Heavy Quark Physics and CP Violation (II)

Jeffrey D. Richman

University of California, Santa Barbara

$$\begin{bmatrix} u \\ \ \end{bmatrix}\begin{bmatrix} c \\ s \end{bmatrix}\begin{bmatrix} \ \\ b \end{bmatrix}$$

XIII Mexican School of Particles and Fields
Oct. 2 - 11, 2008

Outline

- **Lecture 2**
  - **Thinking about symmetries; continuous vs. discrete**
  - **The three kinds of CP violation**
  - **Direct CP violation**
  - **BaBar detector: Tracking, Particle ID (π/K separation)**
  - **Measuring lifetimes and oscillations (first look)**
  - **Silicon vertex detectors**
  - **Pitfalls of data analysis**

Thinking about Symmetries

Symmetries are fundamental to understanding the forces of nature.
<u>We characterize interactions by the symmetries they possess.</u>

In quantum mechanics, symmetries are nearly always represented by unitary transformations (*U*).

$$|\psi\rangle \rightarrow |\psi'\rangle = U|\psi\rangle$$

U modifies the state vector

...while preserving its norm.

$$\langle\psi'|\psi'\rangle = \langle U\psi|U\psi\rangle = \langle\psi|U^{\dagger}U|\psi\rangle = \langle\psi|\psi\rangle$$

$$[U,H] = 0 \quad \Rightarrow \quad U \text{ is a symmetry of } H$$

If *U* is a symmetry, then

$$H|\psi\rangle = i\hbar\frac{d}{dt}|\psi\rangle \;\Rightarrow\; H\big(\underbrace{U|\psi\rangle}\big) = i\hbar\frac{d}{dt}\big(\underbrace{U|\psi\rangle}\big)$$

Solution to Schrodinger eq'n.

Also a solution to Sch. eq'n.

Continuous Symmetry Transformations

- Continuous symmetry transformations can be written as a function of a real parameter θ, which can be a vector of parameters.

$$U(\theta) = e^{-i\cdot\theta\cdot G} \quad (\text{ where } G^\dagger = G \text{ since } U \text{ is unitary})$$

$$\cong I - i\cdot\delta\theta\cdot G \quad \text{for small } \delta\theta$$

"Generator" of the transformation: a QM observable!

- Example: the translation operator is

$$U(\vec{x}) = e^{-i\vec{P}\cdot\vec{x}/\hbar} = e^{-i(P_x x + P_y y + P_z z)/\hbar}$$

Suppose: $[H, U(\vec{x})] = 0$ for arb. $\vec{x}$

$\Rightarrow$ translational invariance along $\hat{x}$

$\Rightarrow [H, \vec{P}\cdot\hat{x}] = 0$ then momentum will be conserved (additively); see next slide

Some consequences of symmetries

1. Conserved quantum numbers

$$0 = \langle \psi_b | [H, G] | \psi_a \rangle = \langle \psi_b | HG - GH | \psi_a \rangle$$
$$= (g_b - g_a) \langle \psi_b | H | \psi_a \rangle$$
$$\Rightarrow \begin{cases} g_b = g_a & \text{(quantum number conserved)} \\ \text{or} \quad \langle \psi_b | H | \psi_a \rangle = 0 & \text{(no transition)} \end{cases}$$

2. Relations between amplitudes

$$0 = \langle \phi | U^\dagger H U - H | \psi \rangle = \langle U\phi | H | U\psi \rangle - \langle \phi | H | \psi \rangle$$
$$\Rightarrow \langle U\phi | H | U\psi \rangle = \langle \phi | H | \psi \rangle$$

Same amplitudes for these transitions!

3. Existence of multiplets (states with same energies)

$$[H, U] = 0 \quad \Rightarrow \quad \langle U\psi | H | U\psi \rangle = \langle \psi | H | \psi \rangle$$

Testing for Violation of Symmetries

1. Non-conserved quantum numbers

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

$$J^P = 0^- \to \underbrace{0^-0^-}_{\eta_P = \eta_{\pi^+}\eta_{\pi^-}(-1)^\ell = +1 \qquad (\ell = 0)}$$

Violates parity (weak decay).

2. Broken relationships between amplitudes

$$\Gamma(B^0 \to K^+\pi^-) \neq \Gamma(\overline{B}^0 \to K^-\pi^+)$$

Violates CP

3. Masses of particles in multiplet not the same

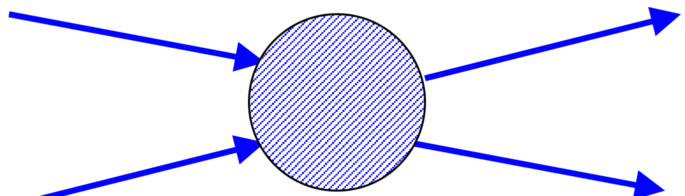
$$\begin{pmatrix} p \\ n \end{pmatrix} \qquad m_p = 938.27 \text{ MeV}/c^2 \qquad m_n = 939.57 \text{ MeV}/c^2$$

I-spin violation (quark masses, EM interaction)

Conservation laws from continuous symmetry transformations

$|\psi_a(\vec{p}_a)\rangle$

$|\psi_b(\vec{p}_b)\rangle$



$|\psi_c(\vec{p}_c)\rangle$

$|\psi_d(\vec{p}_d)\rangle$

momentum eigenstates

$$\langle\psi_c,\psi_d|H|\psi_a,\psi_b\rangle = \langle\psi_c,\psi_d|U^\dagger UHU^\dagger U|\psi_a,\psi_b\rangle \qquad [U,H]=0$$

$$= \langle\psi_c,\psi_d|U^\dagger HU|\psi_a,\psi_b\rangle$$

$$= \langle\psi_c,\psi_d|e^{+i\vec{P}\cdot\vec{x}/\hbar}He^{-i\vec{P}\cdot\vec{x}/\hbar}|\psi_a,\psi_b\rangle$$

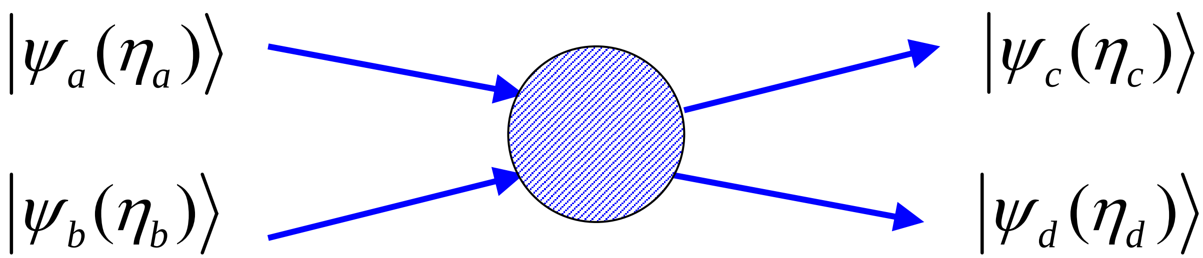
$$= \langle\psi_c,\psi_d|H|\psi_a,\psi_b\rangle e^{+i[(\vec{p}_c+\vec{p}_d)-(\vec{p}_a+\vec{p}_b)]\cdot\vec{x}/\hbar}$$

Momentum is *additively* conserved!

$$\Rightarrow \begin{cases} \vec{p}_a + \vec{p}_b = \vec{p}_c + \vec{p}_d \\ \text{or} \quad \langle\psi_c,\psi_d|H|\psi_a,\psi_b\rangle = 0 \end{cases}$$

(or else transition is not allowed)

Conservation laws from <u>discrete</u> symmetry transformations



C eigenstates for simplicity

$$0 = \langle \psi_c, \psi_d | [H, C] | \psi_a, \psi_b \rangle = \langle \psi_c, \psi_d | H \eta_c \eta_d - \eta_a \eta_b H | \psi_a, \psi_b \rangle$$

$$= (\eta_c \eta_d - \eta_a \eta_b) \langle \psi_c, \psi_d | H | \psi_a, \psi_b \rangle$$

C is unitary & hermitian (discrete xf)

$$\Rightarrow \begin{cases} \eta_c \eta_d = \eta_a \eta_b \\ \text{or} \quad \langle \psi_c, \psi_d | H | \psi_a, \psi_b \rangle = 0 \end{cases}$$

The *C* eigenvalue is <u>*multiplicatively*</u> conserved!

(or else transition is not allowed)

Three Kinds of *CP* Violation

We have seen that CP violation arises as an <u>interference effect</u>.

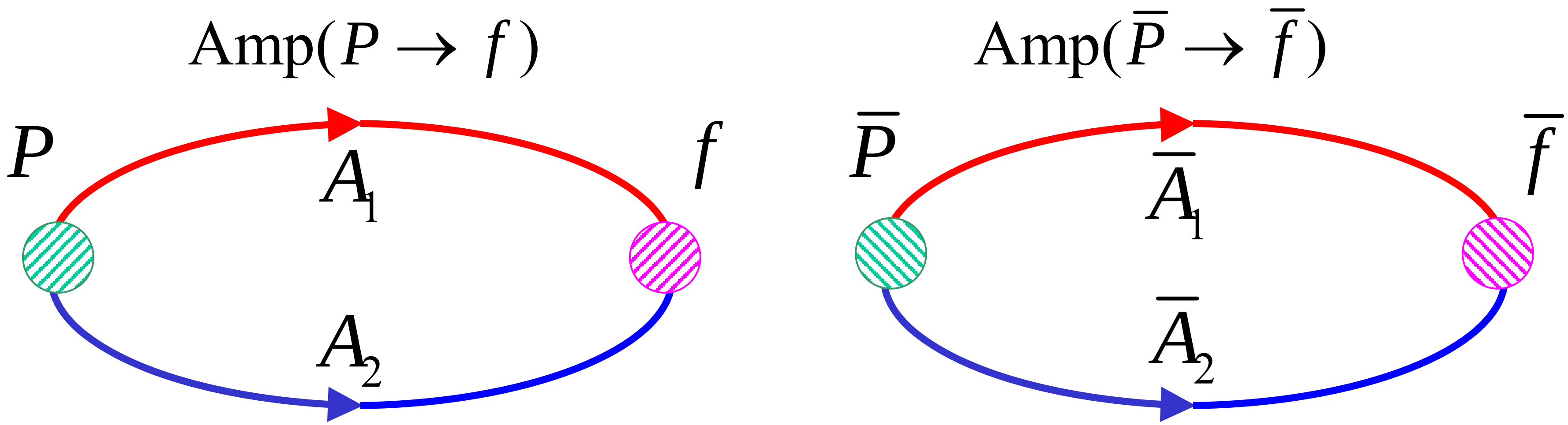
- Need at least two interfering amplitudes
- Need relative CP-violating phase
- Need relative CP-conserving phase

A single CP-violating amplitude by itself will not produce observable CP violation!

<u>Classification of CP-violating effects in particle transitions</u>
(based on the sources of amplitudes that are present).

1. CP violation in oscillations ("indirect CP violation")
2. CP violation in decay ("direct CP violation")
3. CP violation in the interference between mixing and decay

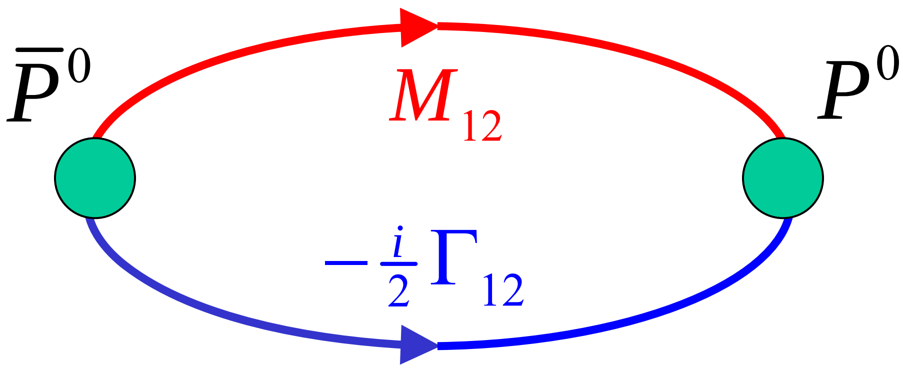
Direct CP violation: interfering decay amplitudes



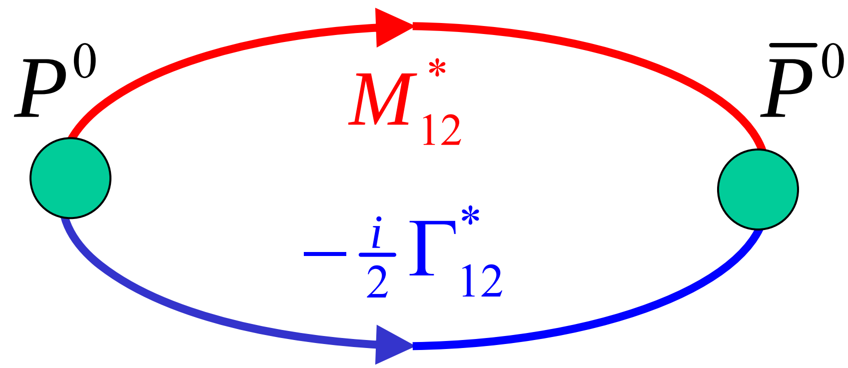
Direct CP violation seems the most straight-forward: it doesn't involve mixing to generate one of the amplitudes.

- Can occur in decays of both neutral & charged particles
- But the CP-conserving phases are from strong (QCD) interactions between the mesons ("final-state interactions"). These strong phases cannot be predicted reliably.

CP Violation in oscillations



$\mathrm{Amp}(\bar{P}^0 \to P^0)$



$\mathrm{Amp}(P^0 \to \bar{P}^0)$

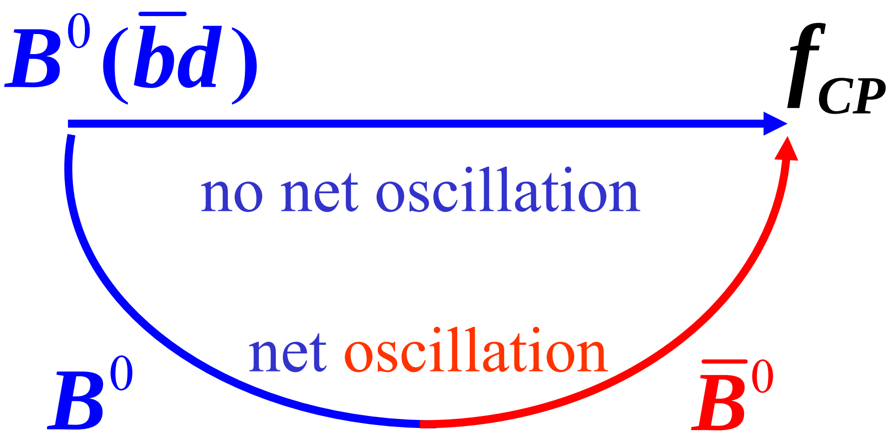
M_{12} = transition amplitude via intermediate states that are virtual (off-shell)

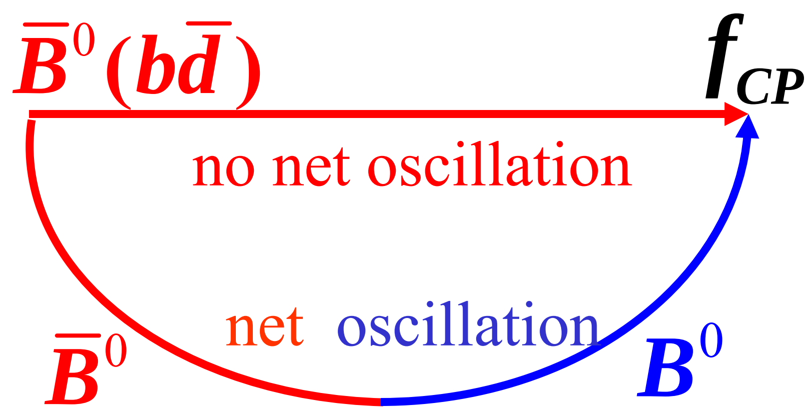
Γ_{12} = transition amplitude via intermediate states are are real (on-shell: both P^0 and $\bar{P}^0$ can decay into these!)

- The "-i" is a CP conserving phase factor. It doesn't change sign!
- M_{12} and Γ_{12} behave like CP-violating phase factors, as long as they are not relatively real.

Time-dependent CP asymmetries from the interference between mixing and decay amplitudes

By modifying the mixing measurement, we can observe whole new class of CP-violating phenomena: pick final states that both B^0 and $\bar{B}^0$ can decay into. (Often a CP eigenstate, but doesn't have to be.)





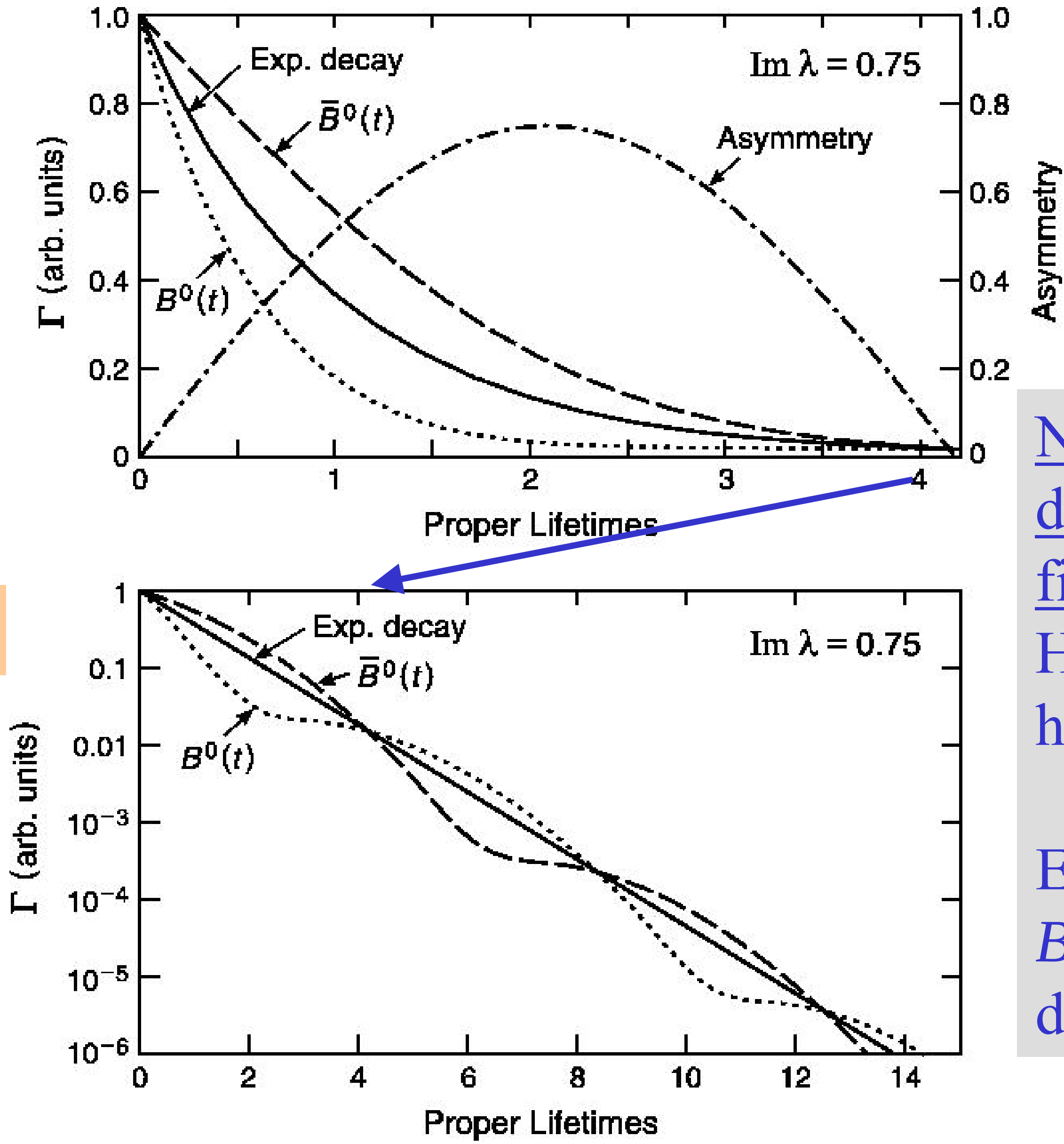
$$\Gamma(B^0_{phys}(t) \to f_{CP})$$

$$\Gamma(\bar{B}^0_{phys}(t) \to f_{CP})$$

Preview: the strange behavior of $B^0 \rightarrow J/\psi\ K_s$

Linear scale

Log scale



Non-exponential decay law in this final state!

How does this happen?

Even stranger: B^0 and $\bar{B}^0$ behave differently. Why?

Conjugate amplitudes and direct CP violation

What is the relation between an amplitude and its conjugate?

$$\left.\begin{aligned} CP\left|P\right\rangle &= e^{i\theta(P)}\left|\overline{P}\right\rangle \\ CP\left|\overline{P}\right\rangle &= e^{-i\theta(P)}\left|P\right\rangle \\ (CP)^2\left|P\right\rangle &= \left|P\right\rangle \end{aligned}\right\}$$

Often, people choose a specific phase convention. I like to keep the non-physical CP phase explicit.

$$A = \left\langle f \middle| H \middle| P \right\rangle = \left\langle f \middle| (CP)^\dagger (CP) H (CP)^\dagger (CP) \middle| P \right\rangle$$

$$= \left\langle \overline{f} \middle| (CP) H (CP)^\dagger \middle| \overline{P} \right\rangle e^{i[\theta(P)-\theta(f)]}$$

assume $[H,CP]=0$

$$= \left\langle \overline{f} \middle| H \middle| \overline{P} \right\rangle e^{i[\theta(P)-\theta(f)]}$$

$$= \overline{A} e^{i[\theta(P)-\theta(f)]} \qquad \Rightarrow \left|\frac{\overline{A}}{A}\right| = 1 \quad \text{if CP conserved}$$

Amplitude analysis for direct CP violation

$$A = |A_1| e^{i(\varphi_1 + \delta_1)} + |A_2| e^{i(\varphi_2 + \delta_2)}$$

$$\bar{A} = (|A_1| e^{i(-\varphi_1 + \delta_1)} + |A_2| e^{i(-\varphi_2 + \delta_2)}) e^{-i[\theta(P) - \theta(f)]}$$

$$\text{Asymmetry} = \frac{|\bar{A}|^2 - |A|^2}{|\bar{A}|^2 + |A|^2} = \frac{2\sin(\varphi_1 - \varphi_2)\sin(\delta_1 - \delta_2)}{\left|\frac{A_2}{A_1}\right| + \left|\frac{A_1}{A_2}\right| + \cos(\varphi_1 - \varphi_2)\cos(\delta_1 - \delta_2)}$$

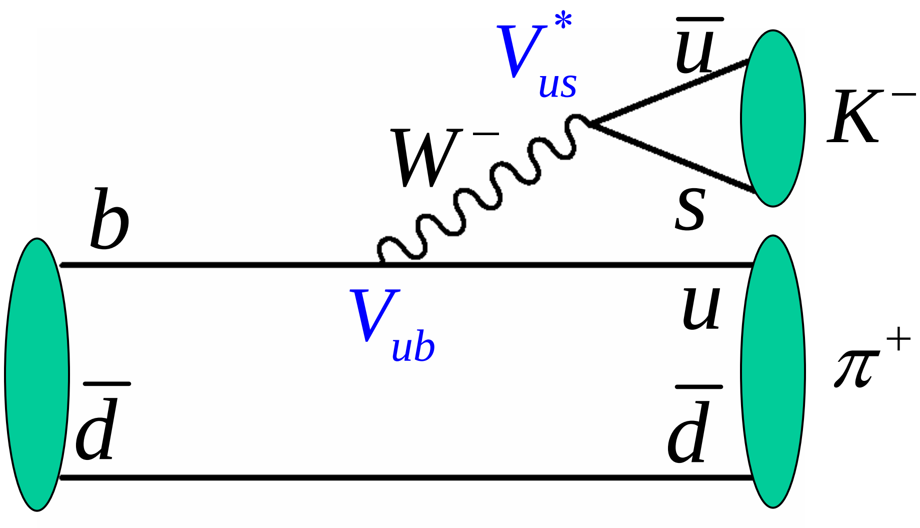
Problems with interpreting measurements of direct CP asymmetries:

1. we often don't know the difference δ_1-δ_2 , so we cannot extract ϕ_1-ϕ_2 from the asymmetry.
2. we often don't know the relative magnitude of the interfering amps.

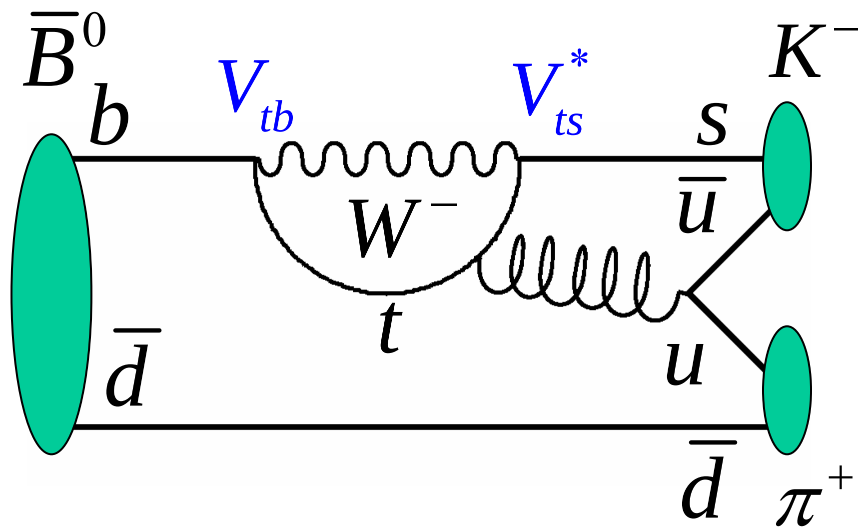
Direct CP violation in $B \rightarrow K^- \pi^+$

Interference between tree and penguin amplitudes produces a CP asymmetry in $B \rightarrow K^- \pi^+$. Both processes are suppressed!

External spectator



Gluonic penguin



In the Wolfenstein convention, the CP-violating phase factor comes from $V_{ub} \propto e^{-i\gamma}$.

Identifying B signals at the $\Upsilon(4S)$

Suppose that you have a large collection of events, say 300 M.
How do you identify and measure a specific B decay process?

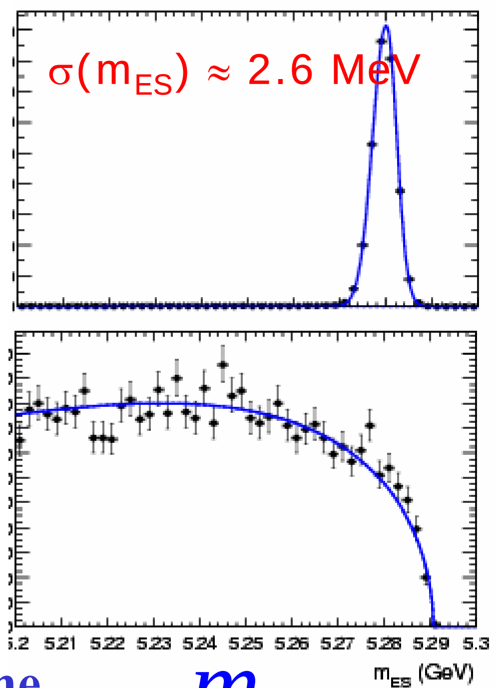
Beam energy-substituted mass | **Energy difference** | **Event shape**

$$m_{ES} = \sqrt{E_{beam}^{*2} - \left|\vec{p}_B^{\,*}\right|^2}$$

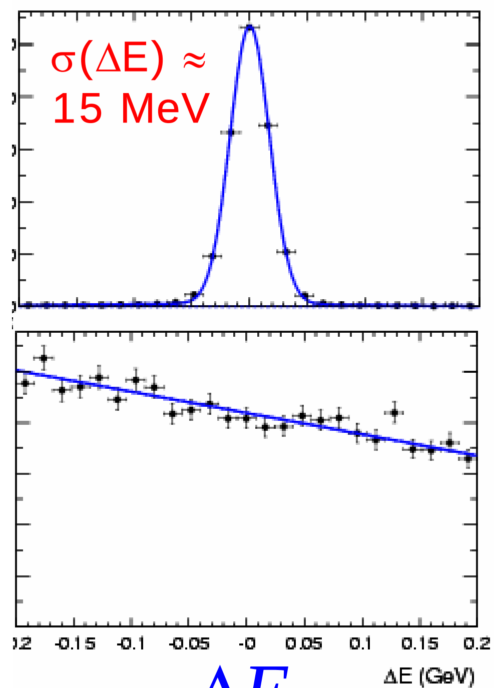
$$\Delta E = E_B^* - E_{beam}^*$$

$B\bar{B}$ events

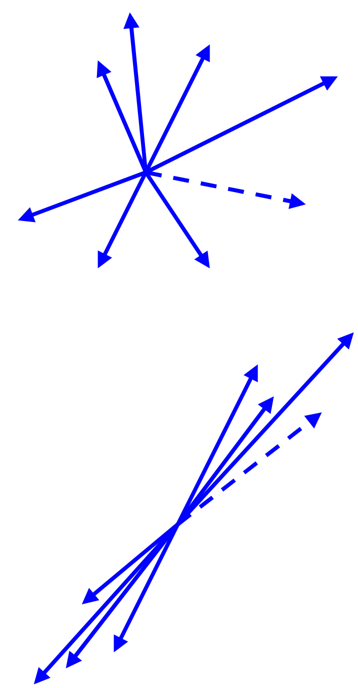
$q\bar{q}$ events
$(q=u,d,s,c)$



m_{ES}



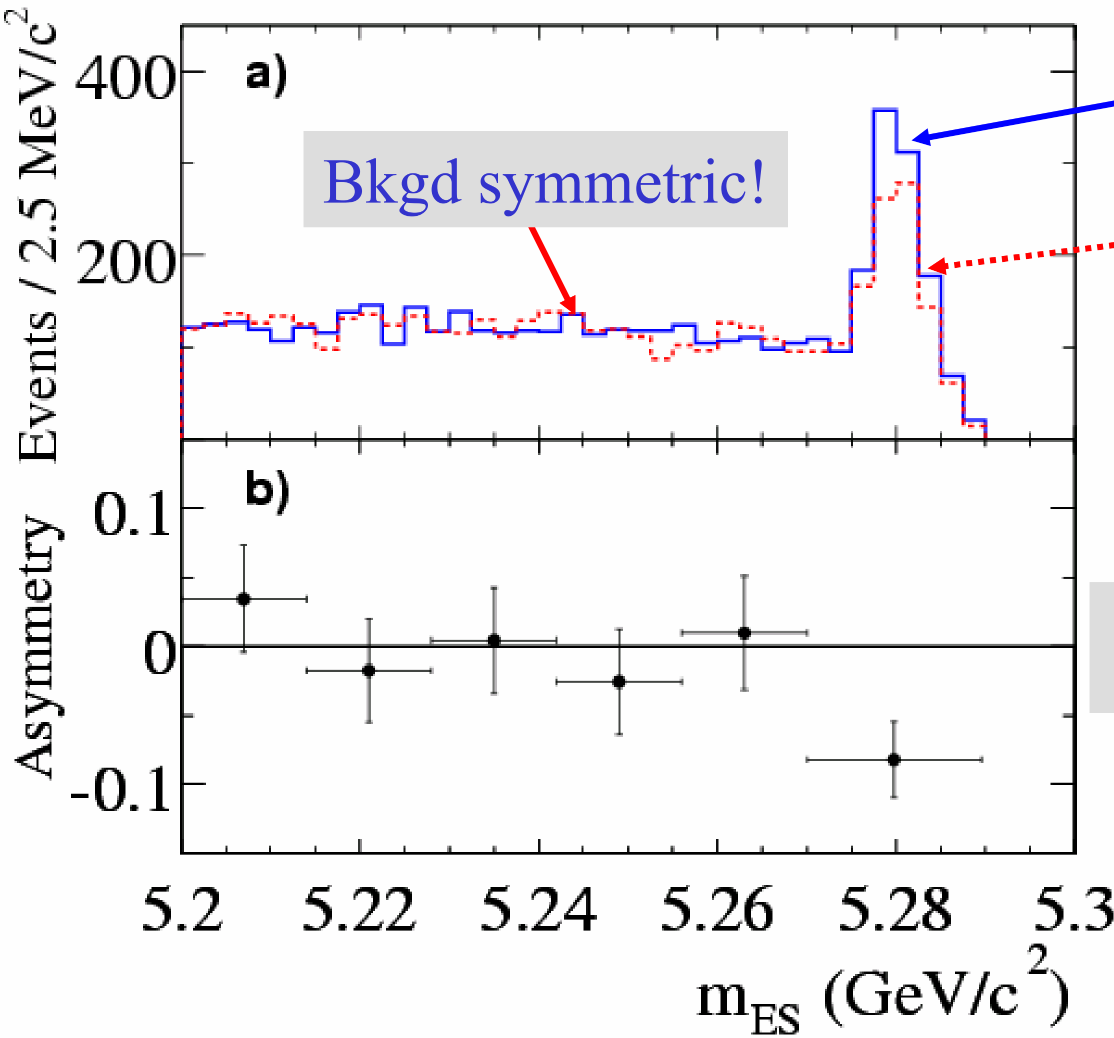
ΔE



* e^+e^- CM frame

"Direct" CP violation in $B^0 \rightarrow K^+\pi^-$ vs. $\bar{B}^0 \rightarrow K^-\pi^+$

$$N(B\bar{B}) = 227 \times 10^6 \qquad B(B \to K\pi) \approx 2 \times 10^{-5}$$



$$n\left(B^0 \to K^+\pi^-\right) = 910$$

$$n\left(\bar{B}^0 \to K^-\pi^+\right) = 696$$

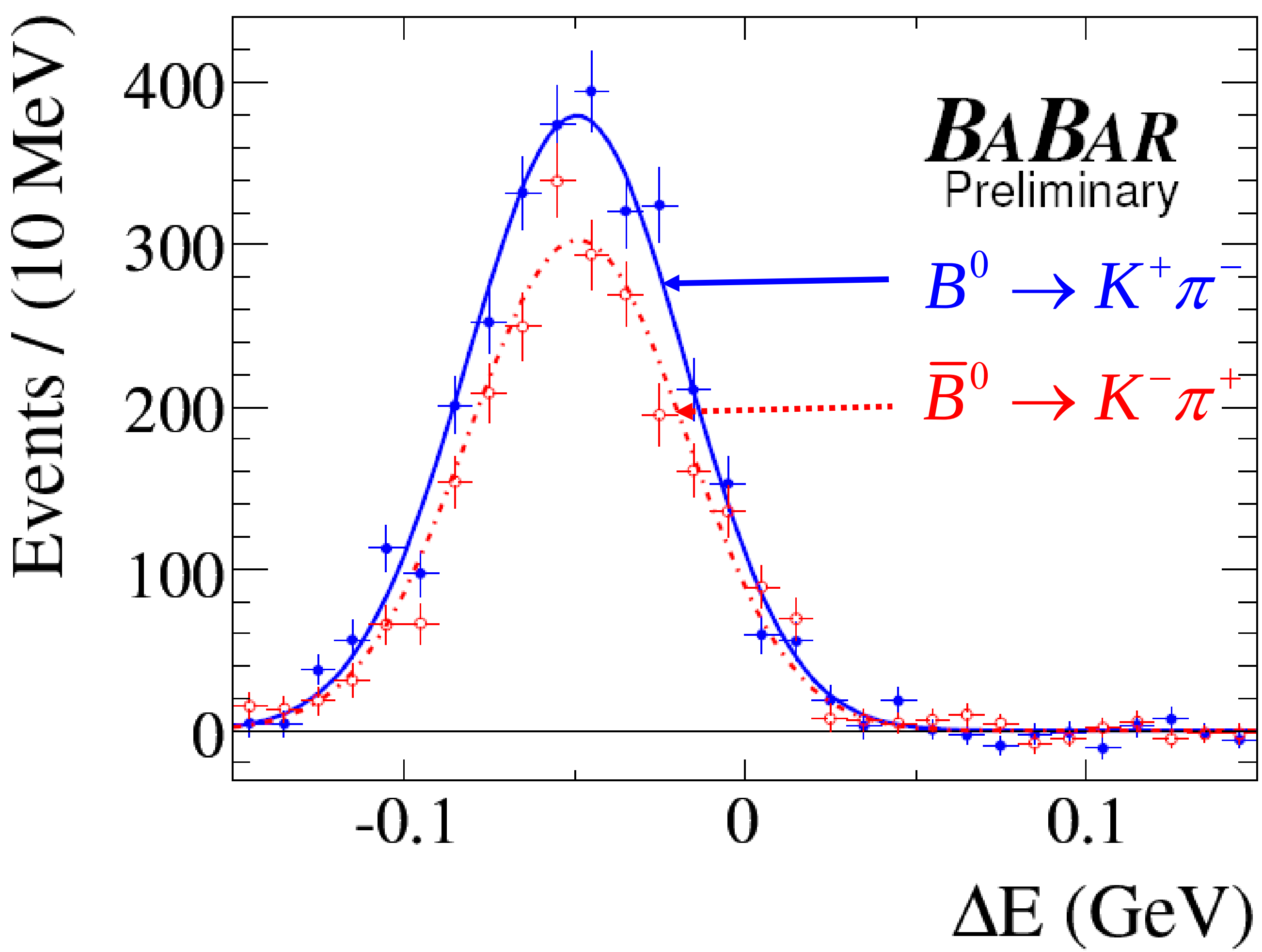
$$A = \frac{696 - 910}{696 + 910} = -0.133$$

$$A_{K\pi} = -0.133 \pm 0.030 \pm 0.009$$

Phys.Rev.Lett.93:131801,2004.

hep-ex/0407057

"Direct" CP violation in $B^0 \rightarrow K^+\pi^-$ vs. $B^0 \rightarrow K^-\pi^+$ (update)



$N(B\bar{B}) = 467 \times 10^6$

BABAR-CONF-08/014
SLAC-PUB-13326
arXiv:0807.4226 [hep-ex]

$$\mathcal{A}_{K\pi} = -0.107 \pm 0.016^{+0.006}_{-0.004}$$

CP violation and aliens from outer space

We can use our knowledge of CP violation to determine whether alien civilizations are made of matter or antimatter without having to touch them.

$$A_{CP} = \frac{\Gamma(\overline{B}^0 \to K^- \pi^+) - \Gamma(B^0 \to K^+ \pi^-)}{\Gamma(\overline{B}^0 \to K^- \pi^+) + \Gamma(B^0 \to K^+ \pi^-)} \simeq -13\%$$

$b\overline{d}$ $\qquad\qquad$ $\overline{b}d$

$$K^- = \overline{u}s$$
$$\pi^- = \overline{u}d$$

We have these inside of us.

Finally: a practical application for particle physics!

Is the difference between matter and antimatter merely one of convention, or is there a difference in their behavior?

CPT symmetry guarantees
$$\begin{cases} m(a) = m(\bar{a}) \\ \Gamma(a) = \Gamma(\bar{a}) \\ \tau(a) = \tau(\bar{a}) \end{cases}$$

C violation by itself does not truly distinguish between matter and antimatter, because a parity flip would restore equality:

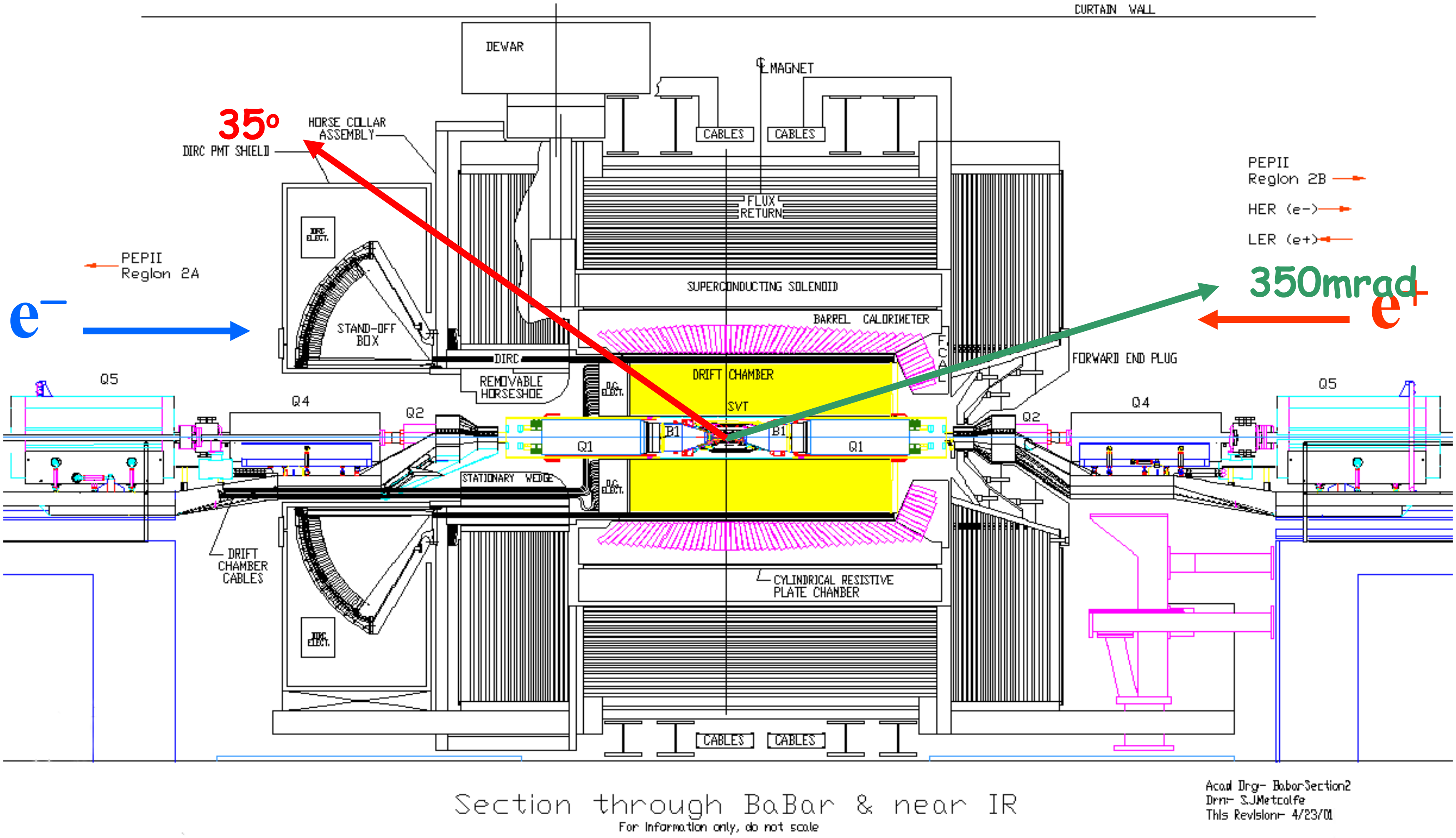
$$\sum_{\substack{\text{all final-state} \\ \text{helicities}}} \Gamma\left(\mu^- \to e^- \bar{\nu}_e \nu_\mu\right) = \sum_{\substack{\text{all final-state} \\ \text{helicities}}} \Gamma\left(\mu^+ \to e^+ \nu_e \bar{\nu}_\mu\right)$$

We want to observe a true decay-rate difference!

$$\underbrace{\Gamma_i(a \to f_i)}_{\text{rate (process)}} \neq \underbrace{\Gamma_i(\bar{a} \to \bar{f}_i)}_{\text{rate (anti-process)}}$$

C *and* CP violation

BABAR Detector



Thinking about charged particle momentum measurement

A detector is a solution to a set of problems.

- **High B-field→** better momentum resolution but also causes trajectories of low-p to curl up!

$$p_\perp\left({}^{\mathrm{GeV}}\!/\!_c\right) = 0.3 \cdot B(T) \cdot \rho(\mathrm{m})$$

$$\frac{\delta p_\perp}{p_\perp} \propto \frac{\varepsilon L^2}{B}$$

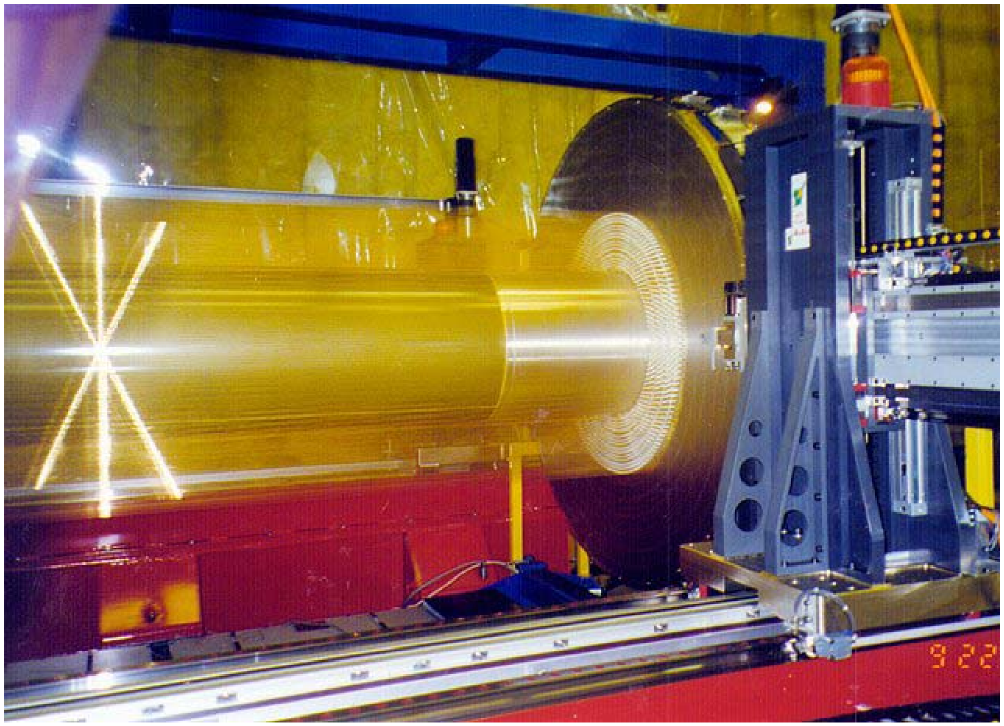
ε is point resolution

- **Large radius→** better momentum resolution, but increases cost of detector systems outside the drift chamber, especially expensive CsI crystals for photon detection.
- **Material**: want to minimize multiple-Coulomb-scattering→use low-mass gas (He/isobutane), but get less ionization/track

$$\theta_{\mathrm{mcs}} \approx \frac{0.014}{p\left({}^{\mathrm{GeV}}\!/\!_c\right)\beta}\sqrt{\frac{x}{X_0}}$$

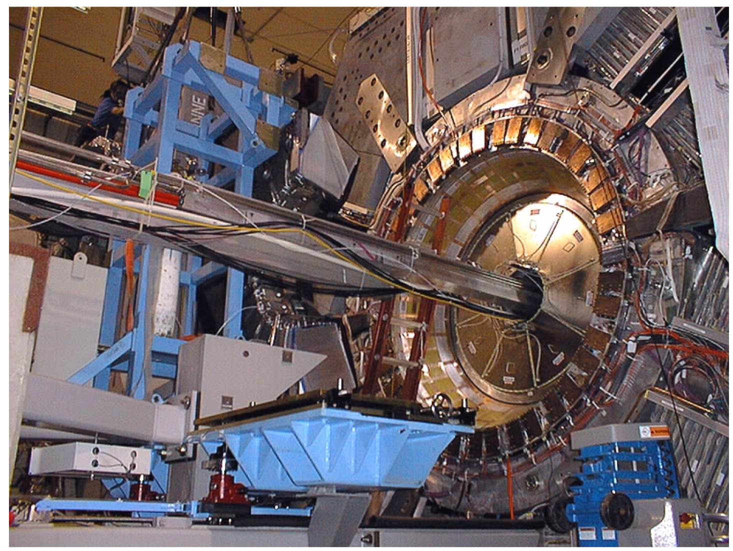
BABAR Drift Chamber

- 40 layers of wires (7104 cells) in 1.5 Tesla magnetic field
- Helium:Isobutane 80:20 gas, Al field wires, Beryllium inner wall, and all readout electronics mounted on rear endplate
- Particle identification from ionization loss (7% resolution)



16 axial, 24 stereo layers

$$\frac{\sigma(p_T)}{p_T} = 0.13\% \times p_T + 0.45\%$$



Charged hadron particle identification in $B \rightarrow K\pi$

Particle ID is based on the idea of measuring particle velocity.

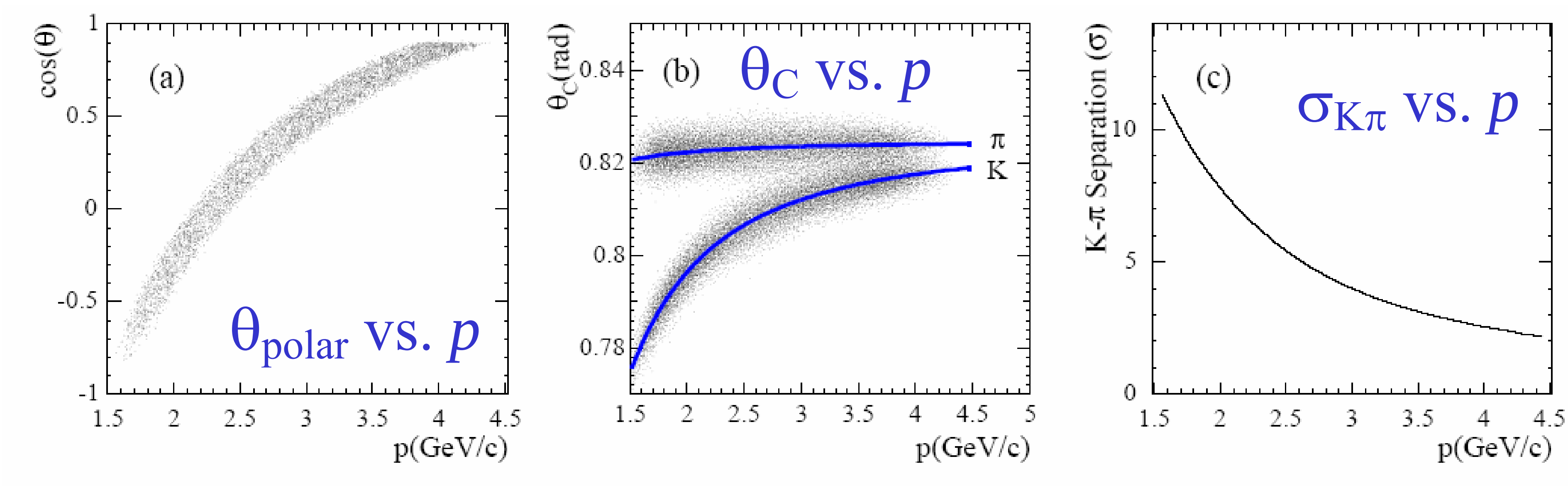
$$p = m\underbrace{\beta\gamma}$$

Tracker in B field: measures p particle ID device measures v

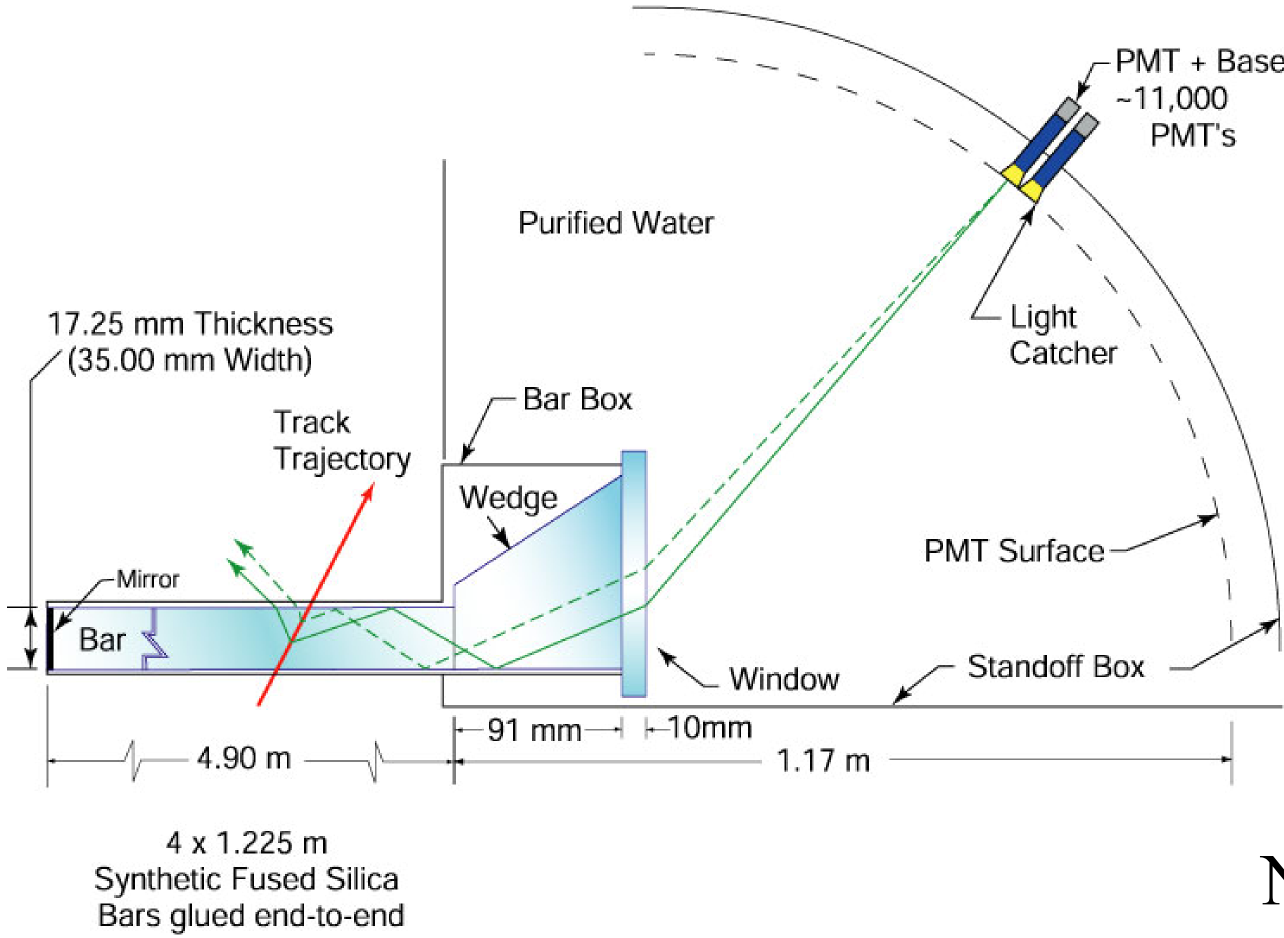
Primary methods:

- time-of-flight over known distance (fast organic scintillator)
- dE/dx (Bethe-Bloch formula)
- Cherenkov radiation

BABAR DIRC



Charged *K/π* separation using the *BABAR* DIRC



$$\cos\theta_C = \frac{1}{\beta \cdot n}$$

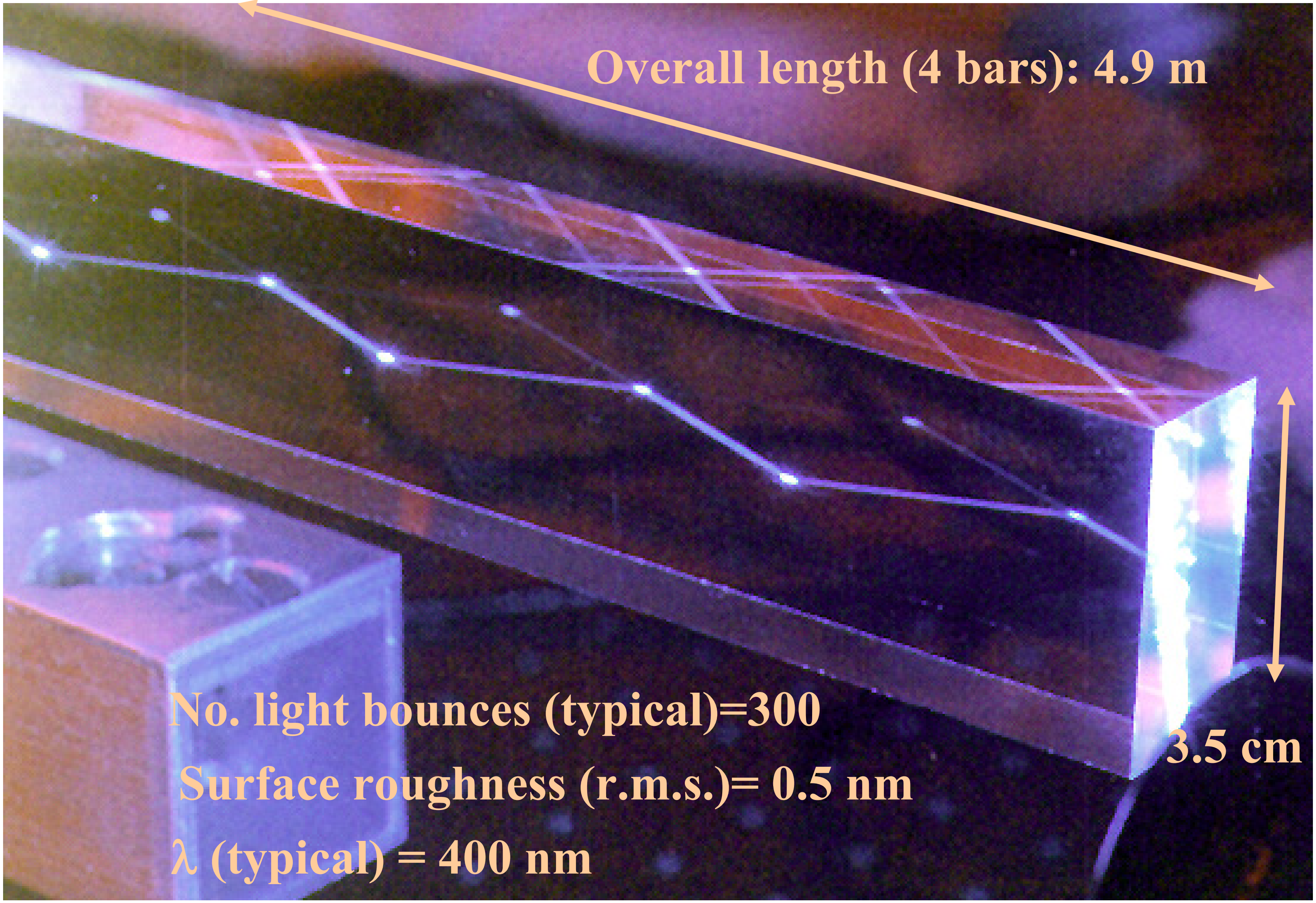
$$n = 1.473$$

Num. r.l.=0.19 X_0

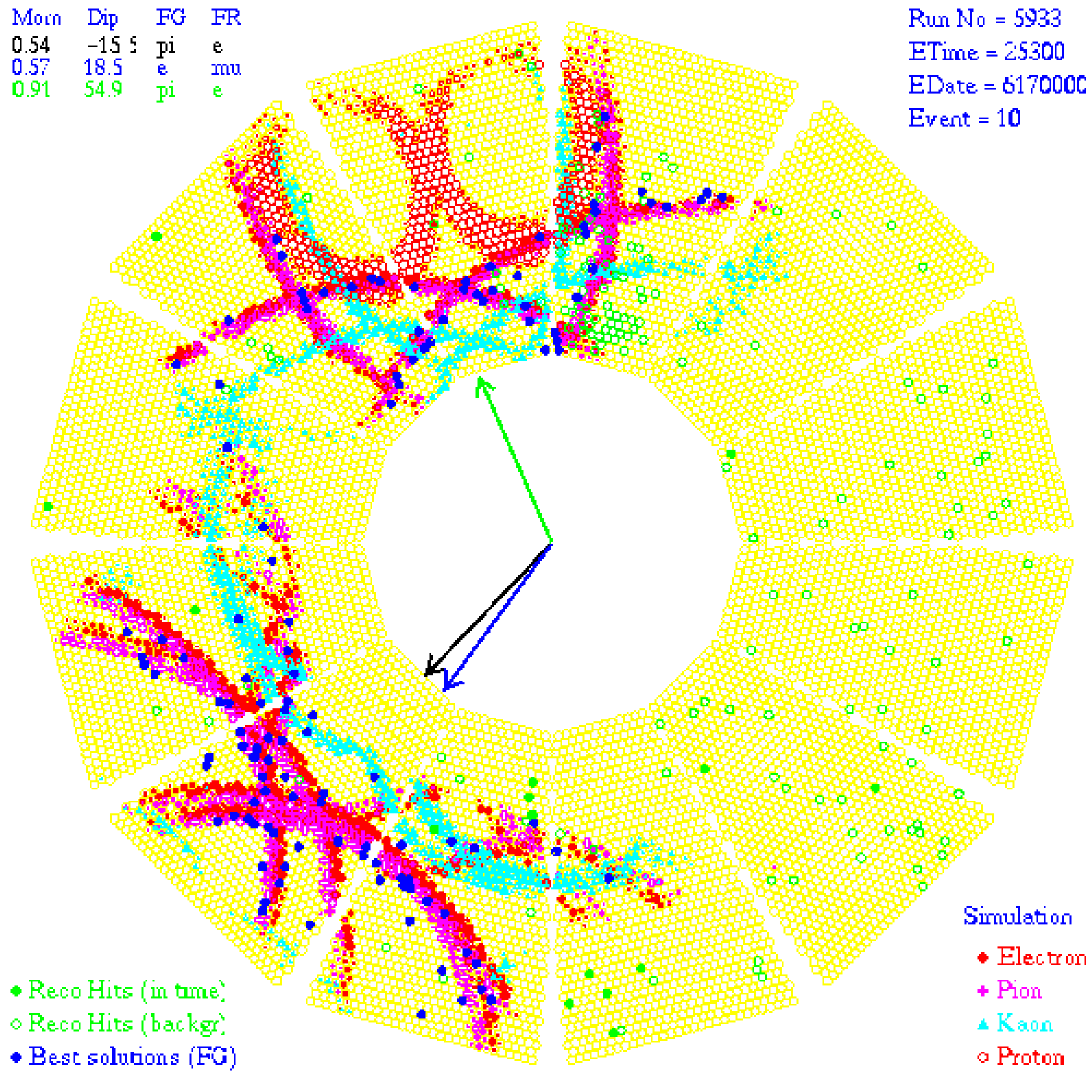
$\sigma(\theta_C)$ = 3 mrad

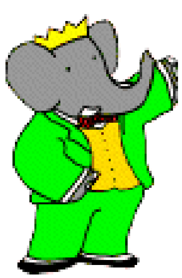
Number of Cherenkov photons=20-60

BaBar DIRC quartz bar

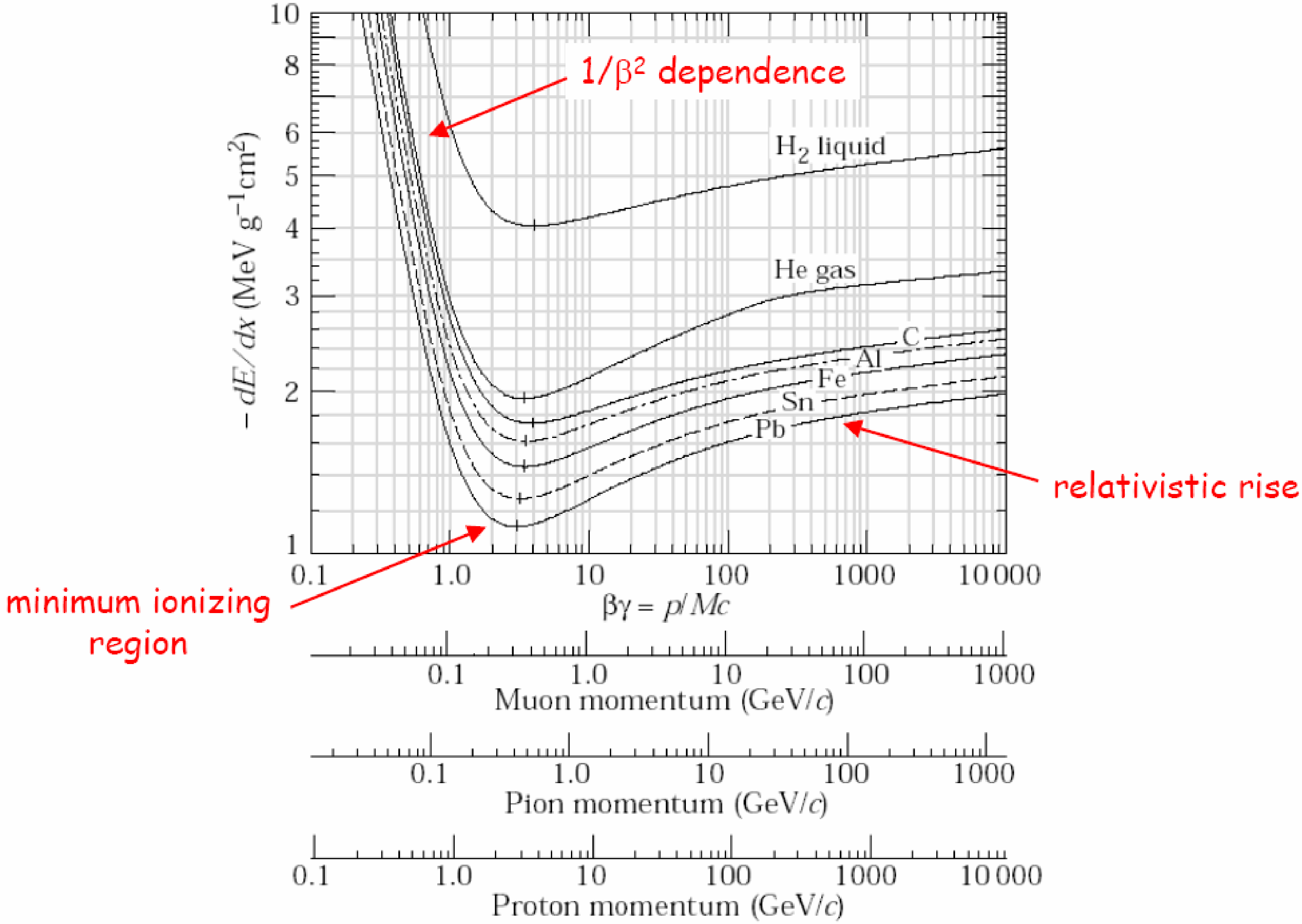


Comparing Hits with Cherenkov Signature





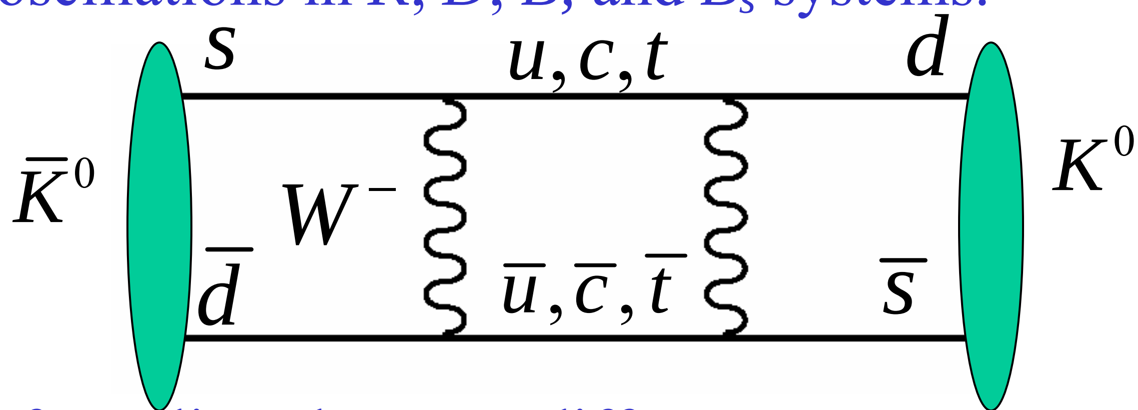
Measuring velocity from dE/dx



A closer look at oscillations

A single, general formalism based on time-dependent perturbation theory describes meson oscillations in *K*, *D*, *B*, and B_s systems.

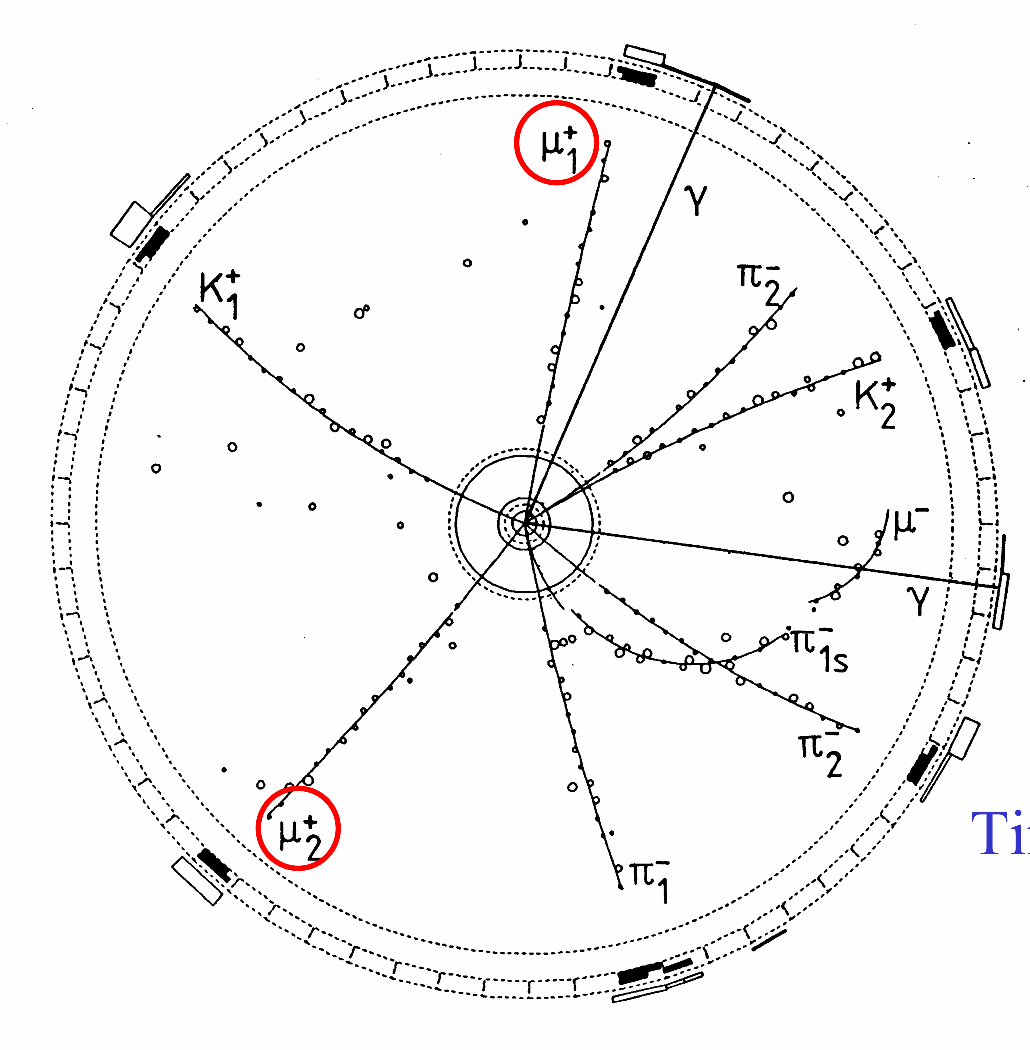
$$\left.\begin{array}{l} K^0\overline{K}^0 \\ D^0\overline{D}^0 \\ B^0\overline{B}^0 \\ B_s^0\overline{B}_s^0 \end{array}\right\} \boxed{P^0\overline{P}^0}$$



Common formalism, but very different parameter values→behavior in each case is very different!

Key point: since the weak interactions induce transitions between P^0 and $\overline{P}^0$, these flavor-eigenstate particles are not eigenstates of the total Hamiltonian, and <u>they do not have definite masses or lifetimes.</u> (They are superpositions of states P_L and P_H that do. Want to calculate Δm and $\Delta\Gamma$!)

Discovery of $B^0\bar{B}^0$ Oscillations



ARGUS experiment (1987)

$$\Upsilon(4S) \to B^0\bar{B}^0 \to B_1^0 B_2^0$$
$$B_1^0 \to D_1^{*-}\mu_1^+\nu_1,\ D_1^{*-} \to \bar{D}^0\pi_1^-$$
$$B_2^0 \to D_2^{*-}\mu_2^+\nu_2,\ D_1^{*-} \to D^-\pi^0$$

103 pb^{-1} ~ 110,000 B pairs

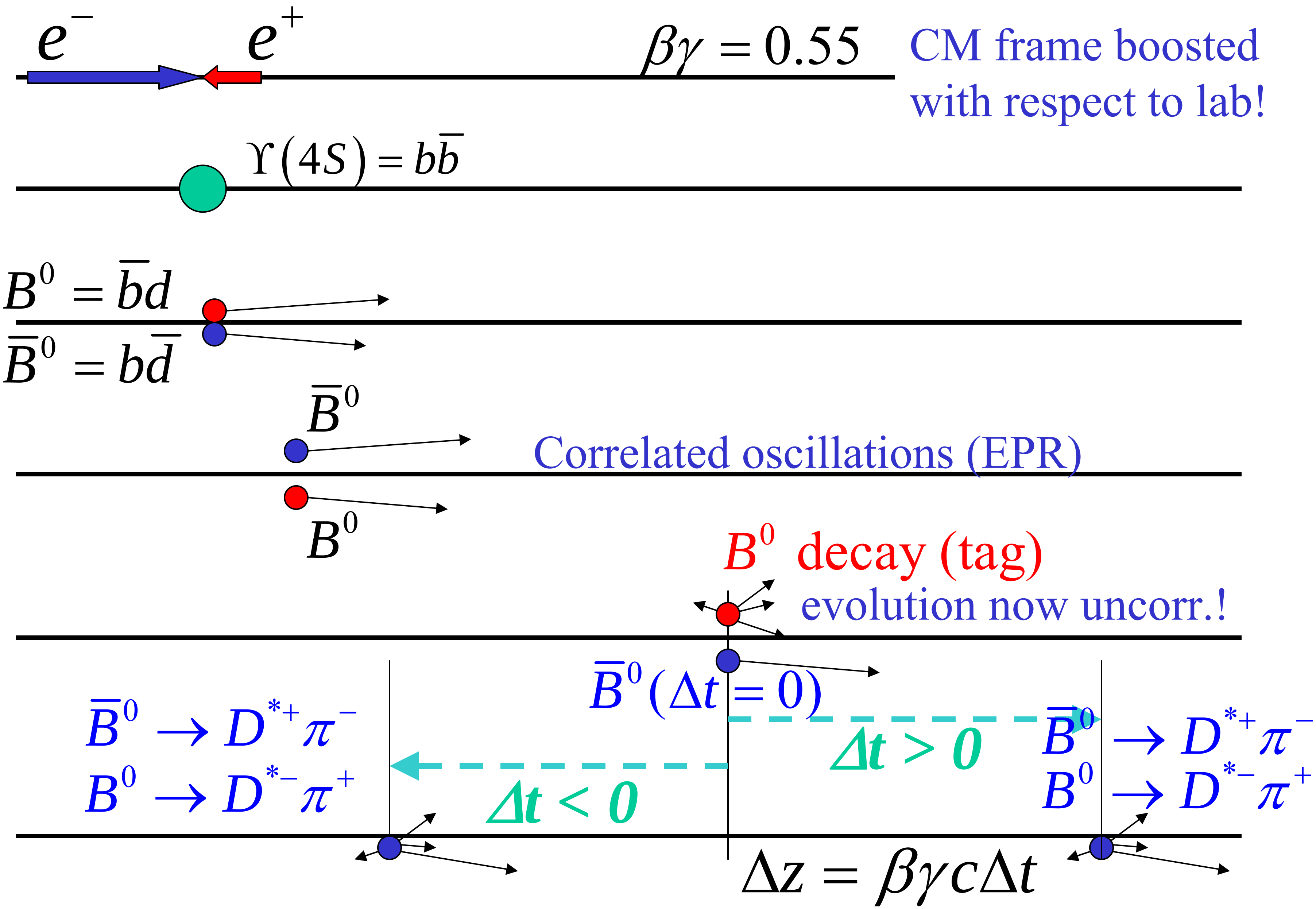
$$\chi_d = 0.17 \pm 0.05$$

ARGUS, PL B **192**, 245 (1987)

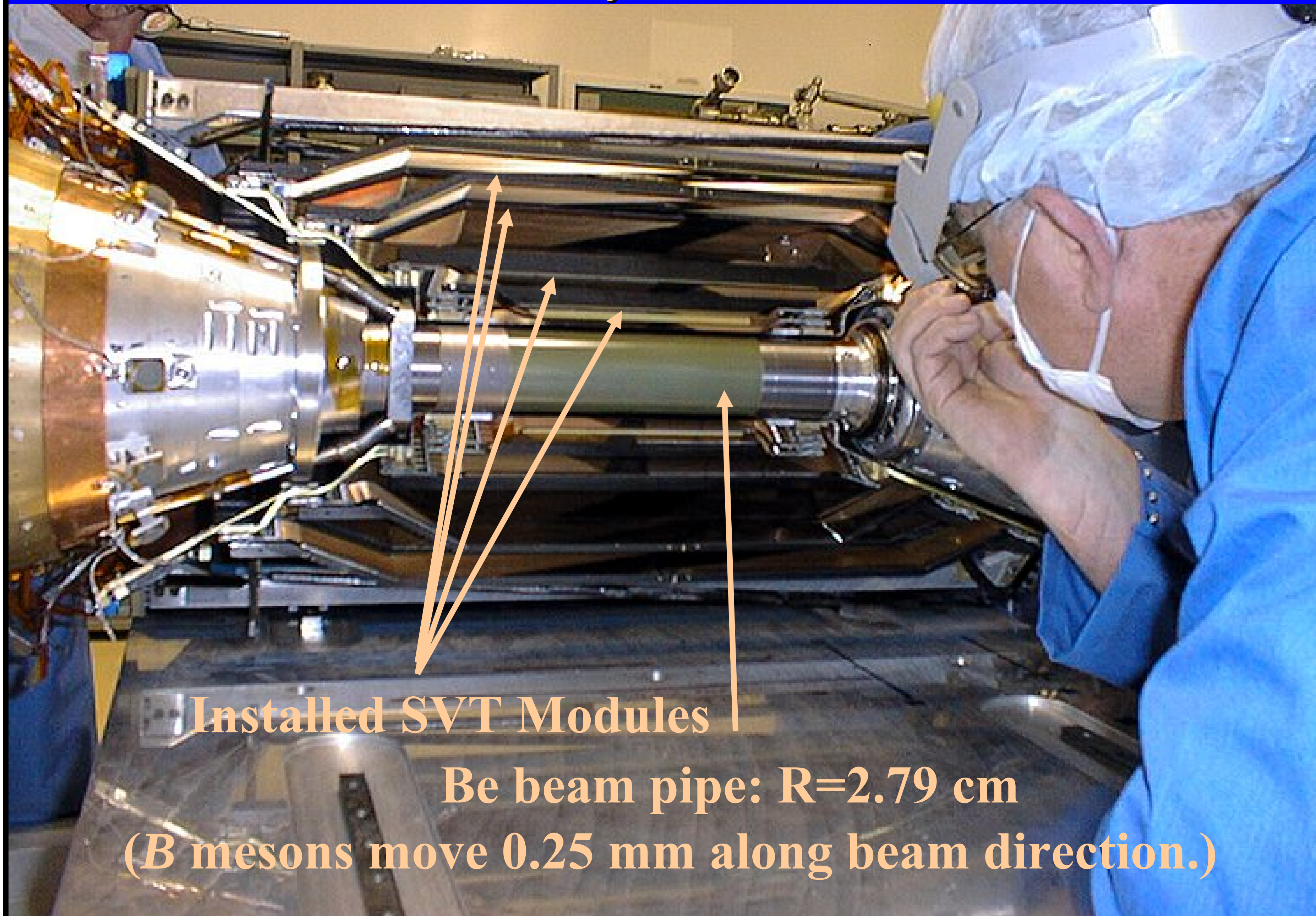
Time-integrated mixing rate: 21%

(fig. courtesy D. MacFarlane)

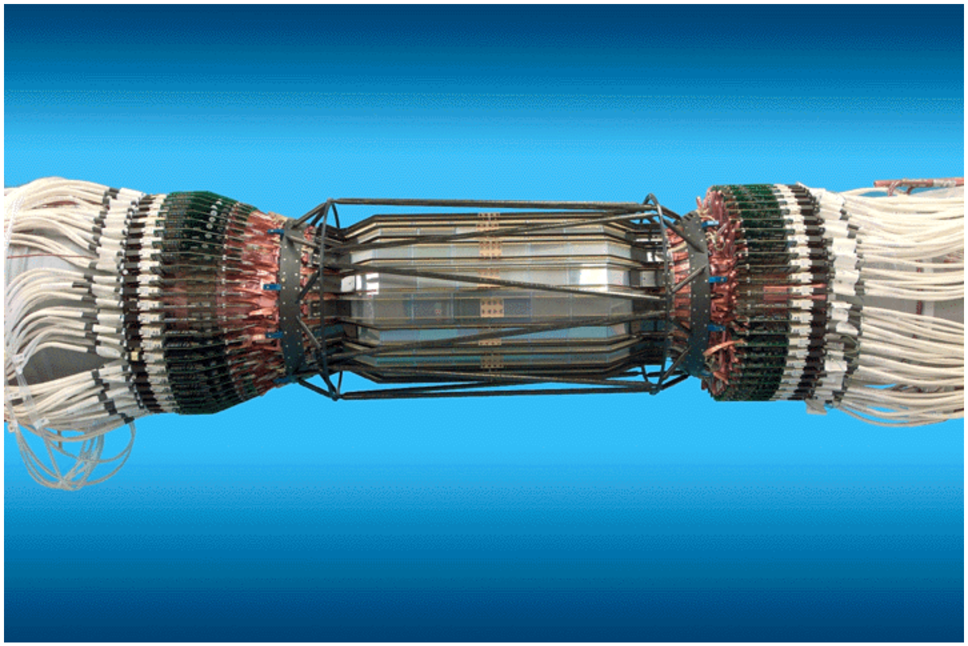
Time-dependent oscillation measurement



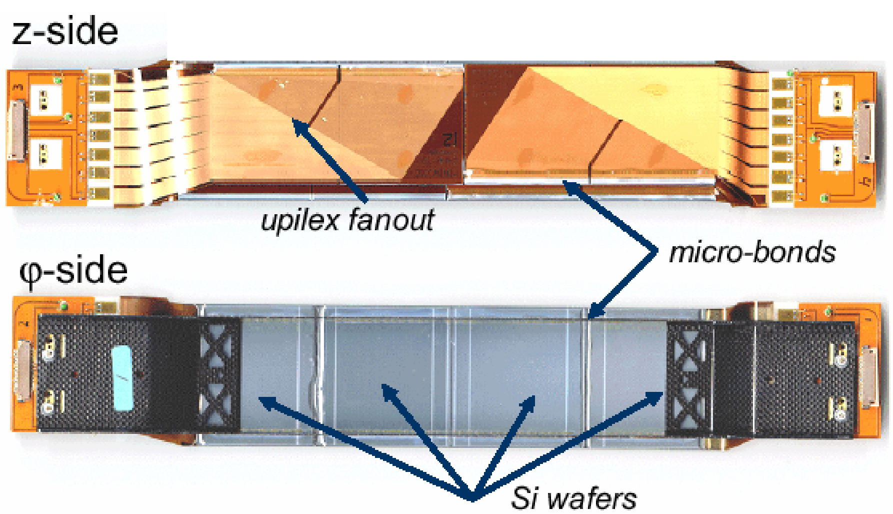
Innermost Detector Subsystem: Silicon Vertex Tracker

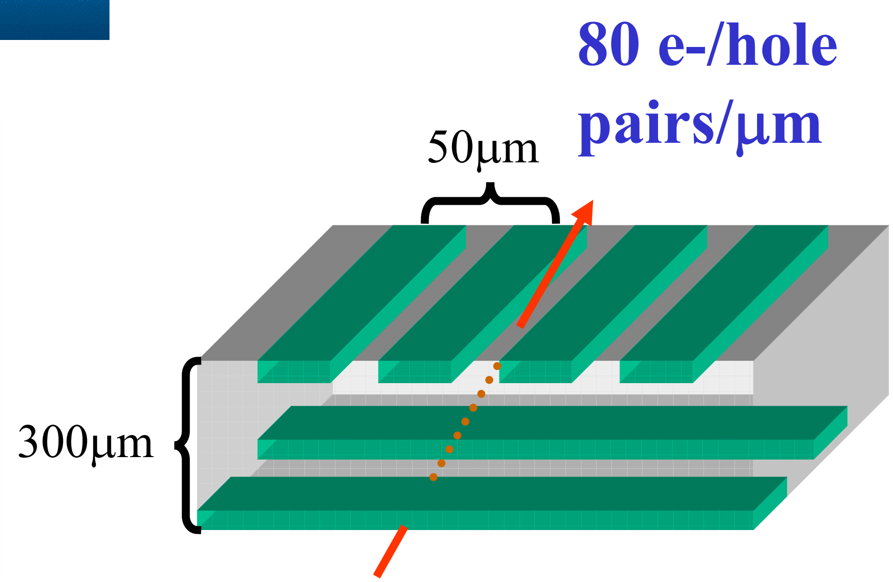


BaBar Silicon Vertex Tracker (SVT)



- 5 concentric layers
- 340 Si sensors (wafers)
- Strips on both sides
- AC coupled
- 140 K readout chans.
- 10-40 μm hit resol.
- about 70 cm long





Measurement of Decay Time Distributions

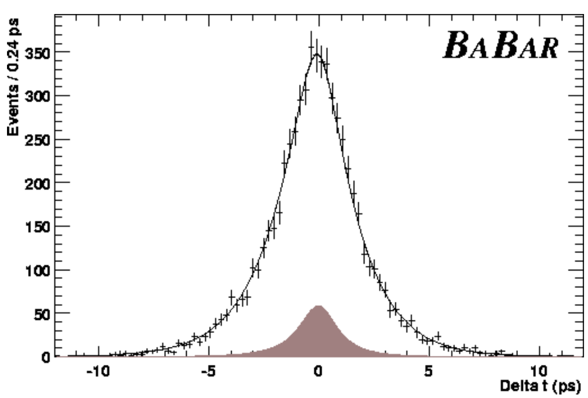
$$\tau(B^0) = [1.546 \pm 0.032\ (\text{stat}) \pm 0.022\ (\text{sys})]\ \text{ps} \qquad \tau(D^0) \simeq 0.41\ \text{ps}$$

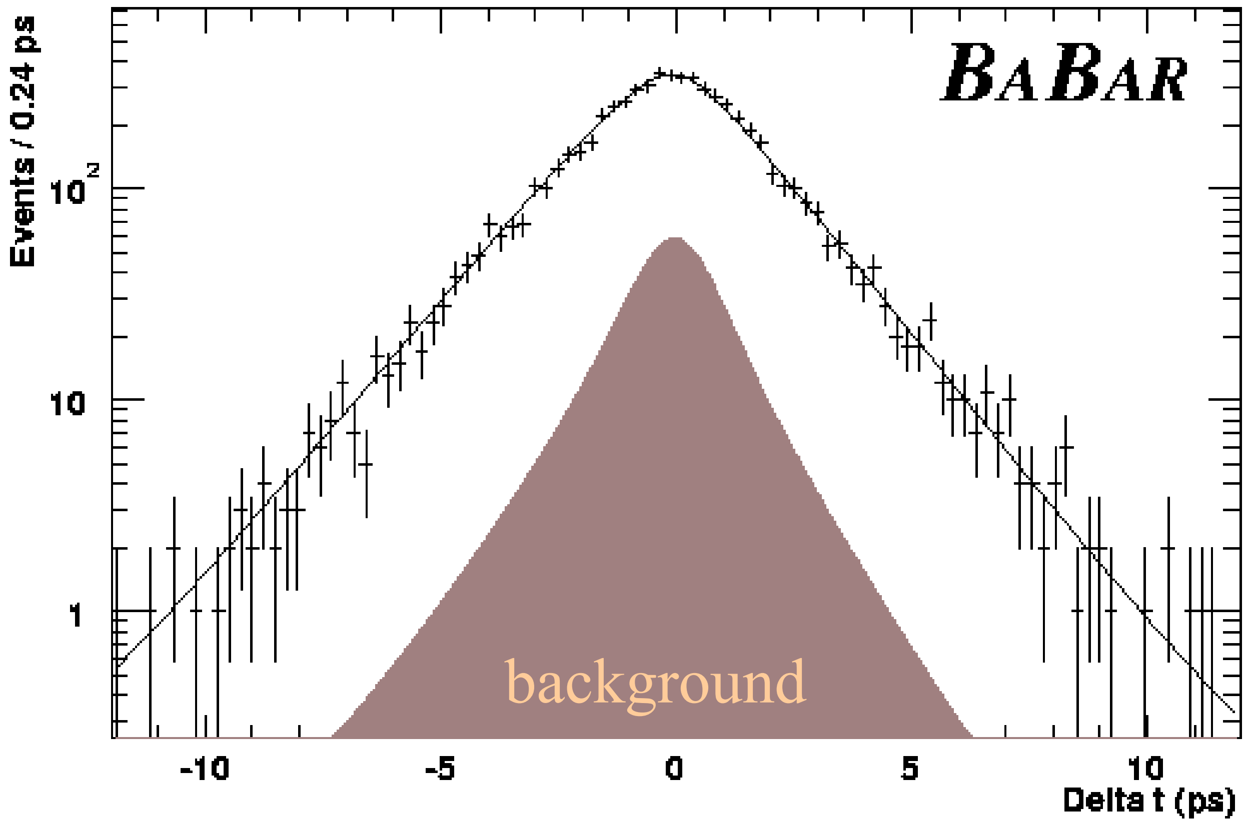
$$\tau(B^+) = [1.673 \pm 0.032\ (\text{stat}) \pm 0.022\ (\text{sys})]\ \text{ps} \qquad \tau(D^+) \simeq 1.04\ \text{ps}$$

$$\frac{\tau(B^+)}{\tau(B^0)} = 1.082 \pm 0.026\ (\text{stat}) \pm 0.011\ (\text{sys}) \qquad \frac{\tau(D^+)}{\tau(D^0)} \simeq 2.5$$

B^0 decay time distribution

(linear scale)





Measuring the $B^0\bar{B}^0$ oscillation frequency

$$\left(\frac{dN}{dt}\right)_{\text{nomix}} = \frac{1}{4\tau_B} \cdot e^{-\Gamma t} \cdot \left[1 + \cos(\Delta m_d \cdot t)\right]$$

$$\left(\frac{dN}{dt}\right)_{\text{mix}} = \frac{1}{4\tau_B} \cdot e^{-\Gamma t} \cdot \left[1 - \cos(\Delta m_d \cdot t)\right]$$

$$\Rightarrow \mathrm{A}_{\text{mix}} = \frac{\left(\frac{dN}{dt}\right)_{\text{nomix}} - \left(\frac{dN}{dt}\right)_{\text{mix}}}{\left(\frac{dN}{dt}\right)_{\text{nomix}} + \left(\frac{dN}{dt}\right)_{\text{mix}}} = \cos(\Delta m \cdot t)$$

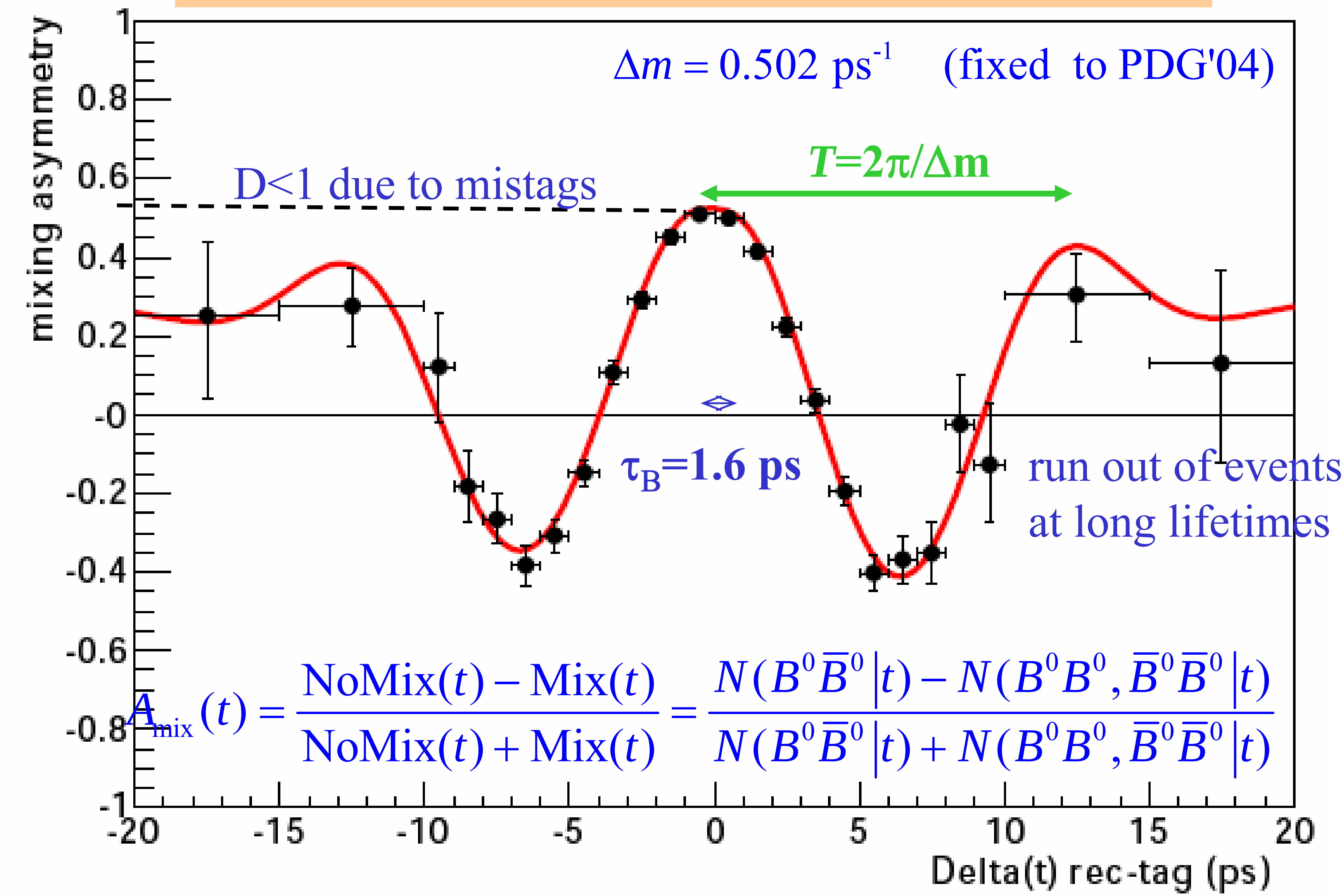
very simple!

amplitude=1

How do you actually do this measurement? Basic question: did the *B* oscillate or not? Need to know this as a function of time!

1. When it was produced, was the meson a B^0 or $\bar{B}^0$?
2. When it decayed, was the meson a B^0 or a $\bar{B}^0$?
3. What is the time difference between production and decay?

Mixing asymmetry vs. Δt



Does a mass really have units of s^{-1} ?

$$\mathrm{A}_{\mathrm{mix}} = \cos(\Delta m \cdot t)$$

1. Put in c^2

$$(\Delta m)c^2 \cdot t \sim ET$$

2. Divide by $\hbar \sim ET$ since phase must be dimensionless

$$\frac{(\Delta m)c^2 \cdot t}{\hbar} \sim \text{dimensionless!}$$

$$\frac{(\Delta m)c^2}{\hbar} = 0.5 \text{ ps}^{-1} \qquad B^0 \overline{B}^0$$

$$(\Delta m)c^2 = (0.5 \cdot 10^{12} \text{ s}^{-1}) \cdot (66 \cdot 10^{6} \text{ eV} \cdot 10^{-23} \text{ s}) \approx 3 \cdot 10^{-4} \text{ eV}$$

Explains why we don't worry about B_{H} and B_{L} in most analyses!

Oscillations in the $K^0\bar{K}^0$ System

Most striking feature of $K^0\bar{K}^0$ system: huge lifetime splitting between mass eigenstates. (This is quite different from the $B^0\bar{B}^0$ system, where the mass splitting is very small!)

$$\frac{\tau\left(K_S^0\right)}{\tau\left(K_L^0\right)} \simeq \frac{52 \text{ ns}}{0.09 \text{ ns}} \simeq \frac{15.5 \text{ m}}{2.7 \text{ cm}}$$

$$\simeq 580$$

Major experimental implication: a neutral K beam evolves over distance into a nearly pure K_L^0 beam.

$$\Delta\Gamma = \Gamma\left(K_L^0\right) - \Gamma\left(K_S^0\right) \simeq -\Gamma\left(K_S^0\right) \simeq -10^{-10} \text{ s}^{-1}$$

$$\Delta M = M\left(K_L^0\right) - M\left(K_S^0\right) = (0.5304 \pm 0.0014) \times 10^{10} \text{ s}^{-1}$$

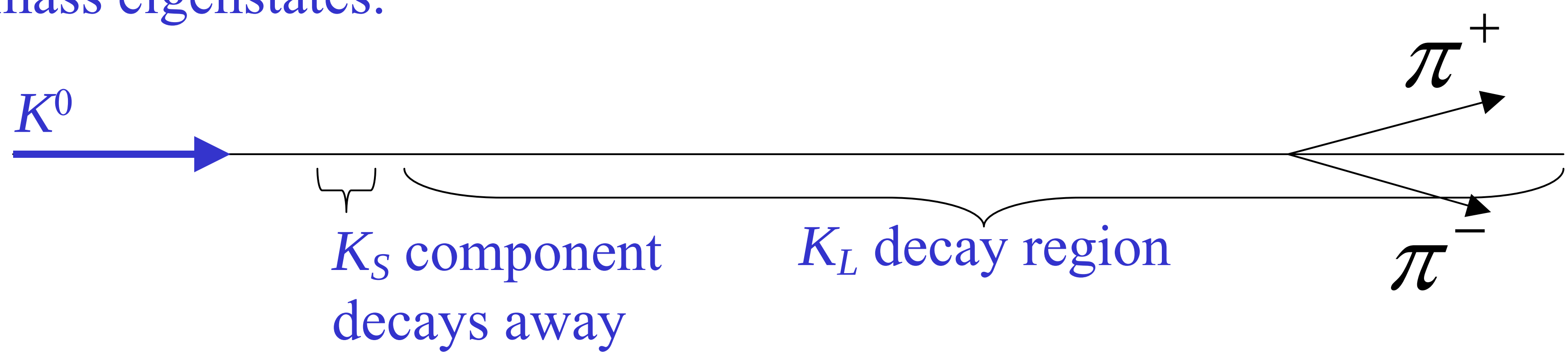
$$\simeq 3.5 \times 10^{-6} \text{ eV}$$

$$\Delta\Gamma \approx -2\Delta M$$

The mass and lifetime splittings are comparable!

CP Violation in mixing: observation of $K_L \rightarrow \pi^+ \pi^-$

Exploit the large lifetime difference between the two neutral K mass eigenstates.



Demonstrates that K_L^0 decays into both CP=-1 (usually) and CP=+1 final states → K_L^0 is not a CP eigenstate.

$$\eta_{+-} \equiv \frac{A\left(K_L^0 \rightarrow \pi^+\pi^-\right)}{A\left(K_S^0 \rightarrow \pi^+\pi^-\right)} \qquad \eta_{00} \equiv \frac{A\left(K_L^0 \rightarrow \pi^0\pi^0\right)}{A\left(K_S^0 \rightarrow \pi^0\pi^0\right)}$$

both are $2\text{x}10^{-3}$

Key point: K_L beam is "self-tagging." (Tagging = method in which we identify a particle P_1 by studying a particle P_2 that is produced in association with particle P_1.)

Pitfalls of data analysis

- Historically, there are many examples where measurements have been affected by biases in the data analysis.
- How can this happen?
  - If the person performing the analysis is happier getting a result that is similar to (or different from) a previous result, this can bias the measurement.
  - If the person performing the analysis wants to get as big a signal as possible and tunes cuts using the data, this can bias the measurement.
  - If the person performing the analysis believes that a certain answer must be true, this can bias the measurement. (For example, they might discard data that disagrees with the result they want!)

Embarrassing moments in particle physics

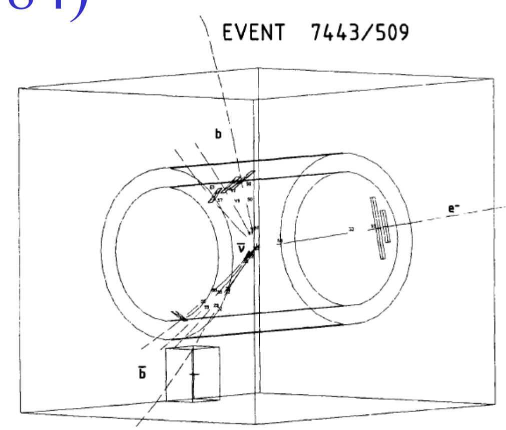
1. “Discovery” of the ζ(8.1)—Crystal Ball expt. (1984)

- Observation of peaks in photon-energy spectrum in two independent decay channels.
- Not confirmed in subsequent data sample
- Only presented at conferences; not published

2. “Discovery” of top quark – UA1 experiment (1984)

- Observation of 6th quark (top) incorrectly inferred from CERN experiment
- top quark finally discovered at Fermilab at much higher mass

UA1

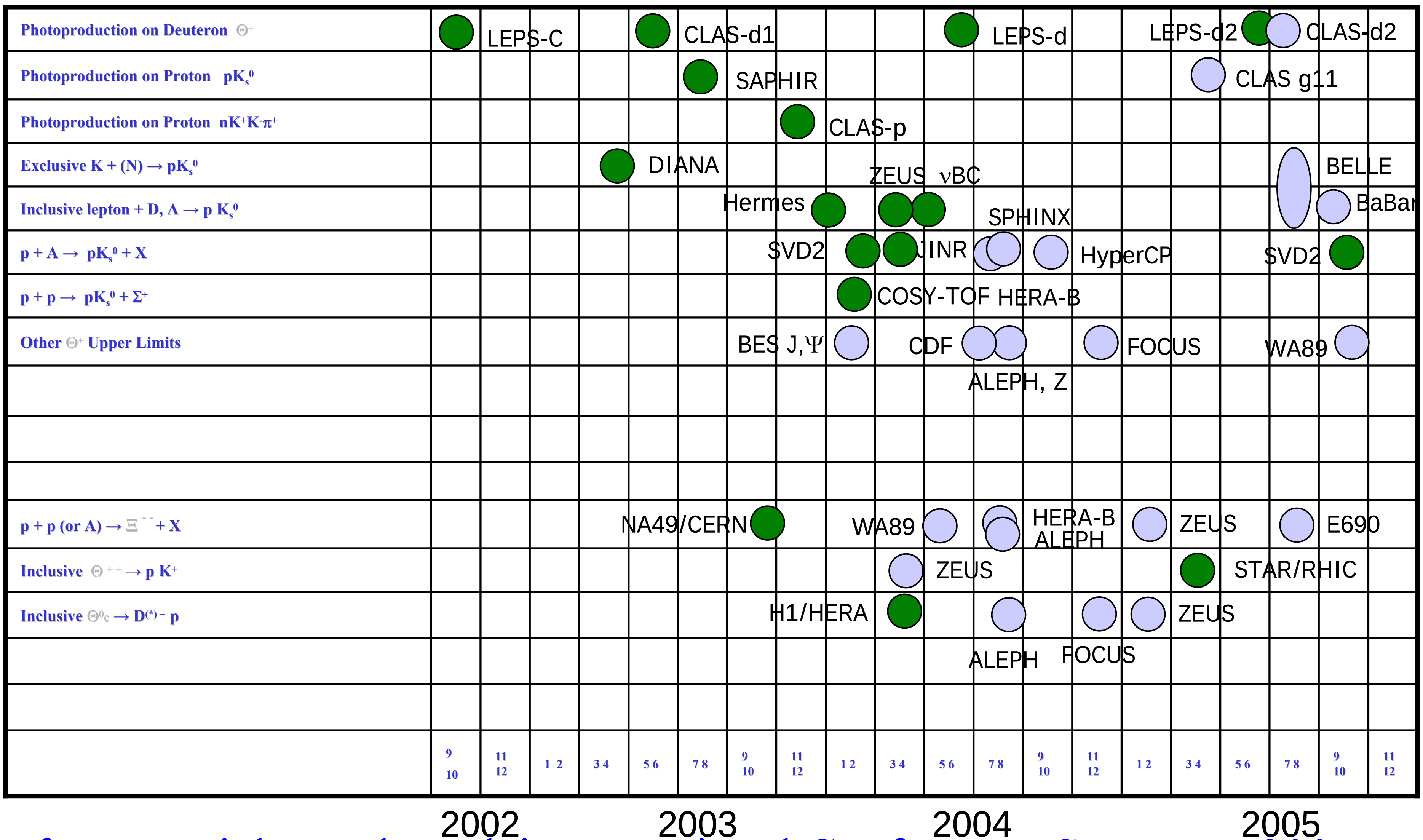


3. “Discovery” of penta-quark states (2002-2004)

- remarkable bandwagon effect (next slide)

Slide courtesy of Reinhard Schumacher

Pentaquark Exp’ts Timeline



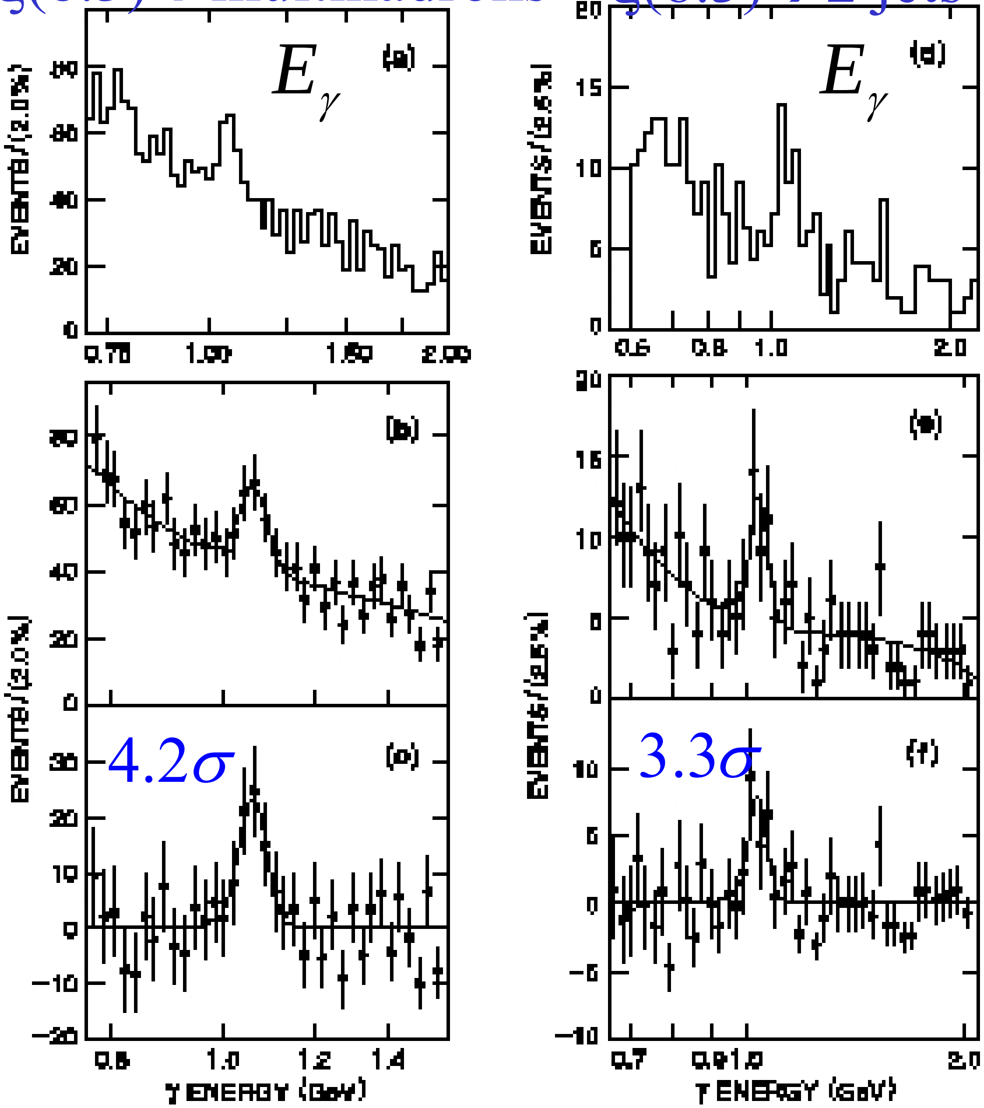
from Particles and Nuclei International Conference, Santa Fe, 2005

Some common problems

- People often stop looking for mistakes when they obtain a desirable result.
- Background shape or normalization estimated incorrectly.
- Backgrounds peaking under signal not correctly determined.
- Signal significance estimated incorrectly.
- Signal is created artificially as “reflection” of another signal.
- Errors determined incorrectly.
- Correlations not taken into account.
- Shapes used in fit are not adequate to describe the data.
- Bugs in program.
- Systematic errors underestimated.
- Systematic errors incomplete.
- Unstated/incorrect assumptions.
- Changes in experimental conditions not fully taken into account.
- Average of many bad measurements might not give a good measurement.

“Evidence for a Narrow Massive State in the Radiative Decays of the Upsilon”—Crystal Ball Collaboration (summer 1984)

$\zeta(8.3)\rightarrow$multihadrons $\zeta(8.3)\rightarrow$2 jets



Crystal Ball claimed evidence for the decay

$$Y(1S)\rightarrow\gamma X$$

Monochromatic photon corresponds to two-body decay to a new particle:

$$X=\zeta(8.3)$$

$$M(\zeta)=(8322\pm8\pm24)\ \mathrm{MeV}/c^2$$

<u>Completely absent in subsequent data sample!</u>

Blind Analysis

- Basic principle: it's OK to be stupid.
  It's not OK to be biased!

- Translation: if an analysis isn't perfectly optimized, it's OK. But it's not OK to perform an analysis that will give a non-reproducible result when more data are obtained.

- All studies are performed in such a way as to *hide* information on the value of the final answer.

- Avoids any subconscious experimenter bias
  - e.g. agreement with the Standard Model!

- Not needed for certain kinds of "easy" analyses.

Blind analysis technique

- **Adopted by BaBar for most analyses and is gradually becoming more common in HEP. (Developed by kaon expts.)**
- **Main idea: develop event selection using Monte Carlo samples or data control samples that will not be used to extract the signal yield.**

Advantages	Disadvantages
• Leads to much more structured & organized analysis procedures • Focus is on sources of uncertainty rather than on the central value • Optimization of evt. selection is independent of actual signal • Avoids many kinds of bias • Increased credibility	• Usually delays looking at data • Usually slows things down • May discover important effect late in the analysis • Analysis may be optimized based on unrealistic MC • Requires a lot of discipline!

An unblinding party in BaBar

End of Lecture 2

Backup Slides

Some early discoveries in symmetry breaking

There has been a long history of discovering and understanding symmetry breaking in the weak interactions.

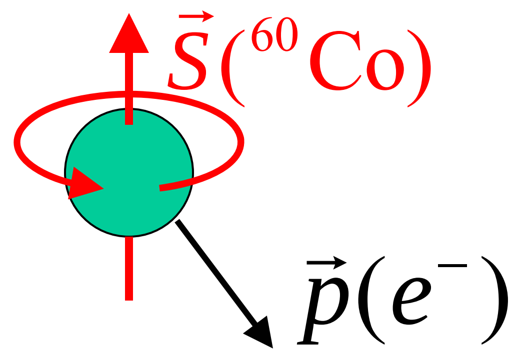
- τ–θ puzzle: *P*-violation in *K* decay
  T.D. Lee and C.N. Yang Nobel prize (1957)

$$K^+(\text{"}\tau^+\text{"}) \to \pi^+\pi^+\pi^-$$

$$K^+\left(\text{"}\theta^+\text{"}\right) \to \pi^+\pi^-$$

- P-violation in β-decay of polarized ^{60}Co nuclei: C.S. Wu

$$^{60}\mathrm{Co} \to {}^{60}\,\mathrm{Ni} + e^- + \bar{\nu}$$



Steps in a typical BaBar blind data analysis

Generate signal MC sample (Theory issues!)

Develop control samples in data to test features of signal MC (mass resolution, mass scale, selection efficiencies)

Generate background MC samples; classify back-grounds using MC truth info and investigate kinematic distributions.

Develop control samples in data to test features of background MC (or avoid background MC altogether).

Develop ideas on how to separate S and B. Avoid event selection cuts with high degree of dependence on theoretical models.

Steps in a typical BaBar blind data analysis (II)

Optimization of analysis sensitivity (iterative).

- Optimize $S / \sqrt{S + B}$ or $S / \sqrt{S + B}$
- Which variables are most reliable? Simplify to reduce systematic uncertainties.
- Which variables to fit?
- Select variables not to use in selection or fit but as key properties of signal.
- Blind analysis: neither signal nor background estimates in optimization use data that will be used for actual result. Validate samples used for optimization with control samples in data.

Develop fitting procedure

- Investigate correlations between variables used in fit
- Validation of fitter ("toy" MC samples)

Steps in a typical BaBar blind data analysis (III)

Investigate systematic uncertainties
- Multiplicative (% of central value, e.g., tracking efficiency)
- Additive (due to uncertainties in shapes used in fit)
- Parameters can be added to the fit to transfer some systematic uncertainties to statistical uncertainties!

Internal review
- Requires detailed documentation
- After unblinding for simple analysis
- Before unblinding for complicated analysis

Unblinding "party" (usually very late at night)

Fitting; goodness of fit? Check extra distribs. Make "s-plots"
Final systematic errors
Final internal documentation, formal review process. Paper!