



Measurement of $\sin 2\phi_1$

Stephen L. Olsen
U. of Hawaii

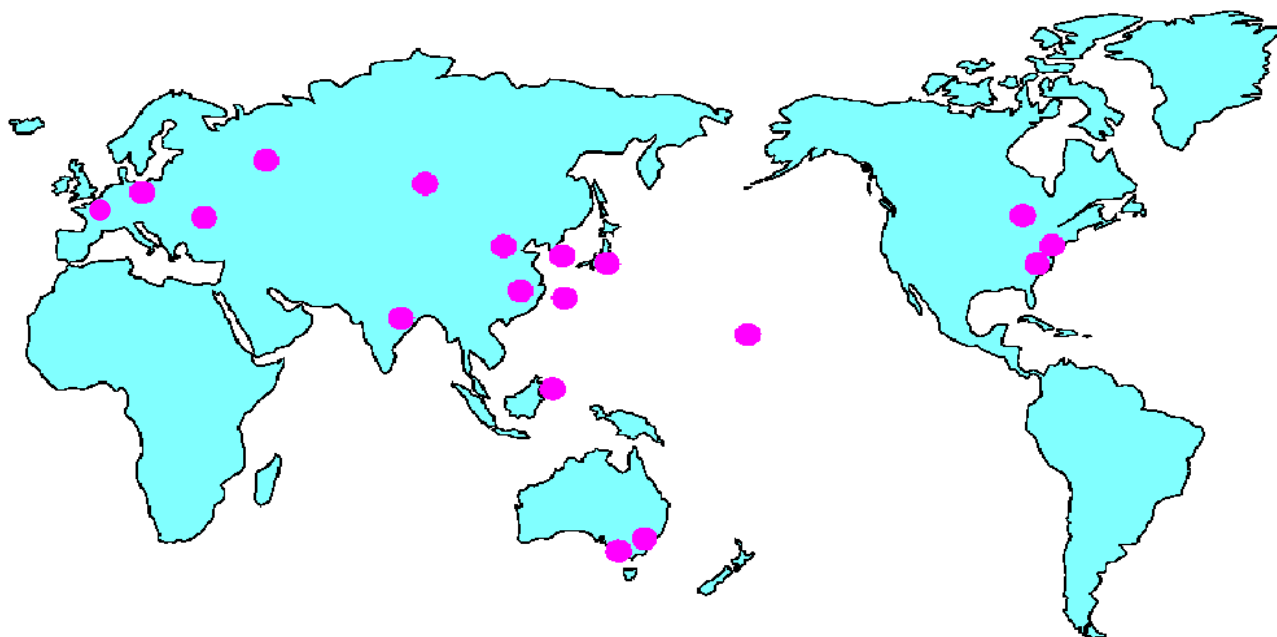


LP01
Rome

Representing the Belle Collaboration



The *Belle* Collaboration



A World-Wide Activity Involving 50 Institutions

July 23-28, 2001

LP01, Rome

The Belle Collaboration



The Belle Collaboration

Observation of $B \rightarrow J/\psi K_1(1270)$

The Belle Collaboration

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Outline

- Introduction
- **KEKB/Belle** performance
- Measurement of $\sin 2\phi_1$
- Results & conclusions



CPV à la Kobayashi-Maskawa

CPV due to complex phases in the Quark generation mixing matrix:

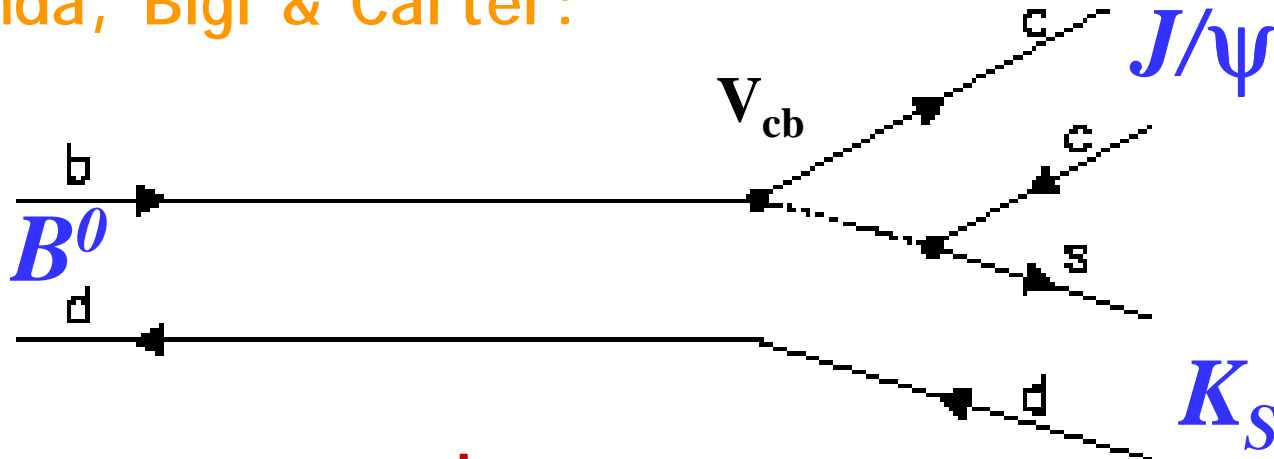
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Usually put in the V_{td} and V_{ub} corners



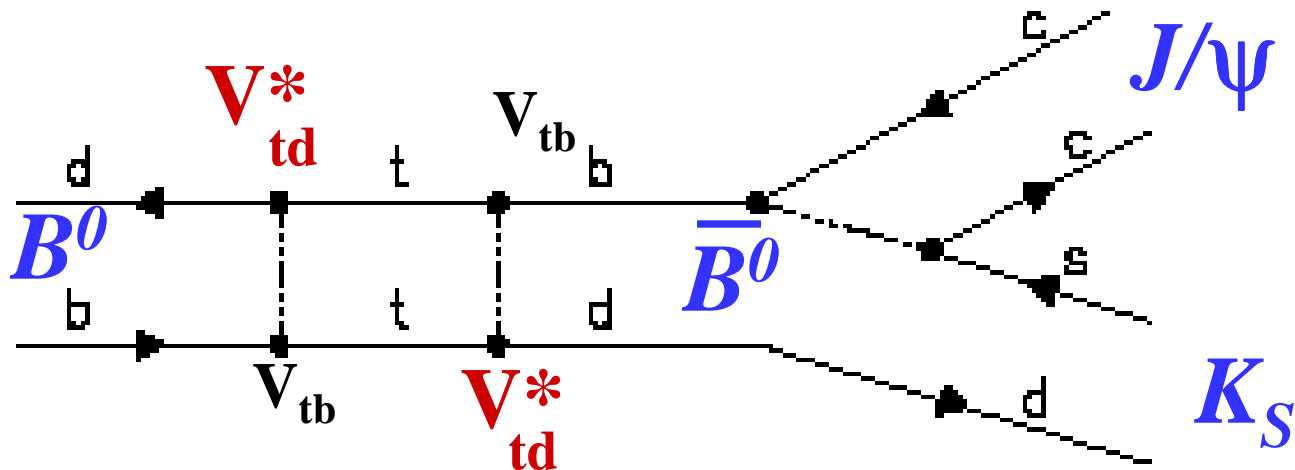
$\sin 2\phi_1$ from $B \rightarrow f_{CP} + B \leftrightarrow \bar{B} \rightarrow f_{CP}$ interf.

Sanda, Bigi & Carter:



+

$$\propto V_{td}^{*2}$$



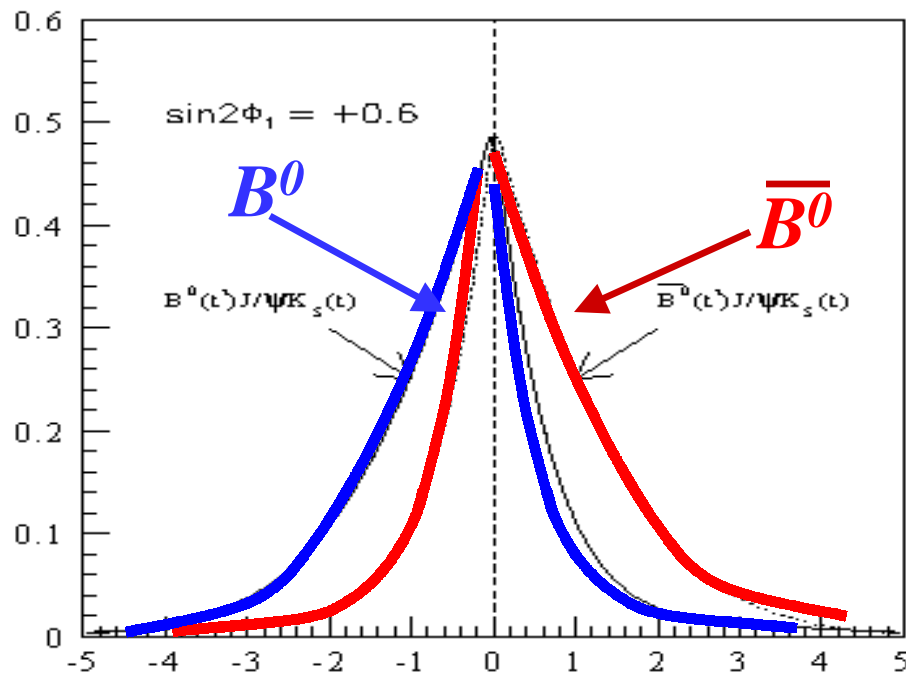


Mixing-induced CPV asymmetry

$$A(t) \equiv \frac{\Gamma(\overline{B}_d^0 \rightarrow f_{CP}) - \Gamma(B_d^0 \rightarrow f_{CP})}{\Gamma(\overline{B}_d^0 \rightarrow f_{CP}) + \Gamma(B_d^0 \rightarrow f_{CP})} = -\xi_f \sin 2\phi_1 \sin \Delta mt$$

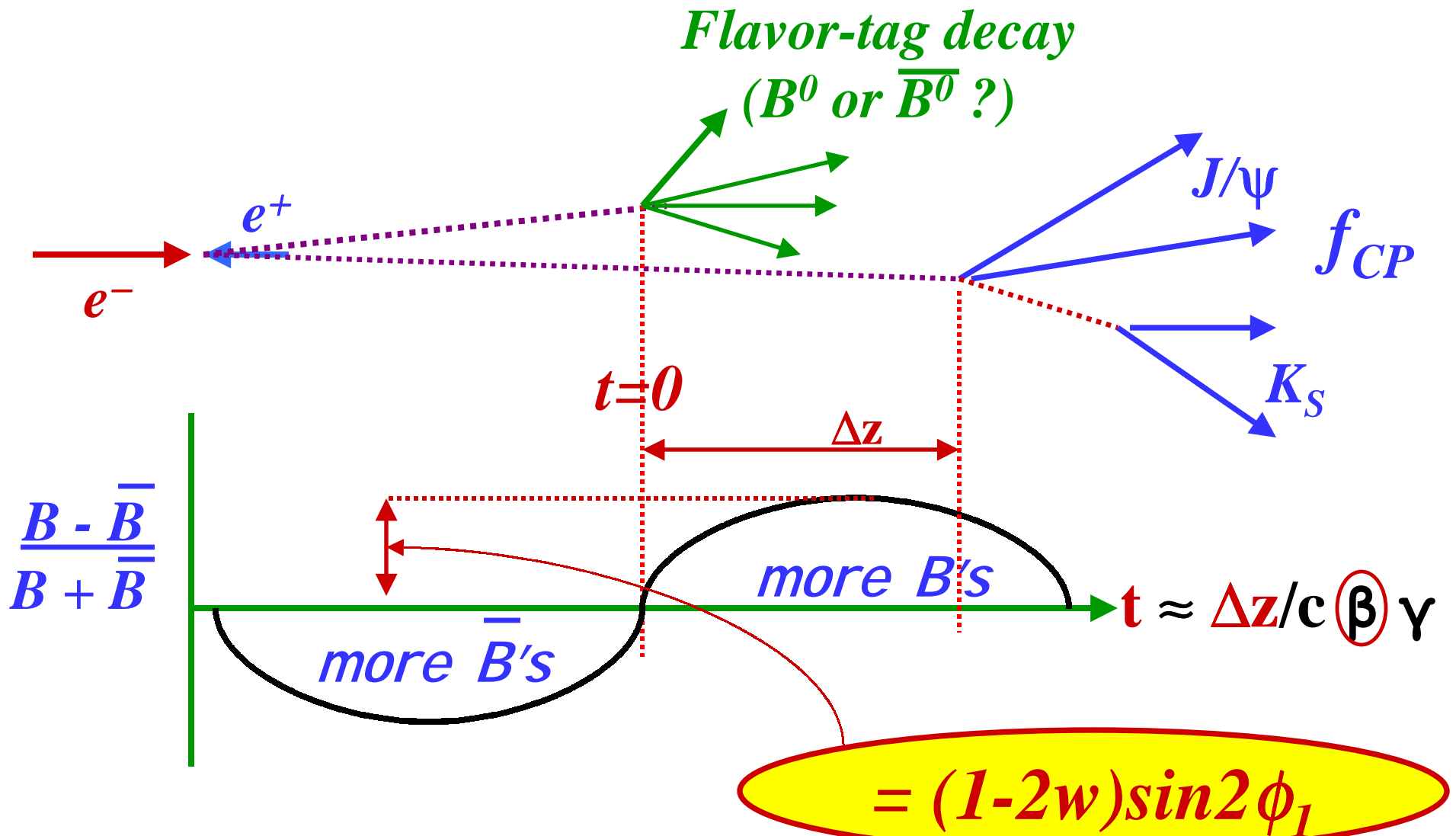
$\xi_f = \pm 1$ for $CP = \pm 1$

PDG notation!





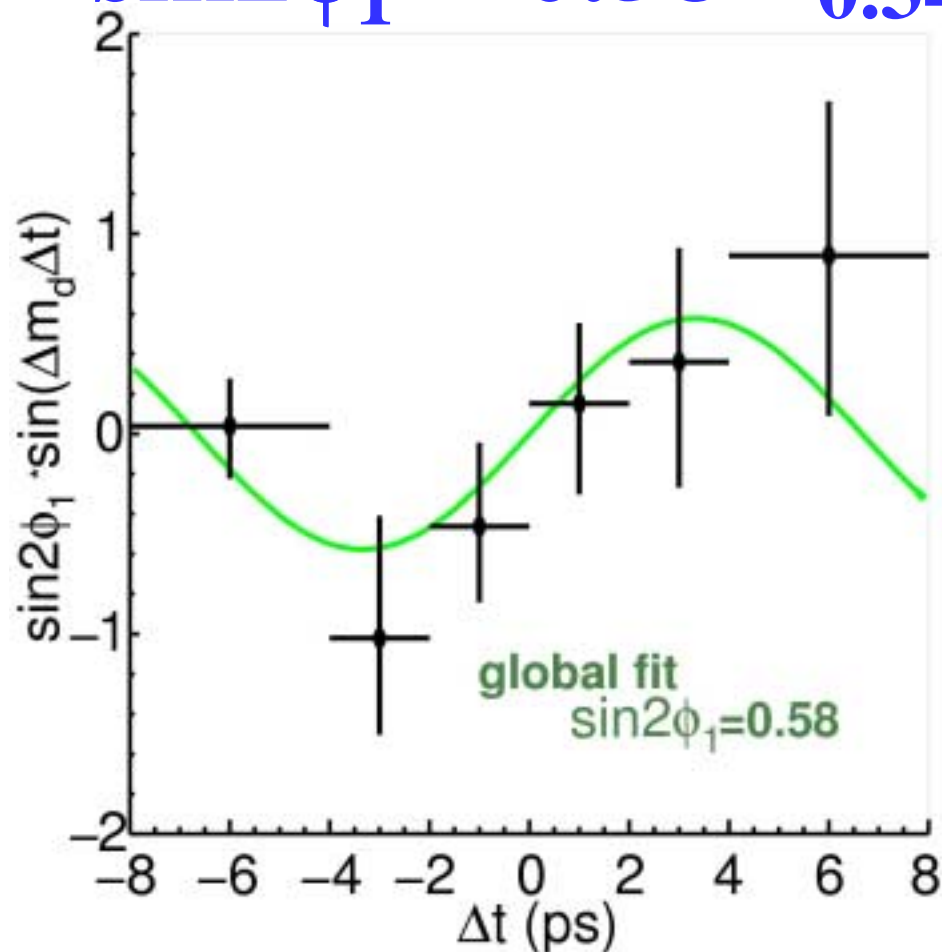
What do we measure?





Previous result (using 10.5 fb⁻¹)

$$\sin 2\phi_1 = 0.58 \quad \begin{matrix} +0.32 & +0.09 \\ -0.34 & -0.10 \end{matrix}$$



**Today:
Results from
29.1 fb⁻¹
4x more events**

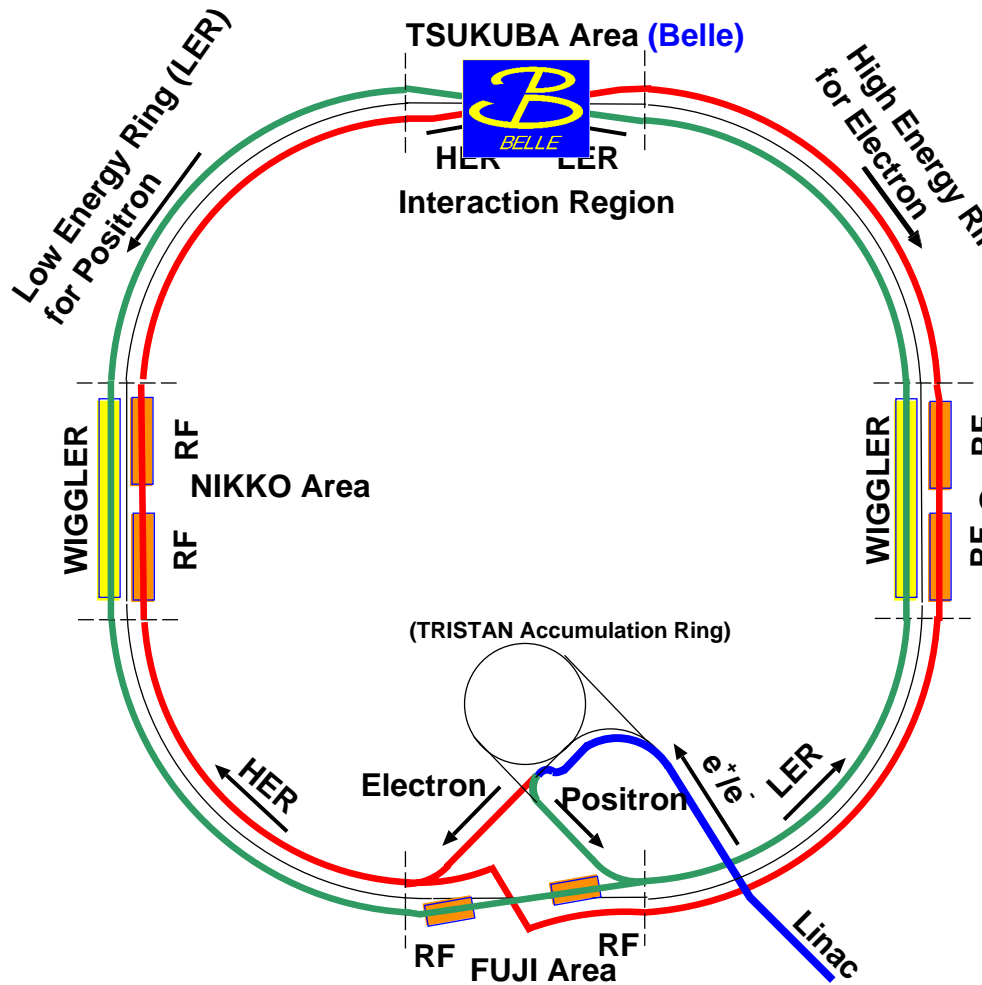


What's needed?

- **Lots of B mesons** ($Br(B \rightarrow f_{CP}) \sim 10^{-3}$)
 - very high Luminosity \Rightarrow **KEKB**
- **Find CP eigenstate decays**
 - high quality $\sim 4\pi$ detector \Rightarrow **Belle**
- **Tag other B's flavor**
 - good particle id
- **Measure decay-time difference**
 - Asymmetric energies
 - good vertexing (**@KEKB: $\gamma(\beta) c\tau \approx 200\mu\text{m}$**)



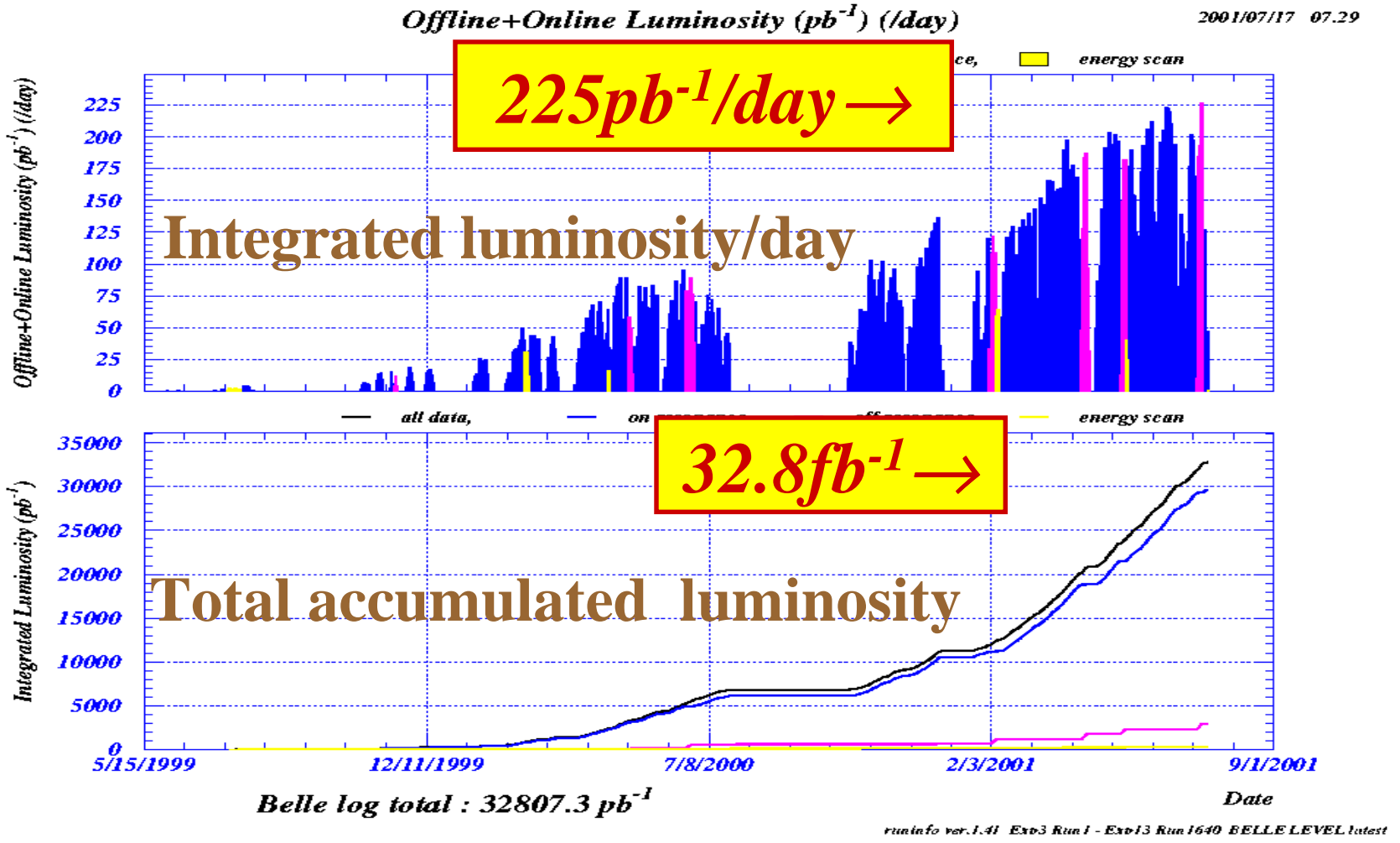
KEKB asymmetric e^+e^- collider



- Two separate rings
 - e^+ (LER) : 3.5 GeV
 - e^- (HER) : 8.0 GeV
- E_{CM} : 10.58 GeV at Y(4S)
- Luminosity
 - target: $10^{34} \text{ cm}^{-2}\text{s}^{-1}$
 - achieved: $4 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$
- ± 11 mrad crossing angle
- Small beam sizes:
 - $\sigma_y \approx 3 \mu\text{m}$; $\sigma_x \approx 100 \mu\text{m}$

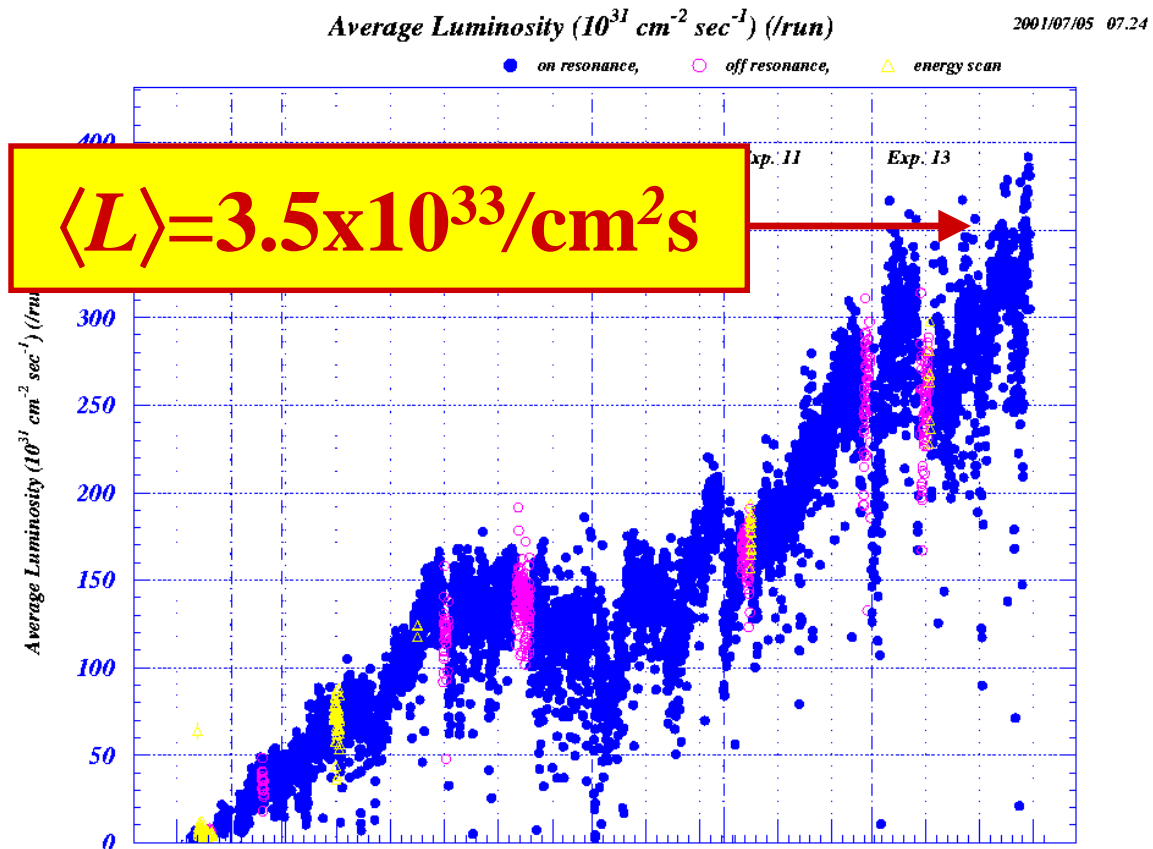


KEKB performance





Average luminosity during run

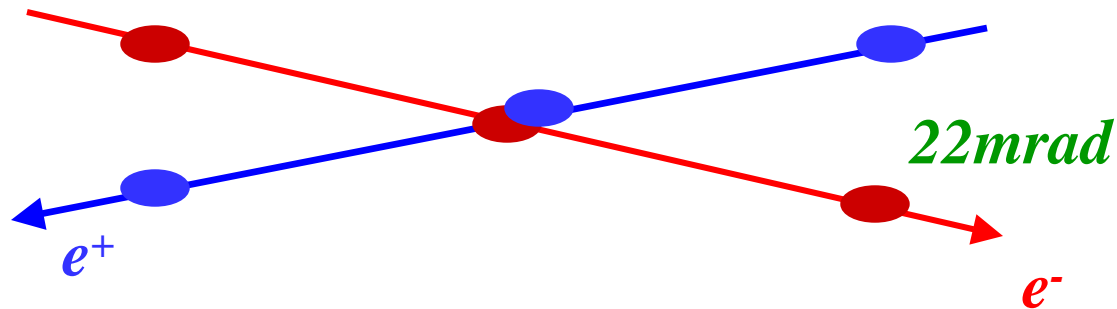


All-time $L_{peak} = 4.5 \times 10^{33} / \text{cm}^2 \text{ s}$



KEKB's Special Features

- Small beam sizes \Rightarrow **low beam currents**
 - 4.5×10^{33} with less than 1 Amp in each ring
- ± 11 mrad beam crossing angle

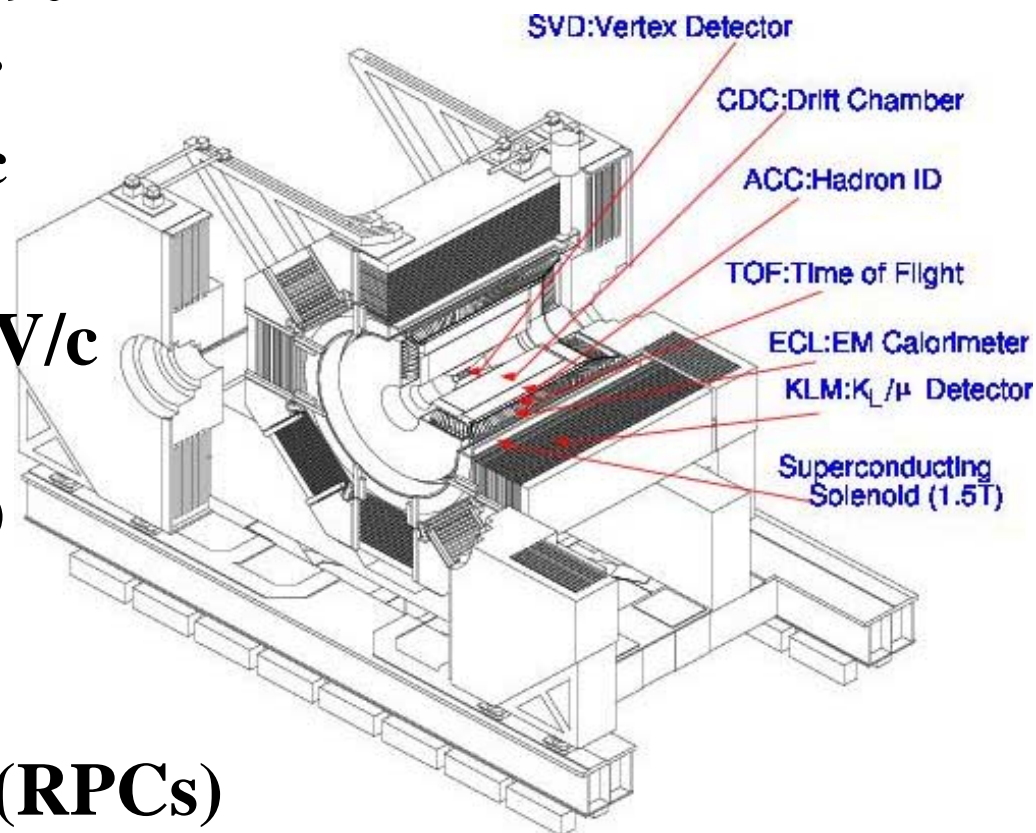


- **No bending magnets near the IR**
- **Fewer spent particles into *Belle***
- **Synchrotron X-rays easily expelled**



Detector Performance

- ◆ **Silicon Vertex Detector**
 - ◆ $\sigma \sim 55\mu\text{m}$ for $1\text{GeV}/c$ @ 90°
- ◆ **Central Drift Chamber**
 - ◆ $\sigma_p/p \sim 0.35\%$ @ $1\text{GeV}/c$
 - ◆ $\sigma_\pi(dE/dx) \sim 7\%$
- ◆ **K^\pm id up to $p_{\text{lab}}=3.5\text{ GeV}/c$**
 - ◆ TOF ($\sigma \sim 95\text{ ps}$)
 - ◆ Aerogel ($n = 1.01 \sim 1.03$)
- ◆ **γ, e^\pm with CsI crystals**
 - ◆ $\sigma_E/E_\gamma \sim 1.8\%$ @ 1GeV
- ◆ **KL and μ^\pm with KLM (RPCs)**
 - ◆ μ^\pm : effic. $> 90\%$; $\sim 2\%$ fakes





KEKB/*Belle* summary

- **World record luminosity**
 - ~10 B mesons/sec
- **Backgrounds are tolerable:**
 - SVD occupancy < 4%
 - CDC inner layer occupancy < 10%
 - CsI pedestals endcap < 1MeV; barrel < 500keV
- **Headroom for improvement:**
 - Plans: $Lum \Rightarrow 10^{34}$; $r_{IPpipe} 2.0 \Rightarrow 1.5$ cm



B → CP Eigenstate Decays

Use **~all** low-background $c\bar{c}K^0$ modes

CP odd

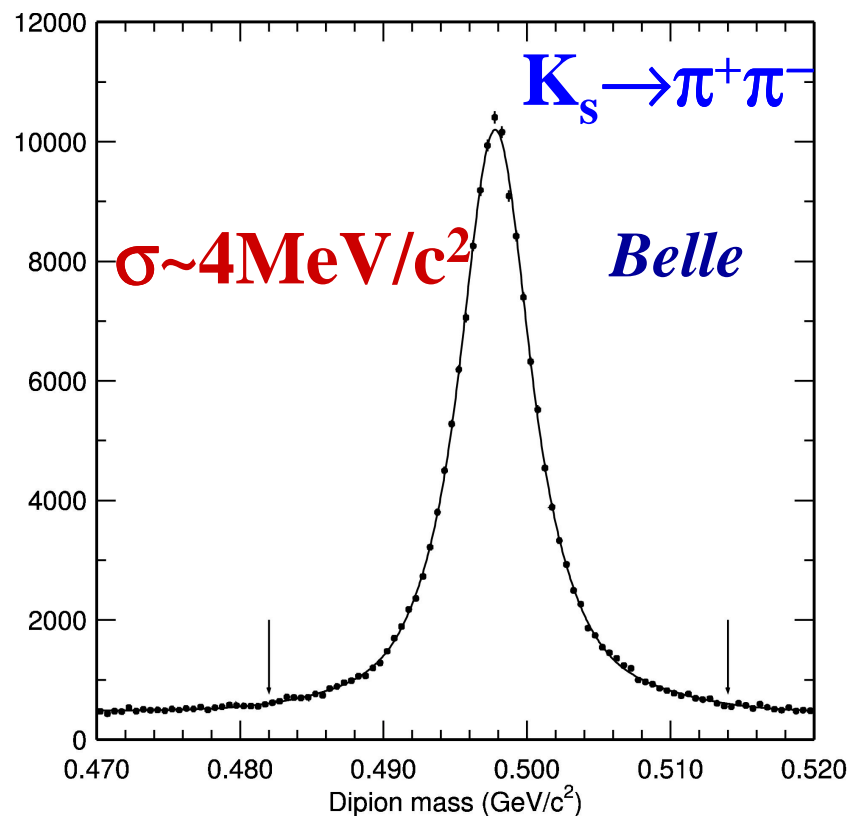
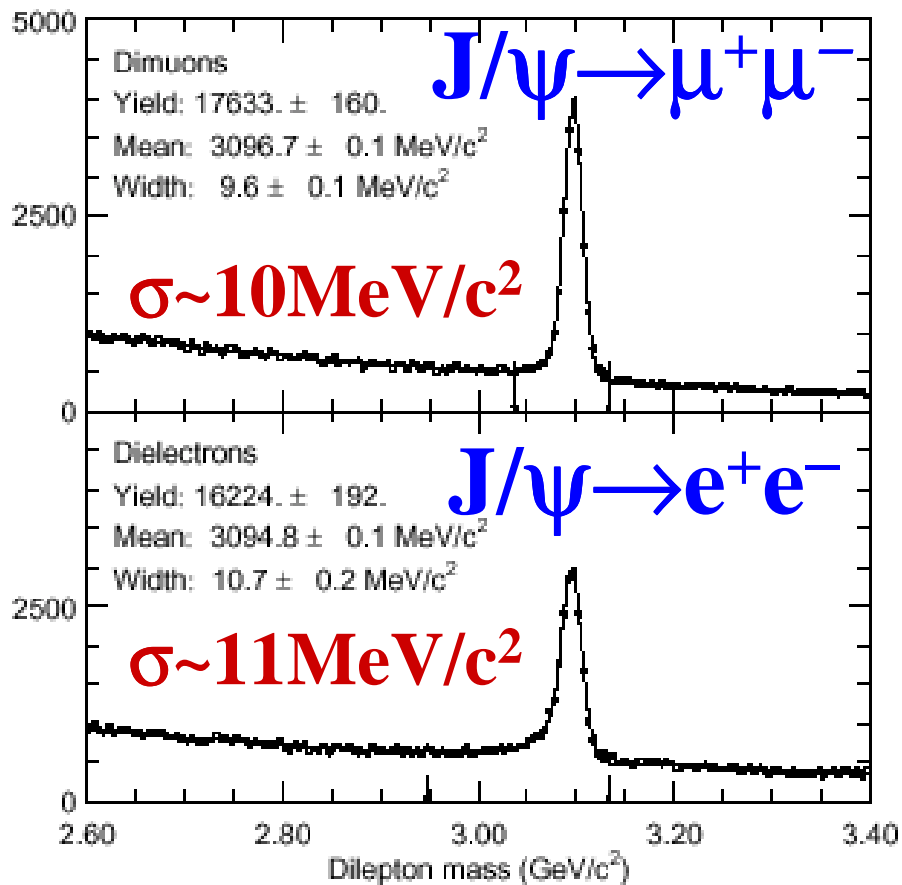
$$\begin{aligned} B_{CP} \rightarrow & J/\psi K_S (\rightarrow \pi^+\pi^- \text{ \& } \pi^0\pi^0) \\ & \psi(2S) (\rightarrow l^+l^- \text{ \& } J/\psi\pi^+\pi^-) K_S \\ & \chi_{c1} (\rightarrow J/\psi\gamma) K_S \\ & \eta_c (\rightarrow K_S K^+\pi^-, K^+K^-\pi^0) K_S \end{aligned} \left. \vphantom{B_{CP}} \right\} \xi_f = -1$$

CP even

$$\begin{aligned} & J/\psi K_L \\ & J/\psi K^{*0} (\rightarrow K_S\pi^0) \text{ (mostly)} \end{aligned} \left. \vphantom{B_{CP}} \right\} \xi_f = +1$$



Golden mode: $B^0 \rightarrow J/\psi K_S (\rightarrow \pi^+ \pi^-)$

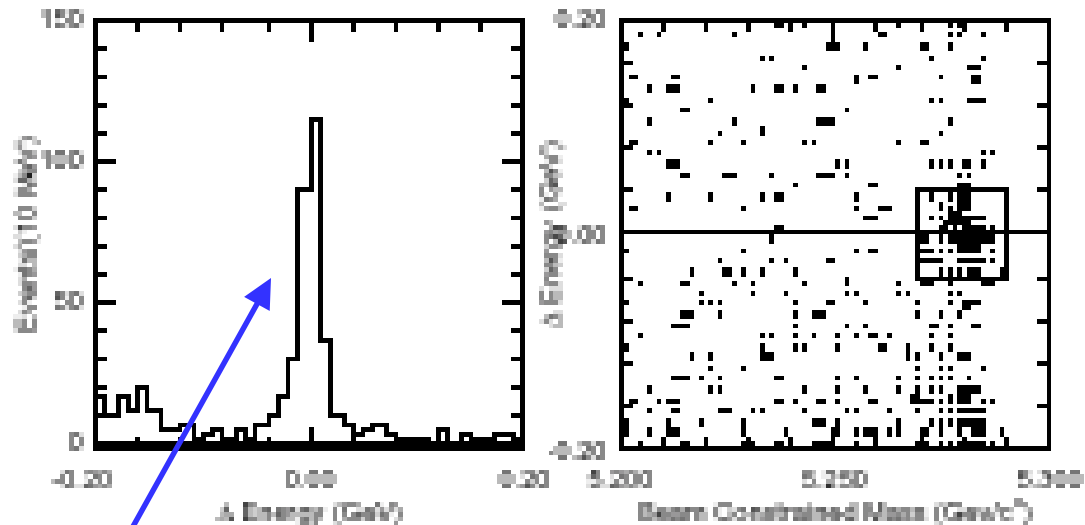


Biggest contributor to the f_{cp} event sample



$B^0 \rightarrow J/\psi K_S(\rightarrow \pi^+\pi^-)$ (cont'd)

457 events
~3% bkgd

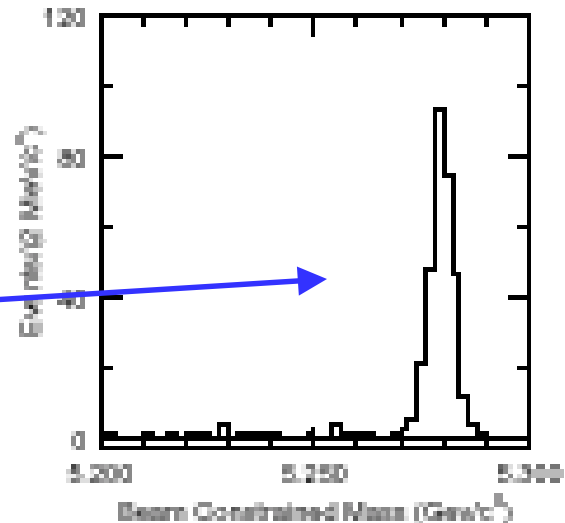


Energy difference:

$$\Delta E \equiv E_{J/\psi} + E_{K_S} - E_{CM}/2$$

Beam-constrained mass:

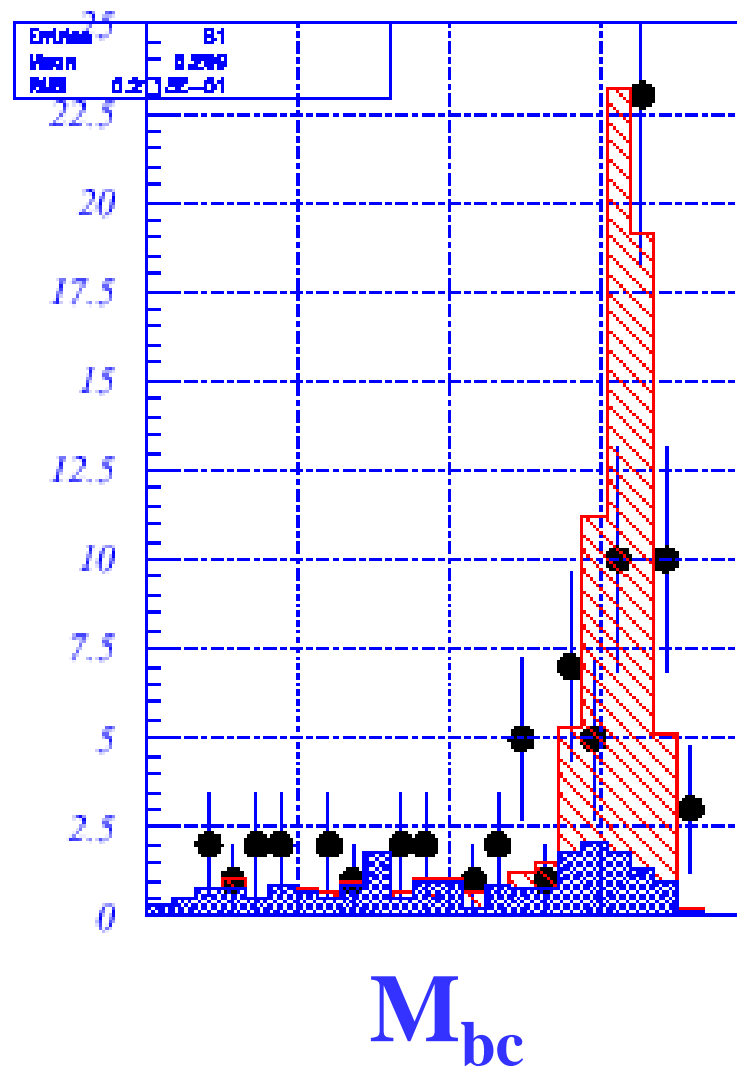
$$m_{bc} = \sqrt{(E_{CM}/2)^2 - (\vec{p}_{J/\psi} + \vec{p}_{K_S})^2}$$





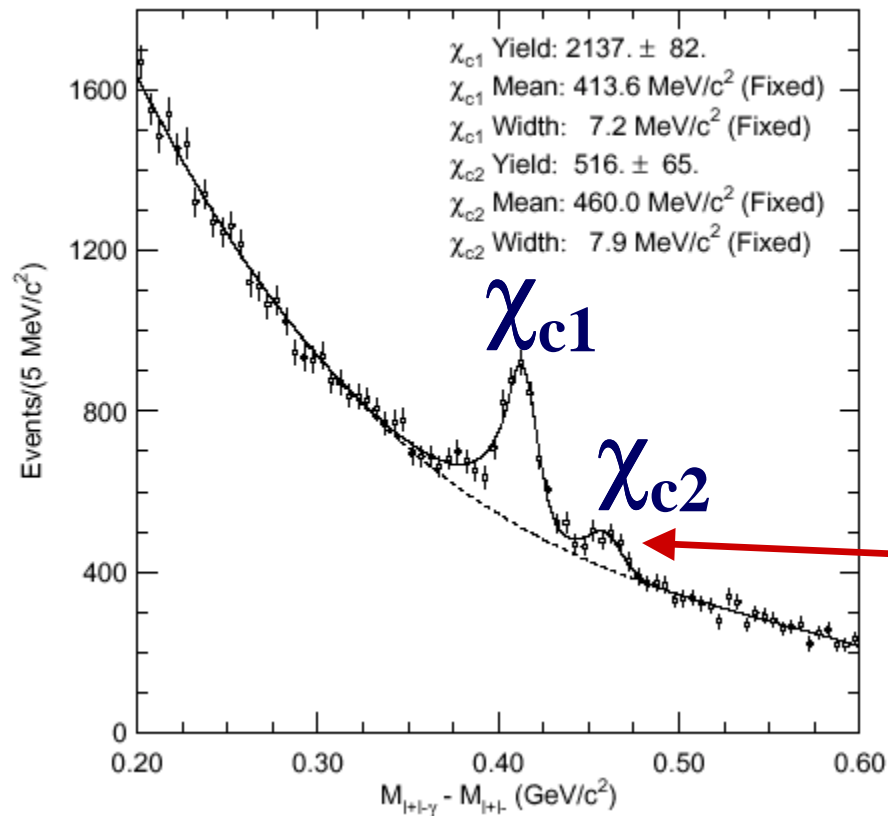
For $B \rightarrow J/\psi K_S$; use $K_S \rightarrow \pi^0 \pi^0$

Total events = 76
Bkgd \approx 9 evts (12%)





Other charmonium modes



**1st observation
of inclusive
 $B \rightarrow \chi_{c2} X$**

$$M(l^+l^-\gamma) - M(l^+l^-)$$



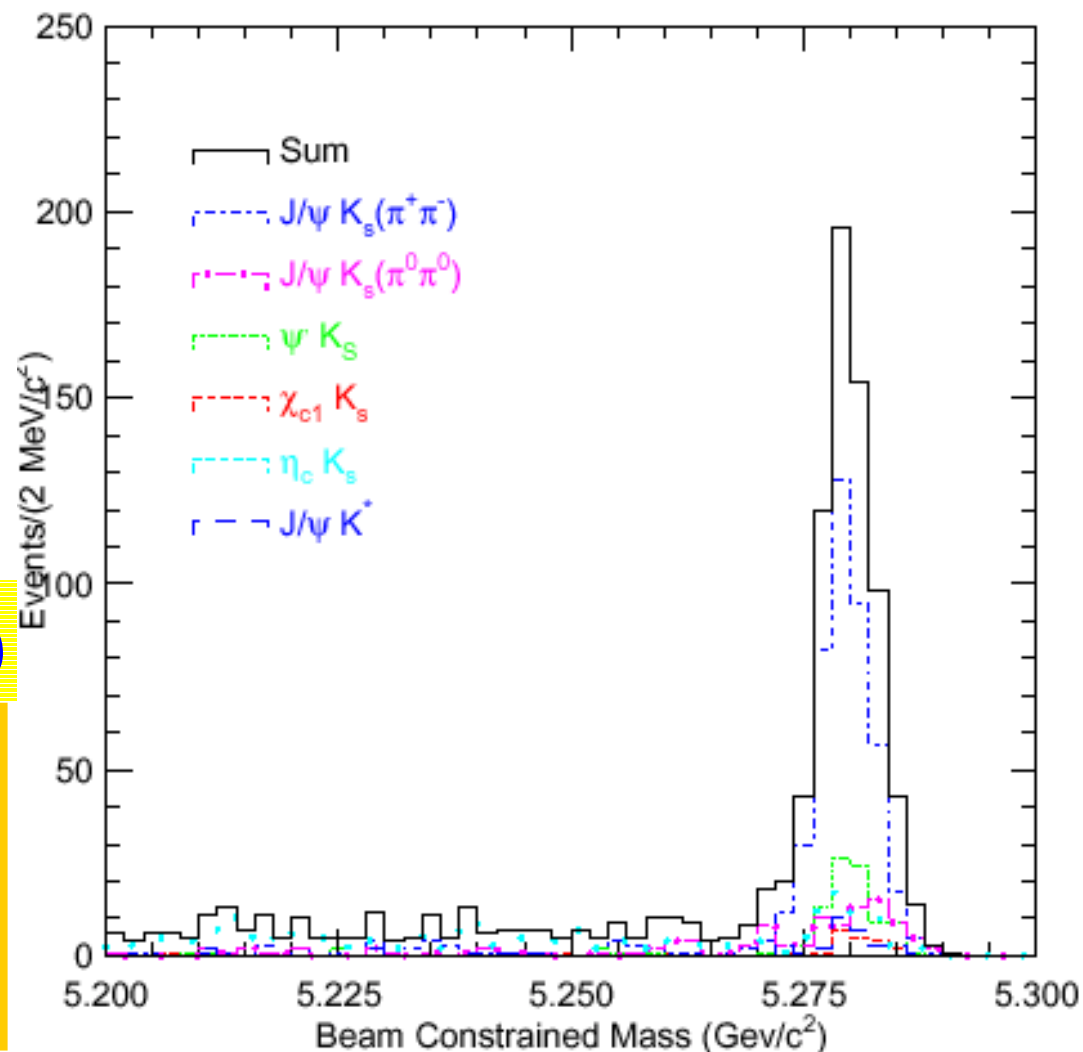
All CP-1 modes

$B^0 \rightarrow$ other modes

290 candidates
46 background
(Purity = 84%)

$B^0 \rightarrow J/\psi K_S(\rightarrow \pi^+ \pi^-)$

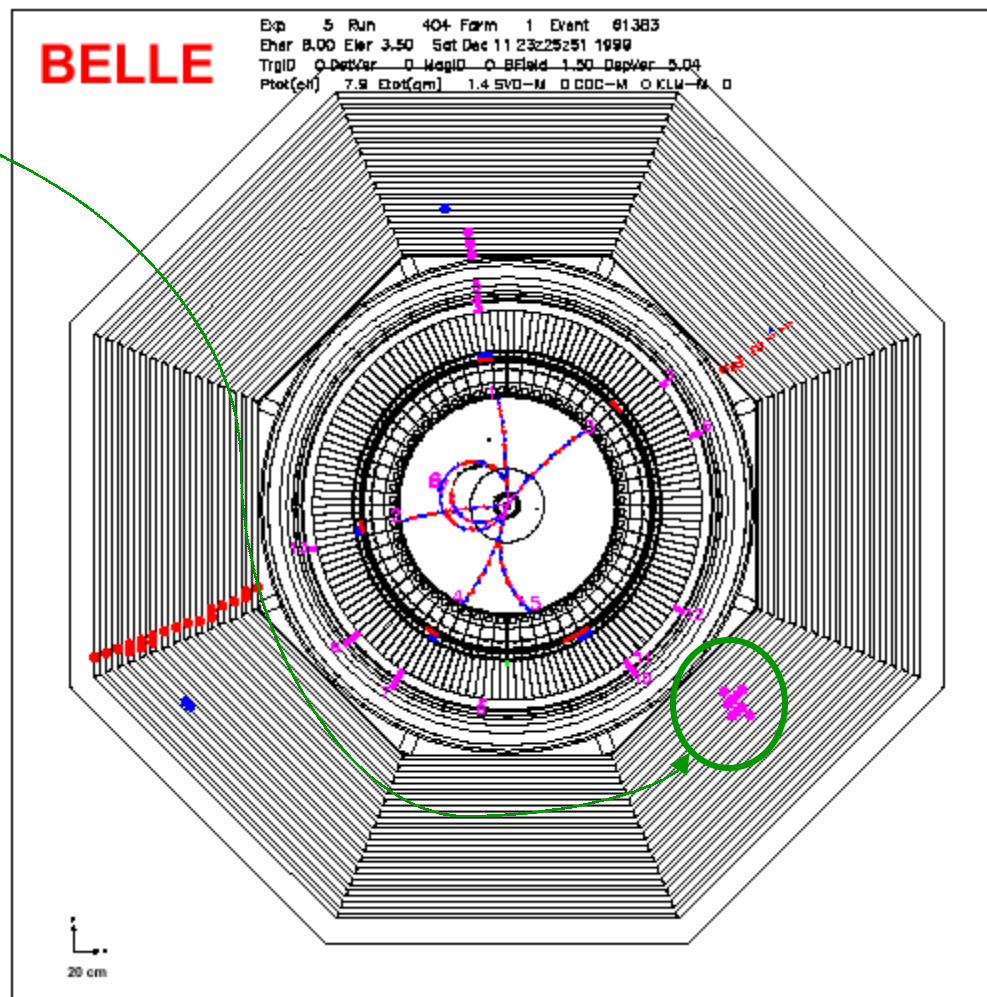
457 candidates
~12 background
(Purity = 97%)





$B^0 \rightarrow J/\psi K_L$

- 1) $J/\psi \rightarrow l^+ l^- + K_L$
- 2) Assume $B \rightarrow J/\psi K_L$:
compute \vec{P}_{KL}
- 3) Remove reconstructed
 $B \rightarrow J/\psi K, J/\psi K^*, \dots$
- 4) Cut on a likelihood
based on kinematical
and shape quantities
- 5) Plot $P_B^* = |\vec{P}_{J/\psi} + \vec{P}_{KL}|$



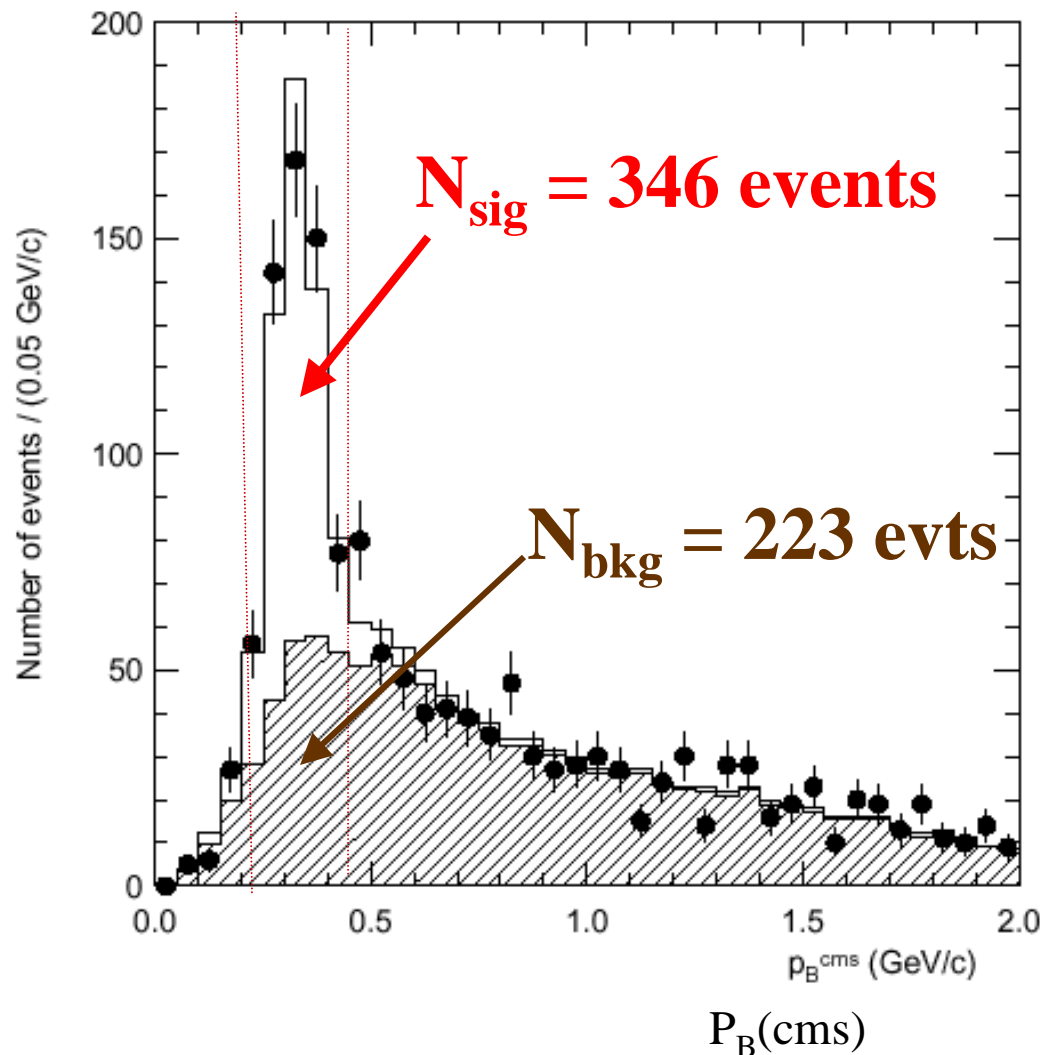


$B^0 \rightarrow J/\psi K_L$ signal yield

$$\mathbf{P}_B^* = |\vec{\mathbf{P}}_{J/\psi}^* + \vec{\mathbf{P}}_{K_L}^*|$$

$B^0 \rightarrow J/\psi K_L$

569 total events
346 signal
(Purity = 61%)





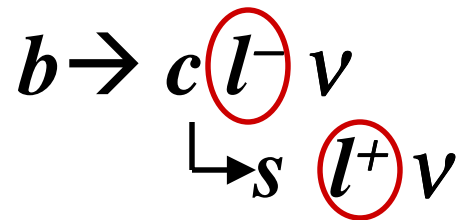
Flavor-tag the other B meson

Use *inclusive* flavor-specific properties:

▪ *Inclusive Leptons:*

▪ *high-p* l^-

▪ *intermed-p* l^+

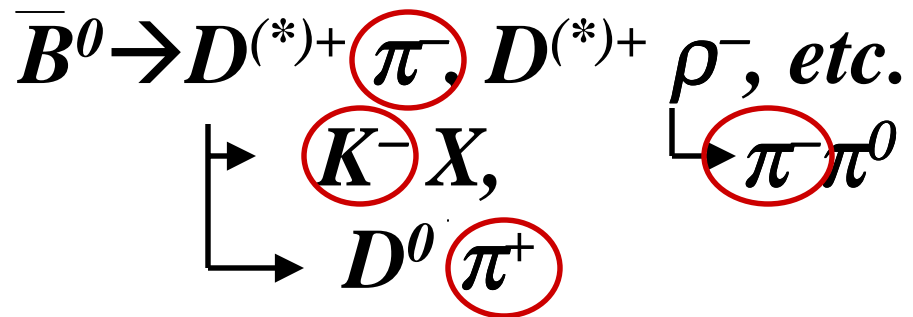


▪ *Inclusive Hadrons:*

▪ *high-p* π^-

▪ *intermed-p* K^-

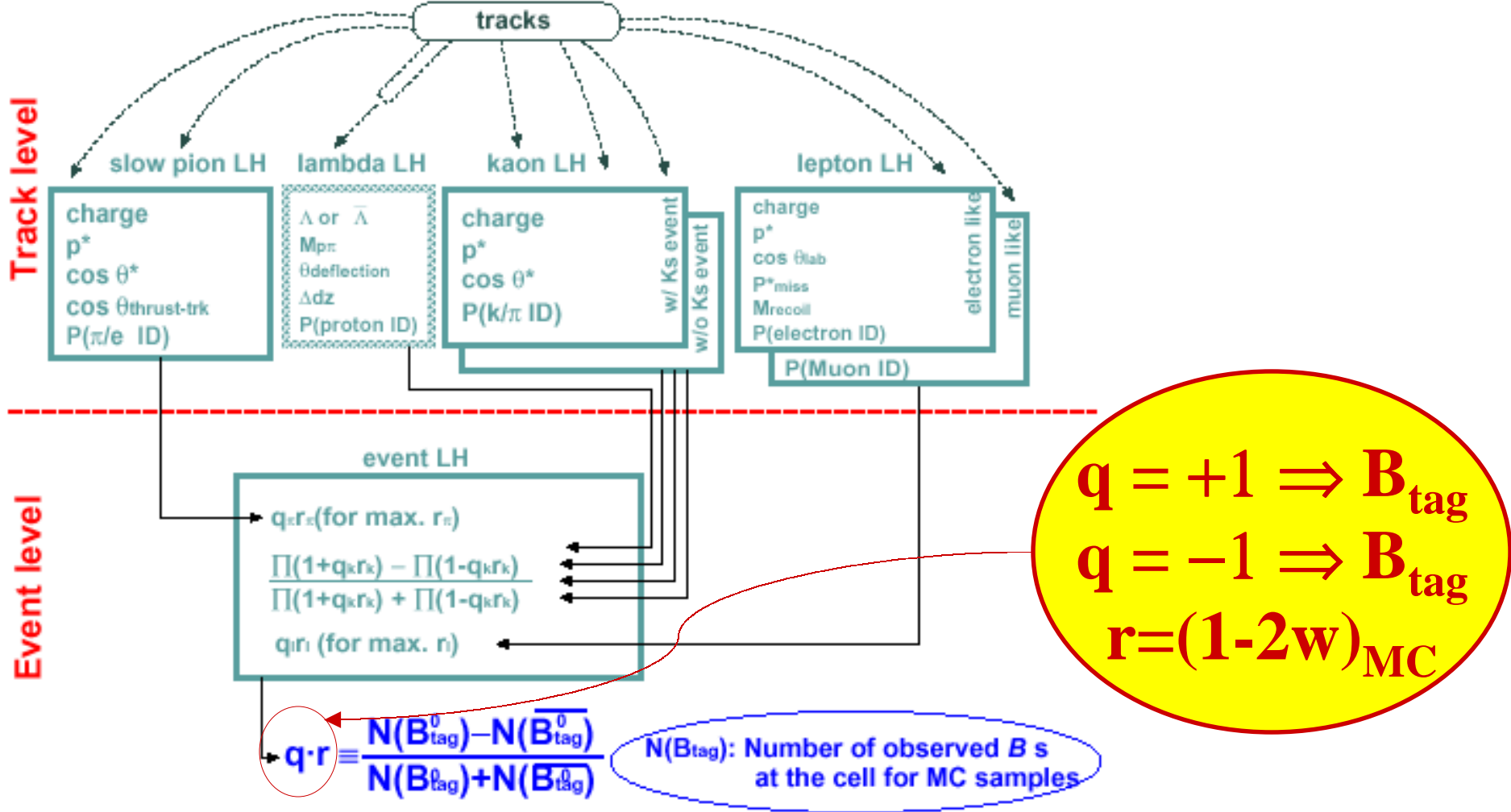
▪ *low-p* π^+



Also need to consider *correlations*



2-level Multi-dimensional flavor tagging

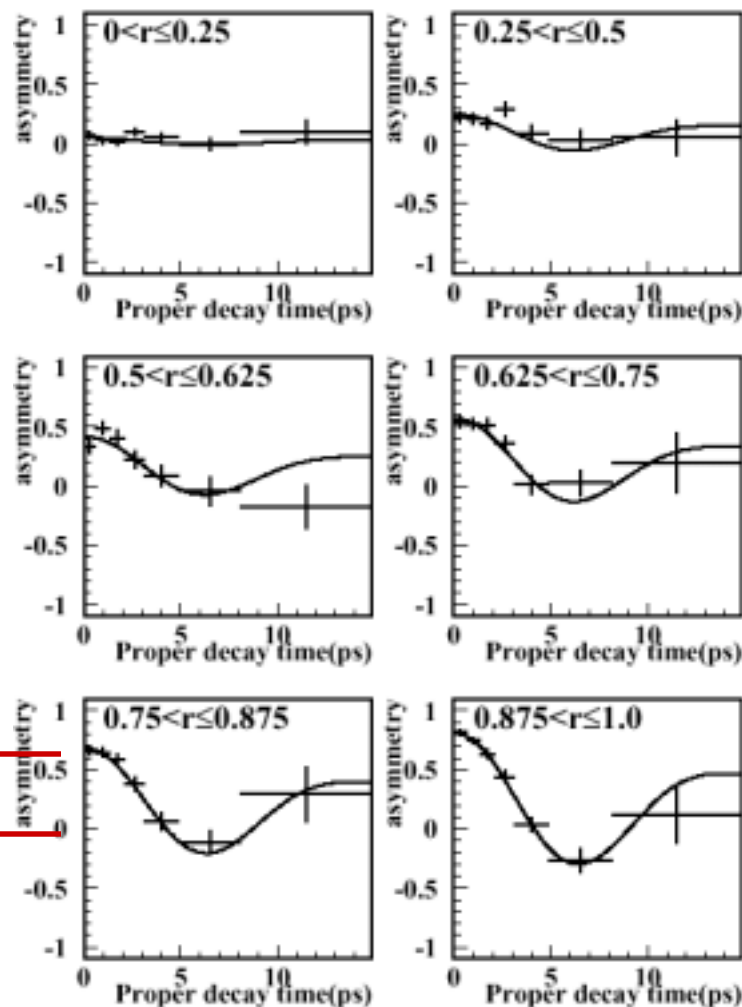




Determination of wrong tag fraction w_l

get w from $B \leftrightarrow \bar{B}$
mixing amplitude:
 $(1-2w_l)\cos(\Delta m_d \Delta t)$

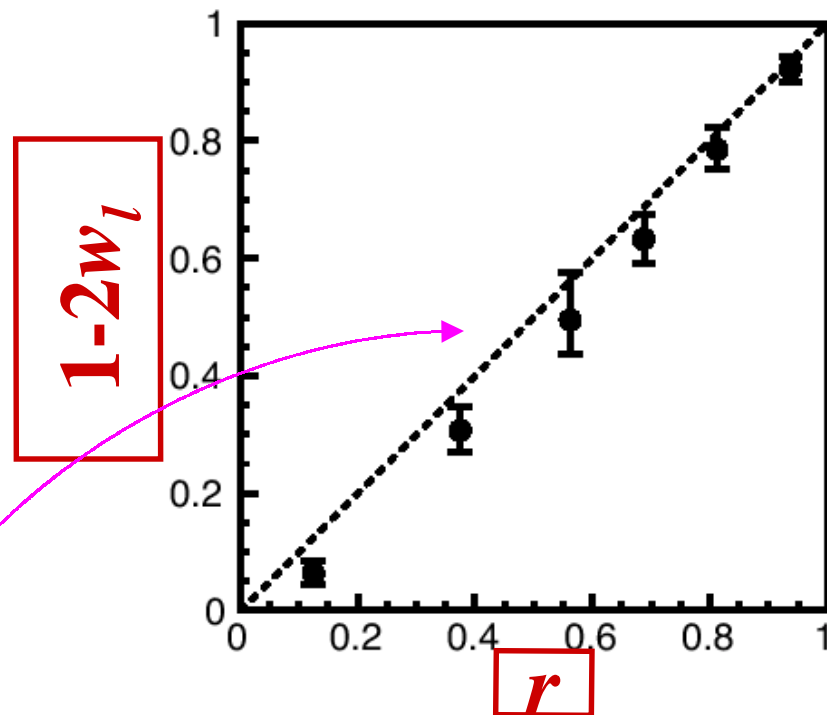
$B^0 \rightarrow D^* \bar{l} \nu$





Multi-dimensional Flavor Tagging

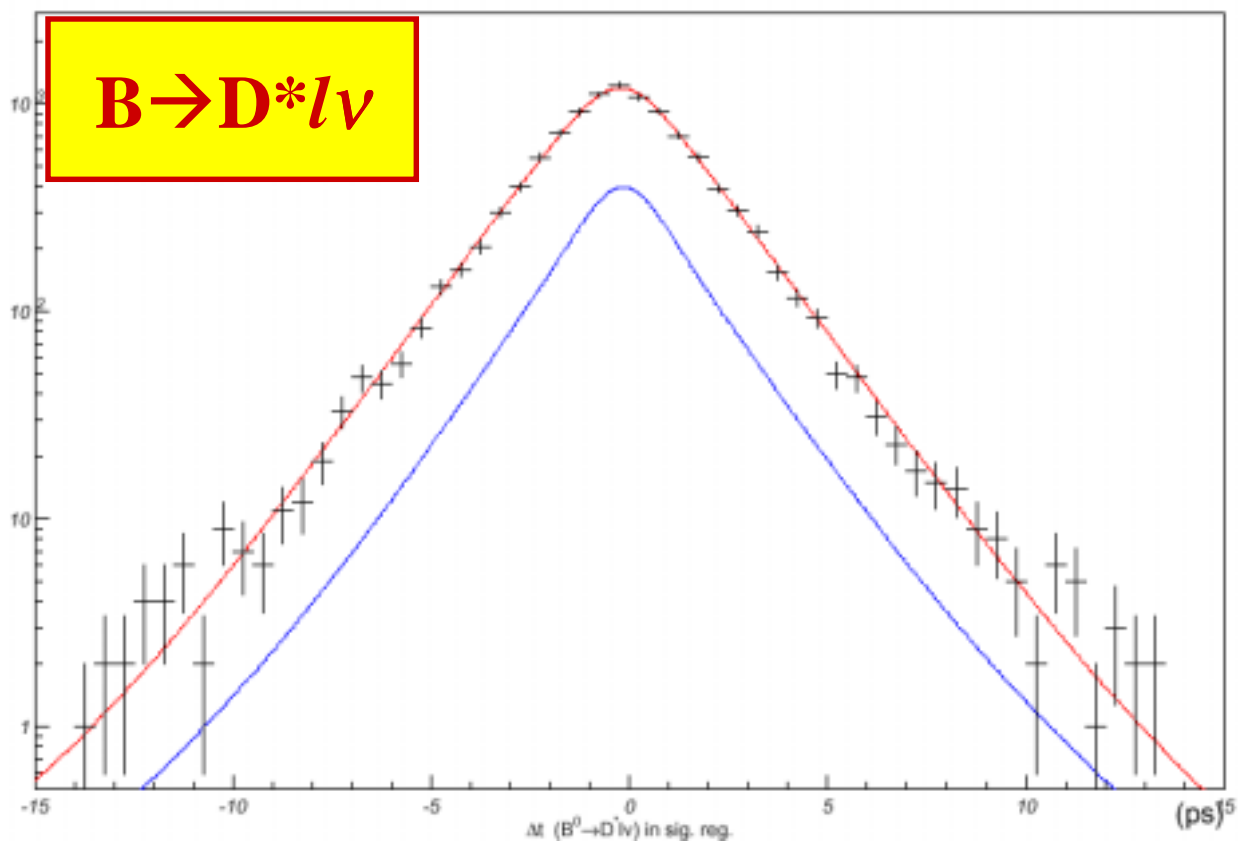
- Uses all events
 - Efficiency > 99%
- $\mathcal{E}_{\text{effective}} = 27.0 \pm 1.2\%$
- Includes correlations
- Use MC- r as a classifier
- Use data- w for CP fits



MC-determined $r \approx 1-2w$ measured from data



Validation: B lifetimes



$$\tau_{B^0} = 1.55 \pm 0.02 \text{ps}$$

$$\text{PDG: } 1.55 \pm 0.03 \text{ps}$$

$$\tau_{B^+} = 1.64 \pm 0.03 \text{ps}$$

$$\text{PDG: } 1.65 \pm 0.03 \text{ps}$$

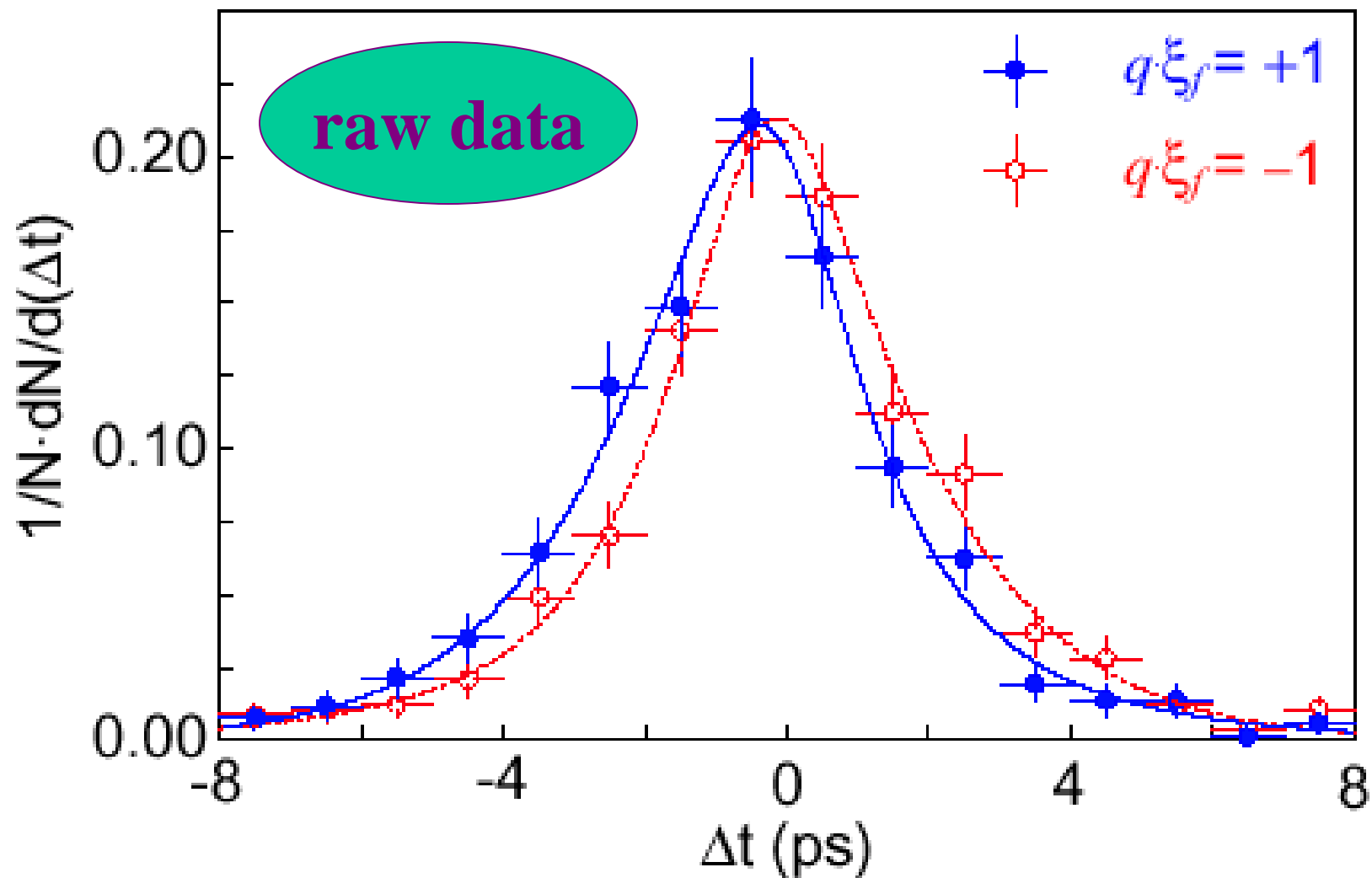


Timeline

- **July 6:** end Y(4S) running
- **July 9:** finish data processing
- **July 11:** find w_l 's
- **July 12:** **Open the box!!**
- **July 13:** PRL draft → Collab
- **July 18:** PRL submitted
- **July 23:** Announce results



Combine q, ξ_f & Δt





CP is violated in B decays!!

- Large effect
- Apparent in the raw data
- Many σ



Event-by-event Likelihood

$$\mathcal{L}_i = \int ((1 - f_{bk}) \mathcal{P}_{sig} + f_{bk} \mathcal{P}_{bk}) \times \mathcal{R}(\Delta t - \Delta t') d\Delta t'$$

$$\mathcal{P}_{sig} = \frac{e^{-|\Delta t|/\tau_B}}{2\tau_B} (1 - \xi_f q (1 - 2w) \sin 2\phi_1 \sin \Delta m \Delta t)$$



Event-by-event Likelihood

$$\mathcal{L}_i = \int ((1 - f_{bk}) \mathcal{P}_{sig} + f_{bk} \mathcal{P}_{bk}) \times \mathcal{R}(\Delta t - \Delta t') d\Delta t'$$

background frac.

From Sidebands & MC

resolution function B-lifetime studies

$$\mathcal{P}_{sig} = \frac{e^{-|\Delta t|/\tau_B}}{2\tau_B} (1 - \xi_f q (1 - 2w) \sin 2\phi_1 \sin \Delta m \Delta t)$$

b-flavor tag

PDG

$\xi_f = \pm 1$ for $CP = \pm 1$

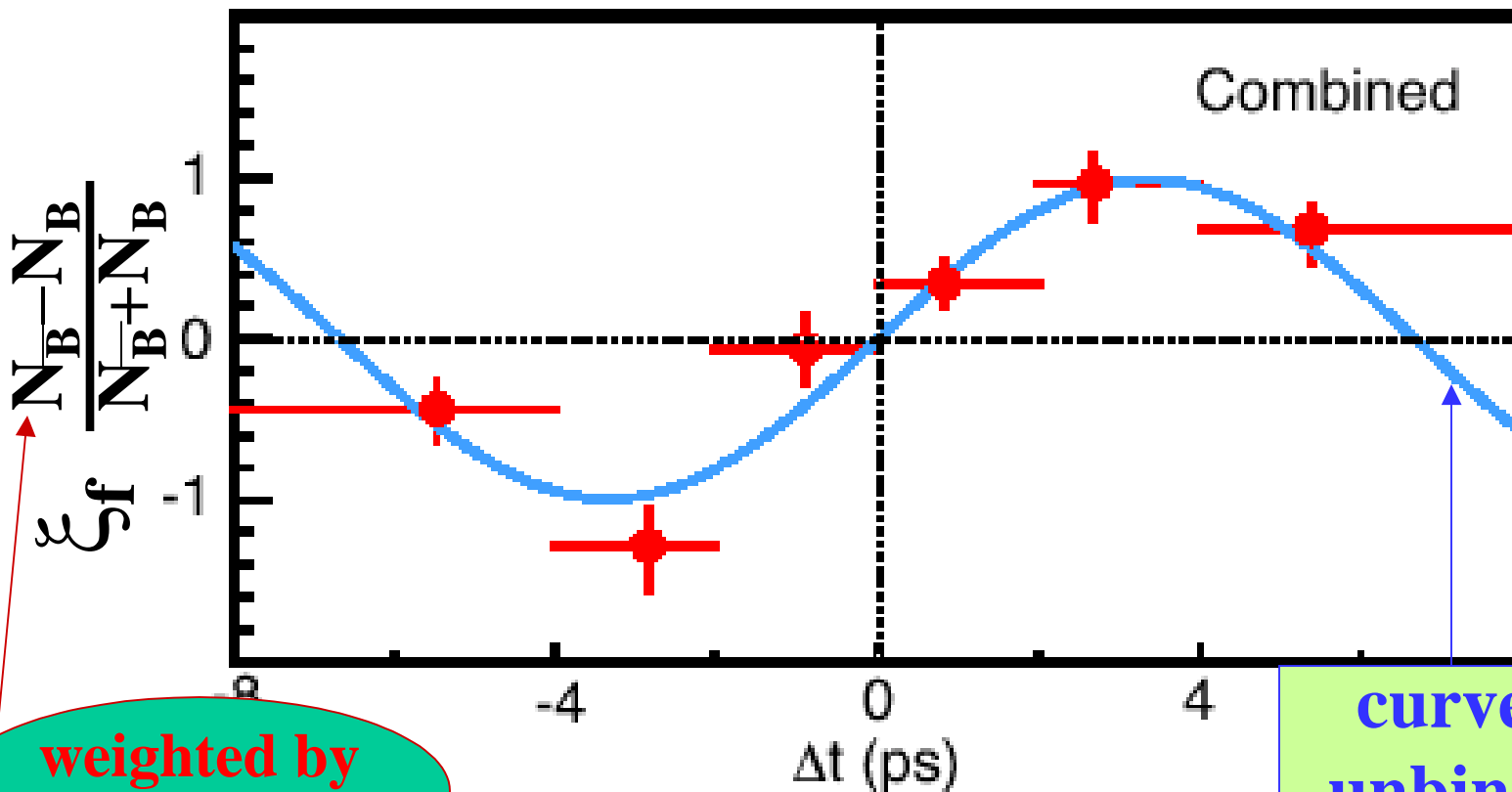
free parameter

wrong-tag frac.



$\sin 2\phi_1$ value that maximizes $\prod_i L_i$

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



weighted by CP sensitivity

curve from unbinned fit

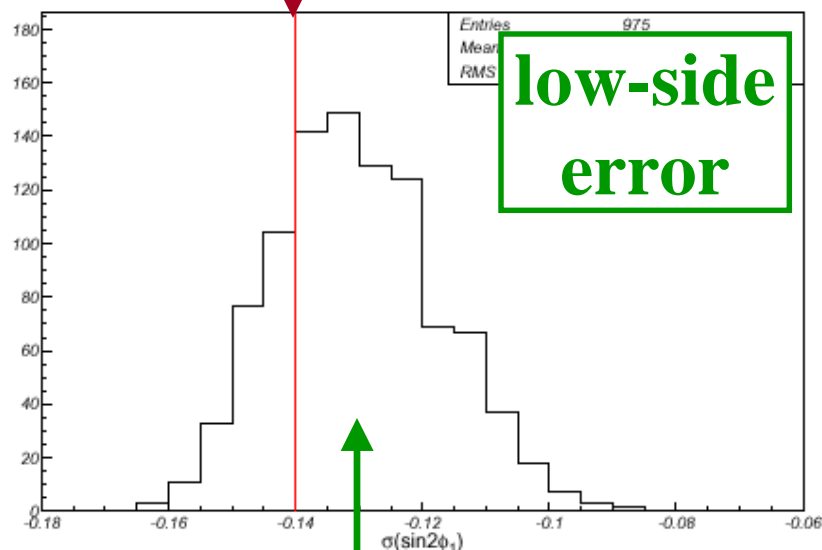


Do the fits & errors make sense?

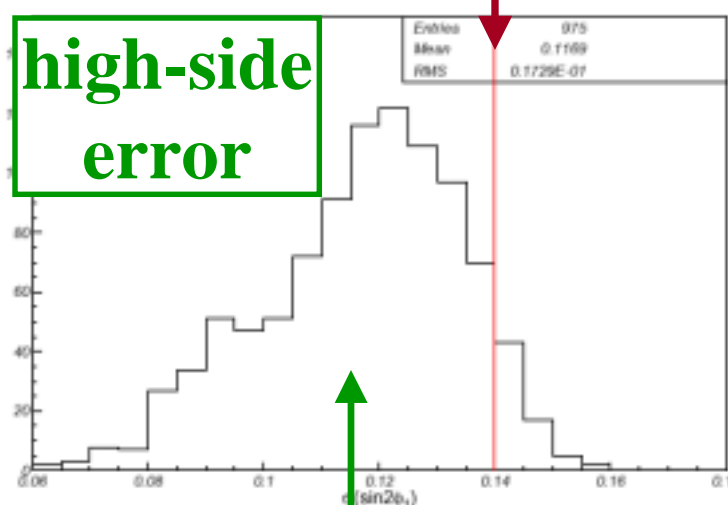
Use toy MC: run 1K similar expts
with $\sin 2\phi_1$ (input)=0.99

our
fit:

-0.14



+0.14



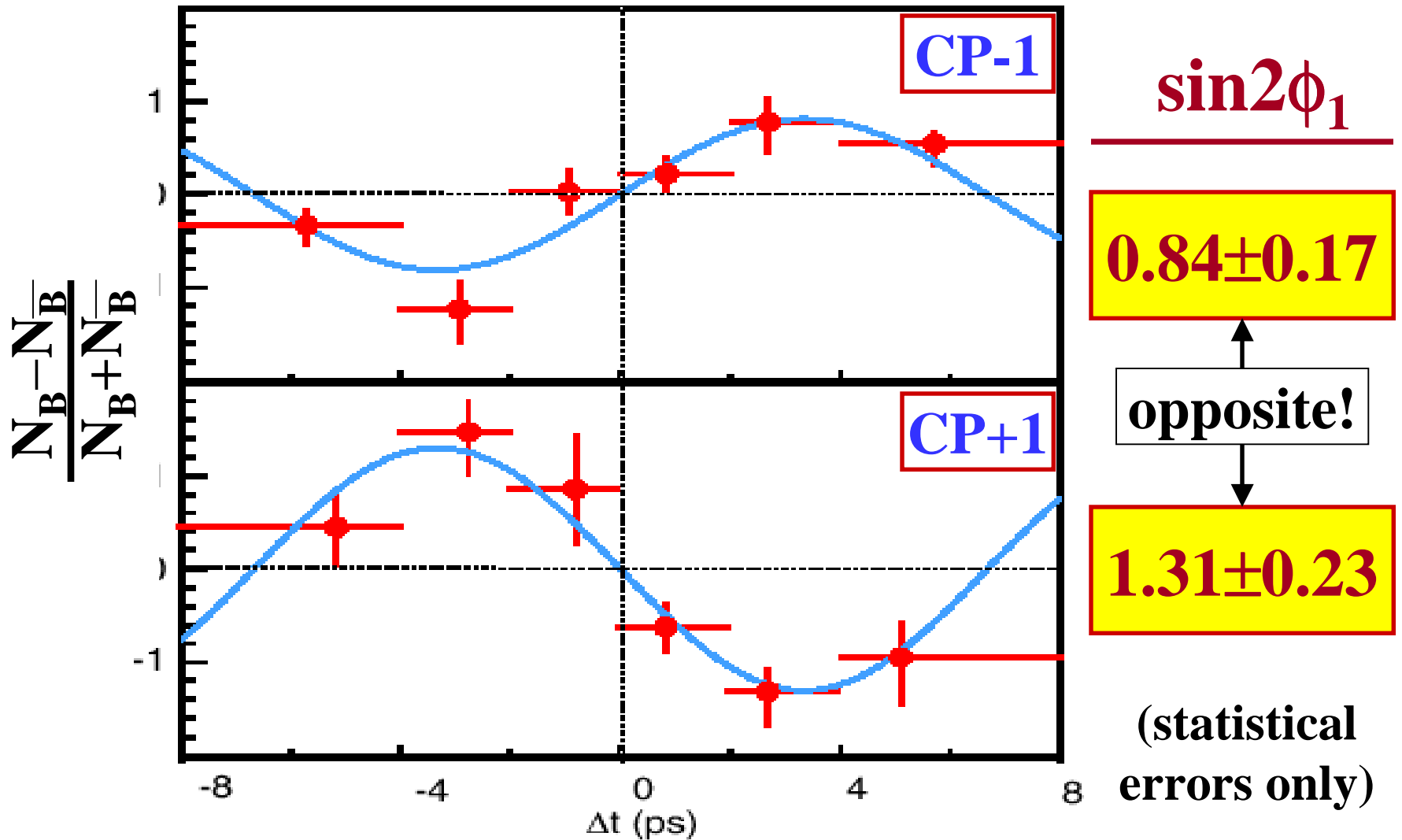
Toy MC
means:

-0.128

+0.116



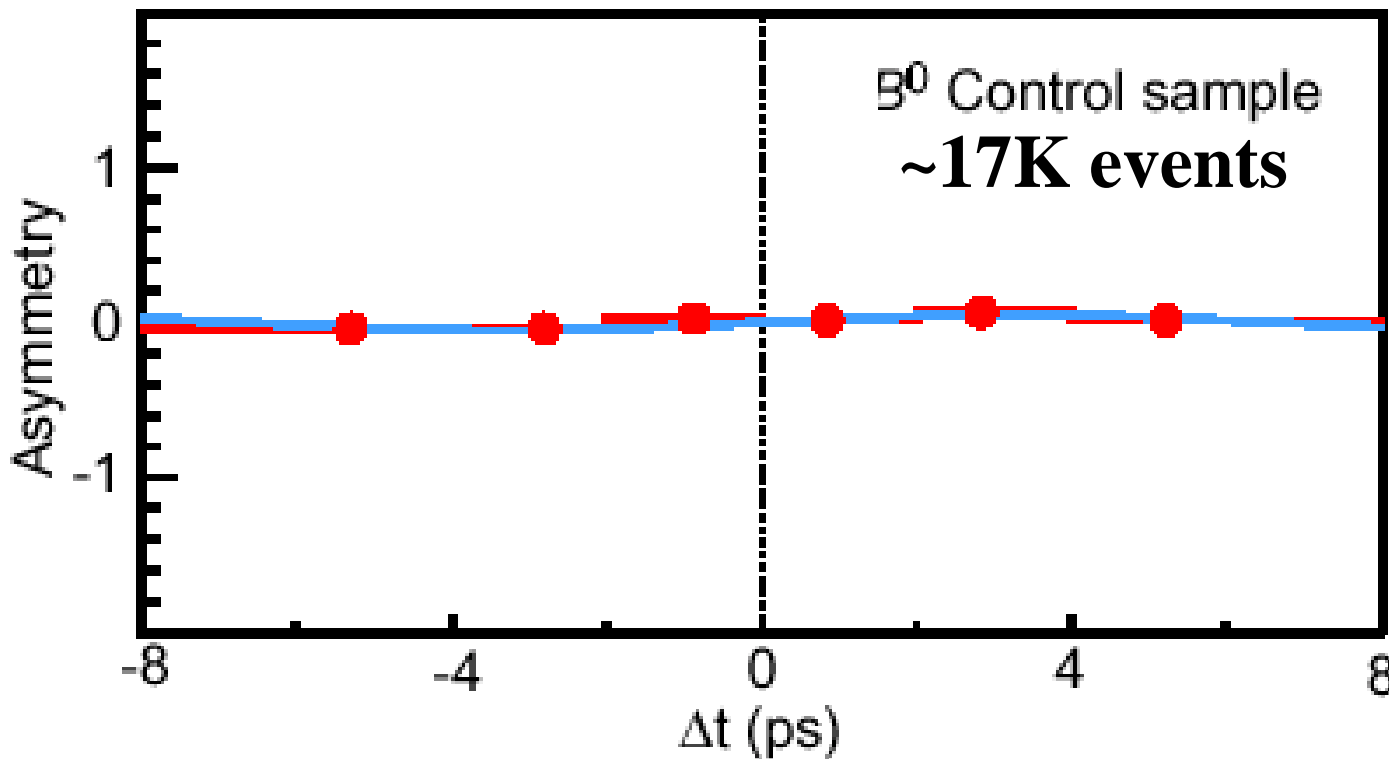
Compare CP -1 and CP+1





Control sample: $B^0 \rightarrow$ non-CP states

use: $B^0 \rightarrow D^{(*)-}\pi^+, D^{*-}\rho^+, D^{*-}l^+\nu, J/\psi K^*(K^+\pi^-)$



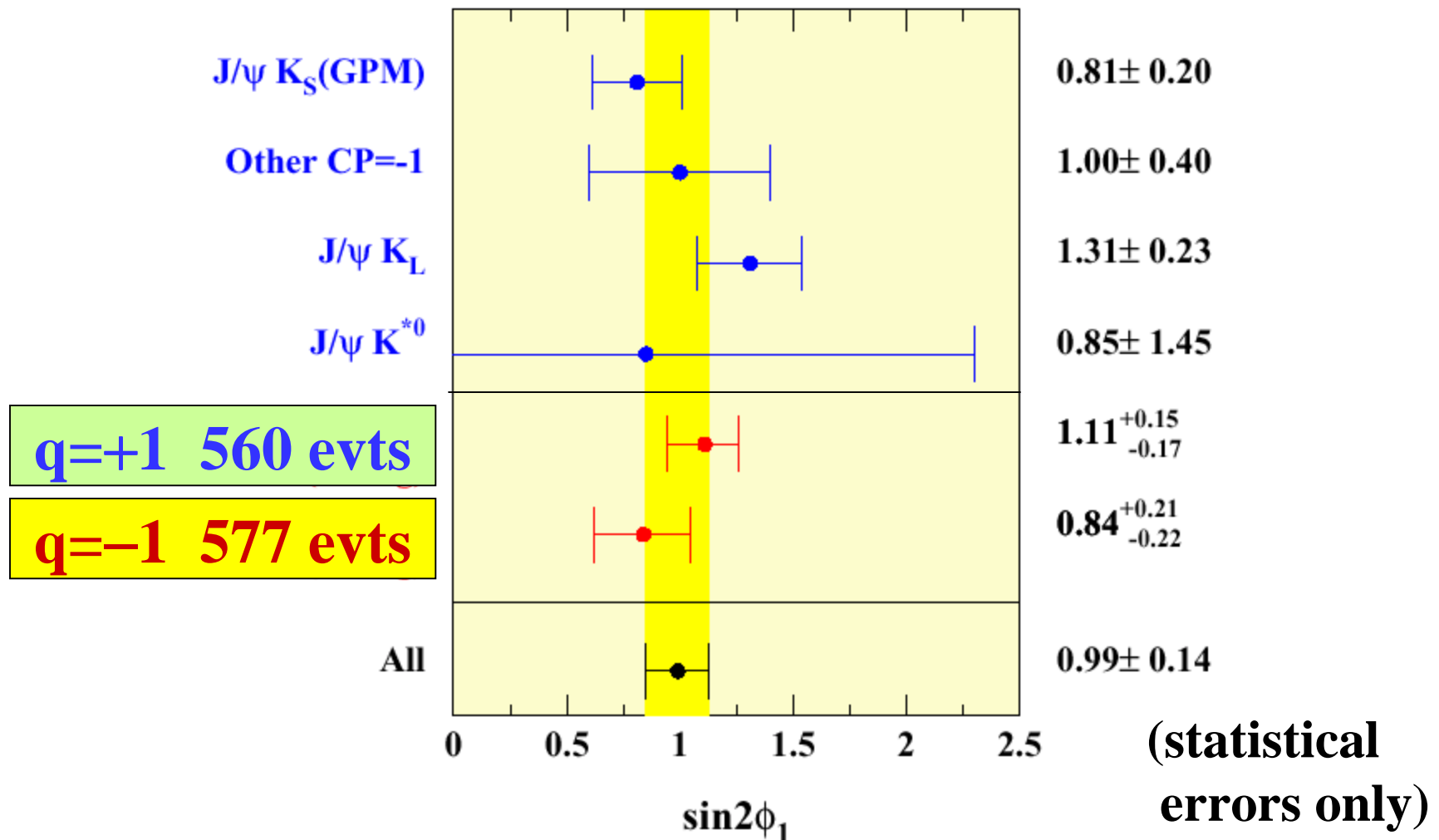
“ $\sin 2\phi_1$ ”

0.05 ± 0.04

(statistical error only)



$\sin 2\phi_1$ from various subsamples



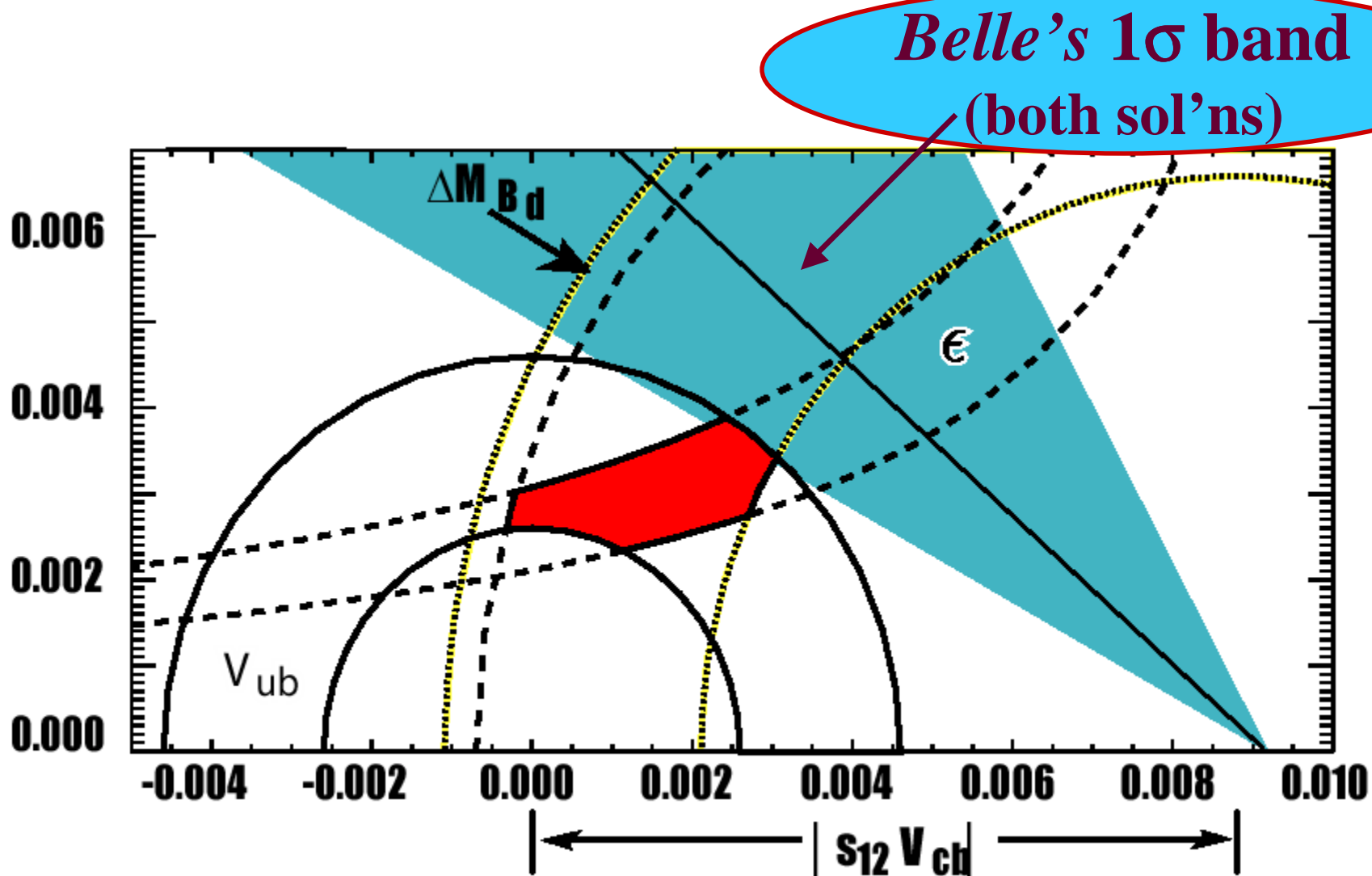


CP fit : Systematic Error

Vertex algorithm	± 0.04
Flavor tagging	± 0.03
Resolution function	± 0.02
K_L background fraction	± 0.02
Background shapes	± 0.01
Δm_d and τ_{B_0} errors	± 0.01
Total	± 0.06



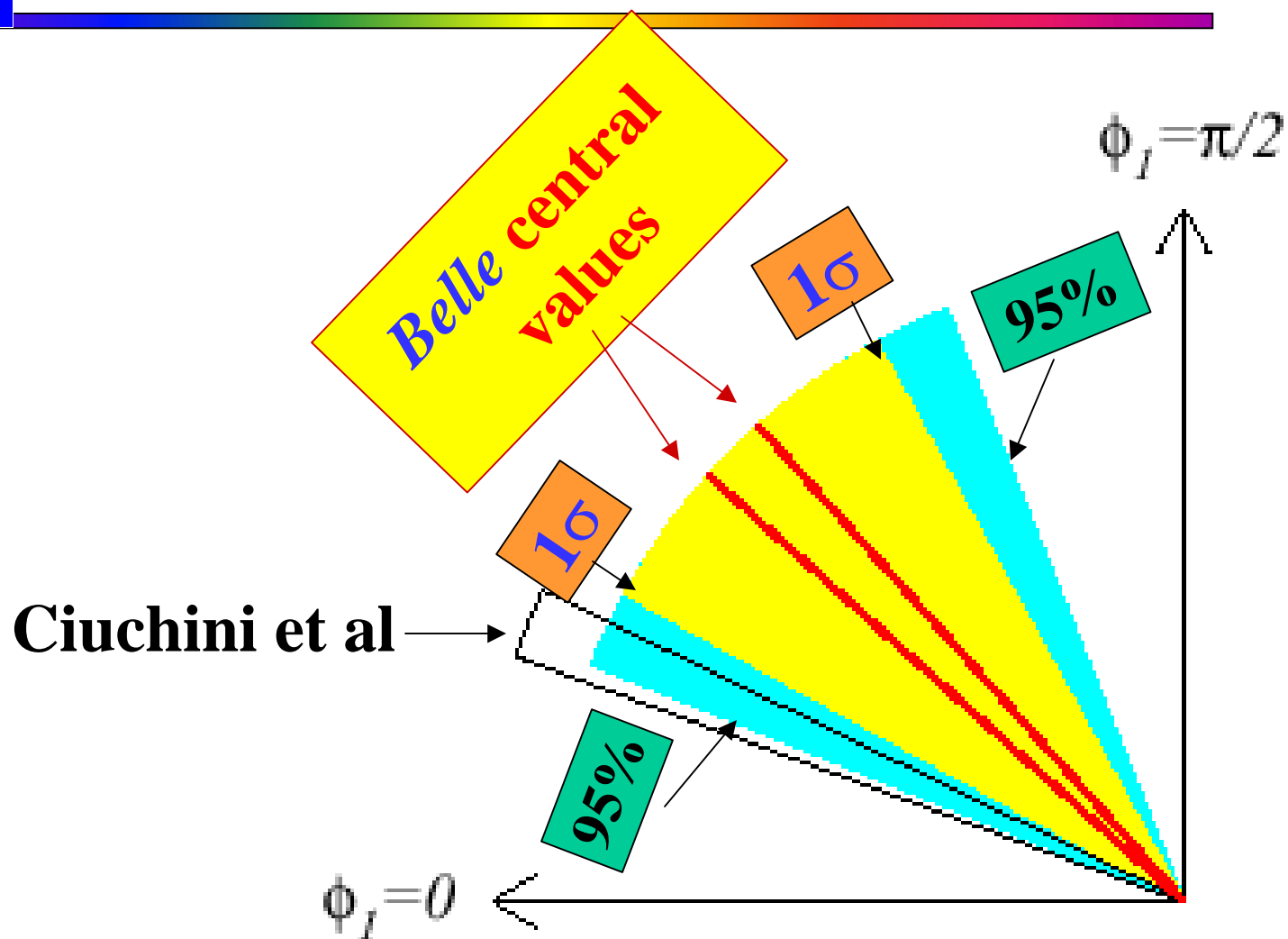
Compare with CKM constraints



Belle's 1σ band
(both sol'ns)



Compare with constraints (cont'd)





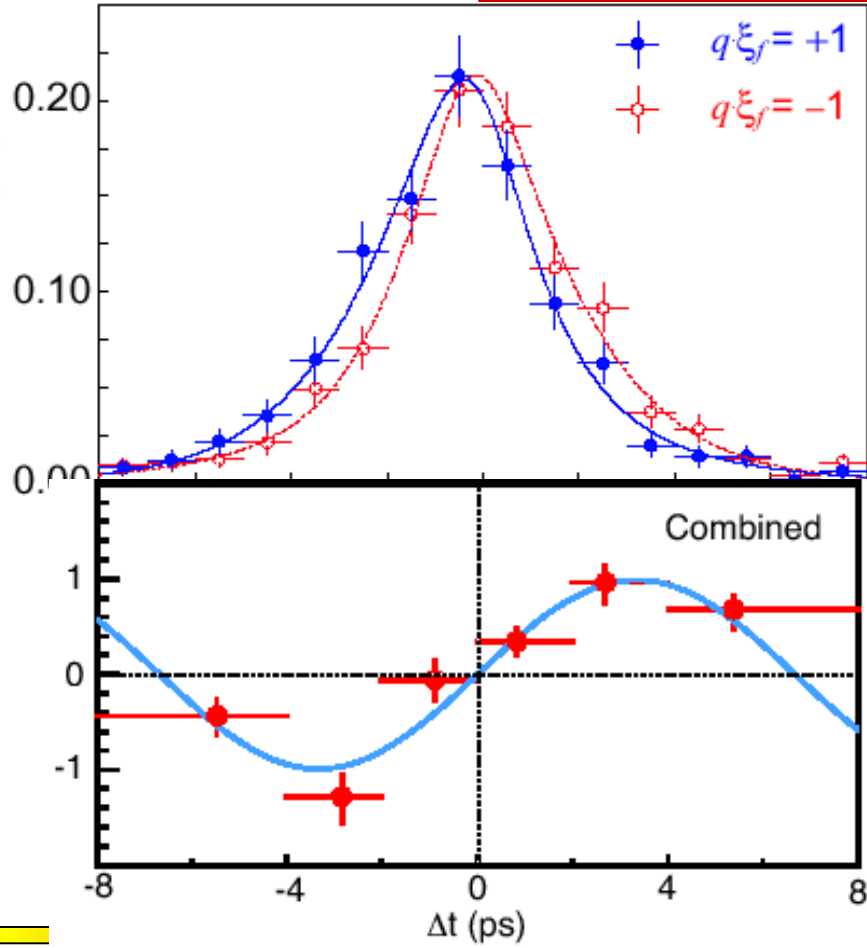
Conclusions

● CP is violated in B decay

>6σ!!

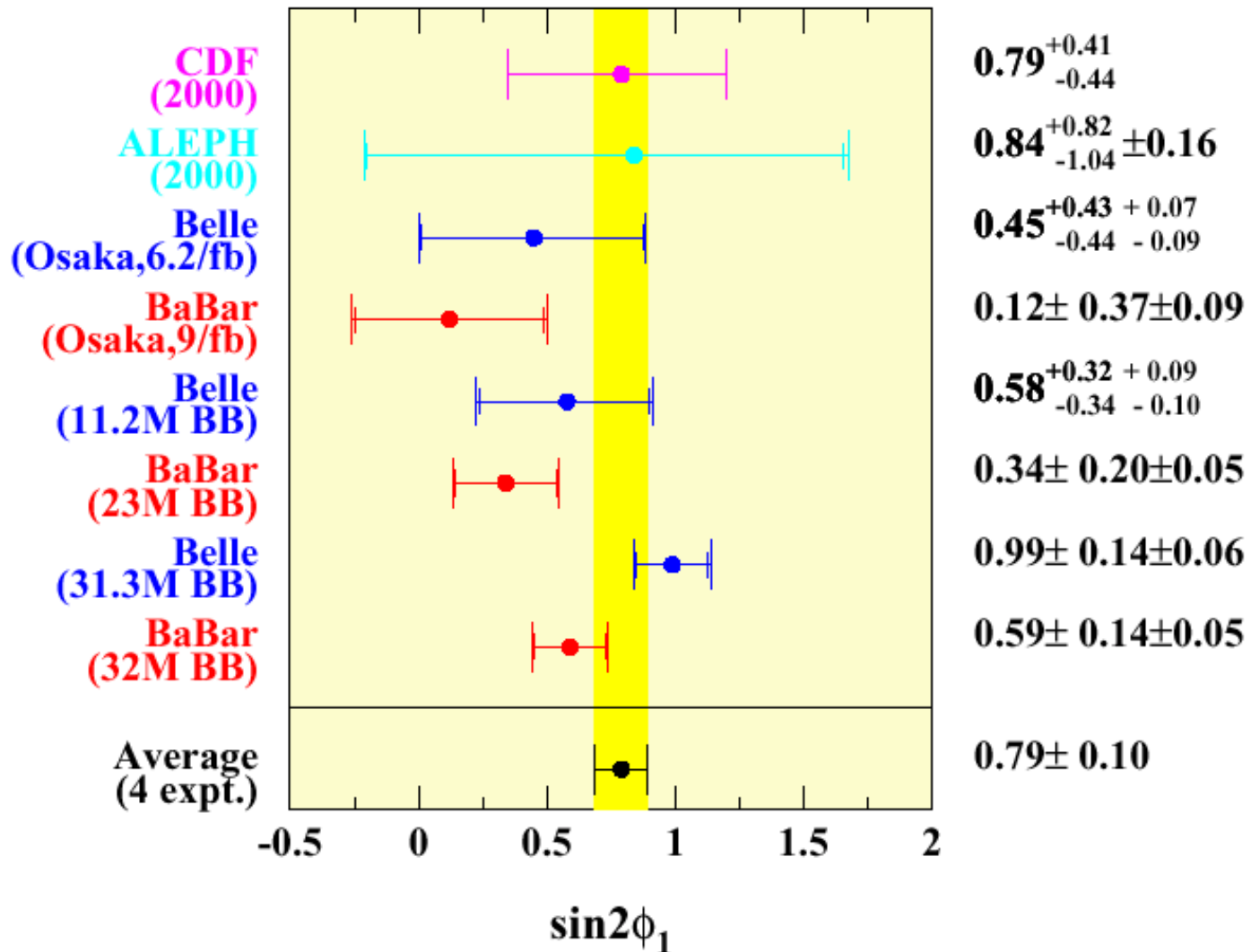
● $\sin 2\phi_1$ is large:

$0.99 \pm 0.14 \pm 0.06$
 $>0.7 @ 95\%CL$





Compare with other experiments





Variations on a theme

Old data; old analysis:	0.58 ± 0.33
Old data; new analysis:	0.54 ± 0.34
New data; new analysis:	1.06 ± 0.14

Allow Δm_d to float	$\sin 2\phi_1$	Δm_d (PDG:0.472)
	1.00 ± 0.14	$0.478 \pm 0.057 \text{ ps}^{-1}$

Allow τ_{B_0} to float	$\sin 2\phi_1$	τ_{B_0} (PDG:1.550)
	1.00 ± 0.14	$1.66 \pm 0.07 \text{ ps}$