

EVIDENCE FOR THE RARE DECAY

$$B^+ \rightarrow \bar{\Lambda}^0 p \mu^+ \mu^-$$

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CLHCP2025 Workshop

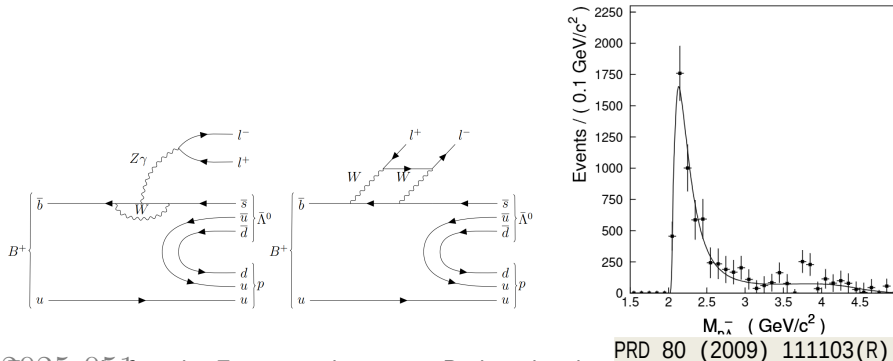
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MOTIVATION

- ▶ Essentially a $b \rightarrow s\ell^+\ell^-$ process
- ▶ EWP baryonic decays, sensitive to both NP and $\bar{\Lambda}^0 p$ threshold enhancement effects
- ▶ SM based prediction puts BF of $B^+ \rightarrow \bar{\Lambda}^0 p \mu^+ \mu^-$ at about 1.08×10^{-7} [J. Phys.G 41 (2014) 065002]
- ▶ BABAR measured $\mathcal{B}(B^+ \rightarrow \bar{\Lambda}^0 p \nu \bar{\nu}) < 3.0 \times 10^{-5}$ [PRD 100 (2019) 111101], given expected BF of 7.9×10^{-7} . However a recent paper claimed that the prediction on $B^+ \rightarrow \bar{\Lambda}^0 p \nu \bar{\nu}$ should be **20x smaller** [EPJC 83 (2023) 4, 300].
- ▶ Threshold enhancement effects, observed significantly near the $\bar{\Lambda}^0 p$ invariant mass threshold, play a crucial role in four-body baryonic B decays, as confirmed by Belle's study of $B^+ \rightarrow \bar{\Lambda}^0 p \pi^+ \pi^-$ [PRD 80 (2009) 111103(R)].



LHCb-PAPER-2025-051 **Figure.** Left : the Feynman diagrams. Right: the threshold enhancement effect.

SEARCH STRATEGY

Normalization and Signal Analysis:

- Normalization channel: $B^+ \rightarrow \bar{\Lambda}^0 p J/\psi (\rightarrow \mu^+ \mu^-)$, BF 9×10^{-7} [PRL 131 (2023) 031901].
- BF calculation:

$$\mathcal{B}_{\text{low(high)}}(B^+ \rightarrow \bar{\Lambda}^0 p \mu^+ \mu^-) = \frac{N_{\text{L(H)}}(B^+ \rightarrow \bar{\Lambda}^0 p \mu^+ \mu^-)}{N(B^+ \rightarrow J/\psi \bar{\Lambda}^0 p)} \times \frac{\epsilon(B^+ \rightarrow J/\psi \bar{\Lambda}^0 p)}{\epsilon_{\text{L(H)}}(B^+ \rightarrow \bar{\Lambda}^0 p \mu^+ \mu^-)} \times \mathcal{B}(B^+ \rightarrow J/\psi \bar{\Lambda}^0 p) \times \mathcal{B}(J/\psi \rightarrow J/\psi \rightarrow \mu^+ \mu^-), \quad (0.1)$$

- Data: 2016-2018 using StrippingB2DibaryonMuMuLine.
- Blinded analysis: the signal window $5150 < M(\bar{\Lambda}^0 p \mu^+ \mu^-) < 5400$ MeV was excluded
- Signal region: $M(\mu^+ \mu^-) < 2850$ MeV; normalization: $|M(\mu^+ \mu^-) - M(J/\psi)^{\text{PDG}}| < 50$ MeV.
- MVA setup for background suppression.

Search Regions:

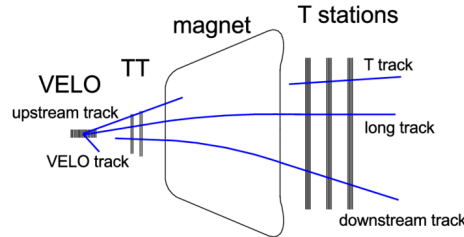
- Threshold-mass-enhanced region: $m(\bar{\Lambda}^0 p) < 2.8 \text{ GeV}/c^2$.
- High-mass region: $m(\bar{\Lambda}^0 p) > 2.8 \text{ GeV}/c^2$.

DATA/MC REWEIGHTING

- ▶ To correct tracking efficiency differences, weights from momentum and pseudorapidity are applied to long tracks using **TrackingCalib**.
- ▶ To correct the L0 trigger efficiency, a data-driven method reweights simulation using efficiency maps derived from $B^+ \rightarrow J/\psi K^+$ data with the **TISTOS** technique.
- ▶ To correct for particle identification simulation, PID variables for protons and muons are corrected in MC using the **PIDCorr** package across η , P_T , and nTracks dimensions .
- ▶ To correct for kinematic differences, a **Gradient Boosted Reweigher** using data-driven sWeights is applied to variables($B^+ p_T$, $B^+ \chi_{\text{DTF}}^2$, $B^+ \chi_{\text{IP}}^2$, $B^+ \text{DIRA}$ and nTracks)
- ▶ To account for resonant contributions in data not modeled by the phase-space MC, efficiency corrections are applied in the dimensions of $\mathbf{m}(\bar{\Lambda}^0 J/\psi)$ and $\mathbf{m}(\rho J/\psi)$ [**Normalization channel**]

SELECTION

- ▶ StrippingB2DibaryonMuMuLine and StrippingB2DibaryonMuMu_SSLine are utilized for data.
- ▶ The full trigger requirement comprises “L0 (L0Muon || L0DiMuon) & HLT1 & HLT2”
- ▶ $M(\mu^+\mu^-)$ requirements: $M(\mu^+\mu^-) < \mathbf{2850\ MeV}$ for signal channel,
 $|M(\mu^+\mu^-) - M(J/\psi)^{PDG}| < \mathbf{50\ MeV}$ for normalization channel.
- ▶ A BDT is chosen to be used to separate signal candidates from combinatorial background candidates for LL and DD mode.
 - B^+ :PT,log(IP χ^2),log(1-DIRA),log(χ^2 /nodf) DTF,log(DLS) DTF
 - Final state Particles: $\sum_{daughter}\log(IP\chi^2),\sum_{daughter}ETA$
 - Λ LL (DD): log(1-DIRA),log(IP χ^2), log(DLS),log(FD χ^2) (DLS : Decay length)



BDT-PID OPTIMIZATION

► $\text{PIDp} = \text{p_MC15TuneV1_ProbNNp} \times (1 - \text{p_MC15TuneV1_ProbNNk})$

$$\text{PIDmu} = \min(\text{mum_MC15TuneV1_ProbNNmu}, \text{mup_MC15TuneV1_ProbNNmu}).$$

- Based on PIDp, PIDmu and BDT, **a three-dimensional optimization** is performed to find the optimal optimization point using $\frac{\epsilon}{(\frac{5}{2} + \sqrt{B})}$.

- ϵ is the signal efficiency and B the expected background yield within the signal region of

$$|m(\bar{\Lambda} p \mu^+ \mu^-) - m_{B^+}| < 20 \text{ MeV}.$$

PHYSICS BACKGROUND

- ▶ Considering two main physical backgrounds, $B^+ \rightarrow \bar{\Lambda}^0 p \pi^+ \pi^-$ and $B^+ \rightarrow \Lambda_c^- (\rightarrow \Lambda \mu^- \bar{\nu}_\mu) p \pi^+$

Decay	Branching Fraction	Reference
$B^+ \rightarrow \bar{\Lambda}^0 p \pi^+ \pi^-$	$(1.13 \pm 0.13) \times 10^{-5}$	PDG
$B^+ \rightarrow \bar{\Lambda}_c^- (\rightarrow \Lambda \mu^- \bar{\nu}_\mu) p \pi^+$	$(2.3 \pm 0.4) \times 10^{-4} \times (3.48 \pm 0.17)\%$	PDG

- ▶ The estimated background yield (S) is determined by the equation:

$$S = \int \mathcal{L} dt \times \sigma_{b\bar{b}} \times 2 \times f_u \times \mathcal{B} \times \epsilon_{tot},$$

- ▶ Expected background yields for $B^+ \rightarrow \bar{\Lambda}^0 p \pi^+ \pi^-$ and $B^+ \rightarrow \bar{\Lambda}_c^- (\rightarrow \Lambda \mu^- \bar{\nu}_\mu) p \pi^+$ in $\bar{\Lambda}^0$ LL and DD mode.

Decay	$\mathcal{B}$	LL	DD
$B^+ \rightarrow \bar{\Lambda}^0 p \pi^+ \pi^-$	$(1.13 \pm 0.13) \times 10^{-5}$	< 0.01	< 0.02
$B^+ \rightarrow \bar{\Lambda}_c^- (\rightarrow \Lambda \mu^- \bar{\nu}_\mu) p \pi^+$	$(8.00 \pm 1.45) \times 10^{-6}$	< 0.47	< 0.97

FIT MODEL

Fit Components:

- ▶ **Signal PDF:** Double-Sided Crystal Ball (DSCB) function.
- ▶ **Background PDF:** Exponential function.
- ▶ **Parameter Definitions:**

$$\begin{aligned}\mu_{\text{signal/norm}}^{\text{LL/DD}} &= \mu_{\text{MC}}^{\text{LL/DD}} + \delta^{\text{LL/DD}}, \\ \sigma_{\text{signal/norm}}^{\text{LL/DD}} &= \sigma_{\text{MC}}^{\text{LL/DD}} \times \text{scale}^{\text{LL/DD}}.\end{aligned}$$

- ▶ **Yields:**

$$N_{\text{signal/norm}}^{\text{LL/DD}} = N_{bb} \times \mathcal{B}_{\text{signal/norm}} \times \epsilon_{\text{signal/norm}}^{\text{LL/DD}}.$$

Fit Parameters:

- ▶ **Free Parameters:** N_{bb} , $\text{BF}_{\text{signal}}$, $\delta^{\text{LL/DD}}$, $\text{scale}^{\text{LL/DD}}$, background yields, and slope.
- ▶ **Fixed Parameters:** From MC or PDG, including μ , σ , $\alpha_{L/R}$, and $n_{L/R}$ for LL/DD modes.

Simultaneous Fits:

- ▶ Performed for normalization and signal channels in both LL and DD categories.

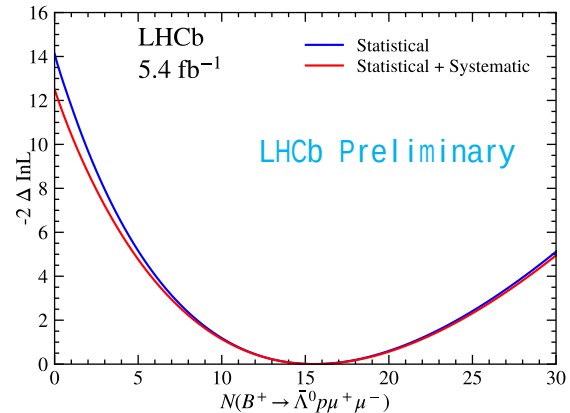
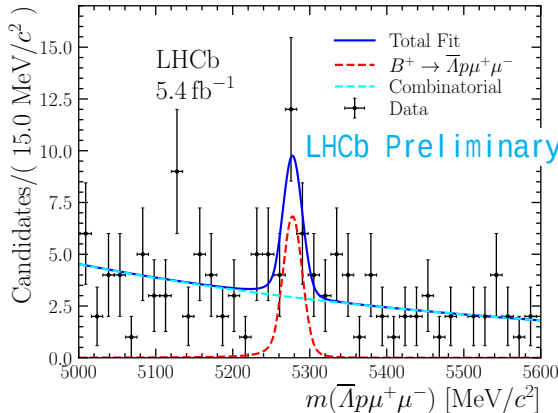
FIT RESULTS: LOW MASS REGION

Low Mass Region ($m(\bar{\Lambda}^0 p) < 2.8 \text{ GeV}/c^2$):

- A signal excess is found in this region with a branching fraction:

$$\mathcal{B} = (1.70 \pm 0.60_{\text{stat}} \pm 0.19_{\text{syst}} \pm 0.14_{\text{ext}}) \times 10^{-8}$$

- Statistical significance: 3.7σ , and significance at 3.5σ after considering systematic uncertainties from signal & background shapes
- The significance is calculated using the likelihood ratio test: $\sqrt{-2 \ln(\mathcal{L}_0/\mathcal{L}_S)}$, where $\mathcal{L}_S$ and $\mathcal{L}_0$ are the maximum likelihoods from the baseline fit and the signal-free fit, respectively.



FIT RESULTS: HIGH MASS REGION

High Mass Region ($m(\bar{\Lambda}^0 p) > 2.8 \text{ GeV}/c^2$):

- ▶ No signal excess is found.
- ▶ An upper limit on the branching fraction is set at:

$$\mathcal{B} < 2.4 \times 10^{-9} \text{ @ } 90\% \text{ CL}$$

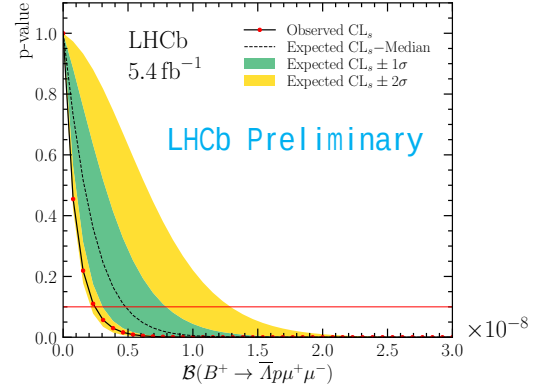
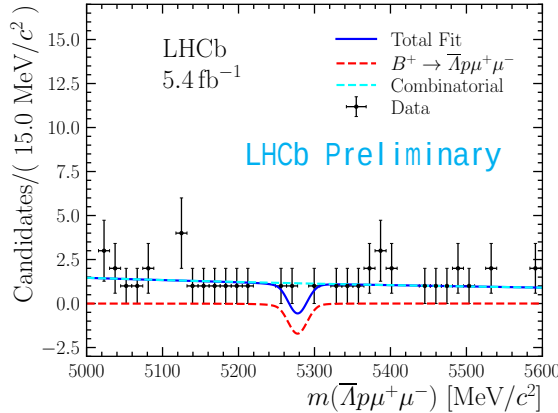


Figure. Left: Fit result for the high mass region. Right: Upper limit determination.

FIT RESULTS: FULL REGION

- We measure the branching fraction:

$$\mathcal{B} = (1.53 \pm 0.65_{\text{stat}} \pm 0.18_{\text{syst}} \pm 0.13_{\text{ext}}) \times 10^{-8}$$

- Statistical significance: 2.9σ , and significance at 2.8σ after considering systematic uncertainties from signal & background shapes

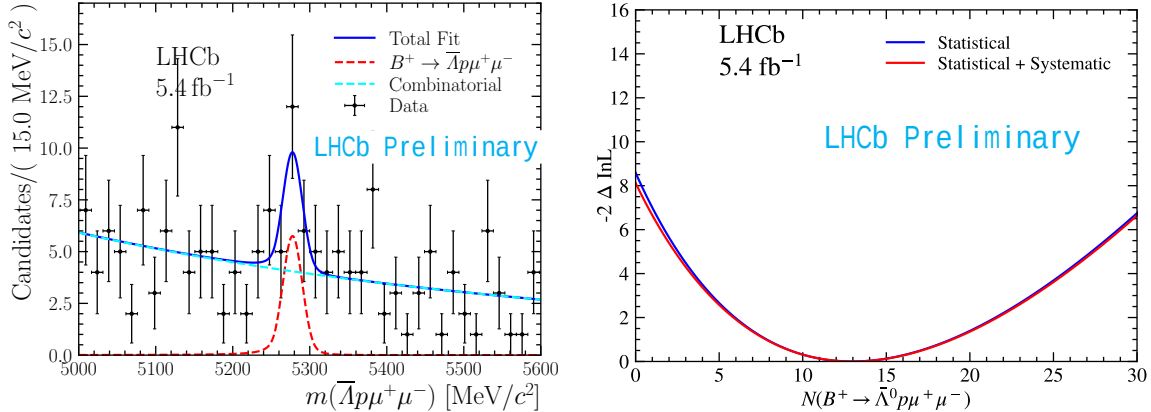


Figure. Fit result for the full region.

SYSTEMATIC UNCERTAINTIES

Table. Summary of the systematic uncertainties of the branching fraction of signal channel. The overall systematic uncertainty is calculated as sum in quadrature of all the sources.

Systematic source	$m(\bar{\Lambda}^0 p) < 2.8$	$m(\bar{\Lambda}^0 p) > 2.8$	Full region
Simulated sample size	0.6	0.6	0.6
Kinematic correction	2.1	2.2	2.2
Tracking efficiency	0.8	0.8	0.8
Trigger efficiency	2.0	4.4	3.4
PID efficiency	2.8	2.9	2.9
Fit bias	4.1	11.5	4.0
Signal shape	7.0	7.0	6.2
Background shape	3.5	3.5	3.8
Model correction (normalization)	2.6	2.6	2.6
Signal decay model	4.1	4.1	4.1
Total systematic	10.9	15.8	10.9
External BF	8.24	8.24	8.24

SUMMARY

Low Mass Region ($m(\bar{\Lambda}^0 p) < 2.8 \text{ GeV}/c^2$):

- Signals are found in this region with a branching fraction¹:

$$\mathcal{B}_{\text{low}} = (1.70 \pm 0.60_{\text{stat}} \pm 0.19_{\text{syst}} \pm 0.14_{\text{ext}}) \times 10^{-8}$$

- Signal significance: 3.5σ , confirming a threshold enhancement effect.

High Mass Region ($m(\bar{\Lambda}^0 p) > 2.8 \text{ GeV}/c^2$):

- No significant signal is observed, an upper limit on the branching fraction at 90% confidence level is set:

$$\mathcal{B}_{\text{high}} < 2.4 \times 10^{-9}$$

Full region:

- The total branching fraction is measured:

$$\mathcal{B}(B^+ \rightarrow \bar{\Lambda}^0 p \mu^+ \mu^-) = (1.53 \pm 0.65_{\text{stat}} \pm 0.18_{\text{syst}} \pm 0.13_{\text{ext}}) \times 10^{-8}$$

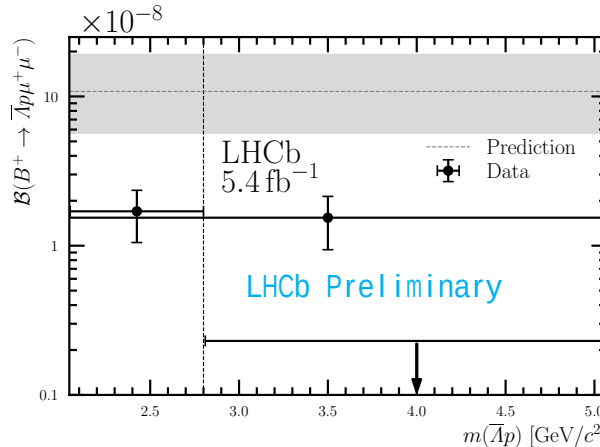
- Signal significance: 2.8σ , an upper limit on the branching fraction at 90% confidence level is set:

$$\mathcal{B}(B^+ \rightarrow \bar{\Lambda}^0 p \mu^+ \mu^-) < 2.45 \times 10^{-8}$$

SUMMARY

- The first search for the semileptonic decay $b \rightarrow s \mu^- \mu^+$ with a baryon-antibaryon pair reports evidence of a signal with 3.5σ significance in the low-mass region, measuring a branching fraction of order 10^{-8} .
- The result, while lower than the [prediction](#), is compatible within 2σ and hints at threshold enhancement, providing new insights into baryonic form factors.

Figure. The partial and total branching fraction results are presented in regions of $m(\bar{\Lambda}p)$. The allowed phase-space range of $m(\bar{\Lambda}p)$ is shown as $[m_{\bar{\Lambda}} + m_p, m - 2m_\mu]$. Also shown is the prediction from Ref.[\[J. Phys. G41309 \(2014\) 065002\]](#), with its $\pm 1\sigma$ range represented by the shaded area.



BACK UP

BACK UP

BDT VARIABLES

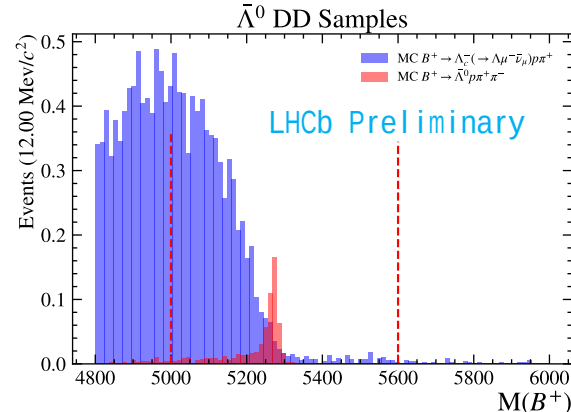
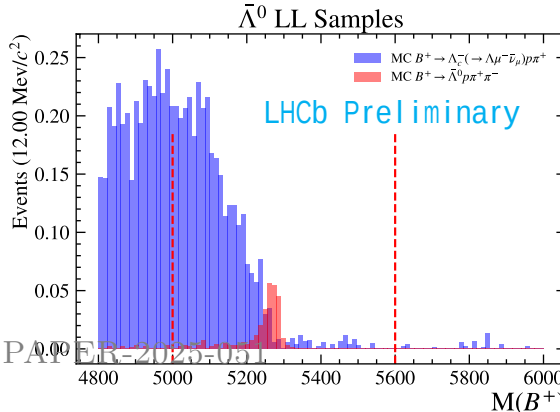
Variable category	Description
B^+ candidate variables	▶ PT: Transverse momentum ▶ $\log(IP\chi^2)$: Logarithm of impact parameter χ^2 ▶ $\log(1-DIRA)$: Logarithm of (1 - DIRA angle) ▶ $\log(\chi^2/nodf)$ DTF: Logarithm of χ^2/ndf from decay tree fit ▶ $\log(DLS)$ DTF: Logarithm of decay length significance from DTF
Final state particle variables	▶ $\sum_{daughter} \log(IP\chi^2)$: Sum of $\log(IP\chi^2)$ over all daughters ▶ $\sum_{daughter} \text{ETA}$: Sum of pseudorapidity over all daughters
Λ candidate variables	▶ $\log(1-DIRA)$: Logarithm of (1 - DIRA angle) ▶ $\log(IP\chi^2)$: Logarithm of impact parameter χ^2 ▶ $\log(DLS)$: Logarithm of decay length significance ▶ $\log(FD\chi^2)$: Logarithm of flight distance χ^2 (for LL mode)

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- Considering two main physical backgrounds, $B^+ \rightarrow \bar{\Lambda}^0 p \pi^+ \pi^-$ and $B^+ \rightarrow \Lambda_c^- (\rightarrow \Lambda \mu^- \bar{\nu}_\mu) p \pi^+$

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- Removing the PID requirement, **IsMuon==1**, in the stripping line and the PID requirement, `p_ProbNNp,mum_ProbNNmu,mup_ProbNNmu`, in the pre-selection, subsequent selection based on the strip & truth, trigger, pre-selection criteria
- Using the P and ETA of particles ($\mu^+/\mu^-/p$) of the samples to give PIDweights with the help of PIDCalib2
- The distribution graph of B^+ mass with PIDweight is shown below.



- The estimated background yield (S) is determined by the equation:

$$S = \int \mathcal{L} dt \times \sigma_{b\bar{b}} \times 2 \times f_u \times \mathcal{B} \times \epsilon_{tot},$$

- Expected background yields for $B^+ \rightarrow \bar{\Lambda}^0 p \pi^+ \pi^-$ and $B^+ \rightarrow \bar{\Lambda}_c^- (\rightarrow \Lambda \mu^- \bar{\nu}_\mu) p \pi^+$ in $\bar{\Lambda}^0$ LL and DD mode.

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SOURCES OF UNCERTAINTY

► Branching fraction uncertainty

- Propagated from PDG uncertainties:

$$\mathcal{B}(B^+ \rightarrow \bar{\Lambda}^0 p J/\psi) = (1.46 \pm 0.12) \times 10^{-5}, \quad \mathcal{B}(J/\psi \rightarrow \mu^+ \mu^-) = (5.961 \pm 0.033) \times 10^{-2}$$

► MC Statistics

- Incorporated via Gaussian constraint in the fit: $\mu = \epsilon_{\text{MC}}, \sigma = \delta_{\epsilon}^{\text{stat}}$

► Reweighting

- Multiple sets of BGRweighter parameters are tested, and the resulting efficiency differences are taken as a systematic uncertainty.

► Tracking Efficiencies

- Estimated using a data-driven approach with track-type weighting
- Systematic uncertainty assessed by comparing efficiency from with tracking weights and without tracking weights

► Trigger Efficiencies

- Evaluated with the TISTOS method
- The trigger efficiencies will be determined with a different binning and the difference with respect to thenominal efficiencies will be assigned as uncertainties.

► Particle Identification (PID) Efficiencies

- Recalculated using PIDCalib2 with adaptive kernel density estimation
- Systematic uncertainty assessed by comparing efficiency from PIDCalib weights and PIDCorr

methods

SOURCES OF UNCERTAINTY

► Fixed parames

- Sets of 1000 values are generated from the covariance matrix of the fit to simulated samples
- For each new set of fixed values, the fits will be redone and the measured yields stored
- Systematic is assigned as the σ value of the fitted result: 0.3%

► background model

Substitute the exponential background PDF in the fitting with a first order Chebyshev polynomial.

► signal model

Substitute the Double-sided Crystal Ball (DSCB) signal PDF in the fitting with Johnson's SU

SOURCES OF UNCERTAINTY

- ▶ $B^+ \rightarrow \bar{\Lambda}^0 p \mu^+ \mu^-$ **decay modeling**
 - Using signal decay model based on $B^+ \rightarrow K_1(1270)^+ \mu^+ \mu^-$, under the assumption that the $\bar{\Lambda} p$ pair originates solely from the $X(2085)$ resonance, sharing the same J^P quantum numbers as the $K_1(1270)^+$.
 - An associated uncertainty arises from efficiency variations under different signal model hypotheses.
- ▶ $B^+ \rightarrow \bar{\Lambda}^0 p J/\psi$ **decay modeling**
 - Multiple sets of BGRweighter parameters are tested, and the resulting efficiency differences are taken as a systematic uncertainty.
- ▶ **Fit bias**
 - The bias in the branching fraction $\mathcal{B}$ is evaluated from the pull distribution using 2000 toy studies