CP Violation

Andreas Hoecker, CERN

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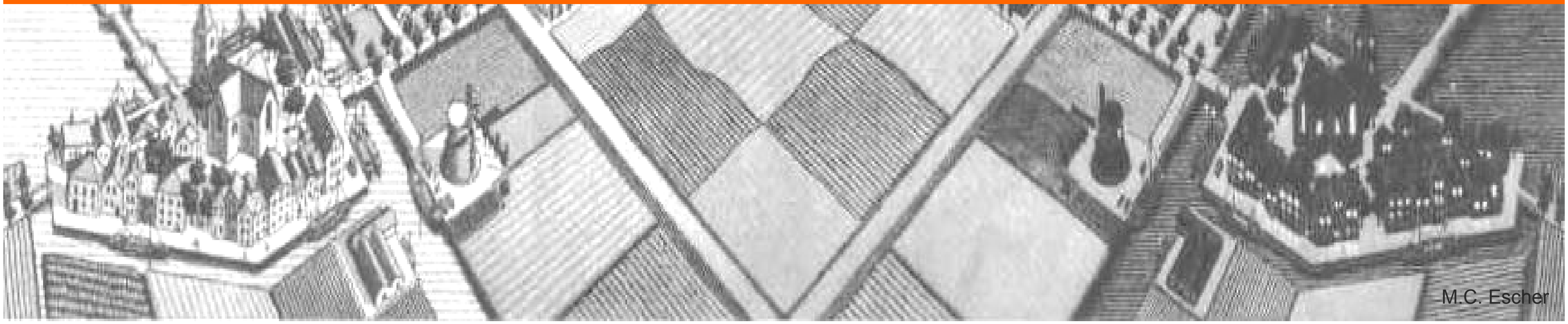
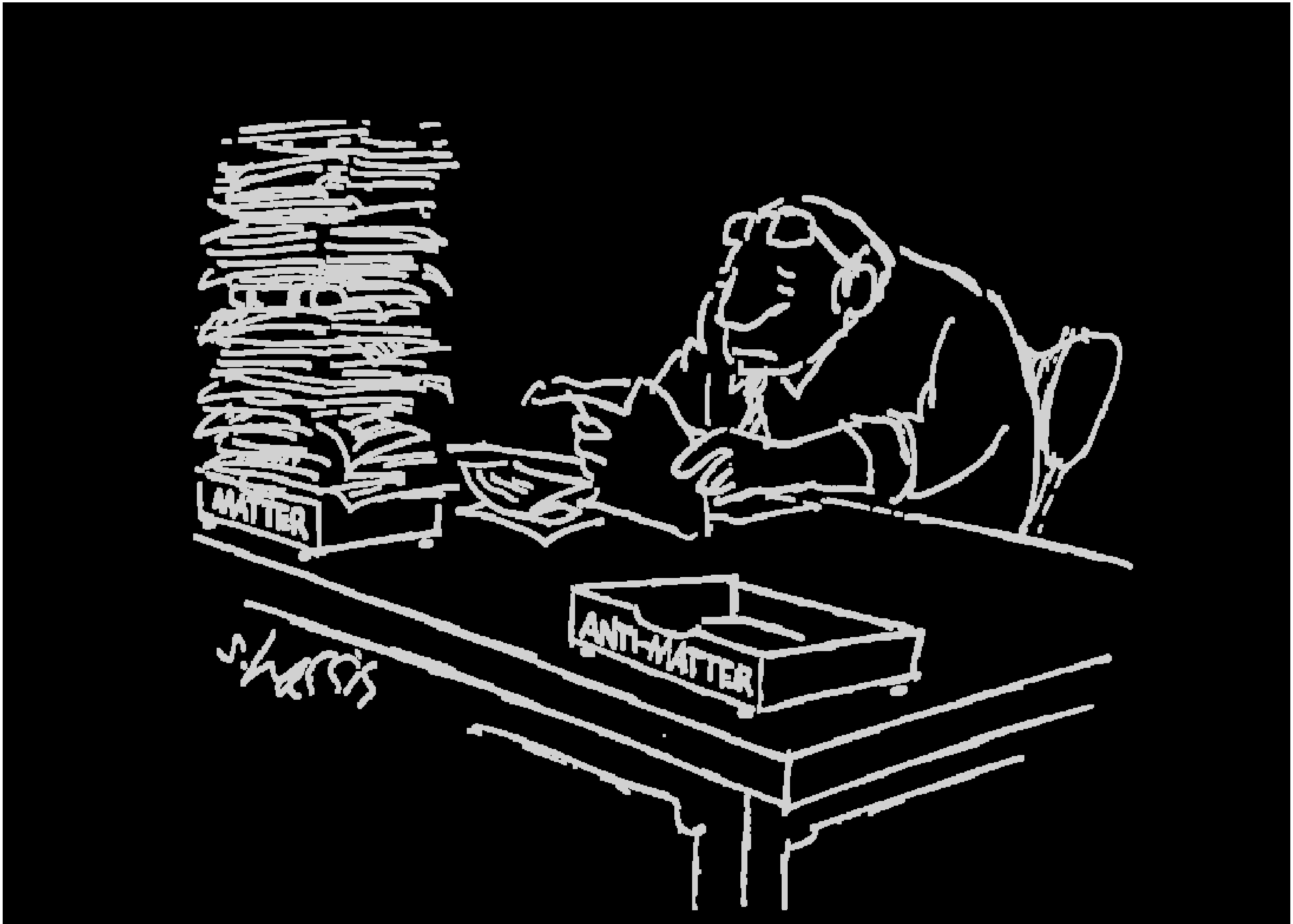



MATTER
ANTI-MATTER
S. Harris

Sakharov Conditions

(*) Bigi-Sanda, *CP* Violation, 2000

- The Universe is not empty* !
- The Universe is almost empty* !

$$\frac{\Delta n_{\text{baryon}}}{n_\gamma} = \frac{n_{\text{baryon}} - n_{\overline{\text{baryon}}}}{n_\gamma} \sim O\left(10^{-10}\right)$$

Sakharov conditions (1967) for Baryogenesis

1. Baryon number violation
2. *C* and *CP* violation
3. Departure from thermodynamic equilibrium (non-stationary system)

So, if we believe to have understood CPV in the quark sector, and **if** it cannot account for the observed baryon asymmetry … what does it signify ?

A sheer **accident of nature** ?

What would be the **consequence** of a **different** value for the **CKM phase** ?

The understanding of **matter-antimatter symmetry violation** is **crucial** if we want to move closer into the heart of the **Big Bang**

The Role of the *CP*-Violating CKM Phase

- If the SM extensions do not violate *CP* (this would be rather unnatural), **could the CKM phase generate the observed baryogenesis ?**

- KM *CP*-violating asymmetries, d_{CP}, must be proportional to the Jarlskog invariant *J*

$$d_{CP} = J \cdot \tilde{F}_U \cdot \tilde{F}_D$$

where: $J = \mathrm{Im}\left(V_{ud}V_{cs}V_{us}^*V_{cd}^*\right) \simeq A^2\lambda^6\eta$, and: $\tilde{F}_U = \left(m_t^2 - m_c^2\right)\cdot\left(m_t^2 - m_u^2\right)\cdot\left(m_c^2 - m_u^2\right)$

$= \left(3.1 \pm 0.2\right) \times 10^{-5}$ $\qquad \tilde{F}_D = \left(m_b^2 - m_s^2\right)\cdot\left(m_b^2 - m_d^2\right)\cdot\left(m_s^2 - m_d^2\right)$

- Since non-zero quark masses are required, *CP* symmetry can only be broken where the Higgs field has already condensed to $v_T \neq 0$

- To make d_{CP} dimensionless, we divide by dimensioned parameter $D = T_c$ at the EW scale ($T_c = T_{EW} \sim 100$ GeV), with $[D] = \mathrm{GeV}^{12}$

$$\hat{d}_{CP} = \frac{d_{CP}}{D^{12}} \approx 10^{-19} \ll \eta \approx O\left(10^{-10}\right)$$

➡ KM *CP* violation probably *irrelevant* for baryogenesis !

Themes

I. Introduction
- History
- Symmetries

II. *P* and *CP* Violation
- Electric and weak dipole moments
- *digression:* The strong *CP* problem
- The discovery of *CP* violation in the kaon system
- Neutral meson mixing and different *CP* violation types

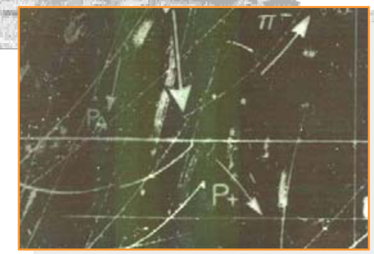
III. *CP* Violation in the Standard Model
- The CKM matrix and the Unitarity Triangle

IV. *CP* Violation in the *B* system
- The *B* Factories
- The measurement of sin(2β)

V. The global CKM fit

VI. Outlook to the LHC

CP Violation is a Family History of Flavour



- Discovery of strange particles (Rochester, Butler) (1946-47)
- Neutral kaons can mix (Gell-Mann, Pais) (1952)
- K_L discovery (Lederman *et al.*) (1956)
- Parity (*P*) violation: possible explanation (Lee, Yang) (1956)
- *P* Violation found in β decay (Wu *et al.*) (1957)
  later: maximum *P* and *C* violation, but *CP* invariance
- Cabibbo-Theory (1963)
- ➡ *CP* violation (CPV) discovered (Cronin, Fitch *et al.*) (1964)
- GIM-Mechanism (Glashow, Illiopolous, Maiani) (1970)
- *J*/ψ Resonance: *c* quarks (Ting, Richter) (1974)

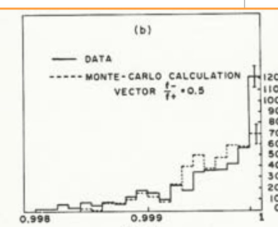
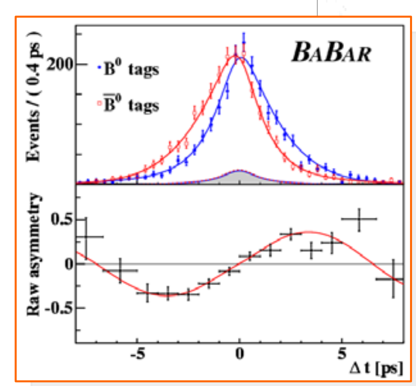


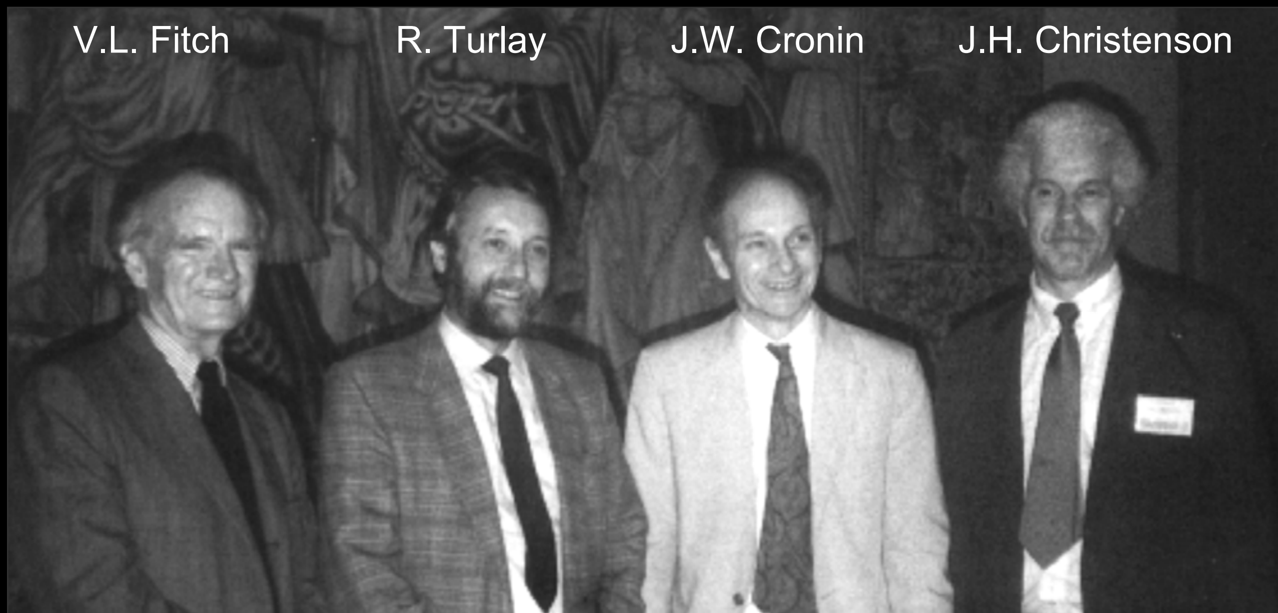
FIG. 2.2. Results obtained by Christenson *et al.* (1964). (a) Experimental distribution of m^* compared with a Monte Carlo calculation. (b) Angular distribution of events with 490 MeV < m^* < 510 MeV. The calculated curves are normalized to the observed number of events in both cases.

CP Violation is a Family History of Flavour

- CPV Phase requires 3 families (Kobayashi-Maskawa) (1973)
- Discovery of τ lepton: 3[rd] family (Perl et al.) (1975)
- Υ resonance: *b* quarks (Lederman *et al.*) (1977)
- Neutral B_d mesons mix (ARGUS) (1987)
- *t*-Quark discovery (CDF) (1995)
- ν-Oscillation discovery (Super-K) (1998)
- Direct *CP* violation in *K* system (NA31, NA48, KTeV) (1999)
- Start of B_d Factories: BABAR (PEP II), Belle (KEKB) (1999)
- ➡ CPV in B_d system : $\sin(2\beta) \neq 0$ (BABAR, Belle) (2001)
- Direct CPV in B_d system (BABAR, Belle) (2004)
- B_s mesons oscillate (CDF) (2006)
- D^0 mesons oscillate (BABAR & Belle) (2007)



Discovery of *CP* violation:



PRL 13, 138 (1964)

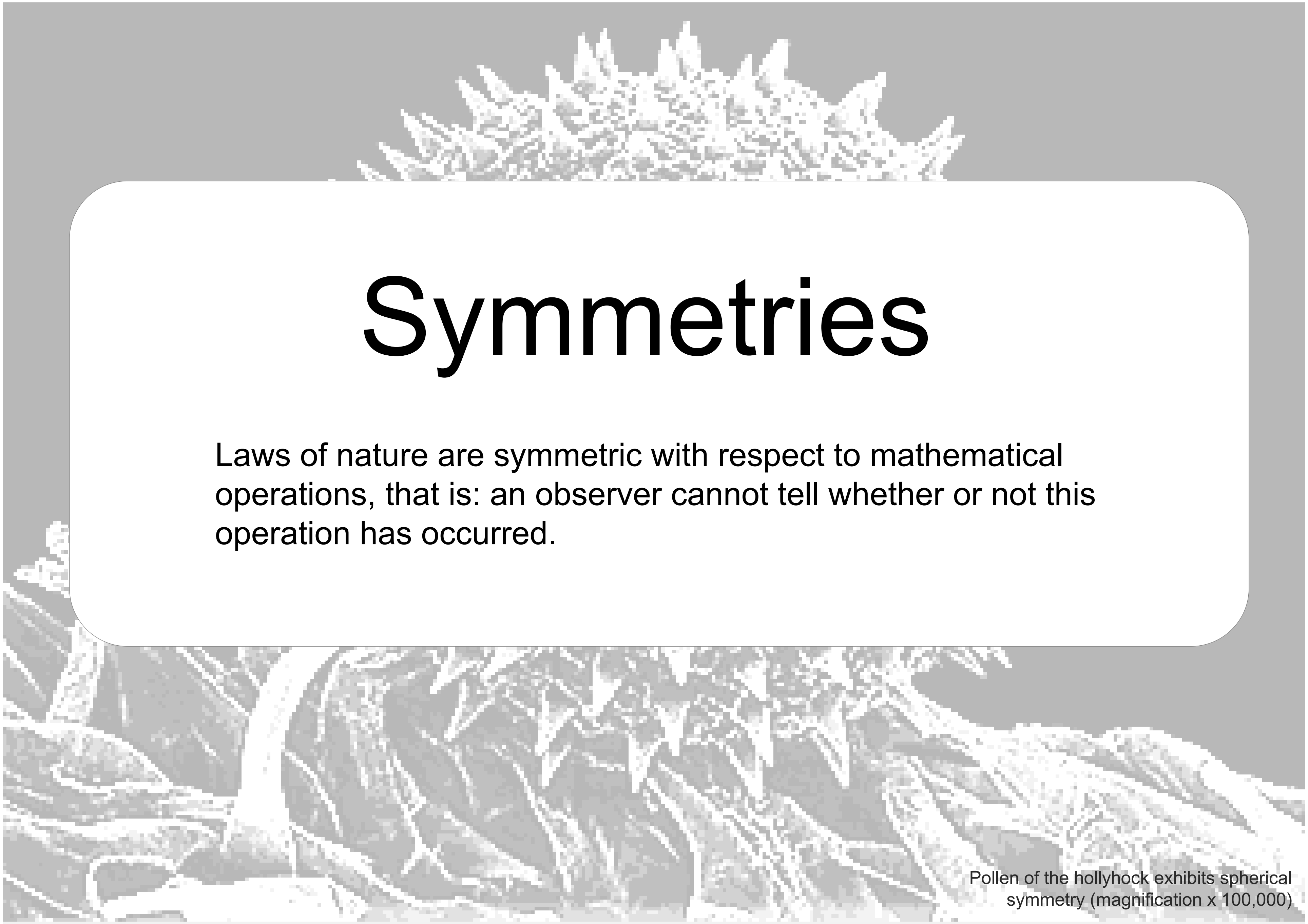
Evolution of working conditions (example BABAR) :

… 623 physicists (in 2005).

BABAR: PRL 87, 091801 (2001)
Belle: PRL 87, 091802 (2001)

Symmetries

Laws of nature are symmetric with respect to mathematical operations, that is: an observer cannot tell whether or not this operation has occurred.



Pollen of the hollyhock exhibits spherical symmetry (magnification x 100,000)

Continuous Symmetries and Conservation Laws

In general, if U is a symmetry of the Hamiltonian H, one has: $[H,U]=0 \;\Rightarrow\; H=U^{\dagger}HU$

$$\langle f'|H|i'\rangle = \langle Uf|H|Ui\rangle = \langle f|U^{\dagger}HU|i\rangle = \langle f|H|i\rangle$$

- Accordingly, the Standard Model Lagrangian satisfies local gauge symmetries (the physics must not depend on local (and global) phases that cannot be observed):

U(1) gauge transformation	➔	**Electromagnetic interaction**
SU(2) gauge transformation	➔	**Weak interaction**
$SU(3)_C$ gauge transformation	➔	**Strong interaction (QCD)**

- Conserved additive quantum numbers:
  - Electric charge (processes can move charge between quantum fields, but the sum of all charges is constant)
  - Similar: color charge of quarks and gluons, and the weak charge
  - Quark (baryon) and lepton numbers (however, no theory for these, therefore believed to be only approximate asymmetries) → evidence for lepton flavor violation in "neutrino oscillation"

Discrete Symmetries

Discrete symmetry transformations lead to multiplicative conservation laws

The following discrete transformations are fundamental in particle physics:

- **Parity *P*** ("handedness"):

  Reflection of space around an arbitrary center;
  P invariance → cannot know whether we live in *this* world, or in *its mirror* world

- **Particle-antiparticle transformation *C*** :

  Change of all additive quantum numbers (for example the electrical charge) in its opposite ("charge conjugation")

- **Time reversal *T*** :

  The time arrow is reversed in the equations;
  T invariance → if a movement is allowed by a the physics law, the movement in the opposite direction is also allowed

In particle physics:

$$P|e_L^-\rangle = |e_R^-\rangle$$
$$P|\pi^0\rangle = -|\pi^0\rangle$$
$$P|n\rangle = +|n\rangle$$
$$C|e_L^-\rangle = |e_L^+\rangle$$
$$C|u\rangle = |\bar{u}\rangle$$
$$C|d\rangle = |\bar{d}\rangle$$
$$C|\pi^0\rangle = +|\pi^0\rangle$$

Time reversal symmetry (invariance under change of time direction) does certainly not correspond to our daily experience. The macroscopic violation of *T* symmetry follows from maximising thermodynamic entropy (leaving a parking spot has a larger solution space than entering it). In the microscopic world of single particle reactions thermodynamic effects can be neglected, and *T* invariance is realised.

Discrete Symmetries

Discrete symmetry transformations lead to multiplicative conservation laws

The following discrete transformations are fundamental in particle physics:

- Parity ***P*** ("handedness"):

In particle physics:

These are interesting because it is not obvious whether the laws of nature should look the same for any of these transformations, and the answer was surprising when these symmetries were first tested !

$$C|d\rangle = |\bar{d}\rangle$$

$$C|\pi^0\rangle = +|\pi^0\rangle$$

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The *CPT* Theorem

The *CPT* theorem (1954): "**Any Lorentz-invariant local quantum field theory is invariant under the successive application of *C*, *P* and *T***"

Proofs: G. Lüders, W. Pauli (1954); J. Schwinger (1951)
Derived from Lorentz invariance and principle of locality

- Fundamental consequences:
  - Relation between spin and statistics: fields with integer spin ("bosons") commute and fields with half-numbered spin ("fermions") anticommute → Pauli exclusion principle
  - Particles and antiparticles have **equal mass and lifetime**, equal magnetic moments with opposite sign, and **opposite quantum numbers**

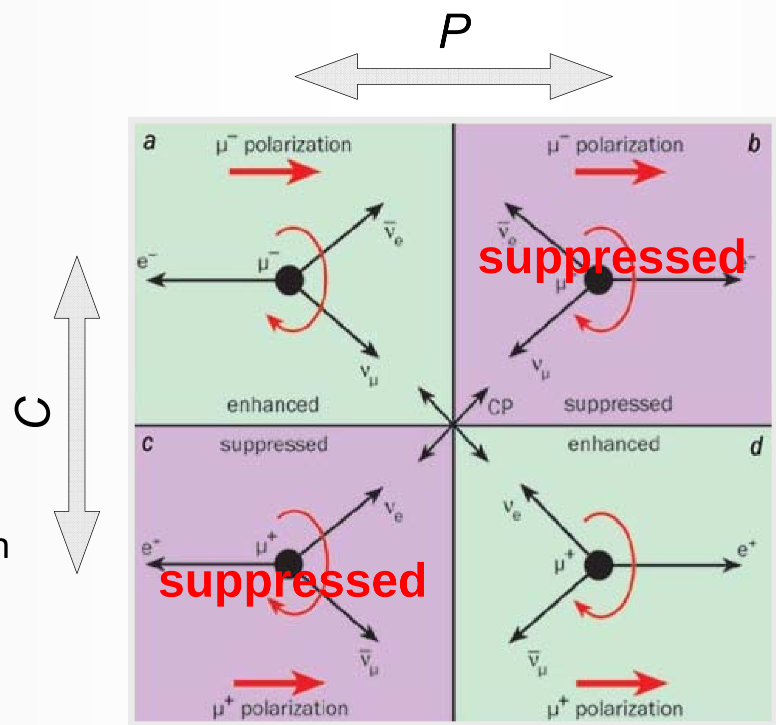
- Best experimental test: $\left|\left(m_{K^0} - m_{\bar{K}^0}\right) / m_{K^0}\right| < 10^{-18}$

P and *C* Violation in Weak Interaction

- **Weak interaction mediated by *V–A* current violates *C* and *P***
- Consider the collinear decay of a polarized muon: $\mu^-_{\text{polarized}} \rightarrow e^- + \nu_\mu + \bar{\nu}_e$

The preferred emission direction of the light left-handed electron is opposite to the muon polarization.

Similar situation for *C* transformation (*i.e.* replace all particles with their antiparticles).



P transformation (*i.e.* reversing all three directions in space) yields constellation that is suppressed in nature.

Applying *CP*, the resulting reaction—in which an antimuon preferentially emits a positron in the same direction as the polarization—is observed.

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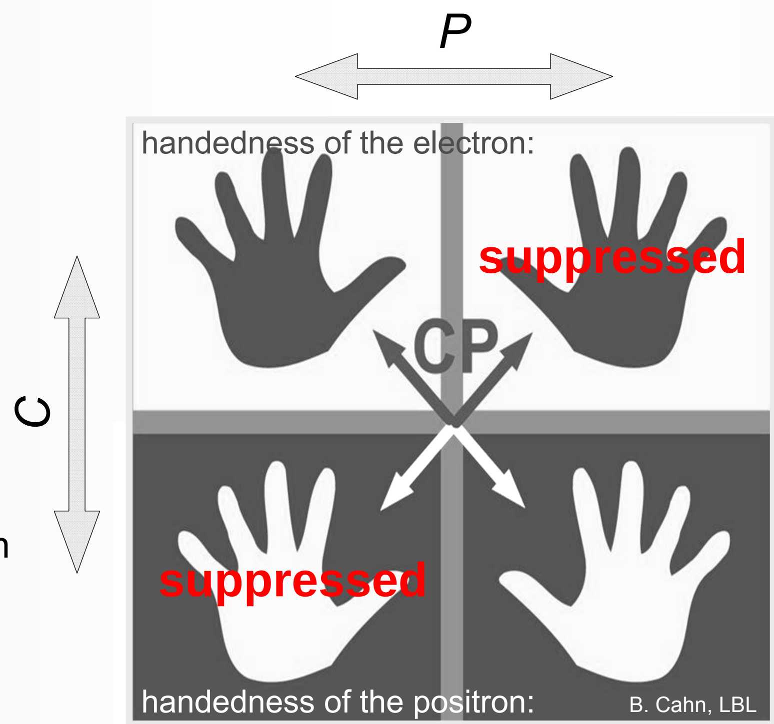

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CP Violation

CP Symmetry requires that **processes and their anti-processes have** the **same rates**

1. Due to the *CPT* theorem, *CP* symmetry also requires *T* symmetry
2. *CP violation* would enable us to distinguish between particles and antiparticles, and between past and future in an absolute way !

Dipole moments

- Can there be *CP* violation in the electromagnetic or neutral weak current ?

Let's modify the Standard Model Lagrangian to allow for *CP* violation through electromagnetic and weak dipole moments:

$$L_{CP} = -\frac{i}{2}\bar{\ell}\sigma^{\mu\nu}\gamma_5\ell\left(d_\ell^{\mathrm{EM}} F_{\mu\nu} + d_\ell^{\mathrm{weak}} Z_{\mu\nu}\right)$$

where $F_{\mu\nu}$ and $Z_{\mu\nu}$ are electric and weak field strength tensors.

In the nonrelativistic limit one obtains the Pauli equation with the additional terms:

$$L_{CP} \to d_\ell^{\mathrm{EM}}\vec{\sigma}\vec{E} + d_\ell^{\mathrm{weak}}\vec{\sigma}\vec{Z}$$

A shift in the energy of the system when applying an external electric or weak field

But…. why do these dipole moments violate *CP* symmetry ?

Dipole Moments and *CP* Violation

- Spin is the only explicit "direction" of an elementary particle. Hence the dipole moment must be proportional to it

$$\vec{d} \propto \vec{s}$$

- The electric dipole moment is the average of a charge density distribution → polar vector

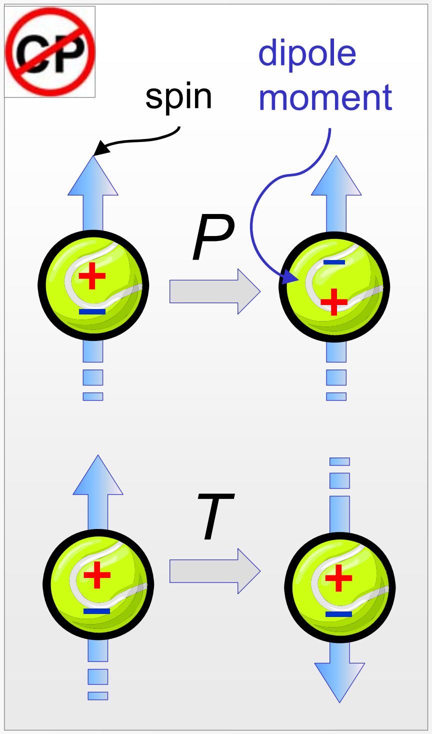
$$\vec{d} = \int d^3x \cdot \rho(\vec{x}) \cdot \vec{x}$$

- The spin has the form of angular momentum → axial vector

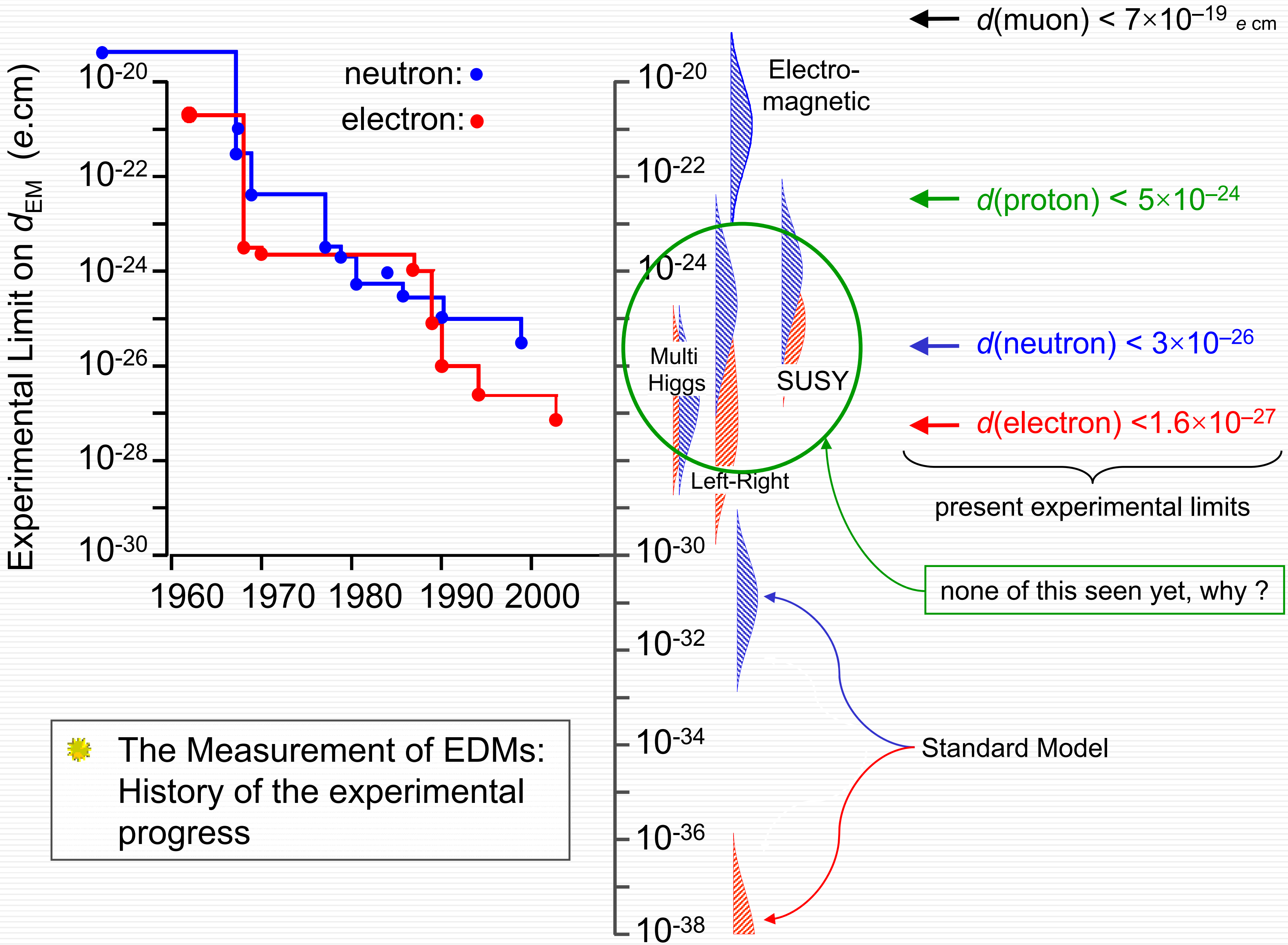
$$\vec{s} \propto \vec{r} \times \vec{p}$$

- Parity transformation gives: $P\vec{d} = -\vec{d}\ ,\quad P\vec{s} = \vec{s} \underset{P\text{ invariance}}{\Rightarrow} \vec{d} = 0$

- Time reversal transformation gives $T\vec{d} = \vec{d}\ ,\quad T\vec{s} = -\vec{s} \underset{T\text{ invariance}}{\Rightarrow} \vec{d} = 0$



→ Non-vanishing electric or weak dipole moments require the presence of a *P*- and *T*-violating (=*CP*-violating) interaction



- The Measurement of EDMs: History of the experimental progress

digression: CP Violation in the QCD Lagrangian

- It was found in 1976 that the perturbative QCD Lagrangian was missing a term L_θ

$$L_{\rm QCD} = \underbrace{L_{\rm pQCD}}_{\text{perturbative QCD}} + \underbrace{L_\theta}_{P,T\text{-violating}}, \quad \text{where:} \quad L_\theta = \theta \frac{\alpha_s}{8\pi} \underbrace{G^a_{\mu\nu}\tilde{G}^{\mu\nu,a}}_{\text{Gluon field tensors}}, \text{ and } \underbrace{\tilde{G}^{\mu\nu,a} = \frac{1}{2}\varepsilon_{\mu\nu\alpha\beta}G^{\alpha\beta,a}}_{\textit{dual}\text{ field tensor}}$$

that breaks through an axial triangle *anomaly* diagram the $U(1)_A$ symmetry of $L_{\rm pQCD}$, which is not observed in nature

When classical symmetries are broken on the quantum level, it is denoted an *anomaly*

- The term $G^a_{\mu\nu}G^{\mu\nu,a}$ contained in $L_{\rm pQCD}$ is *CP*-even, while $G^a_{\mu\nu}\tilde{G}^{\mu\nu,a}$ is *P*-and *T*-odd, since:

$$GG \propto \sum_a \left(\left|\vec{E}_a\right|^2 + \left|\vec{B}_a\right|^2\right) \xrightarrow{P,T} \sum_a \left(\left|\vec{E}_a\right|^2 + \left|\vec{B}_a\right|^2\right)$$

$$G\tilde{G} \propto \sum_a \left(\vec{E}_a \cdot \vec{B}_a\right) \xrightarrow{P,T} -\sum_a \left(\vec{E}_a \cdot \vec{B}_a\right)$$

color electric and magnetic fields

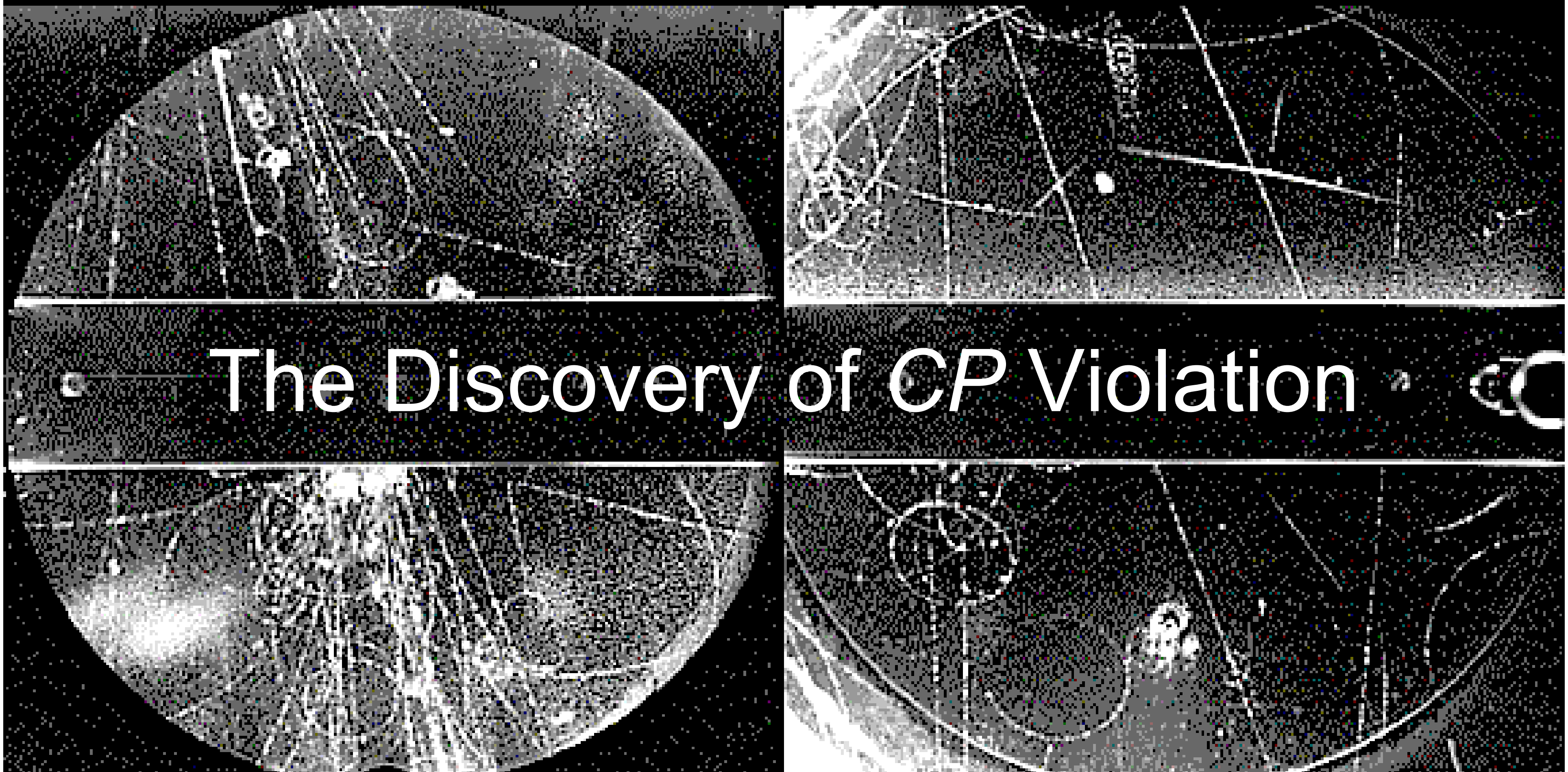
Relativistic invariants, similar to electric field tensors: $F_{\mu\nu}F^{\mu\nu}$, $F_{\mu\nu}\tilde{F}^{\mu\nu}$

$$\underbrace{\partial_\mu F^{\mu\nu} = j^\nu, \ \partial_\mu \tilde{F}^{\mu\nu} = 0}_{\text{Maxwell equations}}$$

- This *CP*-violating term contributes to the EDM of the neutron:

$$\underbrace{d_n \simeq \theta \cdot 5 \times 10^{-16} \text{ ecm, so that } \theta \text{ tiny or zero}}_{\text{"Strong } CP \text{ (finetuning) Problem"}}$$

➡ Axion ???



The Discovery of *CP* Violation

The Discovery of *CP* Violation in $K^0 \to \pi^+\pi^-$ Decays

- Experimentally one does not observe the neutral "flavor eigenstates" K^0 and $\bar{K}^0$ but rather long- and short-lived neutral states: K_L and K_S
  - Their observed pionic decays are: $K_S \to (\pi\pi)^0$ and $K_L \to (\pi\pi\pi)^0$
  - And it was believed that: $CP|K_S\rangle = +|K_S\rangle$ and $CP|K_L\rangle = -|K_L\rangle$

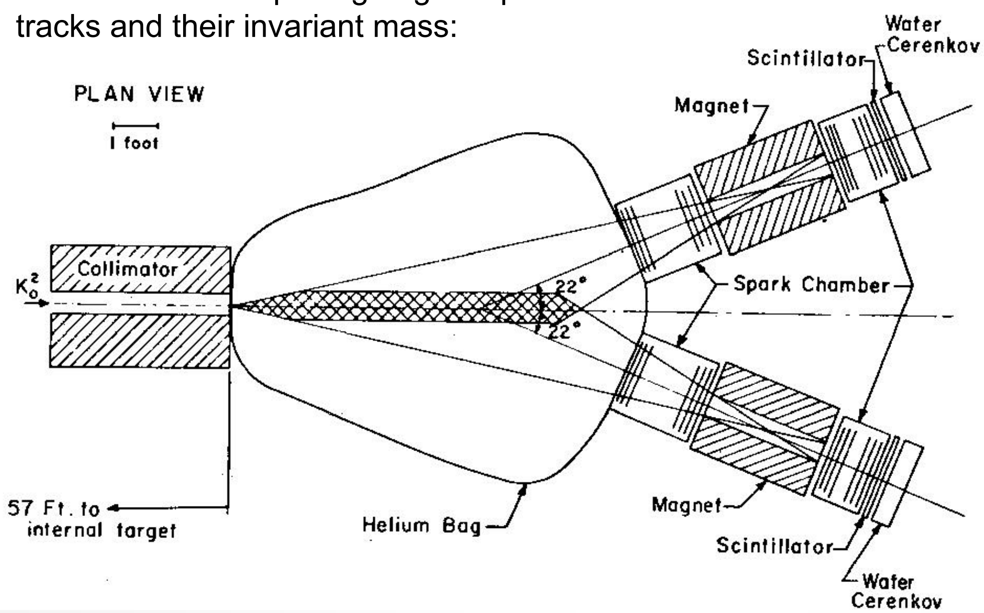
Larger phase space of 2π decay:
$\Rightarrow \tau_{K_L} / \tau_{K_S} \simeq 580$

- **However**, Cronin, Fitch et al. discovered in 1964 the *CP*-violating decay: $K_L \to \pi^+\pi^-$

Jim Cronin

Val Fitch

Measurement of opening angle of pion tracks and their invariant mass:



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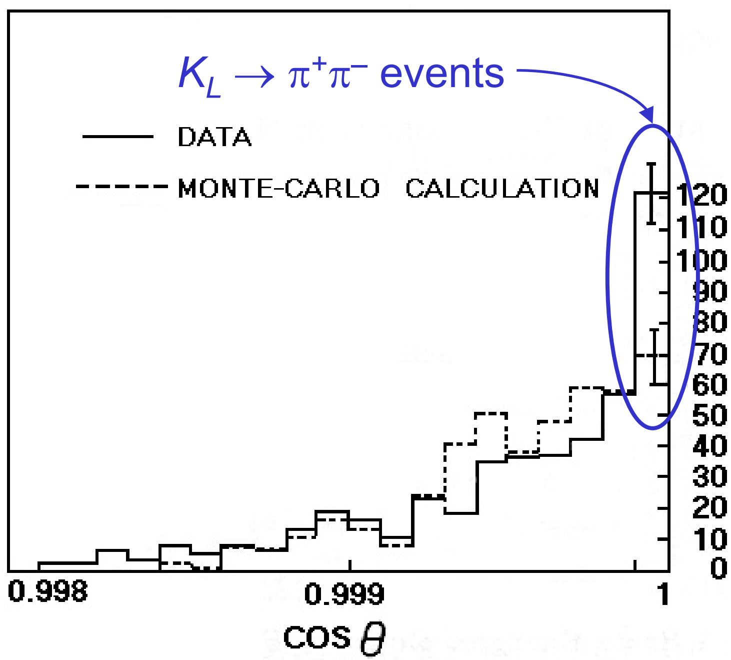
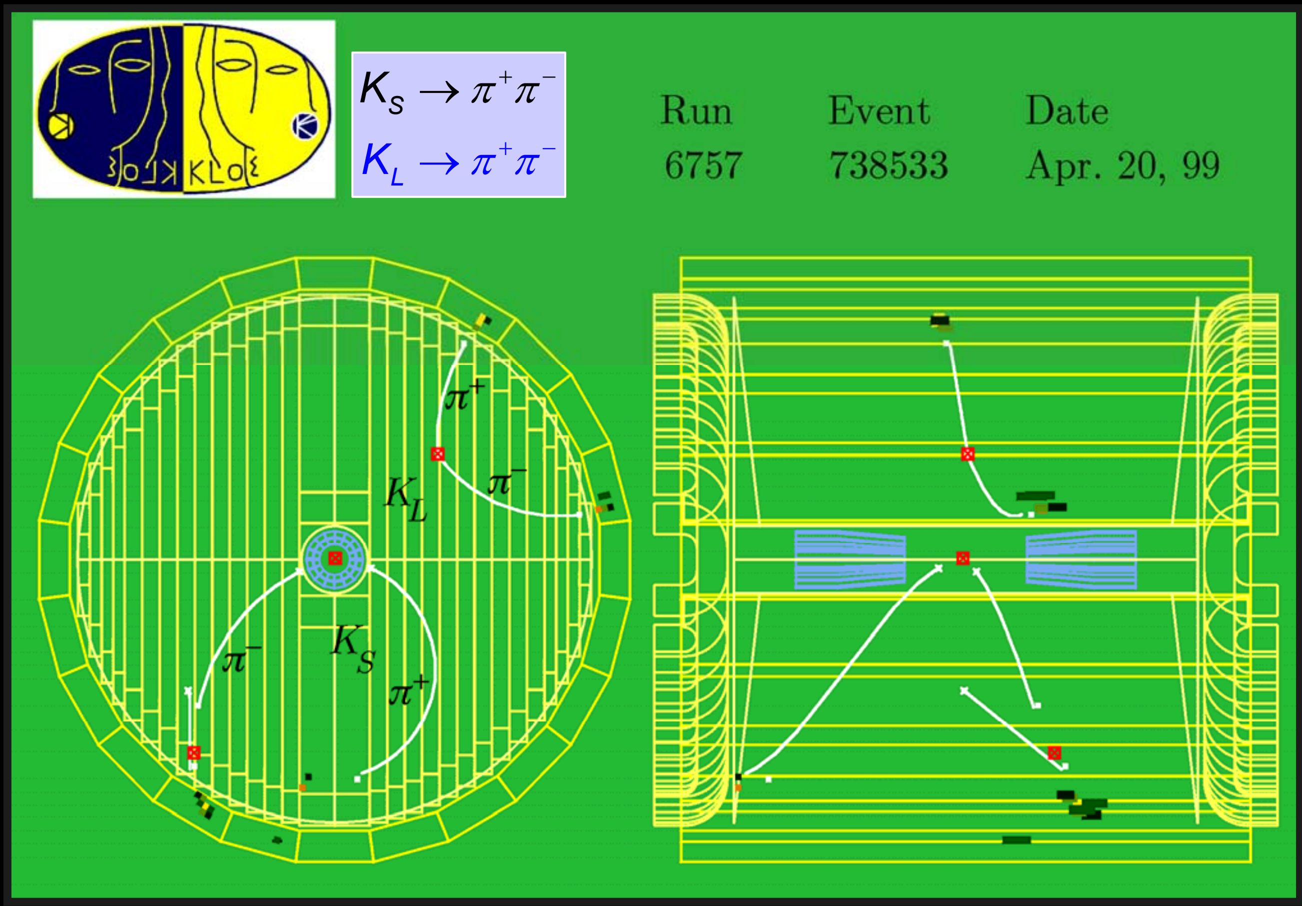


Today’s most precise measurement of amplitude ratio:

$$|\varepsilon| = \left| \frac{A(K_L \to \pi^+\pi^-)}{A(K_S \to \pi^+\pi^-)} \right| = (2.282 \pm 0.017) \times 10^{-3}$$

The KLOE experiment at the ϕ Factory DAΦNE (Frascati, Italy) can detect **single** *CP*-violating decays:

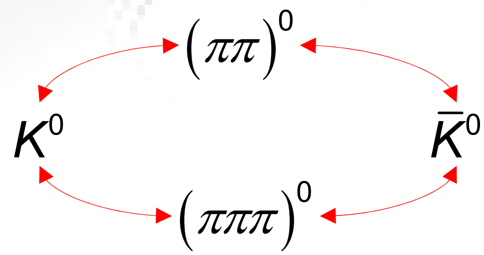
$e^+e^- \to \phi \to K^0\bar{K}^0$ and equivalently: $e^+e^- \to \phi \to K_S K_L$



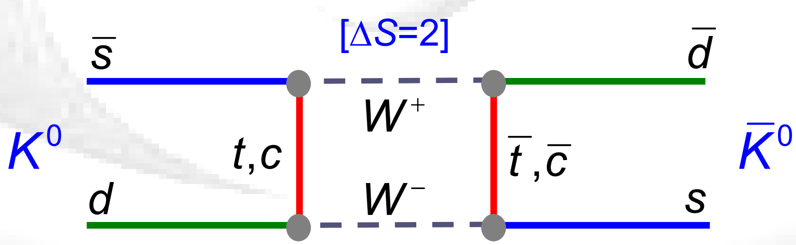
Note that the quantum coherence is broken after the decay of one of the two K^0's

Neutral Kaon Mixing

- Neutral kaons "**mix**" through the charged weak current, which does not conserve strangeness, neither *P* nor *C*. Weak interaction *cannot* distinguish K^0 from $\bar{K}^0$
- Simple picture: they mix through common virtual states:



- Because $\Delta m(K) = m(K_L) - m(K_S) = 3.5 \times 10^{-12}$ MeV > 0, a K^0 will change with time into a $\bar{K}^0$ and vice versa
- These oscillations are described in QCD by $\Delta S = 2$ Feynman "box" diagrams:

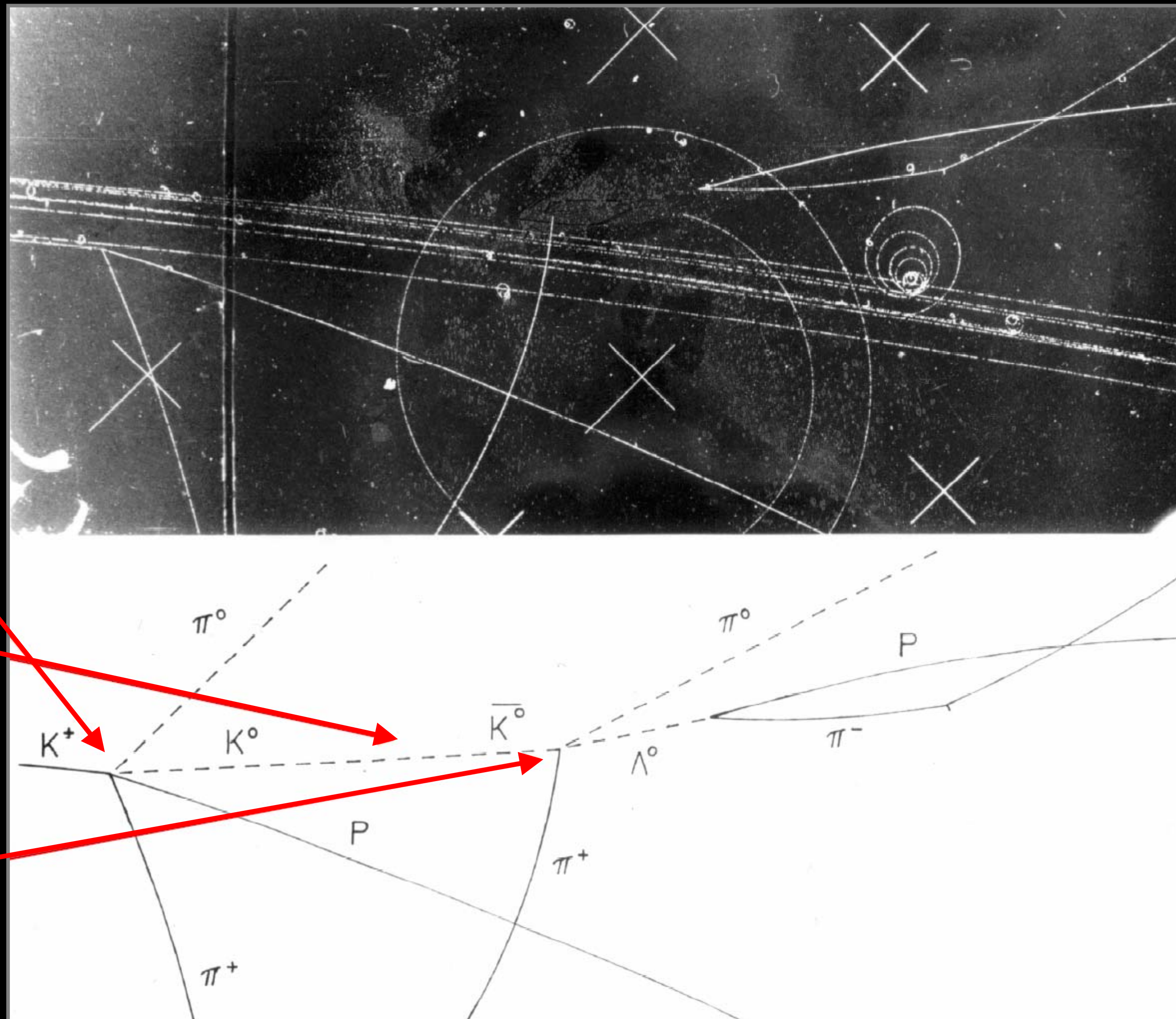


Observing K^0 Mixing

The $\bar{s}$ in the K^+ is transferred to the K^0

The $\bar{s}$ in the K^0 mixes to a s making a $\bar{K}^0$

The s is transferred to a Λ^0 (*uds* baryon)



1971, Graham Thompson

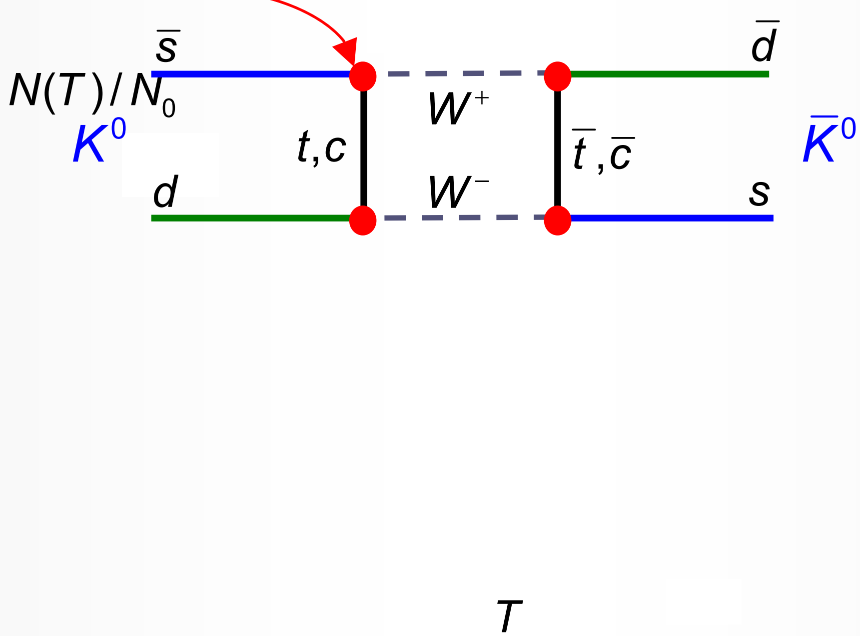
There are in Fact Four Meson Systems with Mixing

- Pairs of self-conjugate mesons that can be transformed to each other via flavor changing weak interaction transitions are:

$|K^0\rangle = |\bar{s}d\rangle \qquad |D^0\rangle = |c\bar{u}\rangle \qquad |B_d^0\rangle = |\bar{b}d\rangle \qquad |B_s^0\rangle = |\bar{b}s\rangle$

All measured by now !

- They have very different oscillation frequencies that can be understood from the CKM couplings occurring in the box diagrams



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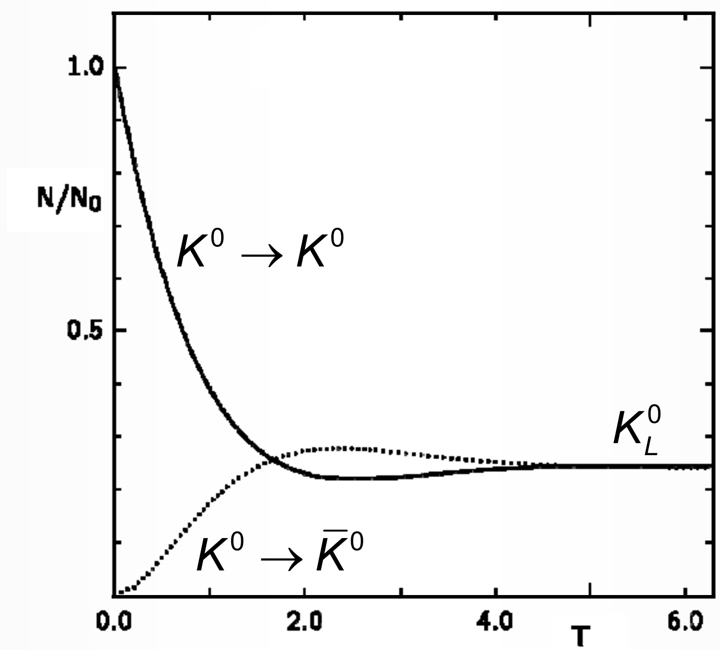

mixing probability:

χ ~ 50%

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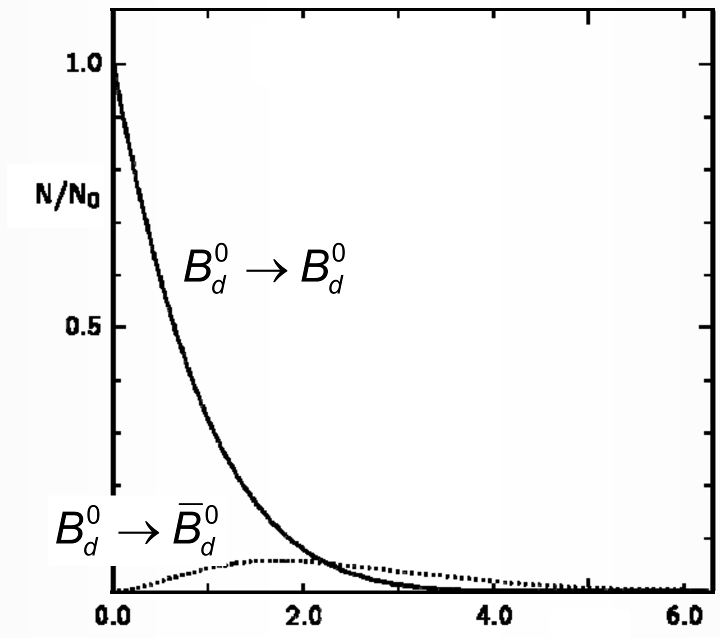

mixing probability:

$\chi = 18\%$

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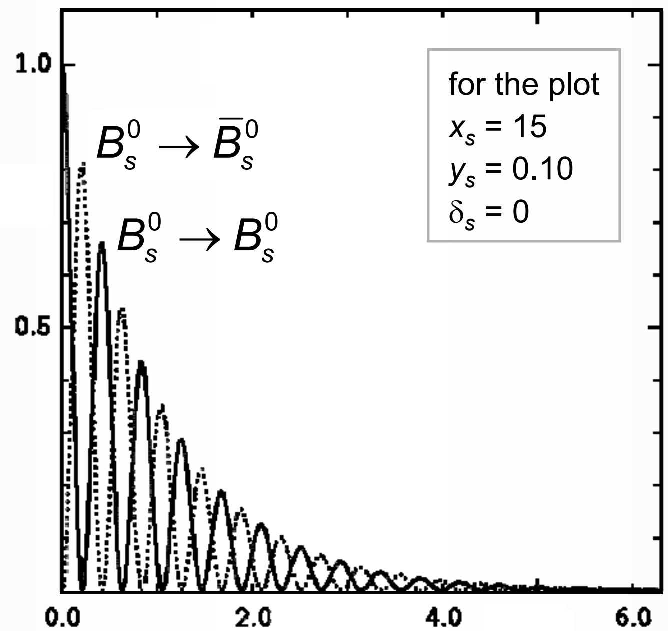


mixing probability:

$\chi \sim 50\%$

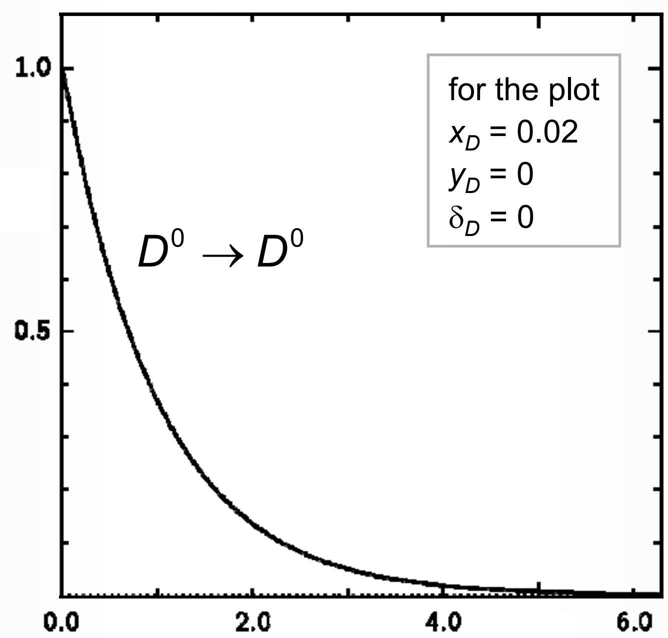
There are in Fact Four Meson Systems with Mixing

- Pairs of self-conjugate mesons that can be transformed to each other via flavor changing weak interaction transitions are:

$$|K^0\rangle = |\bar{s}d\rangle \qquad |D^0\rangle = |c\bar{u}\rangle \qquad |B_d^0\rangle = |\bar{b}d\rangle \qquad |B_s^0\rangle = |\bar{b}s\rangle$$

All measured by now !

- They have very different oscillation frequencies that can be understood from the CKM couplings occurring in the box diagrams



mixing probability:

$\chi \sim 2\times10^{-6}$

Three Types of *CP* Violation

- The *CP* violation discovered by Cronin, Fitch *et al*. involves two types of CPV:
  - ***CP* Violation in mixing:**

$$\text{Prob}(K^0 \to \bar{K}^0) \neq \text{Prob}(\bar{K}^0 \to K^0)$$

  - ***CP* Violation in interference of decays with and without mixing:**

$$\text{Prob}(K^0(t) \to \pi^+\pi^-) \neq \text{Prob}(\bar{K}^0(t) \to \pi^+\pi^-)$$

also called:
"indirect CPV"

- There is another, conceptually "simpler" type of *CP* violation :
  - ***CP* Violation in the decay:**

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

also called:
"direct CPV"

"Direct" *CP* Violation = *CP* Violation in Decay

- General signature: rate differences between *CP*-conjugated processes:

$$\Gamma\left(|i\rangle \rightarrow |f\rangle\right) \neq \bar{\Gamma}\left(|\bar{i}\rangle \rightarrow |\bar{f}\rangle\right)$$

- It **must** involve interference of amplitudes contributing to the processes.
  - To obtain interference, we need **phases that change sign under *CP***
  - Example: if the decay amplitudes are given by: $\{a_{1,2}, \phi_{1,2} \in \mathbb{R}\}$

$$A\left(|i\rangle \rightarrow |f\rangle\right) = a_1 e^{i\theta_1} e^{i\phi_1} + a_2 e^{i\theta_2} e^{i\phi_2}$$

$$\bar{A}\left(|\bar{i}\rangle \rightarrow |\bar{f}\rangle\right) = \left(a_1 e^{i\theta_1} e^{-i\phi_1} + a_2 e^{i\theta_2} e^{-i\phi_2}\right) \underbrace{e^{-2i(\xi_i - \xi_f)}}_{\text{unphysical phase}}$$

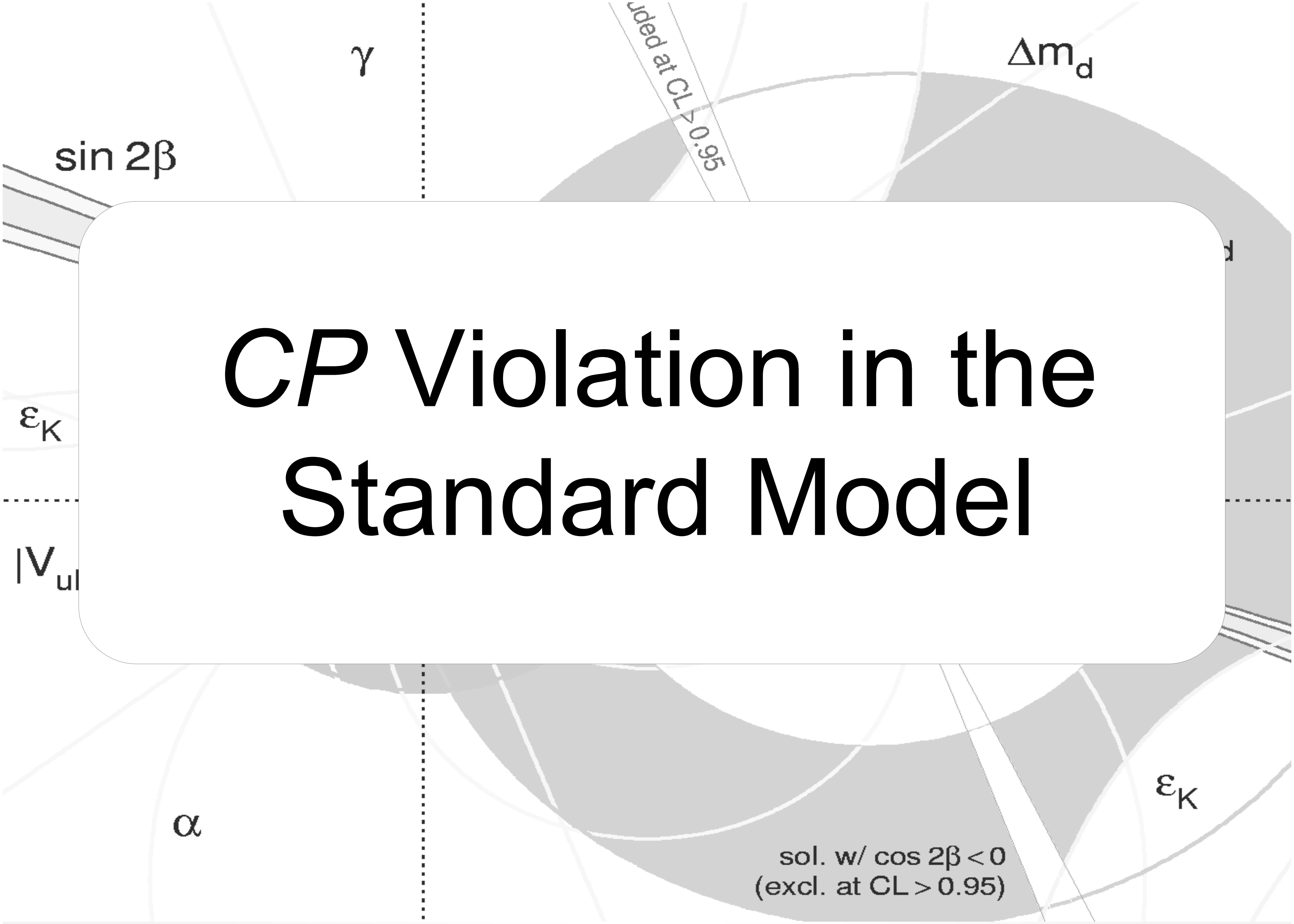
ϕ_j Alters sign under *CP* ("weak phase")

θ_j *CP* invariant ("strong phase")

where: $\Gamma\left(|i\rangle \rightarrow |f\rangle\right) \propto \left|A\left(|i\rangle \rightarrow |f\rangle\right)\right|^2$ and $\bar{\Gamma}\left(|\bar{i}\rangle \rightarrow |\bar{f}\rangle\right) \propto \left|\bar{A}\left(|\underline{i}\rangle \rightarrow |\bar{f}\rangle\right)\right|^2$

We can define the following *CP* asymmetry A_{CP}:

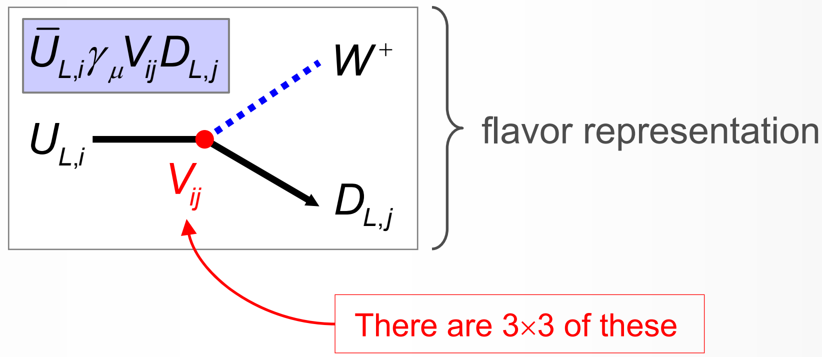
$$A_{CP} = \frac{\bar{\Gamma}\left(|\bar{i}\rangle \rightarrow |\bar{f}\rangle\right) - \Gamma\left(|i\rangle \rightarrow |f\rangle\right)}{\bar{\Gamma}\left(|\bar{i}\rangle \rightarrow |\bar{f}\rangle\right) + \Gamma\left(|i\rangle \rightarrow |f\rangle\right)} = \frac{2a_1 a_2 \sin(\theta_1 - \theta_2)\sin(\phi_1 - \phi_2)}{a_1^2 + a_2^2 + 2a_1 a_2 \cos(\theta_1 - \theta_2)\cos(\phi_1 - \phi_2)}$$



CP Violation in the Standard Model

3-Generation Quark Mixing in Standard Model

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



- Since mass and flavor eigenstates are not the same → quark mixing:

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

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:

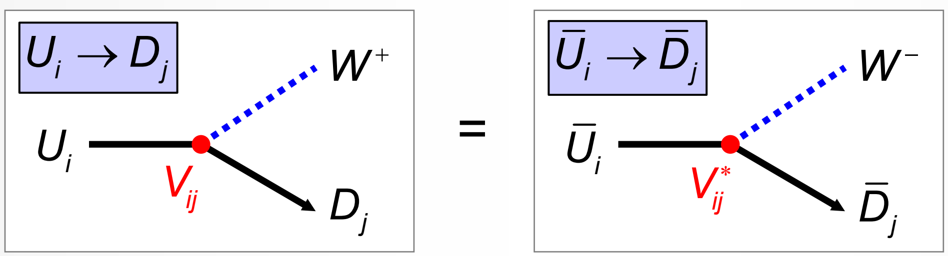
Recall:
$P\hat{x} = -\hat{x},\ P\hat{p} = -\hat{p}$
$T\hat{x} = \hat{x},\ T\hat{p} = -\hat{p}$

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

→ 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: $A(U_i \rightarrow D_j) = \bar{A}(\bar{U}_i \rightarrow \bar{D}_j)$ (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

- Unitarity condition:

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

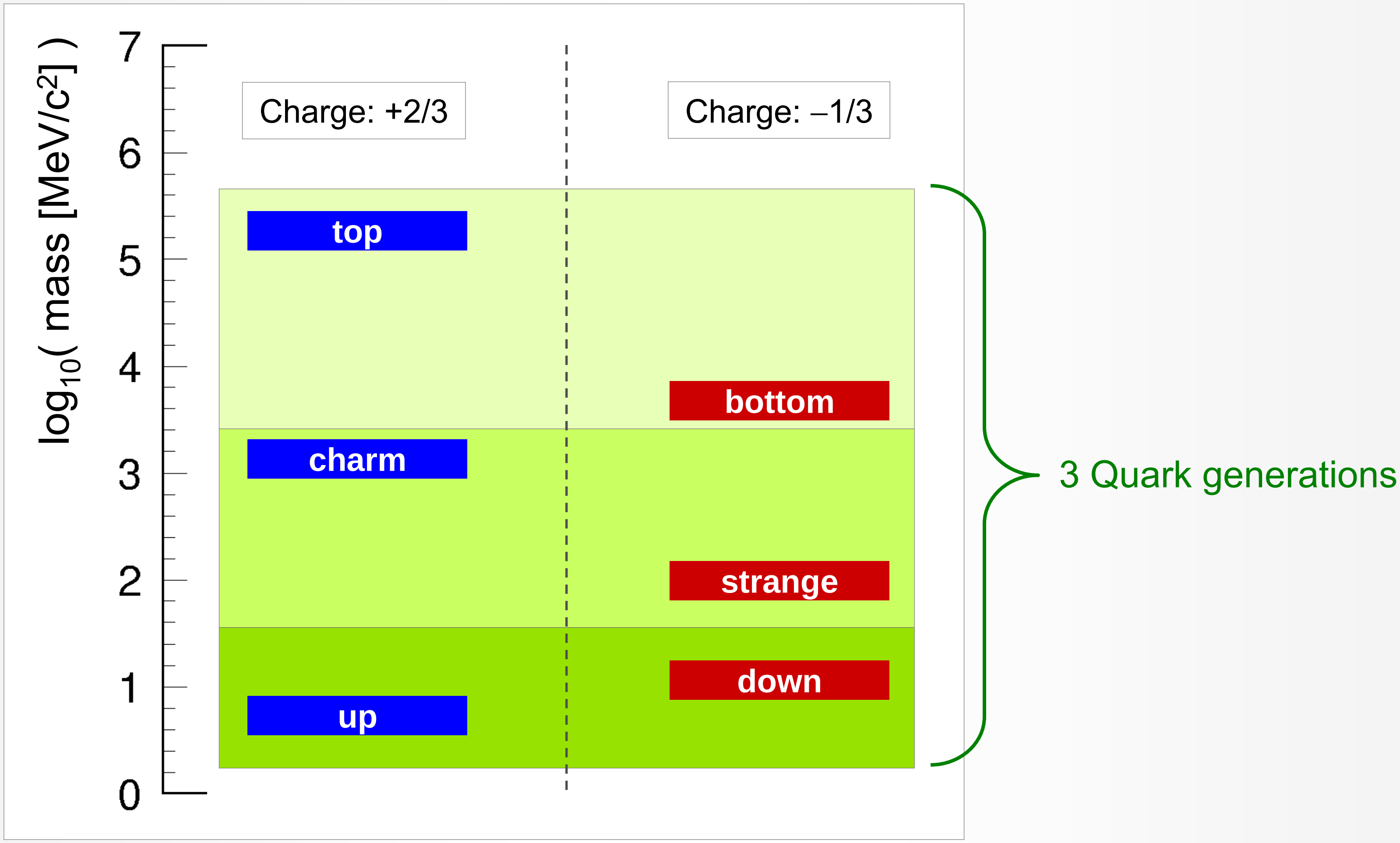
- The unitarity condition sets strong constraints on the V_{ij}, which initially has $2N^2$ unknowns (N is number of generations):

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) are organized in 3 generations:



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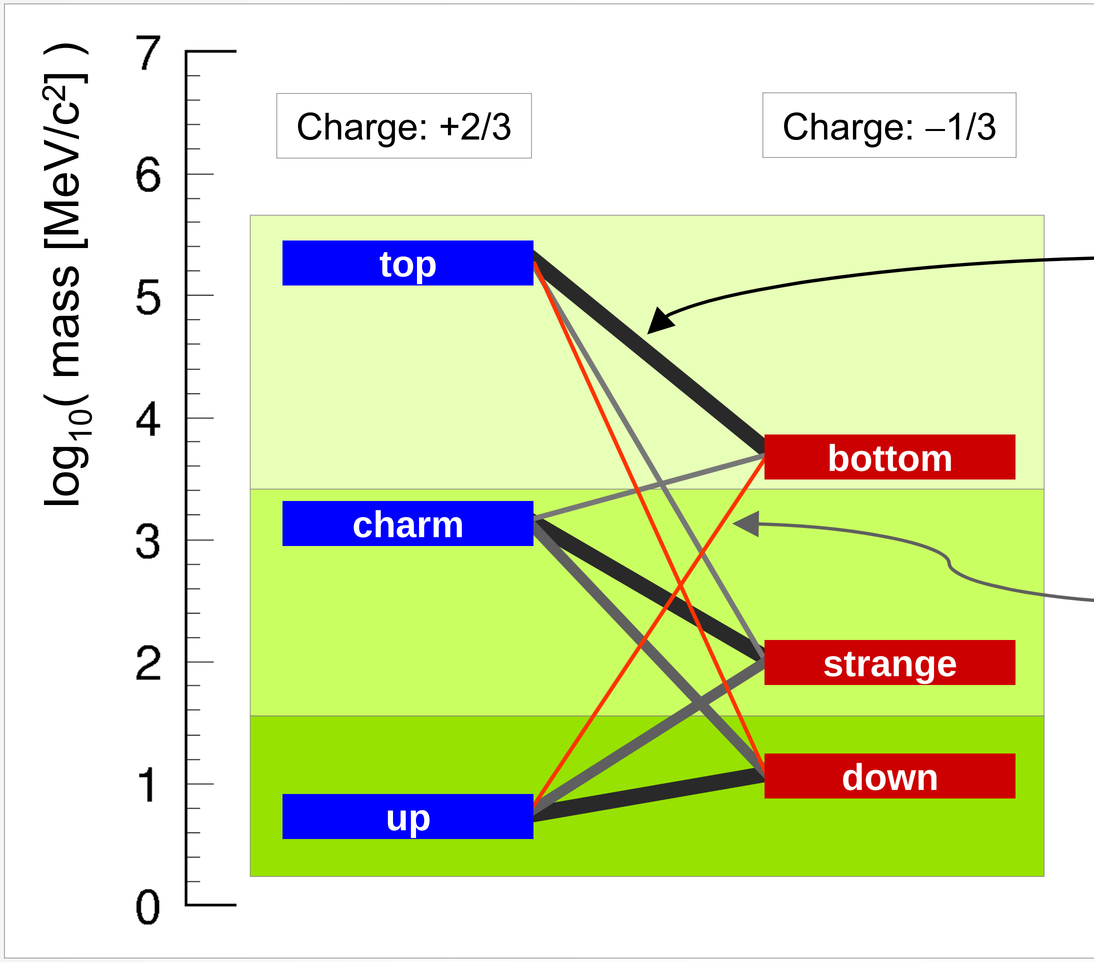


Flavour-changing transition by charged weak current (boldness indicates transition probability $\propto |V_{ij}|$)

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 small
- 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:

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

multiplying a line with its complex conjugate

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

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

multiply

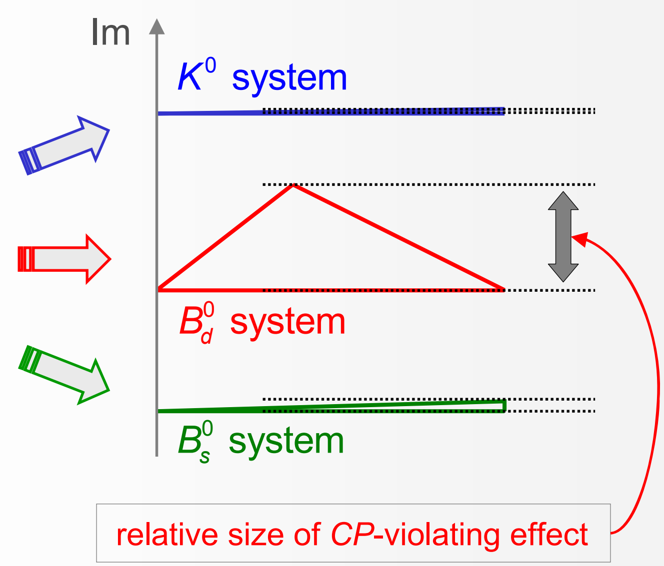
$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- The 6 complex "**Unitarity Triangles**" involve different physics processes

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

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

$$O(\lambda) + O(\lambda) + O(\lambda^5) = 0$$
$$O(\lambda^3) + O(\lambda^3) + O(\lambda^3) = 0$$
$$O(\lambda^4) + O(\lambda^2) + O(\lambda^2) = 0$$



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

multiply multiply

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

* *

CKM-type *CP* violation is always a rare phenomenon:

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

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

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

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

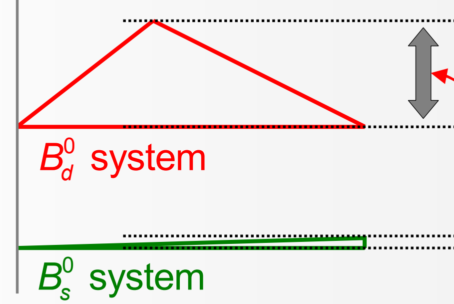
$$V_{ud}V_{td}^* + V_{us}V_{ts}^* + V_{ub}V_{tb}^* = 0$$

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

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

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

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

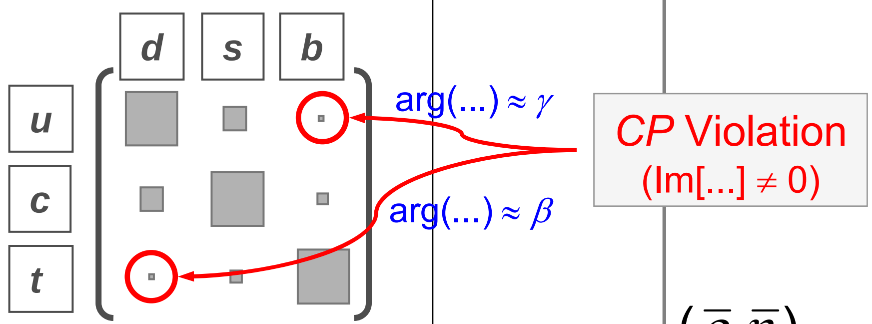


relative size of *CP*-violating effect

The CKM Matrix and the Unitarity Triangle

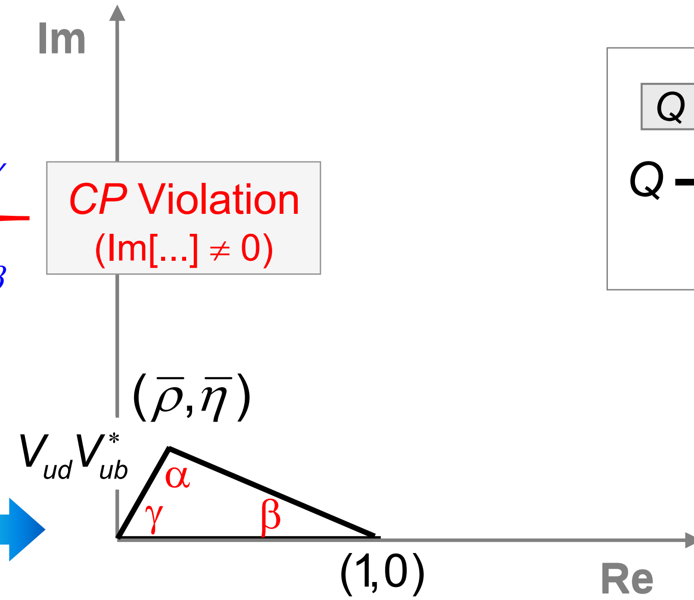
Kobayashi -Maskawa, 1973

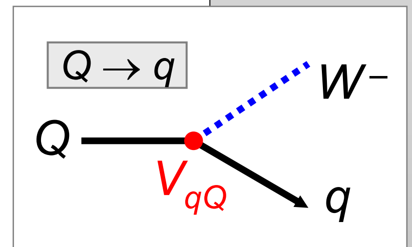
$V_{\rm CKM} =$



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

$$\left(\propto A\lambda^3 \propto -A\lambda^3 \propto A\lambda^3\right)$$





$$\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} + 1 + \frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*} = 0$$

phase invariant : $\bar\rho + i\bar\eta$

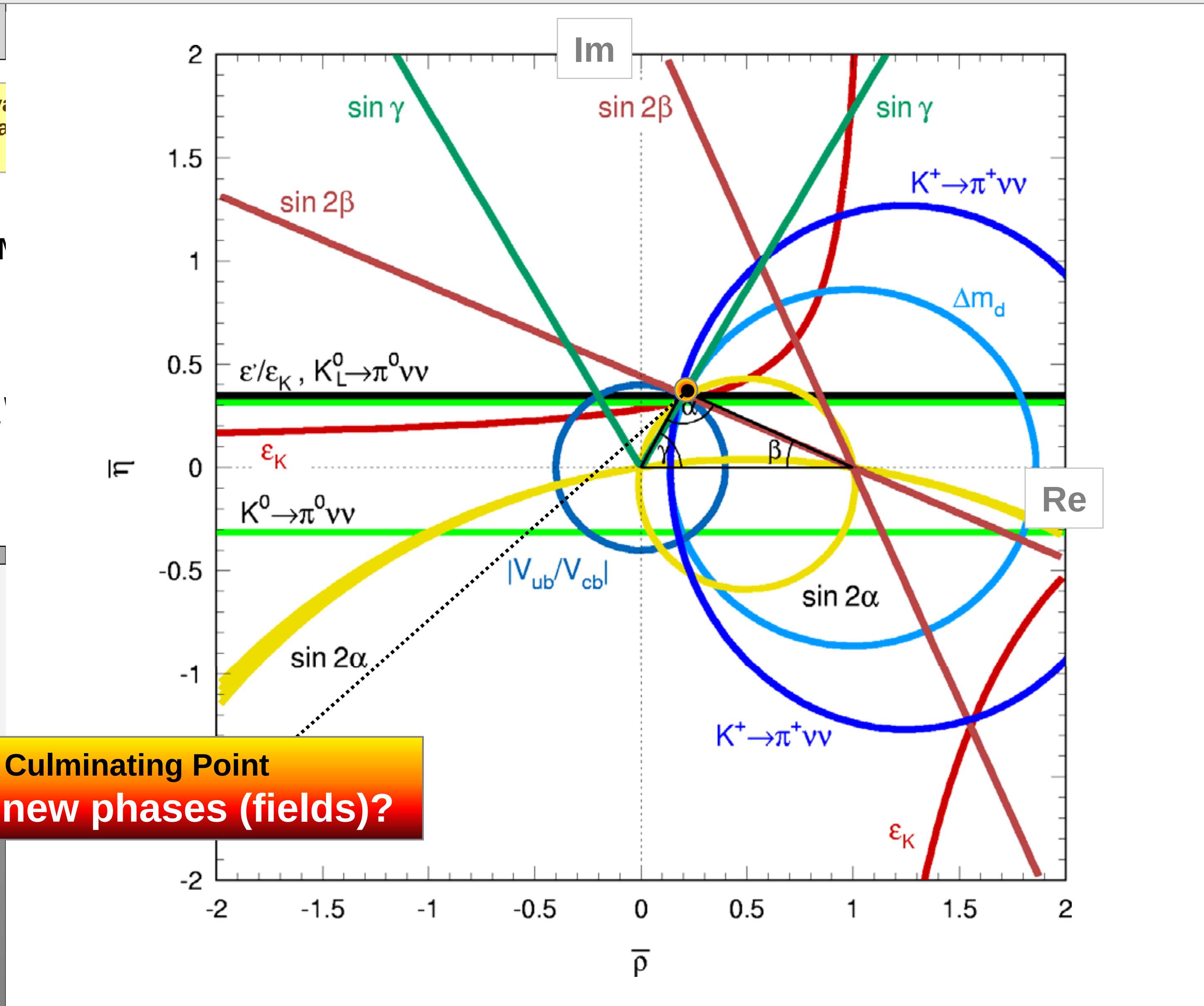
The CKM Matrix and the Unitarity Triangle

Kobaya
-Maska
1973

V_{CKI}

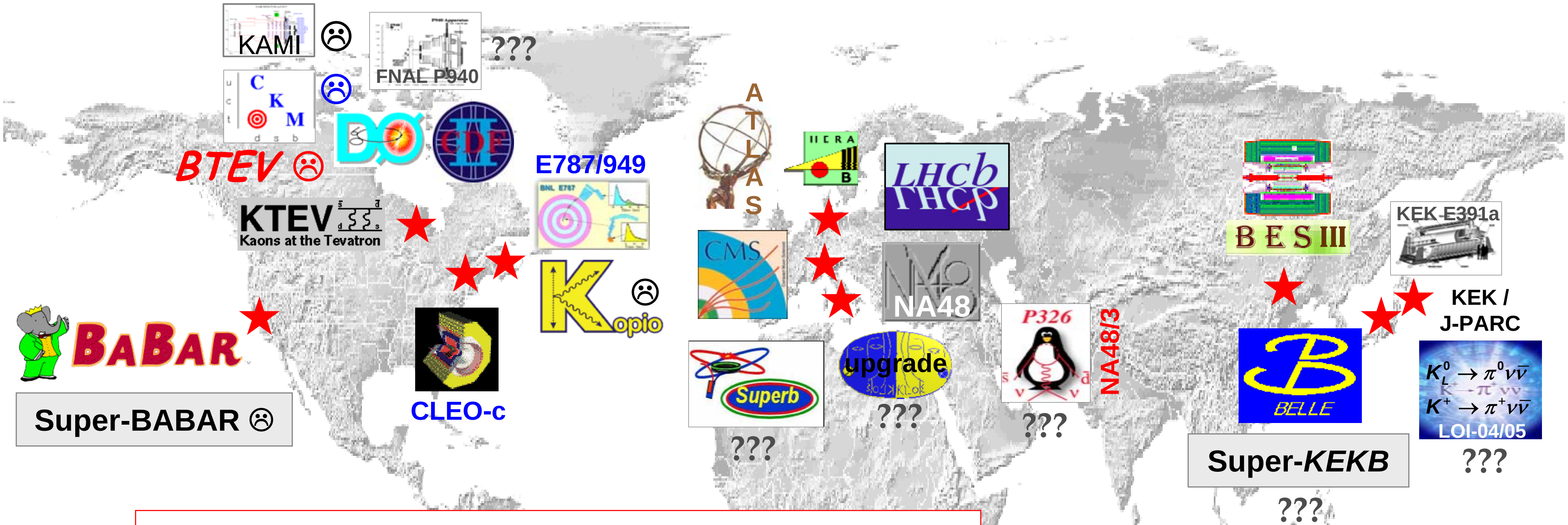
V_{ud}

$(\propto$



W−
q

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

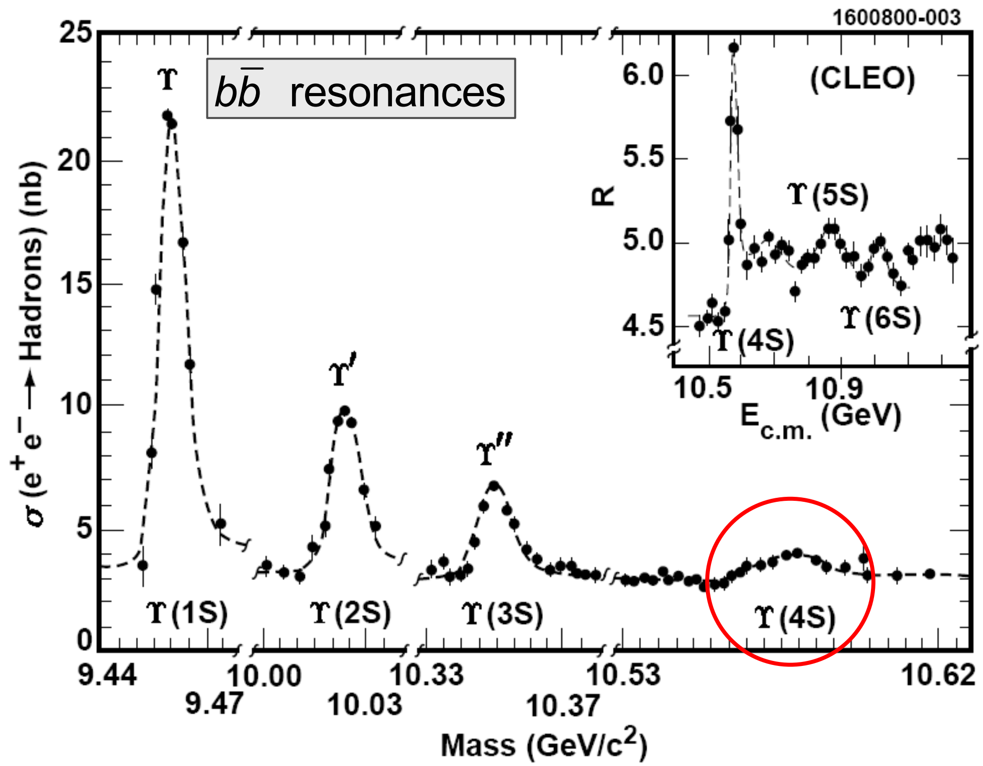
The study of *CP* violation, mixing and rare decays of *B* mesons allows to over-determine the Unitarity Triangle (UT)

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)



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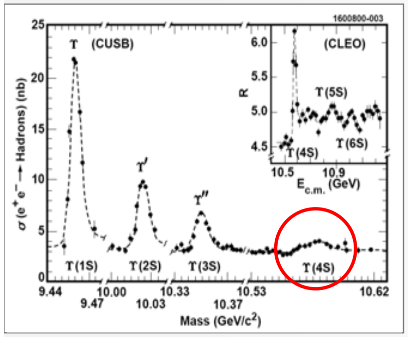
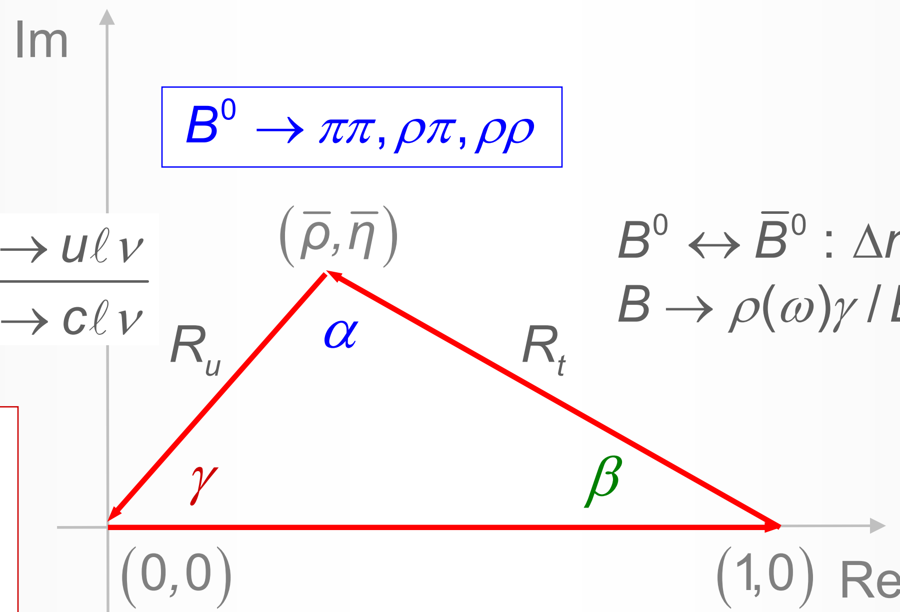


the B_d is also produced by the hadron machines

$$\frac{b \to u \ell \nu}{b \to c \ell \nu}$$

$$B^0 \to \pi\pi, \rho\pi, \rho\rho$$



$B^0 \leftrightarrow \bar{B}^0 : \Delta m_d$

$B \to \rho(\omega)\gamma \,/\, B \to K^{(*)}\gamma$

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

$B \to D_{K_S^0\pi^+\pi^-}K^{(*)}$

$B^0 \to DK_S^0$, ...

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

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

$B^0 \to J/\psi K_S^0$, ...

$B^0 \to \phi K_S^0$, ...

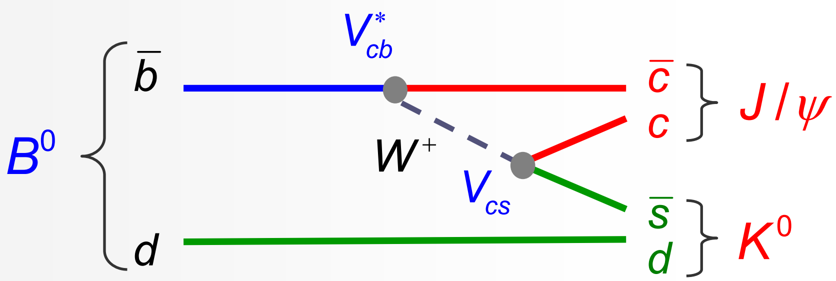
$b \to s\bar{s}s$

The Measurement of β (… or more precisely: $\sin 2\beta$)

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

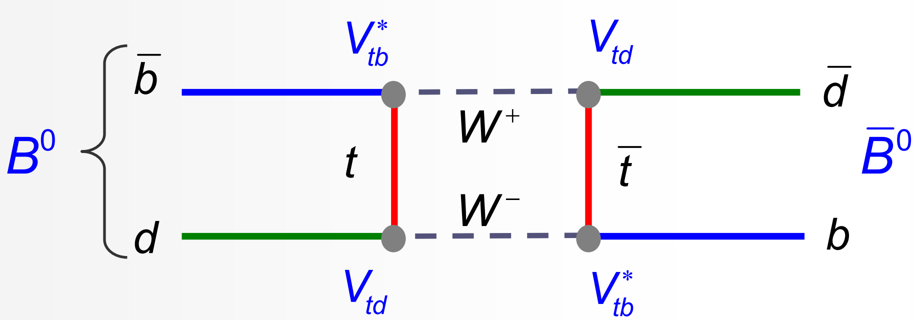
$$\beta = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$

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 (?)" $J/\psi K^0$



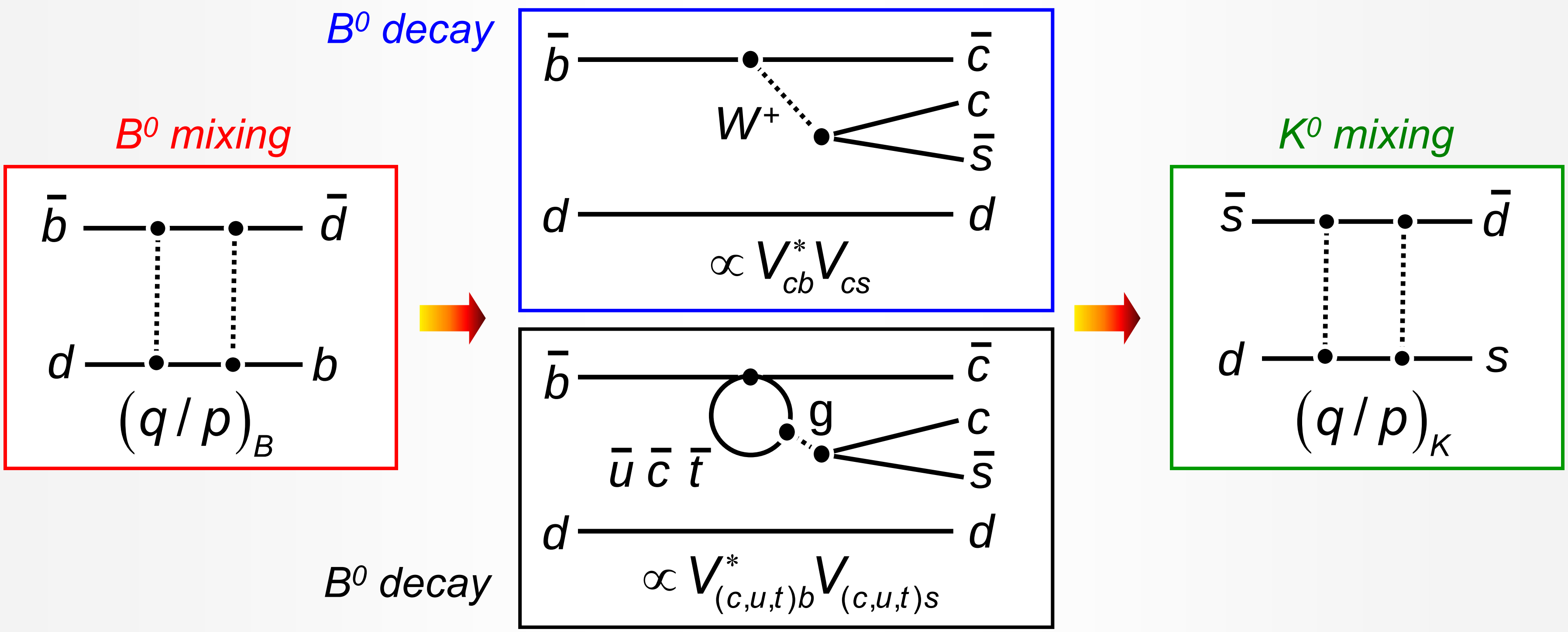
$\Rightarrow \quad \propto \left(V_{td}V_{tb}^*\right)^2$ not bad ☺

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

The Golden Channel: $B^0, \bar{B}^0 \to J/\psi K^0$

Relative phase:

$$\arg\left[\frac{A\left(B^0 \to J/\psi K^0\right)}{A\left(B^0 \underset{\text{mix}}{\to} \bar{B}^0 \to J/\psi \bar{K}^0 \underset{\text{mix}}{\to} J/\psi K^0\right)}\right] = \arg\left[\frac{V_{cs}V_{cb}^*}{\left(V_{td}V_{tb}^*\right)^2 \cdot V_{cs}^*V_{cb} \cdot \left(V_{cd}^*V_{cs}\right)^2}\right] = \arg\left[\frac{\left(V_{cd}V_{cb}^*\right)^2}{\left(V_{td}V_{tb}^*\right)^2}\right] = -2\beta$$



Single weak phase:

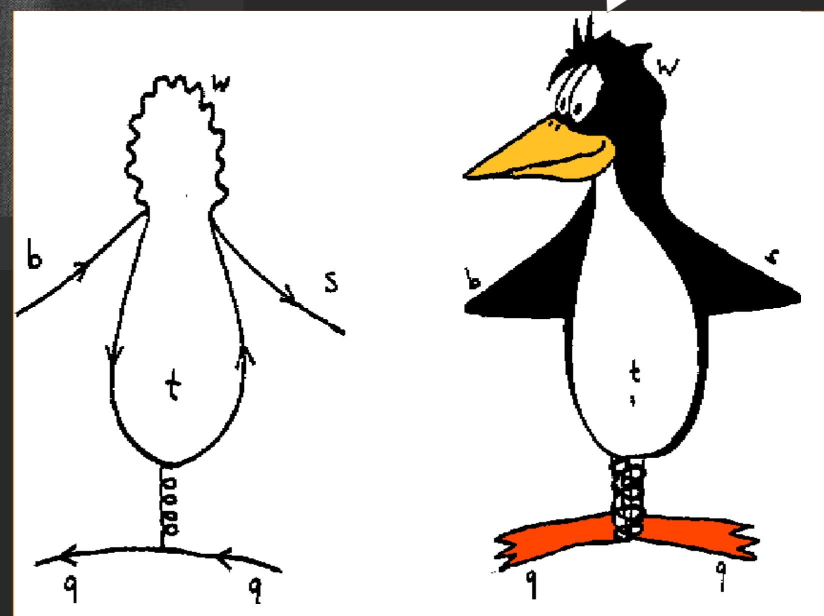
1. Clean *CP* phase
2. No direct CPV

A controversy…

Mirror image of Richard Feynman

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

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:

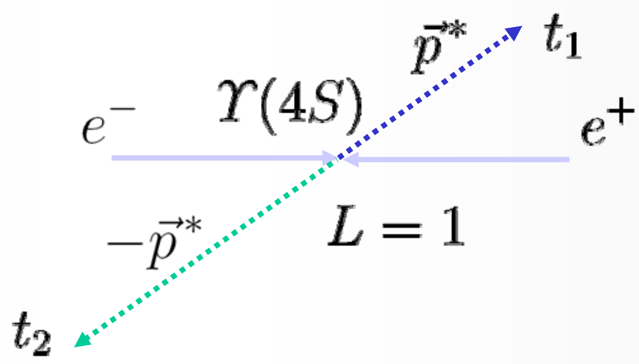
1. Identify a final state that is ***CP* eigenstate** (e.g., $J/\psi\ K_S$)
2. Determine the **flavour** of the **decaying *B*^{0}** (assume here it is a B^0)
3. How can we do this if $J/\psi\ K_S$ **can be reached by both *B* flavors** ?
4. If we could produce the $B^0\bar{B}^0$ pairs in a **coherent** 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:

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

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)

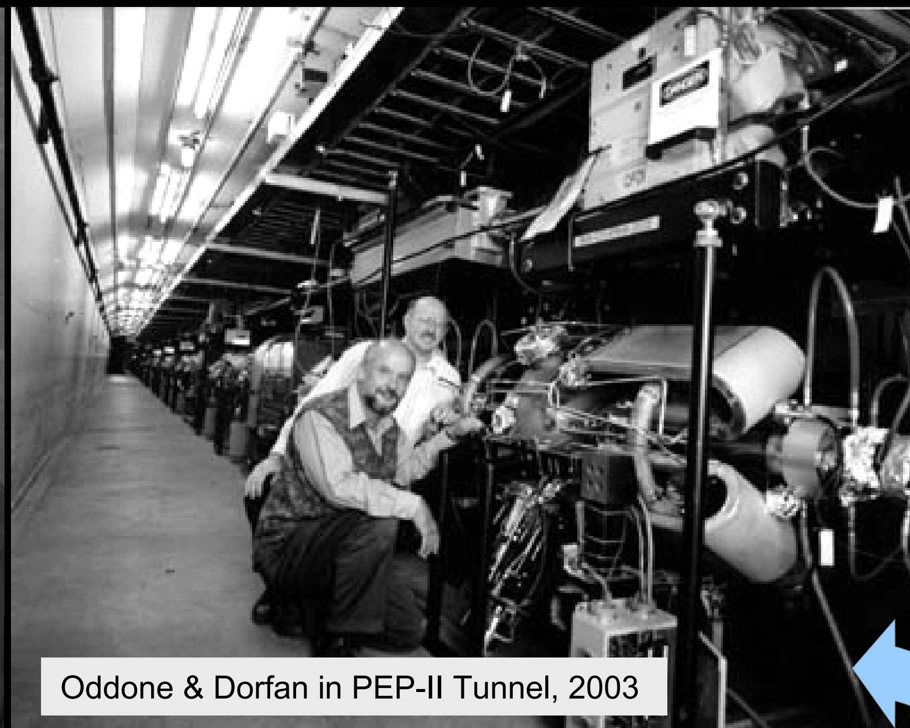
Cannot perform decay-time-dependent measurements ?

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**, right? What we need is an **asymmetric-energy *B* Factory** with luminosity of order $5\text{x}10^{33}$

Pier Oddone,LBL (now: FNAL)



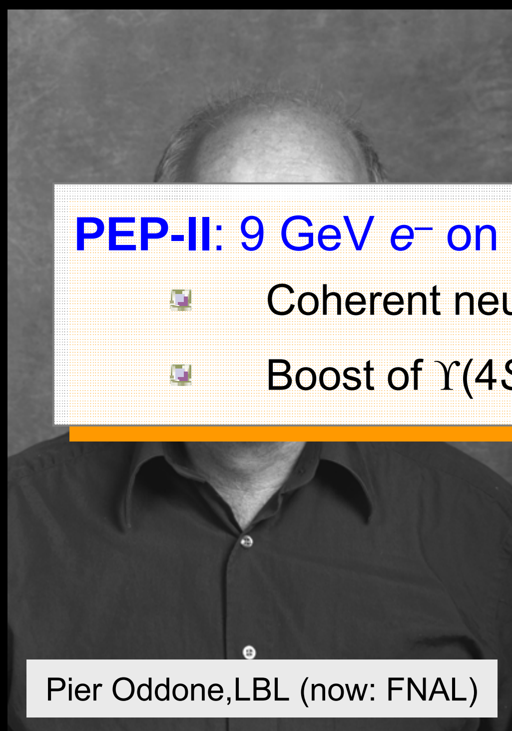
Oddone & Dorfan in PEP-II Tunnel, 2003

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

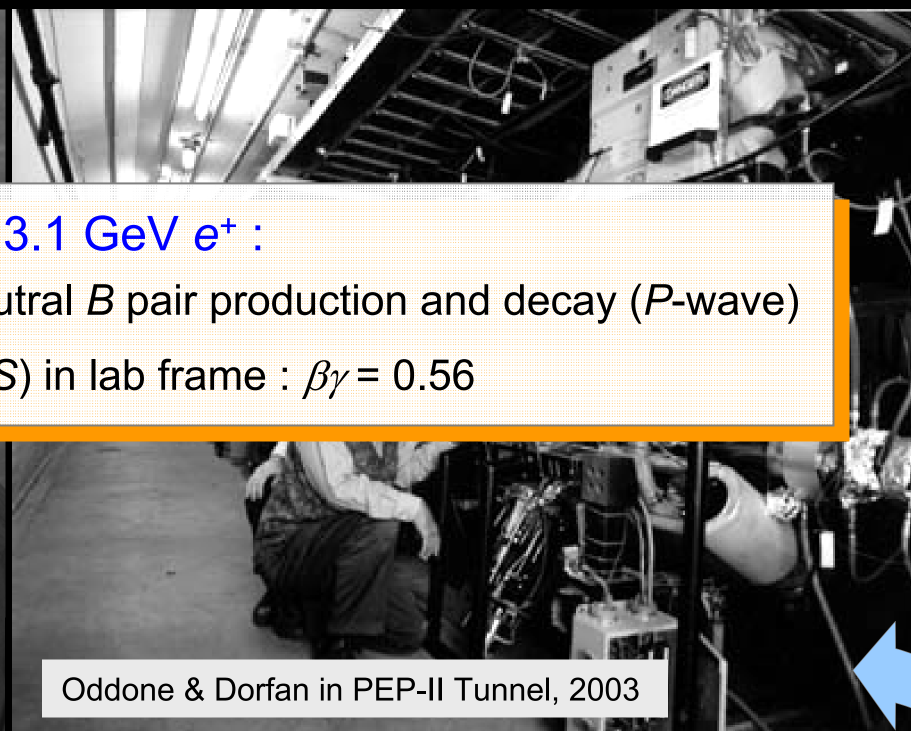
Pier Oddone's Clever Idea (1987)

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**, right? What we need is an **asymmetric-energy *B* Factory** with luminosity of order $5\text{x}10^{33}$



Pier Oddone,LBL (now: FNAL)



Oddone & Dorfan in PEP-II Tunnel, 2003

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 : $\beta\gamma = 0.56$

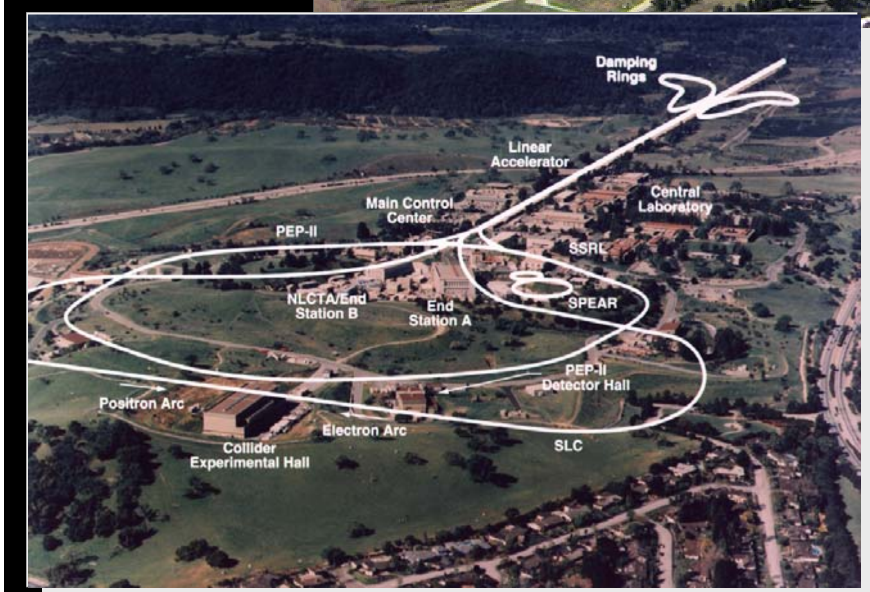
10 years later exist two asymmetric *B* Factories :
PEP-II at SLAC and KEKB at KEK

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

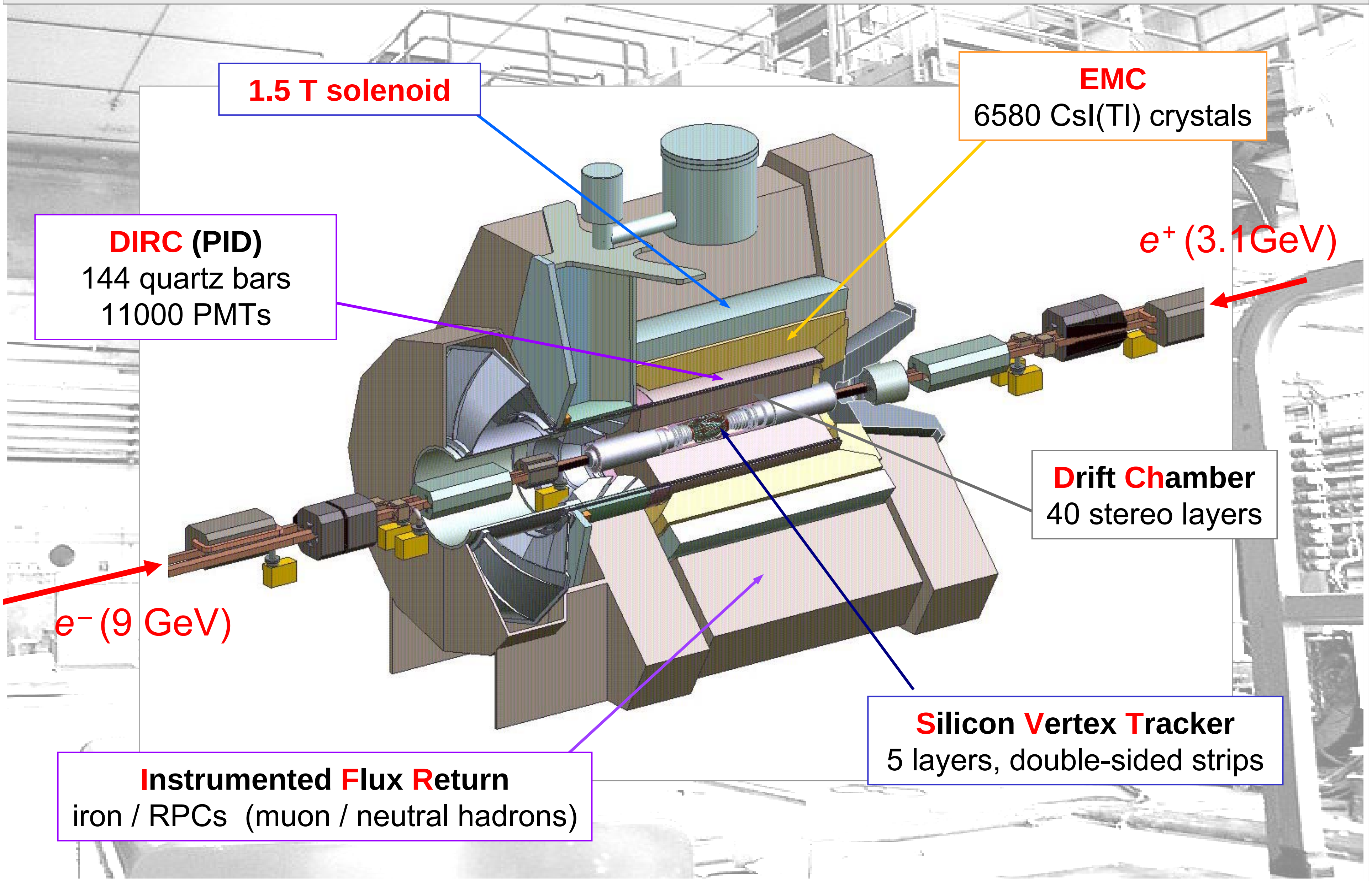
SLAC

Stanford
Linear
Accelerator
Center

PEP-II delivered $\int L$ = 500 fb^{-1}
Peak record: 1.2 10^{34} cm^{-2}s^{-1}



The BABAR Detector



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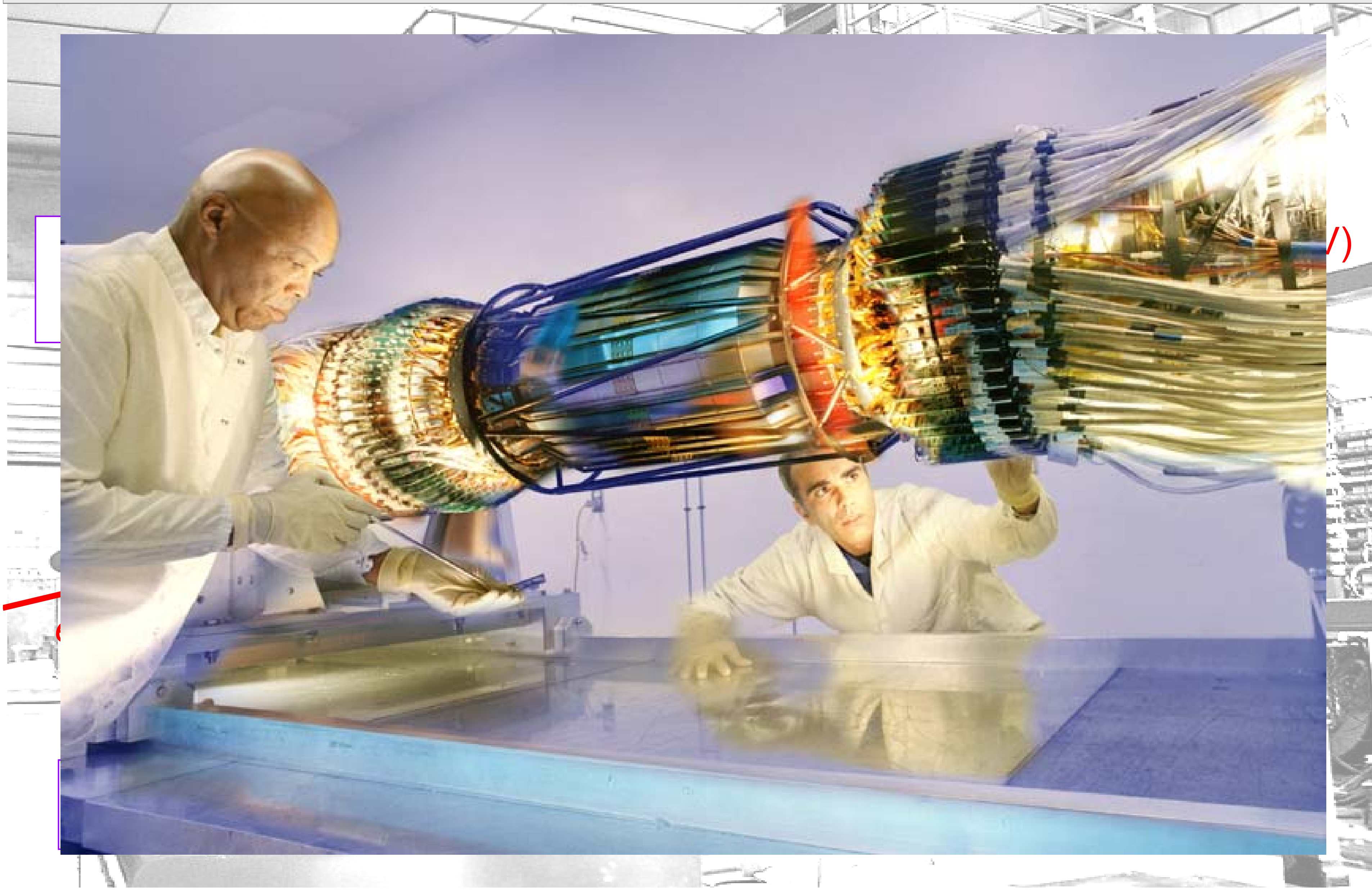

The BABAR Detector

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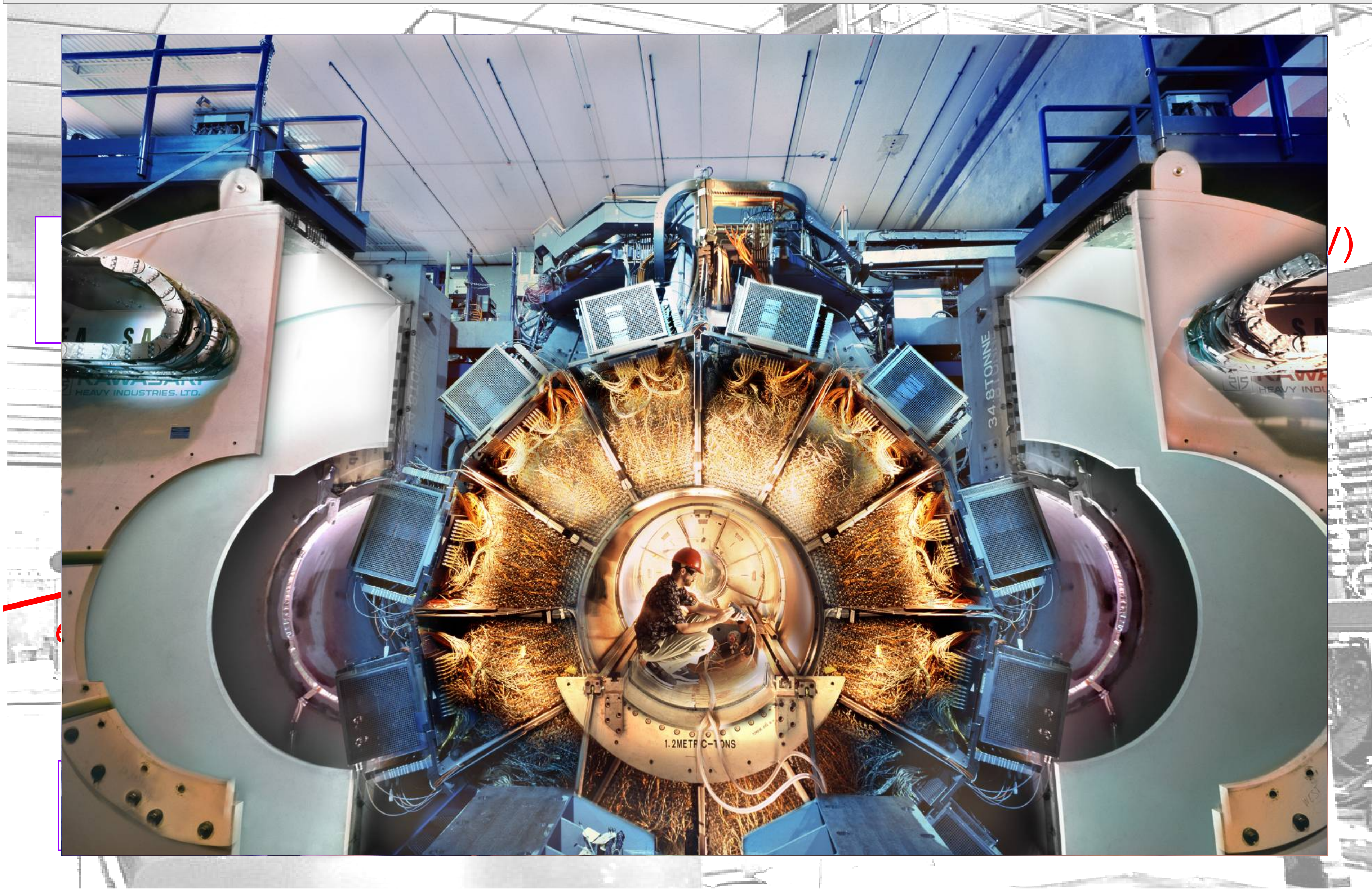
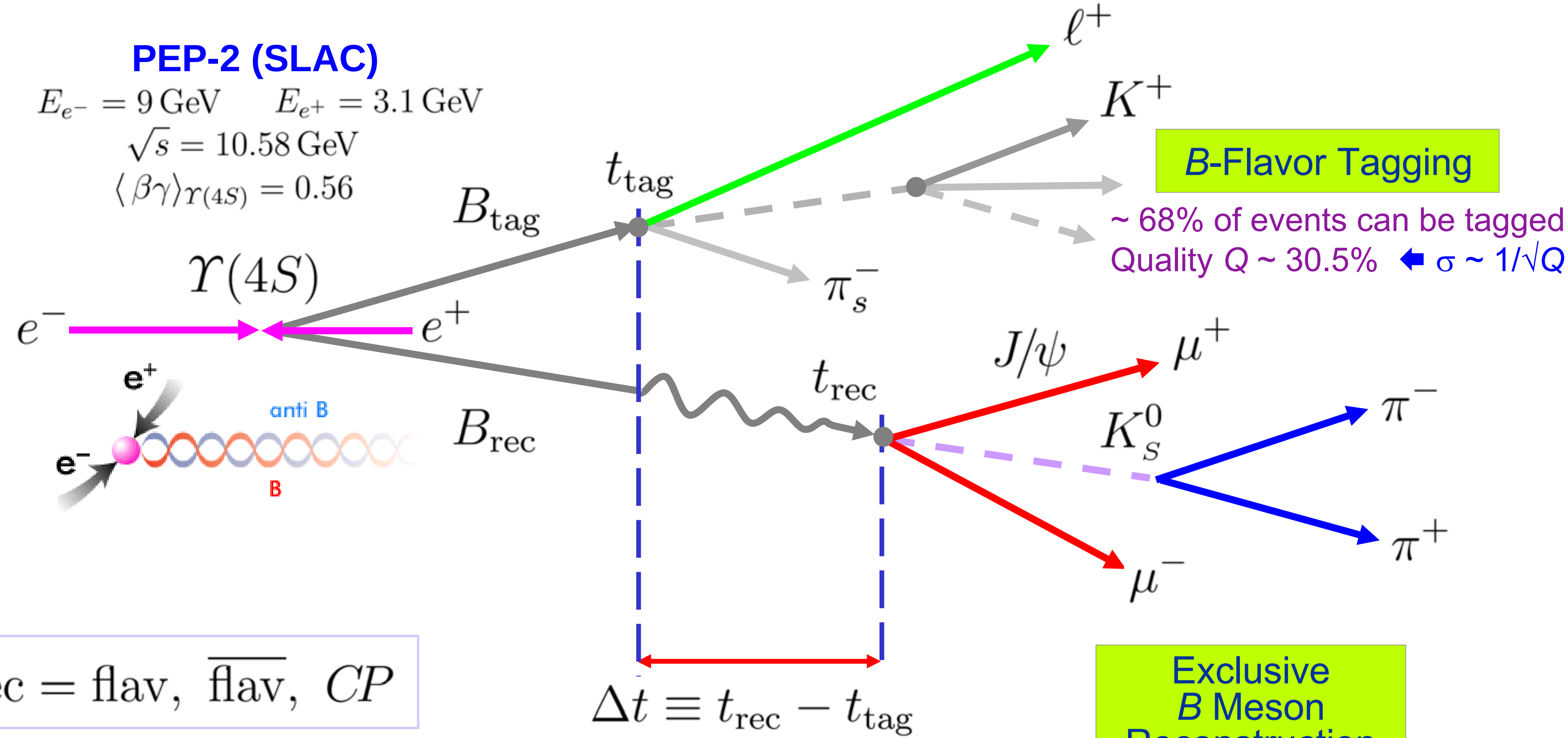


Analysis Technique at the *B* Factories



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

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

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

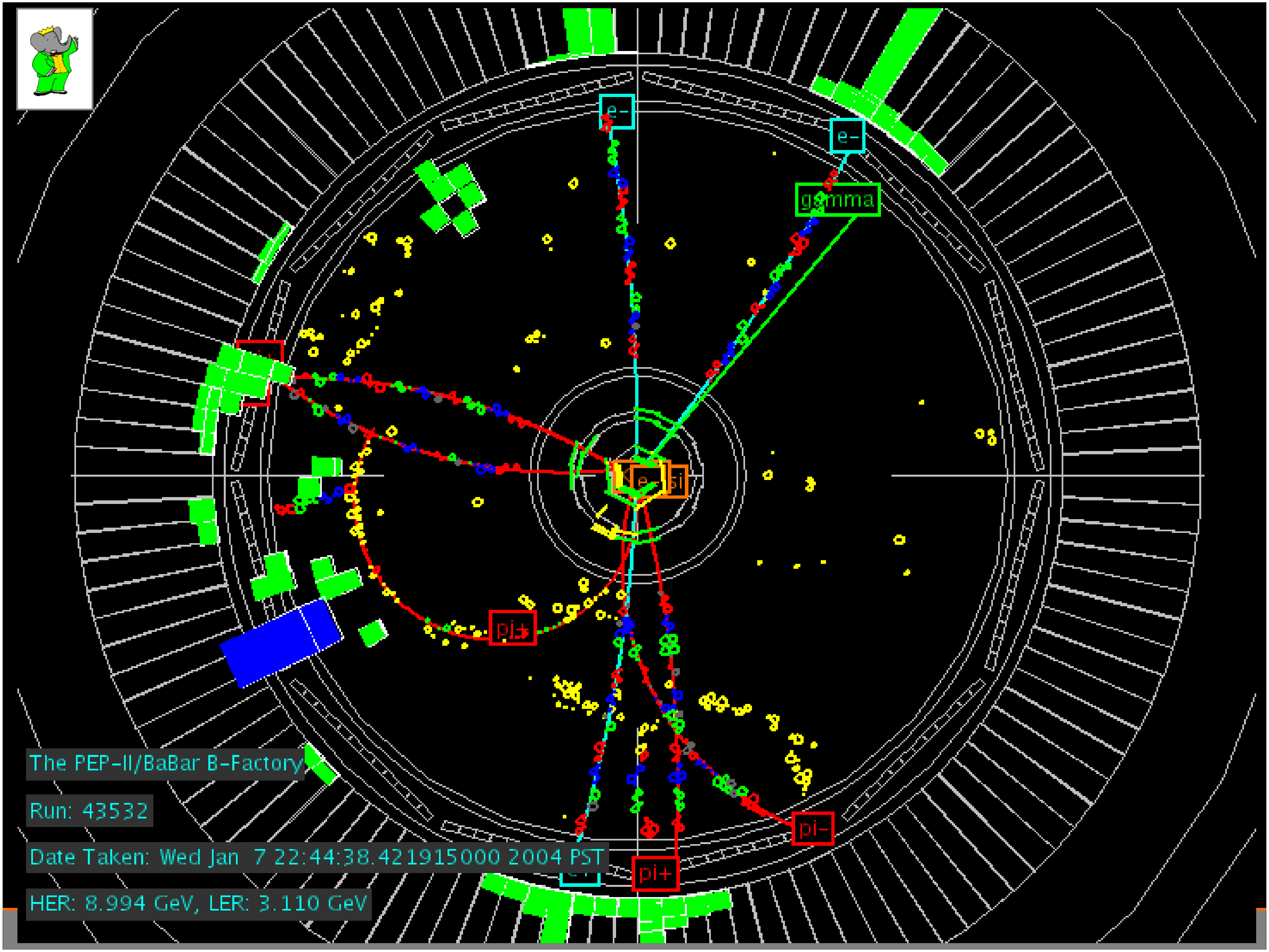
$$f_{B^0} = X\ell^+\nu,\ XK^+,\ X\pi_s^-, \ldots$$

Vertexing &
Time Difference
Determination

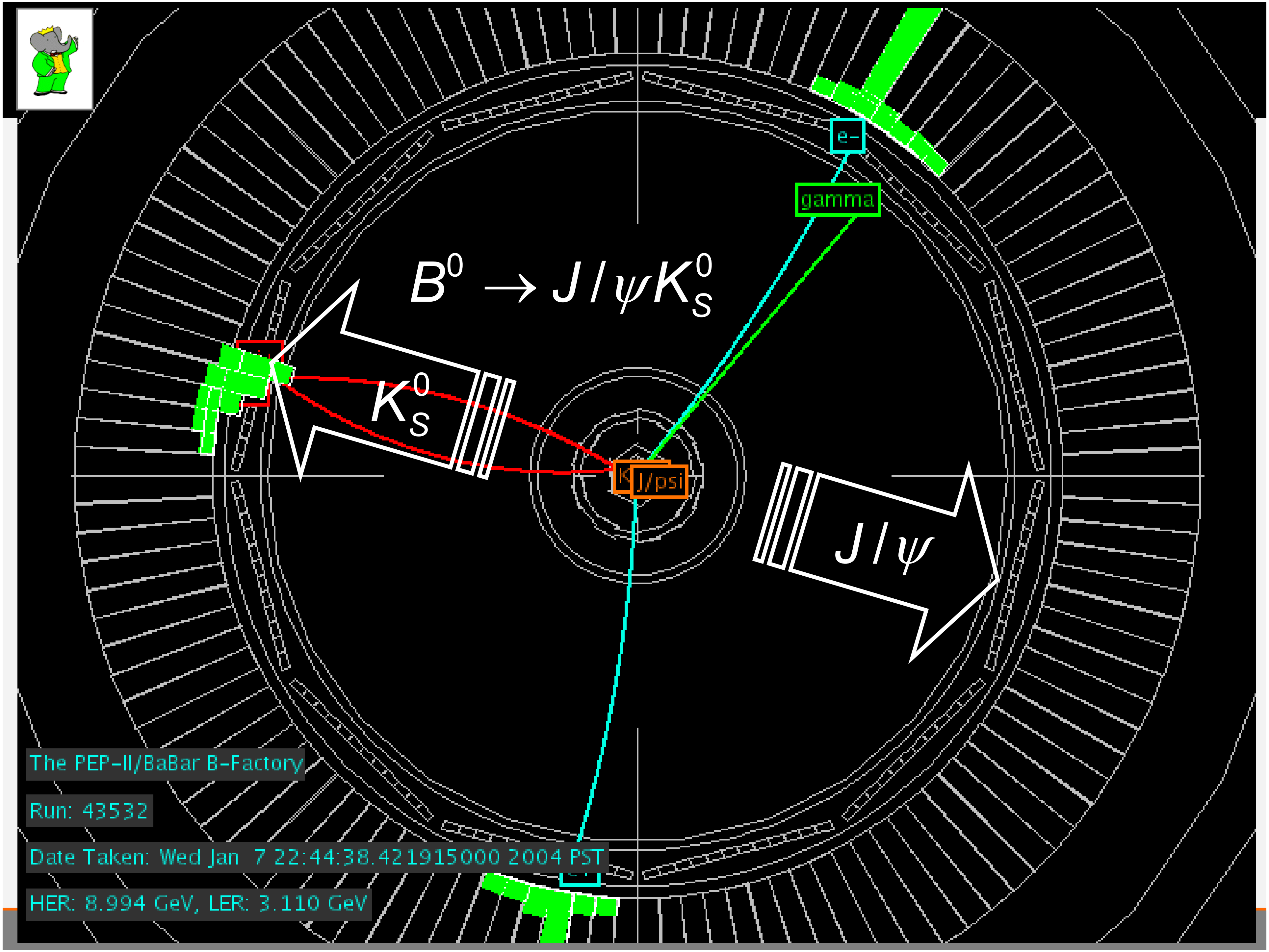
Exclusive
B Meson
Reconstruction

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

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



e-
e-
gamma
e-
si
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



$B^0 \to J/\psi K_S^0$
K_S^0
J/ψ
e-
gamma
J/psi
The PEP-II/BaBar B-Factory
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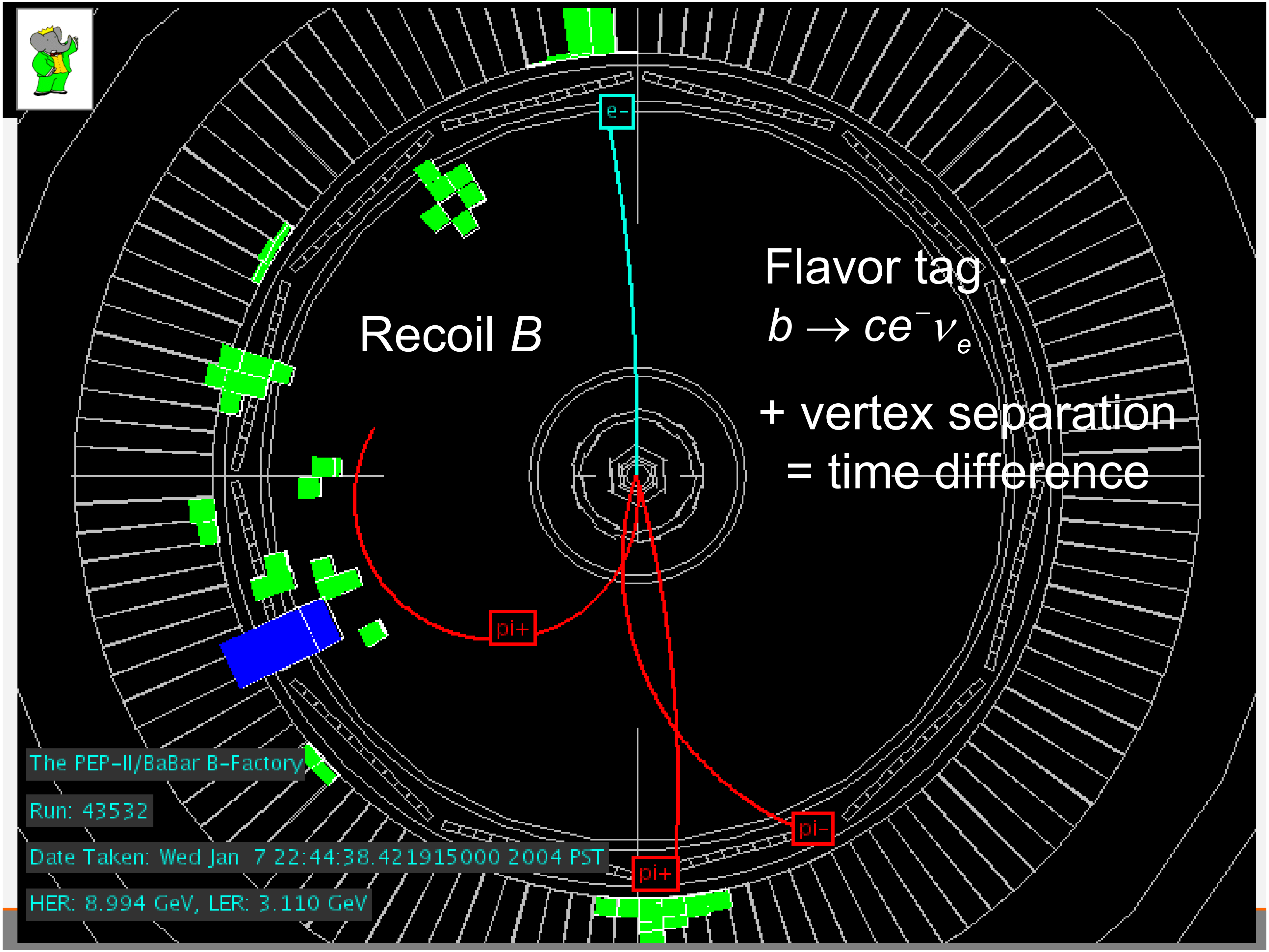


e-
Flavor tag :
$b \to c e^{-} \nu_{e}$
Recoil B
+ vertex separation
= time difference
pi+
pi-
pi+
The PEP-II/BaBar B-Factory
Run: 43532
Date Taken: Wed Jan 7 22:44:38.421915000 2004 PST
HER: 8.994 GeV, LER: 3.110 GeV

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

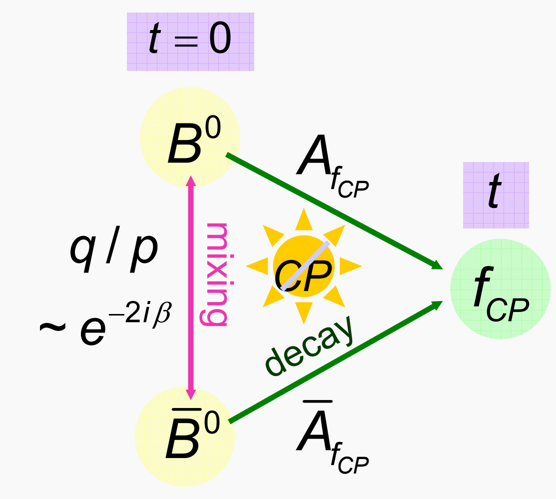
- *CP* Violation due to the interference of decays with and without mixing

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

$$A_{f_{CP}}(t) = \frac{\Gamma(\bar{B}^0(t) \to f_{CP}) - \Gamma(B^0(t) \to f_{CP})}{\Gamma(\bar{B}^0(t) \to f_{CP}) + \Gamma(B^0(t) \to f_{CP})}$$

$$= S_{f_{CP}} \sin(\Delta m_d t) - C_{f_{CP}} \cos(\Delta m_d t)$$

with : $S_{f_{CP}} = \sin(2\beta)$ and $C_{f_{CP}} = 0$ for $B \to J/\psi K^0, \phi K^0$



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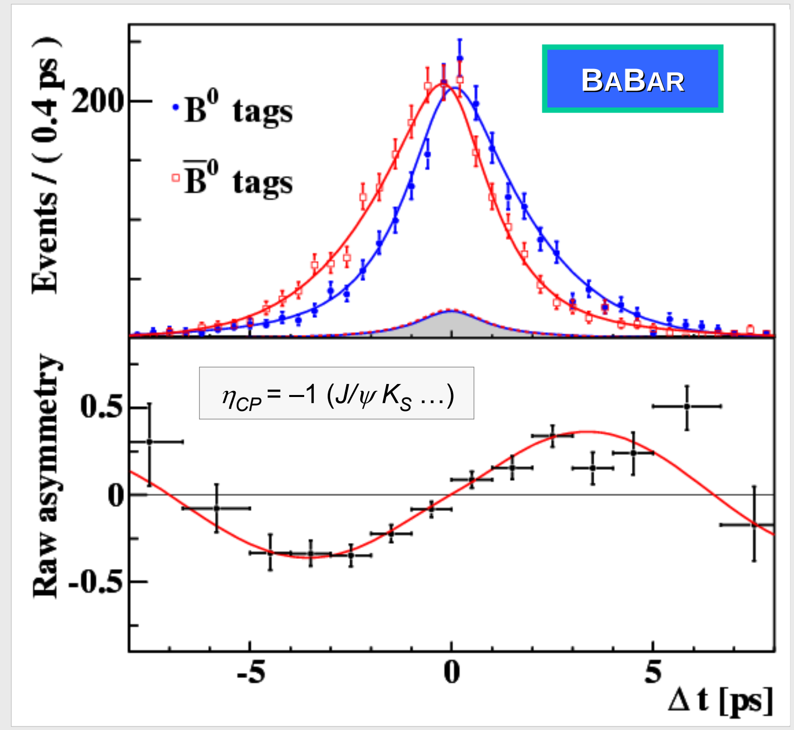

$$\sin(2\beta)|_{WA} = 0.681 \pm 0.025$$

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

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

First observed by NA48 and KTeV in kaon system

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

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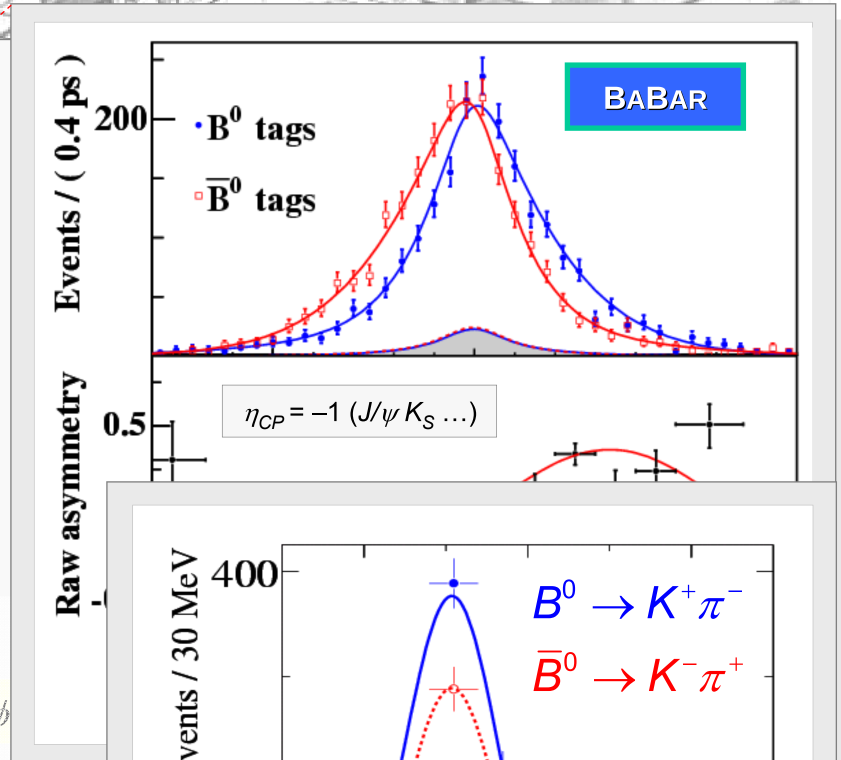
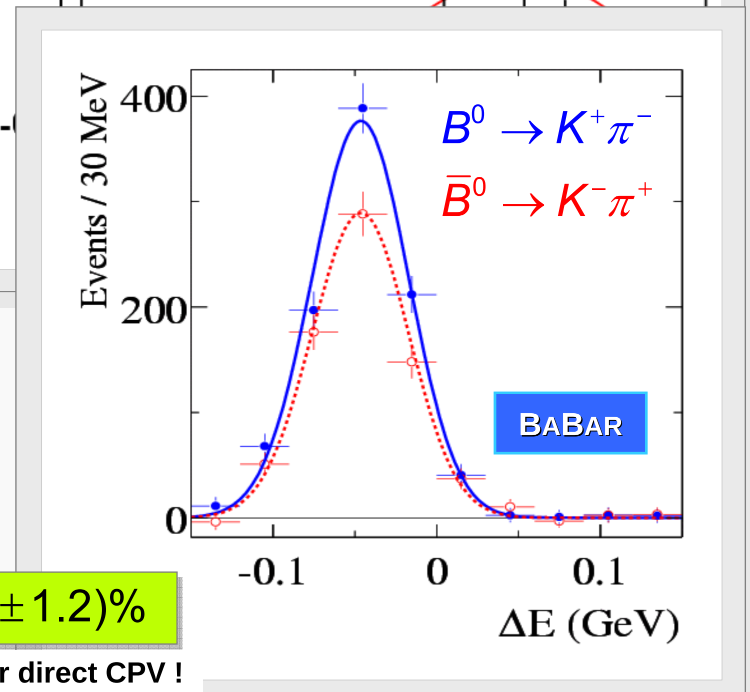


- Direct *CP* Violation is due to interference of decay amplitudes with different weak and hadronic phases

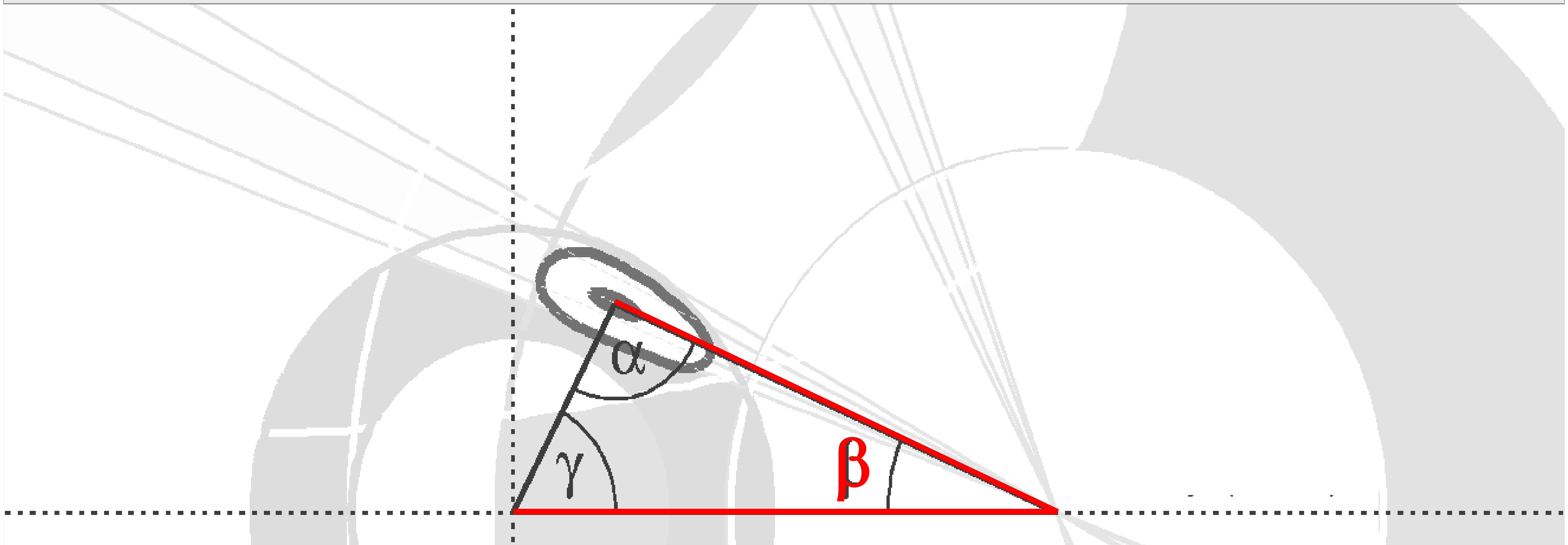
$$\mathrm{Prob}(\bar{B} \to \bar{f}) \neq \mathrm{Prob}(B \to f)$$

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



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

A Standard Model Prediction for $\sin(2\beta)$? **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 $\sin(2\beta)$.

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.: ρ and η

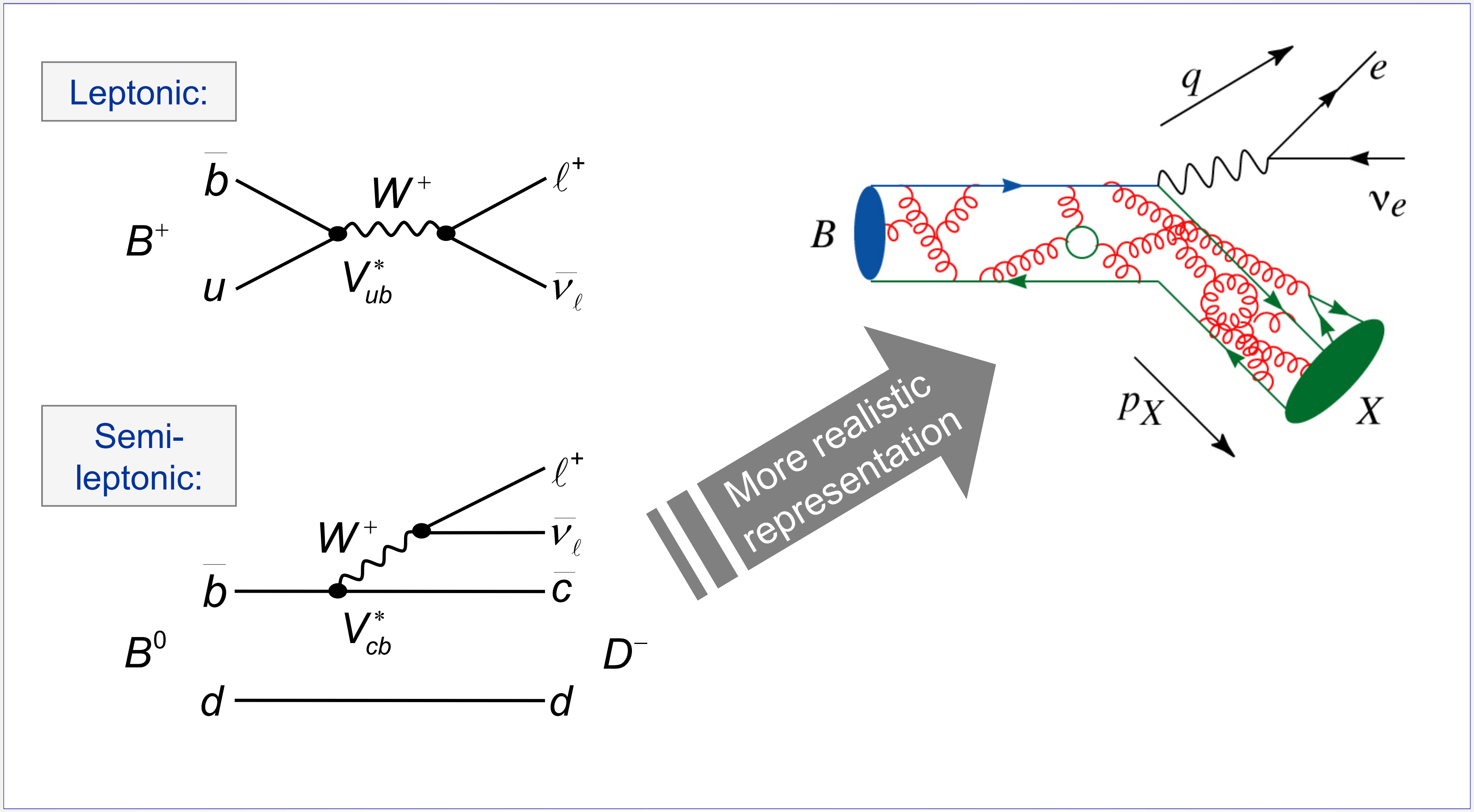
$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \Leftrightarrow \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}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

- 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 $b \to d$ loop transitions determine $|V_{td}|$
  4. The leptonic decay $B^+ \to \tau^+\nu$ ($\bar{b}d \to W^+$ "tree annihilation") determines $|V_{ub}|$

Flavour Physics: Theoretical Tools

The Electroweak physics to be studied is often hidden in an hadronic environment



Flavour Physics: Theoretical Tools

Theoretical tools help us to extract the fundamental electroweak quantities

Lattice Gauge Theory	Example: matrix elements in meson anti-meson mixing, decay constants, …
Chiral Perturbation Theory Low-energy effective theory, $m(u,d,s) \ll m(\rho)$	$\|V_{us}\|$ from $K \to \pi \ell \nu$
Heavy Quark Effective Theory (HQET) $m_Q \gg \Lambda_{QCD}$ and develop Lagrangian in $(1/m_Q)^n$	$\|V_{cb}\|$ from $B \to D^* \ell \nu$ at zero recoil
Heavy Quark Expansion Perturbative QCD + expansion in local operators (OPE)	$\|V_{cb}\|$ from $B \to X_c \ell \nu$ inclusive
QCD Factorization (nowadays: SCET) Color transparency	$B \to$ heavy+light branching fractions
QCD Sum Rules Quark hadron duality	α_s, quark masses, condensates, …
Flavour Symmetries Use SU(2) and SU(3) symmetries between decay amplitudes	$B \to \pi\pi$ isospin analysis, …

FIT INPUT

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 ± 0.005) 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 an[illegible]ysis
$S_{\rho\rho,L}^{+-}$	-0.05 [illegible] 0.17
$C_{\rho\rho,L}^{+-}$	$-0.06 \pm$ [illegible]3
$S_{\rho\rho,L}^{00}$	[illegible]
$C_{\rho\rho,L}^{00}$	[illegible].4 ± 0.[illegible] ± 0.2
$\mathcal{B}_{\rho\rho,L}$ all charges	Input[illegible]o i[illegible]spin analysis
$B^0 \to (\rho\pi)^0 \to 3\pi$	Time-d[illegible]ndent Dalitz analysis
$B^- \to D^{(*)}K^{(*)-}$	Inputs to 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
[illegible]	(493.677 ± 0.016) MeV
[illegible]	$(3.4833 \pm 0.0066) \times 10^{-12}$ MeV
[illegible]	(5.2794 ± 0.0005) GeV
m_{B_s}	(5.3696 ± 0.0024) GeV
m_W	(80.423 ± 0.039) GeV
G_F	1.16639×10^{-5} 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 RESULTS

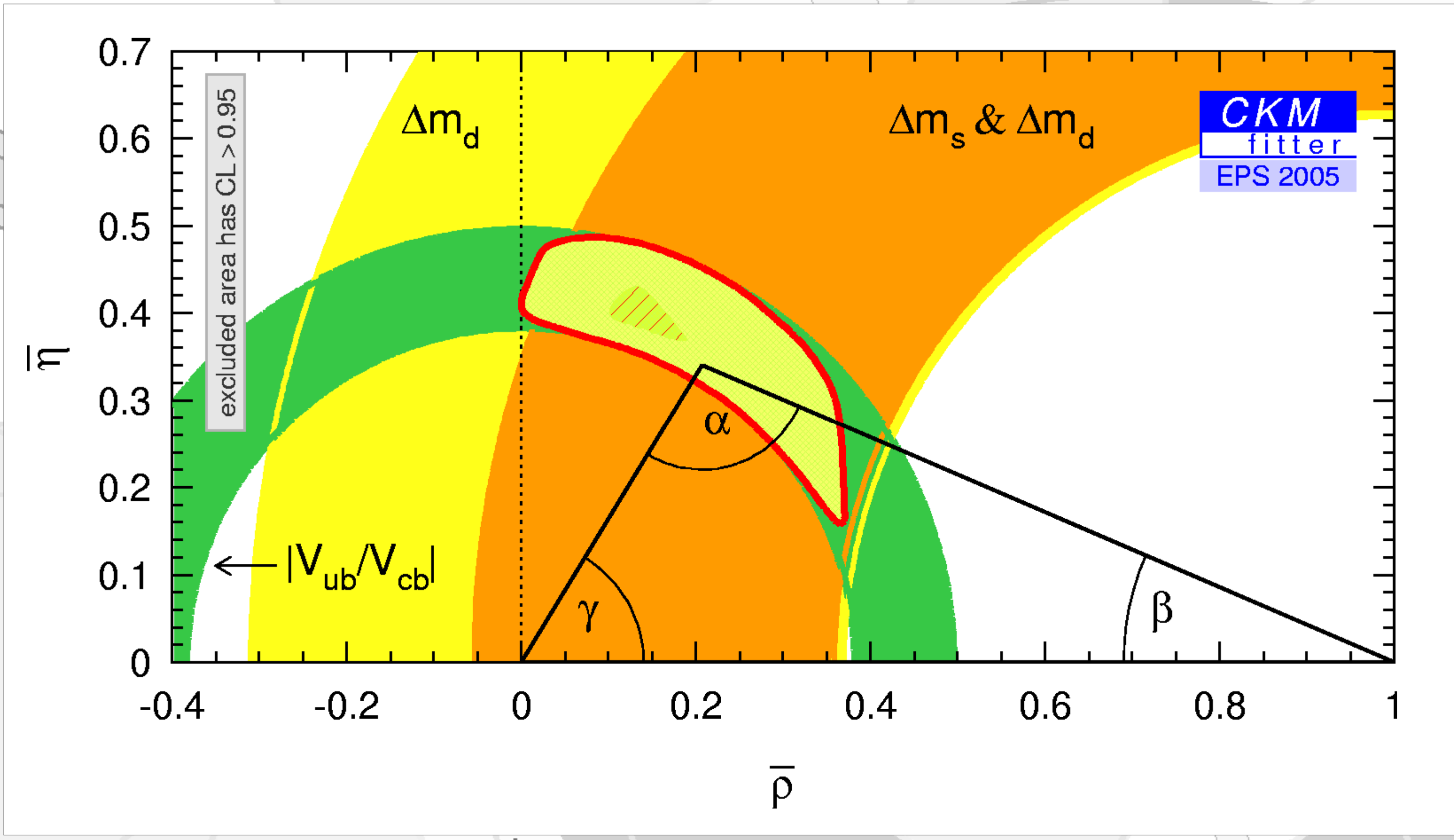
Observable	Central ± 1 σ	± 2 σ	± 3 σ
A	0.807 [+0.018 -0.018]	0.807 [+0.036 -0.036]	0.807 [+0.053 -0.054]
λ	0.2265 [+0.0008 -0.0008]	0.2265 [+0.0015 -0.0015]	0.2265 [+0.0023 -0.0023]
ρbar	0.141 [+0.029 -0.017]	0.141 [+0.097 -0.034]	0.141 [+0.115 -0.050]
ηbar	0.343 [+0.016 -0.016]	0.343 [+0.032 -0.056]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

Observable	Central ± 1 σ	± 2 σ	± 3 σ
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.[illegible] [+[illegible]0053 -0.0075]
R_u	0.371 [+0.016 -0.015]	0.371 [+0.033 -0.028]	[illegible]71 [+0[illegible]
R_t	0.925 [+0.018 -0.030]	0.925 [+0.034 -0.[illegible]	0.925 [+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].30]	0.63 [+0.18 -0.34]
Δm_s [ps^{-1}] (meas. not in the fit)	17.7 [+6.4 -2.1]	17.7 [+10.9 -4.1]	[illegible] [+13.7 -5.3]
$\|\varepsilon_K\|$ [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 -0.9[illegible]	[illegible].10 [+[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]4. -21.]	128. [+75. -27.]
B_K (lattice value not in the fit)	[illegible]	0.75 [illegible].41 -0.20]	0.75 [+0.54 -0.24]
$\xi_{SU(3)}$ (lattice va[illegible] not in the fit)	1.106 [+0.018 -0.01[illegible]	1.28 [+0.10 -0.27]	1.28 [+0.15 -0.31]
f_{B_s} [GeV] [illegible]lattice [illegible] not i[illegible] fit)	0.242 [+0.0[illegible] 0.021]	0.242 [+0.016 -0.031]	0.242 [+0.025 -0.037]
[illegible]	0.9[illegible] [+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]$_{ub}\|$	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]$_{us}\|$ (meas. not in the fit)	0.2275 [+0.0011 -0.0012]	0.2275 [+0.0023 -0.0023]	0.2275 [+0.0034 -0.0035]
[illegible] (meas. not in the fit)	[illegible] 0.00016]	[illegible] 0.00032]	[illegible] 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]

Results for Summer 2007

http://CKMfitter.in2p3.fr

The Unitarity Triangle from the global CKM fit



Inputs:

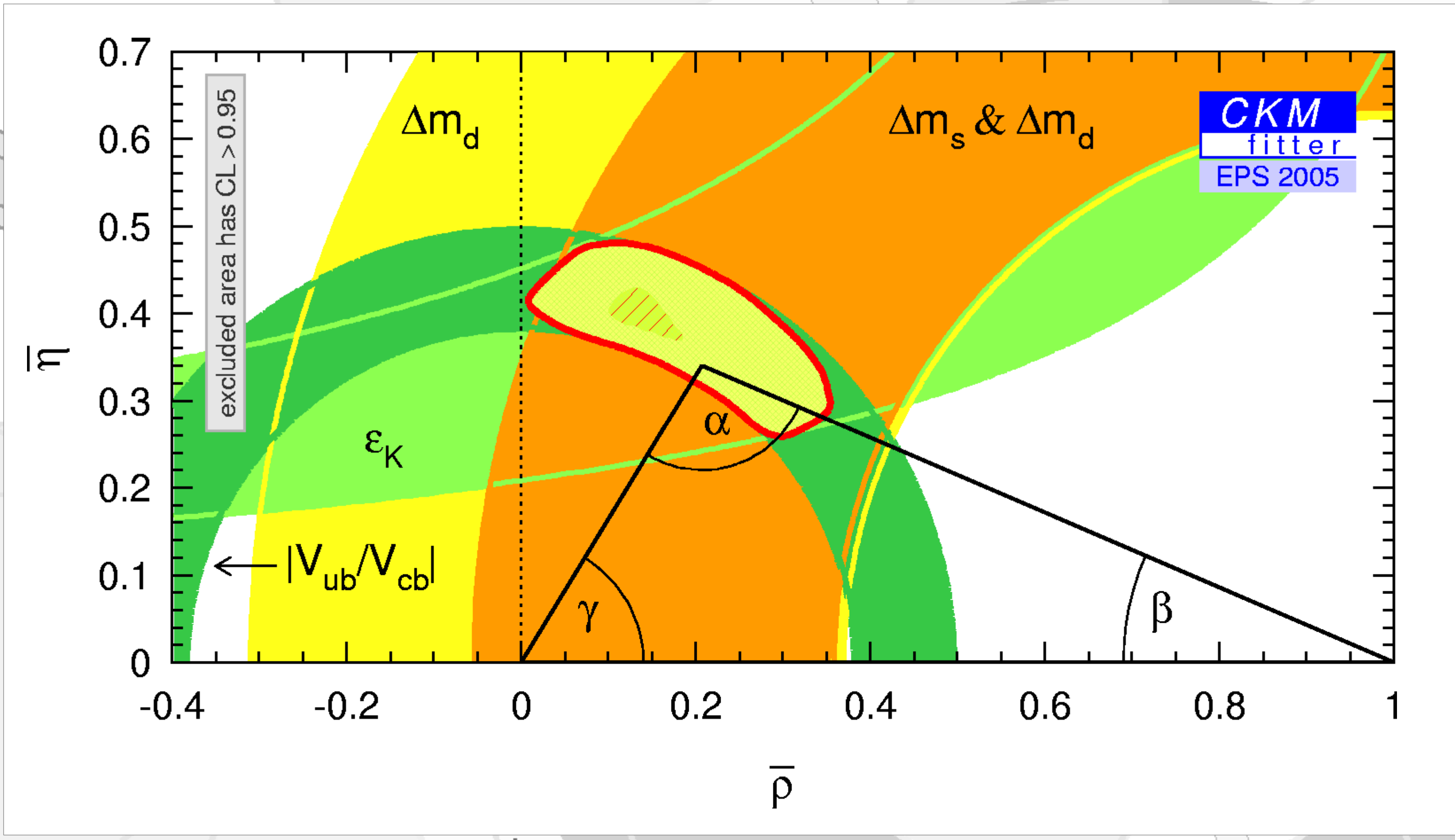
$\left|\frac{V_{ub}}{V_{cb}}\right|$

Δm_d

Δm_s lower limit

$B \to \tau\nu$

The Unitarity Triangle from the global CKM fit



Inputs:

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

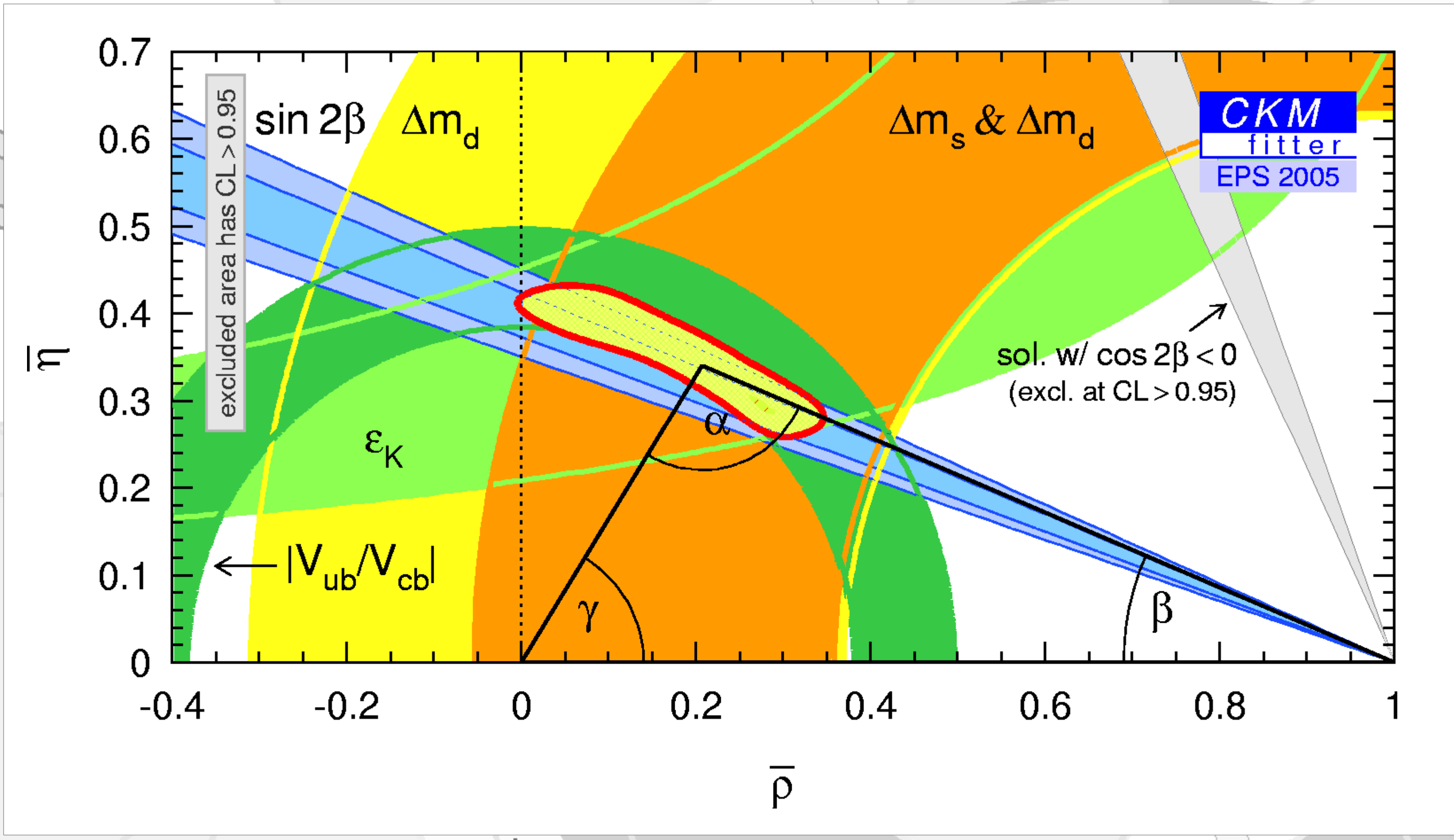
Δm_d

Δm_s
lower limit

$B \to \tau\nu$

$|\varepsilon_K|$

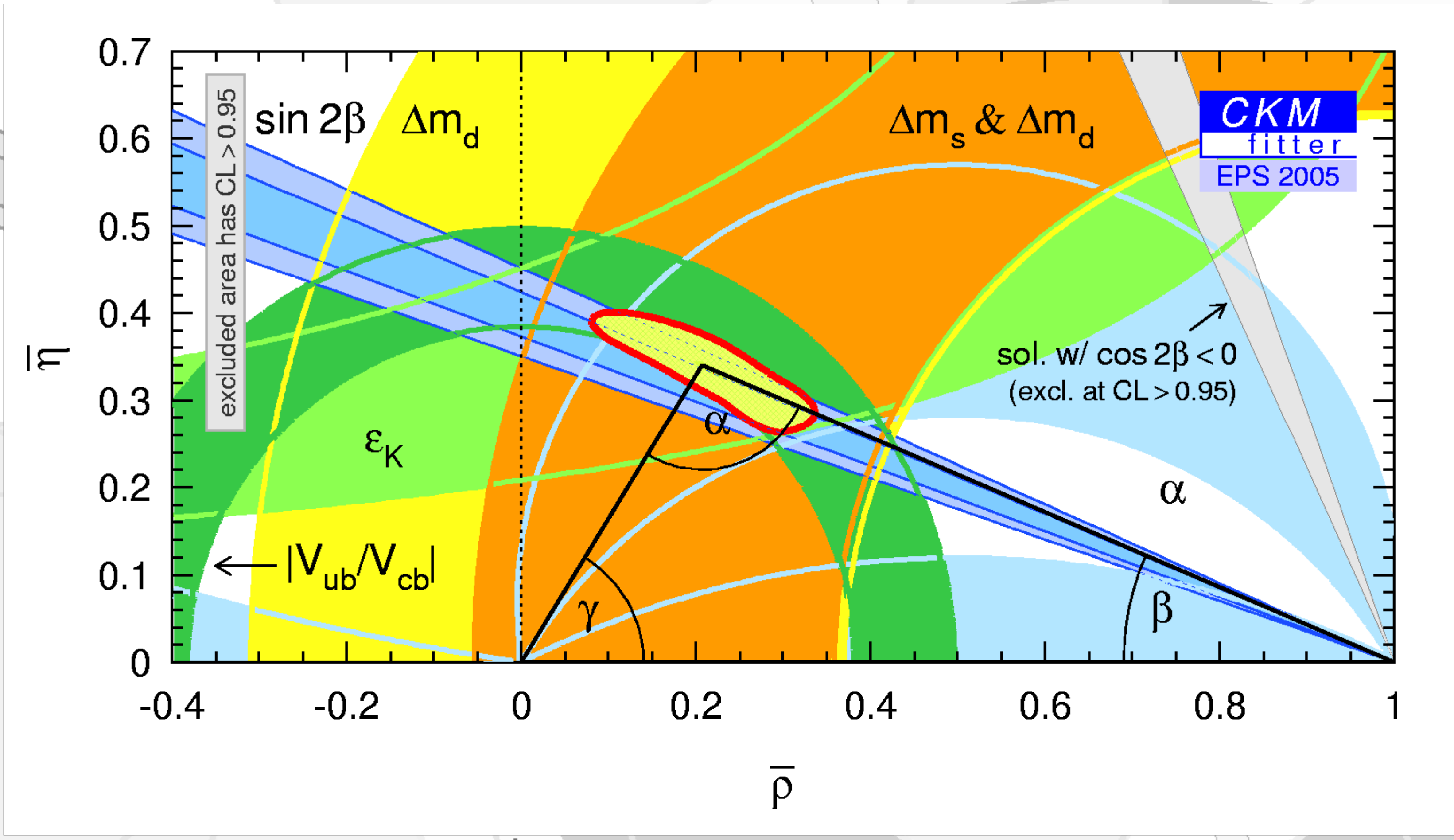
The Unitarity Triangle from the global CKM fit



Inputs:

- $\left|\frac{V_{ub}}{V_{cb}}\right|$
- Δm_d
- Δm_s lower limit
- $B \to \tau\nu$
- $|\varepsilon_K|$
- $\sin 2\beta$ & $\cos 2\beta$

The Unitarity Triangle from the global CKM fit



Inputs:

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

Δm_d

Δm_s lower limit

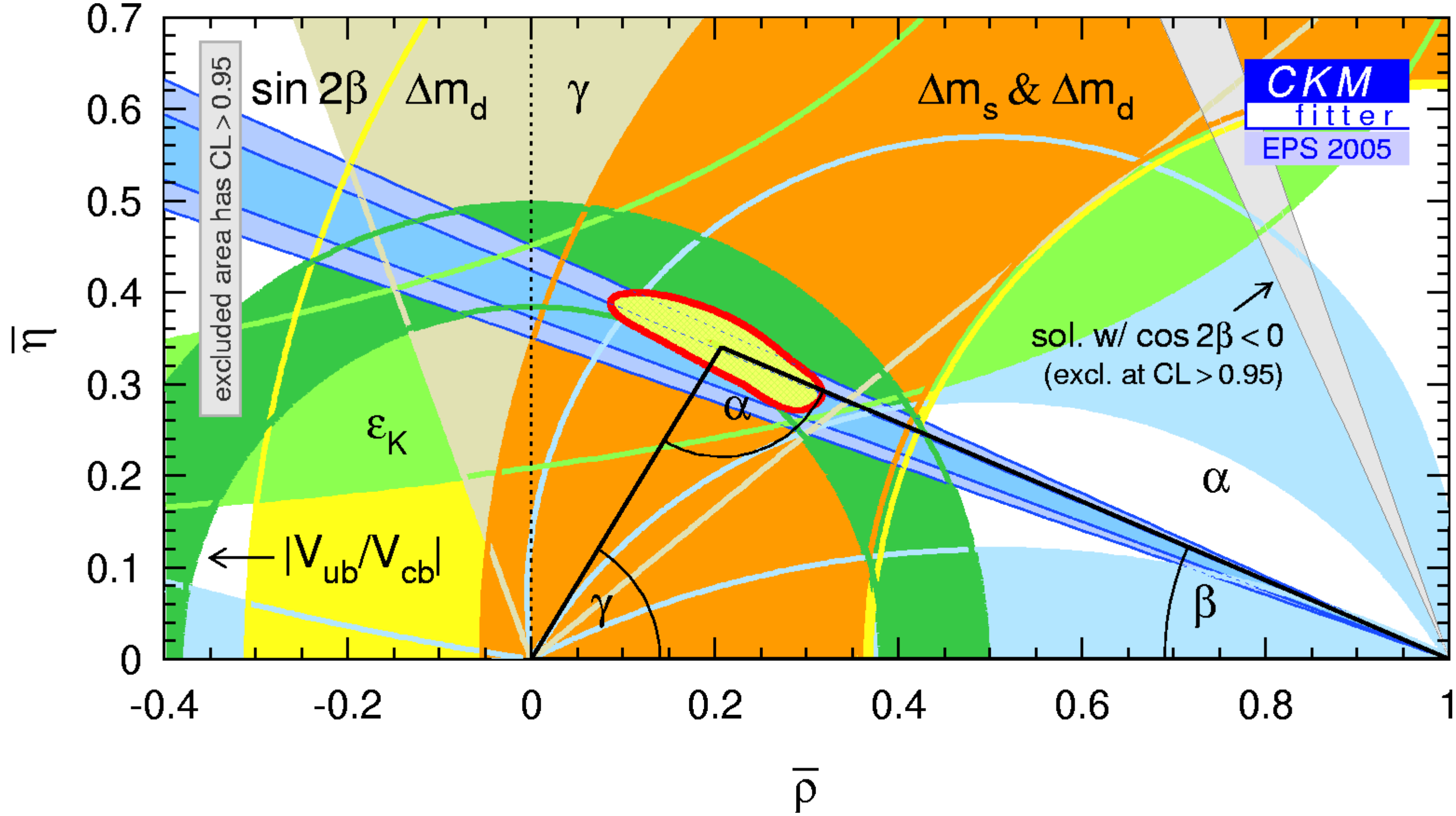
$B \to \tau\nu$

$|\varepsilon_K|$

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

α

The Unitarity Triangle from the global CKM fit



Inputs:

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

Δm_d

Δm_s lower limit

$B \to \tau\nu$

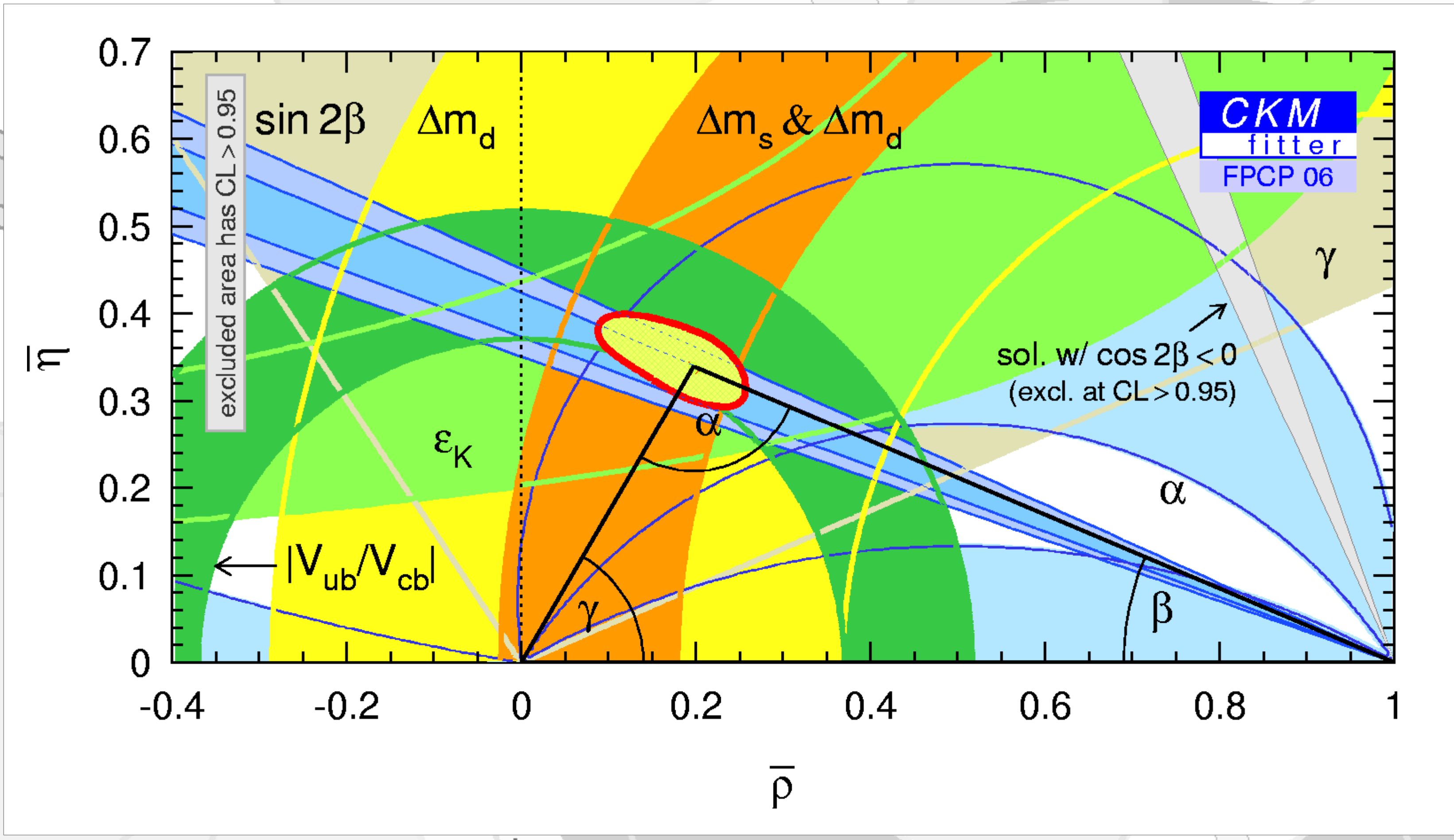
$|\varepsilon_K|$

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

α

γ

The Unitarity Triangle from the global CKM fit



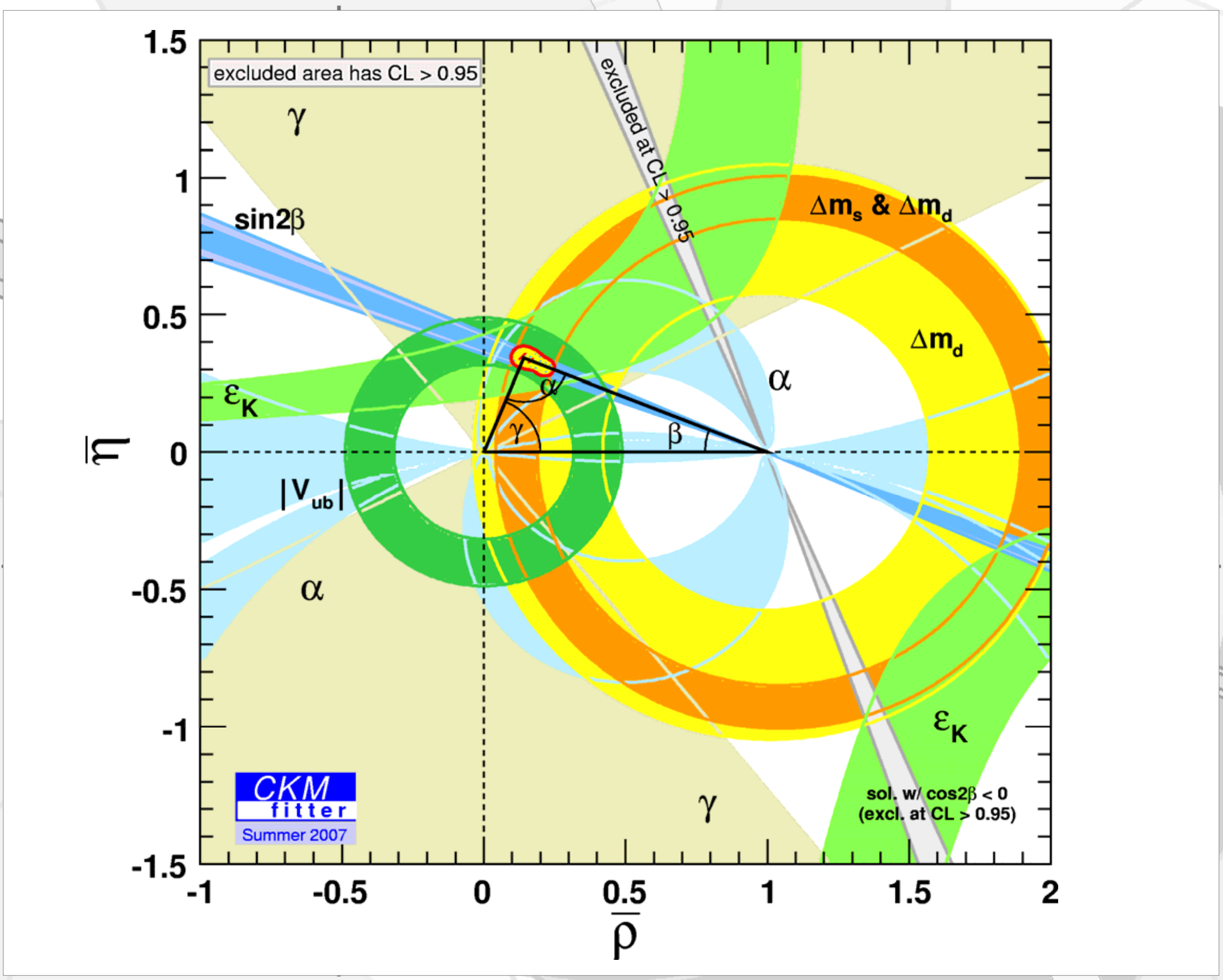
Inputs:

- $\left|\frac{V_{ub}}{V_{cb}}\right|$
- Δm_d
- Δm_s lower limit
- $B \to \tau\nu$
- $|\varepsilon_K|$
- $\sin 2\beta$ & $\cos 2\beta$
- α
- γ
- Δm_s

The Unitarity Triangle from the global CKM fit

SUMMER 2007

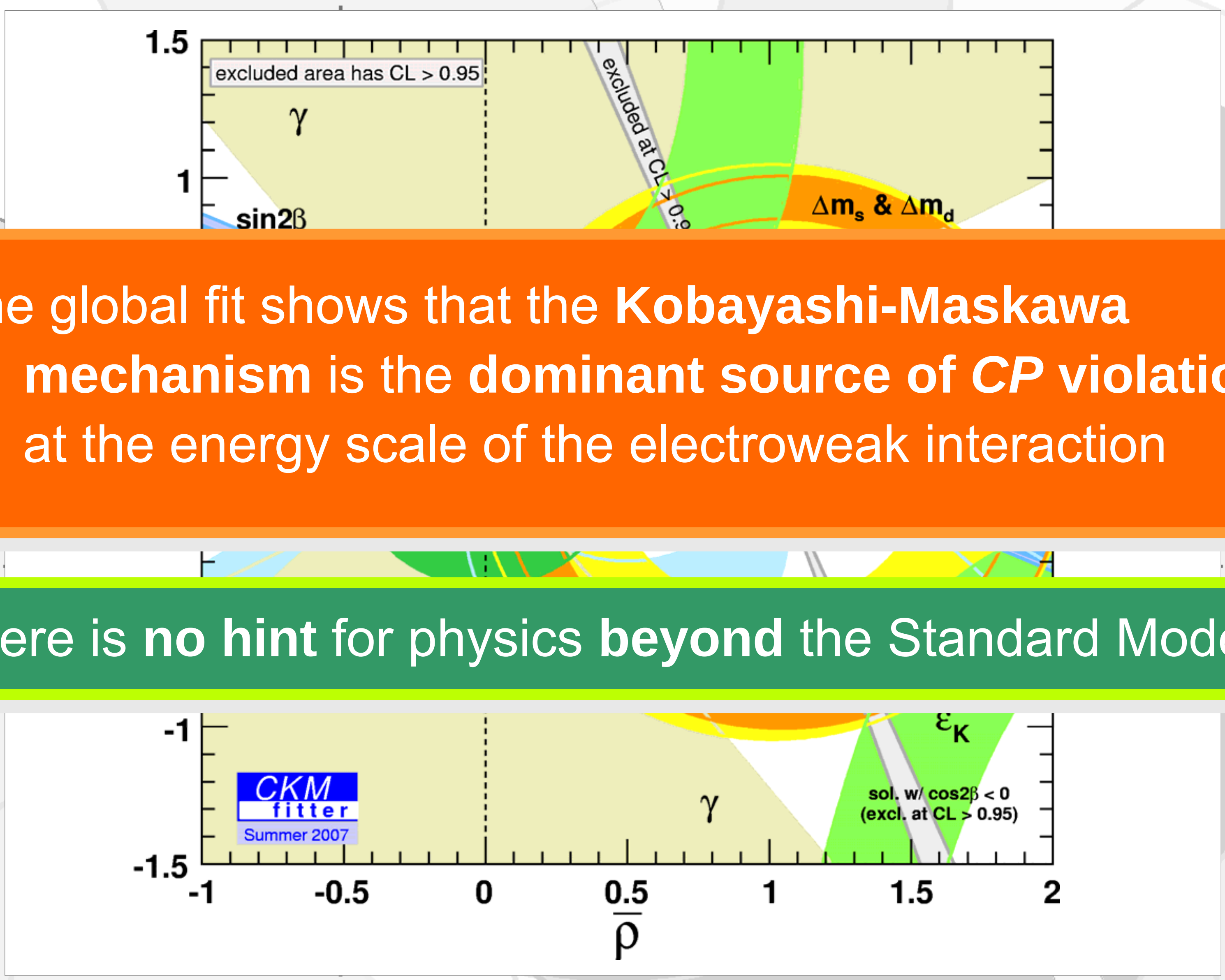
The big picture



The Unitarity Triangle from the global CKM fit

SUMMER 2007

The big picture

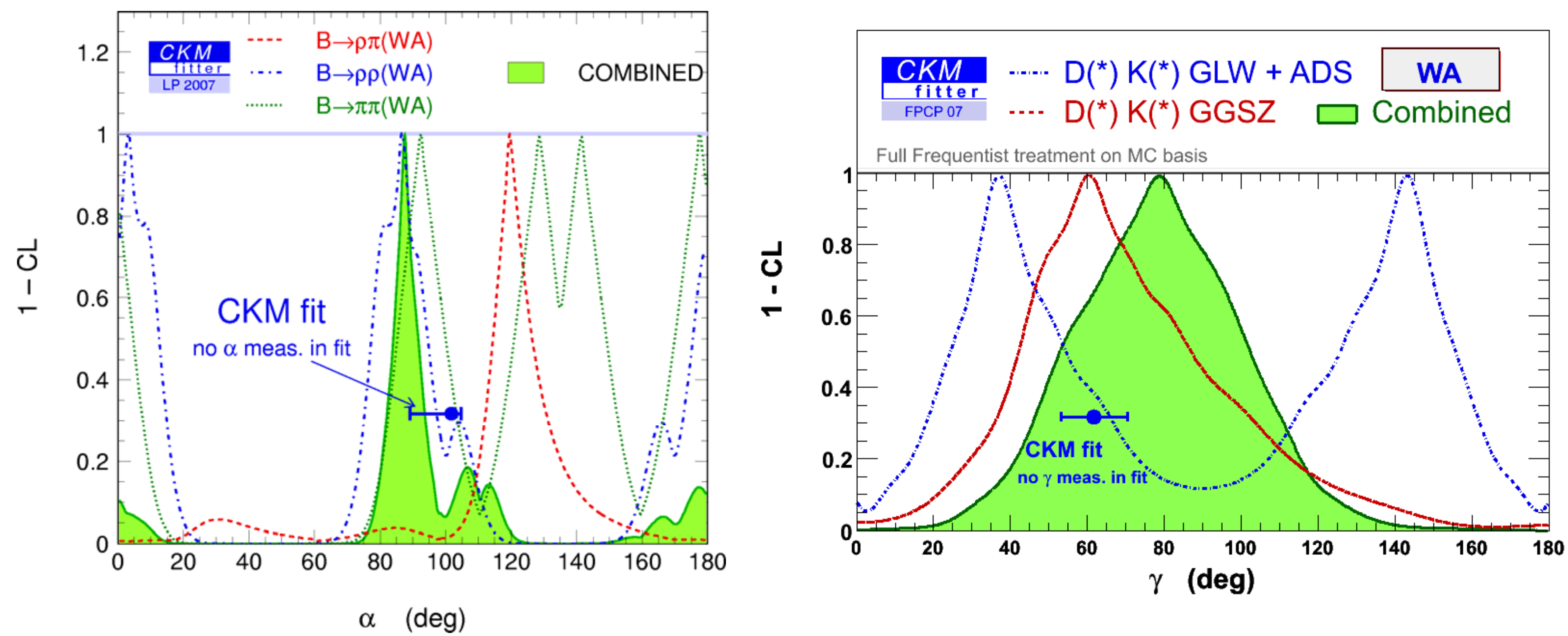


The global fit shows that the **Kobayashi-Maskawa mechanism** is the **dominant source of *CP* violation** at the energy scale of the electroweak interaction

There is **no hint** for physics **beyond** the Standard Model

The CKM Angles α and γ

- Both angle measurements involve Cabibbo-suppressed modes and hence require very large data samples.

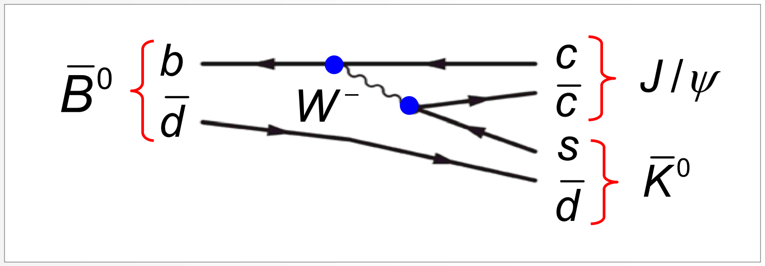


- Both measurements are in agreement with the expectation from the global CKM fit

Are All Measurements Consistent ?

- Compare tree and loop diagrams:

  → more sensitivity to unknown heavy fields from loop diagrams



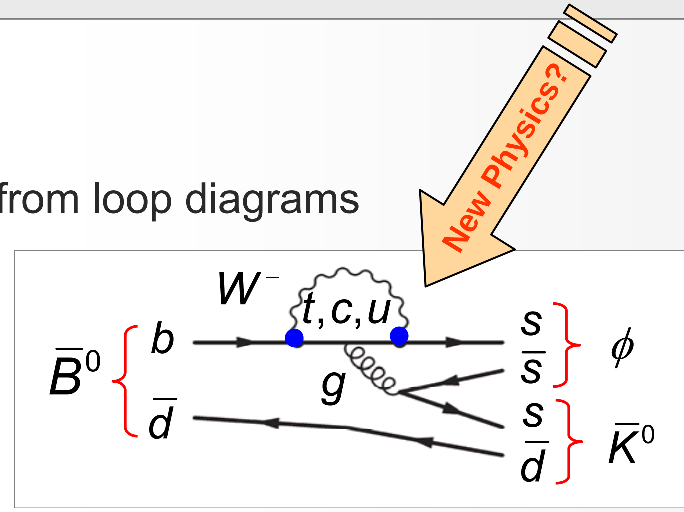
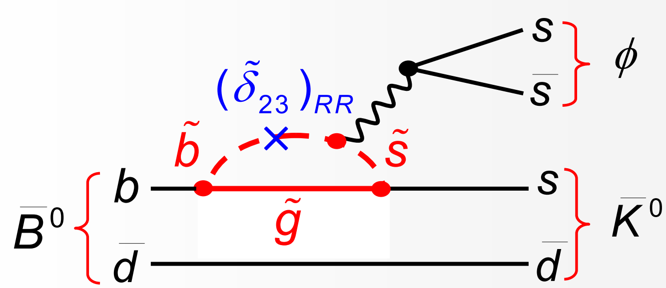


Diagram:	Tree	"Penguin"-loop diagram
CP observable:	$\sin(2\beta)[J/\psi\ K^0]$	$\sin(2\beta)[\phi K^0]$

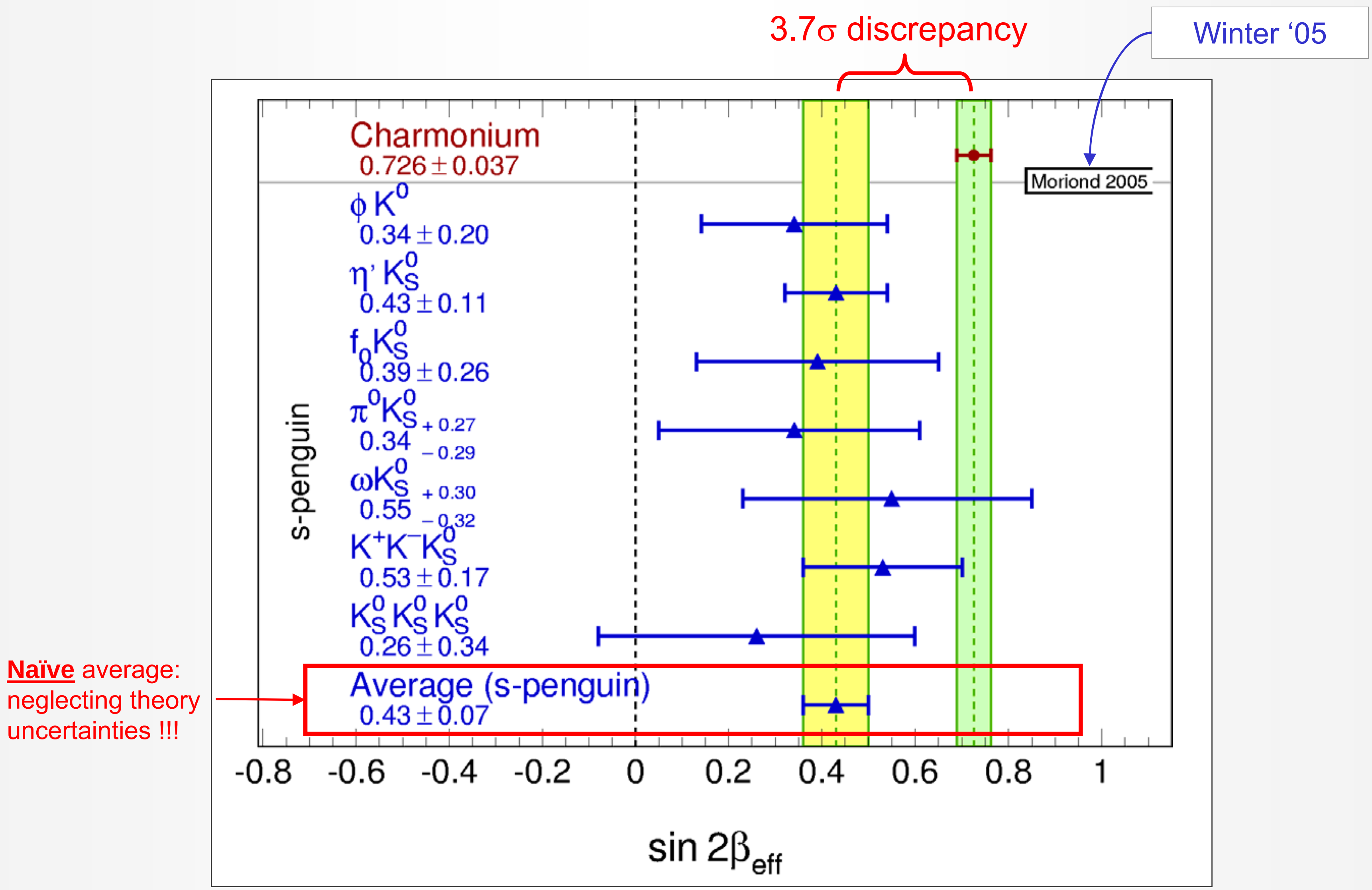
- The penguin diagram prefers heavy virtual fields in the loop; penguin-to-tree ratio:

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

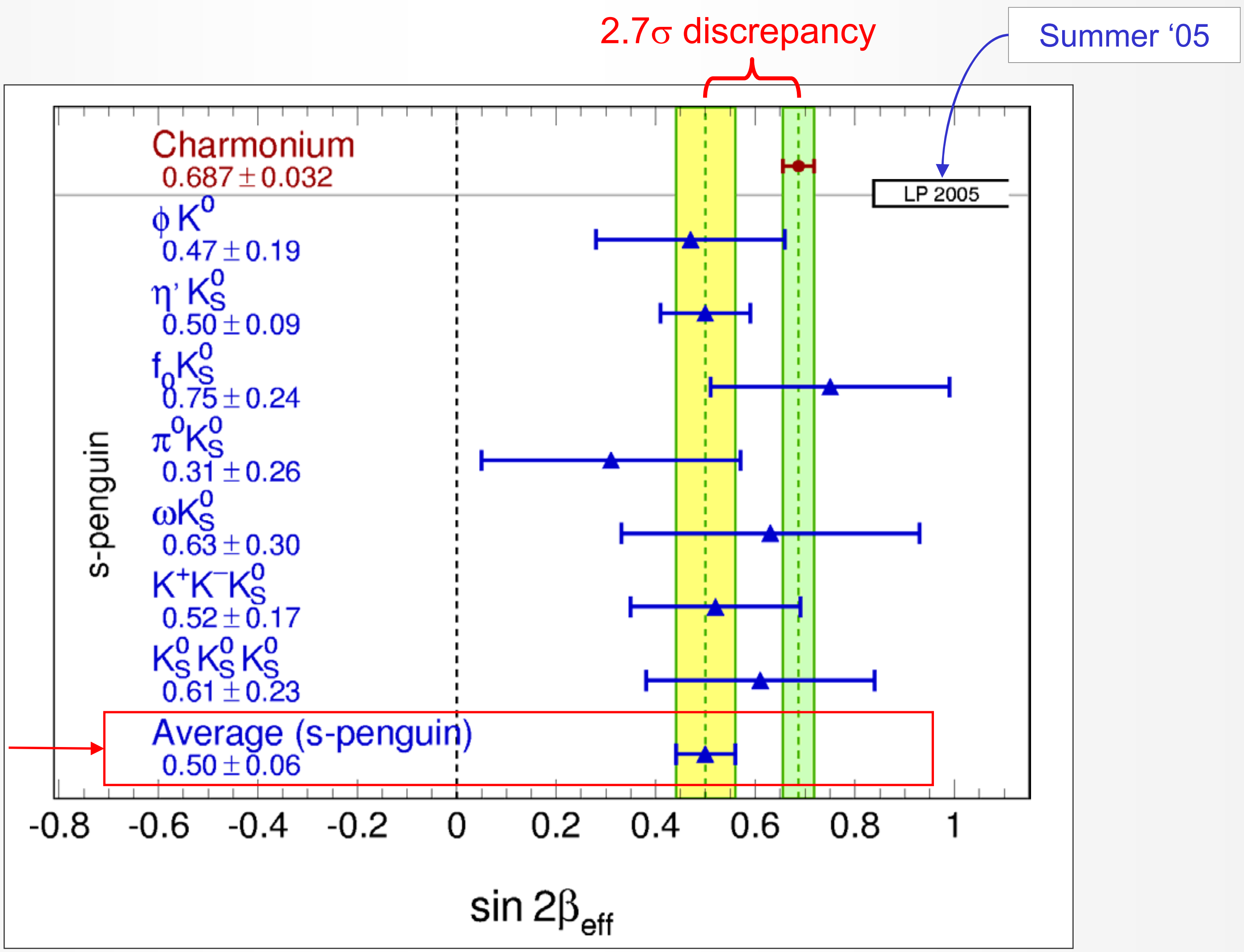
- GUT-inspired example for SUSY penguin diagram:



CP Violation in Penguin Modes

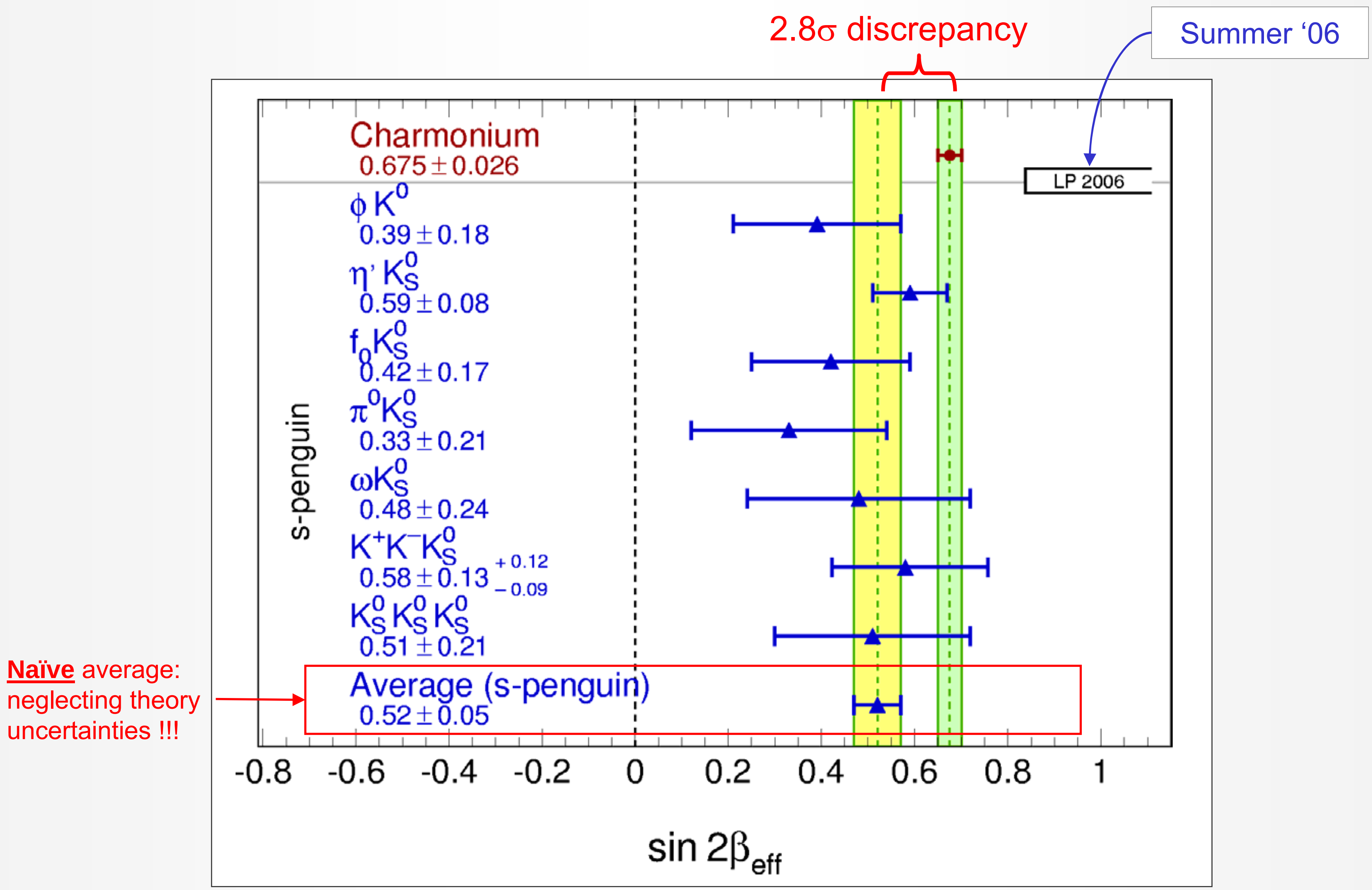


CP Violation in Penguin Modes



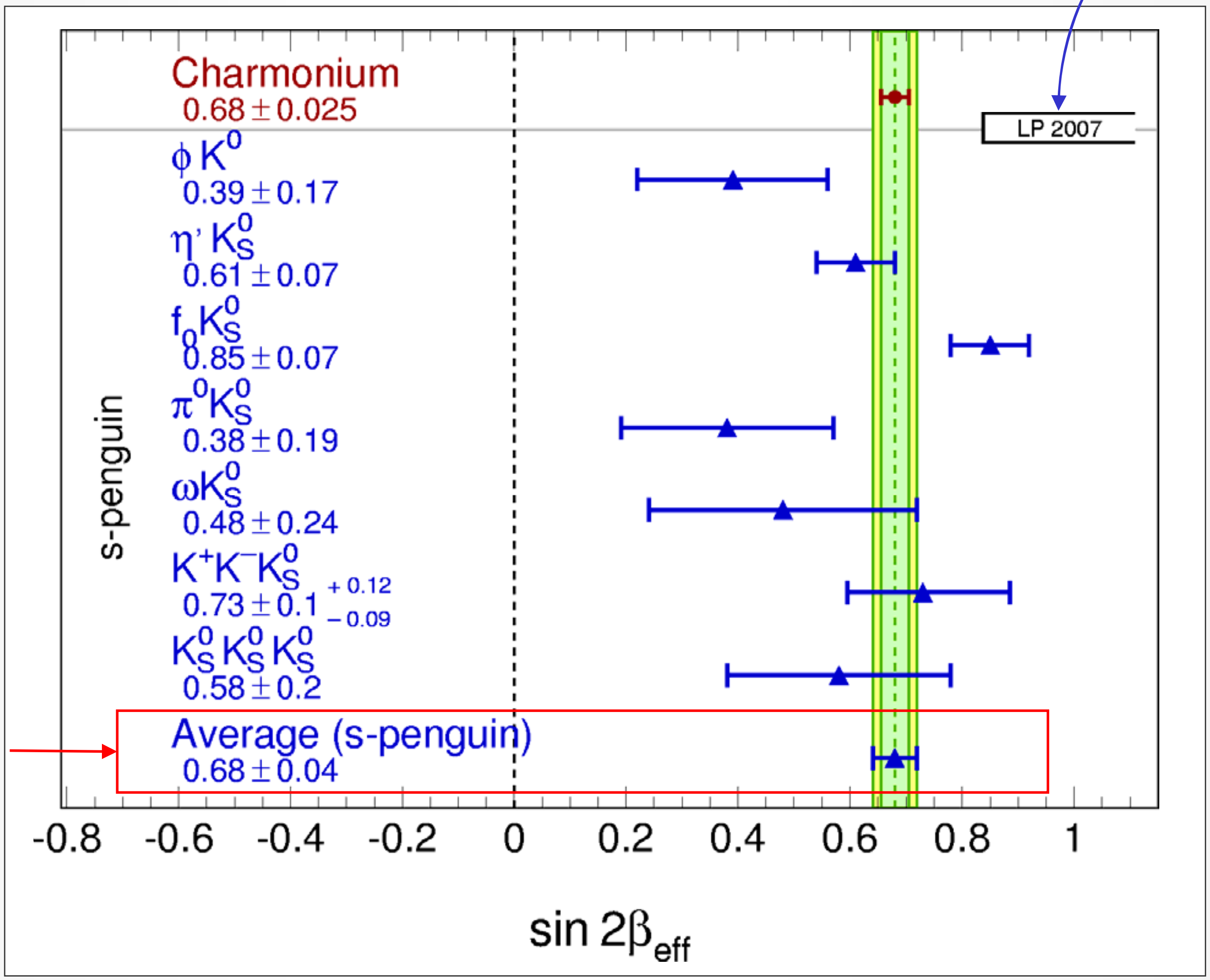
Naïve average: neglecting theory uncertainties !!!

CP Violation in Penguin Modes



CP Violation in Penguin Modes

Summer '07

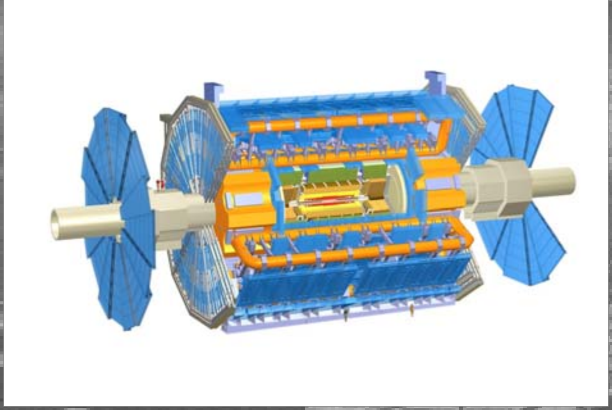


Naïve average: neglecting theory uncertainties !!!

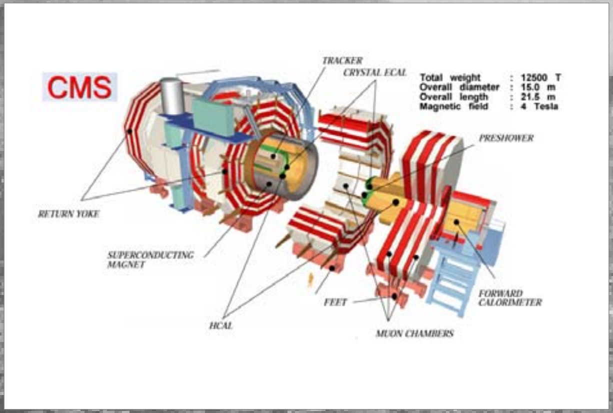
Naïve average has bad CL, which may indicate that it is indeed problematic

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

ATLAS



CMS



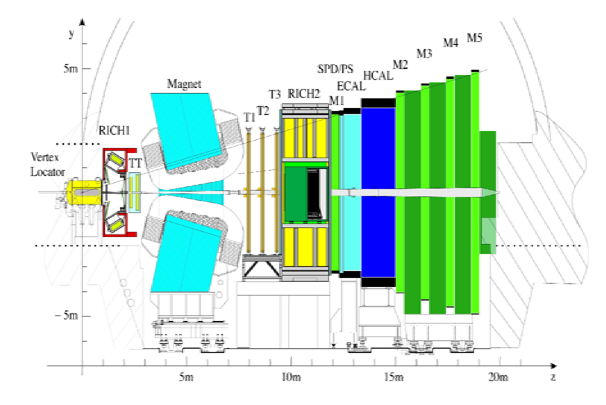
ALTAS and CMS concentrate on "high-p_T" discovery physics.

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

LHCb 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

LHCb

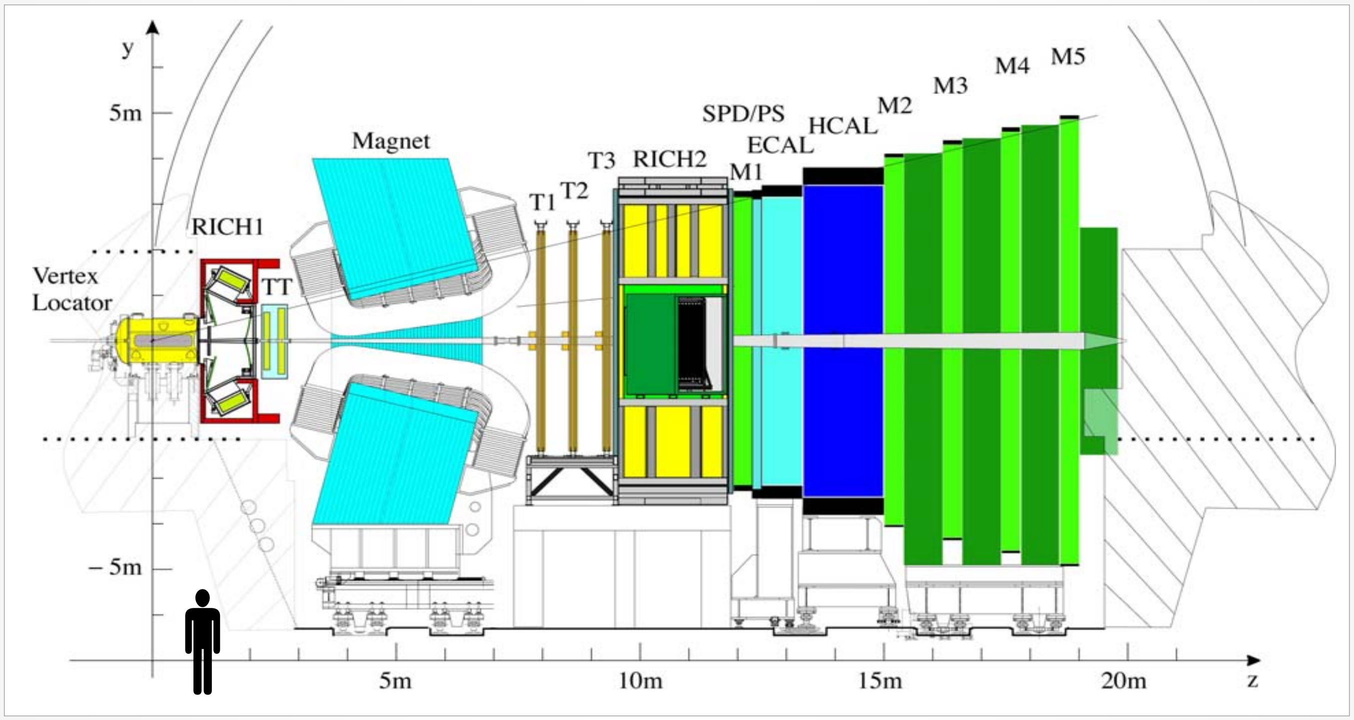


B Physics at Tevatron and LHC

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

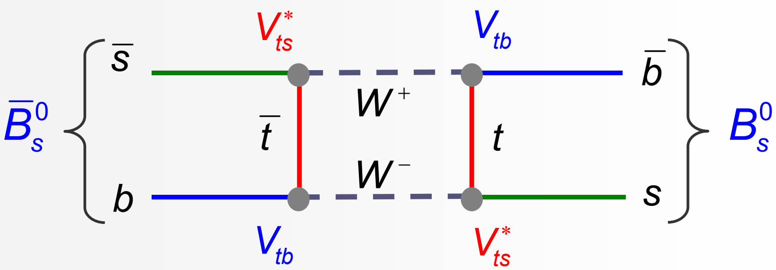
Weaknesses: Worse tagging (no quantum coherence) and background; no rare modes with neutrinos can be reconstructed; less efficient for π^0;

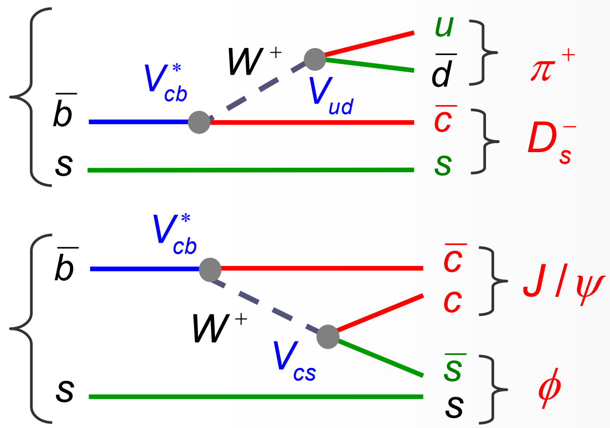


B Physics at Tevatron and LHC

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

- B_s mixing frequency and phase:





mixing frequency:

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

mixing phase:

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

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

➡ Phase: not measured yet; CKM fit prediction very precise

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

Conclusions

- *CP* Violation is **required** for **Baryogenesis**
- *P*, *C*, *T* are good symmetries for elctromagnetic and strong interactions
- ***C***, ***P*** are maximally-, ***CP*** is (marginally) **violated in weak interaction**
- *CP* violation **observed** in ***K*** and ***B*** system
- No non-flavour *CP* violation found so far
- All observed *CP*-violating phenomena are described by **single CKM phase**
- **New Physics** scenarios, in particular SUSY, provide **large number** of ***CP*-violating sources** appearing in leading order loops
- Non-observation of beyond-SM FCNC's and *CP* violation creates conflict with *O*(TeV) expectation for new physics scale → **"flavour problem"**
- Solution requires the new physics (if exists) to be **minimal flavour-violating** (this is a quite natural feature of, e.g., gauge-mediated SUSY breaking models)

Siumulated Higgs-boson event at CMS, CERN