Study of $B \to p\bar{p}K$ Decays

$$B^+ \to (c\bar{c})K^+ \to p\bar{p}K^+$$

$$B^0 \to (c\bar{c})K_S^0 \to p\bar{p}K_S^0$$

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Charmonium(-like) states in $B \to p\bar{p}K$

- **Motivation**
  - measure the branching fractions of the decays $B^+ \to p\bar{p}K^+$ and $B^0 \to p\bar{p}K_S^0$ for intermediate charmonium(-like) states such as $\eta_c(2S)$, $\psi(3770)$, $X(3872)$ and $\chi_{c0}(2P)$ (was $X(3915)$).
  - will be of interest for future experiment PANDA which plans to study charmonium and charmed particle production in pp annihilations.

- **Analysis features**
  - based on blind analysis (3.5 GeV/c^2 – 4.0 GeV/c^2)
  - continuum suppression using modified Fox-Wolfram moments
  - two dimensional unbinned likelihood fit for signal yield extraction (past work)
  - three dimensional unbinned likelihood fit for signal yield extraction (ongoing work)
  - test mode $J/\psi \to pp$, and $\eta_c \to pp$ in $B^\pm \to ppK^\pm$, $B^0 \to ppK_S^0$

Charged Track Selection

- Charged Track Selection Criteria

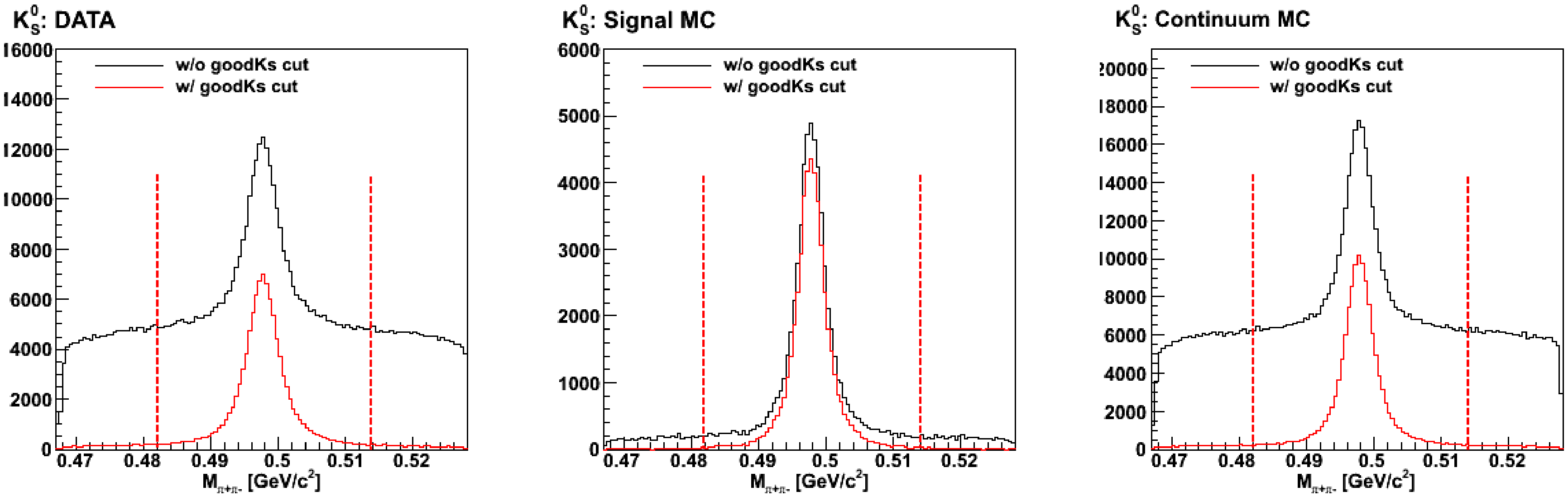
Selection Criterion	modes	
	ppK^+	ppK_S^0
|dr| of p+	< 0.3 cm	< 0.3 cm
|dz| of p+	< 3.0 cm	< 3.0 cm
|dr| of p+	< 0.3 cm	< 0.3 cm
|dz| of p+	< 3.0 cm	< 3.0 cm
PID(p+|K)	> 0.6	> 0.6
PID(p+|π)	> 0.6	> 0.6
PID(p-|K)	> 0.6	> 0.6
PID(p-|π)	> 0.6	> 0.6
|dr| of K	< 0.3 cm	
|dz| of K	< 3.0 cm	
PID(K|π)	> 0.6	

K_S^0 Selection / Reconstruction

- ***K_S^0* Reconstruction**
  - reconstructed from $\pi^+\pi^-$ (stored in MDST_Vee2 table)
  - Mass constraint & Vertex Finding Simultaneously (vertex err == 0)
- ***K_S^0* Selection**
  - *goodKs* condition : *goodKs* > 0
  - invariant mass cut : 0.482 GeV/c^2 < $m(\pi^+\pi^-)$ < 0.514 GeV/c^2 ($\pm 4\sigma$)

    ($m(K^0_S)$ ~ 0.498 GeV/c^2, σ ~ 0.004 GeV/c^2, 4σ ~ 0.016 GeV/c^2)

- **Reconstructed *K_S^0* mass distributions w/ and w/o *goodKs* cut**

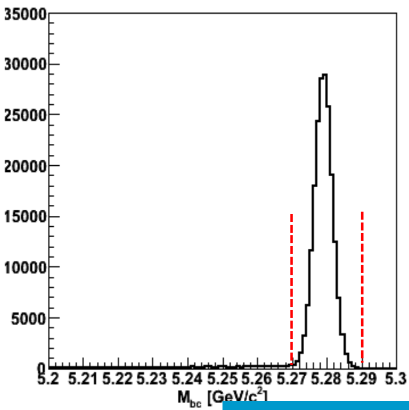


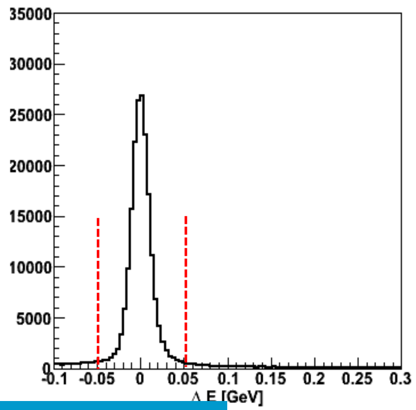
B reconstruction

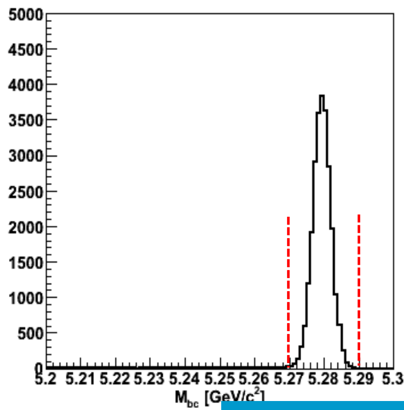
- ***B* reconstruction**
  - B^+ : reconstructed by *p, pbar* and K^+
  - B^0 : reconstructed by *p, pbar* and $K^0{}_s$
  - Mass constraint & Vertex Finding Simultaneously (vertex err == 0)
- **The Candidate and Signal Region**
  - determined from signal MC

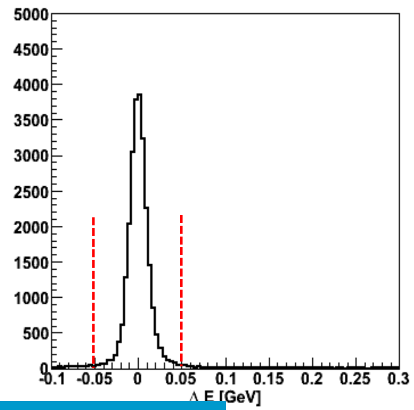
	M_{bc} (GeV/c^2)	ΔE (GeV)
Candidate Region	$5.20 < M_{bc} < 5.30$	$-0.10 < \Delta E < 0.30$
Signal Region	$5.27 < M_{bc} < 5.29$	$-0.05 < \Delta E < 0.05$

- **M_{bc} distribution with $|\Delta E| < 0.05$ GeV and ΔE distribution with 5.27 GeV/c^2 < M_{bc} < 5.29 GeV/c^2**







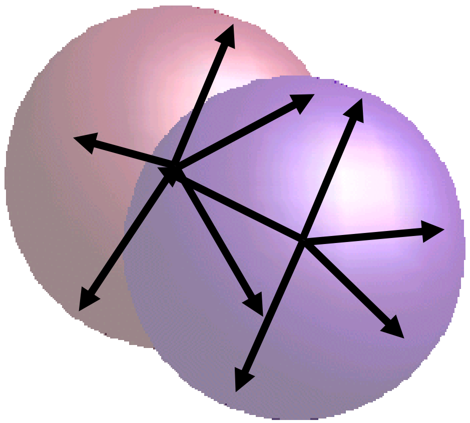


Data

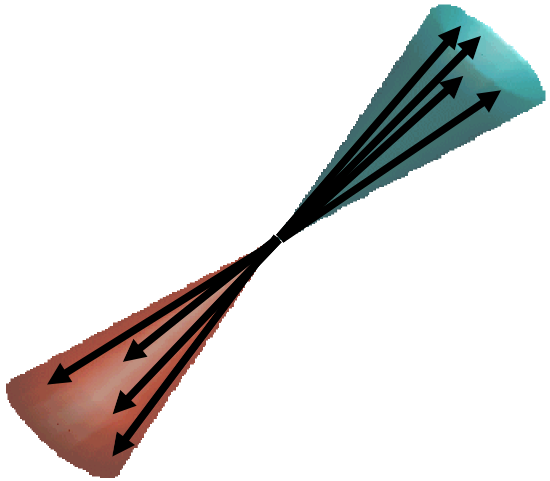
	Exp. #	N(BB)
Data Sets		
HadronB(J) on-resonance	Exp. 7 to Exp. 65	772×10^6
Signal Samples: Signal MC		
$B^+ \to ppbarK^+$	Exp. 7 to Exp. 65	455,233
$B^0 \to ppbarK^0{}_s$	Exp. 7 to Exp. 65	102,620
$B^+ \to J/\psi K^+ \to ppbarK^+$	Exp. 7 to Exp. 65	0.1M
$B^+ \to \eta_c K^+ \to ppbarK^+$	Exp. 7 to Exp. 65	0.1M
$B^+ \to J/\psi K^0{}_s \to ppbarK^0{}_s$	Exp. 7 to Exp. 65	0.1M
$B^+ \to \eta_c K^0{}_s \to ppbarK^0{}_s$	Exp. 7 to Exp. 65	0.1M
Background Samples: Generic continuum MC		
on-resonance charm MC	Exp. 7 to Exp. 65	1 stream
on-resonance uds MC	Exp. 7 to Exp. 65	1 stream

Continuum Background

- **Continuum events**
  - $e^+e^- \rightarrow qq$ where q = u, d, s, and c
  - the dominant background for charmless *B* decays
  - about a three times larger cross section than $e^+e^- \rightarrow \Upsilon(4S) \rightarrow BB$ events
  - "**back-to-back**" jet-like while the signal *BB* events are "**spherical**"



$e^+e^- \rightarrow \Upsilon(4S) \rightarrow BB$ (Spherical)



$e^+e^- \rightarrow qq$ (Jet-like)

Event shape

Continuum Suppression

- **Likelihood method based on Event Shape Variables: KSFW and cosθ$_B$**
  - **KSFW (Kakuno Super Fox Wolfram) moments**

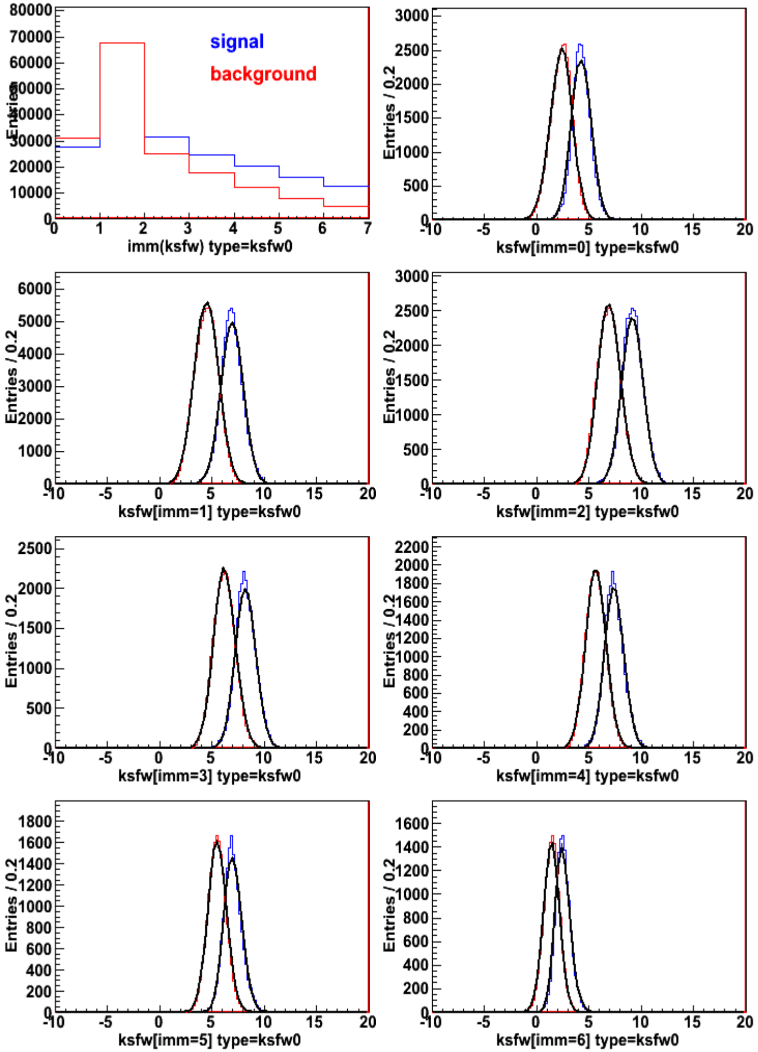
    event-shape variable calculated by Fisher method using angles of momenta, etc.
  - **cosθ$_B$**

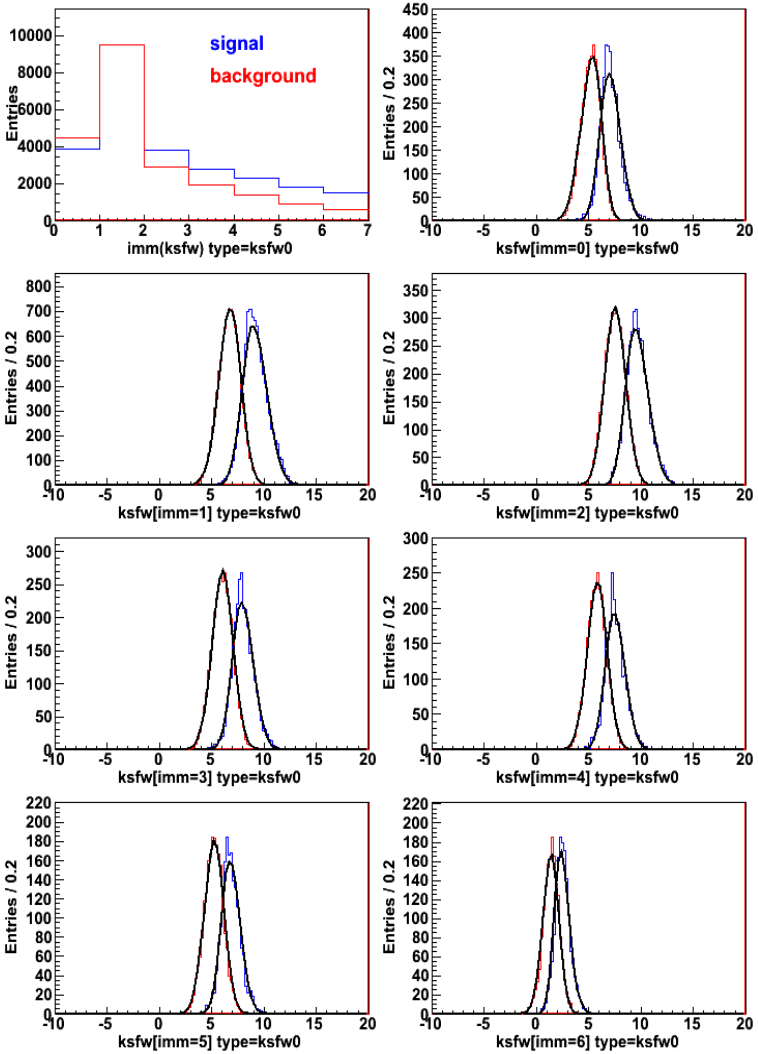
    the cosine of the angle between the B flight direction and the beam direction in Υ(4S) rest frame

- **Data samples**
  - **Signal sample** $B^+ \to ppK^+$ / $B^+ \to ppK_S^0$ signal MC
  - **Background sample** on-resonance continuum (uds + charm) MC

IV. Continuum Suppression

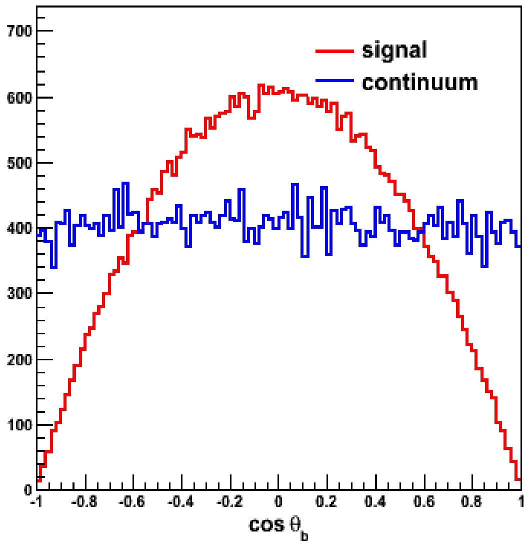
KSFW moments distributions

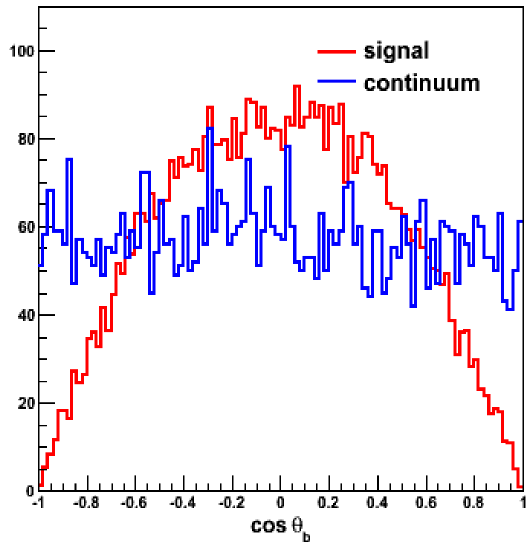




IV. Continuum Suppression

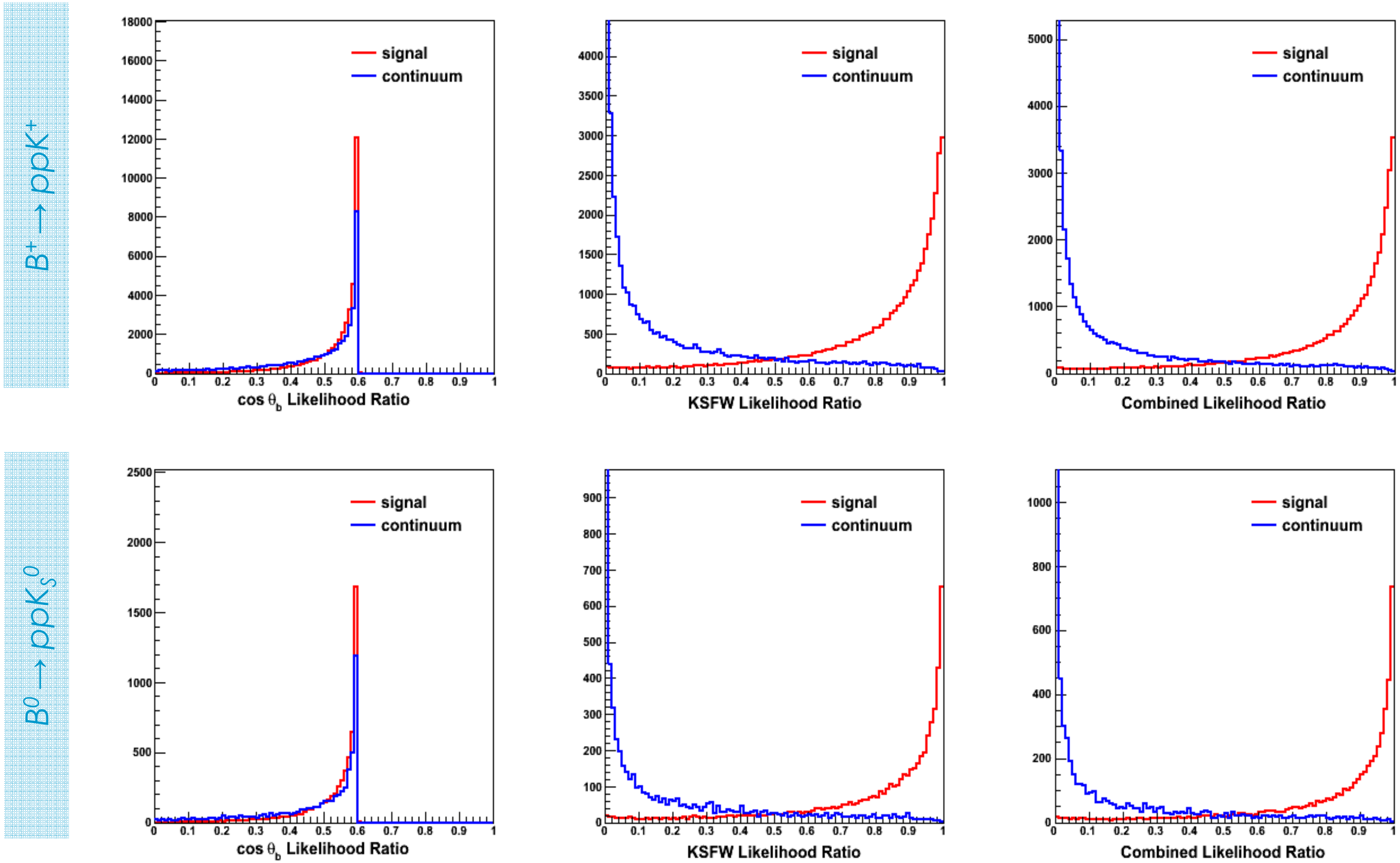
cos θ_B





IV. Continuum Suppression

Likelihood Ratio



cos θ_B likelihood ratio | KSFW likelihood ratio | combined likelihood ratio

IV. Continuum Suppression

Optimization of LR Cut

- **Likelihood Ratio**

$$individual \quad LR = \frac{P_{signal}}{P_{signal} + P_{background}}$$

$$combined \quad LR = \frac{LR_{KSFW} \times LR_{cosb}}{LR_{KSFW} \times LR_{cosb} + (1 - LR_{KSFW}) \times (1 - LR_{cosb})}$$

- **Figure-Of-Merit Study**

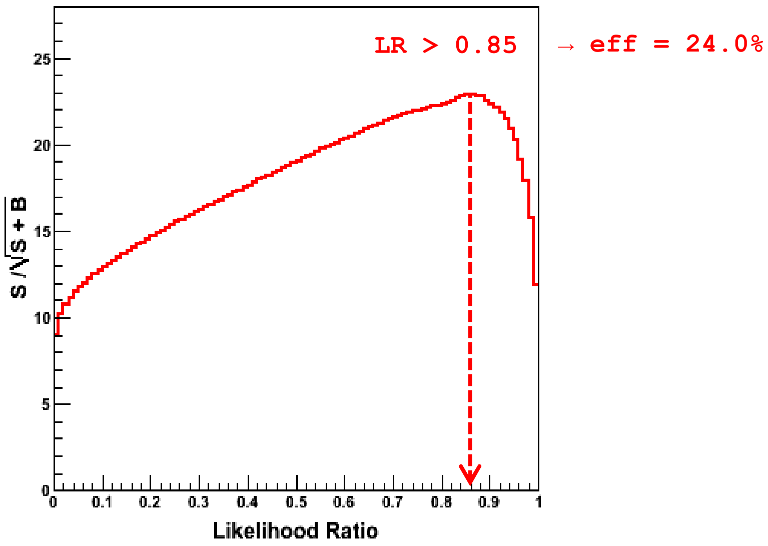
$$\frac{S}{\sqrt{S+B}}$$

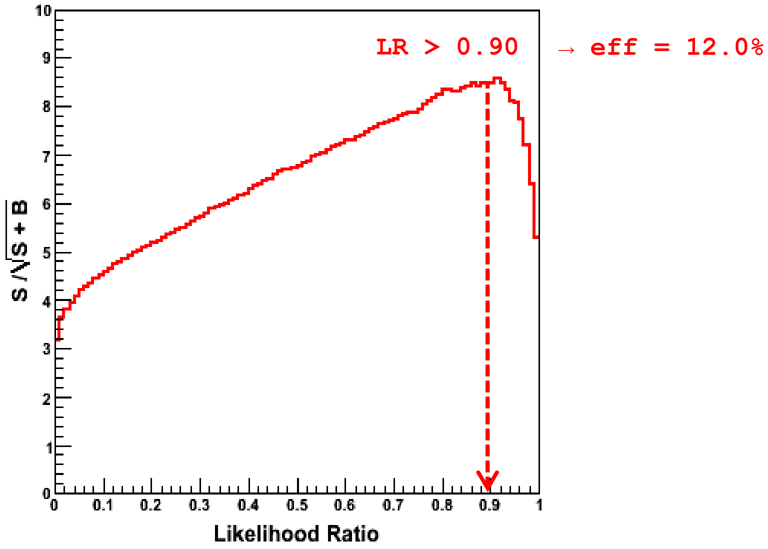
S the expected numbers of signal events
B the expected numbers of background events

- **Estimation of S / B**
  - *S* calculated from the signal MC using PDG branching fractions with 772 x 10^6 BB pairs
  - *B* calculated from on-resonance continuum MC data (uds + charm) normalized to real data

Optimization of LR Cut

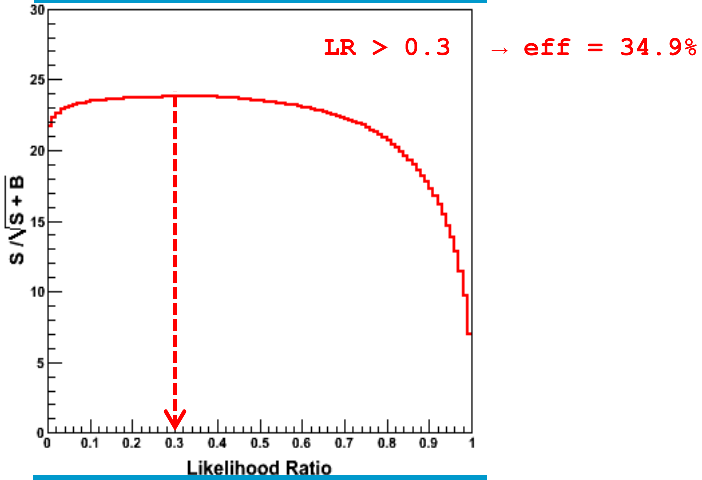
- Figure-Of-Merit Plots as a function of likelihood ratio

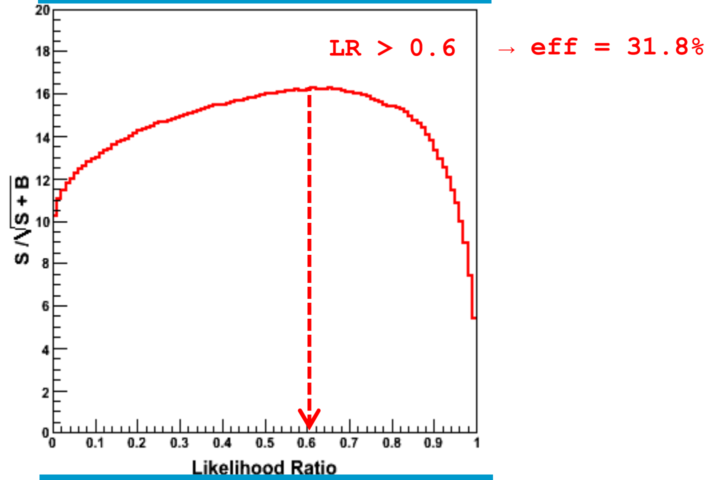


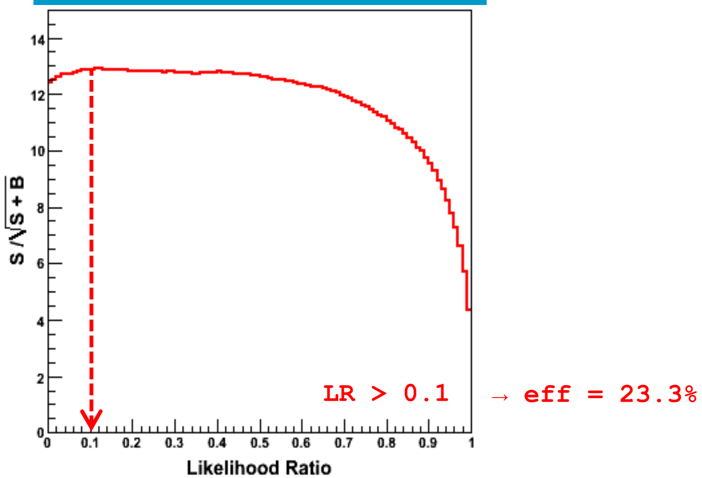


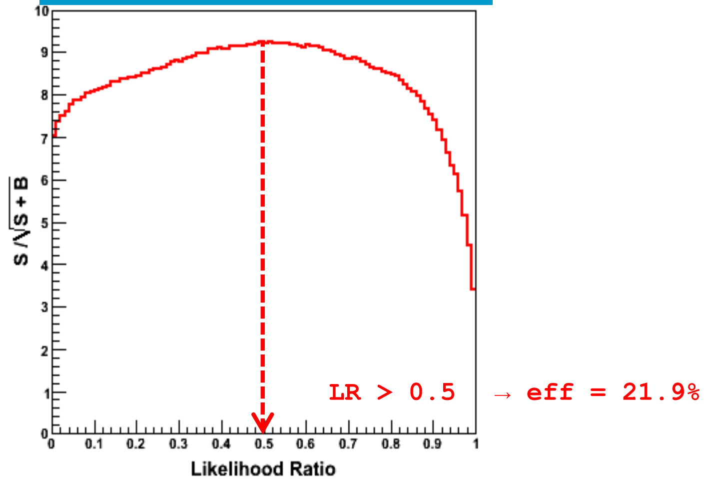
Optimization of LR Cut (NEW)

- Figure-Of-Merit Plots as a function of likelihood ratio of control samples









Signal Yield Extraction

- **Signal Yield Extraction** 3-Dimensional Unbinned Likelihood Fit on $M_{bc} - \Delta E - M_{pp}$ plane

- **Test modes**
  $B^+ \to J/\psi K^+ \to ppK^+$
  $B^+ \to \eta_c K^+ \to ppK^+$
  $B^0 \to J/\psi K^0_s \to ppK^0_s$
  $B^0 \to \eta_c K^0_s \to ppK^0_s$

- **Determination of Signal and Background PDFs**

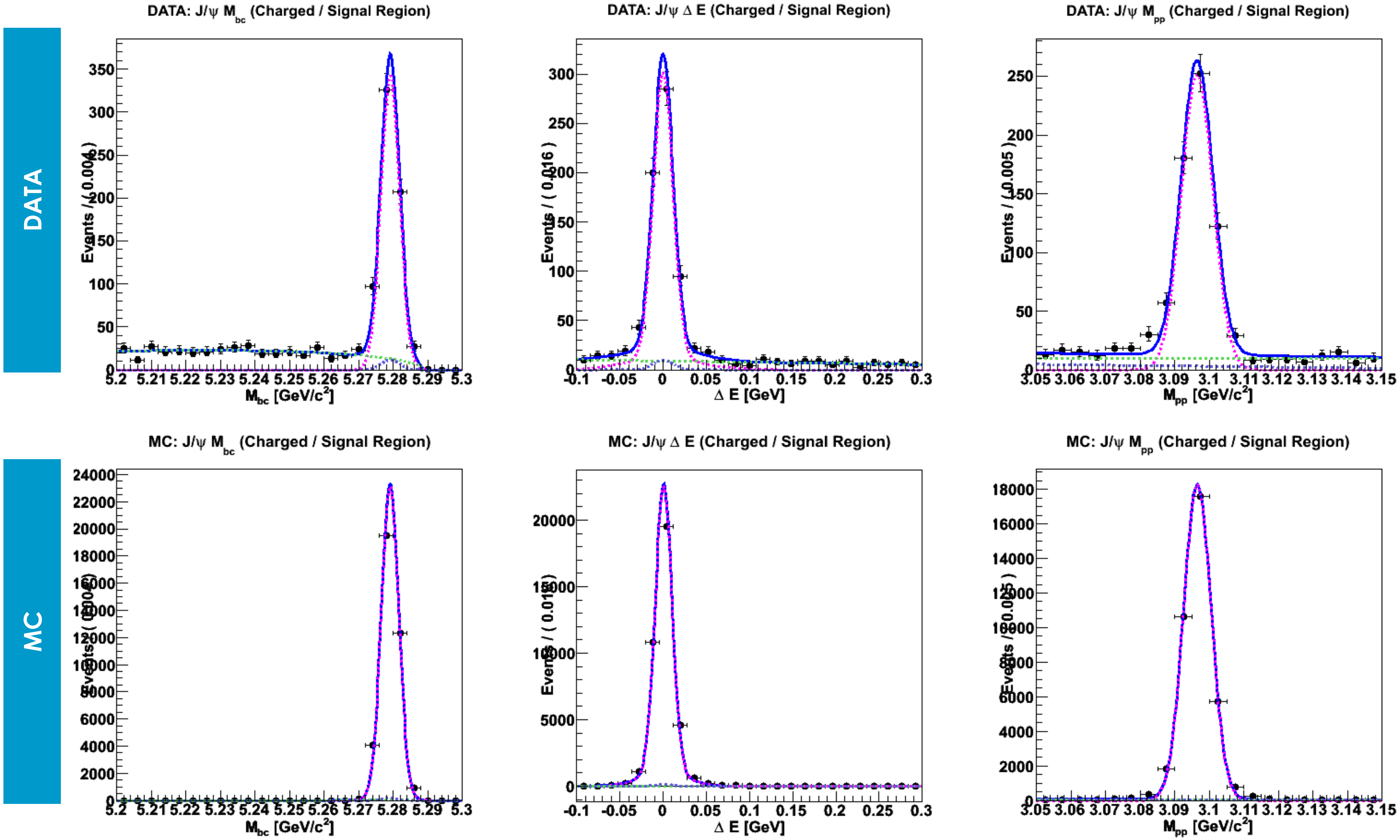
PDF	M_{bc}	ΔE	M_{pp}
Signal * resonant	Gaussian	double Gaussian	Gaussian - J/ψ Voigtian - η_c
Background 1 combinatoric	Argus	1^{st} order polynomial	const.
Background 2 ** non resonant "peaking bkg"	Gaussian	double Gaussian	1^{st} order polynomial

* $B^+ \to (cc)K^+ \to ppK^+$
** $B^+ \to ppK^+$

(parameters floated)

V. Signal Yield Extraction

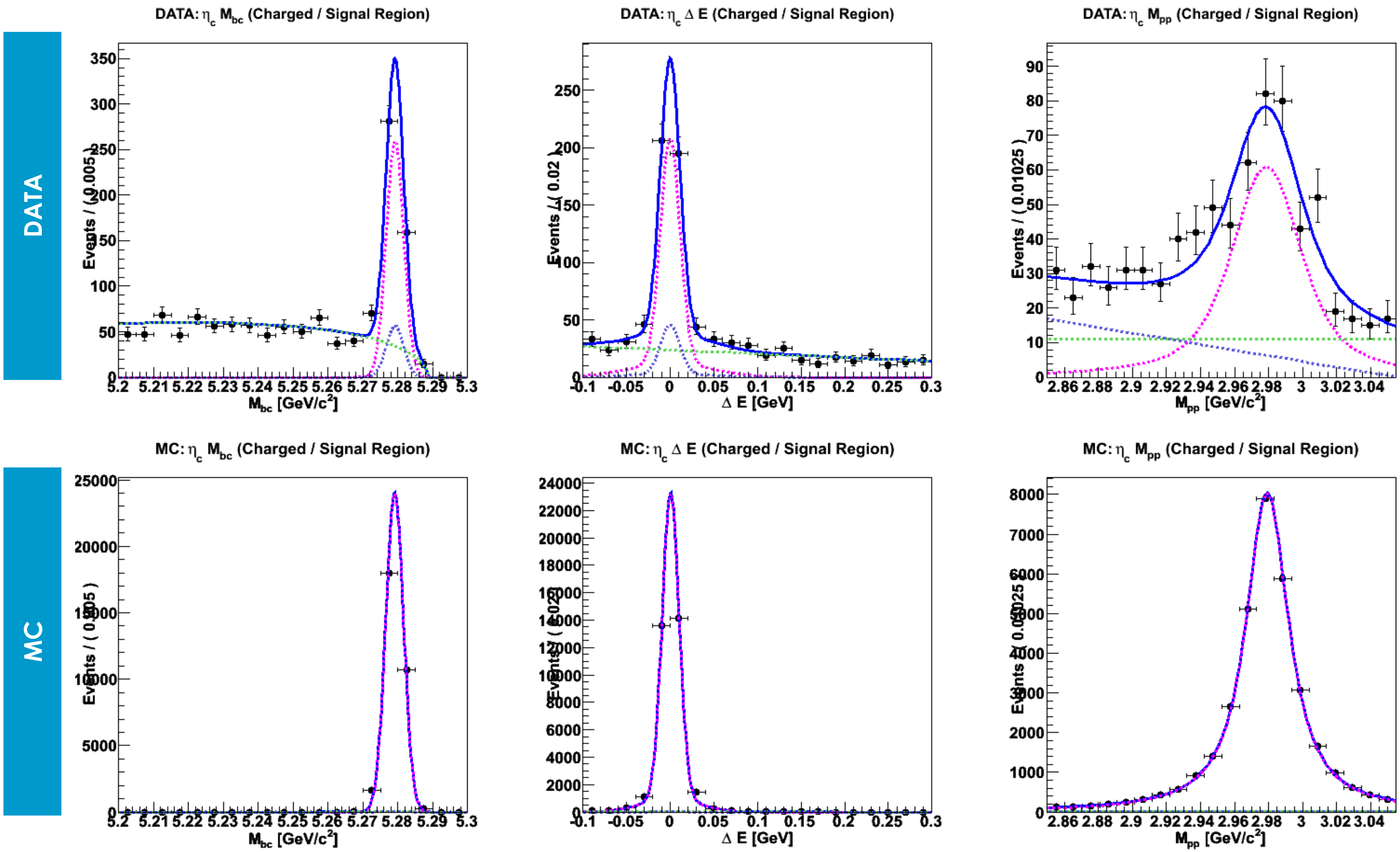
$B^+ \to J/\psi(1S)K^+ \to p\bar{p}K^+$



projections onto signal region

V. Signal Yield Extraction

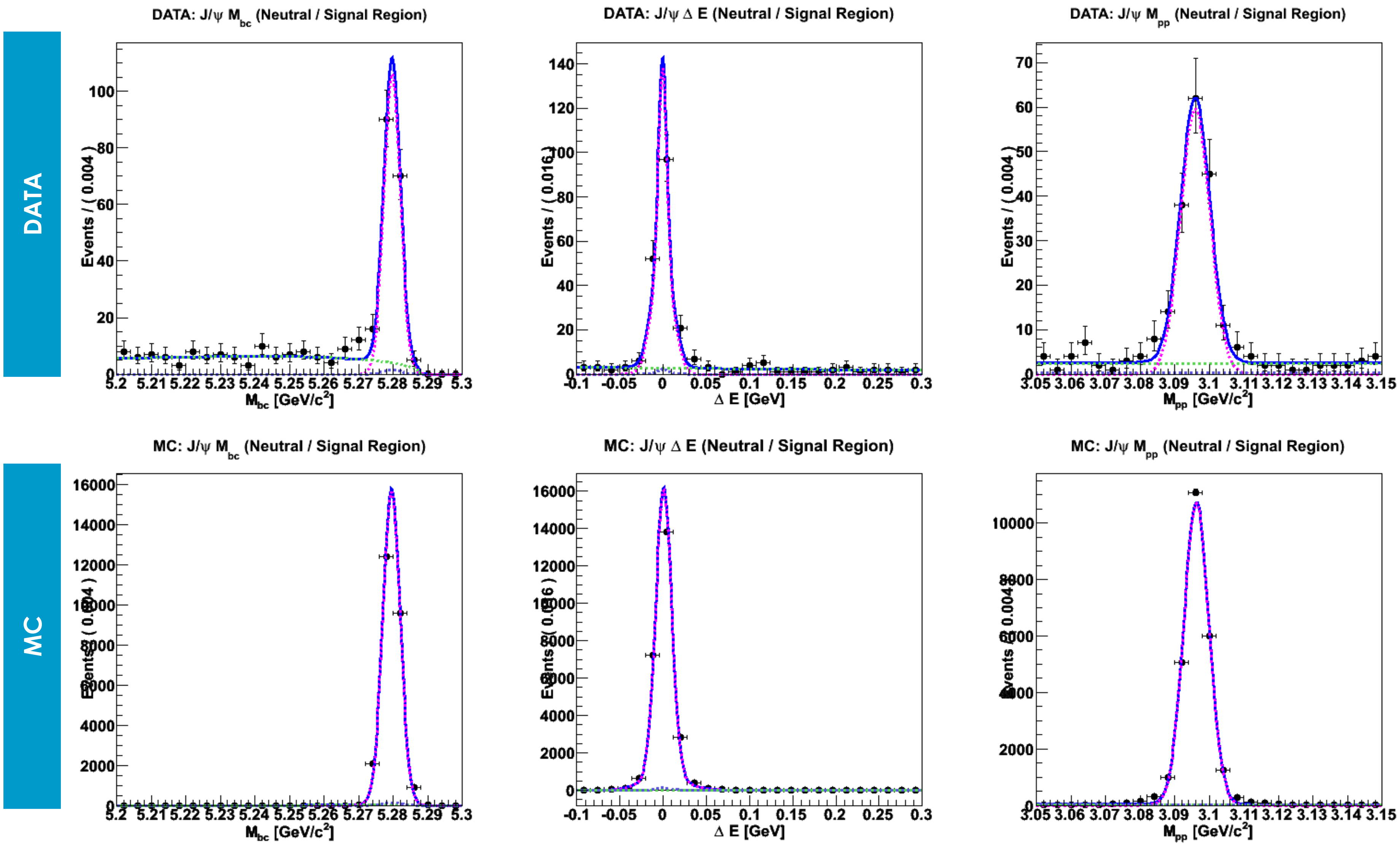
$B^+ \to \eta_c(1S)K^+ \to p\bar{p}K^+$



projections onto signal region

V. Signal Yield Extraction

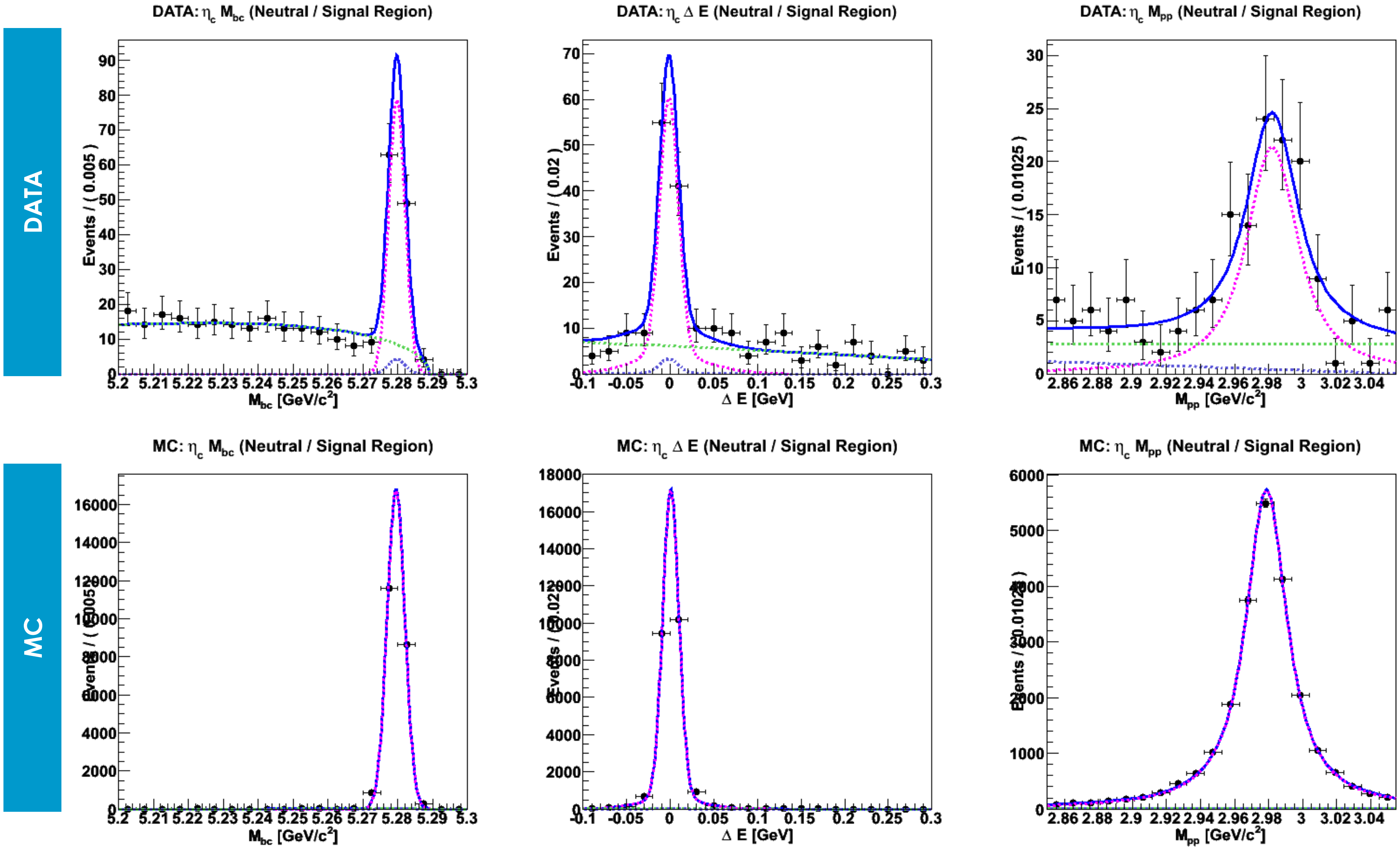
$B^0 \to J/\psi(1S)K^0_S \to p\bar{p}K^0_S$



projections onto signal region

V. Signal Yield Extraction

$B^0 \to \eta_c(1S)K^0_S \to p\bar{p}K^0_S$



projections onto signal region

Branching Fractions

- Calculation of Branching Fractions

$$\mathcal{B}(B \to (c\bar{c})K) \times \mathcal{B}((c\bar{c}) \to p\bar{p}) = \frac{N_{measured}}{N_{B\bar{B}}} \times \frac{1}{\varepsilon_{total}}$$

$$\varepsilon_{total} = \varepsilon_{MC} \times f_{KID/KOS}{}^{*} \times f_{protonPID} \times f_{anti-protonPID}$$

*

- Efficiency Correction Factors

Modes	MC Eff.	KID / K0S	proton PID	anti-proton PID	Total Eff.
$B^+ \to J/\psi K^+ \to ppK^+$	0.3489	0.9916	0.9860	0.9760	0.3329
$B^+ \to \eta_c K^+ \to ppK^+$	0.3179	0.9919	0.9856	0.9757	0.3032
$B^0 \to J/\psi K^0{}_s \to ppK^0{}_s$	0.2325	0.9789	0.9866	0.9774	0.2195
$B^0 \to \eta_c K^0{}_s \to ppK^0{}_s$	0.2191	0.9789	0.9868	0.9762	0.2066

Summary of Results

Modes	Yield	Eff. (%)	Significance (σ)	Mass (MeV/c^2)	Product BF (10^{-6})
$B^+ \to J/\psi K^+ \to p\bar{p}K^+$	596.2 ± 26.5	34.9	40.1	3096.44 ± 0.21	2.21 ± 0.10 ± 0.06
$B^+ \to \eta_c K^+ \to p\bar{p}K^+$	378.4 ± 29.9	31.8	18.1	2978.75 ± 2.10	1.54 ± 0.12 ± 0.04
$B^0 \to J/\psi K^0_s \to p\bar{p}K^0_s$	158.6 ± 13.1	23.3	20.8	3095.91 ± 0.37	0.89 ± 0.07 ± 0.03
$B^0 \to \eta_c K^0_s \to p\bar{p}K^0_s$	106.3 ± 5.0	21.9	9.8	2982.13 ± 0.01	0.63 ± 0.03 ± 0.02

Modes	Mass (MeV/c^2)		Product Branching Fraction (10^{-6})	
	measured*	PDG 2014	measured	PDG 2014
$B^+ \to J/\psi K^+ \to p\bar{p}K^+$	3096.44 ± 0.21	3096.92 ± 0.01	2.21 ± 0.10 ± 0.06	2.18 ± 0.07
$B^+ \to \eta_c K^+ \to p\bar{p}K^+$	2978.75 ± 2.10	2983.6 ± 0.7	1.54 ± 0.12 ± 0.04	1.45 ± 0.23
$B^0 \to J/\psi K^0_s \to p\bar{p}K^0_s$	3095.91 ± 0.37	3096.92 ± 0.01	0.89 ± 0.07 ± 0.03	0.93 ± 0.04
$B^0 \to \eta_c K^0_s \to p\bar{p}K^0_s$	2982.13 ± 0.01	2983.6 ± 0.7	0.63 ± 0.03 ± 0.02	0.60 ± 0.11

* statistical error only

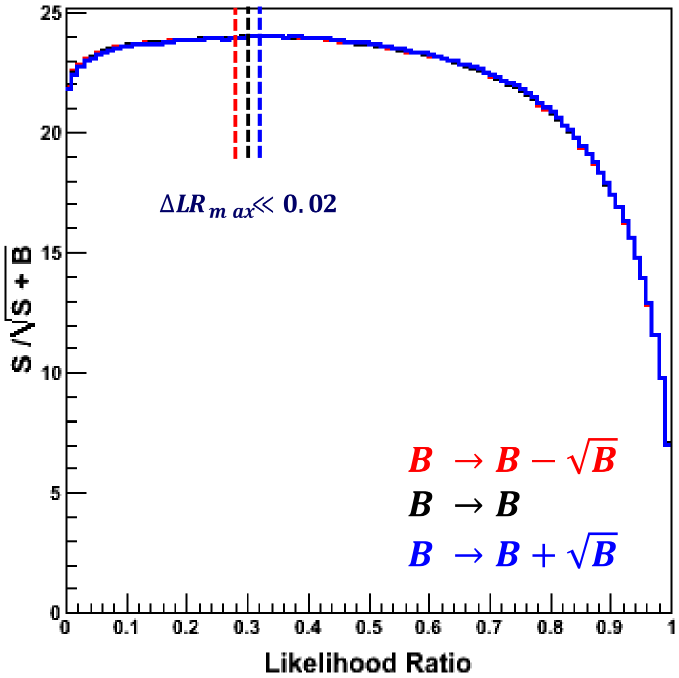
Systematic Uncertainties of Branching Fraction

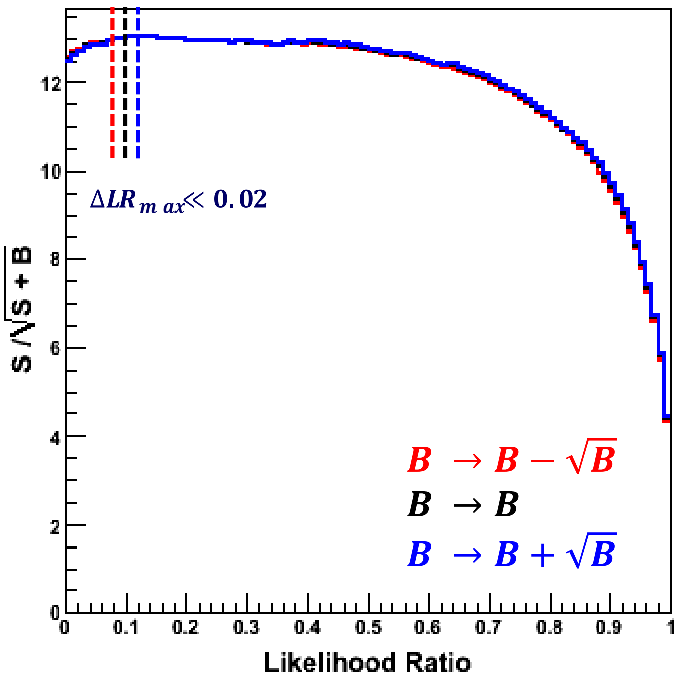
- **Tracking Efficiency** 0.35% per charged track (BN #1165)
- **K_S^0 reconstruction efficiency** use global result $R = \frac{S_{data}}{S_{MC}} = (97.89 \pm 0.41 \pm 0.60)\%$ (BN #1207)
- **Proton Identification (PID)** (BN #1279)
- **K/π Identification (KID)** (BN #779)
- **Statistical Error of MC sample** 0.15~0.19% calculated from fitted yield of signal MC
- **# of BB Pairs Error** Total N(BB) for Exp. 7 – 65 = (771.581 ± 10.566) x 10^6 (Belle Homepage)

Likelihood Ratio Cut Systematic Errror

- estimated from the control samples : $B^+ \rightarrow J/\psi K^+ \rightarrow ppK^+$ & $B^0 \rightarrow J/\psi K^0_s \rightarrow ppK^0_s$
- compare the branching fractions calculated using the LR cuts determined varying the expected number of background B by as much as 0.02.

$$\frac{S}{\sqrt{S+B}}$$





Fitting Systematic Error

- estimate by varying the order of the background polynomial function

  ① 1st order polynomial → 2nd order polynomial

  ② constant → 1st order polynomial

  ③ 1st order polynomial → 2nd order polynomial

PDF	M_{bc}	ΔE	M_{pp}
Signal * resonant	Gaussian	double Gaussian	Gaussian - J/ψ Voigtian - η_c
Background 1 combinatoric	Argus	1st order polynomial ①	constant ②
Background 2 ** non resonant "peaking bkg"	Gaussian	double Gaussian	1st order polynomial ③

* $B^+ \to (c\bar{c})K^+ \to p\bar{p}K^+$

** $B^+ \to p\bar{p}K^+$

(parameters floated)

Summary of Systematic Uncertainties of Branching Fraction

- List of Systematical Errors for Each Decay Mode (%)

Selection Criterion	$B^+ \to$ ppbarK^+		$B^0 \to$ ppbarK^0_s	
	$B^+ \to J/\psi\ K^+ \to ppK^+$	$B^+ \to \eta_c\ K^+ \to ppK^+$	$B^0 \to J/\psi\ K^0_s \to ppK^0_s$	$B^0 \to \eta_c\ K^0_s \to ppK^0_s$
Tracking efficiency	1.05	1.05	0.70	0.70
Proton identification (PID)	0.82	0.81	0.80	0.79
K/π Identification (KID)	0.87	0.88	-	-
K^0_s reconstruction efficiency	-	-	0.73	0.73
Likelihood ratio cut	1.35	1.35	1.53	1.53
MC statistical error	0.19	0.18	0.16	0.15
Fitting systematic error	0.50	1.43	0.63	0.75
Number of BB pairs error	1.37	1.37	1.37	1.37
Total	2.55	2.88	2.51	2.54

Summary & Plans

Summary

- Studying the decay B → (ccbar)K → ppbarK to measure the branching fraction for ***η_c(2S), Ψ(3770), X(3872), X(3915)*** to ppbar with 711 fb^{-1} integrated luminosity based on the blind analysis.
- The masses and the branching fractions of decays to ppbar of η_c & J/ψ control samples are measured from 3-D fit and the results are consistent with PDG.
- The LR cut is determined for each decay mode
- Systematic error study was done. (Would more studies be needed?)

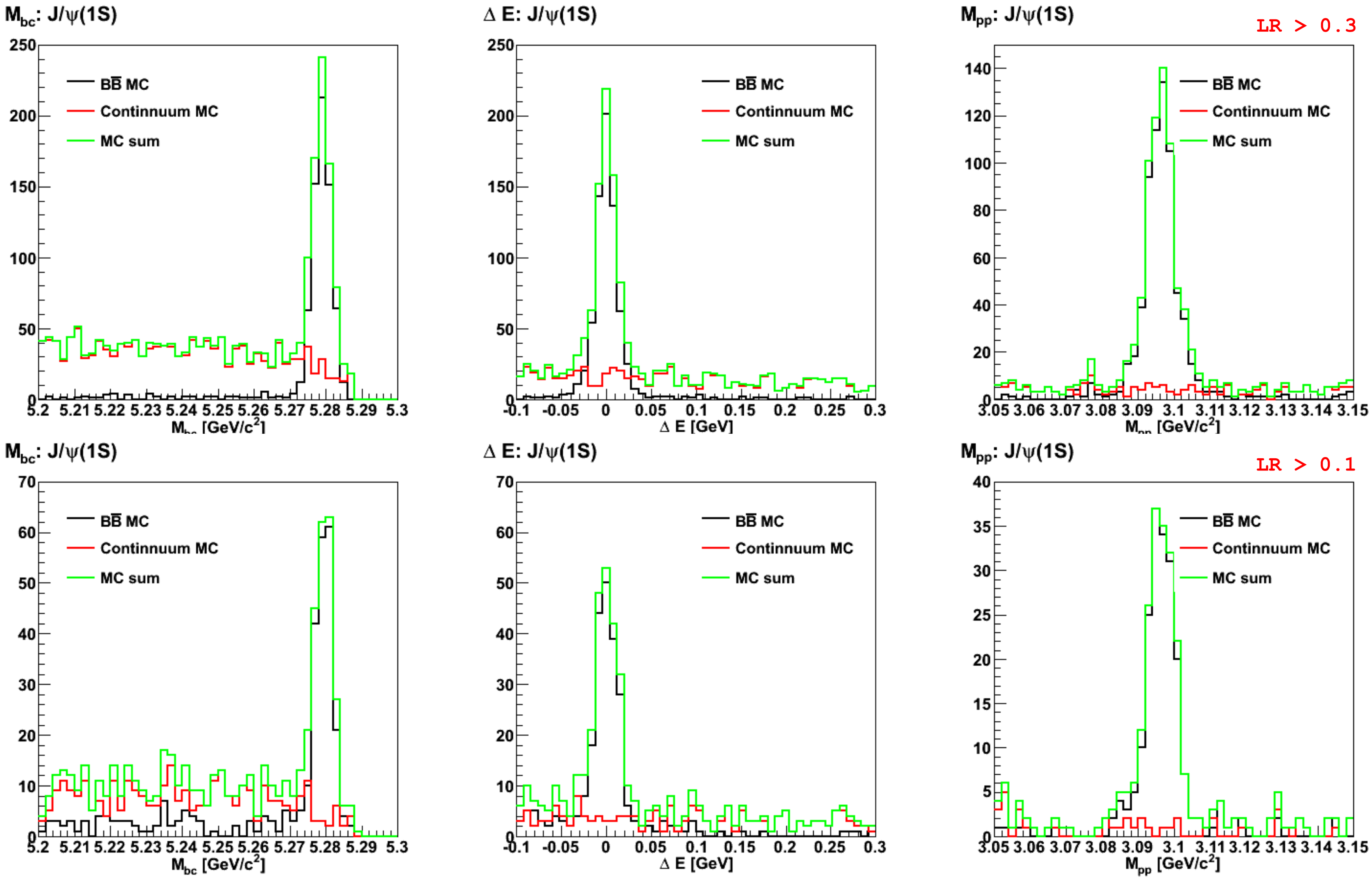
Plan

- study more streams of continuum and BB generic MC to model the background PDF of blind region
- estimate the expected upper limits for the branching fractions of ***η_c(2S), Ψ(3770), X(3872), and X(3915)***
- update the Belle Note #1347
- open the blind box this summer

$J/\psi(1S) \to p\bar{p}$

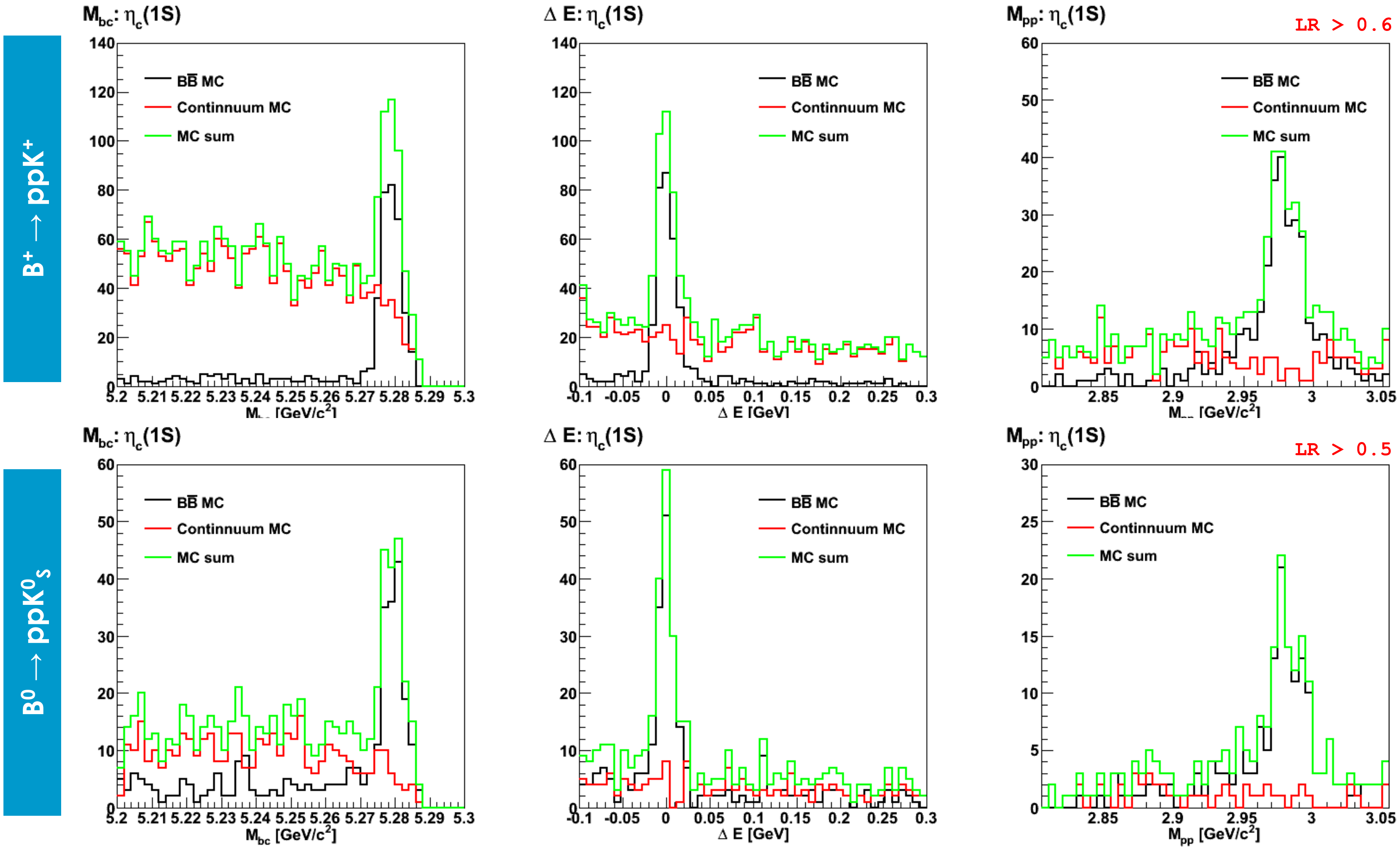
$B^+ \to p\bar{p}K^+$

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



projections onto signal region

$\eta_c(1S) \to p\bar{p}$

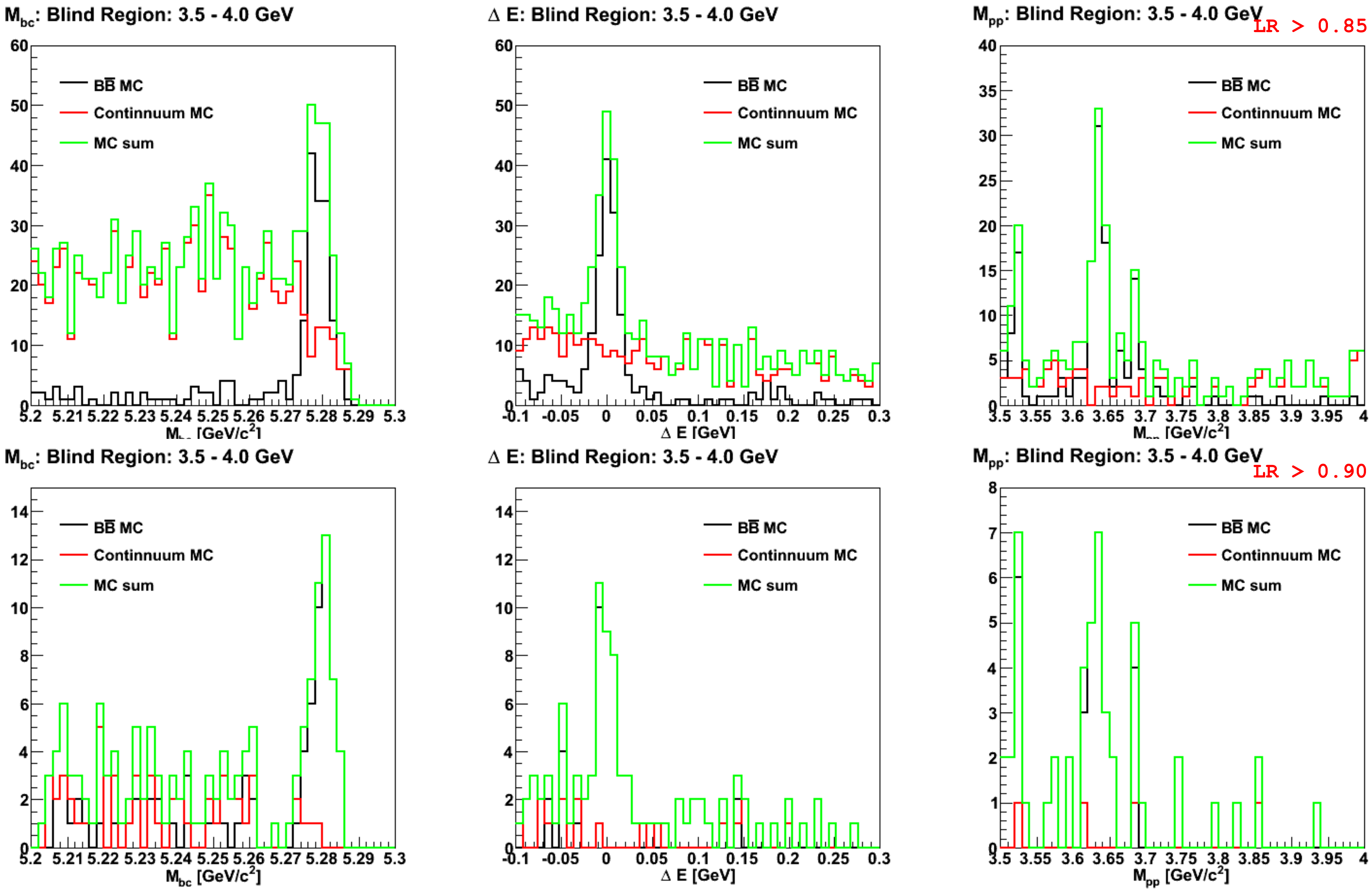


projections onto signal region

$(c\bar{c}) \to p\bar{p}$

$B^+ \to ppK^+$

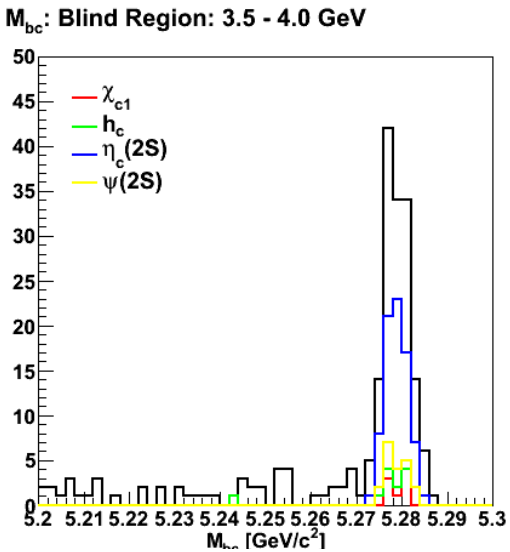
$B^0 \to ppK^0_S$

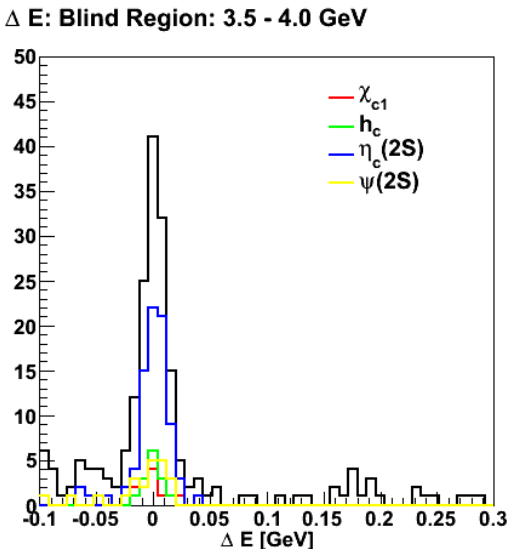


projections onto signal region

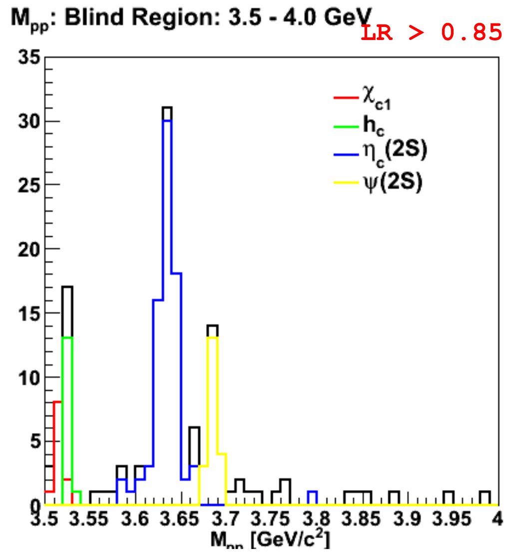
BB Generic MC $(c\bar{c}) \to p\bar{p}$

$B^+ \to p\bar{p}K^+$

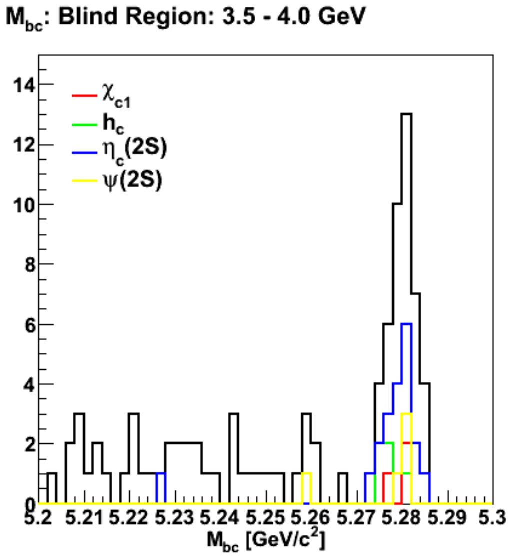


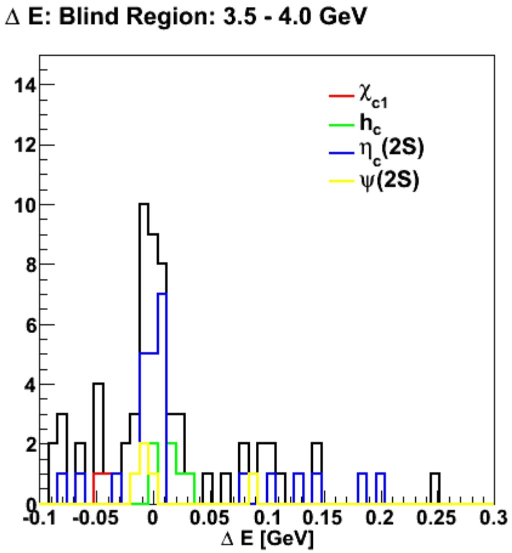


LR > 0.85

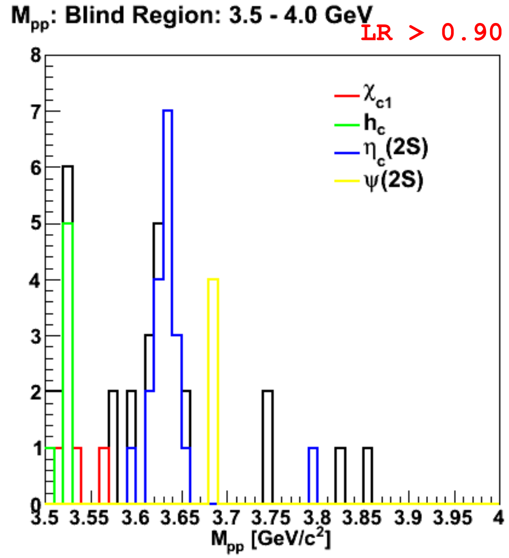


$B^0 \to p\bar{p}K^0_S$





LR > 0.90



projections onto signal region