LHCb

INFN Istituto Nazionale di Fisica Nucleare

STVDIORVM UNIVERSITAS MEDIOLANENSIS

Measurement of matter-antimatter differences in beauty baryon decays

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Physics Motivations

- CP violation (*CPV*) necessary condition for baryogenesis

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- Matter ≠ Antimatter
- CKM mechanism introduced in the Standard Model to include *CPV*

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$$V_{CKM} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3\left[1-\left(1-\frac{\lambda^2}{2}\right)(\rho+i\eta)\right] & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

$$\underbrace{\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix}}_{\text{weak eigenstates}} = V_{\mathrm{CKM}} \underbrace{\begin{pmatrix} d \\ s \\ b \end{pmatrix}}_{\text{mass eigenstates}}$$

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No phases ⇒ no *CPV*

THE 

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{\text{CKM}} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

weak eigenstates mass eigenstates

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3 generation $\Rightarrow$ *CPV*!

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{\mathrm{CKM}} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

weak eigenstates mass eigenstates

Physics Motivations

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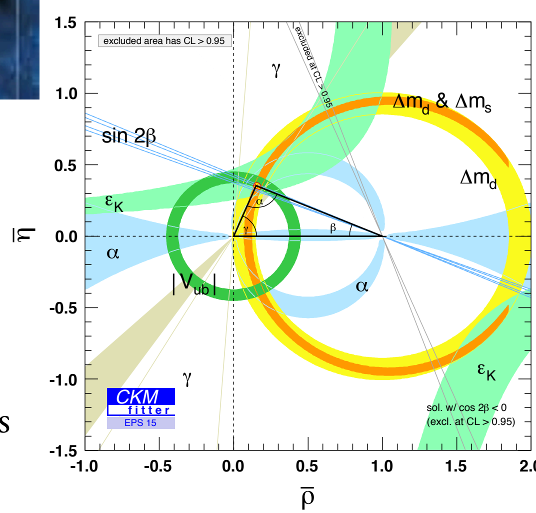
$$V_{CKM} = \boxed{\begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3\left[1-\left(1-\frac{\lambda^2}{2}\right)(\rho + i\eta)\right] & -A\lambda^2 & 1 \end{pmatrix}} + O(\lambda^4)$$

3 generation ⇒ *CPV*!

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{\mathrm{CKM}} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

weak eigenstates   mass eigenstates

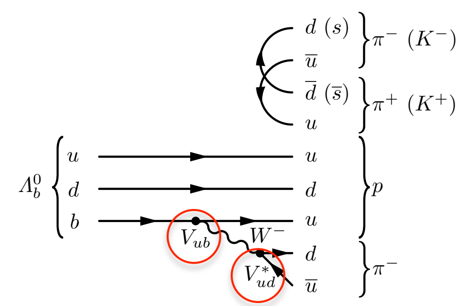


On cosmologic scale it doesn't work, but explain what we see in the experiments!!!

Physics Motivations

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

$$\left|A\left(\Lambda_b^0 \to phhh\right)\right|^2 =$$



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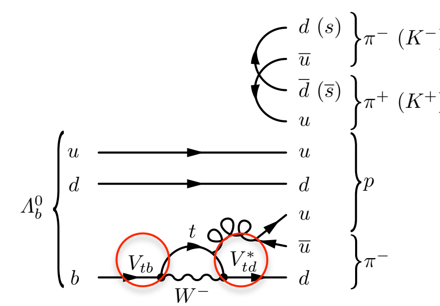

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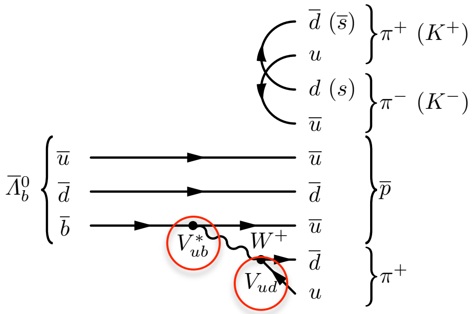
Interference:

$$\alpha = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right) \approx 90^\circ$$

$$\left|A\left(\overline{\Lambda}_b^0 \to \overline{p}\overline{h}\overline{h}\overline{h}\right)\right|^2 =$$



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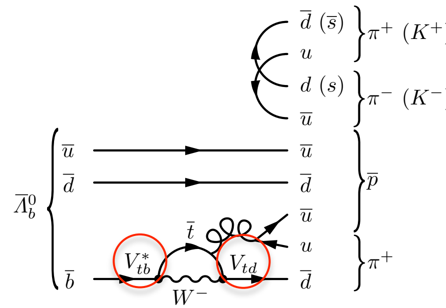

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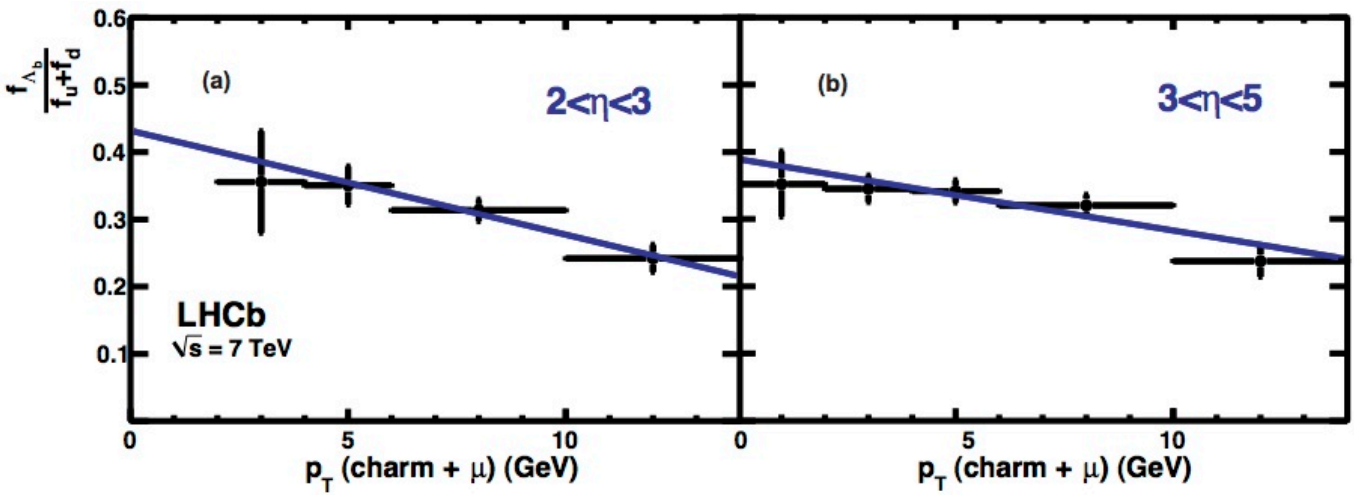
- $\left|A\left(\Lambda_b^0 \to phhh\right)\right|^2 \neq \left|A\left(\overline{\Lambda}_b^0 \to \overline{p}\overline{h}\overline{h}\overline{h}\right)\right|^2$
- Non negligible interference between tree and penguin diagrams
- Sensitive to new physics through loops

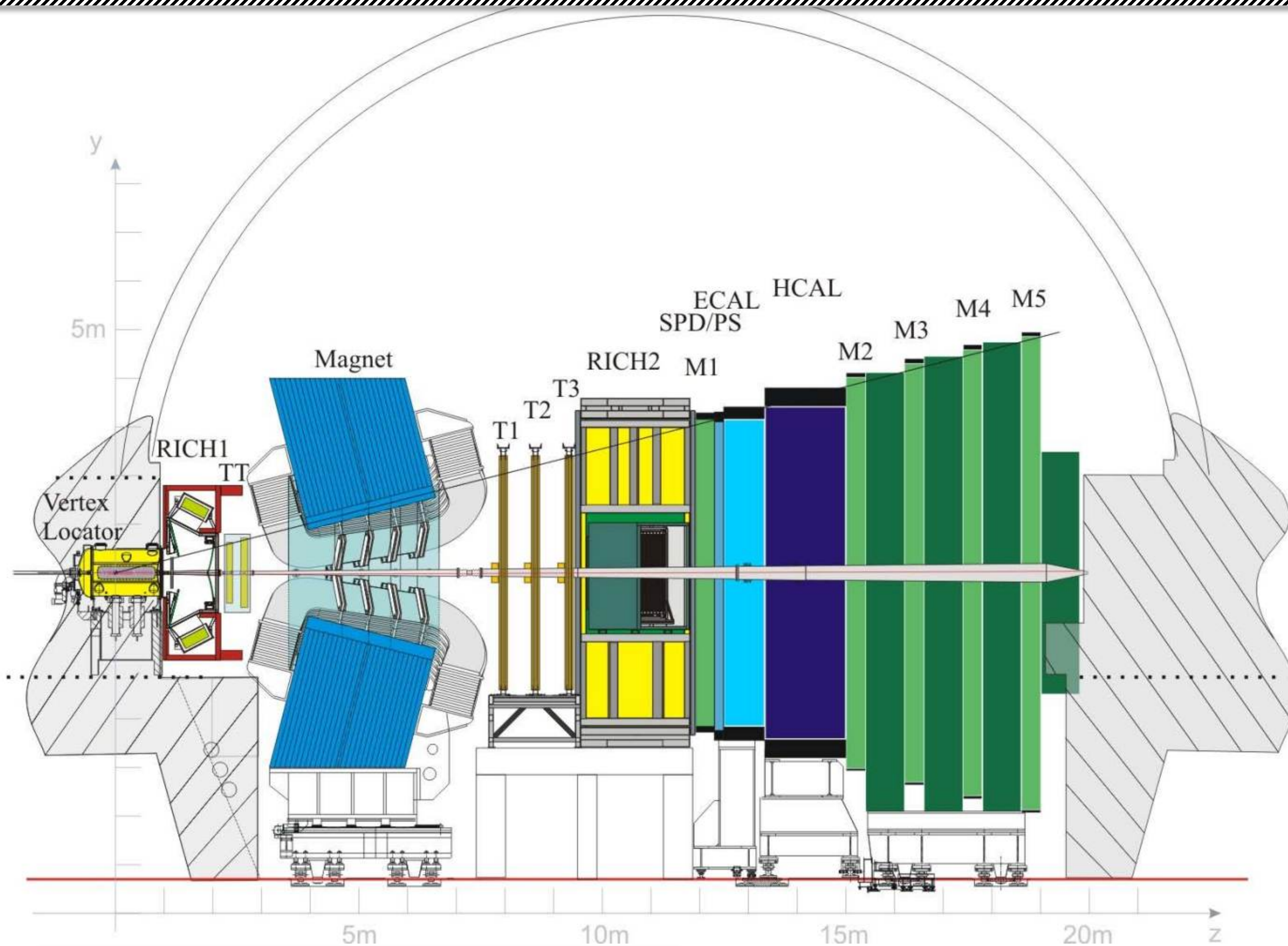
LHCb Experiment

- Collisions *pp* at 7-8-13 TeV in 2011-2012-2015
- Experiment dedicated to the heavy flavour physics (*CPV*, rare decays, spettroscopies):
  - Acceptance LHCb/1fb^{-1} at 7 Tev:
    - 10^{11} coppie $b\bar{b}$: $\sigma(pp \to b\bar{b}X) = (75.3 \pm 14.0)\mu b$
    - 10^{12} coppie $c\bar{c}$: $\sigma(pp \to c\bar{c}X) = (1.23 \pm 0.19) mb$
- Copious production of heavy b-baryon

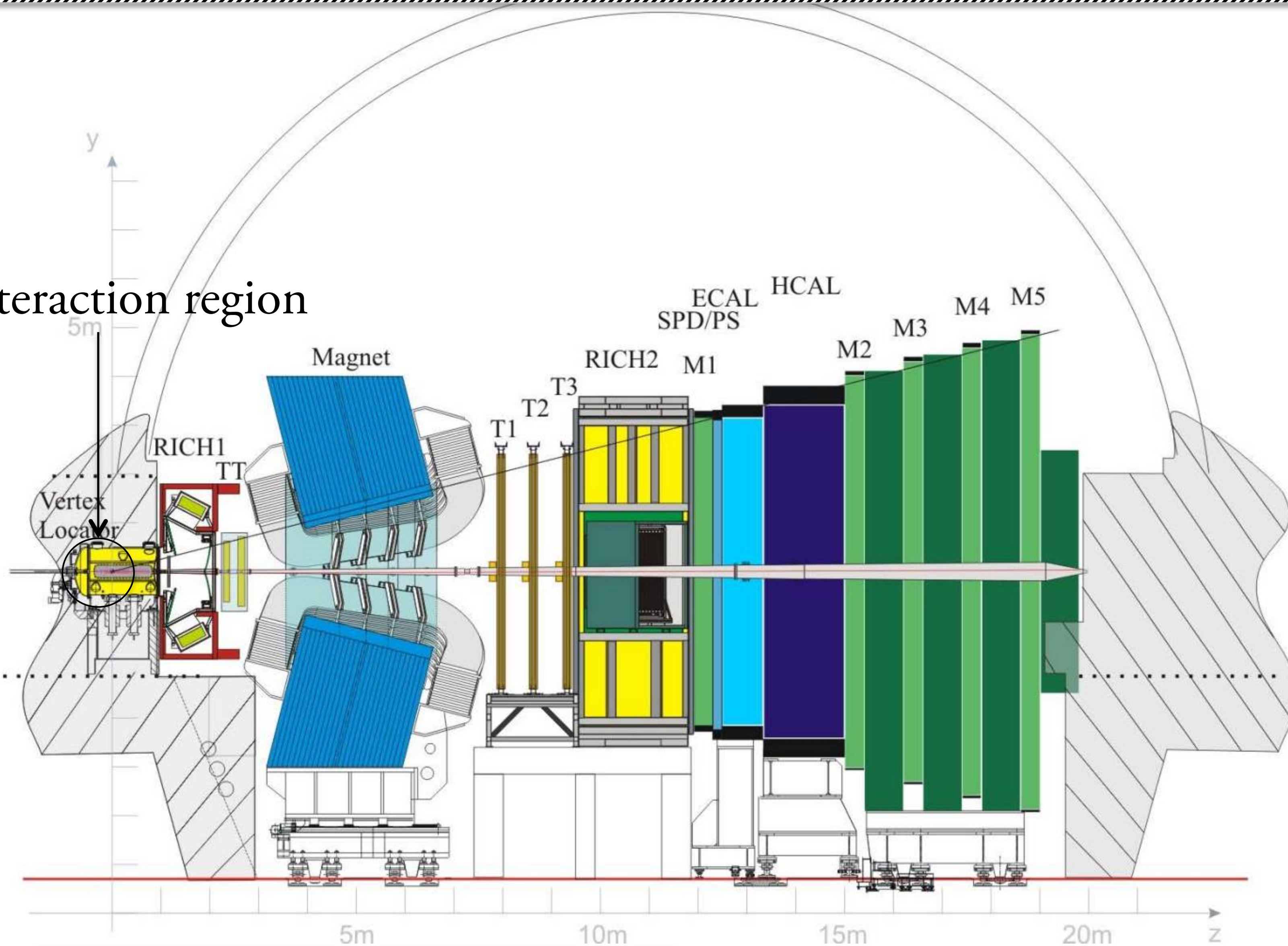


Precision measurements on heavy baryons become possible

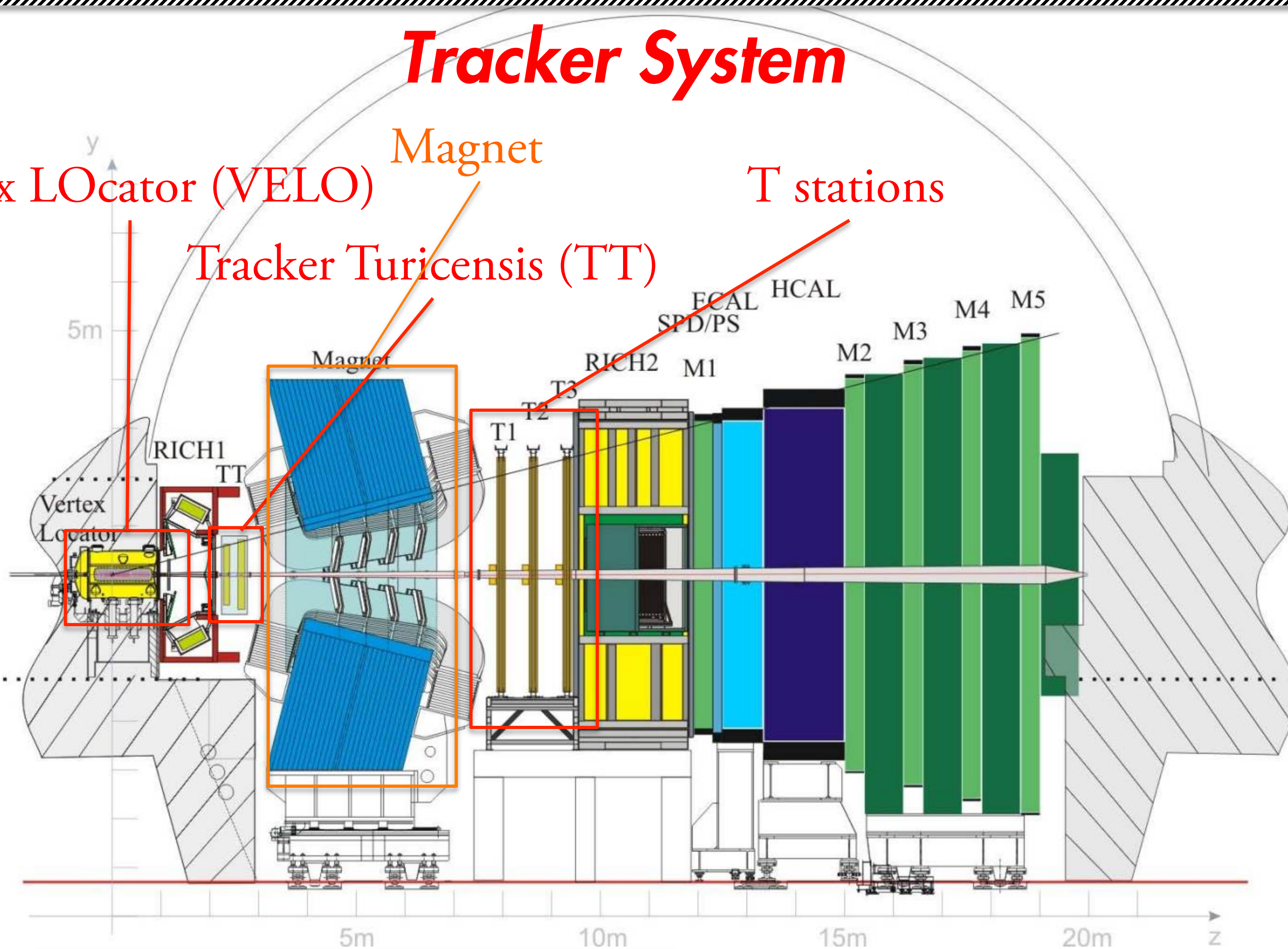
LHCb detector (side view)



LHCb detector (side view)

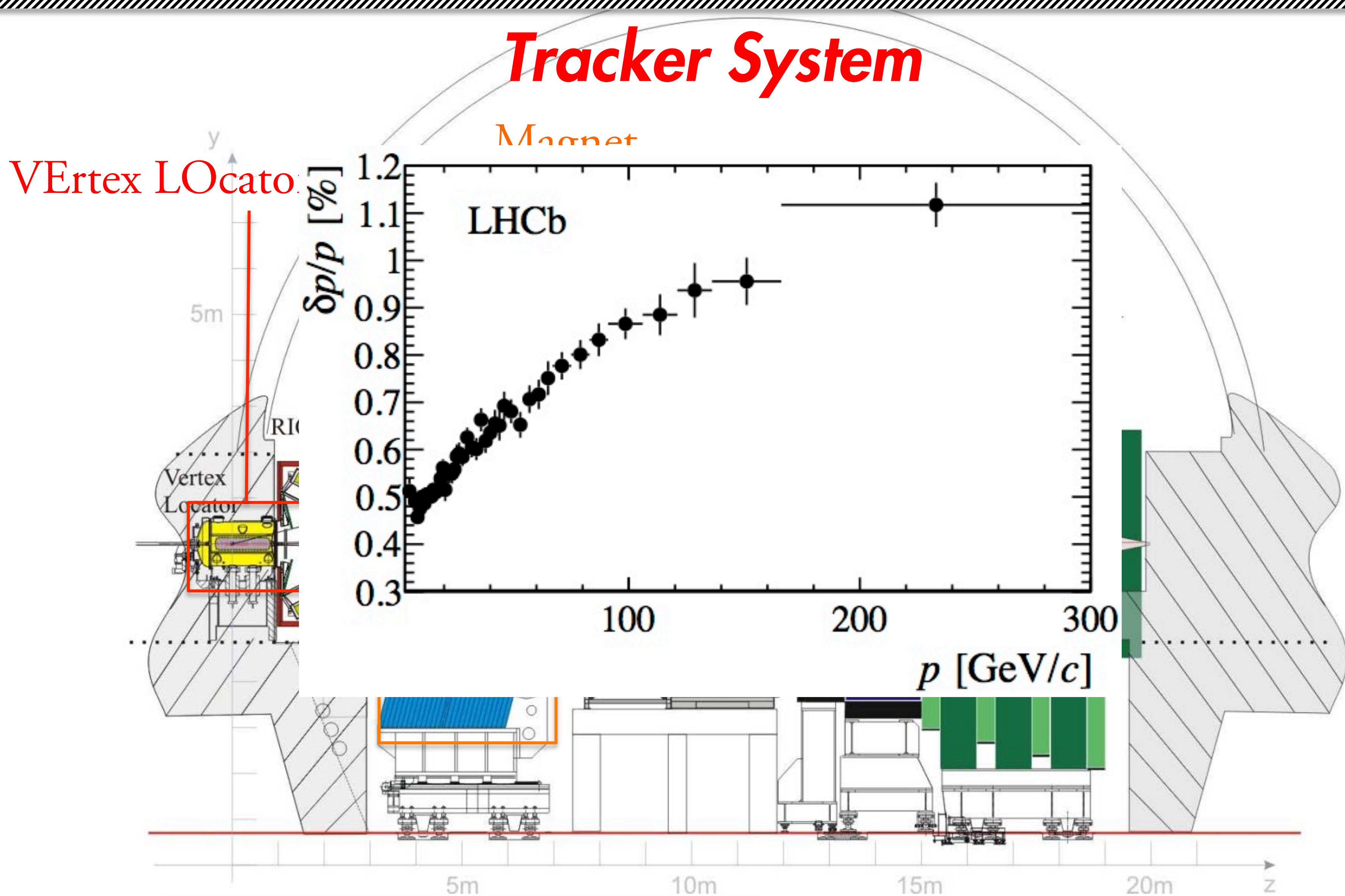


LHCb detector (side view)



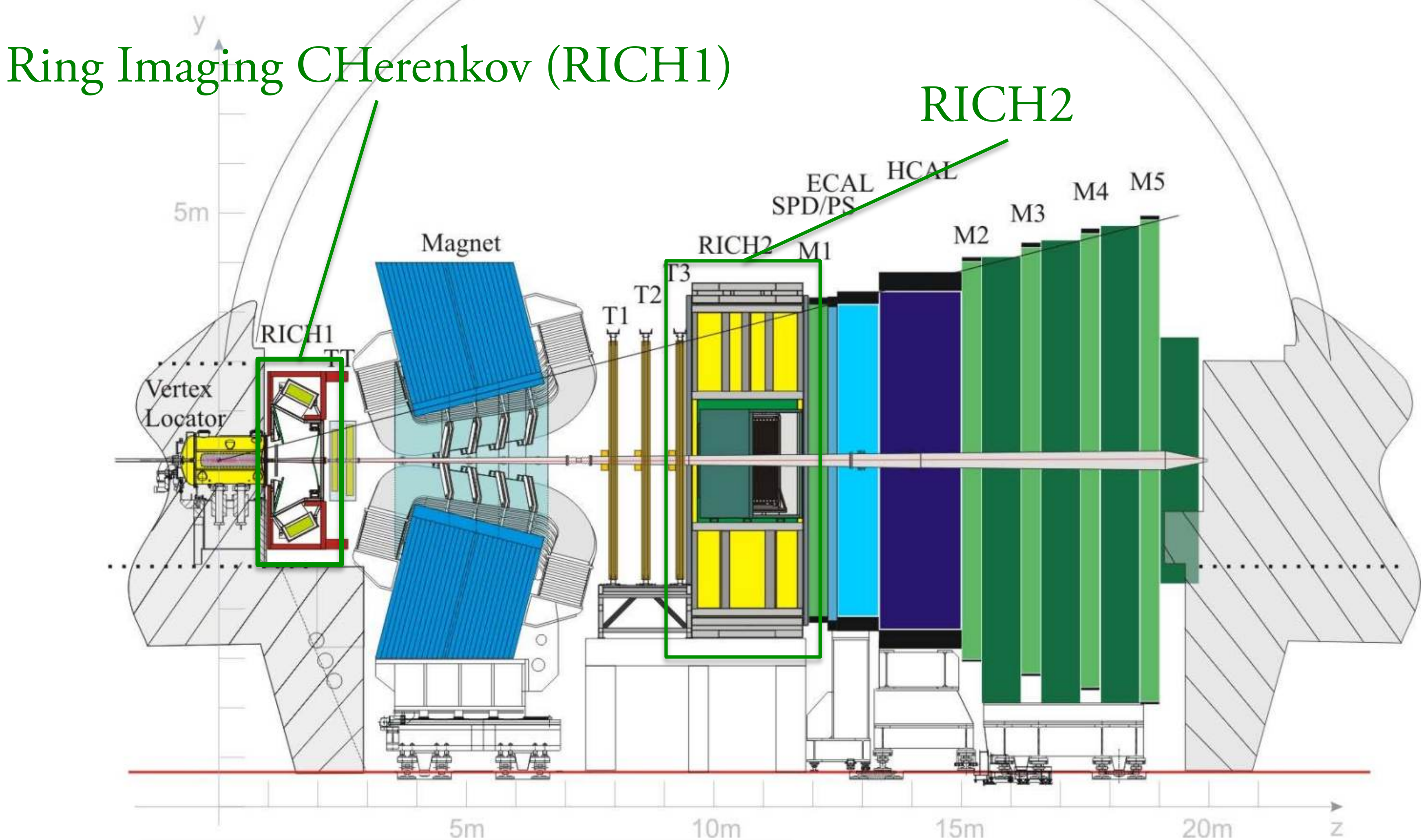
LHCb detector (side view)

Tracker System



LHCb detector (side view)

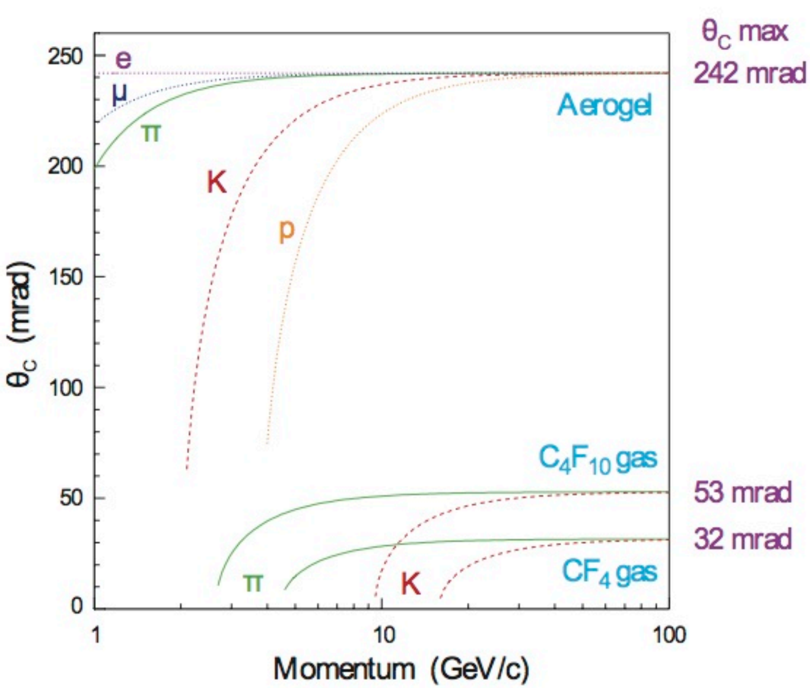
Particle Identification System

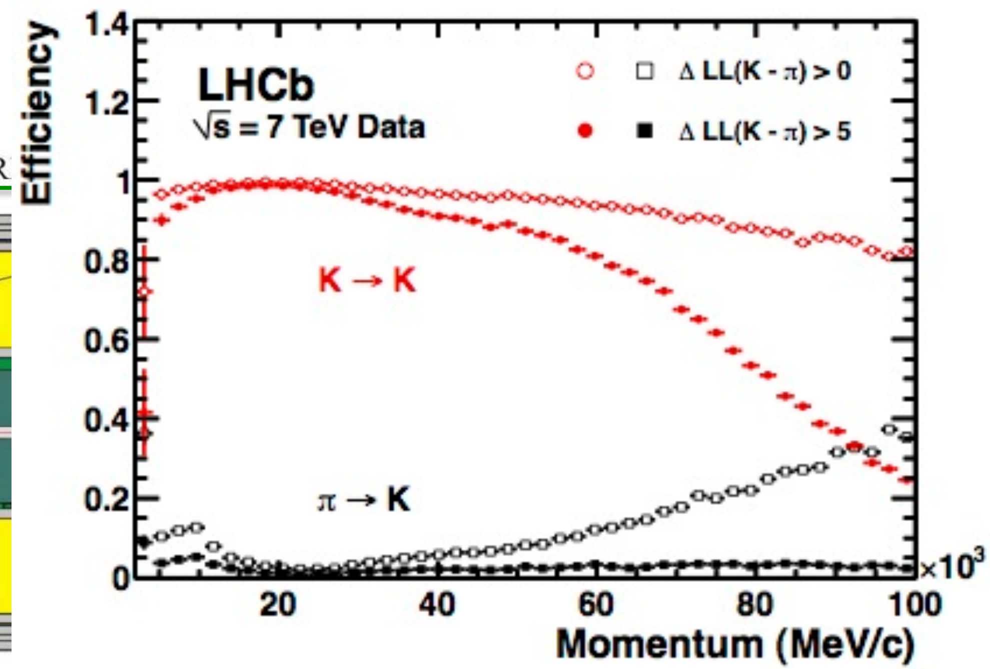


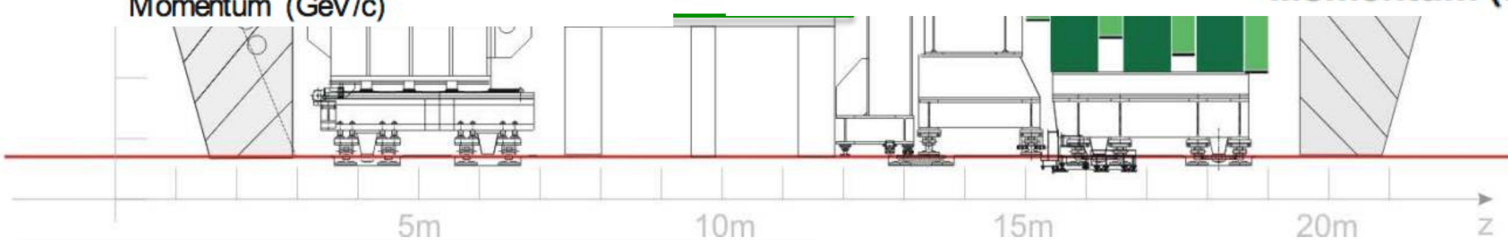
LHCb detector (side view)

Particle Identification System

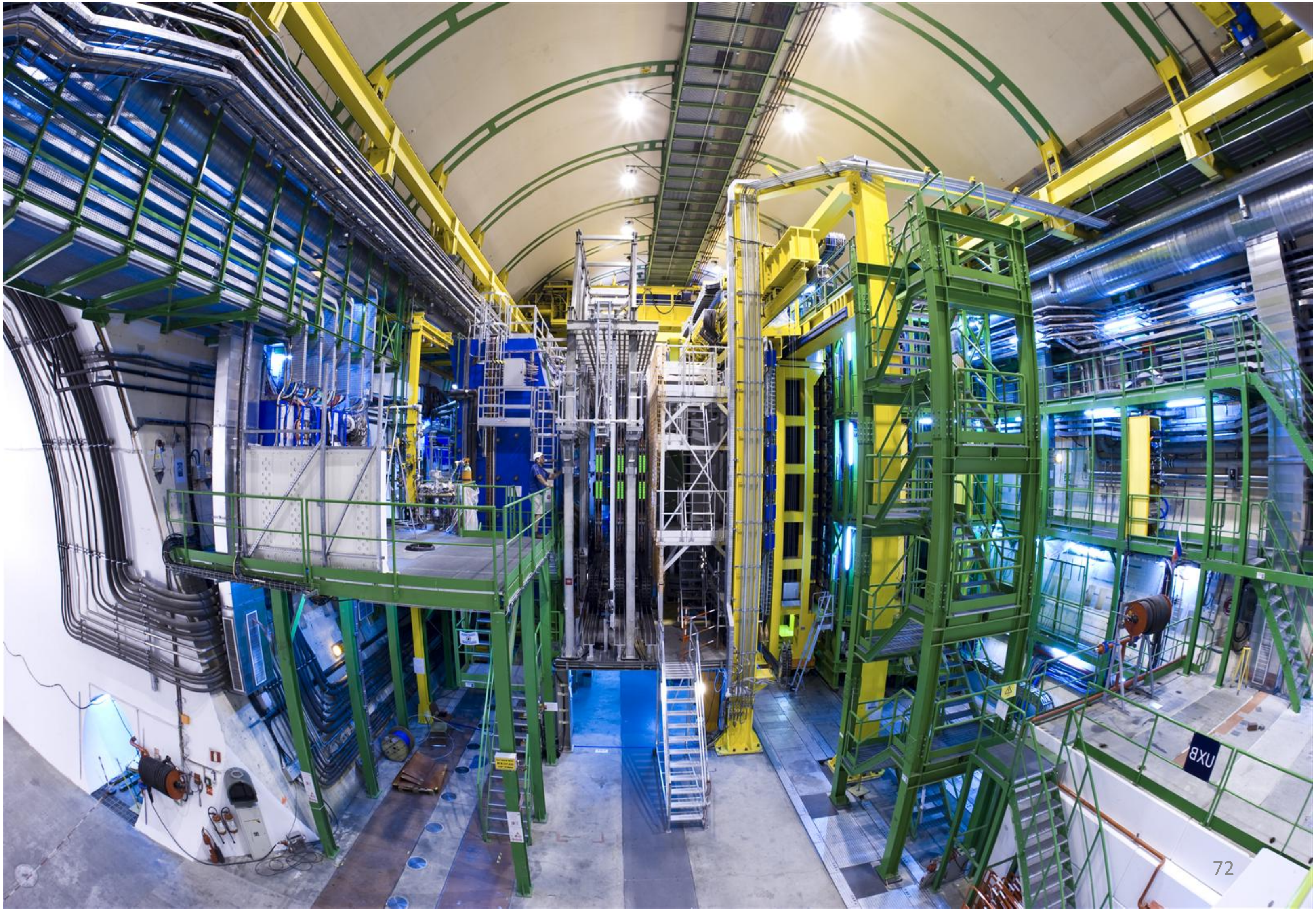
Ring Imaging CHerenkov (RICH1)



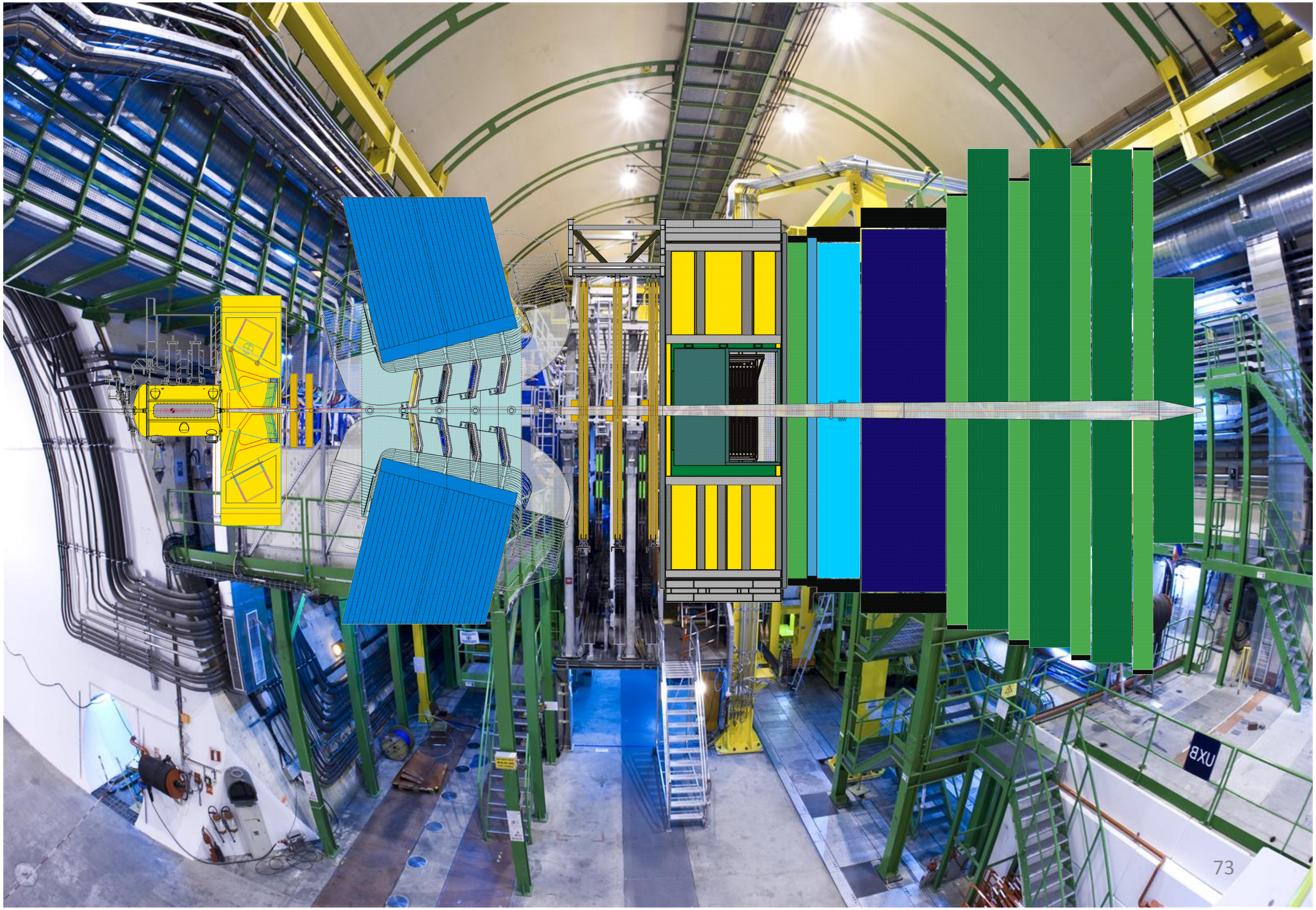




LHCb detector (side view)



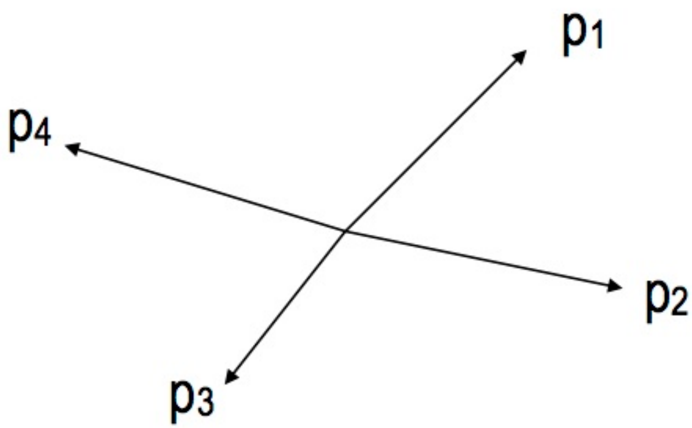
LHCb detector (side view)



Experimental technique

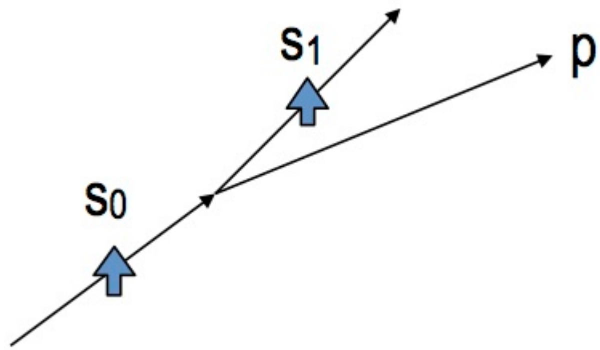
$\hat{\mathrm{T}}$-odd observable definition

Using 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 spins and momenta



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

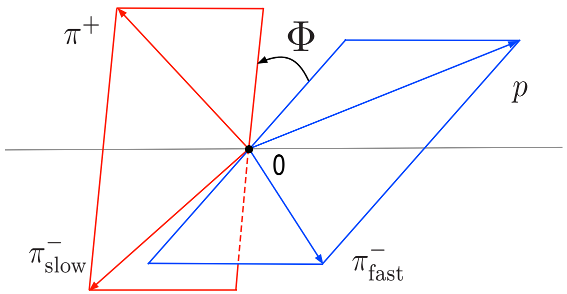
- We build the $\hat{\mathrm{T}}$-odd observable using the final state momenta
- In our case the observable is also P-odd

P- CP- violating asymmetries

Asymmetries

- Two different asymmetries for particle and antiparticle

$C_{\hat{T}} \propto \sin\Phi$



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

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

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- CP violating observable

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

- P violating observable

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

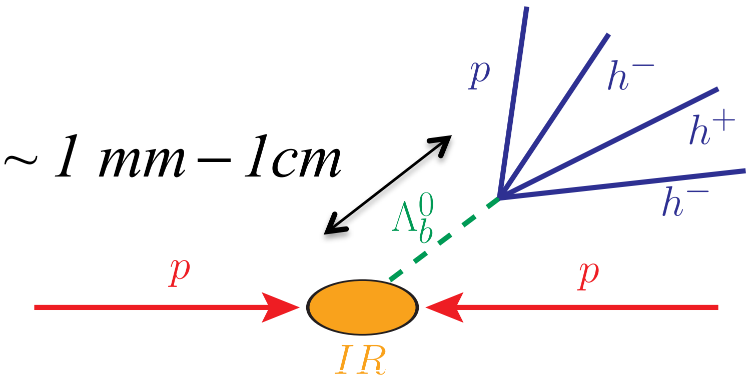
Largely insensitive to:

- production asymmetries $\Lambda_b^0 / \bar{\Lambda}_b^0$
- reconstruction asymmetries $h^+/\ h^-$

$\rightarrow$ Systematic uncertainty reduced

Selection

Decay topology

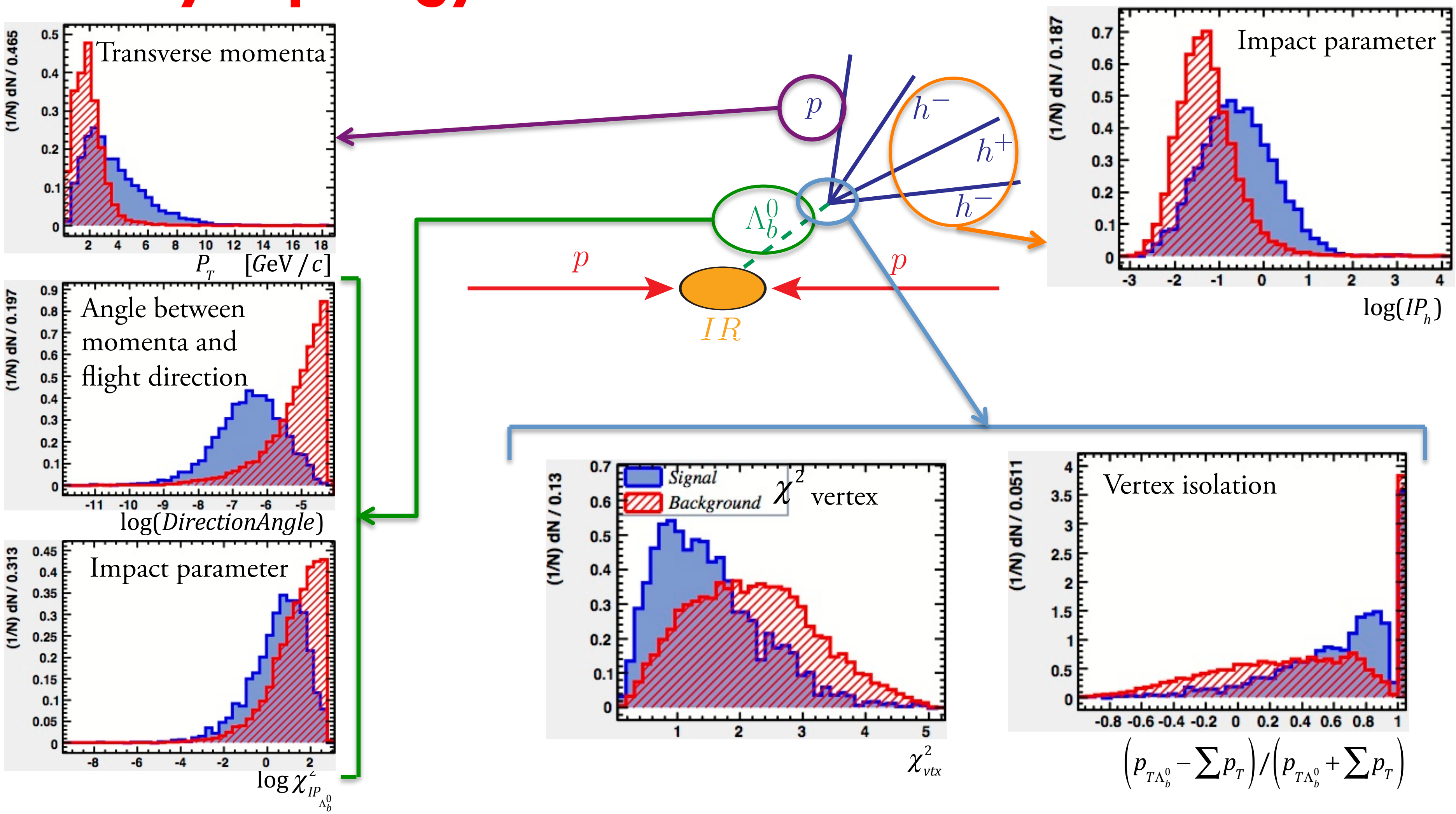


$$p = 10\ GeV\ : s = \gamma\beta c\tau \sim 1mm$$

$$p = 100\ GeV\ : s = \gamma\beta c\tau \sim 1cm$$

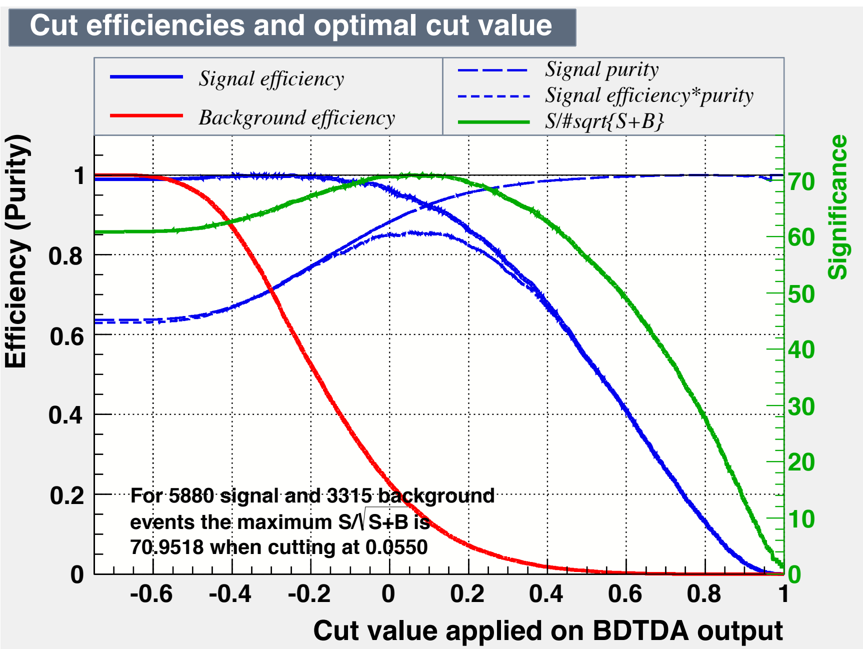
Selection

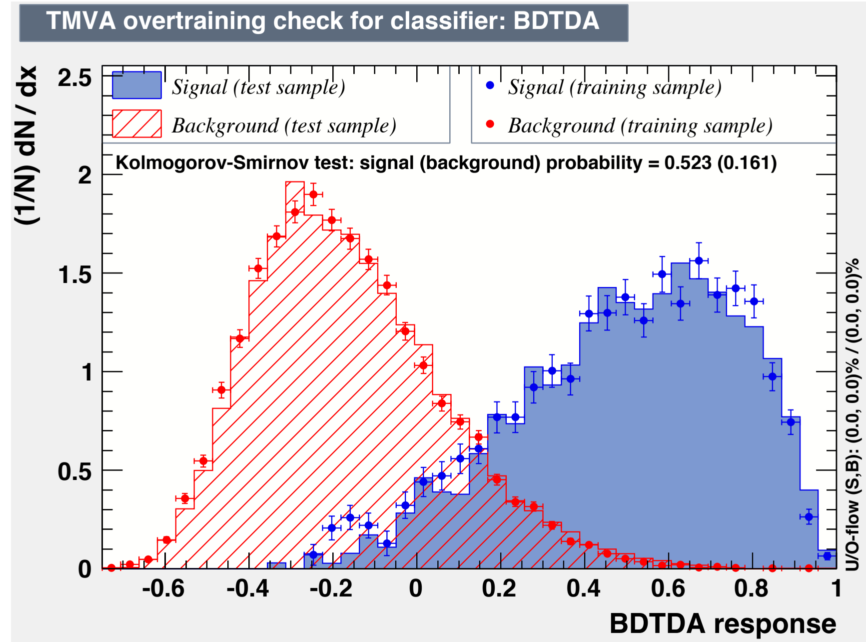
Decay topology



Multivariate classifier

Output multivariate classifier





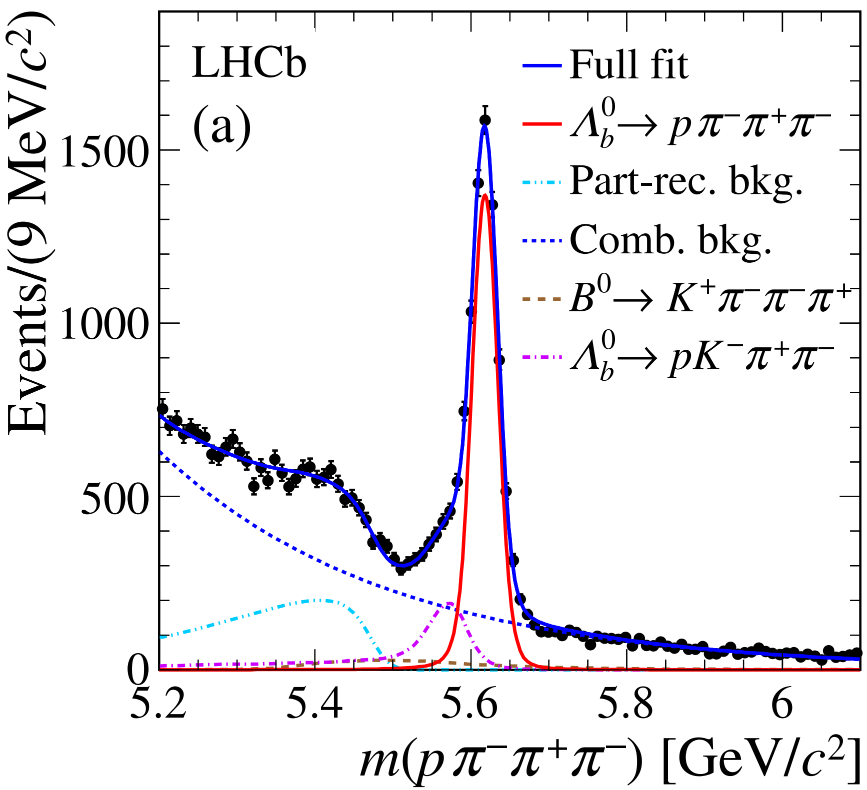
Significance Optimization

$$\frac{S}{\sqrt{(S+B)}}$$

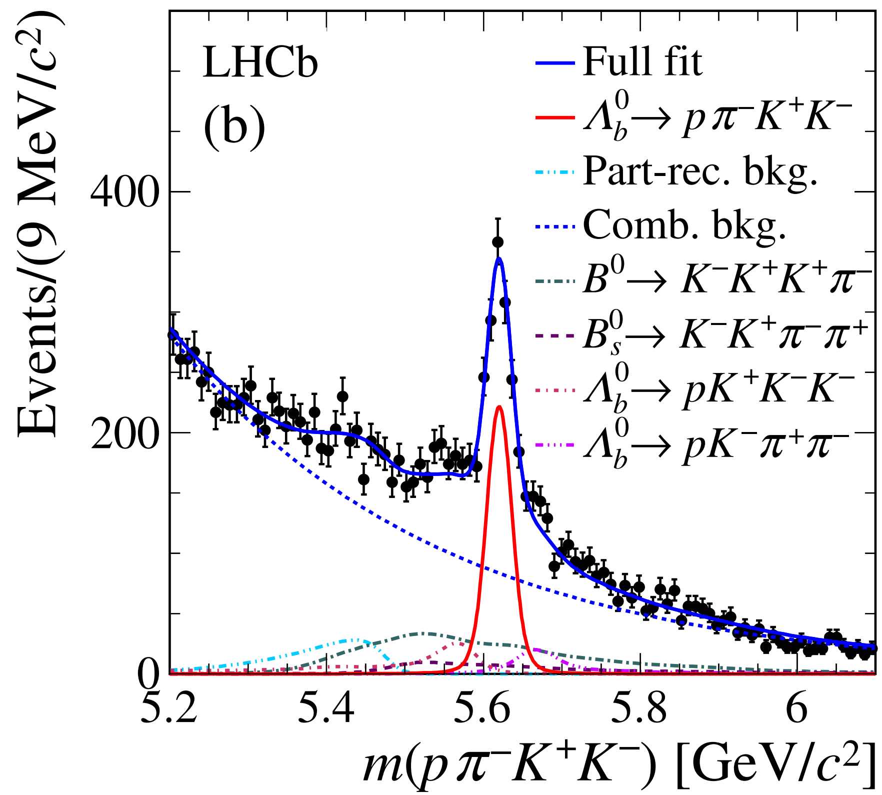
- Efficienza segnale $\sim 90\%$
- Reiezione fondo $\sim 90\%$

First observations

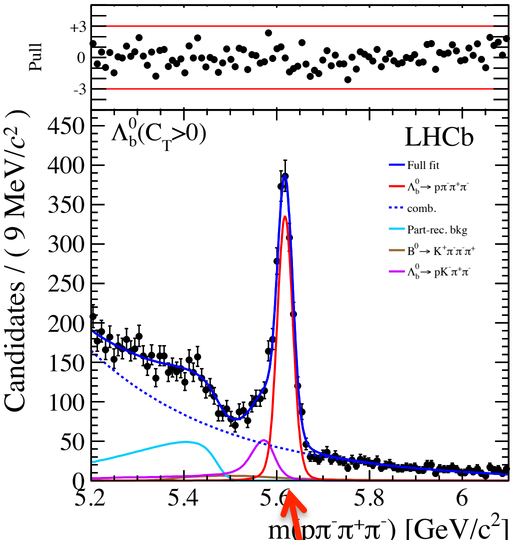
$N_{\Lambda_b^0} = 6646 \pm 105$

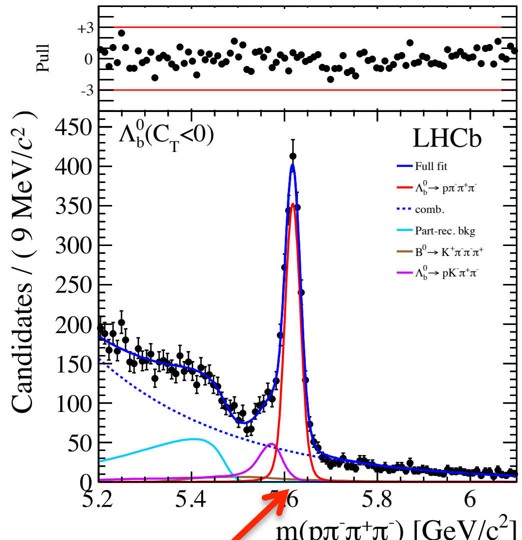


$N_{\Lambda_b^0} = 1030 \pm 56$



Asymmetries measurement





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

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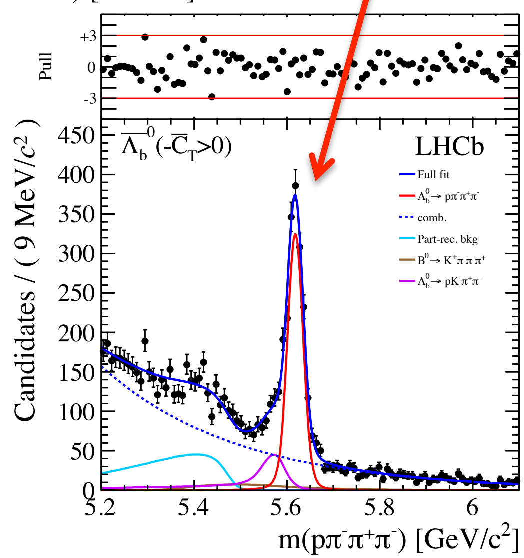
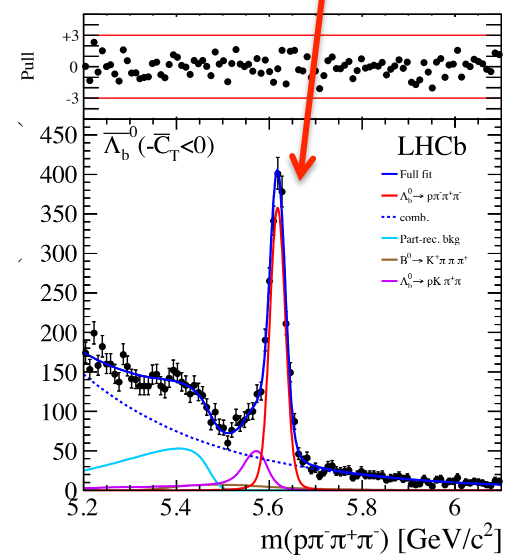
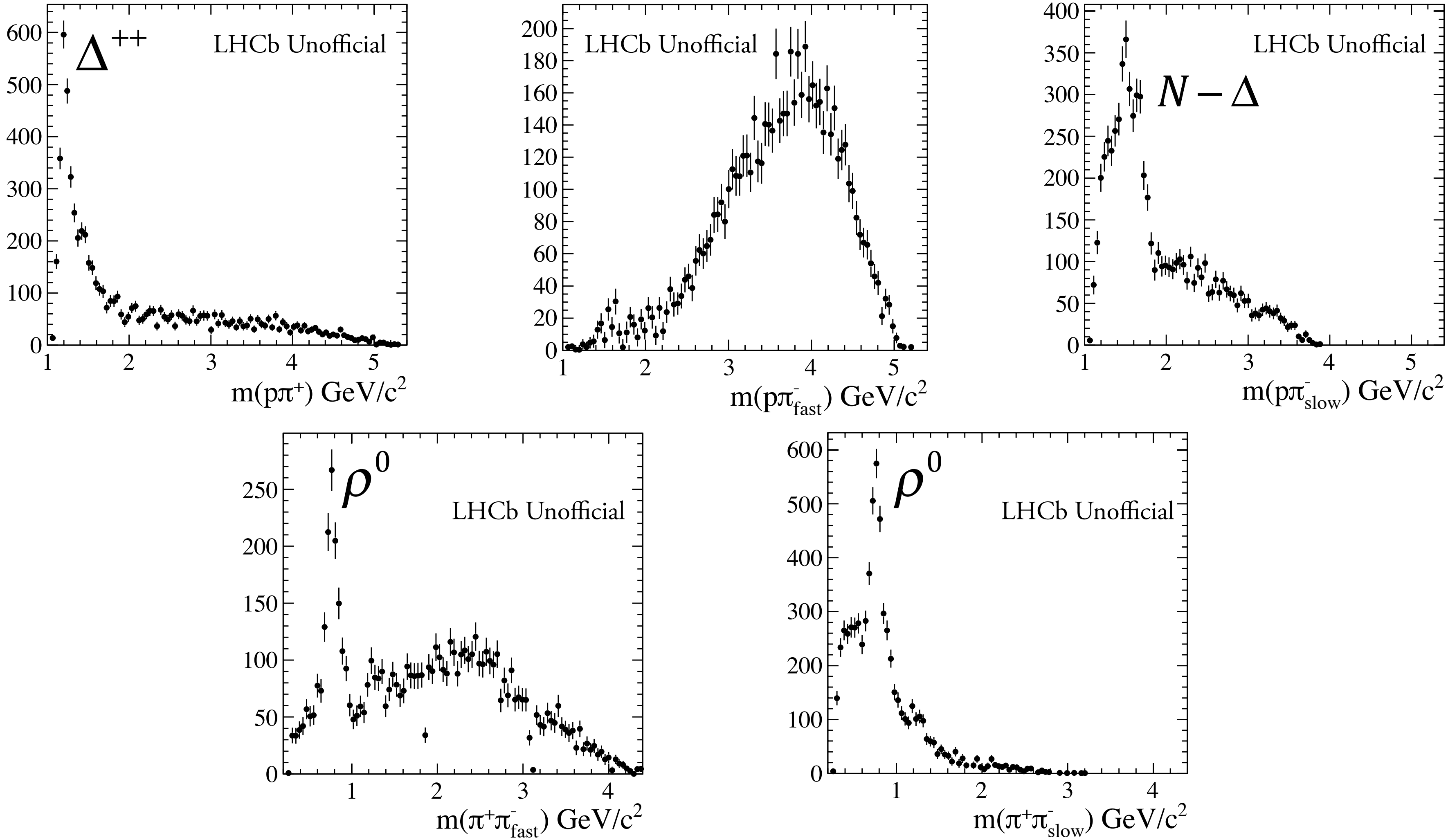




Signal distribution in phase space

$$\Lambda_b^0 \rightarrow p\pi^-\pi^+\pi^-$$



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

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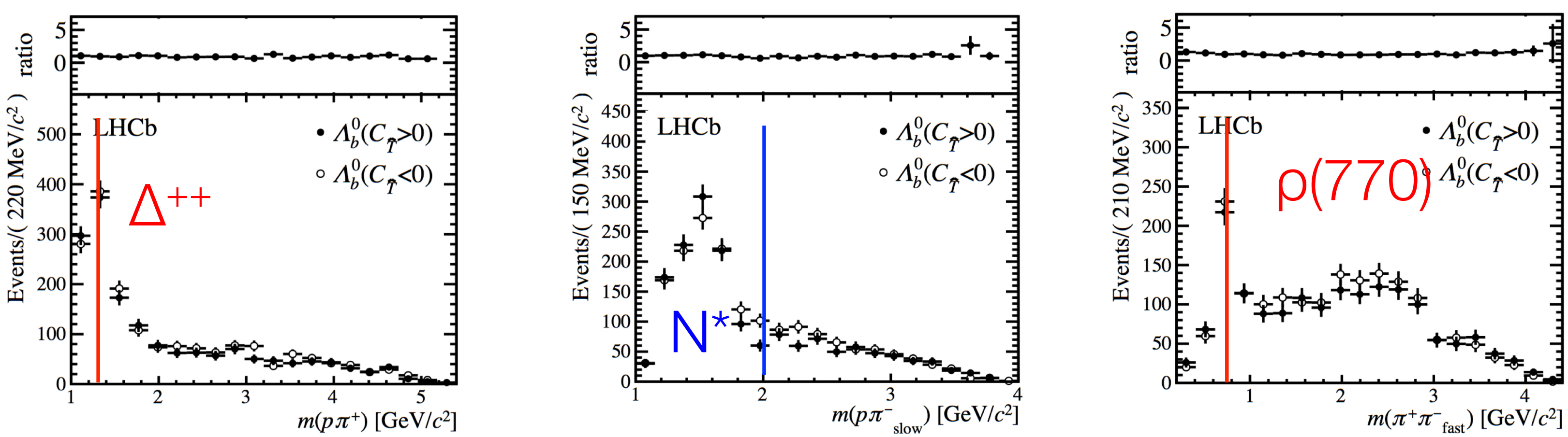
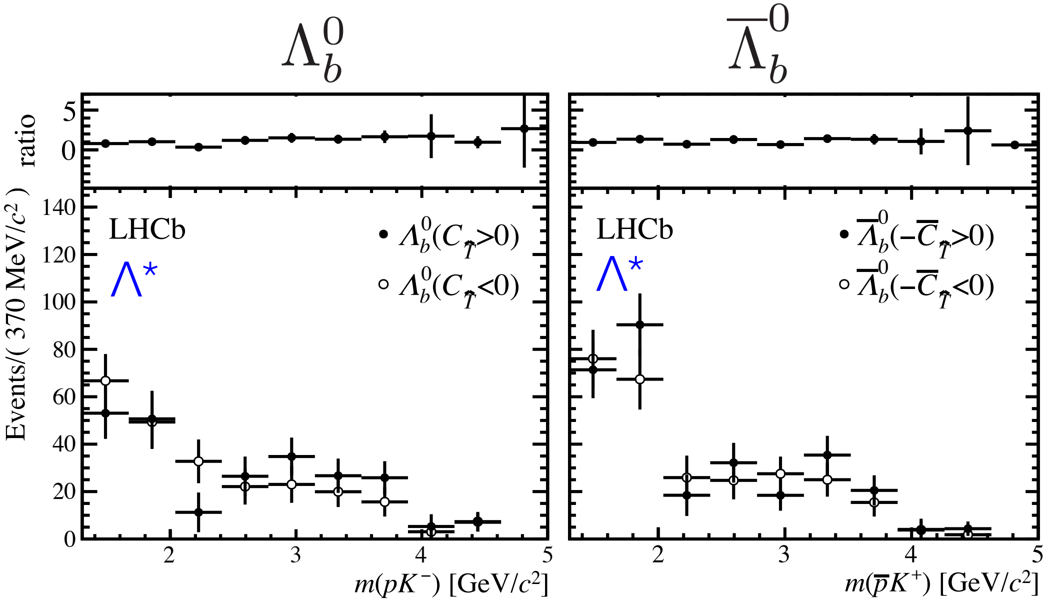


Binning definition $\Lambda_b^0 \to p\pi^- K^+ K^-$



Divide phase space with/ without Λ^* resonances

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

Results

Integrated

(compatible with P- CP-conservation hypothesis)

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

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

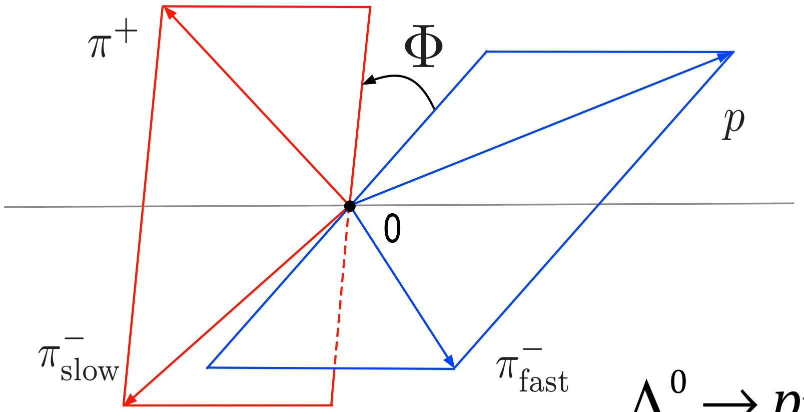
$a_{CP}^{\hat{T}\text{-odd}} = (-0.93 \pm 4.54 \pm 0.42)\%$

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

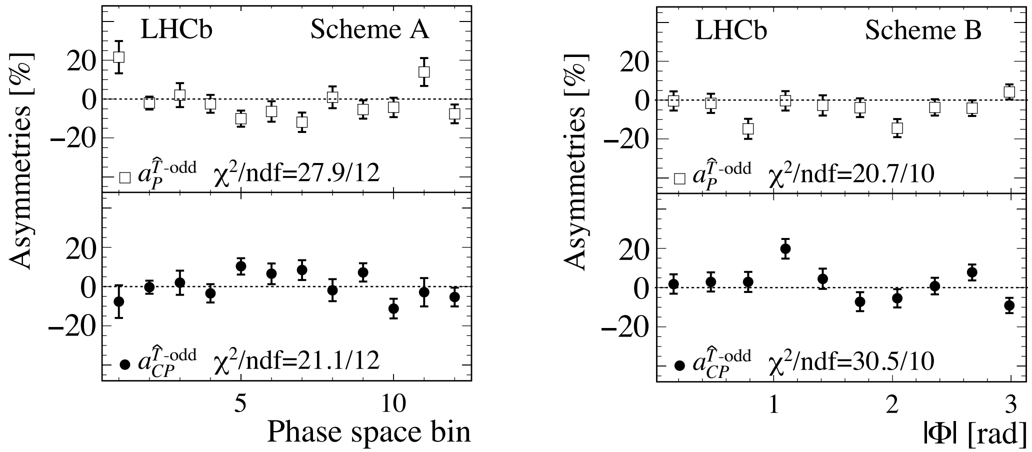
$a_P^{\hat{T}\text{-odd}} = (-3.71 \pm 1.45 \pm 0.32)\%$

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

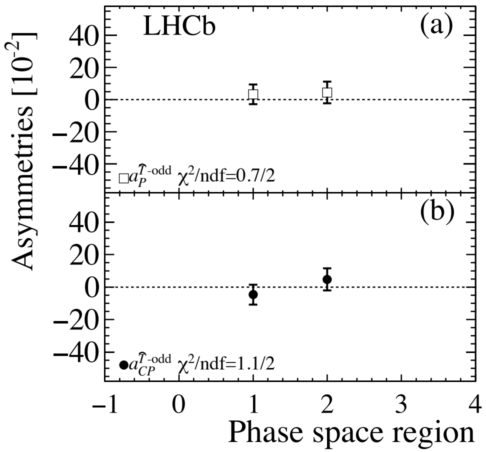
In phase space



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



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



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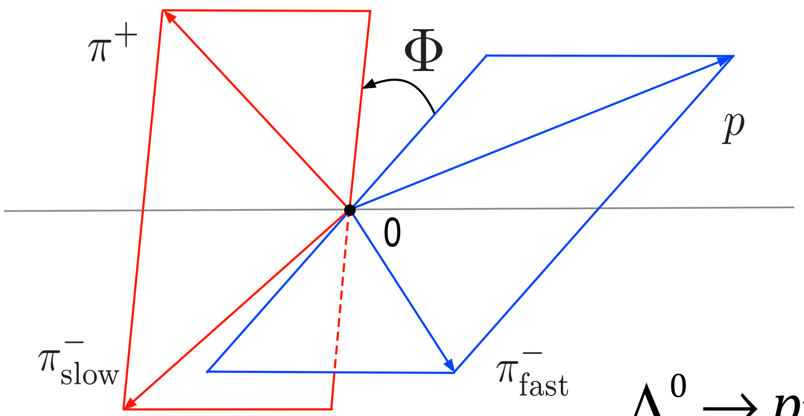
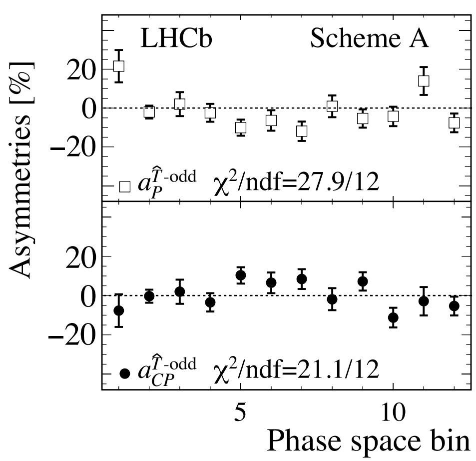
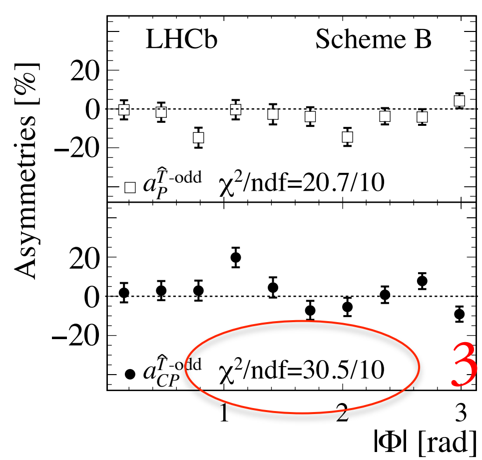


In phase space

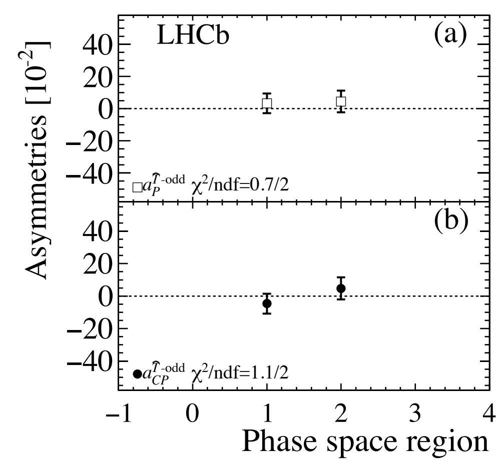
$\Lambda_b^0 \to p\pi^- \pi^+ \pi^-$





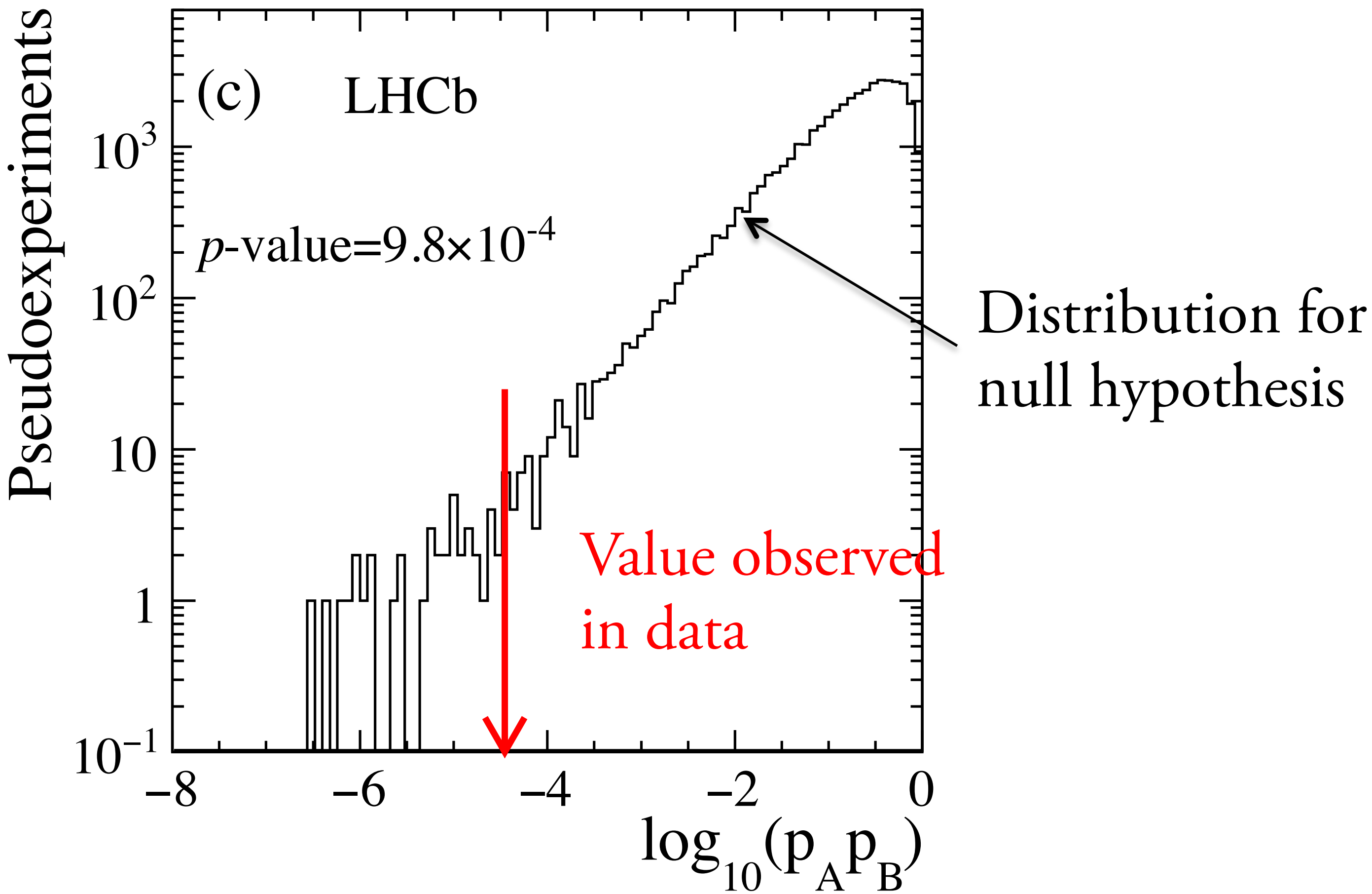
3.4 σ

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



Results

Permutation test assigning randomly the flavour



Significance at 3.3 σ for CP violation in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$

Final Conclusion

- First observation of these decay modes
- First evidence of *CPV* in baryons in $\Lambda_b^0 \rightarrow p\pi^-\pi^+\pi^-$
- Error limited by the statistics ⟶ Already studies on the new 2016 data on going
- Need to double the statistics for the observation (possible in 2016)

Submitted to Nature Physics

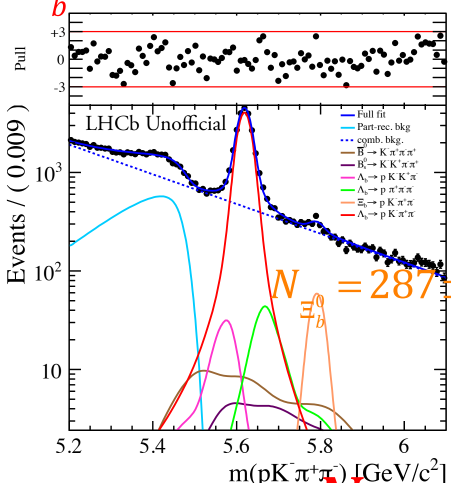
nature physics

Awarded by SIF in 2015 Congress

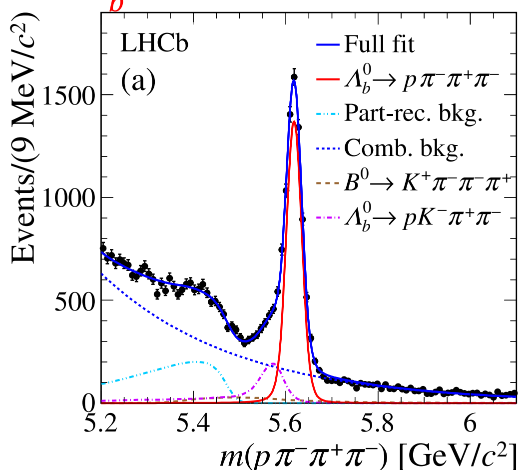
Back-up

First observations

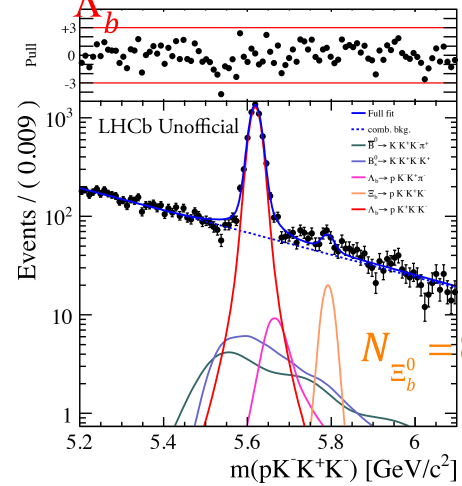
$N_{\Lambda_b^0} = 19877 \pm 195$



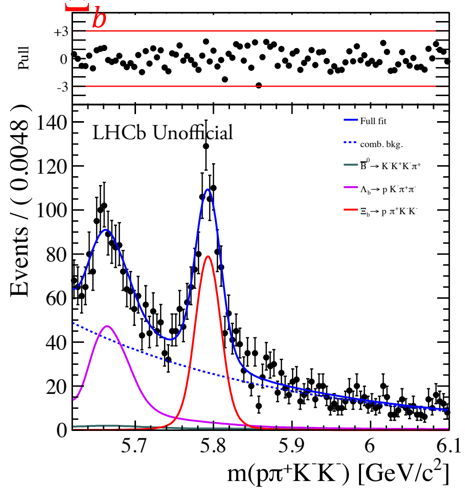
$N_{\Lambda_b^0} = 6646 \pm 105$



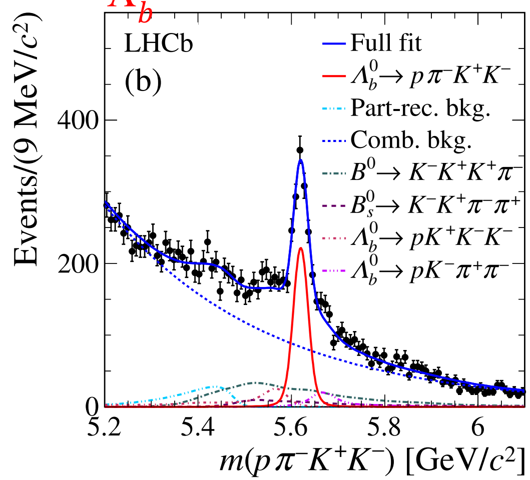
$N_{\Lambda_b^0} = 5297 \pm 83$



$N_{\Xi_b^0} = 709 \pm 45$

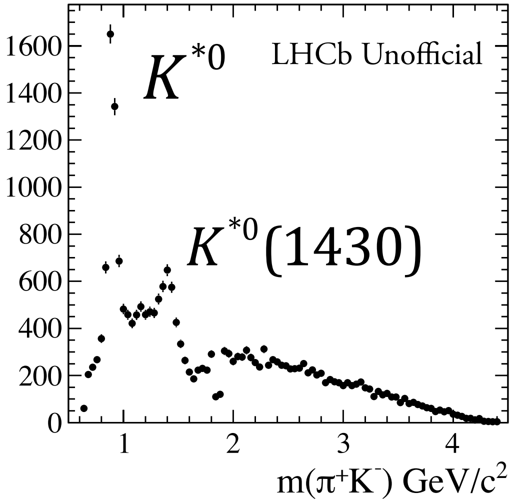


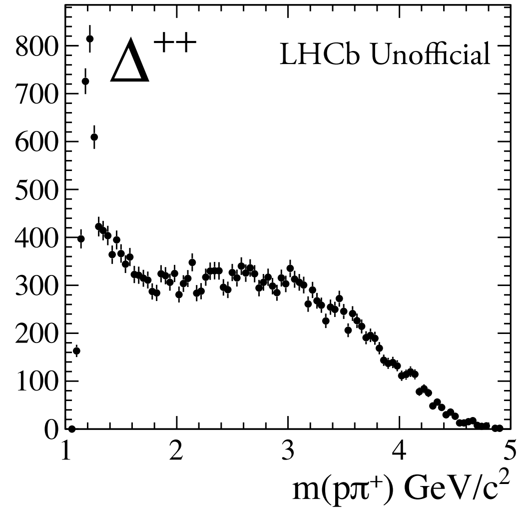
$N_{\Lambda_b^0} = 1030 \pm 56$

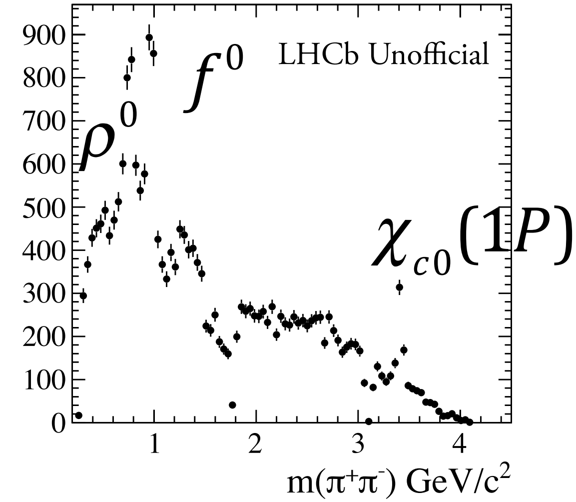


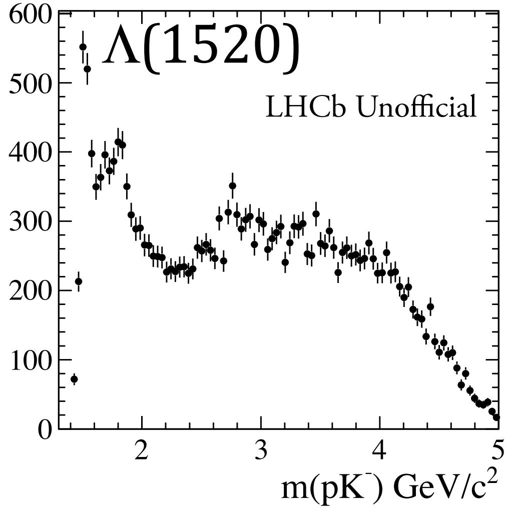
Signal distribution in phase space

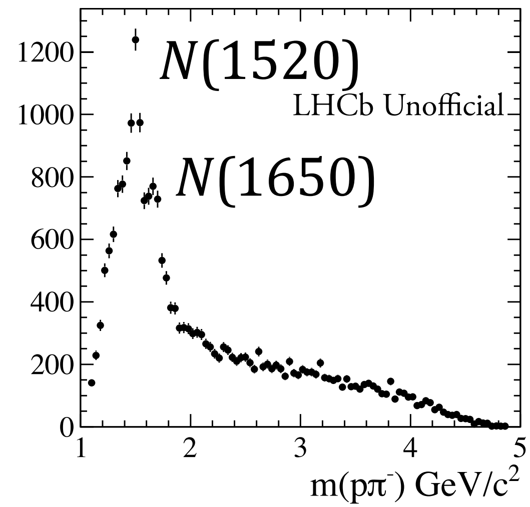
$$\Lambda_b^0 \rightarrow pK^-\pi^+\pi^-$$











Systematic uncertainties

Experimental bias $\Delta a_{CP}^{\hat{T}\text{-odd}}, \Delta a_{P}^{\hat{T}\text{-odd}} \sim 0.3\%$

Estimated with a high statists control sample $\Lambda_b^0 \to \Lambda_c^-(\to pK^-\pi^+)\pi^-$
$\sim 114\text{k}$ events

Cabibbo favoured $\longrightarrow$ negligible *CPV*

C_T resolution $\Delta a_{CP}^{\hat{T}\text{-odd}}, \Delta a_{P}^{\hat{T}\text{-odd}} \sim 0.05\%$

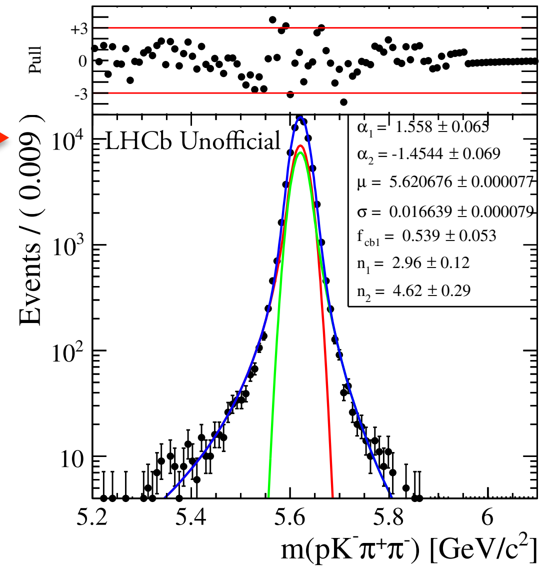
The finite CT resolution could induce migration between the categories $C_T>0$ e $C_T<0$ $\longrightarrow$ estimated with MC

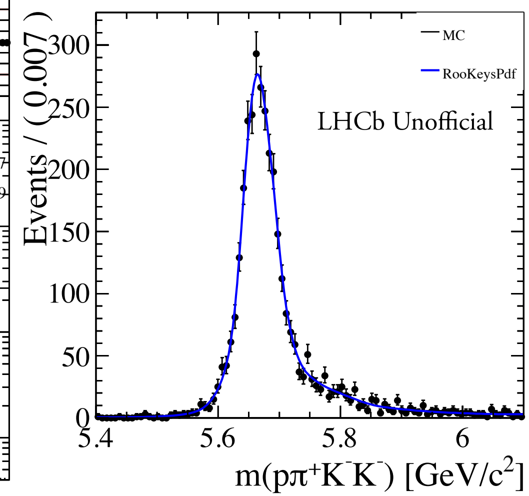
Fit model $\Delta a_{CP}^{\hat{T}\text{-odd}}, \Delta a_{P}^{\hat{T}\text{-odd}} \sim 0.03-0.3\%$

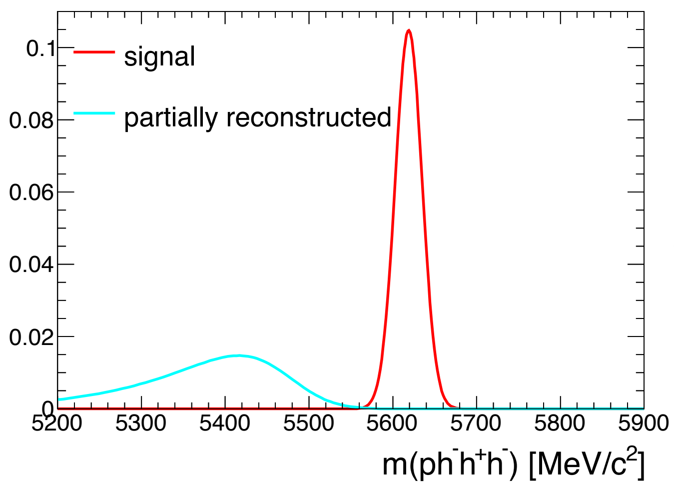
Estimated with simulated pseudoexperiments and using alternative fit model for signal and background

Fit model parametrization

- **Signal**
  double Crystal Ball
- **Combinatorics**
  exponential







- Λ_b^0 **partially reconstructed**
  argus convoluted with gaussian
  π^0, γ not reconstructed
- **Cross feed**
  parametrized from MC

Signal Parametrization

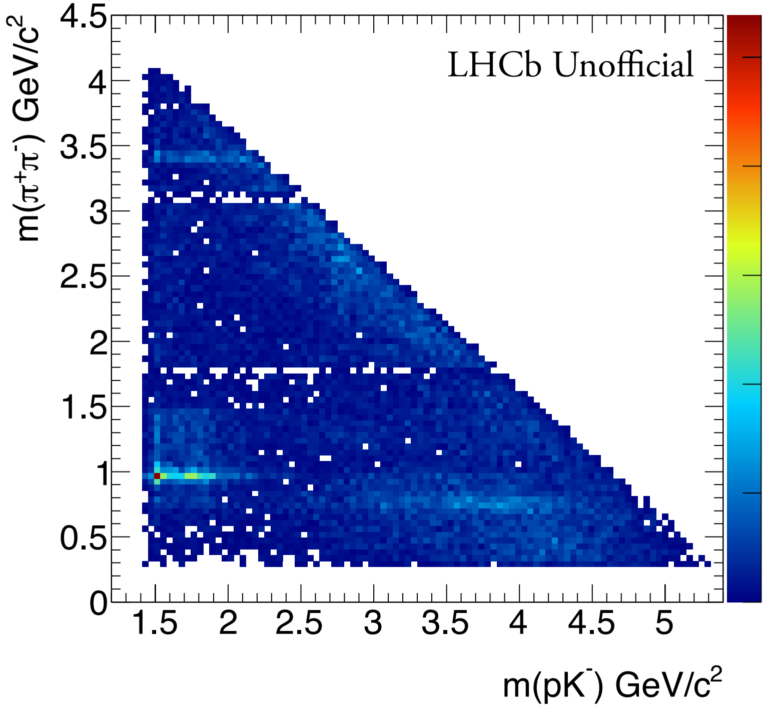
Double Crystal Ball

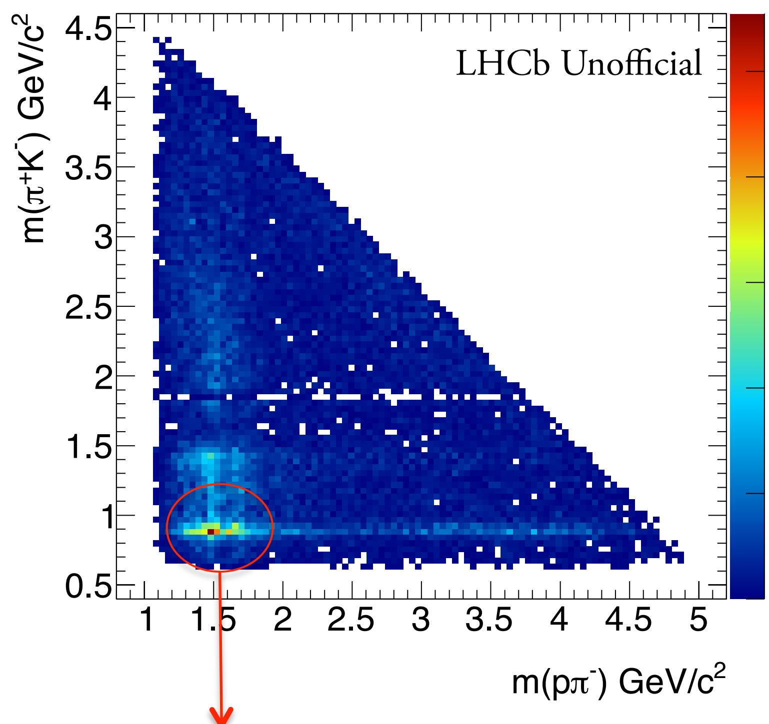
$$pdf_{sig} = f \cdot CB^{+}(x;\mu,\sigma,\alpha^{+},n^{+}) + (1-f)\cdot CB^{-}(x;\mu,\sigma,\alpha^{-},n^{-})$$

$$\mathrm{CB}(x;\mu,\sigma,\alpha,n) = N \cdot \begin{cases} \dfrac{\left(\dfrac{n}{|\alpha|}\right)^{n} e^{-\frac{1}{2}\alpha^{2}}}{\left(\dfrac{n}{|\alpha|} - |\alpha| - \dfrac{x-\mu}{\sigma}\right)^{n}} & x < -|\alpha| \\ e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^{2}} & x > -|\alpha| \end{cases}$$

Signal distribution in phase space

$$\Lambda_b^0 \to pK^-\pi^+\pi^-$$



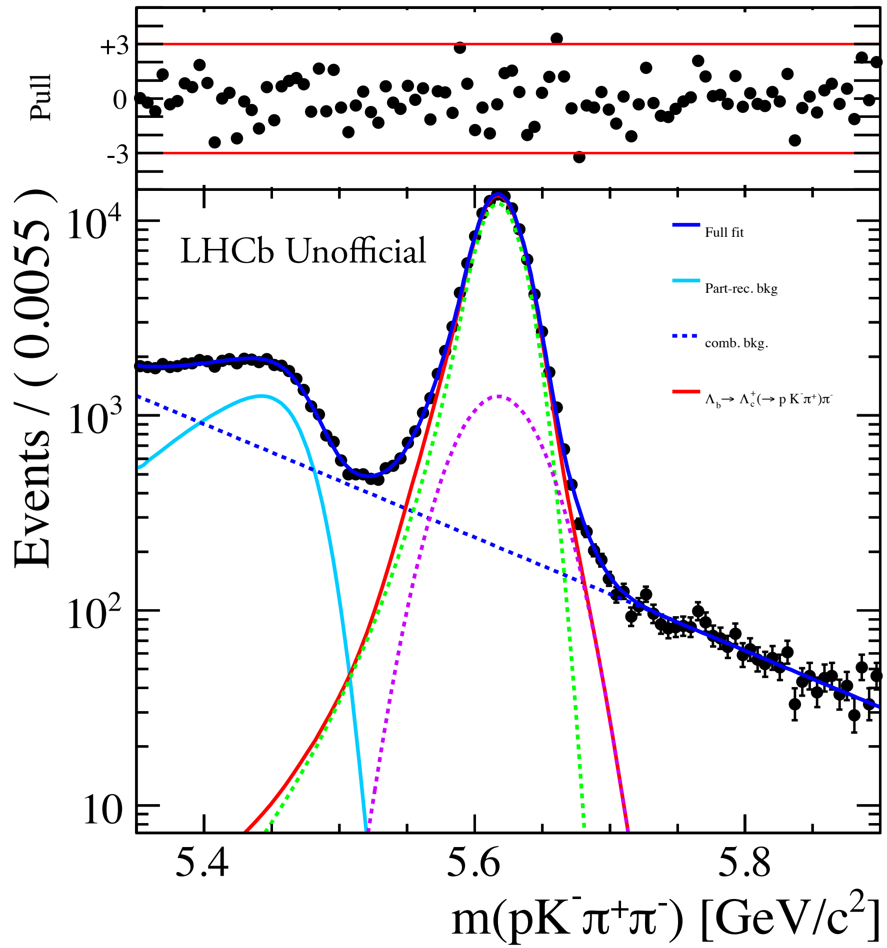


Hint for associated production of resonances

$$\Lambda_b^0 \to N(1520)(\to p\pi^-)K^{*0}(\to K^-\pi^+)$$

$\Lambda_b^0 \to \Lambda_c^+\left(\to pK^-\pi^+\right)\pi^-$ control sample

$$N_{sig} = 113612 \pm 399$$



$\Lambda_b^0 \to \Lambda_c^+\left(\to pK^-\pi^+\right)\pi^-$ control sample

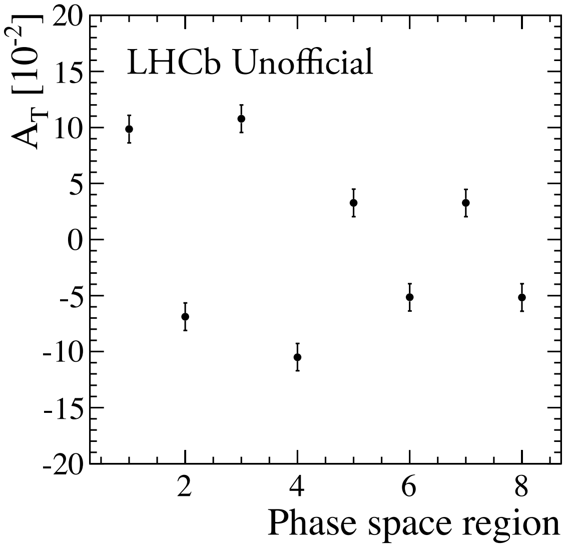
Asimmetrie integrate nello spazio delle fasi:

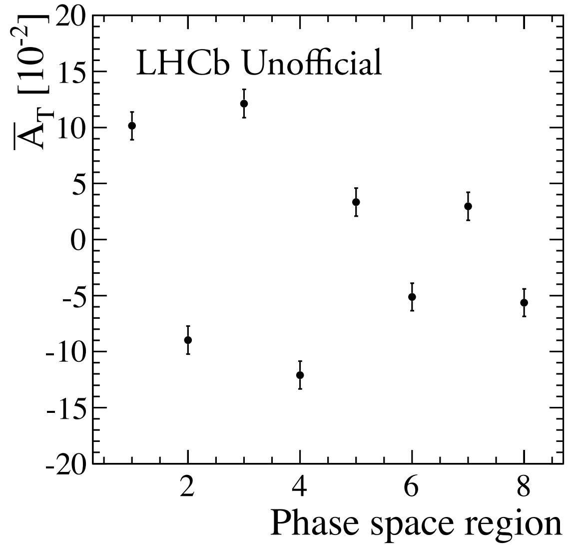
$$A_T = (-0.10 \pm 0.43)\%$$

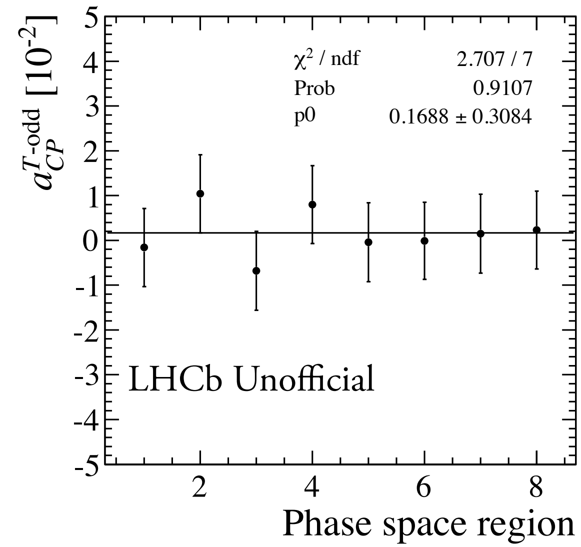
$$\bar{A}_T = (-0.41 \pm 0.44)\%$$

$$a_{CP}^{T\text{-odd}} = (-0.15 \pm 0.31)\%$$

Asimmetrie in bin dello spazio delle fasi:

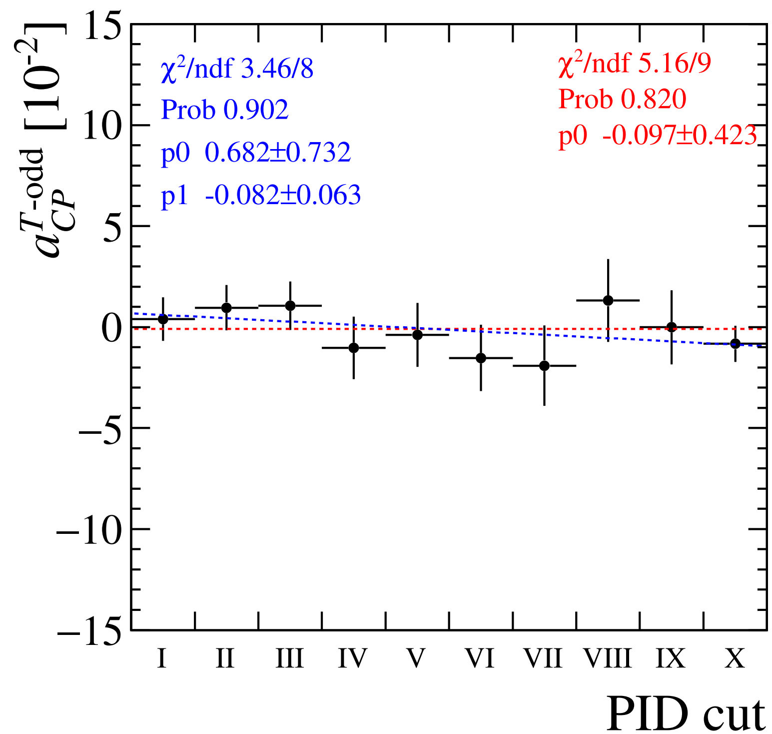






$\Lambda_b^0 \rightarrow \Lambda_c^+\left(\rightarrow pK^-\pi^+\right)\pi^-$ control sample

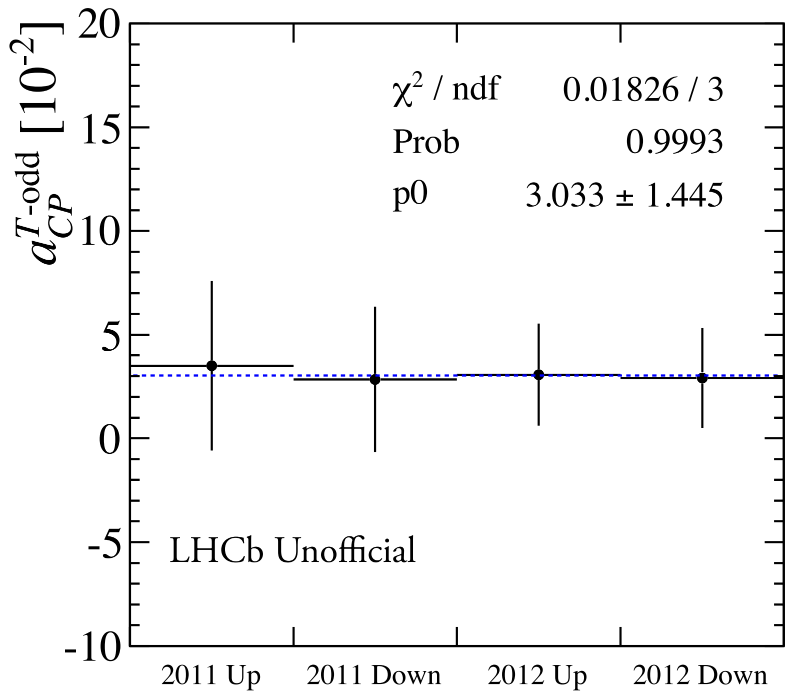
PID cuts	I	II	III	IV	V
PID_p	$(0.05, 0.10)$	$(0.1, 0.15)$	$(0.15, 0.20)$	> 0.2	> 0.2
PID_K	> 0.05	> 0.05	> 0.05	$(0.05, 0.10)$	$(0.10, 0.15)$
PID_π	> 0.05	> 0.05	> 0.05	> 0.05	> 0.05
N_{events}	10322 ± 127	9046 ± 122	7873 ± 132	4691 ± 80	4432 ± 129
PID cuts	**VI**	**VII**	**VIII**	**IX**	**X**
PID_p	> 0.2	> 0.2	> 0.2	> 0.2	> 0.2
PID_K	$(0.15, 0.20)$	> 0.2	> 0.2	> 0.2	> 0.2
PID_π	> 0.05	$(0.05, 0.60)$	$(0.60, 0.85)$	$(0.85, 0.95)$	$(0.95, 1.00)$
N_{events}	4047 ± 72	2861 ± 65	2596 ± 101	3058 ± 58	13015 ± 120



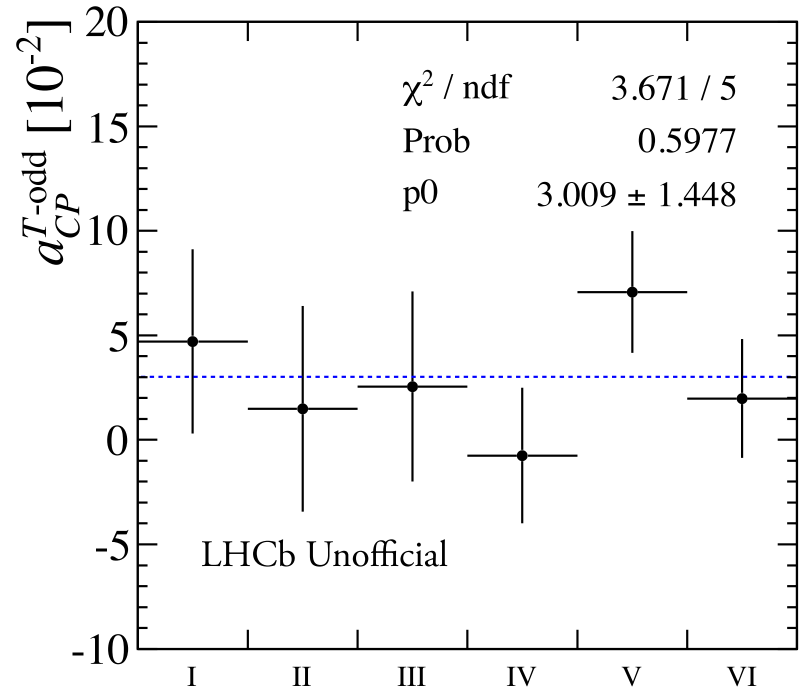
Control check

Stability of the results

per year & magnet polarity

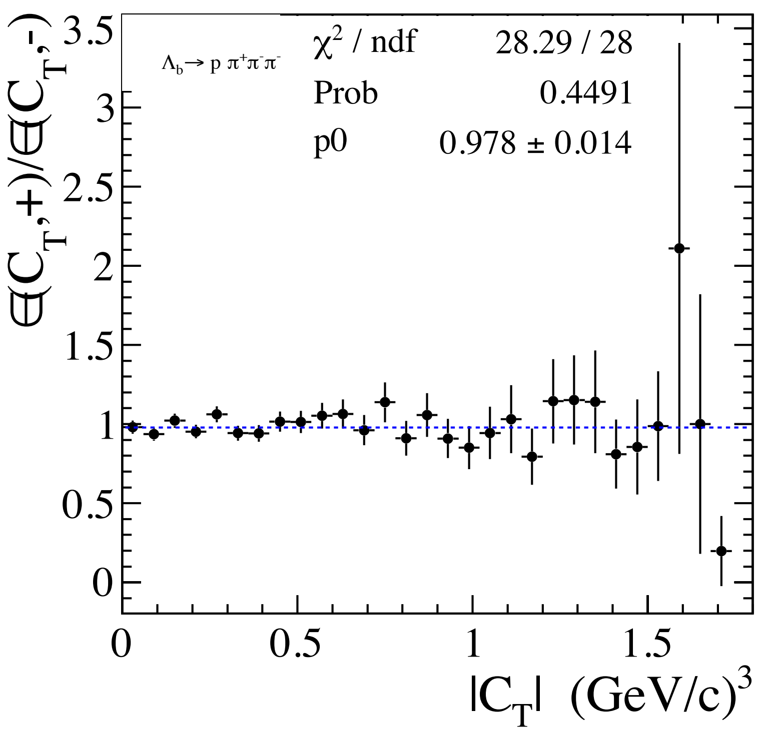


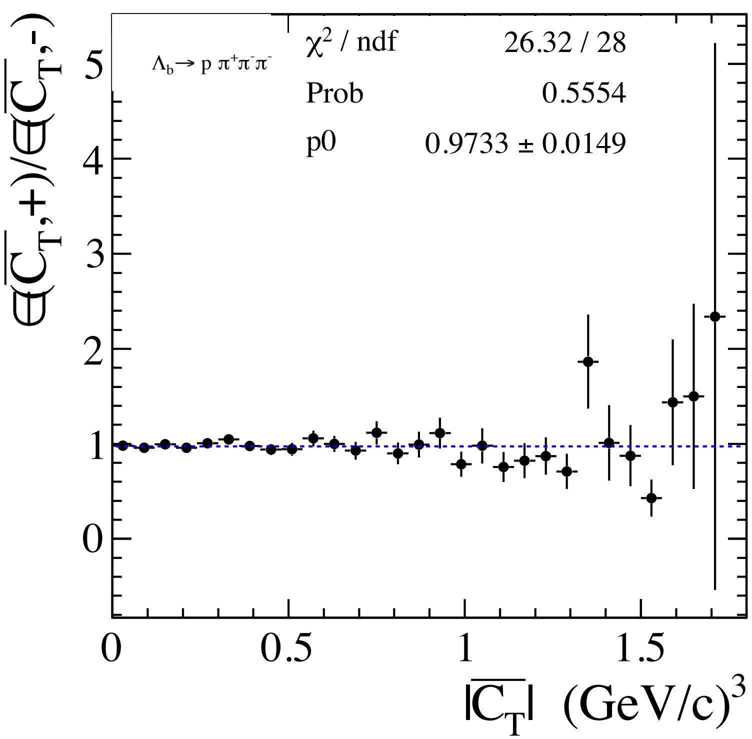
per periods within the major technical stops



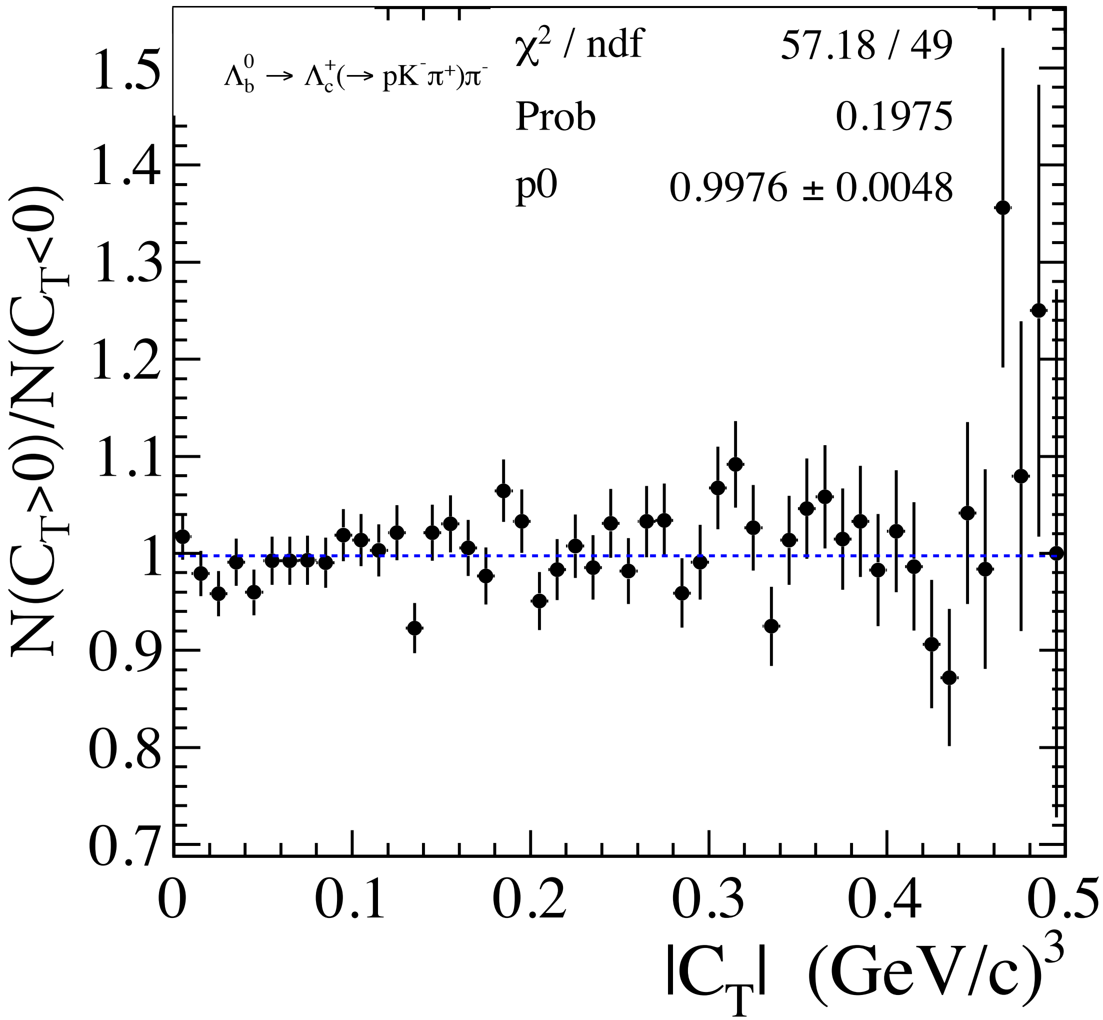
Signal reconstruction efficiency (MC)

$$\epsilon(C_T, \pm) = \frac{(C_T \gtrless 0)_{rec}}{(C_T \gtrless 0)_{gen}}$$

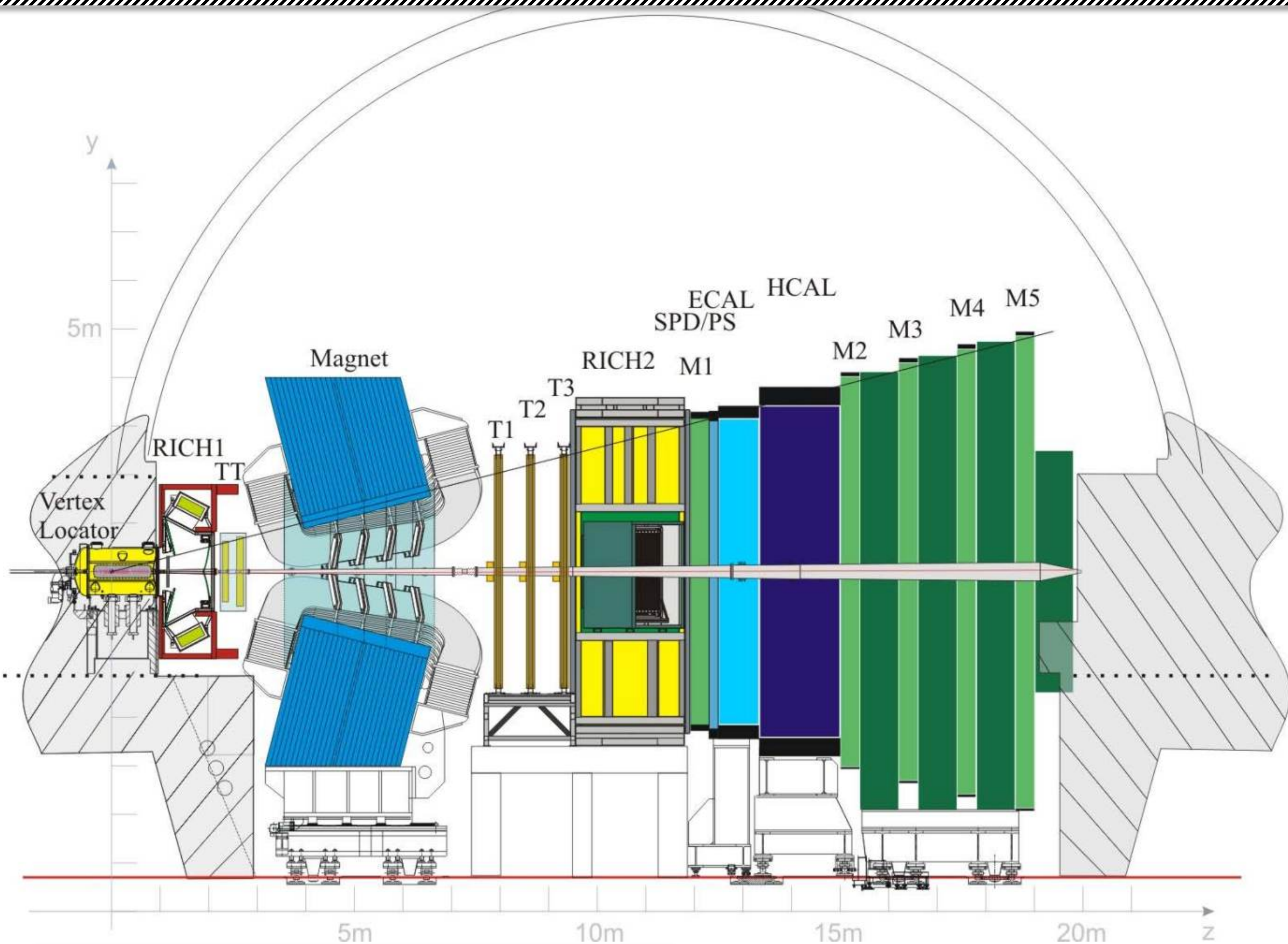




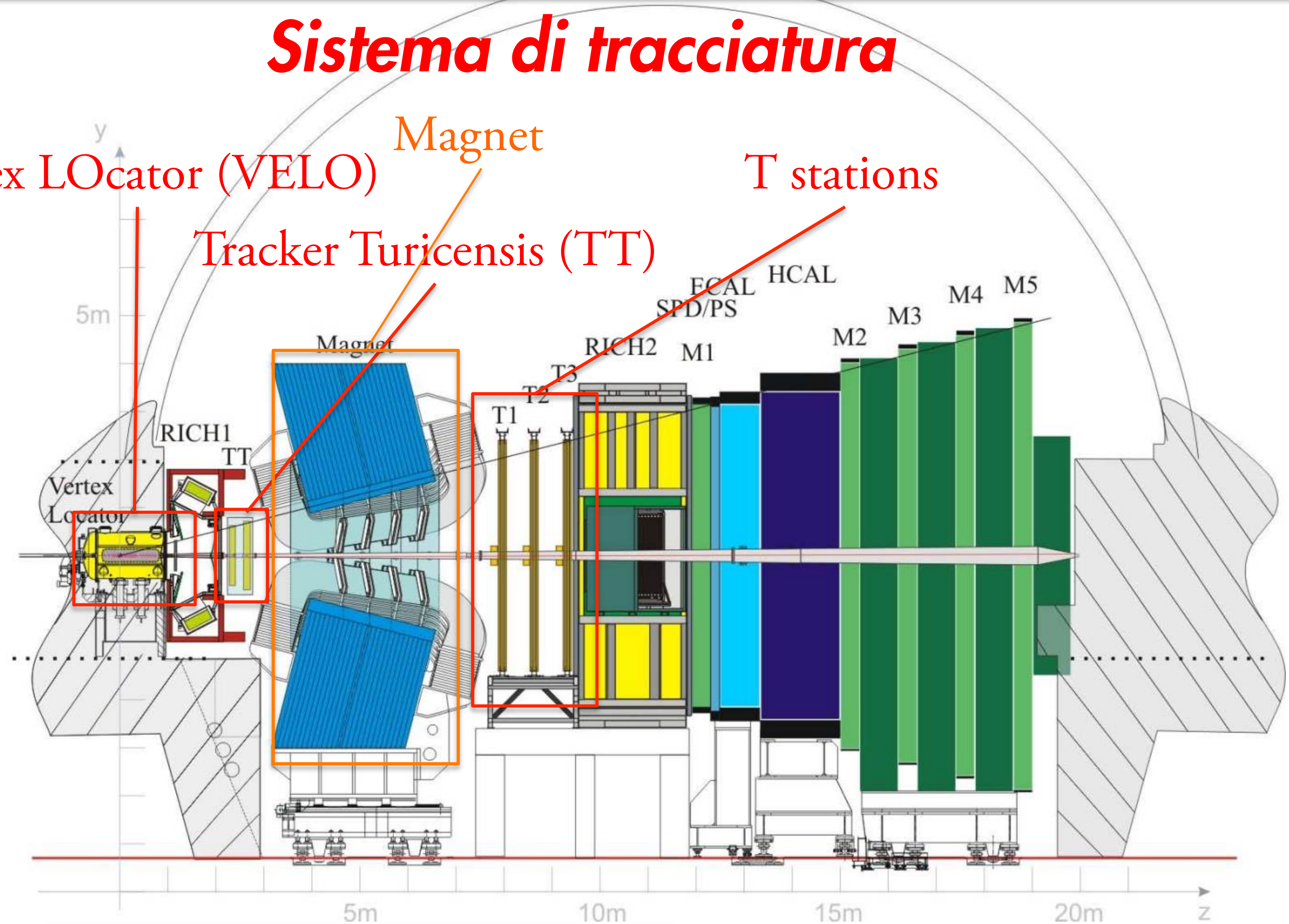
Signal reconstruction efficiency (control sample)



LHCb detector

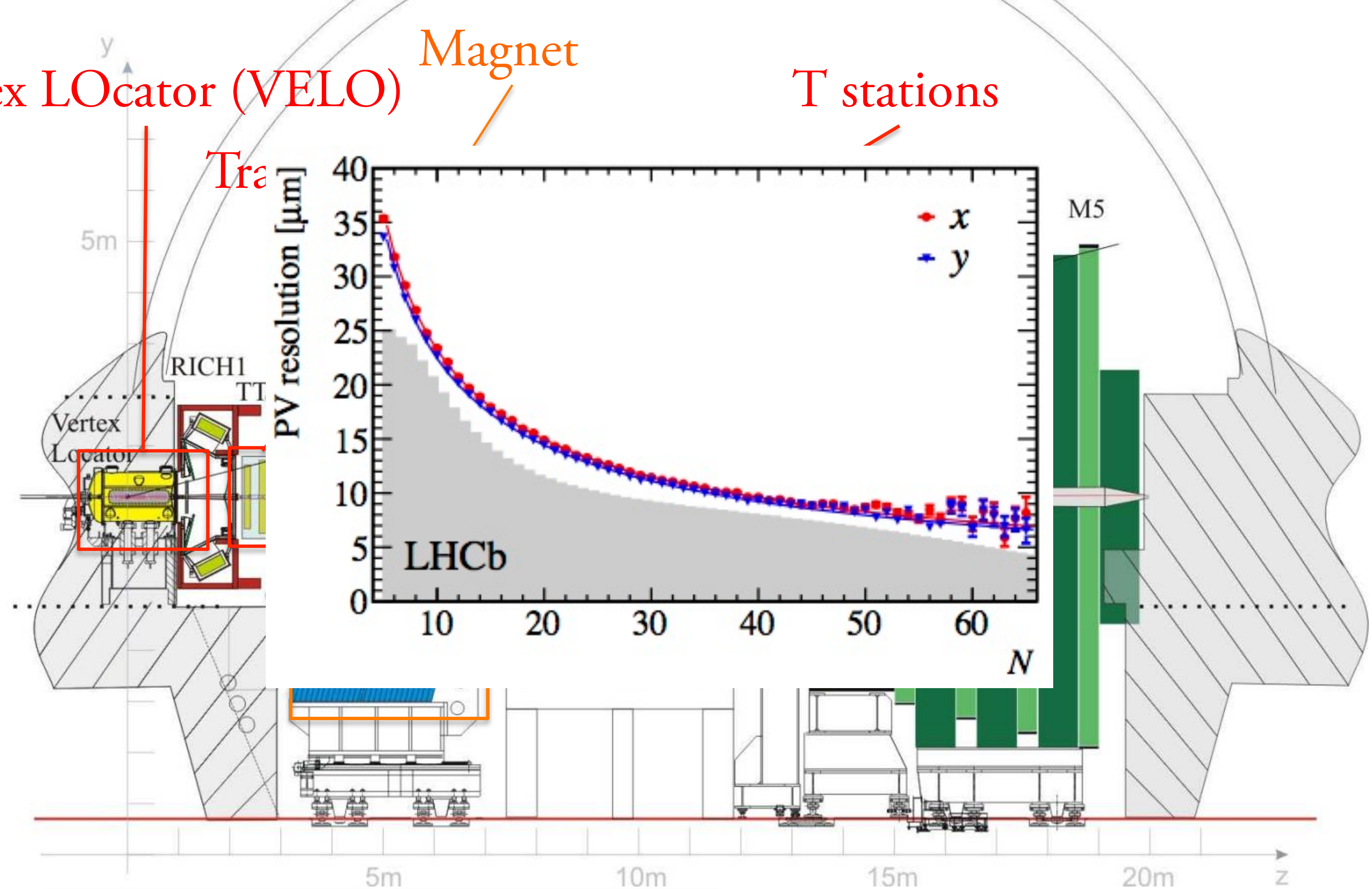


LHCb detector



LHCb detector

Sistema di tracciatura



LHCb detector

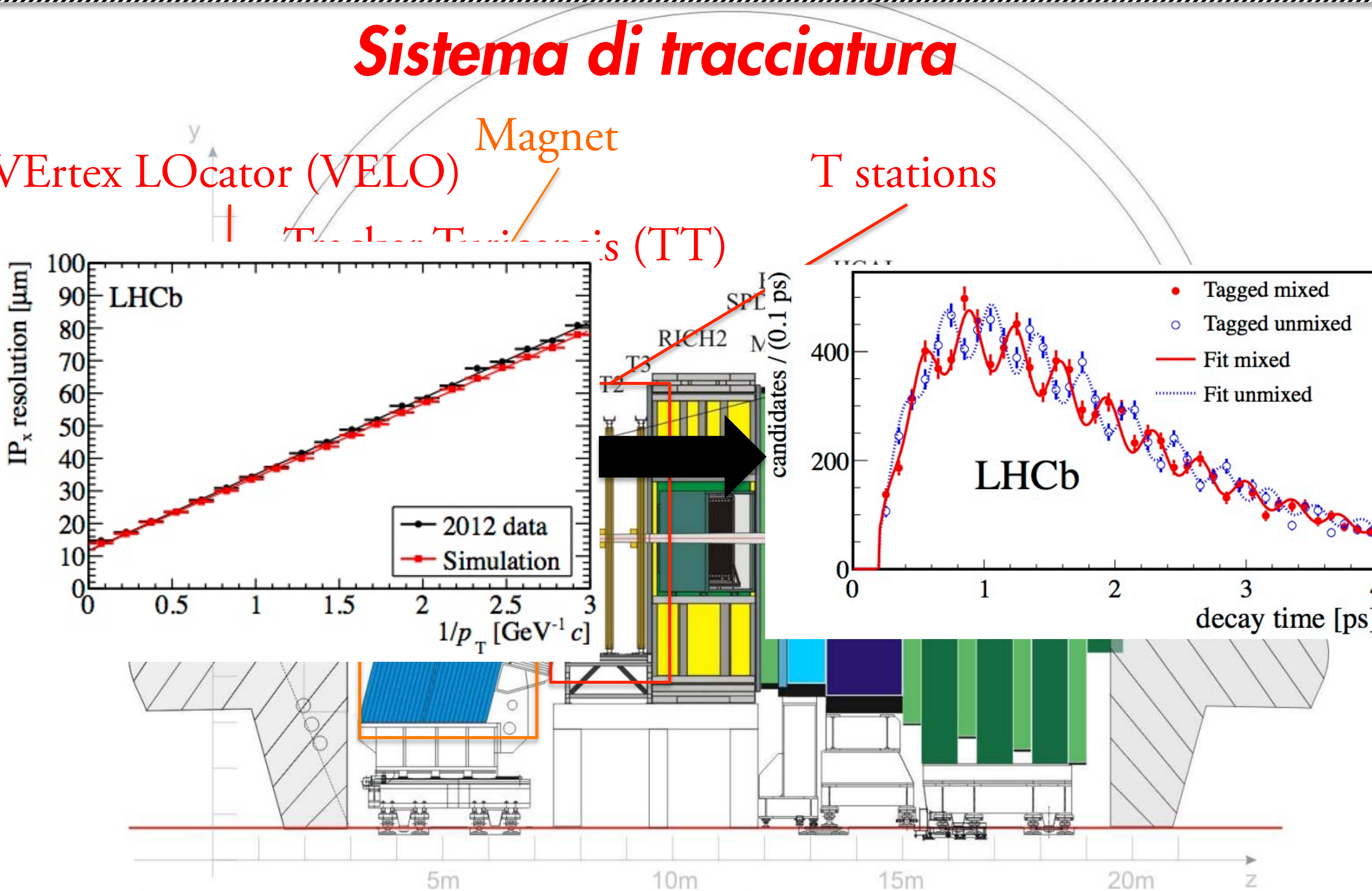
Sistema di tracciatura

VErtex LOcator (VELO)

Magnet

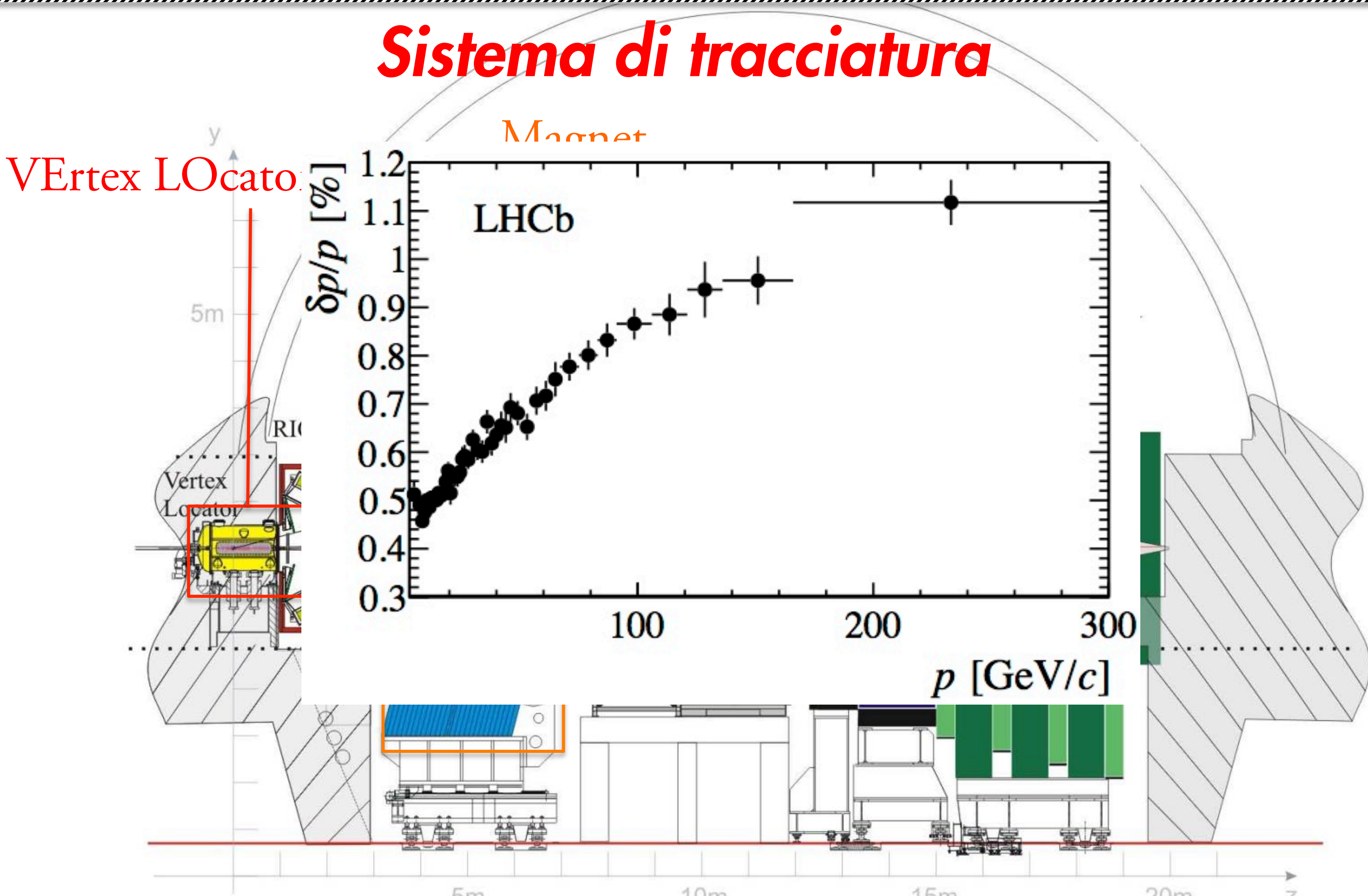
T stations

Tracker Turicensis (TT)



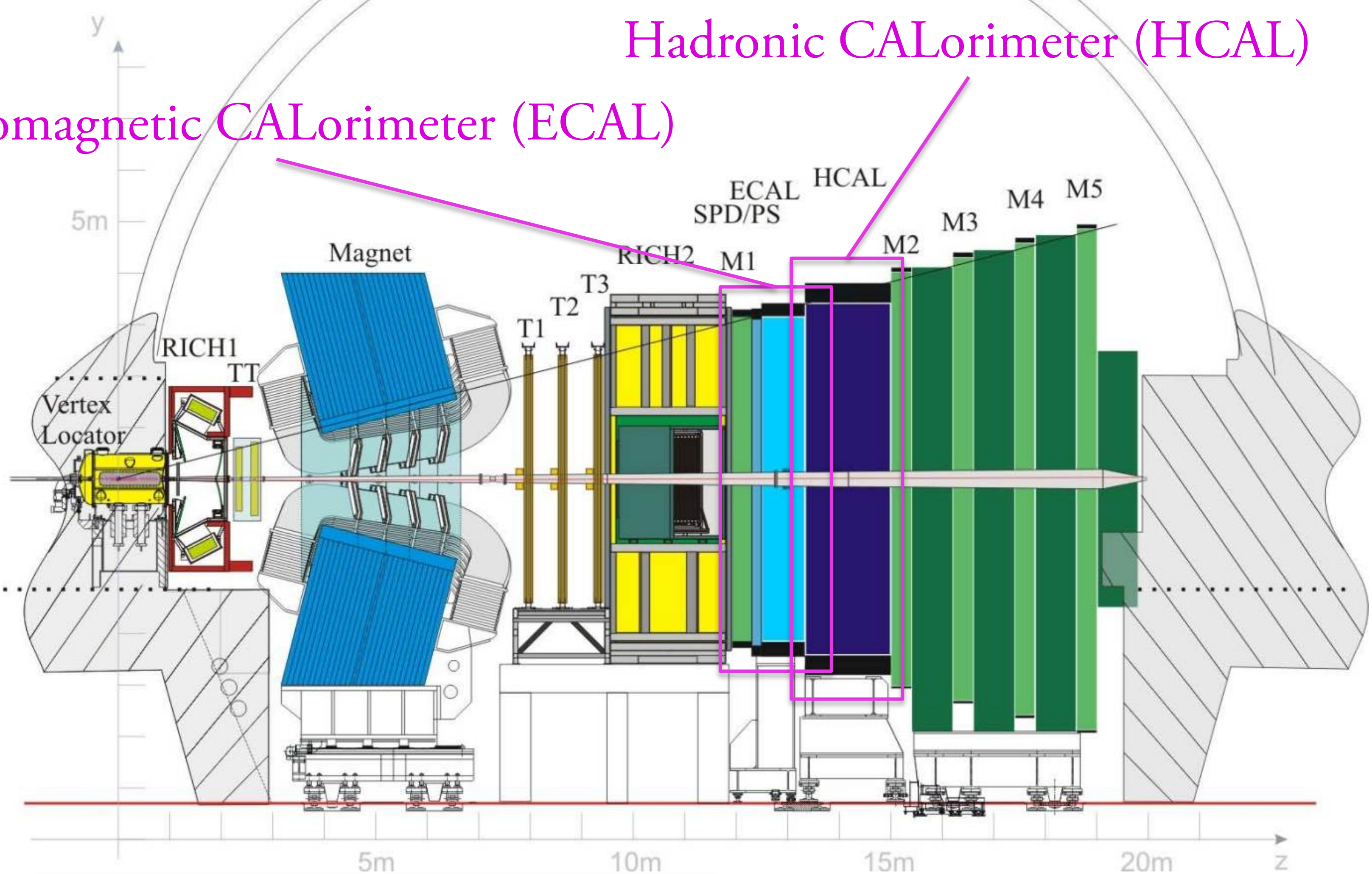
LHCb detector

Sistema di tracciatura



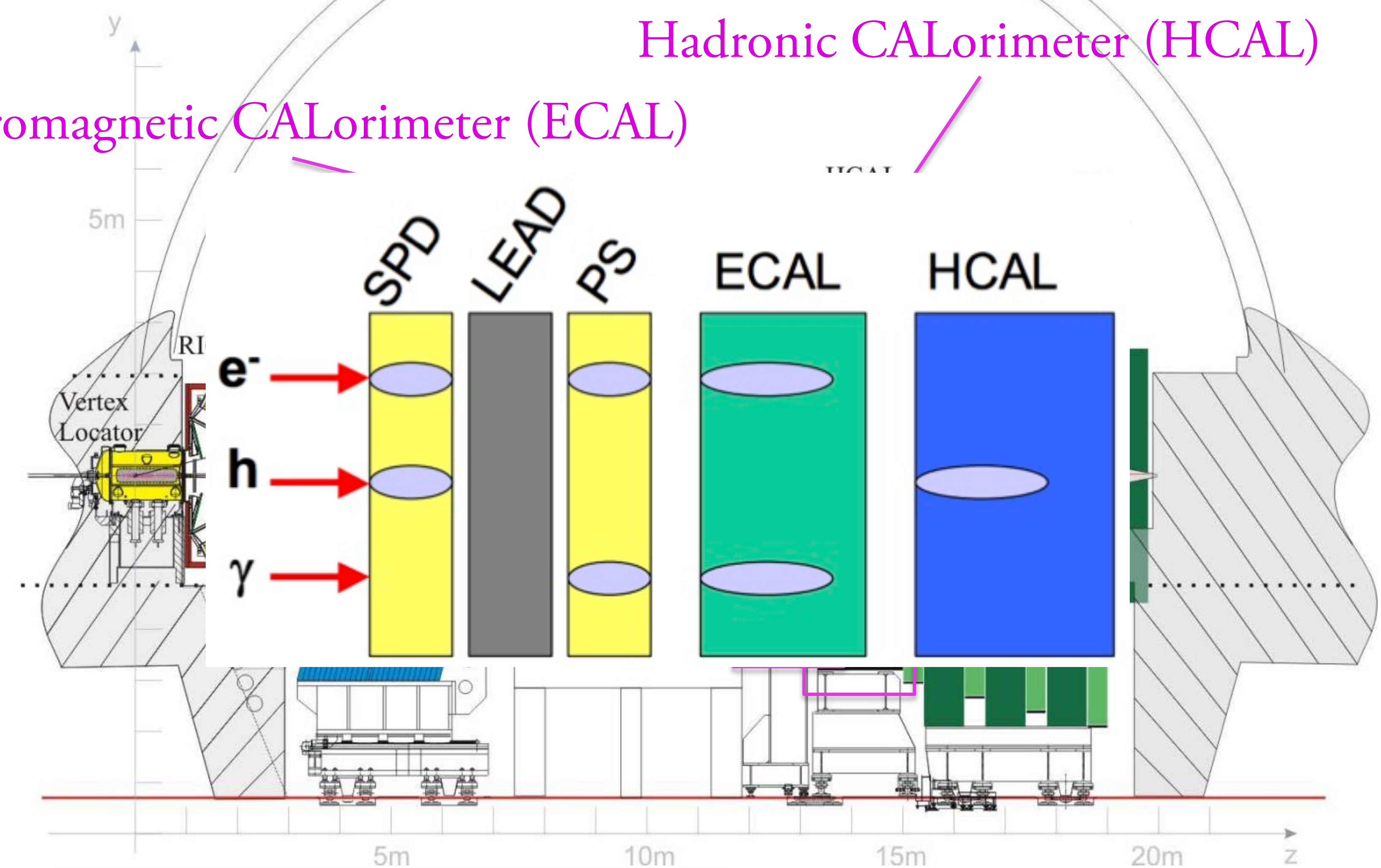
LHCb detector

Sistema di Calorimetria



LHCb detector

Sistema di Calorimetria

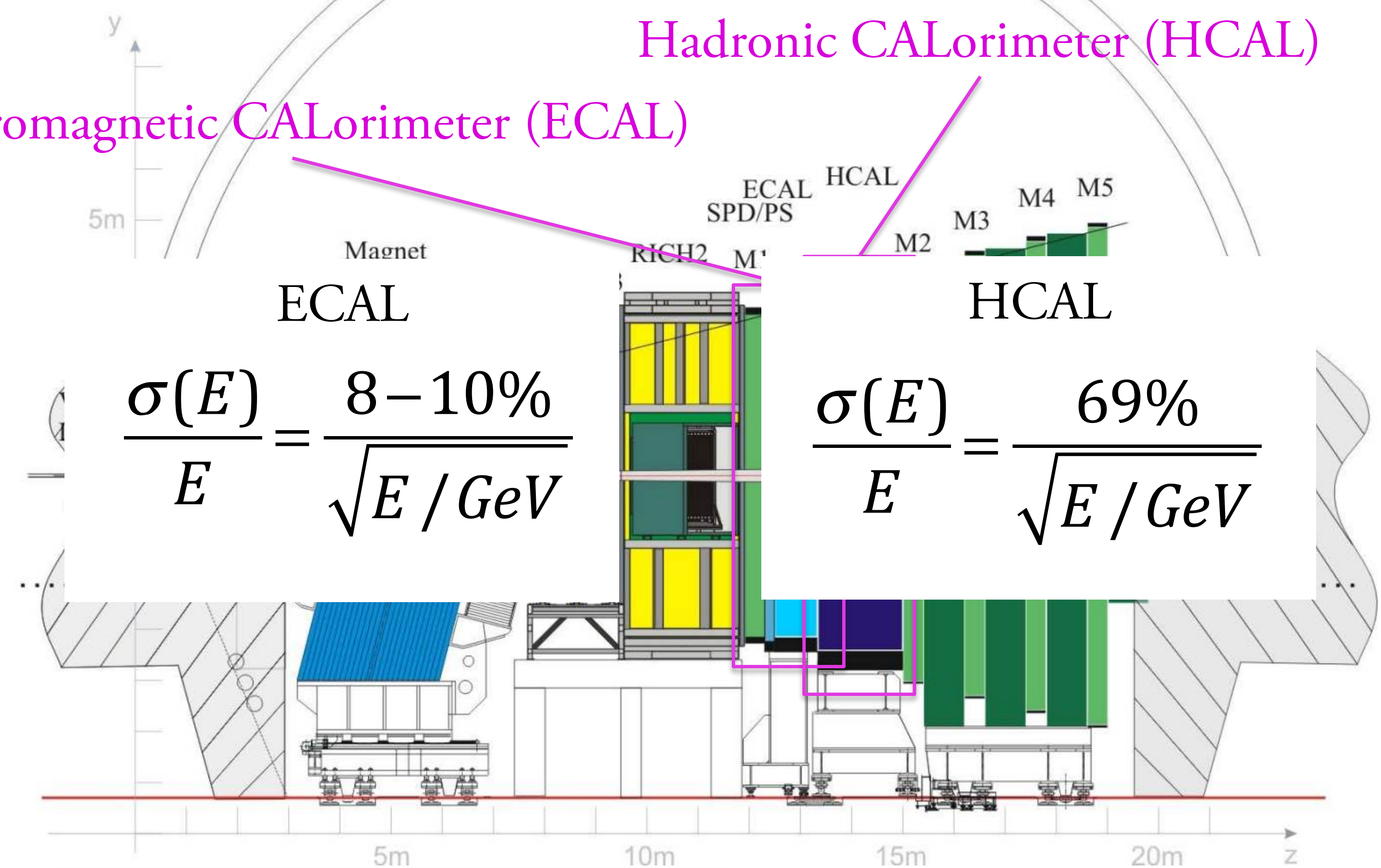


LHCb detector

Sistema di Calorimetria

Hadronic CALorimeter (HCAL)

Electromagnetic CALorimeter (ECAL)



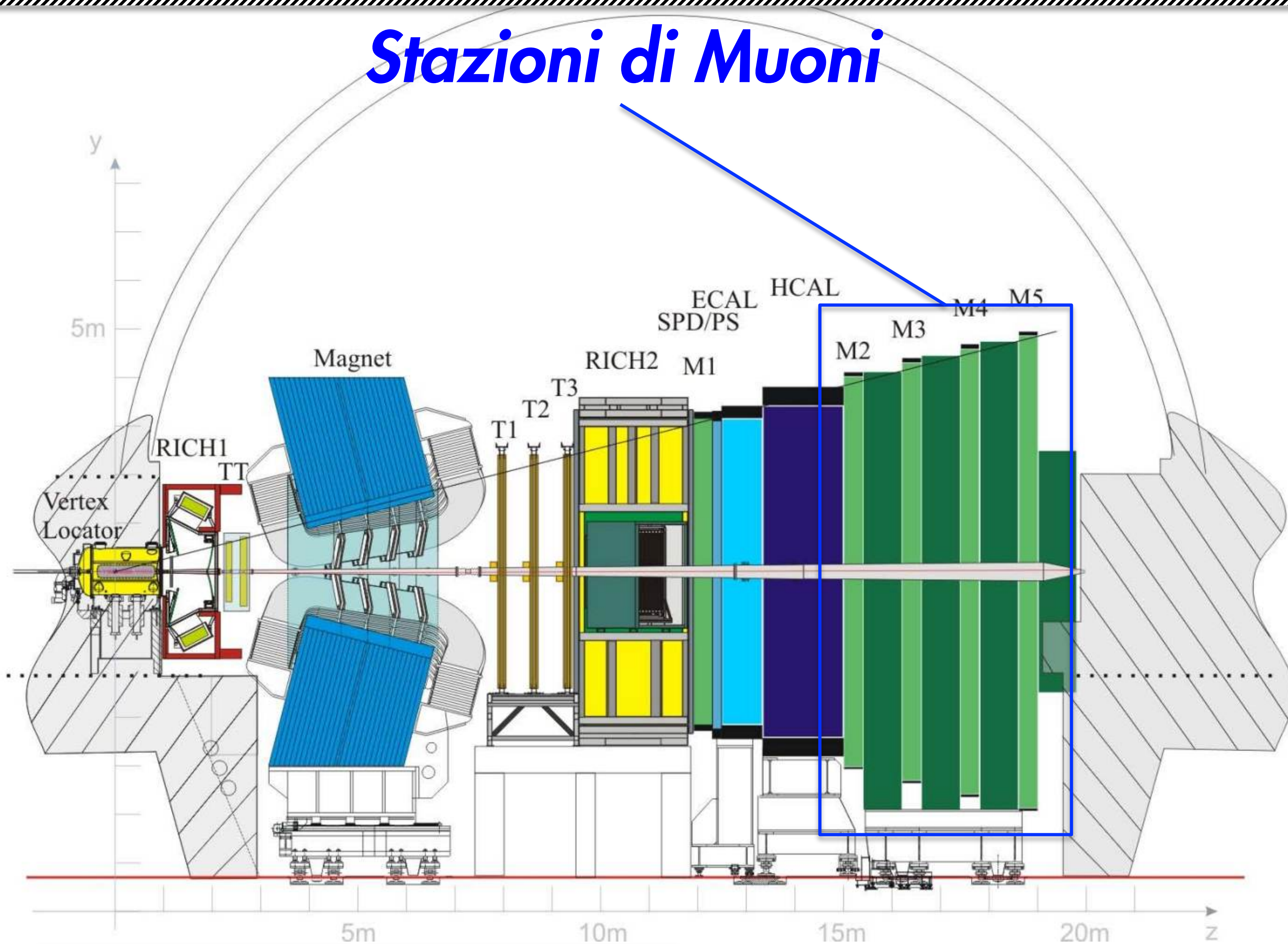
ECAL

$$\frac{\sigma(E)}{E} = \frac{8-10\%}{\sqrt{E/GeV}}$$

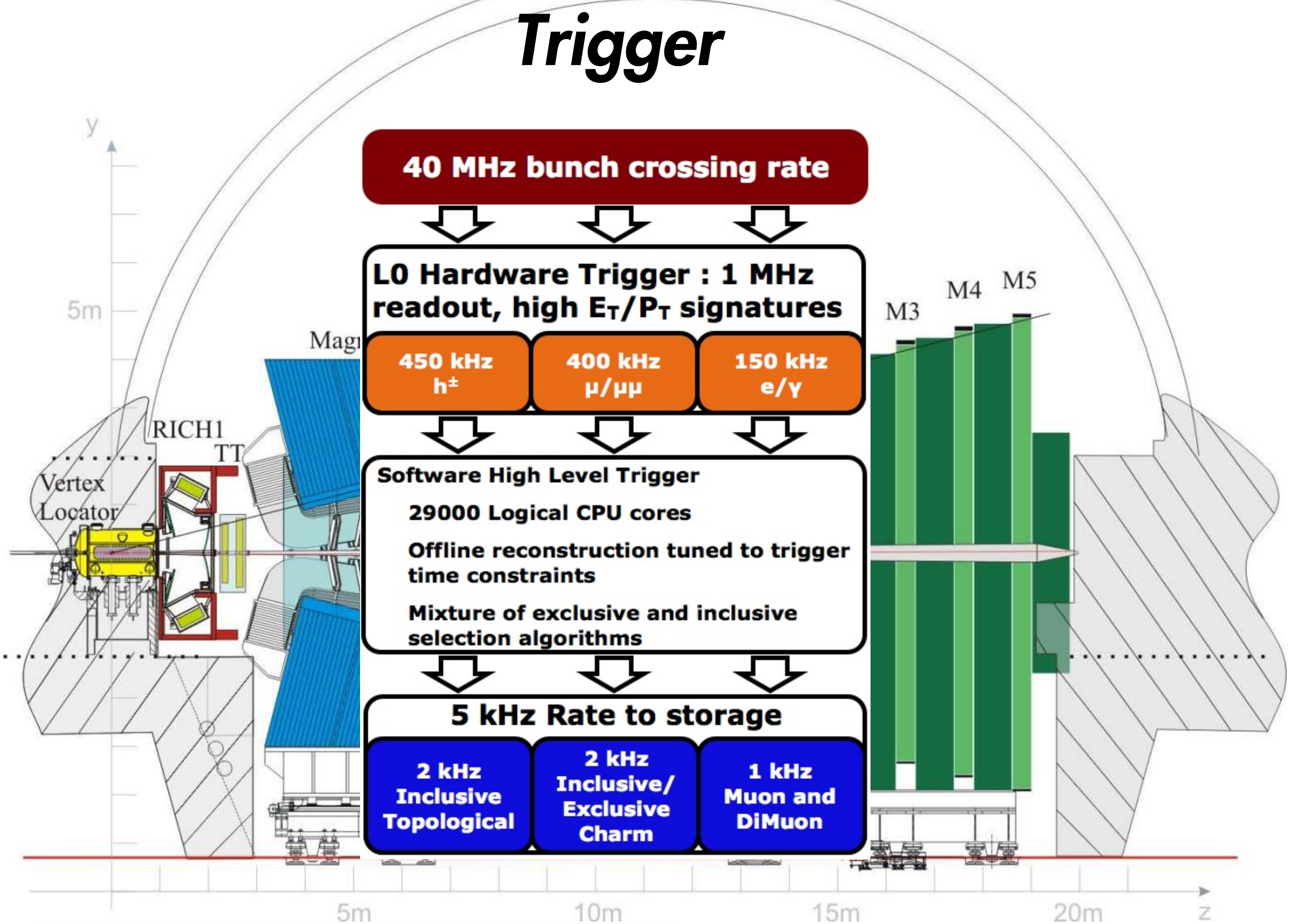
HCAL

$$\frac{\sigma(E)}{E} = \frac{69\%}{\sqrt{E/GeV}}$$

LHCb detector



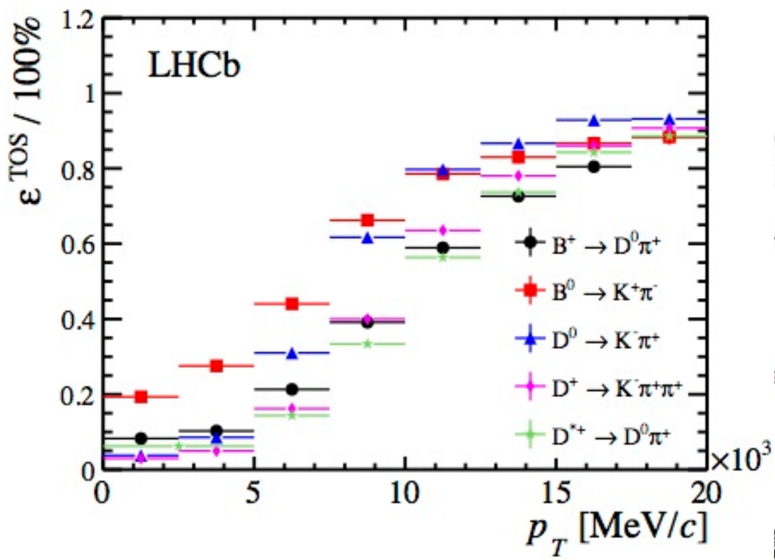
LHCb detector



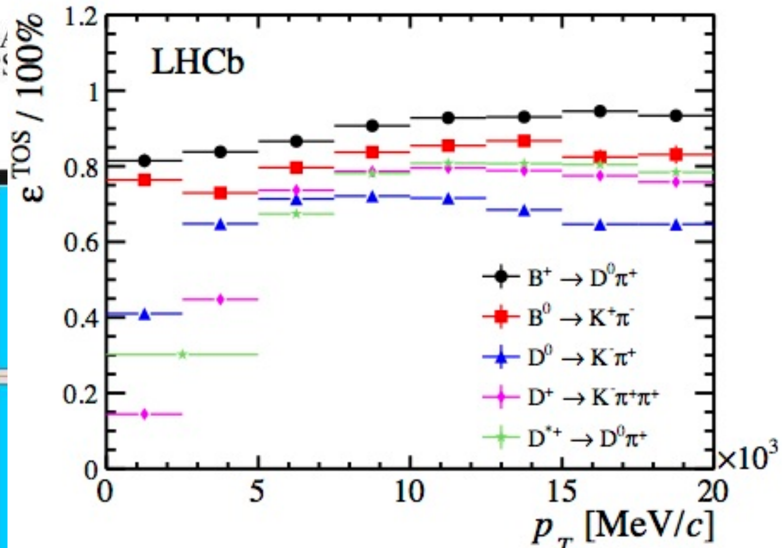
LHCb detector

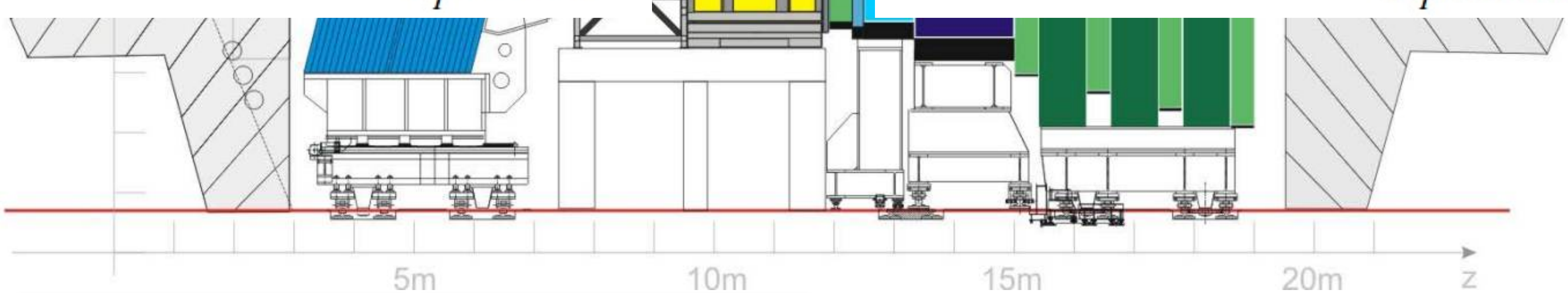
Trigger

L0 trigger efficiency



HLT1 trigger efficiency





LHCb detector

Trigger

L0 trigger efficiency HLT1 trigger efficiency