Cracking the Unitarity Triangle

— A Quest in *B* Physics —

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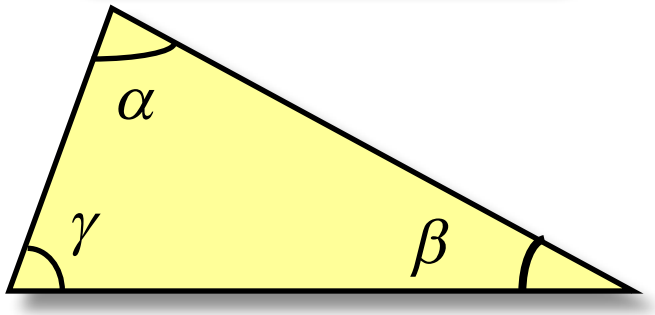
Outline

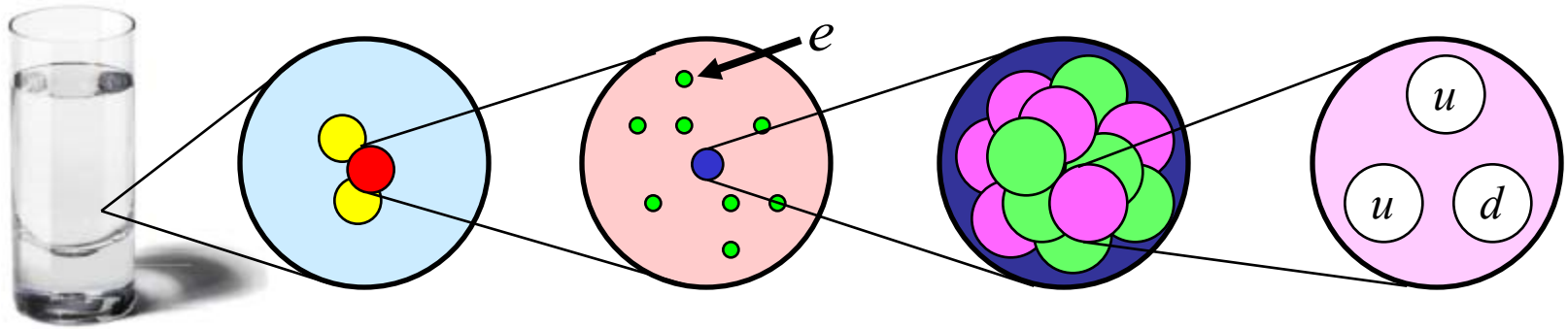
- Introduction to the Unitarity Triangle
  - The Standard Model, the CKM matrix, and *CP* violation
  - *CP* asymmetry in the B^0 meson decays
- Experiments at the *B* Factories
- Results from *BABAR* and Belle
  - Angles α, β, γ from *CP* asymmetries
  - $|V_{ub}|$ from semileptonic decays
  - $|V_{td}|$ from B^0 and B_s mixing
- Current status and outlook

The Unitarity Triangle



Results presented in this talk are produced by the *BABAR*, Belle, and CLEO Experiments, the Heavy Flavor Averaging Group, the CKMfitter Group, and the UT*fit* Collaboration

What are we made of?



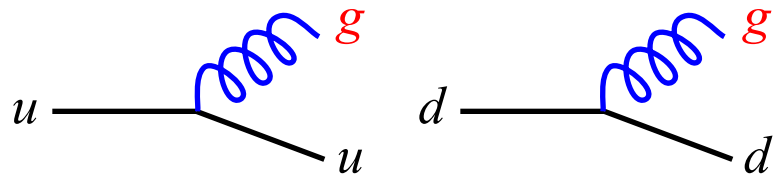
- Ordinary matter is made of electrons and up/down quarks
  - Add the neutrino and we have a complete "kit"
  - We also know how they interact with "forces"

leptons		quarks	
$Q = 1$	e	u	$Q = +2/3$
$Q = 0$	e	d	$Q = 1/3$

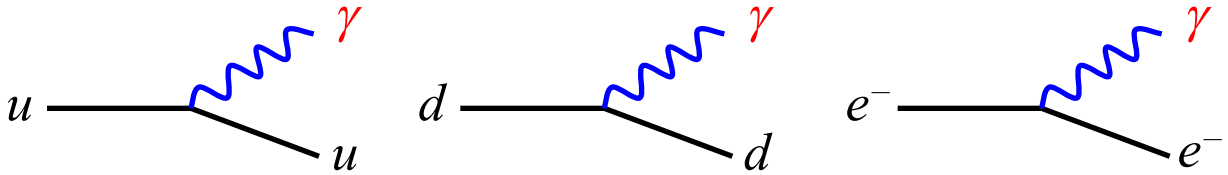
	strong	E&M	weak
u	Yes	Yes	Yes
d	Yes	Yes	Yes
e^-	No	Yes	Yes
ν_e	No	No	Yes

Simplified Standard Model

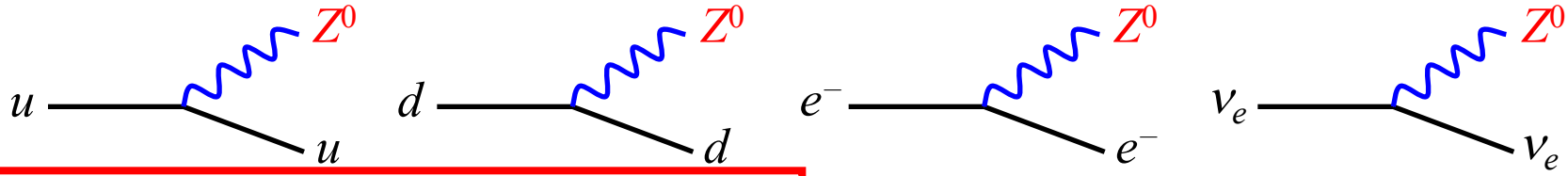
- Strong force is transmitted by the gluon

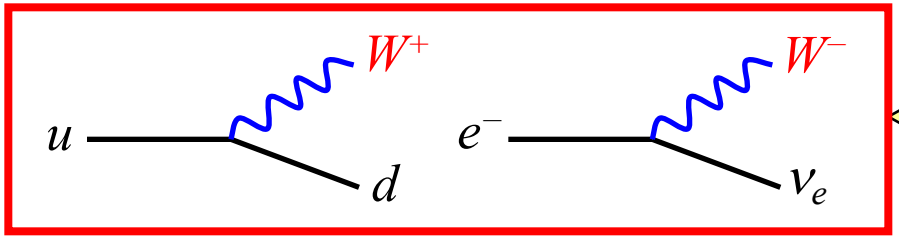


- Electromagnetic force by the photon



- Weak force by the $W^{\pm}$ and Z^0 bosons





Note $W^{\pm}$ can "convert"
$u \leftrightarrow d$, $e \leftrightarrow \nu$

Three generations

- We've got a neat, clean, predictive theory of "everything"

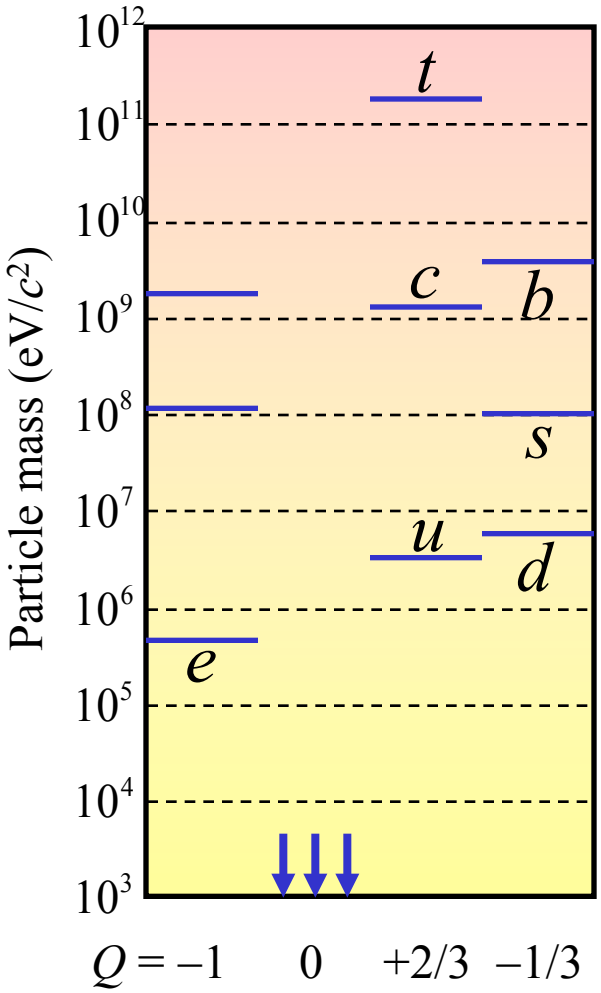
	leptons	quarks
1st generation	e^-	u
	ν_e	d
2nd generation	μ^-	c
	ν_μ	s
3rd generation	τ^-	t
	ν_τ	b

strong	E&M	weak
g	γ	$W^\pm$
		Z^0

It turns out there are two "extra" copies of particles

- Why 3 sets (= generations) of particles?
  - How do they differ?
  - How do they interact with each other?

A spectrum of masses



- The generations differ only by the masses
  - ⇐ The structure is mysterious
- The Standard Model has no explanation for the mass spectrum
  - All 12 masses are inputs to the theory
  - The masses come from the interaction with the Higgs particle
    - ... whose nature is unknown
    - We are looking for it with the Tevatron, and with the Large Hadron Collider (LHC) in the future

The origin of mass is one of the most urgent questions in particle physics today

If there were no masses

- Nothing would distinguish u from c from t
  - We could make a mixture of the wavefunctions and pretend it represents a physical particle

$$\begin{matrix} u \\ c \\ t \end{matrix} = \mathbf{M} \begin{matrix} u \\ c \\ t \end{matrix} \qquad \begin{matrix} d \\ s \\ b \end{matrix} = \mathbf{N} \begin{matrix} d \\ s \\ b \end{matrix}$$

M and **N** are arbitrary 3×3 unitary matrices

- Suppose $W^{\pm}$ connects $u' \leftrightarrow d'$, $c' \leftrightarrow s'$, $t' \leftrightarrow b'$

$$\begin{matrix} u \\ c \\ t \end{matrix} = \mathbf{M}^{1} \begin{matrix} u \\ c \\ t \end{matrix} \qquad \mathbf{M}^{1} \begin{matrix} d \\ s \\ b \end{matrix} = \mathbf{M}^{1}\mathbf{N} \begin{matrix} d \\ s \\ b \end{matrix} = \mathbf{V} \begin{matrix} d \\ s \\ b \end{matrix}$$

Weak interactions between u, c, t, and d, s, b are "mixed" by matrix **V**

  - That's a poor choice of basis vectors

Turn the masses back on

- Masses uniquely define the u, c, t, and d, s, b states
  - We don't know what creates masses
    ➔ We don't know how the eigenstates are chosen
    ➔ **M** and **N** are arbitrary
  - **V** is an arbitrary 3×3 unitary matrix

$$\begin{matrix} u \\ c \\ t \end{matrix} \quad W^{\pm} \quad \mathbf{V} \begin{matrix} d \\ s \\ b \end{matrix} = \begin{matrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{matrix} \begin{matrix} d \\ s \\ b \end{matrix}$$

Cabibbo-Kobayashi-Maskawa matrix

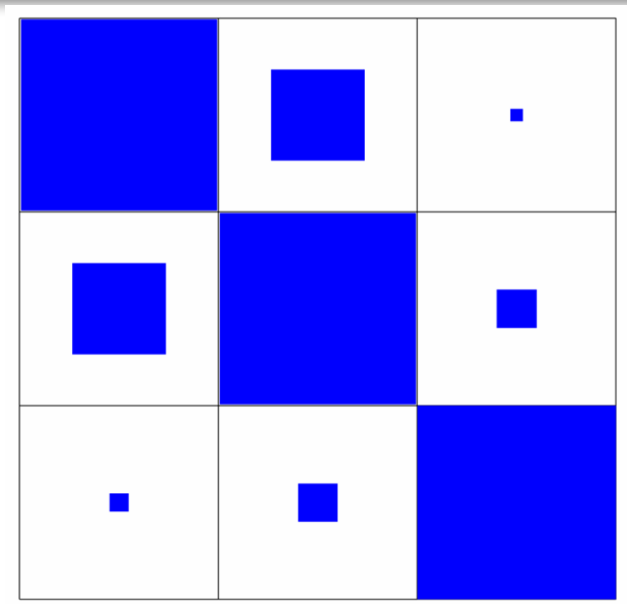
or **CKM** for short

- The Standard Model does not predict **V**
  - ... for the same reason it does not predict the particle masses

Structure of the CKM matrix

- The CKM matrix looks like this ➔
  - It's not completely diagonal
  - Off-diagonal components are small
    - Transition across generations is allowed but suppressed

$$\mathbf{V} = \begin{matrix} 0.974 & 0.226 & 0.004 \\ 0.226 & 0.973 & 0.042 \\ 0.008 & 0.042 & 0.999 \end{matrix}$$



There seems to be a "structure" separating the generations

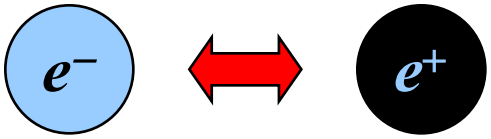
- Matrix elements can be complex
  - Unitarity leaves 4 free parameters, one of which is a complex phase

This phase causes "*CP* violation"

Kobayashi and Maskawa (1973)

What are we made of, again?

- Dirac predicted existence of anti-matter in 1928
  - Positron (= anti-electron) discovered in 1932



- Our Universe contains (almost) only matter

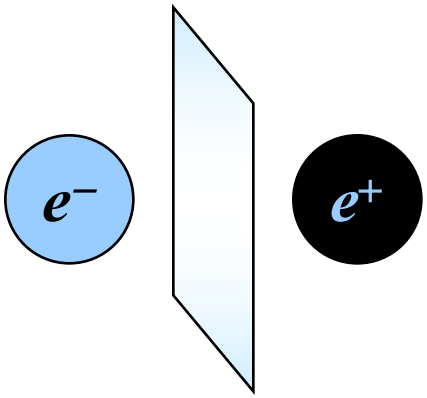
> I do not believe in the hole theory, since I would like to have the asymmetry between positive and negative electricity in the laws of nature (it does not satisfy me to shift the empirically established asymmetry to one of the initial state)
>
> Pauli, 1933 letter to Heisenberg

- Translation: he would like the laws of physics to be different for particles and anti-particles

CP symmetry

C	charge conjugation	particle ↔ anti-particle
P	parity	$x \to -x$, $y \to -y$, $z \to -z$

- *C* and *P* symmetries are broken in weak interactions
  - Lee, Yang (1956), Wu et al. (1957), Garwin, Lederman, Weinrich (1957)
- Combined *CP* symmetry seemed to be good
  - Anti-Universe can exist as long as it is a mirror image of our Universe
- To create a matter-dominant Universe,



CP symmetry must be broken

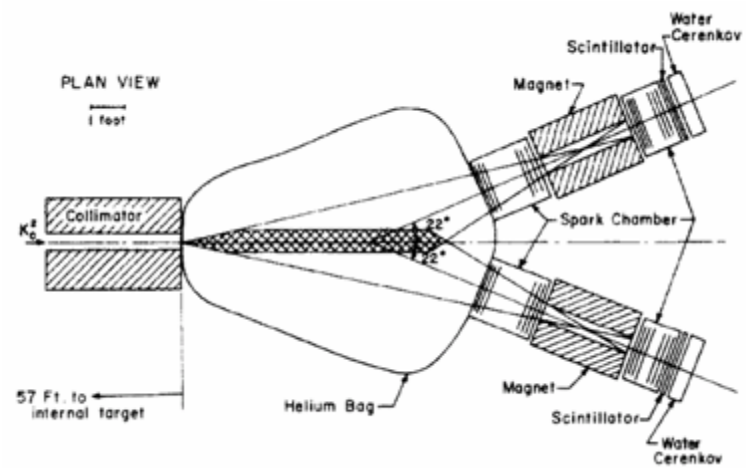
One of the three necessary conditions (Sakharov 1967)

CP violation

- *CP* violation was discovered in K_L decays — Christenson *et al.* (1964)
  - K_L decays into either 2 or 3 pions

K_L	+	+	(33%)	$CP = 1$
K_L	+		(0.3%)	$CP = +1$

Final states have different *CP* eigenvalues



  - Couldn't happen if *CP* was a good symmetry of Nature

➔ Laws of physics apply differently to matter and antimatter

- The complex phase in the CKM matrix causes *CP* violation
  - It is the only source of *CP* violation in the Standard Model

Nothing else?

CP violation and New Physics

Are there additional (non-CKM) sources of *CP* violation?

- The CKM mechanism fails to explain the *amount* of matter-antimatter imbalance in the Universe
  - ... by several orders of magnitude
- New Physics beyond the SM is expected at 1-10 TeV scale
  - e.g. to keep the Higgs mass < 1 TeV/c^2
  - Almost all theories of New Physics introduce new sources of *CP* violation (e.g. 43 of them in supersymmetry)

New sources of *CP* violation almost certainly exist

  - Precision studies of the CKM matrix may uncover them

The Unitarity Triangle

- $\mathbf{V}^\dagger\mathbf{V} = \mathbf{1}$ gives us

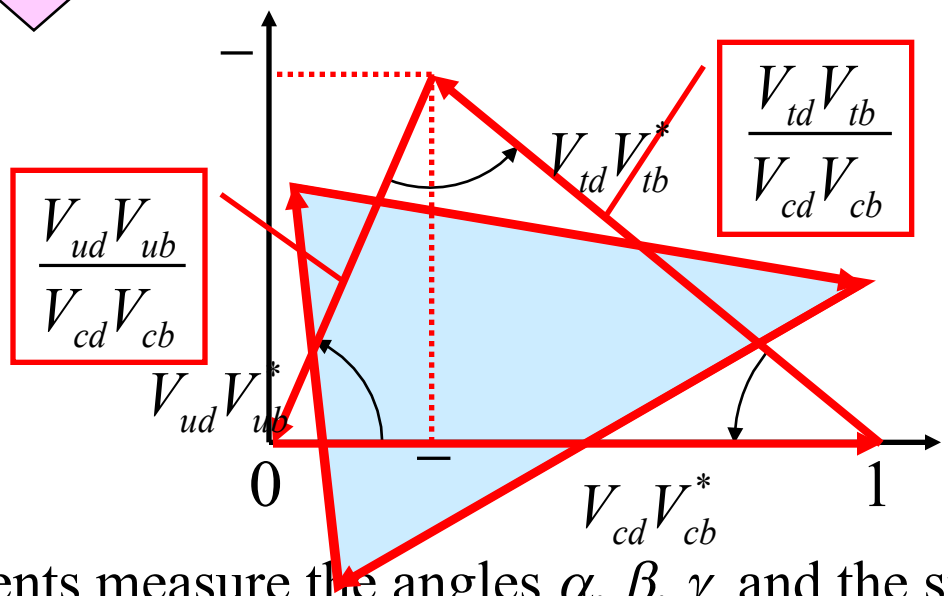
$$V_{ud}V_{us}^* + V_{cd}V_{cs}^* + V_{td}V_{ts}^* = 0$$

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

$$V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0$$

This one has the 3 terms in the same order of magnitude

A triangle on the complex plane

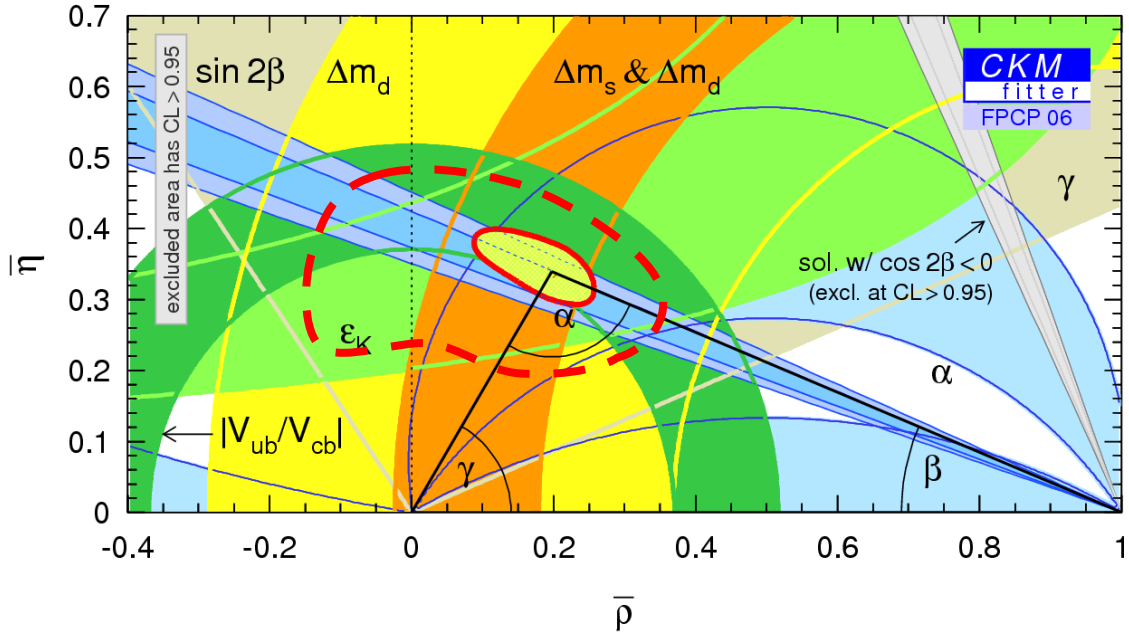


- Experiments measure the angles α, β, γ and the sides

The UT 1998 → 2006

- We did know something about how the UT looked in the last century
  - By 2005, the allowed region for the apex has shrunk to about 1/10 in area

The improvements are due largely to the ***B* Factories** that produce and study ***B* mesons** in quantity



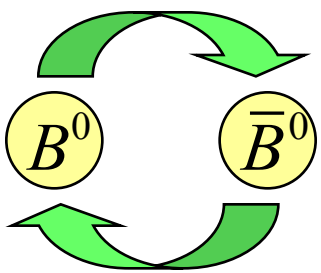
Anatomy of the B^0 system

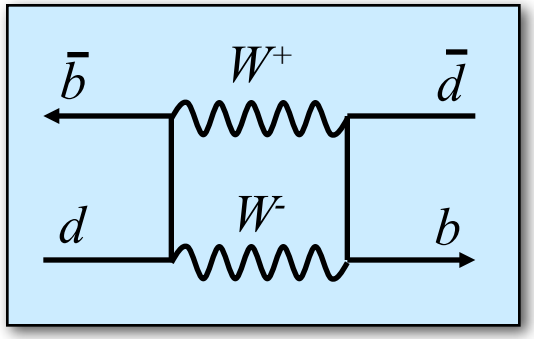
- The B^0 meson is a bound state of $\bar{b}$ and d quarks

Particle	charge	mass	lifetime
$B^0 = (\bar{b}d)$	0	5.28 GeV/c^2	1.5 ps
$\bar{B}^0 = (b\bar{d})$	0	5.28 GeV/c^2	1.5 ps

Indistinguishable from the outside

  - They turn into each other spontaneously

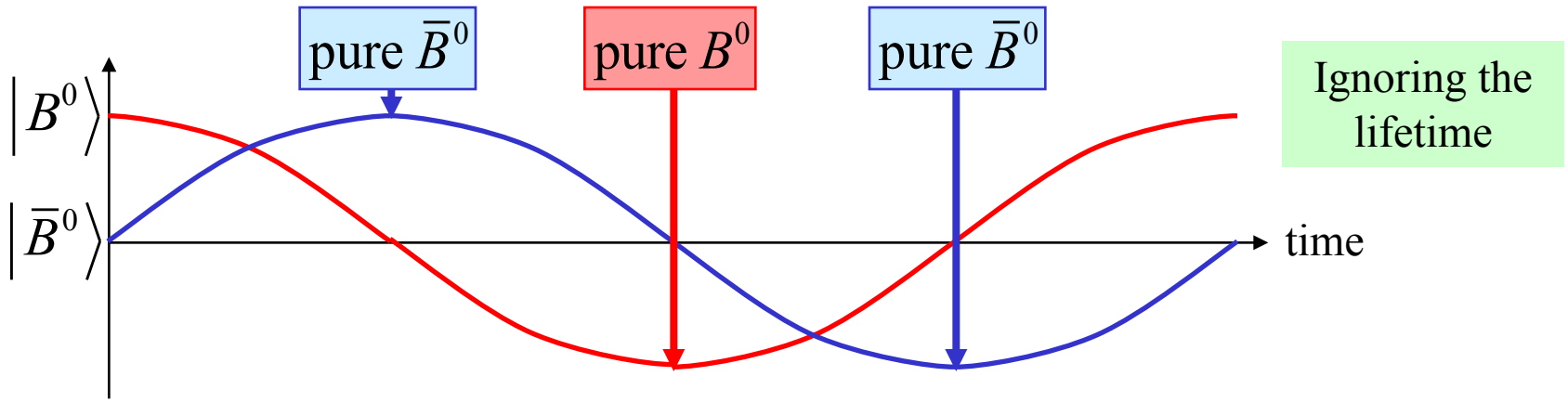




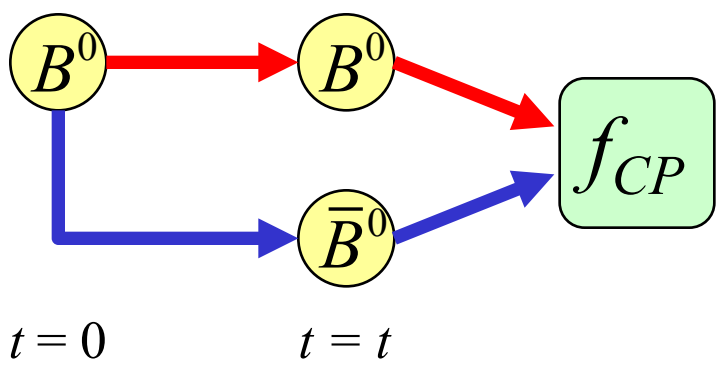
  - This is called the **B^0-$\bar{B}^0$ mixing**

Time-dependent Interference

- Starting from a pure $|B^0\rangle$ state, the wave function evolves as



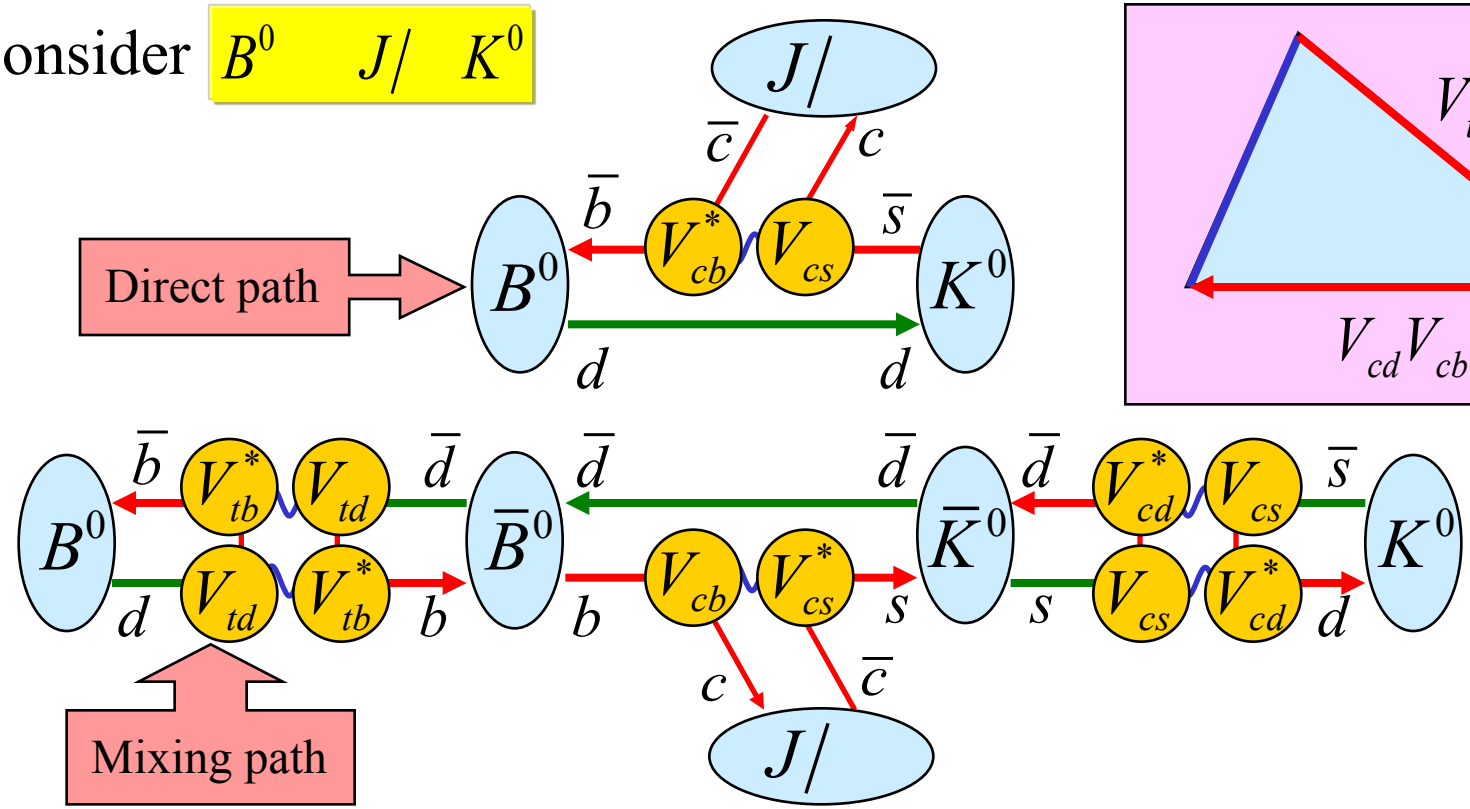
- Suppose B^0 and $\bar{B}^0$ can decay into a same final state f_{CP}

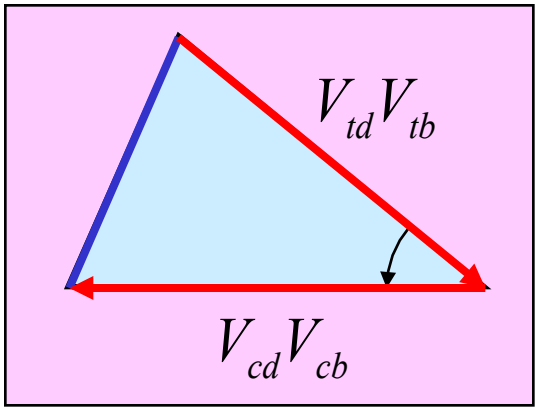


- Two paths can interfere
- Decay probability depends on:
  - the decay time t
  - the relative complex phase between the two paths

The Golden Mode

- Consider $B^0 \quad J/ \quad K^0$





- Phase difference is

$$\arg(V_{cs}V^*_{cb}) \quad \arg(V^2_{td}V^{*2}_{tb}V_{cb}V^*_{cs}V^2_{cs}V^{*2}_{cd}) = 2 \quad \arg(V_{cd}V^*_{cb}) \quad \arg(V_{td}V^*_{tb}) \quad = \quad 2$$

Time-dependent *CP* Asymmetry

- Quantum interference between the direct and mixed paths makes $B^0(t) \quad J/ \quad K^0$ and $\bar{B}^0(t) \quad J/ \quad K^0$ different
- Define time-dependent *CP* asymmetry:

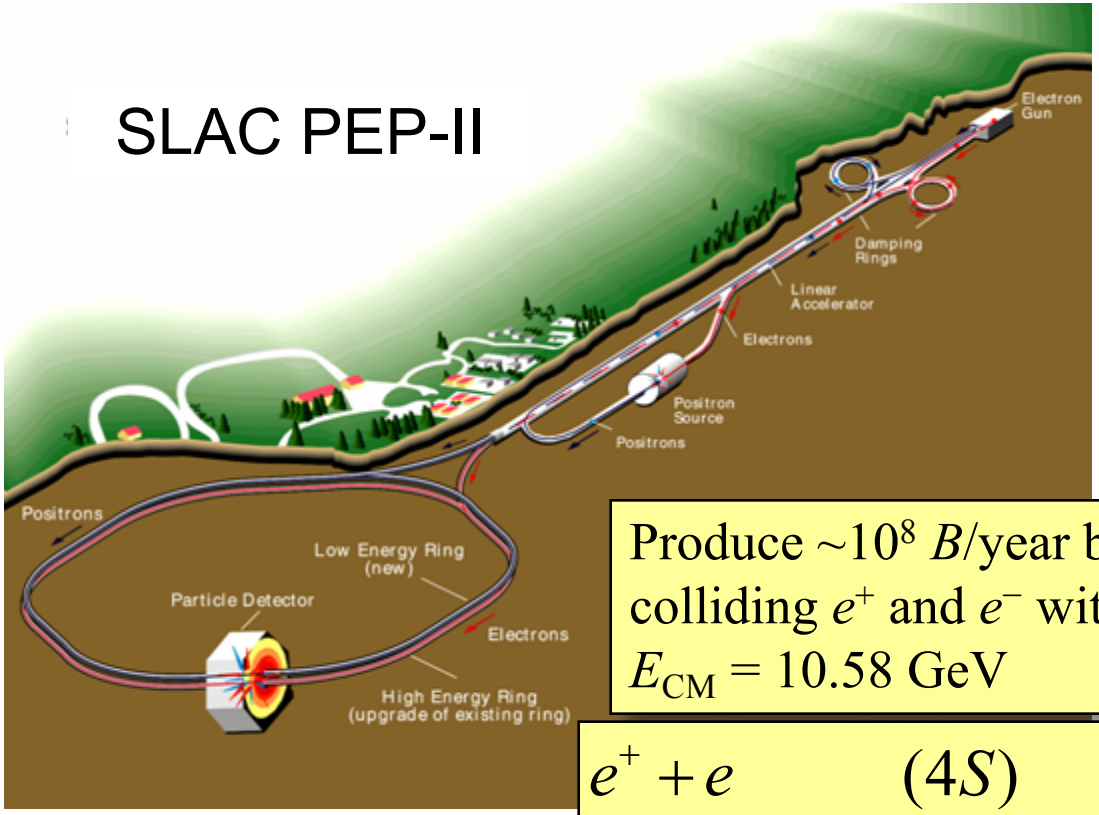
$$A_{CP}(t) = \frac{N(\bar{B}^0(t) \quad J/ \quad K_S^0) \quad N(B^0(t) \quad J/ \quad K_S^0)}{N(\bar{B}^0(t) \quad J/ \quad K_S^0) + N(B^0(t) \quad J/ \quad K_S^0)} = \sin(2 \quad)\sin(\quad mt)$$

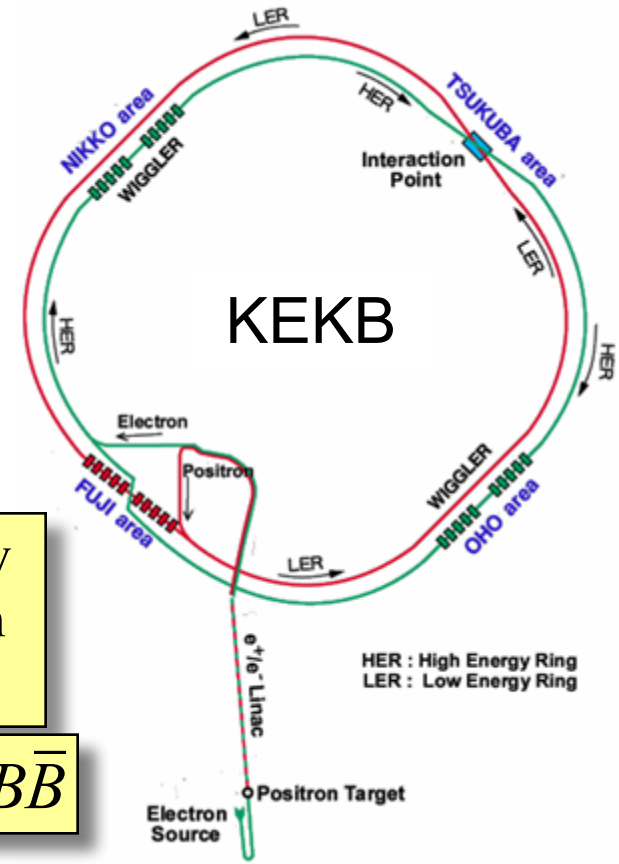
  - We can measure the angle of the UT
- What do we have to do to measure $A_{CP}(t)$?
  - Step 1: Produce and detect $B^0 \to f_{CP}$ events
  - Step 2: Separate B^0 from $\bar{B}^0$
  - Step 3: Measure the decay time t

Solution:
Asymmetric
B Factory

B Factories

- Designed specifically for precision measurements of the *CP* violating phases in the CKM matrix





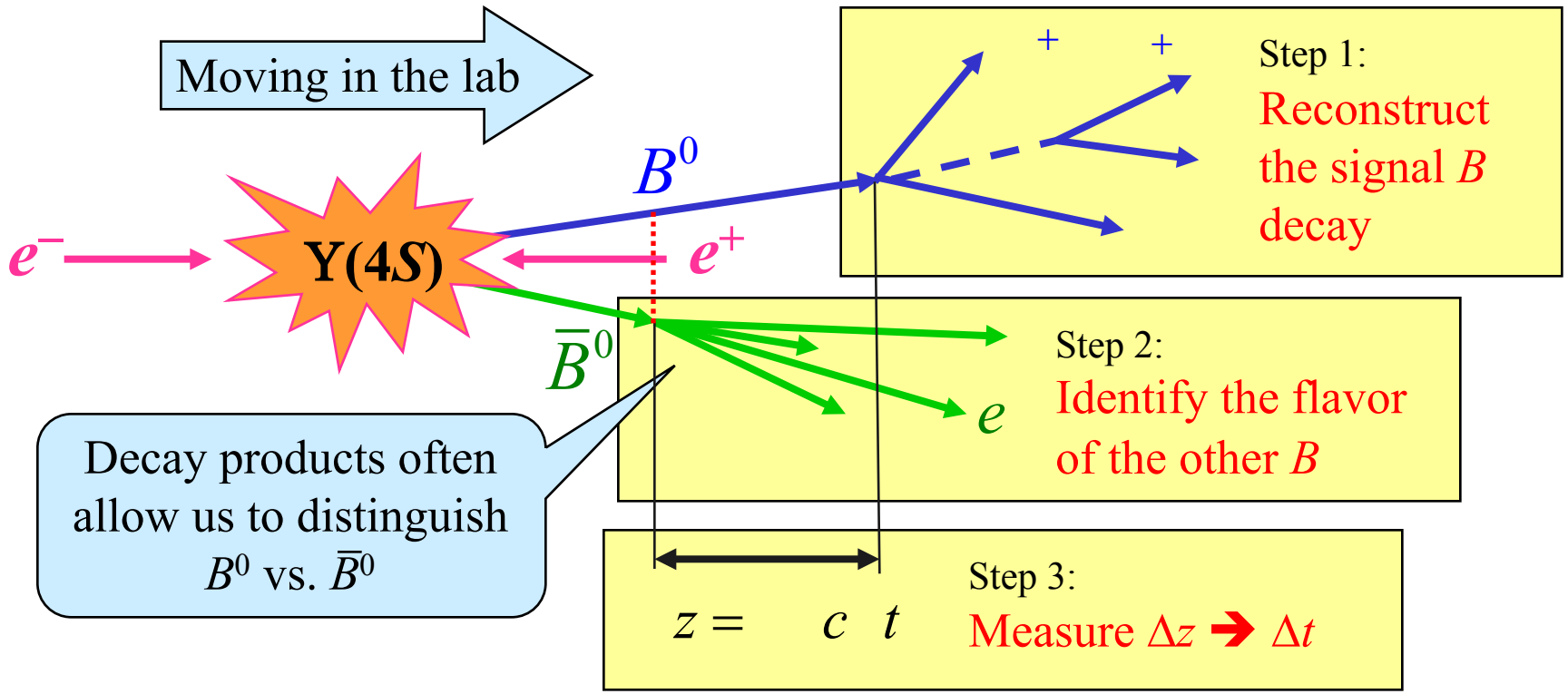
Produce ~10^8 B/year by colliding e^+ and e^- with E_{CM} = 10.58 GeV

$$e^+ + e \qquad (4S) \qquad B\bar{B}$$


Linac
I-280
BABAR
PEP-II

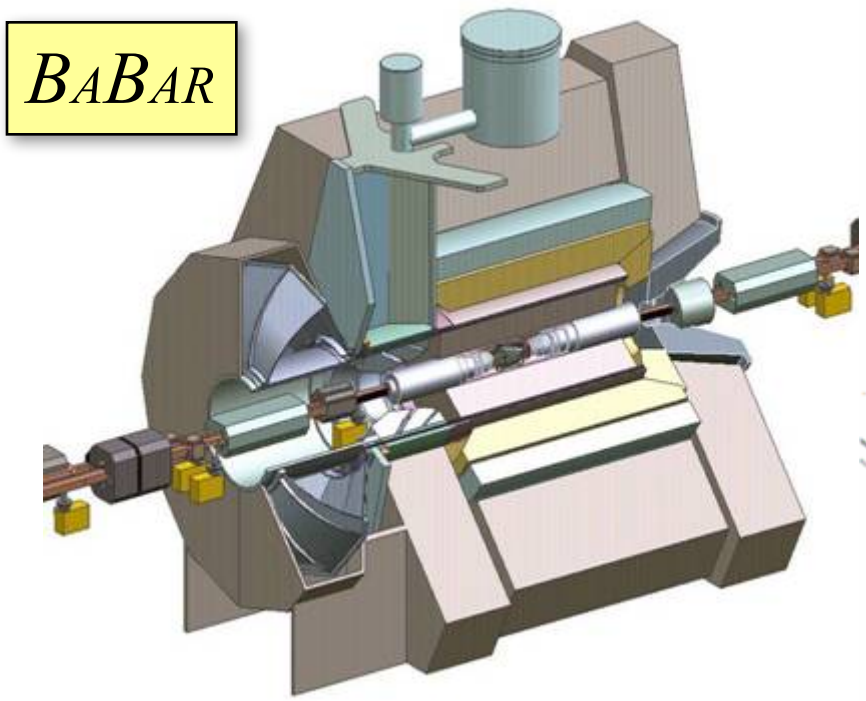
Asymmetric *B* Factory

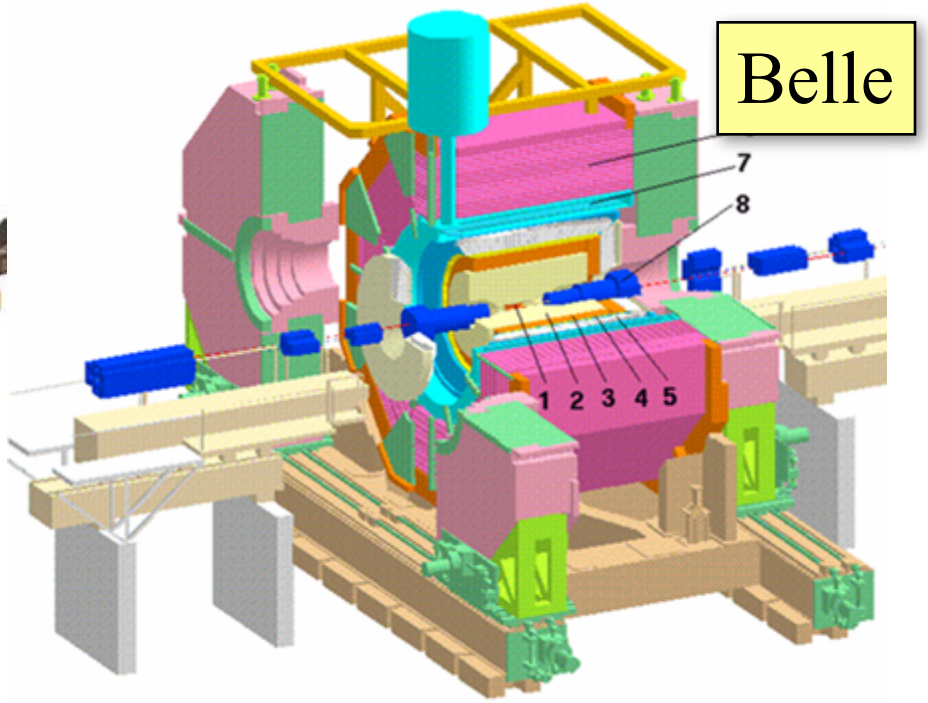
- Collide e^+ and e^- with $E(e^+) \neq E(e^-)$
  - PEP-II: 9 GeV e^- vs. 3.1 GeV e^+ → $\beta\gamma = 0.56$

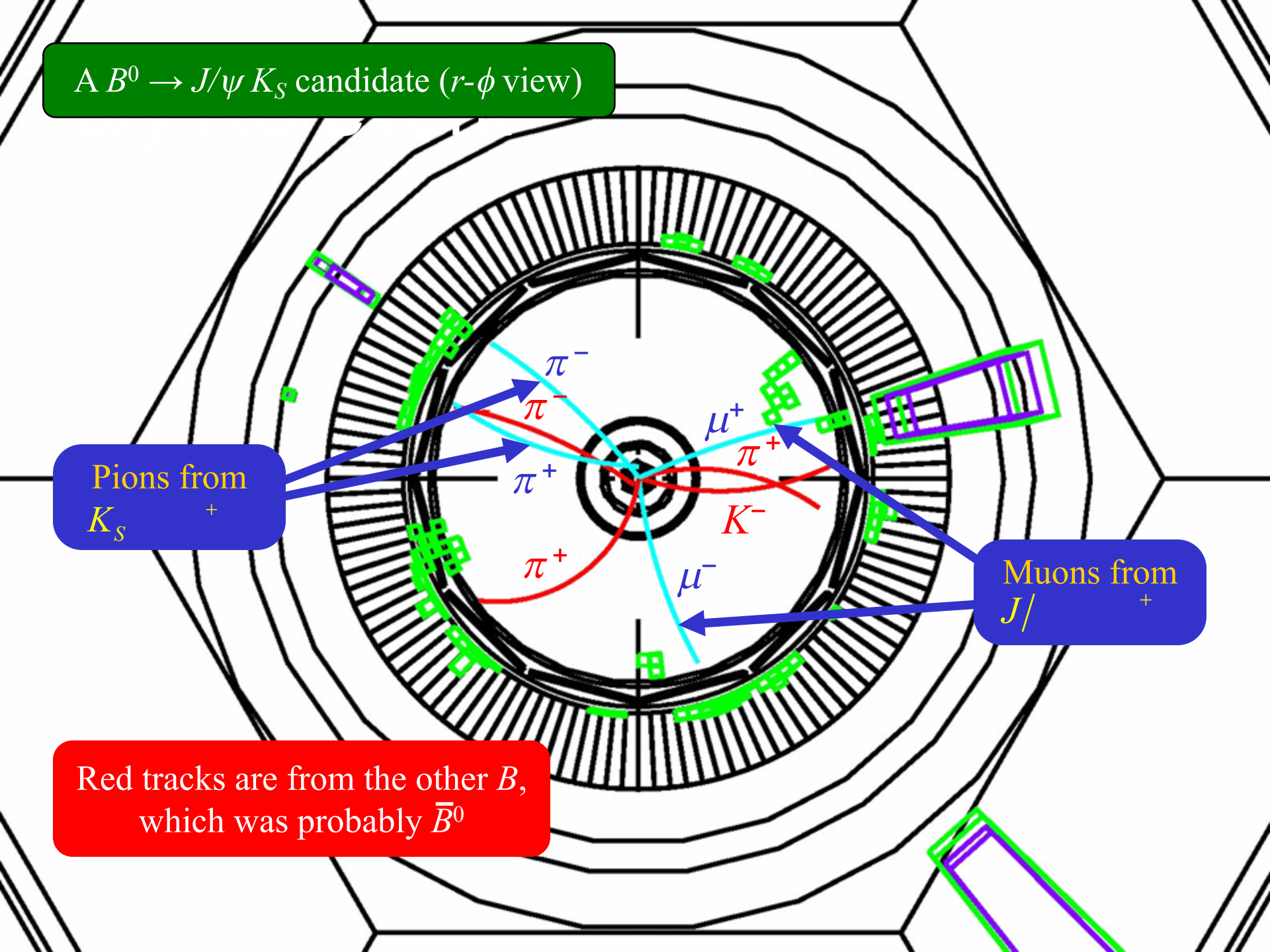


Detectors: *BABAR* and Belle

- Layers of particle detectors surround the collision point
  - We reconstruct how the *B* mesons decayed from their decay products





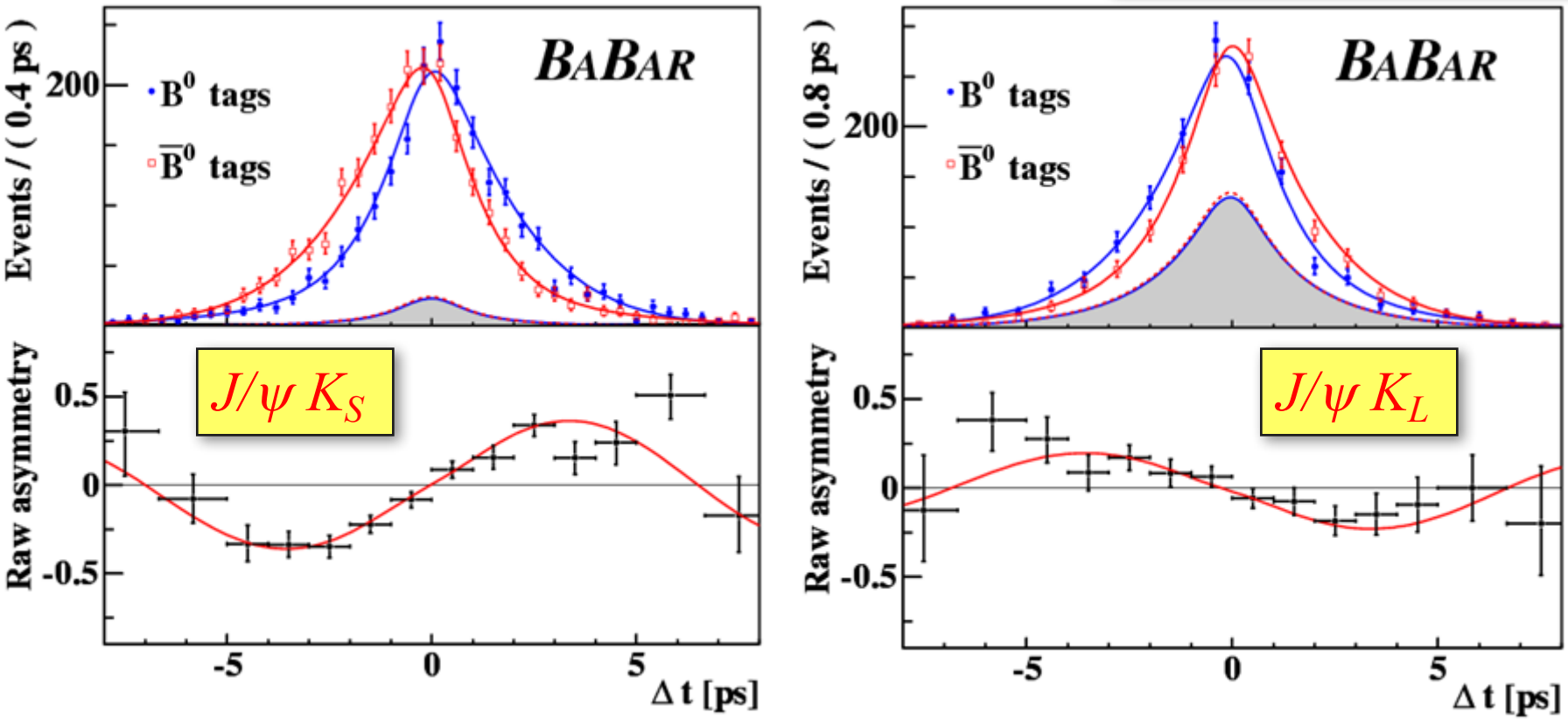

A $B^0 \rightarrow J/\psi\, K_S$ candidate (r-ϕ view)
π^-
π^-
μ^+
π^+
π^+
K^-
π^+
μ^-
Pions from
K_S
+
Muons from
$J/$
+
Red tracks are from the other B,
which was probably $\bar{B}^0$

CPV in the Golden Channel

- *BABAR* measured in $B^0 \to J/\psi + K_S$ and related decays

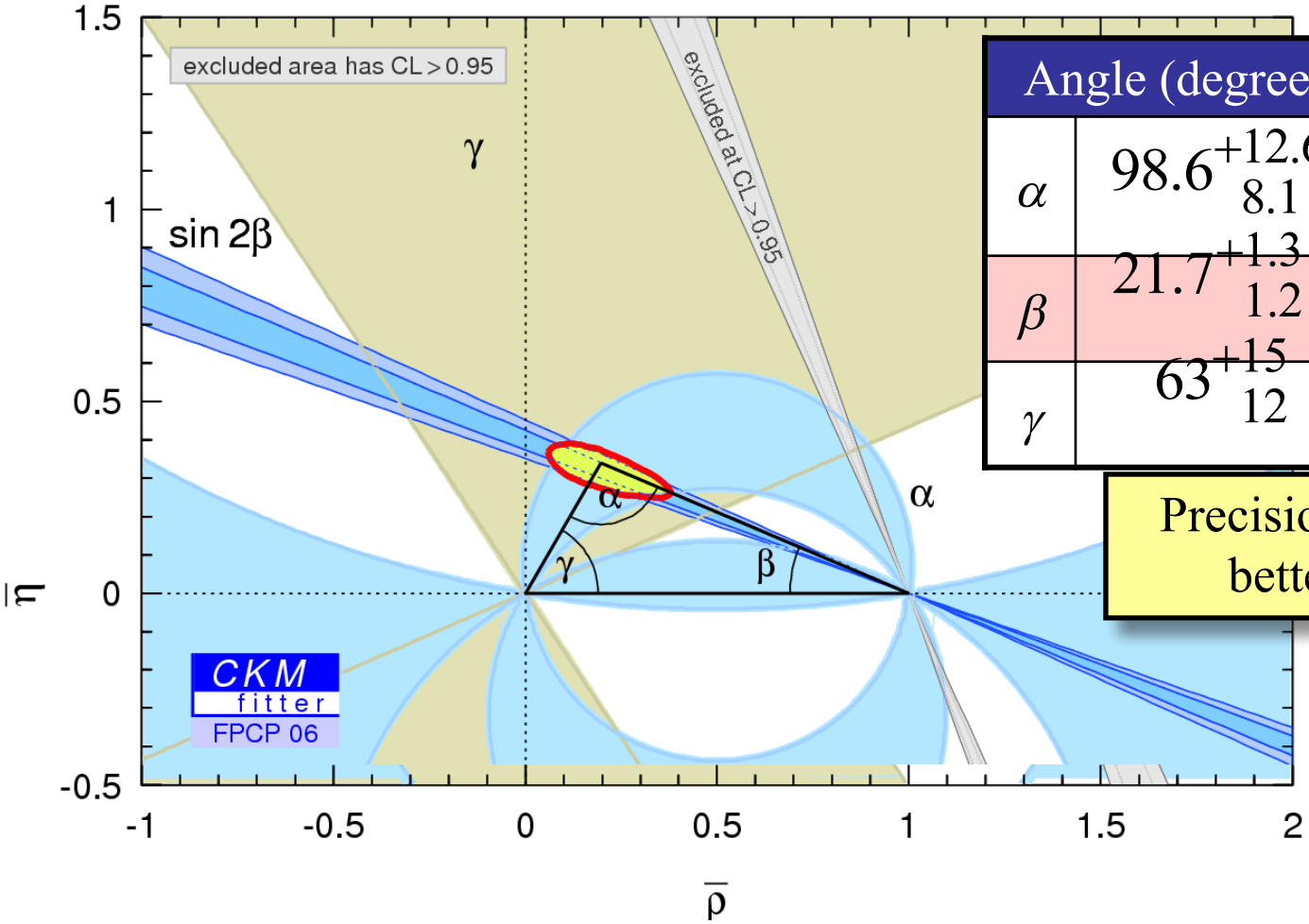
$\sin 2 \quad = 0.722 \pm 0.040(\text{stat.}) \pm 0.023(\text{syst.})$

227 million $B\bar{B}$ events



Three angles of the UT

- *CP* violation measurements at the *B* Factories give



Angle (degree)		Decay channels
α	$98.6^{+12.6}_{8.1}$	$B^0 \to \pi\pi, \rho\pi, \rho\rho$
β	$21.7^{+1.3}_{1.2}$	$B^0 \to (cc)K^0$
γ	63^{+15}_{12}	$B^0 \to D^{(*)}K^{(*)}$

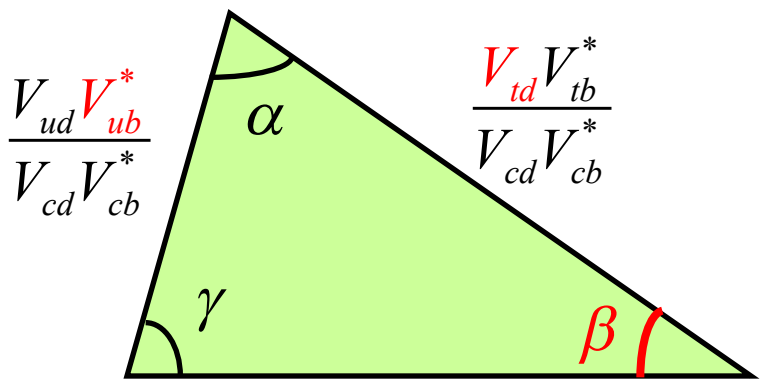
Precision of β is 10 times better than α and γ

CKM precision tests

- Measured angles agree with what we knew before 1999

  The CKM mechanism is responsible for the bulk of the *CP* violation in the quark sector

  - But is it *all*?
- We look for small deviation from the CKM-only hypothesis by using the precise measurement of angle β as the reference

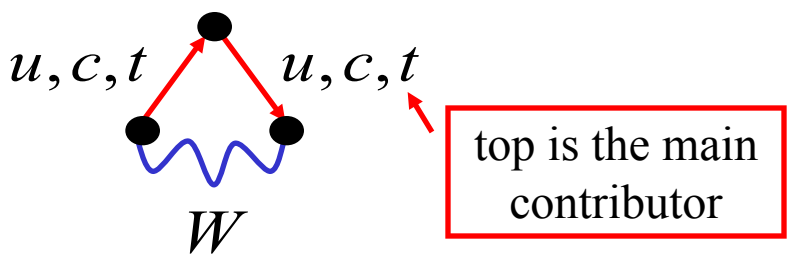


Next steps

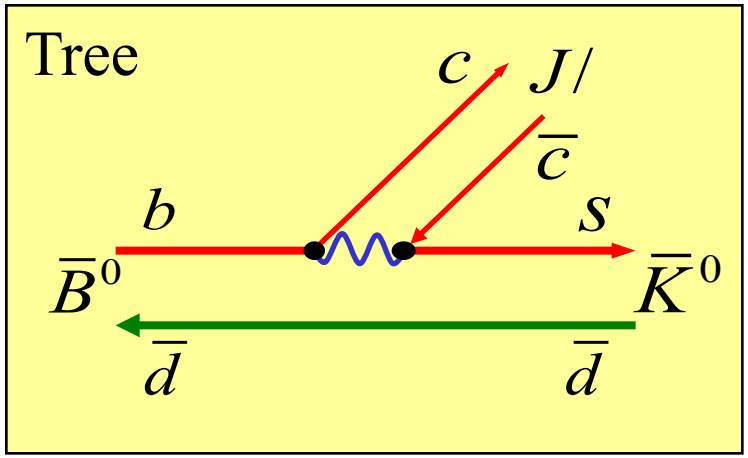
- Measure β with different methods that have different sensitivity to New Physics
- Measure the sides

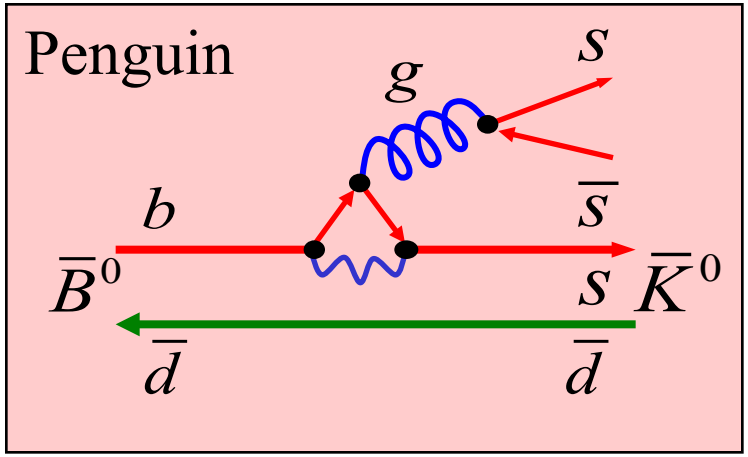
Angle β from penguin decays

- The Golden mode is $b \quad c\bar{c}s$
- Consider a different decay e.g., $b \quad s\bar{s}s$
  - b cannot decay directly to s
  - The main diagram has a loop



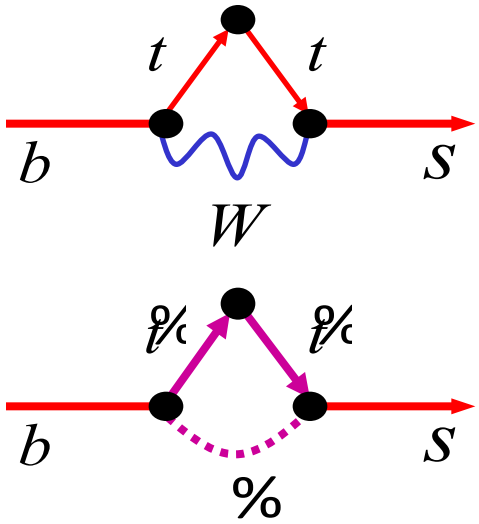
  - The phase from the CKM matrix is identical to the Golden Mode
- We can measure angle β in e.g. $B^0 \to \phi + K_S$





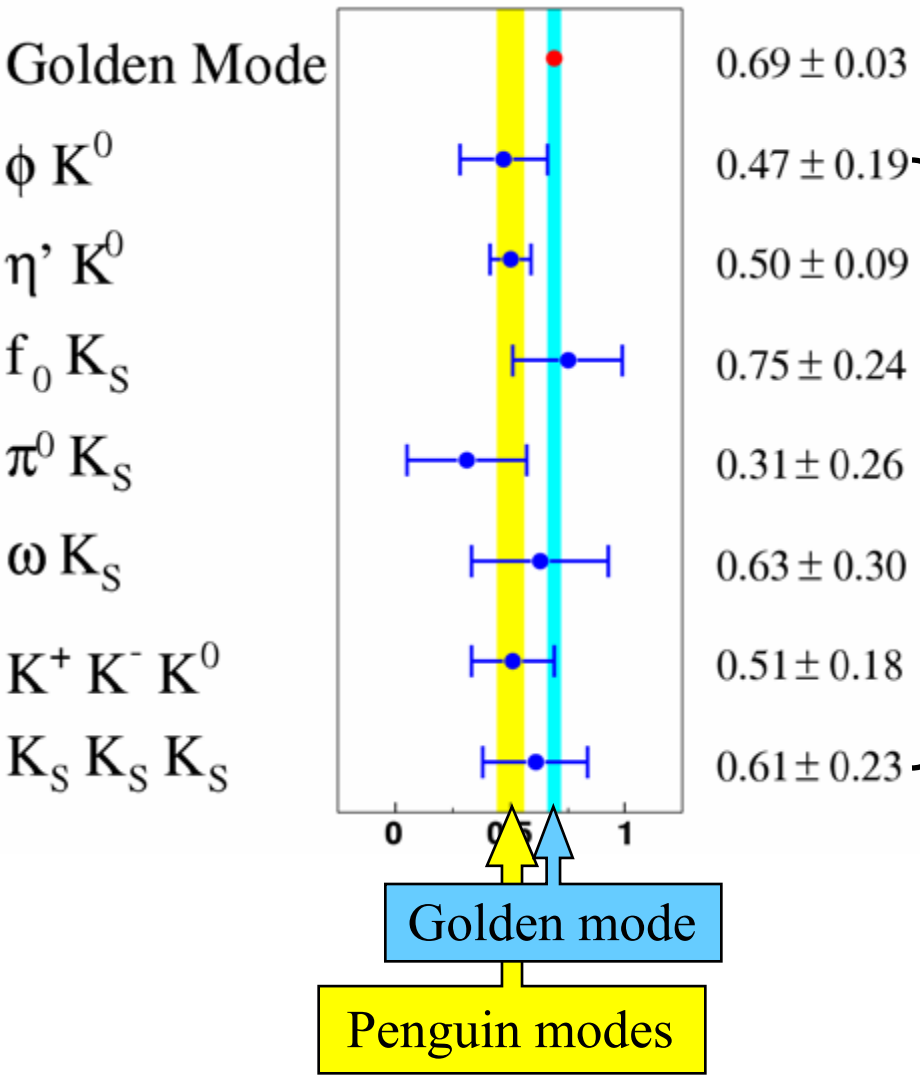
New Physics in the loop

- The loop is entirely virtual
  - W and t are much heavier than b
  - It could be made of heavier particles unknown to us
- Most New Physics scenarios predict multiple new particles in 100-1000 GeV
  - Lightest ones close to m_{top} = 174 GeV
  - Their effect on the loop can be as big as the SM loop
  - Their complex phases are generally different



Comparing penguins with trees is a sensitive probe for New Physics

Strange hints



- Measured *CP* asymmetries show a suspicious trend

$\sin 2 \quad (\text{penguin}) < \sin 2 \quad (\text{tree})$

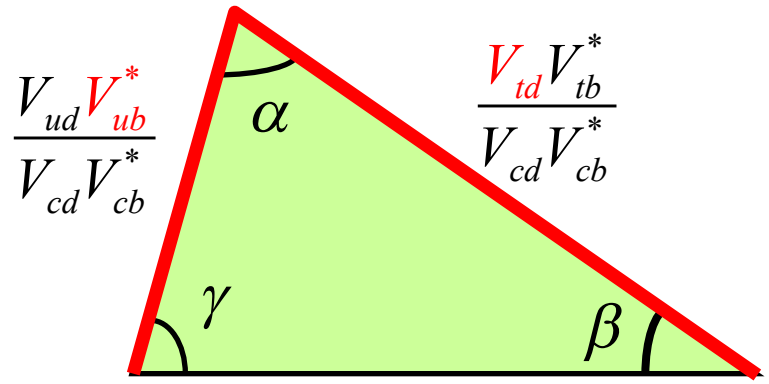
Penguin decays

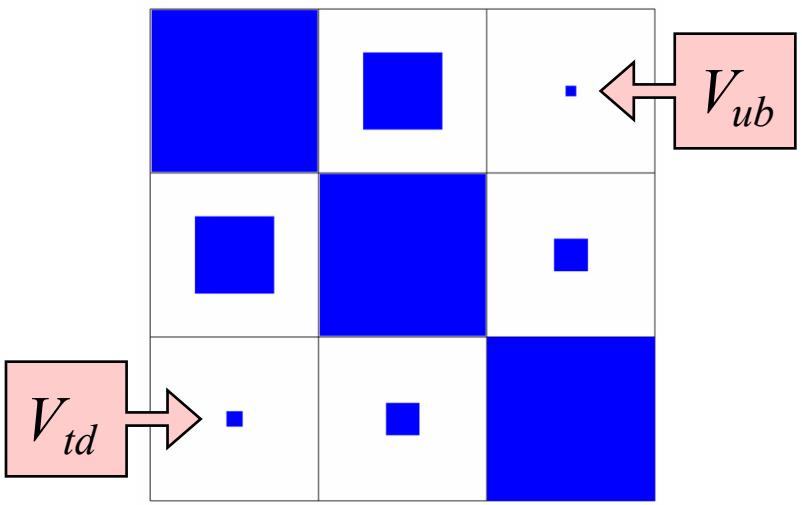
- Naive average of penguins give $\sin 2\beta = 0.50 \pm 0.06$
- Marginal consistency from the Golden Mode (2.6σ deviation)

Need more data!

The sides

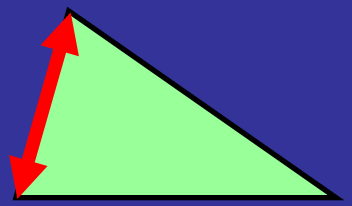
- To measure the lengths of the two sides, we must measure $|V_{ub}| \approx 0.004$ and $|V_{td}| \approx 0.008$
  - The smallest elements – not easy!



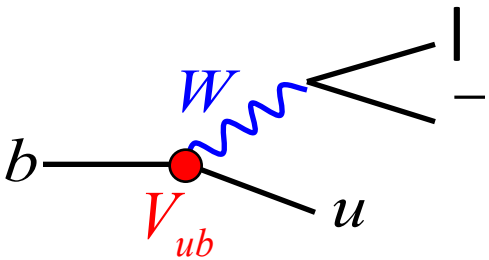


- Main difficulty: Controlling theoretical errors due to hadronic physics
  - Collaboration between theory and experiment plays key role

$|V_{ub}|$ – the left side

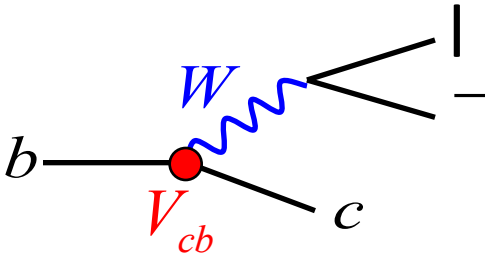


- $|V_{ub}|$ determines the rate of the $b \to u$ transition
  - Measure the rate of $b \to u\ell\nu$ decay ($\ell = e$ or μ)



$$(b \quad u\ell \quad) = \frac{G_F^2}{192 \quad ^2} |V_{ub}|^2 m_b^5$$

  - The problem: $b \to c\ell\nu$ decay is much faster

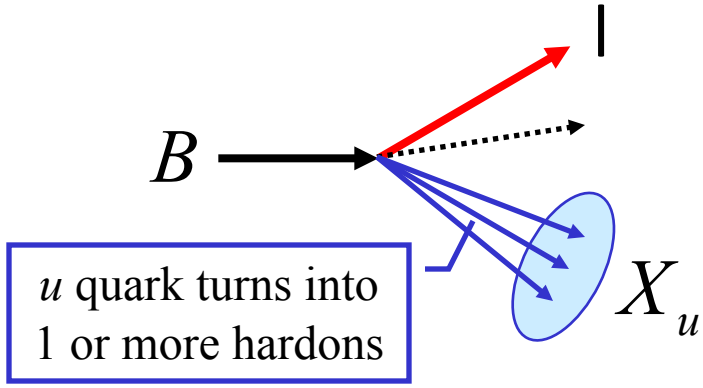


$$\frac{(b \quad u\ell \quad)}{(b \quad c\ell \quad)} \quad \frac{|V_{ub}|^2}{|V_{cb}|^2} \quad \frac{1}{50}$$

  - Can we overcome a 50× larger background?

Detecting $b \to u\ell\nu$

- Use $m_u << m_c$ → difference in kinematics

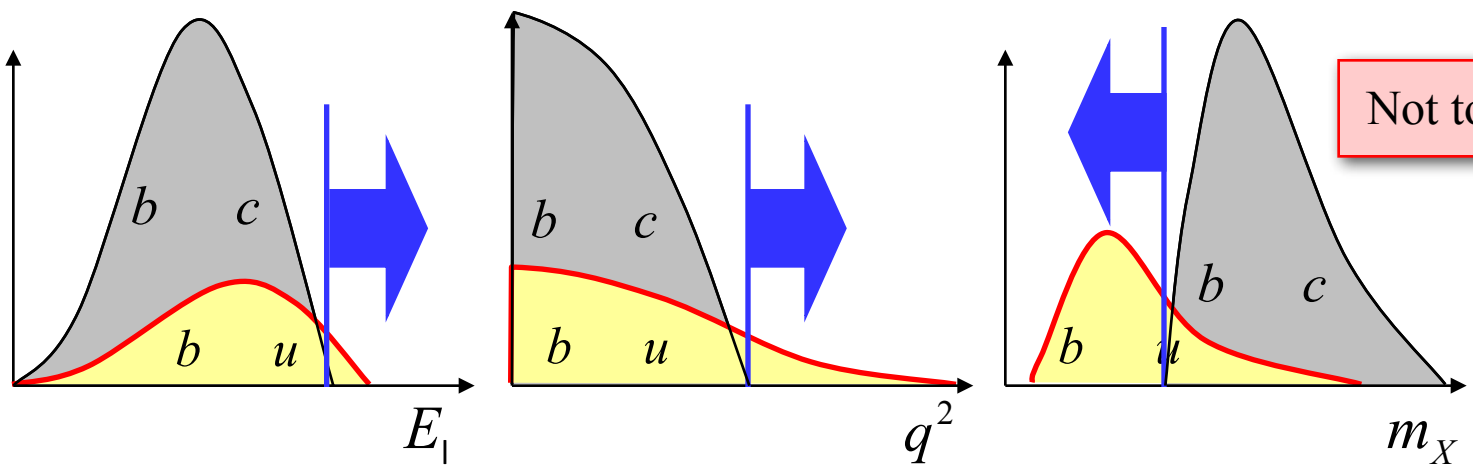


E_ℓ = lepton energy

q^2 = lepton-neutrino mass squared

m_X = hadron system mass

- Signal events have smaller m_X → Larger E_ℓ and q^2



Not to scale!

Figuring out what we see

- Cut away $b \to c\ell\nu$ → Lose a part of the $b \to u\ell\nu$ signal
  - We measure $(B \quad X_u l \quad) \cdot f_C = |V_{ub}|^2 \quad C$

Total $b \to u\ell\nu$ rate

Fraction of the signal that pass the cut

Cut-dependent constant predicted by theory

- Predicting f_C requires the knowledge of the b quark's motion inside the B meson ➔ Theoretical uncertainty
  - Theoretical error on $|V_{ub}|$ was ~15% in 2003
- Winter 2006:

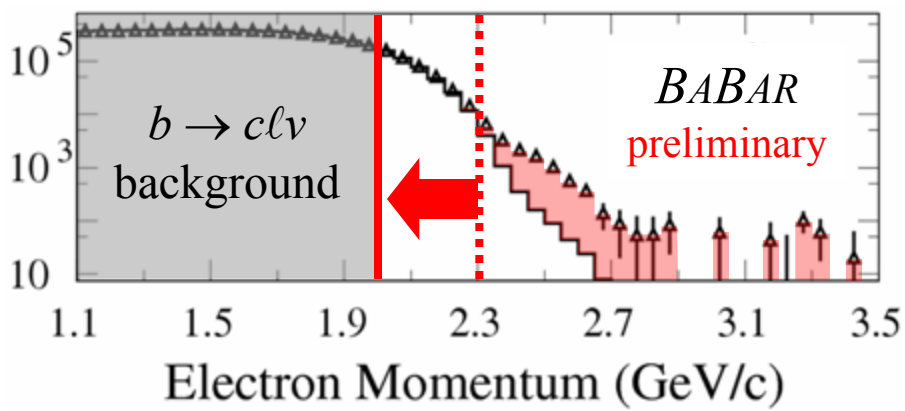
$$V_{ub}/V_{ub} = (3.5_{\text{expt}} \quad 2.8_{\text{model}} \quad 4.1_{\text{SF}} \quad 4.2_{\text{theory}})\% = 7.4\%$$

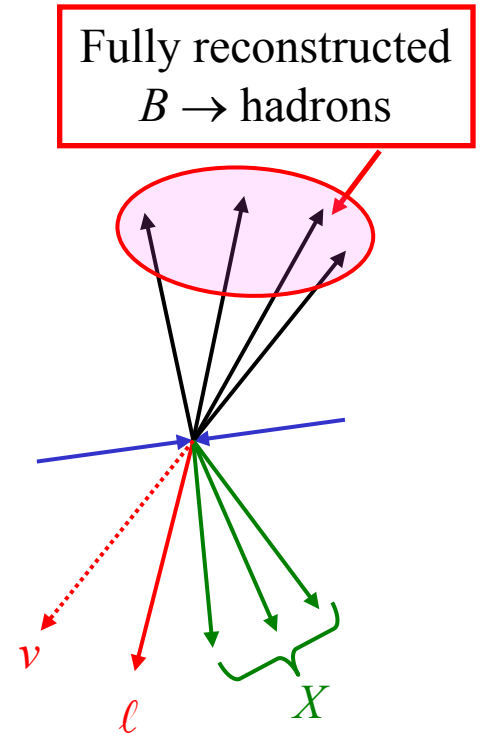
HFAG Moriond 2006 average

  - What happened in the last 2+1/2 years?

Progress since 2003

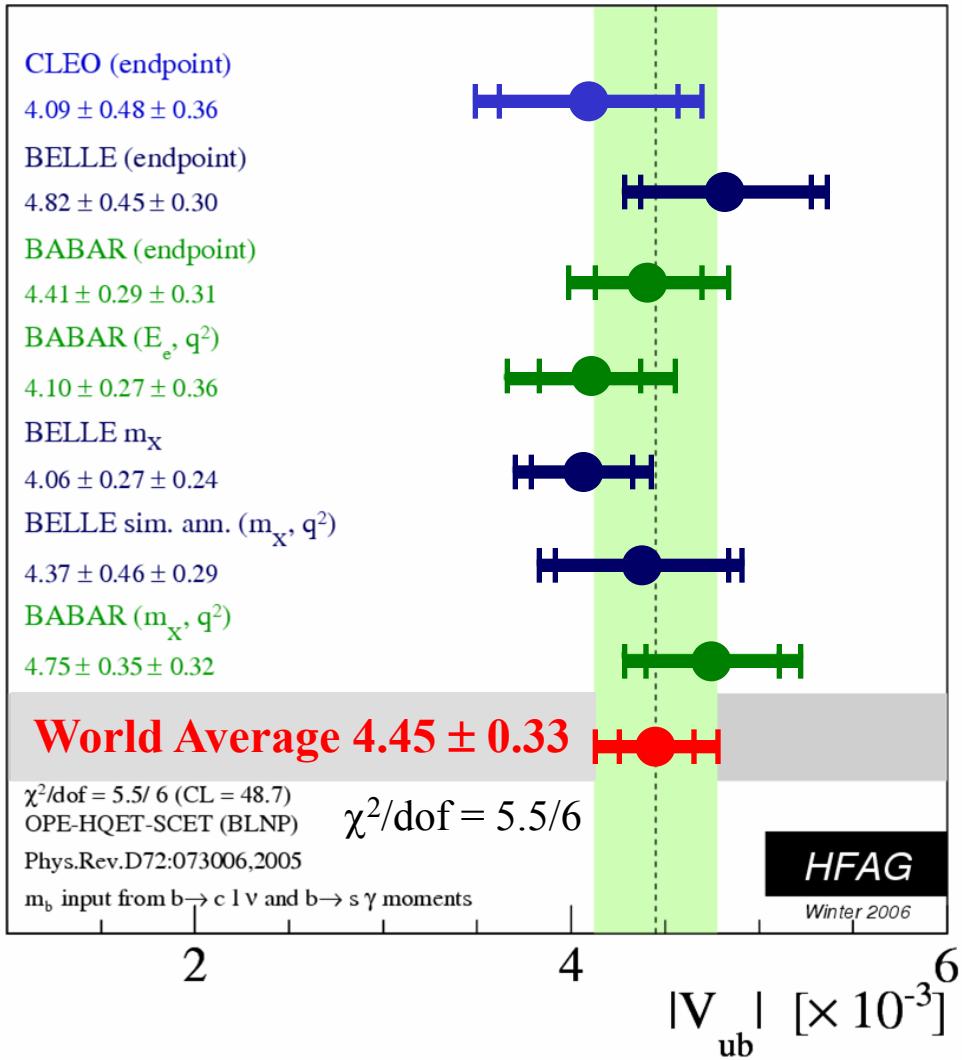
- Experiments combine E_ℓ, q^2, m_X to maximize f_C
  - Recoil-B technique improves precisions
  - Loosen cuts by understanding background better



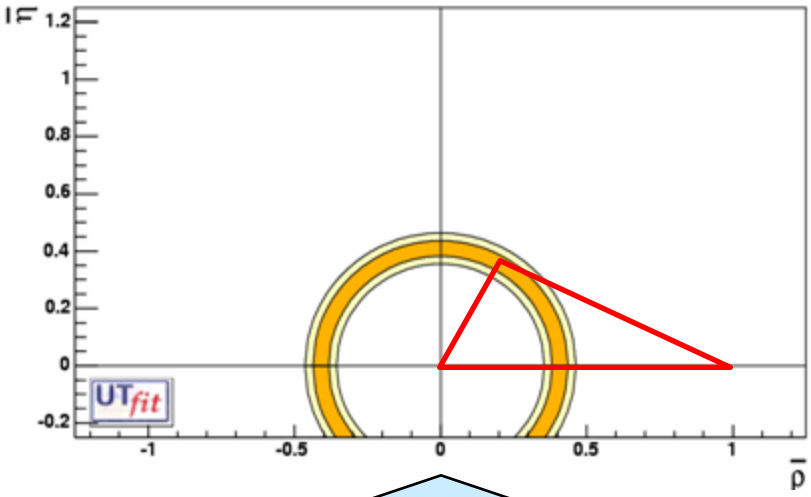


- Theorists understand the b-quark motion better
  - Use information from $b \to s\gamma$ and $b \to c\ell\nu$ decays
  - Theory error has shrunk from ~15% to ~4% in the process

Status of $|V_{ub}|$

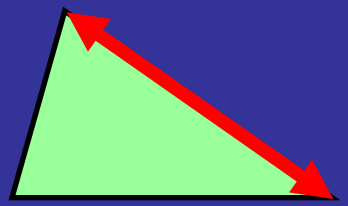


- $|V_{ub}|$ determined to ±7.4%
  - c.f. $\sin 2\beta$ is ±4.7%



Measures the length of the left side of the UT

$|V_{td}|$ – the right side

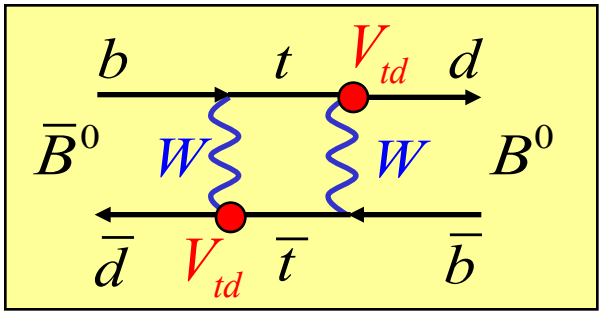


- Why can't we just measure the $t \to d$ decay rates?
  - Top quarks are hard to make
  - $(t \quad d)/\ (t \quad b) = V_{td}^2 / V_{tb}^2 < 10^{\ 4}$
- Must use loop processes where $b \to t \to d$
  - Best known example: B^0-$\bar{B}^0$ mixing combined with B_s^0-$\bar{B}_s^0$ mixing

B^0 oscillation frequency → m_d

B_s oscillation frequency → m_s

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



  - $\Delta m_d = (0.509 \pm 0.004)\ \text{ps}^{-1}$
  - News from the Tevatron:

$m_s = 17.33^{+0.42}_{0.21} \pm 0.07$ CDF

$17 < \quad m_s < 21\ (90\%\text{CL})$ DØ

$$\frac{|V_{td}|}{|V_{ts}|} = 0.208^{+0.008}_{0.007}$$

Radiative penguin decays

- Look for a different loop that does $b \to t \to d$
  - Radiative-penguin decays

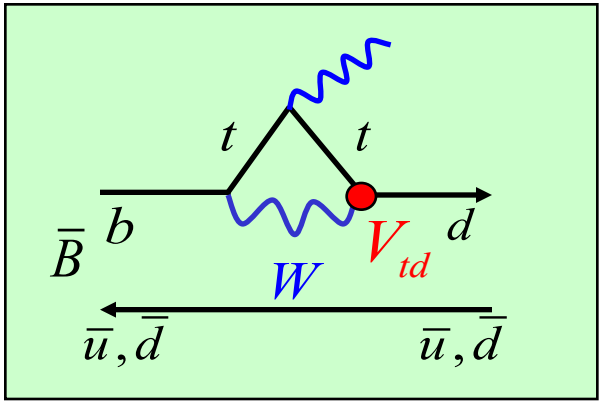
$$\frac{(B \qquad)}{(B \quad K^* \ )} \quad \frac{|V_{td}|^2}{|V_{ts}|^2}$$

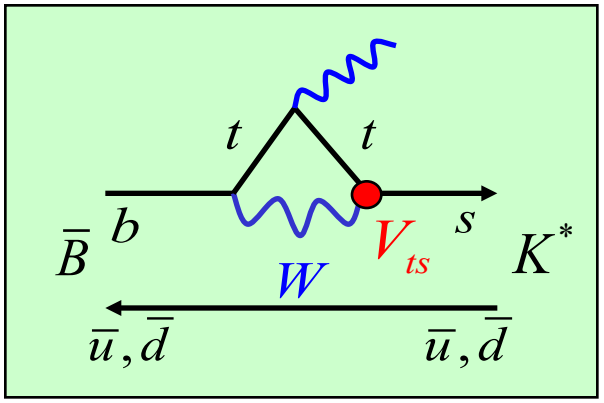
  - $\mathrm{B}(B \quad K^* \ ) = (4.0 \pm 0.2) \cdot 10^{\ 5}$
  - Latest results from the B Factories:

	$\mathrm{B}(B \to \rho\gamma)$
BABAR	$(0.6 \pm 0.3) \times 10^{-6}$
Belle	$(1.3 \pm 0.3) \times 10^{-6}$
Average	$(1$ 10^{-6}

$$|V_{td}/V_{ts}| = 0.18 \pm 0.03$$

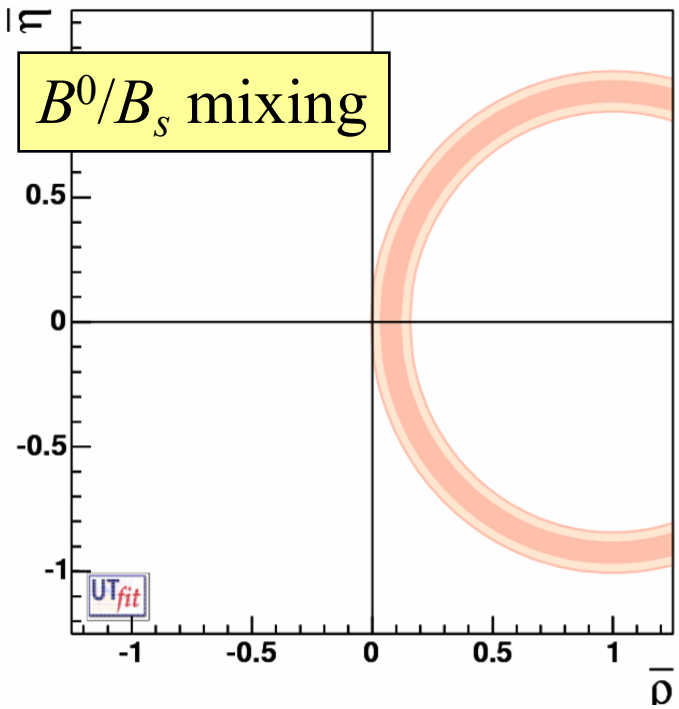
  - Tra

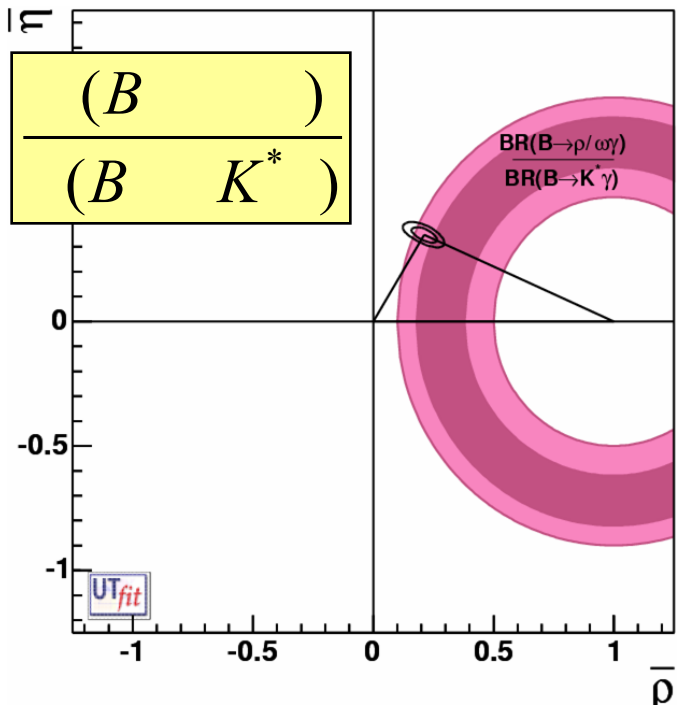




Impact on the UT

- We can now constrain the right side of the UT

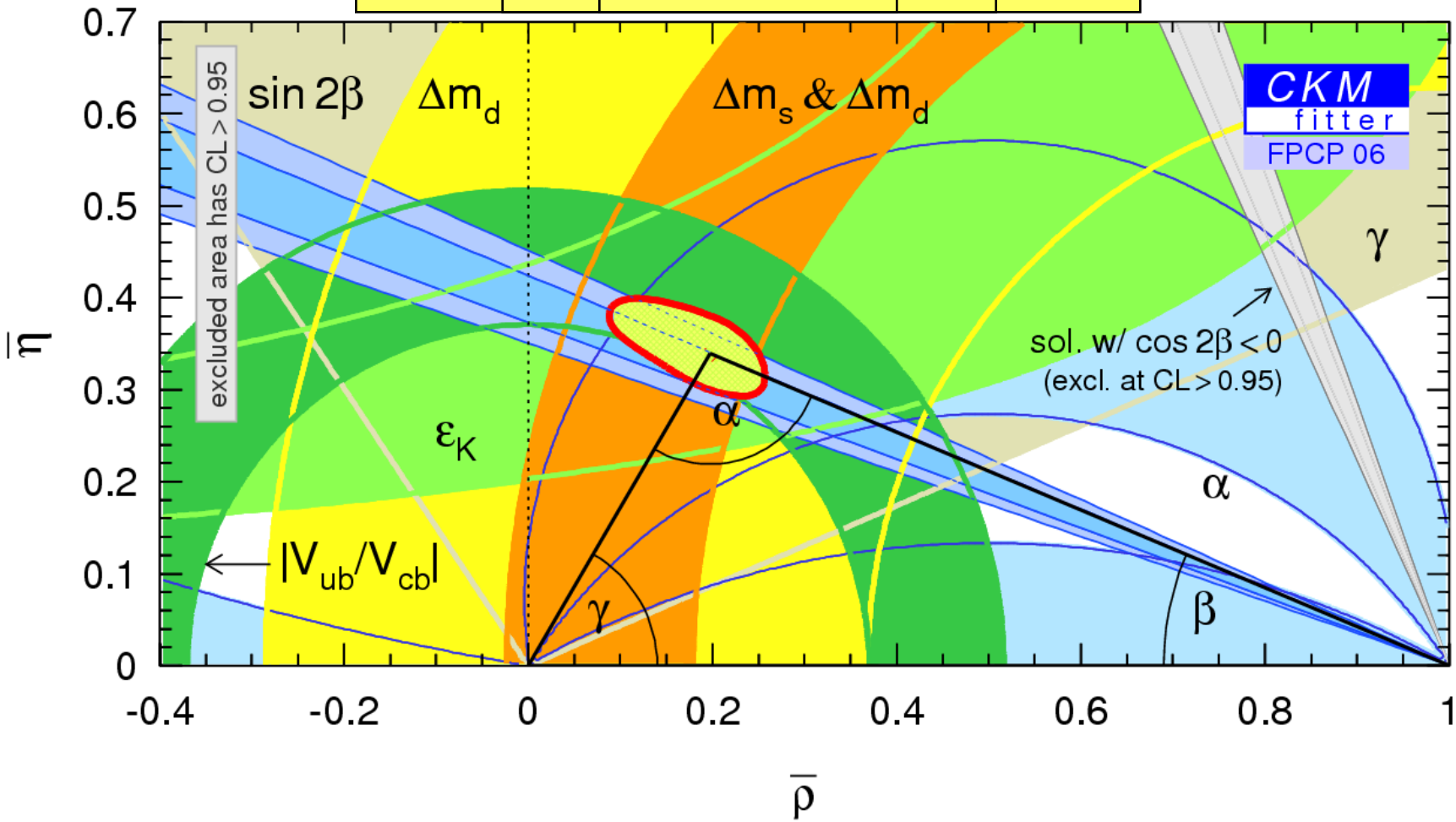




- Mixing measurements pinned down $|V_{td}/V_{ts}|$ as precisely as $\sin 2\beta$
- $B \to \rho\gamma$ provides a crosscheck, with sensitivity to New Physics

The UT today

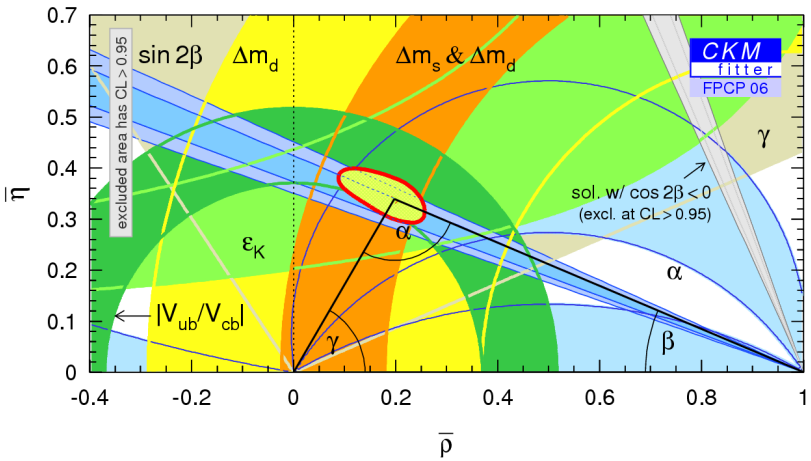
Angl Sid Combined ays etries

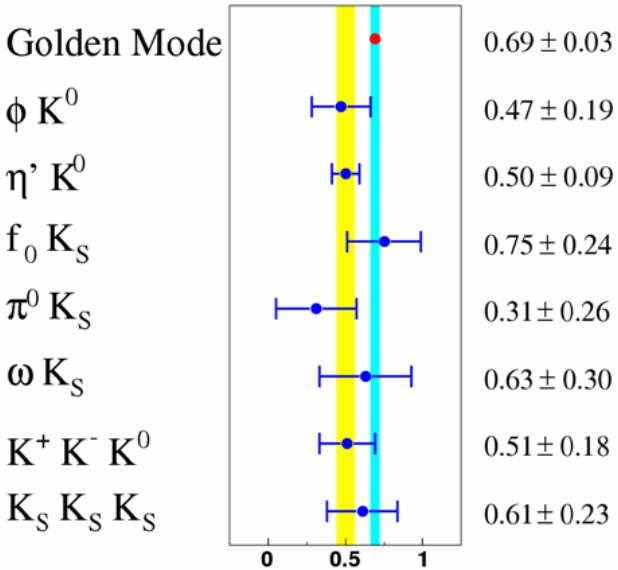


The UT today

- The *B* Factories have dramatically improved our knowledge of the CKM matrix
  - All angles and sides measured with multiple techniques
  - New era of precision CKM measurements in search of NP
- The Standard Model is alive
  - Some deviations observed ➔ require further attention

New Physics seems to be hiding quite skillfully

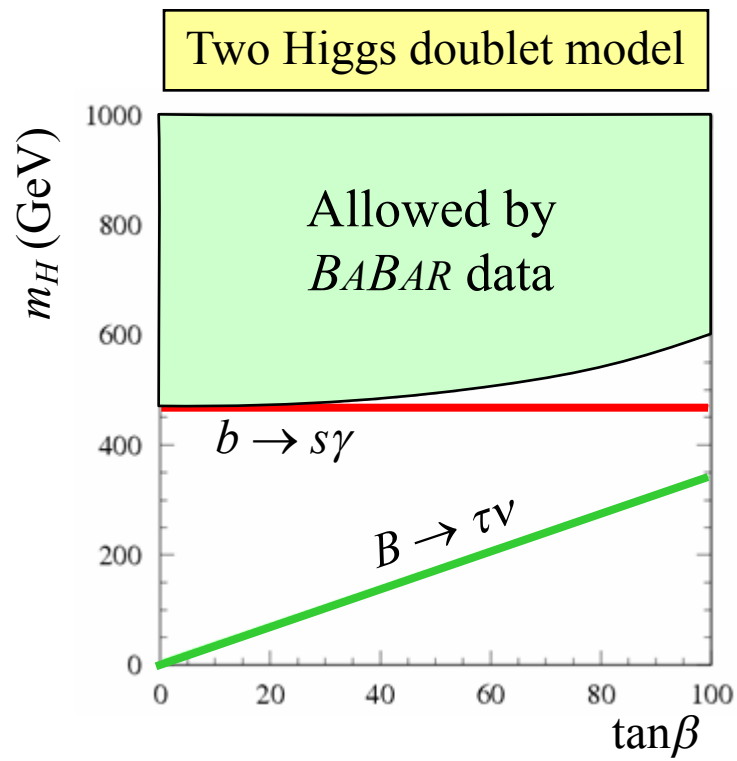




Constraining New Physics

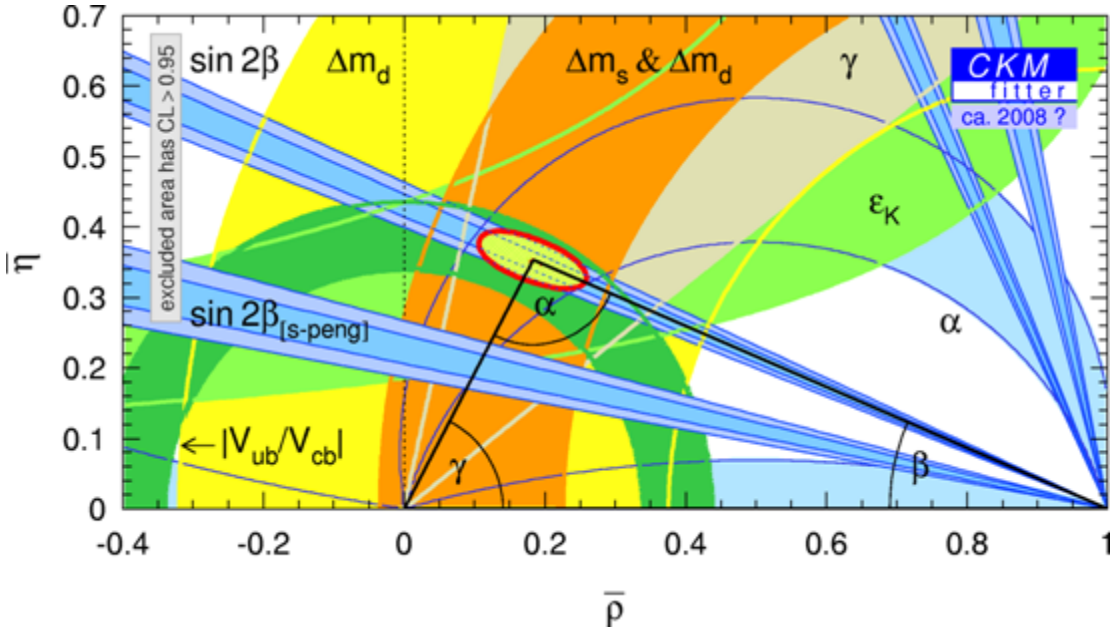
- New Physics at ~TeV scale should affect low-energy physics
  - Effects may be subtle, but we have precision
  - Even absence of significant effects helps to identify NP
- In addition to the UT, we explore:
  - rare B decays into $X_s\gamma$, $X_s\ell^+\ell^-$, $\tau\nu$
  - D^0 mixing and rare D decays
  - lepton-number violating decays

Precision measurements at the B Factories place strong constraints on the nature of New Physics



Outlook

- The *B* Factories will pursue increasingly precise measurements of the UT and other observables over the next few years
- Will the SM hold up?
  - Who knows?
- At the same time, we are setting a tight web of constraints on what New Physics can or cannot be



What the *B* Factories achieve in the coming years will provide a foundation for future New Physics discoveries