RECENT RESULTS FROM BELLE

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- Introduction
- Experimental apparatus
- Measurement of $\sin 2\phi_1$
- Measurement of CP violation in:
  - $B^0 \to \pi^+\pi^-$
  - $B^0 \to \eta' K_S$, ϕK_S and $K^+K^-K_S$
  - $B^0 \to J/\psi\pi^0$
- New result on $b \to s\ell^+\ell^-$ decay
- Summary

CP Violation

Fundamental quantity: distinguishes matter from anti-matter.

A bit of history:

- First seen in K^0 decays in 1964
- Discovery of $B^0 - \bar{B}^0$ mixing at ARGUS in 1987 indicated that the effect could be large in B decays
- Many experiments were proposed to measure it, some general purpose experiments tried to do it
- Measured in the $B^0 - \bar{B}^0$ system in 2001 by the two dedicated spectrometers Belle and BaBar at asymmetric e^+e^- colliders - B factories

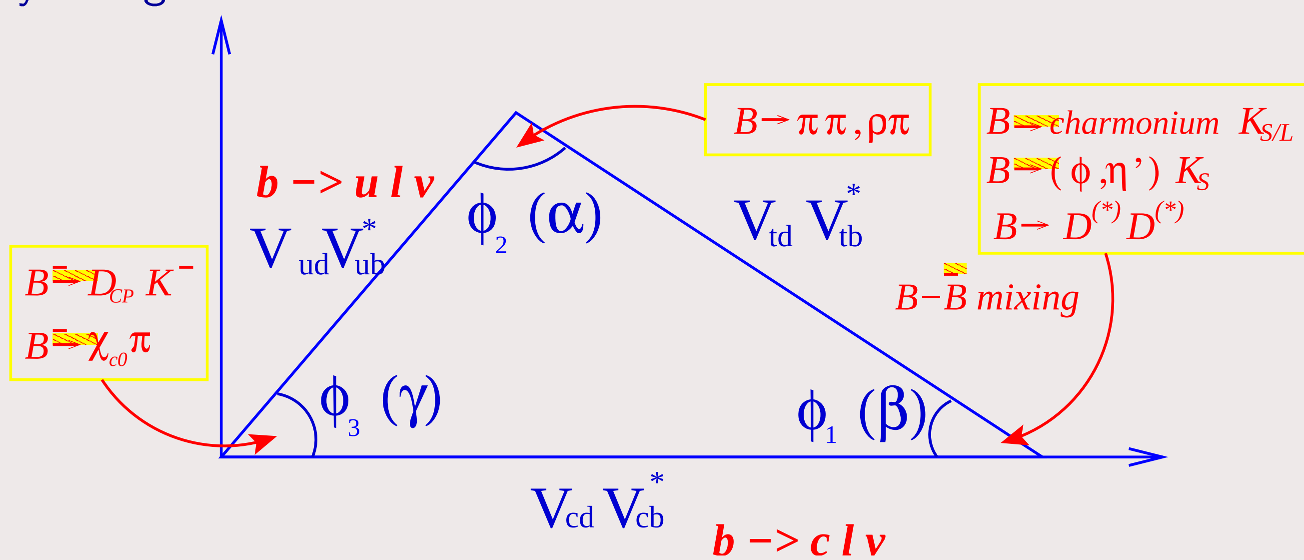
CP Violation in the Standard Model

CP violation is accommodated as an irreducible phase in the weak interaction mixing matrix (CKM)

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\varrho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\varrho - i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

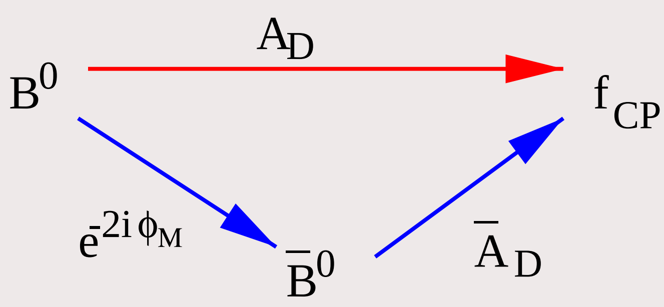
Unitarity of V leads to conditions the matrix elements have to satisfy, e.g. $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$.

$\longrightarrow$ unitarity triangle



CP Violation in B decays

CP violation effects in B decays are potentially large due to the interference of amplitudes for the direct decay to a CP final state f_{CP} and the decay after mixing.



This results in a decay rate asymmetry:

$$A_{CP}(t) \equiv \frac{\Gamma(\bar{B}^0(t) \to f_{CP}) - \Gamma(B^0(t) \to f_{CP})}{\Gamma(\bar{B}^0(t) \to f_{CP}) + \Gamma(B^0(t) \to f_{CP})}$$

$$= A_f \cos \Delta m_d t + S_f \sin \Delta m_d t$$

$$A_f = \frac{|\lambda_f^2| - 1}{|\lambda_f^2| + 1}$$

$$S_f = \frac{2Im(\lambda_f)}{|\lambda_f^2| + 1}$$

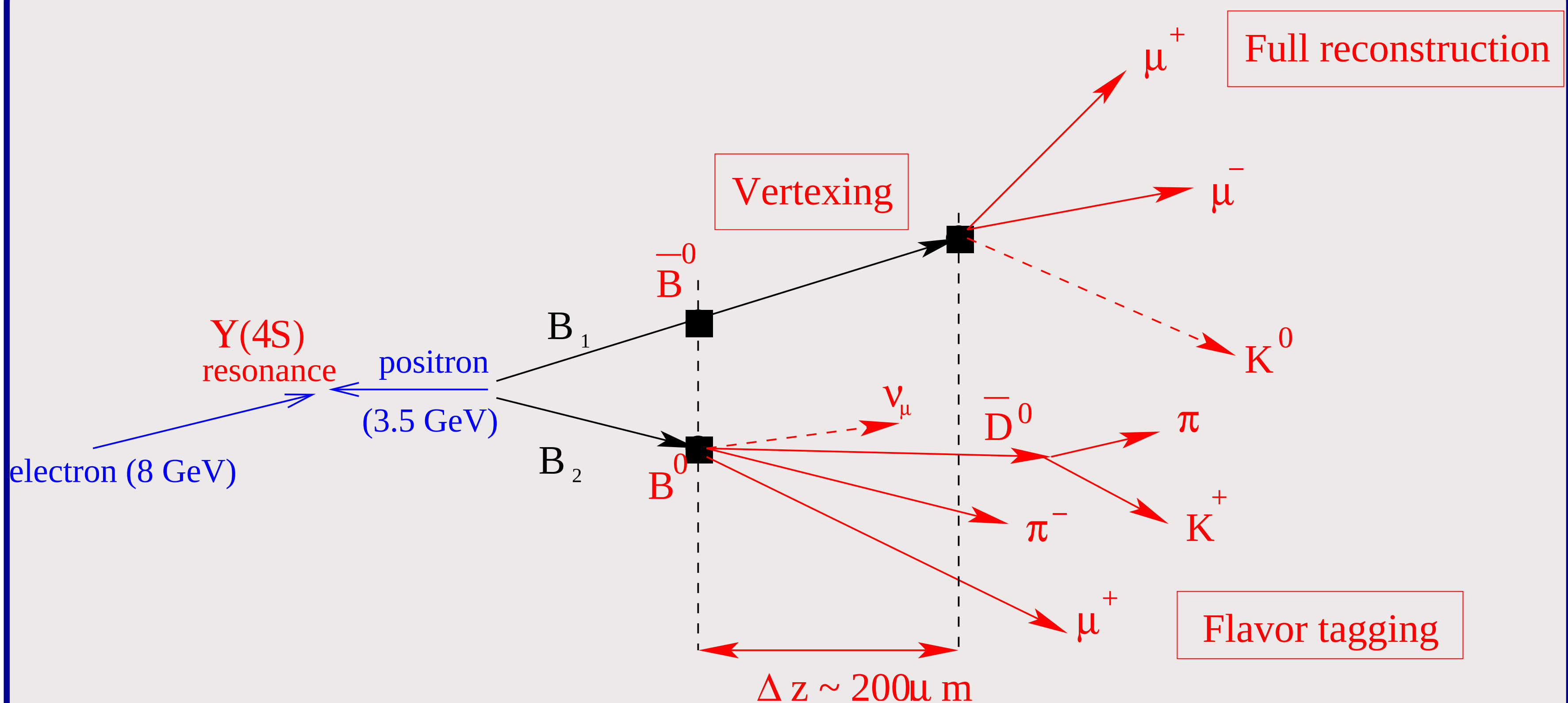
$$\lambda_f \equiv e^{-2i\phi_M} \frac{\mathrm{A_D}(\bar{B} \to \bar{f}_{CP})}{\mathrm{A_D}(B \to f_{CP})}$$

Standard model predictions

	$b \to c\bar{c}s$	$b \to c\bar{c}d$	$b \to s\bar{s}s$	$b \to u\bar{u}d$
example	$J/\psi K_S$	$J/\psi \pi^0$	ϕK_S	$\pi^+\pi^-$
A_f	0	0	small	$\neq 0$
S_f	$\sin 2\phi_1$	$\sin 2\phi_1$	$\sin 2\phi_1$	"$\sin 2\phi_2$"

N.B. $A_f \neq 0 \to \Gamma(\bar{B} \to \bar{f}_{CP}) \neq \Gamma(B \to f_{CP})$
$\to$ direct CP violation

Measurement of CP violation - principle



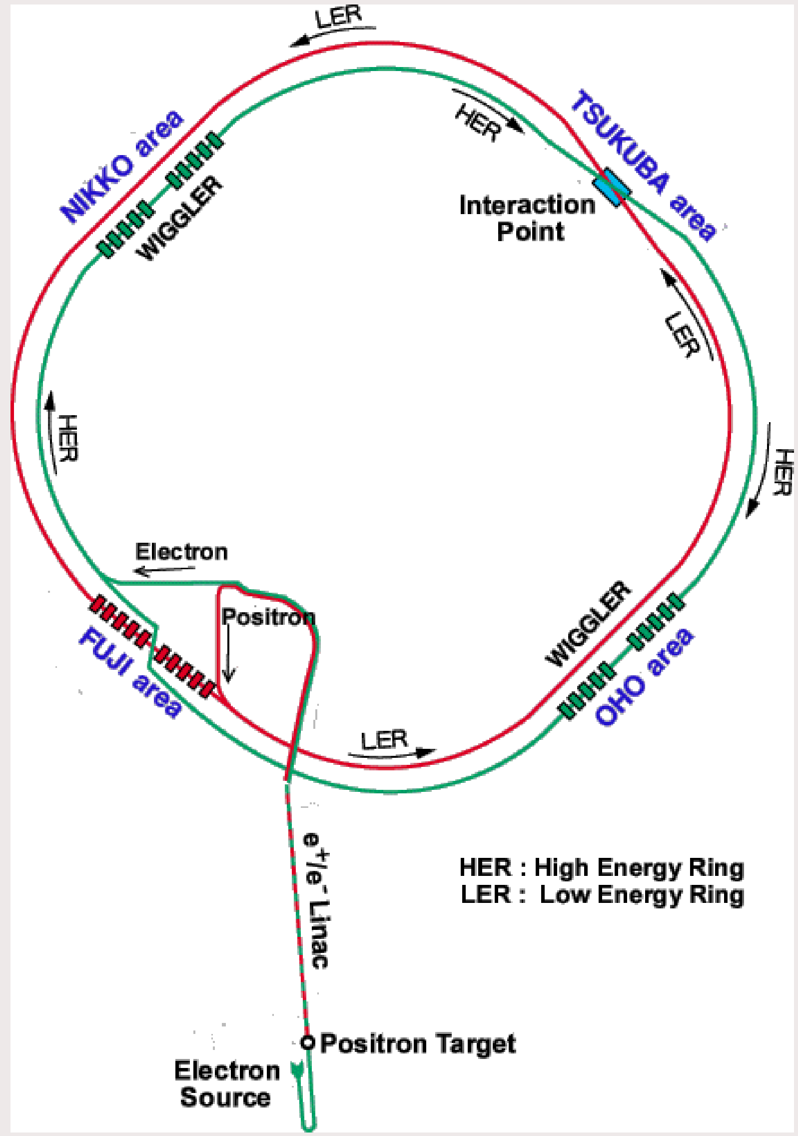
Needed:
a large number of $B\bar{B}$ pairs (100 M)
$\rightarrow B$-factory $=$
a high luminosity e^+e^- collider
with asymmetric beam energies

and a spectrometer with
- precise vertexing (Δt from Δz)
- accurate tracking in magnetic field (momenta of decay products)
- efficient identification of e, μ, π, K (tagging of the B flavour)

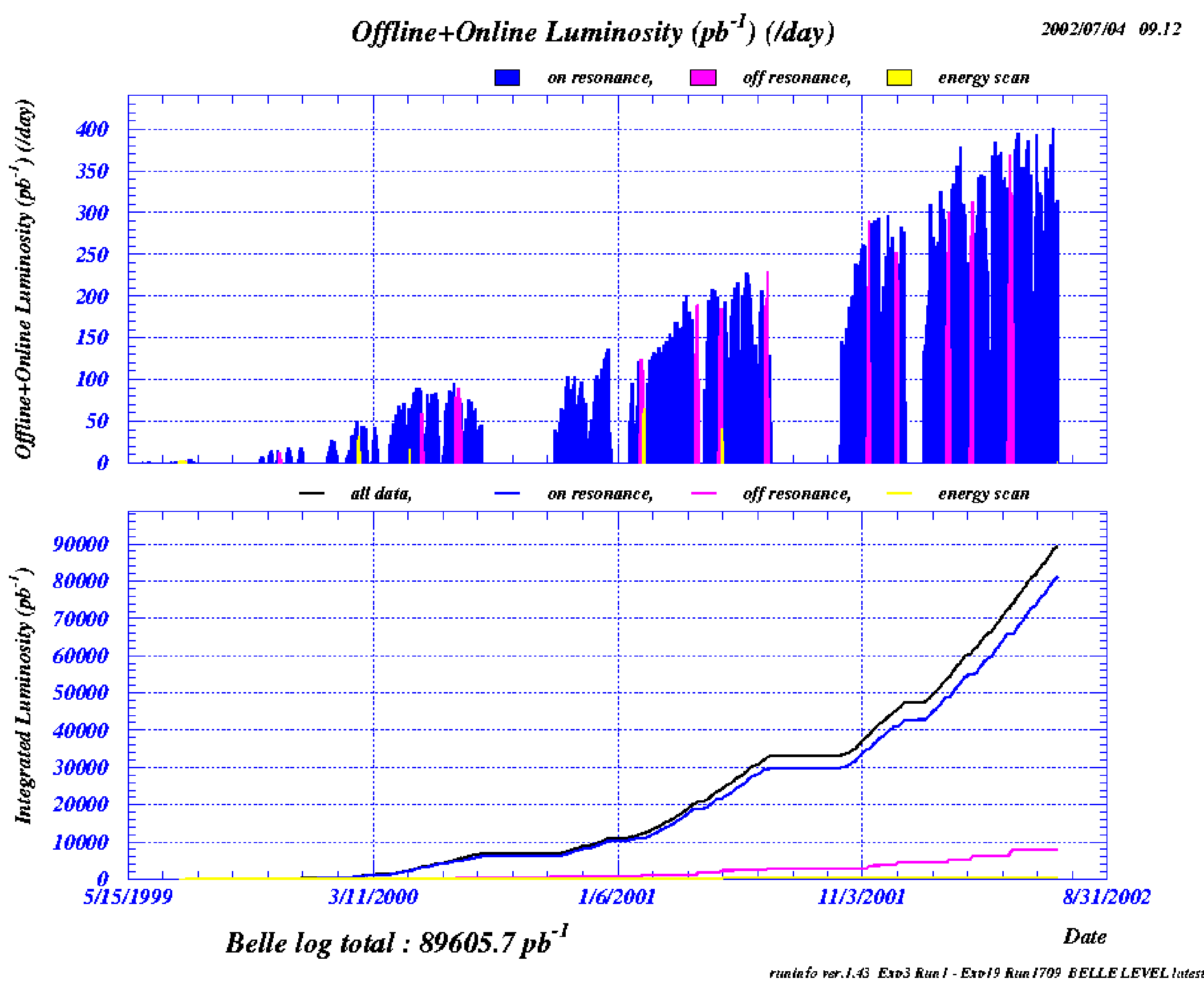
KEKB Accelerator performance 1

peak luminosity $= 7.348 \cdot 10^{33}$ cm^{-2}s^{-1}

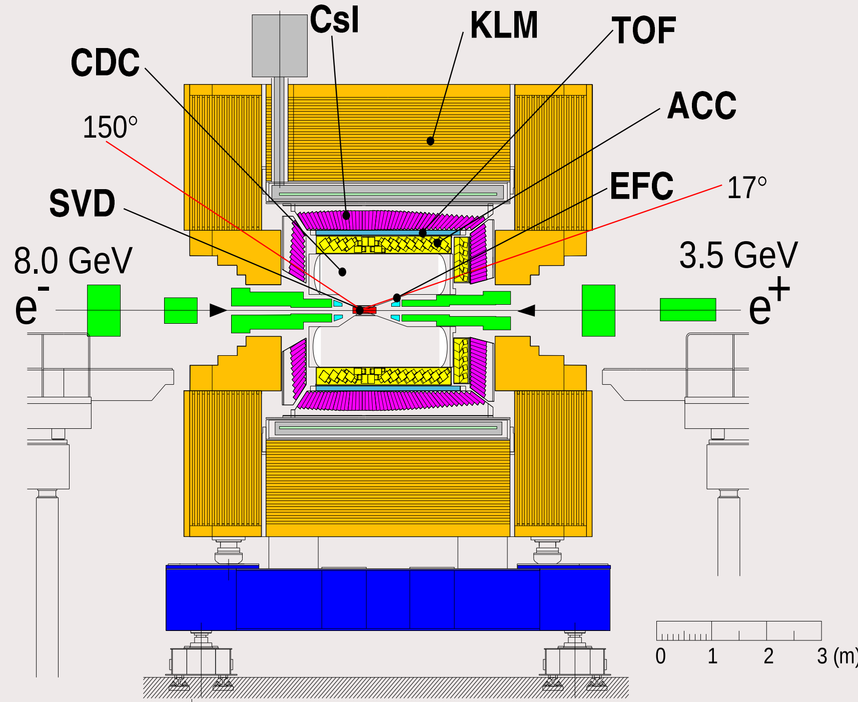
integrated luminosity :
shift = 142.7 /pb
day = 391.0 /pb
24h = 409.8 /pb
7days = 2524. /pb
month = 7348. /pb



KEKB accelerator performance 2



Belle Detector performance



Tracking and vertexing

- Central Drift Chamber (CDC)
  50 layers
  $\frac{\sigma_{p_T}}{p_T} \approx 0.35\%$ at 1 GeV/c
- Silicon Vertex Detector (SVD)
  3 double-sided silicon layers
  impact parameter $\sigma = 55\ \mu$m
  for 1 GeV/c tracks (90^0)

Particle identification:

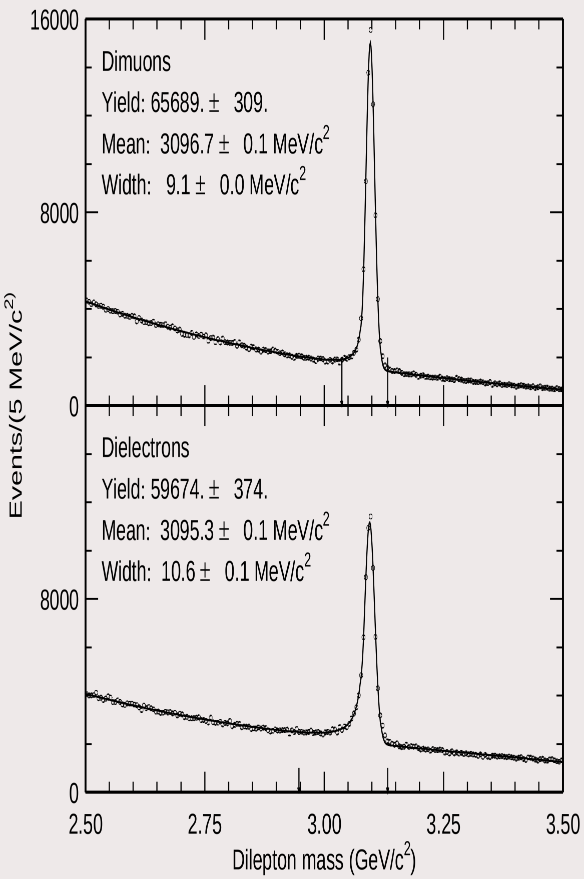
Identify $K^\pm$ up to 3.5 GeV/c (efficiency $\approx 90\%$, fake rate $\approx 6\%$)

- Aerogel Cherenkov Counter (ACC): ref.index 1.01-1.03
- Time of Flight (TOF): $\sigma = 95$ ps
- dE/dx in CDC: $\sigma_{dE/dx} \approx 7\%$

Electron id: Electromagnetic calorimeter (CsI) $\frac{\sigma_E}{E} \approx 1.8\%$ at 1 GeV

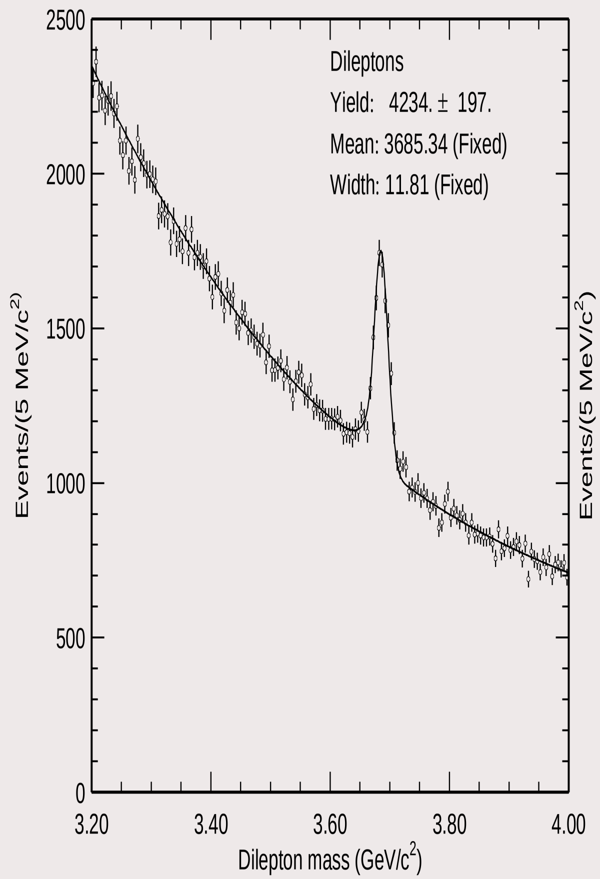
K_L and Muon detector (KLM): 14 layers, $\epsilon_\mu > 90\%$ at fake rate 2%

Reconstruction of $B^0 \to (c\bar{c})K_S$ decay modes



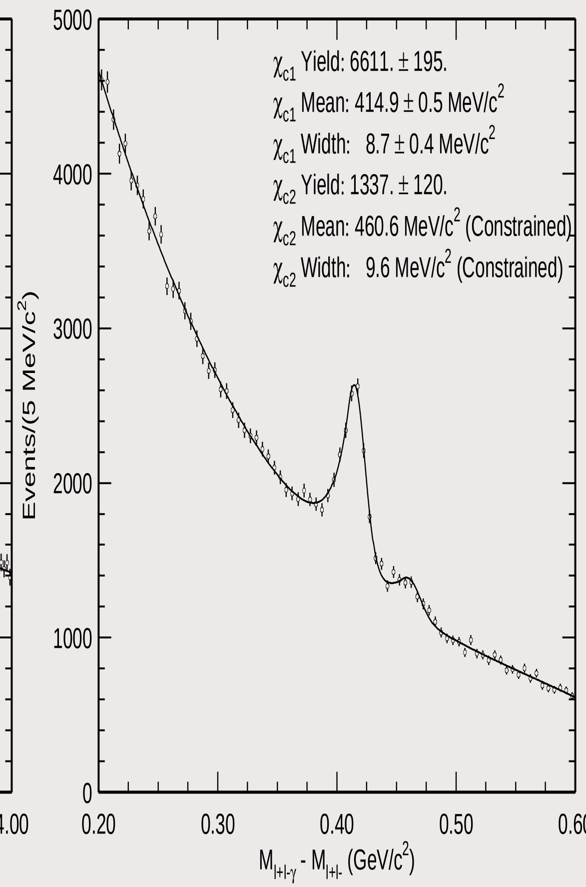
$J/\psi \to \mu^+\mu^-, e^+e^-$

$\sigma_M = 9.6(10.7)\mathrm{GeV/c^2}$



$\psi(2s) \to \mu^+\mu^-, e^+e^-$

$\sigma_M = 12.1\mathrm{GeV/c^2}$



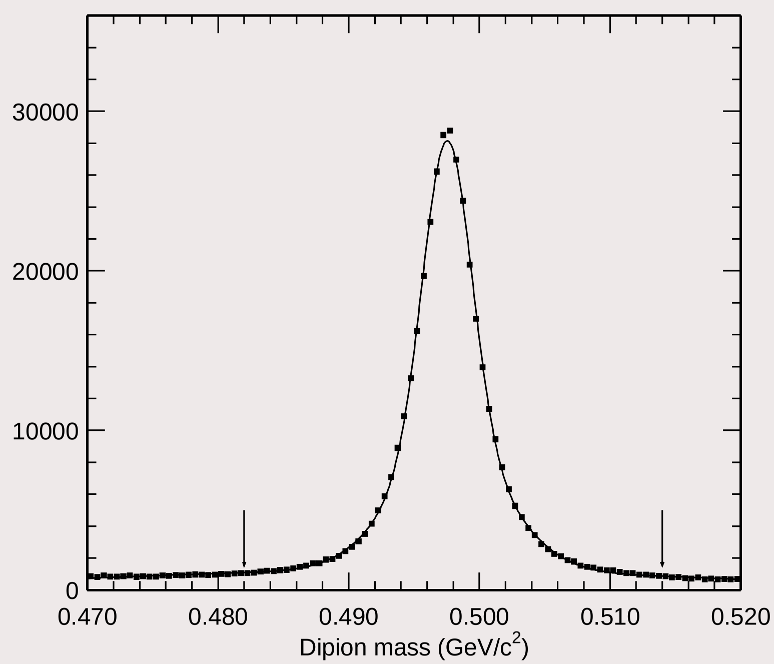
$\chi_{c1}, \chi_{c2} \to J/\psi\gamma$

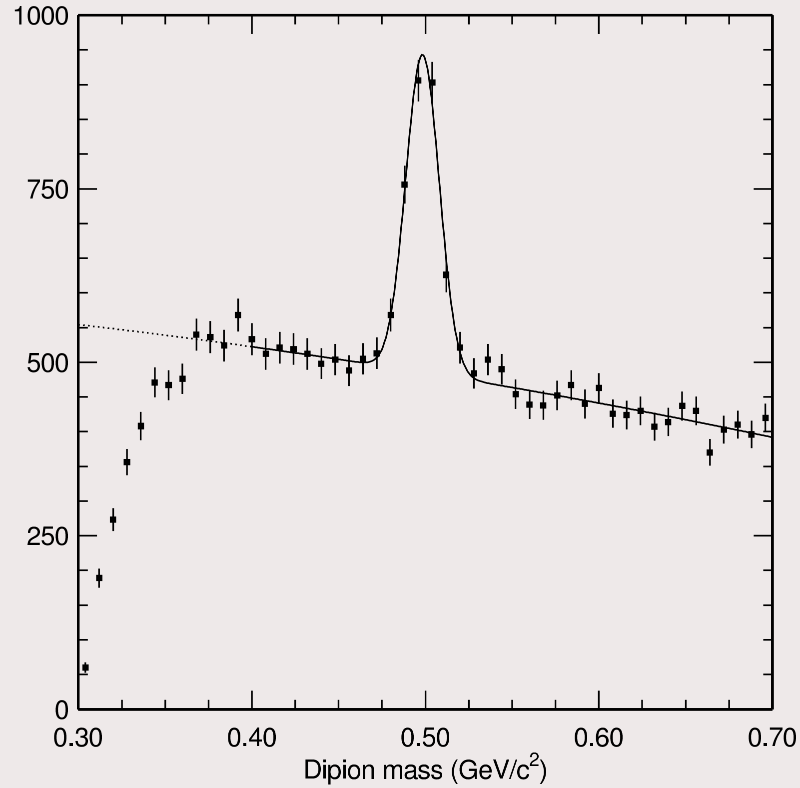
$\sigma_{\Delta M} = 7.0\mathrm{GeV/c^2}$

Reconstruction of $B^0 \to (c\bar{c}) K_S$ decay modes

$K_S \to \pi^+\pi^-$

$\sigma_M = 4.1 \mathrm{GeV/c^2}$



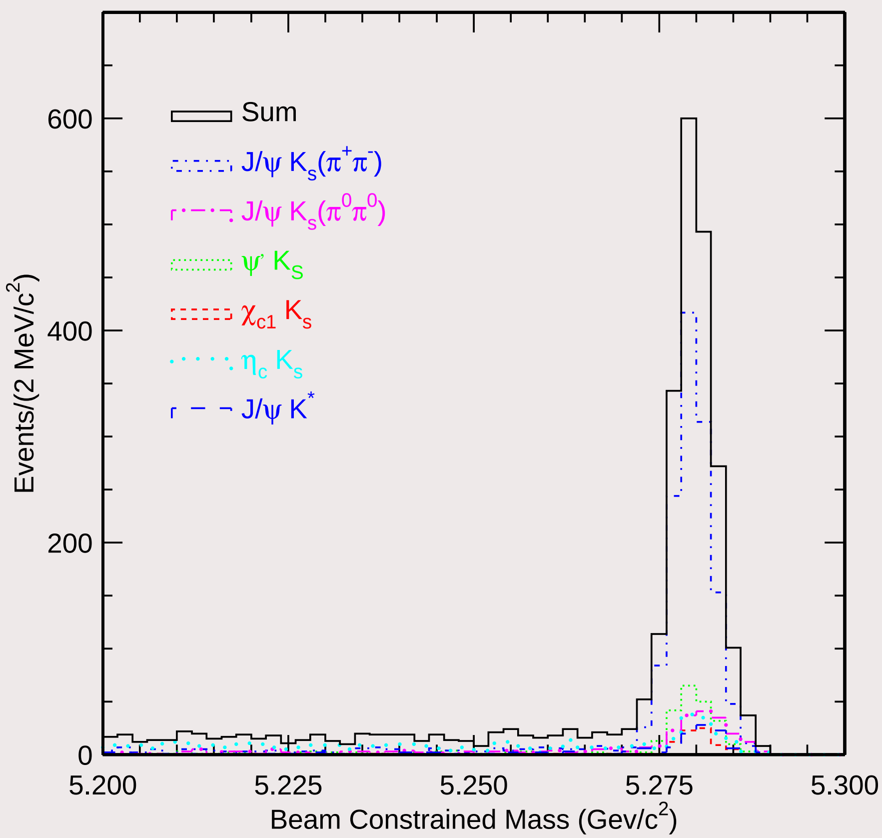


$K_S \to \pi^0\pi^0$

$\sigma_M = 9.3 \mathrm{GeV/c^2}$

Reconstruction of $b \to c\bar{c}s$ CP eigenstates

Reconstructed decay modes for full statistics (78 fb^{-1}, 85M $B\bar{B}$)



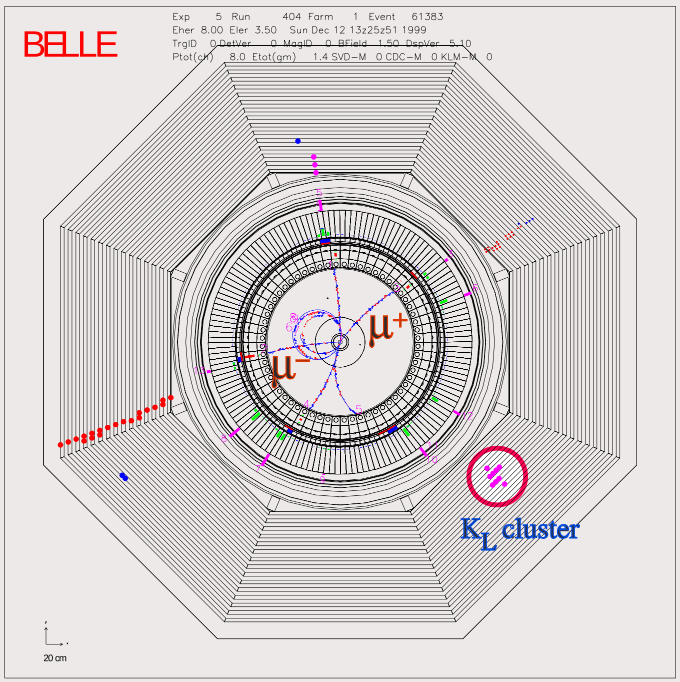
$$M_{bc} = \sqrt{E^2_{\rm beam} - \vec{p}^{\,2}_{\rm Bcandidate}}$$

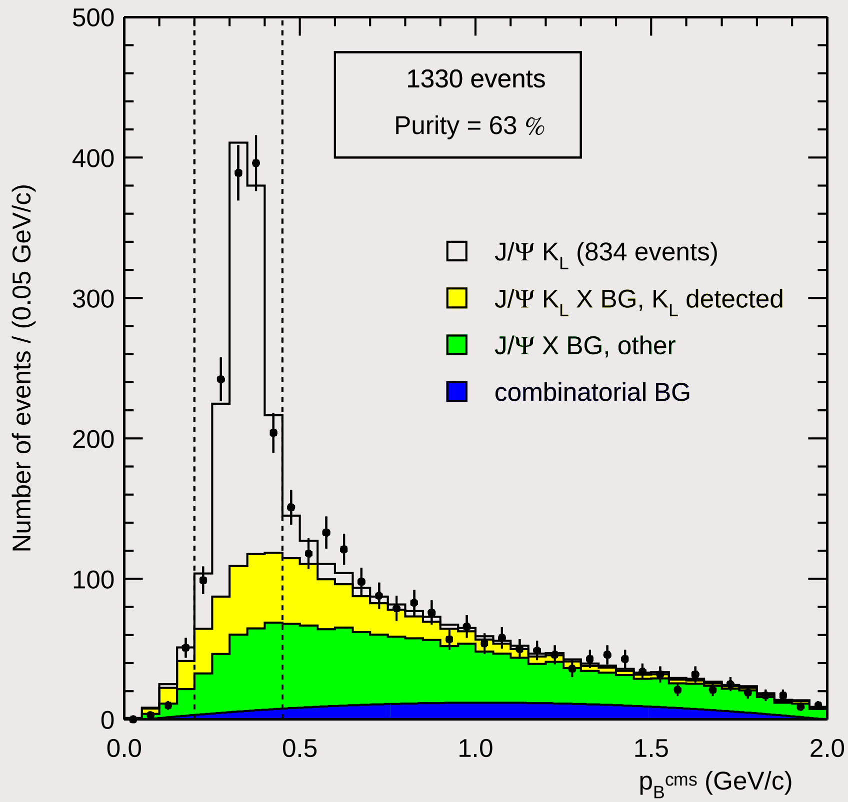
$B^0 \to$	events	$\frac{S}{S+N}$
$J/\psi K_S(K_S \to \pi^+\pi^-)$	1285	.976
$J/\psi K_S(K_S \to \pi^0\pi^0)$	188	.824
$\psi(2S)K_S$		
$(\psi(2S) \to \ell^+\ell^-)K_S$	91	.957
$(\psi(2S) \to J/\psi\pi^+\pi^-)$	112	.911
$\chi_{c1}K_S$	77	.958
$\eta_c(\eta_c \to K_S K\pi)K_S$	72	.646
$\eta_c(\eta_c \to KK\pi^0)K_S$	49	.725
$\eta_c(\eta_c \to p\bar{p})K_S$	21	.936
$J/\psi K^*(K^* \to K_S\pi^0)$	101	.917
total $CP = -1$	1996	.935
$J/\psi K_L$, $CP = +1$	1330	.627
Total	3326	.807

2958 events are used in the fit

Reconstruction of $CP = +1$: $B^0 \to J/\psi K_L$

- detection of K_L in the KLM
- K_L direction, no energy





- $p^* \approx 0.35$ GeV/c for signal events
- background shape is determined from MC, and its size from the fit to the data

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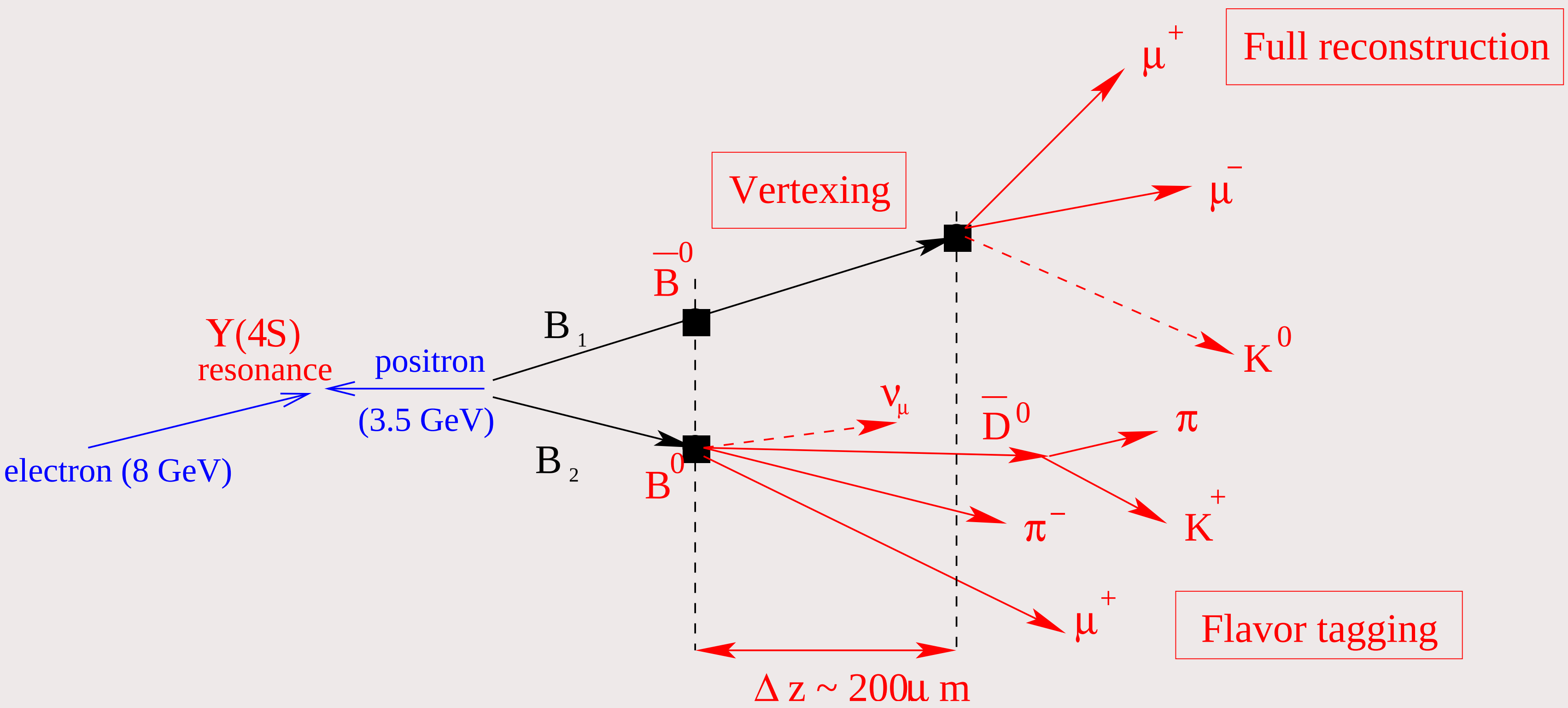
Measurement of CP violation - continued



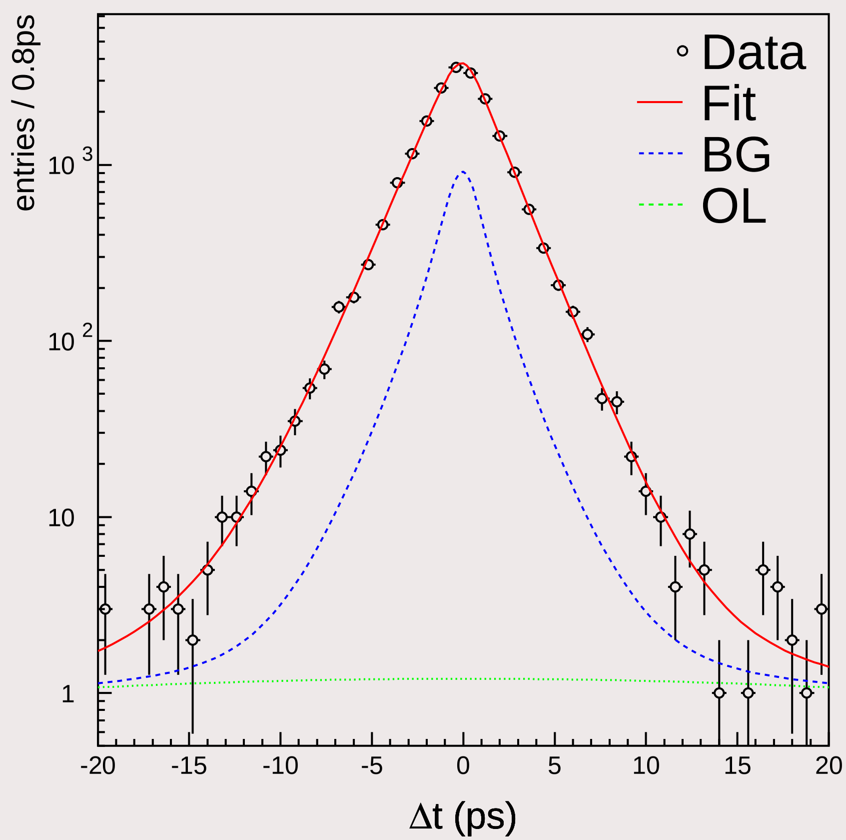
Determine Δt from $\Delta z = \beta\gamma c \Delta t$:

- clock start: resolution on tag side 140 μm ($\epsilon = 91\%$) - charm decays
- clock stop: resolution on CP side 75 μm ($\epsilon = 92\%$)

N.B. typically $\Delta z = \beta\gamma c \tau_B = 200\ \mu$m

Vertexing - check with lifetime measurement

Use $B^0 \to D^- \pi^+$, $D^{*-}\pi^+$, $D^{(*)-}\rho^+$, $B^0 \to J/\psi K_S$ and $B^0 \to J/\psi K^{*0}$ decays



- time resolution: 1.43 ps
- B^0 lifetime 1.551 ± 0.018 (stat) ps
- PDG: 1.542 ± 0.016 ps

Flavour tagging 1

Identify $B^0/\bar{B}^0$ by the charges of the decay products of the associated B

Inclusive leptons

- high momentum ℓ^- — $b \to c\ell^-\nu$
- intermediate momentum ℓ^+ — $c \to s\ell^+\nu$

Inclusive hadrons

- high momentum π^+ — $B^0 \to D^{(*)-}\pi^+,\ D^{(*)-}\rho^+(\rho^+ \to \pi^+\pi^0), \ldots$
- intermediate momentum K^+ — $\to K^+X$
- low momentum π^- — $D^{(*)-} \to \bar{D}^0\pi^-$

Efficiency $> 99.5\%$, $\epsilon_{\text{effective}} = 28.8 \pm 0.5\%$

Flavour tagging 2

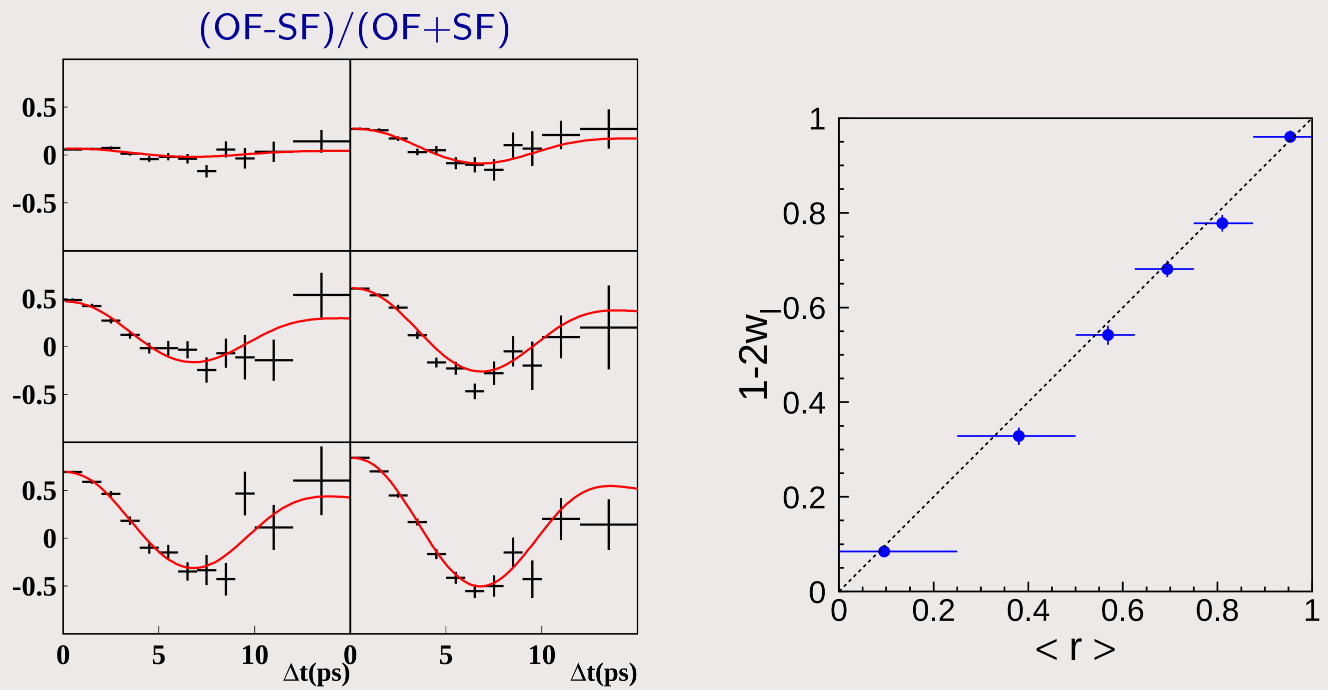
Tagging is not perfect: there is always a chance w that the tag is fake (less for leptons, more for kaons).

$\rightarrow$ The asymmetry oscillation is reduced, $\sin \Delta m_d t \rightarrow (1-2w) \sin \Delta m_d t$.

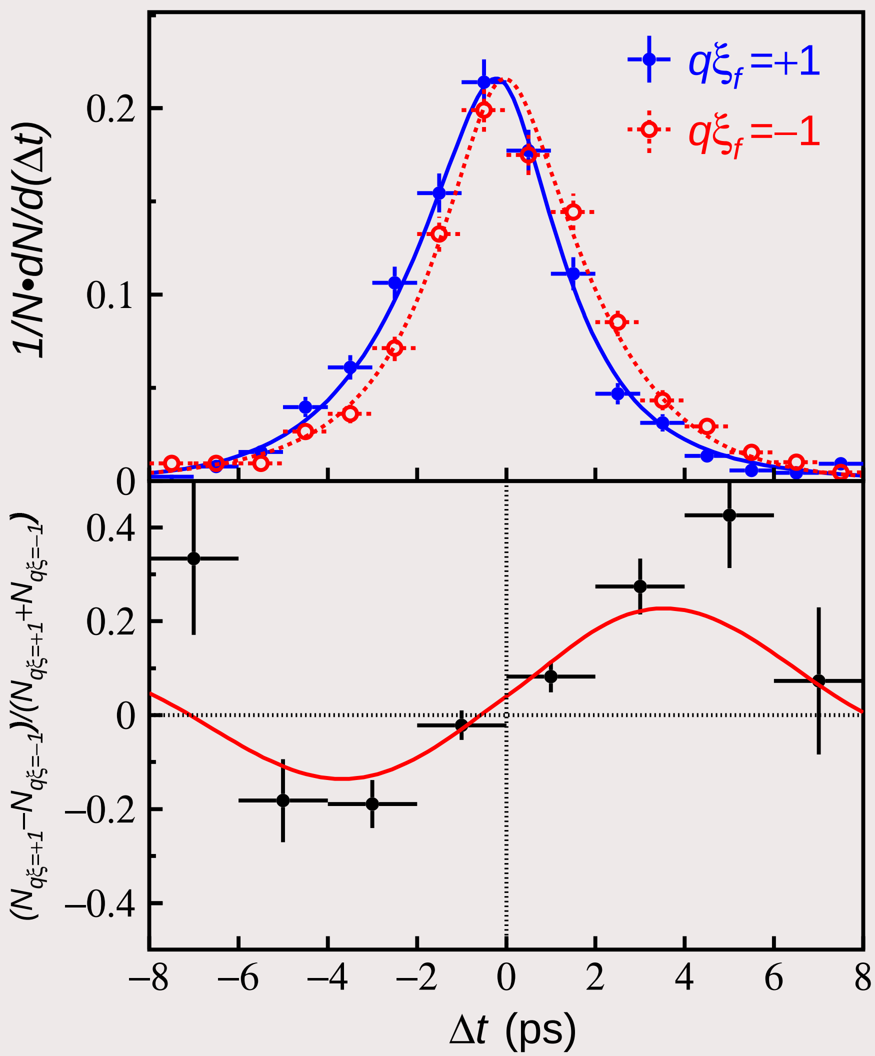
$\rightarrow$ Needed: w for each event.

Classify events into six cathegories in a tag quality variable r.

Calibrate the relation $(1-2w)$ vs. r with data: measure the $B^0 \bar{B}^0$ mixing amplitude (using $\bar{B}^0 \rightarrow D^{(*)+} \ell^- \nu$ decays) in 6 intervals in r



Result with full statistics (78 fb^{-1}, 85M $B\bar{B}$)



CP is violated! Red points differ from blue.

Red points: $\bar{B}^0 \to f_{CP=-1}$ (or $B^0 \to f_{CP=+1}$)

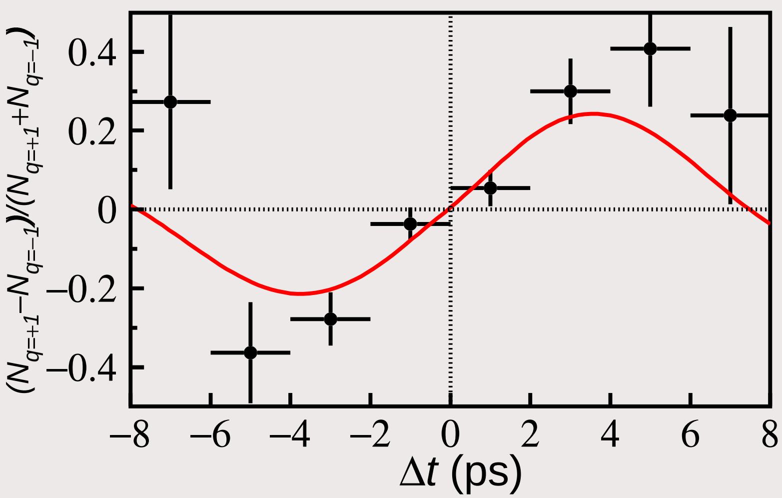
Blue points: $B^0 \to f_{CP=-1}$ (or $\bar{B}^0 \to f_{CP=+1}$)

$$S_{ccs} = \sin 2\phi_1 = 0.719 \pm 0.074 \pm 0.035$$

$$|\lambda_{ccs}| = 0.950 \pm 0.046 \pm 0.026$$

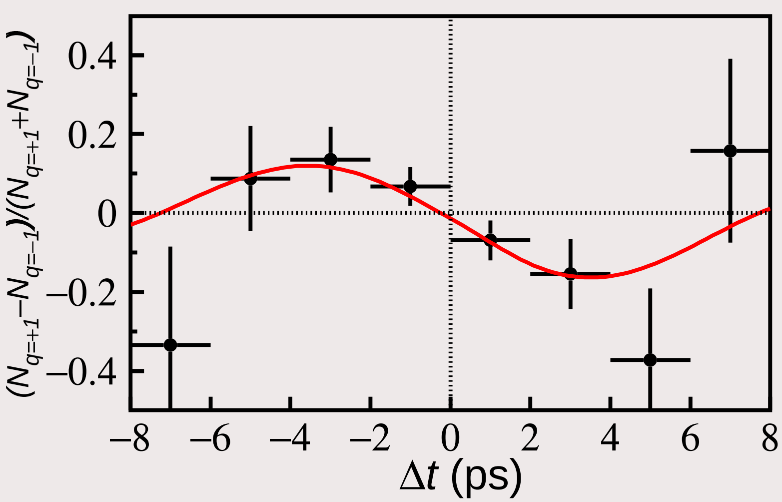
A_{ccs} is consistent with 0

Comparison between $CP = +1$ and $CP = -1$



$CP = -1$ sample

$\sin 2\phi_1 = 0.716 \pm 0.083$



$CP = +1$ sample

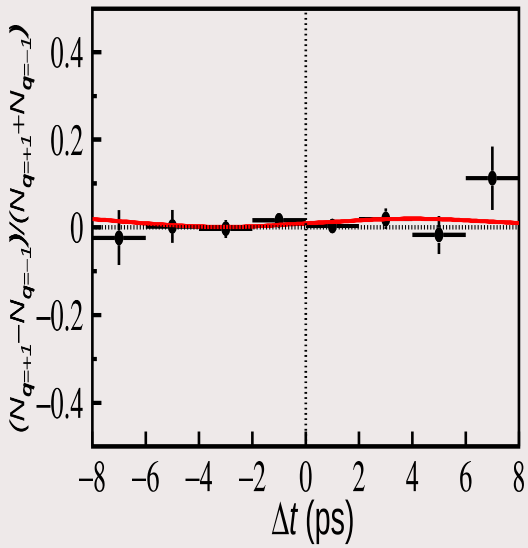
$\sin 2\phi_1 = 0.78 \pm 0.17$

N.B. Plotted: raw asymmetry. The amplitude of $\pm \sin 2\phi_1 \sin \Delta m_d \Delta t$ is reduced due to wrong tagging by a factor $(1 - 2w)$.

Checks, systematic errors

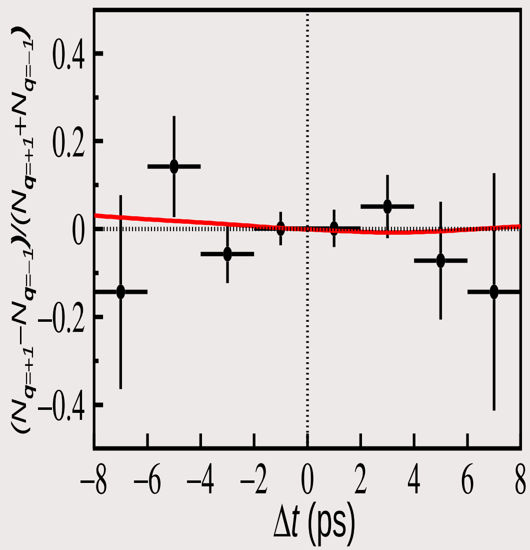
Same analysis for flavour specific final states, where there should be no asymmetry

$B^0 \to D^{*\pm}\pi^{\mp}$



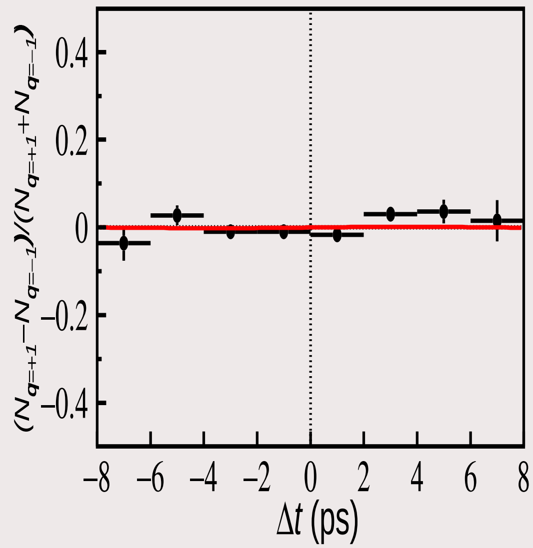
"$\sin 2\phi_1$" $= 0.035 \pm 0.032$

$B^0 \to J/\psi K^{*0}$, $K^{*0} \to K^+\pi^-$



"$\sin 2\phi_1$" $= -0.021 \pm 0.093$

$B^0 \to D^*\ell\nu$



"$\sin 2\phi_1$" $= 0.004 \pm 0.017$

Systematic errors:

vertexing	0.022	resolution function	0.014
possible bias in $\sin 2\phi_1$ fit	0.011	$J/\psi K_L$ background fraction	0.010
Δm_d	< 0.010	τ_B	< 0.010

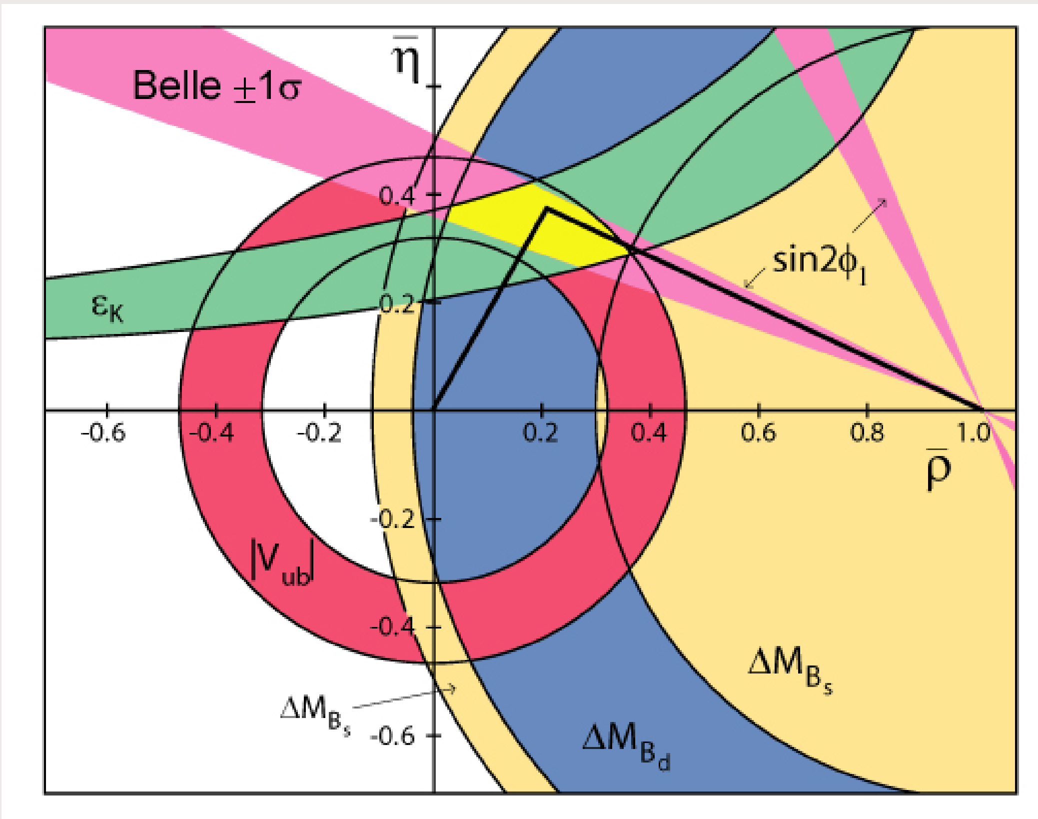
Comparison to the previous result

- More data: 41.8 $fb^{-1} \rightarrow 78$ fb^{-1}
  - All data have been reprocessed with consistent analysis code
- Better understanding of the detector
  - Better tracking quality
  - Better SVD alignment

$\sin 2\phi_1$ with the first 41.8 fb^{-1} data sample $= 0.78 \pm 0.10$

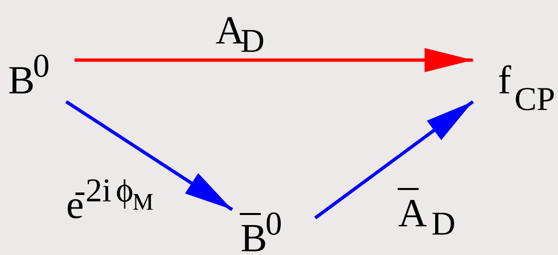
to be compared with 0.82 ± 0.12 (Feb. 02 result on the same data set)

$\rho - \eta$ plane

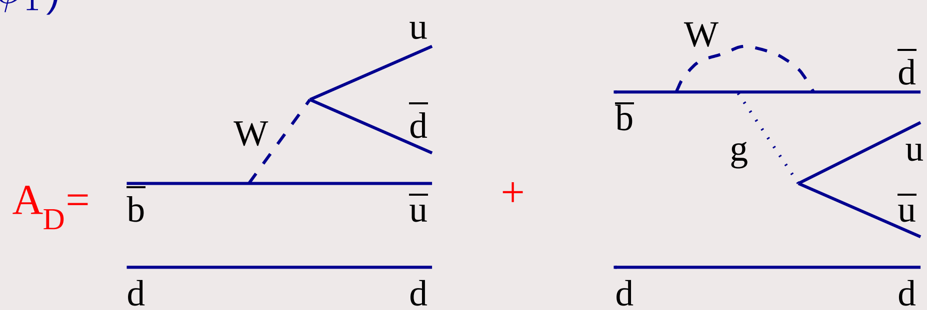


- Triangle: as determined from other measurements (PDG2002 compilation)
- Belle: present result on $\sin 2\phi_1$

CP violation in $b \to u\bar{u}d$



Decay amplitude A_D is a sum of a tree process (involving ϕ_2) and a penguin process (involving ϕ_1)



$$S_{\pi\pi} \sin \Delta m_d \Delta t + A_{\pi\pi} \cos \Delta m_d \Delta t$$

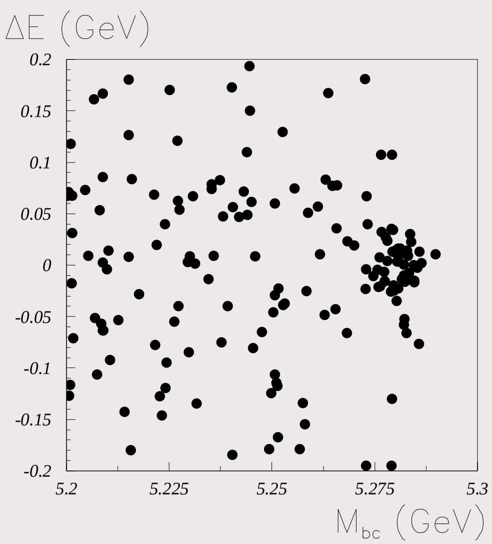
with

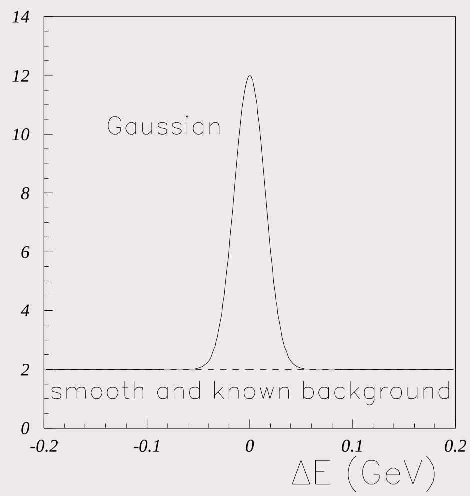
$$S_{\pi\pi} \neq \sin 2\phi_2$$

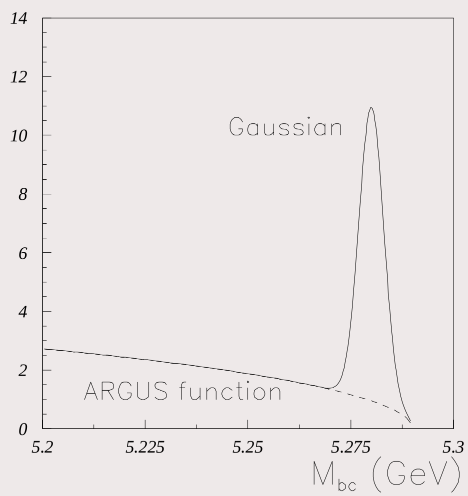
$$A_{\pi\pi} \neq 0$$

$\to |\lambda_{\pi\pi}| \neq 1$ and $\Gamma(B^0 \to \pi^+\pi^-) \neq \Gamma(\bar{B}^0 \to \pi^+\pi^-)$ (direct CP violation)

B reconstruction method







Two variables (in c.m.s. frame):

- $\Delta E = E(B_{\mathrm{candidate}}) - E_{\mathrm{beam}}$
- $M_{bc} = \sqrt{E^2_{\mathrm{beam}} - \vec{p}^{\,2}_{\mathrm{Bcandidate}}}$

Reconstruction of $B^0 \to \pi^+\pi^-$

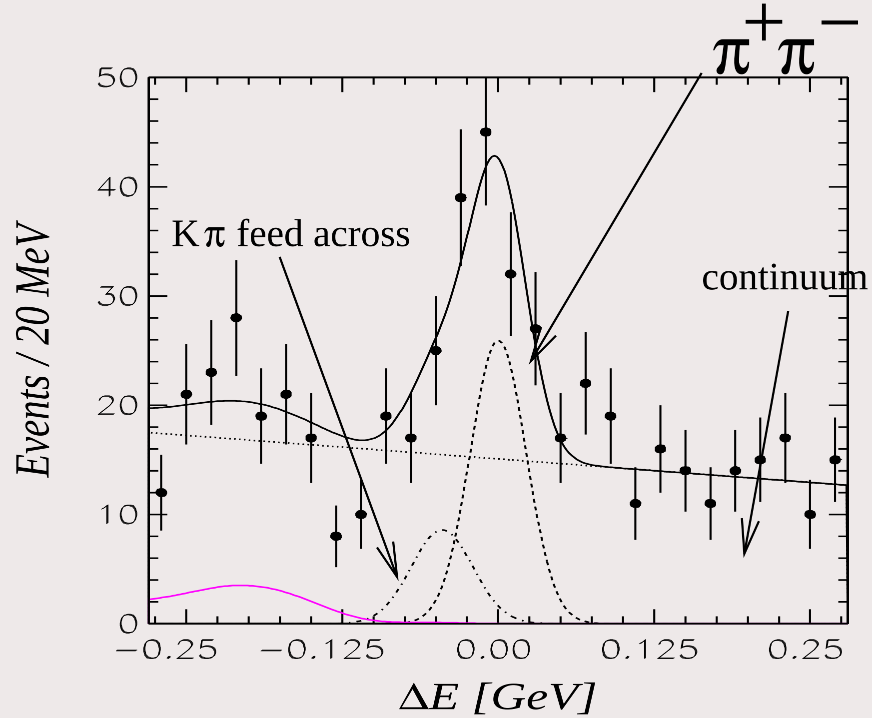
Data sample 41.8 fb^{-1}

Signal region:

- $5.271\mathrm{GeV/c^2} < M_{bc} < 5.287\mathrm{GeV/c^2}$
- $|\Delta E| < 0.067$ GeV

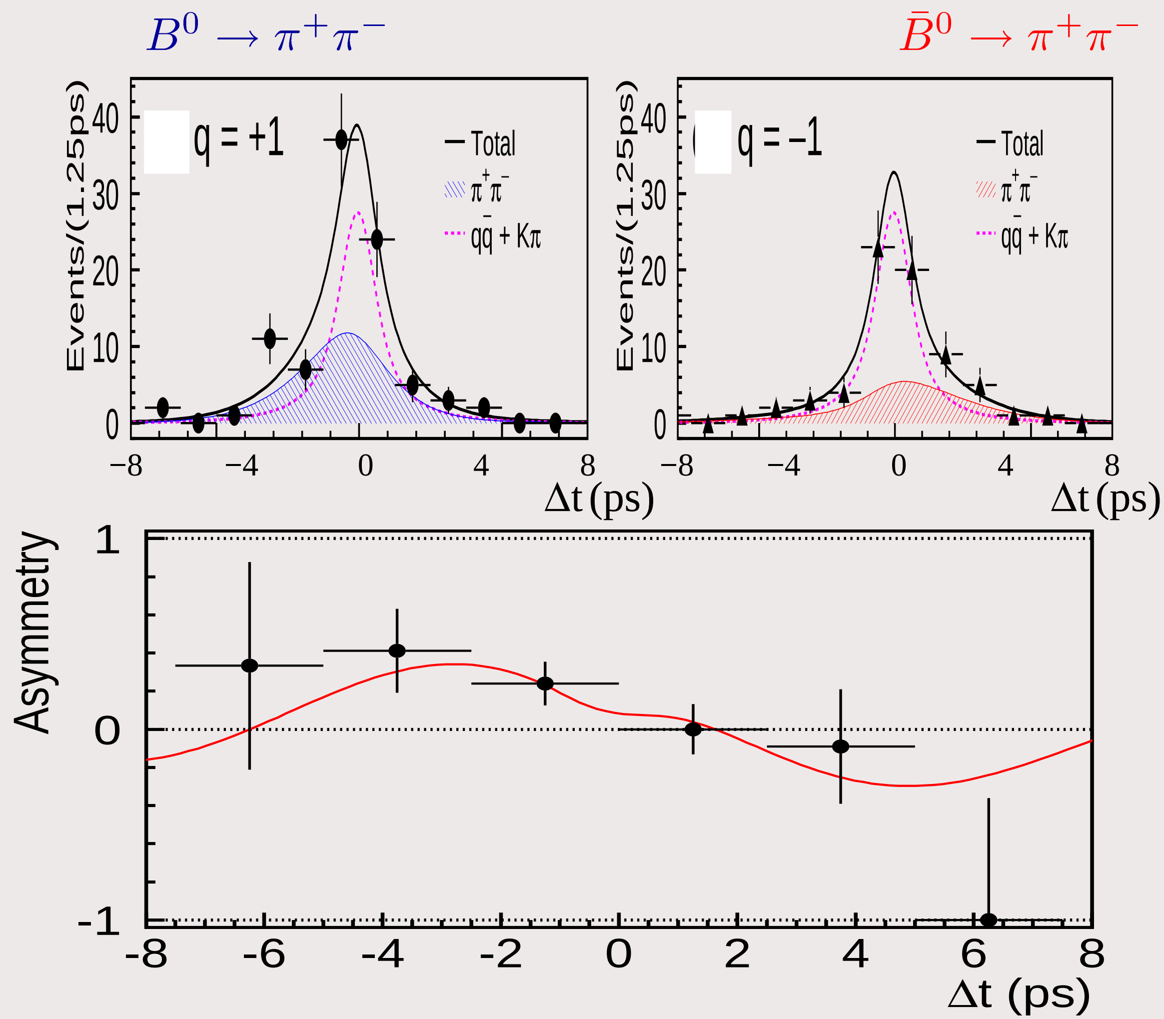
$$N(\pi\pi) = 73.5 \pm 13.8 \;\; \text{events}$$

$$(28.4 \pm 12.5 \;\; K\pi \;\text{feed} - \text{across})$$



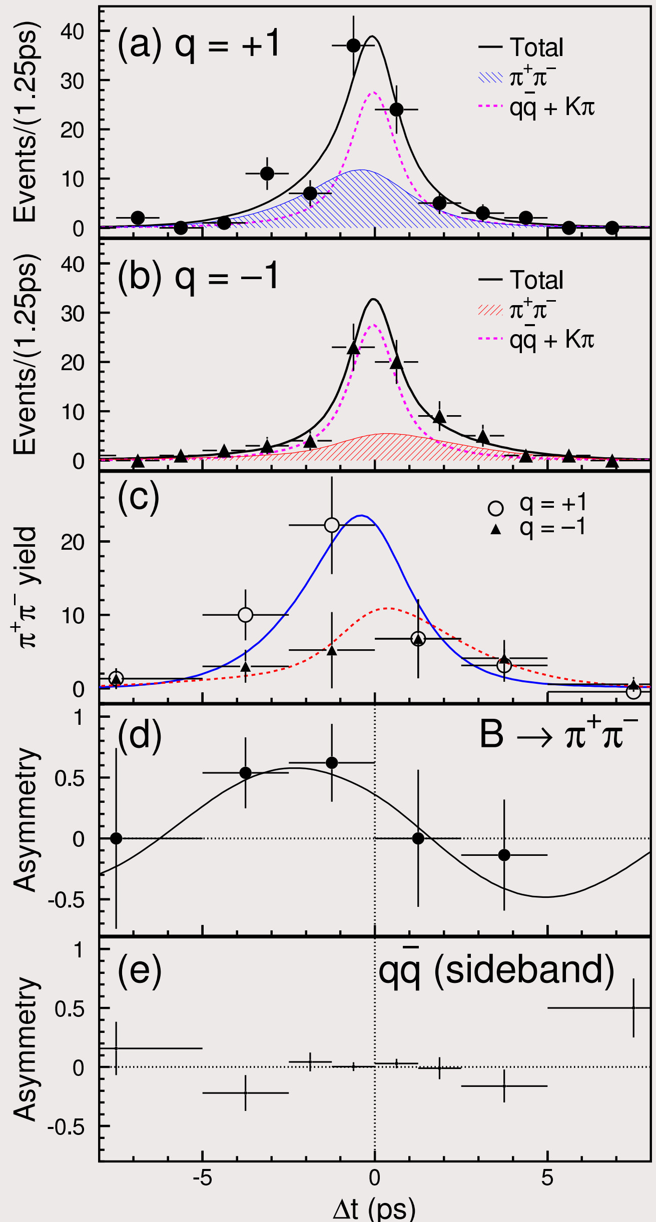
ΔE distribution after M_{bc} cut

Δt distribution in $B^0 \to \pi^+\pi^-$



Raw asymmetry

CP violation: $S_{\pi\pi}$ and $A_{\pi\pi}$



$$S_{\pi\pi} = -1.21^{+0.38+0.16}_{-0.27-0.13}$$

$$A_{\pi\pi} = +0.94^{+0.25}_{-0.31} \pm 0.09$$

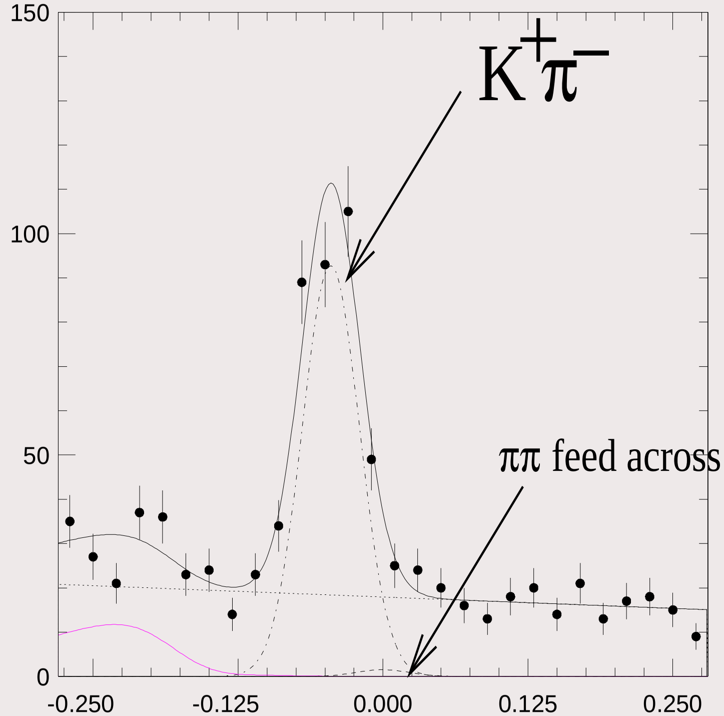
$A_{\pi\pi} \neq 0 \rightarrow$ direct CP violation,
$\Gamma(B^0 \rightarrow \pi^+\pi^-) \neq \Gamma(\bar{B}^0 \rightarrow \pi^+\pi^-)$

$A_{\pi\pi} > 0$ with 99.6% CL.
$S_{\pi\pi} < 0$ with 99.6% CL.

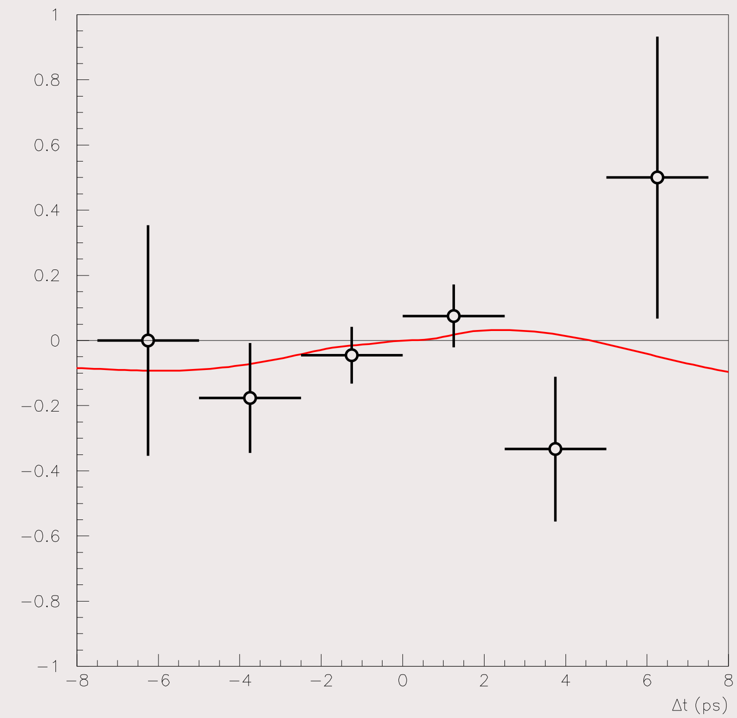
(data sample 41.8 fb^{-1})

Check: $B^0 \to K\pi$

$N(K\pi) = 289.5 \pm 21.5$



Observed asymmetry

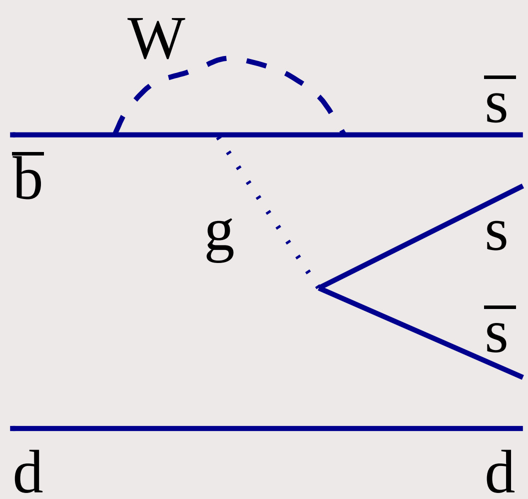


consistent with null asymmetry

$S_{K\pi} = 0.15 \pm 0.24$

$A_{K\pi} = 0.07 \pm 0.17$

CP violation in $b \to s\bar{s}s$



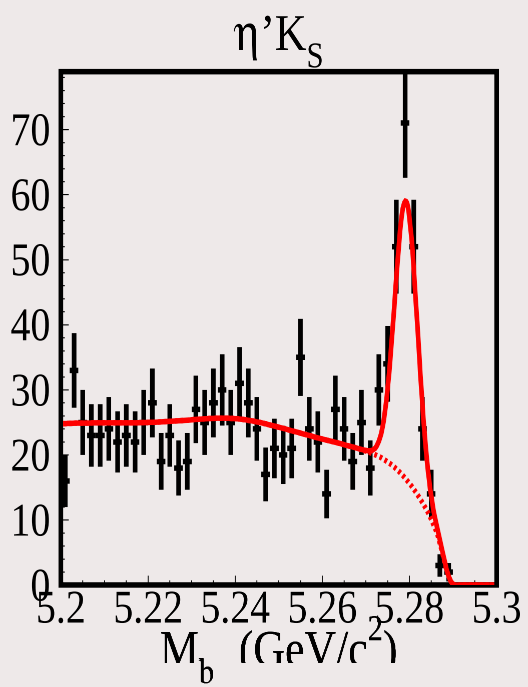
Standard Model:

- $S_{sss} = \sin 2\phi_1 \; (b \to c\bar{c}s)$
- $A_{sss} \approx 0$

But: $BR(B^0 \to \eta' K^0) = 5.8 \cdot 10^{-5}$ unexpectedly large
$\to$ contribution from new physics?

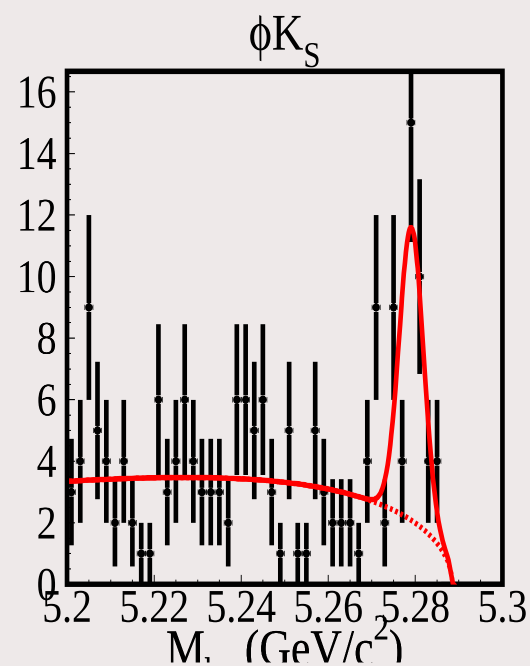
$B^0 \to \eta' K_S,\ \phi K_S,\ K^+K^-K_S$

$B^0 \to \eta' K_S$
$\eta' \to \pi^+\pi-\eta, \rho\gamma,\ \eta \to \gamma\gamma$



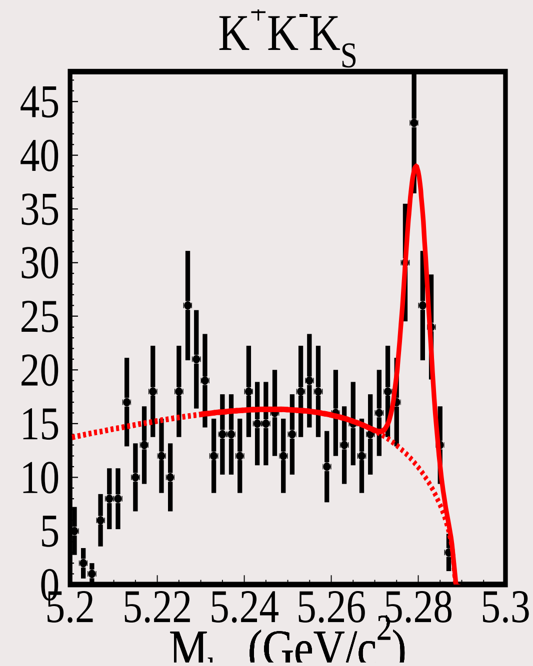
$N(B^0 \to \eta' K_S) =$
147.9 ± 14.6

$B^0 \to \phi K_S$
$\phi \to K^+K^-,\ K_S \to \pi^+\pi^-$



$N(B^0 \to \phi K_S) = 35.4 \pm 2.9$

$B^0 \to K^+K^-K_S$
$K^+K^- \neq \phi,\ K_S \to \pi^+\pi^-$



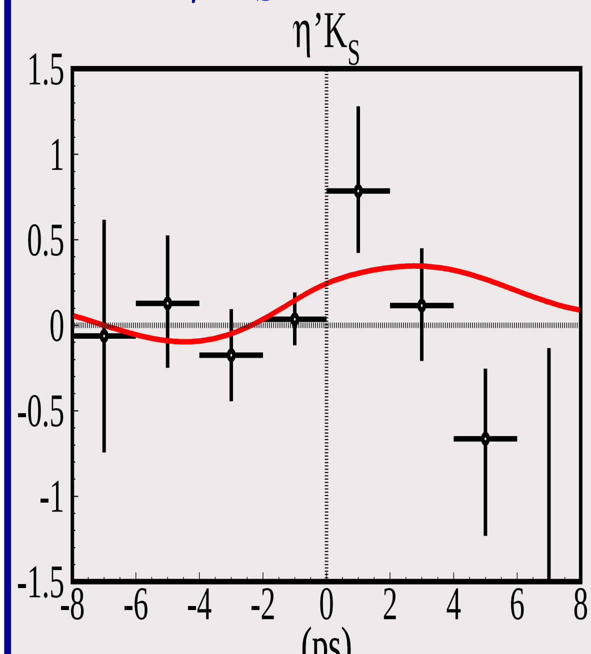
$N(B^0 \to K^+K^-K_S) =$
$= 94.3 \pm 7.3$

data sample 78 fb^{-1}

CP violation in $b \to s\bar{s}s$ - results

Raw asymmetries

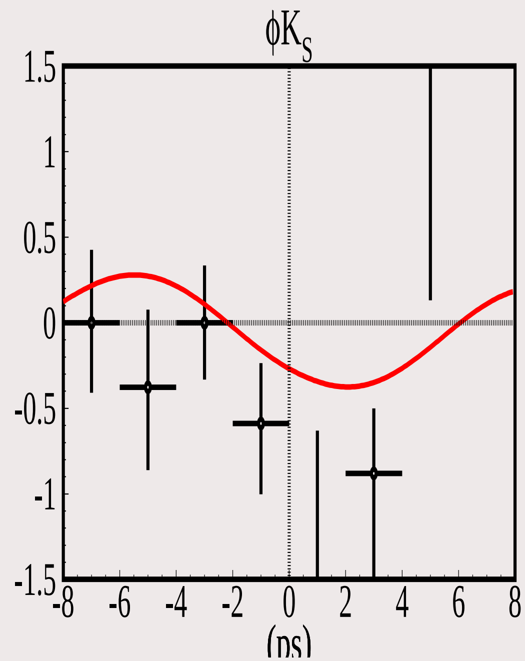
$B^0 \to \eta' K_S$



$-S_{\eta' K} = 0.76 \pm 0.36^{+0.05}_{-0.06}$

$A_{\eta' K} = +0.26 \pm 0.22 \pm 0.03$

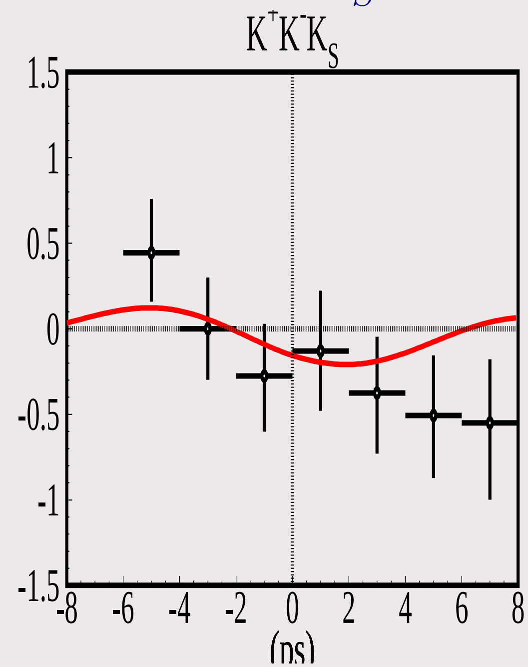
$B^0 \to \phi K_S$



$-S_{\phi K} = 0.73 \pm 0.64 \pm 0.18$

$A_{\phi K} = -0.56 \pm 0.41 \pm 0.12$

$B^0 \to K^+ K^- K_S$



$-S_{KKK} =$
$= 0.52 \pm 0.46 \pm 0.11^{+0.27}_{-0.03}$

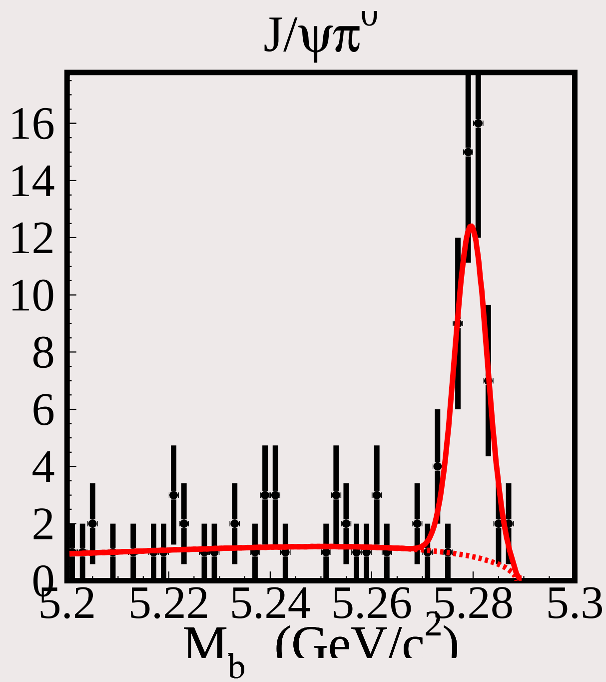
$A_{KKK} =$
$= -0.42 \pm 0.36 \pm 0.09^{+0.03}_{-0.22}$

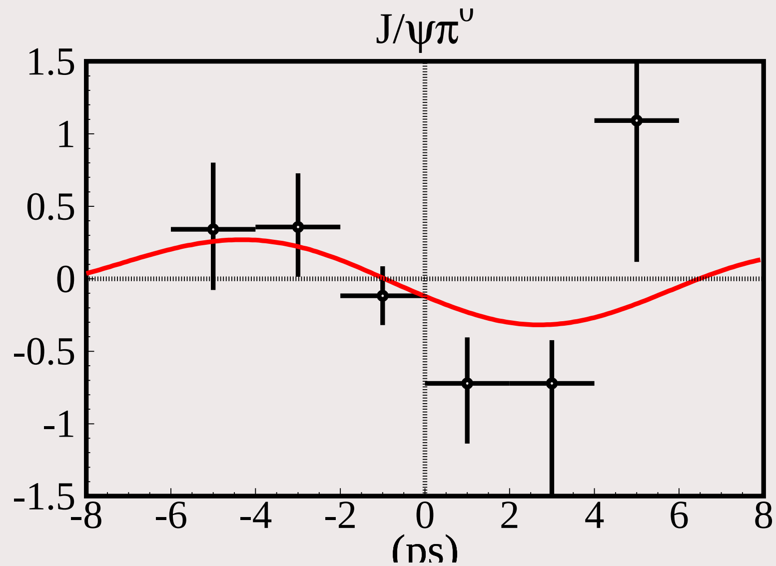
last error: uncert. in $CP\pm$ fractions, $w = (3^{+16}_{-3})\%$

to be compared with $S_{ccs} = 0.719 \pm 0.074 \pm 0.035$

CP violation in $B^0 \to J/\psi\pi^0$

$B^0 \to J/\psi\pi^0$ is a $b \to c\bar{c}d$ transition to a $CP = +1$ eigenstate.





$-S_{J/\psi\pi} = +0.93 \pm 0.49 \pm 0.08$

$N(J/\psi\pi^0) = 49.1 \pm 1.3$

$A_{J/\psi\pi} = -0.25 \pm 0.39 \pm 0.06$

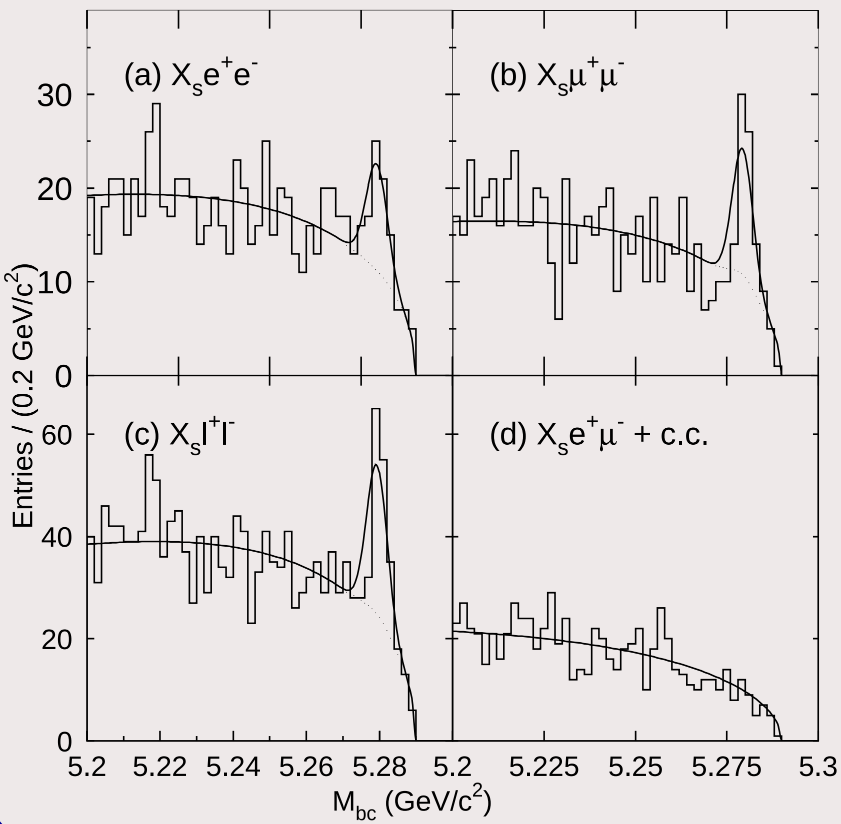
data sample 78 fb^{-1}

Measurement of $B \to X_s \ell^+ \ell^-$

- FCNC process $b \to s\ell\ell$ was first measured in $B \to K\ell\ell$ by Belle
- Inclusive $b \to s\ell\ell$ measurement is a model independent probe for new physics

Inclusive measurement: pseudo-reconstruction of $B \to X_s \ell^+ \ell^-$,
for X_s use $K^\pm$ or K_S with 0-4 π (0 or 1 π^0) - accounts for 78% of $b \to s\ell\ell$

M_{bc} after ΔE cut

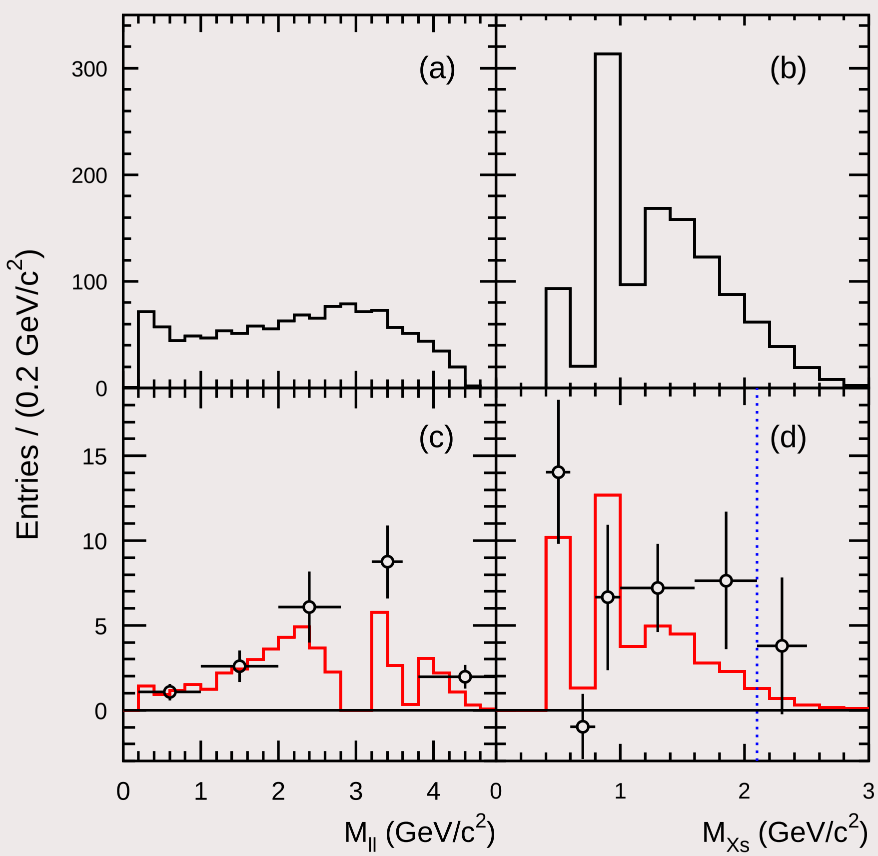


- background from $B \to X_s J/\psi (\to \ell^+\ell^-)$, $X_s \psi(2S) (\to \ell^+\ell^-)$ removed by $M_{\ell\ell}$ veto
- contamination from $B \to X_s \pi^+\pi^-$ (4.5 events for $\mu\mu$, 0.2 for ee) is subtracted

data sample 60 fb^{-1}

$M_{\ell\ell}$ and $M(X_s)$ distributions

$BR(B \to X_s \ell^+ \ell^-) = (6.1 \pm 1.4^{+1.3}_{-1.1}) \cdot 10^{-6}$ for $M_{\ell\ell} > 0.2$ GeV/c^2



mass spectra assumed in MC (SM calculation, model by A. Ali et al.)

observed spectra
with eff. corrected predictions

In K and K^* regions consistent with exclusive measurements.

Summary

- Belle has accumulated 89.6 fb^{-1} data (78 fb^{-1} on $\Upsilon(4S)$, 85 M $B\bar{B}$ pairs) at the KEKB asymmetric B factory
- CP violating parameters are measured to be

  $$S_{ccs} = 0.719 \pm 0.074 \pm 0.035,\ |\lambda_{ccs}| = 0.950 \pm 0.046 \pm 0.026$$

  $$S_{\pi\pi} = -1.21^{+0.38+0.16}_{-0.27-0.13},\ A_{\pi\pi} = +0.94^{+0.25}_{-0.31} \pm 0.09 \text{ (with 41.8 fb}^{-1}\text{)}$$

- Time dependent CP violation was measured in $b \to s\bar{s}s$ snd $b \to c\bar{c}d$
- Inclusive $b \to s\ell\ell$ was measured by pseudo-reconstruction:

  $$BR(B \to X_s\ell^+\ell^-) = (6.1 \pm 1.4^{+1.3}_{-1.1}) \cdot 10^{-6}$$