Lecture 3

The Violation of Symmetry between Matter and Antimatter

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Lecture Themes

I. Introduction
- Antimatter
- Discrete Symmetries

II. The Phenomena of *CP* Violation
- Electric and weak dipole moments
- The strong *CP* problem
- The discovery of *CP* violation in the kaon system

III. *CP* Violation in the Standard Model
- The CKM matrix and the Unitarity Triangle
- *B* Factories
- *CP* violation in the *B*-meson system and a global CKM fit
- The Future at the LHC

IV. *CP* Violation and the Genesis of a Matter World
- Baryogenesis and *CP* violation
- Models for Baryogenesis

CP Violation in the Standard Model

We have learned that different types of *CP* violation have been observed … we will later see that there is also *CP* violation in meson systems other than kaons.

All these phenomena can be described by a *unique* parameter in the Standard Model !

The Standard Model

- The Standard Model forces and their gauge bosons:

Electromagnetic interaction	⇔	Photons (γ)
Strong interaction (QCD)	⇔	Gluons (g)
Weak interaction	⇔	Neutral (Z^0) and **charged ($W^{\pm}$)**

- Left-handed quarks are fermions organized in *doublets:*

up-type quarks (U_i):
down-type quarks (D_i):

$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix} \begin{matrix} Q = +2/3 \\ Q = -1/3 \end{matrix}$$

…and similar for the leptons.

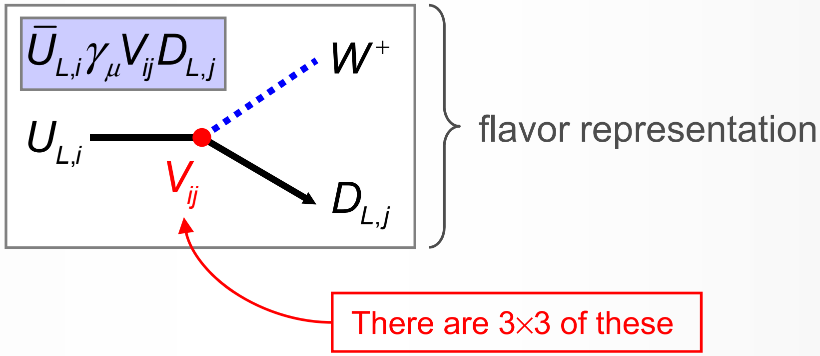
- The charged weak current is of $V-A$ type:

$$\bar{U}_i \gamma^{\mu} \underbrace{(1-\gamma_5)} D_i = \bar{U}_{L,i} \gamma^{\mu} D_{L,i}$$

The operator projects upon left-handed particles (and right-handed antiparticles) – which means that the $W^{\pm}$ boson is *blind* to the right-handed particles (and left-handed antiparticles)

Three-Generation Quark Mixing

- The charged weak current generates **transitions between generations**, i.e., the flavoured quarks are not the same as the physical quarks:



- *Again*: since mass and flavor eigenstates are not the same → quark mixing:

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

Quark mixing would simplify (= reduced parameter space) if some of the quarks had equal masses and would hence not be distinguishable !

Cabibbo-Kobayashi-Maskawa (CKM) matrix – 1973 (KM)

CP Violation in the Standard Model

- What does *CP* or *T* conjugation with the Hamiltonian *H* ?
  - Simple exercise:

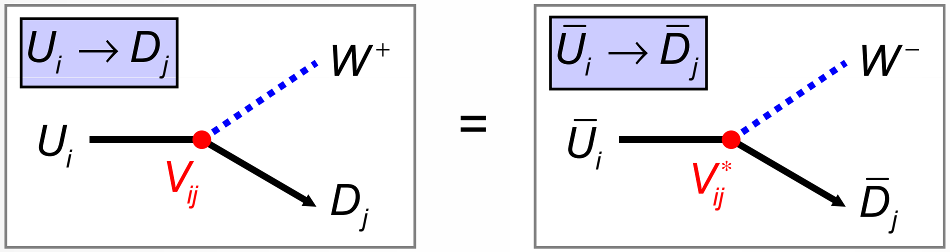
Recall:
$P\hat{x} = -\hat{x},\ P\hat{p} = -\hat{p}$
$T\hat{x} = \hat{x},\ T\hat{p} = -\hat{p}$

$$[\hat{x},\hat{p}] = i\hbar \Rightarrow \begin{cases} P[\hat{x},\hat{p}]P^{-1} = PiP^{-1}\hbar \overset{P\text{-invariance}}{\overbrace{\Rightarrow}} PiP^{-1} = i \\ T[\hat{x},\hat{p}]T^{-1} = TiT^{-1}\hbar \overset{T\text{-invariance}}{\overbrace{\Rightarrow}} TiT^{-1} = -i \end{cases}$$

→ The *T* (and *CP*) operations are **anti-unitary**, which is **complex conjugation** !

Since $H = H(V_{ij})$, complex V_{ij} would generate $[T,H] \neq 0$ → *CP* violation

- *CP* conservation is: $A(U_i \to D_j) = \bar{A}(\bar{U}_i \to \bar{D}_j)$ (up to unphysical phase)



only, if: $V_{ij} = V_{ij}^*$

The Quark-Mixing Matrix

- The $|V_{ij}|^2$ are transition probabilities and hence the matrix must be unitary
  - For example, a *t* quark can decay into a *d*, *s*, or *b* quark and nothing else; thus, the sum of the decay probabilities into these quarks must be one:

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

- Unitarity condition: $$VV^\dagger = 1 \quad \Leftrightarrow \quad \sum_j V_{ij} V_{jk}^* = \delta_{ik}$$

- The unitarity condition sets strong constraints on the V_{ij} , which initially has $2N^2$ unknowns (N is number of generations)

Quark-Mixing Matrices for Different Generations

- Example for $N = 1$ generation:
  - 2 Unknowns – module and phase: $|V|e^{i\phi}$
  - Unitarity determines $|V| = 1$
  - The phase is arbitrary (non-physical): $\bar{U}_L \gamma_\mu e^{i\phi} D_L \quad \rightarrow \quad \bar{U}_L \gamma_\mu D_L'$ …with same physics
  - ➡ No phase, no CPV

- Example for $N = 2$ generations:
  - 8 Unknowns – 4 moduli and 4 phases
  - Unitarity gives 4 constraints : $VV^\dagger = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$
  - For 4 quarks, we can adjust 3 relative phases
  - ➡ Only 1 parameter, a rotation (= Cabibbo) angle left: no phase → no CPV

Quark-Mixing Matrices for Different Generations

- Example for $N = 3$:
  - 18 Unknowns – 9 moduli and 9 phases
  - Unitarity gives 9 constraints
  - For 6 quarks, we can adjust 5 relative phases
  - ⟹ 4 Unknown parameters left, 3 rotation (Euler) angles and **1 phase → CPV** !

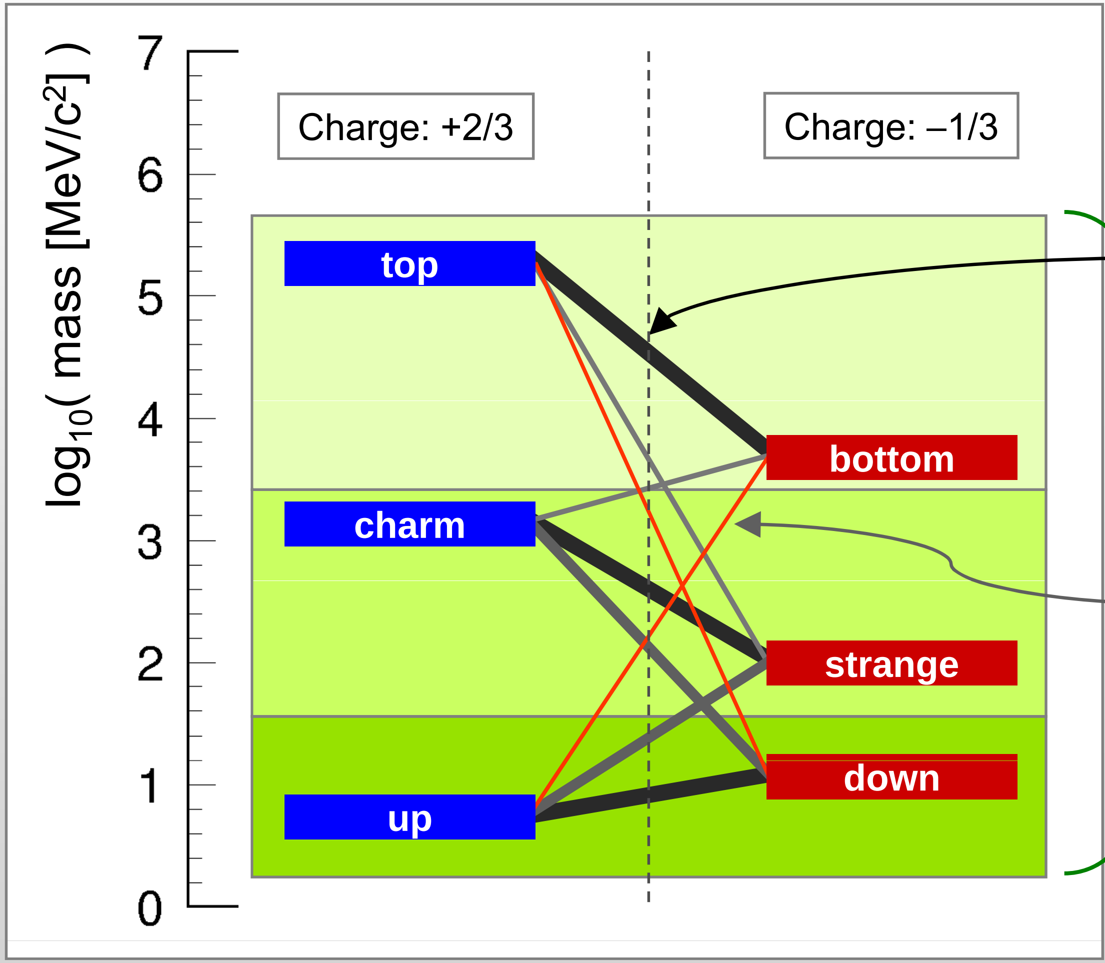
- Example for $N = 4$:
  - 32 Unknowns, 16 unitarity constraints, 7 arbitrary phases
  - ⟹ 9 Unknown parameters left, 6 rotation angles and 3 phases → lots of CPV !

- For N generations:

$$\begin{cases} \text{Number of rotation angles}: & \frac{1}{2}N(N-1) \\ \text{Number of phases}: & \frac{1}{2}(N-1)(N-2) \end{cases}$$

Quark Flavours in the Standard Model

- Quarks (as leptons) in the SM are organized in 3 generations:



Flavour-changing transition by charged weak current (boldness indicates transition probability ∝ $|V_{ij}|$)

3 Quark generations

Smallest couplings are complex → ***CP* violation**

The CKM Matrix in the Wolfenstein Parameterization

- The 3-generation CKM matrix has 4 unknowns, one of which is a phase
- Flavor-changing transitions between families are allowed, but are <u>small</u>
- We can develop the CKM matrix elements around the small flavor-changing transition between the 1st and the 2nd family (the Cabibbo mixing), denoted $\lambda \approx 0.2$:

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

- Decay-rate measurements give: $\Gamma(i \to j\bar{\ell}\nu) \propto |V_{ij}|^2 \times F^2(i \to j)$

Strong-interaction form factor (taken from theory)

$$(|V|)_{ij} = \begin{pmatrix} 0.9738 \pm 0.0003 & 0.2257 \pm 0.0021 & 0.0043 \pm 0.0003 \\ 0.230 \pm 0.011 & 0.96 \pm 0.10 & 0.0416 \pm 0.0006 \\ - & - & > 0.78^{[95\%\ \text{C.L.}]} \end{pmatrix}$$

- **How can we determine the *CP*-violating phase ?**

The CKM Matrix and the “Unitarity Triangle(s)”

- The 9 unitarity conditions of the 3×3 generations CKM matrix:

$$|V_{id}|^2 + |V_{is}|^2 + |V_{ib}|^2 = 1 \quad \forall i \in \{u,c,t\}$$

$$\sum_{j=1}^{3} V_{ij} V_{kj}^* = 0 \;, \quad \forall i \neq k \in \{1,2,3\}$$

multiply multiply multiply

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \end{pmatrix}$$

CKM-type *CP* violation is <u>always</u> a rare phenomenon:

1. Either the *CP* asymmetry is small
2. Or/and the decay rate is suppressed

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

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

$$V_{ud}V_{cd}^* + V_{us}V_{cs}^* + V_{ub}V_{cb}^* = 0$$

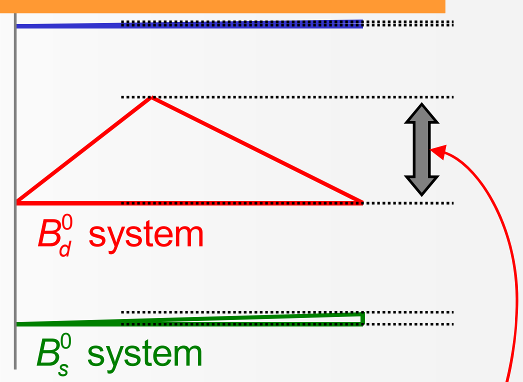
$$V_{ud}V_{td}^* + V_{us}V_{ts}^* + V_{ub}V_{tb}^* = 0$$

$$V_{cd}V_{td}^* + V_{cs}V_{ts}^* + V_{cb}V_{tb}^* = 0$$

$$O(\lambda) + O(\lambda) + O(\lambda^5) = 0$$

$$O(\lambda^3) + O(\lambda^3) + O(\lambda^3) = 0$$

$$O(\lambda^4) + O(\lambda^2) + O(\lambda^2) = 0$$



relative size of *CP*-violating effect

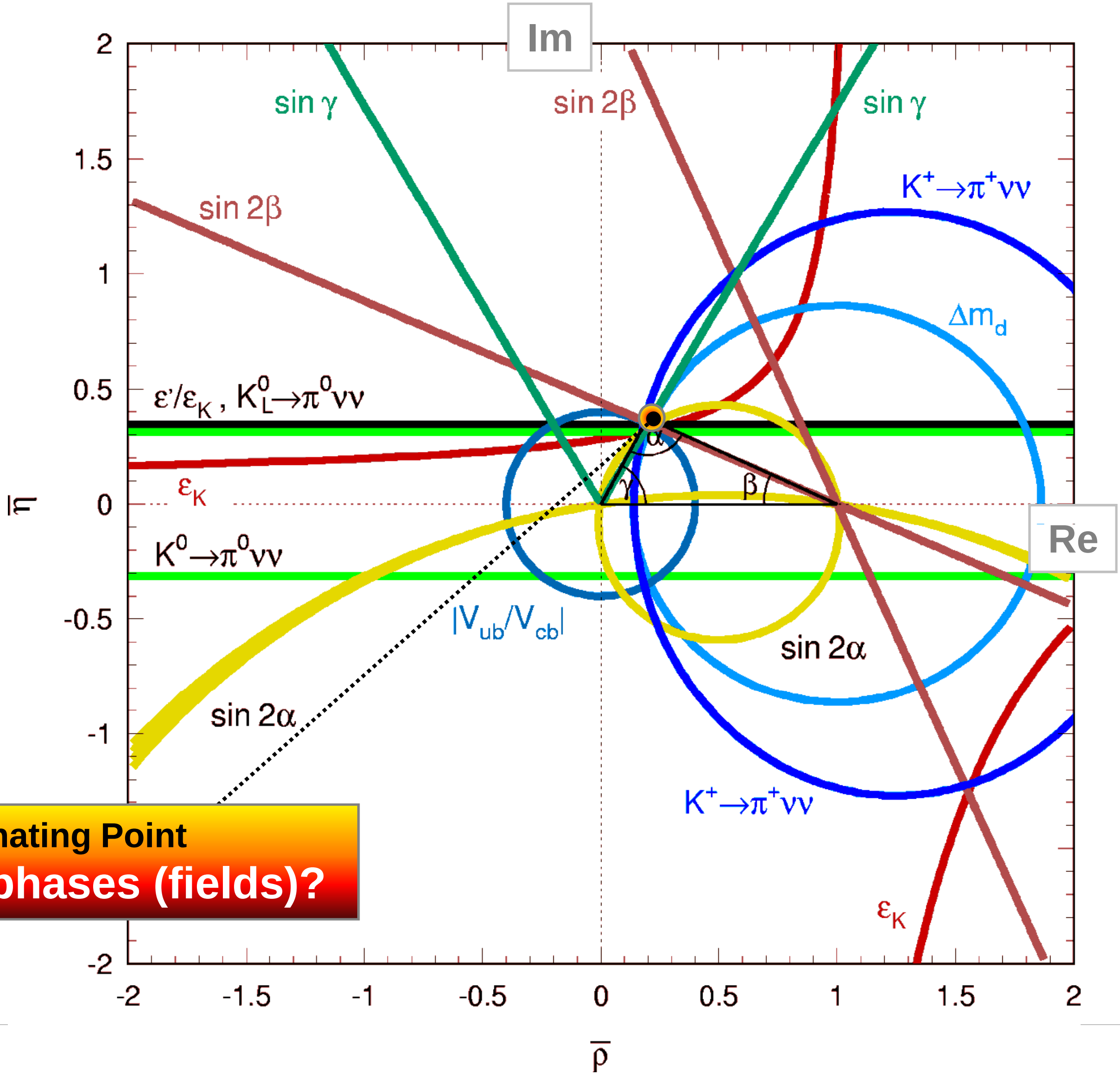
The CKM Matrix and the Unitarity Triangle

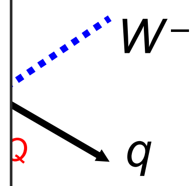
Kobaya
-Maska
1973

V_{CKI}

V_{ud}

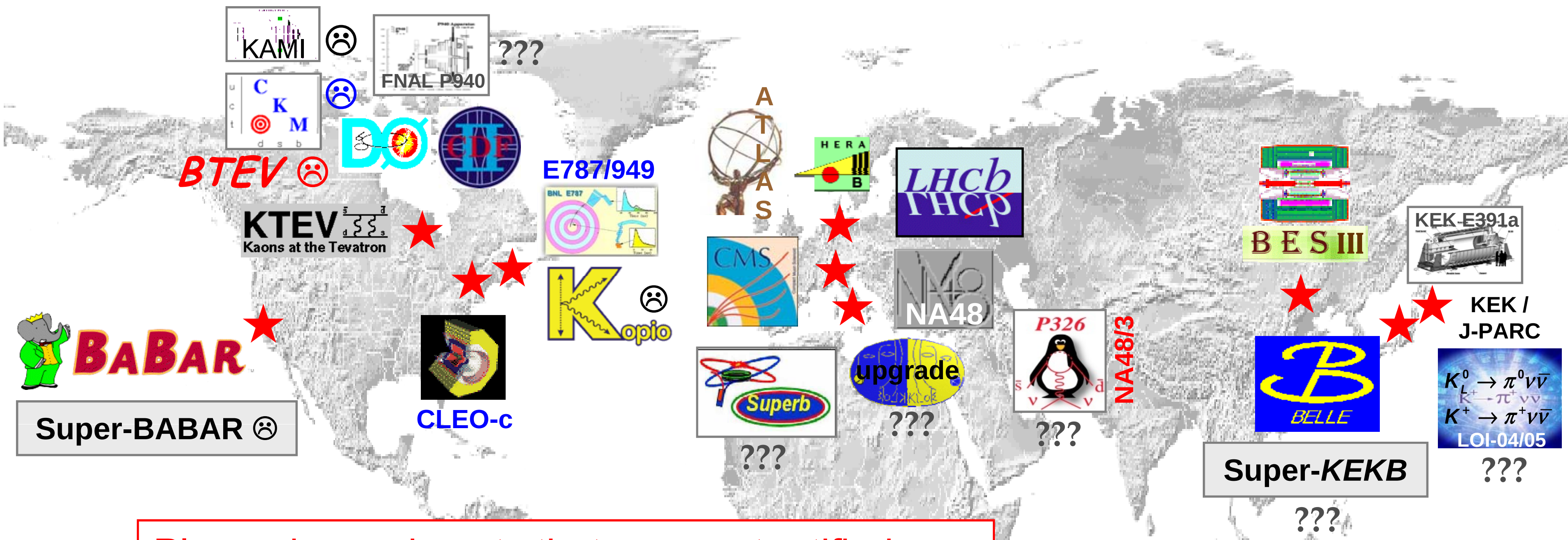
$(\propto$





Culminating Point

SM or new phases (fields)?



Planned experiments that were not ratified

Approved experiments (mostly in construction)

New proposals

Currently running or recently ended programs

CKM Physics and *CP* Violation

Worldwide Experimental Facilities

The *B*-Meson System

The study of *CP* violation, mixing and rare decays of *B* mesons allows to over-determine the Unitarity Triangle (UT)

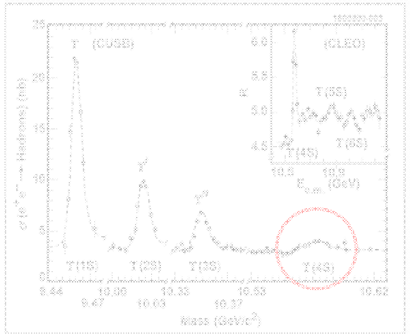
1. Relative *CP*-violating effects are expected to be large
2. Requires dedicated experiments
3. Goal: measure all three angles, α, β, γ, and the sides of the UT

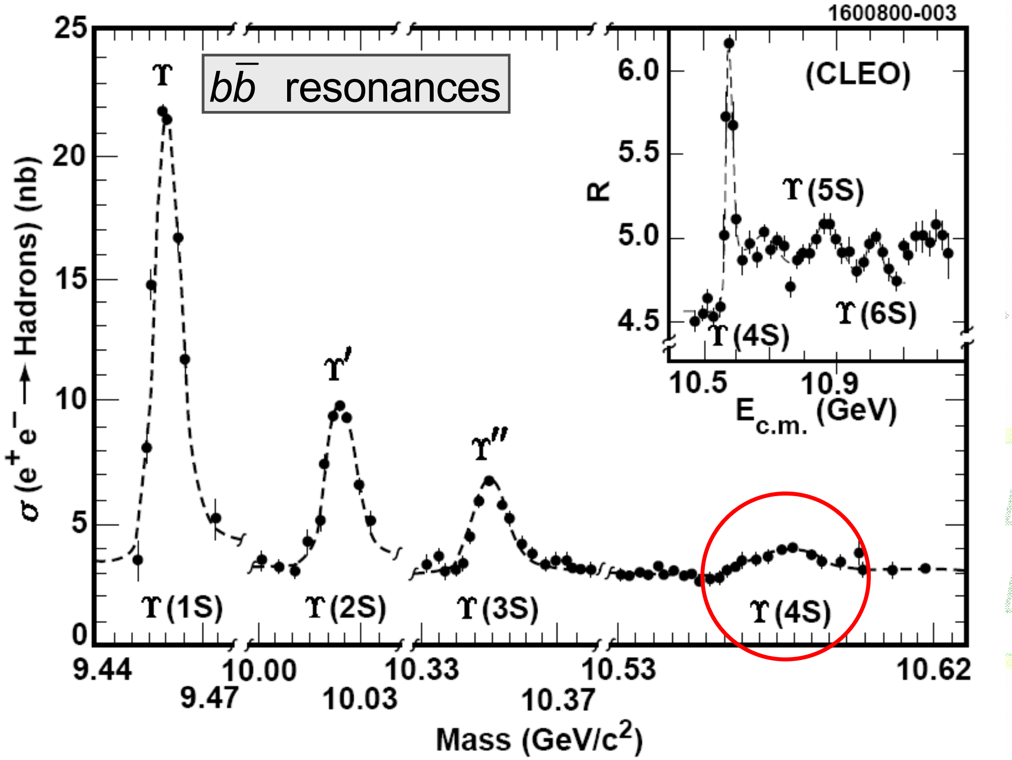
$$\alpha = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right) \qquad \beta = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right) \qquad \gamma = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

concentrate lecture on this measurement

The B_d System ($e^+e^- \to \Upsilon(4S)$ factories)

the B_d is also produced by the hadron machines





$B \to D^{(*)}K^{(*)}$

$B \to D_{K^0_S\pi^+\pi^-}K$

$B^0 \to DK^0_S, \ldots$

$B^0 \to D^*\pi(\rho)$

$K^{(*)}\gamma$

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

$B^0 \to J/\psi K^0_S, \ldots$

$B^0 \to \phi K^0_S, \ldots$

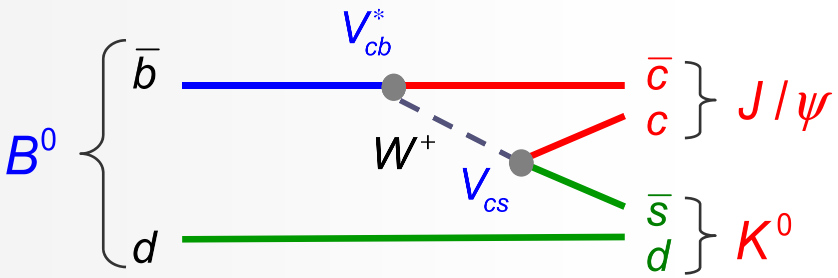
$b \to s\bar{s}s$

The Measurement of β (… or more precisely: sin2β)

We need to identify the processes that involve the CKM matrix elements that occur in the definition of β:

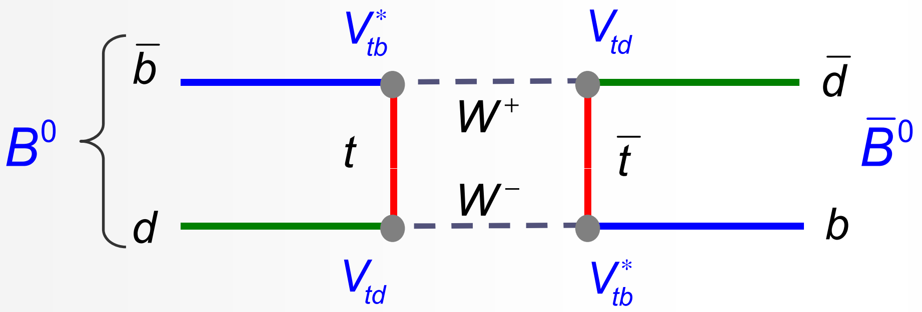
$$\beta = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$

1. The decay $b \to c$:



$\Rightarrow \quad \propto V_{cs}V_{cb}^*$ is that what we want ? 😐

2. Like for the K^0, the B^0 can first mix and then decay into the "*CP* eigenstate (?)" $J/\psi K^0$

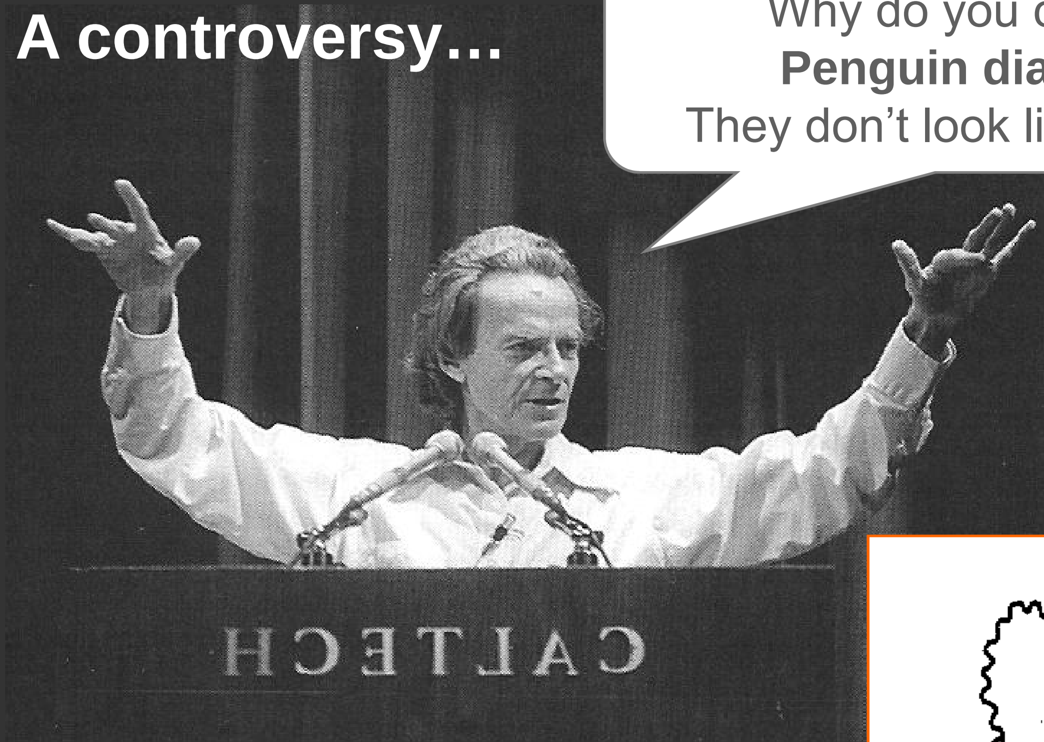


$\Rightarrow \quad \propto \left(V_{td}V_{tb}^*\right)^2$ not bad ☺

2. Also the K^0 in the decay must mix for interference $\Rightarrow \quad \propto \left(V_{cd}V_{cs}^*\right)^2$ good ☺

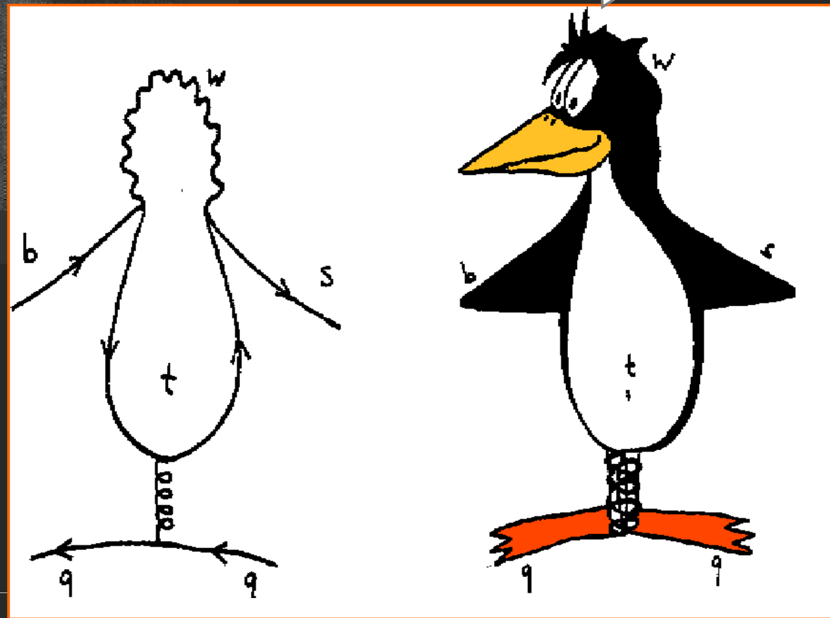
A controversy…

Why do you call these **Penguin diagrams**? They don't look like penguins!



Mirror image of Richard Feynman

I've never seen a **Feynman diagram** that looks like **you** ☺



Courtesy: G. Hamel de Monchenault

What are the Experimental Requirements ?

- The Observable :

$$A_{CP}(t) = \frac{\Gamma(\bar{B}^0(t) \to J/\psi K_S) - \Gamma(B^0(t) \to J/\psi K_S)}{\Gamma(\bar{B}^0(t) \to J/\psi K_S) + \Gamma(B^0(t) \to J/\psi K_S)} = \sin(2\beta) \cdot \sin(\Delta m_d t)$$

- We need to measure:

1. Identify a final state that is ***CP* eigenstate** (e.g., $J/\psi K_S$)
2. Determine the **flavour** of the **decaying B^0** (assume here it is a B^0)
3. How can we do this if $J/\psi K_S$ **can be reached by both *B* flavors** ?
4. If we could produce the $B^0\bar{B}^0$ pairs in a **coherent** quantum state, we could **"tag" the flavor of the decaying B^0 from the flavor of the other *B***, not decaying into a *CP* eigenstate → see later
5. Since the coherence is destroyed once one of the two *B*'s decays, we **need** the **decay time difference between the two *B*'s** to calculate the flavor of the tagged *B* at the time when the B^0 decayed: $t \to \Delta t$

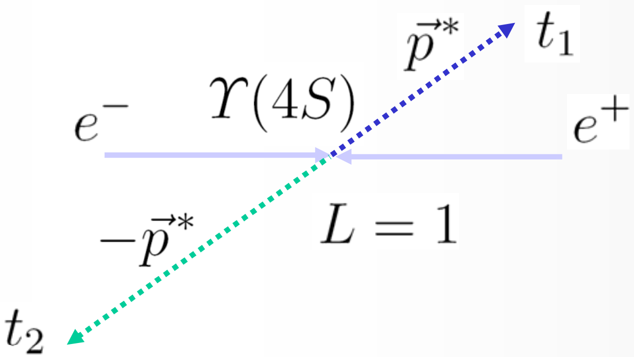
We must determine the decay time difference of the *B*'s by measuring their decay vertices

digression: Quantum Mechanics for $\Upsilon(4S) \to B\bar{B}$ Decay

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

$J^{PC} = 1^{--}$

Two pseudoscalar bosons in a *P*-wave
➡ antisymmetric wave function



proper times:

$$t \equiv (t_1 + t_2)/2$$
$$\Delta t \equiv t_2 - t_1$$

- initial state:

$$\left|\Upsilon(4S) \to B^0\bar{B}^0\right\rangle \propto \left(\left|B^0,\vec{p}^*\right\rangle\left|\bar{B}^0,-\vec{p}^*\right\rangle - \left|\bar{B}^0,\vec{p}^*\right\rangle\left|B^0,-\vec{p}^*\right\rangle\right)$$
$$= \left(\left|B_H,\vec{p}^*\right\rangle\left|B_L,-\vec{p}^*\right\rangle - \left|B_L,\vec{p}^*\right\rangle\left|B_H,-\vec{p}^*\right\rangle\right)\frac{1}{2pq}$$

flavor and mass eigenstates:

$$\left|B^0\right\rangle = \frac{1}{2p}\left(\left|B_L\right\rangle + \left|B_H\right\rangle\right)$$
$$\left|\bar{B}^0\right\rangle = \frac{1}{2q}\left(\left|B_L\right\rangle - \left|B_H\right\rangle\right)$$

- double proper-time wave function:

$$\left|\left(\Upsilon(4S) \to B^0\bar{B}^0\right)_{\text{phys}}(t,\Delta t)\right\rangle \propto e^{-2i\mu t}\begin{pmatrix} + e^{+i\Delta\mu\Delta t/2}\left|B_H,\vec{p}^*\right\rangle\left|B_L,-\vec{p}^*\right\rangle \\ - e^{-i\Delta\mu\Delta t/2}\left|B_L,\vec{p}^*\right\rangle\left|B_H,-\vec{p}^*\right\rangle \end{pmatrix}$$

where:

$$\mu = M - i\Gamma/2$$
$$\Delta\mu = \Delta M - i\Delta\Gamma/2$$

Quantum Coherence at $\Upsilon(4S) \to B\bar{B}$ Decay

Quantum coherence (due to synchronous evolution)
➡ for $\Delta t = 0$, the system is the superposition of:

one B^0	and **one** $\bar{B}^0$
one B_H	and **one** B_L
one $B_{CP=+1}$	and **one** $B_{CP=-1}$

An **Einstein-Podolsky-Rosen** phenomenon:

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

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

However, at the $\Upsilon(4S)$:

$$\left.\begin{aligned} p_B^* &= 340\ \text{MeV}/c \\ (\beta\gamma)_B^* &= 0.064 \end{aligned}\right\} \Rightarrow$$

flight distance $d^* \sim 30\ \mu\text{m}$
(beyond experimental reach)

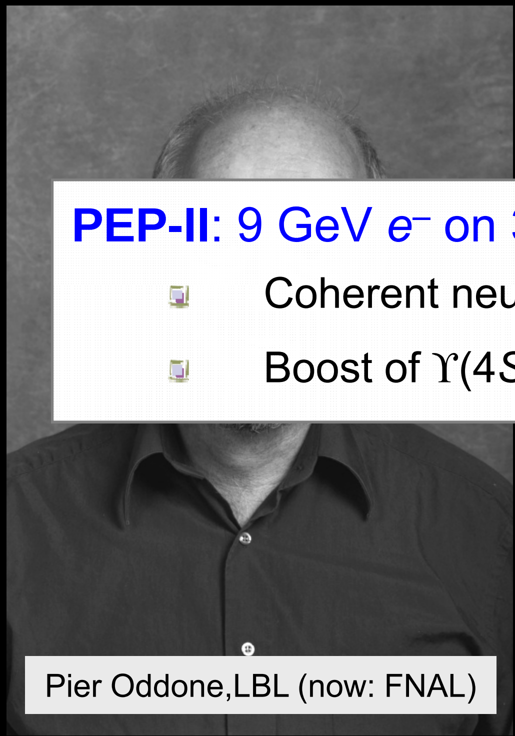
➡ Cannot perform decay-time-dependent measurements ?

Pier Oddone's Clever Idea (1987)

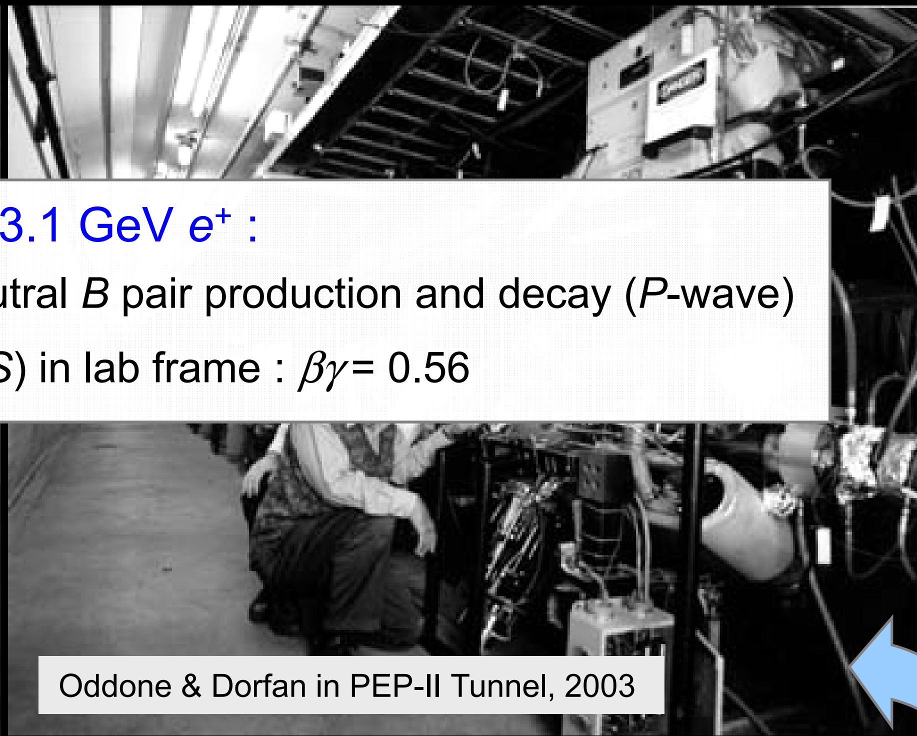
Why not produce the $\Upsilon(4S)$ with a strong boost?
One could deduce the Δt from the **distance between the two *B* vertices along the boost axis**. What we need is an **asymmetric-energy *B* Factory** with peak luminosity of order $5\text{x}10^{33}\ \text{cm}^{-2}\text{s}^{-1}$

PEP-II: 9 GeV e^- on 3.1 GeV e^+ :

- Coherent neutral *B* pair production and decay (*P*-wave)
- Boost of $\Upsilon(4S)$ in lab frame : $\beta\gamma = 0.56$



Pier Oddone,LBL (now: FNAL)



Oddone & Dorfan in PEP-II Tunnel, 2003

10 years later exist two asymmetric *B* Factories :
PEP-II at SLAC and KEKB at KEK

The *B* Factories: PEP-2 (SLAC, USA) and KEK-B (KEK, Japan)

SLAC

Stanford Linear Accelerator Center

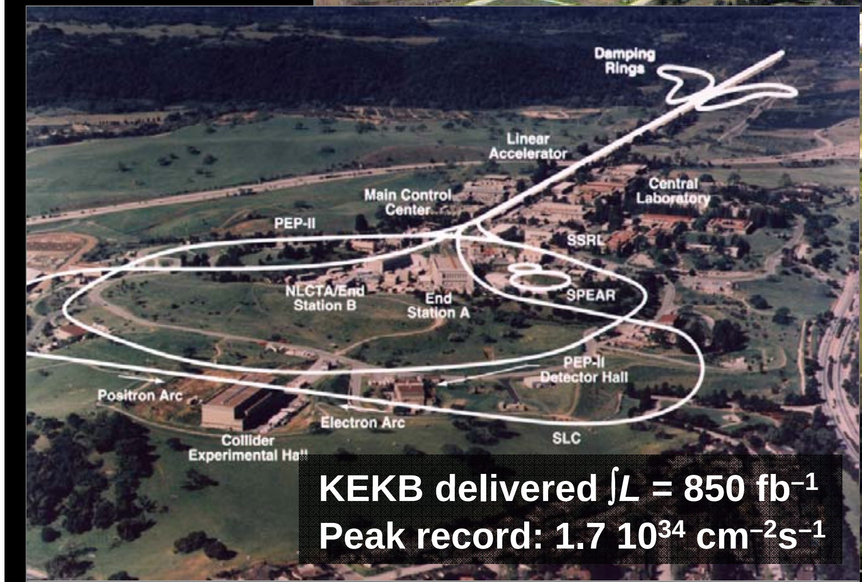
Linac

Fixed Target Experiments

BABAR

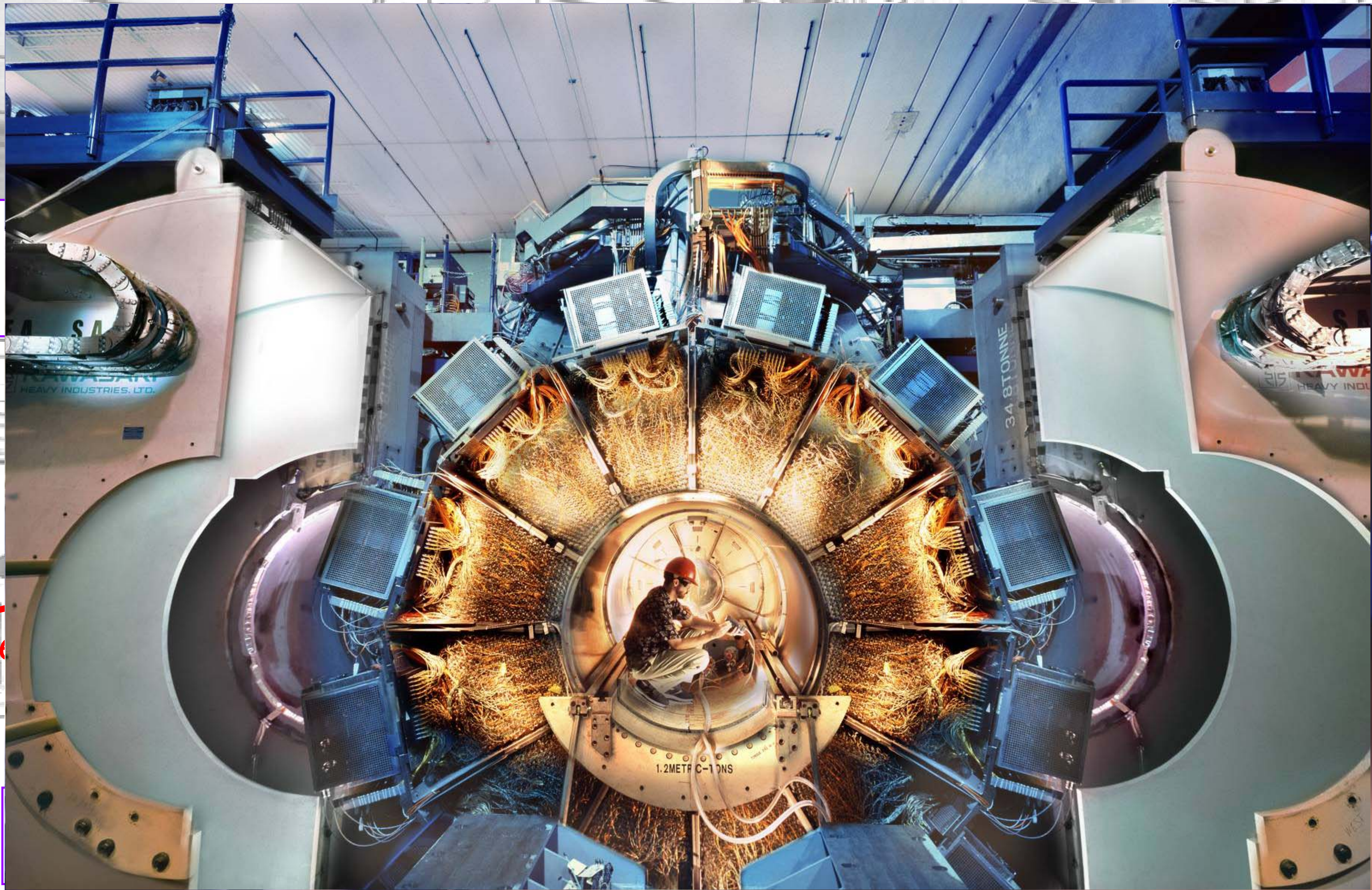
SLD (& MARK II)

PEP-II delivered $\int L$ = 557 fb^{-1}
Peak record: 1.2 10^{34} cm^{-2}s^{-1}



KEKB delivered $\int L$ = 850 fb^{-1}
Peak record: 1.7 10^{34} cm^{-2}s^{-1}

The BABAR Detector



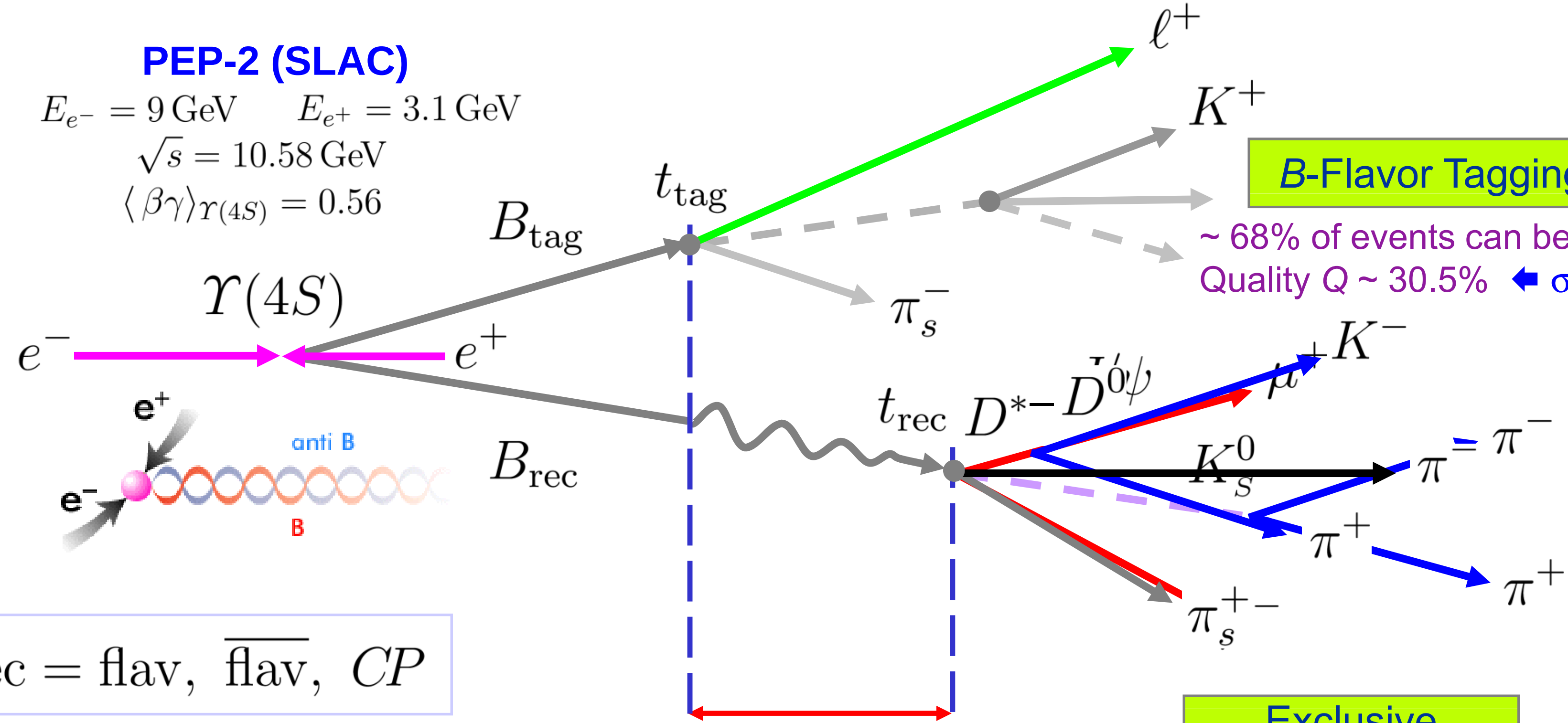
Analysis Technique at the *B* Factories

PEP-2 (SLAC)

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

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

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



B-Flavor Tagging

~ 68% of events can be tagged.
Quality Q ~ 30.5% ⬅ σ ~ 1/√Q

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

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

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

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

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

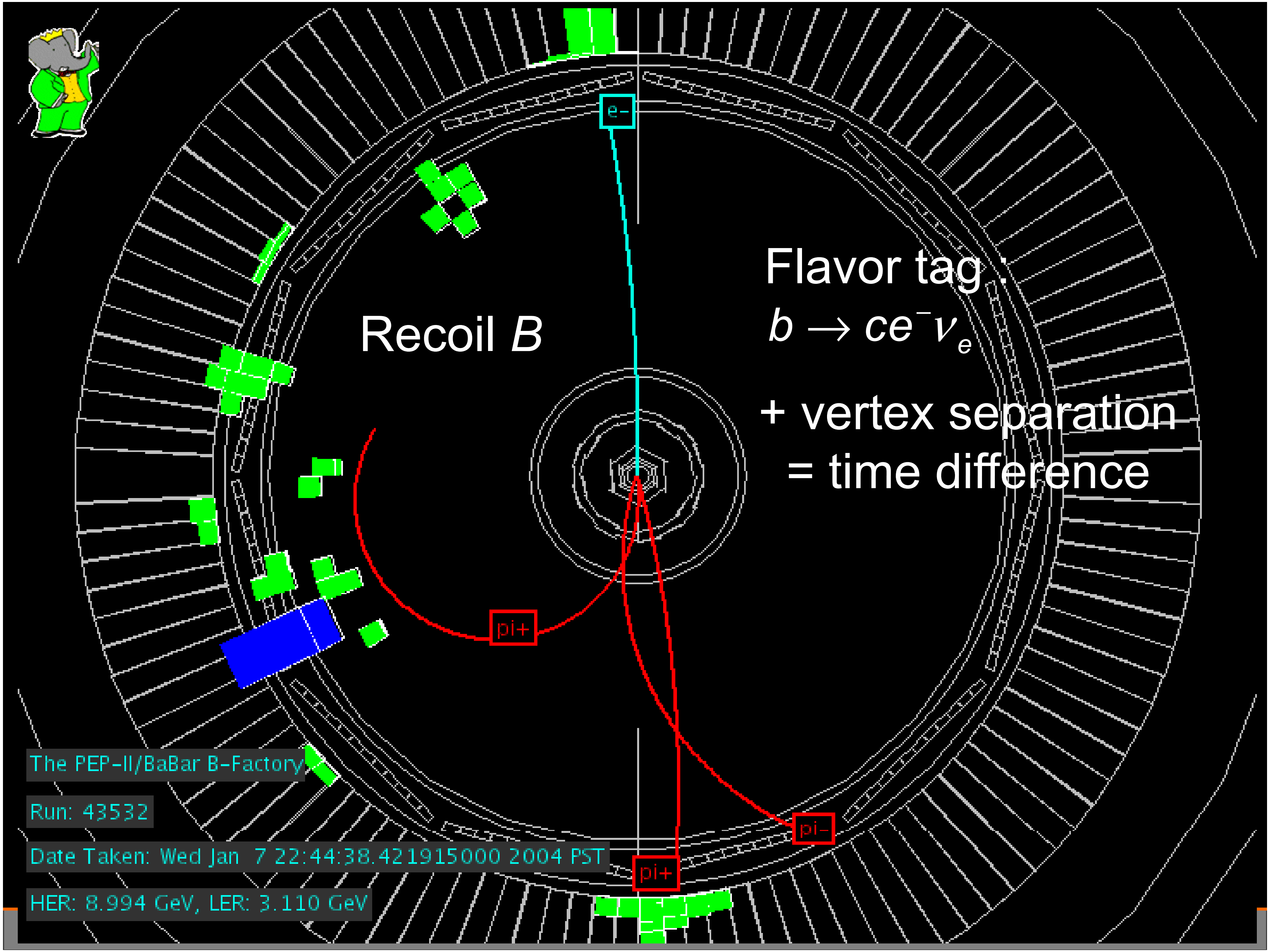
$$\Delta t \equiv t_{rec} - t_{tag}$$

Vertexing & Time Difference Determination

Exclusive *B* Meson Reconstruction

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

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


Flavor tag :
$b \to c e^- \nu_e$
+ vertex separation
= time difference
Recoil B
e-
pi+
pi-
pi+
The PEP-II/BaBar B-Factory
Run: 43532
Date Taken: Wed Jan 7 22:44:38.421915000 2004 PST
HER: 8.994 GeV, LER: 3.110 GeV

Discovery of *CP* Violation in the *B* System

- *CP* Violation due to the interference of decays with and without mixing

$$\text{Prob}(\bar{B}^0(t) \to f_{CP}) \neq \text{Prob}(B^0(t) \to f_{CP})$$

with : = $\sin(2\beta)$ and = 0 for $B \to J/\psi K^0$, ϕ

- Direct *CP* Violation is due to interference of decay amplitudes with different weak and hadronic phases

$$\text{Prob}(\bar{B} \to \bar{f}) \neq \text{Prob}(B \to f)$$

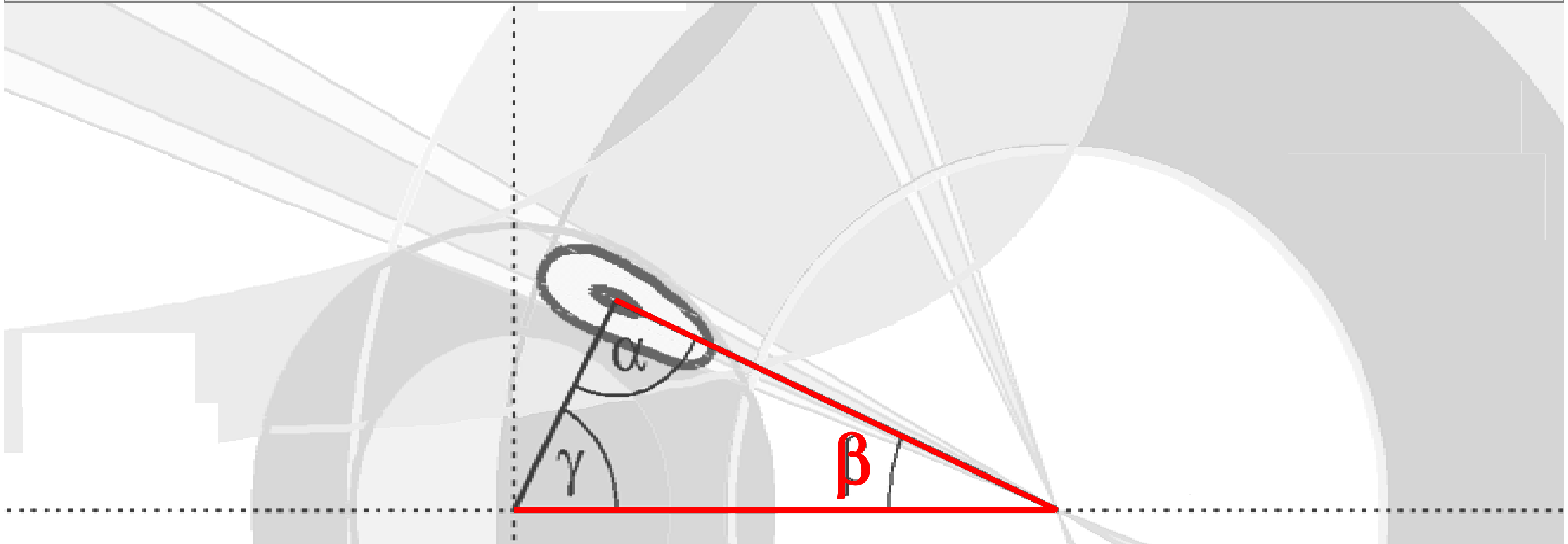
$$A_{CP}|_{WA} = -(9.7 \pm 1.2)\%$$

Already seven charmless modes with evidence or hints for direct CPV !

Wonderful measurements …

… what do they tell us ?

A Standard Model Prediction for sin(2β) ? **How ?**



Since the CKM matrix describes all *CP*-violating effects by a single phase, and the complete quark-mixing matrix depends only on 4 parameters, we can constrain it (for example, using the *CP* measurements in the kaon sector) and hence obtain a prediction for sin(2β).

We can even **overconstrain** the CKM matrix by a global fit using all the available information, and thus **search for inconsistencies that would reveal the presence of new physics** !

The Global CKM Fit

- To determine (and then predict) the phase of the CKM matrix we need to measure processes that involve the matrix elements V_{ub} and V_{td}, i.e.: $\underline{\rho \text{ and } \eta}$

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

- Some processes are already well established:
  1. The rate of $b \to u$ transitions determine $|V_{ub}|$
  2. Indirect *CP* Violation in the kaon system (ε) is sensitive to V_{td}
  3. Neutral B_d mixing determines $|V_{td}|$ (reduce theory uncertainty by also using neutral B_s mixing)
  4. Mixing-induced *CP* violation in *B* system determines $\sin(2\beta)[\arg(V_{td})]$

- Some processes need larger data samples, now approached by the *B* factories:
  1. *CP*-violation measurements in $B^0 \to \pi^+\pi^-$, $\rho^+\pi^-$ $\rho^+\rho^-$ determine $\alpha(\bar{\rho},\bar{\eta})$
  2. Direct-*CP*-violation measurements in $B \to DK$ determine $\gamma = \arctan\left(\frac{\bar{\eta}}{\bar{\rho}}\right)$
  3. The rates of $b \to d$ <u>loop</u> transitions determine $|V_{td}|$
  4. The leptonic decay $B^+ \to \tau^+\nu$ ($\bar{b}d \to W^+$ "tree annihilation") determines $|V_{ub}|$

Parameter	Value ± Error(s)
$\|V_{ud}\|$ (nuclei)	0.97377 ± 0.00027
$\|V_{us}\|$ $(K_{\ell 3})$	0.2258 ± 0.0010
$\|V_{ub}\|$	$(3.86 \pm 0.09 \pm 0.47) \times 10^{-3}$
$\|V_{cb}\|$	$(41.50 \pm 0.90) \times 10^{-3}$
$\|\varepsilon_K\|$	$(2.232 \pm 0.007) \times 10^{-3}$
Δm_d	$(0.507 \pm 0.005)\ \mathrm{ps}^{-1}$
Δm_s	CDF measurement
$\sin(2\beta)_{[c\bar{c}]}$	0.681 ± 0.025
$S_{\pi\pi}^{+-}$	-0.61 ± 0.08
$C_{\pi\pi}^{+-}$	-0.38 ± 0.07
$C_{\pi\pi}^{00}$	$-0.36^{+0.33}_{-0.31}$
$\mathcal{B}_{\pi\pi}$ all charges	Inputs to isospin a[illegible]lysis
$S_{\rho\rho,L}^{+-}$	0.05 [illegible] 0.17
$C_{\rho\rho,L}^{+-}$	0.06 ± [illegible]3
$S_{\rho\rho,L}^{00}$	0[illegible] ± [illegible] ± 0[illegible]
$C_{\rho\rho,L}^{00}$	[illegible].4 ± 0[illegible] ± 0.2
$\mathcal{B}_{\rho\rho,L}$ all charges	Inpu[illegible] to i[illegible]spin analysis
$B^0 \to (\rho\pi)^0 \to 3\pi$	Time-d[illegible]ende[illegible] Dalitz analysis
$B^- \to D^{(*)}K^{(*)-}$	Inputs [illegible] GLW analysis
$B^- \to D^{(*)}K^{(*)-}$	[illegible]puts to ADS analysis
$B^- \to D^{(*)}K^{(*)-}$	G[illegible]SZ Dalitz analyses
$\mathcal{B}(B^- \to \tau^-$[illegible]	Experimental likelihoods
$\overline{m}_c(m_c)$	$(1.24 \pm 0.037 \pm 0.095)$ GeV
$\overline{m}_t(m_t)$	(163.8 ± 2.0) GeV
$m_{[illegible]}$	(493.677 ± 0.016) MeV
[illegible]m_K	$(3.4833 \pm 0.0066) \times 10^{-12}$ MeV
[illegible]	(5.2794 ± 0.0005) GeV
m_{B_s}	(5.3696 ± 0.0024) GeV
m_W	(80.423 ± 0.039) GeV
G_F	$1.16639 \times 10^{-5}\ \mathrm{GeV}^{-2}$
f_K	(159.8 ± 1.5) MeV
B_K	$0.79 \pm 0.02 \pm 0.09$
$\alpha_s(m_Z^2)$	0.1176 ± 0.0020
η_{cc}	Calculated from $\overline{m}_c(m_c)$ and α_s
η_{ct}	0.47 ± 0.04
η_{tt}	0.5765 ± 0.0065
$\eta_B(\overline{\mathrm{MS}})$	0.551 ± 0.007
f_{B_s}	$(268 \pm 17 \pm 20)$ MeV
B_s	$1.29 \pm 0.05 \pm 0.08$
f_{B_s}/f_{B_d}	$1.20 \pm 0.02 \pm 0.05$
B_s/B_d	1.00 ± 0.02

FIT INPUT

Observable	Central ± 1 σ	± 2 σ	± 3 σ
A	0.807 [+0.018 -0.018]	0.807 [+0.036 -0.036]	0.807 [+0.053 -0.054]
λ	0.2265 [+0.0008 -0.0008]	0.2265 [+0.0015 -0.0015]	0.2265 [+0.0023 -0.0023]
ρbar	0.141 [+0.029 -0.017]	0.141 [+0.097 -0.034]	0.141 [+0.115 -0.050]
ηbar	0.343 [+0.016 -0.016]	0.343 [+0.032 -0.056]	0.343 [+0.049 -0.069]
J [10^{-5}]	3.01 [+0.19 -0.18]	3.01 [+0.40 -0.5[illegible]	[illegible]
sin2α	-0.02 [+0.10 -0.16]	-0.02 [+0.19 -0.5[illegible]	[illegible]
sin2α (meas. not in the fit)	-0.41 [+0.43 -0.09]	-0.41 [+0.55 -0.1[illegible]	[illegible]
sin2β	0.688 [+0.025 -0.024]	0.688 [+0.049 -0[illegible]	[illegible]
sin2β (meas. not in the fit)	0.800 [+0.020 -0.086]	0.800 [+0.037 -0[illegible]	[illegible]
α (rad)	1.583 [+0.078 -0.050]	1.583 [+0.293 -0[illegible]	[illegible]
α (rad) (meas. not in the fit)	1.78 [+0.05 -0.22]	1.78 [+0.10 -0.2[illegible]	[illegible]
α (rad) (dir. meas.)	1.525 [+0.111 -0.092]	0.005 [+0.144 -0[illegible] 1.53 [+0.55 -0.1[illegible] [+0.059 -0.251]	[illegible]
β (rad)	0.379 [+0.017 -0.017]	0.379 [+0.035 -0[illegible]	[illegible]
β (rad) (meas. not in the fit)	0.464 [+0.017 -0.066]	0.464 [+0.032 -0[illegible]	[illegible]
β (rad) (dir. meas.)	0.375 [+0.017 -0.017]	0.375 [+0.035 -0[illegible]	[illegible]
γ (rad)	1.179 [+0.048 -0.079]	1.179 [+0.092 -0[illegible]	[illegible]
γ (rad) (meas. not in the fit)	1.179 [+0.047 -0.083]	1.179 [+0.091 -0[illegible]	[illegible]
γ (rad) (dir. meas.)	-1.80 [+0.54 -0.54] | 1.34 [+0.53 -0.55]	-1.80 [+0.93 -0.8[illegible] [+0.92 -0.88]	[illegible]

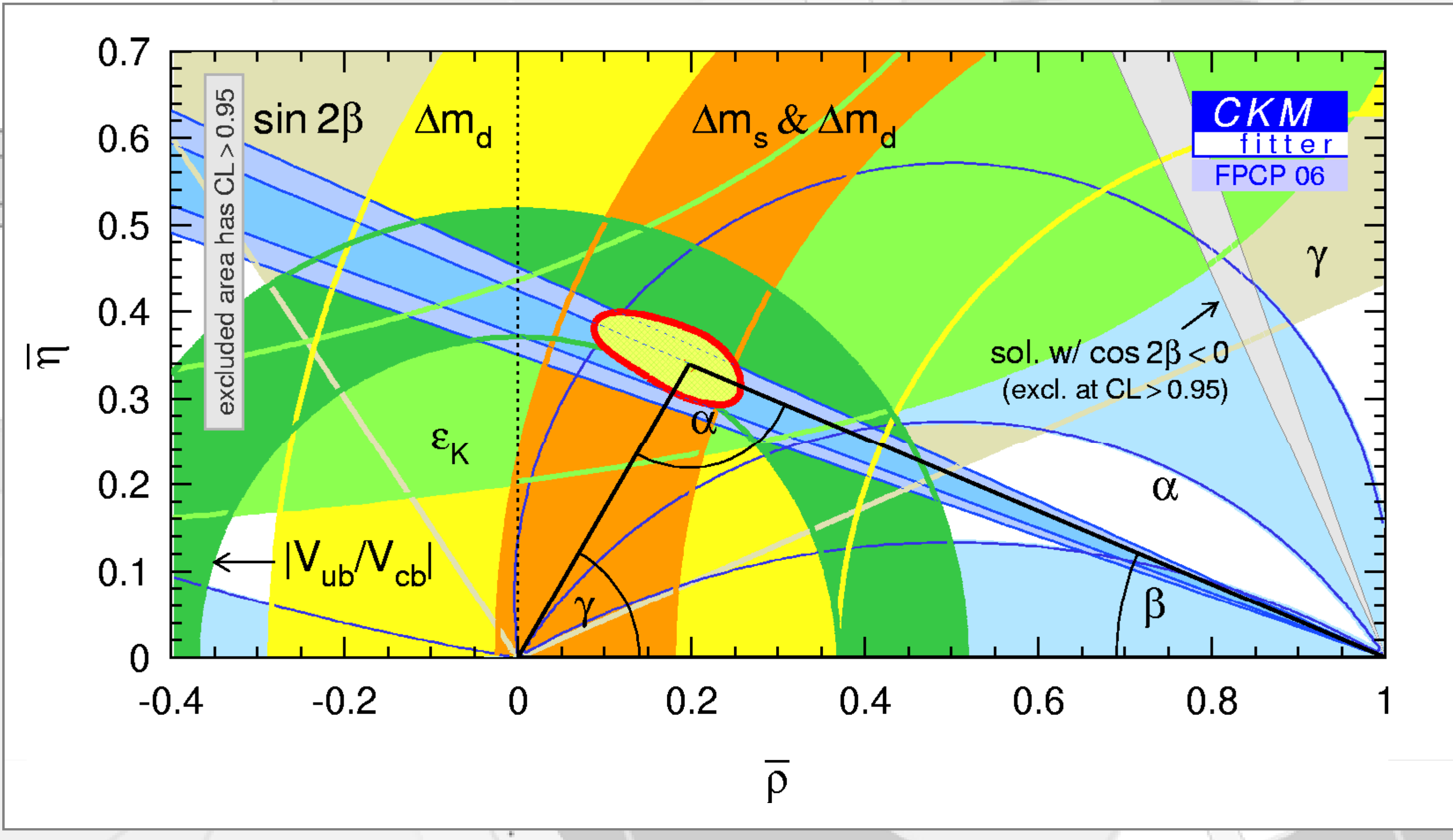
β$_s$ =arg(-VcsVcb*/VtsVtb*) (rad)	-0.01839 [+0.00089 -0.00086]	-0.0184 [+0.0018 -0.0030]	-0.0184 [+0.0027 -0.0038]
sin2β$_s$	-0.0368 [+0.0018 -0.0017]	-0.0368 [+0.0035 -0.0061]	-0.0[illegible]0053 -0.0075]
R$_u$	0.371 [+0.016 -0.015]	0.371 [+0.033 -0.028]	[illegible]371 [+0.0[illegible]
R$_t$	0.925 [+0.018 -0.030]	0.925 [+0.034 -0.1[illegible]	0.9[illegible] [+0.050 -0.12[illegible]
Δm$_d$ [ps^{-1}] (meas. not in the fit)	0.63 [+0.06 -0.12]	0.63 [+0.12 [illegible]	0.63 [+0.1[illegible]
Δm$_s$ [ps^{-1}] (meas. not in the fit)	17.7 [+6.4 -2.1]	17.7 [+10.9 -4.1]	[illegible]7 [+13.7 -5.3]
|ε$_K$| [10^{-3}] (meas. not in the fit)	2.4 [+0.8 -0.7]	[illegible]1.1 -1.1]	2.4 [+1.4 -1.2]
m$_c$ [GeV/c^2] (meas. not in the fit)	1.10 [+0.59 -0.90]	[illegible]10 [+0.[illegible]1.10]	1.10 [+1.00 -1.10]
m$_t$ [GeV/c^2] (meas. not in the fit)	128.[illegible]9. -12.]	128. [illegible]. -21.]	128. [+75. -27.]
B$_K$ (lattice value not in the fit)	[illegible] [+0.17 -[illegible]	0.75 [illegible].41 -0.20]	0.75 [+0.54 -0.24]
ξ$_{SU(3)}$ (lattice val[illegible] not in the fit)	1.106 [+0.018 -0.01[illegible] [illegible]0 -0.06[illegible]	1.28 [+0.10 -0.27]	1.28 [+0.15 -0.31]
f$_{B_s}$ [GeV] [illegible]ttice value not in [illegible] fit)	0.242 [+0.0[illegible] 0.021]	0.242 [+0.016 -0.031]	0.242 [+0.025 -0.037]
[illegible]	0.97400 [+0.00017 -0.00018]	0.97400 [+0.00035 -0.00035]	0.97400 [+0.00053 -0.00053]
|V$_{us}$|	[illegible]2653 [+0.00075 -0.00077]	0.2265 [+0.0015 -0.0015]	0.2265 [+0.0023 -0.0023]
[illegible]b|	0.00357 [+0.00017 -0.00017]	0.00357 [+0.00035 -0.00028]	0.00357 [+0.00054 -0.00036]
[illegible]	0.0405 [+0.0032 -0.0029]	0.0405 [+0.0051 -0.0037]	0.0405 [+0.0067 -0.0043]
|V$_{ud}$| (meas. not in the fit)	0.97417 [+0.00023 -0.00023]	0.97417 [+0.00046 -0.00046]	0.97417 [+0.00069 -0.00070]
[illegible]s| (meas. not in the fit)	0.2275 [+0.0011 -0.0012]	0.2275 [+0.0023 -0.0023]	0.2275 [+0.0034 -0.0035]
|V$_{ub}$| (meas. not in the fit)	0.00357 [+0.00017 -0.00016]	0.00357 [+0.00035 -0.00032]	0.00357 [+0.00054 -0.00048]
|V$_{cd}$|	0.22638 [+0.00076 -0.00076]	0.2264 [+0.0015 -0.0015]	0.2264 [+0.0023 -0.0023]
|V$_{cs}$|	0.97316 [+0.00018 -0.00018]	0.97316 [+0.00036 -0.00036]	0.97316 [+0.00054 -0.00054]
|V$_{cb}$| (meas. not in the fit)	0.04143 [+0.00086 -0.00087]	0.0414 [+0.0017 -0.0018]	0.0414 [+0.0026 -0.0026]
|V$_{td}$|	0.00868 [+0.00025 -0.00033]	0.00868 [+0.00049 -0.00110]	0.00868 [+0.00072 -0.00128]
|V$_{ts}$|	0.0407 [+0.0009 -0.0008]	0.0407 [+0.0017 -0.0017]	0.0407 [+0.0026 -0.0026]
|V$_{tb}$|	0.999135 [+0.000036 -0.000037]	0.999135 [+0.000071 -0.000074]	0.99914 [+0.00011 -0.00011]
B(B->τν) [10^{-4}]	0.96 [+0.12 -0.10]	0.96 [+0.40 -0.22]	0.96 [+0.56 -0.30]
B(B->τν) [10^{-4}] (meas. not in the fit)	0.93 [+0.11 -0.12]	0.93 [+0.37 -0.24]	0.93 [+0.55 -0.30]
B(B->μν) [10^{-6}]	0.38 [+0.05 -0.04]	0.38 [+0.16 -0.09]	0.38 [+0.22 -0.12]
B(B->eν) [10^{-11}]	0.89 [+0.12 -0.09]	0.89 [+0.38 -0.21]	0.89 [+0.52 -0.28]
B(B->e$^+$e$^-$) [10^{-15}]	2.24 [+0.12 -0.18]	2.24 [+0.24 -0.43]	2.24 [+0.38 -0.54]
B(B->μ$^+$μ$^-$) [10^{-11}]	9.6 [+0.5 -0.8]	9.6 [+1.0 -1.8]	9.6 [+1.6 -2.3]
B(B$_s$->e$^+$e$^-$) [10^{-14}]	7.4 [+0.3 -0.6]	7.4 [+0.7 -1.4]	7.4 [+1.1 -1.7]
B(B$_s$->μ$^+$μ$^-$) [10^{-9}]	3.14 [+0.15 -0.25]	3.14 [+0.31 -0.59]	3.14 [+0.49 -0.72]

FIT RESULTS

Results for Summer 2007

http://CKMfitter.in2p3.fr

The Unitarity Triangle from the global CKM fit



Inputs:

$\left|\frac{V_{ub}}{V_{cb}}\right|$

Δm_d

Δm_s lower limit

$B \to \tau\nu$

$|\varepsilon_K|$

$\sin 2\beta$ & $\cos 2\beta$

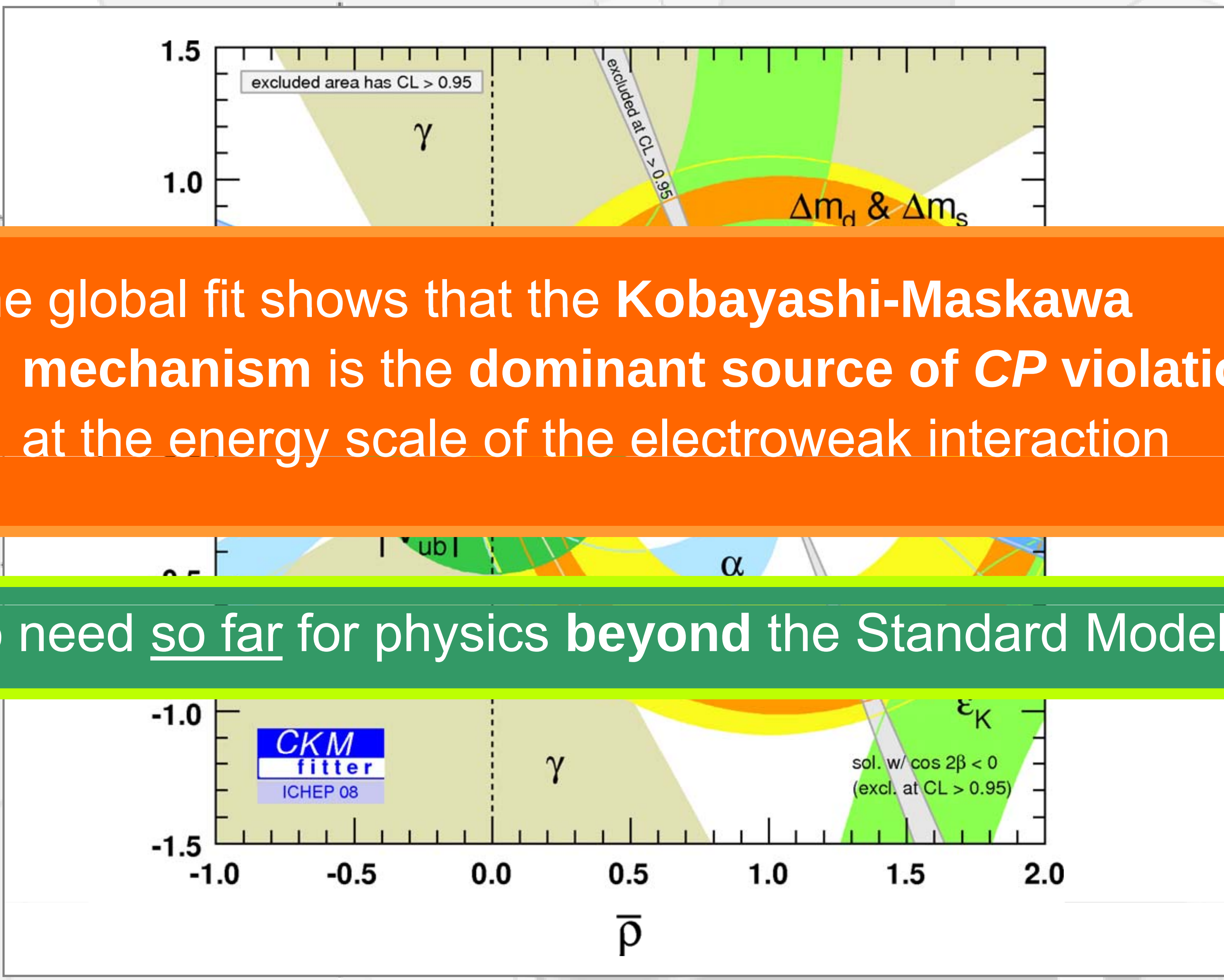
α

γ

Δm_s

SUMMER 2008

The big picture



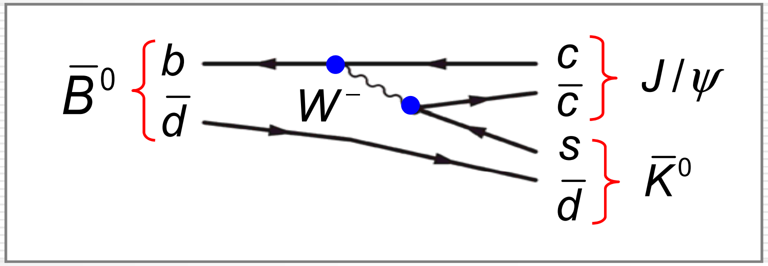
The global fit shows that the **Kobayashi-Maskawa mechanism** is the **dominant source of *CP* violation** at the energy scale of the electroweak interaction

No need so far for physics **beyond** the Standard Model

digression: Are All Measurements Consistent ?

- Almost, but not quite all yet …

  → more sensitivity to unknown heavy fields from loop diagrams



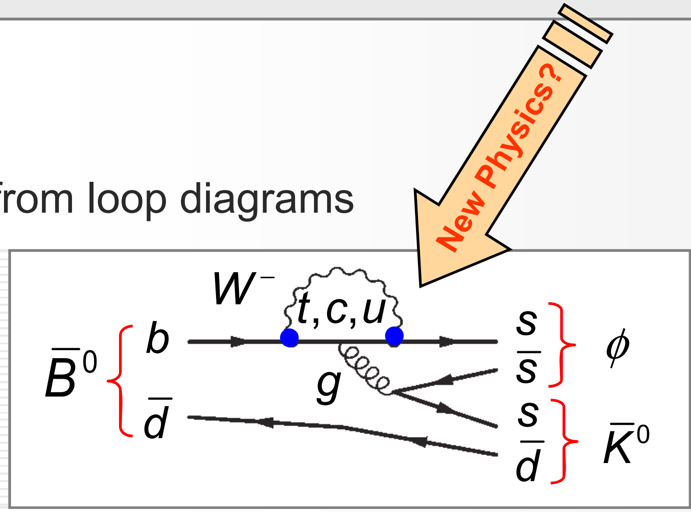
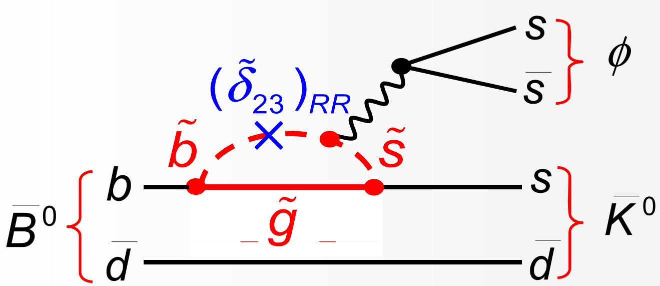


Diagram:	Tree	"Penguin"-loop diagram
CP observable:	$\sin(2\beta)[J/\psi\, K^0]$	$\sin(2\beta)[\phi K^0]$

- The penguin diagram prefers heavy virtual fields in the loop; penguin-to-tree ratio:

$$\left|\frac{A^{\rm penguin}_{Q\text{-heavy}} - A^{\rm penguin}_{q\text{-light}}}{A^{\rm tree}}\right| \approx \frac{\alpha_s}{12\pi}\ln\left(\frac{m^2_{Q\text{-heavy}}}{m_b^2}\right)$$

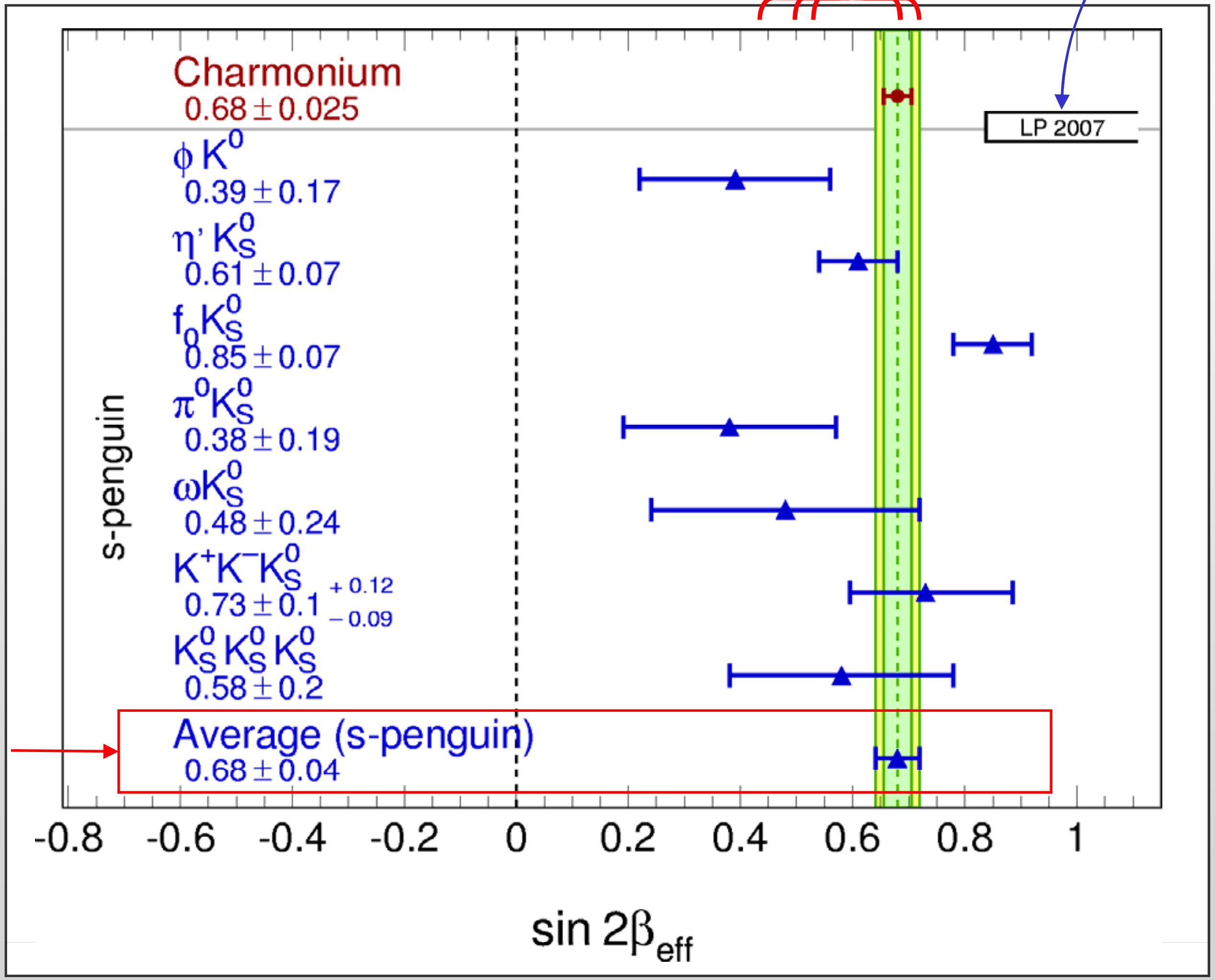
- GUT-inspired example for SUSY penguin diagram:



digression: CP Violation in Penguin Modes

2.7σ / 3.8σ discrepancy

Summer '07

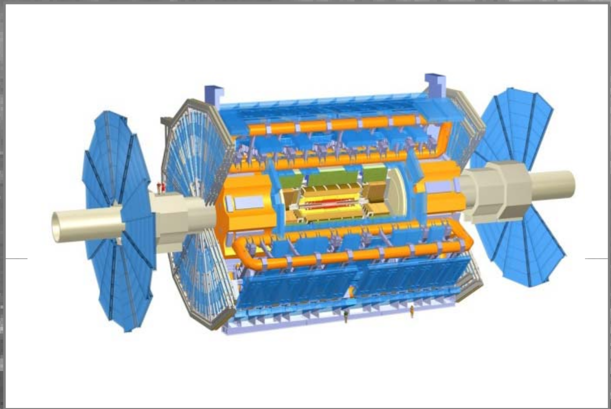


Naïve average: neglecting theory uncertainties !!!

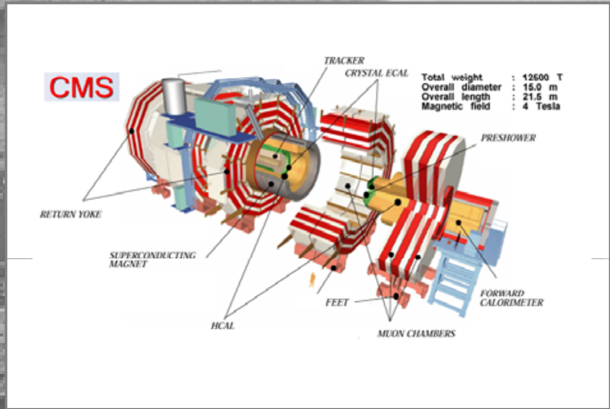
Naïve average has bad CL, which may indicate that it is indeed problematic

The Future of *B* Physics and *CP* Violation at the LHC

ATLAS



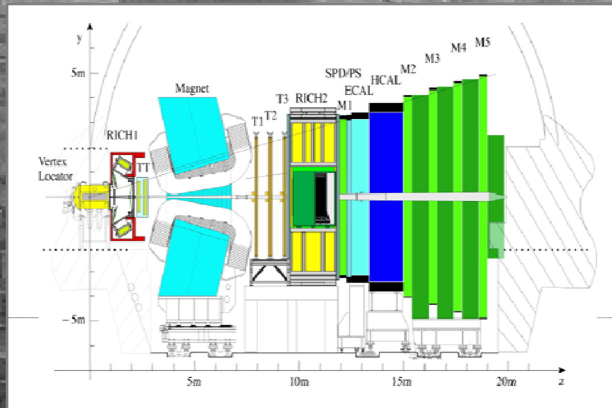
CMS



ALTAS and CMS concentrate on "high-p_T" discovery physics.

Their *B*-physics potential relies on the low-p_T performance of the Trigger systems.

LHCb



LHCb is **not** a fixed-target experiment (looks like one). It concentrates on low-p_T *B* physics.

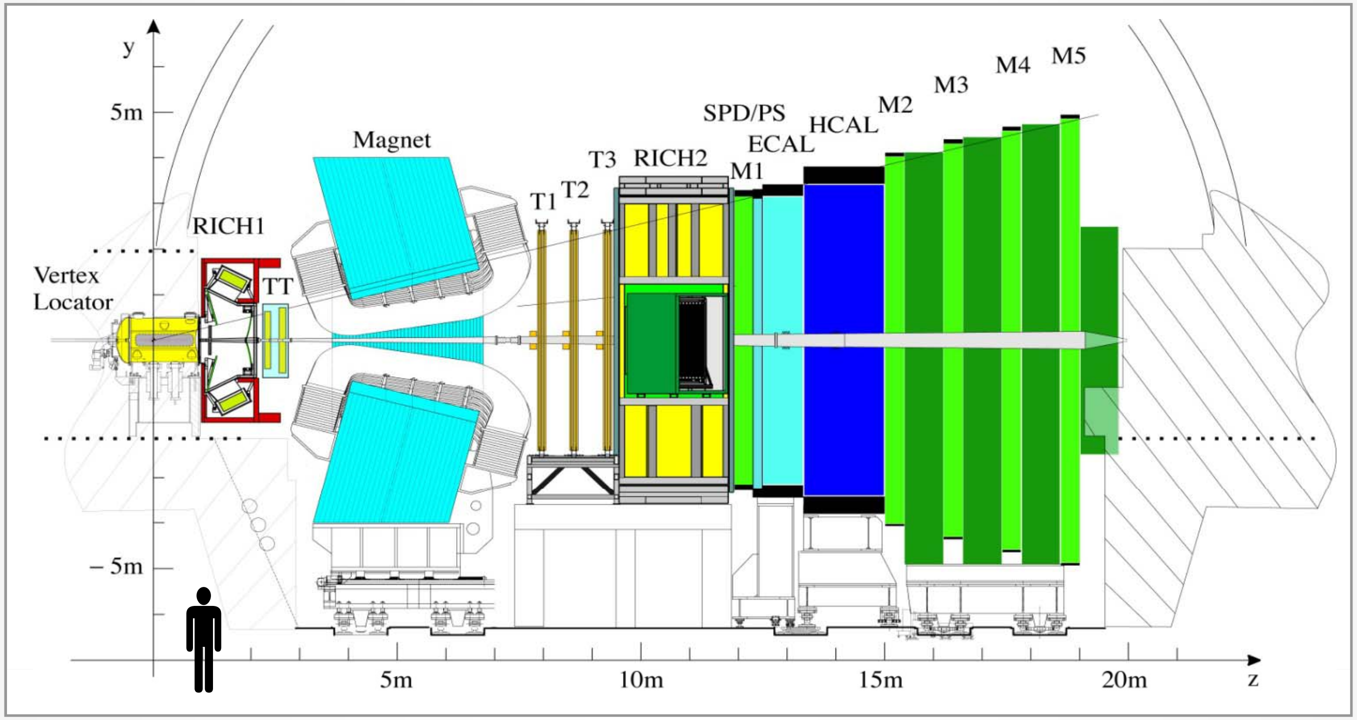
Virtues over ATLAS & CMS: Low-p_T track trigger, particle ID & better mass resolution

B Physics at Tevatron and LHC

B physics at hadron colliders is complementary to the e^+e^- *B* factories.

Strengths: High statistics; accesses the B_s; sensitive to very rare modes, if clean signature; production of *b* baryons and B_c mesons

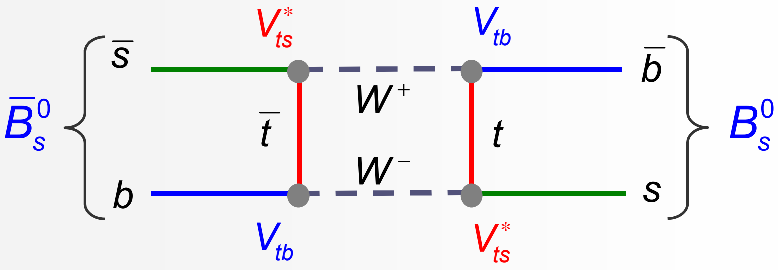
Weaknesses: Worse tagging (no quantum coherence) and background; no rare modes with neutrinos can be reconstructed; less efficient for π^0;

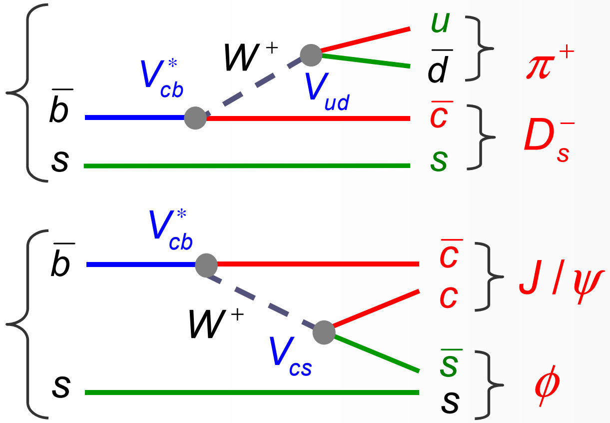


digression: B Physics at Tevatron and LHC

Prime Measurements: (**many, many** more interesting measurements to be done!)

- B_s mixing frequency and phase:





mixing frequency:

$$\Delta m_s \propto \left|V_{ts}V_{tb}^*\right|^2$$

mixing phase:

$$2\beta_s \approx -2\arg V_{ts}V_{tb}^*$$

➡ <u>Frequency</u>: **just measured by CDF!** CKM fit prediction not very precise yet (needs γ)

➡ <u>Phase</u>: not measured yet, but precisely known in SM: **excellent** probe for new physics

- $B_s \to \mu^+\mu^-$: FCNC (box & EW-penguin-mediated) rare decay
  (BR ~ $3 \cdot 10^{-9}$; current limit (CDF) < $5.8 \cdot 10^{-8}$ at 95% CL)

CP Violation and the Genesis of a Matter World