Study of charmless $b-$hadron decays with the LHCb spectrometer

Juan Sebastian Ordonez-Soto

Supervisors: Eric Cogneras and Stéphane Monteil

Comité de Suivi Individuel

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Laboratoire de Physique de Clermont

ÉCOLE DOCTORALE DES SCIENCES FONDAMENTALES
Université Clermont Auvergne

Outline

1. **Research project**
    - Scientific context
    - Progress and main results
2. **Professional project**
3. **Doctoral School and complementary activities**
4. **Outlook**
    - Planning for 2025-2027
    - Documentation
5. **Questions and discussion**

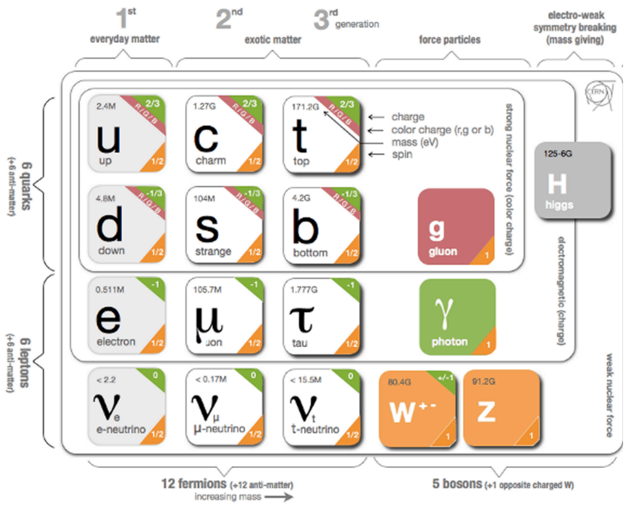
Research project

Standard model and flavour physics

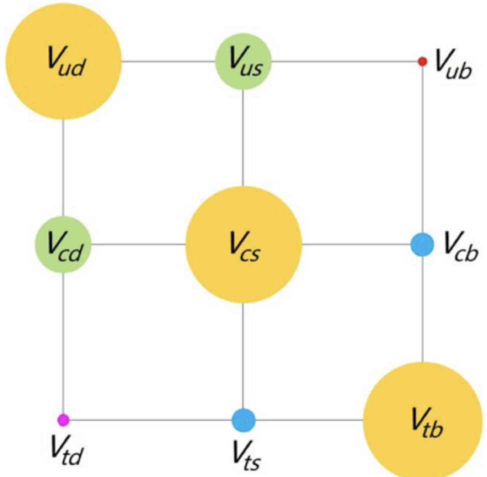
Flavour physics studies how quarks change flavour — and tests the Standard Model with high precision

- The Standard Model (SM) is the quantum field theory which describes strong and electroweak interactions
  - Based on: local gauge invariance $\mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$ and spontaneous symmetry breaking
- Flavour physics relates to the existence of different families of quarks and how they couple to each other.
- In the SM, quark mixing arises through charged weak currents mediated by the $W^{\pm}$ bosons and is quantified by the Cabbibo-Kobayashi-Maskawa (CKM) matrix

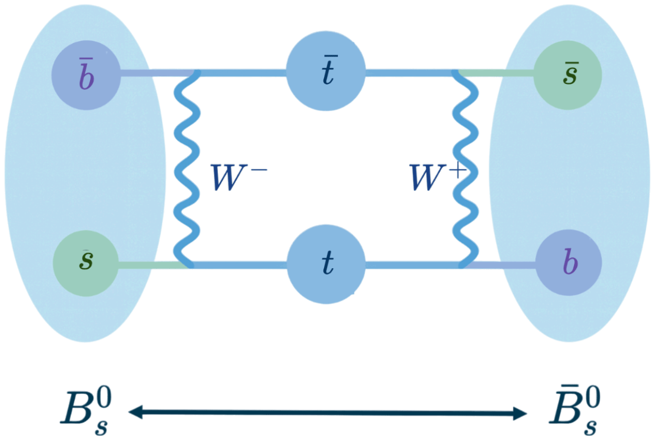
Elementary particles in the SM



Quark mixing (CKM)



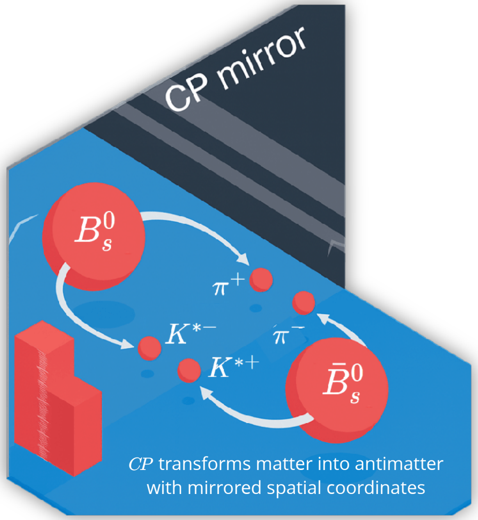
Neutral meson oscillations

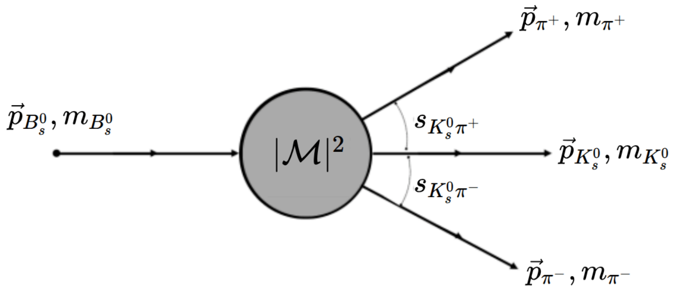


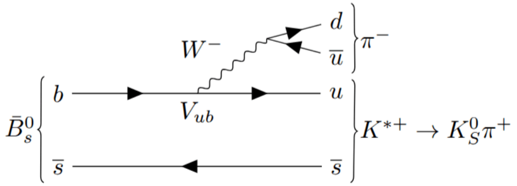
CP violation in three-body charmless B decays

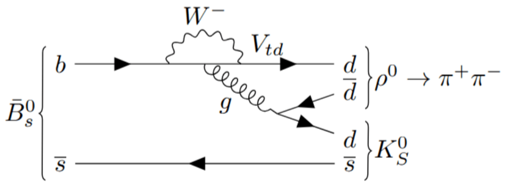
Three-body $B^0_{(s)}$ decays turn CP violation into interference patterns of interference across phase space

- CP symmetry is the combination of charge (C) and parity (P) conjugations.
  - In the SM, it arises solely from a non-zero complex phase in the CKM matrix $\Rightarrow V_{ij} \neq V_{ij}^*$
- Observable CP asymmetries arise from the interference of decay amplitudes with different weak and strong phases.
- Charmless three-body B decays, such as $B^0_{(s)} \to K^0_s \pi^+ \pi^-$, provide many interfering decay pathways.
  - Resonant intermediate states produce a rich structure across phase space, making them excellent laboratories for CP-violation studies







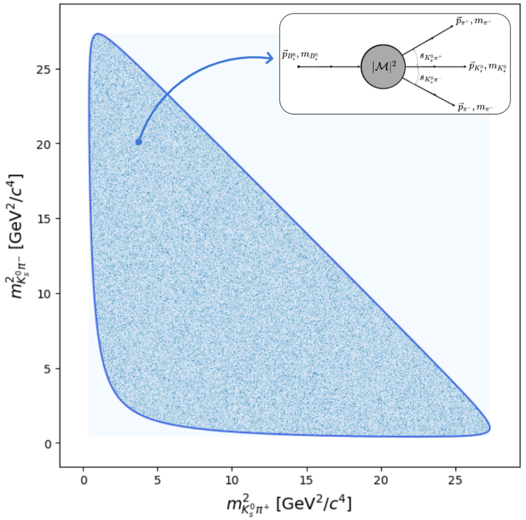


Amplitude Analysis of $B^0_{(s)} \to K^0_S \pi^+ \pi^-$ decays

Amplitude analysis turns interference patterns across the Dalitz plot into measurements of resonant dynamics and CP violation

- Dalitz plot (DP) $\Rightarrow$ Two-dimensional representation of the phase space of three-body decays.
- Intermediate resonances appear as characteristic structures across this phase space.
  - Isobar model (IM) $\Rightarrow$ Parameterization of the decay amplitude $\mathcal{M}$.
    - Coherent sum of a non-resonant (NR) component and resonant amplitudes.
- By fitting the interference pattern, we determine the magnitude and phase of each contribution.
  - Comparing the amplitudes of $B^0_{(s)}$ and $\bar{B}^0_{(s)}$ decays gives access to CP-violating observables.

Dalitz plot



$$|\mathcal{A}(s_+, s_-)|^2 = \left| \sum_j a_j e^{i\phi_j} F_j(s_+, s_-) \right|^2$$

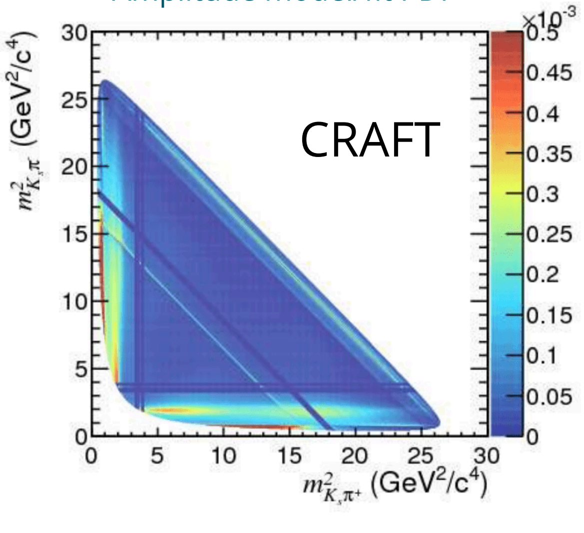
Isobar amplitudes

$$c_k = a_k e^{i\phi_k} = x_k + i y_k$$

CP asymmetry observable

$$\mathcal{A}^{CP}_{\text{raw}} = \frac{|\bar{c}_k|^2 - |c_k|^2}{|\bar{c}_k|^2 + |c_k|^2}.$$

Amplitude model/fit PDF

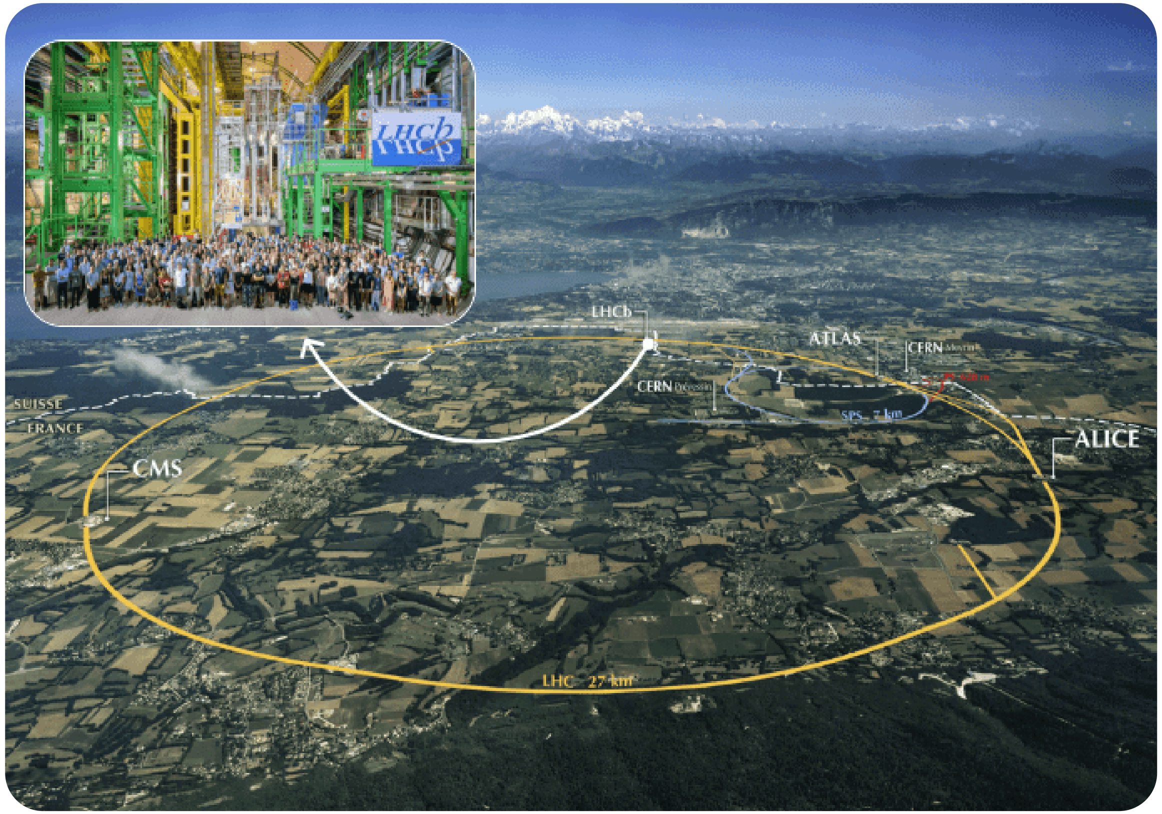


The experimental environment: LHC and LHCb

The LHC produces heavy-flavour particles in abundance — LHCb is designed to study how they decay

- The LHC collides protons at very high energies, producing large samples of b- and c- hadrons.
- LHCb is one of the four major LHC experiments and is specialised in heavy-flavour physics.
  - Precise reconstruction of decay vertices, particle trajectories and particle identities.
- This thesis uses $B^0_{(s)} \to K^0_s \pi^+ \pi^-$ candidates from pp collisions recorded by LHCb during: 2011 & 2012 (Run 1) and 2015-2018 (Run 2)

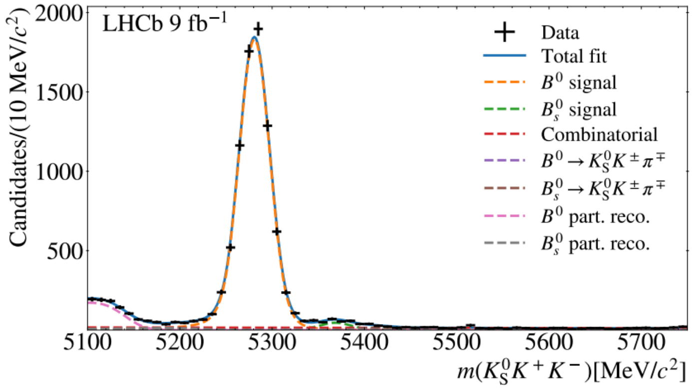
- LHCb studies the subtle differences between matter and antimatter through heavy-flavour decays.
  - CP violation searches
  - Rare decays
  - HF production and spectroscopy

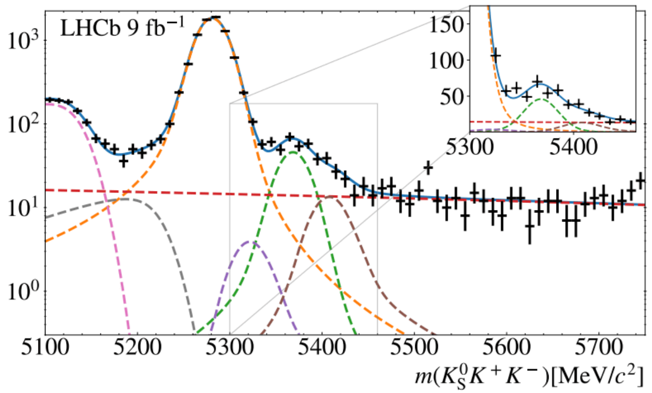


Branching Fraction measurement of $B^0_{(s)} \to K^0_S h^+ h^-$ decays

Analysis finally completed and published

- Contributed to the efforts for completing the measurement of Branching Fractions (BF) of $B^0_{(s)} \to K^0_s hh'$ (6 modes) using Run 1 and Run 2 data
  - This analysis was performed in collaboration with LPNHE and the U. of Warwick $\Rightarrow$ B(s)->Kshh' μ-group
  - Previous measurement done with Run 1 data only
  - Main result: Observation of the $B^0_s \to K^0_s K^+ K^-$ decay
- This work is the starter point towards Amplitude Analysis $\Rightarrow$ My thesis





Selection of the signal → **Signal yield measurement** mass fit on data → **Efficiency evaluation** from MC → **Systematics evaluation** → **Relative BF determination**

Ratio of average efficiencies from simulated data

Ratio of hadronisation fractions

$$\frac{BF(B^0_{(s)} \to K^0_S hh')}{BF(B^0 \to K^0_S \pi^+\pi^-)} = \frac{\bar{\varepsilon}_{B^0 \to K^0_S \pi^+\pi^-}}{\bar{\varepsilon}_{B^0_{(s)} \to K^0_S hh'}} \frac{N_{B^0_{(s)} \to K^0_S hh'}}{N_{B^0 \to K^0_S \pi^+\pi^-}} \frac{f_d}{f_{d(s)}}$$

Ratio of yields from an invariant-mass fit

Time integrated Amplitude Analysis of $B_s^0 \to K_S^0\pi^+\pi^-$

Physics motivation

The charmless decay $B_s^0 \to K_S^0\pi^+\pi^-$ will provide access to the first establishment of:

- The direct CP asymmetries of the quasi-two-body decays with an untagged time-integrated (TI) Dalitz analysis:
  - Flavour specific: $\bar{B}_s^0 \to K_0^{*+}(1430)\pi^-$, $\bar{B}_s^0 \to K^{*+}(892)\pi^-$
  - CP-eigenstate: $B_s^0 \to \rho^0 K_S^0$
- Fit Fractions of the different amplitudes contributing to the decay.

Precedents

- This analysis follows a similar strategy to that of the $B_d^0 \to K_S^0\pi^+\pi^-$ amplitude analysis with Run I data.
  - We use our own fitter: CRAFT (Clermont Roofit-based Amplitude Fitter Tool)

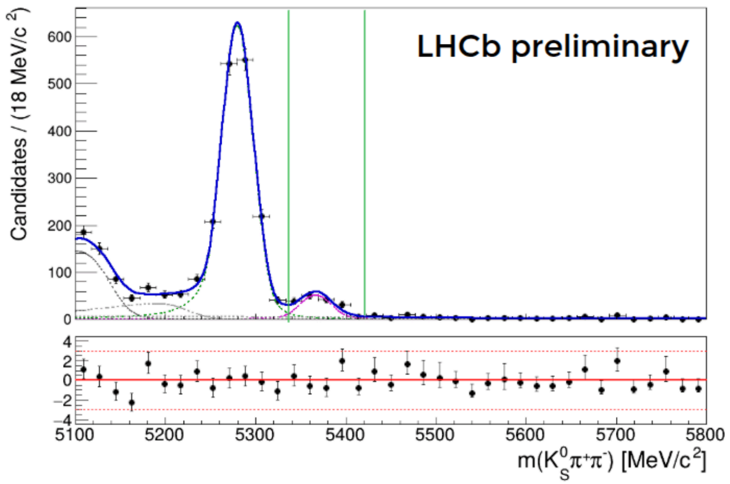
Data samples

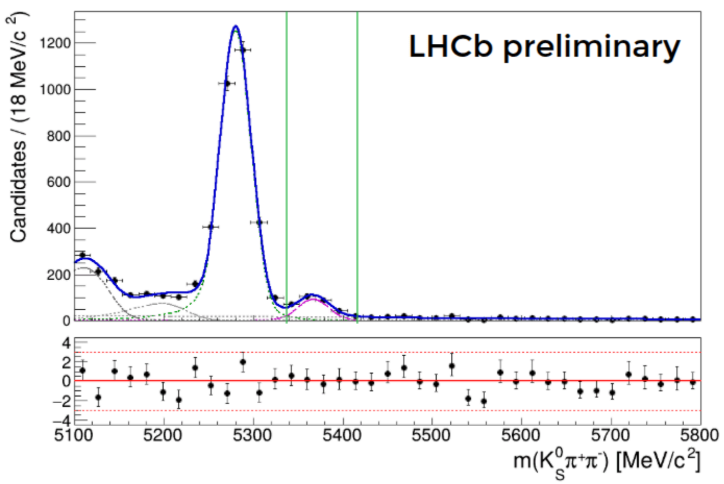
- This analysis inherits samples and selections from the B2KShh' Branching Fraction Analysis.
  - 14 samples: Run 1 (2011, 2012a, 2012b), Run 2 (2015-2018). Two K_S^0 reco categories: DD and LL.
  - The selection is optimized with a tight optimization targeting $B_s^0 \to K_s^0\pi^+\pi^-$ signal candidates.

Time integrated Amplitude Analysis of $B_s^0 \to K_S^0\pi^+\pi^-$

Analysis strategy

- Stages:
  1. Selection of $B_s^0 \to K_S^0\pi^+\pi^-$ signal candidates
  2. Fit the invariant-mass spectrum $K_S^0\pi^+\pi^-$, define a signal window around B_s^0 signal peak, and determine the fraction of signal and bkg. (both combinatorial and $B_d^0 \to K_S^0\pi^+\pi^-$)
  3. Obtain the spline histogram of the efficiency variation across the DP, evaluated from signal MC.
  4. Determine a model for the different background components .
  5. Fit simultaneously the different samples and educate the final model.





The vertical green lines indicate the selected signal window around the B_s^0 peak.

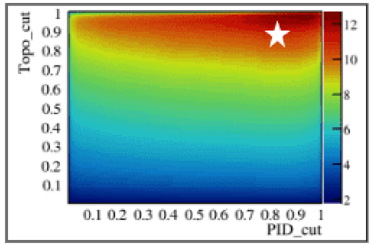
The approx. number of $B_s^0 \to K_S^0\pi^+\pi^-$ candidates in the signal window and hence entering the DP fit is **1.02K**

- Total: ~1.2K signal candidates
- Run 1:
  - Total: ~186
  - DD: ~116
  - LL: ~70
- Run 2:
  - Total: ~1K
  - DD: ~637
  - LL: ~365

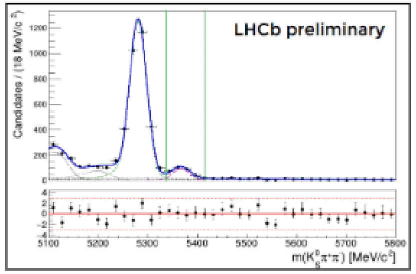
Time integrated Amplitude Analysis of $B_s^0 \to K_S^0 \pi^+ \pi^-$

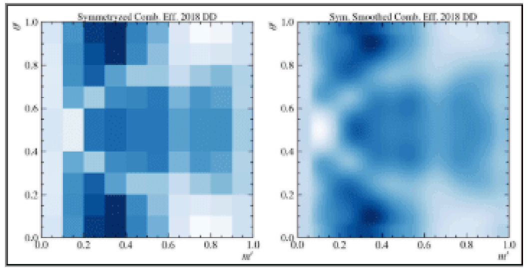
Schematic of the analysis workflow

Selection of the signal candidates



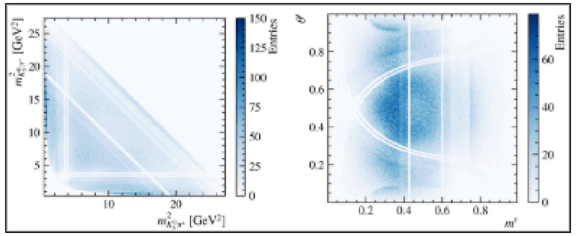
Signal and bkg. fractions from invariant-mass fit

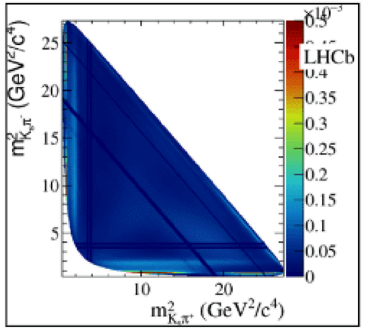




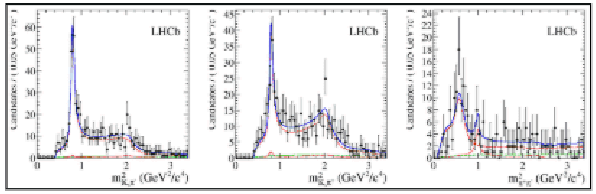
Efficiency evaluation over the sqDP from signal MC

Background models: combinatorial & Bd2KSpipi





Simultaneous DP Fit: nominal model and observables determination



Time integrated Amplitude Analysis of $B_s^0 \to K_S^0\pi^+\pi^-$

Model building

- A preliminary DP fit on data is conducted using a **Baseline model**.
- The model parameterizes the signal amplitude as the **isobar** sum of four resonances plus a non-resonant (NR) contribution.

$$|\mathcal{A}(s_+, s_-)|^2 = \left|\sum_j a_j e^{i\phi_j} F_j(s_+, s_-)\right|^2$$

a_j and ϕ_j (x_j, y_j in cartesian) describe the relative magnitude and phase. **Floating parameters in the fit.**

$$\Downarrow$$

$$\mathcal{S}(s_+, s_-) \propto |\mathcal{A}(s_+, s_-)|^2 + |\bar{\mathcal{A}}(s_+, s_-)|^2$$

Untagged time-integrated Dalitz signal PDF.

$$\Downarrow$$

$$\mathcal{P}(s_+, s_-) = f_{\rm sig}\frac{\epsilon(s_+, s_-)\mathcal{S}(s_+, s_-)}{N_{\rm sig}} + \sum_i f_{{\rm bkg}_i}\frac{\mathcal{B}_i(s_+, s_-)}{N_{{\rm bkg}_i}}$$

Total Dalitz PDF

- Relevant additional contributions have been tested, one by one, and accepted according to a defined algorithm.

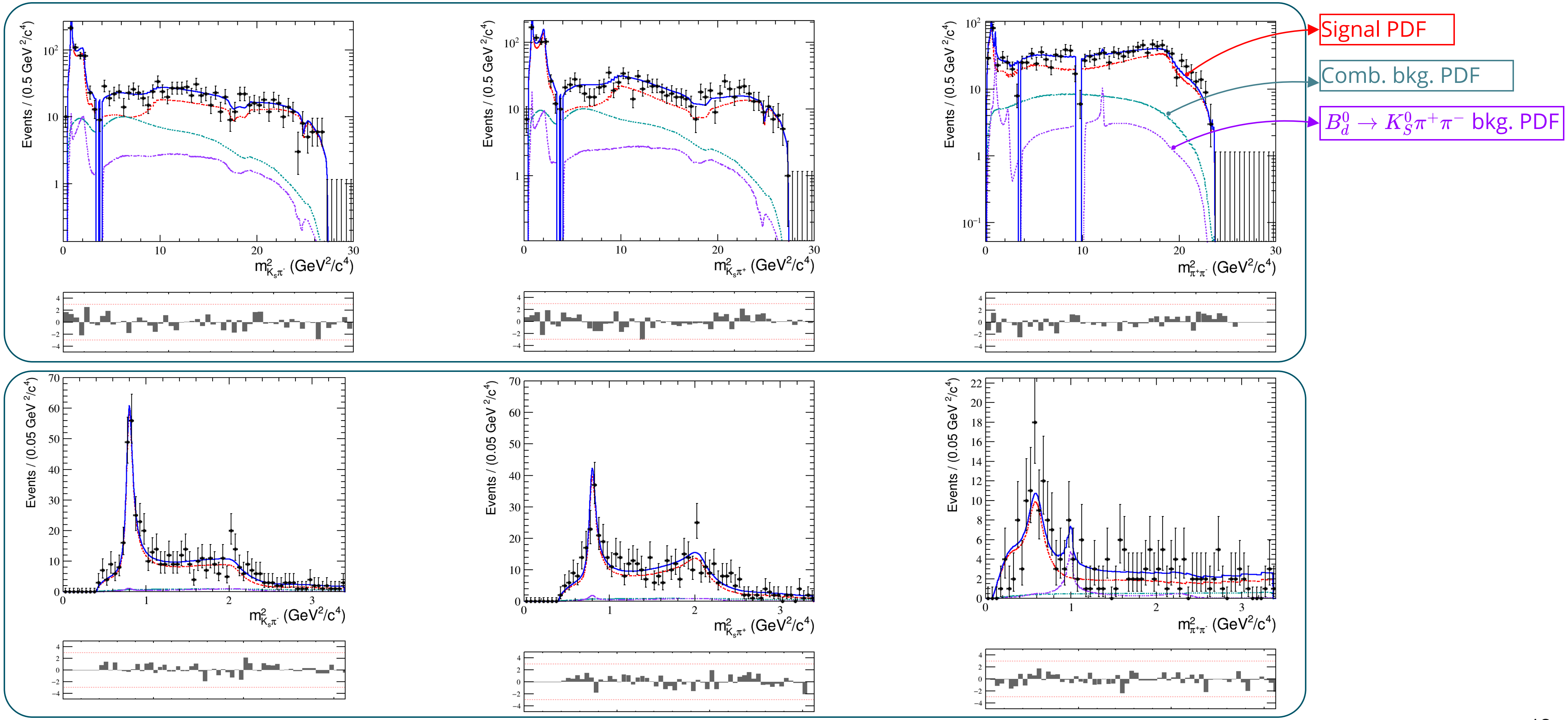
Nominal model

Resonance	Parameters	Lineshape
NR		Flat
S-wave		
$(K\pi)_0^{*\pm}$	$\mathrm{Re}(c_0) = 0.204 \pm 0.103$ $\Im(c_0) = 0$ $\mathrm{Re}(c_1) = 1$ $\Im(c_1) = 0$	EFKLLM
$f_0(500)$	$m_0 = 513 \pm 32$ $\Gamma_0 = 335 \pm 67$ $\kappa = 0$	Red. K-Matrix
$f_0(1370)$	$m_0 = 1380 \pm 70$ $\Gamma_0 = 220 \pm 80$	T-Matrix pole
P-wave		
$K^{*\pm}(892)$	$m_0 = 891.66 \pm 0.26$ $\Gamma_0 = 50.8 \pm 0.9$	RBW
$\rho^0(770)$	$m_0 = 775.26 \pm 0.25$ $\Gamma_0 = 149.8 \pm 0.8$	GS
$K^{*\pm}(1680)$	$m_0 = 1717 \pm 27$ $\Gamma_0 = 332 \pm 110$	Flatté
D-wave		
$K_2^{*\pm}(1430)$	$m_0 = 1425.6 \pm 1.5$ $\Gamma_0 = 98.5 \pm 2.7$	RBW

Time integrated Amplitude Analysis of $B_s^0 \to K_S^0\pi^+\pi^-$

Fit results with the nominal model

All 14 sub-samples (7 data-taking periods x 2 K_S^0 reconstruction categories) are combined in the plots below.



Time integrated Amplitude Analysis of $B_s^0 \to K_S^0 \pi^+ \pi^-$

Fit results with the nominal model

- The results of the fit with the nominal model are gathered below, in terms of :
  - Complex amplitudes (isobar parameters).
  - Fit fractions and raw CP asymmetries.
  - Interference fit fractions

	x_j	y_j	a_j	ϕ_j
Resonance	Real part	Imaginary part	Magnitude	Phase (°)
NR	-1.76 ± 0.27	0.28 ± 0.27	1.78 ± 0.28	$171.1^{+11.4}_{-12.3}$
$(K\pi)_0^{*+}$	-2.81 ± 0.22	-1.10 ± 0.30	3.02 ± 0.21	$-158.7^{+6.9}_{-7.4}$
$(K\pi)_0^{*-}$	-2.61 ± 0.19	-0.07 ± 0.33	2.61 ± 0.19	$-178.4^{+8.0}_{-8.1}$
$f_0(500)$	0.14 ± 0.48	0.52 ± 0.15	0.54 ± 0.18	$75.4^{+61.1}_{-60.9}$
$f_0(1370)$	-0.31 ± 0.38	-0.83 ± 0.21	0.89 ± 0.15	$-110.2^{+28.5}_{-44.1}$
$K^{*+}(892)$	1.71 ± 0.13	0.00	1.71 ± 0.13	0.0 ± 0.0
$K^{*-}(892)$	-2.00	0.00	2.00	180.0
$\rho^0(770)$	-0.47 ± 0.55	1.13 ± 0.29	1.22 ± 0.13	$112.7^{+30.4}_{-28.6}$
$K^{*+}(1680)$	0.17 ± 0.34	1.07 ± 0.20	1.08 ± 0.20	$81.1^{+25.4}_{-21.5}$
$K^{*-}(1680)$	0.15 ± 0.48	-1.07 ± 0.21	1.08 ± 0.21	$-82.2^{+30.7}_{-30.5}$
$K_2^{*+}(1430)$	1.16 ± 0.18	0.14 ± 0.22	1.17 ± 0.17	$6.8^{+11.7}_{-12.9}$
$K_2^{*-}(1430)$	0.56 ± 0.17	-0.72 ± 0.22	0.91 ± 0.20	$-52.1^{+14.3}_{-13.0}$

Resonance	Fit fraction (%)	Raw CP asymm.
$K^*(892)$	$21.87^{+1.91}_{-1.56}$	0.158 ± 0.075
$(K\pi)_0^*$	$50.46^{+4.68}_{-4.45}$	-0.143 ± 0.065
$K_2^*(1430)$	$6.95^{+1.94}_{-1.64}$	-0.247 ± 0.232
$K^*(1680)$	$7.39^{+1.78}_{-1.74}$	-0.002 ± 0.276
$\rho^0(770)$	$9.47^{+1.72}_{-1.90}$	–
$f_0(500)$	$1.84^{+2.10}_{-0.99}$	–
$f_0(1370)$	$4.97^{+2.46}_{-2.00}$	–
NR	$20.16^{+6.92}_{-6.42}$	–

Resonance	$K^*(892)$	$(K\pi)_0^*$	K_2^*	$K^*(1680)$	ρ^0	$f_0(500)$	$f_0(1370)$	NR
$K^*(892)$	21.87	0.00	0.70	1.82	0.12	-0.02	0.56	0.00
$(K\pi)_0^*$		50.46	2.15	0.00	1.28	0.14	1.49	-21.15
K_2^*			6.95	0.29	-0.42	-0.25	0.63	-4.45
$K^*(1680)$				7.39	-0.87	-0.67	0.53	0.00
ρ^0					9.47	0.00	0.00	0.00
$f_0(500)$						1.84	0.16	2.34
$f_0(1370)$							4.97	-7.48
NR								20.16

Time integrated Amplitude Analysis of $B_s^0 \to K_S^0\pi^+\pi^-$

Summary

- The analysis is in an advanced status with most of the pieces in place: Optimized selection for signal candidates $\Rightarrow$ Invariant-mass fits to the $K_S^0\pi^+\pi^-$ spectrum $\Rightarrow$ Models for the remaining backgrounds and efficiency maps across the phase space $\Rightarrow$ Simultaneous Dalitz plot fit and nominal model.
- Results from the nominal model have been presented, including: isobar parameters, fit fractions and interference fit fractions and the raw CP asymmetry.
- Most of the systematic uncertainties have been already computed.

Outlook

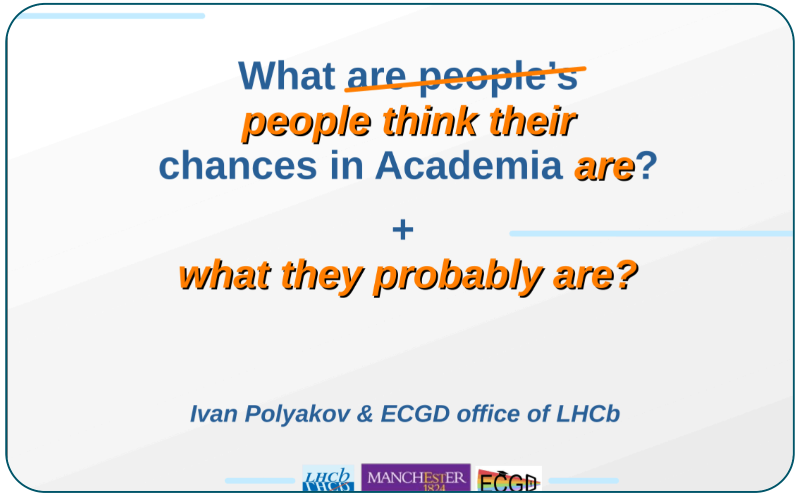
- The remaining systematic uncertainties are work in progress and are expected to be estimated in the following weeks.
- Following two previous talks in the BnoC/B2CC working group (WG), the analysis will enter the WG review as soon as the syst. unc. are completed $\Rightarrow$ End of this month/beginning next month
- Depending on the internal review process, a publication could be foreseen by the end of this year or the beginning of the next one.

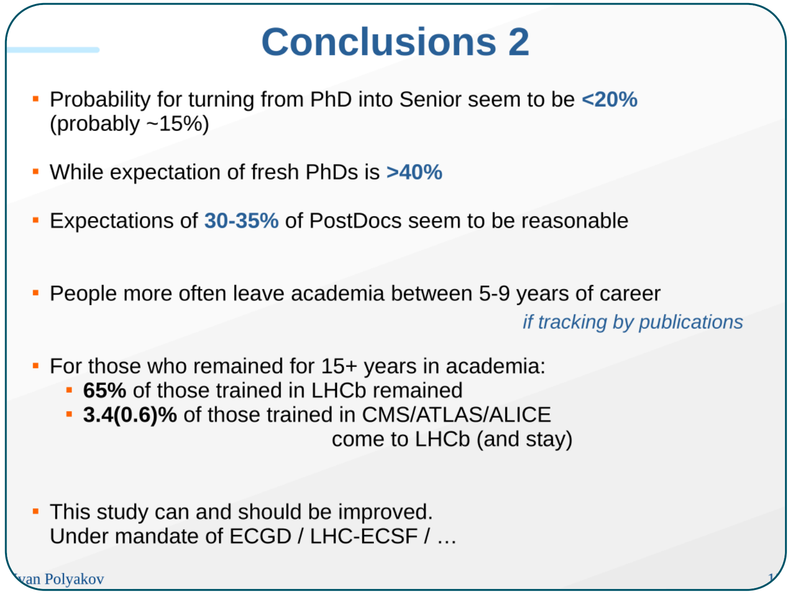
Professional project

Prospects for life after PhD

- During the first two years of my PhD I have:
  - Confirmed that I enjoy research and I would see myself in the mid-term pursuing a career in Academia
    - I will look for a PostDoc position
  - Become more aware of the difficulties in Academia in the long-term
    - In practice, the chances of finding a position seem to be low (even at the PostDoc level).

- In an scenario in which Academia does not go well for me in the short/mid or long term, I would contemplate:
  - Move to industry ⇒ "Data science" related
  - Look for positions related to education
    - Including high school level
  - Others ⇒ To be planned





Chances in Academia talk -116th LHCb week

Doctoral School and complementary activities

Doctoral School Modules

French Module

Learning French for Foreign PhD Students

(2/2) ED Specialty Modules

- Neural networks and artificial intelligence
- Statistical data analysis and Machine learning

(0/2) Communication Modules

- International Conference
- Scientific days ED

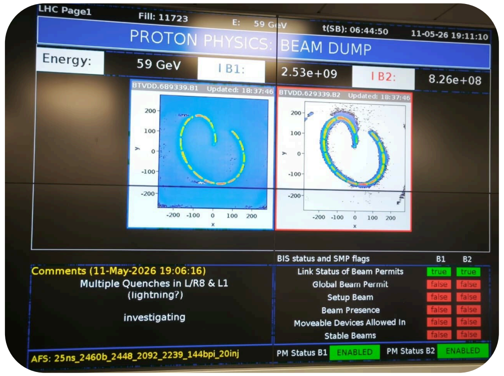
Ethics in Research and Scientific Integrity

Complementary activities

Outreach

Contributed to science communication initiatives, including the international Masterclass organized by the IPPOG.

Service to the collaboration



- Acted as **Data Manager** and **SciFi piquet** during the last data taking period of the Run 3
- I've been appointed as the **Flavour Tagging liaison** for the BnoC/B2CC WG (02/2026-01/2028).

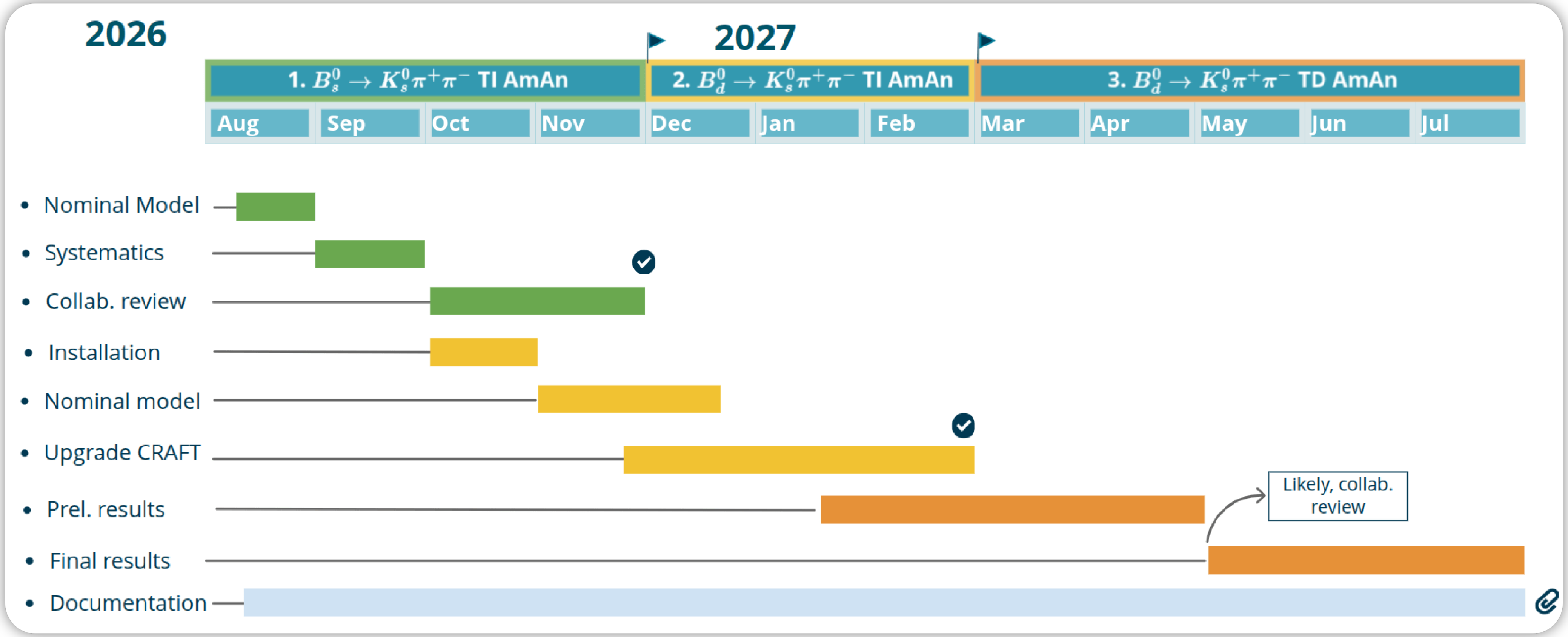
Academic events

- As part of my PhD education, I've attended two schools related to my research interests:
  - **Trans-European School of High Energy Physics** (11-19 Jul 2025, Stara Lesna, Slovakia)
    - Experimental Particle Physics, Standard Model and Beyond, Neutrino physics, etc
  - **Flavour physiscs at LHC School** (15-19 Jun 2026, CERN)
    - Training in the physics and tools of relevance to the flavour programme of the LHC
- Also, attended my first collaboration week: **119th LHCb Week** (23-27 Feb 2026, CERN)

Outlook

Timeline

1. Complete the Time Integrated Amplitude Analysis of the $B_s^0 \to K_s^0\pi^+\pi^-$ decay
2. Carry out an upgraded Time Integrated AmAn of the $B^0 \to K_s^0\pi^+\pi^-$ using Run 1 and Run 2 data
3. Perform the Time Dependent AmAn of the $B^0 \to K_s^0\pi^+\pi^-$ decay



Papers and internal notes

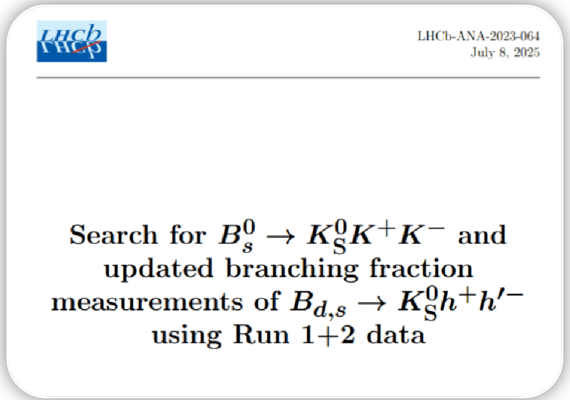
The work presented here is either already documented or currently being documented in parallel with the progress of the analysis.

Branching Fraction Analysis

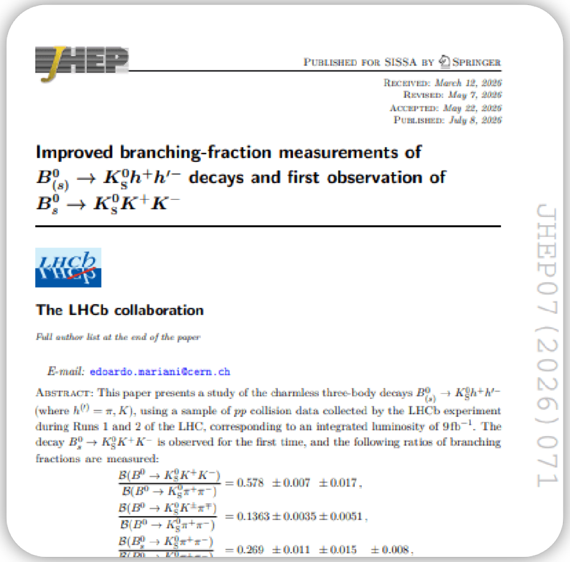
- Internal documentation:
  - Analysis Note: LHCb-ANA-2023-064
  - Paper: LHCb-PAPER-2024-029
- Paper published:
-   - JHEP (July 8, 2026).
    - Arxiv (Mar 9, 2026)

Time Integrated Amplitude Analysis

- Two updates presented to the BnoC group
- Internal note written in parallel and currently under review by the LPCA team.


LHCb-ANA-2023-064
July 8, 2025

Search for $B_s^0 \to K_S^0 K^+ K^-$ and updated branching fraction measurements of $B_{d,s} \to K_S^0 h^+ h'^-$ using Run 1+2 data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Improved branching-fraction measurements of $B^0_{(s)} \to K^0_S h^+ h'^-$ decays and first observation of $B^0_s \to K^0_S K^+ K^-$

The LHCb collaboration

Full author list at the end of the paper

E-mail: edoardo.mariani@cern.ch

ABSTRACT: This paper presents a study of the charmless three-body decays $B^0_{(s)} \to K^0_S h^+ h'^-$ (where $h^{(\prime)} = \pi, K$), using a sample of pp collision data collected by the LHCb experiment during Runs 1 and 2 of the LHC, corresponding to an integrated luminosity of $9\,\mathrm{fb}^{-1}$. The decay $B^0_s \to K^0_S K^+ K^-$ is observed for the first time, and the following ratios of branching fractions are measured:

$$\frac{\mathcal{B}(B^0 \to K^0_S K^+ K^-)}{\mathcal{B}(B^0 \to K^0_S \pi^+ \pi^-)} = 0.578 \pm 0.007 \pm 0.017\,,$$
$$\frac{\mathcal{B}(B^0 \to K^0_S K^\pm \pi^\mp)}{\mathcal{B}(B^0 \to K^0_S \pi^+ \pi^-)} = 0.1363 \pm 0.0035 \pm 0.0051\,,$$
$$\frac{\mathcal{B}(B^0_s \to K^0_S \pi^+ \pi^-)}{\ldots} = 0.269 \pm 0.011 \pm 0.015 \pm 0.008\,,$$

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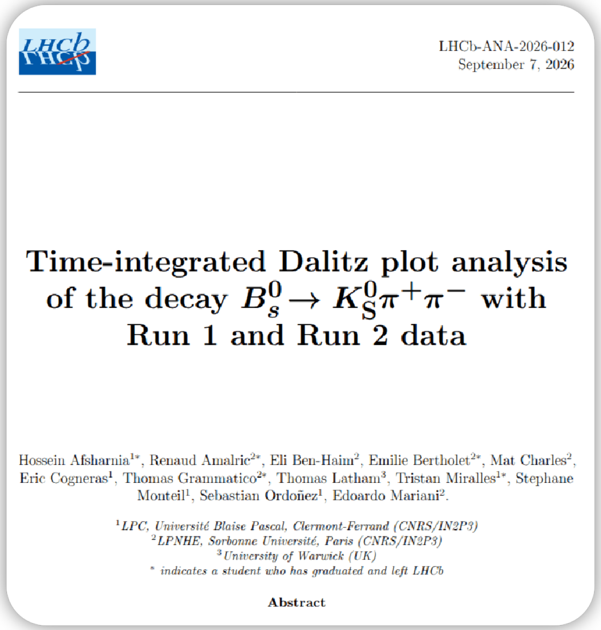
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Time-integrated Dalitz plot analysis of the decay $B_s^0 \to K_S^0 \pi^+ \pi^-$ with Run 1 and Run 2 data

Hossein Afsharnia[1*], Renaud Amalric[2*], Eli Ben-Haim[2], Emilie Bertholet[2*], Mat Charles[2], Eric Cogneras[1], Thomas Grammatico[2*], Thomas Latham[3], Tristan Miralles[1*], Stephane Monteil[1], Sebastian Ordoñez[1], Edoardo Mariani[2].

[1] *LPC, Université Blaise Pascal, Clermont-Ferrand (CNRS/IN2P3)*
[2] *LPNHE, Sorbonne Université, Paris (CNRS/IN2P3)*
[3] *University of Warwick (UK)*
* *indicates a student who has graduated and left LHCb*

Abstract

Thank you!

Questions and discussion