# Probing rare B meson decays

Vipin Gaur

Tata Institute of Fundamental Research, Mumbai

**7 April 2016**

# Outline

- Introduction
- Study of
  - $B^0 \rightarrow \eta\,\pi^0$ — PRD **92**, 011101(R) (2015)
  - $B_s^0 \rightarrow K^0\overline{K}^0$ — arXiv:1512.02145 **(To appear in PRL)**
  - $B \rightarrow \phi\,\phi\,K$
  - $B^\pm \rightarrow K_S^0 K_S^0 h^\pm$
- Summary

# $B^0 \to \eta\,\pi^0$

- Highly suppressed decay: proceeds mainly via $b \to u$ Cabibbo- & colour-suppressed tree diagram and $b \to d$ penguin
- Predicted BF is (2-12) x $10^{-7}$

A.R. Williamson et al, PRD **74**, 014003 (2006) H. Wang et al, Nucl. Phys. **B738**, 243 (2006)

- The BF can be used to constrain isospin-breaking effects on the value of CP violating phase $\sin 2\phi_2$ measured in $B \to \pi\pi$

M. Gronau et al, PRD **71**, 074017 (2005) S. Gardner, PRD **72**, 034015 (2005)

- It can also help constrain CP violating parameters governing the time dependence ($S_{CP}$) of $B^0 \to \eta' K^0$

M. Gronau et al, PLB **596**, 107 (2004) M. Gronau et al, PRD **74**, 093003 (2006)

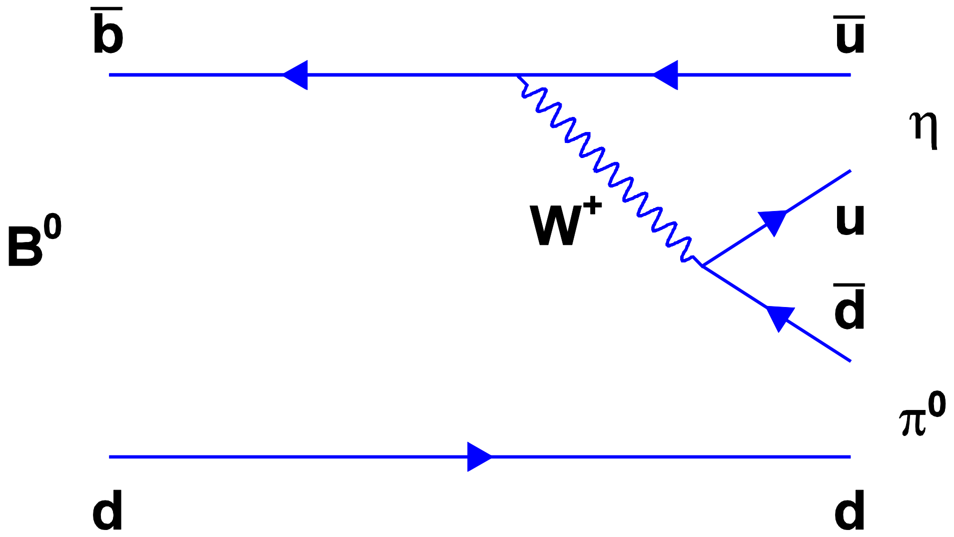
- Previous experimental status:

BF ($B^0 \to \eta\pi^0$) $< 2.5 \times 10^{-6}$ at 90% CL (140 fb$^{-1}$)

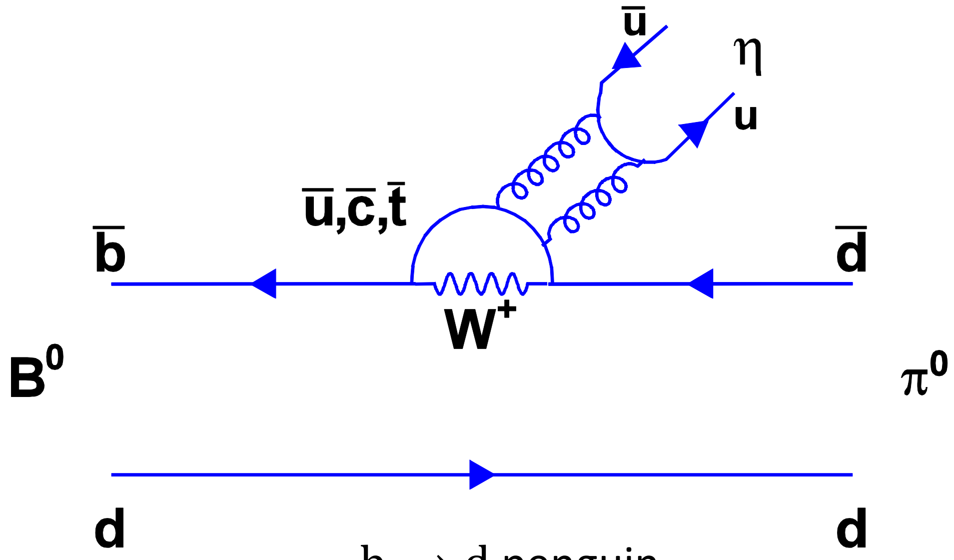
PRD **71**, 091106(R) (2005)

BF ($B^0 \to \eta\pi^0$) $< 1.5 \times 10^{-6}$ at 90% CL (418 fb$^{-1}$)

PRD **78**, 011107(R) (2008)




$b \to u$ tree diagram




$b \to d$ penguin

- Candidate η mesons are reconstructed via
  - $\eta \rightarrow \gamma\gamma$
  - $\eta \rightarrow \pi^+\pi^-\pi^0$

- Continuum background suppression: implement an NN based on 19 event-shape variables

$$C'_{NB} = \ln\left(\frac{C_{NB} - C_{NB}^{MIN}}{C_{NB}^{MAX} - C_{NB}}\right)$$

- NN output ➔ $C_{NB}$
- Translate $C_{NB}$ to $C'_{NB}$

- A simultaneous 3D fit to $M_{bc}$, $\Delta E$ and $C'_{NB}$ is performed to obtain the BF

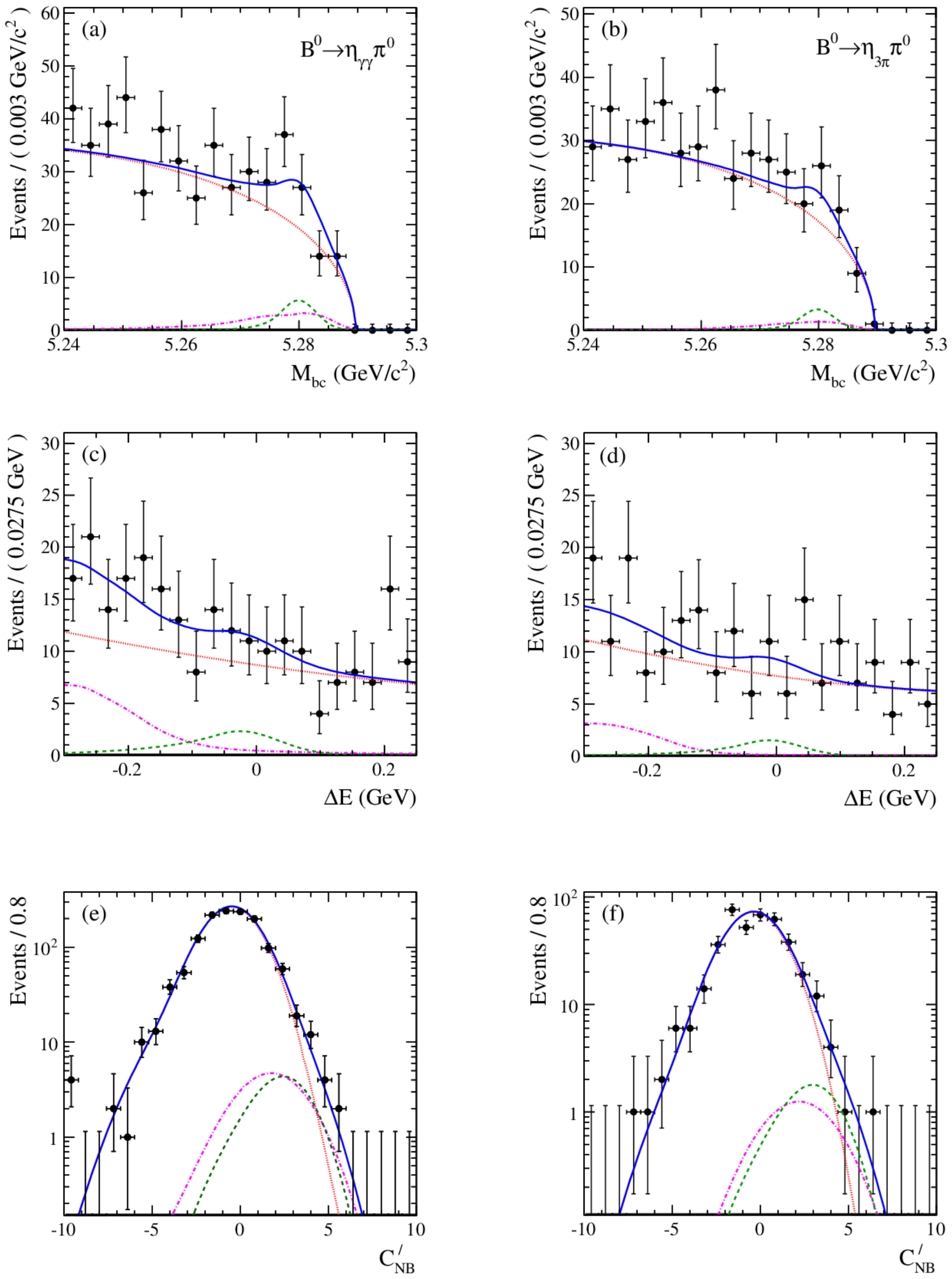
- Fit components:

Signal, Continuum background, Rare B background

- Measured BF is $(4.1^{+1.7+0.5}_{-1.5-0.7})$ x $10^{-7}$ with a significance of 3.0 standard deviations **(First evidence)**

- Upper limit: BF $(B^0 \rightarrow \eta\pi^0) < 6.5$ x $10^{-7}$ at 90% CL

694 fb$^{-1}$ 753 M $B\bar{B}$



- Isospin-breaking correction due to $\pi^0 - \eta - \eta'$ mixing to the value of $\phi_2/\alpha$ measured in $B \rightarrow \pi\pi$ is

M. Gronau et al, PRD **71**, 074017 (2005)

$$\left|(\Delta\alpha - \Delta\alpha_0)_{\pi^0-\eta-\eta'}\right| < 1.6^0 \text{ at 90\% CL}$$

- By replacing BF $(B^0 \rightarrow \eta\pi^0)$ with our measurement, we obtain

$$\left|(\Delta\alpha - \Delta\alpha_0)_{\pi^0-\eta-\eta'}\right| < 0.97^0 \text{ at 90\% CL}$$

- 40% improvement on this value with respect to the previous value

- Isospin symmetry provides triangle relations for $B \rightarrow \pi\pi$ and $\overline{B} \rightarrow \pi\pi$, which are governed by $I = 0$ and $I = 2$ amplitudes
- Allows us to extract the phase $\phi_2/\alpha = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right)$ from time-dependent CP asymmetries, $S_{\pi\pi}$ and $C_{\pi\pi}$, in $B^0(t) \rightarrow \pi^+\pi^-$
- The asymmetries determine $\sin(2\alpha_{eff}) = \frac{S_{\pi\pi}}{\sqrt{1-C_{\pi\pi}^2}}$
- The shift $\Delta\alpha = \alpha_{eff} - \alpha$ is caused by the penguin amplitude
- We define a measurable phase $\Delta\alpha_0$ in terms of angles in B and $\overline{B}$ triangles, $\phi = \mathrm{Arg}(A_{+-}A_{+0}^*)$ and $\overline{\phi} = \mathrm{Arg}(\overline{A}_{+-}\overline{A}_{-0}^*)$
- $\Delta\alpha_0 = \frac{1}{2}(\overline{\phi} - \phi)$

# $B_s^0 \to K^0\overline{K}^0$



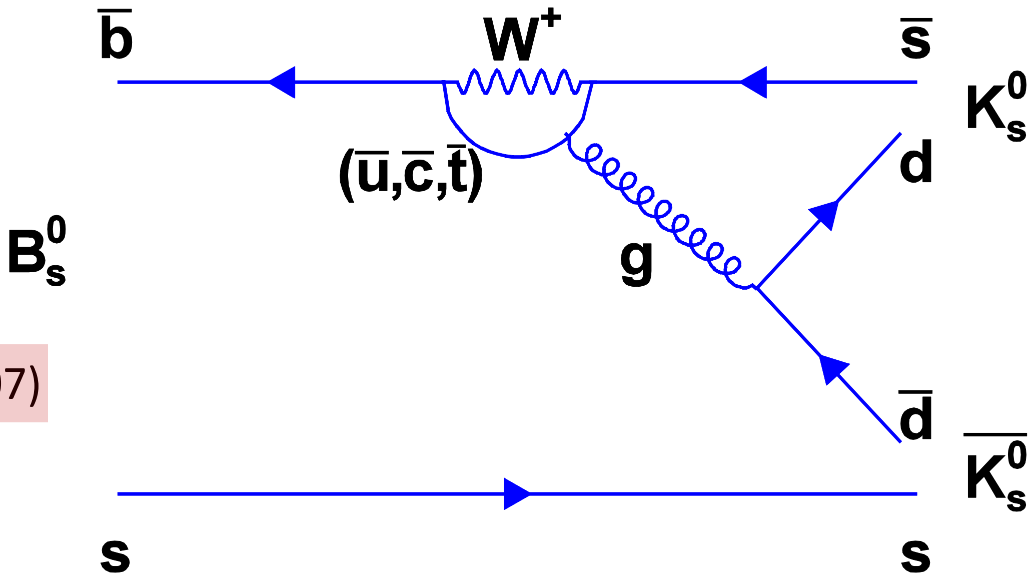
- All two body decays $B_s^0 \to h^+h'^-$ (where $h'$ is either a π or K) have now been observed except for the neutral combinations

- $B_s^0 \to K^0\overline{K}^0$ is of particular interest because of its large predicted BF $(1.6 - 2.7)$ x $10^{-5}$

  C.H. Chen, PLB **520**, 33 (2001) | A. Ali et al, PRD **76**, 074018 (2007)

- The presence of non-SM particles or couplings may enhance the BF up to $3.0$ x $10^{-5}$

  Q. Chang et al, J. Phys. G: Nucl. Part. Phys. **41**, 105002 (2014)




The decay proceeds mainly via $\overline{b} \to \overline{s}$ penguin

- Direct CP asymmetry ($A_{CP}$) of this decay mode is a promising observable to search for new physics (NP)

- $A_{CP}$ is not more than 1% in SM, but can be 10 times larger in presence of SUSY while the BF remains unaffected

  A. Hayakawa et al, PTEP 2014, 023B04 | S. Baek et al, JHEP12 (2006) 019

- Previous experimental status: $\mathrm{BF}(B_s^0 \to K^0\overline{K}^0) < 6.6$ x $10^{-5}$ at 90% confidence level

  PRD **82**, 072007 (2010)

23.6 fb^-1

- Data set used corresponds to $(6.53 \pm 0.66) \times 10^6$ $B_s^0\,\overline{B}_s^0$ pairs produced in three $\Upsilon(5S)$ decay channels: $B_s^0\,\overline{B}_s^0$, $B_s^{*0}\,\overline{B}_s^0 + B_s^0\,\overline{B}_s^{*0}$, and $B_s^{*0}\,\overline{B}_s^{*0}$

- $K^0$ mesons are reconstructed via the decay $K_S^0 \rightarrow \pi^+\pi^-$ based on an NN technique

- Continuum background suppression: implement a second NN that distinguishes jet-like continuum events from spherical $B_s^{(*)0}\,\overline{B}_s^{(*)0}$ events based on 19 event-shape variables

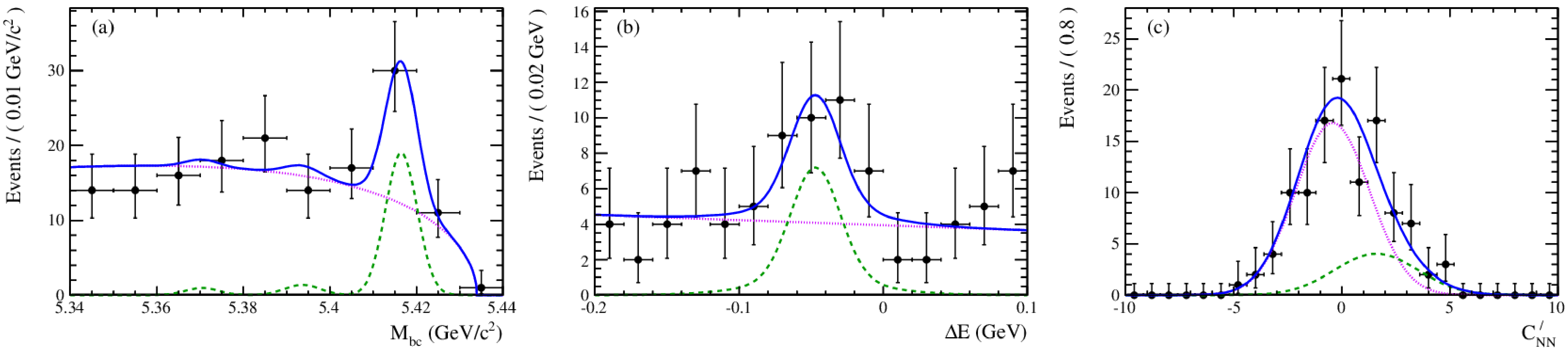
  - NN output ➔ $C_{NN}$
  - Translate $C_{NN}$ to $C'_{NN}$

$$C'_{NN} = \ln\left(\frac{C_{NN} - C_{NN}^{MIN}}{C_{NN}^{MAX} - C_{NN}}\right)$$

$$BF(B_s^0 \rightarrow K^0\,\overline{K}^0) = \frac{Y_s}{2\,.\,N_{B_s^0\,\overline{B}_s^0}\,.\,(0.5)\,.\,BF_{K^0}^2\,.\,\varepsilon}$$

- $Y_s$ is the fitted signal yield, $BF_{K^0} = (69.20 \pm 0.05)\%$ is the BF for $K_S^0 \rightarrow \pi^+\pi^-$, ε = (46.3 ± 0.1)% is the signal efficiency, factor 0.5 accounts for 50% probability for $K^0\,\overline{K}^0 \rightarrow K_S^0\,K_S^0$, and ε is corrected for a factor 1.01 ± 0.02 for each $K_S^0$

# Signal enhanced projection plots




- A 3D $\Delta E - M_{bc} - C'_{NN}$ fit is performed to extract the signal yield
- Fit components: signal and continuum background
- Observed $29.0^{+8.5}_{-7.6}$ signal events with a significance exceeding 5 standard deviations including systematic uncertainty
- $BF\,(B_s^0 \rightarrow K^0\,\overline{K}^0) = \left(19.6^{+5.8}_{-5.1}\,(\text{stat}) \pm 1.0\,(\text{syst}) \pm 2.0\,(N_{B_s^0\,\overline{B}_s^0})\right)\ \text{x}\ 10^{-6}$

121.4 $fb^{-1}$ data collected at the $\Upsilon(5S)$ resonance

# $B \to \phi\,\phi\,K$

- The penguin & tree amplitudes may interfere if $m_{\phi\phi}$ is within the $\eta_c$ resonance region
- No *CP* violation is expected from the interference within SM as the relative weak phase between these amplitudes arg $(V_{tb}\, V^*_{ts} / V_{cb}\, V^*_{cs}) \approx 0$
- *NP* contributions to the penguin loop in $B \to \phi\phi K$ decay could introduce a non zero relative *CP* violating phase
- For $B^{\pm} \to \phi\phi K^{\pm}$ statistical significance of *CP* violation can exceed 5 standard deviations with $10^9$ B mesons

M. Hazumi, PLB 583 (2004) 285-292

- $B \to \phi\phi K$ may be sensitive to glueball production in B decays

C-K. Chua, PLB 544 (2002) 139-144

- Experimental status:

$BF(B^+ \to \phi\phi K^+) = (5.6 \pm 0.5 \pm 0.3) \times 10^{-6}$ $(464 \times 10^6)$

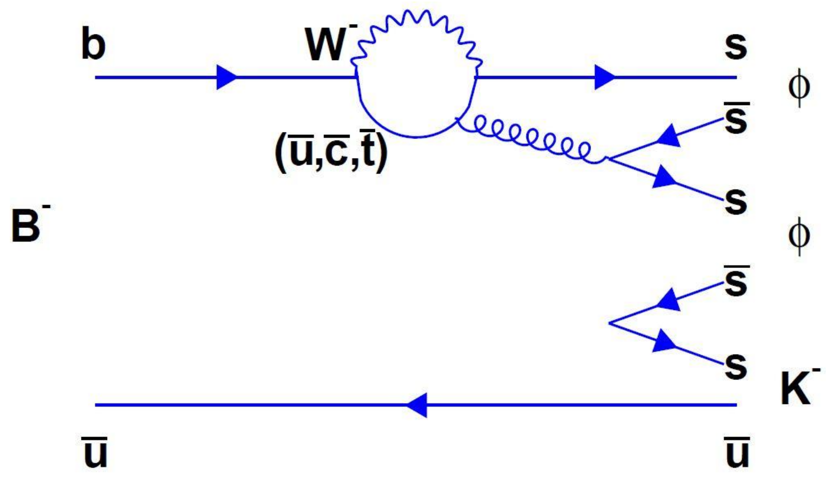
$BF(B^0 \to \phi\phi K^0) = (4.5 \pm 0.8 \pm 0.3) \times 10^{-6}$ J.P. Lees, PRD **84**, 012001 (2011)

$(78\ fb^{-1})$

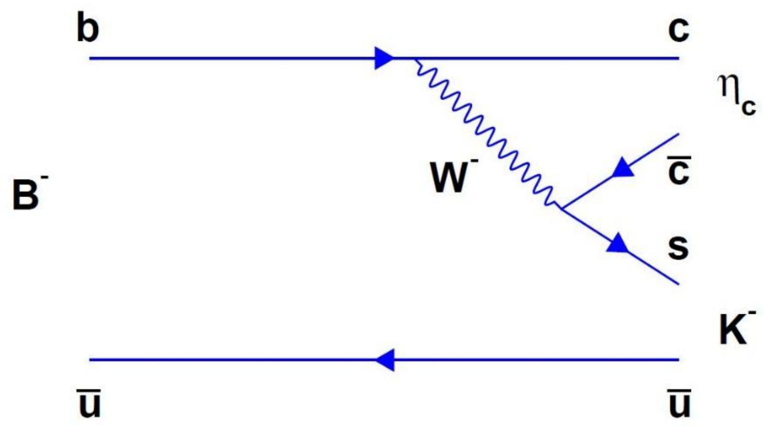
$BF(B^{\pm} \to \phi\phi K^{\pm}) = (2.6^{+1.1}_{-0.9} \pm 0.3) \times 10^{-6}$ H.C. Huang, PRL **91**, 241802 (2003)

(For $\phi\phi$ invariant mass below 2.85 GeV/$c^2$)

- Possible SM amplitude contributing to the decay
- Allows us to search for a new *CP* violating phase



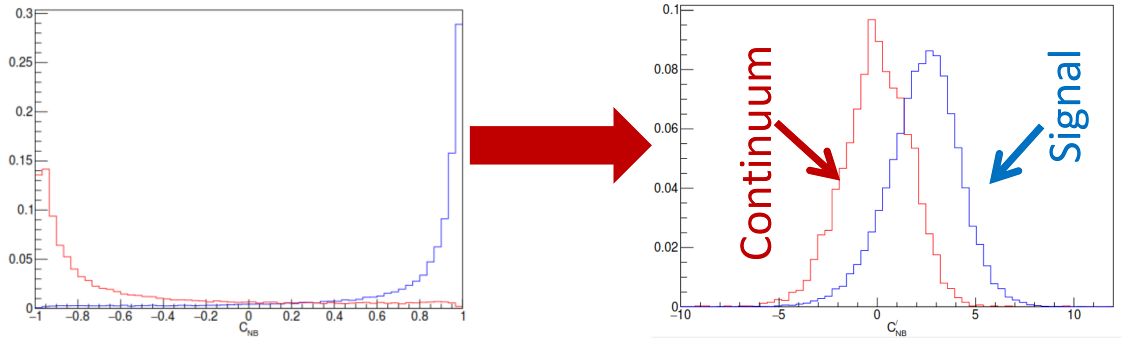

- Final state can also occur through $B \to \eta_c K$, $\eta_c \to \phi\phi$



- ❑ Reconstruct $B^+ \rightarrow \phi\phi K^+, \phi \rightarrow K^+K^-$

- ❑ Continuum background suppression: implement an NN that distinguishes jet-like continuum events from spherical $B\overline{B}$ events based on 7 event-shape variables

  - ➢ NN output ➔ $C_{NB}$
  - ➢ Translate $C_{NB}$ to $C'_{NB}$




$$C'_{NB} = \ln\left(\frac{C_{NB} - C_{NB}^{MIN}}{C_{NB}^{MAX} - C_{NB}}\right)$$

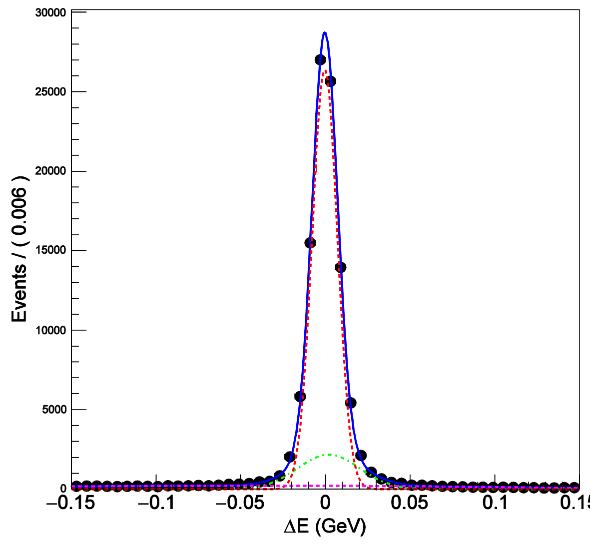
- ❑ Easy to model Gaussian like shape, relative signal efficiency is 90 % & continuum suppression is close to 87 %

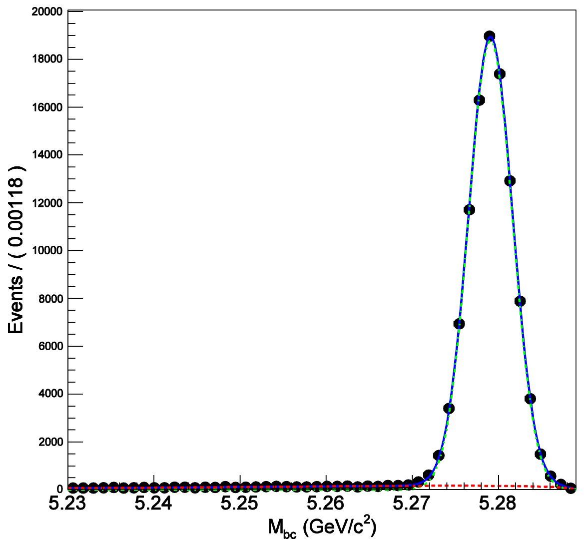
- ❑ We intend to perform a 3D $\Delta E - M_{bc} - C'_{NB}$ fit for extracting signal yield

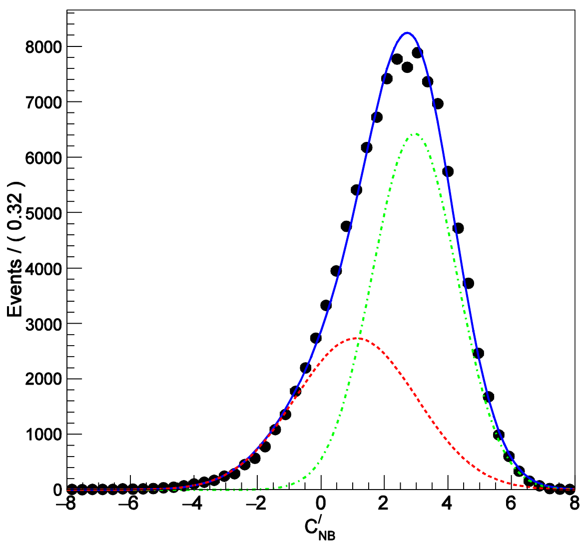
- ❑ The fit shall have following components:

  - ➢ Signal
  - ➢ Continuum background
  - ➢ Generic B background (Due to B decays via the dominant $b \rightarrow c$ transition)

# 3D ΔE-$M_{bc}$-$C'_{NB}$ fit for signal component




2 Gaussian with common mean
+
$1^{st}$ order Chebychev polynomial

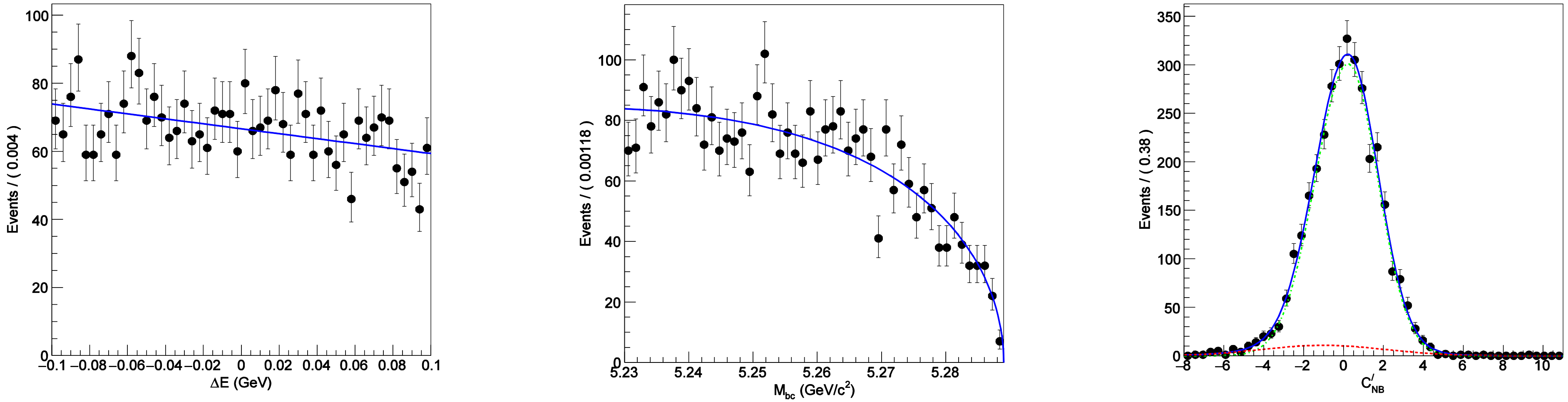
X

Gaussian
+
Argus

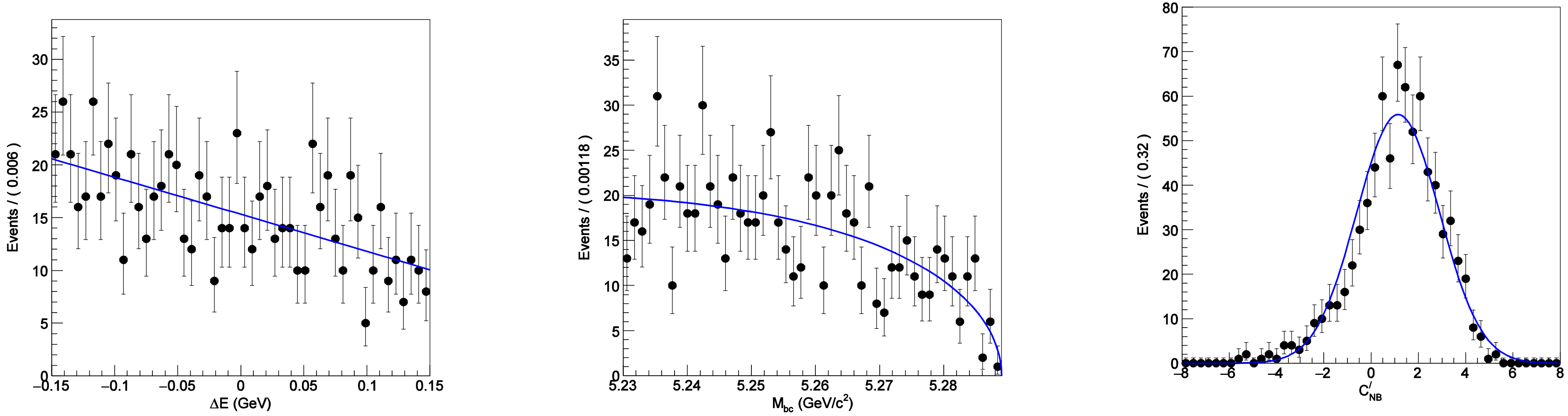
X

2 Gaussian with different mean

# 3D $\Delta E$-$M_{bc}$-$C'_{NB}$ fit for continuum component



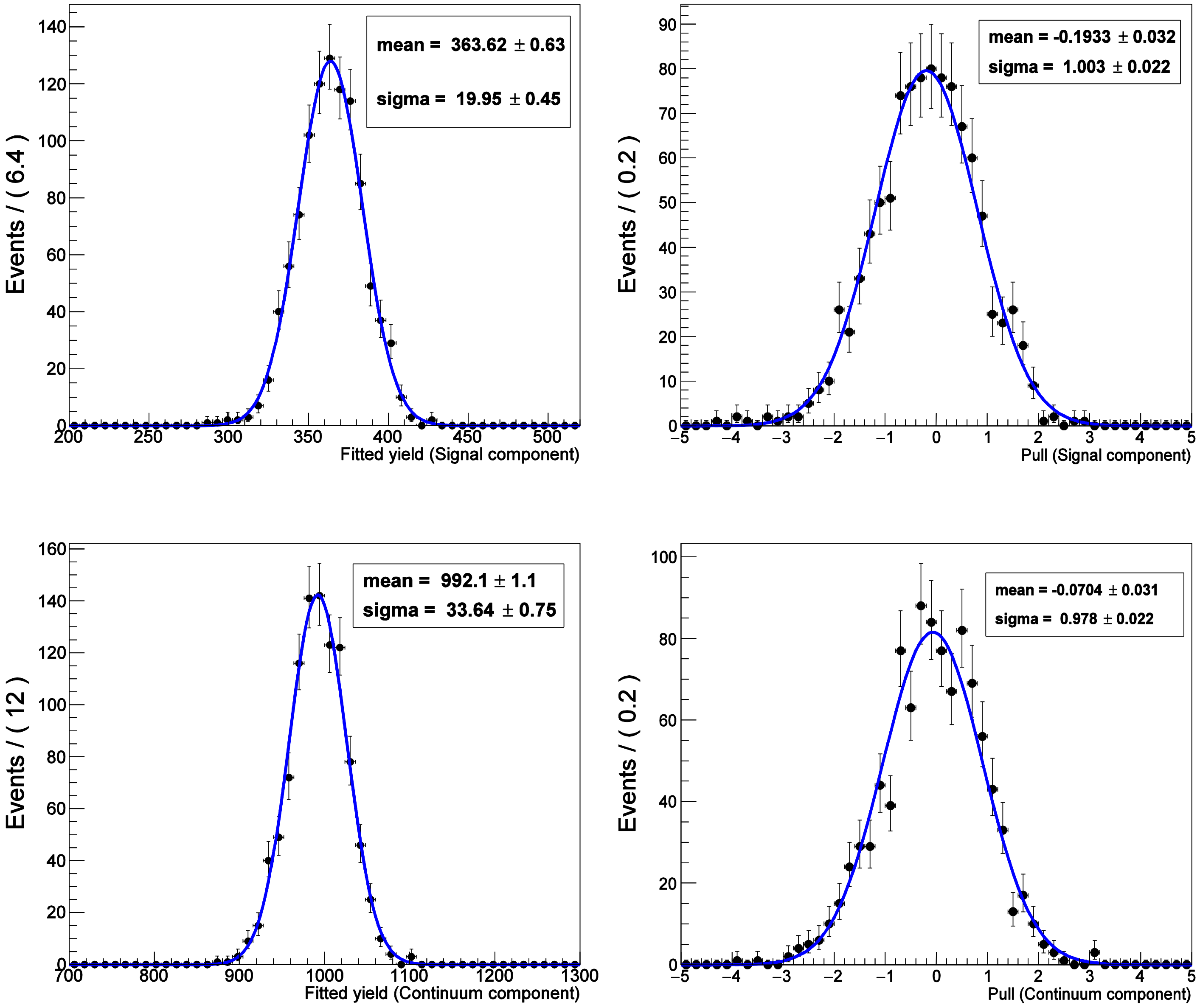

# 3D $\Delta E$-$M_{bc}$-$C'_{NB}$ fit for generic B component



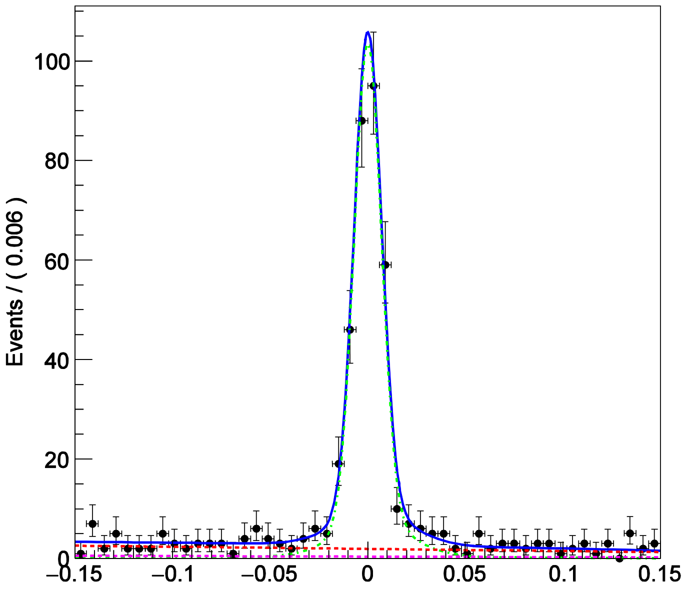

Chebychev poly. X Argus X Gaussian

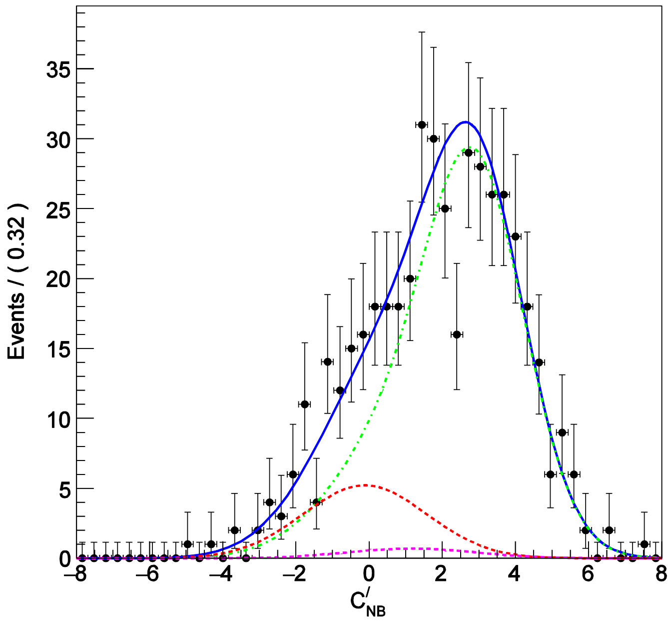
# Pure TOY

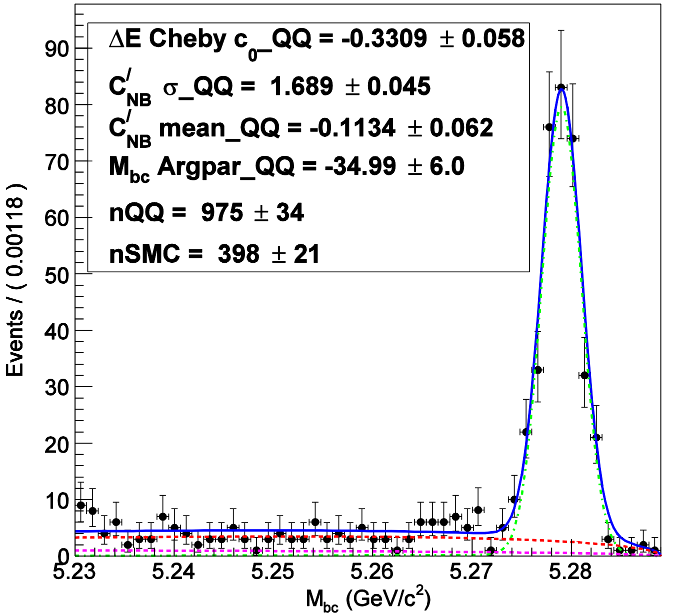
- We prepare an ensemble of 1000 pseudo-experiments, each having a data set of similar size to what is expected in the full ϒ(4*S*) sample
- PDF shapes are used to generate these toy datasets.
- We then fit to the ensemble of pseudo-experiments to check for the error coverage and any pre-set bias
- If none of them were present, we would expect the fit to yield a Gaussian distribution with zero mean and unit width for each of the floated parameters



# Signal enhanced projection plots




**Components:**

1. Signal
2. Continuum background
3. Generic B background

## $\Delta E - M_{bc} - C'_{NB}$ 3D fit

# $B^{\pm} \rightarrow K^0_S\, K^0_S\, h^{\pm}$

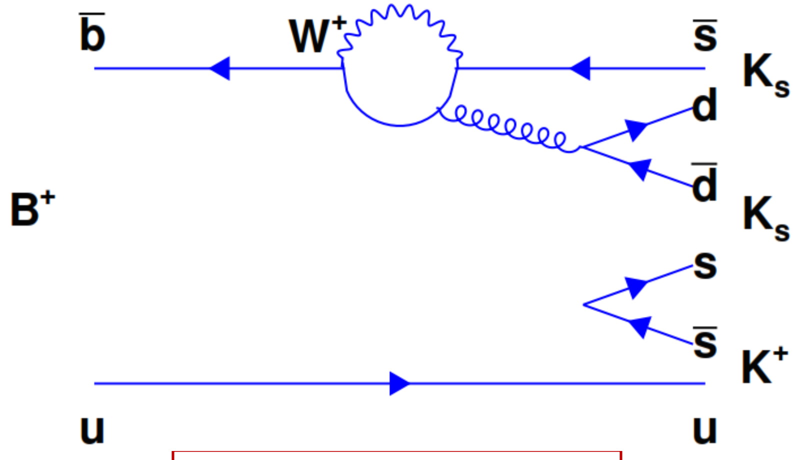
- Charmless decays of *B* mesons to three body final states:

$$B^+ \rightarrow K^0_S\, K^0_S\, K^+ \text{ (b} \rightarrow \text{s transition)}$$
$$B^+ \rightarrow K^0_S\, K^0_S\, \pi^+ \text{ (b} \rightarrow \text{d transition)}$$

- Possible to study the quasi two body resonances through the full amplitude analysis of the Dalitz plot

- Search for direct *CP* asymmetry

- Experimental status:




Suppressed in *SM*: Offers a useful probe for physics beyond *SM*

- BF($B \rightarrow K^0_S K^0_S K$) = (13.4 ± 1.9 ± 1.5) x $10^{-6}$
- Signal yield = 66.5 ± 9.3 events

78 $fb^{-1}$ data

- BF($B \rightarrow K^0_S K^0_S K$) = (10.6 ± 0.5 ± 0.3) x $10^{-6}$
- Signal yield = 636 ± 28 events
- $A_{CP}$ = $(4^{+5}_{-5} \pm 2)$ %

426 $fb^{-1}$ data

- For $B^+ \rightarrow K^0_S K^0_S \pi^+$ Belle has set a 90 % confidence level upper limit of 3.2 x $10^{-6}$ on BF
- BaBar also set an upper limit of 5.1 x $10^{-7}$ on the BF

- $K^0$ mesons are reconstructed via the decay $K_S^0 \rightarrow \pi^+\pi^-$ based on an NN technique

- Continuum background suppression: implement a second NN that distinguishes jet-like continuum events from spherical $B\overline{B}$ events based on 6 event-shape variables

  - NN output ➔ $C_{NB}$
  - Translate $C_{NB}$ to $C'_{NB}$

$$C'_{NB} = \ln\left(\frac{C_{NB} - C_{NB}^{MIN}}{C_{NB}^{MAX} - C_{NB}}\right)$$

- Easy to model Gaussian like shape, relative signal efficiency is 85 % & continuum suppression is close to 91 %

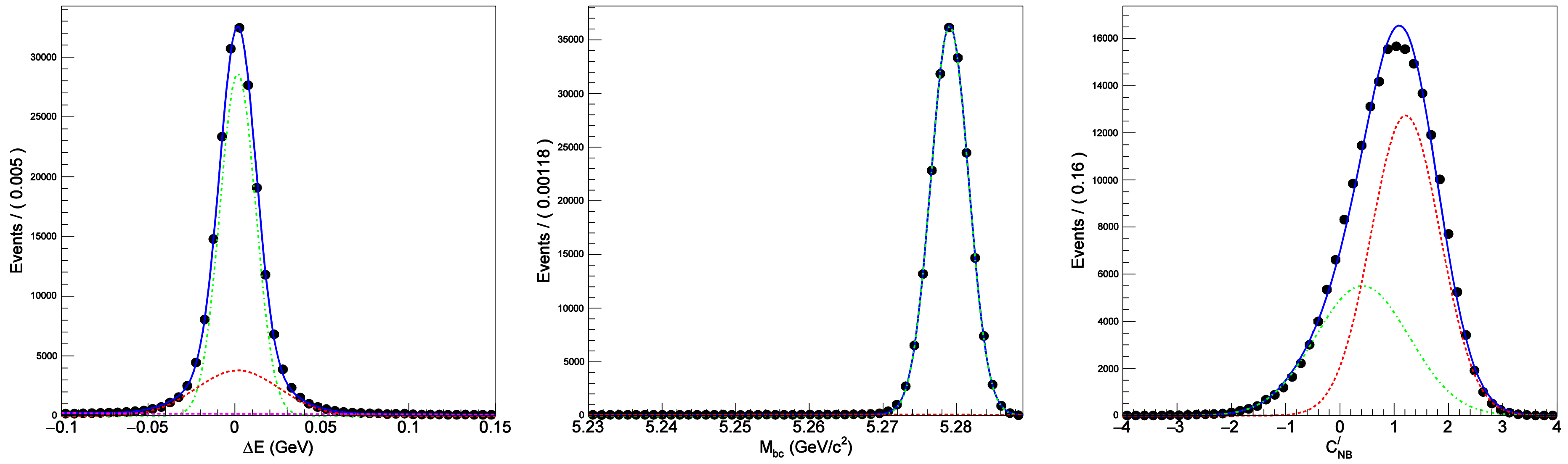
- Intend to perform a 2D $\Delta E - C'_{NB}$ fit for extracting signal yield

- Fit will include following components:

  - **Signal**
  - **Continuum background**
  - **Generic B background** (Due to B decays via the dominant b → c transition)
  - **Rare (combinatorial) B background**
  - **Rare (peaking) B background**

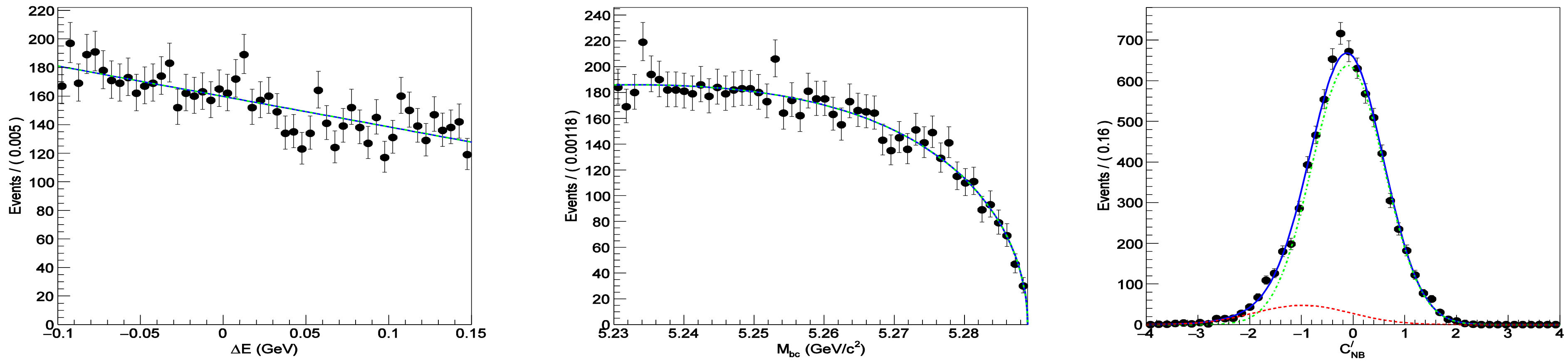
  } Due to B decays in which one of the B decays via b → u, d, s

# 3D $\Delta E$-$M_{bc}$-$C'_{NB}$ fit for signal component



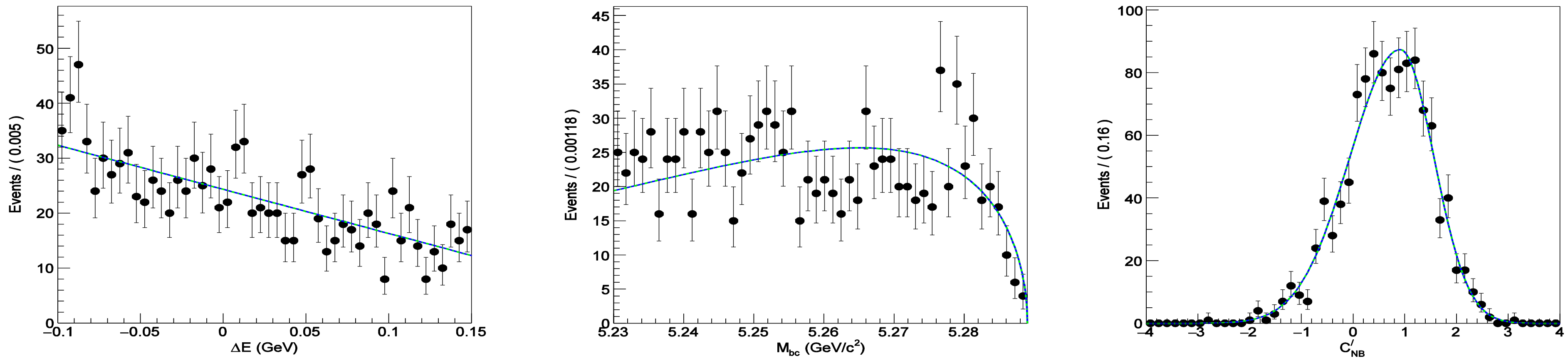

2G + Chebychev X G + Argus X 2G

# 3D $\Delta E$-$M_{bc}$-$C'_{NB}$ fit for continuum component



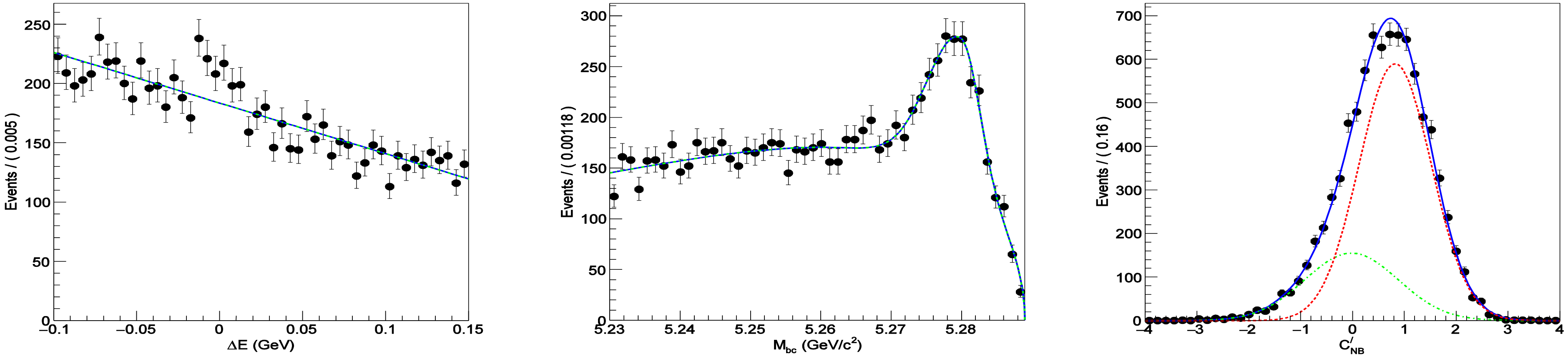

Chebychev poly. X Argus X 2G

# 3D $\Delta E$-$M_{bc}$-$C'_{NB}$ fit for generic B component



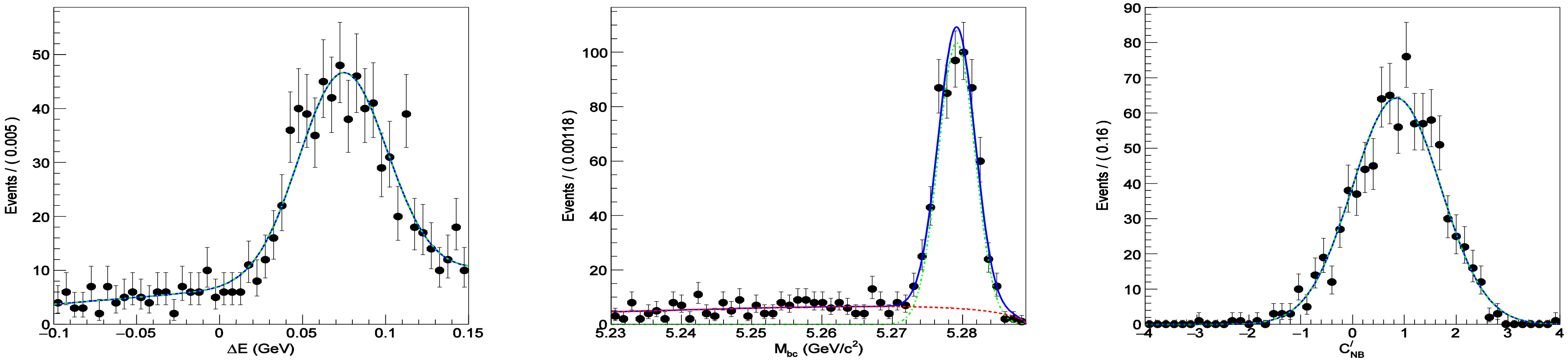

Chebychev poly. X Argus X Asymmetric Gaussian

# 3D ΔE-$M_{bc}$-$C'_{NB}$ fit for rare combinatorial component




Chebychev poly. X Asymmetric G+Argus X 2G

# 3D ΔE-$M_{bc}$-$C'_{NB}$ fit for rare peaking component




G+Chebychev poly. X G+Argus X Gaussian

# GSIM ensemble test

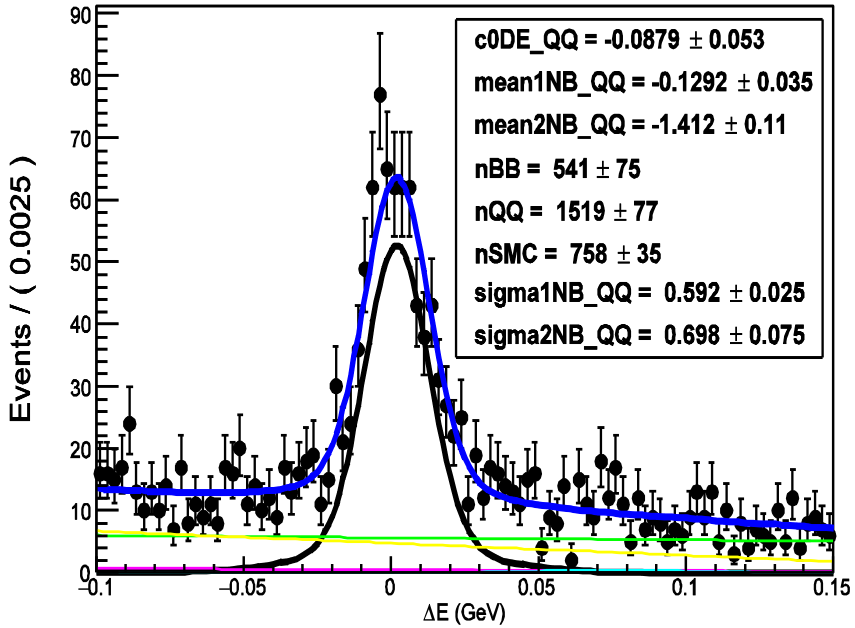
- Results of the pure toy test won't tell us if there is a bias inherent on the fit because of the unaccounted for correlation between the fit variables

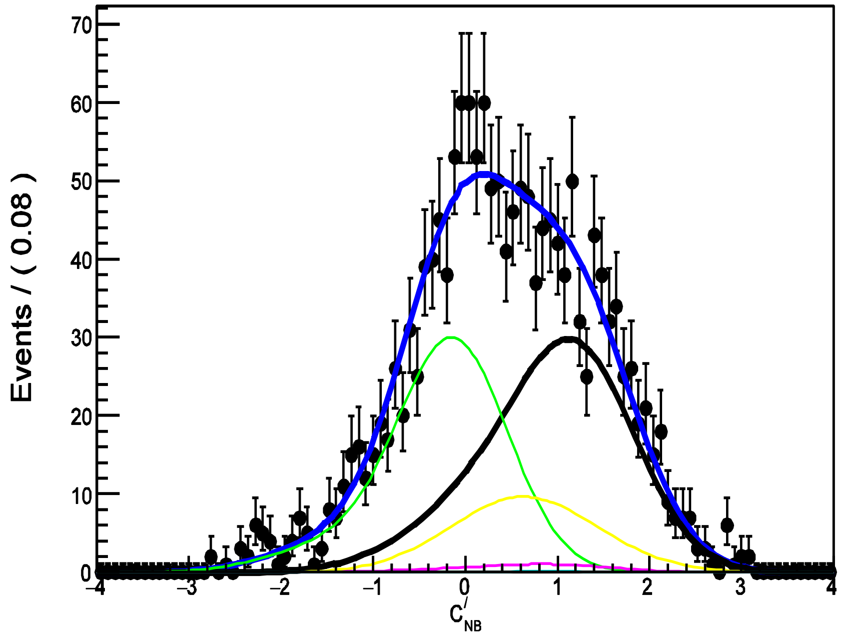
- Therefore, we perform an ensemble test comprising 250 pseudo-experiments where signal is embedded from the corresponding MC sample and PDF shapes are used to generate the dataset for all type of background events

- We also perform a linearity test where several 2D GSIM ensemble tests are carried out with an assumed signal yield ranging from 692 to 852

- This is particularly important as we do not know for sure whether our expectation of 772 would really hold in the data or not

## $\Delta E - C'_{NB}$ 2D fit



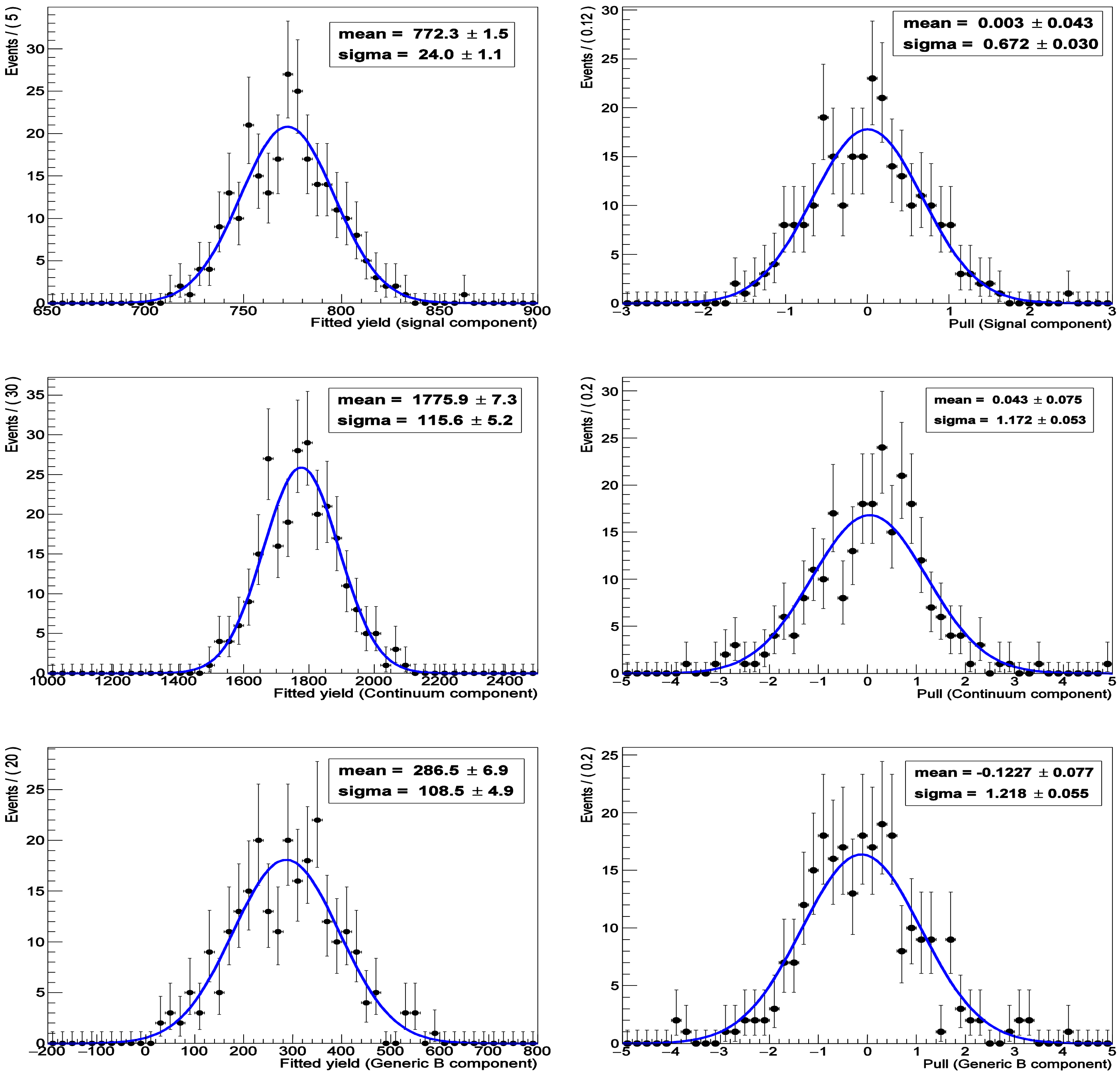



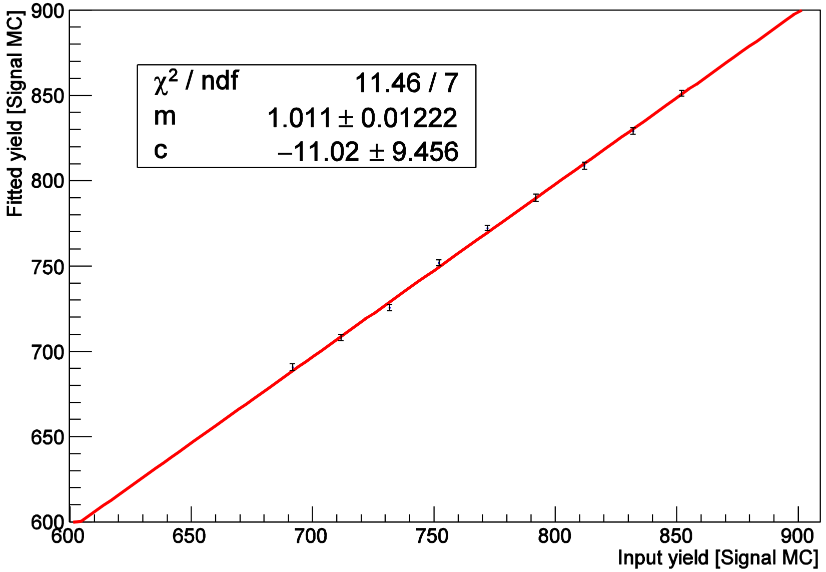

**Components:**

1. **Signal**
2. **Continuum background**
3. **Generic B background**
4. **Rare (combinatorial) B background**
5. **Rare (peaking) B background**

Signal enhanced projection plots

# GSIM ensemble test




GSIM linearity test

# Summary/To do..

- First evidence of $B^0 \rightarrow \eta\pi^0$ (3σ)
- Measured BF is $\left(4.1^{+1.7+0.5}_{-1.5-0.7}\right)$ x $10^{-7}$
- Upper limit: BF $\left(B^0 \rightarrow \eta\pi^0\right) < 6.5$ x $10^{-7}$ at 90% CL

- First observation of $B_s^0 \rightarrow K^0\,\bar{K}^0$ (5.1σ)
- $\mathrm{BF}\left(B_s^0 \rightarrow K^0\,\bar{K}^0\right) = \left(19.6^{+5.8}_{-5.1}\,(\mathrm{stat}) \pm 1.0\,(\mathrm{syst}) \pm 2.0\left(N_{B_s^0\,\bar{B}_s^0}\right)\right)$ x $10^{-6}$

- To perform GSIM ensemble test, control sample study and unblind data for B → ϕϕK

- To perform control sample study and unblind data for $B^+ \rightarrow K_S^0\,K_S^0\,K^+$


Thank You
上部作業中
頭上注意

# $B^0 \to \eta\,\pi^0$

| Source | Uncertainty (%) |
|---|---|
| PDF parametrization | +10.2<br>-9.2 |
| Fit bias | +0.0<br>-2.6 |
| $\pi^0/\eta \to \gamma\gamma$ reconstruction | 6.0 |
| Tracking efficiency | 0.3 |
| PID efficiency | 0.6 |
| $C_{NB}$ selection efficiency | +2.1<br>-2.2 |
| MC statistics | 0.4 |
| Nonresonant contributions | +0.0<br>-10.8 |
| BF($\eta \to \gamma\gamma$) | 0.5 |
| BF($\eta \to \pi^+\pi^-\pi^0$) | 1.2 |
| Number of $B\bar{B}$ pairs | 1.3 |
| Total | +12.2<br>-15.9 |

$C_{NB} > 0.1$ rejects 85% of continuum background events while retaining 90% of signal events

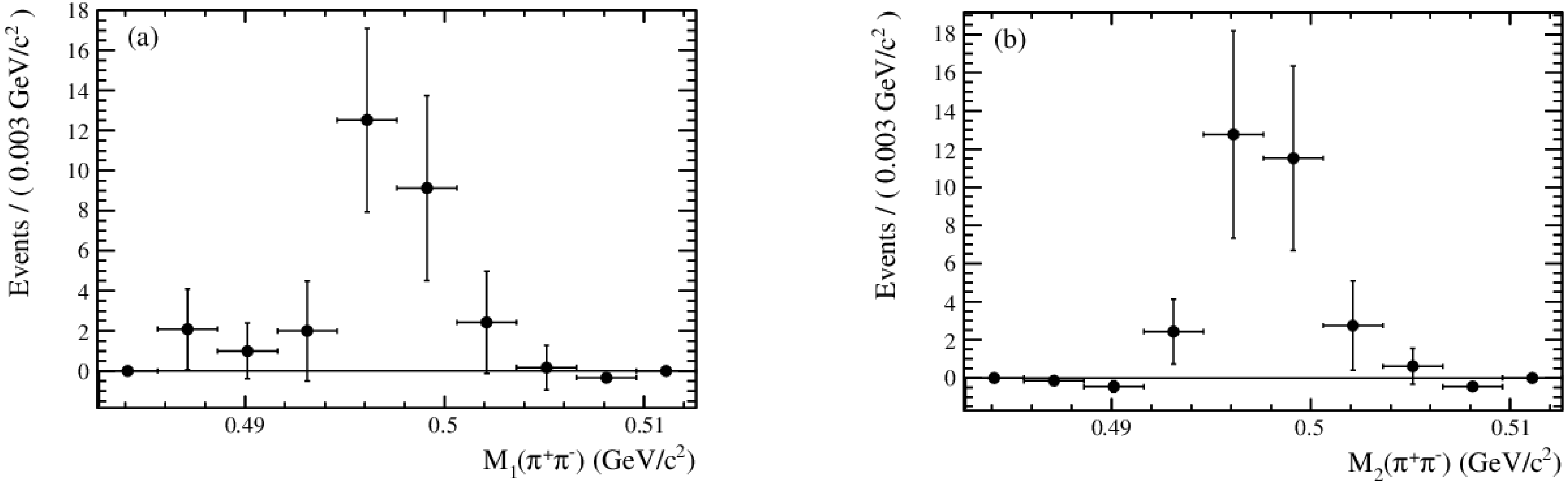
BCS is based on $\chi^2$ value resulting from η or, if necessary, $\pi^0$ mass constrained fits

Control sample:

$B^0 \to \bar{D}^0 (\to K^+ \pi^- \pi^0)\, \pi^0$
BF ($B^0 \to \bar{D}^0 \pi^0$) = (2.63 ± 0.14) x $10^{-4}$
BF ($\bar{D}^0 \to K^+ \pi^- \pi^0$) = (7.3 ± 0.5) x $10^{-4}$

This decay has four photons, as do signal decays, and its topology is identical to that of $B^0 \to \eta_{3\pi}\pi^0$

# $B_s^0 \to K^0\overline{K}^0$




- Background subtracted distributions of $M(\pi^+\pi^-)$

(a) Higher momentum $K_S^0$ candidates
(b) Lower momentum $K_S^0$ candidates

- $K_S^0$ selection is removed for $\pi^+\pi^-$ pair being plotted

- **No $B_s^0 \to K_S^0\,\pi^+\,\pi^-$ contribution is observed**

- Quantitatively checked by performing signal fit for events in the mass sidebands of each $K_S^0$ [$M(\pi^+\pi^-) \in (0.460, 0.485)\mathrm{GeV}/c^2$ and $M(\pi^+\pi^-) \in (0.510, 0.530)\mathrm{GeV}/c^2$]

- The extracted signal yields for higher and lower momentum $K_S^0$ are found to be consistent with zero

# $B_s^0 \to K^0\overline{K}^0$

| Source | Uncertainty (%) |
|---|---|
| PDF parametrization | 0.2 |
| Calibration factor | +0.9 -0.8 |
| $f_{B_s^{(*)}\overline{B}_s^{(*)}}$ | +1.2 -1.1 |
| Fit bias | +0.0 -2.6 |
| $K_S^0 \to \pi^+\pi^-$ reconstruction | 4.0 |
| $C_{NN}$ selection | 0.9 |
| MC sample size | 0.2 |
| $BF(K_S^0 \to \pi^+\pi^-)$ | 0.1 |
| Total (without $N_{B_s^0\overline{B}_s^0}$) | +4.4 -5.1 |
| $N_{B_s^0\overline{B}_s^0}$ | 10.1 |

In addition there is a 10.1% uncertainty due to the number of $B_s^0\overline{B}_s^0$ pairs. As this large uncertainty does not arise from our analysis, we quote it separately

$B_s^{*0}\overline{B}_s^0$ or $B_s^0\overline{B}_s^{*0}$ and $B_s^{*0}\overline{B}_s^{*0}$ dominate with production fractions (7.3±1.4)% and (87.0±1.7)% respectively

$K^0$ mesons are reconstructed in $K_S^0 \to \pi^+\pi^-$ with the utilization of a multivariate analysis based on a neural network which uses following

- $K_S^0$ momentum in laboratory frame
- Distance between two helices in z direction
- Flight length in the x–y plane
- Angle between $K_S^0$ momentum and the vector joining $K_S^0$ decay vertex to the IP
- Angle between pion momentum and $K_S^0$ momentum in $K_S^0$ rest frame
- Shorter distance in x–y plane between the IP and two child helices and pion hit information in the SVD and CDC

$C_{NN}$ > -0.1 rejects 85% continuum background while retaining 83% of signal

BCS is based on $\chi^2 = \left(\frac{M_{\pi\pi}-m_{K_S^0}}{\sigma_{\pi\pi}}\right)_1^2 + \left(\frac{M_{\pi\pi}-m_{K_S^0}}{\sigma_{\pi\pi}}\right)_2^2$

Control samples used:

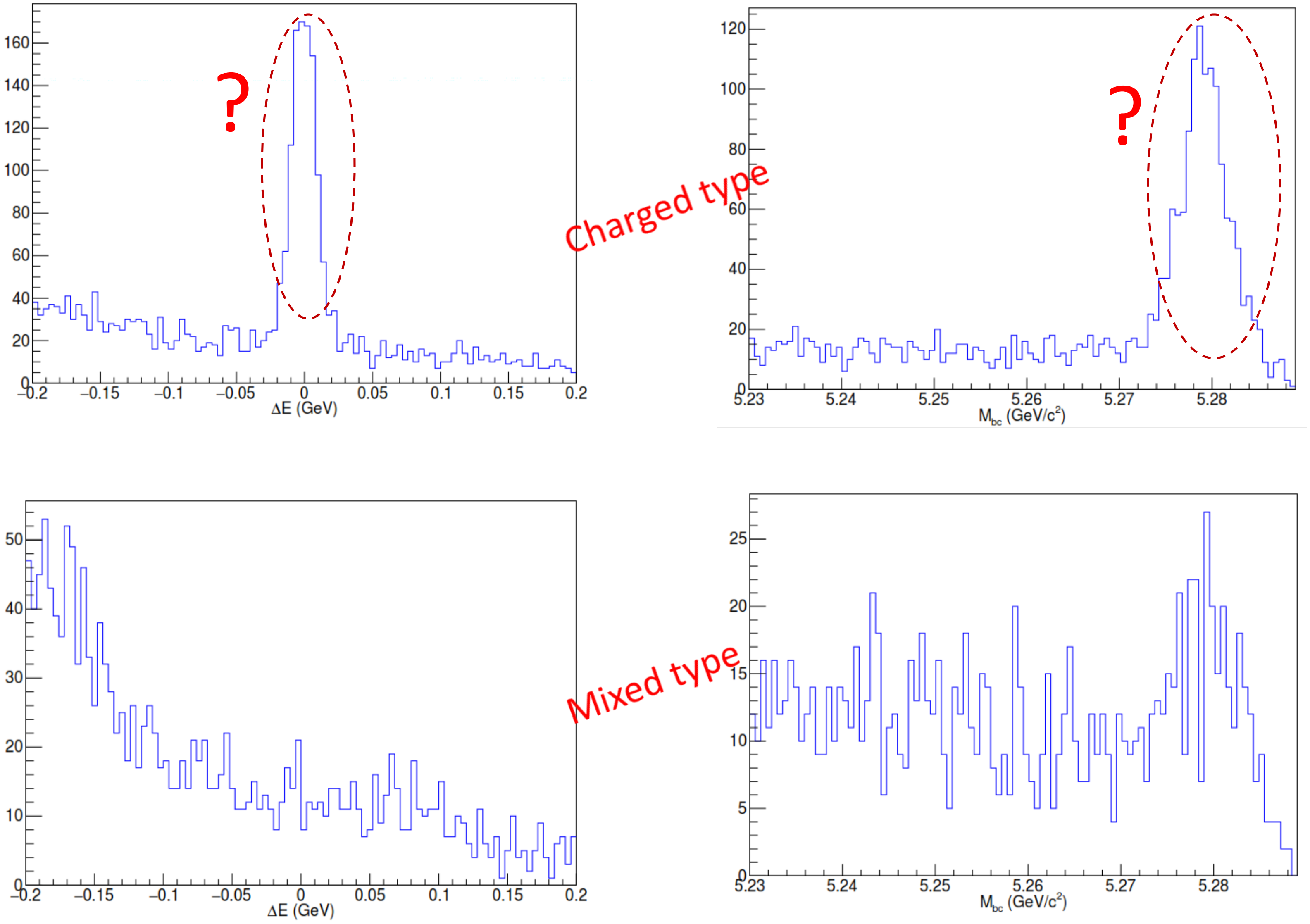
$B_s^0 \to D_s^-\pi^+$ for adjusting peak positions of $\Delta E$ and $M_{bc}$
$BF(B_s^0 \to D_s^-\pi^+) = (3.04 \pm 0.23) \times 10^{-3}$

$B^0 \to D^-(\to K^+\pi^-\pi^-)\pi^+$ for adjusting σ of ΔE, Mbc & $C'_{NN}$ and peak position of $C'_{NN}$
$BF(B^0 \to D^-\pi^+) = (2.68 \pm 0.13) \times 10^{-3}$
$BF(D^- \to K^+\pi^-\pi^-) = (5.27 \pm 0.23) \times 10^{-4}$

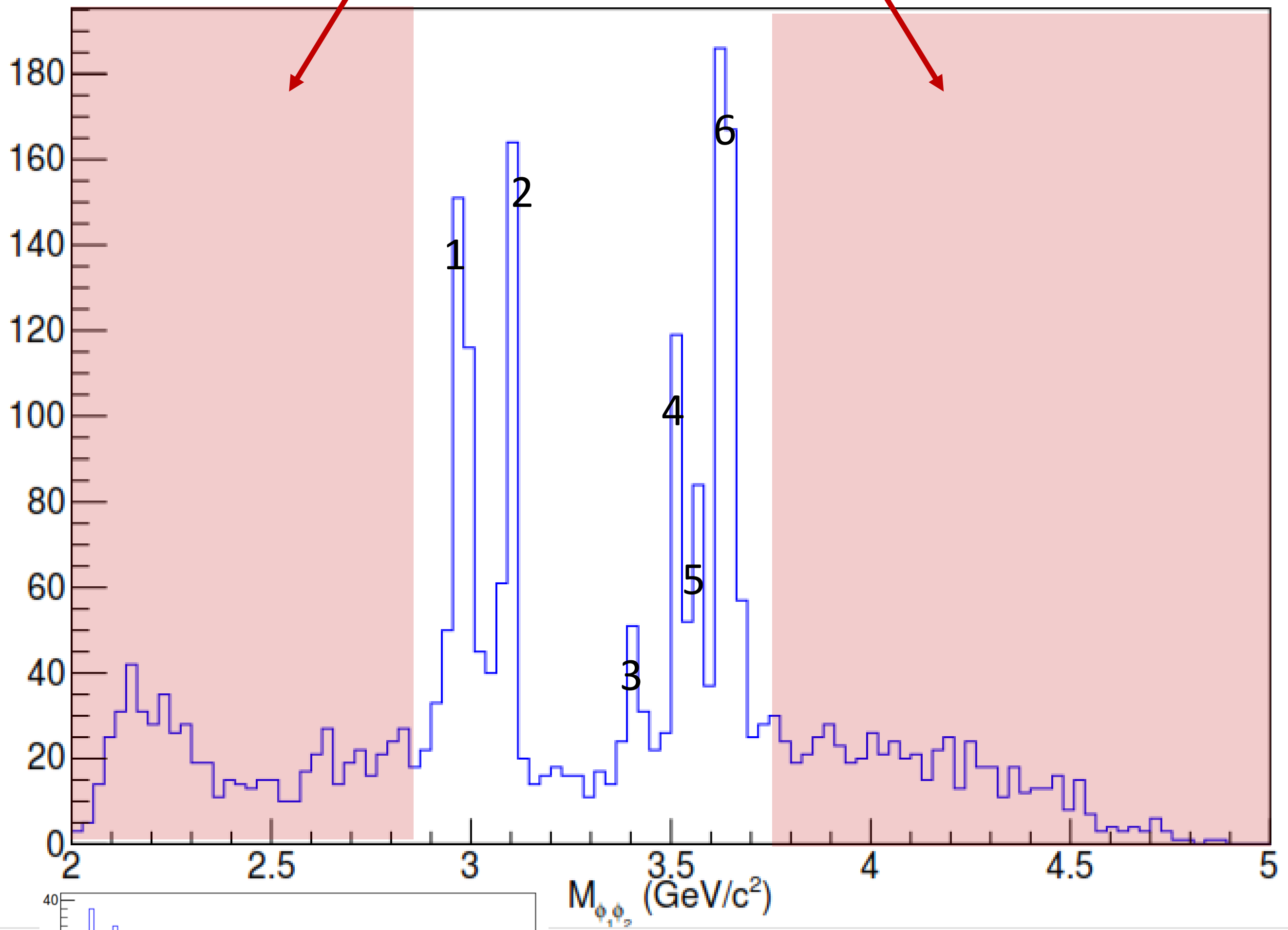
# $B \to \phi \phi K$

# B background

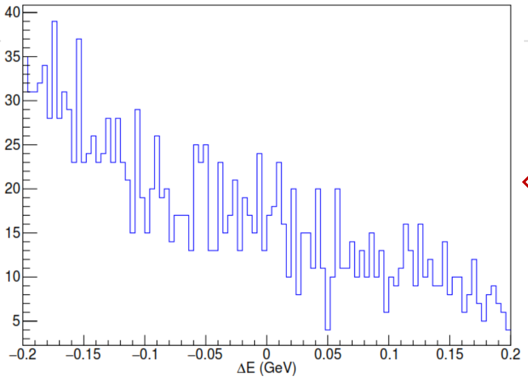
Due to B decays via the dominant
b → c transition



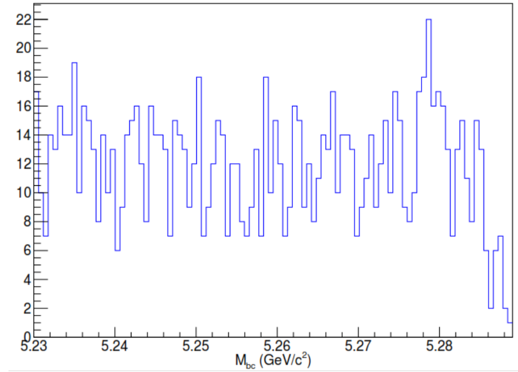
Intend to use these regions in the fit




1. $\eta_c(1S)$
2. $J/\psi(1S)$
3. $\chi_{c0}(1P)$
4. $\chi_{c1}(1P)$
5. $\chi_{c2}(1P)$ & $\psi(2S)$
6. $\eta_c(2S)$




After charm veto



$\eta_C(1S)$
Mass = 2980.3 ± 1.2 MeV and width Γ = 28.6 ± 2.2 MeV
$\eta_C(2S)$
Mass = 3637 ± 4 MeV and width Γ = 14 ± 7 MeV

The decay width of $\eta_C$ is sufficiently large to provide a sizable interference

To have the interference between resonant and direct amplitudes, invariant mass of the ϕϕ system (**m**) should be in the $\eta_C$ resonance region

To be specific, we require that the difference between m and $\eta_C$ mass (**M**) should satisfy **|m-M| < 3Γ**, where **Γ** is the width of the $\eta_C$ resonance

Control modes:

1. $B^+ \to D_s^+\overline{D_0}, D_s^+ \to \phi\pi^+, \overline{D_0} \to K^-\pi^+$ BF$[B^+ \to D_s^+\overline{D_0}, D_s^+] \to (10.0 \pm 1.7)x10^{-3}$
2. $D^0 \to K_s \pi^+ \pi^-$, $BF[K_S^0 \to \pi^+\pi^-\pi^0] = (3.5^{+1.1}_{-0.9})x10^{-7}$

BF$[D^0 \to K_s K^+ K^-] = (4.47 \pm 0.34)x10^{-3}$

control sample study

- To rely less on MC simulations but more on data for suppressing possible systematic effects
- Choose a decay process that has advantage of a large BF but at the same time does not suffer from background that much
- It has a similar topology as our signal decay

- $B \to \phi\phi K$ is sensitive to potential glueball production
- (example $2^{++}$ tensor with $m_\xi$ ~ 1.9 – 2.3 GeV)
- Thus it may provide us useful information for understanding quark fragmentation in B decays
- Simple modeling shows that $BF(B \to \xi K)\ BF(\xi \to p\bar{p},\ p\bar{p} \to \phi\phi)$ ~ $1 \times 10^{-6}$ and $\xi$ appears as a spike in the $p\bar{p}$ spectrum with ~ 30 events per 100 $fb^{-1}$

With $464 \times 10^6$ BB-bar pairs
$B^+$ yield $(\phi\phi K^{\pm}) = 225 \pm 21$
$B^0$ yield $(\phi\phi K^0_S) = 52 \pm 10$

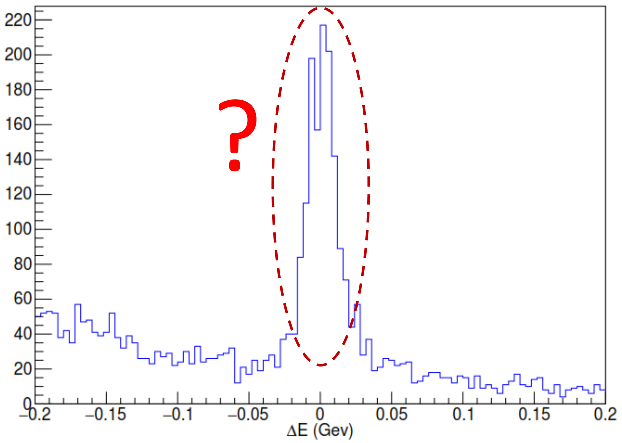
374
86

- We use an event generator that is based on LUND fragmentation model for the estimation of $BF_{NP}$
- The model tells how a multiparton jet system is allowed to fragment
- Assume BF($b \rightarrow sg^* \rightarrow s\bar{s}s$)] ≈ 1%
- Use the default value of $s\bar{s}$ popping probability in JETSET7.4, which is consistent with the ratio of the BF between $B \rightarrow J/\psi\ K\ \phi$ and $B \rightarrow J/\psi\ K$
- We estimate $BF_{NP}$ to be ≈ 5 x $10^{-6}$ for BF($b \rightarrow sg^* \rightarrow s\bar{s}s$)] = 1%

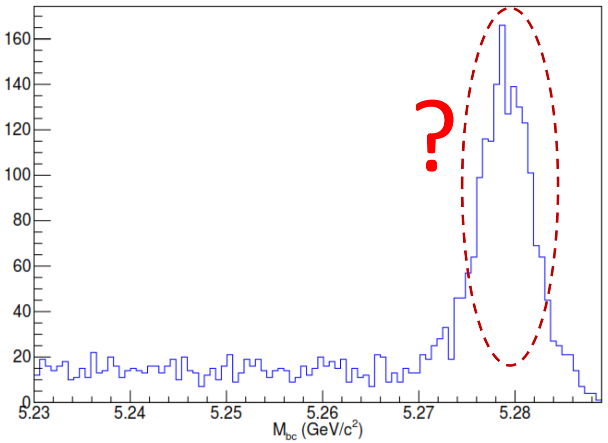
# $B^{\pm} \to K_s^0\ K_s^0\ h^{\pm}$

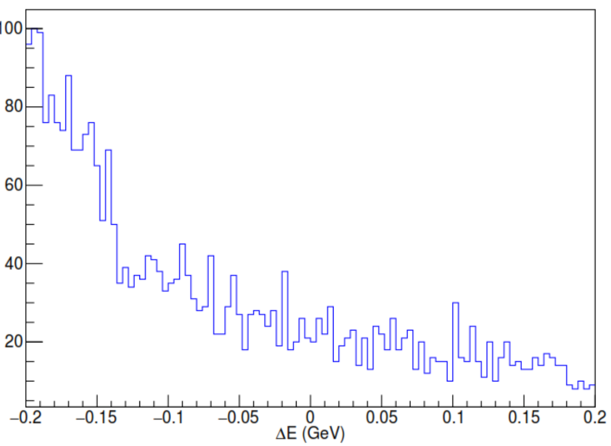
# B background

Due to B decays via the dominant
b → c transition

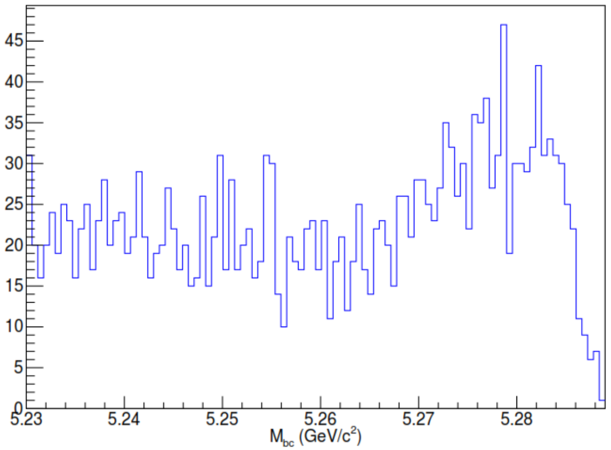


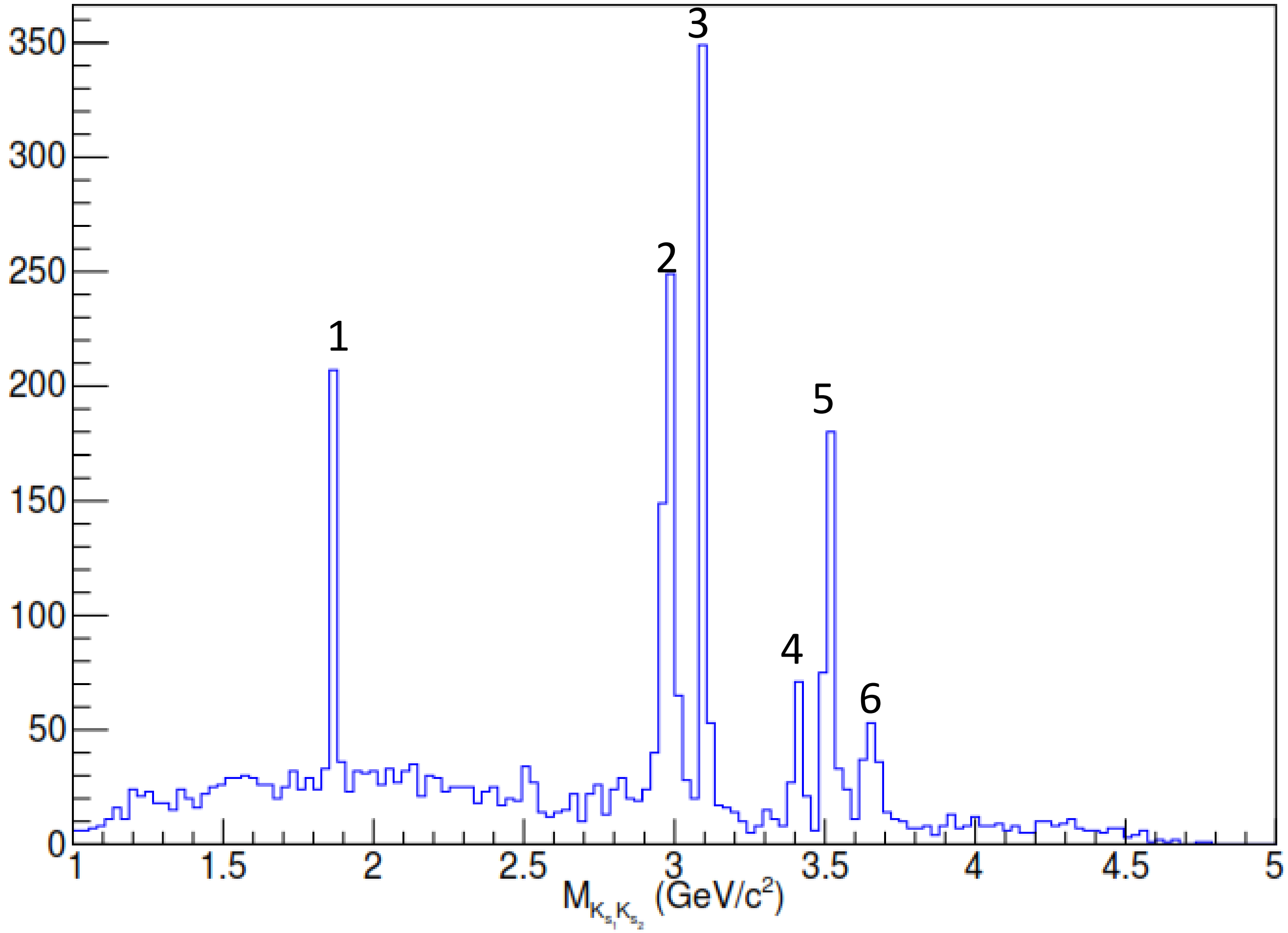

Charged type



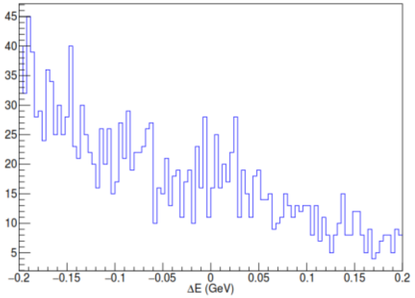




Mixed type

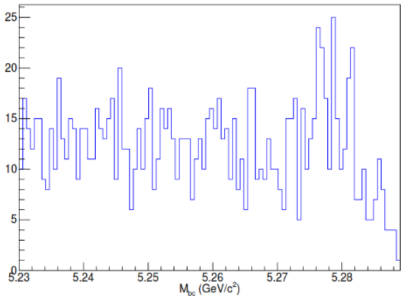





1. $D^0$
2. η(1S)
3. J/ψ(1S)
4. $\chi_{c0}$(1P)
5. $\chi_{c2}$(1P)
6. ψ(2S)

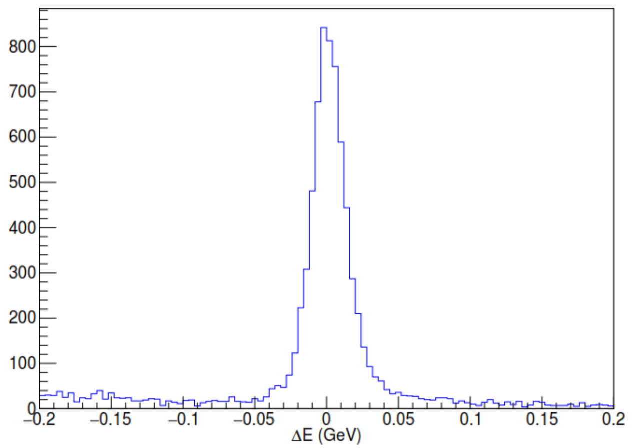



After charm veto

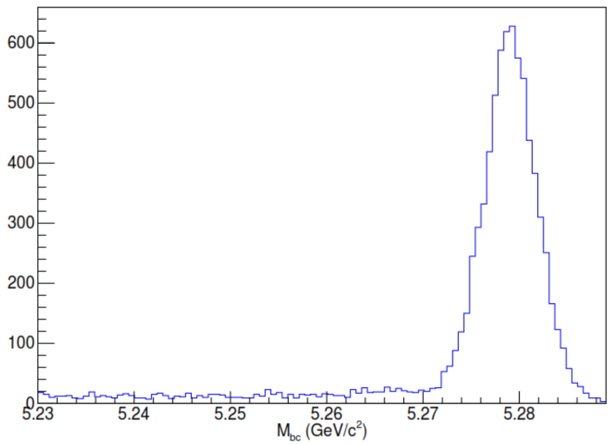


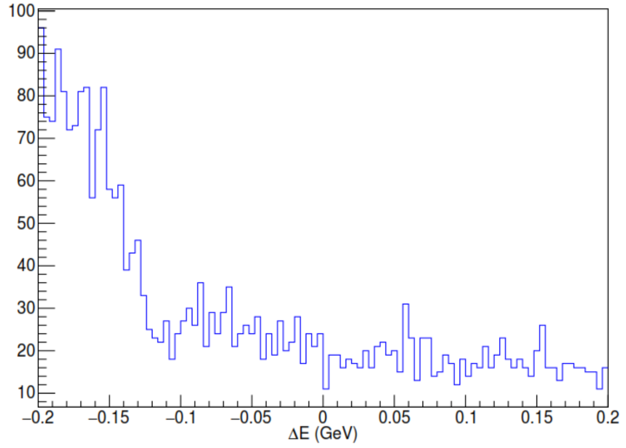
# B background

Due to B decays in which one of the B decays via b → u, d, s

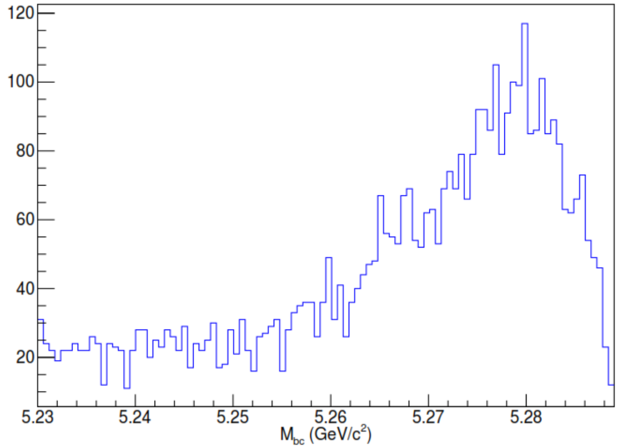



Charged type



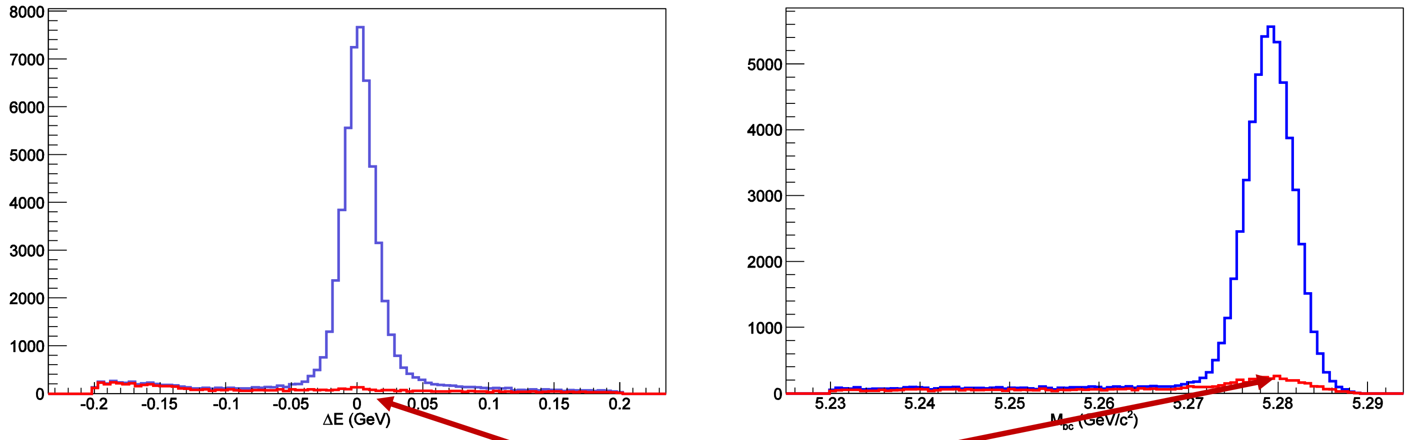




Mixed type



# Rare B background
# Charged type MC

| Signal modes | % contribution |
|---|---|
| $B \to K_s\, K_s\, K$ | 64 |
| $B \to f_0(1370)\, K$ | 3.62 |
| $B \to f_2'(1500)\, K$ | 2.68 |




**After removing signal modes**

Pure TOY

- We prepare an ensemble of 250 pseudo-experiments, each having a data set of similar size to what is expected in the full $\Upsilon(4S)$ sample

- PDF shapes are used to generate these toy datasets.

- We then fit to the ensemble of pseudo-experiments to check for the error coverage and any pre-set bias

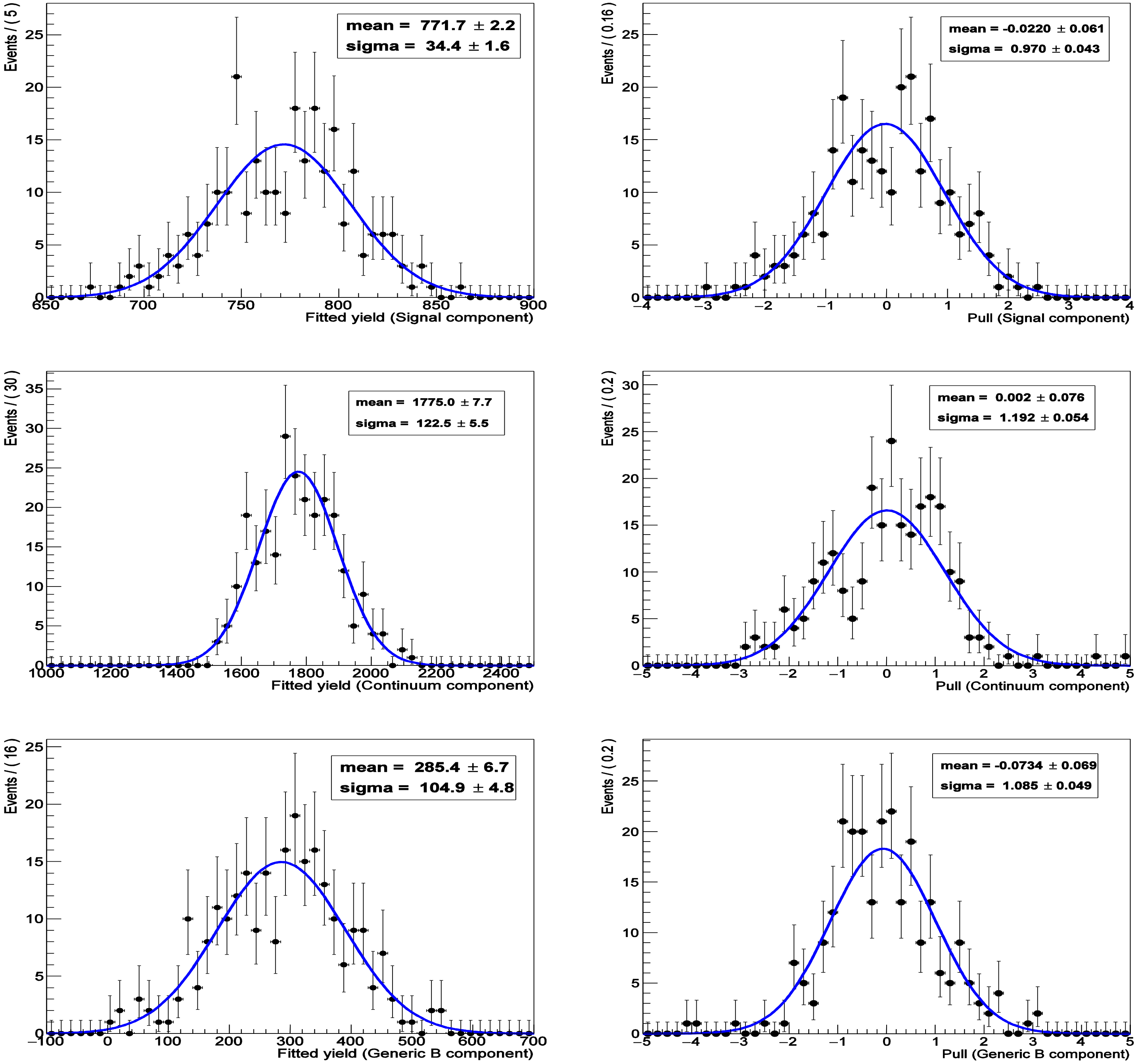
- If none of them were present, we would expect the fit to yield a Gaussian distribution with zero mean and unit width for each of the floated parameters

$$P_i = \frac{(X_{obs})_i - X_{true}}{(\sigma_{stat})_i}$$

measured and true values of the measured quantity X

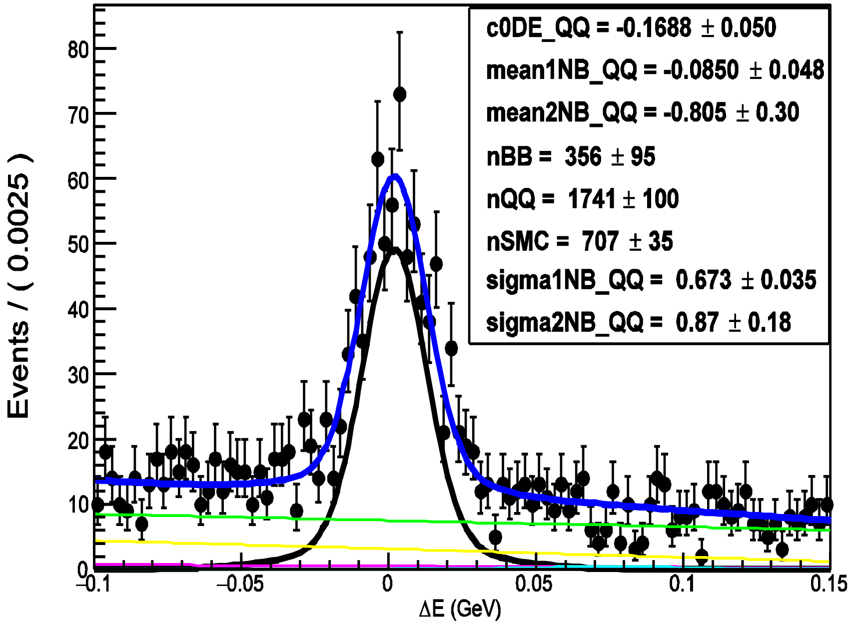
statistical uncertainty in the $i^{th}$ measurement

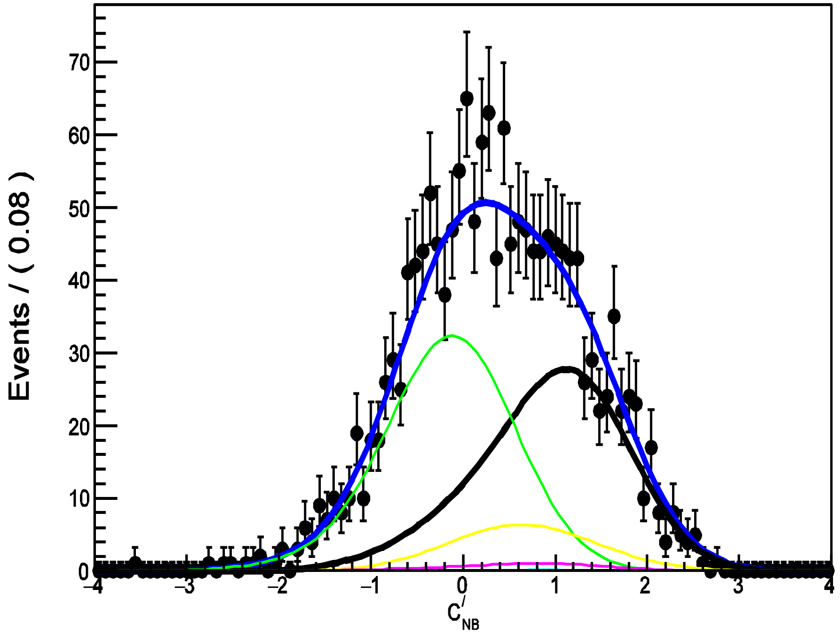
# Pure TOY


mean = 771.7 ± 2.2
sigma = 34.4 ± 1.6
Events / ( 5 )
Fitted yield (Signal component)
mean = -0.0220 ± 0.061
sigma = 0.970 ± 0.043
Events / ( 0.16 )
Pull (Signal component)
mean = 1775.0 ± 7.7
sigma = 122.5 ± 5.5
Events / ( 30 )
Fitted yield (Continuum component)
mean = 0.002 ± 0.076
sigma = 1.192 ± 0.054
Events / ( 0.2 )
Pull (Continuum component)
mean = 285.4 ± 6.7
sigma = 104.9 ± 4.8
Events / ( 16 )
Fitted yield (Generic B component)
mean = -0.0734 ± 0.069
sigma = 1.085 ± 0.049
Events / ( 0.2 )
Pull (Generic B component)

# Signal enhanced projection plots






**Components:**

1. **Signal**
2. **Continuum background**
3. **Generic B background**
4. **Rare (combinatorial) B background**
5. **Rare (peaking) B background**

$$\Delta E - C'_{NB}\ \text{2D fit}$$

# Rare B background
# Charged type MC

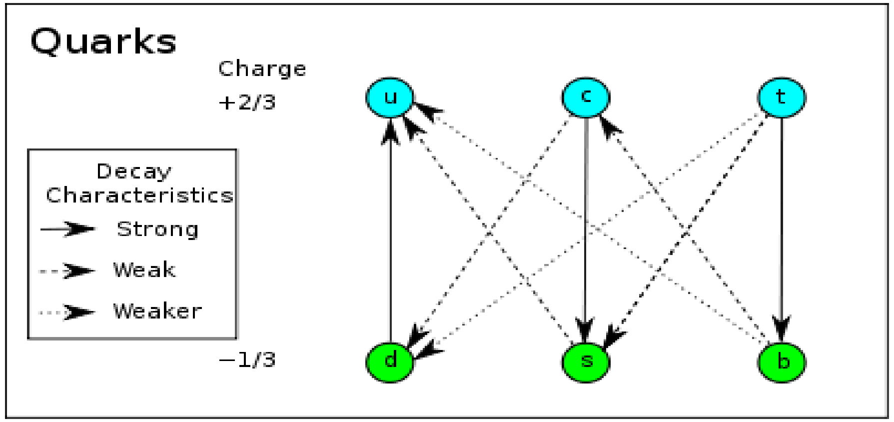
| Signal modes | % contribution |
|---|---|
| $B \rightarrow K_s\ K_s\ K$ | 64 |
| | |
| $B \rightarrow f_0(1370)\ K$ | 3.62 |
| $B \rightarrow f_2'(1500)\ K$ | 2.68 |

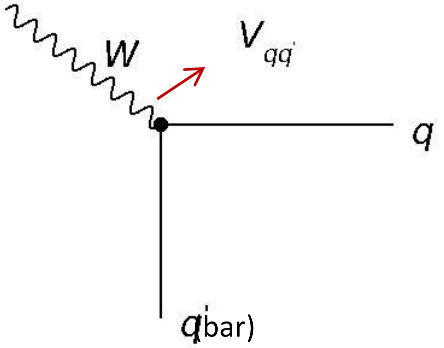
$$f_0(1370) \rightarrow K^0\overline{K^0}, 2\pi^+2\pi^-$$

$$f_2'(1500) \rightarrow K^0\overline{K^0}$$

$$K^0 \rightarrow 50\%\ K_S^0\ 50\%\ K_L^0$$

# Introduction to CKM matrix




❖ CKM matrix describes the probability of a transition from one quark i to another quark j. These transitions are proportional to $|V_{ij}|^2$

❖ 3×3 Unitarity matrix ⇒ 4 independent parameters (1 irreducible phase)

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

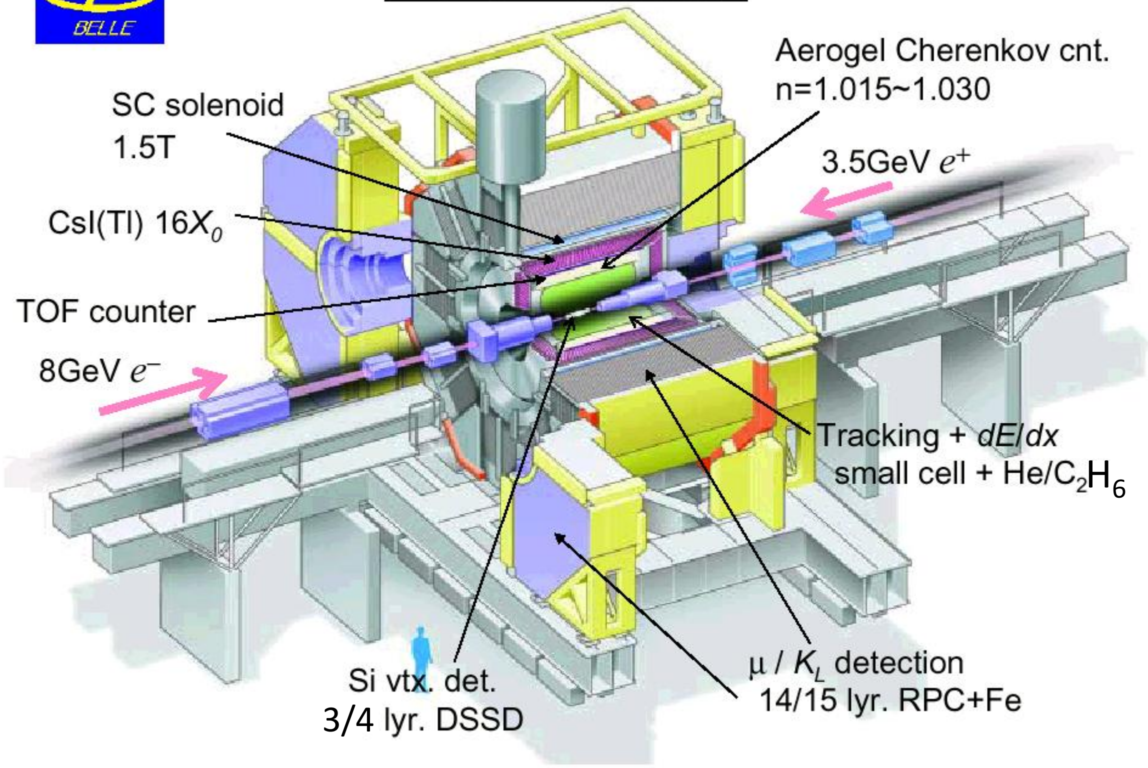
## Wolfenstein parameterization

$$V_{CKM} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

Unitarity $V^\dagger V=1$

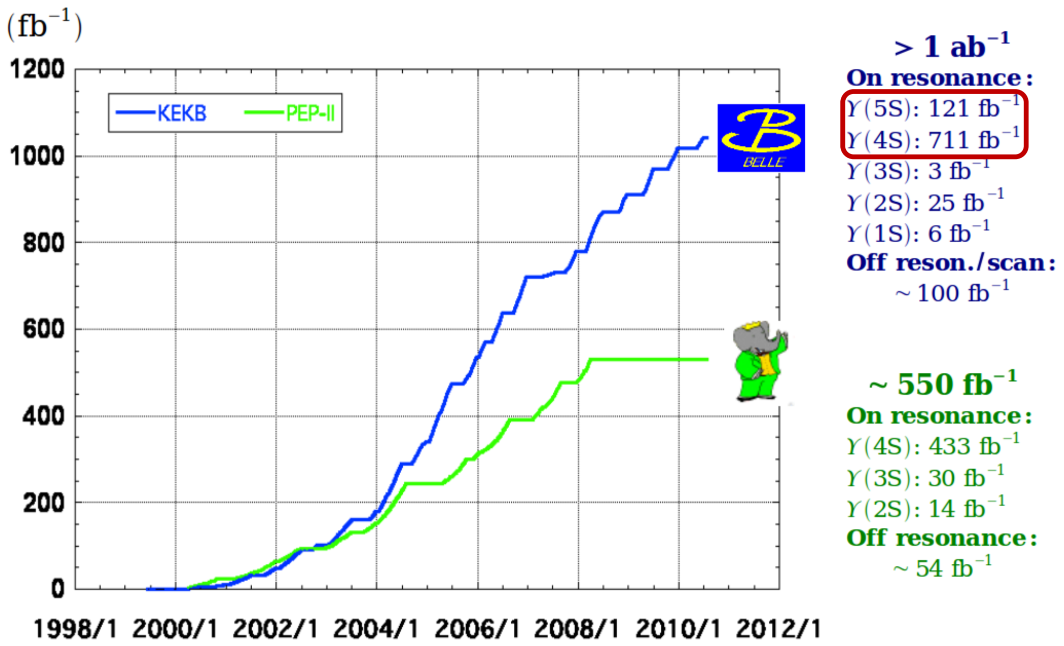
$\lambda = 0.22$, $A = 0.81$, $\rho = 0.14$ and $\eta = 0.35$

# Belle Detector




- Operated at the KEKB collider in Tsukuba, Japan (1999 – 2010)
- Asymmetric beam energy at the $\Upsilon(4S)$ resonance (8 GeV $e^-$ on 3.5 GeV $e^+$)
- Recorded 772 million $B\overline{B}$ pairs
- All analyses presented here are based on the full Belle data sample

## Integrated luminosity of B factories



## CDC (Central Drift Chamber)

$$\sigma_{p_t} / p_t \approx 0.5\% \sqrt{(1 + p_t^2)}$$

P < 0.8 GeV/c

❖ It is a cylindrical wire drift chamber immersed in a 1.5 T magnetic field

❖ The magnetic field of superconducting solenoid bends the charged particles according to their momenta

❖ CDC provides important information about particle identification from the energy loss (dE/dx) of charged particles and precisely determine their momenta

## TOF (Time of Flight Counter)

0.8 GeV/c to 1.2 GeV/c

❖ TOF measurements are performed with scintillating plastic counters

❖ TOF measures the velocity of charged particles. The velocity is measured by particle's time of flight and flight length

❖ For the same momentum, a heavy particle will travel slower than a light particle

❖ Thus, TOF system can identify particles of different masses by measuring their flight time difference

# ACC (Aerogel Cherenkov Counter)

❖ ACC is used as a part of Belle PID system to extend momentum coverage beyond the reach of the ***dE/dx*** measurement by CDC and time of flight measurement by TOF

❖ In the momentum region below 1 GeV/c K/π separation is performed by ***dE/dx*** measurements from CDC and TOF measurements. ACC extends it up to 3.5 GeV/c

❖ When a charged particle moves in a medium with refractive index n, it emits Cherenkov light if it its velocity is greater than the threshold ***c/n*** or $\beta > 1/n$

❖ For a fixed ***n***, the threshold momentum is proportional to their masses

❖ So there are regions where pion produce Cherenkov light while kaons does not, depending on the refractive index of the matter

❖ π with momentum 2 GeV/c emit light in the matter if n > 1.002 while n > 1.030 is necessary for K with the same momentum

$$\beta = \frac{p}{\sqrt{p^2 + m^2}} > 1/n$$

- The typical electron identification efficiency is 90% with a small fake rate of 0.3%

- Muons are also identified with 90% efficiency (2% fake rate) for charged tracks with momenta larger than 0.8 GeV

- The acceptance of Belle detector is asymmetric (covering the polar angle from $17^0$ to $150^0$) to match the boost from the asymmetric 8 on 3.5 GeV energy collisions

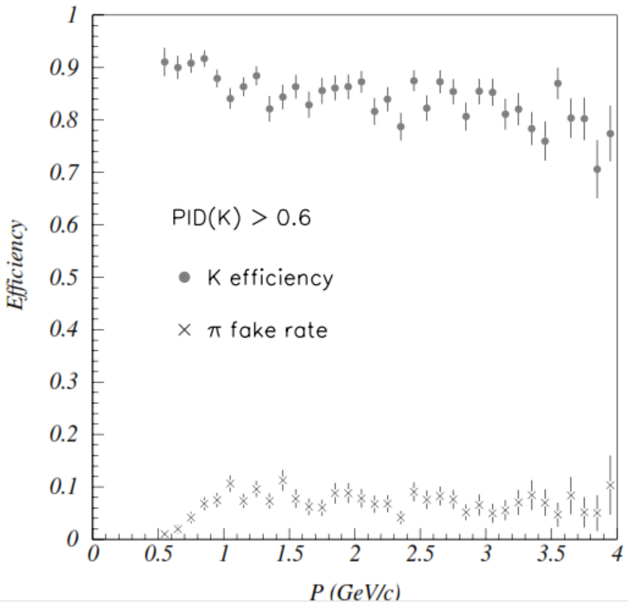



Fig. 53. K efficiency and π fake rate, measured with $D^{*+} \to D^0(K\pi) + \pi^+$ decays, for the barrel region. The likelihood ratio cut $PID(K) \geqslant 0.6$ is applied.

## 3.9 Extreme Forward Calorimeter (EFC)

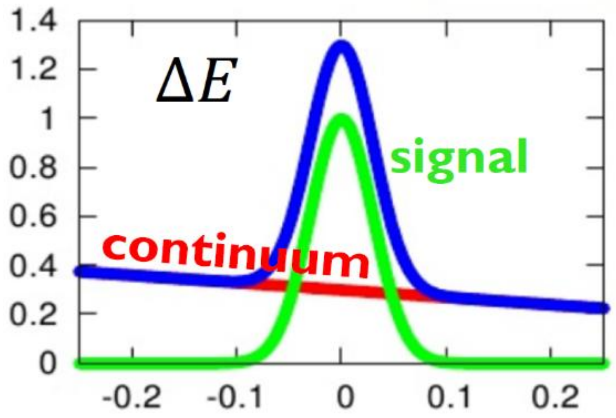
The Extreme Forward Calorimeter (EFC) extends the range of electron and photon calorimetry to the extreme forward $6.4^0 < \theta < 11.5^0$ and backward regions $163.3^0 < \theta < 171.2^0$ to detect electrons and photons very close to the beam pipe. The EFC is attached to front

# Analysis Technique

- To identify *B* decays, two kinematic variables are used: $\Delta \mathrm{E}$ and $\mathrm{M_{bc}}$

Energy difference

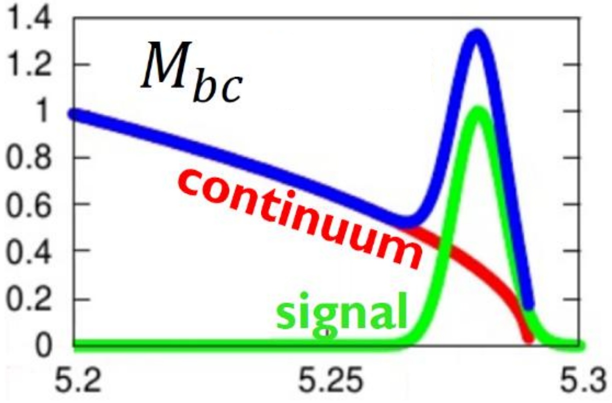
$$\Delta E = \sum_i E_i - E_{beam}$$




GeV

Beam-energy-constrained mass

$$M_{bc} = \sqrt{E_{beam}^2 - |\sum_i \vec{p}_i|^2}$$

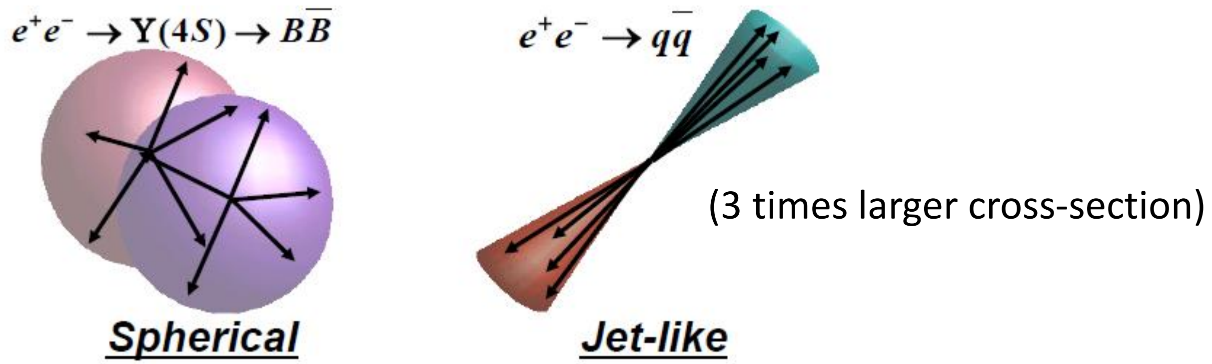



GeV/c$^2$

$\vec{p}_i$ and $E_i$ are the momentum and energy of $i^{th}$ daughter of the reconstructed *B* meson in the centre-of-mass frame

# Analysis Technique (contd.)

- Continuum events are the primary source of background: $e^+e^- \rightarrow q\bar{q}$ (q = u, d, s and c) → fragmentation → hadrons as two back-to-back jets
- To suppress this background, variables describing the event shape topology are combined in a multivariate analyzer, such as a neural network (NN) or a Fisher discriminant




- Use an unbinned extended maximum likelihood (ML) fit based on different discriminating variables
- The fit usually includes signal, continuum, charm and charmless B background components

# Fox Wolfram moments

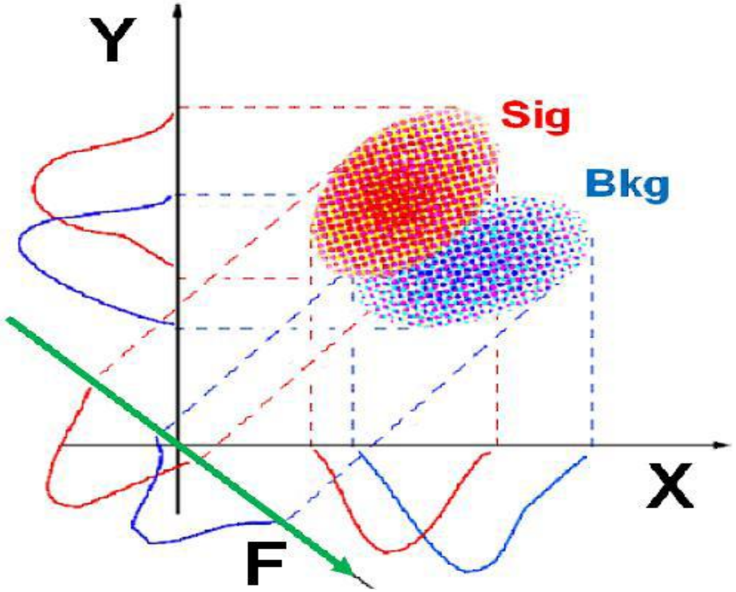
$$H_l = \sum_{ij} |p_i||p_j| P_l(\cos\theta_{ij})$$

- i,j= particles
- Momentum of particle i and j
- Legendre polynomial
- Angle between particle i and j

# Fisher Discriminant

The variable: $F = \sum_{i=1}^{N} \alpha_i x_i$

1. The discriminant F is a linear combination of the input variables $x_i$ (such as FW moments)
2. Multi variables can be combined into a single variable
3. Project multi dimensional data onto one dimension (axis)
4. Find the axis (best set of $\alpha_i$) to separate signal and background maximally



# The maximum likelihood method

Suppose we have a sample of ***n*** independent observations $x_1, x_2, \ldots, x_n$, from a distribution **f(x|θ)** where **θ** is the parameter to be estimated

The method then consists of calculating the likelihood function

$$L(\theta \mid x) = f(x_1 \mid \theta) f(x_2 \mid \theta) \ldots\ldots\ldots f(x_n \mid \theta)$$

which can be recognized as the probability for observing the sequence of values $x_1, x_2, \ldots, x_n$

The principle now states that this probability is a maximum for the observed values

Thus, the parameter **θ** must be such that ***L*** is a maximum. If ***L*** is a regular function, **θ** can be found by solving the equation

$$\frac{d(\ln L)}{d\theta} = 0$$

It is easier to maximize the logarithm of ***L*** rather than ***L*** itself

Extended: A poisson fluctuation is introduced on the number of generated events

# Change in the accelerator design

- High current version to the “nano-beam” collider

- Smaller beam energy asymmetry (7 GeV/on 4 GeV instead of 8 GeV on 3.5 GeV)
- Change beam energies to solve the problem of short lifetime for the LER

Beam-beam parameter

Lorentz factor

Beam current

$$L = \frac{\gamma_{e\pm}}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_{e\pm}\xi_y^{e\pm}}{\beta_y^*}\right)\left(\frac{R_L}{R_{\xi_y}}\right)$$

Lumi. reduction factor (crossing angle)& Tune shift reduction factor (hour glass effect) 0.8 ~ 1 (short bunch)

Classical electron radius

Beam size ratio@IP 1 ~ 2 % (flat beam)

Vertical beta function@IP

**(1) Decrease $\beta_y^*$** ← **“Nano-beam” scheme**

**(2) Increase beam currents**

(3) Increase $\xi_y$

# Belle II

- Just outside the beam pipe, silicon strip detector is replaced by a two-layer silicon pixel detector
- Silicon strip detector extends from just outside the pixel detector to a larger radius than in Belle
- Central tracking device—a large volume drift chamber—has smaller drift cells than in Belle and extends to a larger radius
- Completely new particle identification devices in the barrel and endcap regions are of the Cherenkov imaging type, with very fast read-out electronics
- Replacement of the endcap scintillator crystal (CsI(Tl)) with a faster and radiation tolerant version (pure CsI)

# Performance of Belle II

- Vertex resolution is improved by the excellent spatial resolution of the two innermost pixel detector layers

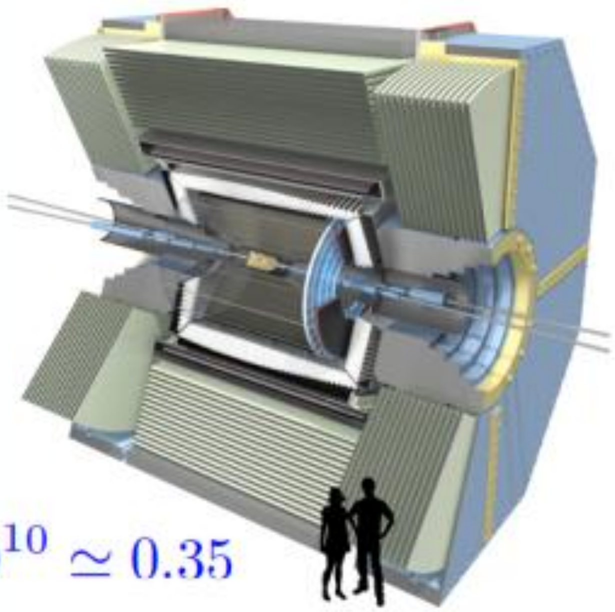
- Efficiency for reconstructing $K_S$ decays to two charged pions with hits in the silicon strip detector is improved because the silicon strip detector occupies a larger volume

- New particle identification devices in the barrel and endcap regions extend the very good pion/kaon separation

- New electronics of the electromagnetic calorimeter considerably reduce the noise pile up, which is of particular importance for missing-energy studies

The photons are collected by a spherical mirror with focal length **f** and focused onto the photon detector placed at the focal plane. The result is a circle with radius $\mathbf{r = f\,\theta_C}$

# Performance of Belle II



$$0.9^{10} \simeq 0.35$$

Belle II covering ≳90% of $4\pi$,
and ⟨N(track)⟩ ~ 10 per event

- **Hermeticity**
  - minimal trigger for, e.g. Dalitz analysis
  - precision $\tau$ measurements

- **Neutral particles** $\pi^0$, $K_S^0$, $K_L^0$ and for $\eta$, $\eta'$, $\rho$+, etc.

- ***other notable features***
  - Lepton universality: good PID for both $\mu^\pm$ and $e^\pm$, & we can find $\tau^\pm$
  - high flavour-tagging efficiency

# Golden mode(s) for Belle II

Methods and processes where Super $B$-factory can provide important insight into NP complementary to other experiments:

- Missing energy modes
  - $B^+ \to \ell^+ \nu_\ell \qquad (\ell^+ = e^+,\ \mu^+,\ \tau^+)$
  - $B \to D^* \tau \nu_\tau$, $B \to X_c \ell \nu_\ell$, $B \to X_u \ell \nu_\ell$, $B \to K^{(*)} \nu \overline{\nu}$
- Inclusive measurements
  - $B \to X_s \gamma$, $B \to X_s \ell \ell$
- Decay modes with neutrals in the final state
  - $B \to K_S^0 \pi^0 \gamma$, $B \to \eta' K_S^0$
  - $B \to \gamma\gamma$
- excellent flavor tagging performance (10× better than at hadron colliders)
- Lepton Flavor Violating $\tau$ decays

*Detailed description of physics program at Super B-factories described in arXiv: 1002.5012 and arXiv: 1008.1541.*

90% C.L. upper limit

There is a 90% probability of a measured value $B_m$ being not more than 1.28 $\sigma$ below the true value

$B_0 < B_m + 1.28\ \sigma$

95% C.L. upper limit $\Rightarrow B_0 < B_m + 1.64\ \sigma$

99% C.L. upper limit $\Rightarrow B_0 < B_m + 2.33\ \sigma$

$772\times10^6$ BB(bar) pairs, 711 $fb^{-1}$, 1 barn = $10^{-28}\ m^2$, $\boldsymbol{L} = 2.11\times10^{34}\ cm^{-2}\ s^{-1}$, $\int \boldsymbol{L}\, dt = 1000\ fb^{-1}$

COM = 10.58 GeV, Lorentz boost = 0.425, $E_{e-}$ = 8 GeV, $E_{e+}$ = 3.5 GeV

# Chebyshev polynomial

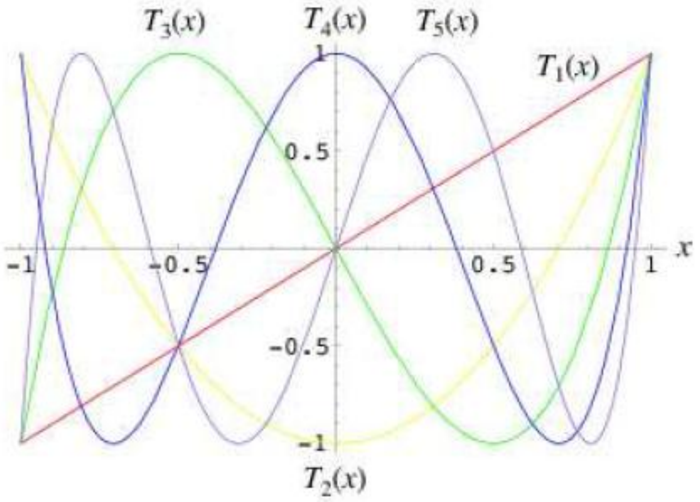
$$Tn(z) = \frac{1}{4\pi i} \oint \frac{(1-t^2)t^{-n-1}}{(1-2tz+t^2)} dt$$

1. The Chebyshev polynomials are denoted by $T_n$ (x)

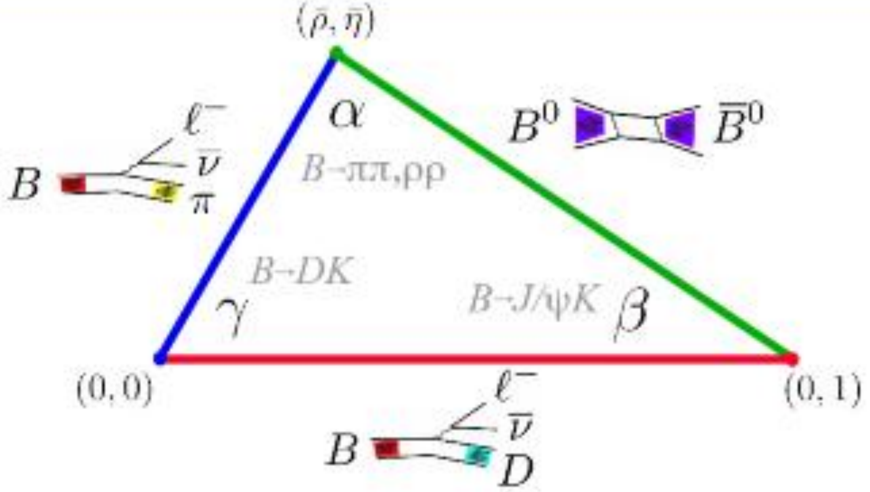
2. They are used as an approximation to a least square fit

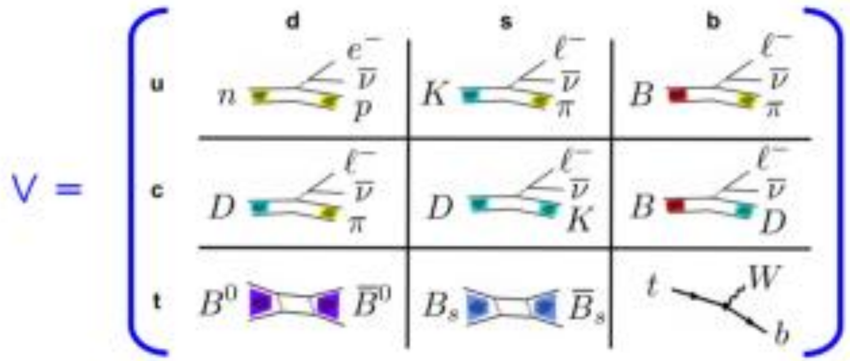
3. The use of Chebyshev polynomials over regular polynomials is recommended because of their superior stability in fits

4. Chebyshev polynomials and regular polynomials can describe the same shapes, but a clever re-organization of power terms in Chebyshev polynomials results in much lower correlations between the coefficients in a fit, and thus a more stable fit behaviour




$x \in [-1, 1]$ and $n = 1, 2, ..., 5$




| | | | |
|---|---|---|---|
| $B \to \pi\pi, \rho\rho$ | Φ 2 | $B \to D\, l\, \nu$ / $b \to c\, l\, \nu$ | $\lvert V_{cb} \rvert$ |
| $B \to D^{(*)} K^{(*)}$ | Φ 3 | $B \to \pi\, l\, \nu$ / $b \to u\, l\, \nu$ | $\lvert V_{ub} \rvert$ |
| $B \to J/\psi\, K_s$ | Φ 1 | $M \to l\, \nu\, (\gamma)$ | $\lvert V_{UD} \rvert$ |
| $B_s \to J/\psi\, \Phi$ | $\beta_s$ | | |
| $K \to \pi\, \nu$ anti-$\nu$ | ρ, η | | |

| Observables | Belle or LHCb* | Belle II | | LHCb | |
|---|---|---|---|---|---|
| | (2014) | 5 $ab^{-1}$ | 50 $ab^{-1}$ | 8 $fb^{-1}$(2018) | 50 $fb^{-1}$ |
| $\sin 2\beta$ $\beta = (21.4 \pm 0.8)^0$ | $0.667 \pm 0.023 \pm 0.012 (0.9^\circ)$ | $0.4^\circ$ | $0.3^\circ$ | $0.6^\circ$ | $0.3^\circ$ |
| $\alpha$ [°] | $85 \pm 4$ (Belle+BaBar) | 2 | 1 | | |
| $\gamma$ [°] $(B \to D^{(*)} K^{(*)})$ | $68 \pm 14$ | 6 | 1.5 | 4 | 1 |
| $2\beta_s (B_s \to J/\psi \phi)$ [rad] | $0.07 \pm 0.09 \pm 0.01^*$ | | | 0.025 | 0.009 |