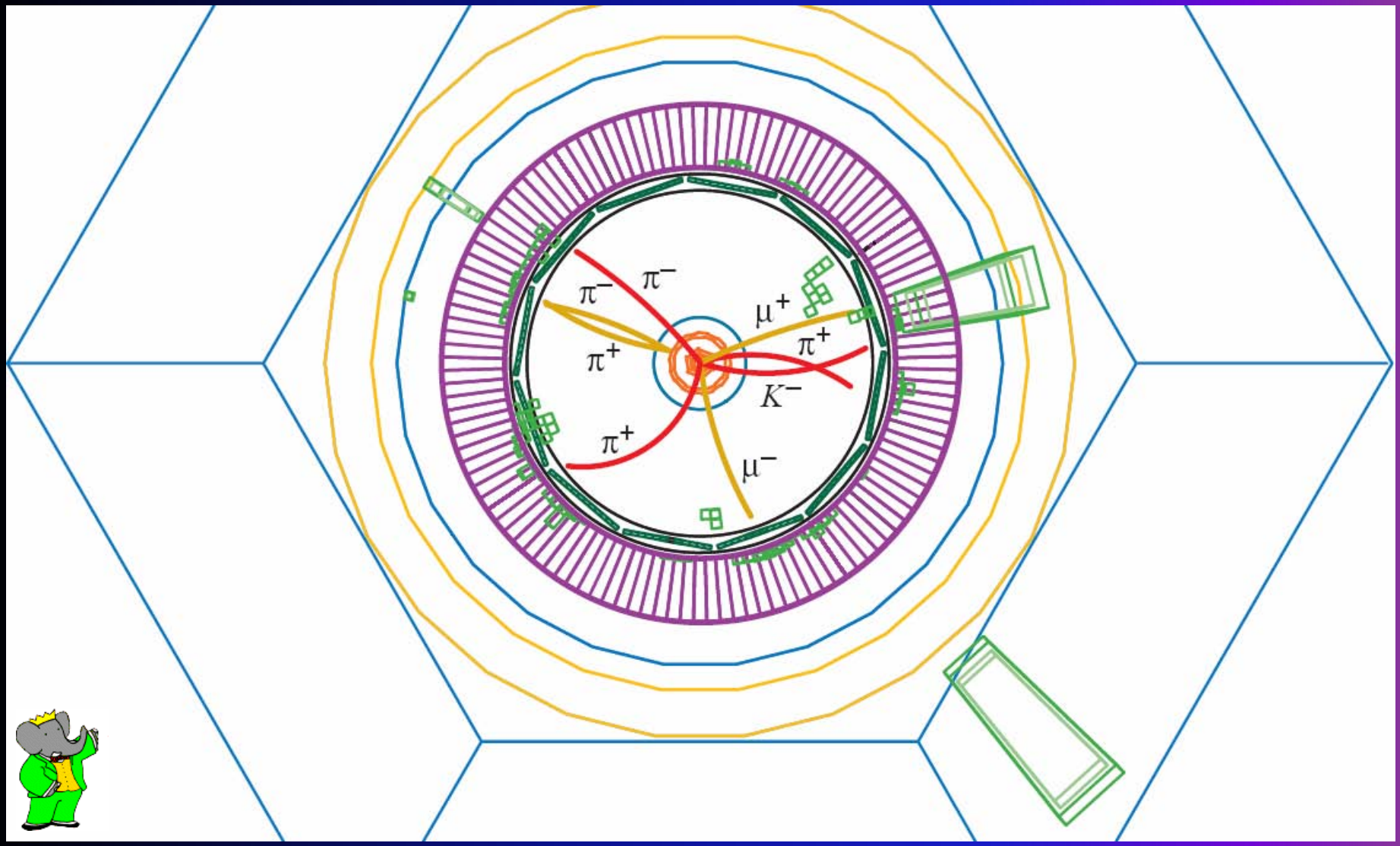
CP Violation in the *B* System: The Measurement of sin2β



The KM Model

1973 : M. **Kobayashi** and T. **Maskawa** realized the connection

CP violation $\Rightarrow$ third generation of quarks

u	**c**	**t**
d	**s**	**b**

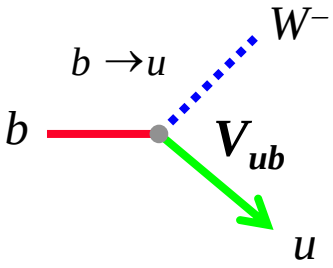
quark doublets

Cabibbo-Kobayashi-Maskawa matrix $\mathbf{V}$:

Transition matrix between quark- flavor and mass eigenstates

Couplings of the W boson to the flavor-changing charged quark currents

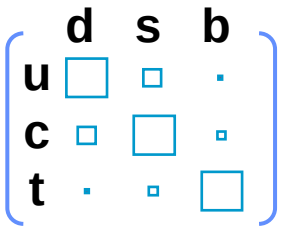
$$\mathbf{V} = \begin{pmatrix} V_{ud} & & \\ & V_{cs} & \\ & & V_{tb} \end{pmatrix}$$



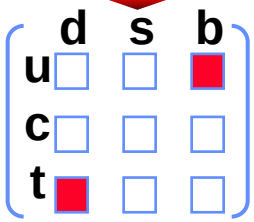
Complex matrix described by 4 independent real parameters (e.g. three angles, one phase)

usual phase convention: keep all elements real except the smallest two

Wolfenstein parametrization: $\lambda \sim 0.22 \quad A \sim 0.83$



$$\mathbf{V} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$



CP violation in the Standard Model $\Leftrightarrow$ $\eta \neq 0$

The Unitarity Triangle

The CKM Matrix is complex and unitary

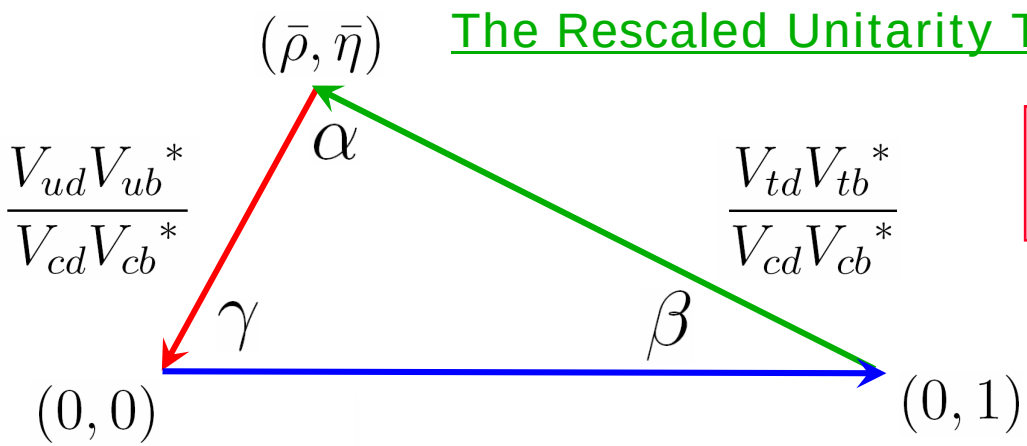
$$\begin{pmatrix} V_{ud}^* & V_{cd}^* & V_{td}^* \\ V_{us}^* & V_{cs}^* & V_{ts}^* \\ V_{ub}^* & V_{cb}^* & V_{tb}^* \end{pmatrix} \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

9 unitarity relations

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

useful representation of the unitarity of the CKM matrix (consistency of the KM model)

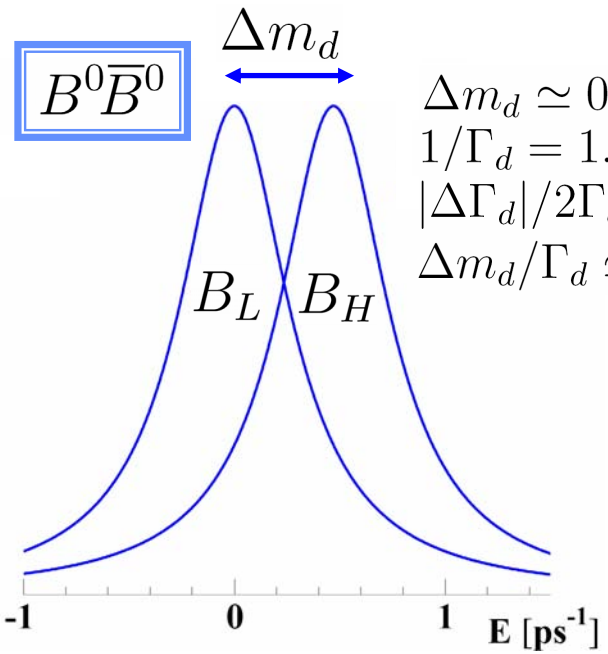
The Rescaled Unitarity Triangle



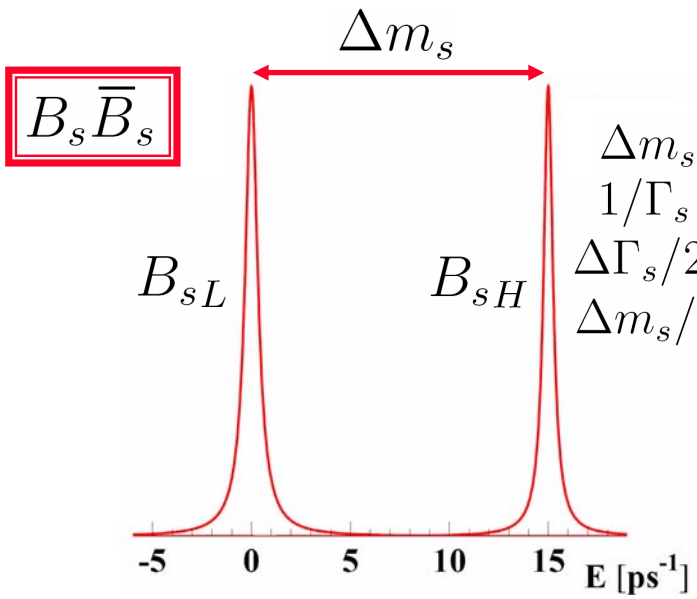
CP Violation $\Leftrightarrow$ $\gamma \neq 0$ or π
$\propto$ area of the Triangle

Experimentally: constraints on the coordinates of the apex of the Rescaled Triangle in the complex plane

The Neutral B Meson Systems



$\Delta m_d \simeq 0.5\,\mathrm{ps}^{-1}$
$1/\Gamma_d = 1.56\,\mathrm{ps}$
$|\Delta\Gamma_d|/2\Gamma_d \ll 1$
$\Delta m_d/\Gamma_d \simeq 0.75$



$\Delta m_s > 14\,\mathrm{ps}^{-1}$
$1/\Gamma_s = 1.47\,\mathrm{ps}$
$\Delta\Gamma_s/2\Gamma_s \approx -0.10$
$\Delta m_s/\Gamma_s \sim 20 - 40$

Mixing Parameters of B Systems

Empirically, for both B systems

$$\begin{cases} |\Gamma_{12}| \ll |M_{12}| \\ \Delta\Gamma \ll \Delta m \end{cases}$$

★ $$(\Delta m)^2 - \frac{1}{4}(\Delta\Gamma)^2 = 4|M_{12}|^2 - |\Gamma_{12}|^2$$ ➡ $$\boxed{\Delta m \simeq 2\,|M_{12}|}$$

★ $$\Delta m\,\Delta\Gamma = 4\mathrm{Re}(\Gamma_{12}^* M_{12})$$

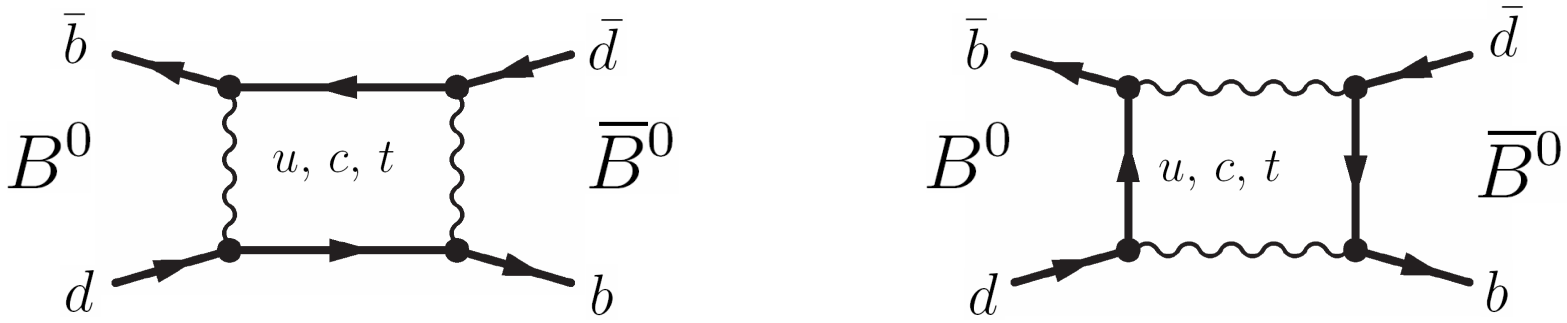
➡ $$\boxed{\Delta\Gamma \simeq 2\,\frac{\mathrm{Re}(\Gamma_{12}^* M_{12})}{|M_{12}|} = 2\,|M_{12}|\,\mathrm{Re}\left(\frac{\Gamma_{12}}{M_{12}}\right)}$$

★ $$\frac{q}{p} = -2\,\frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{\Delta m - \frac{i}{2}\Delta\Gamma}$$

➡ $$\boxed{\frac{q}{p} \simeq -\frac{M_{12}^*}{|M_{12}|}\left[1 + \frac{1}{2}\,\frac{\mathrm{Im}(\Gamma_{12}^* M_{12})}{|M_{12}|^2}\right] = -\frac{M_{12}^*}{|M_{12}|}\left[1 - \frac{1}{2}\,\mathrm{Im}\left(\frac{\Gamma_{12}}{M_{12}}\right)\right]}$$

again one finds the condition for no CP violation in mixing: $\mathrm{Im}(\Gamma_{12}^* M_{12}) = 0$

Standard Model Predictions



$$\boxed{M_{12}^d \simeq -\underbrace{\frac{G_F^2 m_W^2}{12\pi^2}\, m_B}_{\text{known}} \times \underbrace{\eta_B\, S_0(m_t^2/m_W^2)}_{\text{calculable perturbatively}} \times \underbrace{\left(f_B^2 B_B\right)}_{\text{non perturbative}} \times \underbrace{\left(V_{tb}V_{td}^*\right)^2 e^{-2i\xi_B}}_{\text{weak phase}}}$$

with $S_0(m_t^2/m_W^2) \approx 0.55 \times m_t^2/m_W^2$ and $\eta_B \approx 0.6$

In contrast to the neutral kaon system, the common decay states are only a small fraction all B decays, and they contribute with alternating signs

In the SM, Γ_{12} can be approximated by the absorptive part of the box diagram

$$\boxed{\frac{\Gamma_{12}^d}{M_{12}^d} \simeq -\frac{3\pi}{2\, S_0(m_t^2/m_W^2)}\, \frac{m_b^2}{m_W^2} \left(1 + \frac{8}{3}\, \frac{m_c^2}{m_b^2}\, \frac{V_{cb}V_{cd}^*}{V_{tb}V_{td}^*}\right)}$$

Width Difference

$$\frac{\Delta\Gamma}{\Delta m} \simeq \mathrm{Re}\left(\frac{\Gamma_{12}}{M_{12}}\right) \propto -\frac{3\pi}{2}\frac{m_b^2}{m_t^2} \sim -3\times 10^{-3}$$

a recent complete calculation gives

$$\frac{\Delta\Gamma_d}{\Gamma_d} \approx -0.3\%$$

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using $\Delta m_d \simeq 0.72\Delta\Gamma_d$ one gets

$$\frac{\Delta\Gamma_d}{\Gamma_d} \approx -4\times 10^{-3}$$

(order of magnitude)

The ratio $\Delta\Gamma/\Delta m$ is independent from CKM factors, and ~ applies to both B^0 and B_s systems

$$\Gamma_s \sim \Gamma_d \quad \Rightarrow \quad \frac{\Delta\Gamma_s}{\Gamma_s} \sim \left(\frac{\Delta m_s}{\Delta m_d}\right)\frac{\Delta\Gamma_d}{\Gamma_d}$$

not necessarily small

very small

can be large (>40)

Note: in B_s system, common final states are *not* Cabibbo-suppressed

Conclusion

$\Delta\Gamma_d$ is a very small quantity and can be safely neglected in most calculations

$\Delta\Gamma_s$ can be as large as 5-10%, and needs to be taken into account

Indirect CP Violation

define

$$\delta_d \equiv \frac{1-|q/p|^2}{1+|q/p|^2} = \frac{2\,\mathrm{Re}\,\varepsilon_B}{1+|\varepsilon_B|^2}$$

null is CP is conserved in mixing

In the Standard Model, one gets

$$\delta_d \simeq \frac{1}{2}\,\mathrm{Im}\left(\frac{\Gamma_{12}}{M_{12}}\right) \simeq -4\pi\,\frac{m_c^2}{m_t^2}\,\frac{R_c}{R_t}\,\sin\beta$$

$$\delta_d \sim -5\times 10^{-4}$$

order of magnitude !
not a way
to measure $\sin\beta$!

δ_s is further suppressed by a factor $|V_{td}/V_{ts}|^2 \sim 10^{-2}$

Therefore, for both systems, expect very small effects of CP violation in mixing

to an excellent approximation

$$\frac{q}{p} \simeq -\frac{M_{12}^*}{|M_{12}|} = -e^{-i\varphi_M}$$

where φ_M is the mixing phase

More Parameterizations

The usual Wolfenstein parameterization at order $\mathcal{O}(\lambda^4)$

$$V_{CKM} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-(\rho+i\eta)) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

This is good enough for the B0 system, but not for the Bs system

$$V_{CKM} = \begin{pmatrix} 1-\lambda^2/2 \boxed{-\lambda^4/8} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda \boxed{-A^2\lambda^5(\rho+i\eta-1/2)} & 1-\lambda^2/2 \boxed{-(1/8+A/2)\lambda^4} & A\lambda^2 \\ A\lambda^3(1-(\rho+i\eta)\boxed{(1-\lambda^2/2)}) & -A\lambda^2 \boxed{-A\lambda^4(\rho+i\eta-1/2)} & 1 \boxed{-A^2\lambda^4/2} \end{pmatrix} + \mathcal{O}(\lambda^6)$$

(one possible parameterization)

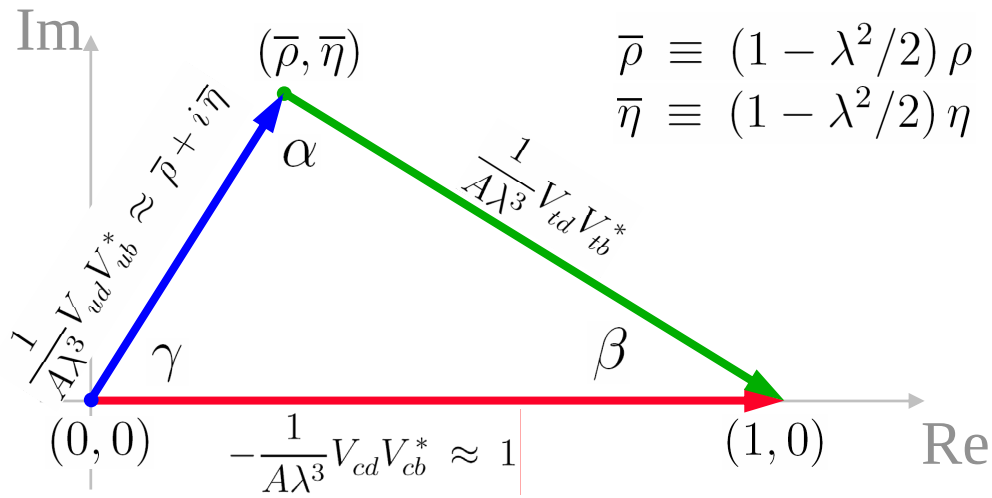
Unitarity Triangle(s)

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

$$\beta \equiv \arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right]$$

$$\gamma \equiv \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right]$$

$$\alpha \equiv \pi - \beta - \gamma$$

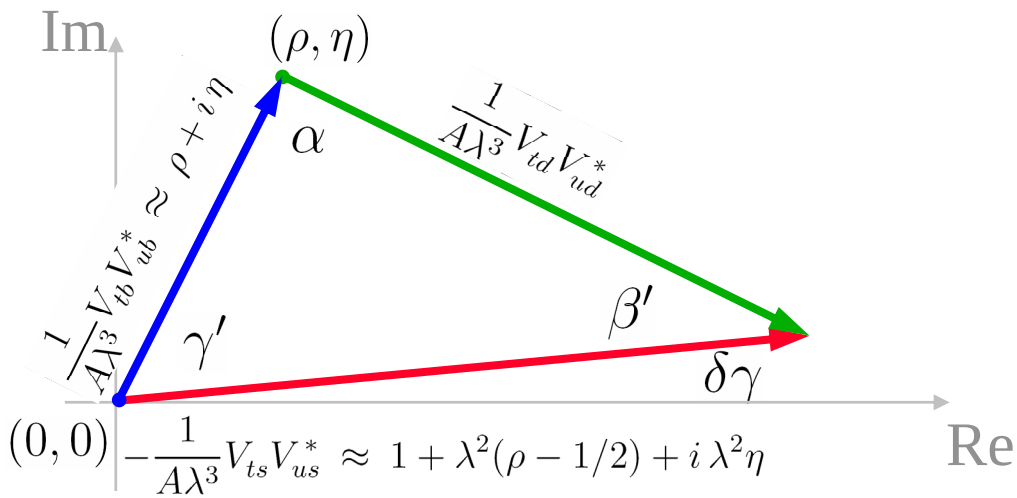


★ $$V_{td}V_{ud}^* + V_{ts}V_{us}^* + V_{tb}V_{ub}^* = 0$$

$$\delta\gamma \approx \lambda^2\eta \sim \mathcal{O}(10^{-2})$$

$$\beta' \approx \beta + \delta\gamma$$

$$\gamma' \approx \gamma - \delta\gamma$$

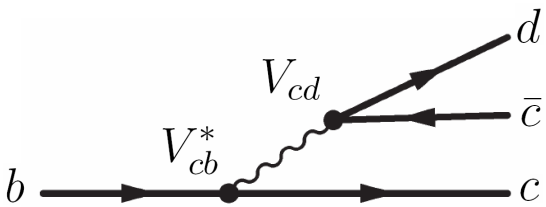


Mixing Phase

The base of the Unitarity Triangle

$$V_{cd}V_{cb}^* = R_c\, e^{i\,\phi_{c\bar{c}d}}$$

$$R_c \approx A\lambda^3$$



usual phase convention (Wolfenstein)

$$\phi_{c\bar{c}d} = \pi + \mathcal{O}(\lambda^4) \simeq \pi$$

In the B systems, to a very good approximation

$$\left(\frac{q}{p}\right)_{q=d,s} \simeq -\frac{M_{12}^*}{|M_{12}|} = \frac{V_{tq}V_{tb}^*}{V_{tq}^*V_{tb}}\, e^{2i\xi_B}$$

therefore q/p is a pure phase, with

$$\arg\left[(q/p)_{q=d,s}\right] \simeq -2\,\phi_M^q + 2\,\phi_{c\bar{c}d} + 2\,\xi_B$$

$$\begin{cases} \phi_M^d = \beta & \text{(large)} \\ \phi_M^s = -\delta\gamma & \text{(very small)} \end{cases}$$

CKM phase convention

CP phase convention

Case of a CP Eigenstate

Consider the decay $B^0 \to f_{CP}$

$$\langle f_{CP}|H|\overline{B}^0\rangle = \sigma_{f_{CP}}\, e^{-2i\xi_B} \frac{\langle f_{CP}|(CP)H(CP)^\dagger|B^0\rangle}{\langle f_{CP}|H|B^0\rangle} \langle f_{CP}|H|B^0\rangle$$

$\langle f_{CP}|(CP)H(CP)^\dagger|B^0\rangle$ is obtained from $\langle f_{CP}|H|B^0\rangle$ by complex-conjugating the CKM matrix elements

e.g. $(V_{cb}V_{cd}^*) \mapsto (V_{cb}^*V_{cd})$

$$\Rightarrow \quad \frac{\overline{A}_{f_{CP}}}{A_{f_{CP}}} = \sigma_{f_{CP}}\, e^{-2i\xi_B}\, e^{-2i\phi_{c\bar{c}d}} \frac{\sum_j a_j e^{i\delta_j} e^{-i\phi_j}}{\sum_j a_j e^{i\delta_j} e^{+i\phi_j}}$$

the ϕ_j are weak phases relative to $V_{cd}V_{cb}^*$

and:

$$\lambda_{f_{CP}} = \sigma_{f_{CP}}\, e^{-2i\,\phi_M} \frac{\sum_j a_j e^{i\delta_j} e^{-i\phi_j}}{\sum_j a_j e^{i\delta_j} e^{+i\phi_j}}$$

$$\begin{cases} \phi_M = \beta & \text{for } B^0 \text{ decays} \\ \phi_M = -\delta\gamma & \text{for } B_s \text{ decays} \end{cases}$$

case of a dominating amplitude with weak phase $\phi_{f_{CP}}$

$$\lambda_{f_{CP}} = \sigma_{f_{CP}}\, e^{-2i\,(\phi_M - \phi_{f_{CP}})} \quad \Rightarrow \quad \begin{cases} |\,\lambda_{f_{CP}}\,| = 1 \\ \mathrm{Im}\,\lambda_{f_{CP}} = -\,\sigma_{f_{CP}}\, \sin 2(\phi_M - \phi_{f_{CP}}) \end{cases}$$

Three Types of *CP* Violation

★ *CP* violation in *B* mixing (known as indirect *CP* violation)

$$\{|B_L\rangle, |B_H\rangle\} \neq \{|B^0_{CP=+1}\rangle, |B^0_{CP=-1}\rangle\} \Longleftrightarrow \boxed{\left|\frac{q}{p}\right| \neq 1}$$

negligible in SM

★ *CP* violation in the decay (known as direct *CP* violation)

$$\boxed{\begin{gathered} C_{f_{CP}} = \frac{1-|\lambda_{f_{CP}}|^2}{1+|\lambda_{f_{CP}}|^2} \neq 0 \\ \Leftrightarrow |A_{f_{CP}}| \neq |\bar{A}_{f_{CP}}| \end{gathered}}$$

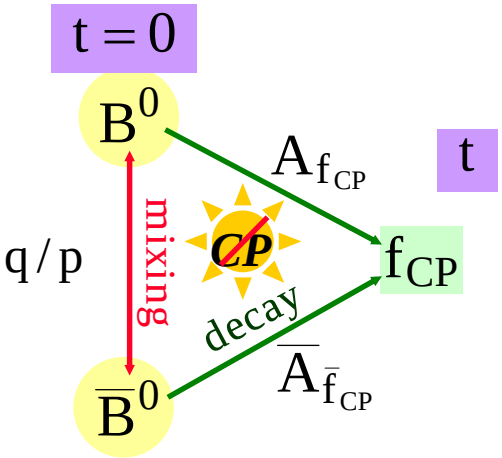
interfering decay amplitudes with different weak and strong phases

(only type of *CP* violation for charged modes)

★ *CP* violation in the interference of the decays with and without mixing (known as mixing-induced *CP* violation)

$$\boxed{\begin{gathered} S_{f_{CP}} = \frac{2\mathrm{Im}\lambda_{f_{CP}}}{1+|\lambda_{f_{CP}}|^2} \neq 0 \\ \Leftrightarrow \arg\lambda_{f_{CP}} \neq 0, \pi \end{gathered}}$$

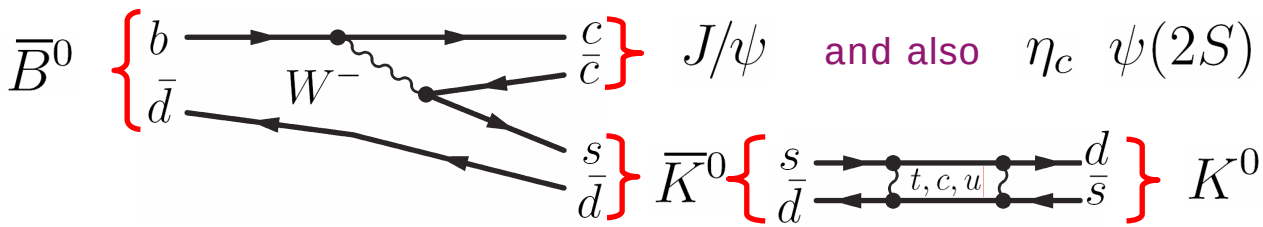
(not only for *CP* modes)



The Golden Channel

★ interference between $B^0 \to J/\psi K^0$ and $\overline{B}^0 \to J/\psi \overline{K}^0$

possible thanks to $K^0\overline{K}^0$ mixing



$$\sigma_{J/\psi K^0_S} = -1$$
$$\sigma_{J/\psi K^0_L} = +1$$

$$\lambda_{J/\psi K^0_{S,L}} = \sigma_{J/\psi K^0_{S,L}} \left(\frac{q}{p}\right)_d \left(\frac{V_{cb}V_{cs}^*}{V_{cb}^*V_{cs}}\right) \left(\frac{q}{p}\right)_K$$

$$= \mp \underbrace{\left(\frac{V_{tb}V_{td}^*}{V_{tb}^*V_{td}}\right)}_{B^0 \text{ mixing}} \underbrace{\left(\frac{V_{cb}V_{cs}^*}{V_{cb}^*V_{cs}}\right)}_{\text{Decay}} \underbrace{\left(\frac{V_{cs}V_{cd}^*}{V_{cs}^*V_{cd}}\right)}_{K^0 \text{ mixing}}$$

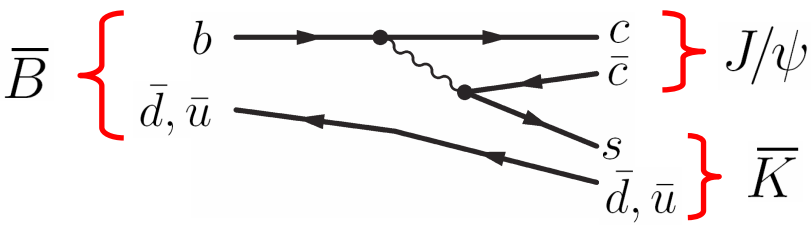
$$\lambda_{J/\psi K^0_{S,L}} = \mp e^{-2i\beta}$$

$$a^{CP}_{J/\psi K^0_{S,L}} = \pm \sin 2\beta \, \sin(\Delta m_d t)$$

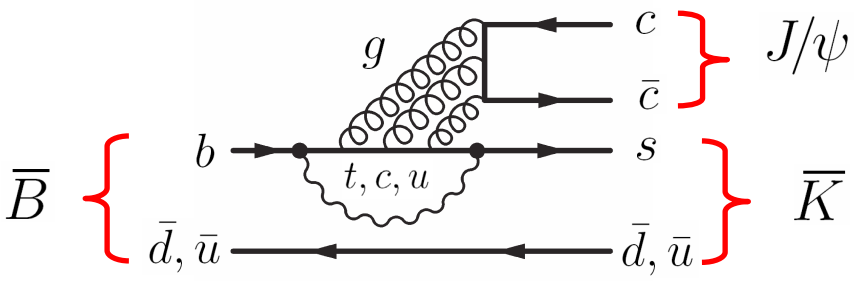
- theoretically clean way to measure sin2β
- clear exp. signatures
- relatively large BF

Golden Channel: $B \to J/\psi K_{S,L}$

- Question: Why "theoretically clean"?
- Main contributing amplitudes



Dominant diagram:
color-suppressed tree



Gluonic penguin diagam

leading Penguin contribution
has same weak phase as Tree

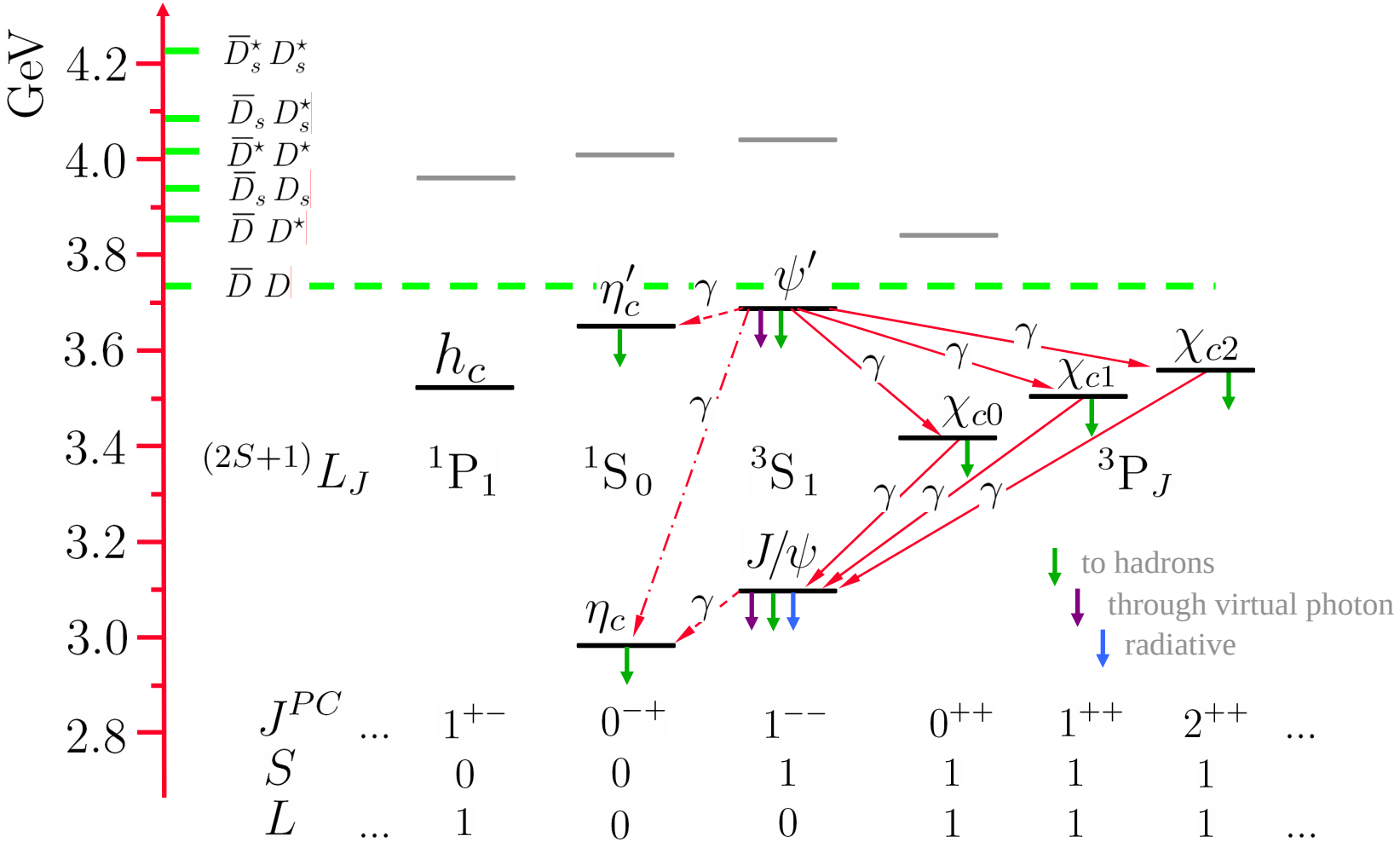
$$\mathcal{A}(\overline{B} \to J/\psi\, \overline{K}) = V_{cb}V_{cs}{}^{*}(T + P^{(c)} - P^{(t)}) + \underbrace{V_{ub}V_{us}{}^{*}(P^{(u)} - P^{(t)})}_{\propto \lambda^2 \times \text{small}}$$

$$\left|\frac{\overline{A}_{J/\psi\, K_S^0}}{A_{J/\psi\, K_S^0}}\right| - 1 \lesssim 10^{-2}$$

Answer: in SM expect very little direct *CP* violation

(but independent experimental checks are needed)

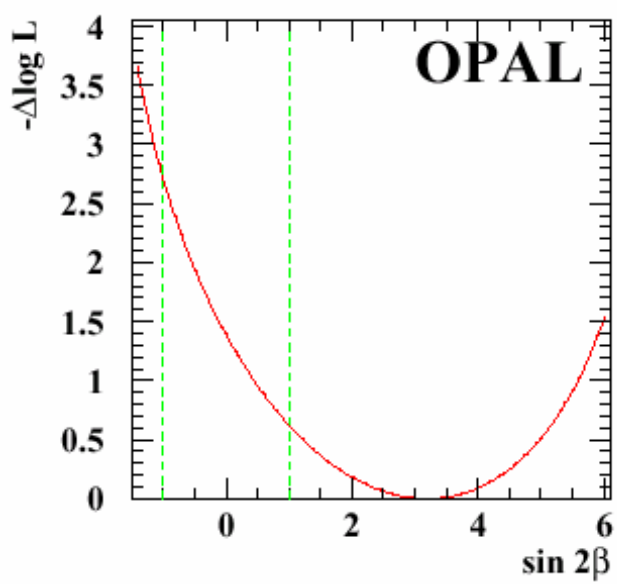
The Charmonium System

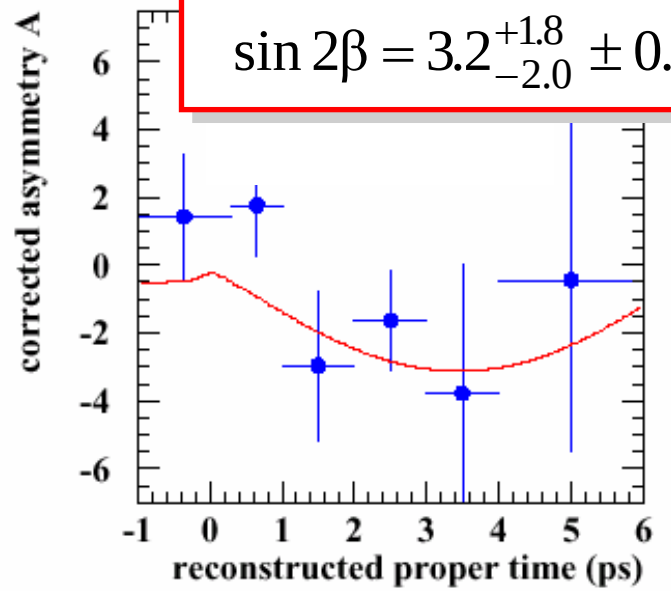


Early Measurements of sin2β

At LEP

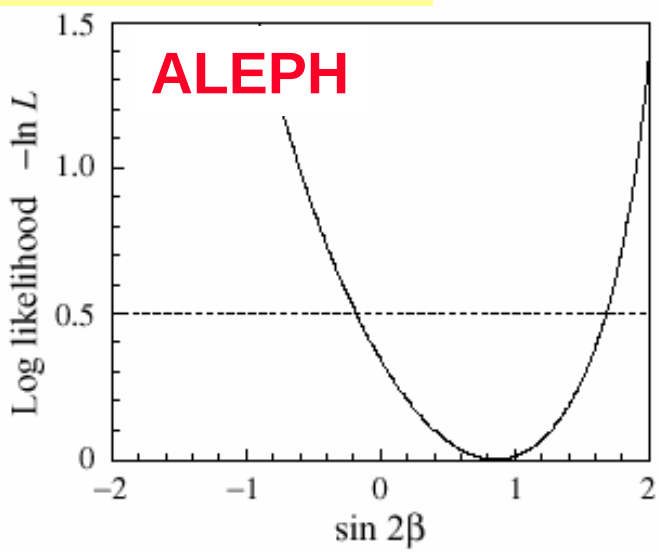
OPAL EPJ **C**5 (1998)

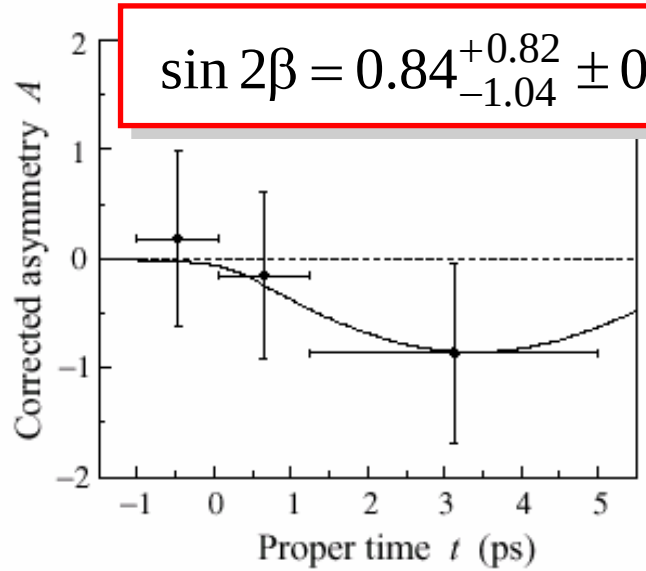




$$\sin 2\beta = 3.2^{+1.8}_{-2.0} \pm 0.5$$

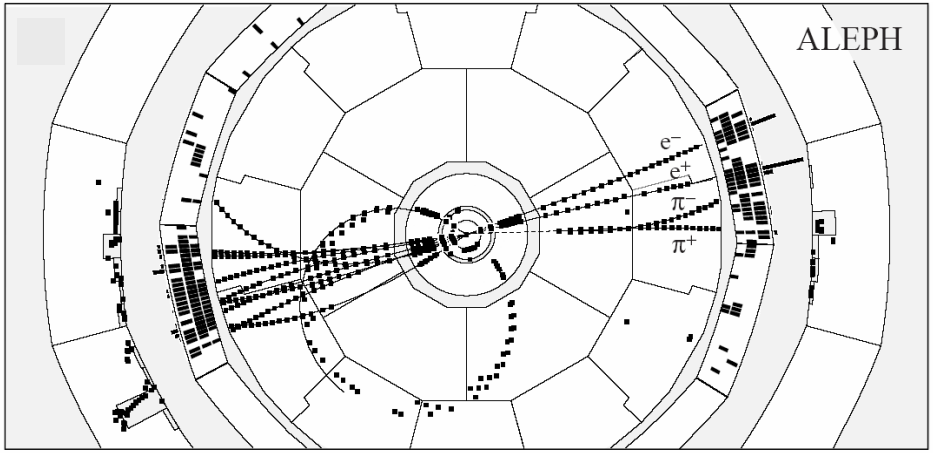
ALEPH PL 492 (2000)

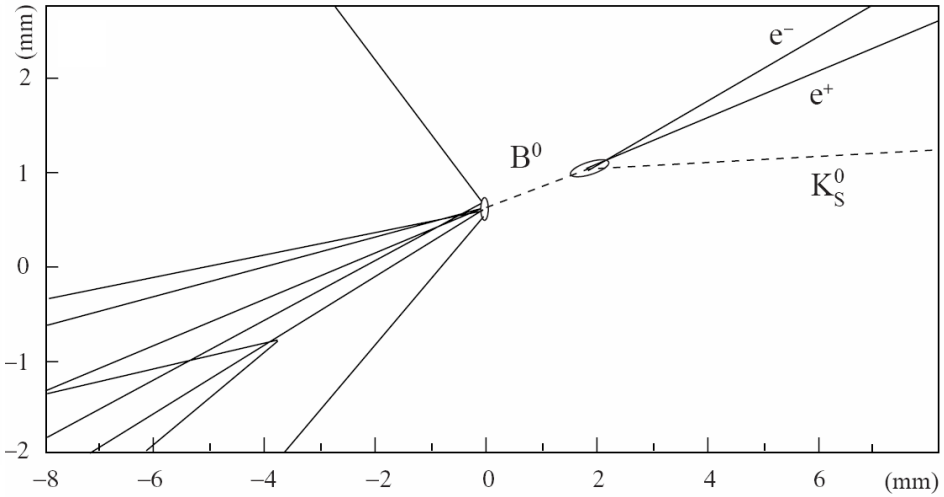


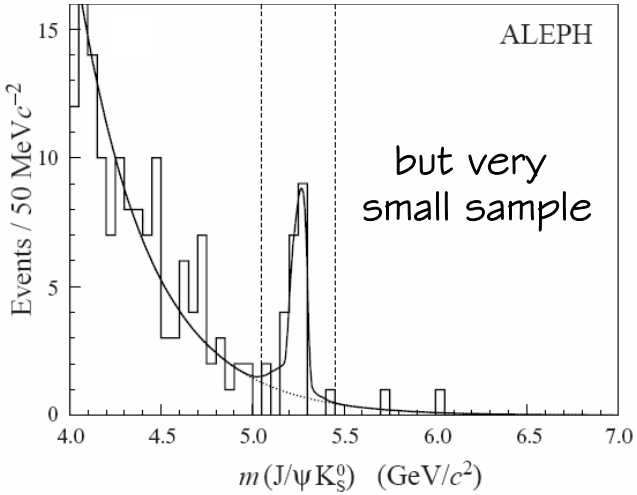


$$\sin 2\beta = 0.84^{+0.82}_{-1.04} \pm 0.16$$

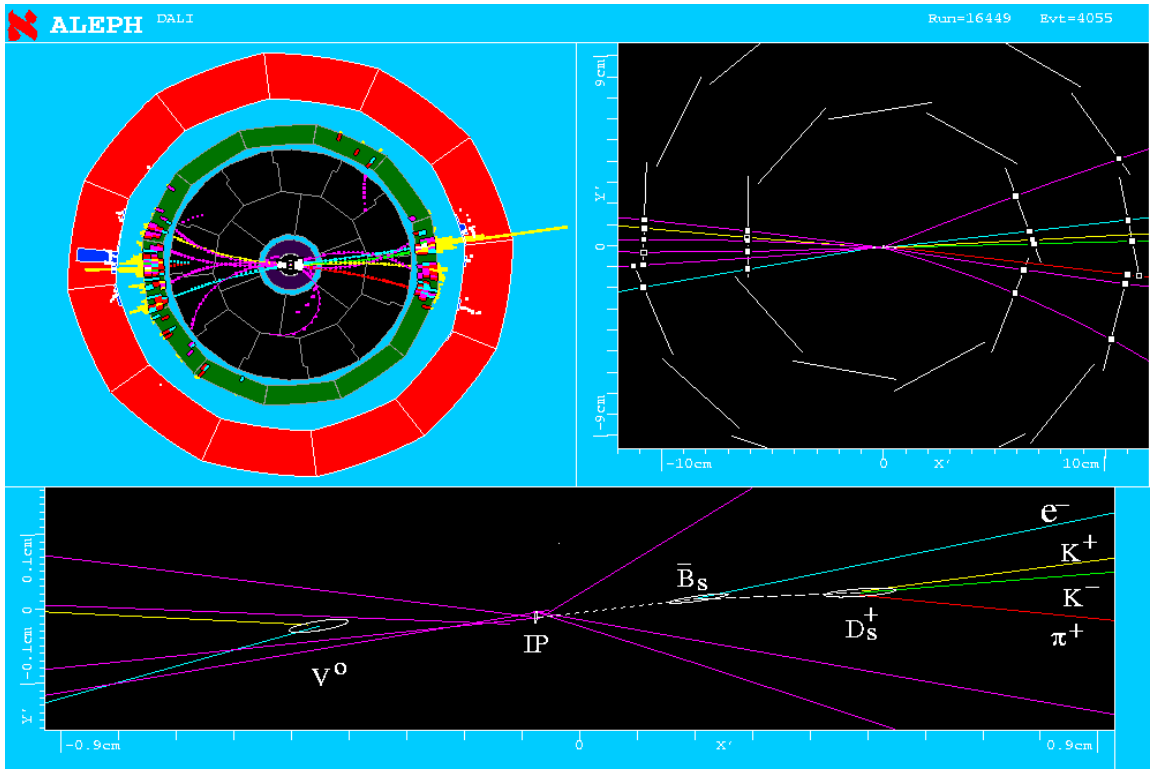
ALEPH: a J/ψ Ks Candidate







but very small sample



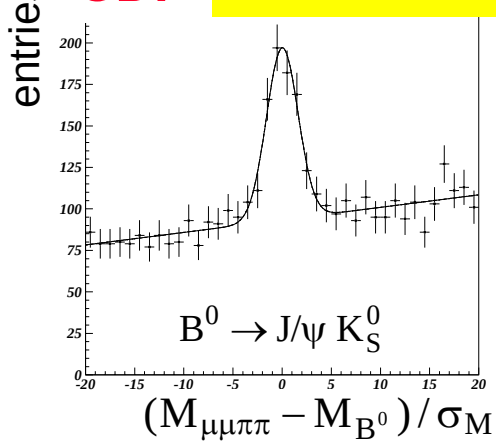
At the Z, also access to the Bs physics

At the Tevatron

CDF Run 1 (110 pb^{-1})

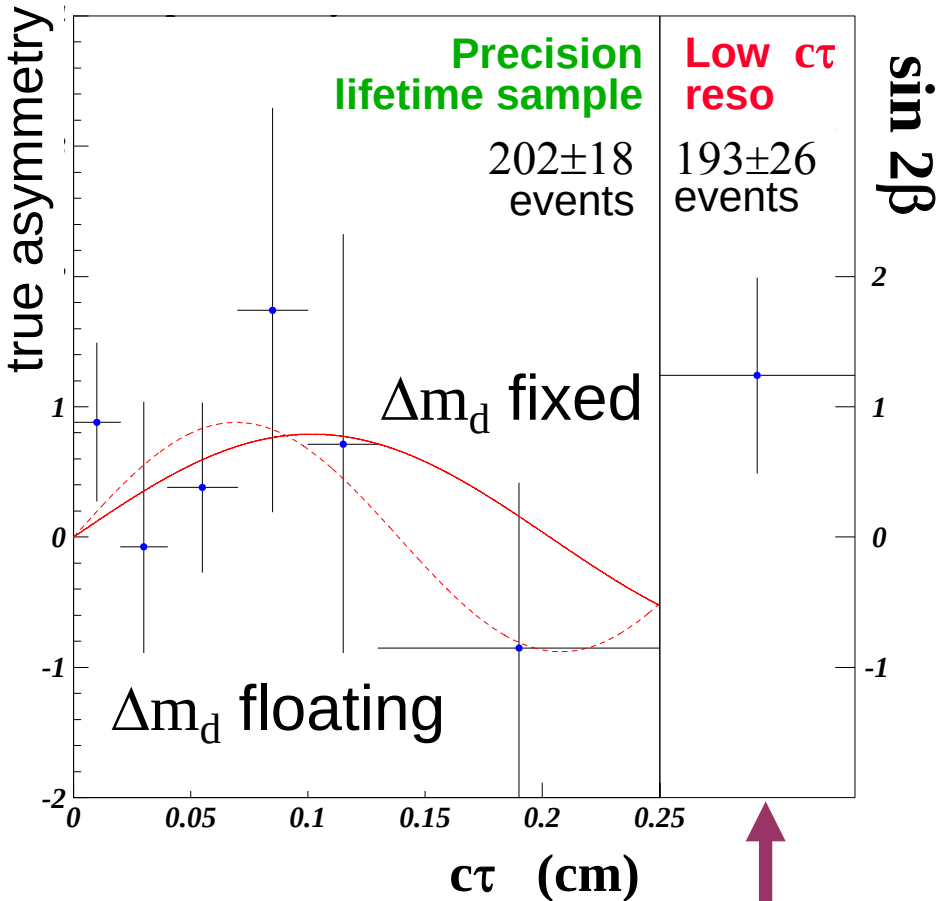
$$\sin 2\beta = 0.79 \pm 0.39 \pm 0.16$$

CDF ~400 events



Time-dependent <u>and</u> time-integrated meas.

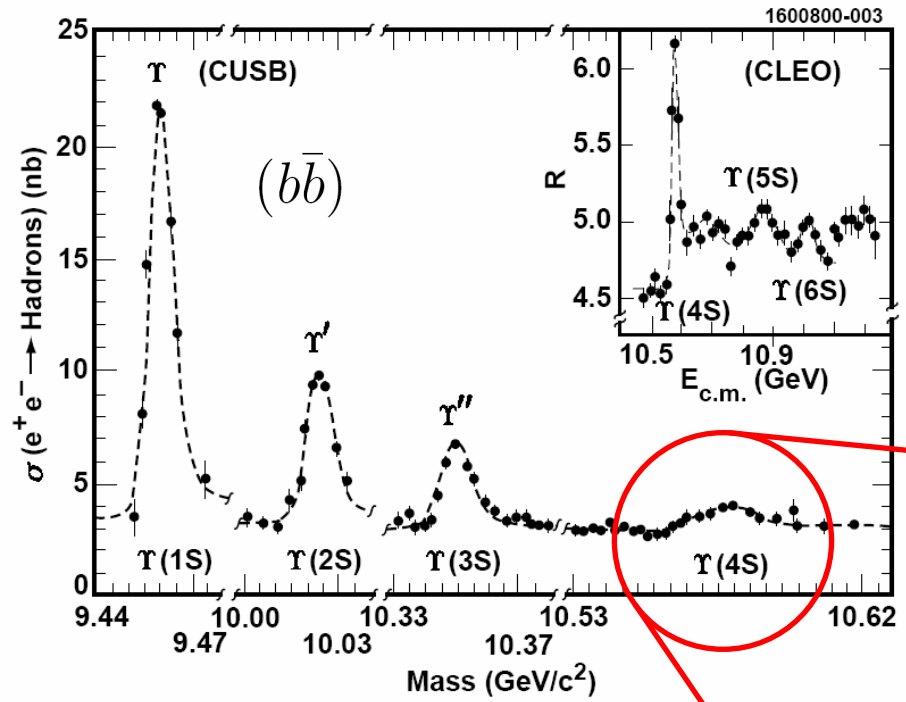
CDF PR **D**61 (2000)



$$A^{int}_{J/\psi K^0_S} = -\frac{x_d}{1+x_d}\sin 2\beta \approx -0.47 \sin 2\beta$$

Physics at the Y(4S)

The Y(4S) Region



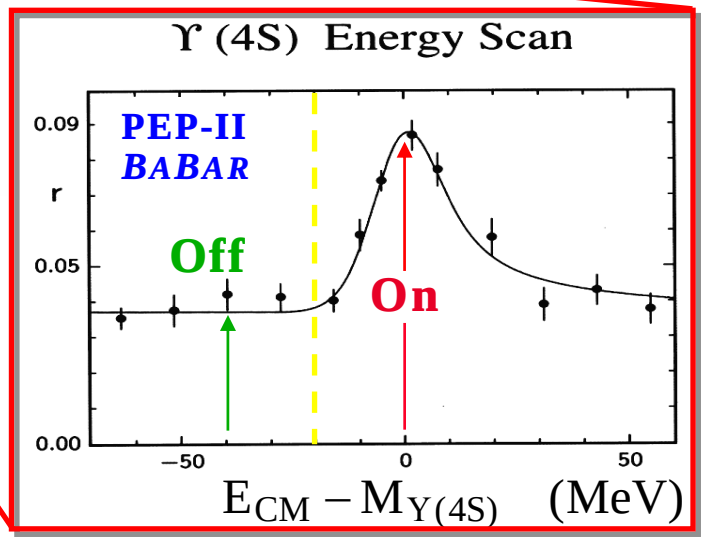
The cleanest way
to produce B mesons

e^+e^- collisions around
$\sqrt{s} = 10.58\,\text{GeV}$

production of $B\overline{B}$ pairs
with a cross section of 1.1 nb
over a continuum of ~3 nb

$b\bar{b}$	$\approx 1.1\,\text{nb}$
$c\bar{c}$	$\approx 1.3\,\text{nb}$
$d\bar{d},\ s\bar{s}$	$\approx 0.3\,\text{nb}$
$u\bar{u}$	$\approx 1.4\,\text{nb}$

$50\%/50\%$
B^+B^- & $B^0\overline{B}^0$

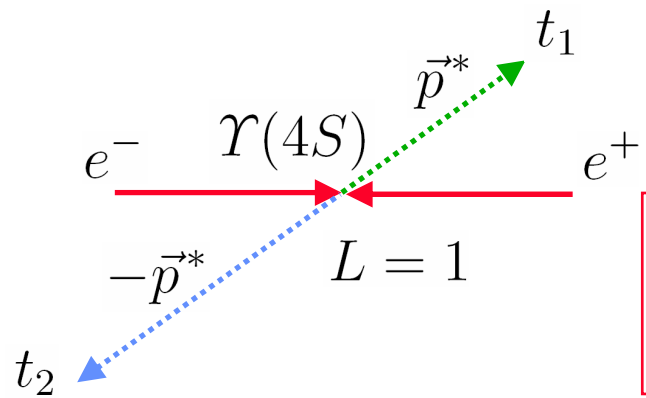


Quantum Mechanics of the Υ(4S)

$$e^+e^- \to \underset{J^{PC}=1^{--}}{\Upsilon(4S)} \to B^0\overline{B}^0$$

two pseudoscalar bosons in a P-wave

➡ antisymmetric wave function



proper times

$$t \equiv \frac{t_1+t_2}{2}$$
$$\Delta t \equiv t_2 - t_1$$

★ initial state

$$|\Upsilon(4S)\to B^0\overline{B}^0\rangle \sim |B^0,\vec{p}^*\rangle|\overline{B}^0,-\vec{p}^*\rangle - |\overline{B}^0,\vec{p}^*\rangle|B^0,-\vec{p}^*\rangle$$
$$\sim |B_H,\vec{p}^*\rangle|B_L,-\vec{p}^*\rangle - |B_L,\vec{p}^*\rangle|B_H,-\vec{p}^*\rangle$$

★ double proper-time wave function

$$|\{\Upsilon(4S)\to B\overline{B}^0)\}_{\rm phys}(t,\Delta t)\rangle$$
$$\sim e^{-2i\omega t}\left[e^{+i\Delta\omega\Delta t/2}|B_H,\vec{p}^*\rangle|B_L,-\vec{p}^*\rangle - e^{-i\Delta\omega\Delta t/2}|B_L,\vec{p}^*\rangle|B_H,-\vec{p}^*\rangle\right]$$

with $\omega = M - \frac{i}{2}\Gamma$ and $\Delta\omega = \Delta m - \frac{i}{2}\Delta\Gamma$

Quantum Coherence

quantum coherence (due to synchronous evolution)

for $\Delta t = 0$ the system is the superposition of

$$\left\{ \begin{array}{c} \text{one } B^0 \text{ one } \overline{B}^0 \\ \text{one } B_{CP=+1} \text{ one } B_{CP=-1} \\ \text{one } B_H \text{ one } B_L \end{array} \right.$$

an EPR situation

the measure of the flavor (or CP) of one meson (e.g. from its decay products) determines the flavor (or CP) at the same proper time (it is opposite)

this property is exploited for B flavor tagging

For the study of time evolution, one needs to measure Δt

$p^* = 340\,\mathrm{MeV}/c$
$(\beta\gamma)^* = 0.064$

flight distance
$\mathrm{d}^* \sim 30\,\mu\mathrm{m}$

beyond experimental reach

In the Y(4S) CoM frame, only time integrated measurements are possible

even with infinite resolution, only t can be measured since the actual position of the Y(4S) in the luminous region is not known

Time-Integrated Measurements

Because Δt is an algebraic quantity, only Δt -even quantities can be obtained with a time-integrated measurement

★ Flavor mixing is Δt -even

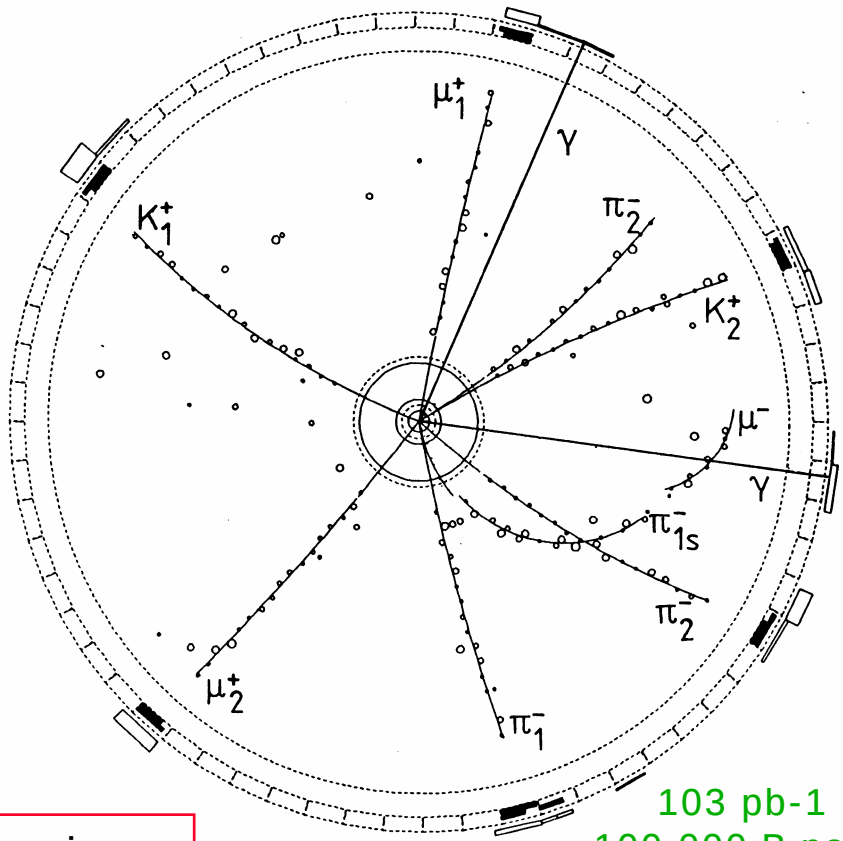
$$a_{\mathrm{mix}}(\Delta t) \sim \cos(\Delta m \Delta t)$$

➡ a time-integrated measurement is possible

★ *CP* asymmetries are Δt -odd

$$a^{CP}(\Delta t) \sim \sin(\Delta m \Delta t)$$

➡ $$\int_{-\infty}^{+\infty} a^{CP}(\Delta t) d\Delta t = 0$$



103 pb-1
100,000 B pairs

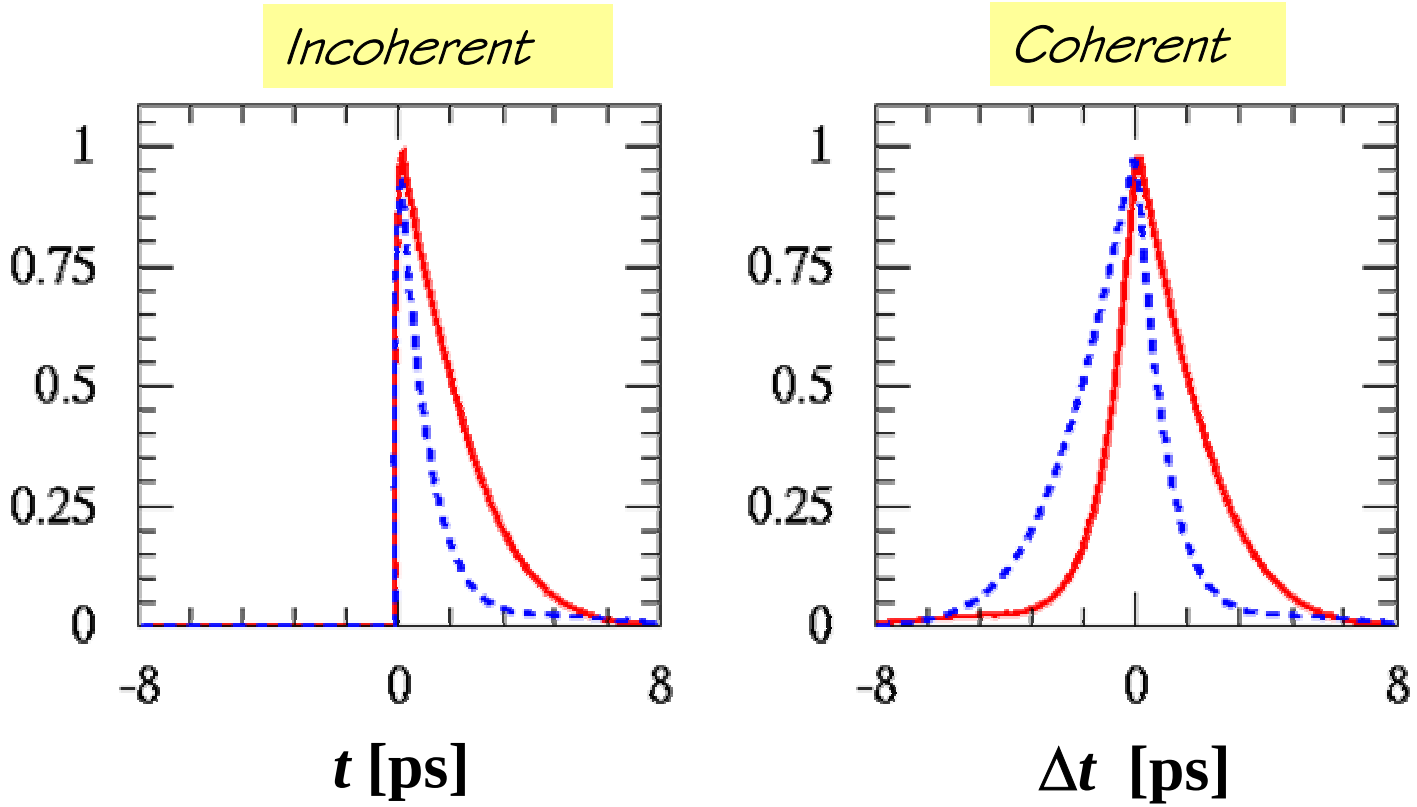
ARGUS, 1987
Discovery of BB mixing
$\chi_d = 0.17 \pm 0.05$

Time-dependent *CP* studies at the Υ(4S) require:

➡ the measurement of Δt

➡ of the order of 100 million B mesons (or more)

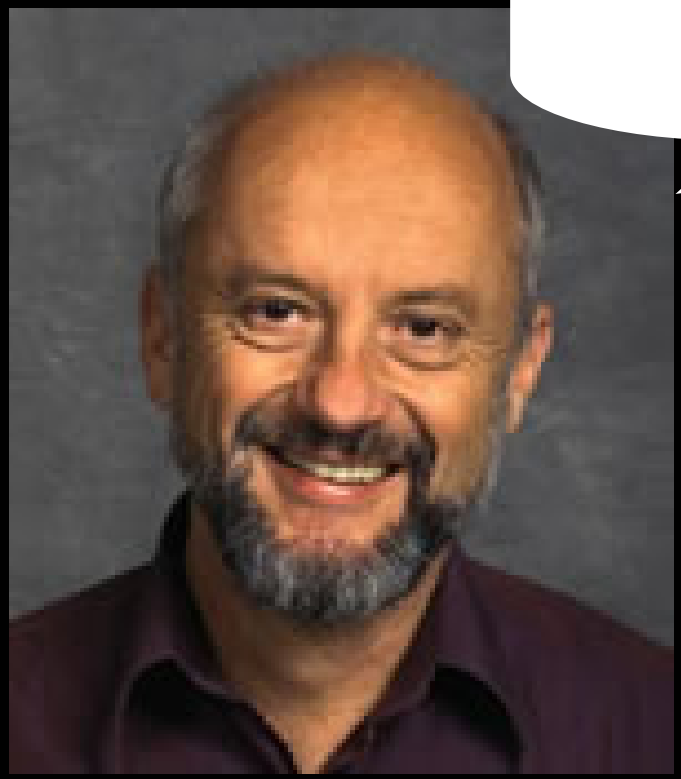
Evolution for $B^0(\bar{B}^0)$ state at $t_{CP} = 0$



For coherent source, integrated asymmetry is zero: must do a time-dependent analysis

Oddone's Clever Idea (1987)

why not produce the Y(4S) with a boost?
One could deduce the Δt from the **distance between the two B vertices along the boost axis.**
What we need is a **beam-energy asymmetric B Factory** with luminosity of order 5×10^{33}



Pier Oddone, Berkeley Lab

Duh!
Who's that guy?
It's a **theorist idea!**

But Pier is an **experimentalist**

Then he's even **crazier than a theorist!**

quoted by Tony Sanda

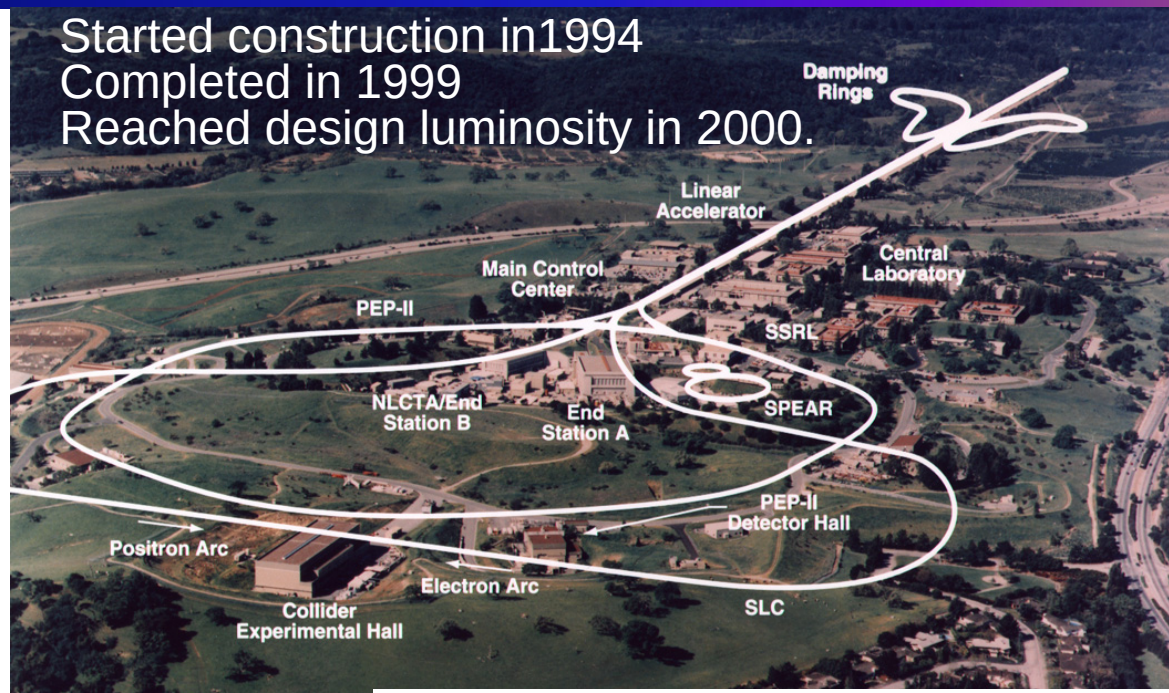
10 years later, two asymmetric B Factories :
PEP-II at SLAC and KEK-B at KEK...

PEP II/*BABAR* at SLAC

Stanford Linear Accelerator Center

PEP II
Asymmetric
B Factory

Started construction in1994
Completed in 1999
Reached design luminosity in 2000.

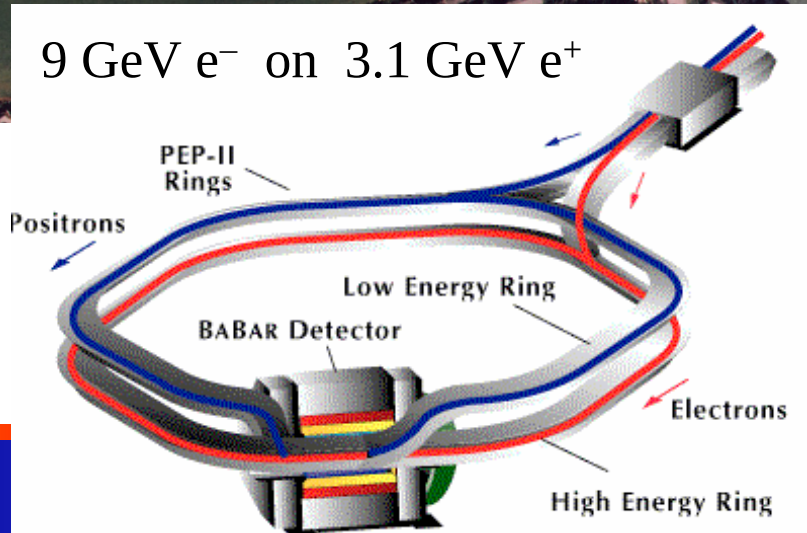


Luminosity records
(as of May 26, 2003)

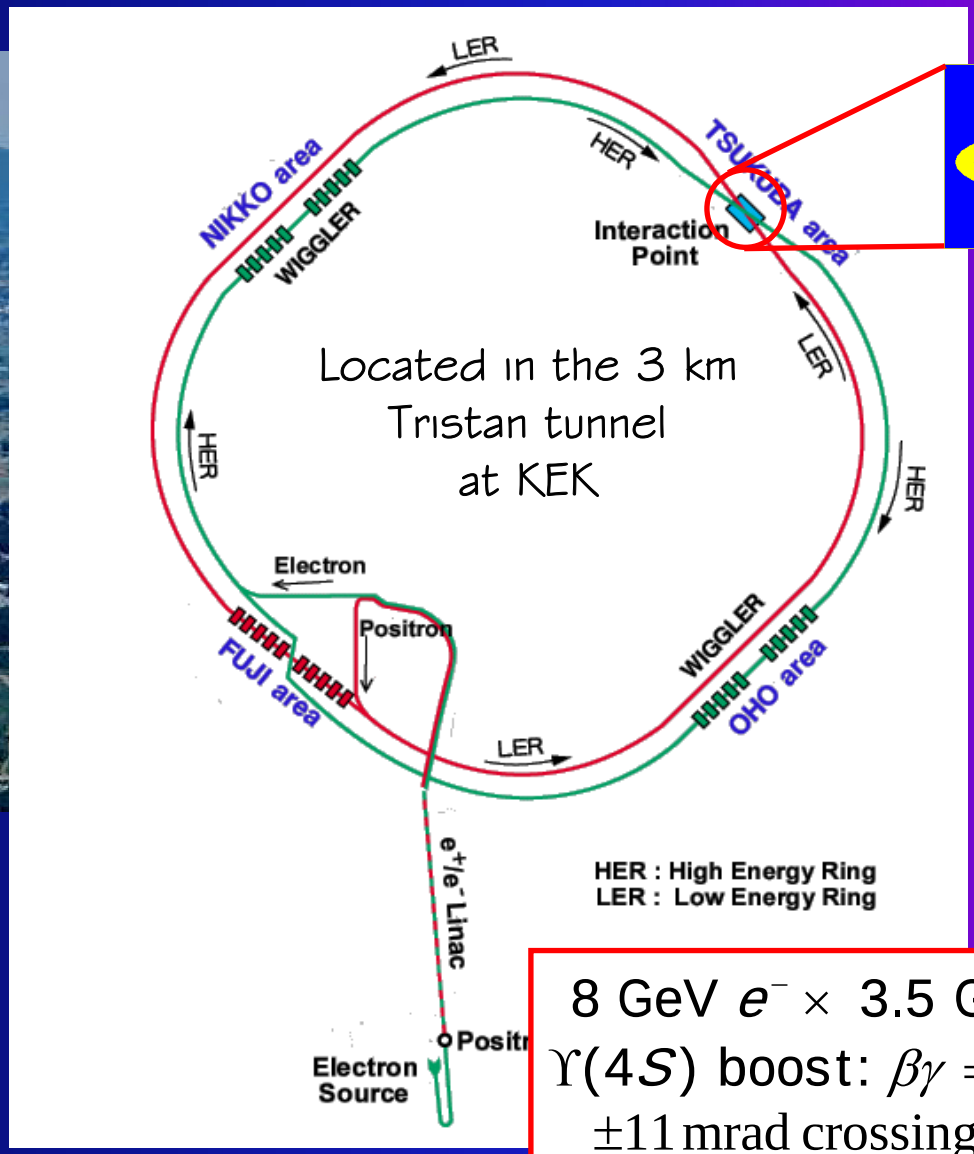
PEP-II/***BABAR*** at SLAC

design peak:	3 10^{33}	$cm^{-2}s^{-1}$
best peak:	6.1 10^{33}	$cm^{-2}s^{-1}$
total recorded:	123.3	fb^{-1}
since last fall:	28.9	fb^{-1}
best month:	7.4	fb^{-1}

9 GeV e^- on 3.1 GeV e^+



KEK-B Storage Rings



BELLE

KEK-B/Belle at KEK

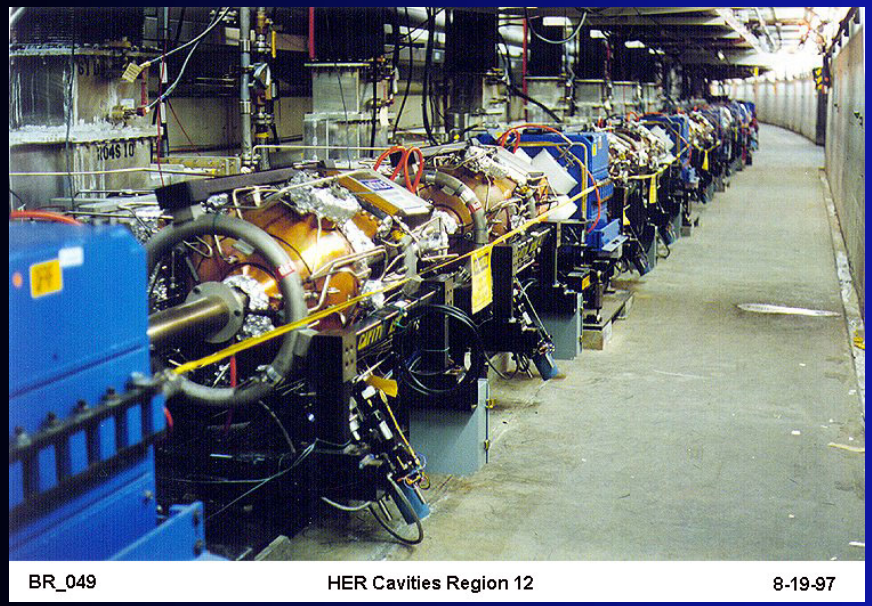
design peak:	10 10^{33}	$cm^{-2}s^{-1}$
best peak:	10.6 10^{33}	$cm^{-2}s^{-1}$
total recorded:	146.1	fb^{-1}
since last fall:	56.6	fb^{-1}
best month:	11.4	fb^{-1}

8 GeV $e^- \times$ 3.5 GeV e^+

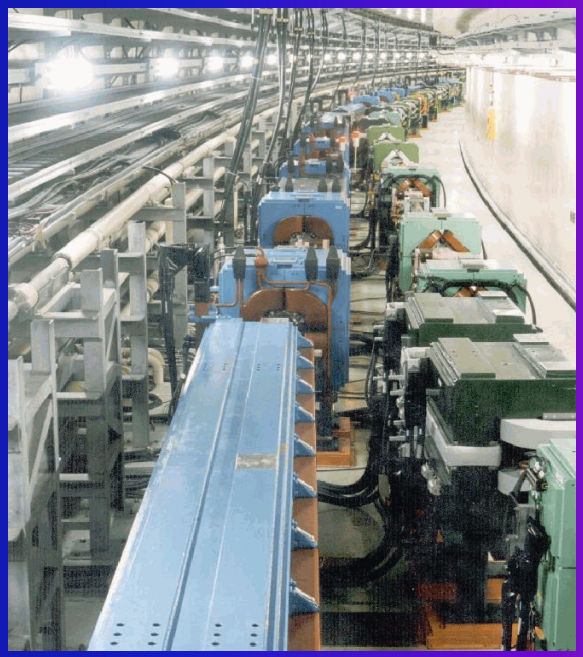
$\Upsilon(4S)$ boost: $\beta\gamma = 0.425$

± 11 mrad crossing angle

PEP-II

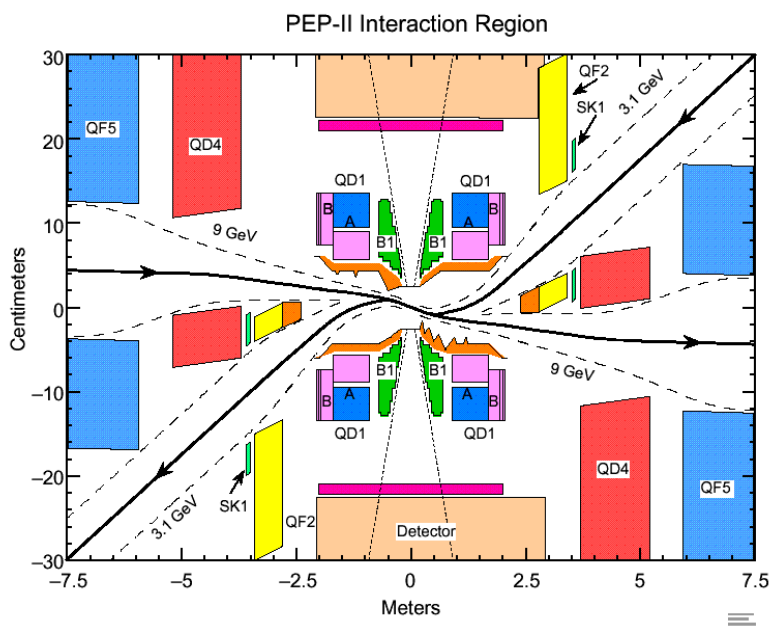


KEK-B



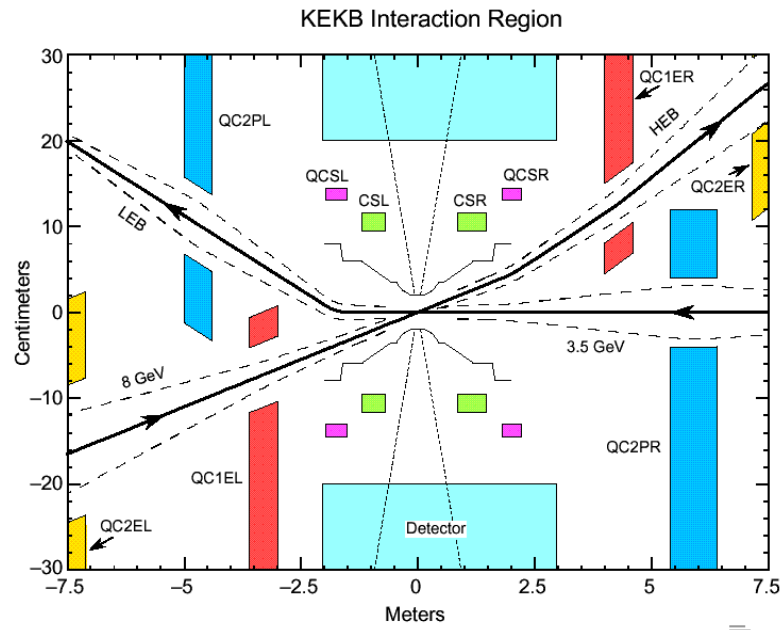
Interaction Regions

PEP-II



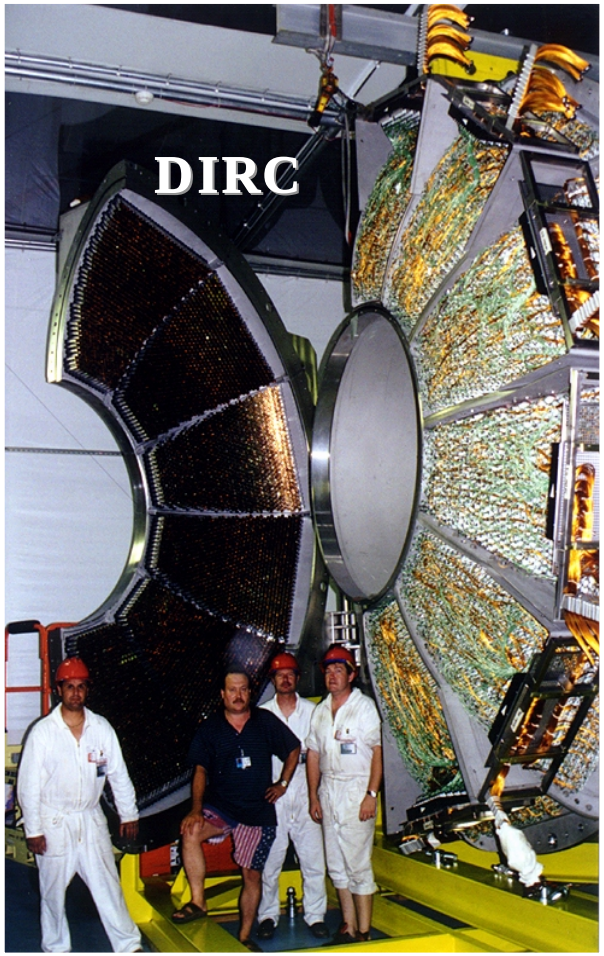
head-on collisions

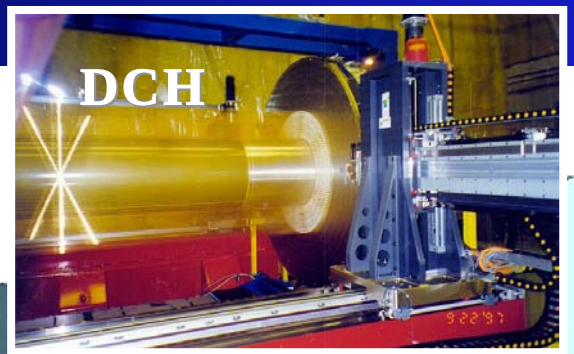
KEK-B

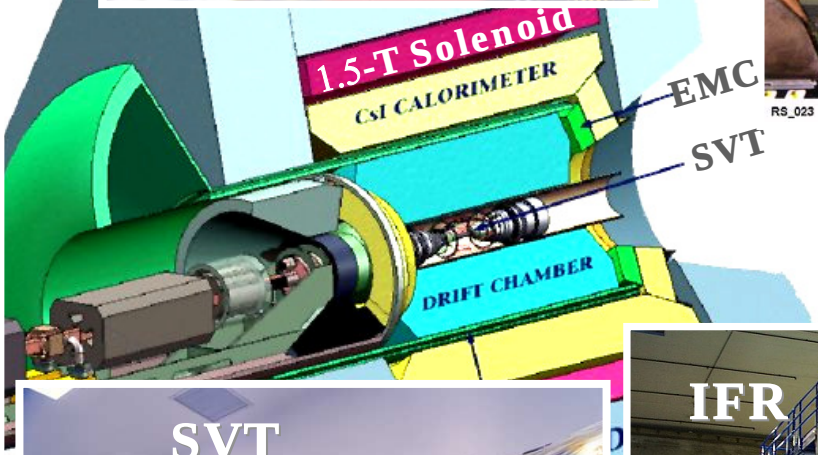


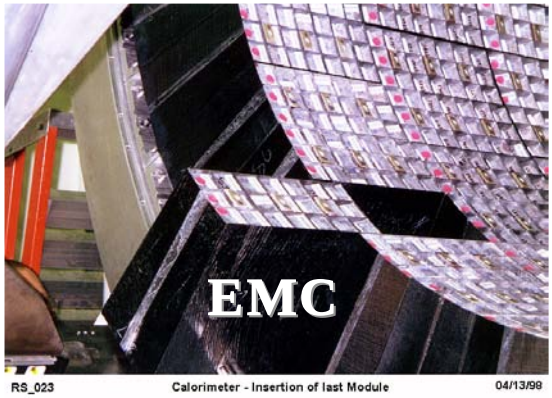
small crossing angle
(11 mrad)

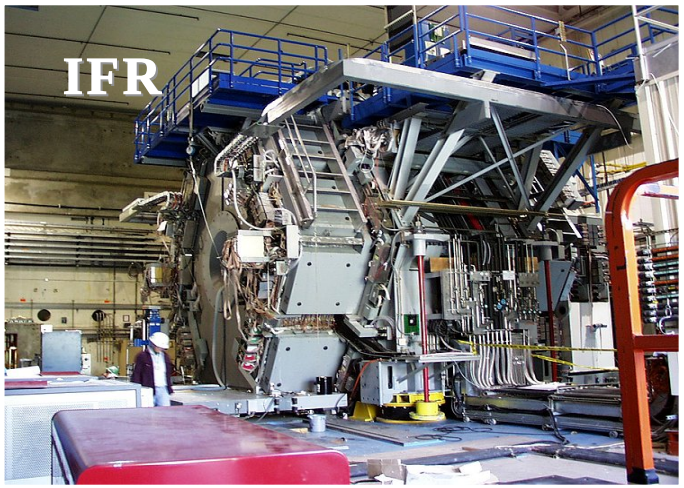
The *BABAR* Detector



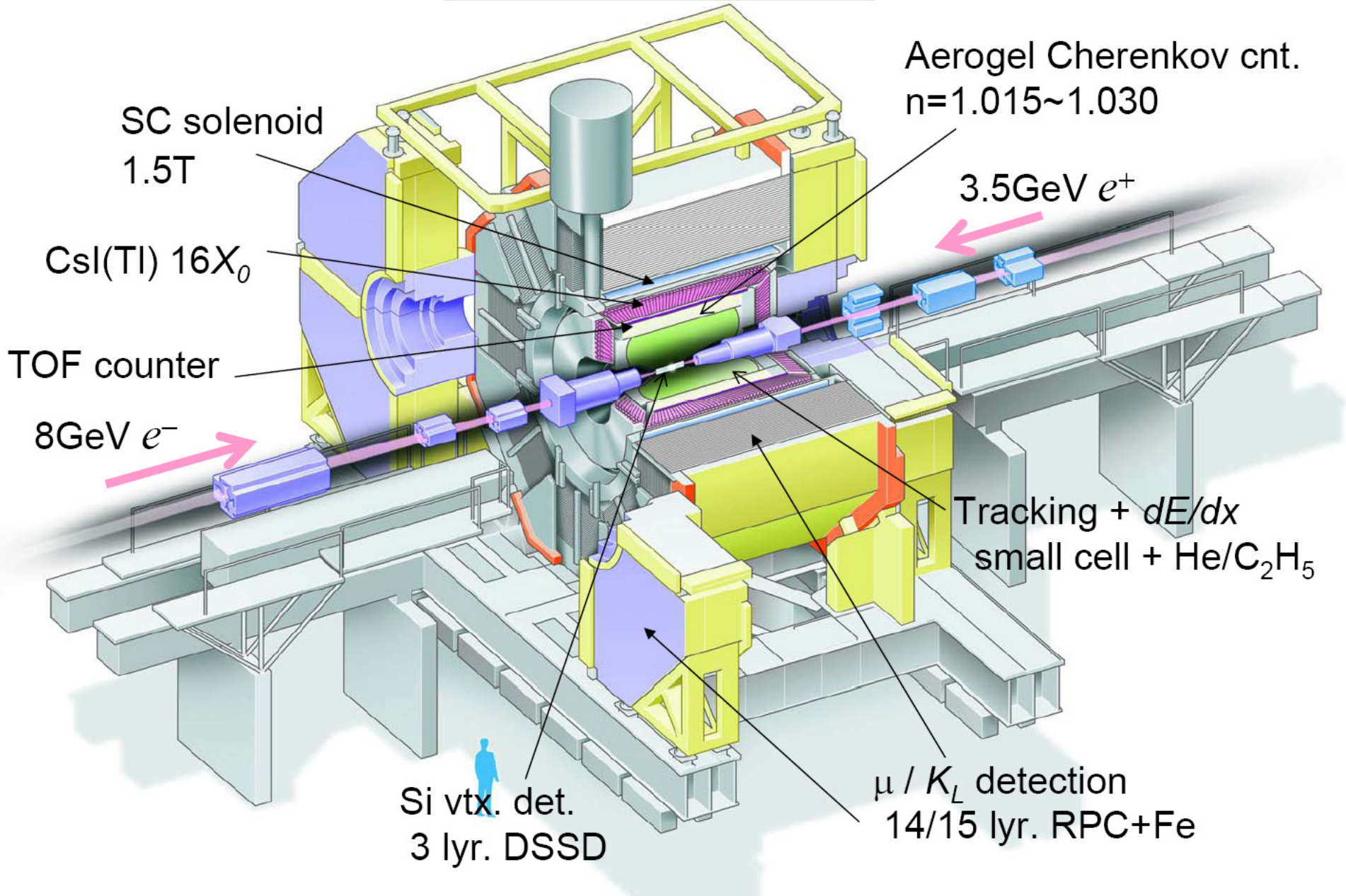








Belle Detector



Introduction to Time-Dependent *CP* Analyses at *B* Factories

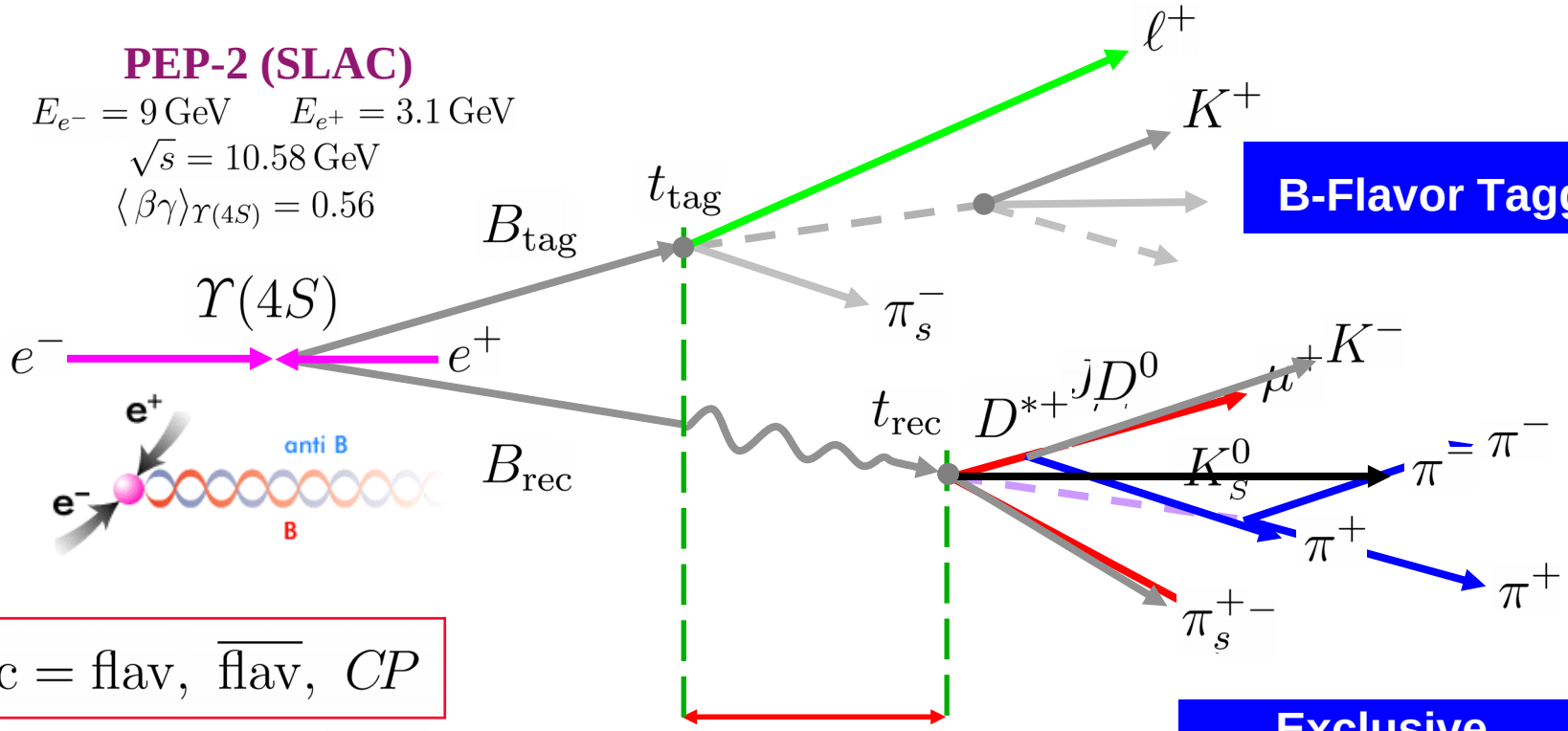
Analysis Technique at *B* Factories

PEP-2 (SLAC)

$E_{e^-} = 9\,\mathrm{GeV} \qquad E_{e^+} = 3.1\,\mathrm{GeV}$

$\sqrt{s} = 10.58\,\mathrm{GeV}$

$\langle \beta\gamma \rangle_{\Upsilon(4S)} = 0.56$



B-Flavor Tagging

$$\mathrm{rec} = \mathrm{flav},\ \overline{\mathrm{flav}},\ CP$$

$$f_{\mathrm{flav}} = D^{*-}\pi^+, \ldots$$

$$f_{CP} = J/\psi\, K_S^0,\ J/\psi\, K_L^0, \ldots$$

$$\Delta t \equiv t_{\mathrm{rec}} - t_{\mathrm{tag}}$$

Exclusive B Meson Reconstruction

Vertexing & Time Difference Determination

$$\mathrm{tag} = B^0,\ \overline{B}^0$$

$$f_{B^0} = X\ell^+\nu,\ XK^+,\ X\pi_s^-, \ldots$$

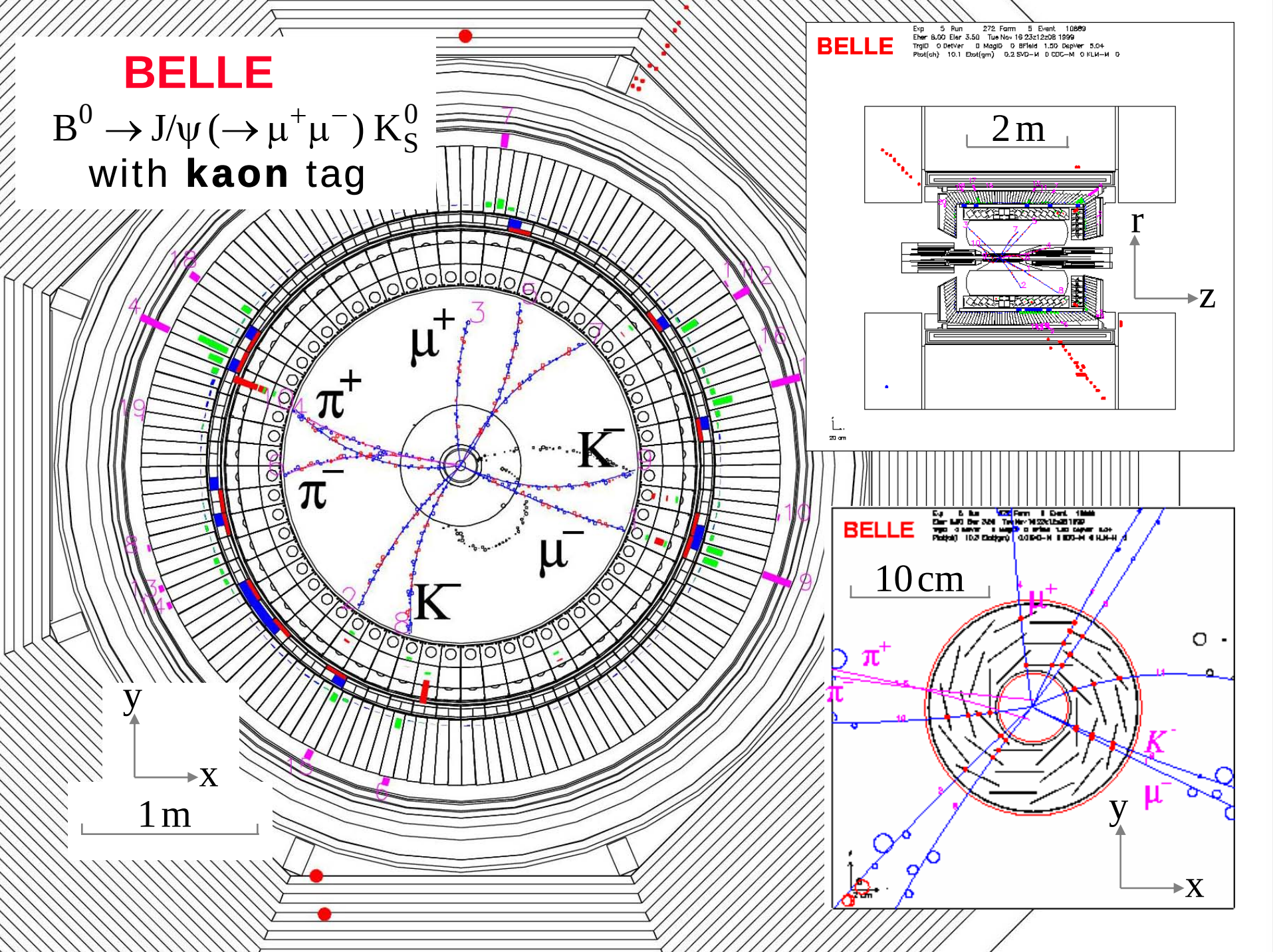
$$\Delta t \approx \Delta z / c \langle \beta\gamma \rangle_{\Upsilon(4S)}$$

$$\langle \Delta z \rangle_{B\overline{B}} \approx 260\,\mu\mathrm{m}$$

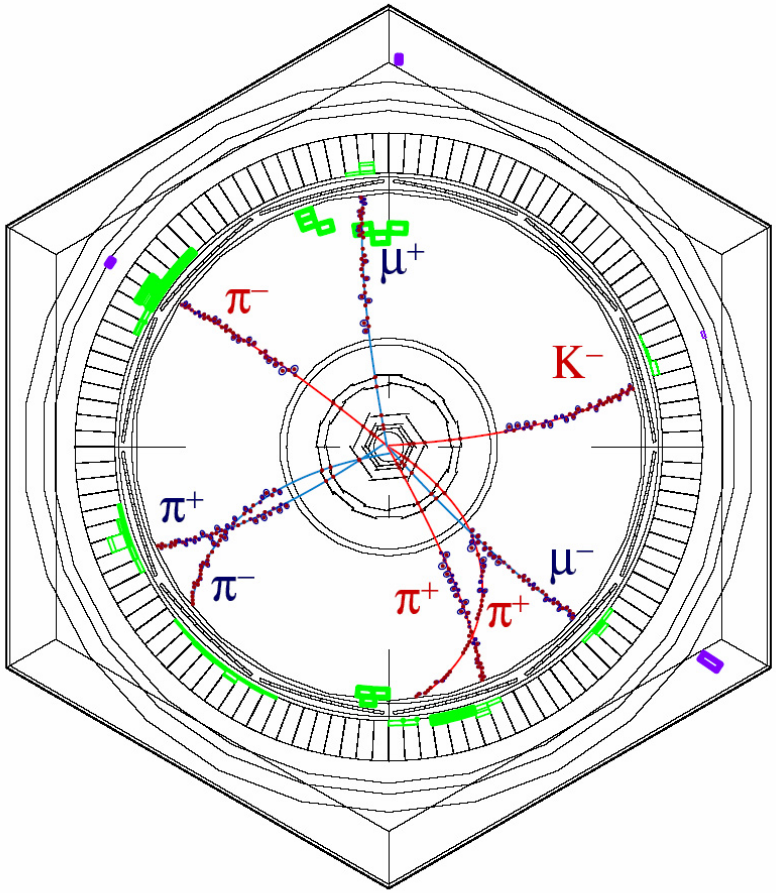
BELLE

$B^0 \to J/\psi(\to \mu^+\mu^-)\, K^0_S$

with **kaon** tag



A Fully Reconstructed Event



A candidate in the mode

$$B^0_{CP} \to \psi(2S)\, K^0_S, \quad K^0_S \to \pi^+\pi^-$$

with: $\psi(2S) \to \mu^+\mu^-$

The other *B* meson is **fully-reconstructed** in the mode:

$$\overline{B}^0 \to D^{*+}\pi^-_f$$

$$D^{*+} \to D^0\pi^-_s$$

$$D^0 \to K^-\pi^+$$

Kinematics at the Y(4S)

★ Exclusive reconstruction: B candidate from tracks and clusters in the event

in the lab $P = (E, \vec{p})$ boost back → $P^* = (E^*, \vec{p}^*)$ in the center-of mass frame (CoM)

★ Define two largely independent analysis variables

The beam-energy substituted mass

$$m_{\rm ES} \equiv \sqrt{{E^*_{\rm beam}}^2 - {p^*}^2}$$

with $E^*_{\rm beam} = \sqrt{s}/2$

half-CoM energy

The energy difference

$$\Delta E \equiv E^* - E^*_{\rm beam}$$

★ Uncertainties

$$\sigma^2_{m_{ES}} = \frac{1}{4}\sigma^2_{\sqrt{s}} + \left[\frac{p^*}{m_B}\right]^2 {\sigma_{p^*}}^2 \approx \frac{1}{4}\sigma^2_{\sqrt{s}}$$

dominated by beam energy spread

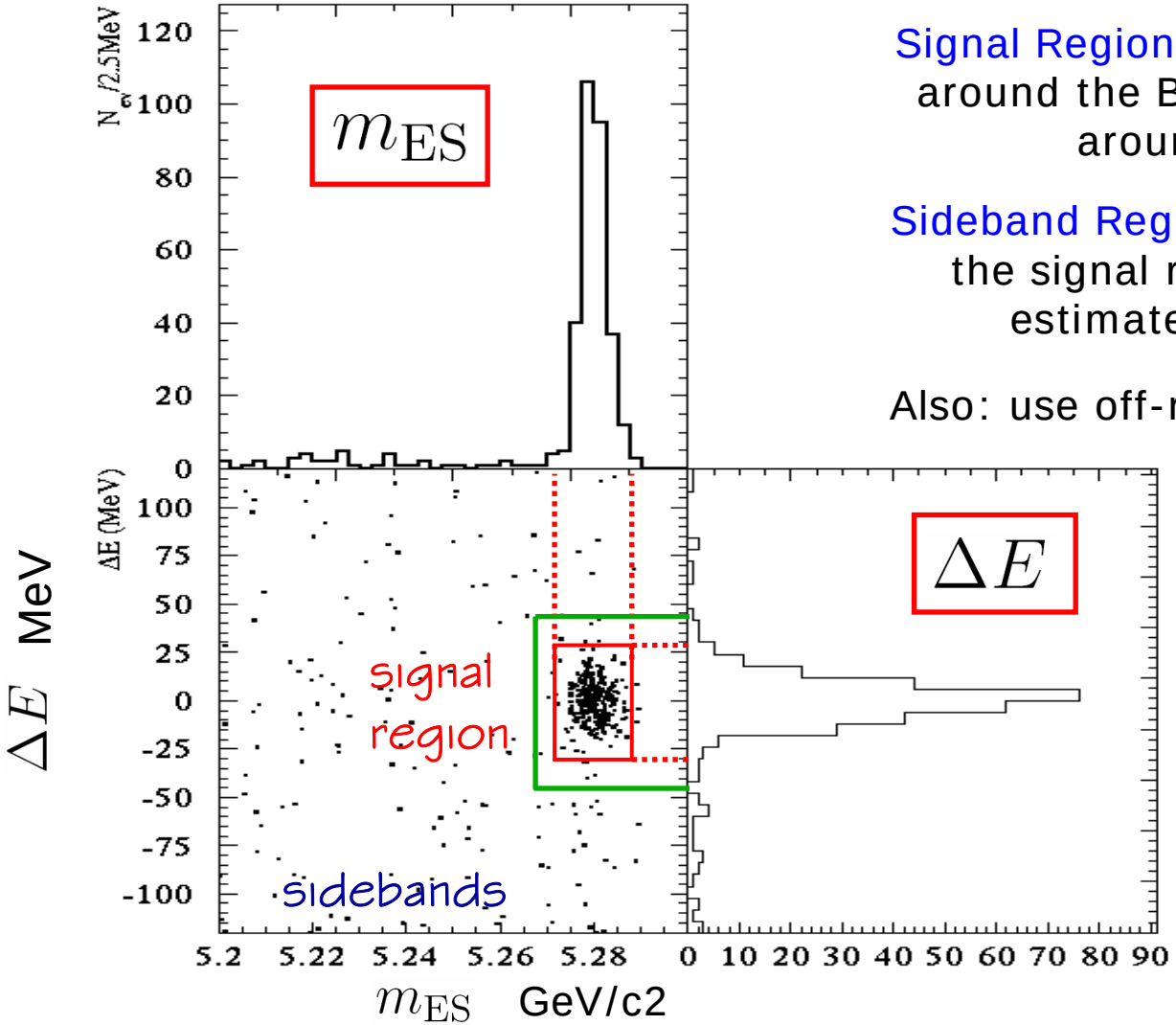
$$\sigma^2_{\Delta E} = \frac{1}{4}\sigma^2_{\sqrt{s}} + \sigma^2_{E^*} \approx \sigma^2_{E^*}$$

dominated by energy resolution

$$\sigma_{m_{ES}} \approx 2.6\,\mathrm{MeV}/c^2$$

$$\sigma_{\Delta E} \approx 10 \leftrightarrow 40\,\mathrm{MeV}$$

Signal Region and Sidebands



Signal Region: typically 3-sigma around the B mass in m_{ES} and around 0 in ΔE

Sideband Region: defined outside the signal region in order to estimate backgrounds

Also: use off-resonance data

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

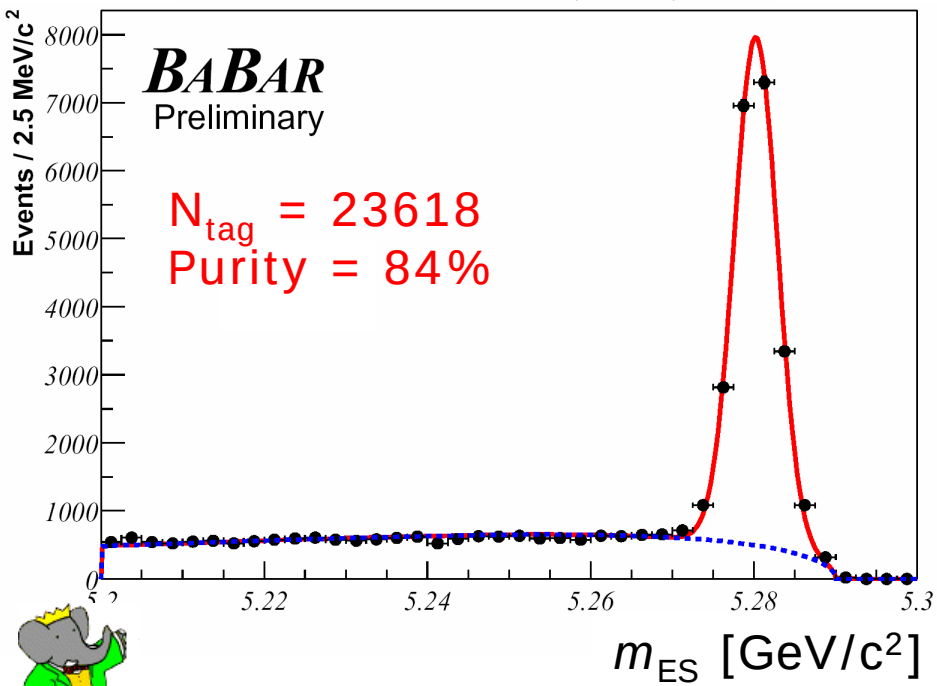
Flavor Specific Final States: Neutrals

Self-tagging modes

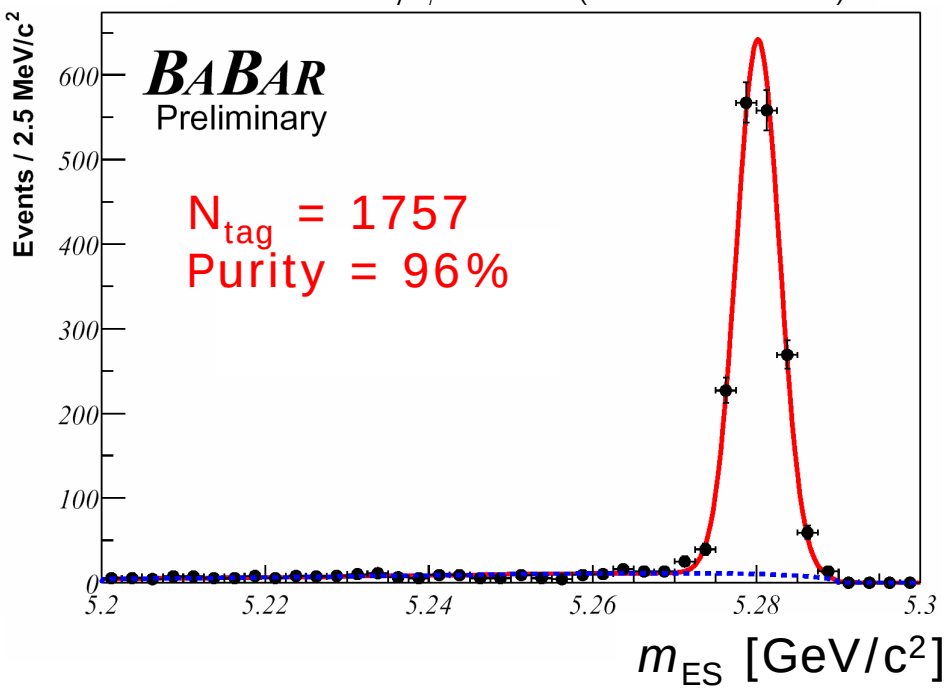
Note: charge conjugate decays are implied, unless specified

Nov 1999- June 2002 data
82 fb^{-1} on-peak – 89 million BB pairs

$$B^0 \to D^{(*)-}\pi^+/\rho^+/a_1^+$$



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



Also: charged modes, an important control sample

$CP = -1$ Sample

CP = –1 sample

Samples of B decays to *CP*-eigenstates with charmonium

$$B^0 \to J/\psi\,(\to \ell^+\ell^-)\,K^0_S$$

$$B^0 \to J/\psi\,K^0_S(\to \pi^0\pi^0)$$

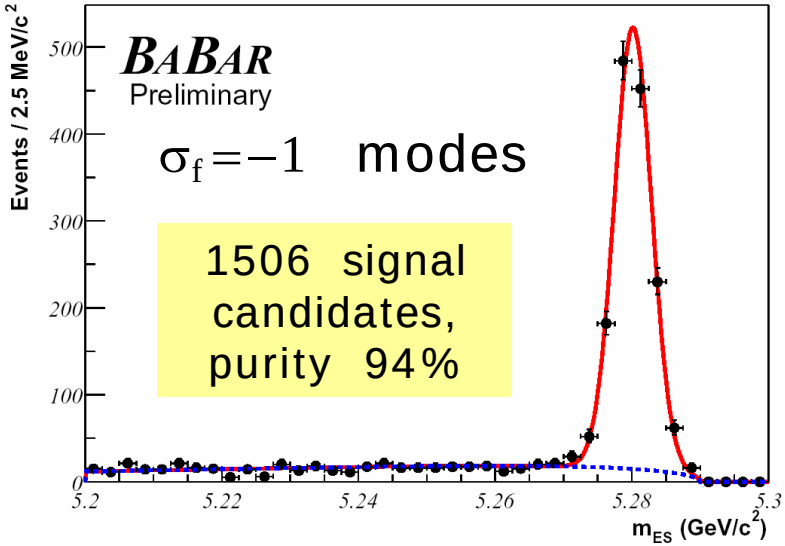
$$B^0 \to \psi(2S)(\to \ell^+\ell^-,\ J/\psi\,\pi\pi)\,K^0_S$$

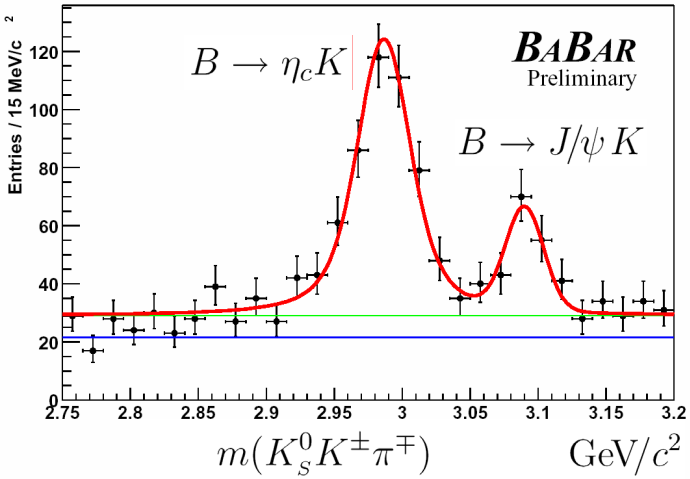
$$B^0 \to \chi_{c1}(\to J/\psi\,\gamma)\,K^0_S$$

and also:

$$B^0 \to \eta_c(\to K^0_S K^\pm \pi^\mp)\,K^0_S$$

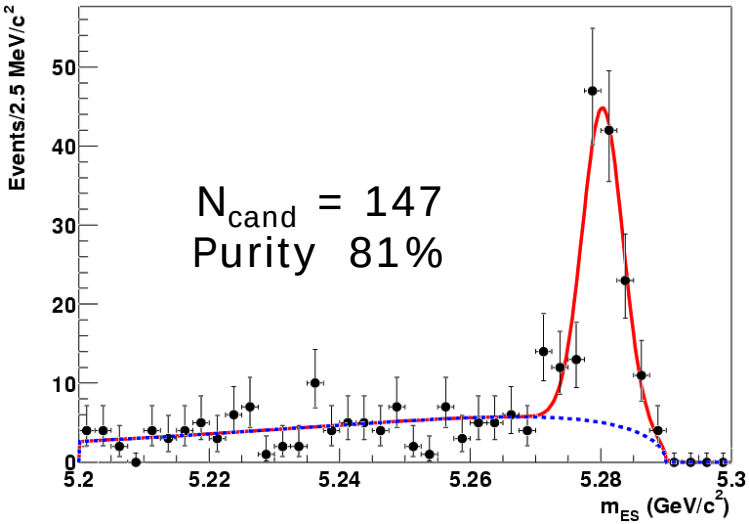
note: the η_c has *CP*= – 1, that is *opposite* to the J/ψ but the decay is S-wave rather than P-wave





here shown, charged control sample

CP Sample



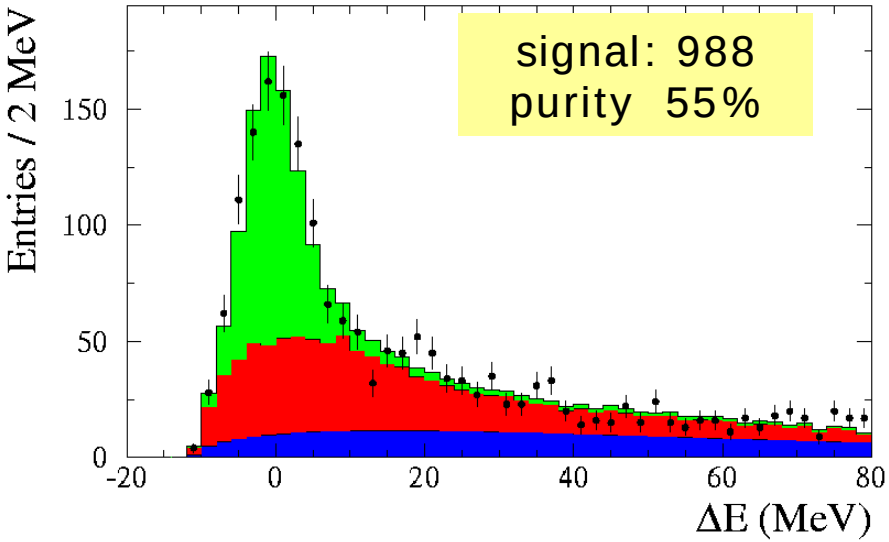
Mixed CP Sample

$$B^0 \to J/\psi\ K^{*0}_{CP}(\to K^0_S \pi^0)$$

P to VV decay mode

angular analysis is used to disentangle the CP-odd and CP-even components

mostly CP-even

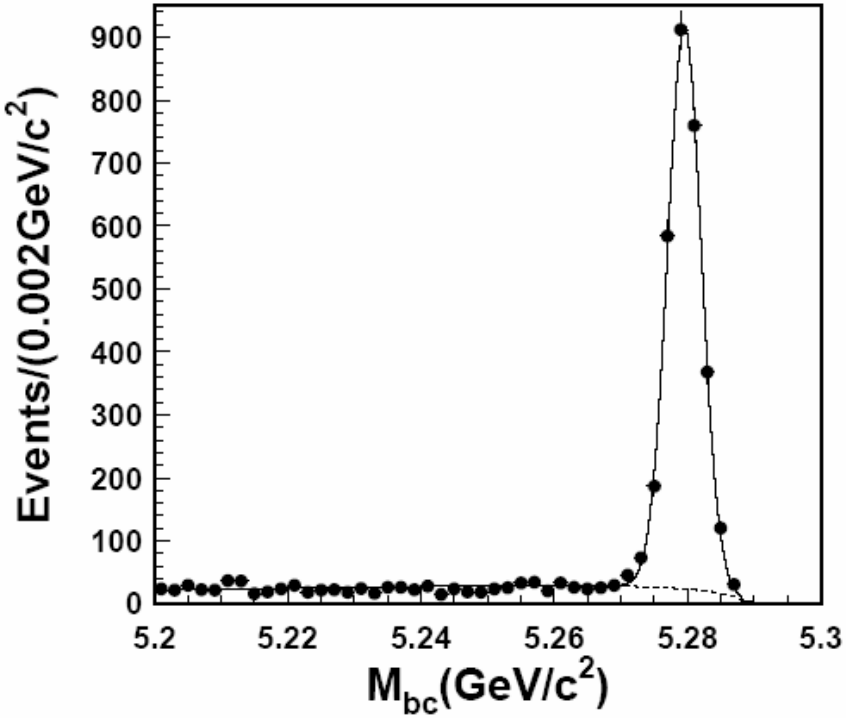


CP=+1 Sample

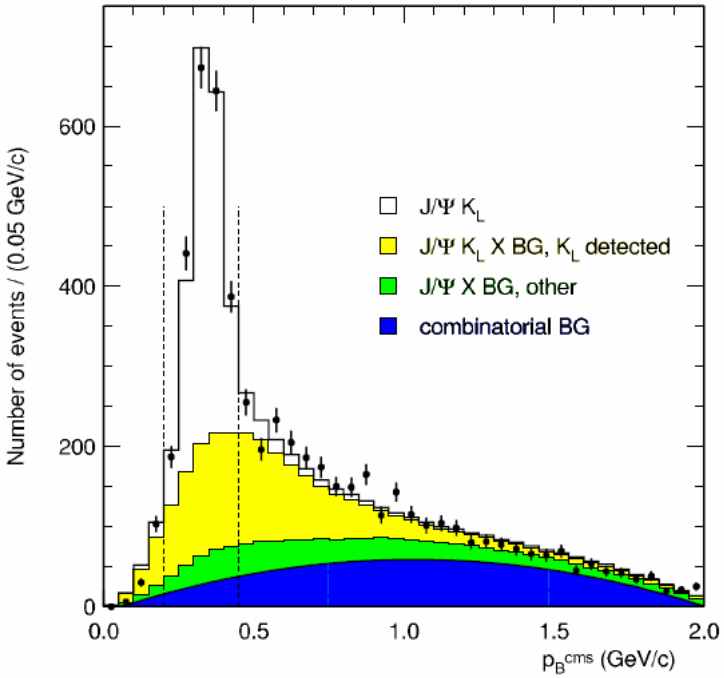
$$B^0 \to J/\psi\ K^0_L$$

K-longs are identified in either the EM Calo or the muon system, but their energy is not measured.

Belle LP2003, 140/fb



CP=-1 Sample



CP=+1 Sample

B Flavor Tagging

★ Underlying physics processes: exploit charge correlations

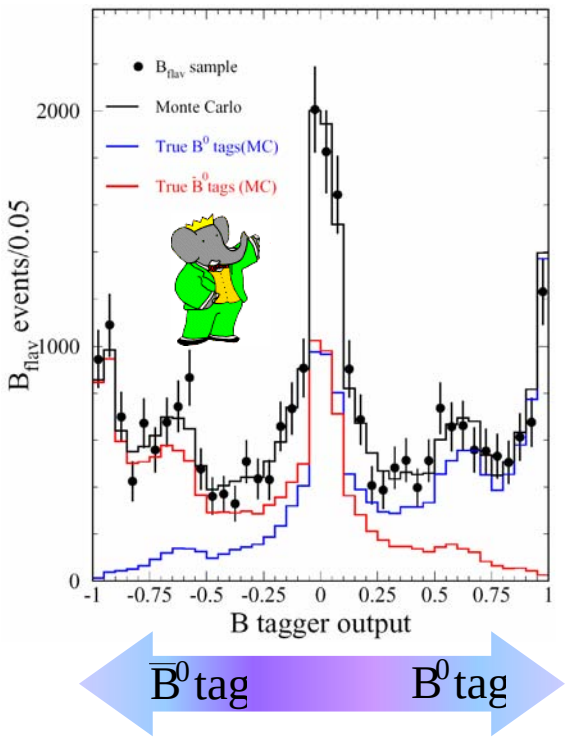
apply momentum cut
e.g. $p^*_\ell > 1\,\mathrm{GeV}/c$

primary leptons $B^0 \to D^{(*)-}\ell^+\nu$

fast track, secondary leptons $B^0 \to D^-\pi^+,\ D^- \to K^{(*)}\ell^-\bar{\nu}$

kaon(s) $B^0 \to \overline{D}X,\ \overline{D} \to K^+X'$

soft pions $B^0 \to D^{*-}X^+,\ D^{*-} \to \overline{D}^0\pi_s^-$



★ Multivariate techniques (Neural Network) used to combine information in an optimal way

- event topology
- track and event kinematics
- particle identification

★ Tagging categories

based on the physics (BABAR) or NN output (Belle)

Tagging Performances

- Tagging performance are measured from the data
  - tagging efficiencies and mis-tagging probabilities determined with physical quantities in simultaneous fits
  - cross-checks with independent high statistics control samples
  - Monte-Carlo used for optimizations and second-order effects

trade systematic error for statistical error

Physics Category	Efficiency ε (%)	Wrong-Tag Fraction w (%)	$Q = \varepsilon \times (1 - 2\,w)^2$ (%)
Lepton	9.1 ± 0.2	3.3 ± 0.6	7.9 ± 0.3
Kaon I	16.7 ± 0.2	9.9 ± 0.7	10.7 ± 0.4
Kaon II	19.8 ± 0.3	20.9 ± 0.8	6.7 ± 0.4
Inclusive	20.0 ± 0.3	31.6 ± 0.9	0.9 ± 0.7
All	65.6 ± 0.5		28.1 ± 0.7

pure

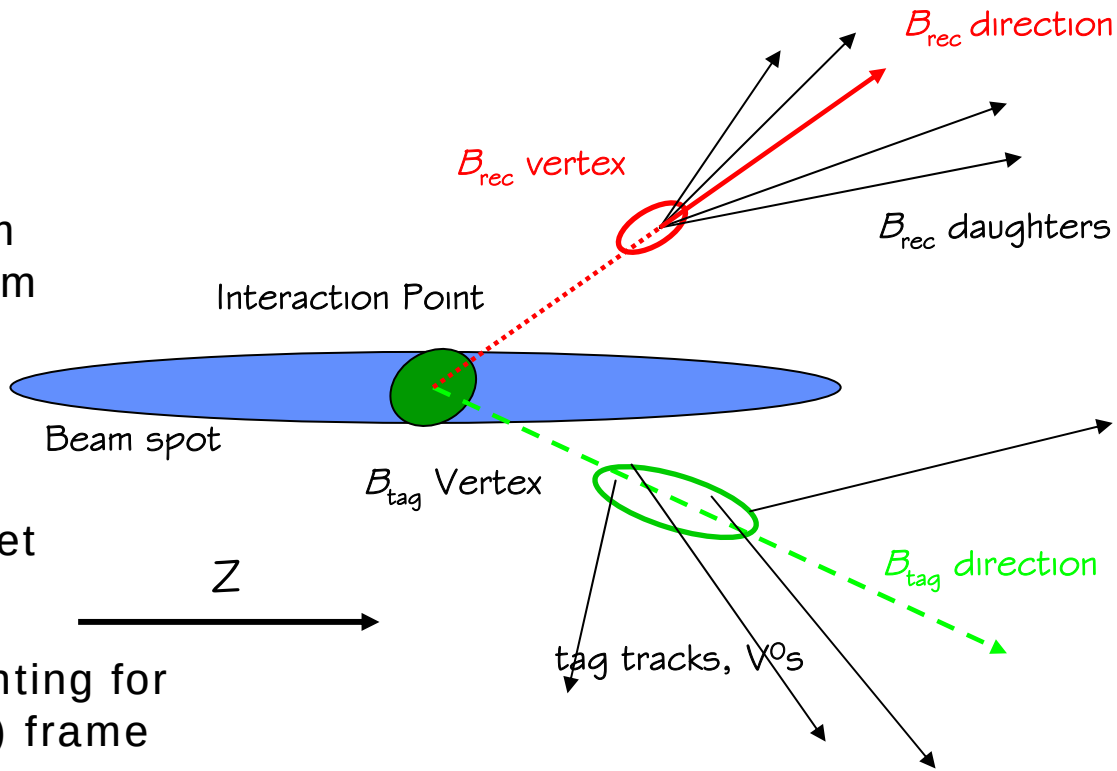
powerful

$$\varepsilon = 65.6 \pm 0.5\% \qquad Q = 28.1 \pm 0.7\%$$

Tagging performance at Belle very similar

Time Measurements

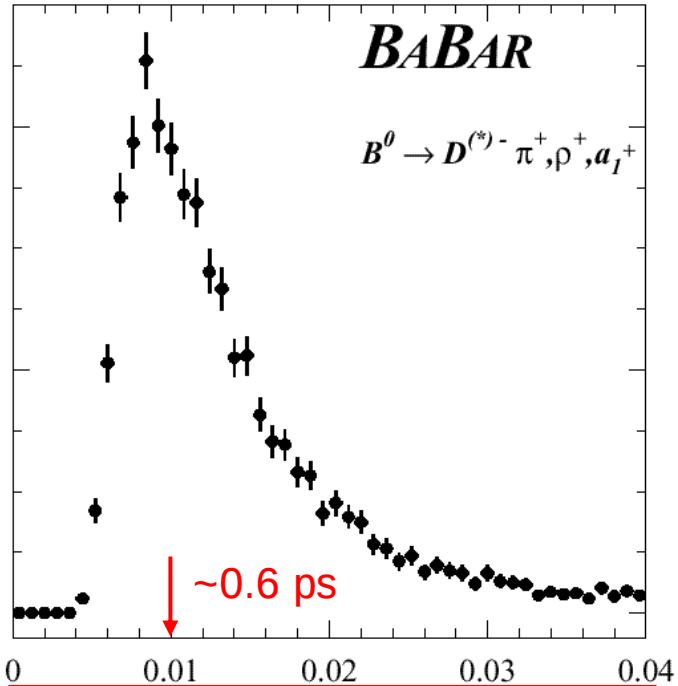
1. Reconstruct B_{rec} vertex from B_{rec} daughters
2. Reconstruct B_{tag} direction from B_{rec} vertex & momentum, beam spot, and $\Upsilon(4S)$ momentum = pseudotrack
3. Reconstruct B_{tag} vertex from pseudotrack plus consistent set of tag tracks
4. Convert from Δz to Δt, accounting for (small) B momentum in $\Upsilon(4S)$ frame



Result: High efficiency (97%) and $\sigma(\Delta z)_{rms} \sim 180\mu m$ versus $<|\Delta z|> \sim \beta\gamma c\tau = 260\mu m$

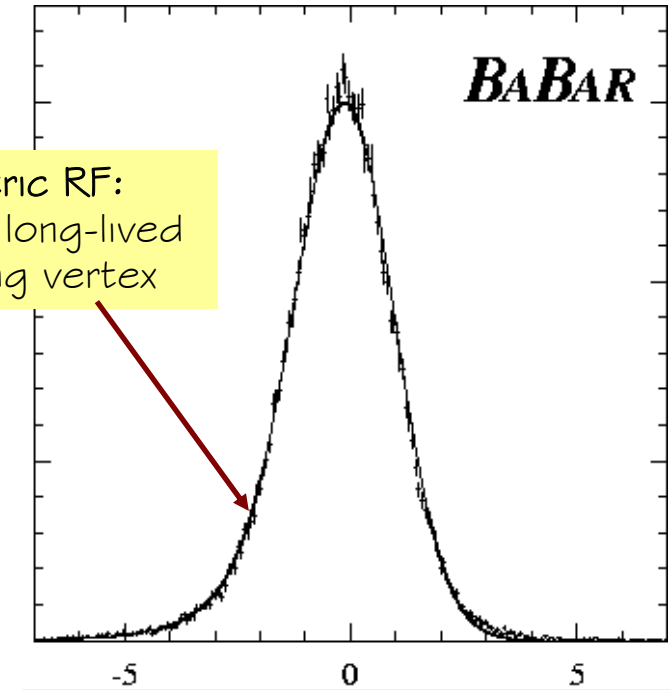
Time Resolution Function

Event-by-event σ(Δt) from vertex errors



σ(Δz) [cm]

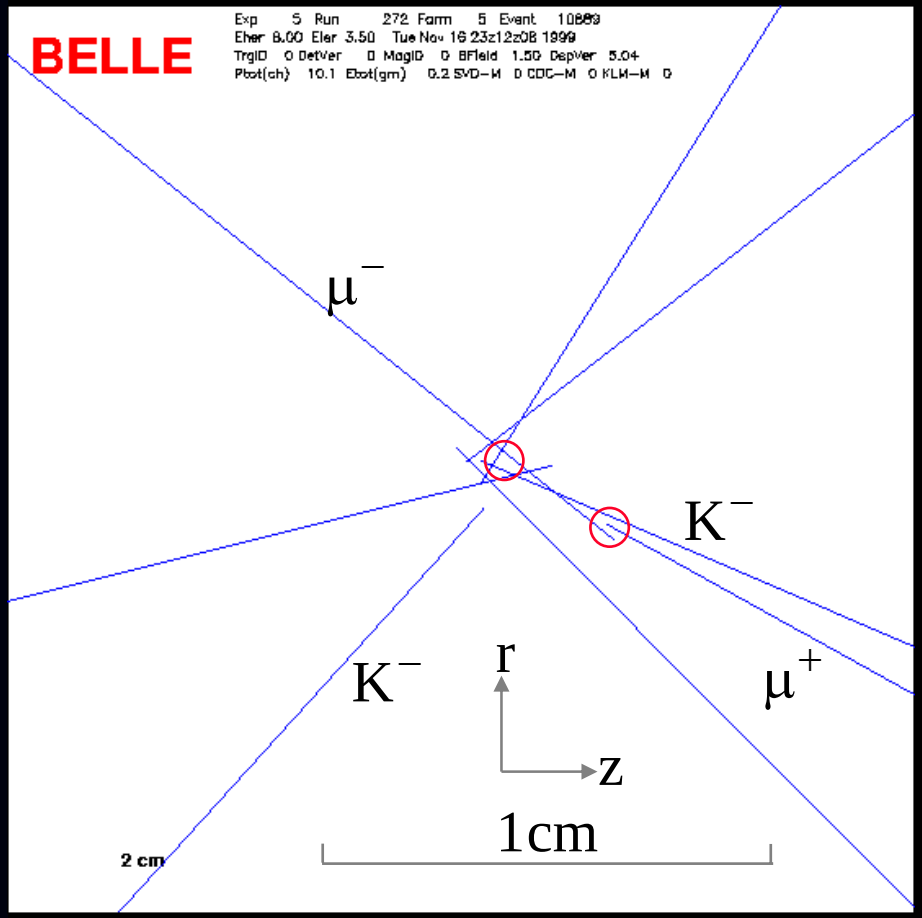
Signal MC: Δt resolution function

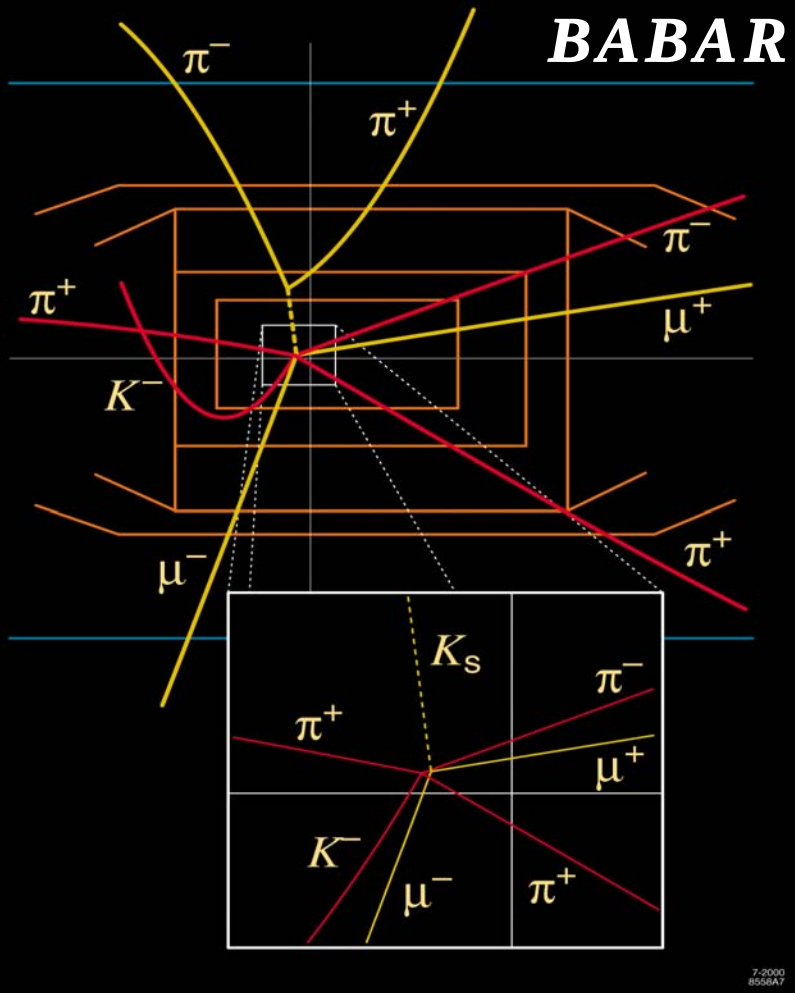


$(\Delta t_{meas} - \Delta t_{true})/\sigma(\Delta t)$

Asymmetric RF: Tracks from long-lived charm in tag vertex

Empirical Models with parameters fit to data: Gaussian convolved with an exponential [lifetime] or Triple Gaussian [mixing, CP]


BELLE
Exp 5 Run 272 Farm 5 Event 10889
Eher 8.00 Eler 3.50 Tue Nov 16 23:12:08 1999
TrgID 0 DetVer 0 MagID 0 BField 1.50 DspVer 5.04
Ptot(ch) 10.1 Etot(gm) 0.2 SVD-M 0 CDC-M 0 KLM-M 0
μ−
K−
K−
μ+
r
z
1cm
2 cm


BABAR
π−
π+
π−
π+
μ+
K−
μ−
π+
Ks
π−
π+
μ+
K−
μ−
π+
7-2000
8558A7

Time-Dependent Event Rates

Differential event rate, as a function of the difference between the proper decay times of the two B mesons in the final state

assume $\Delta\Gamma = 0$

$$\frac{d}{d\Delta t}\mathcal{N}(\Upsilon(4S) \to B\overline{B} \to f_{\rm tag}, f_{\rm rec}) \propto$$
$$\frac{1}{\Gamma}e^{-\Gamma|\Delta t|}\left\{1 - C_{f_{\rm tag},\, f_{\rm rec}} \times \cos(\Delta m\,\Delta t) + S_{f_{\rm tag},\, f_{\rm rec}} \times \sin(\Delta m\,\Delta t)\right\}$$

with $C_{f_{\rm tag},\, f_{\rm rec}} = \dfrac{|a_m|^2 - |a_u|^2}{|a_m|^2 + |a_u|^2}$ and $S_{f_{\rm tag},\, f_{\rm rec}} = \dfrac{2\,{\rm Im}(a_u^* a_m)}{|a_m|^2 + |a_u|^2}$

where one defines

$$a_u \equiv \overline{A}_{f_{\rm tag}} A_{f_{\rm rec}} - A_{f_{\rm tag}} \overline{A}_{f_{\rm rec}}$$
$$a_m \equiv \frac{q}{p}\overline{A}_{f_{\rm tag}} \overline{A}_{f_{\rm rec}} - \frac{p}{q} A_{f_{\rm tag}} A_{f_{\rm rec}}$$

assume $z = 0$

Note - since t is not measured, integrate:

$$\int_{|\Delta t/2|}^{\infty} e^{-2\Gamma t} dt = \frac{1}{\Gamma} e^{-\Gamma|\Delta t|}$$

f_{tag} is Flavor Specific

$$\lambda_f \equiv \frac{q}{p}\frac{\overline{A}_f}{A_f} \quad \text{(if } A_f \neq 0\text{)} \quad \text{and} \quad \overline{\lambda}_f \equiv \frac{p}{q}\frac{A_f}{\overline{A}_f} \quad \text{(if } \overline{A}_f \neq 0\text{)}$$

flavor tagging
$$\begin{cases} B^0\text{tag}\,(+) \;\Leftrightarrow\; \lambda_{f_{\text{tag}}} \approx 0 \\ \overline{B}^0\text{tag}\,(-) \;\Leftrightarrow\; \overline{\lambda}_{f_{\text{tag}}} \approx 0 \end{cases}$$

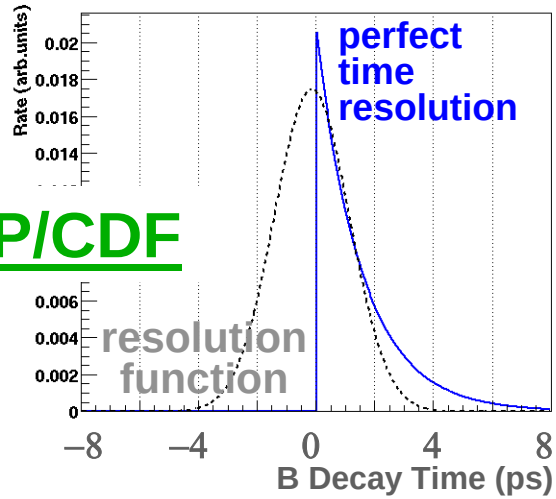
$$\boxed{\begin{aligned} &\frac{d}{d\Delta t}\mathcal{N}(\,f_{\text{rec}},\,\text{tag}=\pm\,) \propto \\ &\qquad \frac{1}{\Gamma}\,e^{-\Gamma|\Delta t|}\,\{\,1 \mp C_{f_{\text{rec}}} \times \cos(\Delta m\,\Delta t) \pm S_{f_{\text{rec}}} \times \sin(\Delta m\,\Delta t)\,\} \end{aligned}}$$

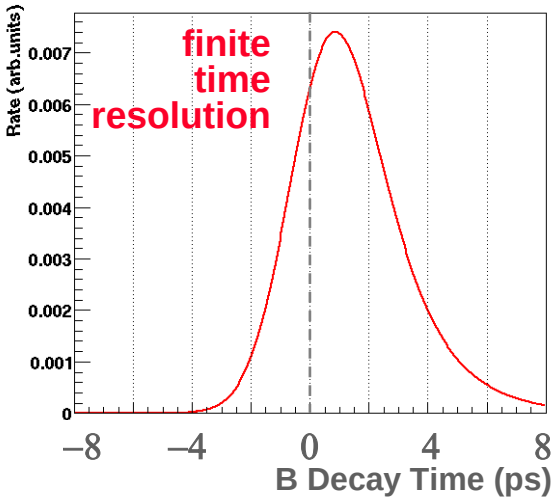
with $C_{f_{\text{rec}}} \equiv \dfrac{1-|\lambda_{f_{\text{rec}}}|^2}{1+|\lambda_{f_{\text{rec}}}|^2}$ and $S_{f_{\text{rec}}} \equiv \dfrac{2\,\text{Im}\,\lambda_{f_{\text{rec}}}}{1+|\lambda_{f_{\text{rec}}}|^2}$

- familiar expressions, but with Δt as time variable
- in the general case, there are non-trivial interference terms

B-Lifetimes: Time Distributions

LEP/CDF

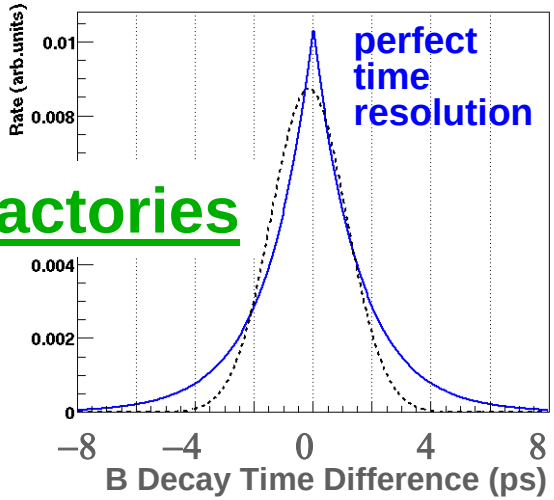


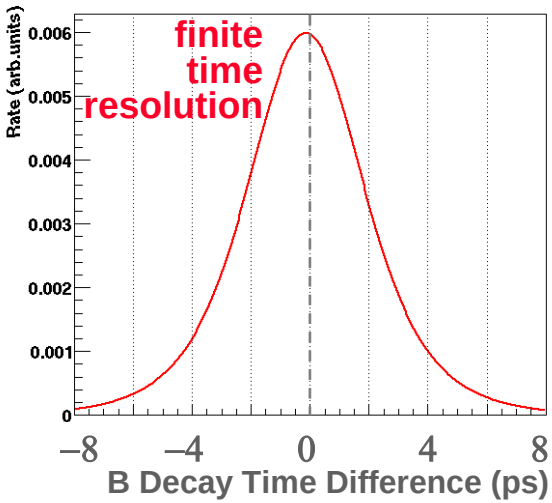


The **production point** of the B meson is known with good accuracy

Control of the resolution function at negative times

B Factories

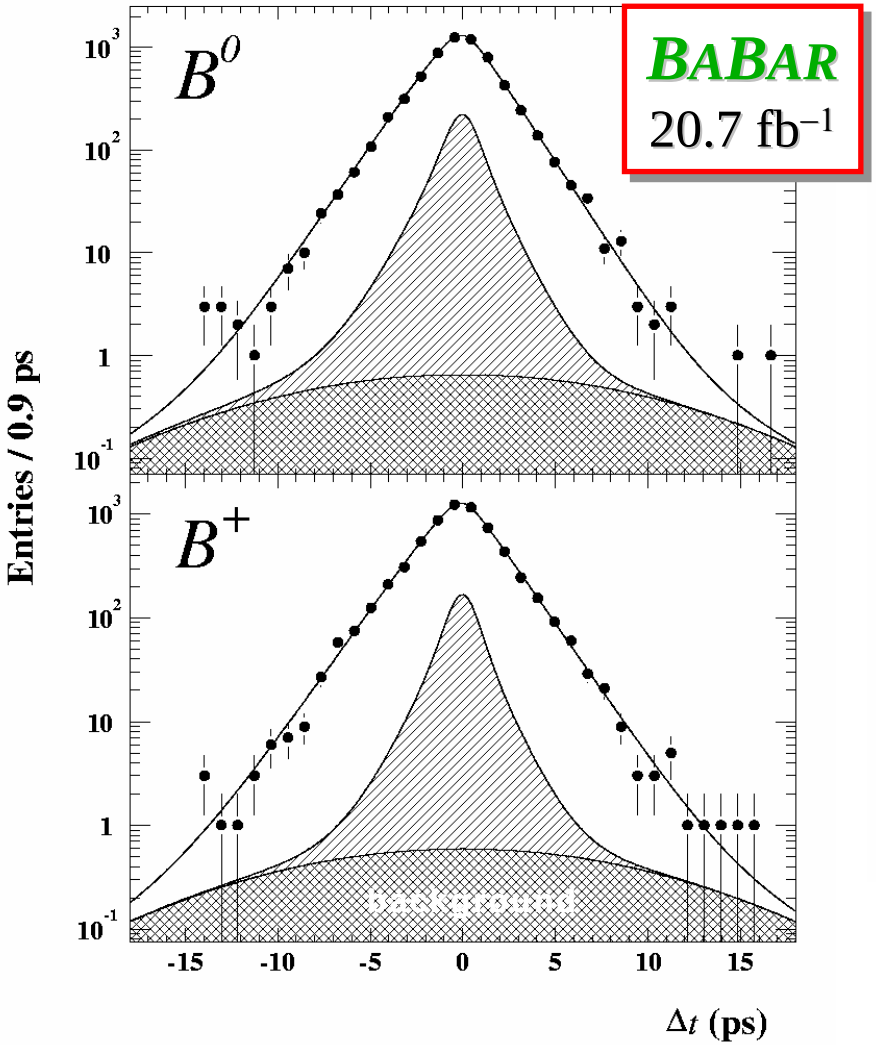


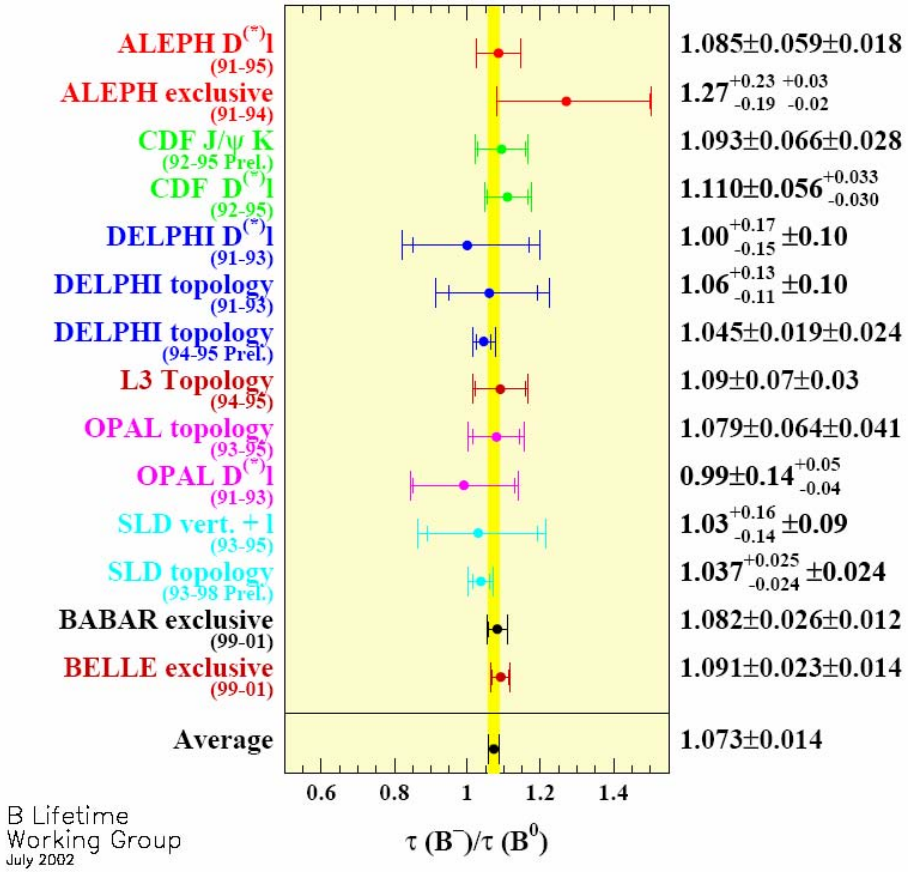


The proper time is deduced from the distance in z between the 2 B vertices

Fit the parameters of the resolution function together with the lifetime

Lifetime Measurements





Proof of principle for time-dependent analyses at *B* Factories

Case of a Flavor Eigenstate, f_{flav}

B_{rec} is reconstructed in a flavor-specific mode

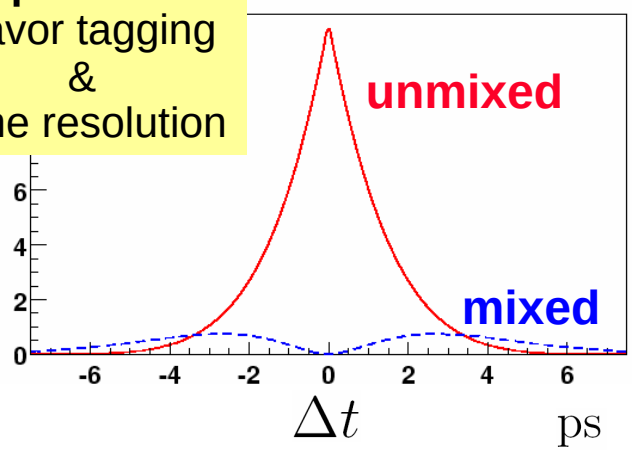
$$\lambda_{f_{\mathrm{flav}}} \equiv \frac{q}{p}\frac{\overline{A}_{f_{\mathrm{flav}}}}{A_{f_{\mathrm{flav}}}} \quad \Rightarrow \quad |\lambda_{f_{\mathrm{flav}}}| \ll 1$$

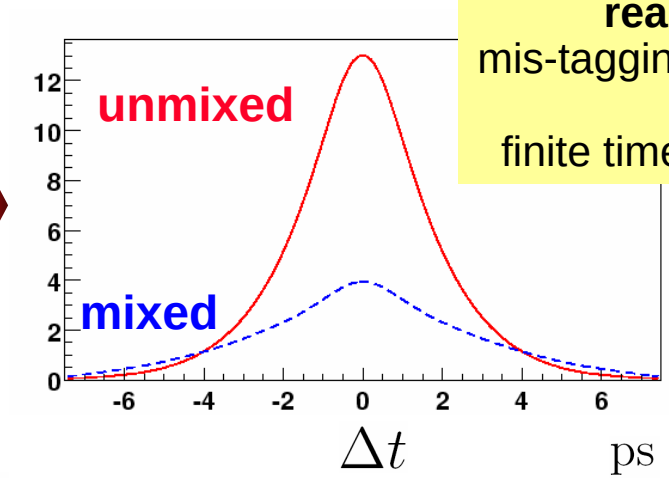
Two categories of events:

UnMixed (+): f_{flav} and f_{tag} have opposite flavor

Mixed (–) : f_{flav} and f_{tag} have same flavor

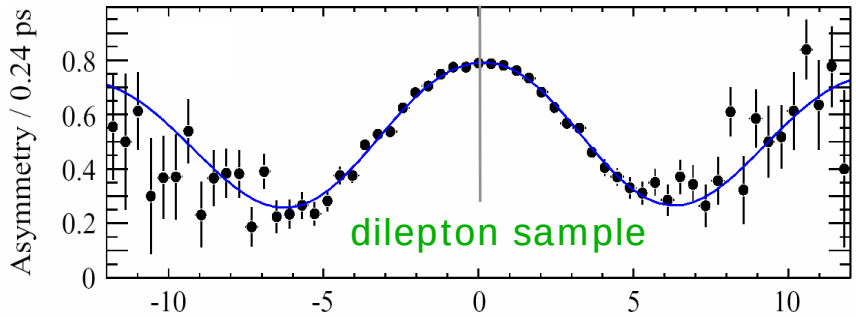
perfect
flavor tagging
&
time resolution

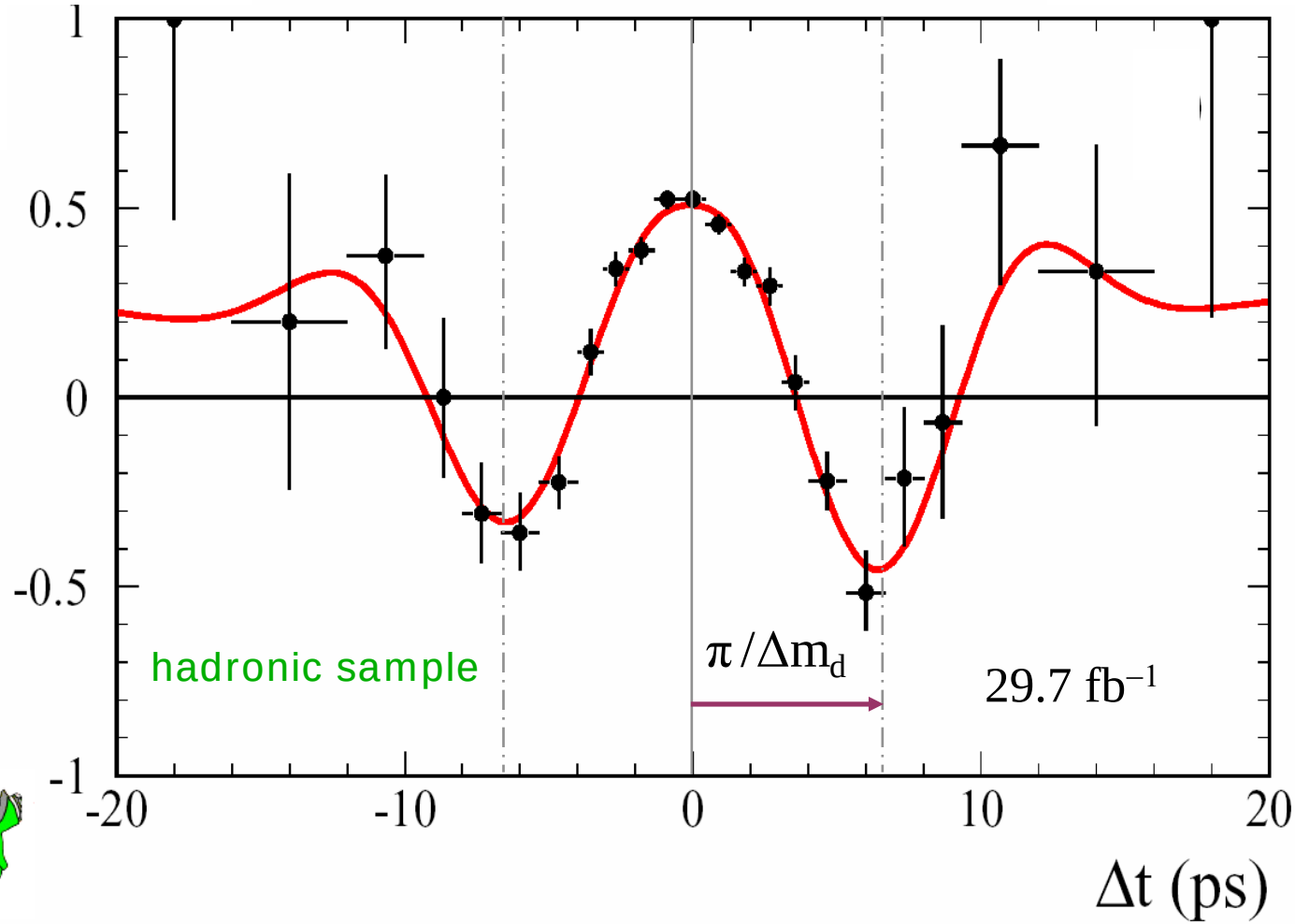


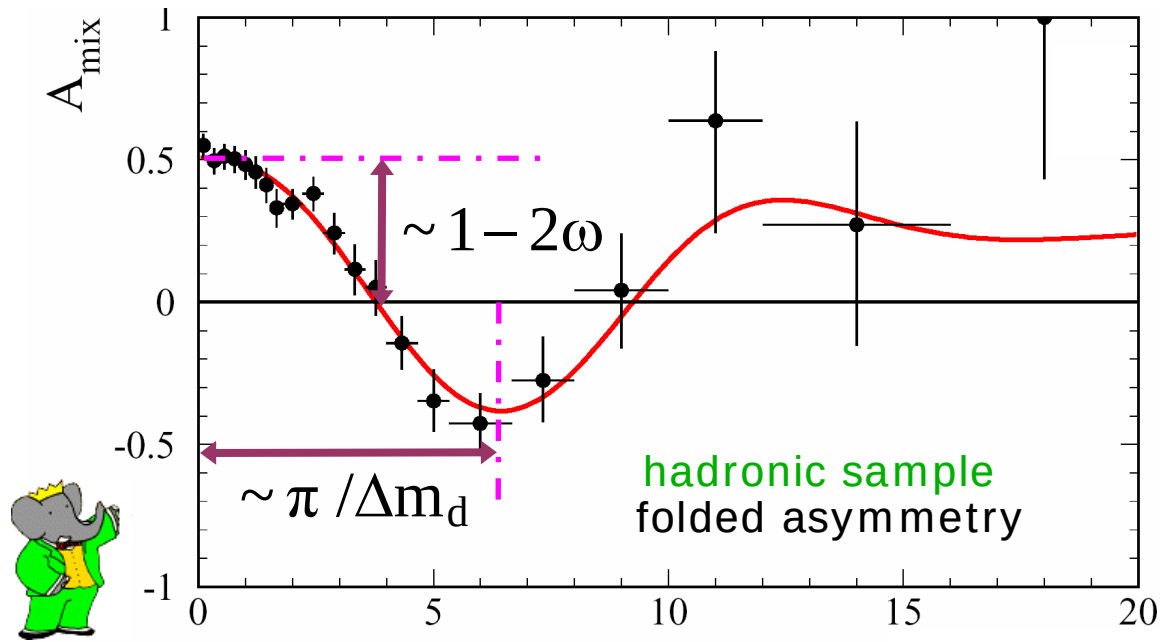


realistic
mis-tagging probability
&
finite time resolution

rate $\approx \frac{1}{\Gamma} e^{-\Gamma|\Delta t|} \{ 1 \pm \cos(\Delta m \, \Delta t) \}$


Asymmetry / 0.24 ps
0.8
0.6
0.4
0.2
0
-10
-5
0
5
10
dilepton sample


1
0.5
0
-0.5
-1
-20
-10
0
10
20
hadronic sample
π/Δm_d
29.7 fb⁻¹
Δt (ps)



(very) simplified fit function

$$a_{\mathrm{mix}}(\Delta t) \sim (1-2\omega)\cos(\Delta m \Delta t) \otimes \mathcal{R}(\Delta t)$$

mis-tagging probabilities

resolution function

Sample used to determine from the data

- probabilities of incorrect *B*-flavor tagging
- parameters of the time-resolution function

Case of a *CP* Eigenstate, f_{CP}

B_{rec} is reconstructed in a *CP* final state

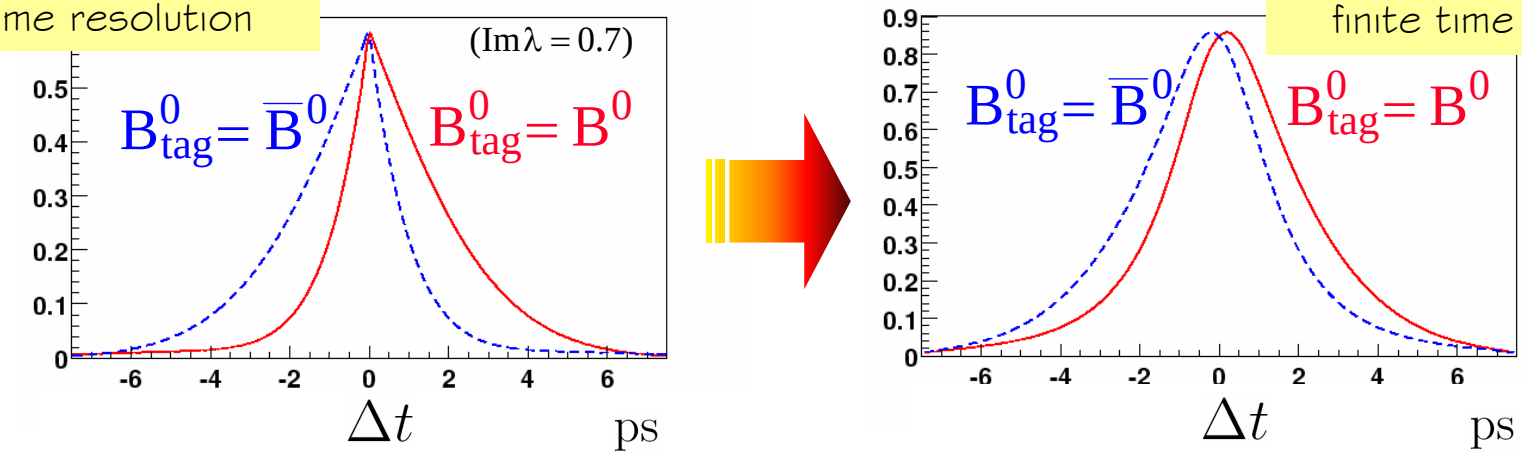
$$\lambda_{f_{CP}} \equiv \frac{q}{p}\frac{\overline{A}_{f_{CP}}}{A_{f_{CP}}}$$

complex *CP*-parameter characterizes interference between decay with or without mixing

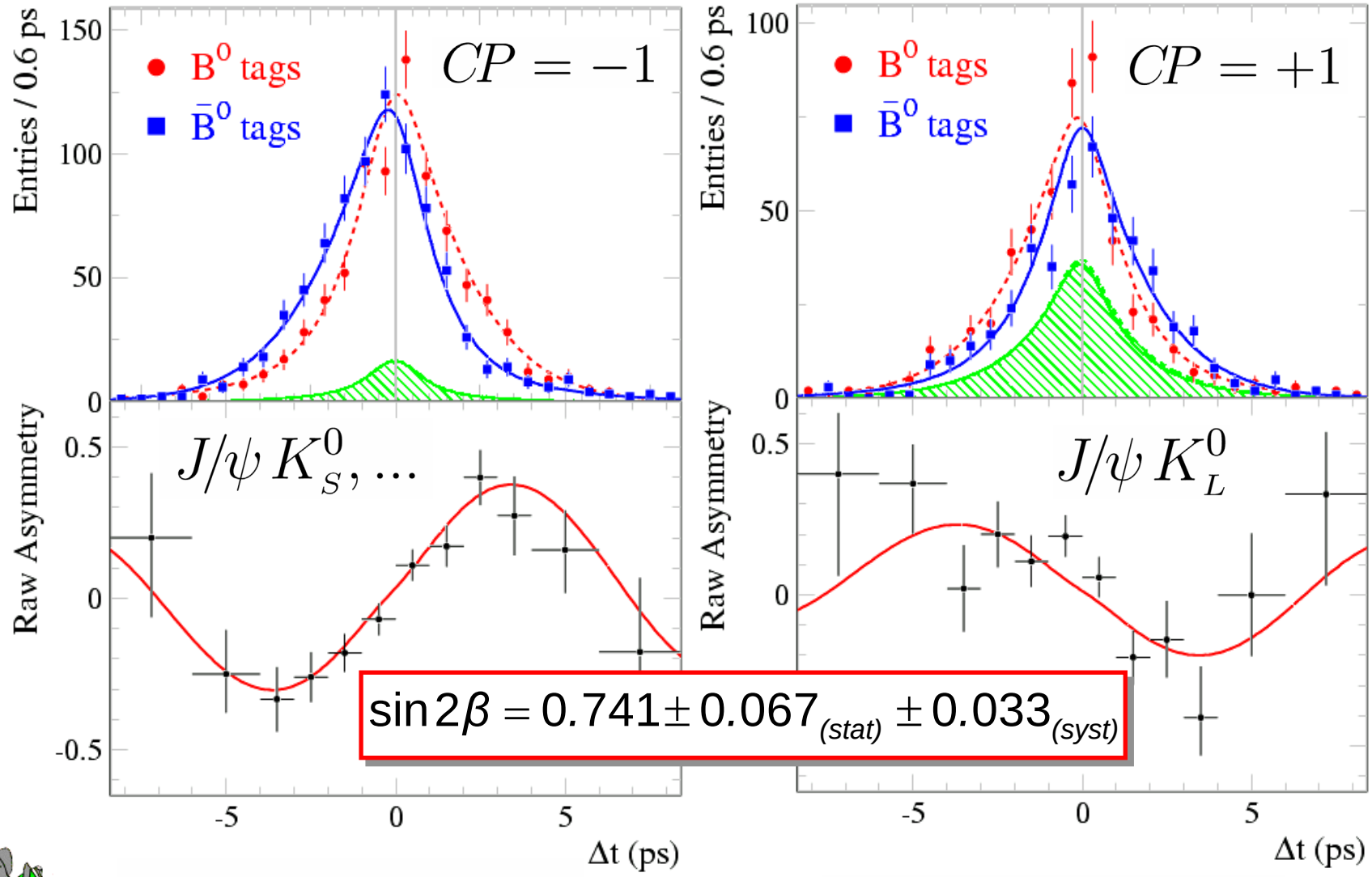
$$|\lambda_{f_{CP}}| \approx 1 \quad \begin{cases} C_{f_{CP}} \approx 0 \\ S_{f_{CP}} \approx \mathrm{Im}\,\lambda_{f_{CP}} \end{cases}$$

perfect flavor tagging & time resolution

realistic mis-tagging probability & finite time resolution



$$\text{rate} \approx \frac{1}{\Gamma} e^{-\Gamma|\Delta t|} \left\{ 1 \pm \mathrm{Im}\,\lambda_{f_{CP}} \times \sin(\Delta m\,\Delta t) \right\}$$



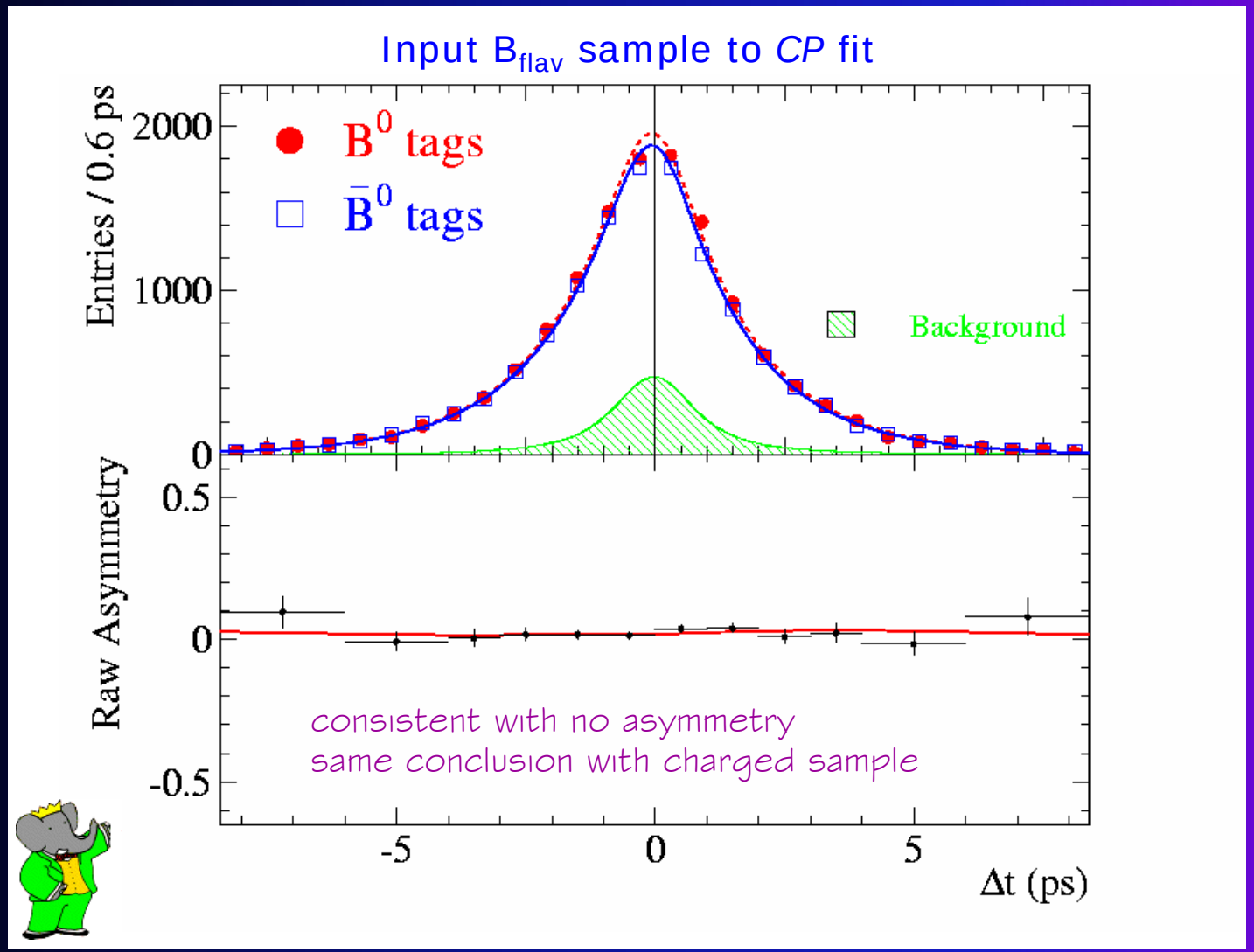
$$\sin 2\beta = 0.741 \pm 0.067_{(stat)} \pm 0.033_{(syst)}$$

$$\lambda_{J/\psi\, K^0_S} = -\, e^{-2i\,\beta}$$

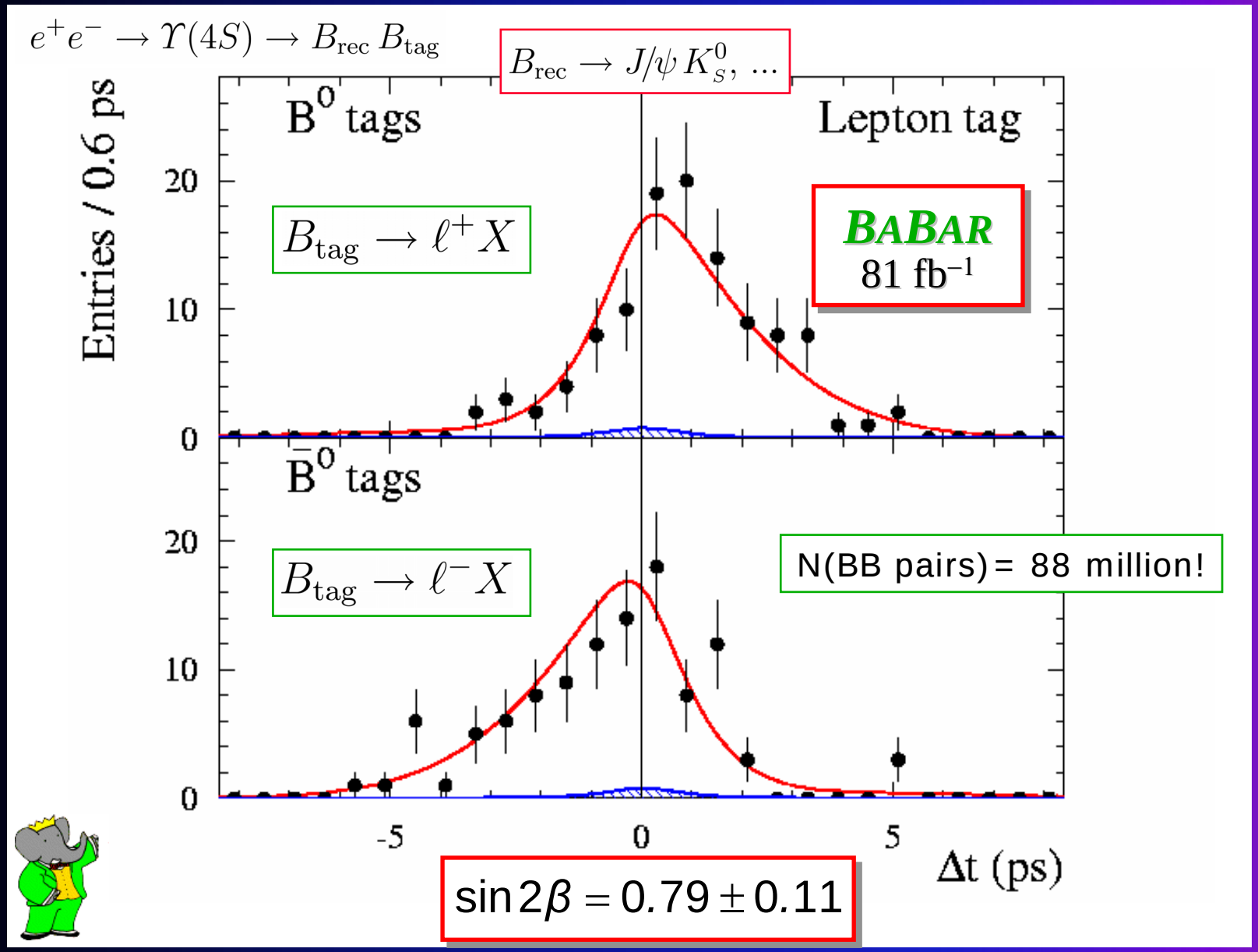
$$\lambda_{J/\psi\, K^0_L} = +\, e^{-2i\,\beta}$$

Control Sample : Flavor Specific

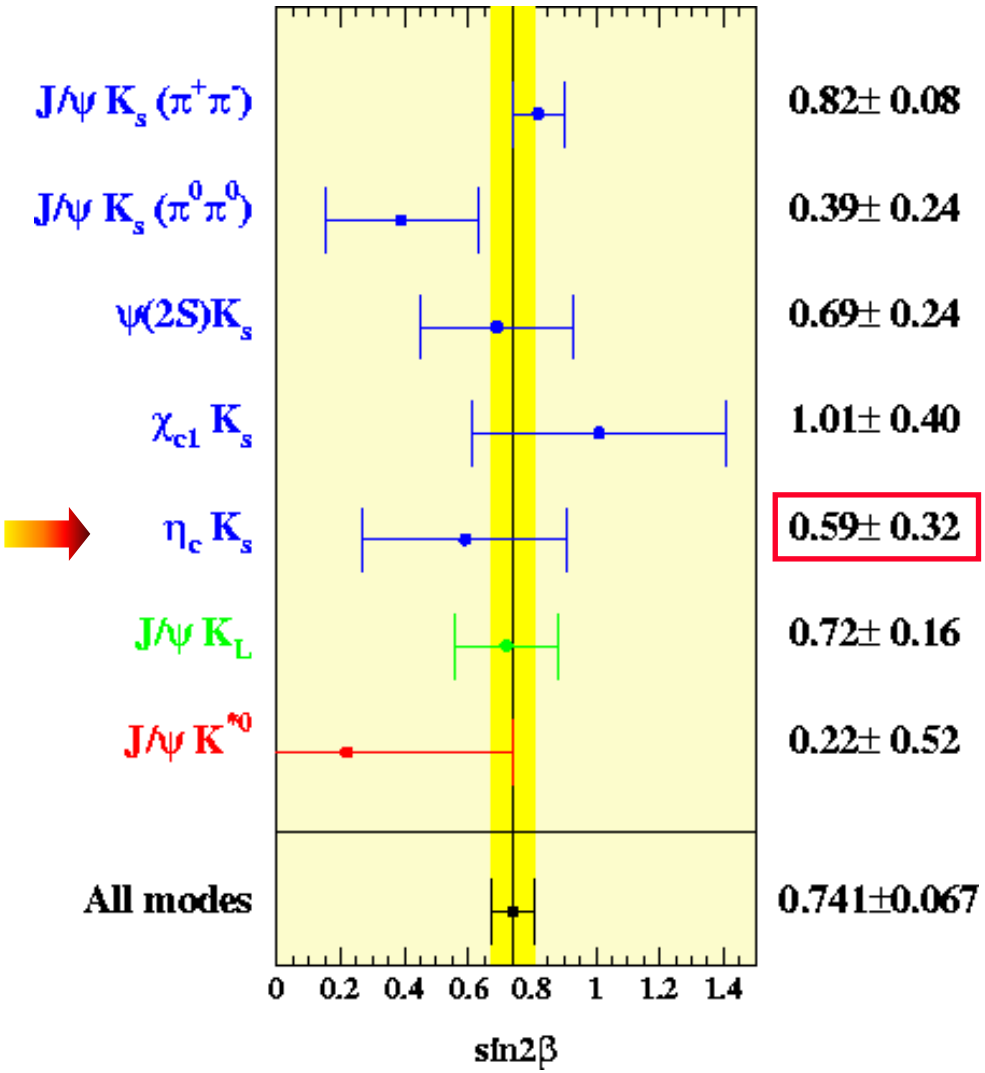
expect no "*CP*" asymmetry



Pure Gold: Lepton Tags

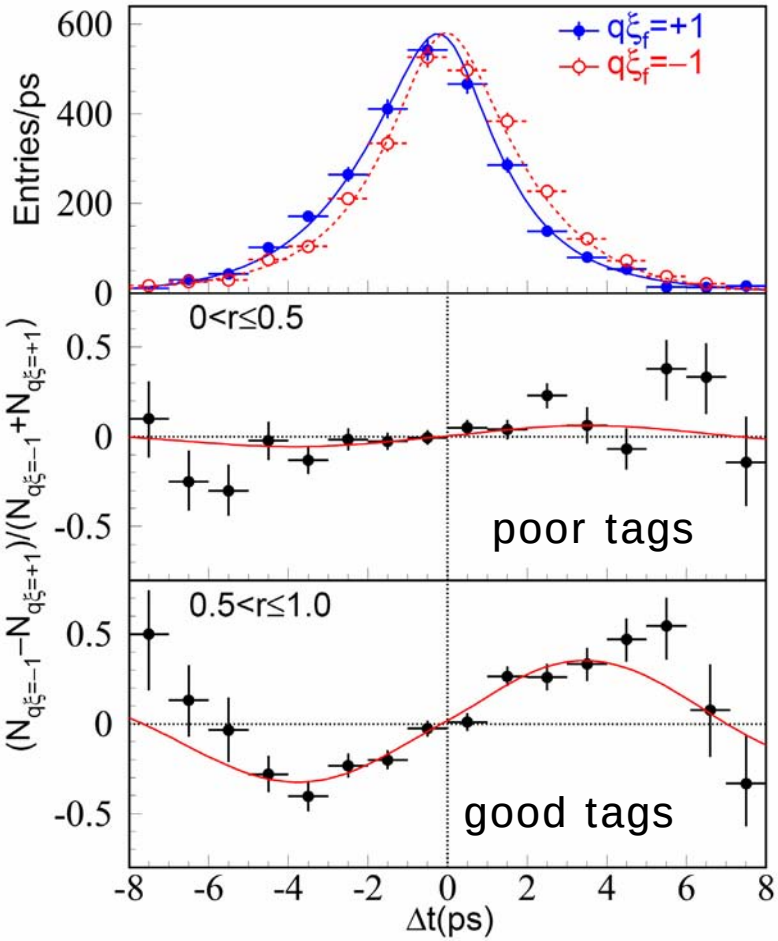


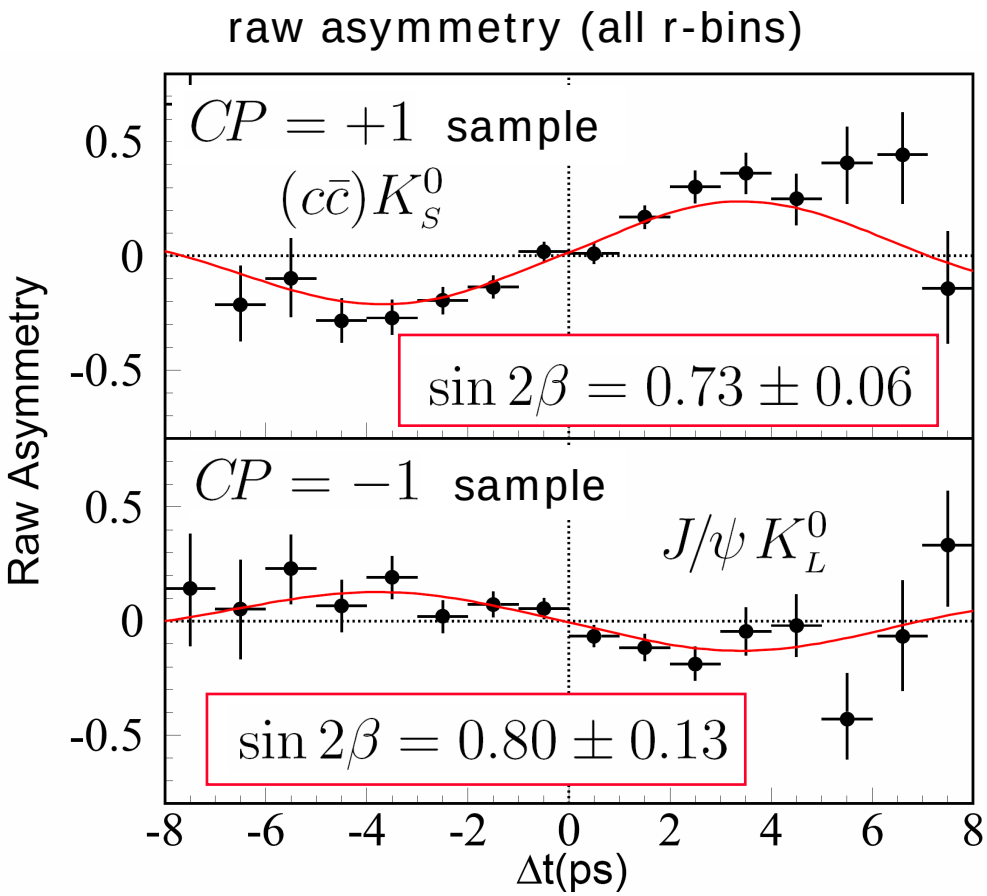
sin2β per Charmonium Mode



Very good consistency between the various measurements

Belle LP2003, 140/fb





$$\sin 2\beta = 0.733 \pm 0.057 \pm 0.028$$

Precision Test of the KM Model

Main experimental constraints on the apex of the UT

- Indirect *CP* violation in the kaon system
- Measurements of $|V_{ub}|$ ($b \to u$ transitions)
- B^0 mixing frequency and ratio of B_s to B^0 mixing frequencies

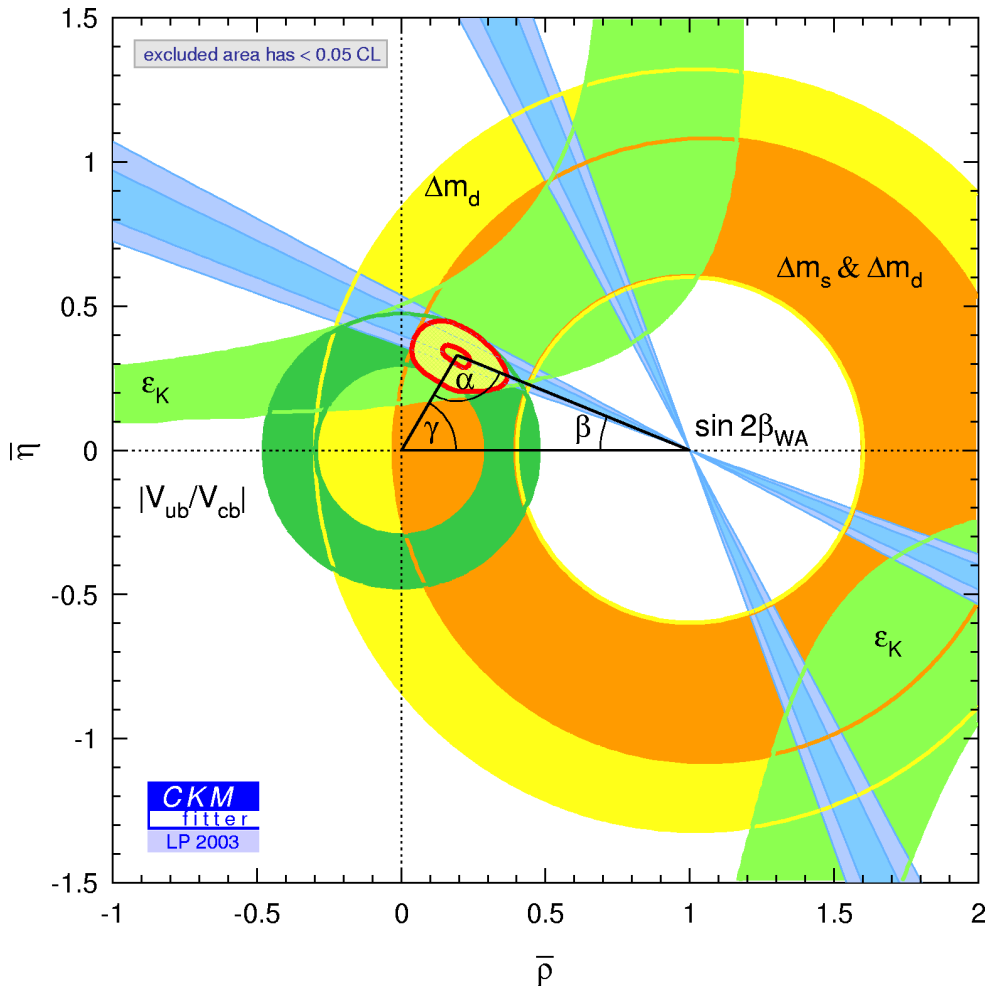
remarkable consistency!

$$\sin 2\beta_{\text{indirect}} = 0.715 \pm 0.055$$

World average (*BABAR* + Belle + ...)

$$\sin 2\beta = 0.739 \pm 0.048$$

Heavy **F**lavor **A**veraging **G**roup LP 2003



Search for Direct *CPV* in $J/\psi K$

★ Search for direct *CP* Violation in the Golden Sample

from $C_{J/\psi K^0_S}$ and $S_{J/\psi K^0_S}$, measure:

$$|\lambda_{J/\psi K^0_S}| = 0.948 \pm 0.051 \pm 0.030$$ *BABAR*

$$|\lambda_{(c\bar{c})K^0_S}| = 1.007 \pm 0.041_{\,(\mathrm{stat})}$$ Belle

In fact: cannot disentangle direct *CPV* from indirect *CPV* in mixing with this measurement

consistent with no direct *CP* violation

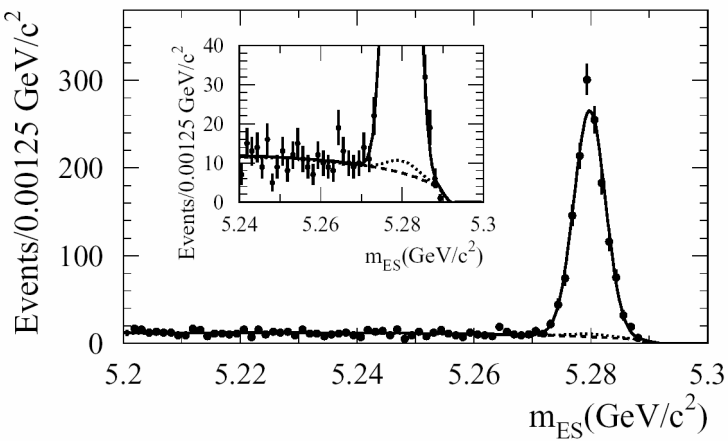
★ Search for direct CP violation in isospin-related charged mode

in 20.7 fb^{-1} select ~1300 candidates

$$\mathcal{A}_{J/\psi K^\pm} \equiv \frac{\mathcal{N}(J/\psi K^-) - \mathcal{N}(J/\psi K^+)}{\mathcal{N}(J/\psi K^-) + \mathcal{N}(J/\psi K^+)}$$

$$\mathcal{A}_{J/\psi K^\pm} = 0.003 \pm 0.030(\mathrm{stat}) \pm 0.004(\mathrm{syst})$$

$B^\pm \to J/\psi K^\pm$



Phys. Rev. D-RC **65** (2001)

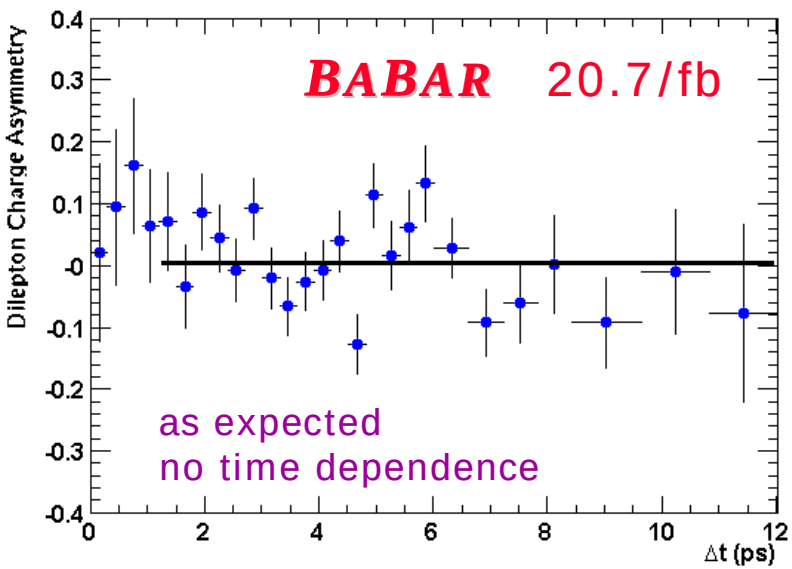
➡ again, no hint of direct *CP* violation...

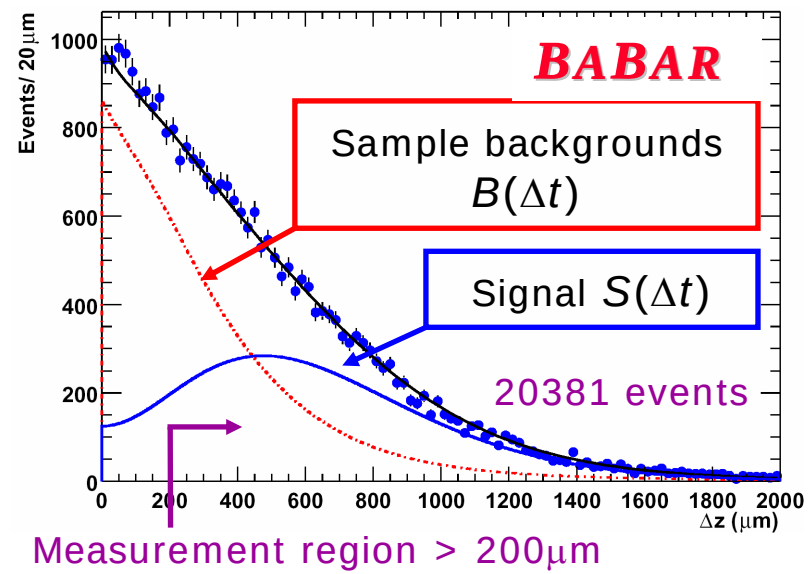
Search for Indirect *CP* Violation

Study asymmetry in same-sign dilepton sample

$$a_T^{\rm exp}(\Delta T) = \frac{\dot{\mathcal{N}}(\ell^+\ell^+, \Delta t) - \dot{\mathcal{N}}(\ell^-\ell^-, \Delta t)}{\dot{\mathcal{N}}(\ell^+\ell^+, \Delta t) + \dot{\mathcal{N}}(\ell^-\ell^-, \Delta t)} = a_T \times \frac{\mathcal{S}(\Delta t)}{\mathcal{S}(\Delta t) + \mathcal{B}(\Delta t)}$$

with $$a_T = \frac{1 - |q/p|^4}{1 + |q/p|^4}$$





$$a_T = (0.5 \pm 1.2 \pm 1.4)\%$$

Phys. Rev. Lett. **89** (2002) 201802

previous (less precise) studies by OPAL, ALEPH, CLEO

Limit on $\Delta\Gamma$ & Search for *CP*, *T*, and *CPT* Violation in Mixing

Using the Hadronic Sample (CP + Flavor Samples)

- Simultaneous fit to time-dependence of CP Sample and Flavor Sample, uncluding tagged and untagged events

hadronic sample: not as statistically powerful as the dilepton sample for study of *CP* and *CPT* in mixing, but complementary

- no assumption made on width difference, indirect *CP* violation, direct *CP* violation, *CPT* conservation
  - exploit all the information from the time distribution
  - prototype of future analyses in BABAR for the simultaneous determination of lifetimes, mixing and time-dependent CP asymmetries

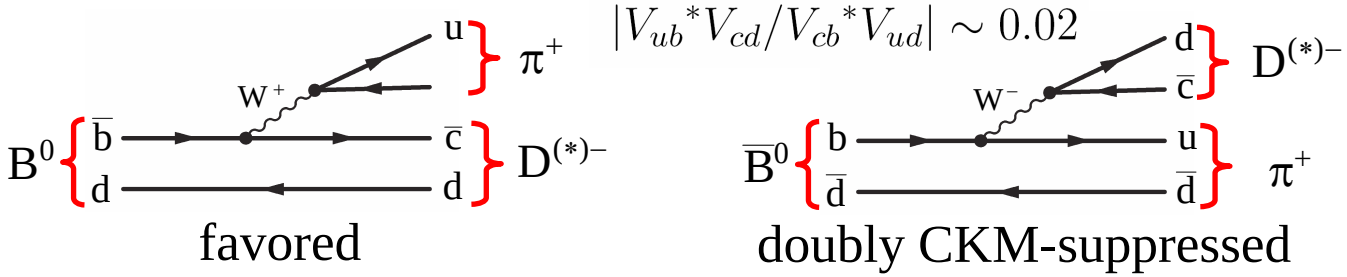
best way to deal with subtle correlations

- Subtle effects to deal with
  - Detector charge asymmetries
  - Doubly-CKM-Suppressed Decays (including interference rec/tag sides)

Doubly CKM-Suppressed Decays

$B \to DX$ decays receive contribution from $b \to u$ transitions at $O(10^{-4})$

$|V_{ub}{}^* V_{cd} / V_{cb}{}^* V_{ud}| \sim 0.02$



On the *rec* side

Exploit interference

$$B^0 \to D^{(*)-}\pi^+ \quad \Longleftrightarrow \quad B^0 \to \overline{B}^0 \to \pi^+ D^{(*)-}$$

relative weak phase: $\sim 2\beta + \gamma$

only tree amplitudes (no penguins!)

Theoretically clean determination of $\sin(2\beta+\gamma)$

Very small time-dependent asymmetry

exclusive and semi-inclusive analyses

Unknown amplitude ratio and strong phase

need experimental determination

Similarly:

$$B_s(\overline{B}_s) \to D_s^- K^+$$

promising way to measure $\sin(\gamma)$ at LHCb/BTeV

Doubly CKM-Suppressed Decays

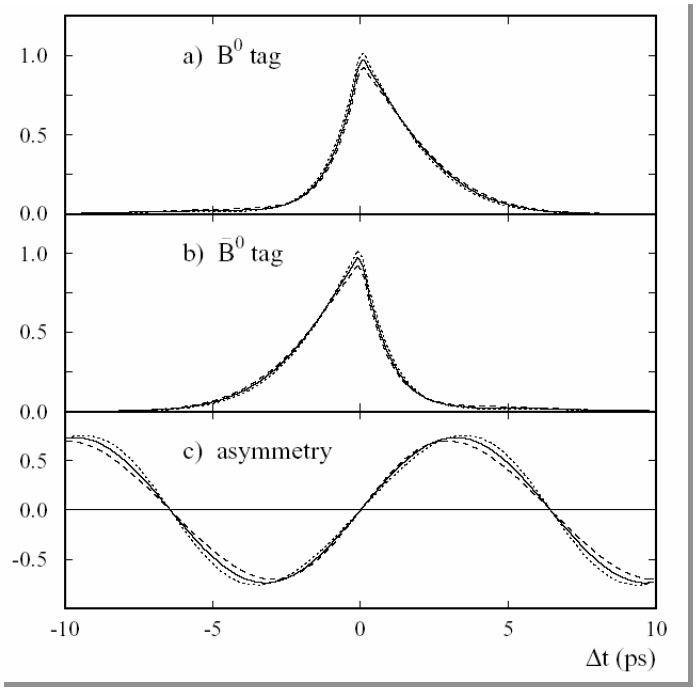
On the *tag* side

Effect of $b \to u$ is small and partially accounted for by measured mis-tag rates

- affects only kaon tags ($\to$ wrong-sign kaons), lepton tags unaffected

Residual time-dependent interference effect

- corrections on $C_{J/\psi K^0_S}$ and $S_{J/\psi K^0_S}$ that depend for each tagging mode on the size and phase of the amplitude ratio



Long, Baak, Cahn, Kirkby
hep-ex/0303030, submitted to PRD

systematic errors

$$\sigma_{DCKM}(\sin 2\beta) \simeq 0.008$$ marginal (total syst. 0.034)

$$\sigma_{DCKM}(|\lambda_{J/\psi K^0_S}|) \simeq 0.024$$ dominant (total syst. 0.030)

Back to Time-Dependent Rates

Differential event rate, as a function of the difference between the proper decay times of the two B mesons in the final state

let $\Delta\Gamma \neq 0$

$$\frac{d}{d\Delta t}\mathcal{N}(\Upsilon(4S) \to B\overline{B} \to f_{\rm tag}, f_{\rm rec}) \propto$$
$$\frac{1}{\Gamma}e^{-\Gamma|\Delta t|}\left\{\cosh\left(\frac{\Delta\Gamma\,\Delta t}{2}\right) + \sigma\sqrt{1-{T_{f_{\rm tag},\,f_{\rm rec}}}^2}\,\sinh\left(\frac{\Delta\Gamma\,\Delta t}{2}\right)\right.$$
$$\left. - C_{f_{\rm tag},\,f_{\rm rec}} \times \cos(\Delta m\,\Delta t) + S_{f_{\rm tag},\,f_{\rm rec}} \times \sin(\Delta m\,\Delta t)\right\}$$

← was = 1!

with $C_{f_{\rm tag},\,f_{\rm rec}} = \dfrac{|a_m|^2 - |a_u|^2}{|a_m|^2 + |a_u|^2}$ $\qquad S_{f_{\rm tag},\,f_{\rm rec}} = \dfrac{2\,{\rm Im}(a_u^* a_m)}{|a_m|^2 + |a_u|^2}$

and ${T_{f_{\rm tag},\,f_{\rm rec}}}^2 \equiv {C_{f_{\rm tag},\,f_{\rm rec}}}^2 + {S_{f_{\rm tag},\,f_{\rm rec}}}^2 \leq 1$

let $z \neq 0$

now, we have

$$a_u \equiv \overline{A}_{f_{\rm tag}} A_{f_{\rm rec}} - A_{f_{\rm tag}} \overline{A}_{f_{\rm rec}}$$
$$a_m \equiv \underbrace{\sqrt{1-z^2}}_{\text{was = 1}}\left(\frac{q}{p}\overline{A}_{f_{\rm tag}}\overline{A}_{f_{\rm rec}} - \frac{p}{q}A_{f_{\rm tag}}A_{f_{\rm rec}}\right) + \underbrace{z\,(\overline{A}_{f_{\rm tag}}A_{f_{\rm rec}} + A_{f_{\rm tag}}\overline{A}_{f_{\rm rec}})}_{\text{was absent}}$$

Life seems to be significantly more complicated!

fortunately, fitted quantities largely uncorrelated

Results of Full Time-Dependent Fit

★ Preliminary results

to be submitted to
Phys. Rev. Lett. & Phys. Rev. D

$$\begin{aligned}
\mathrm{sign}(\mathrm{Re}\,\lambda_{CP}) \times \Delta\Gamma/\Gamma &= -0.008 \pm 0.037 \pm 0.018 \quad [-0.084, +0.068] \\
|\,q/p\,| &= 1.029 \pm 0.013 \pm 0.011 \quad [+1.001, +1.057] \\
(\,\mathrm{Re}\,\lambda_{CP}/\,|\,\lambda_{CP}\,|\,) \times \mathrm{Re}\,z &= 0.014 \pm 0.035 \pm 0.034 \quad [-0.072, +0.101] \\
\mathrm{Im}\,z &= 0.038 \pm 0.029 \pm 0.025 \quad [-0.028, +0.104]
\end{aligned}$$

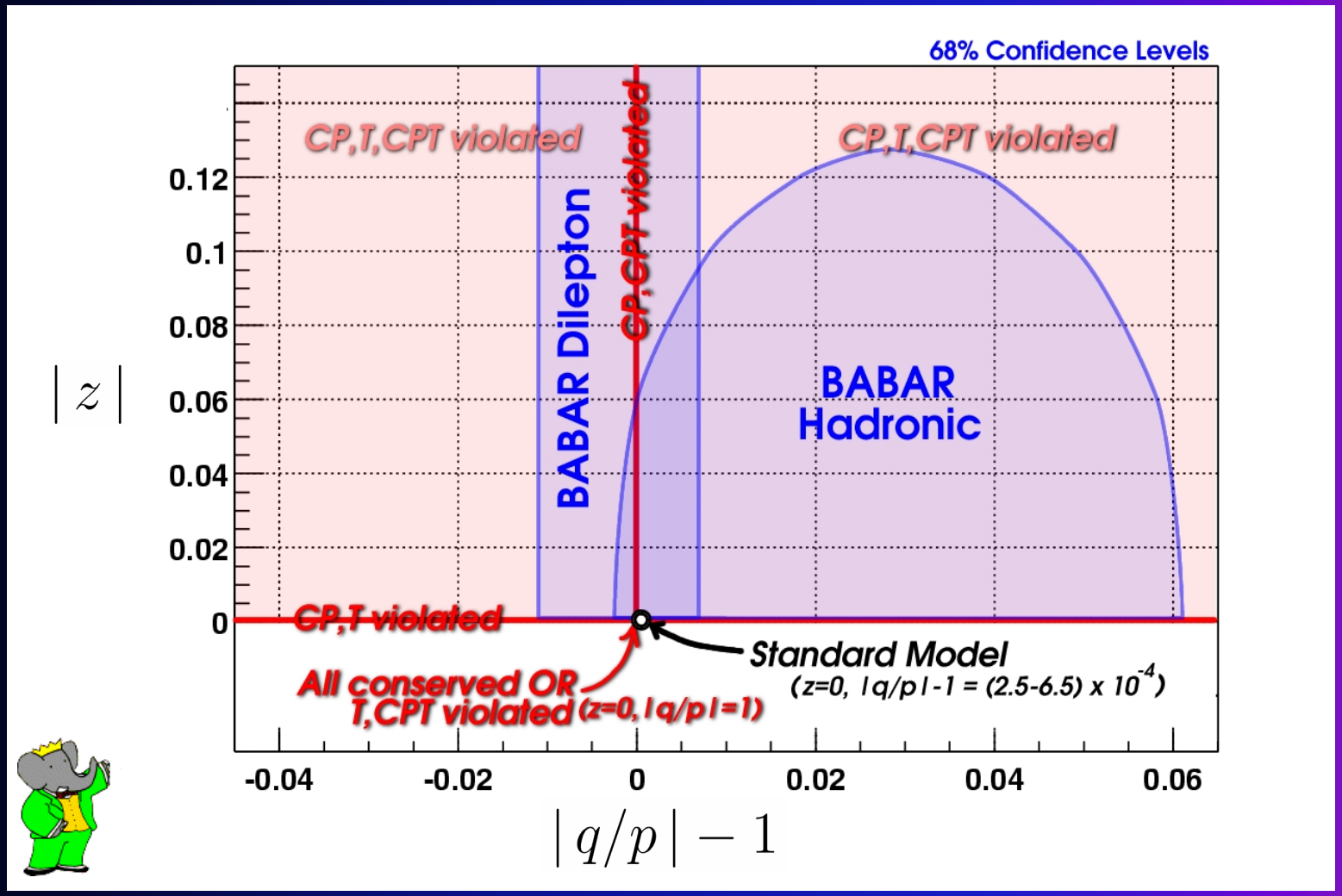
90% CL intervals

- Direct limit on $\Delta\Gamma/\Gamma$
- Test of *CPT* invariance
- Study for indirect *T*/*CP* violation in *B* mixing

★ Cross-checks

$\Delta m \quad \sin 2\beta$	consistent with published values
$\lvert\overline{A}_{CP}/A_{CP}\rvert$	consistent with no direct CPV (4.5%)

Constraints on *CP*/*T* and *CPT* in Mixing



Promising ways to look for New Physics

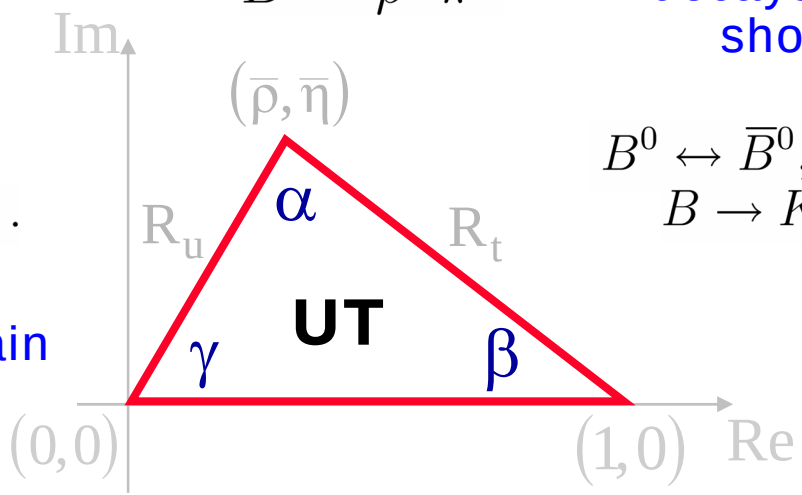
★ measure/constrain angle α

$B \to \pi^+\pi^-$
$B \to \rho^\pm\pi^\mp$

★ measure sin2β in several decays sensitive to different short-distance physics

$B^0 \leftrightarrow \overline{B}^0,\ \Delta m\,(\phi_M = -\beta)$
$B \to K^*\gamma + \rho/\omega\,\gamma$

$B \to \pi/\rho/\omega\,\ell\nu, \ldots$



★ measure/constrain angle γ

$B \to DK^{(*)}$
$B \to DK^0_S$
$B \to K\pi$
$B \to D^*\pi$

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

★ improve UT side measurements

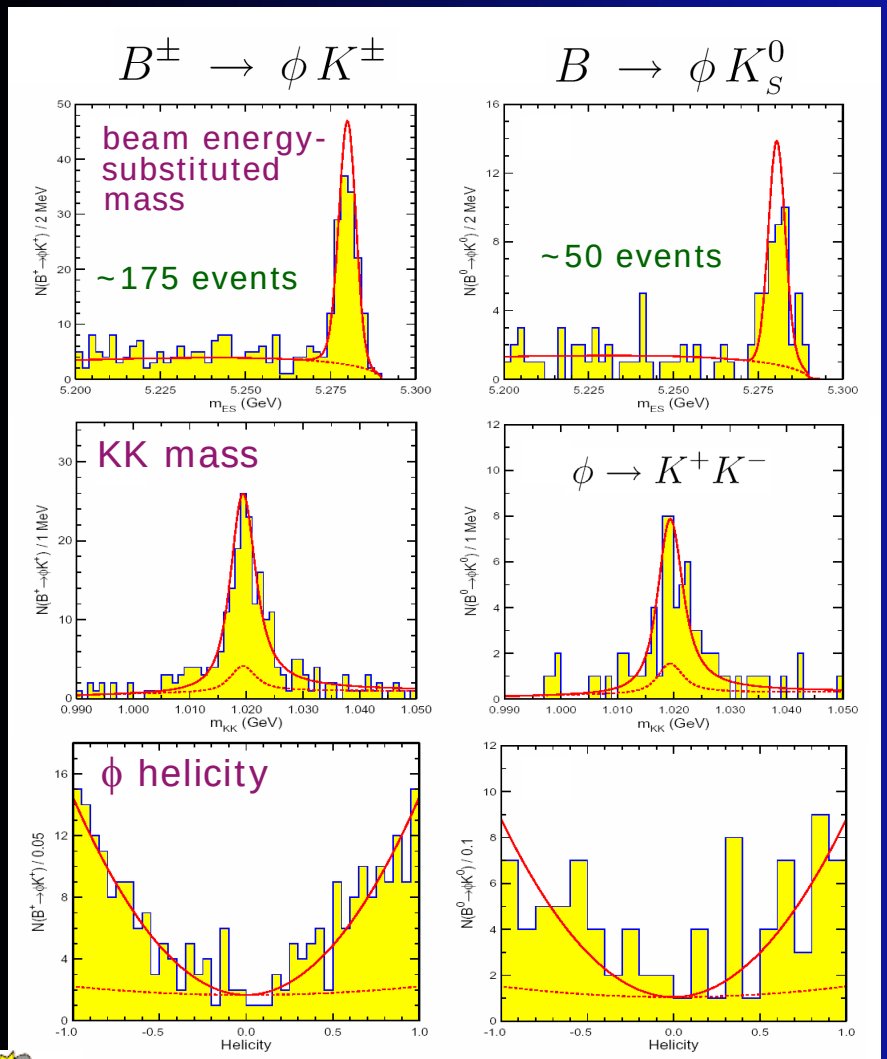
$B \to J/\psi\ K^0_S \quad b \to c\,\bar c\,s$

$B \to \phi\,K^0_S$
$B \to \eta'\,K^0_S \quad b \to s\,\bar s\,s$

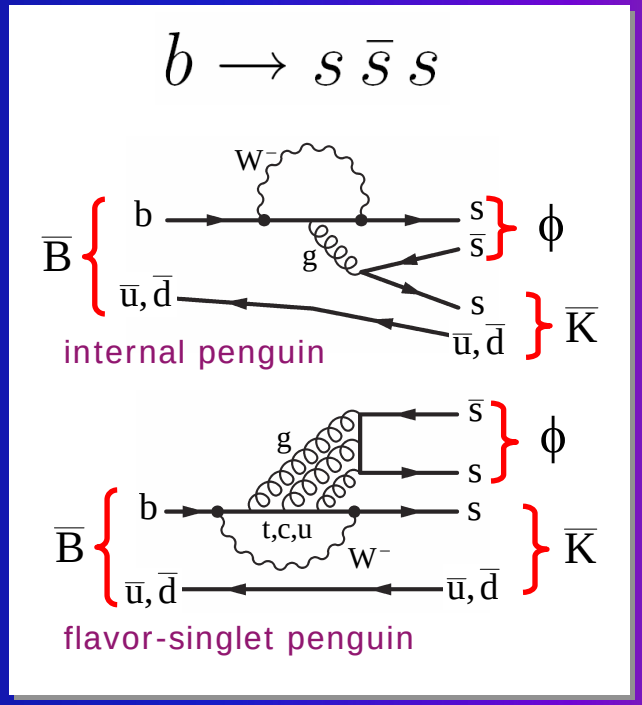
$B \to D^{*\pm}D^\mp$
$B \to D^{*+}D^{*-} \quad b \to c\,\bar c\,d$

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

$B \to \phi K$

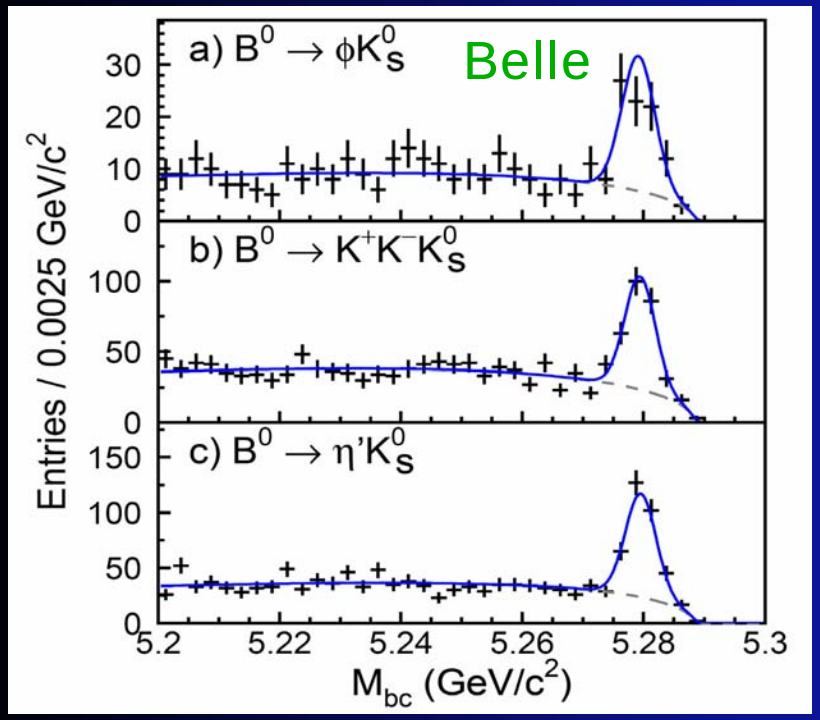


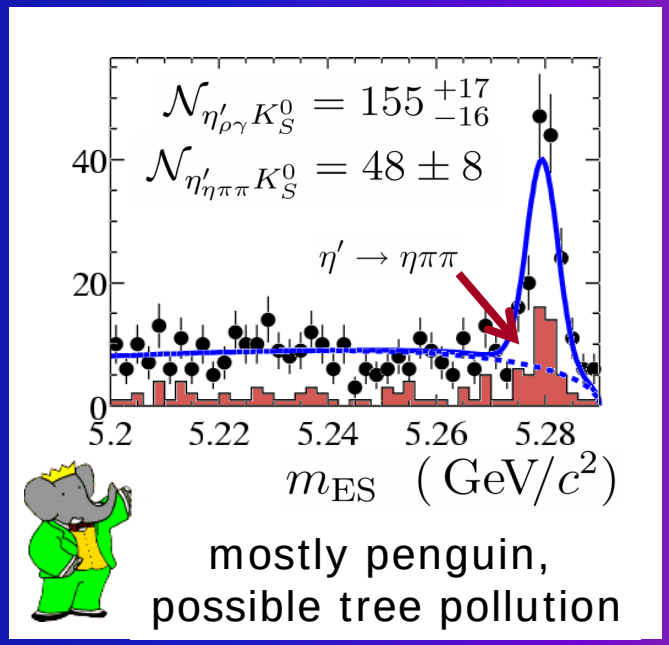
with 89 million BB pairs



- Pure penguin decay, therefore potentially a place to look for New Physics

- In SM, expect $S_{\phi K^0_S} = \sin 2\beta$





Belle 2003 (preliminary)

$$S_{\phi K^0_S} = -0.96 \pm 0.50\,^{+0.09}_{-0.11}$$
$$C_{\phi K^0_S} = +0.15 \pm 0.29 \pm 0.07$$

disagreement?

BABAR 2003 (preliminary)

$$S_{\phi K^0_S} = +0.45 \pm 0.43 \pm 0.07$$
$$C_{\phi K^0_S} = -0.38 \pm 0.37 \pm 0.12$$

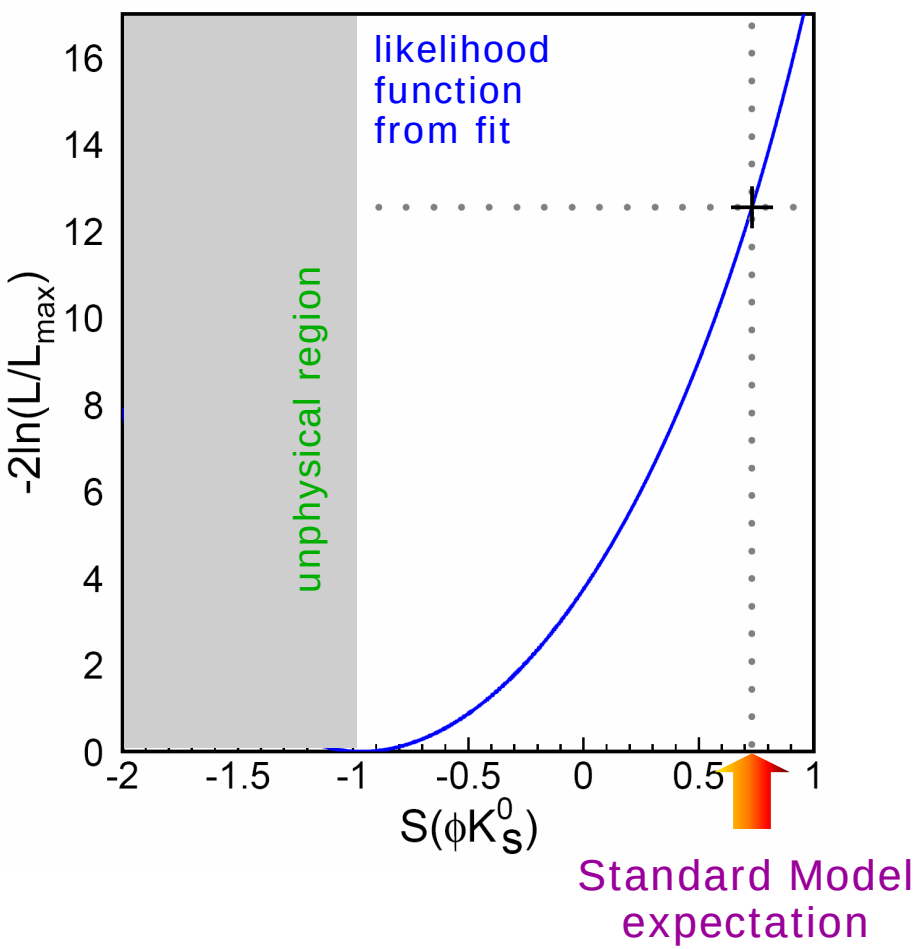
Strongly disagrees with Standard Model expectation!
First evidence for **New Physics** ?

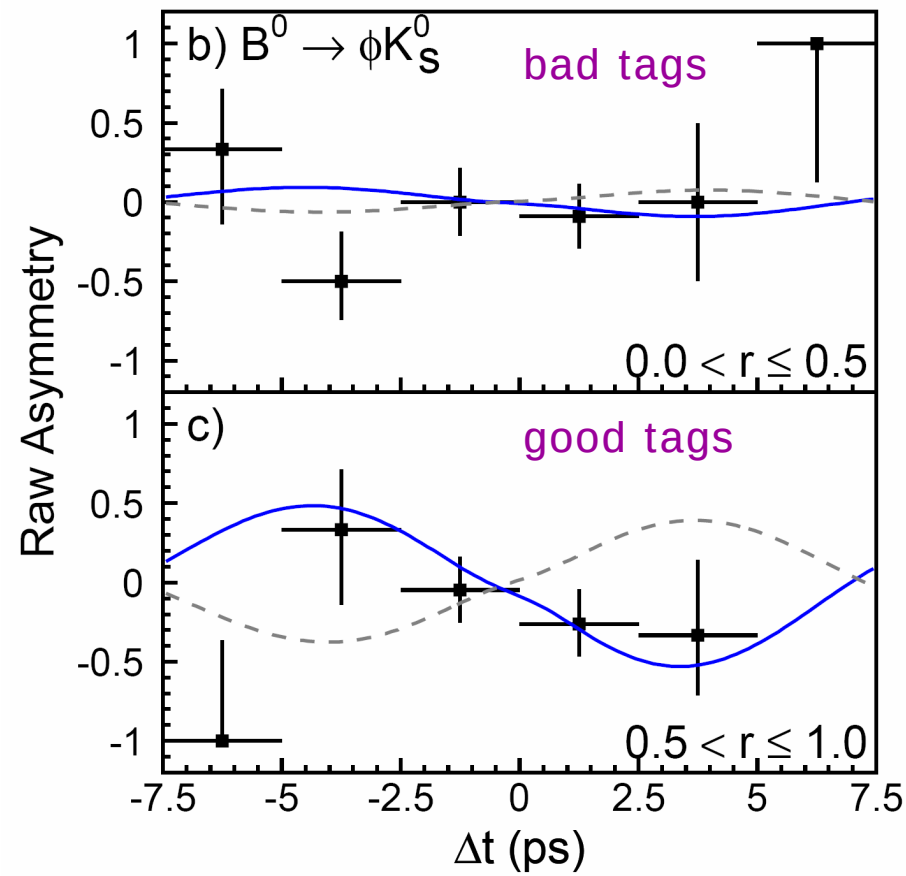
In agreement with SM
Evidence for New Physics not confirmed by BABAR

Hint of New Physics?

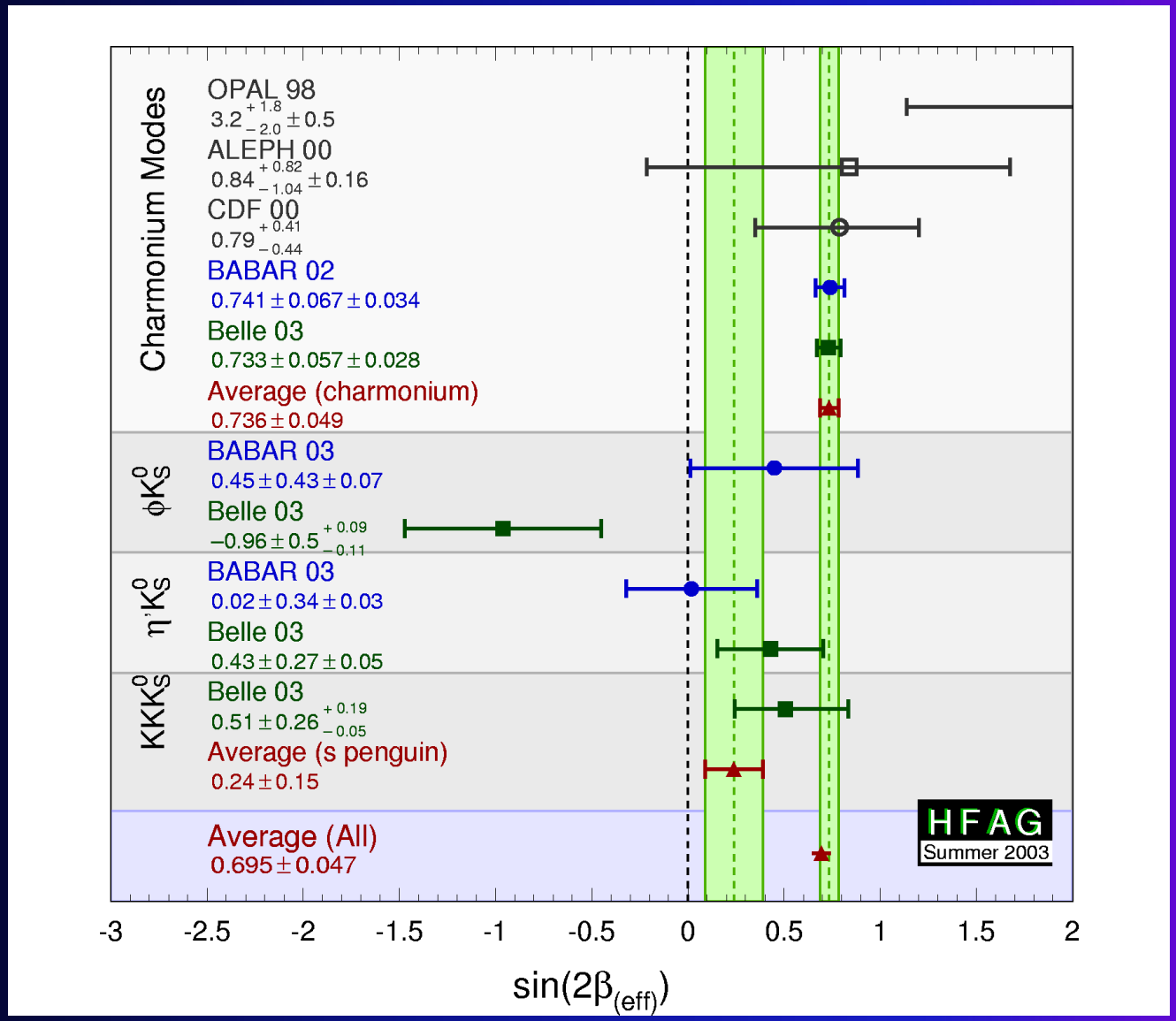
$B \rightarrow \phi K_S^0$

Belle at
Lepton-Photon 2003



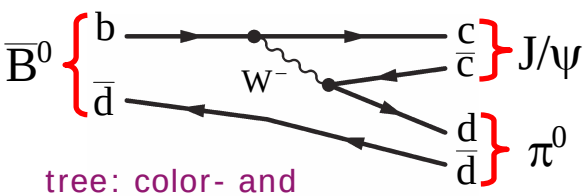


Charmonium versus s Penguin

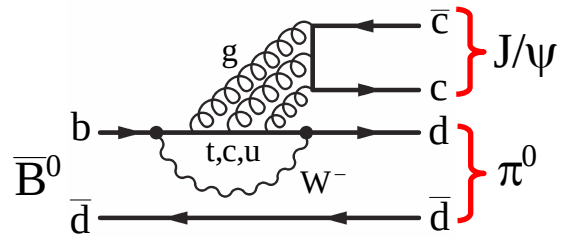


$b \to c\,\bar{c}\,d$

★

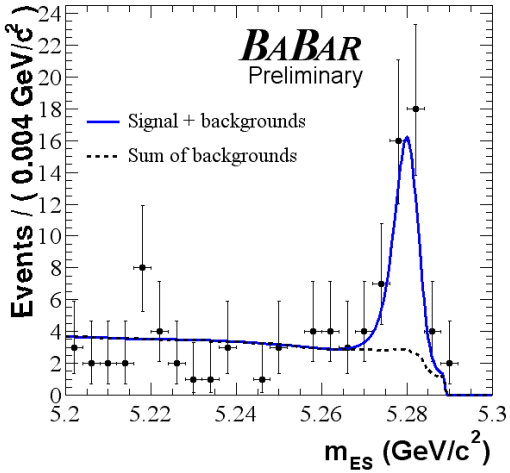


tree: color- and Cabibbo-suppressed



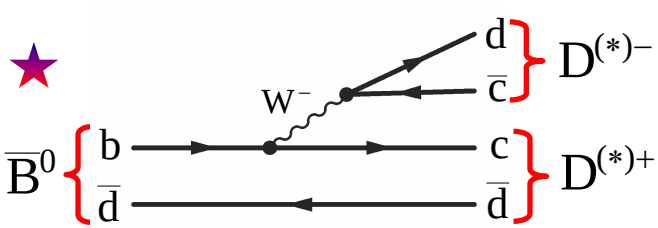
penguin: competing weak phase?

$\mathcal{N}_{J/\psi\pi^0} = 40 \pm 7$

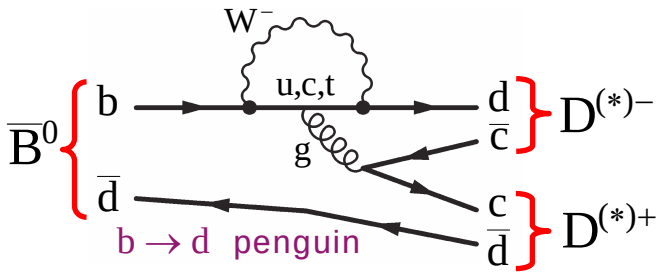


if penguin contribution negligible $S_{J/\psi\pi^0} = -\sin 2\beta$

★



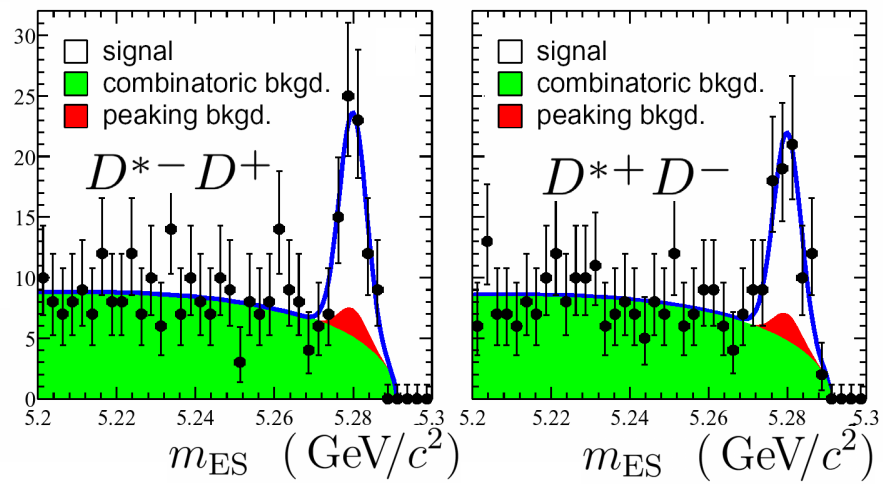
Cabibbo-suppressed tree



$b \to d$ penguin

$\mathcal{N}_{D^{*\pm}D^{\mp}} = 113 \pm 13$

$D^{*-}D^{+}$ not *CP* eigenstate



if penguins are negligible

$$C_{-+} = C_{+-} = 0$$

$$S_{-+} = S_{+-} = -\sin 2\beta$$

$B \to D^{*+} D^{*-}$

$b \to c\,\bar{c}\,d$

★ Sample $\mathcal{N}_{D^{*+}D^{*-}} = 126 \pm 13$

(before flavor-tagging)

★ Vector-Vector decay (L=0,1,2)
possible mix of CP = +1 and CP = –1

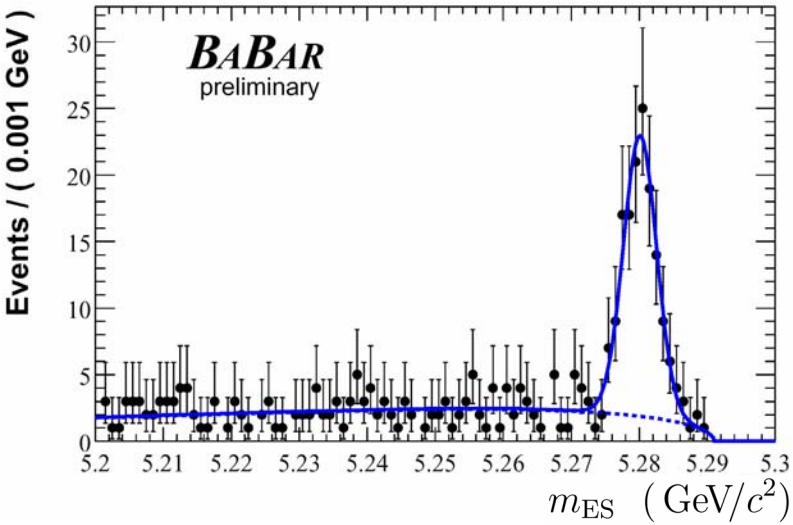
Transversity analysis
➡ mostly CP-even

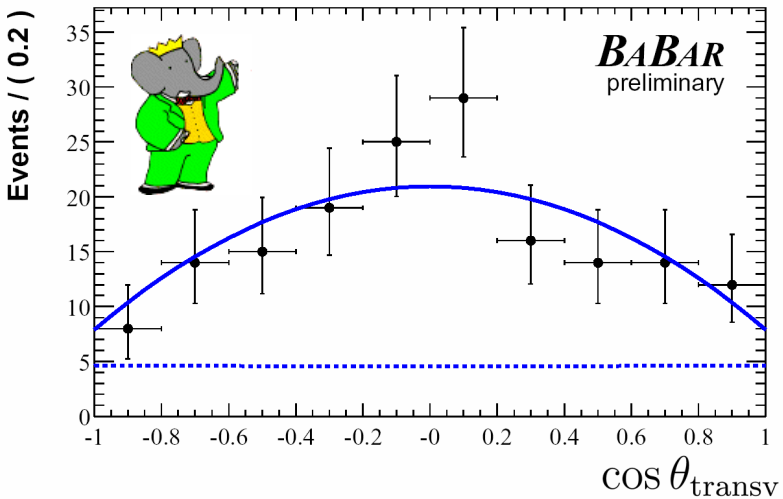
$$R_\perp = 0.07 \pm 0.06\,(\text{stat}) \pm 0.03\,(\text{syst})$$

define CP-even parameter $(\lambda_{D^*D^*})_+$

★ If penguin contribution negligible

$$\text{Im}\,(\lambda_{D^*D^*})_+ = -\sin 2\beta$$
$$|(\lambda_{D^*D^*})_+| = 1$$

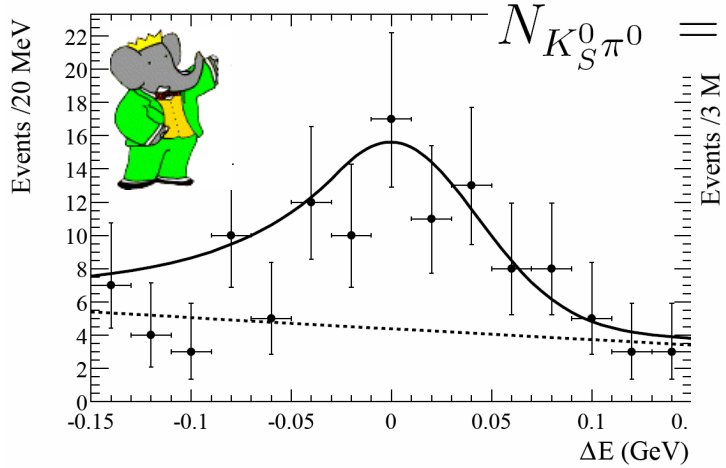




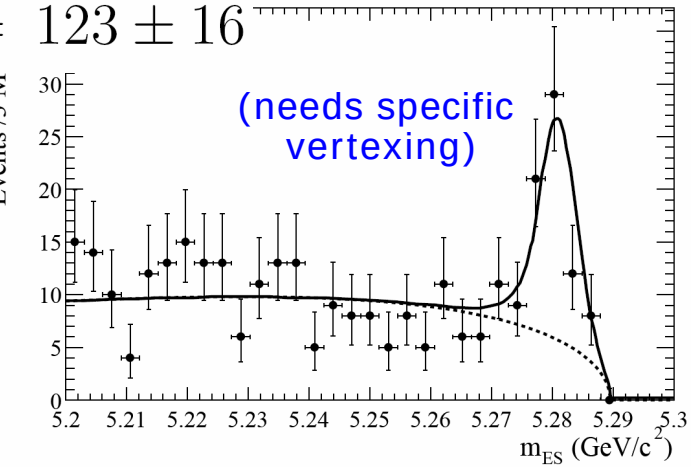
$K_s\pi^0$ Time-Dependent

$b \to d\bar{d}s$

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



$N_{K_S^0\pi^0} = 123 \pm 16$



process dominated by $b \to d\bar{d}s$ Penguin

possible small pollution by CKM and color-suppressed $b \to u\bar{u}s$ Tree

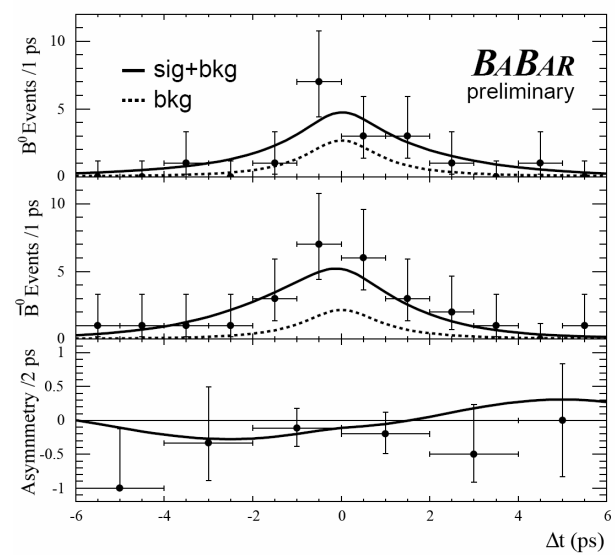
BABAR, 113/fb

(124 million BB pairs)

$$S_{K_S^0\pi^0} = 0.48^{+0.38}_{-0.47} \pm 0.11$$

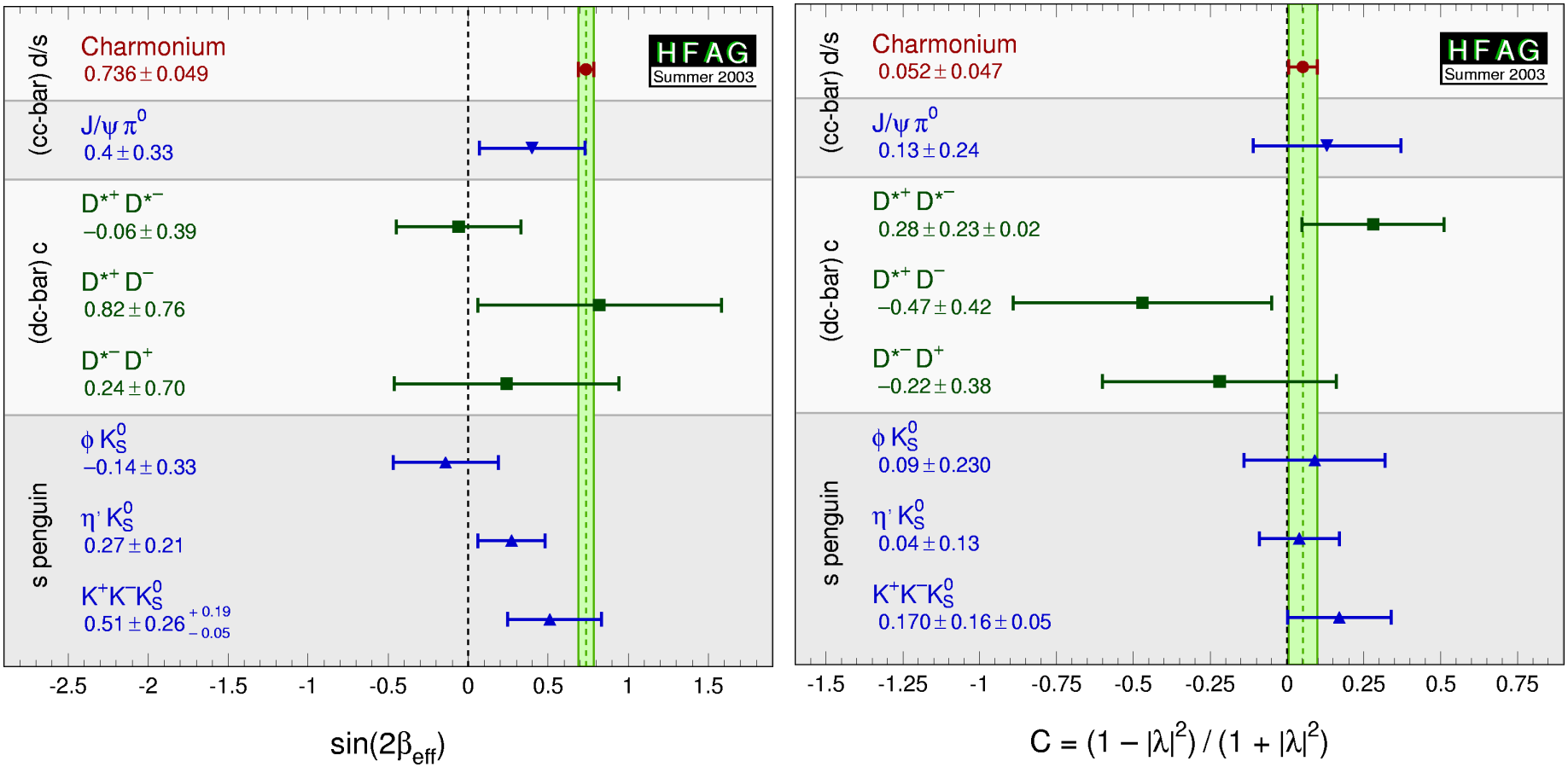
$$C_{K_S^0\pi^0} = 0.40^{+0.27}_{-0.28} \pm 0.10$$

$$S_{K_S^0\pi^0}\,(\text{fixing } C_{K_S^0\pi^0} = 0) = 0.41^{+0.41}_{-0.48} \pm 0.11$$



S consistent with sin2β (Standard Model expectation)

Comparison of Various "sin2β"



very promising way to contradict the Standard Model
(obviously more statistics needed!)