Results from LHCb in charmless b-baryon decays

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on behalf of the LHCb collaboration

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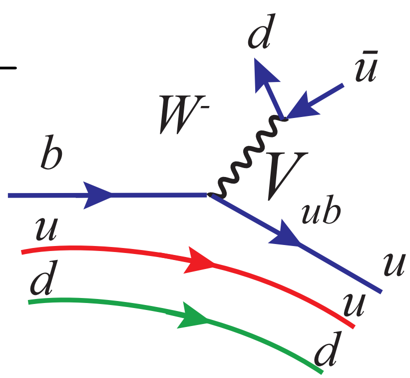
Beauty baryons at LHCb

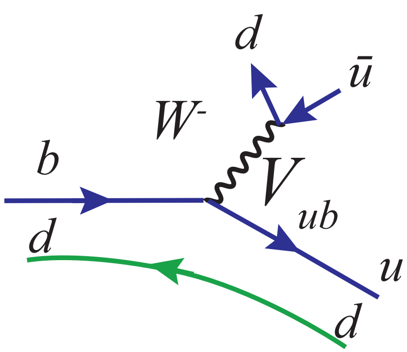
- Most precise measurement of $|V_{ub}|$ using $\Lambda_b^0 \to p\mu^-\bar{\nu}_\mu$ decays
  LHCb: Nature Physics 10 (2015) 1038
- First observation of pentaquarks using $\Lambda_b^0 \to J/\psi p K^-$ decays
  LHCb: Phys. Rev. Lett. 115, 072001 (2015)
- Observation of Ξ'^-_b and Ξ'^*_b in $\Xi_b^0\pi^-$ mode
  LHCb: Phys. Rev. Lett. 114, 062004 (2015)
- Observation of two orbitally excited Λ_b^{*0} states
  LHCb: Phys. Rev. Lett. 109, 172003 (2012)
- Mass, lifetimes and branching ratios measurements
- Search for *CPV* **CDF: Phys. Rev. Lett. 113, 242001**
  LHCb: JHEP 04 (2014) 087 **LHCb: JHEP 07 (2014) 103**
  and other from LHCb presented here....
- At LHCb b-baryons are produced in unprecedented quantities
  - opens a new field in flavour physics for precision measurements

Physics Motivation

- *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 with respect to B mesons

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





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

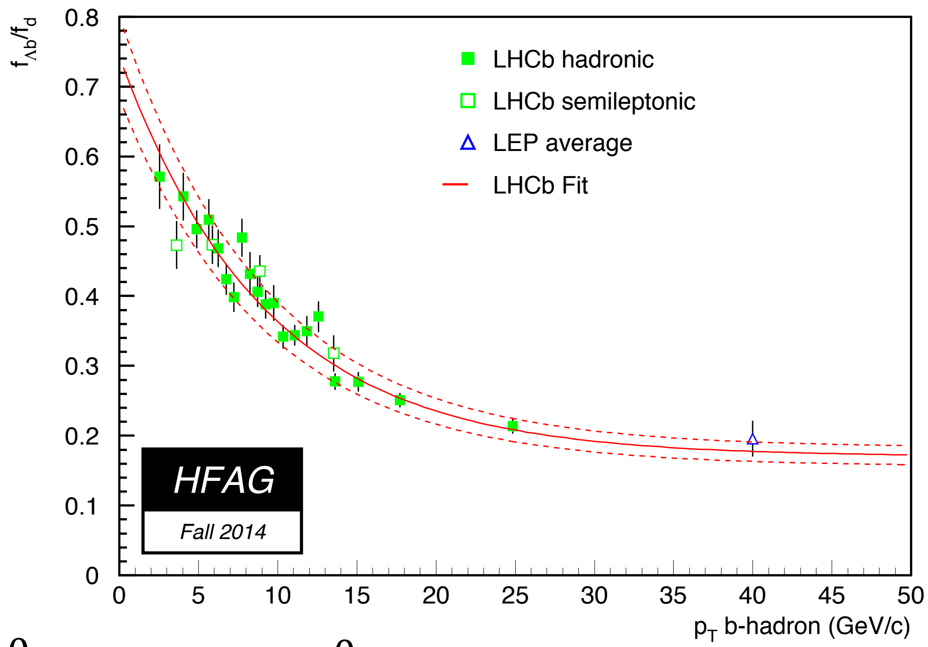
- Same underlying short distance physics as B mesons, with different spin and QCD structure
- New *CPV* sources

b-baryons production

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

$$f_{\Lambda_b^0} = P\left(b \rightarrow \Lambda_b^0\right)$$

$$f_d = P\left(b \rightarrow B^0\right)$$



- Production of Ξ_b^0 is 1/5 the Λ_b^0 production from a naive estimate

Phys.Rev.Lett. 113 (2014) 032001

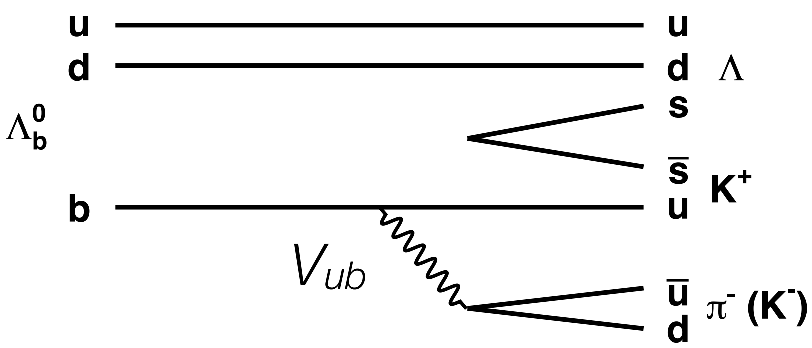
Experimental results

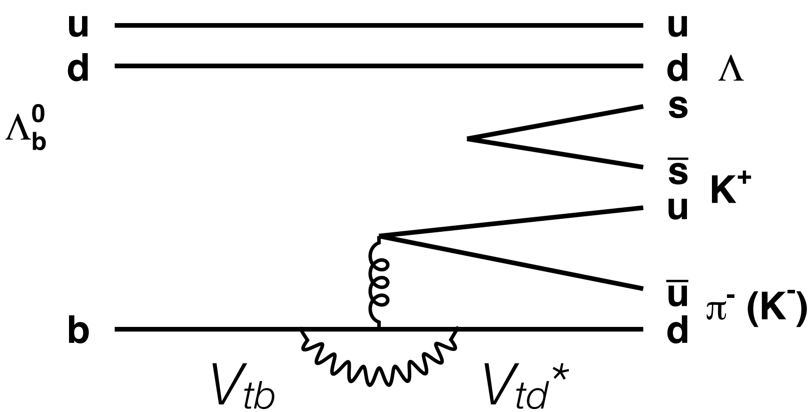
- $\Lambda_b \to \Lambda h^+ h'^-$ 3 body decay, search for *CPV* with $\Delta\mathcal{A}_{CP}$
  - $\Lambda_b \to \Lambda\phi$, search for *CPV* with triple products
- $\Lambda_b \to p\pi^-\pi^+\pi^-$ 4 body decay, search for *CPV* with triple products
- $\Xi_b^- \to p h^- h'^-$ first searches for charmless Ξ_b^- decays

$\Lambda_b^0 \to \Lambda h^+ h'^-$ & $\Lambda_b^0 \to \Lambda\phi$ decays

JHEP 05 (2016) 081

- Never observed before
- Proceed via tree-level (V_{ub}) or loop-induced
- Suppressed decay rates in SM
- Potential *CPV* due to large interference



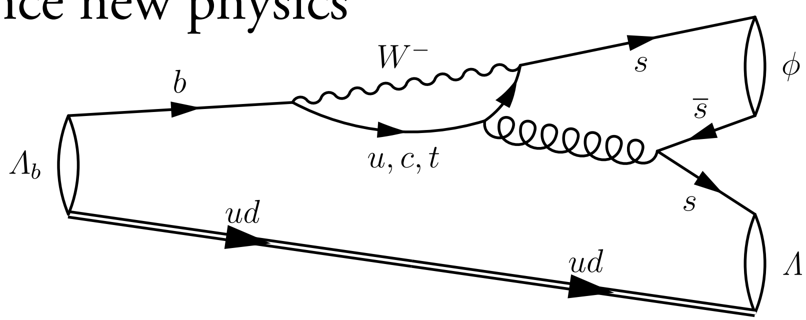


$\Lambda_b^0 \to \Lambda\phi$

Phys. Lett. B759 (2016) 282

- $b \to s\bar{s}s$ transition studied in B^0, B_s 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



$\Lambda_b^0 \to \Lambda h^+ h'^-$ signal yields

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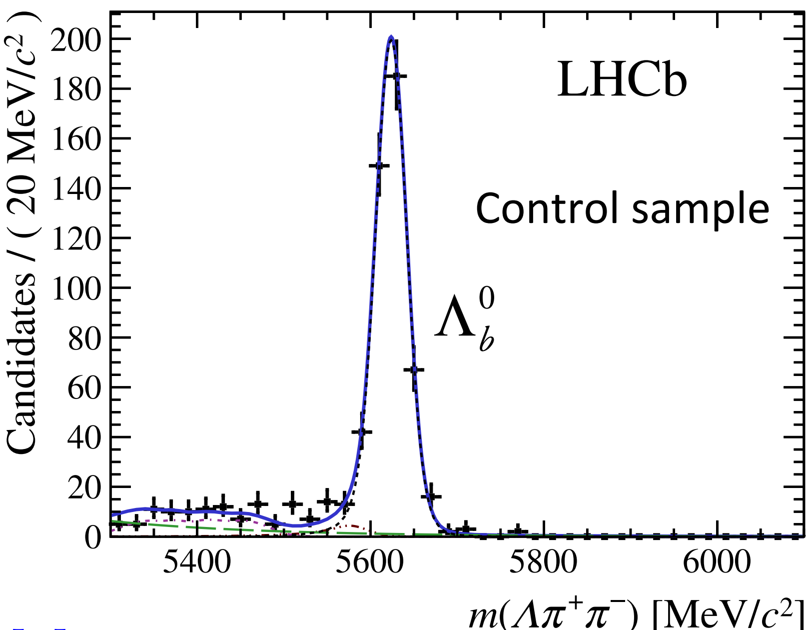
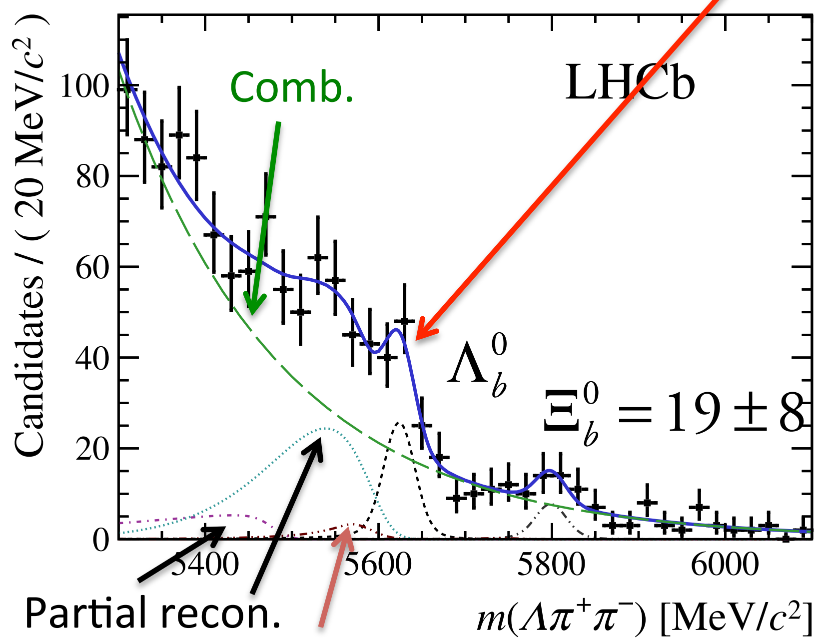
Evidence

$$N_{control}(\Lambda_b^0 \to \Lambda_c^+ \pi^-) = 471 \pm 22 \qquad N_{sig}(\Lambda_b^0 \to \Lambda \pi^+ \pi^-) = 64 \pm 14, \; 4.7\sigma$$





Measurements:

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

$\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \pi^-)$
Control sample

Upper limits at 90 (95)% CL

$$\frac{f_{\Xi_b^0}}{f_{\Lambda_b^0}} \times \mathcal{B}(\Xi_b^0 \to \Lambda \pi^+ \pi^-) < 1.7(2.1) \times 10^{-6}$$

$\Lambda_b^0 \to \Lambda h^+ h'^-$ signal yields

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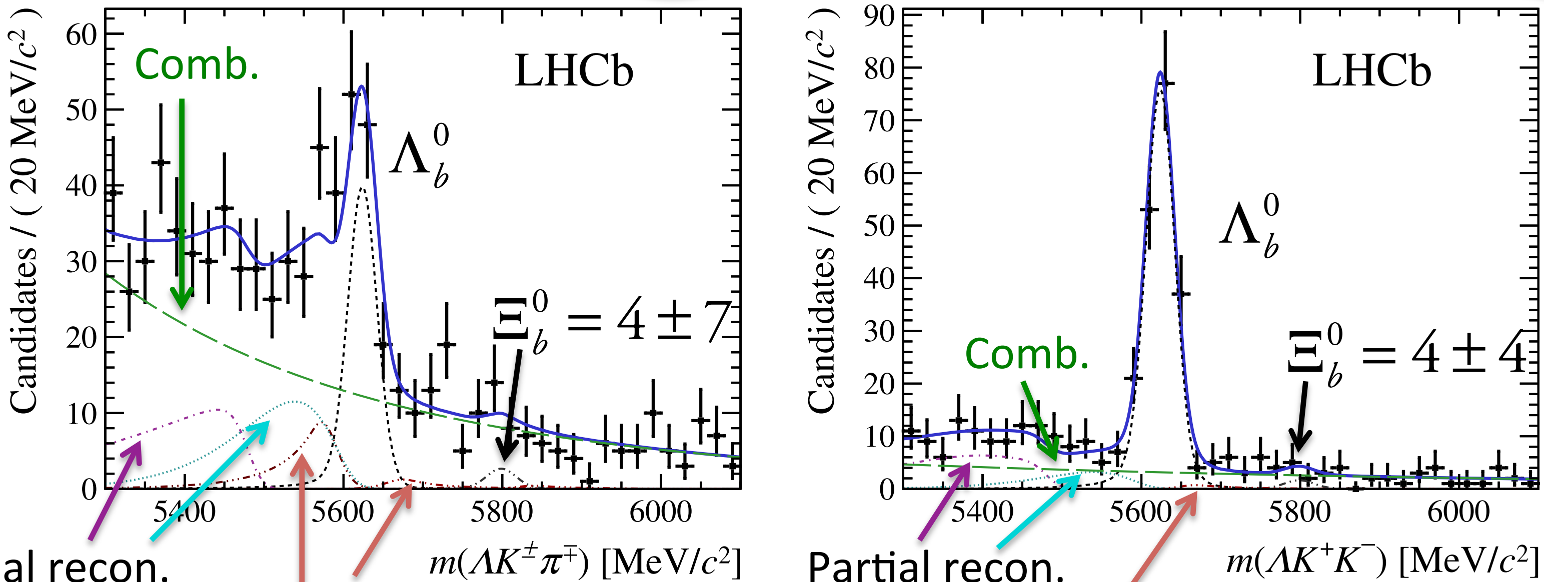
First observation

$N_{sig}(\Lambda K^\pm \pi^\mp) = 97 \pm 14, 8.1\sigma$ $\quad$ $N_{sig}(\Lambda K^+ K^-) = 185 \pm 15, 15.8\sigma$



Measurements:

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

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

Upper limits at 90 (95)% CL

$$\frac{f_{\Xi_b^0}}{f_{\Lambda_b^0}} \times \mathcal{B}(\Xi_b^0 \to \Lambda K^- K^+) < 0.3(0.4) \times 10^{-6}$$

$$\frac{f_{\Xi_b^0}}{f_{\Lambda_b^0}} \times \mathcal{B}(\Xi_b^0 \to \Lambda K^- \pi^+) < 0.8(1.0) \times 10^{-6}$$

Search for CPV

JHEP 05 (2016) 081

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

- N^{corr} = efficiency-corrected yield for Λ_b^0 ($\bar{\Lambda}_b^0$) decays

- Use $\Lambda_b^0 \to (\Lambda\pi^+)_{\Lambda_c^+}\pi^-$ as control model:
  - Negligible CPV effect
  - Production asymmetry $\mathcal{A}_P$ cancel at first order
  - Most detection asymmetry $\mathcal{A}_D$ cancel at first order

$$\mathcal{A}_{CP} = \mathcal{A}_{CP}^{raw} - (\mathcal{A}_P + \mathcal{A}_D)$$

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

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

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

Consistent with CP symmetry

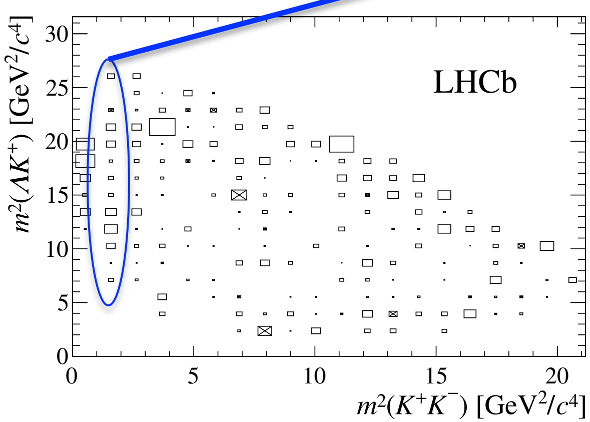
$\Lambda_b^0 \to \Lambda\phi$ signal yields

Phys. Lett. B759 (2016) 282

JHEP 05 (2016) 081

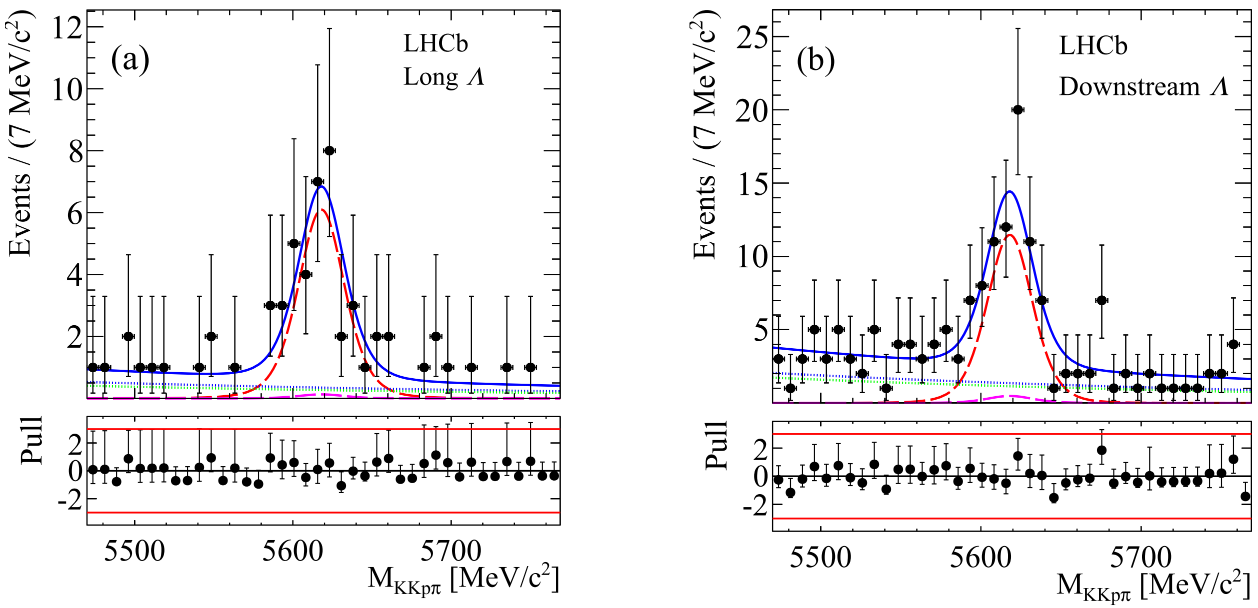
Dalitz plot

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



First observation

$$N_{sig}(\Lambda_b^0 \to \Lambda\phi) = 89 \pm 13, 5.9\sigma$$



$$\mathcal{B}(\Lambda_b^0 \to \Lambda\phi) = (5.18 \pm 1.04 \pm 0.35^{+0.50}_{-0.43} \pm 0.44) \times 10^{-6}$$

Stat. unc.

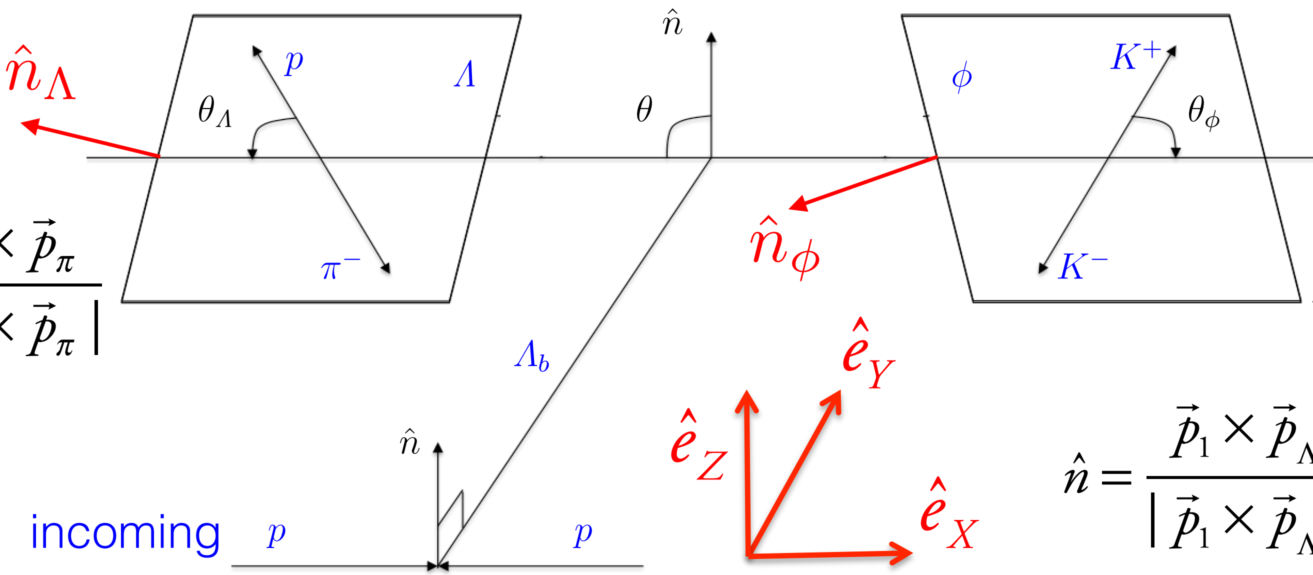
Syst. unc.

$\mathcal{B}(B^0 \to K_s\phi)$ Control sample

$f_d / f_{\Lambda_b^0}$ Fragmentation frac.

Triple product asymmetries

Phys. Lett. B759 (2016) 282



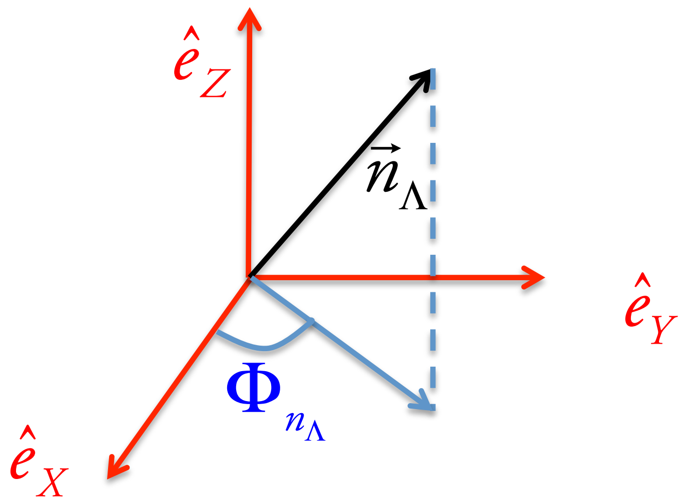
$$\hat{n}_\Lambda = \frac{\vec{p}_p \times \vec{p}_\pi}{|\vec{p}_p \times \vec{p}_\pi|}$$

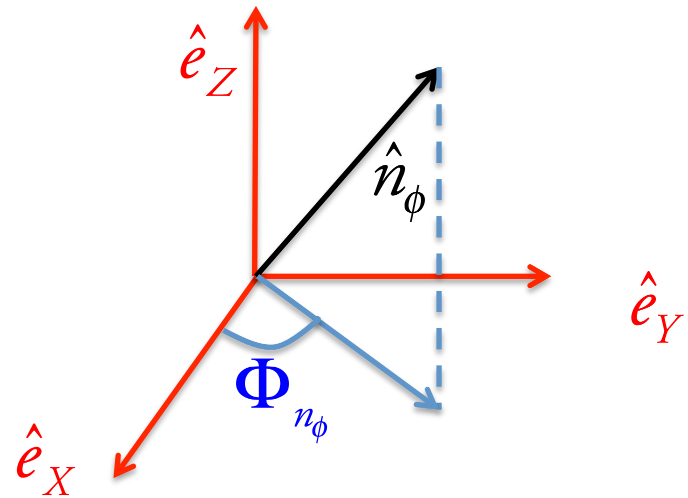
$$\hat{n}_\phi = \frac{\vec{p}_{K^+} \times \vec{p}_{K^-}}{|\vec{p}_{K^+} \times \vec{p}_{K^-}|}$$

$$\hat{n} = \frac{\vec{p}_1 \times \vec{p}_{\Lambda_b^0}}{|\vec{p}_1 \times \vec{p}_{\Lambda_b^0}|}$$

Triple product asymmetries

Phys. Lett. B759 (2016) 282





Triple products $\hat{T}$-odd:

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

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

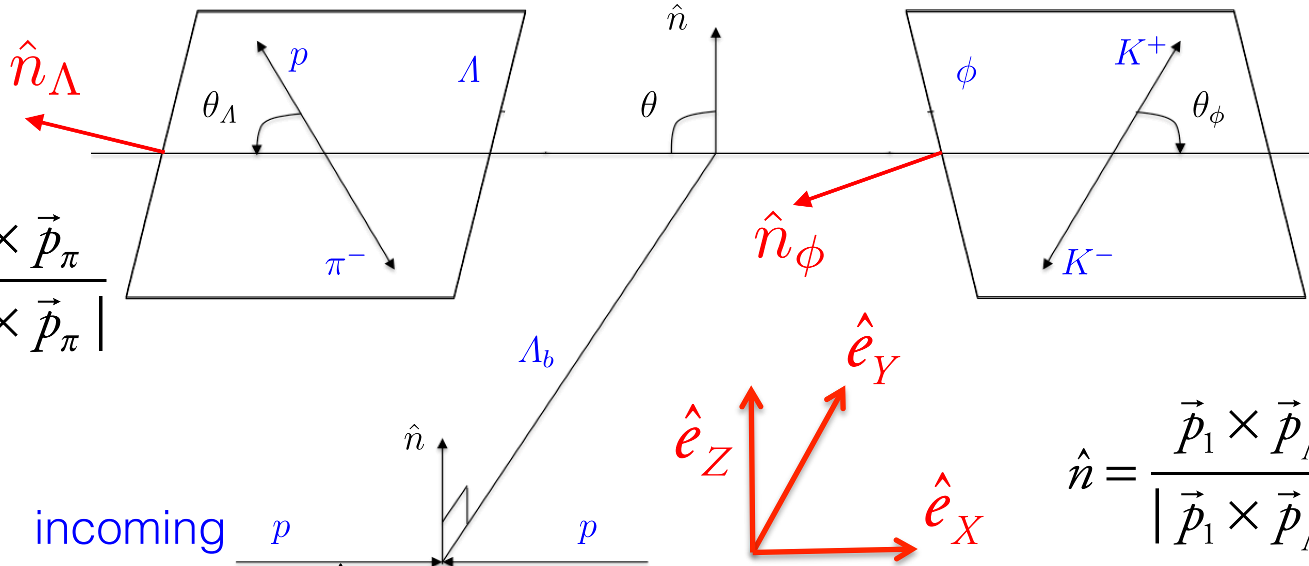
where:

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

$$\vec{n}_\Lambda = \frac{\vec{p}_p \times \vec{p}_\pi}{|\vec{p}_p \times \vec{p}_\pi|}, \vec{n}_\phi = \frac{\vec{p}_{K^+} \times \vec{p}_{K^-}}{|\vec{p}_{K^+} \times \vec{p}_{K^-}|}$$

Triple product asymmetries

Phys. Lett. B759 (2016) 282



$$\hat{n}_\Lambda = \frac{\vec{p}_p \times \vec{p}_\pi}{|\vec{p}_p \times \vec{p}_\pi|}$$

$$\hat{n}_\phi = \frac{\vec{p}_{K^+} \times \vec{p}_{K^-}}{|\vec{p}_{K^+} \times \vec{p}_{K^-}|}$$

$$\hat{n} = \frac{\vec{p}_1 \times \vec{p}_{\Lambda_b^0}}{|\vec{p}_1 \times \vec{p}_{\Lambda_b^0}|}$$

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

Triple products $\hat{T}$-odd:

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

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where:

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

$$\vec{n}_\Lambda = \frac{\vec{p}_p \times \vec{p}_\pi}{|\vec{p}_p \times \vec{p}_\pi|}, \vec{n}_\phi = \frac{\vec{p}_{K^+} \times \vec{p}_{K^-}}{|\vec{p}_{K^+} \times \vec{p}_{K^-}|}$$

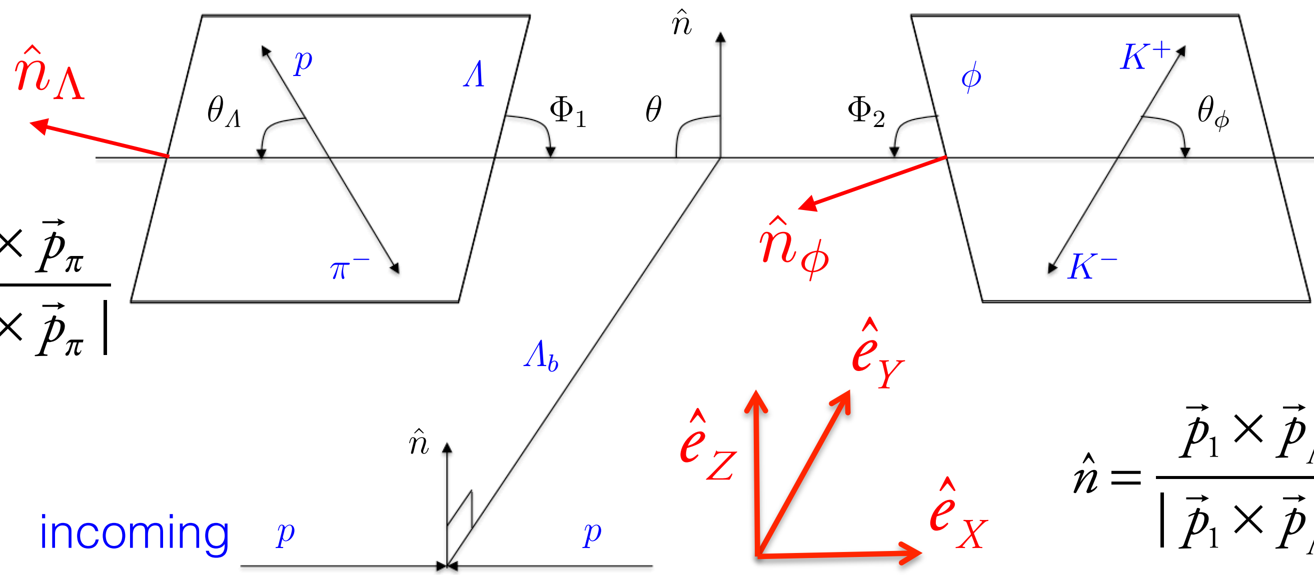
CPV observables, untagged sample:

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

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

Triple product asymmetries

Phys. Lett. B759 (2016) 282



$$\hat{n}_\Lambda = \frac{\vec{p}_p \times \vec{p}_\pi}{|\vec{p}_p \times \vec{p}_\pi|}$$

$$\hat{n}_\phi = \frac{\vec{p}_{K^+} \times \vec{p}_{K^-}}{|\vec{p}_{K^+} \times \vec{p}_{K^-}|}$$

$$\hat{n} = \frac{\vec{p}_1 \times \vec{p}_{\Lambda_b^0}}{|\vec{p}_1 \times \vec{p}_{\Lambda_b^0}|}$$

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

$$A_\Lambda^s = 0.13 \pm 0.12 \pm 0.05$$

$$A_\Lambda^c = -0.22 \pm 0.12 \pm 0.06$$

$$A_\phi^s = -0.07 \pm 0.12 \pm 0.01$$

$$A_\phi^c = -0.01 \pm 0.12 \pm 0.03$$

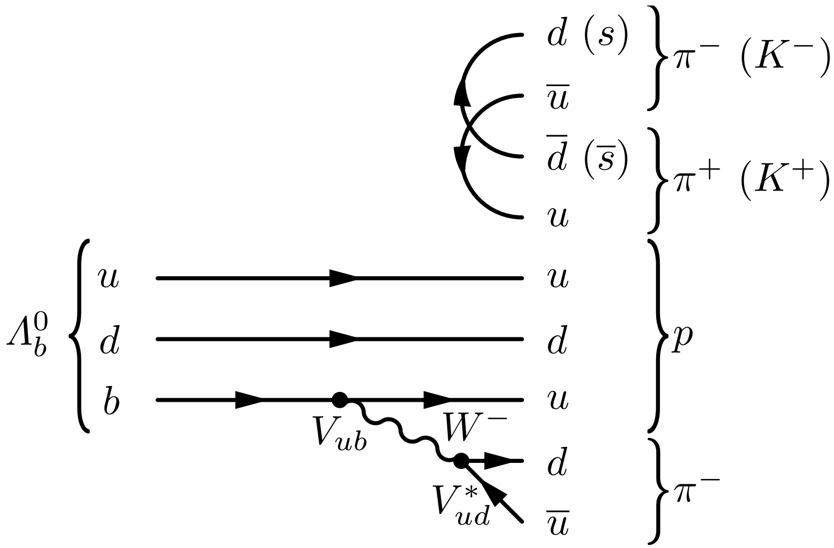
Consistent with CP symmetry

CPV in 4-body charmless decays

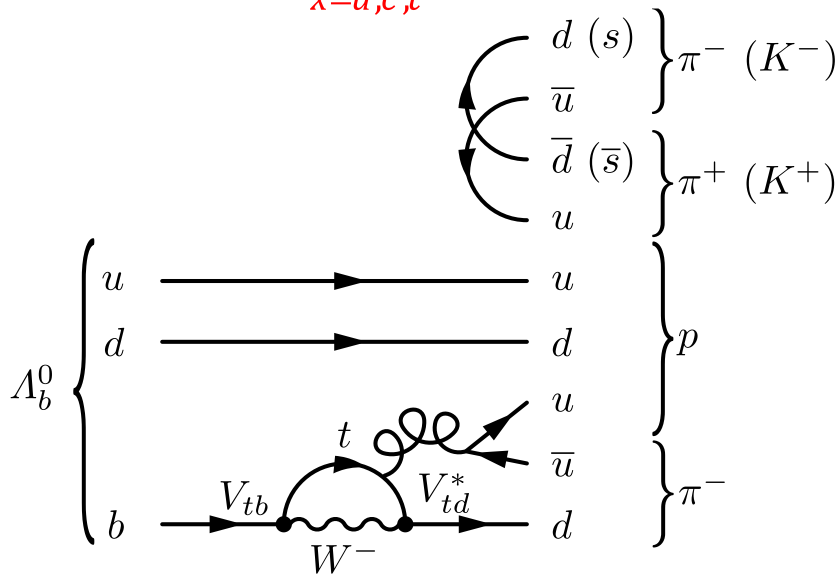
arXiv: 1609.05216, accepted for publication in Nature Physics

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

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



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

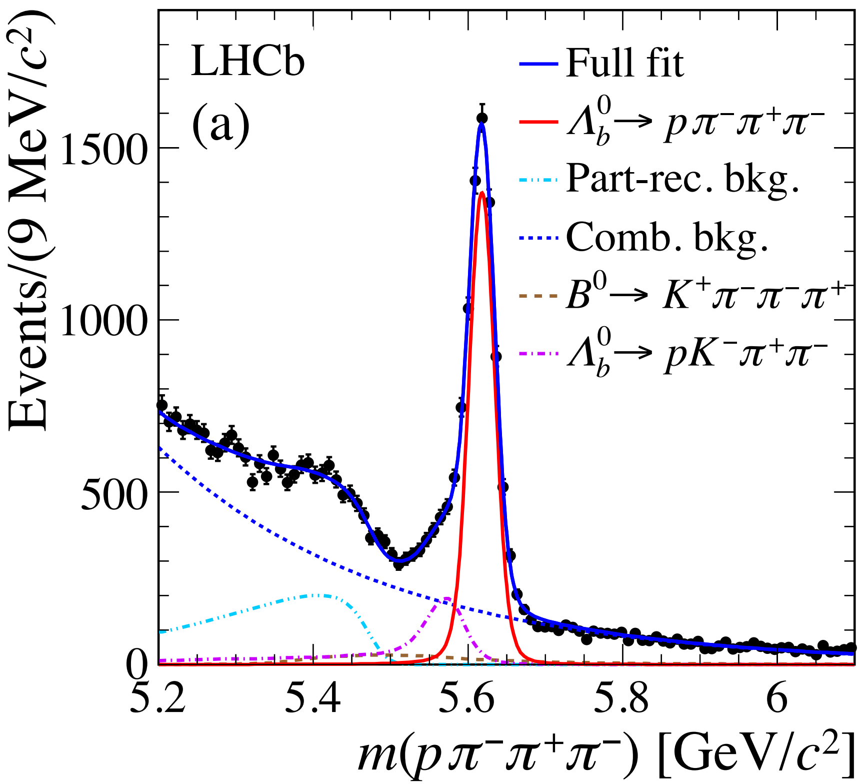


CPV in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ decays

arXiv: 1609.05216, accepted for publication in Nature Physics

- Use 4-body topology to build *P*-violating asymmetries

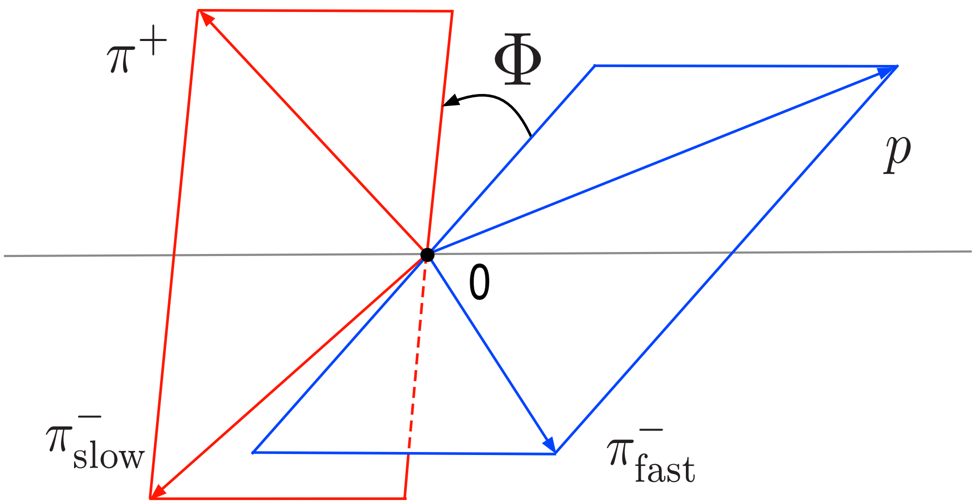
$$N_{sig}(\Lambda_b^0 \to p\pi^-\pi^+\pi^-) = 6646 \pm 105$$



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

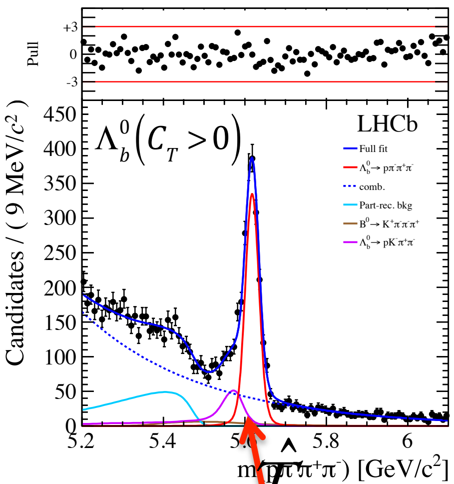
$$C_{\hat{T}} = \vec{p}_p \cdot \left(\vec{p}_{h_1^-} \times \vec{p}_{h_2^+}\right) \propto \sin\Phi, \text{ for } \Lambda_b^0$$

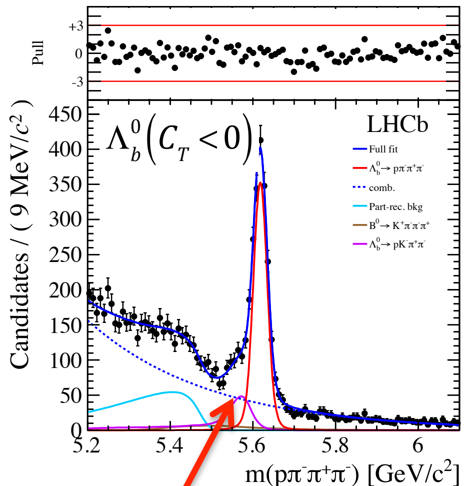
$$\bar{C}_{\hat{T}} = \vec{p}_{\bar{p}} \cdot \left(\vec{p}_{h_1^+} \times \vec{p}_{h_2^-}\right) \propto \sin\bar{\Phi}, \text{ for } \bar{\Lambda}_b^0$$



Asymmetries measurement

arXiv: 1609.05216, accepted for publication in Nature Physics



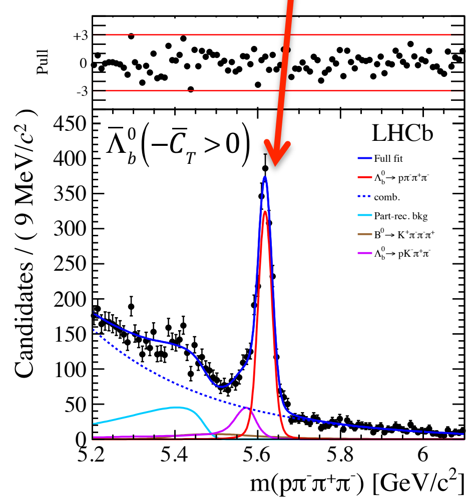


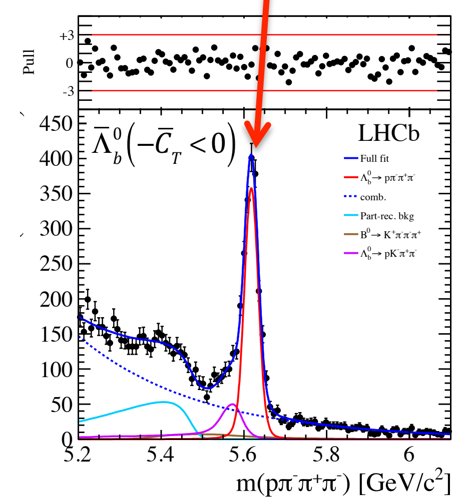
- P-odd, $\hat{T}$-odd asymmetry:

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

- P-odd, $\hat{T}$-odd asymmetry:

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





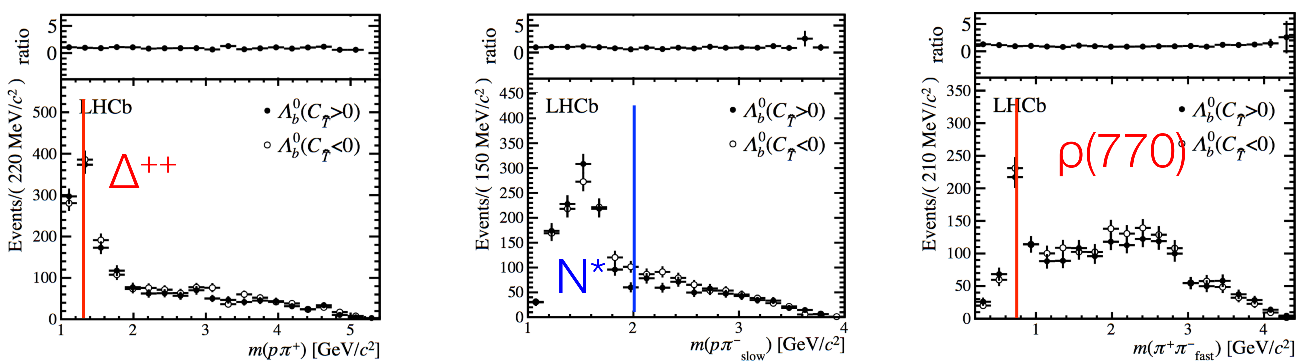
- P violating observable $\quad a_P^{\hat{T}\text{-odd}} = \frac{1}{2}\left(A_{\hat{T}} + \bar{A}_{\hat{T}}\right)$
- CP violating observable $\quad a_{CP}^{\hat{T}\text{-odd}} = \frac{1}{2}\left(A_{\hat{T}} - \bar{A}_{\hat{T}}\right)$

Binning definition $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$

arXiv: 1609.05216, accepted for publication in Nature Physics

	Phase space bin	$m(p\pi^+)$	$m(p\pi^-_{slow})$	$m(\pi^+\pi^-_{slow}), m(\pi^+\pi^-_{fast})$ GeV/c^2	$\|\Phi\|$
Δ^{++}	1	(1.07, 1.23)			$(0, \frac{\pi}{2})$
	2	(1.07, 1.23)			$(\frac{\pi}{2}, \pi)$
	3	(1.23, 1.35)		ρ(770) peak	$(0, \frac{\pi}{2})$
	4	(1.23, 1.35)			$(\frac{\pi}{2}, \pi)$
N^*	5	(1.35, 5.34)	(1.07, 2.00)	$m(\pi^+\pi^-_{slow}) < 0.78$ or $m(\pi^+\pi^-_{fast}) < 0.78$	$(0, \frac{\pi}{2})$
	6	(1.35, 5.34)	(1.07, 2.00)	$m(\pi^+\pi^-_{slow}) < 0.78$ or $m(\pi^+\pi^-_{fast}) < 0.78$	$(\frac{\pi}{2}, \pi)$
	7	(1.35, 5.34)	(1.07, 2.00)	$m(\pi^+\pi^-_{slow}) > 0.78$ and $m(\pi^+\pi^-_{fast}) > 0.78$	$(0, \frac{\pi}{2})$
	8	(1.35, 5.34)	(1.07, 2.00)	$m(\pi^+\pi^-_{slow}) > 0.78$ and $m(\pi^+\pi^-_{fast}) > 0.78$	$(\frac{\pi}{2}, \pi)$
	9	(1.35, 5.34)	(2.00, 4.00)	$m(\pi^+\pi^-_{slow}) < 0.78$ or $m(\pi^+\pi^-_{fast}) < 0.78$	$(0, \frac{\pi}{2})$
	10	(1.35, 5.34)	(2.00, 4.00)	$m(\pi^+\pi^-_{slow}) < 0.78$ or $m(\pi^+\pi^-_{fast}) < 0.78$	$(\frac{\pi}{2}, \pi)$
	11	(1.35, 5.34)	(2.00, 4.00)	$m(\pi^+\pi^-_{slow}) > 0.78$ and $m(\pi^+\pi^-_{fast}) > 0.78$	$(0, \frac{\pi}{2})$
	12	(1.35, 5.34)	(2.00, 4.00)	$m(\pi^+\pi^-_{slow}) > 0.78$ and $m(\pi^+\pi^-_{fast}) > 0.78$	$(\frac{\pi}{2}, \pi)$

Scheme A to exploit resonant structures

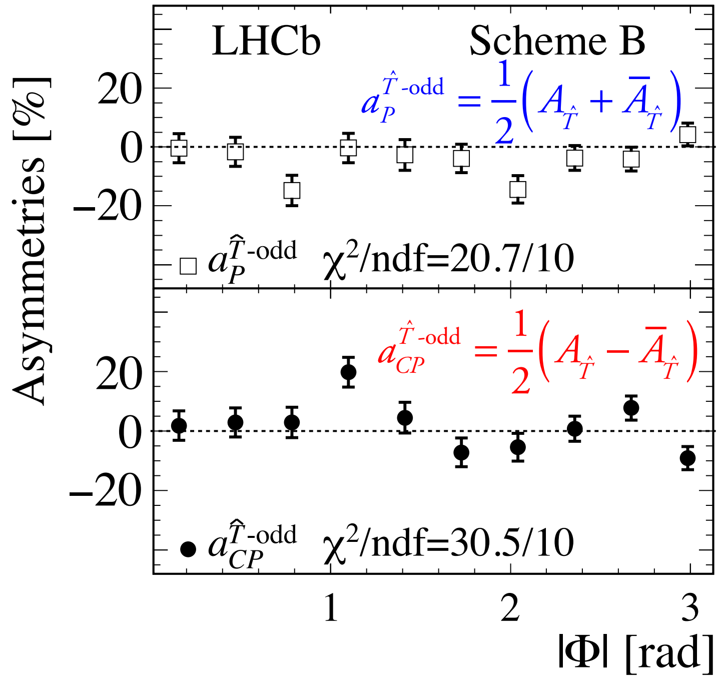


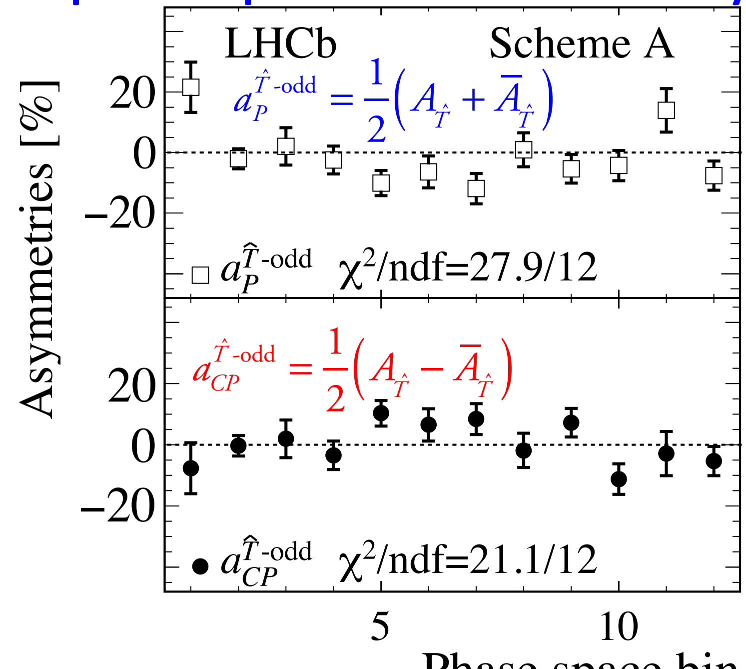
Scheme B to exploit $|\Phi|$ dependence

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

First evidence for *CPV* in baryons

arXiv: 1609.05216, accepted for publication in Nature Physics





Combined results of 2 binning schemes:
CP symmetry p-value=9.8×10^{-4}
3.3σ deviation
P symmetry compatible at 2.2σ

- 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

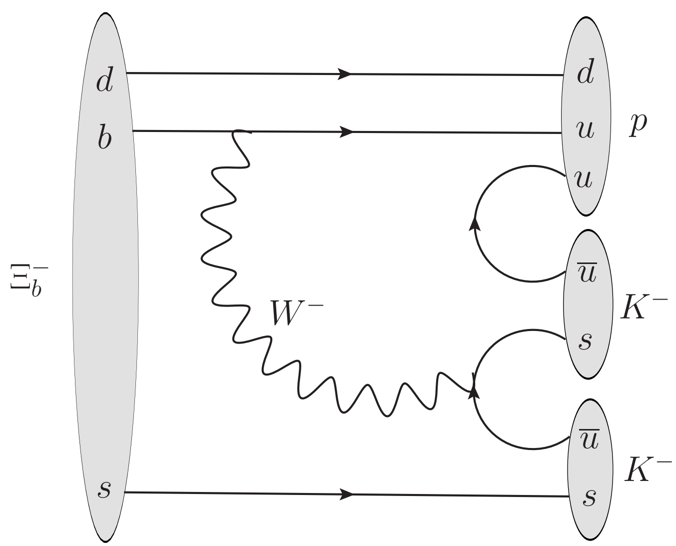
Study of $\Xi_b^- \to p h^- h'^-$ New result

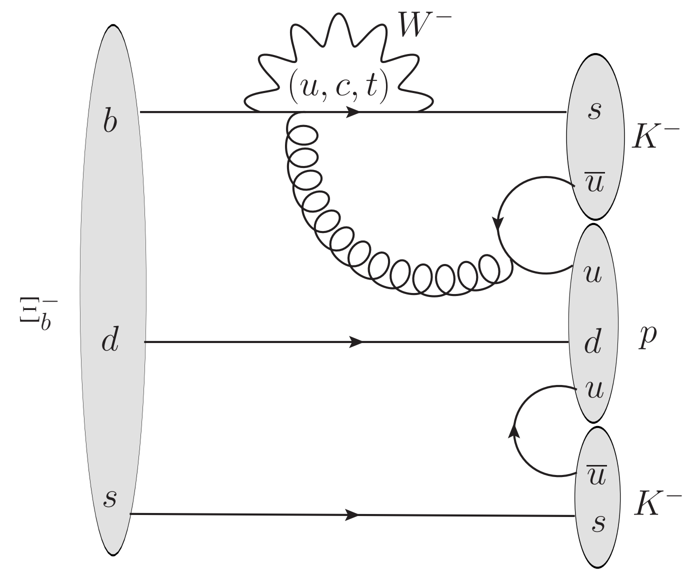
LHCb-PAPER-2016-050

Not only Λ_b^0

- First charmless Ξ_b^- decays
- Promising modes where to search for *CPV* in the future
- Significant *CP* asymmetries have been observed in regions of phase space of $B^- \to \pi^+\pi^-\pi^-, K^-\pi^+\pi^-, K^+K^-K^-, K^+K^-\pi^-$

  Phys. Rev. Lett. 111 (2013) 101801, Phys. Rev. Lett. 112 (2014) 011801, Phys. Rev. D90 (2014) 112004
- Do the equivalent *b*-baryon decays exhibit similar behaviour?





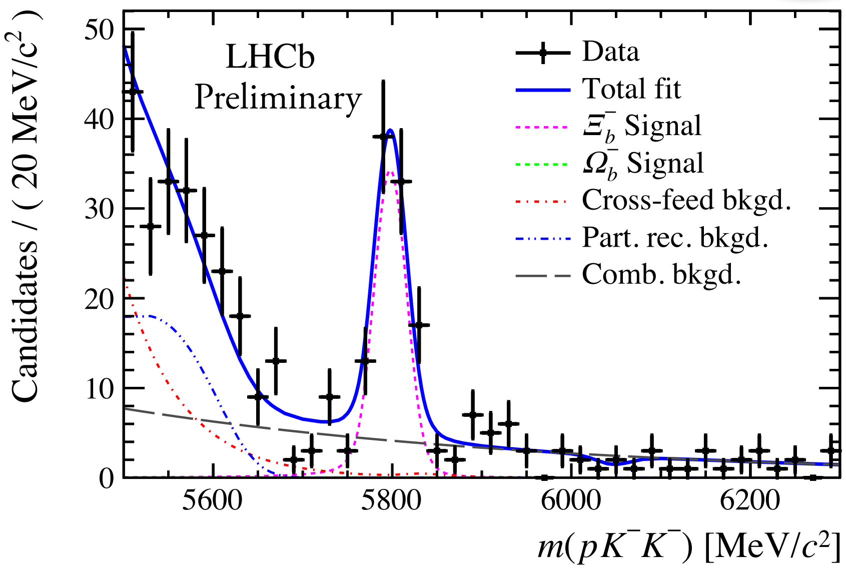
Study of $\Xi_b^- \to p h^- h'^-$

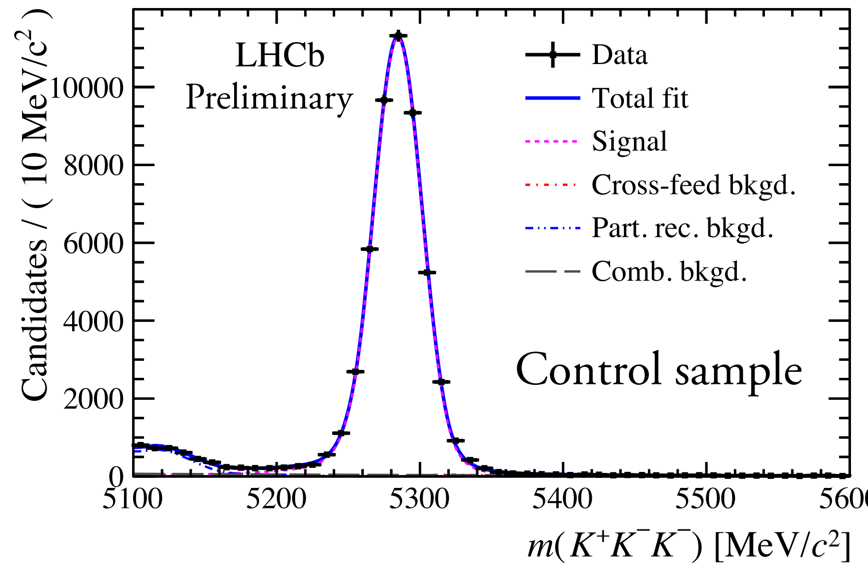
LHCb-PAPER-2016-050

First observation

$N_{sig}(\Xi_b^- \to pK^-K^-) = 82.9 \pm 10.4,\ 8.7\sigma$

$N_{control}(B^- \to K^+K^-K^-) = 50490 \pm 250$





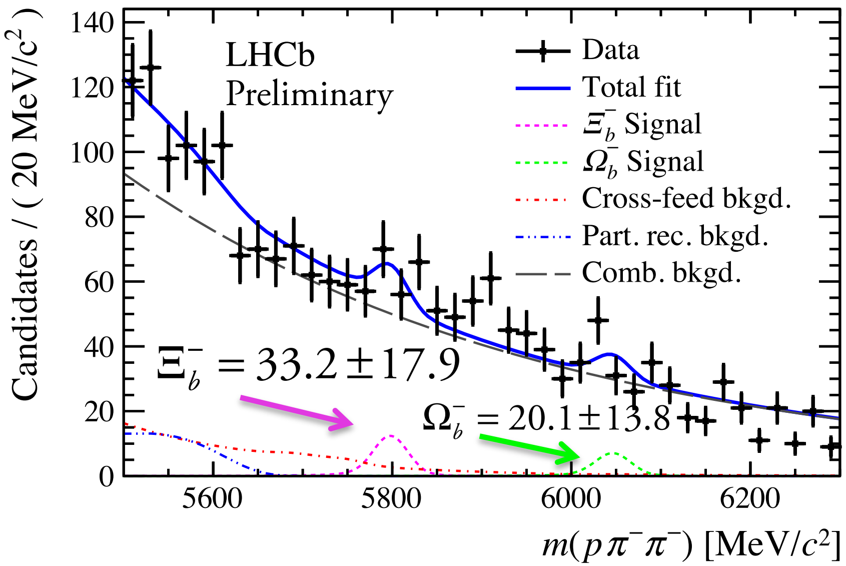
$$\frac{f_{\Xi_b^-}}{f_u}\frac{\mathcal{B}(\Xi_b^- \to pK^-K^-)}{\mathcal{B}(B^- \to K^+K^-K^-)} = \frac{N(\Xi_b^- \to pK^-K^-)}{N(B^- \to K^+K^-K^-)}\frac{\varepsilon(B^- \to K^+K^-K^-)}{\varepsilon(\Xi_b^- \to pK^-K^-)} = (265 \pm 35 \pm 47)\times 10^{-5}$$

Estimated from fit

Estimated from MC +
Data driven for PID cuts

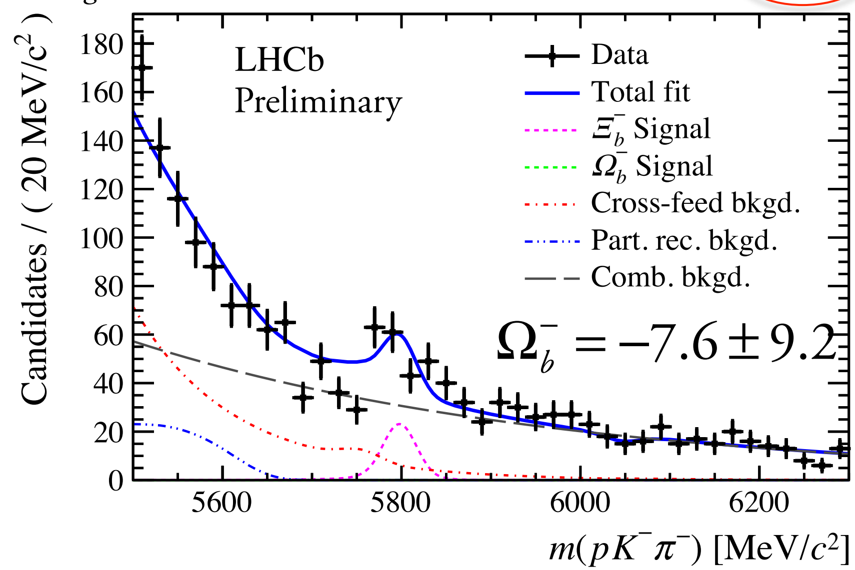
Study of $\Xi_b^- \to p h^- h'^-$

LHCb-PAPER-2016-050



Evidence

$$N_{sig}(\Xi_b^- \to pK^-\pi^-) = 59.6 \pm 16.0,\ 3.4\sigma$$



Upper limits at 90 (95)% CL

$$\frac{f_{\Omega_b^-}}{f_u}\frac{\mathcal{B}(\Omega_b^- \to pK^-K^-)}{\mathcal{B}(B^- \to K^+K^-K^-)} < 18(22)\times 10^{-5}$$

$$\frac{f_{\Omega_b^-}}{f_u}\frac{\mathcal{B}(\Omega_b^- \to pK^-\pi^-)}{\mathcal{B}(B^- \to K^+K^-K^-)} < 51(62)\times 10^{-5}$$

$$\frac{f_{\Omega_b^-}}{f_u}\frac{\mathcal{B}(\Omega_b^- \to p\pi^-\pi^-)}{\mathcal{B}(B^- \to K^+K^-K^-)} < 109(124)\times 10^{-5}$$

Measurements:

$$\frac{\mathcal{B}(\Xi_b^- \to pK^-\pi^-)}{\mathcal{B}(\Xi_b^- \to pK^-K^-)} = 0.98 \pm 0.27 \pm 0.09$$

$$\frac{\mathcal{B}(\Xi_b^- \to p\pi^-\pi^-)}{\mathcal{B}(\Xi_b^- \to pK^-K^-)} < 0.56(0.63)$$

Conclusions

- LHCb opens a new window to search *CPV* in baryon decays. Many b-baryon decays are observed for the first time
- First evidence for *CPV* in baryons is found in decays with a statistical significance of 3.3 σ
- *CPV* is searched for in many decays using Run1 data. With Run2 data, new b-baryons and new decays will be studied.
- Interesting to

  COMPARE THE RESULTS WITH MESONS

  - theoretical predictions are needed and more than welcome

Back-up

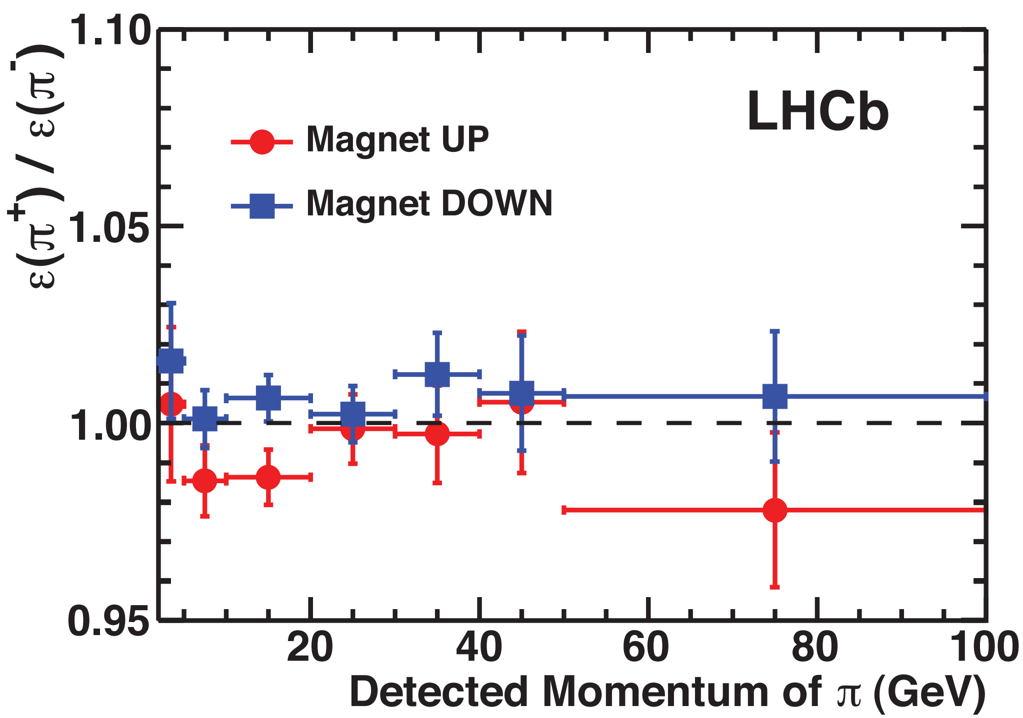
Experimental issue

Detector reconstruction asymmetries

- Detector is made of matter
  - is not *CP* symmetric

$$A_D(\pi\pm) \sim 0.1\% \quad A_D(K\pm) \sim 1\% \quad A_D(p/\bar{p}) \sim 1-2\%$$

- A_D can be measured using "ad hoc" abundand control sample



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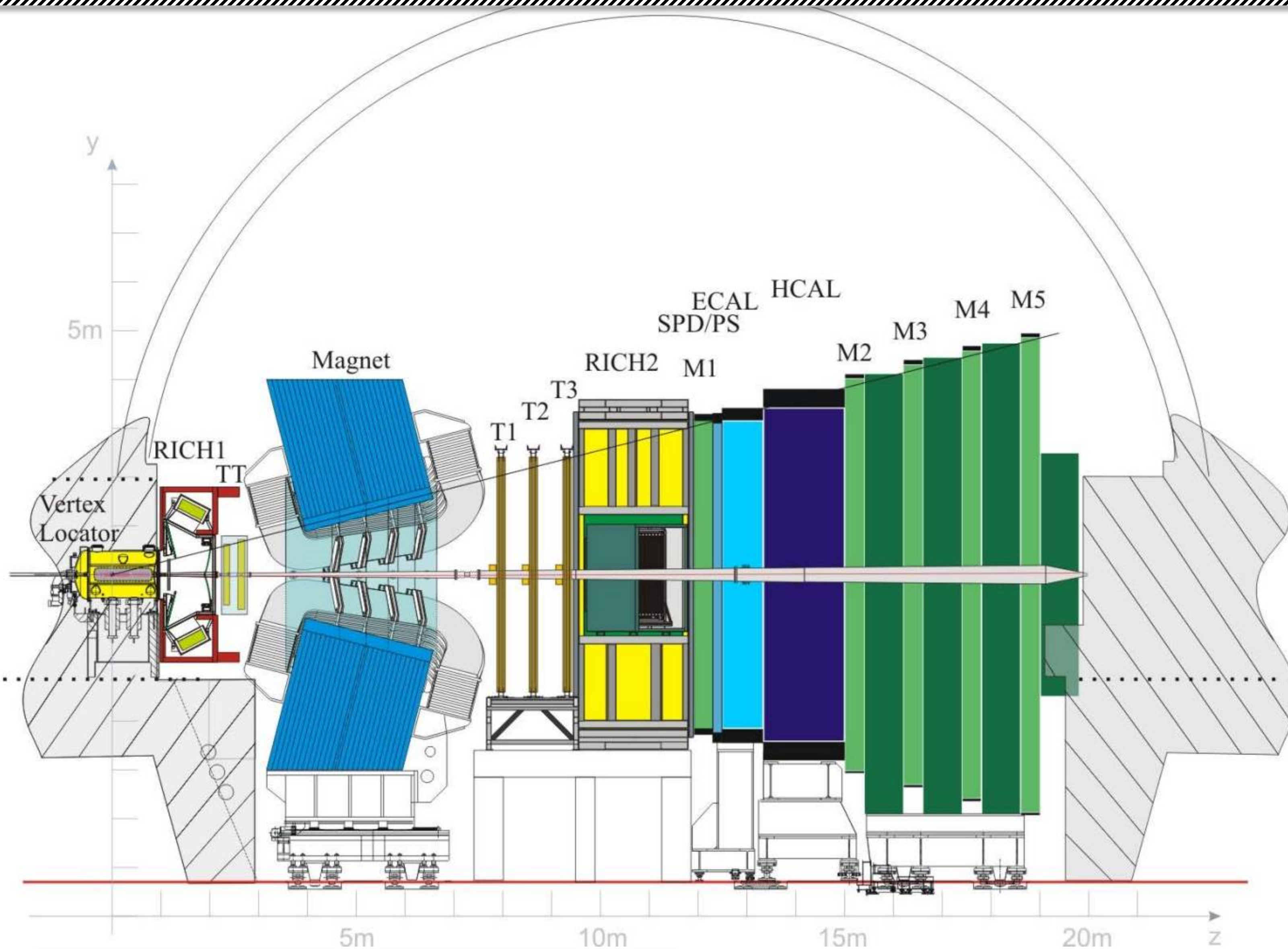
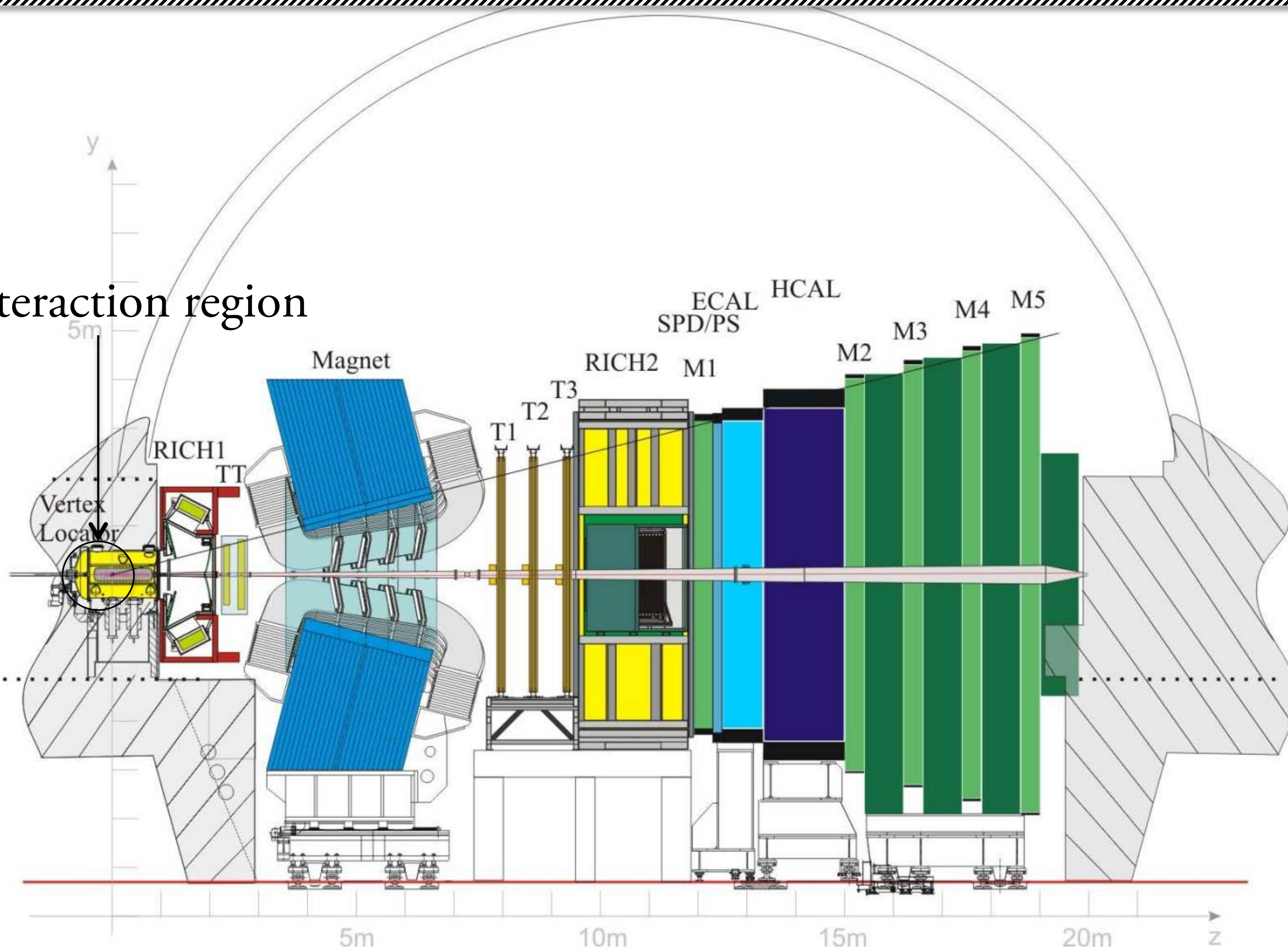
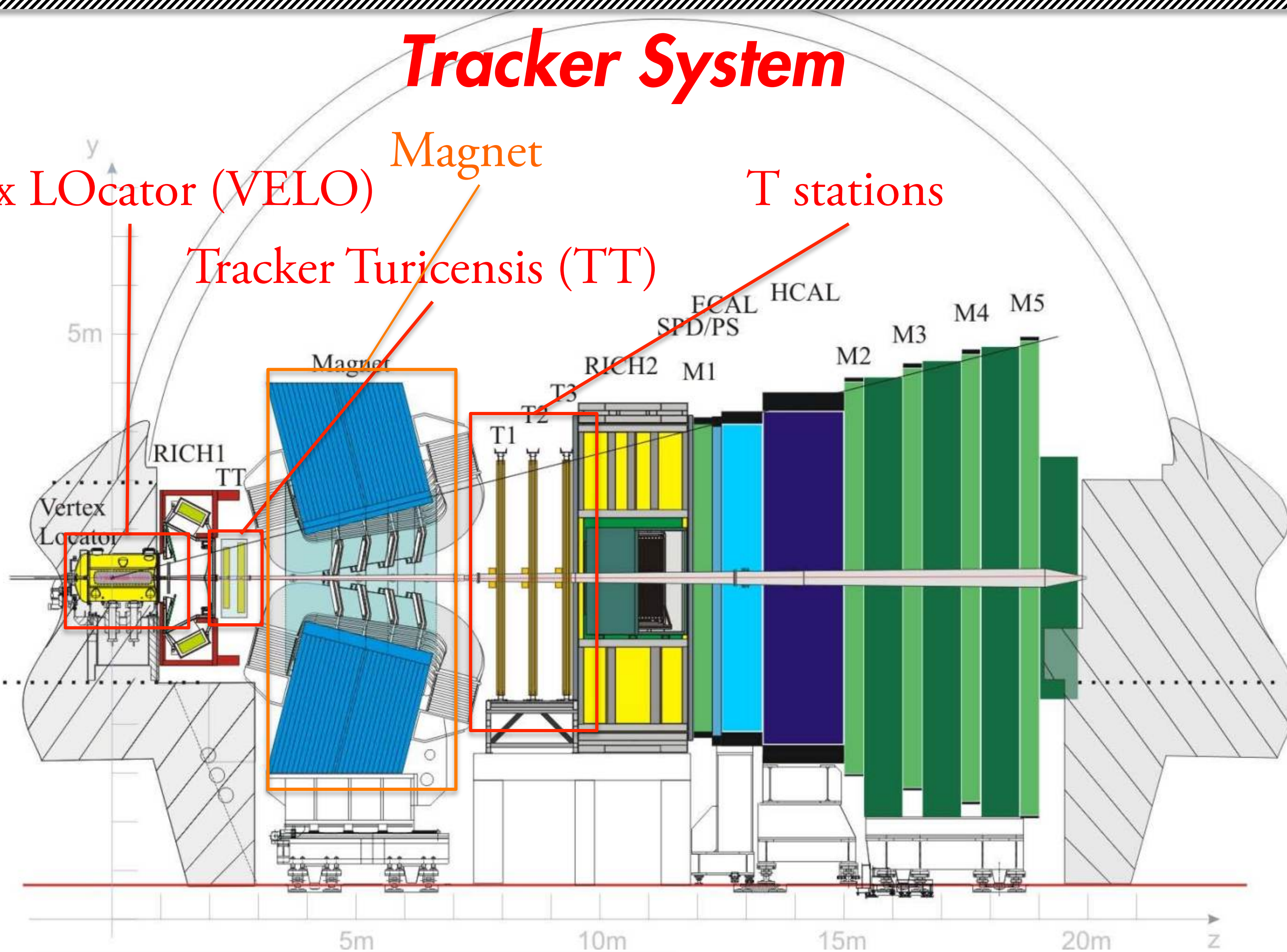
LHCb detector (side view)



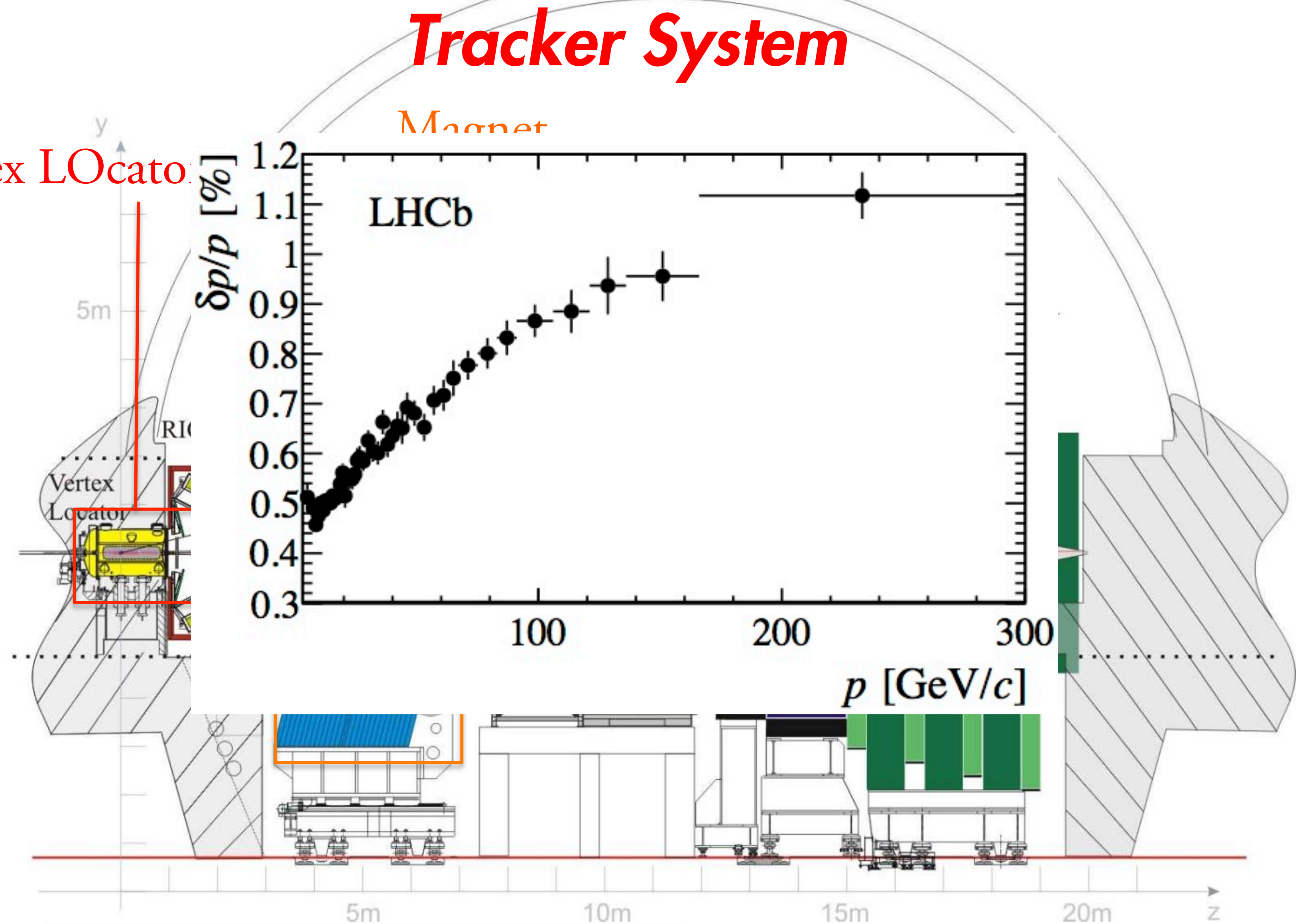
LHCb detector (side view)



LHCb detector (side view)

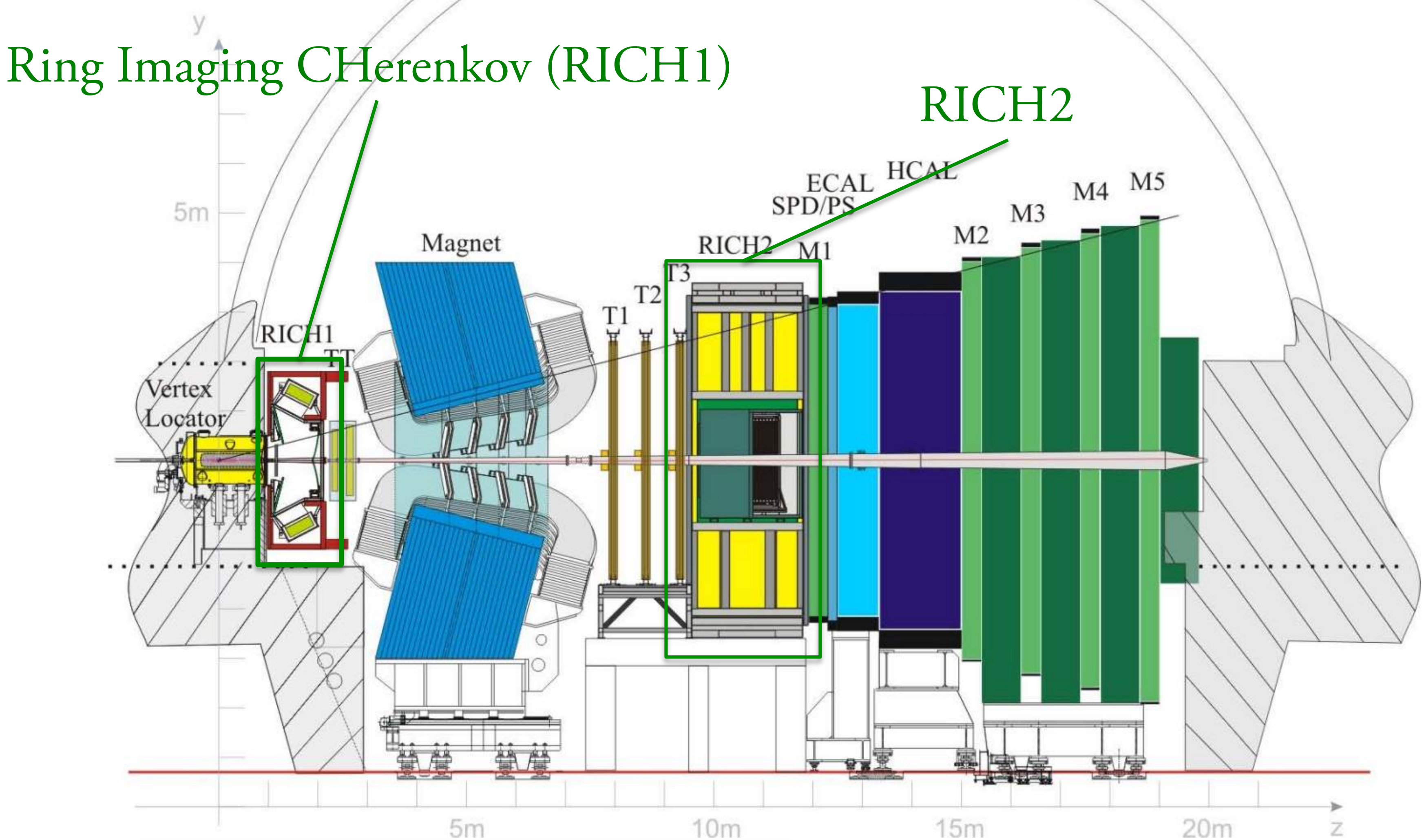


LHCb detector (side view)



LHCb detector (side view)

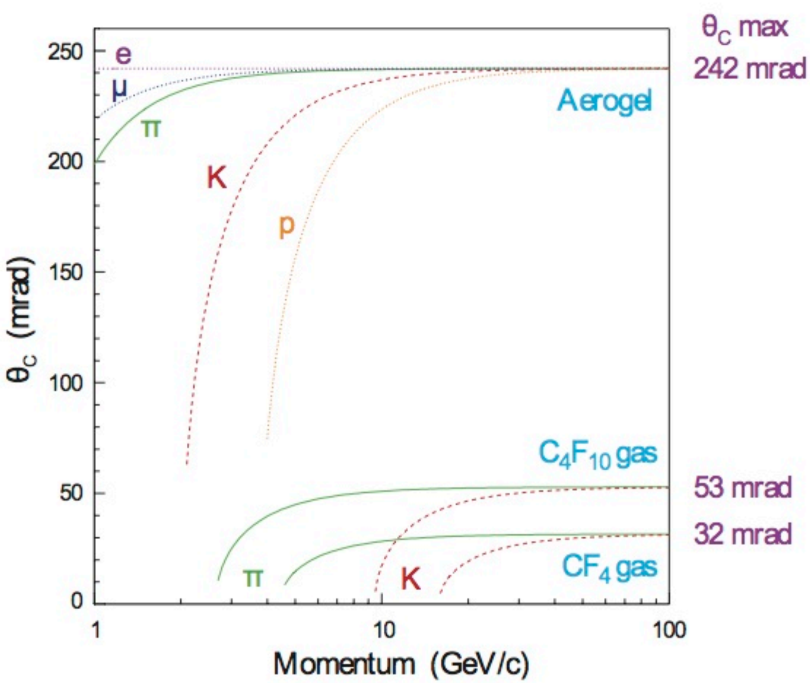
Particle Identification System

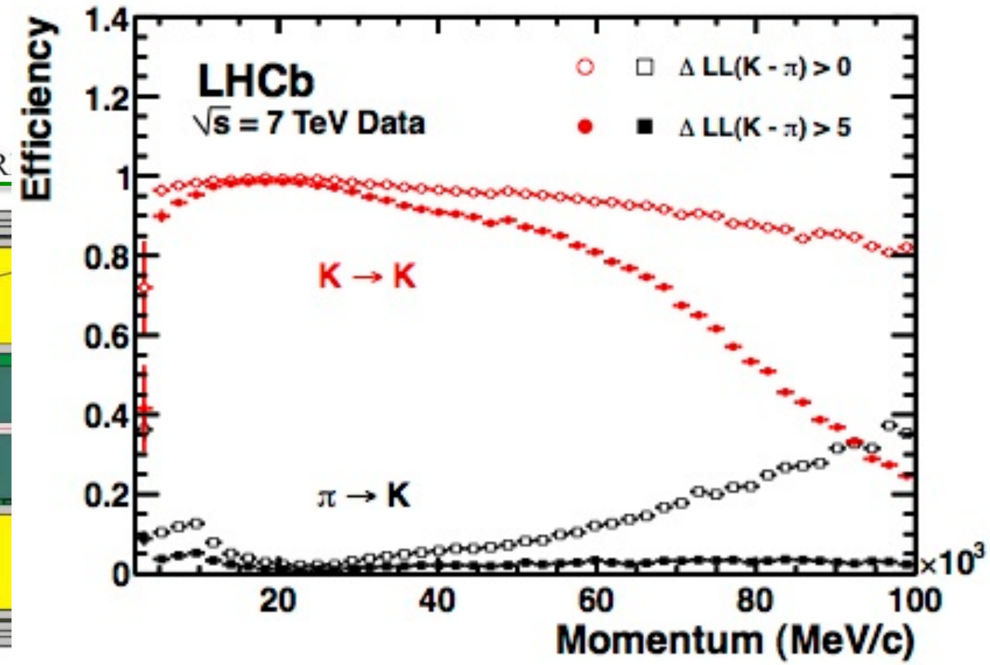


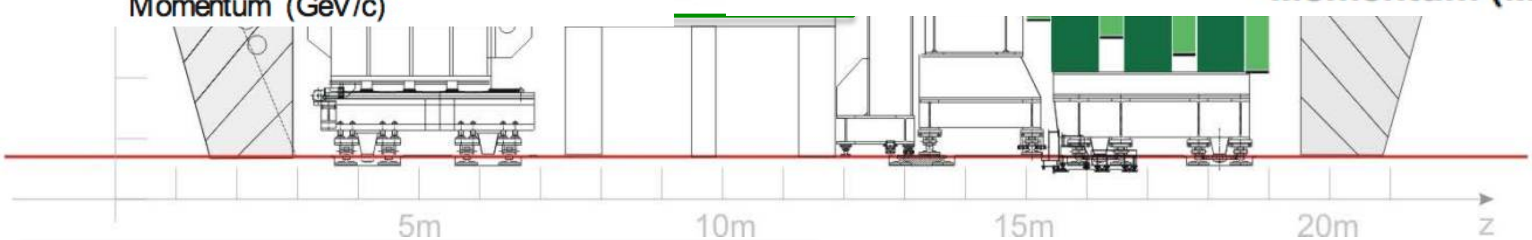
LHCb detector (side view)

Particle Identification System

Ring Imaging CHerenkov (RICH1)



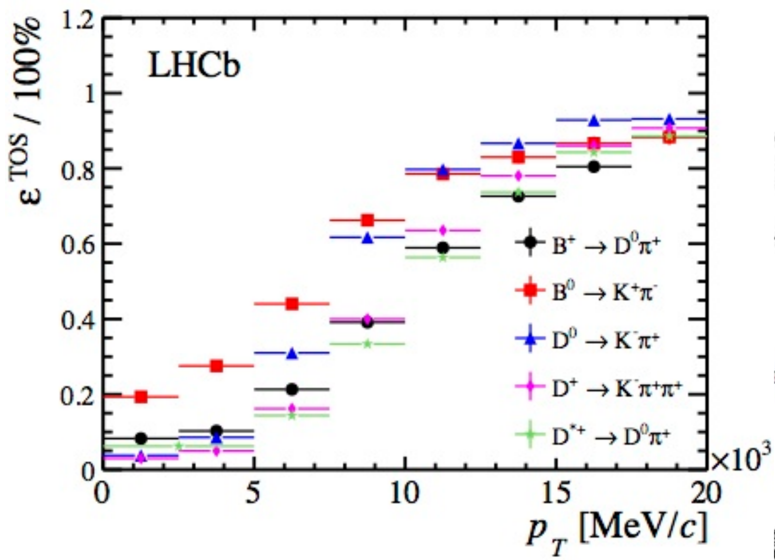




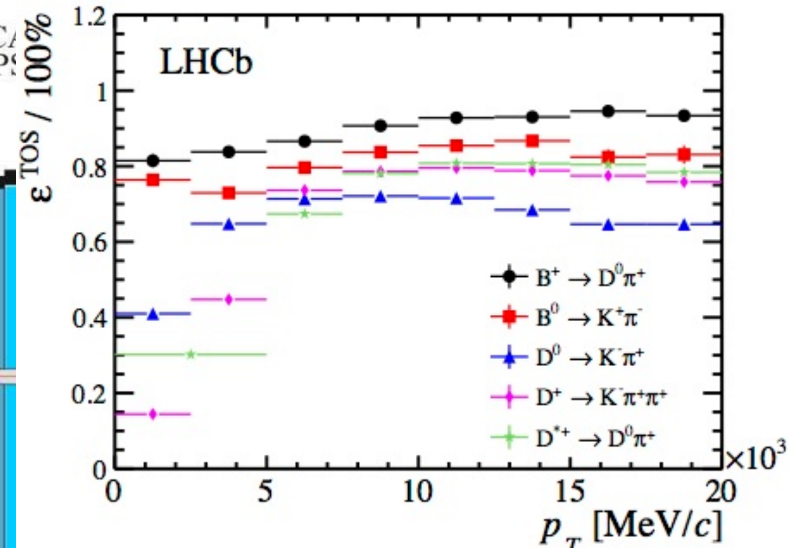
LHCb detector

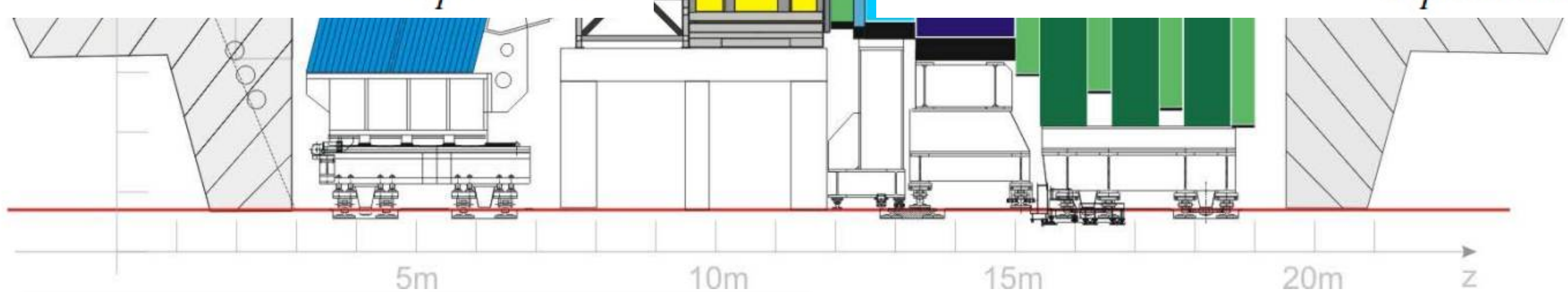
Trigger

L0 trigger efficiency



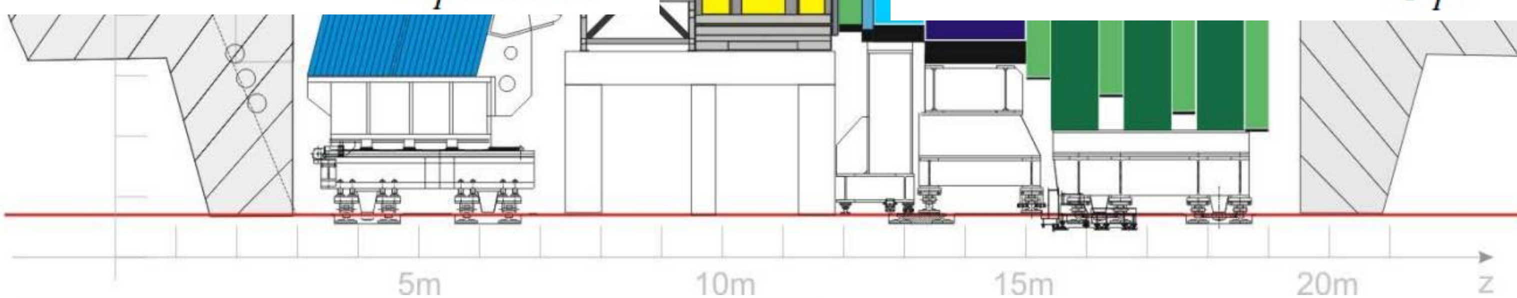
HLT1 trigger efficiency



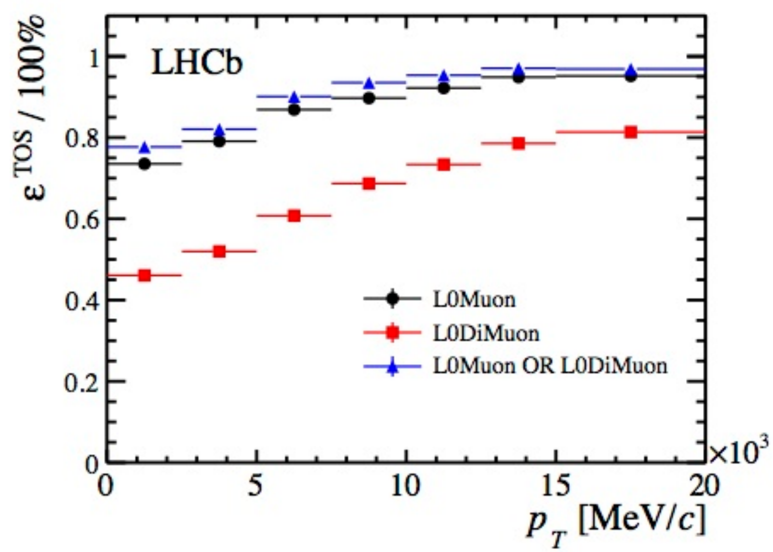


LHCb detector

Trigger



L0 trigger efficiency



HLT1 trigger efficiency