Observation of CP violation in B decay
- By the Belle Collaboration -

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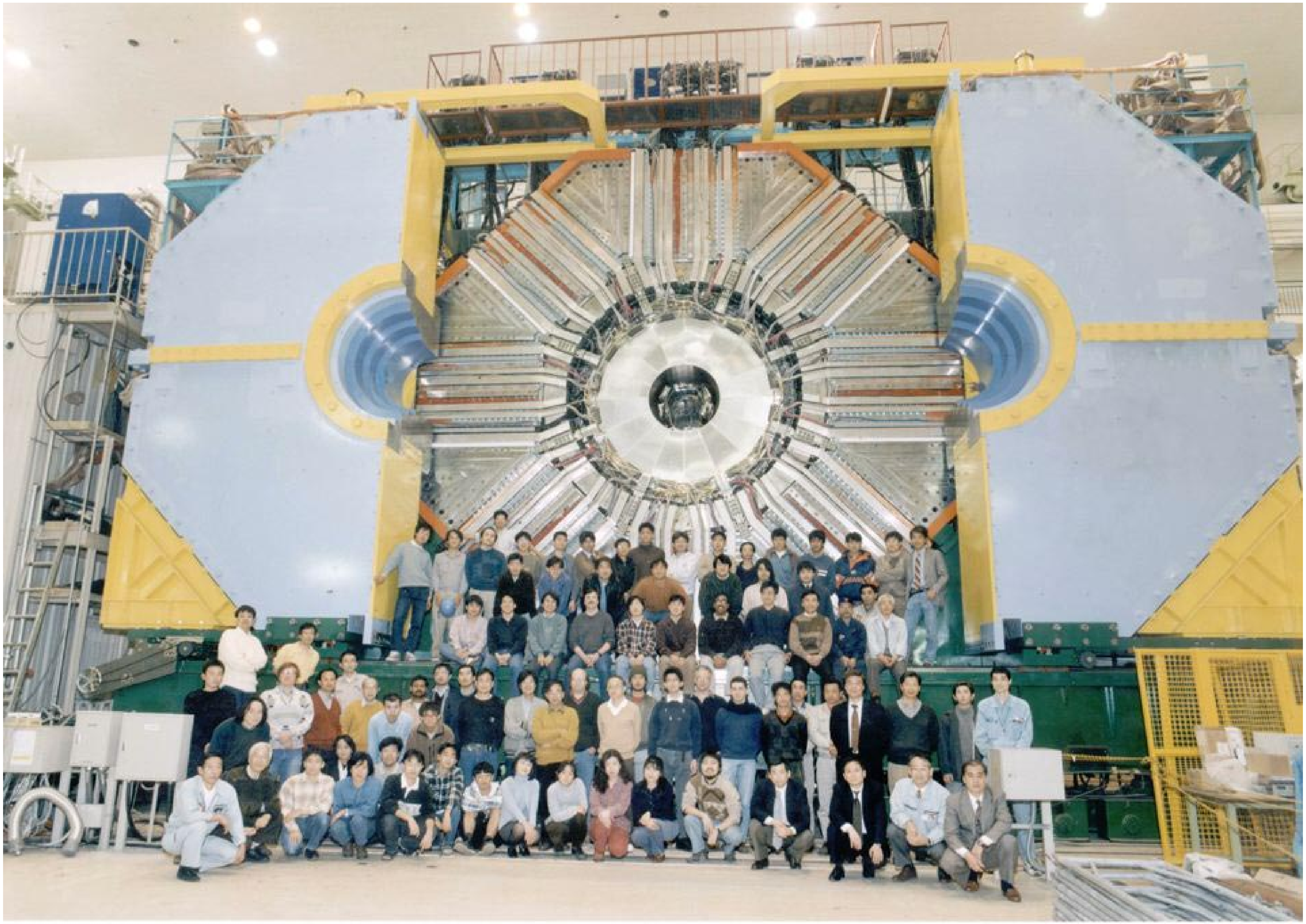
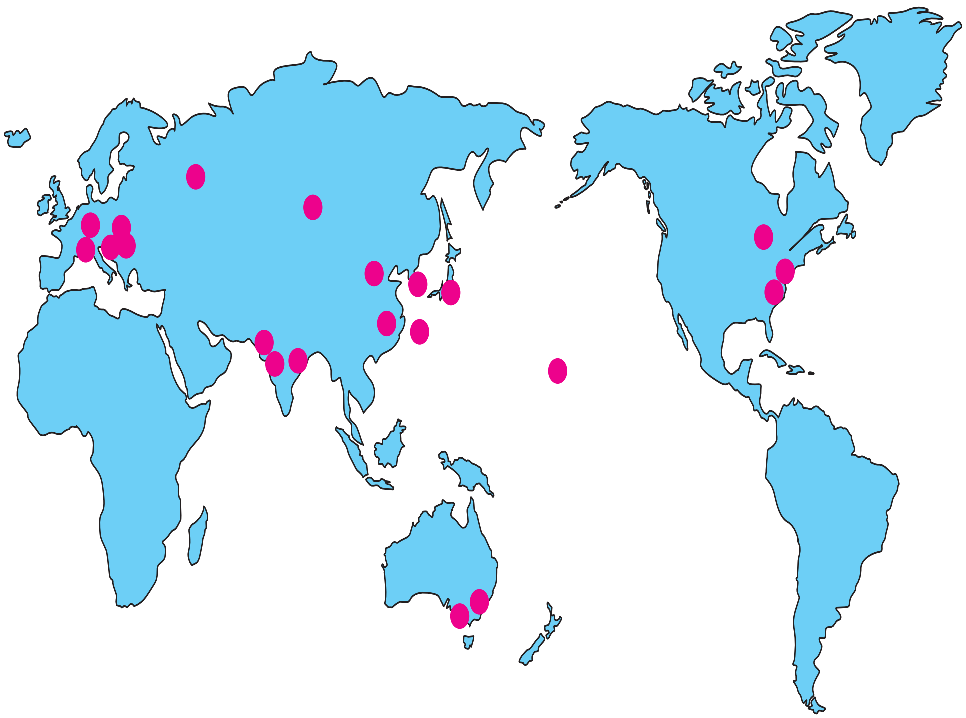
1. Highlights
2. Theoretical background
3. Experimental Detail
4. Conclusion

Belle Collaboration: ~250 physicists



International Collaboration: ~50 Institutions



BELLE Collaboration

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Budker Institute of Nuclear Physics
Chiba University
Chuo University
University of Cincinnati
Frankfurt University
Gyeongsang National University
University of Hawaii
Hiroshima Institute of Technology
Hiroshima College of Maritime Tech.
IHEP, Beijing
ITEP, Moscow
Joint Crystal Collaboration Group
Kanagawa University
KEK
Korea University
Krakow Institute of Nuclear Physics
Kyoto University
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Mindanao State University
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Toyama National Colleg
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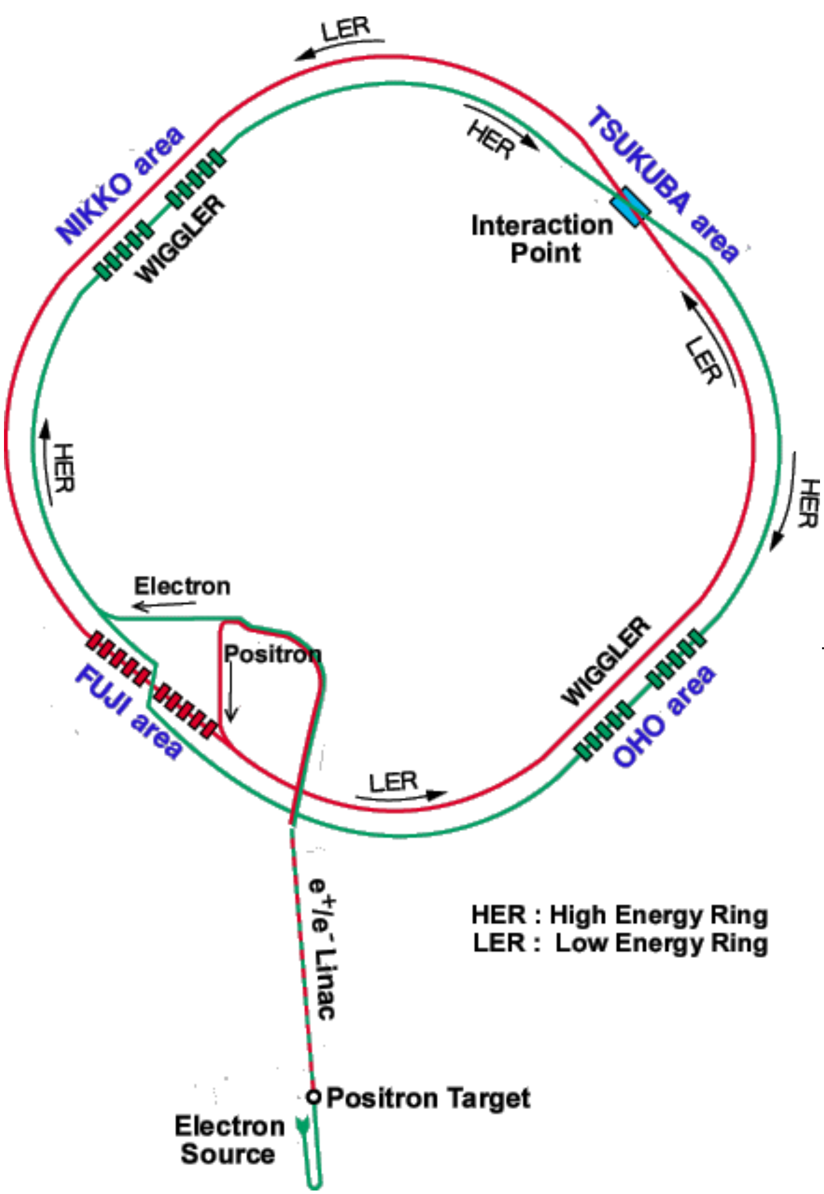
Virginia Polytechnic Ins
Yonsei University

KEK (High-Energy Physics Lab., Tsukuba, Japan)

KEK B-factory (KEK-B)



$$\text{Circ.} = 3016\ m$$

$$E_{e^+} = 3.5\ GeV$$

$$E_{e^-} = 8.0\ GeV$$

$$I_{e^+} = 0.9\ amp$$

$$I_{e^-} = 0.7\ amp$$

$$E_{c.m.} = 10.29\ GeV$$

$$(= M_{\Upsilon(4S)})$$

Luminosity $4.49 \times 10^{33}/s \cdot cm^2$

best among colliders

1. $\Upsilon(4S) \to B^0\bar{B}^0$ **(also B^+B^-)**

   $M_{\Upsilon(4S)} = 10.59$ **GeV,** $2M_B = 10.56$ **GeV.**
   $\to$ $B^0, \bar{B}^0$ **nearly at rest in** $\Upsilon(4S)$ **c.m.**
   ($P_B^* \sim 0.33$ **GeV, or** $\beta_B^* \sim 0.063$**)**

2. **But** $\Upsilon(4S)$ **is moving.**

$$\beta_{\Upsilon(4S)} = \frac{P_{\Upsilon(4S)}}{E_{\Upsilon(4S)}} = \frac{8.0 - 3.5}{8.0 + 3.5} = 0.39$$

3. B^0-$\bar{B}^0$ **mix.**

   Quantum-correlated coherent mixing.

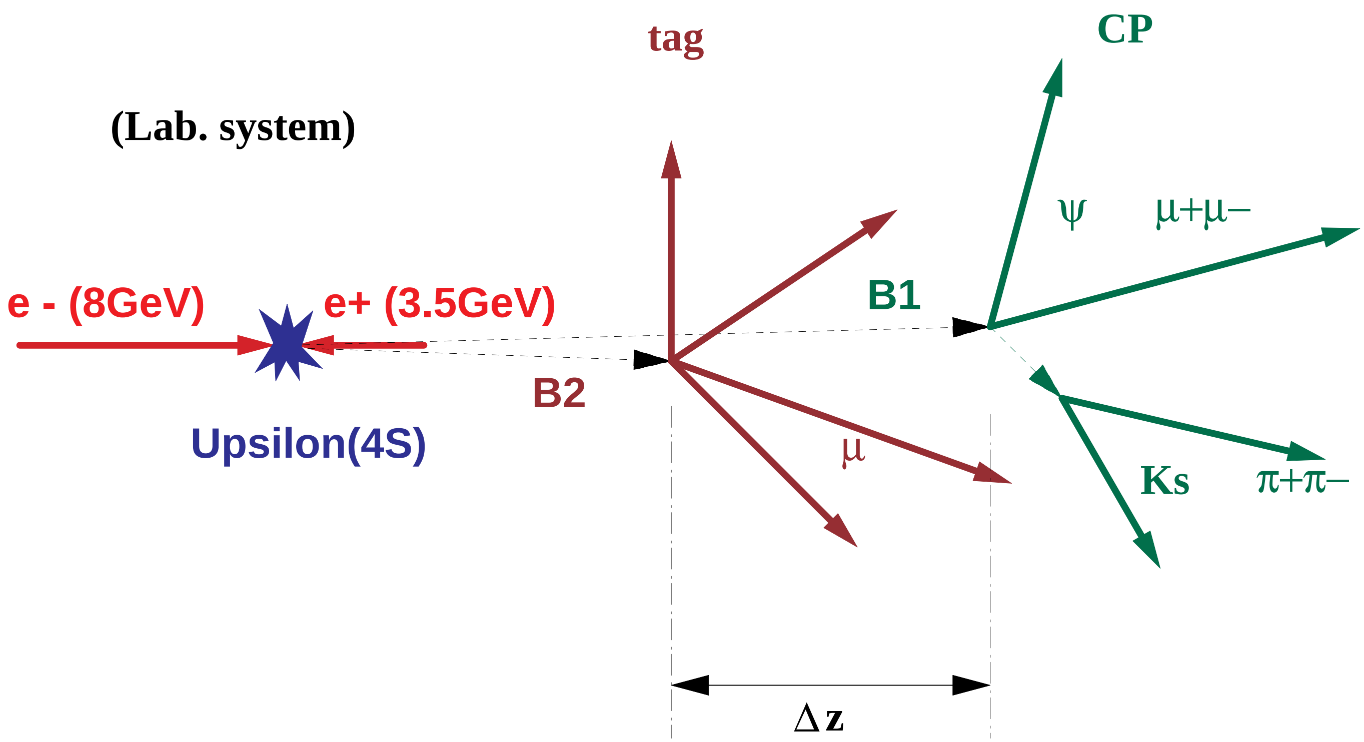
4. **Then,** $B^0, \bar{B}^0$ **decay.**

   $\tau_B \sim$ **1.55 ps** $\to$ **average decay length** $\sim$ **200** μ**m.**

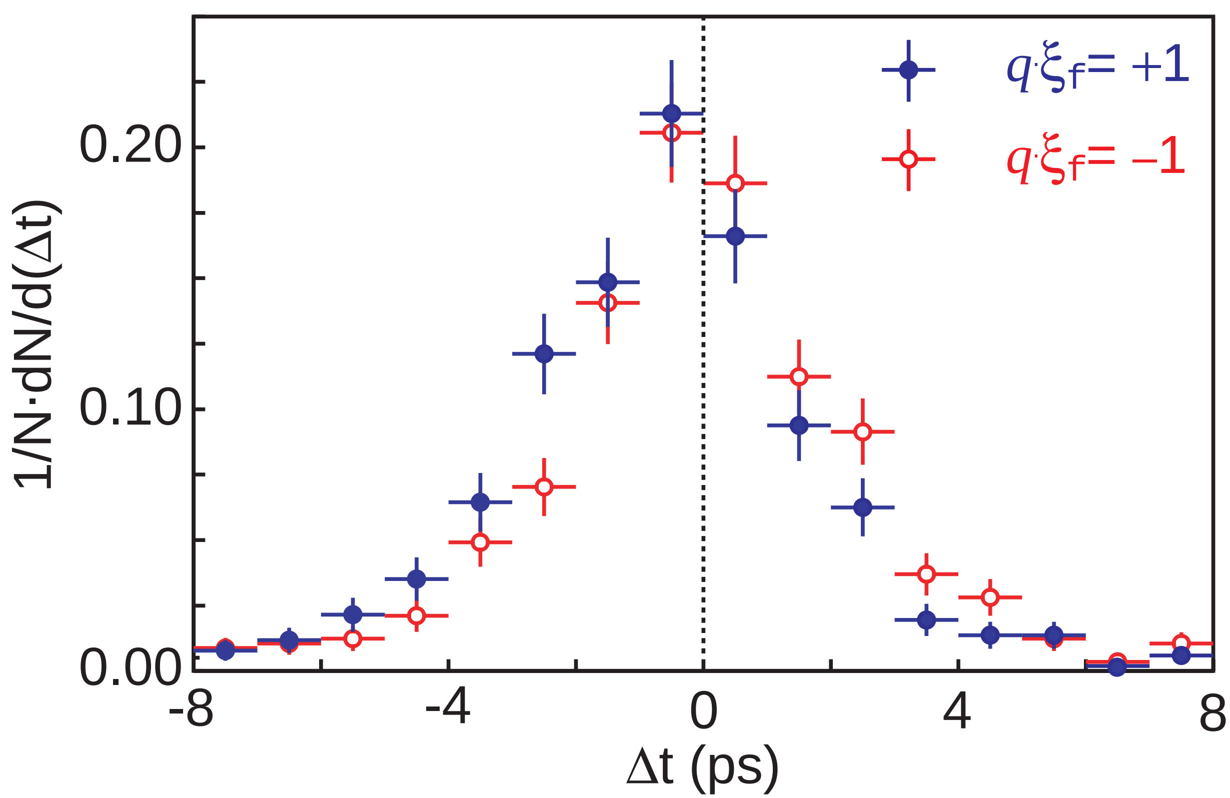
   One B decays to a CP eigenstate $|f_{CP}\rangle$
   ('CP' side; e.g. $|f_{CP}\rangle = J/\Psi K_S$ **. . .)**
   The other to a channel that tells B^0 **or** $\bar{B}^0$
   ('tag' side; e.g. $B^0 \to \mu^+ X$**,** $\bar{B}^0 \to \mu^- X$**)**

Measurement of Δt

$$\Delta t \equiv t_{CP} - t_{tag} = \frac{\Delta z}{\beta\gamma\, c}$$ (t: decay time in rest frame)



$q = +1$ **Tag side is** B^0
$q = -1$ **Tag side is** $\bar{B}^0$, $\xi_f : CP|f_{CP}\rangle = \xi_f |f_{CP}\rangle$ (CP eigenvalue)



Why is this a CP violation?

A, B: **phenomena (or statements)**

$$A \xleftrightarrow[\text{mirror inversion}(P)]{\text{particle} \leftrightarrow \text{antiparticle}(C)} B$$

If A and B occur at the same rate (or both true), then CP is conserved, otherwise, CP is violated.

For $CP(\xi_f) = -1$ (e.g. ΨK_S)

Observation:
A: If tag side is $\bar{B}^0(q = -1)$, the CP side tends to decay earlier than the tag side.

$\downarrow CP$

B: If tag side is $\bar{B}^0$, the CP side tends to decay earlier than the tag side.
(not true!)

$\rightarrow CP$ violation

Similarly for $CP = +1$ or B^0 tag.

($CP+$ and $-$ having different distributions is not CP violation.)

Theoretical Background

Standard-Model quark-W Interaction

$$L_{\text{int}}(t) = \int d^3x \big(\mathcal{L}_{qW}(x) + \mathcal{L}^{\dagger}_{qW}(x)\big)$$

$$\mathcal{L}_{qW}(x) = \frac{g}{\sqrt{8}} \sum_{i,j=1,3} V_{i\,j}\; \bar{U}_i\; \gamma_\mu (1-\gamma_5) D_j\; W^\mu$$

$$U_i \equiv \begin{pmatrix} u \\ c \\ t \end{pmatrix}, \qquad D_j \equiv \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

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

Cabibbo-Kobayashi-Masukawa (CKM) matrix (Unitary)

One can show that,

If V_{ij} are all real (by adjusting quark phases), then

$$(CP)\mathcal{L}_{\text{int}}(CP)^\dagger = \mathcal{L}_{\text{int}}$$

In general, a 3×3 quark mixing matrix cannot be made real $\rightarrow CP$ violation (Kobayashi, Masukawa, 1973)

Our phase convention:

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

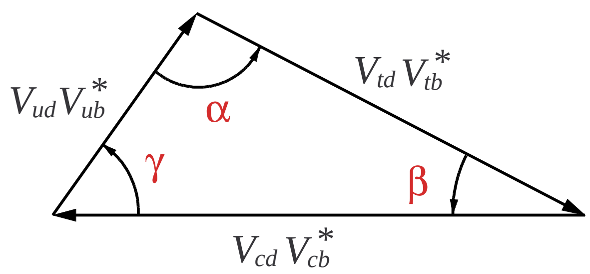
black : $\sim$ real
red : complex

If an interaction does not involve $t-d$ or $u-b$ transitions, then, $(CP)H_{\text{eff}}(CP)^\dagger = H_{\text{eff}}$.

Unitarity Triangle

e.g: orthogonality of d-column and b-column:

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$



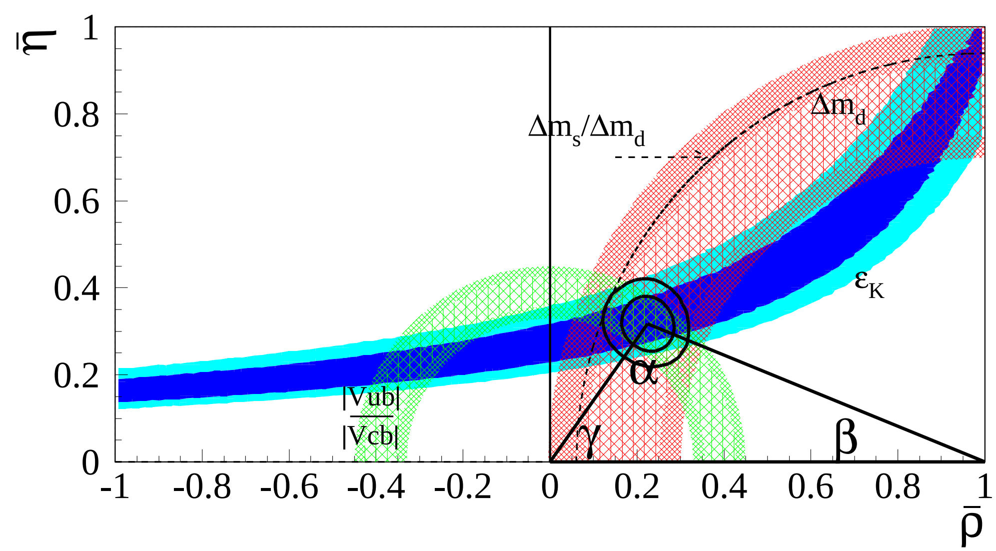
$$\phi_1(\equiv \beta) = -\arg(V_{td}),$$

If the CKM matrix is real, the triangle is a line.

How does the CKM unitarity triangle look?

Experimental inputs:
1. $|V_{ub}/V_{cb}|$ (by $b \to ue\nu$)
2. B^0-$\bar{B}^0$ mixing $\to |V_{td}|$
3. ϵ_K (from Kaon system)

Many people have performed a fit.
One recent example: Ciuchini et.al.:



Normalized to the bottom length of the triangle.
(two bands for each are 68% and 95% c.l.)

CP Violation by Mixing-Decay Interference

$$
\begin{array}{ccc} & \bar{B}^0 & \\ \nearrow & & \searrow \\ B^0 & \longrightarrow & f_{CP} \end{array}
\qquad\qquad
\begin{array}{ccc} & B^0 & \\ \nearrow & & \searrow \\ \bar{B}^0 & \longrightarrow & f_{CP} \end{array}
$$

$$\Gamma_{B^0(\bar{B}^0)\to f_{CP}}(t) = e^{-\gamma t}|pA|^2 \left[1 \pm \Im\left(\frac{q\overline{A}}{pA}\right) \sin \delta m\, t\right]$$

$$\begin{cases} B_a = pB^0 + q\bar{B}^0 \\ B_b = pB^0 - q\bar{B}^0\, , \end{cases} , \qquad \begin{cases} A \equiv Amp(B^0 \to f_{CP}) \\ \bar{A} \equiv Amp(\bar{B}^0 \to f_{CP}) \end{cases}$$

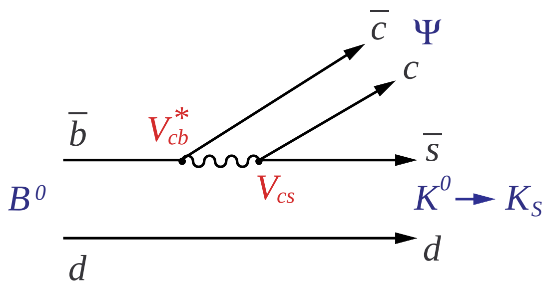
$B_{a,b}$: **eigenstates of mass and decay rate.**

γ: **average decay rate,** $\delta m \equiv m_a - m_b$

Time-dependent asymmetry:

$$A_{CP}(t) \equiv \frac{\Gamma_{\bar{B}^0} - \Gamma_{B^0}}{\Gamma_{\bar{B}^0} + \Gamma_{B^0}} = -\Im\left(\frac{q\overline{A}}{pA}\right) \sin \delta m\, t$$

What is $\Im \frac{q\bar{A}}{pA}$ for $f_{CP} = \Psi K_S$ etc. ?



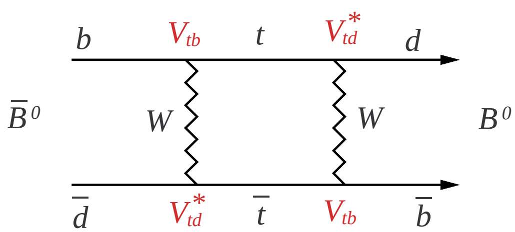
: no V_{td} or V_{ub} in decay

$\rightarrow (CP)H_{\text{eff}}(CP)^\dagger = H_{\text{eff}}$.

(in our convention)

$$A = \langle f_{CP}| \underbrace{}_{(CP)^\dagger(CP)} H_{\text{eff}} \underbrace{}_{(CP)^\dagger(CP)} |B^0\rangle = \xi_f \langle f_{CP}|H_{\text{eff}}|\bar{B}^0\rangle = \xi_f \bar{A} \quad \rightarrow \quad \frac{\bar{A}}{A} = \xi_f$$

$$(CP|f_{CP}\rangle = \xi_f |f_{CP}\rangle\,, \quad CP|B^0\rangle = |\bar{B}^0\rangle)$$



$$\rightarrow \frac{q}{p} = -\frac{V_{td}V_{tb}^*}{V_{td}^*V_{tb}} = -e^{-2i\phi_1}$$

$$\boxed{\Im \frac{q\bar{A}}{pA} = \xi_f \sin 2\phi_1\,.}$$

(No CPV in decay)

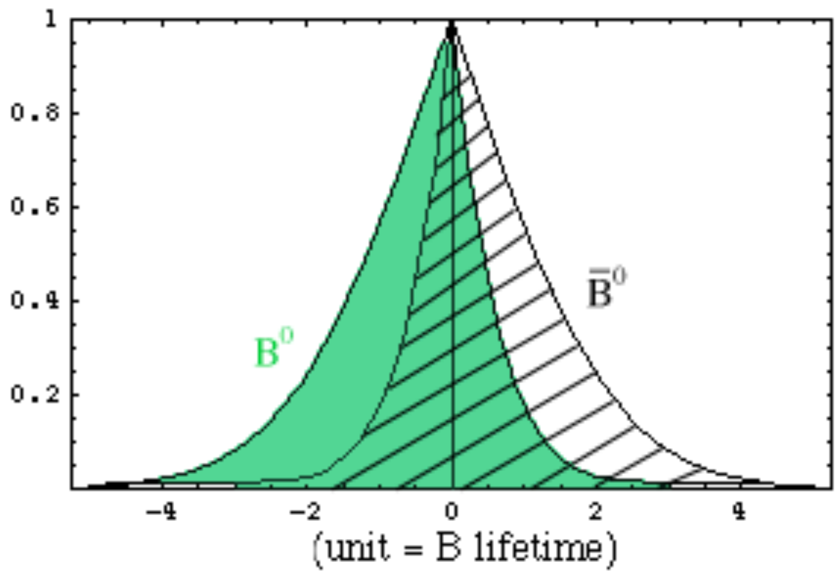
Quantum correlation in $\Upsilon 4S \to B^0\bar{B}^0$ (coherent L=1):

$$\Upsilon 4S \to (B^0\bar{B}^0 - \bar{B}^0 B^0)$$
$$\to e^{-\gamma t}(B^0\bar{B}^0 - \bar{B}^0 B^0)$$

If one finds one side to be $\bar{B}^0$ at t,
then the other side is pure B^0 at the same time t,
then it will evolve as usual.

$\to \Gamma_{B^0(\bar{B}^0)\to f}(t)$ **applies to $\Upsilon 4S$ with**

$t \;\to\; \Delta t \equiv t_{CP} - t_{tag}\,,$ **(and $e^{-\gamma t} \to e^{-\gamma|\Delta t|}$)**

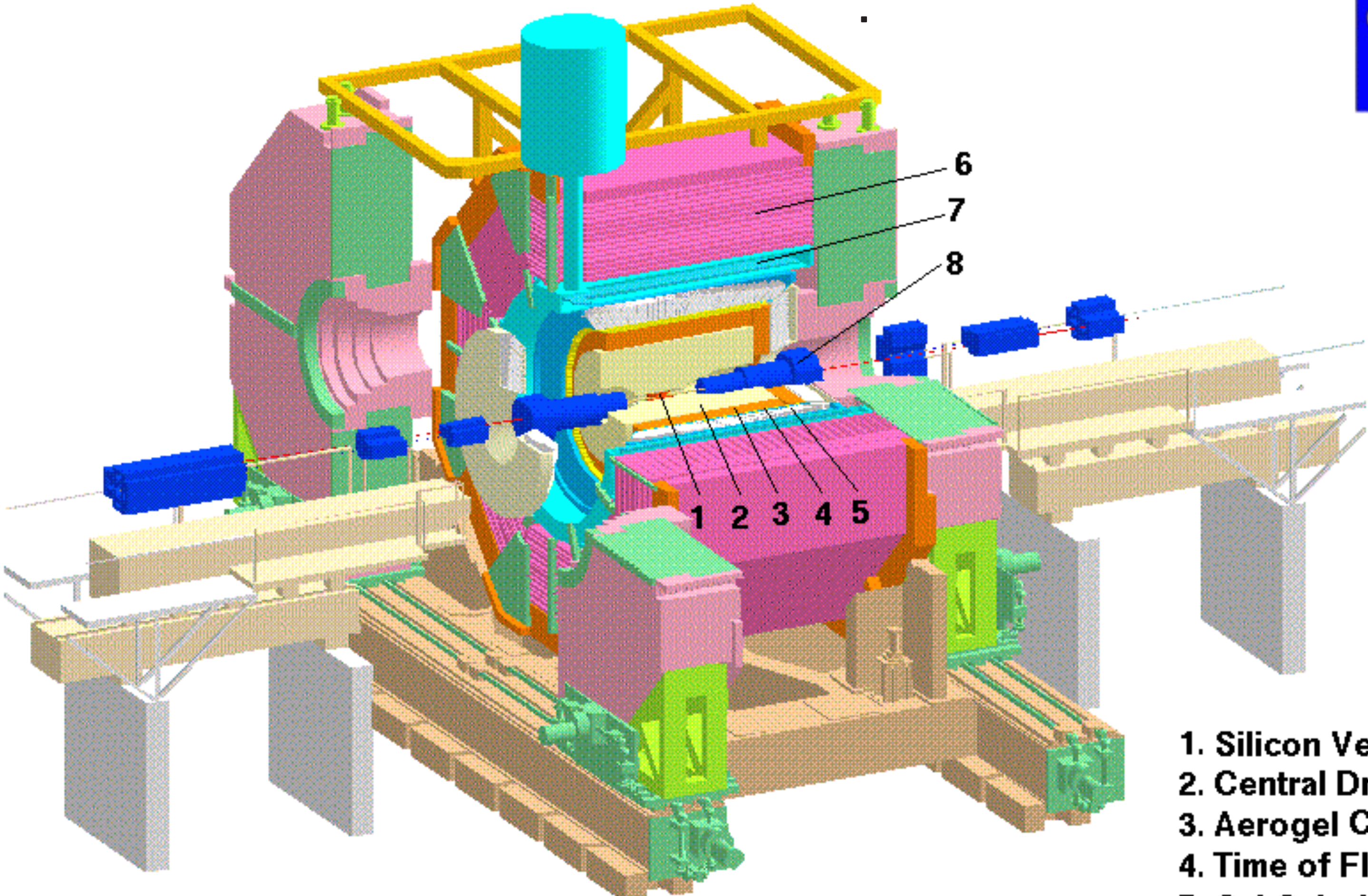


CP-side Reconstruction

CP mode	ξ_{CP}	N_{evt}	N_{bkg}
$\Psi K_S(\rightarrow \pi^+\pi^-)$	$-$	457	11.9
$\Psi K_S(\rightarrow \pi^0\pi^0)$	$-$	76	9.4
$\Psi'(\rightarrow \ell^+\ell^-)K_S$	$-$	39	1.2
$\Psi'(\rightarrow \Psi\pi^+\pi^-)K_S$	$-$	46	2.1
$\chi_{c1}K_S$	$-$	24	2.4
$\eta_c(\rightarrow K^+K^-\pi^0)K_S$	$-$	23	11.3
$\eta_c(\rightarrow K_SK^-\pi^+)K_S$	$-$	41	13.6
$\Psi K^{*0}(\rightarrow K_S\pi^0)$	$+/-$	41	6.7
ΨK_L	$+$	569	223

Detection modes
$\Psi \rightarrow \ell^+\ell^-$ $(\ell = e, \mu)$
$K_S \rightarrow \pi^+\pi^-$
$\Psi' \rightarrow \ell^+\ell^-, \Psi\pi^+\pi^-$
$\chi_{c1} \rightarrow \Psi\gamma$
$\eta_c \rightarrow K^+K^-\pi^0, K_SK^-\pi^+$

BELLE Detector



1. Silicon Vertex Detector
2. Central Drift Chamber
3. Aerogel Cherenkov Counter
4. Time of Flight Counter
5. CsI Calorimeter
6. KLM Detector
7. Superconducting Solenoid
8. Superconducting Final Focussing System

Particle identifications

electrons: EM shower in the EM calorimeter (ECL).

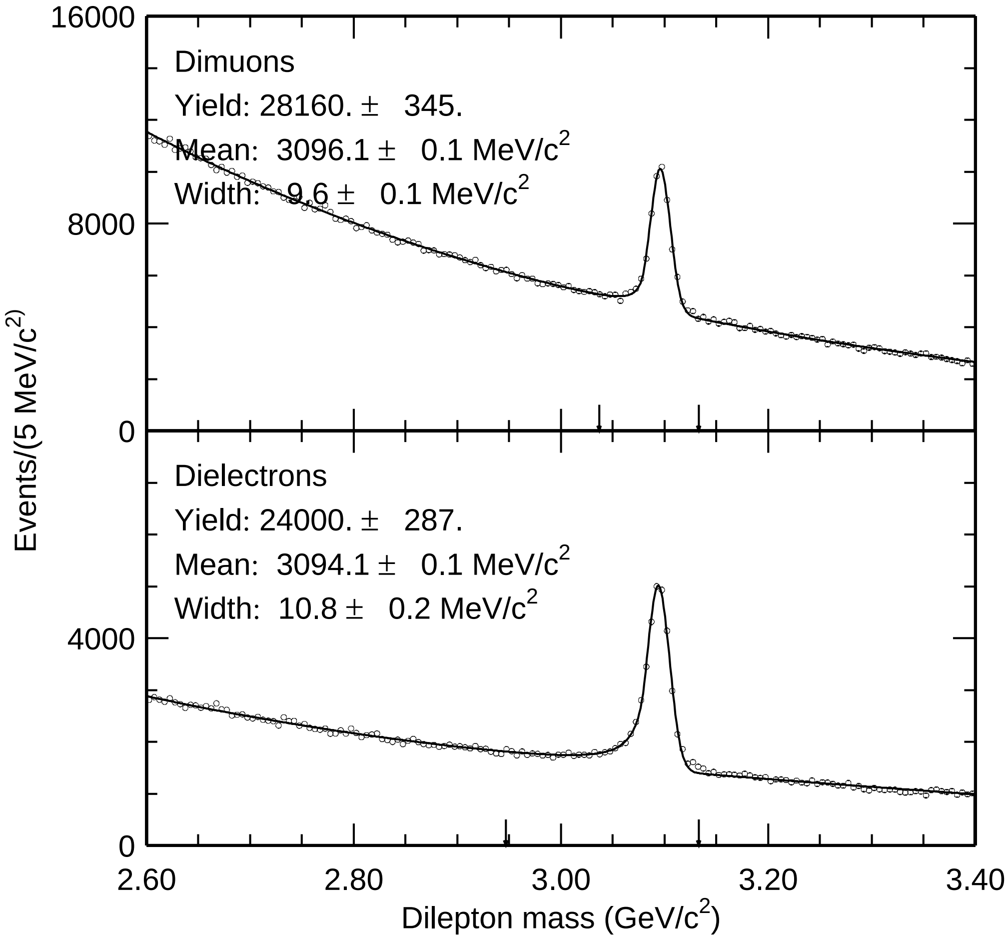
muons: Penetration to KLM.

π/K: Aerogel Cerenkov counters.
Time of flight counter.
Ionization in the drife chamber (dE/dx).

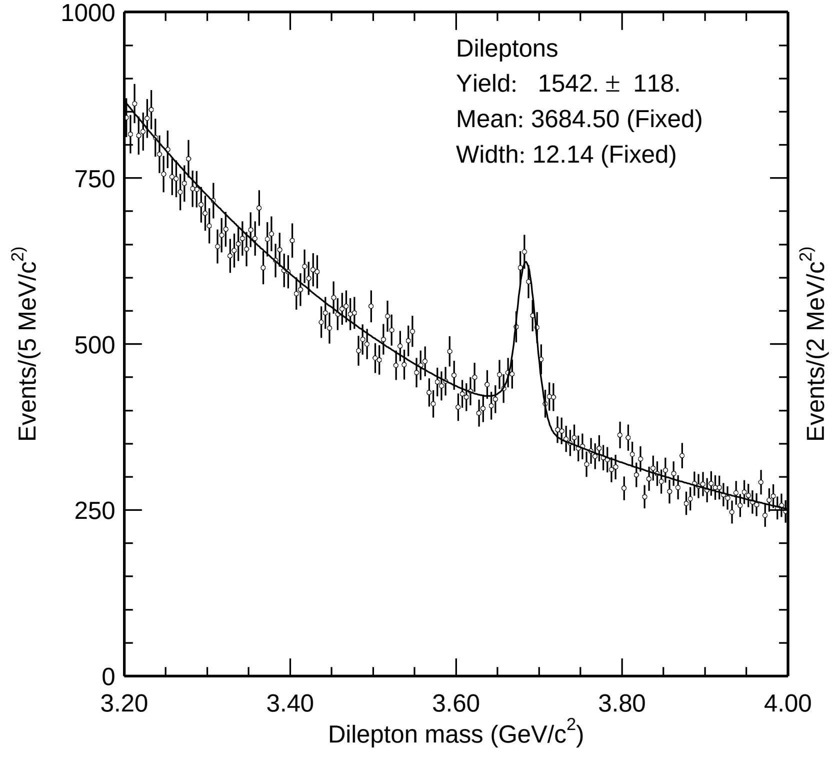
Dataset used for this analysis

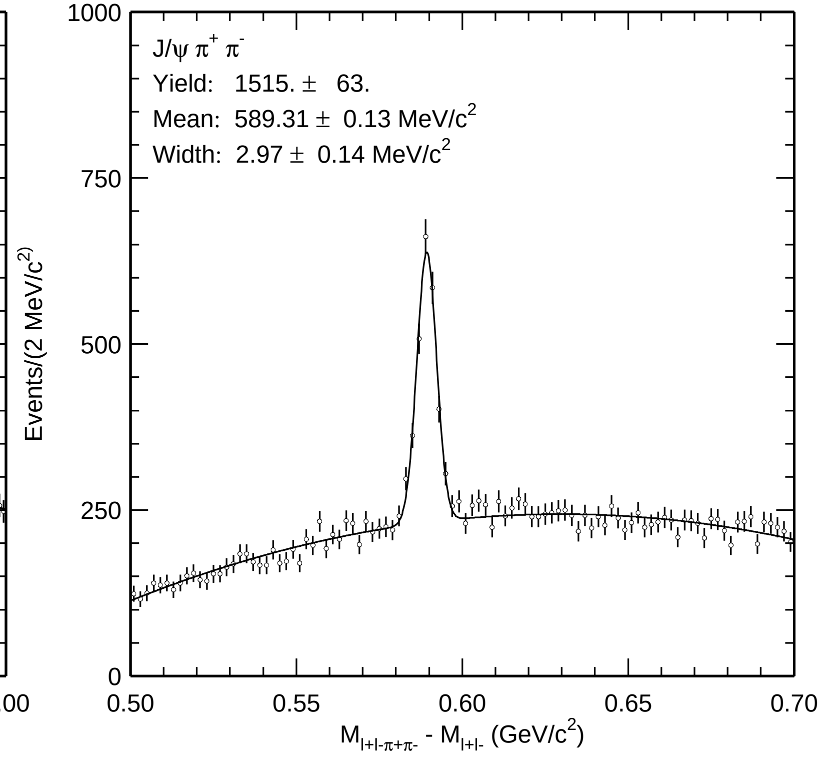
Integrated luminosity = 29.1 fb^{-1}.
31.3 million $B\bar{B}$ pairs created.

$\Psi \to \ell^+\ell^-$ reconstruction

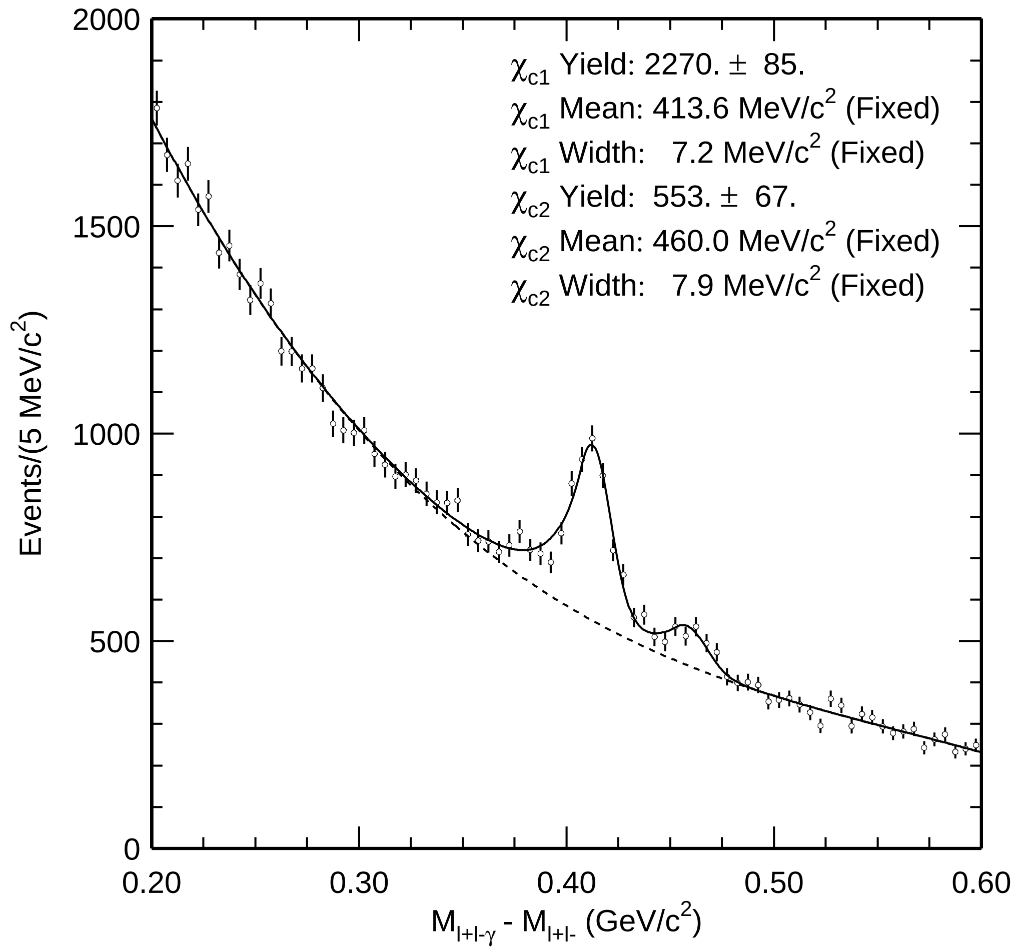


Ψ' reconstruction





$\chi_{c1} \to \Psi\gamma$ reconstruction



χ_{c1}: left peak, χ_{c2}: left peak (violation of factorization!)

Full B Reconstruction

$$B \longrightarrow f_1 \cdots f_n$$

Move to the $\Upsilon 4S$ c.m. and require that candidates satisfy

$$E_{\text{tot}} = E_B^* \equiv \frac{M_{\Upsilon(4S)}}{2}\,, \qquad |\vec{P}_{\text{tot}}| = |\vec{P}_B^*| = 0.33 GeV$$

where

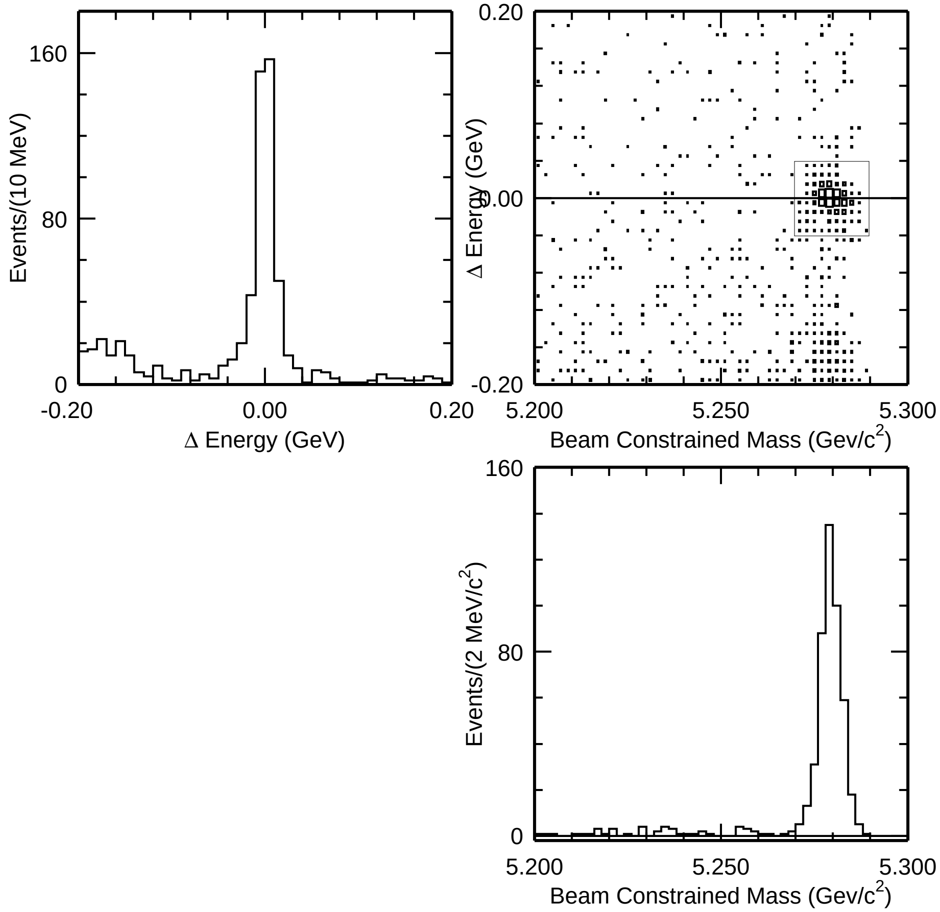
$$E_{\text{tot}} \equiv \sum_{i=1}^{n} E_i\,, \qquad \vec{P}_{\text{tot}} \equiv \sum_{i=1}^{n} \vec{P}_i$$

Instead of E_{tot} and $|\vec{P}_{\text{tot}}|$, we often use

$$\Delta E \equiv E_{\text{tot}} - E_B^* \quad \textbf{(energy difference)}$$

$$M_{\text{bc}} \equiv \sqrt{E_B^{*2} - \vec{P}_{\text{tot}}^2} \quad \textbf{(beam-constrained mass)}$$

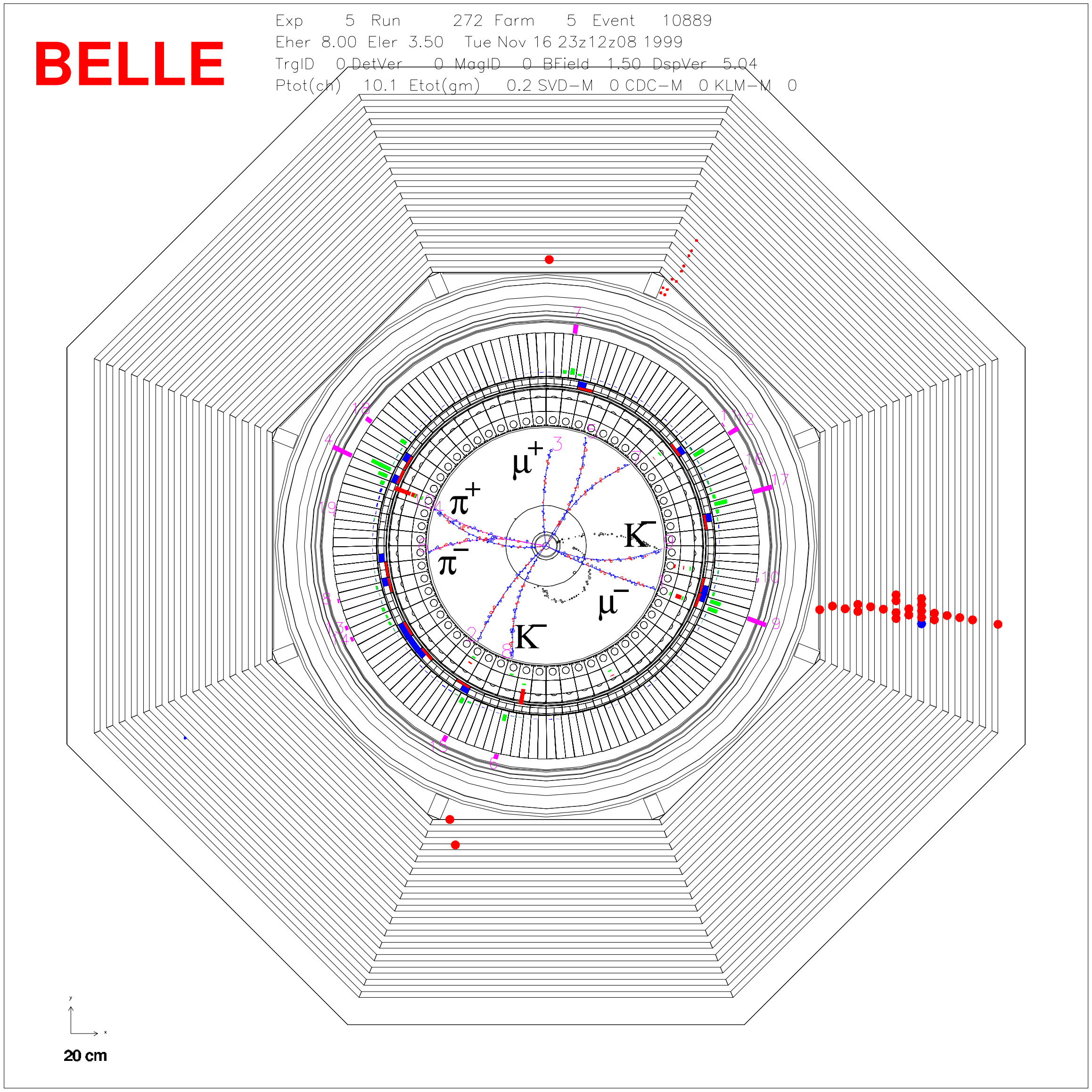
$\Psi K_S(\to \pi^+\pi^-)$



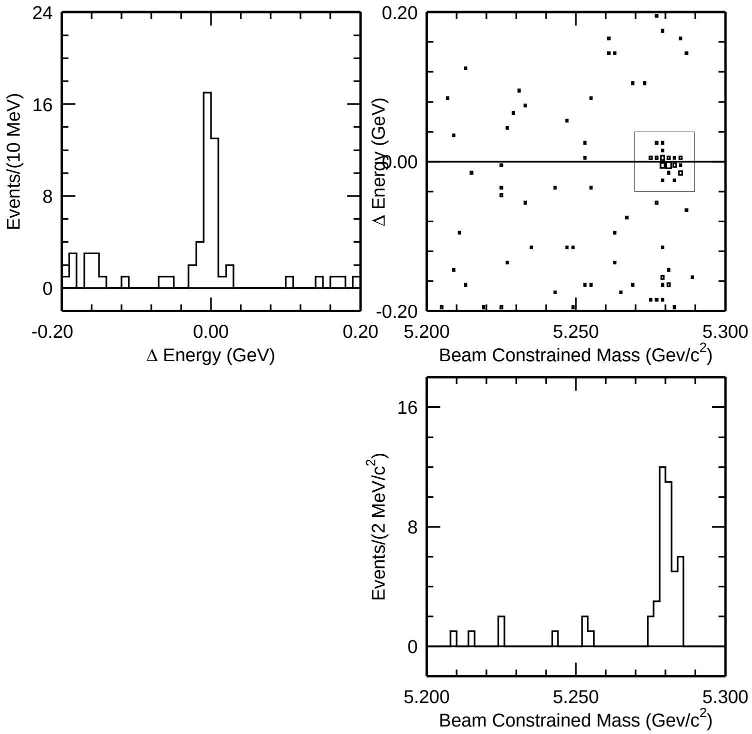
1. **Plot ΔE vs M_{bc}.**
2. **Cut on ΔE, project on M_{bc}.**
3. **Cut on M_{bc}, project on ΔE.**

4. **Estimate background from the sidebands.**

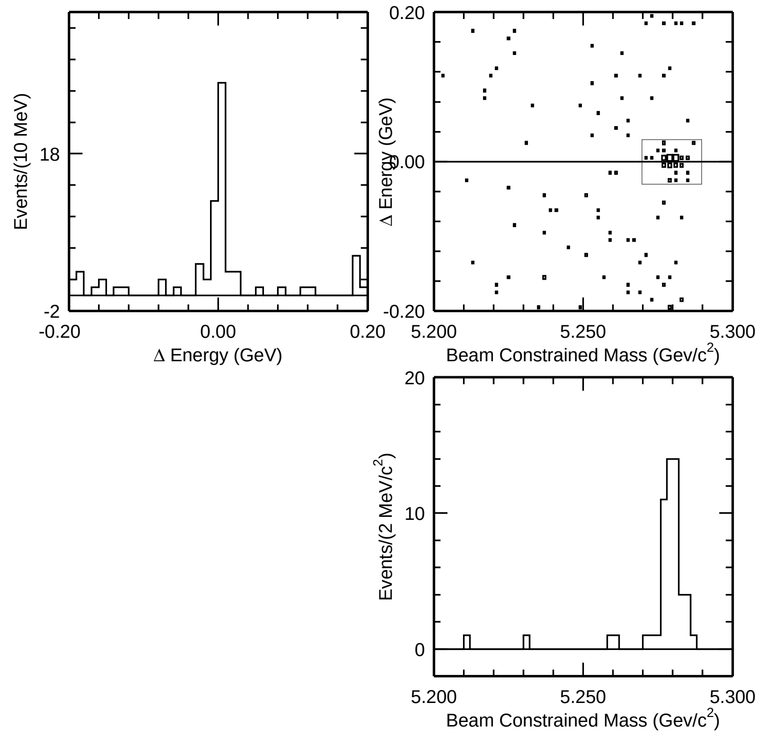
$$\Psi K_S(\rightarrow \pi^+\pi^-)$$



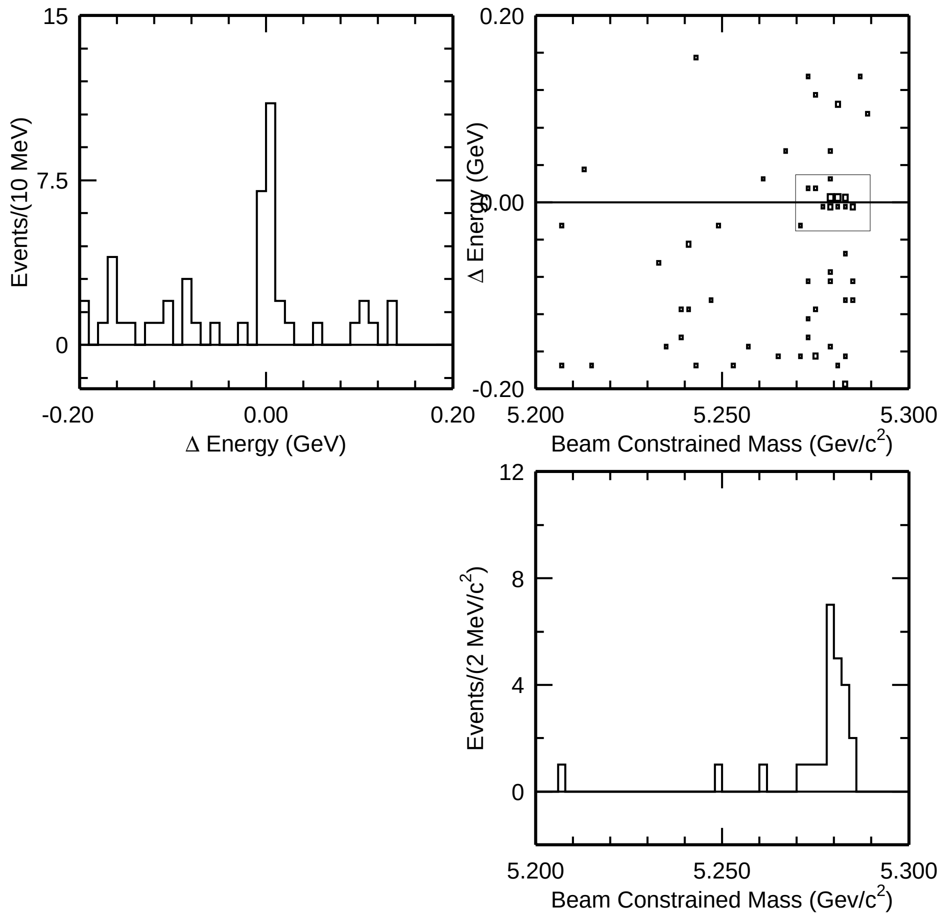
$\Psi'(\to \ell^+\ell^-)K_S$



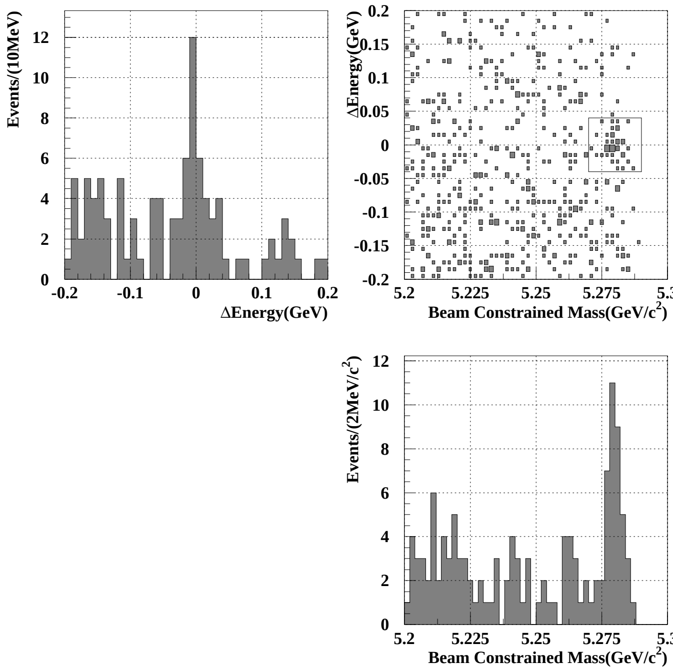
$\Psi'(\to \Psi\pi^+\pi^-)K_S$



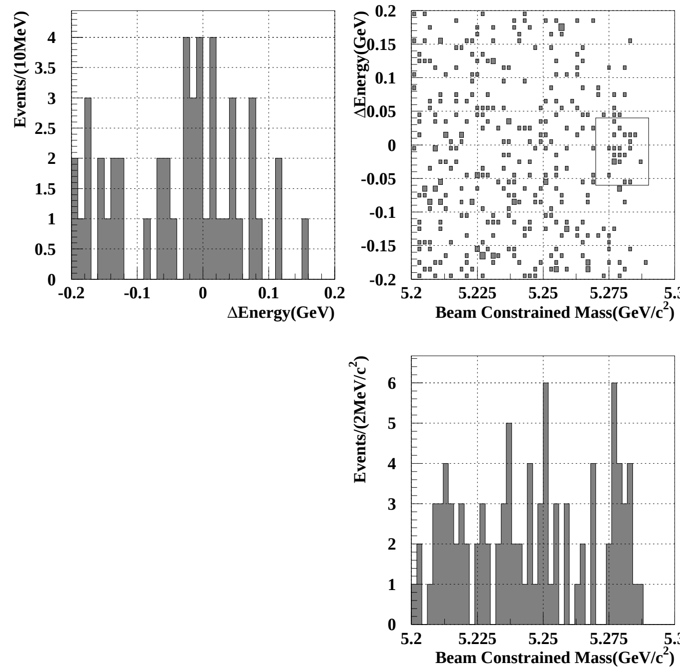
$\chi_{c1} K_S$


15
7.5
0
Events/(10 MeV)
-0.20
0.00
0.20
Δ Energy (GeV)
0.20
0.00
-0.20
Δ Energy (GeV)
5.200
5.250
5.300
Beam Constrained Mass (Gev/c2)
12
8
4
0
Events/(2 MeV/c2)
5.200
5.250
5.300
Beam Constrained Mass (Gev/c2)

$\eta_c(\rightarrow K_S K^+ \pi^-) K_S$



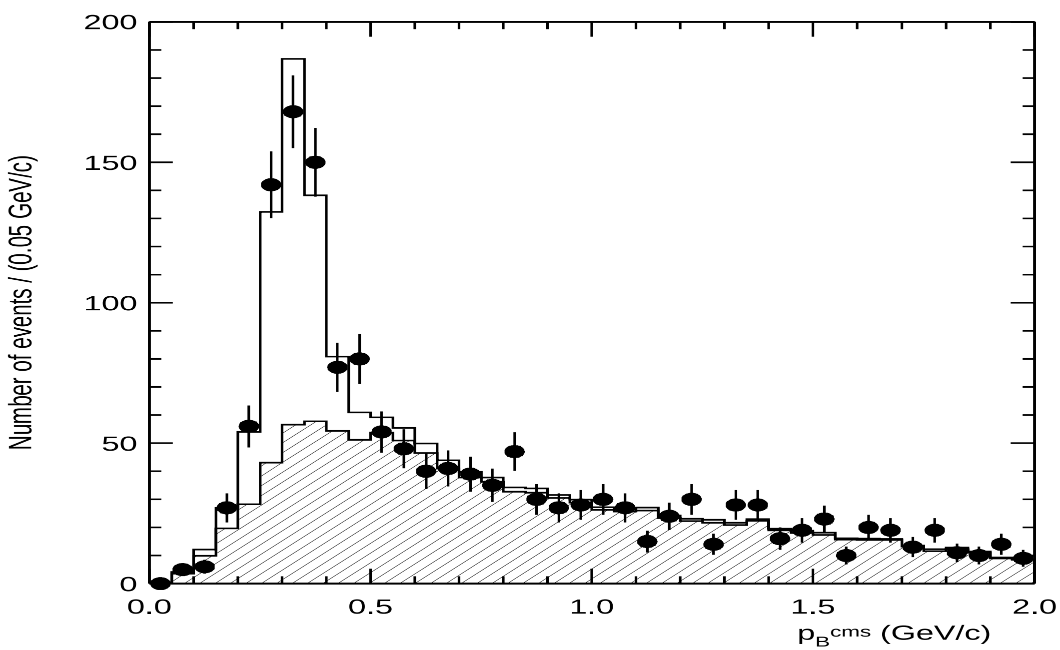
$\eta_c(\rightarrow K^+ K^- \pi^0) K_S$



ΨK_L

K_L: **Only the direction is measured by nuclear interaction in ECL (EM calorimeter) and/or KLM (KL-muon chamber).**

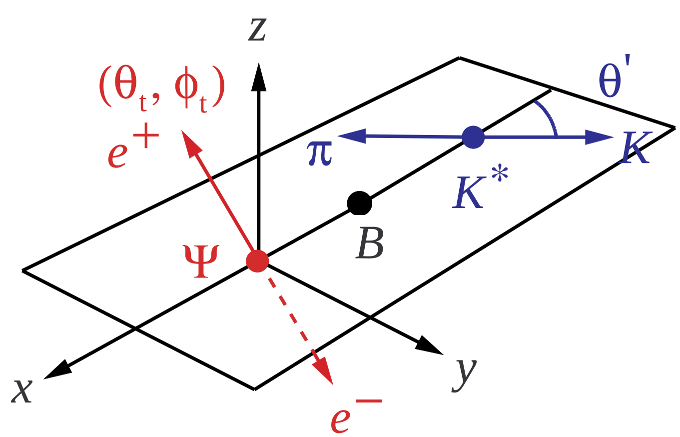
p_B^*: **Cannot obtain both ΔE and M_{bc}**
Assume B mass, extract p_B^* ($\equiv M_{bc}$).



$\Psi K^{*0}(\to K_S \pi^0)$

B **(spin-0)** $\to$ Ψ **(spin-1)** K^{*0} **(spin-1)**
3 polarization states: helicities $= (++, --, 00)$

Extract P (CP) contents by full angular analysis of the isospin-related modes.



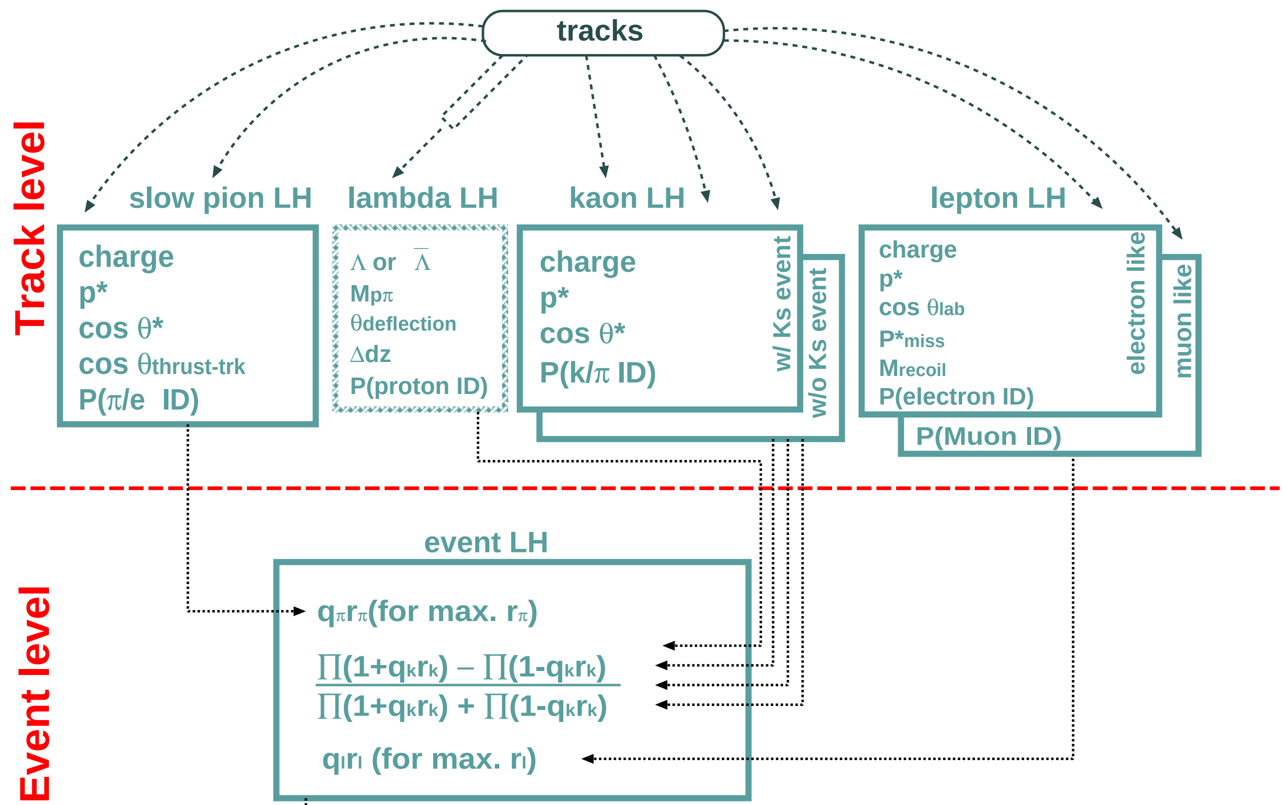
$$\frac{\xi_f = -1}{\text{all}} = 0.19 \pm 0.04(stat) \pm 0.04(sys)$$

Tagging of B Flavor

What distinguish B^0 and $\bar{B}^0$?

1. **Leptons (e, μ)**
   - $b \to \ell^-$: **high-P lepton.**
   - $b \to c \to \ell^+$: **low-P lepton.**
2. **Charged kaons.** $b \to c \to s(K^-)$
3. $\Lambda(\to p\pi^-)$. $b \to c \to s(\Lambda)$
4. **Charged pions.**
   - $\bar{B} \to D^{(*)}\pi^-$ **etc.: high-P pion.**
   - $b \to D^{*+} \to D^0\pi^+$: **low-P pion.**

Multi-dimentional likelihood tagging



$$q\cdot r \equiv \frac{N(B^0_{tag}) - N(\overline{B^0_{tag}})}{N(B^0_{tag}) + N(\overline{B^0_{tag}})}$$

N(B_{tag}): Number of observed *B* s at the cell for MC samples

Check r with data
(actually r is used only to devide the samples)

Control samples

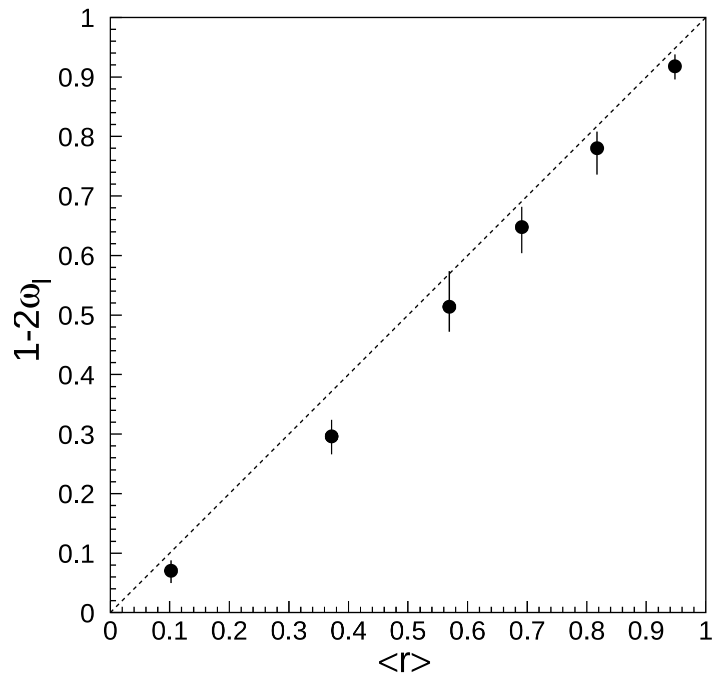
$D^{*-}\ell^+\nu$

$D^{(*)-}\pi^+$

$D^{*-}\rho^+$

$\Psi K^{*0}(\rightarrow K^+\pi^-)$

Use the measured r



$$\epsilon_{\rm eff} = 0.270 \pm 0.008(stat)^{+0.006}_{-0.009}(sys)$$

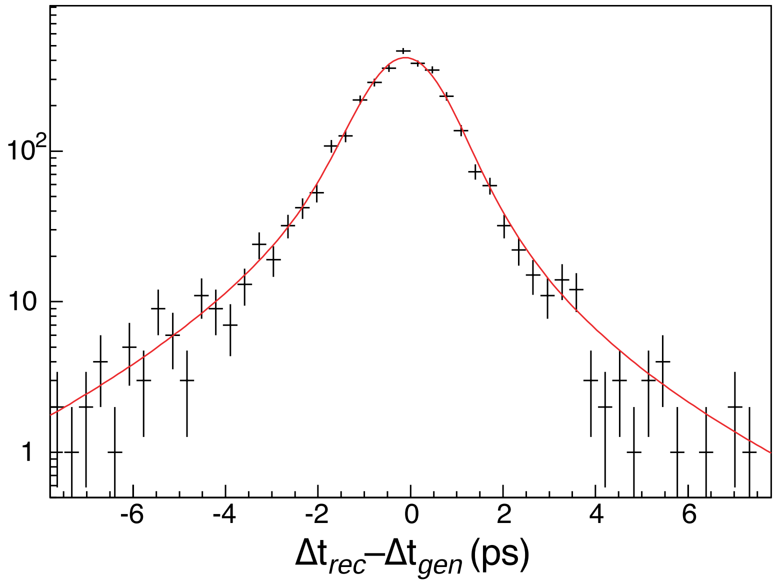
Measurement of Δz (Δt)

- Vertexing -

Use the two charged tracks of $\Psi \rightarrow \ell^+\ell^-$, or $\eta_c \rightarrow KK\pi$.
K_S not used: decay mosly outside of the silicon device.

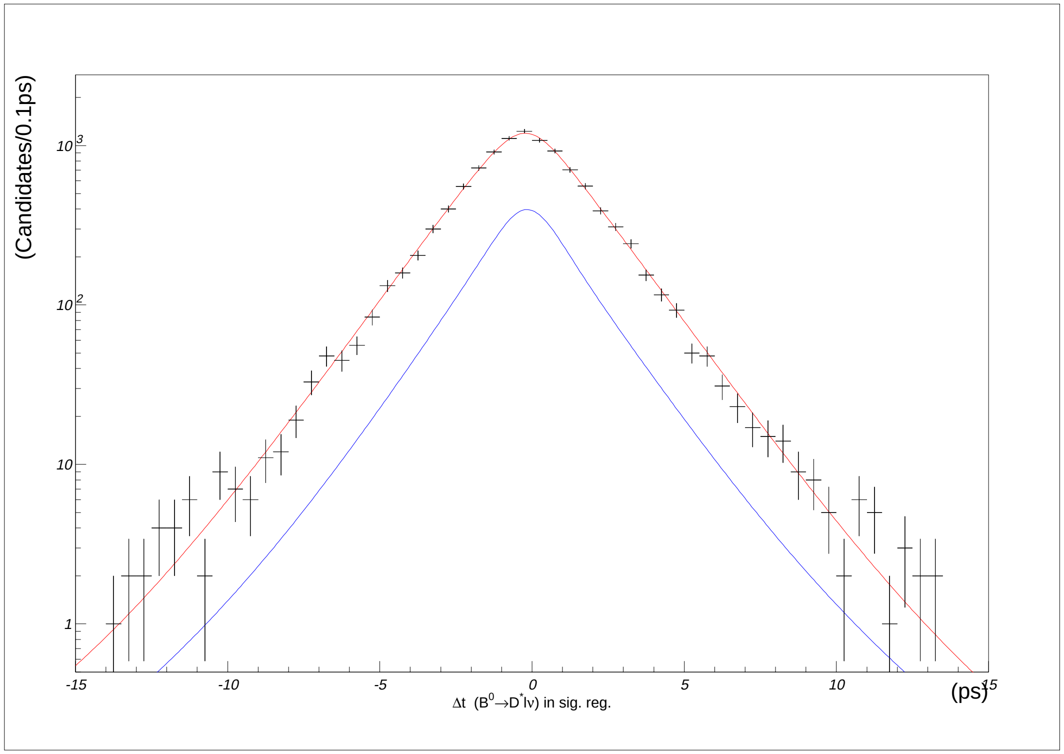
MC	CP side	tag side
ϵ_{vtx}	0.92	0.91
σ_z	75 μm	140 μm

Use 1137 events for fit.



Verify vertexing by measueing B^0 lifetime

$$B^0 \to D^{*-} \ell^+ \nu$$



$\tau_{B^0} = 1.55 \pm 0.02$ **ps (world average:** 1.55 ± 0.03 **ps)**

Event-by-event likelihood fit

Fit the Δt distribution with

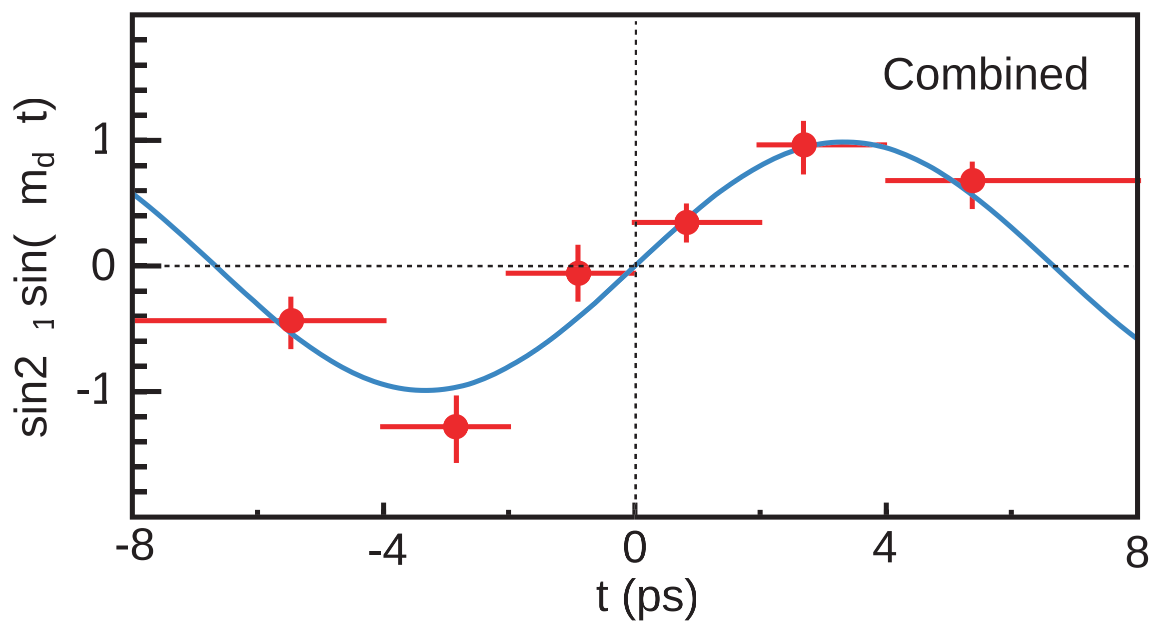
$$P_i(\Delta t) = \int \Big[f_{sig}\mathcal{P}_{sig}(\Delta t', q, r_i, \xi_f) R_{sig}(\Delta t - \Delta t') + (1 - f_{sig})\mathcal{P}_{bkg}(\Delta t') R_{bkg}(\Delta t - \Delta t') \Big] d\Delta t'$$

f_{sig} :	**(signal fraction)**
$\mathcal{P}_{sig} = e^{-\gamma\|\Delta t\|}(1 - \xi_f q r_i \sin 2\phi_1 \sin \delta m \Delta t)$	**(signal before smearing)**
R_{sig} : **2 gaussians**	**(signal resolution)**
$\mathcal{P}_{bkg} = e^{-\frac{\Delta t}{\tau_{bkg}}}$ and $\delta(\Delta t)$	**(bkg before smearing)**
R_{bkg} : **2 gaussians**	**(bkg resolution)**

Use the world averages for γ (B^0 decay rate) and δm
$\rightarrow$ only free parameter is $\sin 2\phi_1$.

Plot time-dependent asymmetry

Fit $\sin 2\phi_1$ **in each** Δt **bin**

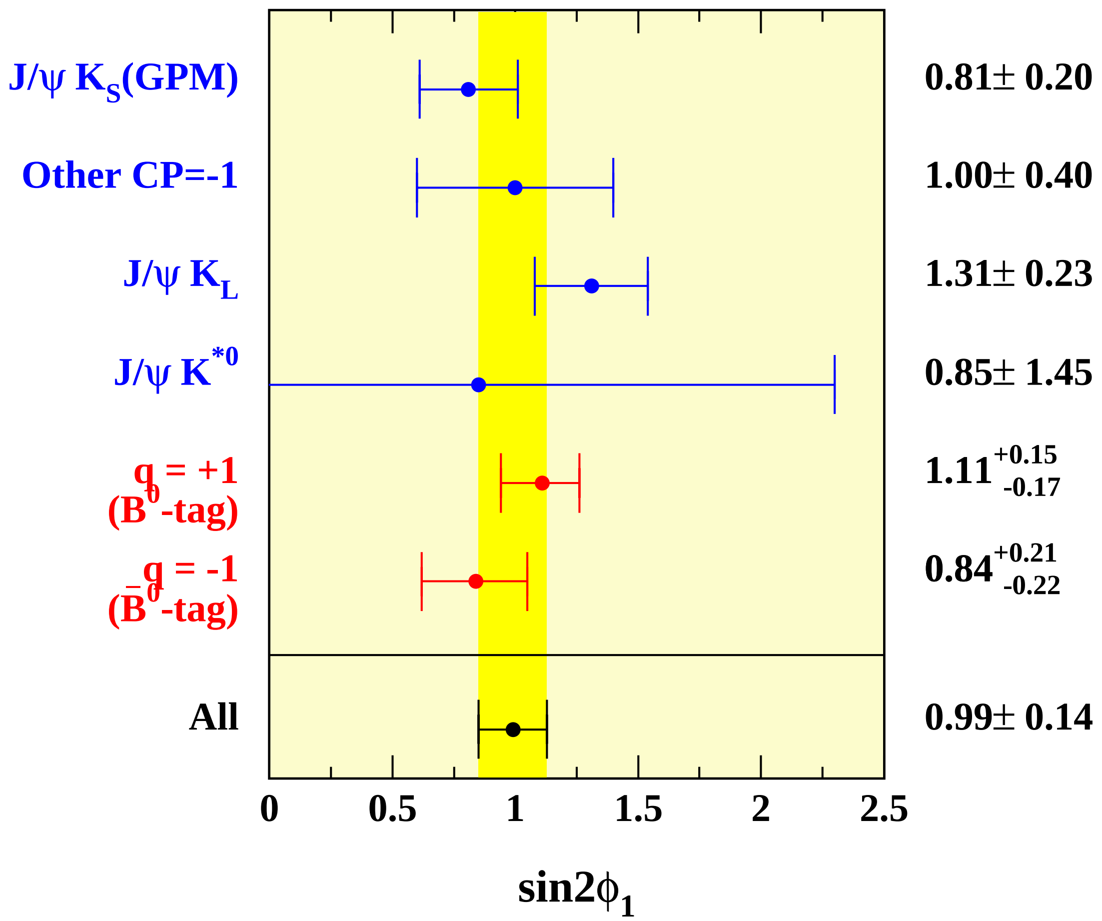


$$\sin 2\phi_1 = 0.99 \pm 0.14(stat) \pm 0.06(sys)$$

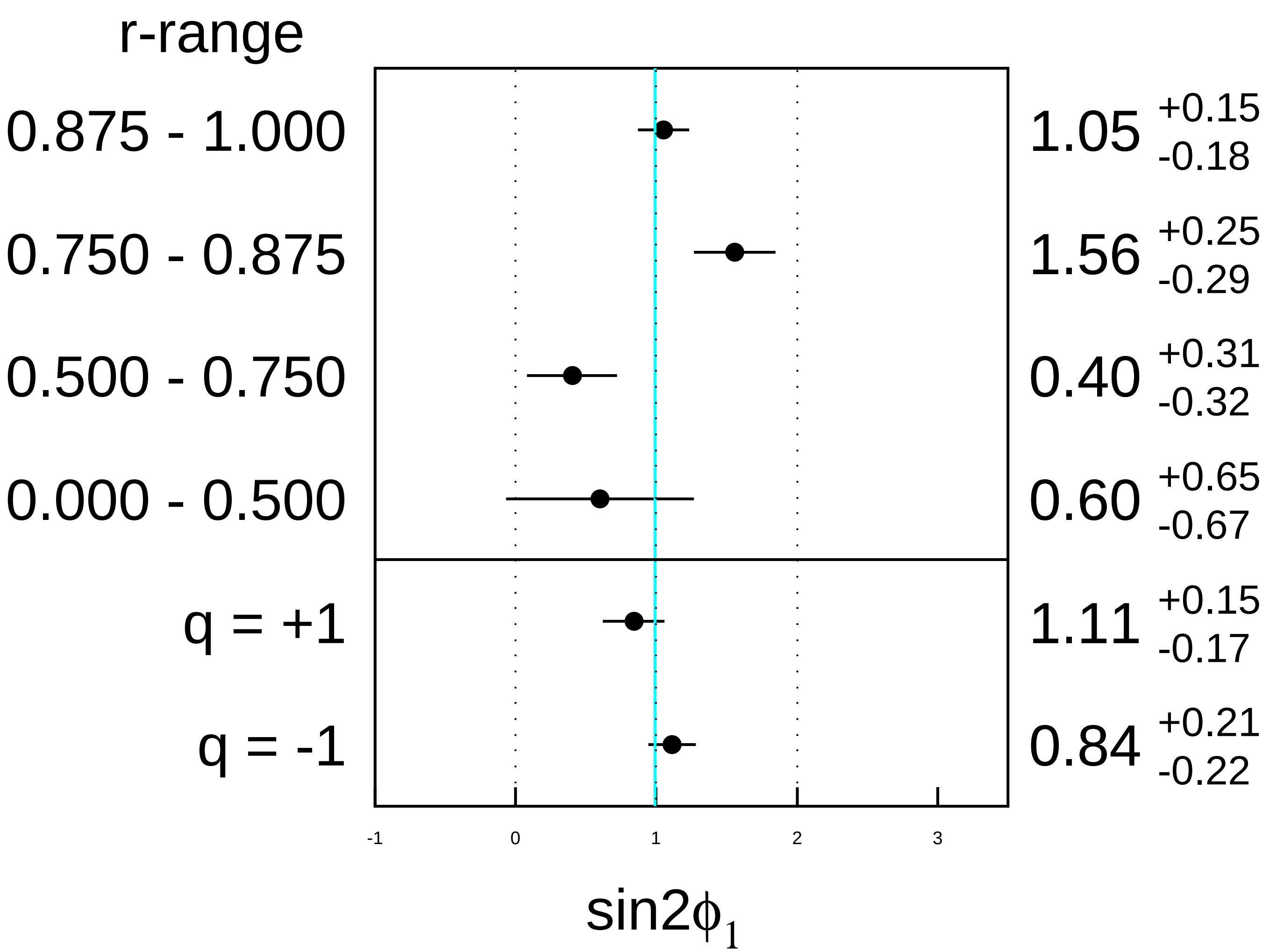
Systematic errors on $\sin 2\phi_1$

vertexing	0.04
tagging	0.03
Δt resolution	0.02
background shapes	0.01
Errors on δm τ_{B^0}	0.01
total	0.06

Mode dependence of $\sin 2\phi_1$

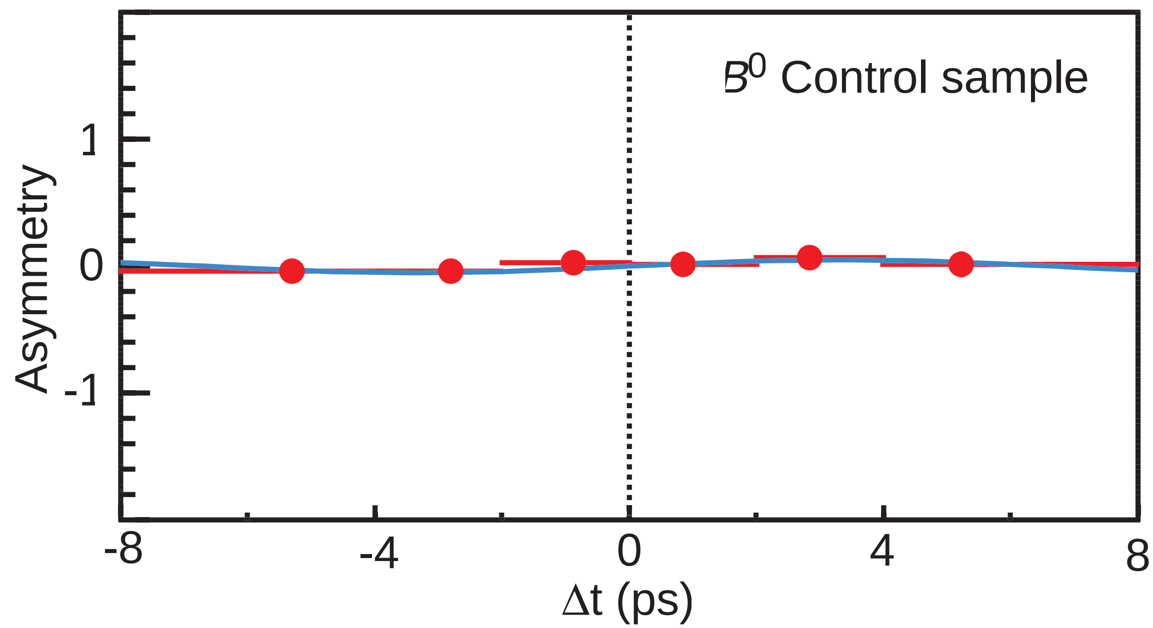


Dependence of $\sin 2\phi_1$ on r



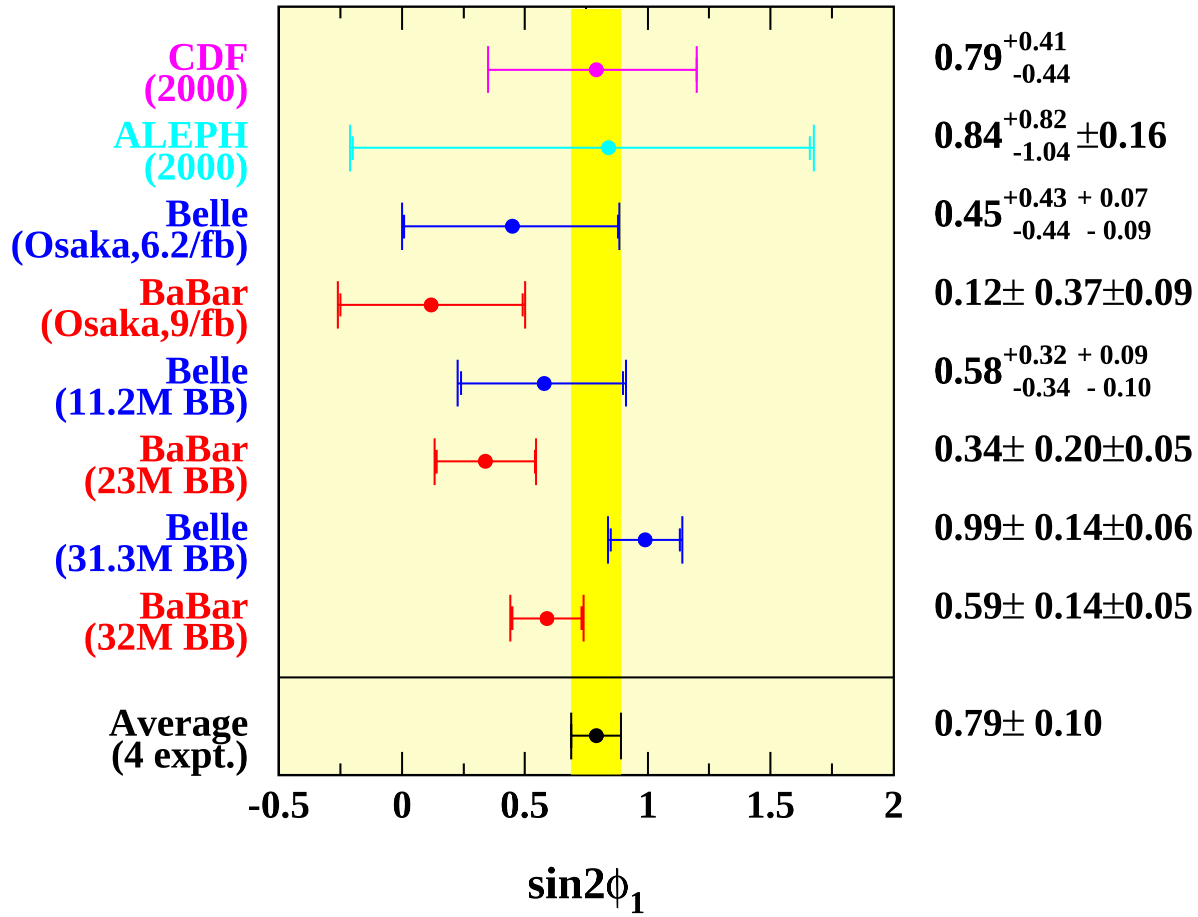
B^0 control modes

No assymetry expected for flavor-specific modes:
$D^{(*)-}\pi^+$, $D^{*-}\rho^+$, $D^{*-}\ell^+\nu$, $\Psi K^{*0}(\to K^+\pi^-)$



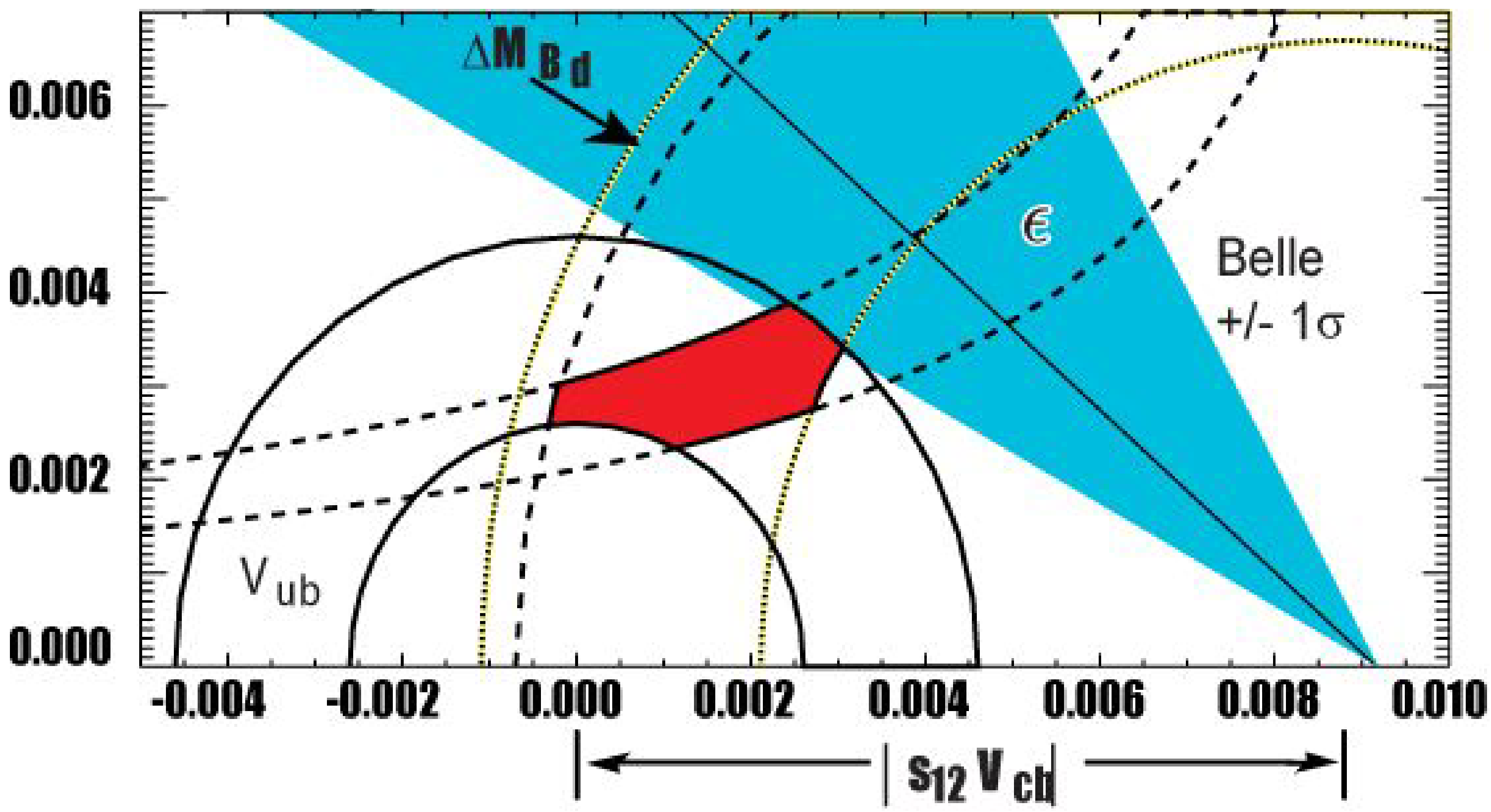
'sin $2\phi_1$' $= 0.05 \pm 0.04$

Comparison with other experiments



BaBar and Belle accouced this summer within 2 weeks of each other.

In terms of the unitarity triangle



Summary

1. We have clearly observed CP violation in B decay. The significance is more than 6 σ.

2. The dependence on Δt, CP eigenvalue, and flavor are as expected.

3. The value of $\sin 2\phi_1$ is consistent with the standard model with Koboyashi-Masukawa mechanism. (a bit largar than?)

4. Further inprovements in statistical/systematic errors are expected soon.

* Upgrade 2002:

- Smaller beampipe: $r = 2cm \rightarrow 1.5cm$.
  25% improvement in vertex resolution.
- New IR design for better background protection.
- New vertex detector:
  more layers (3$\rightarrow$4), more coverage.
- New inner CDC (2-layer small-cell chamber)