Observation of the decay $B_s^0 \to K^0 p\bar{p}$ and measurement of the $B_{(s)}^0 \to K^0 p\bar{p}$ branching fractions

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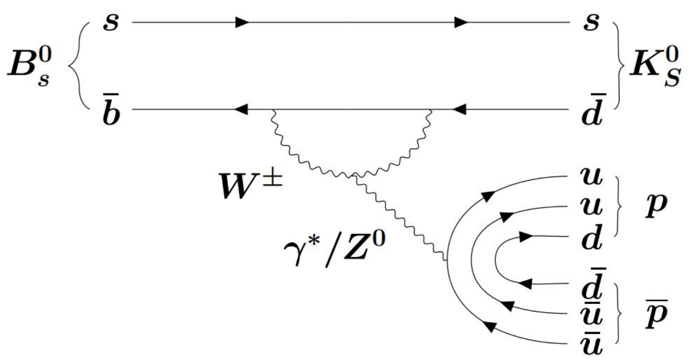
Outline

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

Motivation

- Search for $B_s^0 \to K^0 p\bar{p}$
- Measurement of the $B_{(s)}^0 \to K^0 p\bar{p}$ branching fractions
- Quark decay diagrams:
  - $B^0 \to K^0 p\bar{p}$: $b \to u$ tree and $b \to s$ penguin diagrams
  - $B_s^0 \to K^0 p\bar{p}$: $b \to u$ tree and $b \to d$ 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
- A Key observables for studying CP violation in loop-dominated processes
- A key preparation for furture time-dependent Dalitz analysis

Previous results

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

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

Analysis strategies

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

$$B(B^0_{(s)} \to K^0_S p\bar{p}) = B(B^0 \to K^0_S \pi^+\pi^-) \times \frac{N(B^0_{(s)} \to K^0_S p\bar{p})}{N(B^0 \to K^0_S \pi^+\pi^-)} \times \frac{\varepsilon^{sel}(B^0 \to K^0_S \pi^+\pi^-)}{\varepsilon^{sel}(B^0_{(s)} \to K^0_S p\bar{p})} \times \frac{f_d}{f_{d(s)}}$$

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

Analysis strategies

- Date 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
$B^0 \to K_S^0 p\bar{p}$ (sqDalitz)	11104164
$B_s^0 \to K_S^0 p\bar{p}$ (sqDalitz)	11104124
$B^0 \to K_S^0 \pi^+\pi^-$ (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)

$\Rightarrow$ 8 data samples.

BDT optimization: Punzi ($B_s^0 \to K_S^0 p\bar{p}$)

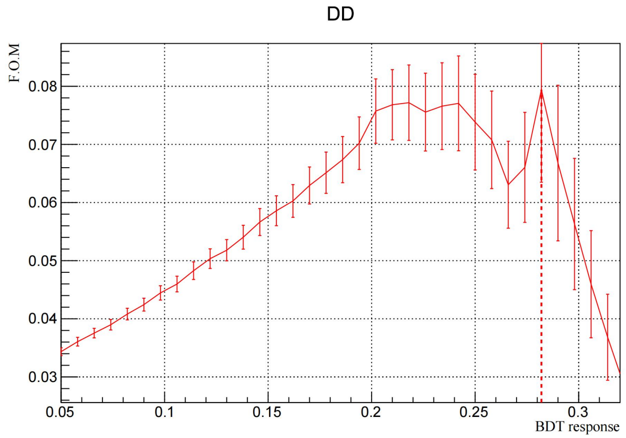
- After the preselection, trigger, and PID, a large amount of background still
- A multivariate analysis (MVA) is employed to further improve the signal-to-background separation
- The selection of the $\mathrm{B_s^0} \to \mathrm{K_S^0 p\bar{p}}$ decay is optimized using the Punzi figure of merit

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

ε_{sig}: signal efficiency estimated by MC samples

a: the excepted 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^+ are seen

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

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

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

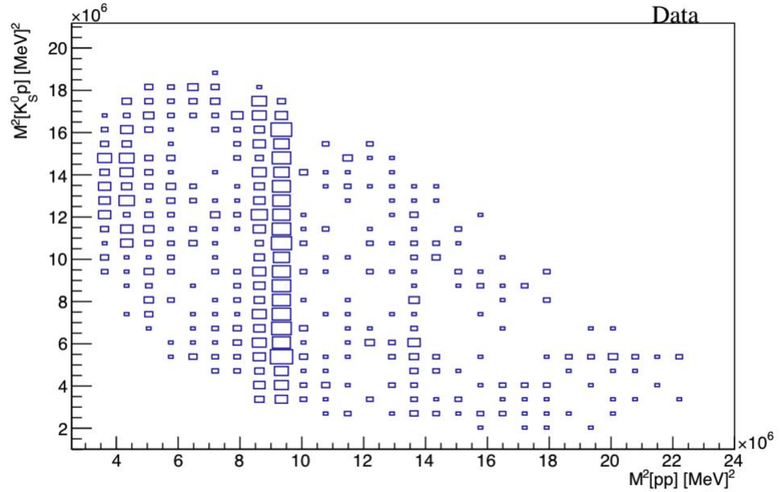
Veto selection $|m(p\bar{p}) - m(J/\psi)| > 25$ MeV/c^2

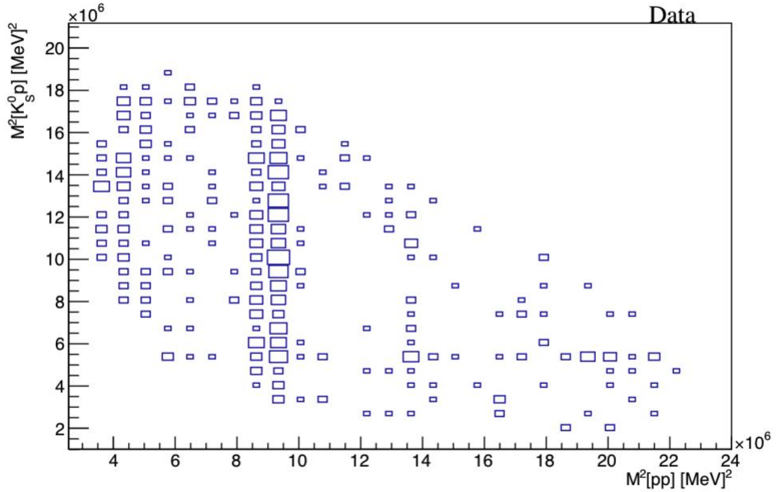
◆ $B^0 \to \psi(2S) K_S^0$ $with\, \psi(2S) \to p\bar{p}$

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

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

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





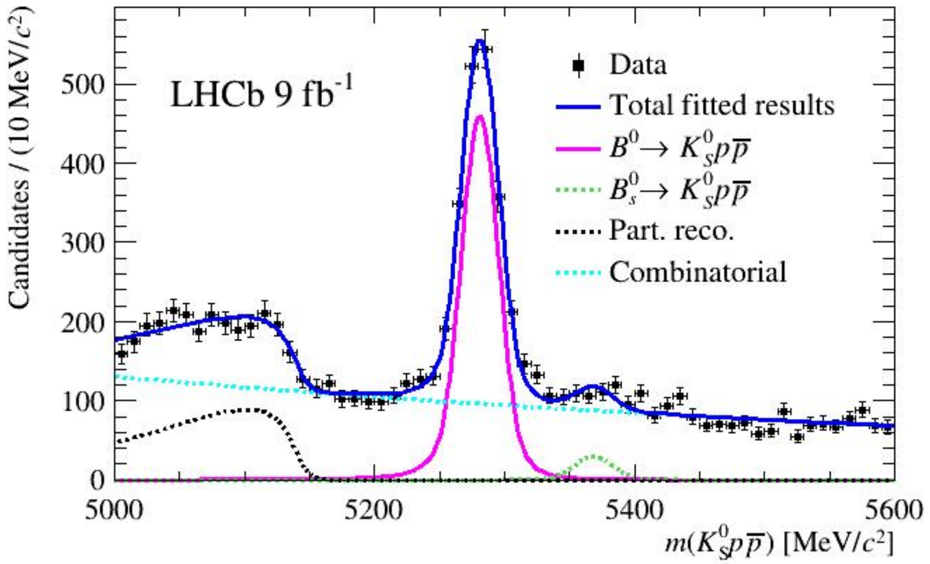
the left is DD and right is LL

Mass fit: $B^0 \to K^0_S p\bar{p}$

- Mass fit the B candidate invariable mass for $B^0 \to K^0_S p\bar{p}$ decay

PDFs:

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



- This table summarizes the signal yield and its statistical

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

Mass fit: $B_s^0 \to K_S^0 p\bar{p}$

➢ Mass fit the B candidate invariable mass for $B_s^0 \to K_S^0 p\bar{p}$ decay

❑ PDFs:

- Combinatorial: Exponential function
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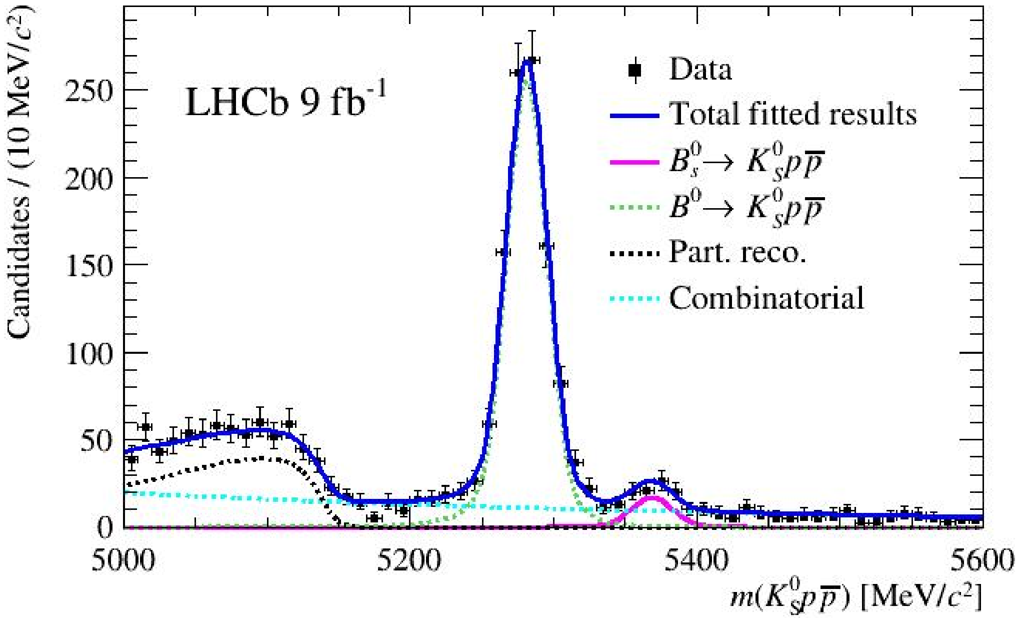


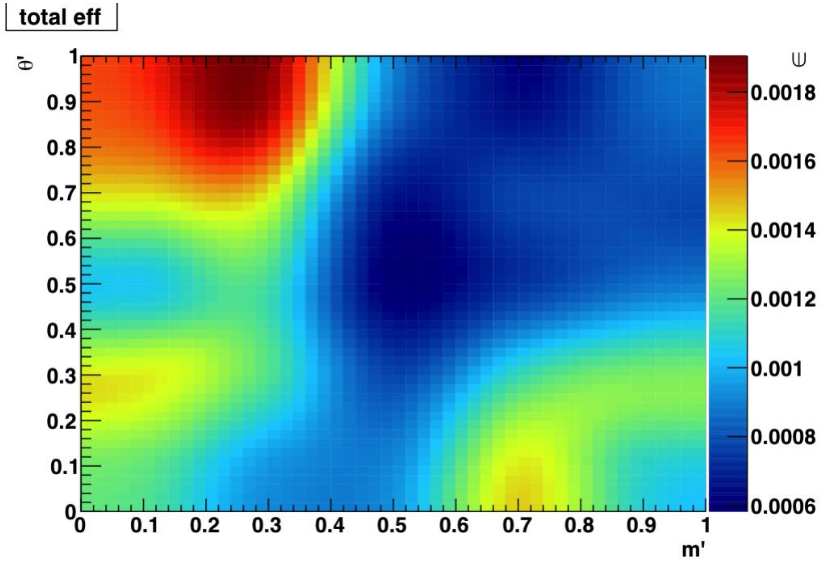
The total yield of $B_s^0 \to K_S^0 p\bar{p}$, combining the LL and DD K_S^0 reconstruction types, is found to be 66 ± 12 with the all selection, corresponding to the yield to statistical uncertainty in excess of 7.1 standard deviations.

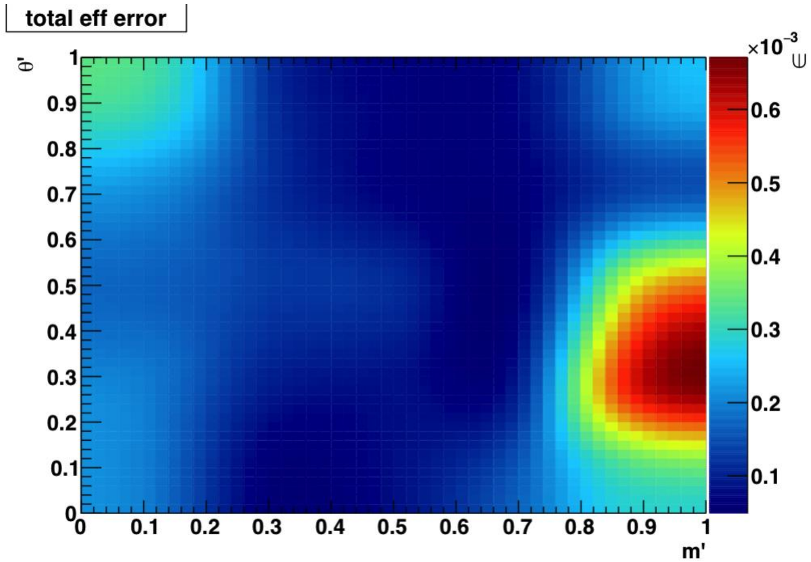
Efficiencies and Uncertainty

- 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





Efficiencies and Uncertainies

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

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

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(%)
$B^0 \to K_S^0 p\bar{p}$	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
$B^0 \to K_S^0 \pi^+\pi^-$	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
$B_s^0 \to K_S^0 p\bar{p}$	DD	0.084 ± 0.006			
	LL	0.034 ± 0.004			

Systematics

- The systematic uncertainties
  a) Fit model (Toy experiment)
  b) Simulation sample size (MC)
  c) Binning scheme (the two-dim efficiency maps)
  d) PID (control sample and differ from the signal tracks)
  e) Tracking
  f) L0: sample statistics and sources of calibration samples
  g) BDT selection: choice of working point
  h) Mass veto: choice of Veto region
  i) B_s^0 lifetime: affects the selection efficiency

	$\frac{\mathcal{B}(B^0 \to K_S^0 p\bar{p})}{\mathcal{B}(B^0 \to K_S^0 \pi^+\pi^-)}$	$\frac{\mathcal{B}(B_s^0 \to K_S^0 p\bar{p})}{\mathcal{B}(B^0 \to K_S^0 \pi^+\pi^-)}$
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%

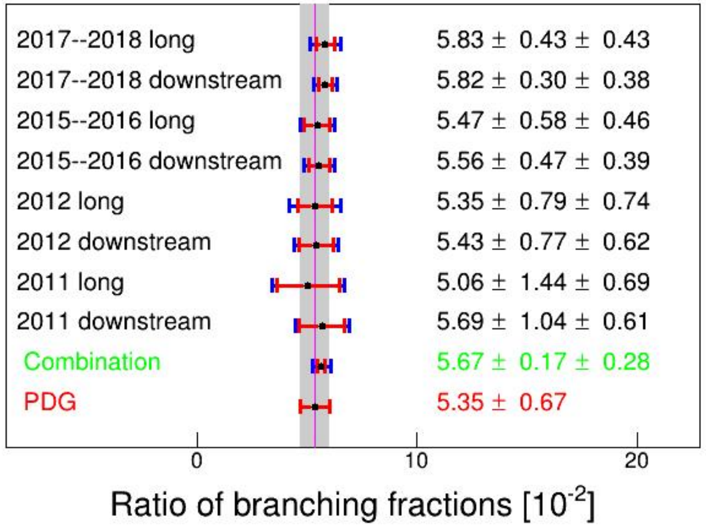
Result

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

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

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

✓ BF($B_s^0 \to K^0 p\bar{p}$) =$(9.14 \pm 1.69 \pm 0.90 \pm 0.33$(PDG) $\pm 0.20(\frac{f_s}{f_d}))\times 10^{-7}$

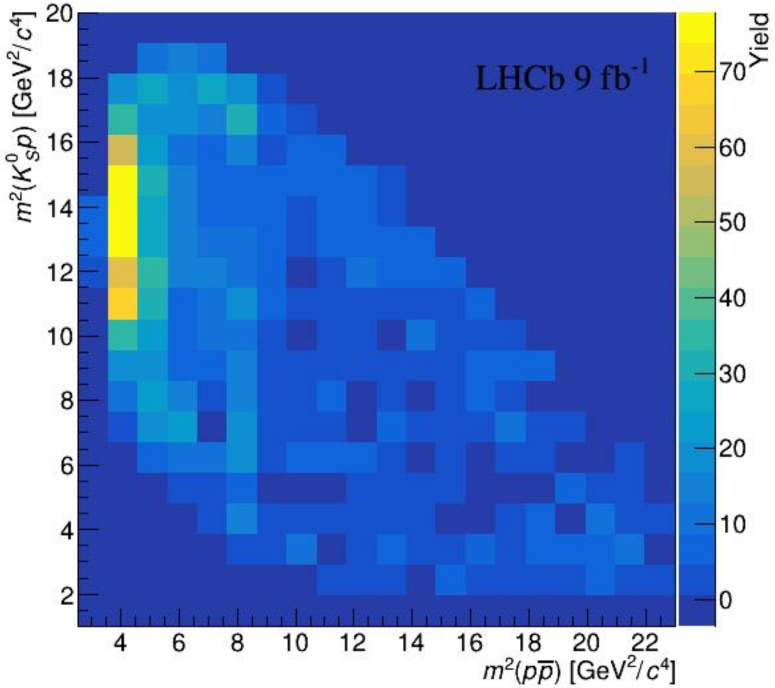


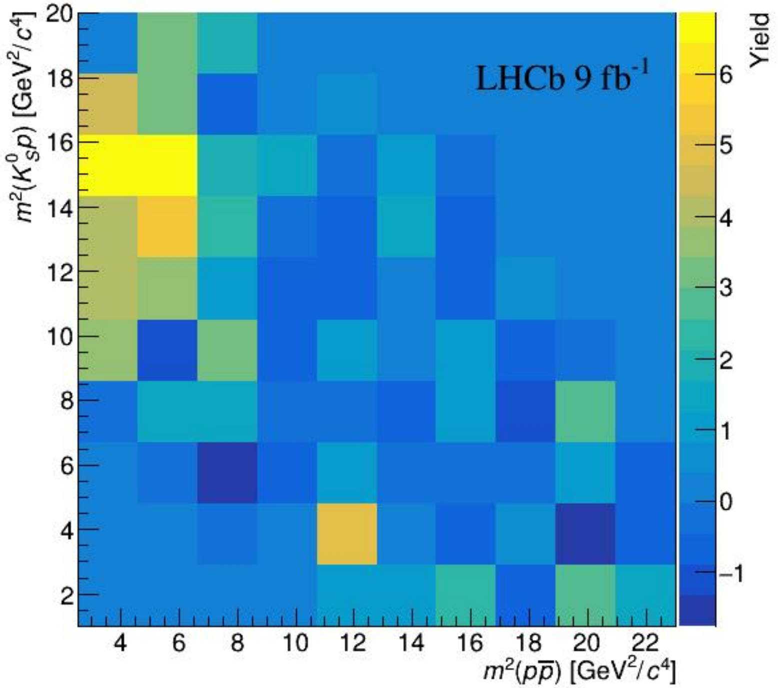
$B^0 \to K_S^0 p\bar{p}$

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, $\frac{f_s}{f_d}$

Check the low-mass enhancement

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





The left is $B^0 \to K_S^0 p\bar{p}$ and right is $B_s^0 \to K_S^0 p\bar{p}$

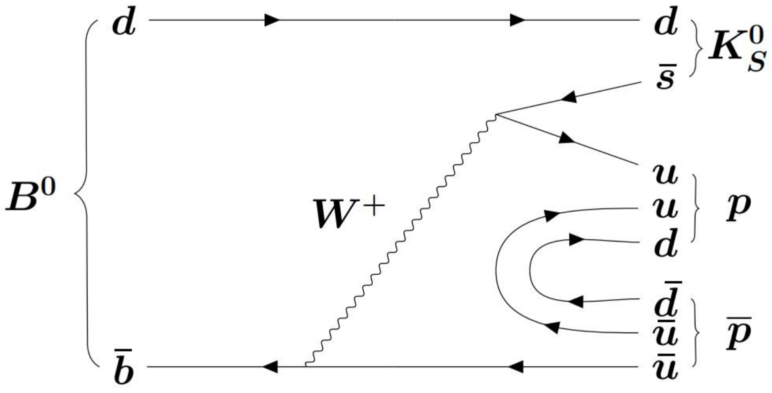
Although the current statistics are limited, particularly for $B_s^0 \to K_S^0 p\bar{p}$ decays, a clear low-mass enhancement is observed in the baryon-antibaryon invariant mass spectra

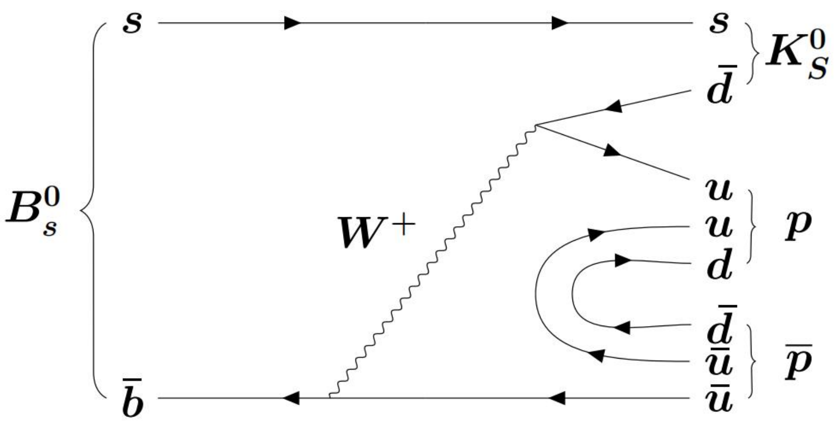
Summary and outlook

- Summary
  - $B_s^0 \to K^0 p\bar{p}$ is observed for the first time, with a measured branching fraction of $(9.14 \pm 1.69 \pm 0.90 \pm 0.33(\mathrm{PDG}) \pm 0.20(\frac{f_s}{f_d})) \times 10^{-7}$ and a significance of 5.6σ
  - $B^0 \to K^0 p\bar{p}$ is $(2.82 \pm 0.08 \pm 0.12 \pm 0.10(\mathrm{PDG})) \times 10^{-6}$, 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: $B^0_{(s)} \to K^0_s p\overline{p}$





Analysis strategy

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

- $\varepsilon^{\mathrm{Geom}}$ 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

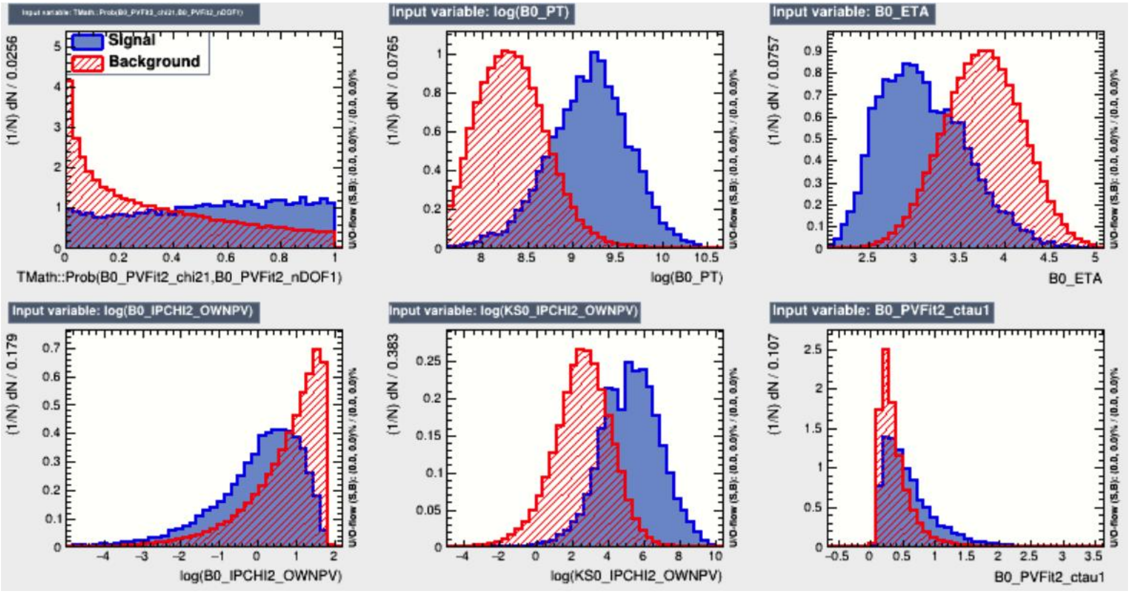
c) mother particle (B)'P_T in the region 2 to 40GeV

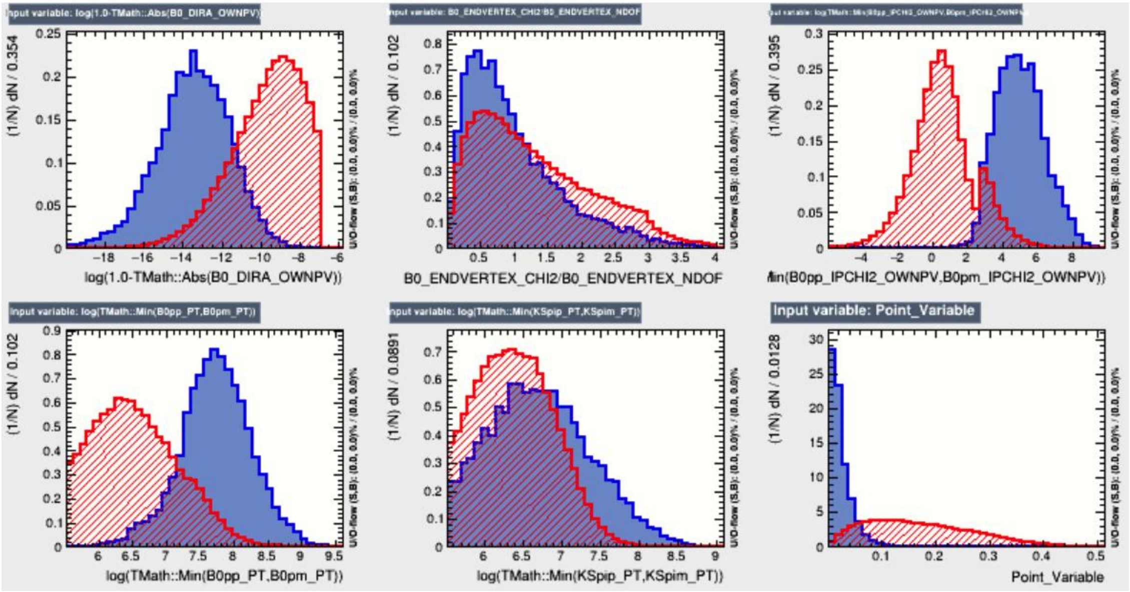
$$\varepsilon^{\mathrm{Geom}} = \frac{n(Reco\ by\ Gauss\ passed\ fiducial\ cuts)}{n(Reco\ by\ Gauss\ passed\ b + c)}$$

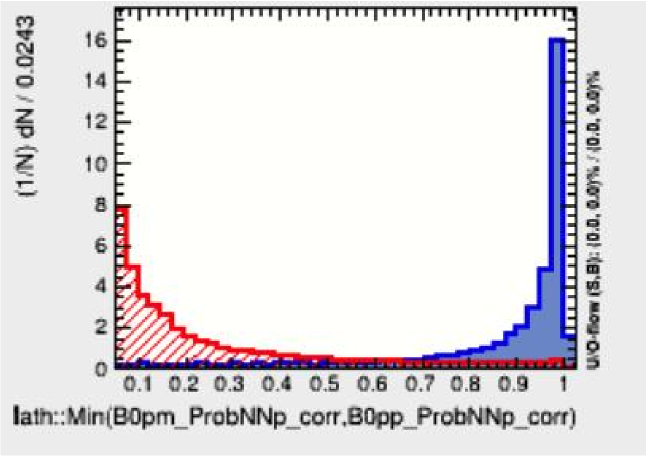
Tigger selection

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

TMVA input variables: DD (2015 and 2016)







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

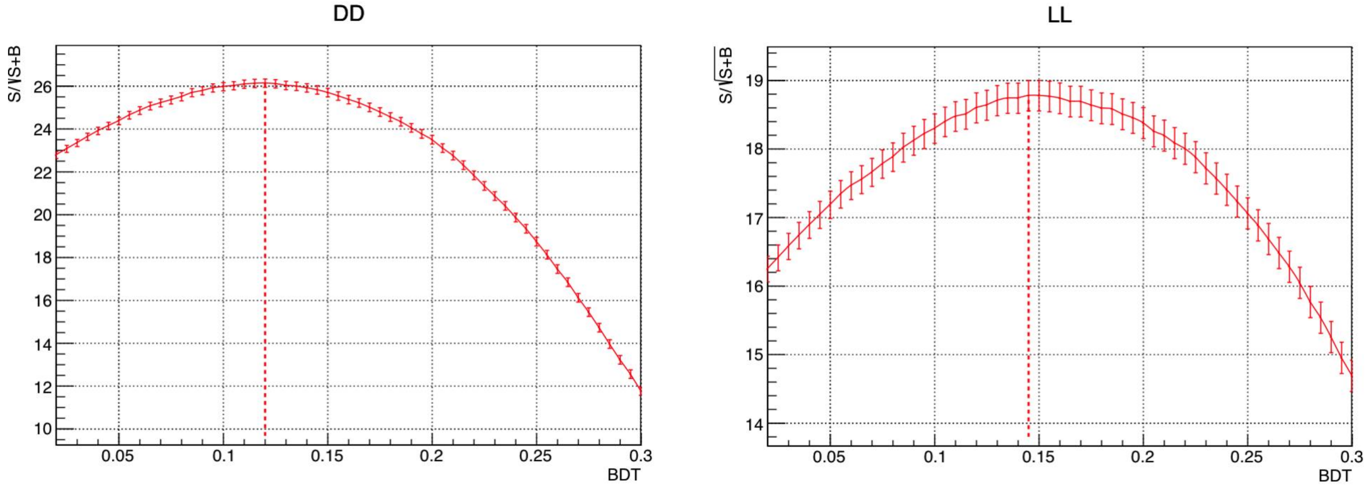
BDT optimization: FoM ($B^0 \to K^0_S p\bar{p}$)

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

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



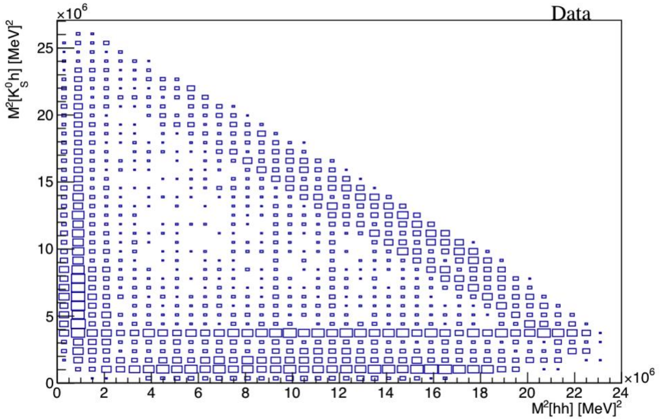
2015 and 2016

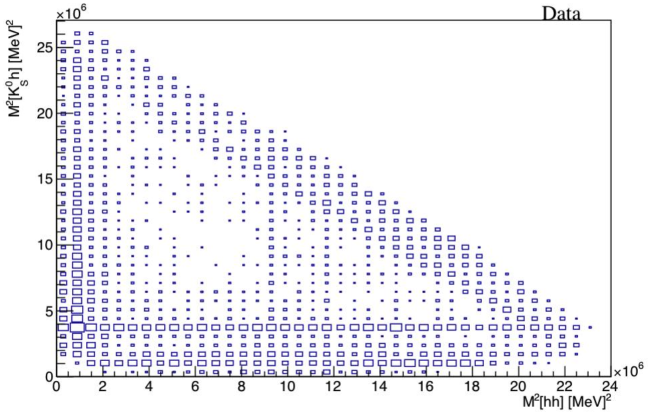
Samples	K^0_S type	S	B	FoM	Working point
2011 and 2012	DD	369.3	108.3	16.900	0.125
	LL	200.2	916.5	12.683	0.105
2015 and 2016	DD	812.5	153.7	26.138	0.120
	LL	395.6	48.2	18.778	0.145
2017 and 2018	DD	1553.7	300.7	36.080	0.135
	LL	765.6	143.2	25.395	0.110

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

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

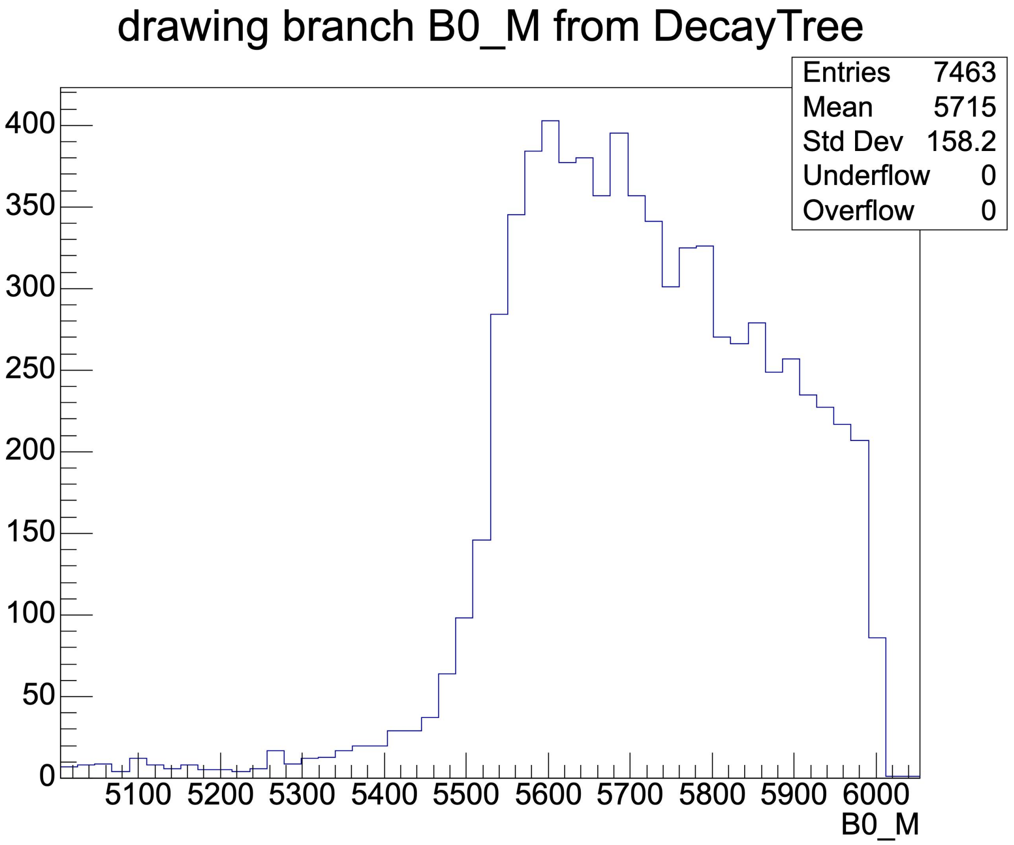
Charm mesons	Charmed Baryons	Charmonia
$D^\pm \to K_S^0\pi^\pm$, $D_s^\pm \to K_S^0\pi^\pm$ $D^\pm \to K_S^0K^\pm$, $D_s^\pm \to K_S^0K^\pm$ $D^0 \to K^\pm\pi^\pm$	$\Lambda_c^+(\overline{\Lambda}_c^-) \to K_S^0 p(\overline{p})$	$J/\psi \to \pi^+\pi^-$ $\chi_{c0} \to \pi^+\pi^-$



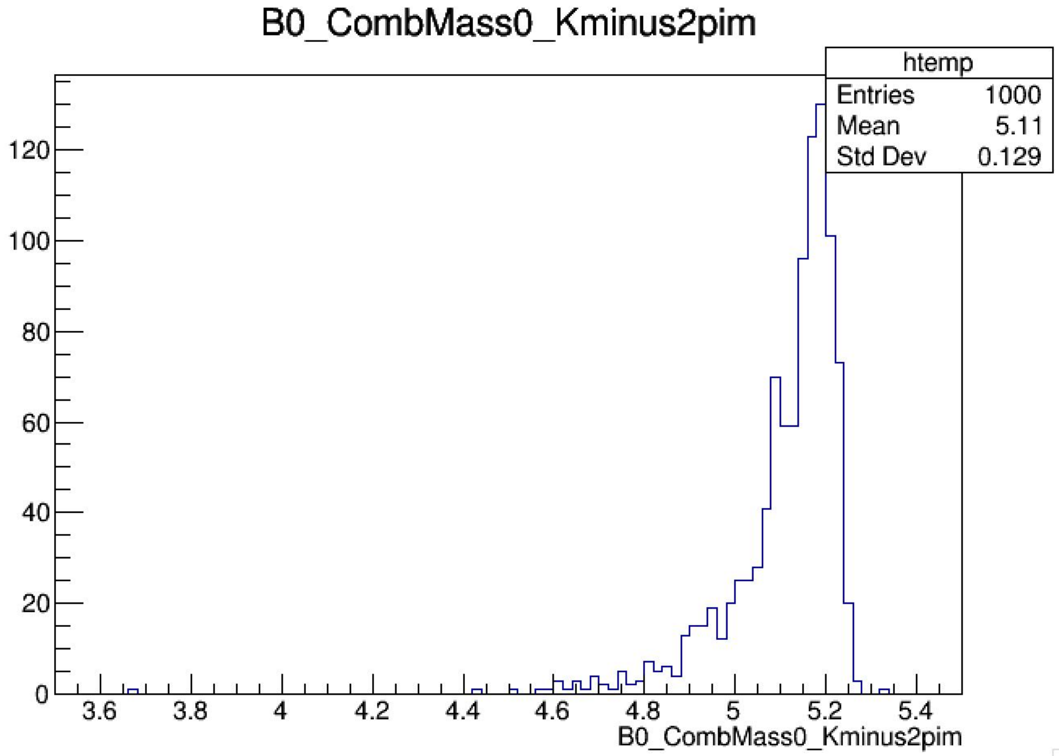


the left is DD and right is LL

Background study

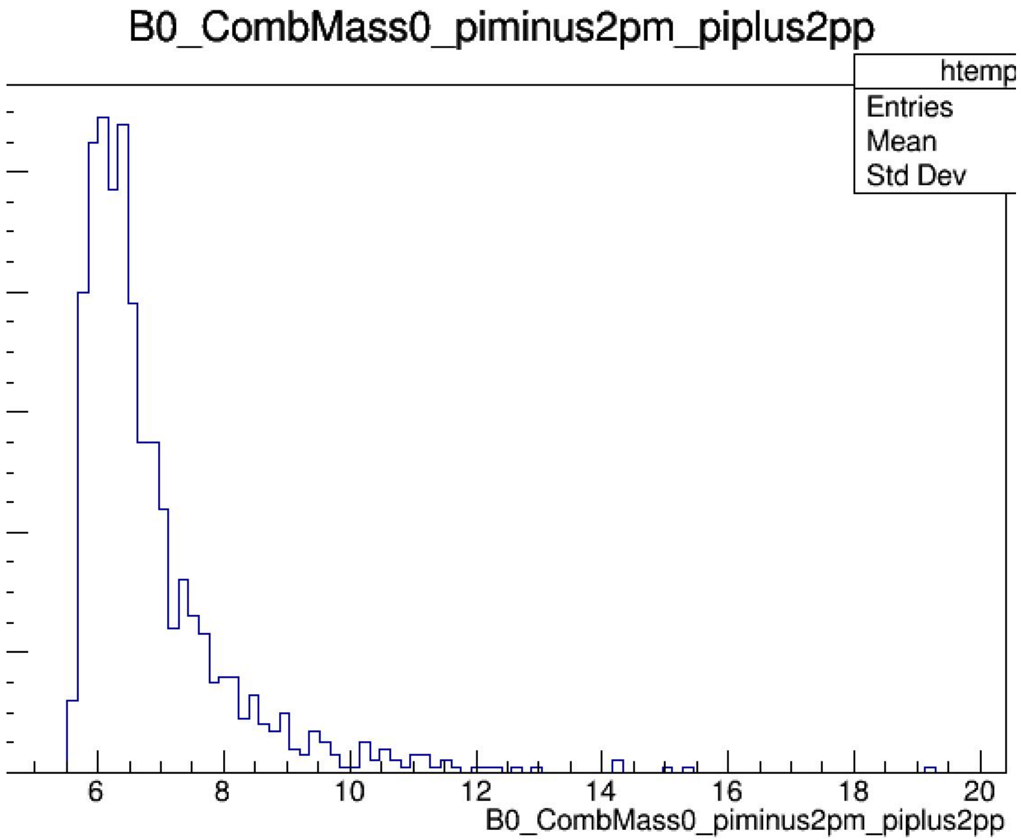


$B^0 \to K_S^0 K^+ K^-$

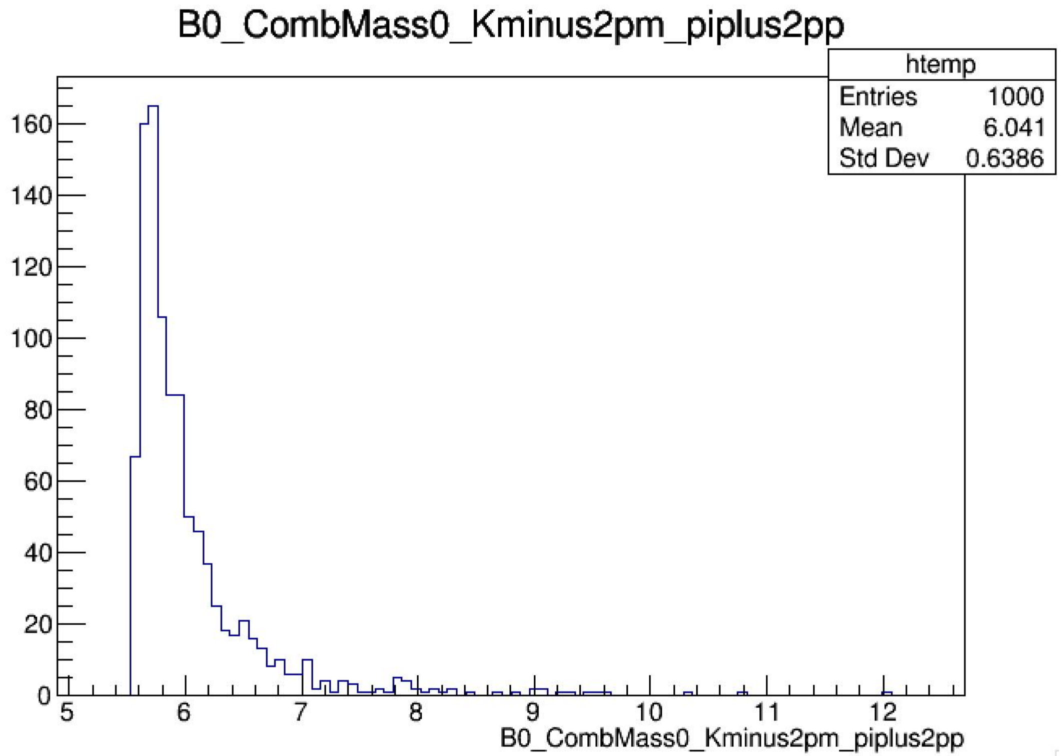


$B^0 \to (\Lambda_c^+ \to K^+ p \pi^-)\bar{p}$

Background study



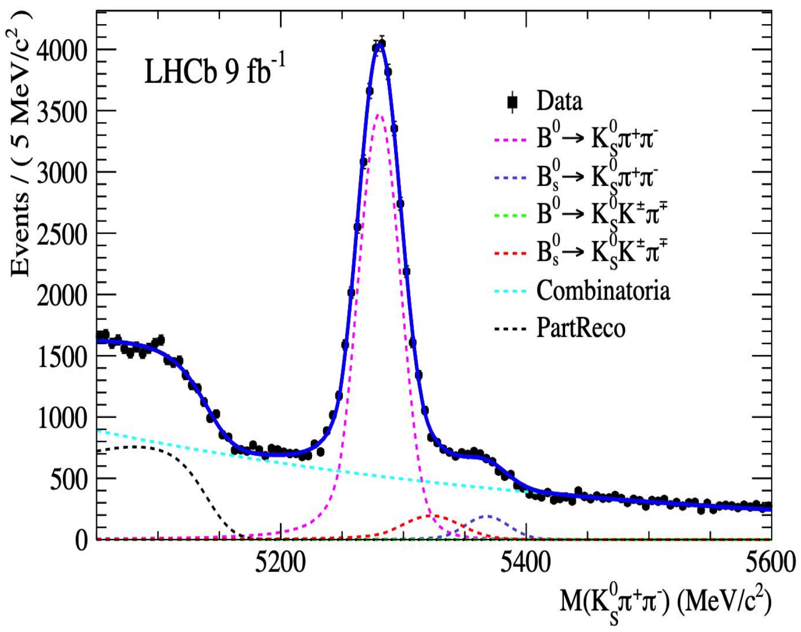
$B^0 \to K_S^0 \pi^+ \pi^-$

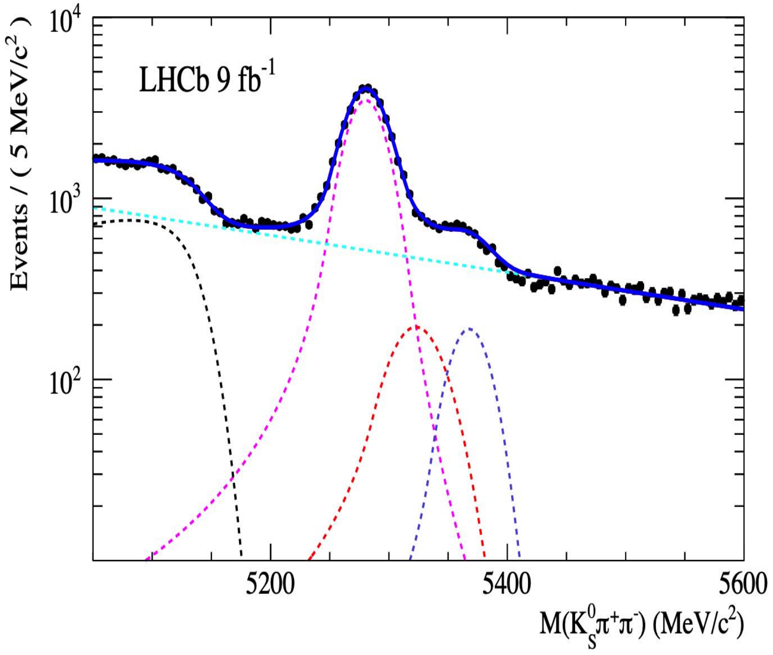


$B^0 \to K_S^0 K^+ \pi^-$

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

- 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
$B^0 \to K_S^0\pi^+\pi^-$	DD	1044 ± 65	2653 ± 96	4794 ± 108	9203 ± 143	32145 ± 230
	LL	772 ± 52	1678 ± 73	3892 ± 85	8109 ± 132	

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

Efficiencies and Uncertainty

- The efficiencys 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:

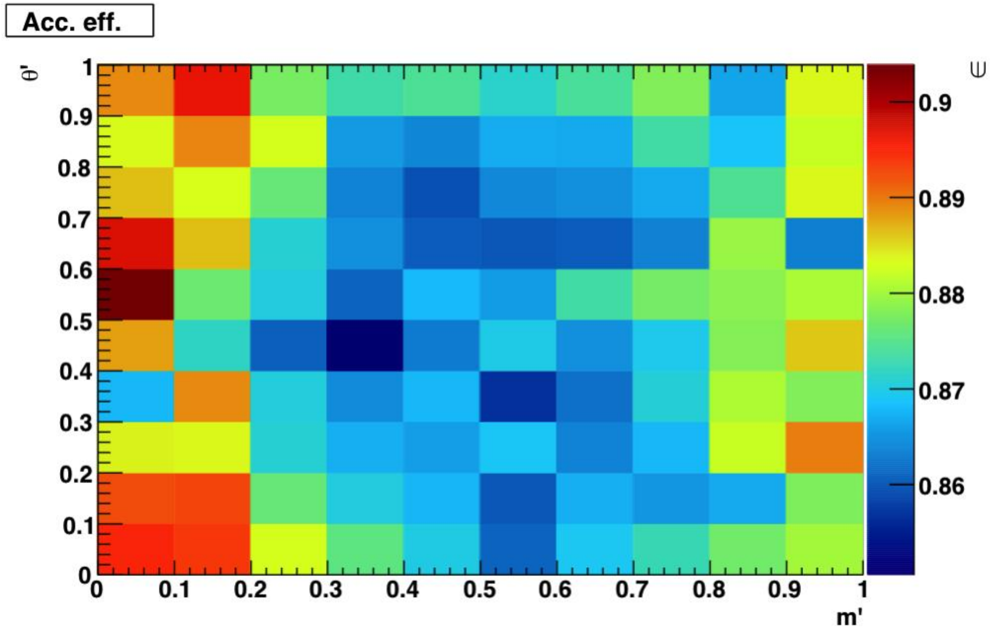
$$m' = \frac{1}{\pi}\cos^{-1}\left(2\frac{m_{p\bar{p}} - m_{p\bar{p}}^{min}}{m_{p\bar{p}}^{max} - m_{p\bar{p}}^{min}} - 1\right)$$

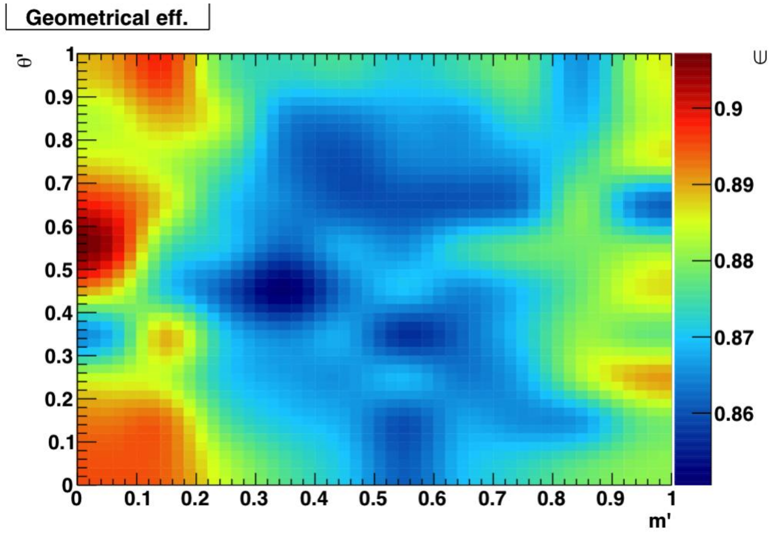
$$\theta' = \frac{1}{\pi}\theta_{p\bar{p}}$$

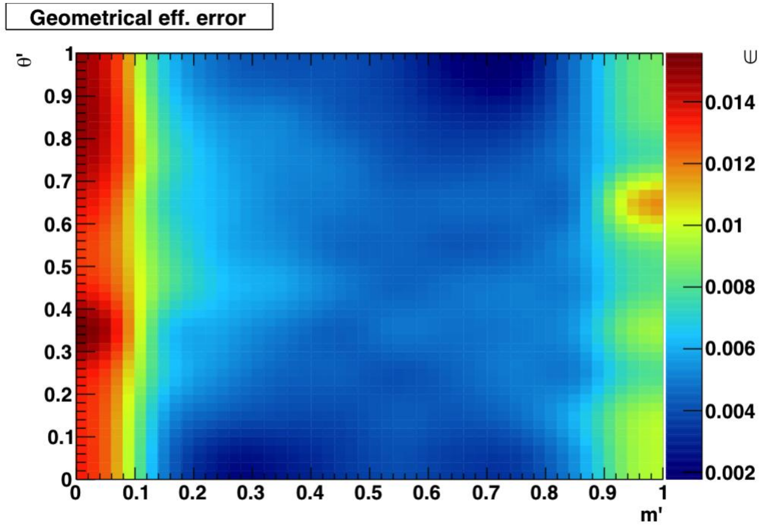
where $m_{p\bar{p}}$ is the combinational mass, $m_{p\bar{p}}^{max} = m_{B^0} - m_{K_S^0}$ and $m_{p\bar{p}}^{min} = m_p + m_{\bar{p}}$ are the boundaries of $m_{p\bar{p}}$, $\theta_{p\bar{p}}$ is the angle between the h$^+$ and the K_S^0 in the $p\bar{p}$ rest frame.

Efficiencies

- Geometriacl efficiency





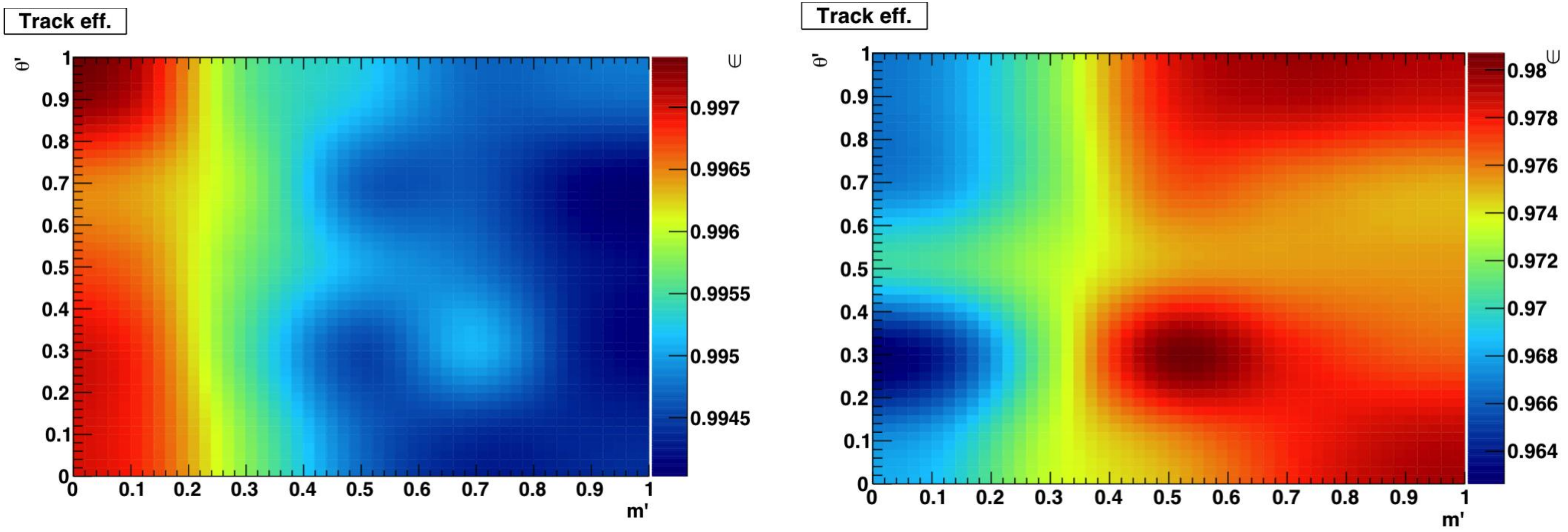


Uncertainties due to MC statistics by Clopper − Pearson in the TEfficiency calss

$B^0 \to K^0_S p\bar{p}$ for 2015 and 2016

Efficiencies and Uncertainty

◆ Tracking efficiency



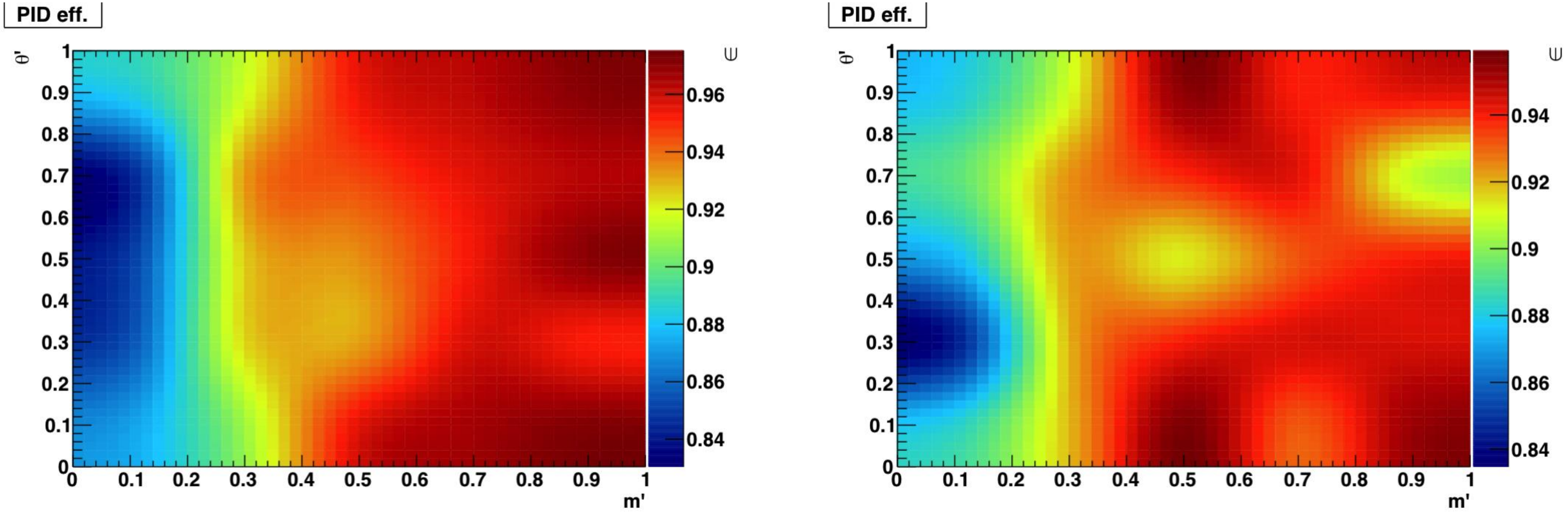
the left is DD and right is LL for 2015 and 2016 to $B^0 \to K_S^0 p\bar{p}$

a) Select the invariant mass region 2.5σ *and is* weighted to match the sWeighted signal event

b) The average correction factor from tracking calibration tables

Efficiencies

◆ PID efficiency



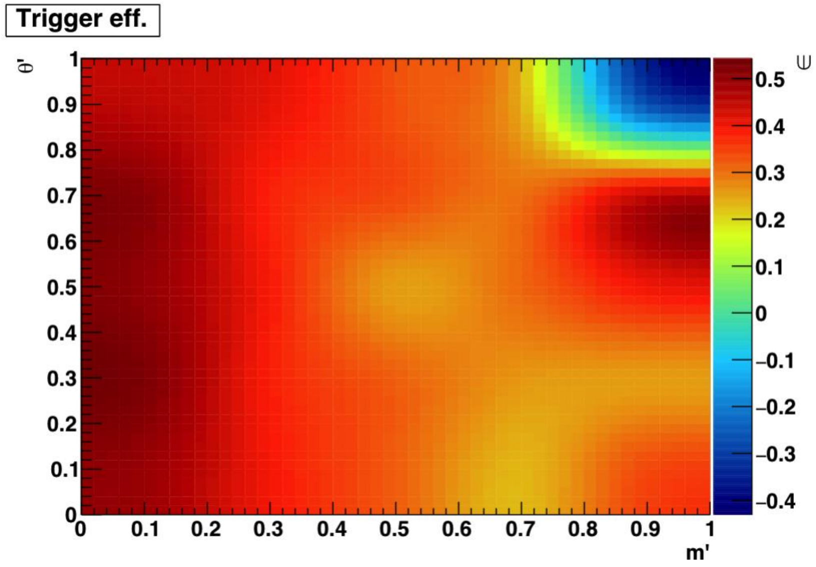
the left is DD and right is LL for 2015 and 2016 to $B^0 \to K_S^0 p\bar{p}$

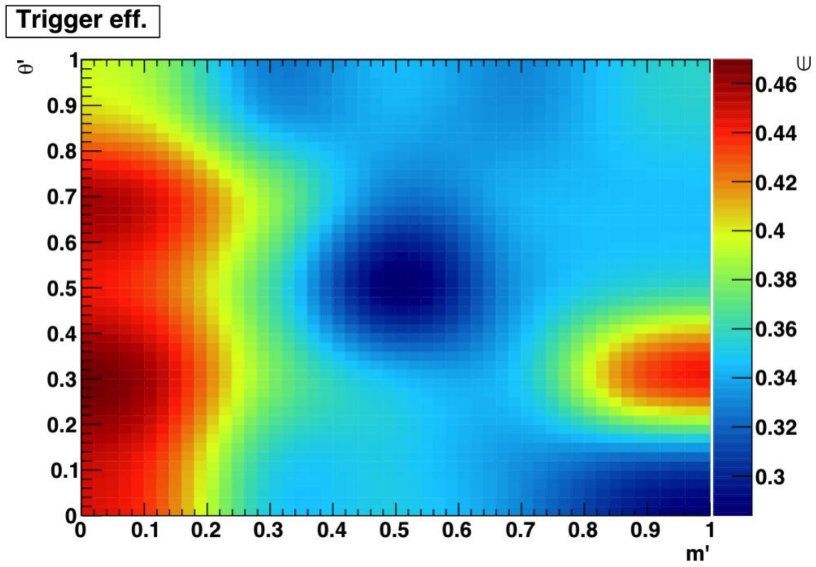
➢ The PID efficiency is determined from calibration data, reweighted to signal kinematics (from MC), using the PIDCalib2 tool. The PIDCalib2 multibody tools with the signal MC samples as the reference (specifically P, η and nSPDHits).

Efficiencies

◆ Trigger efficiency

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



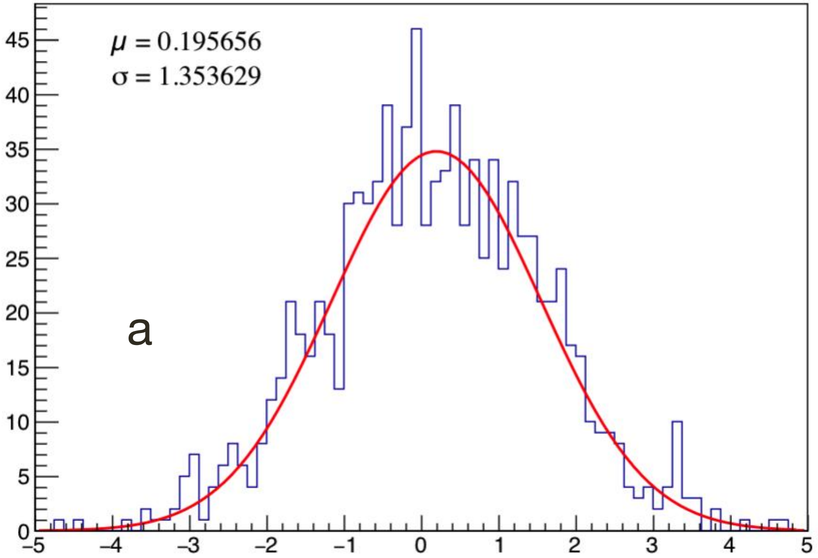


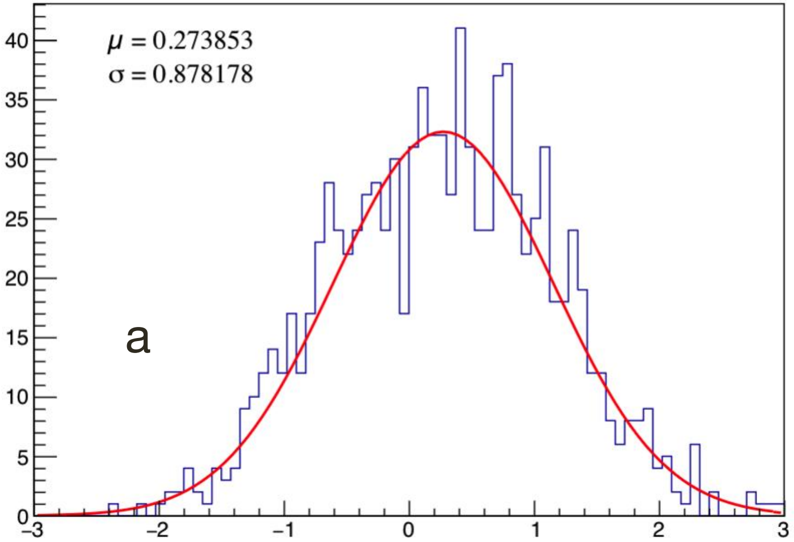
the left is DD and right is LL for 2015 and 2016 to $B^0 \to K_S^0 p\bar{p}$

- The f terms are the factions 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) × 100
  - a) Signal model: Crystal ball → $Student\ +\ Gauss\,function$
  - b) Partial reconstructed bkg model: $\begin{cases} Argus \otimes Gauss\,function \\ M(5100 \to 5600) \end{cases} \to \begin{cases} Not \\ M(5150 \to 5600) \end{cases}$
  - c) Combinatorial bkg model: Exponential function → 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 $B^0 \to K_S^0 p\bar{p}$

Fit model Systematics: $\pi^+\pi^-$ (15, 16)

- The choice of the models (1000 Toy experiment) × 10
  a) Signal model: Crystal ball → $Student\ +\ Gauss\,function$
  b) Partial reconstructed bkg model: $\begin{cases} Argus \otimes Gauss\,function \\ M(5100 \rightarrow 5600) \end{cases} \rightarrow \begin{cases} Not \\ M(5150 \rightarrow 5600) \end{cases}$
  c) Combinatorial bkg model: Exponential function → Second order Chebychev polynomial
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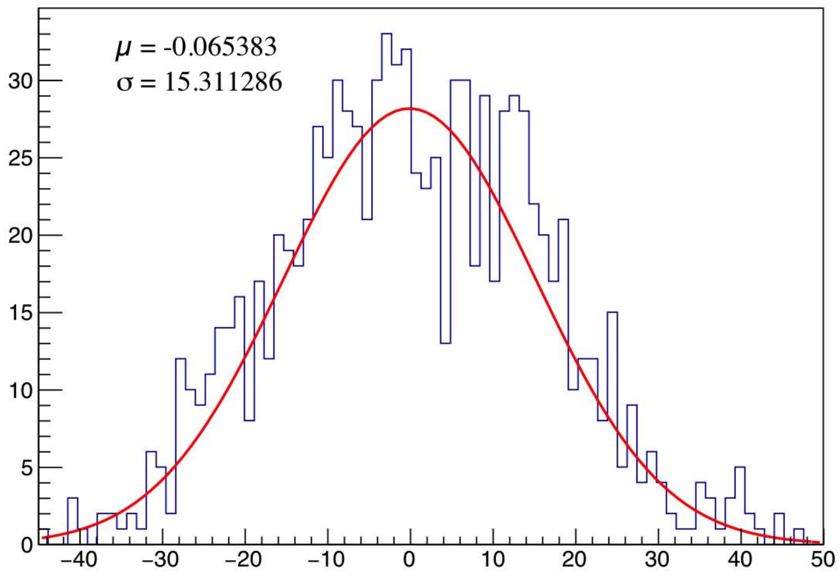
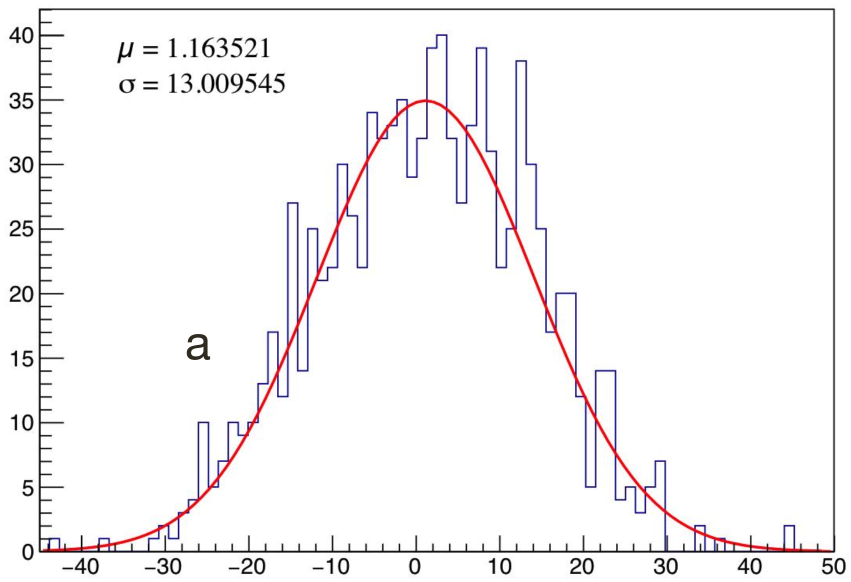


Signal model DD



Signal model LL