Evidence for *CP*-violating Asymmetries in $B^0 \to \pi^+\pi^-$ Decays and Constraints on the CKM angle ϕ_2 at Belle

(hep-ex/0301032, submitted to PRD)

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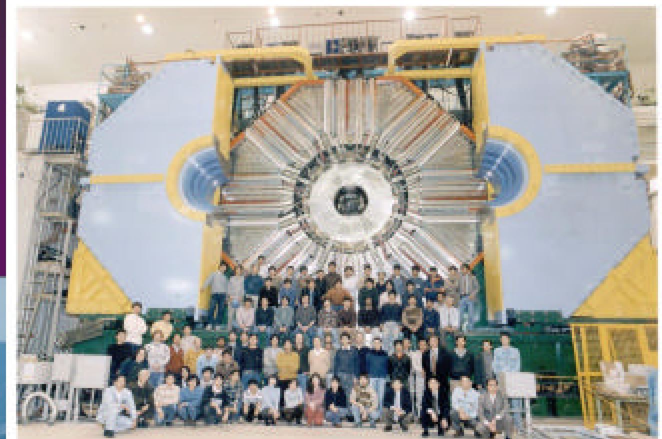
for
the Belle Collaboration

Outline

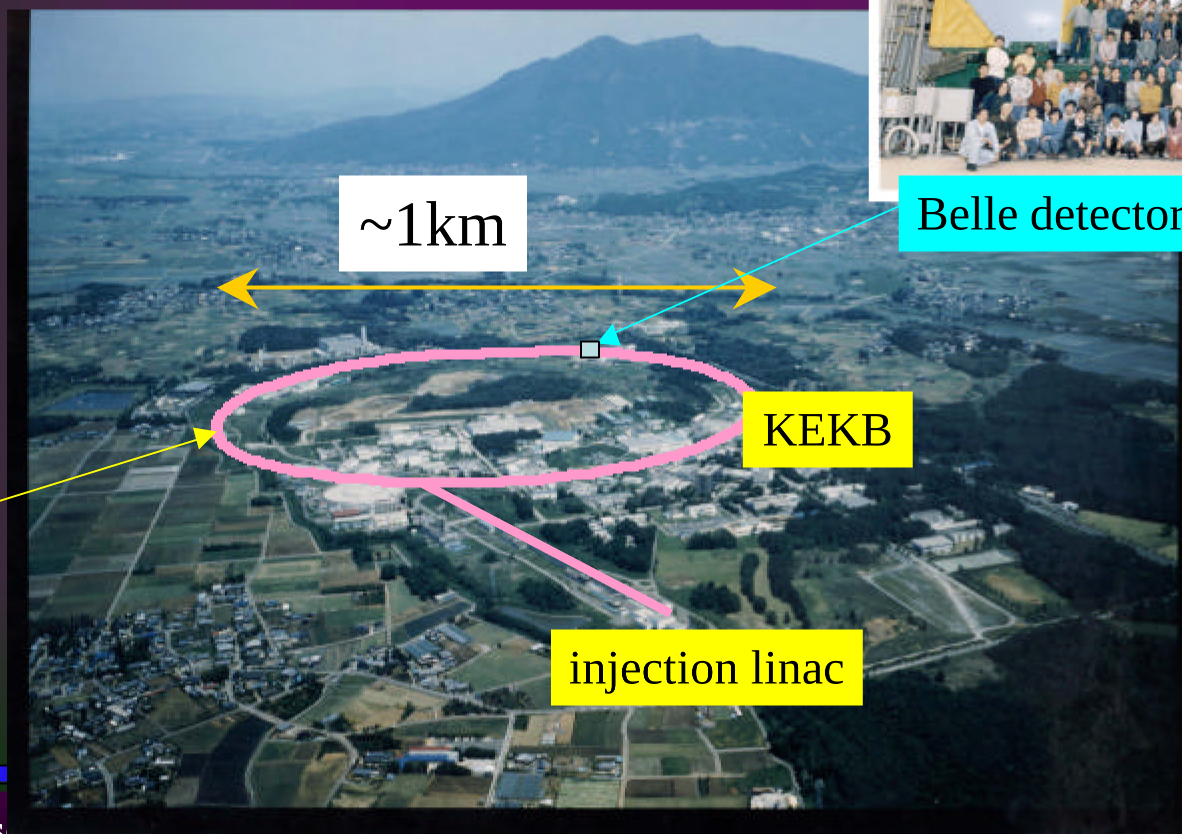
1. The Belle experiment
2. Time-dependent physics at Belle
3. $B^0 \rightarrow \pi^+\pi^-$ analysis
4. Results
   - *CP*-asymmetry parameters A_{pp} and S_{pp}
   - Constraints on the CKM angle f_2
5. Summary

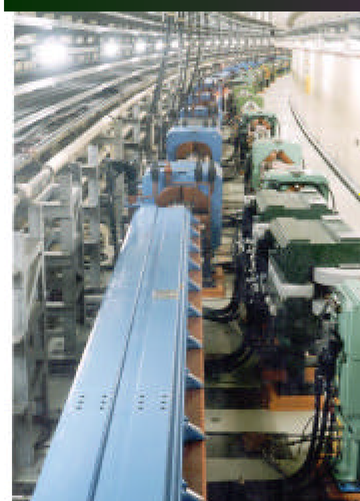
1. The Belle experiment

- B-factory at KEK in Tsukuba, Japan
  - KEKB e+e– collider with asymmetric energy
  - Belle detector (general-purpose spectrometer)
- Physics goals:
  - Test Kobayashi-Maskawa model of CP violation
  - Search for new physics in various rare decays



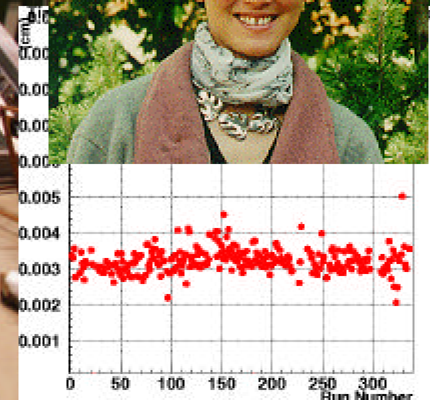
Belle detector & collaboration

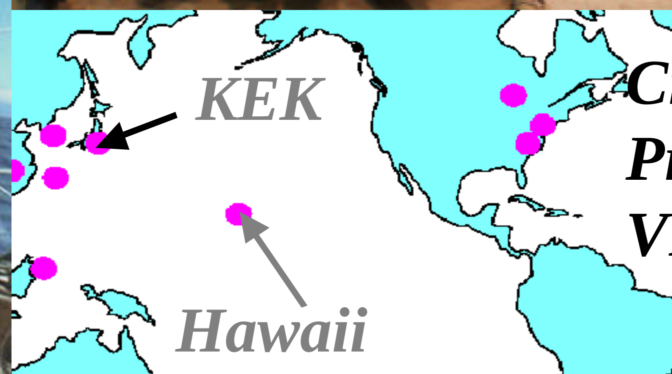




The

A World-Wide A



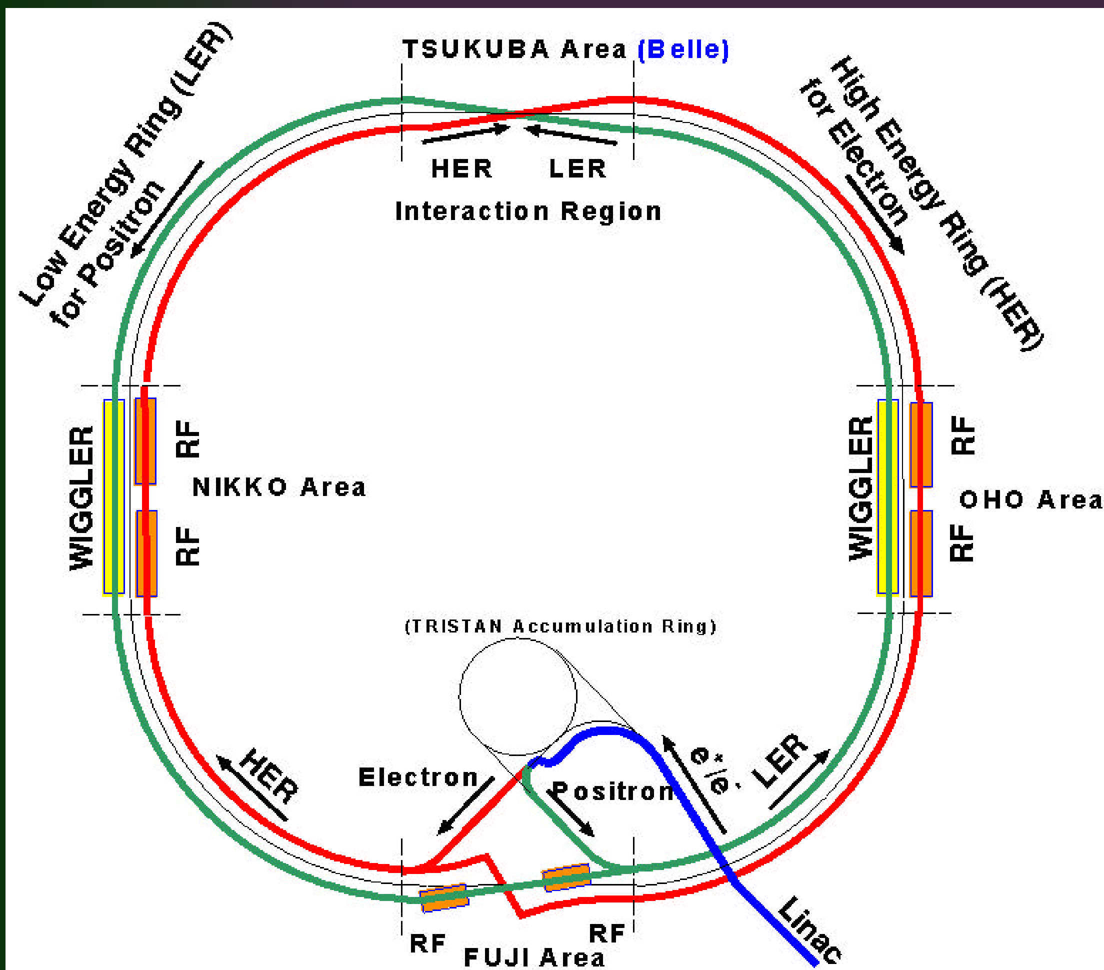


Cincinnati

Princeton

VI

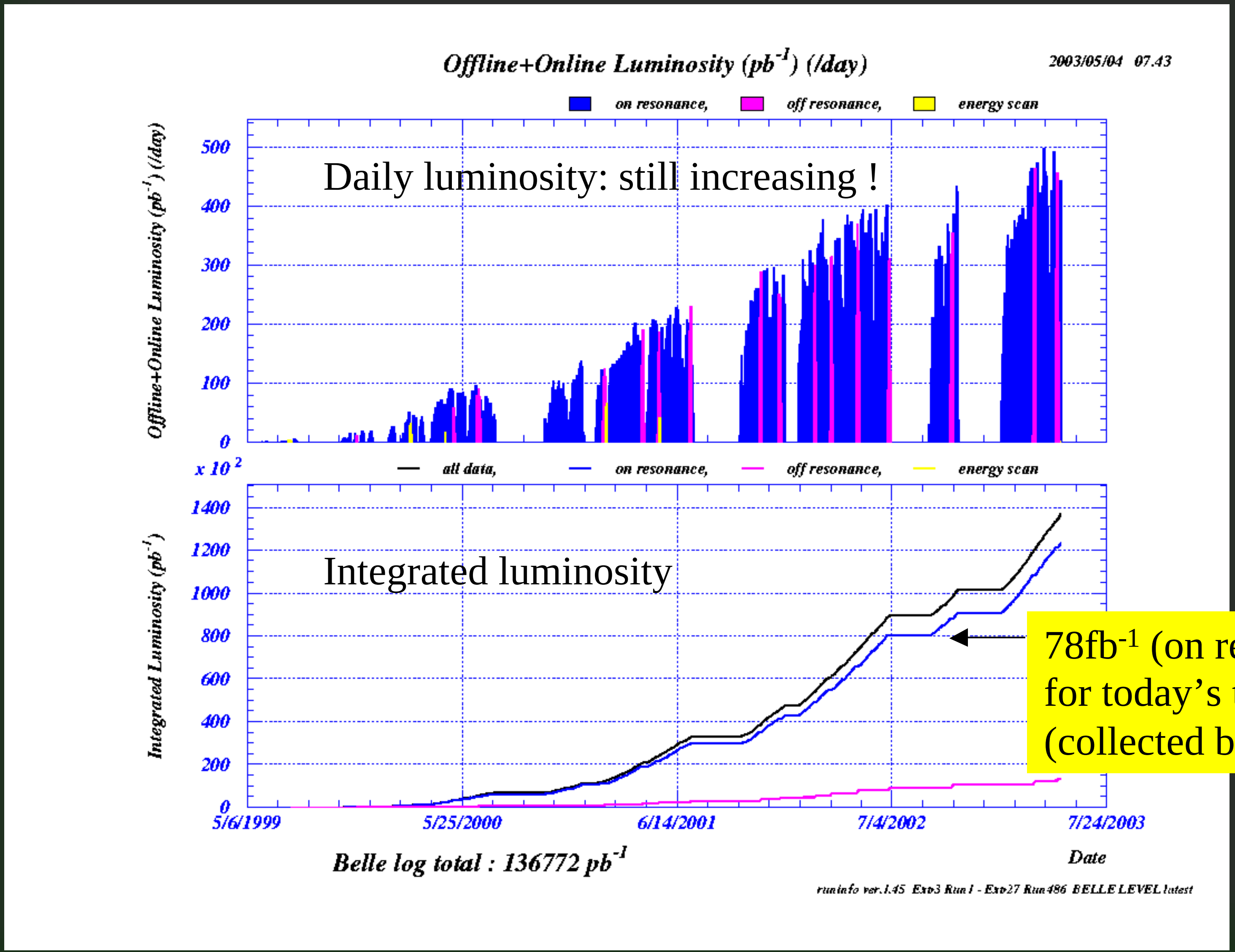
KEKB Collider



Design parameters

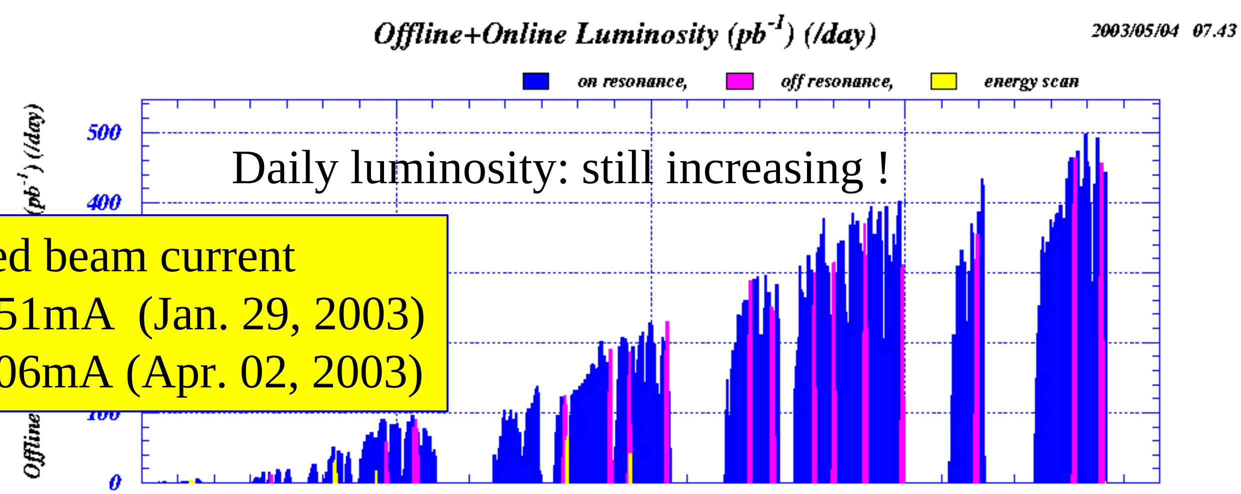
- Two separate storage rings
  - e^+ (LER) : 3.5 GeV, 2.6A
  - e^- (HER) : 8.0 GeV, 1.1A
  - diameter ~ 1km
  - circumference ~ 3km
- E_{CM} : 10.58 GeV at *U*(4S)
- Luminosity 10^{34} $cm^{-2}s^{-1}$
- ±11 mrad crossing angle
- Small beam sizes:
  - s_y »3 mm; s_x » 100 mm

Luminosity history



78fb-1 (on resonance) for today's topic (collected by July 2002)

Luminosity history



achieved beam current

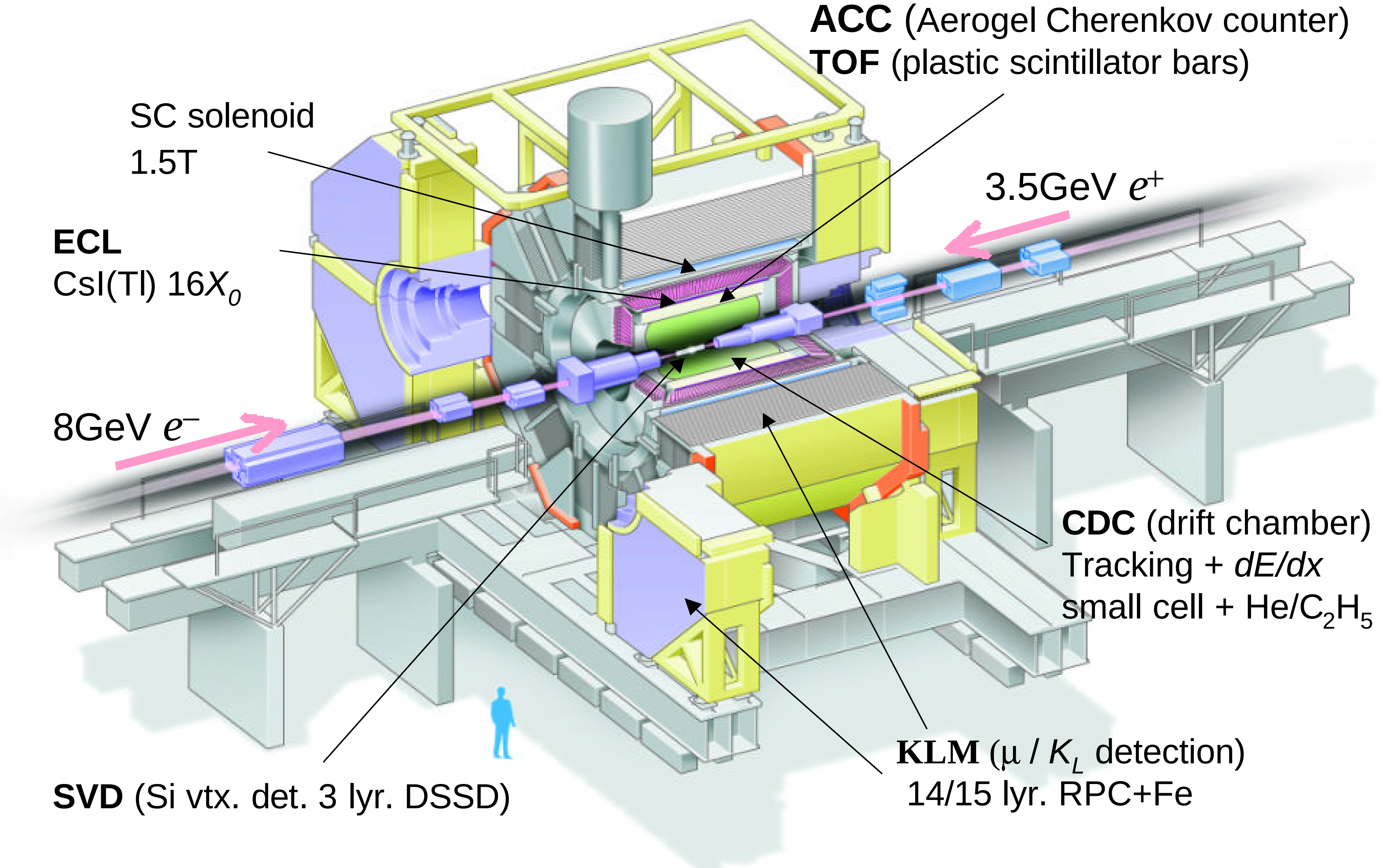
I_{LER}: 1651mA (Jan. 29, 2003)

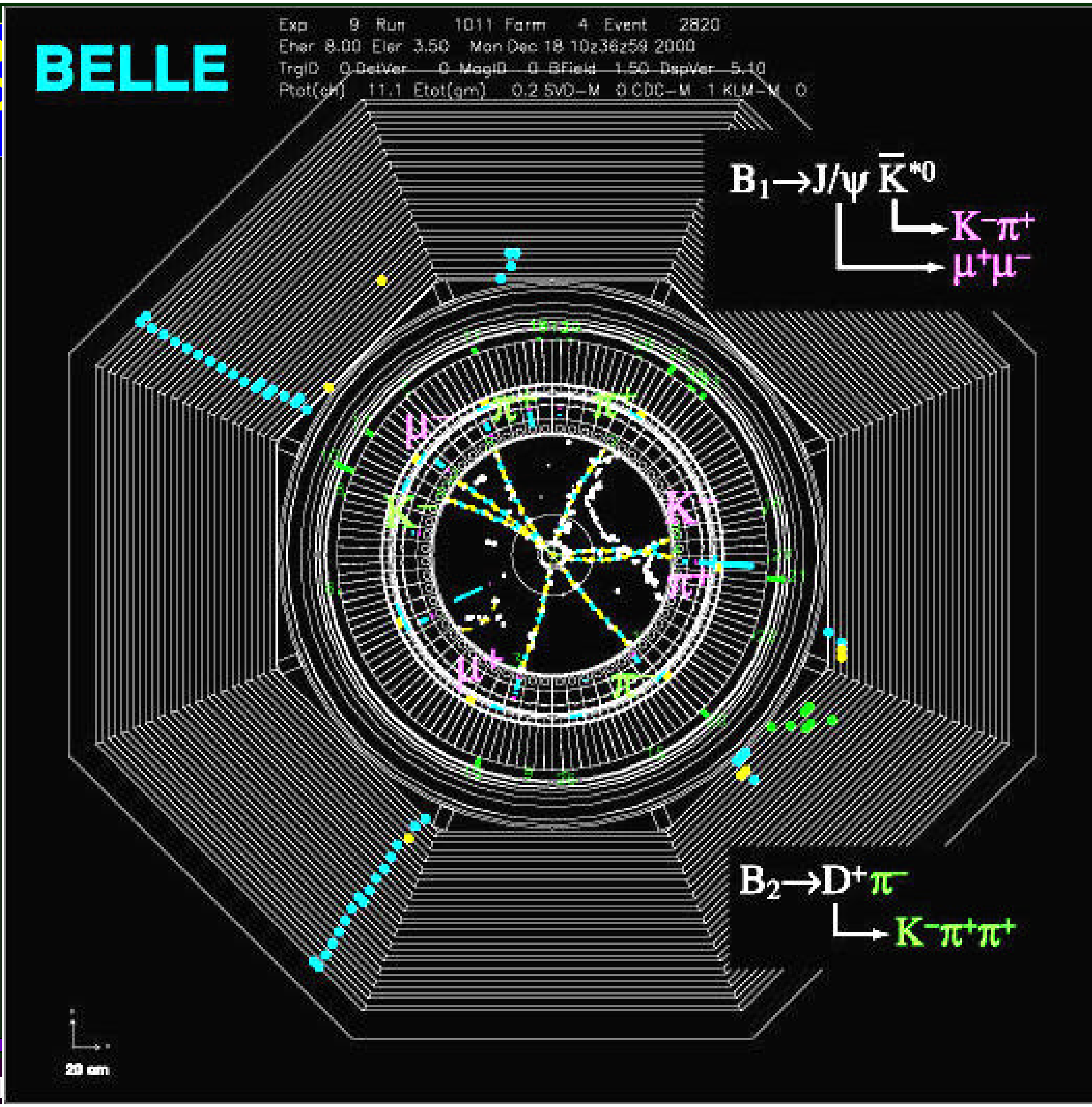
I_{HER}: 1106mA (Apr. 02, 2003)

Luminosity World Records at KEKB

- **Peak Luminosity: 9.7×10^{33} $cm^{-2}s^{-1}$ (Apr. 20, 2003)**
- **Integrated Luminosity (recorded by Belle)**
  - **daily: 514pb-1/day (Apr. 02, 2003)**
  - **monthly: 11.4fb-1/month (March 2003)**
  - **total: 137fb-1 (as of May 04, 2003)**

Belle detector




BELLE
Exp 9 Run 1011 Farm 4 Event 2820
Eher 8.00 Eler 3.50 Mon Dec 18 10:36:59 2000
TrgID 0 DetVer 0 MagID 0 BField 1.50 DspVer 5.10
Ptot(ch) 11.1 Etot(gm) 0.2 SVD-M 0 CDC-M 1 KLM-M 0
$B_1 \to J/\psi\, \bar{K}^{*0}$
$K^-\pi^+$
$\mu^+\mu^-$
$B_2 \to D^+\pi^-$
$K^-\pi^+\pi^+$
μ^-
π^+
π^-
K^-
K^-
π^+
μ^+
π^-
20 cm

Five Physics Groups at Belle

Indirect CPV
(time-dependent analyses)

Direct CPV
Rare Decays

CKM
(Vub, Vcb)

Tau/Charm

Two-photon

3 groups for B physics

2. Time-dependent physics at Belle

Three important topics now

- $B^0 \rightarrow J/\psi K_S$, $J/\psi K_L$ — sin2ϕ1 precision measurement
- $B^0 \rightarrow \phi K_S$, $K^+K^-K_S$, $\eta' K_S$ — CPV beyond SM
- $B^0 \rightarrow \pi^+\pi^-$ — ϕ2, direct CPV

Results based on all the data taken by summer 2002 (78fb-1)
submitted to PRD in Aug, '02, Dec. '02 and Jan. '02, respectively

Other important modes include
$B^0 \rightarrow J/\psi\pi^0$, $D^{*+}D^{*-}$, $D^{*+}D^-$, $D^{*+}\pi^-$, $\rho^+\pi^-$, D^0Ks, inclusive dilepton

Kobayashi-Maskawa model of CP violation

CKM quark mixing matrix

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

4 independent parameters →

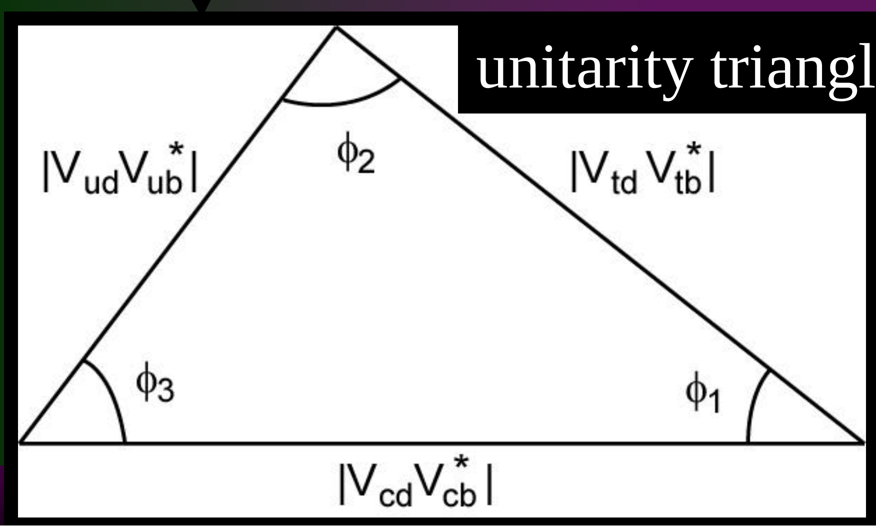
$$\begin{pmatrix} 1-\frac{l^2}{2} & l & Al^3(r-ih) \\ -l & 1-\frac{l^2}{2} & Al^2 \\ Al^3(1-r-ih) & -Al^2 & 1 \end{pmatrix} + O(l^4)$$

$\lambda \sim 0.2, \ A \sim \rho \sim \eta \sim O(1)$

unitarity

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

unitarity triangle



CP violation (CPV) from just one "KM phase" !

Open questions

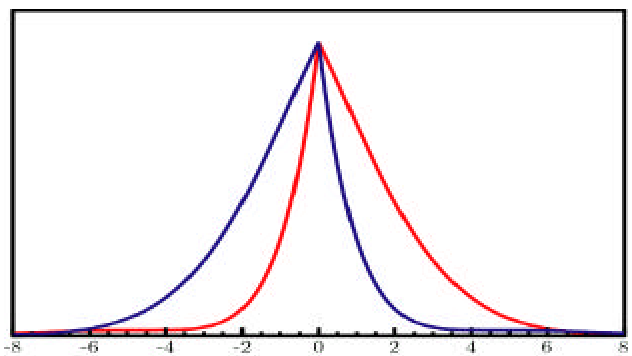
More CPV phases from SUSY etc. ?

Baryogenesis ?

Proper-Time Difference: Δt

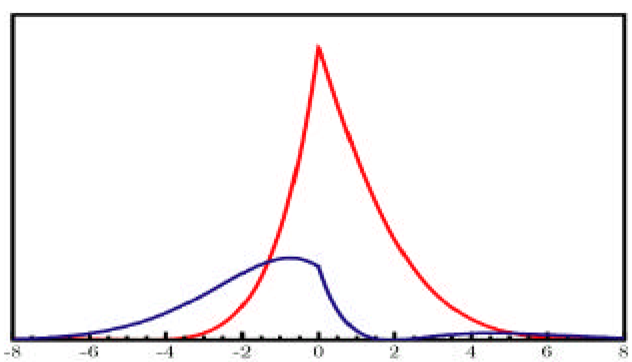
$$f(\overline{B}^0 \to f_{CP};\Delta t) = e^{-\frac{\Delta t}{\tau_{B^0}}}\{1 + [\Sigma \sin(\Delta m_d \Delta t) + A \cos(\Delta m_d \Delta t)]\}$$

$$f(B^0 \to f_{CP};\Delta t) = e^{-\frac{\Delta t}{\tau_{B^0}}}\{1 - [\Sigma \sin(\Delta m_d \Delta t) + A \cos(\Delta m_d \Delta t)]\}$$



$\Sigma = 0.8$
$A = 0.0$

$\tau_B = 1.542$ ps
$\Delta m_d = 0.489$ ps^{-1}

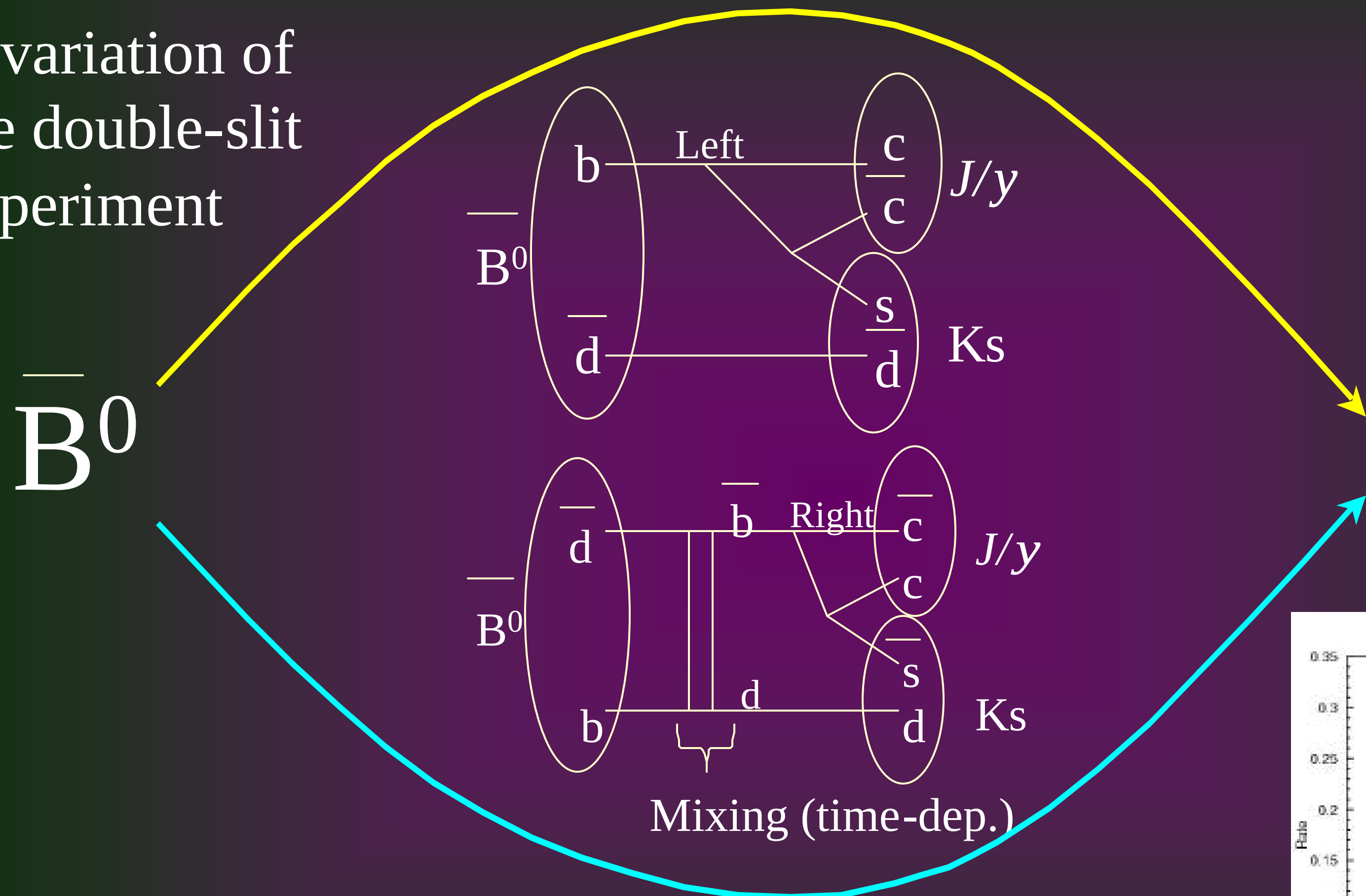


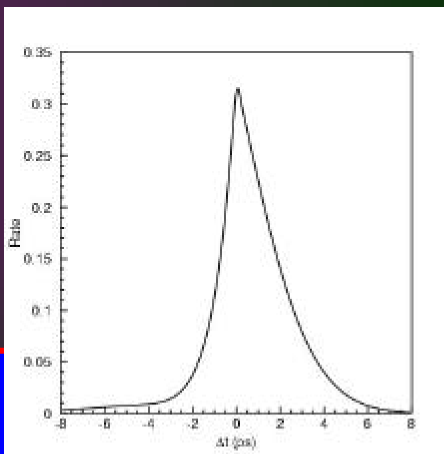
$\Sigma = 0.8$
$A = 0.6$

From **red**/**blue** asymmetry in the observed Δt distributions, we determine the *CP*-violating parameters, Σ and A.

Essence of time-dependent CPV

A variation of the double-slit experiment

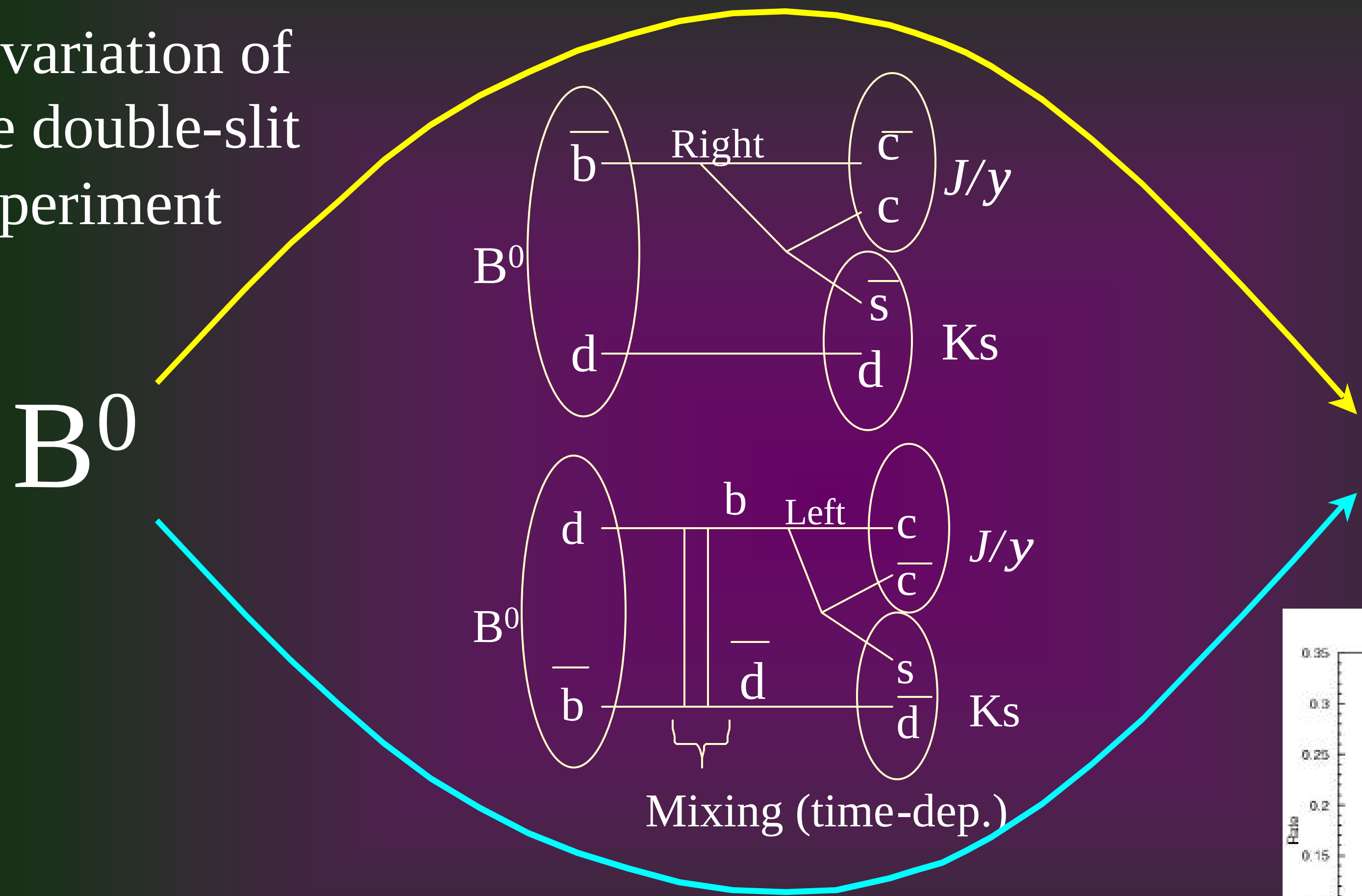


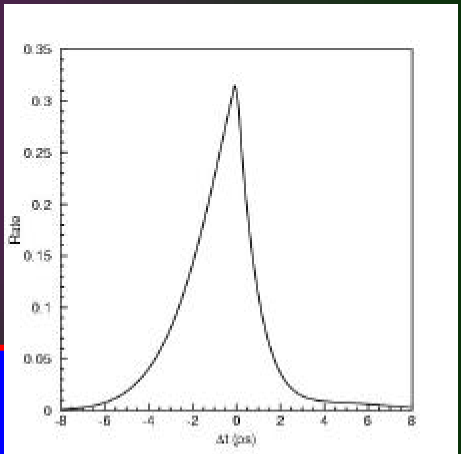


Observe quantum inteference using
a “double-slit” opening/closing in a few pico-seconds
Measure difference between particles and antiparticles (CP violation)

Essence of time-dependent CPV

A variation of the double-slit experiment





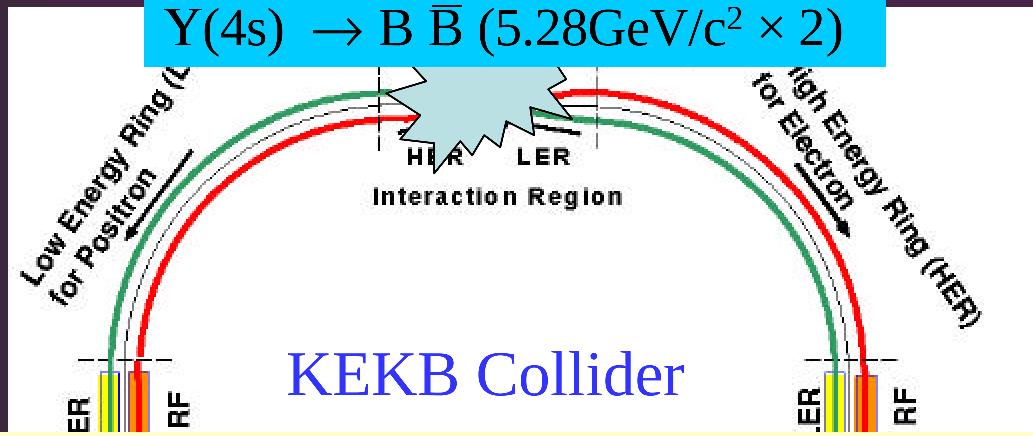
Observe quantum inteference using
a "double-slit" opening/closing in a few pico-seconds
Measure difference between particles and antiparticles (CP violation)

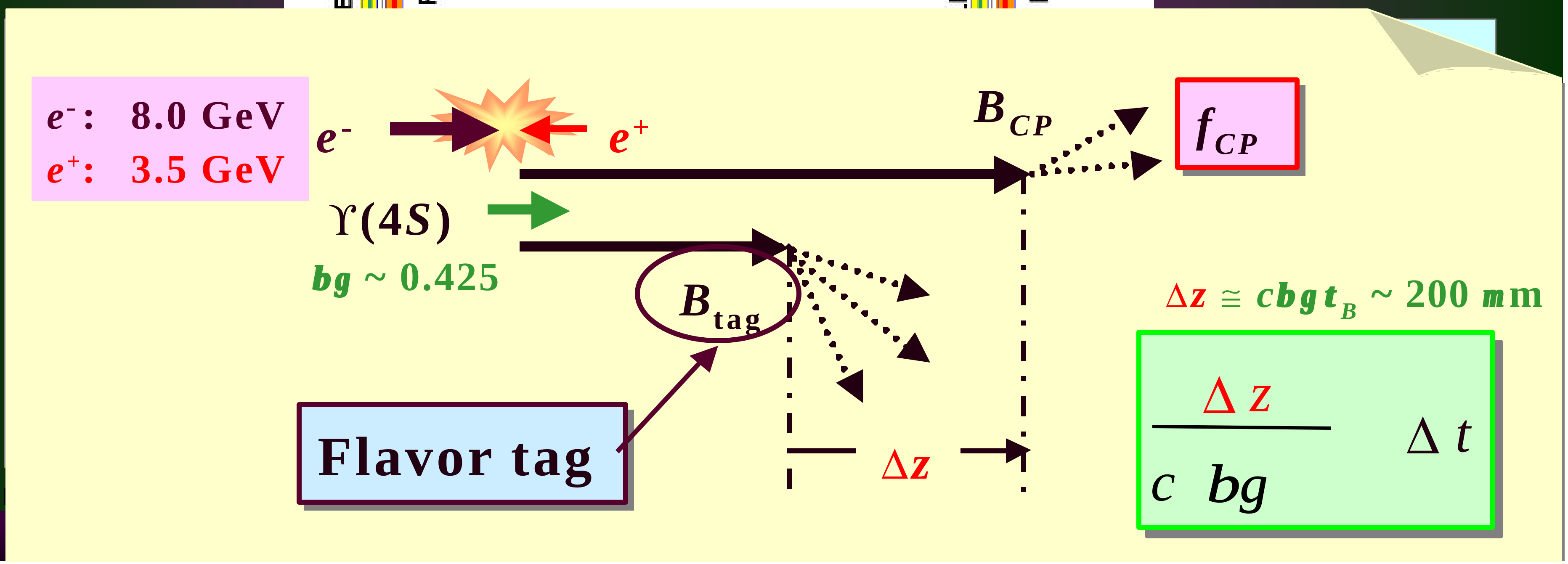
How do we measure time-dependent CPV ?

8GeV electron

$\Upsilon(4s)$ (10.58GeV/c^2)
$\beta\gamma = 0.425$
$\Upsilon(4s) \rightarrow B\,\bar{B}$ (5.28GeV/c^2 × 2)

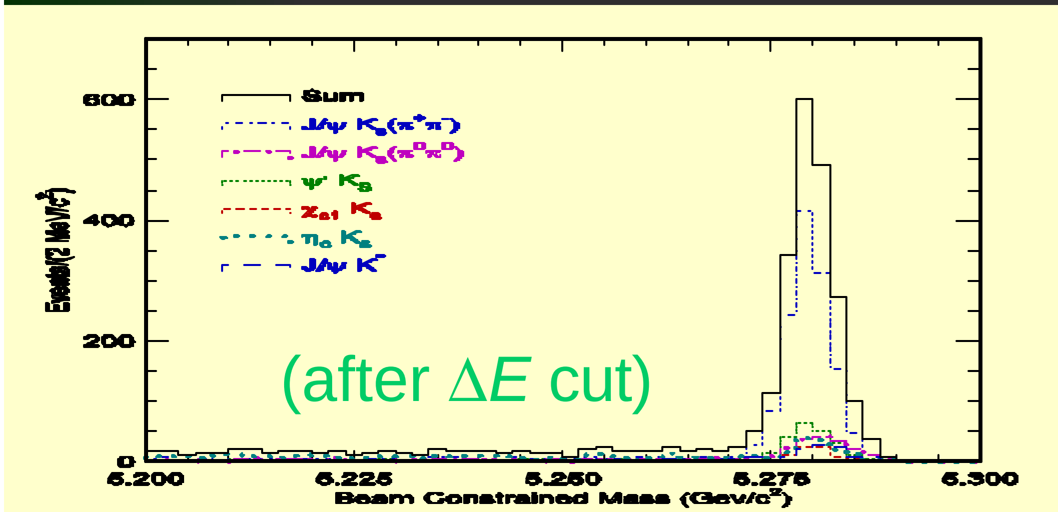
3.5GeV positron

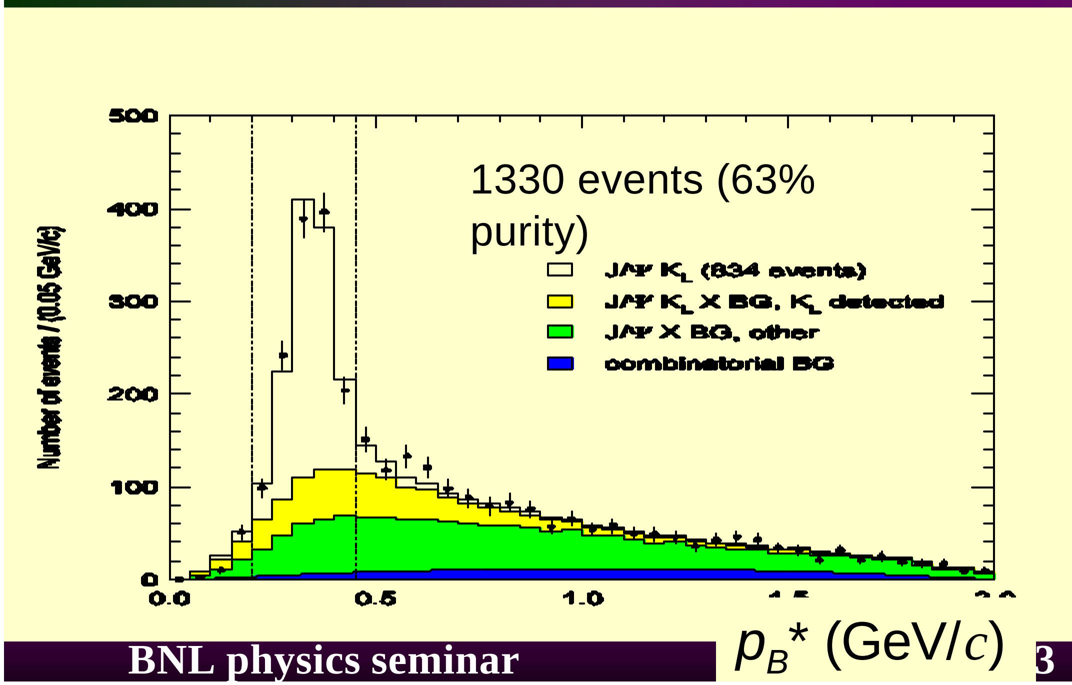




J/y Ks and related modes

L dt = 78 fb-1





$B \to$	CP	# evts.	S/(S+N)
$J/\psi K_S$ ($K_S \to \pi^+\pi^-$)	odd	1285	0.98
$J/\psi K_S$ ($K_S \to \pi^0\pi^0$)	odd	188	0.82
$\psi(2S) K_S$ ($\psi(2S) \to l^+l^-$)	odd	91	0.96
$\psi(2S) K_S$ ($\psi(2S) \to \pi^+\pi^- J/\psi$)	odd	112	0.91
$\chi_{c1} K_S$ ($\chi_{c1} \to \gamma J/\psi$)	odd	77	0.96
$\eta_c K_S$ ($\eta_c \to K_S K^+\pi^-$)	odd	72	0.65
$\eta_c K_S$ ($\eta_c \to K^+K^-\pi^0$)	odd	49	0.73
$\eta_c K_S$ ($\eta_c \to \bar{p}p$)	odd	21	0.94
$J/\psi K^{*0}$ ($K^{*0} \to K_S \pi^0$)	81% even 19% odd	101	0.92
total		1996	0.94
$J/\psi K_L$	even	1330	0.63
total		3326	

2958 events are used in the fit.

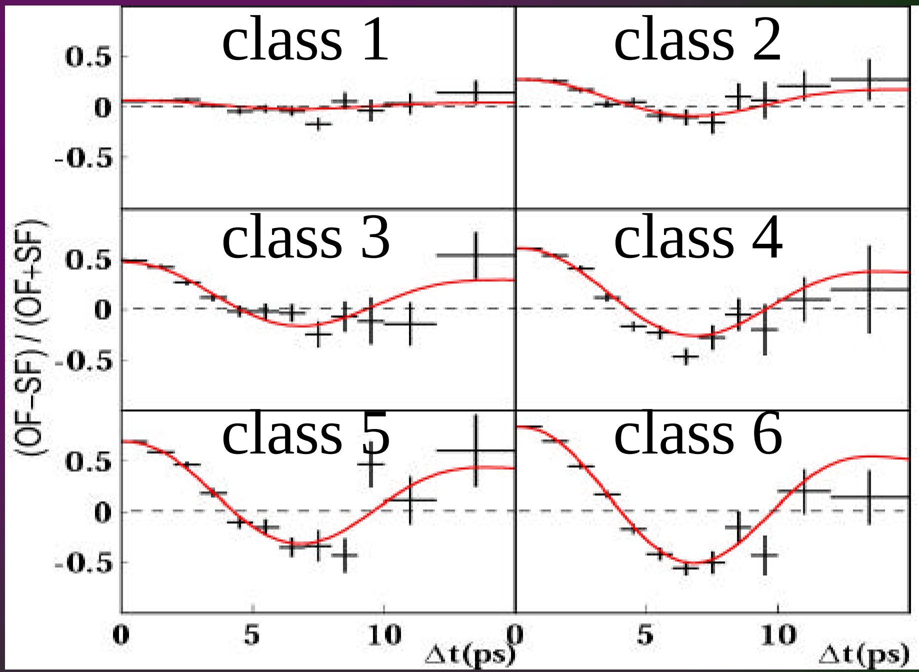
Flavor tagging

Use *inclusive* flavor-specific properties and correlations

- Inclusive Leptons:
  - high-***p l***$^-$
  - intermed-***p l***$^+$
- Inclusive Hadrons:
  - high-***p p***$^+$
  - intermed-***p K***$^+$
  - low-***p p***$^-$

Classify events based on expected dilution

mixing amplitude → wrong tag fraction



$B\overline{B}$-mixing fit → flavor tag performance
("class 6" yields the best performance.)

total effective efficiency = (28.8 ± 0.6) %

Vertex resolution

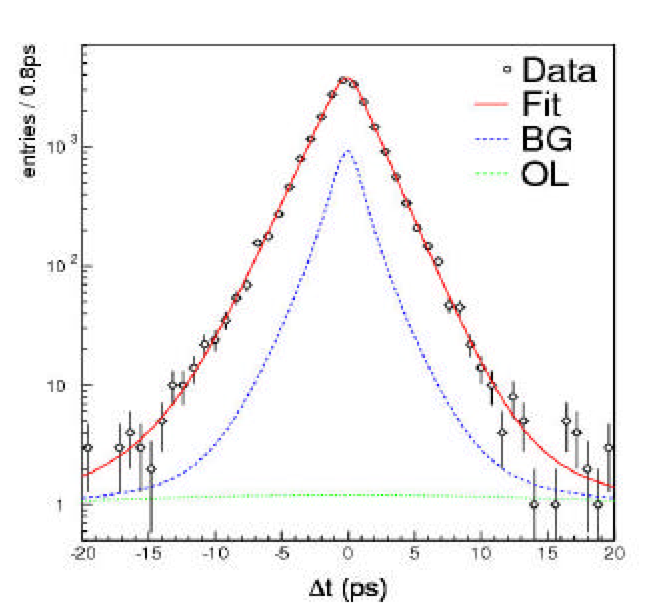
- Resolution dominated by the tag-side vtx.
- *B* lifetime fit with 85 million **B** pairs to obtain resolution parameters

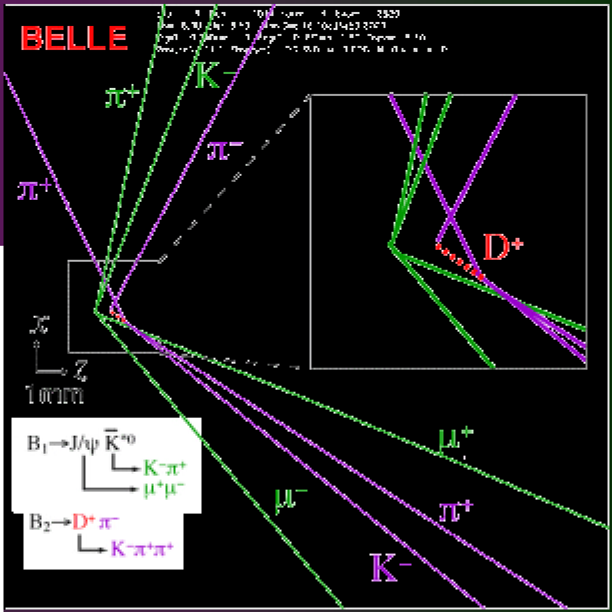
B^0 lifetime
1.551±0.018(stat) ps

(PDG02: 1.542±0.016 ps)

Time resolution (rms) 1.43ps

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

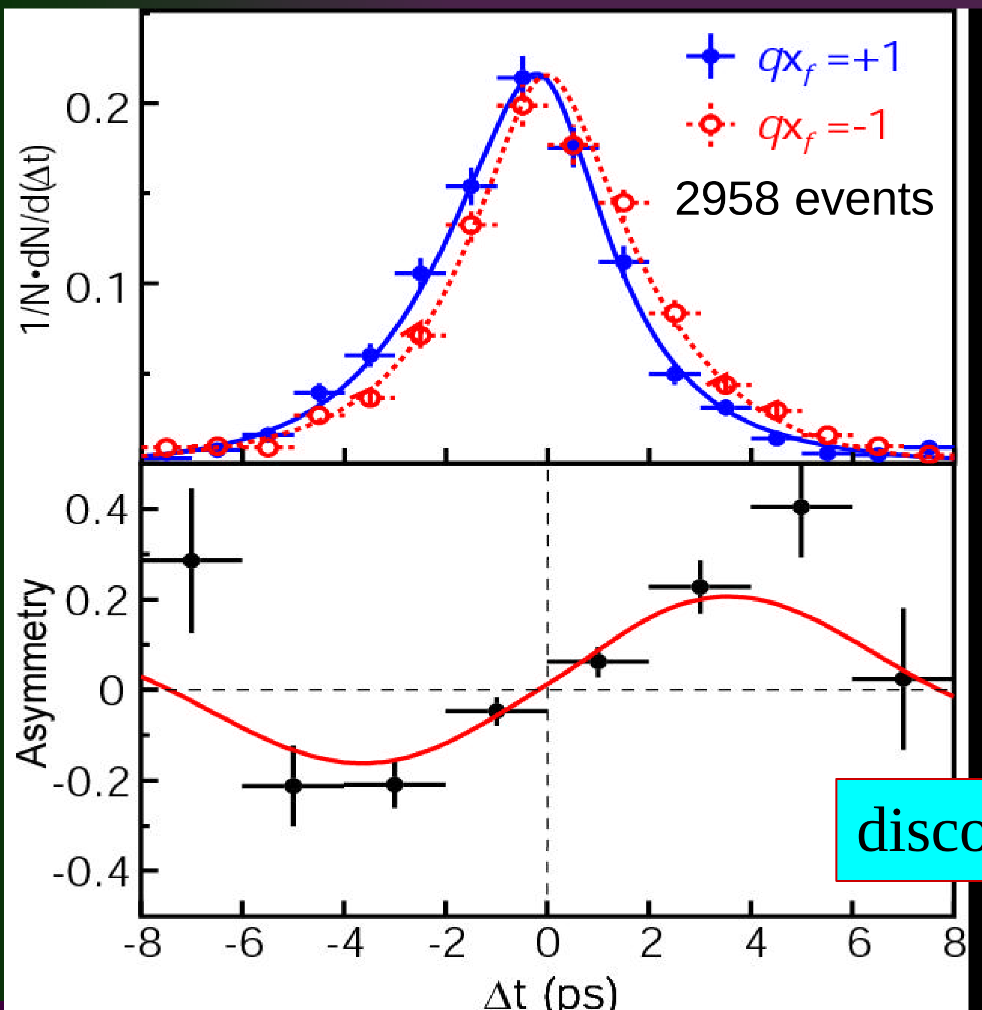




Example vertices

2002 Summer Result

$\sin 2\phi_1 = 0.719 \pm 0.074(\mathrm{stat}) \pm 0.035(\mathrm{syst})$



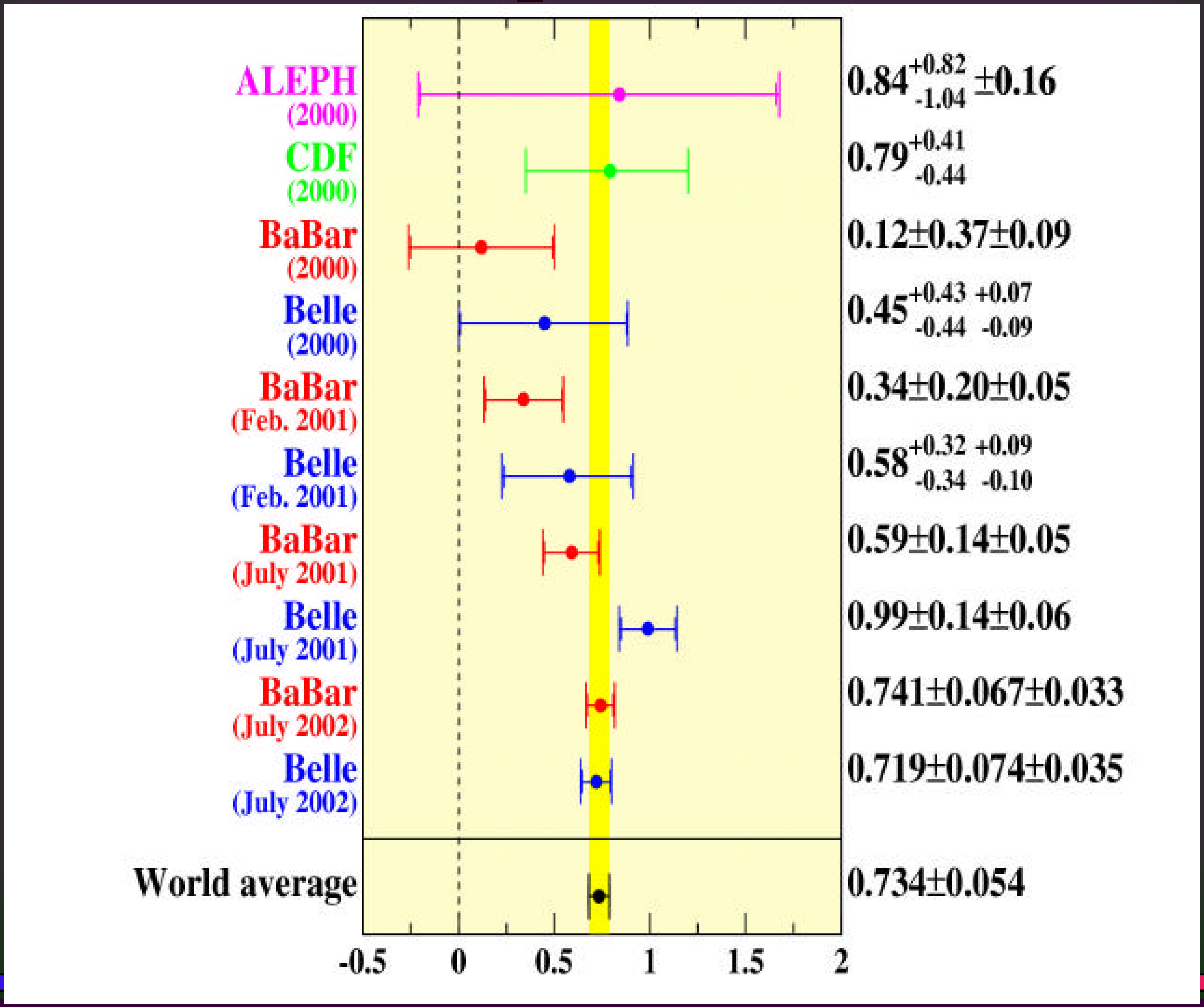
[PRD 66, 071102(R) 2002]

- 78 fb^{-1} (85M $B\bar{B}$)
- 6 $b \rightarrow ccs$ decay modes ($B \rightarrow J/\psi K_S$, $J/\psi K_L$ etc.)

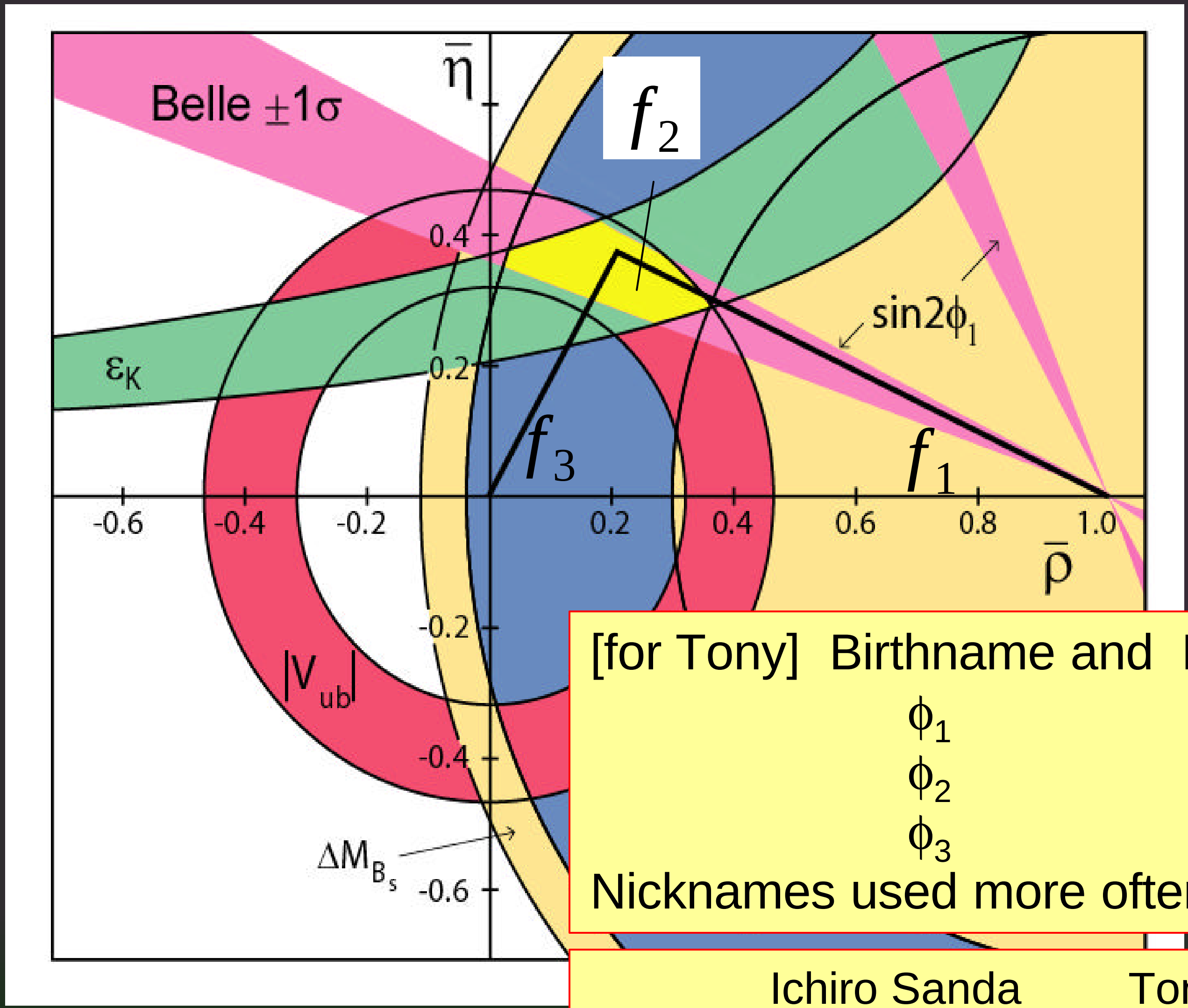
discovery → precision measurement

Discovery of CP violation in B meson system (2001)

$\sin 2\phi_1$ history



Beautiful agreement so far

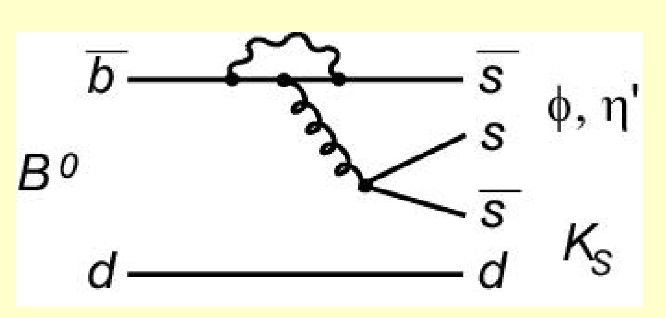


[for Tony]	Birthname and	Nickname
	ϕ_1	β
	ϕ_2	α
	ϕ_3	γ

Nicknames used more often (as usual)

Ichiro Sanda Tony Sanda

CPV in $b \rightarrow s\bar{s}s$



CPV same as J/ψKs

within SM

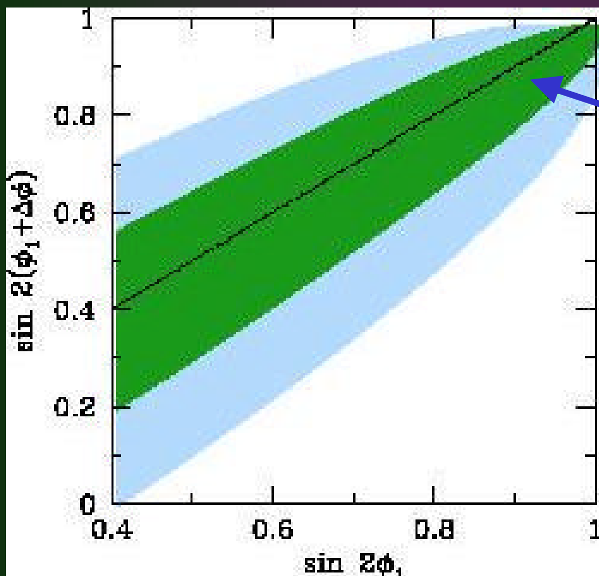
B($B^0 \rightarrow \eta' K^0$) = 5.8×10^{-5} : anomalously large

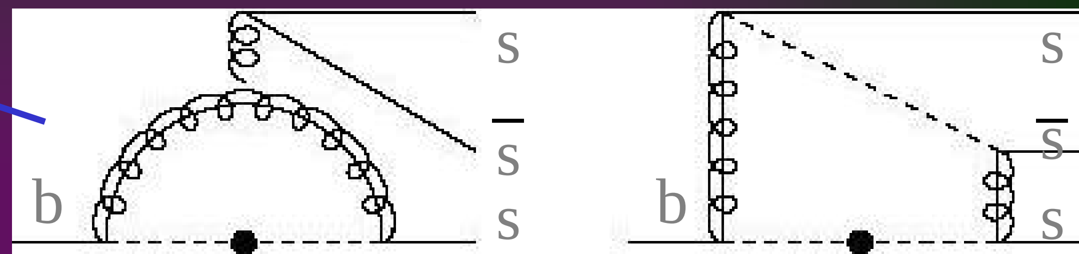
New physics contribution ??
Measure its phase.

New physics through penguin (loop) diagrams

O(1) effect in SUSY GUT

- 1) SUSY SU(5) with right-handed neutrino (Moroi 2000)





$A_{CP}(Dt) = -x_f \, sin2(f_1+f_{NP}) sin(Dm_d Dt)$

New diagram and phase

- 2) SUSY SO(10) in the context of see-saw (Chang-Masiero-Murayama 2002) → deviation up to 50%

Motivated by large θ23 neutrino mixing:
In GUT context, "Atmospheric Neutrinos Can Make Beauty Strange"

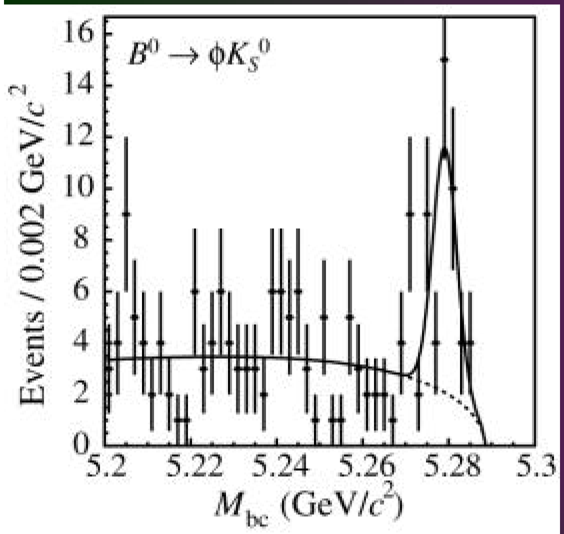
$B^0 \to \phi K_S$, $K^+K^-K_S$, $\eta' K_S$

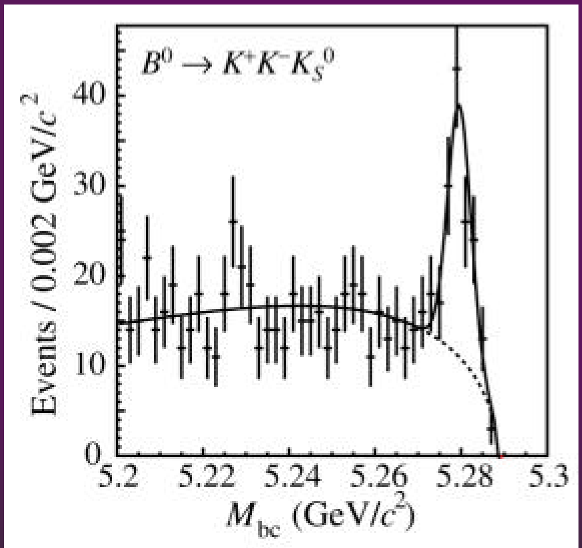
$\int L\,dt$ = 78 fb^{-1}

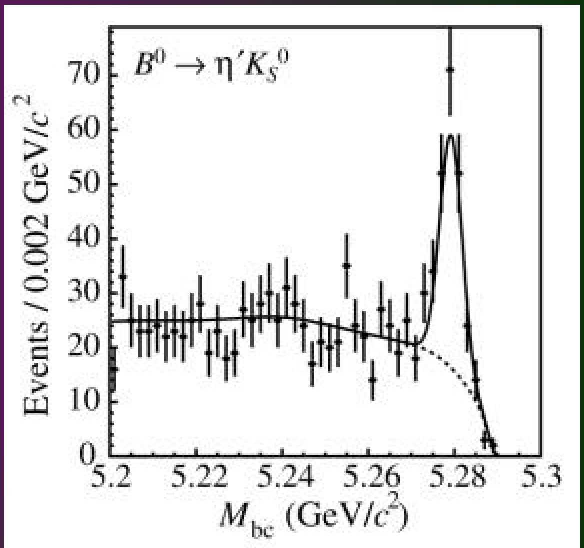
$B^0 \to \phi K_S$ ($K_S \to \pi^+\pi^-$, $\phi \to K^+K^-$)

$B^0 \to K^+K^-K_S$ ($K_S \to \pi^+\pi^-$)
(K^+K^- ϕ)

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







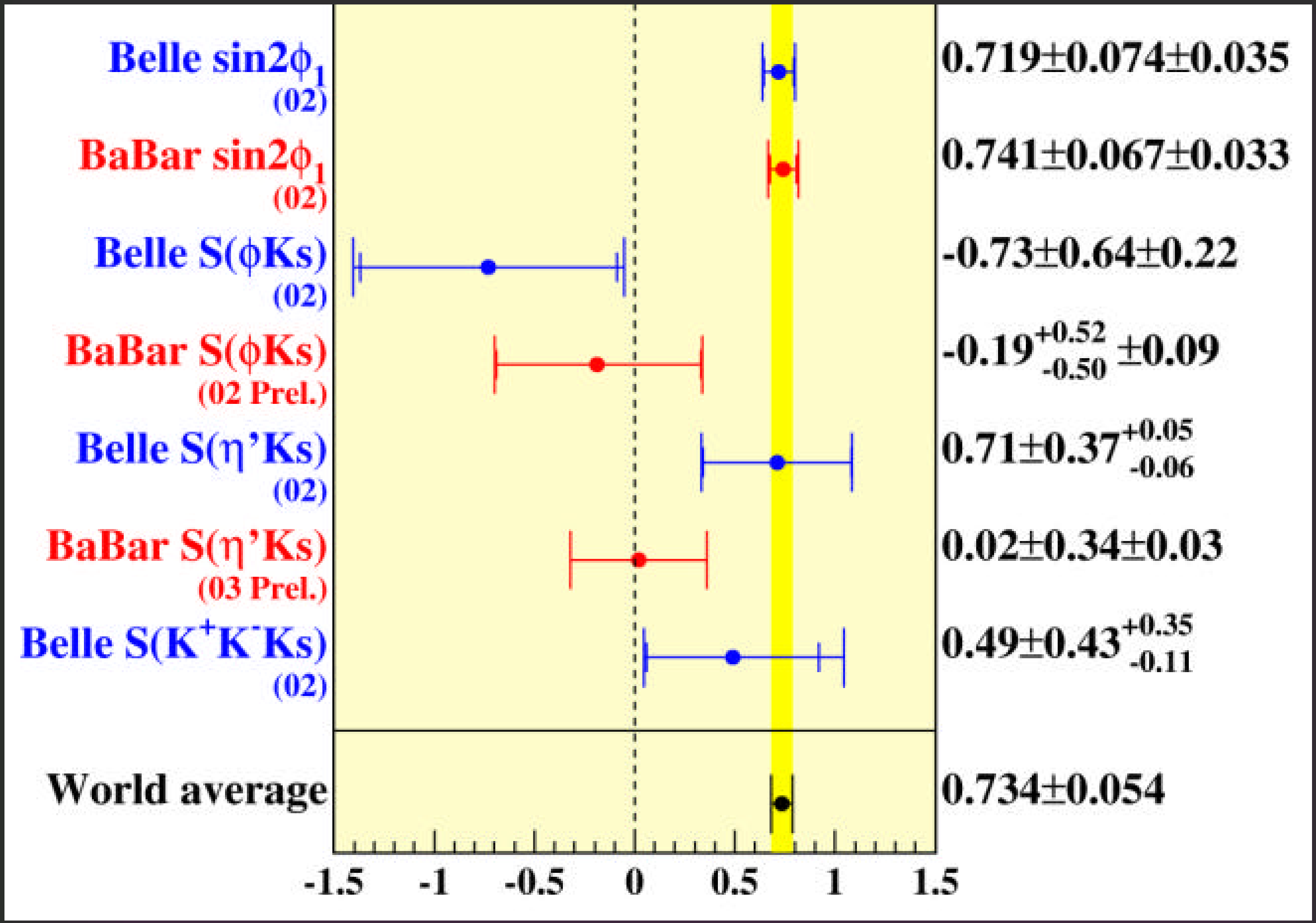
N = 53
purity = 0.67

N = 191
purity = 0.50

N = 299
purity = 0.49

Very hard to do this at hadron machines

Results



One of hot topics now. Need more data !

(one of the motivations for luminosity upgrade in the future)

3. $B^0 \to \pi^+\pi^-$ analysis

Time-dependent decay rate

Time-dependent **(Bigi-Sanda)** *CP* asymmetries in $B^0 \to \pi^+\pi^-$
-- promising way to access the CKM angle f_2

$$P^q_{pp}(\Delta t) = \frac{e^{-|\Delta t|/t_{B^0}}}{4t_{B^0}}[1 + q\cdot\{S_{pp}\sin(\Delta m_d \Delta t) + A_{pp}\cos(\Delta m_d \Delta t)\}]$$

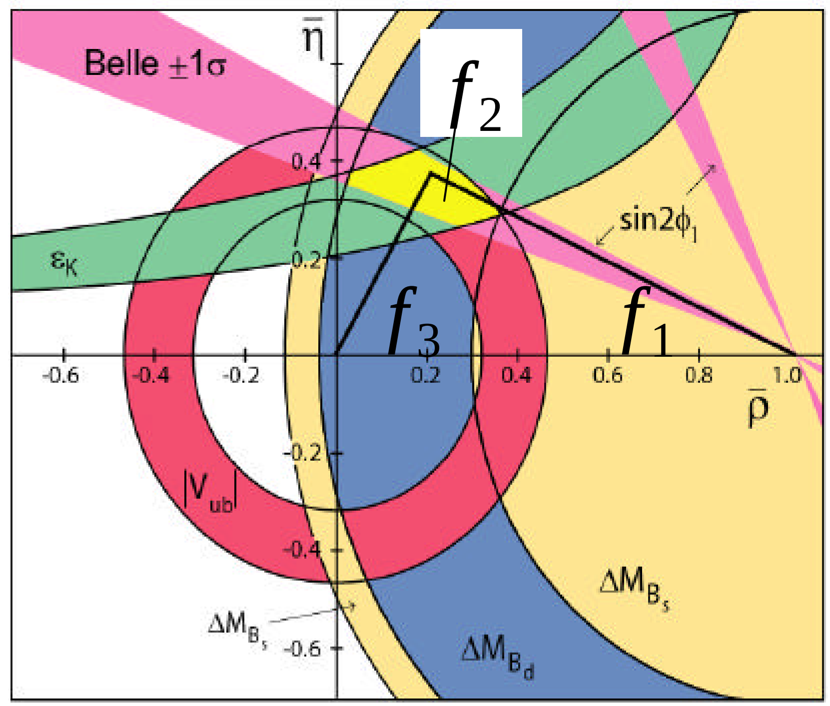
q= { +1 for B^0 tag; –1 for $\overline{B^0}$ tag

note $A_{\pi\pi} = -C_{\pi\pi}$

(Belle) (BaBar)

$A_{\pi\pi} = 0, \ S_{\pi\pi} = \sin 2 f_2$

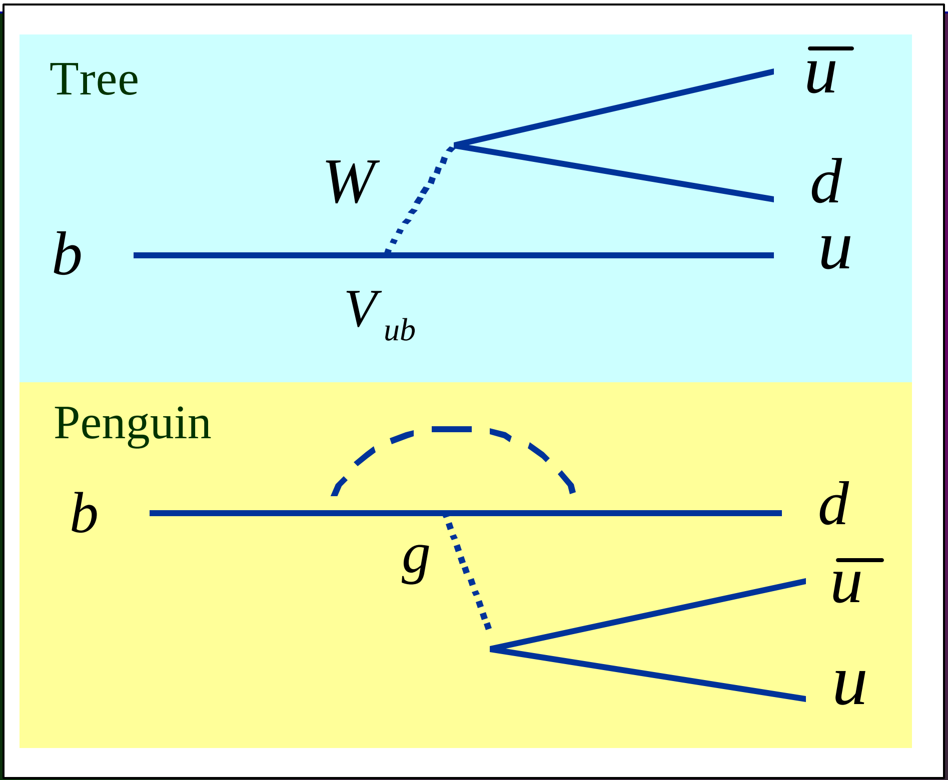
if “penguin” is negligible



Direct *CP* violation in $B^0 \to \pi^+\pi^-$

Penguin diagram seems sizable
($\mathcal{B}(\pi\pi)$, $\mathcal{B}(K\pi)$ measurements)

|P/T| ~ 0.3
(theoretical preference)



"pollution" for precise f_2 measurements → isospin analysis as a solution

wonderful "contribution" for the first observation of direct *CP* violation in *B*-meson decays !

Excellent mode in any case to test the Kobayashi-Maskawa mechanism of *CP* violation

Four key questions

1. $(S_{pp}, A_{pp}) = (0,0)$?
   - *if No* → *CP* violation ! (not necessarily direct *CP* violation)

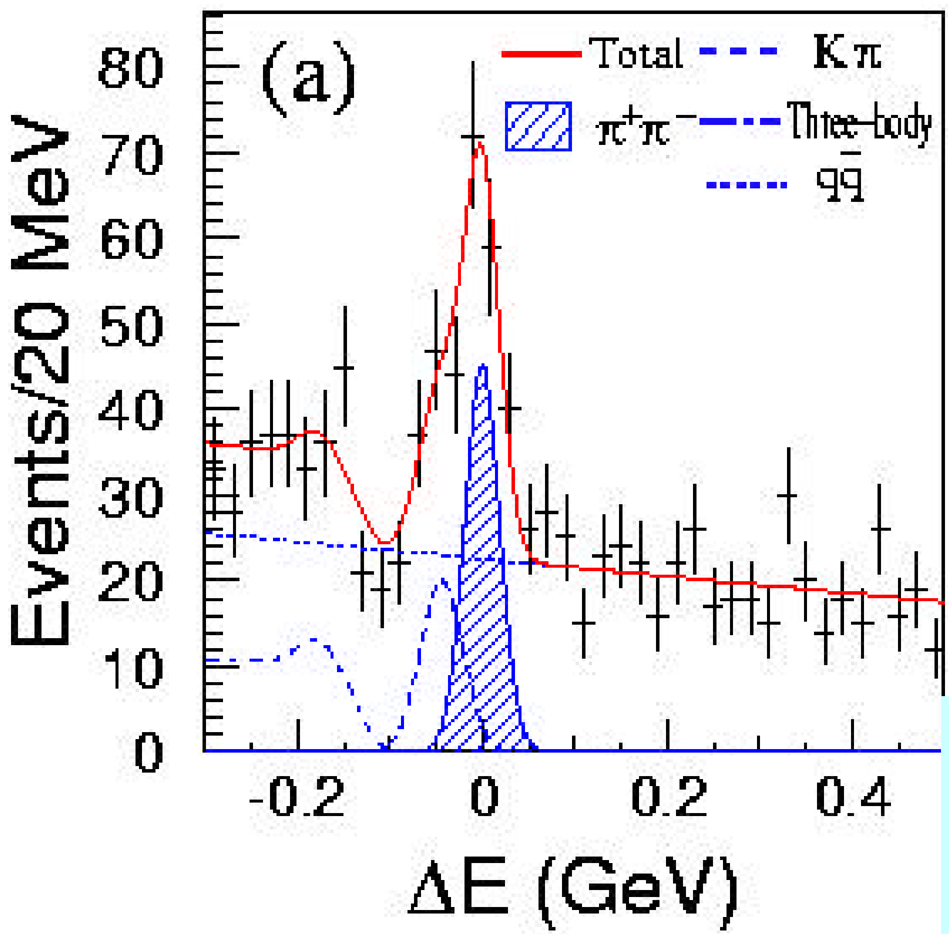
2. A_{pp} ^{1} 0 ?
   - *if Yes* → direct *CP* violation !

3. $(S_{pp}, A_{pp}) = (-\sin 2f_1, 0)$?
   - *if No* → "direct" *CP* violation (death of "superweak")
     - » even $(S_{pp}, A_{pp})=(0,0)$ can establish "direct" *CP* violation

4. f_2 consistent with existing constraints ?
   - *if Yes* → Great Kobayashi-Maskawa mechanism !
   - *if No* → (CKM anyway great); hint for new physics ?

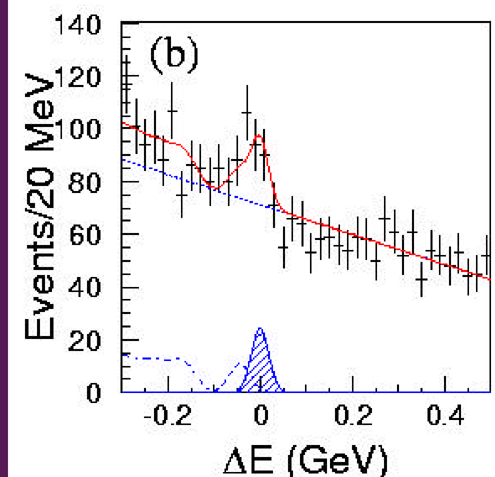
$B^0 \to \pi^+\pi^-$ candidates

LR > 0.825



$\pi^+\pi^-$: 106
Kπ : 41
qq : 128
total : 275

LRmin < LR 0.825



$\pi^+\pi^-$: 57
Kπ : 22
qq : 406
total : 485

dE/dx, TOF and ACC

dE/dx in CDC :

K/p : p<0.8 GeV/c

and 2.5<p<5.0 GeV/c

•50%He+50%C_2H_6

•50 layers

TOF :

K/p in p<1.3 GeV/c

•128 scintillators in f

• s$_T$ < 100ps

ACC :

K/p in 1.2<p<3.5 GeV/c

•Barrel : 960 modules

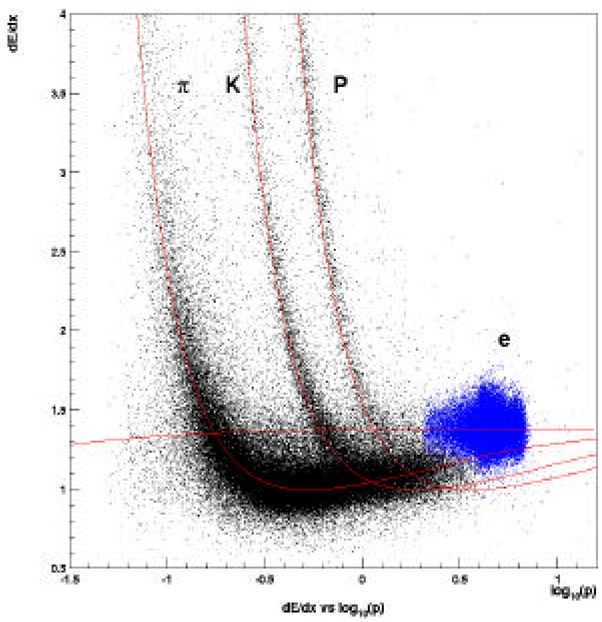
in 60 f -segments

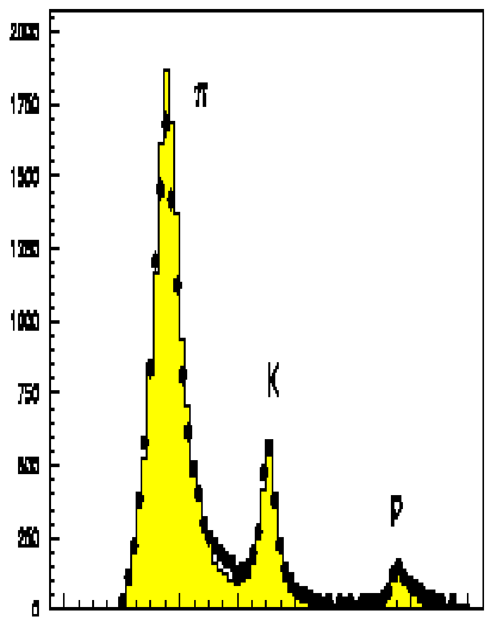
n = 1.010 ~ 1.028

•FWD endcap : 228 modules

in 5 layers

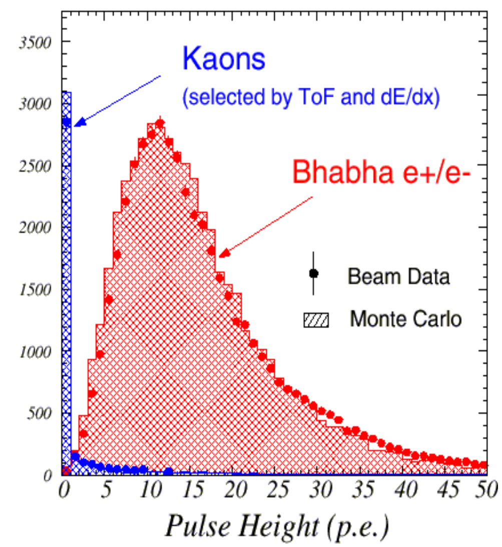
n = 1.030





0.0 0.4 0.8 1.2

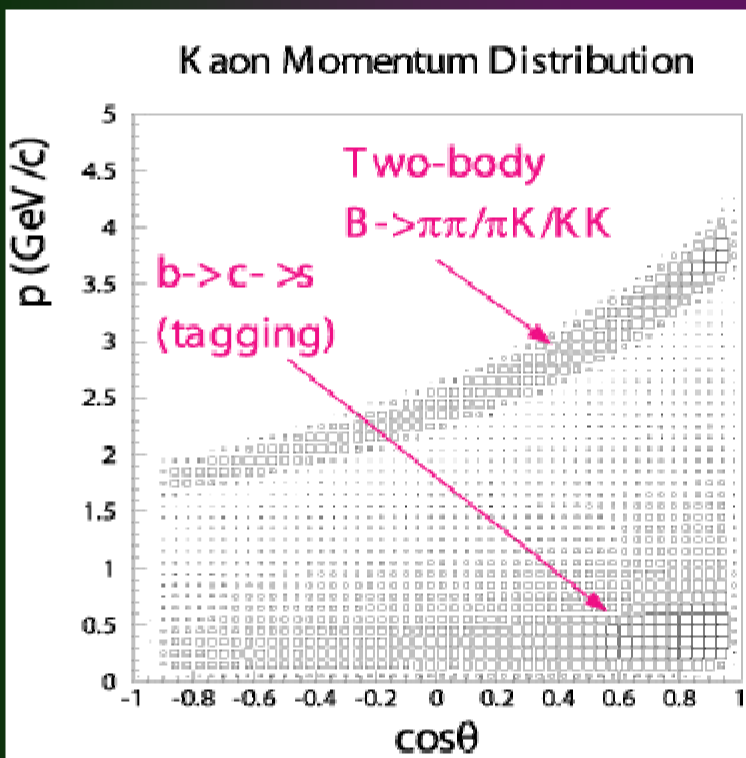
Mass (GeV)

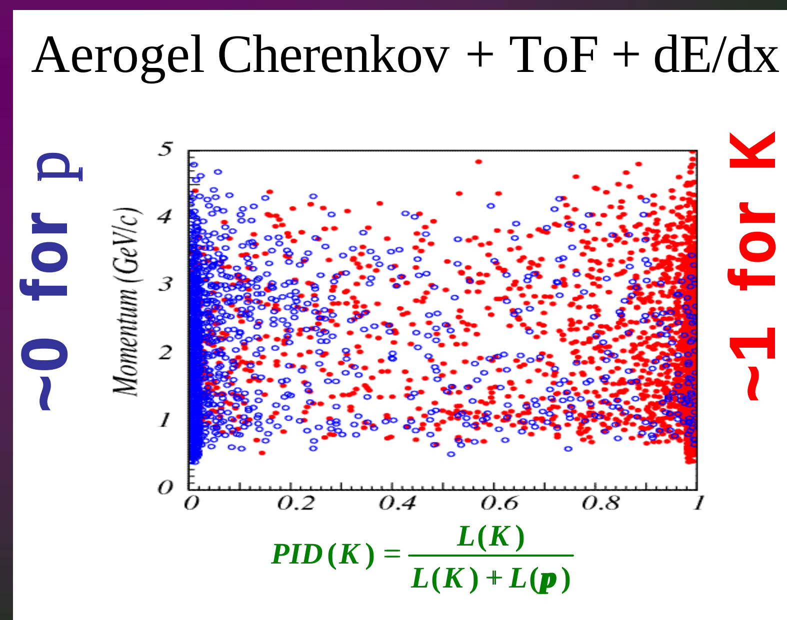


K/π separation for $B^0 \to \pi^+\pi^-$

2-3.5GeV/c
π/K separation

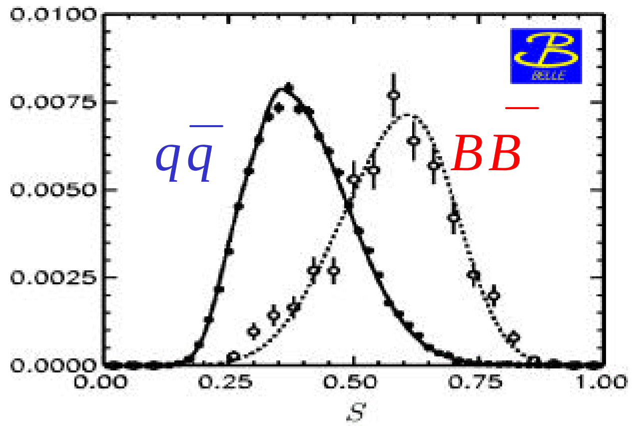
for $\pi^+\pi^-$,
π eff. = 0.91
K fake rate = 0.10

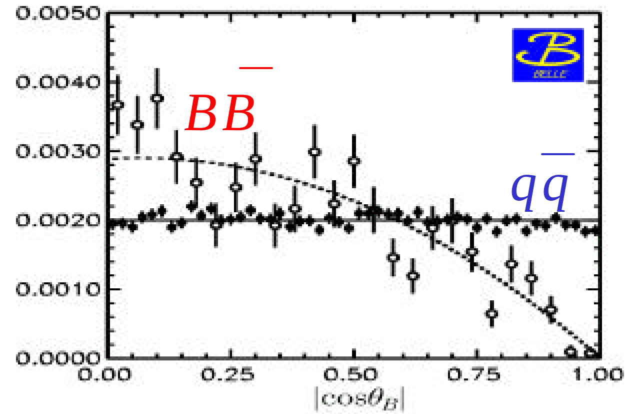




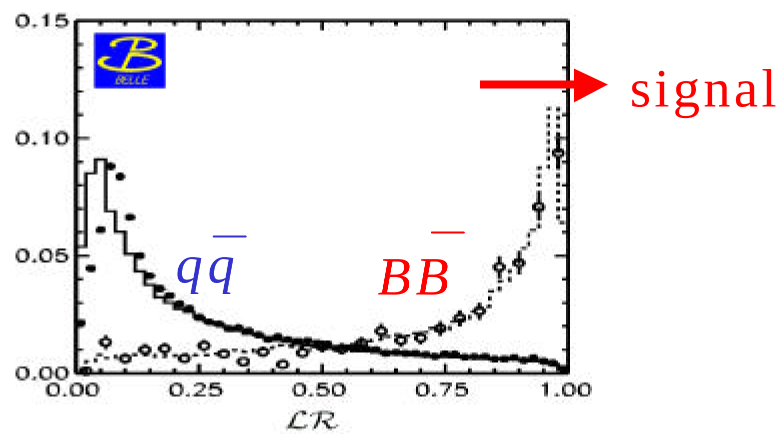
$e^+e^- \to q\bar{q}$ Background Suppression

- $B\bar{B}$ **or** $q\bar{q}$ **likelihood**
  - Construct $B\bar{B}$ or $q\bar{q}$ likelihood with Fisher discriminant, reconstructed B momentum direction, etc.

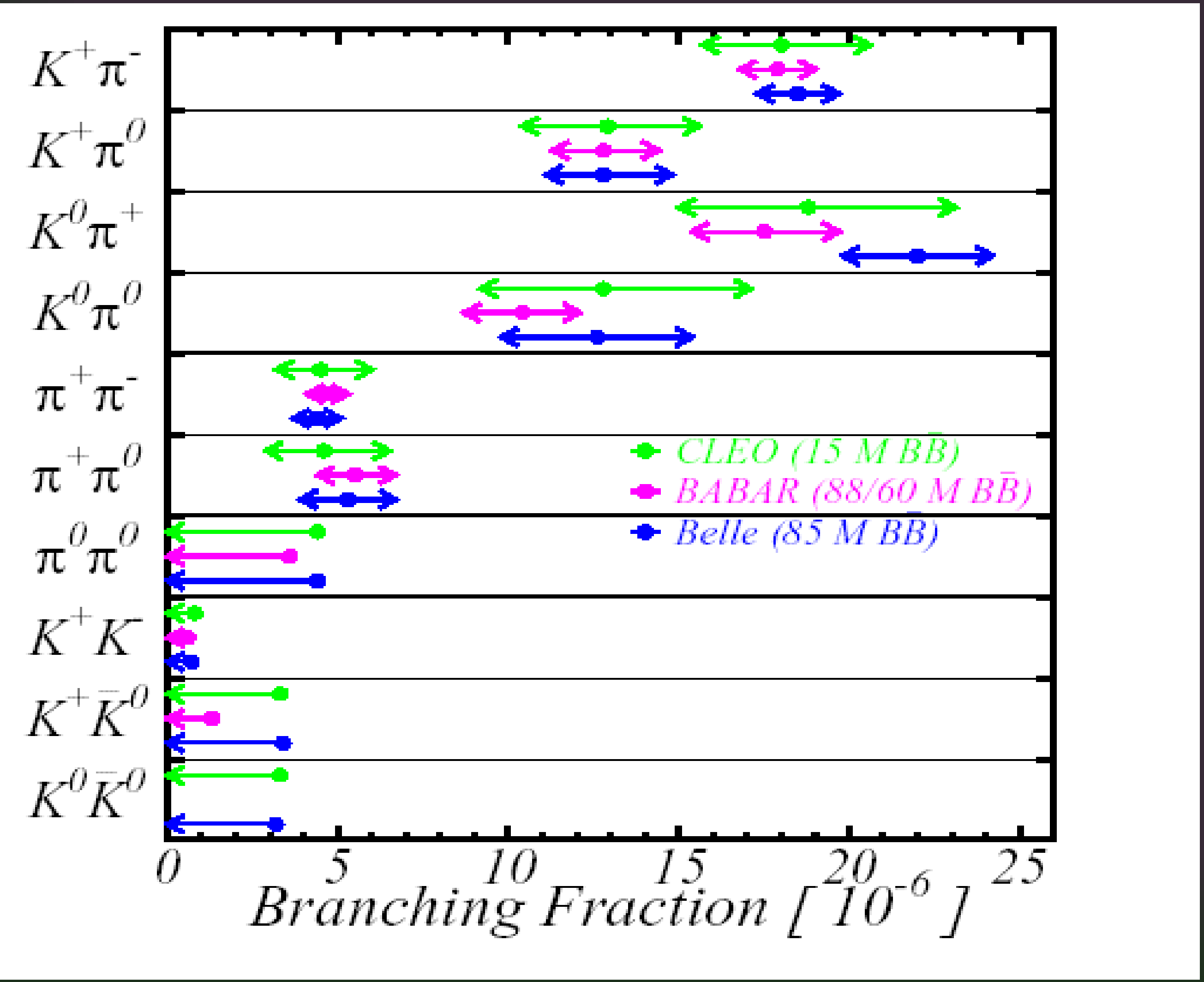




- **Signal selection with likelihood ratio** $L_{BB}/(L_{BB}+L_{qq})$



Branching fraction measurements



Reconstruction summary

- Established techniques for
  - event selection
  - background rejection
  - flavor tagging
  - vertexing
  - time-difference (Δt) fit

Common techniques used for branching fractions, Δm_d, τ_B, $\sin 2 f_1$

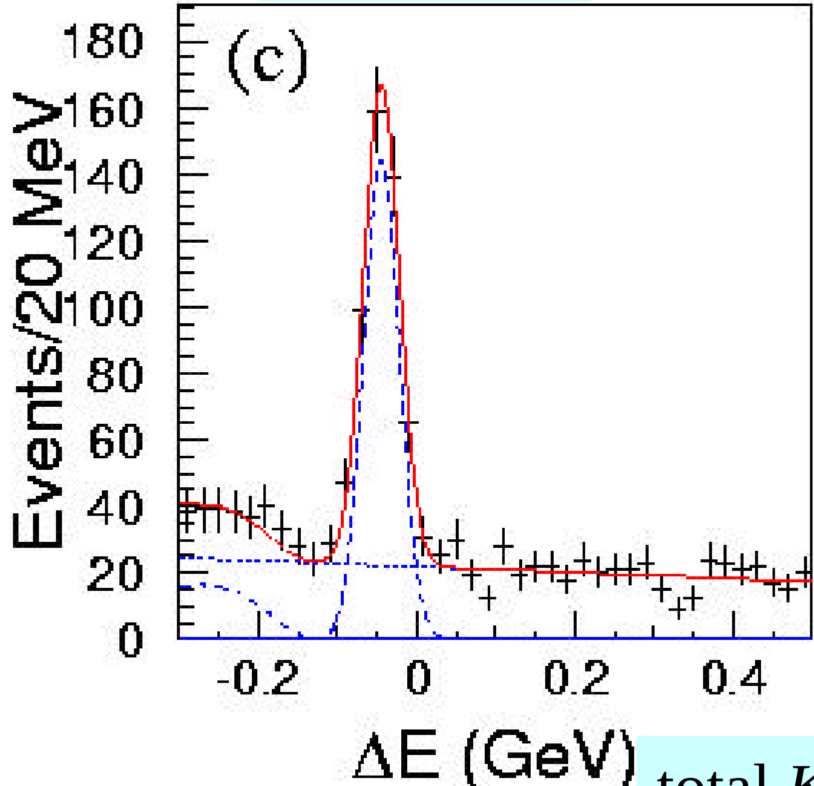
- In particular, background well under control

Now we are able to obtain $A_{\pi\pi}$ and $S_{\pi\pi}$.
But let's go through several crosschecks before opening the box.

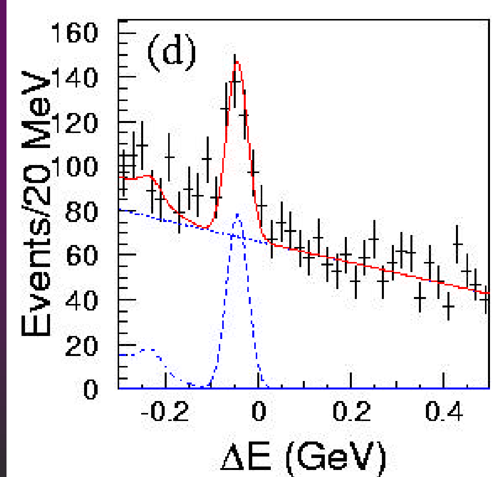
$B^0 \to K^+\pi^-$ control sample

Positively-identified kaons
(reversed particle-ID requirements w.r.t. $\pi\pi$ selection)

LR > 0.825

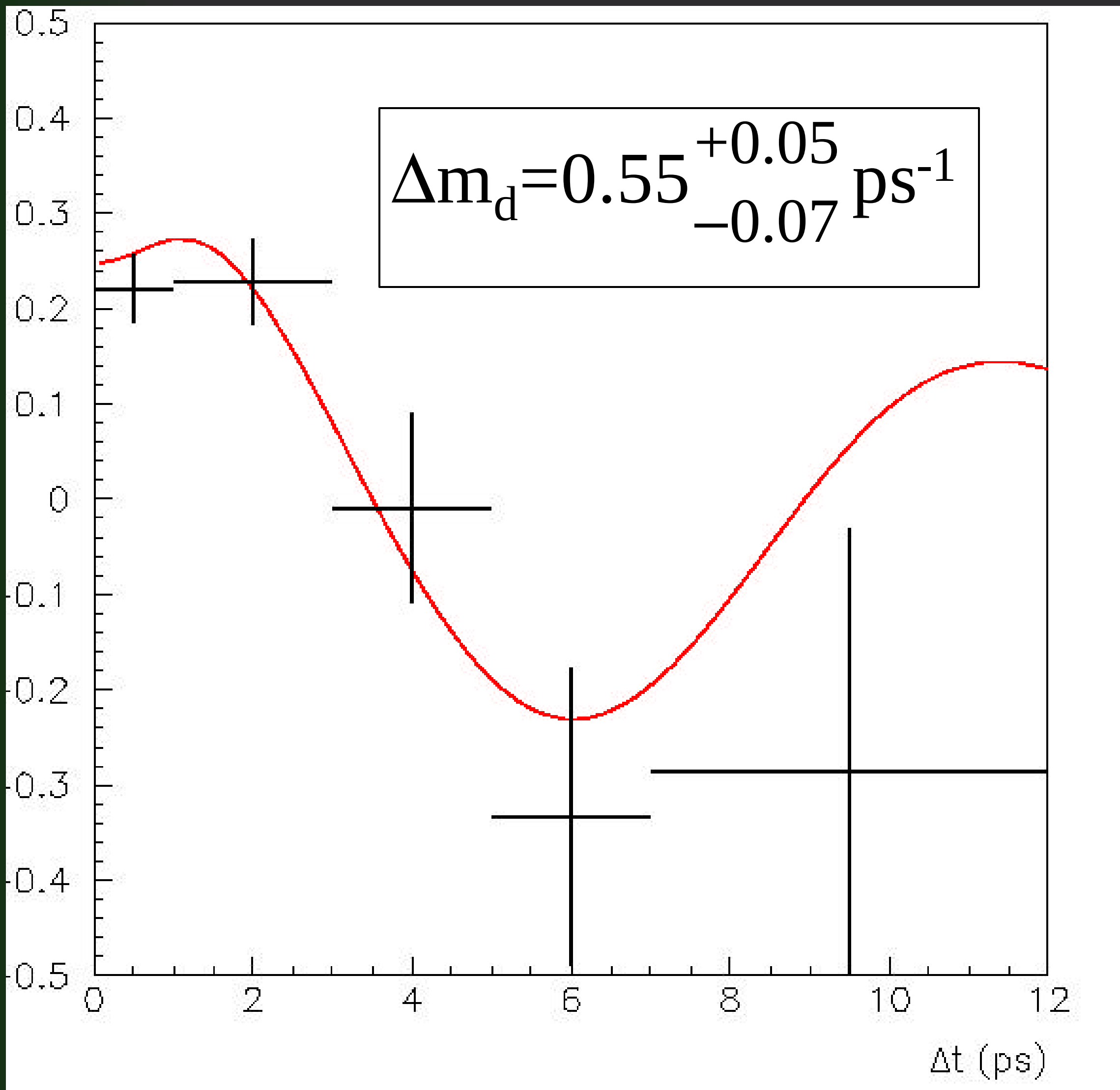


LRmin < LR   0.825



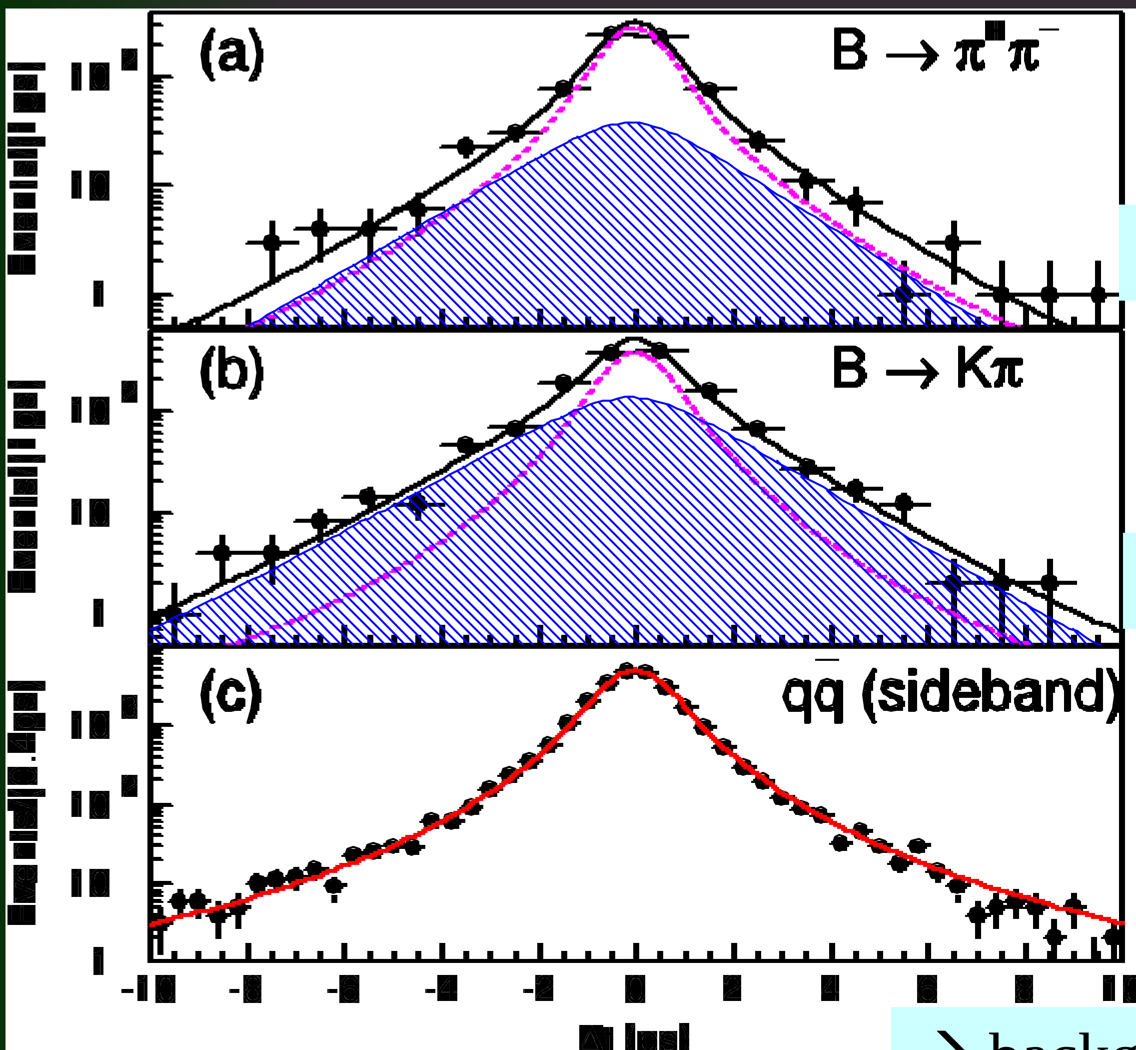
total $K\pi$ yield: 610 events

Mixing fit using $B^0 \to K^+\pi^-$: OK !



Consistent with the world average $(0.489 \pm 0.008)\ ps^{-1}$ PDG2002

Lifetime measurements: also good !



world average (PDG2002)
(1.542 ± 0.016) ps

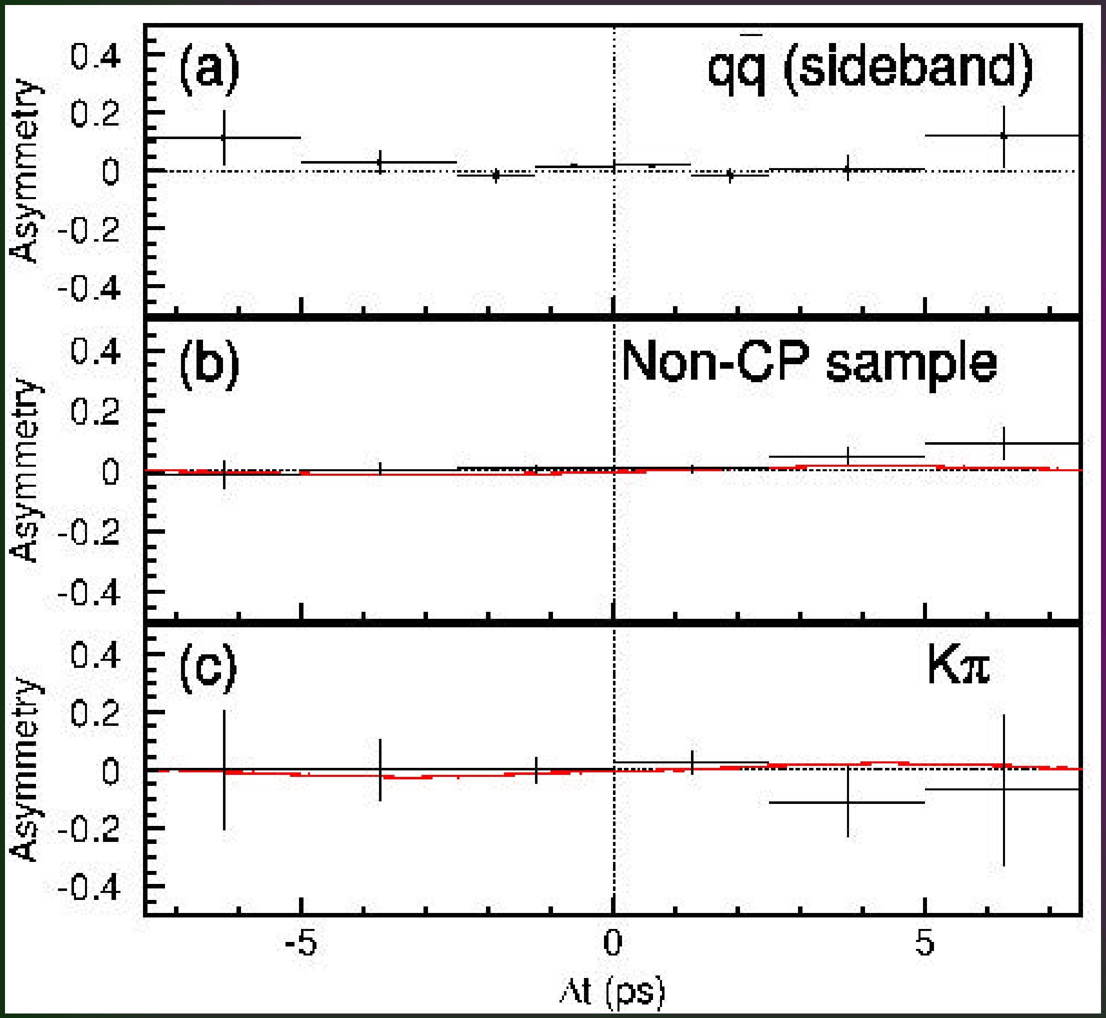
ππ : τ_B=(1.42 ± 0.14) ps

Kπ : τ_B=(1.46 ± 0.08) ps

BG shape fit

→ background treatment is correct !

Null asymmetry tests: OK !



Null asymmetry

$\mathcal{A} = -0.015 \pm 0.022$

$\mathcal{S} = 0.045 \pm 0.033$

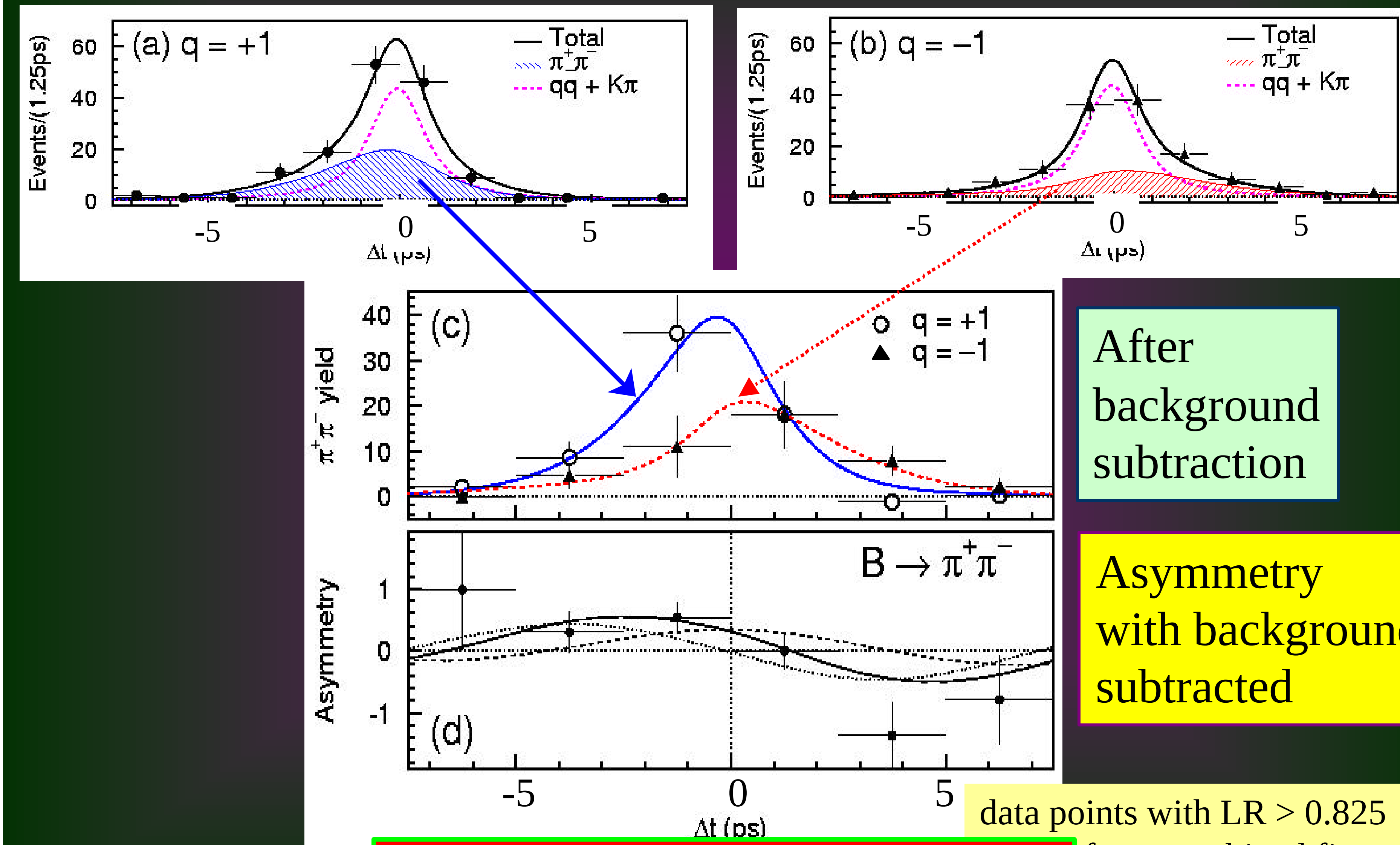
$\mathcal{S}_{K\pi} = 0.08 \pm 0.16$

$\mathcal{A}_{K\pi} = -0.03 \pm 0.11$

(consistent with counting analysis)

4. Results

Fit results



After background subtraction

Asymmetry with background subtracted

data points with LR > 0.825
from combined fit result

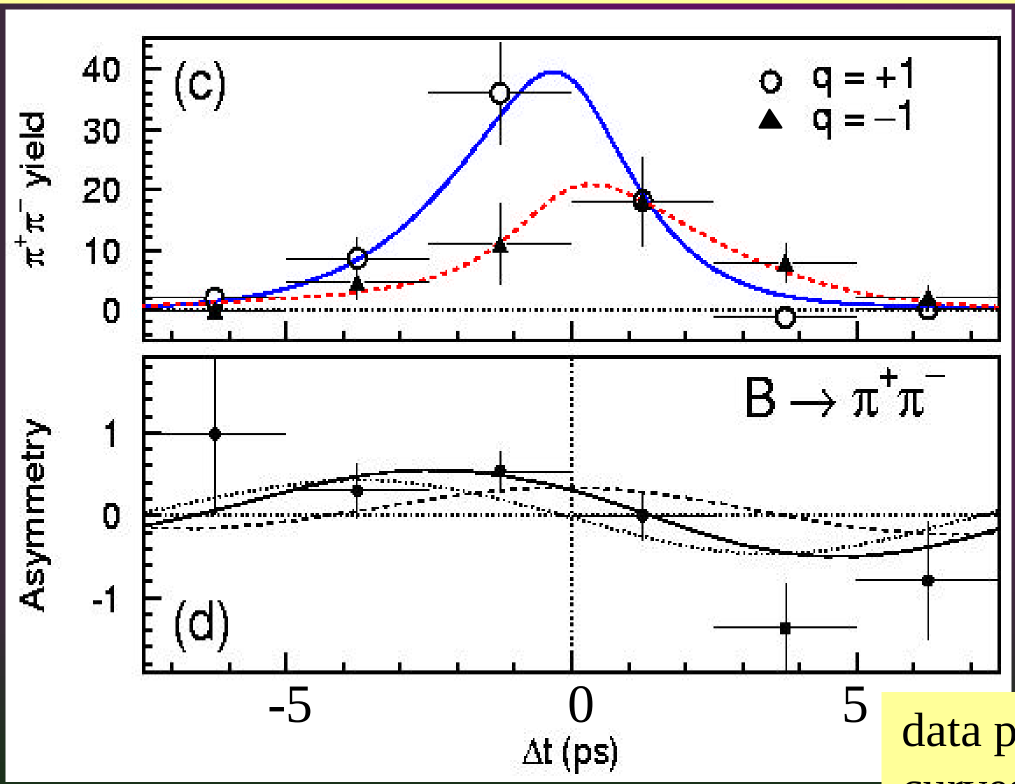
Large *CP* Violation is seen !

Fit results

$$A_{\pi\pi} = +0.77 \pm 0.27(\text{stat}) \pm 0.08(\text{syst})$$

$$S_{\pi\pi} = -1.23 \pm 0.41(\text{stat}) \; {}^{+0.08}_{-0.07} \; (\text{syst})$$

Consistent with previous results and supercede them

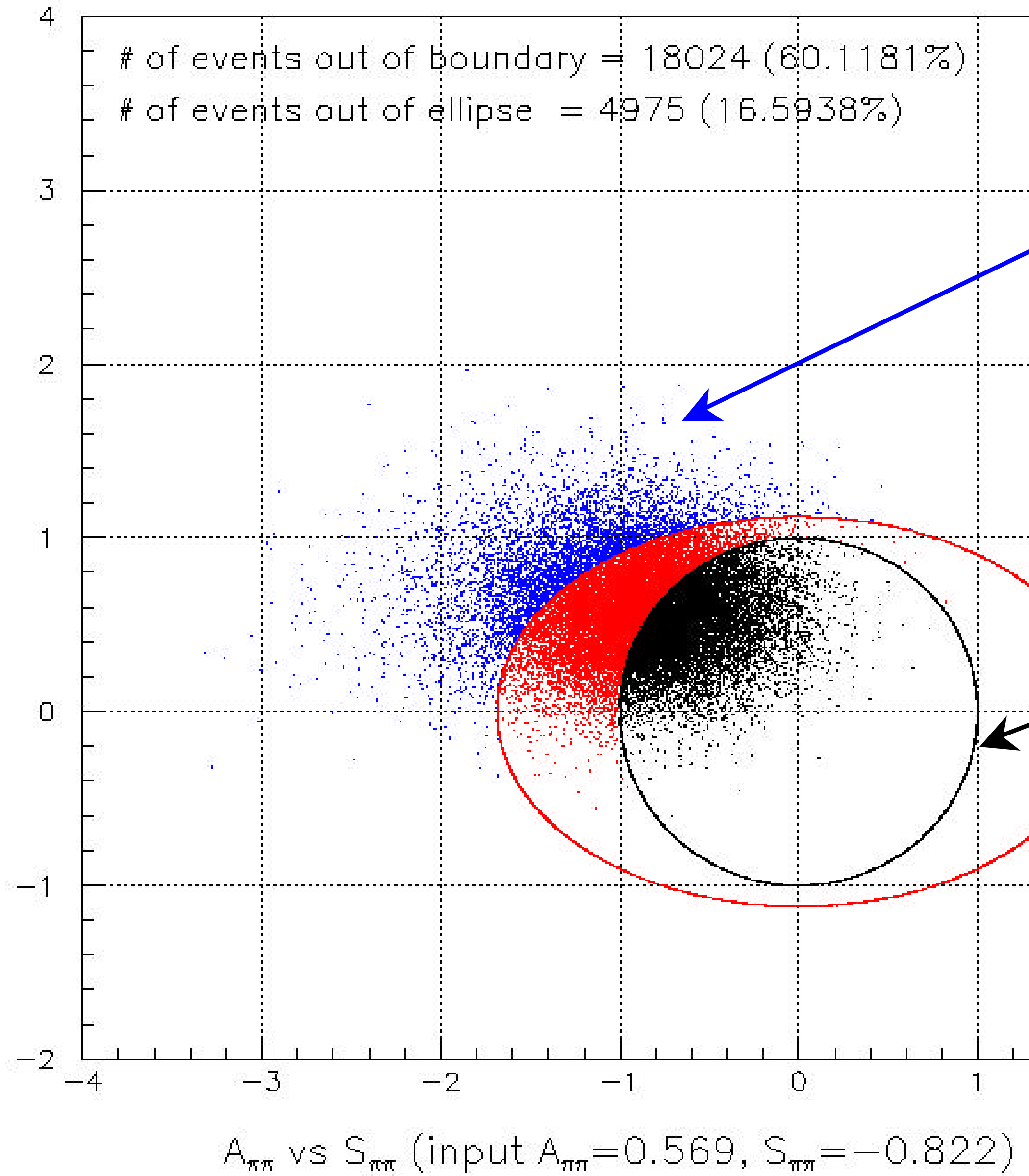


After background subtraction

Asymmetry with background subtracted

data points with LR > 0.825
curves from combined fit result

How often are we outside the physical region ?



Probability that we have fluctuation equal to or larger than the fit to data (input values at the physical boundary)

16.6%

Physical region

$A_{\pi\pi}^2 + S_{\pi\pi}^2 \quad 1$

[Note]
prob. outside the boundary
60.1%
(~independent of statistics)

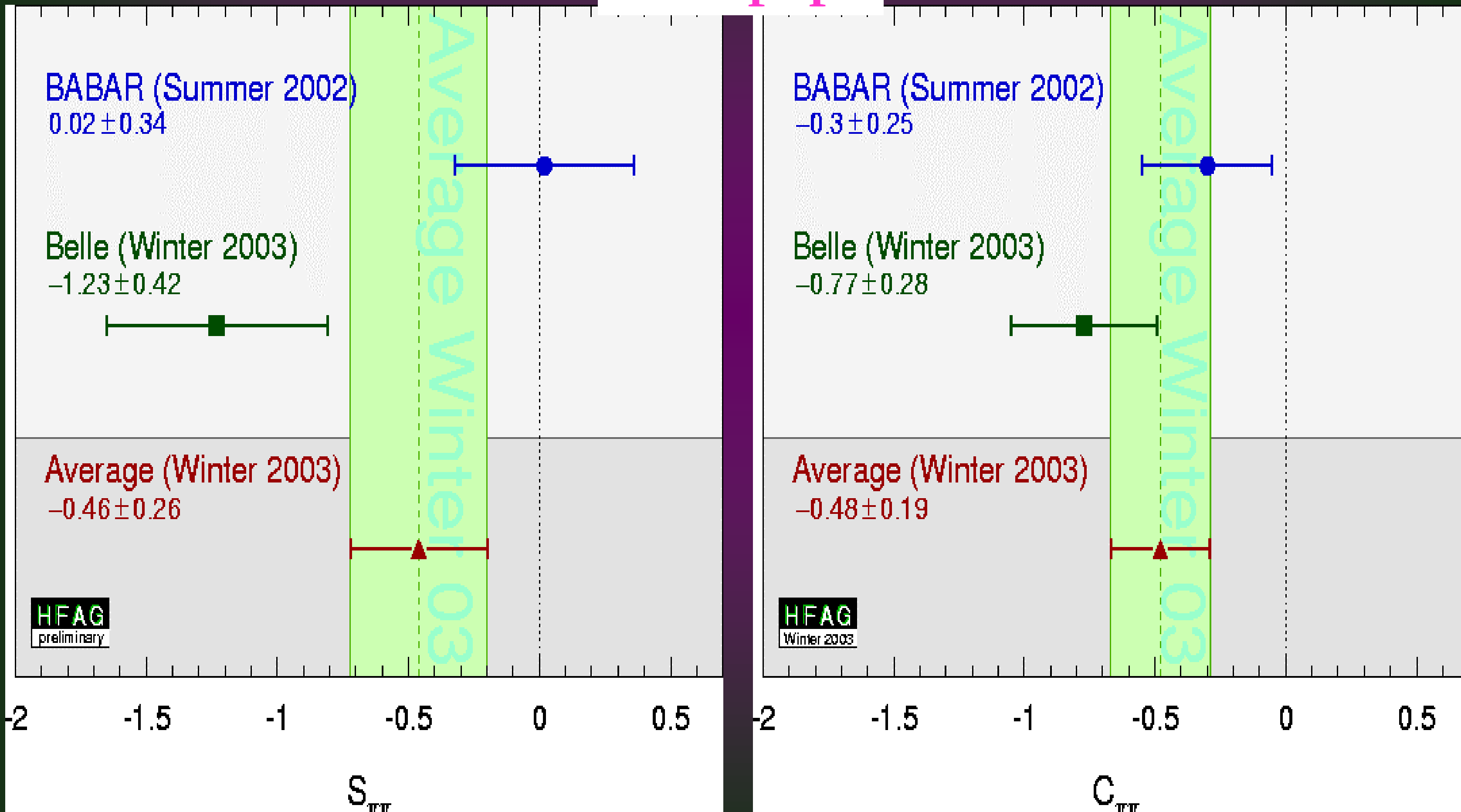
Systematic uncertainties

source	$A_{\pi\pi}$ +error	$A_{\pi\pi}$ –error	$S_{\pi\pi}$ +error	$S_{\pi\pi}$ –error
Background fractions	+0.058	–0.048	+0.044	–0.055
Vertexing	+0.044	–0.054	+0.037	–0.012
Fit bias	+0.016	–0.021	+0.052	–0.020
Wrong tag fraction	+0.026	–0.021	+0.015	–0.016
τ_B, Δm_d, $A_{K\pi}$	+0.021	–0.014	+0.022	–0.022
Resolution function	+0.019	–0.020	+0.010	–0.013
Background shape	+0.003	–0.015	+0.007	–0.002
Total	**+0.08**	**–0.08**	**+0.08**	**–0.07**

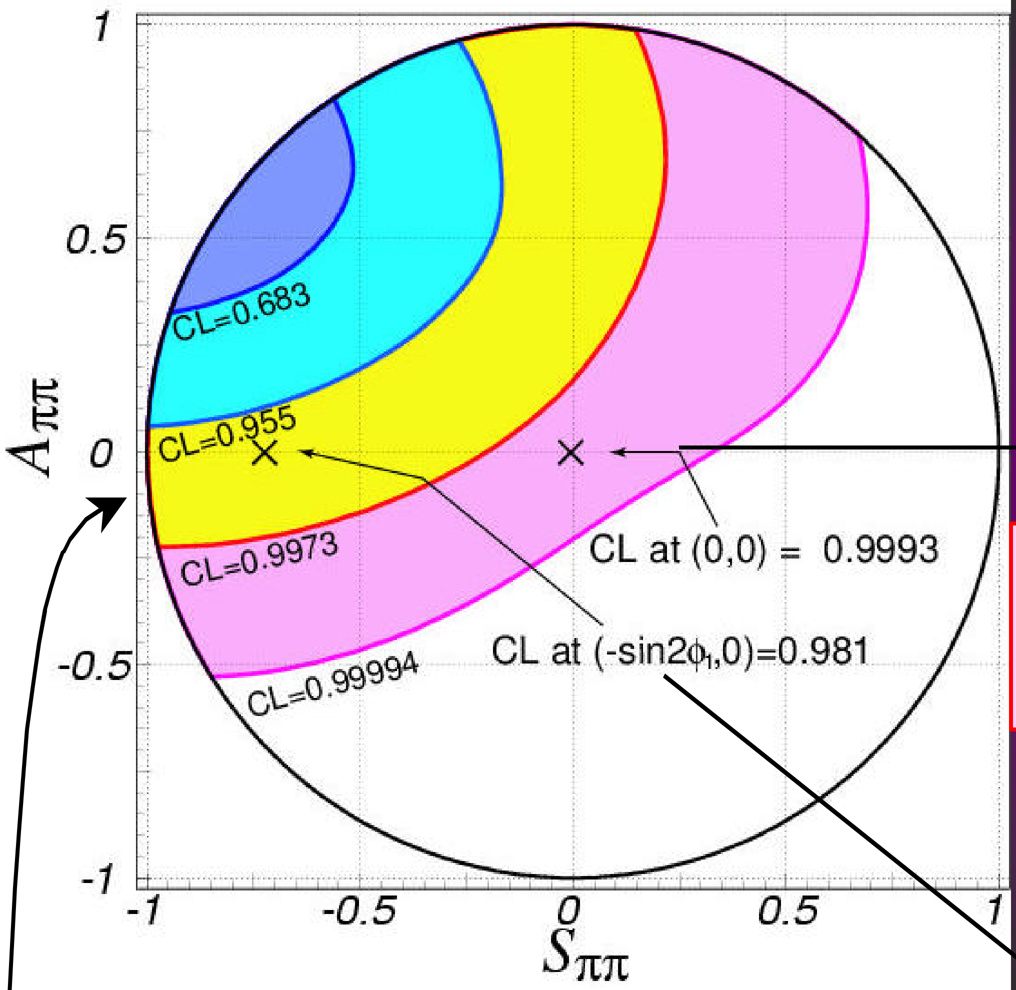
* Actual estimations were done before seeing the fit result, as we adopted a blind analysis technique.

HFAG: Unitarity Triangle Parameters

B⁰ → π⁺π⁻



Confidence regions



- Feldman-Cousins frequentist approach.
- Acceptance regions obtained from MC pseudo-experiments.
- Systematic errors also included.
- Confidence Level (CL) at each point is calculated.

CL for *CP* conservation **3.4s**

1) Evidence for *CP* violation in B^0 ® $\pi^+\pi^-$

2) "Indication" of direct *CP* Violation ($A_{\pi\pi}$>0); "observation" requires more statistics.

3) **CPV from $\bar{B}$-*B* mixing only ("superweak" scenarios):**
e.g. Bigi (2002), Brhlik-Everett-Kane-King-Lebedev (2000)

2.3σ

Constraints on the CKM angle f_2

$$A(B^0 \to p^+ p^-) = -(|T| e^{id_T} e^{if_3}) + |P| e^{id_P}),$$
$$A(\overline{B}^0 \to p^+ p^-) = -(|T| e^{id_T} e^{-if_3}) + |P| e^{id_P}),$$

convention taken from M.Gronau and J.L.Rosner PRD65, 093012 (2002)

$$l_{pp} = e^{if_2} \frac{1 + |P/T| e^{i(d+f_3)}}{1 + |P/T| e^{i(d-f_3)}}$$

4 parameters

$$S_{pp} = [\sin 2f_2 + 2|P/T| \sin(f_1 - f_2) \cos d$$
$$- |P/T|^2 \sin 2f_1] / R_{pp},$$
$$A_{pp} = -[2|P/T| \sin(f_1 + f_2) \sin d] / R_{pp},$$
$$R_{pp} = 1 - 2|P/T| \cos(f_1 + f_2) \cos d + |P/T|^2$$

$$d \equiv d_P - d_T$$

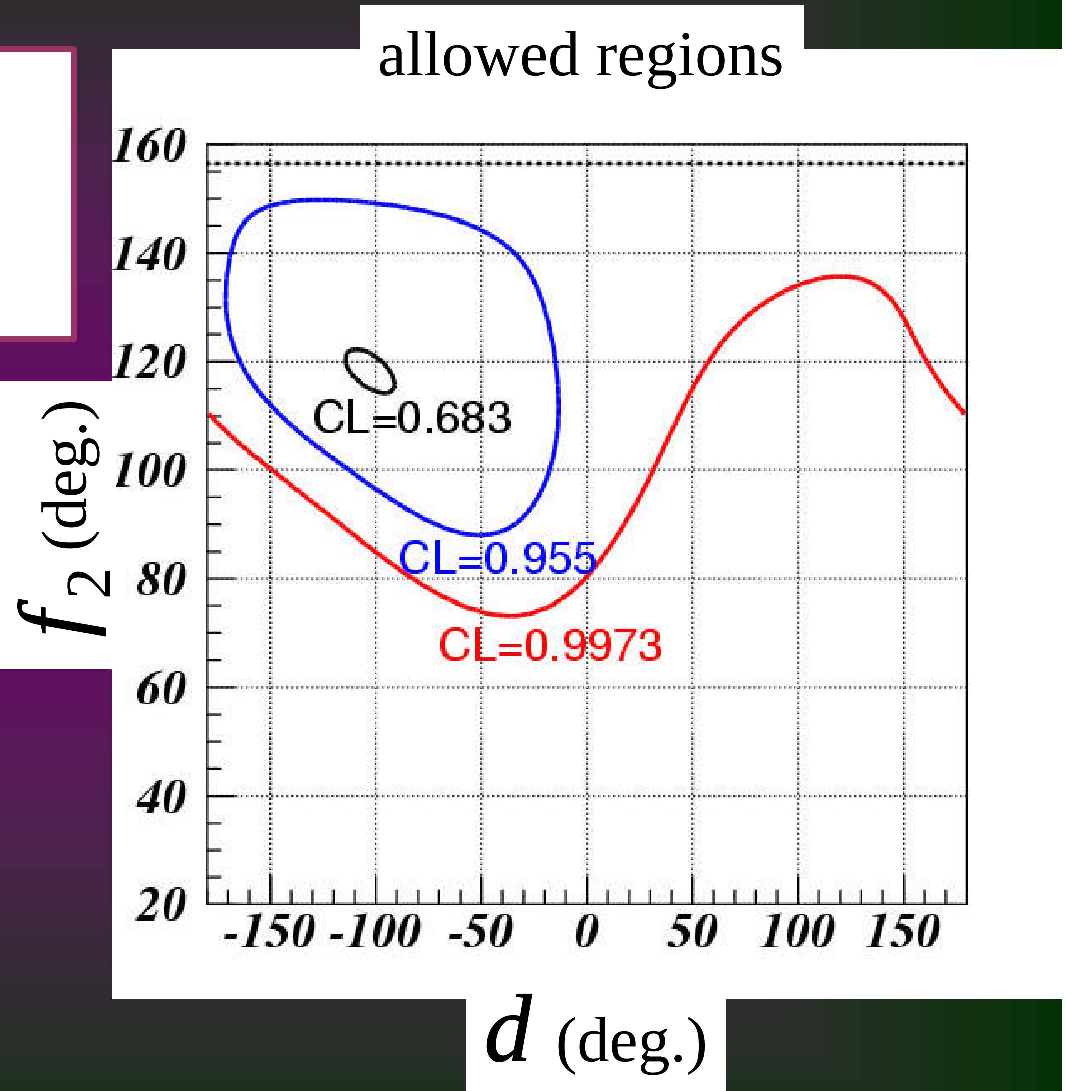
|P/T|	0.15-0.45 (representative)
f_1	21.3 - 25.9deg. (Belle & BaBar combined)

e.g. |P/T| = 0.276 ± 0.064 (Gronau-Rosner PRD65, 013004 (2002)

Constraint on f_2 (1)

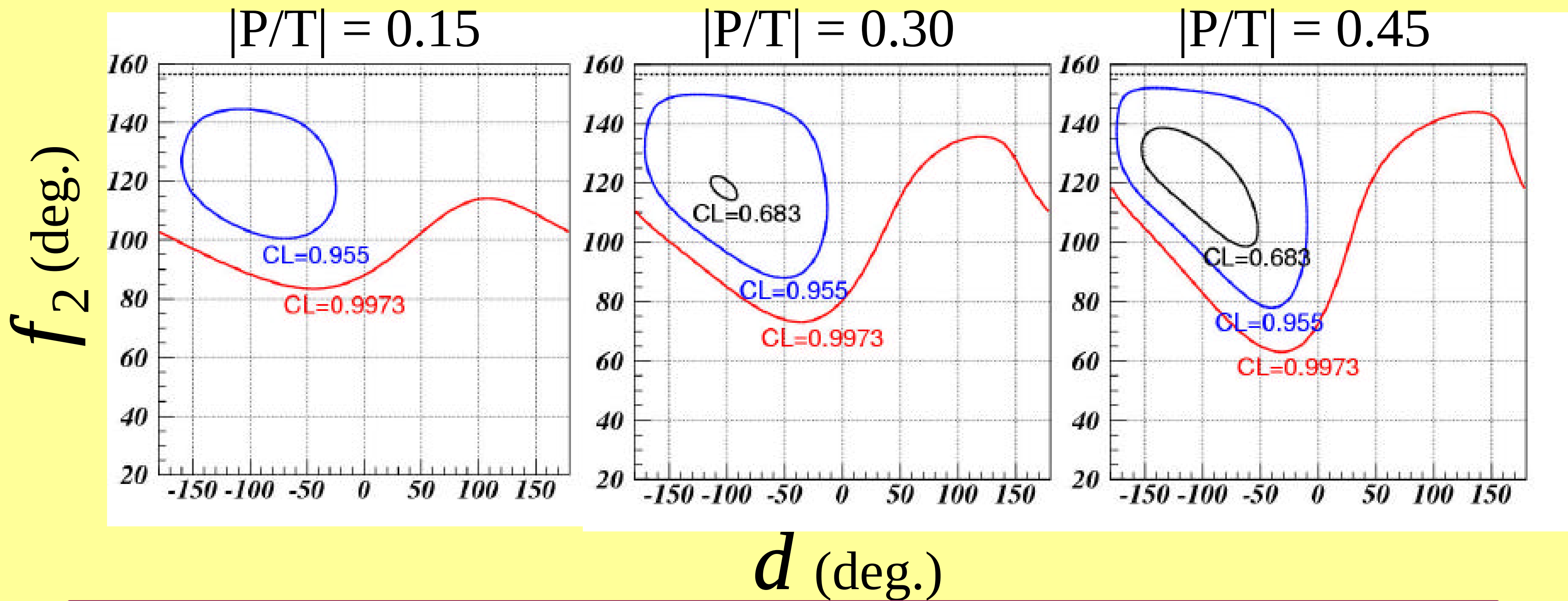
- Input values for f_1 and |P/T|
  - f_1=23.5° (sin2f_1=0.73)
  - |P/T| = 0.3

- f_2 constraint w/o isospin analysis !
  - both Aππ and Sππ large
- less restrictive on d
  - d < 0 favored
  - no constraint on d at 3σ

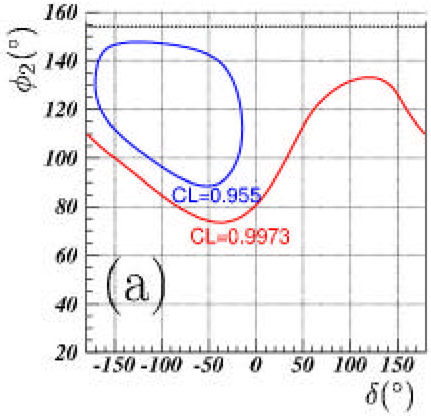
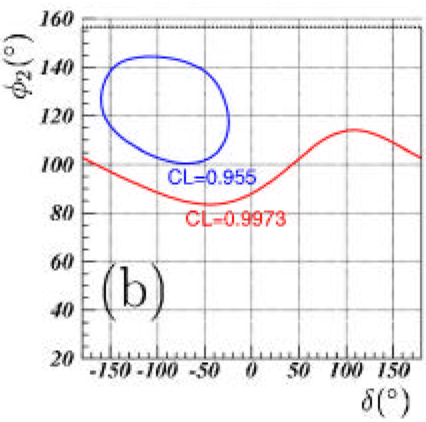
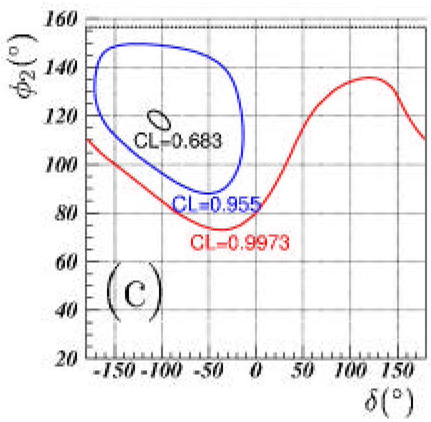
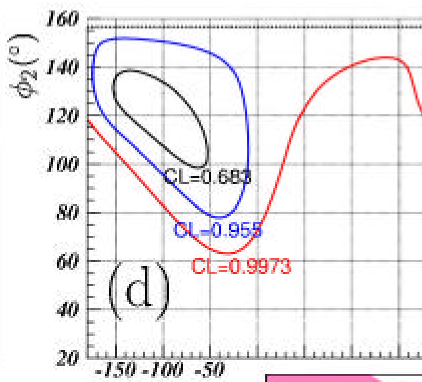
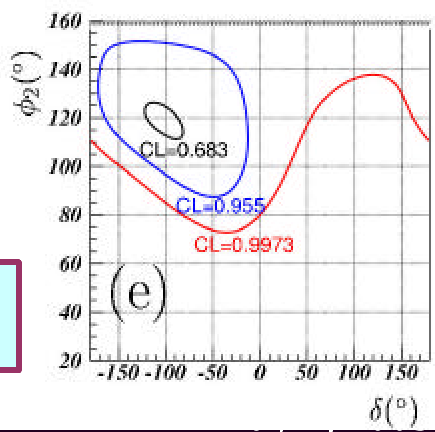


Constraint on f_2 (2)

|P/T| dependence ($f_1 = 23.5°$)



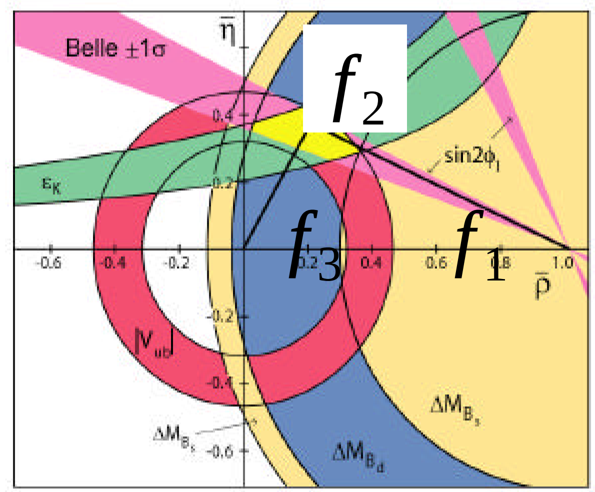
- Consistent with theoretical predictions
- Larger |P/T| favored

ϕ_1 \ $\left\|\frac{P}{T}\right\|$	0.15	0.30	0.45
25.9°			
23.5°			
21.3°			

(95.5% C.L.)

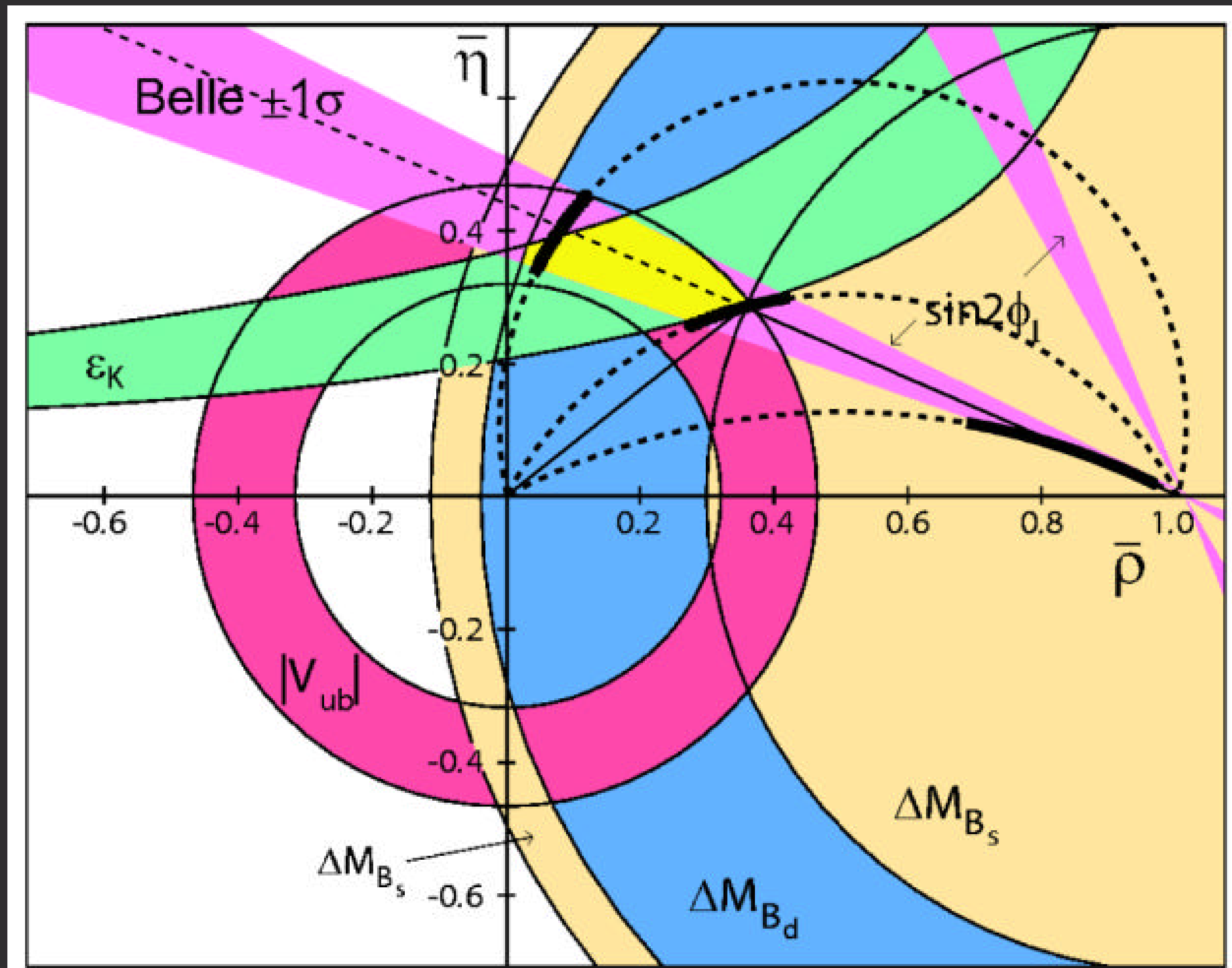
78° f_2 152°

Consistent



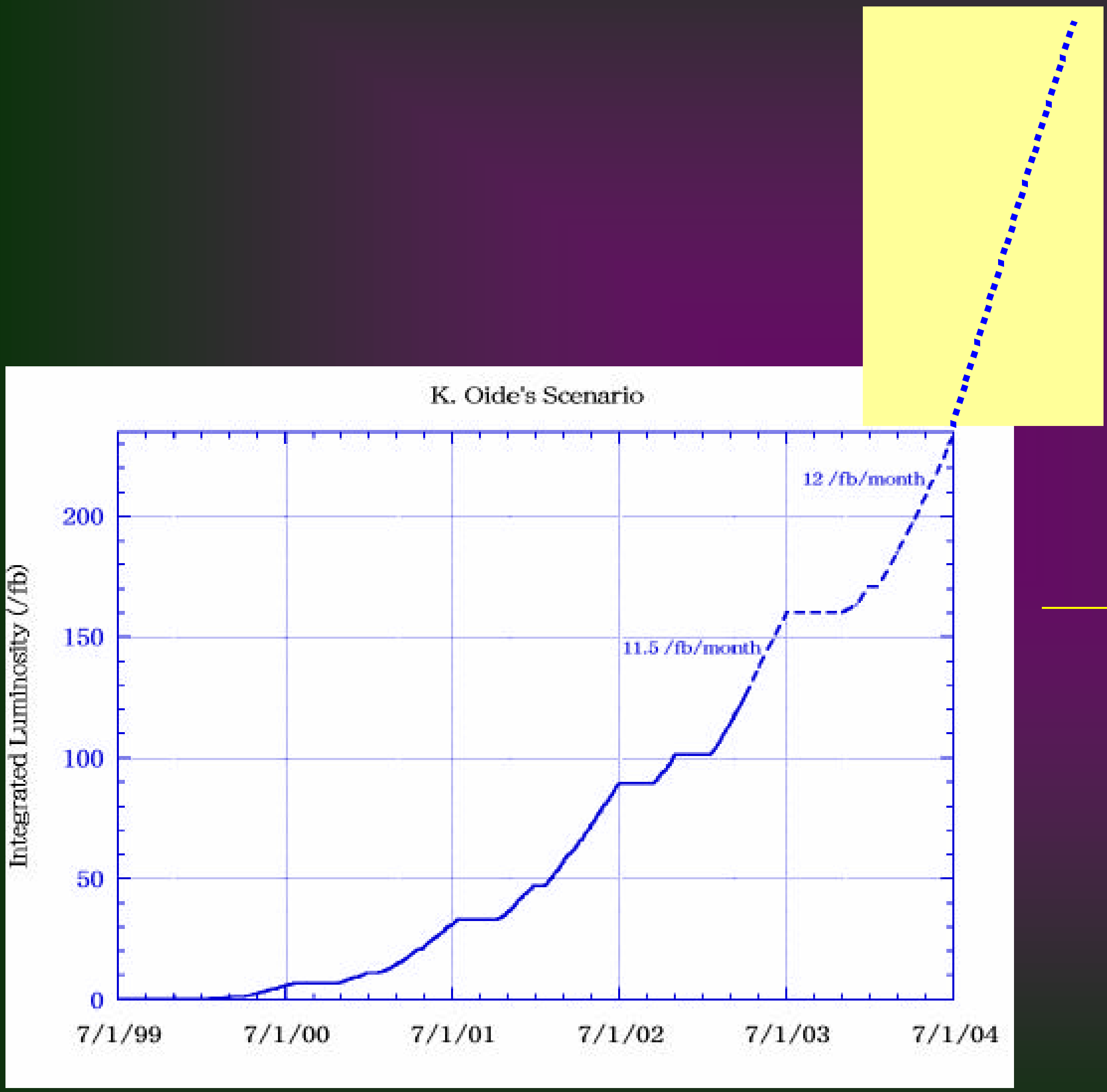
f_1 dependence is small

ϕ_2 constraint "banana"



* not a global fit; sin2φ1 and φ2 results just added to the figure

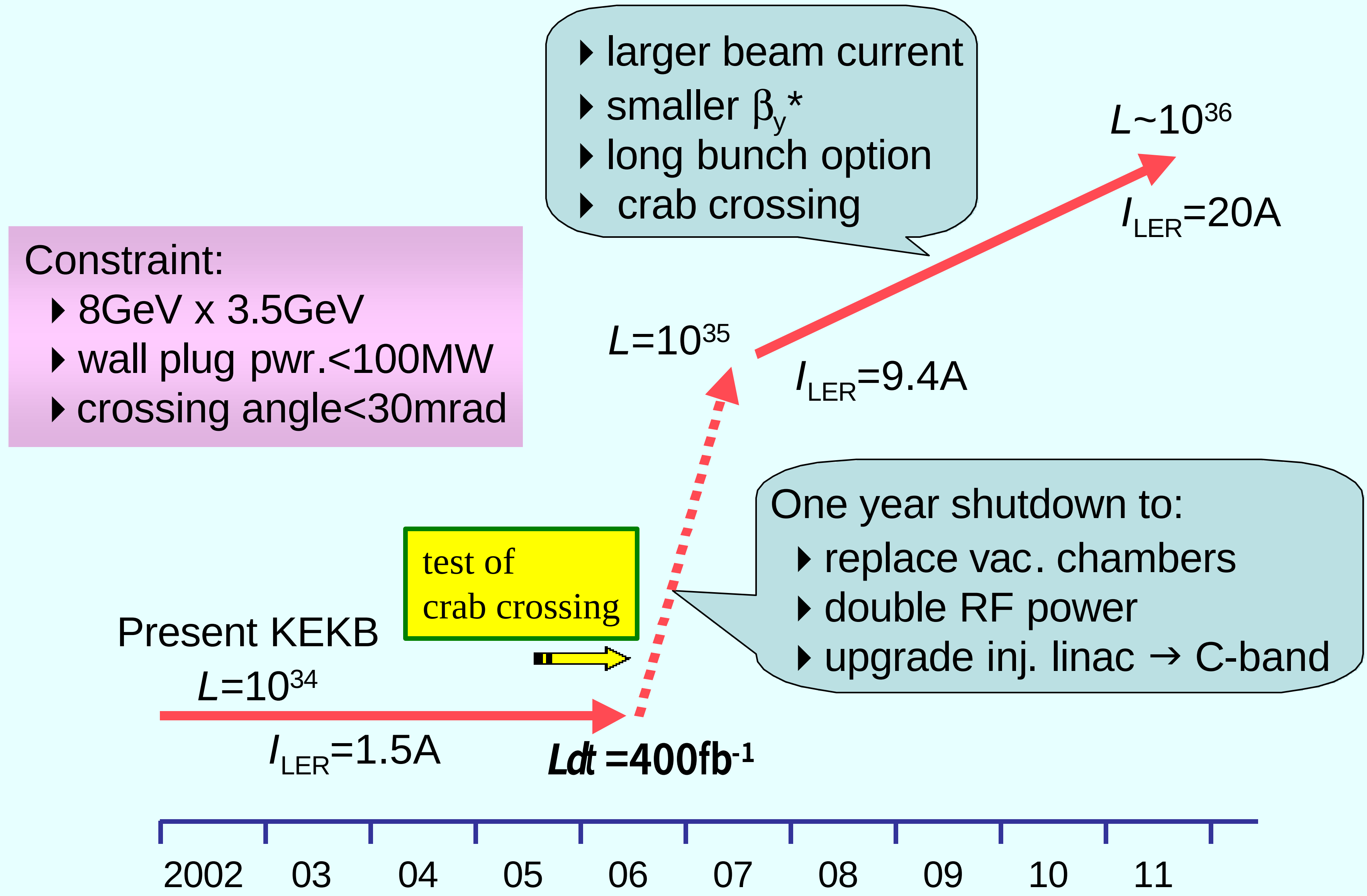
KEKB in the near future



~400fb-1 by ~2005
≈ 5 x ∫Ldt(July 2002)

~160fb-1 by July 1, 2003
≈ 2 x ∫Ldt(July 2002)

KEKB longer-term strategy



5. Summary

- Evidence for *CP* violation in $B^0 \to \pi^+\pi^-$

  CP conservation ruled out at the 99.93% CL (3.4σ)

- Large $A_{\pi\pi}$ value indicates direct CP violation. More Belle data will come (×5 by ~2005) for confirmation.

- First constraints (within the SM) on the CKM angle f_2

$$78^\circ \le f_2 \le 152^\circ \quad (95.5\%\ \text{CL})$$

[for $0.15 < |P/T| < 0.45$ and $f_1 = 23.5^\circ$ ($\sin 2f_1 = 0.73$)]

  Consistent with indirect constraints on the unitarity triangle from other measurements.

  Additional support for Kobayashi-Maskawa mechanism.

The best is yet to come !

Backup Slides

Belle Detector

Quite stable performance up to now

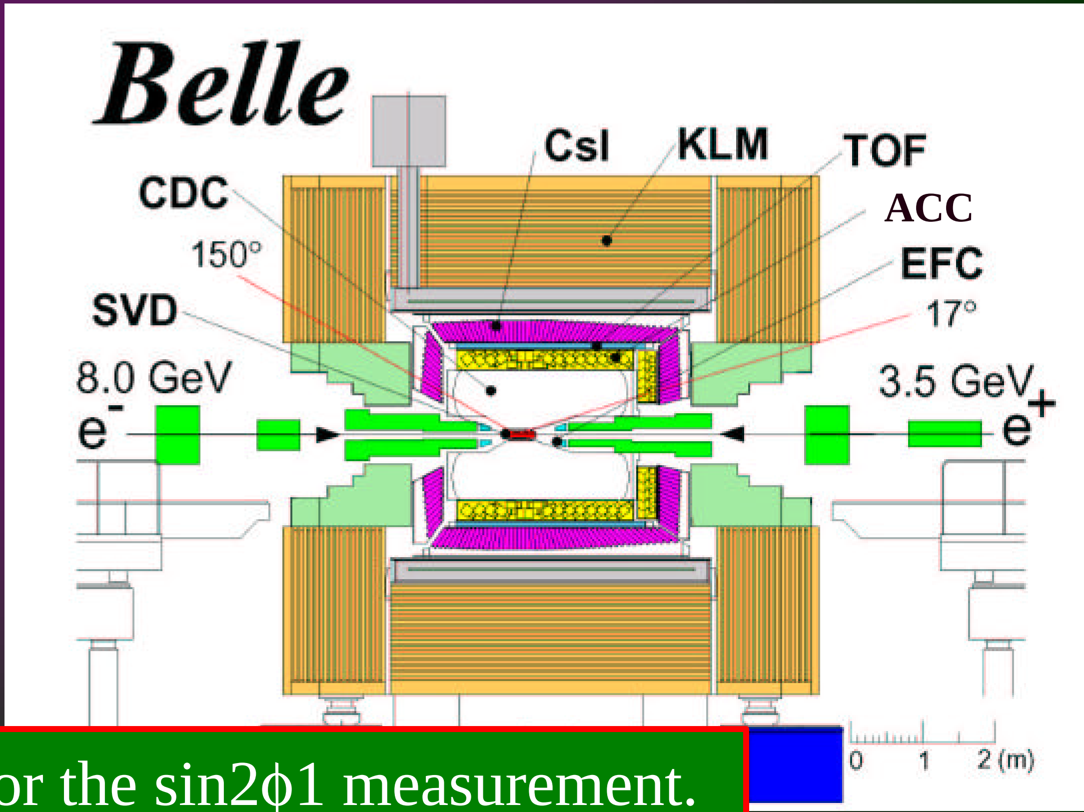
Silicon Vertex Detector (SVD)
Impact parameter resolution
→ 55mm for p=1GeV/c at normal incidence

Central Drift Chamber (CDC)
$(s\,Pt/Pt)^2 = (0.0019Pt)^2 + (0.0030)^2$ (Pt in GeV/c)2

K/p separation with
dE/dx in CDC (s dE/dx =6.9%)
TOF (s TOF = 95ps)
Aerogel Cerenkov (ACC)
Efficiency = ~90%,
Fake rate = ~6% up to 3.5GeV/c

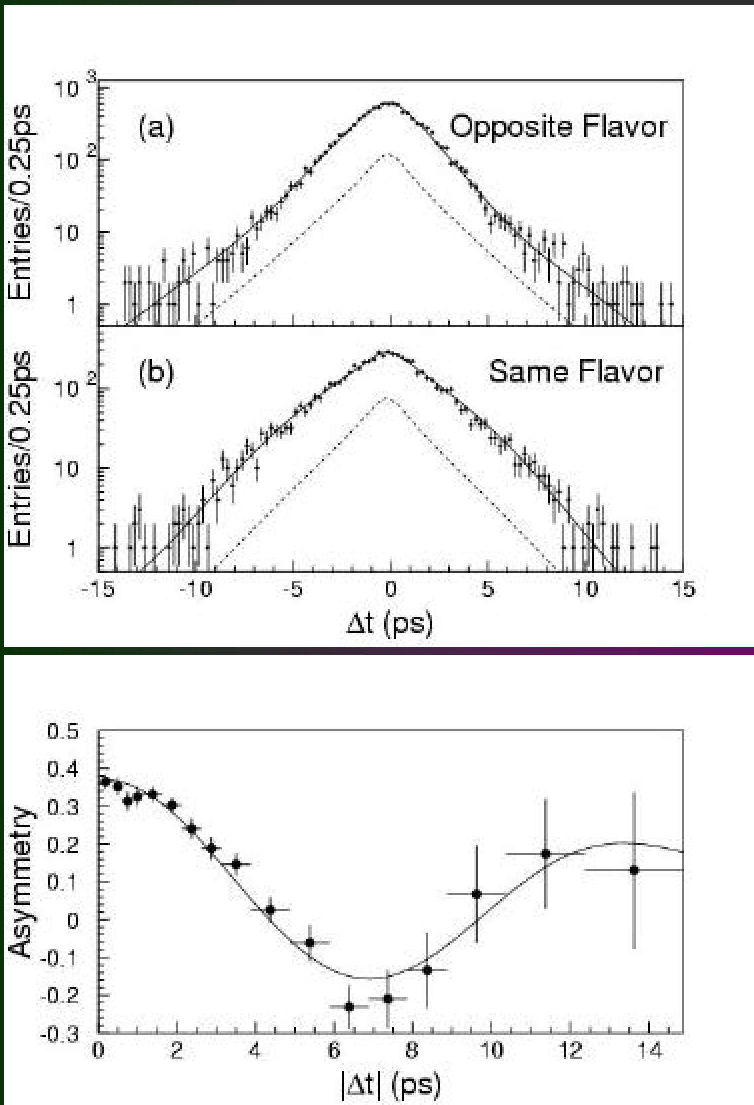
g, e± with CsI crystals (ECL)
s E/E ~ 1.8% @ E=1GeV
e± : efficiency > 90%
(~0.3% fake for p > 1GeV/c)

KL and m± with KLM (RPC chambers)
m± : efficiency > 90%
(<2% fake at p > 1GeV/c)

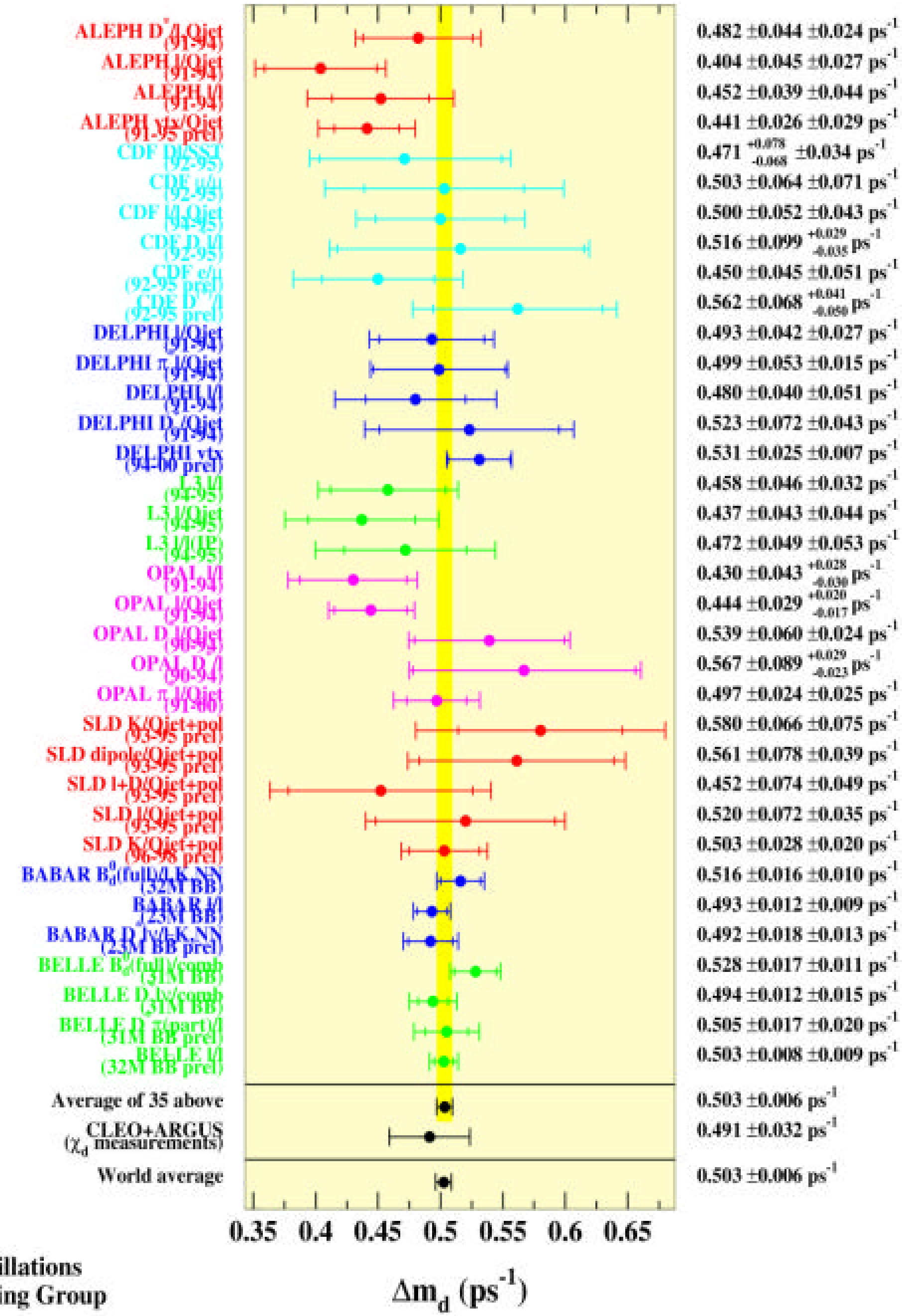


All components are important for the sin2ϕ1 measurement.

Mixing



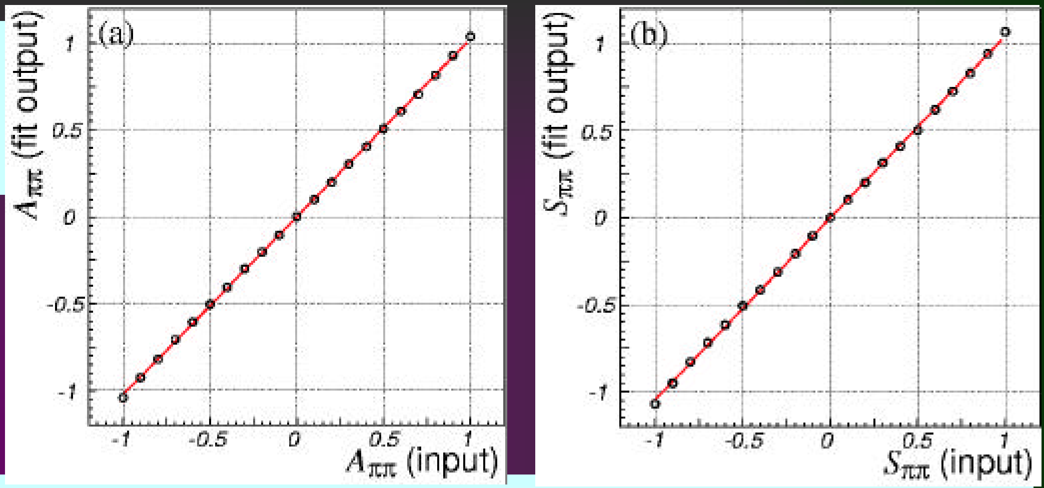
(a)
Opposite Flavor
(b)
Same Flavor
Entries/0.25ps
Δt (ps)
Asymmetry
|Δt| (ps)



ALEPH D*/l,Qjet (91-94)
ALEPH l/Qjet (91-94)
ALEPH l/l (91-94)
ALEPH vtx/Qjet (91-95 prel)
CDF D/l/SST (92-95)
CDF μ/μ (92-95)
CDF l/l,Qjet (94-95)
CDF D/l/l (92-95)
CDF e/μ (92-95 prel)
CDF D*/l (92-95 prel)
DELPHI l/Qjet (91-94)
DELPHI π/l/Qjet (91-94)
DELPHI l/l (91-94)
DELPHI D/Qjet (91-94)
DELPHI vtx (94-00 prel)
L3 l/l (94-95)
L3 l/Qjet (94-95)
L3 l/l(IP) (94-95)
OPAL l/l (91-94)
OPAL l/Qjet (91-94)
OPAL D l/Qjet (90-94)
OPAL D/l (90-94)
OPAL π l/Qjet (91-00)
SLD K/Qjet+pol (93-95 prel)
SLD dipole/Qjet+pol (93-95 prel)
SLD l+D/Qjet+pol (93-95 prel)
SLD l/Qjet+pol (93-95 prel)
SLD K/Qjet+pol (96-98 prel)
BABAR B_d^0(full)/l,K,NN (32M BB)
BABAR l/l (23M BB)
BABAR D*lν/l,K,NN (23M BB prel)
BELLE B_d^0(full)/comb (31M BB)
BELLE D*lν/comb (31M BB)
BELLE D*π(part)/l (31M BB prel)
BELLE l/l (32M BB prel)
Average of 35 above
CLEO+ARGUS (χ_d measurements)
World average
0.482 ±0.044 ±0.024 ps^{-1}
0.404 ±0.045 ±0.027 ps^{-1}
0.452 ±0.039 ±0.044 ps^{-1}
0.441 ±0.026 ±0.029 ps^{-1}
0.471 $^{+0.078}_{-0.068}$ ±0.034 ps^{-1}
0.503 ±0.064 ±0.071 ps^{-1}
0.500 ±0.052 ±0.043 ps^{-1}
0.516 ±0.099 $^{+0.029}_{-0.035}$ ps^{-1}
0.450 ±0.045 ±0.051 ps^{-1}
0.562 ±0.068 $^{+0.041}_{-0.050}$ ps^{-1}
0.493 ±0.042 ±0.027 ps^{-1}
0.499 ±0.053 ±0.015 ps^{-1}
0.480 ±0.040 ±0.051 ps^{-1}
0.523 ±0.072 ±0.043 ps^{-1}
0.531 ±0.025 ±0.007 ps^{-1}
0.458 ±0.046 ±0.032 ps^{-1}
0.437 ±0.043 ±0.044 ps^{-1}
0.472 ±0.049 ±0.053 ps^{-1}
0.430 ±0.043 $^{+0.028}_{-0.030}$ ps^{-1}
0.444 ±0.029 $^{+0.020}_{-0.017}$ ps^{-1}
0.539 ±0.060 ±0.024 ps^{-1}
0.567 ±0.089 $^{+0.029}_{-0.023}$ ps^{-1}
0.497 ±0.024 ±0.025 ps^{-1}
0.580 ±0.066 ±0.075 ps^{-1}
0.561 ±0.078 ±0.039 ps^{-1}
0.452 ±0.074 ±0.049 ps^{-1}
0.520 ±0.072 ±0.035 ps^{-1}
0.503 ±0.028 ±0.020 ps^{-1}
0.516 ±0.016 ±0.010 ps^{-1}
0.493 ±0.012 ±0.009 ps^{-1}
0.492 ±0.018 ±0.013 ps^{-1}
0.528 ±0.017 ±0.011 ps^{-1}
0.494 ±0.012 ±0.015 ps^{-1}
0.505 ±0.017 ±0.020 ps^{-1}
0.503 ±0.008 ±0.009 ps^{-1}
0.503 ±0.006 ps^{-1}
0.491 ±0.032 ps^{-1}
0.503 ±0.006 ps^{-1}
0.35 0.4 0.45 0.5 0.55 0.6 0.65
Δm_d (ps^{-1})
B Oscillations Working Group

Monte Carlo (MC) pseudo-experiments

Generate events according to the PDF used for the fit →



Good linearity over the entire range ←

- PDF is based on data (control samples, sideband) → MC pseudo-experiments are free from possible systematics in Geant-based MC.
- Feldman-Cousins approach for $A_{\pi\pi}$ and $S_{\pi\pi}$ confidence regions
  ← MC pseudo-experiments to determine acceptance regions.
- We quote the **rms** values of the $A_{\pi\pi}$ and $S_{\pi\pi}$ distributions in the MC pseudo-experiments as the **standard errors** of $A_{\pi\pi}$ and $S_{\pi\pi}$.

$A_{\pi\pi}$ error: ±0.27
$S_{\pi\pi}$ error: ±0.41
} larger than errors defined by log-likelihood curves in this measurement

Selection dependence

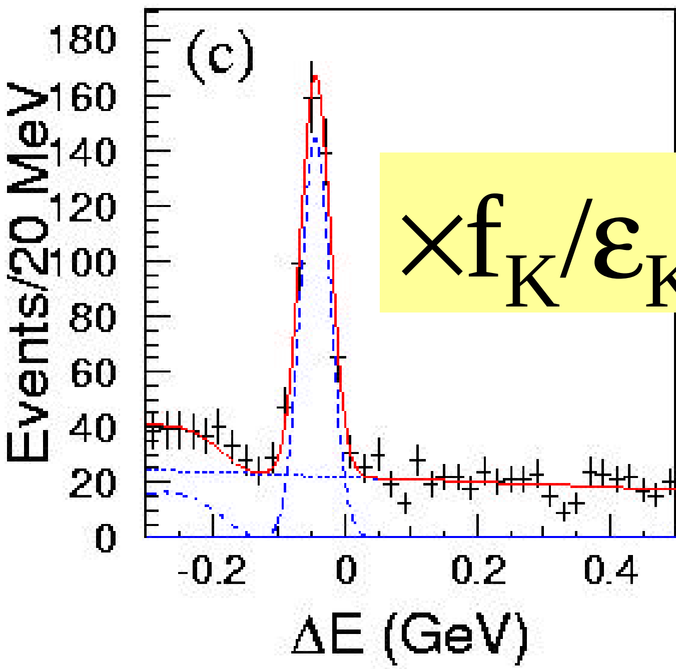
selection	$A_{\pi\pi}$	$S_{\pi\pi}$
default (KID<0.4)	0.77 +0.20 –0.23	–1.23 +0.24 –0.15
LR>0.825	0.84 +0.22 –0.25	–1.19 +0.27 –0.18
LR>0.925	0.69 +0.26 –0.30	–1.24 +0.30 –0.19
|Δt|<15ps	0.77 +0.20 –0.23	–1.25 +0.24 –0.15
|Δt|< 5ps	0.76 +0.20 –0.22	–1.27 +0.26 –0.17
|ΔE|<2s	0.81 +0.20 –0.22	–1.21 +0.25 –0.16
|ΔE|<1s	0.82 +0.21 –0.25	–1.18 +0.29 –0.19
r>0.75	1.02 +0.19 –0.25	–1.24 +0.19 –0.25
r>0.875	0.91 +0.24 –0.31	–1.18 +0.24 –0.31
KID<0.2	0.74 +0.20 –0.23	–1.11 +0.26 –0.17
KID<0.15	0.59 +0.22 –0.24	–1.14 +0.23 –0.14
Sample I ($42fb^{-1}$)	1.00 +0.19 –0.25	–1.14 +0.30 –0.21
Sample II ($36fb^{-1}$)	0.37 +0.32 –0.33	–1.99 +0.70 –0.65

(MINOS errors only)

No particular tendency is observed.

- Crosscheck of Kπ background by Kπ yield and miss-id probability → consistent with the ΔE fit in the π+π– sample

Kπ

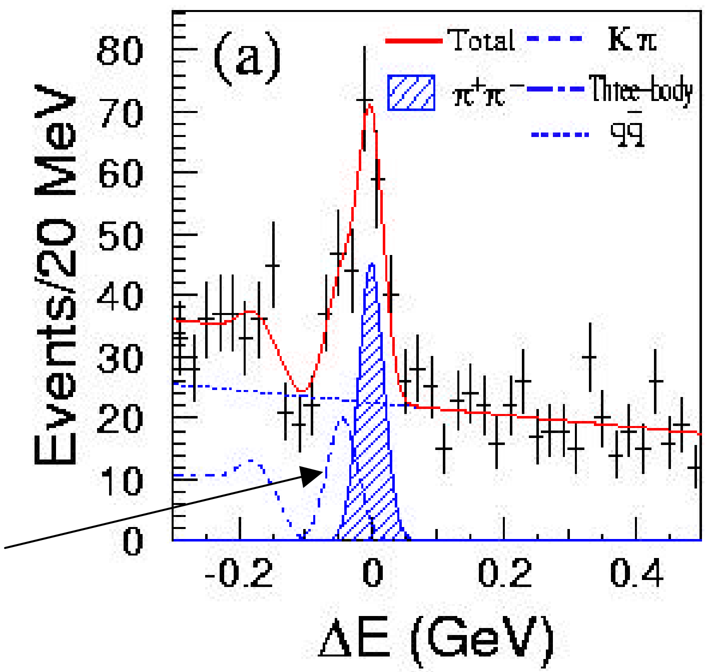


$\times f_K/\varepsilon_K = 45 \pm 3$

(fit)

$56\,^{+15}_{-14}$

ππ



How often are we outside ?

MC pseudo-experiments→ reasonable fraction if true values are close to the boundary.

$\rho_{\pi\pi}$ input	The fractions outside physical boundary(%)	The fraction above the CP violation we observe(%)
0.0	1.8	0.07
0.2	3.3	0.17
0.4	7.3	0.62
0.6	16.4	1.7
0.8	34.4	6.0
1.0	60.1	16.6

$$r = \sqrt{A_{pp}^2 + S_{pp}^2}$$