



# Measurement of $\sin 2\phi_1$

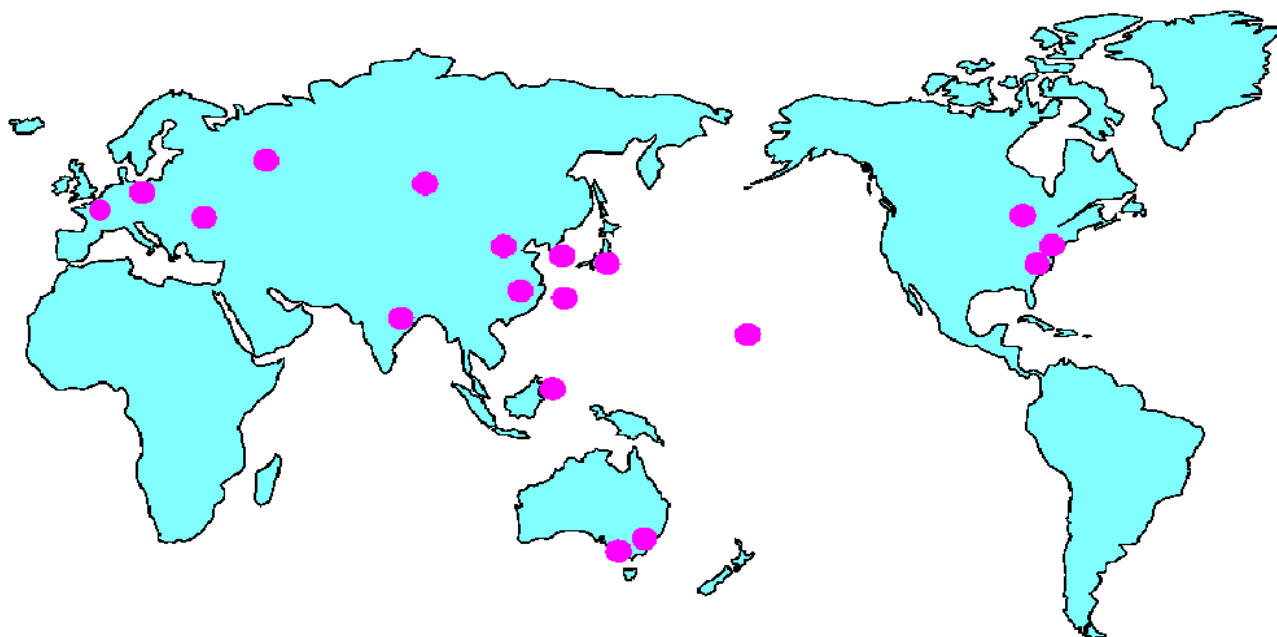
*Stephen L. Olsen*  
*U. of Hawaii*

*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:

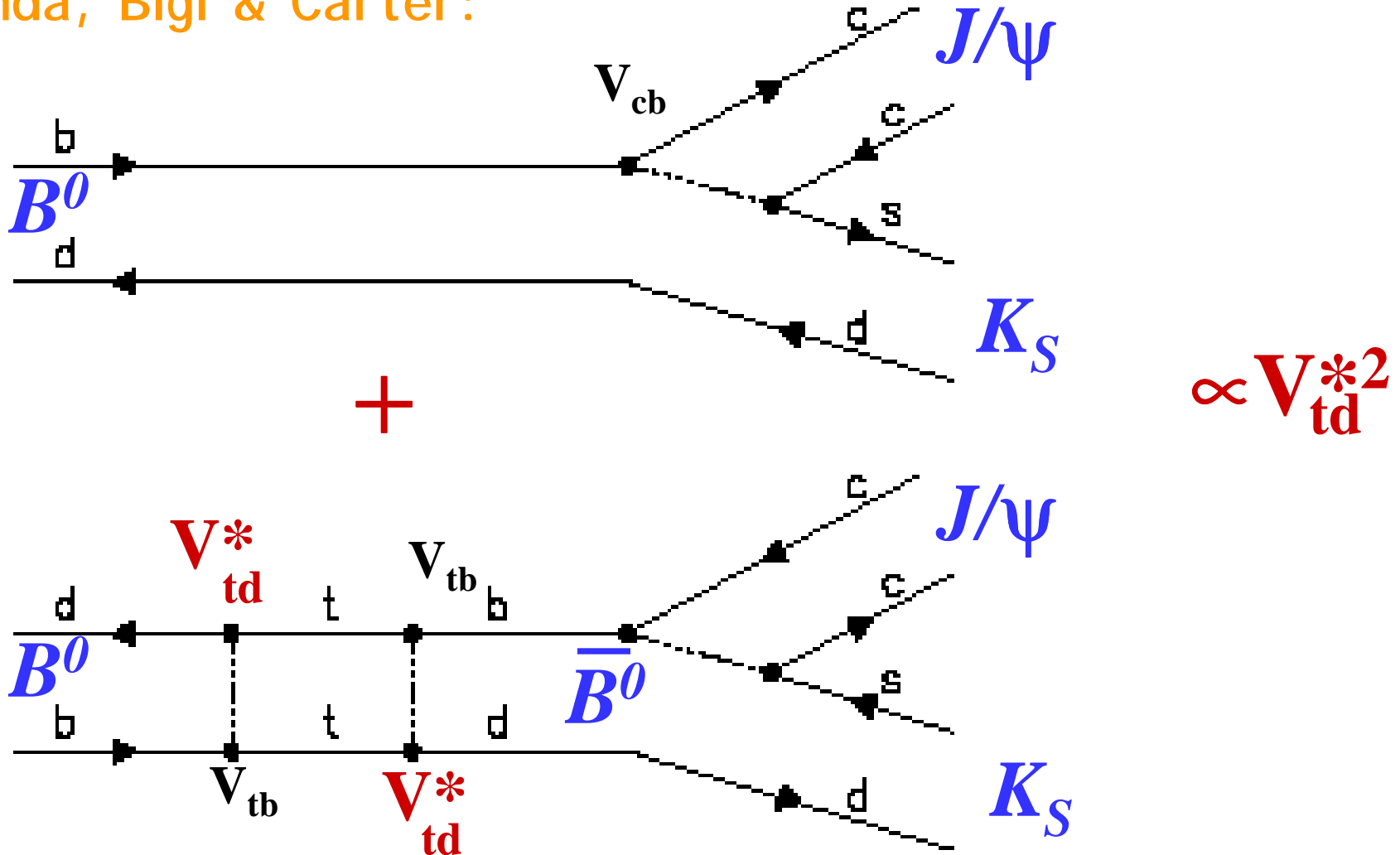
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

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:



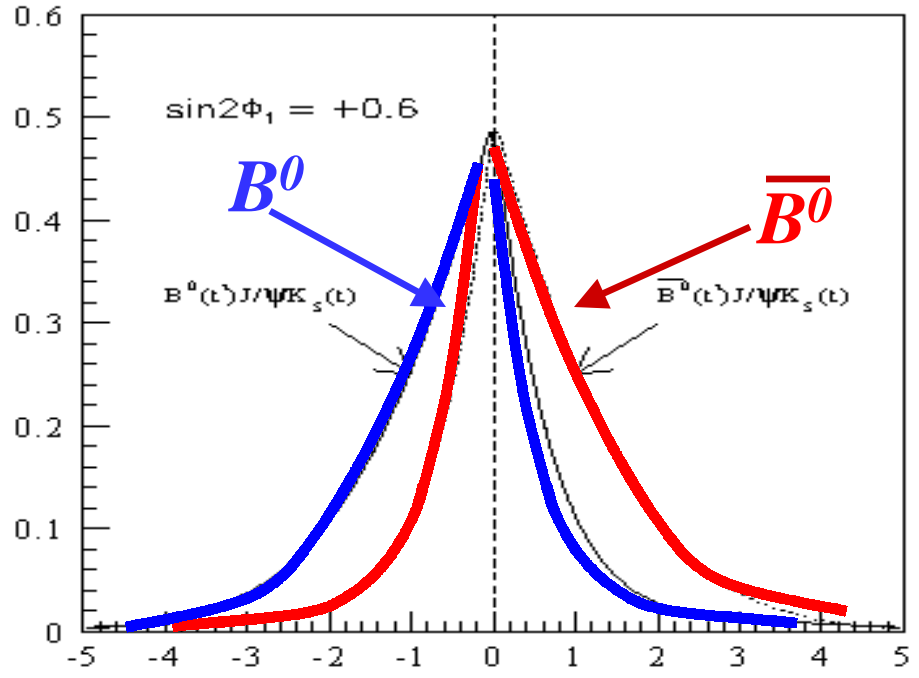


# Mixing-induced CPV asymmetry

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

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

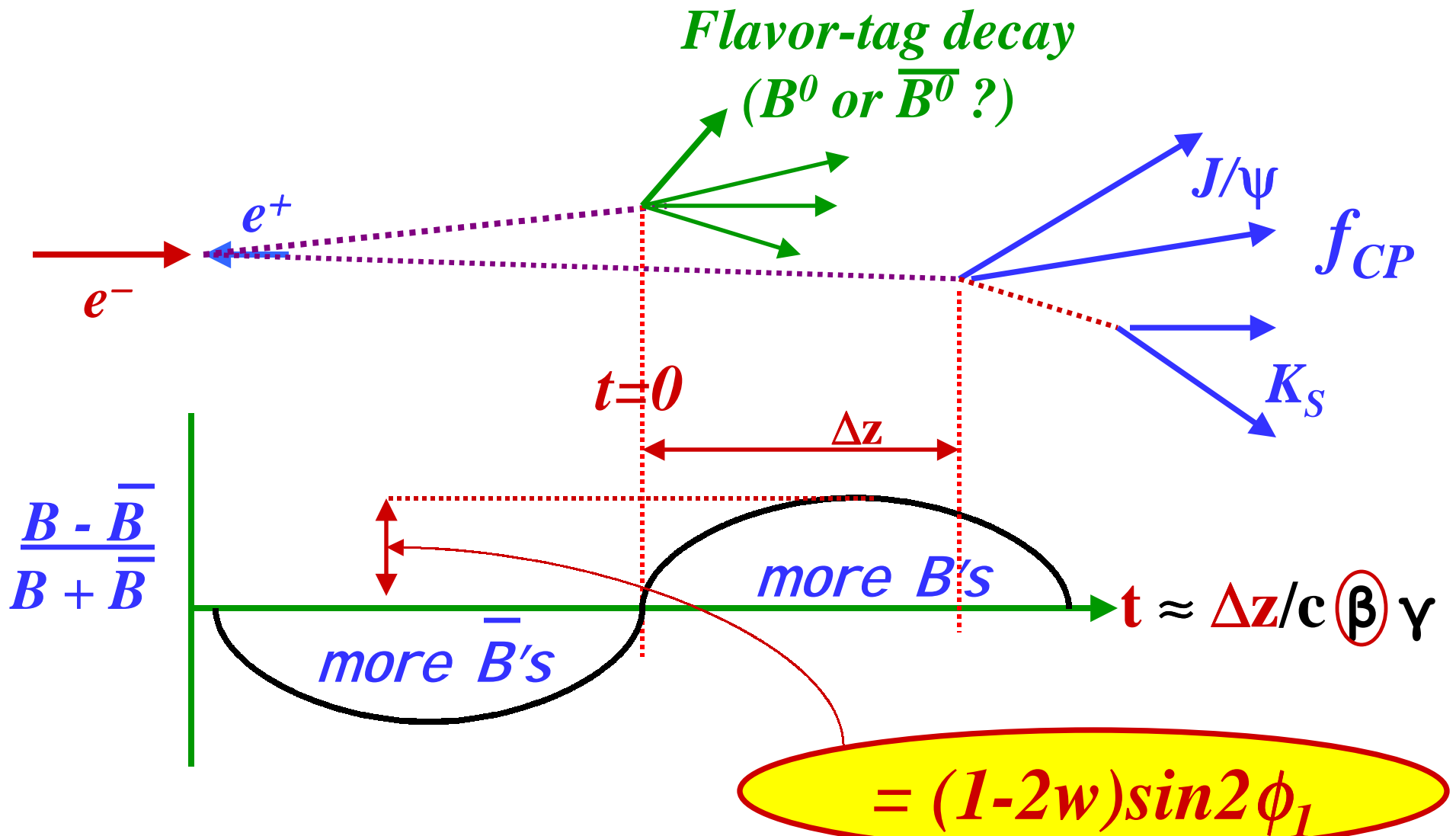
*PDG notation!*



$t$



# What do we measure?

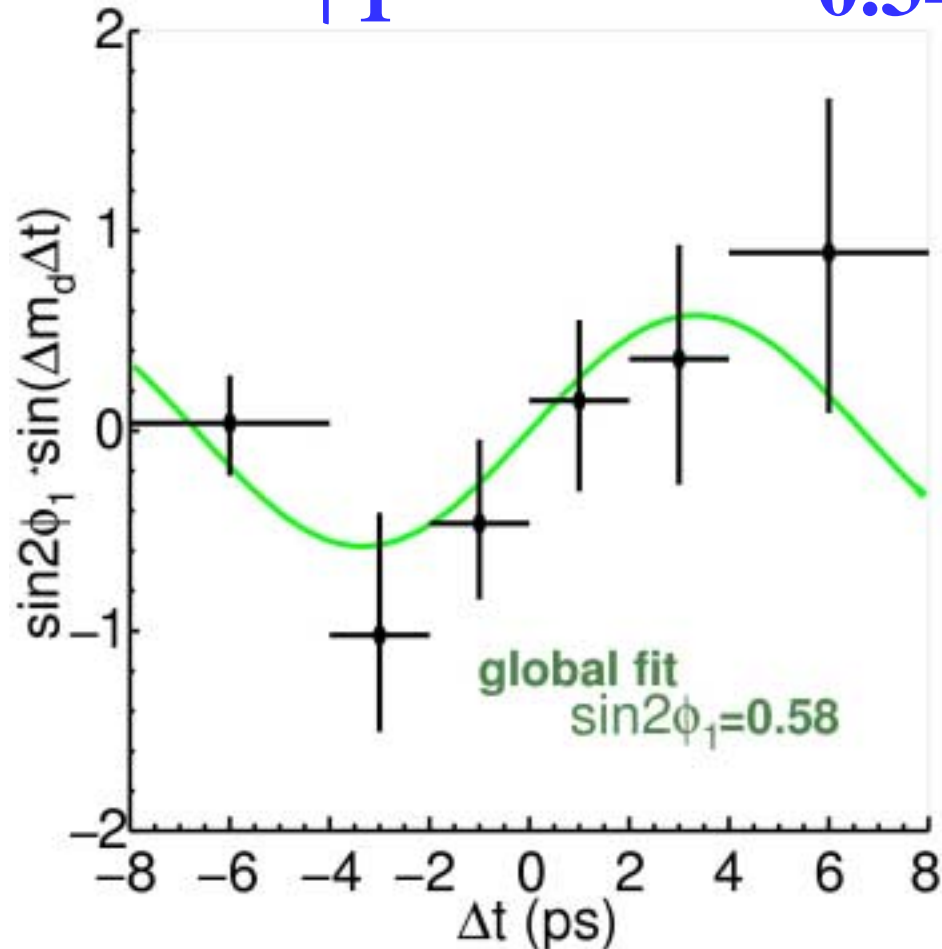






# Previous result (using 10.5 fb<sup>-1</sup>)

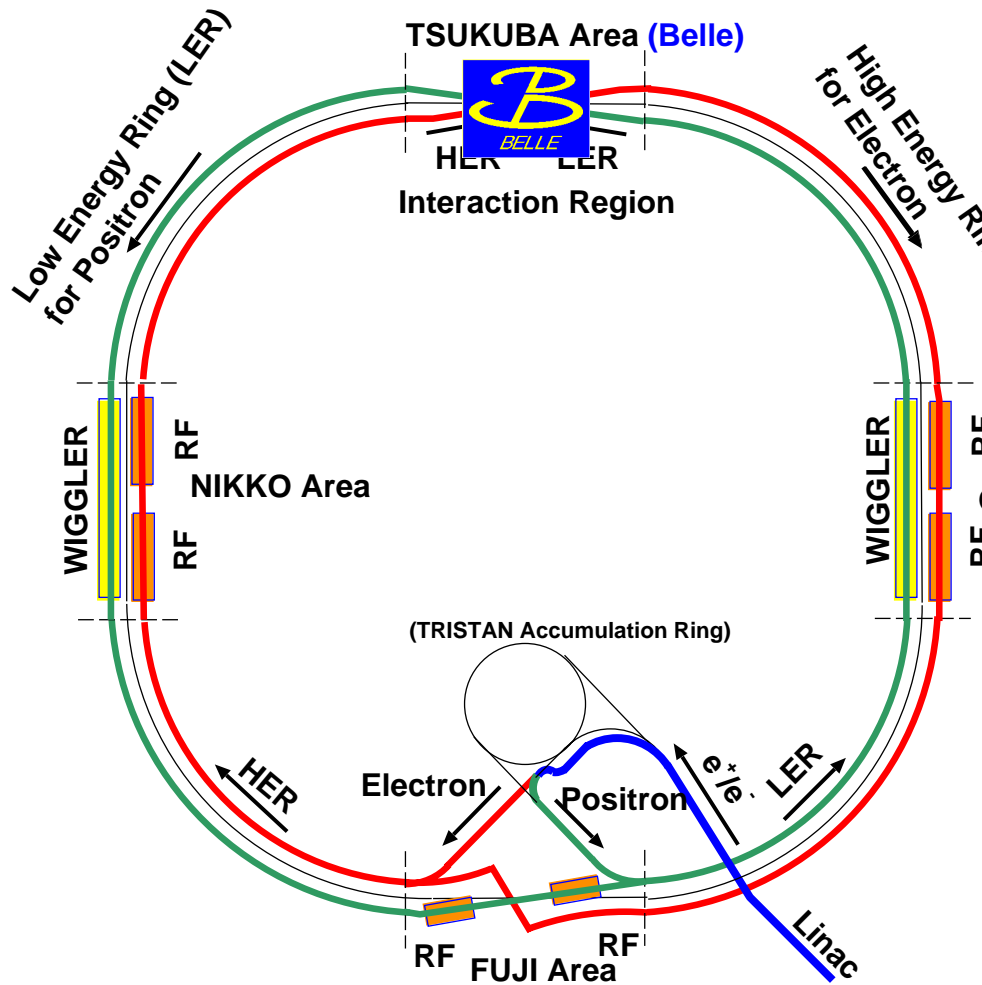
$$\sin 2\phi_1 = 0.58 \quad \begin{matrix} +0.32 & +0.09 \\ -0.34 & -0.10 \end{matrix}$$



**Today:  
Results from  
29.1 fb<sup>-1</sup>  
4x more events**



# 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:  $4 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$
- $\pm 11$  mrad crossing angle
- Small beam sizes:
  - $\sigma_y \approx 3 \mu\text{m}$ ;  $\sigma_x \approx 100 \mu\text{m}$

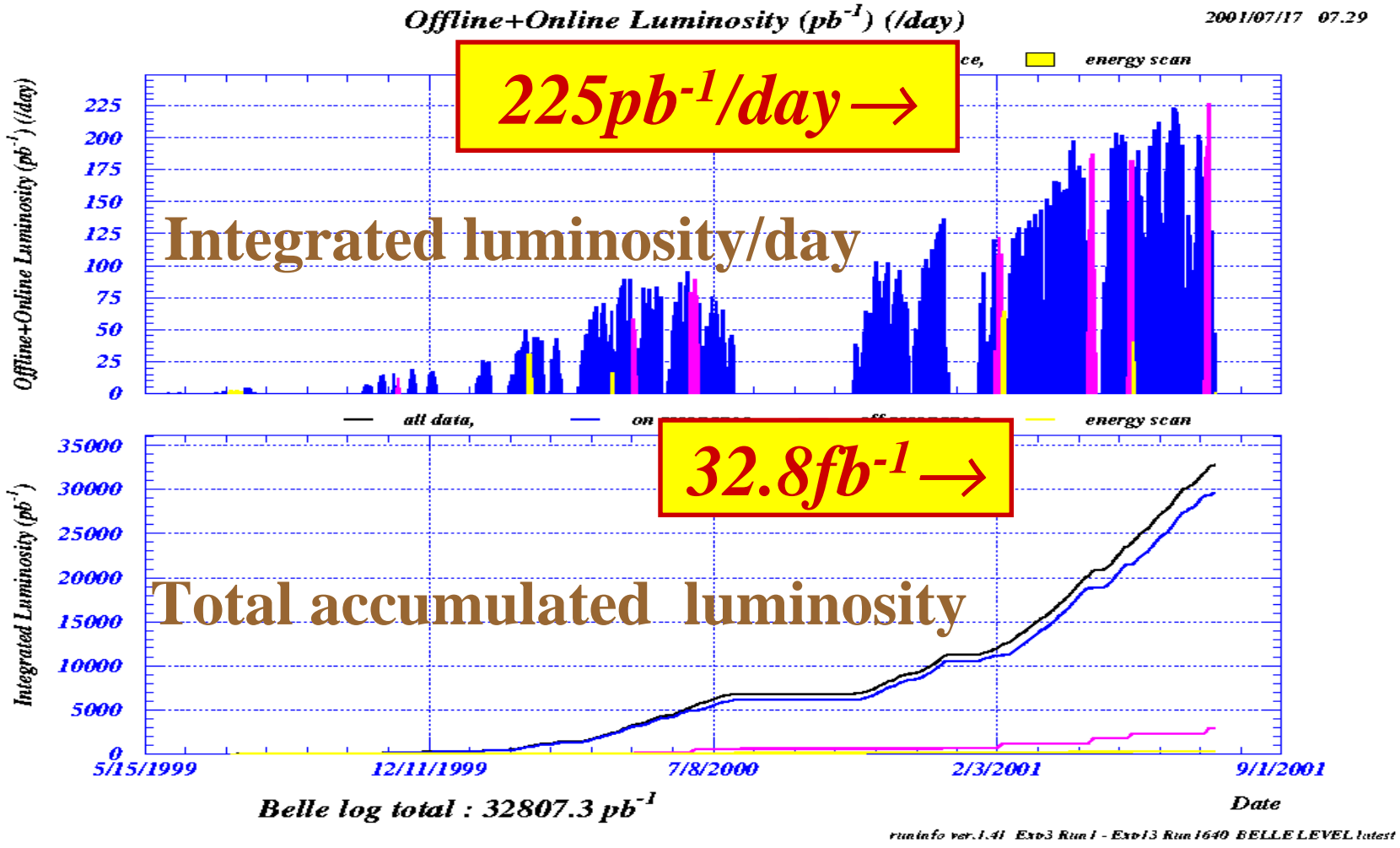


# What's needed?

- **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:  $\gamma(\beta) c\tau \approx 200\mu\text{m}$** )

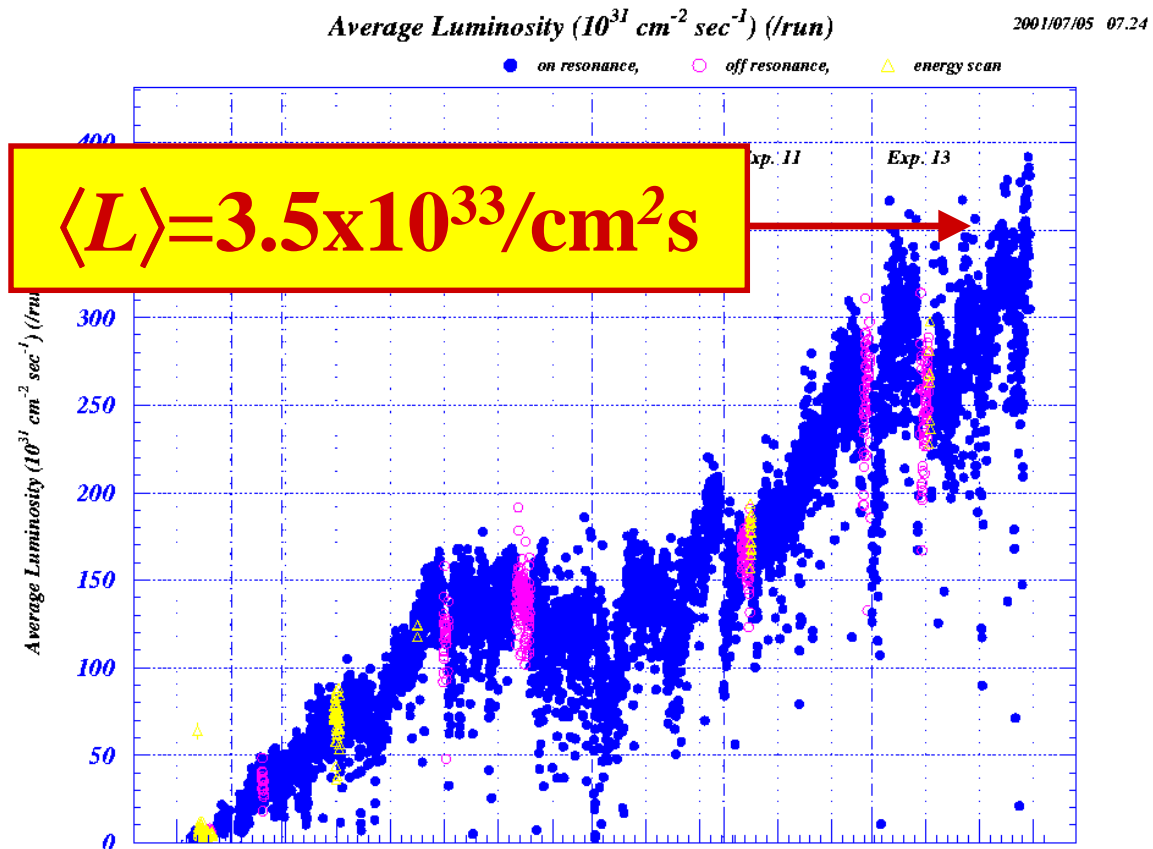


# KEKB performance





# Average luminosity during run

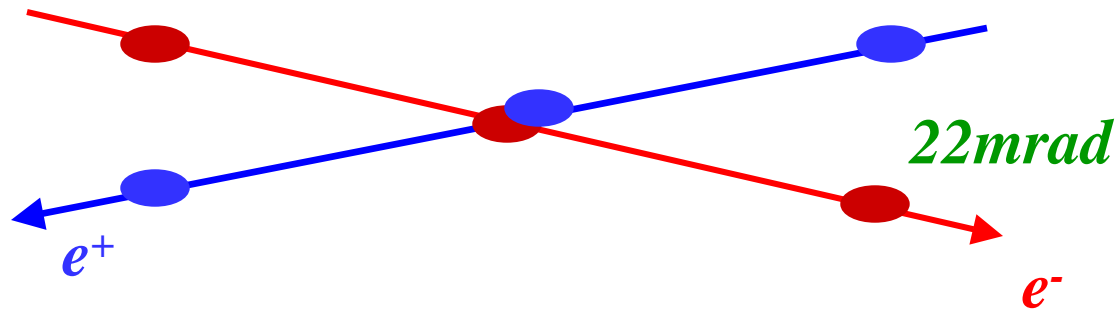


*All-time  $L_{peak} = 4.5 \times 10^{33} / \text{cm}^2 \text{ s}$*



# KEKB's Special Features

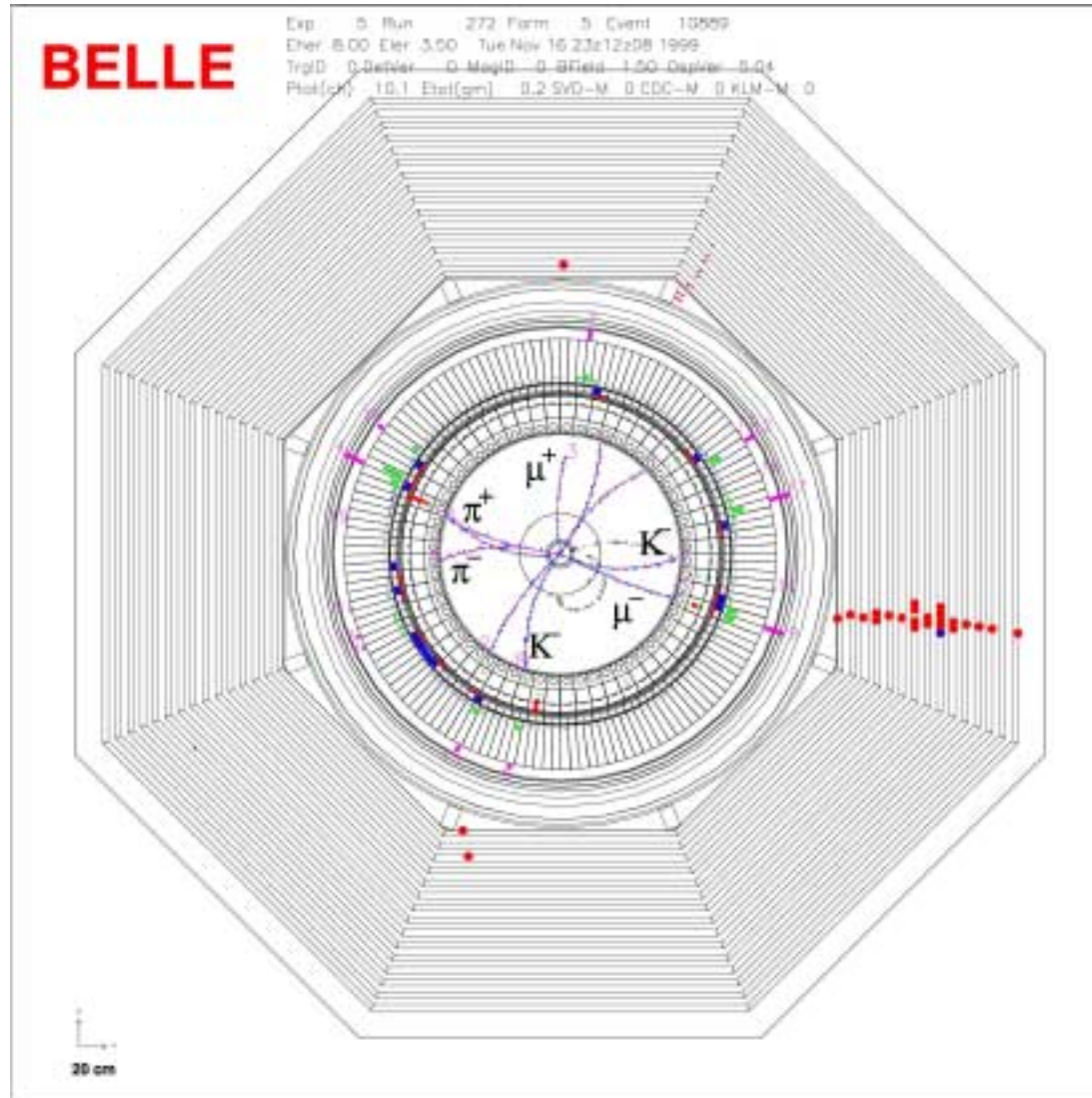
- Small beam sizes  $\Rightarrow$  **low beam currents**
  - $4.5 \times 10^{33}$  with less than 1 Amp in each ring
- $\pm 11$  mrad beam crossing angle



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

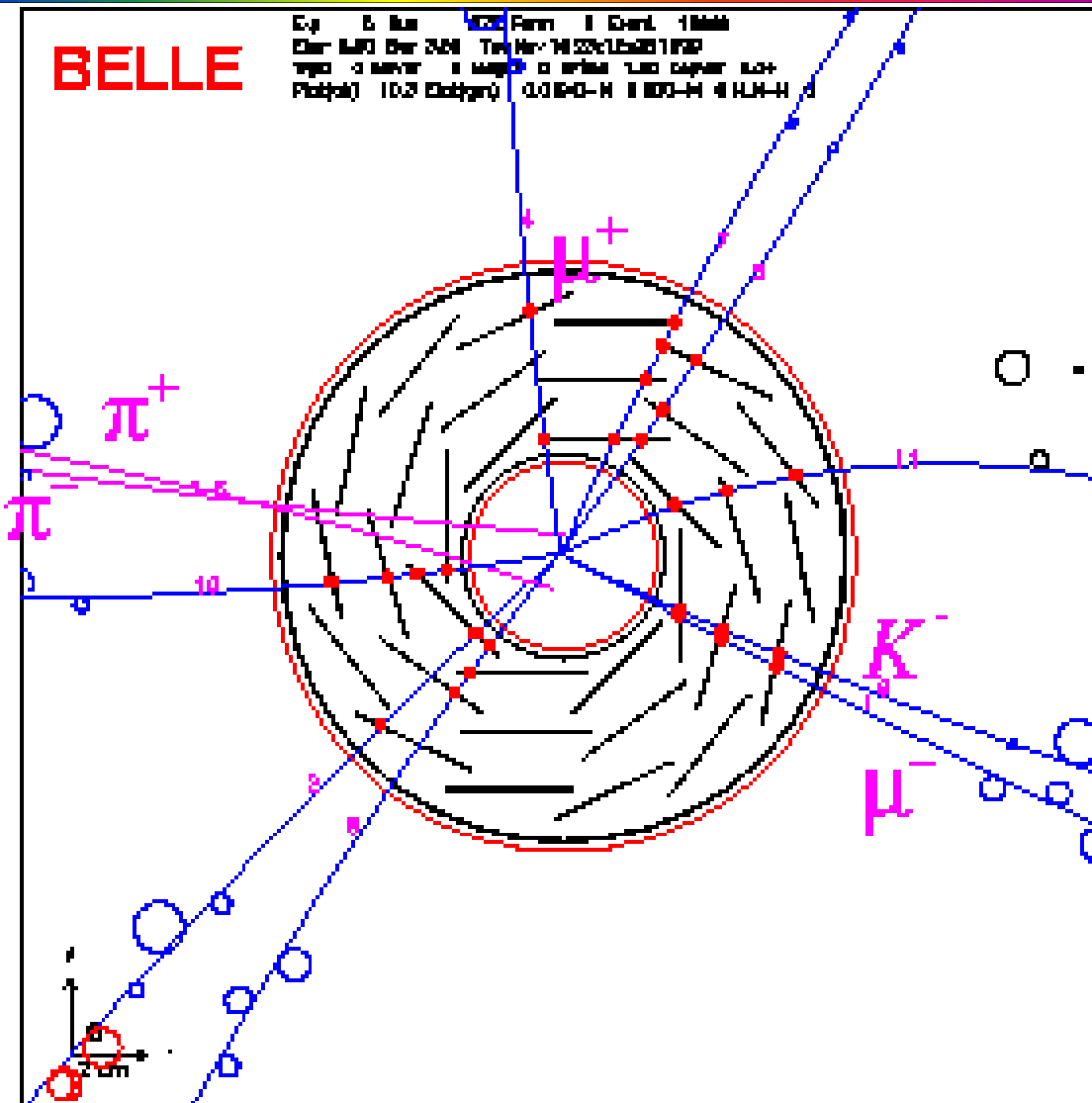


# The Belle detector: ( $B^0 \rightarrow J/\psi K_s$ )





# $B^0 \rightarrow J/\psi K_s$ event vertex

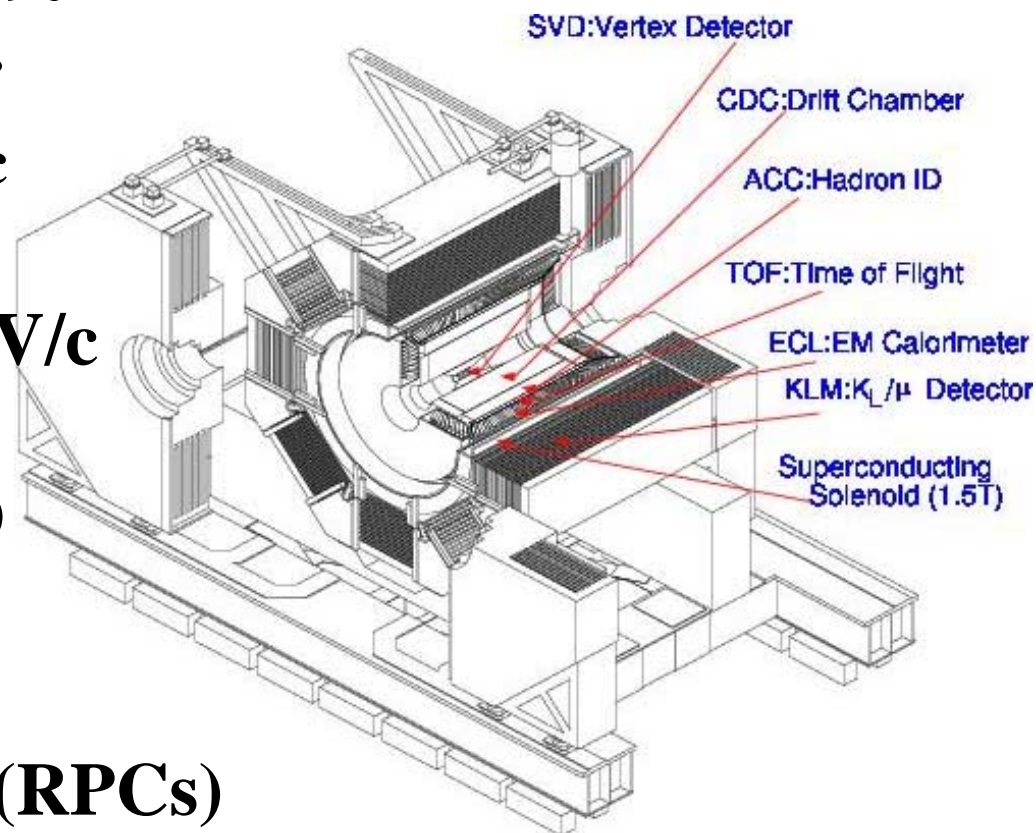






# Detector Performance

- ◆ **Silicon Vertex Detector**
  - ◆  $\sigma \sim 55\mu\text{m}$  for  $1\text{GeV}/c$  @  $90^\circ$
- ◆ **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 ( $n = 1.01 \sim 1.03$ )
- ◆  **$\gamma, e^\pm$  with CsI crystals**
  - ◆  $\sigma_E/E_\gamma \sim 1.8\%$  @  $1\text{GeV}$
- ◆ **KL and  $\mu^\pm$  with KLM (RPCs)**
  - ◆  $\mu^\pm$  : effic.  $> 90\%$  ;  $\sim 2\%$  fakes





# KEKB/*Belle* summary

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- **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**

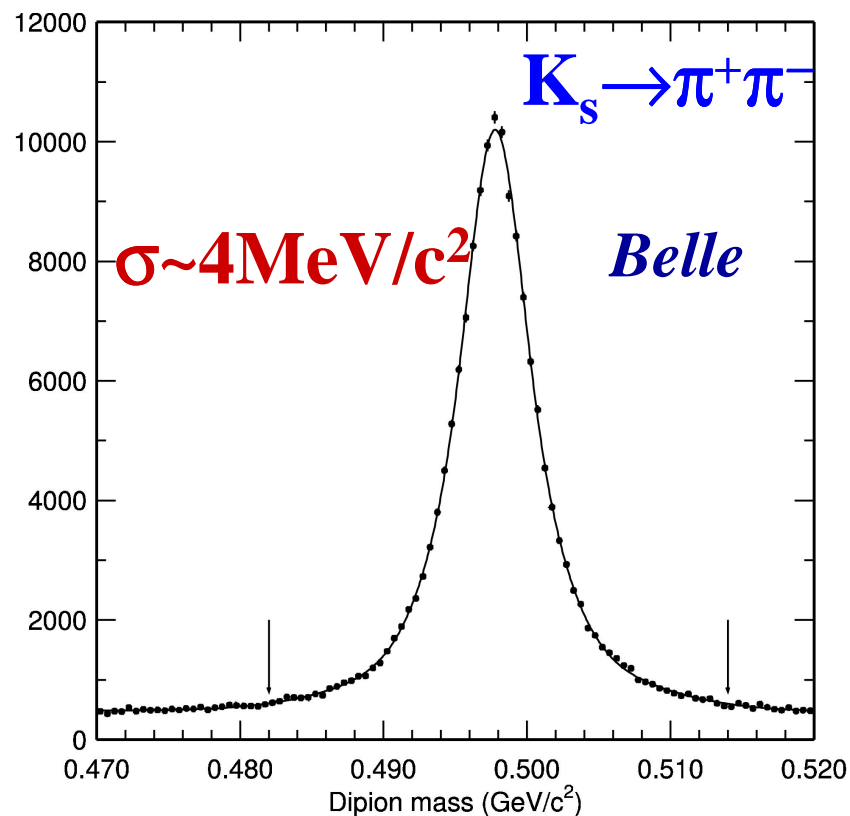
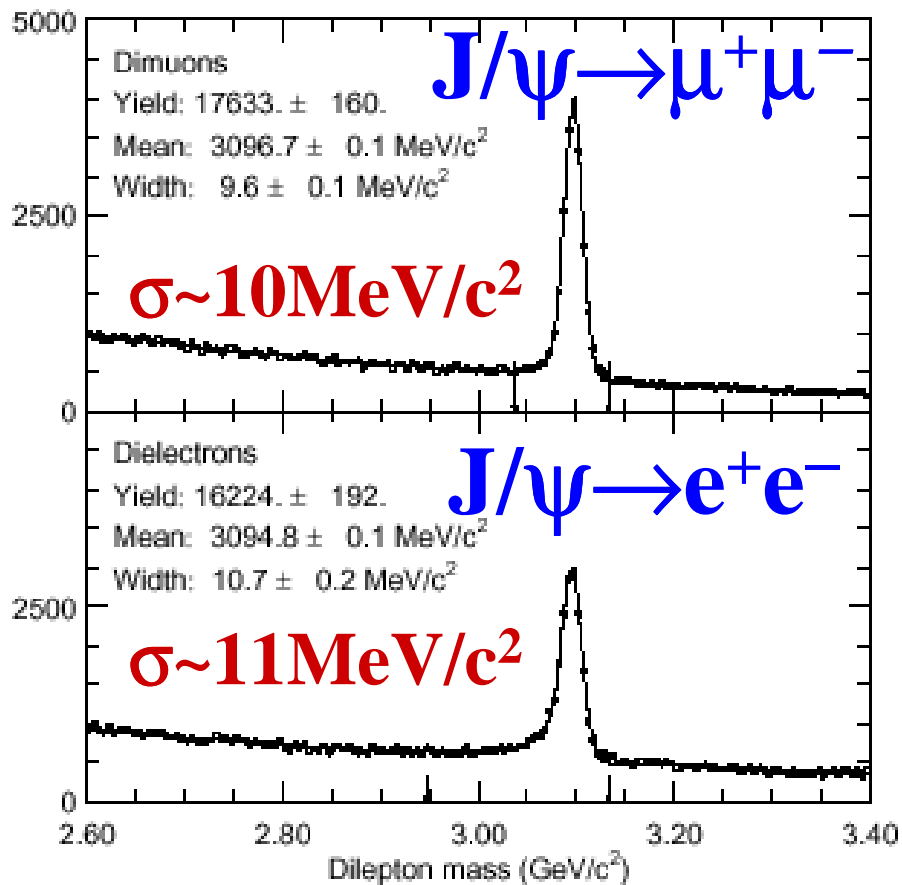
$$\begin{aligned} \mathbf{B}_{\text{CP}} \rightarrow & \mathbf{J}/\psi \mathbf{K}_S (\rightarrow \pi^+\pi^- \text{ \& } \pi^0\pi^0) \\ & \psi(2\text{S}) (\rightarrow l^+l^- \text{ \& } \mathbf{J}/\psi\pi^+\pi^-) \mathbf{K}_S \\ & \chi_{c1} (\rightarrow \mathbf{J}/\psi\gamma) \mathbf{K}_S \\ & \eta_c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

**CP even**

$$\begin{aligned} & \mathbf{J}/\psi \mathbf{K}_L \\ & \mathbf{J}/\psi \mathbf{K}^{*0} (\rightarrow \mathbf{K}_S\pi^0) \text{ (mostly)} \end{aligned} \left. \vphantom{\mathbf{B}_{\text{CP}}} \right\} \xi_f = +1$$



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

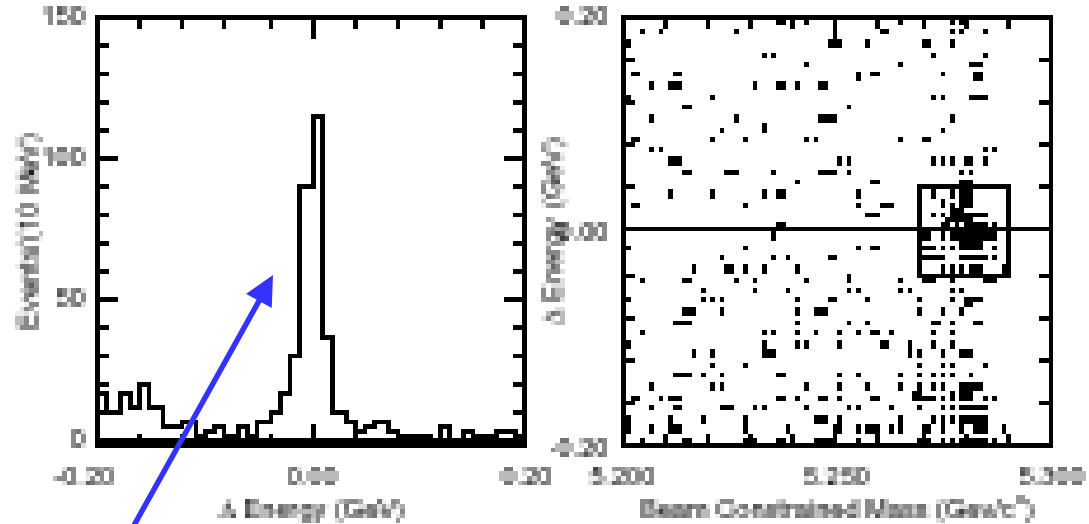


*Biggest contributor to the  $f_{cp}$  event sample*



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

457 events  
~3% bkgd

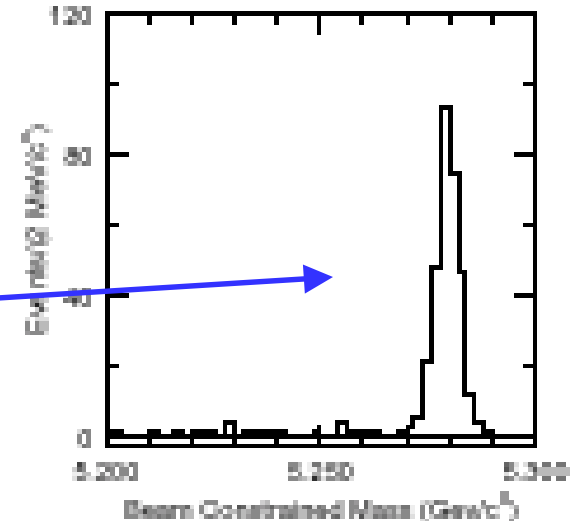


*Energy difference:*

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

*Beam-constrained mass:*

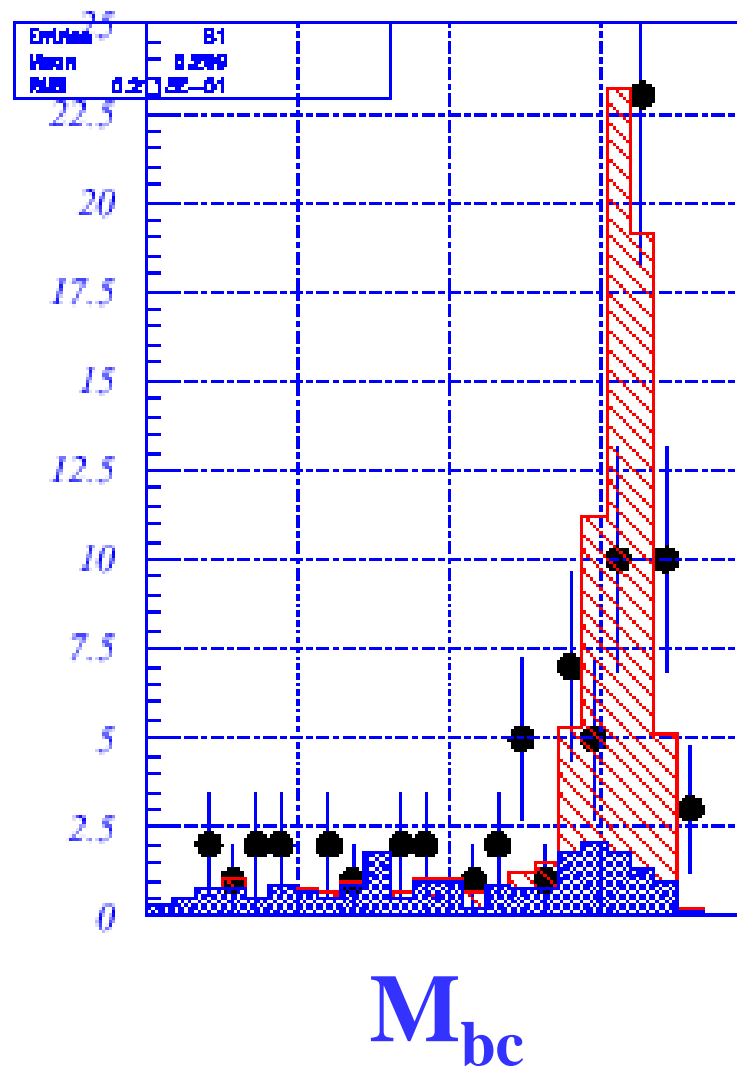
$$m_{bc} = \sqrt{(E_{CM}/2)^2 - (\vec{p}_{J/\psi} + \vec{p}_{K_S})^2}$$





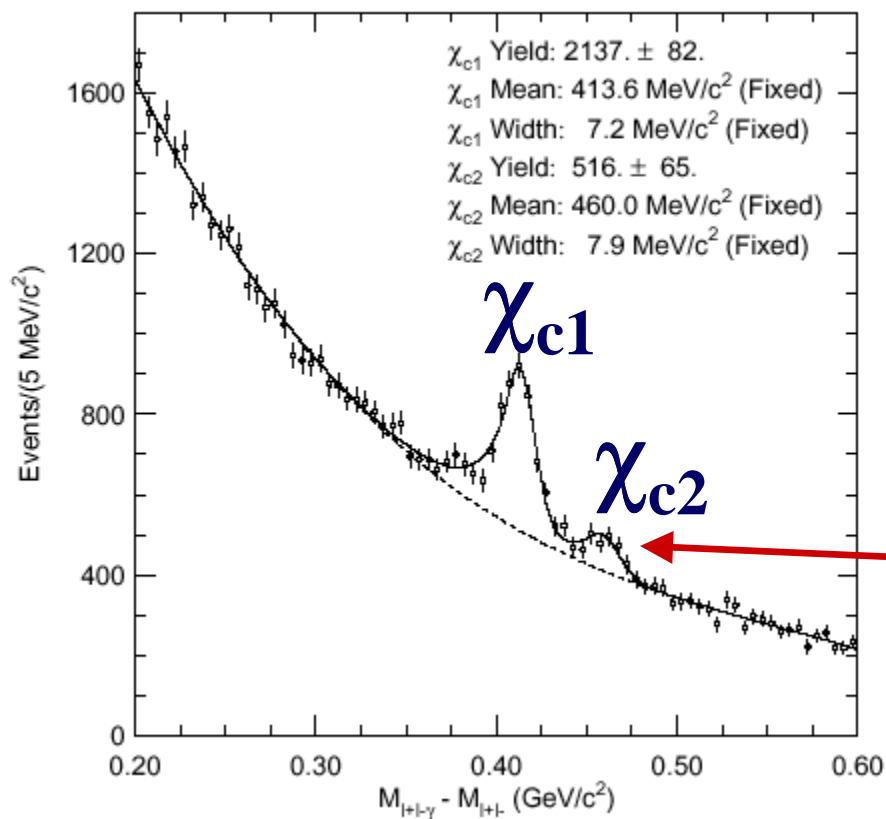
For  $B \rightarrow J/\psi K_S$ ; use  $K_S \rightarrow \pi^0 \pi^0$

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





# Other charmonium modes



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

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



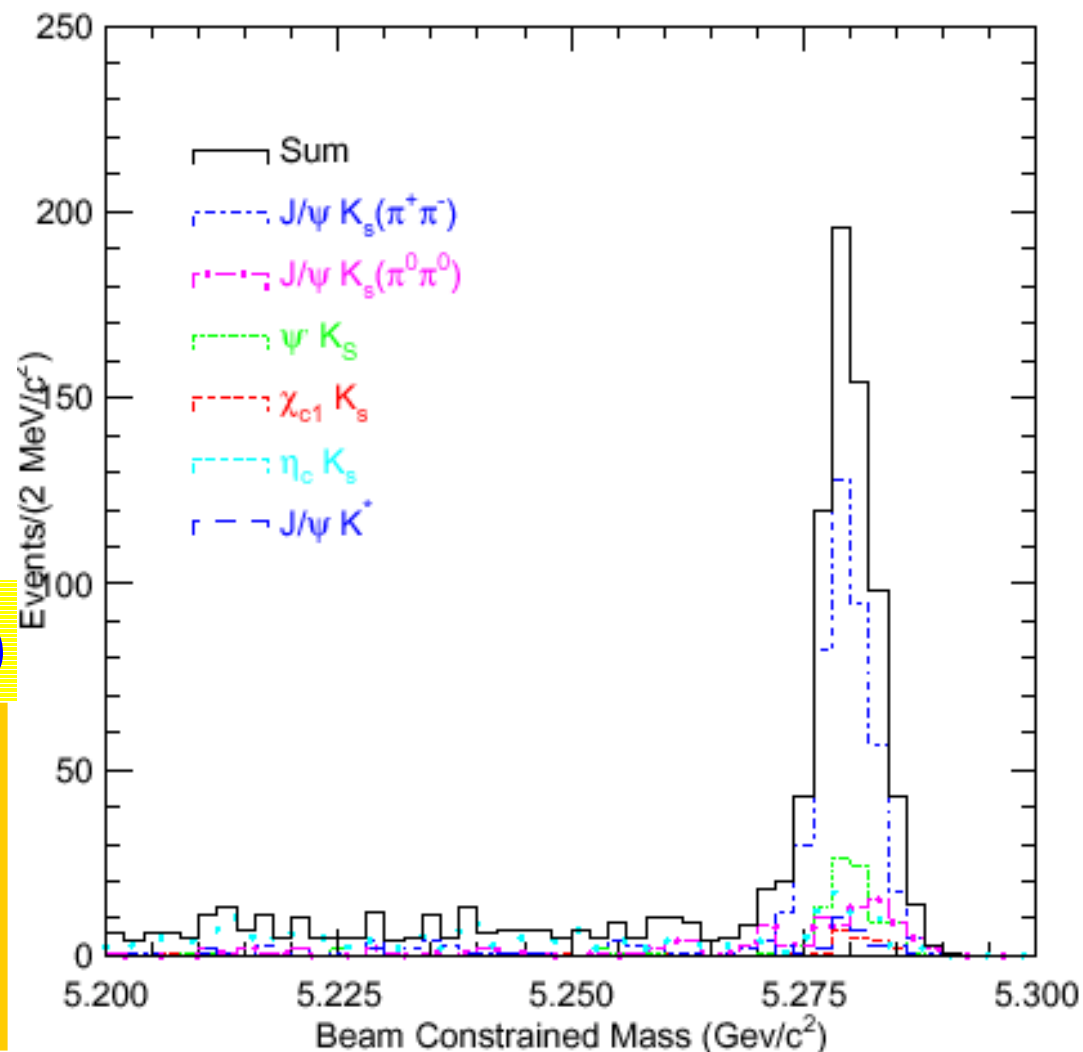
# All CP-1 modes

$B^0 \rightarrow$  other modes

290 candidates  
46 background  
(Purity = 84%)

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

457 candidates  
~12 background  
(Purity = 97%)

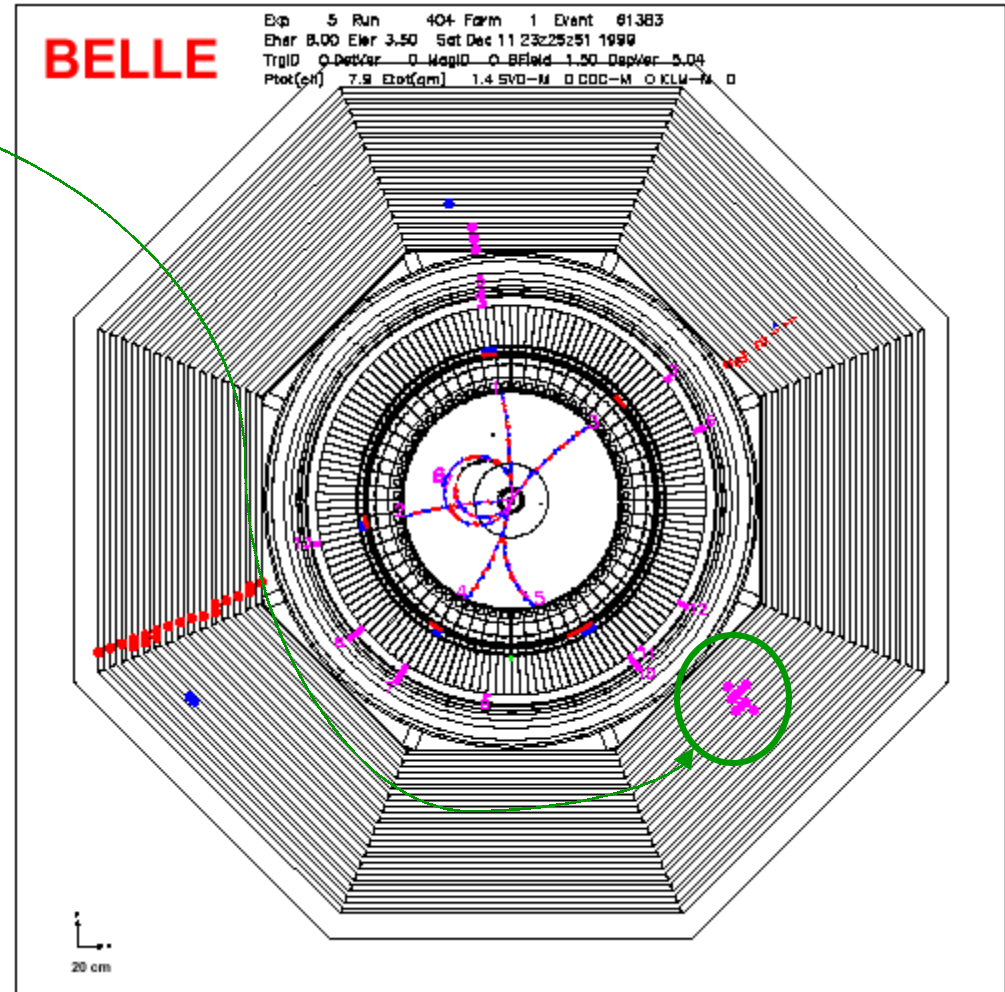






# $B^0 \rightarrow J/\psi K_L$

- 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  $P_B^* = |\vec{P}_{J/\psi} + \vec{P}_{KL}|$



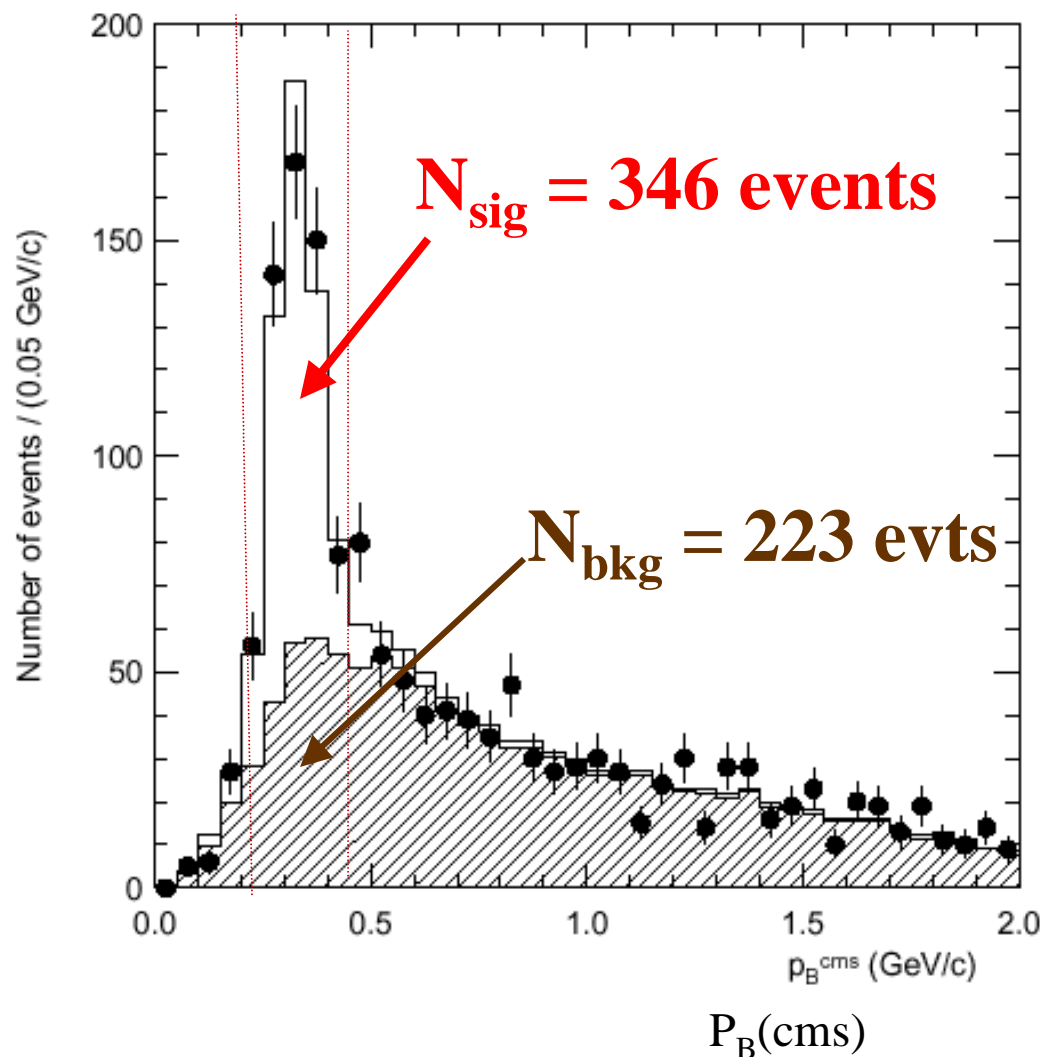


# $B^0 \rightarrow J/\psi K_L$ signal yield

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

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

569 total events  
346 signal  
(Purity = 61%)





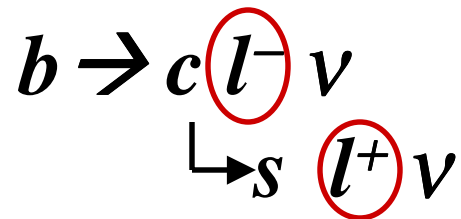
# Flavor-tag the other B meson

Use *inclusive* flavor-specific properties:

▪ *Inclusive Leptons:*

▪ *high-p*  $l^-$

▪ *intermed-p*  $l^+$

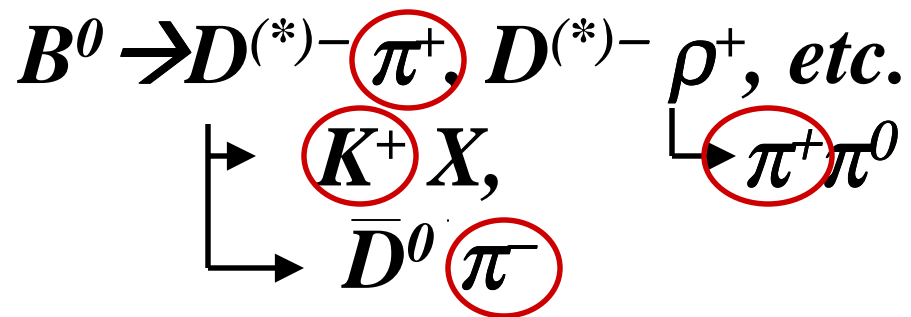


▪ *Inclusive Hadrons:*

▪ *high-p*  $\pi^+$

▪ *intermed-p*  $K^+$

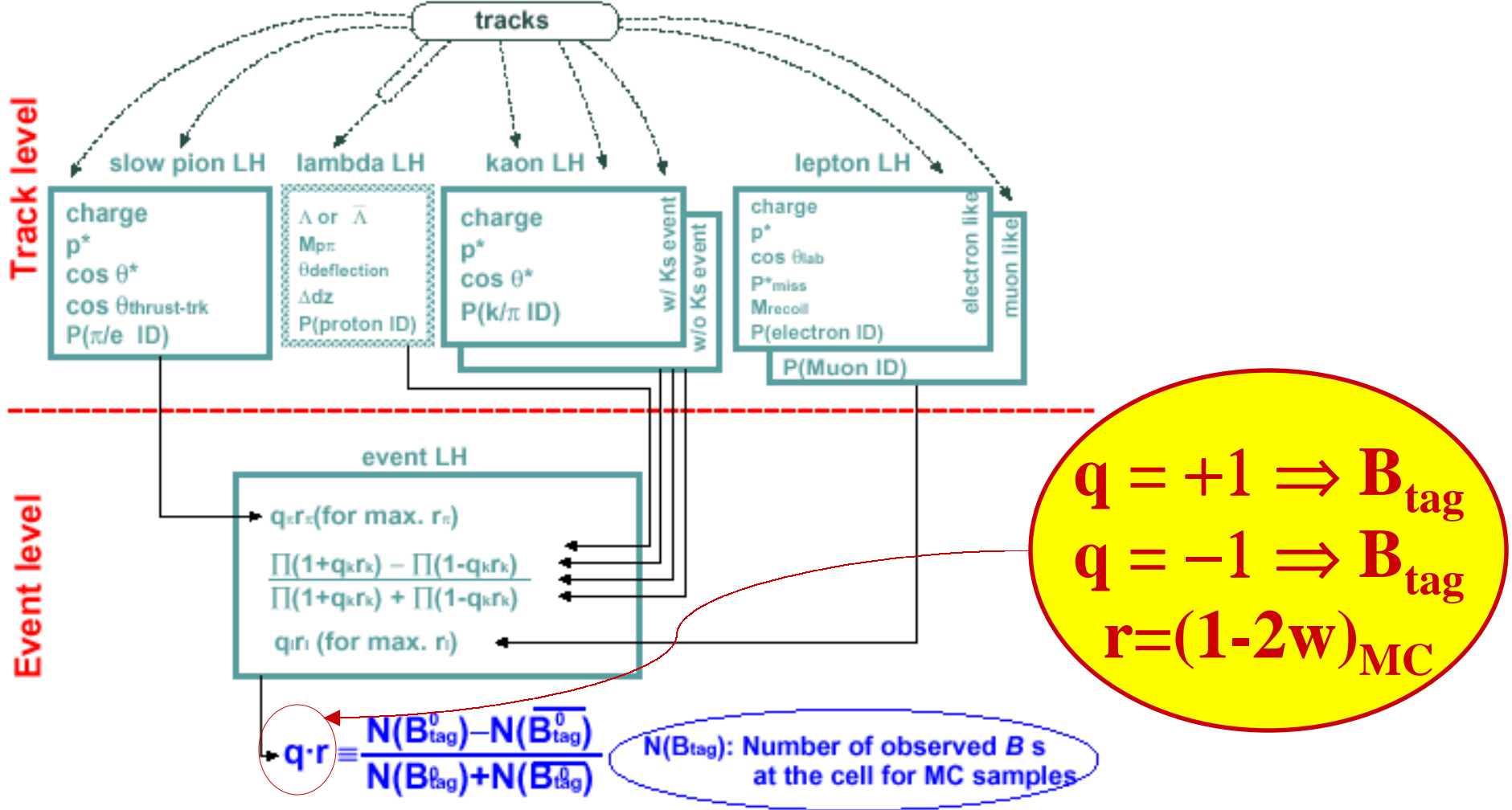
▪ *low-p*  $\pi^-$



Also need to consider *correlations*



# 2-level Multi-dimensional flavor tagging

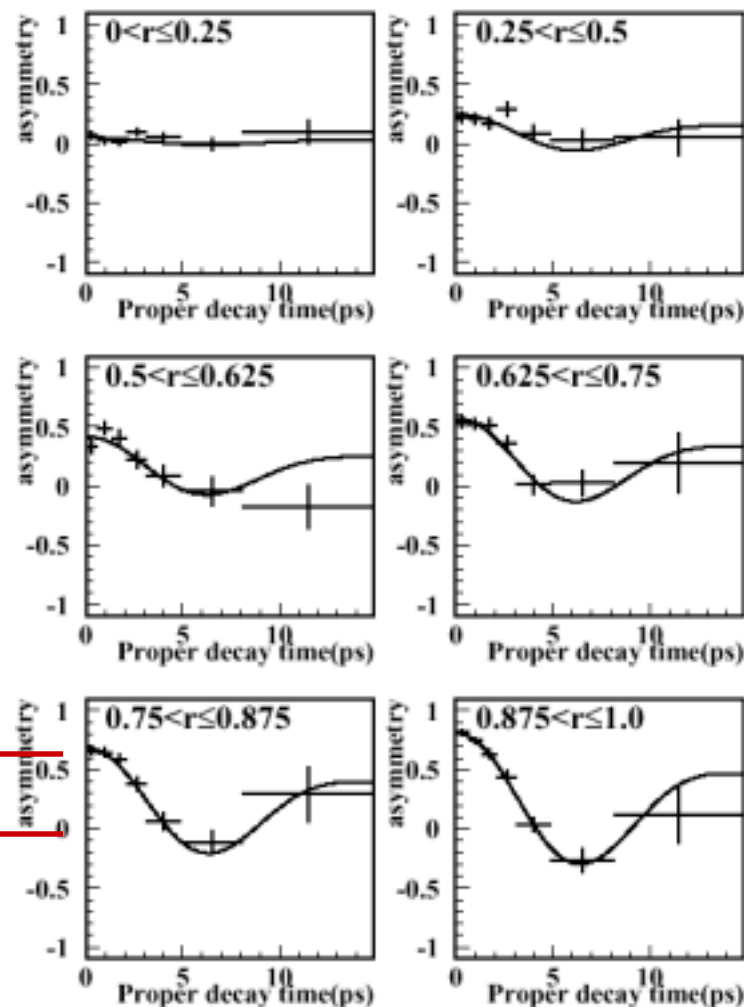




# Determination of wrong tag fraction $w_l$

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

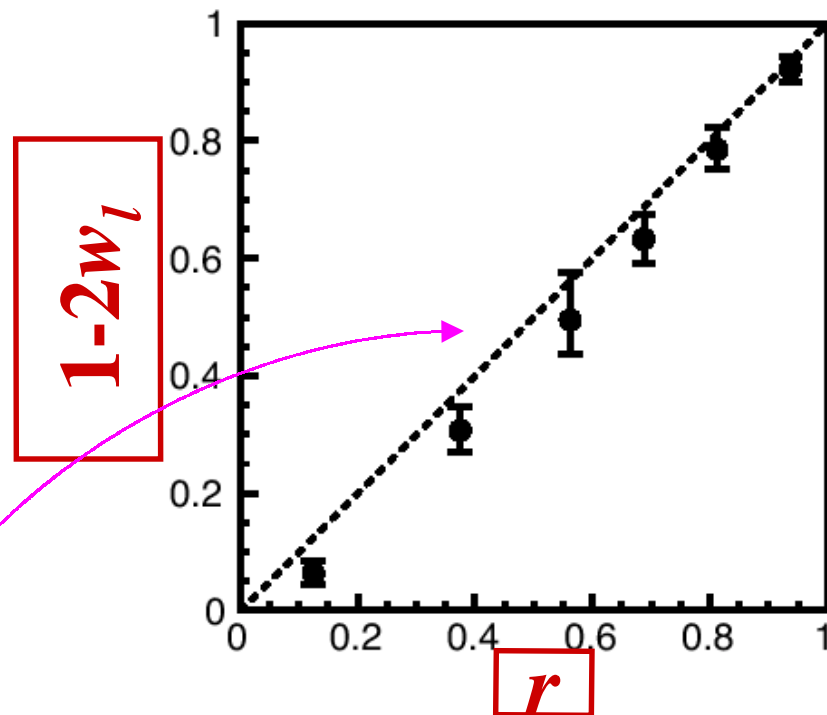
$B^0 \rightarrow D^* \bar{l} \nu$





# 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

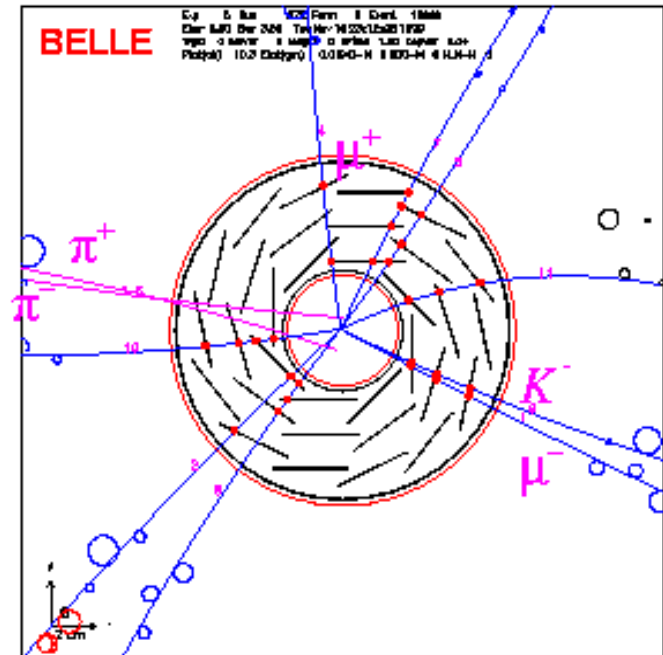


MC-determined  $r \approx 1-2w$  measured from data



# Vertex Reconstruction

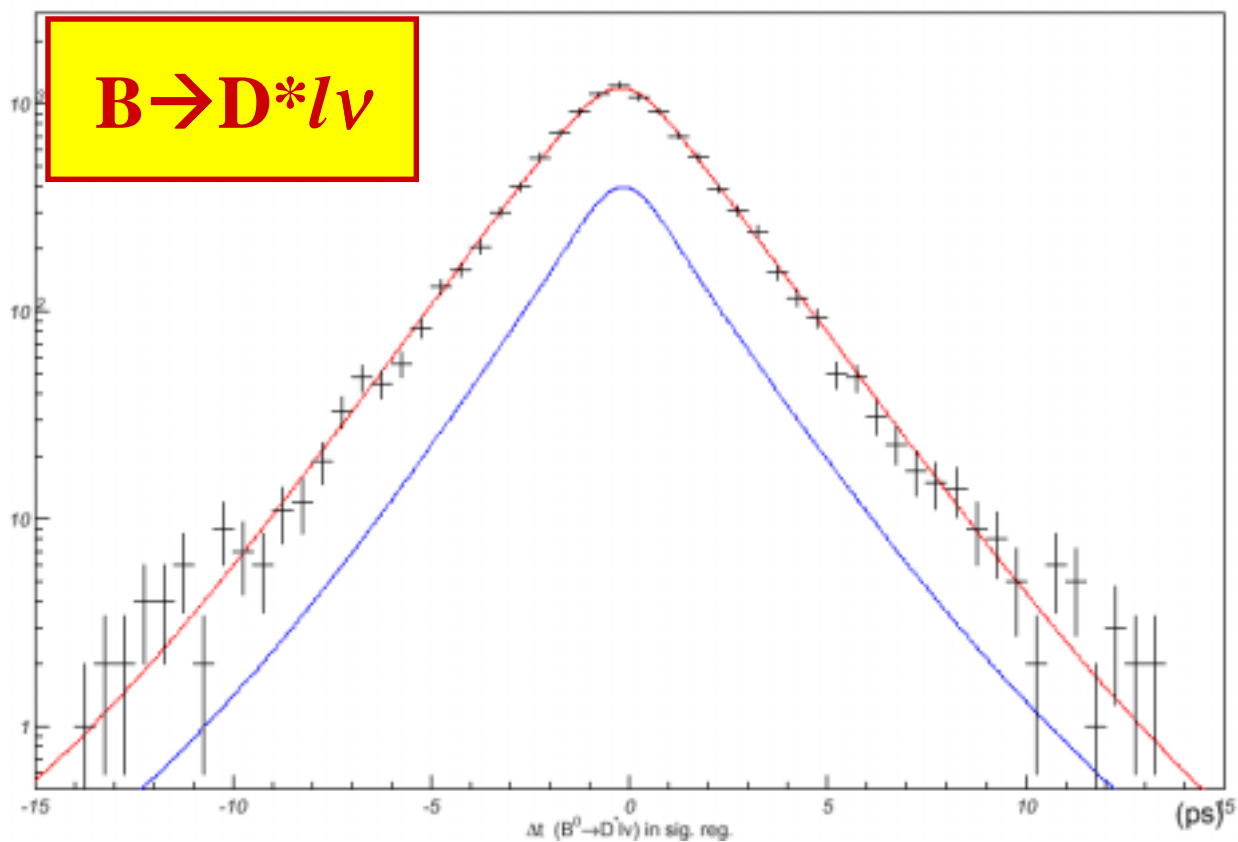
- For  $CP$ -side, use  $J/\psi \rightarrow l^+l^-$ 
  - Reject poorly fit events.  
 $\delta z_{CP} \approx 75 \mu\text{m}$  (rms)
- For  $Tag$ -side
  - use well fit tracks
  - iterate: discard worst track
  - $\delta z_{tag} \approx 140 \mu\text{m}$  (rms)
- Require  $|z_{CP} - z_{tag}| < 2\text{mm}$  ( $\approx 10\tau_B$ )  
 $\sigma_{\Delta t} \approx 1.5 \text{ ps}$
- Tails  $\approx 3\%$ ; Effic.  $\approx 85\%$



**1137 evts used in the CP fit.**



# Validation: B lifetimes



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

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

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

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





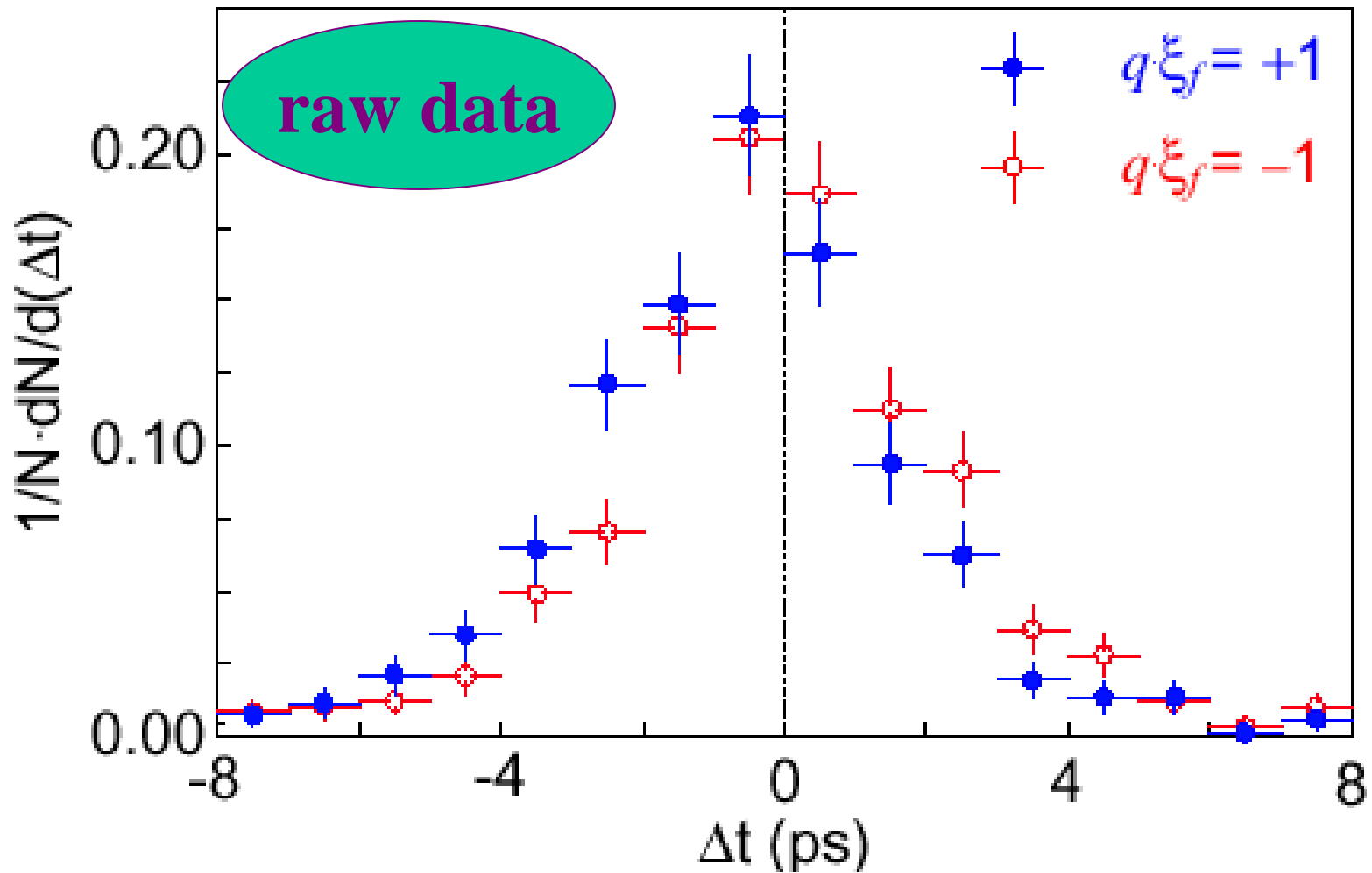
# Timeline

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- **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 $q$ , $\xi_f$ & $\Delta t$





# CP is violated in B decays!!

- Large effect
- Apparent in the raw data
- Many  $\sigma$



# 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  $CP = \pm 1$

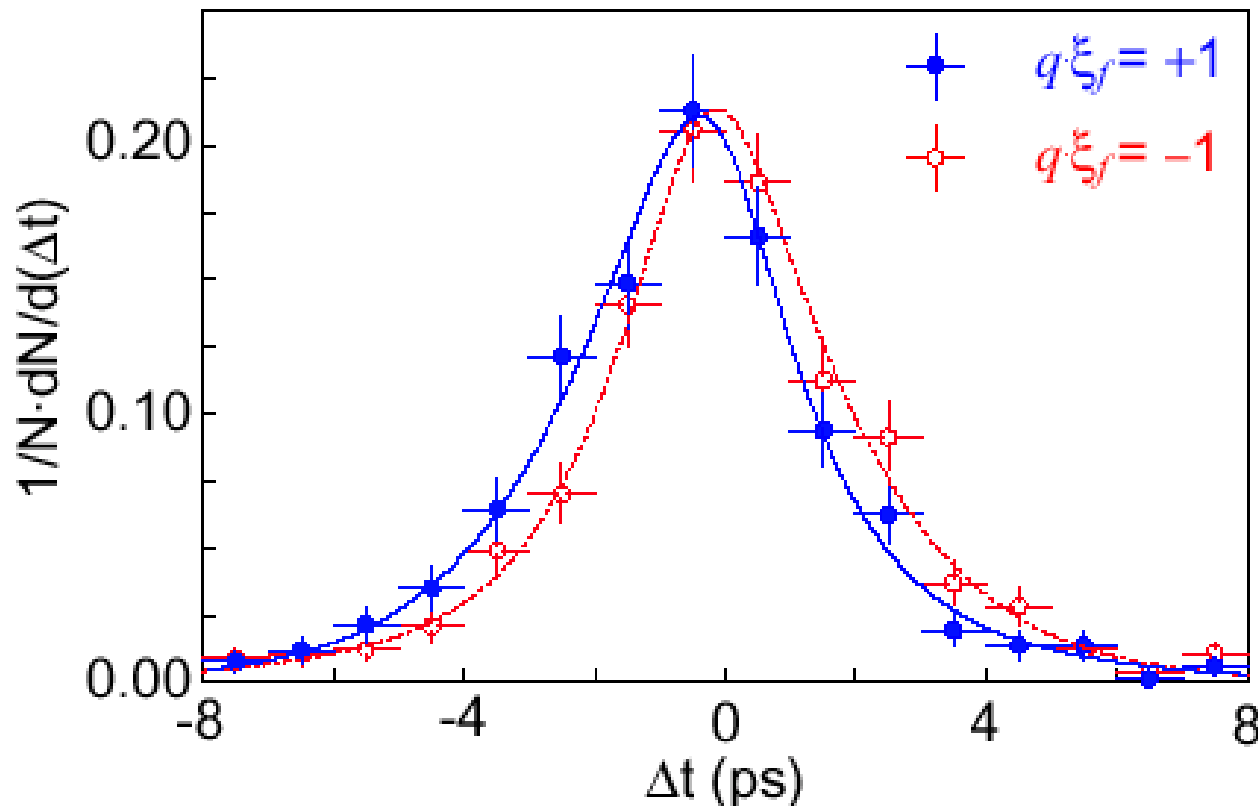
*free parameter*

*wrong-tag frac.*



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

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



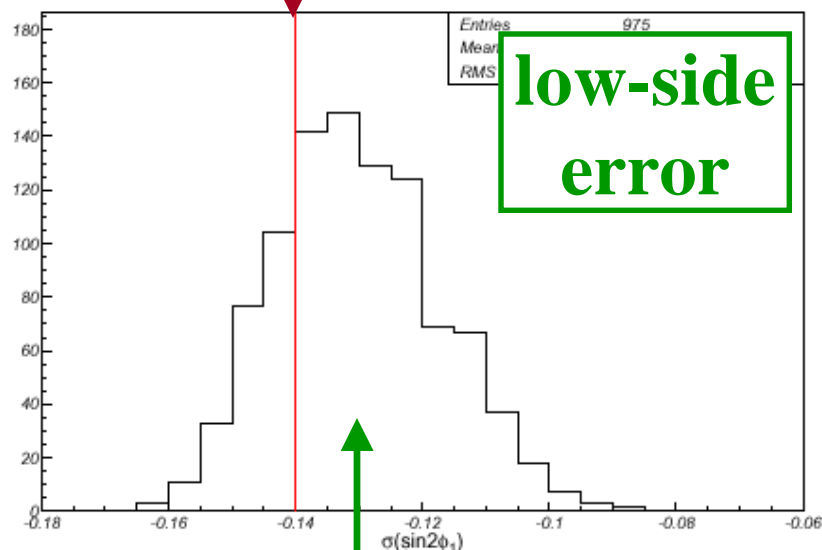


# Do the fits & errors make sense?

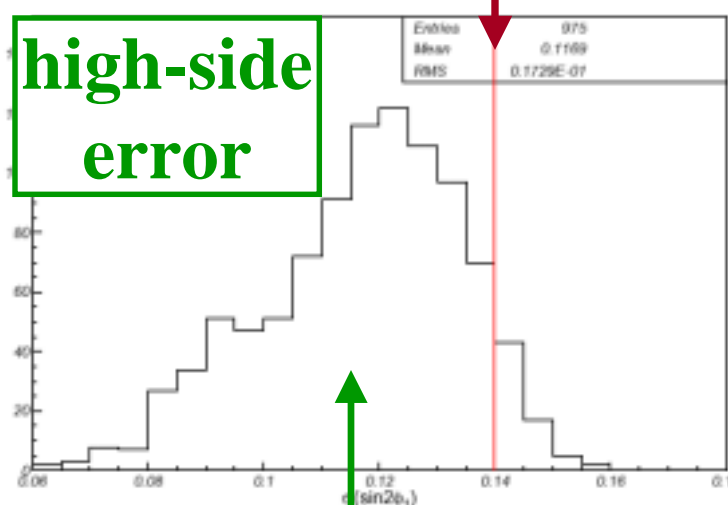
Use toy MC: run 1K similar expts  
with  $\sin 2\phi_1$  (input)=0.99

our  
fit:

**-0.14**



**+0.14**



Toy MC  
means:

**-0.128**

**+0.116**



# asymmetry display

used binned data to examine “goodness of fit”

Plot:

$$\xi_f \frac{N_B - N_{\bar{B}}}{N_B + N_{\bar{B}}} \text{ vs } \Delta t$$

weight events  
by their CP  
sensitivity

divide data  
into  $\Delta t$  bins

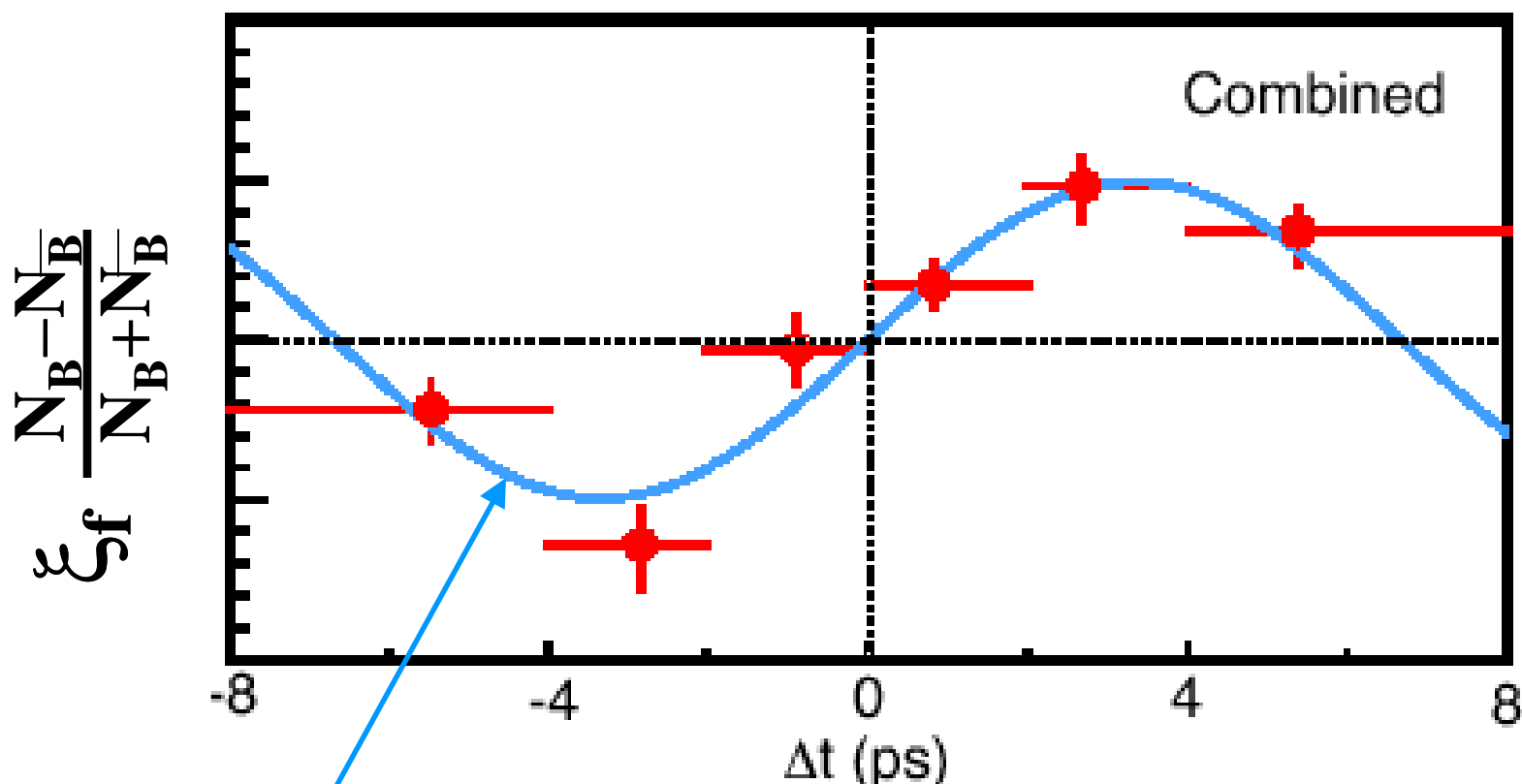
fit for  $\sin 2\phi_{1i}$   
for each  $\Delta t_i$

plot:  
 $\sin 2\phi_{1i} \frac{\sin \Delta m \Delta t_i}{\Delta t_i}$





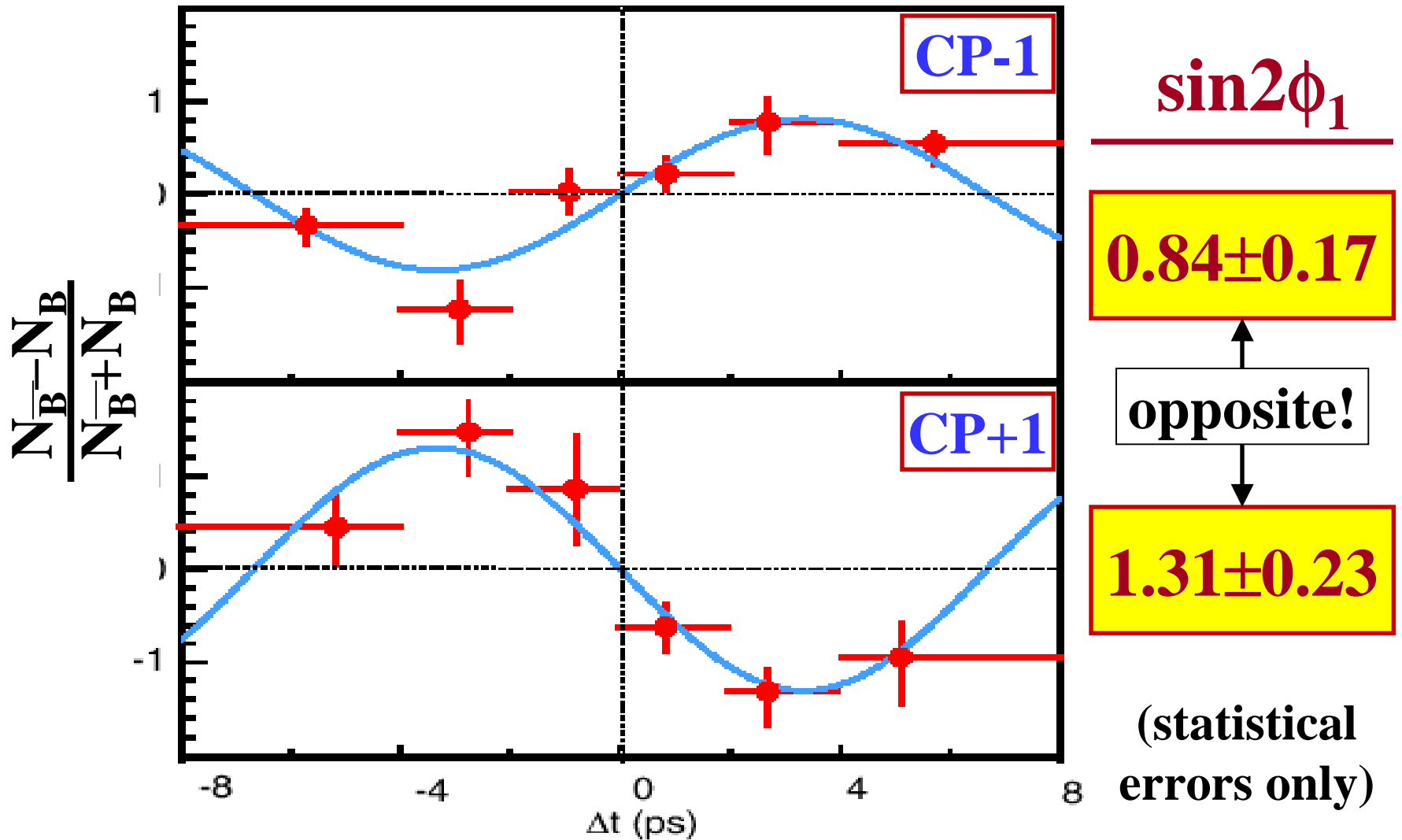
# asymmetry plot: all data



Result from global fit ( $\sin 2\phi_1 = 0.99$ )

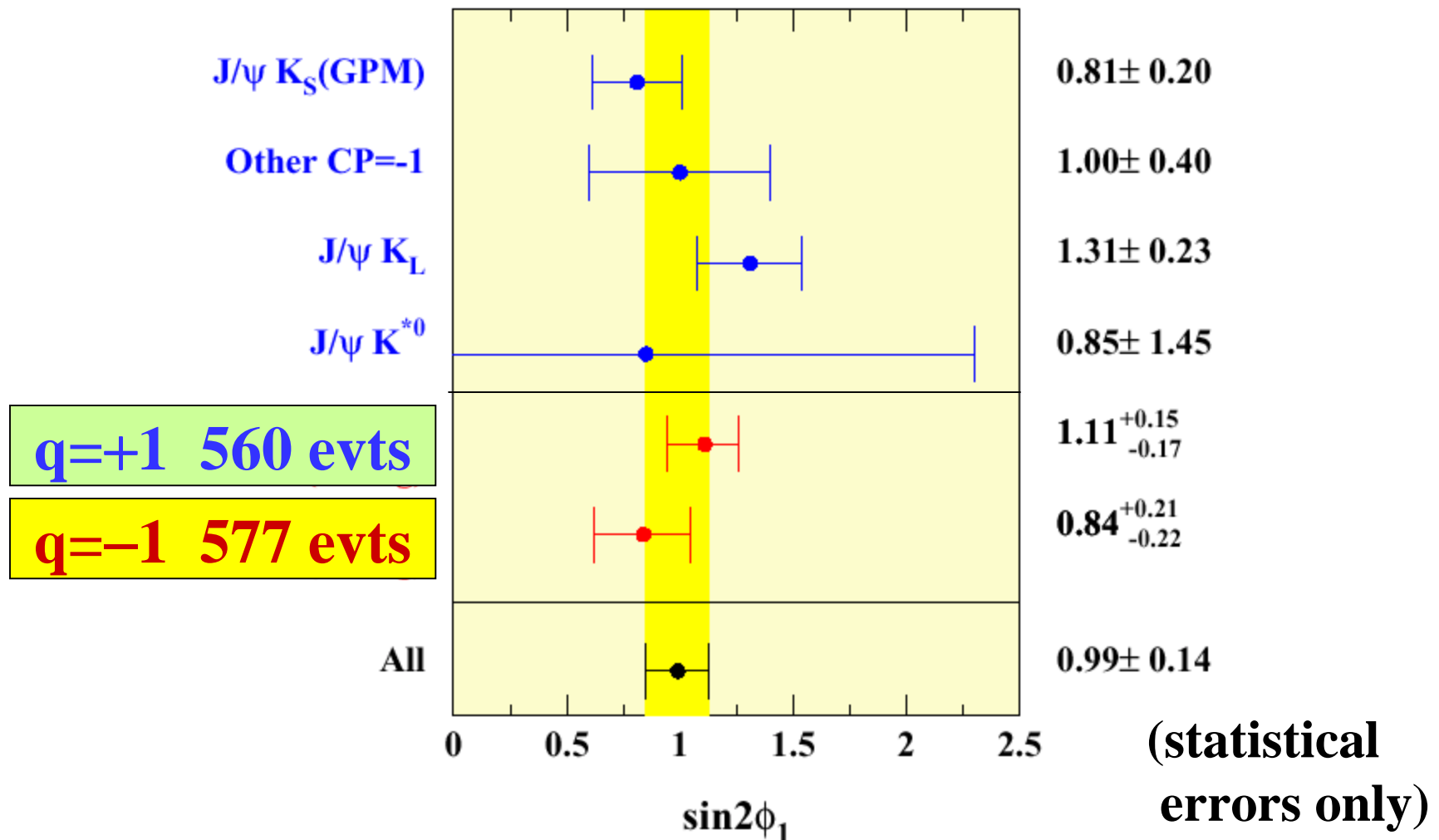


# Compare CP -1 and CP+1





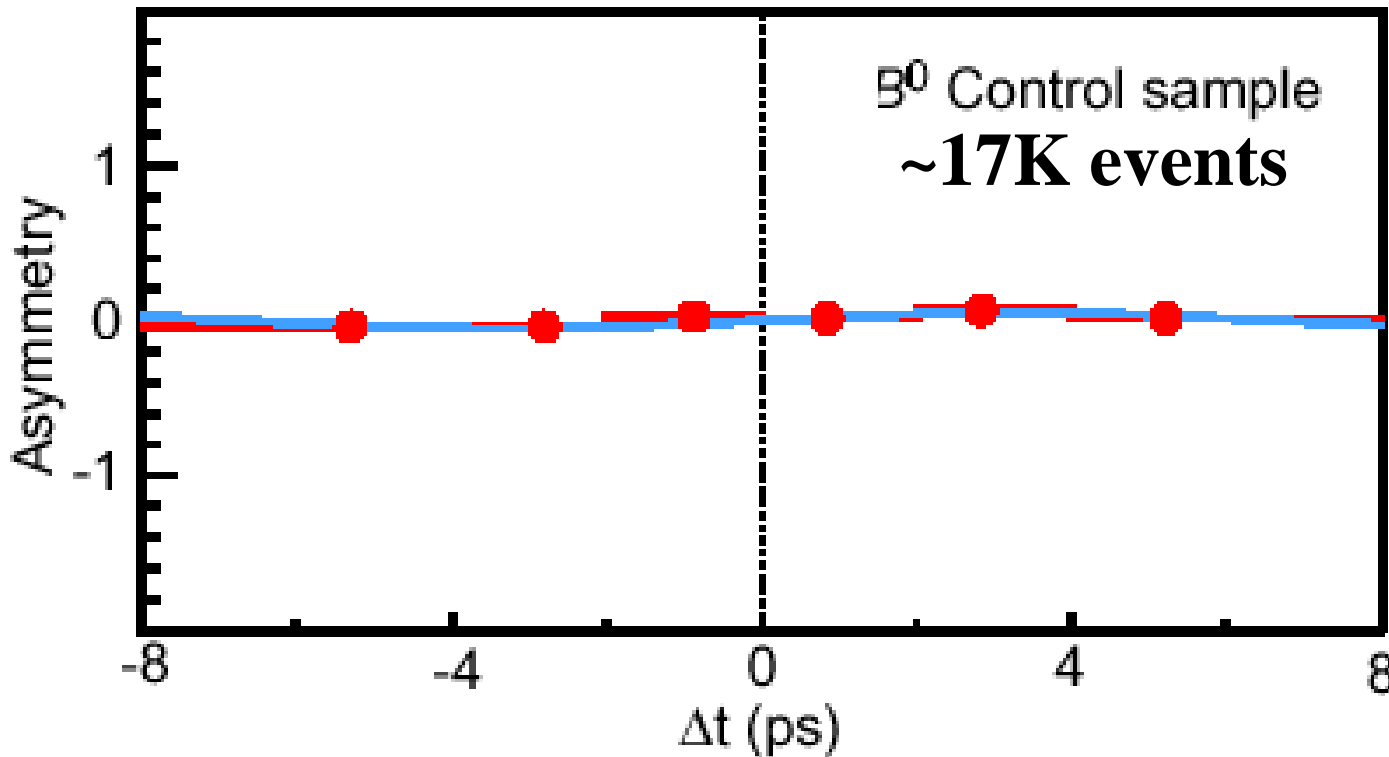
# $\sin 2\phi_1$ from various subsamples





# Control sample: $B^0 \rightarrow \text{non-CP states}$

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



“ $\sin 2\phi_1$ ”

$0.05 \pm 0.04$

(statistical error only)

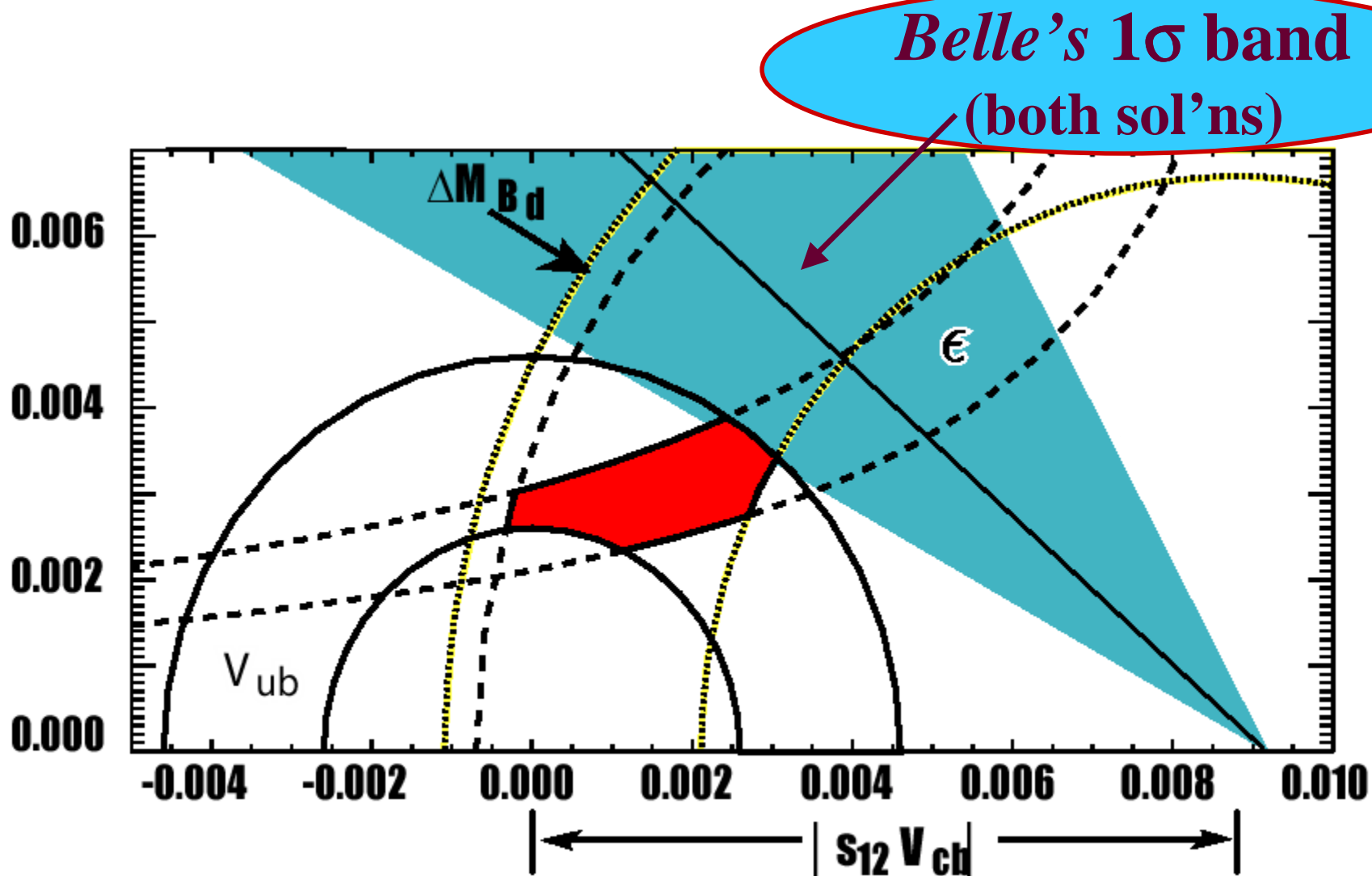


# CP fit : Systematic Error

<b>Vertex algorithm</b>	<b><math>\pm 0.04</math></b>
<b>Flavor tagging</b>	<b><math>\pm 0.03</math></b>
<b>Resolution function</b>	<b><math>\pm 0.02</math></b>
<b><math>K_L</math> background fraction</b>	<b><math>\pm 0.02</math></b>
<b>Background shapes</b>	<b><math>\pm 0.01</math></b>
<b><math>\Delta m_d</math> and <math>\tau_{B_0}</math> errors</b>	<b><math>\pm 0.01</math></b>
<b>Total</b>	<b><math>\pm 0.06</math></b>

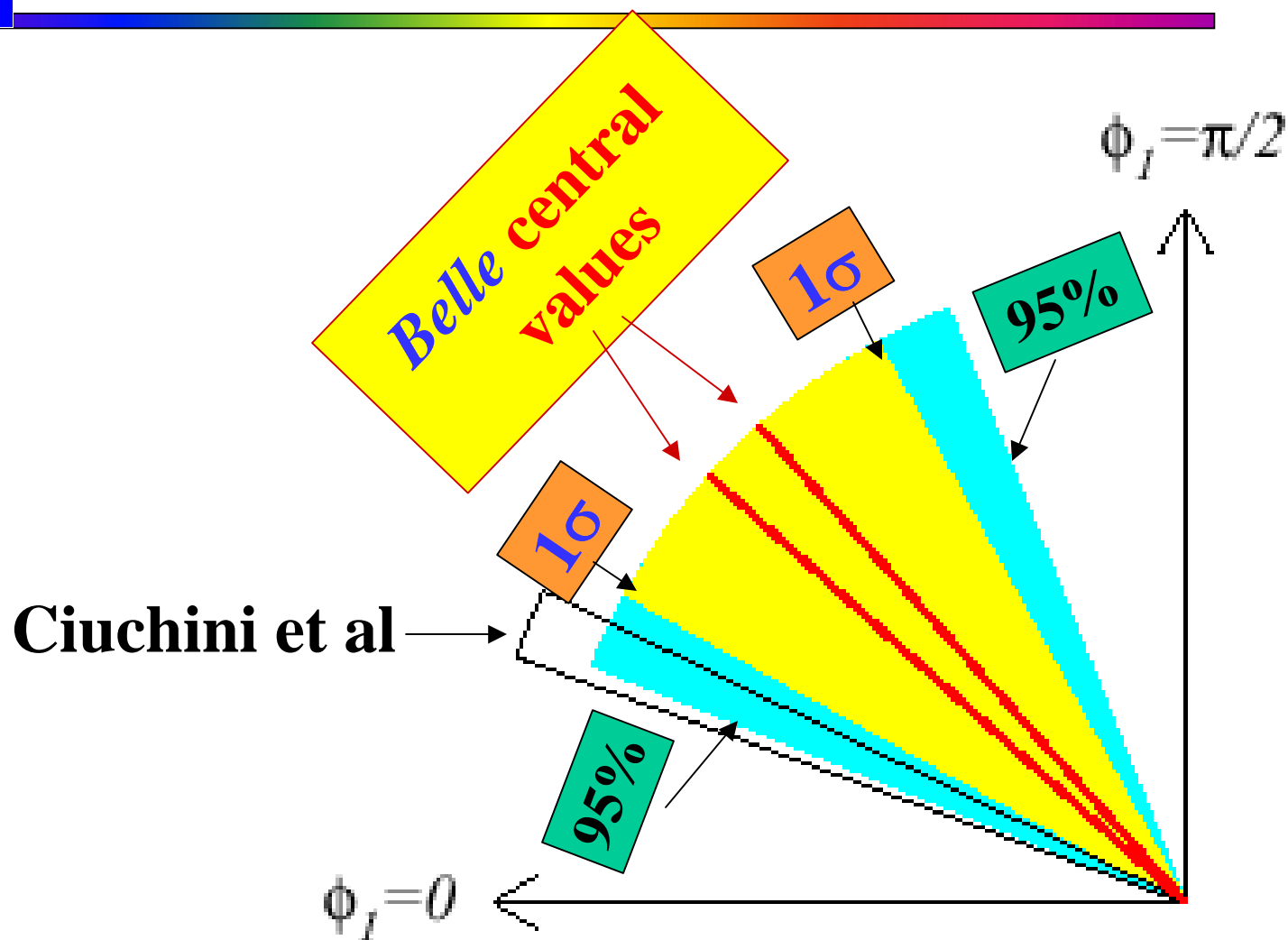


# Compare with CKM constraints





# Compare with constraints (cont'd)





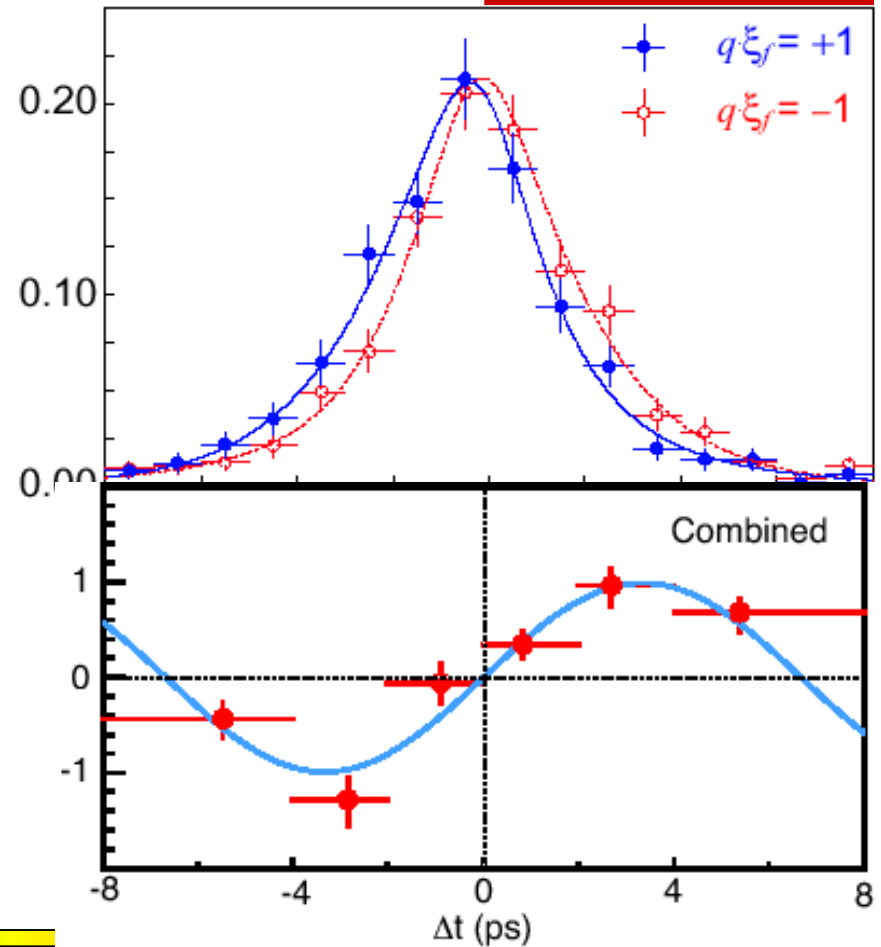
# Conclusions

● CP is violated in B decay

**>6σ!!**

●  $\sin 2\phi_1$  is large:

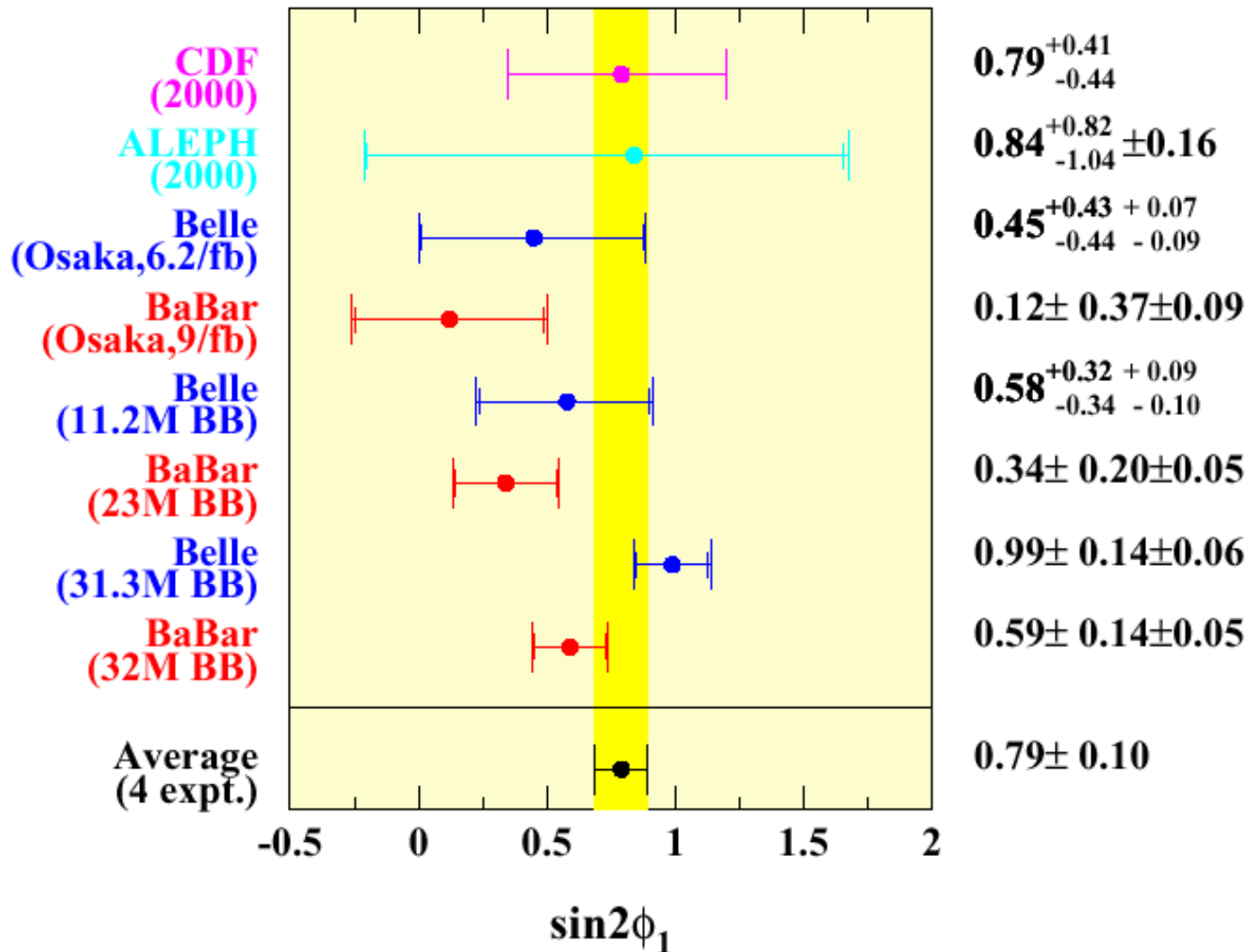
**$0.99 \pm 0.14 \pm 0.06$**







# Compare with other experiments





# Variations on a theme

<b>Old data; old analysis:</b>	<b><math>0.58 \pm 0.33</math></b>
<b>Old data; new analysis:</b>	<b><math>0.54 \pm 0.34</math></b>
<b>New data; new analysis:</b>	<b><math>1.06 \pm 0.14</math></b>

<b>Allow <math>\Delta m_d</math> to float</b>	<b><math>\sin 2\phi_1</math></b>	<b><math>\Delta m_d</math> (PDG:0.472)</b>
	<b><math>1.00 \pm 0.14</math></b>	<b><math>0.478 \pm 0.057 \text{ ps}^{-1}</math></b>

<b>Allow <math>\tau_{B_0}</math> to float</b>	<b><math>\sin 2\phi_1</math></b>	<b><math>\tau_{B_0}</math> (PDG:1.550)</b>
	<b><math>1.00 \pm 0.14</math></b>	<b><math>1.66 \pm 0.07 \text{ ps}</math></b>



# Resolution function

$$R = (1 - f^{\text{tail}})G(\Delta t; \mu^{\text{main}}, \sigma^{\text{main}}) + f^{\text{tail}}G(\Delta t; \mu^{\text{tail}}, \sigma^{\text{tail}})$$

$$\mu = m_0 + m_1 \sigma'_{\text{tag}}$$

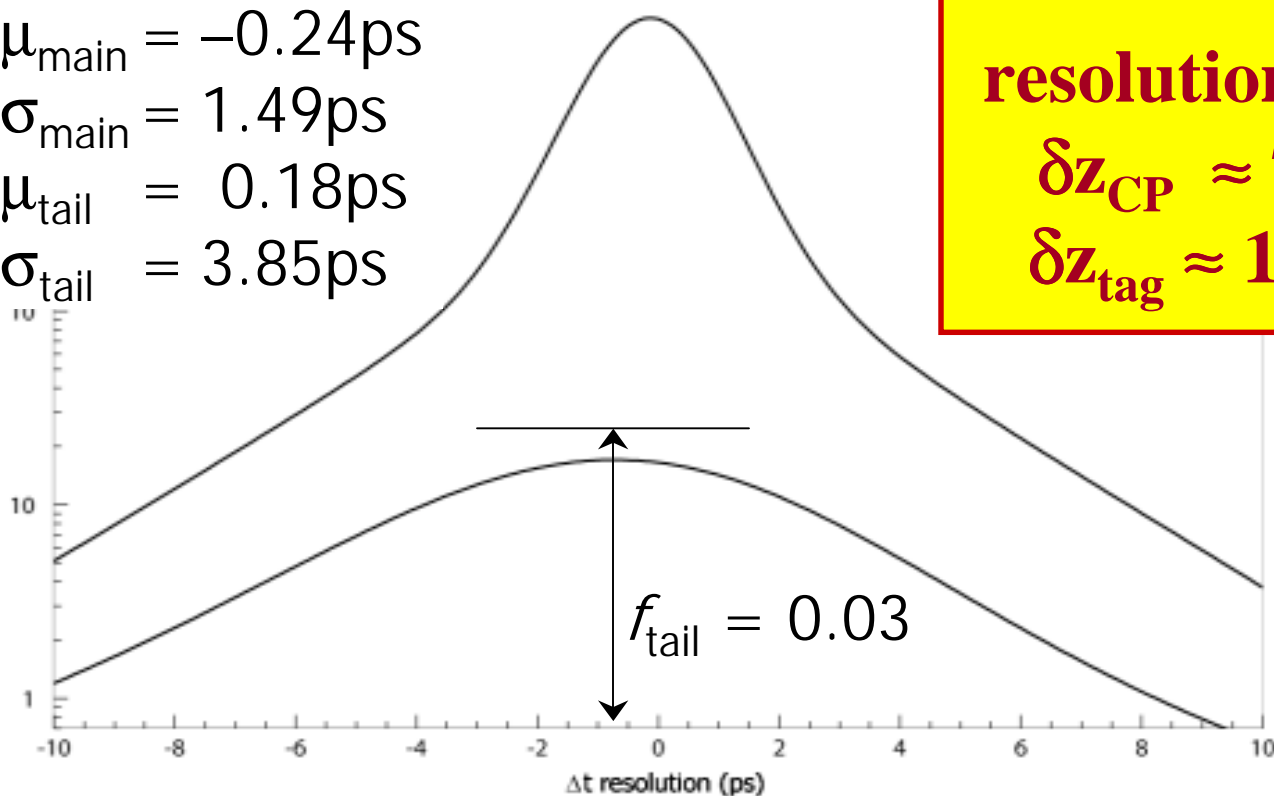
$$\sigma = f(\sigma_{CP}, \sigma_{\text{tag}}; \text{par}_{\text{charm effect}}, \text{par}_{B_{pT} \text{ effect}})$$

$$\mu_{\text{main}} = -0.24\text{ps}$$

$$\sigma_{\text{main}} = 1.49\text{ps}$$

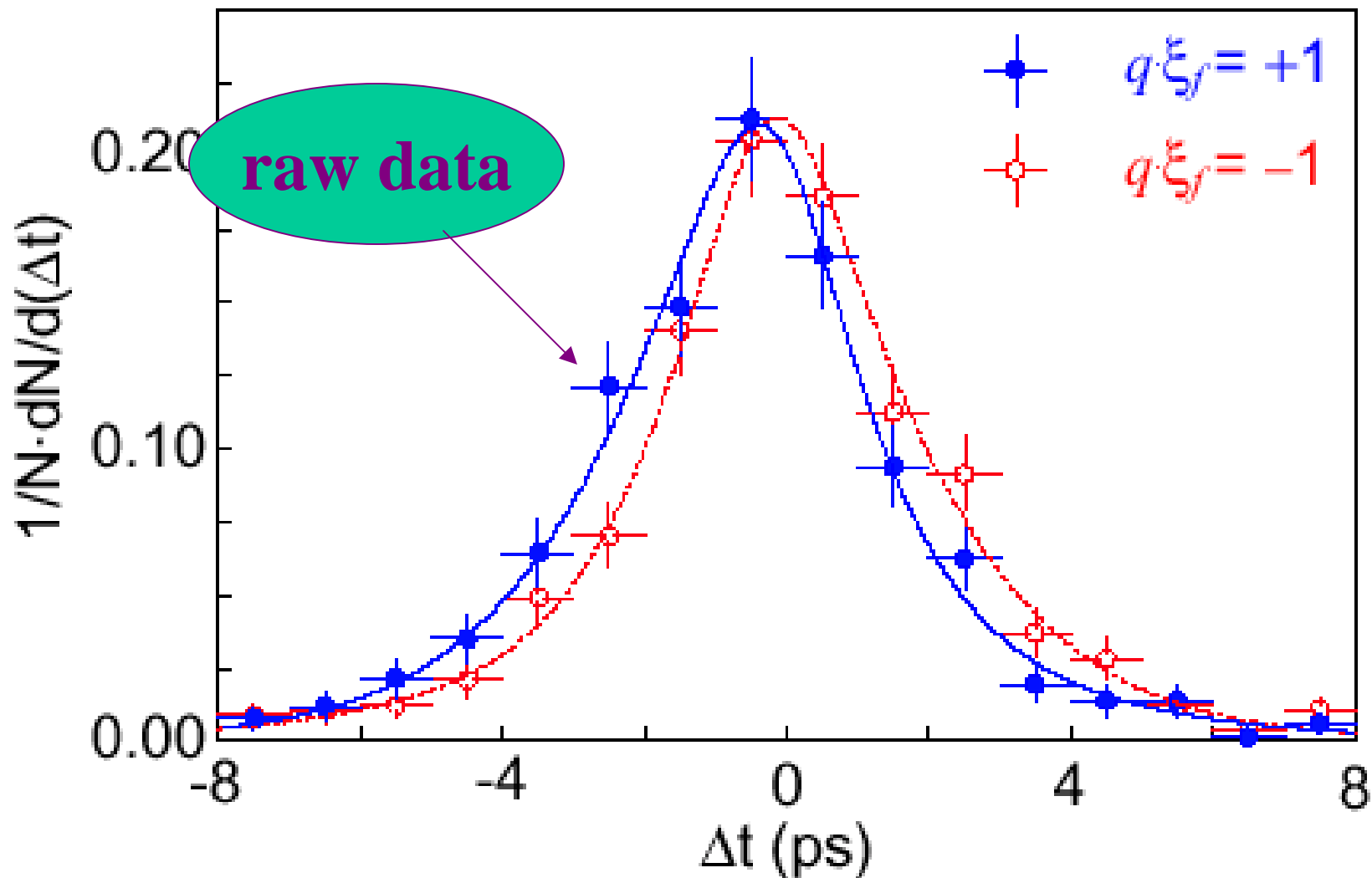
$$\mu_{\text{tail}} = 0.18\text{ps}$$

$$\sigma_{\text{tail}} = 3.85\text{ps}$$





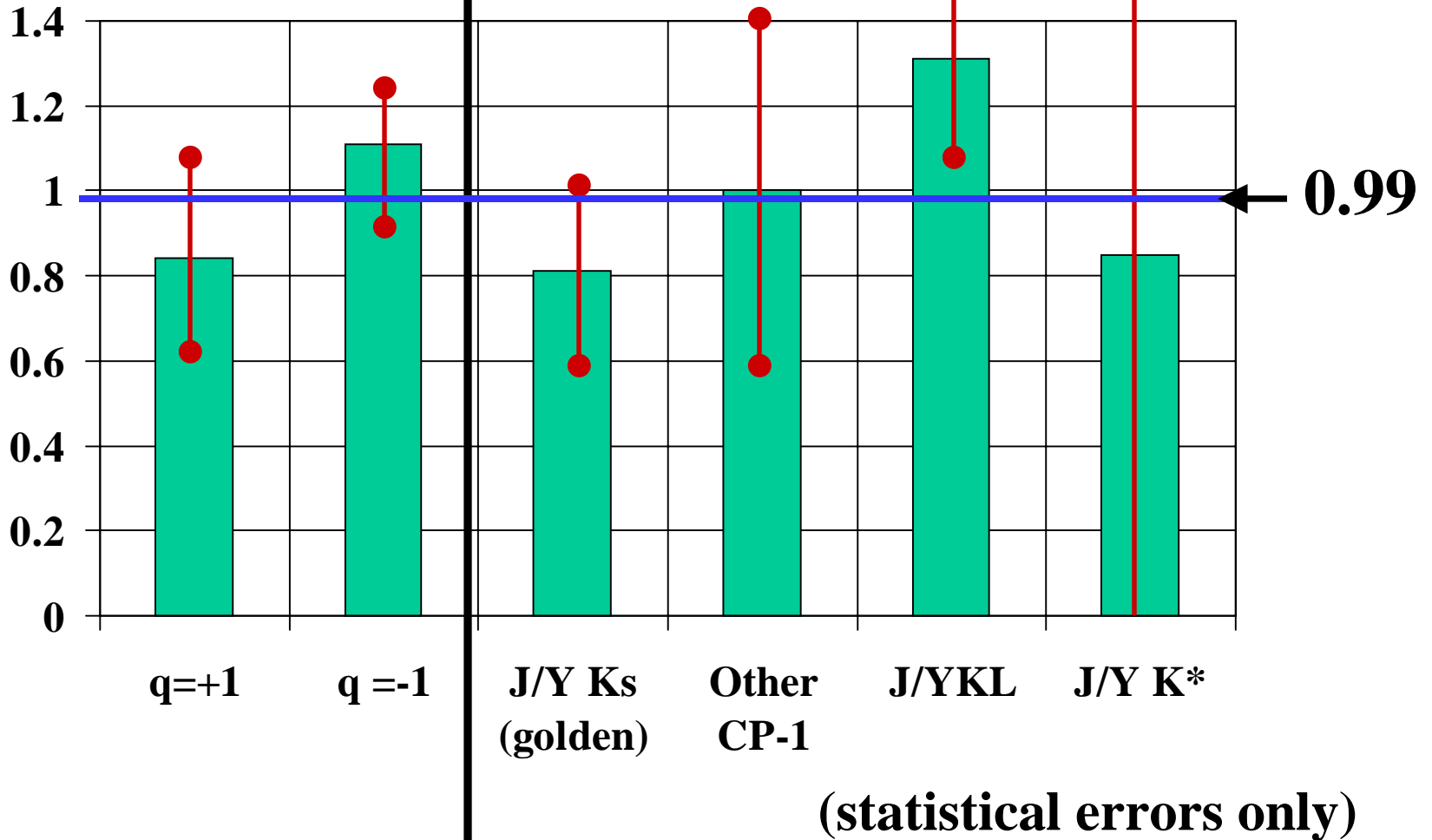
# Combine $q$ , $\xi_f$ & $\Delta t$





# $\sin 2\phi_1$ from various subsamples

$\sin 2\phi_1$





# $\sin 2\phi_1$ for different $r$ values

