \to K^-\pi^+\pi^+)}{\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)} \times \mathcal{R}(x)$$

  where $\mathcal{R}(x) \equiv \frac{N_{\Lambda_b^0 \to \Lambda_c^+\pi^-}(x)}{N_{\overline{B}^0 \to D^+\pi^-}(x)} \times \frac{\varepsilon_{\overline{B}^0 \to D^+\pi^-}(x)}{\varepsilon_{\Lambda_b^0 \to \Lambda_c^+\pi^-}(x)}$ and $x = p_T, \eta$

Data sample 1fb^{-1} at 7 TeV - JHEP08(2014)143





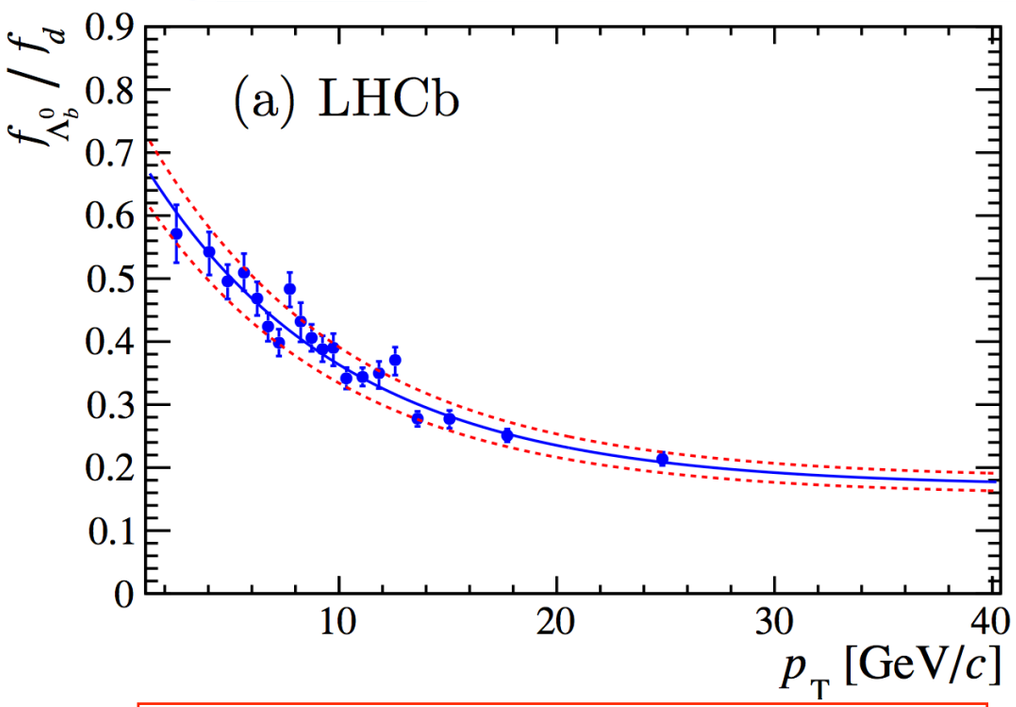
Production kinematic dependence

- Absolute value of $f_{\Lambda_b^0}/f_d$ from LHCb semileptonic analysis
  Phys. Rev. D 85 (2012) 032008
  - obtain most precise branching ratio measurement of *b*-baryon to date (8% precision)

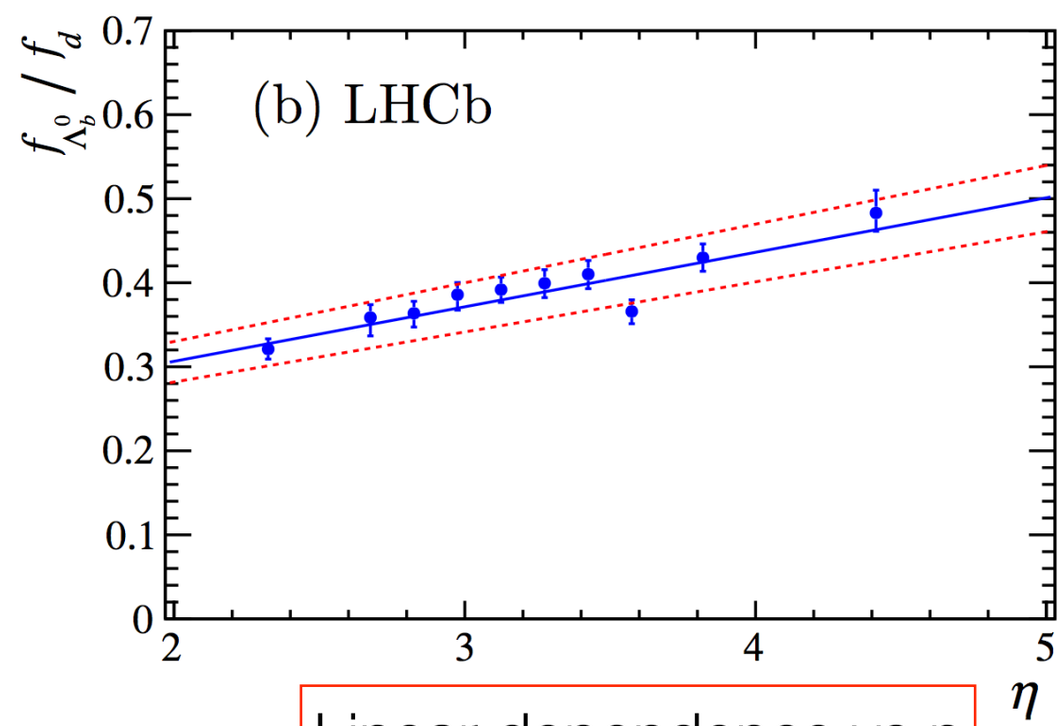
$$\mathcal{B}\left(\Lambda_b^0 \to \Lambda_c^+ \pi^-\right) = \left(4.30 \pm 0.03\ ^{+0.12}_{-0.11} \pm 0.26 \pm 0.21\right) \times 10^{-3}$$

stat. syst. semileptonic analysis $\mathcal{B}(\overline{B}^0 \to D^+\pi^-)$

JHEP08(2014)143



Exponential dependence vs p_T

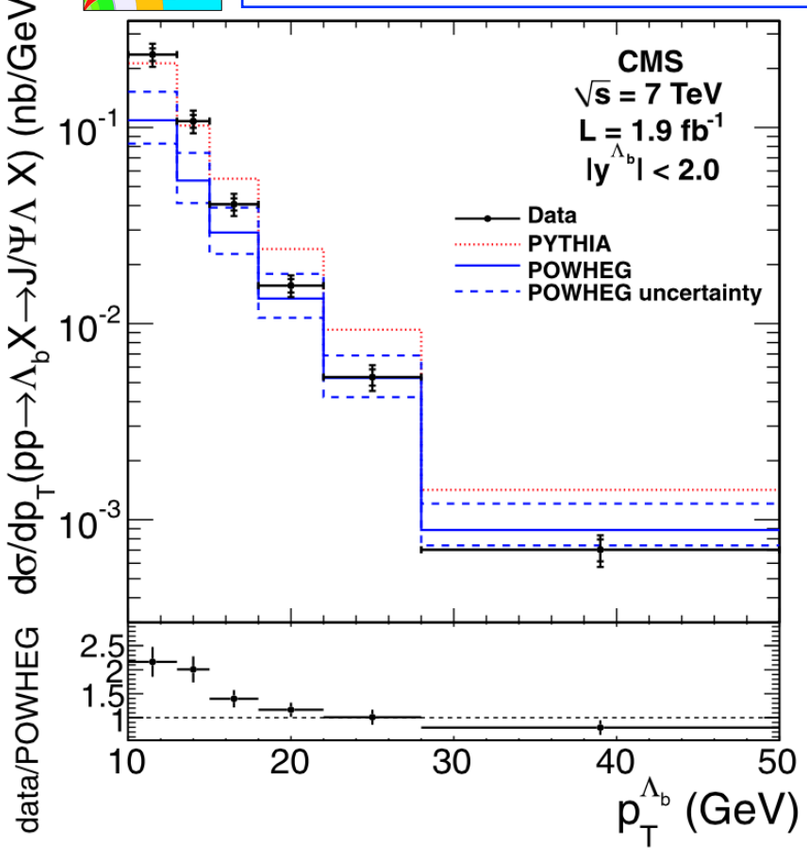


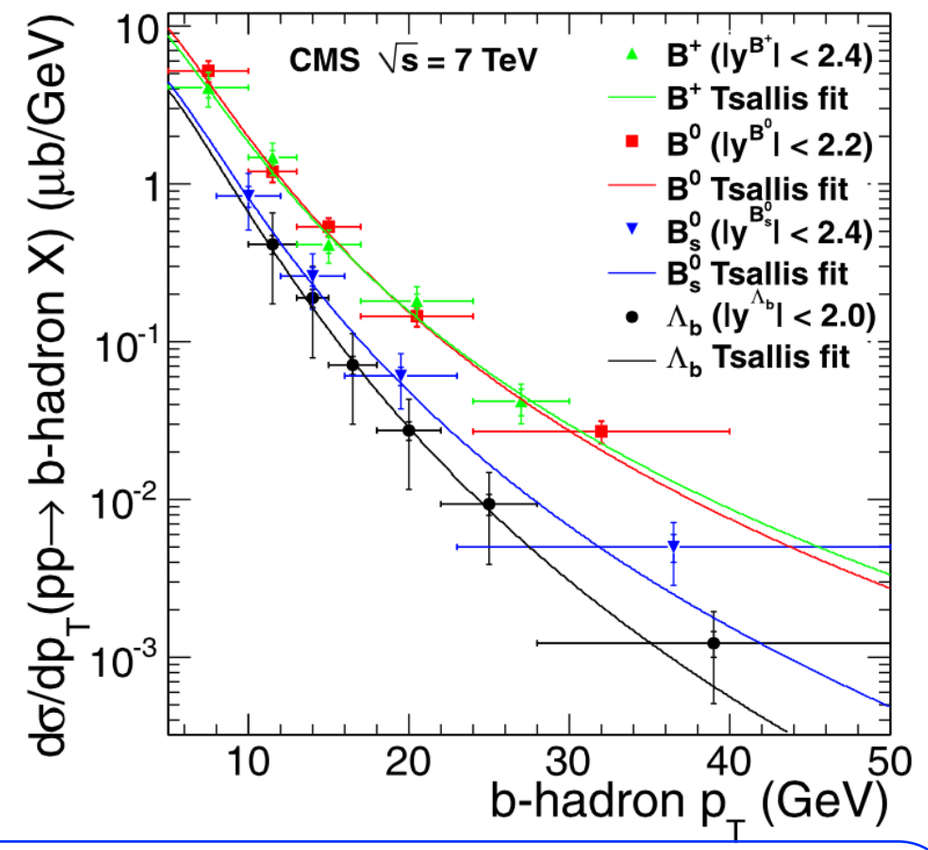
Linear dependence vs η

Λ_b^0 production cross-section

- Measurement of differential production cross-section for Λ_b^0 using $\Lambda_b^0 \to J/\psi\Lambda$ decays with $J/\psi \to \mu^+\mu^-, \Lambda \to p\pi^-$

PLB 714 (2012) 136–157





- p_T distribution falls faster than measured *b*-mesons spectra and than predicted spectra from NLO MC POWHEG and leading-order MC PYTHYA
- Cross-section ratio $\sigma(\overline{\Lambda}_b^0)/\sigma(\Lambda_b^0)$ consistent with 1 and constant vs p_T, and rapidity |*y*|

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**

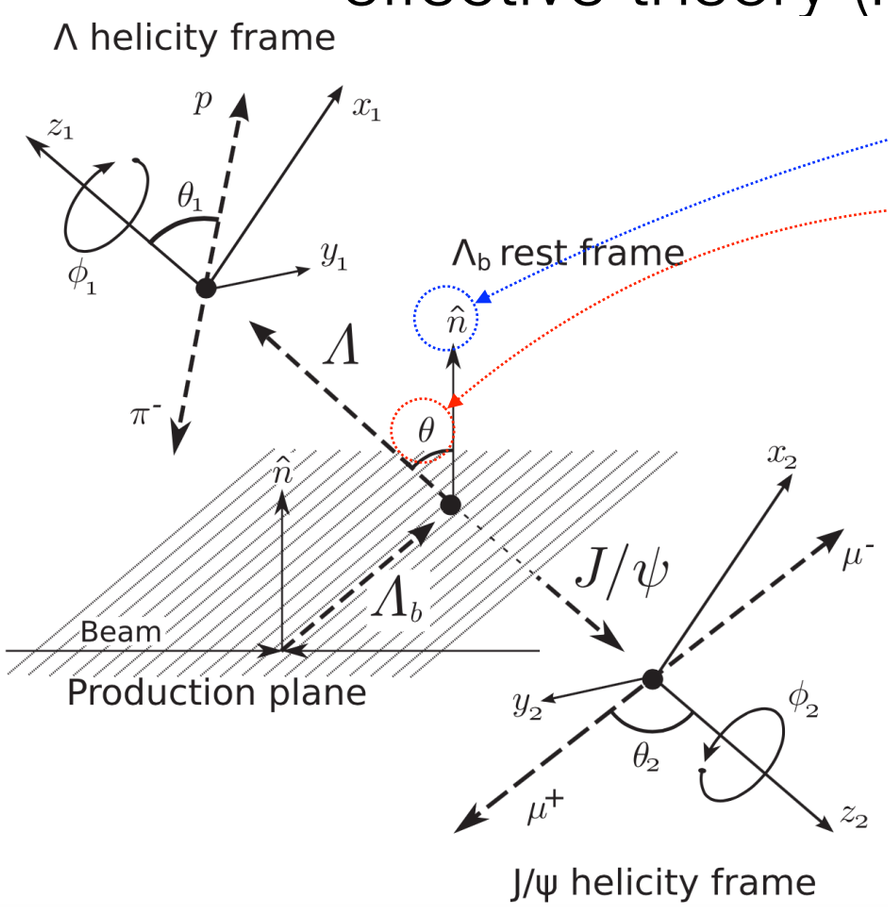
$P(\Lambda_b^0) = (-0.2 \pm 2.3)$ % **Phys.Rev.Lett 115 (2015) 072001**

- Effect of Λ_b^0 polarisation estimated to be negligible on CPV asymmetries **JHEP 04 (2014) 087** **JHEP 1407 (2014) 103**

- Effect studied using MC sample polarised at generation level and control samples

Parity violation in $\Lambda_b^0 \to J/\psi\Lambda$

- Parity violation is not maximal in hadron weak decays and depends on hadron constituents. In *b*-baryons can be predicted by perturbative QCD (pQCD) and heavy quark effective theory (HQET)



$$w(\cos\theta) = \frac{1}{2}(1 + \alpha P \cos\theta)$$

polarisation

angle

parity-violation

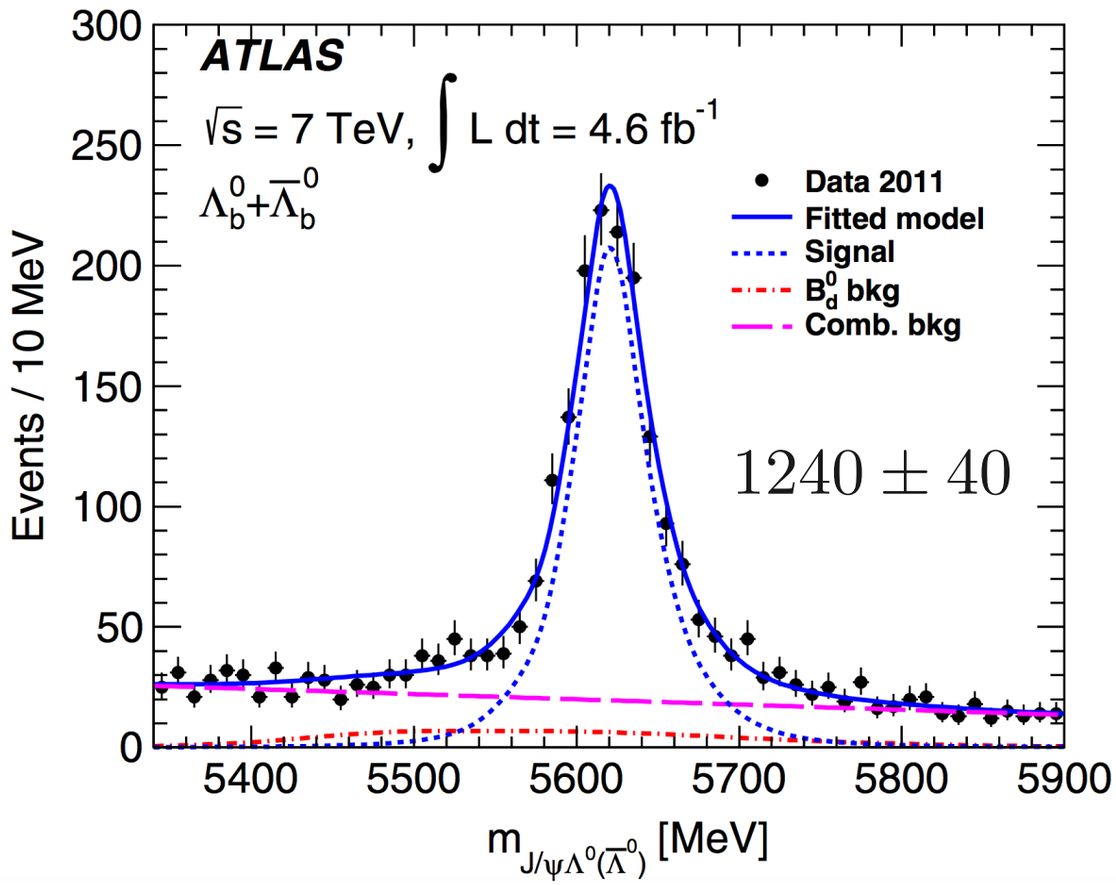
- Λ_b^0 polarisation allowed only to be perpendicular to production plane, due to parity conservation in pp strong interaction

- Use 4 helicity amplitudes to describe the $\Lambda_b^0 \to J/\psi\Lambda$ decay

$$A(\lambda_\Lambda, \lambda_{J/\psi}) : a_+ = A(1/2, 0), a_- = A(-1/2, 0),$$
$$b_+ = A(-1/2, -1), b_- = A(1/2, 1)$$

Parity violation results

ATLAS EXPERIMENT 4.6fb^{-1} data at 7 TeV - PRD 89, 092009 (2014)



Negative helicity states for Λ are preferred.

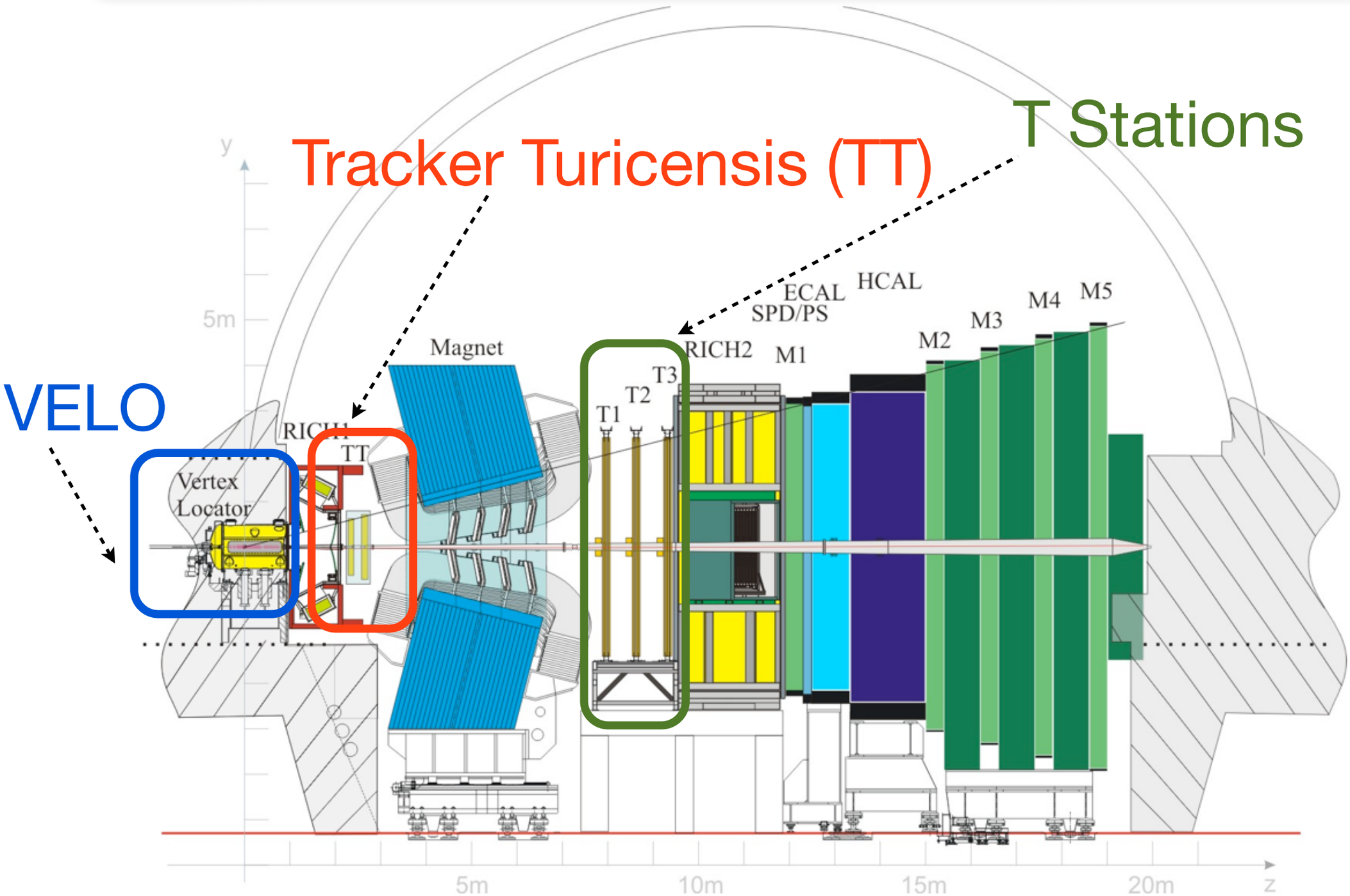
$$|a_+| = 0.17^{+0.12}_{-0.17}(\text{stat}) \pm 0.09(\text{syst})$$
$$|a_-| = 0.59^{+0.06}_{-0.07}(\text{stat}) \pm 0.03(\text{syst})$$
$$|b_+| = 0.79^{+0.04}_{-0.05}(\text{stat}) \pm 0.02(\text{syst})$$
$$|b_-| = 0.08^{+0.13}_{-0.08}(\text{stat}) \pm 0.06(\text{syst})$$

- <P>=0 in a symmetric interval in pseudorapidity
- Assume CP conservation and extract α from a simplified angular analysis with 5 independent parameters

$$\alpha = |a_+|^2 - |a_-|^2 + |b_+|^2 - |b_-|^2$$
$$= 0.30 \pm 0.16 \pm 0.06$$

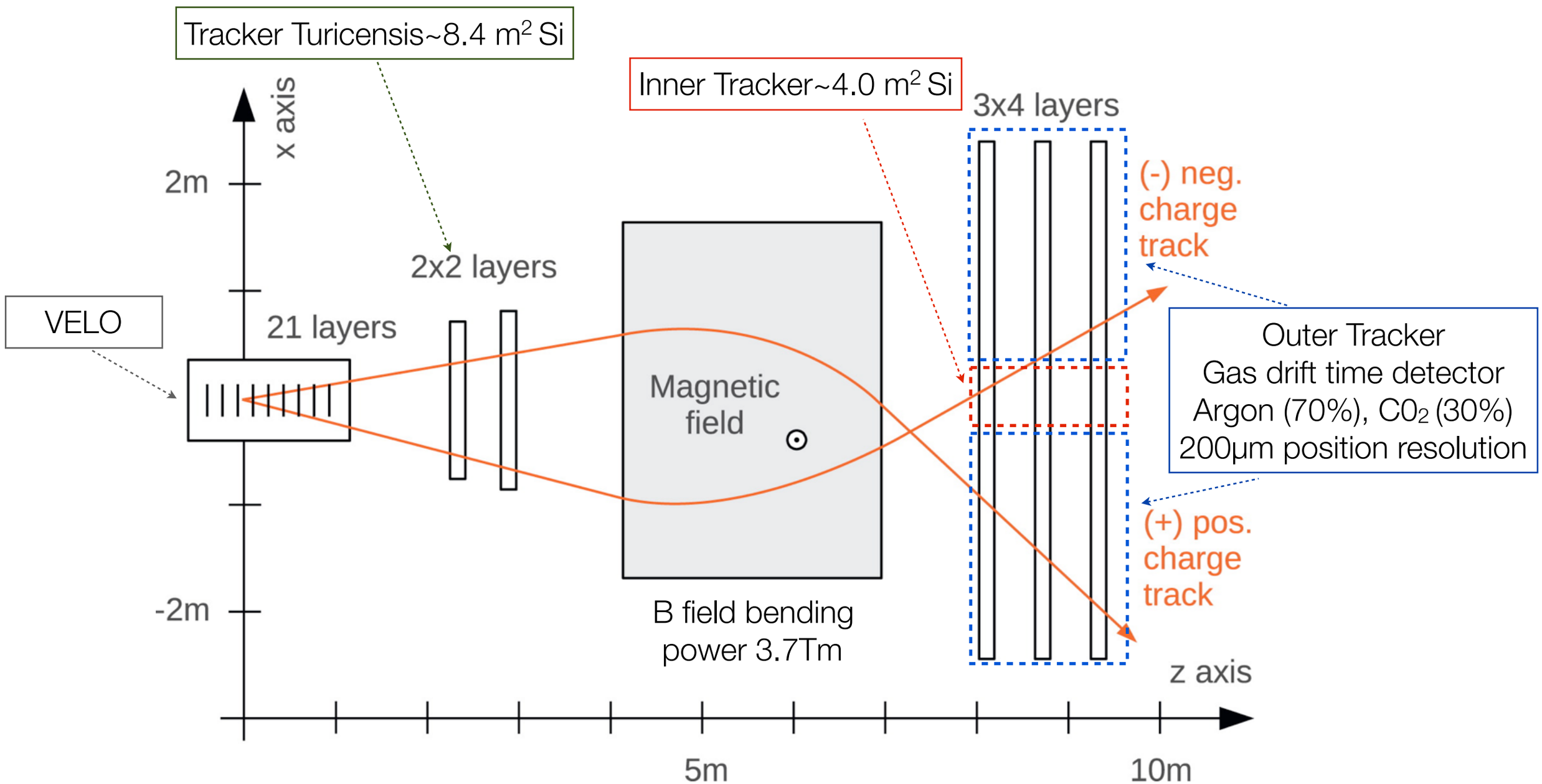
- Consistent with LHCb measurement LHCb $\alpha = 0.05 \pm 0.17 \pm 0.07$ PLB 724, 27 (2013) but not with pQCD [-0.17,-0.14] and HQET predictions 0.78
- LHCb measured $P = 0.06 \pm 0.07 \pm 0.02$

LHCb detector

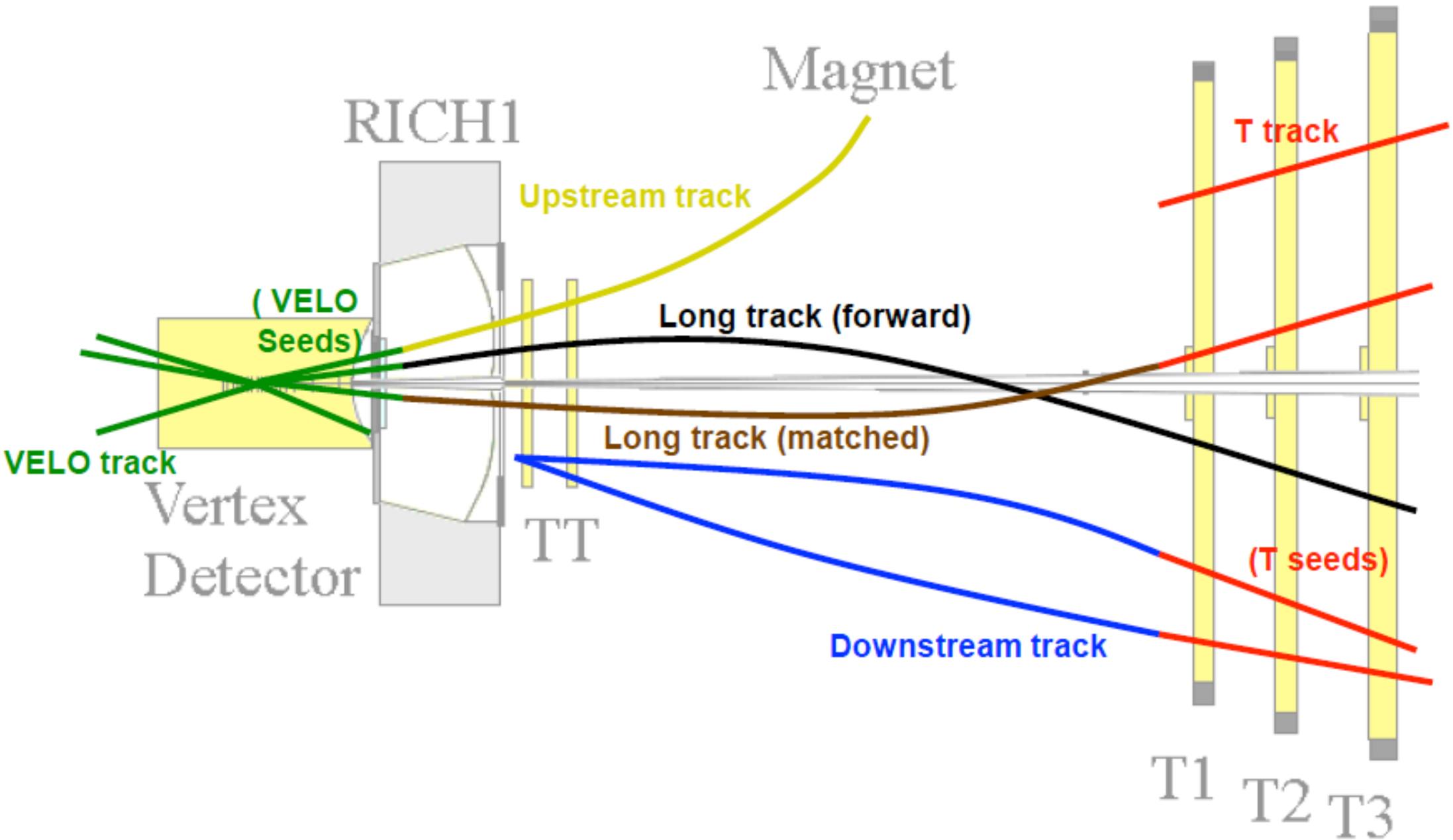


LHCb tracking system

TT: 500μm thick, single sided Si strip detector, pitch~100-200μm, vertical and stereo angle strips arrangement (x-u-v-x)=(0°,-5°,+5°,0°)



Track definitions at LHCb



Ghost track = is a fake track. For example it can be formed by matching a real track segment in the VELO (VELO seed) with a real track segment in the downstream tracker (T seed)