Forty Years of Heavy Flavor Physics and CP Violation

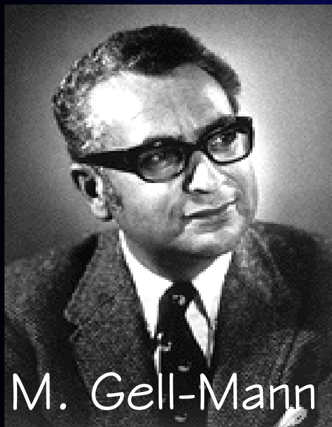
Gautier Hamel de Monchenault

Paris, 1st February 2006

The Standard Model of Quarks & Leptons

The Quark Model

Gell-Mann & Zweig (1964)


M. Gell-Mann

Three « quarks » and their antiparticles (« antiquarks »)

Quark	Up "u"	Down "d"	Strange "s"
Charge	+2/3	-1/3	-1/3

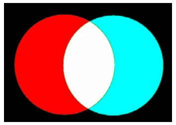
Each quark carries a charge of « color »

Red Blue Green

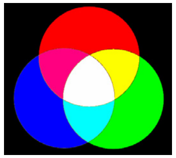
Each antiquark carries a charge of « anticolor »

Antired Antiblue Antigreen

Only the « white » combinations are physical

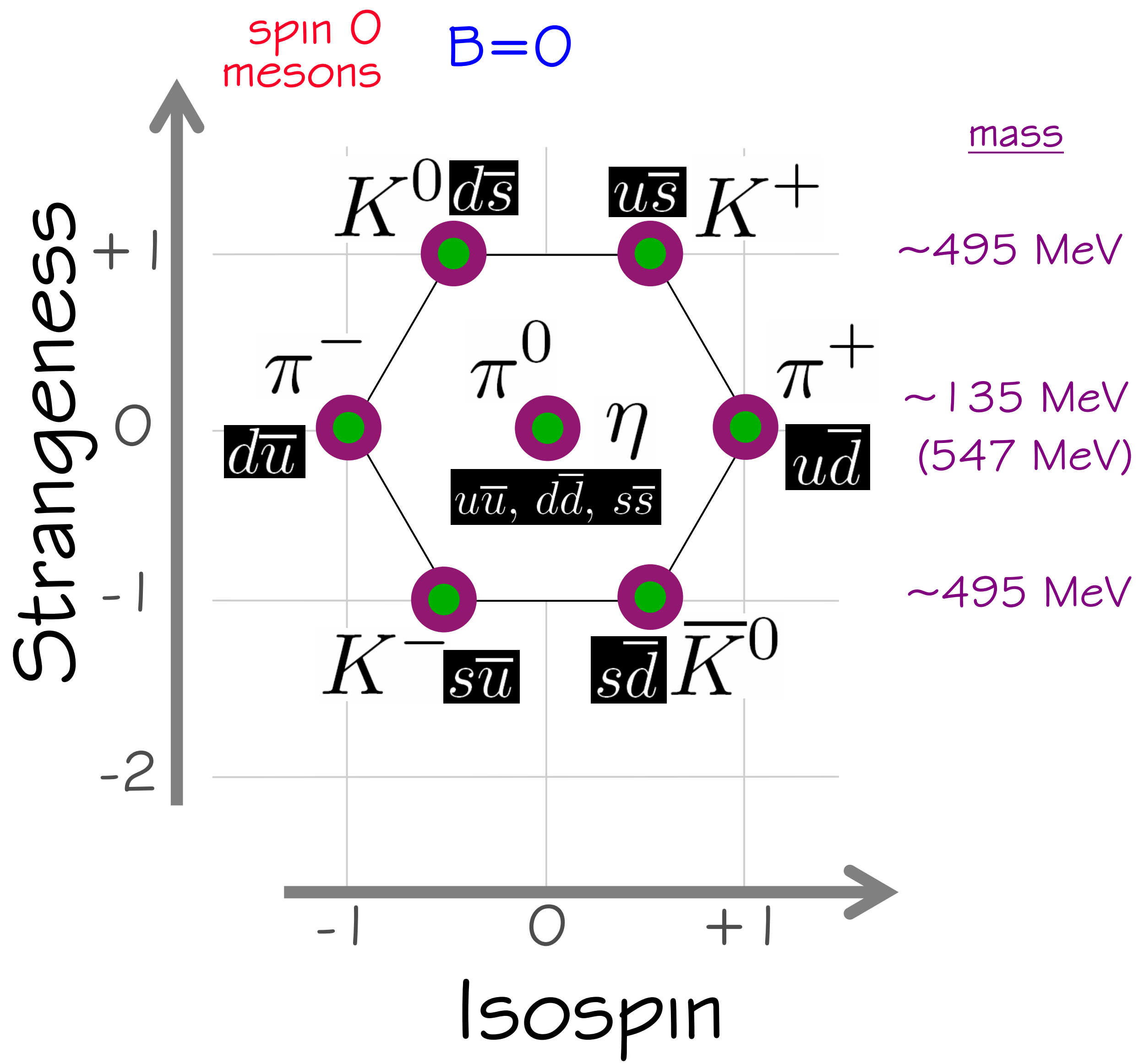


quark-antiquark (« meson ») — integer spin



three quarks (« baryon »)
three antiquarks (« antibaryon ») — ½ integer spin

Mesons



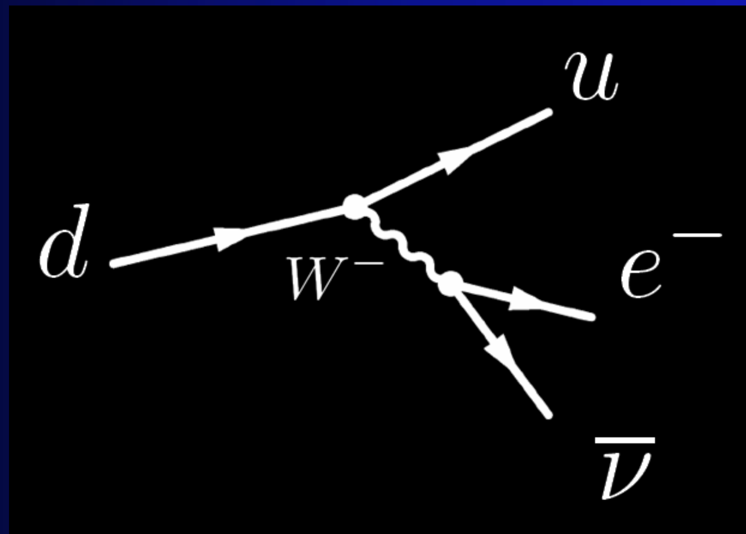
The strange quark « s » carries a charge of strangeness S = -1

The « s » quark is heavier

~1973:
Quantum Chromodynamics (QCD)

- quarks & gluons
- force of « color »
- confinement
- asymptotic freedom

The Electroweak Theory



S. Glashow,
S. Weinberg,
A. Salam
($\sim$1969)

M. Veltman,
G. 't Hooft
(1970-72)


S. Weinberg

unification of
electromagnetic and weak interactions

Three intermediate vector bosons
of weak interactions

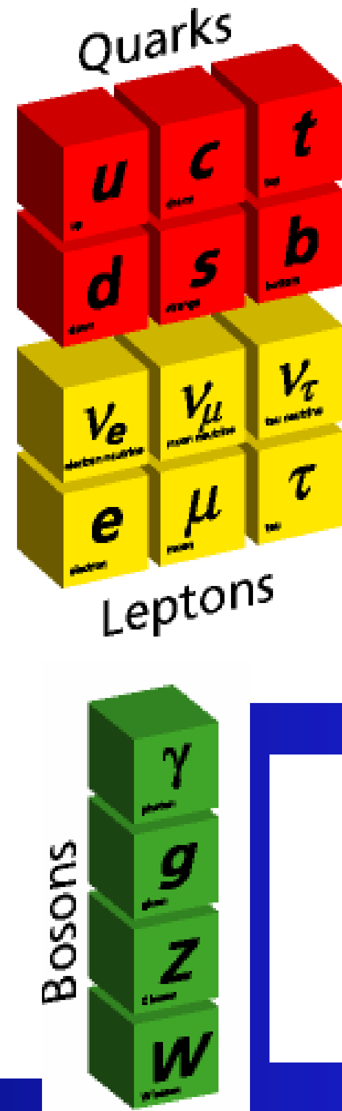
Weak Charged Currents	:	W^+ & W^-	$M \sim 80$ GeV
Weak Neutral Currents	:	Z^0	$M \sim 90$ GeV
		... and the photon	$M = 0$

The Standard Model

Particles of matter
(fermions, spin ½)

- three « families » of quarks
- three « families » of leptons

… and as much antimatter!



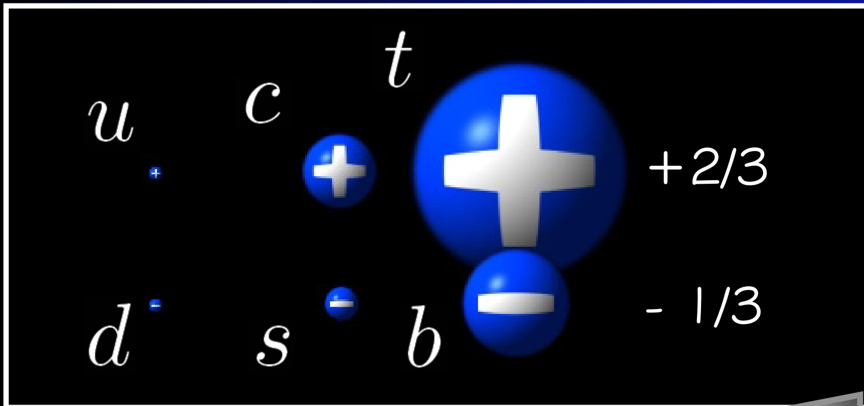
Particles mediating interactions
(vector bosons, spin 1)

Electroweak theory
- the photon
- the three bosons W^+, W^- & Z

Quantum Chromodynamics (QCD)
- eight gluons

\+ one spinless particle
(unknown mass)

the Higgs Boson



<u>masses</u>

m(u) ~ 5 MeV

m(c) ~ 1.5 GeV

m(t) ~ 175 GeV

m(d) ~ 10 MeV

m(s) ~ 0.3 GeV

m(b) ~ 4.5 GeV

mesons

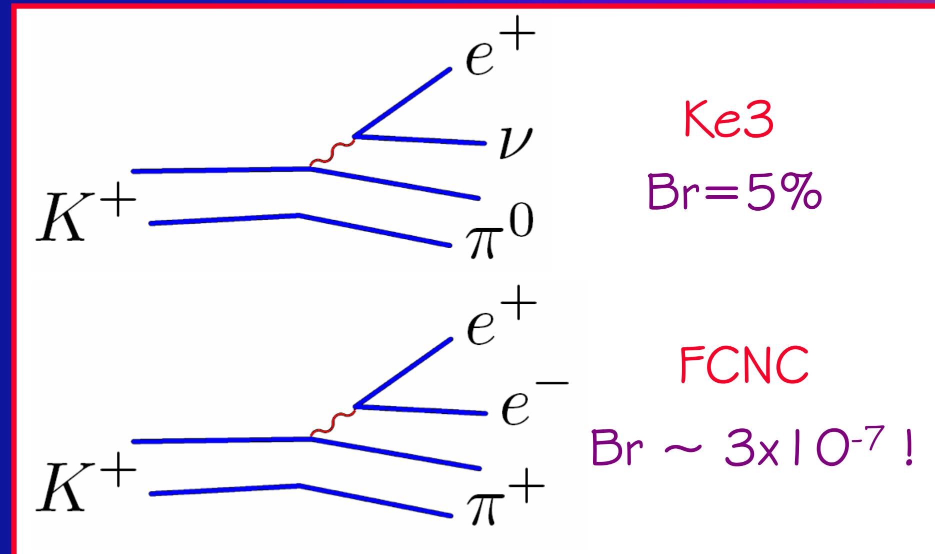
CP

		Q=-2/3			Q=+1/3		
		$\bar{u}$	$\bar{c}$	$\bar{t}$	$\bar{d}$	$\bar{s}$	$\bar{b}$
Q=+2/3	u	$u\bar{u}$	$\overline{D}^0$		$u\bar{d}$	$u\bar{s}$	$u\bar{b}$
	c	D^0	J/ψ		$c\bar{d}$	$c\bar{s}$	$c\bar{b}$
	t						
Q=-1/3	d	$d\bar{u}$	$d\bar{c}$		$d\bar{d}$	K^0	B^0
	s	$s\bar{u}$	$s\bar{c}$		$\overline{K}^0$	ϕ	B_s
	b	$b\bar{u}$	$b\bar{c}$		$\overline{B}^0$	$\overline{B}_s$	Υ

Charm

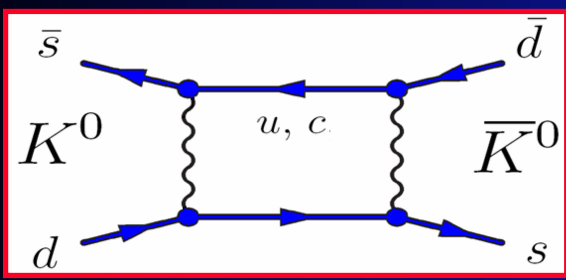
The Prediction of Charm

1967-1970, problem with the GWS electroweak theory:
- Strange particles decay only through Charged Currents
- Flavor Changing Neutral Current (FCNC) are <u>very suppressed</u>



→ prediction of the <u>charm quark c</u>

1970, Glashow-Iliopoulos-Maiani (GIM)
- up-type quark (charge + 2/3)
- four quarks ↔ four leptons
- suppression of FCNC at lowest order (ΔS=0)



from rate of K^0 mixing:
M(charm) ~1.5GeV

two-family quark flavor mixing matrix (Cabibbo)

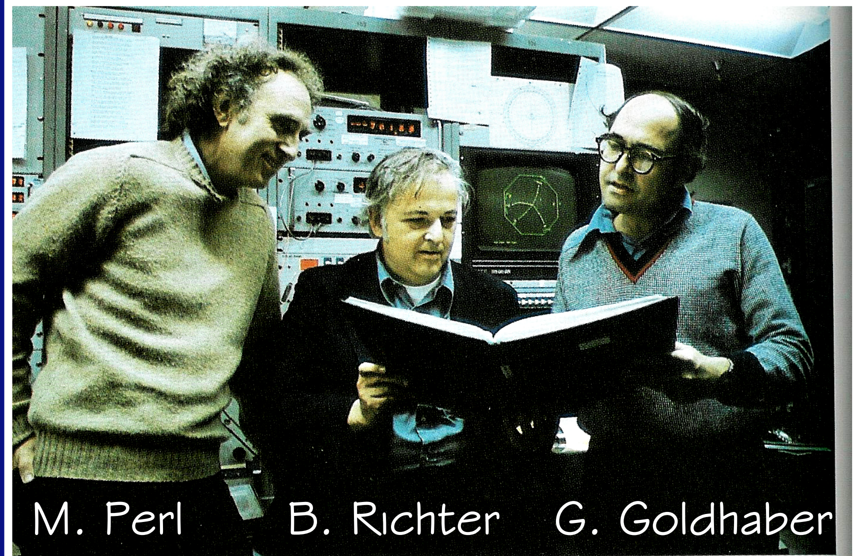
	d	**s**
u	$\cos\vartheta_c$	$\sin\vartheta_c$
c	$-\sin\vartheta_c$	$\cos\vartheta_c$

$$\lambda = \sin\vartheta_c \sim 0.22$$

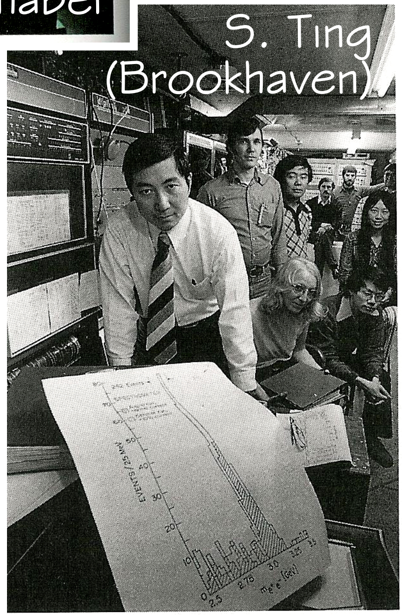
1974, the November Revolution

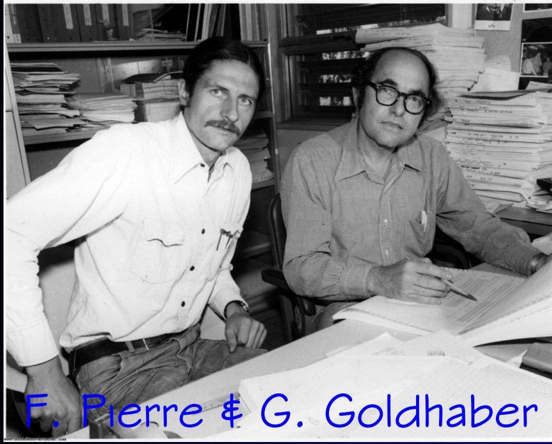
SPEAR (SLAC 1974)

« a ring on a parking lot »



November 1974



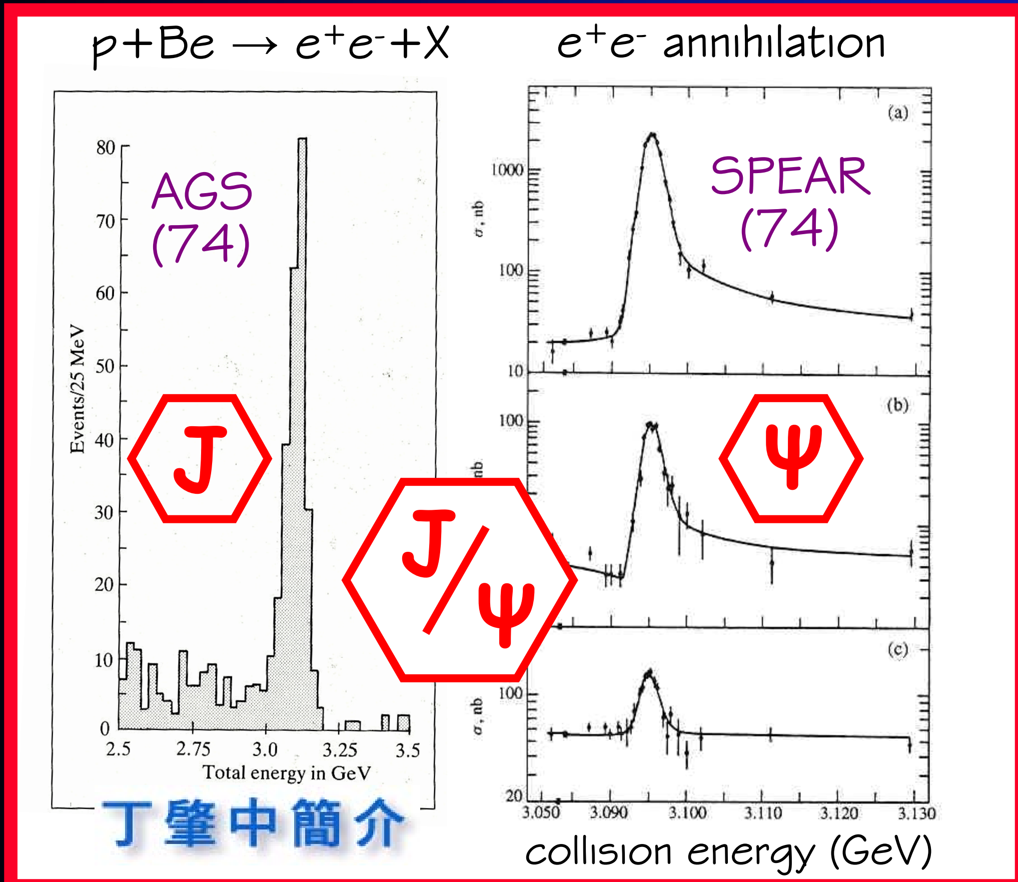


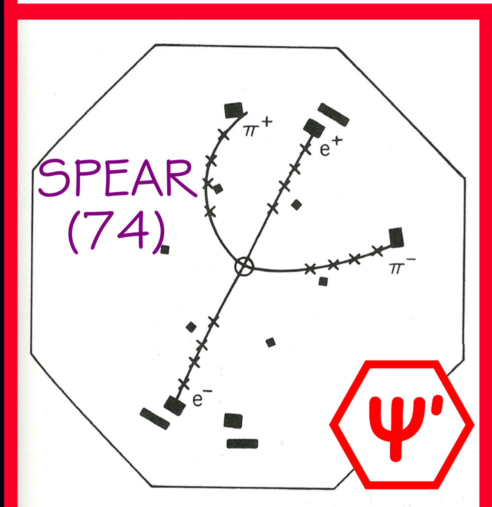
1975

1974: discovery of « charmonium »

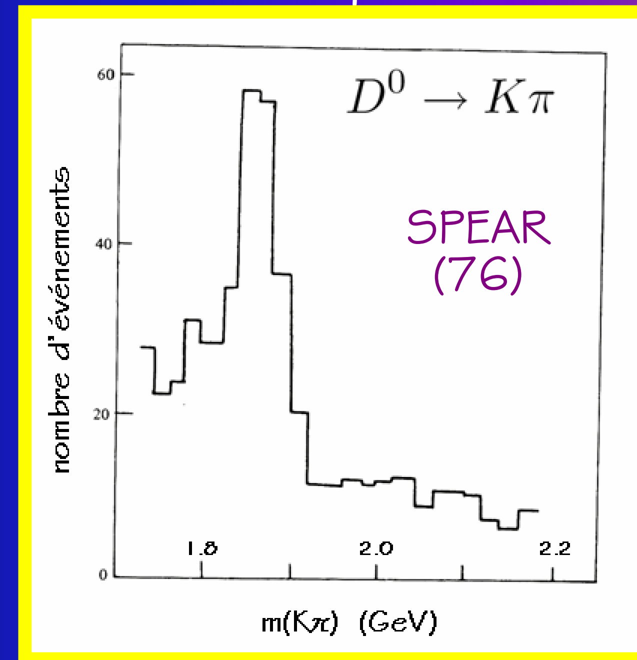
1976: discovery of « open charm »

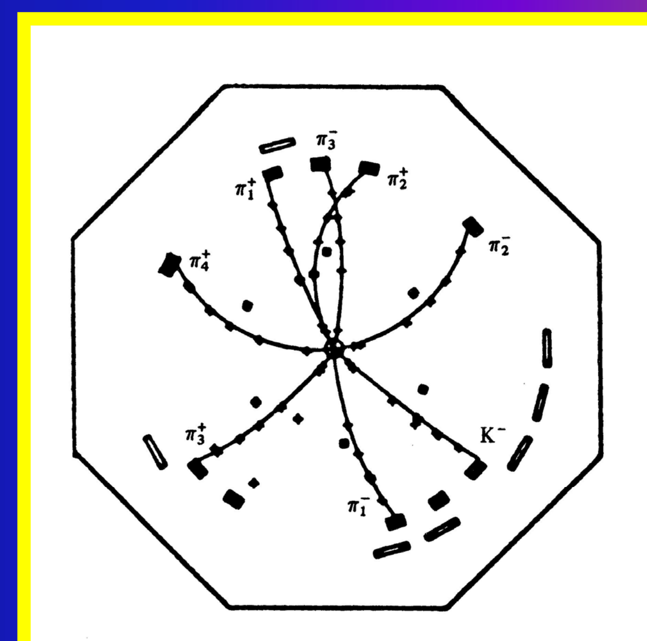
open charm





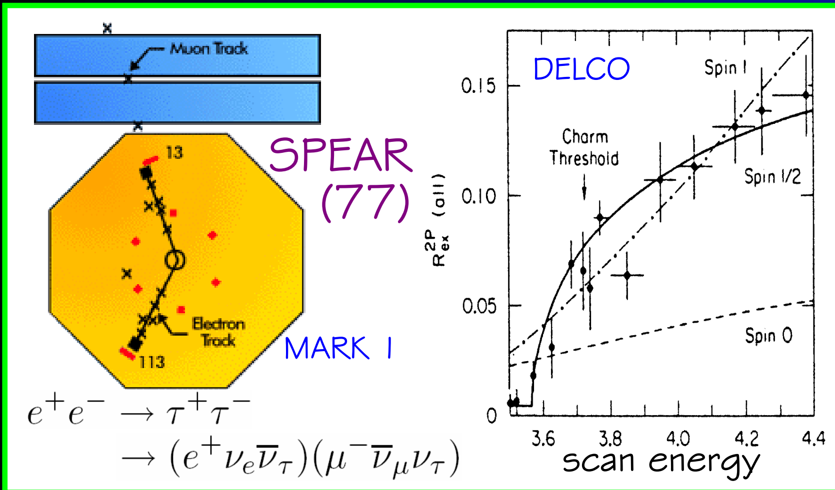
charmonium

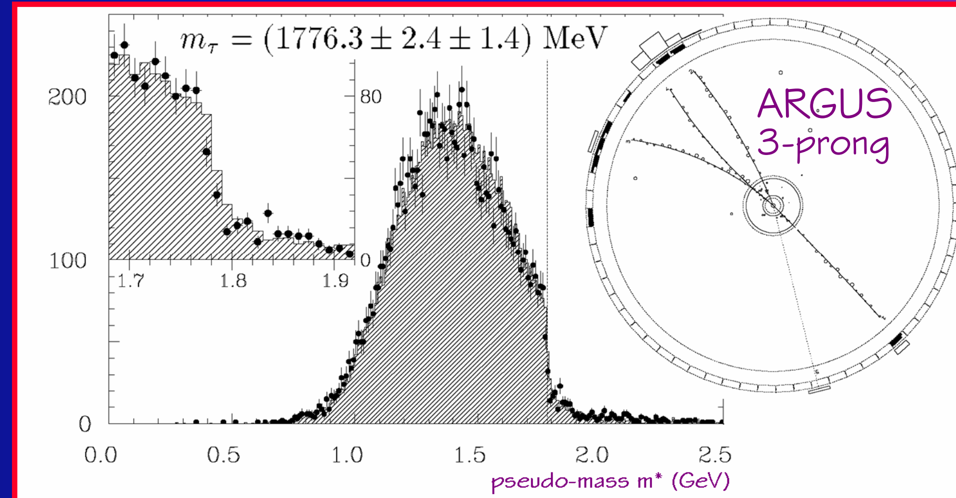




Enters The Third Family

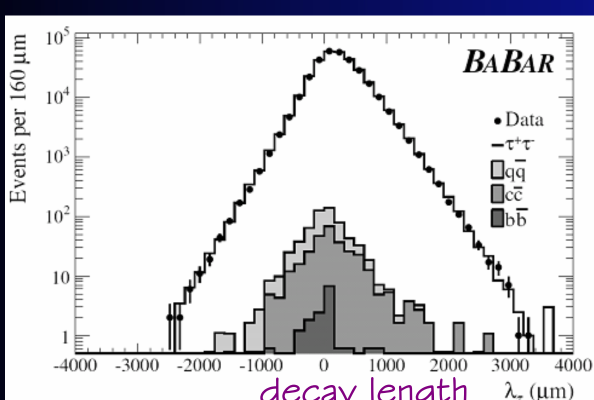
A Third Generation of Leptons



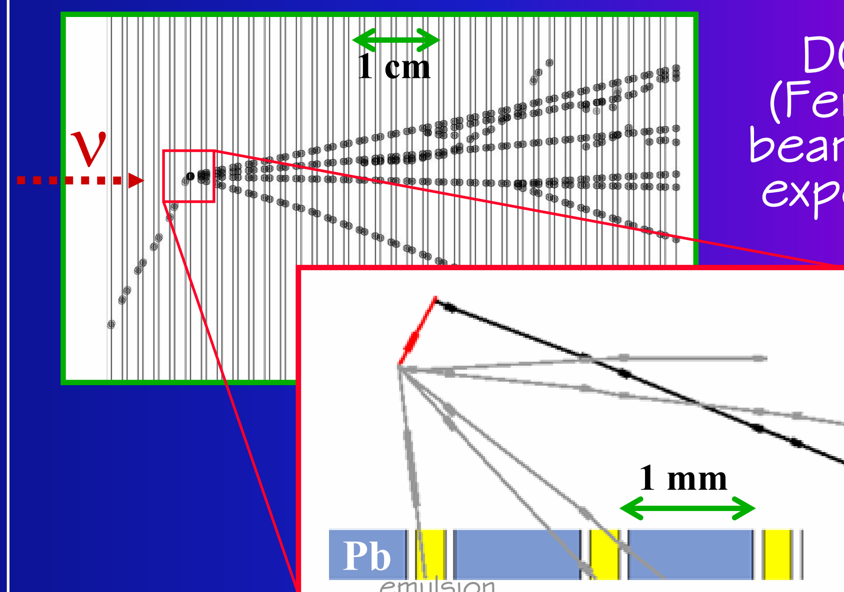


1977: discovery of the tau lepton

- heavy lepton (~1.77 GeV)
- hadronic decays
- short lifetime (290 fs)



2001: detection of the tau-neutrino



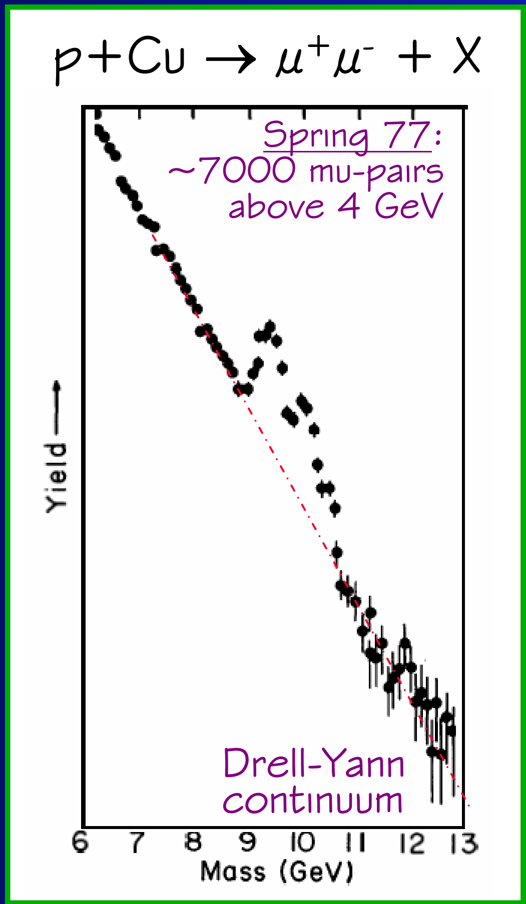
DONUT (Fermilab) beam dump experiment

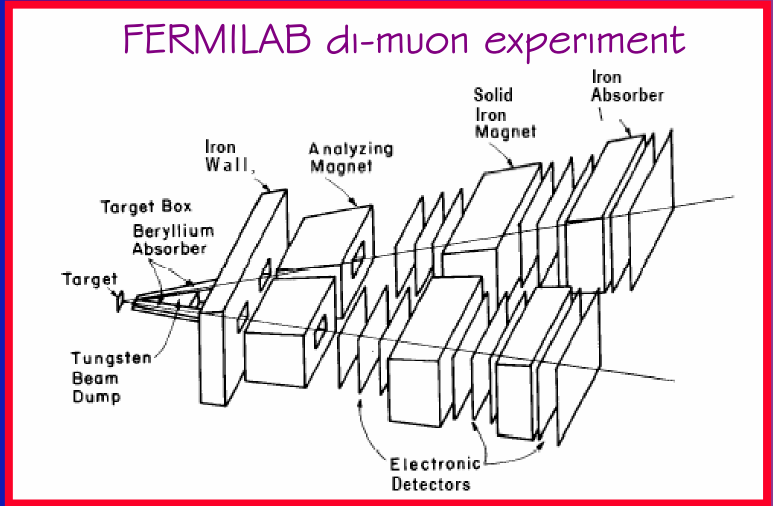
Discovery of the Bottom Quark

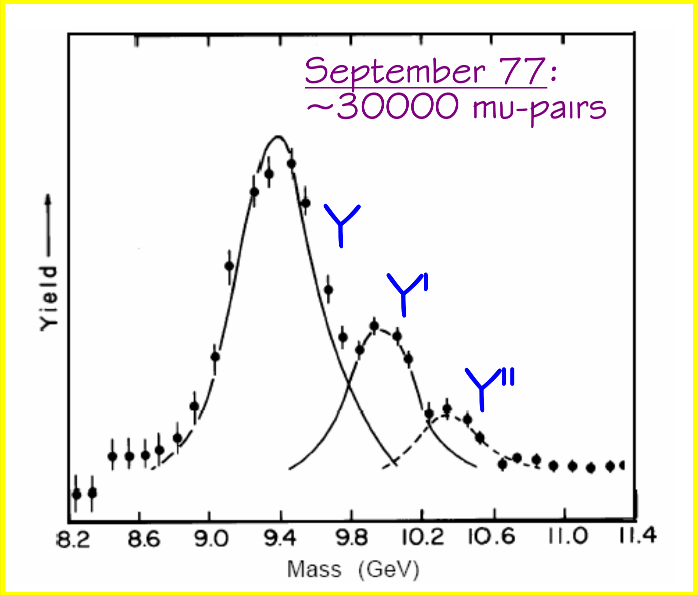
1977, Fermilab: observation of an *excess* of muon pairs around 9.4 GeV of mass, resolved in <u>three resonances</u>

The Upsilon family (bottomium): interpreted as b-bbar bound states, first manifestation of the b-quark!

<u>b-quark</u>: down-type quark (charge -1/3)
M(b) ~ 4.5 GeV

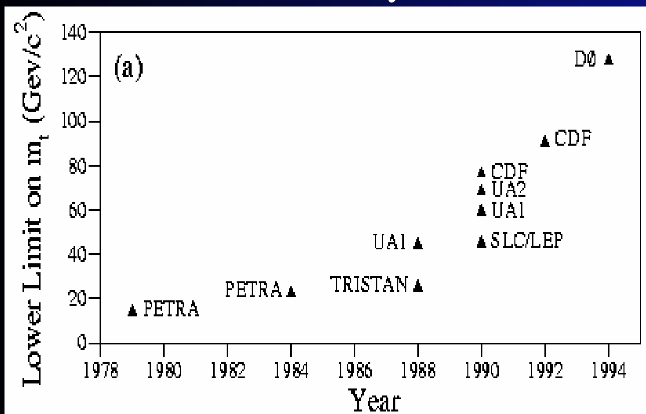




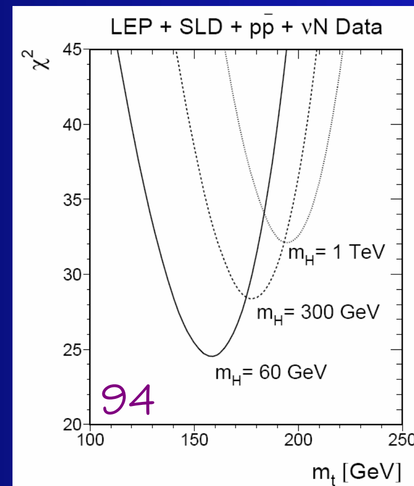


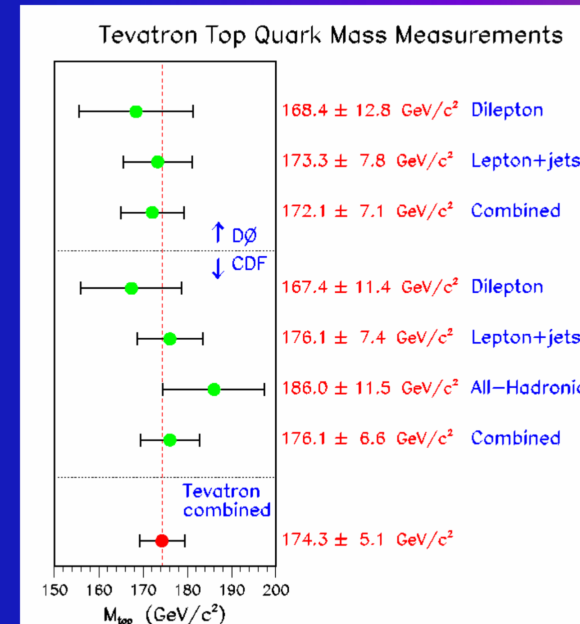
Discovery of the Top Quark

the search for the top lasted for 18 years!

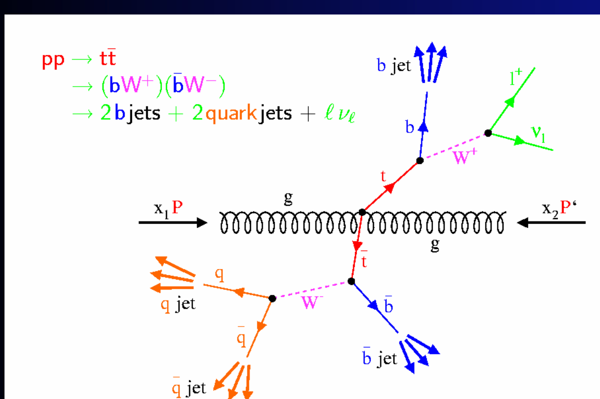


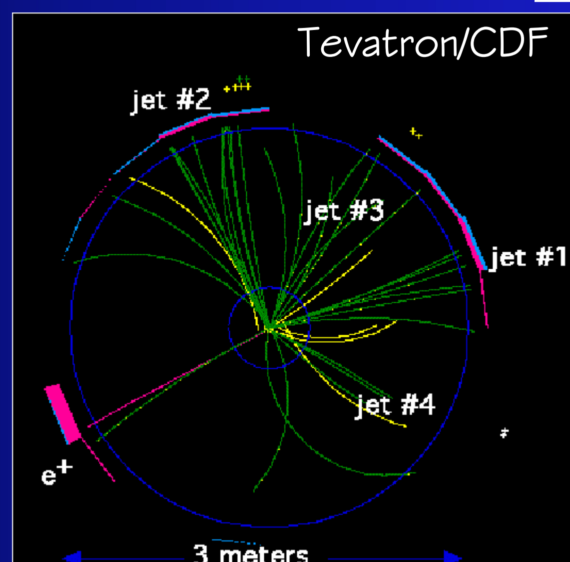
electroweak fits

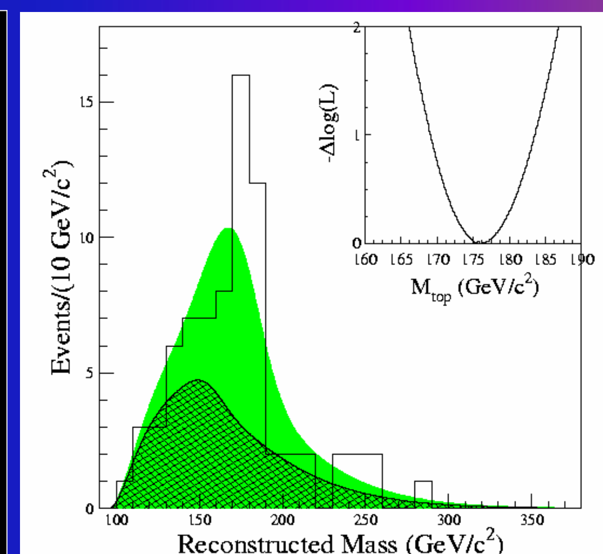




CDF & D0 (94) at the Tevatron (Fermilab): direct observation



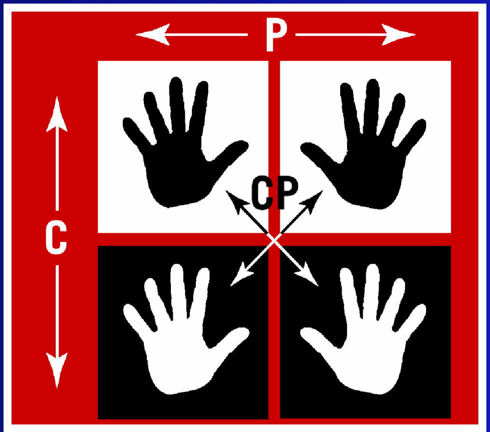


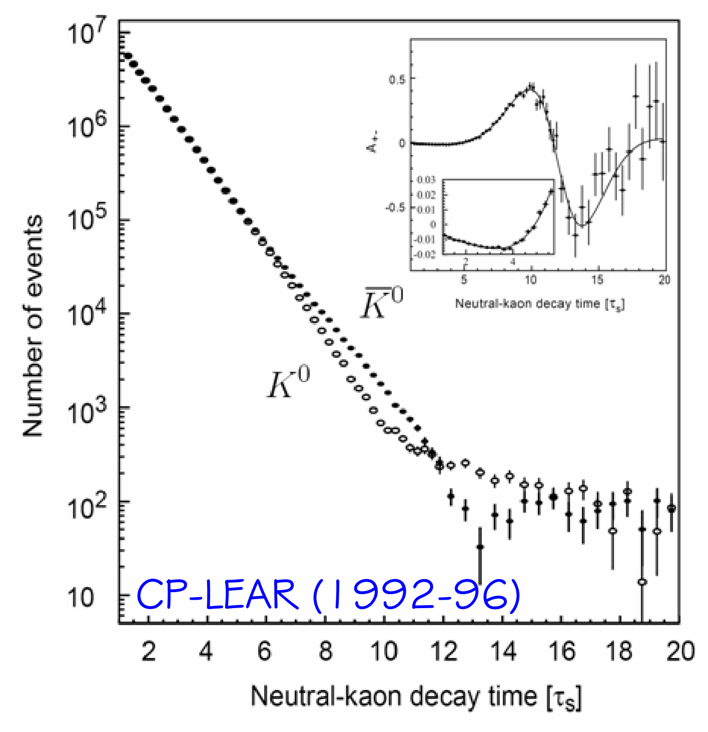


CP Violation
&
the KM Model

CP Violation in the Kaon System

Before 1964 :
Charge-Parity (CP) is
a Good Symmetry
for Weak Interactions





1964 : Christenson, Cronin, Fitch & Turlay
establish experimentally that
CP symmetry is violated in the weak
disintegration of long-lived neutral kaons

- A *CP*-violating process offers an absolute way of distinguishing a world of anti-matter from a world of matter
- Cosmology : CP Violation is one of the three necessary conditions to a global excess of matter in the Universe

CP violation in mixing: $\mathrm{Proba}(\overline{K}^0 \rightarrow K^0) > \mathrm{Proba}(K^0 \rightarrow \overline{K}^0)$

CP violation in the kaon system is a very small effect: 2 Re(ε) ~ 0.3%

The Kobayashi & Maskawa Model

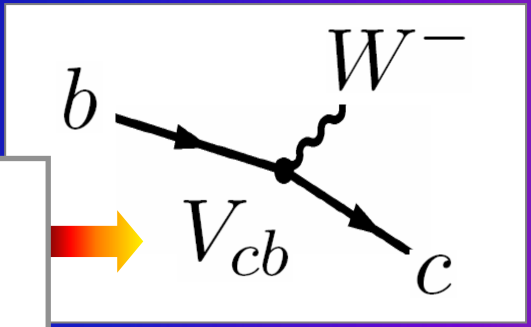
1972, M. Kobayashi & T. Maskawa :
introduction of CP violation in electroweak theory

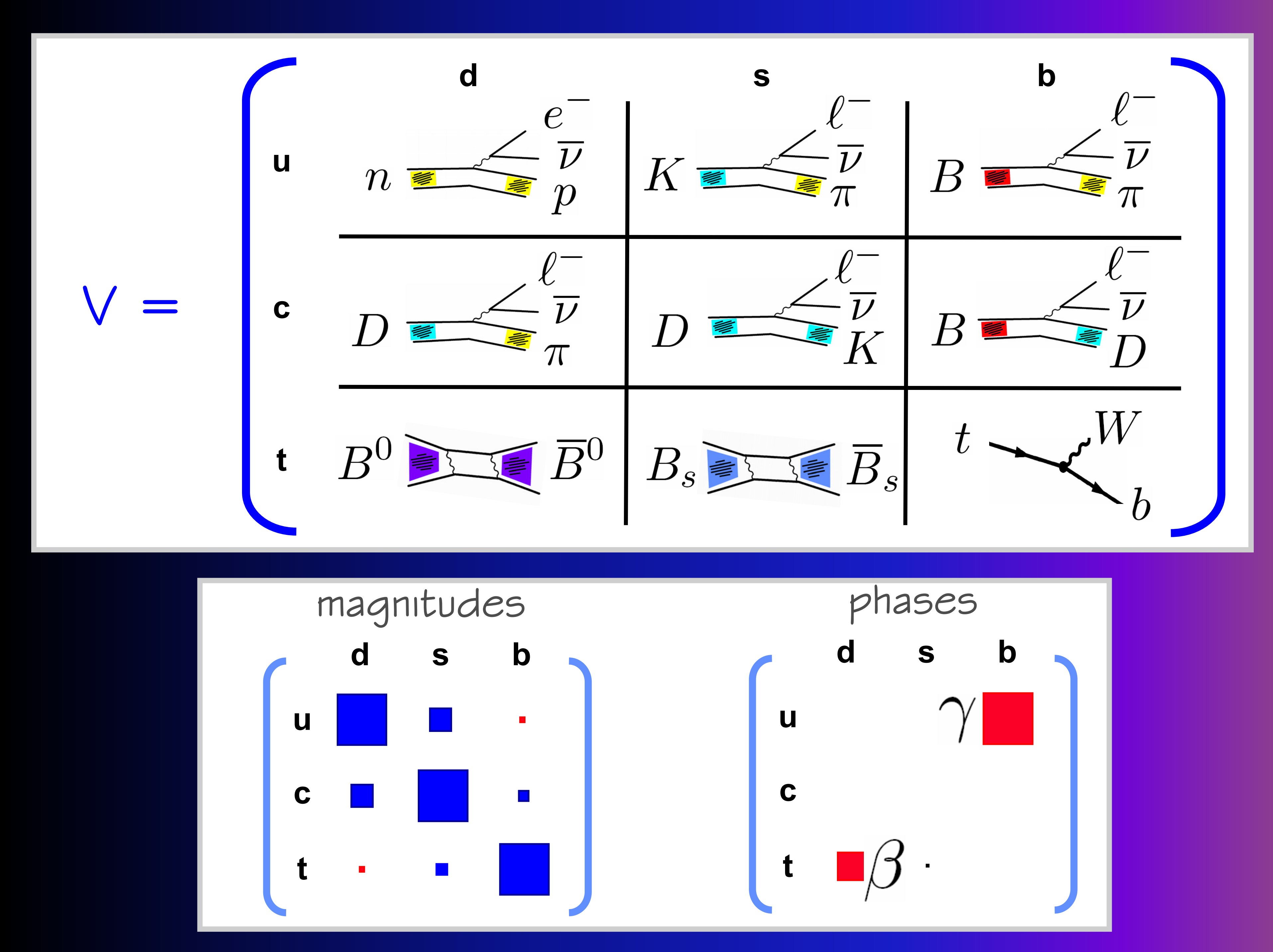
Condition : at least three families of quarks !

Origin of CP violation :
the CKM matrix (« quark flavor mixing matrix »)

3 families → A single CP-violating parameter

Elements of the CKM matrix:
« couplings » between
Down-type quarks
and Up-type quarks





V =
d
s
b
u
c
t
n e^- $\overline{\nu}$ p
K ℓ^- $\overline{\nu}$ π
B ℓ^- $\overline{\nu}$ π
D ℓ^- $\overline{\nu}$ π
D ℓ^- $\overline{\nu}$ K
B ℓ^- $\overline{\nu}$ D
B^0 $\overline{B}^0$
B_s $\overline{B}_s$
t W b
magnitudes
d s b
u
c
t
phases
d s b
u
c
t
γ
β

The Unitarity Triangle

★ The CMK matrix is <u>complex unitary</u>:
determined by 4 real parameters

- sine of <u>Cabibbo angle</u>

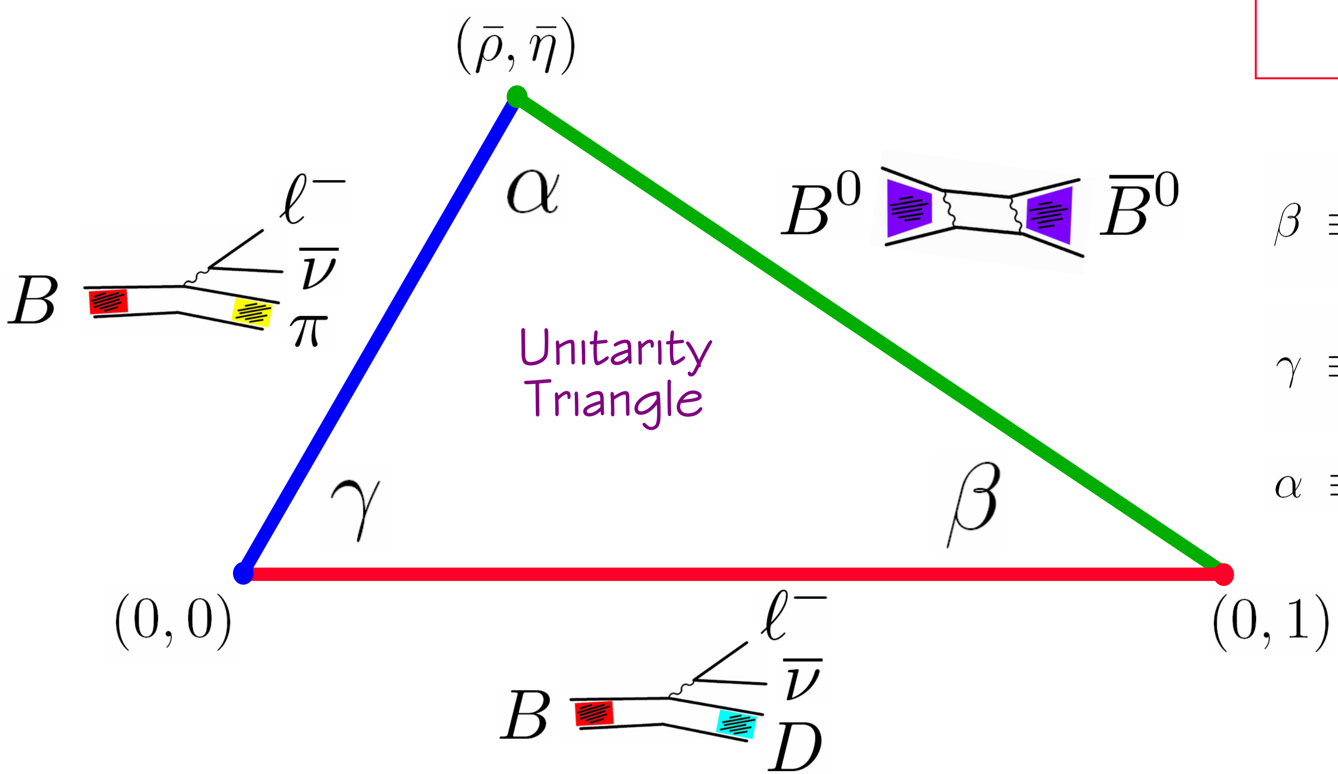
  $\lambda \sim 0.22$

- $b \to c$ transition (in units of λ^2)

  $A \sim 0.83$

- 2 coordinates of the apex of the <u>Unitarity Triangle</u>

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



$$\beta \equiv \arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right] \sim 24^\circ$$

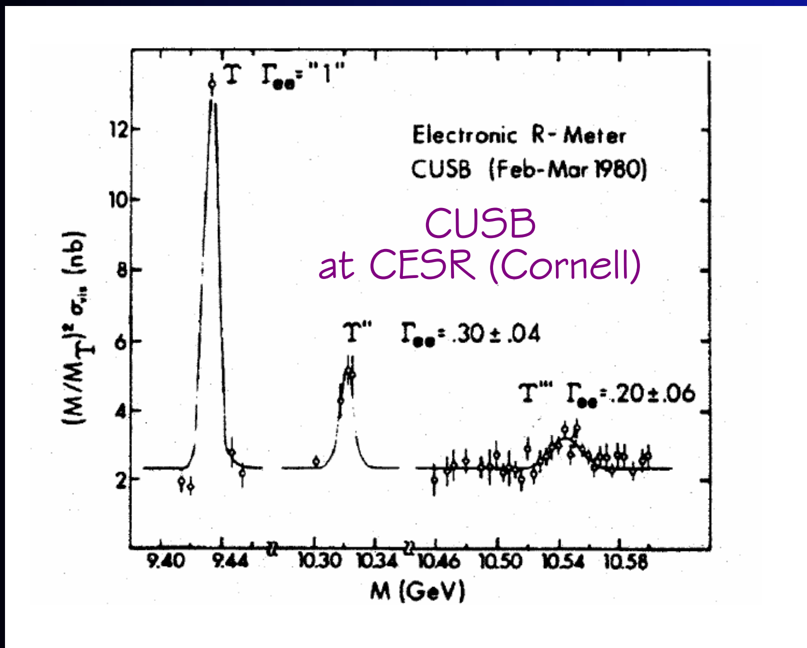
$$\gamma \equiv \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right] \sim 62^\circ$$

$$\alpha \equiv \pi - \beta - \gamma$$

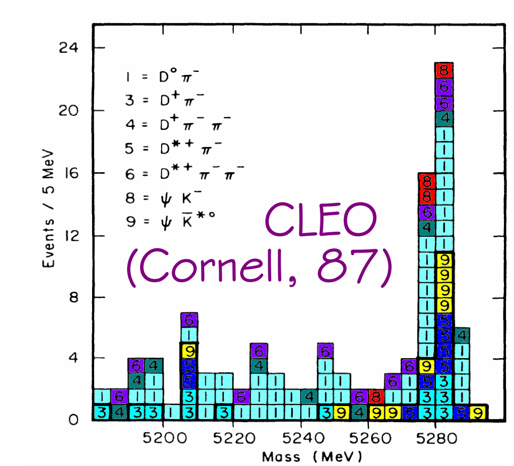
B Physics

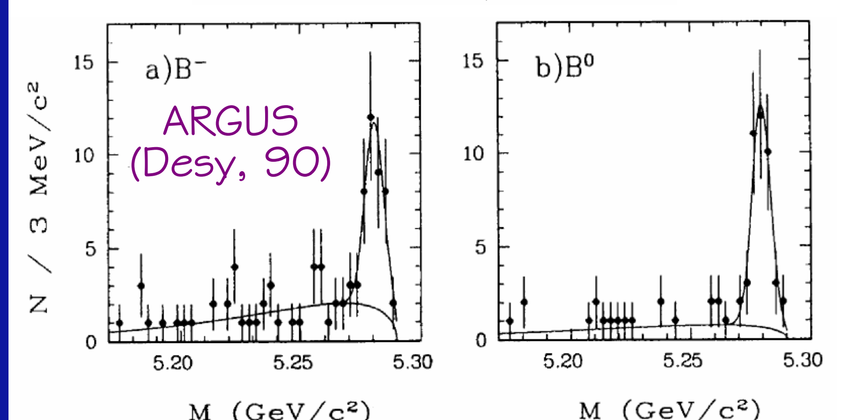
Dawn of B Physics

1980 : Discovery of the Υ(4S) at Cornell



expected natural width < 1 MeV
but measured width ~ 13 MeV
→ Υ(4S) mass just above the
B-meson pair production threshold...



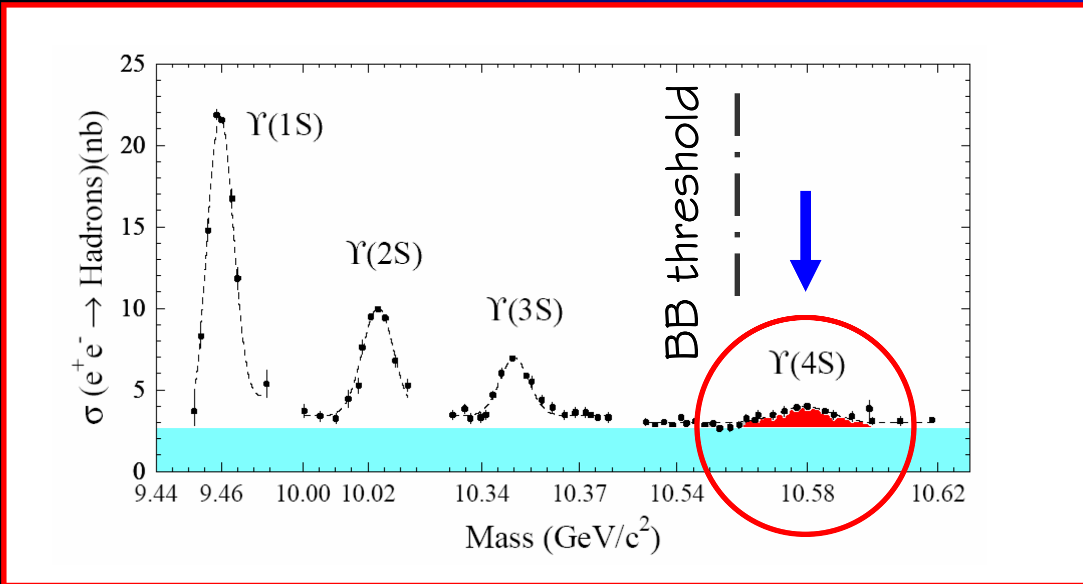


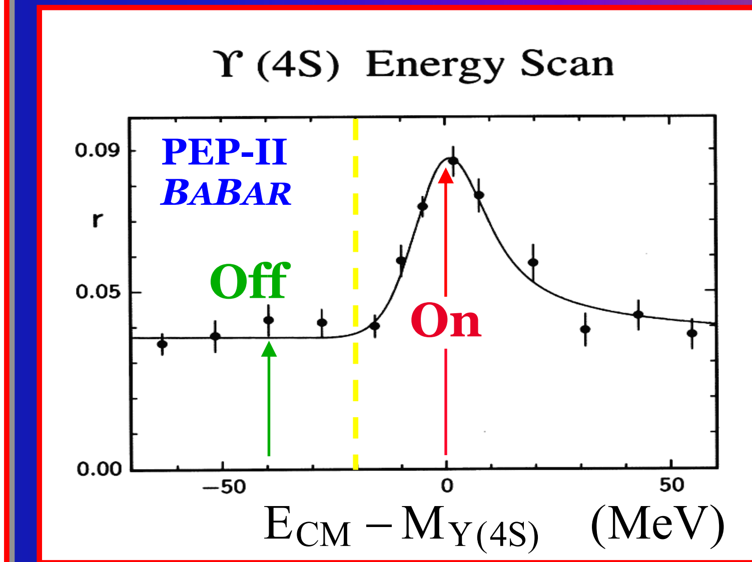
1987: exclusive reconstruction
of $b \rightarrow c$ decay modes
with a charm or charmonium meson
summing over several different modes

Product of branching fractions
typically of the order 10^{-4} to 10^{-5}

Mass (=5.278 GeV) and spin (=0)
of B mesons determined

Physics at the Υ(4S) Resonance





Electron-positron collisions at E= 10.58 GeV

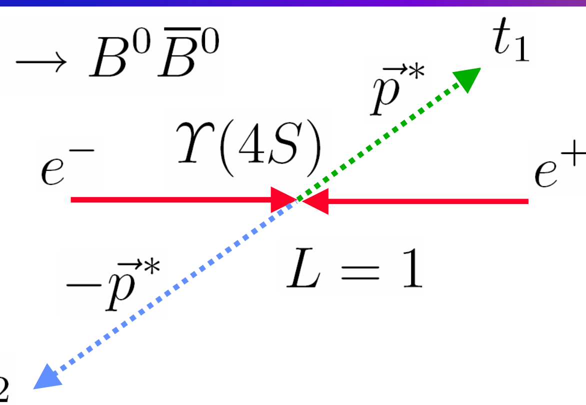
$$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\overline{B}$$ (purity ~ 25%)

B mesons at the Υ(4S)

- produced by pair
- in a P-wave (anti-symmetric)
- in a coherent flavor state
- almost at rest

$$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B^0\overline{B}^0$$

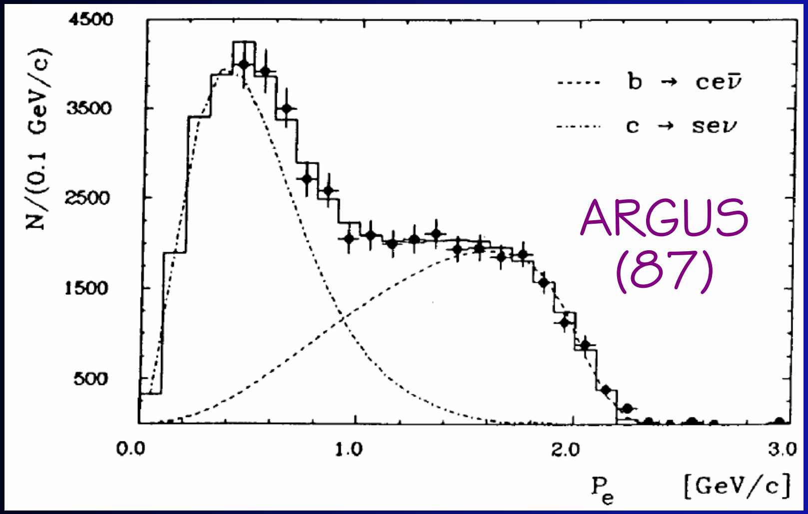
$$J^{PC} = 1^{--}$$

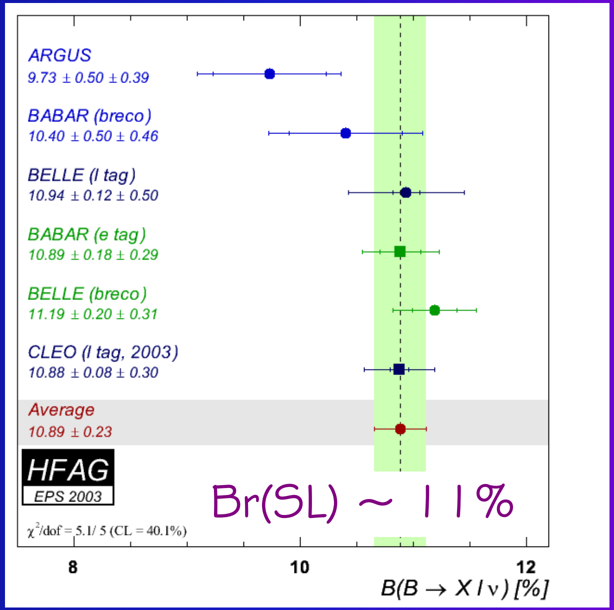


$$\Delta t \equiv t_2 - t_1$$

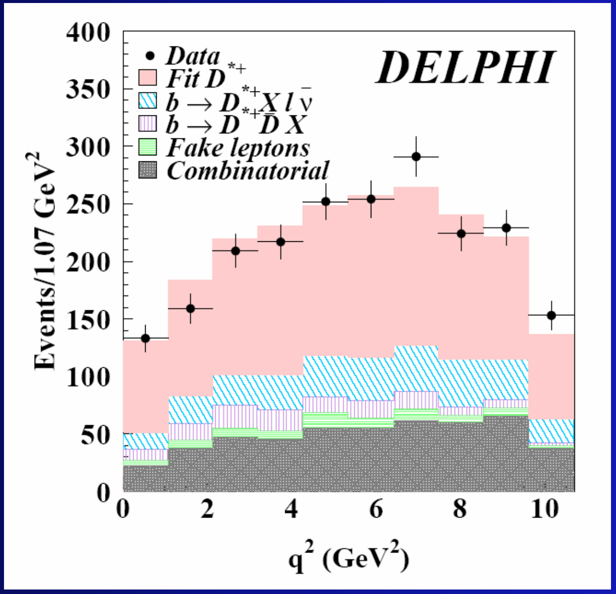
Semileptonic B Decays

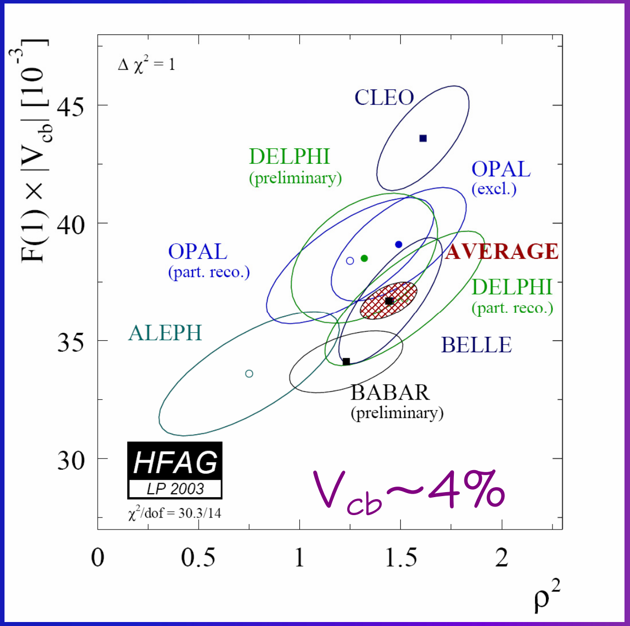
Lepton spectrum at the Y(4S)





V_{cb} using exclusive $B \to D^* \ell \nu$ decays





(thanks to development of the Heavy Quark Effective Theory HQET)

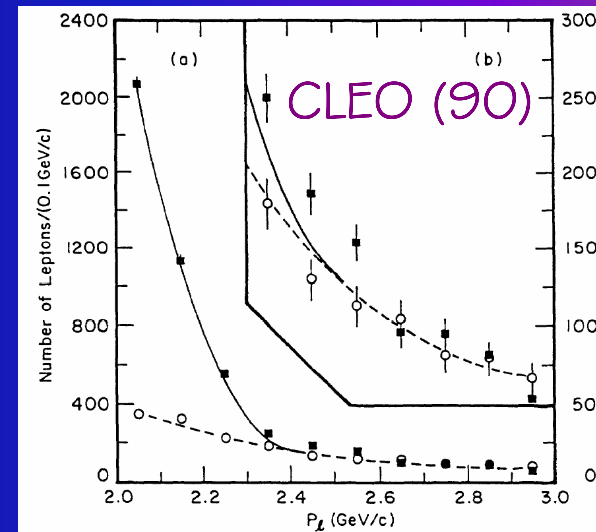
Charmless Semileptonic Decays

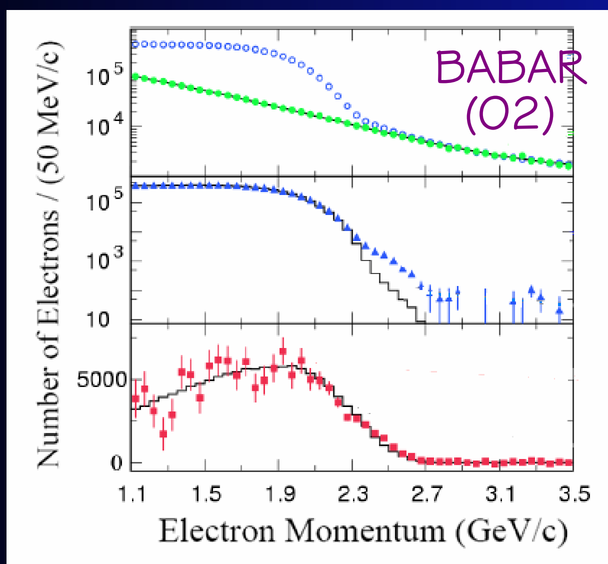
1990, CLEO & ARGUS:
Observation of charmless SL decays

beyond the end-point of the $b \to c$ spectrum

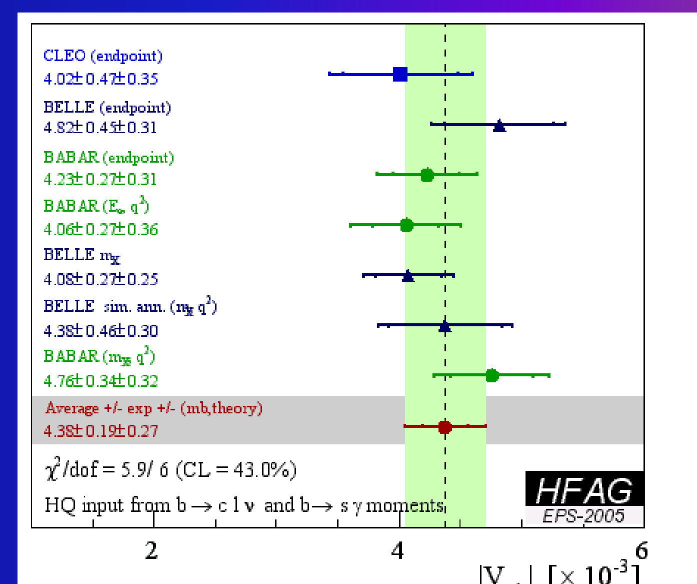
$b \to u$ rate consistent with expectation
→ first test of the KM framework

Lepton spectrum (end-point)



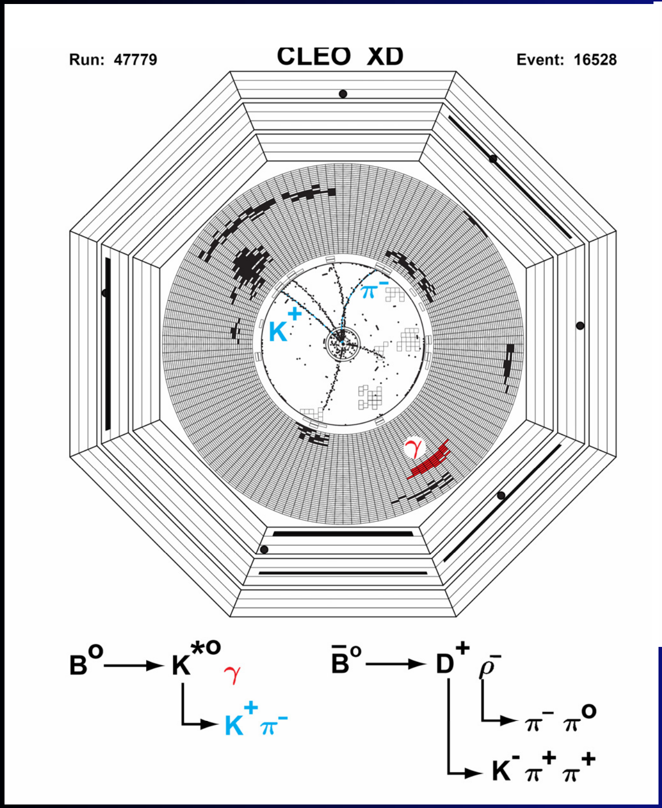


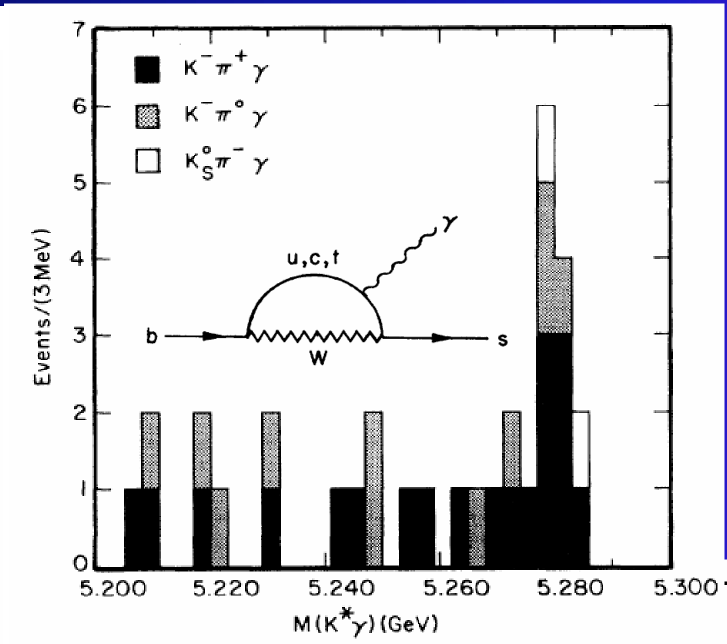
V_{ub}
of order
0.4%



Recent techniques to measure V_{ub} :
increase phase space region
so to decrease
the large extrapolation uncertainties

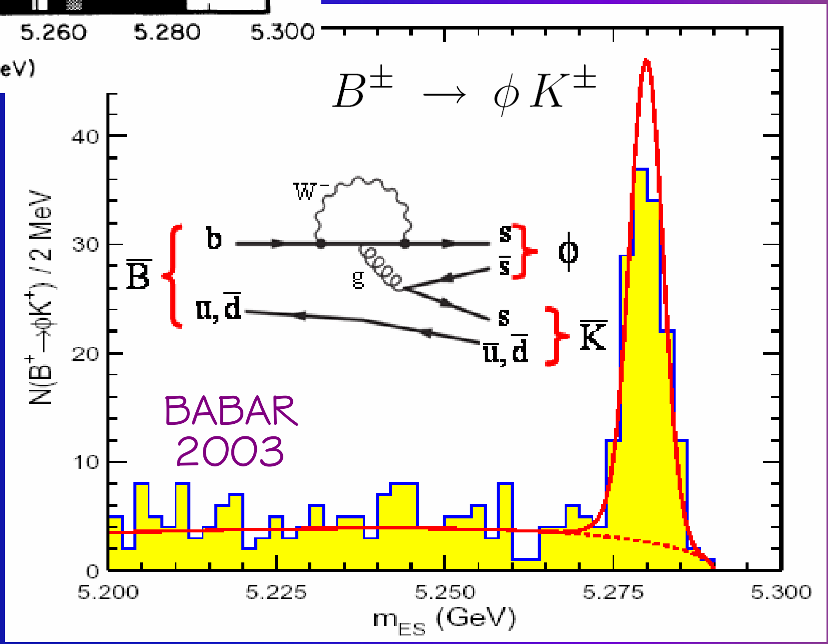
"Penguin" Decays





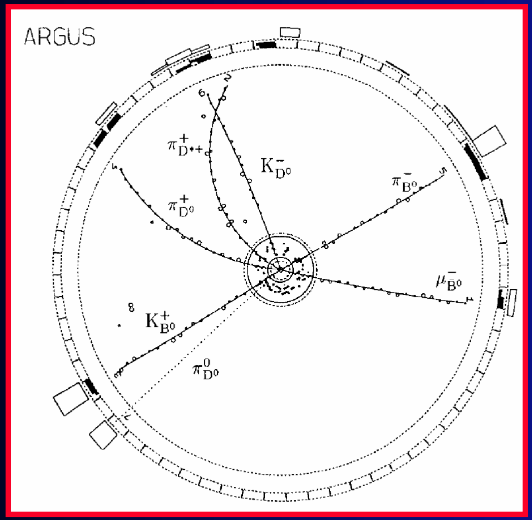
CLEO, 1993:
Observation
of $B \rightarrow K^* \gamma$

Presence of
<u>loop processes</u>
at the rate
expected
in the SM

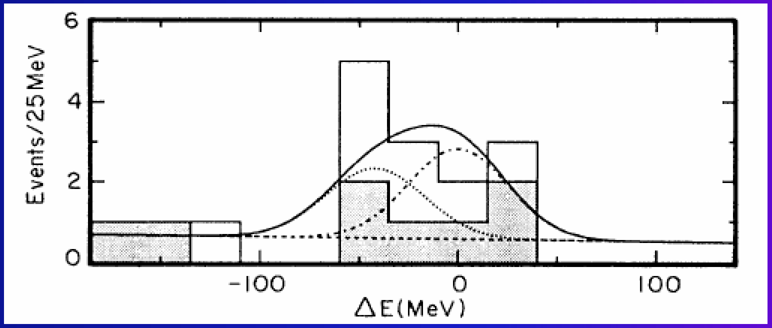


→ Powerful probes of physics
beyond the SM
through virtual effects

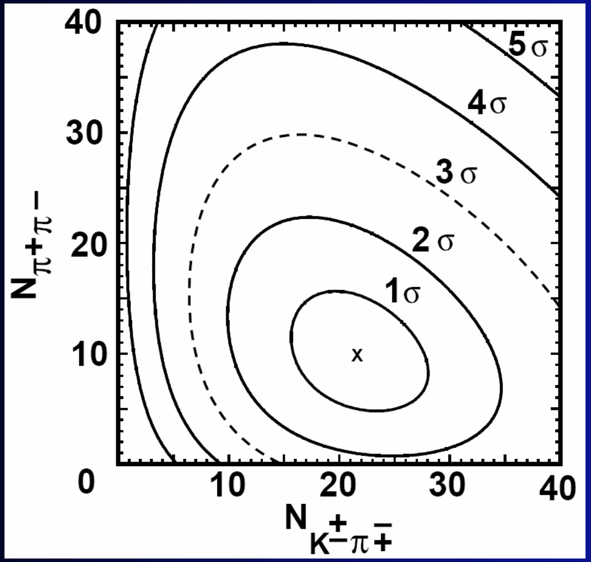
Charmless Two-Body Decays



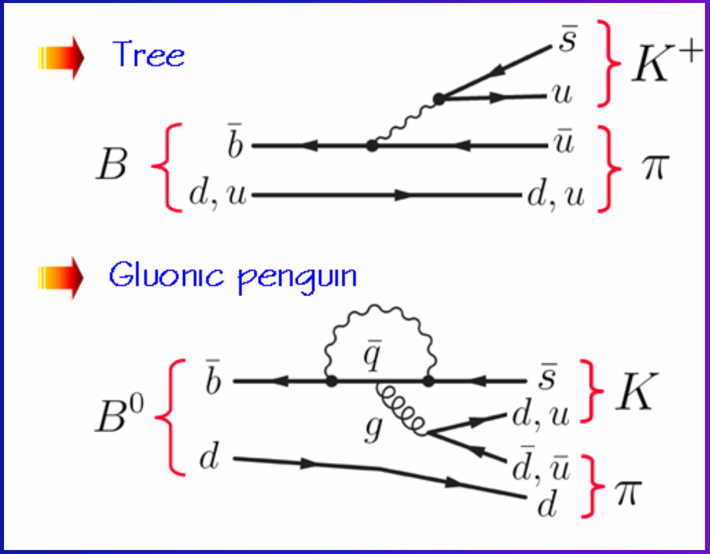
CLEO, 1993 : first evidence for charmless two-body decays



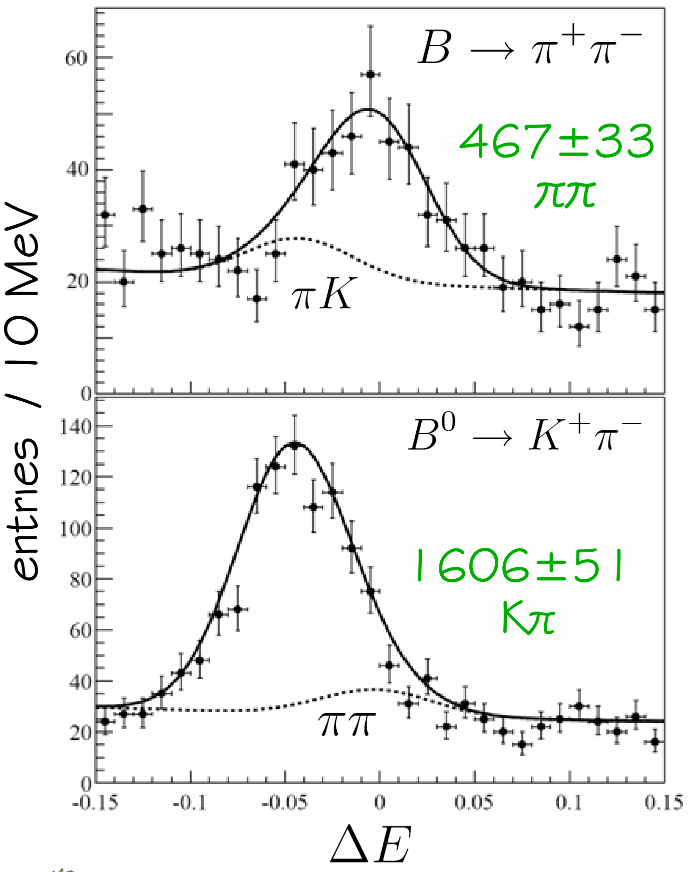
CLEO, 1998 : observation of a "large" rate of $B \to K^+\pi^-$



- penguin contribution is important
- it may also contribute to $B \to \pi^+\pi^-$



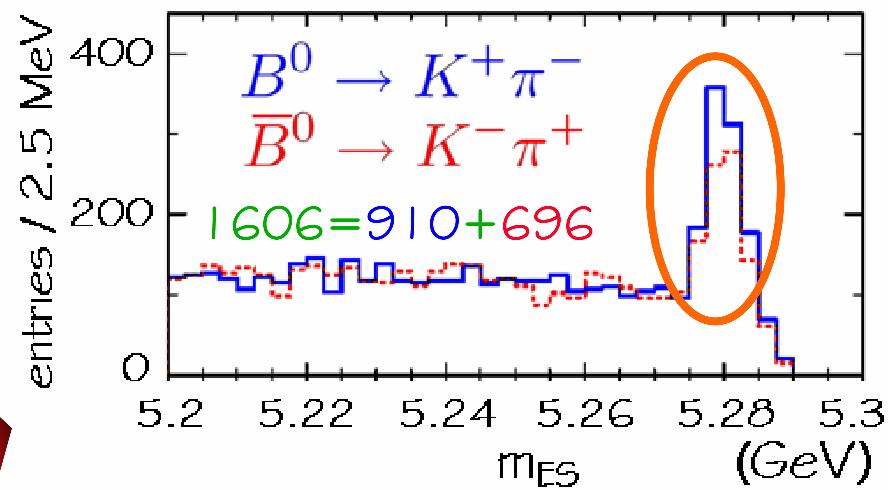
Penguins at Work



$$\frac{\mathrm{Br}(B \to K\pi)}{\mathrm{Br}(B \to \pi\pi)} \sim 4$$

based on 227M B-meson pairs

BABAR, 2004:
Observation of Direct *CP* Violation



$$\mathcal{A}_{K\pi} = -0.133 \pm 0.030 \pm 0.009$$

(a 4.2 sigma effect)

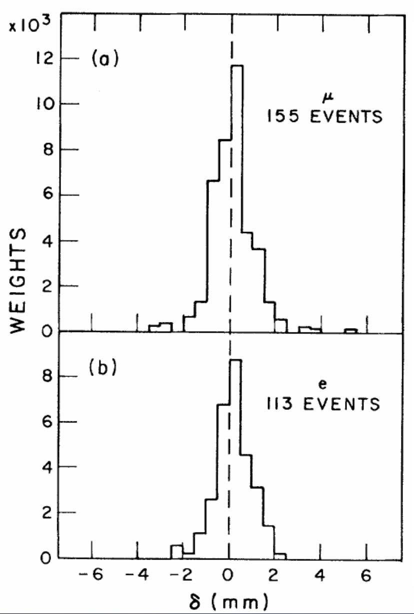
Spectacular manifestation of <u>tree-penguin interference</u>

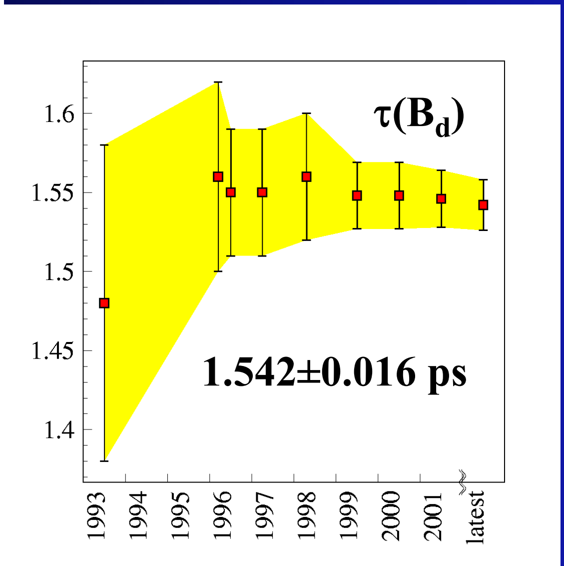
One can not ignore penguin amplitudes in $B \to \pi\pi$!

Flavor Oscillations

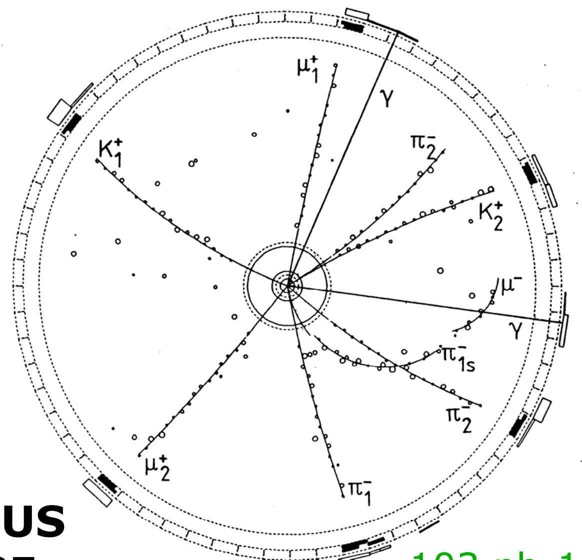
B Lifetime & BB Mixing

MAC-MARKII, 1982 :
long lifetime of B mesons



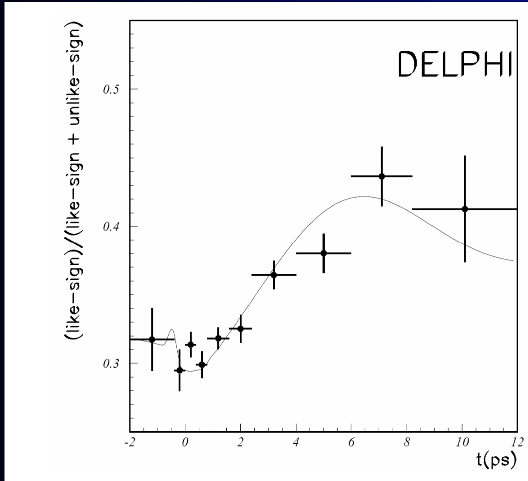


ARGUS, 1987: Observation BB mixing
(~17% of like-sign di-lepton events)



ARGUS
1987
$\chi_d = 0.17 \pm 0.05$

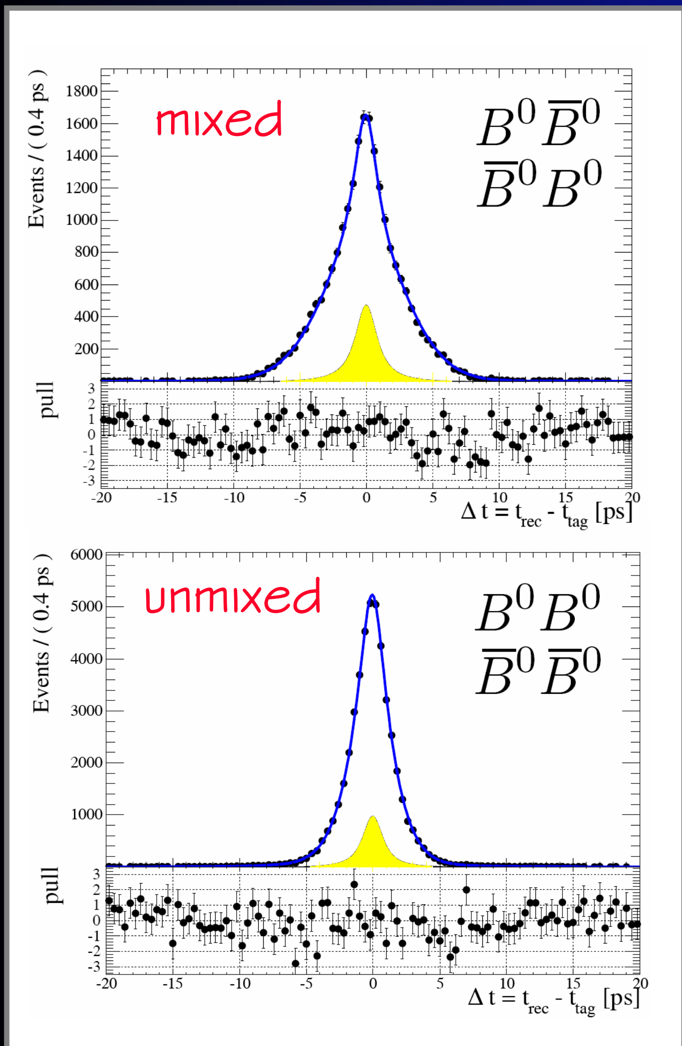
103 pb-1
100,000 B pairs

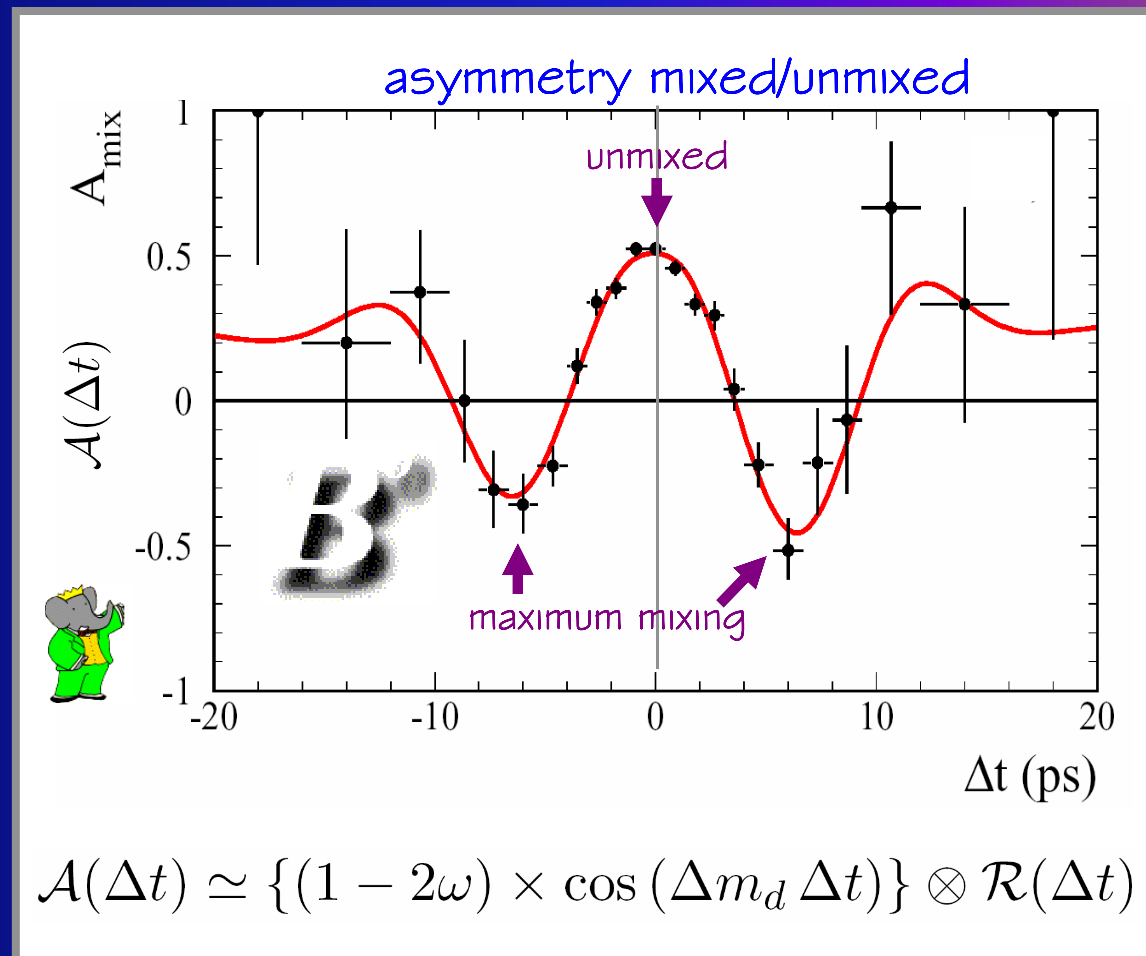


Boom of B Physics at LEP around 1994

- silicon vertex detectors
  → time-dependent analyses
- particle identification
  → exclusive & inclusive reconstruction

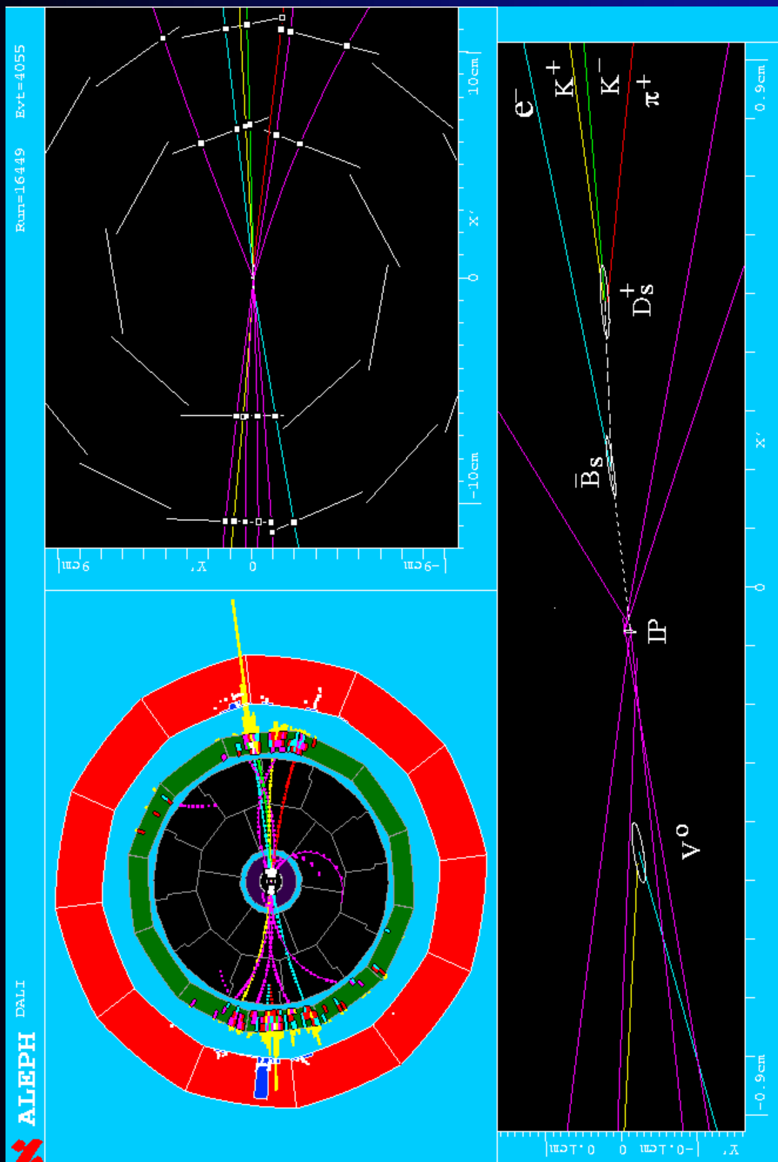
Beauty Oscillations



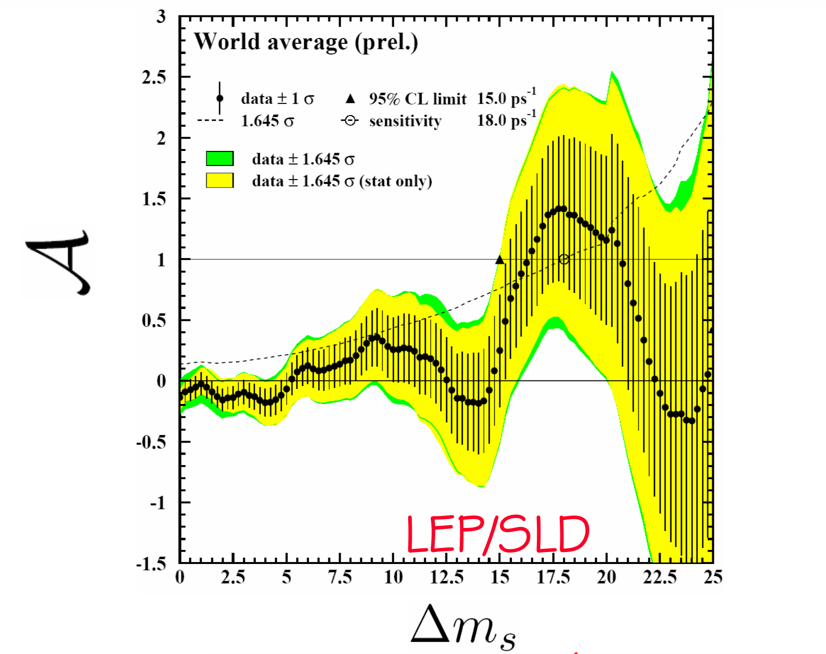


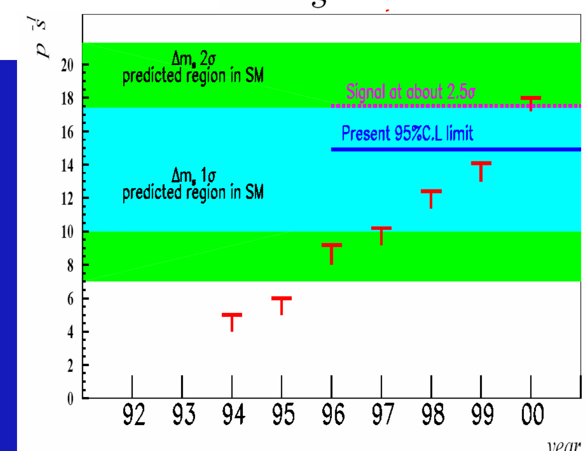
½ period ~ 6 ps
~ 4 B-meson lifetimes

Limit on the Bs Oscillations



$$\mathcal{P}(B_s \rightarrow \overline{B}_s) = \frac{e^{-t/\tau_{B_s}}}{\tau_{B_s}} \{ 1 - \mathcal{A} \cos(\Delta m_s t) \}$$





evolution of the limit

CP Violation in the B System

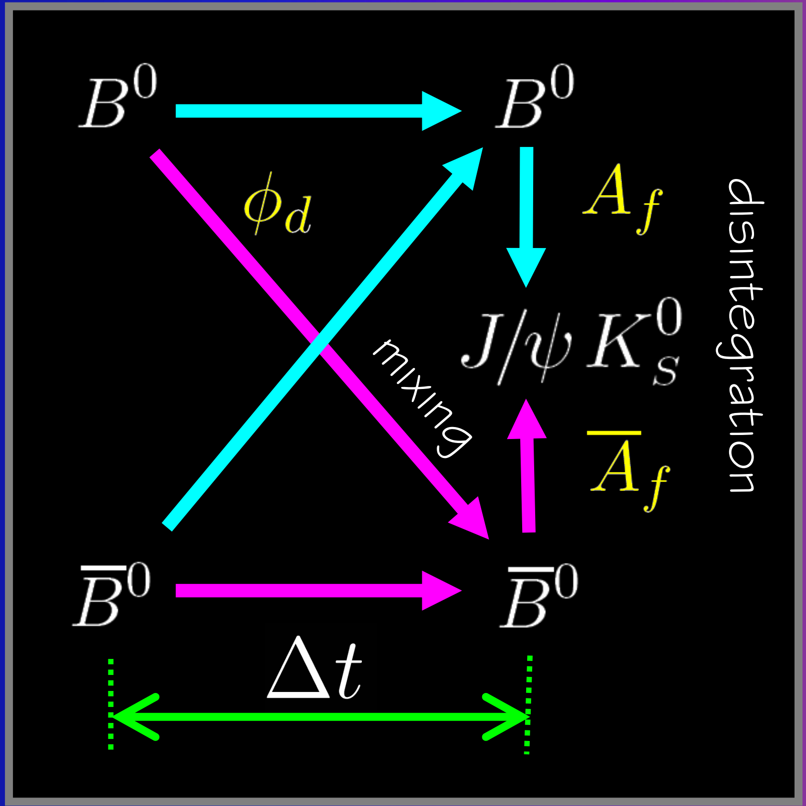
Prediction of Large CP Violation

1975, Pais & Treiman:
expect small CP violation effects in Heavy Flavors (charm and beauty)
(They were only considering CP violation in flavor mixing)

1981, Bigi, Carter & Sanda:
prediction of large CP violation
in interference in B decay to J/ψ Ks
with or without mixing;
possibility of measuring sin2β
with small uncertainty

Need to measure time evolution:
impossible at symmetric Υ(4S) machine
(B mesons travel only ~20 microns in 1 ps)

1987, P. Oddone & al:
- energy-asymmetric Υ(4S) machine
  → measure of Δt
- ultra high luminosity
  → probe rare decays



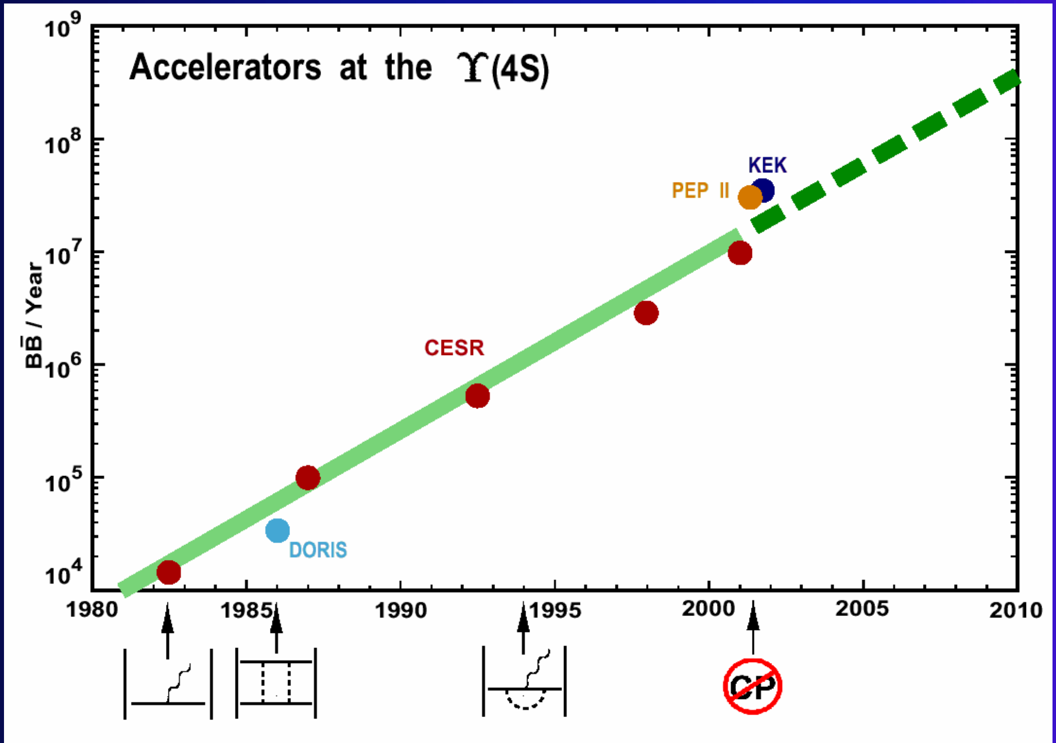
Accelerators at the Υ(4S)

First-generation at the Υ(4S)

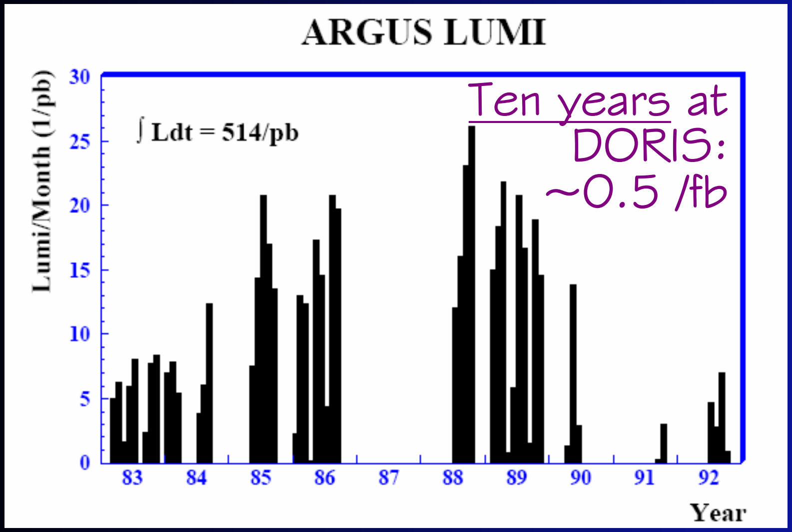
- CESR at Cornell (US), CLEO detector(s) (1980 → 2002)
- DORIS at DESY (Germany), ARGUS detector (1982 → 1992)

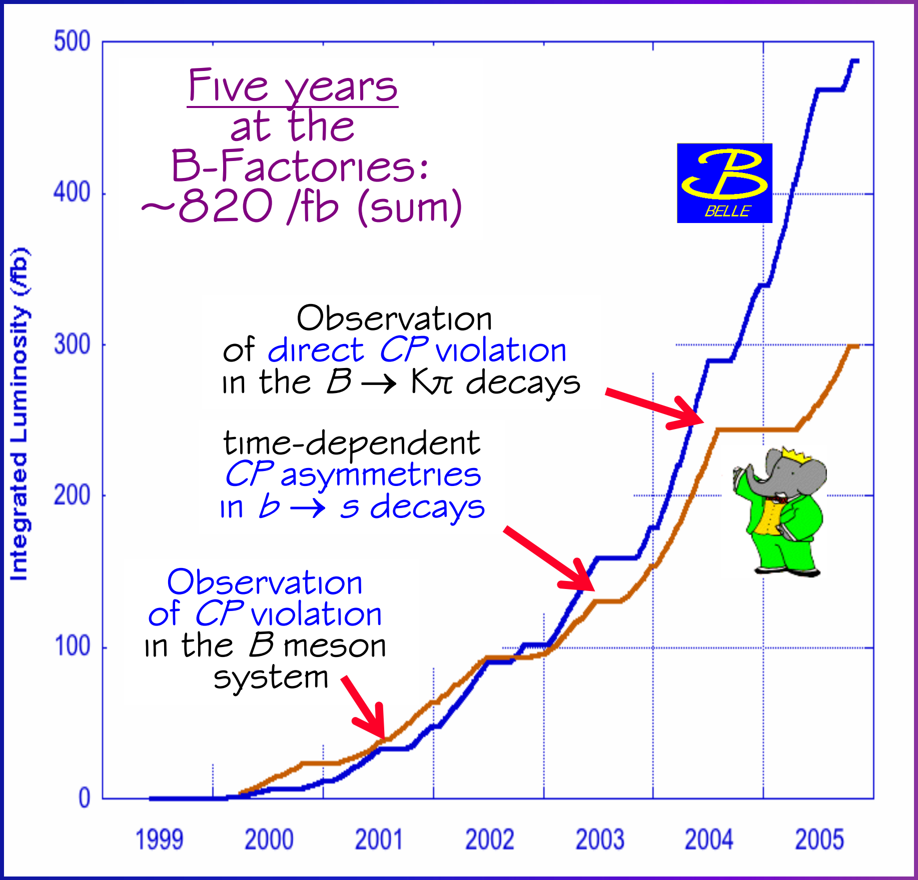
Energy-asymmetric B-Factories

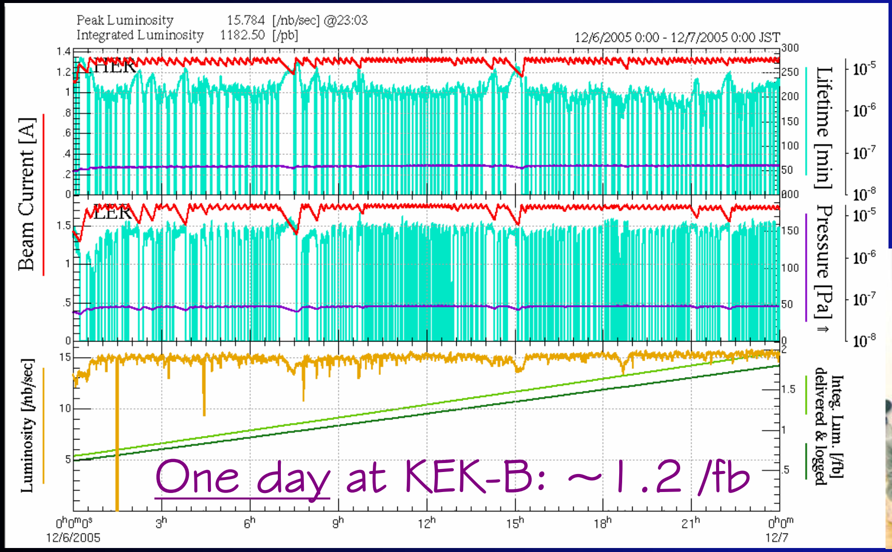
- KEK-B at KEK (Japan), BELLE detector (since 2000)
- PEP-II at SLAC (US), BABAR detector (since 2000)



High Luminosity at B Factories

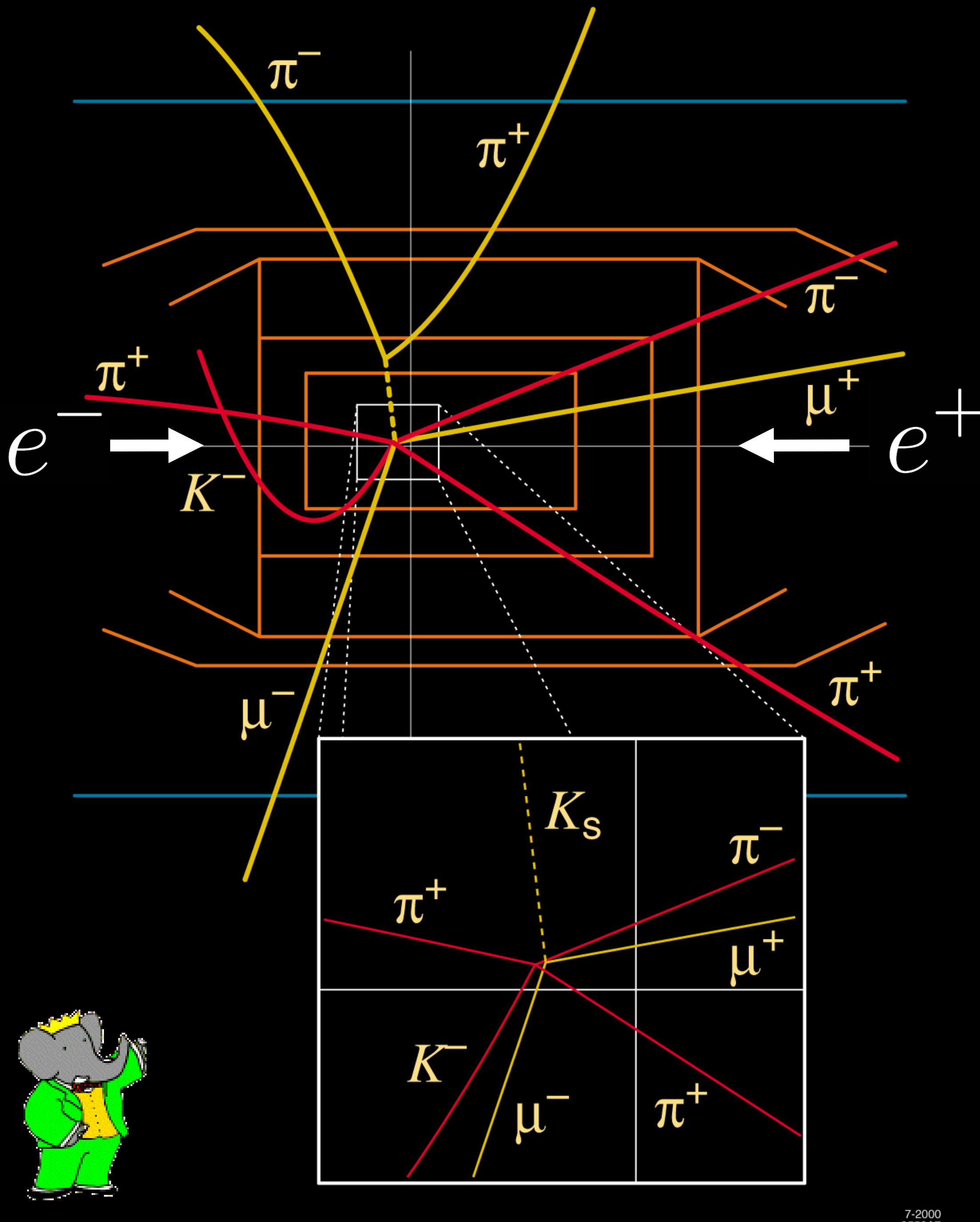




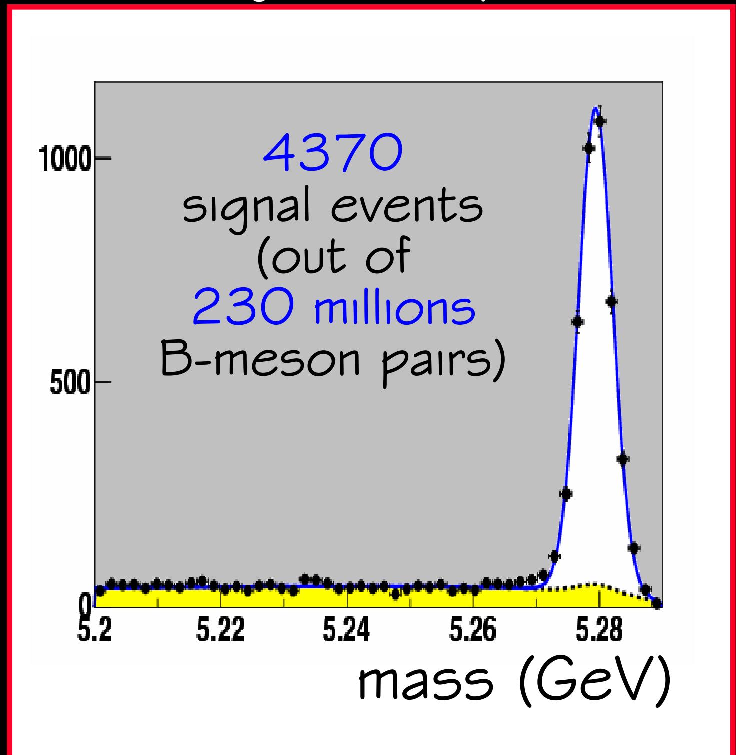


November 2005 : more than 500 /fb delivered to Belle!

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

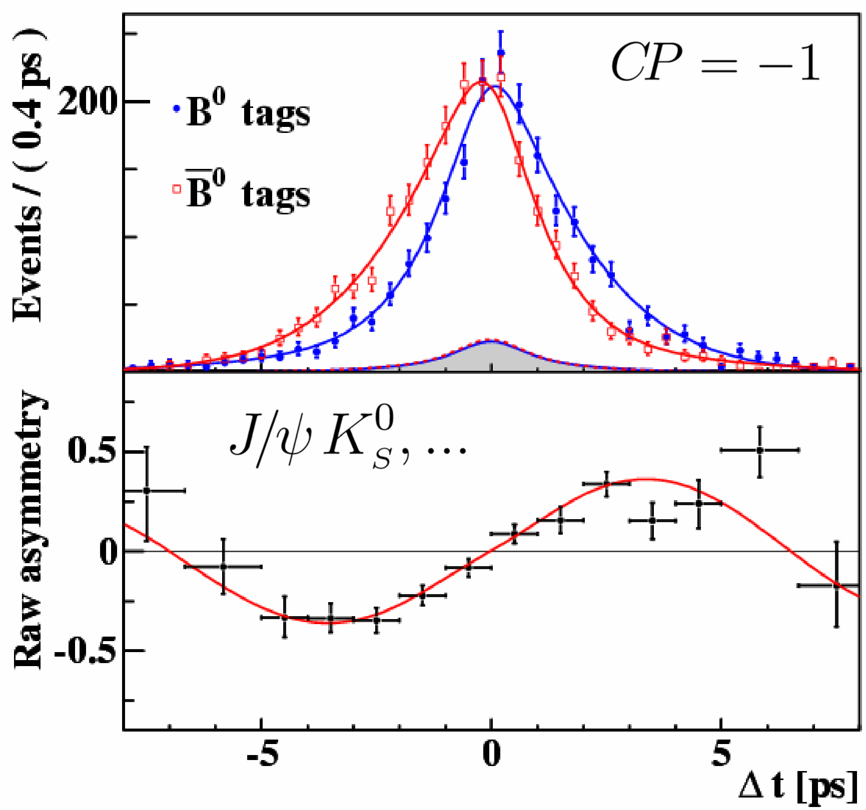


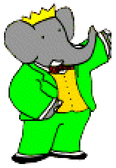
signal sample



Precision Measurement of sin2β

$$\mathcal{A}(\Delta t) \simeq \{(1-2\omega) \times \sin 2\beta \times \sin(\Delta m_d \Delta t)\} \otimes \mathcal{R}(\Delta t)$$

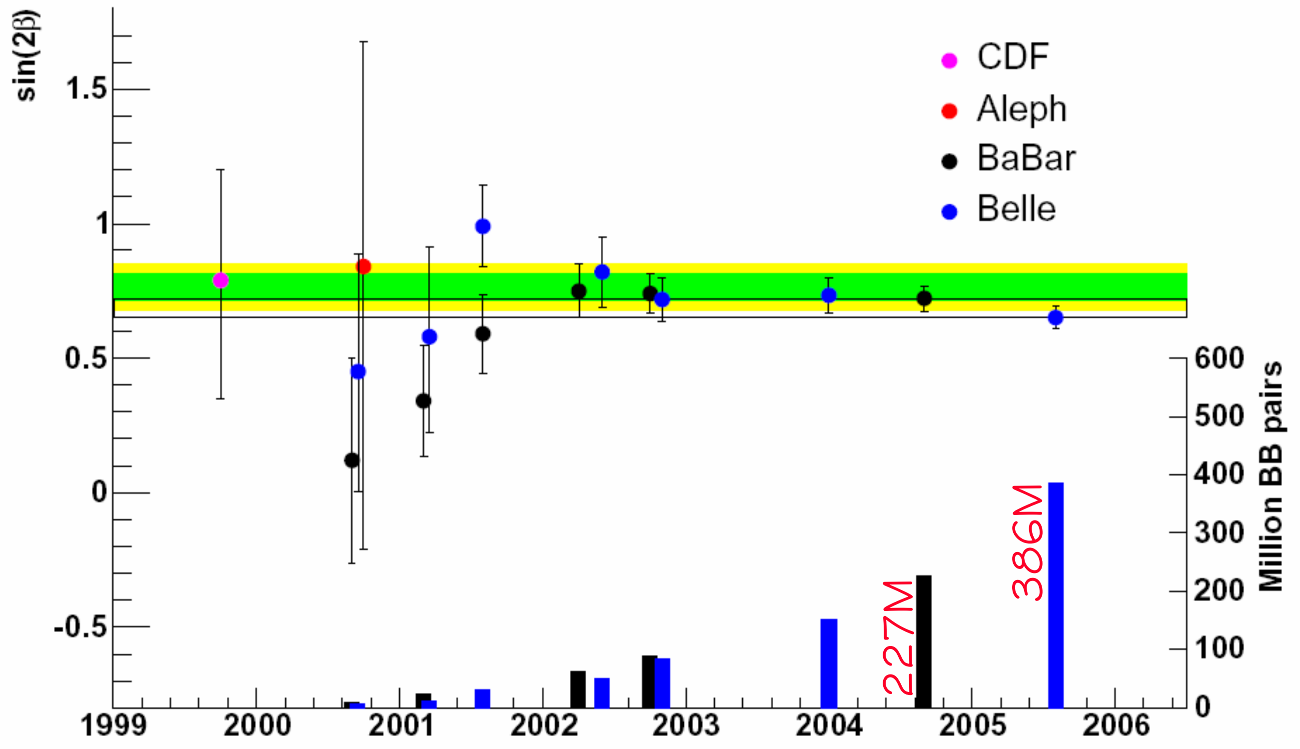




BABAR $\sin 2\beta = 0.722 \pm 0.040\,(\mathrm{stat}) \pm 0.023\,(\mathrm{syst})$

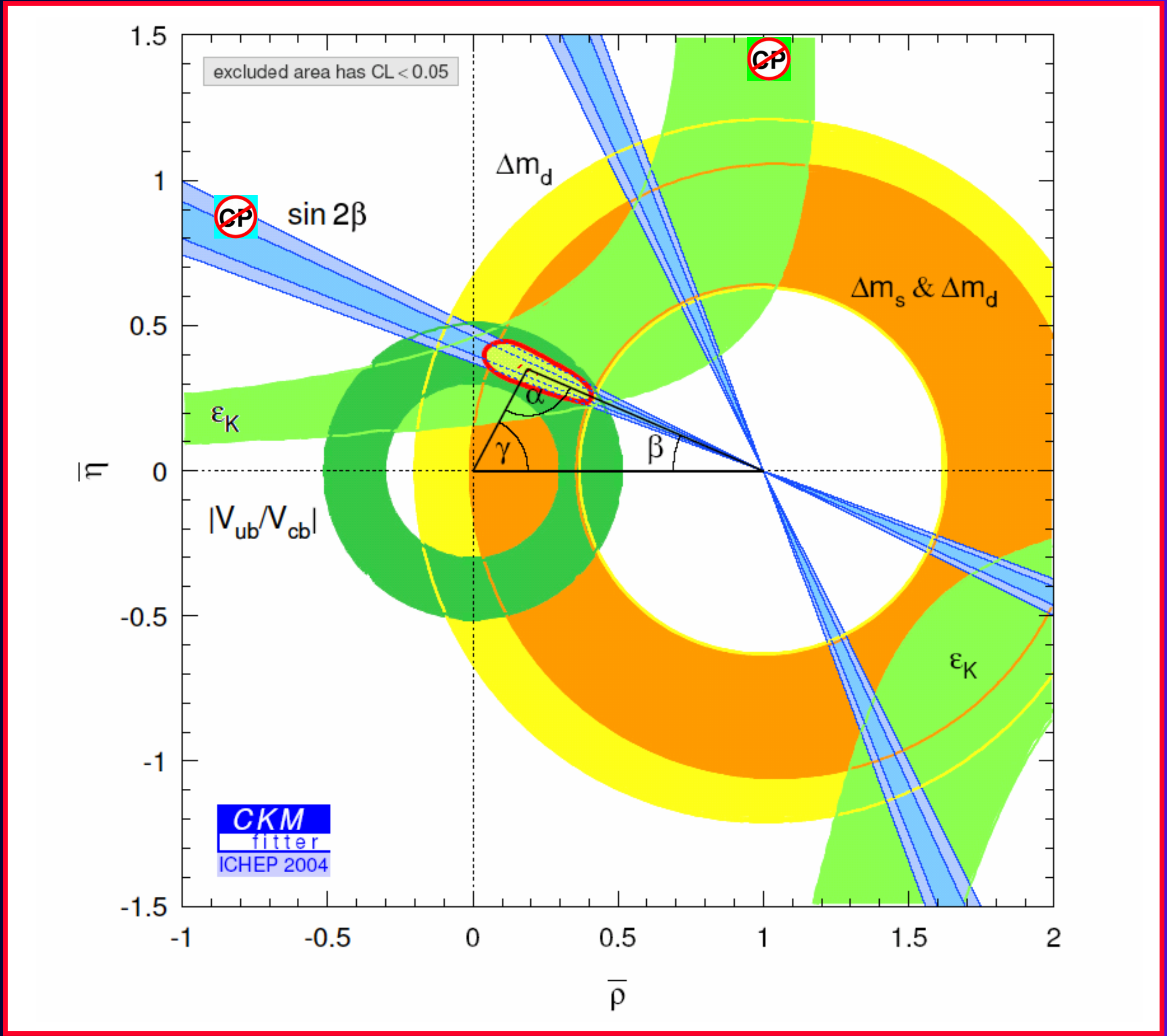
PRL 94, 161803 (2005), (hep-ex/0408127)

Evolution of sin2β measurements



$$\textit{BABAR} \quad \sin 2\beta = 0.722 \pm 0.040\,(\mathrm{stat}) \pm 0.023\,(\mathrm{syst})$$
$$\text{Belle} \quad \sin 2\beta = 0.652 \pm 0.039\,(\mathrm{stat}) \pm 0.020\,(\mathrm{syst})$$

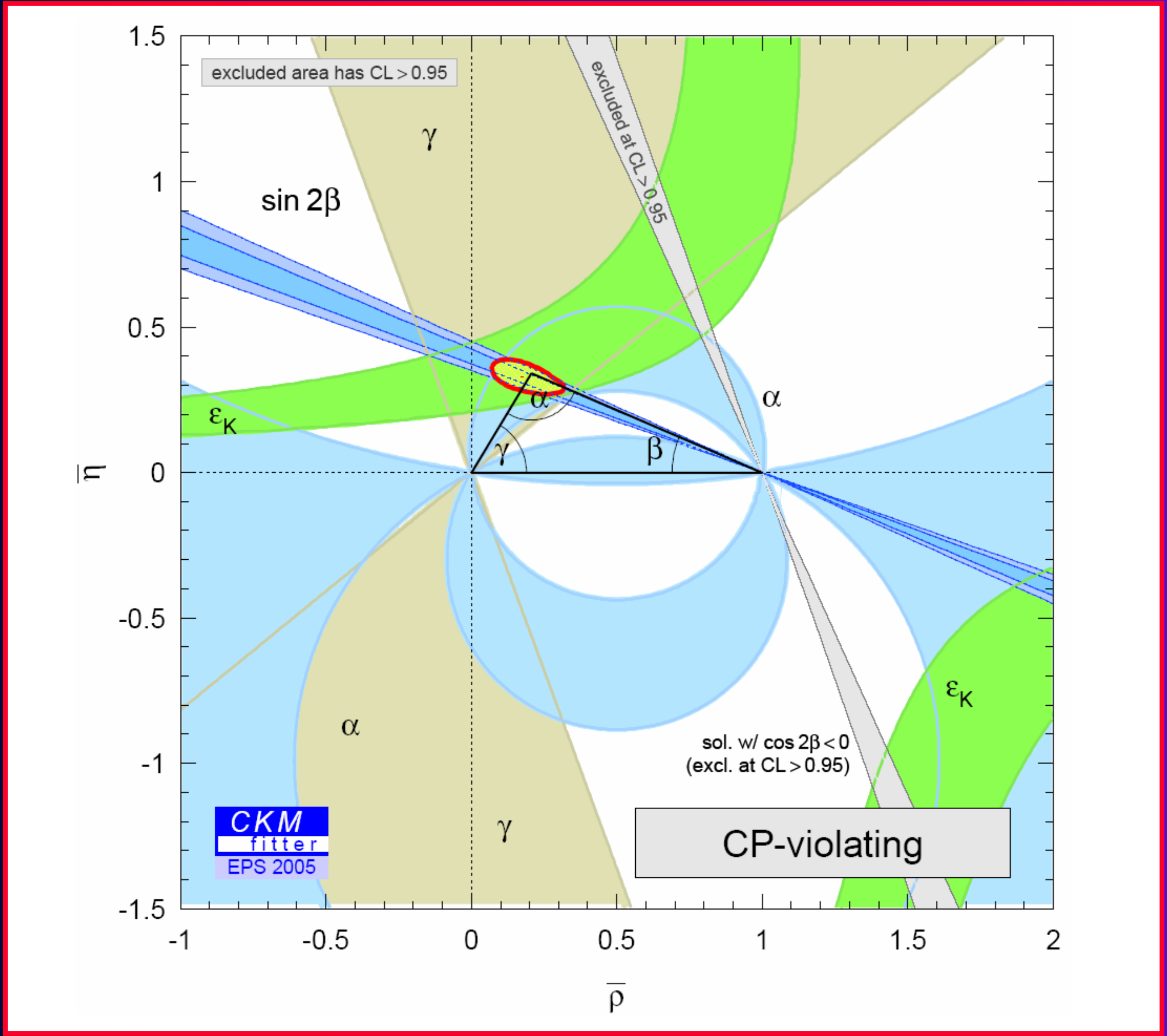
Precision Test of the Standard Model



BABAR+BELLE
(2004)

A. Höcker *et al.*

A New Era for CP Violation



2005: Apex of the Unitarity Triangle with <u>CP-violating</u> quantities only!

40 Years of Heavy Flavors and CP Violation

Heavy Flavors: study of the three generations of quarks & leptons and of the transitions between them

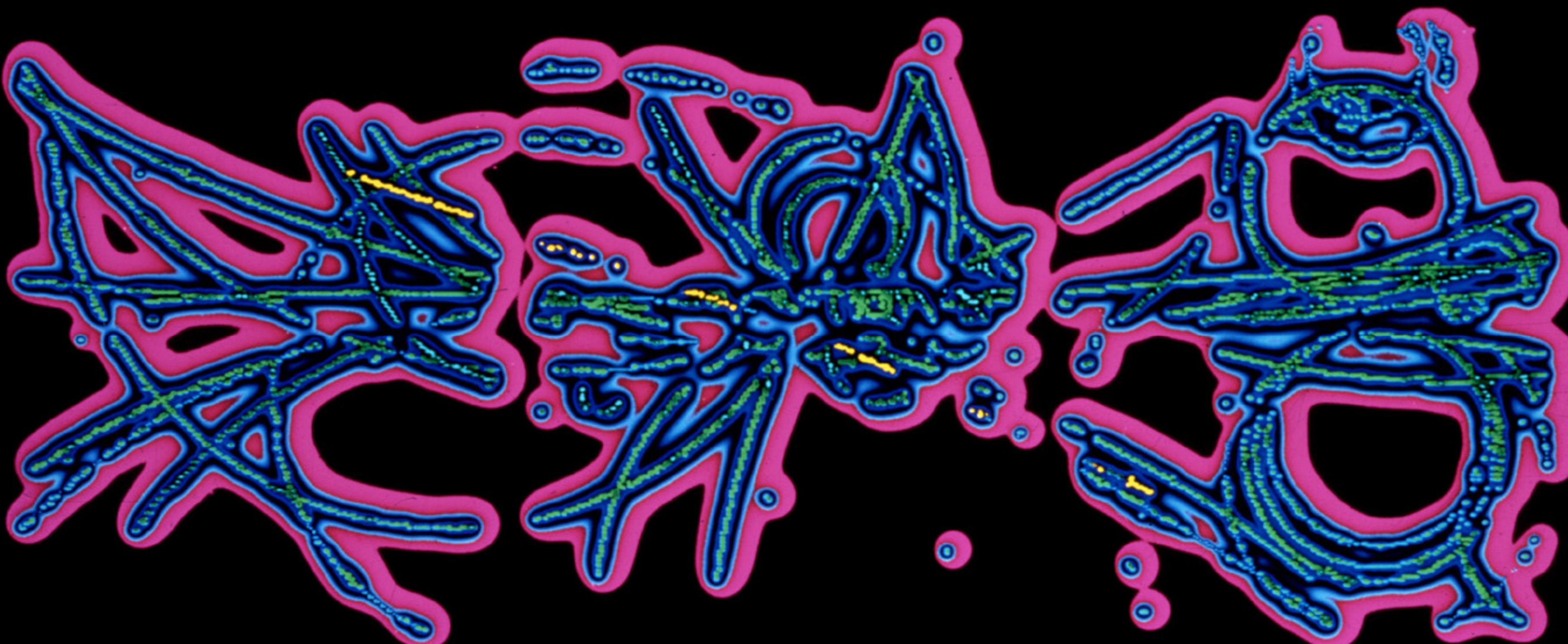
One of the pillars of the Standard Model of particle physics

Fundamental questions:

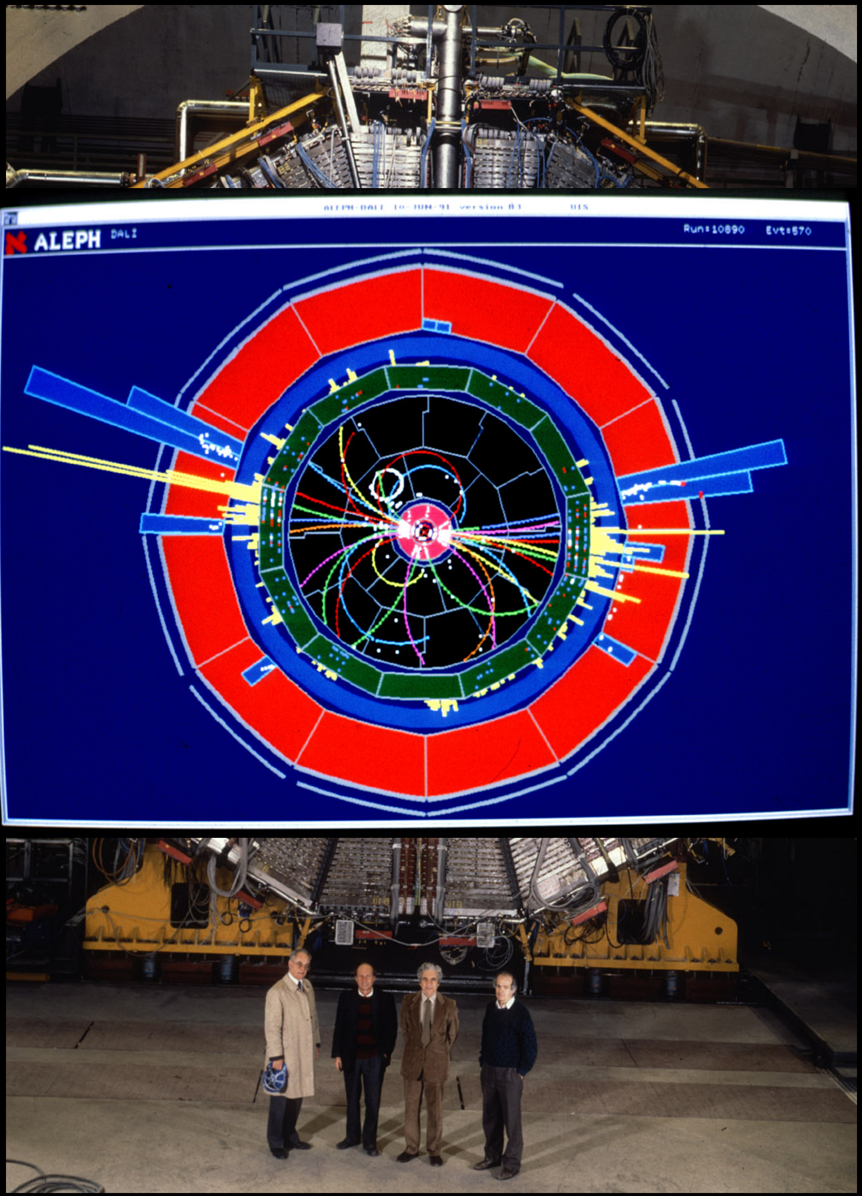
- Why three generations of quarks & leptons?
- Why is CP symmetry violated in the quark sector?
- How is flavor affected the physics beyond the Standard Model?
- What is the connection with the cosmic asymmetry?

In 40 years, a lot has been learned on the phenomenology of Heavy Flavor Physics and CP violation…
… expect much more in the coming years on these fascinating subjects!

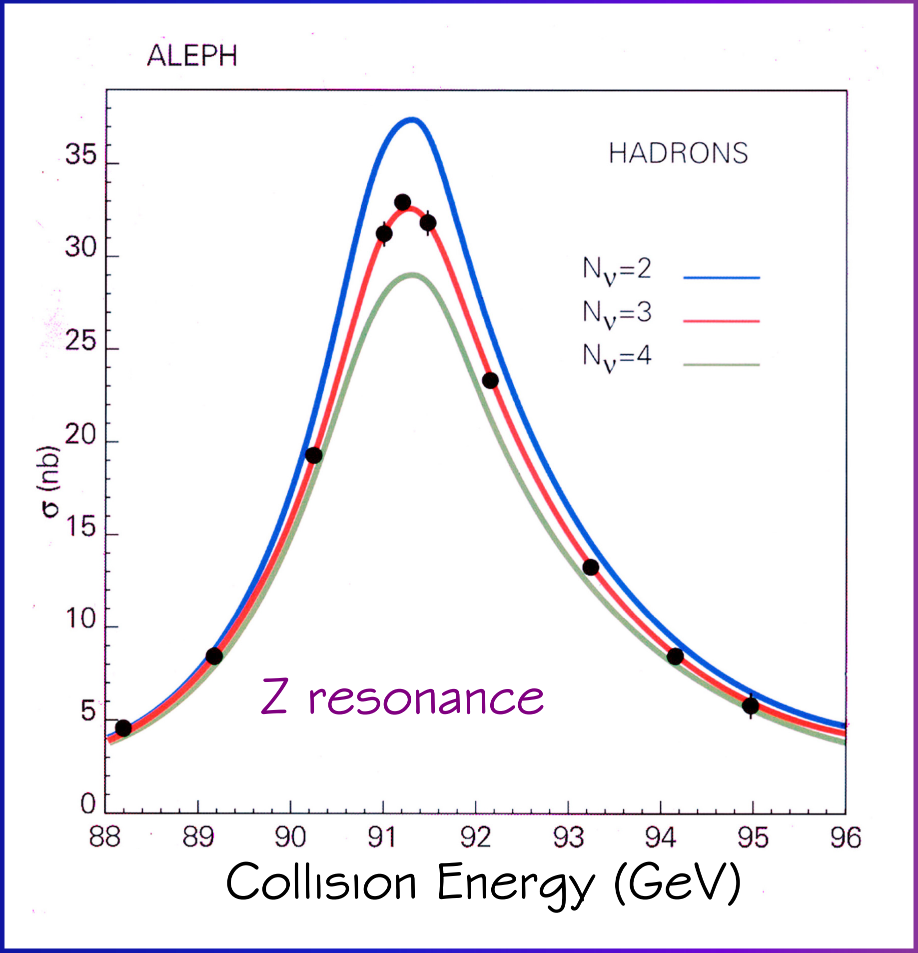
- Today : BABAR & BELLE (also CLEO-c, CDF & D0,…)
- Tomorrow : LHCb (CERN, 2007+)
- Longer term : Study of CP Violation in the neutrino sector?



Three Families of Light Neutrinos



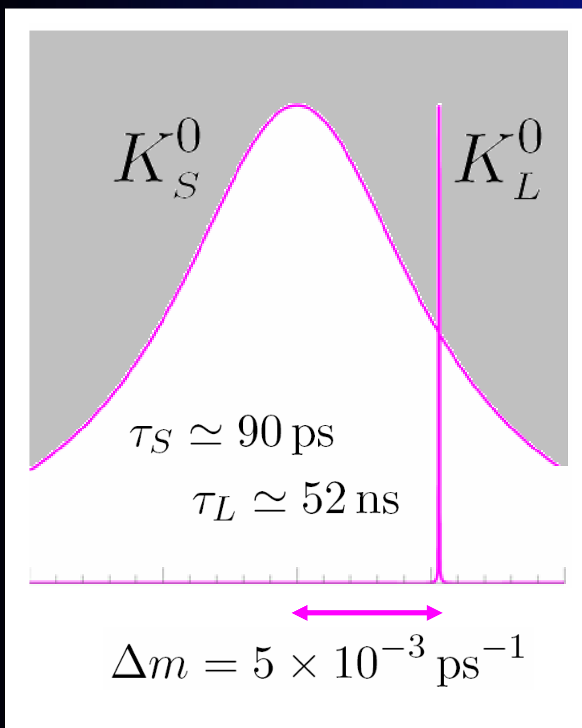
LEP - I (CERN, 1989-94)
ALEPH, DELPHI, L3, OPAL
experiments



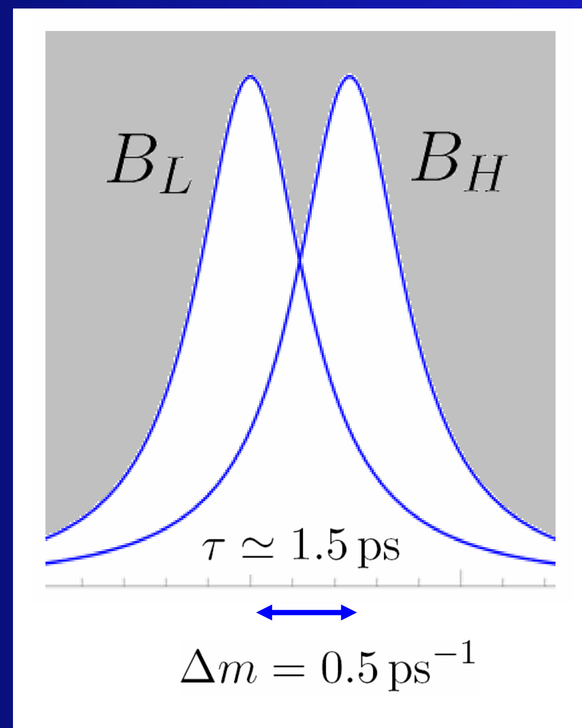
Flavor Oscillations

Three very different situations:

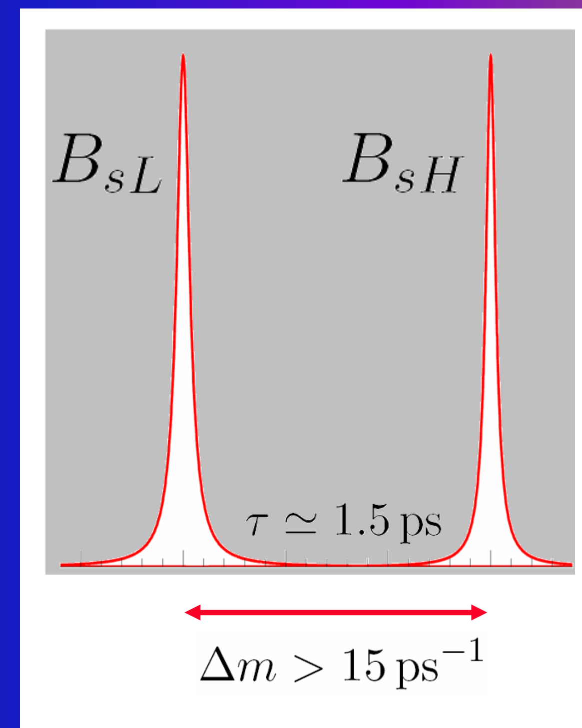
Kaon system



B-meson system

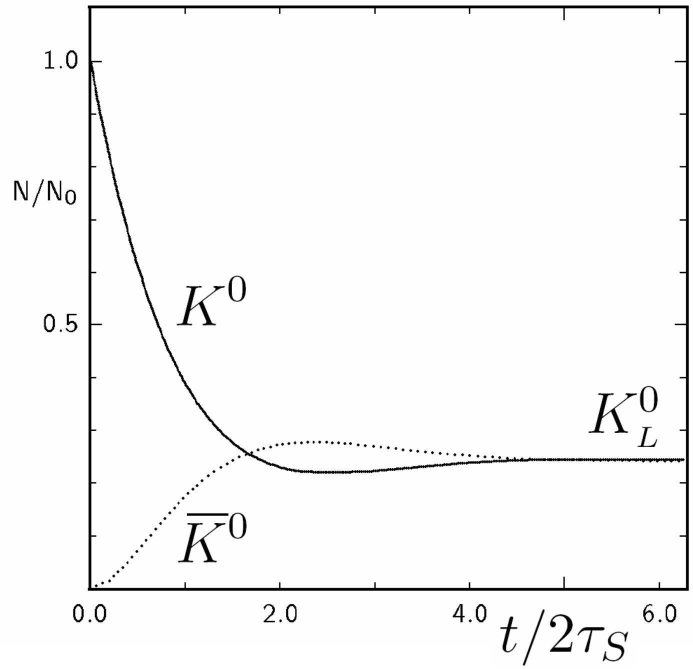


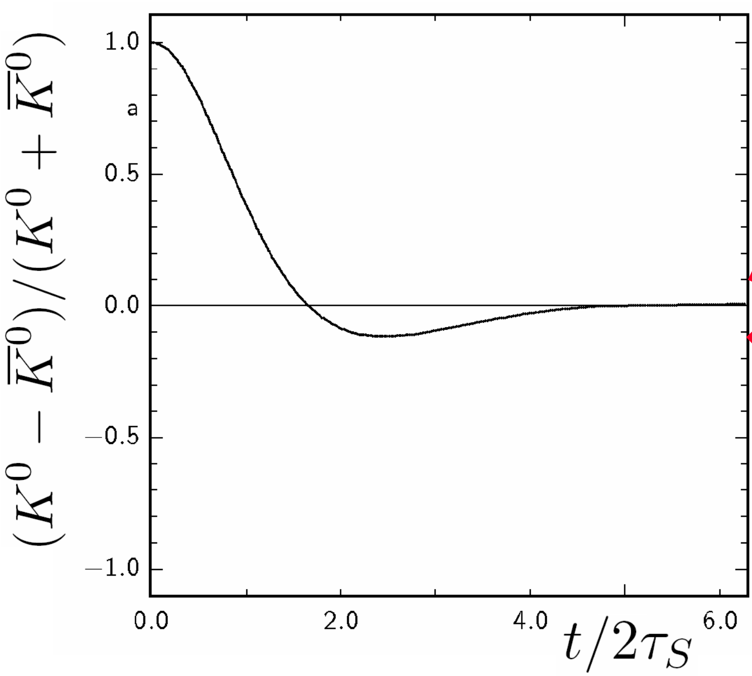
Bs-meson system

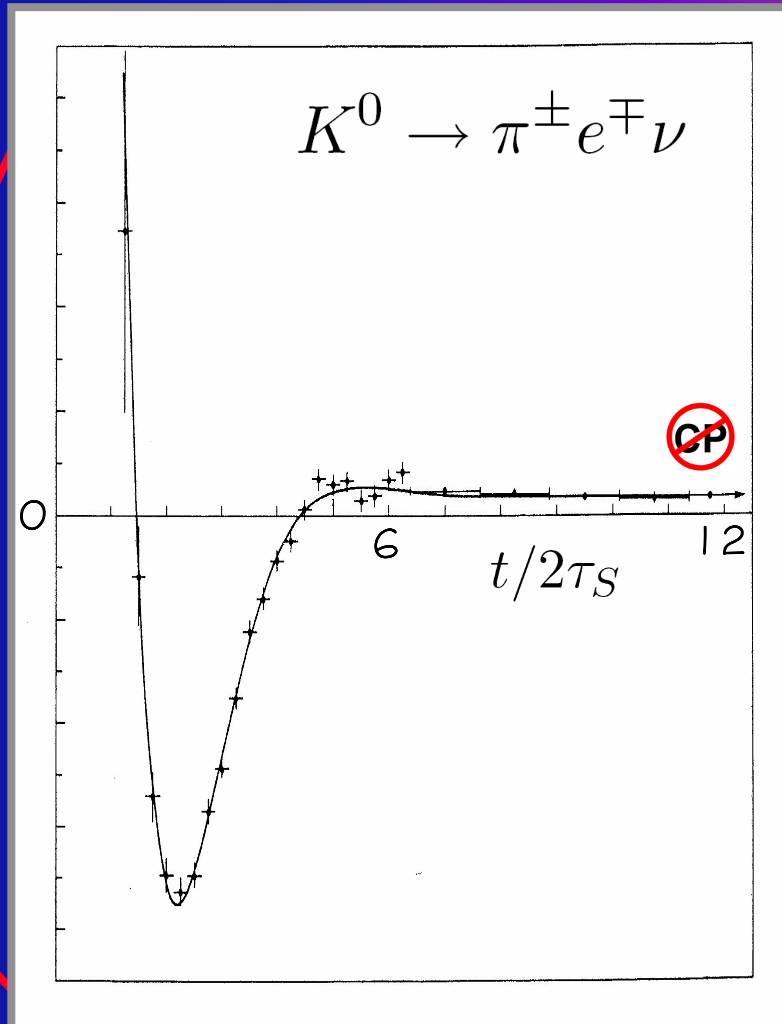


$\Delta m = 2\pi \times$ frequency of flavor oscillations ($1\,\text{ps}^{-1} \rightarrow 160$ GHz)

Neutral Kaon Semileptonic Asymmetry

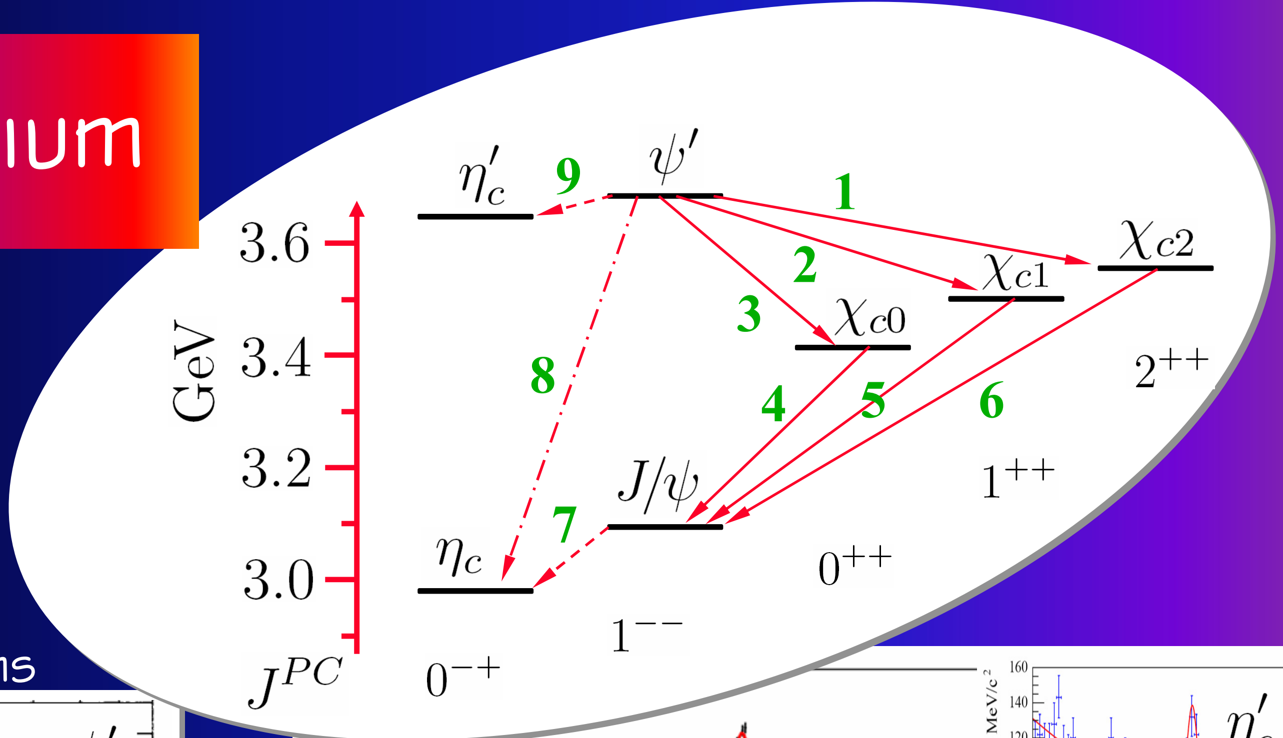




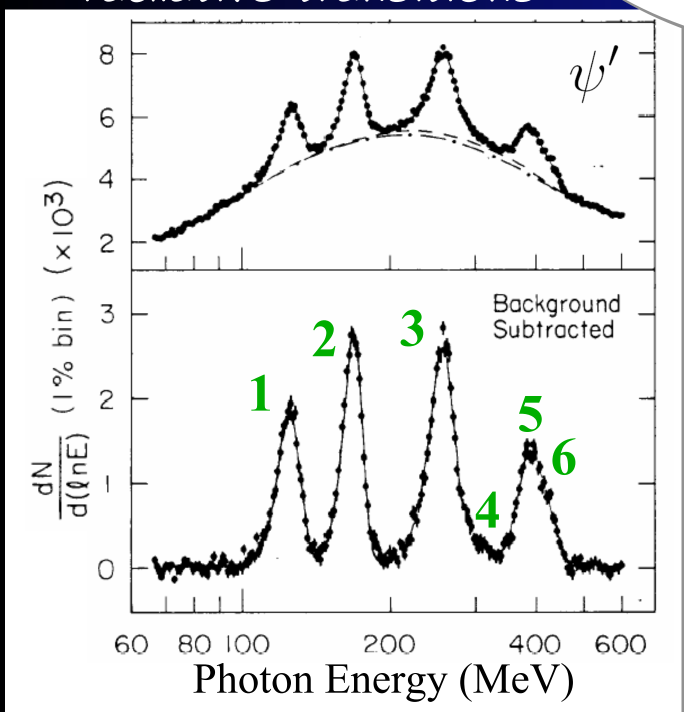


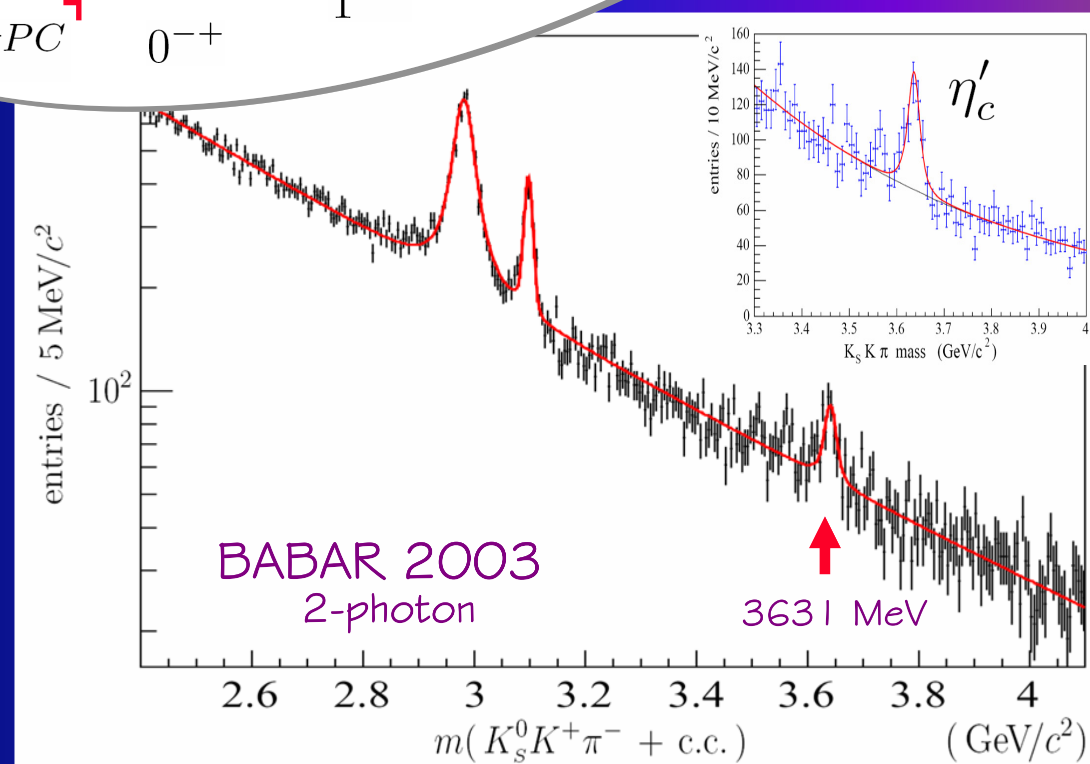
Gjesdal et al. (CERN, 1974)

Charmonium

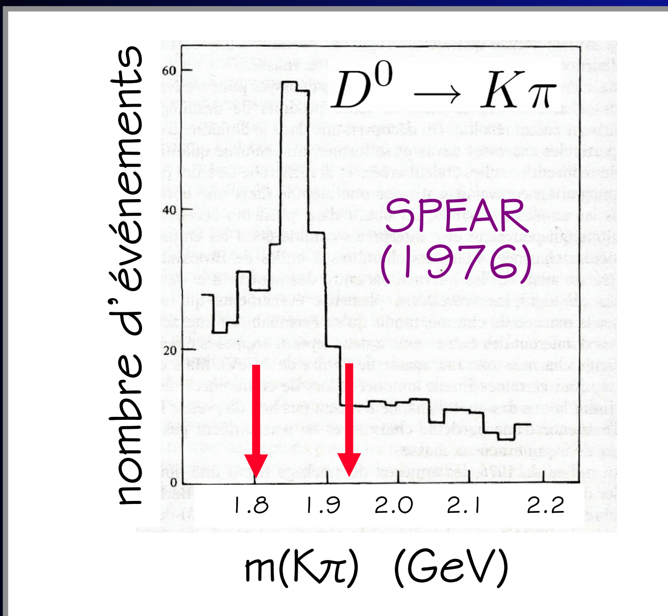


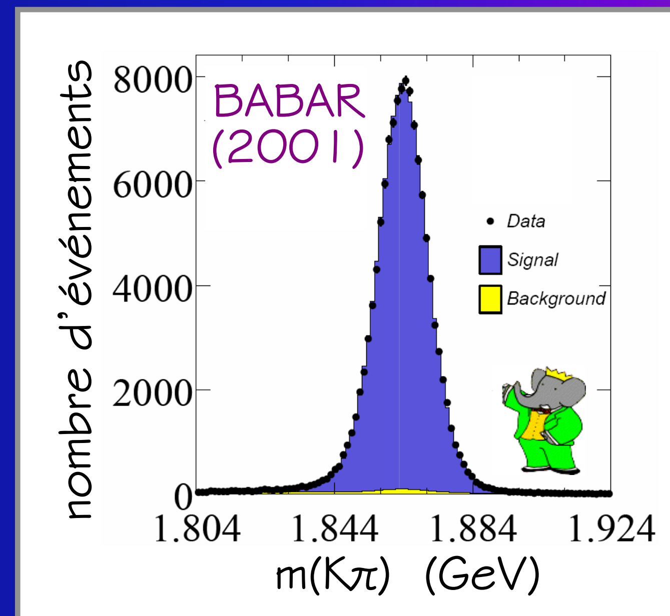
Crystal Ball at SPEAR radiative transitions





25 Years of Progress in Particle Physics



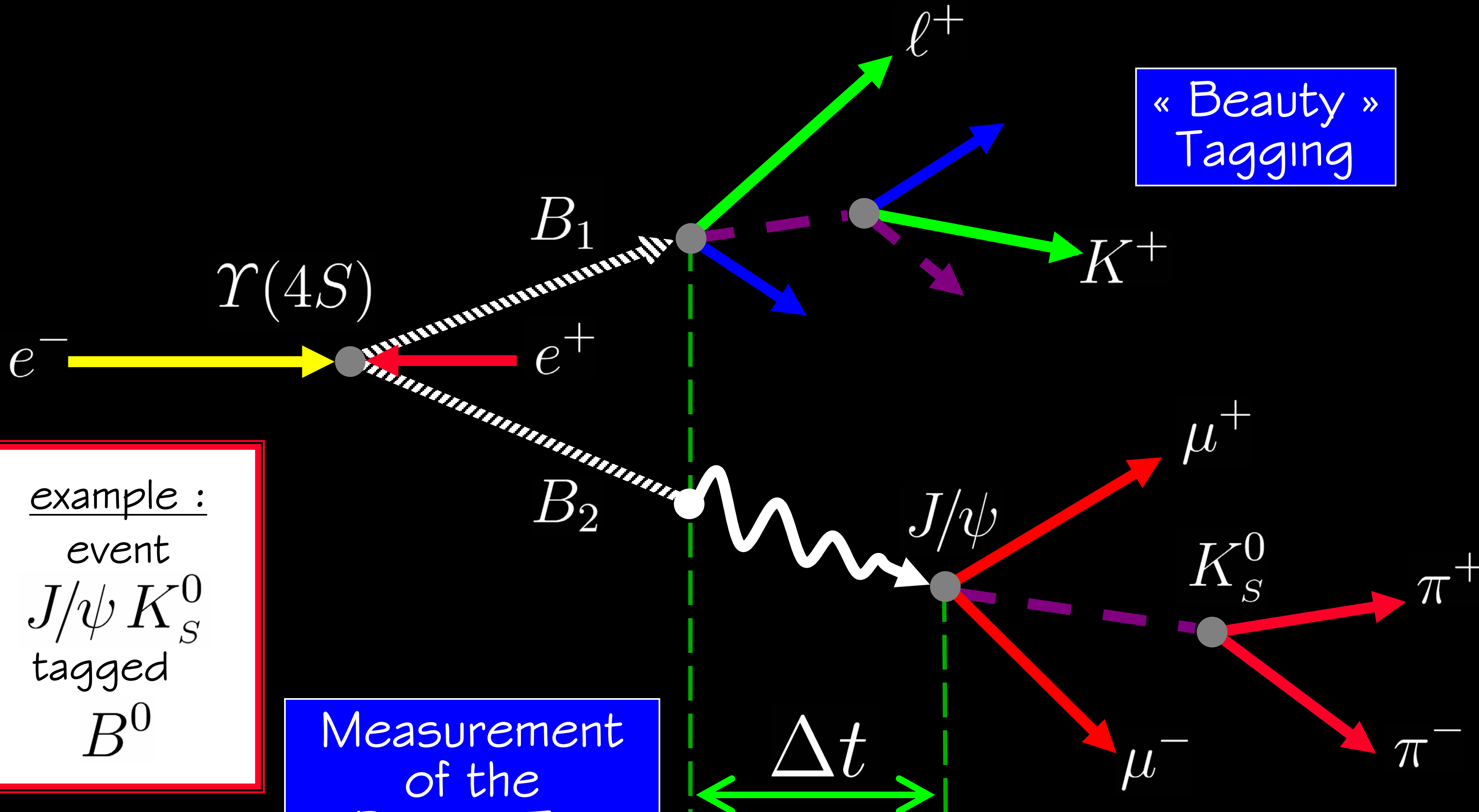


1976 : discovery of
the charmed meson D-zero
at SPEAR

2001 : D-zero signal
at BABAR

- thousands of events
- excellent mass resolution
- no background

CP Analysis at B Factories



« Beauty » Tagging

example :

event

$J/\psi\, K_S^0$

tagged

B^0

Measurement of the « Proper Time Différence »

Complete « Reconstruction » of the B-Meson