Cracking the Unitarity Triangle

— Latest Results from BABAR —

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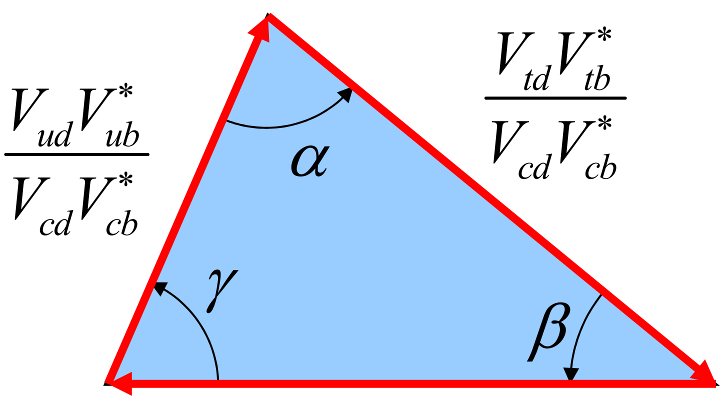
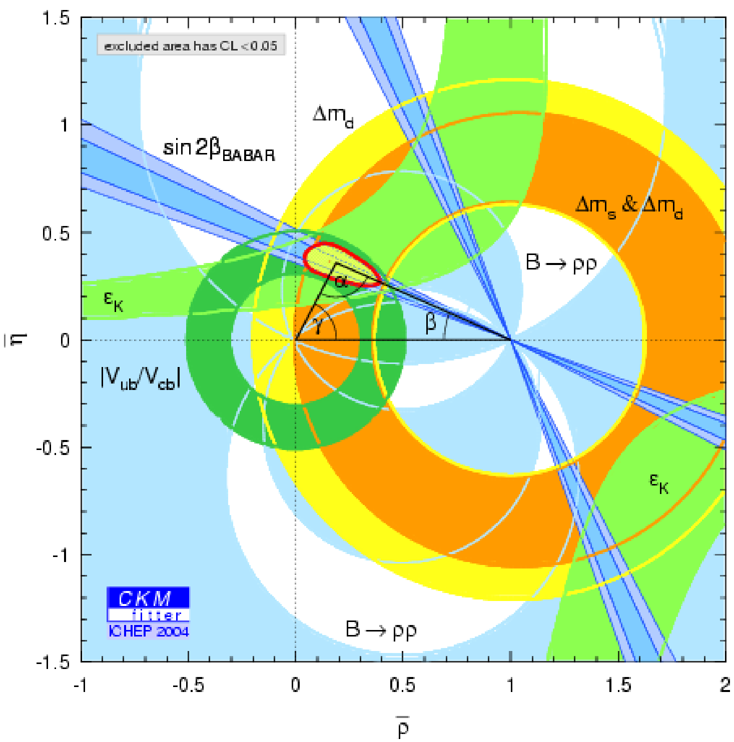
Unitarity Triangle

- Already seen it a few times this week

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





- How is this triangle "measured" experimentally?
  - Using CP violation, of course, … right?

How to Violate CP

- Complex coupling constant (= weak phase)
  - CKM matrix in the SM has 1 such phase
- Interference between ≥ 2 diagrams with different phases
  - e.g., tree and penguin diagrams for $B^0 \to K^+\pi^-$ (Carlo's talk)
- With 2 diagrams, the size of the CPV is

$$\mathcal{A}_{CP} = \frac{2|A_1||A_2|\sin\Delta\phi\sin\Delta\delta}{|A_1|^2+|A_2|^2}$$

weak phase difference

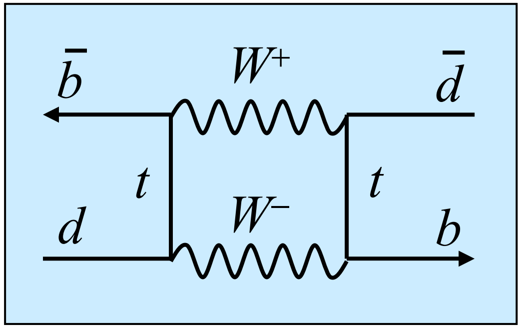
strong phase difference

  - CKM information in the weak phase $\Delta\phi$
  - $|A_1|/|A_2|$ ratio, $\Delta\delta$ usually not calculable

Observing CPV doesn't necessarily teach us much about its origin

B^0 Mixing to the Rescue

- B^0 and $\bar{B}^0$ mix, i.e., they turn into each other
  - Weak phase = $\arg\left(V_{tb}^2 V_{td}^{*2}\right) = 2\beta$



- Mass eigenstates are linear combinations

$$\left|B_L\right\rangle = p\left|B^0\right\rangle + q\left|\bar{B}^0\right\rangle$$
$$\left|B_H\right\rangle = p\left|B^0\right\rangle - q\left|\bar{B}^0\right\rangle$$

$$p^2 + q^2 = 1$$

  - B_H and B_L differ in mass (Δm), but not in lifetime ($\Delta\Gamma = 0$)
  - A little exercise in QM gives us

Pure B^0 state after time t ⇨

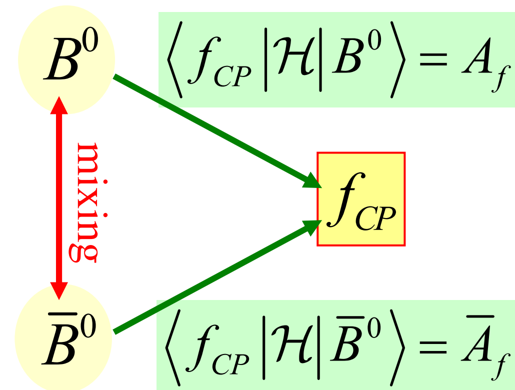
$$\left|B^0(t)\right\rangle = e^{-im_B t} e^{-\Gamma t}\left\{\cos\frac{\Delta m t}{2}\left|B^0\right\rangle - i\frac{q}{p}\sin\frac{\Delta m t}{2}\left|\bar{B}^0\right\rangle\right\}$$

Pure $\bar{B}^0$ state after time t ⇨

$$\left|\bar{B}^0(t)\right\rangle = e^{-im_B t} e^{-\Gamma t}\left\{-i\frac{p}{q}\sin\frac{\Delta m t}{2}\left|B^0\right\rangle + \cos\frac{\Delta m t}{2}\left|\bar{B}^0\right\rangle\right\}$$

Mixing and Interference

- Pure B^0 state, after time t, decays into a CP eigenstate f_{CP}
  - Both B^0 or $\bar{B}^0$ can decay into f_{CP}
    → Interference between "mixed" and "unmixed" paths



- Calculate the CP asymmetry
  - Neat problem for undergrad. QM

$$\mathcal{A}_{CP}(t) = \frac{N(\bar{B}^0(t) \to f_{CP}) - N(B^0(t) \to f_{CP})}{N(\bar{B}^0(t) \to f_{CP}) + N(B^0(t) \to f_{CP})} = C_f \cos(\Delta m t) + S_f \sin(\Delta m t)$$

$$C_f = \frac{1 - |\lambda_f|^2}{1 + |\lambda_f|^2} \qquad S_f = \frac{-2\,\mathrm{Im}\lambda_f}{1 + |\lambda_f|^2} \qquad \lambda_f = \eta_f \frac{q}{p} \cdot \frac{\bar{A}_f}{A_f}$$

decay term

CP eigenvalue

mixing term

Golden Modes

- Suppose the decay $B^0 \to f_{CP}$ goes through a single diagram
  - A_{CP} and $\bar{A}_{CP}$ differ only by the sign of the weak phase $\frac{A_{CP}}{\bar{A}_{CP}} = e^{2i\phi}$
- Mixing term q/p is known to be almost pure phase
  - Weak phase is 2β ➡ $\lambda_f = \eta_f \frac{q}{p} \frac{A_{CP}}{\bar{A}_{CP}} = \eta_f e^{2i\beta} e^{2i\phi}$
- Things get nice and simple

$$C_f = 0, \quad S_f = -\eta_f \sin(2\beta + 2\phi)$$

$$\mathcal{A}_{CP}(t) = -\eta_f \sin(2\beta + 2\phi)\sin(\Delta m t)$$

For "golden" decays, the amplitude S_f of the time-dependent CP asymmetry measures the weak phase

Measuring CP Violation

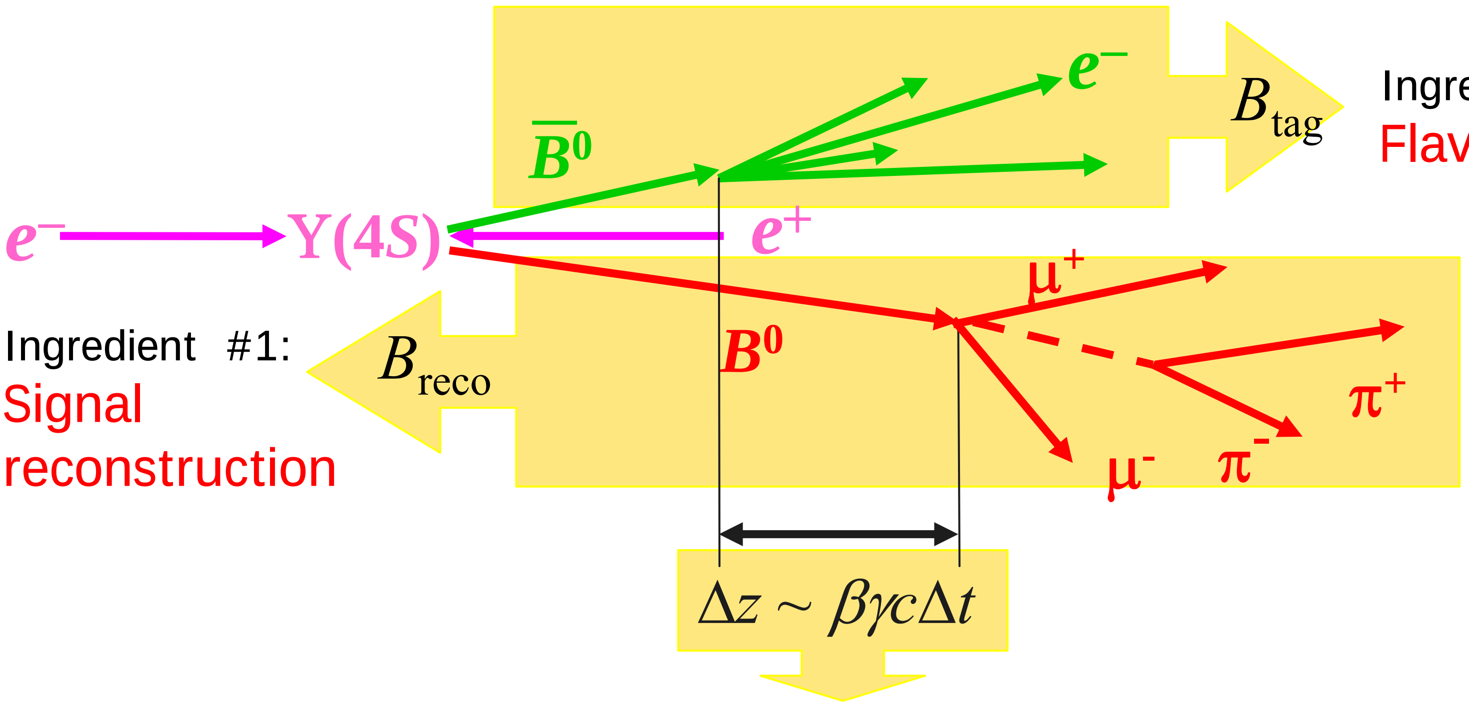
$$\mathcal{A}_{CP}(t) = \frac{N(\bar{B}^0(t) \to f_{CP}) - N(B^0(t) \to f_{CP})}{N(\bar{B}^0(t) \to f_{CP}) + N(B^0(t) \to f_{CP})} = C_f \cos(\Delta m t) + S_f \sin(\Delta m t)$$

- Experiment must do 3 things:
  - Produce and detect $B \to f_{CP}$ events
    - Typical branching fraction: $10^{-4} - 10^{-5}$
    - Need a lot of lot of lot of lot of B's
  - Separate B^0 from $\bar{B}^0$ = "Flavor tagging"
    - Use $\Upsilon_{4S} \to B^0\bar{B}^0$ and tag one B
  - Measure the decay time
    - Measure the flight length $\beta\gamma ct$
    - But B's are almost at rest in Υ_{4S} decays

Solution:
Asymmetric
B Factory

Three Ingredients

$$A_{CP}(t) = \frac{N(\overline{B}^0(t) \to f_{CP}) - N(B^0(t) \to f_{CP})}{N(\overline{B}^0(t) \to f_{CP}) + N(B^0(t) \to f_{CP})} = C_f \cos(\Delta m t) + S_f \sin(\Delta m t)$$



Ingredient #2: Flavor tagging

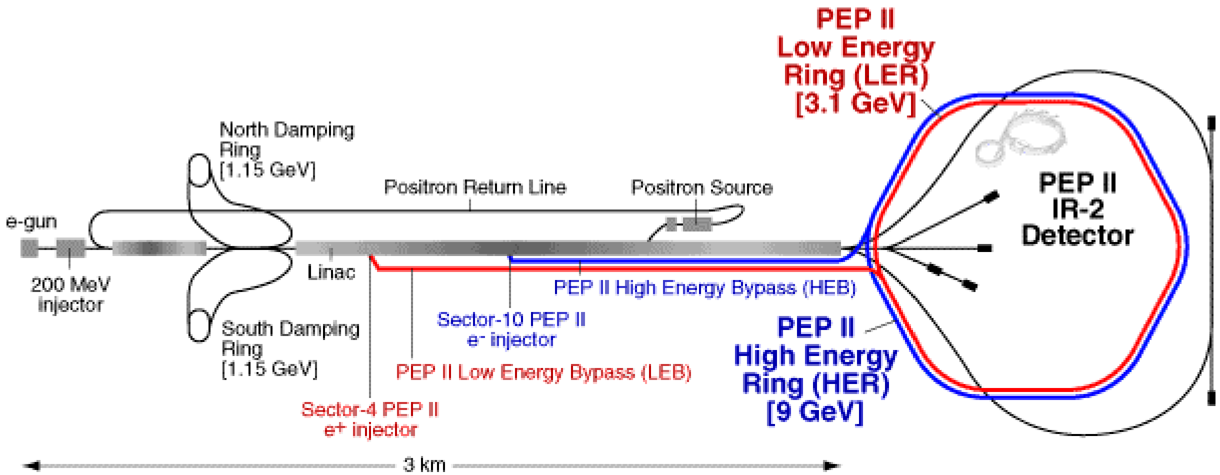
Ingredient #1: Signal reconstruction

Ingredient #3: Δt determination

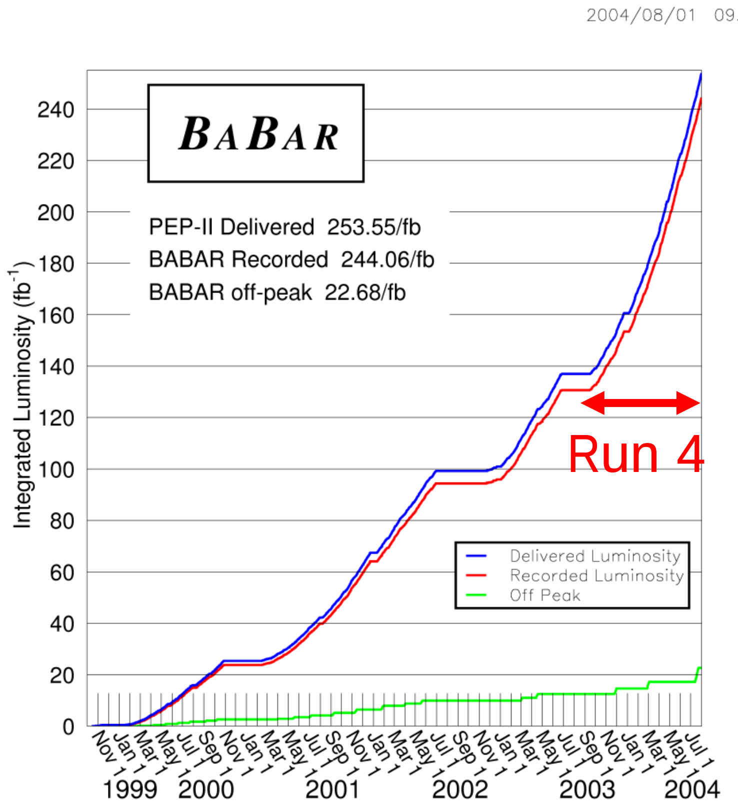
Asymmetric B Factory

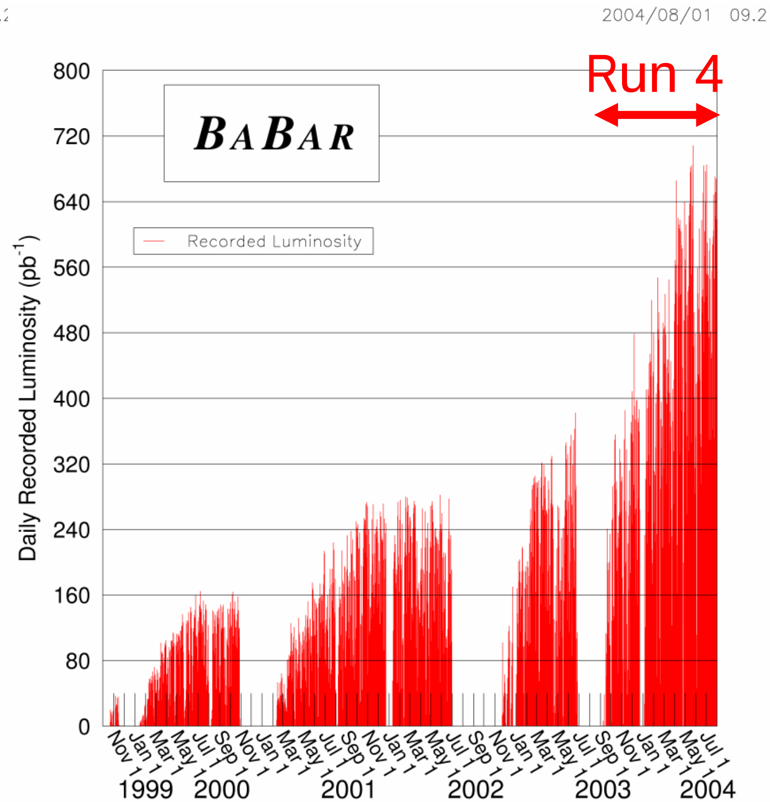
- Collides e^+e^- at $E_{CM} = m(\Upsilon_{4S})$ but with $E(e^+) \neq E(e^-)$
  - PEP-II: 9 GeV e^- vs. 3.1 GeV e^+ → $\beta\gamma = 0.56$
    - The boost allows measurement of Δt
- Collides lots of them: 2.4A(e^+) × 1.6A(e^-)
  - PEP-II luminosity 9.2×10^{33}/cm^2/s = 9.2 Hz/nb
    - That's >3x the design

$$\sigma(e^+e^- \to b\bar{b}) \sim 1\,\text{nb}$$



PEP-II Luminosity



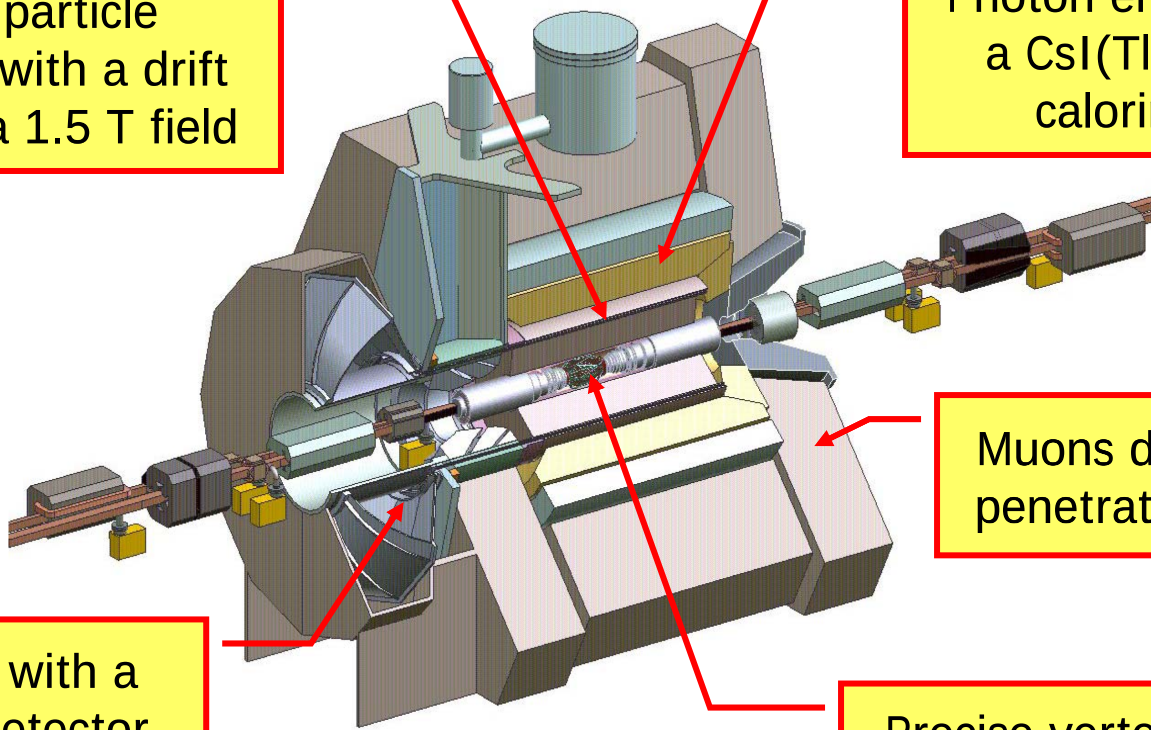


- BABAR has accumulated 244 fb^{-1} of data
  - Run 4 (Sep’03-Jul’04) was a phenomenal success

Detector: BaBar

Charged particle momentum with a drift chamber in a 1.5 T field

Photon energy with a CsI(Tl) crystal calorimeter



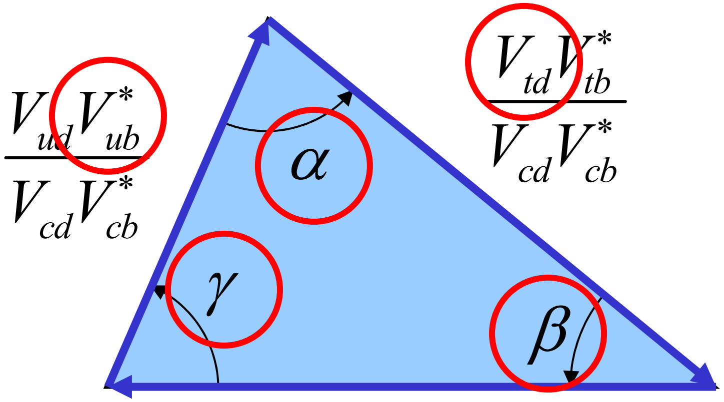
Muons detected after penetrating iron yoke

Particle ID with a Cerenkov detector (DIRC in BaBar, aerogel in Belle)

Precise vertex with a silicon strip detector

Physics Results

- Will walk through the 3 angles and 2 sides

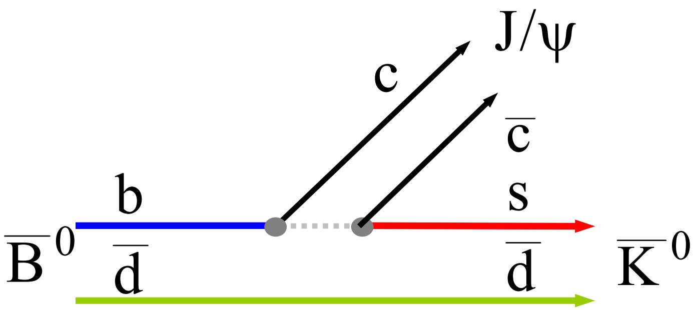


- Almost everything is **PRELIMINARY**
- All ICHEP 2004 results from BABAR/Belle are found at
  - http://www.slac.stanford.edu/BFROOT/www/Public/ichep2004/
  - http://belle.kek.jp/conferences/ICHEP2004/
- BABAR results use data samples between 80 to 227M $B\bar{B}$ events

Angle β from $b \to c\bar{c}s$

- "Golden mode" of CP violation
  - Tree diagram dominates →
  - No weak phase in decay

$$\mathcal{A}_{CP}(t) = -\eta_f \sin(2\beta)\sin(\Delta m t)$$

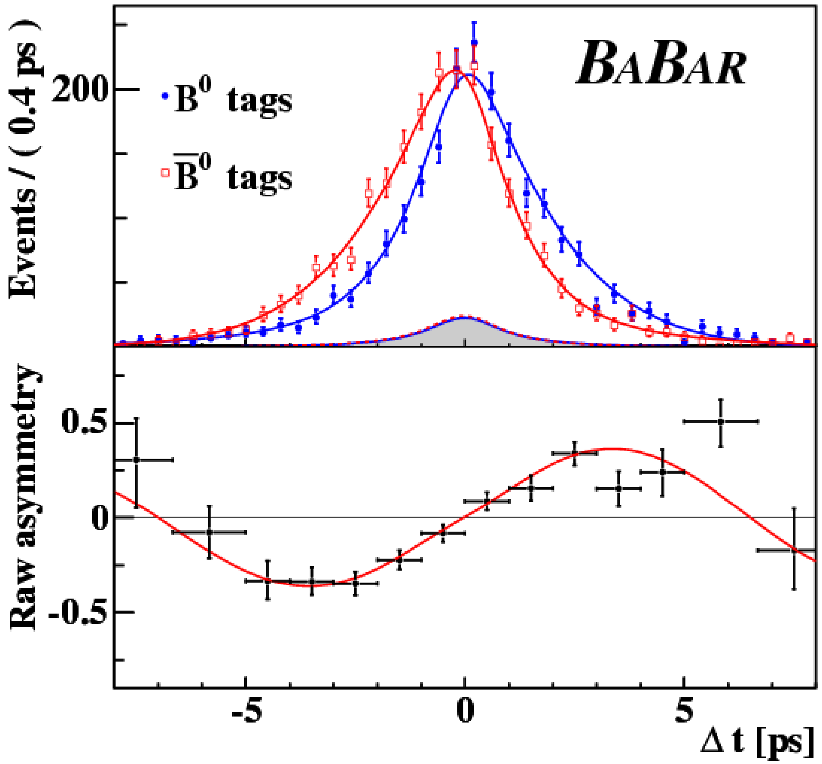


Clean measurement of angle β

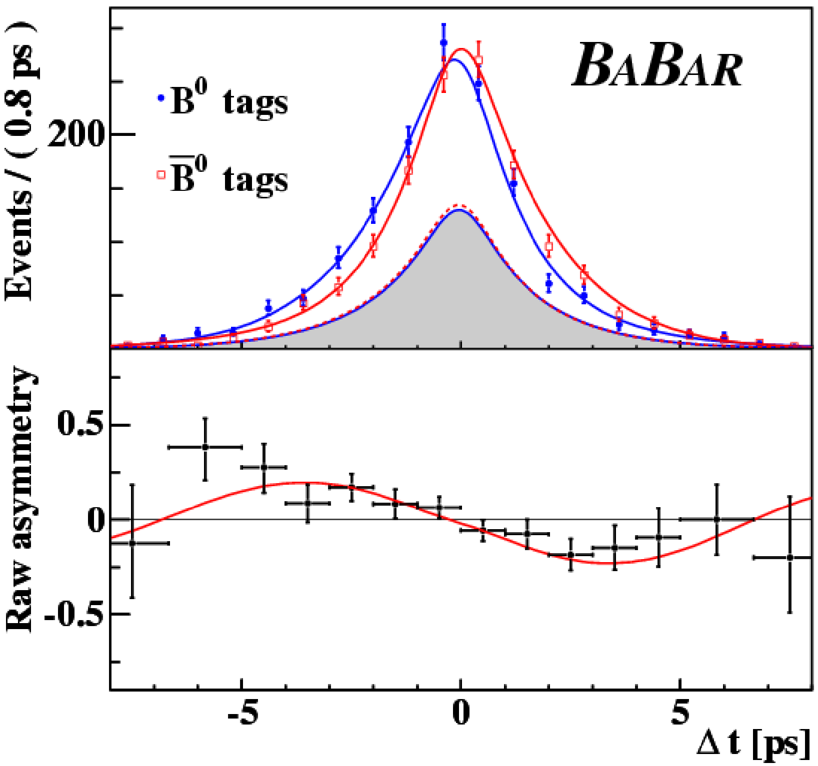
- $c\bar{c}$ pair can be J/ψ, ψ_{2S}, χ_{c1}, or η_c
  - They are all CP = –1
- $s\bar{d}$ pair can be K_S (CP = +1), K_L (–1), or K^{*0} (mixed)
- Total 7730 candidates (78% purity) found in 227 M $B\bar{B}$ events

Time-Dependent A_{CP} Fit

$(c\bar{c})\ K_S$ (CP odd) modes



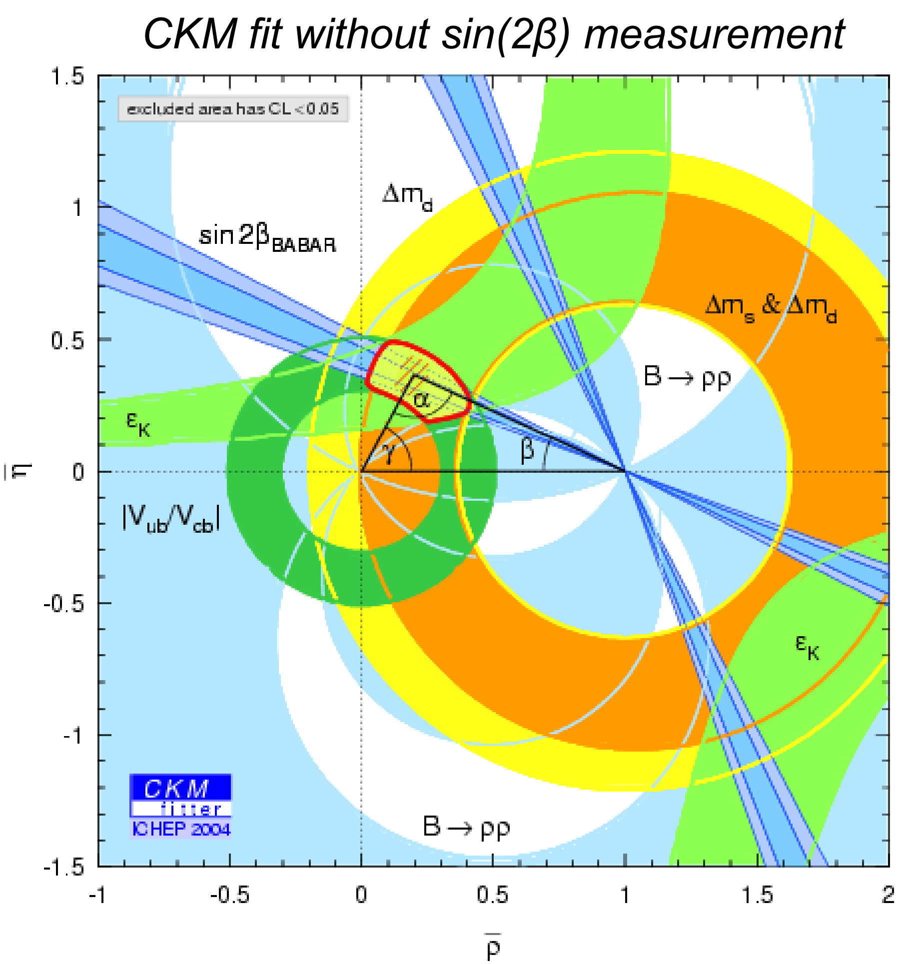
$J/\psi\ K_L$ (CP even) mode

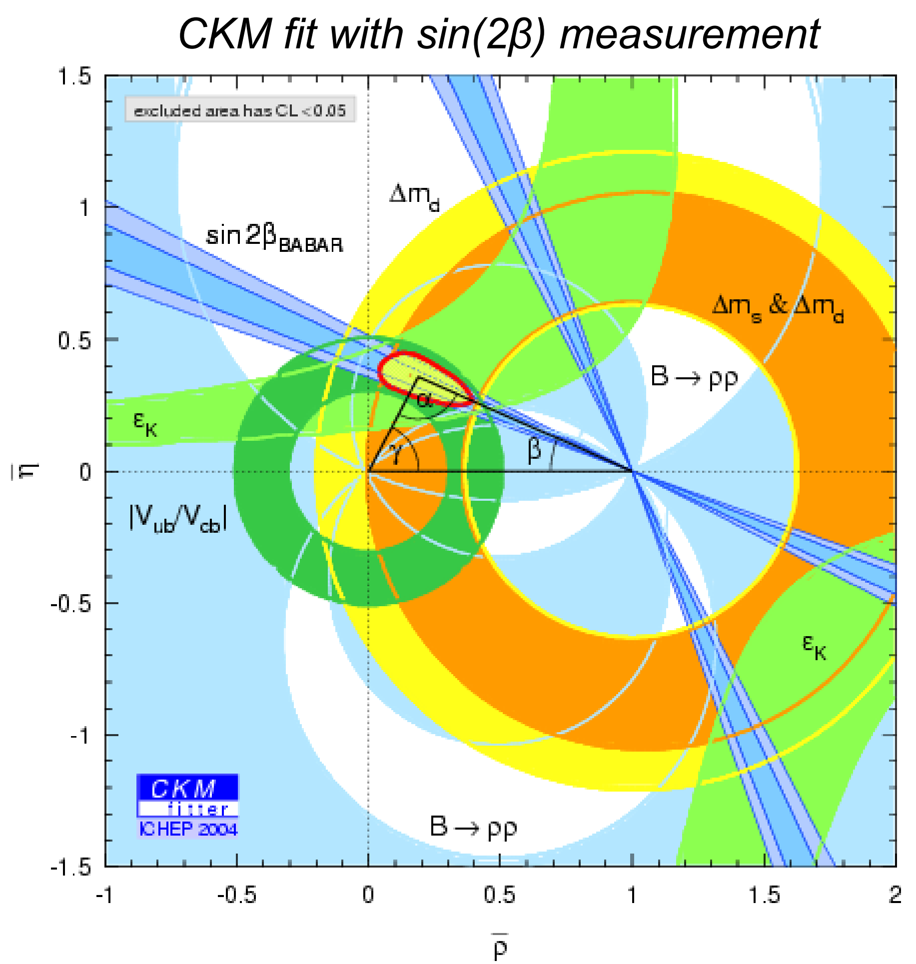


$$\sin 2\beta = 0.722 \pm 0.040\ (\mathrm{stat}) \pm 0.023\ (\mathrm{sys})$$

205 fb^{-1}

Unitarity Triangle

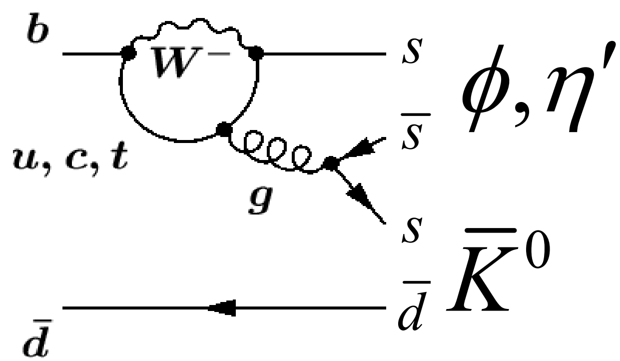




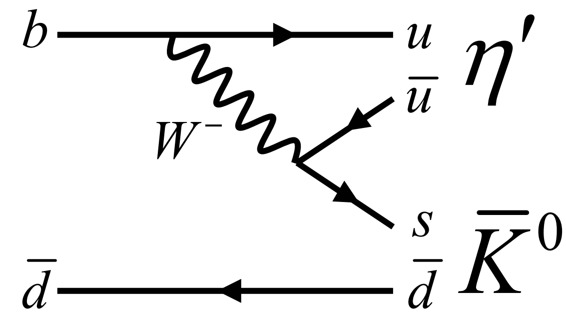
- Precise measurement of $\sin 2\beta$ agree with the SM expectation

Angle β from $b \to s\bar{s}s$

- $b \to s\bar{s}s$ decay dominated by the "penguin" diagram
  - In the SM, $\mathcal{A}_{CP}^{b\to s\bar{s}s} = \mathcal{A}_{CP}^{b\to c\bar{c}s} = \sin 2\beta$
  - New Physics may enter the loop
    → $\mathcal{A}_{CP}$ may not agree!

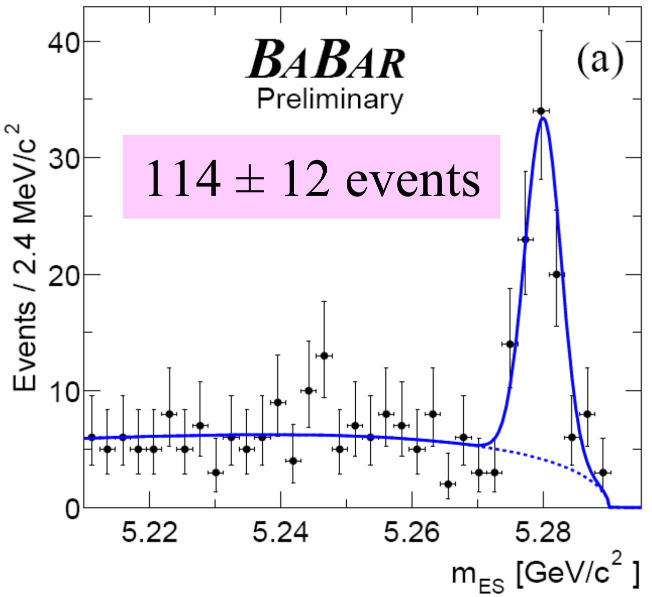


- ϕK_S is pure-penguin
  - Small BF: 7.6×10^{-6}
- $\eta' K_S$ has tree diagrams too
  - Suppressed by small V_{ub}
  - $\mathcal{A}_{CP}$ affected by 0.01 to 0.1
  - Larger BF: 5.5×10^{-5}

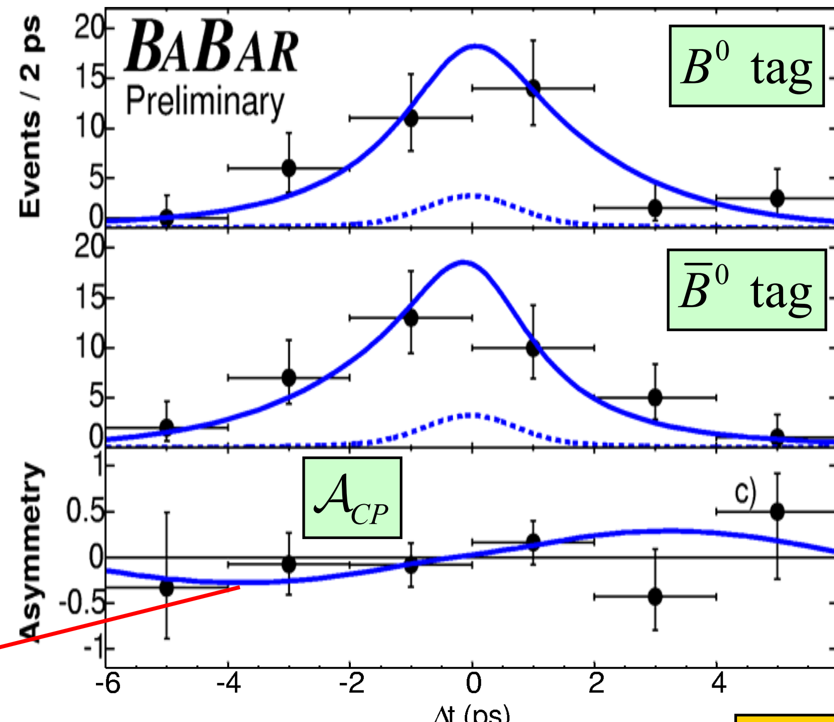


$B^0 \to \phi K_S$

$B^0 \to \phi K_S$ candidates



Time-dependent CP asymmetry



$S_{\phi K_S} = 0.29 \pm 0.31(\text{stat})$

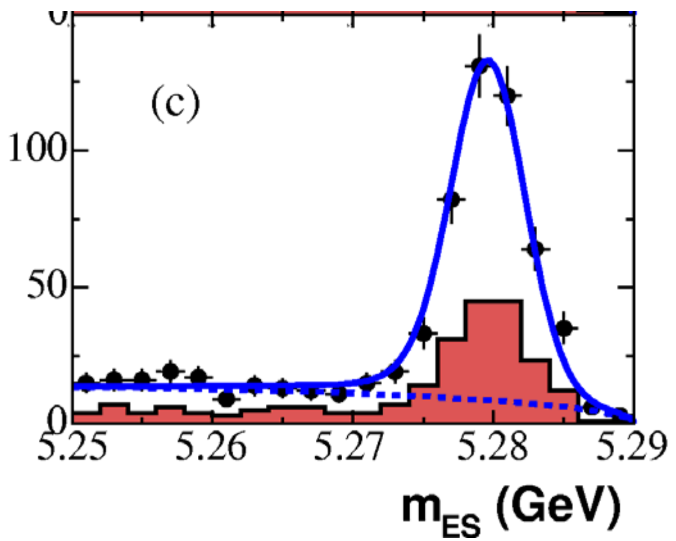
205 fb^{-1}

- Combining ϕK_S and ϕK_L together, we get

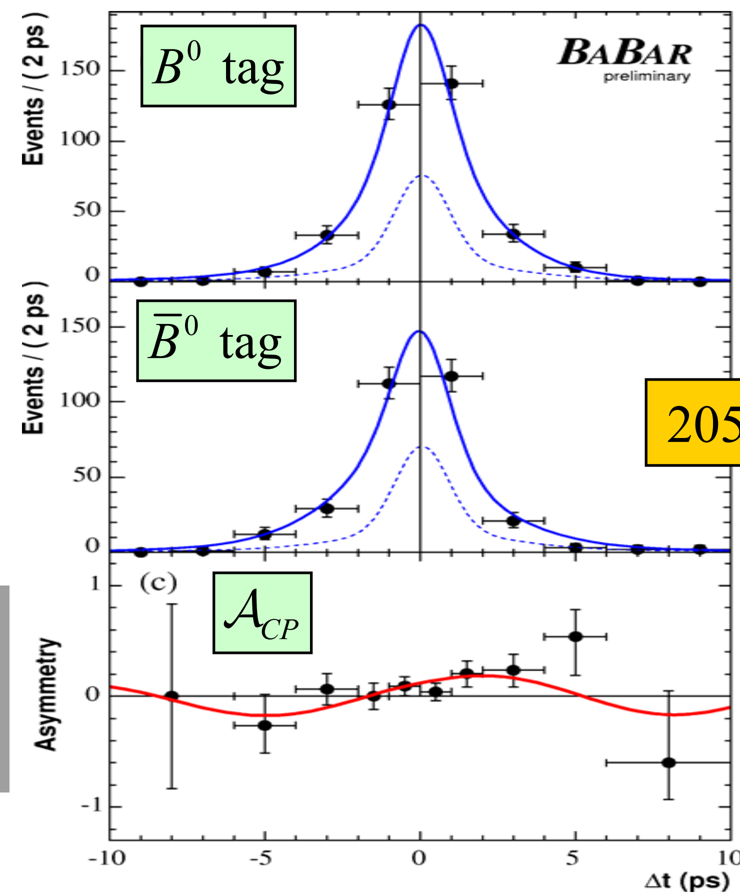
$$S_{\phi K^0} = 0.50 \pm 0.25(\text{stat})^{+0.07}_{-0.04}(\text{syst}), \quad C_{\phi K^0} = 0.00 \pm 0.23(\text{stat}) \pm 0.05(\text{syst})$$

$B^0 \to \eta' K_S$

$B^0 \to \phi K_S$ candidates



Time-dependent CP asymmetry



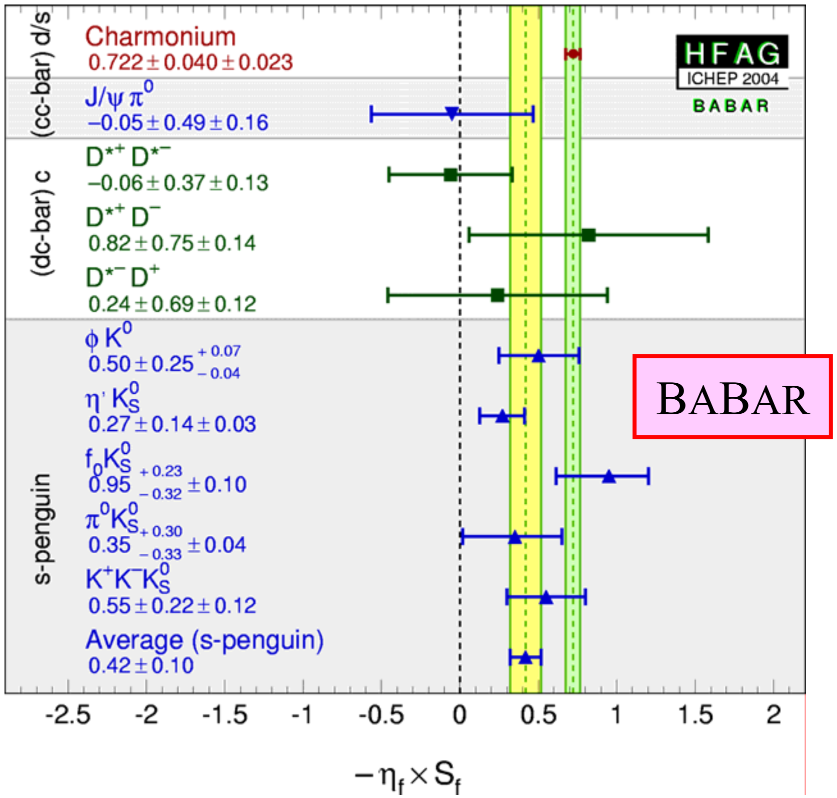
205 fb^{-1}

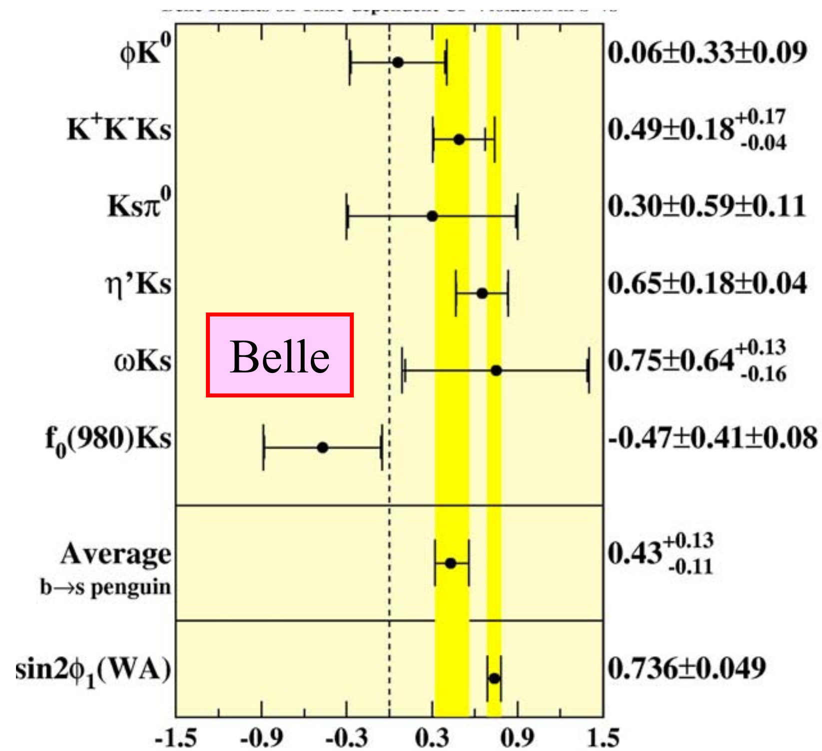
$$S_{\eta' K^0} = 0.27 \pm 0.14(\text{stat}) \pm 0.03(\text{syst})$$

$$C_{\eta' K^0} = -0.21 \pm 0.10(\text{stat}) \pm 0.03(\text{syst})$$

S is 3.0σ from $\sin 2\beta$ from $c\bar{c}s$

Status of Angle β





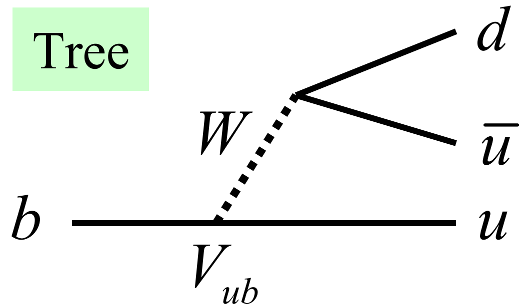
- Measurements of CPV in *s*-penguin channels improving rapidly
- Average $S < \sin 2\beta$ by 2.7σ (BABAR), 2.4σ (Belle)

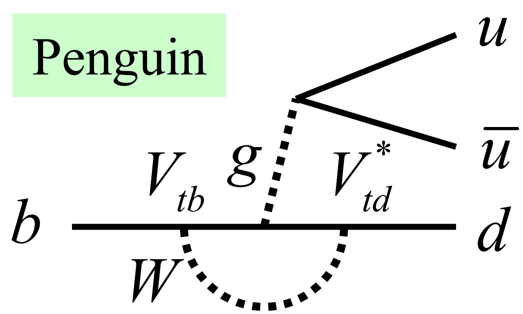
Angle α

- Consider $b \to u\bar{u}d$ decay
  - Example: $B^0 \to \pi^+\pi^-$
  - Decay involves V_{ub} → Weak phase γ
  - CP asymmetry should measure

$$\sin(2\beta + 2\gamma) = -\sin 2\alpha$$

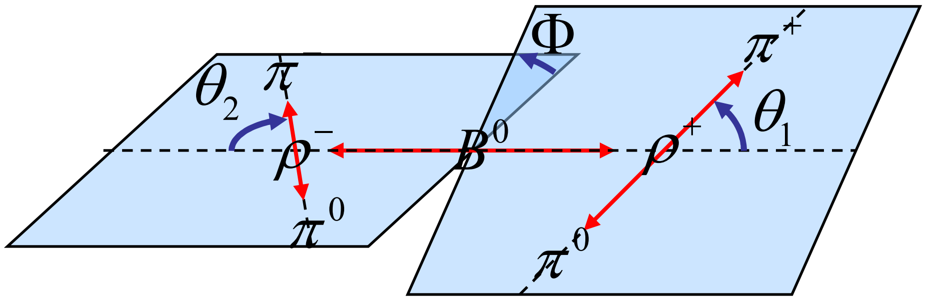
- Not so fast – There are penguins
  - We can measure $\sin 2\alpha$ only if the penguins are much smaller than the tree
  - It's about 1/3 in $B^0 \to \pi^+\pi^-$
    - Not so good…
  - Is there a better way?





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

- $B^0 \to \rho^+\rho^-$ has much smaller penguin
  - Known from small $\mathcal{B}(B^0 \to \rho^0\rho^0) < 1.1\times10^{-6}$ (90%C.L.) 205 fb^{-1}
  - $\mathcal{B}(B^0 \to \rho^+\rho^-) = (30 \pm 4 \pm 5)\times10^{-6}$
- ρ is vector meson → η_{CP} depends on the polarization
  - Determine the polarization from decay-angle distribution



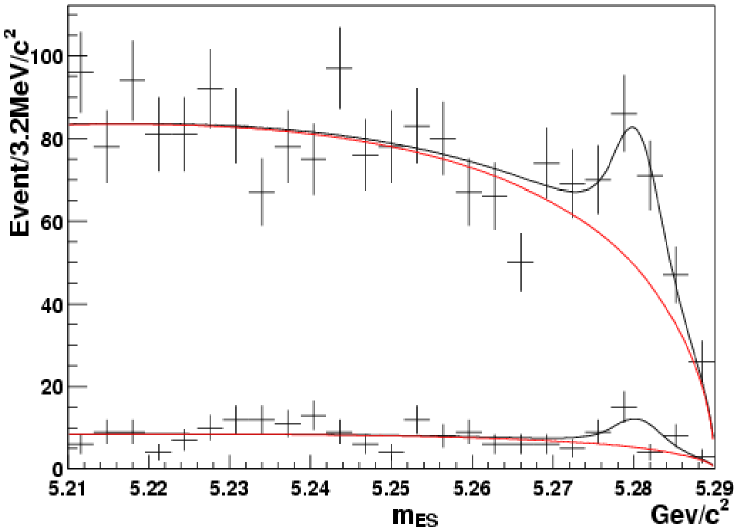
$$\text{Longitudinal} \propto \cos^2\theta_1 \cos^2\theta_2$$

$$\text{Transverse} \propto \sin^2\theta_1 \sin^2\theta_2$$

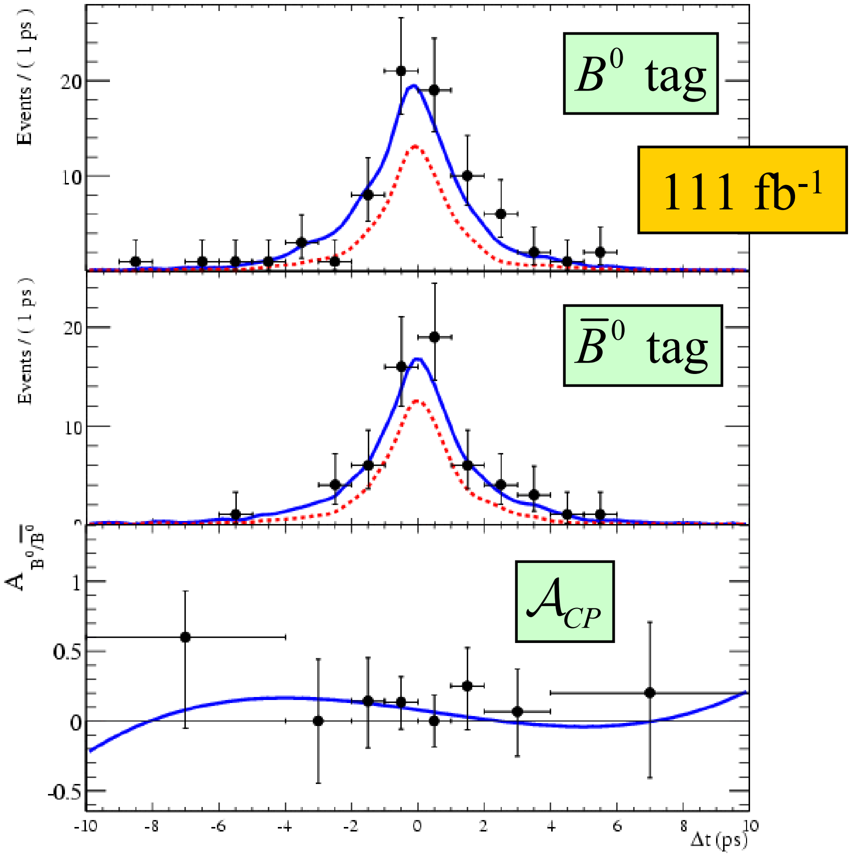
  - Longitudinal fraction $f_L = 0.99 \pm 0.03^{+0.04}_{-0.03}$
  - Almost pure CP eigenstate

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

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



Time-dependent CP asymmetry



- Simultaneously fit for f_L and S, C of the long. component

$$S_{long} = -0.42 \pm 0.42(stat) \pm 0.14(syst)$$

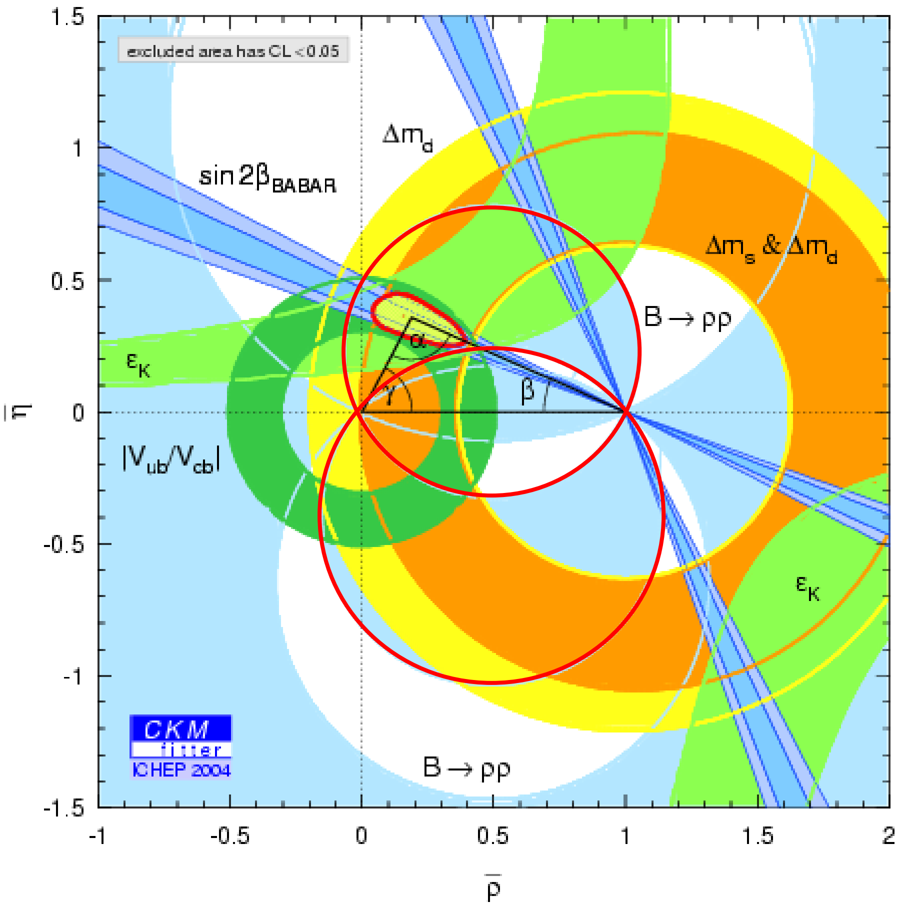
$$C_{long} = -0.17 \pm 0.27(stat) \pm 0.14(syst)$$

Status of Angle α

- $\mathcal{A}_{CP}$ in $B^0 \to \rho^+\rho^-$ combined with BFs for $B^0 \to \rho^+\rho^-$, $B^+ \to \rho^+\rho^0$, and $B^0 \to \rho^0\rho^0$

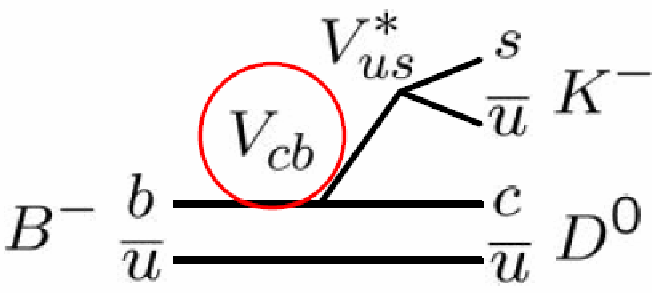
$$\alpha = \begin{bmatrix} 96 \pm 10(\text{stat}) \pm 4(\text{syst}) \\ \pm 11(\text{penguin}) \end{bmatrix} \text{deg}$$

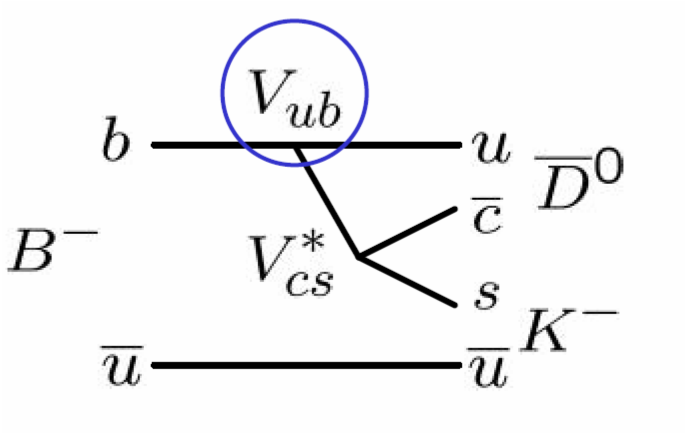
  - A promising method for measuring α
  - Agrees with the SM with a large error



Angle γ

- Hard to find a good channel that measure γ
  - A lot of not-so-good techniques are being studied
- Example: $B^- \rightarrow D^0 K^-$, $D^0 \rightarrow K_S \pi^+ \pi^-$
  - 2 decay diagrams →
  - Weak phases differ by γ
  - If D^0 decays into a CP eigenstate, interference violates CP
- Back to the old question
  - How do we know the relative amplitudes?
  - How do we know the strong phase?





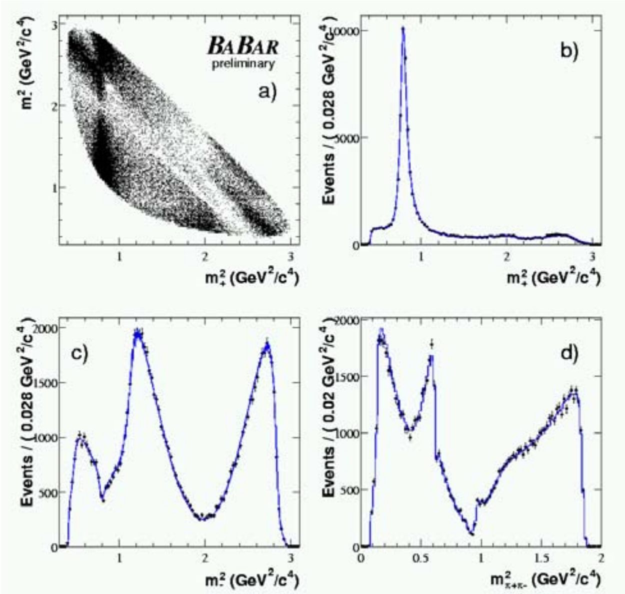
$B^- \to D^0 K^-$, $D^0 \to K_S \pi^+ \pi^-$

- Suppose we know the amplitude for $D^0 \to K_S\pi^+\pi^-$ as a function of $m_+ = m(K_S\pi^+)$ and $m_- = m(K_S\pi^-)$
  - Total decay amplitude should be

$$M_-(m_-, m_+) = f(m_-, m_+) + r_B e^{i(\delta-\gamma)} f(m_+, m_-) \quad \text{for } B^- \to K_S\pi^+\pi^-K^-$$

$$M_+(m_-, m_+) = f(m_+, m_-) + r_B e^{i(\delta+\gamma)} f(m_-, m_+) \quad \text{for } B^+ \to K_S\pi^+\pi^-K^+$$

- Experiments must
  - Determine $f(m_-,m_+)$ from fit to the $D^0 \to K_S\pi^+\pi^-$ Dalitz plot →
  - Fit the decay rates for B^+ and B^- and extract r_B, δ and γ

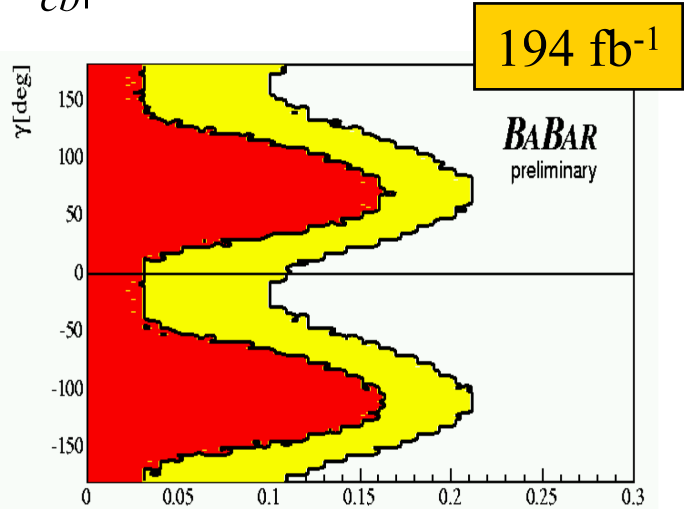


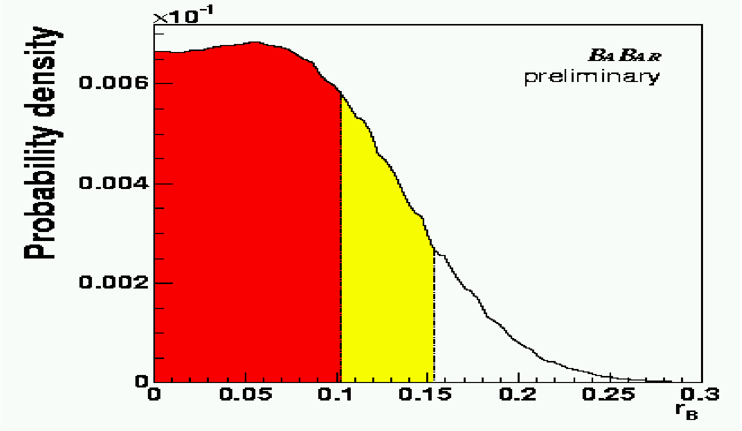
Status of Angle γ

- Sensitivity is proportional to $r_B \sim |V_{ub}|/|V_{cb}|$ ← small
  - No sensitivity for $r_B < 0.1$ with current statistics
  - Bayesian probability with flat prior gives $r_B < 0.18$ (90% C.L.)
- Combining D^0K^- and D^0K^{*-}

$$\gamma = (88 \pm 41 \pm 19 \pm 10)°$$

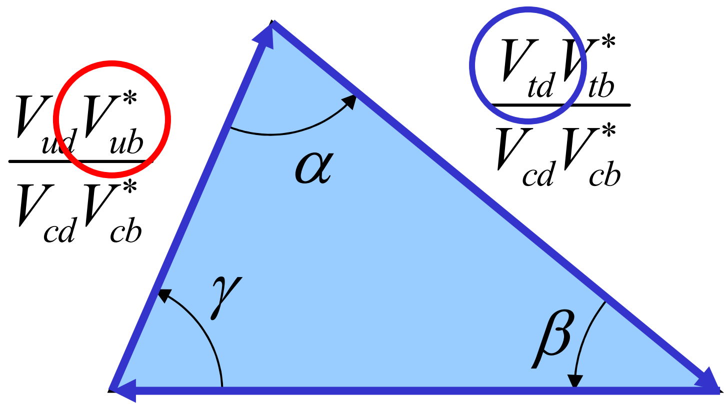
  - Not a precision measurement…
  - Future: combine multiple methods to constrain r_B better





The Sides

- In addition to the angles, we measure the lengths of the sides

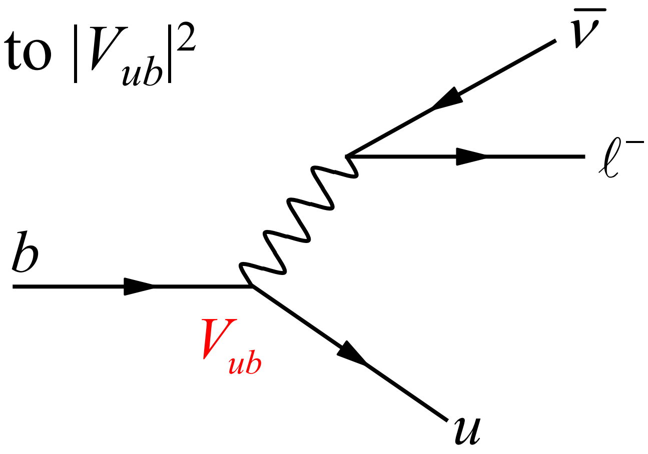


  - Uncertainties of the "left" and "right" sides are dominated by the smallest CKM elements V_{ub} and V_{td}

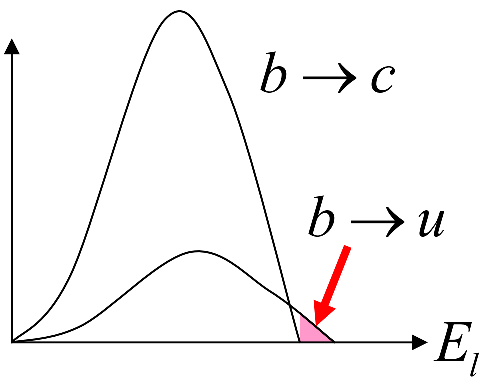
"Left" Side – $|V_{ub}|$

- Rate of $b \to u\ell\nu$ decay is proportional to $|V_{ub}|^2$
  - Leptonic part is free from strong final-state interaction

$$\frac{\Gamma(b \to u\ell\bar{\nu})}{\Gamma(b \to c\ell\bar{\nu})} \approx \frac{|V_{ub}|^2}{|V_{cb}|^2} \approx \frac{1}{50}$$



- Must suppress 50× larger $b \to c\ell\nu$ decays
- Traditional approach: select events with large lepton energy
  - "Endpoint" above kinematical limit for the $b \to c\ell\nu$ decay
  - Only ~6% of $b \to u\ell\nu$ events are accessible



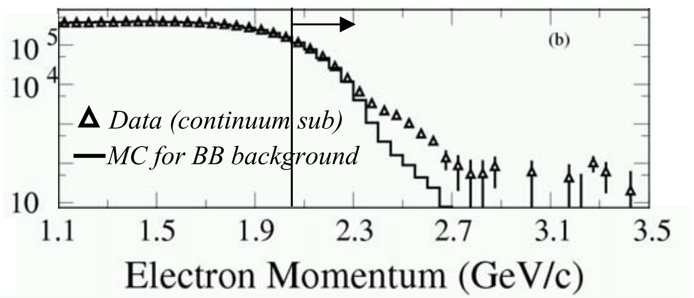
Lepton Endpoint

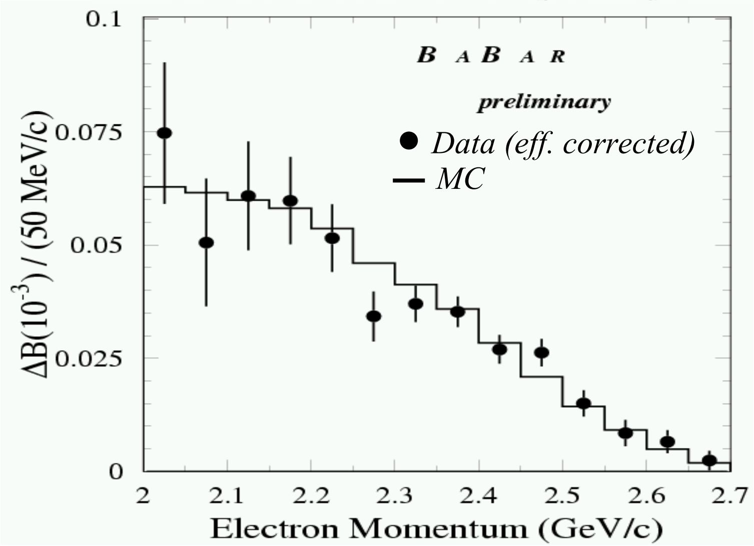
- Select electrons in $2.0 < E_\ell < 2.6$ GeV
  - Accurate subtraction of background is crucial!
  - Data taken below the Υ_{4S} resonance for non-BB background
  - Fit the E_ℓ spectrum with $b \to u\ell\nu$, $B \to D\ell\nu$, $B \to D^*\ell\nu$, $B \to D^{**}\ell\nu$, etc. to extract

$$\mathcal{B}(B \to X_u e\nu) = (1.73 \pm 0.22_{exp} \pm 0.33_{theo}) \times 10^{-3}$$

  - Turn into

$$|V_{ub}| = (3.94 \pm 0.25_{exp} \pm 0.37_{theo} \pm 0.19_{HQET}) \times 10^{-3}$$





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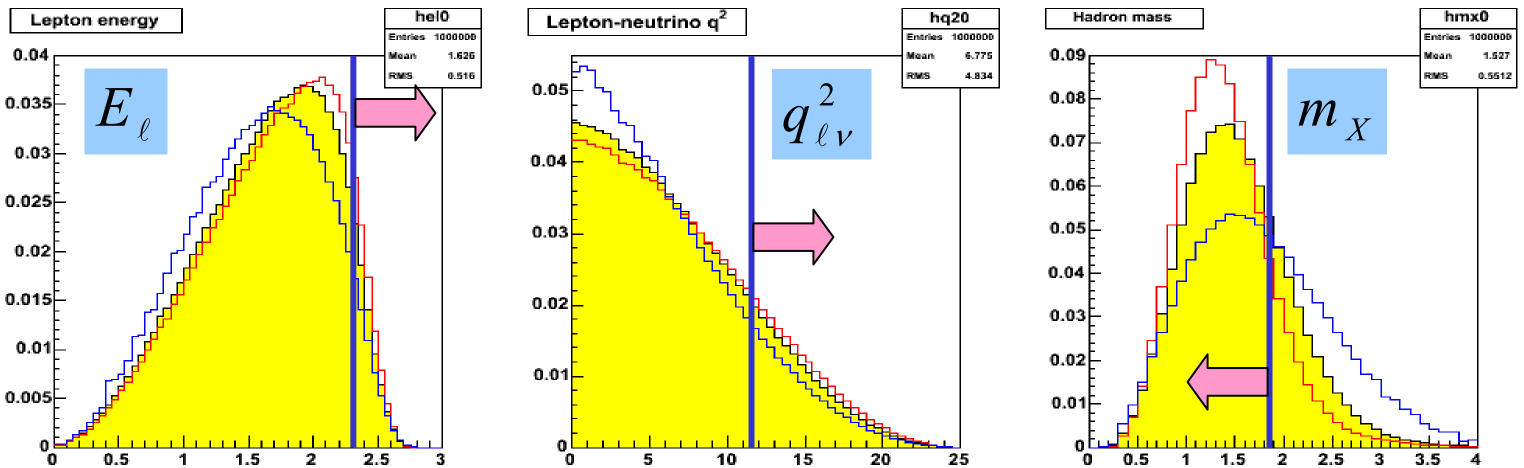
Hadronic Mass and q^2

- E_ℓ is not the only kinematic variable available
  - There are 3 independent variables
  - Consider m_X (hadronic mass) and q^2 (lepton-neutrino mass^2)
- ~70% of $b \to u\ell\nu$ has $m_X < m_D$
  - High efficiency + smaller extrapolation
- Cut on q^2 is less efficient (~20%) but smaller theoretical errors

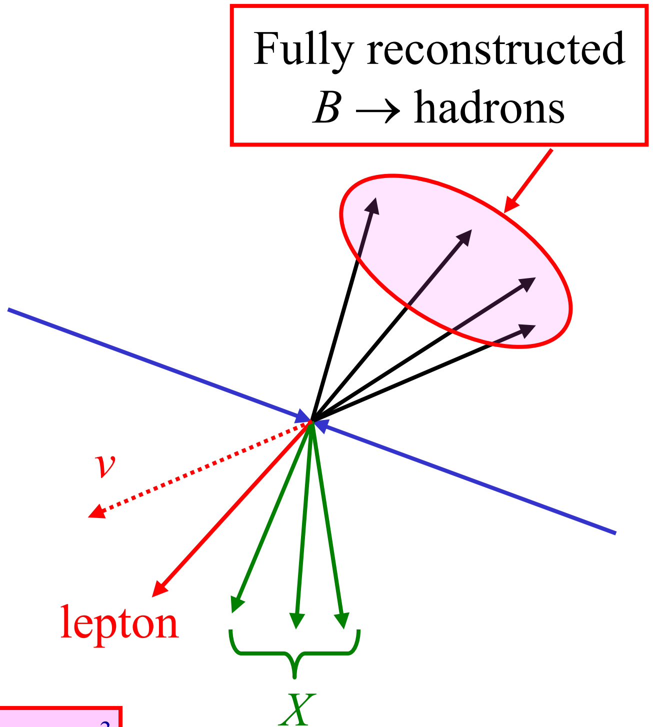


Recoil Method

- Must reconstruct all decay products to measure m_X or q^2
  - E_ℓ was much easier
- B mesons produced in pairs
  - Reconstruct one B in any mode
    → Rest of the event contains exactly one recoil B
  - Find a lepton in the recoil B
    → Remaining part must be X in $B \to X\ell\nu$
  - Calculate m_X and q^2
- For $m_X < 1.7$ GeV and $q^2 > 8$ (GeV)^2

$$\Delta\mathcal{B}(B \to X_u l\nu) = (0.88 \pm 0.14_{stat} \pm 0.13_{exp\ syst} \pm 0.02_{(m_b,a)\ syst}) \times 10^{-3}$$

$$|V_{ub}| = (4.92 \pm 0.39_{stat} \pm 0.36_{exp\ syst} \pm 0.46_{theo\ syst}) \times 10^{-3}$$



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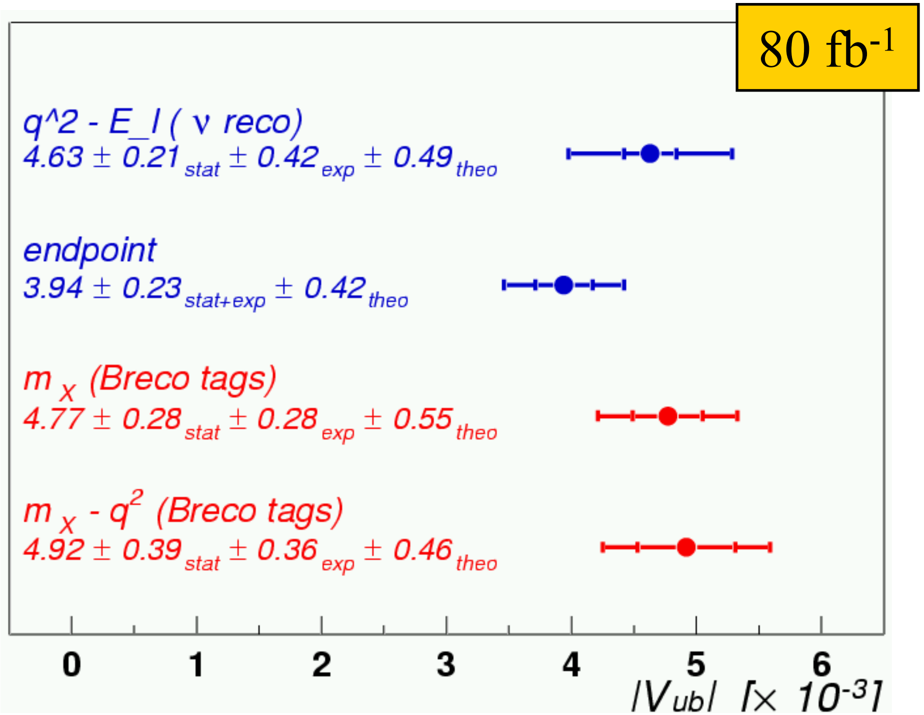
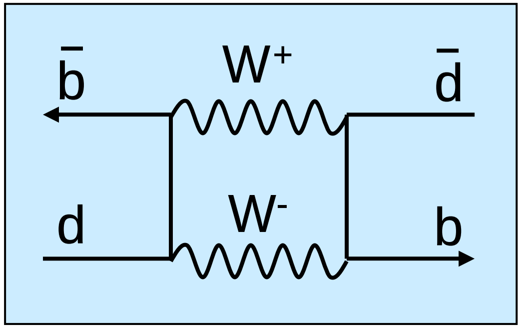
Status of $|V_{ub}|$

- Different approaches for $|V_{ub}|$ pursued to tackle theoretical uncertainty
  - Largest error from the "shape function"
  - Determined by CLEO measurement of photon energy spectrum in $b \to s\gamma$
- Future improvement from
  - New techniques ← More data helps
  - Theoretical progress
  - Better measurement of $b \to s\gamma$



"Right" Side – $|V_{td}|$

- B^0 mixing involves virtual top exchange
  - Once B_s mixing rate is measured

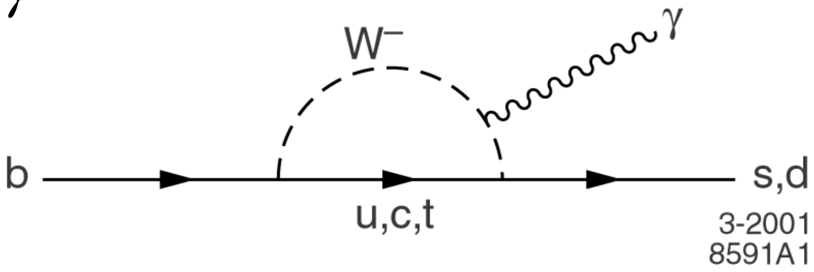


B^0 mixing rate → B_s mixing rate →

$$\frac{\Delta m_d}{\Delta m_s} \approx \frac{|V_{td}|^2}{|V_{ts}|^2}$$

  - What can we do besides waiting for Tevatron?
- Radiative penguin decays $b \to s/d\,\gamma$

$$\frac{\Gamma(b \to d\gamma)}{\Gamma(b \to s\gamma)} \approx \frac{|V_{td}|^2}{|V_{ts}|^2}$$



  - Expect

$$\mathcal{B}(B^+ \to \rho^+\gamma) \approx \mathcal{B}(B^+ \to K^{*+}\gamma)\frac{|V_{td}|^2}{|V_{ts}|^2} = 1.6\times10^{-6}$$

← Reachable at B Factories

$B \to \rho\gamma$

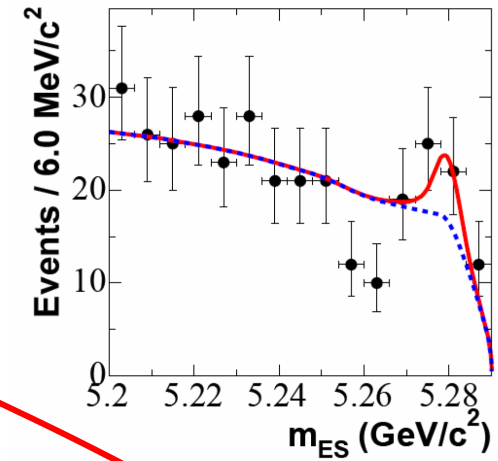
- Main background from non-*BB* events
  - Jet-like geometry → Use event shape variables → Neural Net
- $B \to K^* \gamma$ is 40× larger
  - Particle ID with the Cherenkov detector
- Combine $\rho^+\gamma$, $\rho^0\gamma$ and $\omega\gamma$, assuming

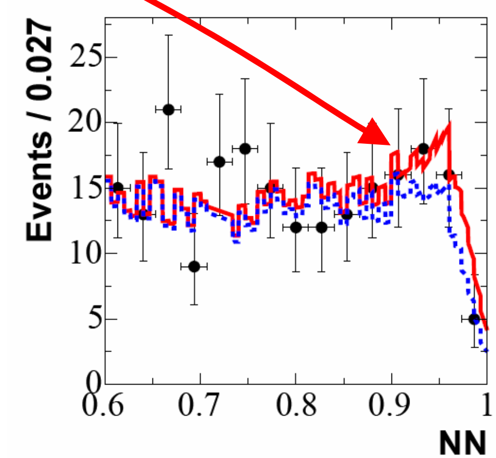
$$\Gamma(B^+ \to \rho^+\gamma) = 2\Gamma(B^0 \to \rho^0\gamma) = 2\Gamma(B^0 \to \omega\gamma)$$

$$\mathcal{B}(B^+ \to \rho^+\gamma) = (0.6 \pm 0.3 \pm 0.1) \times 10^{-6}$$
$$< 1.2 \times 10^{-6} \text{ (90\%C.L.)}$$

191 fb^{-1}

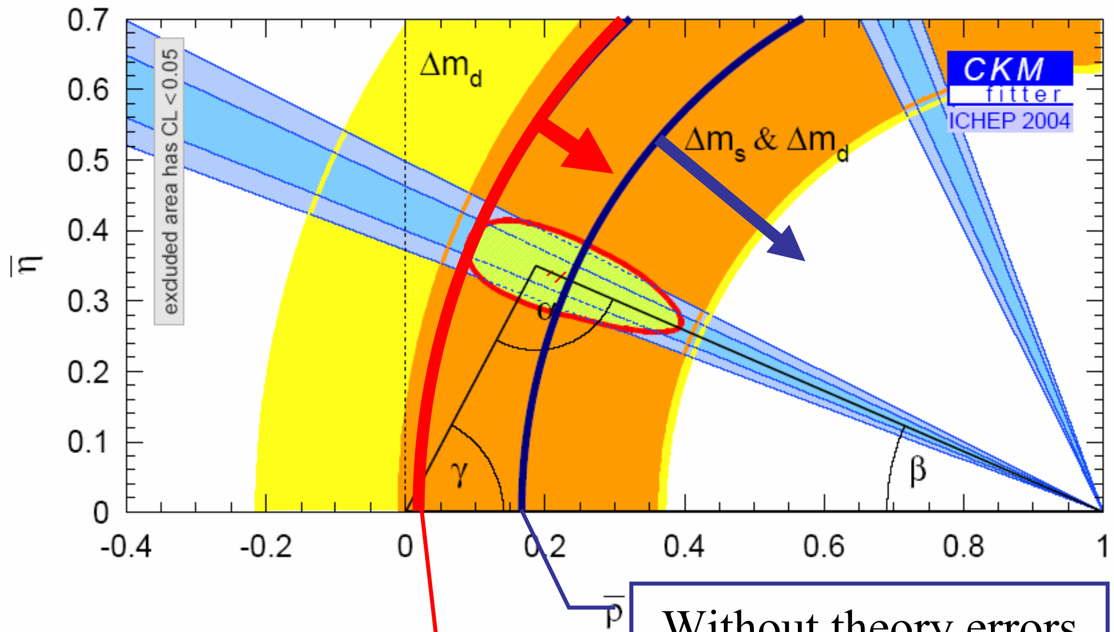
  - A little smaller than expected by the SM





Status of $|V_{td}|$

- $\mathcal{B}(B \to \rho\gamma)$ limits the length of the "right" side
  - Bound comparable to that from the mixing
- Theory errors from ρ vs. K^* form factor difference and weak annihilation
- Observing $B \to \rho\gamma$ with additional statistics will be *very* interesting



Summary

- The unitarity triangle is under attack from all directions
  - Huge data sample allow more and more measurements
- In addition to $\sin 2\beta$, many measurements are reaching interesting precisions
  - CPV in penguin decays, $B \to \rho\rho$, $B \to u\ell\nu$, $B \to \rho\gamma$, ...
- Will we crack the unitarity triangle?