Beauty Physics and *CP* Violation (I)

the experimental program

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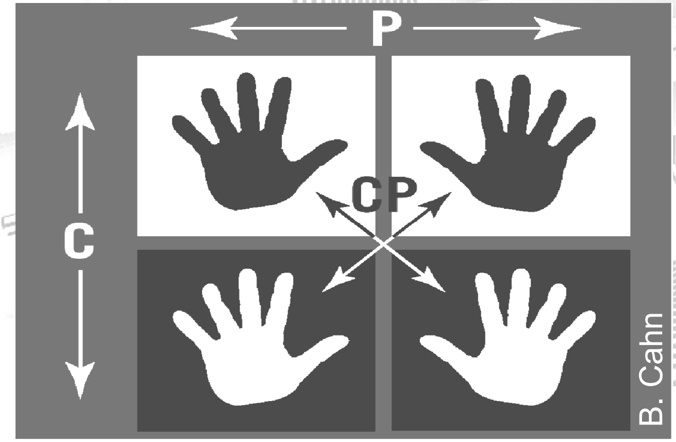


Experimental lecture at the Helmholz School on Heavy Quark Physics

Dubna, June 6-16, 2005

CP Violation is Flavor Physics !

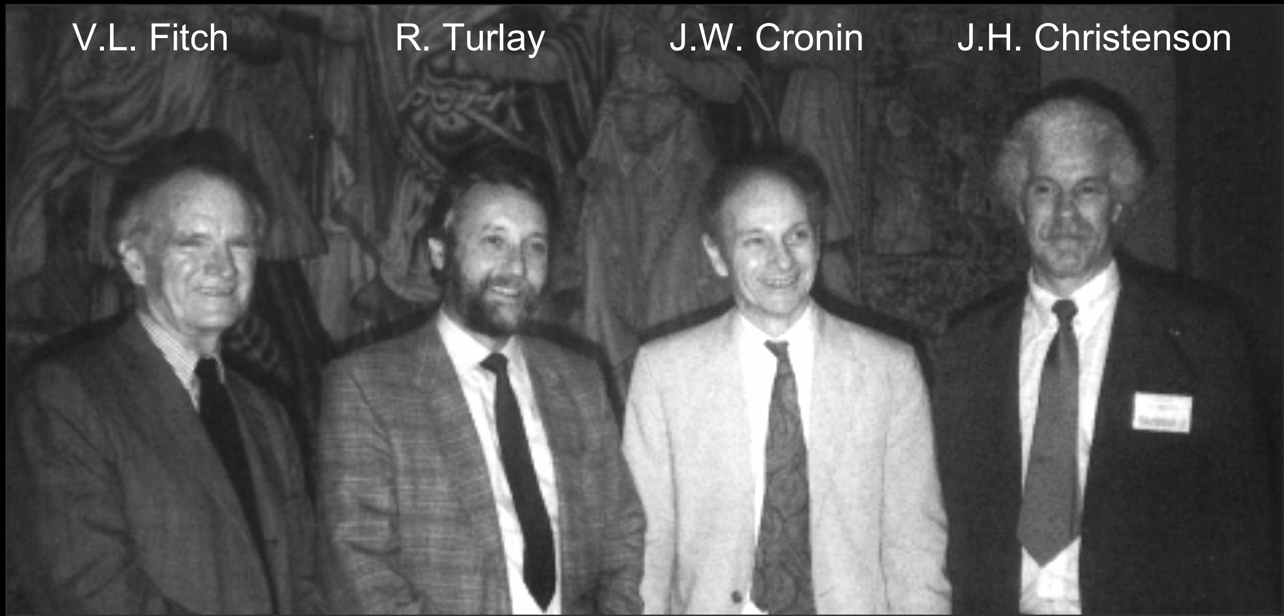
- Discovery of strange particles (Rochester, Butler) (1946, '47)
- Neutral kaons can mix (Gell-Mann, Pais) (1952)
- K_L discovery (Lederman *et al.*) (1956)
- *P* violation: possible explanation (Lee, Yang) (1956)
- *P* violation found in β decay (Wu *et al.*) (1957)
  later: maximum *P* and *C* violation, but *CP* invariance
- Cabibbo-Theory (1963)

➡ *CP* violation (CPV) discovered (Cronin, Fitch *et al.*) (1964)

...37 Years later

- GIM-Mechanism (Glashow, Illiopolous, Maiani) (1970)
- CPV phase requires 3 families (Kobayashi-Maskawa) (1973)
- J/ψ resonance: *c* quarks (Ting, Richter) (1974)
- Discovery of τ lepton: 3rd family (Perl et al.) (1975)
- Υ resonance: *b* quarks (Lederman *et al.*) (1977)
- Broad $\Upsilon(4S)$ (CLEO) (1980)
- *B* mesons live long ($|V_{cb}|$ small) (MAC, MARK II) (1983)
- *B* mesons oscillate (ARGUS) (1987)
- *t*-quark discovery (CDF) (1995)
- $\varepsilon'/\varepsilon \neq 0$ (NA31, NA48, KTeV) (1999)
- Start of *B* Factories: BABAR (PEP II), Belle (KEKB) (1999)
- ➡ CPV in *B* system : $\sin(2\beta) \neq 0$ (BABAR, Belle) (2001)
- ➡ Direct CPV in *B* system : $A_{CP}(K^+\pi^-) \neq 0$ (BABAR, Belle) (2004)

Discovery of *CP* violation:



PRL 13, 138 (1964) [cited: 1067 times]

Evolution of working conditions (example BABAR) :

… 623 physicists (in early 2005).

BABAR: PRL 87, 091801 (2001) [cited: 308 times]

Belle: PRL 87, 091802 (2001) [cited: 319 times]

The *BABAR* Collaboration

11 Countries
80 Institutions
623 Physicists

USA [38/311]
California Institute of Technology
UC, Irvine
UC, Los Angeles
UC, Riverside
UC, San Diego
UC, Santa Barbara
UC, Santa Cruz
U of Cincinnati
U of Colorado
Colorado State
Harvard U
U of Iowa
Iowa State U
LBNL
LLNL
U of Louisville
U of Maryland
U of Massachusetts, Amherst
MIT
U of Mississippi
Mount Holyoke College
SUNY, Albany
U of Notre Dame
Ohio State U
U of Oregon
U of Pennsylvania
Prairie View A&M U
Princeton U
SLAC
U of South Carolina
Stanford U
U of Tennessee
U of Texas at Austin
U of Texas at Dallas
Vanderbilt
U of Wisconsin
Yale

Canada [4/24]
U of British Columbia
McGill U
U de Montréal
U of Victoria

China [1/5]
Inst. of High Energy Physics, Beijing

France [5/53]
LAPP, Annecy
LAL Orsay
LPNHE des Universités Paris VI et VII
Ecole Polytechnique, Laboratoire Leprince-Ringuet
CEA, DAPNIA, CE-Saclay

Germany [5/24]
Ruhr U Bochum
U Dortmund
Technische U Dresden
U Heidelberg
U Rostock

Italy [12/99]
INFN, Bari
INFN, Ferrara
Lab. Nazionali di Frascati dell' INFN
INFN, Genova & Univ
INFN, Milano & Univ
INFN, Napoli & Univ
INFN, Padova & Univ
INFN, Pisa & Univ & ScuolaNormaleSuperiore
INFN, Perugia & Univ
INFN, Roma & Univ "La Sapienza"
INFN, Torino & Univ
INFN, Trieste & Univ

The Netherlands [1/4]
NIKHEF, Amsterdam

Norway [1/3]
U of Bergen

Russia [1/13]
Budker Institute, Novosibirsk

Spain [2/3]
IFAE-Barcelona
IFIC-Valencia

United Kingdom [11/75]
U of Birmingham
U of Bristol
Brunel U
U of Edinburgh
U of Liverpool
Imperial College
Queen Mary , U of London
U of London, Royal Holloway
U of Manchester
Rutherford Appleton Laboratory
U of Warwick

To start with …

1. The Universe is empty* !
2. The Universe is almost empty* !

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

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

- Initial condition ?
- Dynamically generated ?

Sakharov rules (1967) to explain Baryogenesis

1. Baryon number violation
2. *CP* violation
3. No thermic equilibrium (non-stationary system)

- So, if we believe to have understood CPV in the quark sector, what does it signify ?
- A sheer accident of nature ?
- What would be the consequence of a different CKM phase ?

The Search for New Physics in the *B* System

- Since the precise measurement of sin2β in $b \to c\bar{c}s$ decays (in perfect agreement with the SM), there is considerable effort at *B* Factories towards the search for specific signs of New Physics (NP). WHY ?

  - The gauge hierarchy Problem (Higgs sector, scale ~ 1 TeV)
  - Baryogenesis (CKM CPV too small)
  - The strong *CP* Problem (why is $\theta \sim 0$?)
  - Grand Unification of the gauge couplings
  - ... many more

see, *e.g.*, the instructive talk by Yuval Grossman at LP'03: hep-ph/0310229

- Conflict between limits from flavor physics $\gg$ 1 TeV (*e.g.*, K^0, D^0, B^0 mixing), and NP scale (1 TeV) ➡ NP cannot have a generic flavor structure

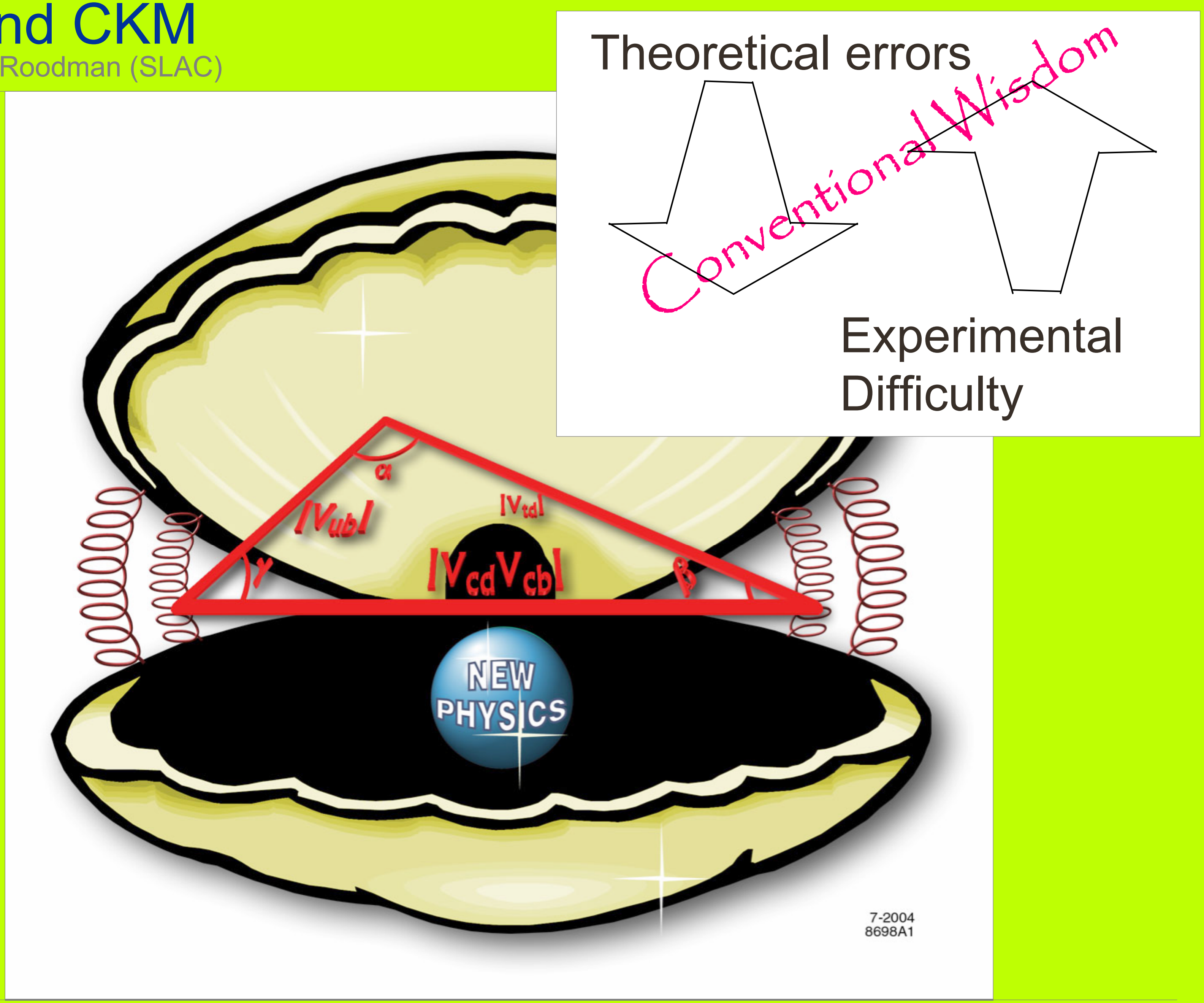
$$\frac{\delta_{Qq}}{\Lambda_{\rm NP}} \sim \frac{V^*_{tQ}V_{tq}}{m_W} \sim \begin{cases} O(10^{-6}) & \text{for } Q=s,\ q=d \\ O(10^{-4}) & \text{for } Q=b,\ q=d \end{cases}$$

New Physics: some possibilities

- Minimal flavor violation (MFV) models : *CP* violation is completely governed by CKM
  - ➡ precision tests in rare processes
  - Q : why ?
- The NP is essentially flavor blind up to large scales
  - ➡ test of *CP* violation in flavor conserving processes (EDM, …)
  - Q : and what about the leptons ?
- Intermediate solutions (example : only $b \to s$ transitions are affected by low energy NP), …
  - Q : why would these two families by special ?
- … and other still unknown alternatives, which certainly will give the correct answer

QCD and CKM

as seen by A. Roodman (SLAC)



Lecture Themes

I. Beauty Physics and *CP* Violation – the experimental program

- Heavy meson production and decay
- *B* Physics and *CP* Violation
- The *B* Factories
- Physics at the $\Upsilon(4S)$: time-integrated and time-dependent measurements

II. sin(2β) and the triumph of the Standard Model

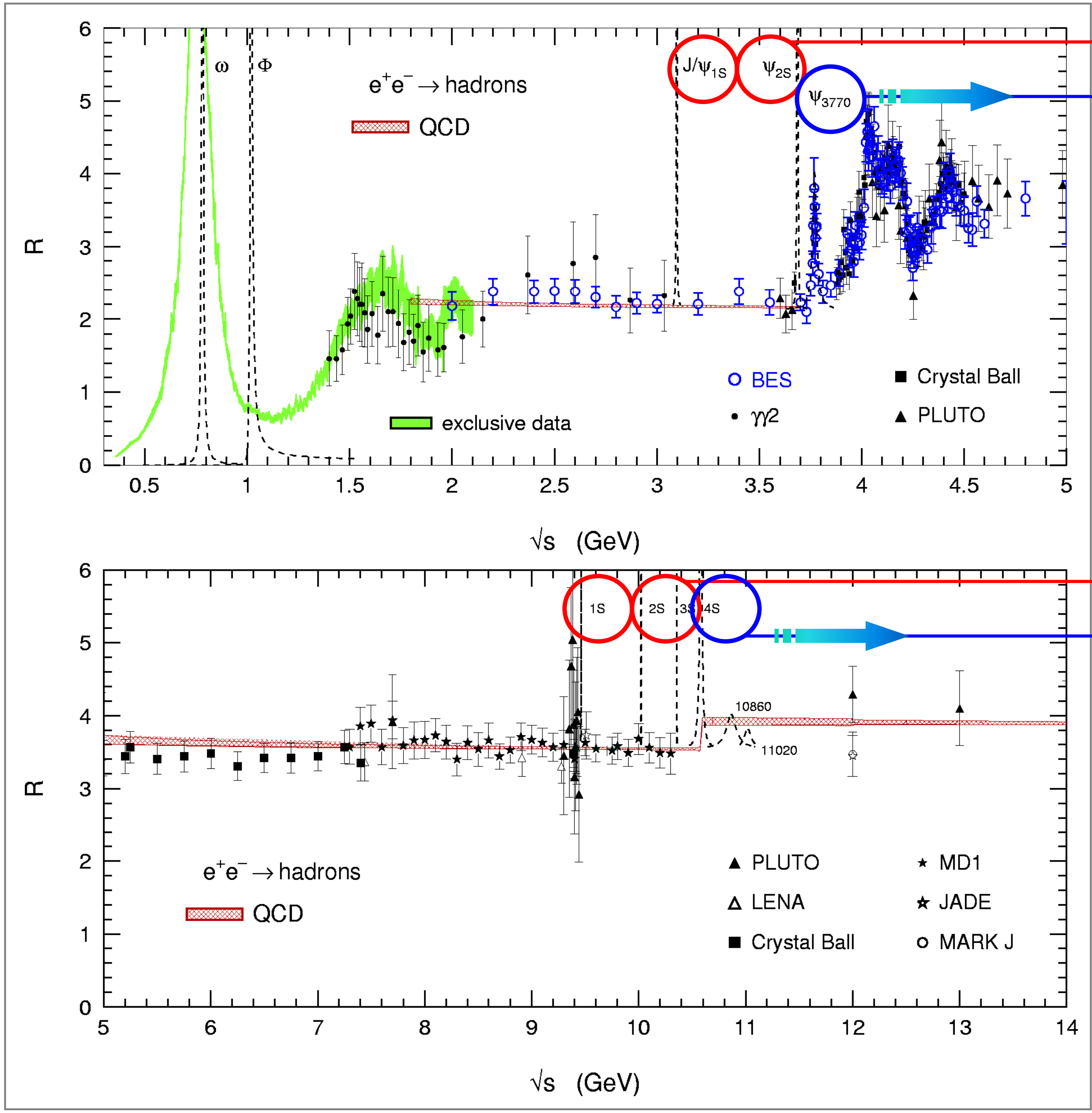
- *CP* violation: experimental facts
- *CP* violation in the *B* system
- The measurement of sin(2β) in tree and loop (penguin) decays
- Briefing on radiative *B* decays

III. Rare *B* decays: towards the full unitarity triangle … and beyond

- Leptonic *B* Decays
- Charmless *B* decays and the measurement of α
- $B \to K\pi$ decays (direct *CP* violation) and other charmless modes
- Towards γ
- Flavor, CPV and CKM: the present picture and the experimental future

Heavy Meson Production and Decay

Production of Heavy "Oniums" in e^+e^- Annihilation



narrow $|c\bar{c}\rangle$ states
(weak/em decays only)

broad $|c\bar{c}\rangle$ states
(strong decays to *D*'s)

CLEO-c (Cornell)
$\sqrt{s} \approx m(J/\psi)$, $m(\psi_{3770})$, and above

narrow $|b\bar{b}\rangle$ states
(weak/em decays only)

broad $|b\bar{b}\rangle$ states
(strong decays to *B*'s)

BABAR (PEP-II), Belle (KEK-B)
$\sqrt{s} = m(\Upsilon_{4s})$

Heavy-light Mesons

★ The broad $|c\bar{c}\rangle$ and $|b\bar{b}\rangle$ states decay strongly into heavy-light mesons carrying *c* and *b* quarks, respectively:

Quark content	Pseudoscalar $^1S_0$ mesons		Vector $^3S_1$ mesons	
	Name	Mass (GeV/c²)	Name	Mass (GeV/c²)
$\|c\bar{u}\rangle$	D^0	1865	D^{*0}	2007
$\|c\bar{d}\rangle$	D^+	1869	D^{*+}	2010
$\|c\bar{s}\rangle$	D_s	1969	D_s^*	2112
$\|\bar{b}u\rangle$	B^+	5279	B^{*+}	5325
$\|\bar{b}d\rangle$	B^0	5279	B^{*0}	5325
$\|\bar{b}s\rangle$	B_s	5370	B_s^*	~ 5416

Electromagnetic mass splitting:

$m(D^*) - m(D) > m(\pi)$

➡ $D^* \to D\pi$, $D\gamma$ exist

$m(B^*) - m(B) < m(\pi)$

➡ $B^* \to B\gamma$ only

Spectroscopic implications

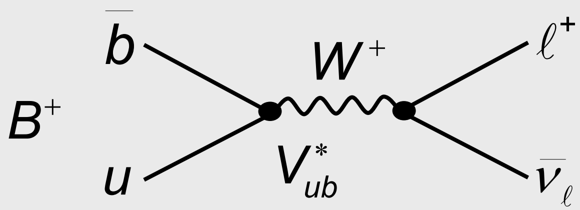
The hyperfine splitting in the *B* system is smaller than in *D*'s since the chromomagnetic moments μ_Q (quarks have spin ½) of the heavy quarks scale as $\mu_Q \sim g/2m_Q$:

$$\frac{m_{B^*} - m_B}{m_{D^*} - m_D} \approx \left(\frac{m_b}{m_c}\right)^{-1} \approx \frac{1}{3}$$

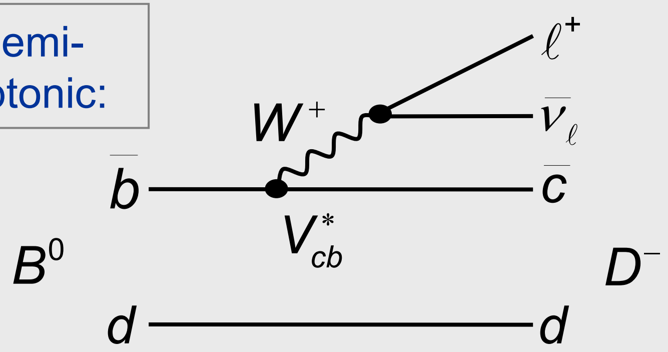
and also: $$m_{B^*}^2 - m_B^2 = m_{D^*}^2 - m_D^2 + \Lambda_{\rm QCD}^3 (1/m_c - 1/m_b)$$

Leptonic, Semileptonic and Hadronic *B* Decays

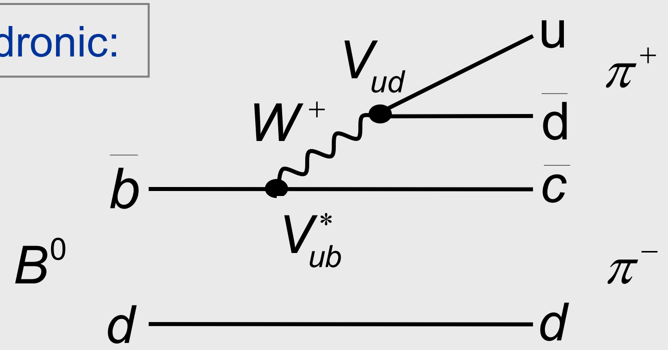
Leptonic:



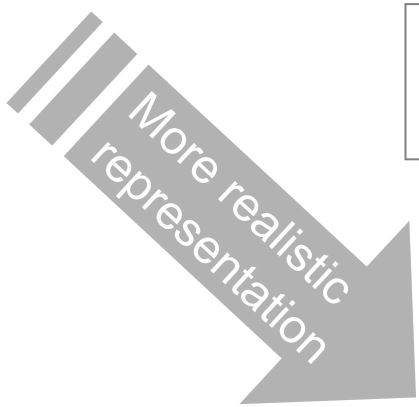
Semi-leptonic:

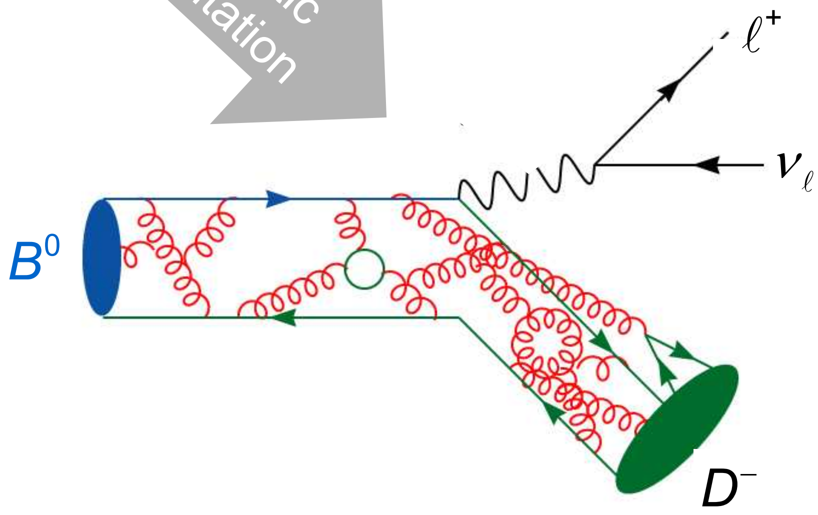


Hadronic:



Flavor changing charged currents are weak decays governed by the CKM matrix





Simplicity of weak interaction is overshadowed by complexity of strong interaction

…discussed to much detail in the theoretical lectures!

digression: Heavy Quark Symmetry

Why is hadron interaction with heavy Q's favorable ?

- Systems with large momentum transfer are
short distance scales ➨ asymptotically free ➨ perturbative QCD ➨ alike electromagnetism

- Quarkonium states with size $R_{QQ} \ll R_{\text{had}} \sim 1/\Lambda_{\text{QCD}} \sim 1$ fm much like hydrogen

- Qq states have size $R_{Qq} \sim R_{\text{had}}$ & typical momenta Λ_{QCD} ➨ more complicated

- But: for $m_Q \to \infty$, $\lambda_Q \ll R_{\text{had}}$ so that the "light degrees of freedom" (quark-gluon cloud) are blind to the quantum numbers (flavor, spin) of the heavy quark

- Interaction via color field of Q only

- Light degrees of freedom are invariant of Q change in Qq systems with fixed 4-momentum (static color field) ➨ SU($2_{\text{spin}} n_Q$) symmetry group

[compare to: same chemistry for different isotopes, since e^- sees charge of nucleos only; spin symmetry analogous small hyperfine structure: nuclear spin decouples for $m_N \to \infty$]

B Physics and *CP* Violation

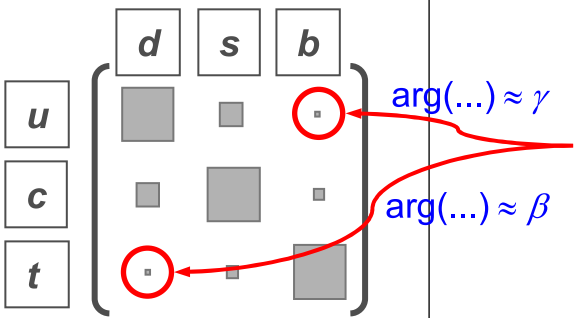
α β γ

- *CP* Violation (CPV) in the *B* (and *K*) System(s):
  - CPV in interference of decays with and without mixing
  - CPV in mixing
  - CPV in interference between decay amplitudes
- Neutral B_d and B_s Mixing
- Precise Determination of the CKM Elements $|V_{ub}|$, $|V_{cb}|$
- Detection of Rare Decays:
  - Determination of weak phases
  - Search for new physics and direct CPV

The CKM Matrix and the Unitarity Triangle

Kobayashi-Maskawa, 1973

$$V_{\rm CKM} =$$

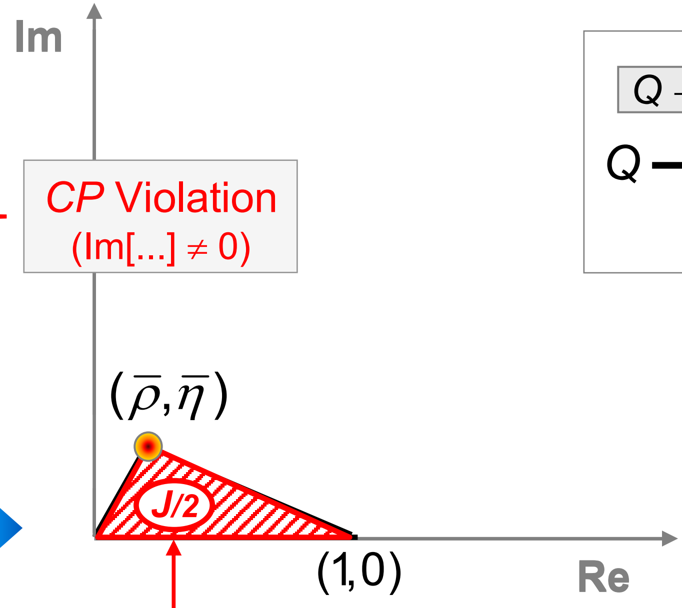


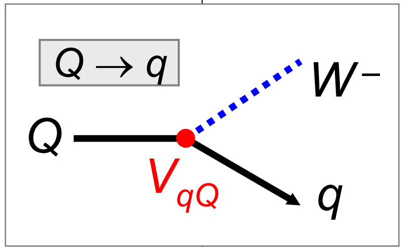
$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

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

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

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

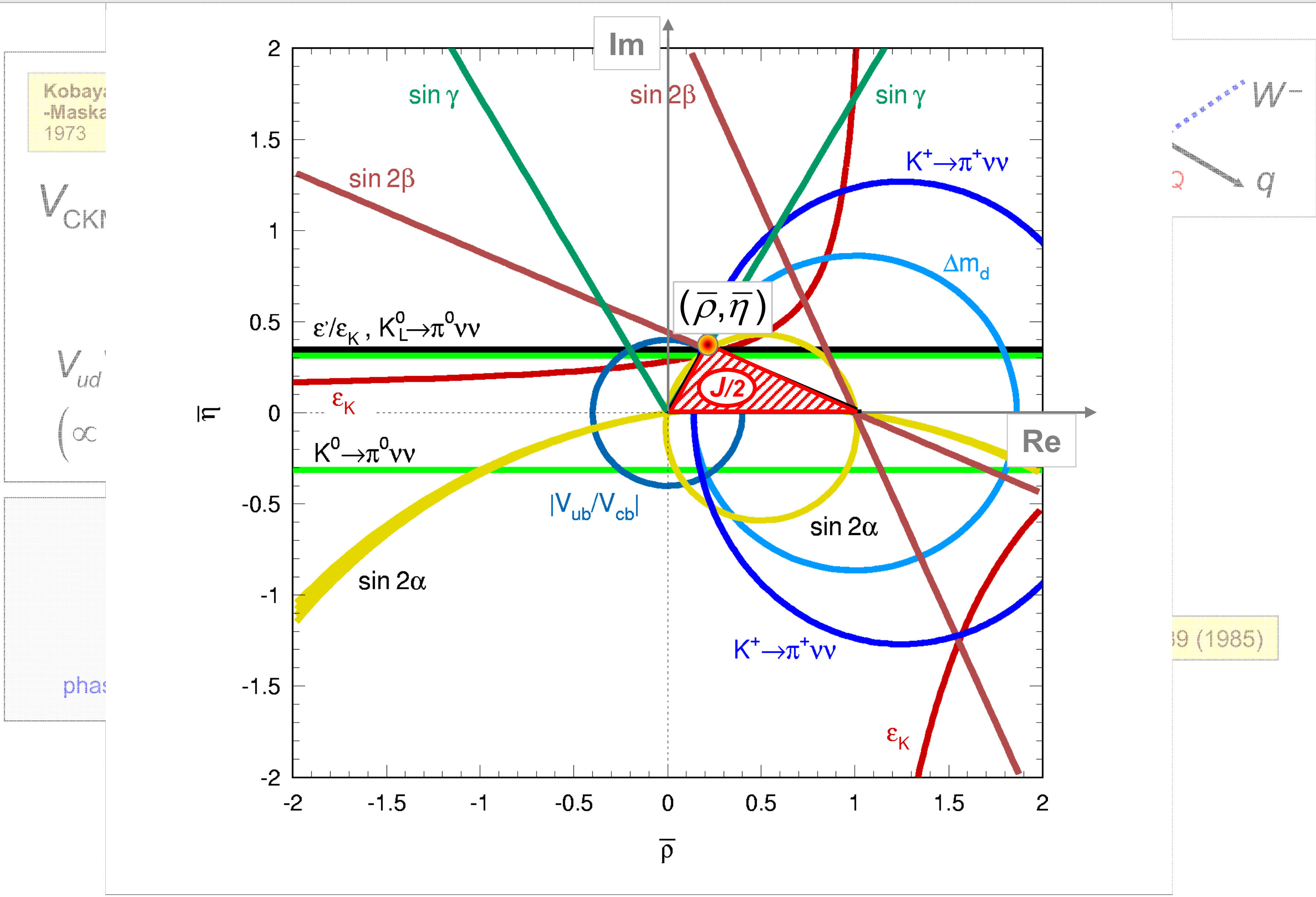




Jarlskog invariant
J = 0 ⇔ no VCP

Jarlskog, PRL 55, 1039 (1985)

The CKM Matrix and the Unitarity Triangle



The CKM Matrix and the Unitarity Triangle

- Understand the origin of *CP* violation

  The KM mechanism
  does it account for all the effects of *CP* violation observed in the quark sector?

- If possible, reveal inconsistencies between experimental data and theoretical predictions

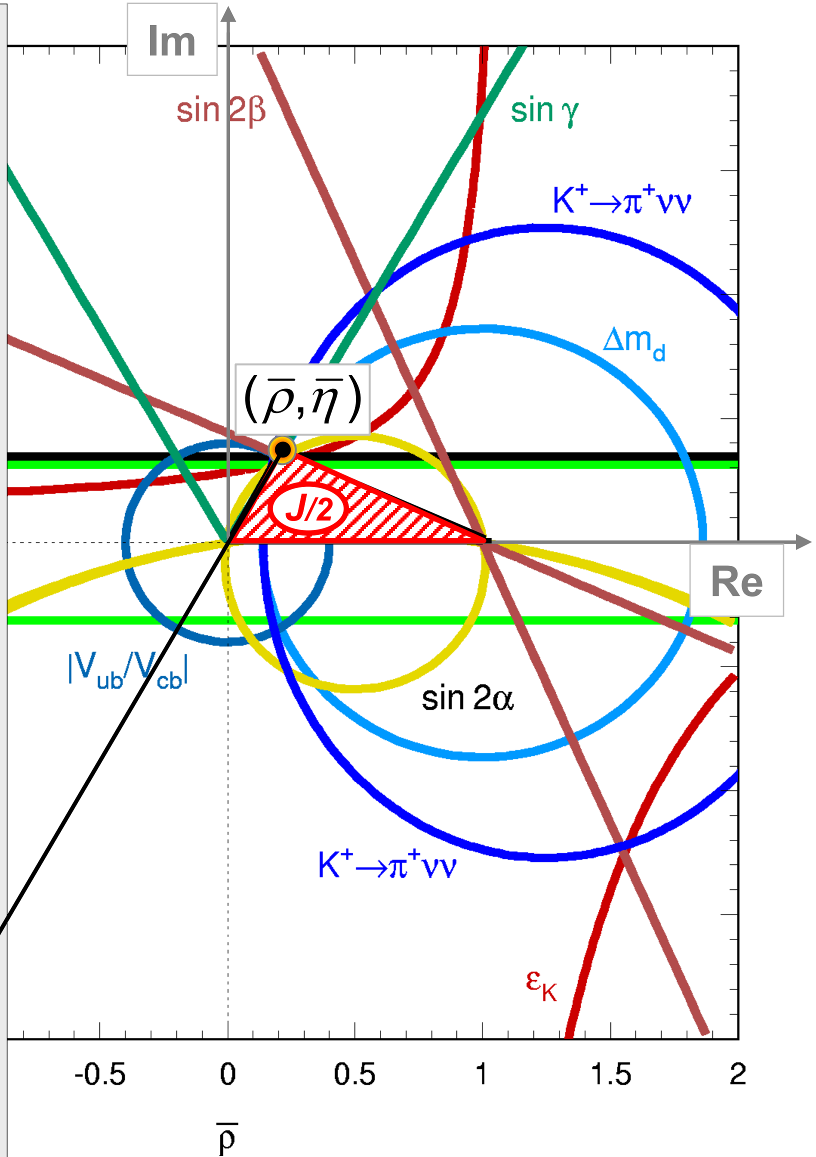
  Manifestation of New Physics
  in decay and/or flavor mixing processes for the considered heavy quark systems?

  Evidence for new sources of CPV?

- Studies in the different neutral heavy meson systems are complementary

  Study charged mesons too!

Culminating Point
SM or new phases (fields)?



digression : The Unitary Wolfenstein Parameterization

- The standard parameterization uses Euler angles and one CPV phase → unitary !

$$V = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

- Now, define $s_{12} \equiv \lambda$ $s_{23} \equiv A\lambda^2$ $s_{13}e^{-i\delta} \equiv A\lambda^3(\rho - i\eta)$

Buras *et al.*,
PRD 50, 3433 (1994)

- And insert into *V* → *V* is still unitary ! With this one finds (to all orders in λ) :

$$\rho + i\eta = \frac{\sqrt{1 - A^2\lambda^4}(\bar{\rho} + i\bar{\eta})}{\sqrt{1-\lambda^2}\left[1 - A^2\lambda^4(\bar{\rho} + i\bar{\eta})\right]}$$

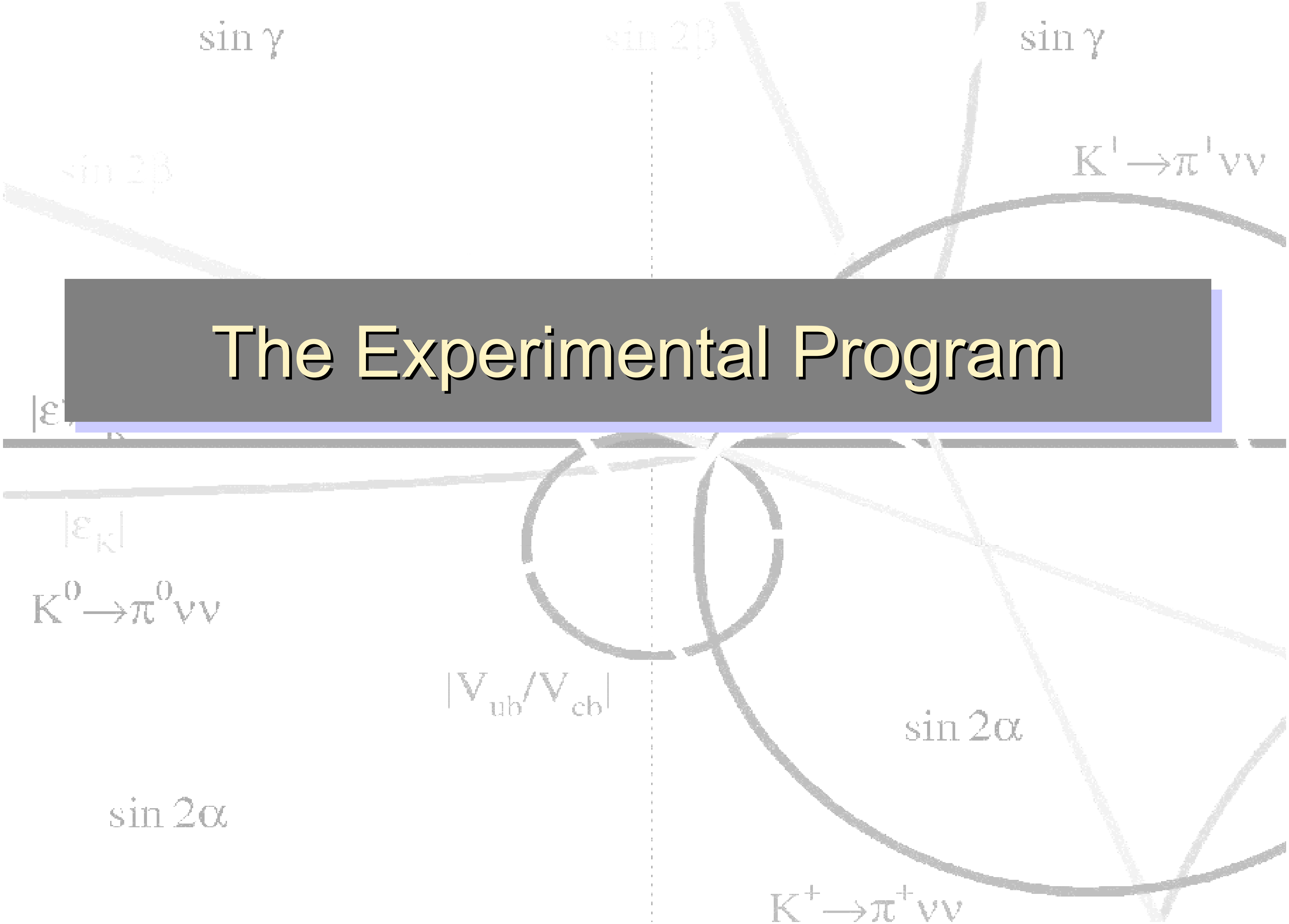
where: $$\bar{\rho} + i\bar{\eta} = -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}$$

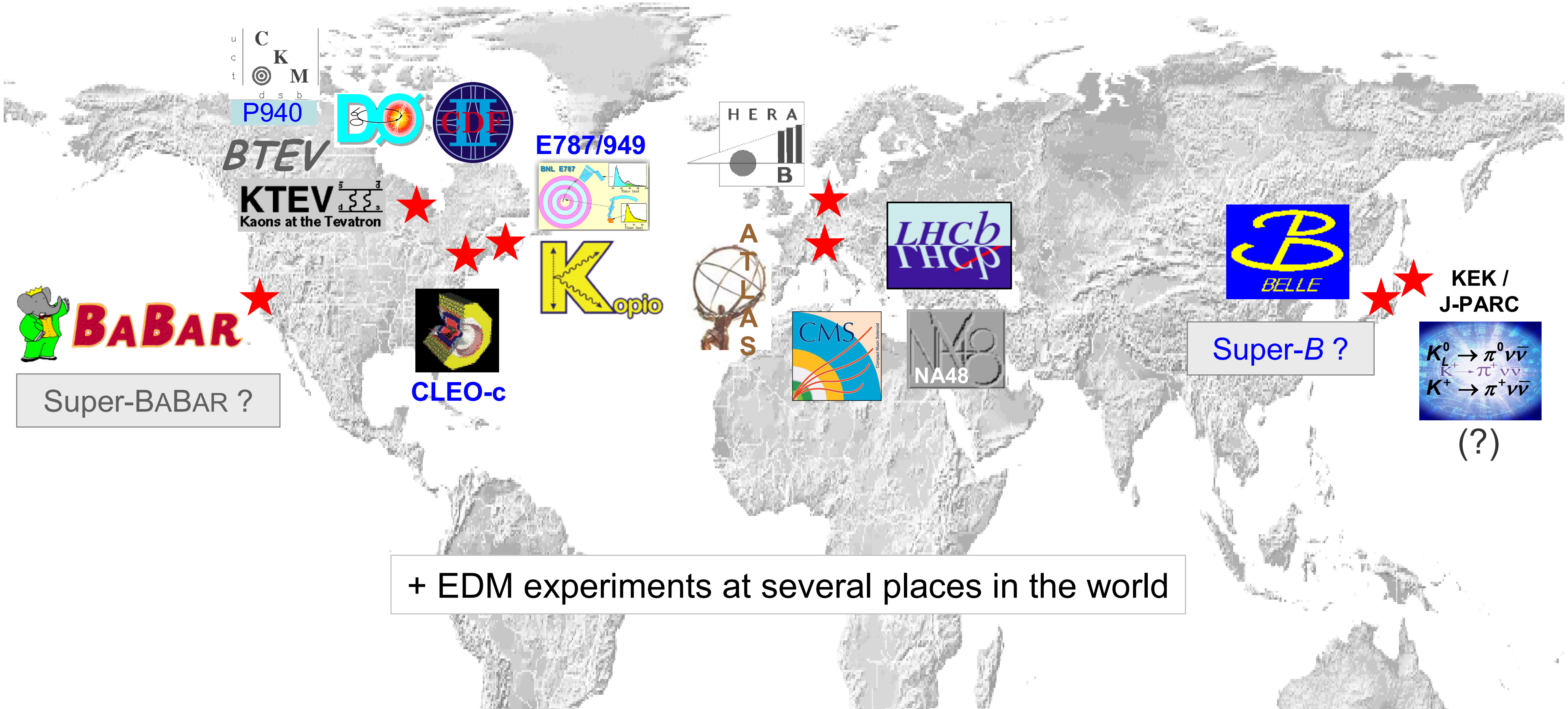
- If one wishes (not necessary for the analysis), one can Taylor expand in λ and finds :

$$\bar{\rho} = \rho\left(1 - \frac{\lambda^2}{2}\right) + \left(\frac{1}{2}A^2\rho - \frac{1}{8}\rho - A^2\left(\rho^2 - \eta^2\right)\right)\lambda^4 + O(\lambda^6)$$

$$\bar{\eta} = \eta\left(1 - \frac{\lambda^2}{2}\right) + \left(\frac{1}{2}A^2\eta - \frac{1}{8}\eta - 2A^2\rho\eta\right)\lambda^4 + O(\lambda^6)$$

The Experimental Program

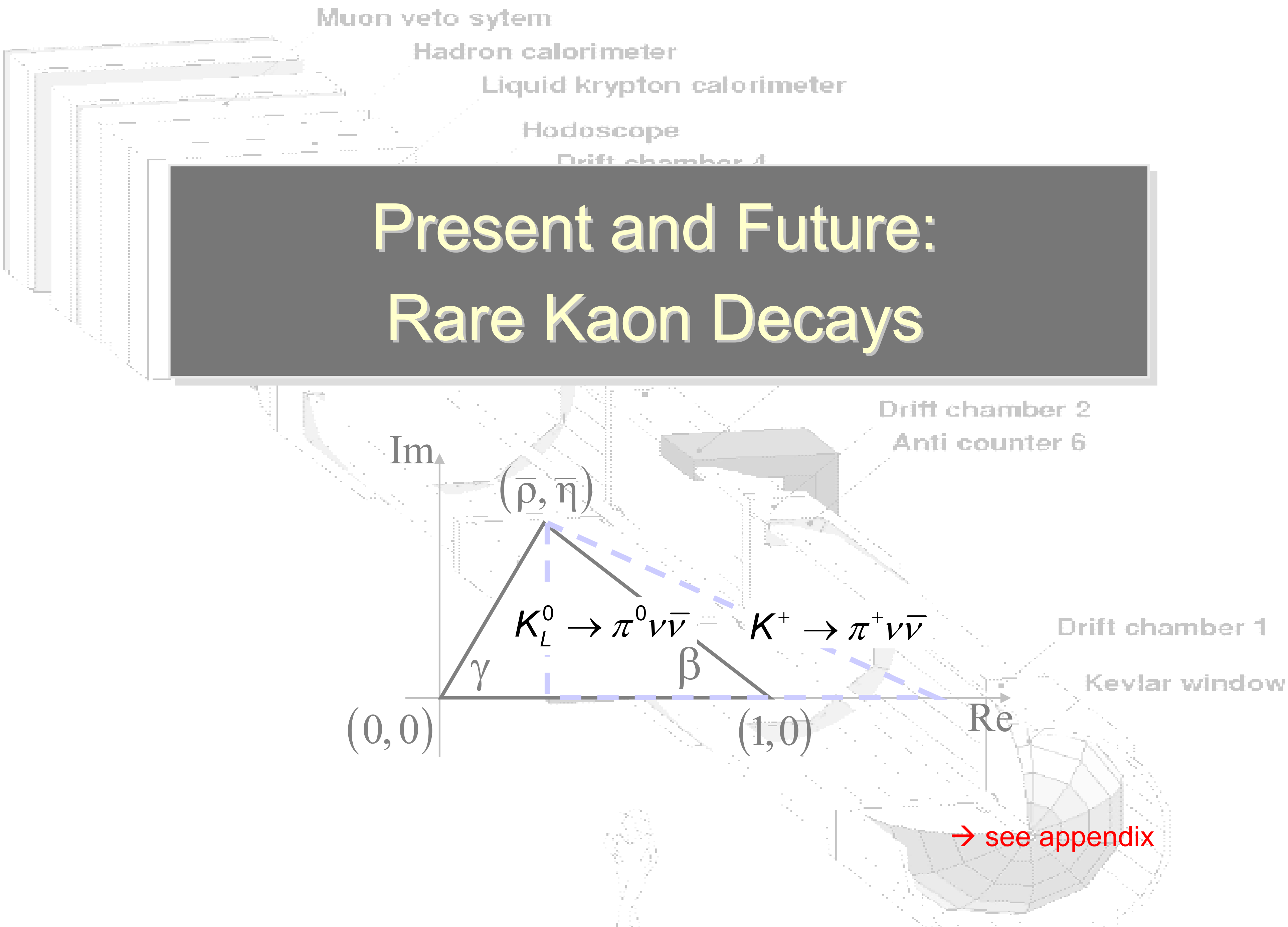




Present and future - Worldwide Program on

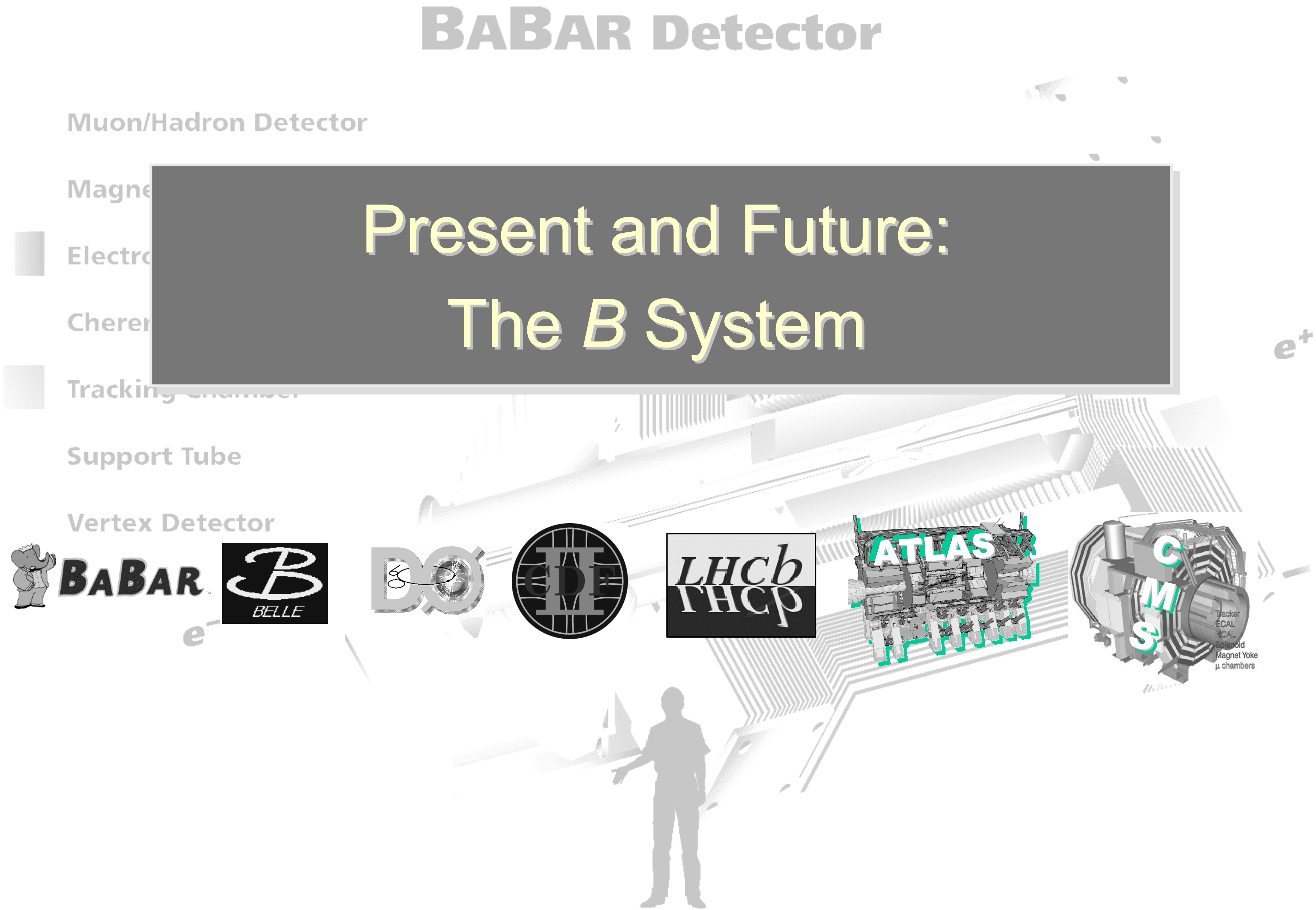
Flavor Physics and *CP* Violation

Present and Future: Rare Kaon Decays

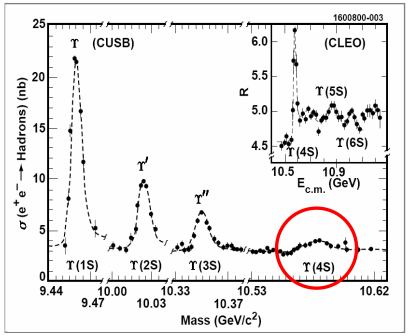


→ see appendix

Present and Future:
The *B* System



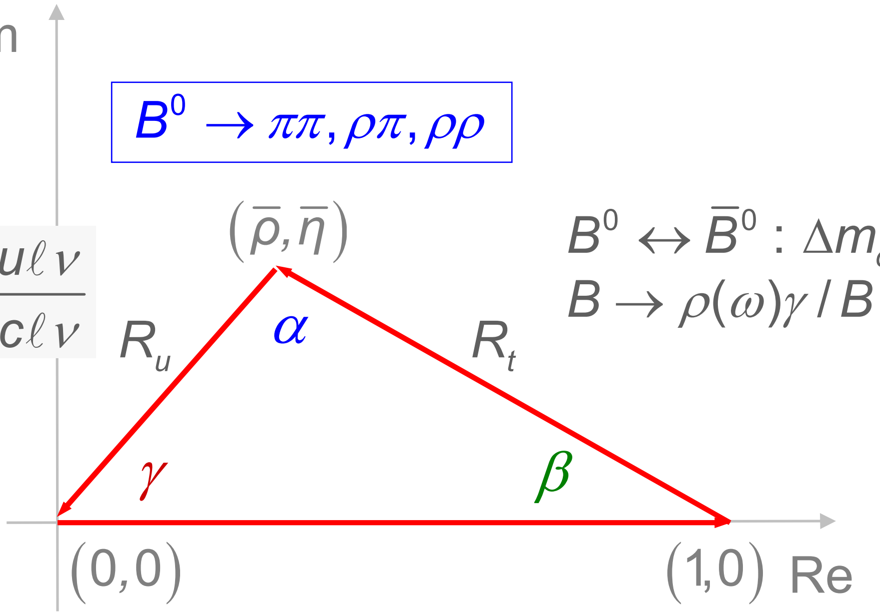
The B_d System ($e^+e^- \to \Upsilon(4S)$ factories)



the B_d is also produced by the hadron machines

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

$b \to u \ell \nu$ / $b \to c \ell \nu$



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

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

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

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

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

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

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

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

$B^0 \to J/\psi \pi^0$

$B^0 \to D_{(s)}^{(*)+}D^{(*)-}$

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

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

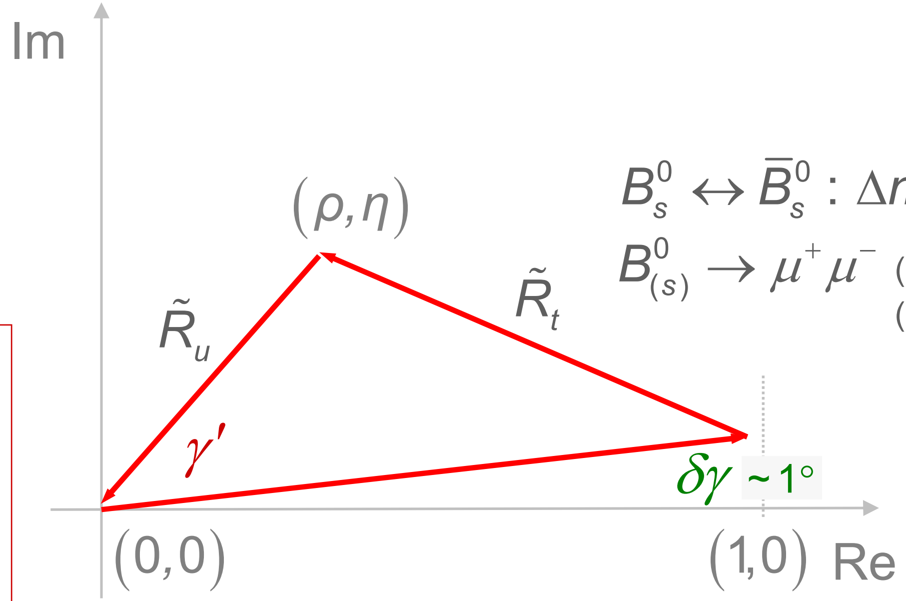
$b \to s\bar{s}s$

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

The B_s System (hadron machines)

$p\bar{p}$ (Tevatron) or
pp interaction (LHC)

the B_s is not produced by the $\Upsilon(4S)$ B factories



$B_s^0 \leftrightarrow \bar{B}_s^0 : \Delta m_s / \Delta m_d$

$B_{(s)}^0 \to \mu^+\mu^-$ (BR for $B_d^0 \sim 2\times10^{-10}$)
(BR for $B_s^0 \sim 4\times10^{-9}$)

$B_s^0 \to D_s K$
$B_s^0 \to K^+K^-$
$B_s^0 \to J/\psi K_S^0$
$B_s^0 \to D_s^+ D_s^-$, ...

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

$B_s^0 \to J/\psi\phi$, ...
$B_s^0 \to \phi\phi$, ...

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

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

After the *B*-Physics pioneers, Argus, CLEO and den LEP Experiments ...

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

SLAC

Stanford
Linear
Accelerator
Center

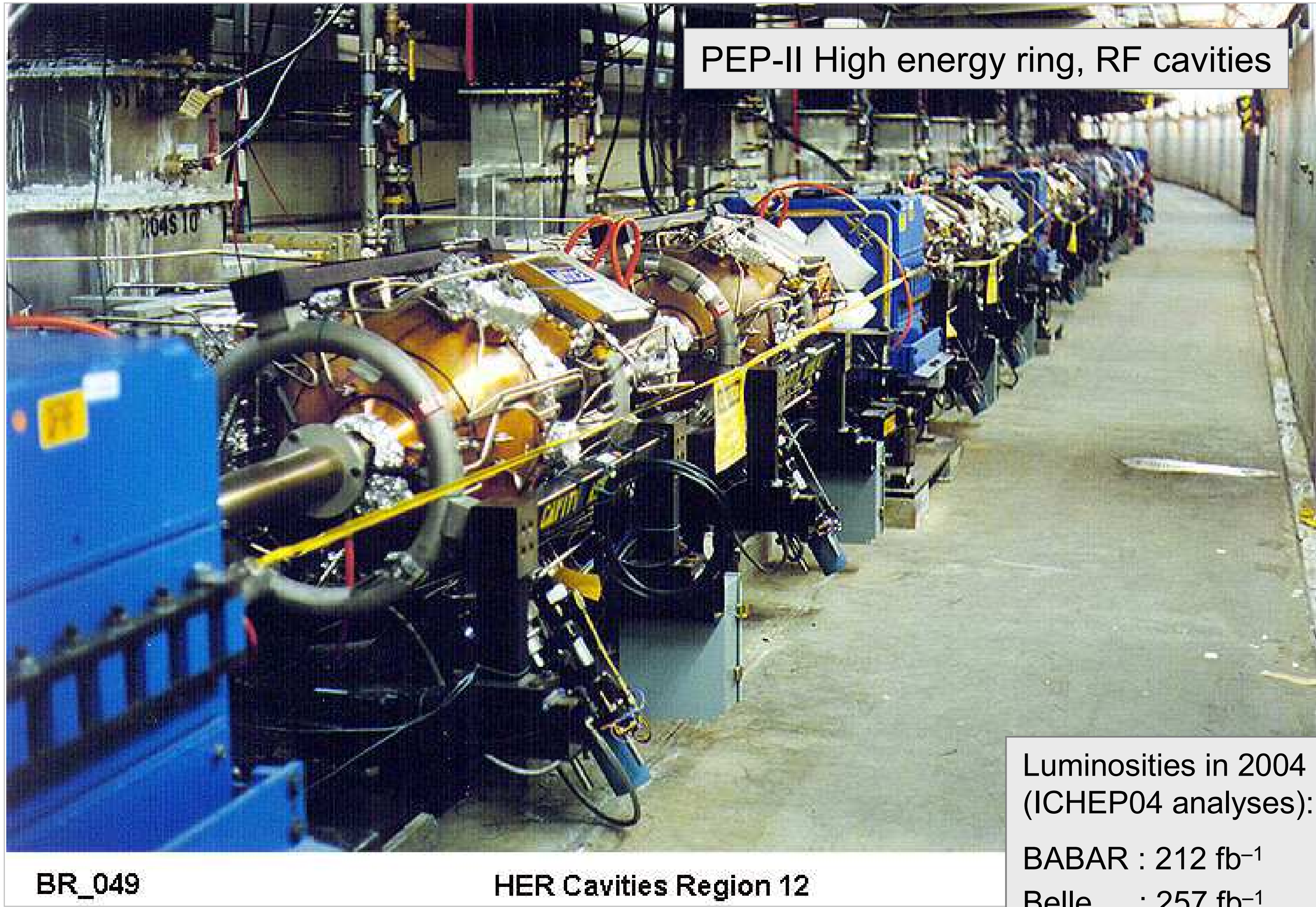
Linac

Fixed Target
Experiments

BABAR

SLD (& MARK II)

PEP-II at SLAC: Asymmetric-Energy e^+e^- Collider

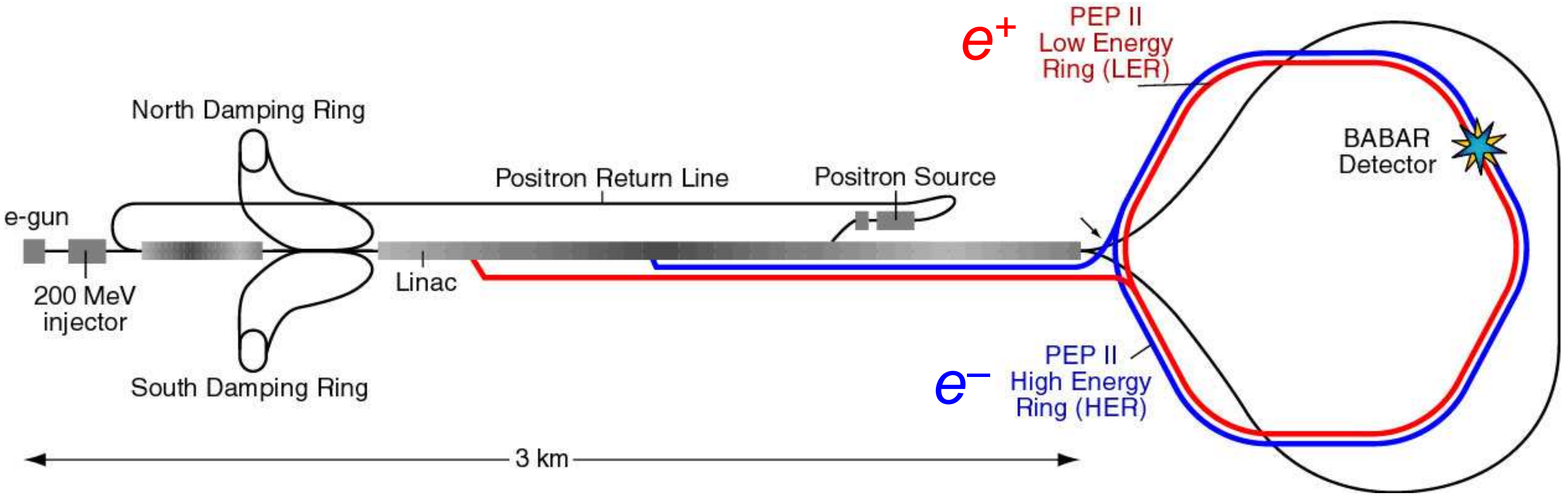


Luminosities in 2004 (ICHEP04 analyses):

BABAR : 212 fb^{-1}

Belle : 257 fb^{-1}

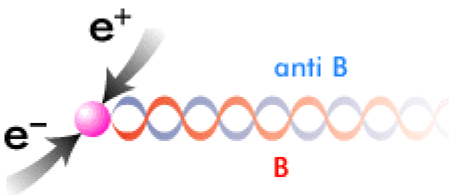
The Asymmetric-Energy *B* Factory PEP-II



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

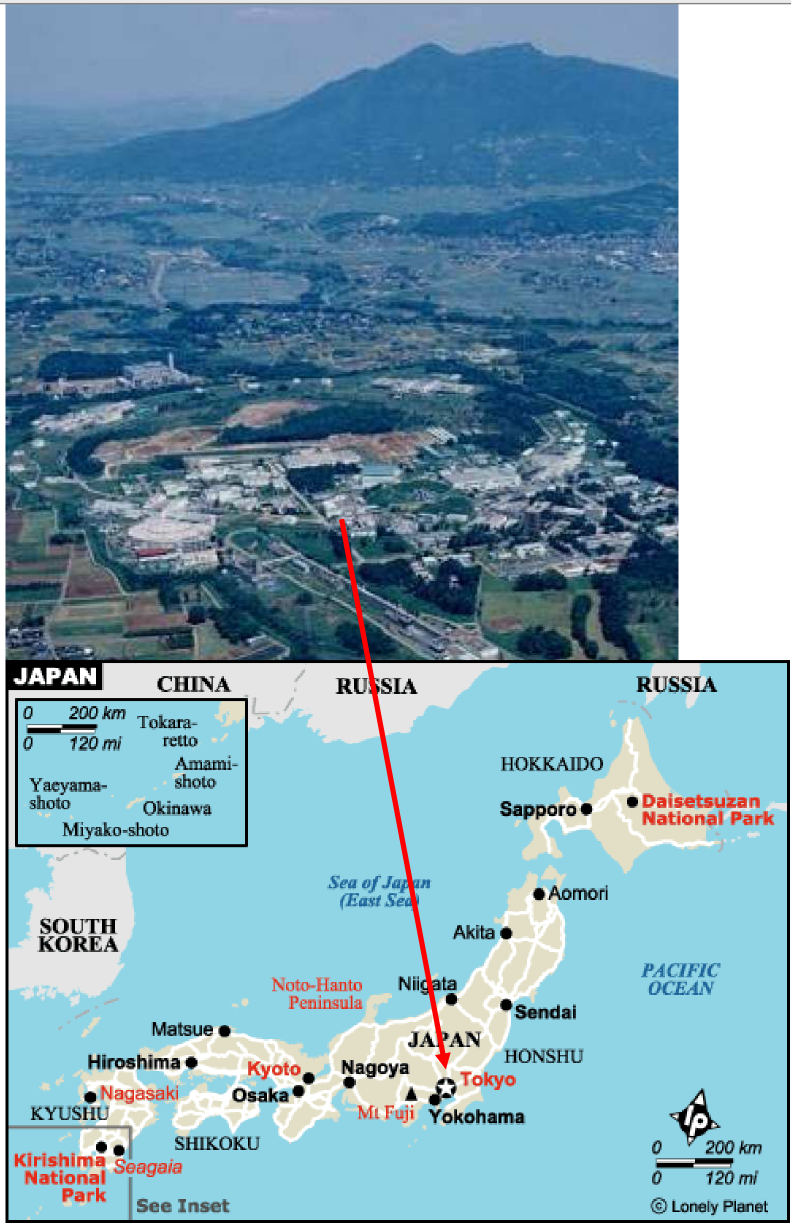
$$e^+e^- \to \Upsilon(4S) \to B\bar{B}$$

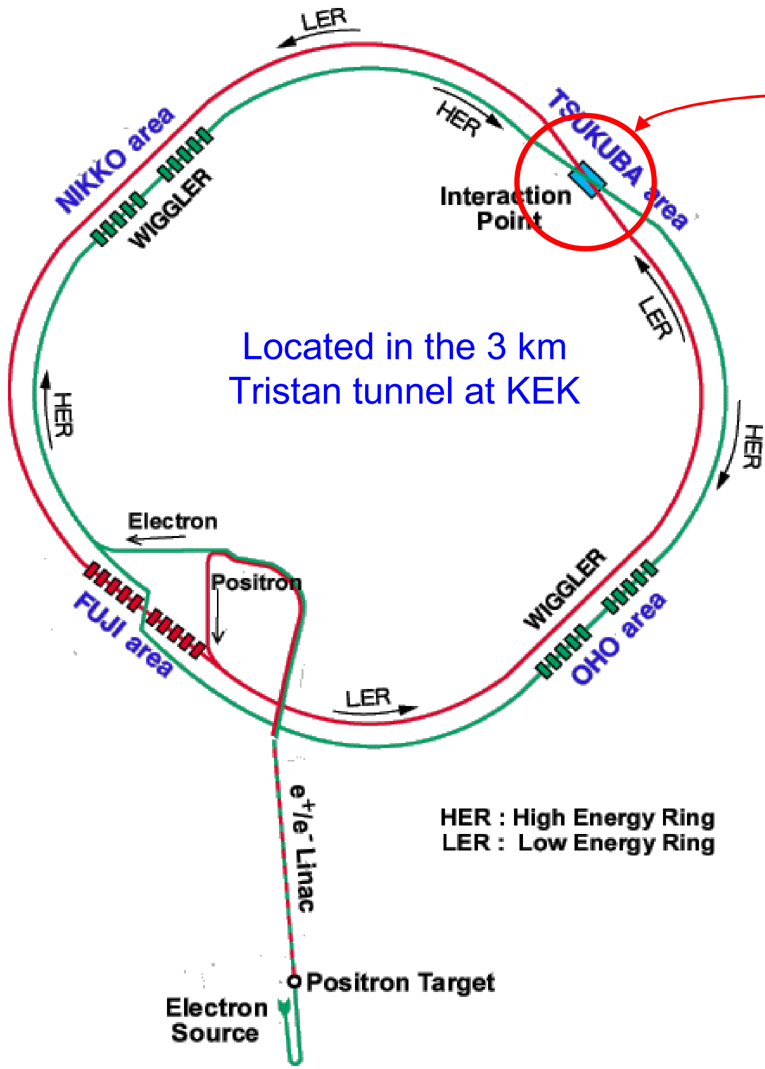
- coherent neutral *B* pair production and decay (*P*-wave)



- boost of $\Upsilon(4S)$ in lab frame : $\beta\gamma = 0.56$

The Asymmetric-Energy *B* Factory KEKB





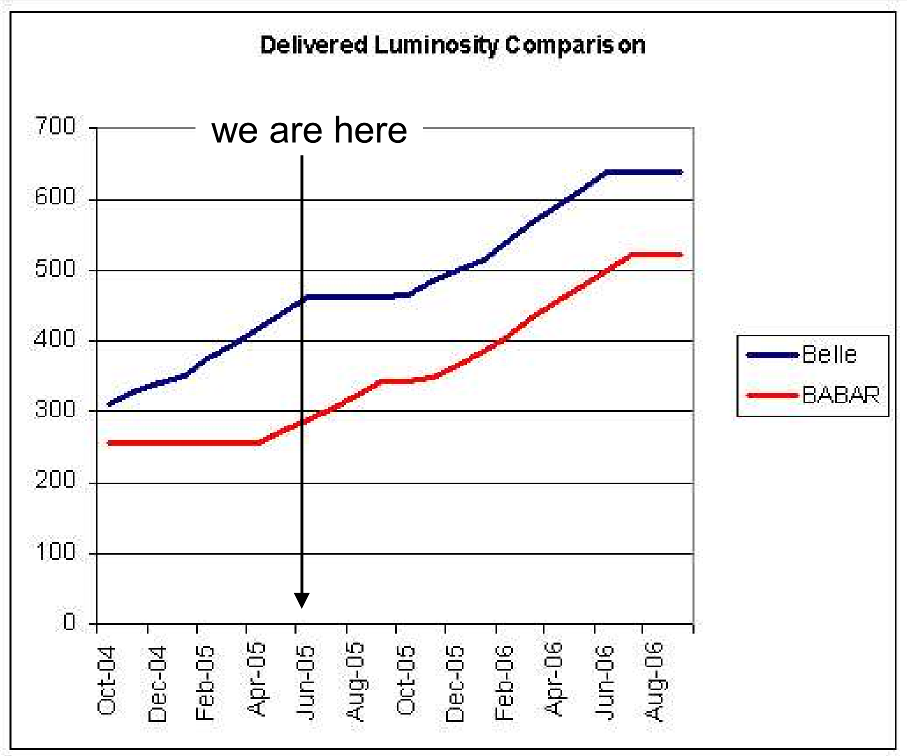
Located in the 3 km
Tristan tunnel at KEK

8 GeV e^- colliding with 3.5 GeV e^+
$\beta\gamma$=0.425 and ±11 mrad crossing angle

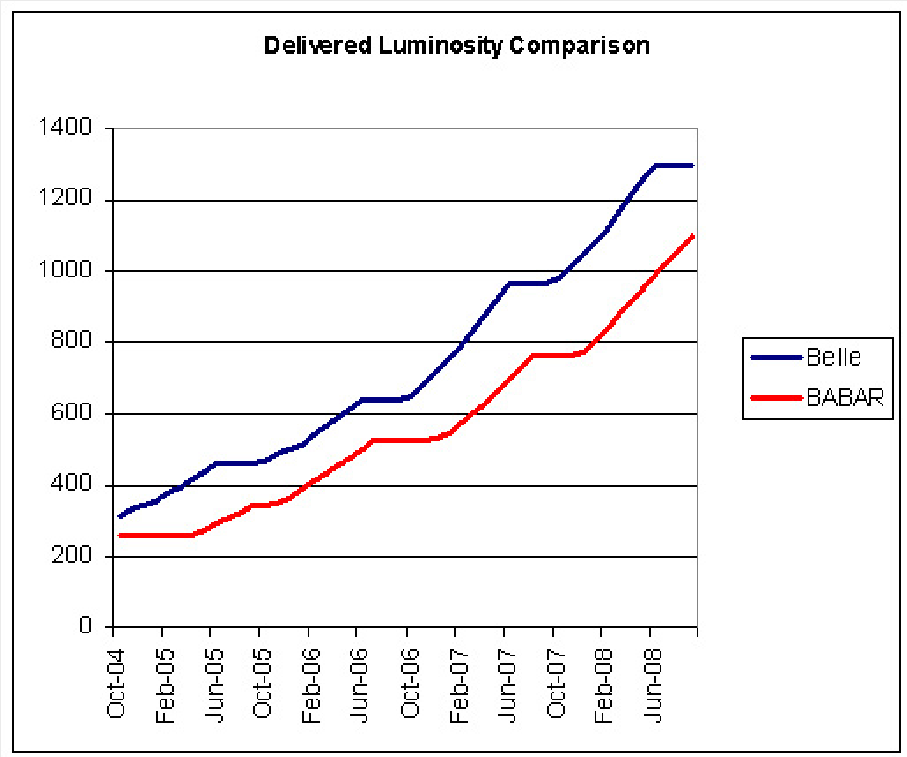
BABAR and Belle: Accumulated Luminosities

Peak luminosity records : BABAR: 9.2×10^{-33} cm^{-2}s^{-1} ; Belle: 15.8×10^{-33} cm^{-2}s^{-1}

integrated: 262 fb^{-1} ; 445 fb^{-1}



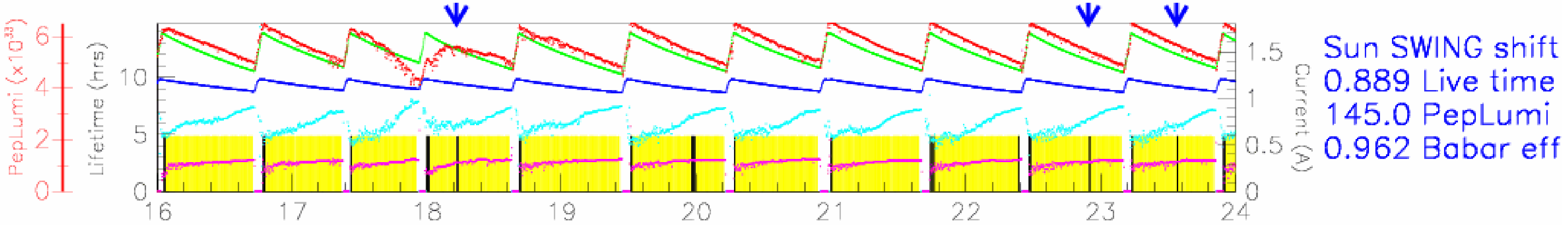
Double data by summer 2006



Double again by Sep 2008

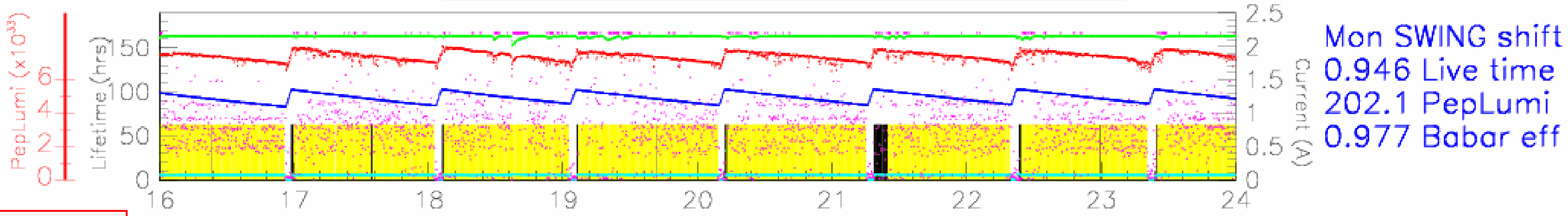
"Trickle Injection"

Best shift, without trickle Inj.



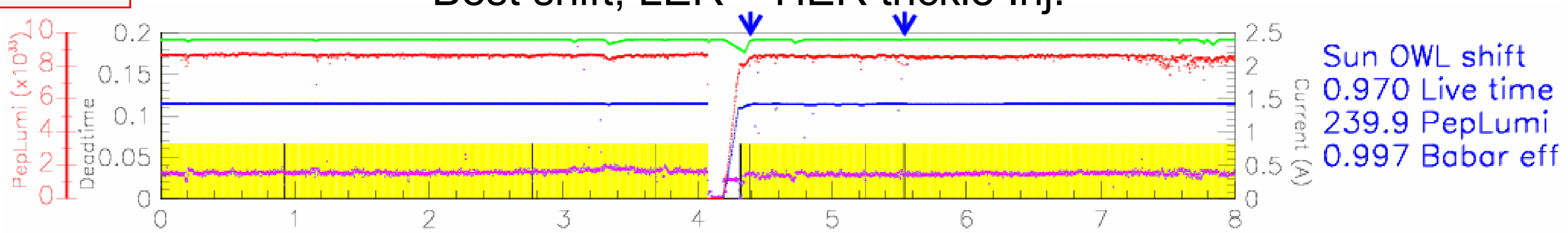
Nov 2003

Best shift, LER trickle Inj.



Mar 2004

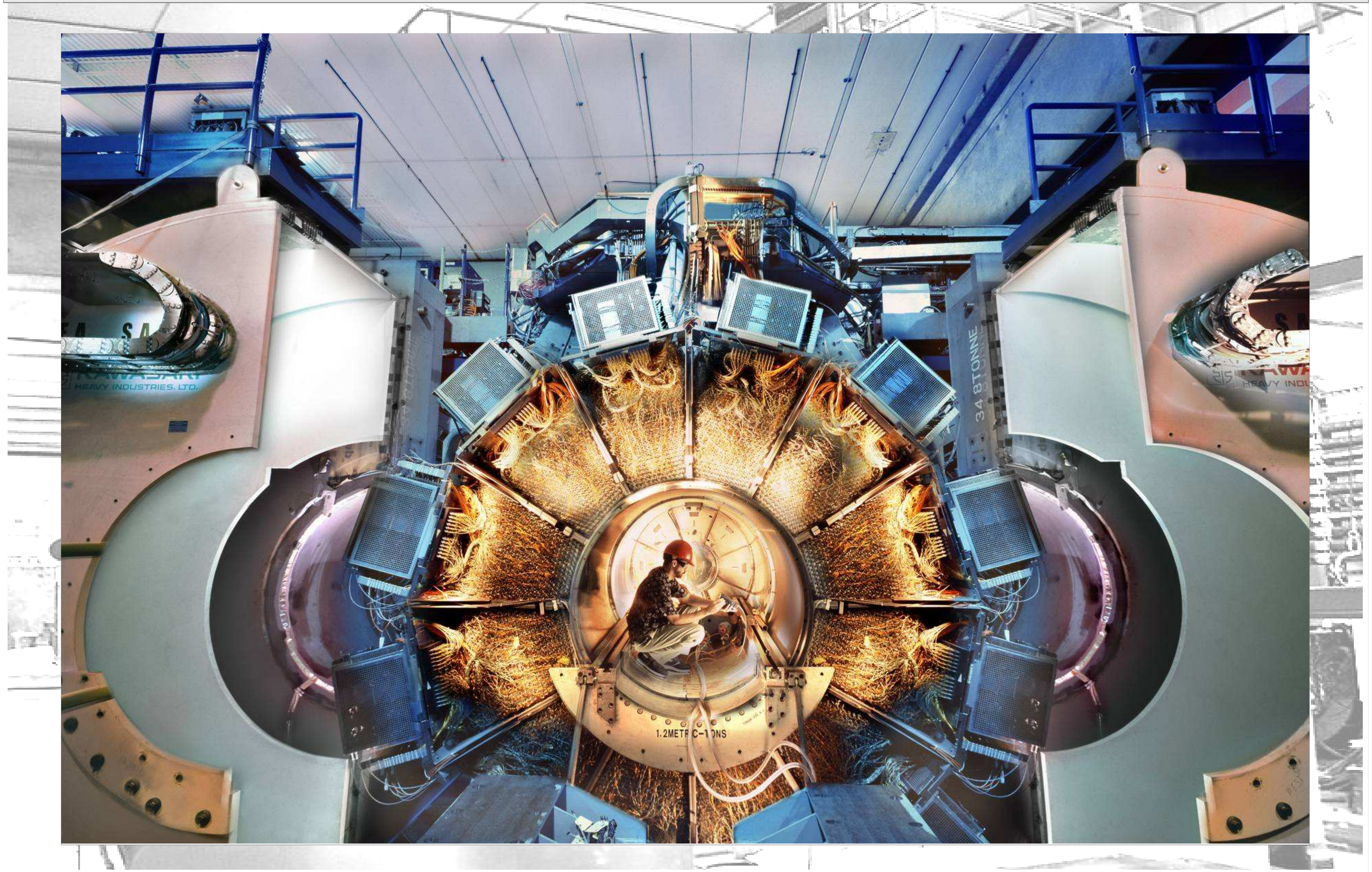
Best shift, LER + HER trickle Inj.



PEP-II : ~5 Hz continuous
KEKB : every ~5-10 min

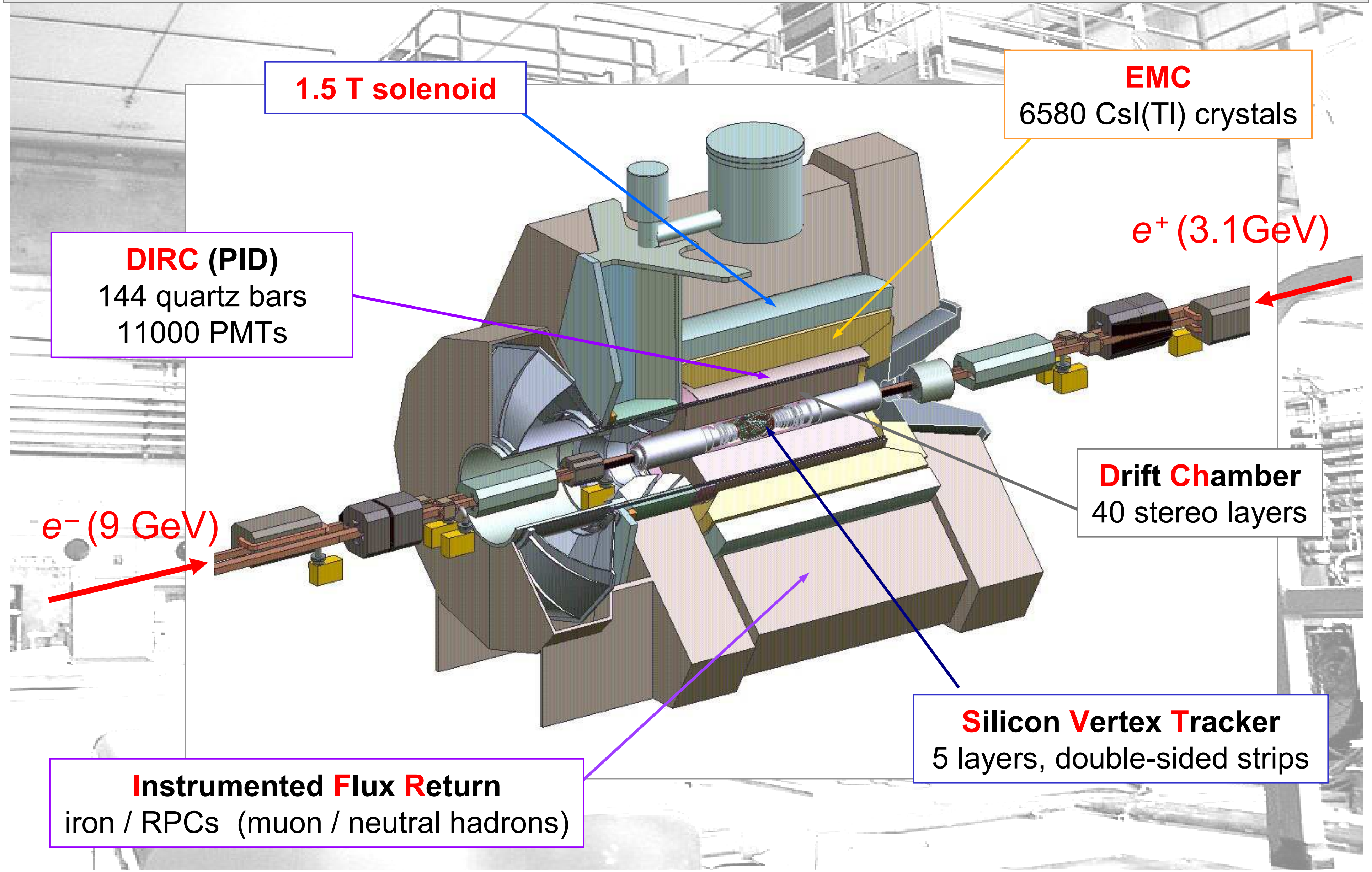
- PEP-II Lumi (red)
- HER current (blue)
- LER current (green)

The BABAR Detector

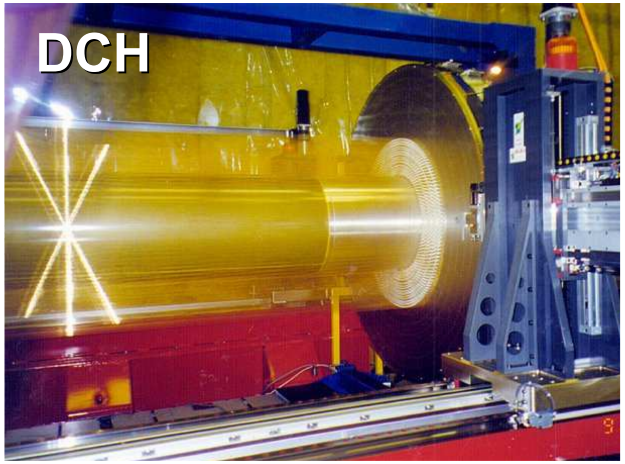


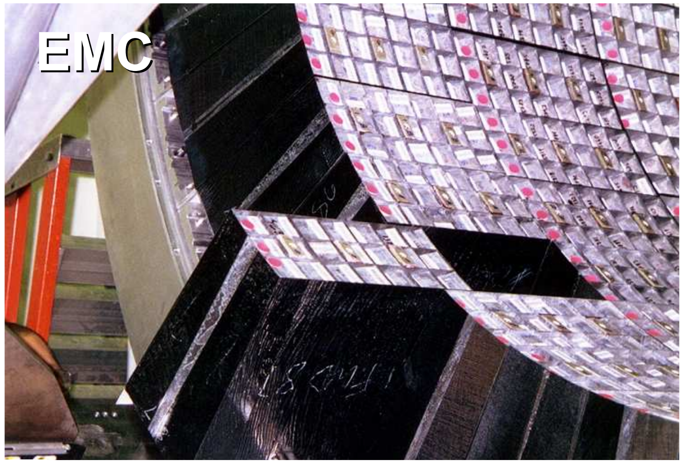
The BABAR Detector

BABAR, NIM A479, 1 (2002)



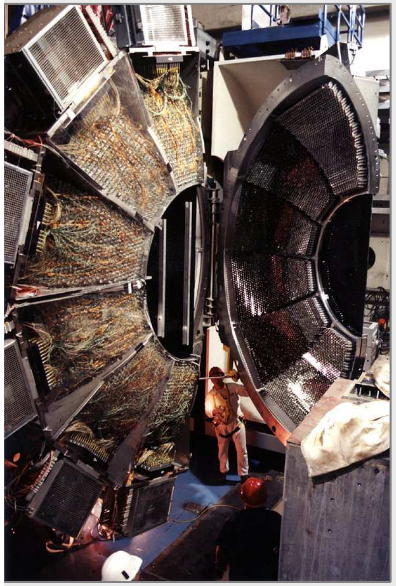
The BABAR Detector

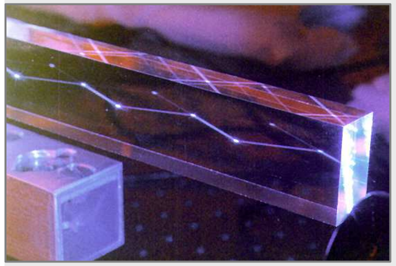


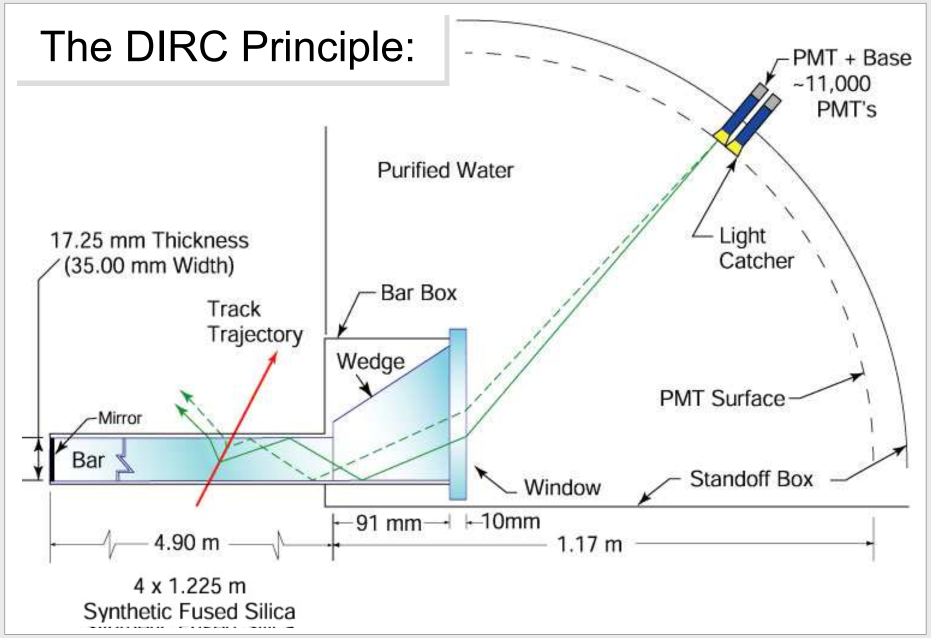


Particle Identification for BABAR: DIRC Čerenkov Detector

Detection of
Internally
Reflected
Čerenkov light



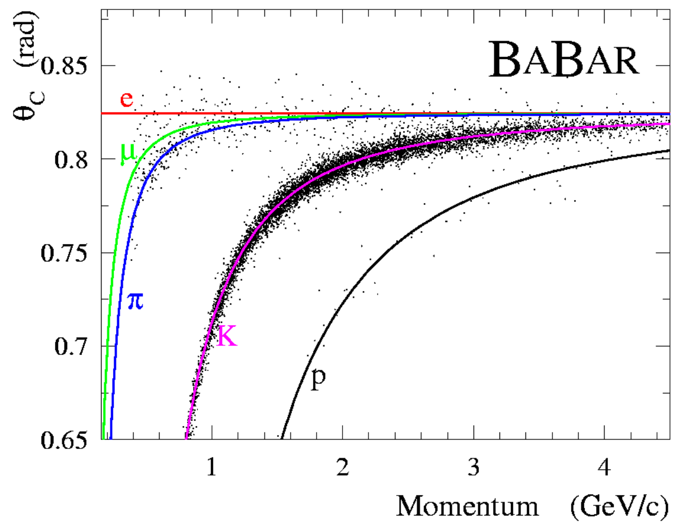


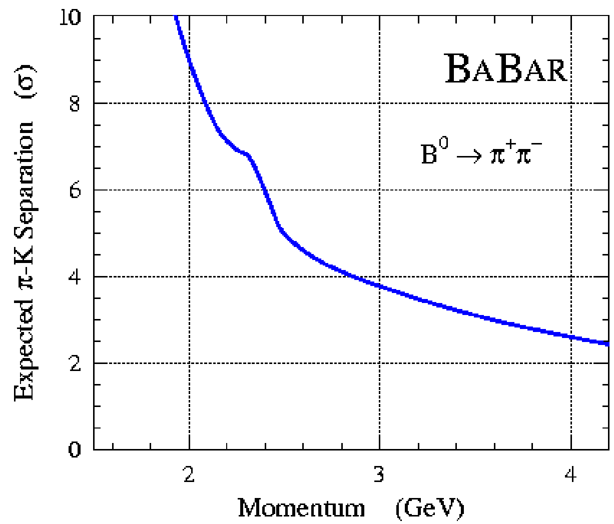


Emitted Čerenkov angle:

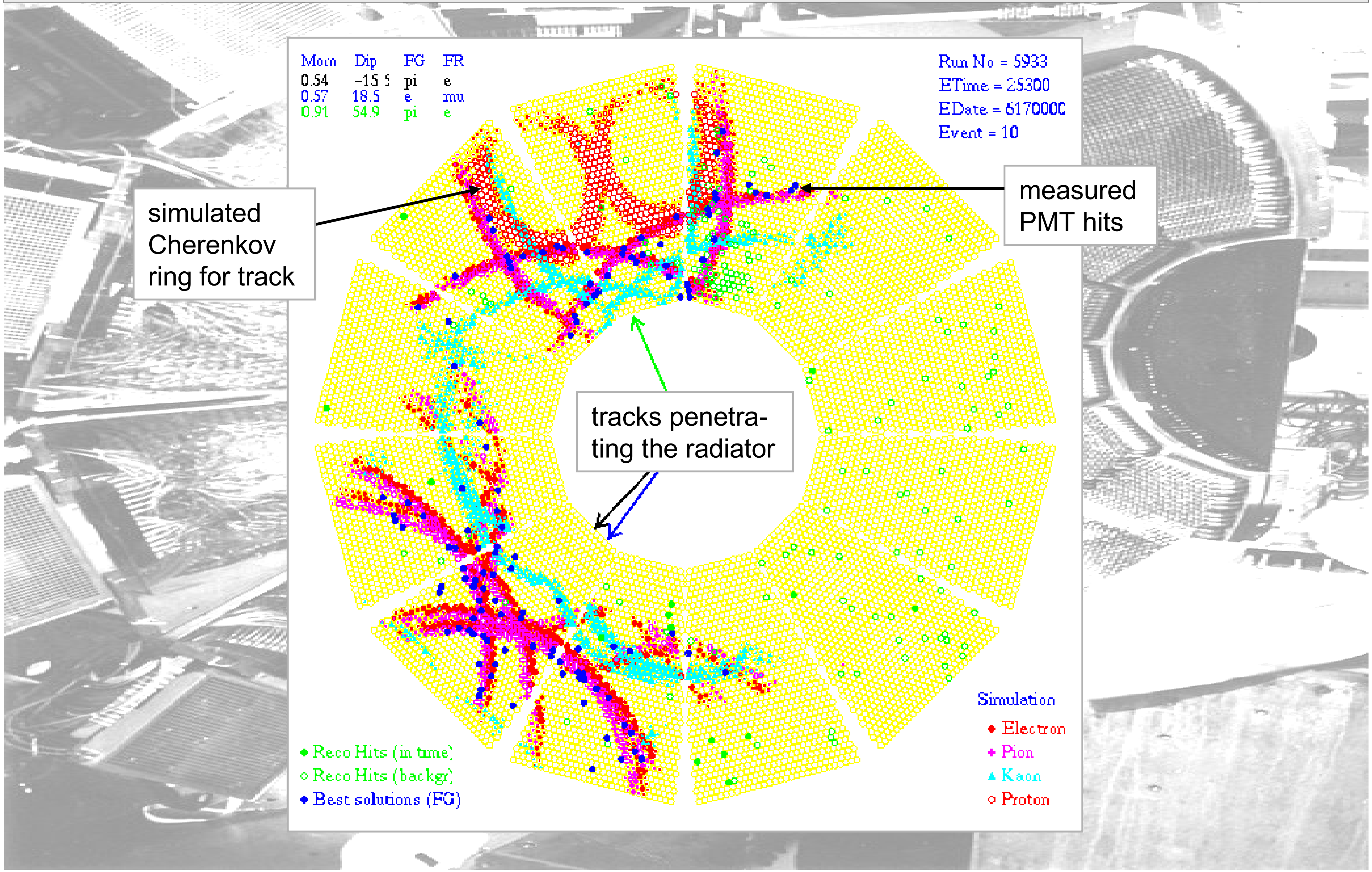
$$\cos\theta_C = \frac{1}{n\sqrt{1+m^2/p^2}}$$

Excellent $\pi/K/p$ separation up to 4 GeV/c

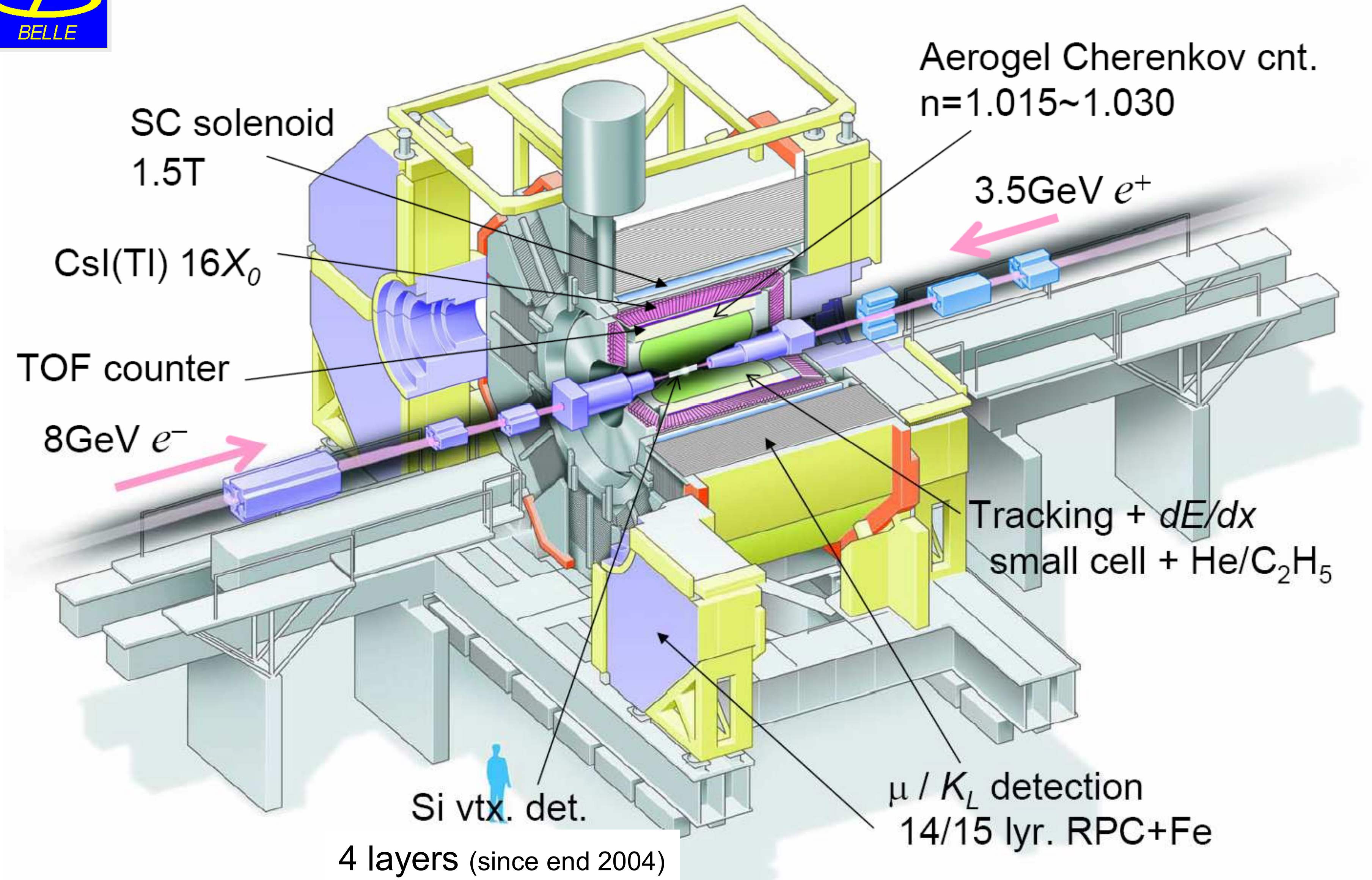




Particle Identification for BABAR: DIRC Čerenkov Detector

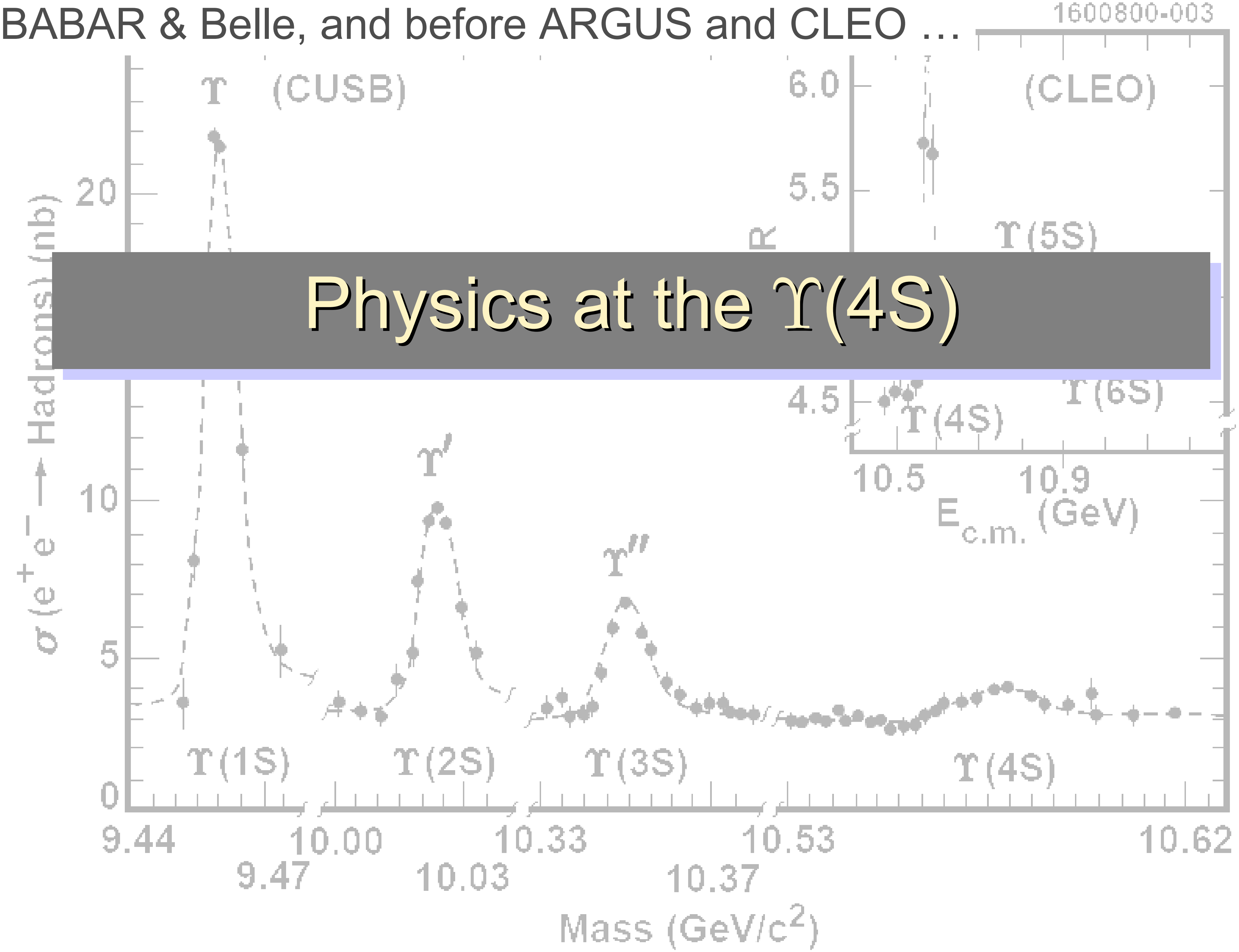


The Belle Detector

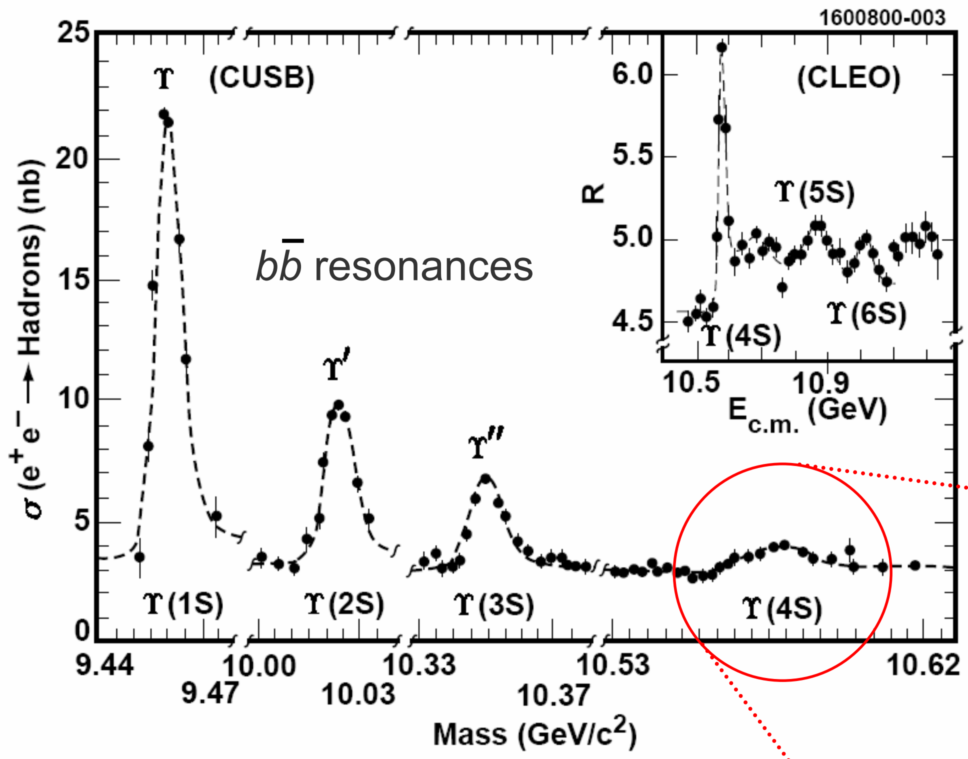


BABAR & Belle, and before ARGUS and CLEO …

Physics at the Υ(4S)

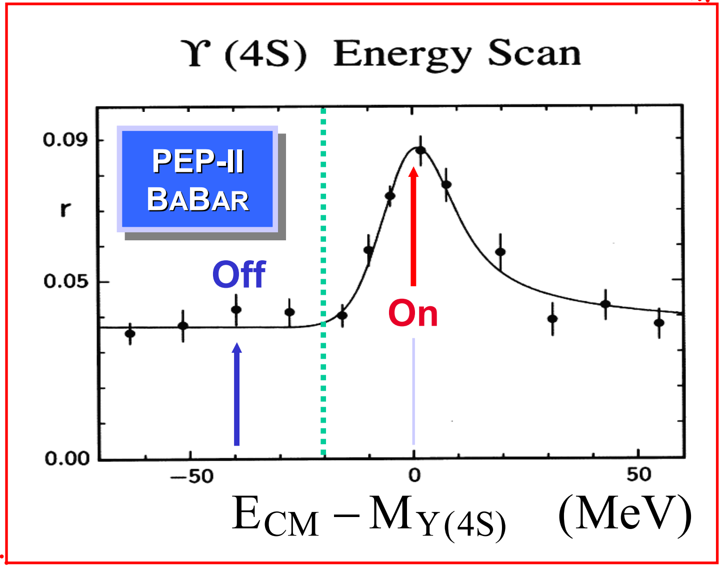


Physics at the $\Upsilon(4S)$



The cleanest way to produce B mesons: e^+e^- collisions at $\sqrt{s}$ = 10.58 GeV

Production of coherent $B\bar{B}$ pairs with a cross section of 1.1 nb (over a continuum of ~3 nb)



production cross section

$b\bar{b}$	≈ 1.1 nb
$c\bar{c}$	≈ 1.3 nb
$s\bar{s}$	≈ 0.3 nb
$d\bar{d}$	≈ 0.3 nb
$u\bar{u}$	≈ 1.4 nb

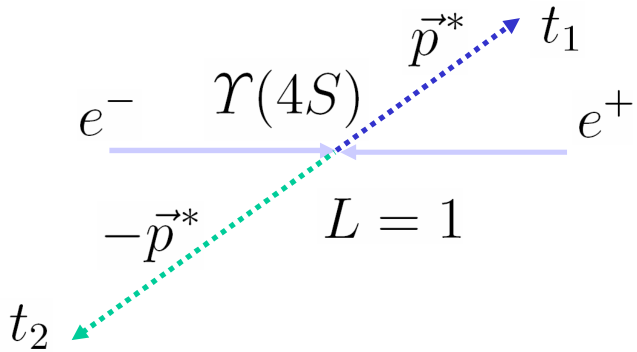
$\Upsilon(4S) \to B^+B^-$, $B^0\bar{B}^0$ to approx. 50% each

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

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 measure 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)

this property is exploited for *B* flavor tagging (see later)

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

$$p^* = 340 \text{ MeV}/c$$
$$(\beta\gamma)^* = 0.064$$

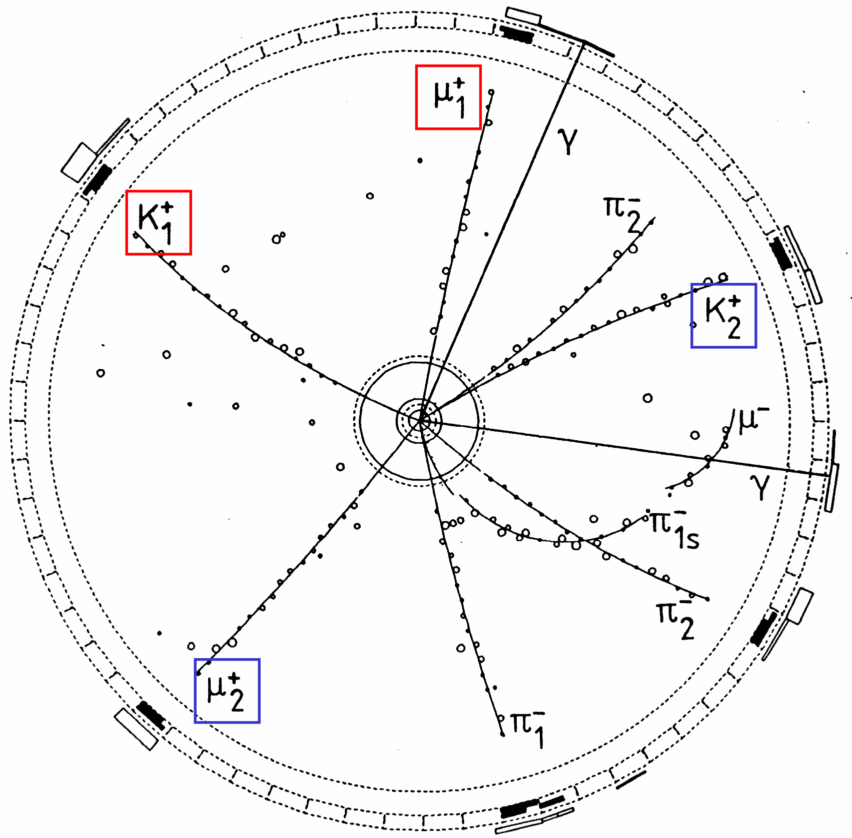
➡ flight distance $d^* \sim 30\ \mu\text{m}$ (beyond experimental reach)

➡ At a "symmetric" *B*-Factory, only time-integrated measurements are possible

Time-Integrated Measurements at the $\Upsilon(4S)$

Because $\Delta t \subset \{-\infty, +\infty\}$, only Δt -even quantities can be obtained with a time-integrated measurement

ARGUS, 1987
Discovery of *BB* mixing



Flavor mixing is Δt -even

$$a_{\rm mix}(\Delta t) \propto \cos(\Delta m \Delta t)$$

➡ a time-integrated measurement **is** possible

CP asymmetries are Δt -odd

$$a_{CP}(\Delta t) \propto \sin(\Delta m \Delta t)$$

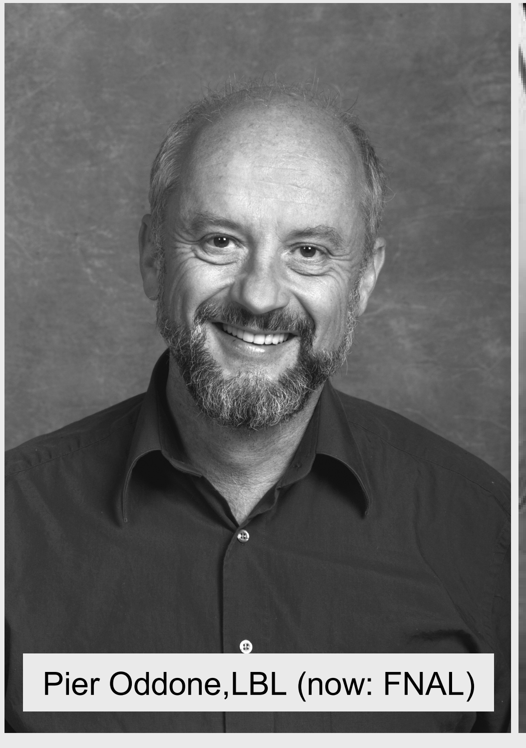
➡ a time-integrated measurement **is not** possible

➡ Time-dependent *CP* studies at the $\Upsilon(4S)$ require the measurement of Δt of the order of 100 million *B* mesons (or more)

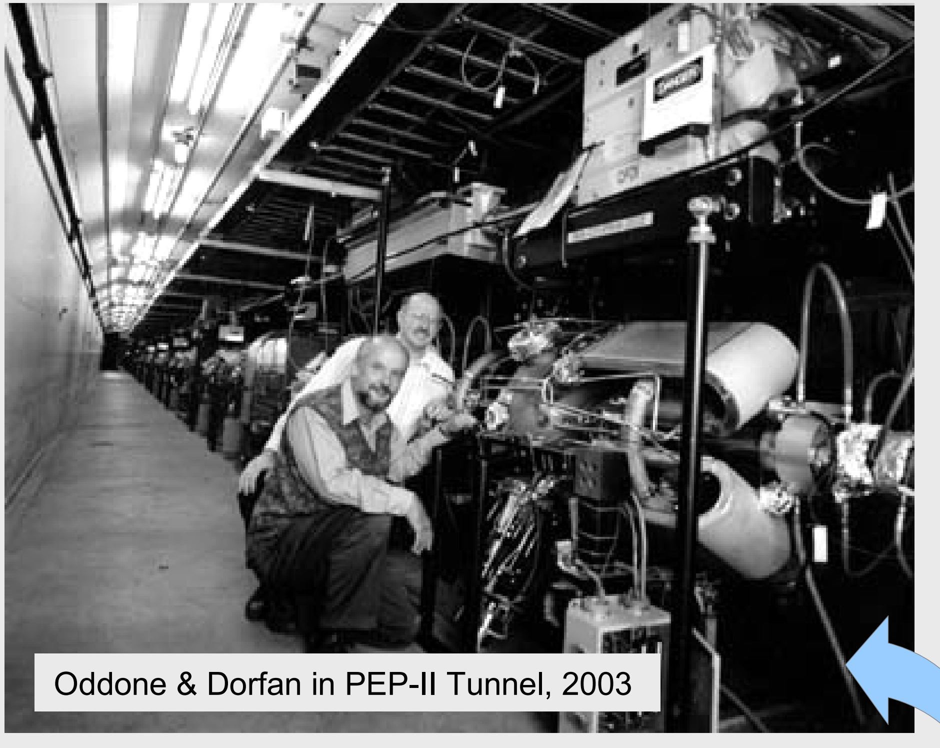
Pier Oddone's Clever Idea (1987)

Why not produce the Υ(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 $5\text{x}10^{33}$



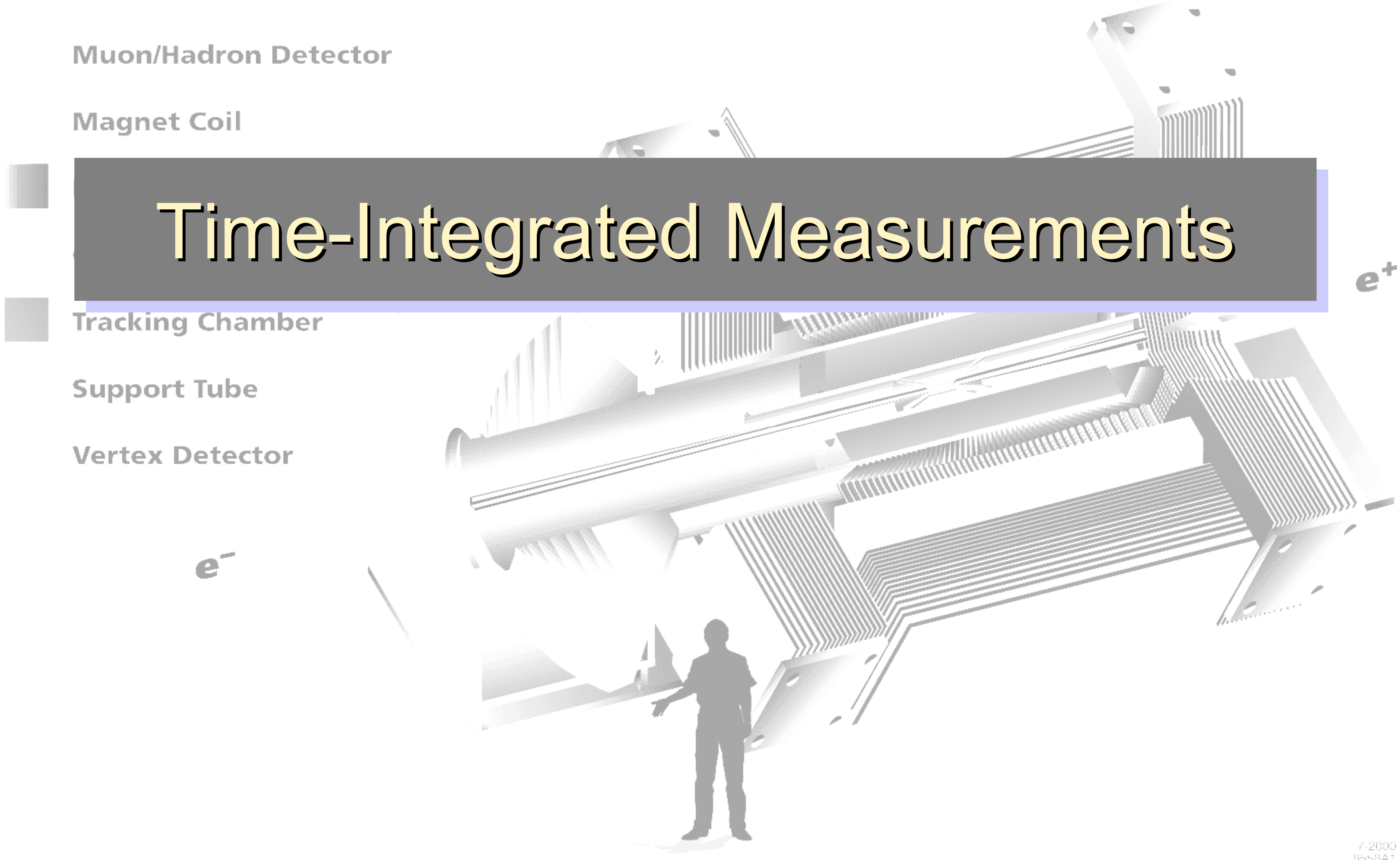
Pier Oddone,LBL (now: FNAL)



Oddone & Dorfan in PEP-II Tunnel, 2003

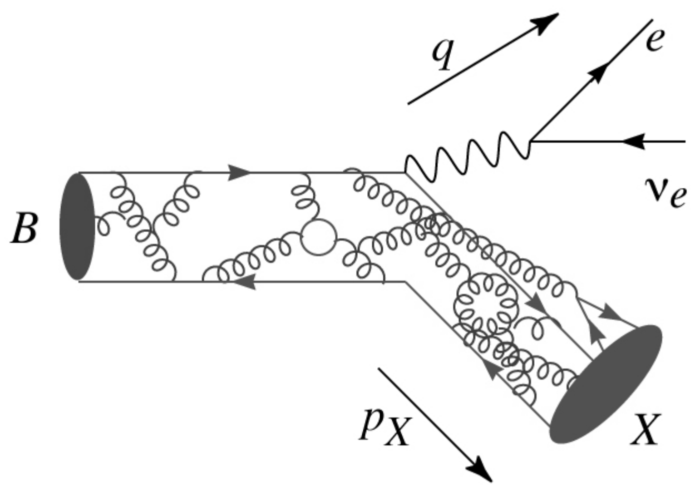
10 years later exist two asymmetric *B* Factories :
PEP-II at SLAC and KEKB at KEK

Time-Integrated Measurements



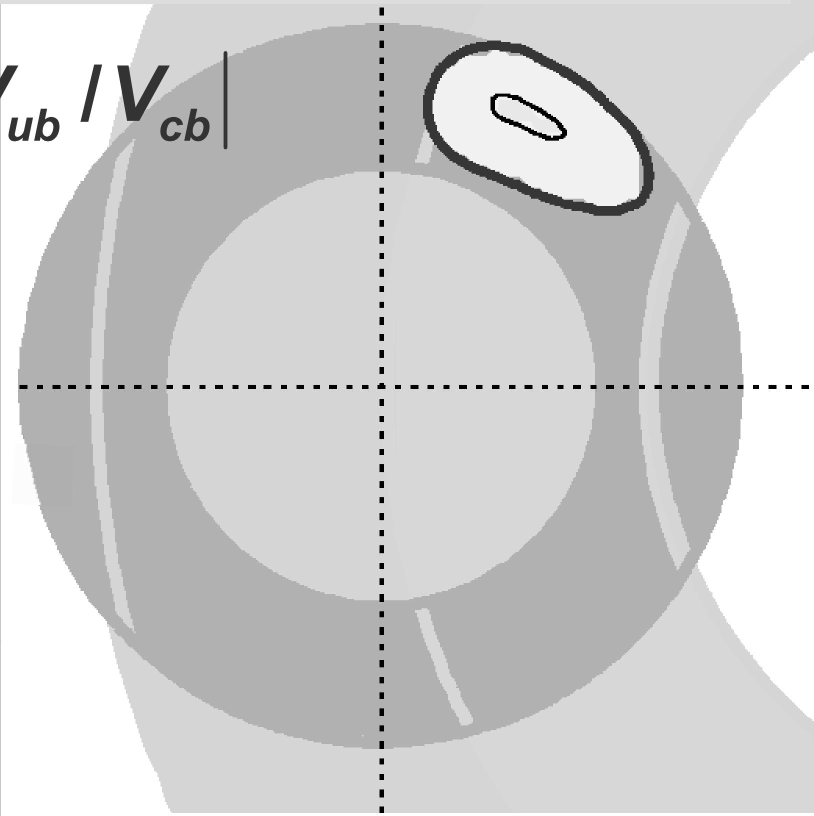
The Elements $|V_{ub}|$ and $|V_{cb}|$

— semileptonic *B* decays —



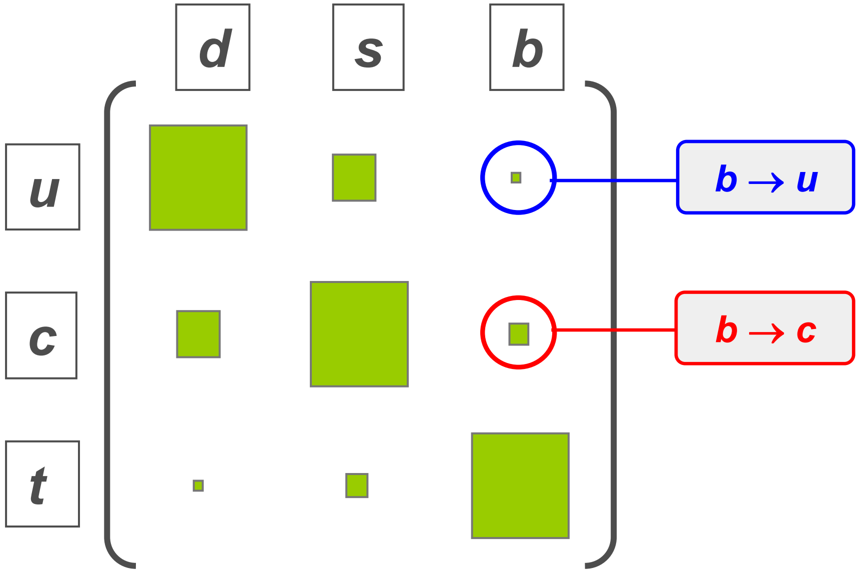
$$|V_{ub}| = A\lambda^3\sqrt{\rho^2+\eta^2} \quad \text{et} \quad |V_{cb}| = A\lambda^2$$

$$\Rightarrow \text{circle in } (\rho,\eta) \text{ plane}$$



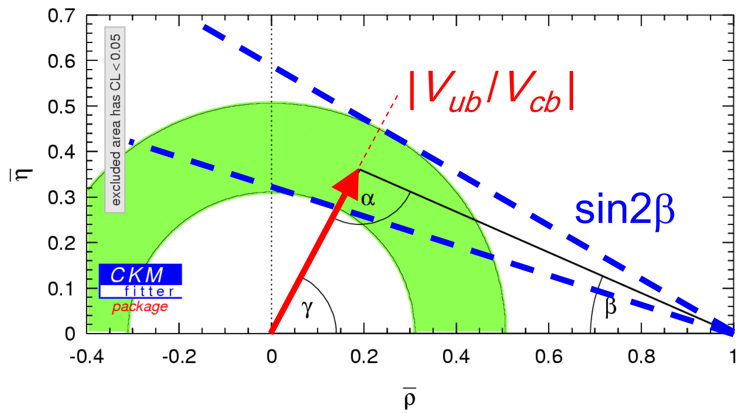
$|V_{cb}|$ and $|V_{ub}|$

- For $|V_{cb}|$ and $|V_{ub}|$ exist exclusive and inclusive semileptonic approaches



	exclusive	inclusive
$b \to u$	$B \to \pi \ell\nu$	$B \to X_u \ell\nu$
$b \to c$	$B \to D^* \ell\nu$	$B \to X_c \ell\nu$
dominant uncertainties	Form factor	OPE ($\lvert V_{cb,ub}\rvert$) and shape function ($\lvert V_{ub}\rvert$)

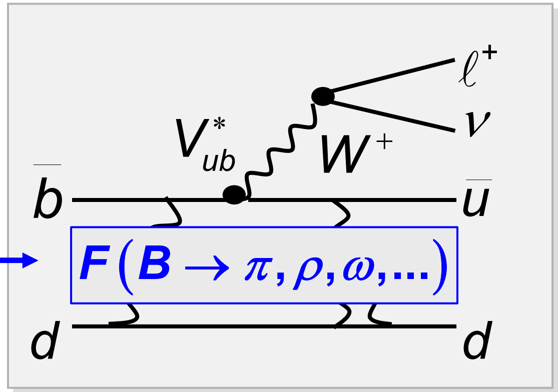
- $|V_{ub}|$ ($\to \rho^2 + \eta^2$) is crucial for the SM prediction of $\sin(2\beta)$
- $|V_{cb}|$ ($\to A$) is important in the kaon system (ε_K, BR($K\to\pi\nu\nu$), …)



$|V_{ub}|$ (and $|V_{cb}|$) : Principle of Exclusive Measurements

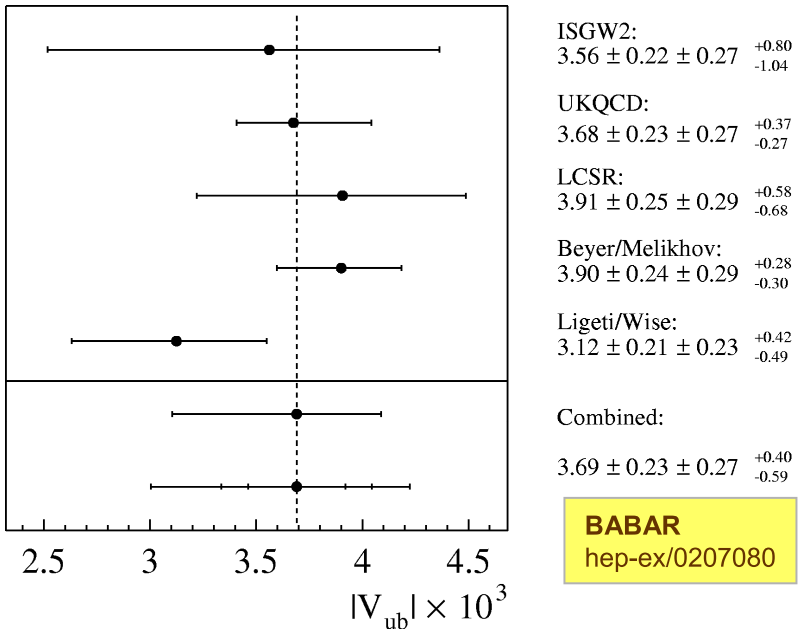
- Pure tree decay
- Decay rate is proportional to CKM element $|V_{ub}|^2$

$$\mathrm{BR}\left(B^0 \to h^- \ell^+ \nu\right) \propto \left|V_{ub}\right|^2 F_B^2(q^2)$$



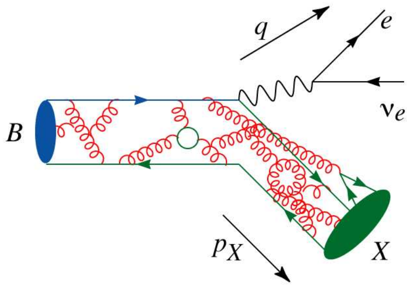
Problem:

- form factor is model dependent !
- would need unquenched lattice calculation to become model-independent...



BABAR
hep-ex/0207080

$|V_{ub}|$ (and $|V_{cb}|$) : Principle of Inclusive Measurements



$$\simeq \frac{d\Gamma}{d(PS)} \sim \left|V_{[u,c]b}\right|^2 \times \left(\underbrace{\text{quark model}}_{\text{free quark decay}} + \underbrace{\sum_n C_n \left(\frac{\Lambda_{QCD}}{m_b}\right)^n}_{\text{non-perturbative corrections}} \right)$$

☺ : relation between $\sum_{X_u} \Gamma(B \to X_u \ell \bar{\nu})$ and $|V_{ub}|$ known to ~ 5%

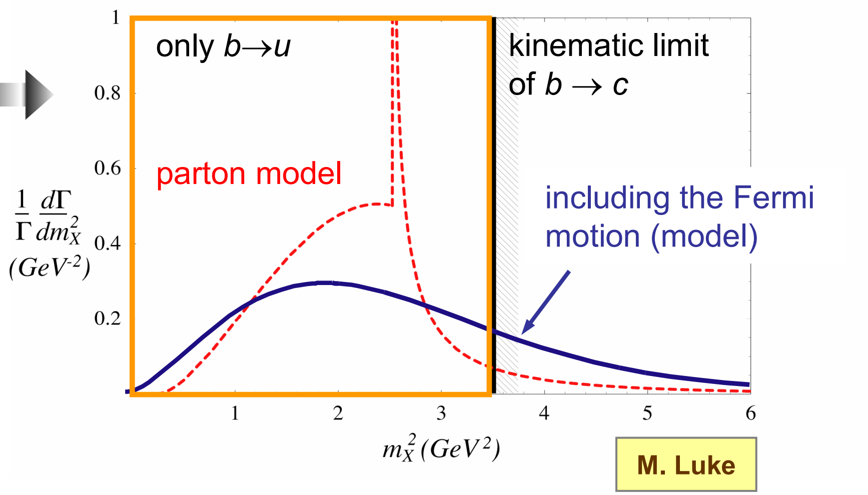
☹ : background from $b \to c$ dominant : $\Gamma(B \to X_c \ell \bar{\nu}) / \Gamma(B \to X_u \ell \bar{\nu}) \sim 100$

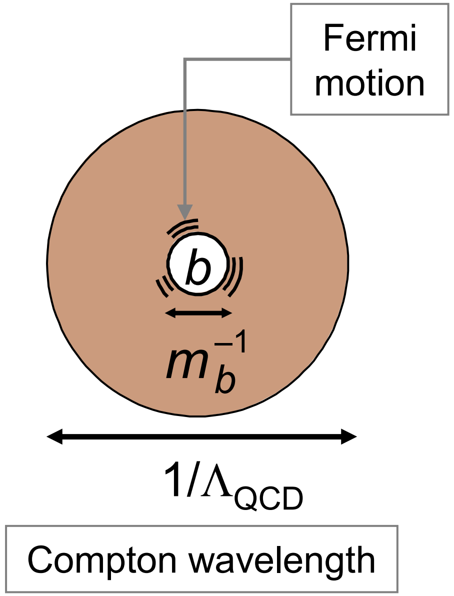
→ needs severe cuts to eliminate charm background

Hadronic mass spectrum in *b→u* decays

Fermi motion can be determined from γ spectrum in $b \to s\,\gamma$

Belle, hep-ex/0403004



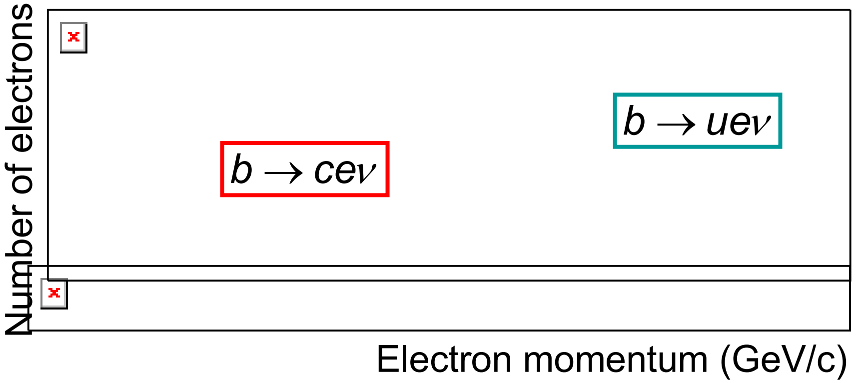


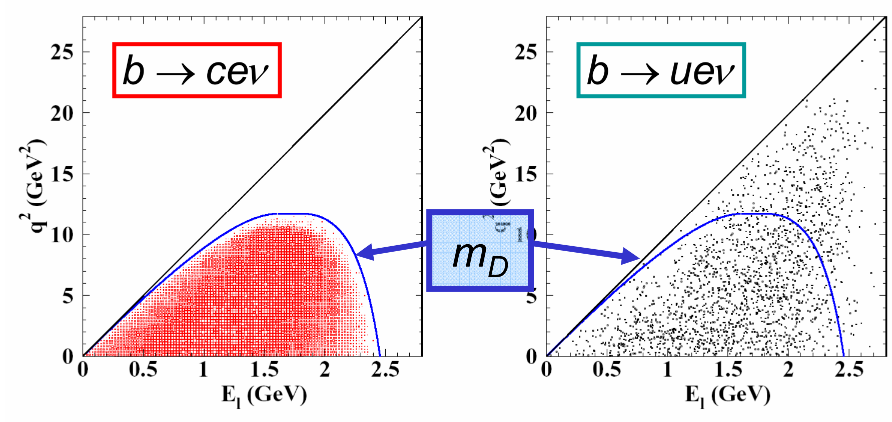
$|V_{ub}|$: Results

$b \to ce\nu$ background rejection with cut on …

★ … the electron endpoint

… the invariant mass $q^2(e,\nu)$





$$|V_{ub}| = \left(3.94 \pm 0.25_{\text{stat+sys}} \pm 0.37_{\text{SF}} \pm 0.19_{\text{HQE}}\right) \times 10^{-3}$$
« electron endpoint »

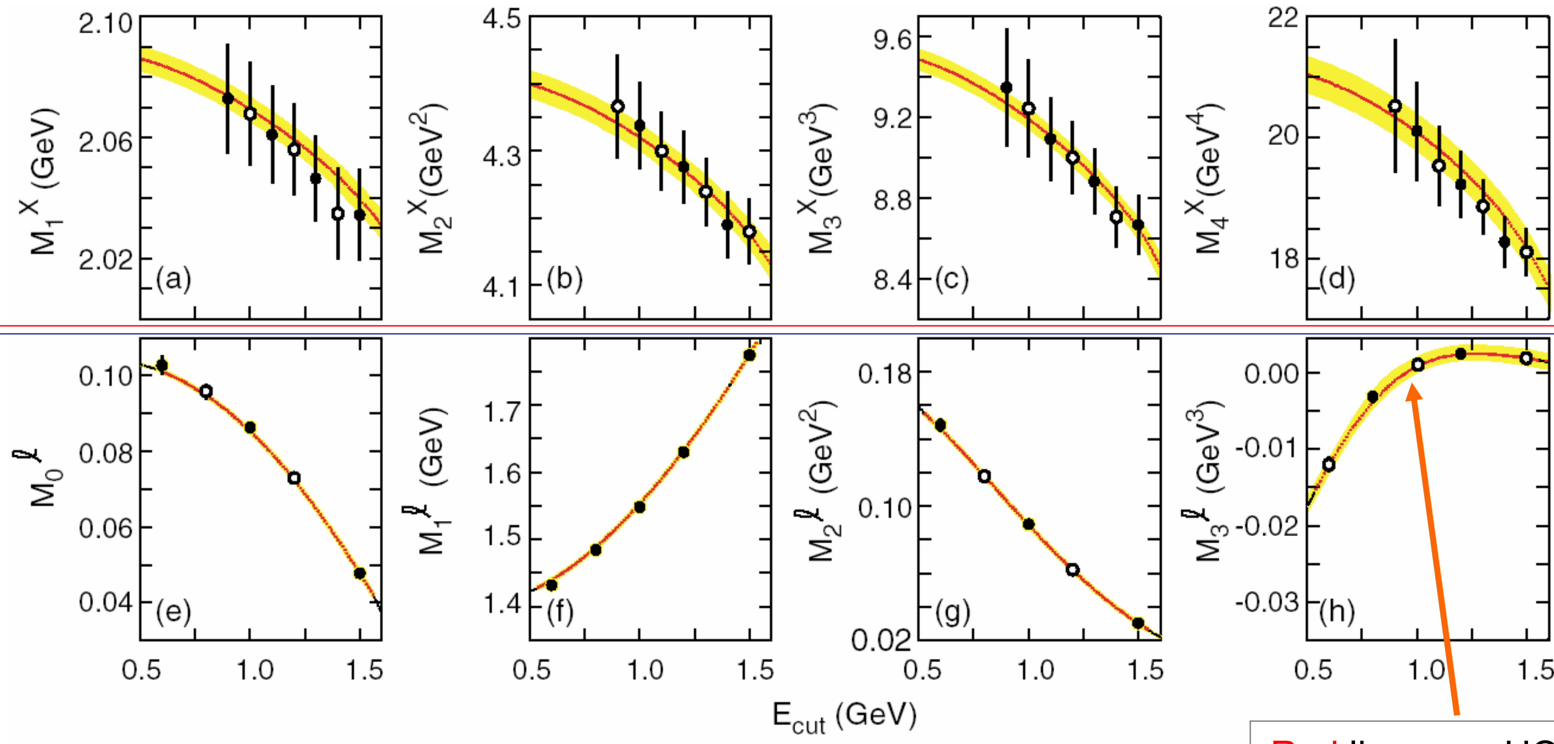
$$|V_{ub}| = \left(4.57 \pm 0.47_{\text{stat+syst}}\ {}^{+0.59}_{-0.29}{}_{\text{SF}} \pm 0.22_{\text{HQE}}\right) \times 10^{-3}$$
« ν reco »

BABAR, hep-ex/0408045, hep-ex/0408075

$|V_{cb}|$ - Moments Analysis

Hadronic mass moments

BABAR, PRL93, 11803, (2004)



Lepton energy moments

Red line : HQE fit
Yellow band : uncertainty

$$|V_{cb}| = \left(41.1 \pm 0.4_{\rm stat} \pm 0.4_{\rm HQE} \pm 0.6_{\rm theo}\right) \times 10^{-3}$$

2% precision !

Summary of $|V_{ub}|$ and $|V_{cb}|$ Results

- $|V_{cb}|$: moments analyses have 1.5–2% precision !

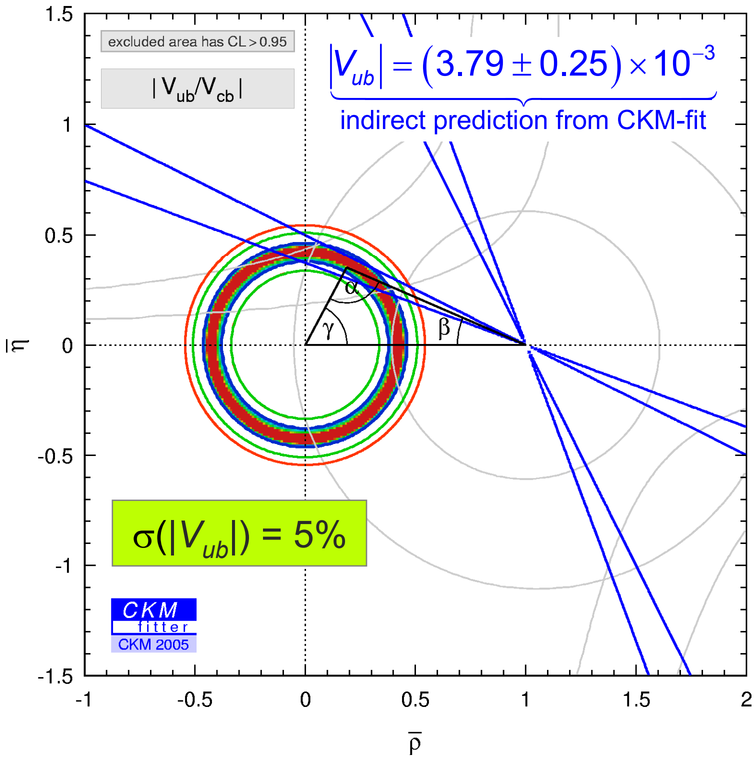
CKM-05

$$|V_{cb}|_{\rm inclusive} = \left(42.0 \pm 0.6_{\rm exp} \pm 0.8_{\rm theo}\right) \times 10^{-3}$$
$$|V_{cb}|_{\rm exclusive} = \left(40.2 \pm 2.1_{\rm exp} \pm 1.8_{\rm theo}\right) \times 10^{-3}$$

- $|V_{ub}|$: reduced conflict between excl. and incl.
  - SF params. from $b \to c l \nu$, OPE from Bosch *et al*.
  - reduction of central value 4.6 → 4.1×10^{-3}
  - $\pi \ell \nu$ result goes up with Lattice FF (unquenched)

CKMfitter average

$$|V_{ub}|_{\rm average} = \left(4.05 \pm 0.13_{\rm exp} \pm 0.50_{\rm theo}\right) \times 10^{-3}$$



Time-dependent Measurements
Meson anti-Meson Mixing

The four Meson anti-Meson Systems

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

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

- They are flavor eigenstates with definite quark content
  - most useful to understand particle production and decay

- Apart from the flavor eigenstates there are mass eigenstates:
  - eigenstates of the Hamiltonian
  - states of definite mass and lifetime

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

recall !

- Since flavor eigenstates are not mass eigenstates the flavor eigenstates are mixed with one another as they propagate through space and time

- If *CP* were a good symmetry, the mass eigenstates would be *CP* eigenstates with *CP* eigenvalues ±1

B^0 Mixing: Principle

- An initially produced B^0 or $\bar{B}^0$ evolves in time into a superposition of these. Let $|B^0(t)\rangle$ ($|\bar{B}^0(t)\rangle$) be the flavor state of a B meson that was a B^0 ($\bar{B}^0$) at $t = 0$.

- Schrödinger equation governs time evolution of the coherent B^0-$\bar{B}^0$ System:

$$i\frac{d}{dt}\begin{pmatrix} |B^0(t)\rangle \\ |\bar{B}^0(t)\rangle \end{pmatrix} = \underbrace{\left(M - \tfrac{i}{2}\Gamma\right)}_{\equiv\, H \text{ (effective Hamiltonian)}}\begin{pmatrix} |B^0(t)\rangle \\ |\bar{B}^0(t)\rangle \end{pmatrix}$$

The mass matrix M and the decay matrix Γ are t-independent Hermetian 2×2 matrices.

T conservation	➡	$\lvert H_{21}\rvert = \lvert H_{12}\rvert$
CP conservation	➡	$\lvert H_{21}\rvert = \lvert H_{12}\rvert$, $H_{11} = H_{22}$
CPT conservation	➡	$H_{11} = H_{22}$

- $\Delta B = 2$ box diagrams with W exchange induce non-zero (dispersive and absorbtive) off-diagonal elements in ***H***

- Mass states are eigenvectors of ***H*** with eigenvalues $\mu_{L,H} = m_{L,H} - (i/2)\Gamma_{L,H}$

➡ $$\frac{q}{p} \equiv -\sqrt{\frac{H_{21}}{H_{12}}} = \frac{\Delta m + i\Delta\Gamma/2}{2M_{12} - i\Gamma_{12}}$$

with the defs:

$$\Delta m_B \equiv M_H - M_L \simeq 2|M_{12}|$$
$$\Delta\Gamma_B \equiv \Gamma_H - \Gamma_L = 2\mathrm{Re}\left(M_{12}\Gamma_{12}^*\right)/|M_{12}|$$

- Expect $\Delta\Gamma_d/\Gamma_d \ll 1$, since common final states of B^0 and $\bar{B}^0$ are Cabibbo-suppressed
(note: not expected to be true for the B_s)

B^0 Mixing: Principle (cont.)

- The time evolution of the mass eigenstates is governed by their eigenvalues μ_L and μ_H:

$$\left|B_{L,H}(t)\right\rangle = e^{-i\mu_{L,H}t}\left|B_{L,H}\right\rangle$$

- The time evolution of the physical states $\left|B^0(t)\right\rangle$ ($\left|\bar{B}^0(t)\right\rangle$) is found by eliminating the mass eigenstates by the flavor eigenstates:

$$\left|B^0(t)\right\rangle = g_+(t)\left|B^0\right\rangle + \frac{q}{p}g_-(t)\left|\bar{B}^0\right\rangle$$

$$\left|\bar{B}^0(t)\right\rangle = \frac{p}{q}g_-(t)\left|B^0\right\rangle + g_+(t)\left|\bar{B}^0\right\rangle$$

where:

$$g_+(t) = e^{-i(\mu_L+\mu_H)t/2}\begin{bmatrix} +\cosh(\Delta\Gamma t/4)\cos(\Delta m t/2) \\ -i\cdot\sinh(\Delta\Gamma t/4)\sin(\Delta m t/2)\end{bmatrix}$$

$$g_-(t) = e^{-i(\mu_L+\mu_H)t/2}\begin{bmatrix} -\sinh(\Delta\Gamma t/4)\cos(\Delta m t/2) \\ +i\cdot\cosh(\Delta\Gamma t/4)\sin(\Delta m t/2)\end{bmatrix}$$

- So that one finds for the time dependent mixing asymmetry:

$$A_{\rm mix}(t) \equiv \frac{N(\text{unmixed}) - N(\text{mixed})}{N(\text{unmixed}) + N(\text{mixed})}(t) = \frac{\cos(\Delta m t)}{\cosh(\Delta\Gamma t/2)} + O\left(\left|\frac{q}{p}\right| - 1\right)$$

where:

$$\text{unmixed}: \quad e^+e^- \to B^0(t)\bar{B}^0(t)$$

$$\text{mixed}: \quad e^+e^- \to B^0(t)B^0(t)$$

and: $A_{\rm mixing}(t=0) = 1$

digression: CP / T and/or *CPT* Violation ?

★ assuming *CPT* conservation [as it was implicit in the previous slides]

➡ $$|q/p|^2 \neq 1 \quad \Rightarrow \quad \text{Prob}(P^0 \to \overline{P}^0,\, t) \neq \text{Prob}(\overline{P}^0 \to P^0,\, t)$$

T and *CP* violation

★ allowing for *CPT* non-conservation

$$\text{Prob}(\overline{P}^0 \to \overline{P}^0,\, t) - \text{Prob}(P^0 \to P^0,\, t) \;=\; 2\left(\text{Re}(z)\,\sinh\left(\frac{\Delta\Gamma}{2}\,t\right) \;-\; \text{Im}(z)\,\sin\left(\Delta m\, t\right)\right)$$

➡ $$z \neq 0 \quad \Rightarrow \quad \text{Prob}(\overline{P}^0 \to \overline{P}^0,\, t) \neq \text{Prob}(P^0 \to P^0,\, t)$$

CPT and *CP* violation

The K^0 System

In the $K^0\bar{K}^0$ system,

both oscillation (x_K) and damping (y_K) parameters are of order unity

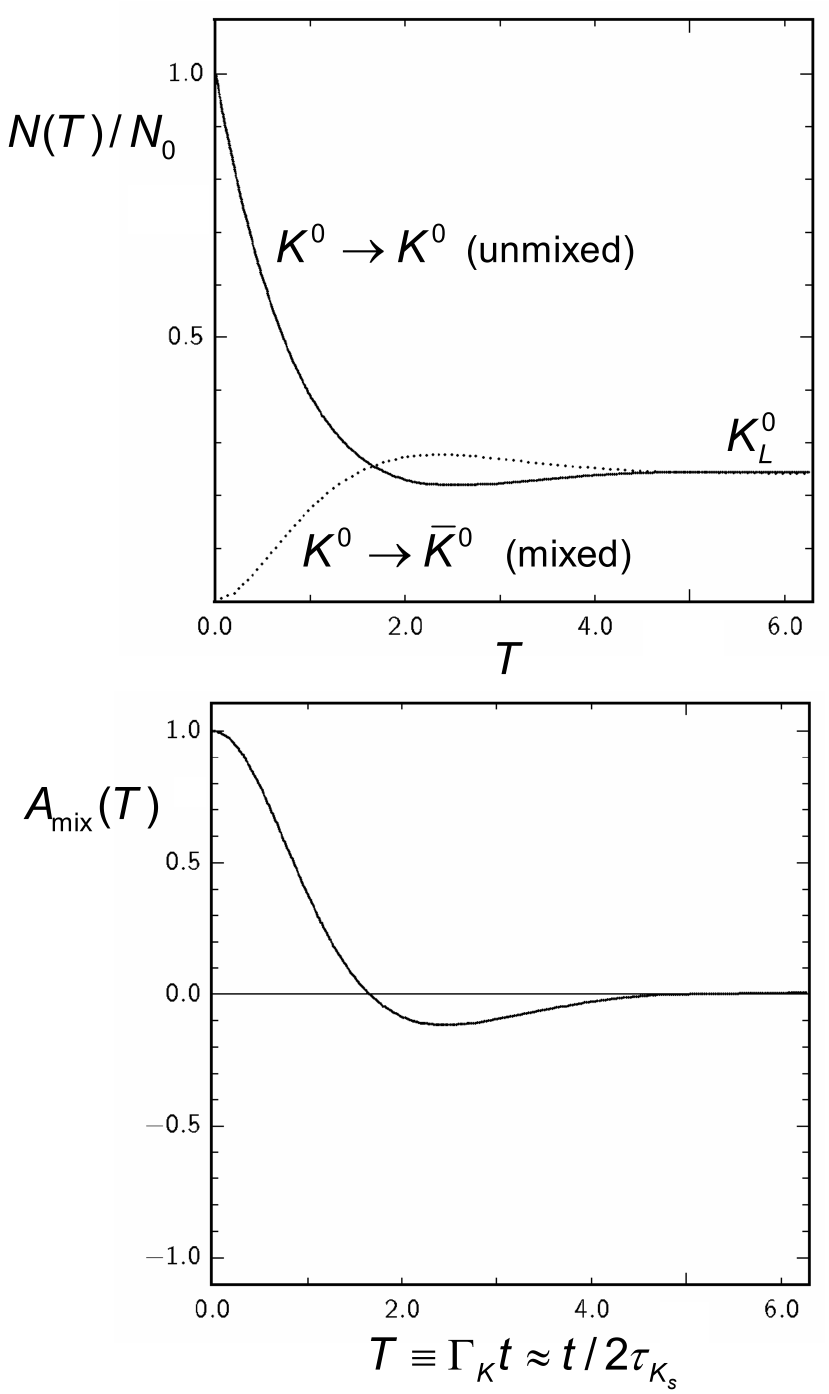
- ★ $x_K \equiv \Delta m_K / \Gamma_K \sim 0.95$
- ★ $y_K \equiv \Delta\Gamma_K / 2\Gamma_K \sim -0.996$

CP violation in mixing ("indirect") is small

- ★ $\delta_K \cong 1 - |q/p|^2 \sim 0.003$

The relaxation process soon dominates leaving only K_L^0 after not much than one oscillation

following 4 pages - courtesy: G. Hamel de Monchenault



The B_d System

In the $B_d^0 \bar{B}_d^0$ system,

to a very good approximation

- ★ the decay widths are equal: $y_d \sim 0$
- ★ no indirect *CP* violation: $\delta_d \sim 0$

therefore

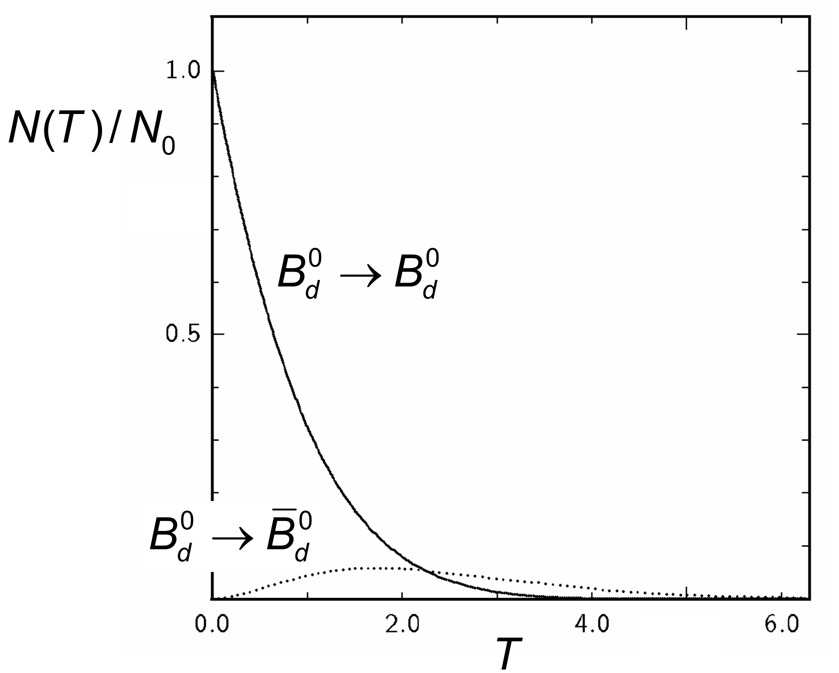
$$A_{\text{mix}}(t) \simeq \cos(\Delta m_d t) = \cos(x_d / \tau_d \cdot t)$$

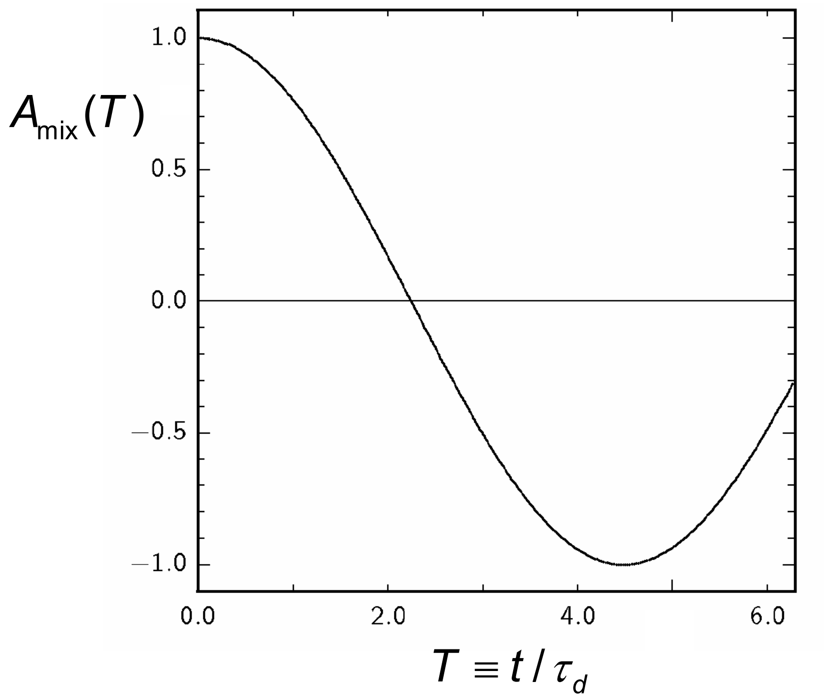
with:

- ★ $x_d \sim 0.72$

The mixing probability is

$$\chi_d = \frac{x_d^2 + y_d^2}{2(1 + x_d^2)} \sim 18\%$$





The B_s System

In the $B_s^0\bar{B}_s^0$ system,

★ x_s is very large

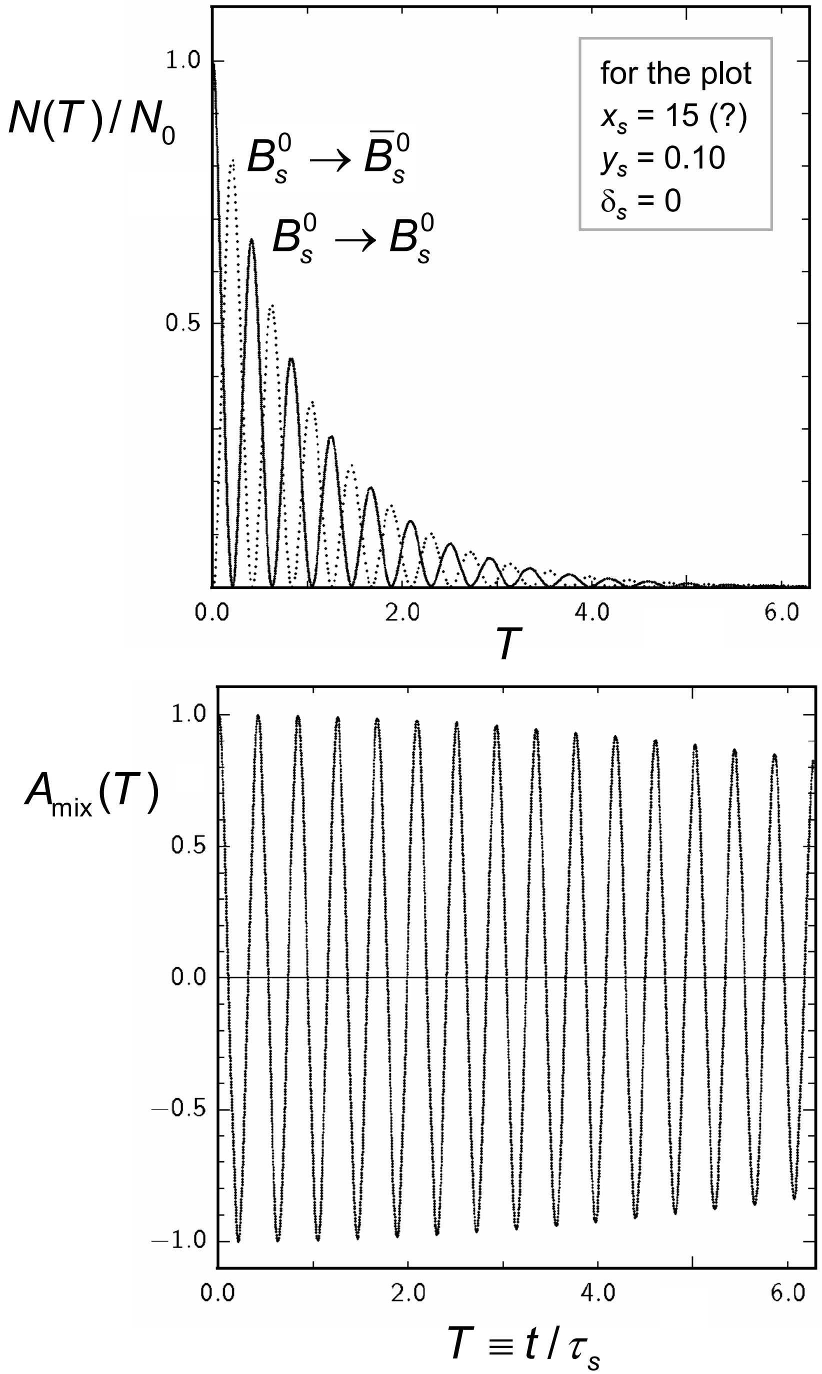
present lower limit $x_s > 21$ (95% CL)

★ y_d is small, but probably not negligible

present upper limit $2y_s < 0.46$ (95% CL)

The mixing probability is close to 50%

present upper limit $\chi_s > 50\%$ (95% CL)



The D^0 System

In the $D^0\bar{D}^0$ system,

- x_D is very small: strongly CKM suppressed

  present lower limit $x_D < 0.002$

- y_D is very small: only few common states

  $CP = +1: \ \pi\pi,\ K\bar{K},\ K_L^0\pi^0$

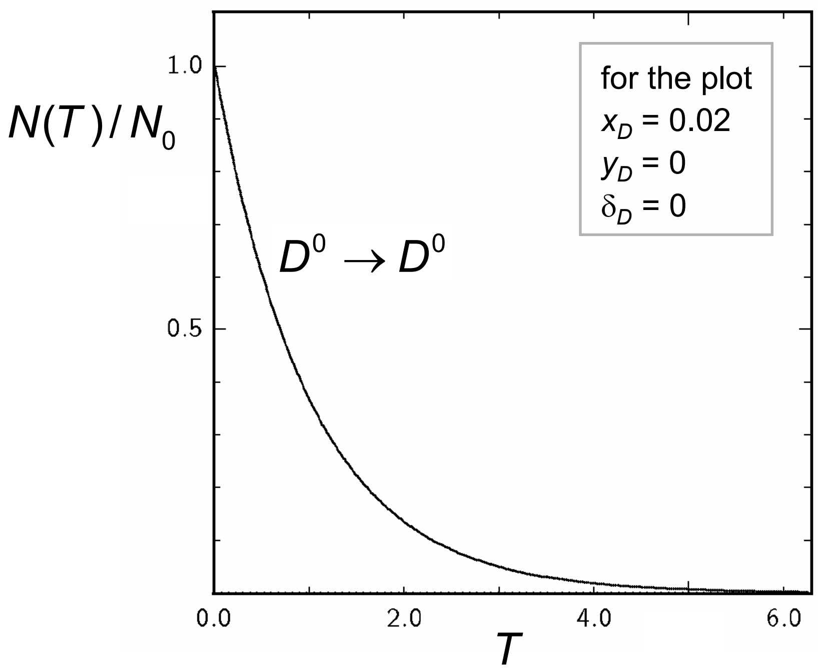
  $CP = -1: \ K_S^0\pi^0,\ K_S^0\omega$

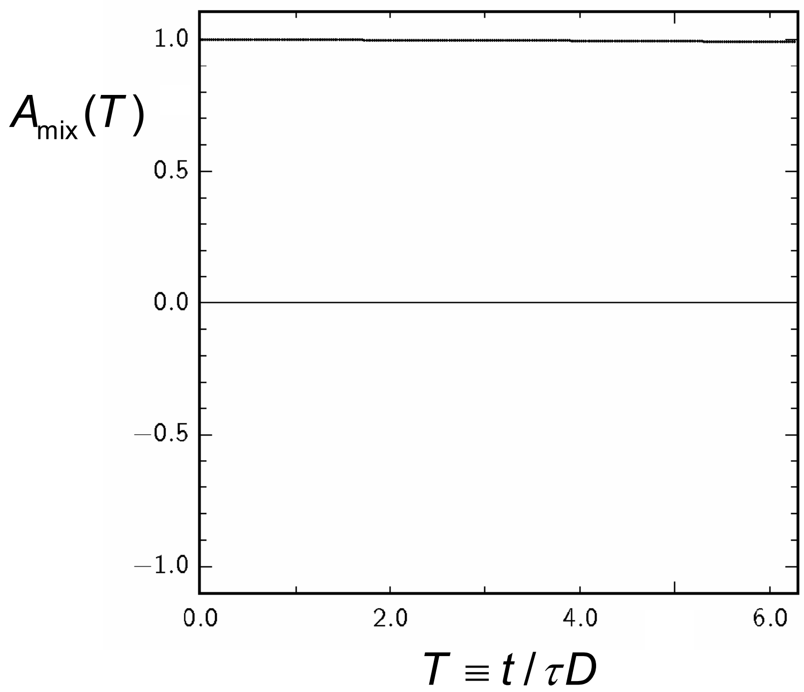
therefore

$$A_{\text{mix}}(t) \approx 1 - \frac{x_D^2 + y_D^2}{2\tau_D^2} t^2$$

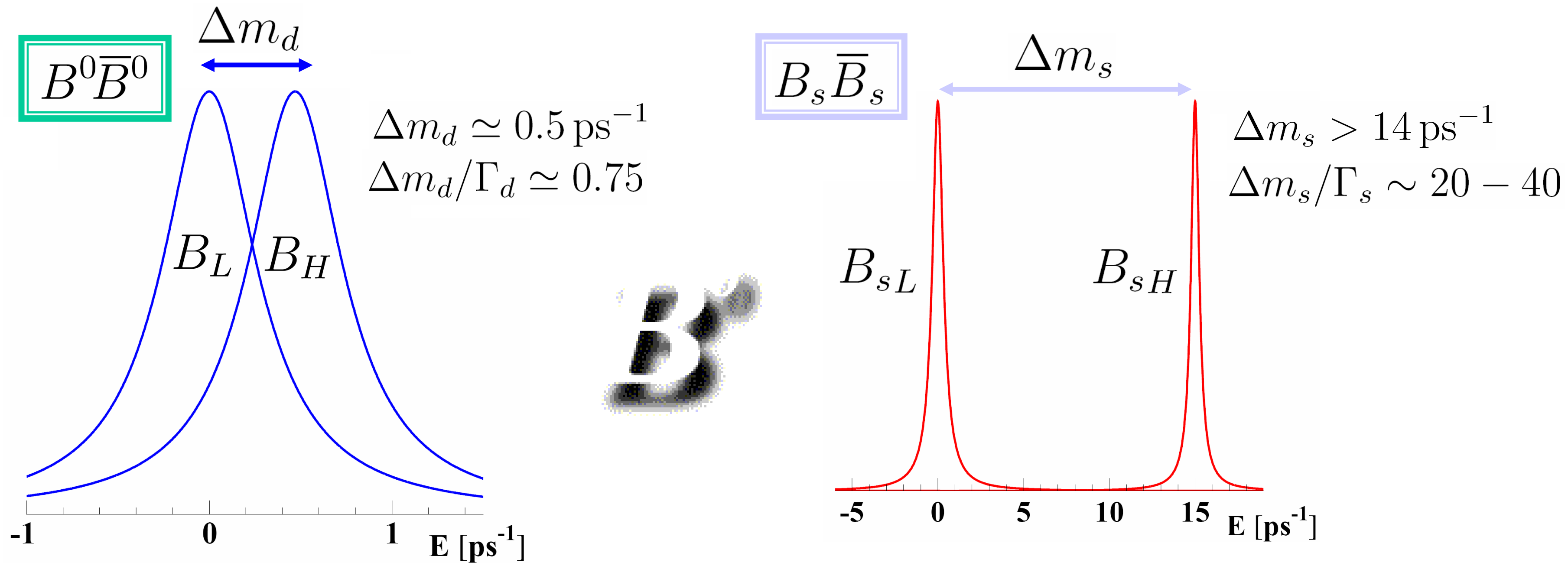
The mixing probability is tiny: $\chi_s \sim 2\times10^{-6}$

Interesting system to look for new physics



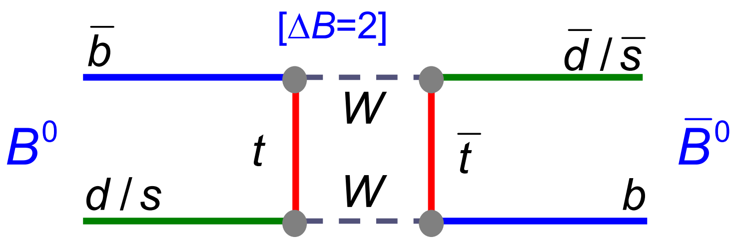


The Neutral *B* System



B^0 Mixing in the Standard Model

- Effective FCNC Processes (*CP* conserving — top loop dominates in box diagram):



$\arg\left(V_{td}V_{tb}^*\right)^2 = -2\beta$

Perturbative QCD

CKM Matrix Elements

$$\Delta m_q = \frac{G_F^2}{6\pi^2} m_{B_q} m_W^2 \, \eta_B \, S(x_t) \, f_{B_q}^2 B_q \left|V_{tq}V_{tb}^*\right|^2 \quad (\text{for } q = d,s)$$

Loop integral
(top loop dominates)

Non-perturbative: Lattice
(eff. 4 fermion operator)

- Dominant theoretical uncertainties : $\sigma_{\text{rel}}\left(f_{B_{d/s}}\sqrt{B_{d/s}}\right) \simeq 16\%$
- Improved error indirect via Δm_s : $\sigma_{\text{rel}}\left(\xi = f_{B_s}\sqrt{B_s} / f_{B_d}\sqrt{B_d}\right) \simeq 5\%$
  [SU(3) breaking correction]

} consider in fit that Lattice results are correlated !

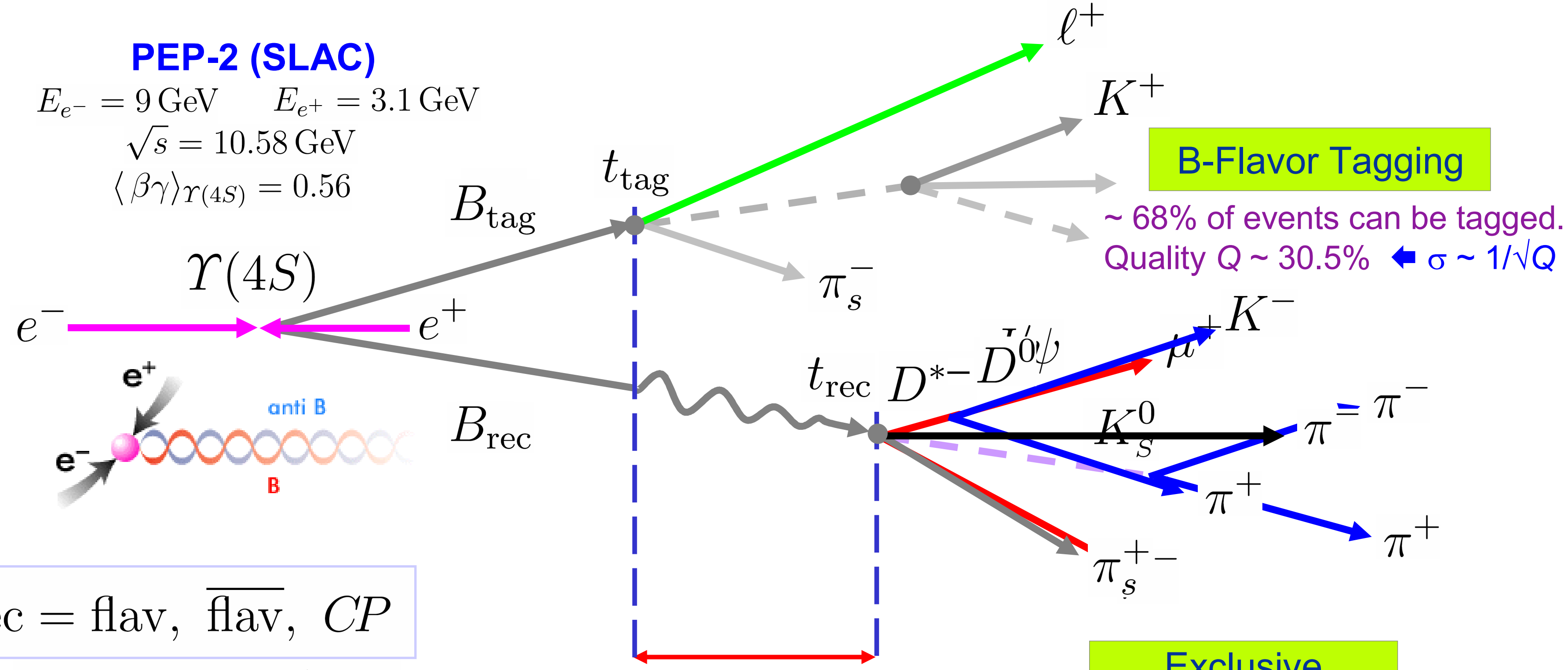
Analysis Technique at the *B* Factories

PEP-2 (SLAC)

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

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

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



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

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

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

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

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

Vertexing & Time Difference Determination

Exclusive *B* Meson Reconstruction

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

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

B^0 Mixing Experimentally

- Mixing asymmetry neglecting all *CP* and *CPT*-violating effects and assuming $\Delta\Gamma_d$=0

$$A^0_{\rm mix}(t) \equiv \frac{N^0(\text{unmixed}) - N^0(\text{mixed})}{N^0(\text{unmixed}) + N^0(\text{mixed})}(t) = \cos(\Delta m_d t)$$

- Including experimental mistag probability "ω" and finite vertex resolution "*R(t' – t)*":

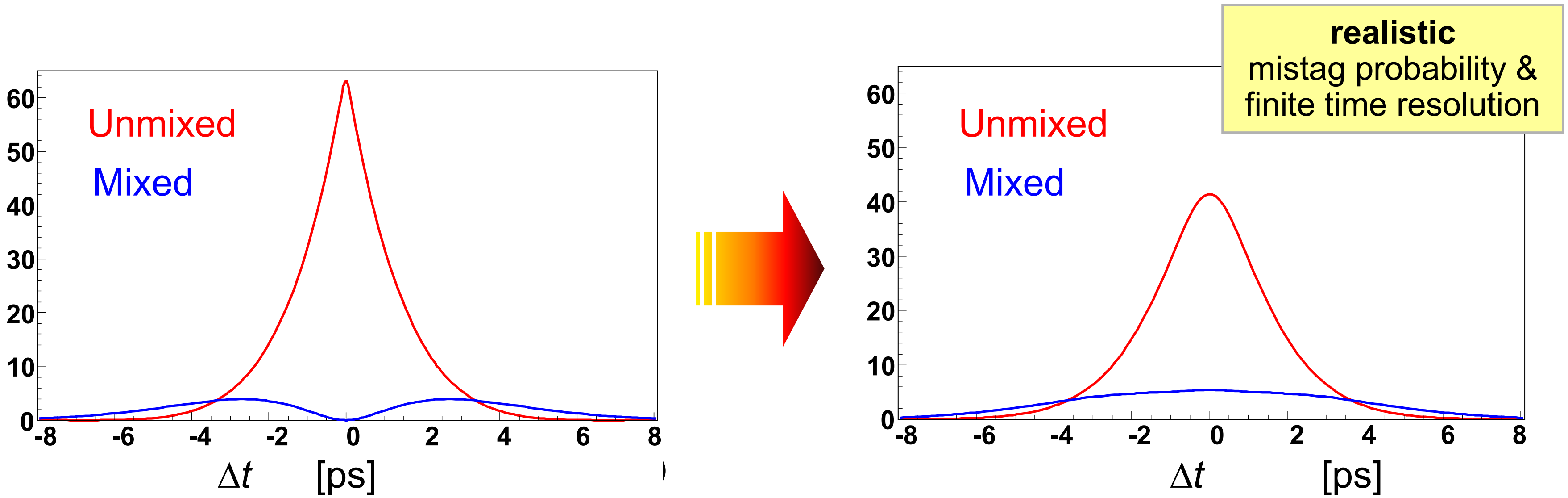
$$A^{\rm meas}_{\rm mix}(t) \equiv \frac{N^{\rm meas}(\text{unmixed}) - N^{\rm meas}(\text{mixed})}{N^{\rm meas}(\text{unmixed}) + N^{\rm meas}(\text{mixed})}(t') = (1-2\omega)\cos(\Delta m_d t') \otimes R(t'-t)$$

convolution

B^0 Mixing Experimentally (cont.)

- Two categories of events:

Unmixed (+) : f_{flav} and f_{tag} have opposite flavor
Mixed (–) : f_{flav} and f_{tag} have same flavor

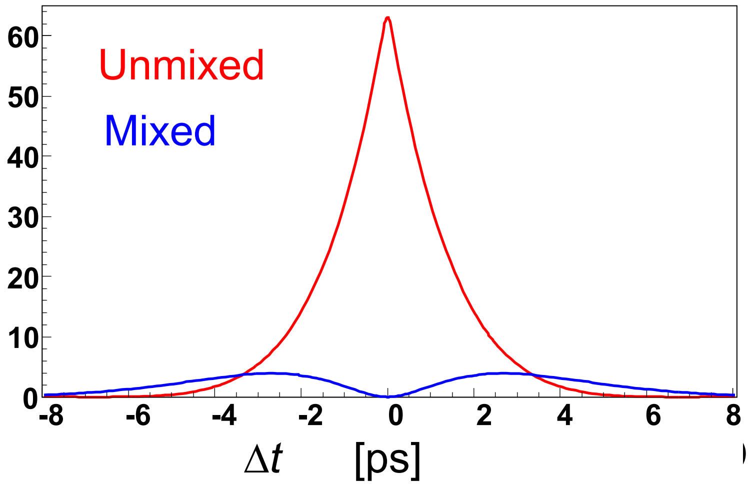


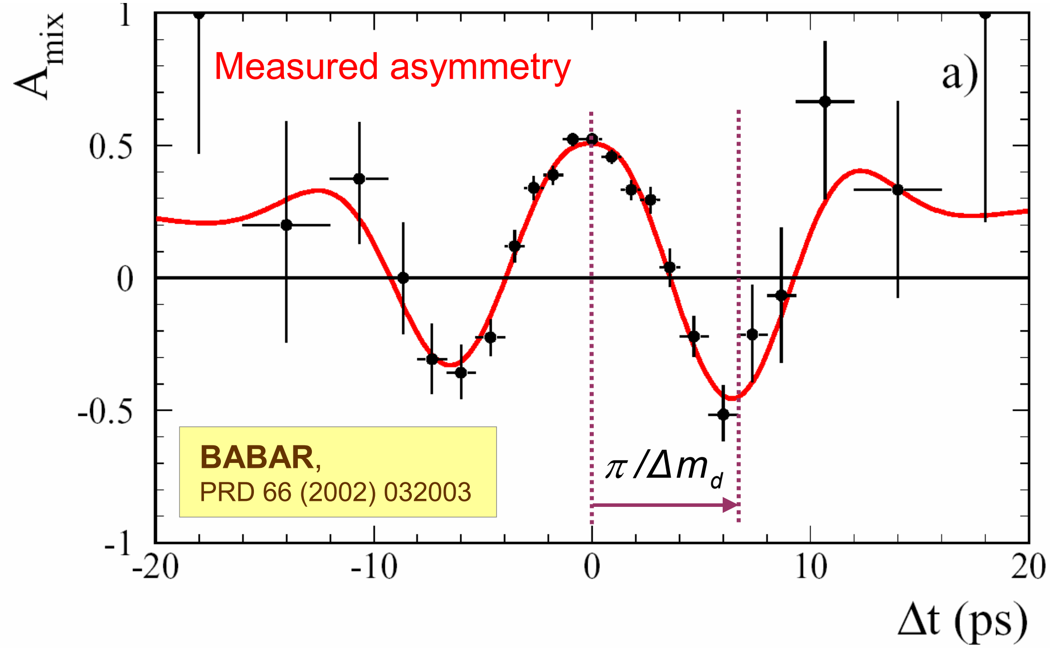
Rates:
$$\begin{cases} N^0(\text{unmixed})(t) = 1 + \cos(\Delta m_d t) \\ N^0(\text{mixed})(t) = 1 - \cos(\Delta m_d t) \end{cases}$$

B^0 Mixing Experimentally (cont.)

- Two categories of events:

Unmixed (+) : f_{flav} and f_{tag} have opposite flavor
Mixed (–) : f_{flav} and f_{tag} have same flavor





Rates:
$$\begin{cases} N^0(\text{unmixed})(t) = 1 + \cos(\Delta m_d t) \\ N^0(\text{mixed})(t) = 1 - \cos(\Delta m_d t) \end{cases}$$

B^0 Mixing

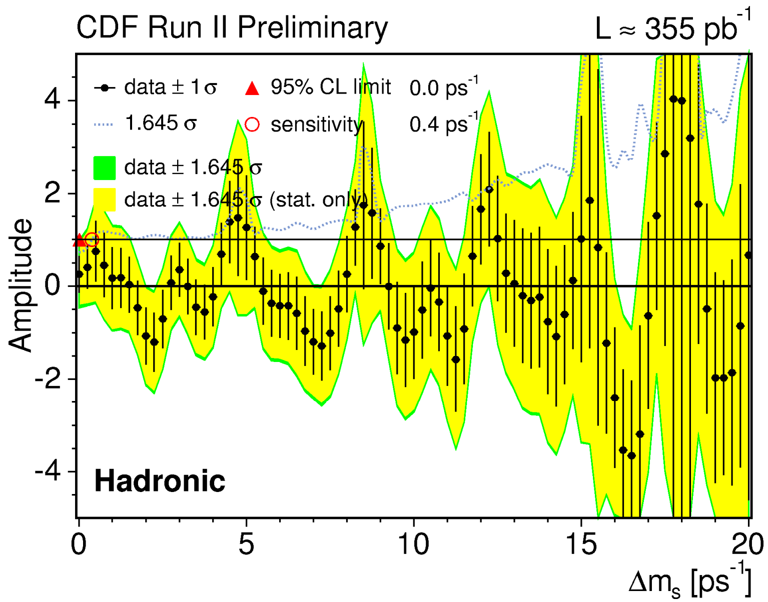
- $\Delta m_d = (0.510 \pm 0.005)\ \text{ps}^{-1}$ HFAG – Winter 2005

- No signal yet for Δm_s → upper limit :

  $\Delta m_s > 14.5\ \text{ps}^{-1}$ at 95% CL

  [CDF: WA sensitivity 18.1 → 18.6 ps^{-1}]

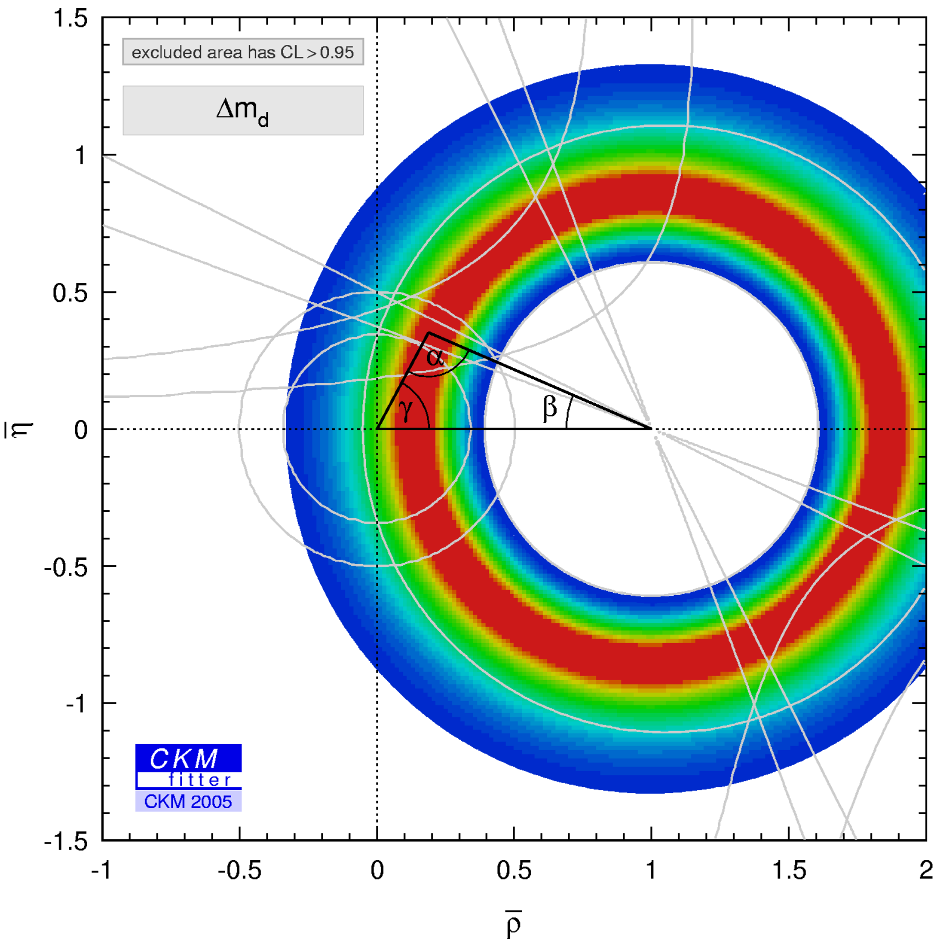
$$P_{B_s^0 \to B_s^0(\bar{B}_s^0)} \propto e^{-t/\tau}\left(1 \pm A\cos\Delta m_s t\right)$$



[CKM constraint dominated by theory error]

CKM fit predicts : $\Delta m_d = 0.47\,^{+0.23}_{-0.12}\ \text{ps}^{-1}$

CKM fit predicts : $\Delta m_s = 18.3\,^{+6.5}_{-2.3}\ \text{ps}^{-1}$



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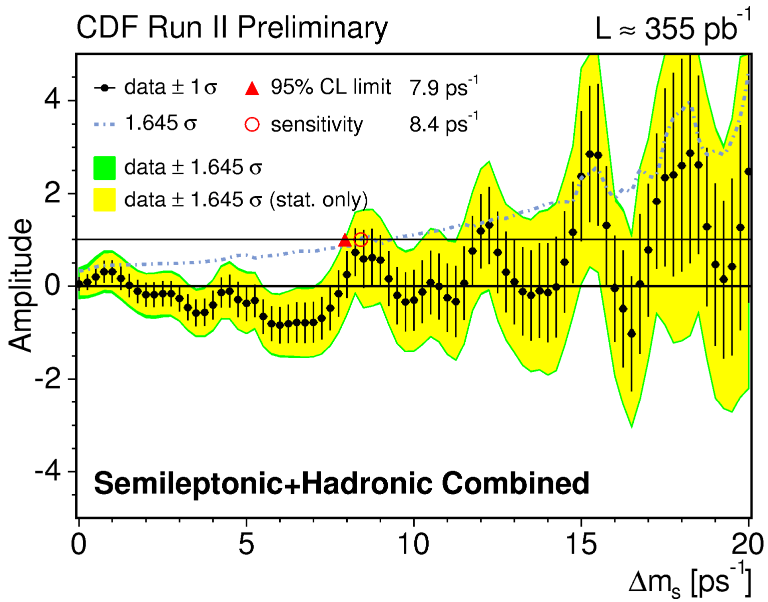

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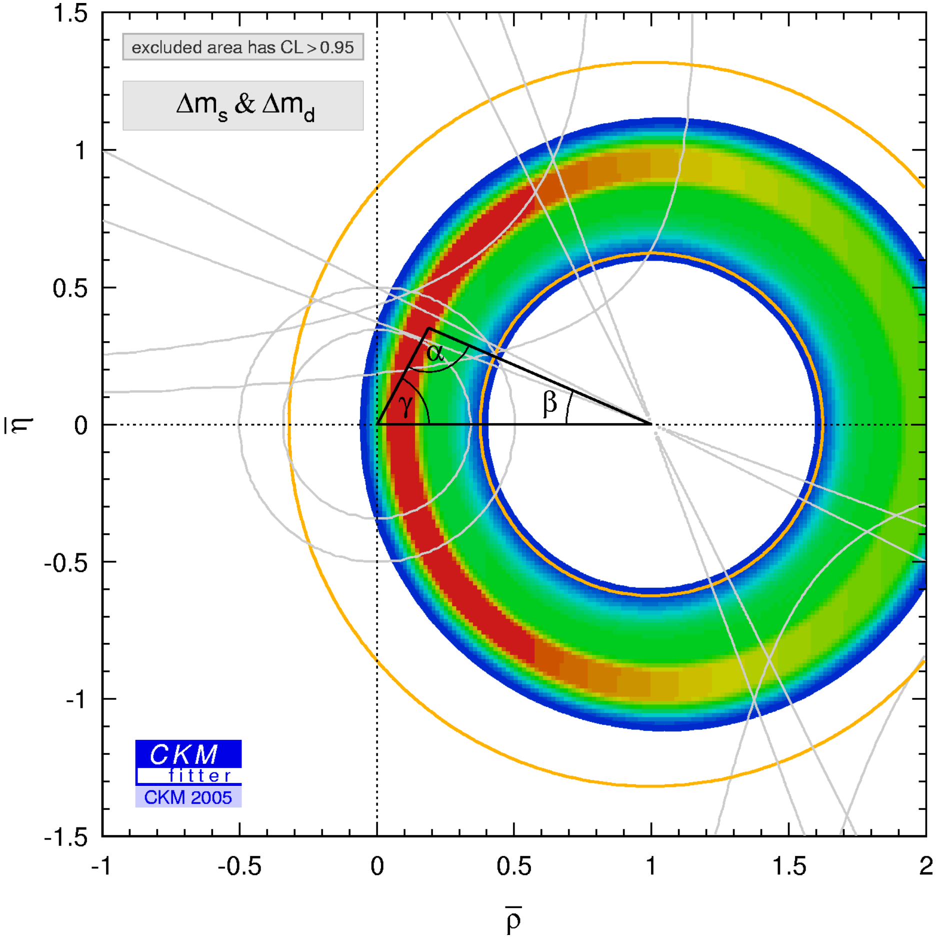

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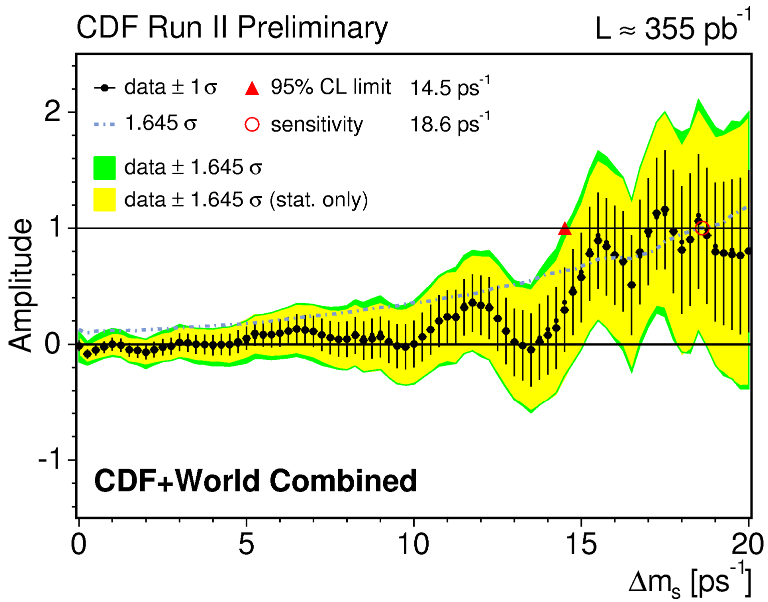
$$P_{B_s^0 \rightarrow B_s^0(\bar{B}_s^0)} \propto e^{-t/\tau}\left(1 \pm A \cos \Delta m_s t\right)$$



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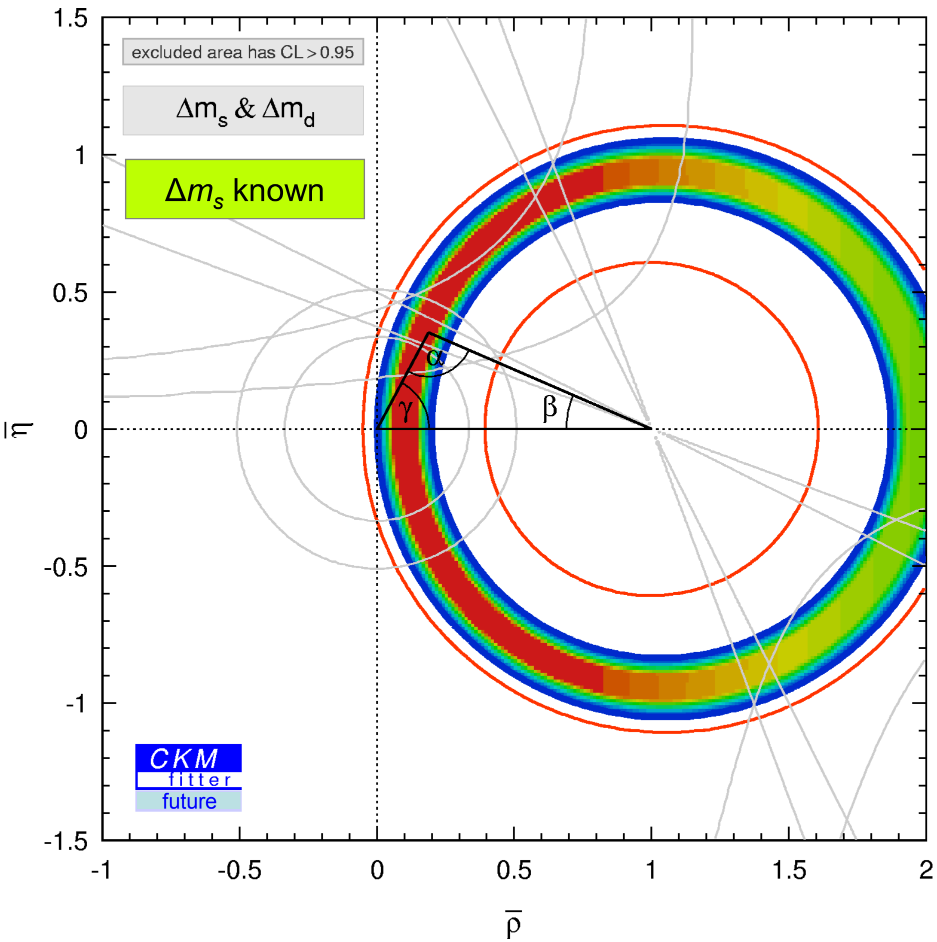
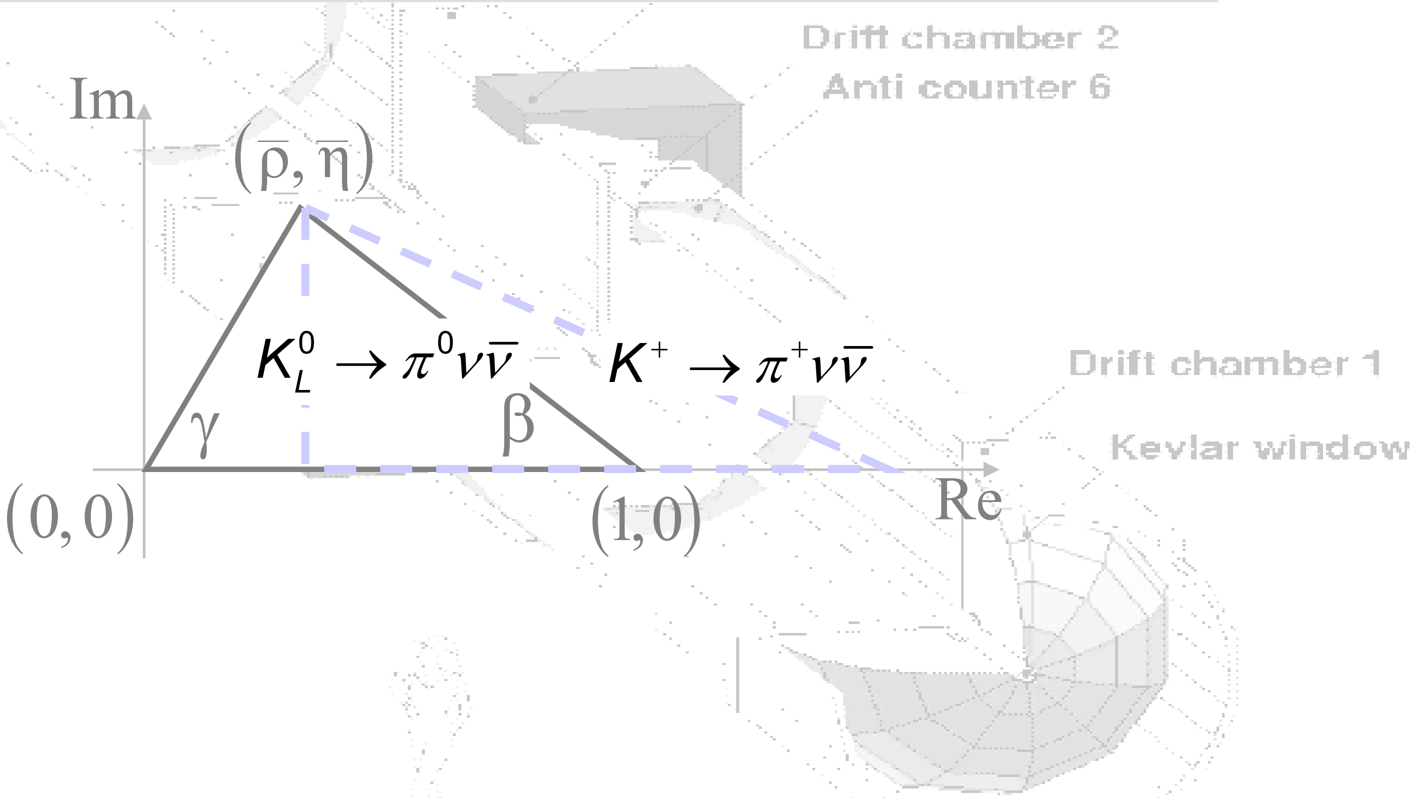


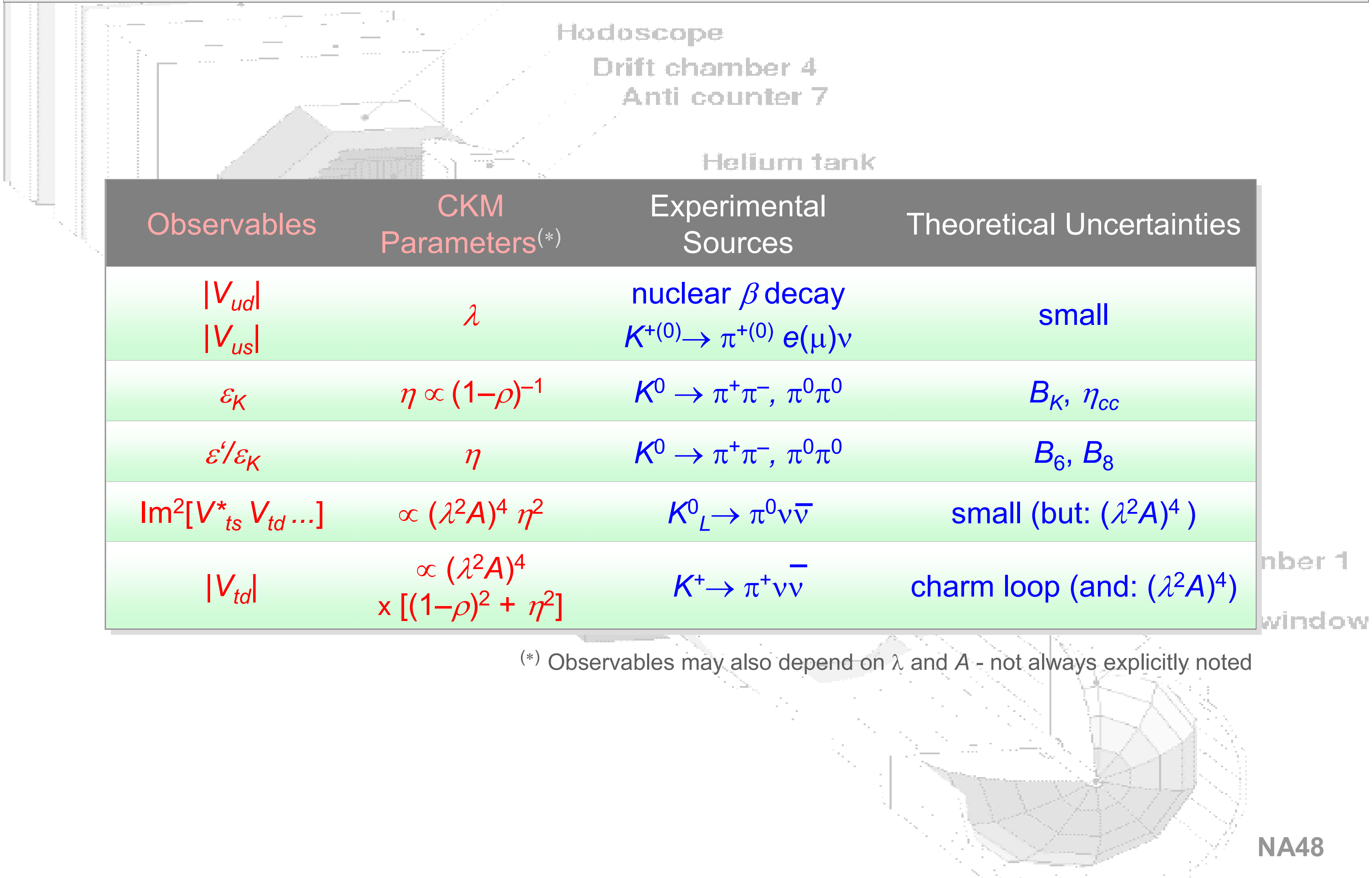
appendix

- rare kaon decays
- detector images

Present and Future: Rare Kaon Decays

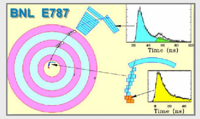


The CKM Matrix: Impact of (mostly) K Physics



Observables	CKM Parameters(*)	Experimental Sources	Theoretical Uncertainties
$\lvert V_{ud}\rvert$ $\lvert V_{us}\rvert$	λ	nuclear β decay $K^{+(0)} \to \pi^{+(0)}\, e(\mu)\nu$	small
ε_K	$\eta \propto (1-\rho)^{-1}$	$K^0 \to \pi^+\pi^-,\ \pi^0\pi^0$	$B_K,\ \eta_{cc}$
$\varepsilon'/\varepsilon_K$	η	$K^0 \to \pi^+\pi^-,\ \pi^0\pi^0$	$B_6,\ B_8$
$\mathrm{Im}^2[V^*_{ts} V_{td} \ldots]$	$\propto (\lambda^2 A)^4\, \eta^2$	$K^0_L \to \pi^0 \nu\bar{\nu}$	small (but: $(\lambda^2 A)^4$)
$\lvert V_{td}\rvert$	$\propto (\lambda^2 A)^4$ x $[(1-\rho)^2 + \eta^2]$	$K^+ \to \pi^+ \nu\bar{\nu}$	charm loop (and: $(\lambda^2 A)^4$)

(*) Observables may also depend on λ and A - not always explicitly noted



E787 and E949 at BNL :

- Low energy beam (710 MeV) on scint. target to stop the K^+
- π^+ is stopped in scint. (RS) and decay chain $\pi - \mu - e$ is observed
- 4π photon veto
- selection efficiency : ~ 0.2%

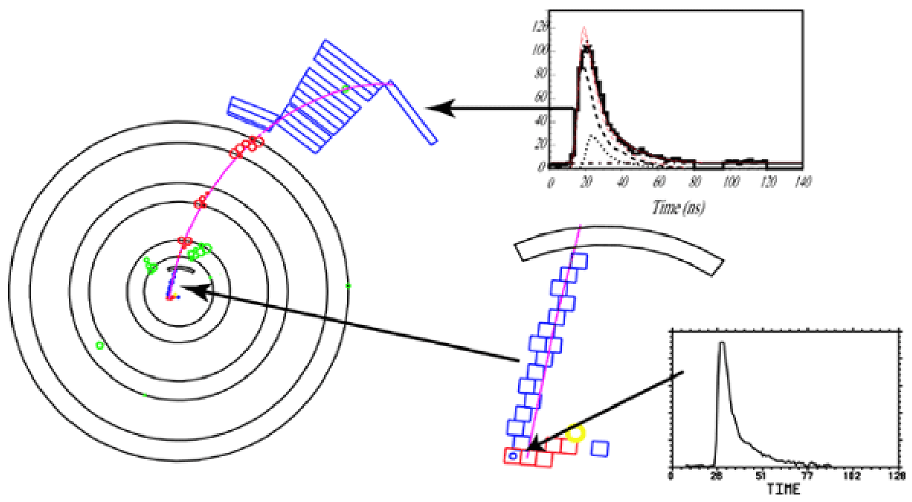
Processus	Evénements
$K^+ \rightarrow \mu^+ \nu_\mu$	6343000000
$K^+ \rightarrow \pi^+ \pi^0$	2113000000
$K^+ \rightarrow \mu^+ \nu_\mu \gamma$	55000000
Bdf. faisceau	25000000
$K^+ n \rightarrow K^0 p$, $K^0 \rightarrow \pi^+ l^- \nu$	46000
$K^+ \rightarrow \pi^+ \nu \nu$	**1**

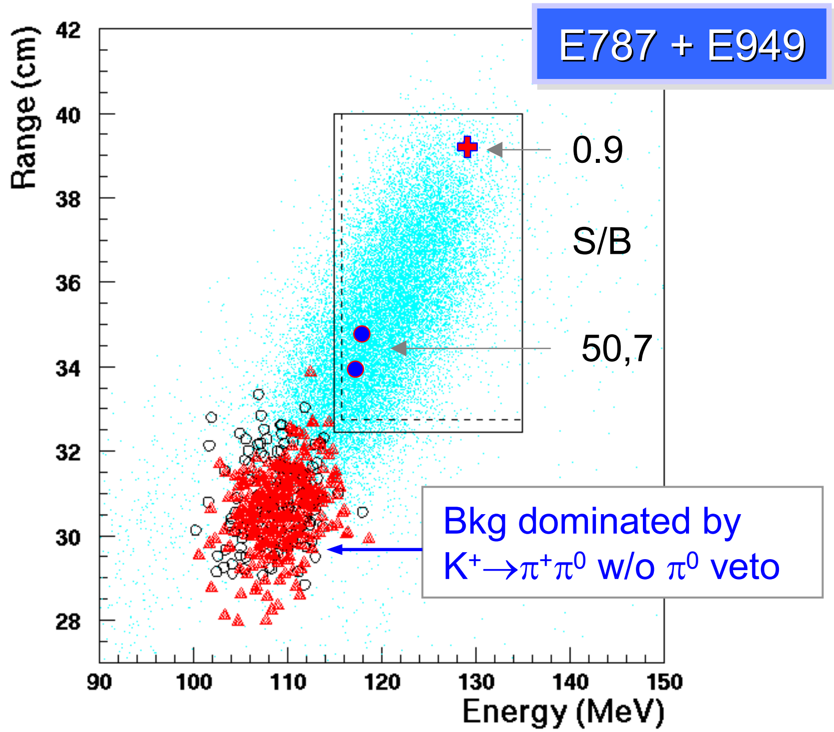
$K^+ \to \pi^+ \nu\bar{\nu}$

E787 and E949 at BNL :

- Low energy beam (710 MeV) on scint. target to stop the K^+
- π^+ is stopped in scint. (RS) and decay chain $\pi - \mu - e$ is observed
- 4π photon veto
- selection efficiency : ~ 0.2%

Singal event at E949 :





$$\mathrm{BR}\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = \left(1.5^{+1.3}_{-0.9}\right) \times 10^{-10}$$

$$\mathrm{SM} \Rightarrow (0.67 \pm 0.27) \times 10^{-10}$$

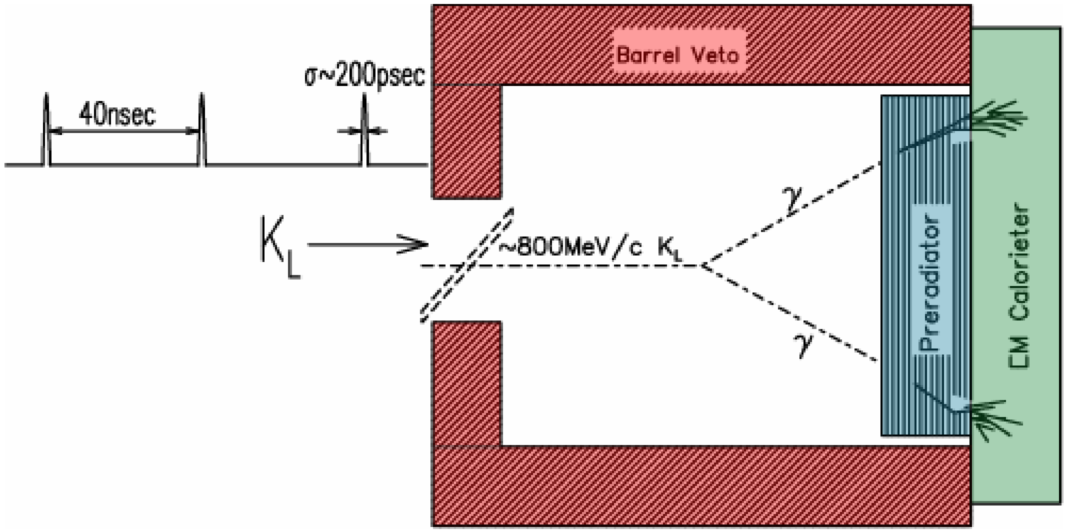
Goal : sensitivity/event ~ 10^{-11}

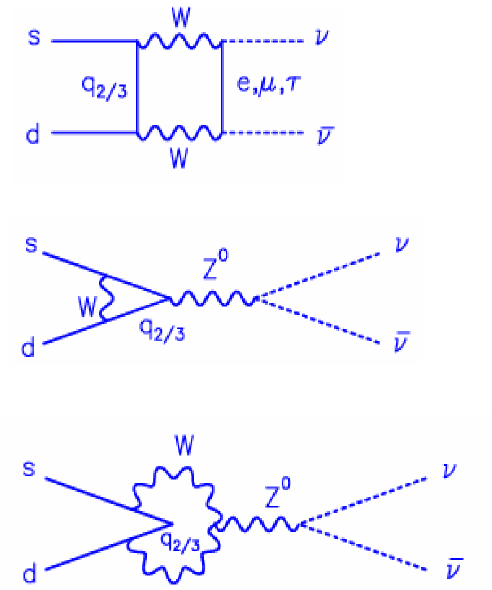
~ 10 events in 3 years

$K_L \rightarrow \pi^0 \nu\bar{\nu}$

Approved experiment at BNL to search for : $K_L \rightarrow \pi^0 \nu\nu$ with BR ~ 3×10^{-11}

Full event reconstruction and particle identification



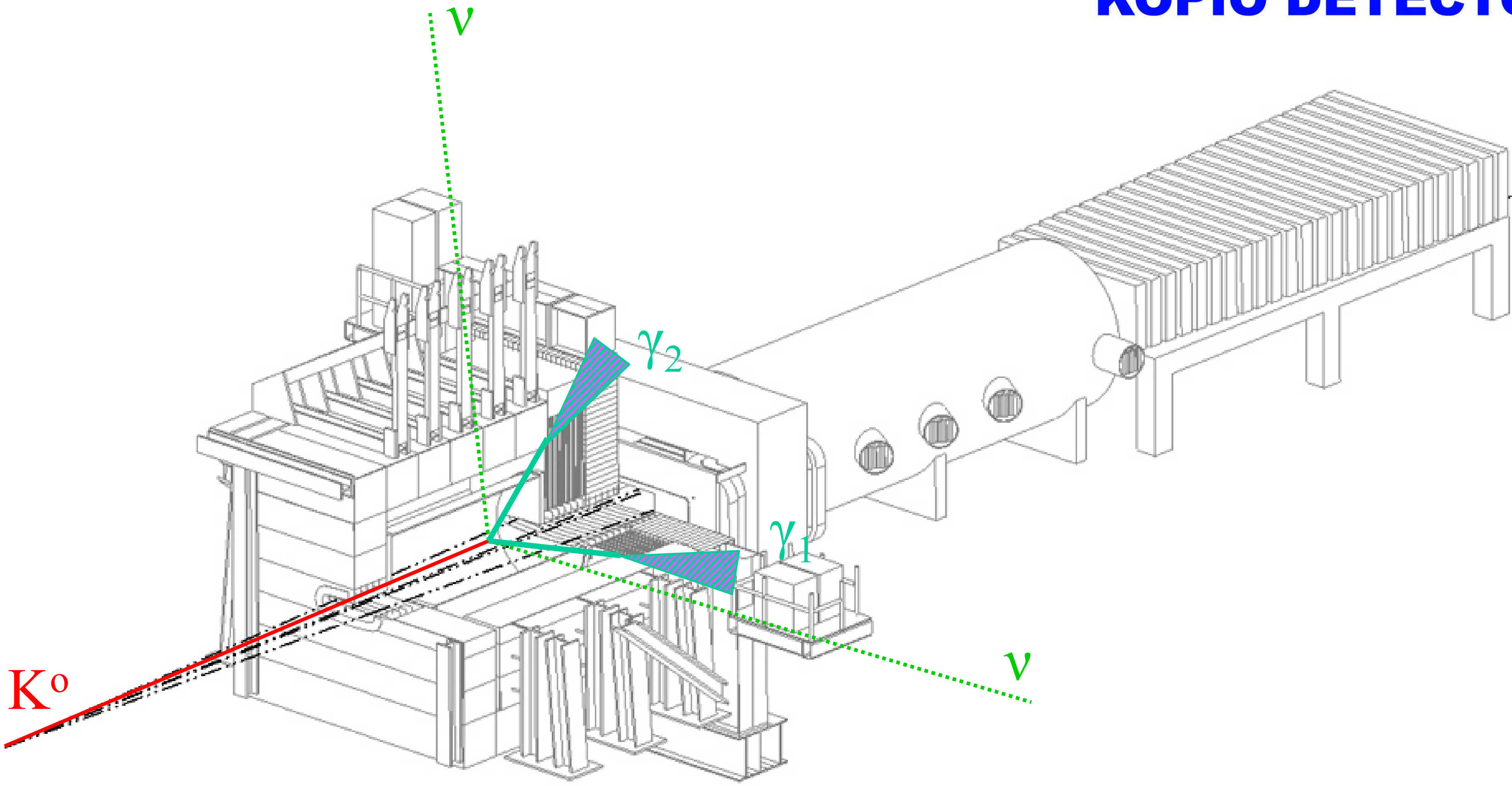


Mesure ultra pure

- measure K_L flight time
- direction of converted photon
- photon energies
- veto on all other emitted particles

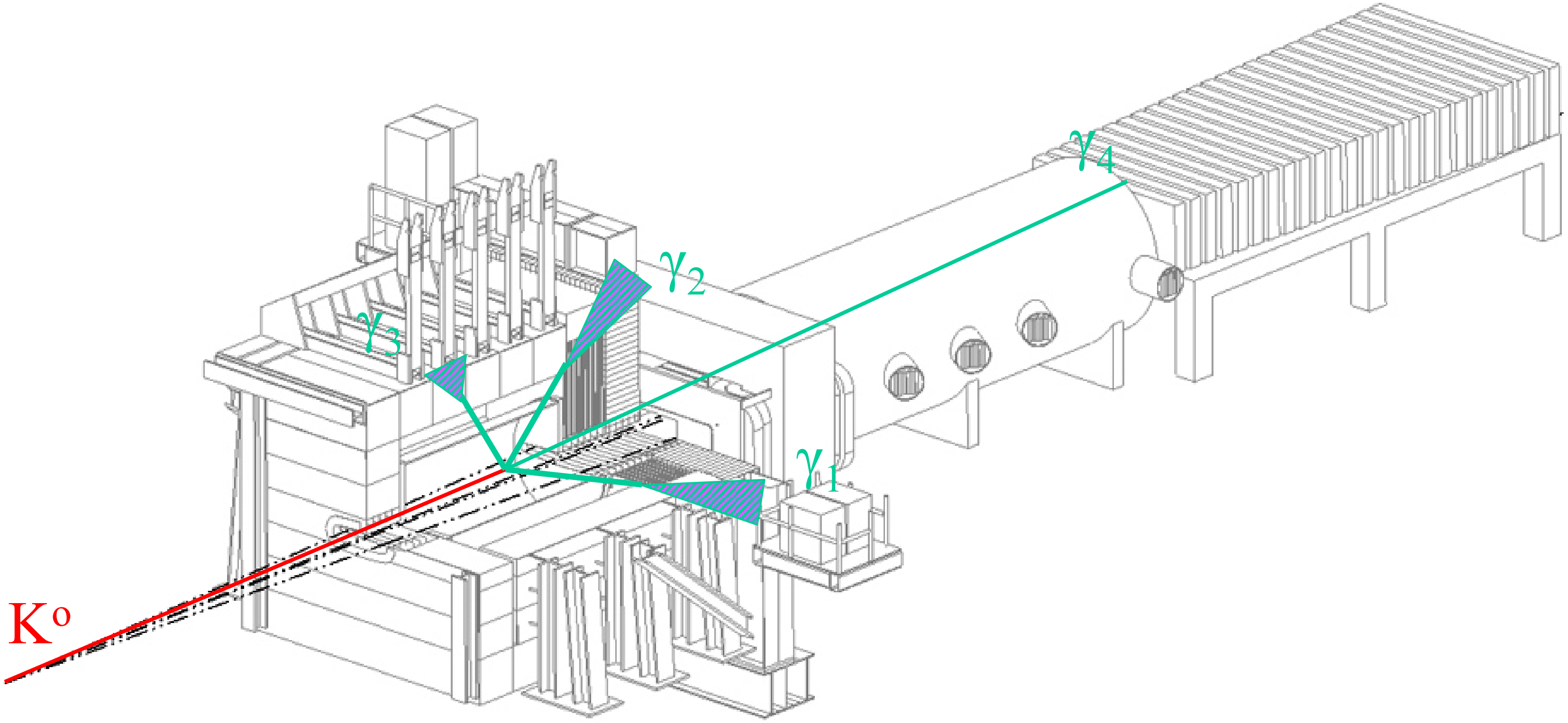
K0PI0 forecasts 40 signal events (SM) with $S/B = 2/1$

KOPIO DETECTOR



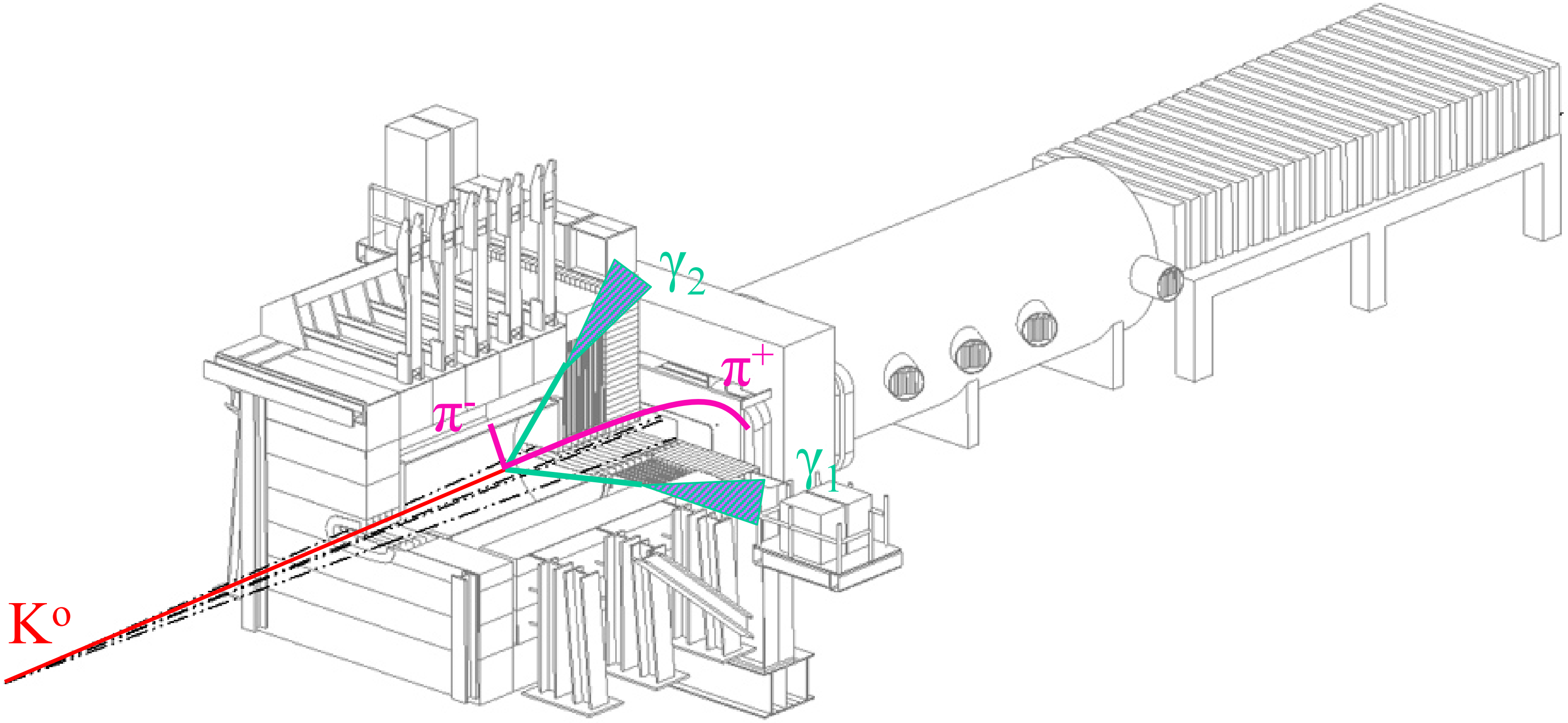
Background event: $K_L \rightarrow \pi^0 \pi^0$

KOPIO DETECTOR

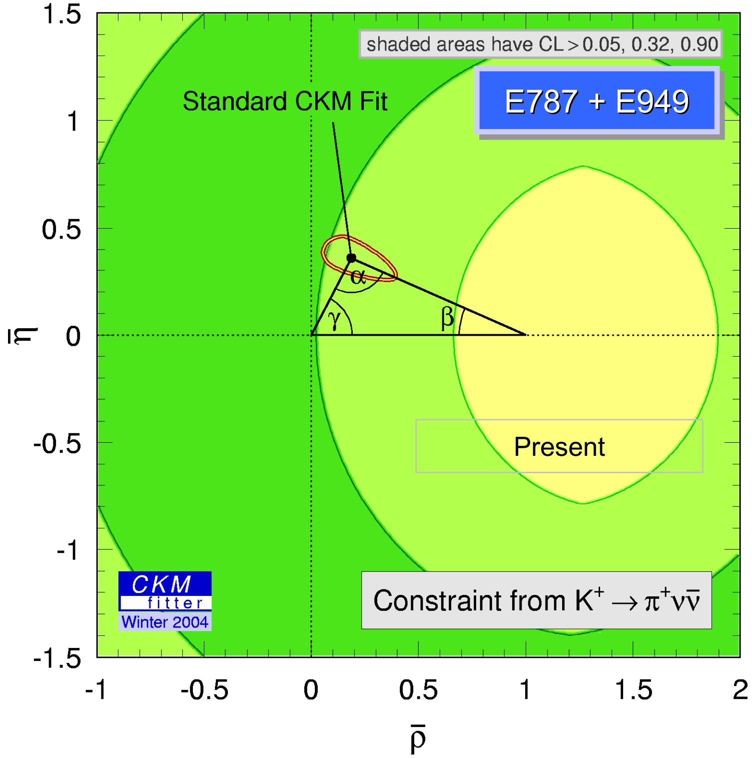


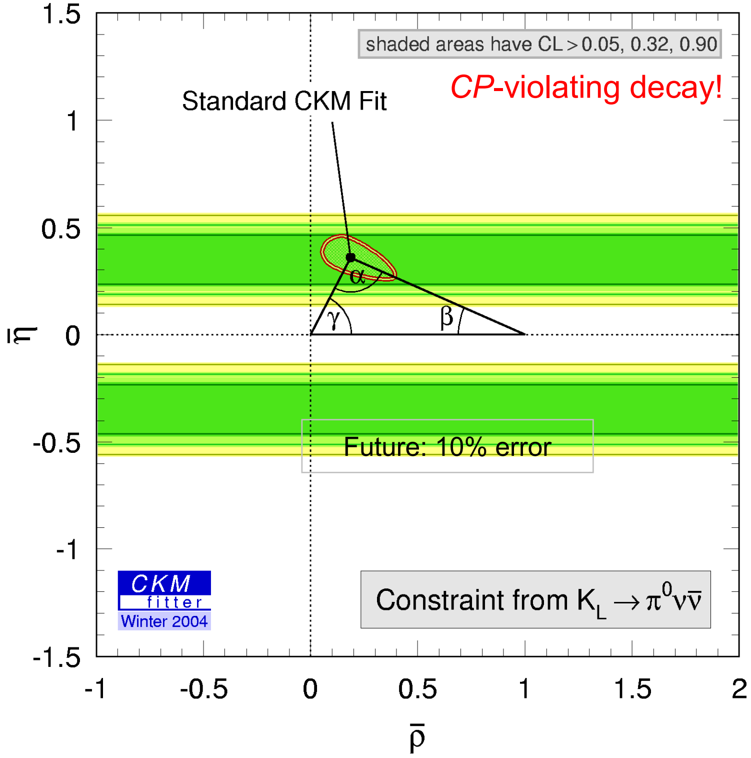
Background event: $K_L \to \pi^+\pi^-\pi^0$

KOPIO DETECTOR



Rare Kaon Decays and the Unitarity Triangle

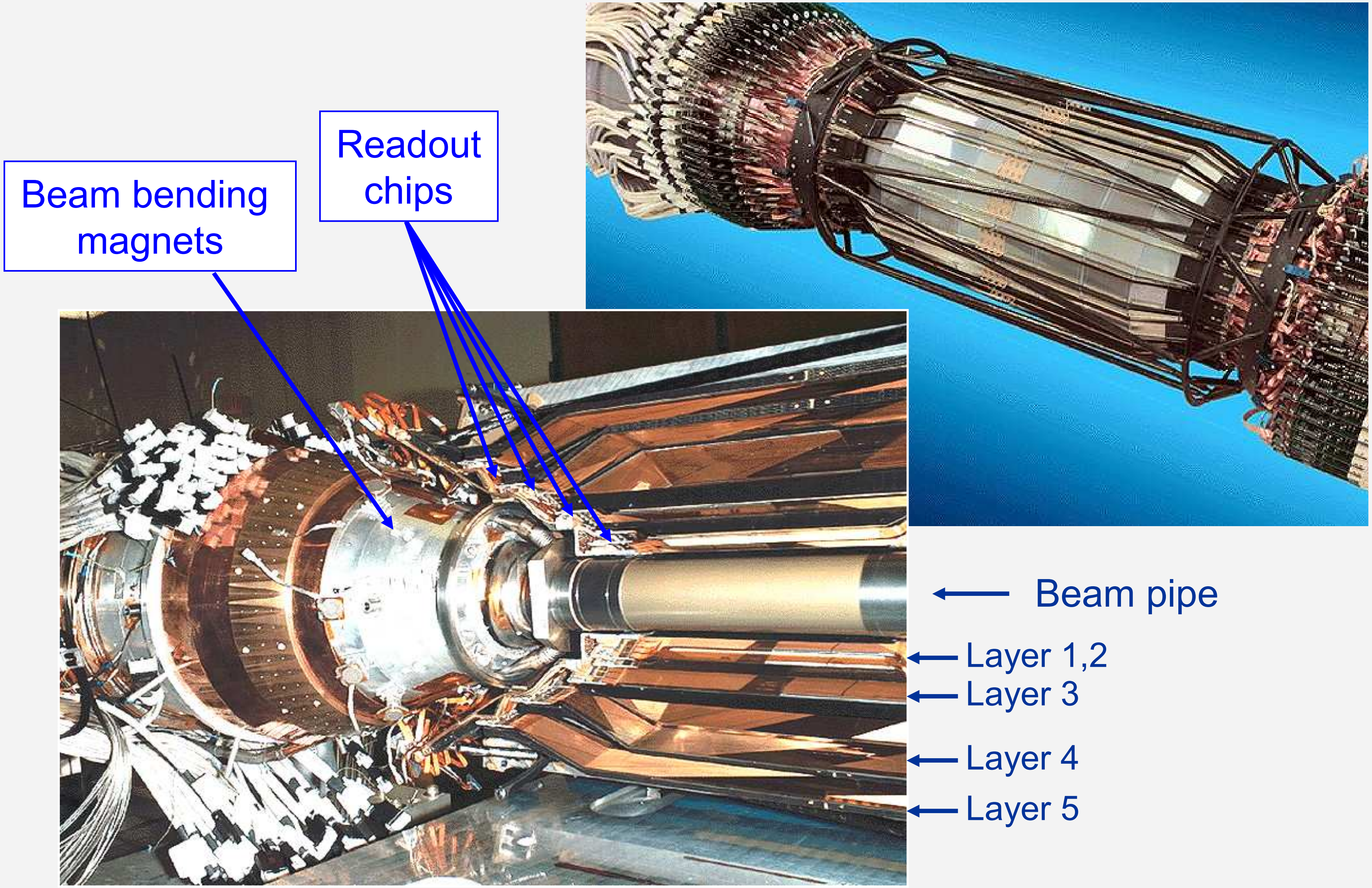




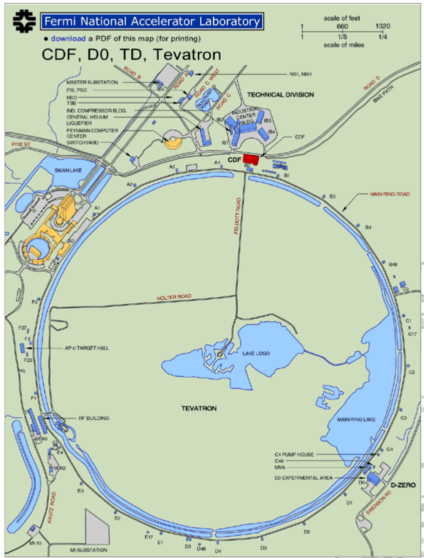
Observations:

- Precision on λ ($|V_{ud}|$, $|V_{us}|$) is sufficient for CPV studies
- Interpretation of ε_K and ε'/ε dominated by theory errors
- $K_L \to \pi^0 \nu\nu$ et $K^+ \to \pi^+ \nu\nu$ sensitive to New Physics :
  - however, parameter errors $\sigma(m_c)[K^+]$, $\sigma(m_t)$, $\sigma(|V_{cb}|)$ are a concern

The Silicon Vertex Detector

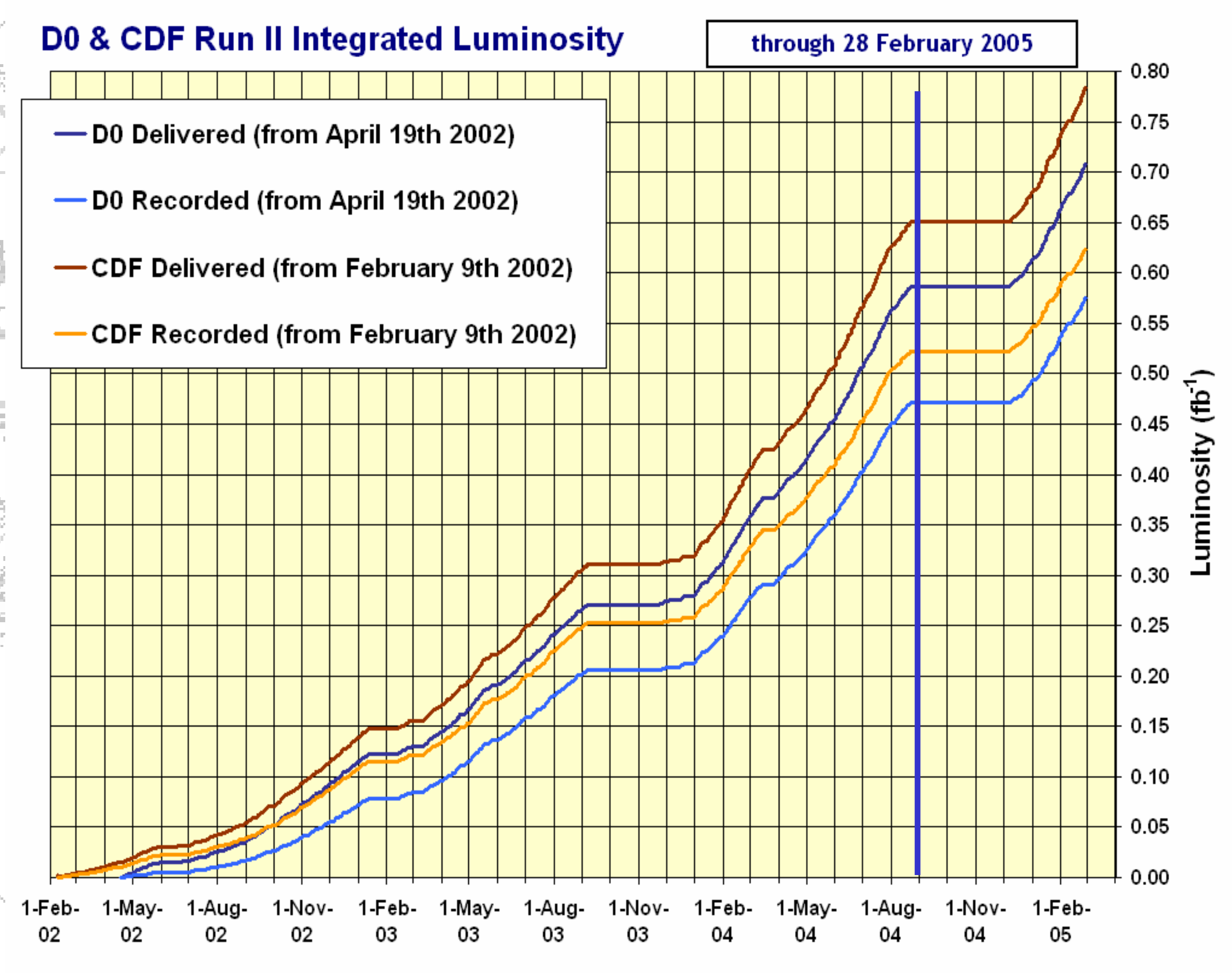


Also the Tevatron is Running well !

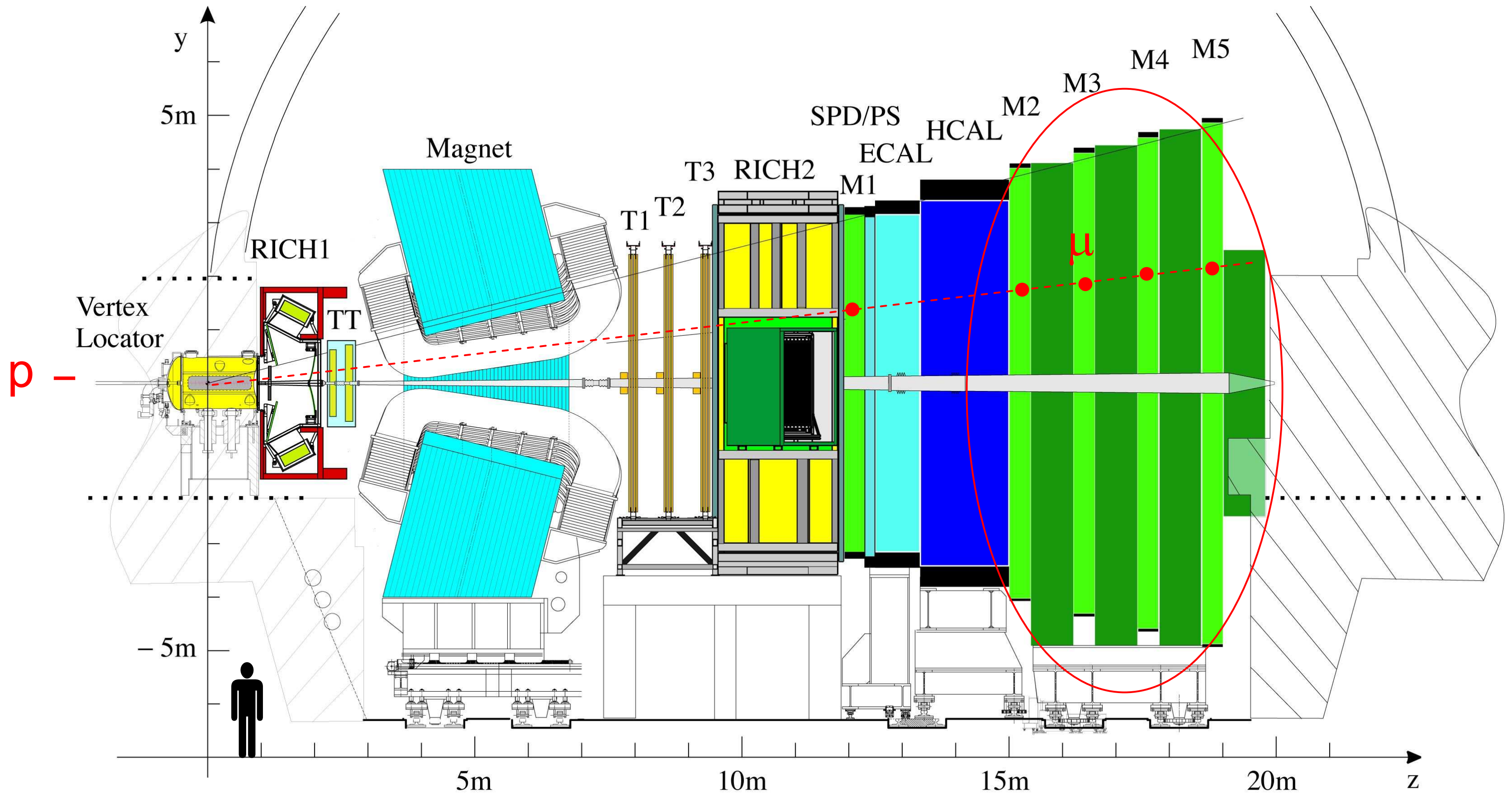


Difficult start, but now on design

Required luminosity to measure SM B_s mixing frequency: ≈ 2 fb^{-1}



The Near Future of *B* Physics: LHCb



Muon system to identify muons, also used in first level of trigger

Efficiency ~ 95% for pion misidentification rate < 1%