FLAVOUR PHYSICS AT LHC RUN II:
Three-body charmless *B*-hadrons decays at LHCb

L. Henry, on behalf of the LHCb collaboration

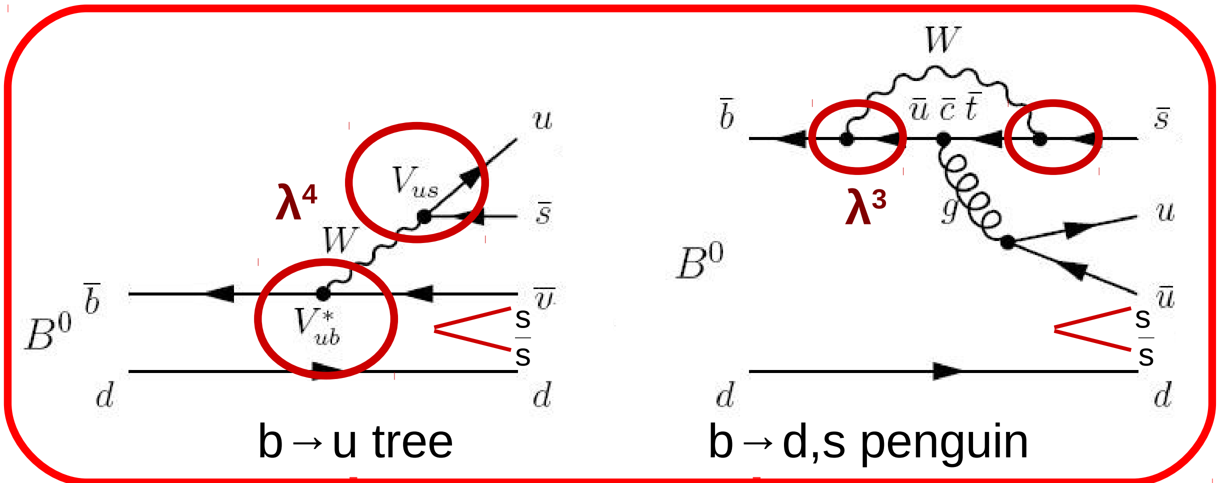
Benasque, 25/05/2017

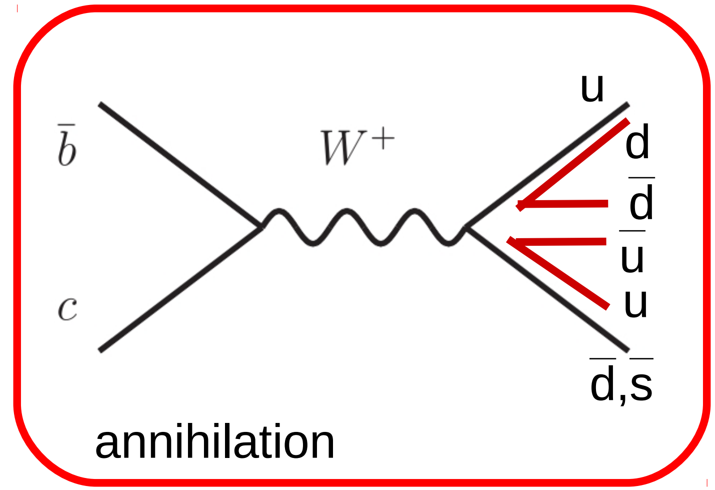
Outline

- Motivations.
- The LHCb detector at LHC
- Results on three-body charmless decays from LHCb Run I analysis
  - Observation of the decay $B_s \to \phi \pi^+ \pi^-$ and evidence for $B_d \to \phi \pi^+ \pi^-$. [Phys. Rev. D 95 (2017) 012006]
  - First observation of a baryonic B_s decay. [arXiv:1704.07908]
  - Search for $H_b^- \to p h^- h'^-$. [arXiv:1612.02244]
  - Update of $B_{d,s} \to K_S h^+ h'^-$ branching fractions. [LHCB-PAPER-2017-010] **(NEW!)**
- Prospects for Run II and further.

Physics case of charmless hadronic *B* decays

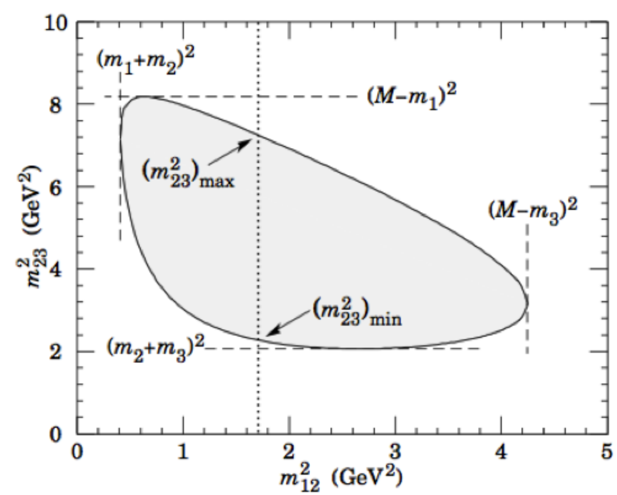
- Charmless *b*-hadron decays proceed through various processes.





can interfere → CP violation

- BSM particles can contribute inside of loops or instead of W+.
- Three-body decays allow access to phases between quasi two-body decays (Q2B) using
  - angular analyses;
  - Dalitz-plot analyses.
- No trigonometric ambiguity!



Three-body charmless decays at LHCb

- Many channels not yet observed
  - Suppressed decays (BR < 10^{-5})
  - Includes decays of B_s, Λ_b, *b*-baryons etc.→not accessible by *B* factories.

- Hadronic final states (except for $\pi^0 \to \gamma\gamma$).

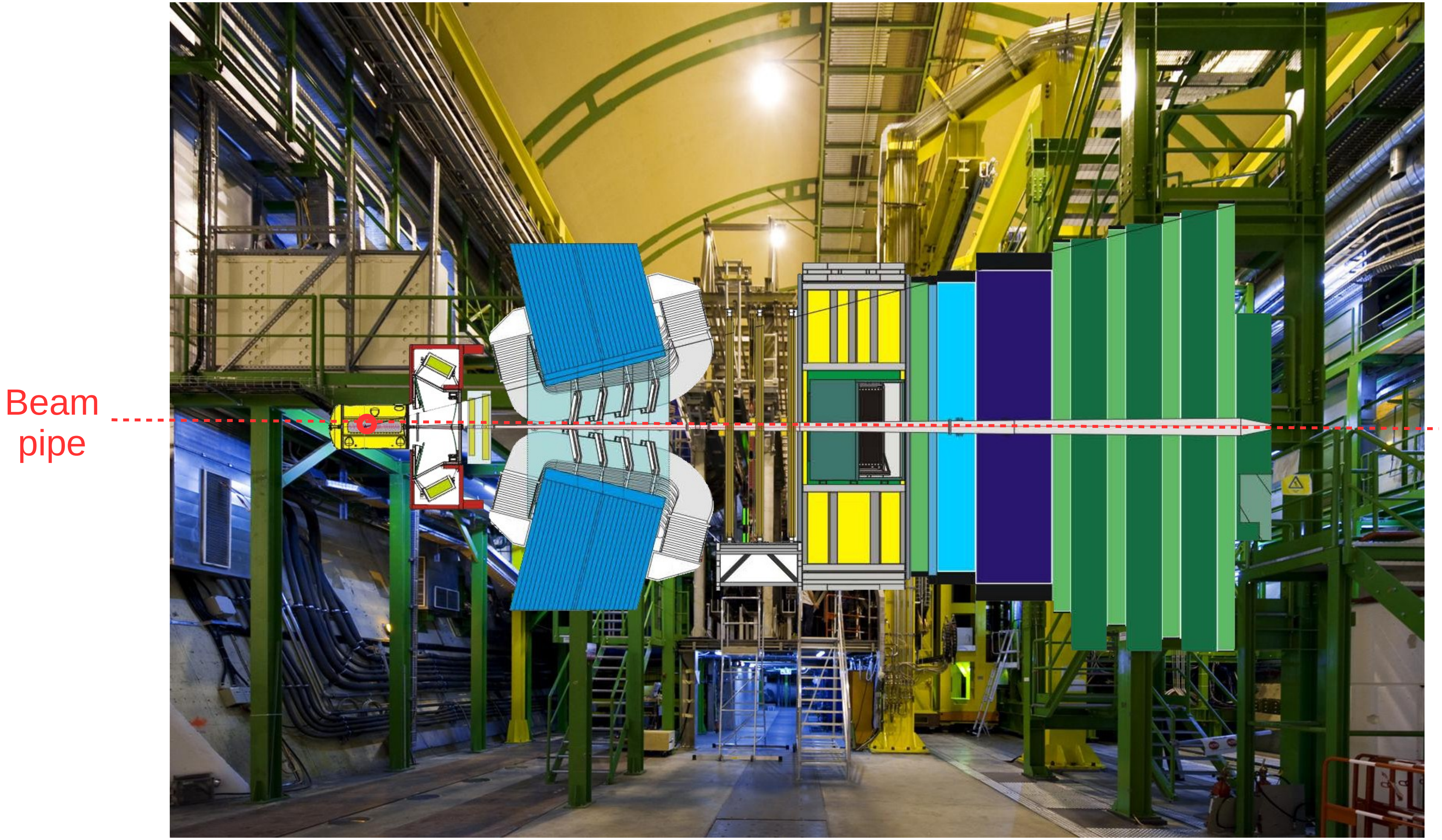
- For most decays, program in two steps:

  1. Observe modes for the first time and extract branching fractions.
  2. Perform angular, Dalitz-plot analyses to access physics observables , e.g. **phases, CPV observables**.

The LHCb detector at LHC

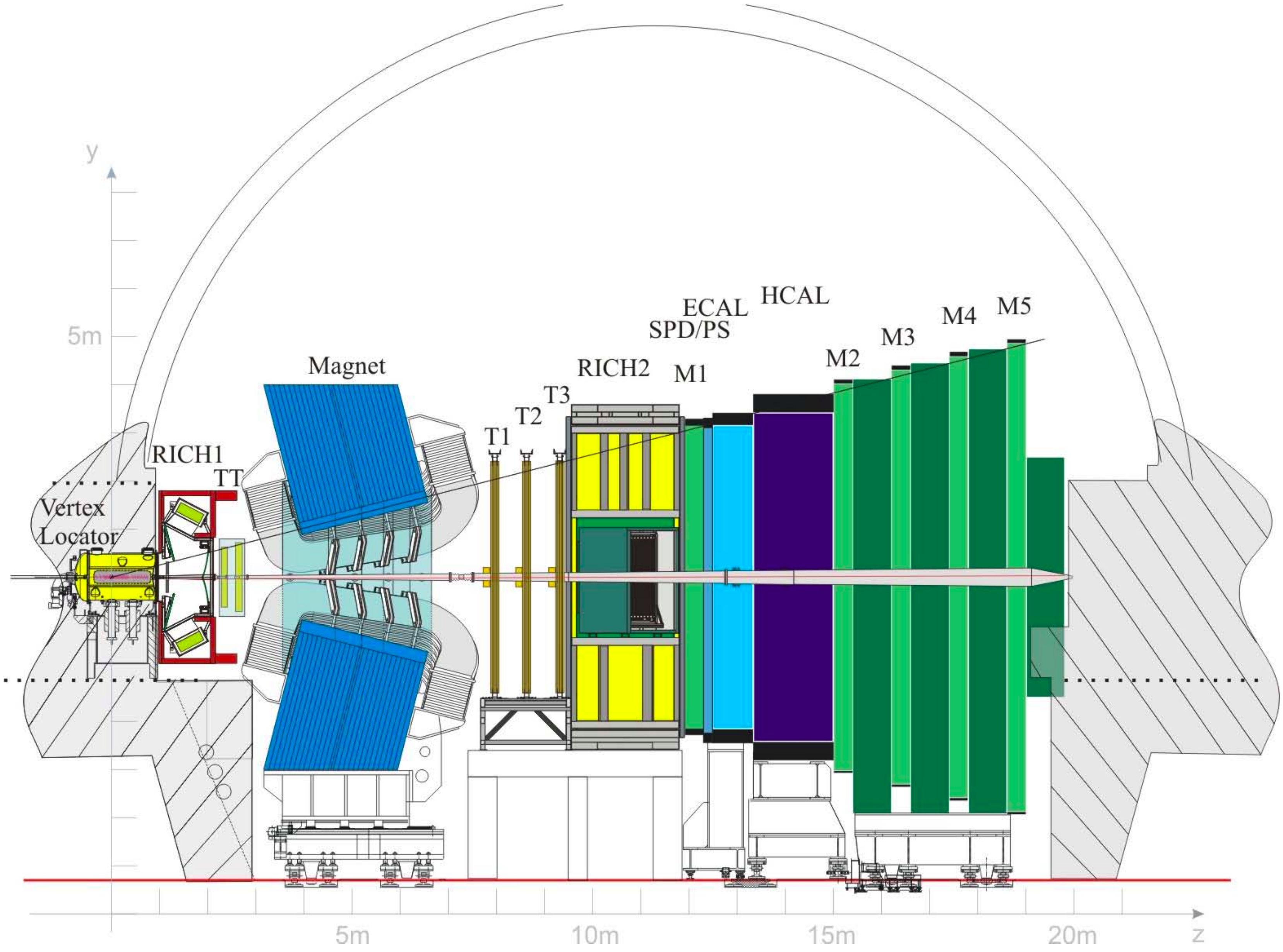
The LHCb detector

The LHCb detector



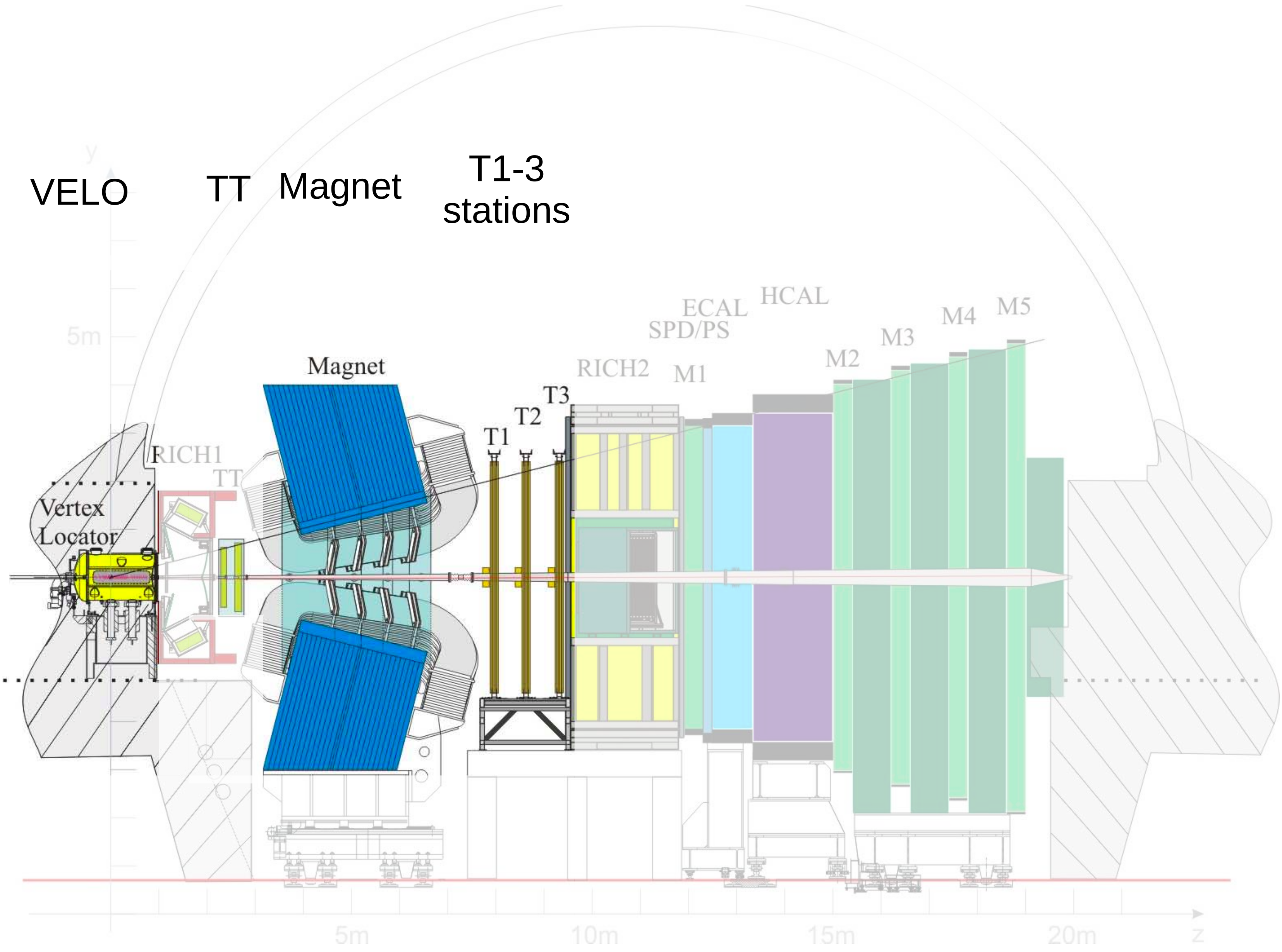
Single-arm forward spectrometer [JINST 3(2008) S08005.]

The LHCb detector: sketch



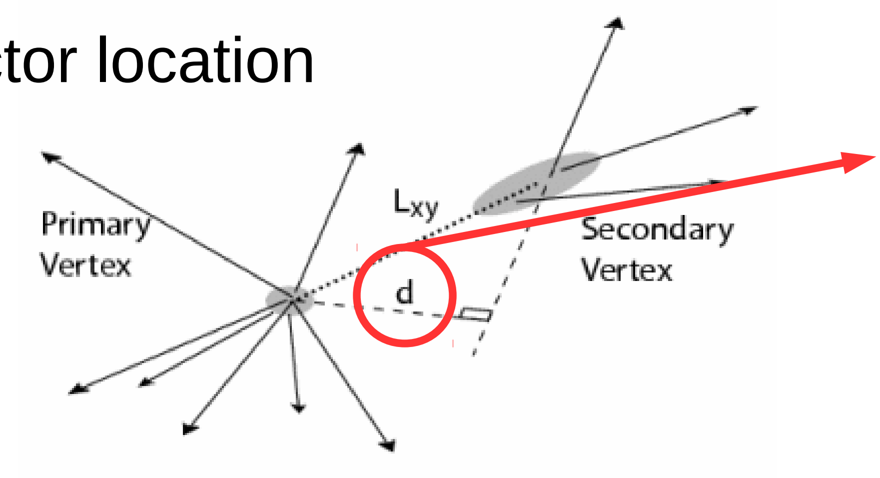
[JINST 3(2008) S08005.]

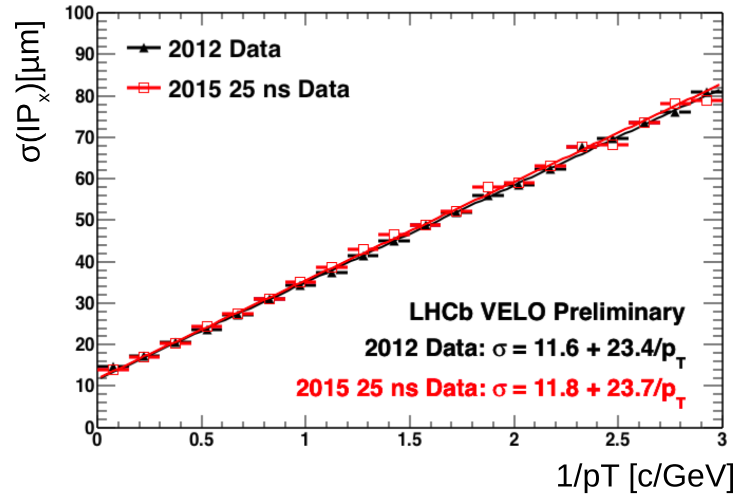
The LHCb detector: tracking subsystems



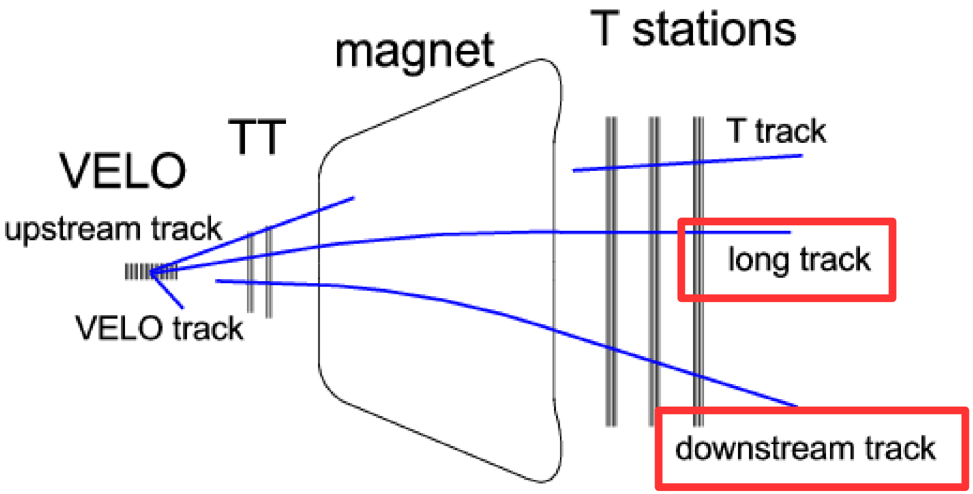
The LHCb detector: tracking subsystems

Vector location





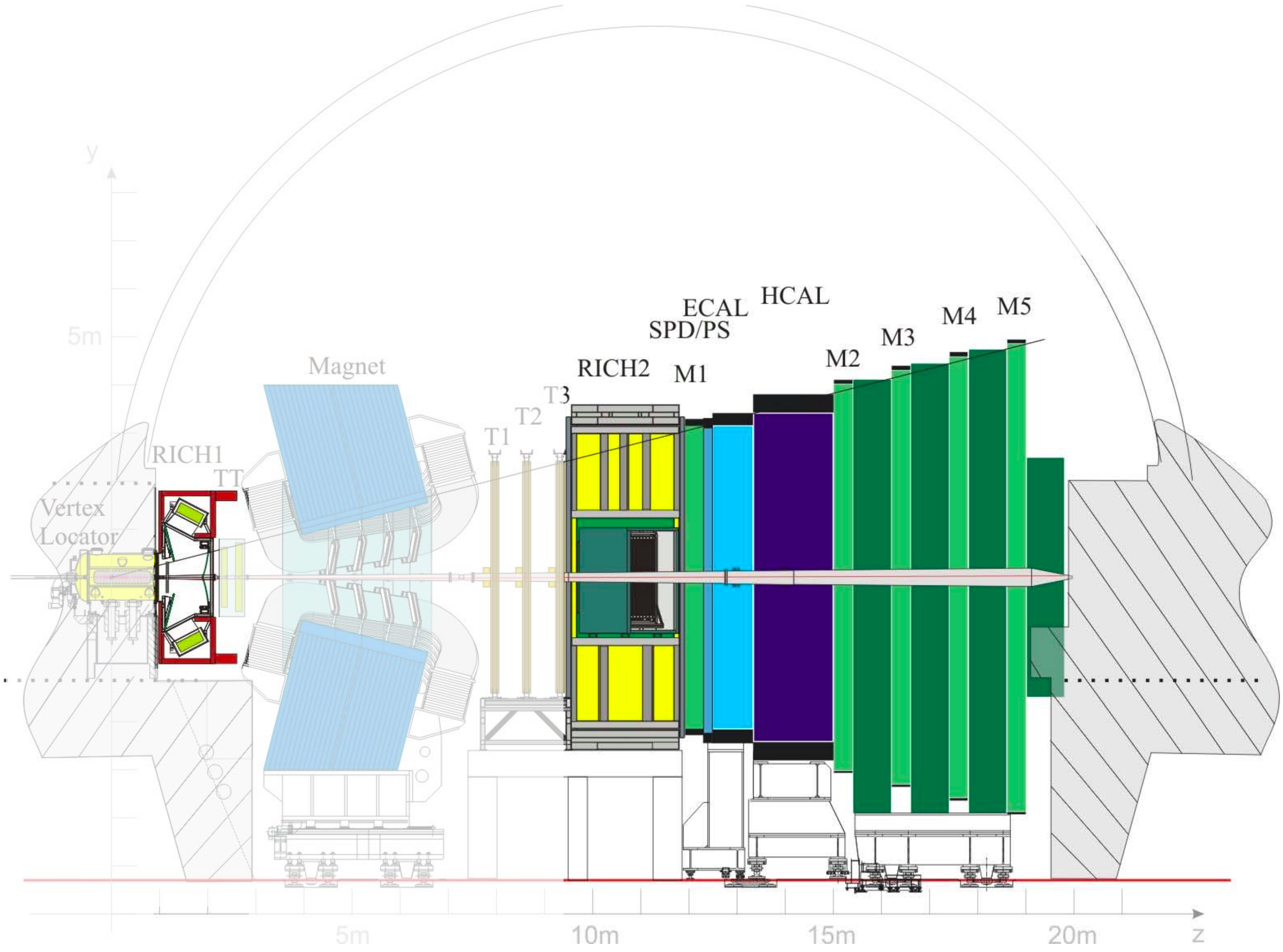
Momentum measurement



LHCb performance paper
arXiv:1412.6352

δp/p ~ 0.5% for Long tracks

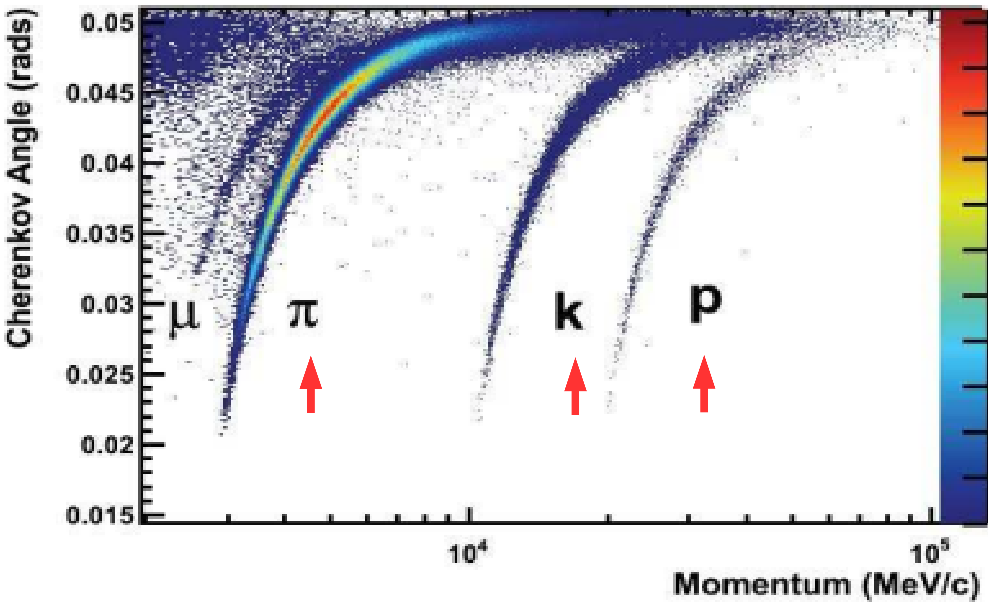
The LHCb detector: particle identification



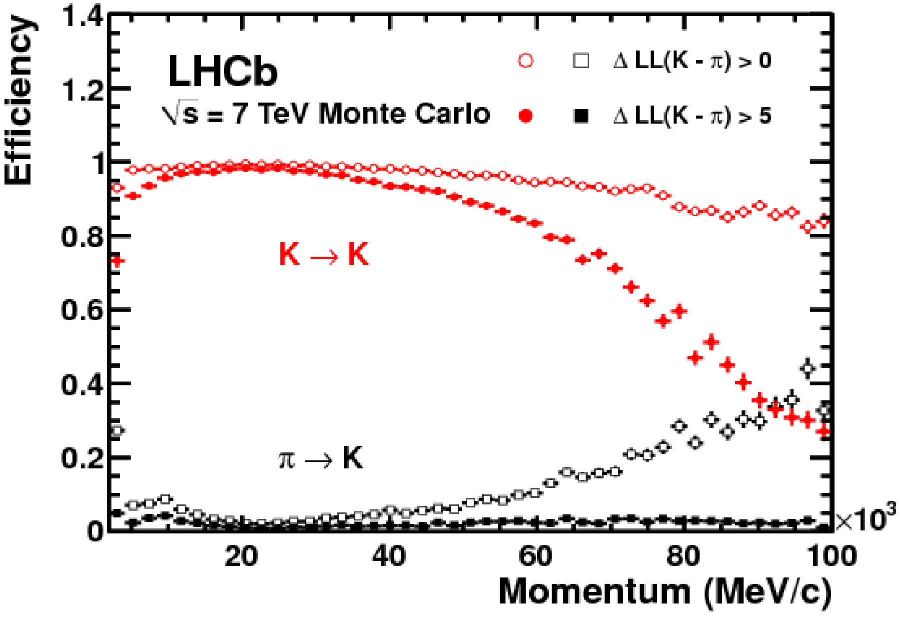
The LHCb detector: particle identification

LHCb performance paper
arXiv:1412.6352

- Fully hadronic final states (except for $\pi^0 \to \gamma\gamma$).



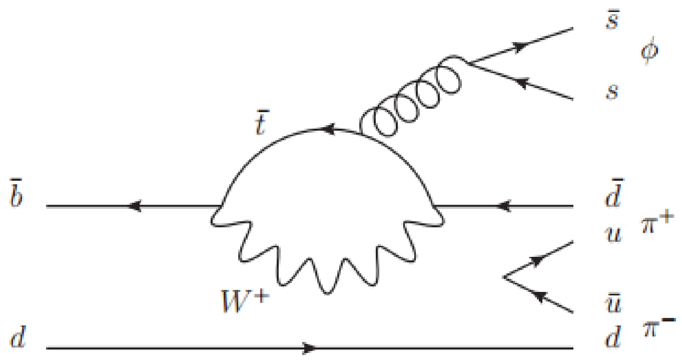
- LHCb particle identification relies on:
  - Cherenkov detectors (RICH);
  - shower development;
  - calorimetry.



Results on three-body charmless decays from LHCb Run I analyses

Search for $B_{d,s} \to \phi\pi^+\pi^-$: measurement of branching fractions

- $B_{d,s} \to \varphi\pi^+\pi^-$ decays proceed through $b \to d,s$ transitions (FCNC).
  - not yet observed.



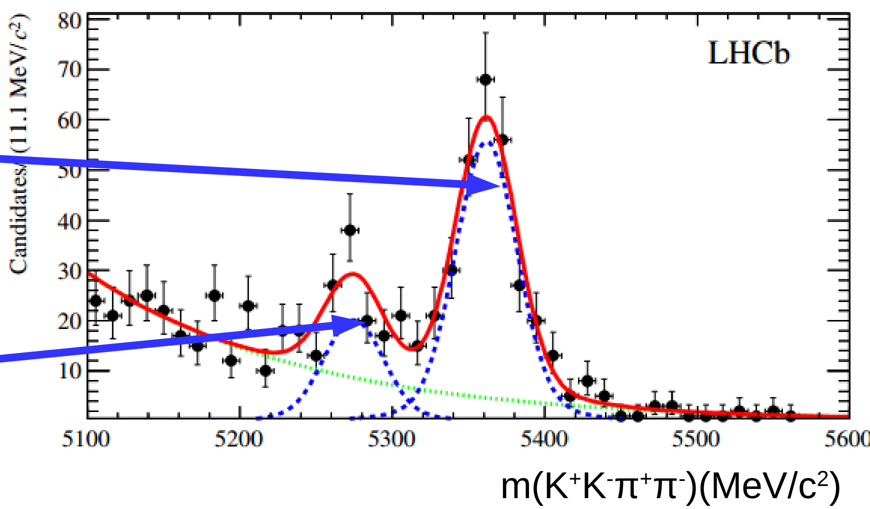
- Depending on intermediate resonance, different ratios between gluonic/EW penguins.
  - for instance, in $B_{d,s} \to \varphi f_0(980)$, gluonic penguin dominates.
- Large CP asymmetries expected in the $\Delta I = 1$ $B_s \to \Phi\rho$ decay [arXiv:1011.6319]
- Charmed and $B_s \to K^*K^*$ backgrounds vetoed.

[Phys. Rev. D 95 (2017) 012006]

$$\mathcal{B}(B_s^0 \to \phi\pi^+\pi^-) = [3.48 \pm 0.23 \pm 0.17 \pm 0.35] \times 10^{-6}$$

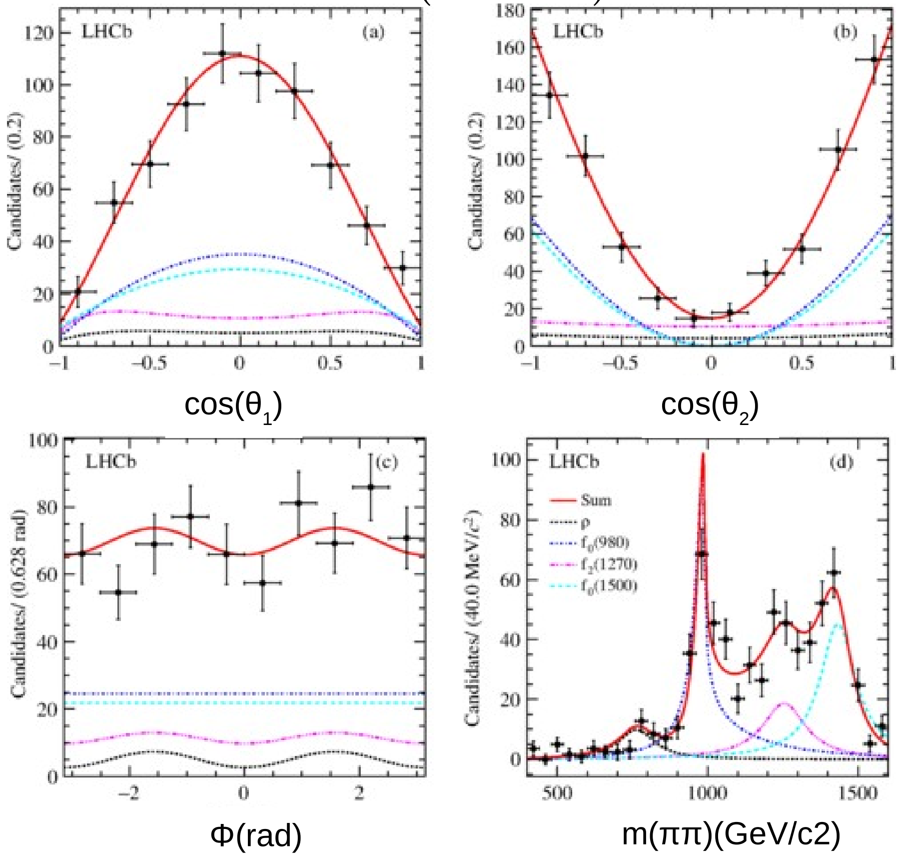
$$\mathcal{B}(B^0 \to \phi\pi^+\pi^-) = [1.82 \pm 0.25 \pm 0.41 \pm 0.14] \times 10^{-7}\,.$$

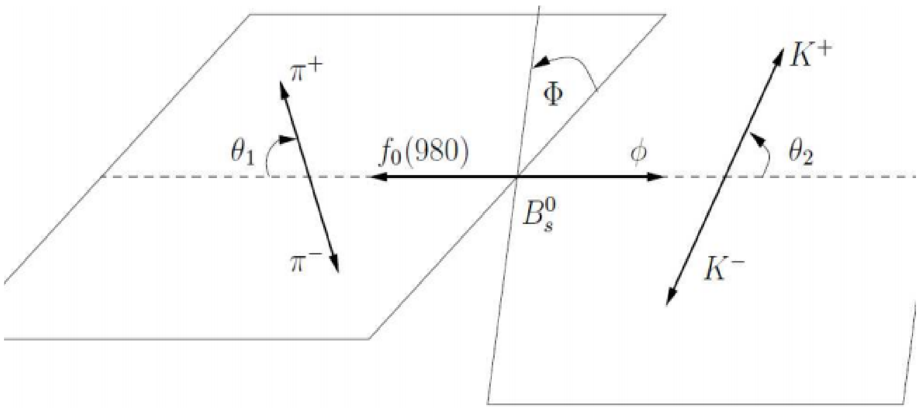
stat syst control



Search for $B_{d,s} \to \varphi\pi^+\pi^-$: amplitude analysis

- Signal distributions (B_s) of angular variables and invariant masses extracted from fit (sPlots).





$f_0(980)$

$f_2(1270)$

$f_0(1500)$

$\rho^0(770)$

[Phys. Rev. D 95 (2017) 012006]

$$\mathcal{B}(B_s^0 \to \phi f_0(980), f_0(980) \to \pi^+\pi^-) = [1.12 \pm 0.16^{+0.09}_{-0.08} \pm 0.11] \times 10^{-6}.$$

$$\mathcal{B}(B_s^0 \to \phi f_2(1270), f_2(1270) \to \pi^+\pi^-) = [0.61 \pm 0.13^{+0.12}_{-0.05} \pm 0.06] \times 10^{-6}$$

→ >=5σ

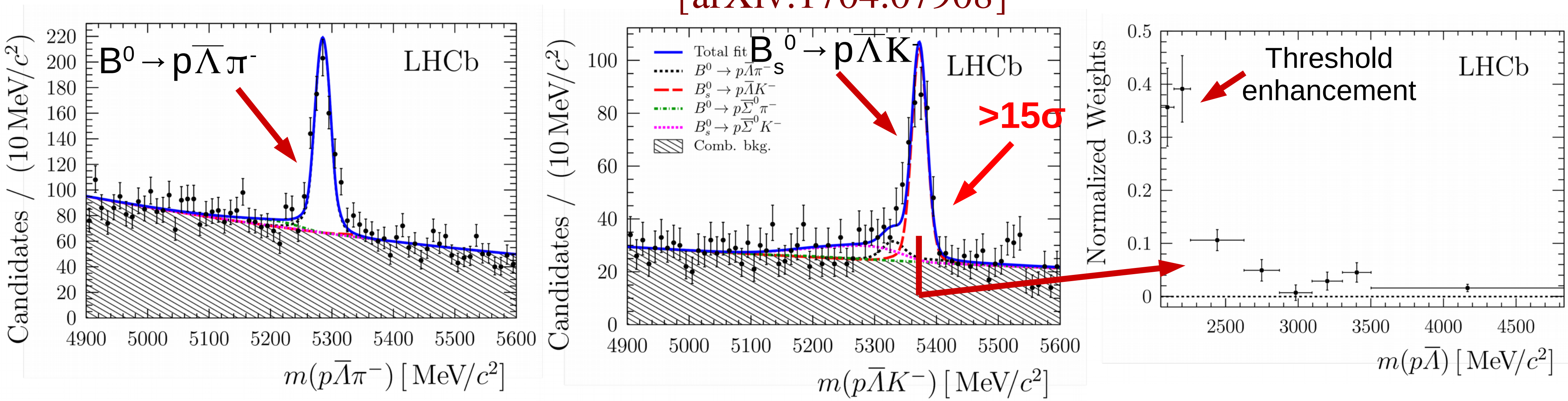
$$\mathcal{B}(B_s^0 \to \phi \rho^0(770)) = [2.7 \pm 0.7 \pm 0.2 \pm 0.2] \times 10^{-7}$$

→ 4σ

First observation of a baryonic B_s decay

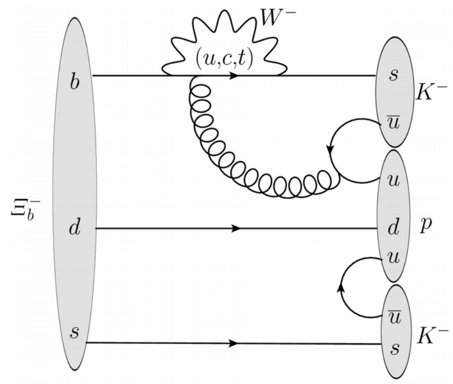
- B_s is the last *B*-meson species where it has to be observed.
  - Previous Belle evidence > 4σ for $B_s \to \overline{\Lambda}_c^- \Lambda \pi^+$.
- Decays under study: $B_{d,s} \to p\overline{\Lambda}h^-$, h = π or K. CP-conjugates implied.
- Theoretical impact:
  - Multi-body baryonic B decays expected to have larger branching fractions than two-body decays (threshold enhancement).
  - Large CPV (~10%) expected in $B^0 \to p\overline{\Lambda}\pi^-$. [arXiv:0801.0022]
  - $B_s \to p\overline{\Lambda}K^-$ is unique as a given final state is accessible by both B_s and $\overline{B}_s$.

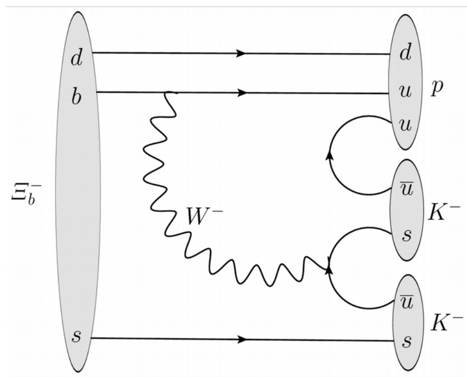
[arXiv:1704.07908]



Search for $H_b^- \to p h^- h'^-$

- H_b is Ξ_b^- or Ω_b^-; h is a pion or a kaon→three final states.
  - No mode yet observed.
- Loop-dominated decays.





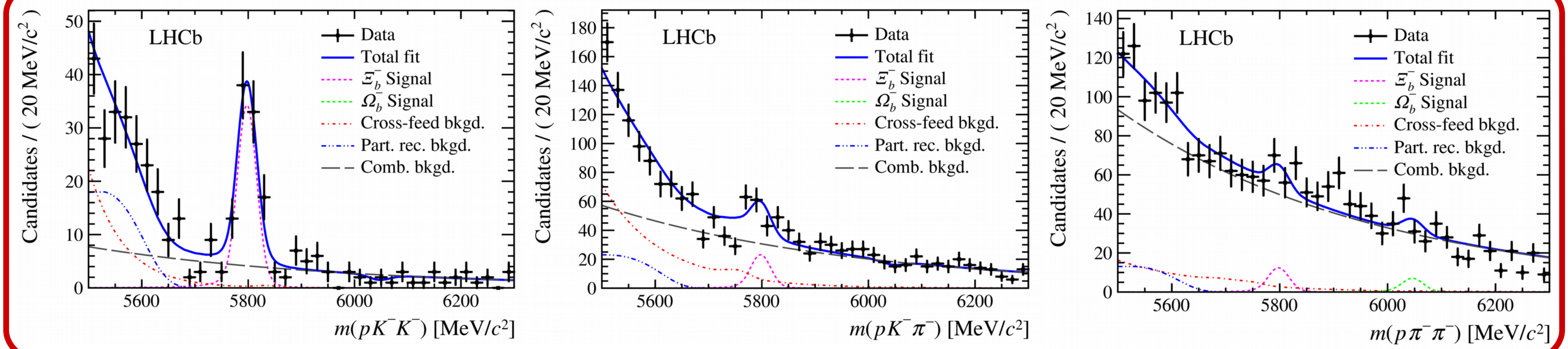
- LHCb has reported in 2017 the first observation of CPV in *b* baryons ($\Lambda_b \to p\pi^+\pi^-\pi^+$ [Nature Physics 13, 391–396 (2017)]).
- Normalized with respect to the $B^- \to K^-K^+K^-$ decay.

$$R_{ph^-h'^-} \equiv \frac{f_{\Xi_b^-}}{f_u} \frac{\mathcal{B}(\Xi_b^- \to ph^-h'^-)}{\mathcal{B}(B^- \to K^+K^-K^-)} = \frac{\mathcal{N}(\Xi_b^- \to ph^-h'^-)}{\mathcal{N}(B^- \to K^+K^-K^-)} \frac{\epsilon(B^- \to K^+K^-K^-)}{\epsilon(\Xi_b^- \to ph^-h'^-)}$$

Yields (from fit)

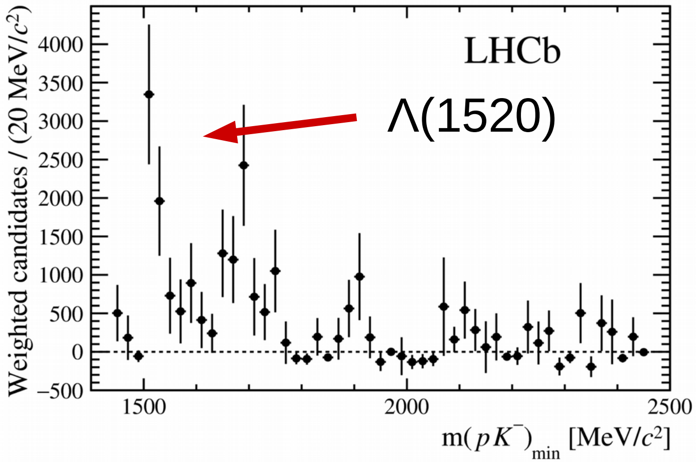
Efficiencies (from Monte-Carlo);
Corrections applied;
5-D phase-space dependency + lifetime.

Search for $H_b^- \to p h^- h'^-$: results



- **First observation of $\Xi_b^- \to pK^-K^-$ (8.7σ)** →can be used as normalisation.
- **First evidence of $\Xi_b^- \to pK^-\pi^-$ (3.4σ)**.
- No evidence for the other decays.
- Dynamics appear in $m(pK^-)$ distribution.

[arXiv:1612.02244]



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

$$\frac{\mathcal{B}(\Xi_b^- \to p\pi^-\pi^-)}{\mathcal{B}(\Xi_b^- \to pK^-K^-)} = 0.28 \pm 0.16\,(\text{stat}) \pm 0.13\,(\text{syst}) \quad < \; 0.56\;(0.63)$$

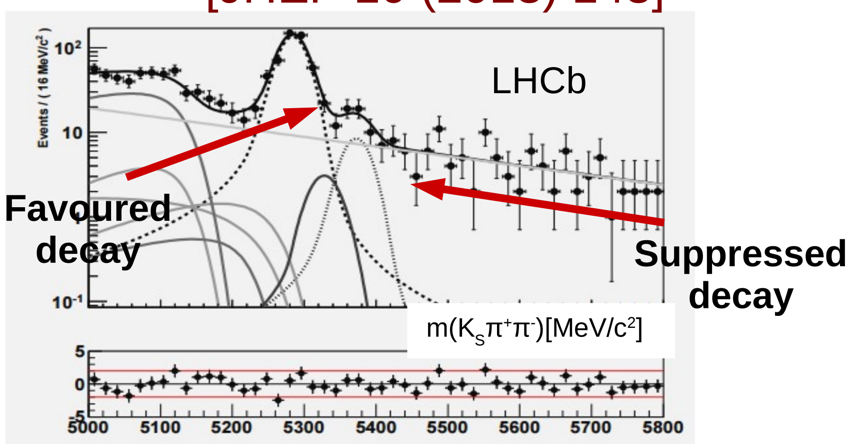
Update of $B_{d,s} \to K_S h^+ h'^-$ branching fractions

- $B_{d,s} \to K_s h^+ h^{-\prime}$, with h, h' = π,K → 8 decays.

$B_d \to K_S \pi^+ \pi^-$	$B_d \to K_S K^+ \pi^-$	$B_d \to K_S K^- \pi^+$	$B_d \to K_S K^+ K^-$
$B_s \to K_S \pi^+ \pi^-$	$B_s \to K_S K^+ \pi^-$	$B_s \to K_S K^- \pi^+$	$B_s \to K_S K^+ K^-$

Green: observed; **Red**: not observed; ▭: favoured decay (see below).

Previous LHCb analysis (1fb^{-1})
[JHEP 10 (2013) 143]

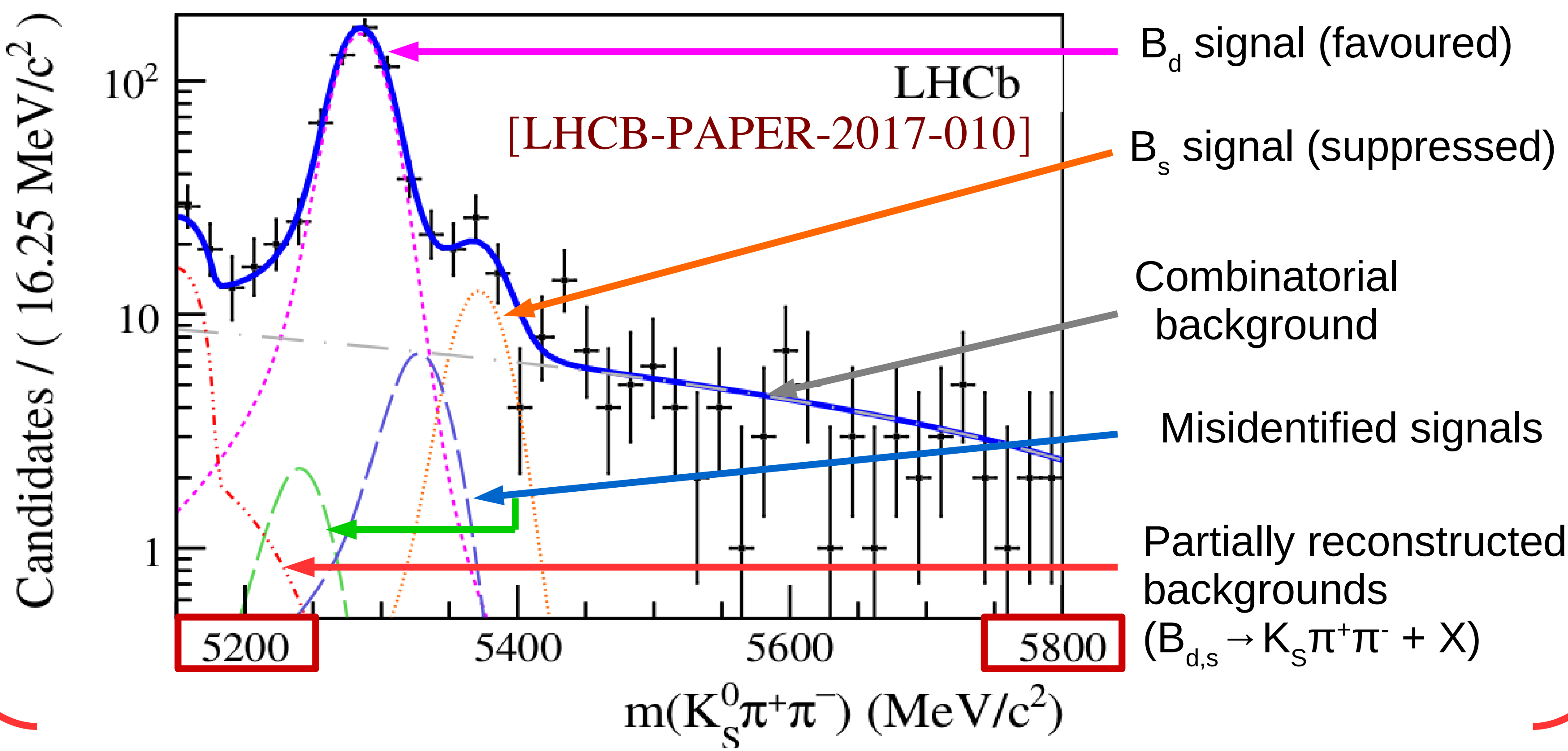


- Observed $B_s \to K_S \pi^+ \pi^-$.
- Confirmed $B_d \to K_S K^\pm \pi^\pm$.
- Observed $B_s \to K_S K^\pm \pi^\pm$.

- Goals of the LHCb analysis using 3fb^{-1}:
  - update measurement of branching fractions;
  - search for $B_s \to K_S K^+ K^-$;
  - prepare Dalitz-plot analyses of all modes.
- Dataset divided into:
  - 4 final states;
  - 2 K_s reconstruction categories;
  - 3 data-taking periods.
    → 24 invariant-mass distributions

Update of $B_{d,s} \to K_S h^+ h'^-$ branching fractions: Modeling the invariant-mass distributions

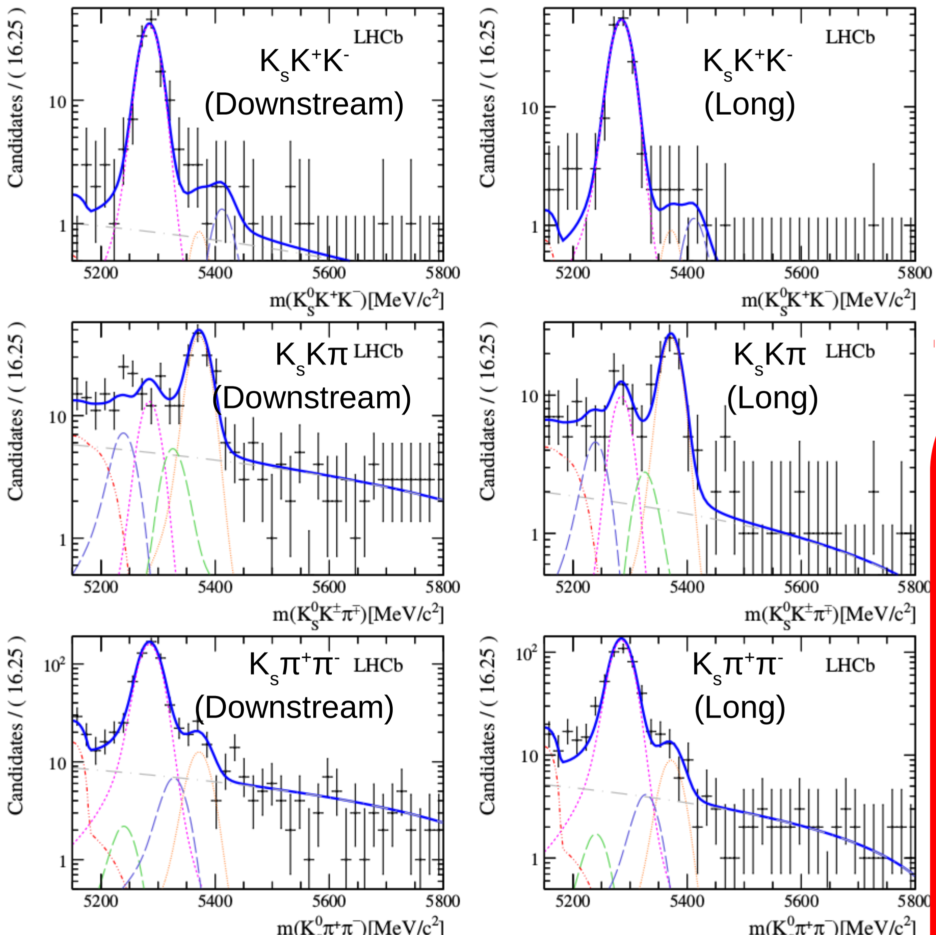
24 x



- Shapes taken from Monte-Carlo, except for combinatorial background.
- B_d and B_s masses and widths fit in data.
- Fast Monte-Carlo developed for partially reconstructed backgrounds modeling.
- Gaussian constraints on misidentified signals and partially recontructed backgrounds yields.

Update of $B_{d,s} \to K_S h^+ h'^-$ branching fractions: Results (**NEW**)

[LHCB-PAPER-2017-010]



$$\frac{\mathcal{B}(B^0_{d,s} \to K^0_S h^+ h'^-)}{\mathcal{B}(B^0 \to K^0_S \pi^+\pi^-)} = \frac{f_{d,s}}{f_d} \frac{N^{\rm corr}_{B^0_{d,s} \to K^0_S h^+ h'^-}}{N^{\rm corr}_{B^0 \to K^0_S \pi^+\pi^-}}.$$

$$N^{\rm corr}_{B^0_{d,s} \to K^0_S h^+ h'^-} = \epsilon^{\rm tot} N_{B^0_{d,s} \to K^0_S h^+ h'^-},$$

$$\frac{\mathcal{B}(B^0 \to K^0_S K^\pm \pi^\mp)}{\mathcal{B}(B^0 \to K^0_S \pi^+\pi^-)} = 0.123 \pm 0.009\,({\rm stat.}) \pm 0.015\,({\rm syst.}),$$

$$\frac{\mathcal{B}(B^0 \to K^0_S K^+ K^-)}{\mathcal{B}(B^0 \to K^0_S \pi^+\pi^-)} = 0.549 \pm 0.018\,({\rm stat.}) \pm 0.033\,({\rm syst.}),$$

$$\frac{\mathcal{B}(B^0_s \to K^0_S \pi^+ \pi^-)}{\mathcal{B}(B^0 \to K^0_S \pi^+\pi^-)} = 0.191 \pm 0.027\,({\rm stat.}) \pm 0.031\,({\rm syst.}) \pm 0.011\,(f_s/f_d)$$

$$\frac{\mathcal{B}(B^0_s \to K^0_S K^\pm \pi^\mp)}{\mathcal{B}(B^0 \to K^0_S \pi^+\pi^-)} = 1.70 \pm 0.07\,({\rm stat.}) \pm 0.11\,({\rm syst.}) \pm 0.10\,(f_s/f_d)$$

$$\frac{\mathcal{B}(B^0_s \to K^0_S K^+ K^-)}{\mathcal{B}(B^0 \to K^0_S \pi^+\pi^-)} = 0.026 \pm 0.011\,({\rm stat.}) \pm 0.007\,({\rm syst.}) \pm 0.002\,(f_s/f_d)$$

Compatible with previous measurements
Dalitz-plot analyses underway.

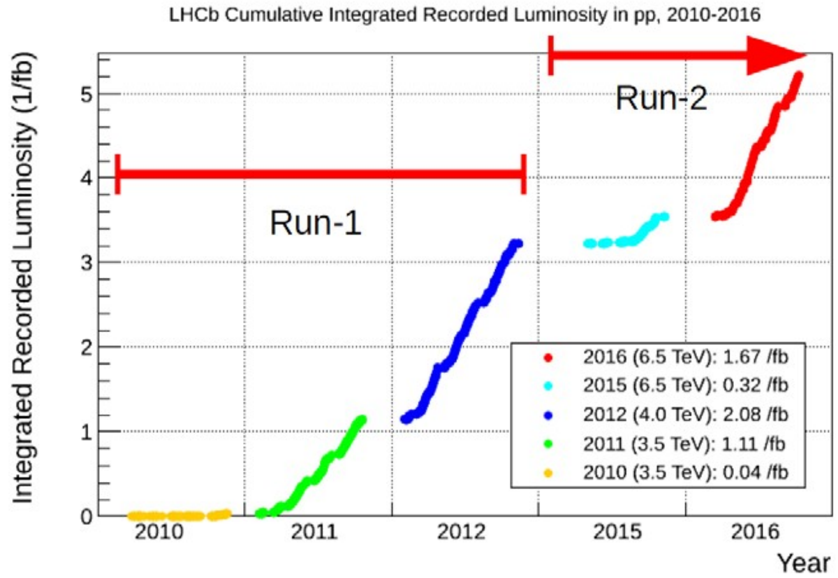
$B_s \to K_S K^+ K^-$: 2.5σ significance.

$$\frac{\mathcal{B}(B^0_s \to K^0_S K^+ K^-)}{\mathcal{B}(B^0 \to K^0_S \pi^+\pi^-)} \in [0.008 - 0.051] \text{ at } 90\% \text{ C.L.}$$

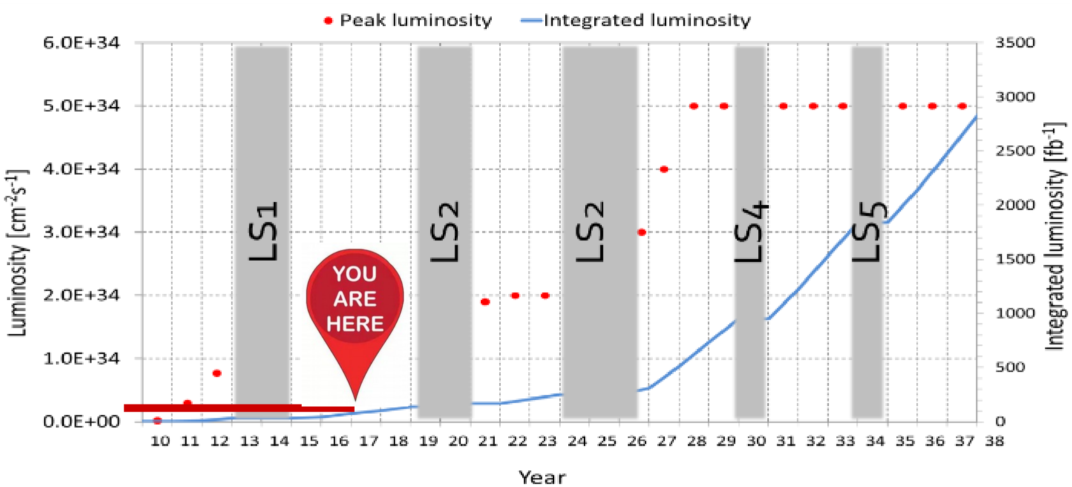
Prospects from Run II and further

Prospects: near and far future of LHCb

- All presented results use only data from Run I of the LHC → 3fb^{-1} at centre-of-mass energy of 7 and 8 TeV.



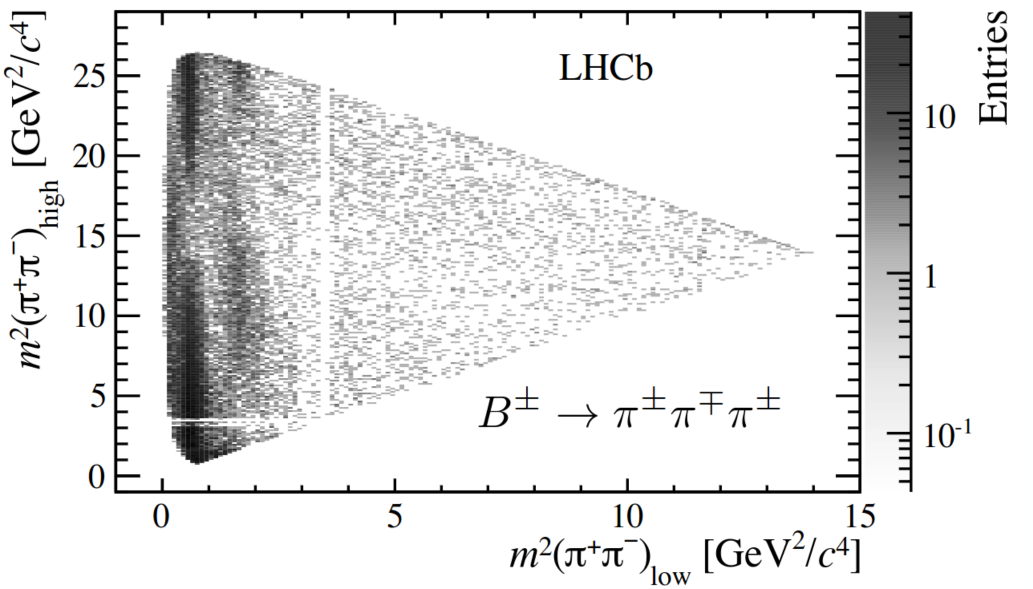
- Run 2 aims at adding 5 fb^{-1} at 13 TeV → more than four times as much data as in Run I.
- Most current charmless analyses are dominated by statistical uncertainties.
- Upgrade planned after 2018, including:
  - massive overhaul of the trigger system;
  - complete change of all the tracking subsystem.
- Expected LHC luminosity delivery.
  [2016 J. Phys.: Conf. Ser.706 022002]



- What can be done with that amount of data?

Prospects: three-body charmless decays

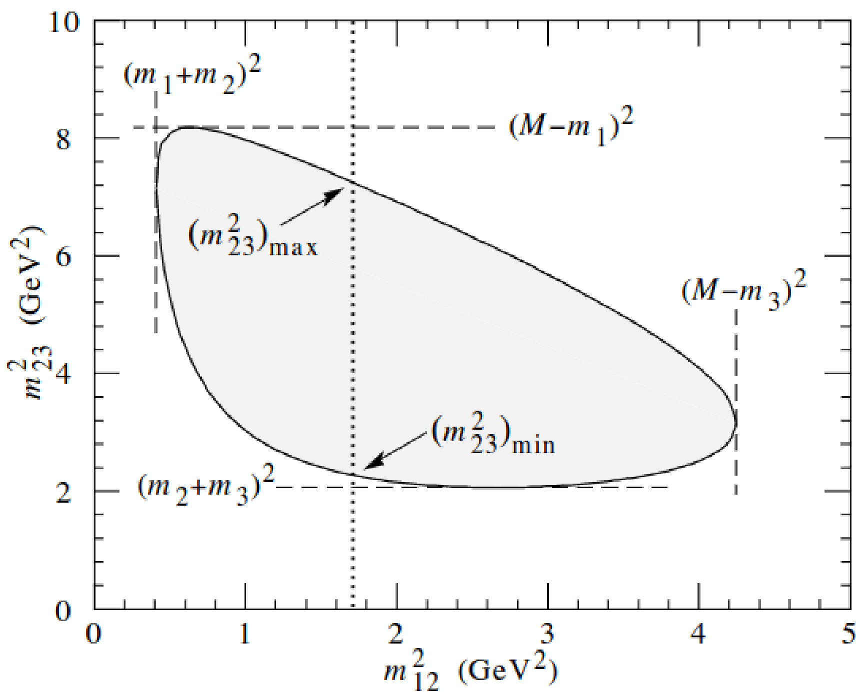
- New channels observed → physics programme of (three-body) charmless decays is expanding.
- Wealth of different channels:
  - Initial hadron: baryon, B^0, B_s, B_c^+
  - Final state: baryonic, V0 particle...
- Work on amplitude analyses already ongoing.
  - Allows to measure many more Q2B branching fractions.
  - Allows to access more physics observables.
- In some cases ($B^+ \to 3h$), data already there (>100k events) but need for refined analysis techniques.

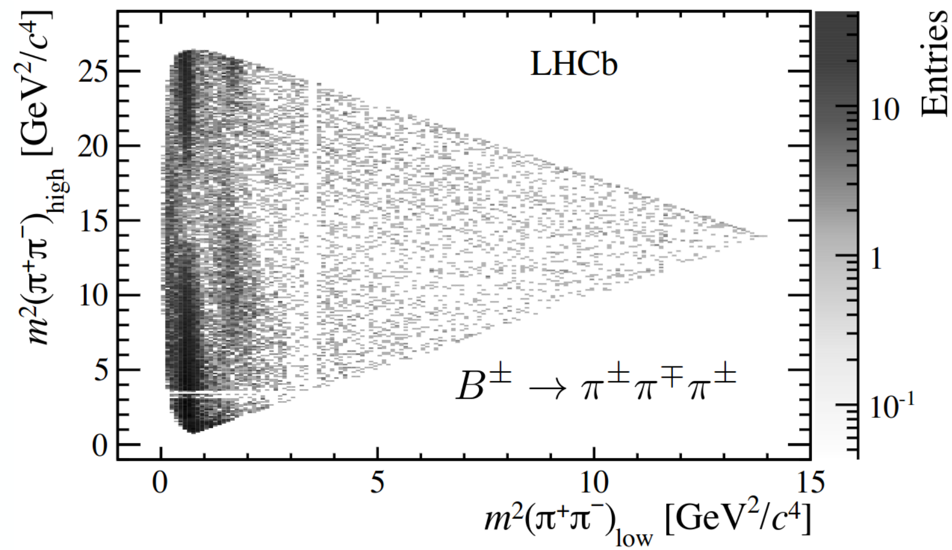


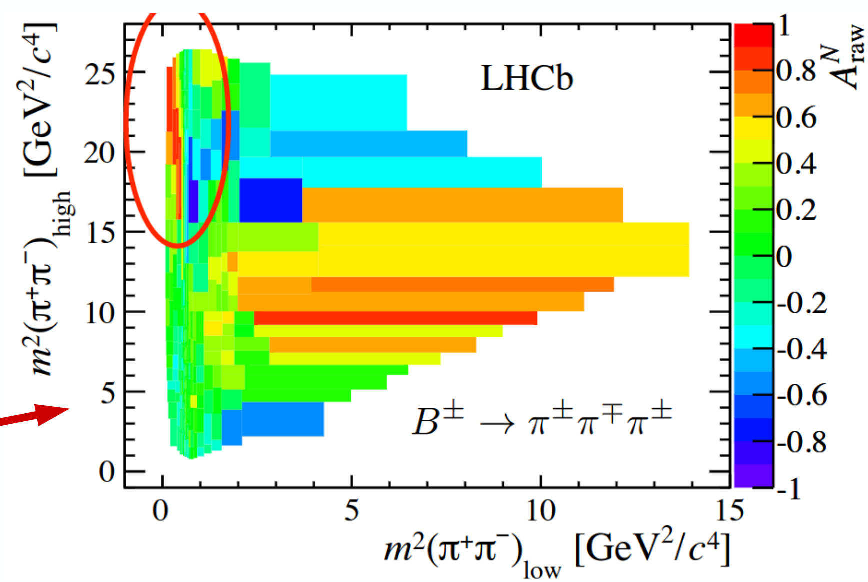
Expected "phase transition" in charmless analyses at LHCb from first observations to fully fledged amplitude analyses.

Prospects: a case for new techniques

- Direct CP asymmetries in $B^+ \to h^+h^-h^+$ (favoured) [PRD 90, 112004 (2014)].
- Large efficiencies, "large" BF→>100k events. "Glimpse" into the future.
- Usual technique: Dalitz-plot analysis.







Phase-space is flat on the Dalitz plot
→irregularities signal underlying dynamics

$A^N_{Raw} = [N(B^+)-N(B^-)]/[N(B^+)+N(B^-)]$

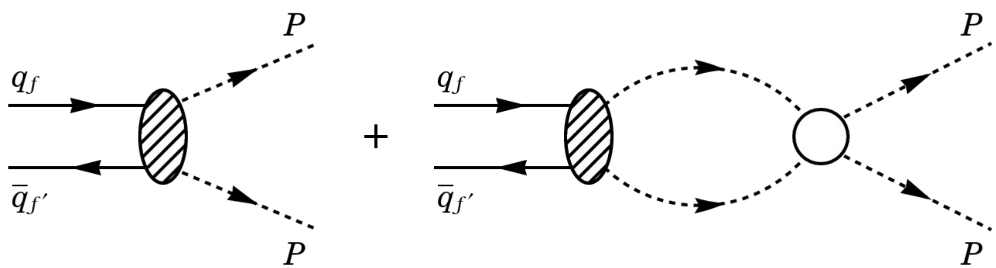
Large, localised, direct CP asymmetries.
Require full amplitude analyses.

Prospects: a case for new techniques

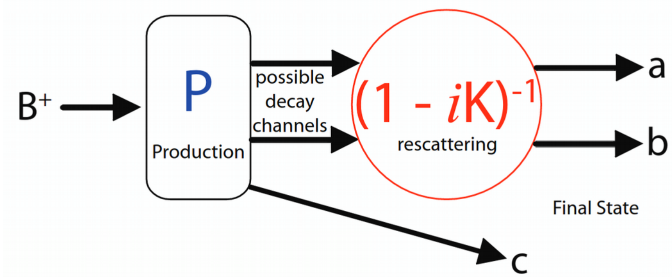
- Most Dalitz-plot amplitudes use isobar model:

$$\mathcal{A}(m_{ij}^2, m_{jk}^2) = \sum_{l=1}^{N} \underbrace{c_l}_{CP\text{ violating}} \underbrace{F_l(m_{ij}^2, m_{jk}^2)}_{\text{Strong dynamics, } CP \text{ conserving}}$$

- Shortcomings:
  - B-meson decays have a large phase space→ nonresonant component not easy to model.
  - Localised, large, direct CP violation can be due to (ππ↔KK) rescattering.



  - There are hints of three-body final-state interactions. Cannot fit into that model.
- Several approaches attempted:
  - adapting the isobar model [arXiv:1506.08332];
  - K-matrix approach;
  - Quasi-model independent (bin the phase space and determine mag/phase in each bin).



Increased datasets will both allow us and force us to develop new and more refined amplitude analysis techniques.

Summary

- Charmless hadronic *B* decays offer vast diversity of channels and physics observables, including
  - branching fractions;
  - weak phases ($\beta_{(s),\text{eff}}$, γ).
  - strong phases.
- **Situation pre-LHCb:** some decays known, some full amplitude analyses performed.
- **Situation post-Run I:** many first observations, especially in new domains (e.g. baryons).
- **Situation Run > II:** many amplitude analyses performed, weak and strong phases measured in those decays.
- But this is not a straight path:
  - transition from counting experiments (branching fractions) to amplitude analyses;
  - need to refine existing tools to face the challenge of handling that much data.