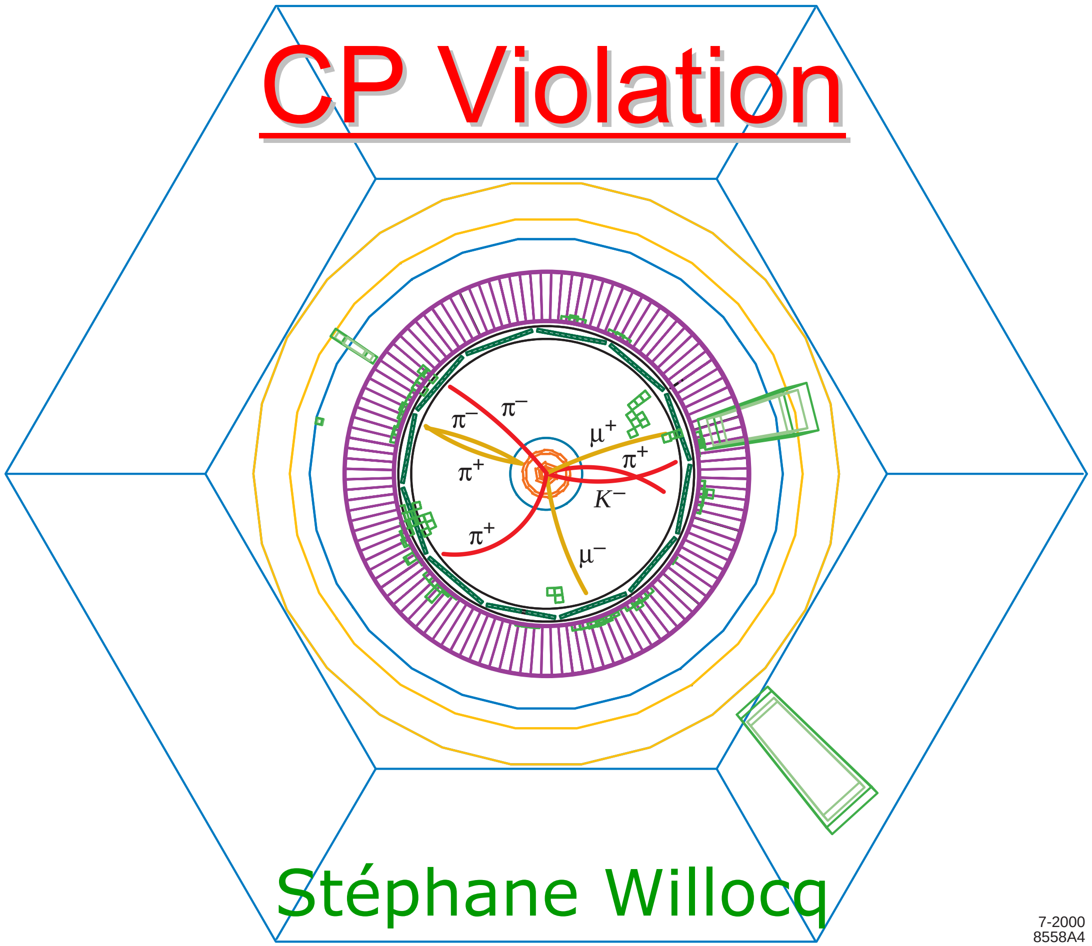
CP Violation



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New England Particle Physics Student Retreat

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Outline

- What is CP Violation? Why is it interesting?
- Fundamental Symmetries
- CP Violation in the Standard Model
- Studies at $e^+ e^-$ Asymmetric B Factories

What is CP Violation?

Observation that the Laws of Physics are not exactly the same under the combined transformation:

Charge conjugation	C	particle $\leftrightarrow$ antiparticle
Parity	P	left-handed helicity $\leftrightarrow$ right-handed helicity

CP symmetry is conserved in strong and electromagnetic interactions

BUT weak interactions violate CP symmetry

Manifestation: *different decay rates in K and B meson decays*

For example, the decay rate for $K^0 \rightarrow \pi^- \mu^+ \nu_\mu$ is slightly higher than that for $\overline{K}^0 \rightarrow \pi^+ \mu^- \overline{\nu}_\mu$ (rate asymmetry = 0.3%)

Why is CP Violation Interesting?

- Phenomenon discovered in 1964 but not yet well understood or tested

- Understanding of the baryon - antibaryon asymmetry of the Universe requires three ingredients: (A. Sakharov, 1967)

  1. Baryon number violating reactions occur
  2. CP Violation (CPV) takes place in these reactions
  3. Reactions occur out of thermal equilibrium (Big Bang)

  $\Rightarrow$ Without CPV all matter would have annihilated with antimatter after the Big Bang

  \+ level of CPV needed is much higher than the Standard Model can allow

- Most extensions of the Standard Model provide new sources of CPV

  $\Rightarrow$ CPV studies are sensitive to New Physics

Fundamental Symmetries (I)

Invariance of field equations under certain transformations

$\rightarrow$ Implies existence of underlying symmetry

$\rightarrow$ Results in conservation laws (or forbidden processes)

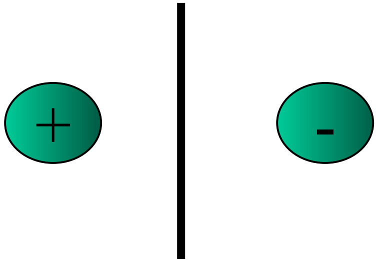
Examples:

- Invariance under translations in space
  $\rightarrow$ Conservation of momentum
- Invariance under translations in time
  $\rightarrow$ Conservation of energy
- Invariance under phase transformations
  $\rightarrow$ Conservation of electric charge

+ There are 3 important discrete symmetries: C, P and T

Fundamental Symmetries (II)

- **Charge Conjugation** *C*
  - Particle $\leftrightarrow$ Anti-particle
  - Charged particles not eigenstates



$$C\,|e^-\rangle = |e^+\rangle \neq \pm|e^-\rangle$$

Neutral particles <u>are</u> (eigenvalue ±1)

$$C\,|\gamma\rangle = -|\gamma\rangle \qquad C\,|\pi^0\rangle = +|\pi^0\rangle$$

Strong and electromagnetic interactions are observed to be invariant under *C*

Fundamental Symmetries (III)

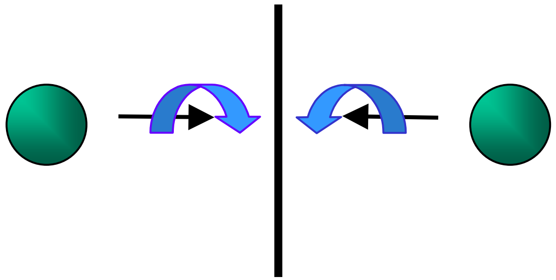
- **Parity** *P*
  - Reflects a system through the origin

    spatial coordinates flipped $\boldsymbol{x} \rightarrow \boldsymbol{-x}$

    but angular momentum unchanged $\boldsymbol{L} \rightarrow \boldsymbol{L}$

  - Particles have intrinsic parity

    $\boldsymbol{P}|\gamma\rangle = -|\gamma\rangle \quad \boldsymbol{P}|\pi^0\rangle = -|\pi^0\rangle$



- Parity operation flips helicity state (left-handed $\rightarrow$ right-handed)

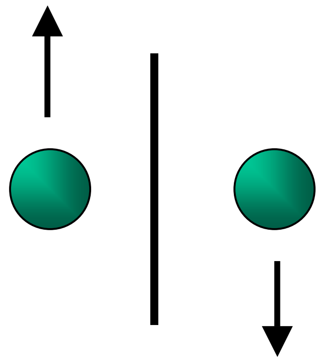
  helicity: projection of spin vector along direction of motion

- Strong and electromagnetic interactions conserve *P*

Fundamental Symmetries (IV)

- **Time reversal *T***
  – Reverses direction of time

  $t \longrightarrow -t$



- Time invariance of a reaction implies equal rate for the time-reversed reaction:

$$p + {}^{27}Al \quad \Leftrightarrow \alpha + {}^{24}Mg$$

Once again, strong and electromagnetic interactions are invariant under *T*

Fundamental Symmetries (V)

- The 3 operations (C,P, and T) are connected through invariance of combined *CPT* for **all** interactions

- *CPT* Theorem: all quantum field theories are invariant under this combo (any order)
  - Consequences:
    - √ particles and antiparticles have same mass and lifetime
    - √ particles obey spin statistics (Fermi or Bose)
    - √ CP violation implies T violation as well

Fundamental Symmetries (VI)

BUT: *weak interactions do NOT conserve either C or P*

- First observation of parity violation in weak decays of ^{60}Co (C.S.Wu et al., 1957)

- Both C and P are completely violated in charged current weak interactions (W couples only to left-handed particles)

$$\mu_L^- \rightarrow e_L^- \, \overline{\nu}_{eR} \, \nu_{\mu L} \quad \xrightarrow{P} \quad \mu_R^- \rightarrow e_R^- \, \overline{\nu}_{eL} \, \nu_{\mu R}$$

observed — not observed

$$\xrightarrow{C} \quad \mu_L^+ \rightarrow e_L^+ \, \nu_{eR} \, \overline{\nu}_{\mu L}$$

not observed

- Combined CP operation yields same muon decay rates

$$\mu_L^- \rightarrow e_L^- \, \overline{\nu}_{eR} \, \nu_{\mu L} \quad \xrightarrow{CP} \quad \mu_R^+ \rightarrow e_R^+ \, \nu_{eL} \, \overline{\nu}_{\mu R}$$

Observation of CPV in the $K^0 - \bar{K}^0$ system

- *Before 1964:*

Strong interaction flavor eigenstates

K^0 ($\bar{s}d$) and $\bar{K}^0$ ($s\bar{d}$) are superpositions

of mass eigenstates K^0_S and K^0_L

$$\left|K_S^0\right\rangle = \frac{1}{\sqrt{2}}\left(\left|K^0\right\rangle + \left|\bar{K}^0\right\rangle\right) \qquad \mathrm{CP} = +1$$

$$\left|K_L^0\right\rangle = \frac{1}{\sqrt{2}}\left(\left|K^0\right\rangle - \left|\bar{K}^0\right\rangle\right) \qquad \mathrm{CP} = -1$$

$\Rightarrow$ CP transforms matter $\leftrightarrow$ antimatter

$$CP\left|K^0\right\rangle = \left|\bar{K}^0\right\rangle$$

Physical states K^0_S and K^0_L are eigenstates of CP if Hamiltonian is invariant under CP

$$\Rightarrow K_S^0 \to \pi^+\pi^- \qquad \mathrm{CP} = +1 \qquad \tau = 1\times10^{-10}\,s$$

$$K_L^0 \to \pi^+\pi^-\pi^0 \qquad \mathrm{CP} = -1 \qquad \tau = 5\times10^{-8}\,s$$

- *Cronin, Fitch, Christenson, Turlay (1964):*

Measure K^0_L decay into CP=+1 state

$$\frac{\Gamma(K_L^0 \to \pi^+\pi^-)}{\Gamma(K_L^0 \to \text{all charged modes})} = (2.0 \pm 0.4)\times10^{-3}$$

$\Rightarrow$ CP violation in kaon weak decays

Other manifestations of CPV also observed in kaon decays but effects are always small, e.g.

$$\frac{\Gamma(K_L^0 \to \pi^- l^+ \nu) - \Gamma(K_L^0 \to \pi^+ l^- \nu)}{\Gamma(K_L^0 \to \pi^- l^+ \nu) + \Gamma(K_L^0 \to \pi^+ l^- \nu)} = (3.27 \pm 0.12)\times10^{-3}$$

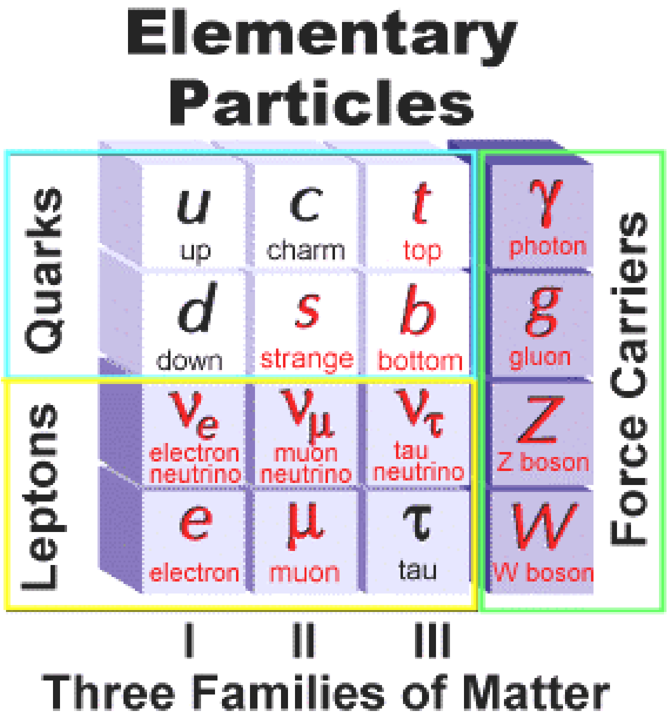
CP Violation in the Standard Model (I)

How does the SM account for CPV in Kaon decays?

- Kobayashi and Maskawa (1973) propose existence of 3rd family of quarks (*before* discovery of charm and tau)

  $\Rightarrow$ CPV originates from an irreducible phase in the quark mixing matrix

  Quark mixing matrix now called Cabibbo-Kobayashi-Maskawa (CKM) matrix



CP Violation in the Standard Model (II)

- CKM matrix originates from the fact that weak eigenstates are different from quark mass eigenstates

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{CKM} \cdot \begin{pmatrix} d \\ s \\ b \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \cdot \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

- CKM matrix plays an important role in charged current weak interaction (e.g. β decay $n \to p\, e^- \nu$ involves a $d \to u$ transition)

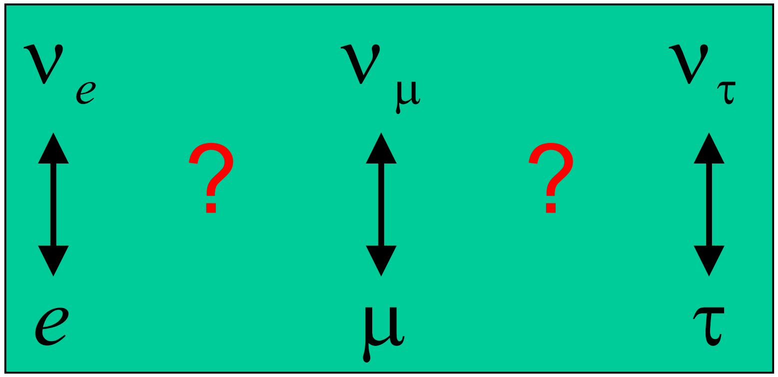
$$H_{CC} = \frac{g^2}{8M_W^2} J_\mu^\dagger J^\mu$$

$$\text{with current } J_\mu = \left(\bar{u}\ \bar{c}\ \bar{t}\right) \gamma_\mu \left(1-\gamma_5\right) V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

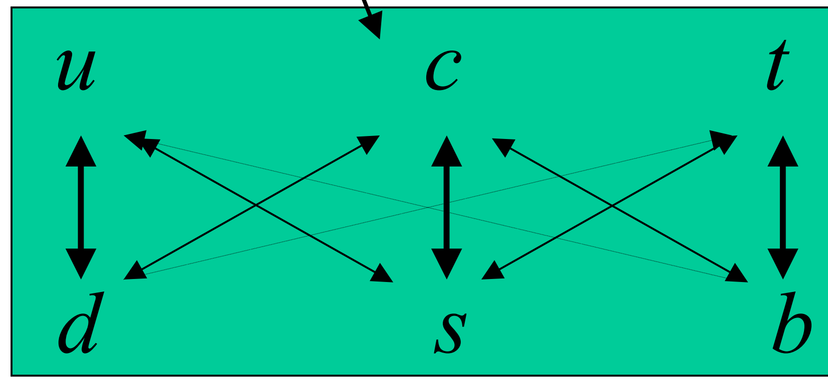
CP Violation in the Standard Model (III)

Properties of CKM matrix

- V_{CKM} governs probability of quark flavor-changing processes

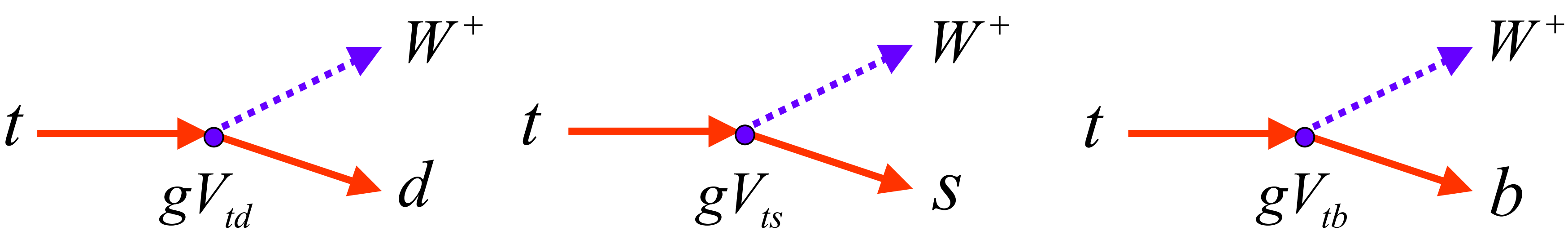


leptons



quarks

Strength of the quark-flavor changing transition is determined by V_{CKM}



Probability $\propto |V_{td}|^2 \approx 0.0001$ $|V_{ts}|^2 \approx 0.0016$ $|V_{tb}|^2 \approx 0.9983$

CP Violation in the Standard Model (IV)

Properties of CKM matrix

- How many parameters?

9 complex elements $\Rightarrow$ 18 parameters (not predicted by the theory)

However, (1) V_{CKM} is unitary: $V_{CKM}^{\dagger} V_{CKM} = V_{CKM} V_{CKM}^{\dagger} = 1$

e.g. $|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2 = 1$

$\Rightarrow$ 9 independent parameters

(2) Quark fields can be redefined to remove 5 arbitrary phases

$\Rightarrow$ 4 independent parameters

3 angles + 1 phase

Note: if only 2 families of quarks $\Rightarrow$ 2x2 matrix $\Rightarrow$ 1 (real) independent param

$\Rightarrow$ no phase and no CPV

$\Rightarrow$ need at least 3 families of quarks to get an irreducible phase in the quark mixing matrix

CP Violation in the Standard Model (V)

Wolfenstein parameterization of CKM matrix

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

λ, A, ρ and η are fundamental parameters of the Standard Model

Expansion in powers of λ $\rightarrow$ hierarchy of transition probabilities

$\lambda = |V_{us}| = 0.2196 \pm 0.0023$ from Kaon decay rates ($s \rightarrow u$)

$A = |V_{cb}| / \lambda^2 = 0.854 \pm 0.041$ from $B \rightarrow D^* l \nu$ decays & lifetime ($b \rightarrow c$)

$\rho = 0.22 \pm 0.10$

$\eta = 0.35 \pm 0.05$

from global fit to available data

$\eta \neq 0 \Rightarrow$ non-zero phase responsible for CP violation

CKM Matrix Unitarity Conditions

$$V_{CKM}^{\dagger} V_{CKM} = V_{CKM} V_{CKM}^{\dagger} = 1$$

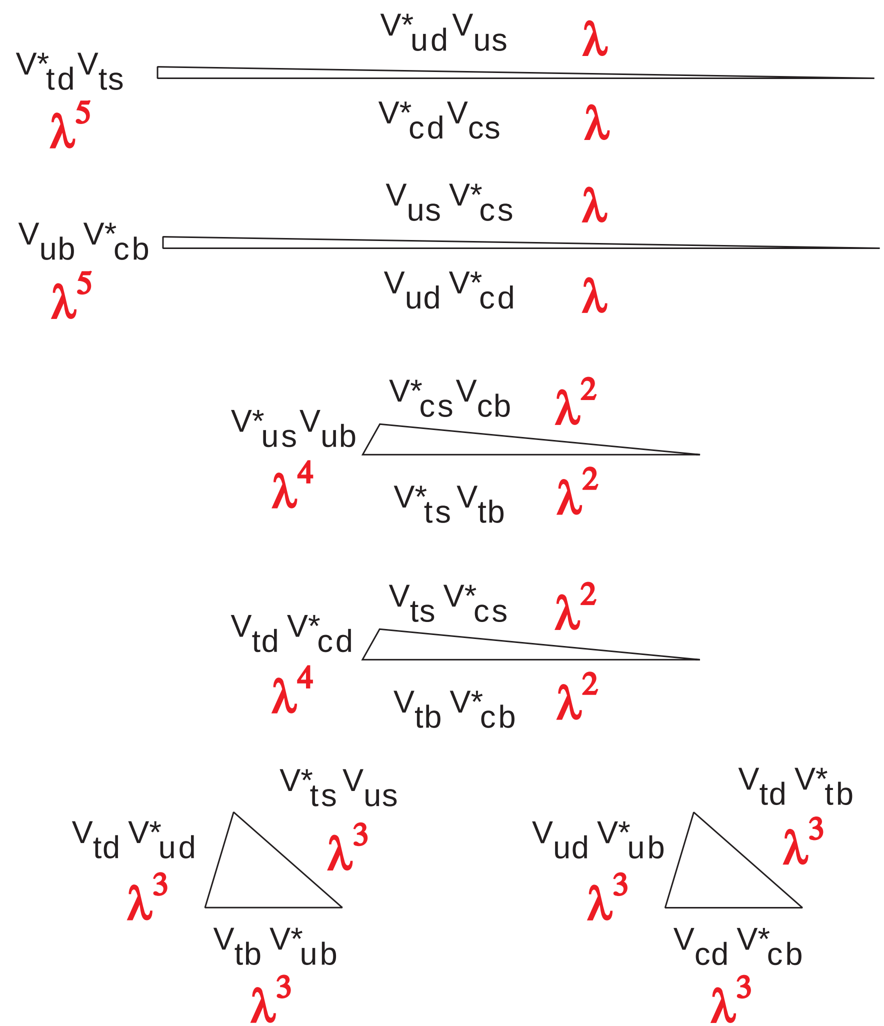
$$\begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

Unitarity requires

$$\sum_{i=1}^{3} V_{ji} V_{ki}^{*} = 0 = \sum_{i=1}^{3} V_{ij} V_{ik}^{*}$$

$$(j,k = 1,2,3 \ \text{and} \ j \neq k)$$

$\Rightarrow$ 6 orthogonality conditions



Represented by 6 triangles in the complex plane

“The” Unitarity Triangle (I)

Unitarity condition between 1st and 3rd columns:

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

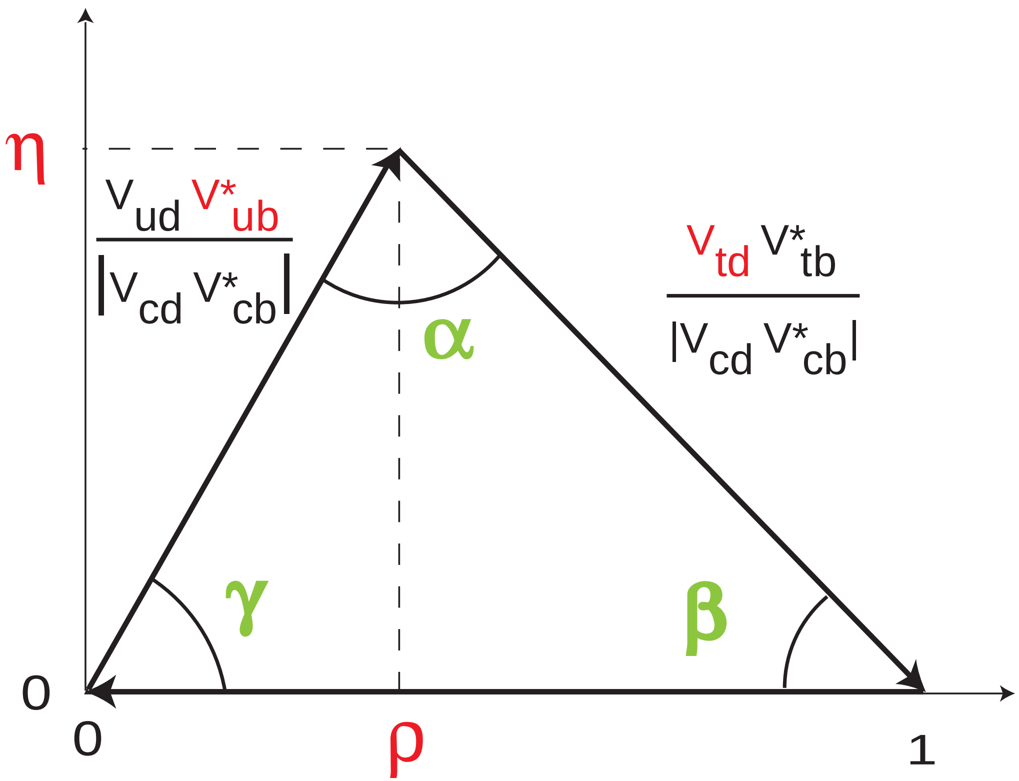
Condition is represented by a triangle with ~equal sides

⇒ angles α, β, γ are large and are different manifestations of the single CP-violating phase

$$\alpha = \arg\left[-\frac{V_{td}\,V_{tb}^{*}}{V_{ud}\,V_{ub}^{*}}\right]$$

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

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



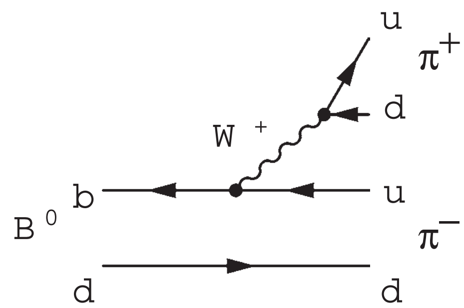
CP Violation in the Standard Model (VI)

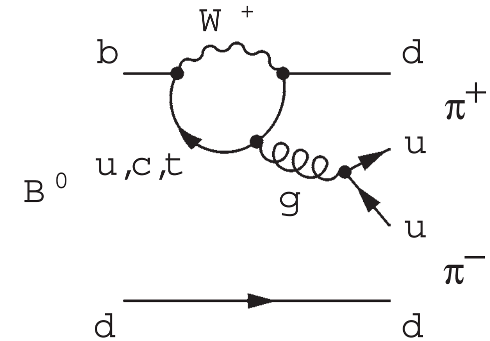
How does the CKM phase give rise to CPV?

Example:

compare decay rate for

$B^0 \to \pi^+\pi^-$ vs. $\bar{B}^0 \to \pi^+\pi^-$





Two diagrams contribute: "Tree" "Penguin"

$B \to f$ amplitudes: $T_f = |T| e^{i\phi^T_{CKM}} e^{i\delta^T_s}$ $\quad P_f = |P| e^{i\phi^P_{CKM}} e^{i\delta^P_s}$

ϕ_{CKM} : weak phase from CKM elements involved

δ_s : phase shift due to strong interactions between final state particles

Decay rate:

$$\Gamma(B \to f) \propto |T_f + P_f|^2 = |T|^2 + |P|^2 + |T||P| e^{i\phi^T_{CKM}} e^{i\delta^T_s} e^{-i\phi^P_{CKM}} e^{-i\delta^P_s}$$

$$+ |T||P| e^{-i\phi^T_{CKM}} e^{-i\delta^T_s} e^{i\phi^P_{CKM}} e^{i\delta^P_s}$$

$$= |T|^2 + |P|^2 + 2|T||P| \cos\left(\Delta\phi_{CKM} + \Delta\delta_s\right)$$

Relative CKM and strong phases: $\Delta\phi_{CKM} = \phi^T_{CKM} - \phi^P_{CKM}$ $\quad \Delta\delta_s = \delta^T_s - \delta^P_s$

CP Violation in the Standard Model (VII)

How does the CKM phase give rise to CPV?

Consider CP-conjugate $\overline{B} \to \overline{f}$ mode

$\overline{B} \to \overline{f}$ amplitudes: $T_{\bar{f}} = |T| e^{-i\phi^T_{CKM}} e^{i\delta^T_s}$ $\quad P_{\bar{f}} = |P| e^{-i\phi^P_{CKM}} e^{i\delta^P_s}$

Decay rate: $\Gamma(\overline{B} \to \bar{f}) \propto \left|T_{\bar{f}} + P_{\bar{f}}\right|^2 = |T|^2 + |P|^2 + 2|T||P|\cos\left(-\Delta\phi_{CKM} + \Delta\delta_s\right)$

⇒ Rates are different for B and $\overline{B}$ decays

$$A_{CP} = \frac{\Gamma(\overline{B} \to \bar{f}) - \Gamma(B \to f)}{\Gamma(\overline{B} \to \bar{f}) + \Gamma(B \to f)} = \frac{2\ |T||P|\ \sin\Delta\phi_{CKM}\ \sin\Delta\delta_s}{|T|^2 + |P|^2 + 2\ |T||P|\ \cos\Delta\phi_{CKM} \cos\Delta\delta_s}$$

⇒ This kind of CPV is referred to as "direct" CPV or "CPV in decay"
it requires two amplitudes with different weak (CKM) and strong phases

In general, CPV originates from a quantum mechanical interference between amplitudes with different phases

CP Violation in B Decays

Why B Factories?

- CPV effects expected to be much larger in some B decay modes than those observed in kaon decays

  Modes involving quark transitions between 3rd and 1st families:

  $$V_{td} = A\lambda^3(1-\rho-i\eta) \quad \text{and} \quad V_{ub} = A\lambda^3(\rho-i\eta)$$

  these elements have large imaginary parts $\Rightarrow$ large weak phases

- CPV phenomenology much richer (many more decay modes)

- Some CPV measurements are particularly clean both theoretically and experimentally, e.g., CPV in $B^0 \rightarrow J/\psi\, K^0_S$ decays

$\Rightarrow$ Opportunity to test the Standard Model in a clean and new way

e+ e- B Factories operating at SLAC (BaBar) and KEK (Belle) since 1999

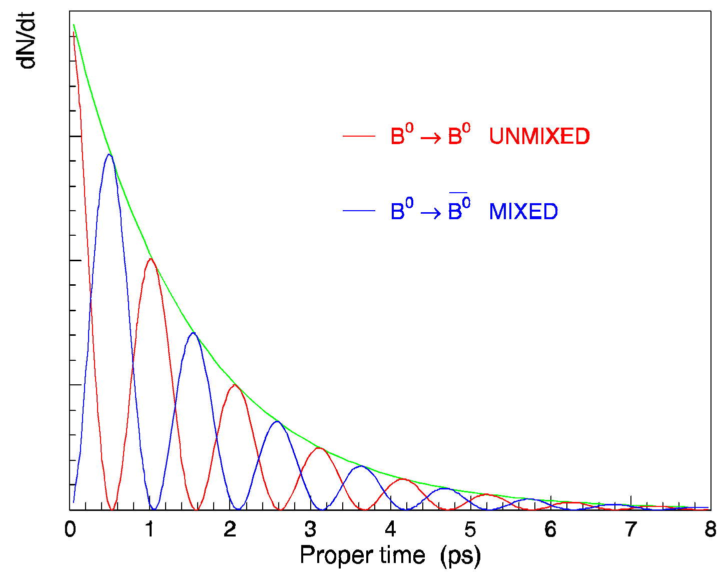
hadron collider experiments (CDF and D0) will also contribute soon

$B^0 - \overline{B}^0$ System

- As in the neutral kaon system, Heavy and Light mass eigenstates are superpositions of flavor eigenstates

$$|B_L\rangle = p|B^0\rangle + q|\overline{B}^0\rangle$$

$$|B_H\rangle = p|B^0\rangle - q|\overline{B}^0\rangle$$



- System characterized by

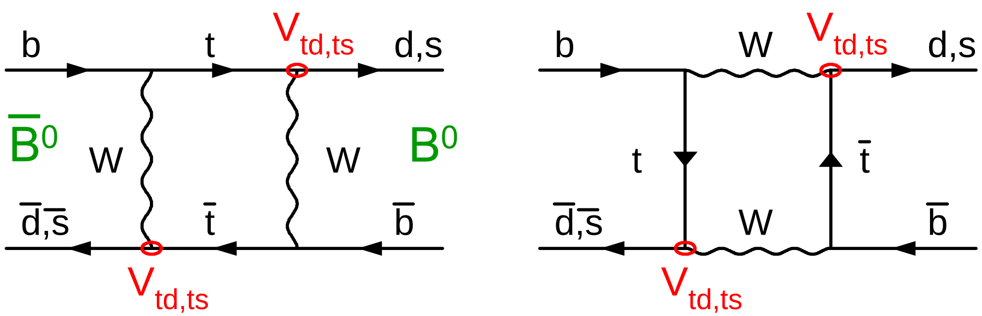
  mass difference $\Delta m = m_H - m_L$

  width difference $\Delta\Gamma = \Gamma_L - \Gamma_H$

- Different time evolution for B_H and B_L

$$|B_H(t)\rangle = |B_H(t=0)\rangle \; e^{(-im_H - \Gamma_H/2)\,t}$$

$$|B_L(t)\rangle = |B_L(t=0)\rangle \; e^{(-im_L - \Gamma_L/2)\,t}$$



leads to $B^0 \leftrightarrow \overline{B}^0$ oscillations with frequency Δm (a.k.a. "mixing")

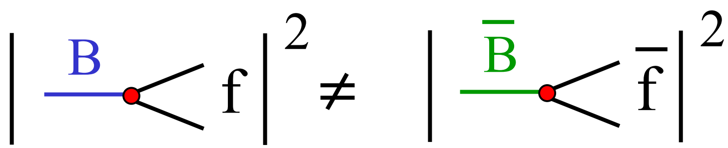
$$\Delta m_d \propto \left| V_{tb}^* V_{td} \right|^2$$

3 Classes of CP Violation (I)

Need 2 amplitudes with different phase structure contributing to the same decay

$\rightarrow$ 3 different ways to achieve this:

1) CP violation in decay (a.k.a. *direct CP violation*)



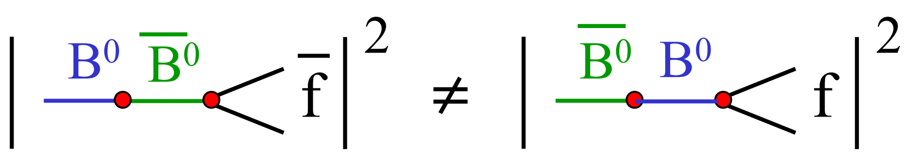
need $$\left| \frac{\langle \bar{f} \mid H \mid \bar{B} \rangle}{\langle f \mid H \mid B \rangle} \right| \neq 1$$

two amplitudes with different weak phases & different strong phases

e.g. compare BR($B^+ \rightarrow K^+\pi^0$) and BR($B^- \rightarrow K^-\pi^0$)

but strong phases are not known

2) CP violation in mixing (a.k.a. *indirect CP violation*)



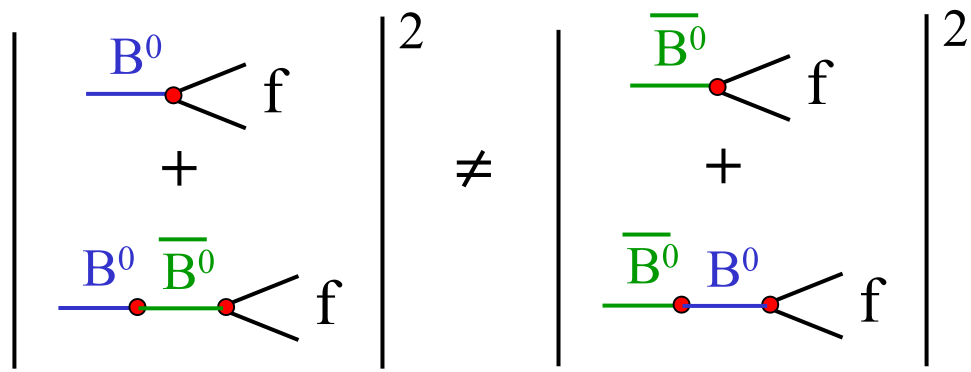
need $$\left| \frac{q}{p} \right| \neq 1$$

Need relative phase between mass and width parts of mixing matrix

CP-violating asymmetries expected to be small in Standard Model

3 Classes of CP Violation (II)

3) CP violation in interference between decays with and without mixing



Final state f is a CP eigenstate (e.g. $J/\psi\, K^0_s$ or $\pi^+ \pi^-$)

need $\arg\left(\frac{q}{p}\,\frac{\langle f\,|\,H\,|\,\overline{B}^0\rangle}{\langle f\,|\,H\,|\,B^0\rangle}\right) \neq 0$ to have CPV (no strong phases needed!)

which can happen even if $\left|\frac{q}{p}\right| = 1$ and $\left|\frac{\langle f\,|\,H\,|\,\overline{B}^0\rangle}{\langle f\,|\,H\,|\,B^0\rangle}\right| = 1$ → only need weak phase

+ asymmetries can be large & do NOT require unknown strong phase

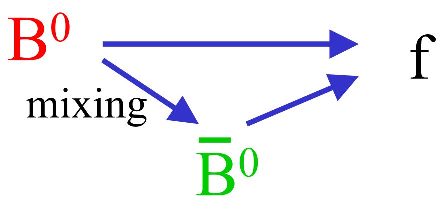
+ small theoretical uncertainties in some cases (e.g. $J/\psi\, K^0_s$)

⇒ most promising way to study CPV via measurements of the angles α, β, γ

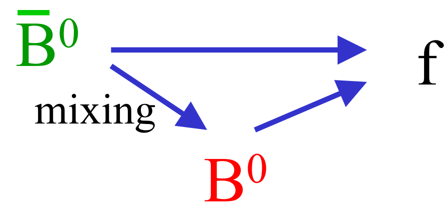
CP Violation in $B^0 \to J/\psi\, K^0_S$ Decays (I)

Consider B^0 decays into CP eigenstates

$\Rightarrow$ Interference between amplitudes for decay with and without mixing



$$\Gamma\left(B^0 \to f\right) \propto 1 - \mathrm{Im}\left(\lambda_{f_{CP}}\right)\sin \Delta m_d t$$

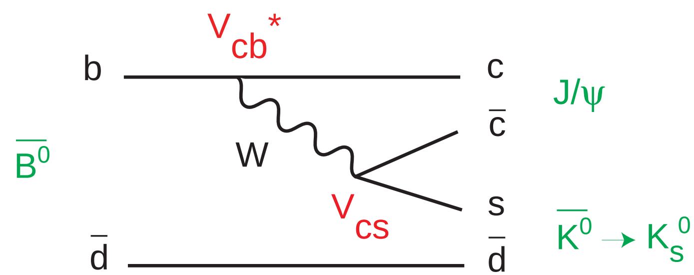


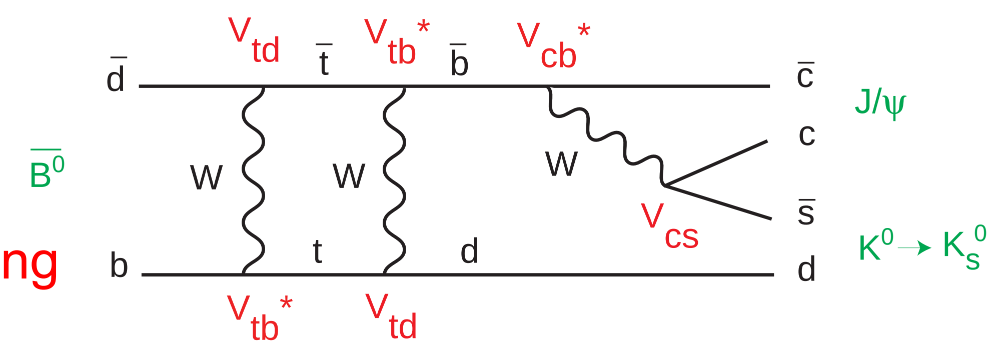
$$\Gamma\left(\overline{B}^0 \to f\right) \propto 1 + \mathrm{Im}\left(\lambda_{f_{CP}}\right)\sin \Delta m_d t$$

$$\lambda_{f_{CP}} = \frac{q}{p}\frac{\langle f \,|\, H \,|\, \overline{B}^0\rangle}{\langle f \,|\, H \,|\, B^0\rangle}$$

$$\frac{q}{p} = \frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*} = e^{-i2\beta}$$

β : weak (CKM) phase from B mixing



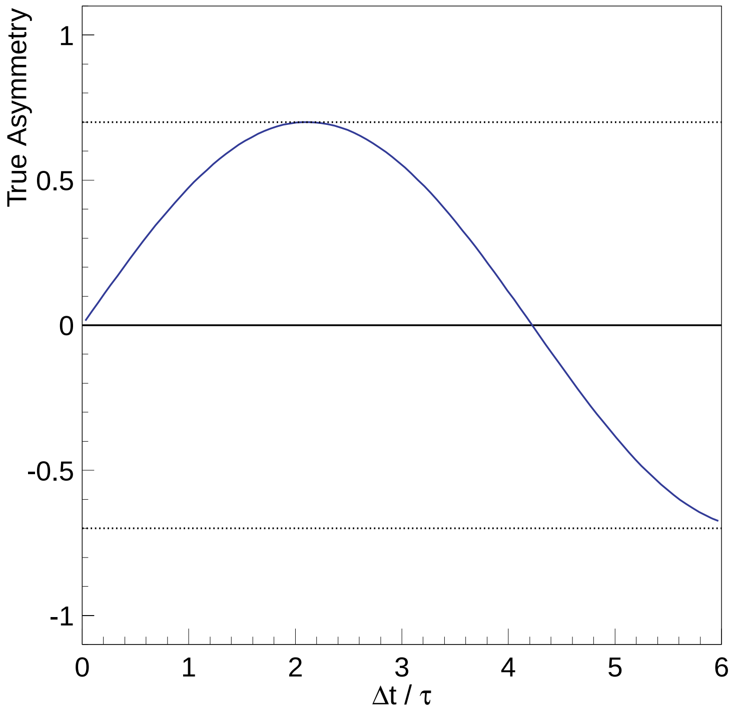


CP Violation in $B^0 \to J/\psi\ K^0_S$ Decays (II)

- *Expect large CP asymmetry*

$$a_{J/\psi\ K_s}(t) = \frac{\Gamma(\overline{B}^0 \to J/\psi\ K^0_s) - \Gamma(B^0 \to J/\psi\ K^0_s)}{\Gamma(\overline{B}^0 \to J/\psi\ K^0_s) + \Gamma(B^0 \to J/\psi\ K^0_s)}$$

$$= \sin 2\beta\ \ \sin \Delta m_d\ t$$



Standard Model fit yields
$\sin 2\beta = 0.75 \pm 0.09$ S.Mele, PRD59, 113011 (1999)

- *Small branching ratio*

$BR(B^0 \to J/\psi\ K^0) = (8.9 \pm 1.2) \times 10^{-4}$

$BR(J/\psi \to l^+ l^-) = (5.9 \pm 0.1) \times 10^{-2}$

$\Rightarrow$ combined BR $\approx 10^{-4}$ for e & μ modes

+ Need to reconstruct $J/\psi \to e^+ e^-, \mu^+ \mu^-$ and $K^0_s \to \pi^+ \pi^-$

(account for detector and selection efficiency ~50%)

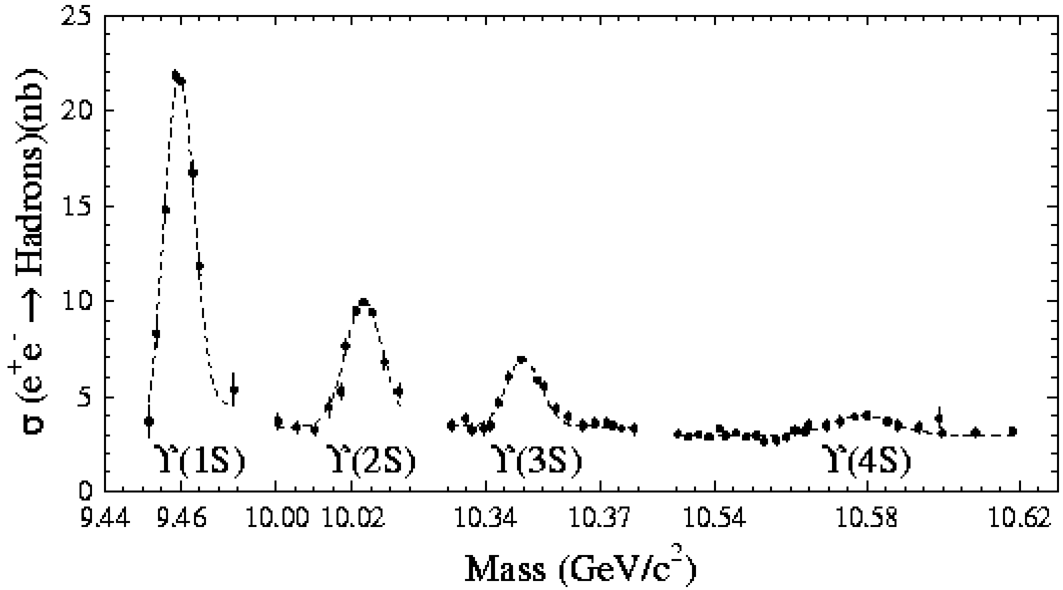
$\Rightarrow$ Requires very large sample of B mesons

$e^+ e^-$ B Factories

- GOAL: Produce 30-100 million $B\bar{B}$ events/year to study CP violation in B decays via

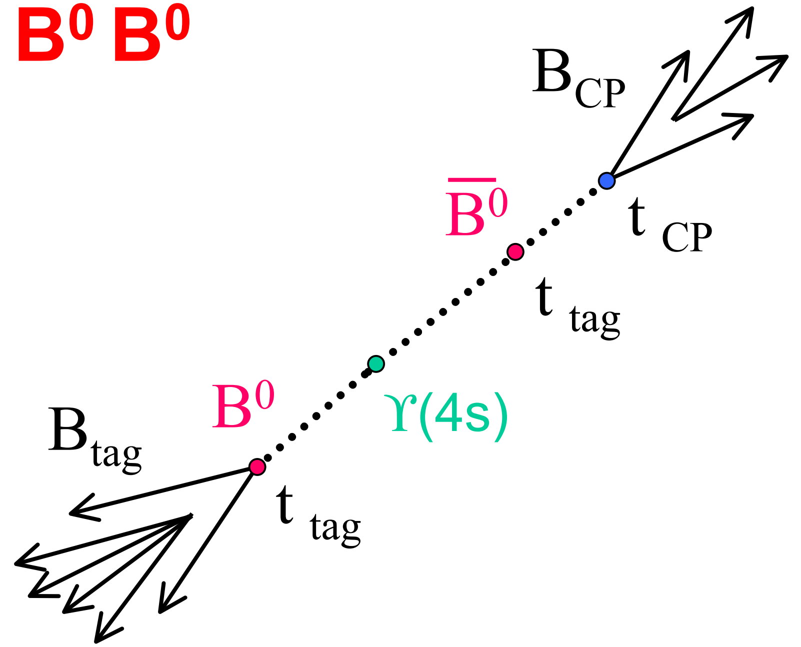
  $e^+ e^- \to \Upsilon(4s) \to B^0 \bar{B}^0$ (50%)

  $B^+ B^-$ (50%)



- High signal-to-background ratio $\sigma_{bb} / \sigma_{hadrons} \approx 0.22$ with σ_{bb}= 1.05 nb
- Clean events <# tracks> ≈ 11 & able to reconstruct π^0 and γ
- No fragmentation products (low combinatorial background)
- Strong kinematical constraints ($p_{\Upsilon(4s)}$ and p_B^*) for background suppression

$\Upsilon(4s) \to B^0 \bar{B}^0$



- $B^0 \bar{B}^0$ system in coherent L=1 state
- B^0 and $\bar{B}^0$ evolve IN PHASE
  $\Rightarrow$ always one B^0 and one $\bar{B}^0$
  until one of them decays
  at time $t = t_{tag}$
- Other B continues to evolve until it decays at time $t = t_{CP}$
- Consider other B decays into CP eigenstate f_{CP}

If B_{tag} is B^0 at time t_{tag} then probability to observe other B decay into f_{CP} is

$$f_+ = \tfrac{1}{4}\Gamma\, e^{-\Gamma|\Delta t|}\left[1 + \mathrm{Im}(\lambda_{f_{CP}})\sin\Delta m_d \Delta t\right]$$

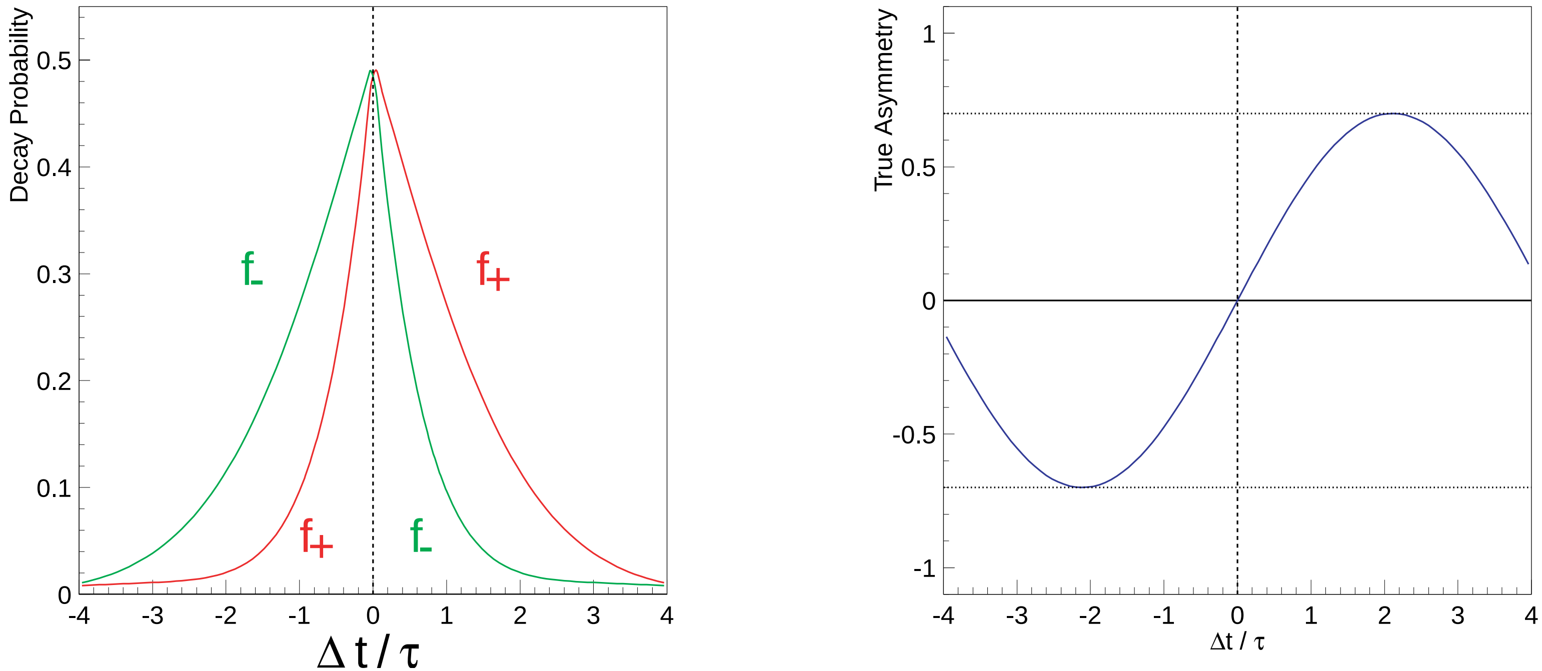
with $\Delta t = t_{CP} - t_{tag}$

if B_{tag} is $\bar{B}^0$ at time t_{tag} then

$$f_- = \tfrac{1}{4}\Gamma\, e^{-\Gamma|\Delta t|}\left[1 - \mathrm{Im}(\lambda_{f_{CP}})\sin\Delta m_d \Delta t\right]$$

$\Upsilon(4s) \rightarrow B^0 \bar{B}^0$

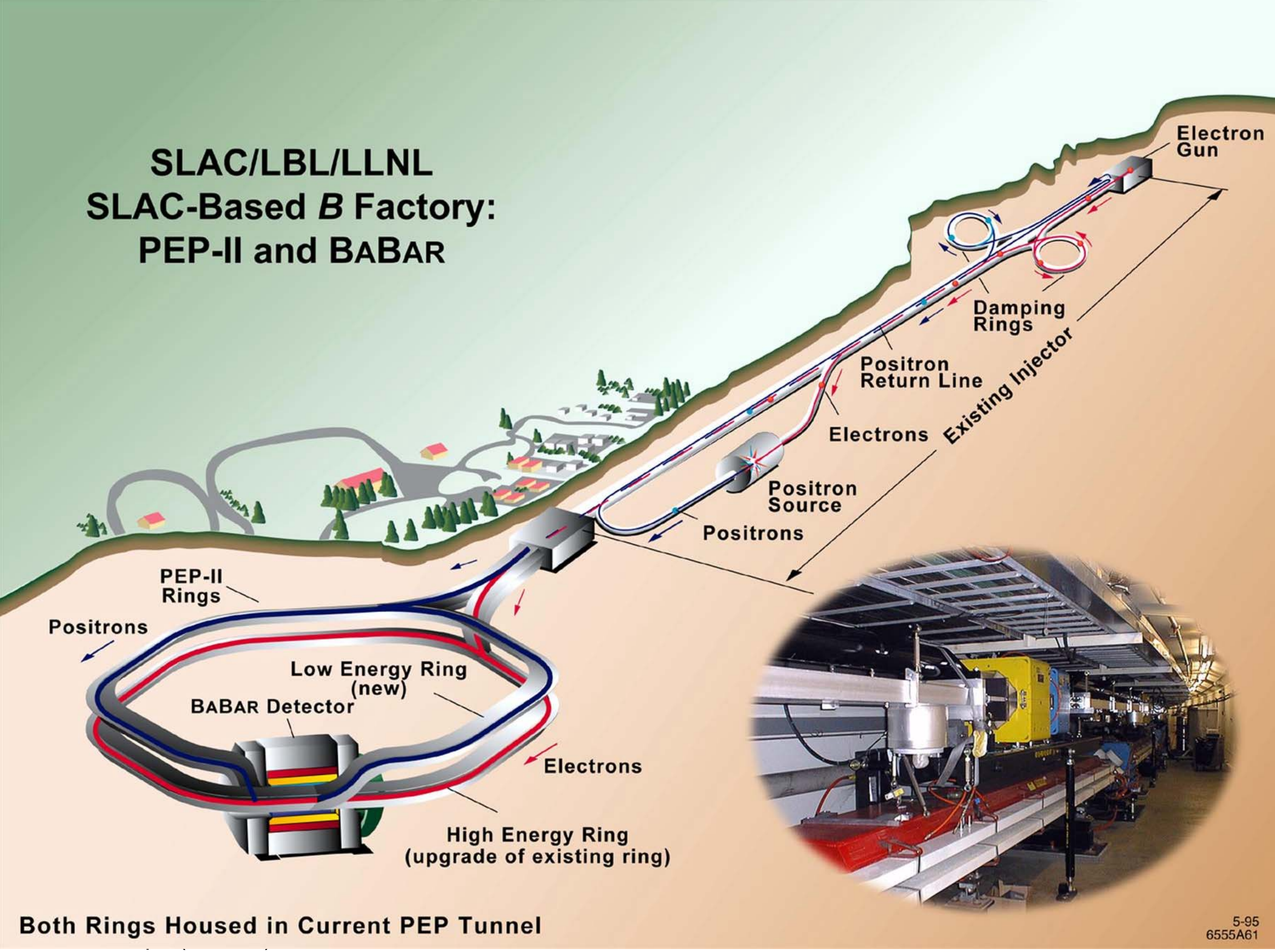
- Different time evolution for $B^0(t = t_{tag}) \rightarrow f_{CP}$ and $\bar{B}^0(t = t_{tag}) \rightarrow f_{CP}$ decays
- Asymmetry depends on $\Delta t = t_{CP} - t_{tag}$ (NB: Δt can be > 0 or < 0)



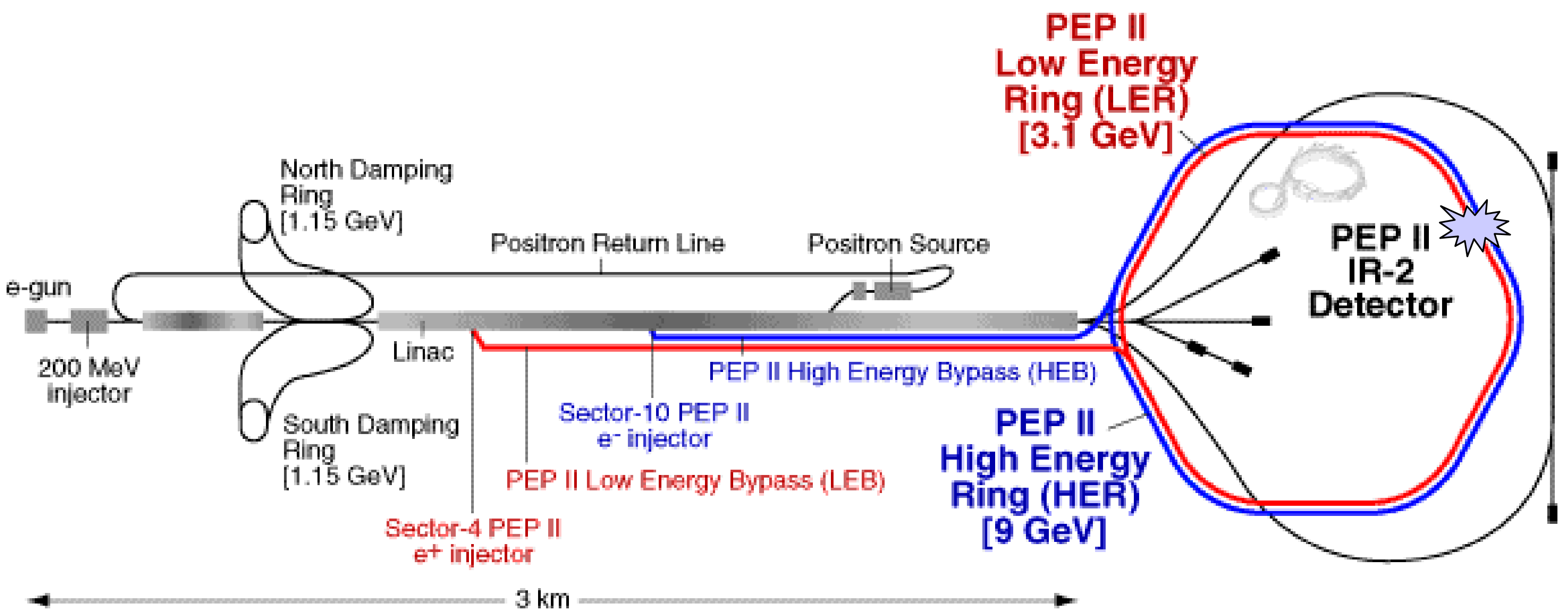
- $\Upsilon(4s)$ rest frame: B mesons produced nearly at rest
  $p_B^* = 340$ MeV/c
  $\rightarrow$ avg distance traveled before decay $\langle L^* \rangle = 30\ \mu m$ (given $\tau_B = 1.55$ ps)

$\Rightarrow$ Symmetric $e^+ e^-$ collider (e.g. CESR) does not allow time reconstruction

$\Rightarrow$ Need unequal beam energies to boost $\Upsilon(4s)$ system and measure Δt

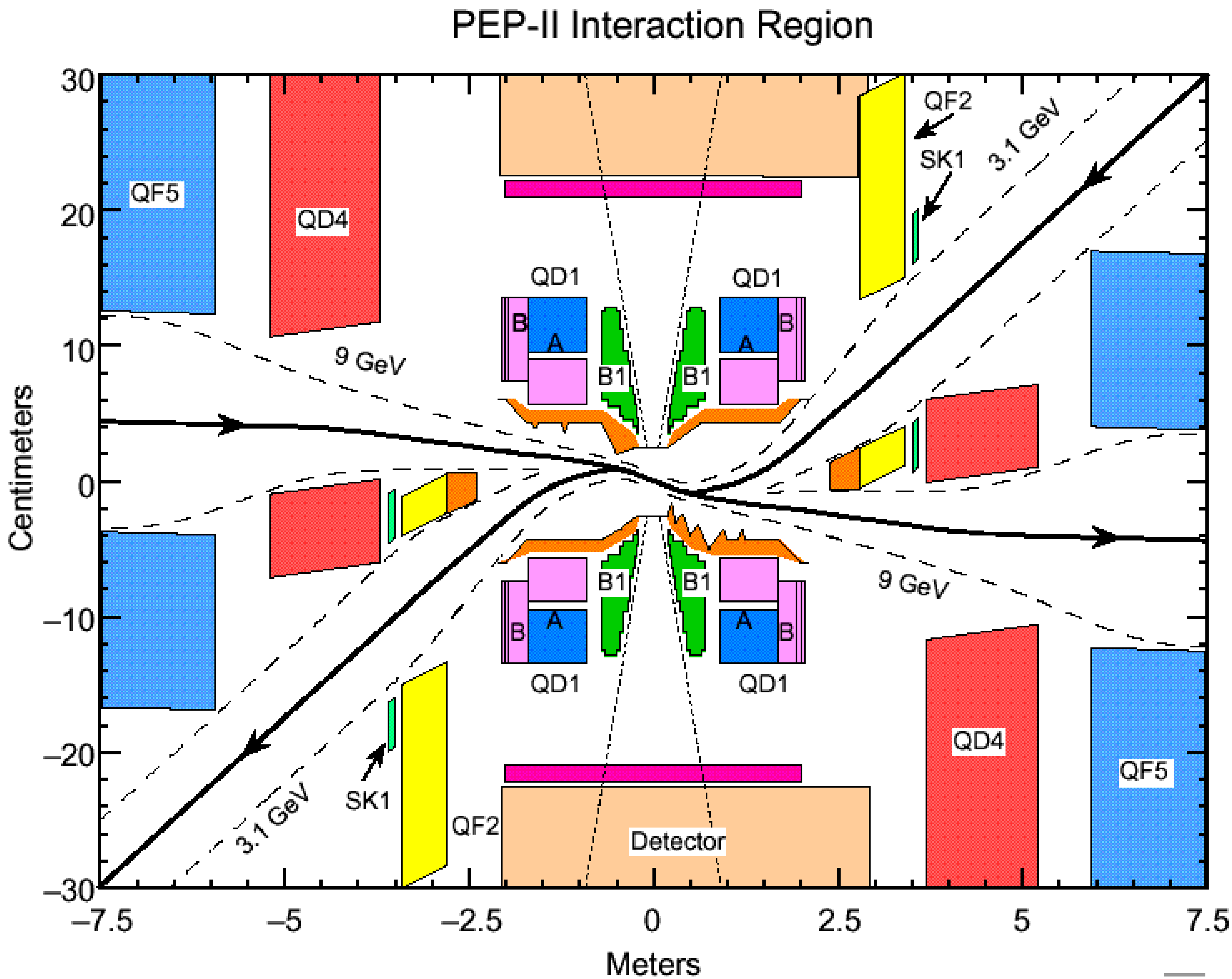

SLAC/LBL/LLNL
SLAC-Based B Factory:
PEP-II and BABAR
Electron Gun
Damping Rings
Positron Return Line
Existing Injector
Electrons
Positron Source
Positrons
PEP-II Rings
Positrons
Low Energy Ring (new)
BABAR Detector
Electrons
High Energy Ring (upgrade of existing ring)
Both Rings Housed in Current PEP Tunnel
5-95
6555A61

PEP-II B Factory @ SLAC



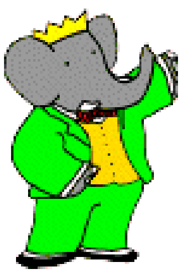
- $E(e^+) = 3.1$ GeV and $E(e^-) = 9.0$ GeV $\Rightarrow$ $\beta\gamma = 0.55$ $\Rightarrow$ $\langle L \rangle = 260\ \mu m$
- Peak luminosity = $3.0 \times 10^{33}\ cm^{-2}\ s^{-1}$ (design)
  $4.6 \times 10^{33}\ cm^{-2}\ s^{-1}$ (achieved)
- Number of bunches = 800
- Positron current = 1775 mA, Electron current = 1060 mA
- IP beam sizes = 150 μm in x, 5 μm in y

PEP-II B Factory @ SLAC

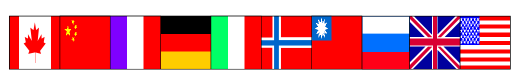


BABAR Collaboration @ SLAC

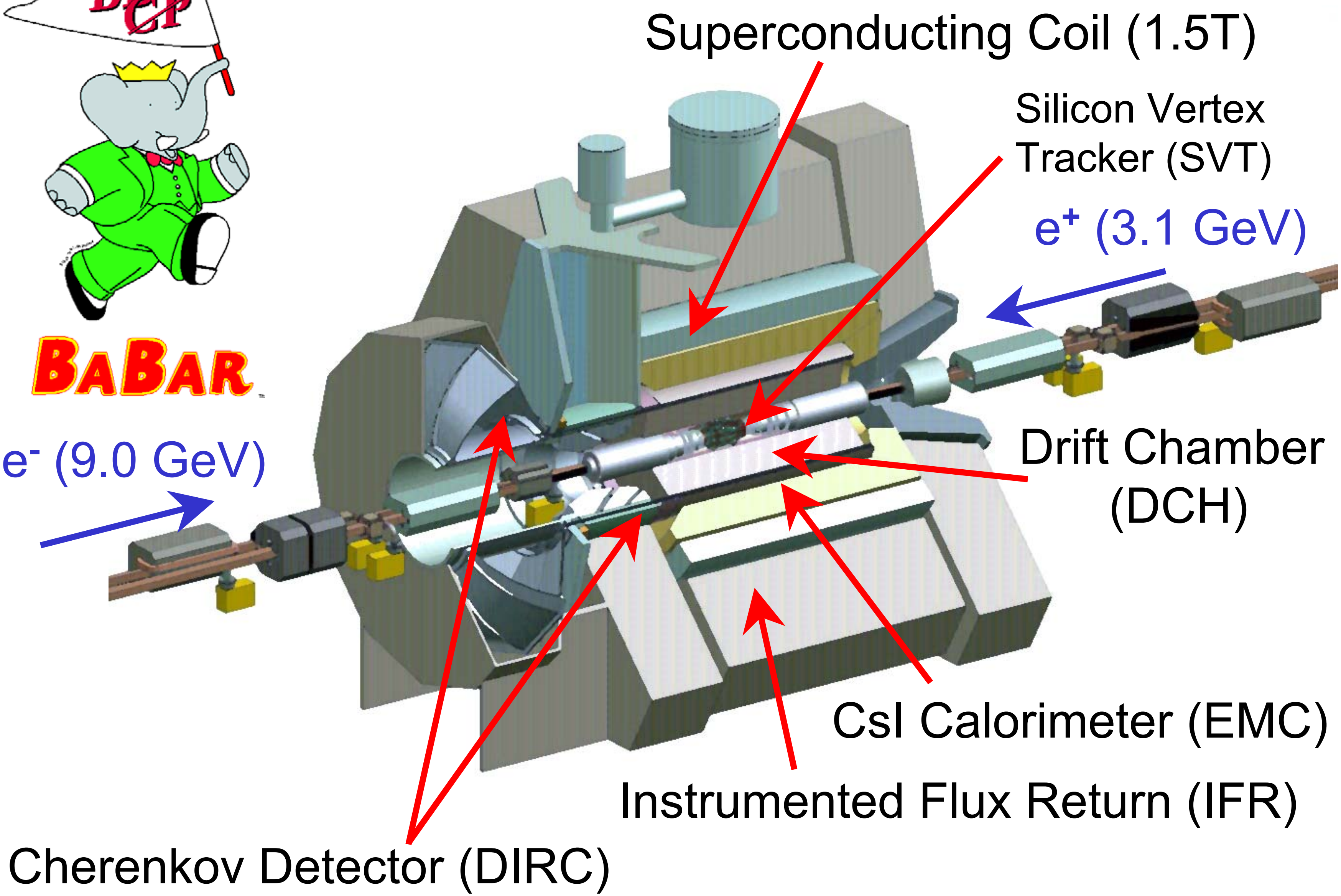
Collaboration meeting @ SLAC July 2002



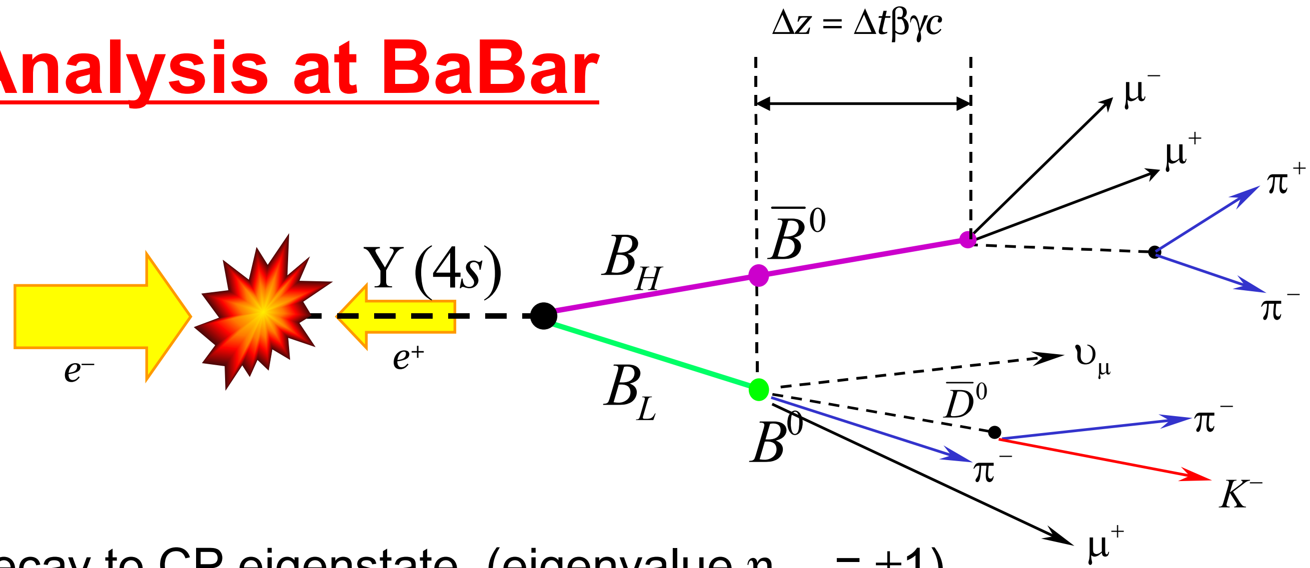
9 Countries
76 Institutions
550 Physicists
July 2002



BABAR Detector @ PEP-II



sin 2β (Blind) Analysis at BaBar



1. Fully reconstruct B decay to CP eigenstate (eigenvalue $\eta_{CP} = \pm 1$)
2. Determine B^0 or $\overline{B}^0$ flavor of the other (tagging) B meson
3. Reconstruct decay vertices of both B mesons
   $\Delta z = z_{CP} - z_{tag}$ $\langle\Delta z\rangle = 260\ \mu m$
   $\Delta t = \Delta z / (\gamma \beta c)$ *SIGNED!*
4. Extract sin 2β with unbinned maximum likelihood fit (value hidden to avoid bias)

$$A_{CP}(\Delta t) = \frac{F_+(\Delta t) - F_-(\Delta t)}{F_+(\Delta t) + F_-(\Delta t)} \cong -\eta_{CP}(D \sin 2\beta)(\sin \Delta m_d \Delta t)$$

$$F_\pm(\Delta t) = \tfrac{1}{4}\Gamma e^{-\Gamma|\Delta t|}\left[1 \pm (-\eta_{CP})\, D \sin 2\beta \ \ \sin \Delta m_d \Delta t\right] \otimes R(\Delta t)$$

Experimental effects: Dilution $D = (1 - 2w)$ and resolution function $R(\Delta t)$

$$\sigma(\sin 2\beta) \propto 1 / (N\, \varepsilon_{tag}\, D^2)^{1/2}$$

Exclusive B Reconstruction (I)

Exploit two kinematical constraints:

→ ***Beam energy substituted mass***

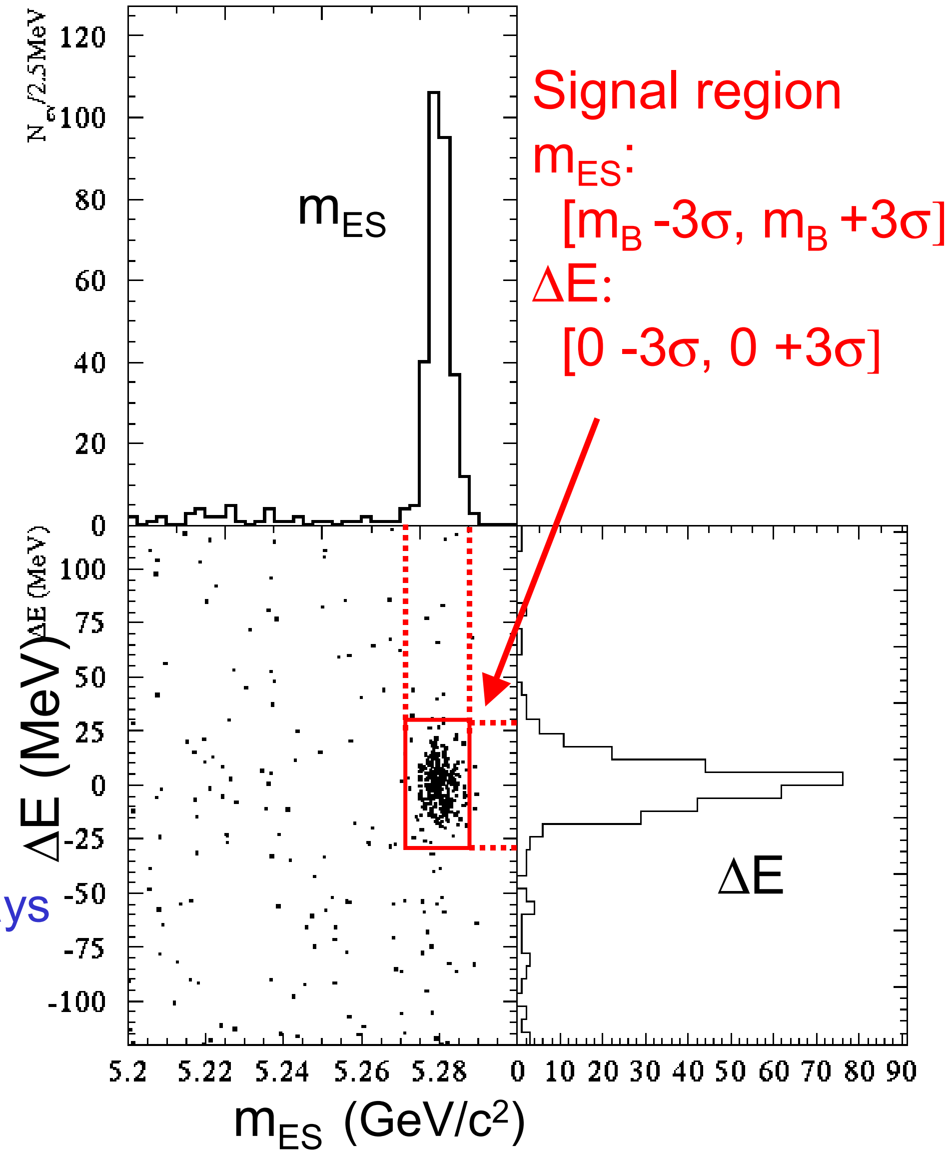
$$m_{ES} = \sqrt{E_{beam}^{*2} - \vec{p}_{Brec}^{\,*2}}$$

resolution ~ 2.6 MeV/c^2
dominated by beam energy spread

→ ***Energy difference***

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

resolution ~10-40 MeV depending
on decay mode
suppress background from other B decays



Exclusive B Reconstruction (II)

Full reconstruction of B decay into

→ ***CP-odd eigenstates:*** $\eta_{CP} = -1$

- $B^0 \to J/\psi\, K^0_s$

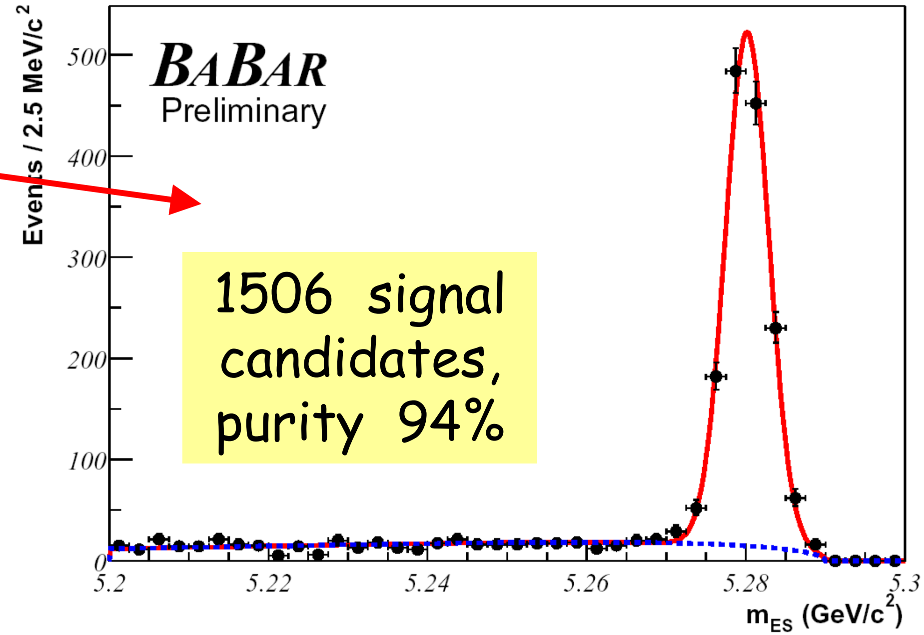
  $J/\psi \to e^+ e^-, \mu^+ \mu^-$
- $B^0 \to \psi(2s)\, K^0_s$

  $\psi(2s) \to e^+ e^-, \mu^+ \mu^-, J/\psi\, \pi^+ \pi^-$
- $B^0 \to \chi_{c1}\, K^0_s$

  $\chi_{c1} \to J/\psi\, \gamma$
- $B^0 \to \eta_c\, K^0_s$

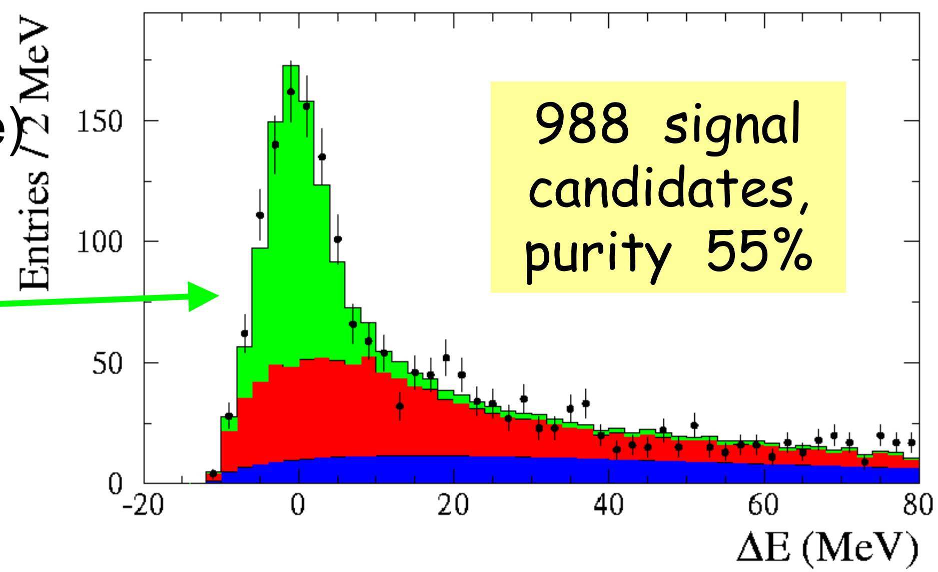
  $\eta_c \to K^0_s K^+ \pi^-, K^+ K^- \pi^0$

with $K^0_s \to \pi^+ \pi^-$ (and $\pi^0 \pi^0$ for J/ψ mode)



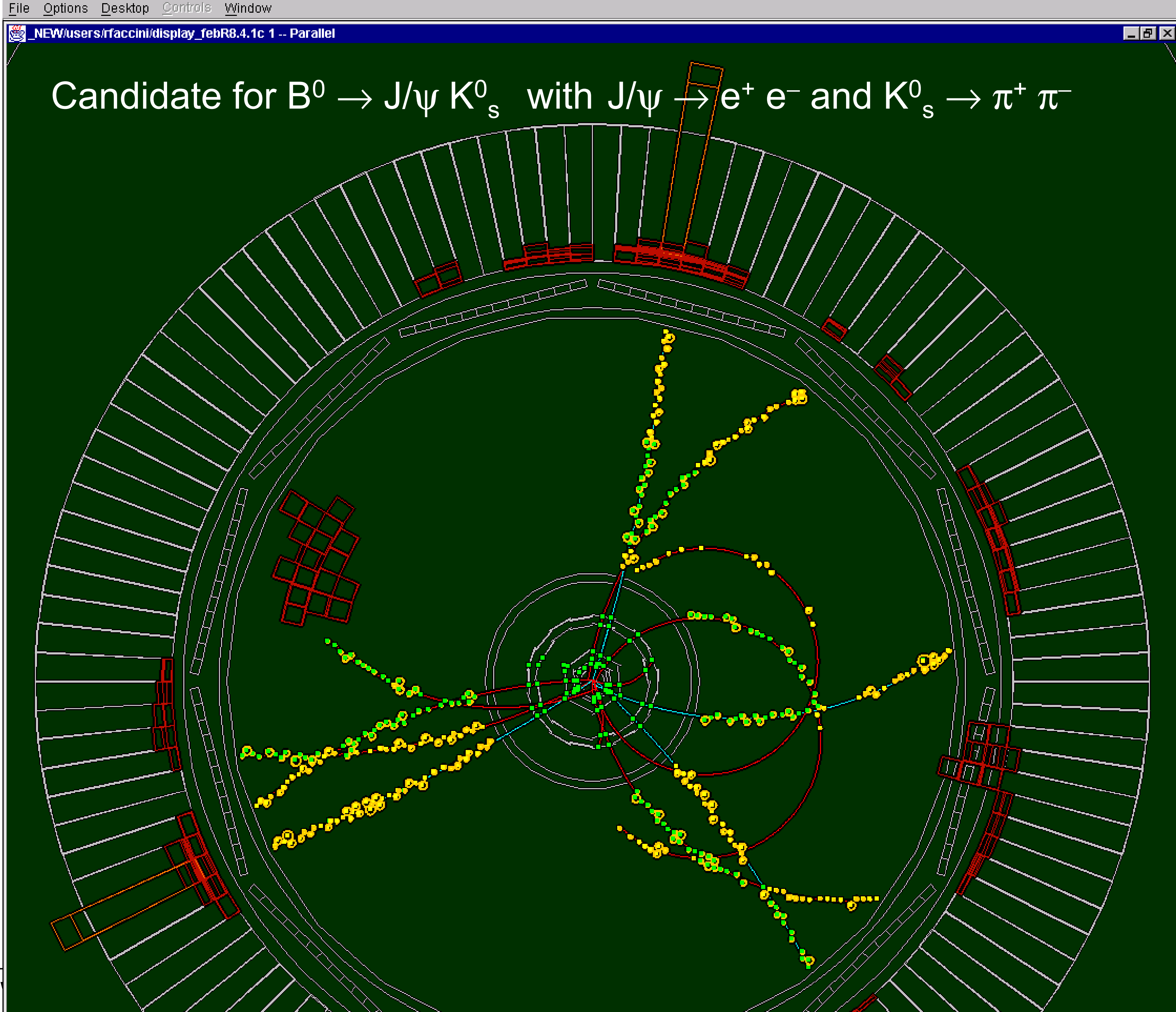
→ ***CP-even eigenstates:*** $\eta_{CP} = +1$

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

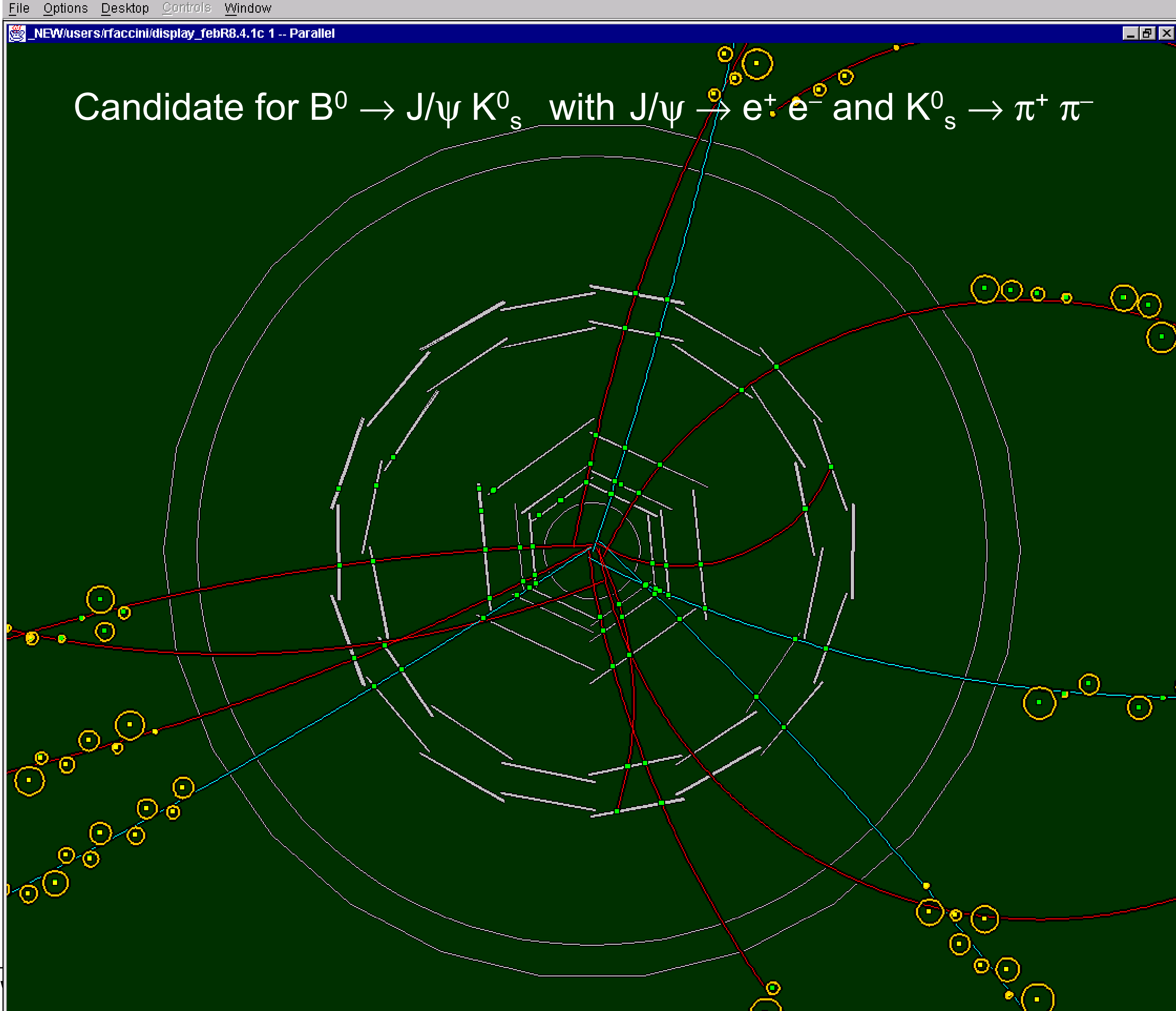


→ ***CP-mixed eigenstates:***

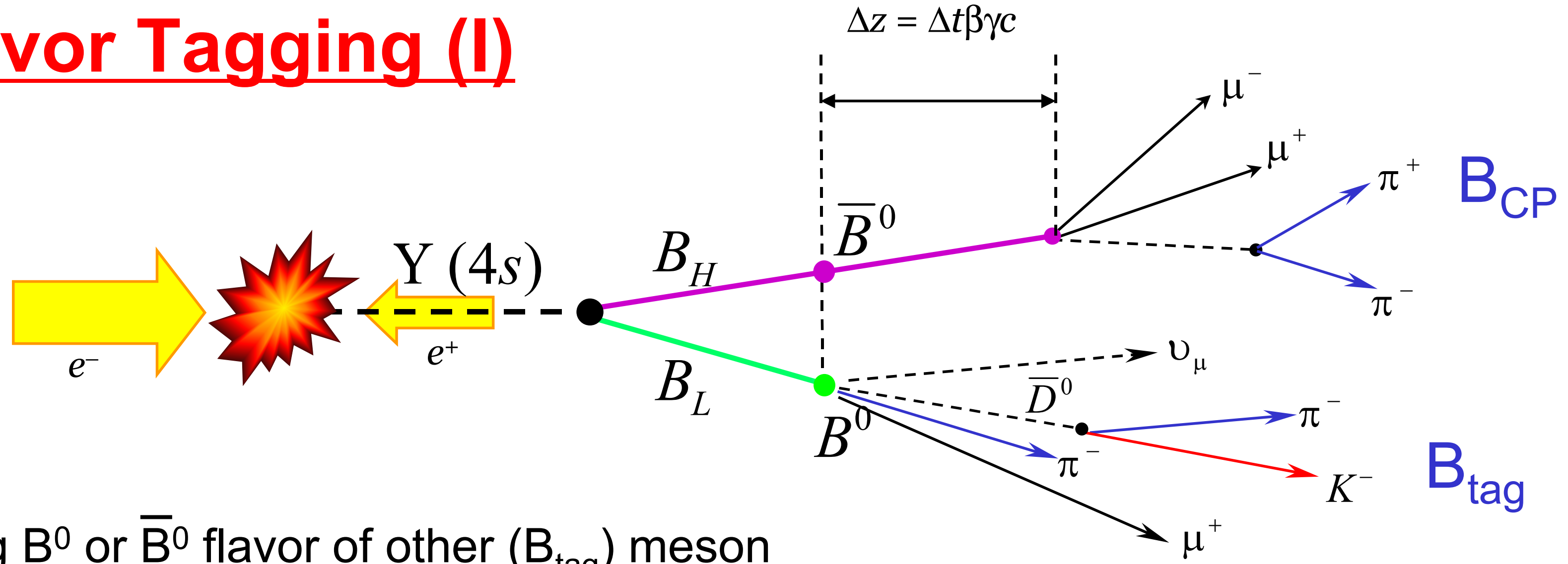
- $B^0 \to J/\psi\, K^{*0}$ $(K^{*0} \to K^0_s\, \pi^0)$


File Options Desktop Controls Window
_NEW/users/rfaccini/display_febR8.4.1c 1 -- Parallel
Candidate for $B^0 \to J/\psi\, K^0_s$ with $J/\psi \to e^+ e^-$ and $K^0_s \to \pi^+ \pi^-$

Candidate for $B^0 \to J/\psi\, K^0_s$ with $J/\psi \to e^+ e^-$ and $K^0_s \to \pi^+ \pi^-$



Flavor Tagging (I)



Need to tag B^0 or $\overline{B}^0$ flavor of other (B_{tag}) meson

B_{CP} has flavor opposite that of B_{tag} at $t = t_{tag}$

Examine all charged particles in the event not included in B_{CP} reco

Ingredients:

- Lepton charge ($B \to l^+ X$ vs. $\overline{B} \to l^- X$)
- Kaon charge ($b \to c \to s$ transition $\Rightarrow B \to K^+ X$ vs. $\overline{B} \to K^- X$)
- Slow pion charge ($B \to D^{*-} X \Rightarrow$ slow π^-)
- Cascade lepton charge

Flavor Tagging (II)

Tag performance extracted directly from data:

- reconstruct one B decay to flavor eigenstate $D^{*-} l^+ \nu_l$, $D^{(*)-} \pi^+$, $D^{(*)-} \rho^+$, …
- tag the rest of the event and measure both mistag rate w and Δm_d

Method	ε_{tag} (%)	w (%)	Q (%)
Lepton	9.1 ± 0.2	3.3 ± 0.6	7.9 ± 0.3
Kaon I	16.7 ± 0.2	10.0 ± 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	31.5 ± 0.9	2.7 ± 0.3
All	65.5 ± 0.5		28.1 ± 0.7

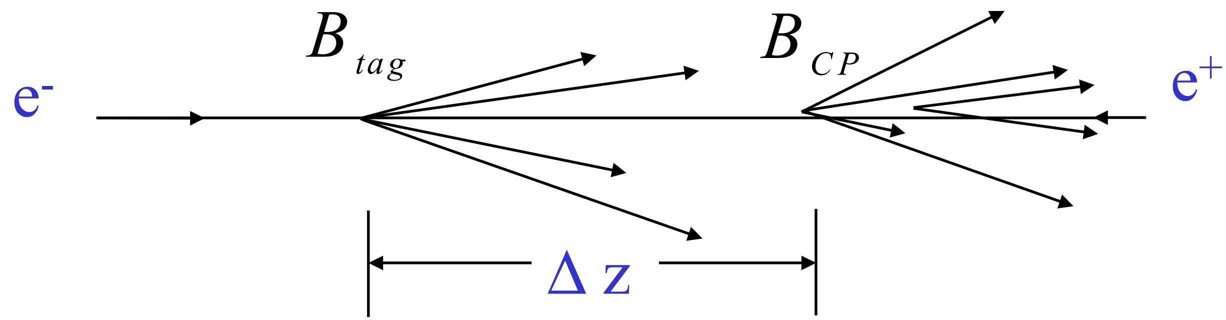
Effectiveness

$Q = \varepsilon\,(1 - 2w)^2$

$= \varepsilon\, D^2$

Proper Time Difference $\Delta t = \Delta z / (\gamma \beta c)$

Measure decay vertex positions for B_{CP} and B_{tag} along boost direction



→ ***B_{CP} vertex:***

* Geometric & kinematic fit $\sigma_z \sim 65\ \mu m$

→ ***B_{tag} vertex:***

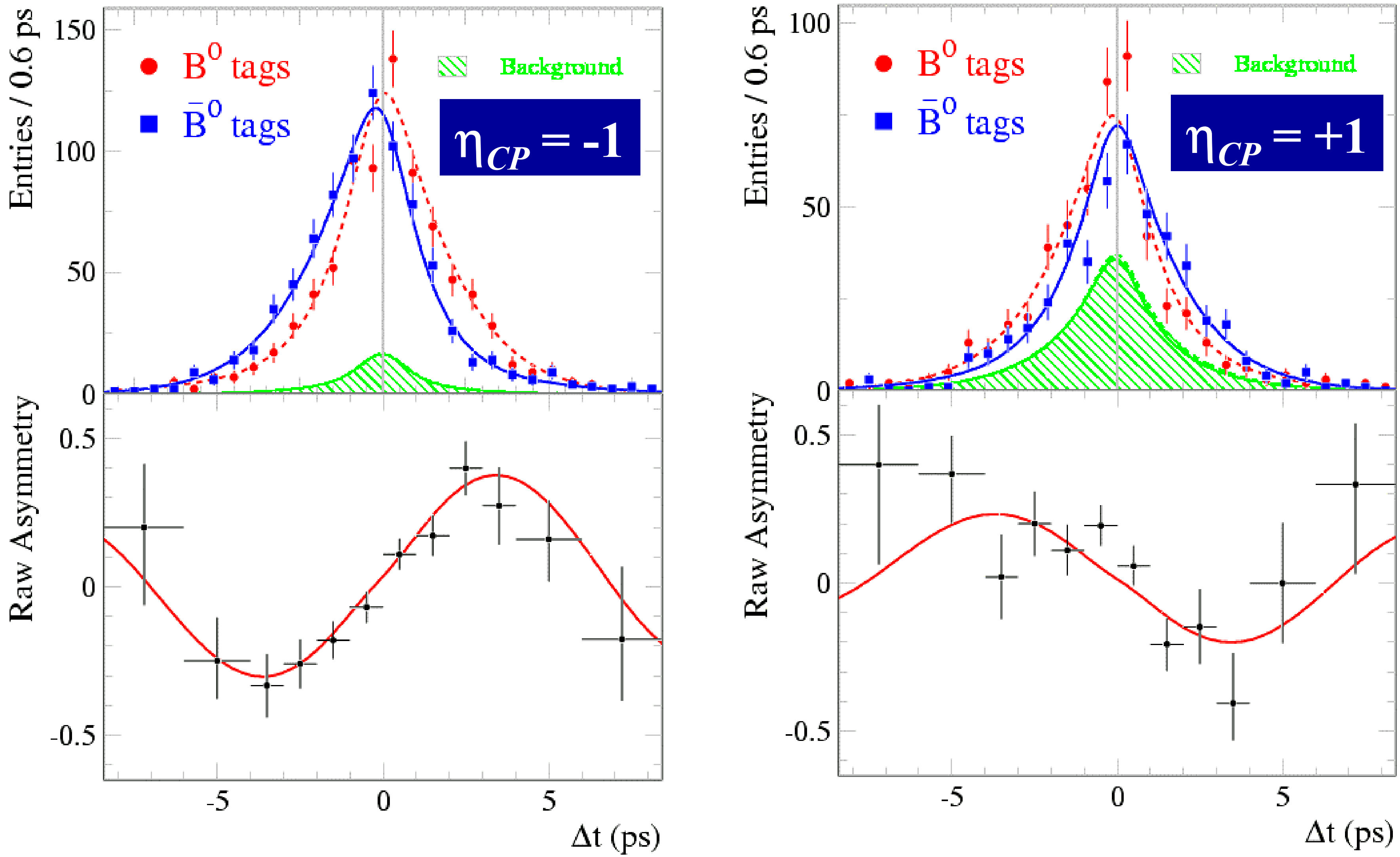
* Fit remaining tracks
* Use beam spot constraint
* Iterate to remove trks with large χ^2 (minimize bias from charm decays)
* Include resultant K^0_s trajectory and B_{CP} momentum vector

$\sigma_z \sim 110\ \mu m$

→ dominates Δz resolution + introduces $\delta z \sim 25\ \mu m$ bias from charm

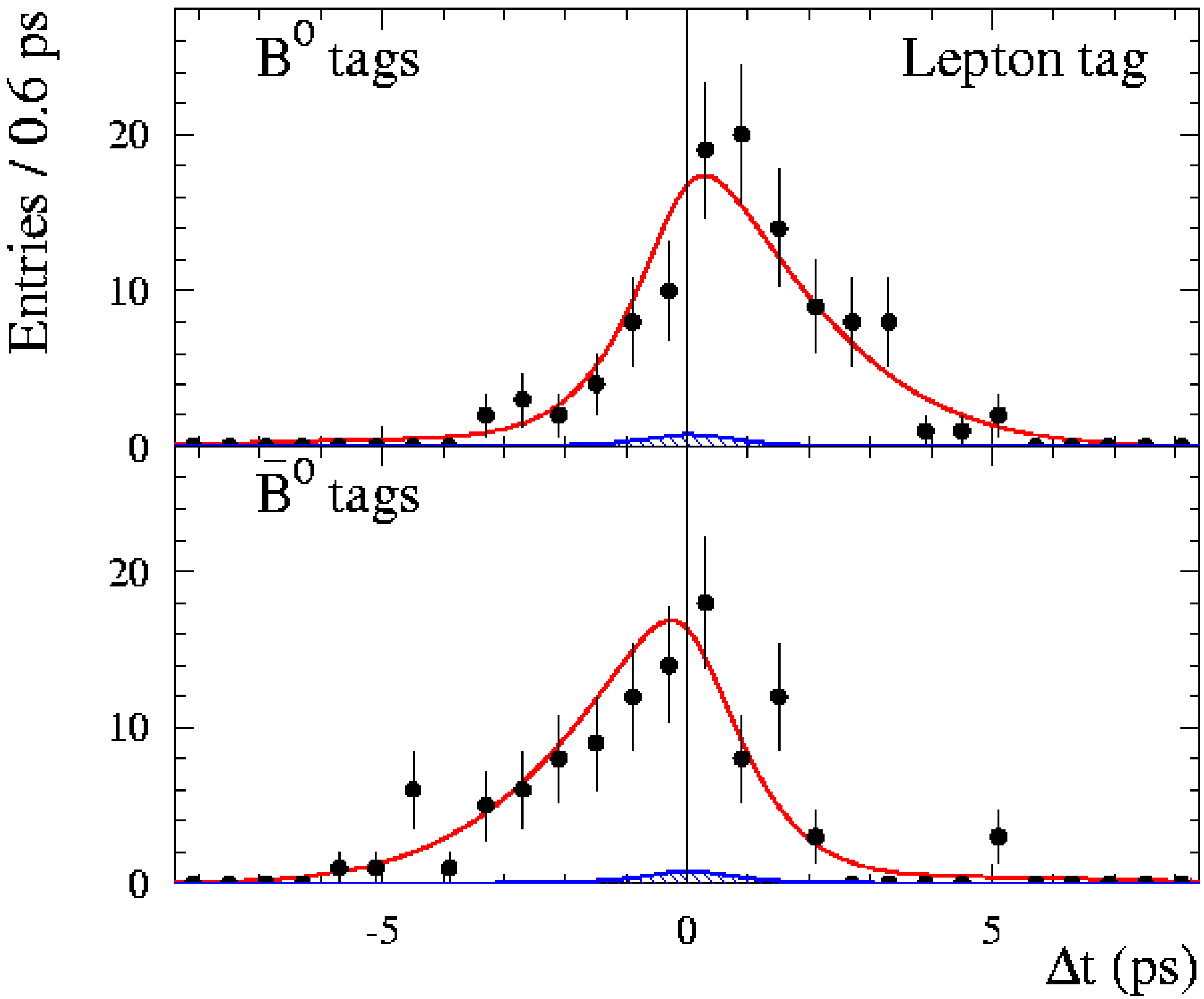
sin 2β Measurement

- **BaBar** 88 x 10^6 $B\bar{B}$ pairs: $\sin 2\beta = 0.741 \pm 0.067\ (stat) \pm 0.033\ (syst)$



sin 2β Measurement with Lepton Tags Only

- **220 lepton-tagged** η_f = -1 events



98% purity
3.3% mistag rate
20% better Δt resolution

$$\sin 2\beta = 0.79 \pm 0.11$$

World sin 2β Measurements

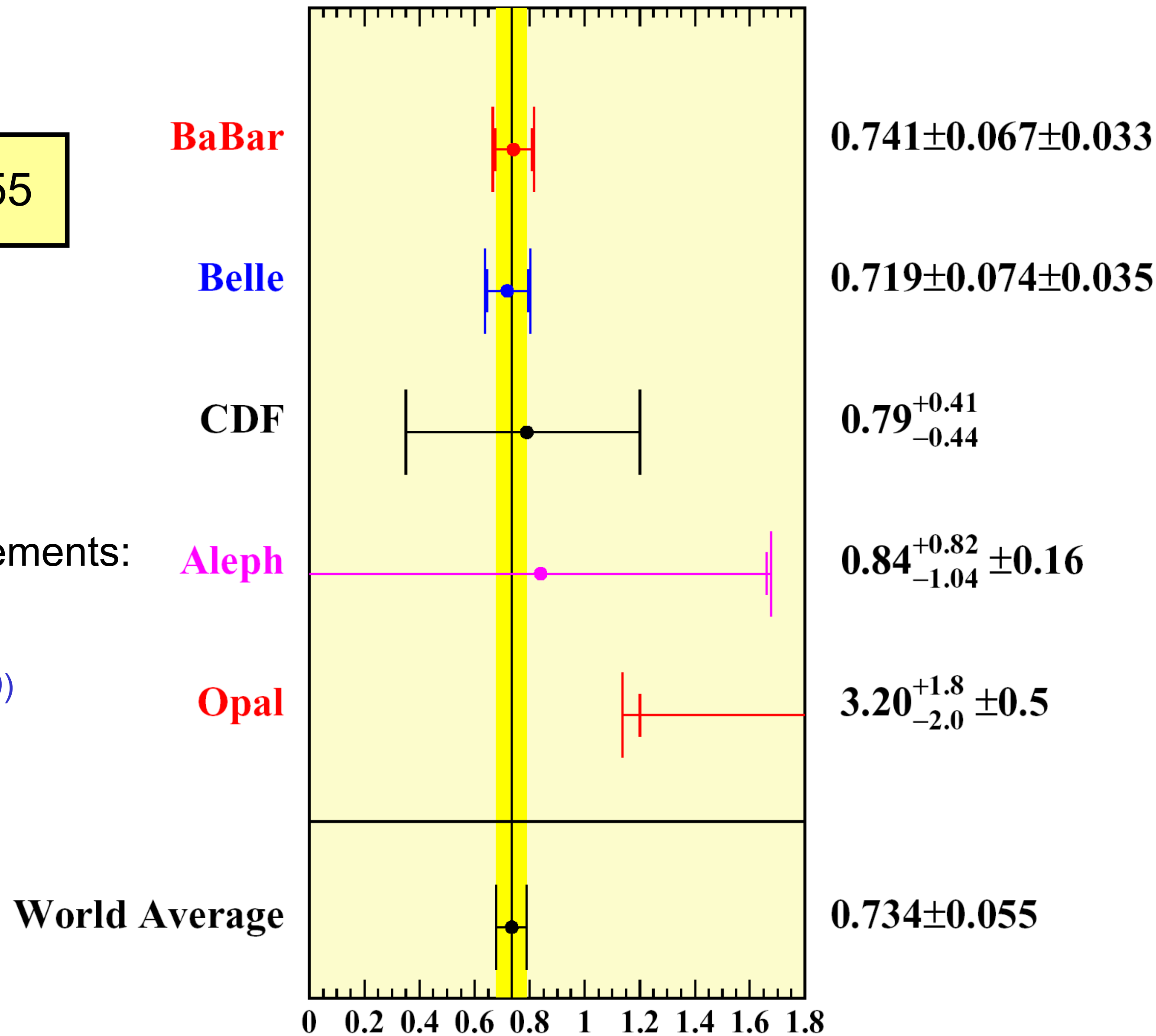
World average

sin 2β = 0.734 ± 0.055

In excellent agreement with value determined indirectly from other B and K decay measurements:

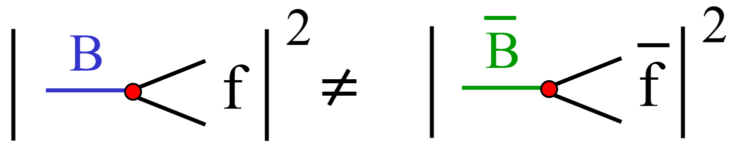
sin 2β = 0.75 ± 0.09

S.Mele, PRD59, 113011 (1999)



CP Violation in Decay

CP Violation in decay:



Search for CP violation in charmless B decays (b → u or b → s transitions)

→ measure decay rate asymmetry

$$A_{CP} = \frac{\Gamma(\bar{B} \to \bar{f}) - \Gamma(B \to f)}{\Gamma(\bar{B} \to \bar{f}) + \Gamma(B \to f)}$$

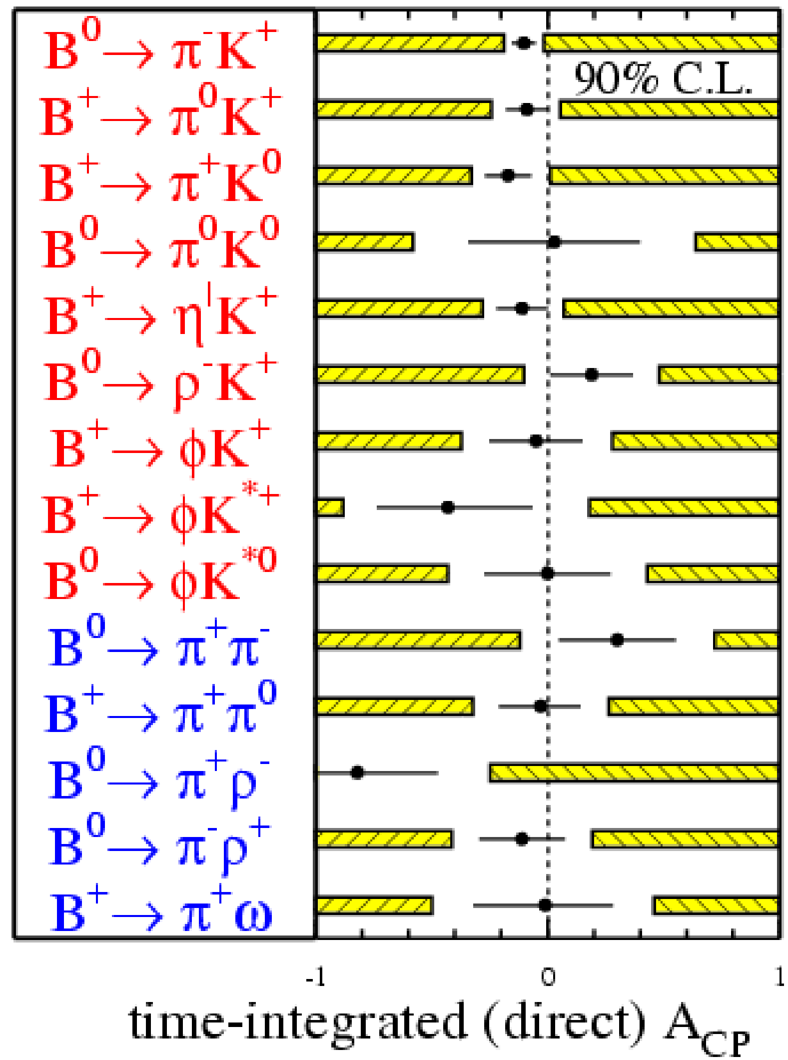
No evidence for direct CPV yet
Uncertainties at the 5-40% level

(similar results from CLEO and BELLE)

Most precise for $B^0 \to K^+\pi^-$ with

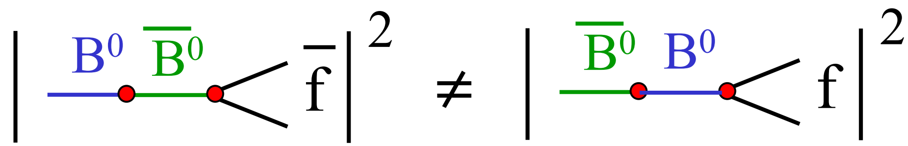
$$A_{CP} = -0.102 \pm 0.050 \text{ (stat)} \pm 0.016 \text{ (syst)}$$

BABAR



CP Violation in Mixing

CP Violation in mixing:



Measure asymmetry in semileptonic decays

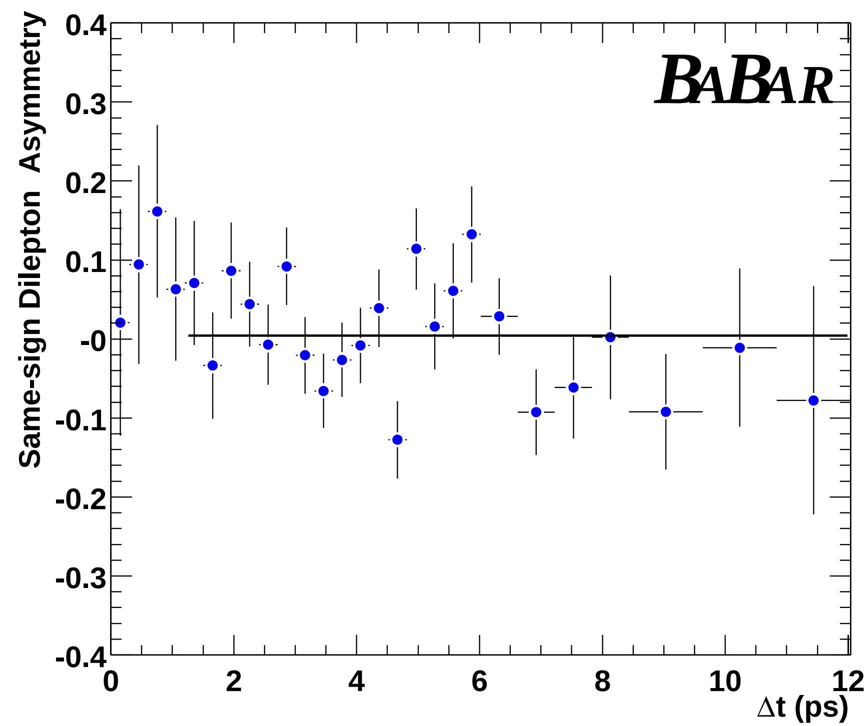
$$a_{SL} = \frac{\Gamma(\overline{B}^0 \to l^+ \nu_l X) - \Gamma(B^0 \to l^- \overline{\nu}_l X)}{\Gamma(\overline{B}^0 \to l^+ \nu_l X) + \Gamma(B^0 \to l^- \overline{\nu}_l X)} = \frac{1 - |q/p|^4}{1 + |q/p|^4}$$

Rate of “wrong” sign leptons
(from mixing)

BaBar: a_{SL} = 0.005 ± 0.012(stat)
± 0.014(syst)

$\Rightarrow$ $|q/p|$ = 0.998 ± 0.006(stat)
± 0.007(syst)

Consistent with small predicted violation



"The" Unitarity Triangle (II)

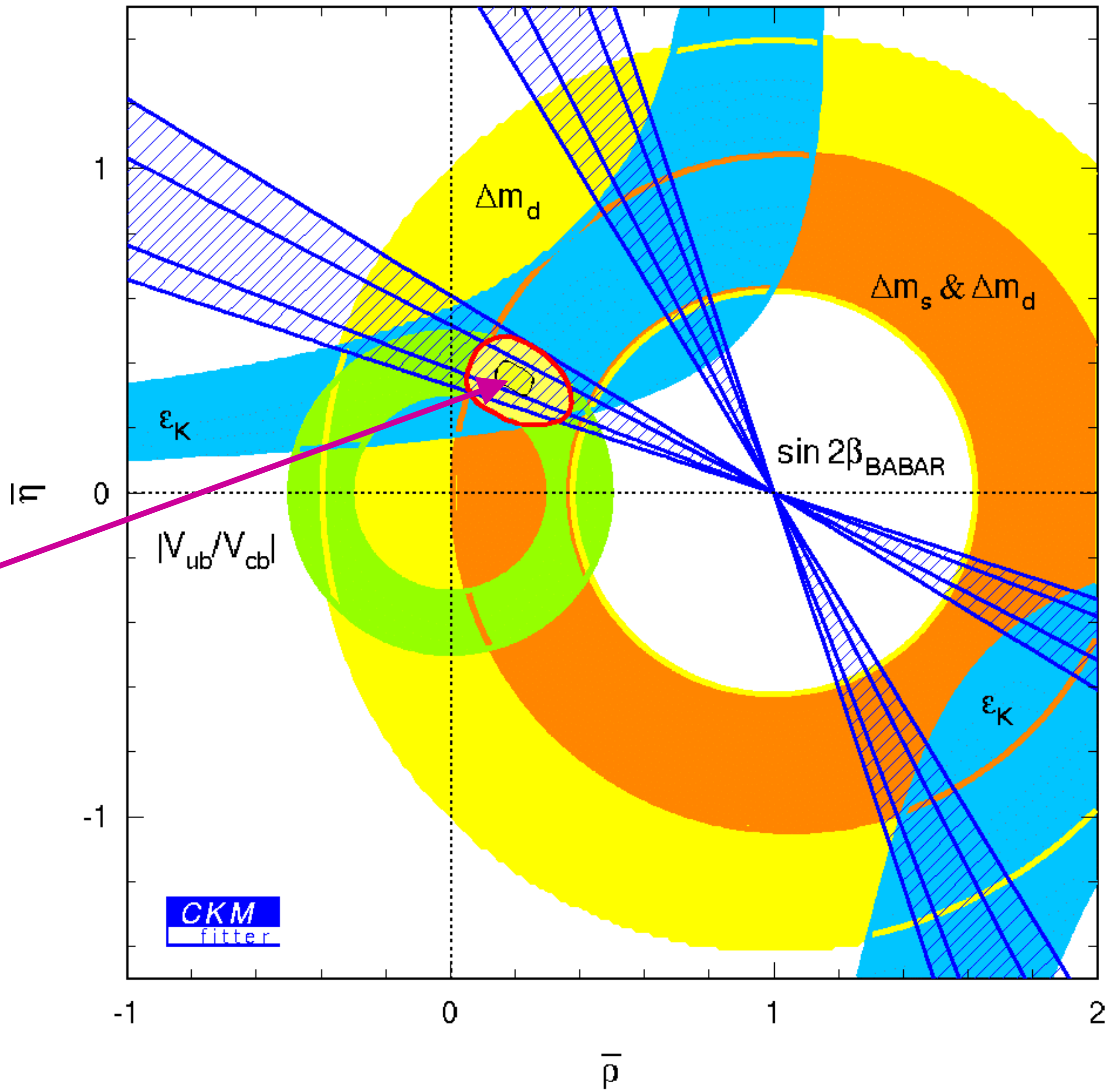
Without sin 2β, ρ and η poorly constrained by exp^t (large theory uncertainties)

- $|V_{ub}| = |A\,\lambda^3\,(\rho - i\eta)|$
  $B \to X_u\, l\, \nu$ decays ($b \to u$)
- $|V_{td}| = |A\,\lambda^3\,(1 - \rho - i\eta)|$
  $B^0 - \overline{B^0}$ oscill. freq. ($d \to t$)
- CPV in Kaon decays
  ε_K measurement ($s \to c$)

All constraints are consistent with one another

GOAL:

Stringent test of SM via precise measurements of the sides and angles of the unitarity triangle



"The" Unitarity Triangle (III)

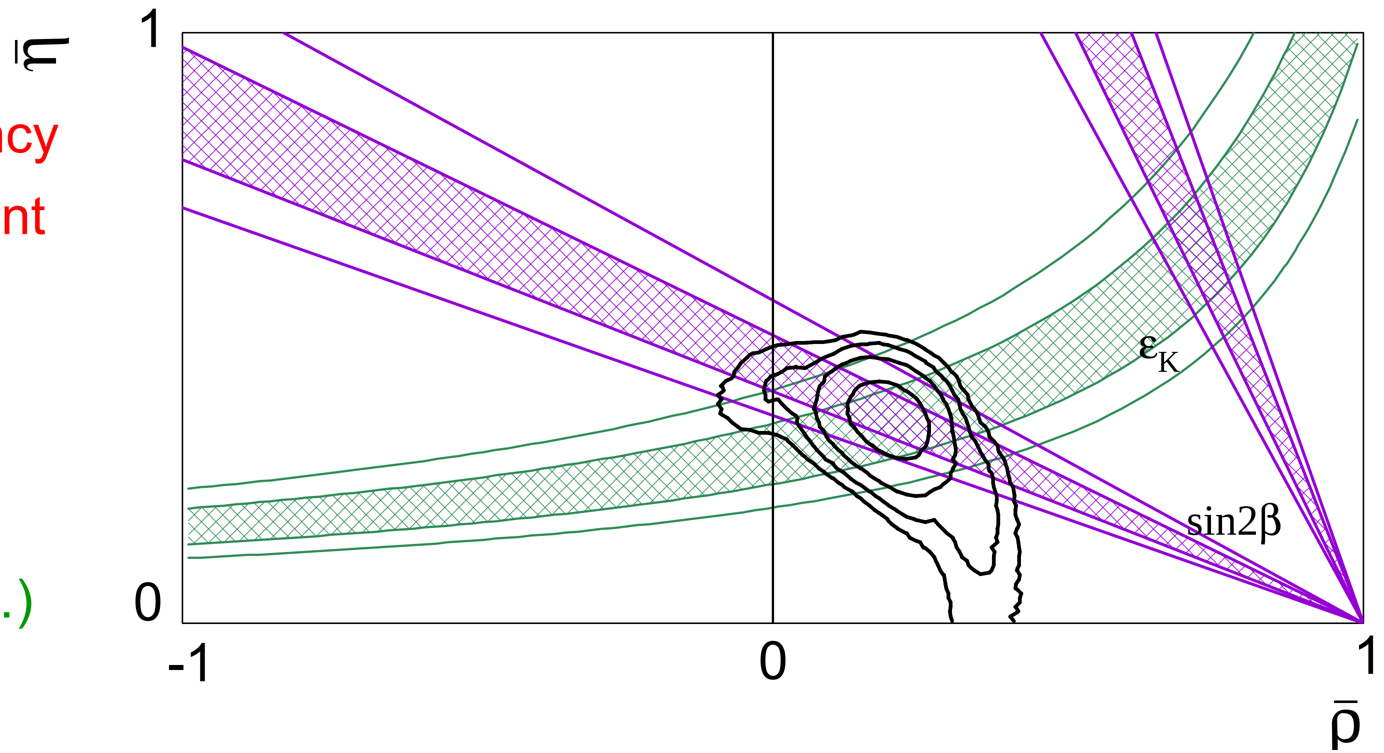
We can now check the consistency of the CKM picture of CPV

Compare constraints from:

1. CPV in the kaon system (ε_K)
2. CPV in $b \to c\bar{c}s$ (e.g. $B^0 \to J/\psi\, K^0_s$)
3. $|V_{ub}|$ and $|V_{td}|$ from $b \to u$ decay rate and B mixing frequency

Excellent consistency between the different observables

CKM matrix provides coherent framework (so far…)

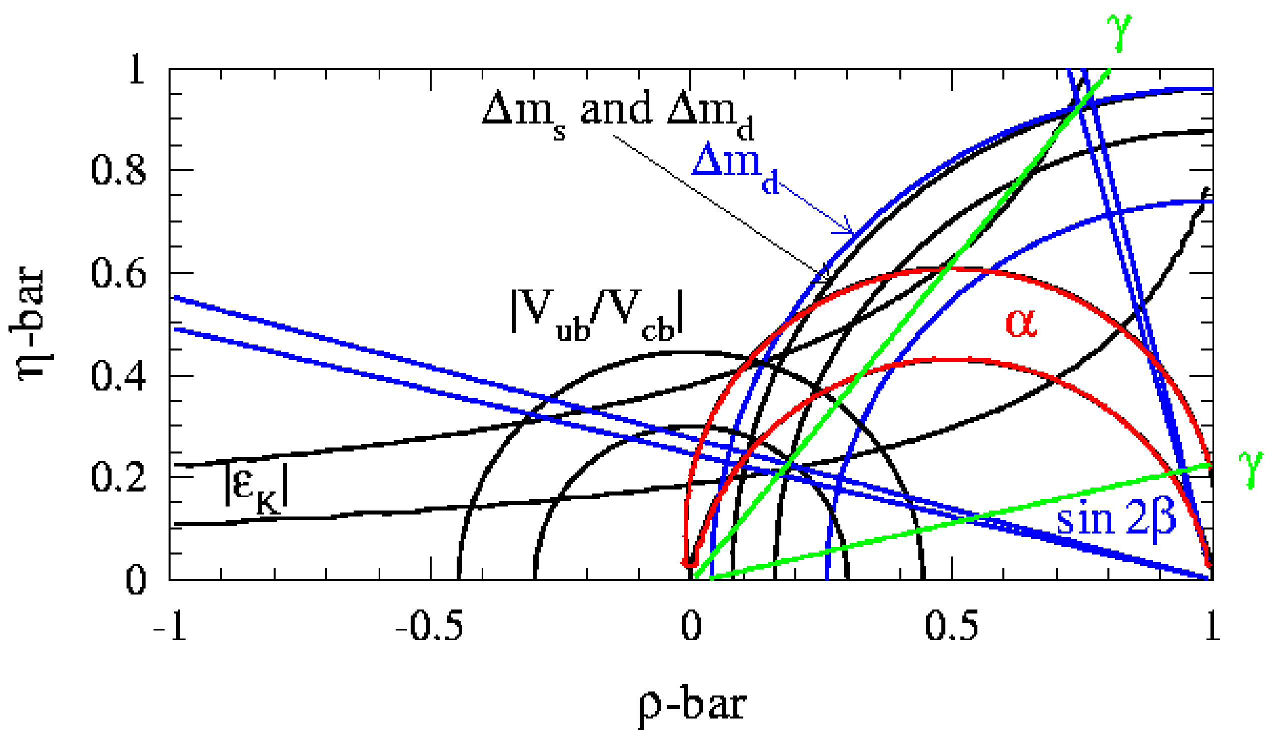


“The” Unitarity Triangle (IV)

Possible situation in 2007 showing inconsistency between the measurement of the sides and of the angles of the triangle:

- Assume uncertainties of 3% in $|V_{cb}|$, 10% in $|V_{ub}|$, <1% in Δm_d and Δm_s
- Assume uncertainties of 1% in sin 2β, 5° in α and 10° in γ

Inconsistency between constraints might look like:



Summary

CP Violation:

- New window into the Standard Model of Particle Physics, relevant to matter-antimatter asymmetry of the Universe, sensitive to New Physics
- CKM quark mixing matrix for 3 families of quarks contains an irreducible phase that induces CP violation in weak charged current interactions
- B Factories have observed (large) CP violation for the first time outside of the neutral kaon system ($B^0 \to J/\psi\, K^0_s$ decays)
- Current data is in excellent agreement with the CKM picture of CPV
- Probing of the SM continues with larger data samples at the B Factories and begins at the Fermilab Tevatron

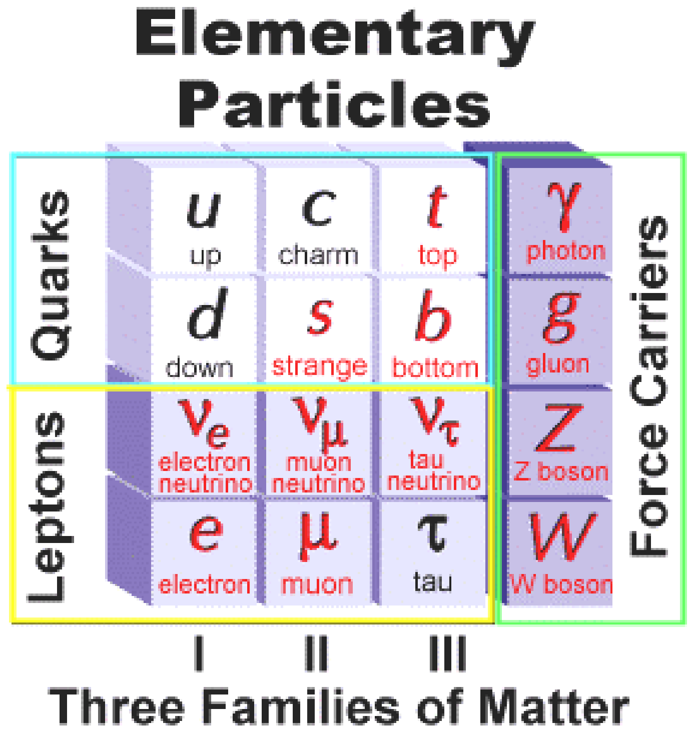
Additional Slides

CP Violation in the Standard Model (I)

(Electroweak) Standard Model:

- Three families of quarks and leptons arranged in left-handed doublets and right-handed singlets

$$\begin{pmatrix} u \\ d \end{pmatrix}_L, \begin{pmatrix} \nu_e \\ e \end{pmatrix}_L, u_R, d_R, e_R \quad \text{for } 1^{st} \text{ family}$$



- Local gauge invariance under $U(1)_Y \otimes SU(2)_L$ symmetry groups yields electromagnetic and weak interactions
- Field equations (Lagrangian) describe electromagnetic ($\mathcal{L}_{EM}$), charged current weak ($\mathcal{L}_{CC}$), and neutral current weak ($\mathcal{L}_{NC}$) interactions, also "Yukawa" interactions between Higgs field ϕ and fermions ($\mathcal{L}_Y$ to provide mass to the fermions)

CP Violation in the Standard Model (II)

Higgs coupling to fermions:

For the first family we have

$$\mathcal{L}_Y = g_e \, \overline{L} \phi \, e_R + g_d \, \overline{Q}_L \phi \, d_R + g_u \, \overline{Q}_L \phi^c u_R + h.c.$$

$$\text{where } L = \begin{pmatrix} \nu_e \\ e \end{pmatrix}_L, \; Q_L = \begin{pmatrix} u \\ d \end{pmatrix}_L, \; \phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}, \; \phi^c = \begin{pmatrix} -\phi^{0*} \\ \phi^- \end{pmatrix}$$

Note: separate terms for up-type quarks (Q = +2/3 e) and

down-type quarks (Q = -1/3 e)

After spontaneous symmetry breaking, we obtain quark mass terms

$$\mathcal{L}_Y^{\text{quark mass}} = \begin{pmatrix} \overline{u} & \overline{c} & \overline{t} \end{pmatrix}_L \tilde{M}_U \begin{pmatrix} u \\ c \\ t \end{pmatrix}_R + \begin{pmatrix} \overline{d} & \overline{s} & \overline{b} \end{pmatrix}_L \tilde{M}_D \begin{pmatrix} d \\ s \\ b \end{pmatrix}_R$$

CP Violation in the Standard Model (III)

Quark mass matrices:

In general, mass matrices $\widetilde{M}_U$ and $\widetilde{M}_D$ are not diagonal

$\Rightarrow$ Need to diagonalize those with matrices V^{up} and V^{down}

$$\mathcal{L}_Y^{\text{quark mass}} = \begin{pmatrix}\bar{u} & \bar{c} & \bar{t}\end{pmatrix}_L V_L^{up\dagger} M_U V_R^{up} \begin{pmatrix} u \\ c \\ t \end{pmatrix}_R + \begin{pmatrix}\bar{d} & \bar{s} & \bar{b}\end{pmatrix}_L V_L^{down\dagger} M_D V_R^{down} \begin{pmatrix} d \\ s \\ b \end{pmatrix}_R$$

$\Rightarrow$ Redefine quark eigenstates to get

$$\mathcal{L}_Y^{\text{quark mass}} = \begin{pmatrix}\bar{u} & \bar{c} & \bar{t}\end{pmatrix}_L M_U \begin{pmatrix} u \\ c \\ t \end{pmatrix}_R + \begin{pmatrix}\bar{d} & \bar{s} & \bar{b}\end{pmatrix}_L M_D \begin{pmatrix} d \\ s \\ b \end{pmatrix}_R$$

CP Violation in the Standard Model (IV)

Charged-current Weak Interaction:

Redefinition of quark mass eigenstates has non-trivial consequence:

$$\mathcal{L}_{CC} = \frac{g}{\sqrt{2}} \begin{pmatrix} \bar{u} & \bar{c} & \bar{t} \end{pmatrix}_L \gamma^\mu V_L^{up} V_L^{down\dagger} \begin{pmatrix} d \\ s \\ b \end{pmatrix}_L W_\mu^+ + h.c.$$

$$V_{CKM} = V_L^{up} V_L^{down\dagger}$$

$$= \frac{g}{\sqrt{2}} \begin{pmatrix} \bar{u} & \bar{c} & \bar{t} \end{pmatrix}_L \gamma^\mu \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix}_L W_\mu^+ + h.c.$$

→ Eigenstates for weak interactions (d', s', b') are linear combinations of mass eigenstates (d, s, b):

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{CKM} \cdot \begin{pmatrix} d \\ s \\ b \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \cdot \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

→ Unitary transformation matrix is Cabibbo-Kobayashi-Maskawa (CKM) *mixing* matrix