Flavour Physics Experiments

School on Flavour Physics
Centro de Ciencias de Benasque
"Pedro Pascual"

Benasque, Spain, July 14-16, 2008

Tatsuya Nakada
(tatsuya.nakada@cern.ch)
EPFL

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Contents

- Introduction and history
- Flavour mixing and oscillations
- …

Introduction and history

Why Flavour Physics?

What is on the moon?

What is on the moon?

Of course going there...

What is on the moon?

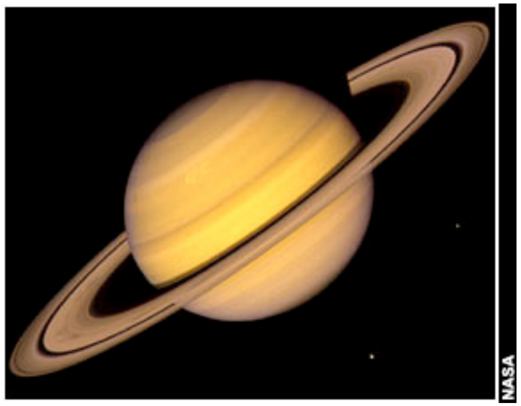
Of course going there...

But you can study a lot from here before

What is on the moon?

Of course going there...

But you can study a lot from here before

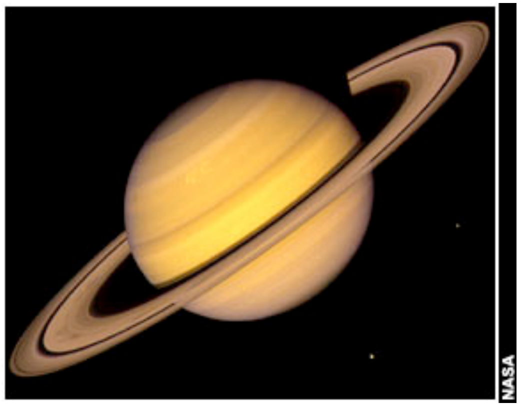


And may be finding something new?

What is on the moon?

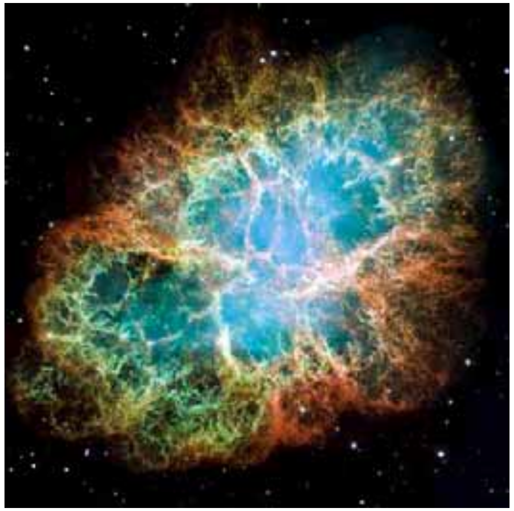
Of course going there...

But you can study a lot from here before



And may be finding something new?

Instruments can be improved and



We see far beyond the direct reach...

Flavour Physics

Excellent track record to probe high energy scale

Start with Isospin (Heisenberg)...

→ p and n are the doublets under SU(2)

similarly π^+, π^0 and π^- are the triplets under O(3)

Flavour Physics

Excellent track record to probe high energy scale

Start with Isospin (Heisenberg)...

$\rightarrow$ p and n are the doublets under SU(2)

similarly π^+, π^0 and π^- are the triplets under O(3)

"Strangeness" played a role in establishing

the concept of flavour quantum numbers

"quark" in early 1960's

(Gell-Mann, Ne'eman, Han-Nambu, Nishijima, Sakata, Zweig, etc.)

SU(3) flavour symmetry: (u, d, s)$\rightarrow\Omega^-$ prediction,

discovered in 1964, Barmes et al.

Flavour Physics

Excellent track record to probe high energy scale

Particle (K^0)-antiparticle ($\overline{K}^0$) mixing:

PHYSICAL REVIEW VOLUME 97, NUMBER 5 MARCH 1, 1955

Behavior of Neutral Particles under Charge Conjugation

M. GELL-MANN,* *Department of Physics, Columbia University, New York, New York*

AND

A. PAIS, *Institute for Advanced Study, Princeton, New Jersey*

(Received November 1, 1954)

Some properties are discussed of the θ^0, a heavy boson that is known to decay by the process $\theta^0 \rightarrow \pi^+ + \pi^-$. According to certain schemes proposed for the interpretation of hyperons and K particles, the θ^0 possesses an antiparticle $\bar{\theta}^0$ distinct from itself. Some theoretical implications of this situation are discussed with special reference to charge conjugation invariance. The application of such invariance in familiar instances is surveyed in Sec. I. It is then shown in Sec. II that, within the framework of the tentative schemes under consideration, the θ^0 must be considered as a "particle mixture" exhibiting two distinct lifetimes, that each lifetime is associated with a different set of decay modes, and that no more than half of all θ^0's undergo the familiar decay into two pions. Some experimental consequences of this picture are mentioned.

$$K^0 \leftrightarrow \pi^+\pi^- \leftrightarrow \overline{K}^0 \Longrightarrow \quad K_1 = \frac{K^0 + K^0}{\sqrt{2}}, \quad K_2 = \frac{K^0 - K^0}{\sqrt{2}}$$

under C symmetry

two very different lifetimes

($\not{C} \rightarrow$ change to CP)

Observation of Long-Lived Neutral *V* Particles*

K. LANDE, E. T. BOOTH, J. IMPEDUGLIA, AND L. M. LEDERMAN,
Columbia University, New York, New York

AND

W. CHINOWSKY, *Brookhaven National Laboratory, Upton, New York*

(Received July 30, 1956)

Phys Rev Lett. 1956

cloud chamber exposure at BNL

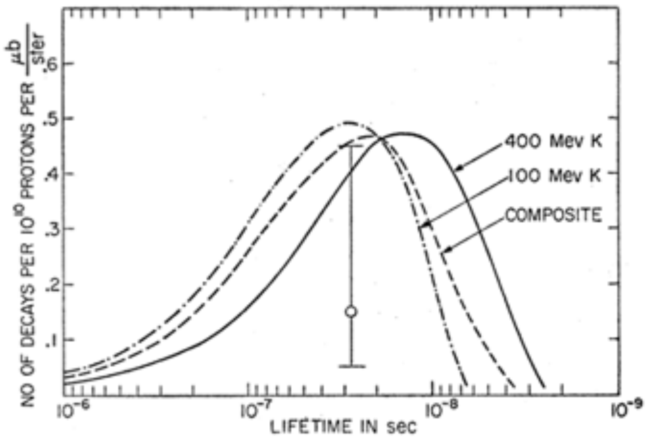


FIG. 2. Detection sensitivity for *K* mesons as function of lifetime. The composite curve is obtained with the spectra of reference 5. The point indicates the observed yield with a production cross section of ~20 μb/sterad.

lifetime for $\pi^+\pi^-$ decay already known to be ~10^{-10} sec

lifetime measurement for
3-body decays ($\pi\mu\nu$, $\pi e\nu$, $\pi^+\pi^-\pi^0$)
>10^{-9} sec

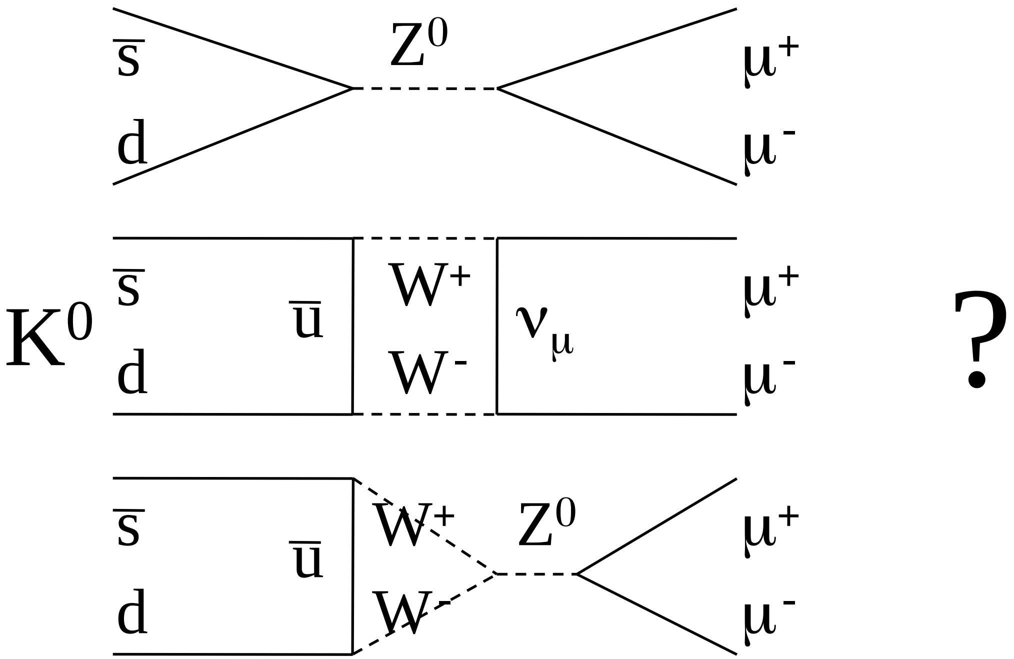
Establish two particle states: short-living, K_S, decays into 2π and long-living, K_L, decays into 3π, $\pi l\nu$: $K^0-\overline{K}^0$ mixing

Flavour Physics

Excellent track record to probe high energy scale

Particle (K^0)-antiparticle ($\overline{K}^0$) mixing: also oscillations $K^0_{t=0} \rightarrow \overline{K}^0(t)$

Very suppressed $K_L \rightarrow \mu^+\mu^-$



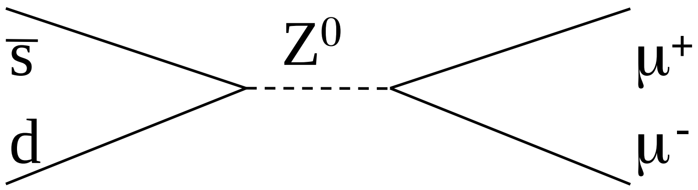
Flavour Physics

Excellent track record to probe high energy scale

Particle (K^0)-antiparticle ($\overline{K}^0$) mixing: also oscillations $K^0_{t=0} \rightarrow \overline{K}^0(t)$

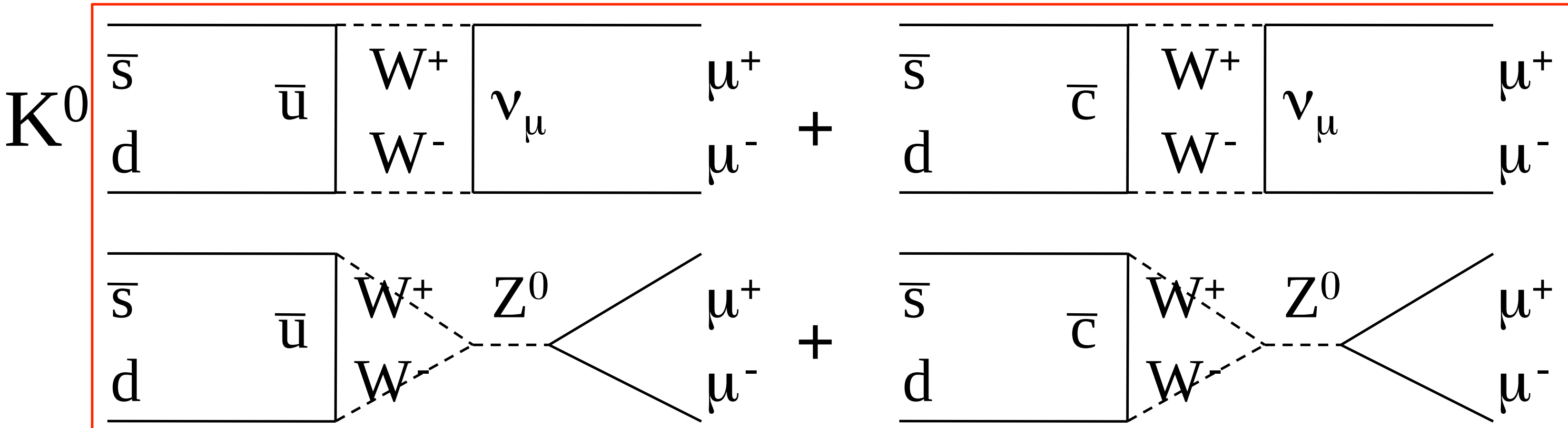
Very suppressed $K_L \rightarrow \mu^+\mu^-$ $\Rightarrow$ SU(2) doublet structure (GIM)

1970



$= 0$

$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix}$$



$= 0$ if $m_u = m_c$

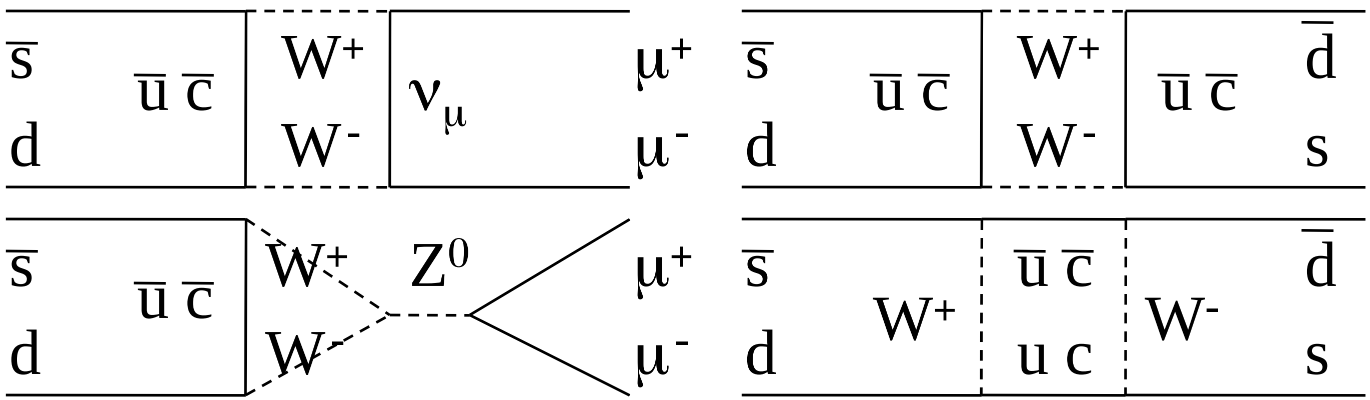
Flavour Physics

Excellent track record to probe high energy scale

Particle (K^0)-antiparticle ($\overline{K}^0$) mixing: also oscillations $K^0_{t=0} \to \overline{K}^0(t)$

Very suppressed $K_L \to \mu^+\mu^-$ $\Rightarrow$ SU(2) doublet structure (GIM)

Δm_K and $Br(K_L \to \mu^+\mu^-)$



$Br(K^0 \to \mu^+\mu^-) = F(m_c, \ldots)$ $\Delta m_K = G(m_c, \ldots)$

Gaillard and Lee, 1974

Flavour Physics

Excellent track record to probe high energy scale

Particle (K^0)-antiparticle ($\overline{K}^0$) mixing: also oscillations $K^0_{t=0} \rightarrow \overline{K}^0(t)$

Very suppressed $K_L \rightarrow \mu^+\mu^-$ $\Rightarrow$ SU(2) doublet structure (GIM)

Δm_K and $Br(K_L \rightarrow \mu^+\mu^-)$ $\Rightarrow$ charm mass ~1.5 GeV/c^2

Flavour Physics

Excellent track record to probe high energy scale

Particle (K^0)-antiparticle ($\overline{K}^0$) mixing: also oscillations $K^0_{t=0} \rightarrow \overline{K}^0(t)$

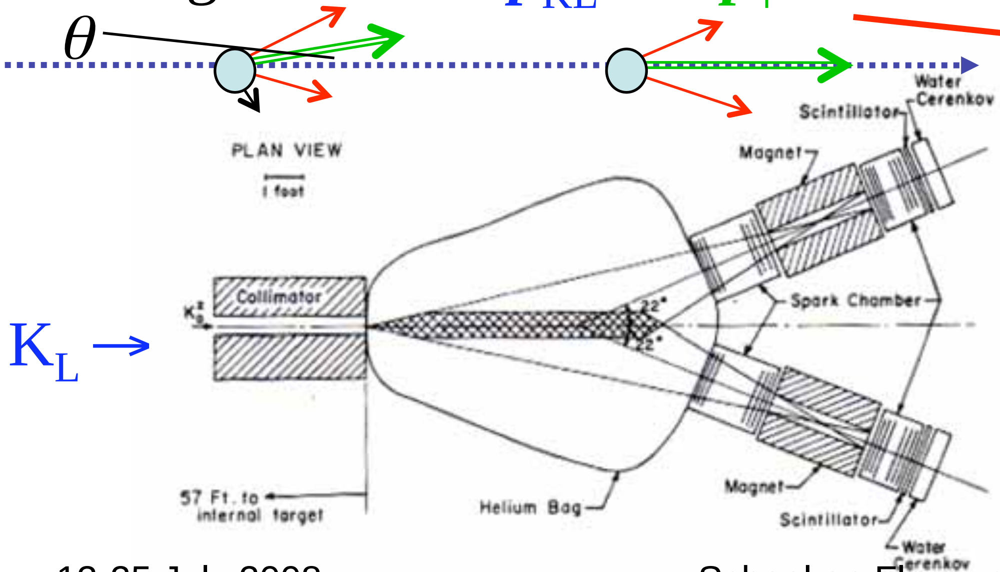
Very suppressed $K_L \rightarrow \mu^+\mu^-$ $\Rightarrow$ SU(2) doublet structure (GIM)

Δm_K and $Br(K_L \rightarrow \mu^+\mu^-)$ $\Rightarrow$ charm mass

CPV 1964, J.H. Christenson et al., $Br(K^0_L \rightarrow \pi^+\pi^-) \neq 0$

$\boldsymbol{p}_{+-} = \boldsymbol{p}_{\pi+} + \boldsymbol{p}_{\pi-}$

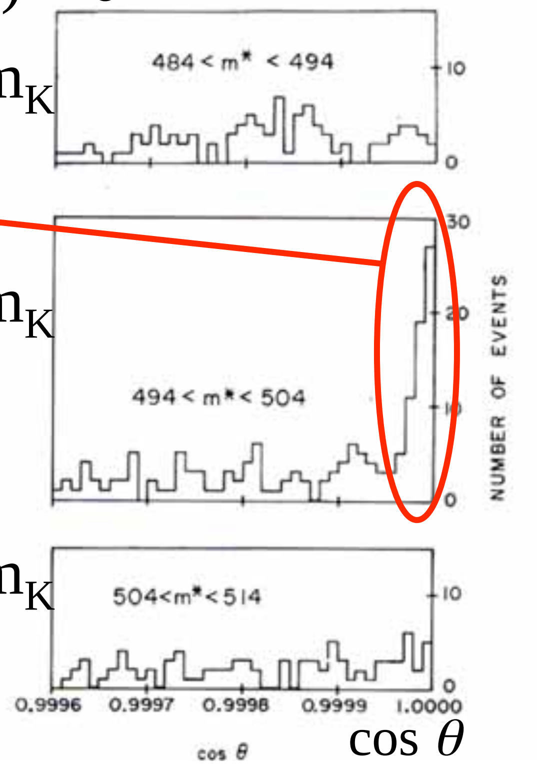
θ = angle between $\boldsymbol{p}_{KL}$ and $\boldsymbol{p}_{+-}$



$m(\pi^+\pi^-) < m_K$

$m(\pi^+\pi^-) = m_K$

$m(\pi^+\pi^-) > m_K$



$\cos\,\theta$

Flavour Physics

Excellent track record to probe high energy scale

Particle (K^0)-antiparticle ($\overline{K}^0$) mixing: also oscillations $K^0_{t=0} \rightarrow \overline{K}^0(t)$

Very suppressed $K_L \rightarrow \mu^+\mu^-$ $\Rightarrow$ SU(2) doublet structure (GIM)

Δm_K and $Br(K_L \rightarrow \mu^+\mu^-)$ $\Rightarrow$ charm mass ~1.5 GeV/c^2

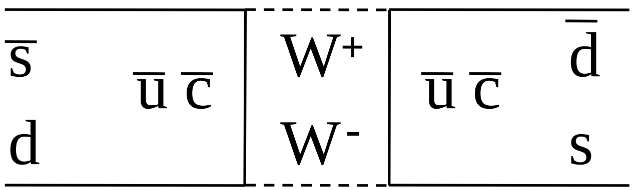
CPV 1964, J.H. Christenson et al., $Br(K^0_L \rightarrow \pi^+\pi^-) \neq 0$

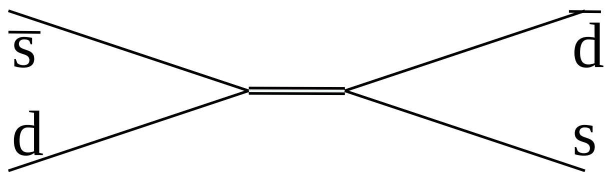
VIOLATION OF *CP* INVARIANCE AND THE POSSIBILITY OF VERY WEAK INTERACTIONS*

L. Wolfenstein
Carnegie Institute of Technology, Pittsburgh, Pennsylvania

(Received 31 August 1964)

"Superweak model", CPV only in $\Delta F = 2$ transitions





No CPV in decay amplitude, i.e. Re $\varepsilon' = 0$

Flavour Physics

an alternative proposal

Progress of Theoretical Physics, Vol. 49, No. 2, February 1973

CP-Violation in the Renormalizable Theory of Weak Interaction

Makoto KOBAYASHI and Toshihide MASKAWA

Department of Physics, Kyoto University, Kyoto

(Received September 1, 1972)

In a framework of the renormalizable theory of weak interaction, problems of CP-violation are studied. It is concluded that no realistic models of CP-violation exist in the quartet scheme without introducing any other new fields. Some possible models of CP-violation are also discussed.

Introduction of the third family
(before the charm discovery)

$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$$

complex mixing matrix

CPV starts with $\Delta F = 1$: CPV in decay amplitude possible, Re $\varepsilon' \neq 0$

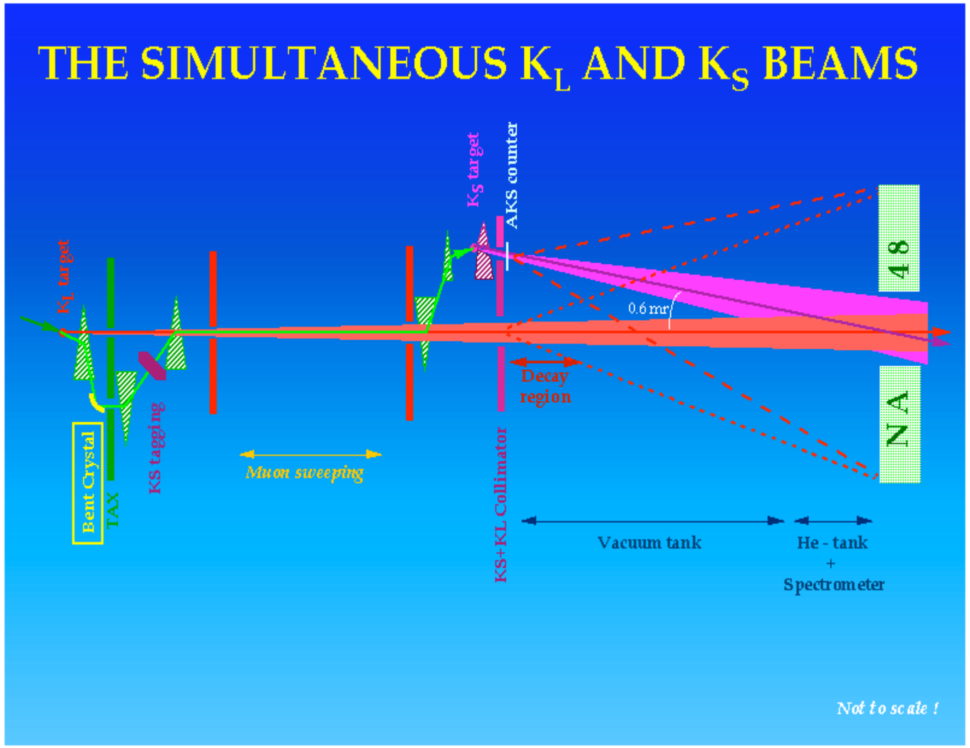
$$|\eta_{+-}|^2 = \frac{\left|A\left(\mathrm{K_L} \to \pi^+\pi^-\right)\right|^2}{\left|A\left(\mathrm{K_S} \to \pi^+\pi^-\right)\right|^2} = \frac{N_\mathrm{S}^{+-}}{N_\mathrm{L}^{+-}} \frac{N\left(\mathrm{K_L} \to \pi^+\pi^-\right)}{N\left(\mathrm{K_S} \to \pi^+\pi^-\right)} = |\varepsilon + \varepsilon'|^2$$

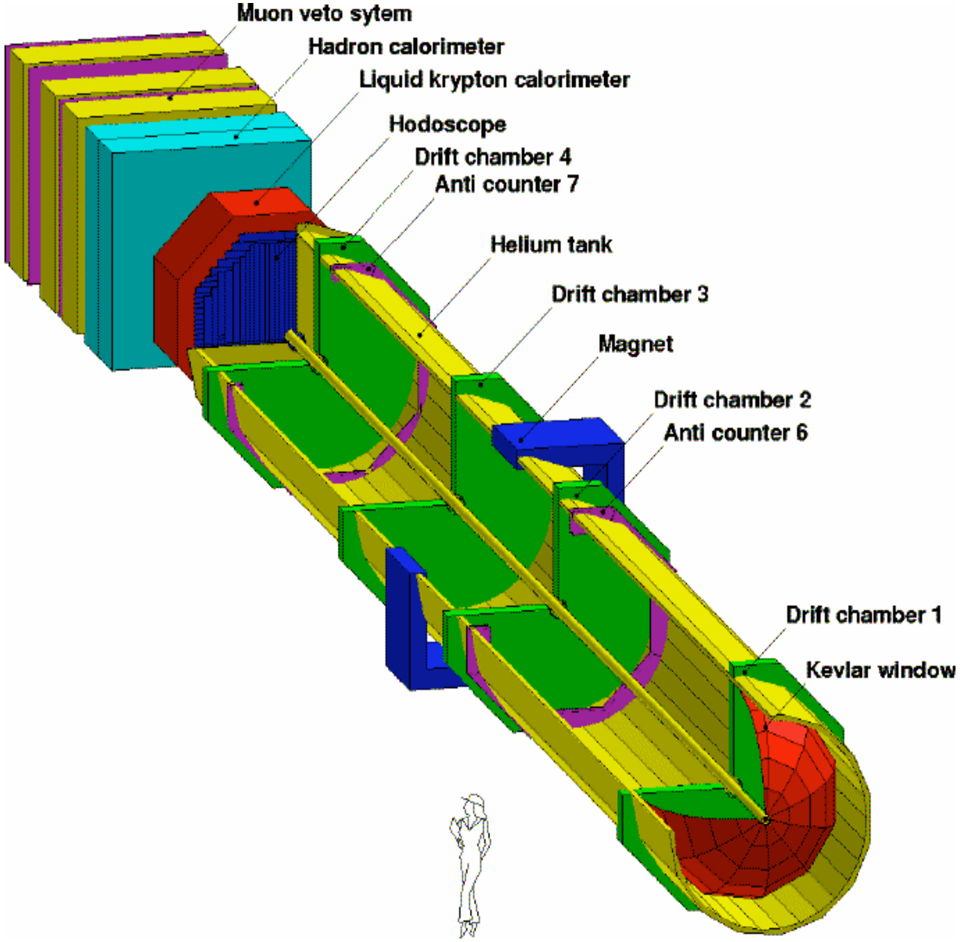
$$|\eta_{00}|^2 = \frac{\left|A\left(\mathrm{K_L} \to \pi^0\pi^0\right)\right|^2}{\left|A\left(\mathrm{K_S} \to \pi^0\pi^0\right)\right|^2} = \frac{N_\mathrm{S}^{00}}{N_\mathrm{L}^{00}} \frac{N\left(\mathrm{K_L} \to \pi^0\pi^0\right)}{N\left(\mathrm{K_S} \to \pi^0\pi^0\right)} = |\varepsilon - 2\varepsilon'|^2$$

$$\frac{|\eta_{00}|^2}{|\eta_{+-}|^2} = 1 - 6\,\mathrm{Re}\,\frac{\varepsilon'}{\varepsilon}$$

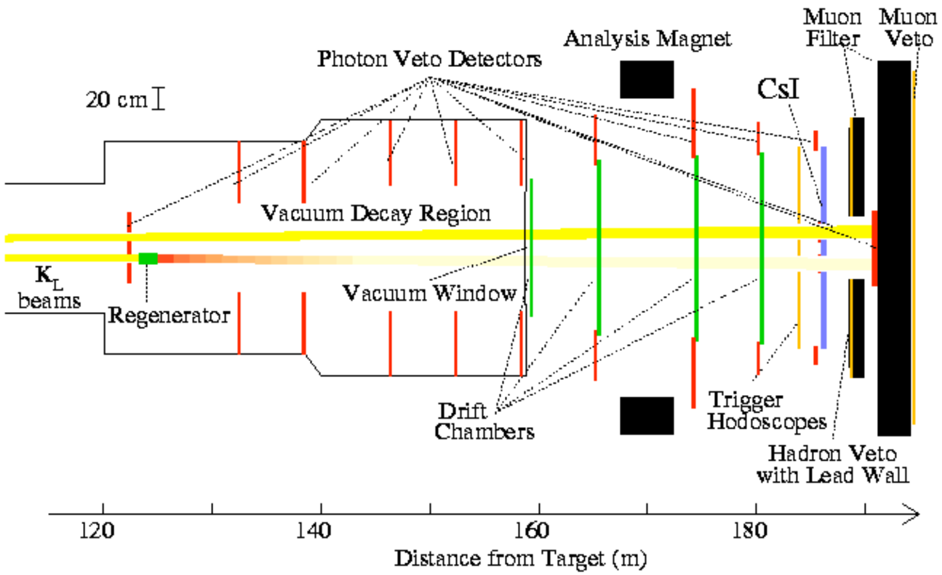
$$= \frac{N_\mathrm{S}^{00} N_\mathrm{L}^{+-}}{N_\mathrm{L}^{00} N_\mathrm{S}^{+-}} \frac{N\left(\mathrm{K_L} \to \pi^0\pi^0\right) N\left(\mathrm{K_S} \to \pi^+\pi^-\right)}{N\left(\mathrm{K_S} \to \pi^0\pi^0\right) N\left(\mathrm{K_L} \to \pi^+\pi^-\right)}$$

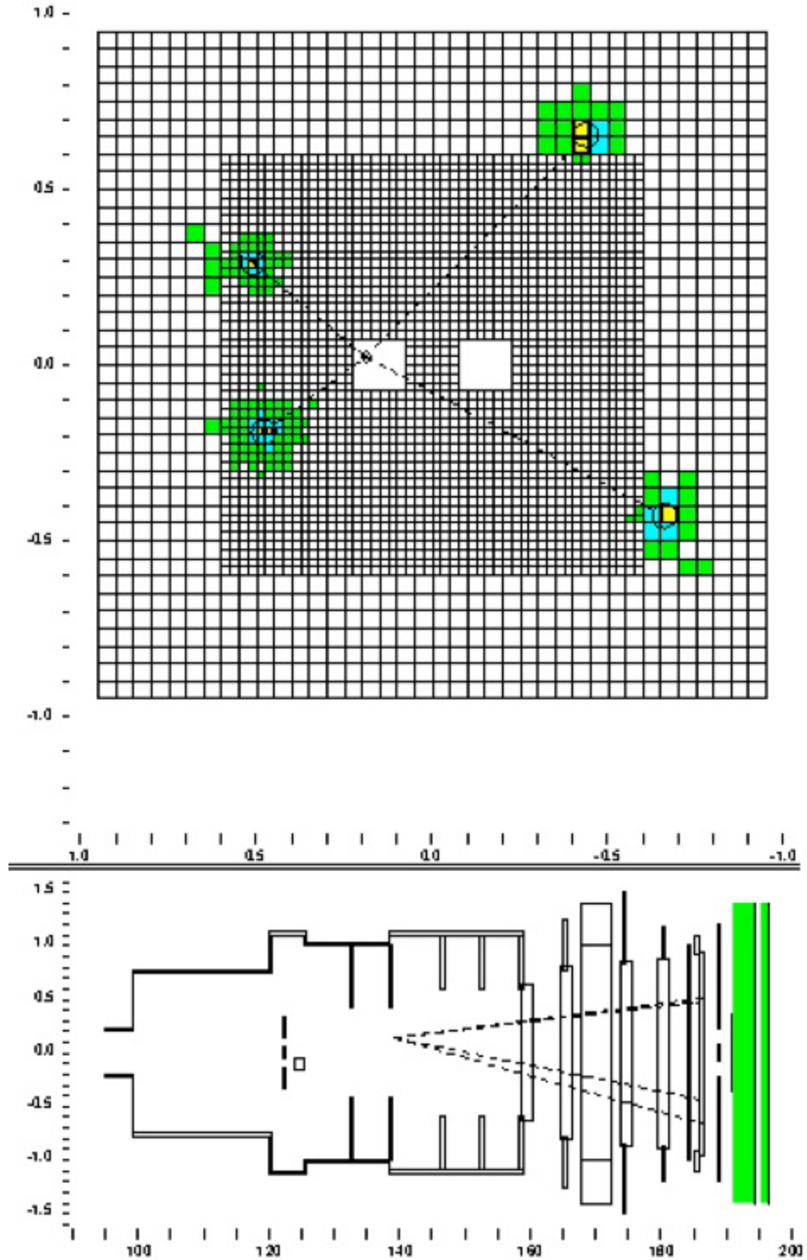
NA48


THE SIMULTANEOUS K_L AND K_S BEAMS
K_L target
Bent Crystal
TAX
KS tagging
Muon sweeping
K_S target
AKS counter
KS+KL Collimator
Decay region
0.6 mr
Vacuum tank
He - tank
+
Spectrometer
N A 4 8
Not to scale !


Muon veto sytem
Hadron calorimeter
Liquid krypton calorimeter
Hodoscope
Drift chamber 4
Anti counter 7
Helium tank
Drift chamber 3
Magnet
Drift chamber 2
Anti counter 6
Drift chamber 1
Kevlar window

KTeV


Photon Veto Detectors
Analysis Magnet
Muon Filter
Muon Veto
20 cm
CsI
Vacuum Decay Region
K_L beams
Regenerator
Vacuum Window
Drift Chambers
Trigger Hodoscopes
Hadron Veto with Lead Wall
120
140
160
180
Distance from Target (m)



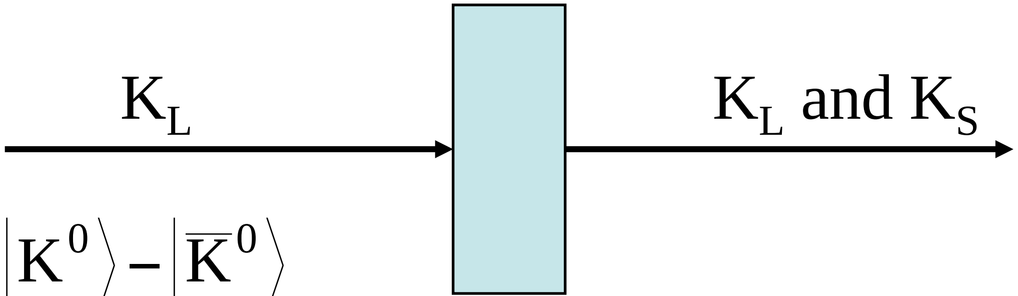
Regeneration

$$\sigma_{\bar{K}n},\ \sigma_{\bar{K}p} > \sigma_{Kn},\ \sigma_{Kp}$$

$$K^0 = (d\bar{s}) \qquad \bar{K}^0 = (\bar{d}s)$$

$$p = (uud),\ n = (udd)$$

material = p and n



$$|K^0\rangle - |\bar{K}^0\rangle$$

$$|K^0\rangle - \alpha|\bar{K}^0\rangle = \frac{1-\alpha}{2}\left(|K^0\rangle + |\bar{K}^0\rangle\right) + \frac{1+\alpha}{2}\left(|K^0\rangle - |\bar{K}^0\rangle\right) = \frac{1-\alpha}{2}|K_S\rangle + \frac{1+\alpha}{2}|K_L\rangle$$

$$\alpha = \sqrt{\frac{\sigma_{\bar{K}N}}{\sigma_{KN}}} \neq 1$$

Measure

$\pi^+\pi^-$ and $\pi^0\pi^0$ at the same time: $N_S^{00} = N_S^{+-}, N_L^{00} = N_L^{+-}$

NA31, NA48

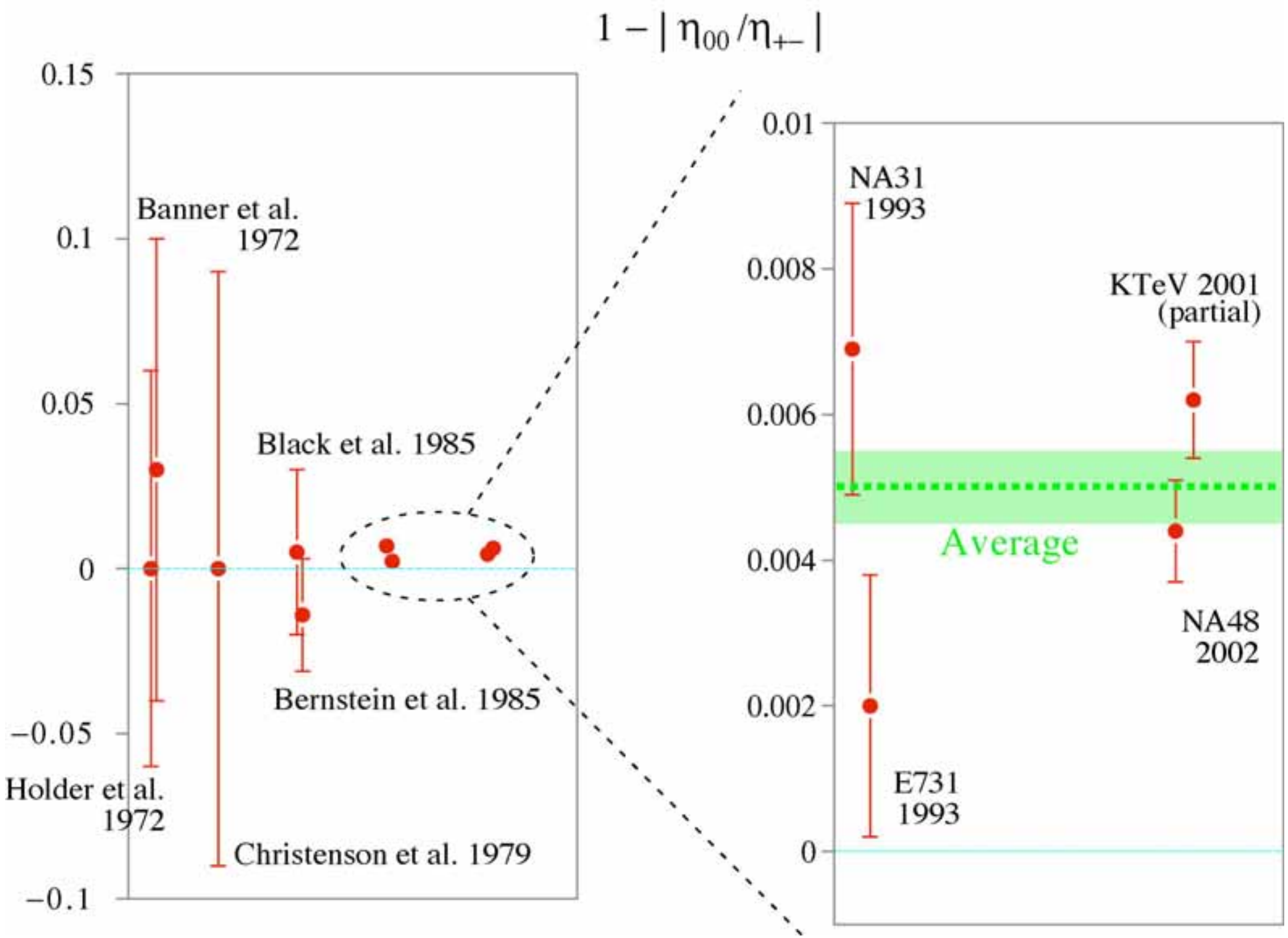
K_L is regenerated from K_S: $N_L^{00} = rN_S^{00}, N_L^{+-} = rN_S^{+-}$

E731, KTeV

No normalization is required,

but efficiencies, acceptances etc. have to be corrected…

Flavour Physics



Effort over 30 years to find Re $\varepsilon' \neq 0$

Charm discovery

Prog. Theor. Phys. Vol. 46 (1971), No. 5

A Possible Decay in Flight of a New Type Particle

Kiyoshi NIU, Eiko MIKUMO and Yasuko MAEDA*

Institute for Nuclear Study University of Tokyo
**Yokohama National University*

August 9, 1971

1971
emulsion exposed in
a JAL Jet cargo plane

one event of
$X \rightarrow \pi^0 +$ one charged hadron

hypo.	$\pi^0\pi^{charged}$	$\pi^0 p$
τ(s)	2.2×10^{-14}	3.6×10^{-14}
M(GeV)	1.78 2.95	

Possibly, the first observation of $D \rightarrow K\pi^0$ decay in 1971

More established discovery was c-$\bar{c}$ bound states in 1974 by J.J. Aubert et al. and J.-E. Augustin et al.

J.J. Aubert et al.

Experimental Observation of a Heavy Particle J†

J. J. Aubert, U. Becker, P. J. Biggs, J. Burger, M. Chen, G. Everhart, P. Goldhagen, J. Leong, T. McCorriston, T. G. Rhoades, M. Rohde, Samuel C. C. Ting, and Sau Lan Wu
Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

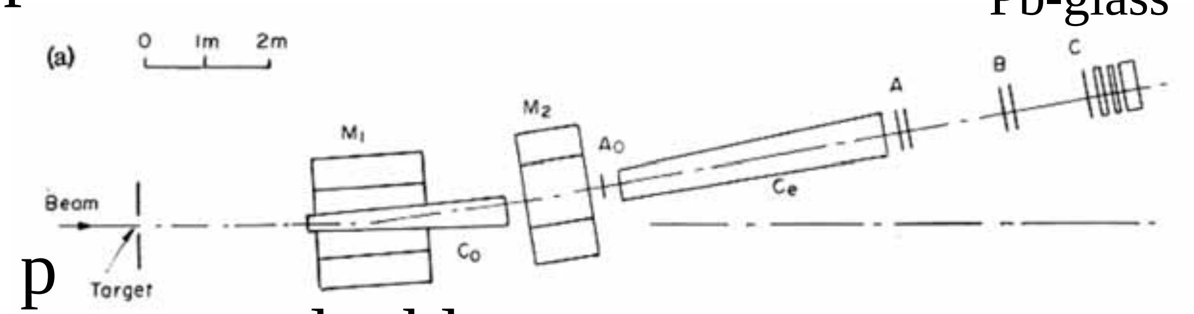
and

Y. Y. Lee
Brookhaven National Laboratory, Upton, New York 11973
(Received 12 November 1974)

We report the observation of a heavy particle J, with mass $m = 3.1$ GeV and width approximately zero. The observation was made from the reaction $p + \mathrm{Be} \to e^+ + e^- + x$ by measuring the e^+e^- mass spectrum with a precise pair spectrometer at the Brookhaven National Laboratory's 30-GeV alternating-gradient synchrotron.

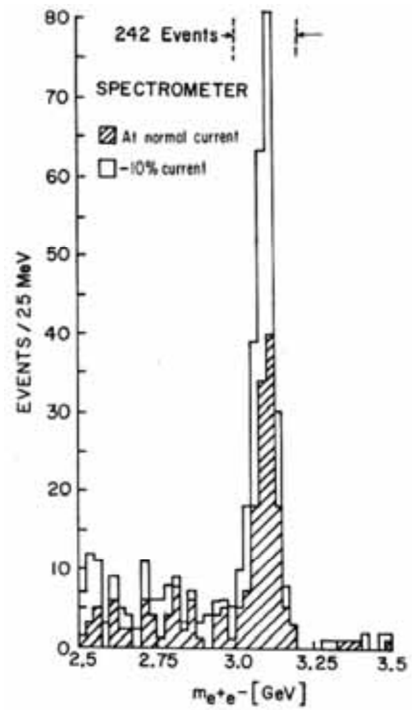
$p+\mathrm{Be} \to e^+e^- + X$

Pb-glass



p

double arm spectrometer



e^+e^- invariant mass

Augustin et al.

Discovery of a Narrow Resonance in e^+e^- Annihilation*

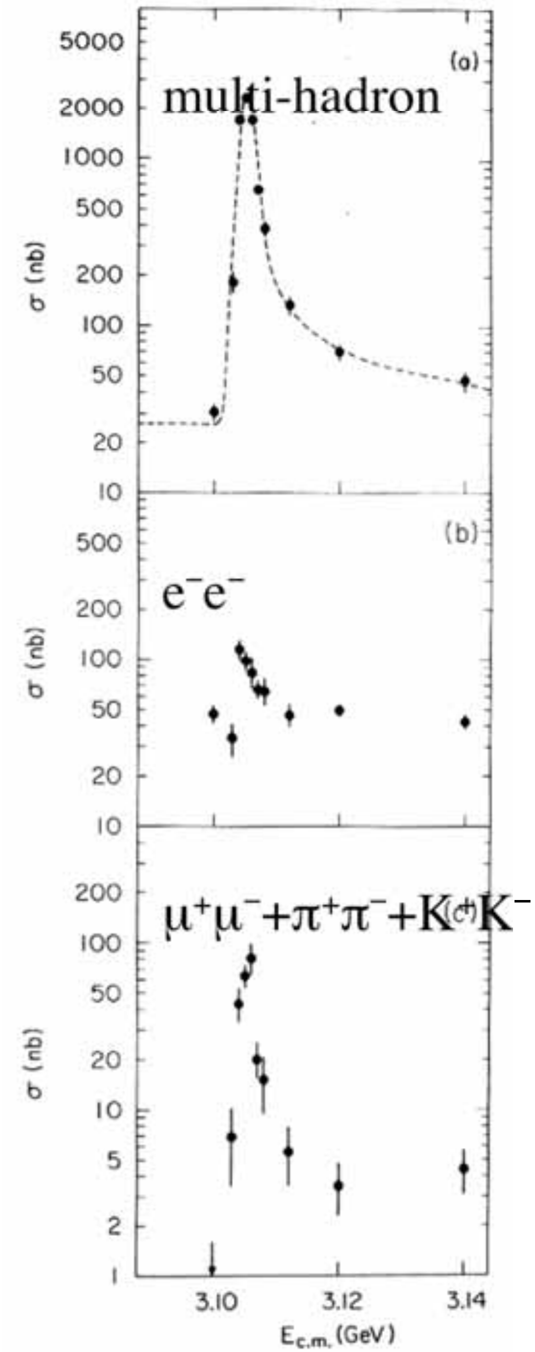
J.-E. Augustin,† A. M. Boyarski, M. Breidenbach, F. Bulos, J. T. Dakin, G. J. Feldman, G. E. Fischer, D. Fryberger, G. Hanson, B. Jean-Marie,† R. R. Larsen, V. Lüth, H. L. Lynch, D. Lyon, C. C. Morehouse, J. M. Paterson, M. L. Perl, B. Richter, P. Rapidis, R. F. Schwitters, W. M. Tanenbaum, and F. Vannucci‡
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

and

G. S. Abrams, D. Briggs, W. Chinowsky, C. E. Friedberg, G. Goldhaber, R. J. Hollebeek, J. A. Kadyk, B. Lulu, F. Pierre,§ G. H. Trilling, J. S. Whitaker, J. Wiss, and J. E. Zipse
Lawrence Berkeley Laboratory and Department of Physics, University of California, Berkeley, California 94720
(Received 13 November 1974)

We have observed a very sharp peak in the cross section for $e^+e^- \to$ hadrons, e^+e^-, and possibly $\mu^+\mu^-$ at a center-of-mass energy of 3.105 ± 0.003 GeV. The upper limit to the full width at half-maximum is 1.3 MeV.

e^+e^- cross section



Augustin et al.

Discovery of a Narrow Resonance in e^+e^- Annihilation*

J.-E. Augustin,† A. M. Boyarski, M. Breidenbach, F. Bulos, J. T. Dakin, G. J. Feldman, G. E. Fischer, D. Fryberger, G. Hanson, B. Jean-Marie,† R. R. Larsen, V. Lüth, H. L. Lynch, D. Lyon, C. C. Morehouse, J. M. Paterson, M. L. Perl, B. Richter, P. Rapidis, R. F. Schwitters, W. M. Tanenbaum, and F. Vannucci‡
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

and

G. S. Abrams, D. Briggs, W. Chinowsky, C. E. Friedberg, G. Goldhaber, R. J. Hollebeek, J. A. Kadyk, B. Lulu, F. Pierre,§ G. H. Trilling, J. S. Whitaker, J. Wiss, and J. E. Zipse
Lawrence Berkeley Laboratory and Department of Physics, University of California, Berkeley, California 94720
(Received 13 November 1974)

We have observed a very sharp peak in the cross section for $e^+e^- \to$ hadrons, e^+e^-, and possibly $\mu^+\mu^-$ at a center-of-mass energy of 3.105 ± 0.003 GeV. The upper limit to the full width at half-maximum is 1.3 MeV.

and slightly later…

Preliminary Result of Frascati (ADONE) on the Nature of a New 3.1-GeV Particle Produced in e^+e^- Annihilation*

C. Bacci, R. Balbini Celio, M. Berna-Rodini, G. Caton, R. Del Fabbro, M. Grilli, E. Iarocci, M. Locci, C. Mencuccini, G. P. Murtas, G. Penso, G. S. M. Spinetti, M. Spano, B. Stella, and V. Valente
The Gamma-Gamma Group, Laboratori Nazionali di Frascati, Frascati, Italy

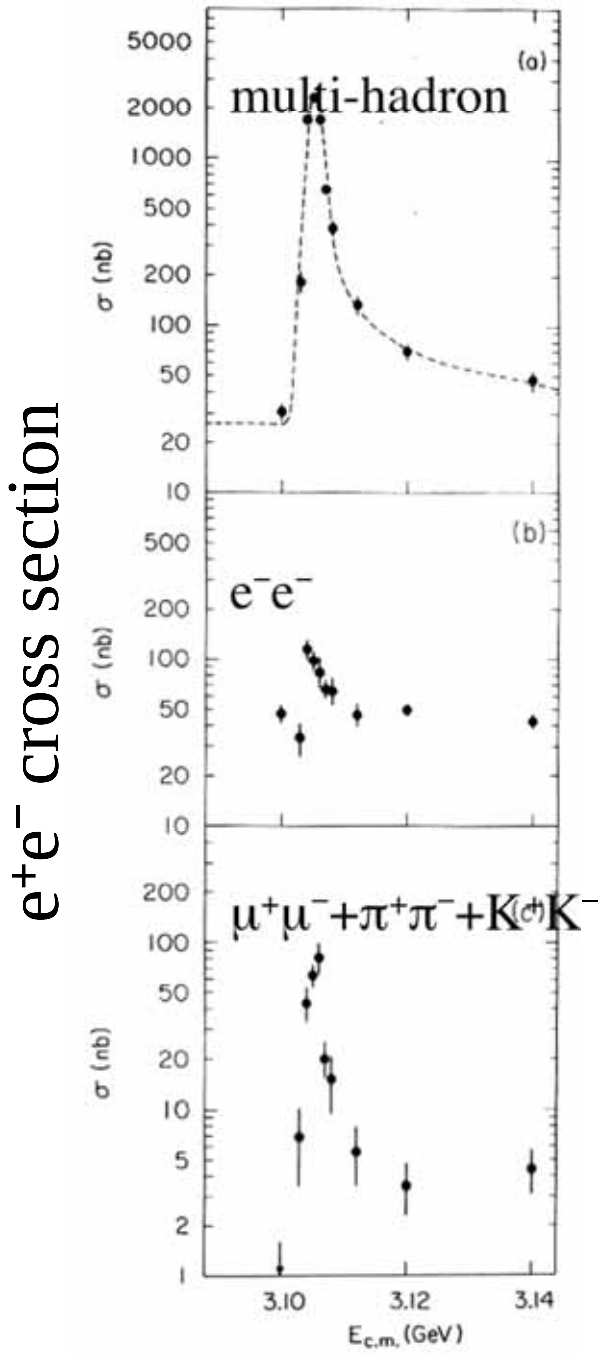
and

B. Bartoli, D. Bisello, B. Esposito, F. Felicetti, P. Monacelli, M. Nigro, L. Paolufi, I. Peruzzi, G. Piano Mortemi, M. Piccolo, F. Ronga, F. Sebastiani, L. Trasatti, and F. Vanoli
The Magnet Experimental Group for ADONE, Laboratori Nazionali di Frascati, Frascati, Italy

and

G. Barbarino, G. Barbiellini, C. Bemporad, R. Biancastelli, F. Cevenini, M. Celvetti, F. Costantini, P. Lariccia, P. Parascandalo, E. Sassi, C. Spencer, L. Tortora, U. Troya, and S. Vitale
The Baryon-Antibaryon Group, Laboratori Nazionali di Frascati, Frascati, Italy
(Received 18 November 1974)

We report on the results at ADONE to study the properties of the newly found 3.1-BeV particle.

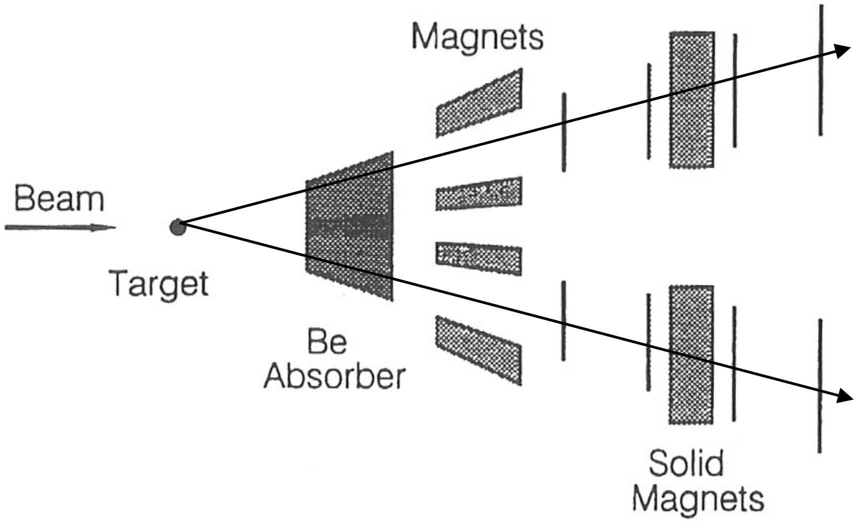


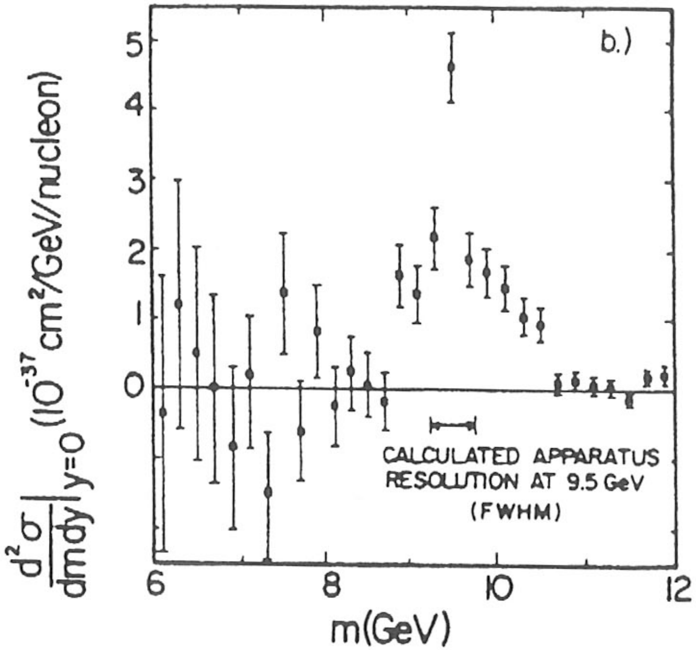
Discovery of a third family member

S. Herb et al. in 1977

E288 experiment @ FNAL

$\Upsilon \to \mu^+ \mu^-$





$m(\mu^+\mu^-)$

$(b\bar{b})$ bound states; $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$

Flavour Physics

Excellent track record to probe high energy scale

Particle (K^0)-antiparticle ($\overline{K}^0$) mixing: also oscillations $K^0_{t=0} \to \overline{K}^0(t)$

Very suppressed $K_L \to \mu^+\mu^-$ ⇒ SU(2) doublet structure (GIM)

Δm_K and $Br(K_L \to \mu^+\mu^-)$ ⇒ charm mass

CPV and very suppressed $B \to \mu^+\mu^-$ ⇒ third family, no topless world

First surprise with the b quark

The b lifetime

JADE

Physics Letters B, 114B(1) (19143) 71

Muons from a multihadron sample were used to determine an upper limit $\tau<1.4\times10^{-12}$ *s (95% CL) on the lifetime of beauty particles. The data were obtained with the JADE detector of PETRA. The result is interpreted within the standard model.*

e.g. V. Barger et al.
$0.8\times10^{-14}<\tau<1.4\times10^{-13}$ sec, J. Phys. G 5, L147 (1979)
i.e. general prejudice was $|V_{cb}| \approx |V_{us}|$

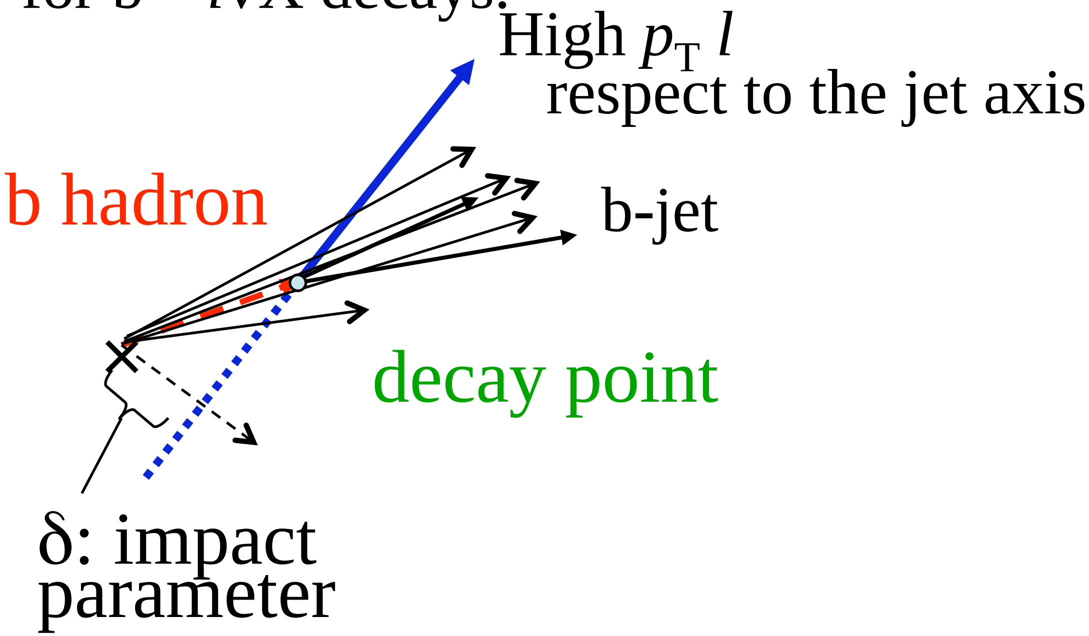
MAC

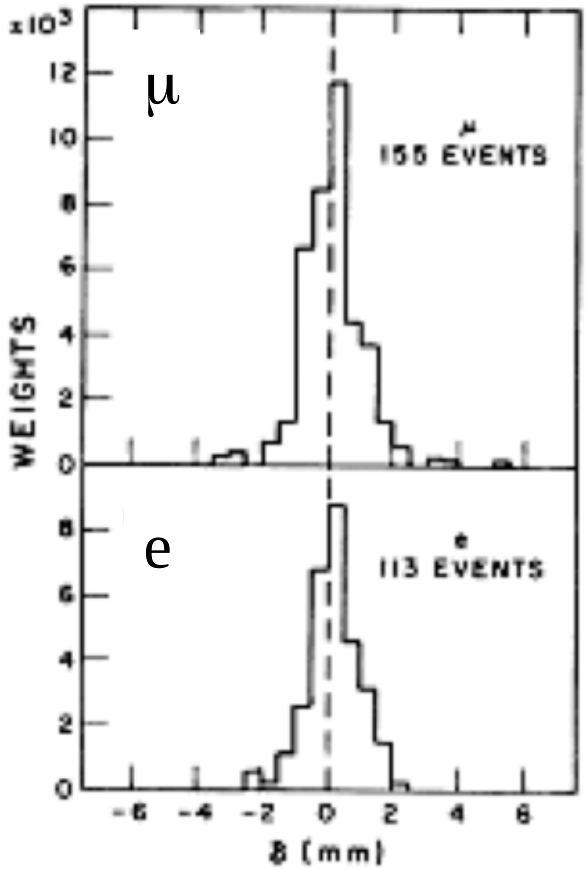
Phys. Rev. Lett. 51, (1983) 1022

Lifetime of Particles Containing *b* Quarks

From a sample of hadronic events produced in e^+e^- collisions, semileptonic decays of heavy particles have been isolated and used to obtain a measurement for the bottom-quark lifetime of $[1.8\pm0.6(\text{stat.})\pm0.4(\text{syst.})]\times10^{-12}$ *sec.*

Impact parameter distributions for $b\to l\nu X$ decays.





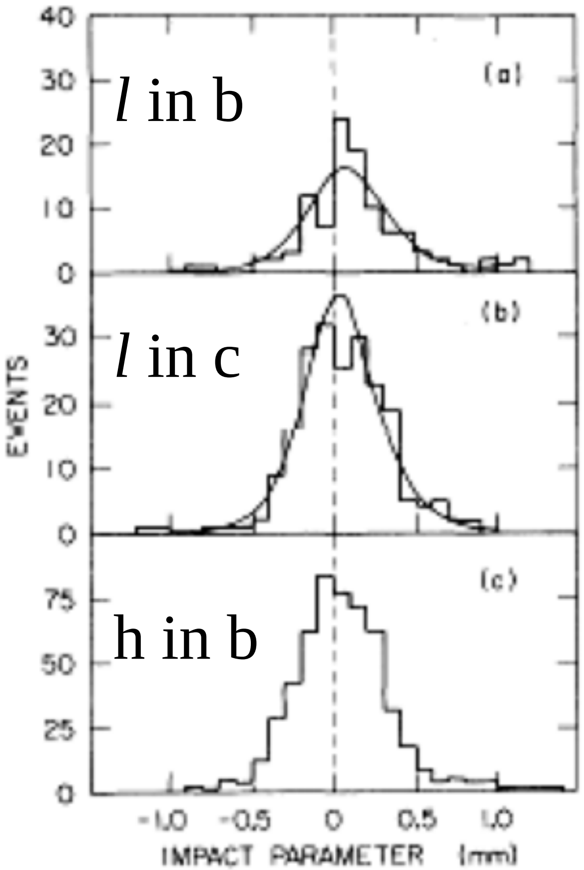
Mark II

Phys. Rev. Lett. 51, (1983) 1316

Measurement of the Lifetime of Bottom Hadrons

The average lifetime of bottom hadrons was measured with the Mark II vertex detector at the storage ring PEP. The lifetime was determined by measuring the impact parameters of leptons produced in bottom decays. $\tau_b=(12.0^{+4.5}_{-3.6}\pm3.0)\times10^{-13}$ *sec was found.*

l impact parameter distributions for b, c→*l*νX decays.



b lifetime is ~10^{-12} sec
$|V_{cb}|$~0.05, i.e.
much smaller than $\sin\theta_{Cabibbo}$ ~0.2

Opened up interesting possibilities for B mesons, e.g. oscillations, CP violation and rare decays (as the kaon system)

Flavour Physics

Excellent track record to probe high energy scale

Particle (K^0)-antiparticle ($\overline{K}^0$) mixing: also oscillations $K^0_{t=0} \rightarrow \overline{K}^0(t)$

Very suppressed $K_L \rightarrow \mu^+\mu^-$ $\Rightarrow$ SU(2) doublet structure (GIM)

Δm_K and $Br(K_L \rightarrow \mu^+\mu^-)$ $\Rightarrow$ charm mass

CPV $\Rightarrow$ third family

Δm_B and top mass

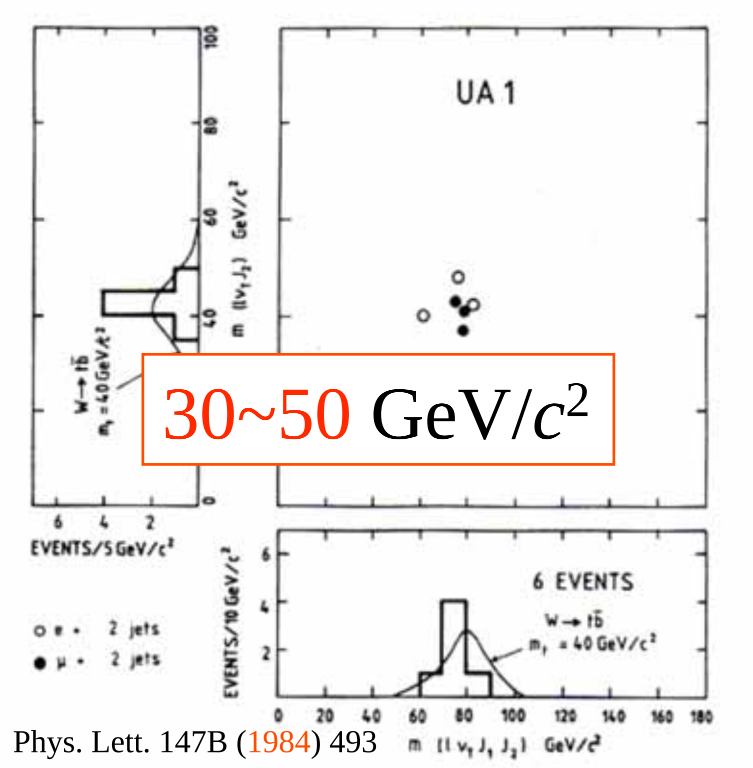
History of m_t

UA1, 1984

$p\bar{p} \to W + X$

$W^+ \to t\,\bar{b}$ ($\bar{b} \to$ jet)

$\quad \hookrightarrow b\,l\,\nu$ ($b \to$ jet)



Phys. Lett. 147B (1984) 493

History of m_t

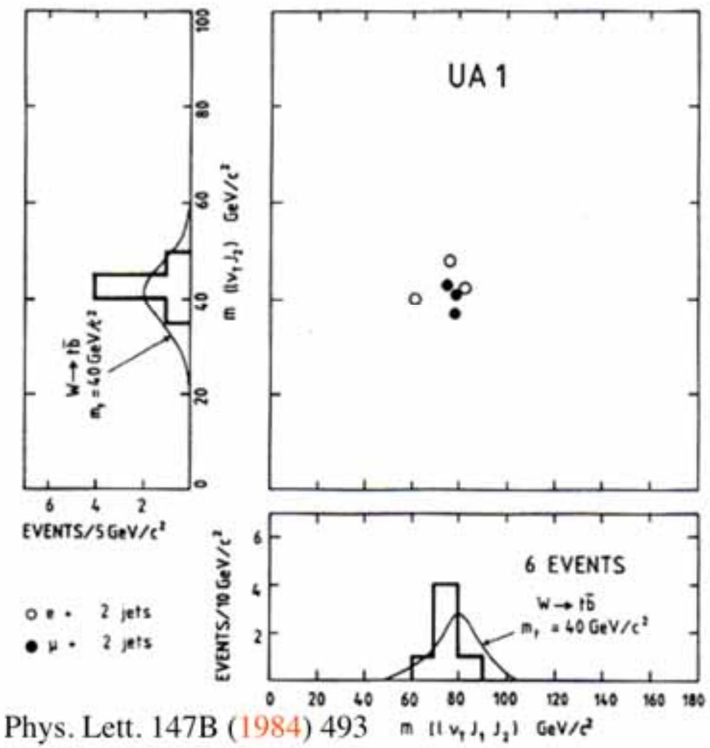
UA1, 1984

$p\bar{p} \to W + X$

$W^+ \to t\bar{b}$ → jet

└→ $bl\nu$

→ jet



Phys. Lett. 147B (1984) 493

Volume 147B, number 6 PHYSICS LETTERS 15 November 1984

ASSOCIATED PRODUCTION OF AN ISOLATED, LARGE-TRANSVERSE-MOMENTUM LEPTON (ELECTRON OR MUON), AND TWO JETS AT THE CERN $p\bar{p}$ COLLIDER

UA1 Collaboration, CERN, Geneva, Switzerland

A clear signal is observed for the production of an isolated large-transverse-momentum lepton in association with two or three centrally produced jets. The two-jet events cluster around the $W^{\pm}$ mass, indicating a novel decay of the Intermediate Vector Boson. The rate and features of these events are not consistent with expectations of known quark decays (charm, bottom). They are, however, in agreement with the process $W \to t\bar{b}$ followed by $t \to b\ell\nu$, where t is the sixth quark (top) of the weak Cabibbo current. If this is indeed so, the bounds on the mass of the top quark are $30\ \mathrm{GeV}/c^2 < m_t < 50\ \mathrm{GeV}/c^2$.

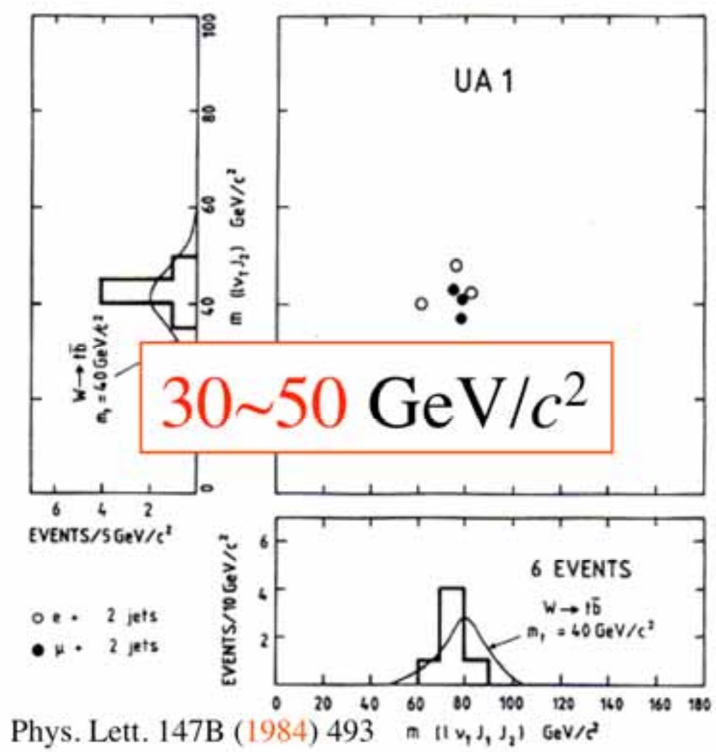
History of m_t

UA1, 1984

$p\bar{p} \to W + X$

$W^+ \to t\bar{b}$ → jet

$t \to b l \nu$ → jet



Phys. Lett. 147B (1984) 493

ARGUS, 1987

$\Upsilon(4S) \to B_d^0 \bar{B}_d^0$

$\to B_d^0 B_d^0$ or $\bar{B}_d^0 \bar{B}_d^0$

$\to \ell^+\ell^+$ or $\ell^-\ell^-$

24.8±7.6±3.8

$\Delta m(B_d) \sim 100 \times \Delta m(K^0)$

Volume 192, number 1,2 PHYSICS LETTERS B 25 June 1987

OBSERVATION OF B^0–$\bar{B}^0$ MIXING

ARGUS Collaboration

Using the ARGUS detector at the DORIS II storage ring we have searched in three different ways for B^0–$\bar{B}^0$ mixing in Υ(4S) decays. One explicitly mixed event, a decay $\Upsilon(4S) \to B^0B^0$, has been completely reconstructed. Furthermore, we observe a 4.0 standard deviation signal of 24.8 events with like-sign lepton pairs and a 3.0 standard deviation signal of 4.1 events containing one reconstructed $B^0(\bar{B}^0)$ and an additional fast $\ell^+(\ell^-)$. This leads to the conclusion that B^0–$\bar{B}^0$ mixing is substantial. For the mixing parameter we obtain $r = 0.21 \pm 0.08$.

Phys. Lett. B 192 (1987) 245

History of m_t

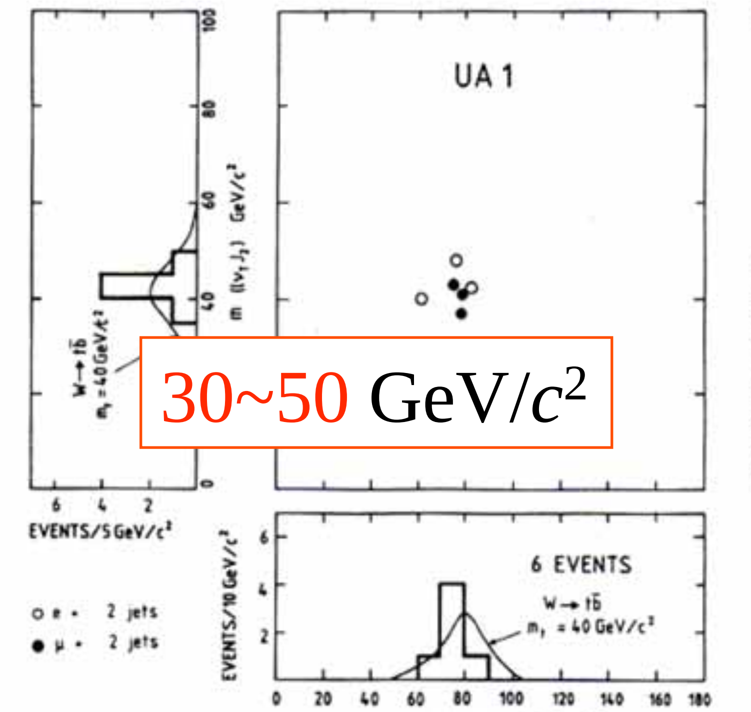
UA1, 1984

$p\bar{p} \to W + X$ → jet

$W^+ \to t\,\bar{b}$

└→ $b l \nu$

↘ jet



Phys. Lett. 147B (1984) 493

ARGUS, 1987

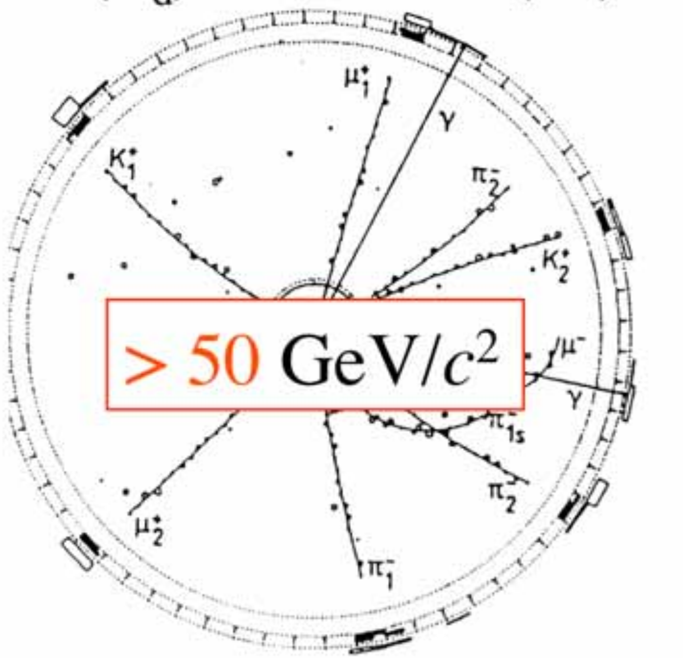
$\Upsilon(4S) \to B_d^0 \overline{B}_d^0$

$\to B_d^0 B_d^0$ or $\overline{B}_d^0 \overline{B}_d^0$

$\to \ell^+ \ell^+$ or $\ell^- \ell^-$

24.8±7.6±3.8

$\Delta m(B_d) \approx 100 \times \Delta m(K^0)$



Phys. Lett. B 192 (1987) 245

History of m_t

UA1, 1984

$p\bar{p} \to W + X$

$W^+ \to t\bar{b}$, with $t \to b l\nu$ (jets)

ARGUS, 1987

$\Upsilon(4S) \to B_d^0 \bar{B}_d^0$

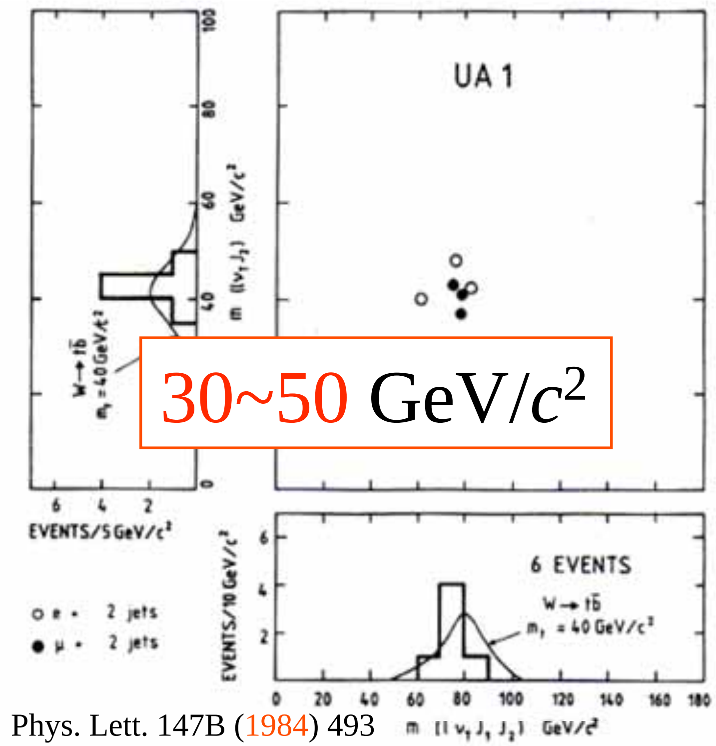
$\to B_d^0 B_d^0$ or $\bar{B}_d^0 \bar{B}_d^0$

$\to \ell^+\ell^+$ or $\ell^-\ell^-$

24.8±7.6±3.8

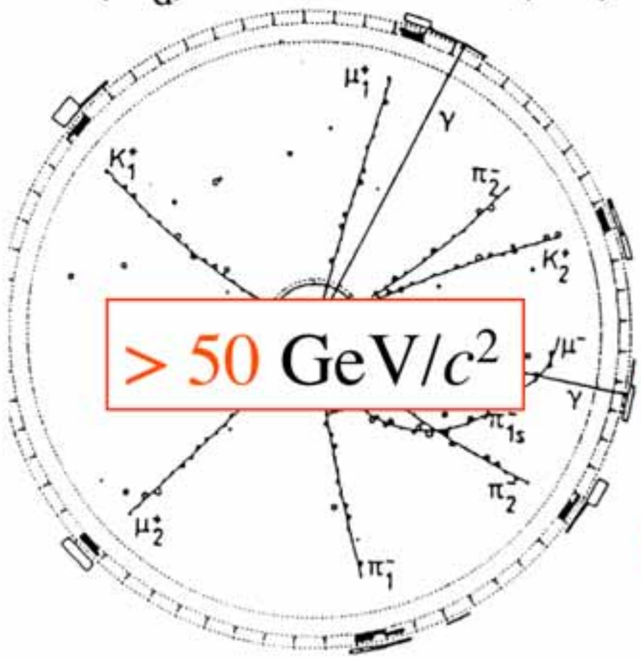
$\Delta m(B_d) \approx 100 \times \Delta m(K^0)$

LEP
electroweak fit
150~210 GeV/c^2



30~50 GeV/c^2

Phys. Lett. 147B (1984) 493



> 50 GeV/c^2

Phys. Lett. B 192 (1987) 245

1995
CDF
$175 \pm 8 \pm 10$ GeV/c^2
D0
$199^{+19}_{-21} \pm 22$ GeV/c^2

Flavour Physics

Excellent track record to probe high energy scale

Particle (K^0)-antiparticle ($\overline{K}^0$) mixing: also oscillations $K^0_{t=0} \rightarrow \overline{K}^0(t)$

Very suppressed $K_L \rightarrow \mu^+\mu^-$ ⇒ SU(2) doublet structure (GIM)

Δm_K and $Br(K_L \rightarrow \mu^+\mu^-)$ ⇒ charm mass

CPV ⇒ third family

Δm_B ⇒ top mass

Flavour Physics

Excellent track record to probe high energy scale

Particle (K^0)-antiparticle ($\overline{K}^0$) mixing: also oscillations $K^0_{t=0} \rightarrow \overline{K}^0(t)$

Very suppressed $K_L \rightarrow \mu^+\mu^-$ ⇒ SU(2) doublet structure (GIM)

Δm_K and $Br(K_L \rightarrow \mu^+\mu^-)$ ⇒ charm mass

CPV ⇒ third family

Δm_B ⇒ top mass

NB: before observing directly c, b or t

Flavour Physics

Excellent track record to probe high energy scale

Particle (K^0)-antiparticle ($\overline{K}^0$) mixing: also oscillations $K^0_{t=0} \rightarrow \overline{K}^0(t)$

Very suppressed $K_L \rightarrow \mu^+\mu^-$ $\Rightarrow$ SU(2) doublet structure (GIM)

Δm_K and $Br(K_L \rightarrow \mu^+\mu^-)$ $\Rightarrow$ charm mass

CPV $\Rightarrow$ third family

Δm_B $\Rightarrow$ top mass

and ν oscillations

Discovery of ν_μ: two neutrinos have been considered by e.g. Sakata&Inoue(1946), Schwinger (1957), Nishijima (1958), Konuma (1958), Kawakami (1958), Kawakami (1958), Konuma (1958), Pontecorvo (1959), Oneda&Pati (1959), Lee and Yang (1960)

-motivated by the headron-lepton unification attempt

-to explain the absence of $\mu \rightarrow e\gamma$ (via e"$\nu\overline{\nu}$")

Flavour Physics

Excellent track record to probe high energy scale

Particle (K^0)-antiparticle ($\overline{K}^0$) mixing: also oscillations $K^0_{t=0} \rightarrow \overline{K}^0(t)$

Very suppressed $K_L \rightarrow \mu^+\mu^-$	$\Rightarrow$ SU(2) doublet structure (GIM)
Δm_K and $Br(K_L \rightarrow \mu^+\mu^-)$	$\Rightarrow$ charm mass
CPV	$\Rightarrow$ third family
Δm_B	$\Rightarrow$ top mass

and ν oscillations

Discovery of ν_μ: BNL spark chamber experiment

OBSERVATION OF HIGH-ENERGY NEUTRINO REACTIONS AND THE EXISTENCE OF TWO KINDS OF NEUTRINOS*

G. Danby, J-M. Gaillard, K. Goulianos, L. M. Lederman, N. Mistry, M. Schwartz,† and J. Steinberger†

Columbia University, New York, New York and Brookhaven National Laboratory, Upton, New York

(Received June 15, 1962)

Almost simultaneously, neutrino flavour mixing

Progress of Theoretical Physics, Vol. 28, No. 5, November 1962

Remarks on the Unified Model of Elementary Particles

Ziro MAKI, Masami NAKAGAWA and Shoichi SAKATA

Institute for Theoretical Physics
Nagoya University, Nagoya

(Received June 25, 1962)

$$\left.\begin{aligned}\nu_1 &= \nu_e \cos\delta + \nu_\mu \sin\delta, \\ \nu_2 &= -\nu_e \sin\delta + \nu_\mu \cos\delta.\end{aligned}\right\} \quad (\delta : \text{real constant}) \qquad (2\cdot 4)$$

NB: Pontecorvo proposed ν-$\overline{\nu}$ mixing in 1957, analogous to the K^0-$\overline{K}^0$ oscillations discovered in 1955

Flavour Physics

Excellent track record to probe high energy scale

Particle (K^0)-antiparticle ($\overline{K}^0$) mixing: also oscillations $K^0_{t=0} \to \overline{K}^0(t)$

Very suppressed $K_L \to \mu^+\mu^-$ $\Rightarrow$ SU(2) doublet structure (GIM)

Δm_K and Br($K_L \to \mu^+\mu^-$) $\Rightarrow$ charm mass

CPV $\Rightarrow$ third family

Δm_B $\Rightarrow$ top mass

and ν oscillations

Discovery of ν_μ: 1962, Lederman-Schwartz-Steinberger et al.

Neutrino mixing by Maki-Nakagawa-Sakata in 1962

NB: one year before the Cabibbo mixing,

12 years before the charm discovery

Flavour Physics

Excellent track record to probe high energy scale

Particle (K^0)-antiparticle ($\overline{K}^0$) mixing: also oscillations $K^0_{t=0} \rightarrow \overline{K}^0(t)$

Very suppressed $K_L \rightarrow \mu^+\mu^-$ ⇒ SU(2) doublet structure (GIM)

Δm_K and $Br(K_L \rightarrow \mu^+\mu^-)$ ⇒ charm mass

CPV ⇒ third family

Δm_B ⇒ top mass

ν mixing pattern

ν oscillations now seen by, Davis, KAMIOKANDE, IMB, SNOW
MACRO, KamLAND, T2K, MINOS...

Flavour Physics

Excellent track record to probe high energy scale

Particle (K^0)-antiparticle ($\overline{K}^0$) mixing: also oscillations $K^0_{t=0} \rightarrow \overline{K}^0(t)$

Very suppressed $K_L \rightarrow \mu^+\mu^-$ ⇒ SU(2) doublet structure (GIM)

Δm_K and $Br(K_L \rightarrow \mu^+\mu^-)$ ⇒ charm mass

CPV ⇒ third family

Δm_B ⇒ top mass

ν mixing pattern ⇒ may be heavy neutrinos?

Quark Flavour Physics Experiments

General observation

Hadron machines have been "discovery" machines,

e.g. charm, beauty, W, Z, and top

Quark Flavour Physics Experiments

General observation

Hadron machines have been "discovery" machines,
e.g. charm, beauty, W, Z, and top

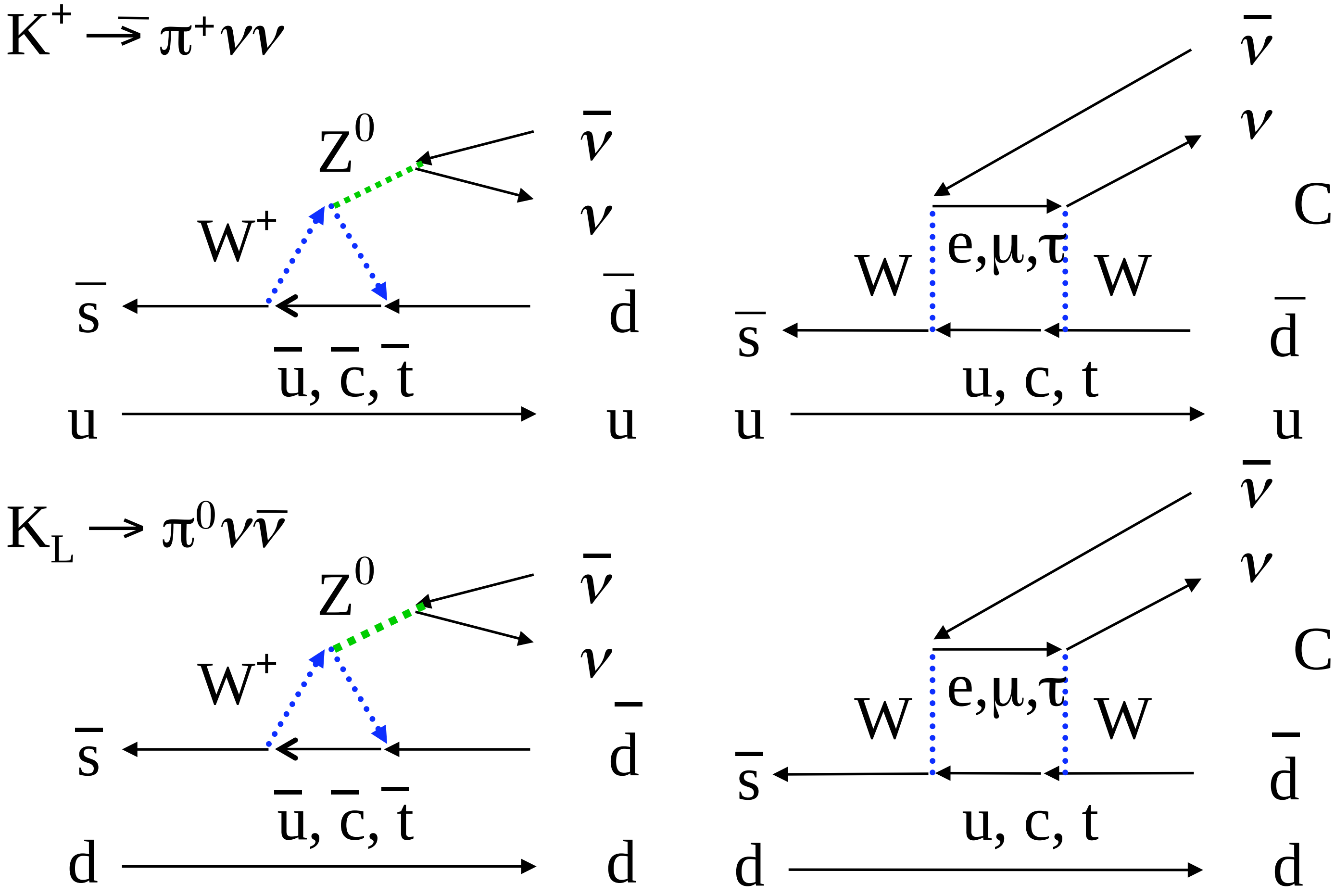
CP violation in the kaon system mainly studied at hadron machines
plus some contribution from KLOE

The newest round of Kaon experiments

The issues are;

precision measurements of ultra rare decays

$K^+ \to \pi^+ \nu\bar{\nu}$ and $K_L \to \pi^0 \nu\bar{\nu}$



CP conserving decay

$|V_{td}V_{ts}^*|$
$|V_{cd}V_{cs}^*|$

CP violating decay

$\mathrm{Im}(V_{td}V_{ts}^*)$

Current Standard Model predictions:

$$\mathrm{Br}(K^+ \to \pi^+ \nu\bar{\nu}) = (0.80 \pm 0.11)\times 10^{-10}$$

(isospin breaking taken into account)

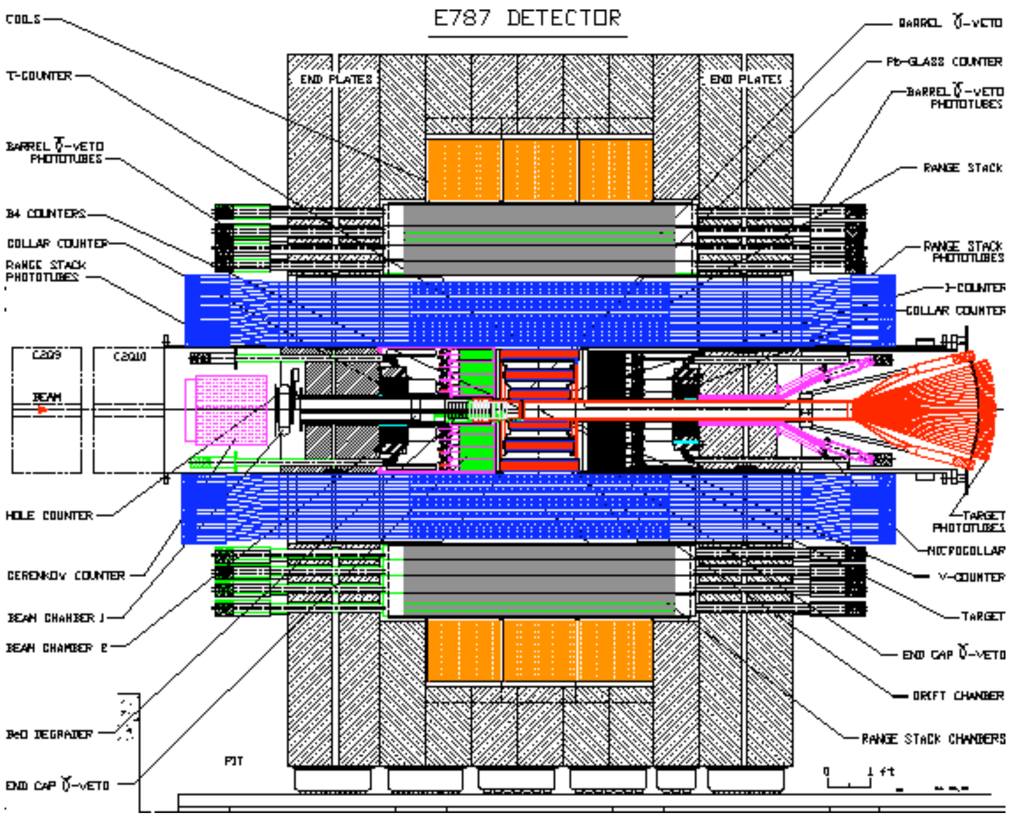
BNL787, 1995 data: $(4.2 {}^{+9.7}_{-3.5})\times 10^{-10}$ PRL 97

based on one event

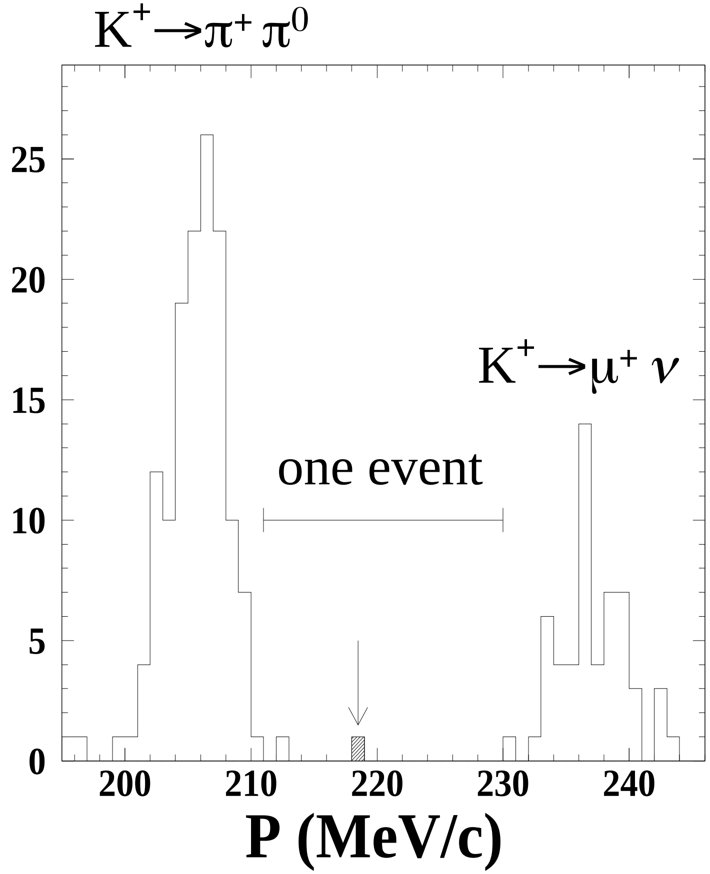
More data taken, no new candidate

BNL787, 1995-97: $(1.5 {}^{+3.4}_{-1.2})\times 10^{-10}$ PRL 2000

Stopped K^+



E787 DETECTOR
COILS
T-COUNTER
BARREL γ-VETO PHOTOTUBES
B4 COUNTERS
COLLAR COUNTER
RANGE STACK PHOTOTUBES
BEAM
HOLE COUNTER
CERENKOV COUNTER
BEAM CHAMBER 1
BEAM CHAMBER 2
BeO DEGRADER
END CAP γ-VETO
END PLATES
END PLATES
BARREL γ-VETO
Pb-GLASS COUNTER
BARREL γ-VETO PHOTOTUBES
RANGE STACK
RANGE STACK PHOTOTUBES
I-COUNTER
COLLAR COUNTER
TARGET PHOTOTUBES
V-COUNTER
TARGET
END CAP γ-VETO
DRIFT CHAMBER
RANGE STACK CHAMBERS
PIT
0 1 ft



K+→π+ π0
K+→μ+ ν
one event
25
20
15
10
5
0
200
210
220
230
240
P (MeV/c)

Current Standard Model predictions:

$$\mathrm{Br}(K^+ \to \pi^+ \nu\bar{\nu}) = (0.80 \pm 0.11)\times 10^{-10}$$

(isospin breaking taken into account)

BNL787, 1995 data: $(4.2\,^{+9.7}_{-3.5})\times 10^{-10}$ PRL 97

based on one event

More data taken, no new candidate

BNL787, 1995-97: $(1.5\,^{+3.4}_{-1.2})\times 10^{-10}$ PRL 2000

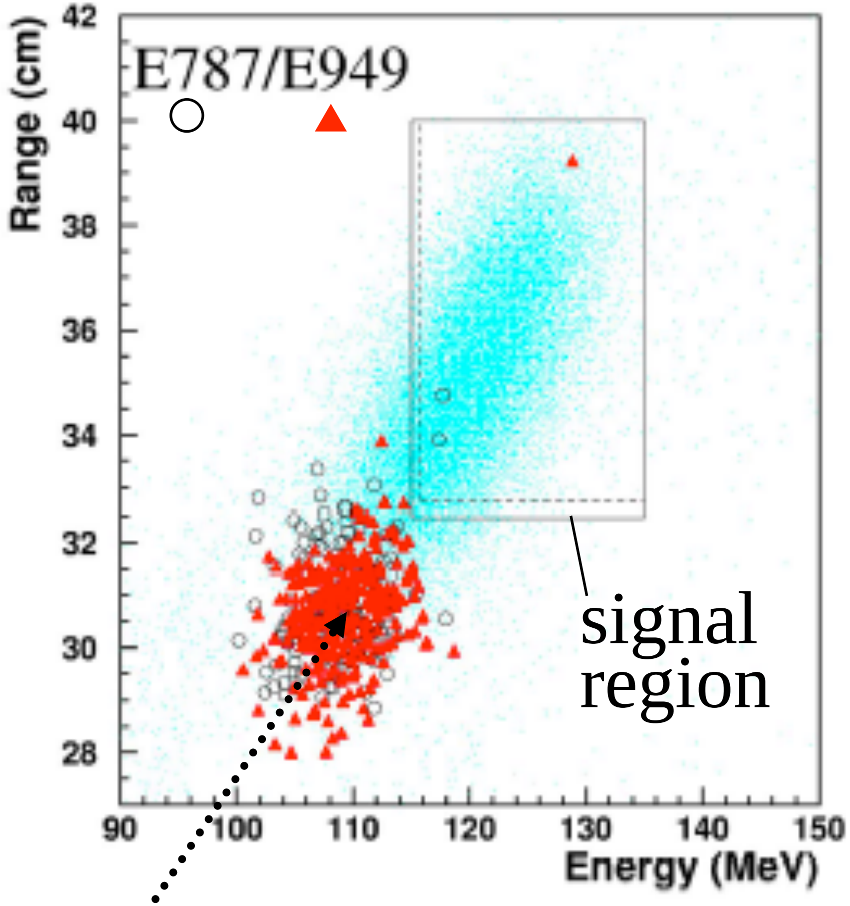
Further data taken, one more candidate

BNL787, 1995-98: $(1.57\,^{+1.75}_{-0.143})\times 10^{-10}$ PRL 2002

E787(95-98)/E949(02) combined results

$(1.47\,^{+1.30}_{-0.89})\times 10^{-10}$ PRL 2004

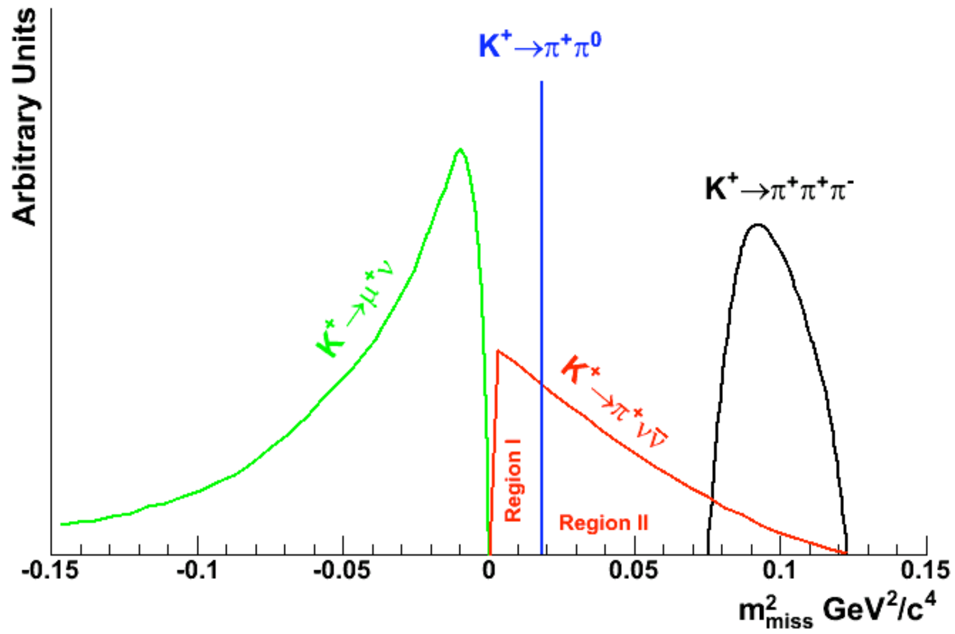
Three candidate events.



$K^+ \rightarrow \pi^+ \pi^0$

Boosting statistics cannot be achieved with stopped K^+ decays

⇒ decay in flight

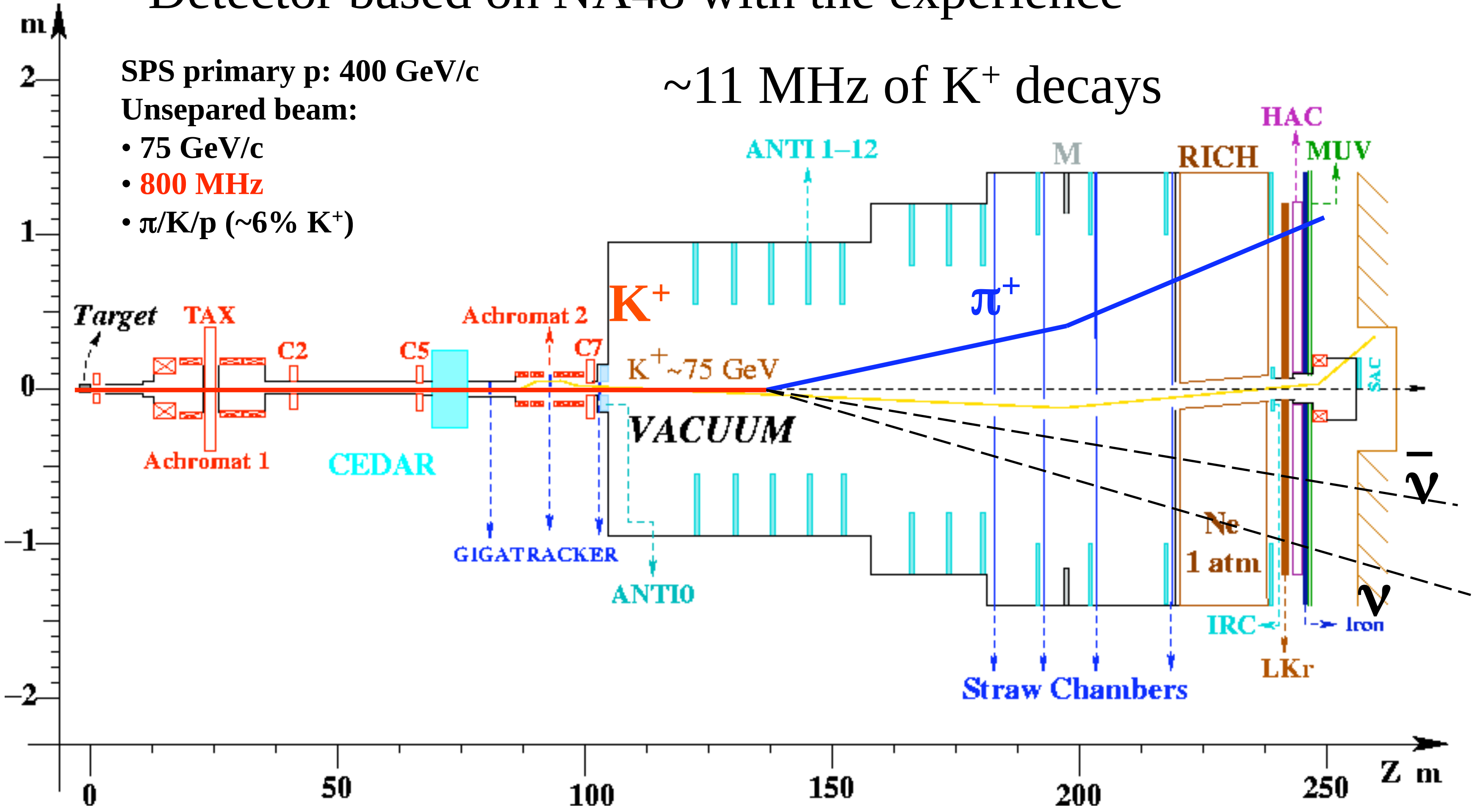


$$m_{miss}^2 \approx m_K^2\left(1-\frac{|P_\pi|}{|P_K|}\right)+m_\pi^2\left(1-\frac{|P_K|}{|P_\pi|}\right)-|P_K||P_\pi|\vartheta_{\pi K}^2$$

Detector based on NA48 with the experience

SPS primary p: 400 GeV/c
Unsepared beam:
- **75 GeV/c**
- **800 MHz**
- **π/K/p (~6% K^+)**

~11 MHz of K^+ decays



Expected performance: 55 events/year with B/S~15%

INFN has approved the funding, CERN approval still to be made

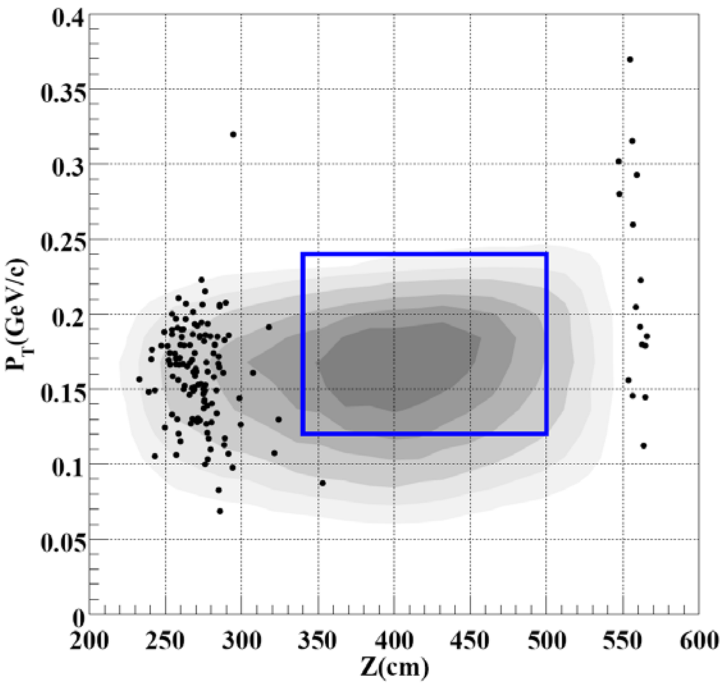
$\mathrm{Br}(K^0 \to \pi^0 \nu \bar{\nu}) \approx 3\times10^{-11}$ Standard Model

$< 1.6\times10^{-6}$ $\pi^0 \to \gamma\gamma$

$< 5.9\times10^{-7}$ $\pi^0 \to ee\gamma$

} 90% CL (KTeV, PLB 99)

E391 at KEK PRL 2008 $< 6.7 \times 10^{-8}$ 90% CL



The experiment will be moved to J-PARC, to be upgraded to E14

Expected performance:

2~3 events (SM Br.)

with ~2 background

with 3×10^7 sec (3 Snowmass years)

Further improvement in plan

Mixing and oscillations

The time evolution of a system with the neutral particle state, $|P\rangle$, and anti-particle state $|\overline{P}\rangle$, can obtained by solving a Schrödinger eq.

$$i\frac{\partial}{\partial t}|\psi(t)\rangle = (H_\mathrm{s} + H_\mathrm{em} + H_\mathrm{w})|\psi(t)\rangle$$

where, H_s and H_em are the strong and electromagnetic interaction Hamiltonians and H_w is the weak interaction Hamiltonian. The general time dependent wave function is given by

$$|\psi(t)\rangle = a(t)|P\rangle + b(t)|\overline{P}\rangle + \sum_f c_f(t)|f\rangle$$

where, $|f\rangle$ is decay final states of P and $\overline{\mathrm{P}}$ generated by the weak interactions. All the states, $|P\rangle$, $|\overline{P}\rangle$, and $|f\rangle$, are the eigenstates of the strong and electromagnetic interactions, and, $|P\rangle$ and $|\overline{P}\rangle$ are at rest (not suitable for the neutrinos.)

$$(H_s + H_{em})|f\rangle = E_f|f\rangle \quad (H_s + H_{em})|P\rangle = m|P\rangle, \ (H_s + H_{em})|\overline{P}\rangle = \overline{m}|\overline{P}\rangle$$

$$F|P\rangle = +|P\rangle, \ F|\overline{P}\rangle = -|\overline{P}\rangle \qquad F\text{: flavour}$$

Note that:

$|a(t)|^2$: fraction of P, $|b(t)|^2$: fraction of $\overline{P}$, $|c_f(t)|^2$: fraction of f

at a given time t

Initially at $t = 0$

$$|a(0)|^2 + |b(0)|^2 = 1$$

$$|c_f(0)|^2 = 0$$

Due to decays, $t > 0$

$$|a(t)|^2 + |b(t)|^2 = \text{decreases}$$

$$|c_f(t)|^2 = \text{increases}$$

while,

$$|a(t)|^2 + |b(t)|^2 + \sum_f |c_f(t)|^2 = 1$$

unitarity of Hamiltonian.

Usually, we are interested in $a(t)$ and $b(t)$ only.

After applying the Wigner-Weiskopf approximation (i.e. ignoring weak interactions between the different final states *f*), and perturbation method (i.e. $H_w \ll H_s + H_{em}$), $a(t)$ and $b(t)$ become the solution of

$$i\frac{\partial}{\partial t}\begin{pmatrix} a(t) \\ b(t) \end{pmatrix} = \boldsymbol{\Lambda}\begin{pmatrix} a(t) \\ b(t) \end{pmatrix} \qquad \boldsymbol{\Lambda} = \boldsymbol{M} - \frac{i}{2}\boldsymbol{\Gamma} = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} - \frac{i}{2}\begin{pmatrix} \Gamma_{11} & \Gamma_{12} \\ \Gamma_{21} & \Gamma_{22} \end{pmatrix}$$

- Diagonal elements of mass (M) and decay matrices (Γ)

$$M_{11} = m_0 + \langle P|H_W|P\rangle + \sum_f \mathbf{P}\left(\frac{\langle P|H_W|f\rangle\langle f|H_W|P\rangle}{m_0 - E_f}\right)$$

P: principal value

$$M_{22} = m_0 + \langle \overline{P}|H_W|\overline{P}\rangle + \sum_f \mathbf{P}\left(\frac{\langle \overline{P}|H_W|f\rangle\langle f|H_W|\overline{P}\rangle}{m_0 - E_f}\right)$$

f’s can be both virtual and real states.

$$\Gamma_{11} = 2\pi\sum_f \left|\langle P|H_W|f\rangle\right|^2 \delta\left(m_0 - E_f\right)$$

$$\Gamma_{22} = 2\pi\sum_f \left|\langle \overline{P}|H_W|f\rangle\right|^2 \delta\left(m_0 - E_f\right)$$

f's are all possible real decay states, due to the delta function, i.e. Γ's are decay widths.

CPT conservation

$$\rightarrow M_{11} = M_{22} \equiv M_0,\ \Gamma_{11} = \Gamma_{22} \equiv \Gamma_0,\ \text{i.e. } \Lambda_{11} = \Lambda_{22} \equiv \Lambda_0$$

Therefore, the diagonal elements are generally assumed to be identical

- Off-diagonal elements of mass (M) and decay matrices (Γ)

$$M_{12} = \langle P|H_W|\overline{P}\rangle + \sum_f \mathrm{P}\left(\frac{\langle P|H_W|f\rangle\langle f|H_W|\overline{P}\rangle}{m_0 - E_f}\right)$$

f's are both virtual and real states commonly accessible from P and $\overline{\mathrm{P}}$

$$\Gamma_{12} = 2\pi\sum_f \langle P|H_W|f\rangle\langle f|H_W|\overline{P}\rangle\delta\left(m_0 - E_f\right)$$

f's are real decay states, common to P and $\overline{\mathrm{P}}$.

Since $M_{21} = M_{12}^*,\ \Gamma_{21} = \Gamma_{12}^*$

$\boldsymbol{M}^\dagger = \boldsymbol{M}$, $\boldsymbol{\Gamma}^\dagger = \boldsymbol{\Gamma}$, but $\boldsymbol{\Lambda}^\dagger = (\boldsymbol{M} - i\boldsymbol{\Gamma}/2)^\dagger = \boldsymbol{M} + i\boldsymbol{\Gamma}/2 \neq \boldsymbol{\Lambda}$

$\Rightarrow |a(t)|^2 + |b(t)|^2$: not conserved

CP (or T) conservation → $\mathrm{Im}(M_{12}/\Gamma_{12}) = 0$, i.e. $|\Lambda_{12}| = |\Lambda_{21}|$

Solutions for $a(t)$ and $b(t)$ with an initial condition, P is produced at $t = 0$, i.e. $a(0) = 1$, $b(0) = 0$, gives

$$|P(t)\rangle = \frac{1}{2}\left(e^{-i\lambda_+ t} + e^{-i\lambda_- t}\right)|P\rangle + \zeta\frac{1}{2}\left(e^{-i\lambda_+ t} - e^{-i\lambda_- t}\right)|\overline{P}\rangle$$

$$\equiv f_+(t)|P\rangle + \zeta f_-(t)|\overline{P}\rangle$$

$$f_\pm(t) = \frac{1}{2}\left(e^{-i\lambda_+ t} \pm e^{-i\lambda_- t}\right)$$

$$\lambda_\pm = \Lambda_0 \pm \sqrt{\Lambda_{12}\Lambda_{21}} \equiv m_\pm - \frac{i}{2}\Gamma_\pm$$

$m_\pm = \mathrm{Re}\,\lambda_\pm$ mass

$\Gamma_\pm = -2\,\mathrm{Im}\,\lambda_\pm$ decay width

are eigenvalues of $\boldsymbol{\Lambda}$

$$\Delta m = m_+ - m_- = 2\,\mathrm{Re}\sqrt{\Lambda_{12}\Lambda_{21}} = 2\,\mathrm{Re}\sqrt{\left(M_{12} - \frac{i}{2}\Gamma_{12}\right)\left(M_{12}^* - \frac{i}{2}\Gamma_{12}^*\right)}$$

$$\Delta\Gamma = \Gamma_+ - \Gamma_- = -4\,\mathrm{Im}\sqrt{\Lambda_{12}\Lambda_{21}} = -4\,\mathrm{Im}\sqrt{\left(M_{12} - \frac{i}{2}\Gamma_{12}\right)\left(M_{12}^* - \frac{i}{2}\Gamma_{12}^*\right)}$$

This can be also written as

$$|P(t)\rangle = \frac{e^{-i\lambda_+ t}}{2}\left(|P\rangle + \zeta|\overline{P}\rangle\right) + \frac{e^{-i\lambda_- t}}{2}\left(|P\rangle - \zeta|\overline{P}\rangle\right)$$

$$\equiv \frac{\sqrt{1+|\zeta|^2}}{2}\left(e^{-i\lambda_+ t}|P_+\rangle + e^{-i\lambda_- t}|P_-\rangle\right)$$

$$|P_\pm\rangle = \frac{1}{\sqrt{1+|\zeta|^2}}\underbrace{\left(|P\rangle \pm \zeta|\overline{P}\rangle\right)}$$

quantum mechanics state mixing

are eigenstates of $\boldsymbol{\Lambda}$ with definite masses, $m_\pm$, and decay widths, $\Gamma_\pm$

$$\zeta = \sqrt{\frac{\Lambda_{21}}{\Lambda_{12}}} = \sqrt{\frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}}}$$

P_+ and P_- decay exponentially

If CP (or T) is conserved,

NB: $\sin[\arg(M_{12}/\Gamma_{12})] = 0$, i.e. $|\Lambda_{12}| = |\Lambda_{21}|$

$$|\zeta| = \sqrt{\left|\frac{\Lambda_{21}}{\Lambda_{12}}\right|} = 1$$

and

$$|\Delta m| = 2|M_{12}|$$

$$|\Delta\Gamma| = 2|\Gamma_{12}|$$

Oscillations between P and $\overline{\text{P}}$

Probability for the initial P remains as P at a given time t:

$$\left|\langle P|P(t)\rangle\right|^2 = \left|f_+(t)\right|^2 = \frac{1}{4}\left(e^{-\Gamma_+ t} + e^{-\Gamma_- t} + 2e^{-\overline{\Gamma} t}\cos\Delta m t\right)$$

Probability for the initial P oscillates to $\overline{\text{P}}$ at a given time t:

$$\left|\langle \overline{P}|P(t)\rangle\right|^2 = \left|\zeta f_-(t)\right|^2 = \frac{|\zeta|^2}{4}\left(e^{-\Gamma_+ t} + e^{-\Gamma_- t} - 2e^{-\overline{\Gamma} t}\cos\Delta m t\right)$$

$$\overline{\Gamma} = \frac{\Gamma_+ + \Gamma_-}{2},\ \Delta m = m_- - m_+$$

Often quoted parameters, x and y

$$x = \frac{\Delta m}{\overline{\Gamma}},\ 2y = \frac{\Gamma_+ - \Gamma_-}{\overline{\Gamma}} \equiv \frac{\Delta\Gamma}{\overline{\Gamma}}$$

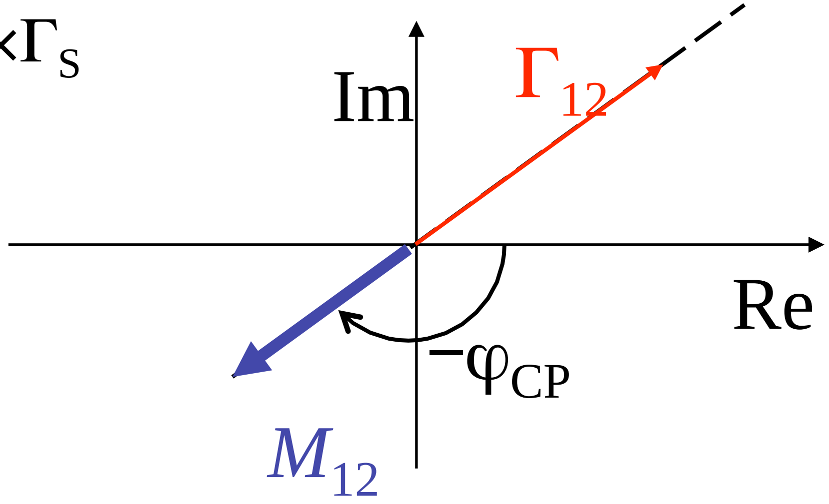
K^0 system: mass eigenstates are K_L and K_S

K_S almost CP=+1

$\Gamma_S = 571\times\Gamma_L$, $\Delta m = m_L - m_S = 0.474\times\Gamma_S$

$$x = \frac{\Delta m}{\overline{\Gamma}} \approx \frac{2\Delta m}{\Gamma_S} \approx 1,\ y = \frac{\Delta\Gamma}{2\overline{\Gamma}} \approx 1$$

Kaon system with a limit of CP conservation

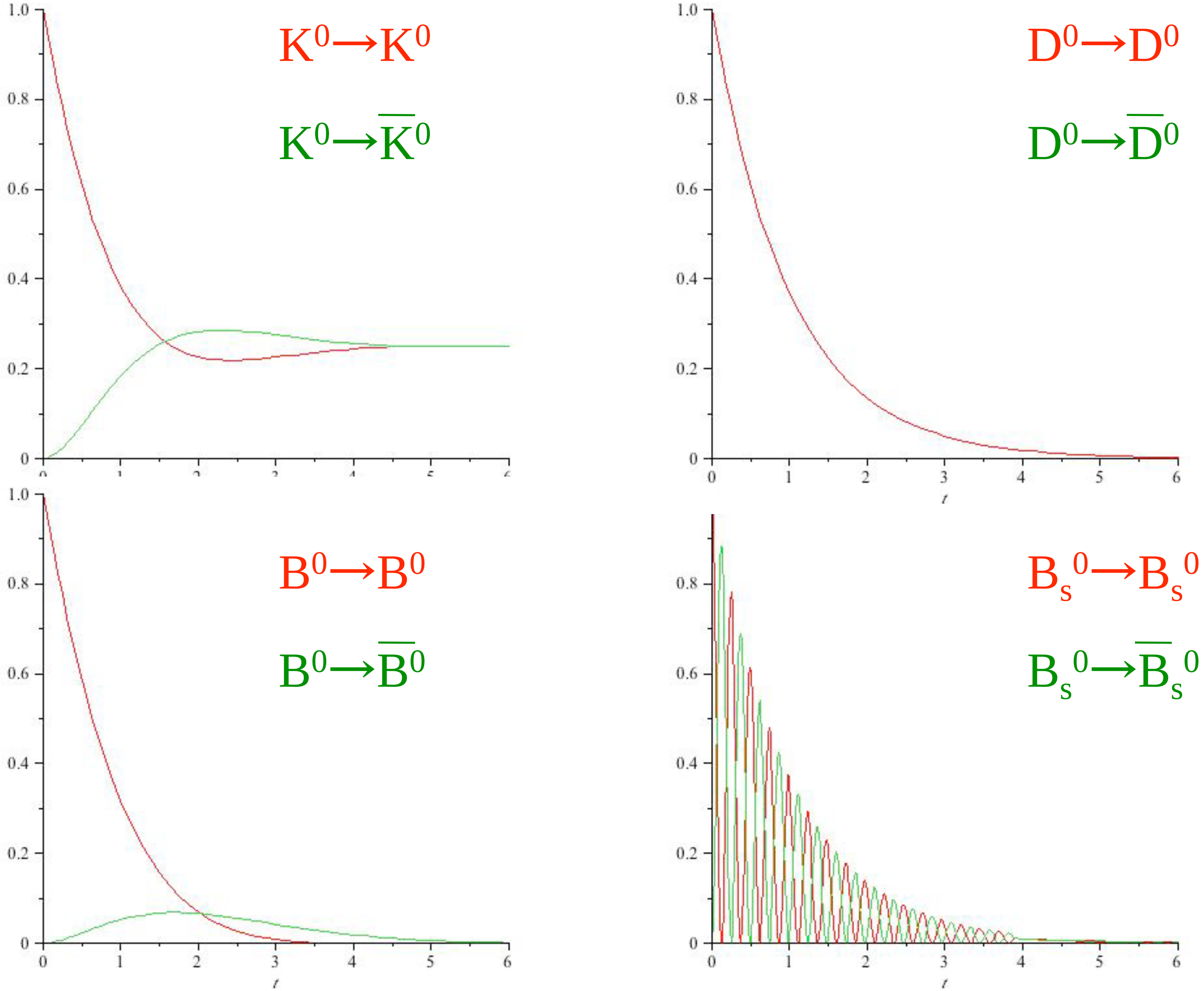


CP=+1 state is lighter and decay faster

D^0 system: $x < 0.03,\ y = 7\times10^{-3}$

B^0 system: $x = 0.776,\ y < 0.09$

Bs system: $x = 25.5,\ y = 0.06$


$K^0 \rightarrow K^0$
$K^0 \rightarrow \overline{K}^0$
$D^0 \rightarrow D^0$
$D^0 \rightarrow \overline{D}^0$
$B^0 \rightarrow B^0$
$B^0 \rightarrow \overline{B}^0$
$B_s{}^0 \rightarrow B_s{}^0$
$B_s{}^0 \rightarrow \overline{B}_s{}^0$
1.0
0.8
0.6
0.4
0.2
0
0 1 2 3 4 5 6
t

Similarly, solutions for $a(t)$ and $b(t)$ with an initial condition, $\overline{\mathrm{P}}$ is produced at t = 0, i.e. $a(0) = 0$, $b(0) = 1$, gives

$$\left|\overline{P}(t)\right\rangle = \frac{1}{\zeta} f_-(t)\left|P\right\rangle + f_+(t)\left|\overline{P}\right\rangle$$

$$= \frac{\sqrt{1+|\zeta|^2}}{2\zeta}\left(e^{-i\lambda_+ t}\left|P_+\right\rangle - e^{-i\lambda_- t}\left|P_-\right\rangle\right)$$

Direct CPT violation observable:

Rates of P at t = 0 remains P at t ⇔ of $\overline{\mathrm{P}}$ at t = 0 remains $\overline{\mathrm{P}}$ at t

Direct CP and T violation observable:

Rates of P at t = 0 oscillates to $\overline{\mathrm{P}}$ at t ⇔ of $\overline{\mathrm{P}}$ at t = 0 oscillates to P at t

$$\left|\left\langle \overline{P} \middle| P(t)\right\rangle\right|^2 = \left|\zeta f_-(t)\right|^2 = \frac{|\zeta|^2}{4}\left(e^{-\Gamma_+ t} + e^{-\Gamma_- t} - 2e^{-\overline{\Gamma} t}\cos\Delta m t\right)$$

$$\left|\left\langle P \middle| \overline{P}(t)\right\rangle\right|^2 = \left|\frac{1}{\zeta} f_-(t)\right|^2 = \frac{1}{4|\zeta|^2}\left(e^{-\Gamma_+ t} + e^{-\Gamma_- t} - 2e^{-\overline{\Gamma} t}\cos\Delta m t\right)$$

Time dependent T and CP asymmetry: $A_T(t)$

$$A_T(t) = \frac{\left|\langle P | \overline{P}(t)\rangle\right|^2 - \left|\langle \overline{P} | P(t)\rangle\right|^2}{\left|\langle P | \overline{P}(t)\rangle\right|^2 + \left|\langle \overline{P} | P(t)\rangle\right|^2}$$

$$= \frac{\frac{1}{|\zeta|^2}\left|f_-(t)\right|^2 - |\zeta|^2\left|f_-(t)\right|^2}{\frac{1}{|\zeta|^2}\left|f_-(t)\right|^2 + |\zeta|^2\left|f_-(t)\right|^2}$$

$$= \frac{1-|\zeta|^4}{1+|\zeta|^4}$$

$A_T(t) \neq 0 \Rightarrow$ observation of T and CP violation in P-$\overline{\mathrm{P}}$ oscillations

done for the neutral kaon system

Identification of the initial state:

Initial state at t = 0: $p\bar{p}$ annihilation at rest

$$\bar{p}p \rightarrow \begin{cases} K^0 K^- \pi^+ \\ \bar{K}^0 K^+ \pi^- \end{cases}$$

S = 0 S = 0

$$K^0 = (d\bar{s}) \quad K^- = (\bar{u}s)$$
$$\bar{K}^0 = (\bar{d}s) \quad K^+ = (u\bar{s})$$

Accompanying charged kaons indicate the flavour of neutral kaons.

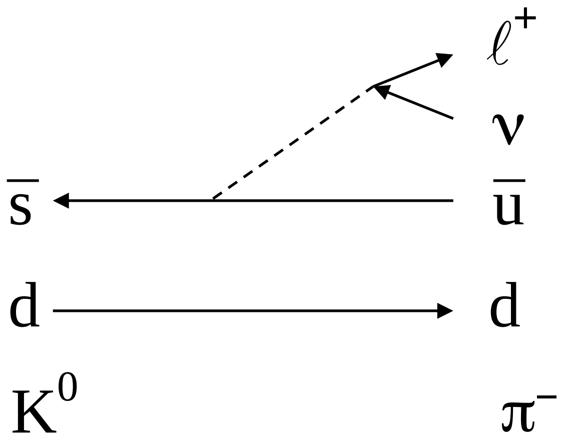
$$\boxed{K^+\pi^- \rightarrow \bar{K}^0,\ K^-\pi^+ \rightarrow K^0}$$

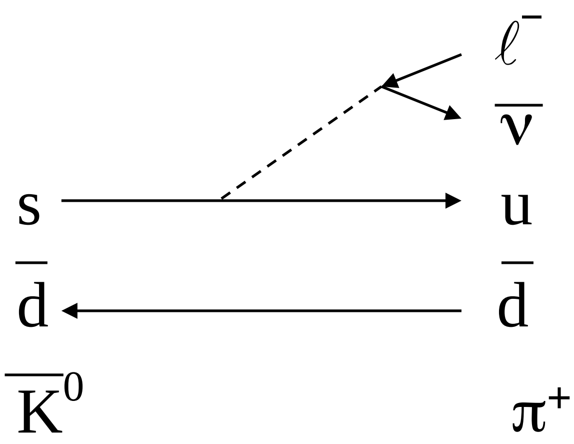
Identification of the final states:

Semileptonic decays are used to directly measure this...

i.e. flavour specific decay modes

$\Delta q = \Delta s$ rule





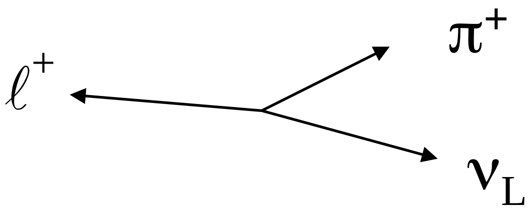
$q = 0$, $s = +1$ → $q = -1$, $s = 0$: $\Delta q = -1$, $\Delta s = -1$

$q = 0$, $s = -1$ → $q = +1$, $s = 0$: $\Delta q = +1$, $\Delta s = +1$

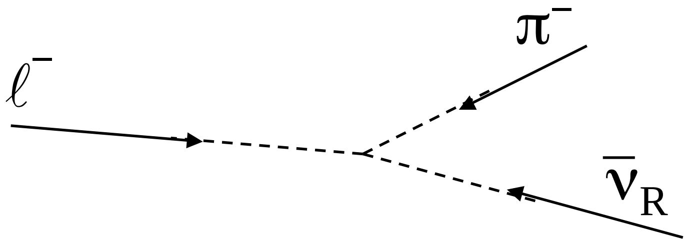
final states are specific to the flavour,

i.e. the particle and the anti-particle

(no hadronic decay mode available for the neutral kaons)



$$\Gamma_{\ell^+\upsilon_L\pi^-} = \int_{\text{phase space}} d\Omega\Big|_{\text{out}} \left| \left\langle \ell^+(p_1)\upsilon_L(p_2)\pi^-(p_3)\middle| H_W \middle| \mathrm{K}^0 \right\rangle \right|^2$$



CPT

$$\int_{\text{phase space}} d\Omega\Big|_{\text{in}} \left| \left\langle \ell^-(-p_1)\overline{\upsilon}_R(-p_2)\pi^+(-p_3)\middle| H_W \middle| \overline{\mathrm{K}}^0 \right\rangle \right|^2$$

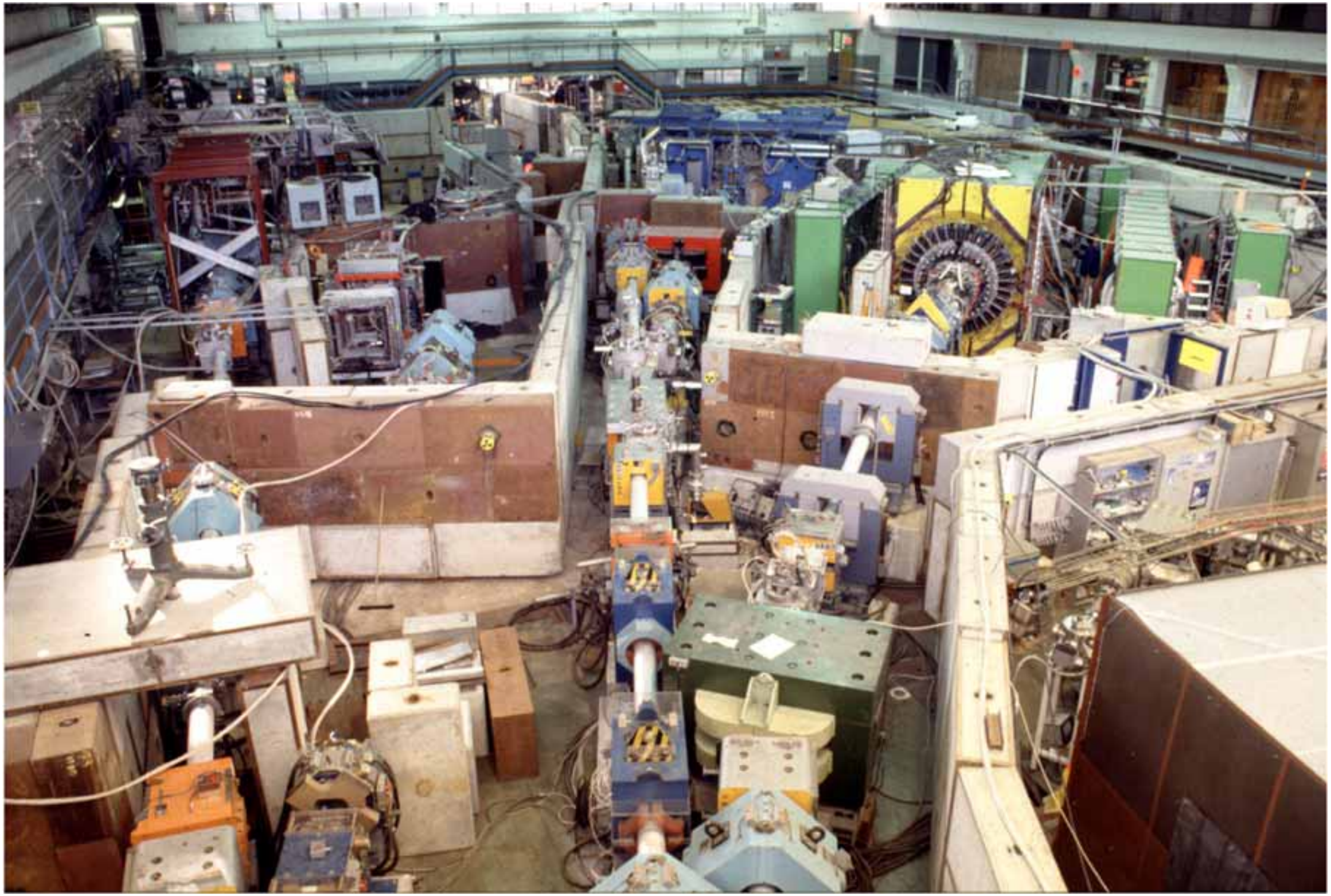
$$= \int_{\text{phase space}} d\Omega\Big|_{\text{out}} \left| \left\langle \ell^-(p_1)\overline{\upsilon}_R(p_2)\pi^+(p_3)\middle| H_W \middle| \overline{\mathrm{K}}^0 \right\rangle \right|^2$$

$$= \overline{\Gamma}_{\ell^-\overline{\nu}_R\pi^+}$$

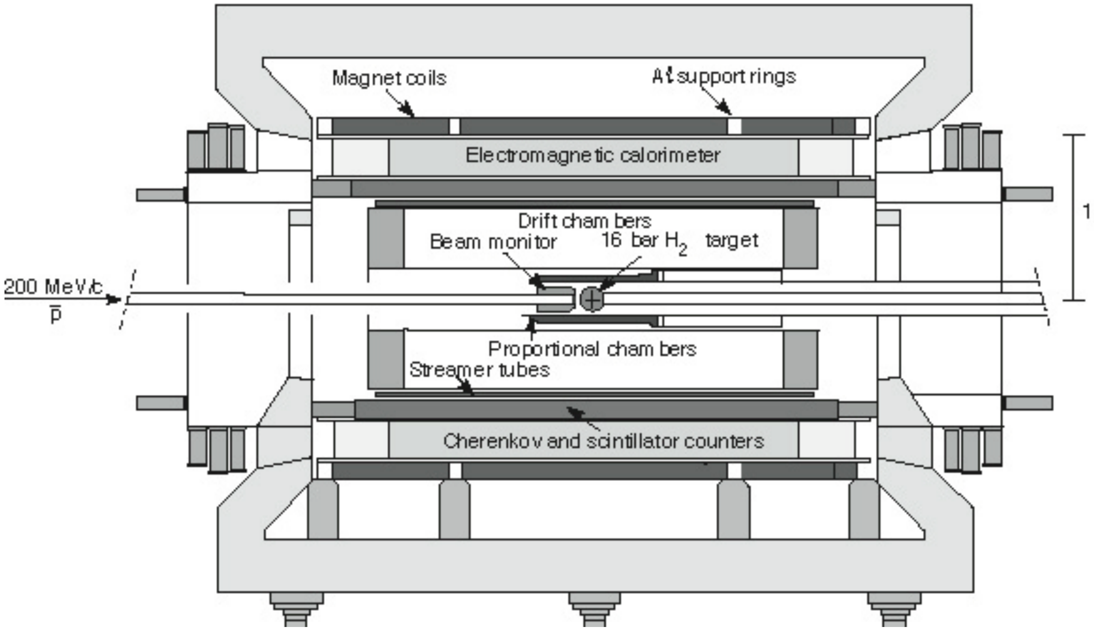
Since the interactions between the final states are weak,

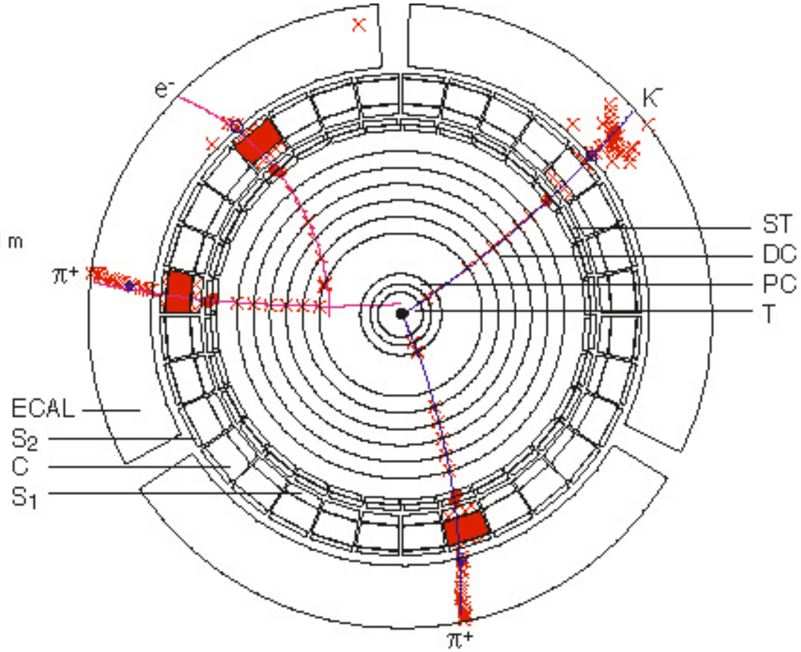
LEAR complex

CPLEAR experiment



CPLEAR experiment



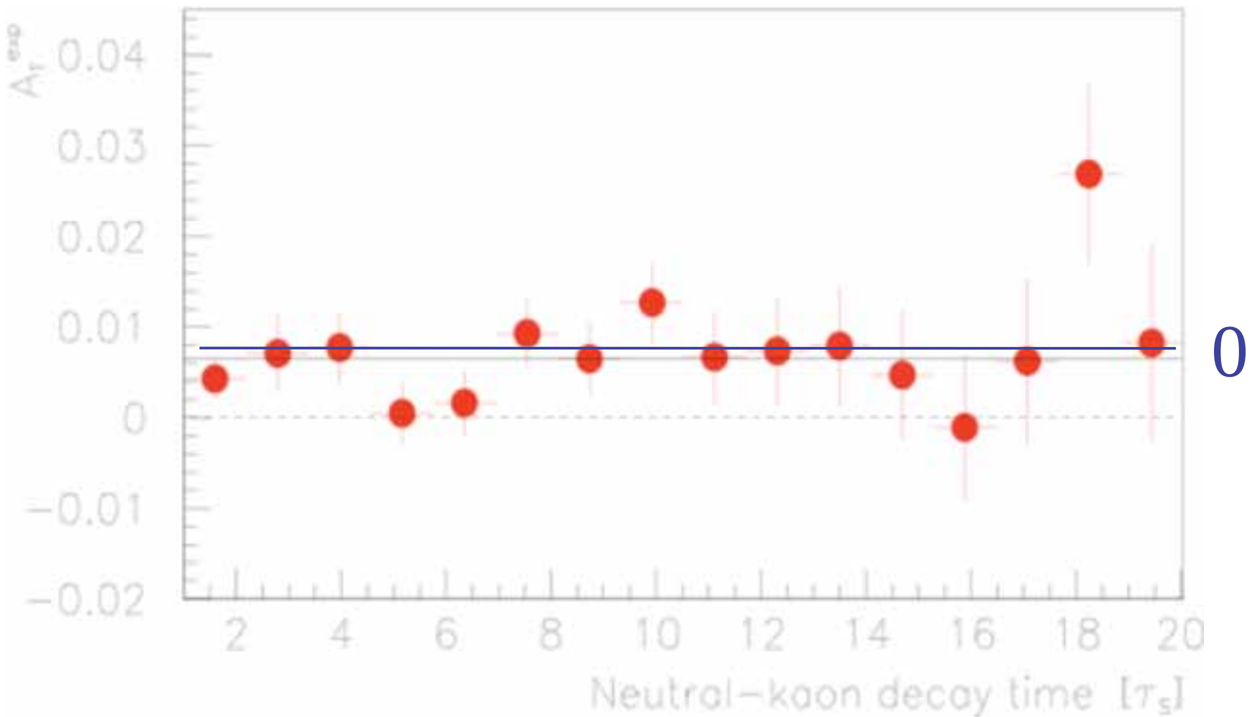


$$p\bar{p} \Rightarrow K^- \pi^+ K^0$$

$$K^0 \rightarrow \overline{K}^0$$

$$\overline{K}^0 \Rightarrow \pi^+ e^- \overline{\nu}$$

$$A_T(t)=\frac{\int d\Omega\left|\left\langle \ell^+\nu_L\pi^-\left|H_W\right|\overline{\mathrm{K}}^0(t)\right\rangle\right|^2-\int d\Omega\left|\left\langle \ell^-\overline{\upsilon}_R\pi^+\left|H_W\right|\mathrm{K}^0(t)\right\rangle\right|^2}{\int d\Omega\left|\left\langle \ell^+\nu_L\pi^-\left|H_W\right|\overline{\mathrm{K}}^0(t)\right\rangle\right|^2+\int d\Omega\left|\left\langle \ell^-\overline{\upsilon}_R\pi^+\left|H_W\right|\mathrm{K}^0(t)\right\rangle\right|^2}$$



$$A_T=(6.6\pm1.6)\times10^{-3}$$

$$A_T(t)=\frac{1-|\zeta|^4}{1+|\zeta|^4} \longrightarrow |\zeta|=0.9967\pm0.0008\neq1$$

Small ~~CP~~ and ~~T~~ in K-$\overline{\mathrm{K}}$ oscillations

Now, including δ_l (CP violating K_L decay lepton charge asymmetry),

$$1-|\zeta| = (3.28 \pm 0.12) \times 10^{-3}$$

From $\zeta = \sqrt{\dfrac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}}}$ and measured Δm and $\Delta\Gamma$

$\sin(\arg M_{12} - \arg \Gamma_{12}) = (6.57 \pm 0.24) \times 10^{-3}$, i.e. $\mathrm{Im}(M_{12}/\Gamma_{12}) \ll 1$

M_{12} and Γ_{12} are not exactly back to back

⇒ even with CP violation

$|\Delta m|=2|M_{12}|$ and $|\Delta\Gamma|=2|\Gamma_{12}|$ are still good for the neutral kaons.

NB:

For the B system, $|\Gamma_{12}|/|M_{12}| \ll 1$, with the SM (and smaller if exists new physics). Even with CP violation, $|\Delta m|=2|M_{12}|$ is a good approximation and $|\Delta\Gamma| = 2|\,\Gamma_{12}\,\{\cos[\arg(\Gamma_{12}/M_{12})]\}\,|$

Most general case…

Time dependent decay rates for a final state f.

Initially P $$R_{\mathrm{f}}(t)=\left|\langle \mathrm{f}|H_W|P(t)\rangle\right|^2=\frac{\left|A_{\mathrm{f}}\right|^2}{2}e^{-\overline{\Gamma}t}\left\{I_+^{\mathrm{f}}(t)+I_-^{\mathrm{f}}(t)\right\}$$

$$I_+^{\mathrm{f}}(t)=\left(1+\left|L_{\mathrm{f}}\right|^2\right)\cosh\frac{\Delta\Gamma}{2}t+2\,\mathrm{Re}\,L_{\mathrm{f}}\sinh\frac{\Delta\Gamma}{2}t$$

$$I_-^{\mathrm{f}}(t)=\left(1-\left|L_{\mathrm{f}}\right|^2\right)\cos\Delta mt+2\,\mathrm{Im}\,L_{\mathrm{f}}\sin\Delta mt$$

$$L_{\mathrm{f}}=\zeta\frac{\overline{A}_{\mathrm{f}}}{A_{\mathrm{f}}}$$

Initially $\overline{\mathrm{P}}$ $$\overline{R}_{\mathrm{f}}(t)=\left|\langle \mathrm{f}|H_W|\overline{P}(t)\rangle\right|^2=\frac{\left|A_{\mathrm{f}}\right|^2}{2\left|\zeta\right|^2}e^{-\overline{\Gamma}t}\left\{I_+^{\mathrm{f}}(t)-I_-^{\mathrm{f}}(t)\right\}$$

Time dependent decay rates for a CP conjugated final state $\overline{\mathrm{f}}$.

Initially P $$R_{\overline{\mathrm{f}}}(t)=\frac{\left|A_{\overline{\mathrm{f}}}\right|^2}{2}e^{-\overline{\Gamma}t}\left\{I_+^{\overline{\mathrm{f}}}(t)+I_-^{\overline{\mathrm{f}}}(t)\right\}$$

Initially $\overline{\mathrm{P}}$ $$\overline{R}_{\overline{\mathrm{f}}}(t)=\frac{\left|A_{\overline{\mathrm{f}}}\right|^2}{2\left|\zeta\right|^2}e^{-\overline{\Gamma}t}\left\{I_+^{\overline{\mathrm{f}}}(t)-I_-^{\overline{\mathrm{f}}}(t)\right\}$$

$$L_{\overline{\mathrm{f}}}=\zeta\frac{\overline{A}_{\overline{\mathrm{f}}}}{A_{\overline{\mathrm{f}}}}$$

CP conjugation $R_{\mathrm{f}}(t)\Leftrightarrow\overline{R}_{\overline{\mathrm{f}}}(t)$ and $R_{\overline{\mathrm{f}}}(t)\Leftrightarrow\overline{R}_{\mathrm{f}}(t)$

For hadronic decays of the neutral kaon system, f can only be a pure CP eigenstate, such as $\pi^+\pi^-$ (or a mixed CP eigenstate as $\pi^+\pi^-\pi^0$):

$$f = \overline{f} = f^{CP}$$

In the case for the neutral D and B systems, f can be

$f = \bar{f} = f^{CP}$

$D \to \pi^+\pi^-$, K^+K^-

$B \to \pi^+\pi^-$, $J/\psi K_S$, etc. $B_s \to K^+K^-$, $J/\psi\phi$ (CP=+1 and −1), etc.

In the case for the neutral D and B systems, f can be

$f = \bar{f} = f^{CP}$

$D \rightarrow \pi^+\pi^-$, K^+K^-

$B \rightarrow \pi^+\pi^-$, $J/\psi K_S$, etc. $B_s \rightarrow K^+K^-$, $J/\psi\phi$ (CP=+1 and −1), etc.

or non CP eigenstates:

D^0 $\rightarrow$	$K^-\pi^+$	$\leftarrow$ $\bar{D}^0$	*one amplitude is very suppressed than others*
$c \rightarrow s + W^+(u\bar{d})$		$\bar{c} \rightarrow \bar{d} + W^-(\bar{u}s)$	
B_s^0 $\rightarrow$	$D_s^-K^+$	$\leftarrow$ $\bar{B}_s^0$	*both amplitudes are similar size*
$\bar{b} \rightarrow \bar{c} + W^+(u\bar{s})$		$b \rightarrow u + W^-(\bar{u}d)$	

In the case of the neutral B system, there exists flavour specific hadronic final states (a la semileptonic decay):

$B \rightarrow D^{-}\pi^{+}$, $B_s^0 \rightarrow D_s^{-}\pi^{+}$, etc. *ideal for the oscillation study*

For hadronic decays of the neutral kaon system, f can only be a pure CP eigenstate, such as $\pi^+\pi^-$ (or a mixed CP eigenstate as $\pi^+\pi^-\pi^0$):

$$f = \overline{f} = f^{CP}$$

In the case for the neutral D and B systems, f can be

$$f = \overline{f} = f^{CP}$$

$D \to \pi^+\pi^-$, K^+K^-

$B \to \pi^+\pi^-$, $J/\psi K_S$, etc. $B_s \to K^+K^-$, $J/\psi\phi$ (CP=+1 and −1), etc.

or non CP eigenstates:

D^0	$\to$	$K^-\pi^+$	$\leftarrow$	$\overline{D}^0$	*one amplitude is very suppressed than others*
$c \to s + W^+(u\overline{d})$				$\overline{c} \to \overline{d} + W^-(\overline{u}s)$	
B_s^0	$\to$	$D_s^-K^+$	$\leftarrow$	$\overline{B}_s^0$	*both amplitudes are similar size*
$\overline{b} \to \overline{c} + W^+(u\overline{s})$				$b \to u + W^-(\overline{u}d)$	

In the case of the neutral B system, there exists flavour specific hadronic final states (a la semileptonic decay):

$B \to D^-\pi^+$, $B_s^0 \to D_s^-\pi^+$, etc. *ideal for the oscillation study*

For CP eigenstates,

$$L_{f^{CP}} = \zeta \frac{\overline{A}_{f^{CP}}}{A_{f^{CP}}}$$

Initially P

$$R_{f^{CP}}(\tau) = \frac{\left|A_{f^{CP}}\right|^2}{2} e^{-\tau}\left\{ I_+^{f^{CP}}(\tau) + I_-^{f^{CP}}(\tau) \right\}$$

$$I_+^{f^{CP}}(\tau) = \left(1 + \left|L_{f^{CP}}\right|^2\right)\cosh(y\tau) + 2\,\mathrm{Re}\,L_f \sinh(y\tau)$$

$$I_-^{f^{CP}}(\tau) = \left(1 - \left|L_{f^{CP}}\right|^2\right)\cos(x\tau) + 2\,\mathrm{Im}\,L_f \sin(x\tau)$$

Initially $\overline{\mathrm{P}}$

$$\overline{R}_{f^{CP}}(\tau) = \frac{\left|A_{f^{CP}}\right|^2}{2\left|\zeta\right|^2} e^{-\tau}\left\{ I_+^{f^{CP}}(\tau) - I_-^{f^{CP}}(\tau) \right\}$$

$\tau = t/\overline{\Gamma}$: time in the unit of the average lifetime

K: x and $y = O(1)$

B_d: $y \approx 0$, i.e. cosh = 1 and sinh = 0, CPV in oscillations ignored, $|\zeta| = 1$

B_s: $y < 1$ but not ignored, CPV in oscillations ignored, $|\zeta| = 1$

For the D system, one does more complicated treatment… (why?)

$y\tau \ll 1$ and $x\tau \ll 1$ and take up to the first order

Assuming CP conservation,

$$I_+^{\mathrm{f}^{CP}}(\tau) = \left(1 + \left|L_{\mathrm{f}^{CP}}\right|^2\right)\cosh(y\tau) + 2\,\mathrm{Re}\,L_{\mathrm{f}^{CP}}\sinh(y\tau) \approx 2(1 + y\tau) \approx 2e^{y\tau}$$

$$I_-^{\mathrm{f}^{CP}}(\tau) = \left(1 - \left|L_{\mathrm{f}^{CP}}\right|^2\right)\cos(x\tau) + 2\,\mathrm{Im}\,L_{\mathrm{f}}\sin(x\tau) = 0$$

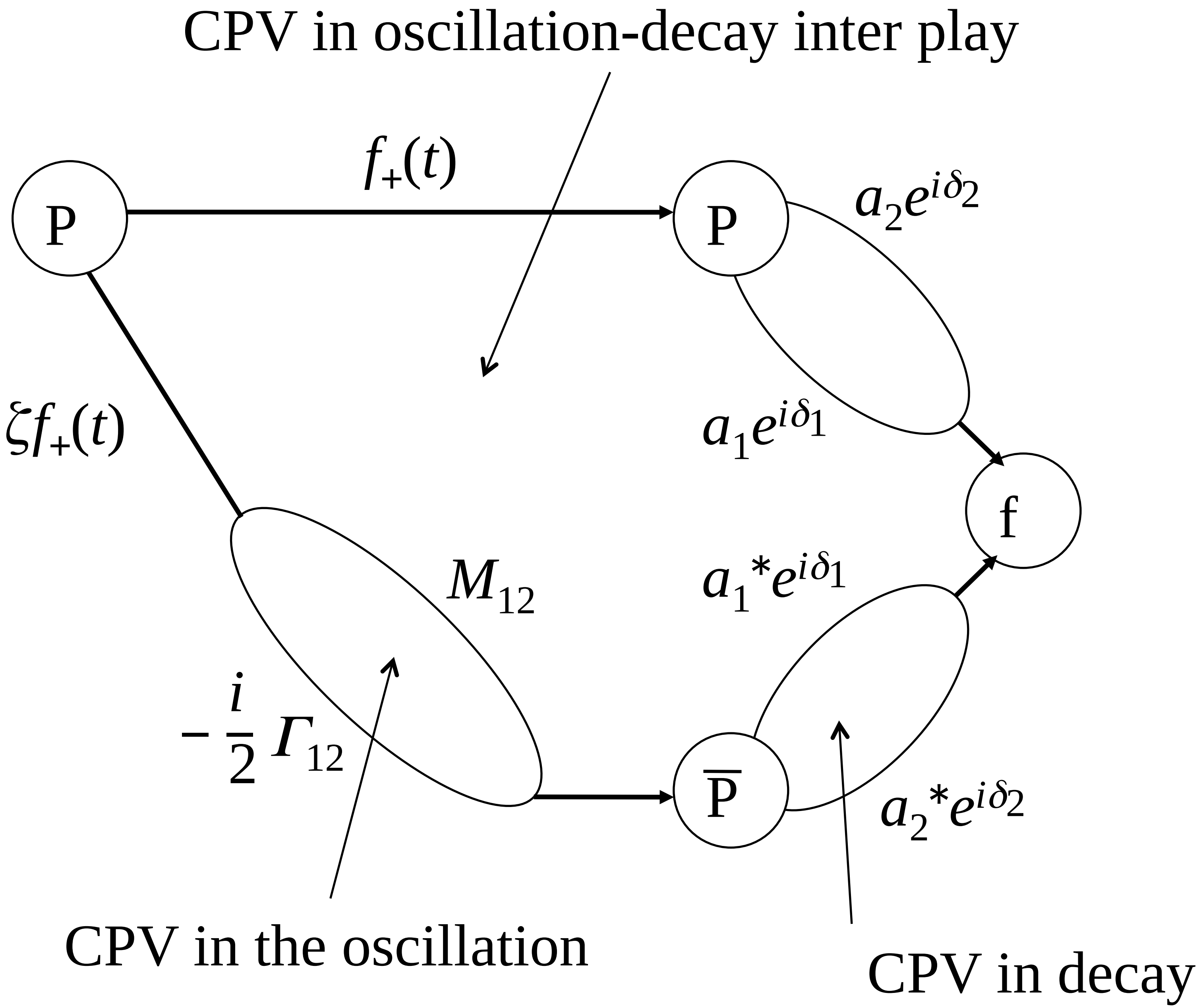
$$\Rightarrow R_{\mathrm{f}^{CP}} \propto (\tau) \propto e^{-(1-y)\tau}$$ measured lifetime is "shifted"

For the D^0 at $t = 0$ decaying in to $K^-\pi^+$, $|L_{K^-\pi^+}| = 1/(\sin\theta_{\mathrm{Cabibbo}})^2 \gg 1$

Assuming CP conservation

$$I_+^{K^-\pi^+}(\tau) + I_-^{K^-\pi^+}(\tau) = 2$$

$$\Rightarrow R_{K^-\pi^+}(\tau) \propto e^{-\tau}$$ measure average lifetime


CPV in oscillation-decay inter play
$f_+(t)$
P
P
$a_2 e^{i\delta_2}$
$\zeta f_+(t)$
$a_1 e^{i\delta_1}$
f
M_{12}
$a_1^* e^{i\delta_1}$
$-\frac{i}{2}\Gamma_{12}$
$\overline{\mathrm{P}}$
$a_2^* e^{i\delta_2}$
CPV in the oscillation
CPV in decay

Quark Flavour Physics Experiments

General observation

Hadron machines have been "discovery" machines,

e.g. charm, beauty, W, Z, and top

CP violation in the kaon system mainly studied at hadron machines

plus some contribution from KLOE

Charm mesons have been successfully exploited by

both fixed target hadron beams and e^+e^- storage rings.

Fixed target charm experiments

Important breakthrough in the middle of 80's:
large number of fully reconstructed D mesons
from the hadronic decays

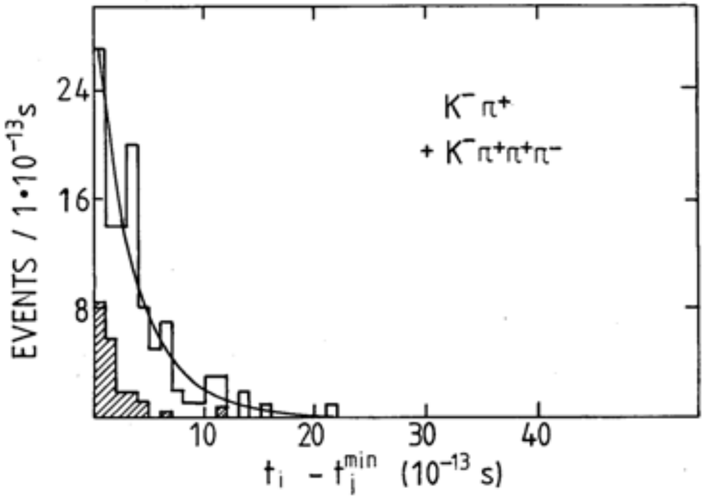
using
Si micro-strip vertex detector and open trigger

$$\frac{\sigma_{c\bar{c}}}{\sigma_{\text{inelastic}}} \approx 10^{-3}$$

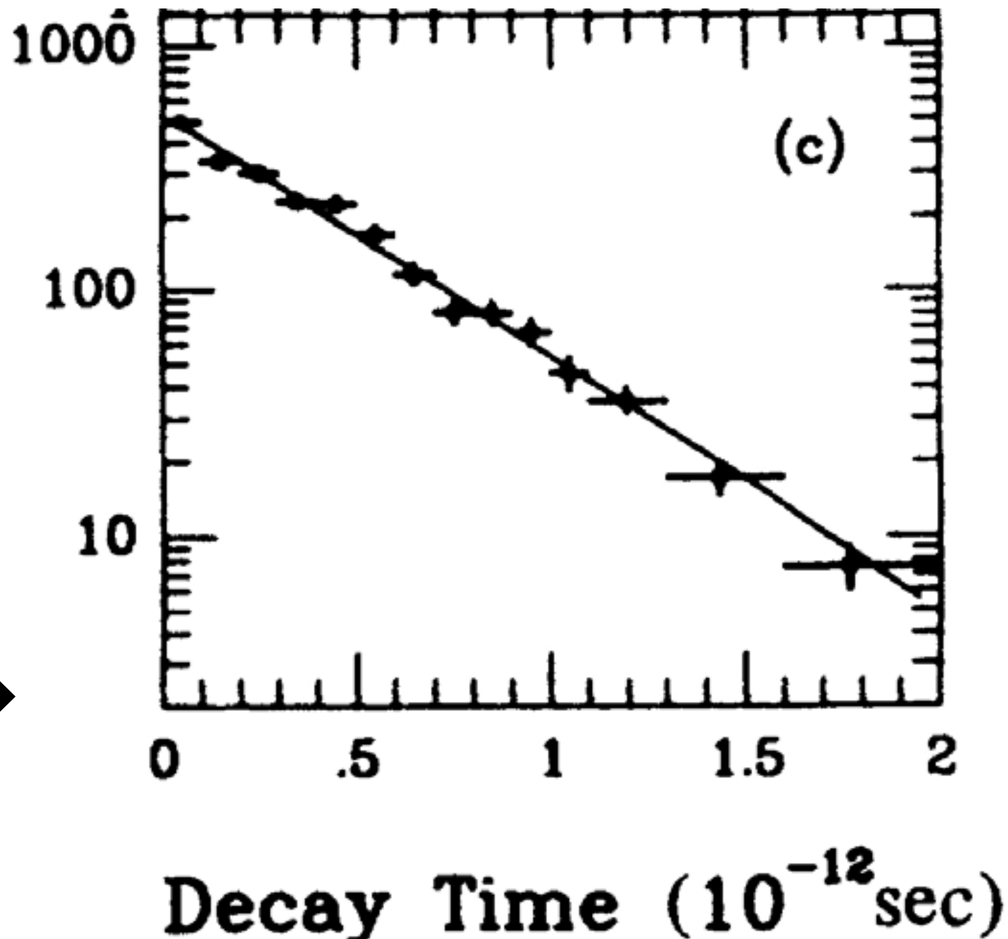
Large amount of data processed by a custom made microprocessor farm

An example: D^0 lifetime

200 GeV/c K and π beam
ACCMOR 1987



Tagged photon beam
E691 1988

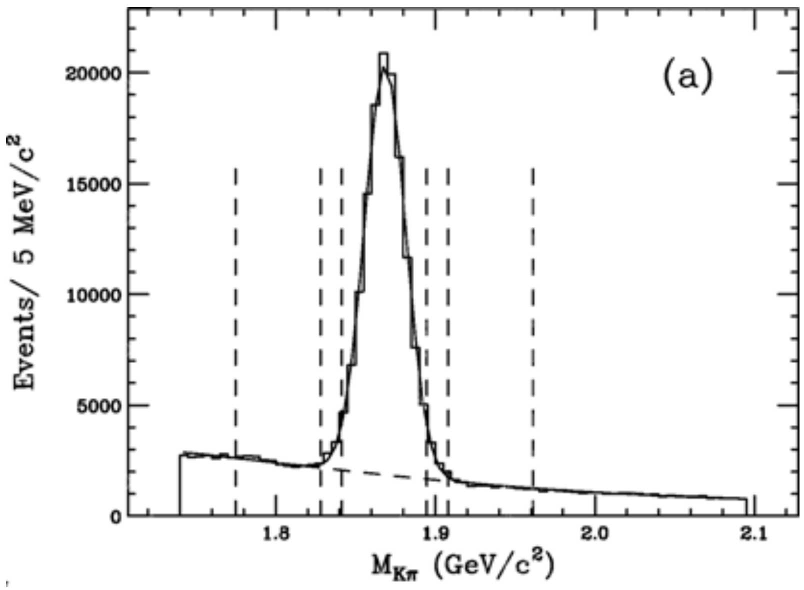


factor ~50 in statistics →

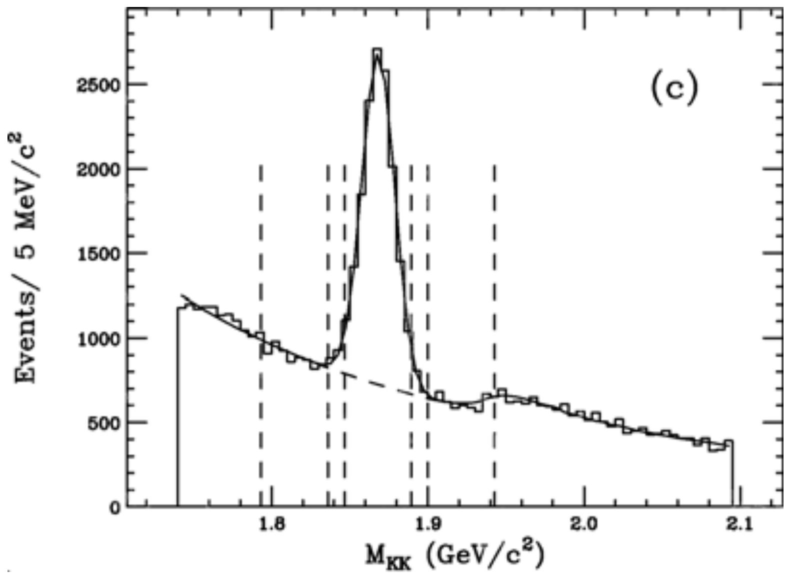
The la(te)st generation of fixed target charm experiments

	beam	statistics	average σ_t
E791	500 GeV π	10^5	40 fs
Focus	up to 300 Gev γ	10^6	30 fs
Selex	600 GeV Σ, π, p	10^4	20 fs

Focus



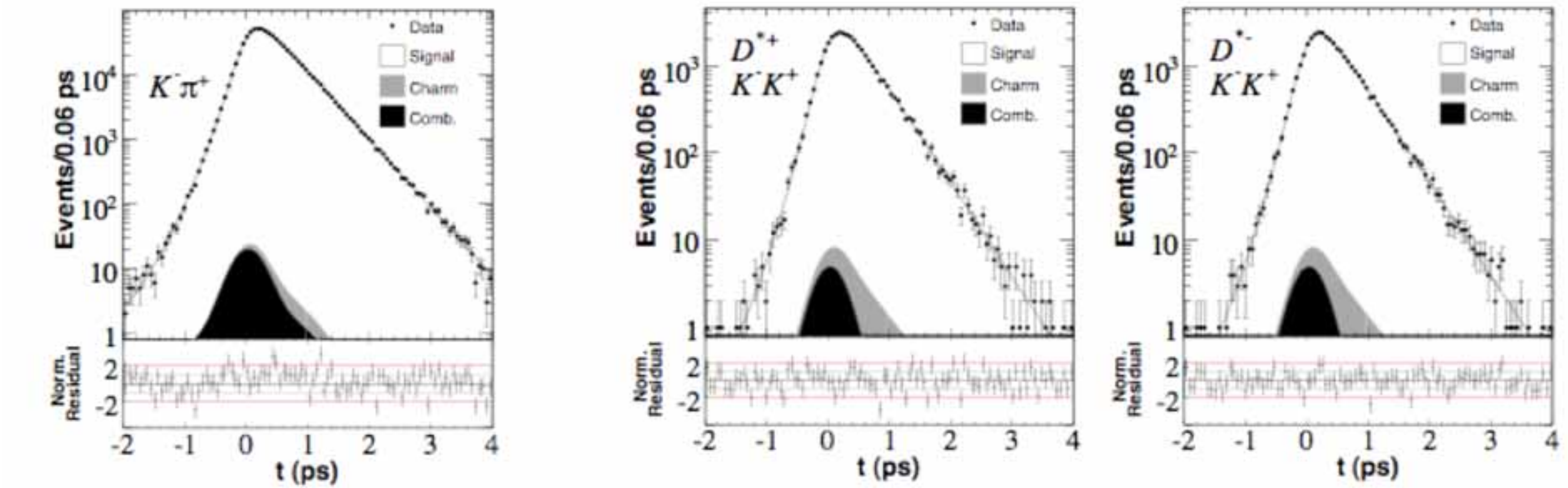
$D^0 \rightarrow K^- \pi^-$ 119738 evts



$D^0 \rightarrow K^+ K^-$ 10331 evts

Remaining big issues are, oscillations and CPV

BABAR lifetime measurements



y(BBAR+BELLE+others) = 0.01132±0.00266

This is more "state mixing".

$\Delta\Gamma$: totally dominated by the long range interactions

Δm: dominant contribution from the long rage interactions

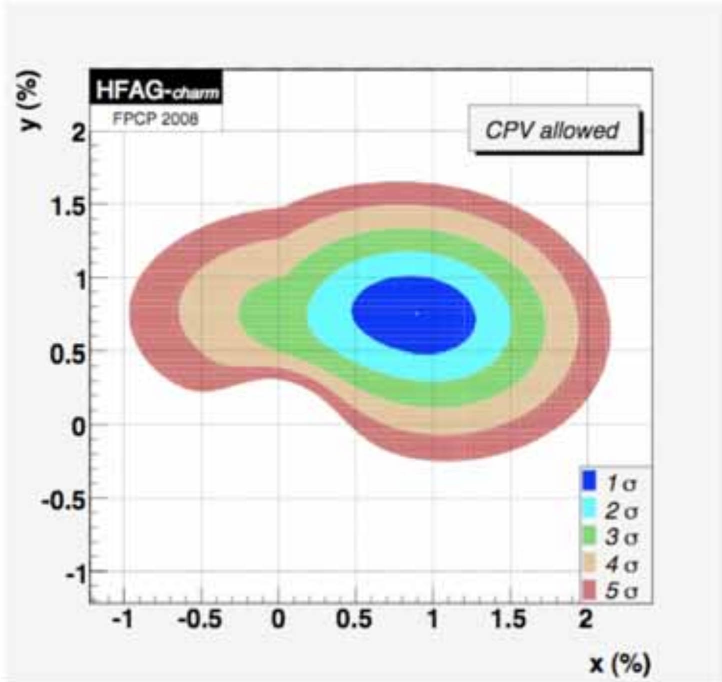
CP violation: due to short range interactions

$\Rightarrow$values of $\Delta\Gamma$ and Δm themselves are not too important

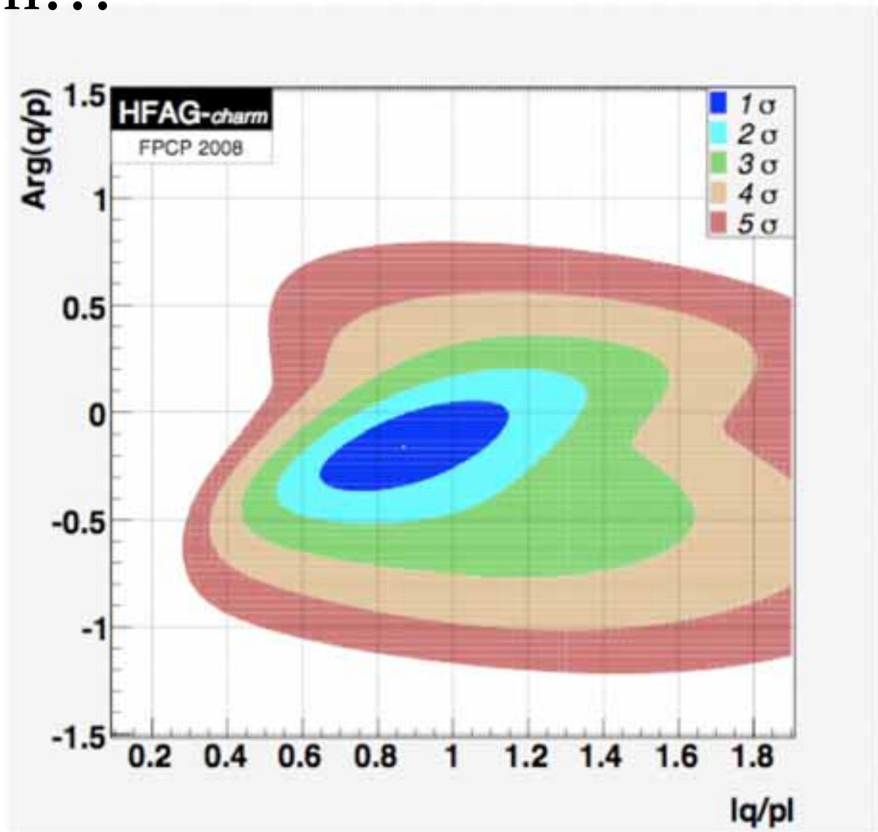
but being able to observe oscillations is an important step to see CP violation.

Better study time dependent decay rates fit for

$D^0_{\tau=0} \to K^+\pi^-(\tau)$ (DCSD or oscillation) or $K_S\pi^+\pi^-$



and CP violation…



CP violation in D→KK and ππ decays

BELLE

$$A_{CP}^{KK} = (-0.41 \pm 0.30 \pm 0.11)\,\% \qquad A_{CP}^{KK} = (0.00 \pm 0.34 \pm 0.13)\,\%$$

$$A_{CP}^{\pi\pi} = (+0.41 \pm 0.52 \pm 0.12)\,\% \qquad A_{CP}^{\pi\pi} = (-0.24 \pm 0.52 \pm 0.22)\,\%$$

After the the discovery of ϒ resonances ($b\bar{b}$ S states) by hadron machine

For many years, B meson study had been dominated by
DORIS, CESR, VEPP and LEP
i.e. at e^+e^- machines
Experiments at hadron machines, fixed target, were “limited”

CERN: Beatrice FNAL:E866/E789/E772, E771
b cross section measurements (with large error bars)
→ simply not enough b's and too small $\sigma_b/\sigma_{inelastic}$

The success of e^+e^- machines continued by PEP-II with BABAR experiment and KEKB with BELLE experiment.

Tevatron experiments (CDF particular) become competitive in some area, e.g. CPV in $B_d \to J/\psi K_S$, and has recently made some unique contributions, i.e. Δm_s measurements and study of CPV in $B_s \to J/\psi\phi$

Current flavour physics situation can be summarised by

We have already a quite complete picture of mass and flavour mixing, in the Standard Model.

$\Downarrow$

The major goal of the future quark flavour physics is to look for flavour changing beyond the Standard Model appearing in the loop processes.

-increased penguin and/or box contributions appearing in branching fractions, oscillation frequencies and/or CP violation, with or without additional mixing parameters

-deviation from the $V-A$ structure

Current Standard Model determination of $|V_{ub}/V_{cb}|$ is limited by the strong interaction theory.

Current Standard Model determination of $|V_{td}/V_{ts}|$ from $\Delta m_d/\Delta m_s$ are limited by the strong interaction theory.
(experimental errors on Δm's are small: $<1\%$)
Theoretical error for $|V_{td}|$ ($|V_{ts}|$) from Δm_d (Δm_s) alone is even much larger, while New Physics may produce
$\mathrm{Box}_d = \mathrm{Box}_d^{SM}(1+d)$, $\mathrm{Box}_s = \mathrm{Box}_s^{SM}(1+d)$
i.e. $\Delta m = |\mathrm{Box}| \neq |\mathrm{Box}^{SM}|$ but $\Delta m_d/\Delta m_s = |\mathrm{Box}_d^{SM}/\mathrm{Box}_s^{SM}|$
(For the penguin modes ($\rho\gamma/K^*\gamma$), experimental errors are still large but will improve, e.g. with LHCb, but theory?)

How much could this be improved? What is still needed from the experiments to improve the theory of hadronic interactions; from BABAR and BELLE then beyond?

arg V_{td} (from J/ψ K_S etc.) experimentally limited, but already good, 1° error; will still improve

For New Physics with $\mathrm{Box}_d = \mathrm{Box}_d^{SM}(1+d)$ however

$$\not{CP}_{J/\psi K_S} = \not{CP}_{J/\psi K_S}^{SM}$$

and even $P=P^{SM}(1+d')$, i.e.

$\not{CP}_{\phi K_S} = \not{CP}_{\phi K_S}^{SM}$, independent check with B_s?

arg V_{ub} experimentally limited with still large error, ~25°, from B→DK$^{(*)}$ decays.

High statistics data essential to make a progress since this is not affected by New Physics. Independent check with B_s.

Understanding of D decays could become a limitation:
CELO-c data will be very important

arg V_{td} + arg V_{ub}, experimental error is large, 10°, a combined error with $B \rightarrow \pi\pi$, $\rho\pi$, $\rho\rho$; tree+penguin+box $\rho\pi$ channel seems particularly attractive for future measurements

> $B \rightarrow 3\pi$ decay description could become a limitation; extra resonances, non-resonant contribution etc. **Any theoretical help?**

CP violation in the decay amplitude in B decays already observed in $B \rightarrow \pi\pi$ and $K\pi$ decays. Theoretical interpretation difficult. Huge statistics for hh′ channels will be available.

> Even for New Physics makes only $P^{NP}=P^{SM}(1+d)$, i.e. no new mixing parameters,
> $|T+P^{NP}| \neq |T+P^{SM}|$ and $\not{CP} \neq \not{CP}^{SM}$
> **Can theory make better predictions?**

First attempt to prove the Lorentz structure in $b \rightarrow s$ penguin process with $B \rightarrow K^{(*0)} l^+ l^-$ decays done; low statistics

208 fb^{-1} BABAR 101 events

357 fb^{-1} BELLE 209 events

~1000 events by 2009?

In general, polarization of γ can be measured by:

$l^+ l^-$ angular distribution in $B \rightarrow K^*$+virtual-$\gamma(\rightarrow l^+ l^-)$ Melikhov et al.

$e^+ e^-$ angular distribution in $B \rightarrow K^*$+real-γ with γ conversion

Grossman et al.

-small statistics

$K\pi\pi$ angular distribution in $B \rightarrow \gamma K^{**}(\rightarrow K\pi\pi)$ final state Gronau et al .

and more theoretical studies are on going.

New Physics with no new mixing parameters would affect this.

B physics at LHC collider mode

Large b cross section (~500μb)

Large $\sigma_{b\bar{b}} / \sigma_{\mathrm{inelastic}}$ (>10^{-3})

at fixed target energies 10^{-6}

$\approx \sigma_{c\bar{c}} / \sigma_{\mathrm{inelastic}}$ at fixed target energies

Different b-hadrons (B_u, B_d, B_s, B_c, Λ_b, Σ_b, Ξ_b etc.)

Many primary particles → well defined b production vertex

To fight against combinatorial backgrounds:

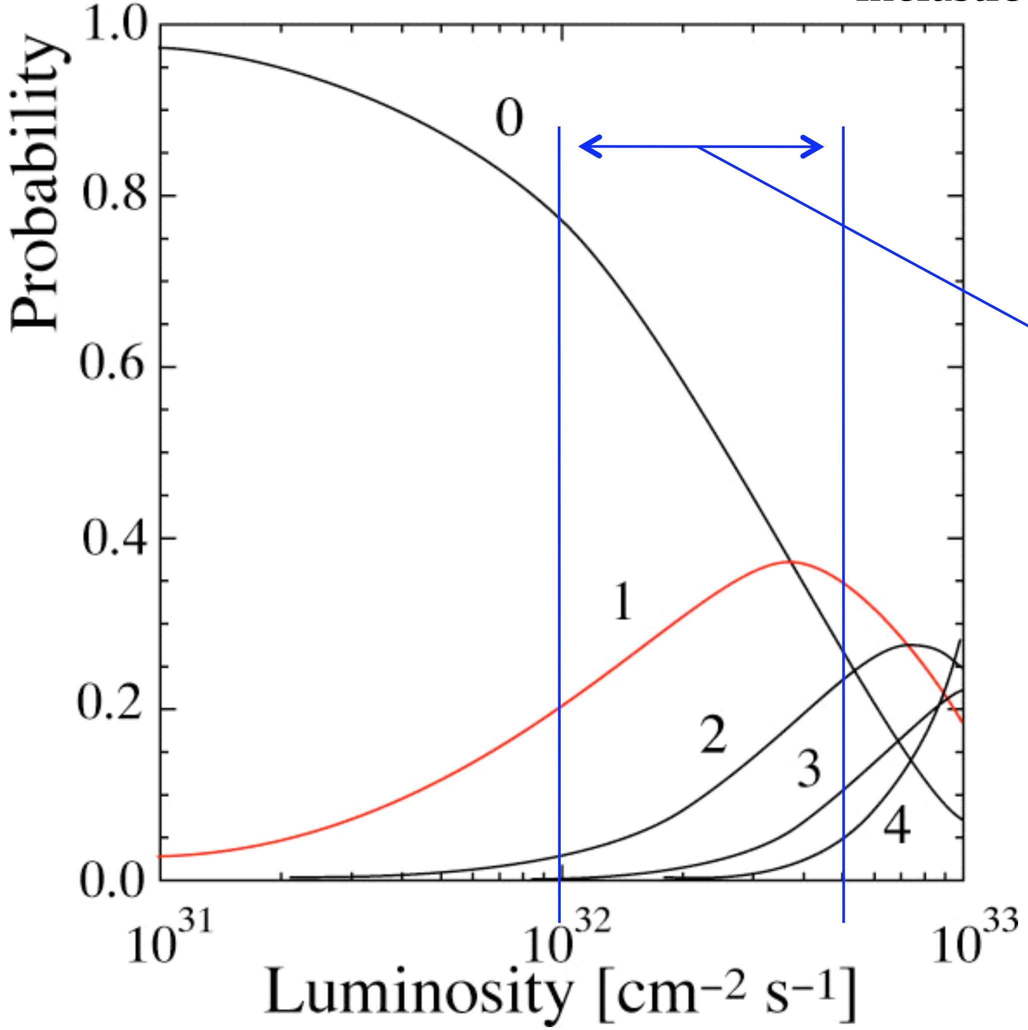
vertexing, PID, and mass resolution

Completely open trigger a la charm fixed-target experiment
- is not an option at LHC
  - too high inelastic event rate
  - interesting decay modes are restricted

Trigger is crucial
- At the first level
  - inclusive signature: p_{T} and displaced tracks/vertices
  - but with very low rejection…
- At the intermediate level
  - semi-exclusive partial reconstruction
- Finally
  - exclusive reconstruction

Bunch crossing frequency: f_{pp} = 40 MHz, i.e. every 25 nsec

Number of pp inelastic interactions in one bunch crossing ($\sigma_{inelastic}$ = 80 mb), 0, 1, 2 …

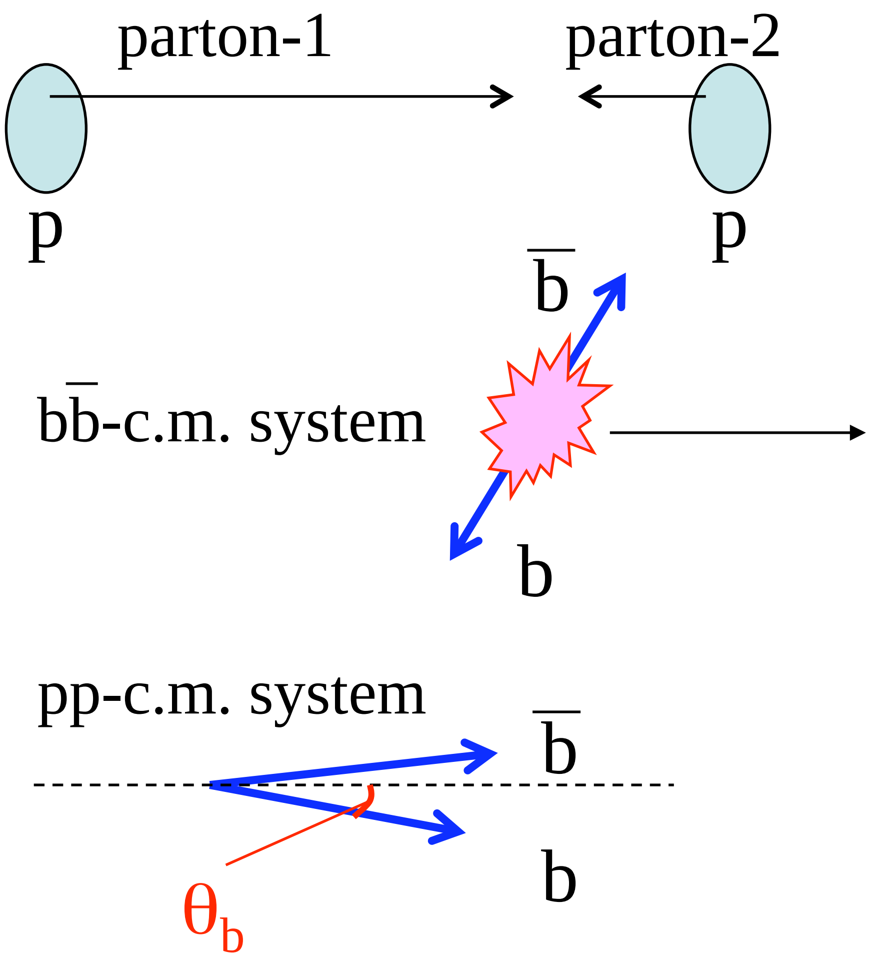


One inelastic interaction per bunch crossing dominates.

- Reconstruction easier (final state and tag)
- Lower radiation level

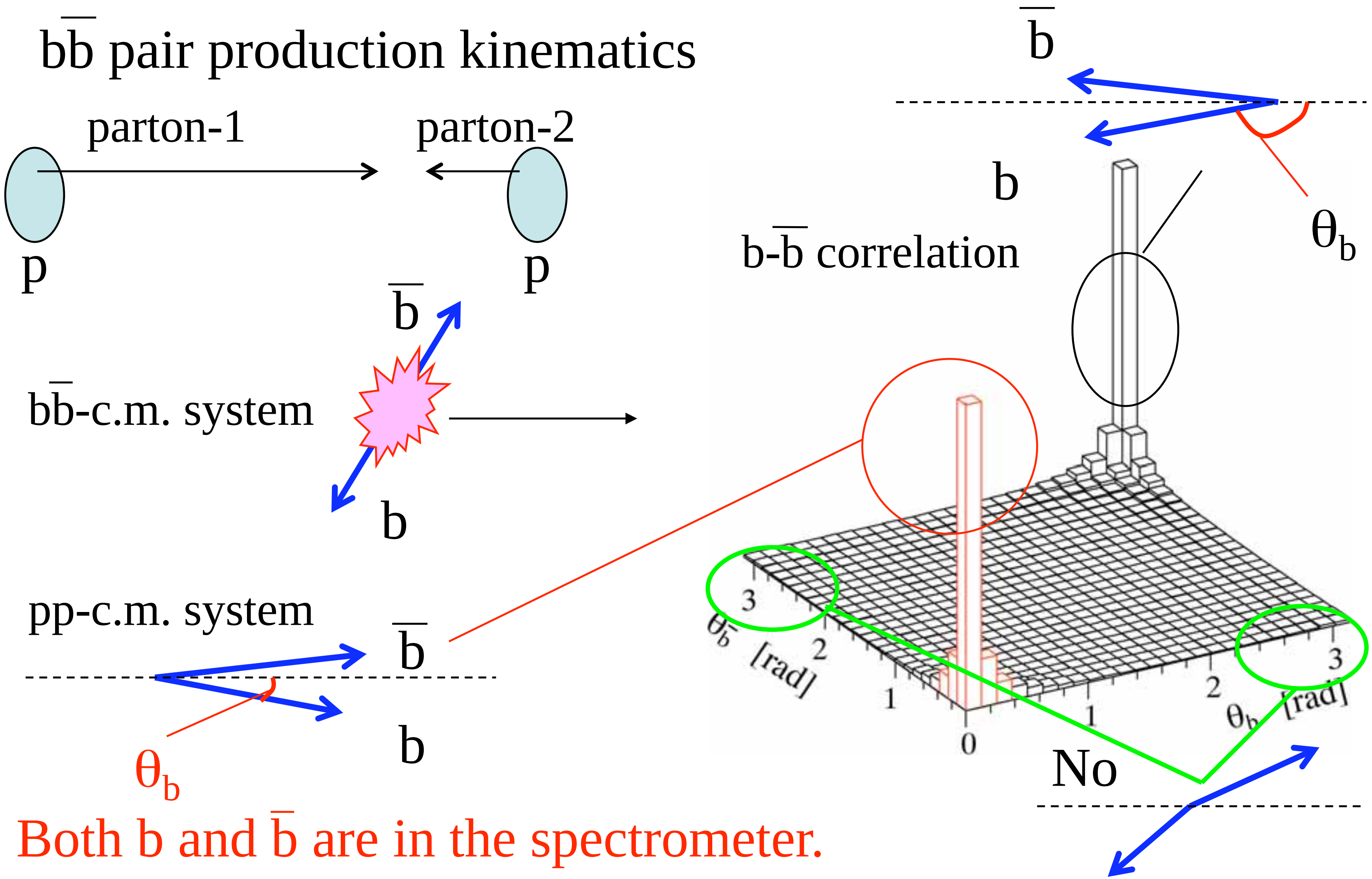
Forward geometry

$b\bar{b}$ pair production kinematics



Forward geometry

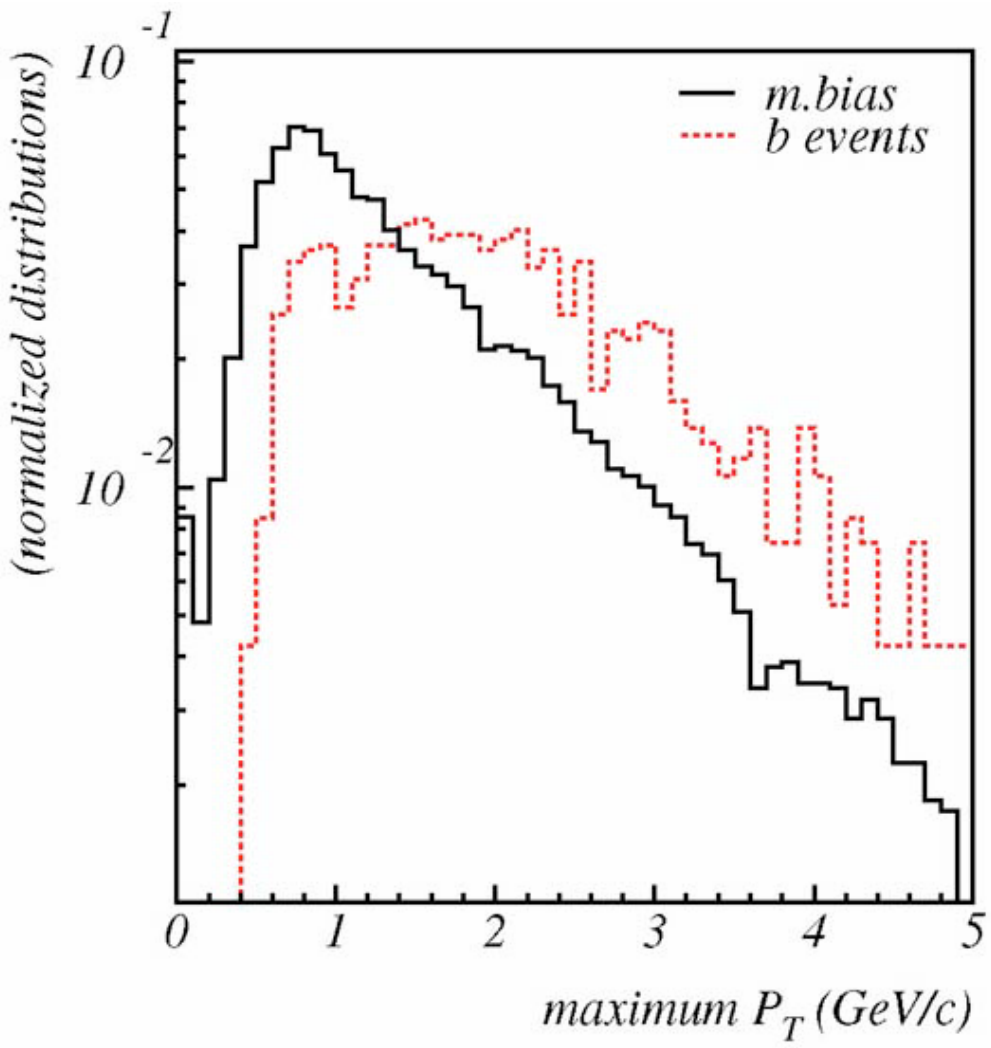
$b\bar{b}$ pair production kinematics

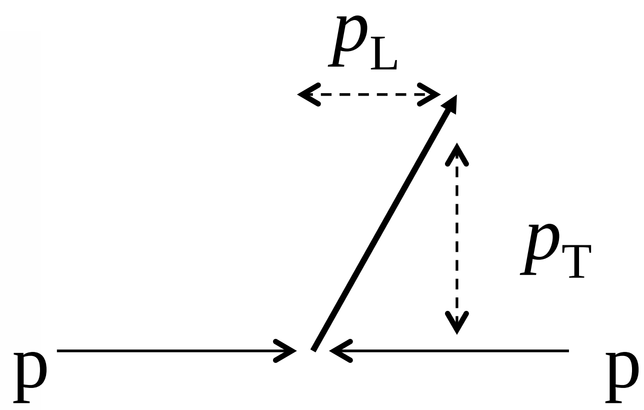


Both b and $\bar{b}$ are in the spectrometer.

f_{pp} @ LHC = 40 MHz → simple first level trigger needed

Single p_T trigger for μ, e, h





muon system:
low track density

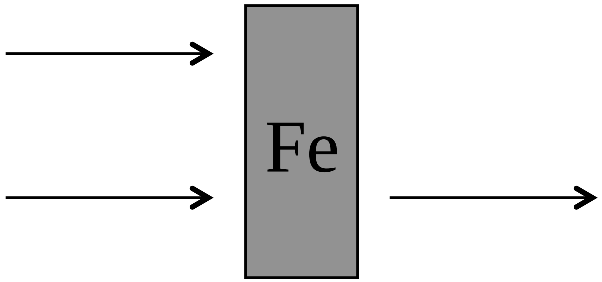
e and h:
calorimeter
E_T measurements

However…. $p > p_{min}$

muon:
identification

$p < p_{min}$

$p > p_{min}$



hadron:
energy resolution

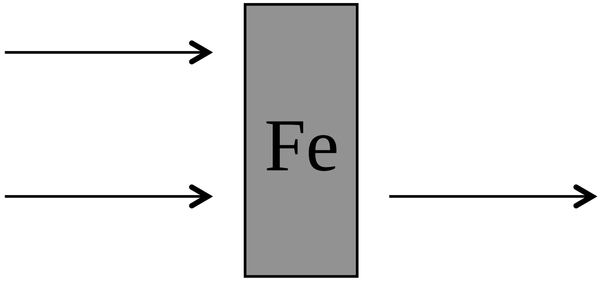
$$\sigma_E/E \approx \sqrt{70\%}/\sqrt{E}$$

However…. $p > p_{\min}$

muon:
identification

$p < p_{\min}$

$p > p_{\min}$

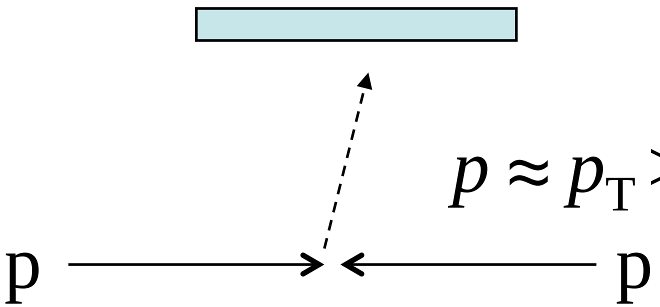


hadron:
energy resolution

$\sigma_E/E \approx \sqrt{70\%}/\sqrt{E}$

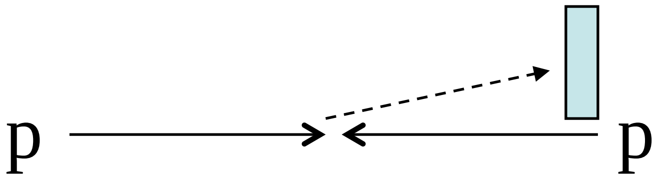
central detector

$p \approx p_T > p_{\min}$



forward detector

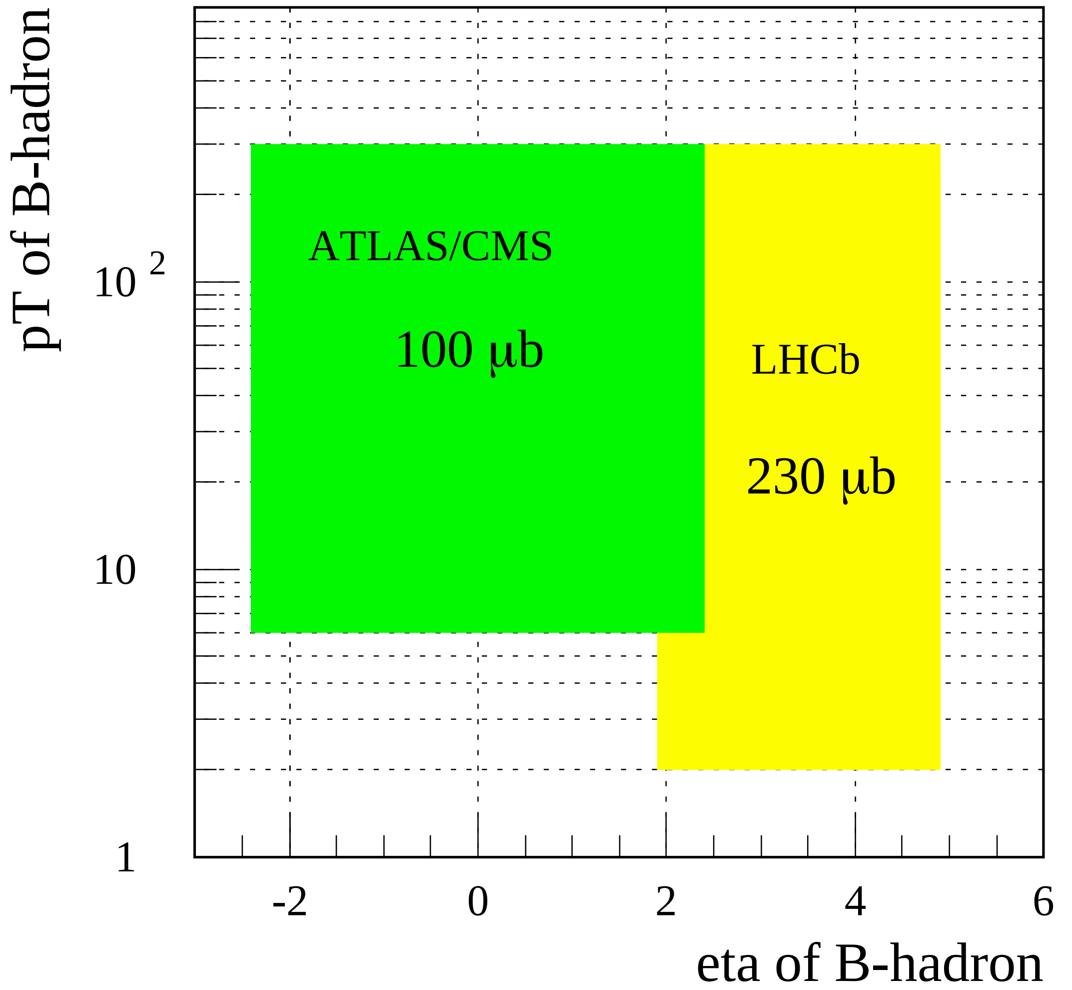
$p \approx p_L > p_{\min}$



p_T threshold can be set low:
→ high b efficiency

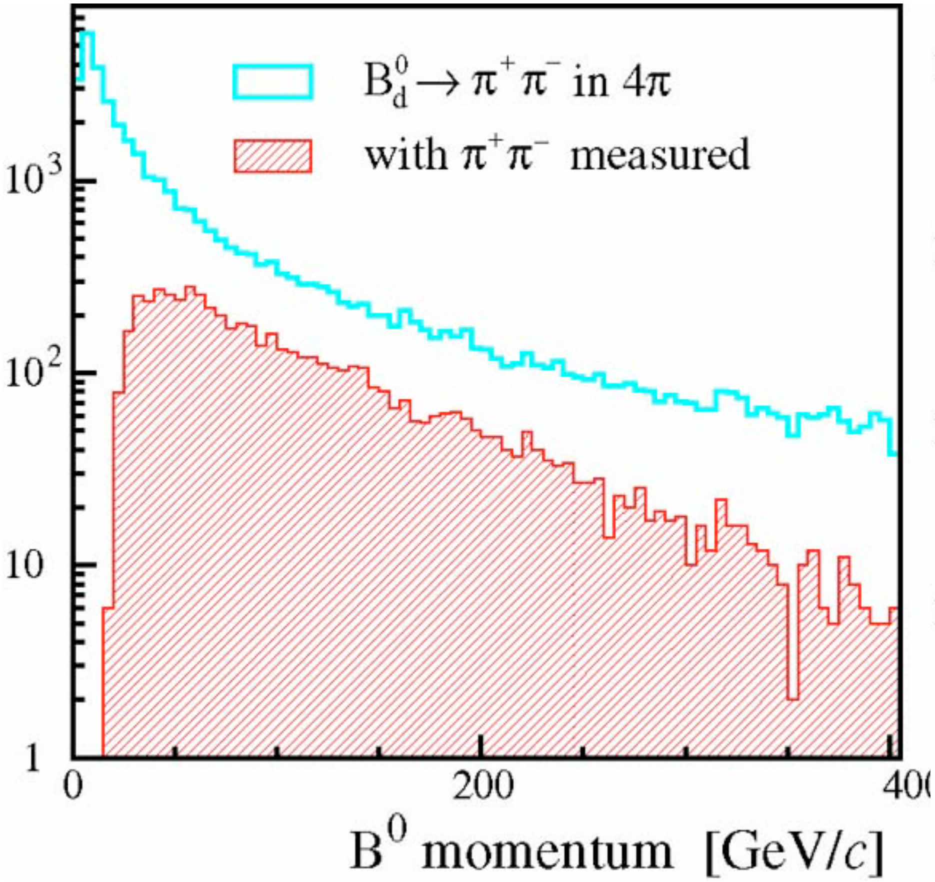
$\sigma_{b\bar{b}}$ expected in pp collisions at $\sqrt{s}$ = 14 TeV: 500μb

5×10^{11} $b\bar{b}$ pairs in 1 year (10^7 s) with $L=10^{32}$ cm^{-2}s^{-1}

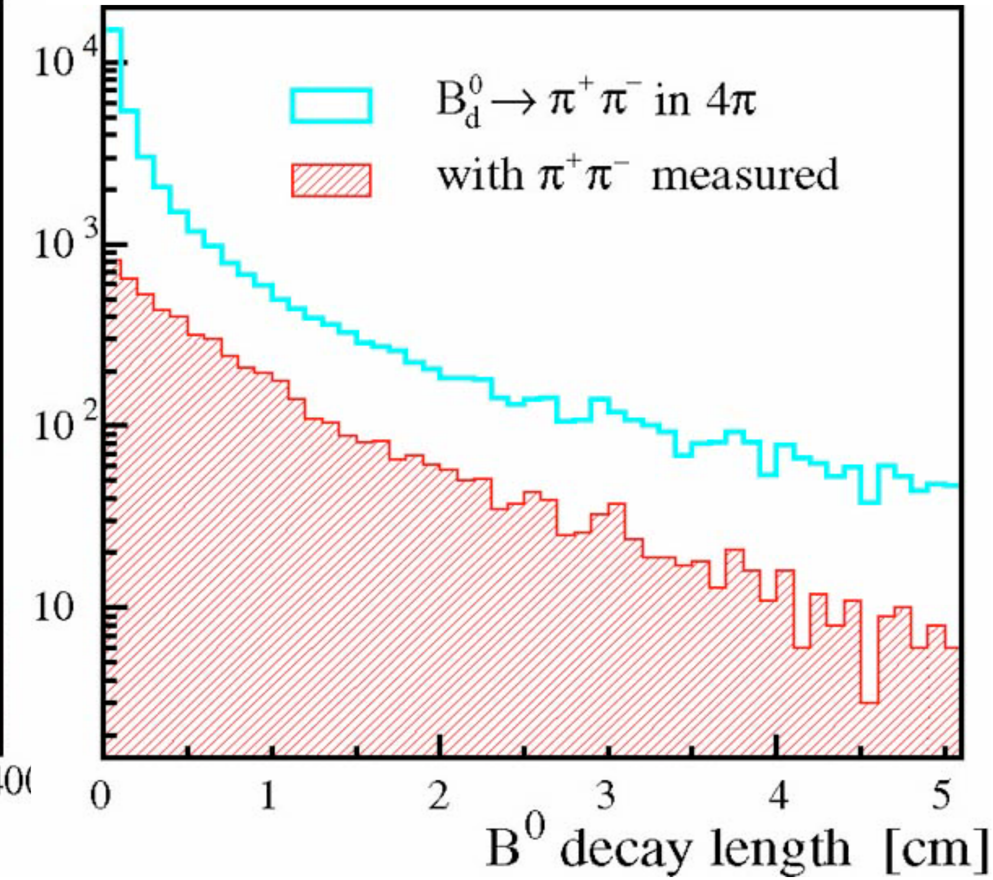


cf. Υ(4S) B factories: 10^8 B-$\overline{\text{B}}$/year @ $L = 10^{34}$ cm^{-2}s^{-1}

Momentum spectrum



decay distance for B mesons



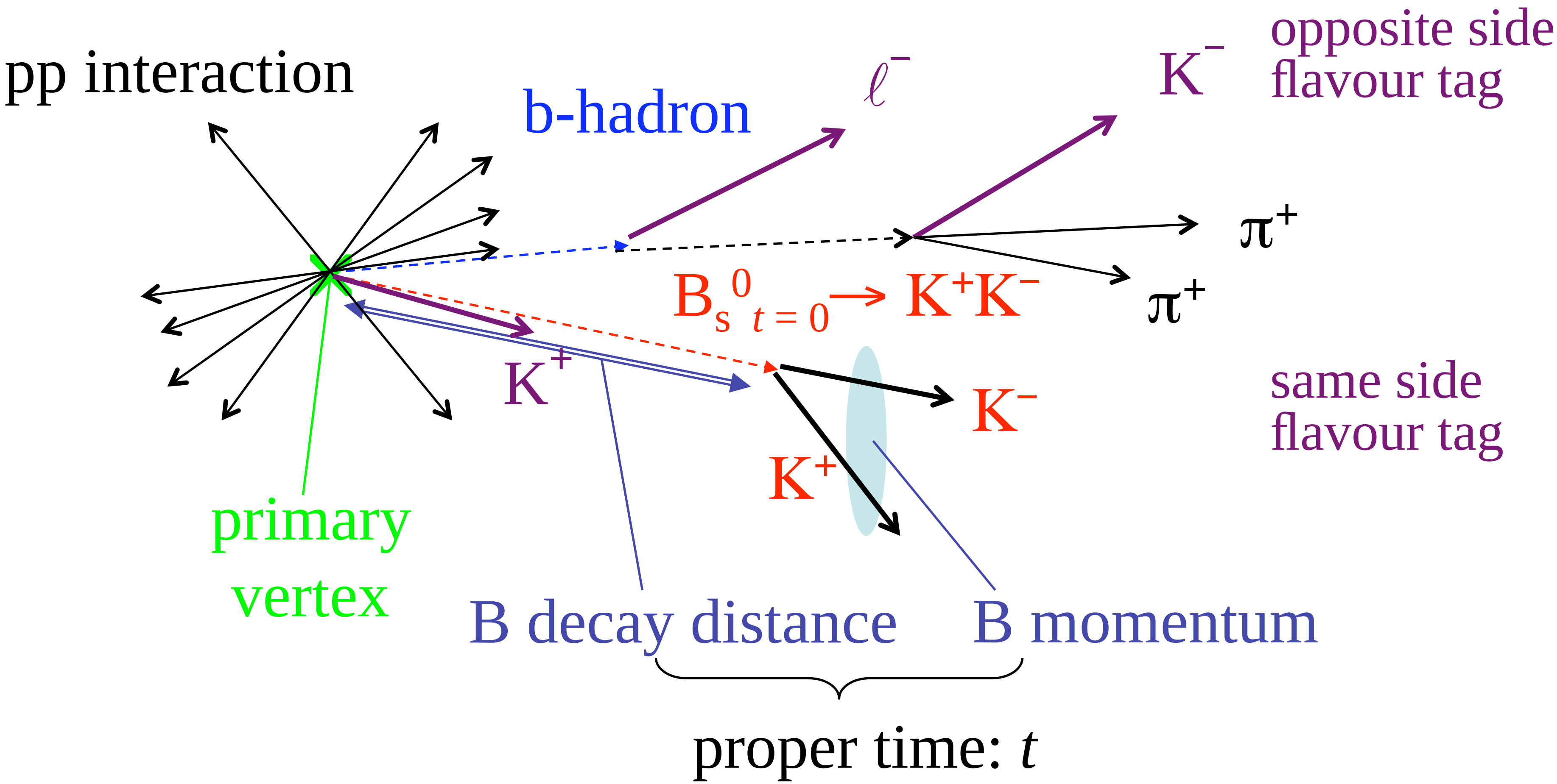
are larger in the forward region.

→ average B decay distance in the detector ~1cm

Good proper time resolution.

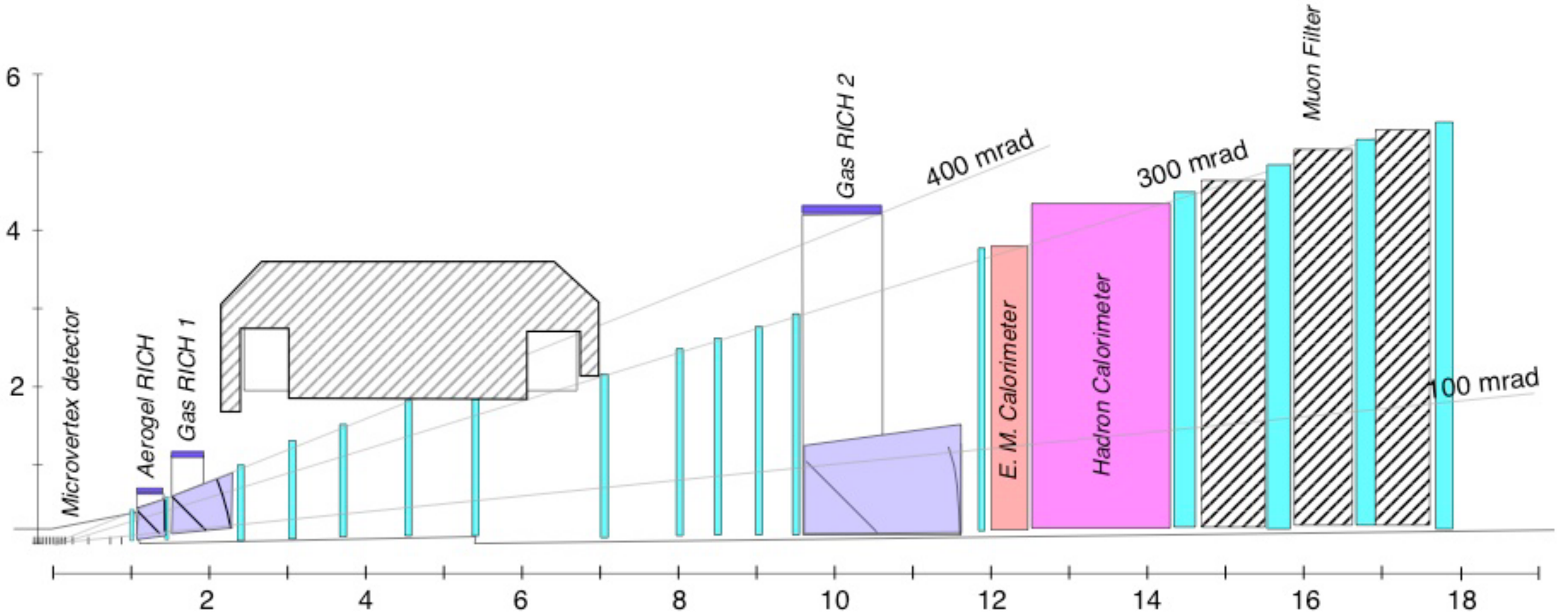
Some detector requirements

What do we measure? (an example)



LHCb Evolution

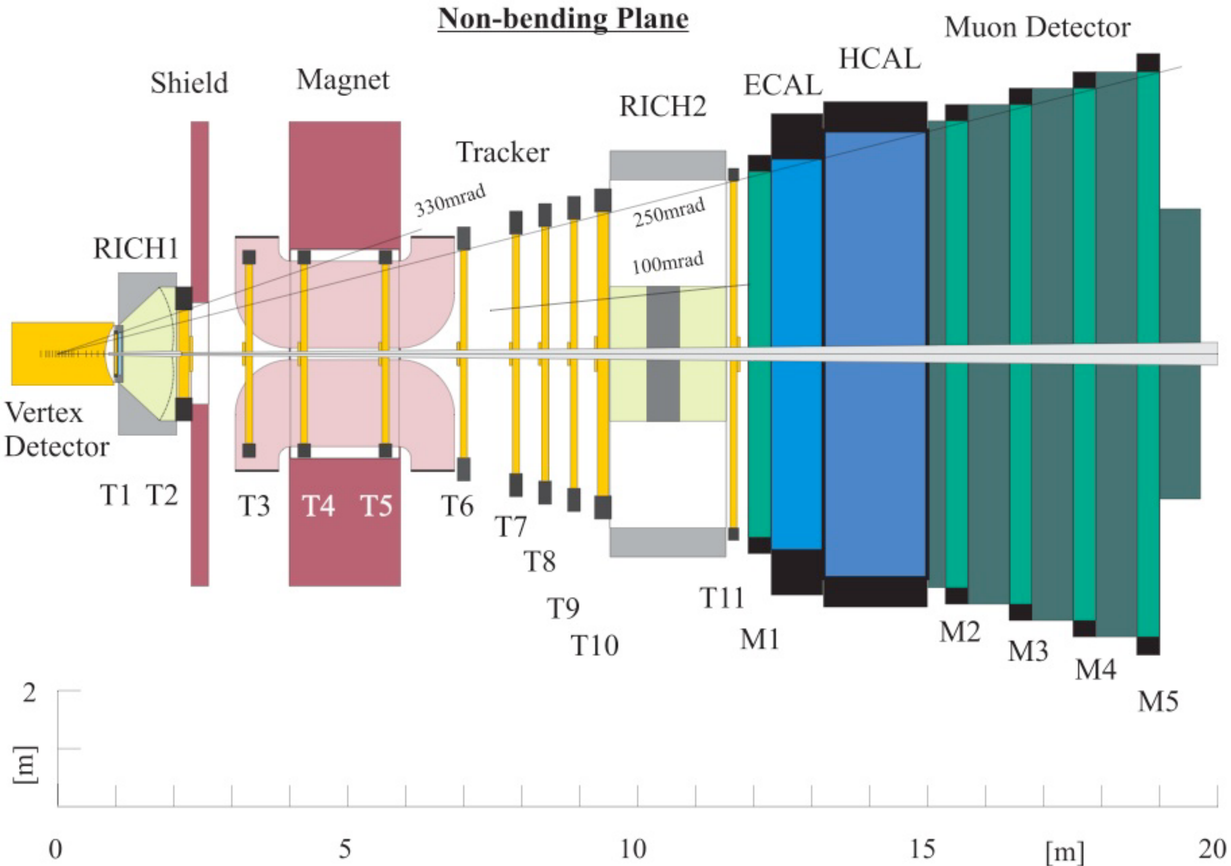
Letter of Intent for LHC-B, August 1995



x-*y* Si micro-strip detector
warm magnet
three RICH's (aerogel + 2-gas) with HPD's
HERA-B tracking system
Pre-shower, Shashlik+$PbWO_4$, Fe-Tilecal+Quarz-W
CSC or Honeycomb or drift tube muon system

L-1 p_T		200 KHz
L-2 tracking + vertex		10 kHz
L-3 full reconstruction		

Technical Proposal for LHCb, February 1998

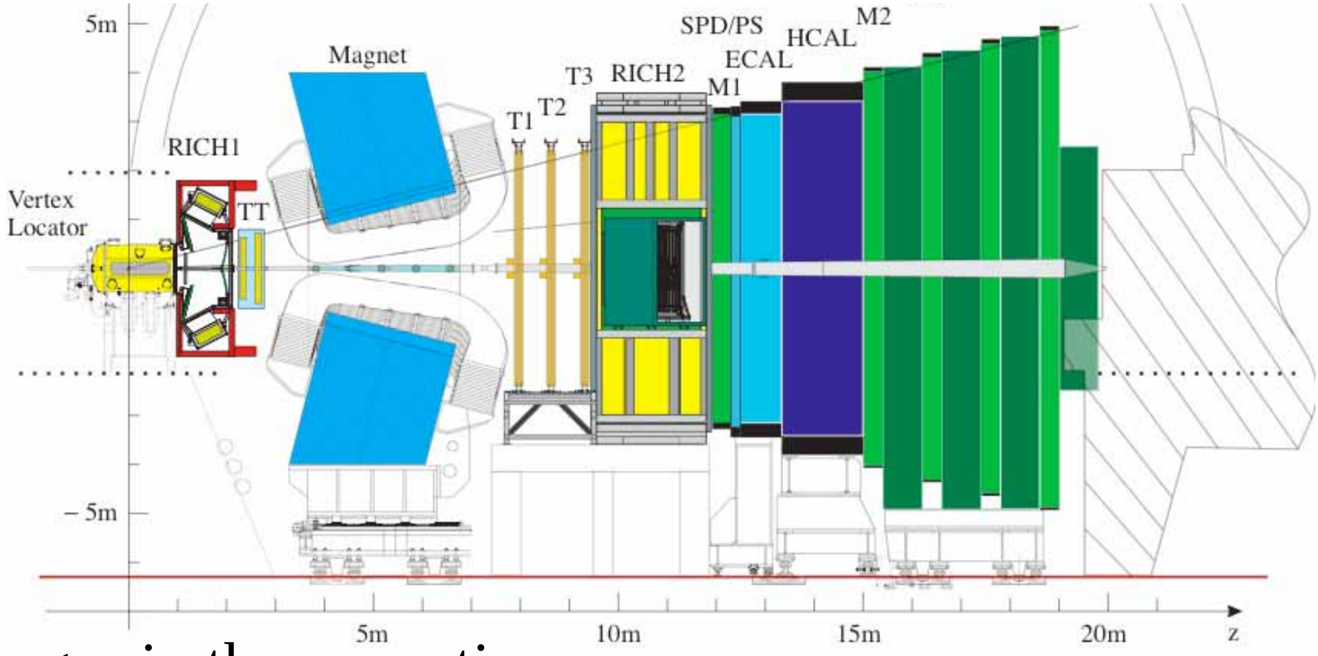


What is different from LoI apart from -B → b?

Super conductive magnet
r-ϕ strip Si vertex detector
Two RICH's (still three radiators)
No inner-part of calorimeters
MRPC+MWPC muon system

L-0 p_T	1 MHz
L-1 tracking + vertex	40 kHz
L-2 vertex with p	5 kHz
L-3 full reconstruction	200 Hz

Reoptimization TDR for LHCb, September 2003



Many changes in the mean time
Be conical beam pipe
Normal conductive magnet
All MWPC (with a little GEM) muon system
Straw chamber + Si tracking system
Greatly reduced tracking stations (nothing in the magnet)
All Si first tracking station
Two level trigger (1 MHz full readout after the first level to CPU farm)

Changes were motivated by:

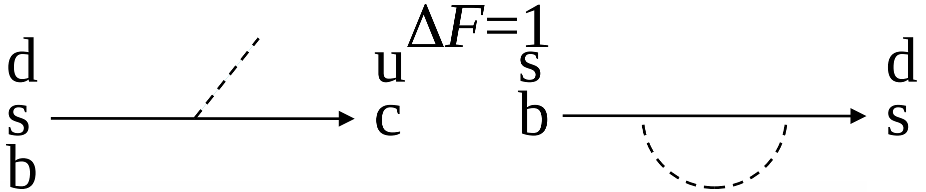
- budgetary constraint (financial and material)
- technical feasibility
- physics flexibility

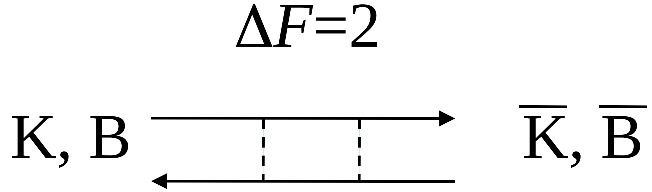
After TP, B physics has evolved a lot: major ones are…

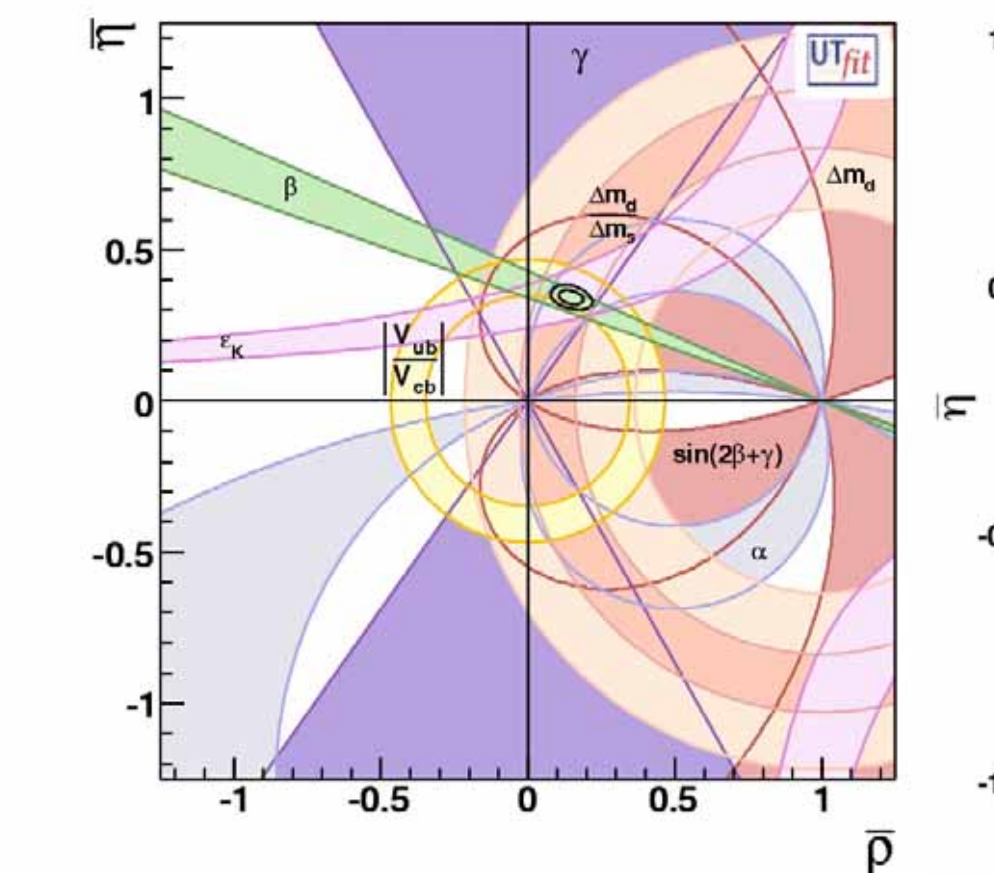
- CPV in $B_d \rightarrow J/\psi K_{S, L}$ measured with $\sigma \approx 0.026$
- $\gamma(\phi_3)$ measured with $\sigma \approx 25°$
- B_s-$\overline{B}_s$ oscillation frequency measured, better than one needs

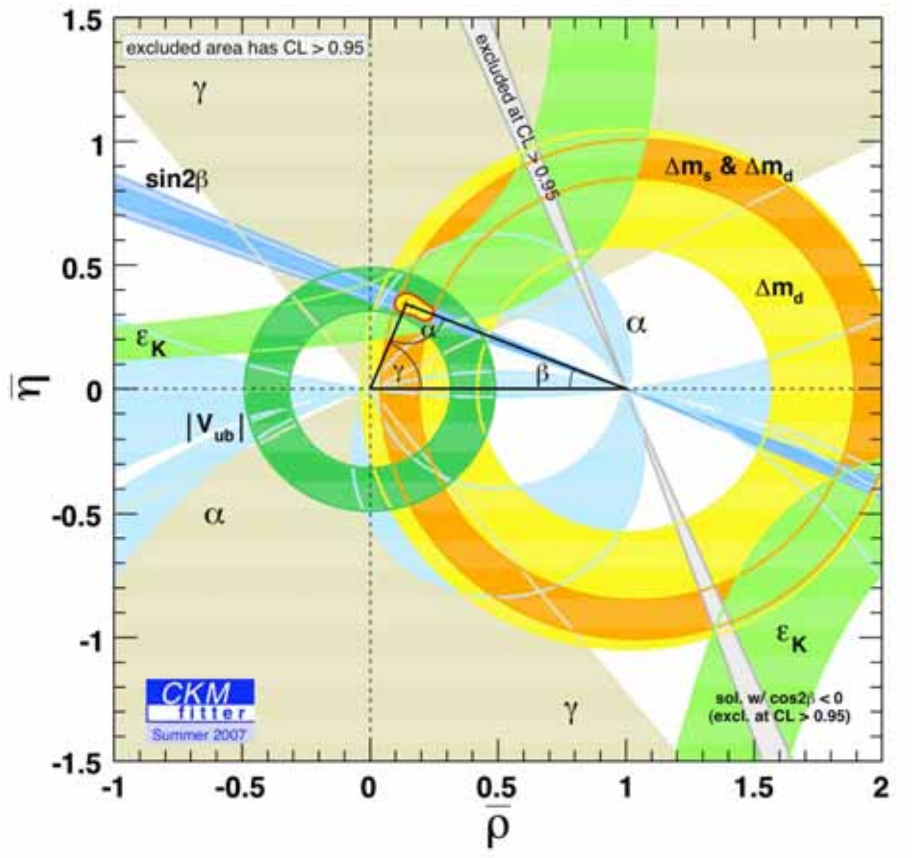
i.e. KM model for CPV is now quantitatively tested

Flavour changing processes, branching fractions, oscillations and CPV, can be described by the four parameters of the CKM matrix (λ, A, ρ, η)









Changes were motivated by:

budgetary constraint (financial and material)

technical feasibility

physics flexibility

After TP, B physics has evolved a lot: major ones are…

CPV in $B_d \to J/\psi K_{S,L}$ measured with $\sigma \approx 0.026$

$\gamma(\phi_3)$ measured with $\sigma \approx 25°$

B_s-$\overline{B}_s$ oscillation frequency measured, better than one needs

i.e. KM model for CPV is now quantitatively tested

No major improvement of the B factory results expected from now on

-BABAR end of run in April, Belle in 1~2 years-

Emphasis on the LHCb physics goal is shifting from

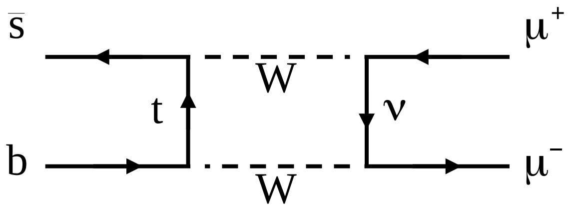
Confirmation of CKM → Search for new physics

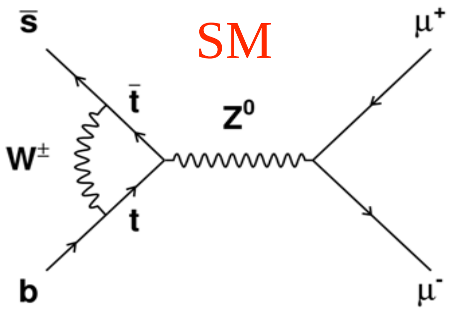
with $\int L dt = 10\ \text{fb}^{-1}$ data by ~2013

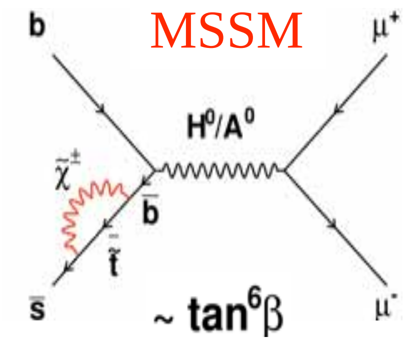
Some notable examples are…

NP search in B_s where the effect could be still large

$B_s \to \mu^+\mu^-$



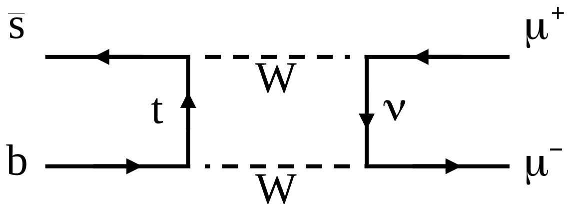


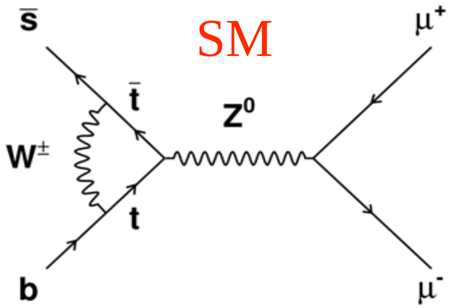


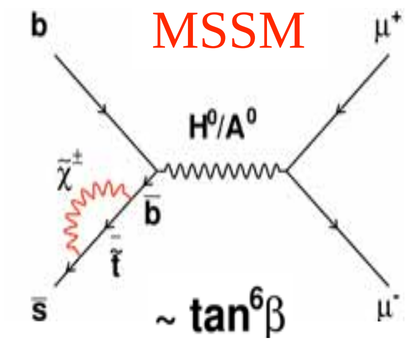
Some notable examples are…

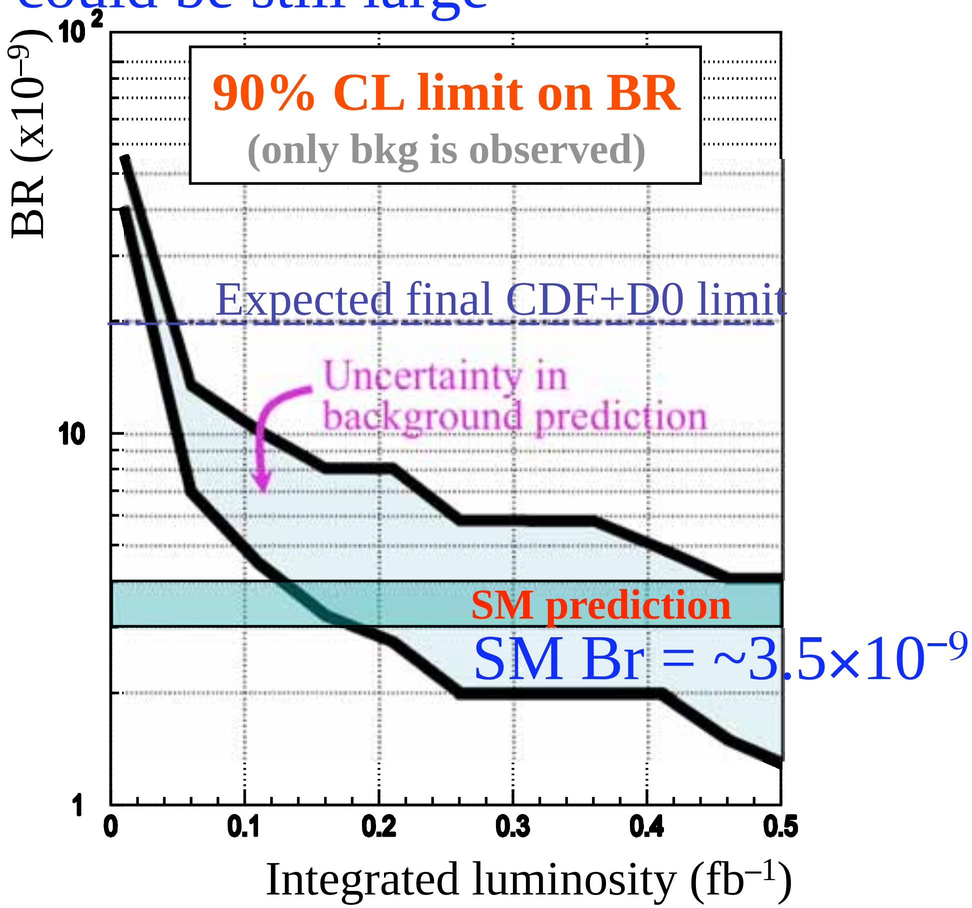
NP search in B_s where the effect could be still large

$B_s \to \mu^+\mu^-$









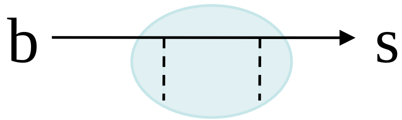
0.05 $fb^{-1} \Rightarrow$ overtake CDF+D0 } 2009
0.5 $fb^{-1} \Rightarrow$ exclude BR values down to SM
2 $fb^{-1} \Rightarrow$ 3σ evidence of SM signal ⟶ nominal 1 year
6 $fb^{-1} \Rightarrow$ 5σ observation of SM signal

Some notable examples are…

NP search in B_s where the effect could be still large

- $B_s \to \mu^+\mu^-$
- CPV in $B_s \to J/\psi\phi$

$$\beta_s^{SM} = -\arg(V_{ts}^2) = -2\lambda^2\eta = -0.0368 \pm 0.0018 \text{ (NB } \arg V_{cb} = 0)$$



SM + new particles with different phase?

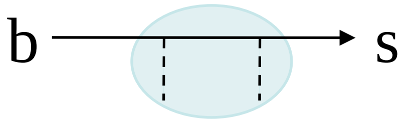
Some notable examples are…

NP search in B_s where the effect could be still large

$B_s \to \mu^+\mu^-$

CPV in $B_s \to J/\psi\phi$

$\beta_s^{SM} = -\arg(V_{ts}^2) = -2\lambda^2\eta = -0.0368 \pm 0.0018$ (NB $\arg V_{cb} = 0$)



SM + new particles with different phase?

$$A_{CP}(t) = \frac{\Gamma\left(\bar{B}_s^0(t)\to f\right) - \Gamma\left(B_s^0(t)\to f\right)}{\Gamma\left(\bar{B}_s^0(t)\to f\right) + \Gamma\left(B_s^0(t)\to f\right)}$$

$$A_{CP}(t) = \frac{-\eta_f \sin\beta_s \sin(\Delta m_s t)}{\cosh\left(\Delta\Gamma_s t/2\right) - \eta_f \cos\beta_s \sinh\left(\Delta\Gamma_s t/2\right)}$$

$\eta_f = \mathrm{CP}(f)$

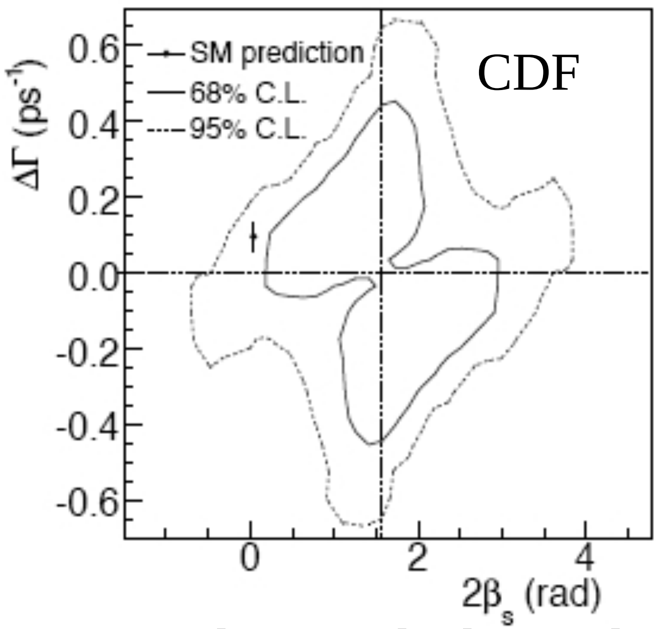
CP(J/ψ)=+1, CP(φ)=+1, $J_{J/\psi\phi}=S+L=0$,

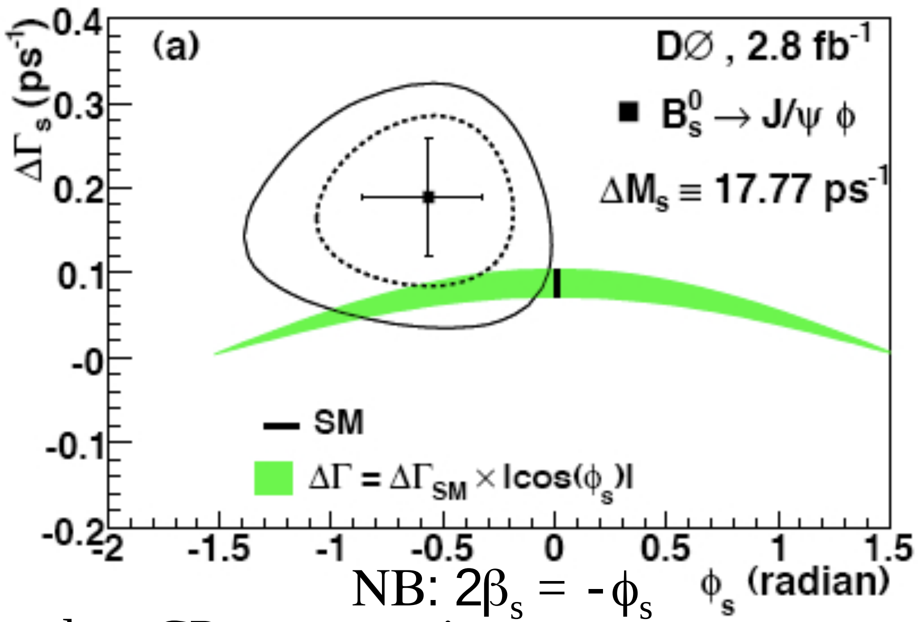
$S=S_{J/\psi}+S_\phi$ $= 0, 1, 2$

$L=L_{J/\psi-\phi}$ $= 0, 1, 2$

$\mathrm{CP}(J/\psi\phi) = (-1)^L$

⇒Angular analysis of the final states needed





NB: $2\beta_s = -\phi_s$

CDF and D0 studied time dependent CP asymmetries

NB: If there were indeed New Physics as suggested by M. Bona et al. (arXiv:0803.0659), who combined all the CDF and D0 results, LHCb would see a 5σ observation of CPV in $B_s \rightarrow J/\psi\phi$ with ~200 pb^{-1}, i.e. 10% of nominal year of data.

LHCb with 0.5 fb^{-1} (expected data in 2009): $\sigma(\beta_s) = 0.046$
down to the level of SM

With 10 fb^{-1}, >3σ evidence of CP violation ($\phi_s \neq 0$), even if only SM

Some notable examples are…

NP search in B_s where the effect could be still large

- $B_s \to \mu^+\mu^-$
- CPV in $B_s \to J/\psi\phi$

overtake Tevatron after several months and down to the SM level in ~one year

Some notable examples are…

NP search in B_s where the effect could be still large

$B_s \rightarrow \mu^+\mu^-$

CPV in $B_s \rightarrow J/\psi\phi$

overtake Tevatron after several months and down to the SM level in ~one year

ATLAS and CMS plan to make B physics in their early period of data taking, ~3 years, collecting 30 fb^{-1} data by ~2011.

$Br(B_s \rightarrow \mu^+\mu^-) <\sim 6\times10^{-9}$ (90%CL)

(They plan to continue this programme at $L=10^{34}$, 4σ in one year)

$\sigma(\beta_s) \approx 0.04$

Some notable examples are…

NP search in B_s where the effect could be still large

$B_s \rightarrow \mu^+\mu^-$

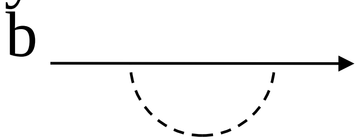
CPV in $B_s \rightarrow J/\psi\phi$

overtake Tevatron after several months and down to the SM level with 2009 data

Probing Flavour Changing Neutral Current $b \rightarrow s$: deviation from the Standard Model prediction in

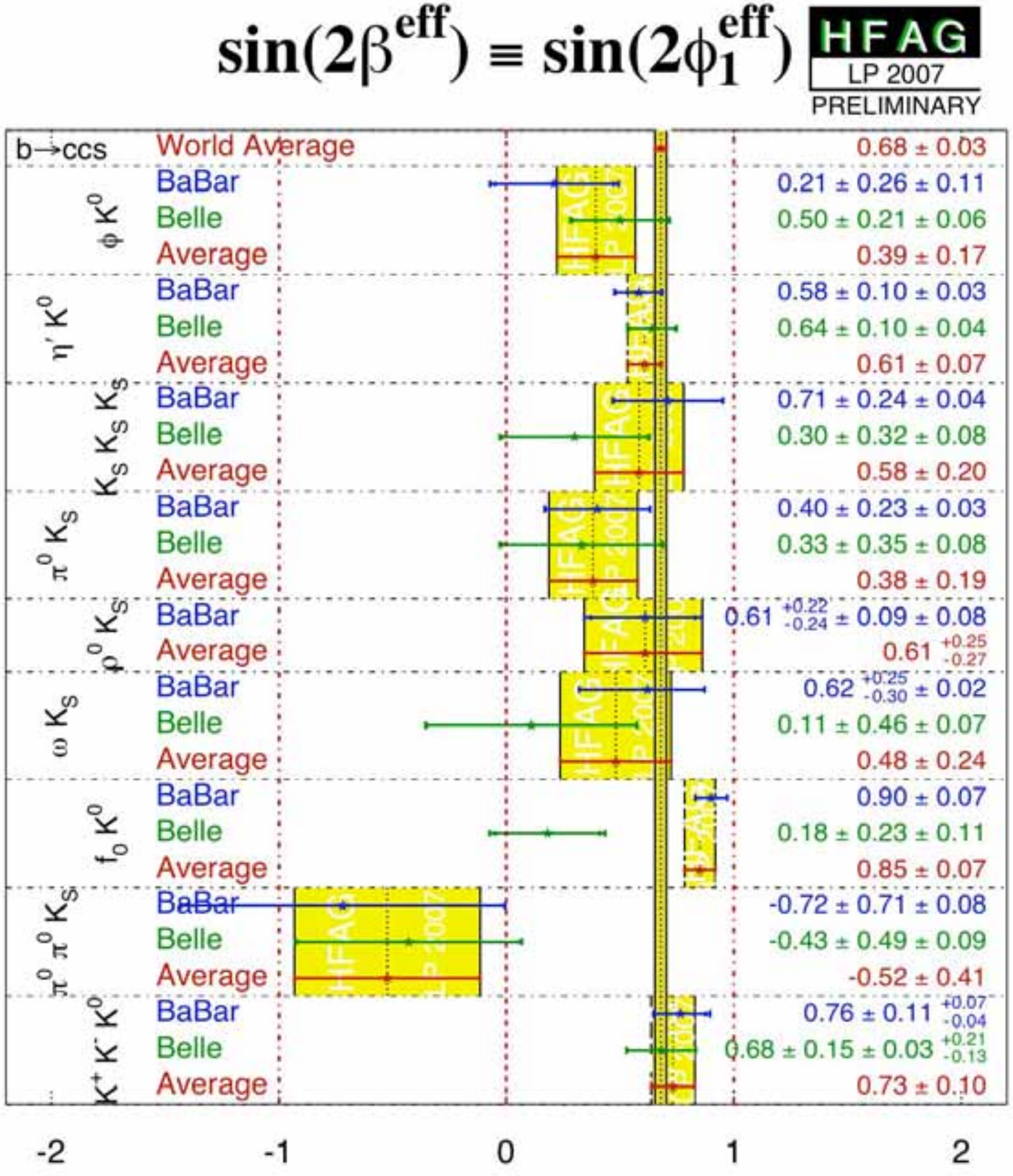
Phase = CP violation $B_s \rightarrow \phi\phi$

Analogous to $B_d \rightarrow \phi K_S$, time dependent CP asymmetry for $B_s \rightarrow \phi\phi$ can measure the BSM phase in $b \rightarrow s$ penguin, $\beta_{s\text{-eff}}$ (for B_s, with only t contribution, SM makes 0 CP asymmetry)



SM + new particles with different phase?

$\sin(2\beta^{eff}) \equiv \sin(2\phi_1^{eff})$



LHCb $B_s \to \phi\phi$ performance with 2 fb^{-1} data

$\sigma(m_{B_s})$	B/S	N_{sig} *)	$\sigma(\tau)$	$\sigma(\beta_{s\text{-eff}})$
12 MeV/c^2	0.4-2.1	4000	42 fs	0.1

*) $Br = 1.4\times10^{-5}$

angular analysis needed to resolve CP=1 and =−1 states

~2013 with 10 fb^{-1} data:

$\sigma(\beta_{s\text{-eff}}) = 0.04$

($B_d \to \phi K_s$ for LHCb, $\sigma(\beta_{d\text{-eff}}) = 0.14$)

Currently
$\sigma(\beta_{d\text{-eff}}) = 0.18$
BABAR+Belle

Some notable examples are…

NP search in B_s where the effect could be still large

- $B_s \to \mu^+\mu^-$
- CPV in $B_s \to J/\psi\phi$

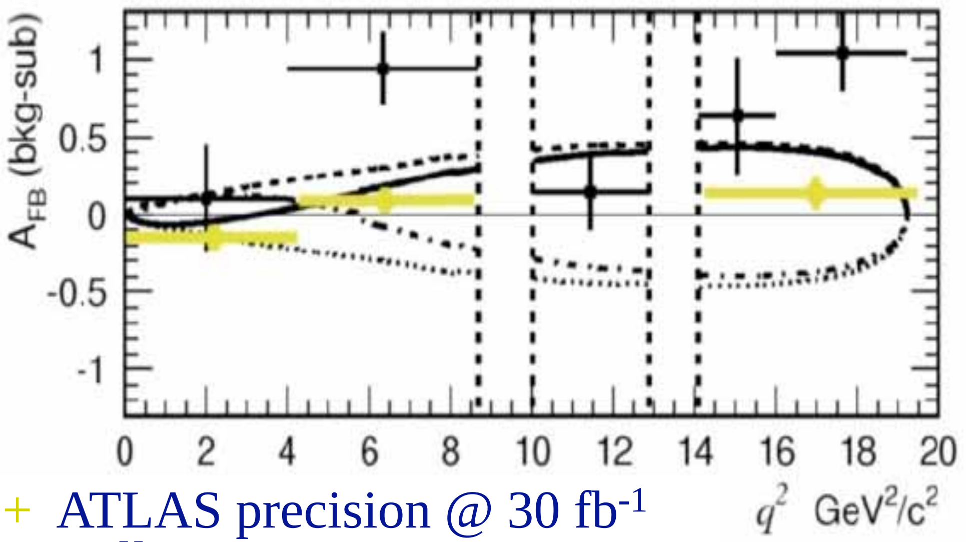
overtake Tevatron after several months and down to the SM level in ~one year

Probing Flavour Changing Neutral Current $b \to s$: deviation from the Standard Model prediction in

- Phase = CP violation $B_s \to \phi\phi$ improvement over B factory ϕK_S
- Lorentz structure = angular distribution or γ polarization
  - $B_d \to K^{*0}\mu^+\mu^-$ far larger statistics than B factory
  - CPV in $B_s \to \phi\gamma$ improvement over B factory $K^*(K_S\pi^0)\gamma$

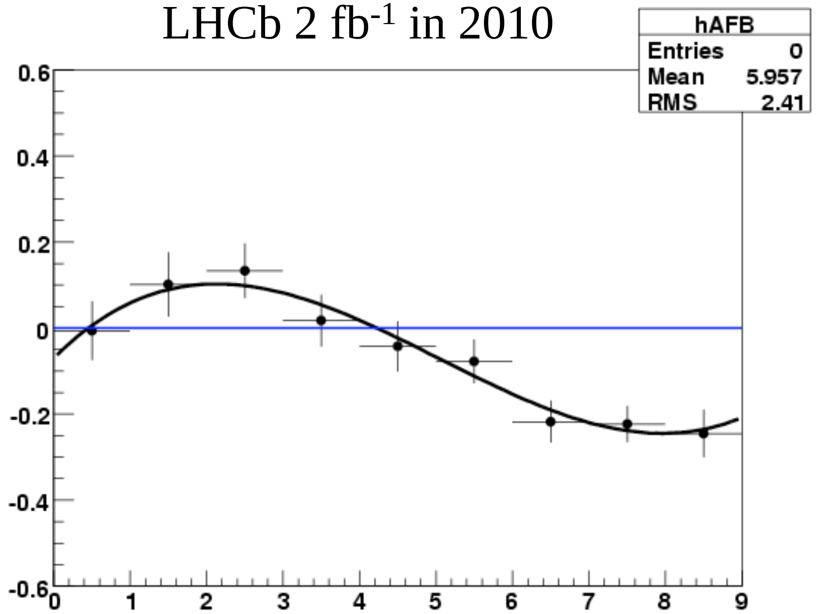
A_{FB} performance

ATLAS 30 fb^{-1} forward-backward asymmetry
three canonical years



+ ATLAS precision @ 30 fb^{-1}
+ Belle 2006
SM model
SM extensions

LHCb 2 fb^{-1} in 2010



By **~2013**, LHCb
zero crossing point with 10 fb^{-1}
$\sigma(s_0) = 0.27\ (\mathrm{GeV}/c^2)^2$ **[19K events]**

Other angular distribution
being studied as well.

LHCb will look for other radiative decays,
e.g. $B_s \rightarrow \phi\gamma$ 57k events with 10 $fb^{-1} \Rightarrow$ CP violation

Some notable examples are…

NP search in B_s where the effect could be still large

$B_s \rightarrow \mu^+\mu^-$

CPV in $B_s \rightarrow J/\psi\phi$

overtake Tevatron after several months and down to the SM level in ~one year

Probing Flavour Changing Neutral Current $b \rightarrow s$: deviation from the Standard Model prediction in

Phase = CP violation $B_s \rightarrow \phi\phi$ improvement over B factory ϕK_S

Lorentz structure = angular distribution or γ polarization

$B_d \rightarrow K^{*0}\mu^+\mu^-$ far larger statistics than B factory

CPV in $B_s \rightarrow \phi\gamma$ improvement over B factory $K^*(K_S\pi^0)\gamma$

FCN current in "up" type quark: NP effect different from "down" type

D: oscillations and CP violation down to the level of SM

much larger statistics than B factory

D physics statistical error with 10 fb^{-1} data (~2013)

$\sigma(x'^2)=6.4\times10^{-5}$

$\sigma(y')=8.7\times10^{-4}$

$\sigma(y_{CP})=5\times10^{-3}$

CP asymmetries for K^+K^- and $\pi^+\pi^-$ $<O(10^{-3})$

Some notable examples are…

NP search in B_s where the effect could be still large

$B_s \to \mu^+\mu^-$

CPV in $B_s \to J/\psi\phi$

overtake Tevatron after several months and down to the SM level in ~one year

Probing Flavour Changing Neutral Current $b \to s$: deviation from the Standard Model prediction in

Phase = CP violation $B_s \to \phi\phi$ improvement over B factory ϕK_S

Lorentz structure = angular distribution or γ polarization

$B_d \to K^{*0}\mu^+\mu^-$ far larger statistics than B factory

CPV in $B_s \to \phi\gamma$ improvement over B factory $K^*(K_S\pi^0)\gamma$

FCN current in "up" type quark: NP effect different from "down" type

D: oscillations and CP violation down to the level of SM

much larger statistics than B factory

γ from tree (only SM) and from tree + penguin (SM+NP): $\sigma_\gamma \approx 3°$

much larger statistics than B factory

And $\tau \to 3\mu$ decays under study now…

$2.2\times10^{10}\times Br(\tau\to3\mu)/2\ fb^{-1}$ L0 triggered events

for τ from $pp\to b\bar{b}X$ and $pp\to c\bar{c}X$ processes

Reconstruction efficiency and S/B under studies

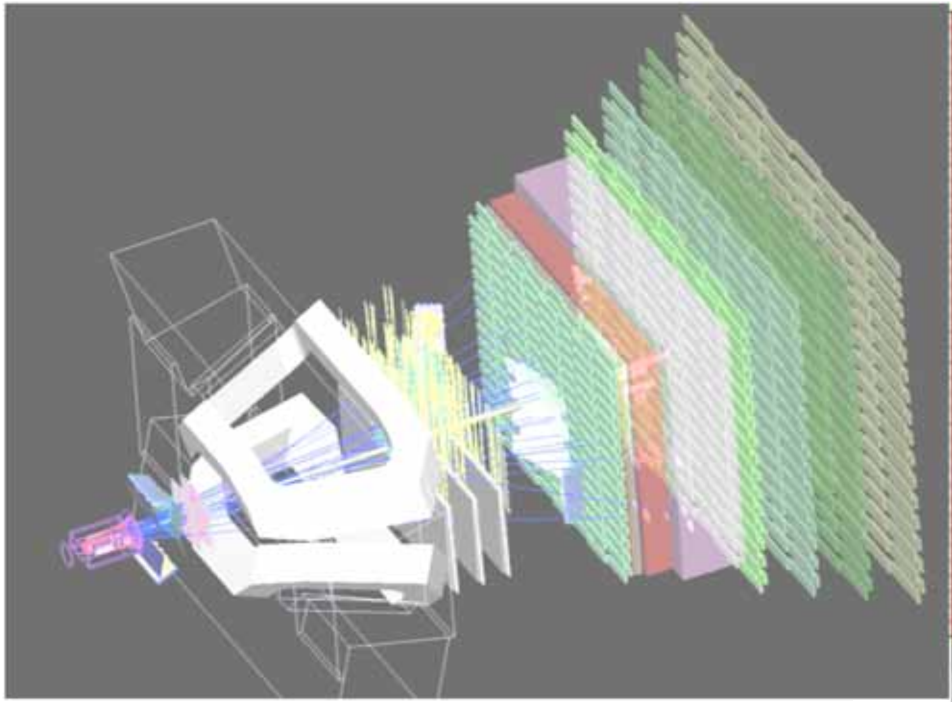
How many Drell-Yan $\tau^+\tau^-$ production?

Current limit from BABAR and Belle $\sim10^{-8}$

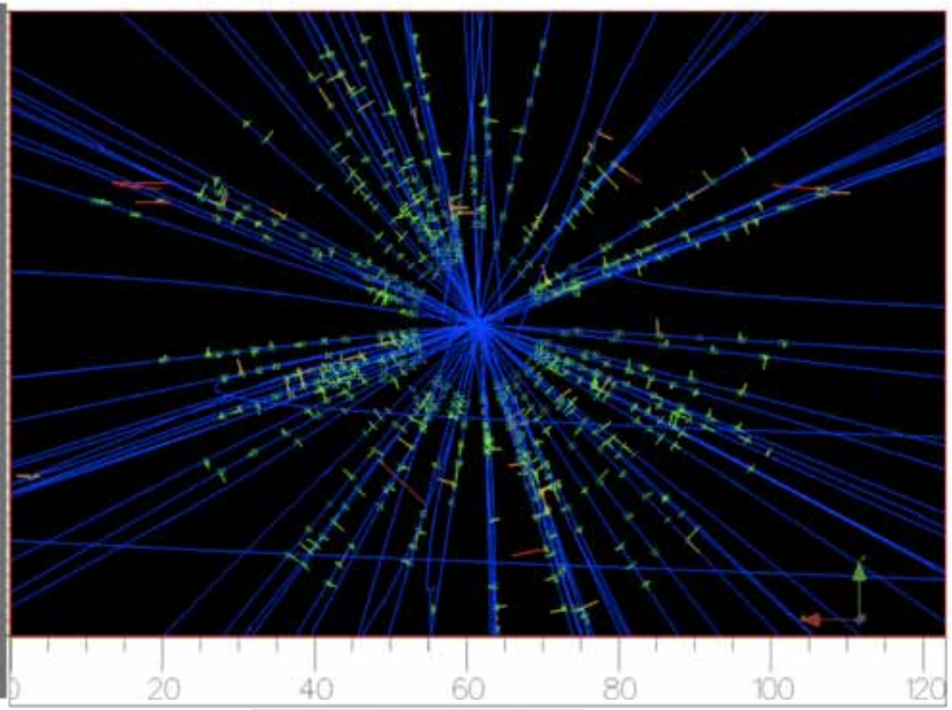
LHCb ready for the beam

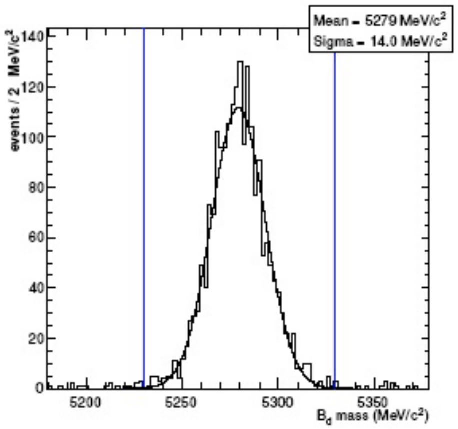
A lot of Monte Carlo events were

generated

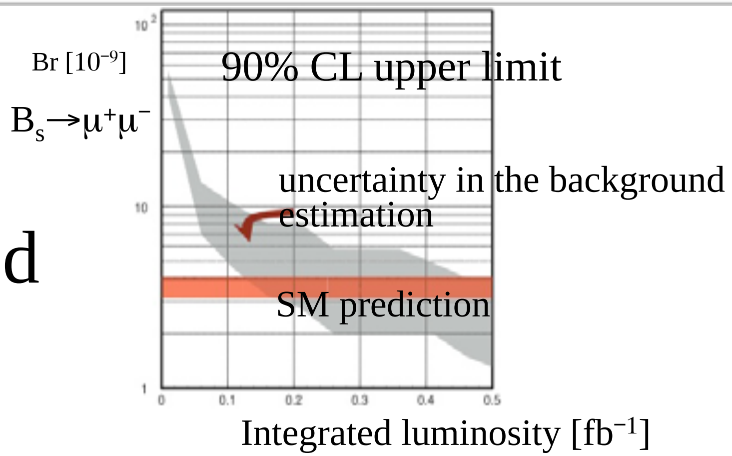


reconstructed

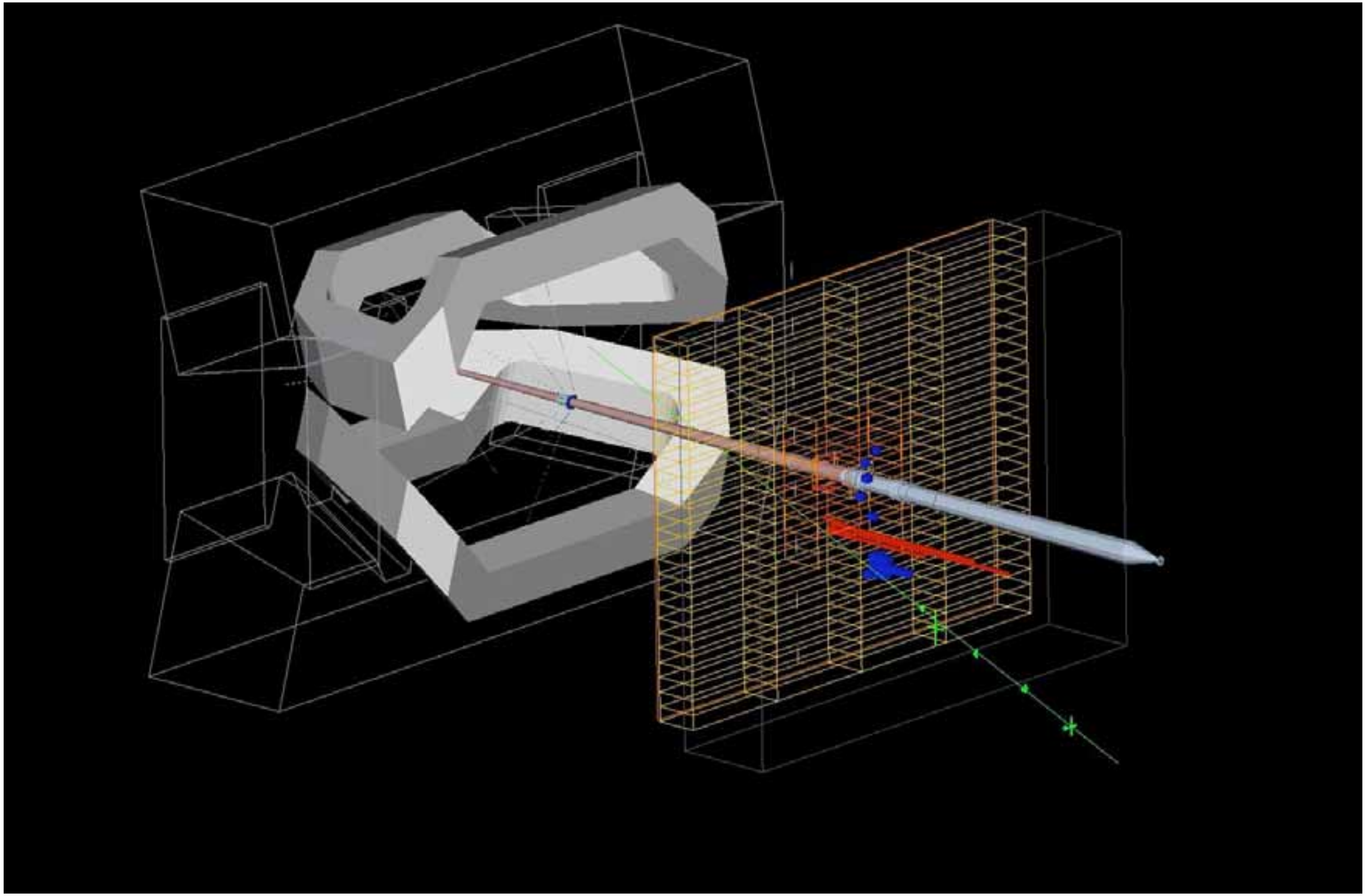




and analysed



Now we also have "properly" triggered cosmic events



going through the calorimeter and muon systems

Summary

Flavour physics has an excellent track record to find physics beyond the direct search at that moment: charm, bottom and top quarks and family structure

Both experimental and theoretical efforts continue to follow this avenue:
K, D and B, as well as lepton sectors

Strong interactions remain to be a “bottle neck” for further progress in many places…

We are looking forward to see 10 TeV pp collisions in our detector very soon!

Followed by finding out which one of the following excitements we will have:

In 2014 at LHC

ATLAS CMS high p_T physics
LHCb flavour physics
Particle Physics

In 2014 at LHC

ATLAS CMS high p_T physics	BSM
LHCb flavour physics	Only SM
Particle Physics	☺

In 2014 at LHC

ATLAS CMS high p_T physics	BSM	Only SM
LHCb flavour physics	Only SM	BSM
Particle Physics	☺	☺

In 2014 at LHC

ATLAS CMS high p_T physics	BSM	Only SM	BSM
LHCb flavour physics	Only SM	BSM	BSM
Particle Physics	☺	☺	☺

In 2014 at LHC

ATLAS CMS high p_T physics	BSM	Only SM	BSM	
LHCb flavour physics	Only SM	BSM	BSM	
Particle Physics	☺	☺	☺	

Oh, no more space left… but the best would be if we find totally unexpected!