

Observation of the decay $B_s^0 \rightarrow K^0 p \bar{p}$ and measurement of the

$B_{(s)}^0 \rightarrow K^0 p \bar{p}$ branching fractions

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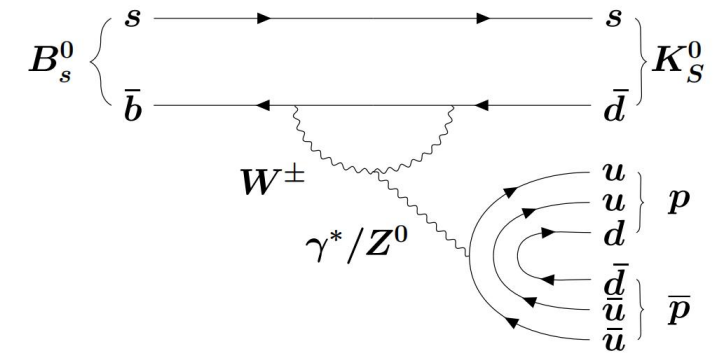
CCNU

1st Nov. 2025

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1. Motivation
2. Previous experimental results
3. Analysis strategies
4. Check the low-mass enhancement
5. Summary and outlook

- Search for $B_s^0 \rightarrow K^0 p \bar{p}$
- Measurement of the $B_{(s)}^0 \rightarrow K^0 p \bar{p}$ branching fractions
- Quark decay diagrams:
 - $B^0 \rightarrow K^0 p \bar{p}$: $b \rightarrow u$ tree and $b \rightarrow s$ penguin diagrams
 - $B_s^0 \rightarrow K^0 p \bar{p}$: $b \rightarrow u$ tree and $b \rightarrow d$ penguin diagrams
- Comparing them with theoretical predictions offers valuable insights into various theoretical frameworks
- Investigate the low-mass enhancement in baryon-antibaryon invariant mass spectra
- Evaluate flavour-symmetry breaking, including isospin, U-spin, and SU(3) symmetry
- Key observables for studying CP violation in loop-dominated processes
- A key preparation for future time-dependent Dalitz analyses



Measurement	$\times 10^{-6}$		
	Belle	BaBar	PDG
$B(B^0 \rightarrow K^0 p \bar{p})$	<u>$2.51^{+0.35}_{-0.29} \pm 0.21$ (2008)</u>	<u>$3.0 \pm 0.5 \pm 0.3$ (2007)</u>	2.66 ± 0.32
$B(B_s^0 \rightarrow K^0 p \bar{p})$			
$B(B^0 \rightarrow K^0 \pi^+ \pi^-)$	<u>$47.5 + 2.4 + 3.7$ (2007)</u>	<u>$50.2 \pm 1.5 \pm 1.8$ (2009)</u>	49.70 ± 1.80

In this analysis, in particular the selection and efficiency determination will provide the basis for the future Dalitz-plot analyses of the decays $B_{(s)}^0 \rightarrow K^0 p \bar{p}$

- In both decays, the K^0 is reconstructed through the two π decay of its short-lived mass eigenstate

$$B(B_{(s)}^0 \rightarrow K_S^0 p \bar{p}) = B(B^0 \rightarrow K_S^0 \pi^+ \pi^-) \times \frac{N(B_{(s)}^0 \rightarrow K_S^0 p \bar{p})}{N(B^0 \rightarrow K_S^0 \pi^+ \pi^-)} \times \frac{\varepsilon^{sel}(B^0 \rightarrow K_S^0 \pi^+ \pi^-)}{\varepsilon^{sel}(B_{(s)}^0 \rightarrow K_S^0 p \bar{p})} \times \frac{f_d}{f_{d(s)}}$$

- Where B is a branching fraction, N stands for the number of signal events from the mass fit and ε is total efficiency
- $\varepsilon^{sel} = \varepsilon^{\text{Geom}} \times \varepsilon^{\text{Reco}} \times \varepsilon^{\text{Trac}} \times \varepsilon^{\text{PID}} \times \varepsilon^{\text{Trig}} \times \varepsilon^{\text{MVA}} \times \varepsilon^{\text{Veto}}$
- $\frac{f_s}{f_d}$ is the average of hadronic and semileptonic measurements from the HFAG
- The $B(B^0 \rightarrow K^0 \pi^+ \pi^-)$ is $(49.7 \pm 0.18) \times 10^{-6}$ from the PDG

- Data samples: the 9 fb^{-1} of data recorded during **Run-1** and **Run-2** of the LHCb
- Stripping Line: StrippingB2KShh_LL_Run1/2_OS_Line,
StrippingB2KShh_DD_Run1/2_OS_Line
- Signal optimization
- Background Studies:
 - Misidentified and Partially Reconstructed Backgrounds
 - Combinatorial background
- Mass Fits
- Efficiencies and Uncertainty
- Systematics

Mode	Mode number
$B^0 \rightarrow K_S^0 p \bar{p}$ (sqDalitz)	11104164
$B_s^0 \rightarrow K_S^0 p \bar{p}$ (sqDalitz)	11104124
$B^0 \rightarrow K_S^0 \pi^+ \pi^-$ (sqDalitz)	13104154

Based on the consistency of the samples, the samples into four groups (2011, 2012, 2015-2016, and 2017-2018) and 2 K_S^0 reconstruction (LL, DD)

⇒ 8 data samples.

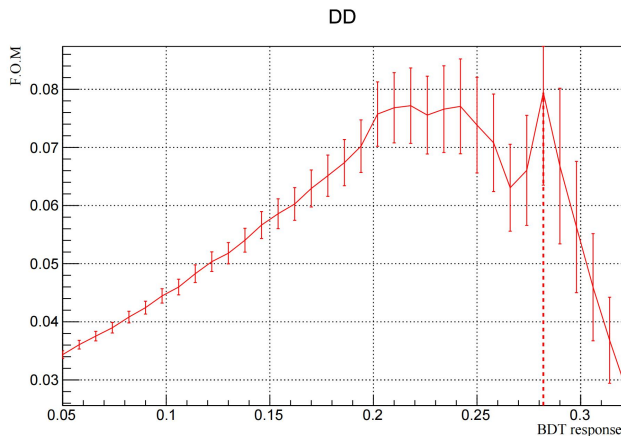
- After the preselection, trigger, and PID, a large amount of background still
- A multivariate analysis (MVA) is employed to further improve the signal-to-background separation
- The selection of the $B_S^0 \rightarrow K_S^0 p \bar{p}$ decay is optimized using the Punzi figure of merit

$$\text{Punzi} = \frac{\varepsilon_{sig}}{\frac{a}{2} + \sqrt{B}}$$

ε_{sig} : signal efficiency estimated by MC samples

a: the expected significance for the signal channel and set to 5

B: the number of background events, estimated by the high sideband region



Samples	K_S^0 type	ε_{sig}	B	FoM	Working point
2011 and 2012	DD	0.472	12.0	0.079	0.226
	LL	0.505	7.0	0.098	0.202
2015 and 2016	DD	0.460	12.0	0.077	0.218
	LL	0.611	6.0	0.123	0.234
2017 and 2018	DD	0.392	15.0	0.062	0.242
	LL	0.534	6.0	0.108	0.242

Mass Veto selection

- By the calculated the mass of $p\bar{p}$ and the mass of $K_S^0 p$, to check the effect of the resonance state, and found that η_c , J/ψ , $\psi(2S)$ and Λ_c^+ is seen

◆ $B^0 \rightarrow \eta_c K_S^0$ with $\eta_c \rightarrow p\bar{p}$

Veto selection $|m(p\bar{p}) - m(\eta_c)| > 45 \text{ MeV}/c^2$

◆ $B^0 \rightarrow J/\psi K_S^0$ with $J/\psi \rightarrow p\bar{p}$

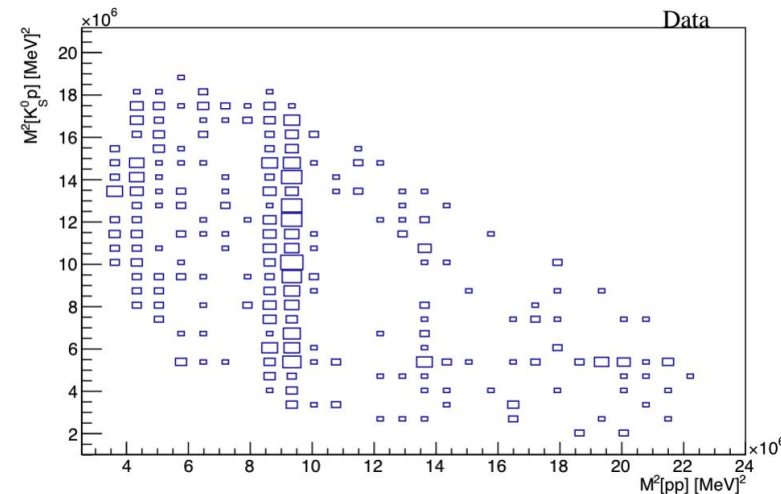
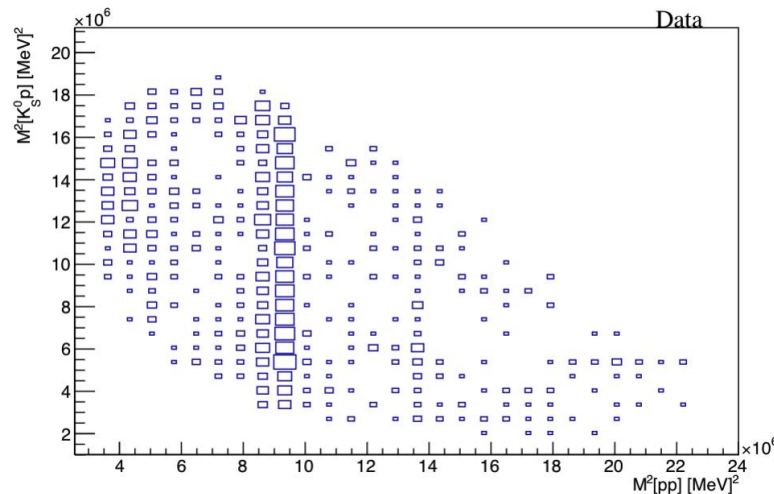
Veto selection $|m(p\bar{p}) - m(J/\psi)| > 25 \text{ MeV}/c^2$

◆ $B^0 \rightarrow \psi(2S) K_S^0$ with $\psi(2S) \rightarrow p\bar{p}$

Veto selection $|m(p\bar{p}) - m(\psi(2S))| > 35 \text{ MeV}/c^2$

◆ $B^0 \rightarrow \Lambda_c^+ \bar{p}$ with $\Lambda_c^+ \rightarrow K_S^0 p$

Veto selection $|m(K_S^0 \bar{p}) - m(\Lambda_c^+)| > 30 \text{ MeV}/c^2$



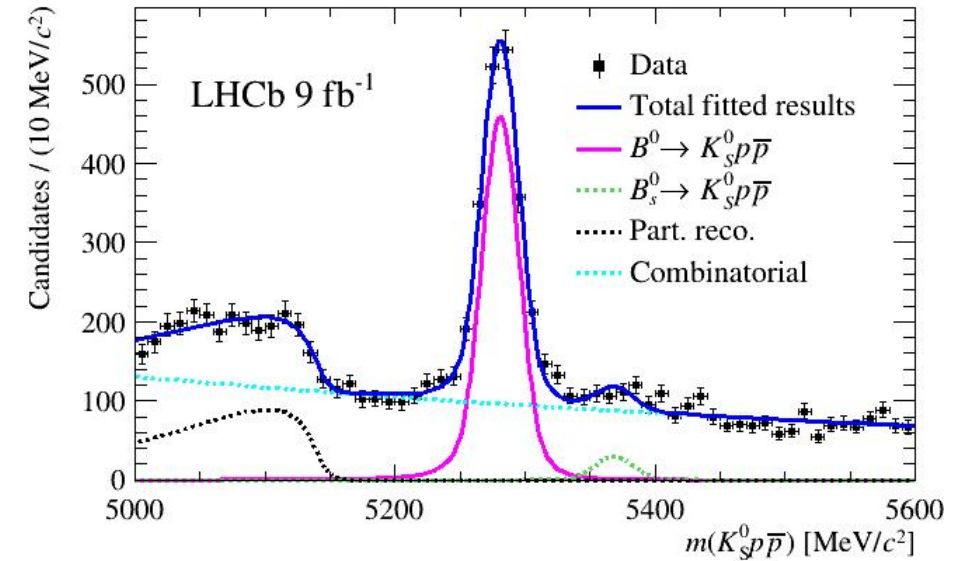
the left is DD and right is LL

Mass fit: $B^0 \rightarrow K_S^0 p \bar{p}$

- Mass fit the B candidate invariable mass for $B^0 \rightarrow K_S^0 p \bar{p}$ decay

PDFs:

- Combinatorial: Exponential function
- Partial reconstructed: Argus $\otimes$ Gauss function
- Signal and B_S^0 : Double-side Crystal ball



- This table summarizes the signal yield and its statistical

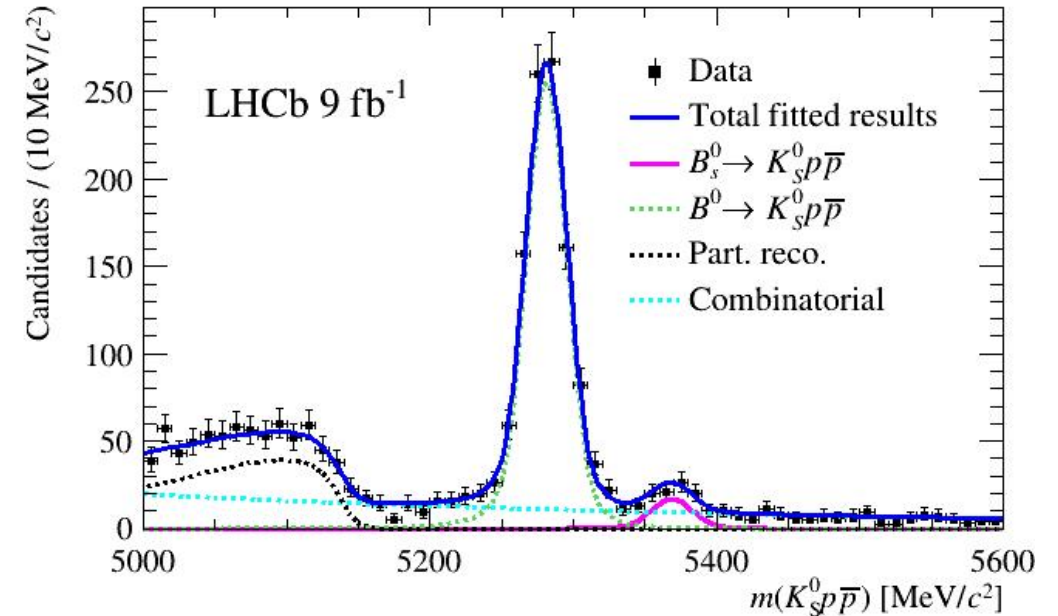
		2011	2012	2015 and 2016	2017 and 2018	Total
$B^0 \rightarrow K_S^0 p \bar{p}$	DD	55 ± 9	135 ± 18	303 ± 24	670 ± 33	1791 ± 52
	LL	25 ± 7	83 ± 12	174 ± 18	346 ± 25	

Mass fit: $B_S^0 \rightarrow K_S^0 p \bar{p}$

- Mass fit the B candidate invariant mass for $B_S^0 \rightarrow K_S^0 p \bar{p}$ decay

PDFs:

- Combinatorial: Exponential function
- Partial reconstructed: Argus $\otimes$ Gauss function
- Signal and B^0 : Double-side Crystal ball

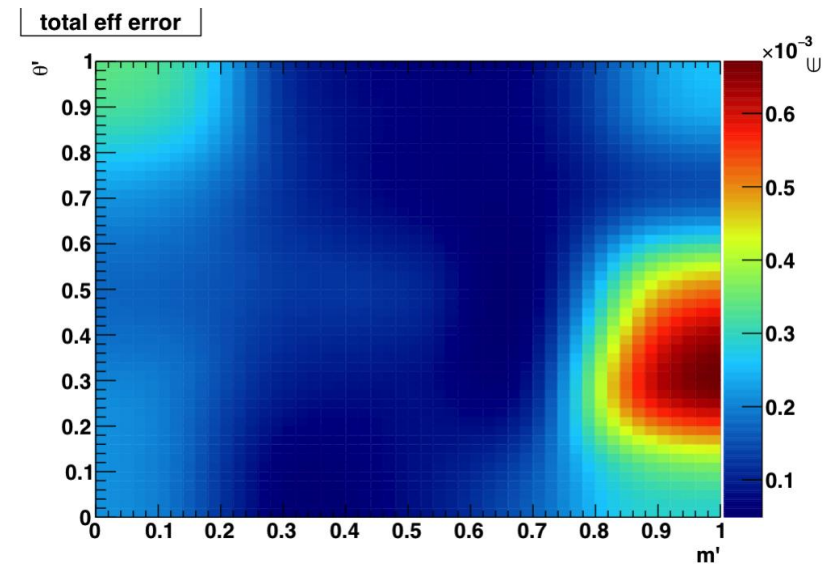
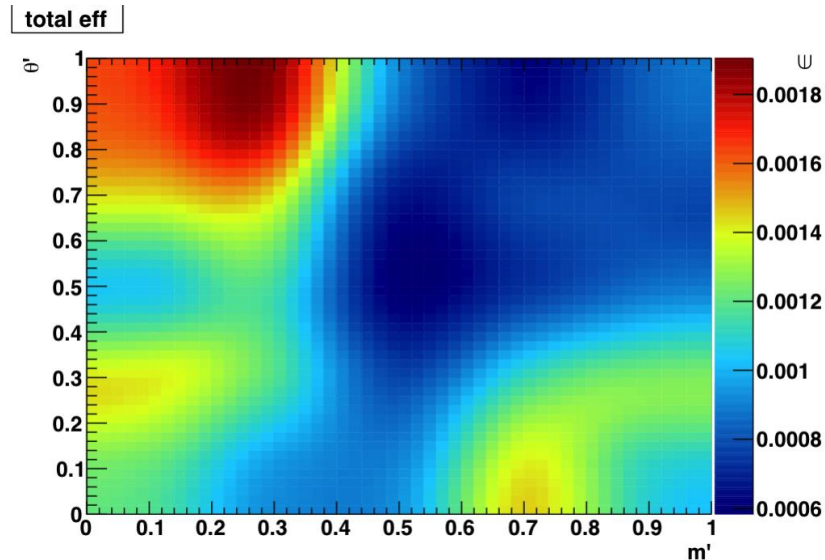


The total yield of $B_S^0 \rightarrow K_S^0 p \bar{p}$, combining the LL and DD K_S^0 reconstruction types, is found to be 66 ± 12 with the all selection, corresponding to the yield to statistical uncertainty in excess of 7.1 standard deviations.

- The total efficiency is obtained by multiplying together the values of the spline for the each contribution at the given point in the plot

$$\mathcal{E} = \varepsilon^{geom} \times \varepsilon^{Sel|geom} \times \varepsilon^{PID|Sel\&geom}$$

- The two-dimensional of total efficiency and its uncertainties are shown in the below



- The average efficiency, obtained from the uniformly binning and sWeight reweighting, as described in this equation

$$\varepsilon^{sel} = \frac{\sum_e W_e}{\sum_e \varepsilon_{e(j)}}$$

where W_e is the signal weight associated to the candidate e , while $\varepsilon_{e(j)}$ represents the efficiency of candidate e , from the corresponding bin j in the squared Dalitz plot

- The result of efficiency are summarized in this table, along with their respective uncertainties

		2011(%)	2012(%)	2015 and 2016(%)	2017 and 2018(%)
$B^0 \rightarrow K_S^0 p \bar{p}$	DD	0.092 ± 0.005	0.096 ± 0.007	0.181 ± 0.006	0.200 ± 0.006
	LL	0.052 ± 0.005	0.057 ± 0.006	0.085 ± 0.004	0.076 ± 0.004
$B^0 \rightarrow K_S^0 \pi^+ \pi^-$	DD	0.102 ± 0.006	0.105 ± 0.008	0.160 ± 0.006	0.160 ± 0.006
	LL	0.082 ± 0.006	0.062 ± 0.005	0.104 ± 0.004	0.104 ± 0.004
$B_S^0 \rightarrow K_S^0 p \bar{p}$	DD	0.084 ± 0.006			
	LL	0.034 ± 0.004			

◆ The systematic uncertainties

- Fit model (Toy experiment)
- Simulation sample size (MC)
- Binning scheme (the two-dim efficiency maps)
- PID (control sample and differ from the signal tracks)
- Tracking
- L0: sample statistics and sources of calibration samples**
- BDT selection: choice of working point
- Mass veto: choice of Veto region
- B_s^0 lifetime: affects the selection efficiency

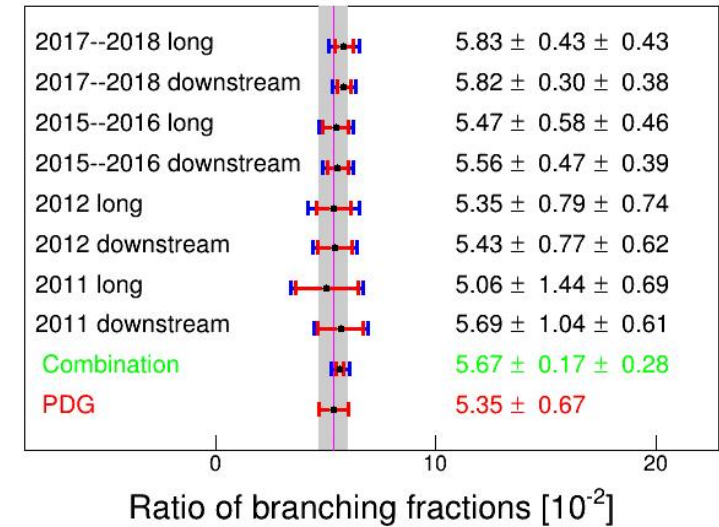
	$\frac{\mathcal{B}(B^0 \rightarrow K_S^0 p \bar{p})}{\mathcal{B}(B^0 \rightarrow K_S^0 \pi^+ \pi^-)}$	$\frac{\mathcal{B}(B_s^0 \rightarrow K_S^0 p \bar{p})}{\mathcal{B}(B^0 \rightarrow K_S^0 \pi^+ \pi^-)}$
Statistical	3.0%	18.4%
Fit model	1.0%	4.7%
Simulation sample size	1.7%	5.5%
Binning	2.4%	2.6%
PID	1.1%	1.2%
Tracking	0.5%	0.5%
L0 trigger	3.6%	5.5%
BDT selection	0.9%	1.2%
Mass veto	0.7%	1.8%
B_s^0 lifetime	—	3.1%
Total systematic	5.0%	9.8%
f_s/f_d	—	2.2%

- By comparison, found that this results were within the margin of error of the previous results

$$\text{BF}(B^0 \rightarrow K^0 \pi^+ \pi^-) = (4.97 \pm 0.18) \times 10^{-5} \text{ from PDG}$$

$$\checkmark \text{BF}(B^0 \rightarrow K^0 p \bar{p}) = (2.82 \pm 0.08 \pm 0.12 \pm 0.10(\text{PDG})) \times 10^{-6}$$

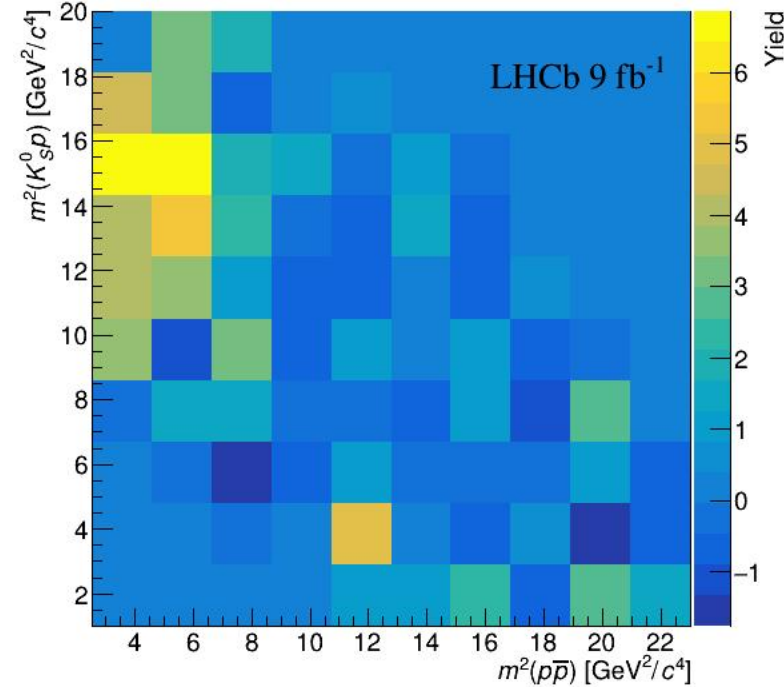
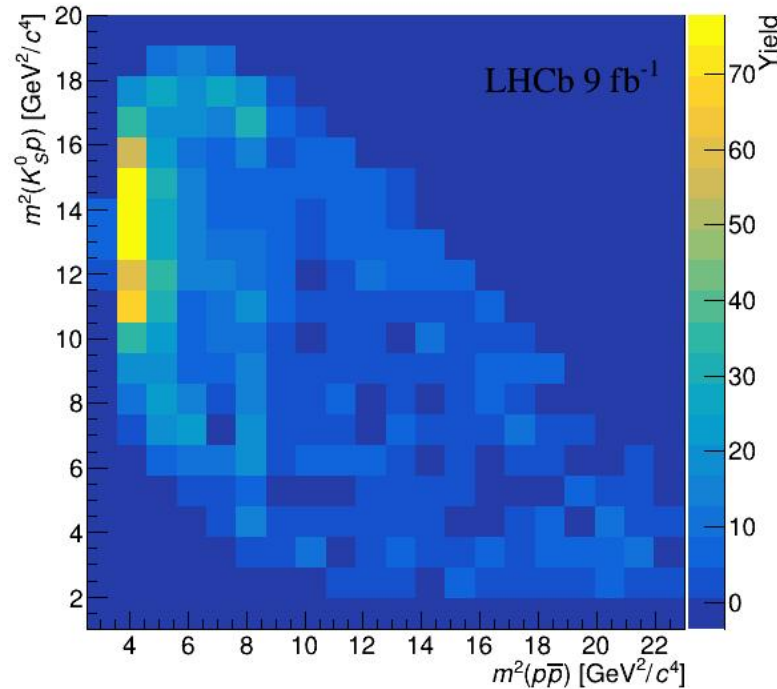
$$\checkmark \text{BF}(B_S^0 \rightarrow K^0 p \bar{p}) = (9.14 \pm 1.69 \pm 0.90 \pm 0.33(\text{PDG}) \pm 0.20(\frac{f_s}{f_d})) \times 10^{-7}$$



$$B^0 \rightarrow K_S^0 p \bar{p}$$

where the first uncertainty is statistical, the second systematic in each case, the third originates from the PDG and the finally originates from ratio of fragmentation fractions of the B^0 and B_S^0 mesons, $\frac{f_s}{f_d}$

- By checked the signal $p\bar{p}$ and $K_S^0 p$ Dalita-plot



The left is $B^0 \rightarrow K_S^0 p\bar{p}$ and right is $B_S^0 \rightarrow K_S^0 p\bar{p}$

Although the current statistics are limited, particularly for $B_S^0 \rightarrow K_S^0 p\bar{p}$ decays, a **clear low-mass enhancement** is observed in the baryon-antibaryon invariant mass spectra

➤ Summary

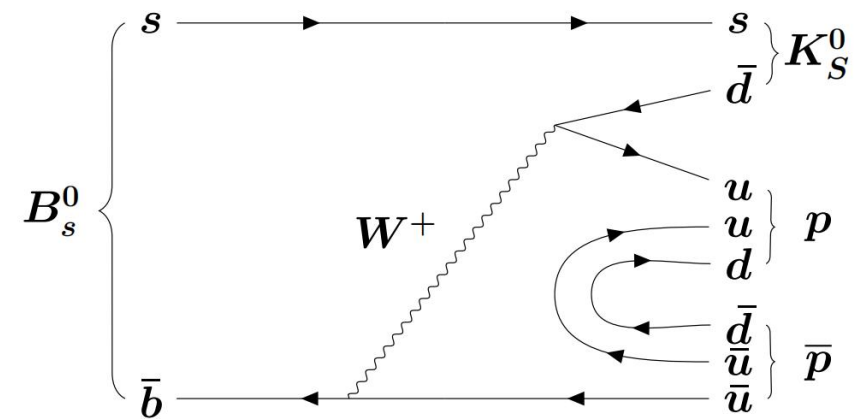
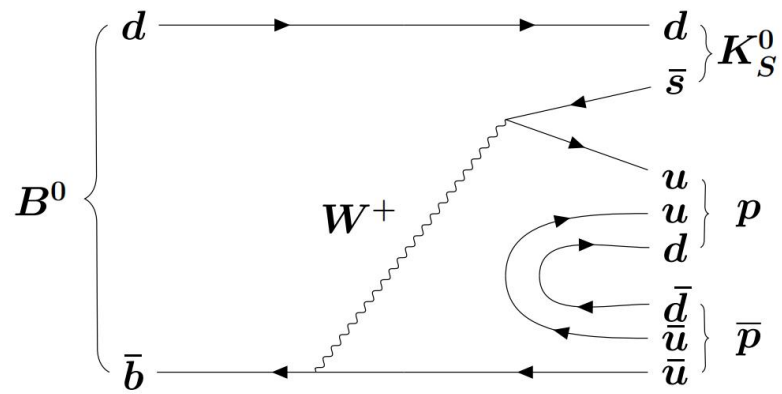
- $B_S^0 \rightarrow K^0 p \bar{p}$ is observed for the first time, with a measured branching fraction of $(9.14 \pm 1.69 \pm 0.90 \pm 0.33(\text{PDG}) \pm 0.20(\frac{f_s}{f_d})) \times 10^{-7}$ and a significance of 5.6σ
- $B^0 \rightarrow K^0 p \bar{p}$ is $(2.82 \pm 0.08 \pm 0.12 \pm 0.10(\text{PDG})) \times 10^{-6}$, which is the most precise measurement to date
- A clear low-mass enhancement in the baryon-antibaryon invariant mass spectra, but this result was not shown in the paper
- Published to JHEP

➤ Outlook

- With higher statistics with Run3, the uncertainty is reduced by a factor of 1.5
- Time-dependent dalitz analyses with Run3 datasets

Back up

Introduction: $B_{(s)}^0 \rightarrow K_S^0 p \bar{p}$



$$\varepsilon = \varepsilon^{\text{Geom}} \times \varepsilon^{\text{Reco}} \times \varepsilon^{\text{Trac}} \times \varepsilon^{\text{PID}} \times \varepsilon^{\text{Trig}} \times \varepsilon^{\text{MVA}} \times \varepsilon^{\text{Veto}}$$

◆ $\varepsilon^{\text{Geom}}$ can be estimated using the Gauss, with the fiducial cuts defined

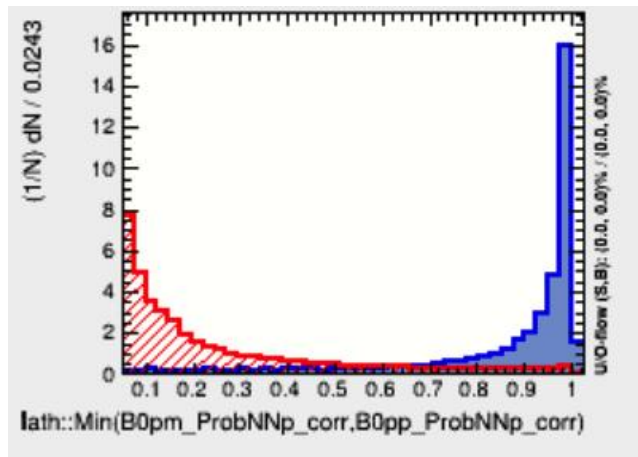
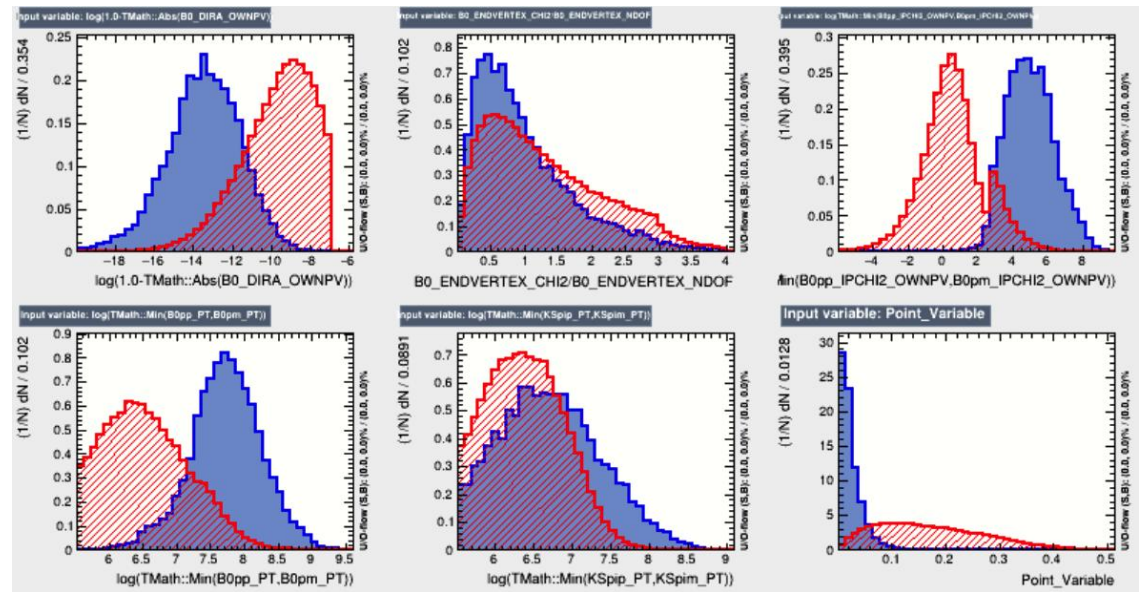
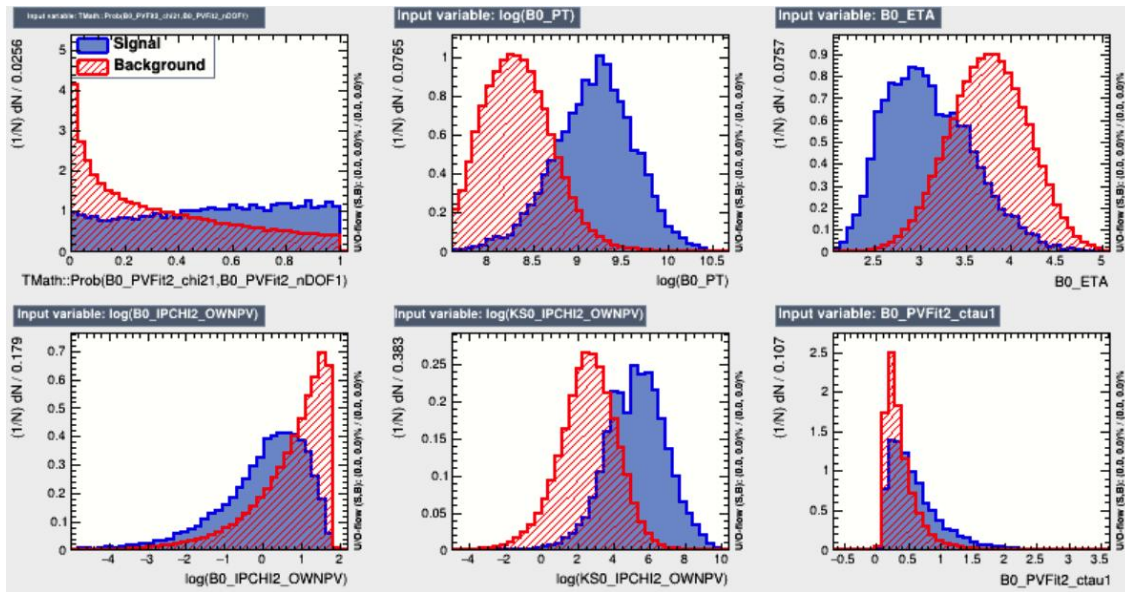
The fiducial cuts can be defined as:

- a) all charged particles in the θ region of 0.01 to 0.4 (cut in DecFiles)
- b) mother particle (B) in the rapidity region 2 to 4.5
- c) mother particle (B)' P_T in the region 2 to 40 GeV

$$\varepsilon^{\text{Geom}} = \frac{n(\text{Reco by Gauss passed fiducial cuts})}{n(\text{Reco by Gauss passed b + c})}$$

Trigger selection

Trigger level		Trigger requirements
L0		L0Hadron TOS OR Muon,Dimuon,MuonHigh,Electron,Hadron,CAL0,Photon TIS
HLT1	Run I	Hlt1TrackAllL0 TOS
	Run II	Hlt1TrackMVA,TwoTrackMVA TOS
HLT2	2011	Hlt2Topo2,3,4BBDT,Simple TOS
	2012	Hlt2Topo2,3,4BBDT TOS
	Run II	Hlt2Topo2,3,4Body TOS



Background: high sideband of data
(5450—5800 MeV/ c^2) and random
selection by random number (30%)
Signal: MC ($5279.65 \pm 3\sigma$)

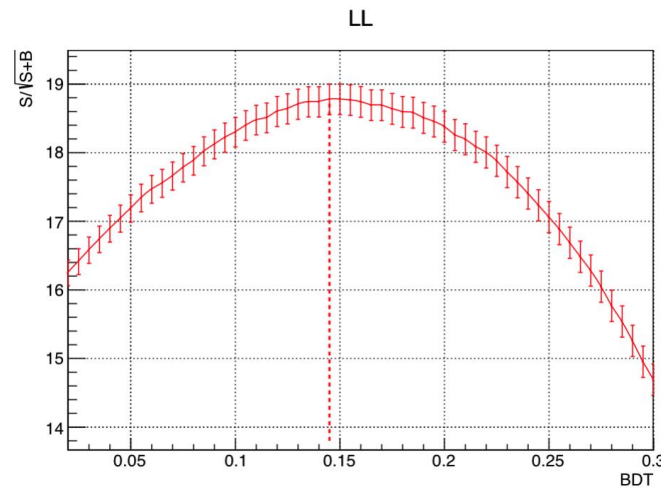
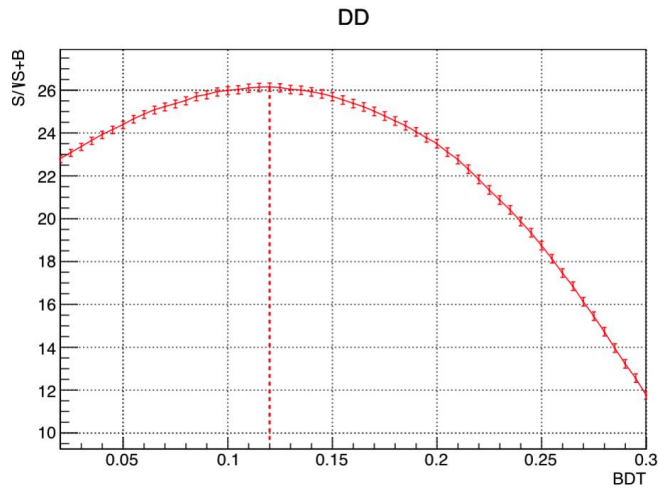
DD: 5234.14—5325.16 MeV/ c^2
LL: 5231.27—5328.03 MeV/ c^2

f_{Nsig} : a scale factor for signal MC

N_{signal} : the number of MC passed loose BDT

B: the number of background events, estimated from extrapolating of the selected background yields in the high sideband region

$$FoM = \frac{S}{\sqrt{S+B}} = \frac{f_{Nsig} * N_{signal}}{\sqrt{f_{Nsig} * N_{signal} + B}}$$



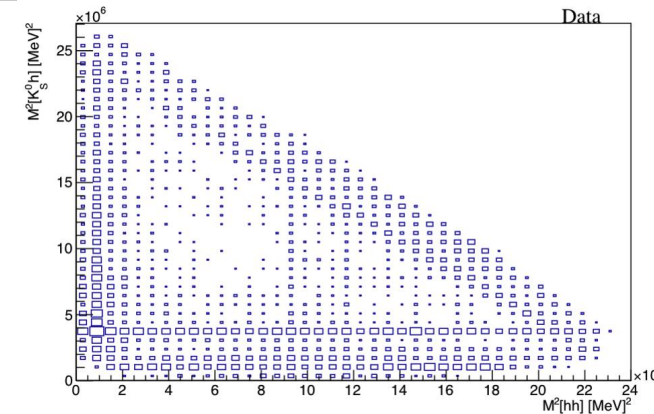
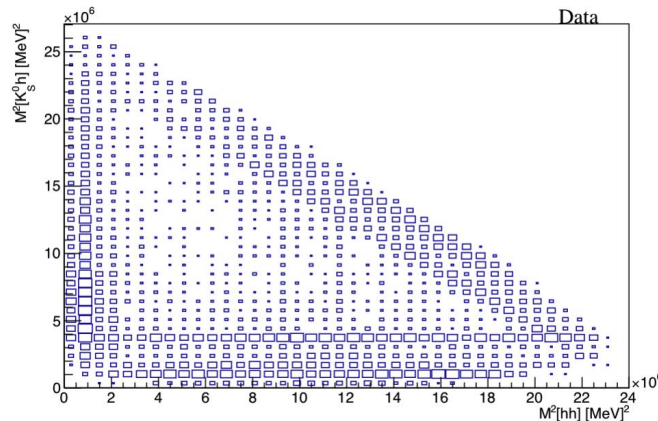
2015 and 2016

Samples	K_S^0 type	S	B	FoM	Working point
2011 and 2012	DD	369.3	108.3	16.900	0.125
	LL	200.2	916.5	12.683	0.105
2015 and 2016	DD	812.5	153.7	26.138	0.120
	LL	395.6	48.2	18.778	0.145
2017 and 2018	DD	1553.7	300.7	36.080	0.135
	LL	765.6	143.2	25.395	0.110

Mass Veto selection: $B^0 \rightarrow K_S^0 \pi^+ \pi^-$

- $B^0 \rightarrow K_S^0 \pi^+ \pi^-$: intermediate charm or charmonium states such as $D^0, D^+, D_s^+, \Lambda_c^+$, or J/ψ are considered
- The backgrounds are removed with **veto**es on the invariant masses of various two-body combinations
 - Veto on **charmed** and **baryons**: ± 30
 - Veto on **charmonia**: ± 48

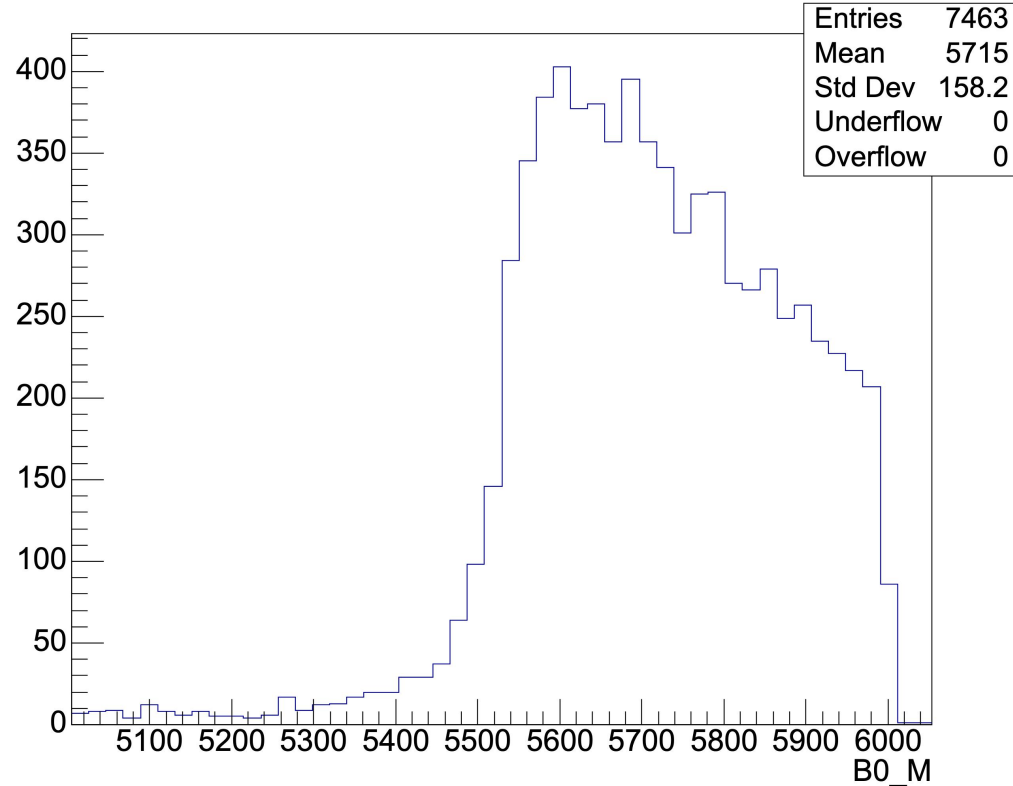
Charm mesons	Charmed Baryons	Charmonia
$D^\pm \rightarrow K_S^0 \pi^\pm, D_s^\pm \rightarrow K_S^0 \pi^\pm$ $D^\pm \rightarrow K_S^0 K^\pm, D_s^\pm \rightarrow K_S^0 K^\pm$ $D^0 \rightarrow K^\pm \pi^\pm$	$\Lambda_c^+ (\bar{\Lambda}_c^-) \rightarrow K_S^0 p (\bar{p})$	$J/\psi \rightarrow \pi^+ \pi^-$ $\chi_{c0} \rightarrow \pi^+ \pi^-$



the left is DD and right is LL

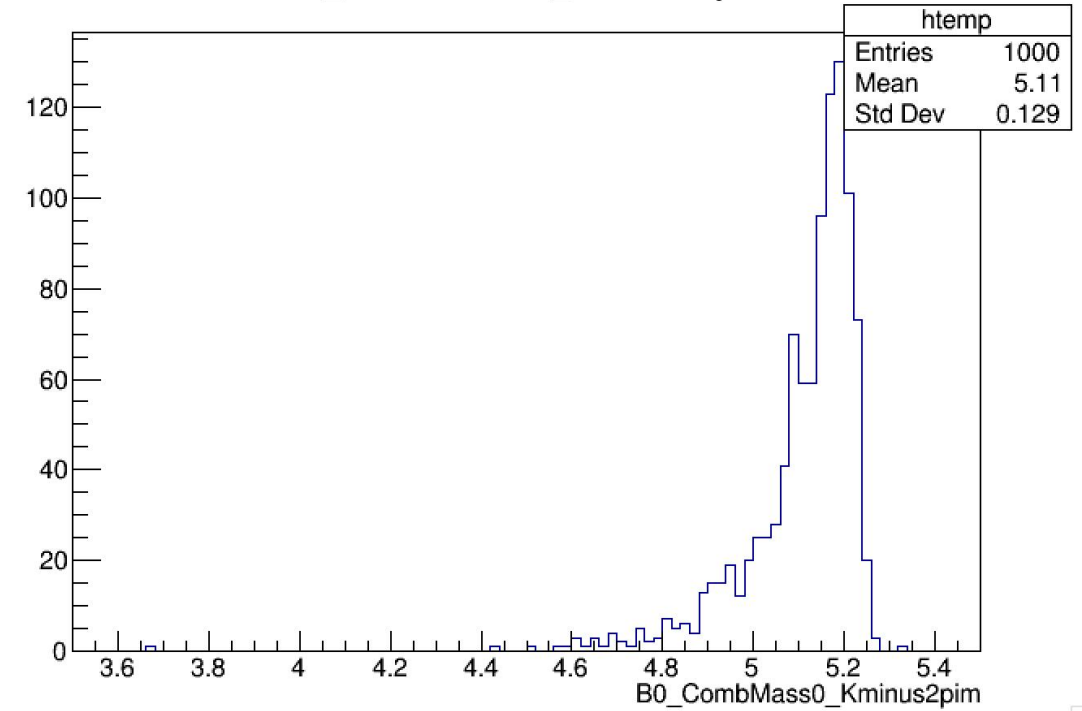
Background study

drawing branch B0_M from DecayTree



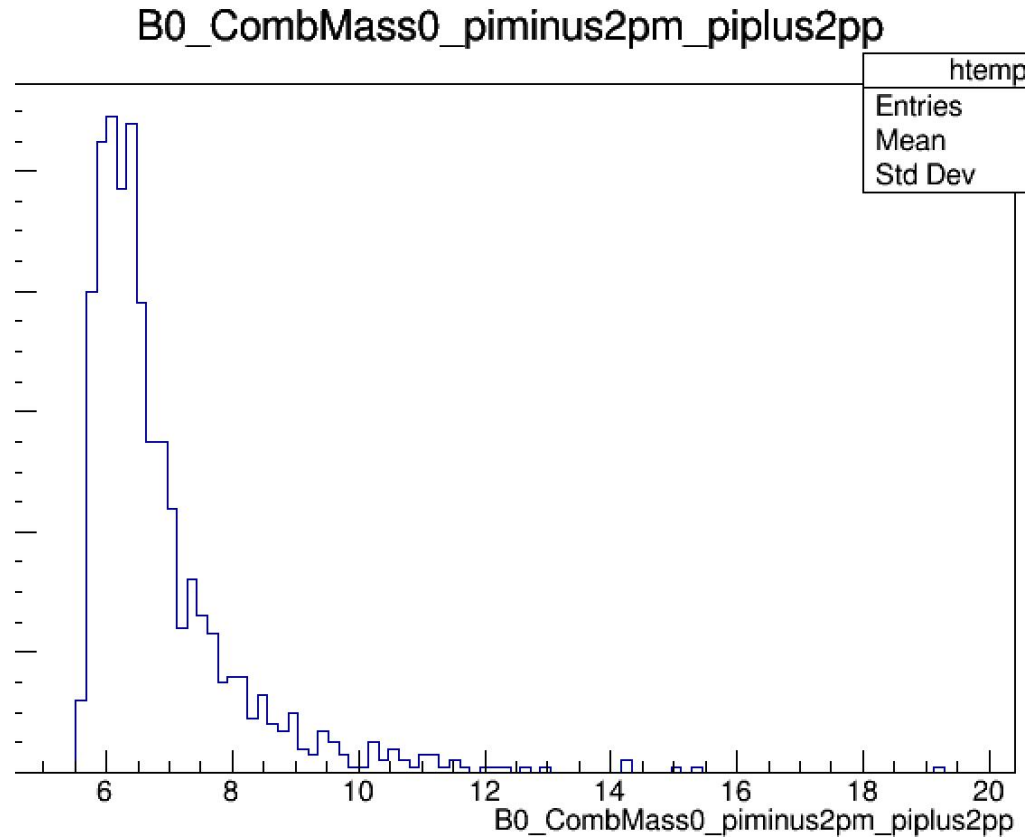
$$B^0 \rightarrow K_S^0 K^+ K^-$$

B0_CombMass0_Kminus2pim

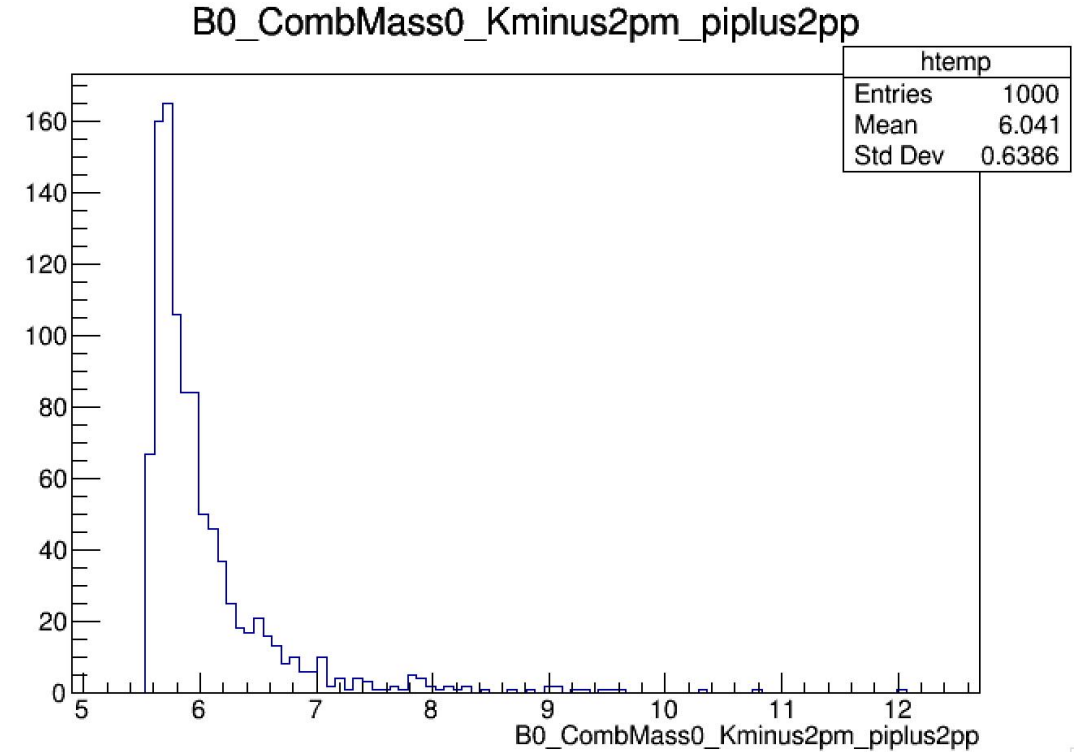


$$B^0 \rightarrow (\Lambda_c^+ \rightarrow K^+ p \pi^-) \bar{p}$$

Background study



$$B^0 \rightarrow K_S^0 \pi^+ \pi^-$$

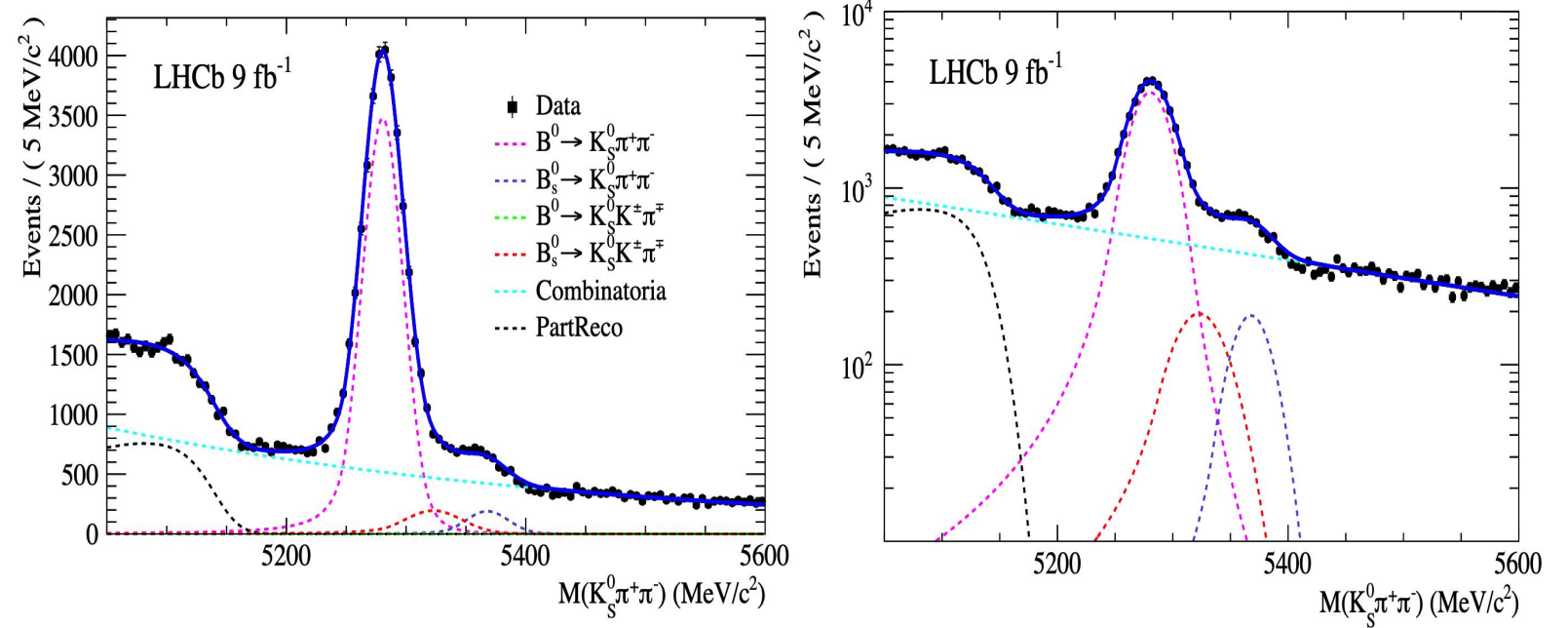


$$B^0 \rightarrow K_S^0 K^+ \pi^-$$

Mass fit: $B^0 \rightarrow K_S^0 \pi^+ \pi^-$

PDFs:

- Combinatorial: Exponential function
- Partial reconstructed: Argus $\otimes$ Gauss function
- Signal and other background: Double-side Crystal ball



	K_S^0 type	2011	2012	2015 and 2016	2017 and 2018	Total
$B^0 \rightarrow K_S^0 \pi^+ \pi^-$	DD	1044 ± 65	2653 ± 96	4794 ± 108	9203 ± 143	32145 ± 230
	LL	772 ± 52	1678 ± 73	3892 ± 85	8109 ± 132	

$$N_{\text{crossfeed}} = N_{B^0 \rightarrow K_S^0 \pi^+ \pi^-} \times \frac{B(B_{(s)}^0 \rightarrow K_S^0 K^\pm \pi^\mp)}{B(B^0 \rightarrow K_S^0 \pi^+ \pi^-)} \times \frac{\varepsilon(B_{(s)}^0 \rightarrow K_S^0 K^\pm \pi^\mp)}{\varepsilon(B^0 \rightarrow K_S^0 \pi^+ \pi^-)} \times \frac{f_{d,s}}{f_d}$$

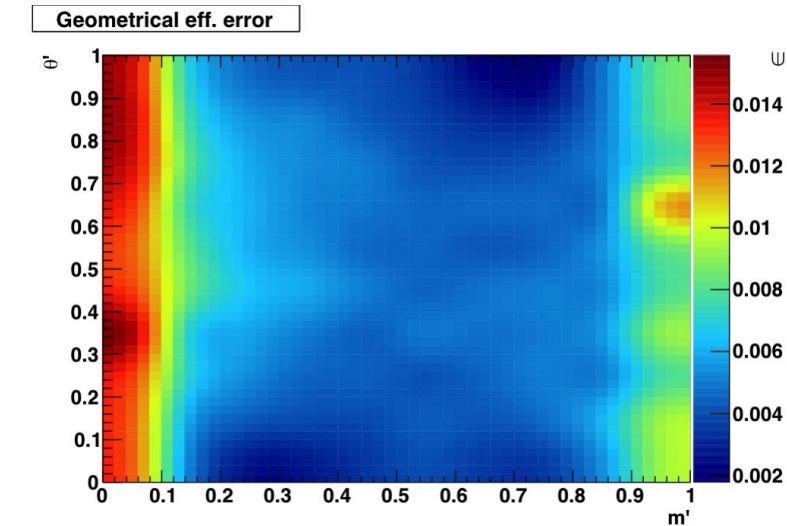
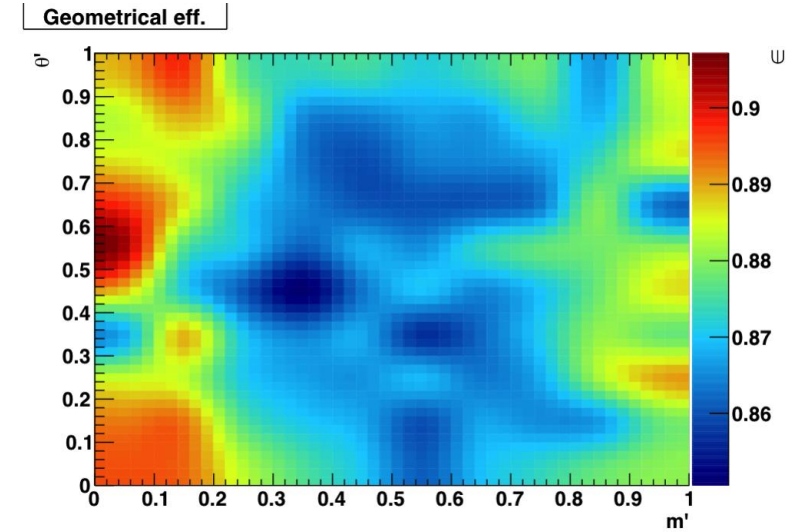
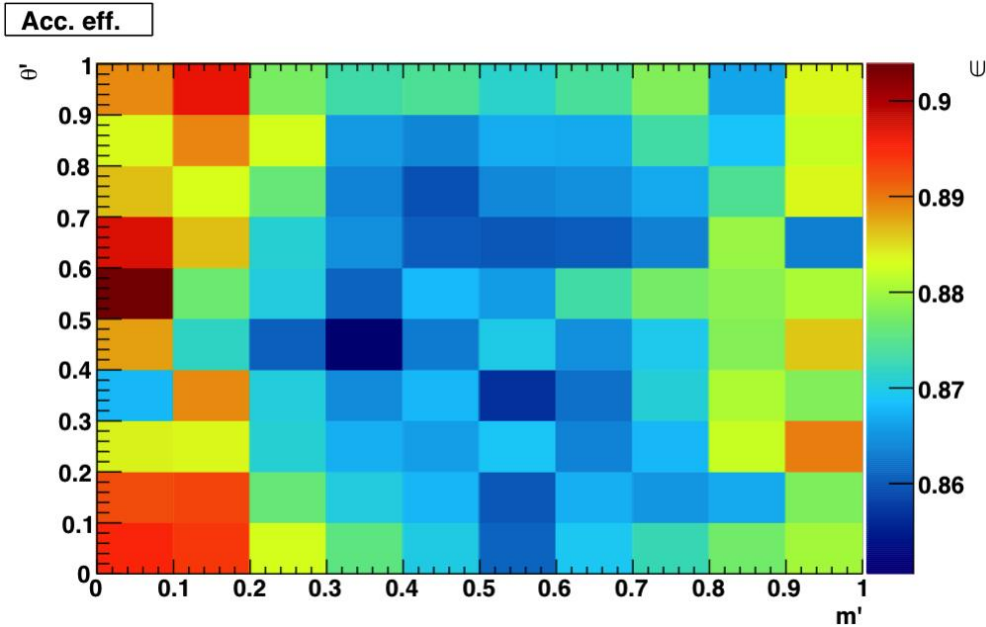
- ◆ The efficiencies depend on the position on the **Dalitz plot**. We extract it from the data using the sPlots method.
- ◆ We apply the concept of a square Dalitz plot (denoted **SDP** in the following).
- ◆ In the following pages:

$$m' = \frac{1}{\pi} \cos^{-1} \left(2 \frac{m_{p\bar{p}} - m_{p\bar{p}}^{\min}}{m_{p\bar{p}}^{\max} - m_{p\bar{p}}^{\min}} - 1 \right)$$

$$\theta' = \frac{1}{\pi} \theta_{p\bar{p}}$$

where $m_{p\bar{p}}$ is the combinational mass, $m_{p\bar{p}}^{\max} = m_{B^0} - m_{K_S^0}$ and $m_{p\bar{p}}^{\min} = m_p + m_{\bar{p}}$ are the boundaries of $m_{p\bar{p}}$, $\theta_{p\bar{p}}$ is the angle between the h^+ and the K_S^0 in the $p\bar{p}$ rest frame.

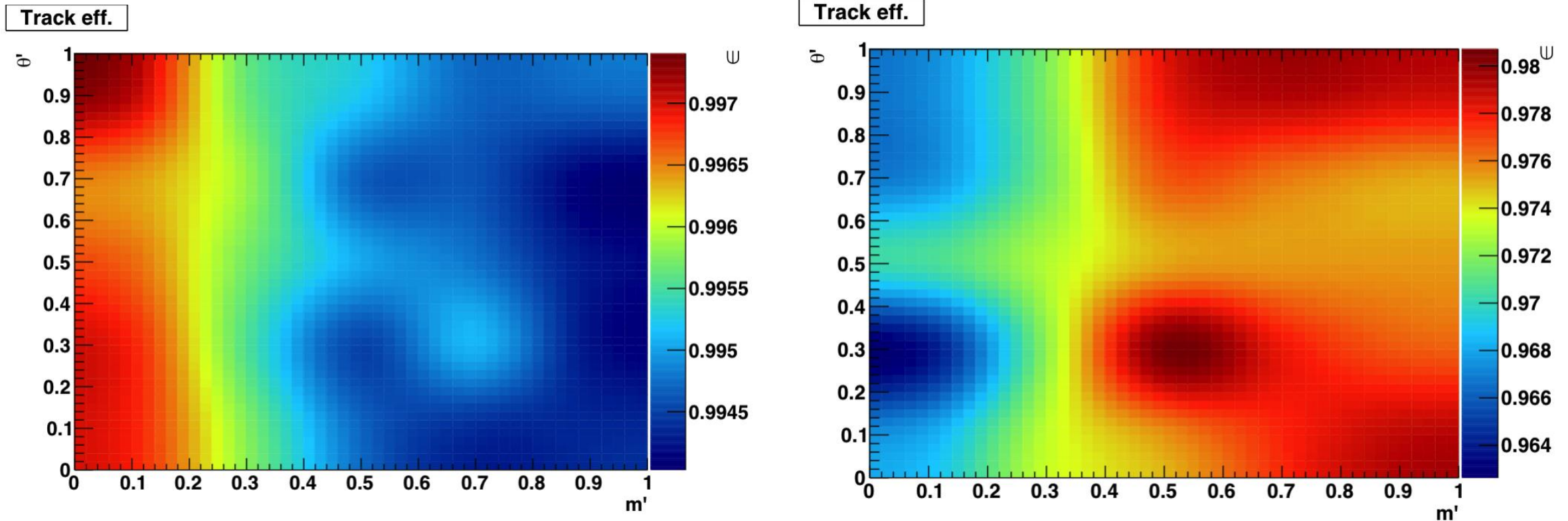
◆ Geometrical efficiency



Uncertainties due to MC statistics by
Clopper – Pearson in the TEfficiency calss

$B^0 \rightarrow K_S^0 p \bar{p}$ for 2015 and 2016

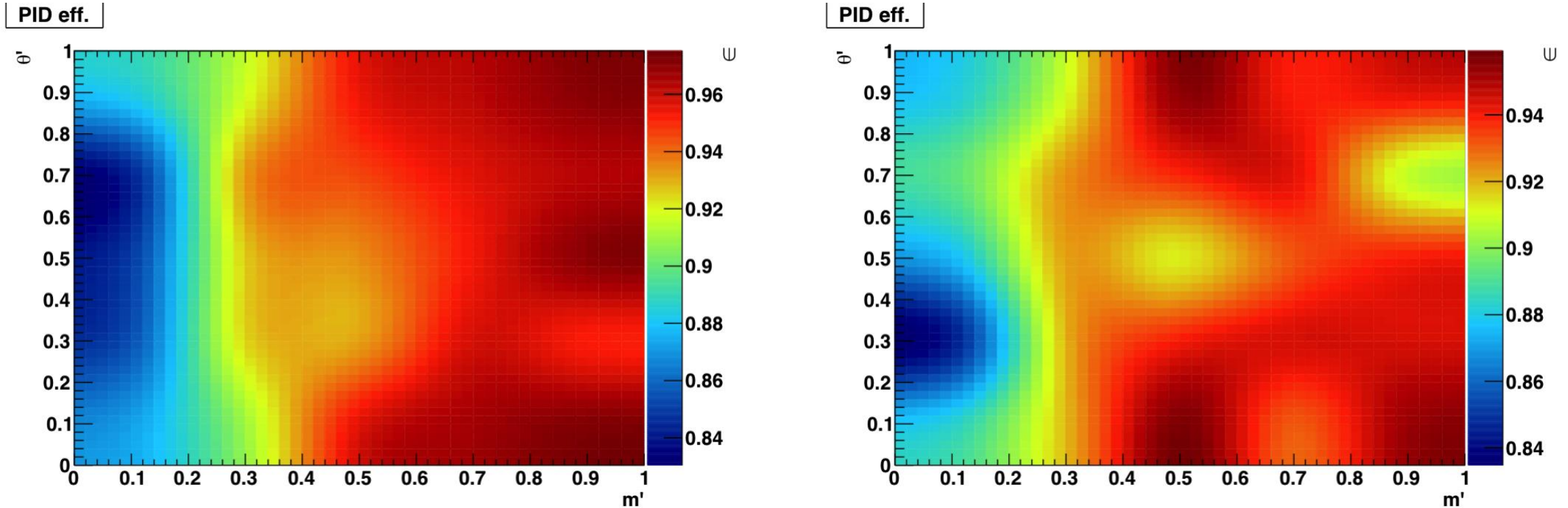
◆ Tracking efficiency



the left is DD and right is LL for 2015 and 2016 to $B^0 \rightarrow K_S^0 p \bar{p}$

- Select the invariant mass region 2.5σ and is weighted to match the sWeighted signal event
- The average correction factor from tracking calibration tables

◆ PID efficiency



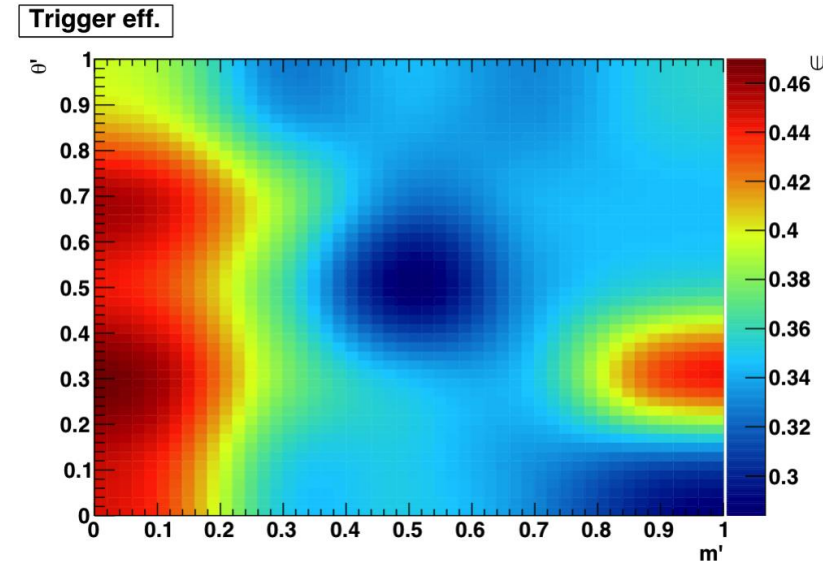
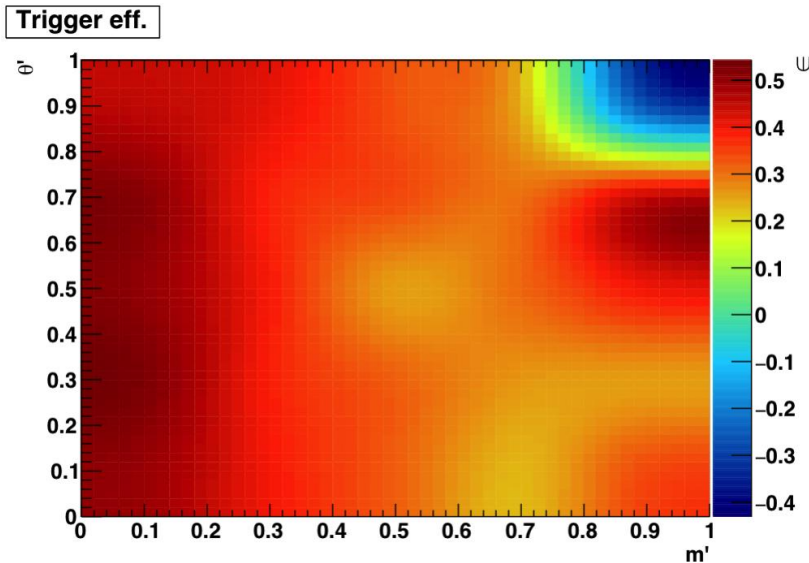
the left is DD and right is LL for 2015 and 2016 to $B^0 \rightarrow K_S^0 p \bar{p}$

- The PID efficiency is determined from calibration data, reweighted to signal kinematics (from MC), using the **PIDCalib2 tool**. The PIDCalib2 multibody tools with the signal MC samples as the reference (specifically **P**, **η** and **nSPDHits**).

Efficiencies

◆ Trigger efficiency

$$\varepsilon^{L0} = \frac{f_{TOS}^{data}}{f_{TOS}^{MC}} \times C_{L0corr}^{TOS} \times \varepsilon_{TOS} + \frac{f_{TIS\&\&TOS}^{data}}{f_{TIS\&\&TOS}^{MC}} \times C_{L0corr}^{TIS\&\&TOS} \times \varepsilon_{TIS\&\&TOS}$$



the left is DD and right is LL for 2015 and 2016 to $B^0 \rightarrow K_S^0 p \bar{p}$

- The f terms are the fractions of each category in data and MC, as labelled ($f_{TOS}^{data} + f_{TIS\&\&TOS}^{data} = f_{TOS}^{MC} + f_{TIS\&\&TOS}^{MC} = 1$),
- C are reweighting factors, which are estimated from the calibration data samples based on reconstructed D^* and Λ_c^- candidates with high purity
- ε are efficiency from MC
- $\varepsilon^{Trig} = \varepsilon^{L0} \times \varepsilon^{HLT}$

Fit model Systematics

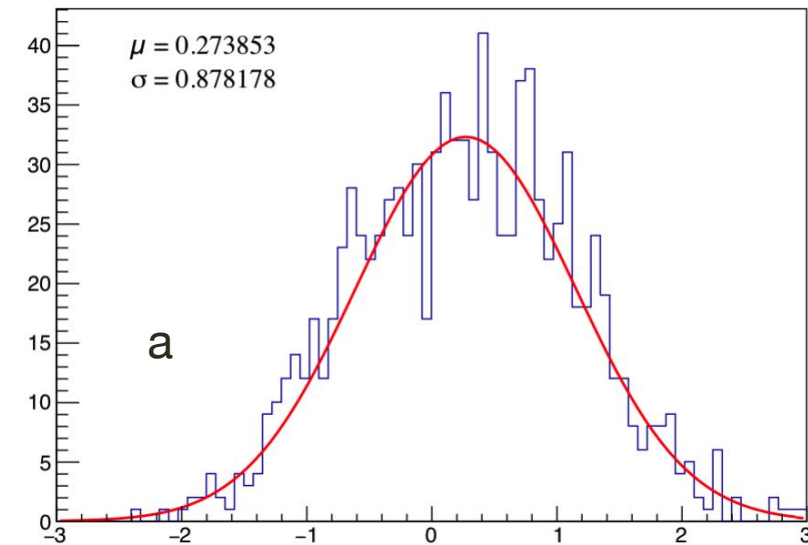
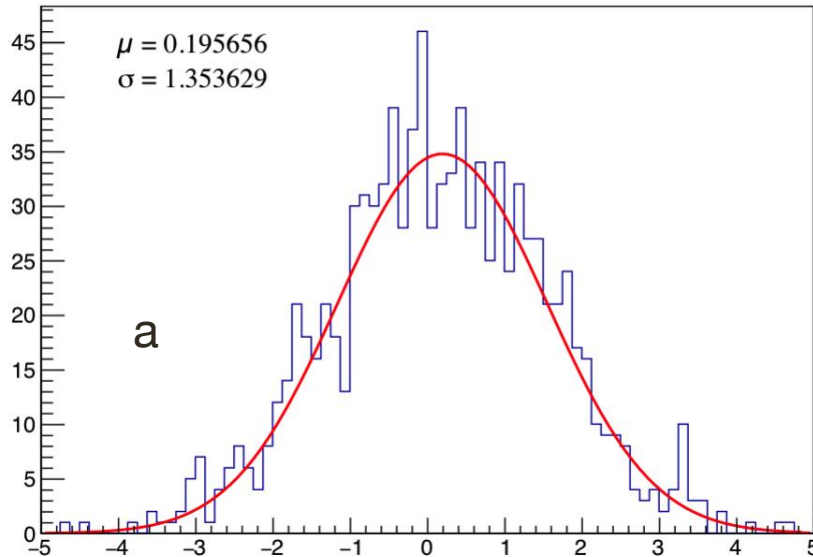
◆ The choice of the models (1000 Toy experiment) $\times$ 100

a) Signal model: Crystal ball $\rightarrow$ *Student* + *Gauss function*

b) Partial reconstructed bkg model: $\begin{cases} \text{Argus} \otimes \text{Gauss function} \\ M(5100 \rightarrow 5600) \end{cases} \rightarrow \begin{cases} \text{Not} \\ M(5150 \rightarrow 5600) \end{cases}$

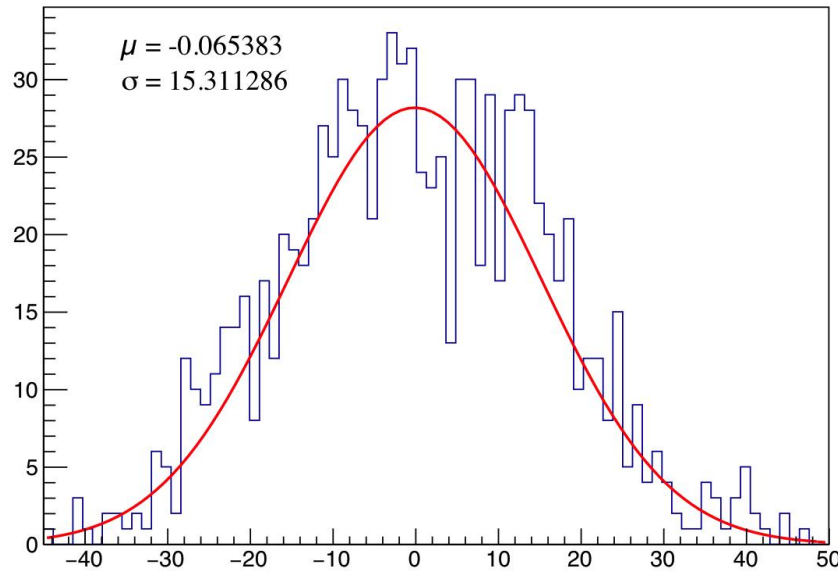
c) Combinatorial bkg model: Exponential function $\rightarrow$ Second order Chebychev polynomial

d) The difference between yields fit by a Gaussian

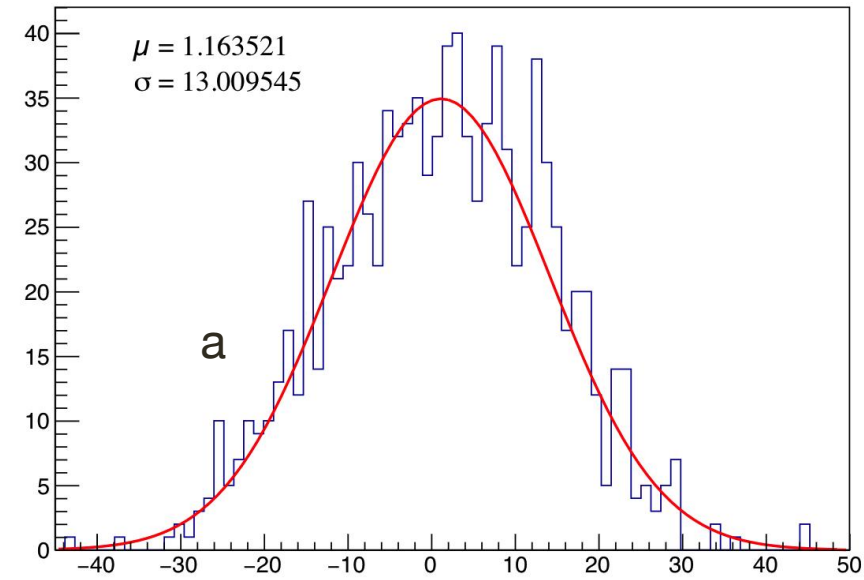


the left is DD and right is LL for 2015 and 2016 to $B^0 \rightarrow K_S^0 p \bar{p}$

- ◆ The choice of the models (1000 Toy experiment) $\times 10$
 - a) Signal model: Crystal ball $\rightarrow$ *Student* + *Gauss function*
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Signal model DD



Signal model LL