Study of $B^0 \to \rho^0\rho^0$

Pit Vanhoefer

Max-Planck-Institut für Physik

pvanhoef at mpp.mpg.de

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

1) Motivation

2)CP Violation

3) Measurement procedure

4)Summary & Outlook

BELLE

Motivation

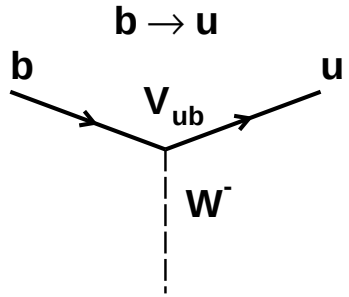
violation of CP symmetry necessary for matter anti-matter asymmetry

CP = C(charge)$\times$$P$(parity); violated by weak interaction

SM has a built-in mechanism generating CP violation: CKM mechanism.

weak and mass eigenstates related through a complex, unitary matrix:

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix}_{\text{weak}} = V_{\text{CKM}} \begin{pmatrix} d \\ s \\ b \end{pmatrix}_{\text{mass}} \equiv \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}_{\text{mass}}$$



Cabibbo-Kobayashi-Maskawa CKM Matrix (Nobel prize 2008)

V_{ij}: quark flavor transition couplings ($W^{\pm}$ exchange).

BUT: CKM mechanism NOT able to produce observed asymmetry in our universe.

CP Violation in the SM

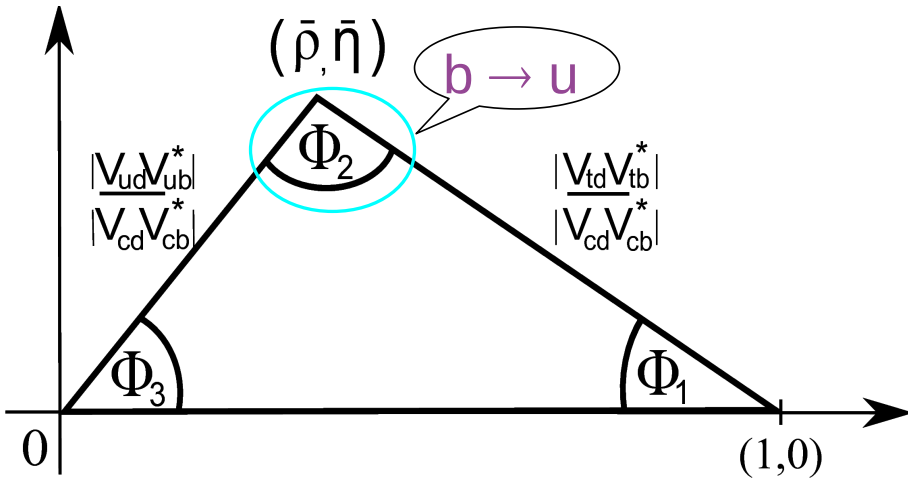
Wolfenstein representation of V_{CKM}, $\lambda = \sin\theta_{\mathrm{C}} \approx 0.22$ (Cabibbo angle)

$$V_{\mathrm{CKM}} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4). \qquad (1)$$

4 free parameters(3 mixing angles, 1 complex phase) for 3 generations of quarks

relevant relation for B meson decays ($\rightarrow$ triangle)

$$\underset{\mathcal{O}(\lambda^3)}{V_{ud}V_{ub}^*} + \underset{\mathcal{O}(\lambda^3)}{V_{cd}V_{cb}^*} + \underset{\mathcal{O}(\lambda^3)}{V_{td}V_{tb}^*} = 0$$



sides with similar length $\Rightarrow$ large CP violation

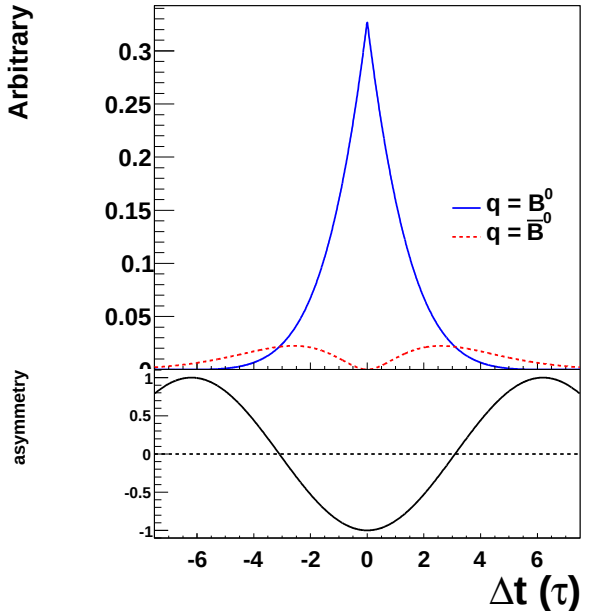
precise determination of the observables

5 observables (3 angles, 2 sides) $\Rightarrow$ over-constraint

confirm SM **or** find new physics

CP Violation in the B System

$$\frac{N_{\bar{B}^0}(t', f_{CP}) - N_{B^0}(t, f_{CP})}{N_{\bar{B}^0}(t', f_{CP}) + N_{B^0}(t, f_{CP})} = \mathcal{A}_{CP}\cos(\Delta m \Delta t) + \mathcal{S}_{CP}\sin(\Delta m \Delta t), \Delta t = t' - t$$



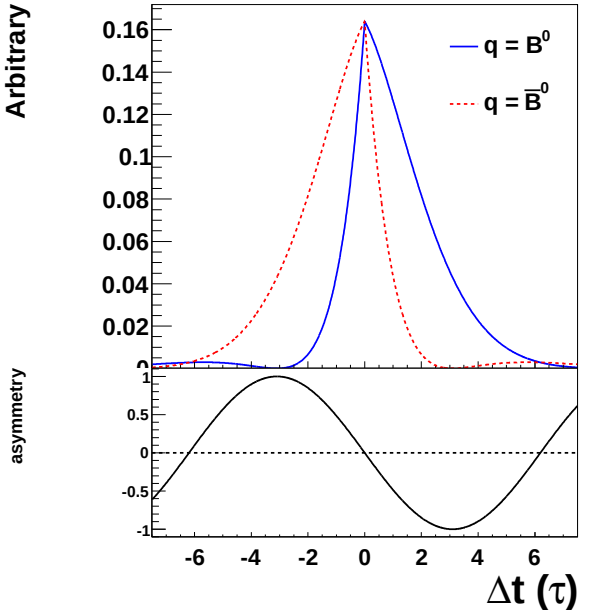
CP asymmetry parameters:

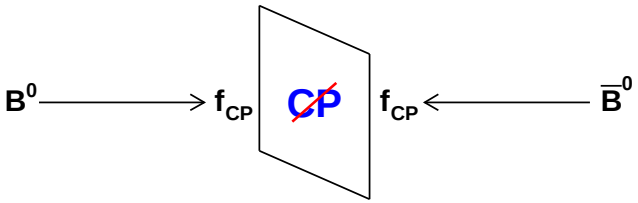
$\leftarrow \mathcal{A}_{CP}$(direct ~~$CP$~~)

different decay rates

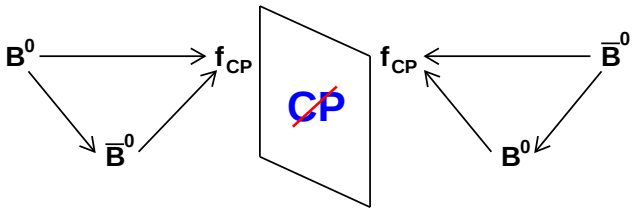
$\mathcal{S}_{CP}$(indirect ~~CP~~)$\rightarrow$

or different time evolution



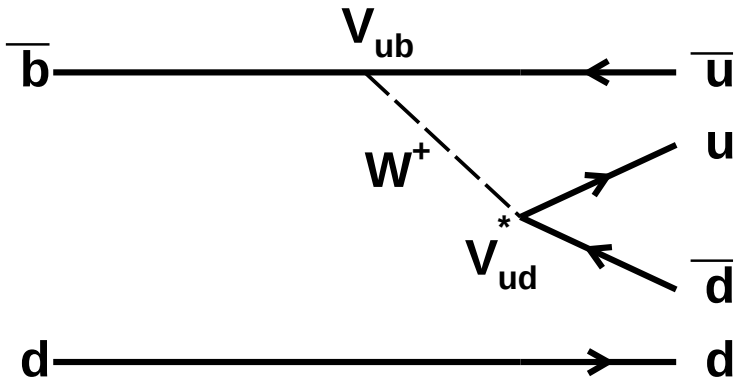


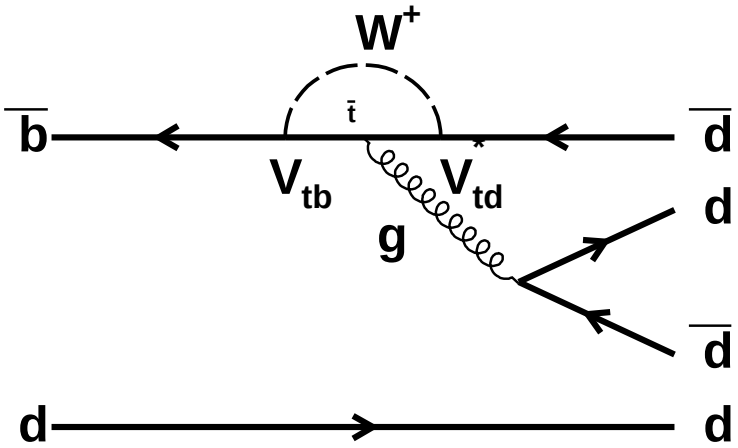
for B and $\bar{B}$ decaying into a CP eigenstate f_{CP}



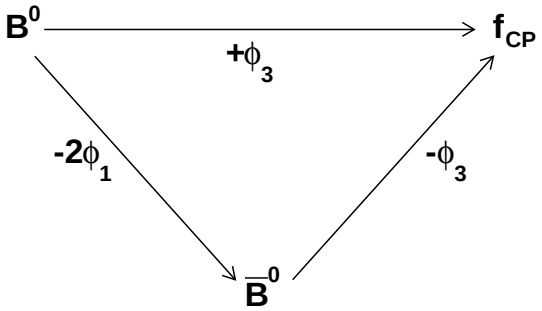
$B^0 \to \rho^0\rho^0$

$B^0 \to \rho^0\rho^0$ is a tree dominated, color-suppressed, Scalar $\to$ Vector Vector decay





assuming unitarity: ϕ_2



$-2\phi_1 - 2\phi_3 \to 2\phi_2$

penguin pollution $\Rightarrow \Delta\phi_2, \mathcal{A}_{CP}$

$\Rightarrow$ measured observable: *effective* $\phi_{2,eff}$

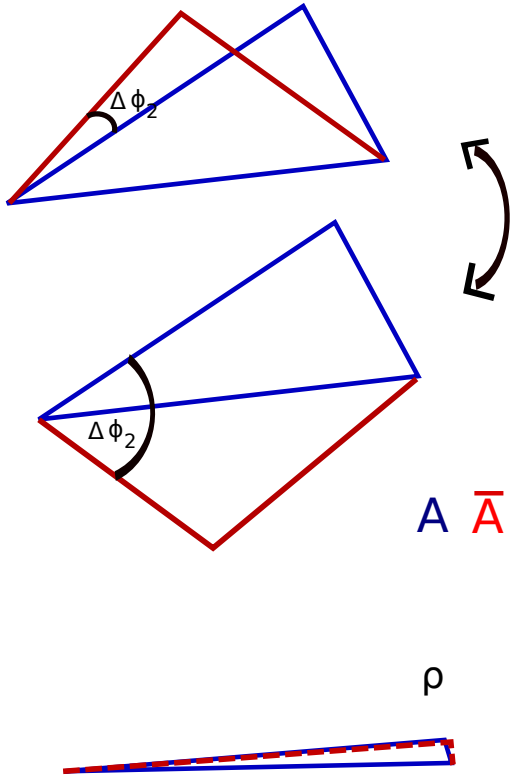
$$\mathcal{S}_{CP} = sin(2\phi_{2,eff}) = sin(2(\phi_2 + \Delta\phi_2))$$

Recover ϕ_2

In $b \to u$ transitions

- measurement of Δt provides $\sin(2\phi_{2,eff}) = \sin(2(\phi_2 + \Delta\phi_2))$
- extraction of $\Delta\phi_2$ through isospin analysis possible

  but 2(sin)$\times$ 4($\Delta\phi_2$) = 8 fold ambiguity



In the ρ system the SM predicts small penguin pollution

- $\mathcal{BR}(B^0 \to \rho^0\rho^0)$ relatively very small

  multiple solutions due to $\Delta\phi_2$ overlap $\Rightarrow$ only 2 fold ambiguity

  $\Rightarrow$ best environment for constraining ϕ_2 with current statistics
- current error on ϕ_2 dominated by the ρ system

  $\Rightarrow$ measurement of $B^0 \to \rho^0\rho^0$ important for the understanding of ϕ_2

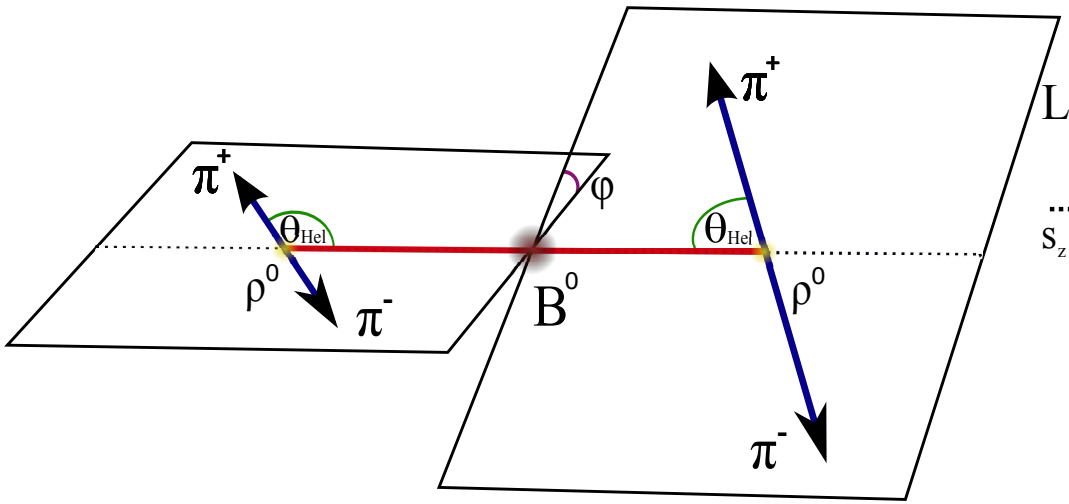
$B^0 \to \rho^0 \rho^0$

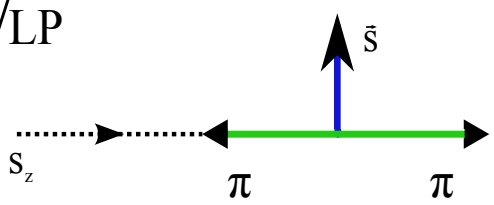
- **Helicity of the ρ**

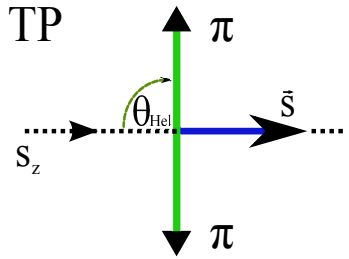
  2 different polarizations, longitudinal(L pol, CP even) and transversal(T pol, CP even & odd)

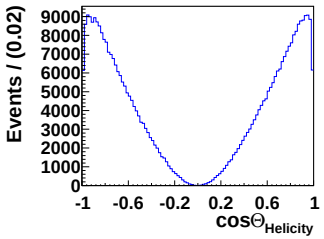
  f_L: fraction of L pol,through helicity analysis (SM: L pol dominant)

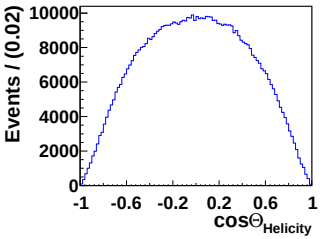
  θ_{Hel}: angle between the B^0 and the π^+ flight directions in the ρ frame











$B^0 \to \rho^0\rho^0$

previous measurements *(theory: G.Bell, V.Pilipp: arXiv:0907.1016v1)*

Experiment	BELLE	BaBar	Theory(L pol)
$\mathcal{BR}(\times 10^{-6})$	0.4±0.4±0.25	0.92±0.32±0.14	$0.44^{+0.66}_{-0.37}$
f_L	-	0.75 ±0.11 ± 0.04	$\sim 1 - 1/m_b^2$
$\mathcal{A}_{CP}^L$	-	-0.2 ± 0.8 ± 0.3	
$\mathcal{S}_{CP}^L$	-	0.3±0.7±0.2	
$B\bar{B}$ pairs ($\times 10^6$)	656.7	465	

$\Rightarrow$ no significant measurement made at Belle (yet, $\sim 2\times$ data)

challenging analysis

- rare decay: $\mathcal{BR} \leq 10^{-6}$
- large backgrounds
- complex helicity structure

$\Longrightarrow$

new method

- no cut-based but multivariate analysis, including event shape to discriminate $q\bar{q}$ and fraction of L pol f_L

Measurement of $\mathcal{BR}(B^0 \to \rho^0\rho^0)$

Extraction of $\mathcal{BR}(B^0 \to \rho^0\rho^0)$:extended unbinned likelihood fit

6 fit dimensions:

$\Delta E, m^1_{\pi^+\pi^-}, m^2_{\pi^+\pi^-}, \mathcal{F}_{evt}, \cos\theta^1_{\mathrm{Hel}}, \cos\theta^2_{\mathrm{Hel}}$

$\Delta E \equiv E_{B_{rec}} - E_{beam}$
$\mathcal{F}_{evt}$: event-shape based fisher discriminant

- multivariate analysis: $\Rightarrow$ precise understanding of signal AND background necessary

  $\to$ modeled 17 components: shape determined from

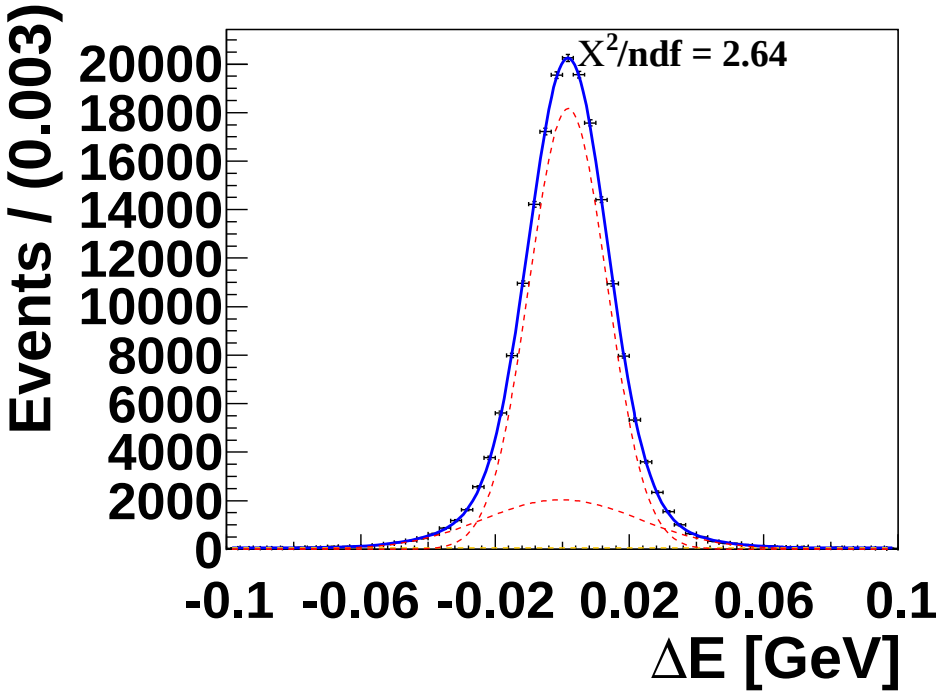
  - signal (L pol, T pol); Monte Carlo(MC)
  - misreconstructed signal (L pol, T pol); MC
  - continuum ($e^+e^- \to q\bar{q}$); data taken at $\sqrt{s} = 10.50GeV < m(\Upsilon(4S))$
  - $B\bar{B}$: charm and charmless $B^0(B^\pm)$ decays; MC
  - peaking background (4πs final states); MC

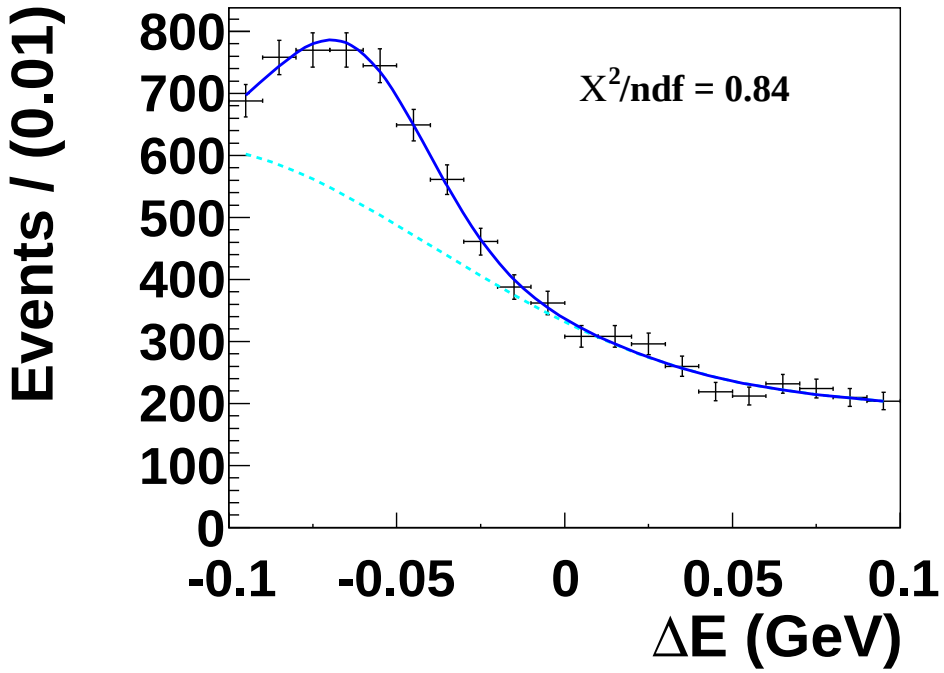
    $\pi^+\pi^-\pi^+\pi^-, a_1^\pm\pi^\mp, a_2^\pm\pi^\mp, b_1^\pm\pi^\mp, f_0f_0, f_0\pi^+\pi^-, \rho^0\pi^+\pi^-, f_0\rho^0.$ (BR known)

Model for $\mathcal{BR}(B^0 \to \rho^0\rho^0)$

$$\Delta E \equiv E_{B_{rec}} - E_{beam}$$

- signal MC(L pol)
- neutral charm decays



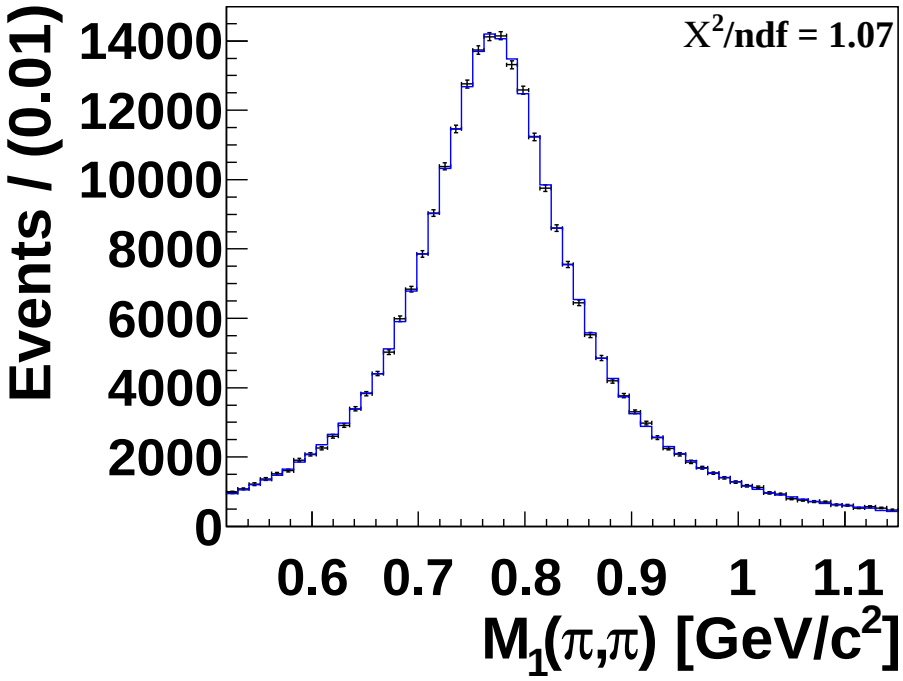


$\mathcal{PDF}(\Delta E)$=2× Gaussian + 1st order chebychev

$\mathcal{PDF}(\Delta E)$=Gaussian + $\sum_{i=1}^{8}$ chebychev$_i$

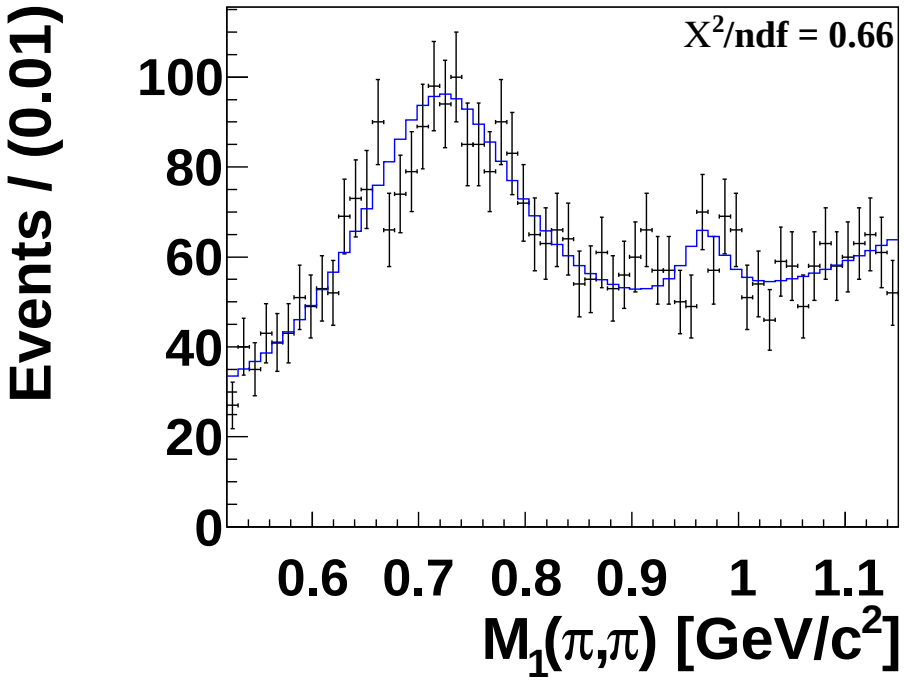
Model for $\mathcal{BR}(B^0 \to \rho^0\rho^0)$

- signal MC(L pol)



$\mathcal{PDF}(m_{\pi^+\pi^-}) = \epsilon_{rec}(m_{\pi^+\pi^-}) \times$ Breit-Wigner

- neutral charmless decays



$\mathcal{PDF}(m_{\pi^+\pi^-}) = 2 \times$ Breit-Wigner + $\sum_{i=1}^{4}$ chebychev$_i$

Toy MC Studies for $\mathcal{BR}(B^0 \to \rho^0\rho^0)$

test fitting procedure with Toy MC

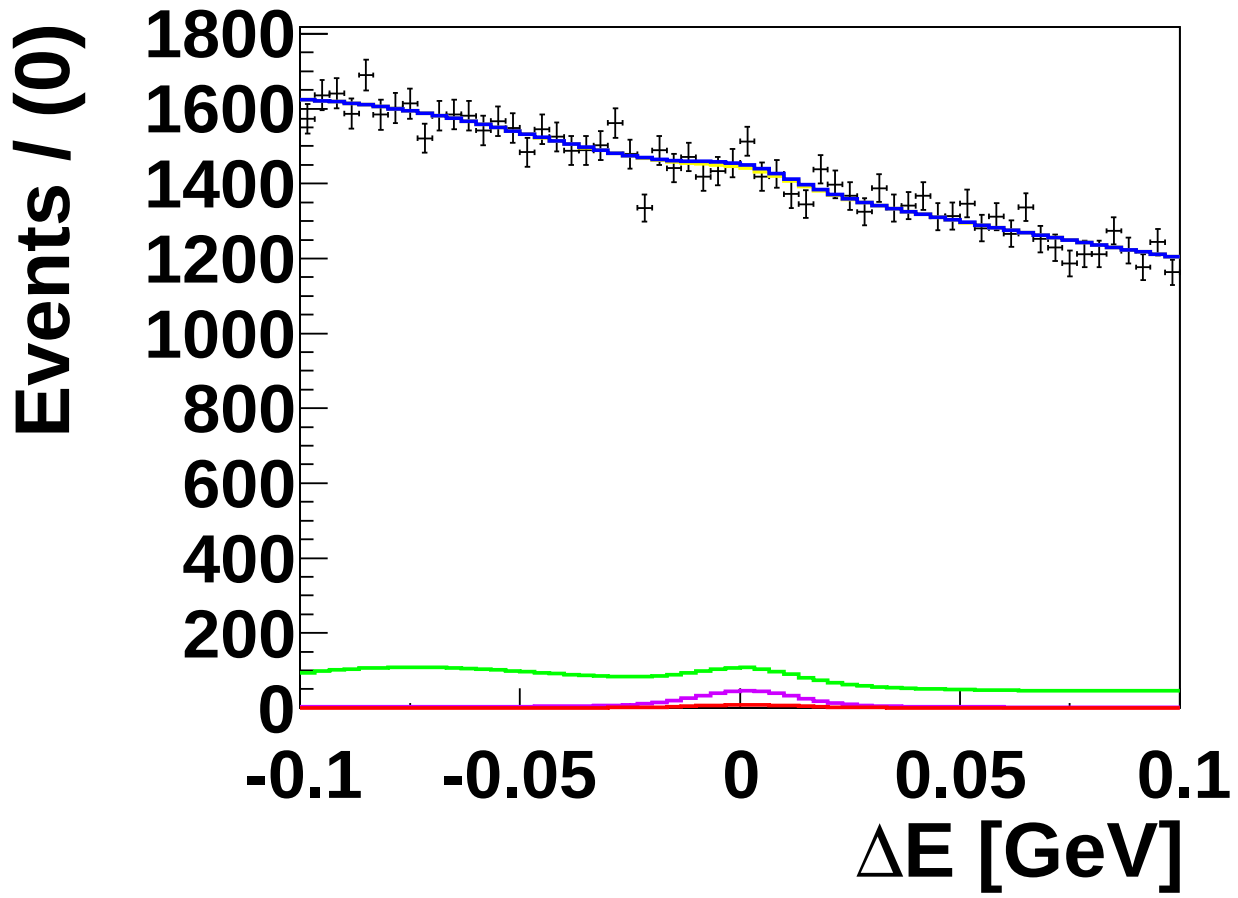
$\Rightarrow$ Toy MC Generator built: events according to $\mathcal{PDF}$ (probability density function)

toy MC example

expected Nr of events

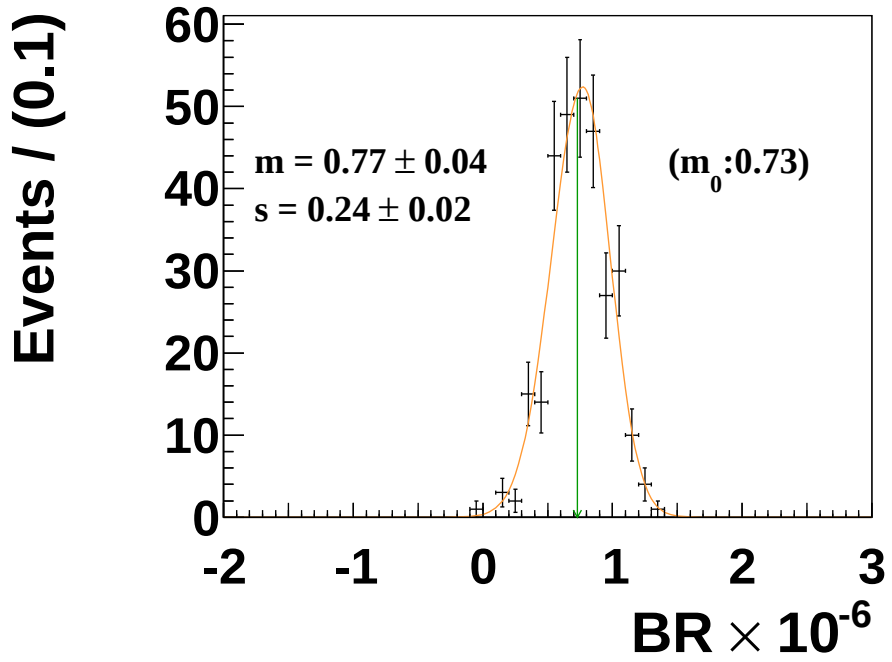
- signal:$\sim$ 100
- 4 πs ff:$\sim$ 1500
- $B\bar{B}$:$\sim$ 10000
- all:$\sim$ 100000

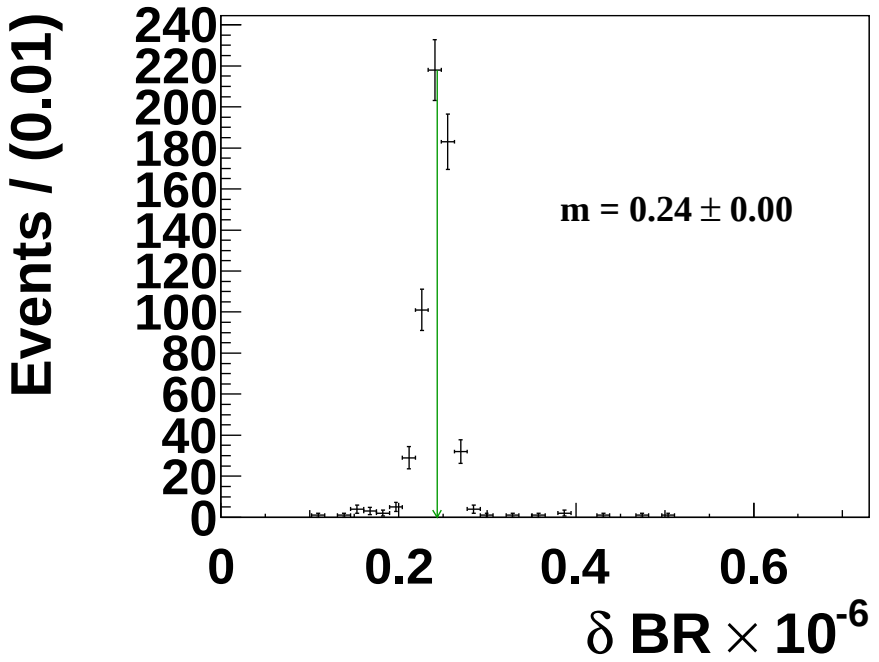
(using world averages)



Toy MC Studies for $\mathcal{BR}(B^0 \to \rho^0\rho^0)$

- performed fits on 300 toy MC samples





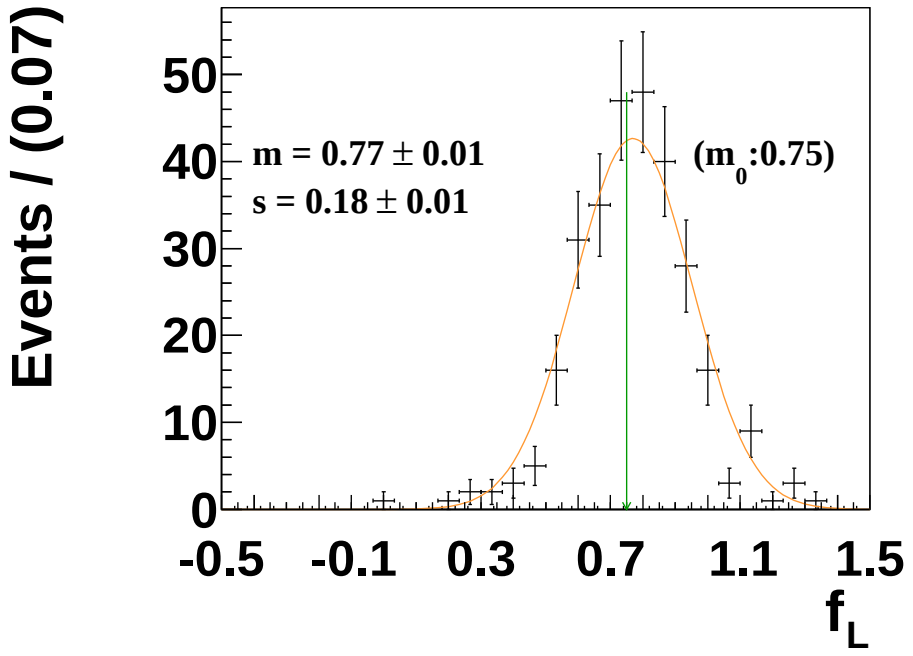
green line is input value

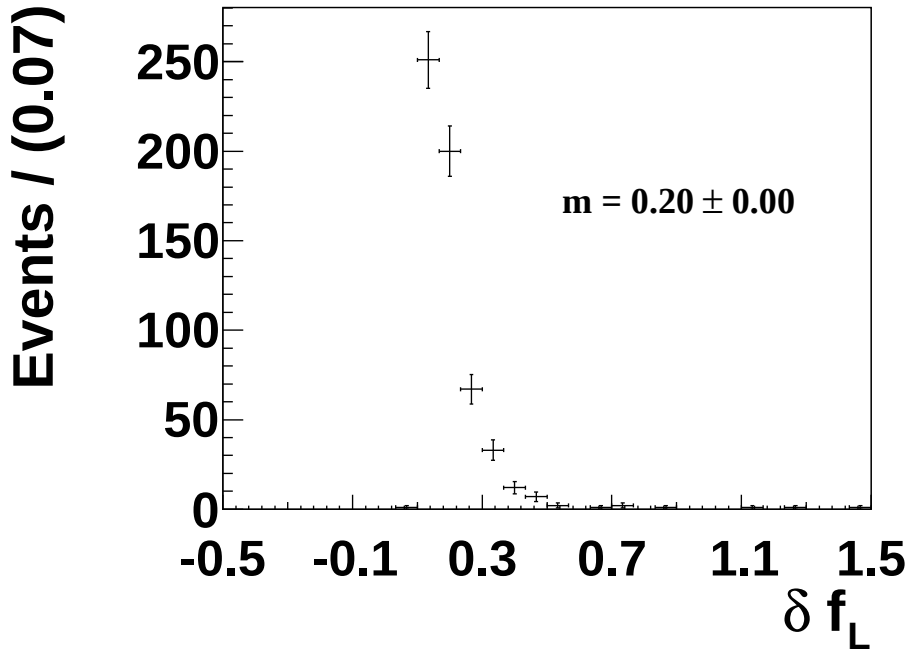
indicates 3 σ significance

$\Rightarrow$ observation with a 3 σ significance possible!

Toy MC Studies

- performed fits on 300 toy MC samples





green line is input value

$\Rightarrow$ measurement of the fraction of L pol f_L possible!

Summary & Outlook

- $B^0 \to \rho^0\rho^0$ plays a important role in constraining ϕ_2

  $\to$ isospin analysis

- also,this measurement is an important test of theory (not shown)

  Scalar$\to$Vector Vector: complicated computations $\leftrightarrow$ assumptions

- new multivariate approach, avoiding cuts and including helicity

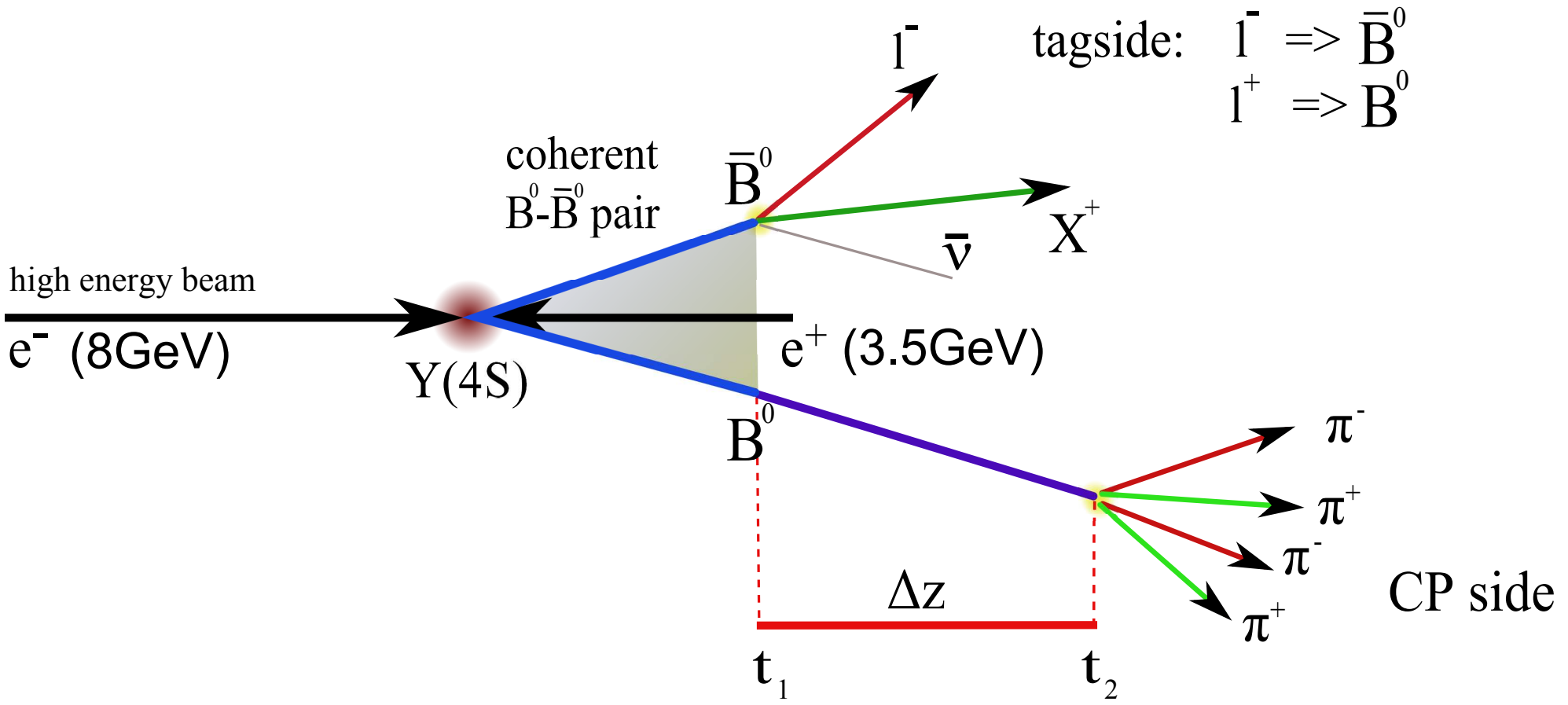
  $\to$ possibility of a 1^{st} observation at Belle

$\Rightarrow$ extraction of CP asymmetry parameters

Backup

Backup

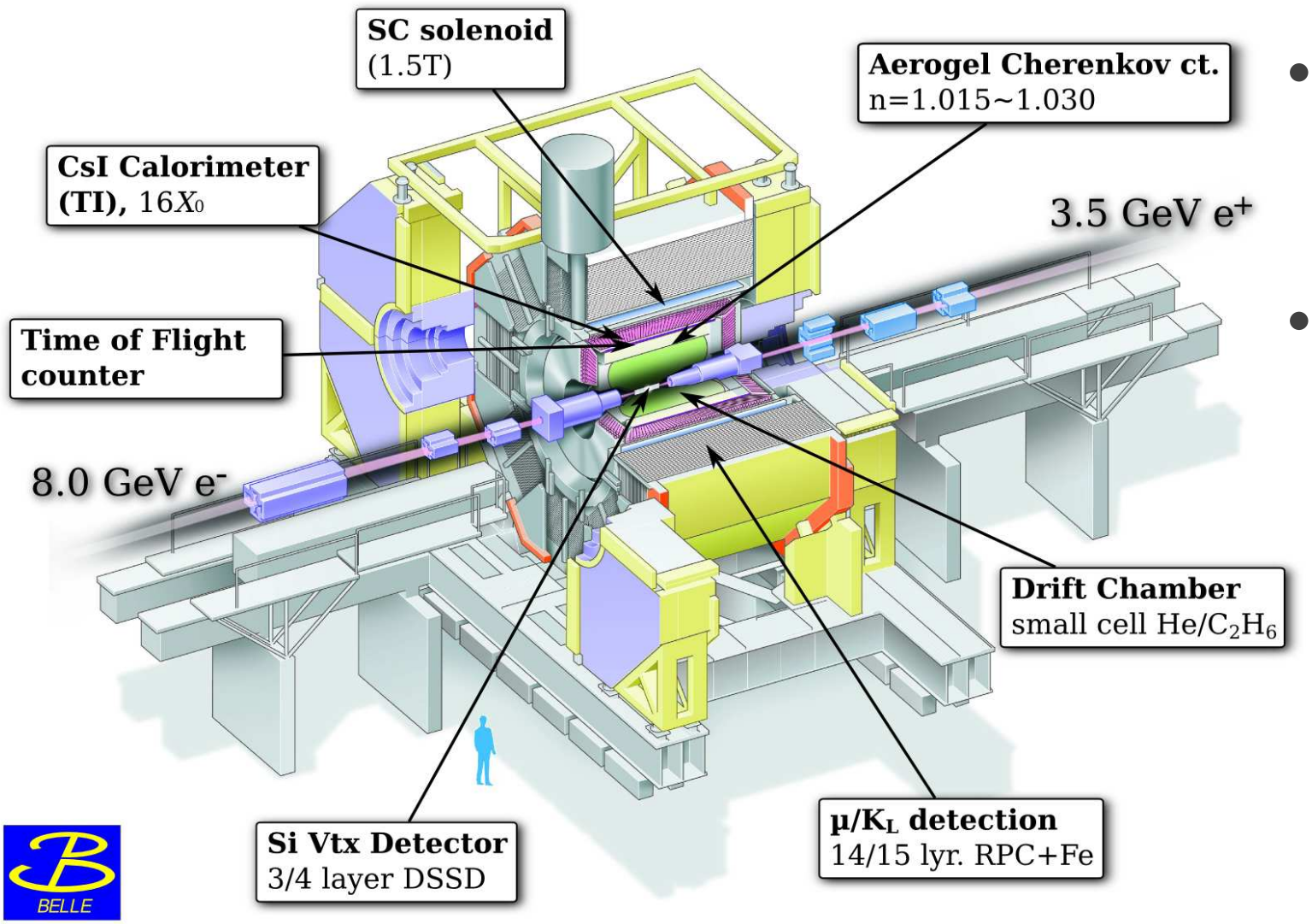
CP Violation measurement



$\Upsilon(4S) \rightarrow$ entangled $B\bar{B}$ pair $\Rightarrow$ opposite side flavor tagging possible

asymmetric beam energies $\Rightarrow$ boost of the CMS $\Rightarrow \Delta t \rightarrow \Delta z$ ($\Delta t \sim ps$, $\Delta z \sim 100\mu$m)

The Experimental Setup



- located in Japan
- asymmetric e^+e^- collider (KEKB) (3.5 GeV on 8 GeV)
- luminosity world-record $\int Ldt = 1014 fb^{-1}$ $\sim$ 772 $\times$ $10^6 B\bar{B}$ pairs

Belle Detector

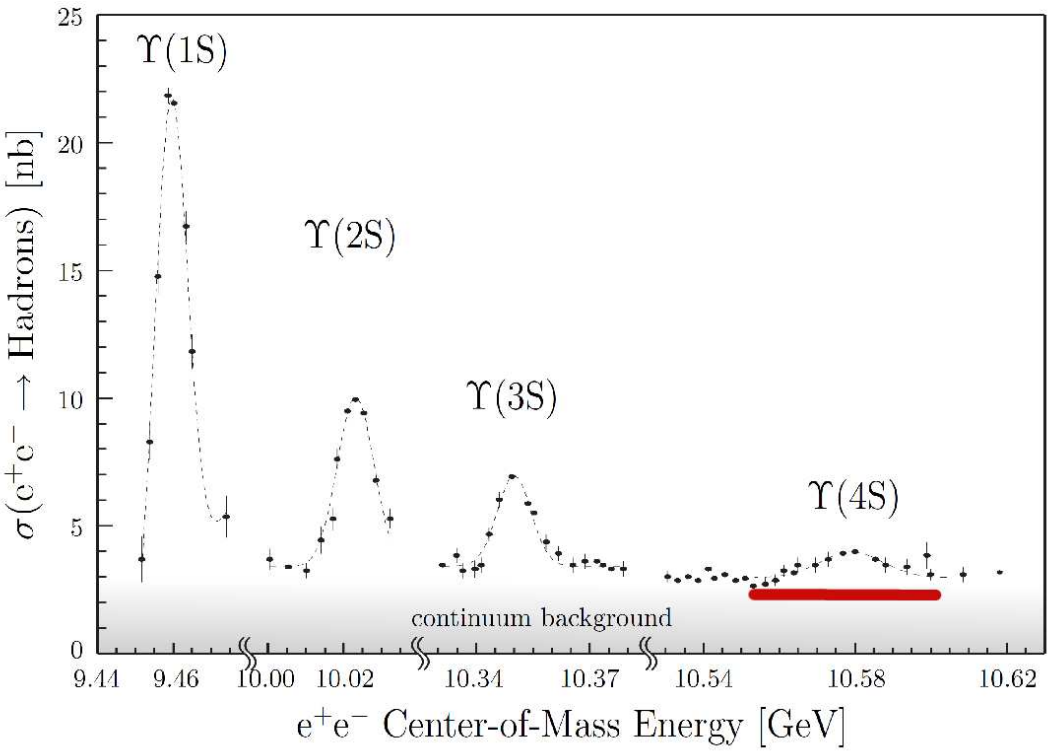
- tracking
- PID

The Belle Experiment

located at the KEKB collider in Japan

CP Violation measurement

Where the Bs come from:



$$m(\Upsilon(4S)) = 10.58 GeV/c^2 \sim 2 \times m(B)$$

$$m(B) = 5.28 GeV/c^2$$

- Υ states:$b\bar{b}$ bound states
- $\Upsilon(4S)$ exclusively into $B\bar{B}$ pairs
- $\Upsilon(4S)$: $J^{PC} = 1^{--}$
- B : $J^{PC} = 0^{--}$

  $\rightarrow$ B pair in p-wave
- asymmetric wave function

  $\rightarrow$ Bs have opposite flavor:

$\Rightarrow$ entangled $B\bar{B}$ pair

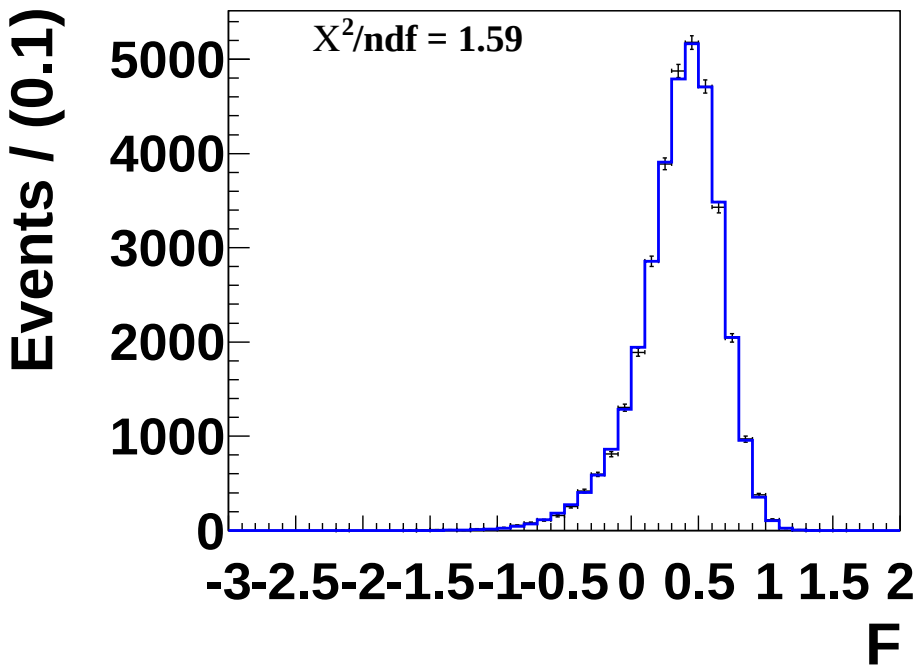
continuum: $e^+e^- \rightarrow q\bar{q}$ (u,d,s,c)

gives large contribution

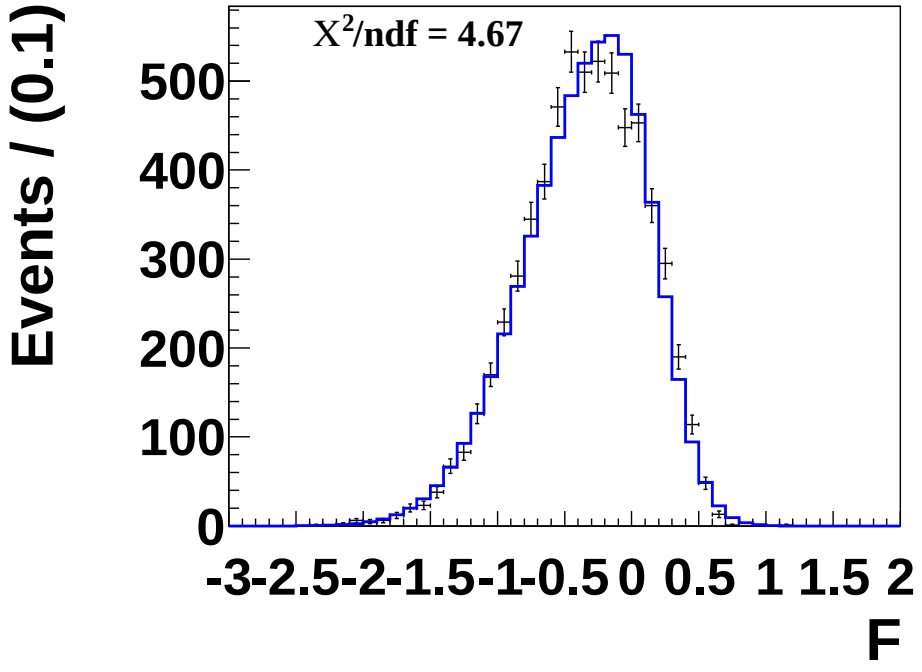
Model for $\mathcal{BR}(B^0 \to \rho^0\rho^0)$

Fisher Discriminant: ($\sum p$, thrust, $cos(\Theta_B)$)

- MC($a_1\pi$)



- off-resonance data

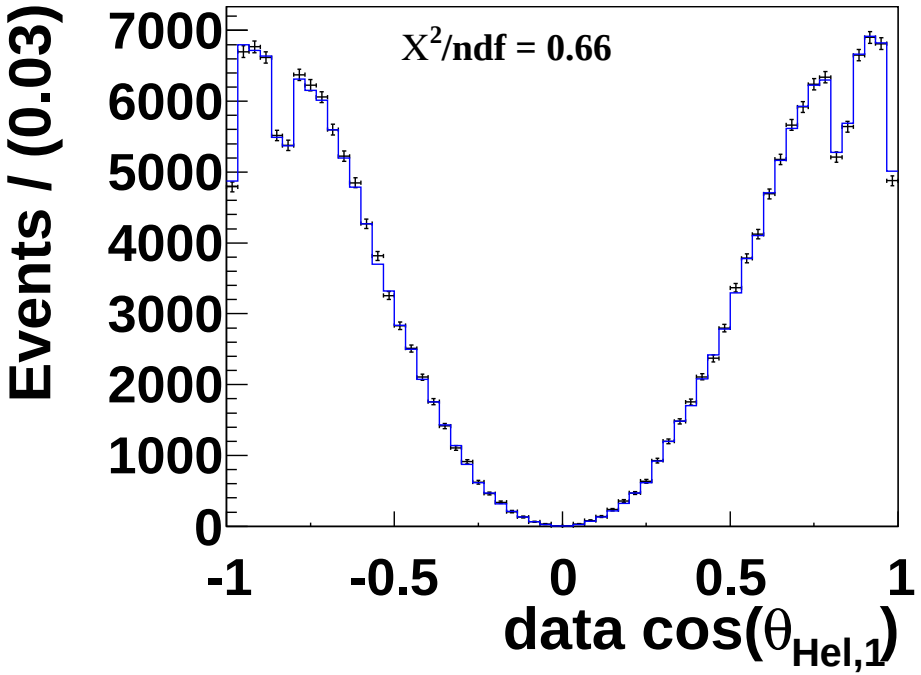


$\mathcal{PDF}$ =double bifurcated gaussian

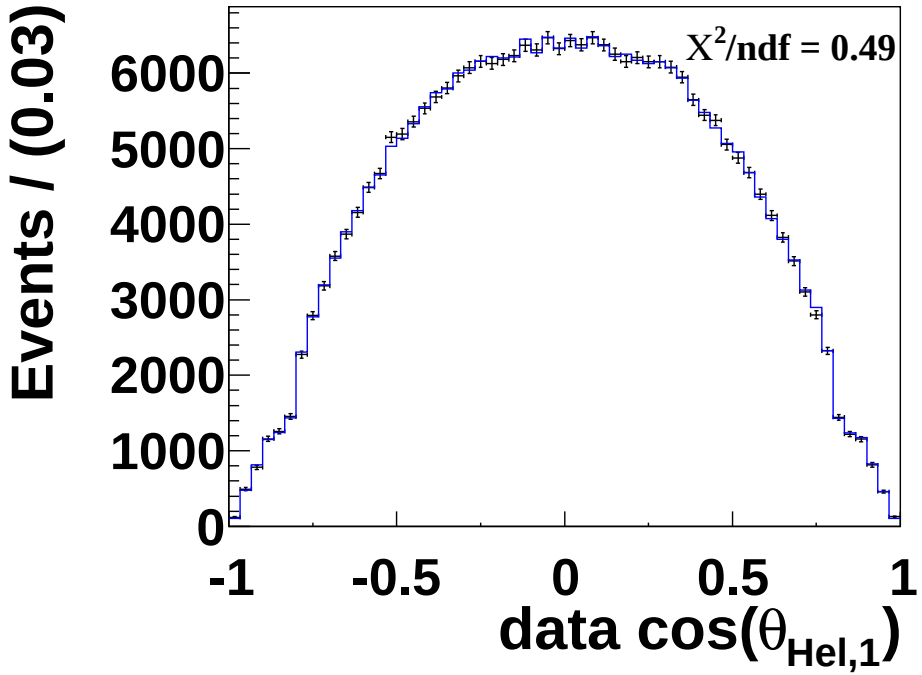
Model for $\mathcal{BR}(B^0 \to \rho^0\rho^0)$

Helicity: weighted with reconstruction efficiency histogram

- signal MC(L pol)



- signal MC(T pol)



$$\frac{1}{\Gamma}\frac{d^2\Gamma}{d\cos\theta^1_{\rm Hel}\, d\cos\theta^2_{\rm Hel}} = \frac{9}{4}\left(f_L \cos^2\theta^1_{\rm Hel}\cos^2\theta^2_{\rm Hel} + \frac{1}{4}(1-f_L)\sin^2\theta^1_{\rm Hel}\sin^2\theta^2_{\rm Hel}\right)$$

Recover ϕ_2

- **extraction of $\Delta\phi_2$ with isospin analysis** (remove penguin pollution)

  for unflavored isospin triplets, e.g. ρ, π

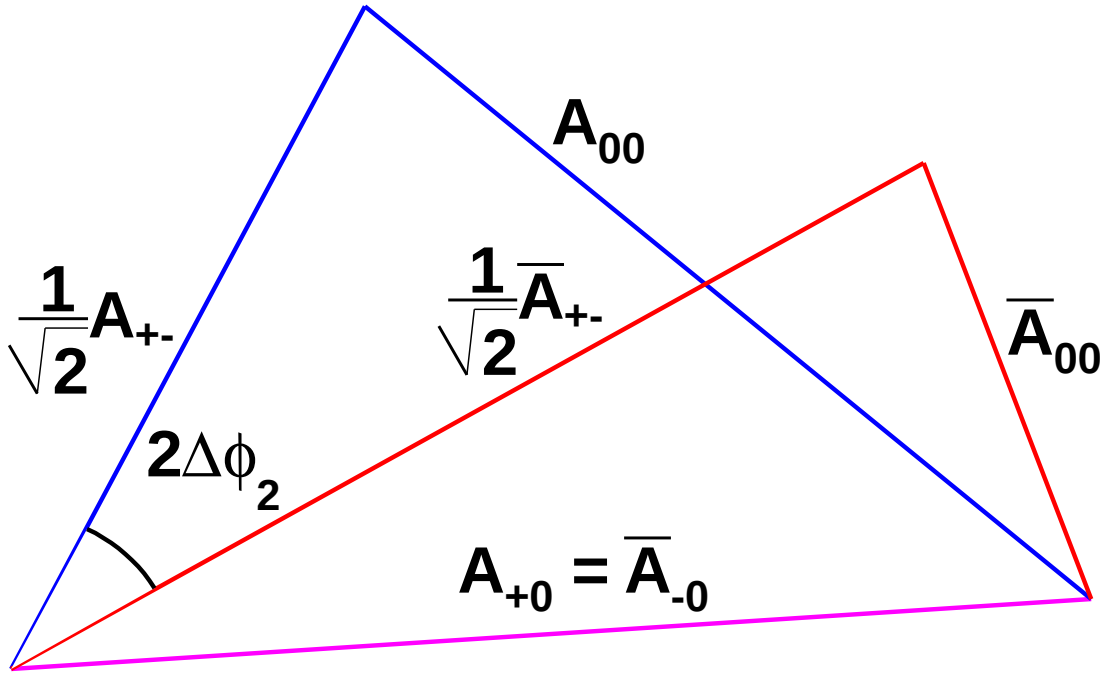
  Bose statistics:$\Rightarrow$ I=0,2 (final states);

  tree I=0,2;

  penguin: I=0 only (gluon; I=0)

  allows to formulate relations of the decay amplitudes A

  e.g. $\bar{A}^{+-} = \mathcal{A}(\bar{B} \to \rho^+\rho^-)$

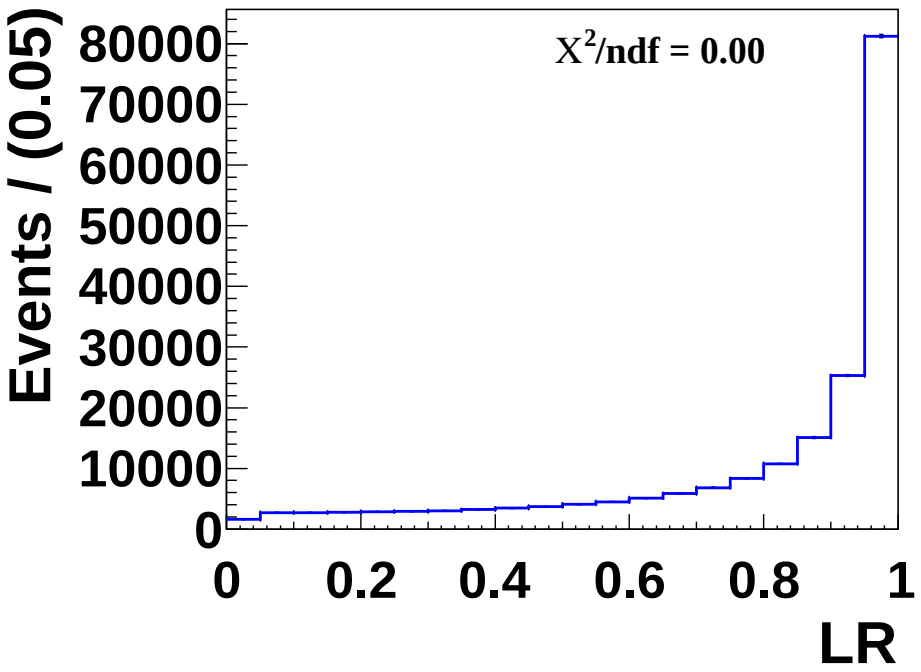


- $\frac{1}{\sqrt{2}}A^{+-} + A^{00} = A^{+0}$
- $\frac{1}{\sqrt{2}}\bar{A}^{+-} + \bar{A}^{00} = \bar{A}^{-0}$
- $A^{+0} = \bar{A}^{-0}$ (no penguin) $\Rightarrow$ geometrical considerations reveal $\Delta\phi_2$

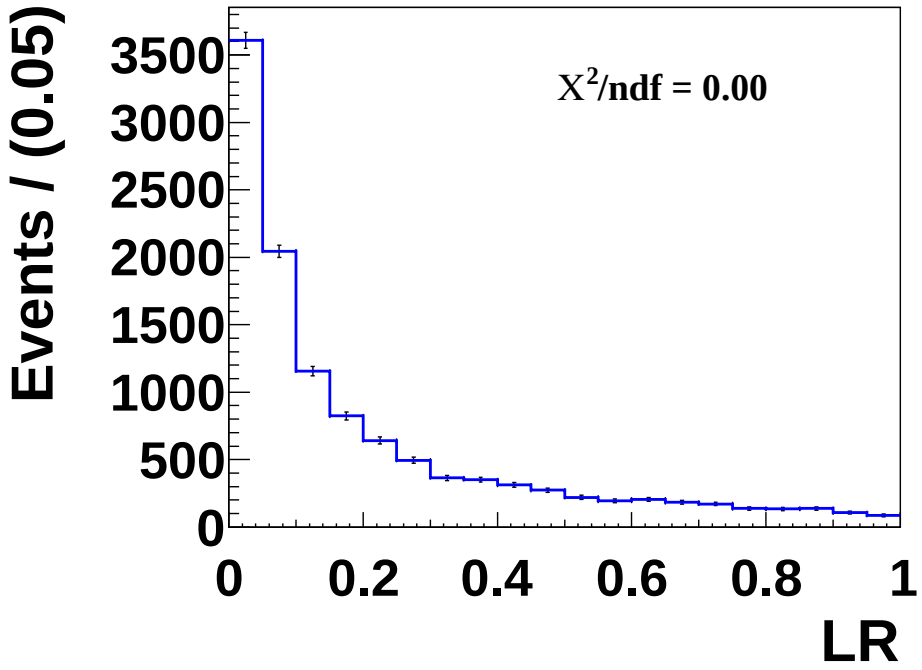
Model for $\mathcal{BR}(B^0 \to \rho^0\rho^0)$

$\mathcal{L}_{B\bar{B}/q\bar{q}}$ consists of event shape variables: $B\bar{B} \to$ spherical, $q\bar{q} \to$ 2 jet like

- signal MC(L pol)

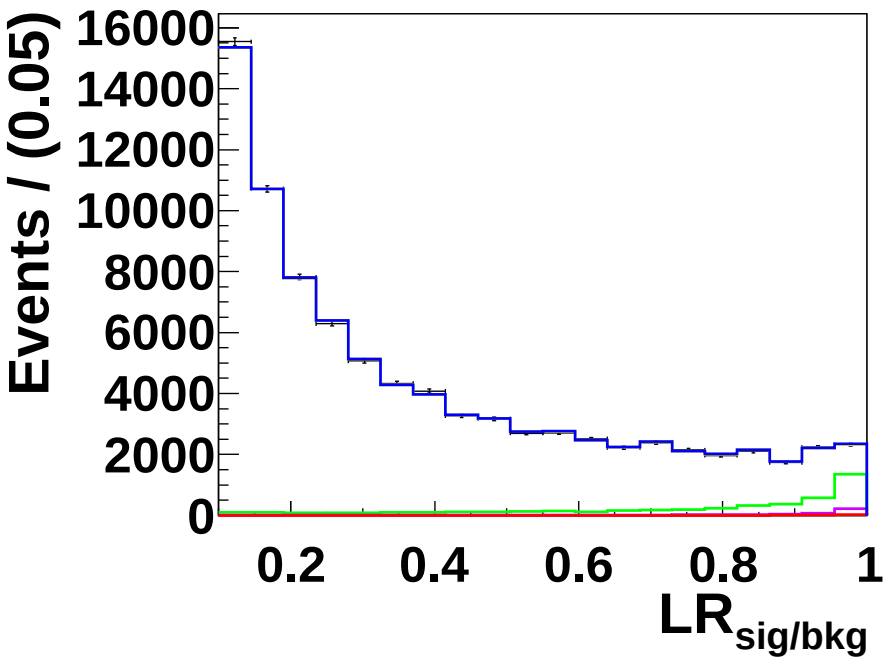


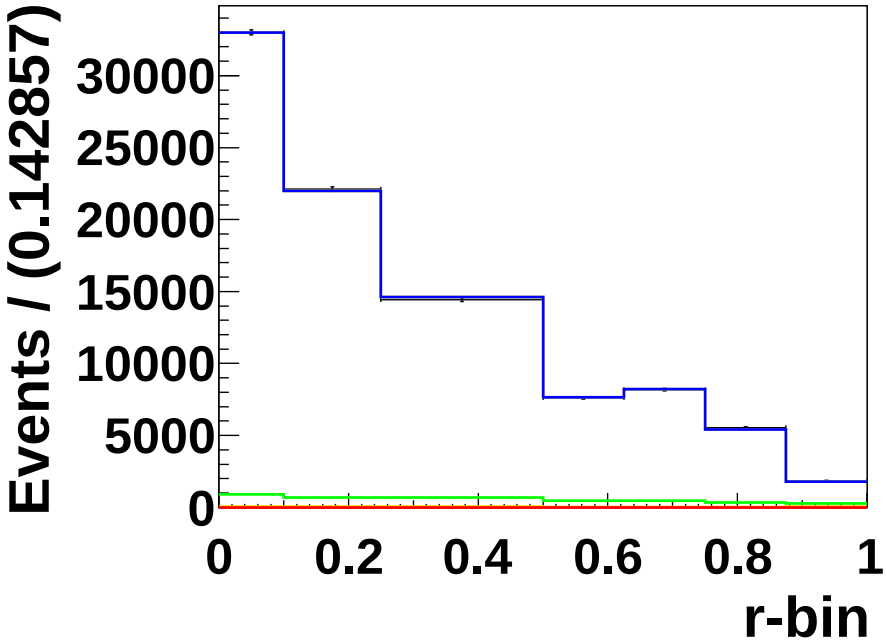
- continuum



$\mathcal{PDF}$ = histogram

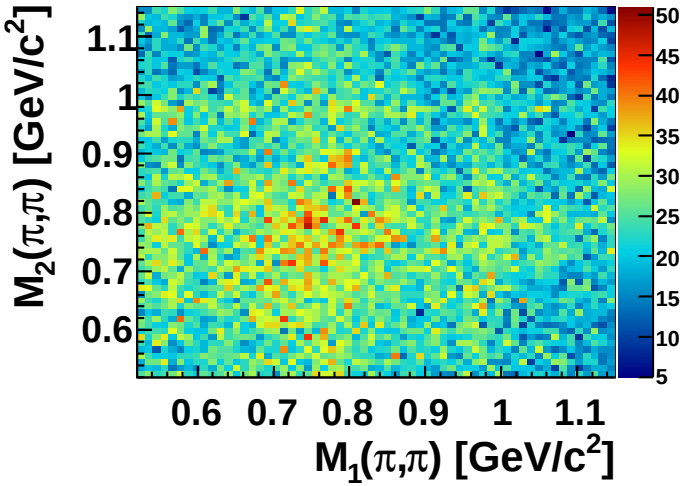
Backup: Toy MC Studies

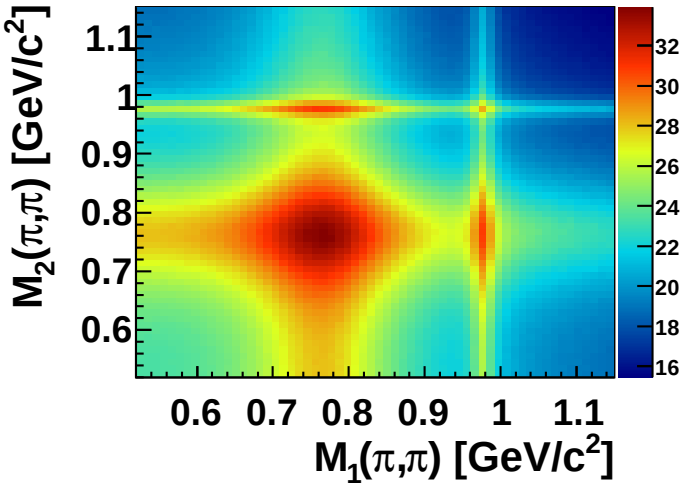


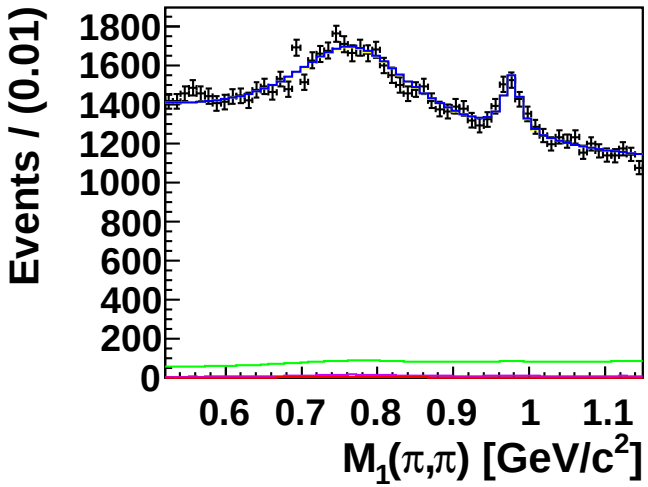


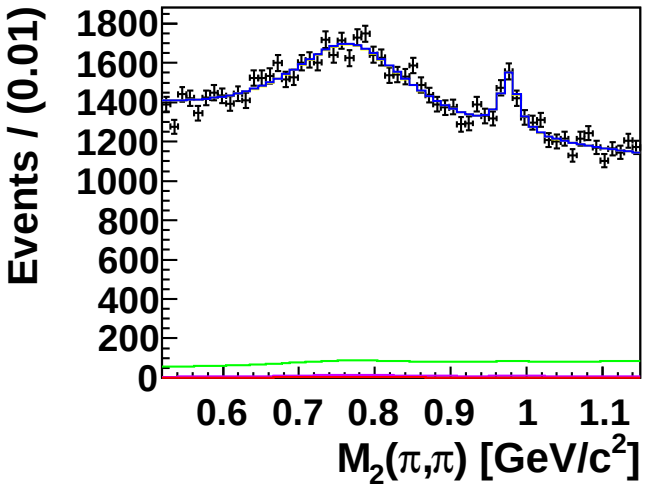
r-bin represents the quality of flavor tagging

Backup: Toy MC Studies

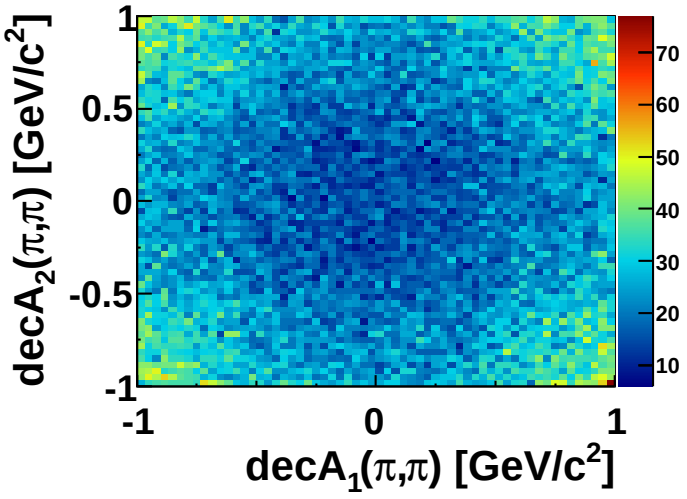


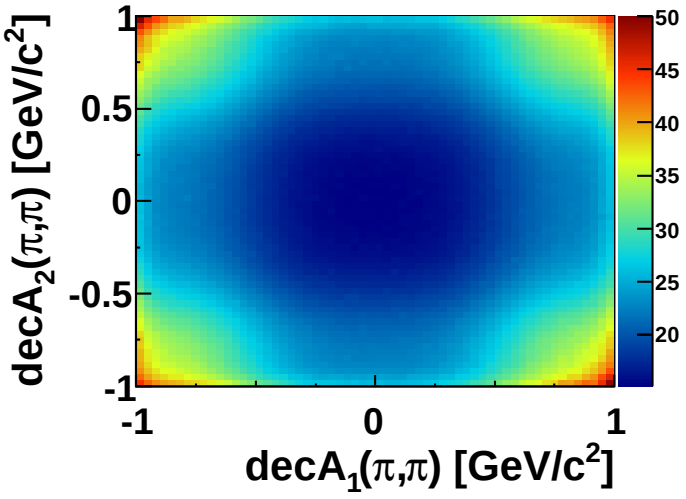


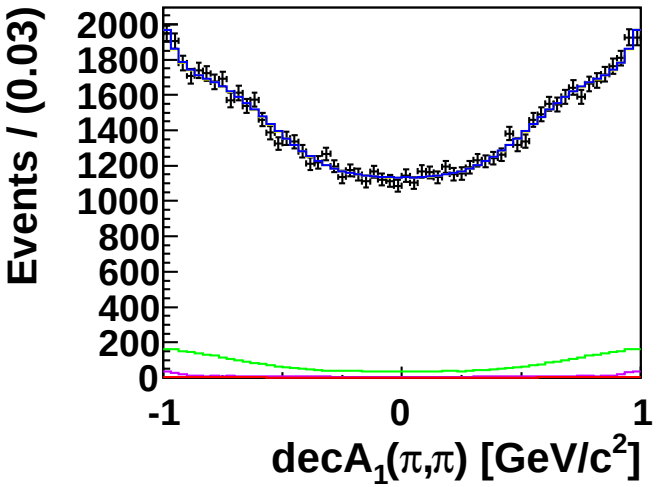


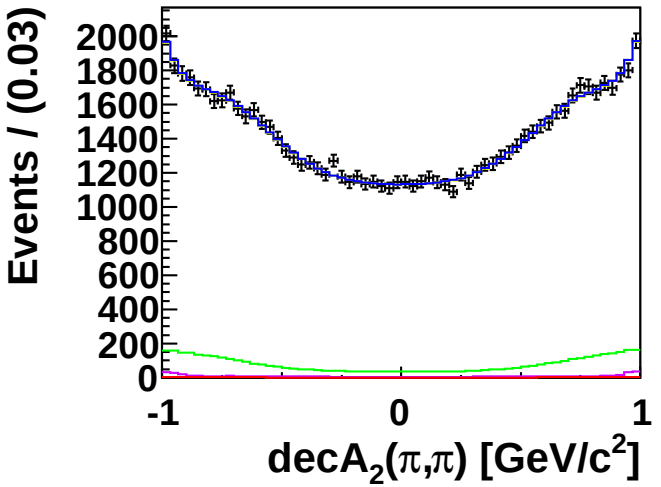


Backup: Toy MC Studies





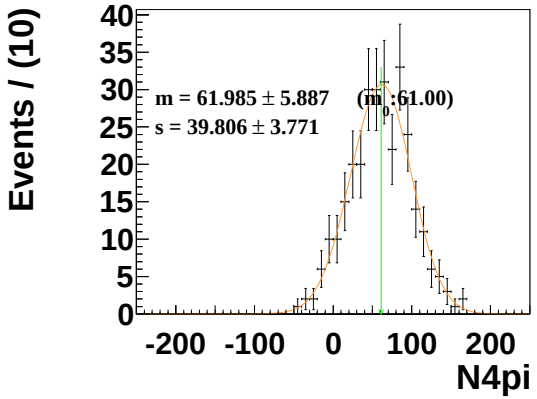


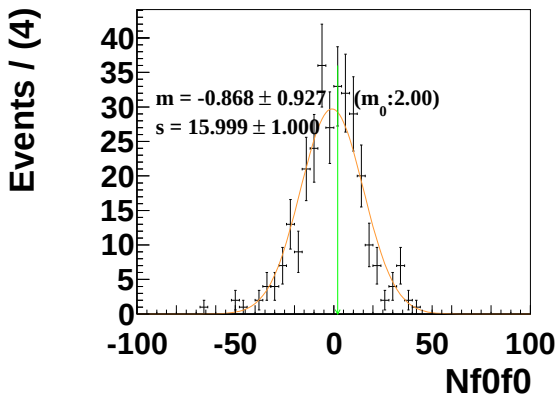


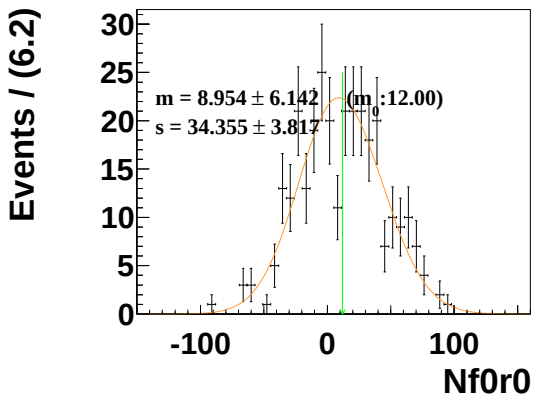
Backup: ToyMC Studies

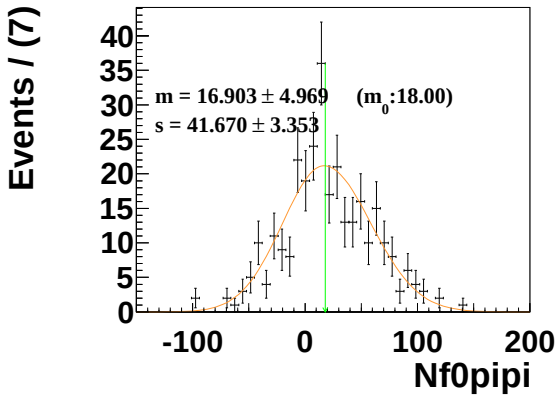
results for $m_{\pi^+\pi^-} \in [0.52, 1.15] GeV/c^2$

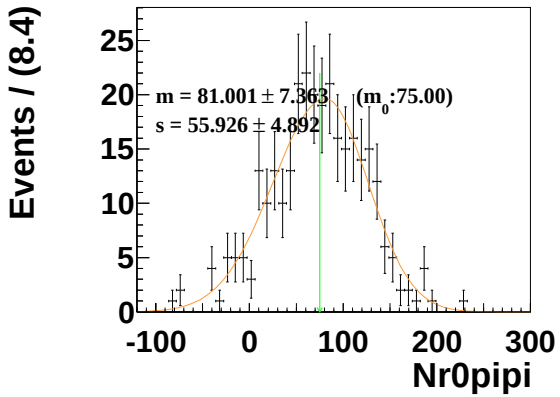
$a_2^{\pm}\pi^{\mp}$ upper limit gives less the 1 event $\Rightarrow$ fixed to 0











Measurement of $\mathcal{BR}(B^0 \to \rho^0\rho^0)$

Reconstruction:

$B^0 \to \rho^0\rho^0$

$\rho^0 \to \pi^+\pi^-$

$\Rightarrow$ 4 charged πs in the detector

- select $\pi^\pm$ candidates: PID criteria
- reconstruct ρ^0 candidates from $\pi^+\pi^-$ pairs

  ρ^0(770): broad resonance($\Gamma \sim 149 MeV$)

  $\to m_{\pi^+\pi^-} \in$ [0.52, 1.7] GeV/c^2

  excludes K^0_S(0.49) and D^0(1.87) [GeV/c^2]
- reconstruct B^0 candidates from $\rho^0\rho^0$ pairs
- charm and strange vetos (due to combinatorics)

  $\to$ removes peaking BKG
- vertexing
- flavor tagging
- select best B^0 candidate (M_{bc})

$$M_{bc} \equiv \sqrt{E^2_{beam} - \vec{p}^{\,2}_{B_{rec}}}$$

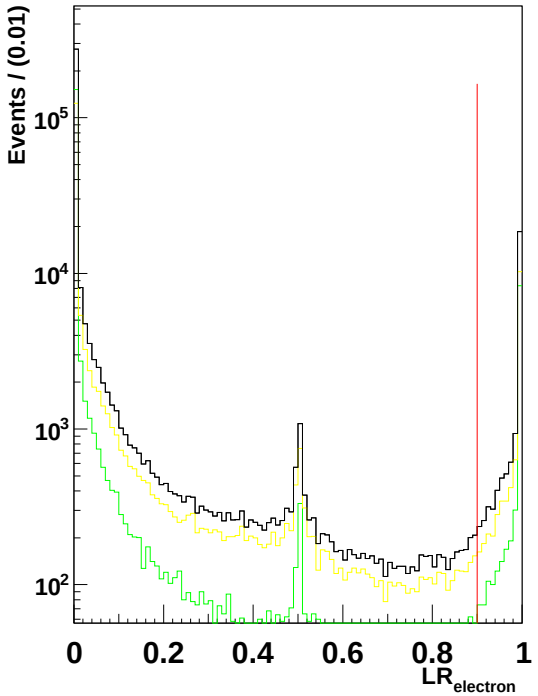
- continuum identification
- randomize events to remove asymmetry due to ordering in the reconstruction

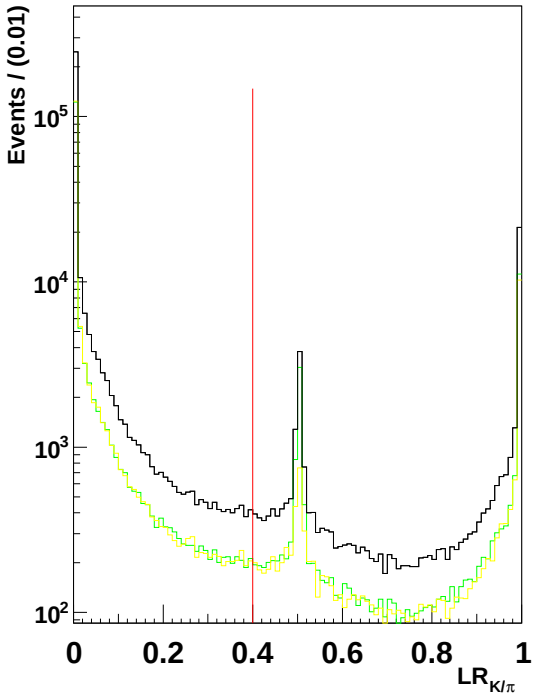
	L pol	T pol
rec Eff	19.6%	27.2%

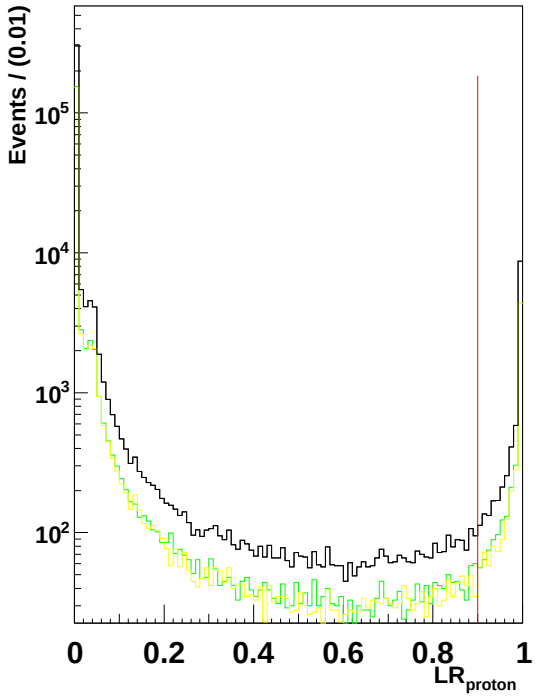
Measurement of $\mathcal{BR}(B^0 \to \rho^0\rho^0)$

- **PID criteria:** information from CDC, TOF and ACC $\rightarrow$ likelihood ratios $\mathcal{LR}_{i/j}$

$\mathcal{LR}_e < 0.9$ $\mathcal{LR}_{K/\pi} < 0.4$ $\mathcal{LR}_{p/\pi} < 0.9$



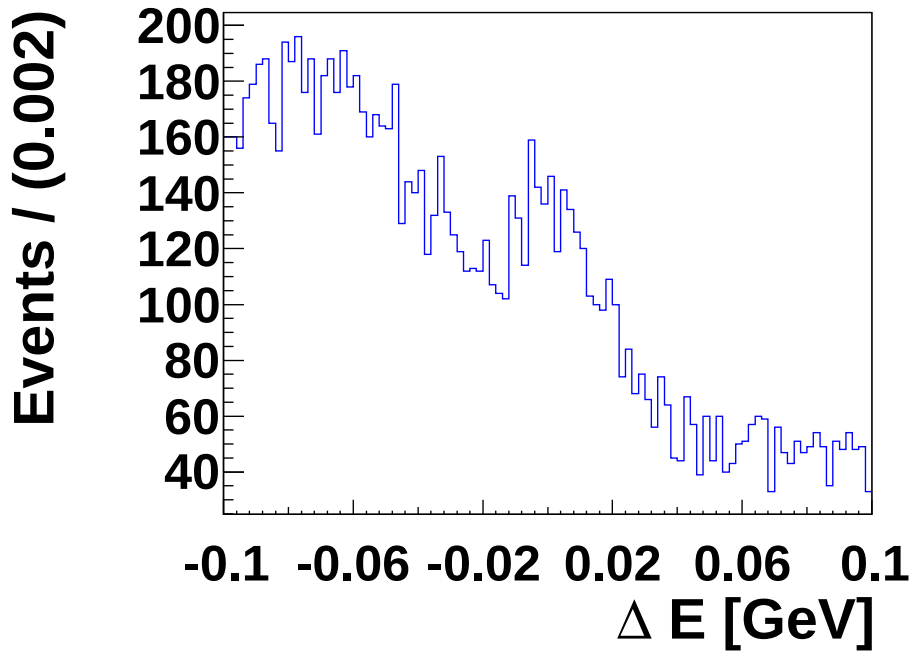


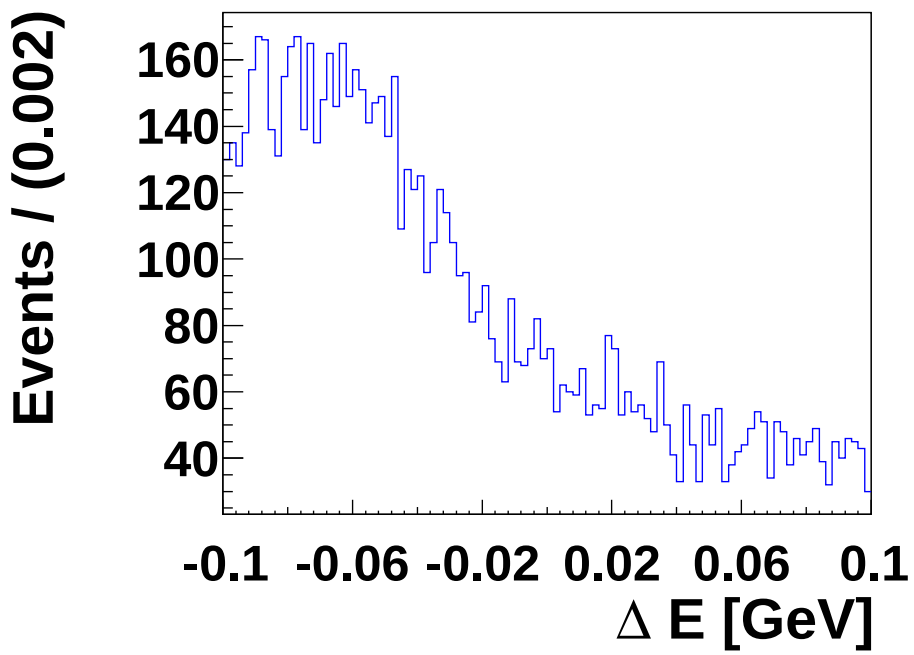


further loose cuts $|dr| < 0.5cm$ & $|dz| < 5cm$

Measurement of $\mathcal{BR}(B^0 \to \rho^0\rho^0)$

- **charm and strange vetos:** removes peaking background with similar final state topology, e.g. $B^0 \to D^-(\pi^-\pi^+\pi^-)\pi^+$ or wrong PID





before and after vetos

Measurement of $\mathcal{BR}(B^0 \to \rho^0\rho^0)$

- **charm and strange vetos:**

Cuts on $M(\pi\pi)$:

$D^0 : 1.86484 \pm 0.02[GeV/c^2]$

$K_s : 0.493677 \pm 0.018[GeV/c^2]$

Cuts on $M(\pi\pi\pi)$:

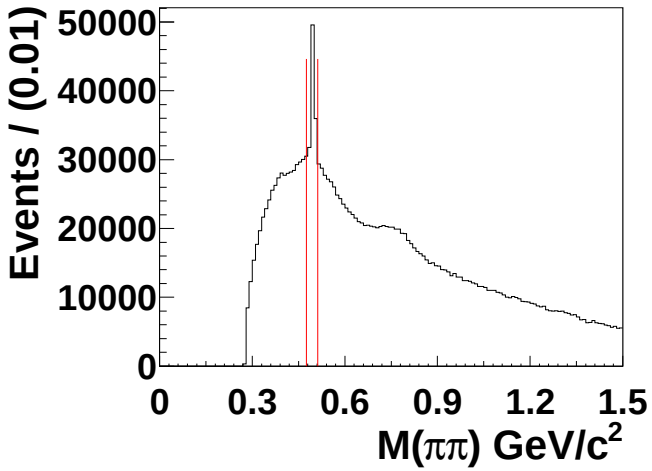
$D^\pm : 1.8696 \pm 0.02[GeV/c^2]$

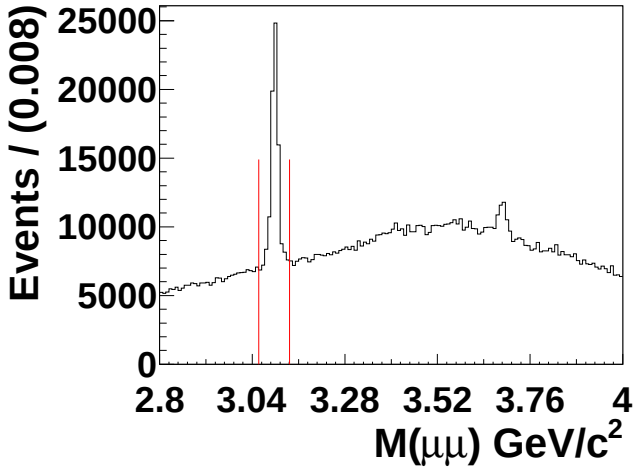
$D_s^\pm : 1.96849 \pm 0.02[GeV/c^2]$

Cuts on $M(\mu\mu)$:

$J\Psi : 3.0969 \pm 0.04[GeV/c^2]$

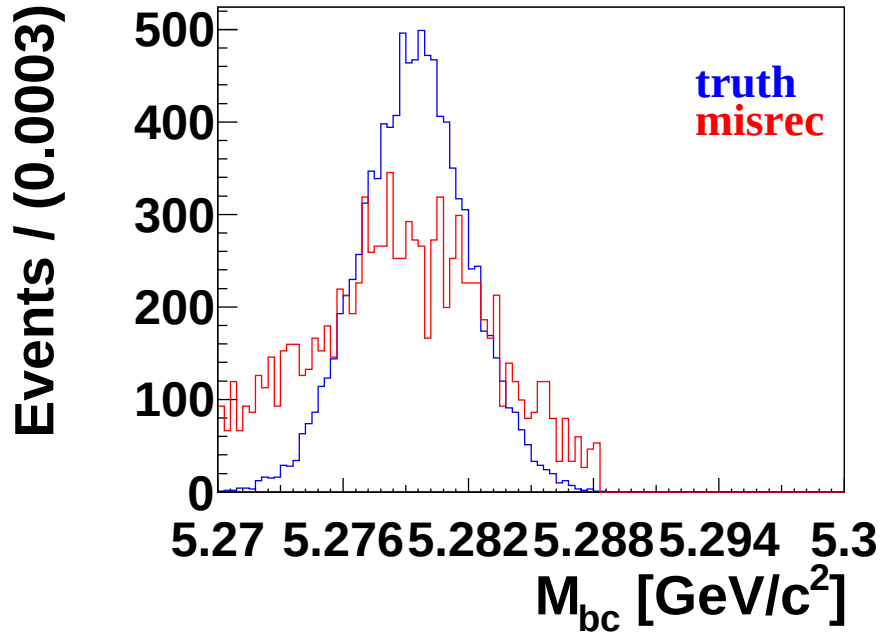
$\to$ loss in $\epsilon_{rec} \sim 4\%$

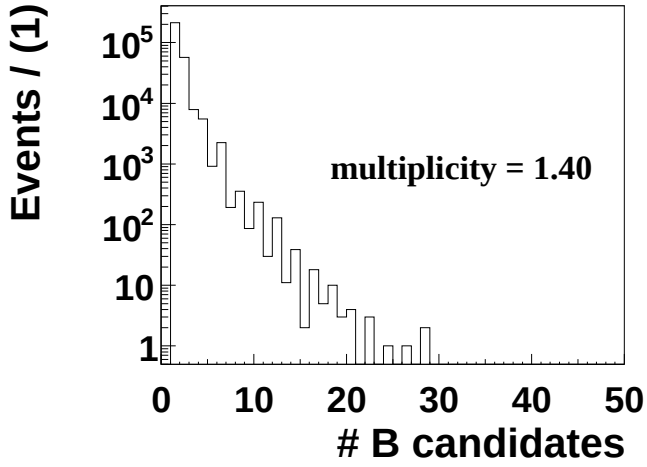




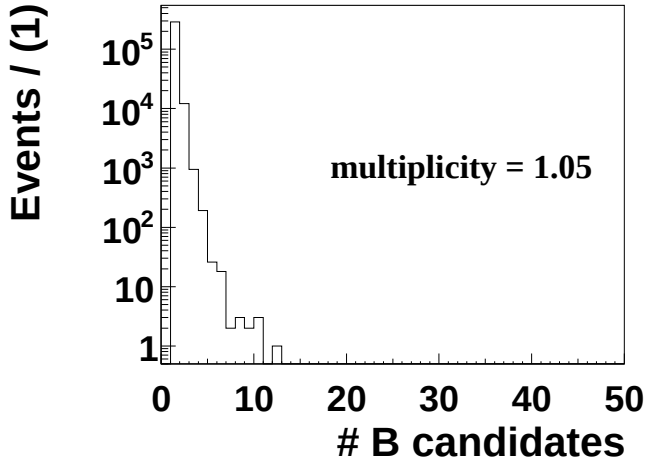
Measurement of $\mathcal{BR}(B^0 \to \rho^0\rho^0)$

- **BCS:** best candidate selection





L(top) and T pol



if 2 candidates with same M_{bc}

$\Rightarrow$ choose combination with highest π^+ and lowest π^- momentum

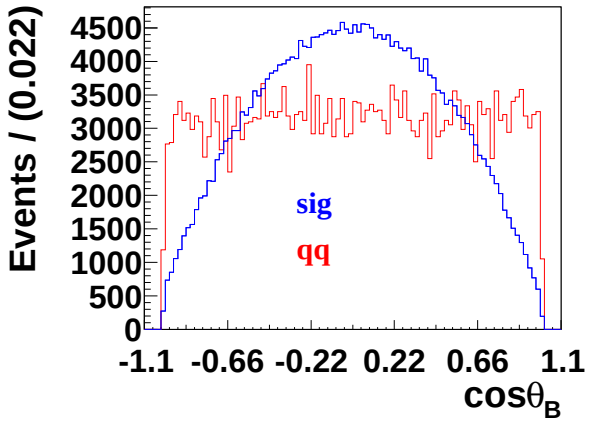
$\to$ purity $= 76\%(L); 92\%(T)$

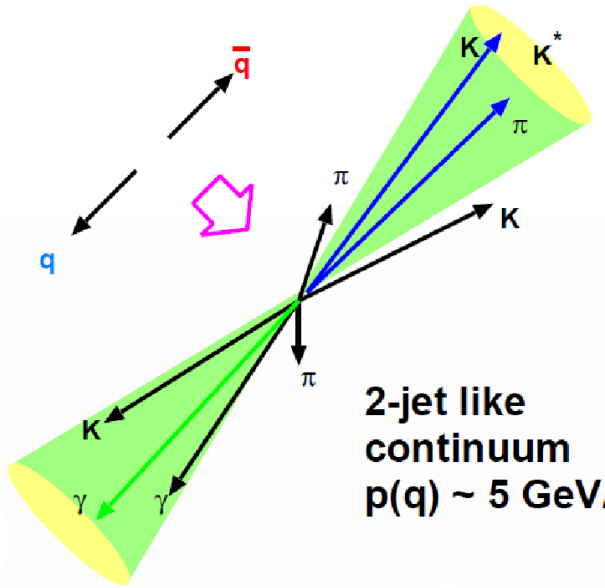
Measurement of $\mathcal{BR}(B^0 \to \rho^0\rho^0)$

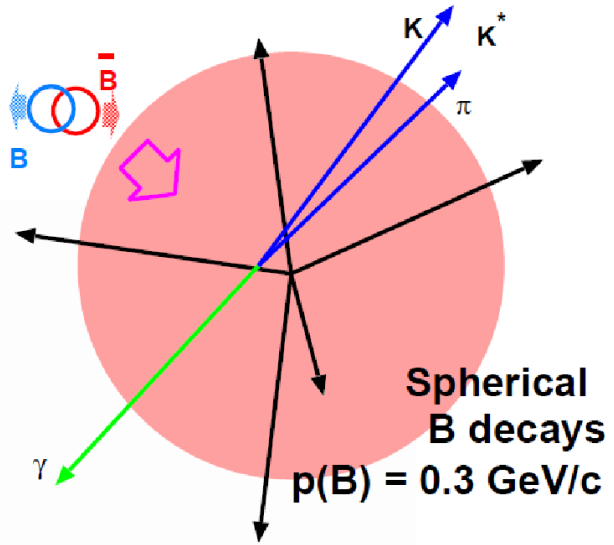
- **continuum identification:** combined event shape variables using fisher discriminant

- $\cos(\theta_B)$

  B flight direction







- fox-wolfram moments: $H_l = \sum_{i,j} \frac{|\vec{p}_i||\vec{p}_j|}{s} P_l(cos\phi_{ij})$ with Legendre poly. P_l

Impact on CKM Angle ϕ_2

- **variation of $\mathcal{BR}(B^0 \to \rho^0\rho^0)$ in isospin analysis**

What could happen?

average from my first fit and BaBar's result A_{pit}

A_{pit} =

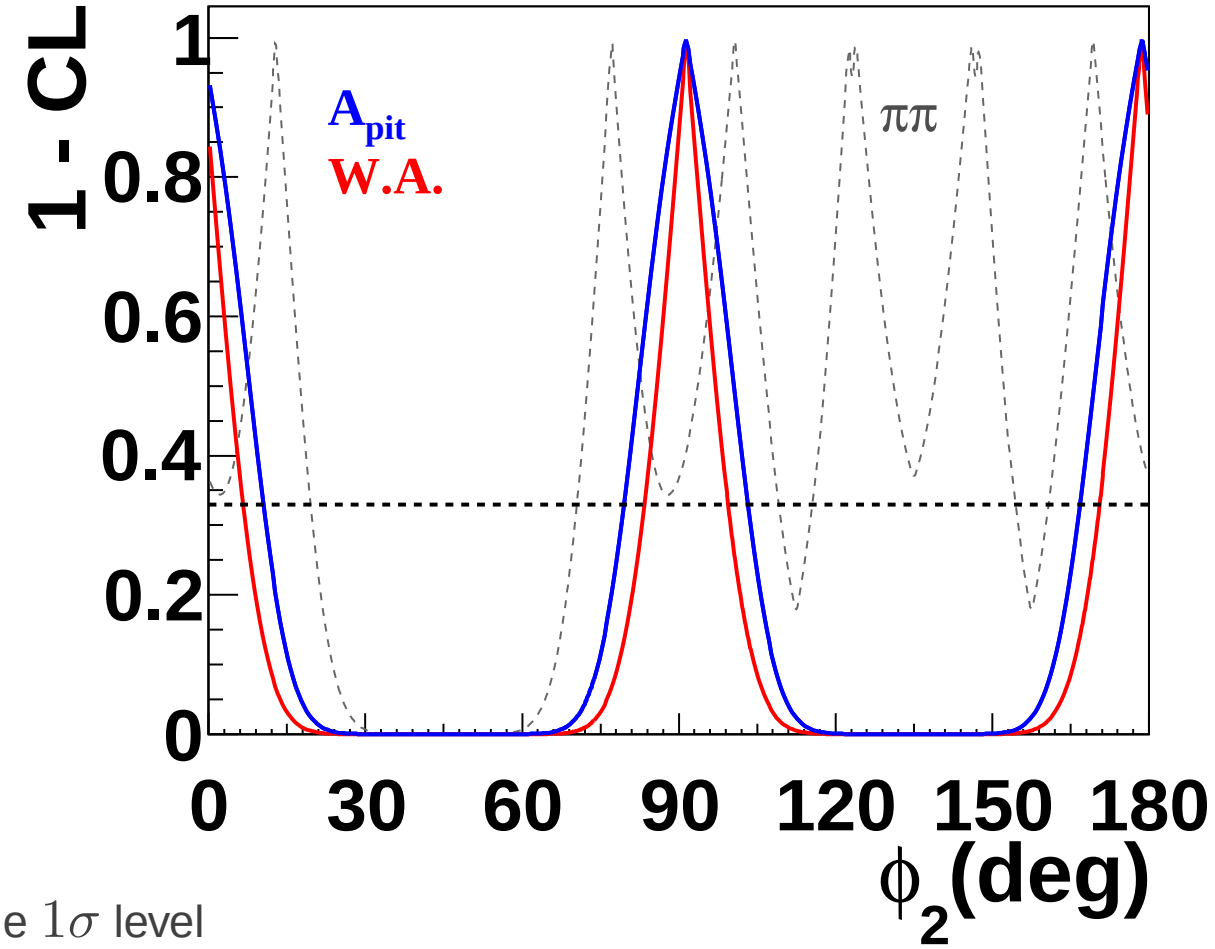
$(XX \pm 0.26) \times 10^{-6}$

$\phi_2 = XX^{+11.6}_{-11.9}$

W.A. =

$(0.73 \pm 0.28) \times 10^{-6}$

$\phi_2 = 91.4^{+8.1}_{-7.9}$



$\Rightarrow \sim 50\%$ increase of the error at the 1σ level