$B \to hh\pi^0$ decays and testing CP violation at LHCb

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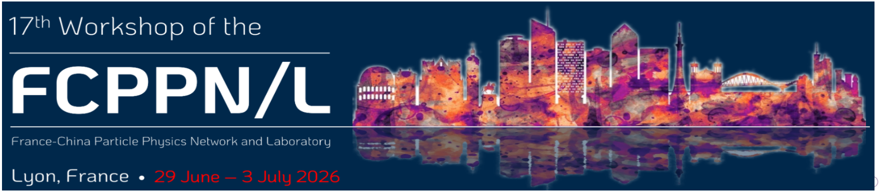


Outline

- Physics Motivation & Context
- Description of the global $h^+h^-\pi^0$ strategy
  - ▷ focus on the Search for $B_s \to K\pi\pi^0$ decay mode
- Application of the method to $h^+h^-\pi^0$ modes
- Conclusion & Outlook

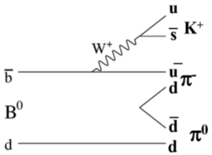
Physics Motivation & Context

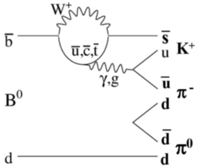
Charmless b-hadron decay :

- No charm quarks in the final states
- Charmless decay rates typically below $\mathcal{O}(10^{-4})$
- Contributions from both $b \to u$ **tree-level** and $b \to s/d$ **penguin** diagrams
  - ▷ Interference between amplitudes can lead to **direct CP violation**, studied across the resonant structure
- Sensitive to CKM matrix angles α, β, γ
- Search for BSM contributions in CP observables

Two-step physics program :

- ▷ Measurement of the branching fractions
- ▷ Access to physics observables via angular and Dalitz-plot analyses





Physics Motivation & Context

$h^+h^-\pi^0$ status :

- Knowledge coming from BABAR and BELLE experiments (measurements $\sim$ 10 years)
- Many decay channels remain unobserved
  - B_s/Λ_b hadrons not accessible by B-Factories $\rightarrow$ LHCb expertise

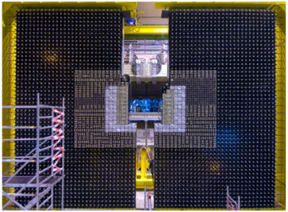
Ongoing activities : LHCb RunII data

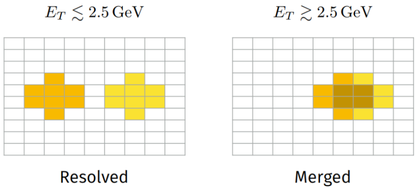
- Collaboration between Clermont - Peking - UCAS - Wuhan universities (link)
  - Search for $B_s \rightarrow K\pi\pi^0$ decay mode [LHCb-ANA-2026-011]
  - Measurement of the branching fraction of $B^0 \rightarrow \pi^+\pi^-\pi^0$ [LHCb-ANA- 2025-050]
  - Measurement of CP asymmetry in $B_s^0 \rightarrow K^+K^-\pi^0$ decay [LHCb-ANA- 2026-xyz]
  - Measurement of branching fraction and CP asymmetry in $\Lambda_b^0 \rightarrow ph\pi^0$ decays [LHCb-ANA-2025-020]
  - Amplitude analysis on $B_d \rightarrow K\pi\pi^0$ (just started)

Physics Motivation & Context

Reconstruction of π^0 objects is difficult !

- $\pi^0 \to \gamma\gamma$: BF $= (98.823 \pm 0.034)\%$ (dominant)
- High combinatorics due to the large number of photons produced during pp collisions.
  - ▷ Challenging to reconstruct a π^0 candidate.





Representation of ECAL cell clusters, front view.

- Resolved : The two photons produce well-separated clusters in the ECAL.
- Merged : Superposition of clusters in the ECAL, making it difficult to distinguish them as separate photons deposits.
  - ▷ Sophisticated reconstruction algorithms are required

Global $h^+h^-\pi^0$ strategy

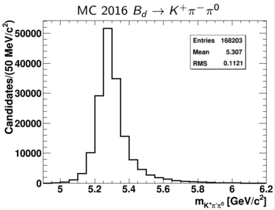
As a case in point : Search for $B_s \rightarrow K\pi\pi^0$ decay mode

$\rightarrow$ Similar methods are employed for the other $h^+h^-\pi^0$ analyses

Global $h^+h^-\pi^0$ strategy - π^0 selection

Signal MC for $B^0 \to K^+\pi^-\pi^0$ shows an asymmetric invariant mass distribution

- $\to$ Correlation observed between $m_{K^+\pi^-\pi^0}$ and photon opening angle
- $\to$ For $m_{K^+\pi^-\pi^0} > 5.4$ GeV$/c^2$, confusion arises between merged and resolved π^0



Sample split by ECAL configuration :

- If γ_1, γ_2 lie in the same region $\to$ that region is assigned
- If not $\to$ the region of the most energetic photon is taken

Cut on photon opening angle $\theta_{\gamma_1\gamma_2}$

One global and common θ_{eff} cut, computed per event that depends on the ECAL region and the associated cellsize

$$\theta_{\text{eff}} = \theta_{\gamma_1\gamma_2} \times \frac{r}{cellsize}$$ with r the distance between PV and ECAL

Cellsize definition : $\boxed{cellsize = \frac{0.12}{area+1}}$

$cellsize_{outer} = \frac{0.12}{0+1} = 0.12$ m $\quad cellsize_{middle} = \frac{0.12}{1+1} = 0.06$ m $\quad cellsize_{inner} = \frac{0.12}{2+1} = 0.04$ m

Global $h^+h^-\pi^0$ strategy - Development of the selection tools

Strategy : Global approach applicable to $B/\Lambda_b \to hh'\pi^0$ decay modes with $h = (K, p, \pi)$

- TOPO MVA
  - Based on B kinematic variables (p_T, η), decay topology, vertex geometry and isolation variables
    $\to$ No π^0 information included
  - One MVA per year, trained on $B_d \to \pi^+\pi^-\pi^0$ (reference channel)
  - Trained using signal MC vs data upper sideband : $m_{\pi\pi\pi^0} > 5.5$ GeV/c^2
  - k-folding with $k = 2$ to avoid statistical bias
- PID MVA
  - Based on particle identification variables : $h_{1,2}$_ProbNN$_i$, with $i = (K, p, \pi)$
    $\to$ Performed PID correction with PIDcorr method
  - One MVA per year and per charge combination
  - Trained on MC samples with PID corrections

Optimization performed per year and per charges with the Punzi FoM :

$$\text{FoM} = \frac{\varepsilon_S(t)}{\frac{a}{2} + \sqrt{B(t)}} \quad \text{with a} = 3$$

Global $h^+h^-\pi^0$ strategy - How to fit the spectrum ?

Some experimental observations :

- The fit strategy was educated on 2016 data from the middle region, where tight selection criteria were applied on both MVAs to suppress most of the background, particularly combinatorial background. Based on this study, we conclude that there is :
  - Large resolution of the signal component $\sim$ 40 MeV
    (mere separation of B_d and B_s components)
  - Large background sources lying in the signal region ($B \to K^*\gamma$, Cross Feeds, partially reconstructed background)

$\rightarrow$ *These observations motivates the choice to fix both the mean value and the resolution in the fit*

Dedicated selection was developed to reduce this background

Global $h^+h^-\pi^0$ strategy - How to fit the spectrum ?

What calibration of MC can be used ?

LHCb internal note (link) : *Study of mass parameters in* $B^- \to D^0(K^-\pi^+)\rho^-(\pi^-\pi^0)$ *and* $B^- \to D^0(K^-\pi^+\pi^0)\pi^-$ *decays with LHCb Run 2 data.*
$\to$ Study performed for various p_T ranges, ECAL regions (outer, middle, inner), and years of data taking

Conclusion of the note :
It was observed with the decays $B^- \to D^0(K^-\pi^+)\rho^-(\pi^-\pi^0)$ and $B^- \to D^0(K^-\pi^+\pi^0)\pi^-$ that :

- The fitted mean value of the Data are well aligned with the PDG B_d mass (5.2794 GeV/c^2) while the mean of the MC samples are usually 5-7 MeV/c^2 larger
- The resolution in Data is 7 to 8% larger, depending on the decay, than that of the corresponding MC sample

$\Rightarrow$ As a consequence, when performing fits with resolved π^0, it may be appropriate to fix the mass resolution to the MC resolution scaled by a factor of 1.07–1.08, and to fix the mean to the PDG value

Global $h^+h^-\pi^0$ strategy - How to fit the spectrum ?

Fit Strategy : a two-step fit procedure

1) Adjust MC kinematics to the data one : Perform the fit with σ floated and extract a data subsample ($m_{K\pi\pi^0_{PDG}} \pm 2\ \sigma_{Fit}$) to GB reweight the MC
2) The fit on the reweighted and calibrated MC sample provides the expected resolution for the signal. Which is then provided as input to the simultaneous fit.

Technical procedure :
Simultaneous fit on 2 charges $\times$ 3 ECAL areas $\times$ 3 years = 18 categories

MC resolution before and after GB reweighting and calibration

	Outer		Middle		Inner	
	MC	After GB + calibration	MC	After GB + calibration	MC	After GB + calibration
2016	42.10 MeV/c^2	43.65 MeV/c^2	42.32 MeV/c^2	44.34 MeV/c^2	50.38 MeV/c^2	53.55 MeV/c^2
2017	41.22 MeV/c^2	42.89 MeV/c^2	42.69 MeV/c^2	44.45 MeV/c^2	50.39 MeV/c^2	53.33 MeV/c^2
2018	40.40 MeV/c^2	42.03 MeV/c^2	40.51 MeV/c^2	42.31 MeV/c^2	48.67 MeV/c^2	51.56 MeV/c^2

Global $h^+h^-\pi^0$ strategy - How to fit the spectrum ?

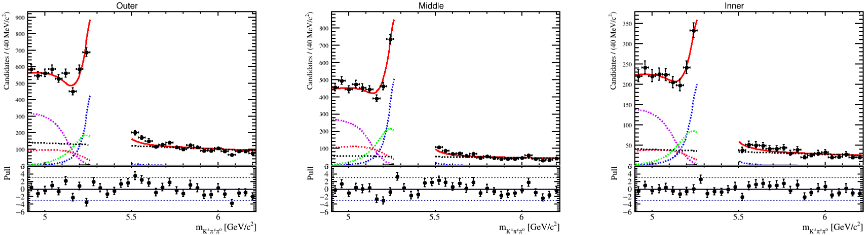
Simultaneous fit - Total projection

→ *The purpose is to observe the mode $B_s \to K\pi\pi^0$*
(A blinding process is being implemented and B_s component not printed)

Fit components :

- $B_d \to K\pi\pi^0$
- $B_{d,s} \to K\pi\pi^0\gamma$
- $B_d \to K_1\gamma$
- $B_{d,s} \to K\pi\pi^0\pi^0$
- $B_d \to K\pi\gamma$
- $B_d \to \pi\pi\pi^0$
- $\Lambda_b \to pK\pi^0$
- $B_s \to KK\pi^0$
- $\Lambda_b \to p\pi\pi^0$

LHCb unofficial



→ Fit validation & systematic studies ongoing

Application of the method to other $h^+h^-\pi^0$ modes

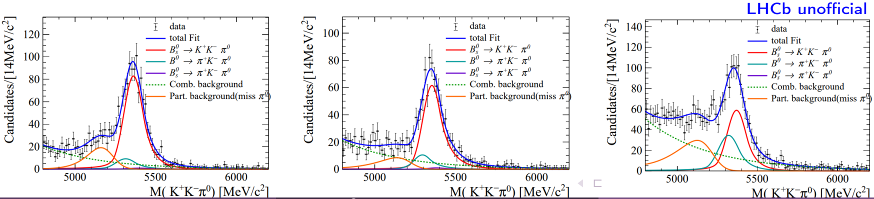
Measurement of CP asymmetry in $B_s^0 \to K^+K^-\pi^0$ decay

- Measurement performed in $K^*(892)$ and $K^*(1430)$ phase space regions
  $\to$ CP asymmetry is resonance-dependent due to different weak/strong phases
  $\to$ Dalitz-plot interference effects can lead to large asymmetry differences between resonances

Table 1: Branching fraction (BF) and CPV in theoretical predictions.

	$B_s^0 \to K^*(892)^+K^-$		$B_s^0 \to K^*(892)^-K^+$	
Model	BF	$\mathcal{A}^{CP}$ (%)	BF	$\mathcal{A}^{CP}$ (%)
QCDF	$(1.9 \pm 0.5) \times 10^{-5}$	$-25.5^{+9.2+16.3}_{-8.8-11.3}$	$(1.9 \pm 0.5) \times 10^{-5}$	$11.0^{+0.5+14.0}_{-0.4-18.8}$
PQCD	$(1.9 \pm 0.5) \times 10^{-5}$	$-55.3^{+4.4+8.5+5.1}_{-4.9-9.8-2.5}$	$(1.9 \pm 0.5) \times 10^{-5}$	$36.6^{+2.3+2.8+1.3}_{-2.3-3.5-1.2}$

$$A_{CP} = \frac{N(K^{*+}K^-) - N(K^{*-}K^+)}{N(K^{*+}K^-) + N(K^{*-}K^+)},$$



Application of the method to other $h^+h^-\pi^0$ modes

Measurement of CP asymmetry in $B^0 \to \pi\pi\pi^0$ decay

- ▷ Branching fraction measurement
  - → Includes both merged and resolved π^0 contributions
  - → Inclusive simultaneous fit

$$\mathcal{R} = \frac{\mathcal{B}(B^0 \to \pi^+\pi^-\pi^0)}{\mathcal{B}(B^0 \to K^+\pi^-\pi^0)} = \frac{N_{B^0 \to \pi^+\pi^-\pi^0}}{N_{B^0 \to K^+\pi^-\pi^0}} \cdot \frac{\epsilon_{B^0 \to K^+\pi^-\pi^0}}{\epsilon_{B^0 \to \pi^+\pi^-\pi^0}}$$

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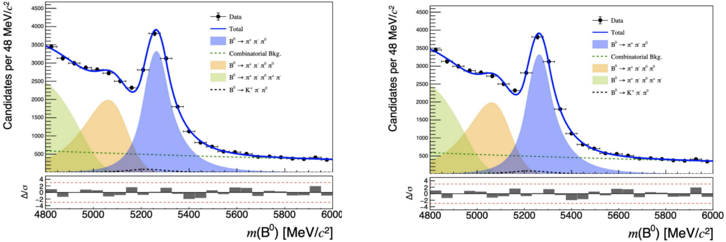
Resolved | Merged



→ GB reweighting and calibration of MC kinematic being implemented

Measurement of branching fraction and CP asymmetry in $\Lambda_b^0 \to ph\pi^0$

- Branching fraction measurement
  - $\to$ includes both merged and resolved π^0 contributions
  - $\to$ Simultaneous fit performed per region of the Dalitz plane

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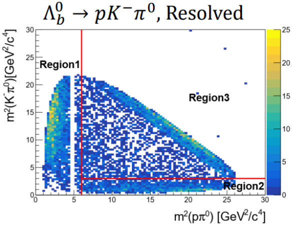

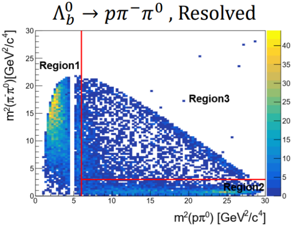

$$\mathcal{B}(\Lambda_b^0 \to ph^-\pi^0) = \frac{N(\Lambda_b^0 \to ph^-\pi^0)}{N(B^0 \to K^+\pi^-\pi^0)} \times \frac{eff(B^0 \to K^+\pi^-\pi^0)}{eff(\Lambda_b^0 \to ph^-\pi^0)} \times \frac{f_d}{f_{\Lambda_b^0}} \times \mathcal{B}(B^0 \to K^+\pi^-\pi^0)$$

- CPV measurement

$\Lambda_b^0 \to pK\pi^0$: $\quad \Delta\mathcal{A}_{CP} = [x.xx \pm 3.81\,(\text{stat}) \pm 0.29\,(\text{syst})]\,\%.$

$\Lambda_b^0 \to p\pi\pi^0$: $\quad \Delta\mathcal{A}_{CP} = [x.xx \pm 3.94\,(\text{stat}) \pm 0.24\,(\text{syst})]\,\%.$

Theoretical predictions

$\sim$ 20% in $\Lambda_b^0 \to pK^-$
$\sim$ 30% in $\Lambda_b^0 \to pK^-$
$-$3.3% in $\Lambda_b^0 \to p\bar{p}$

$\sim$ 5% CPV with opposite signs for $\Lambda_b^0 \to pK^-$ and $\Lambda_b^0 \to p\pi^-$ decays.

Remark : the intervals used in both analysis are not the same
$\to$ For the CPV measurement, the region 3 part was not used (due to the presence of the $\Lambda_b \to ph\gamma$ component)

Summary & Outlook

Developed a strategy applicable to all $B/\Lambda_b \to hh'\pi^0$ decay modes with $h = (K, p, \pi)$

- Generalized selection tools
- An adjustment of the MC kinematics to the data ones with a GB reweighting
- Fit model with fixed mean value and resolution

$\to$ Provides a general framework for branching fraction analyses involving π^0 final states

- Several $h^+h^-\pi^0$ analysis ongoing (expect publications soon !)
- Efforts aims at producing legacy results for RUN II and educate the RUN III for future analyses
- Thesis grant between Clermont and Peking Universities on charmless $h^+h^-\pi^0$ decays (starting this autumn)
- Two Wuhan PhD students got China Scholarship Council funding to work in Clermont for one year

Thank you