

Study of $B^0 \rightarrow \rho^0 \rho^0$ and its impact on the CKM angle ϕ_2

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1) Motivation

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4) Measurement procedure

5) Summary & Outlook



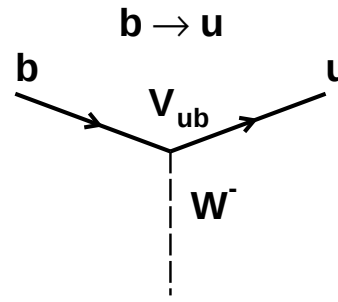
Motivation

violation of CP symmetry necessary for matter anti-matter asymmetry

$CP = C(\text{charge}) \times P(\text{parity})$; 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} , $\lambda = \sin \theta_C \approx 0.22$ (Cabibbo angle)

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

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

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

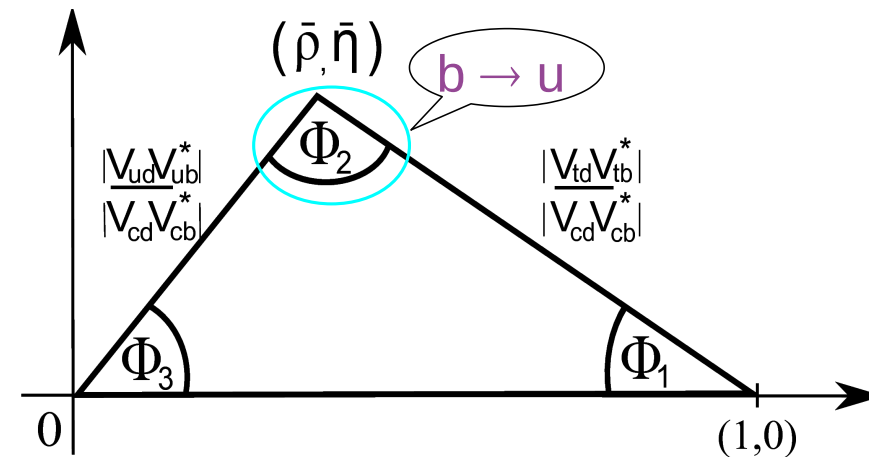
$$\begin{array}{ccccc} V_{ud}V_{ub}^* & + & V_{cd}V_{cb}^* & + & V_{td}V_{tb}^* = 0 \\ \mathcal{O}(\lambda^3) & & \mathcal{O}(\lambda^3) & & \mathcal{O}(\lambda^3) \end{array}$$

sides with similar length $\Rightarrow$ large **CP violation**

precise determination of the observables

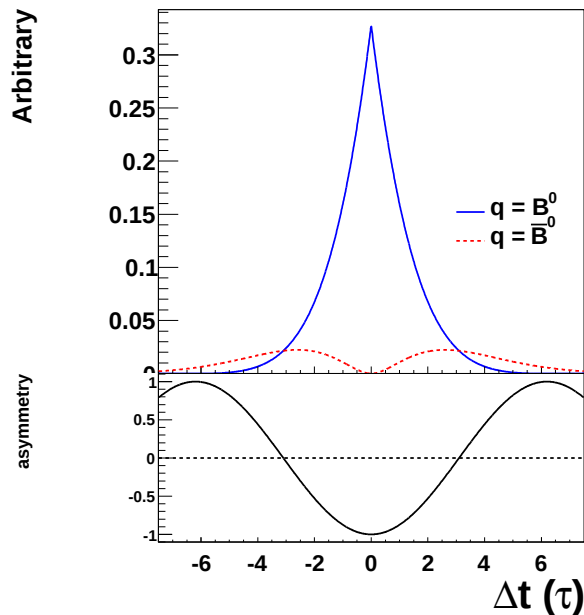
5 observables (3 angles, 2 sides) $\Rightarrow$ over-constraint

confirm SM **or** find new physics



CP Violation in the B System

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



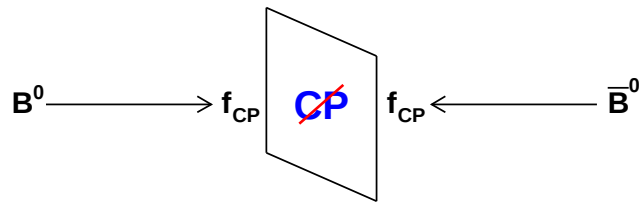
CP asymmetry parameters:

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

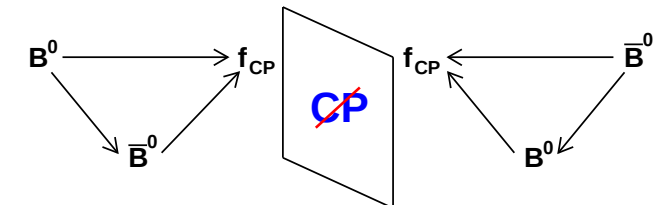
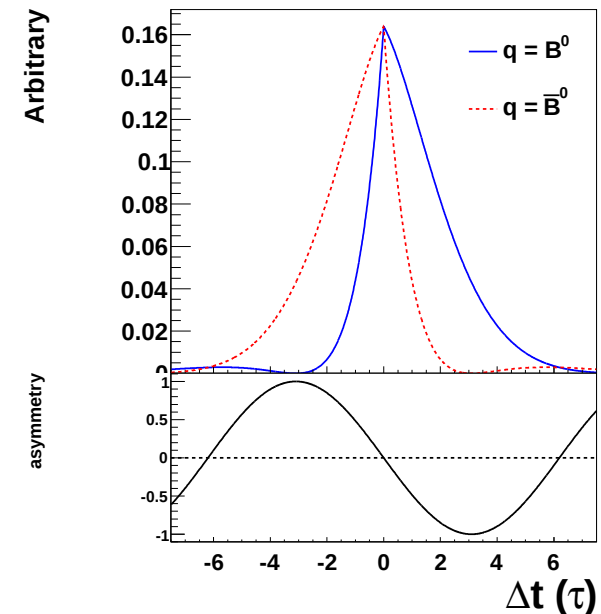
different decay rates

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

or different time evolution

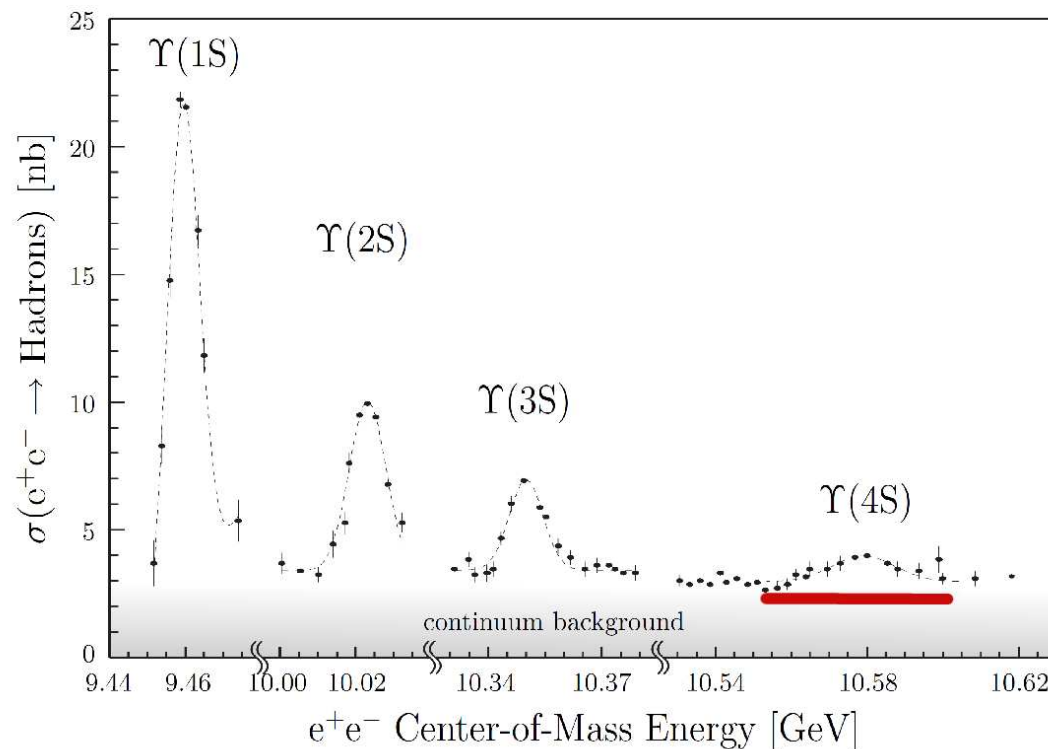


for B and $\bar{B}$ decaying into a CP eigenstate f_{CP}



CP Violation measurement

Where the B s come from:



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

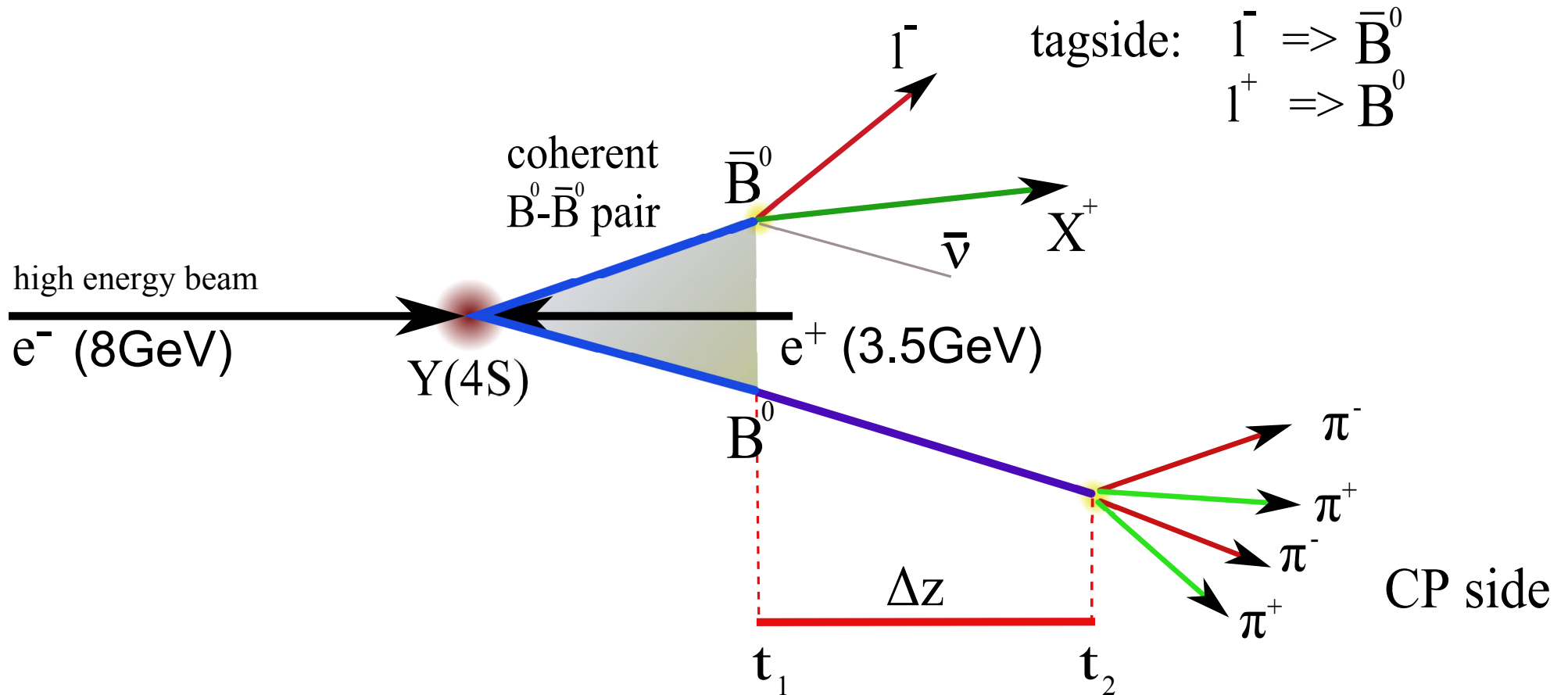
$$m(B) = 5.28 \text{ GeV}/c^2$$

- 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
 $\rightarrow B$ s have opposite flavor:
 $\Rightarrow$ entangled $B\bar{B}$ pair

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

gives large contribution

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 $\Rightarrow \Delta t \rightarrow \Delta z$ ($\Delta t \sim ps$, $\Delta z \sim 100\mu m$)

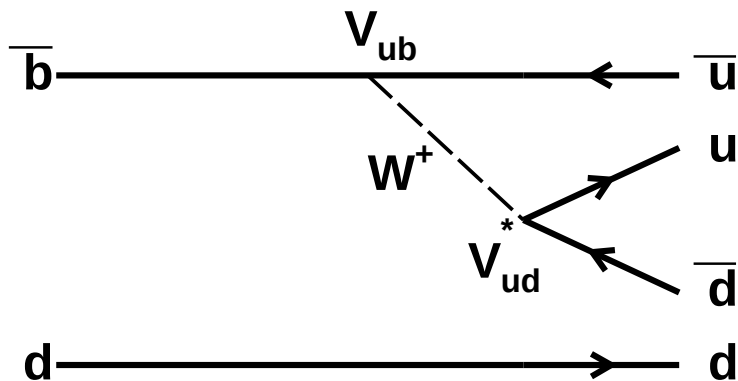
The Belle Experiment

located at the KEKB collider in Japan

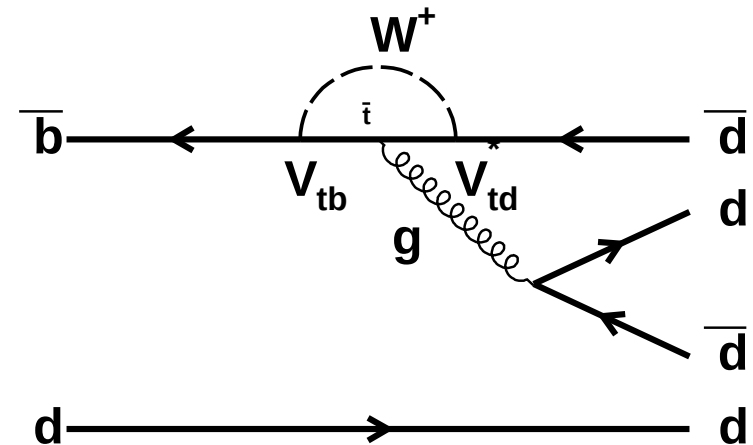


$$B^0 \rightarrow \rho^0 \rho^0$$

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



ϕ_2



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

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

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

Goal: 1st $\mathcal{BR}(B^0 \rightarrow \rho^0 \rho^0)$; 2nd $\mathcal{S}_{CP}, \mathcal{A}_{CP}$

Recover ϕ_2

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

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

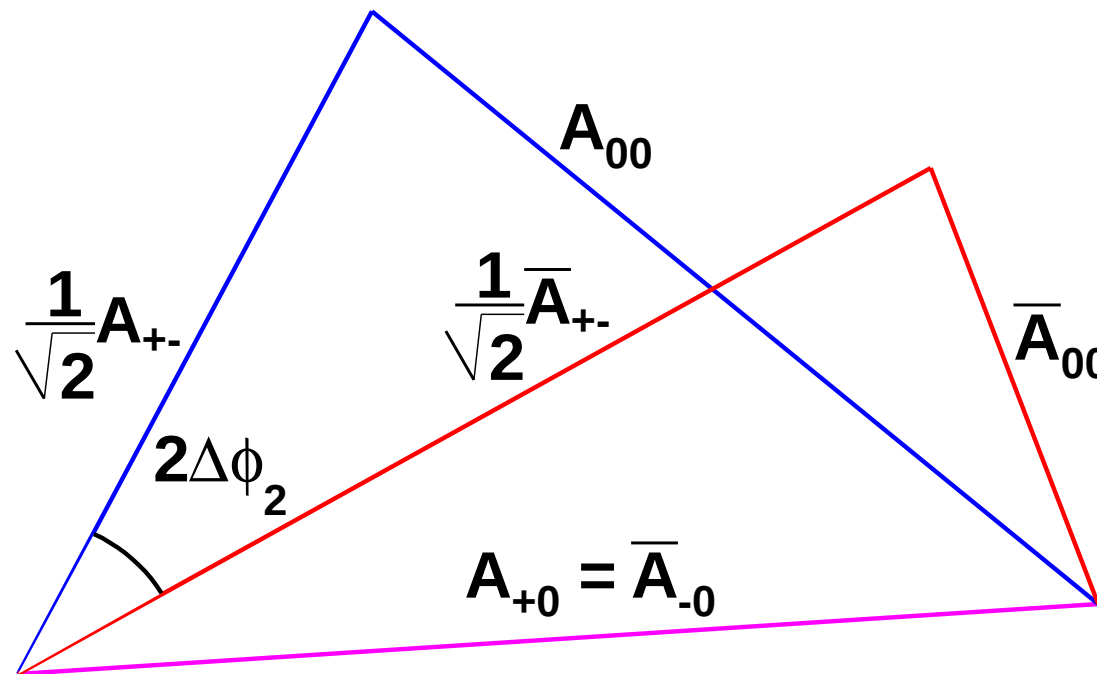
Bose statistics: $\Rightarrow l=0,2$ (final states);

tree $l=0,2$;

penguin: $l=0$ only (gluon; $l=0$)

allows to formulate relations of the decay amplitudes A

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



- $\frac{1}{\sqrt{2}} A^{+-} + A^{00} = A^{+0}$
- $\frac{1}{\sqrt{2}} \bar{A}^{+-} + \bar{A}^{00} = \bar{A}^{-0}$
- $A^{+0} = \bar{A}^{-0}$ (no penguin)

$\Rightarrow$ geometrical considerations reveal $\Delta\phi_2$

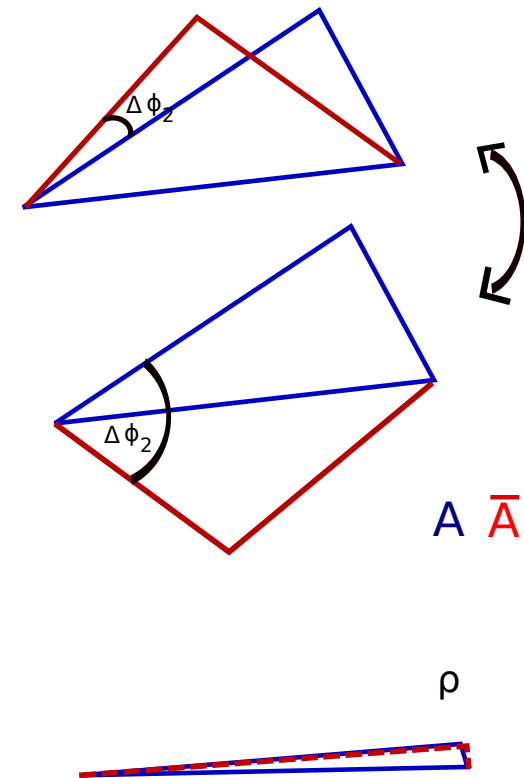
Recover ϕ_2

In $b \rightarrow u$ 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

- $\mathcal{BR}(B^0 \rightarrow \rho^0 \rho^0)$ 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 $B^0 \rightarrow \rho^0 \rho^0$ important for the understanding of ϕ_2



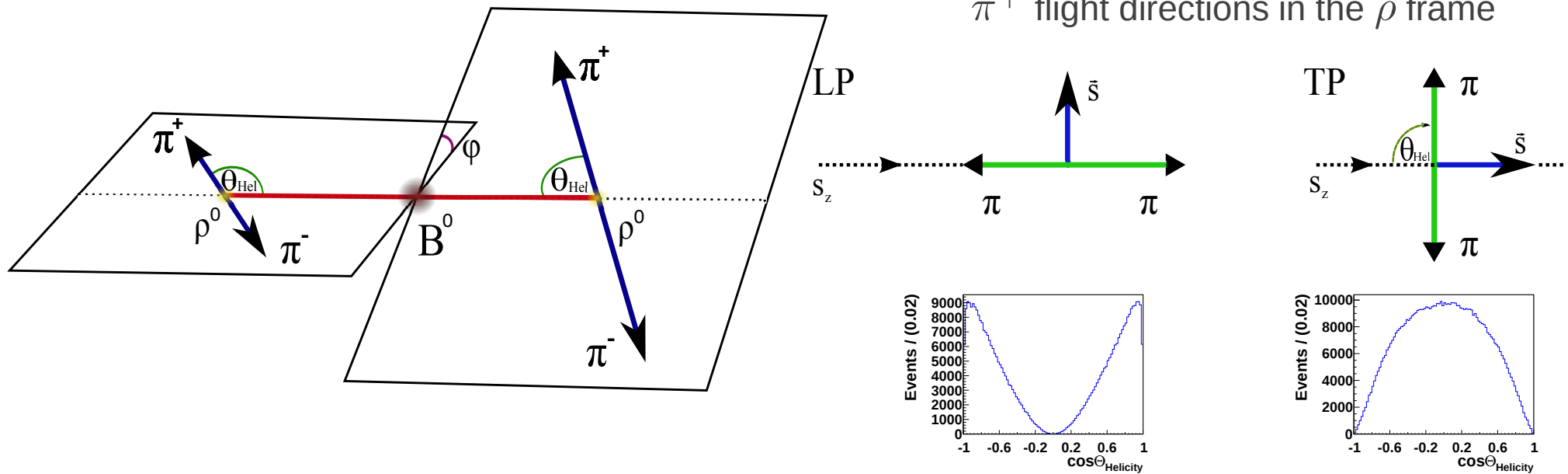
$$B^0 \rightarrow \rho^0 \rho^0$$

- **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



$$B^0 \rightarrow \rho^0 \rho^0$$

previous measurements

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

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

$\Rightarrow$

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 $\mathcal{BR}(B^0 \rightarrow \rho^0 \rho^0)$

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

6 fit dimensions:

$$\Delta E, m_{\pi^+\pi^-}^1, m_{\pi^+\pi^-}^2, \mathcal{L}_{B\bar{B}/q\bar{q}}, \cos \theta_{\text{Hel}}^1, \cos \theta_{\text{Hel}}^2$$

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

$\mathcal{L}_{B\bar{B}/q\bar{q}}$: event-shape
based likelihood

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

$\rightarrow$ modeled 17 components:

shape determined from

– signal (L pol, T pol);

Monte Carlo(MC)

– misreconstructed signal (L pol, T pol);

MC

– continuum ($e^+e^- \rightarrow q\bar{q}$);

data taken at $\sqrt{s} = 10.50 \text{ GeV} < m(\Upsilon(4S))$

– $B\bar{B}$: charm and charmless $B^0(B^\pm)$ decays;

MC

– peaking background (4π s final states);

MC

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

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

test fitting procedure with Toy MC

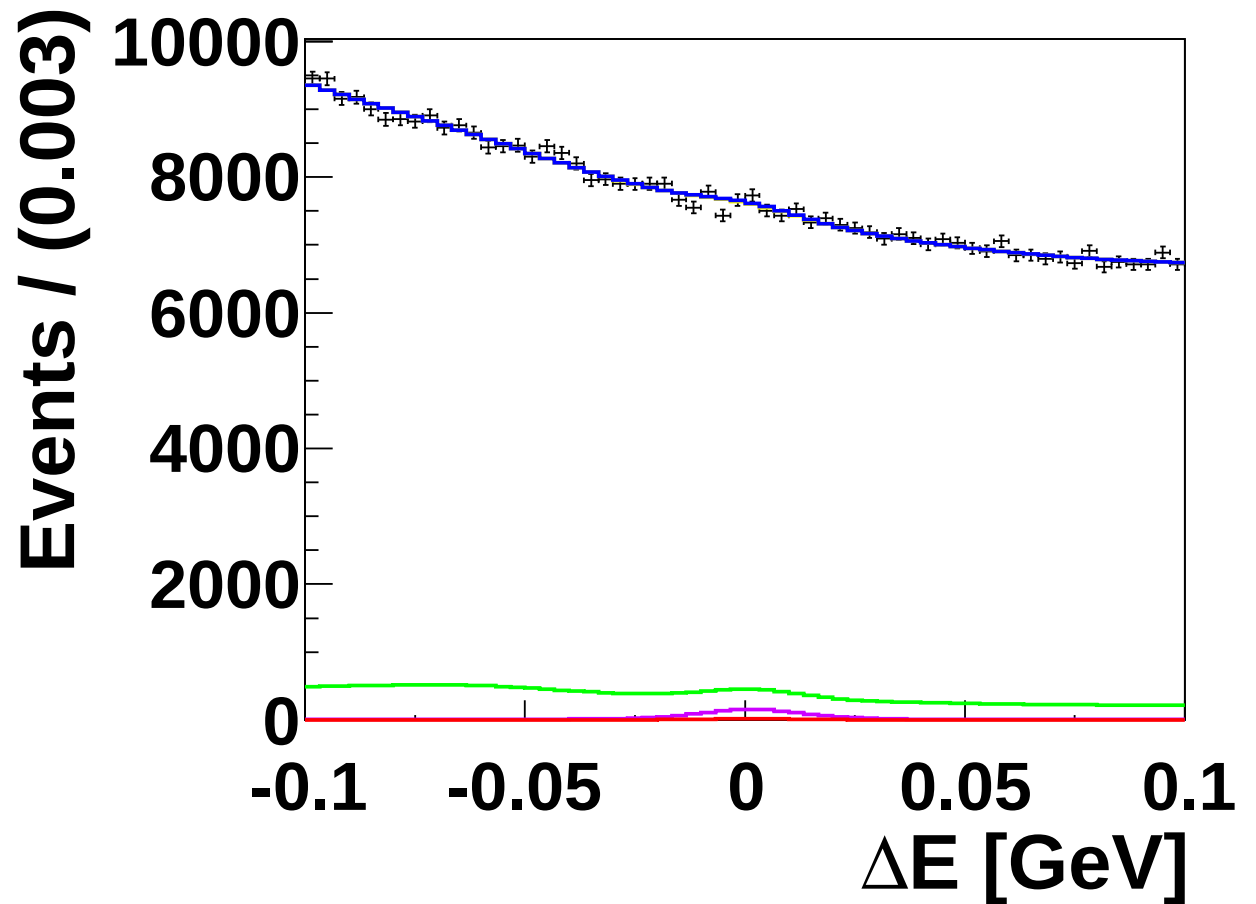
⇒ Toy MC Generator built: events according to $\mathcal{PDF}$ (probability density function)

toy MC example

expected Nr of events

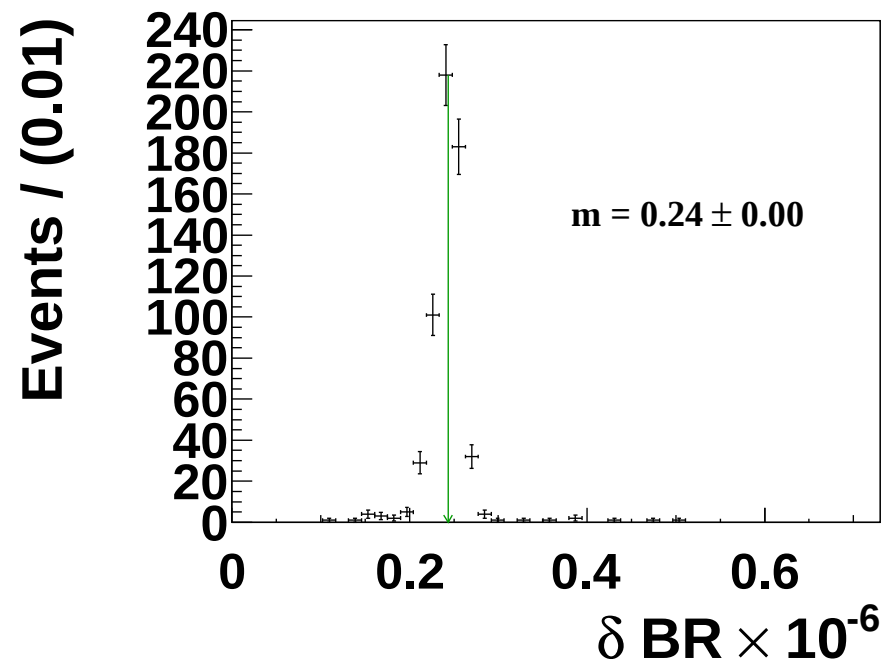
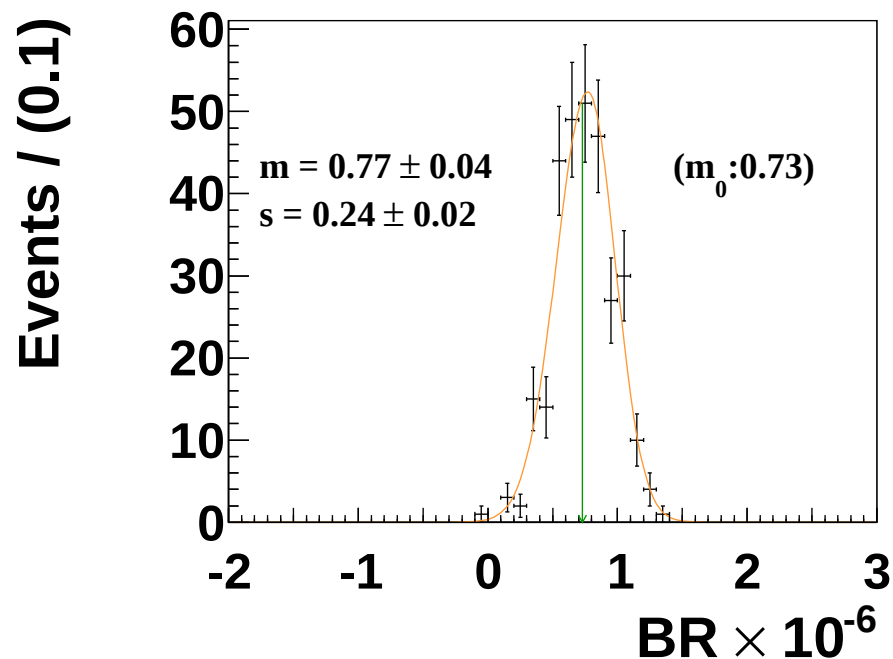
- **signal**: ~ 100
- 4π **ff**: ~ 1600
- $B\bar{B}$: ~ 21000
- **all**: ~ 460000

(using world averages)



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

- performed fits on 300 toy MC samples



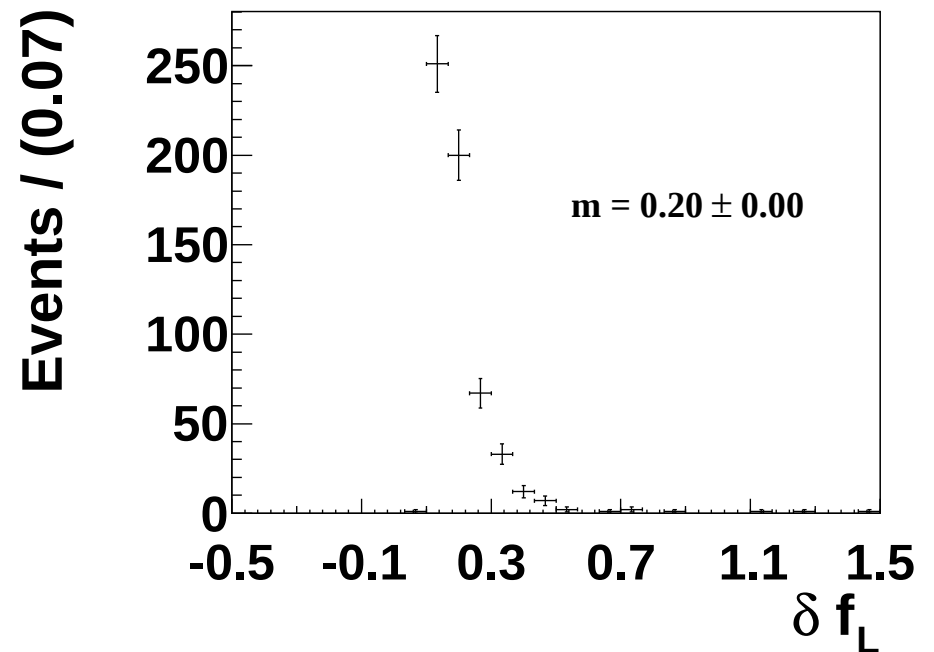
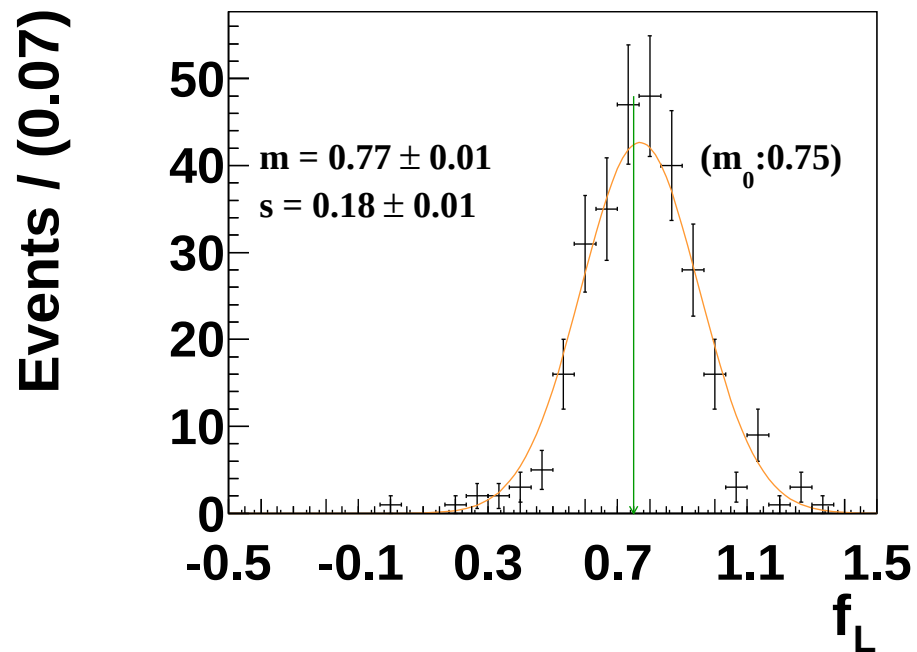
green line is input value

indicates 3σ significance

$\Rightarrow$ observation with a 3σ 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!

Fit to Data

first fit to $0.25 \times$ data,

XX denotes results that cannot be made public

Fit Result:

$$N_{\rho^0 \rho^0} = XX_{-16.41}^{+18.07} \rightarrow \mathcal{BR}(B^0 \rightarrow \rho^0 \rho^0) = XX_{-0.57}^{+0.63} \times 10^{-6}; \quad f_L = XX_{-0.19}^{+0.18}$$

PRE-PRELIMINARY

$$N_{q\bar{q}} = XX \pm 142$$

$$N_{B\bar{B}} = XX \pm 69$$

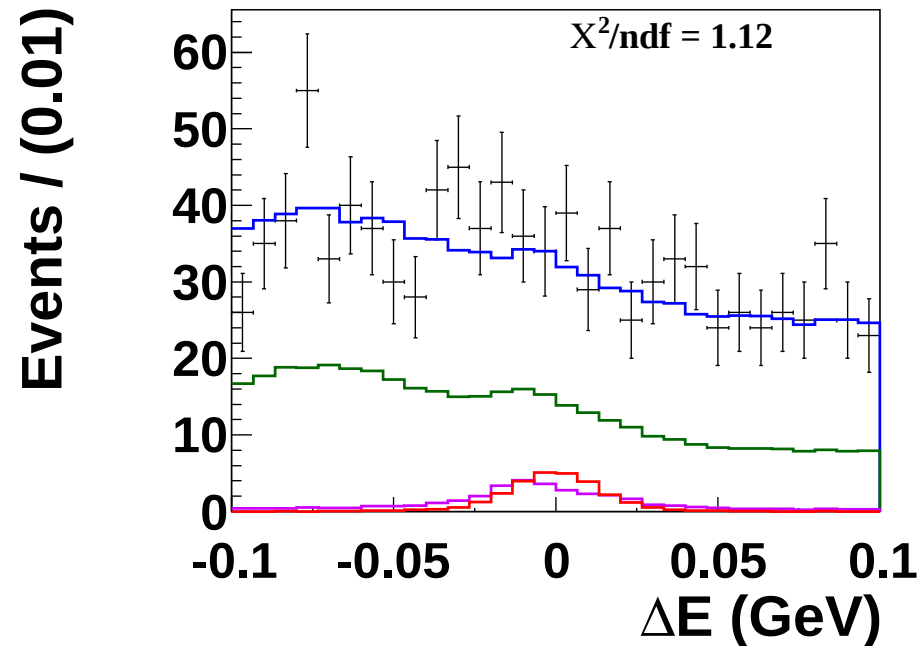
$$N_{4\pi} = XX \pm 23$$

$$N_{\rho^0 \pi \pi} = XX \pm 16$$

$$N_{f_0 \pi \pi} = XX \pm 20$$

$$N_{f_0 f_0} = XX \pm 9$$

$$N_{f_0 \rho^0} = XX \pm 14$$



$$(\mathcal{BR}(B^0 \rightarrow \rho^0 \rho^0): \text{BaBar} = 0.92 \pm 0.32, \text{theory} = 0.44_{-0.37}^{+0.66})$$

Impact on CKM Angle ϕ_2

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

What could happen?

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

$A_{pit} =$

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

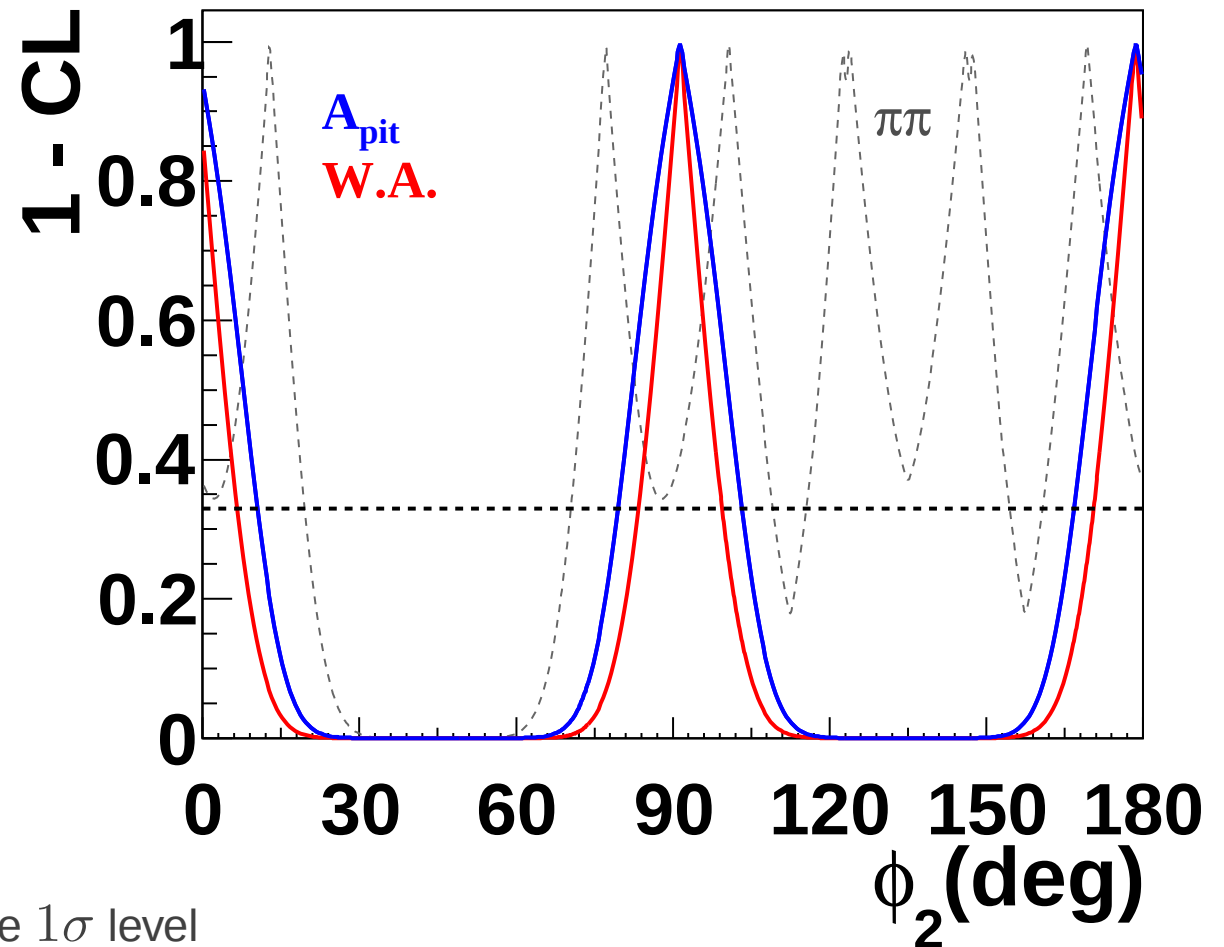
$$\phi_2 = XX_{-11.9}^{+11.6}$$

W.A. =

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

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

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



Summary & Outlook

- $B^0 \rightarrow \rho^0 \rho^0$ plays an important role in constraining ϕ_2
→ isospin analysis
 - also, this measurement is an important test of theory (not shown)
Scalar → Vector Vector: complicated computations $\leftrightarrow$ assumptions
 - new multivariate approach, avoiding cuts and including helicity
→ possibility of a 1st observation at Belle
- ⇒ extraction of CP asymmetry parameters

Backup

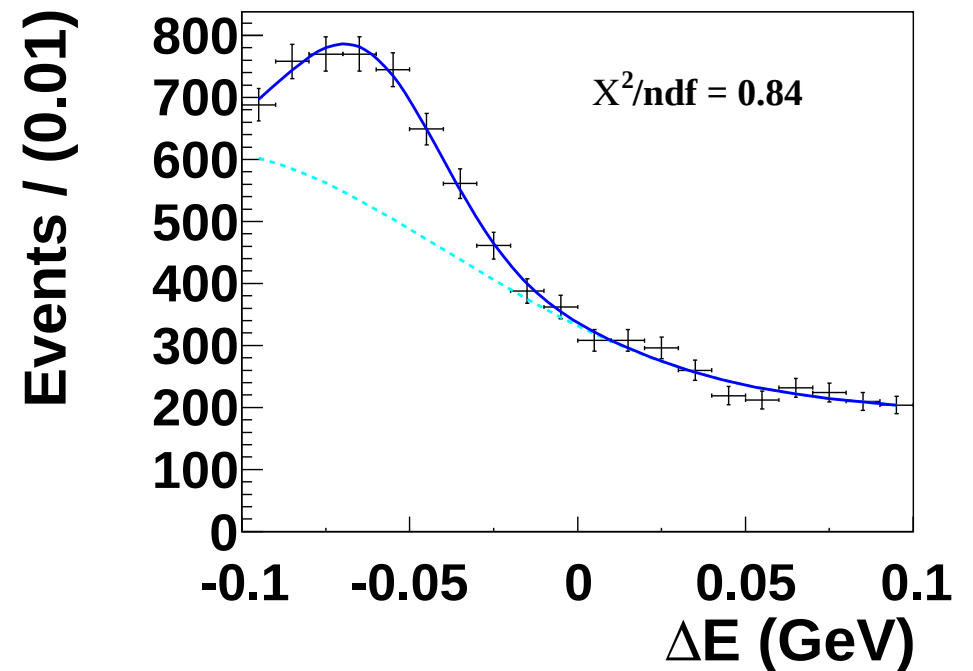
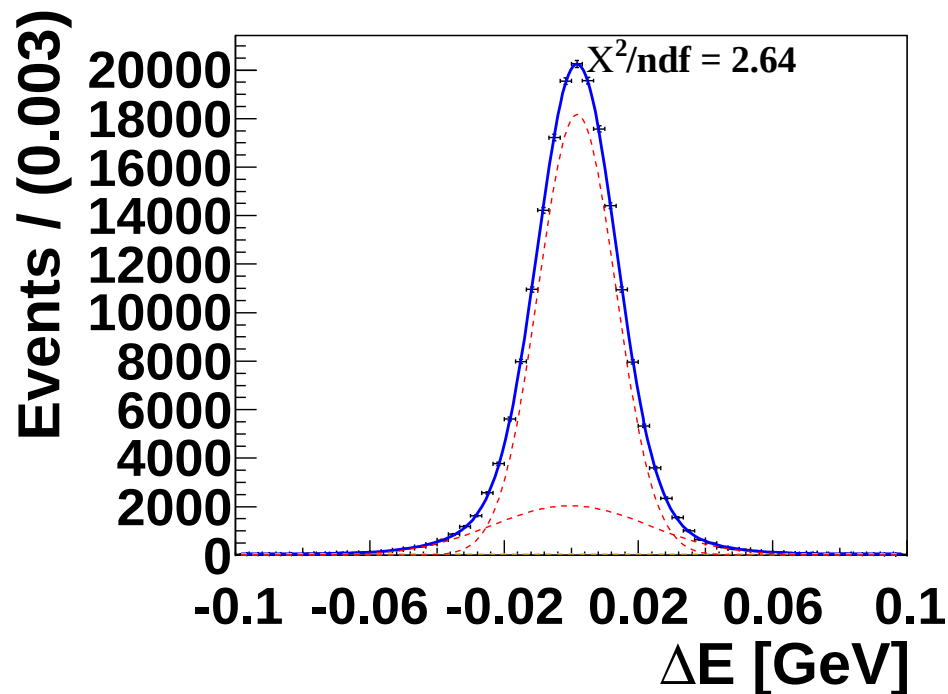
Backup

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

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

- signal MC(L pol)

- neutral charm decays



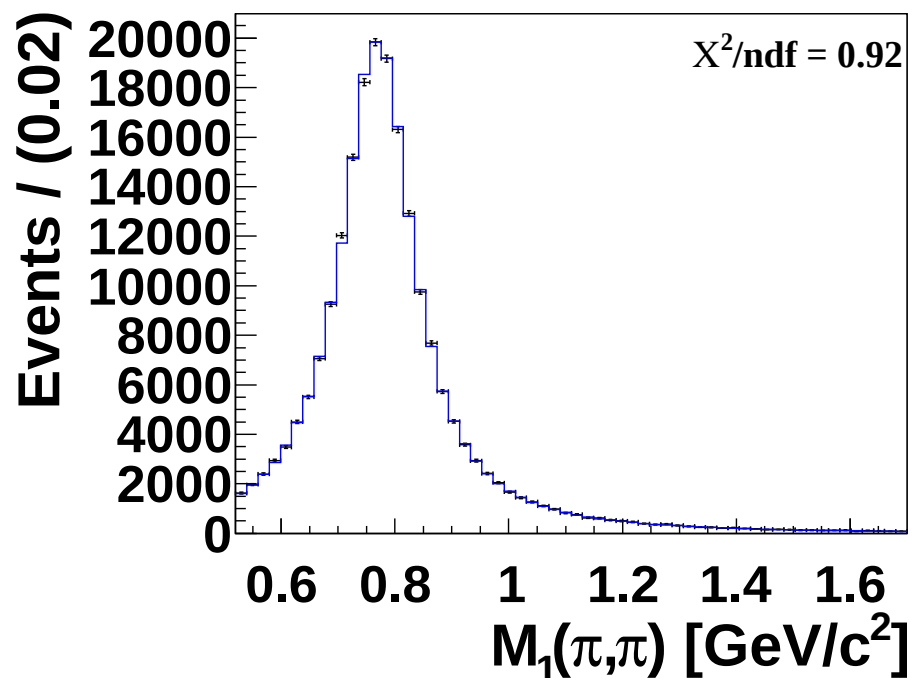
$\mathcal{PDF}(\Delta E) = 2 \times \text{Gaussian} + 1\text{st order chebychev}$

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

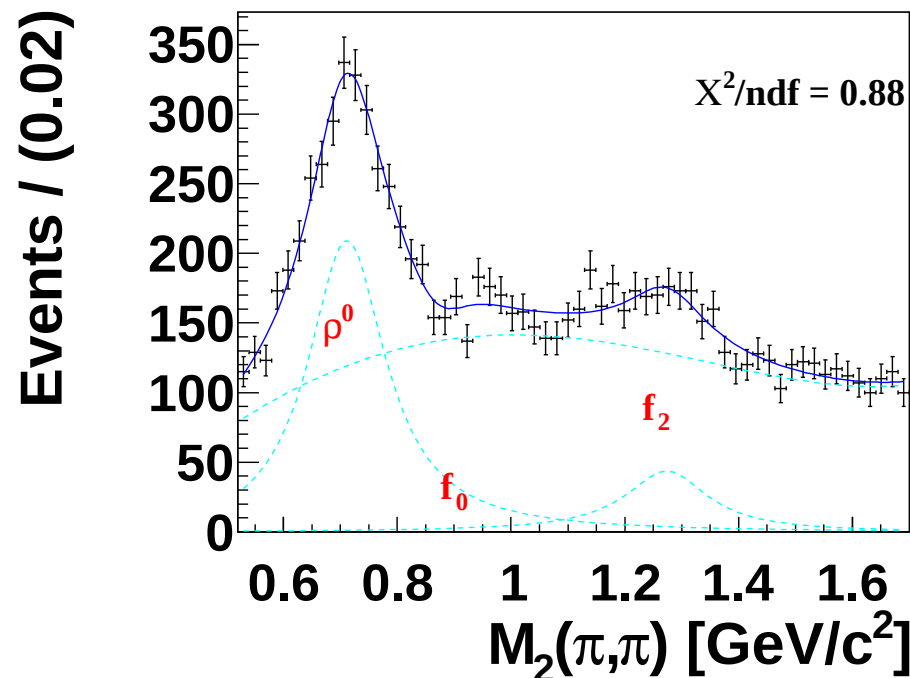
Model for $\mathcal{BR}(B^0 \rightarrow \rho^0 \rho^0)$

- signal MC(L pol)

- neutral charmless decays



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

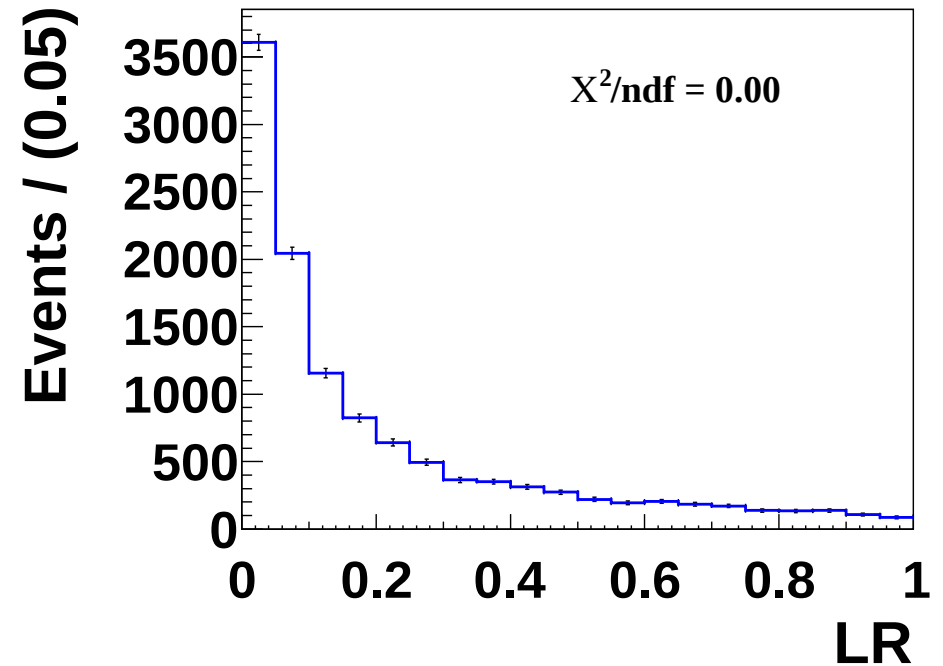
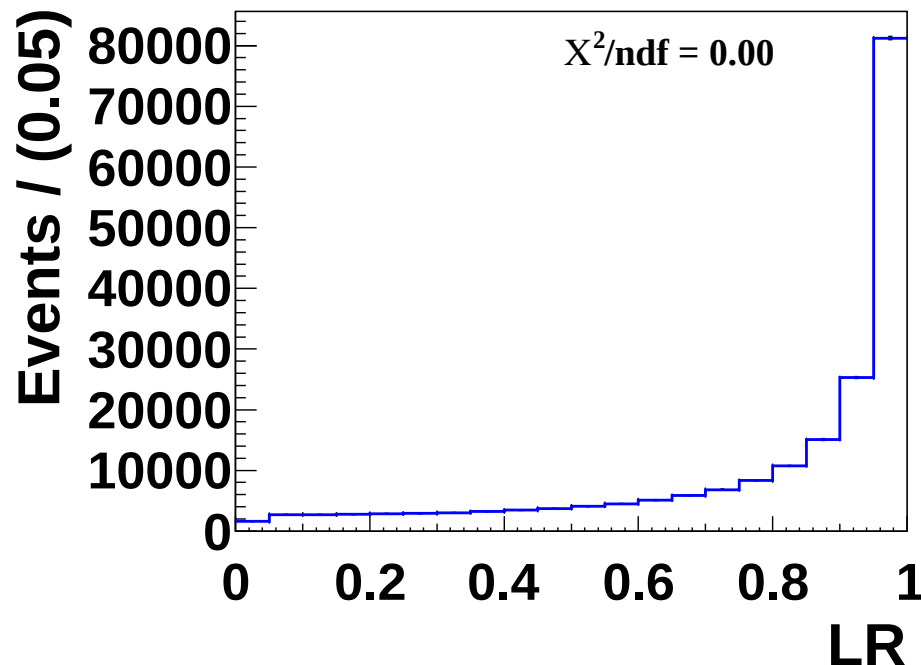


$$\mathcal{PDF}(m_{\pi^+\pi^-}) = 2 \times \text{Breit-Wigner} + \text{Gaussian} + \sum_{i=1}^4 \text{chebychev}_i$$

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

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

- signal MC(L pol)
- continuum



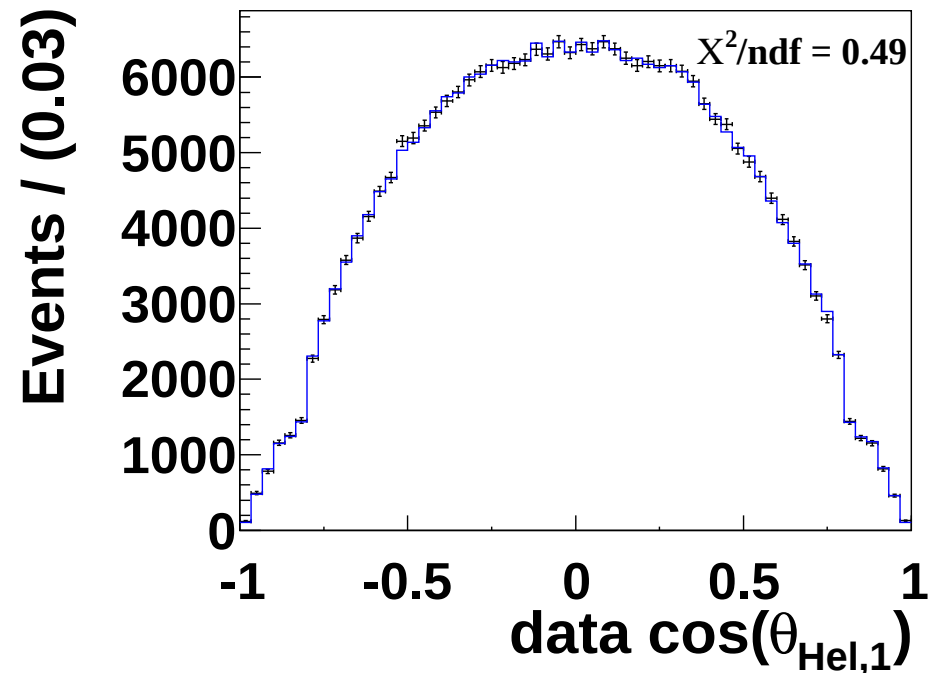
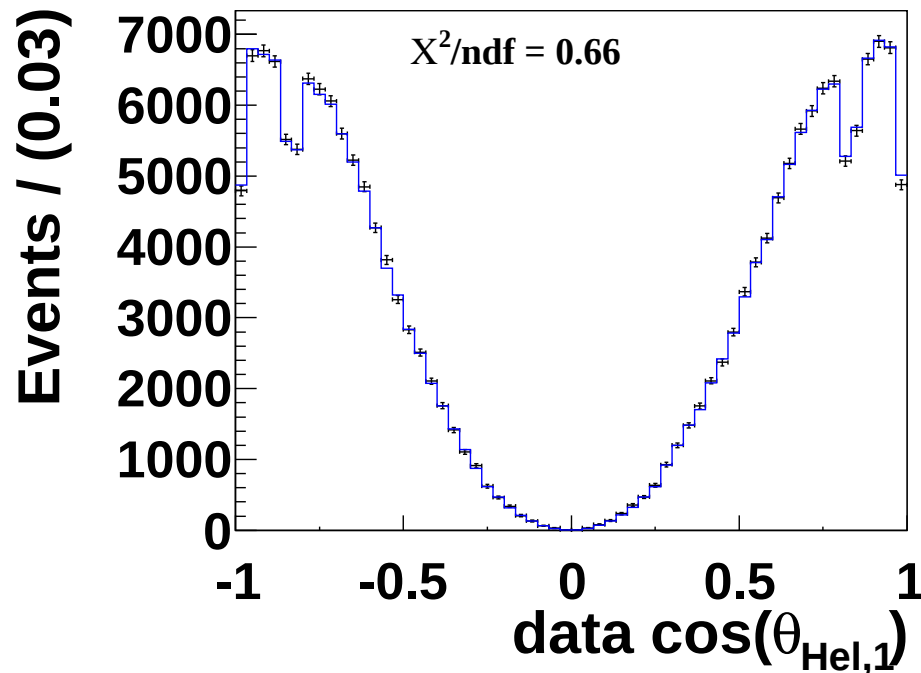
$\mathcal{PDF} = \text{histogram}$

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

Helicity: weighted with reconstruction efficiency histogram

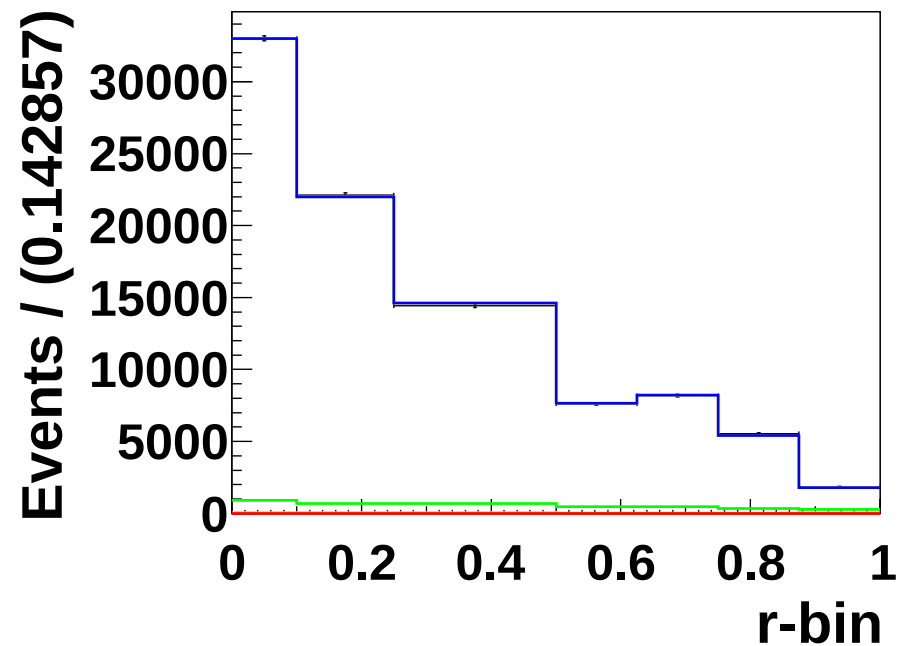
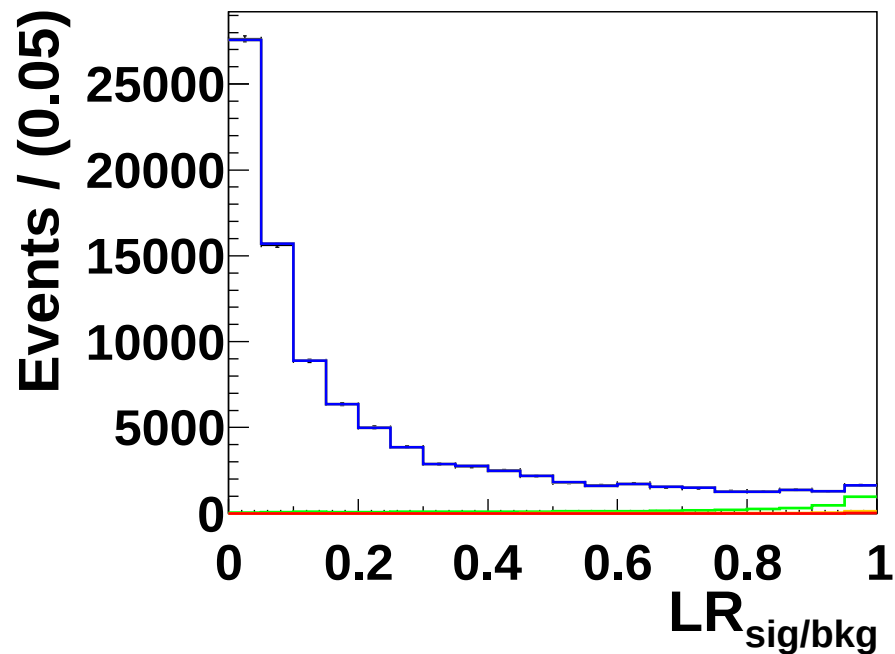
● signal MC(L pol)

● signal MC(T pol)



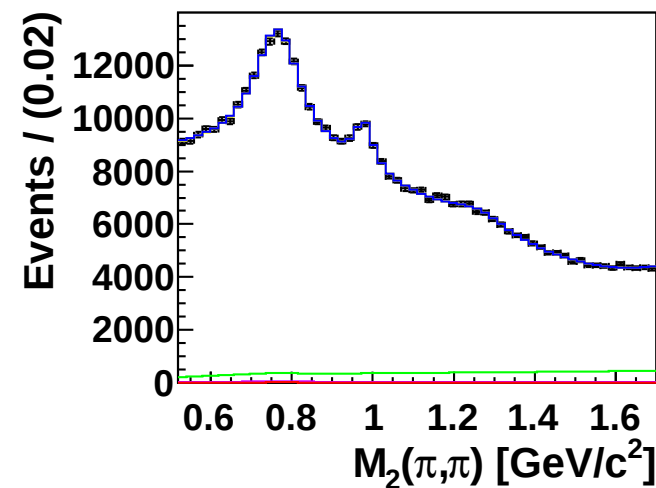
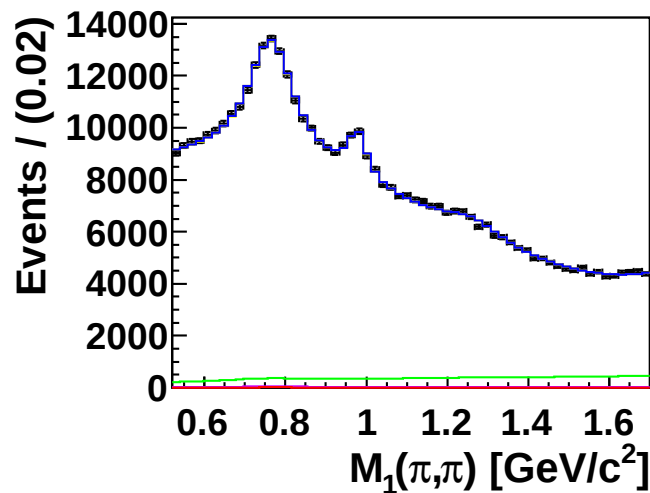
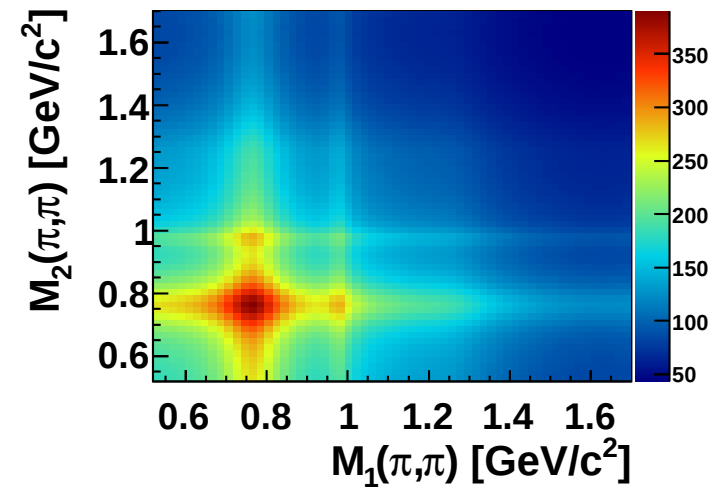
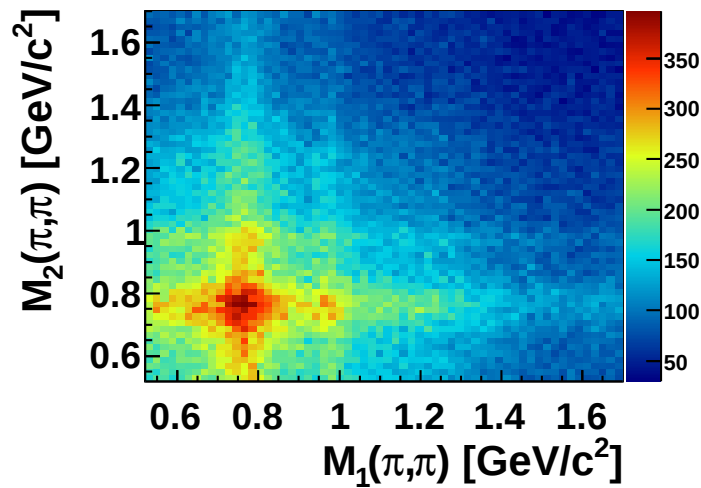
$$\frac{1}{\Gamma} \frac{d^2\Gamma}{d\cos\theta_{\text{Hel}}^1 d\cos\theta_{\text{Hel}}^2} = \frac{9}{4} \left(f_L \cos^2 \theta_{\text{Hel}}^1 \cos^2 \theta_{\text{Hel}}^2 + \frac{1}{4} (1 - f_L) \sin^2 \theta_{\text{Hel}}^1 \sin^2 \theta_{\text{Hel}}^2 \right)$$

Backup: Toy MC Studies

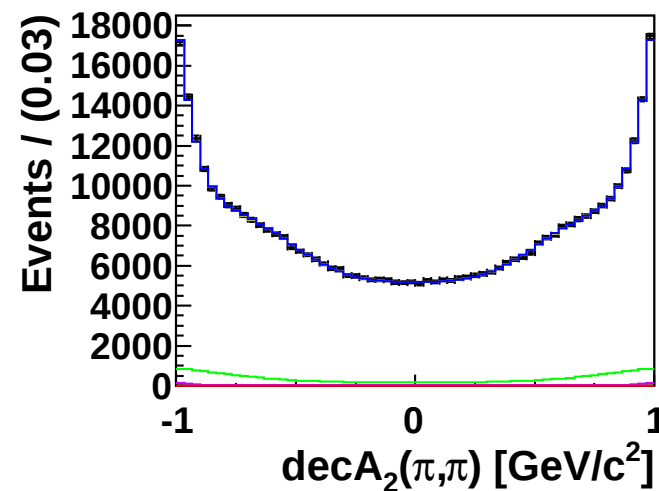
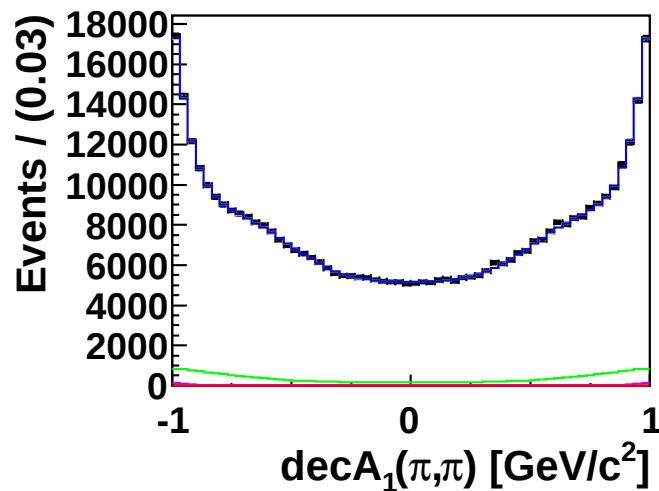
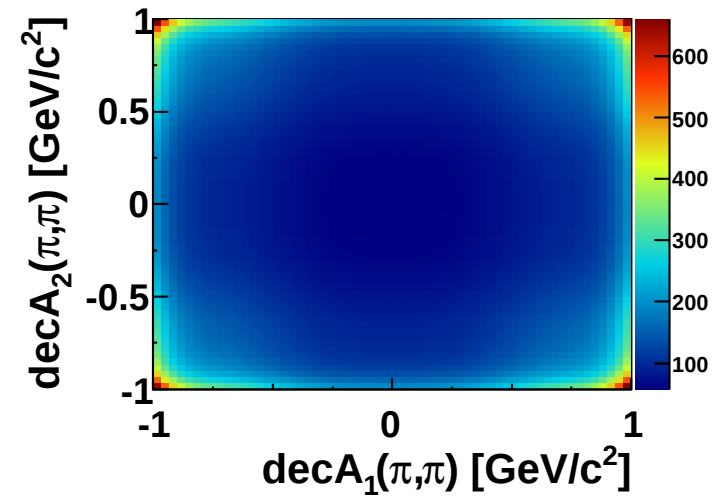
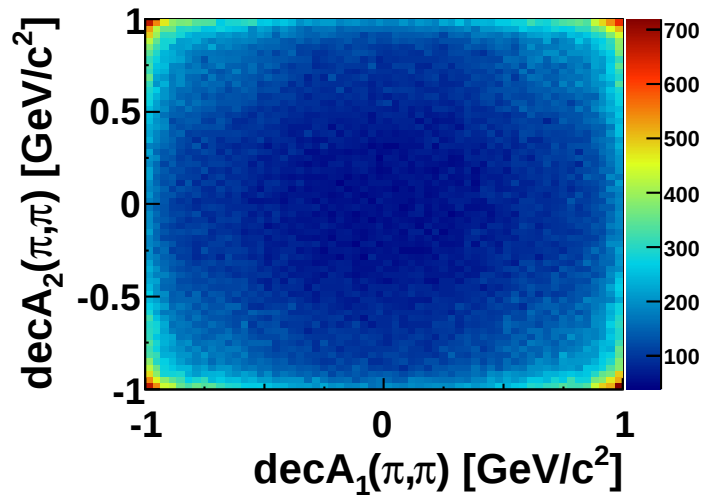


r -bin represents the quality of flavor tagging

Backup: Toy MC Studies



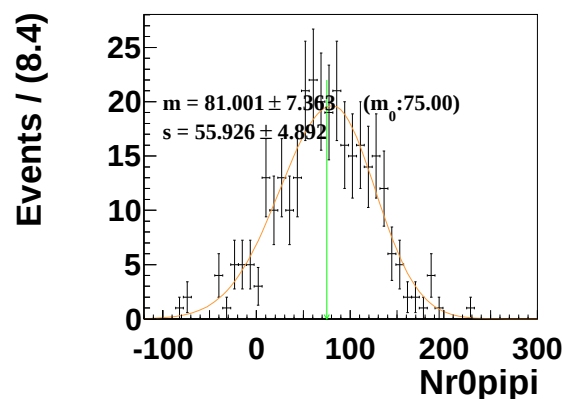
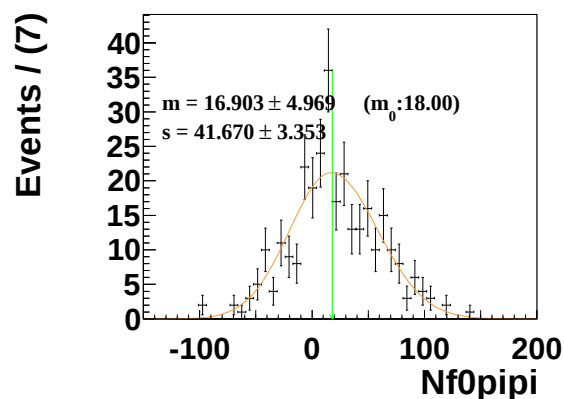
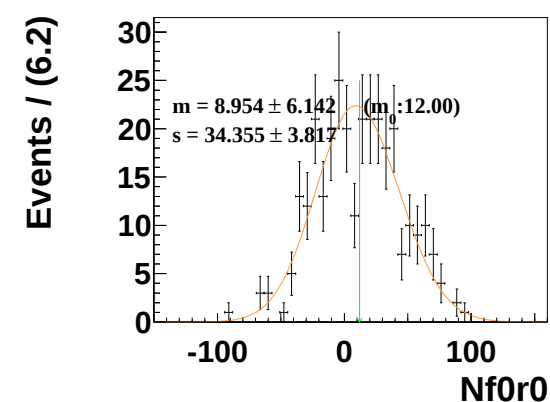
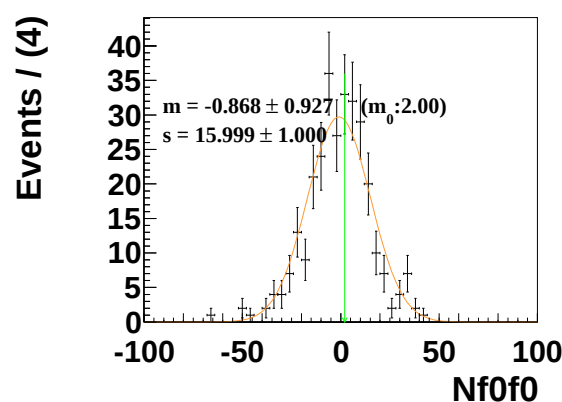
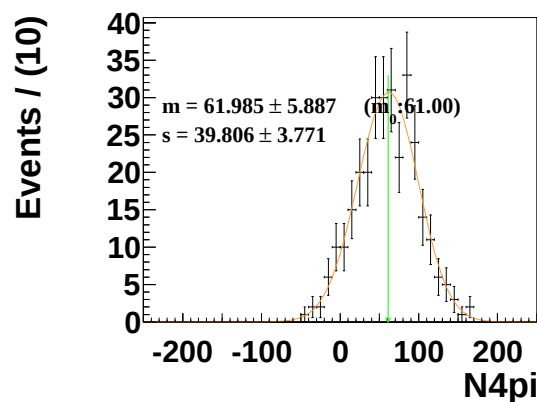
Backup: Toy MC Studies



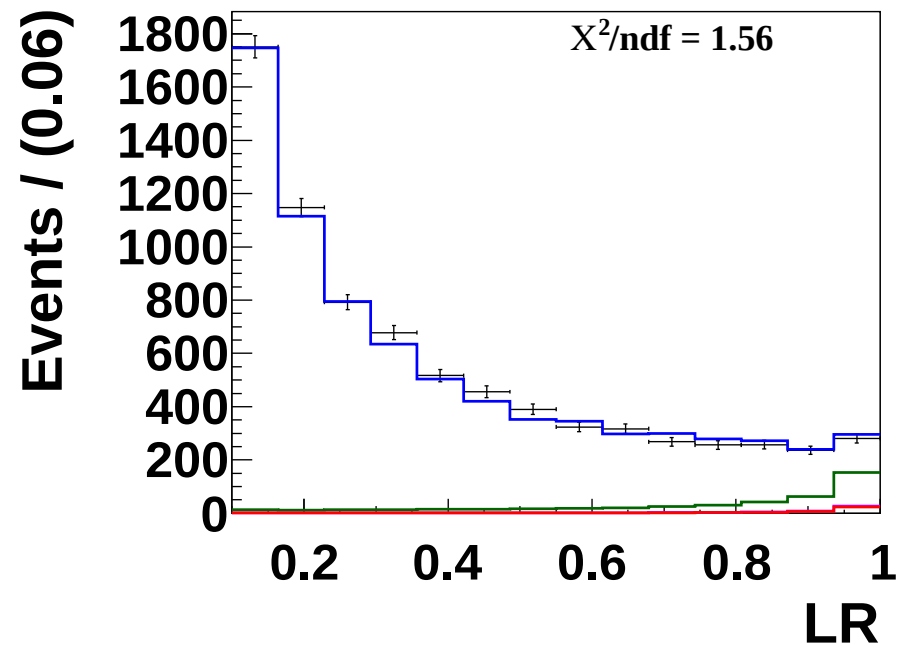
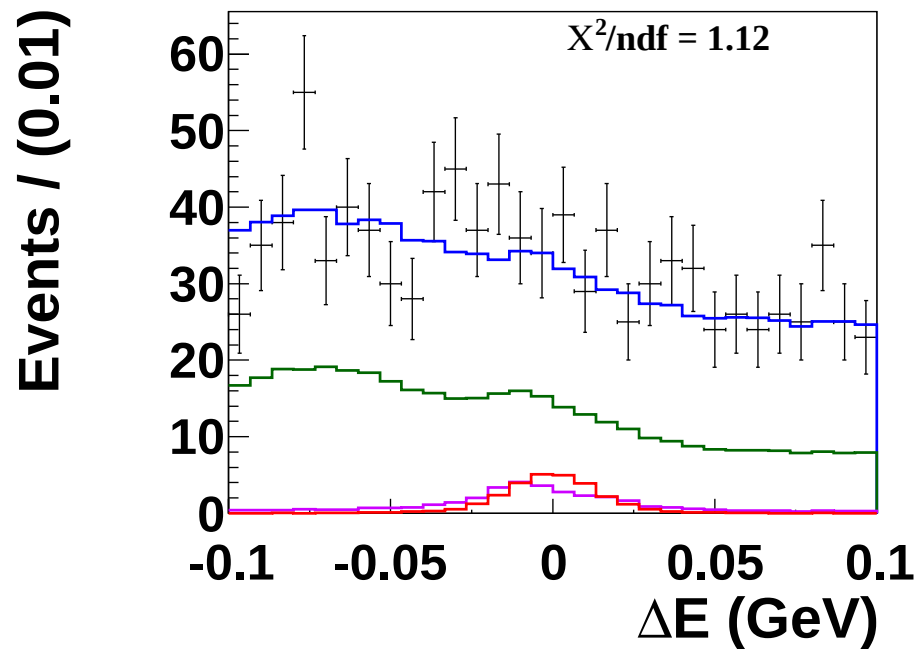
Backup: ToyMC Studies

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

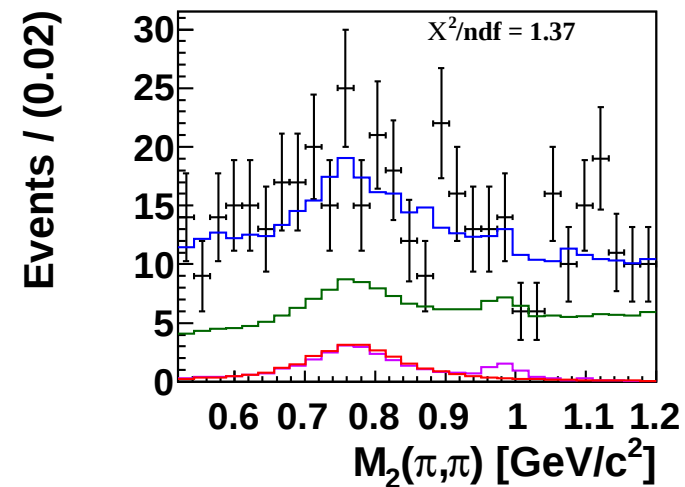
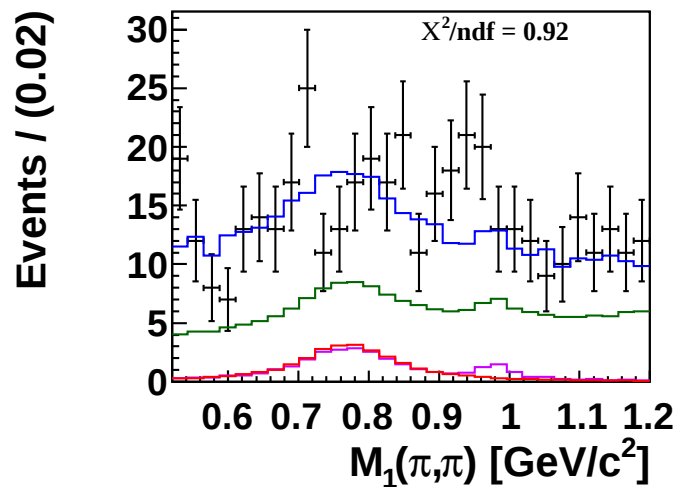
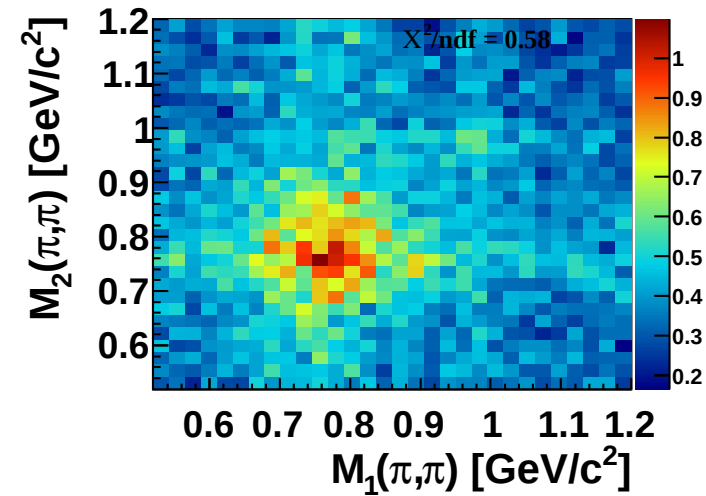
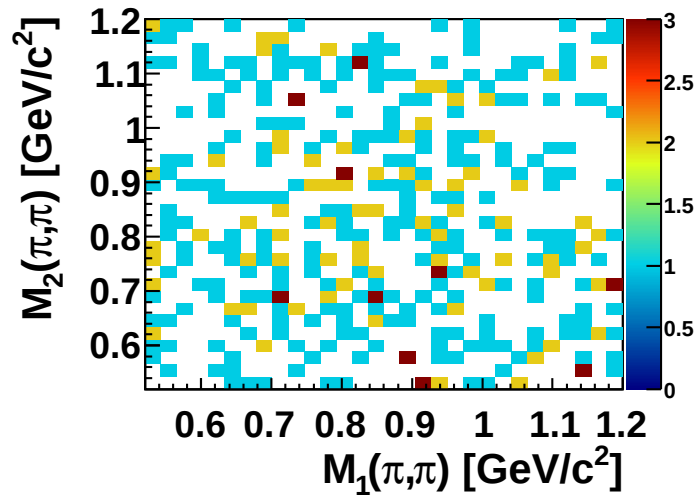
$a_2^\pm \pi^\mp$ upper limit gives less the 1 event $\Rightarrow$ fixed to 0



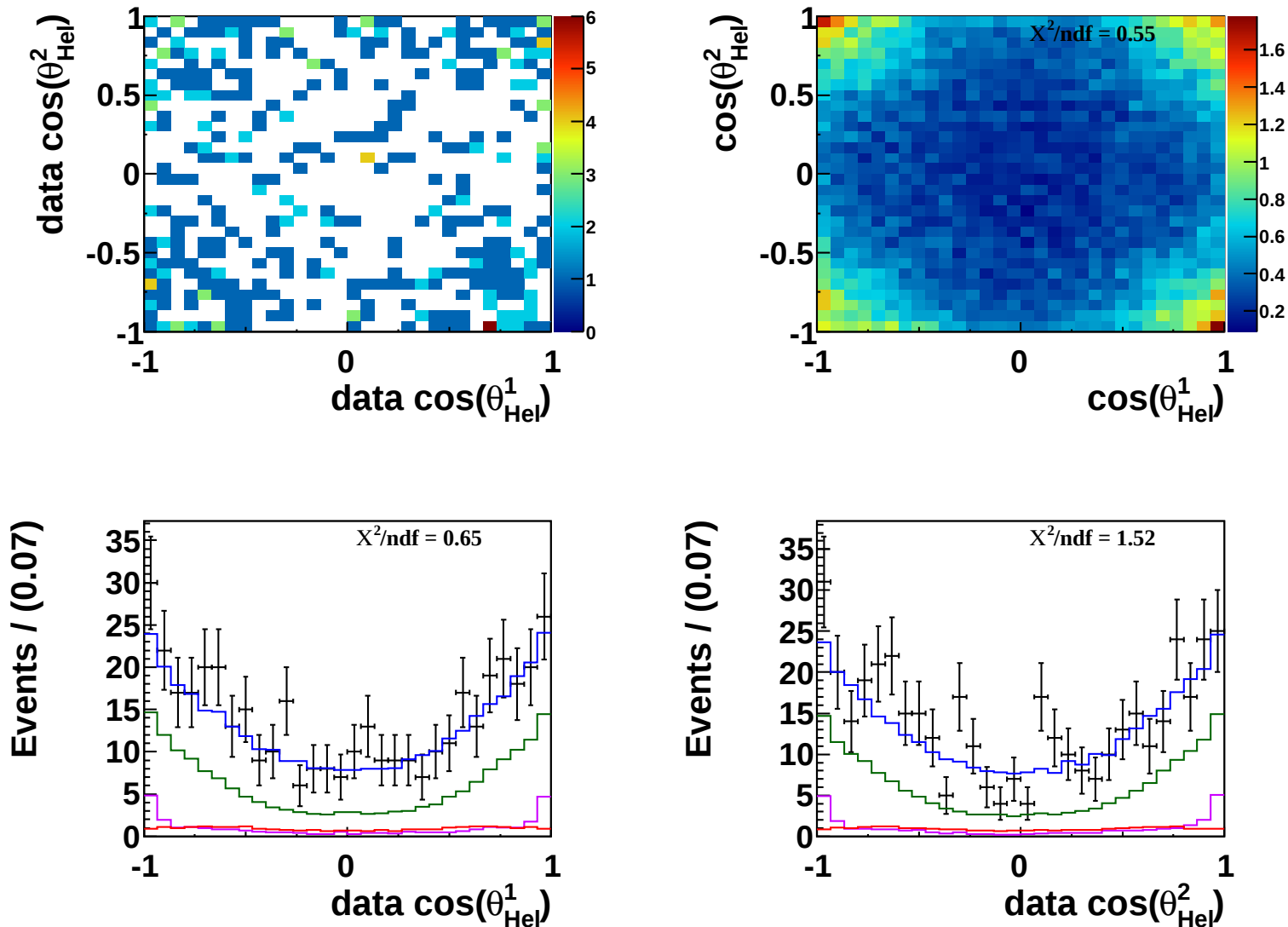
Backup: Fit to Data



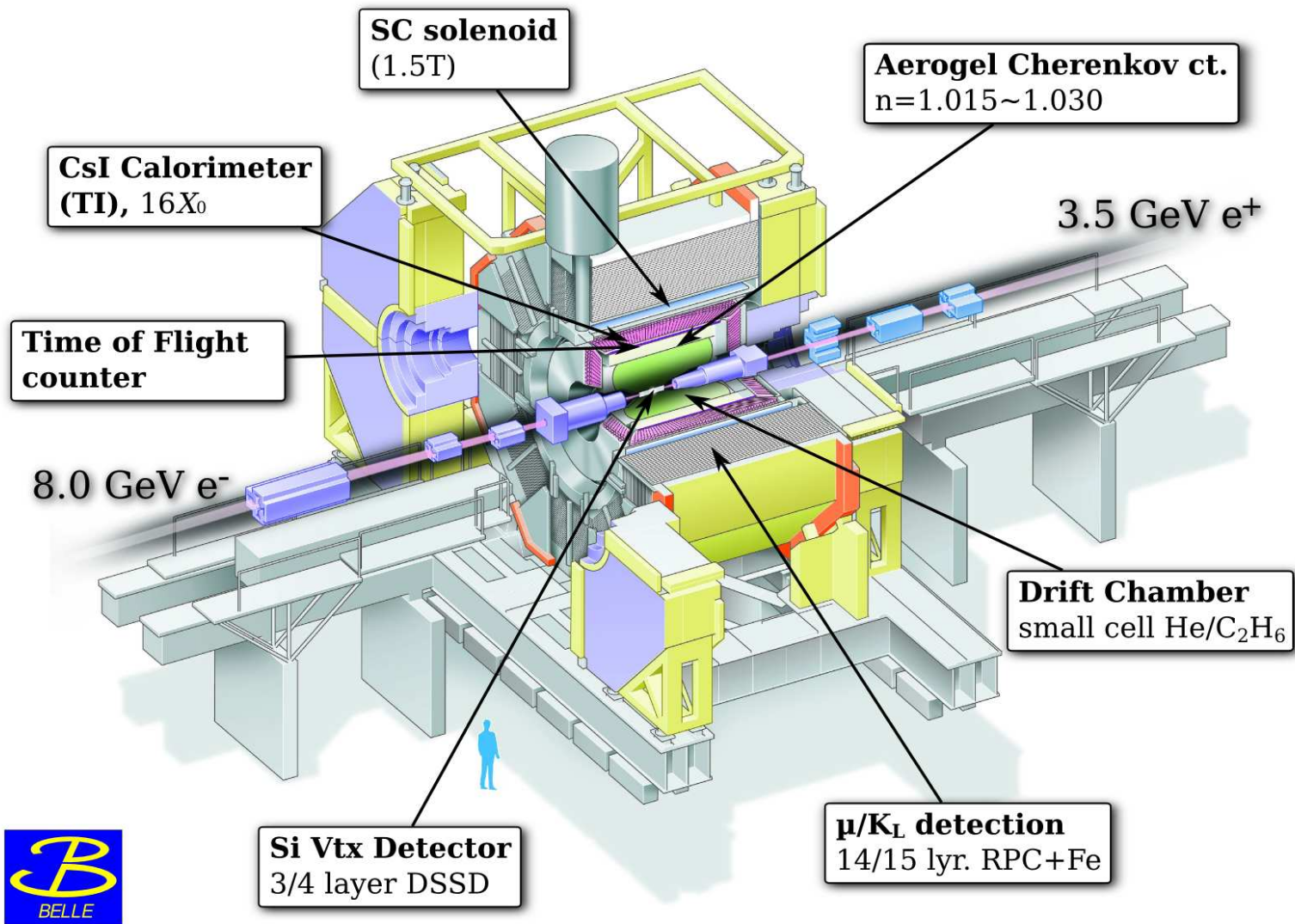
Backup: Fit to Data



Backup: Fit to Data



The Experimental Setup



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

Belle Detector

- tracking
- PID

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

Reconstruction:

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

$\Rightarrow$ 4 charged π s in the detector

- select $\pi^\pm$ candidates: PID criteria
- reconstruct ρ^0 candidates from $\pi^+ \pi^-$ pairs
 $\rho^0(770)$: broad resonance ($\Gamma \sim 149 \text{ MeV}$)
 $\rightarrow m_{\pi^+ \pi^-} \in [0.52, 1.7] \text{ GeV}/c^2$
excludes $K_S^0(0.49)$ and $D^0(1.87) [\text{GeV}/c^2]$
- reconstruct B^0 candidates from $\rho^0 \rho^0$ pairs
- charm and strange vetos (due to combinatorics)
 $\rightarrow$ removes peaking BKG

- vertexing
- flavor tagging
- select best B^0 candidate (M_{bc})

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

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

	L pol	T pol
rec Eff	19.6%	27.2%

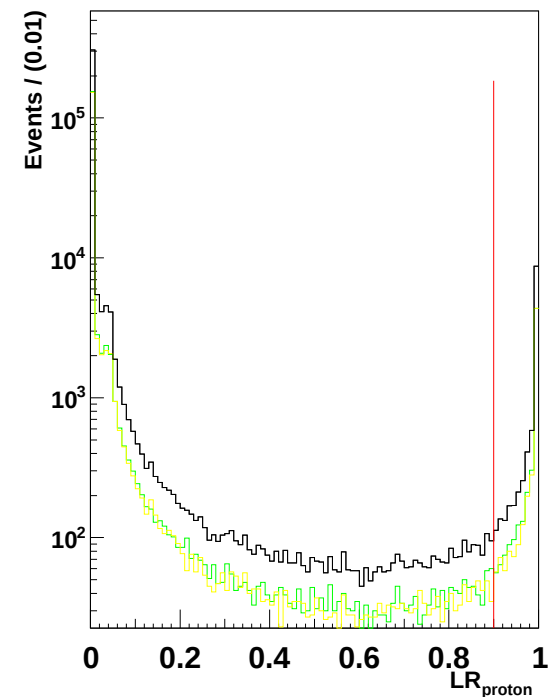
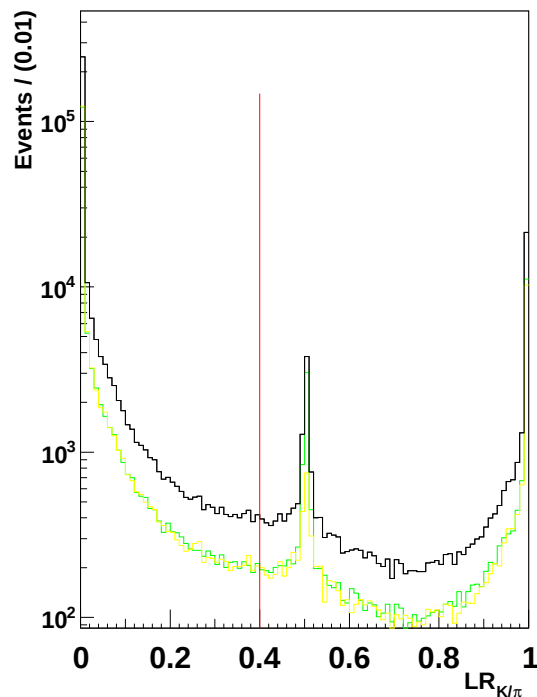
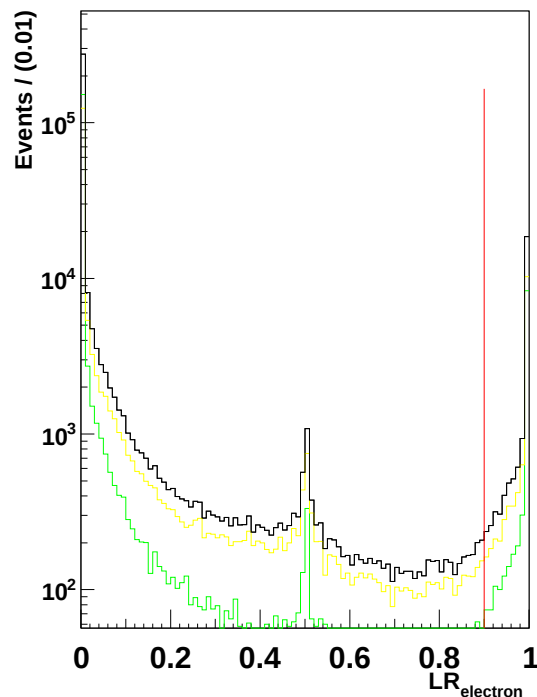
Measurement of $\mathcal{BR}(B^0 \rightarrow \rho^0 \rho^0)$

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

$$\mathcal{LR}_e < 0.9$$

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

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

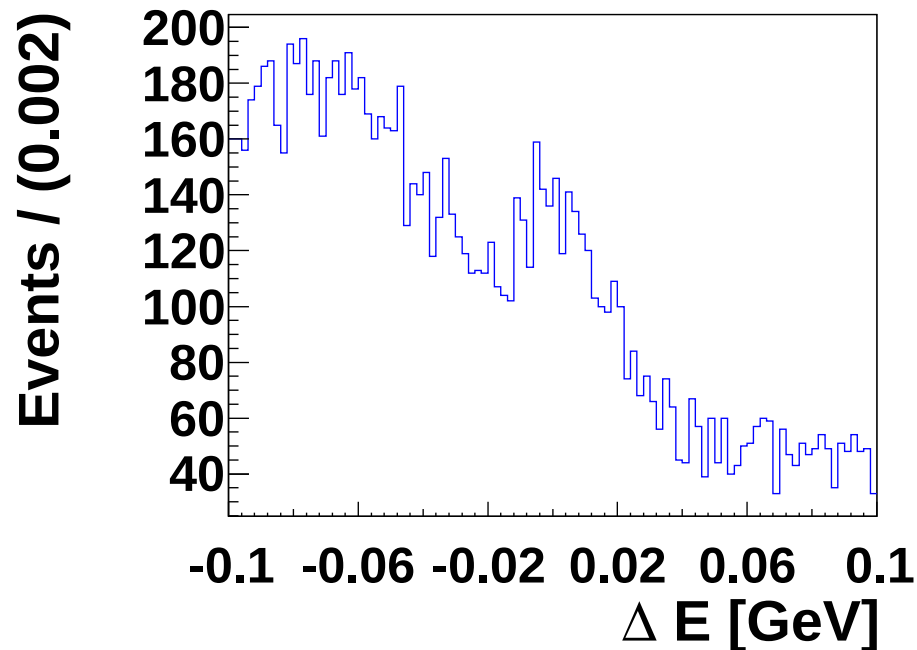


further loose cuts $|dr| < 0.5\text{cm}$ & $|dz| < 5\text{cm}$

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

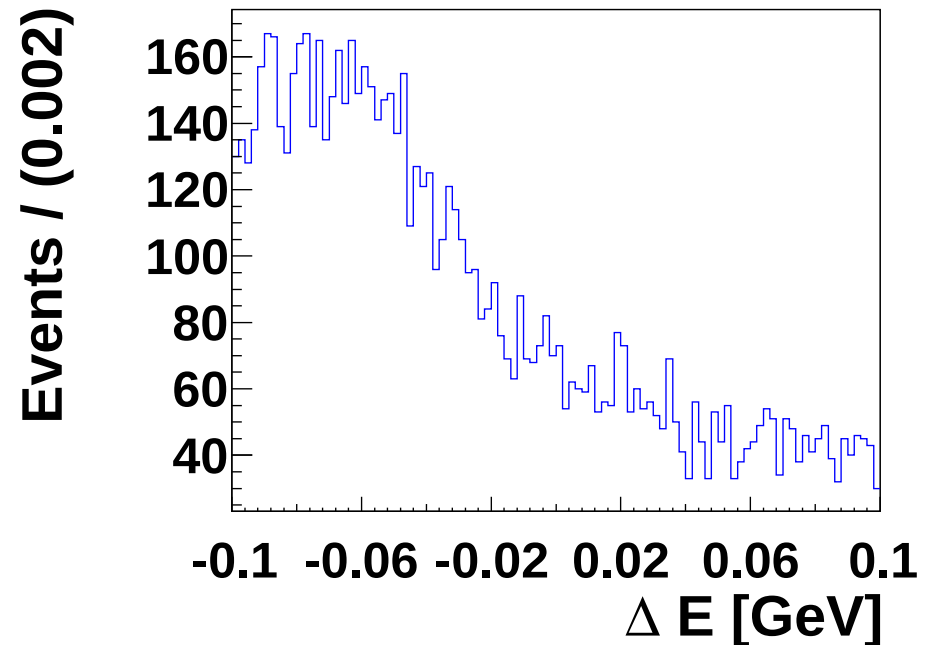
- **charm and strange vetos:** removes peaking background with similar final state

topology, e.g. $B^0 \rightarrow D^-(\pi^-\pi^+\pi^-)\pi^+$ or wrong PID



before

and



after vetos

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

- 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 $M(\pi\pi\pi)$:

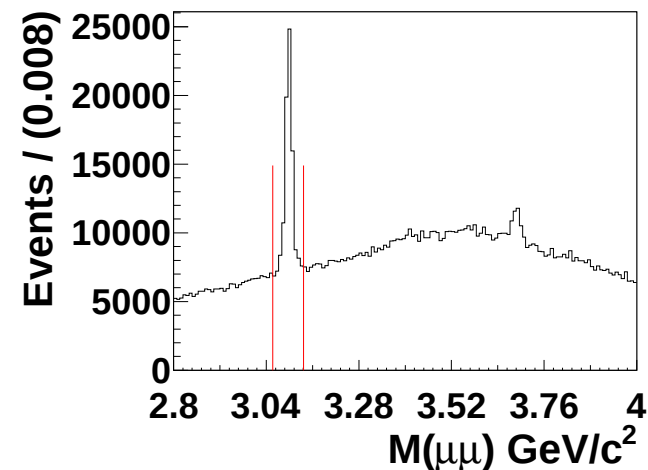
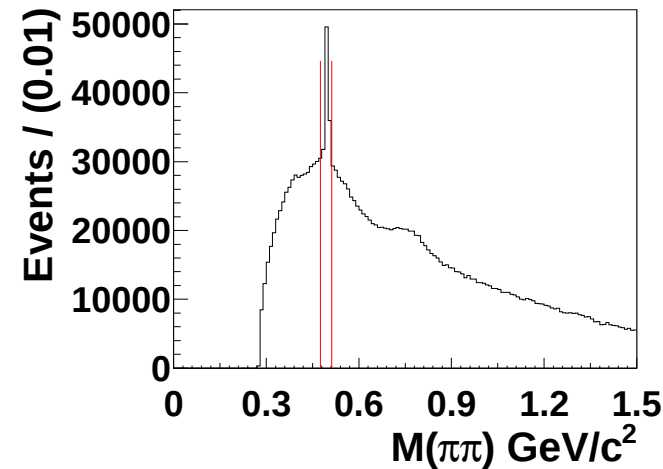
$$D^\pm : 1.8696 \pm 0.02 [GeV/c^2]$$

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

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

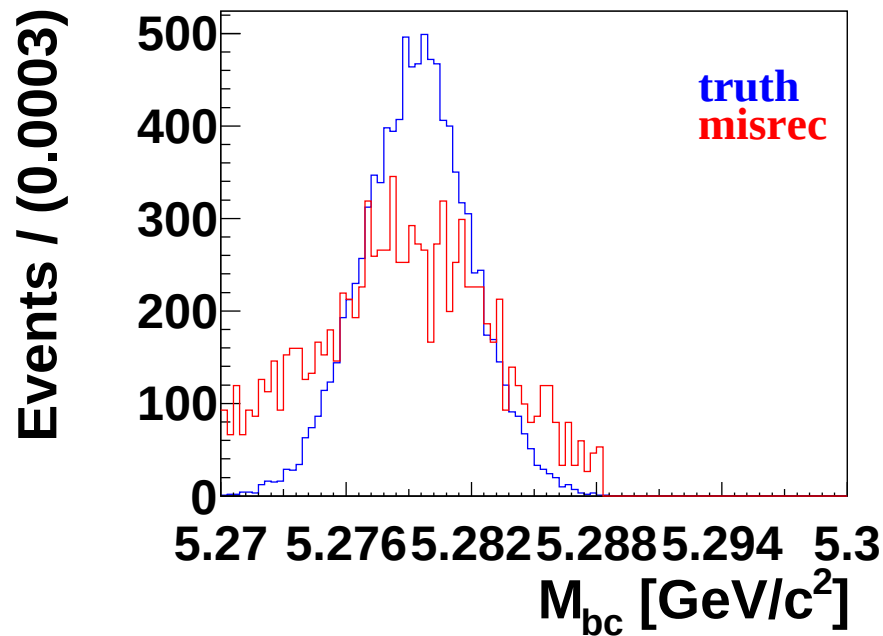
$$J\Psi : 3.0969 \pm 0.04 [GeV/c^2]$$

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



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

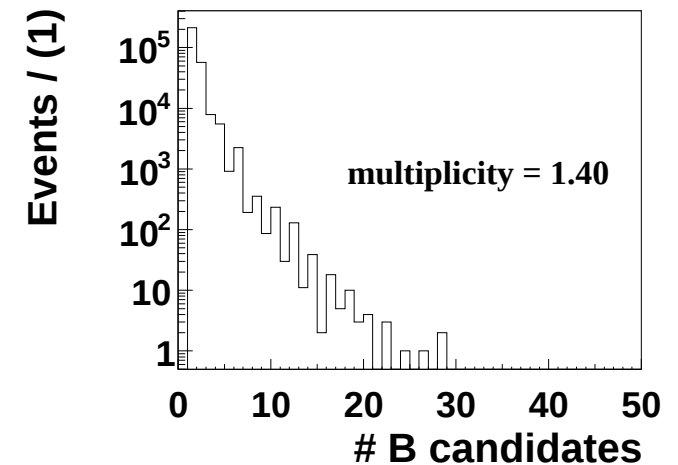
- **BCS:** best candidate selection



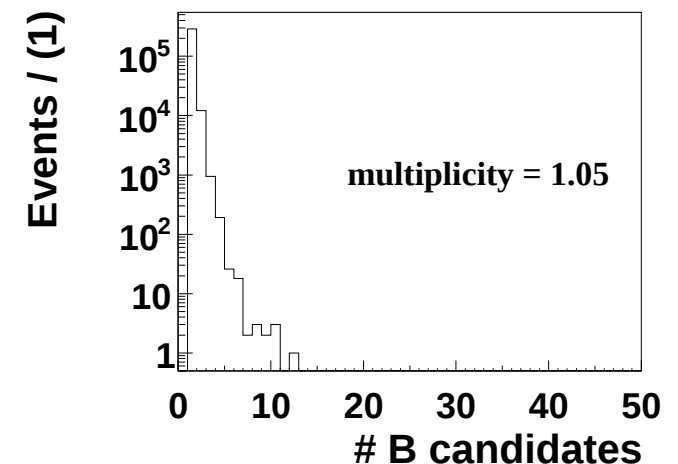
if 2 candidates with same M_{bc}

⇒ choose combination with highest π^+ and lowest π^- momentum

→ purity = 76%(L); 92%(T)



$L(\text{top})$ and T pol

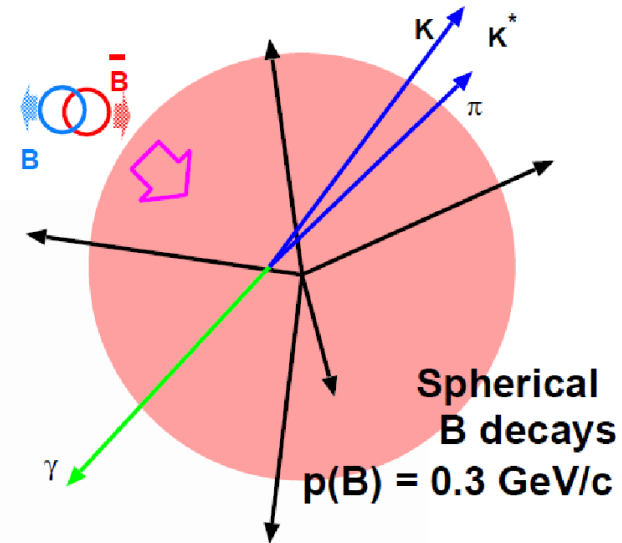
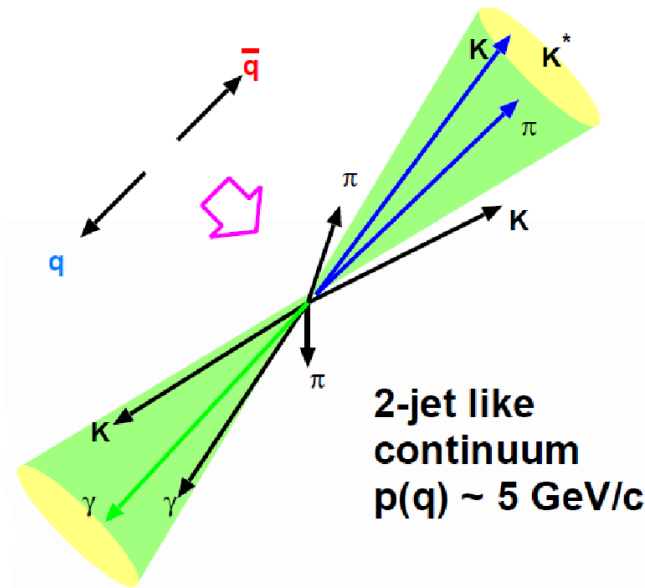
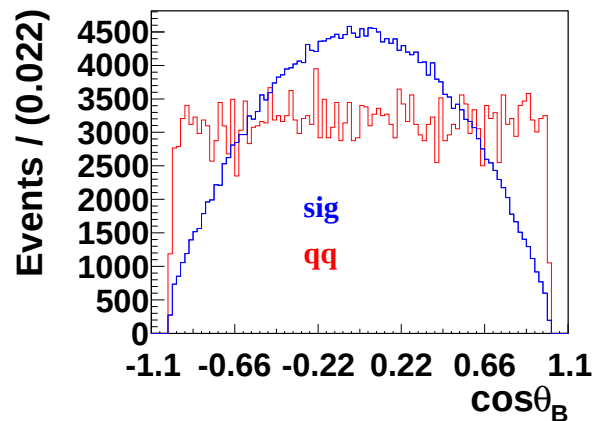


Measurement of $\mathcal{BR}(B^0 \rightarrow \rho^0 \rho^0)$

- **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