Matter and anti-matter: a tiny but important difference

Peter Križan
Univ. of Ljubljana and J. Stefan Institute

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- Introduction with a little bit of history
- How to measure the difference between matter and anti-matter
- Experimental apparatus
- Measurement of CP violation in:
  - $B^0 \to J/\psi K^0$
  - $B^0 \to \pi^+\pi^-$
  - $B^0 \to \eta' K_S$, ϕK_S and $K^+K^-K_S$
- A new window for possible new physics: $b \to s\ell^+\ell^-$ decay
- Summary

Matter and anti-matter: a huge difference in abundance

The universe as we can see it today (which is the present universe close to us, and very much older in the most distant regions we can observe) is made almost exclusively of matter.

However, right after the Big Bang, both were equally present.

How can this be explained?

Three conditions are necessary for a transition from a matter-anti-matter eqully populated universe to the matter dominated one (Saharov):

- baryon number has be violated (i.e. barions can decay into non-barions)
- CP symmetry has to be violated (matter has to behave differently than anti-matter)
- non-equillibrium conditions in the universe are needed

CP Symmetry

CP is a combined symmetry operation:

- C turns a particle into its antiparticle
- P inverts the space

If a particle and its anti-particle behave exactly in the same way, they are CP symmetric.

A violation of CP symmetry is therefore the crucial test of how the matter is different from anti-matter.

CP Violation

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

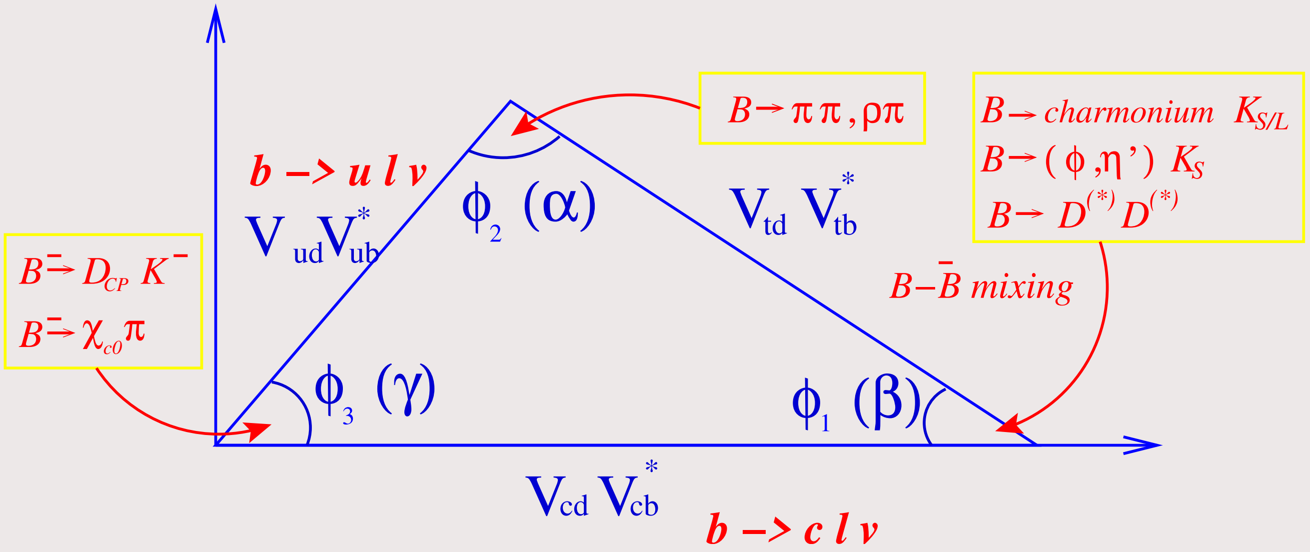
CP Violation in the Standard Model

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

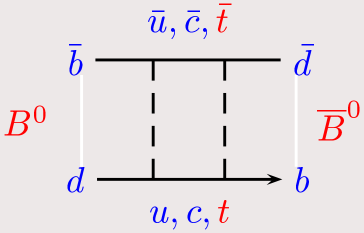
$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\varrho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\varrho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

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

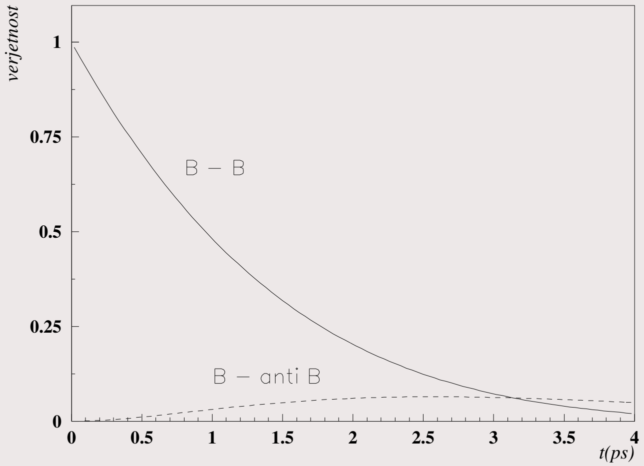
$\rightarrow$ unitarity triangle



Mešanje v sistemu nevtralnih mezonov B^0



mezon B^0 se z znatno verjetnostjo pretvori v $\bar{B}^0$, preden razpade



$$|\langle B^0|B^0(t)\rangle|^2 = e^{-t/\tau}\cos^2\frac{\Delta m t}{2} = \frac{1}{2}e^{-t/\tau}(1+\cos\Delta m t)$$

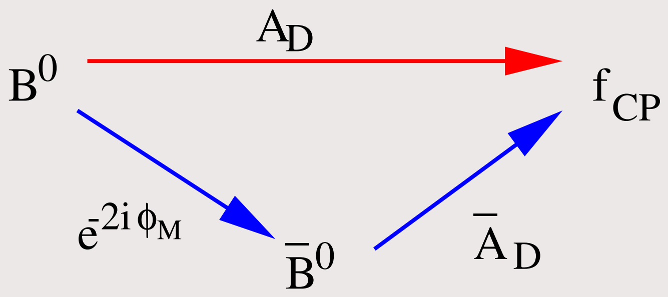
$$|\langle \overline{B^0}|B^0(t)\rangle|^2 = e^{-t/\tau}\sin^2\frac{\Delta m t}{2} = \frac{1}{2}e^{-t/\tau}(1-\cos\Delta m t)$$

$$\boldsymbol{\Delta m = 0.5\ \mathrm{ps}^{-1} \qquad \tau = 1.5\ \mathrm{ps}}$$

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:



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

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

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

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

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

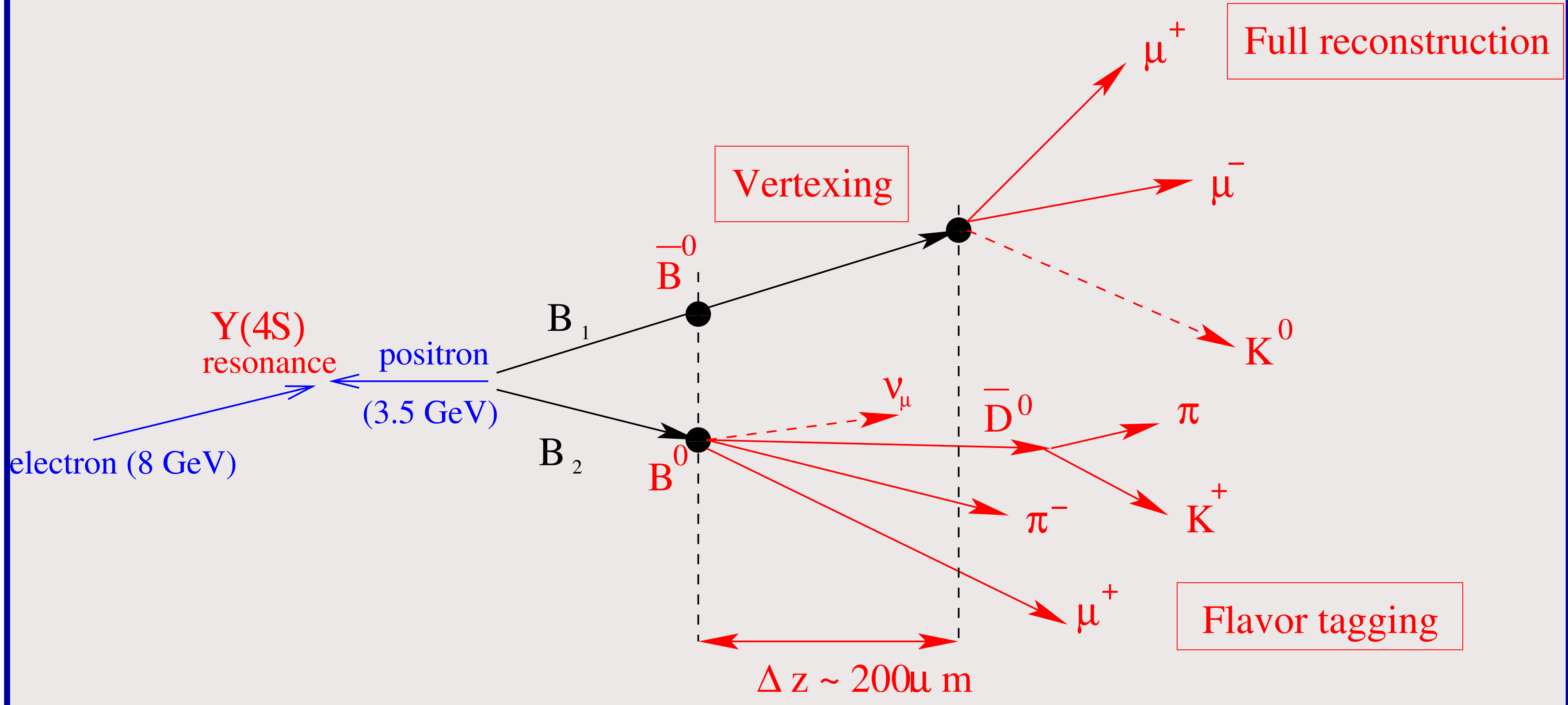
Standard model predictions

	$b \to c\bar{c}s$	$b \to c\bar{c}d$	$b \to s\bar{s}s$	$b \to u\bar{u}d$
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. $A_f \neq 0 \to \Gamma(\bar{B} \to f_{CP}) \neq \Gamma(B \to f_{CP})$

$\to$ direct CP violation

Measurement of CP violation - principle



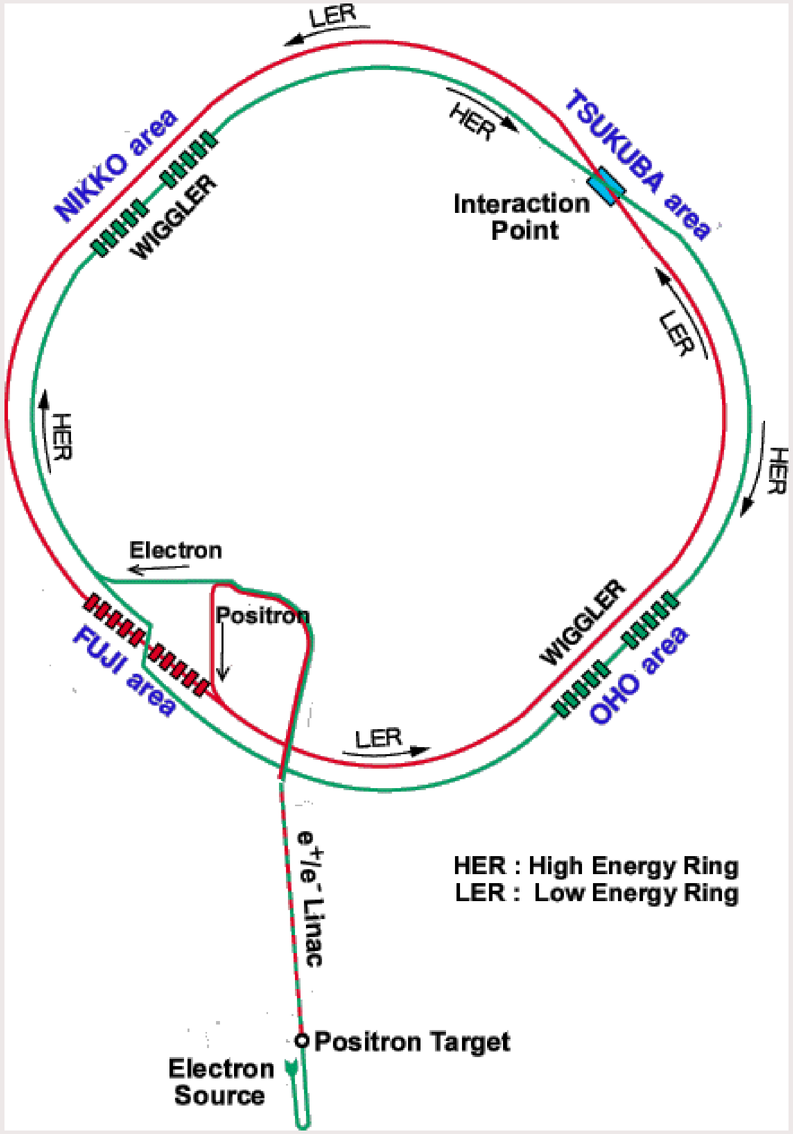
Needed:
a large number of $B\bar{B}$ pairs (100 M)
$\rightarrow$ B-factory $=$
a high luminosity e^+e^- collider
with asymmetric beam energies

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)

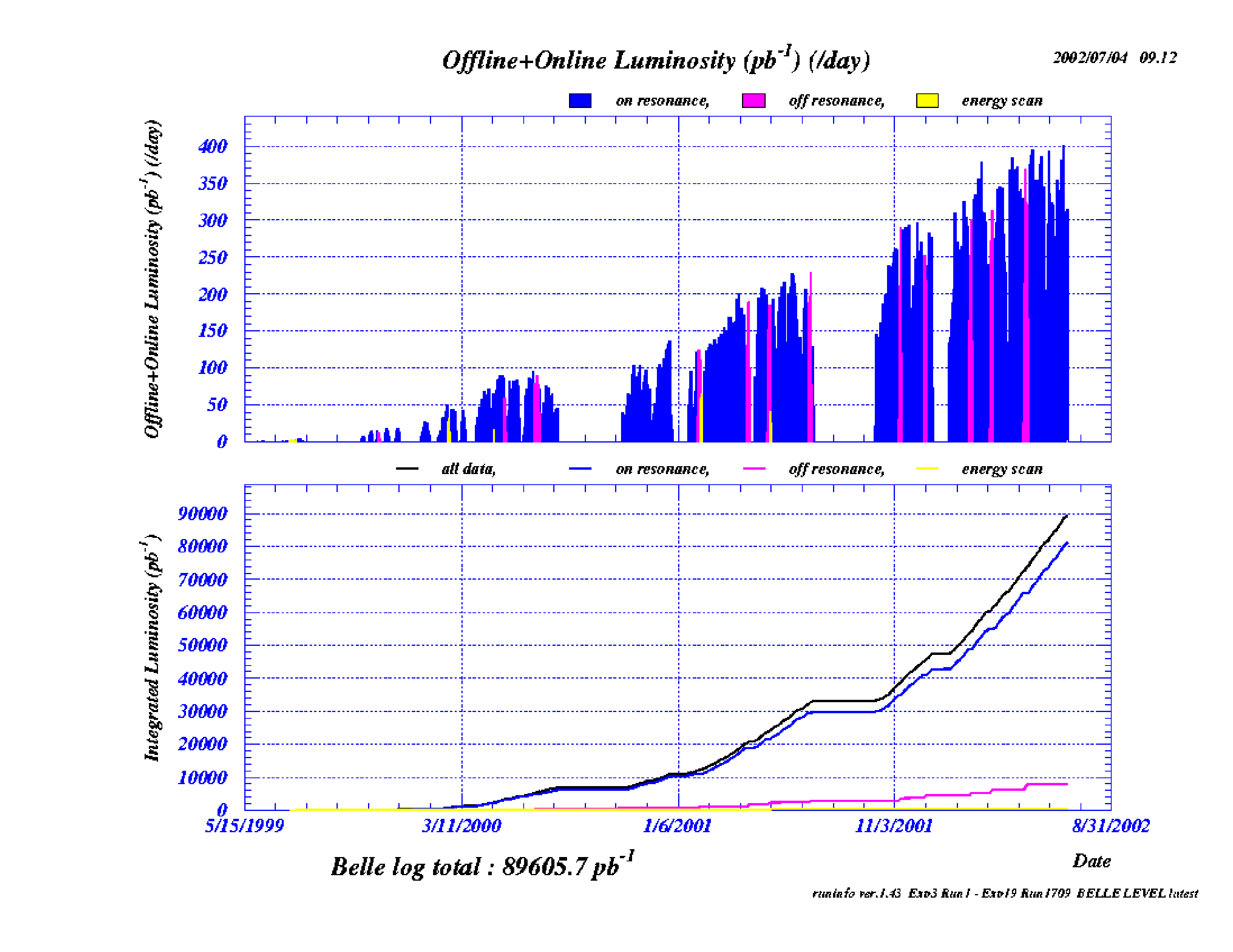
KEKB Accelerator performance 1

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

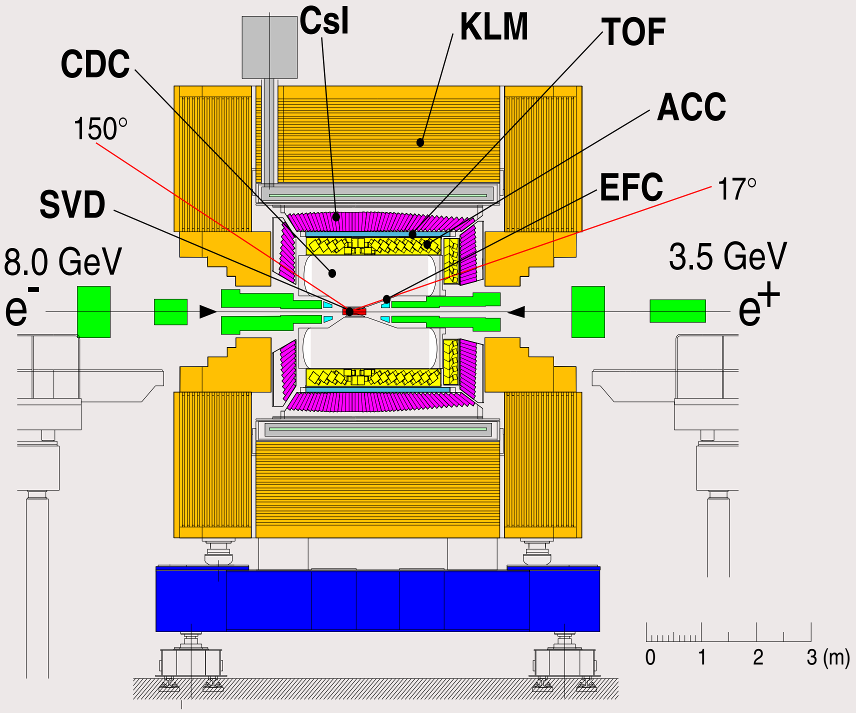
integrated luminosity :
shift = 142.7 /pb
day = 391.0 /pb
24h = 409.8 /pb
7days = 2524. /pb
month = 7348. /pb



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:

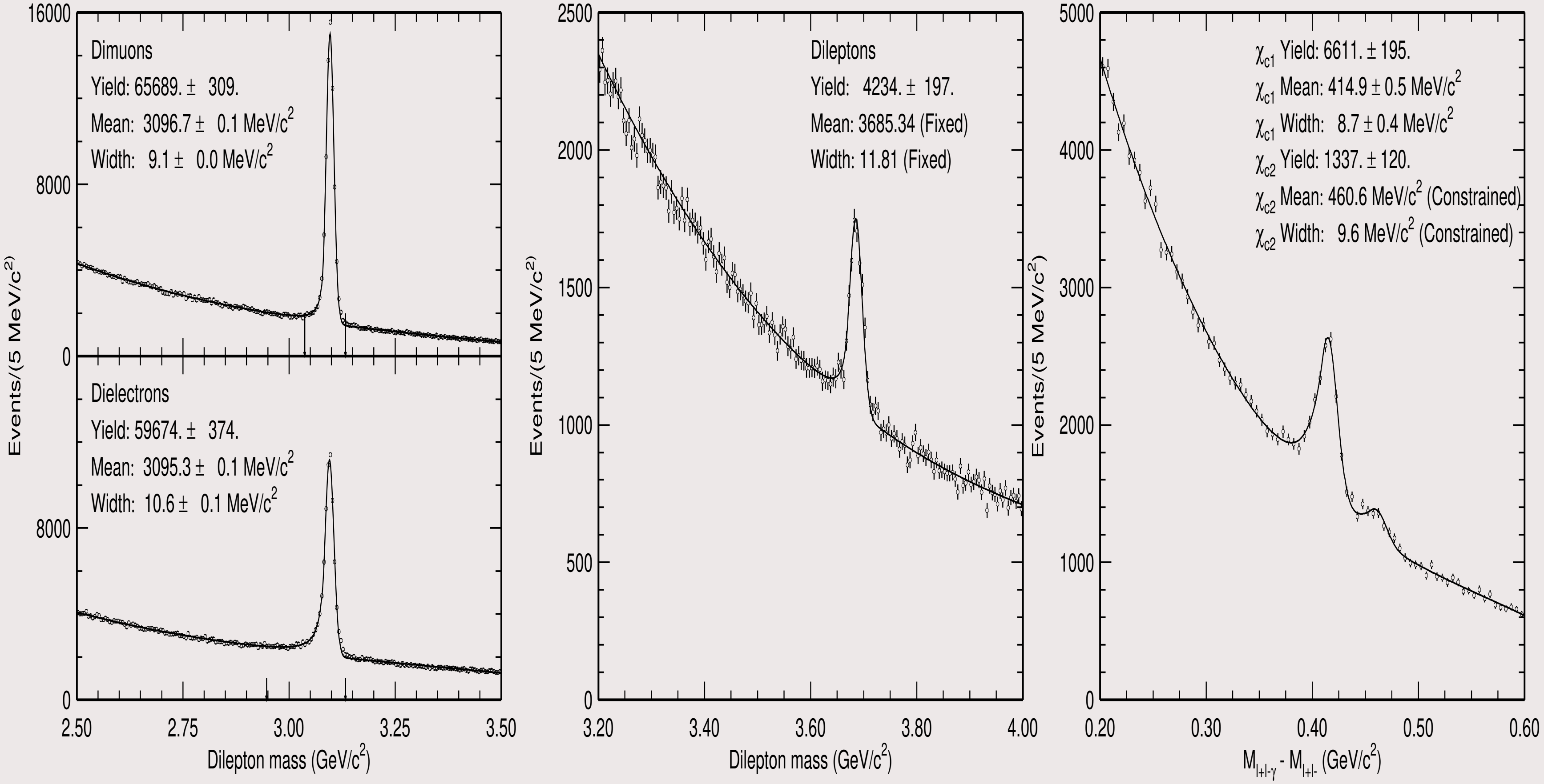
Identify $K^{\pm}$ up to 3.5 GeV/c (efficiency $\approx 90\%$, fake rate $\approx 6\%$)

- 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



$J/\psi \to \mu^+\mu^-, e^+e^-$
$\sigma_M = 9.6(10.7)\mathrm{GeV/c^2}$

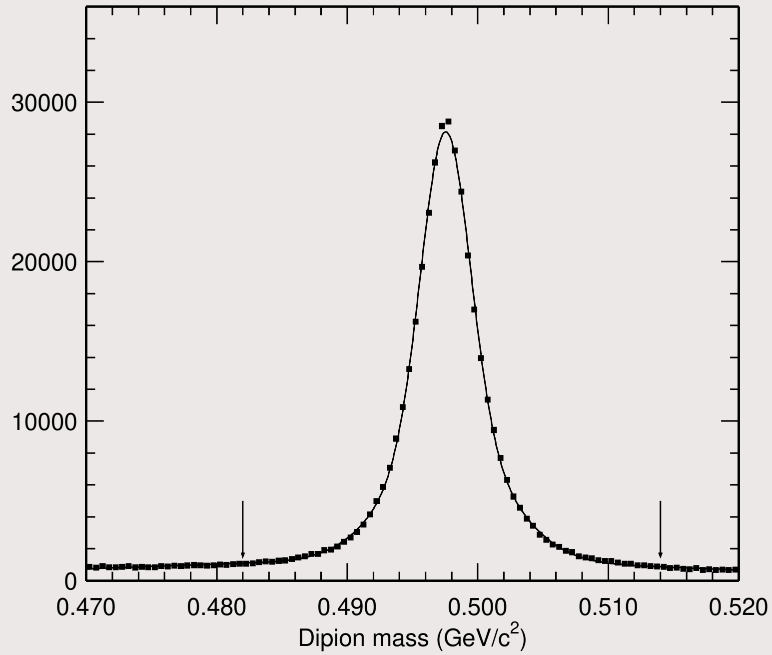
$\psi(2s) \to \mu^+\mu^-, e^+e^-$
$\sigma_M = 12.1\mathrm{GeV/c^2}$

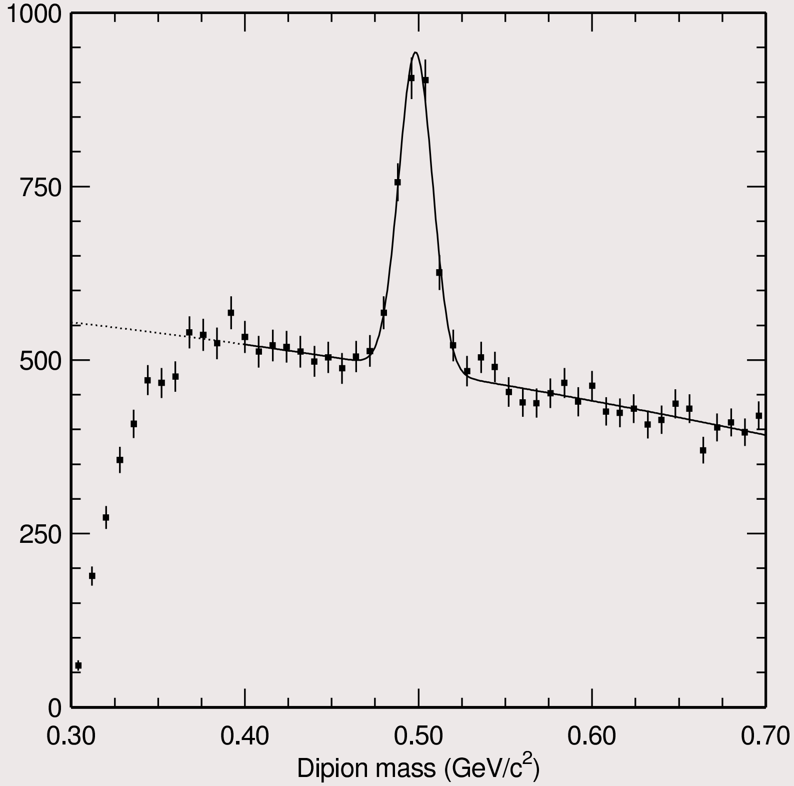
$\chi_{c1}, \chi_{c2} \to J/\psi\gamma$
$\sigma_{\Delta M} = 7.0\mathrm{GeV/c^2}$

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

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

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



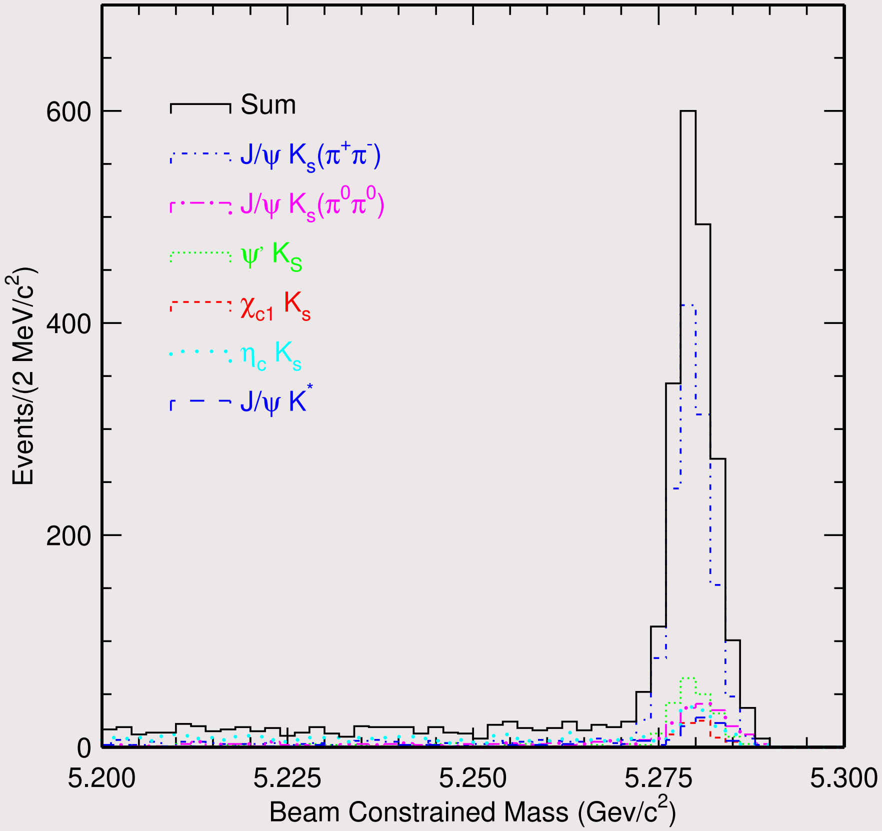


$K_S \to \pi^0\pi^0$

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

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

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



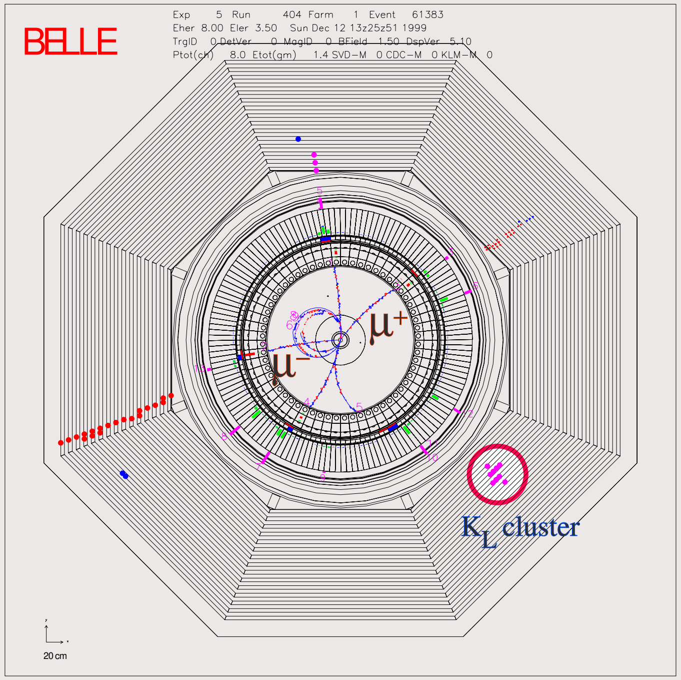
$$M_{bc} = \sqrt{E^2_{\rm beam} - \vec{p}^{\,2}_{\rm Bcandidate}}$$

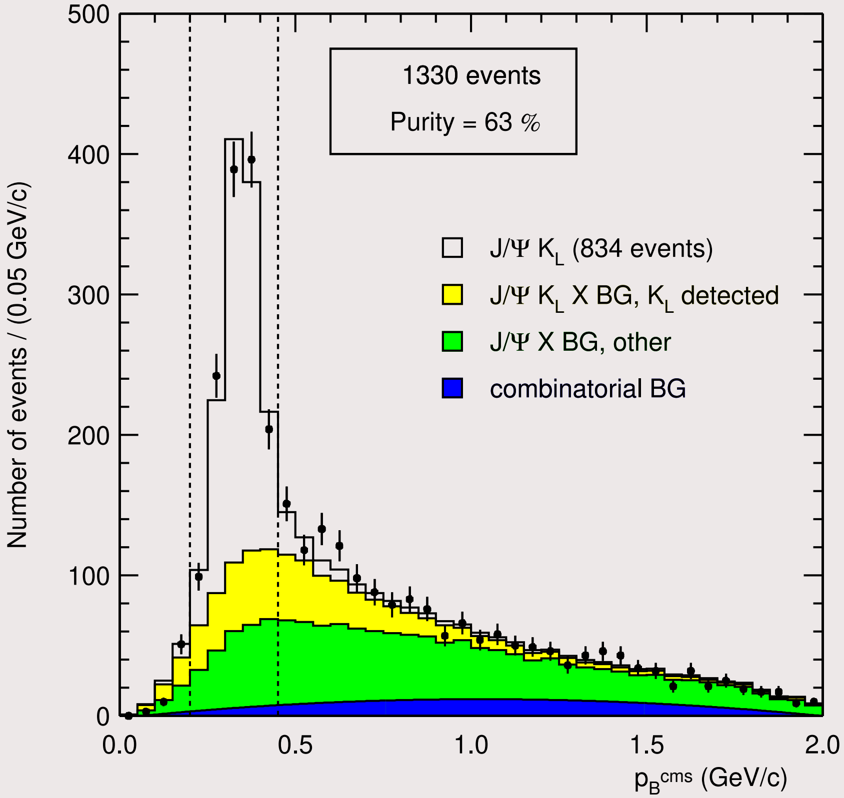
$B^0 \to$	events	$\frac{S}{S+N}$
$J/\psi K_S (K_S \to \pi^+\pi^-)$	1285	.976
$J/\psi K_S (K_S \to \pi^0\pi^0)$	188	.824
$\psi(2S) K_S$		
$(\psi(2S) \to \ell^+\ell^-) K_S$	91	.957
$(\psi(2S) \to J/\psi\pi^+\pi^-)$	112	.911
$\chi_{c1} K_S$	77	.958
$\eta_c (\eta_c \to K_S K \pi) K_S$	72	.646
$\eta_c (\eta_c \to K K \pi^0) K_S$	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 $CP = +1$: $B^0 \to J/\psi K_L$

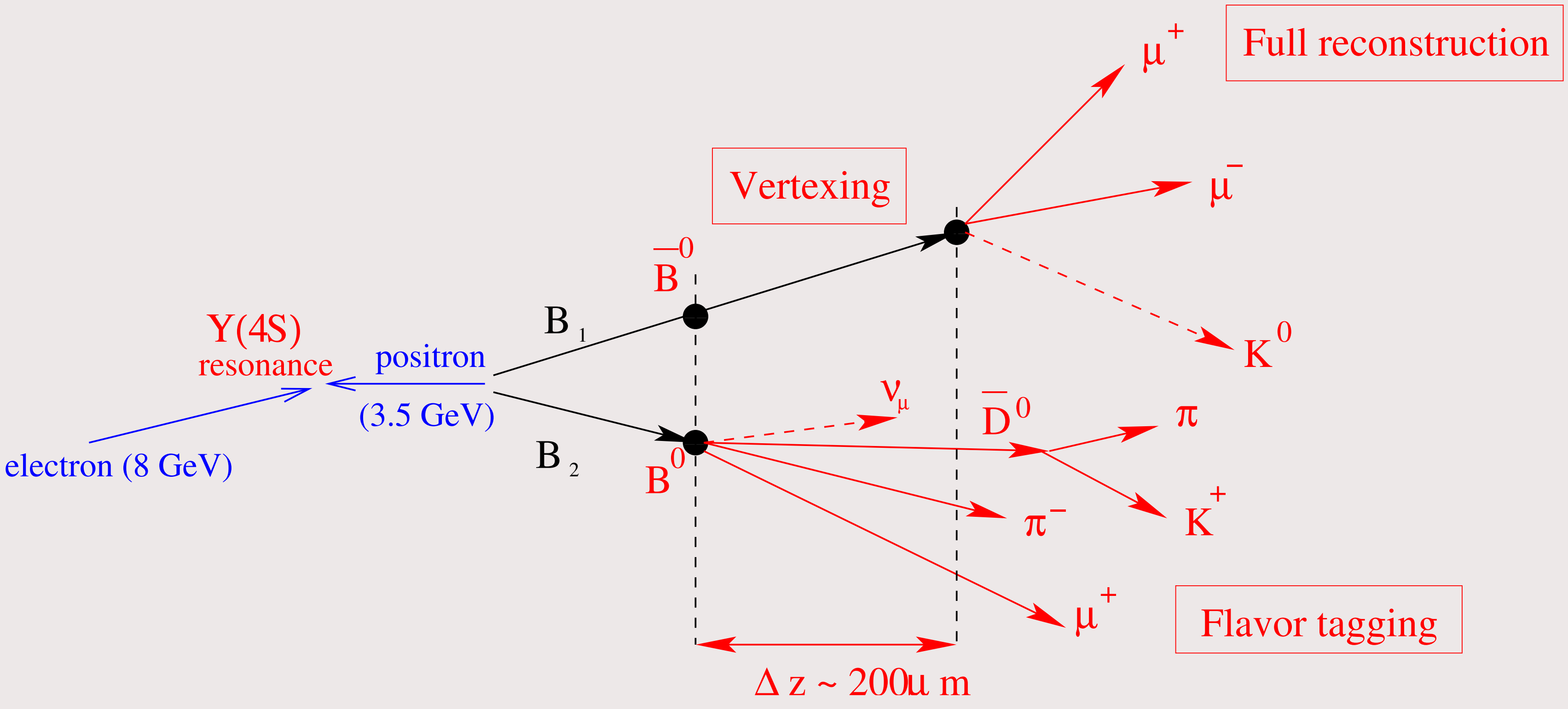
- detection of K_L in KLM and ECL
- K_L direction, no energy





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

Measurement of CP violation - continued



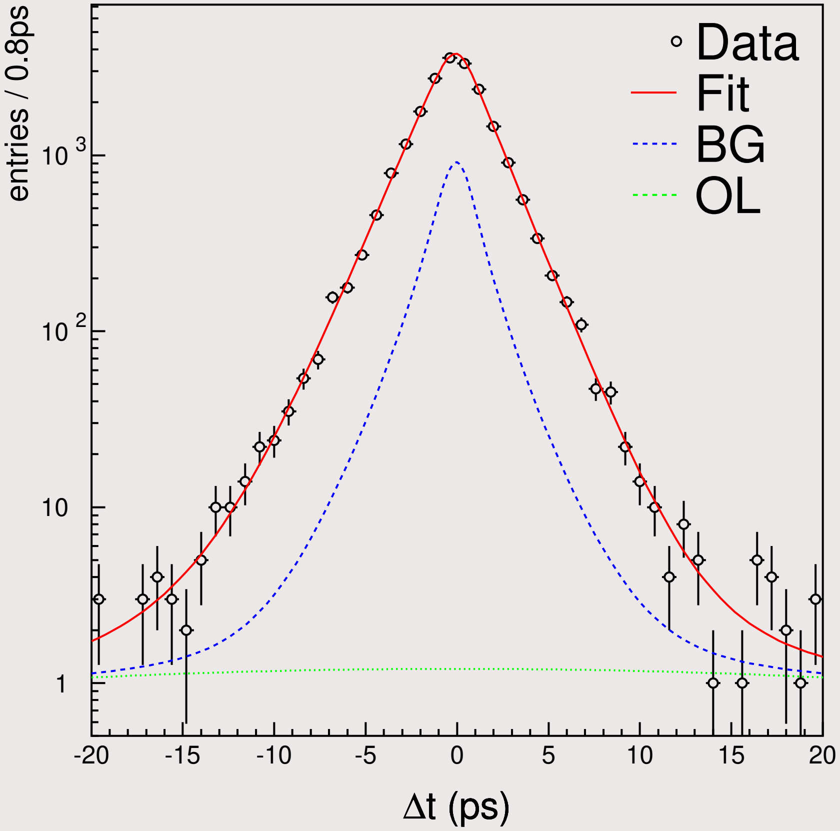
Determine Δt from $\Delta z = \beta\gamma c \Delta t$:

- 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 $\Delta z = \beta\gamma c \tau_B = 200$ μm

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 (preliminary)
- 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^- $\qquad b \to c\ell^-\nu$
- intermediate momentum ℓ^+ $\qquad c \to s\ell^+\nu$

Inclusive hadrons

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

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).

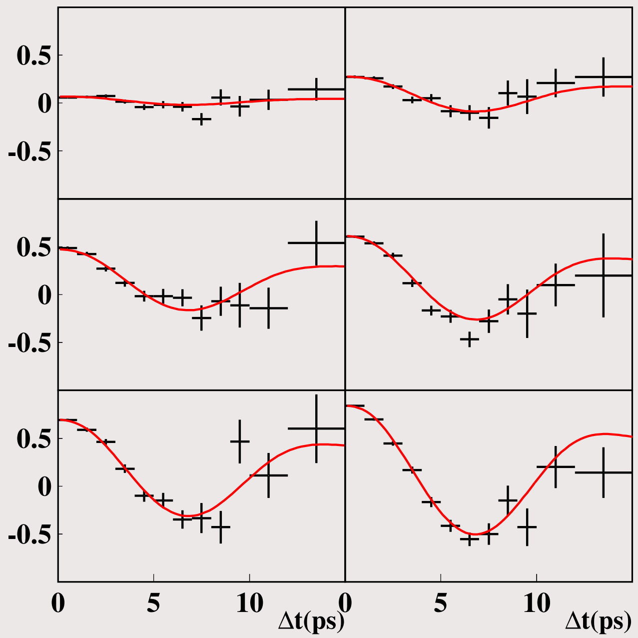
$\rightarrow$ The asymmetry oscillation is reduced, $\sin \Delta m_d t \rightarrow (1 - 2w) \sin \Delta m_d t$.

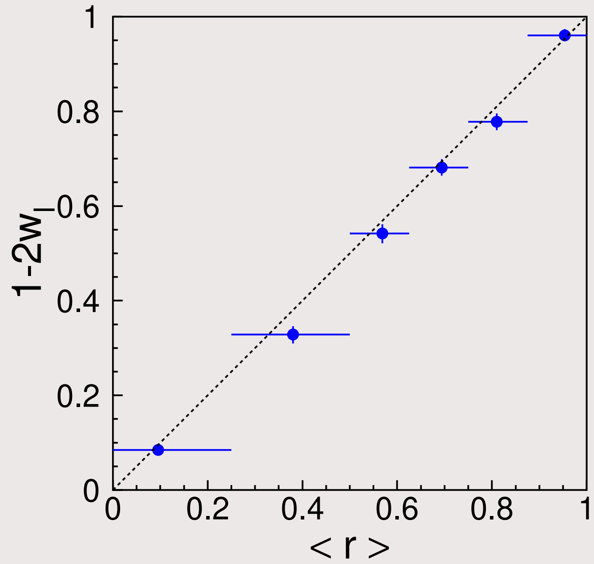
$\rightarrow$ Needed: w for each event.

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

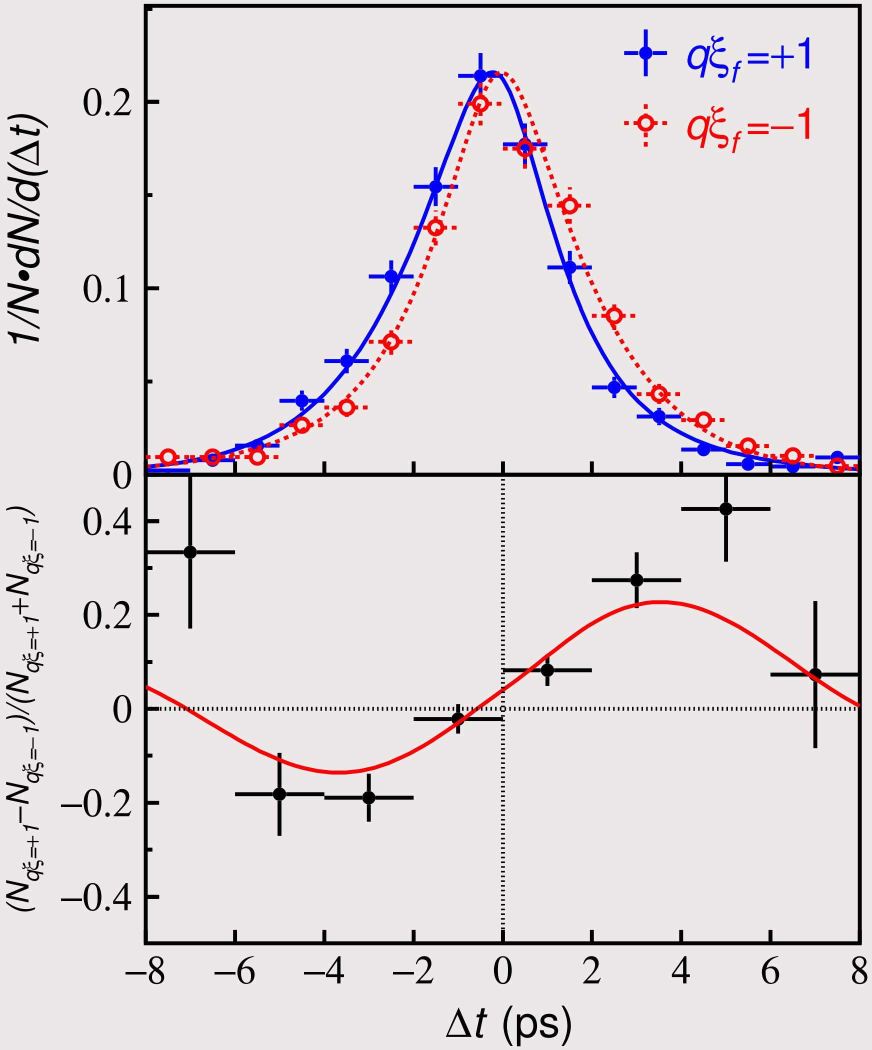
Calibrate the relation $(1-2w)$ vs. r with data: measure the $B^0 \bar{B}^0$ mixing amplitude (using $\bar{B}^0 \rightarrow D^{*+}\ell^-\nu$, $D^{(*)+}\pi^-$ and $D^{(*)+}\rho^-$ decays) in 6 intervals in r

(OF-SF)/(OF+SF)





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 $\bar{B}^0 \to f_{CP=+1}$)

with fixed $A_{ccs} = 0$:

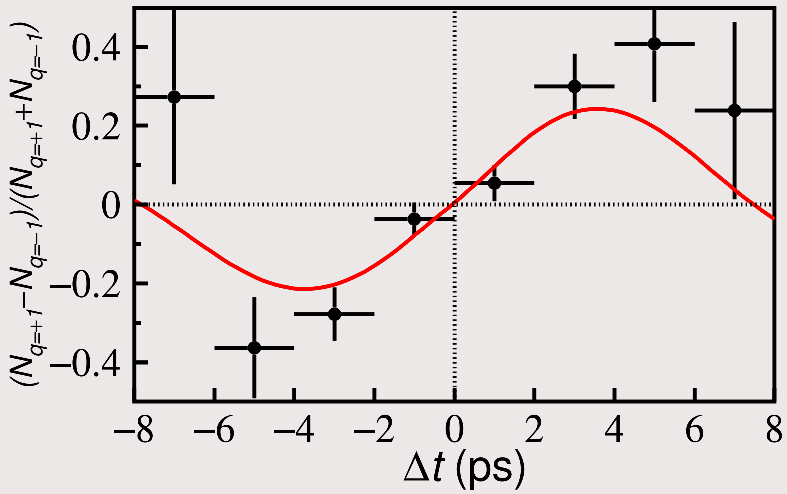
$$-S_{ccs} = \sin 2\phi_1 = 0.719 \pm 0.074 \pm 0.035$$

with free A_{ccs} and S_{ccs}:

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

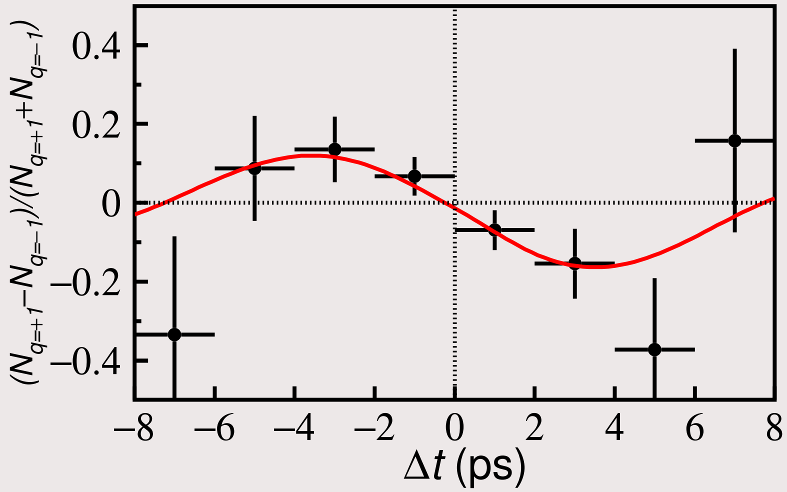
A_{ccs} is consistent with 0

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



$CP = -1$ sample

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



$CP = +1$ sample

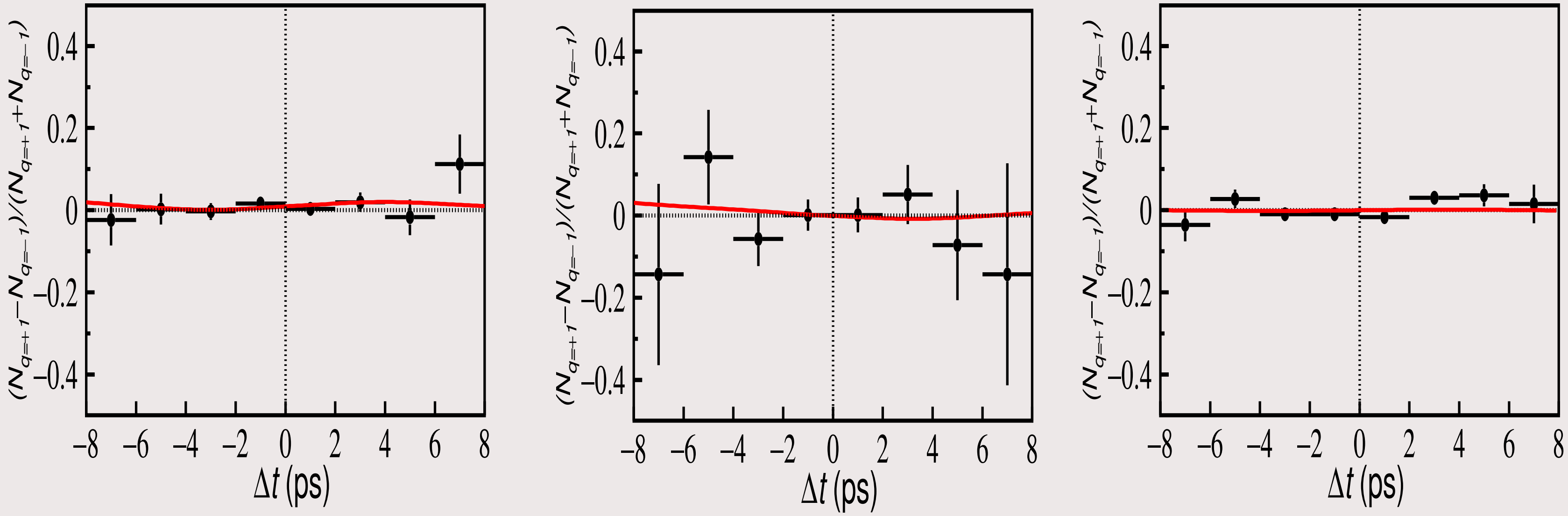
$$\sin 2\phi_1 = 0.78 \pm 0.17$$

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

$B^0 \to D^{*\pm}\pi^{\mp}$ | $B^0 \to J/\psi K^{*0}$, $K^{*0} \to K^+\pi^-$ | $B^0 \to D^*\ell\nu$



"$\sin 2\phi_1$" $= 0.035 \pm 0.032$ | "$\sin 2\phi_1$" $= -0.021 \pm 0.093$ | "$\sin 2\phi_1$" $= 0.004 \pm 0.017$

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

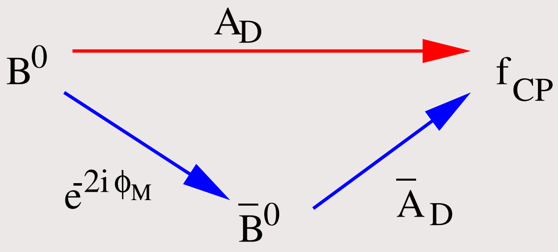
Comparison to the previous result

- 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

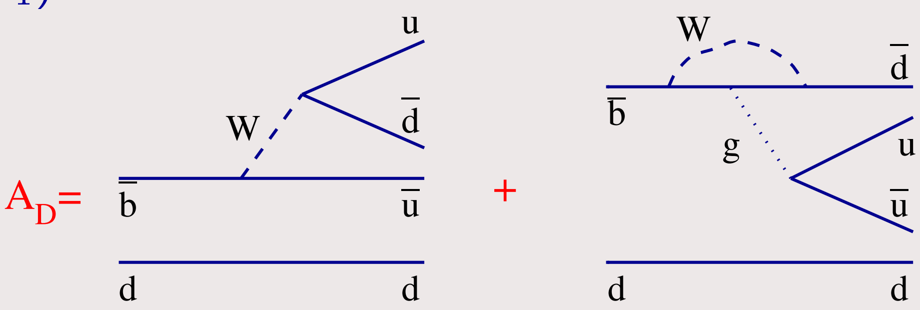
$\sin 2\phi_1$ with the first 41.8 fb^{-1} data sample $= 0.78 \pm 0.10$

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

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)



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

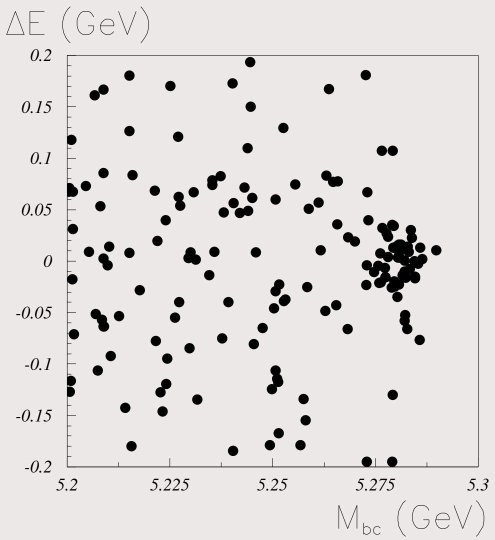
with

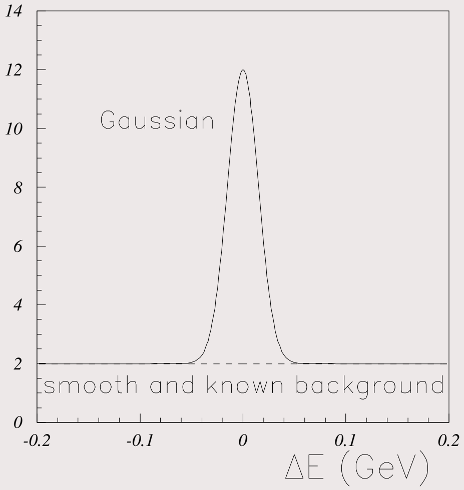
$$S_{\pi\pi} \neq \sin 2\phi_2$$

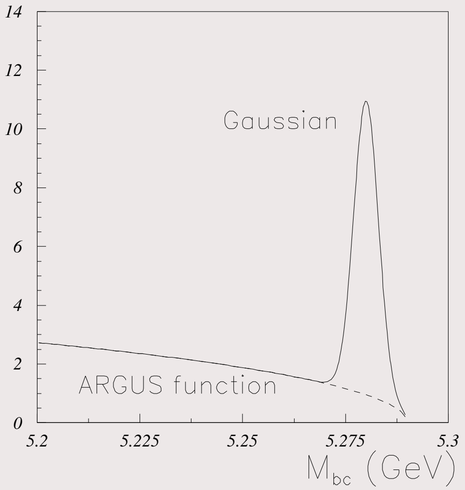
$$A_{\pi\pi} \neq 0$$

$\rightarrow$ $|\lambda_{\pi\pi}| \neq 1$ 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):

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

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

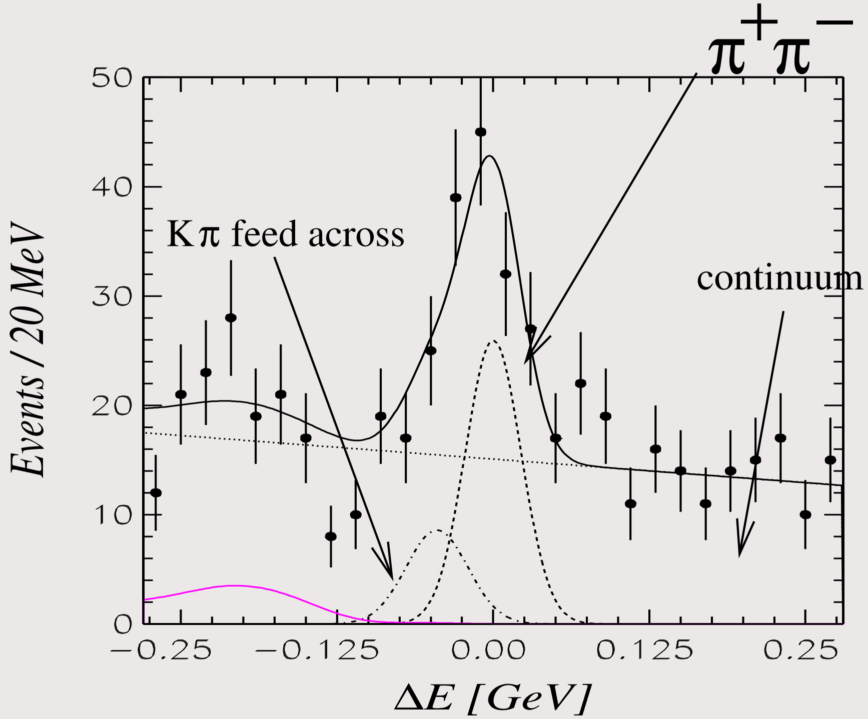
Data sample 41.8 fb^{-1}

Signal region:

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

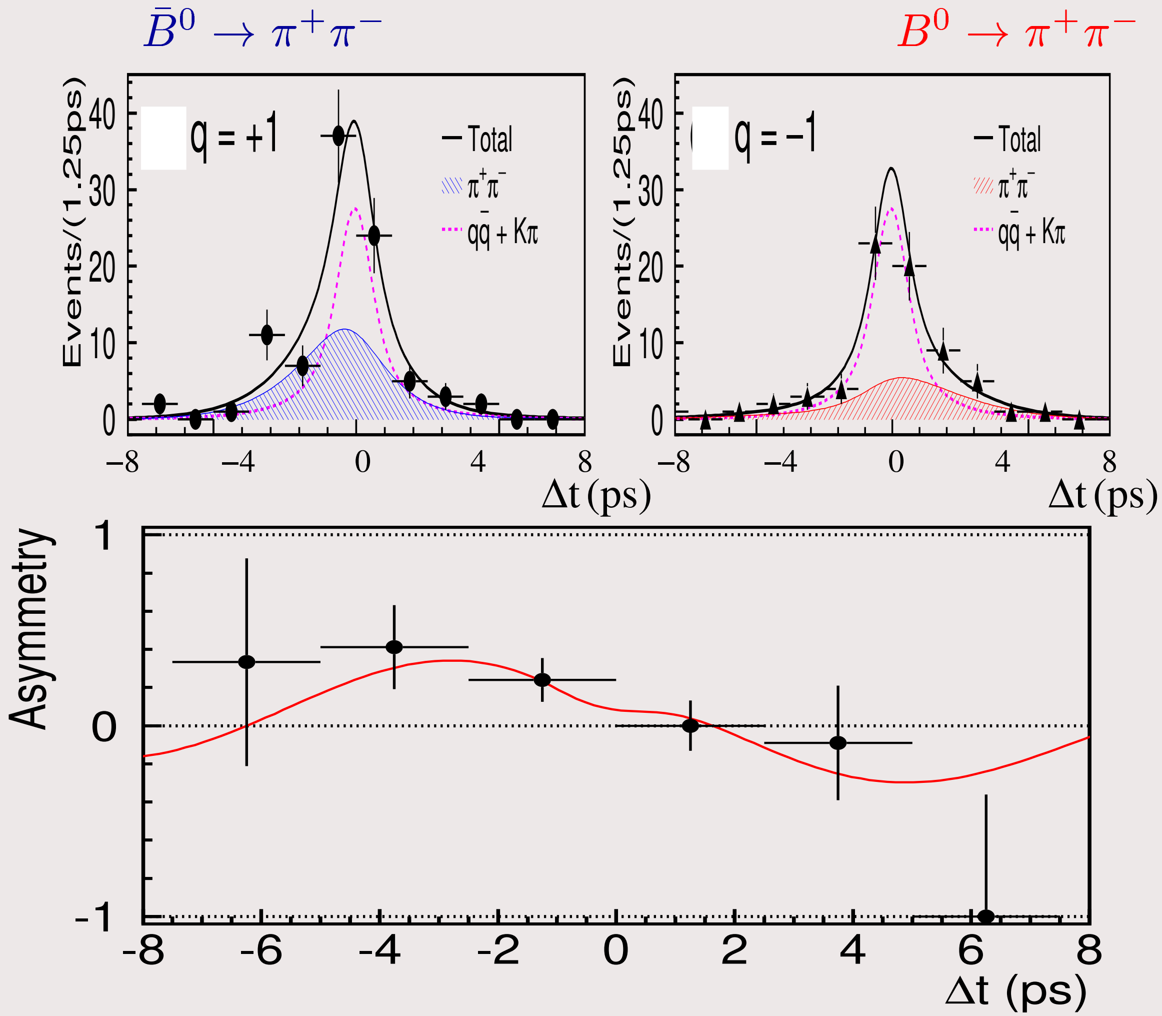
$$N(\pi\pi) = 73.5 \pm 13.8 \quad \text{events}$$

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



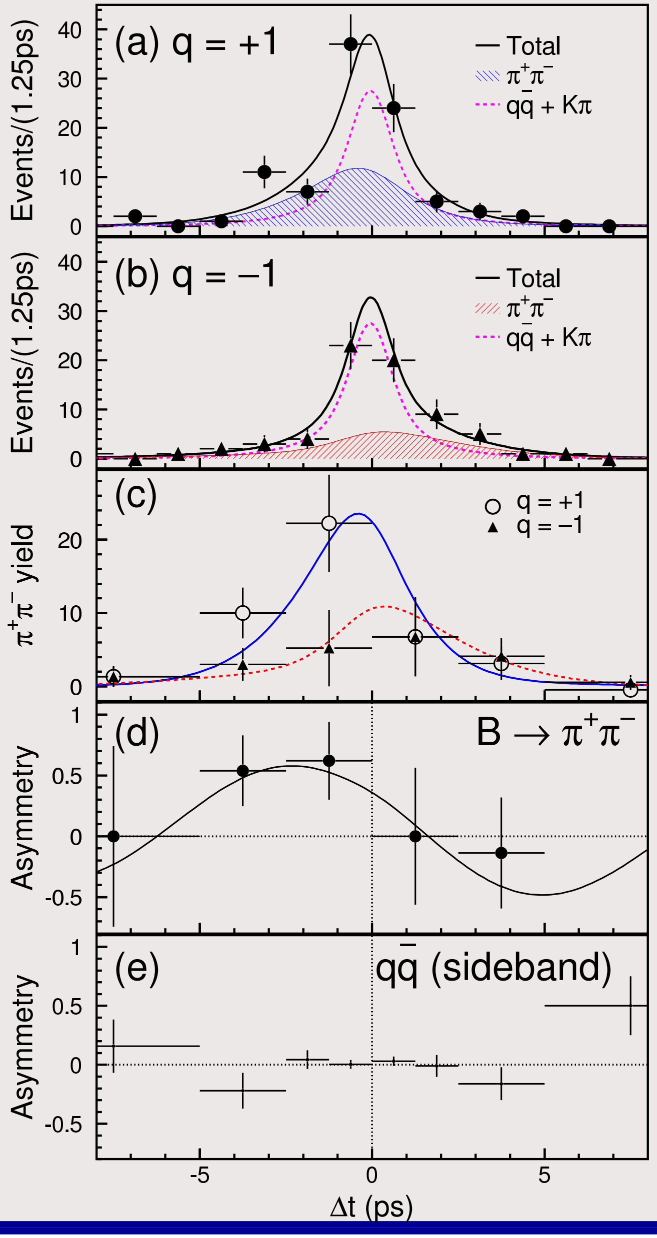
ΔE distribution after M_{bc} cut

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



Raw asymmetry

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



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

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

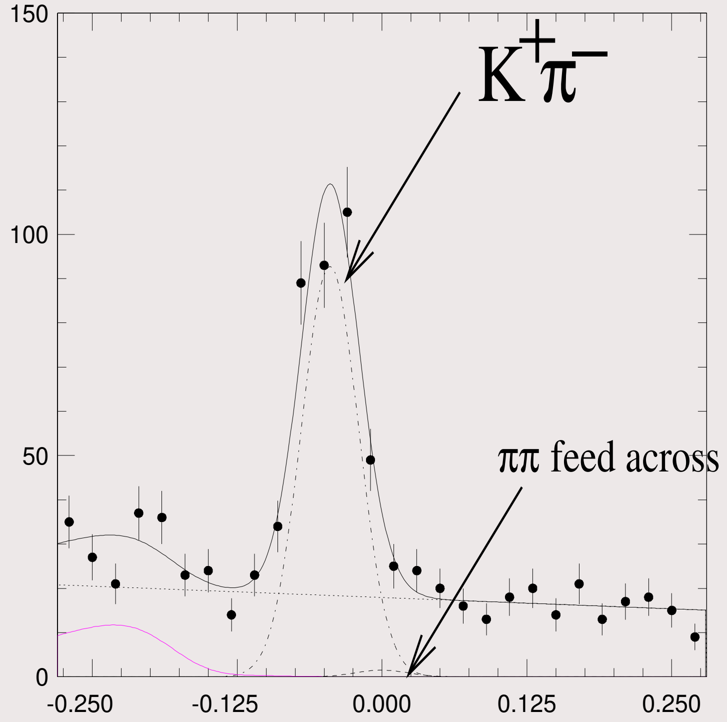
$A_{\pi\pi} \neq 0 \rightarrow$ direct CP violation,
$\Gamma(B^0 \rightarrow \pi^+\pi^-) \neq \Gamma(\bar{B}^0 \rightarrow \pi^+\pi^-)$

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

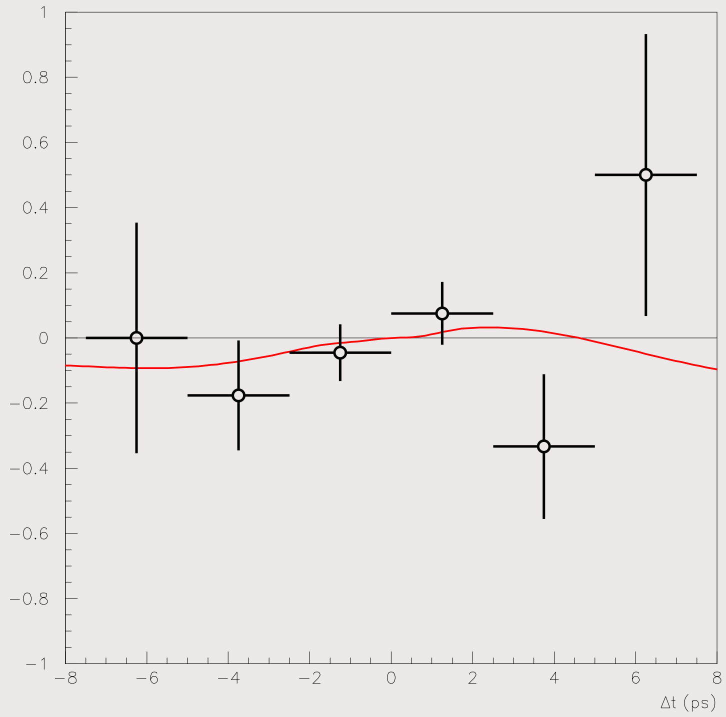
(data sample 41.8 fb^{-1})

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

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



Observed asymmetry

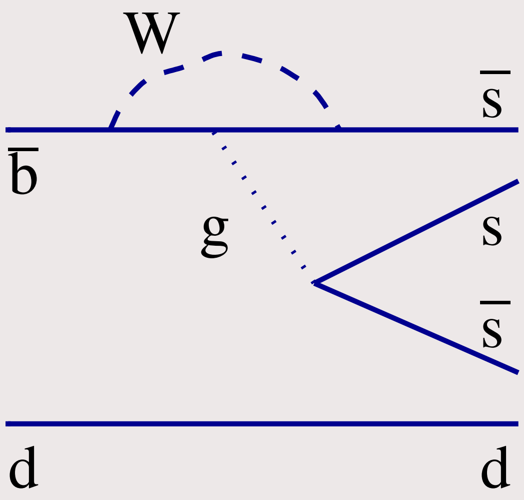


consistent with null asymmetry

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

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

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



Standard Model:

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

$\xi_f = CP$ eigenvalue for the f_{CP}

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

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

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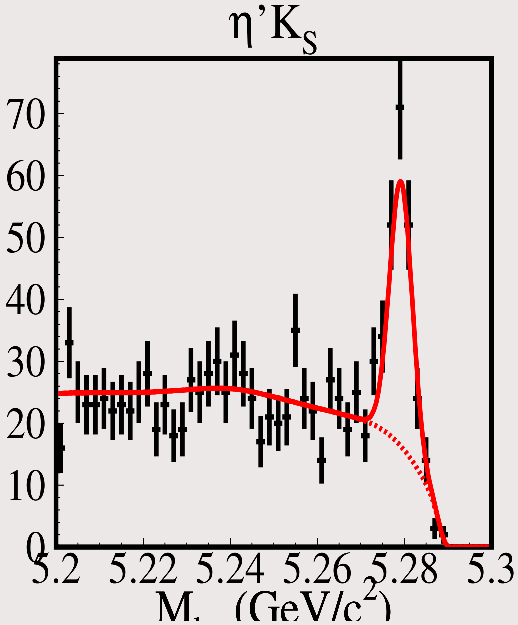
$B^0 \to \eta' K_S$

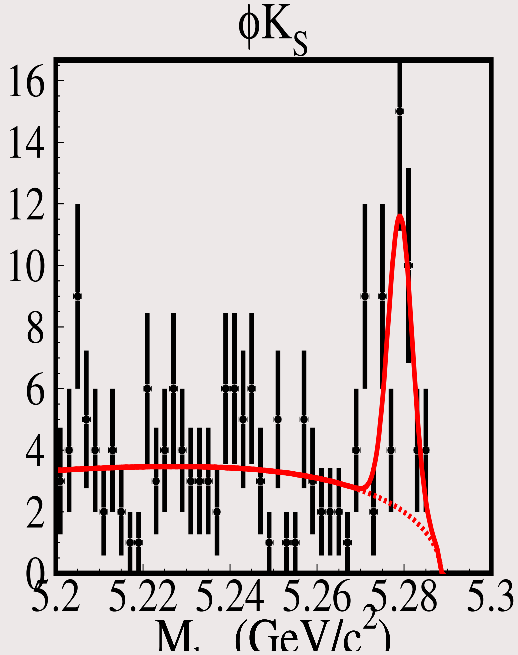
$\eta' \to \pi^+\pi - \eta,\ \rho\gamma,\ \eta \to \gamma\gamma$



$N(B^0 \to \eta' K_S) =$
147.9 ± 14.6

$B^0 \to \phi K_S$

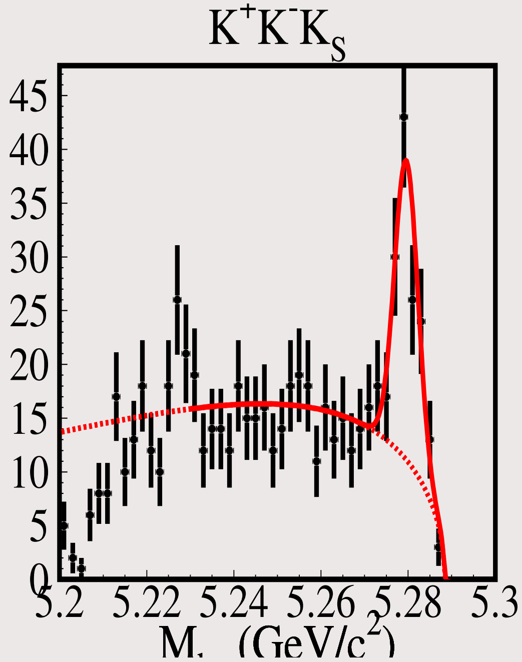
$\phi \to K^+K^-,\ K_S \to \pi^+\pi^-$



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

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

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



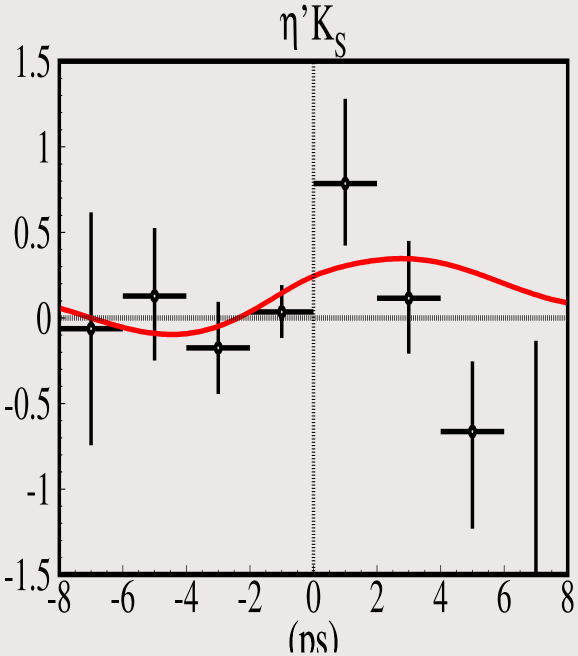
$N(B^0 \to K^+K^-K_S) =$
$= 94.3 \pm 7.3$

data sample 78 fb^{-1}

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

Raw asymmetries

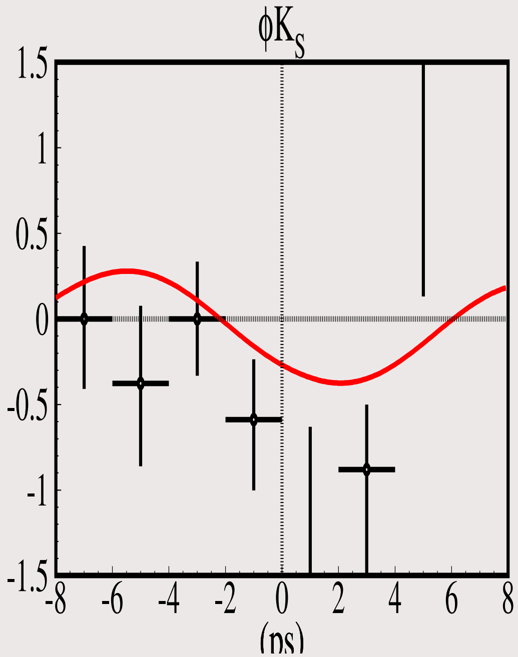
$B^0 \to \eta' K_S$



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

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

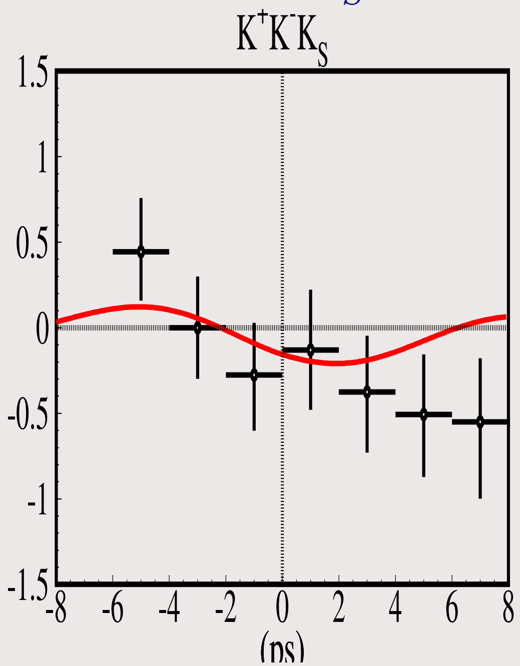
$B^0 \to \phi K_S$



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

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

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



$-S_{KKK} =$

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

$A_{KKK} =$

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

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 $B^0 \to J/\psi\pi^0$

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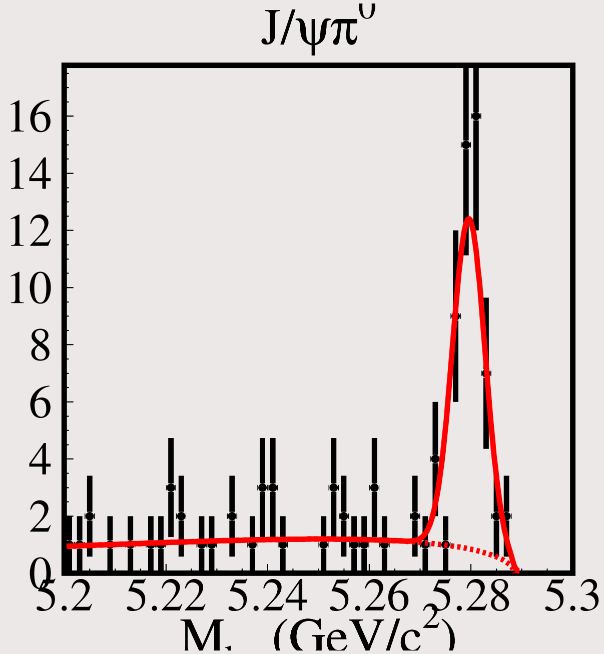
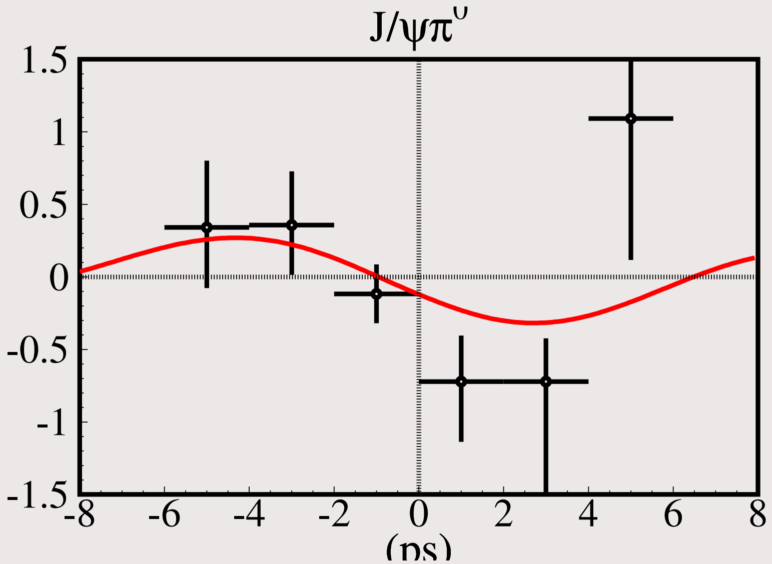
$B^0 \to J/\psi\pi^0$ is a $b \to c\bar{c}d$ transition to a $CP = +1$ eigenstate.





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

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

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

data sample 78 fb^{-1}

$b \to s\ell^+\ell^-$ transitions - a possible window into new physics

Quark b decays either to quark c or u: a quark of charge -1/3 turns into in a quark of charge 2/3. The probability is given by the CKM matrix elements.

In the $b \to s$ transition a quark of charge -1/3 turns into in a quark of of the same charge but different flavour. Such processes (flavour changing neutral currents) are forbiden in the Standard Model (unitarity of the CKM).

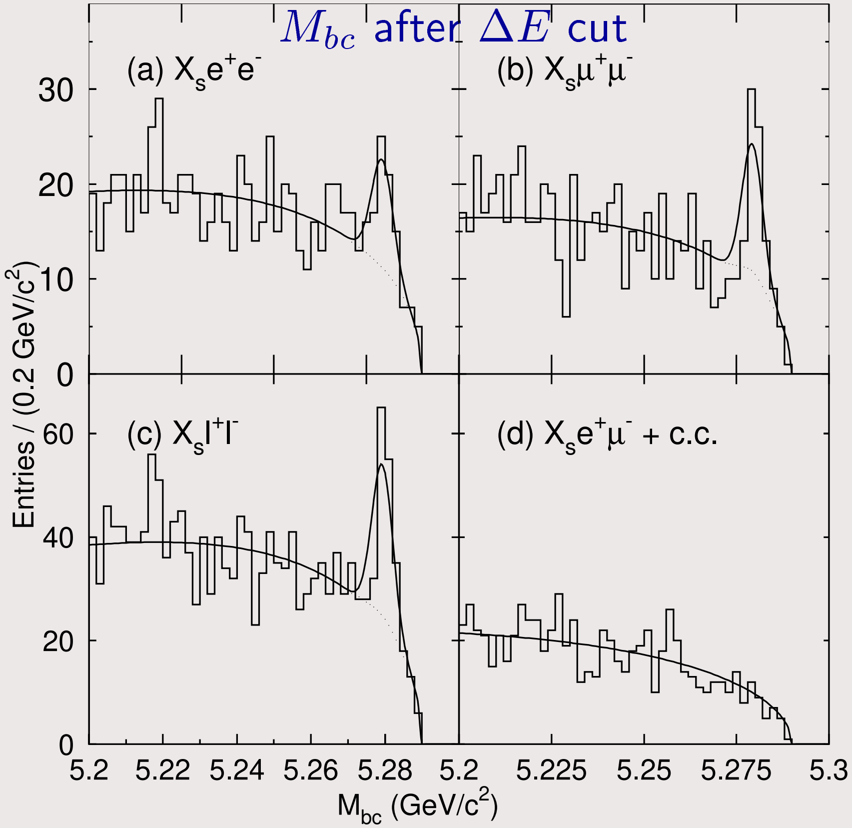
However, such a process can proceed via box diagrams with virtual particle contributions - and there it is an ideal spot to look for yet unobserved partiecles like supersymmetric partners of exsisting particles.

missing plot .....

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 $b \to s\ell\ell$

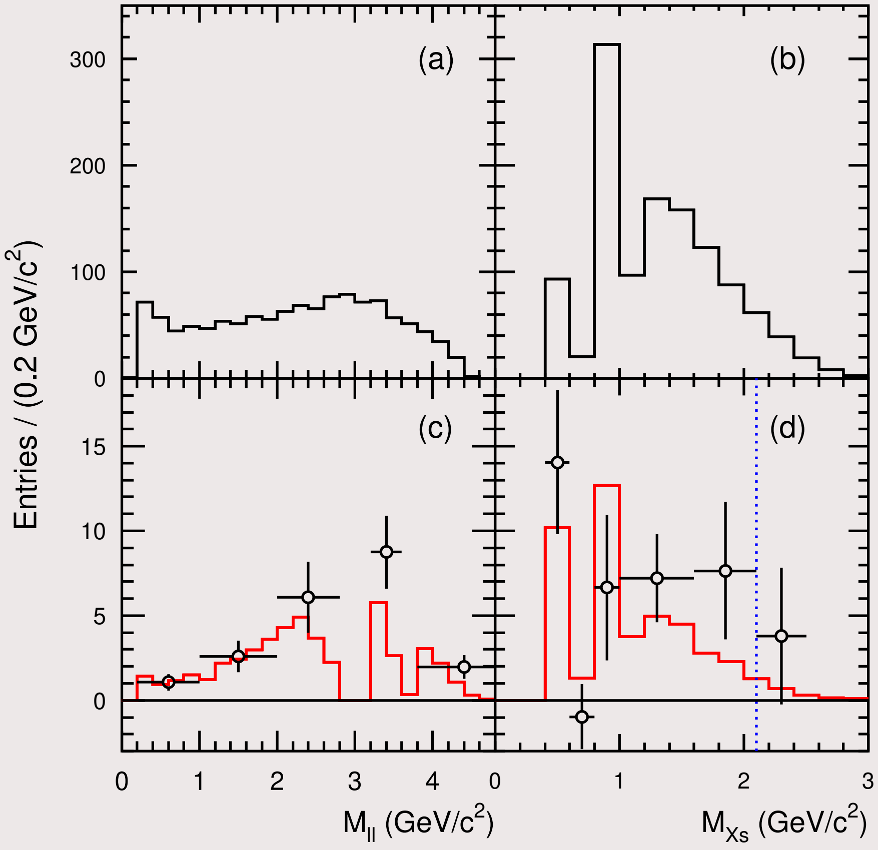


- background from $B \to X_s J/\psi(\to \ell^+\ell^-)$, $X_s\psi(2S)(\to \ell^+\ell^-)$ removed by $M_{\ell\ell}$ veto
- contamination from $B \to X_s\pi^+\pi^-$ (4.5 events for $\mu\mu$, 0.2 for ee) is subtracted

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

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

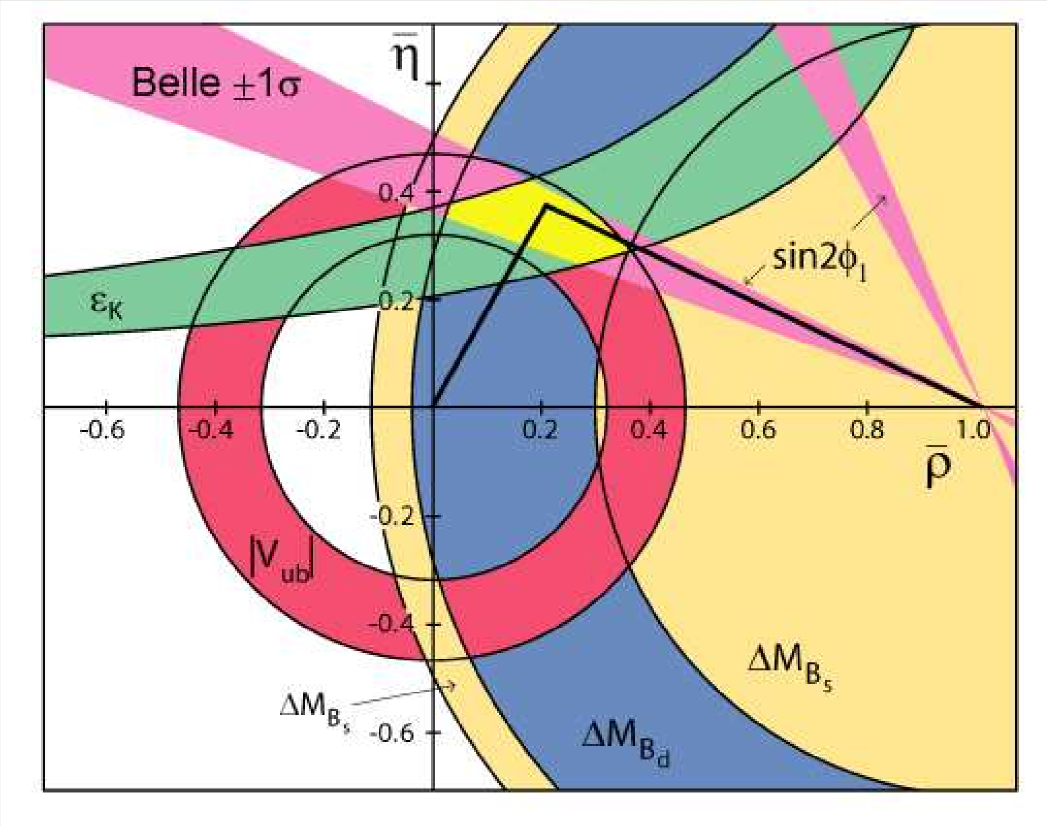
  $S_{\pi\pi} = -1.21^{+0.38}_{-0.27}{}^{+0.16}_{-0.13}$, $A_{\pi\pi} = +0.94^{+0.25}_{-0.31} \pm 0.09$ (with 41.8 fb^{-1})

- 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:

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

$\rho - \eta$ plane



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