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

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Motivation

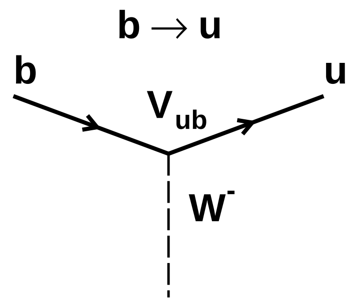
violation of CP symmetry necessary for matter anti-matter asymmetry

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)

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

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

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

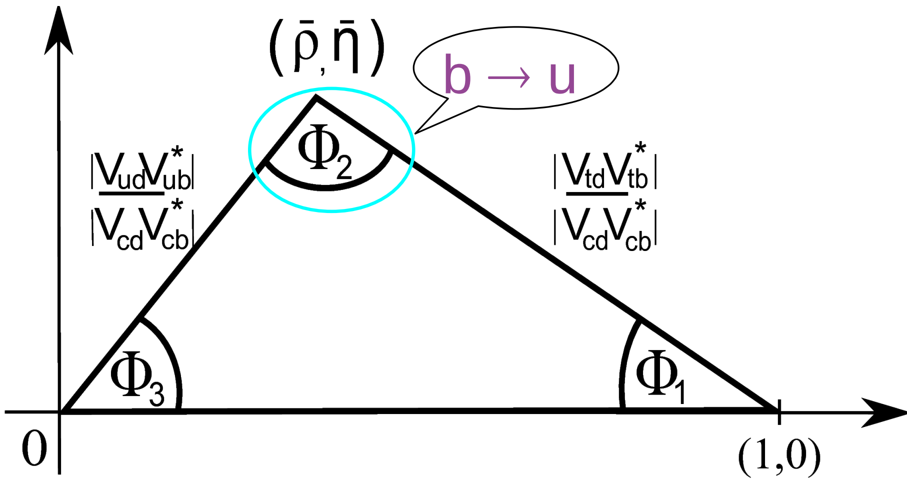
$$\begin{array}{ccccccc} V_{ud}V_{ub}^* & + & V_{cd}V_{cb}^* & + & V_{td}V_{tb}^* & = & 0 \\ \mathcal{O}(\lambda^3) & & \mathcal{O}(\lambda^3) & & \mathcal{O}(\lambda^3) & & \end{array}$$

sides with similar length $\Rightarrow$ large CP violation

precise determination of the observables

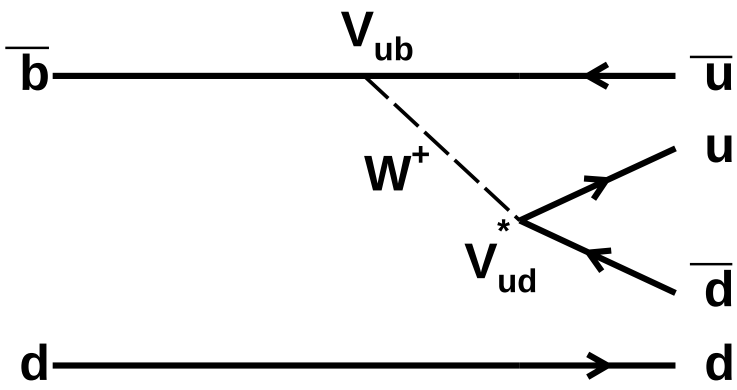
5 observables (3 angles, 2 sides) $\Rightarrow$ over-constraint

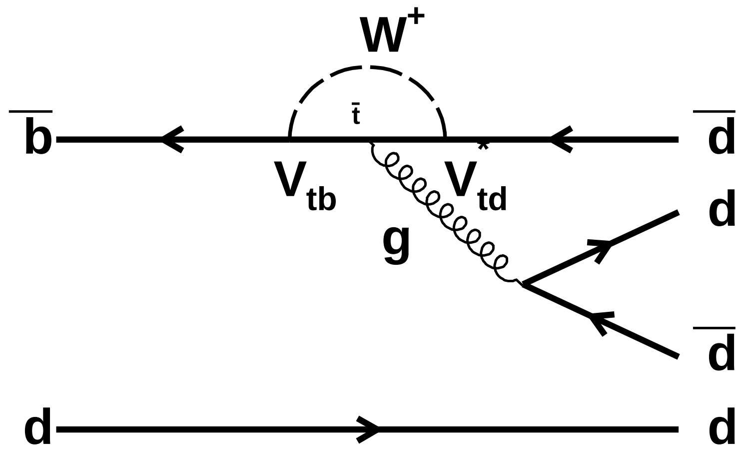
$\boxed{\text{confirm SM **or** find new physics}}$



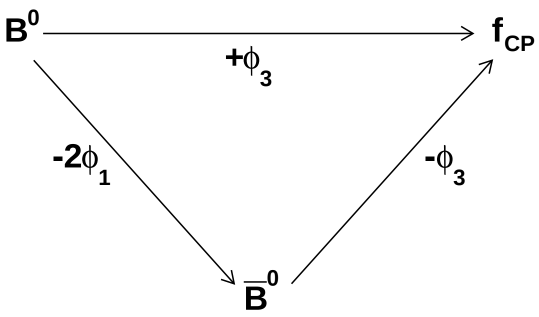
$B^0 \to \rho^0\rho^0$

$B^0 \to \rho^0\rho^0$ 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* $\phi_{2,eff}$

- $\phi_{2,eff} = \phi_2 + \Delta\phi_2$

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

Recover ϕ_2

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

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

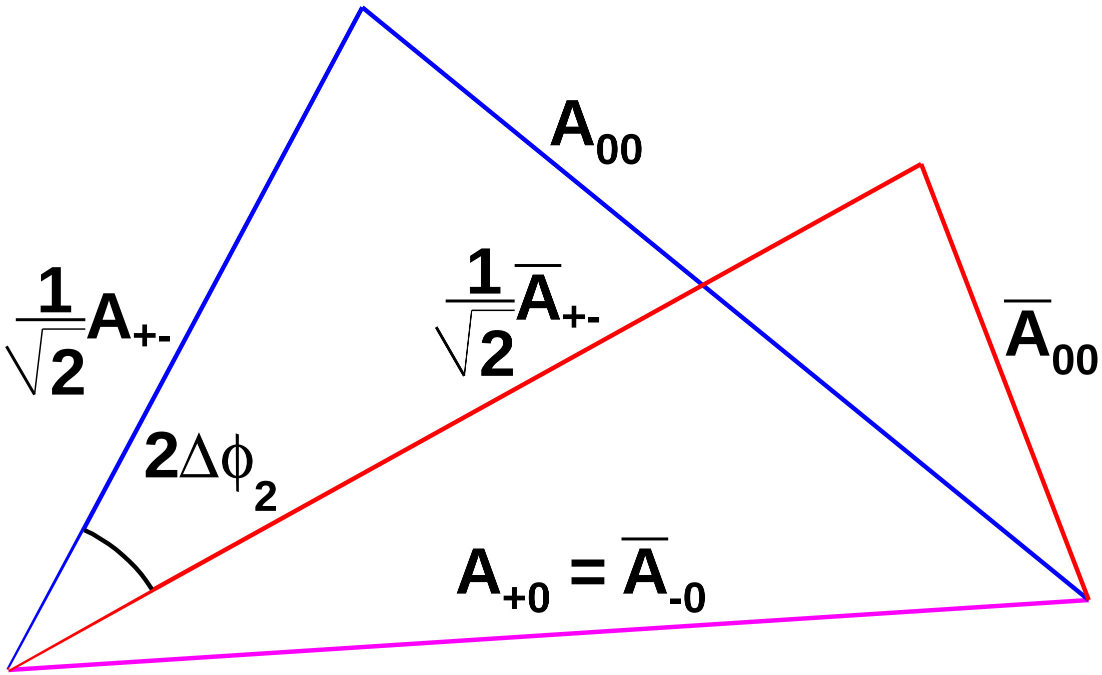
  Bose statistics:$\Rightarrow$ I=0,2 (final states);

  tree I=0,2;

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

  allows to formulate relations of the decay amplitudes A

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



- $\frac{1}{\sqrt{2}}A^{+-} + A^{00} = A^{+0}$
- $\frac{1}{\sqrt{2}}\bar{A}^{+-} + \bar{A}^{00} = \bar{A}^{-0}$

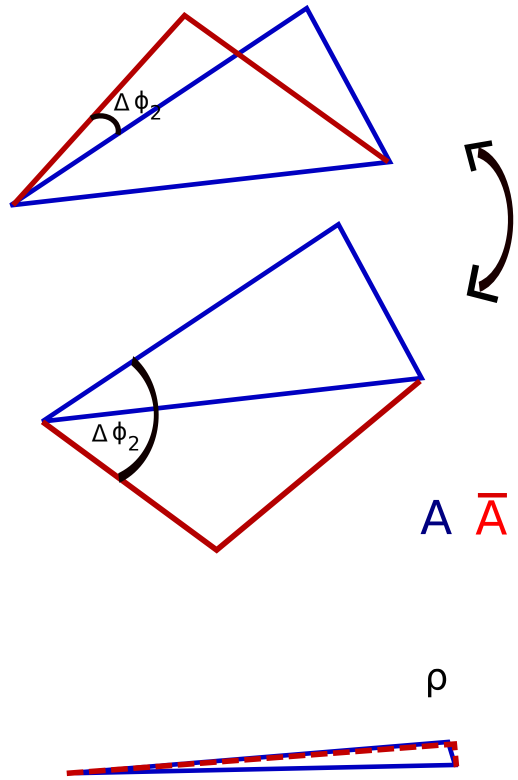
- $A^{+0} = \bar{A}^{-0}$ (no penguin) $\Rightarrow$ simple geometrical considerations

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

Impact on CKM Angle ϕ_2

- **variation of**

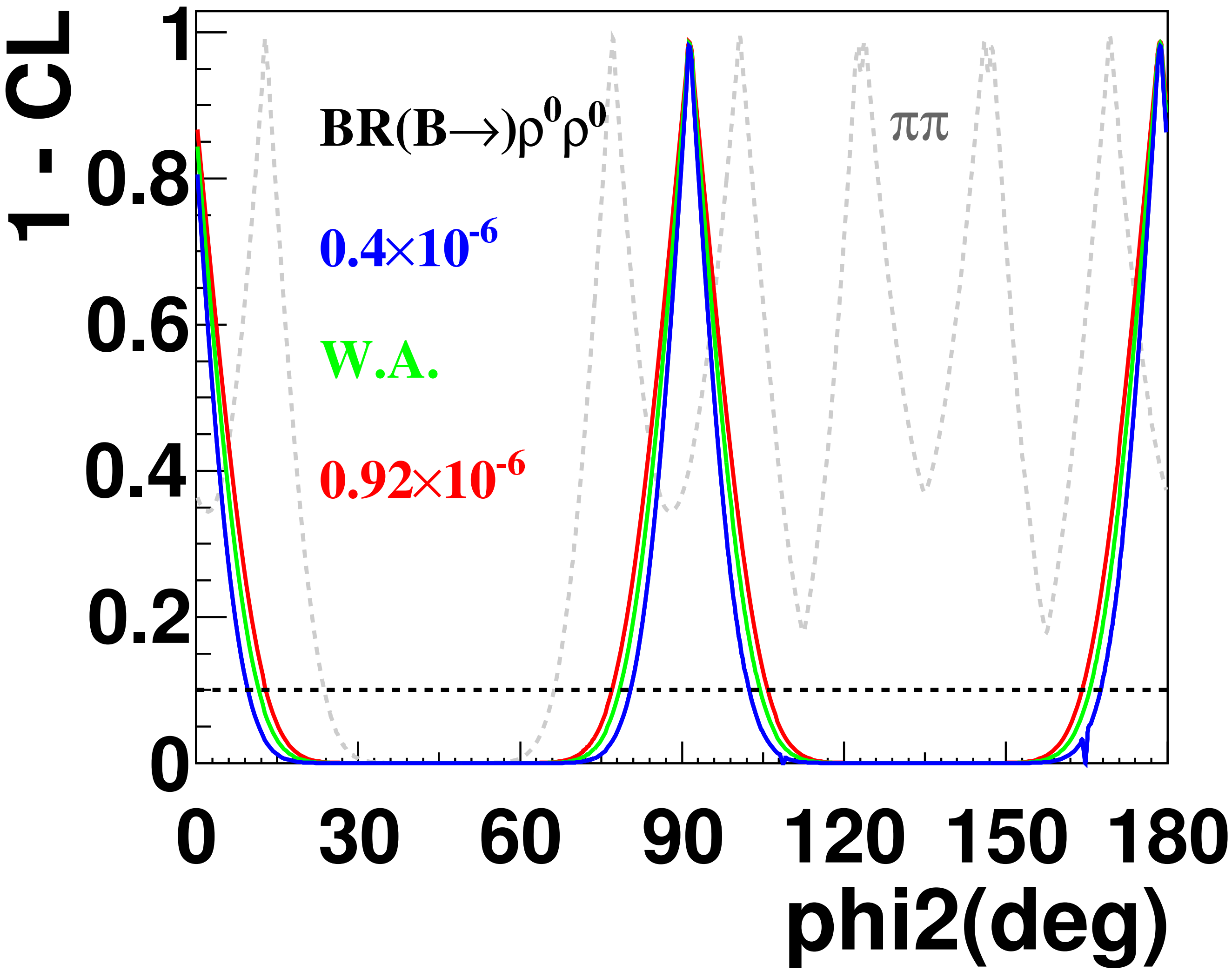
  $\mathcal{BR}(B^0 \to \rho^0\rho^0)$

  in isospin analysis

  W.A. = $(0.73 \pm 0.28) \times 10^{-6}$

  prev. Belle

  Babar



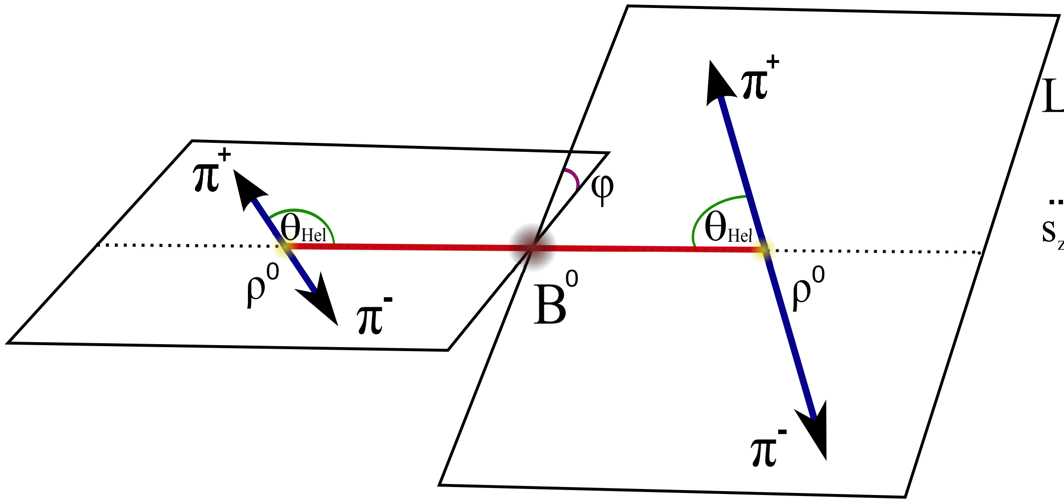
$B^0 \to \rho^0\rho^0$

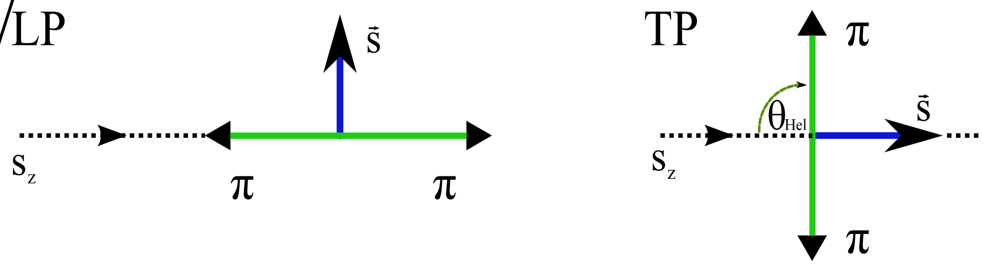
- **Helicity of the ρ** $(\rho^0 \to \pi^+\pi^-)$

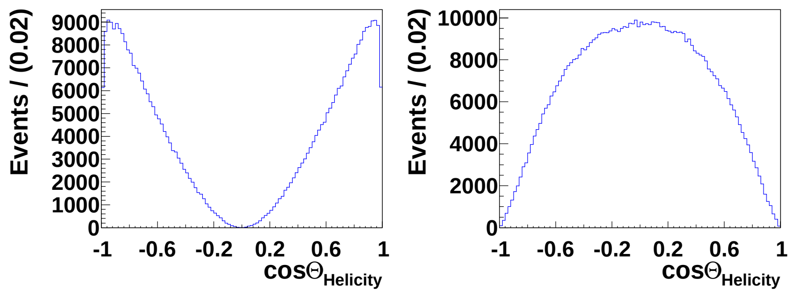
  2 different polarizations, longitudinal(L pol, CP even) and transversal(T pol, CP even & odd)

  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)

$\boxed{\text{challenging analysis}}$ $\Longrightarrow$ $\boxed{\text{new method}}$

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

- 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

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

6 fit dimensions:

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

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

$\rightarrow$ modeled 17 components: shape determined from

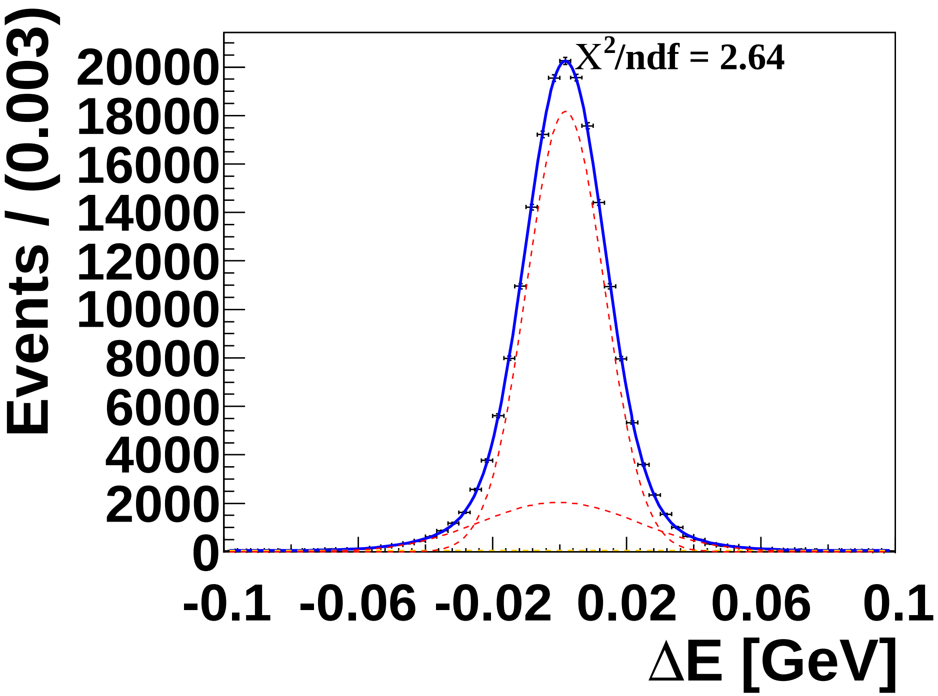
- signal (L pol, T pol); Monte Carlo(MC)
- misreconstructed signal (L pol, T pol); MC
- continuum ($e^+e^- \to q\bar{q}$); data taken at $\sqrt{s} = 10.50GeV < m(\Upsilon(4S))$
- $B\bar{B}$: charm and charmless $B^0(B^\pm)$ decays; MC
- peaking background (4πs final states); MC

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

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

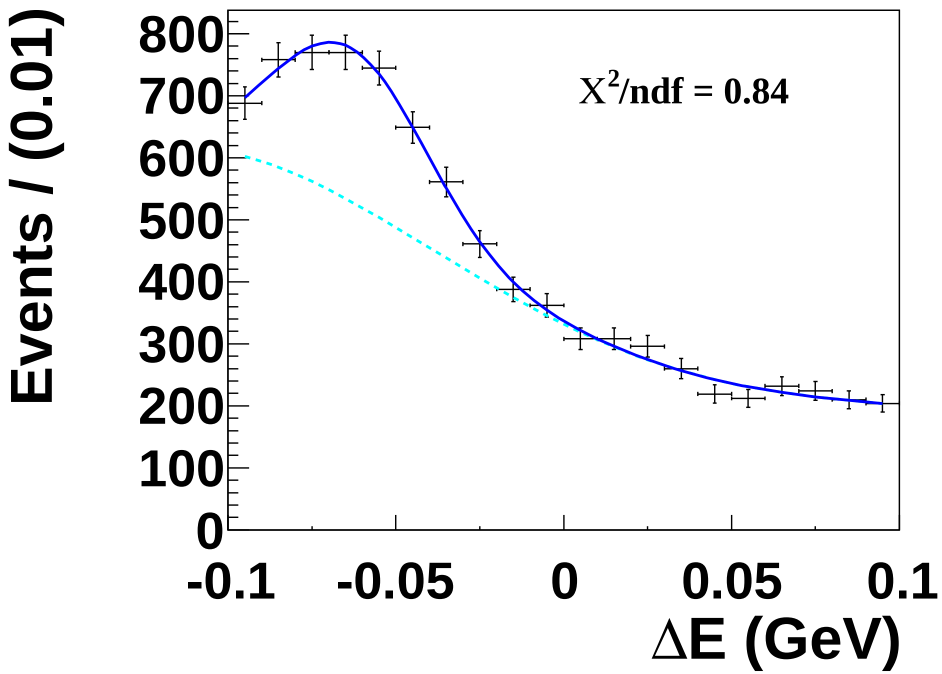
$$\Delta E \equiv E_{B_{rec}} - E_{beam}$$

- signal MC(L pol)



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

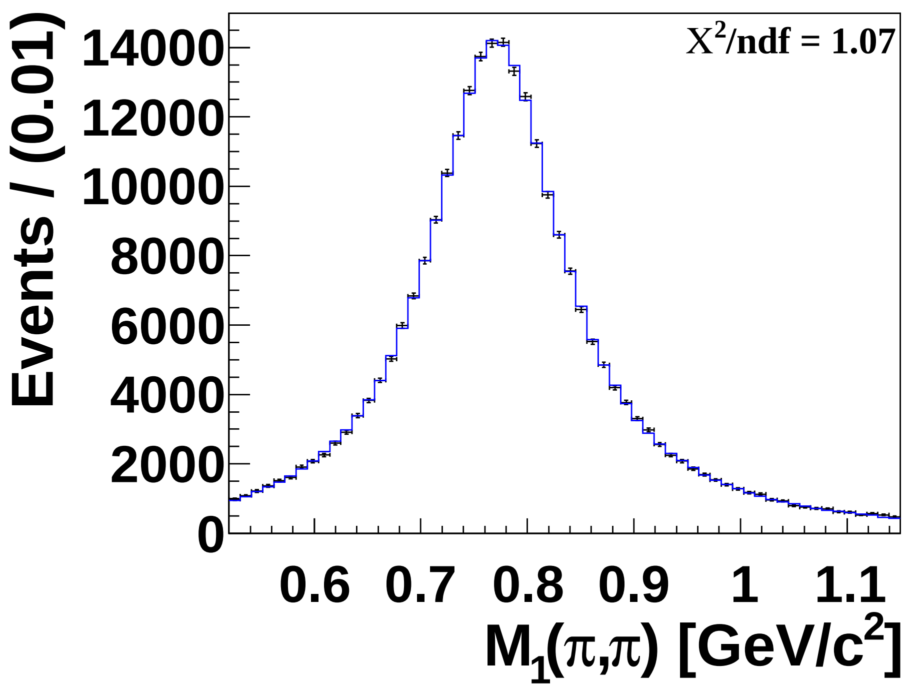
- neutral charm decays



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

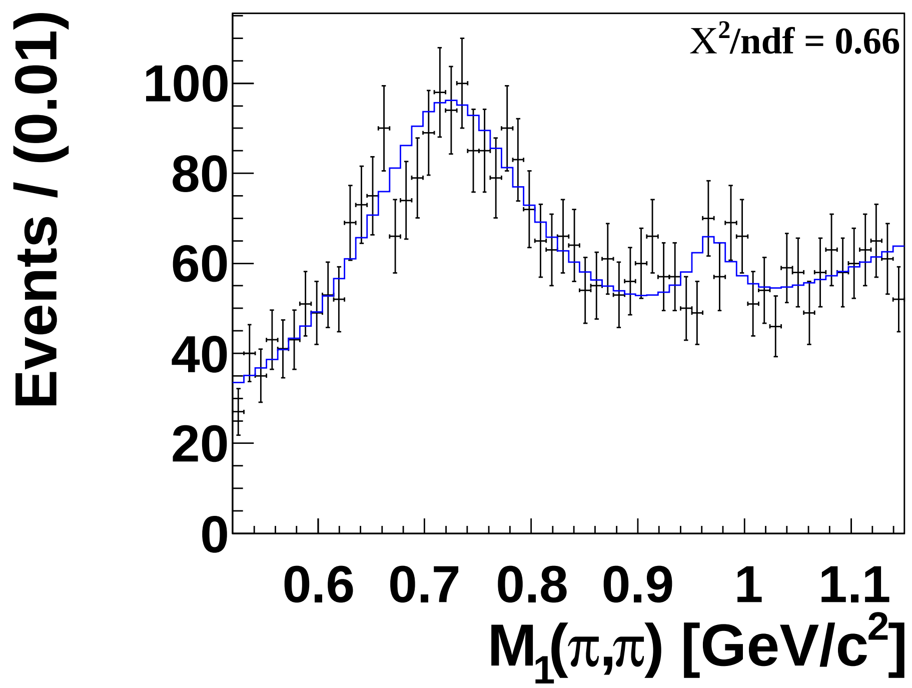
Model for $\mathcal{BR}(B^0 \to \rho^0\rho^0)$

- 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

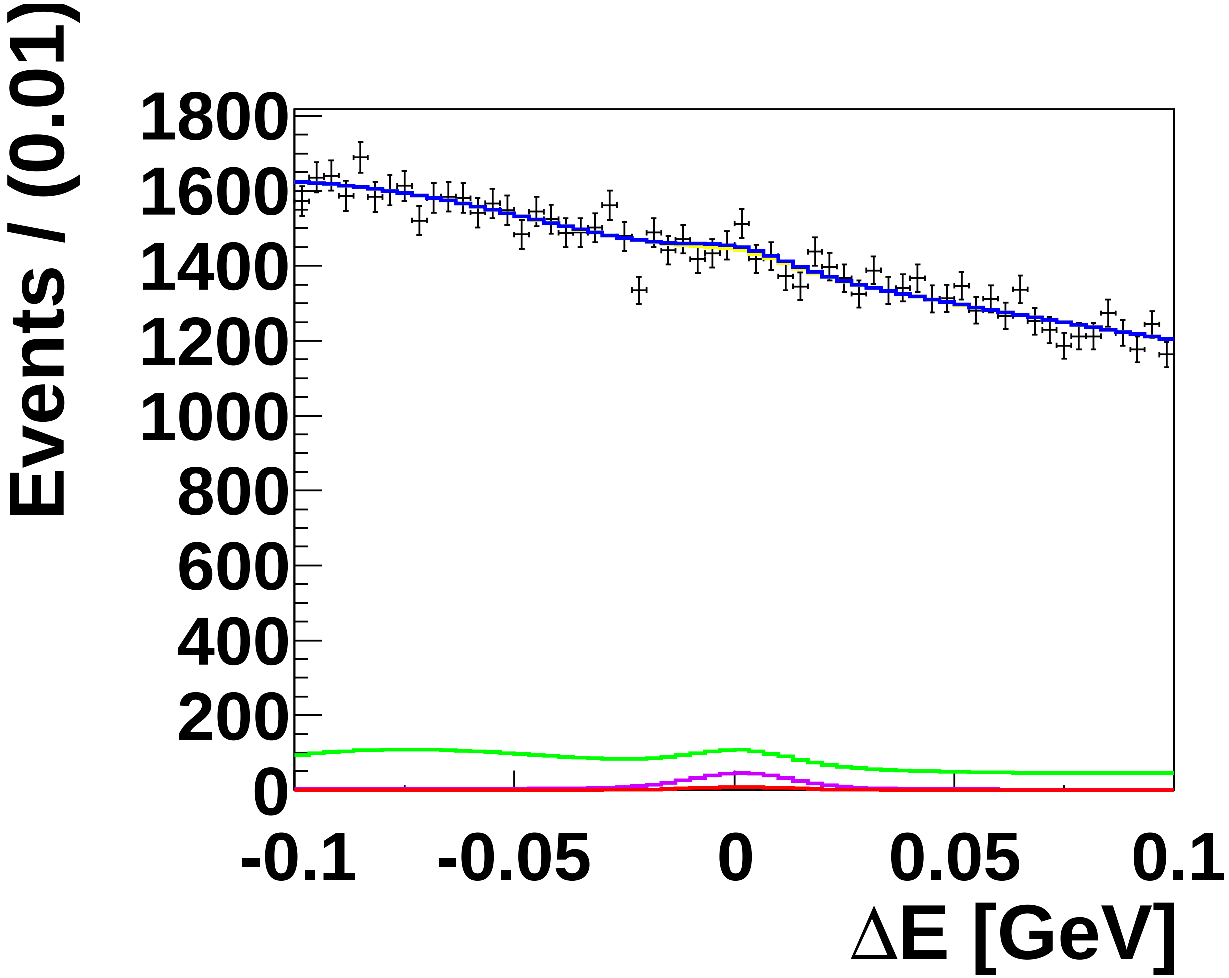
$\Rightarrow$ Toy MC Generator built: events according to $\mathcal{PDF}$ (probability density function)

toy MC example

expected Nr of events

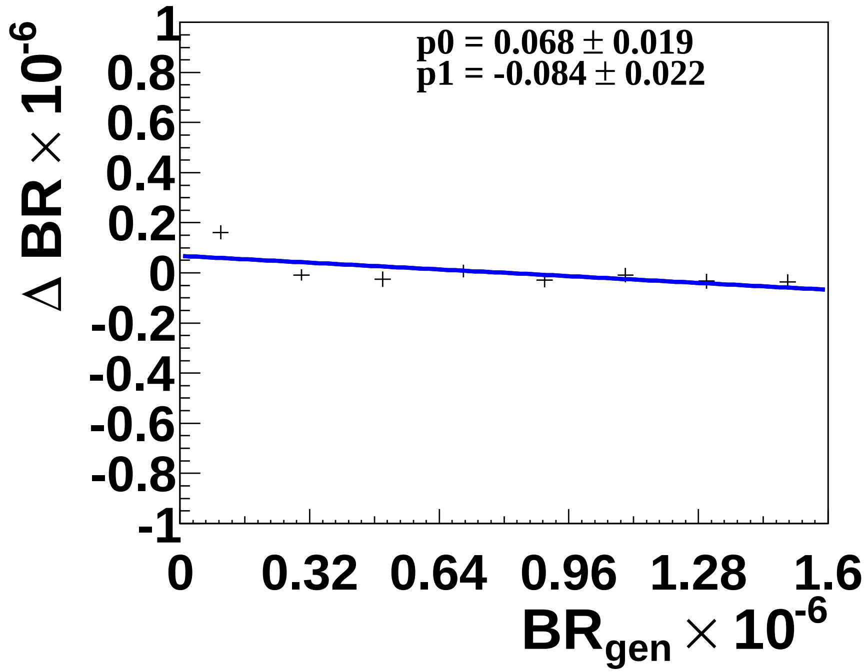
- signal: $\sim$ 100
- 4 πs ff: $\sim$ 1500
- $B\bar{B}$: $\sim$ 10000
- all: $\sim$ 100000

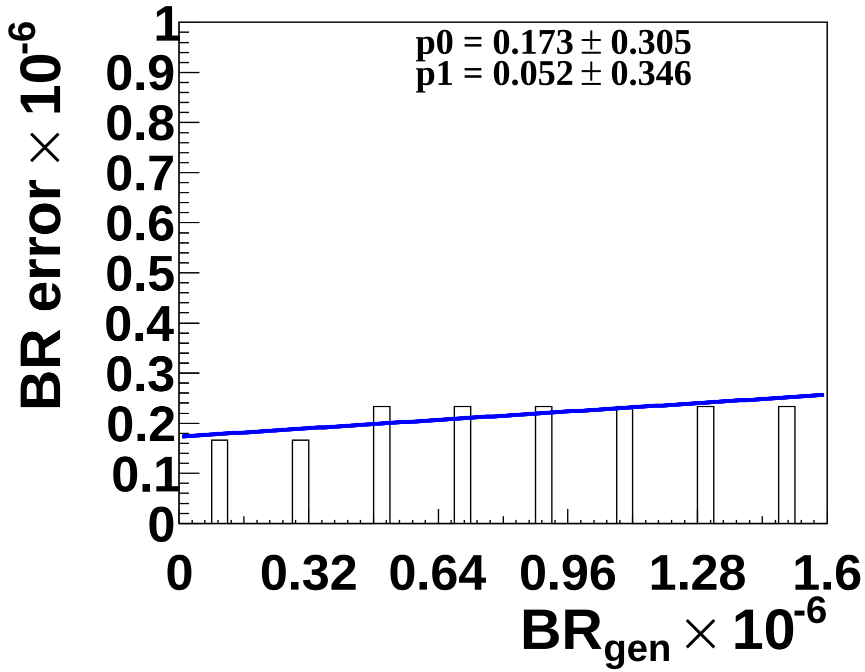
(using world averages)



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

- performed fits on 600 toy MC samples

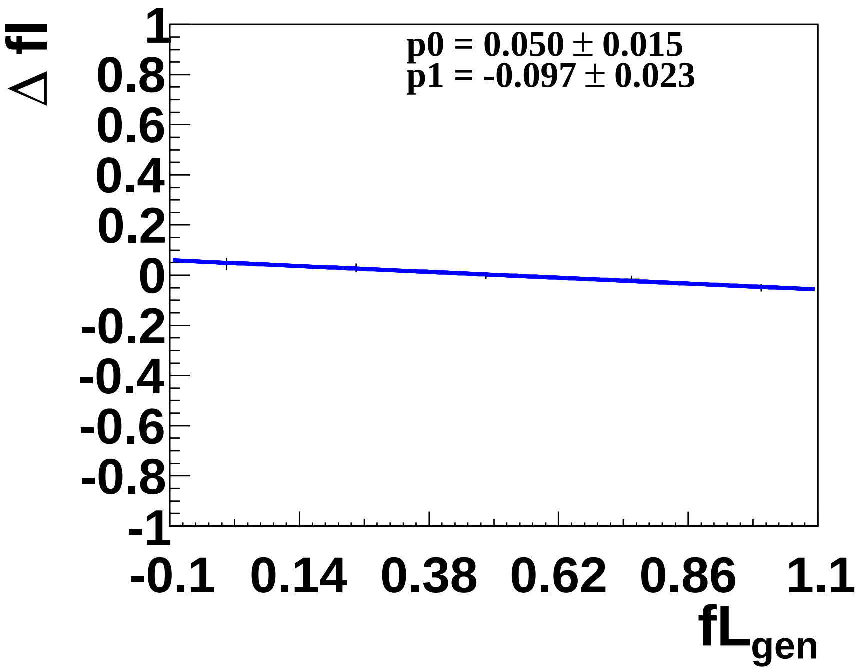


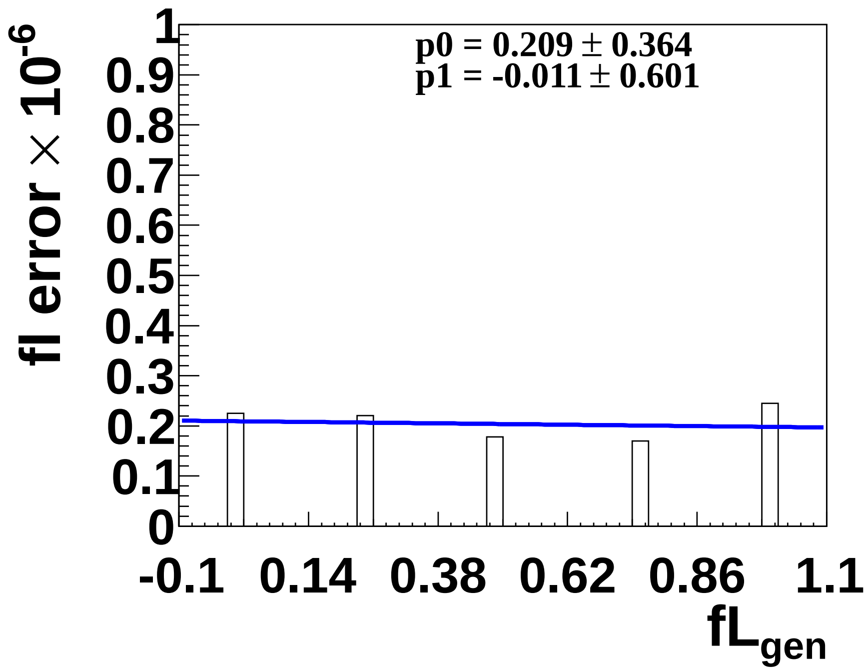


$\Rightarrow$ observation with a 3 σ significance possible if $\mathcal{BR}$ not too small!

Toy MC Studies

- performed fits on 600 toy MC samples, assuming $\mathcal{B}(B^0 \to \rho^0\rho^0) = 0.9 \times 10^{-6}$



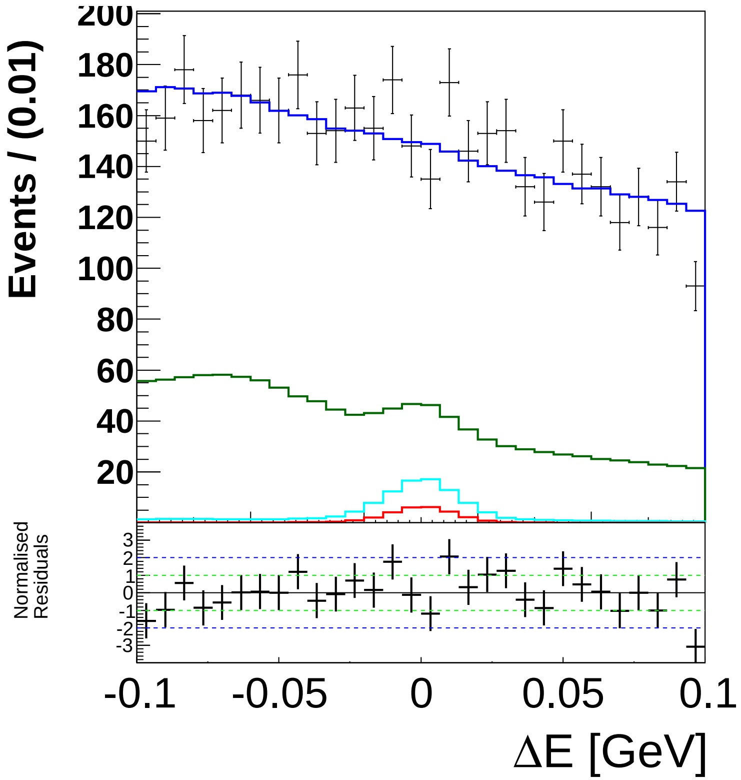


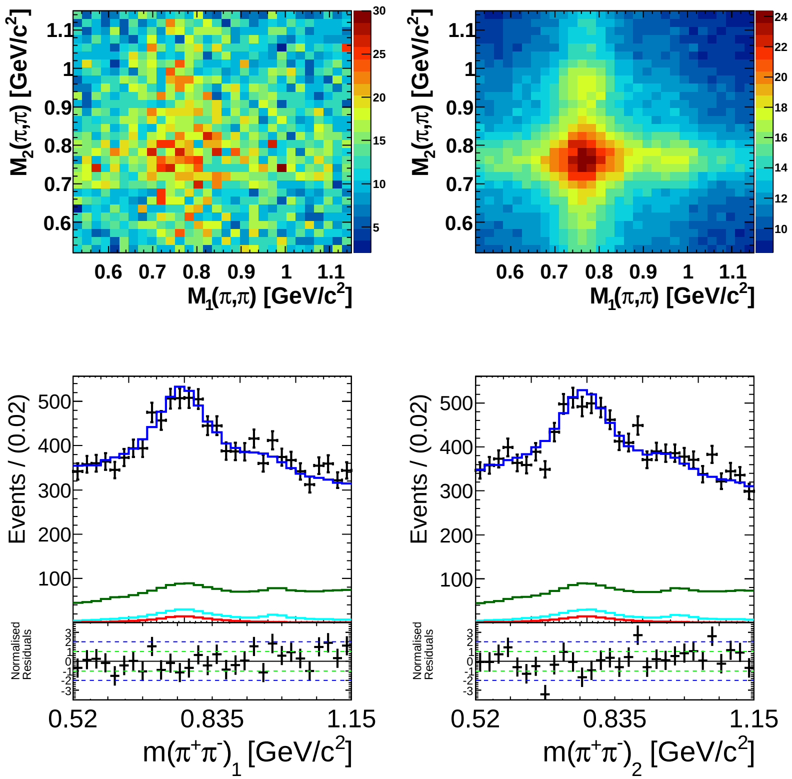
$\Rightarrow$ measurement of the fraction of L pol f_L possible!

Preliminary Fit Result

$$\mathcal{B}(B^0 \to \rho^0\rho^0) = (1.01^{+0.31}_{-0.29}(stat.) \pm 0.09(syst.) \pm syst_{interference}) \times 10^{-6}$$

$$f_L = 0.20^{+0.18}_{-0.23}(stat.) \pm 0.08(syst.) \pm syst_{interference}$$





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

  $\to 1^{st}$ evidence at Belle($\sim 3\sigma$, still after including interference??)

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Backup

Backup

Preliminary Fit Result

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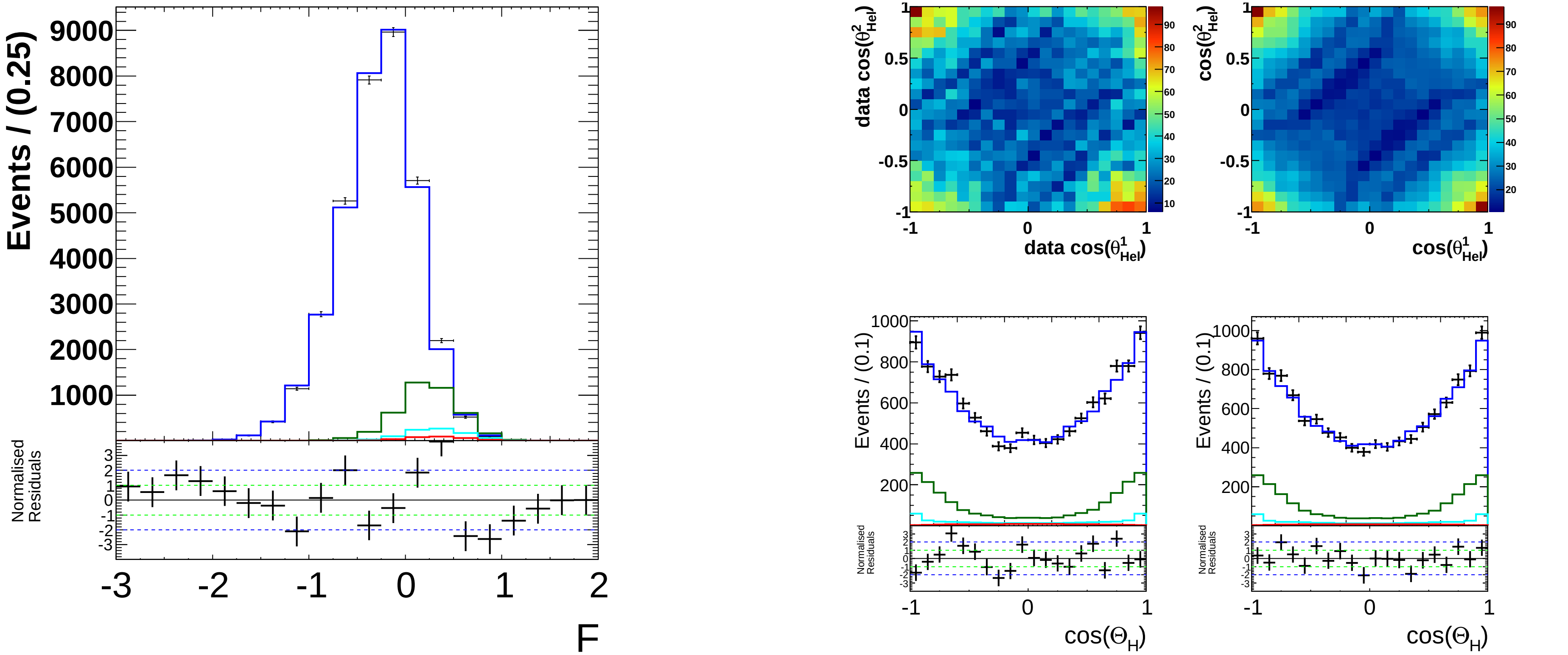
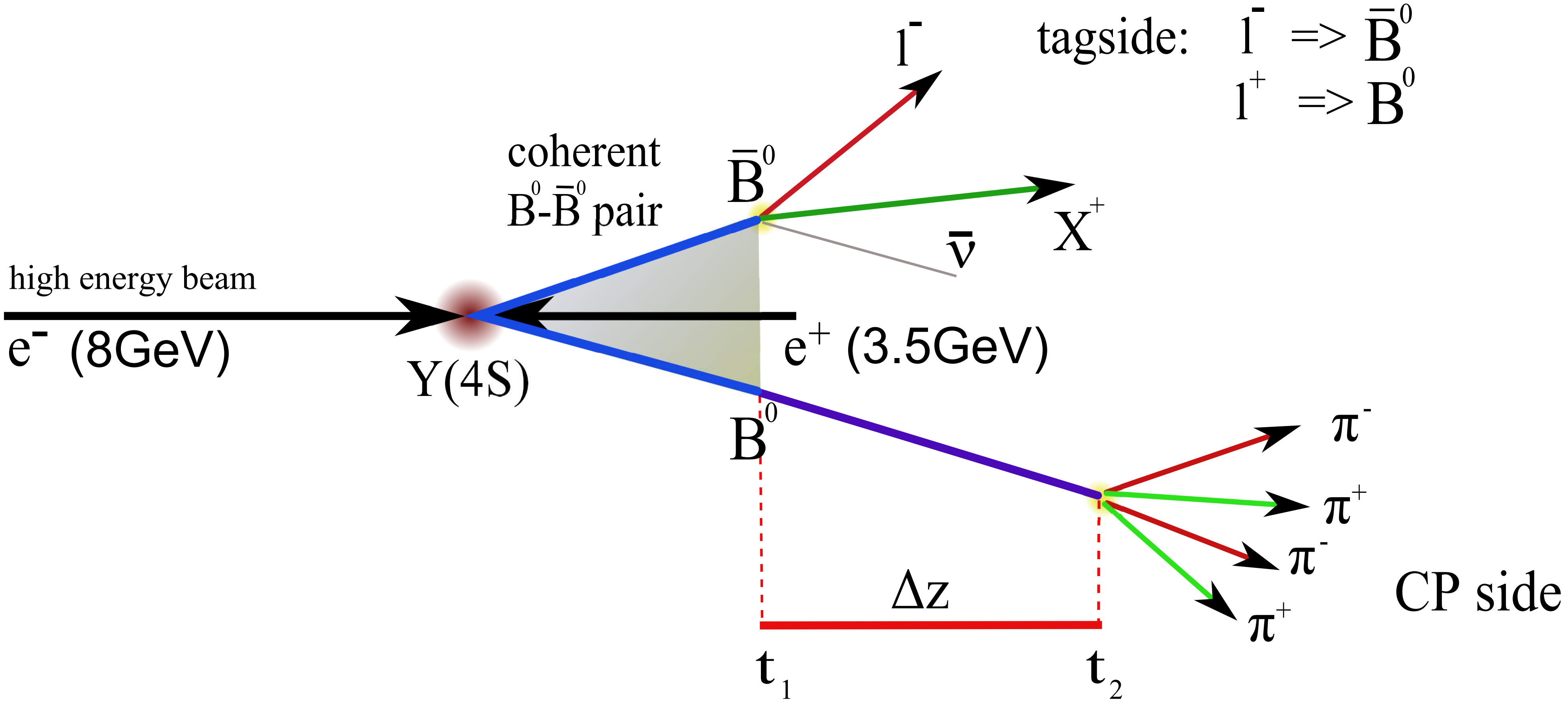


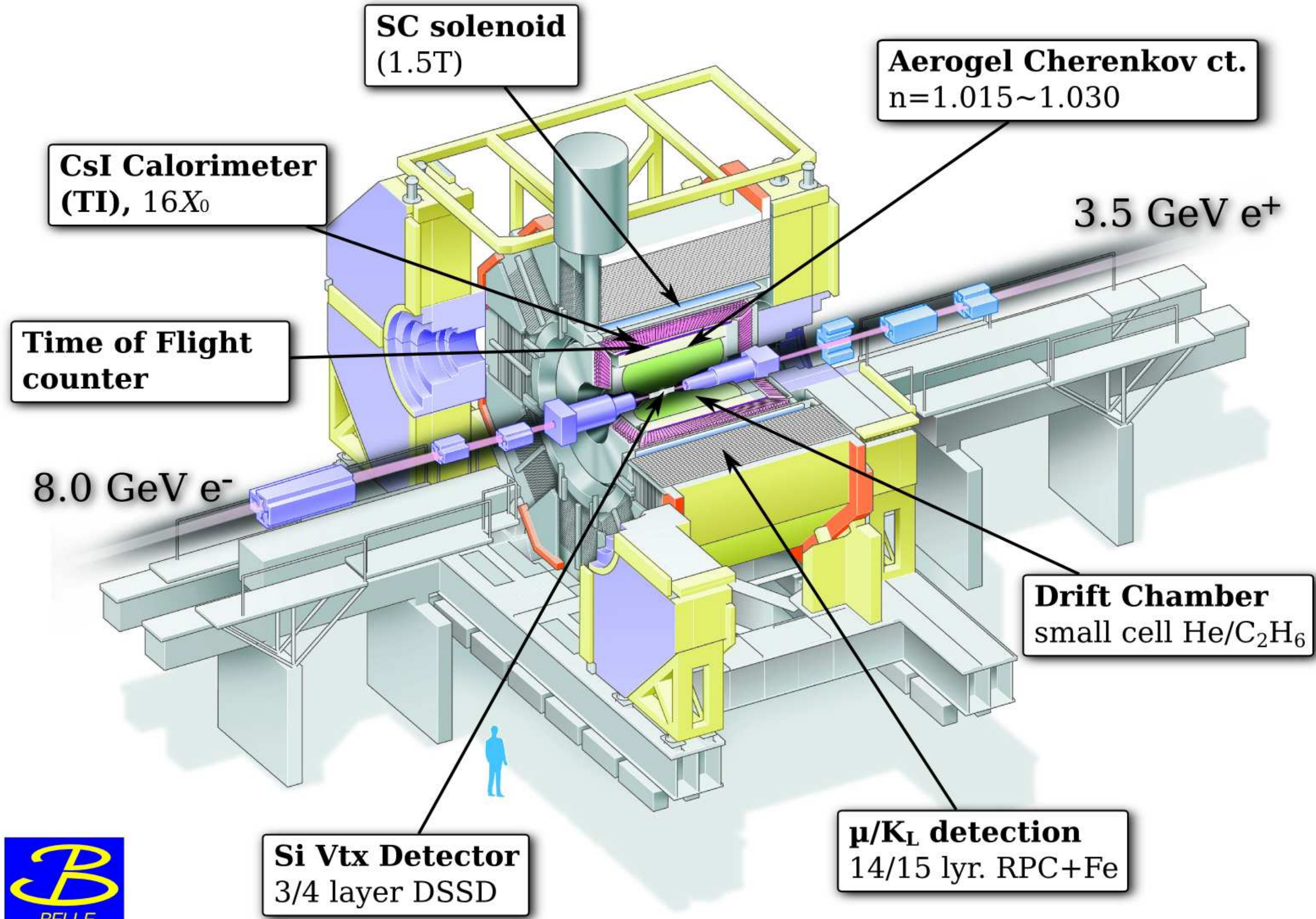
CP Violation measurement



$\Upsilon(4S) \rightarrow$ 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 $\int Ldt = 1014fb^{-1}$ $\sim 772 \times 10^6 B\bar{B}$ pairs

Belle Detector

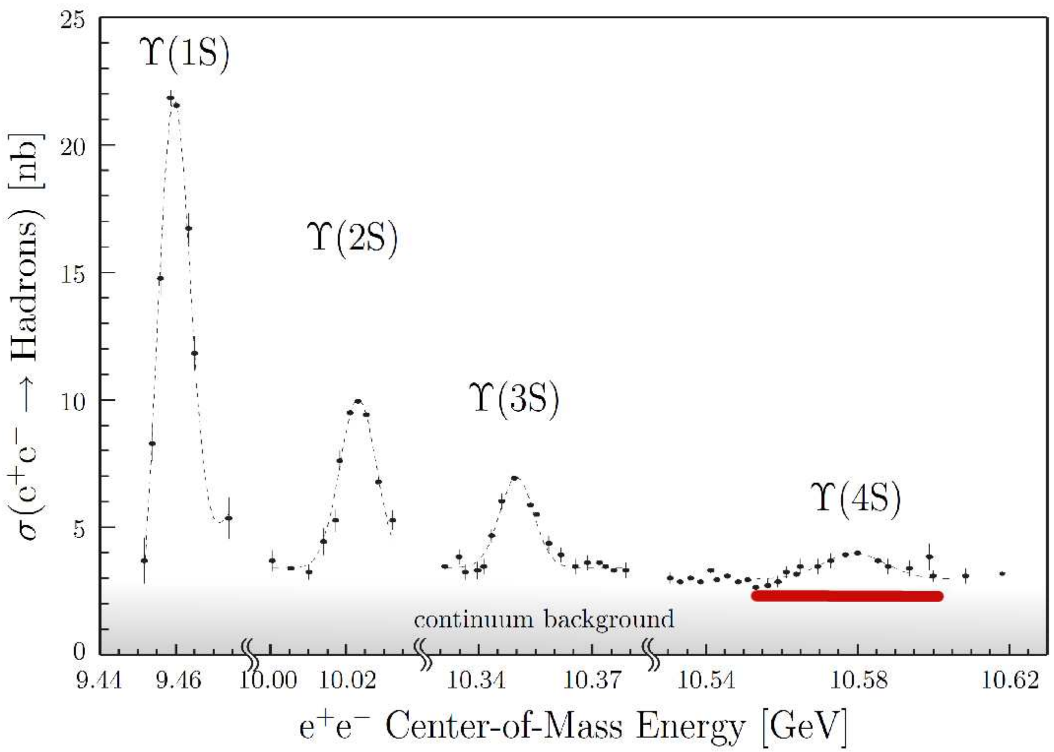
- tracking
- PID

The Belle Experiment

located at the KEKB collider in Japan

CP Violation measurement

Where the Bs come from:



- 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

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

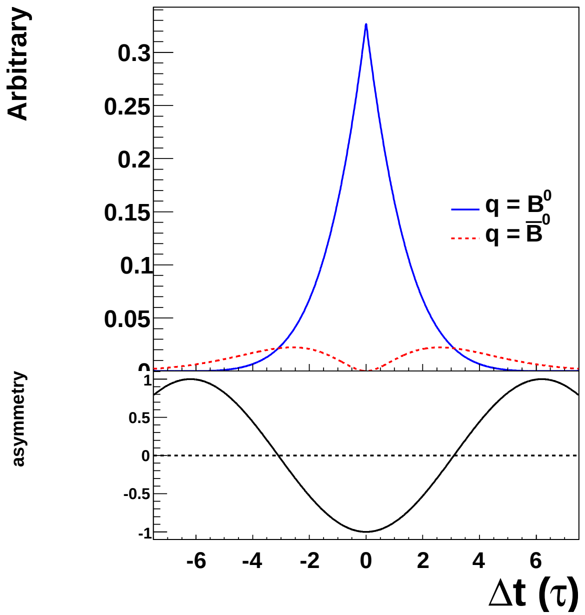
$$m(B) = 5.28GeV/c^2$$

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

gives large contribution

CP Violation in the B System

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



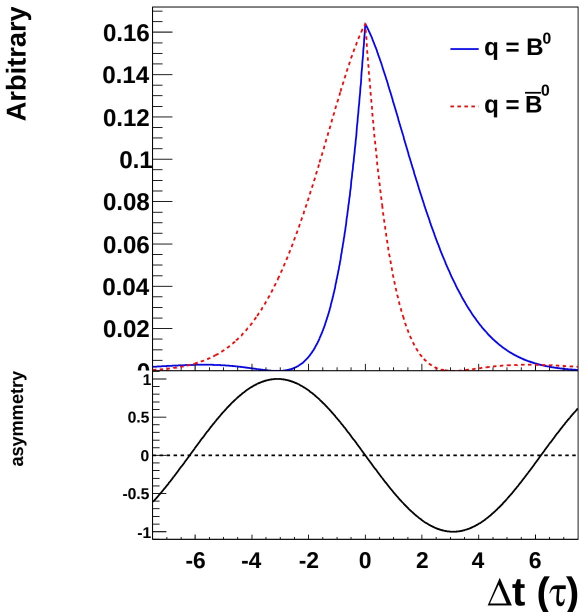
CP asymmetry parameters:

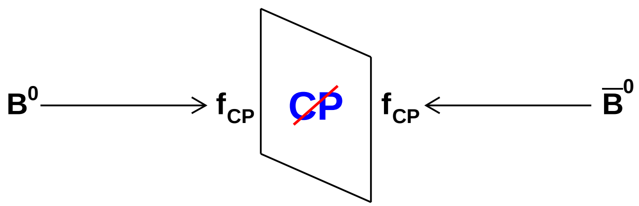
$\leftarrow \mathcal{A}_{CP}$(direct $\cancel{CP}$)

different decay rates

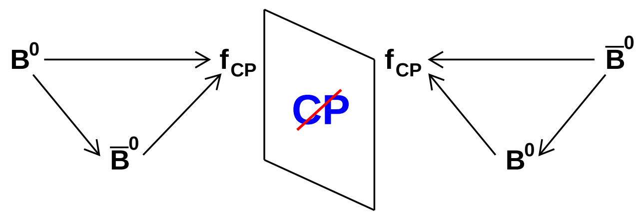
$\mathcal{S}_{CP}$(indirect $\cancel{CP}$)$\rightarrow$

or different time evolution





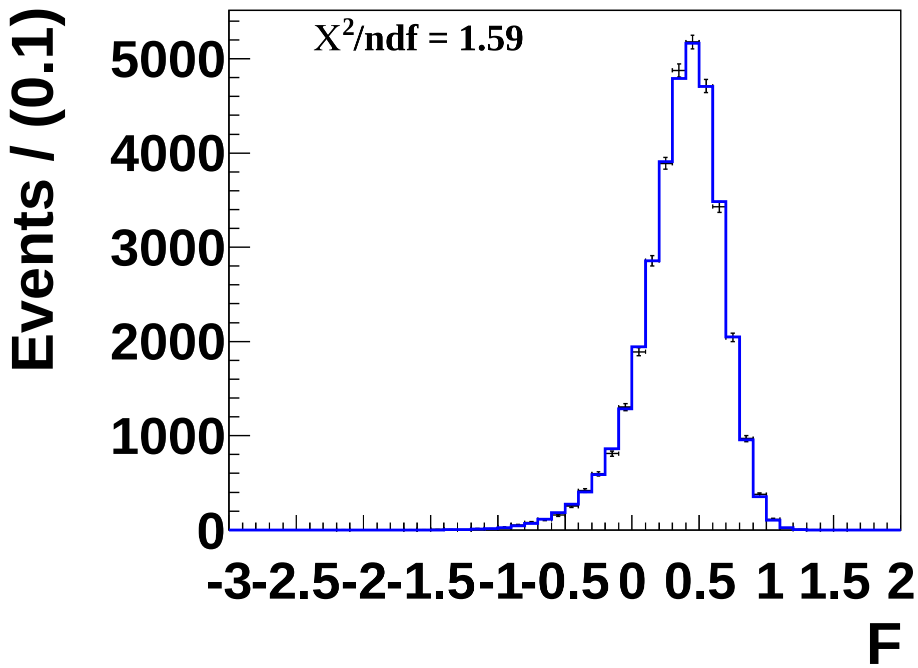
for B and $\bar{B}$ decaying into a CP eigenstate f_{CP}



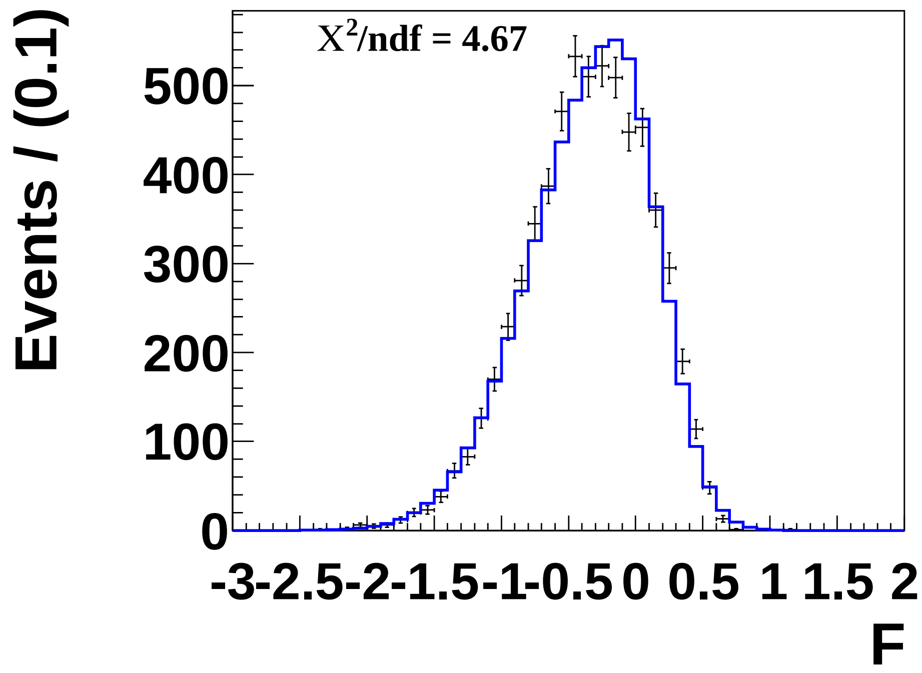
Model for $\mathcal{BR}(B^0 \to \rho^0\rho^0)$

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

- MC($a_1\pi$)



- off-resonance data

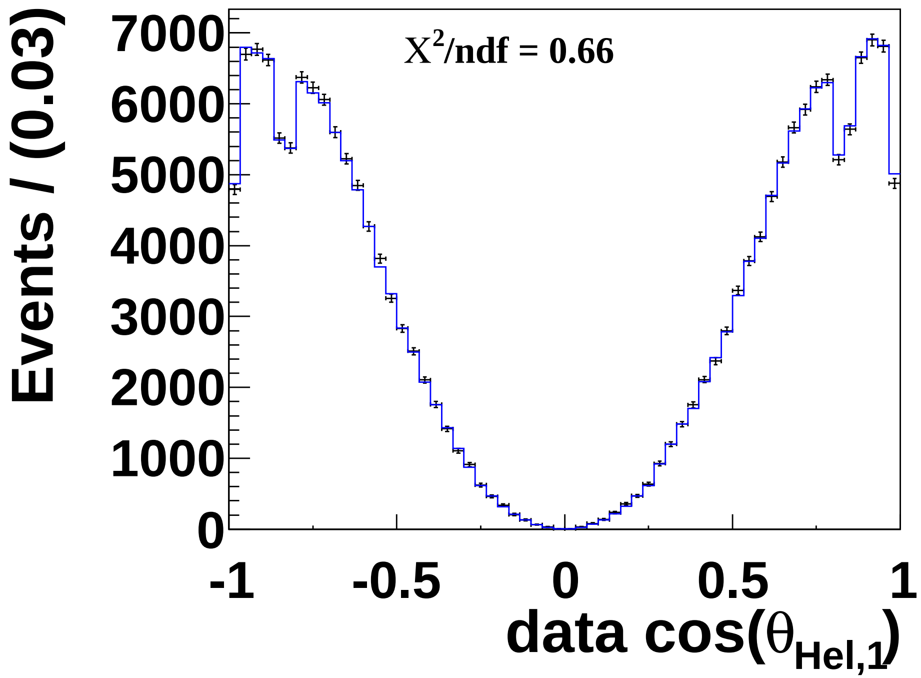


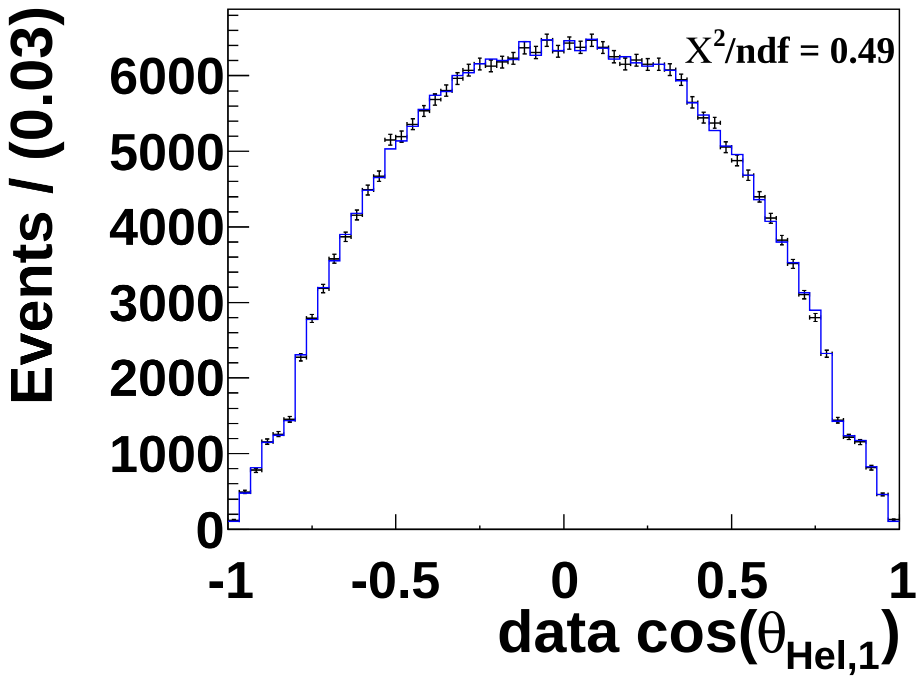
$\mathcal{PDF}$ =double bifurcated gaussian

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

Helicity: weighted with reconstruction efficiency histogram

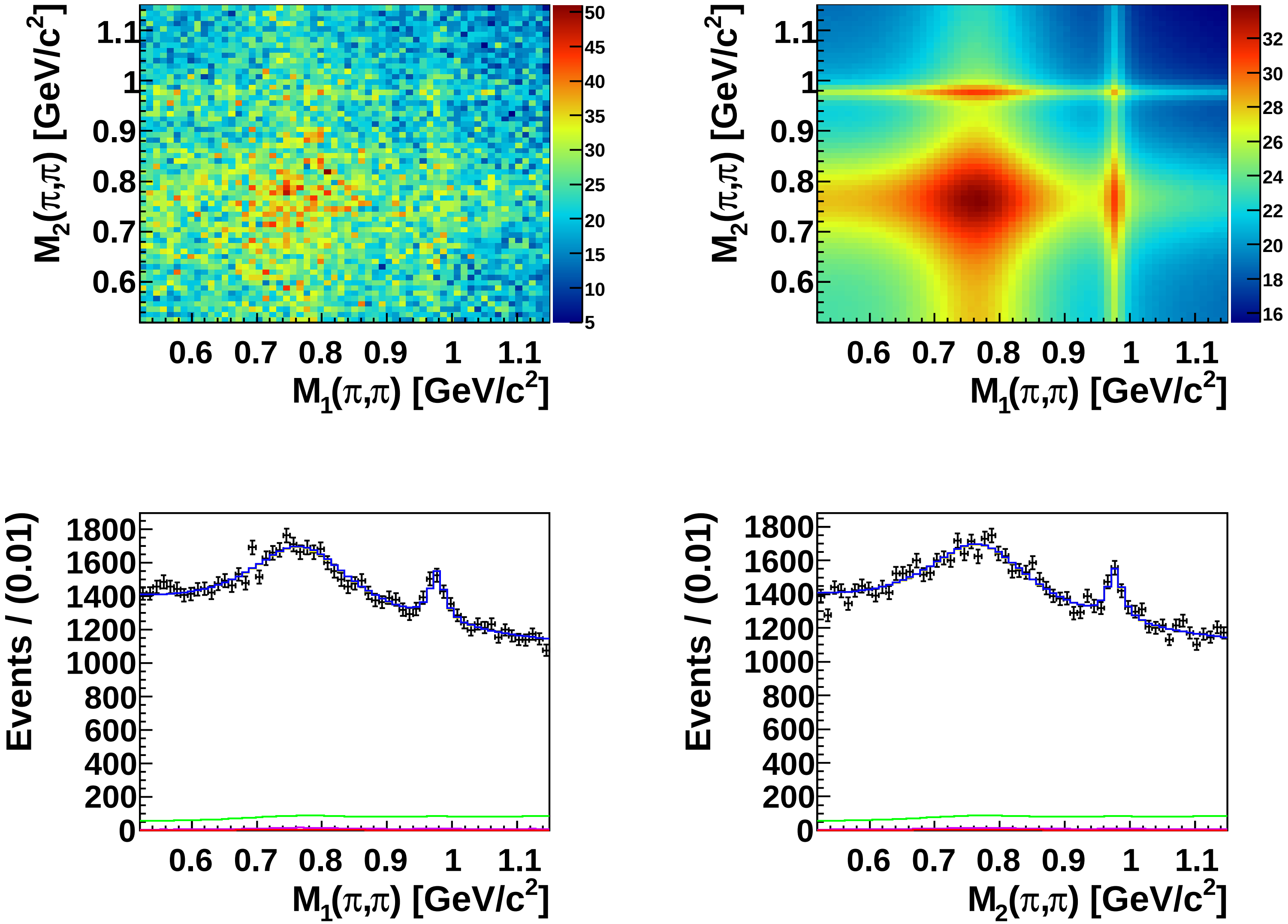
- signal MC(L pol)
- signal MC(T pol)



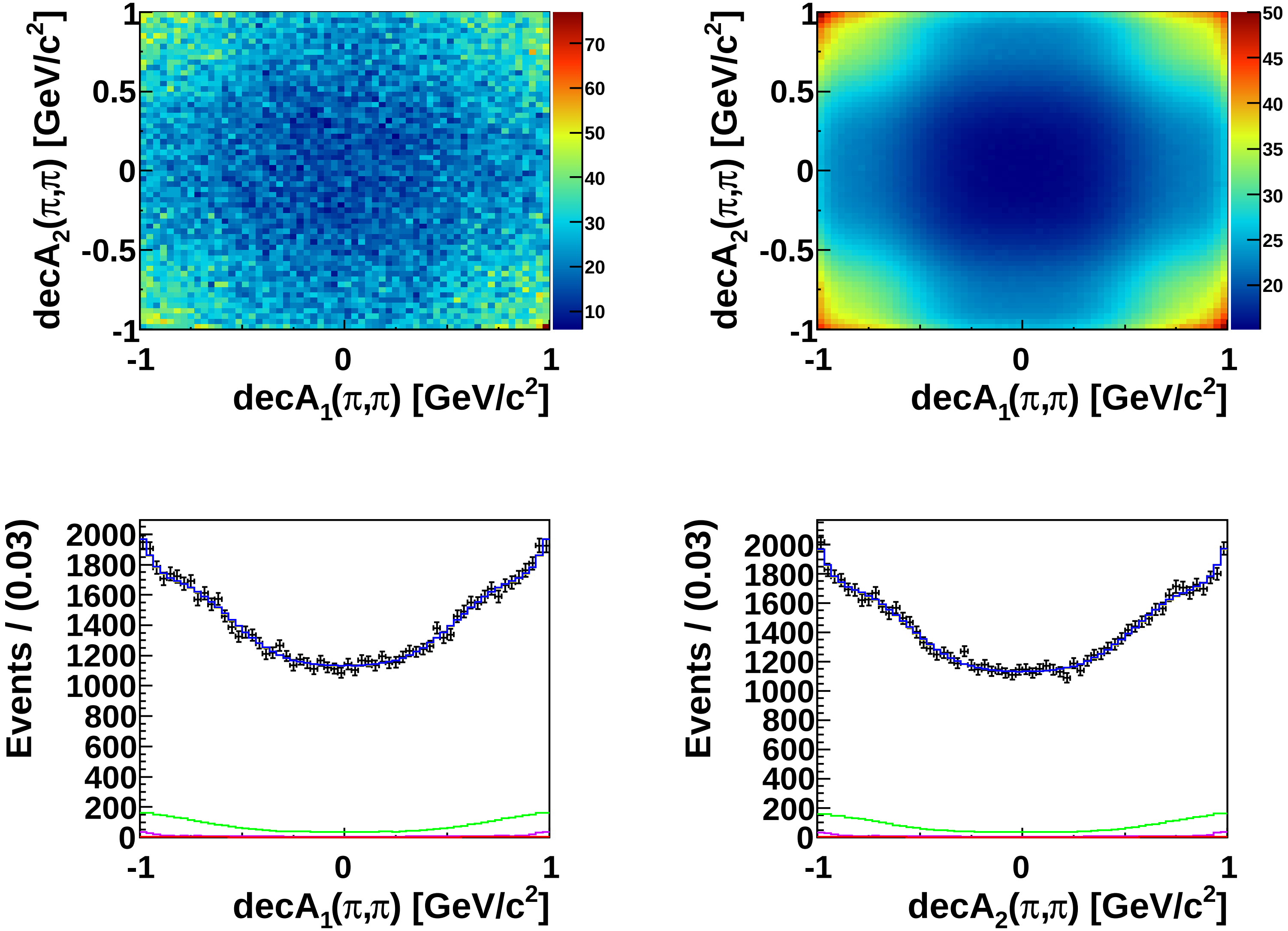


$$\frac{1}{\Gamma}\frac{d^2\Gamma}{d\cos\theta^1_{\mathrm{Hel}}\,d\cos\theta^2_{\mathrm{Hel}}} = \frac{9}{4}\left(f_L\cos^2\theta^1_{\mathrm{Hel}}\cos^2\theta^2_{\mathrm{Hel}} + \frac{1}{4}(1-f_L)\sin^2\theta^1_{\mathrm{Hel}}\sin^2\theta^2_{\mathrm{Hel}}\right)$$

Backup: Toy MC Studies



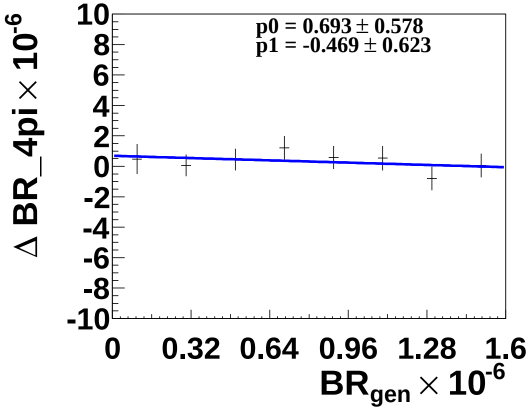
Backup: Toy MC Studies

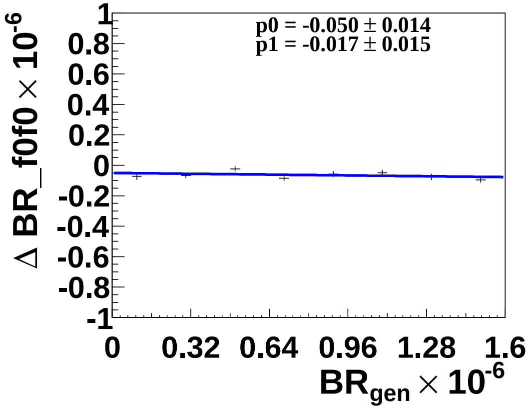


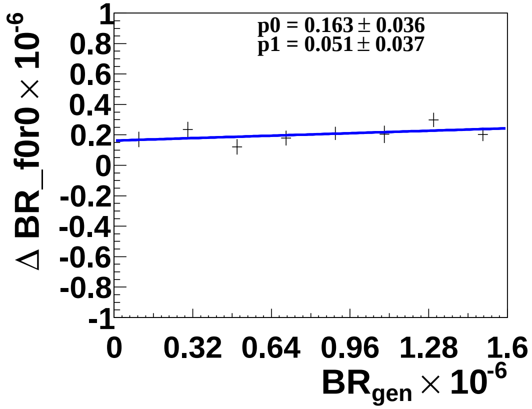
Backup: ToyMC Studies

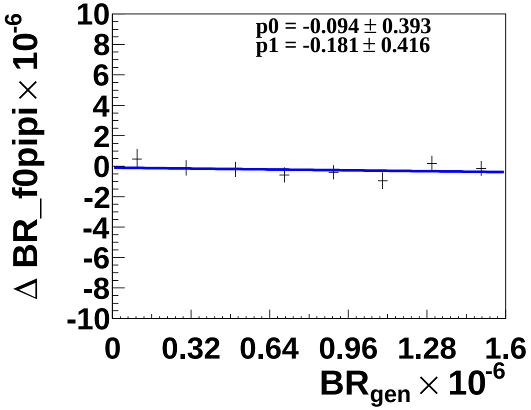
results for $m_{\pi^+\pi^-} \in [0.52, 1.15] GeV/c^2$

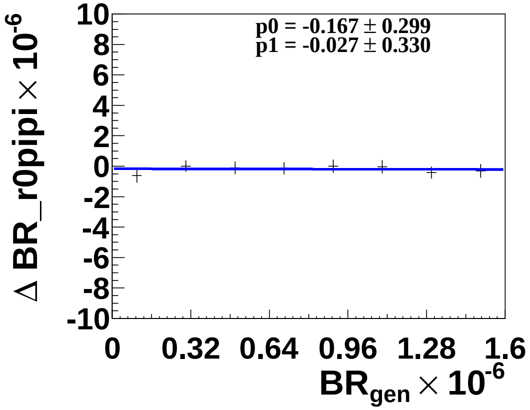
$a_2^{\pm}\pi^{\mp}$ upper limit gives less the 1 event $\Rightarrow$ fixed to 0







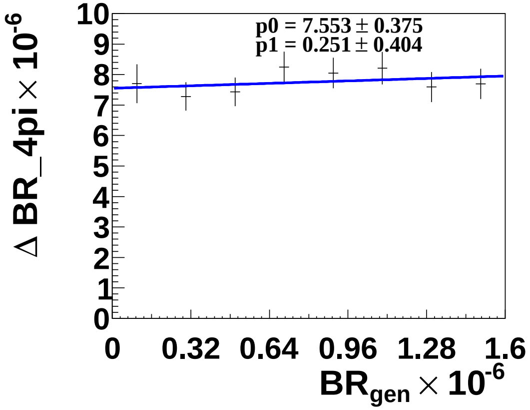


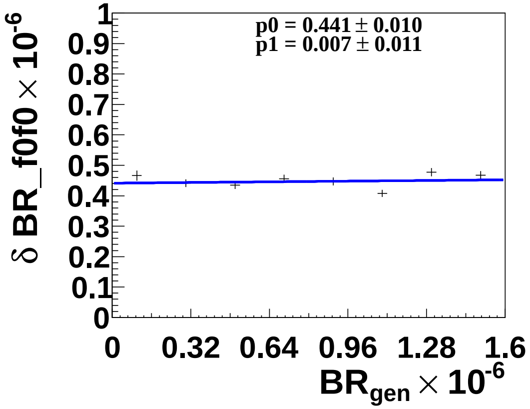


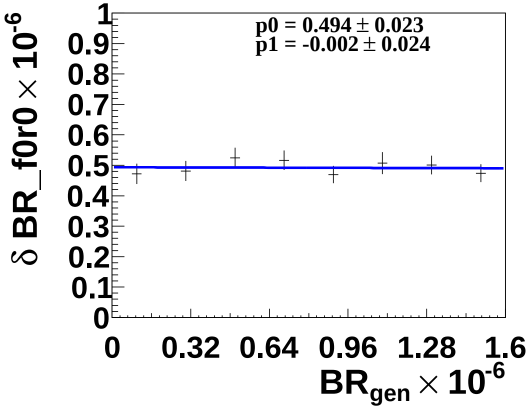
Backup: ToyMC Studies

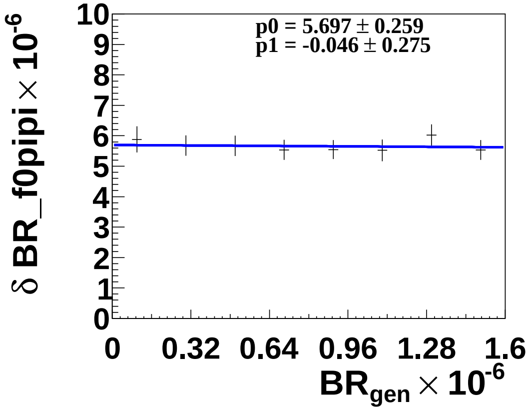
results for $m_{\pi^+\pi^-} \in [0.52, 1.15] GeV/c^2$

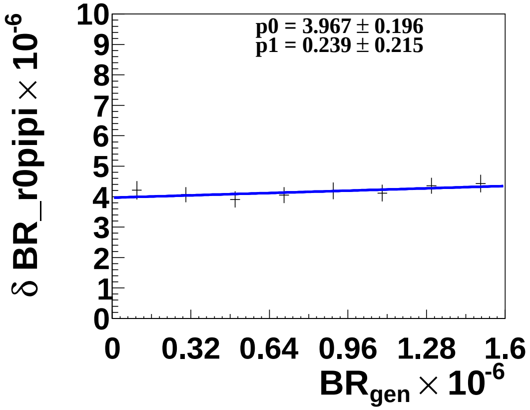
$a_2^\pm \pi^\mp$ upper limit gives less the 1 event $\Rightarrow$ fixed to 0











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_S^0(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})

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

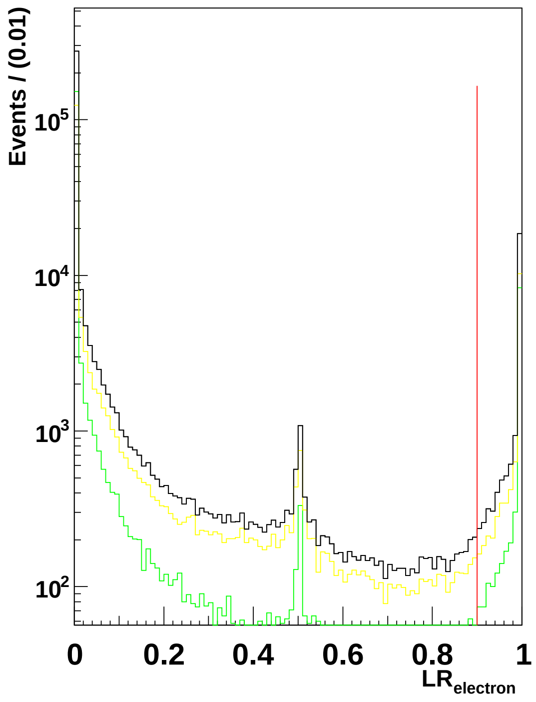
- continuum identification
- randomize events to remove asymmetry due to ordering in the reconstruction

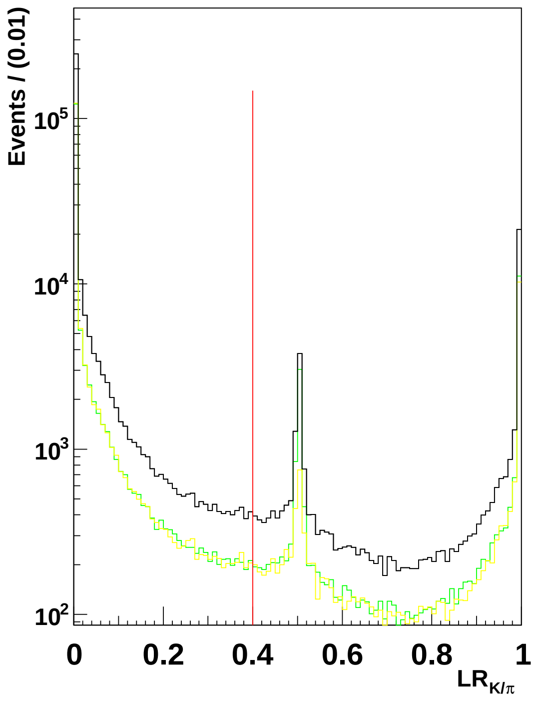
	L pol	T pol
rec Eff	19.6$\%$	27.2$\%$

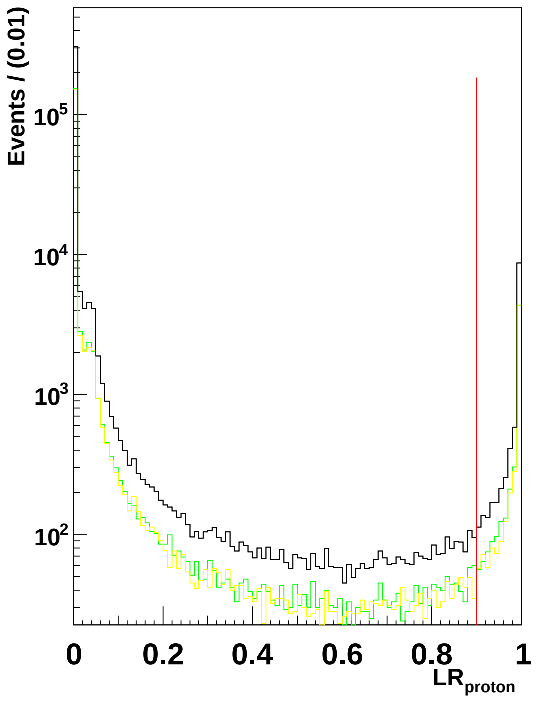
Measurement of $\mathcal{BR}(B^0 \to \rho^0\rho^0)$

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

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



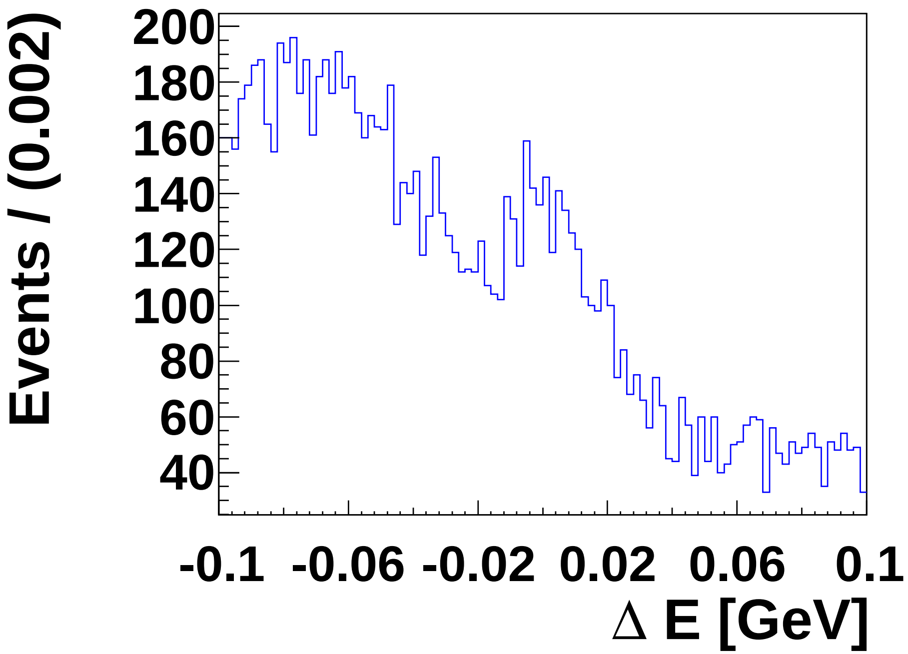


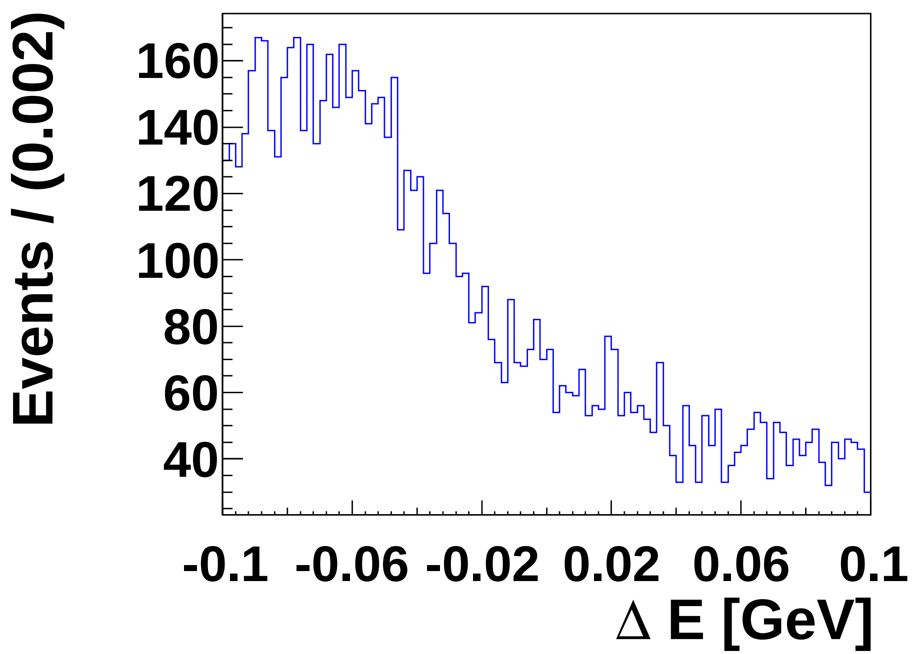


further loose cuts $|dr| < 0.5cm$ & $|dz| < 5cm$

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

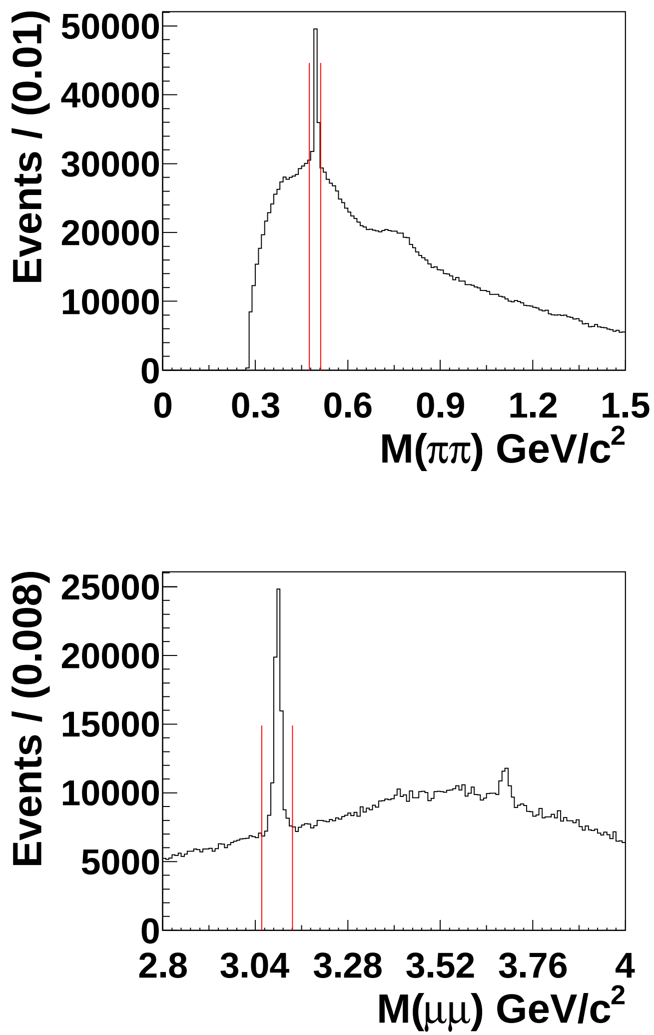




before and after vetos

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

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

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

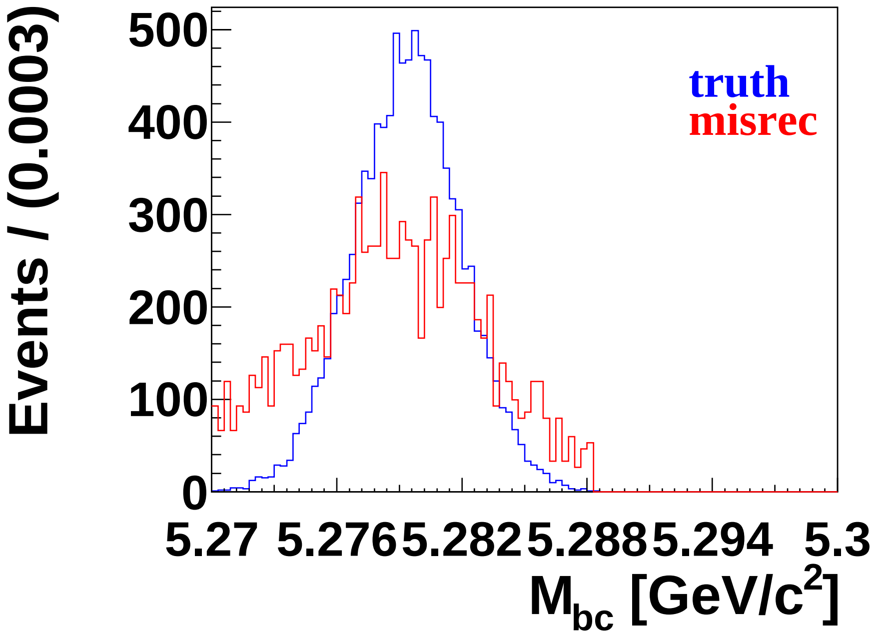
Cuts on $M(\mu\mu)$:

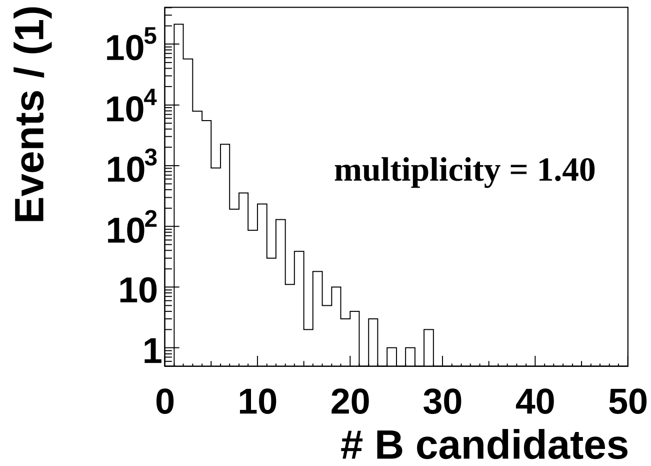
$J\Psi : 3.0969 \pm 0.04 [GeV/c^2]$

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

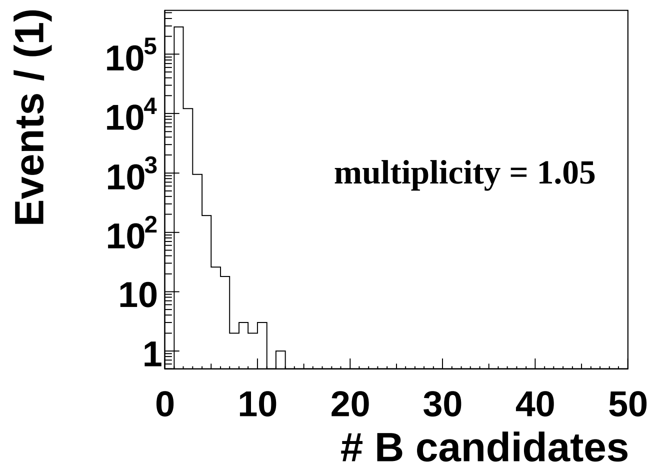
Measurement of $\mathcal{BR}(B^0 \to \rho^0\rho^0)$

- **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

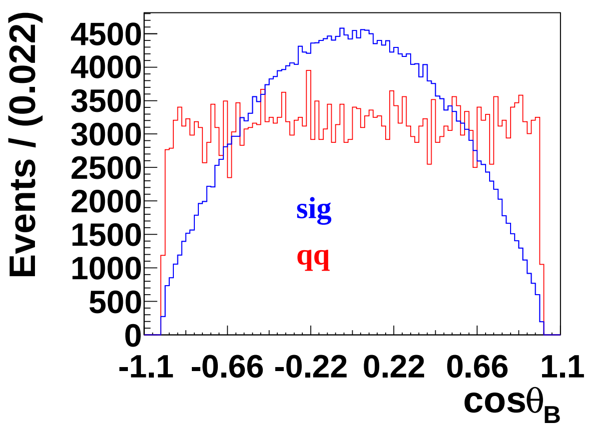
$\rightarrow$ purity $= 76\%(L); 92\%(T)$

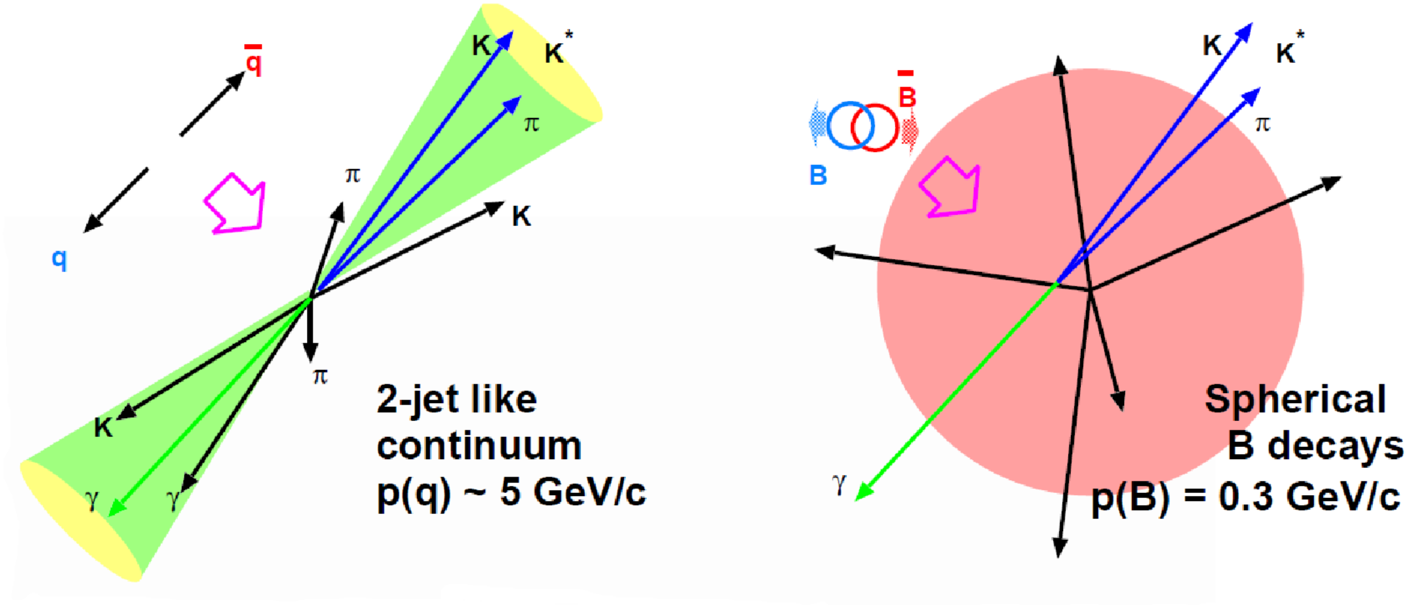
Measurement of $\mathcal{BR}(B^0 \to \rho^0\rho^0)$

- **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