Flavour Physics Experiments

The Taller de Altas Energías
Centro de Ciencias de Benasque
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ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

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- Introduction and history
- Flavour mixing and oscillations
- Standard Model and Flavour Physics
- Flavour Physics beyond the Standard Model
- Future prospects

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

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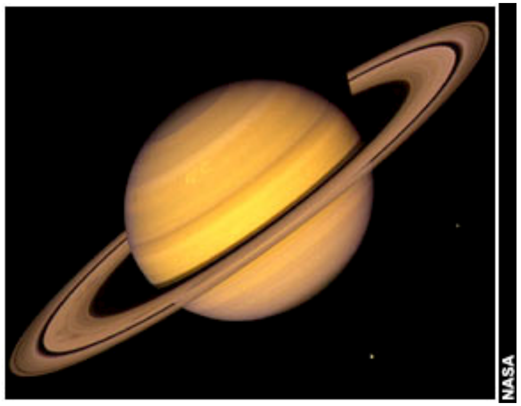
Of course going there...

But you can study a lot from here before

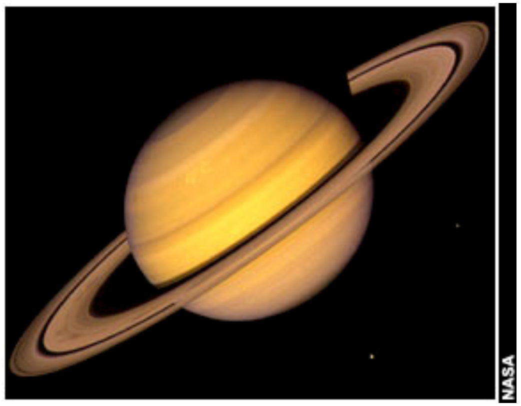


And may be finding something new?

What is on the moon?

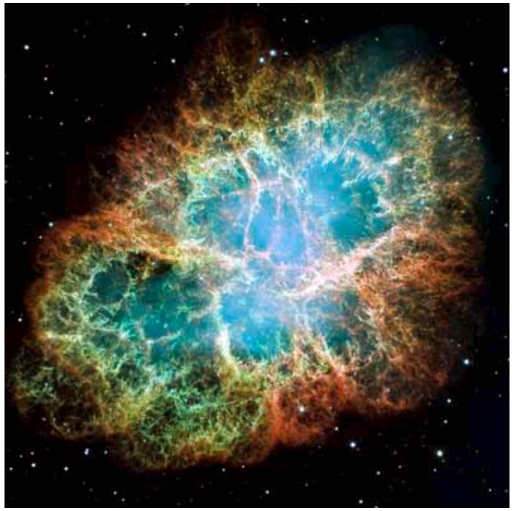
Of course going there...

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)

⇓

p and n (or π^+, π^0 and π^-) are identical when switching off alectromagnetic interactions

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→ 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

$\Downarrow$

discovery of long living particles

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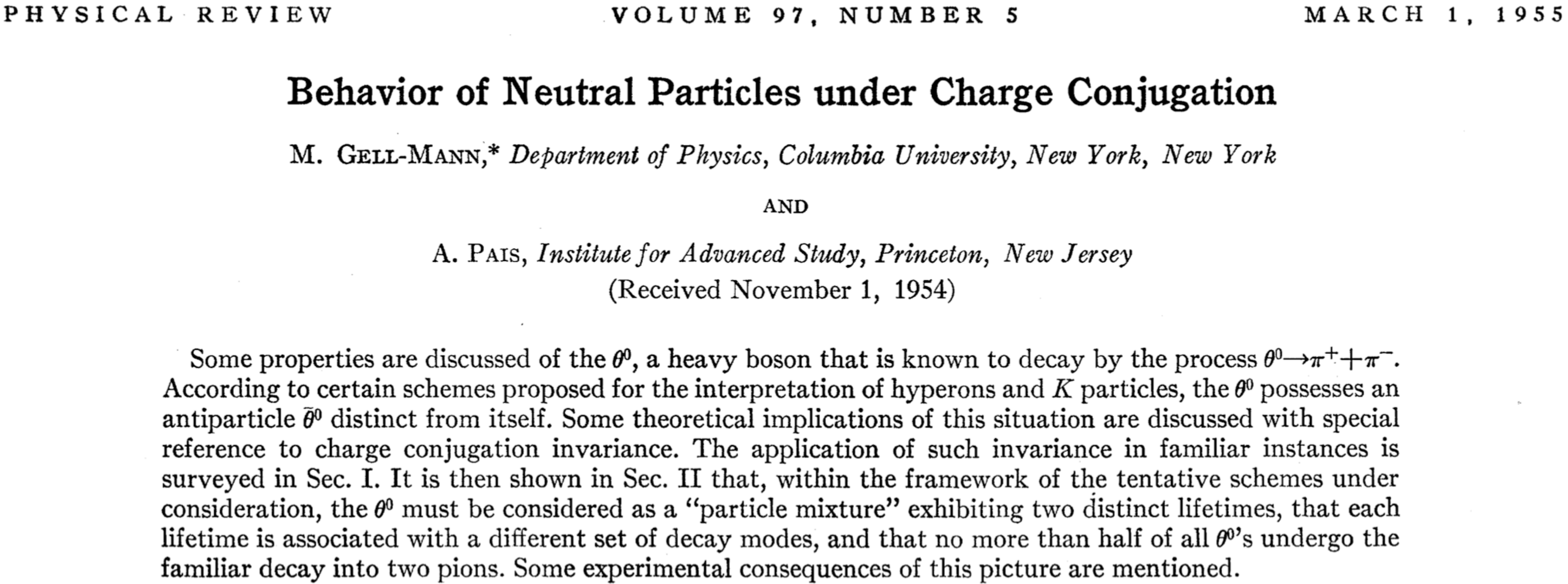
“Strangeness” played a role in establishing
the concept of flavour quantum numbers

“quark” in early 1960’s
(Gell-Mann, Ne’eman, Han-Nambu, Nishijima, Sakata, Zweig, etc.)
SU(3) flavour symmetry: (u, d, s)→Ω^- 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.

$$K^0 \leftrightarrow \pi^+\pi^- \leftrightarrow \overline{K}^0 \Longrightarrow \begin{array}{l} K_1 = \dfrac{K^0 + \overline{K}^0}{\sqrt{2}} \\ K_2 = \dfrac{K^0 - \overline{K}^0}{\sqrt{2}} \end{array}$$

under C symmetry Why?

two very different lifetimes

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

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

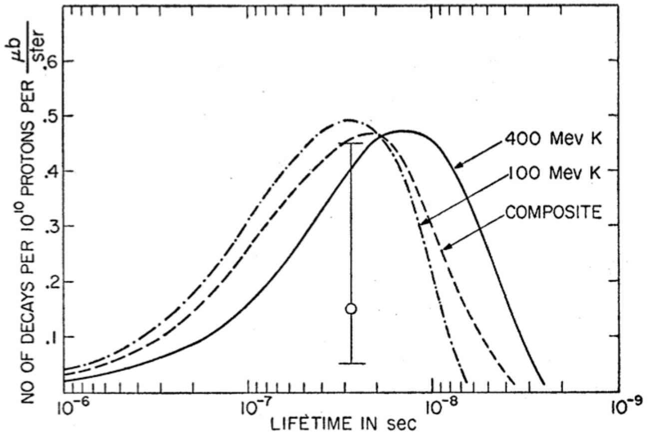


FIG. 2. Detection sensitivity for *K* mesons as function of lifetime. The composite curve is obtained with the spectra of reference 5. The point indicates the observed yield with a production cross section of ~20 μb/sterad.

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

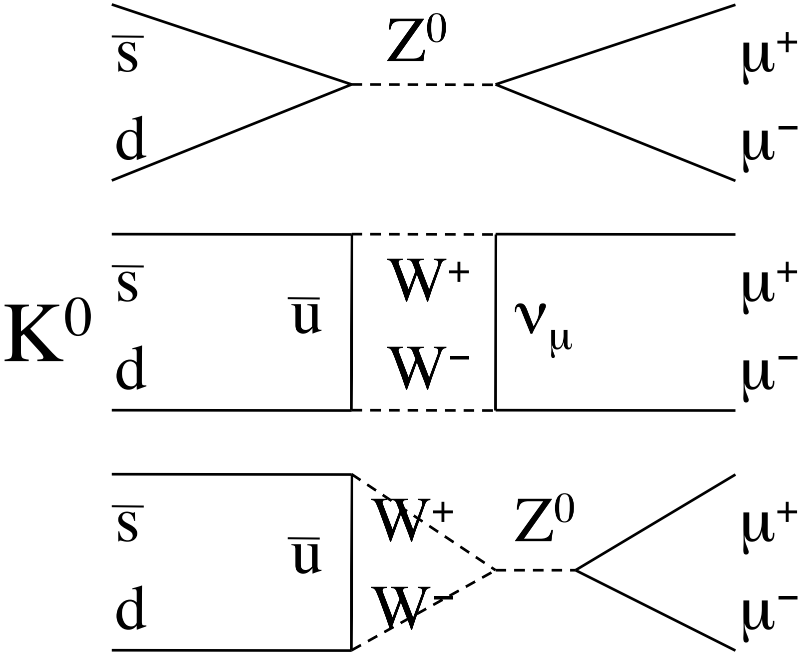
Establish two particle states: short-living, K_S, decays into 2π and long-living, K_L, decays into 3π, $\pi l\nu$: $K^0-\overline{K}^0$ mixing

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



?

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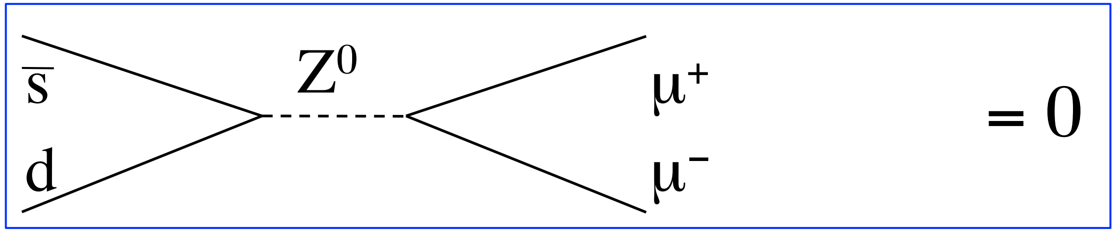
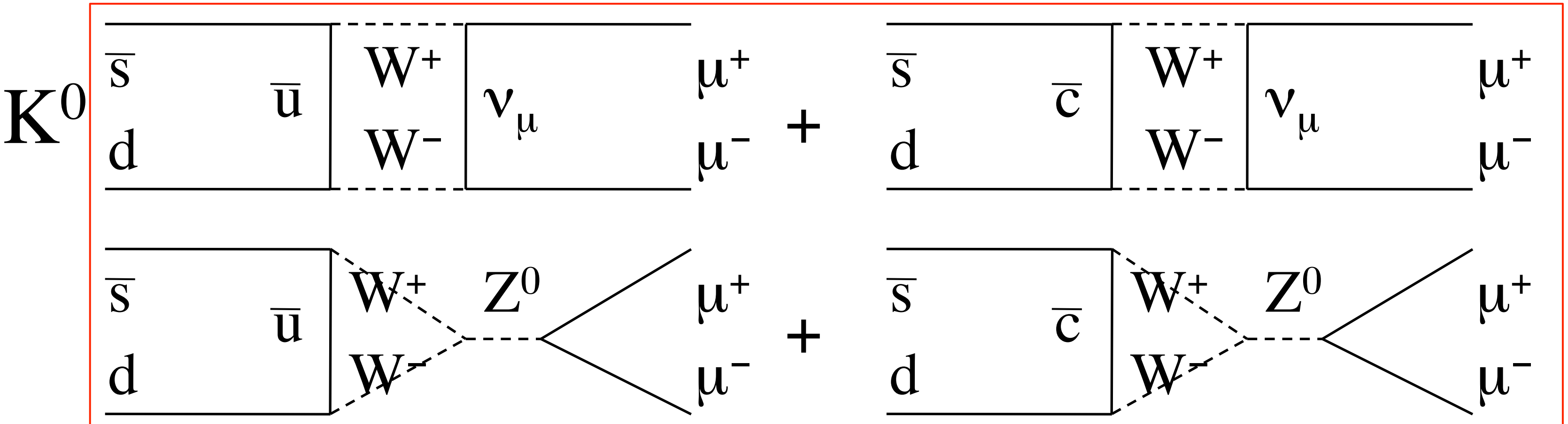
Very suppressed $K_L \rightarrow \mu^+\mu^-$ $\Rightarrow$ SU(2) doublet structure (GIM)



$= 0$

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

1970



Why is this?

$= 0$ if $m_u = m_c$

Flavour Physics

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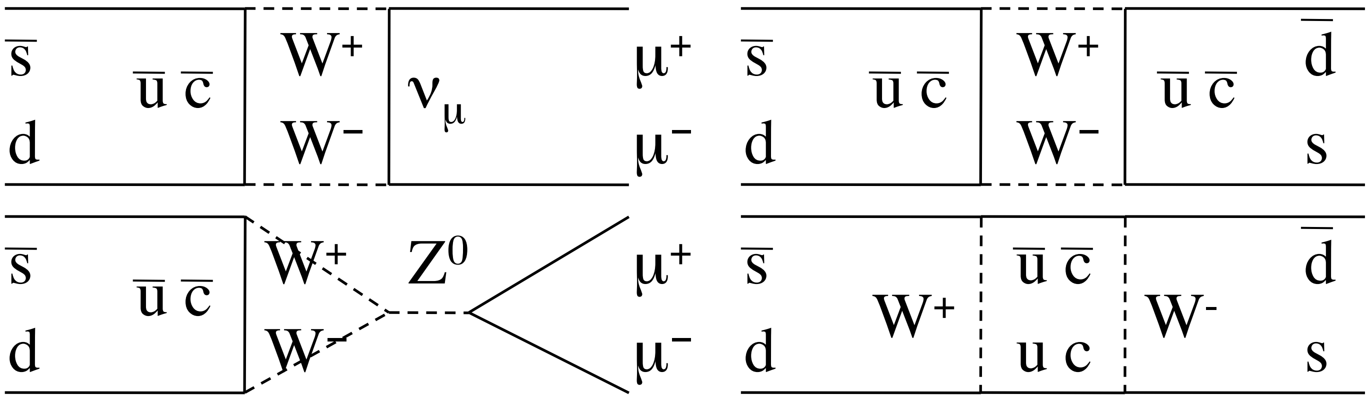
Δm_K and $\mathrm{Br}(K_L\rightarrow\mu^+\mu^-)$



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

Gaillard and Lee, 1974

Flavour Physics

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

Flavour Physics

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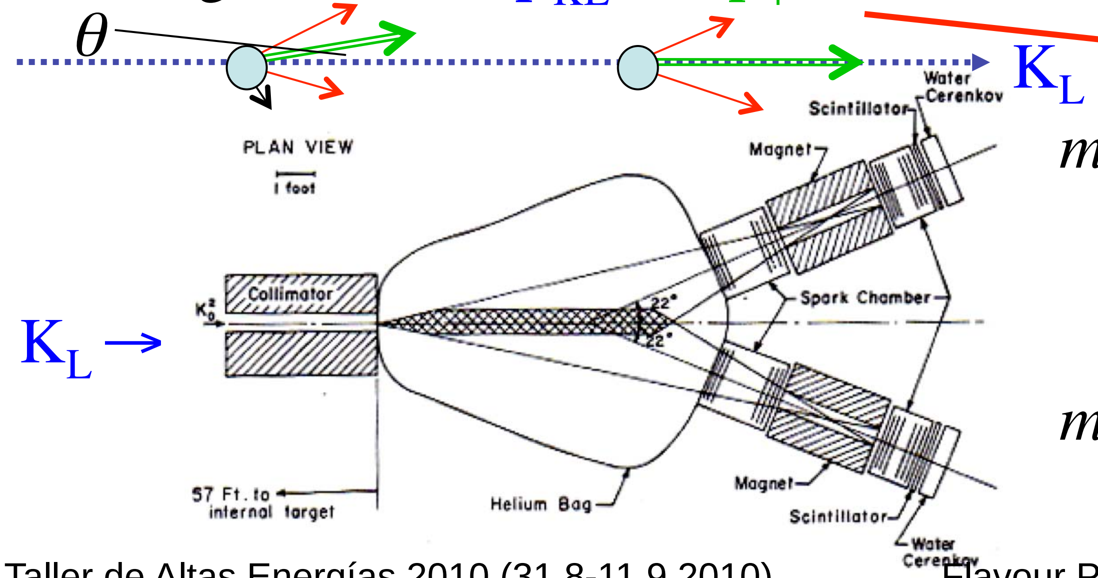
Δm_K and $Br(K_L \to \mu^+\mu^-)$ $\Rightarrow$ charm mass

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

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

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

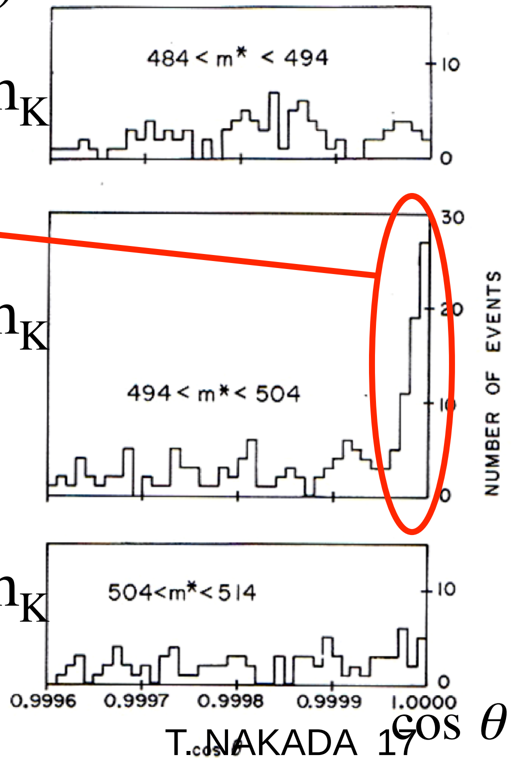


$K_L \to$

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

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

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



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CPV

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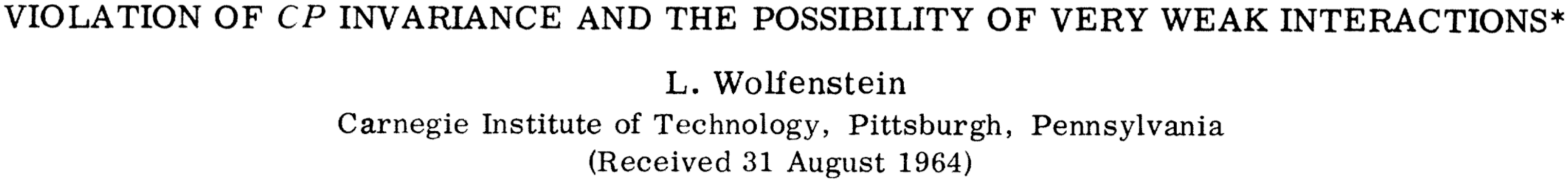


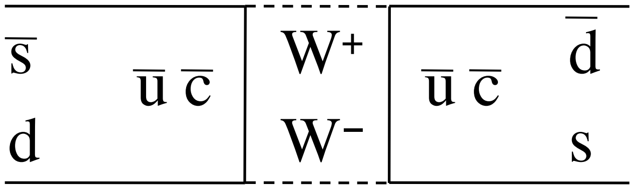
VIOLATION OF *CP* INVARIANCE AND THE POSSIBILITY OF VERY WEAK INTERACTIONS*

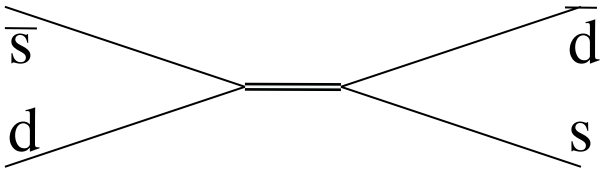
L. Wolfenstein

Carnegie Institute of Technology, Pittsburgh, Pennsylvania

(Received 31 August 1964)

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

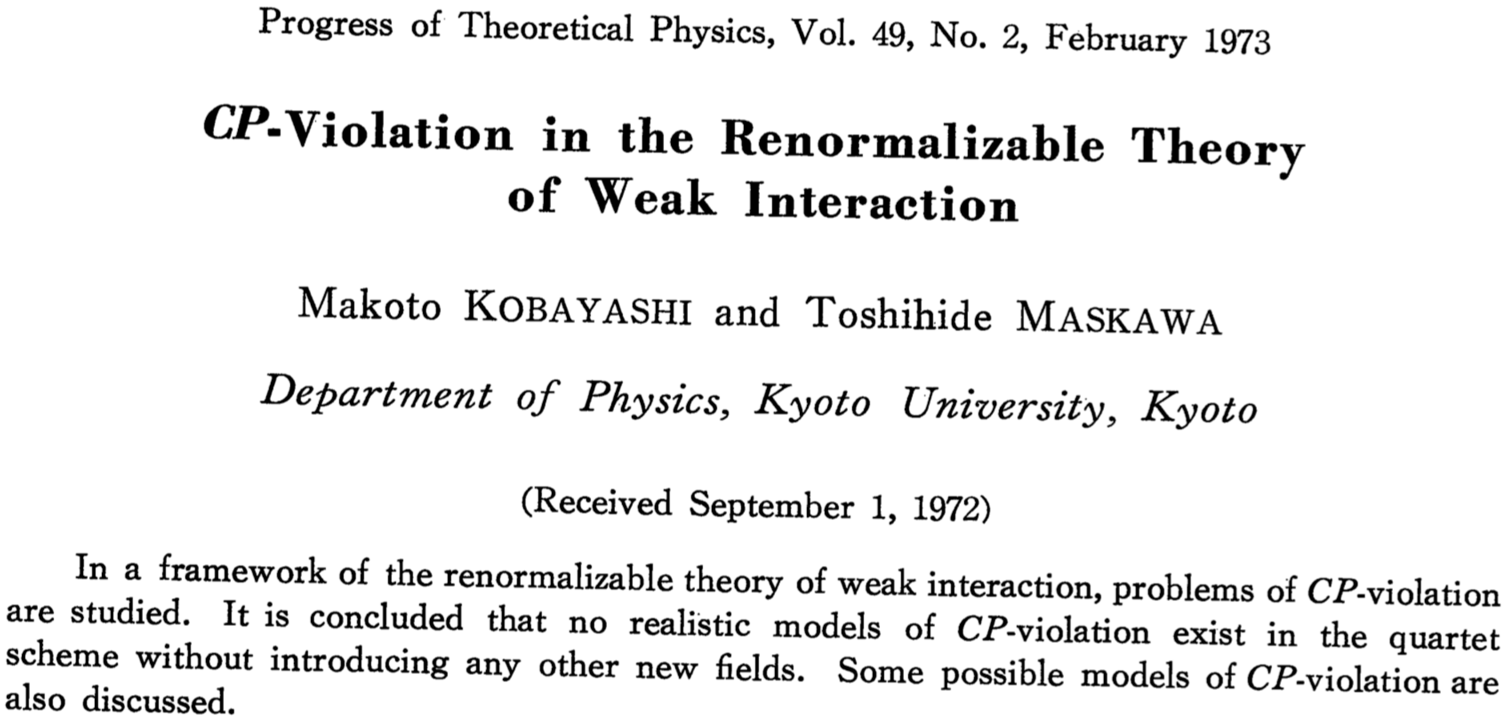




No CPV in decay amplitude, i.e. Re $\varepsilon' = 0$

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 $\varepsilon' \neq 0$

CKM matrix with KM phase

flavour eigenstatetates	⇒	masseigenstates
-non-diagonal mass matrix		-diagonal mass matrix
-flavour conserving		-flavour changing
-Strong and EM interactions		-weak interactions

CKM matrix with KM phase

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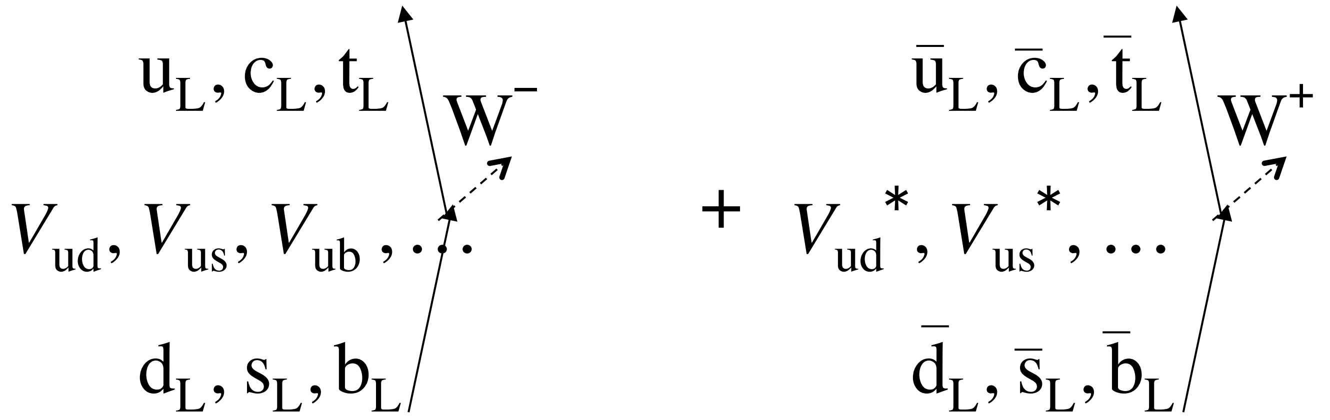

u_L, c_L, t_L

W^-

$V_{ud}, V_{us}, V_{ub}, \ldots$

d_L, s_L, b_L

$+$

$\bar{u}_L, \bar{c}_L, \bar{t}_L$

W^+

$V_{ud}^*, V_{us}^*, \ldots$

$\bar{d}_L, \bar{s}_L, \bar{b}_L$

$$L \propto V_{ij}\, \bar{U}_i\, \gamma^\mu(1-\gamma_5)\, D_j\, W_\mu^\dagger + V_{ij}^*\, \bar{D}_i\, \gamma^\mu(1-\gamma_5)\, U_j\, W_\mu$$

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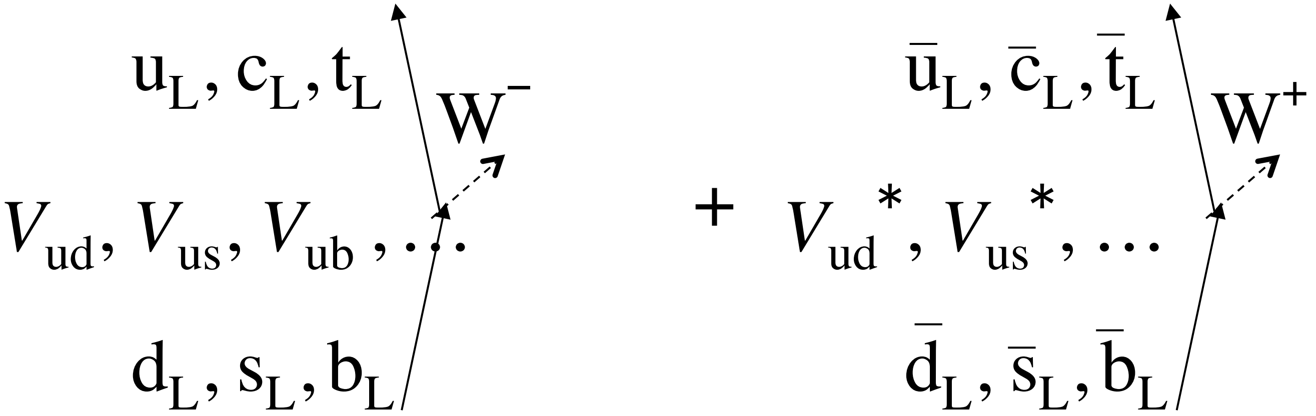

u_L, c_L, t_L W^-

$V_{ud}, V_{us}, V_{ub}, \ldots$

d_L, s_L, b_L

$+$

$\bar{u}_L, \bar{c}_L, \bar{t}_L$ W^+

$V_{ud}^*, V_{us}^*, \ldots$

$\bar{d}_L, \bar{s}_L, \bar{b}_L$

$$L \propto V_{ij}\, \bar{U}_i\, \gamma^\mu(1-\gamma_5)\, D_j\, W_\mu^\dagger + V_{ij}^*\, \bar{D}_i\, \gamma^\mu(1-\gamma_5)\, U_j\, W_\mu$$

$\updownarrow$ CP conjugation

Can you show this?

$$\boxed{L_{CP} \propto V_{ij}\, \bar{D}_i\, \gamma^\mu(1-\gamma_5)\, U_j\, W_\mu + V_{ij}^*\, \bar{U}_i\, \gamma^\mu(1-\gamma_5)\, D_j\, W_\mu^\dagger}$$

If $V_{ij}^* = V_{ij} \rightarrow L = L_{CP}$: i.e. CP conservation

CKM matrix with KM phase

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$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{\mathrm{ud}} & V_{\mathrm{us}} & V_{\mathrm{ub}} \\ V_{\mathrm{cd}} & V_{\mathrm{cs}} & V_{\mathrm{cb}} \\ V_{\mathrm{td}} & V_{\mathrm{ts}} & V_{\mathrm{tb}} \end{pmatrix} \approx \begin{pmatrix} 1-\frac{\lambda^2}{2} & \sim\lambda & ? \\ \sim-\lambda & 1-\frac{\lambda^2}{2} & ? \\ ? & ? & ? \end{pmatrix}$$

$$V_{\mathrm{CKM}}^{\dagger} \times V_{\mathrm{CKM}} = 1$$

$$\lambda = \sin\,\theta_{\mathrm{Cabibbo}} \approx 0.22$$

CKM matrix with KM phase

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With 2×2 matrix, one angle (1-2 rotation)

Can you show this explicitly by using the arbitrary quark phases and unitarity?

CKM matrix with KM phase

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Can you show this explicitly by using the arbitrary quark phases and unitarity?

With 2×2 matrix, one angle (1-2 rotation)

With 3×3 matrix, three angles (1-2, 2-3, 1-3 rotations) and one phase

with three families, some of V_{ij}'s are intrinsically complex

CKM matrix with KM phase

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$$\lambda = \sin\,\theta_{\mathrm{Cabibbo}} \approx 0.22$$

$$\hat{\rho} = \rho\left(1-\frac{\lambda^2}{2}\right),\ \hat{\eta} = \rho\left(1-\frac{\eta^2}{2}\right)$$

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large imaginary part

could be $O(1)$

CKM matrix with KM phase

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CPV in $K^0 \rightarrow \pi\pi$

CKM matrix with KM phase

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CPV in $B_d \rightarrow J/\psi K_S$

CKM matrix with KM phase

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

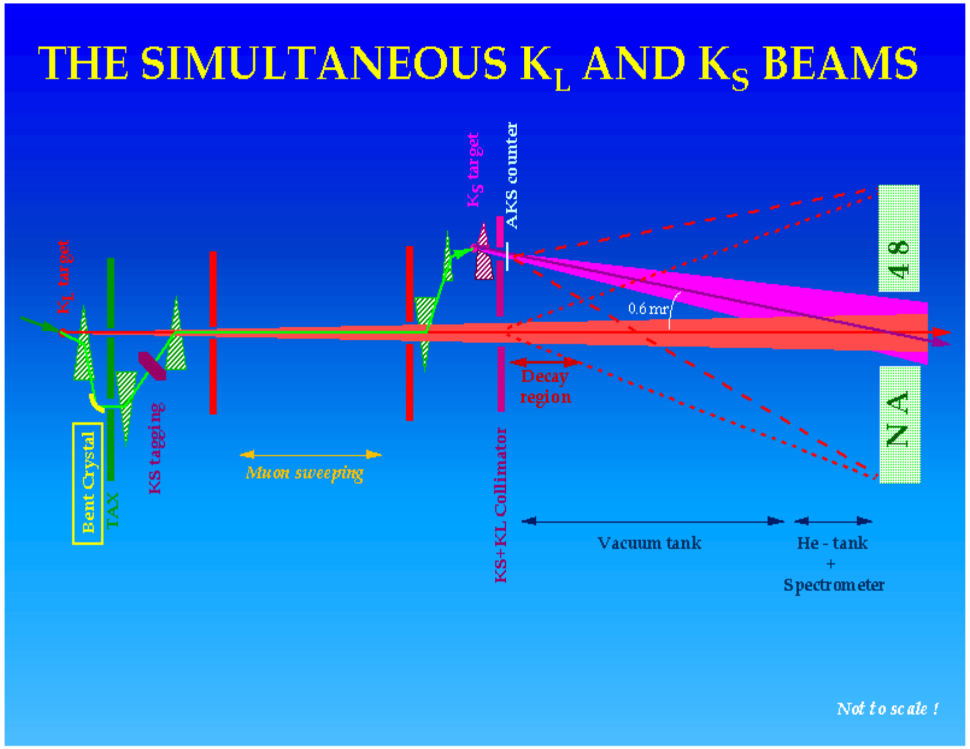
$$\left|\eta_{+-}\right|^2 = \frac{\left|A\left(\mathrm{K_L} \to \pi^+\pi^-\right)\right|^2}{\left|A\left(\mathrm{K_S} \to \pi^+\pi^-\right)\right|^2} = \frac{N_\mathrm{S}^{+-}}{N_\mathrm{L}^{+-}}\frac{N\left(\mathrm{K_L} \to \pi^+\pi^-\right)}{N\left(\mathrm{K_S} \to \pi^+\pi^-\right)} = \left|\varepsilon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

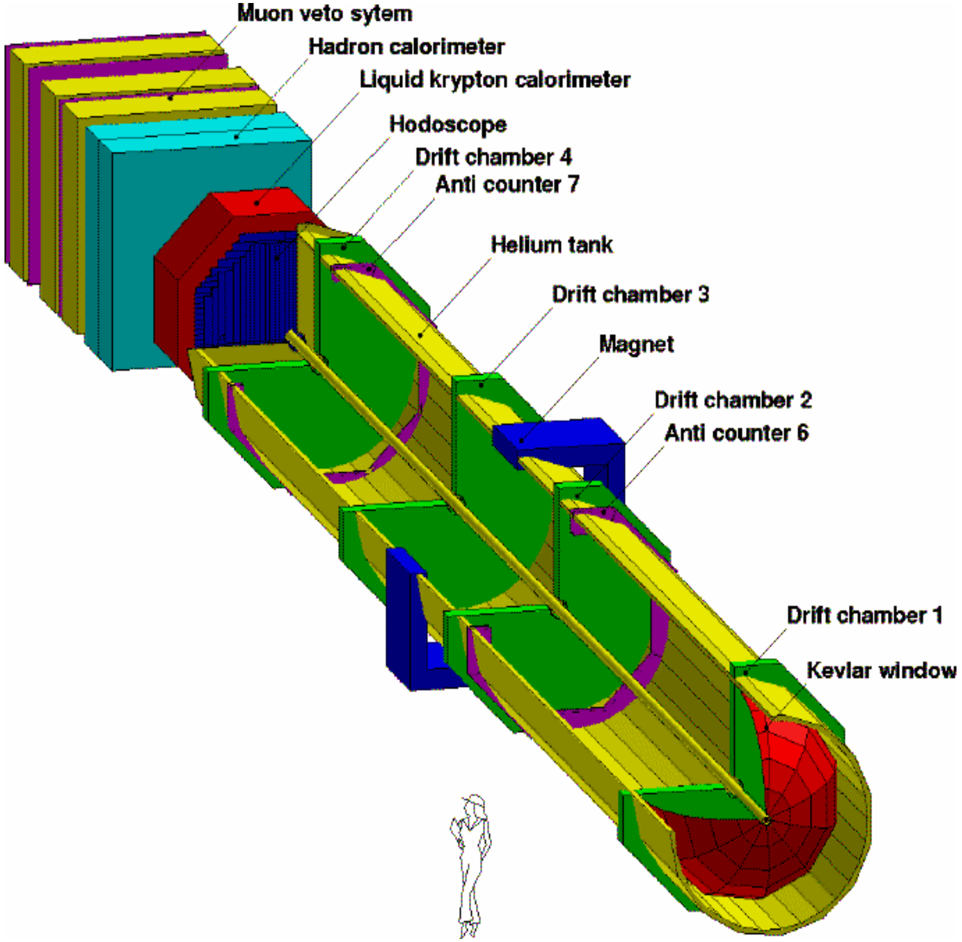
$$\left|\eta_{00}\right|^2 = \frac{\left|A\left(\mathrm{K_L} \to \pi^0\pi^0\right)\right|^2}{\left|A\left(\mathrm{K_S} \to \pi^0\pi^0\right)\right|^2} = \frac{N_\mathrm{S}^{00}}{N_\mathrm{L}^{00}}\frac{N\left(\mathrm{K_L} \to \pi^0\pi^0\right)}{N\left(\mathrm{K_S} \to \pi^0\pi^0\right)} = \left|\varepsilon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

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

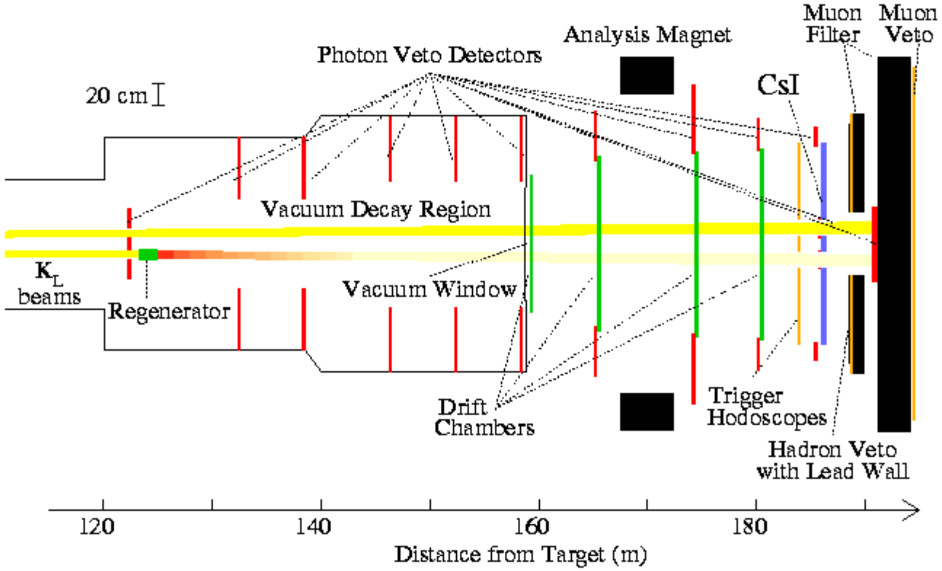
$$= \frac{N_\mathrm{S}^{00}N_\mathrm{L}^{+-}}{N_\mathrm{L}^{00}N_\mathrm{S}^{+-}}\frac{N\left(\mathrm{K_L} \to \pi^0\pi^0\right)N\left(\mathrm{K_S} \to \pi^+\pi^-\right)}{N\left(\mathrm{K_S} \to \pi^0\pi^0\right)N\left(\mathrm{K_L} \to \pi^+\pi^-\right)}$$

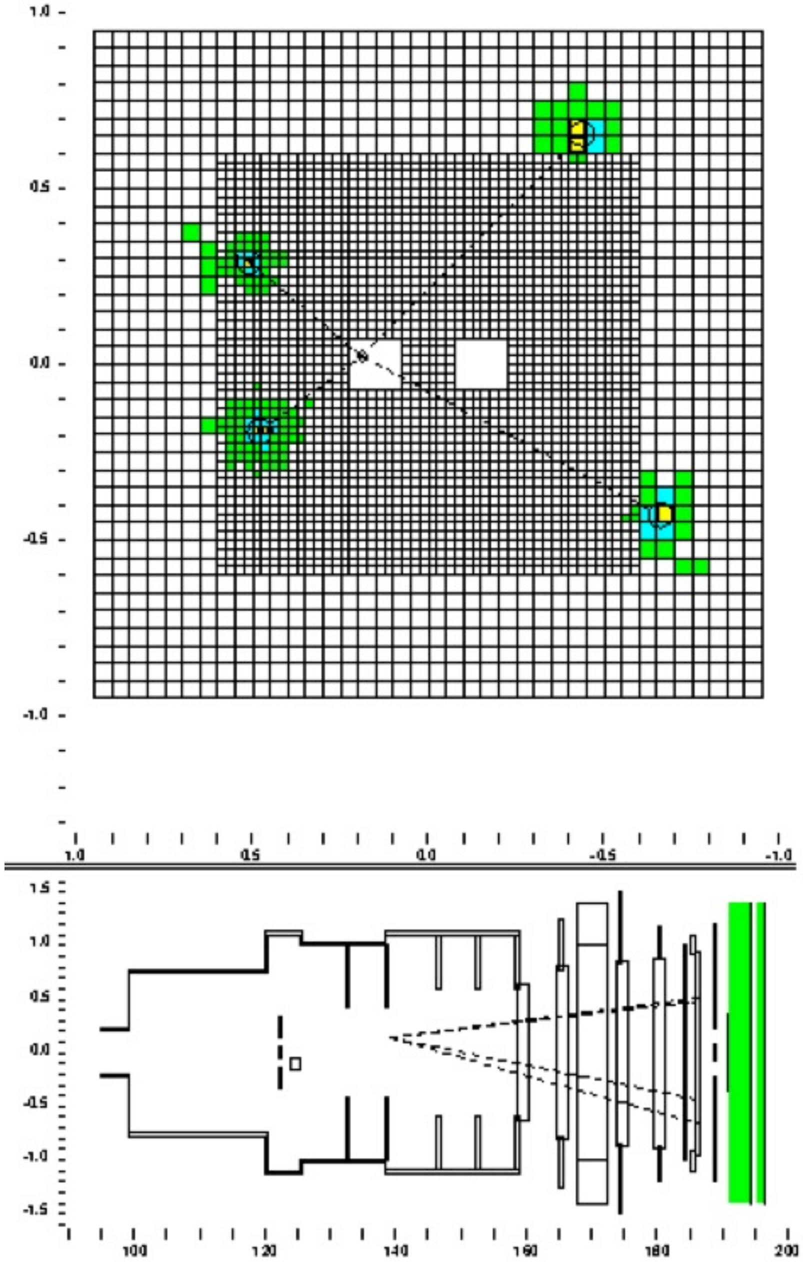
NA48


THE SIMULTANEOUS K_L AND K_S BEAMS



KTeV


Photon Veto Detectors
Analysis Magnet
Muon Filter
Muon Veto
CsI
20 cm
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)


1.0
0.5
0.0
-0.5
-1.0
1.5
100
120
140
160
180
200

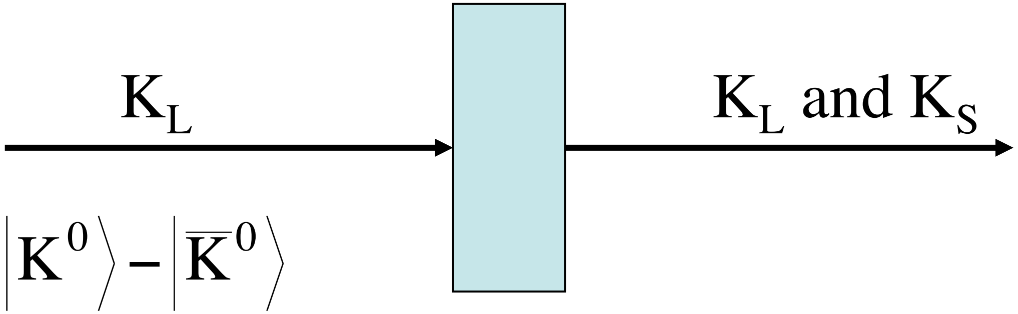
Regeneration

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

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

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

material = p and n



K_L

K_L and K_S

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

Can you demonstrate this?

Measure

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

NA31, NA48

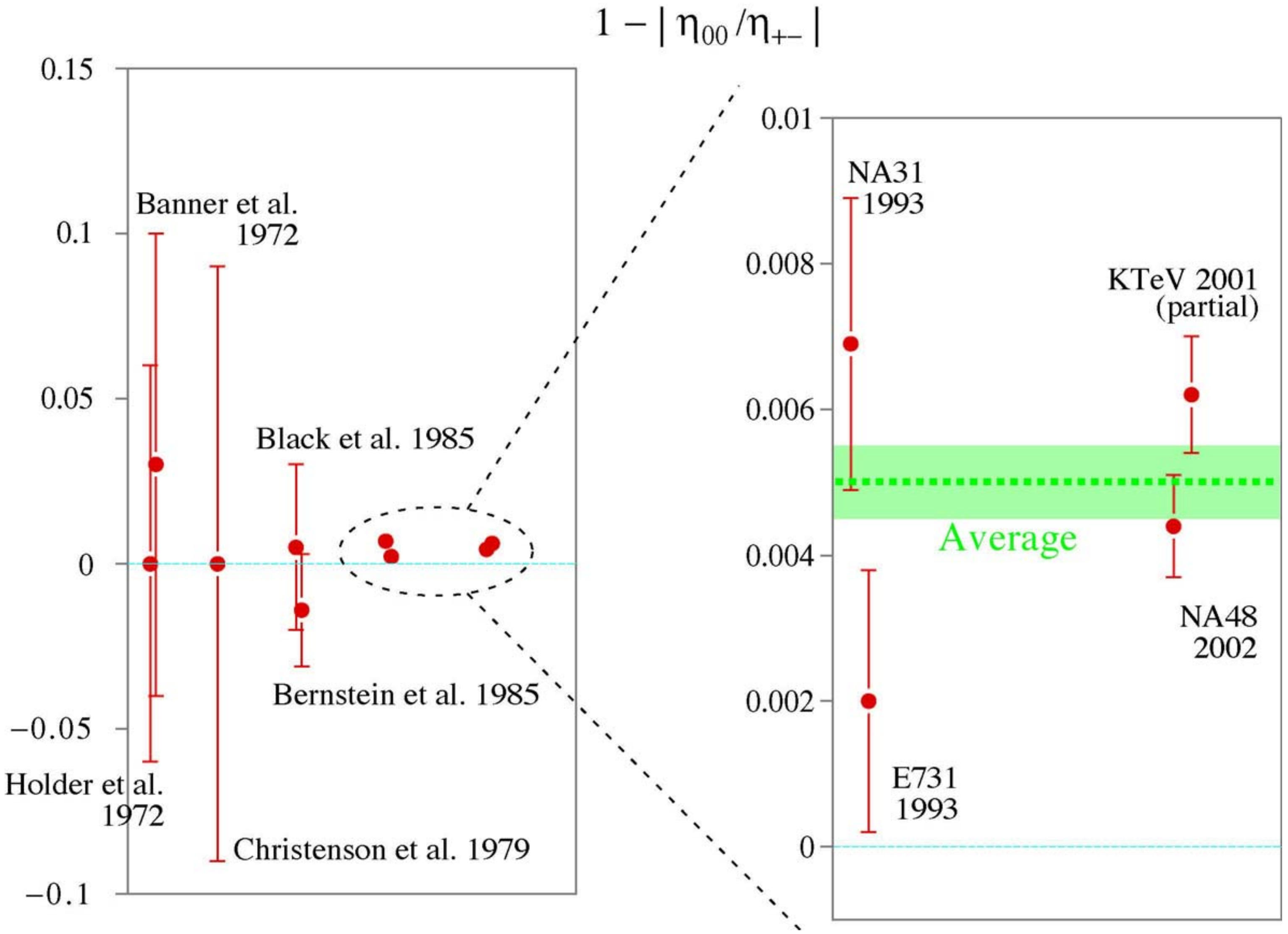
K_L is regenerated from K_S: $N_L^{00} = rN_S^{00}, N_L^{+-} = rN_S^{+-}$

E731, KTeV

No normalization is required,

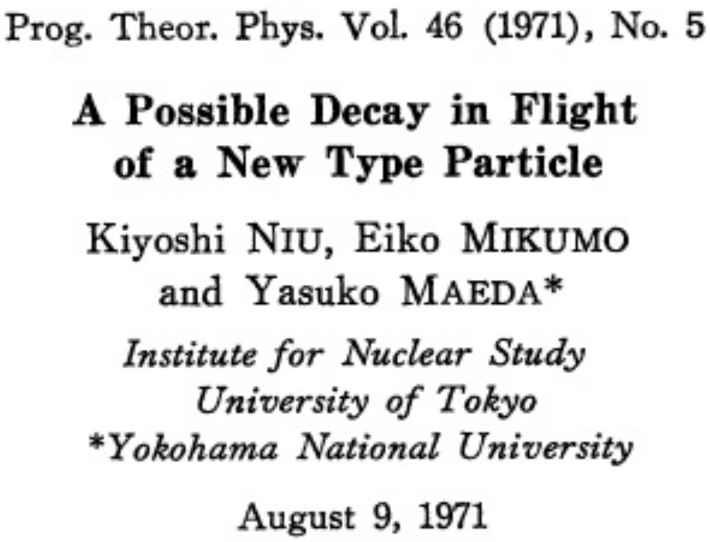
but efficiencies, acceptances etc. have to be corrected…

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

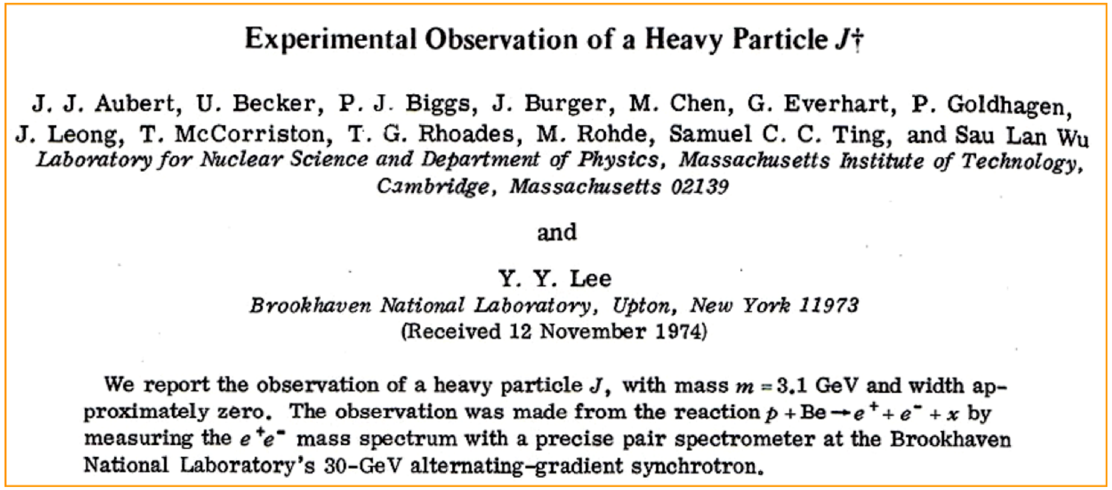
one event of
$X \rightarrow \pi^0 +$ one charged hadron

hypo.	$\pi^0\pi^{\text{charged}}$	$\pi^0 p$
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-$\overline{\text{c}}$ 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

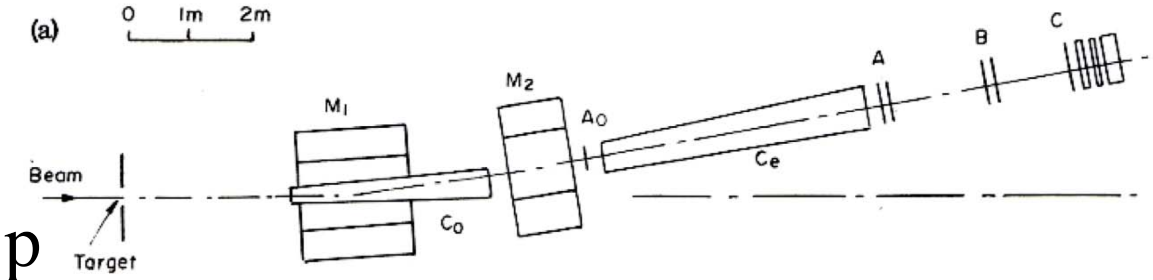
and

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.

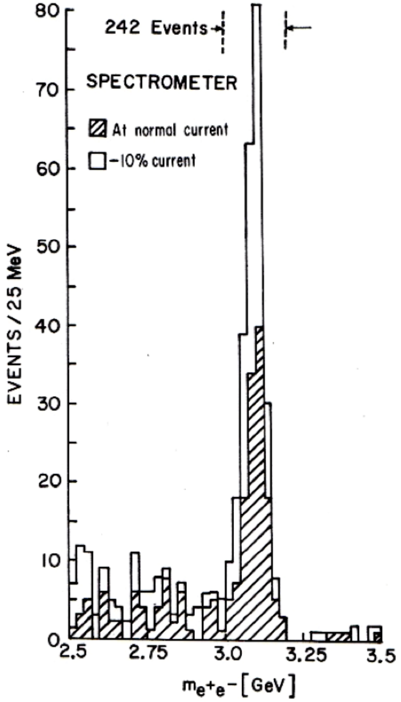
$p+\mathrm{Be}\to e^+e^-+X$



Pb-glass

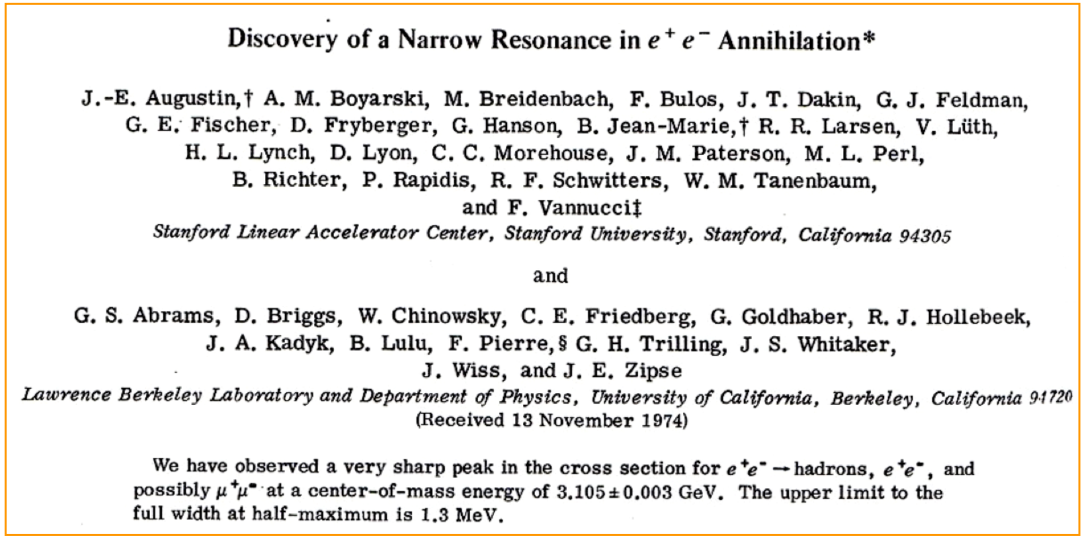
p

double arm spectrometer



e^+e^- invariant mass

Augustin et al.



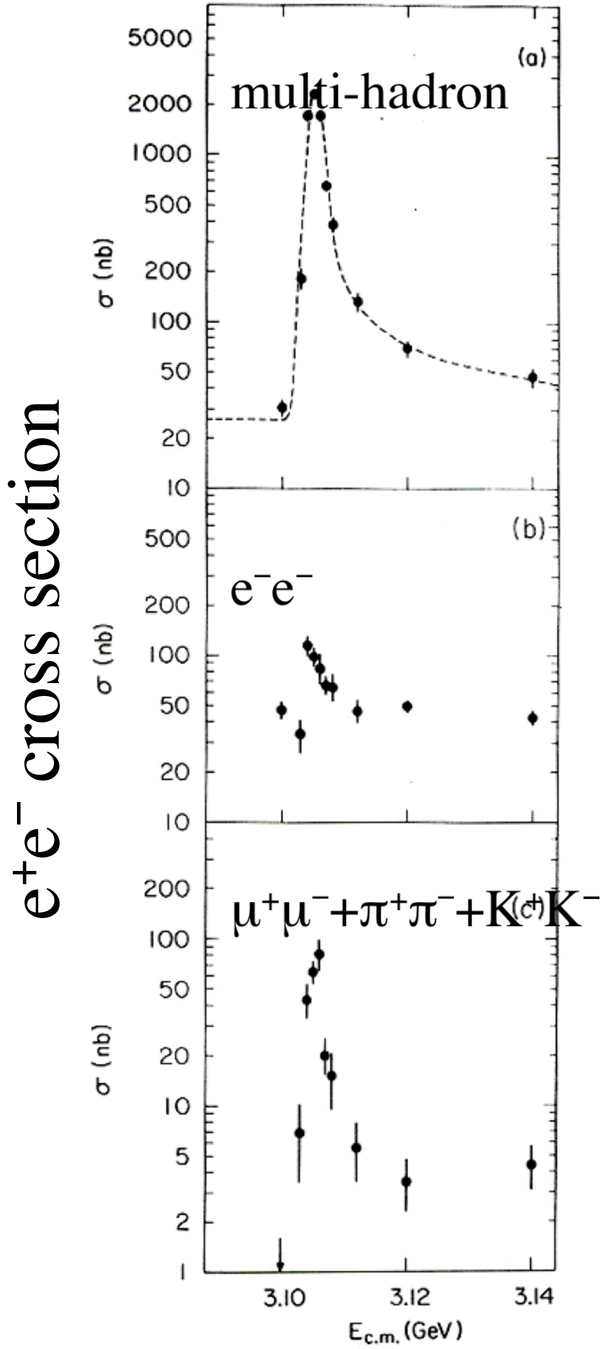
Discovery of a Narrow Resonance in e^+e^- Annihilation*

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

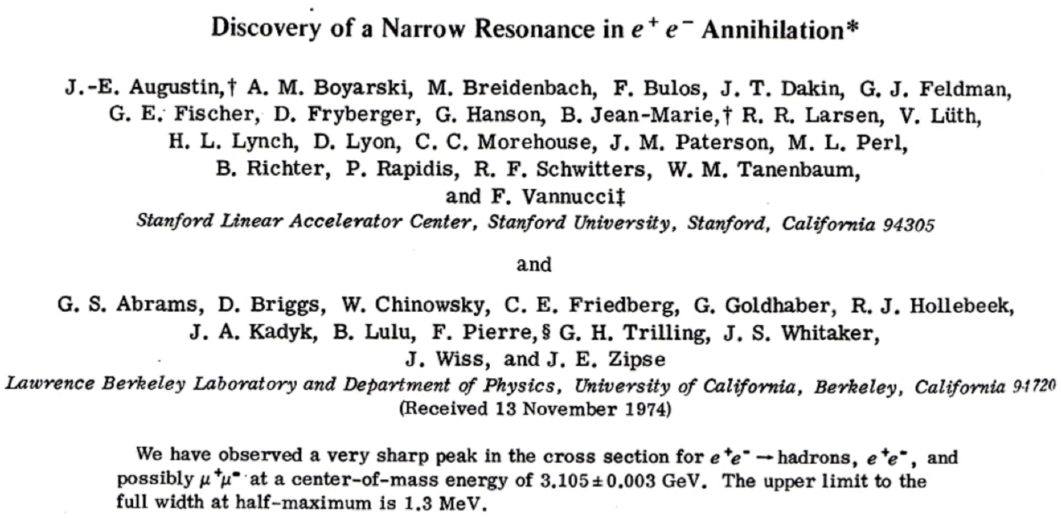
and

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.



Augustin et al.



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J. A. Kadyk, B. Lulu, F. Pierre,§ G. H. Trilling, J. S. Whitaker,
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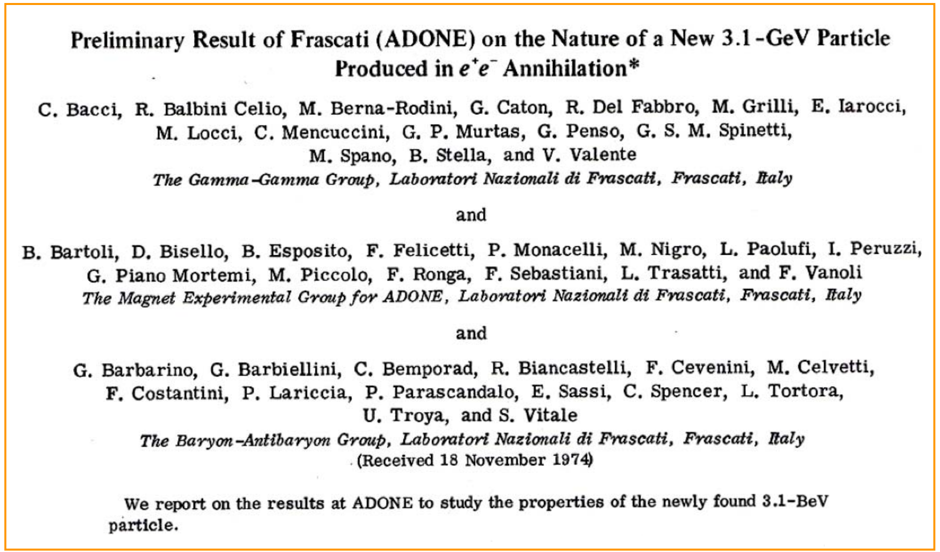
and slightly later…



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

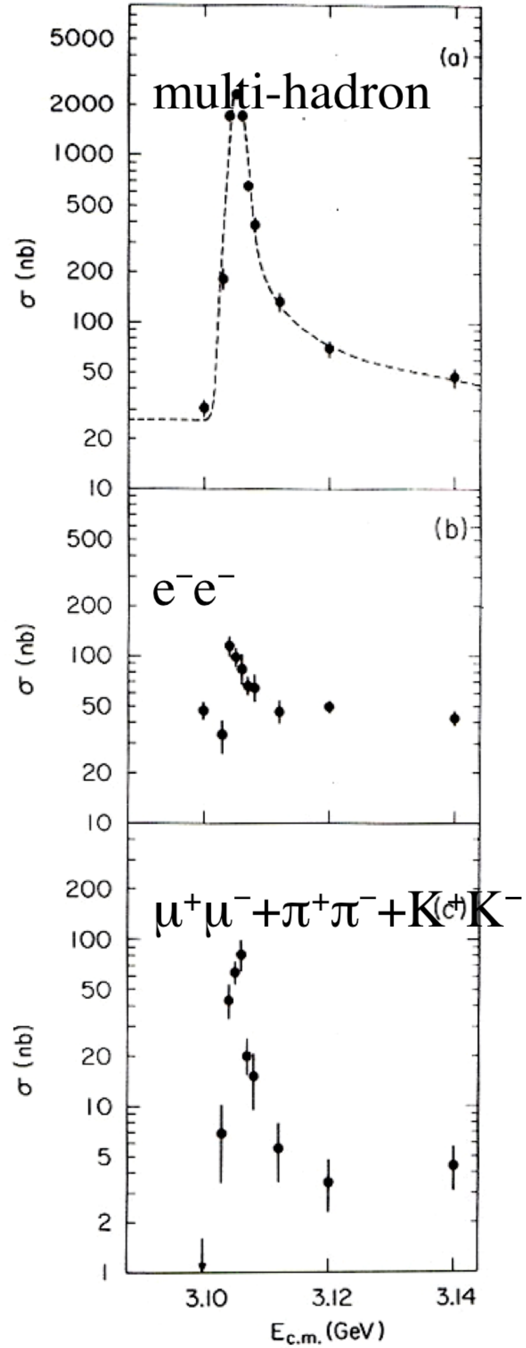
B. Bartoli, D. Bisello, B. Esposito, F. Felicetti, P. Monacelli, M. Nigro, L. Paolufi, I. Peruzzi,
G. Piano Mortemi, M. Piccolo, F. Ronga, F. Sebastiani, L. Trasatti, and F. Vanoli
The Magnet Experimental Group for ADONE, Laboratori Nazionali di Frascati, Frascati, Italy

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.



e^+e^- cross section

multi-hadron

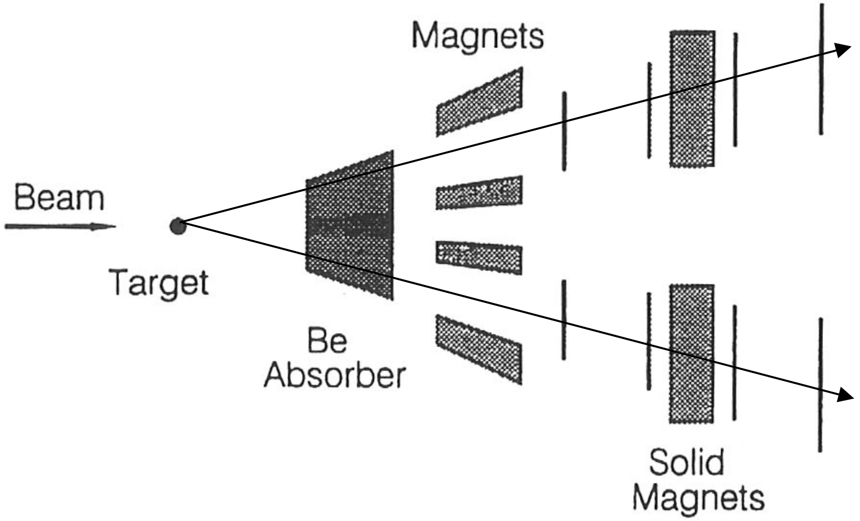
e^-e^-

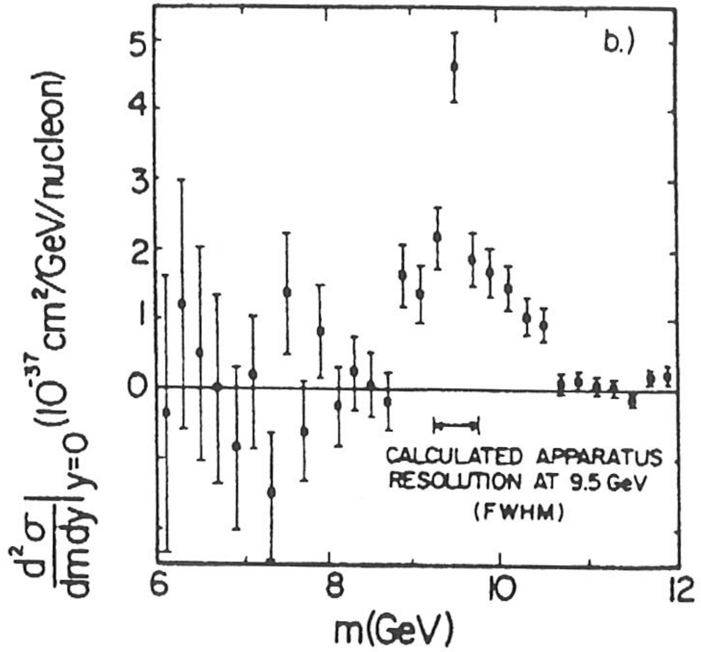
$\mu^+\mu^- + \pi^+\pi^- + K^+K^-$

Discovery of a third family member
S. Herb et al. in 1977

E288 experiment @ FNAL

$\Upsilon \rightarrow \mu^+ \mu^-$





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

$(b\bar{b})$ 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 $K^0_{t=0} \rightarrow \overline{K}^0(t)$

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

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

CPV and very suppressed $B \rightarrow \mu^+\mu^-$ ⇒ 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 $|V_{cb}| \approx |V_{us}|$

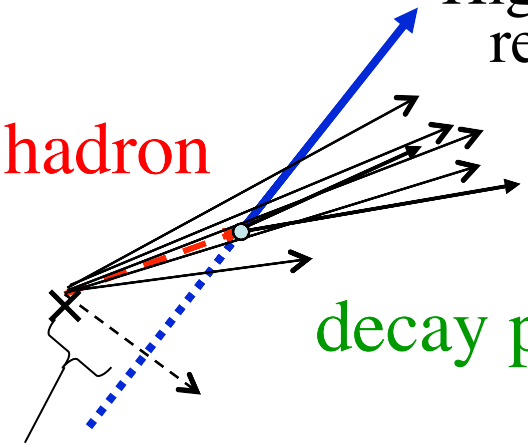
MAC

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 $b\rightarrow l\nu X$ decays.



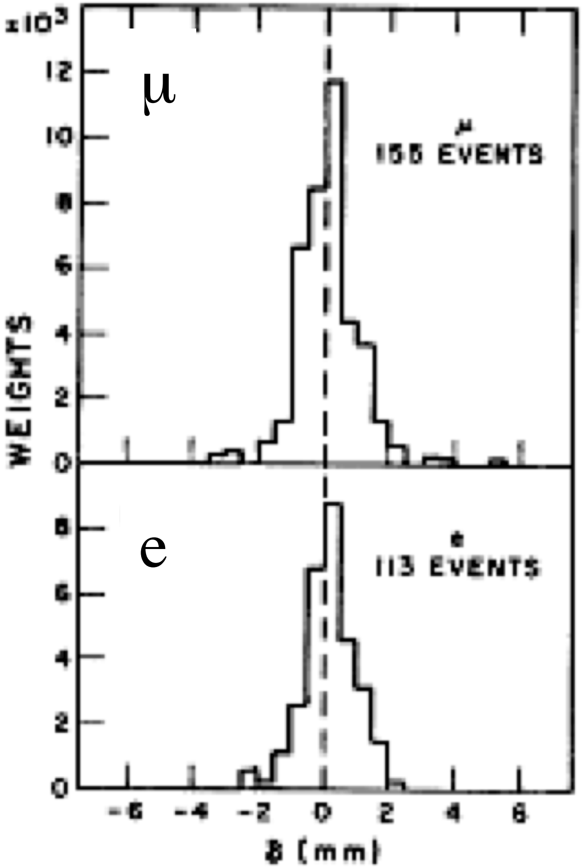
High p_T l respect to the jet axis

b hadron

b-jet

decay point

δ: impact parameter



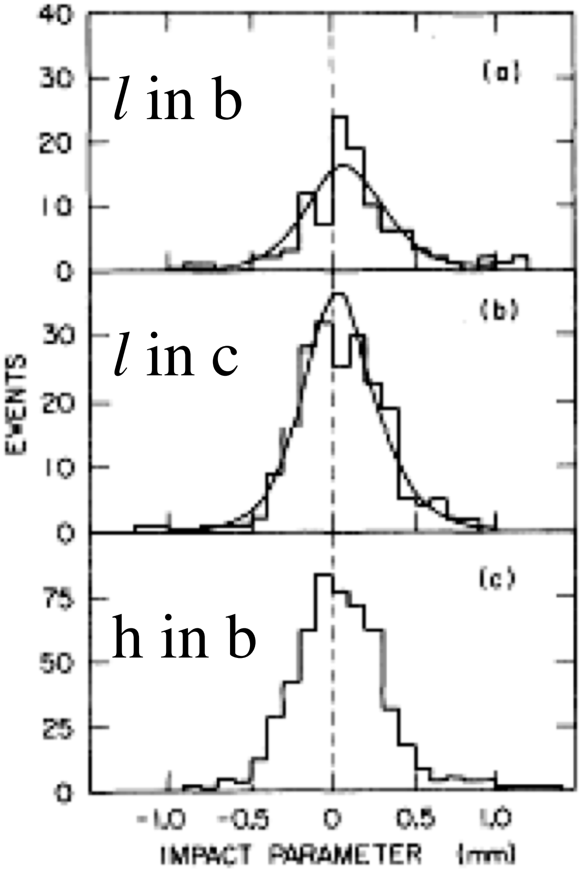
Mark II

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→$l\nu$X decays.



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

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

Flavour Physics

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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 and top mass

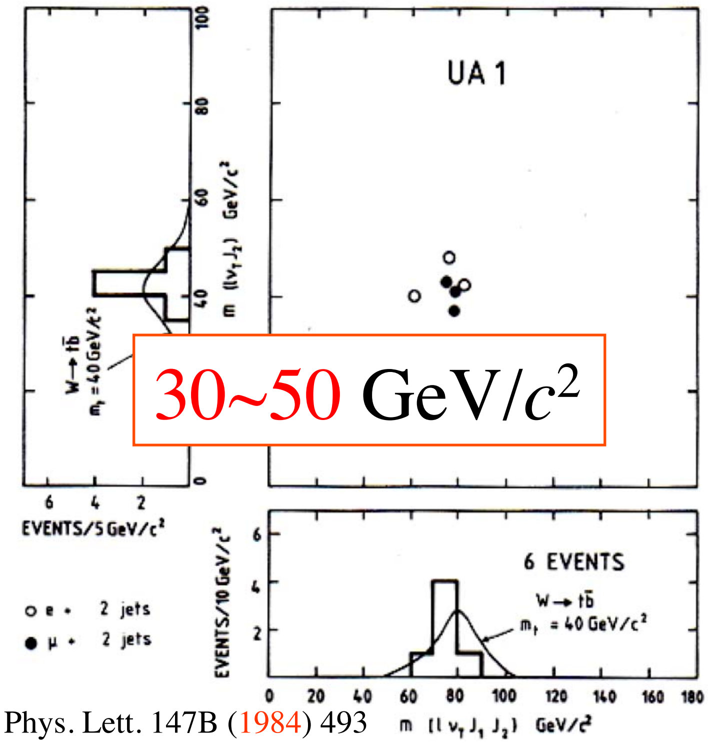
History of m_t

UA1, 1984

$pp \to W+X$

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

$t \to bl\nu$, $b \to$ jet

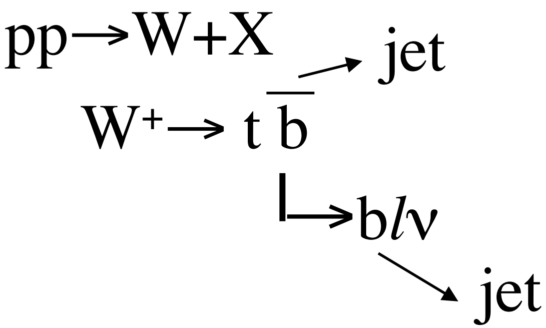


30~50 GeV/c^2

Phys. Lett. 147B (1984) 493

History of m_t

UA1, 1984



$pp \rightarrow W + X$

$W^+ \rightarrow t\,\bar{b}$, $\bar{b} \rightarrow$ jet

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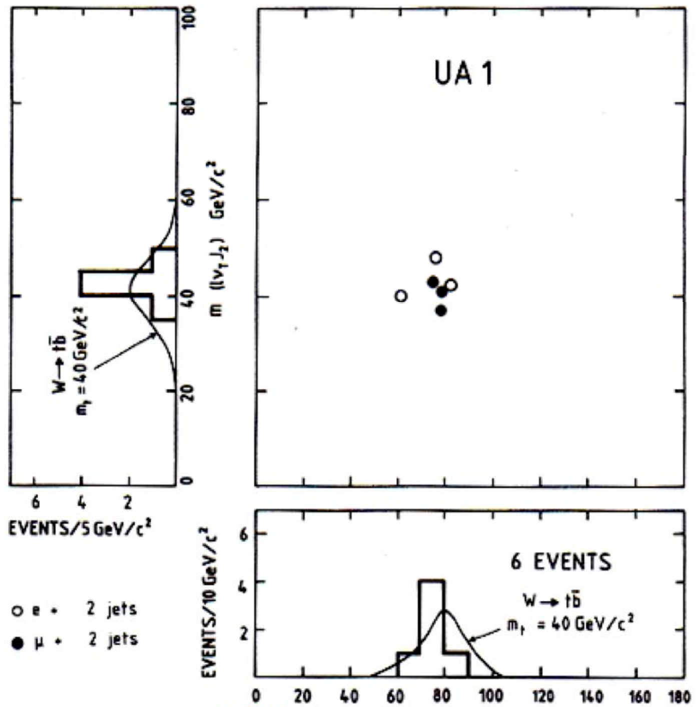
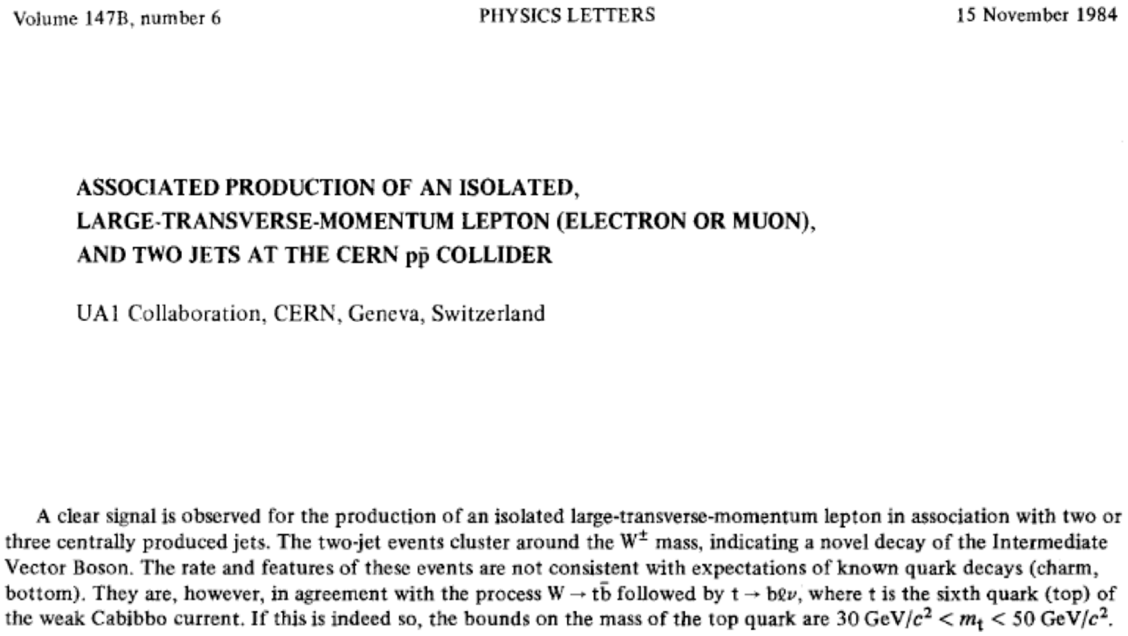


Phys. Lett. 147B (1984) 493



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 $W \rightarrow t\bar{b}$ followed by $t \rightarrow b\ell\nu$, 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

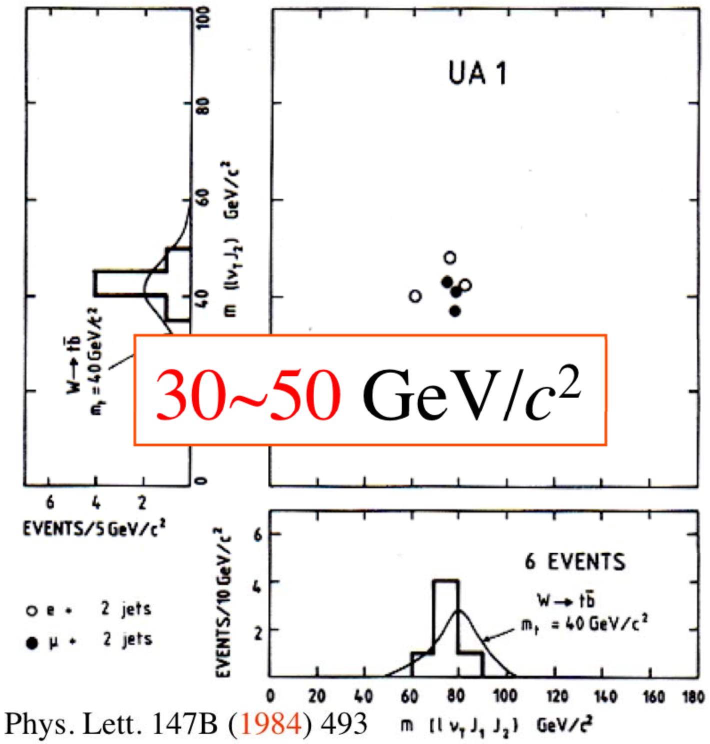
UA1, 1984

$\text{pp} \to W + X \to \text{jet}$

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

$\;\;\;\;\;\;\llcorner\!\!\to b l \nu$

$\to \text{jet}$



30~50 GeV/c^2

Phys. Lett. 147B (1984) 493

ARGUS, 1987

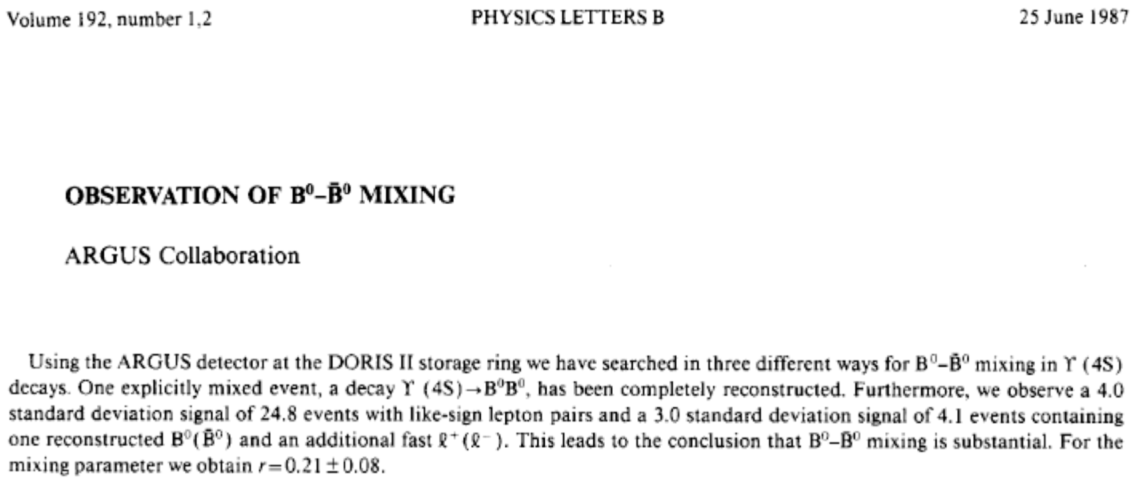
$\Upsilon(4S) \to B_d^{\,0}\bar{B}_d^{\,0}$

$\to B_d^{\,0}B_d^{\,0}$ 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 Υ (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

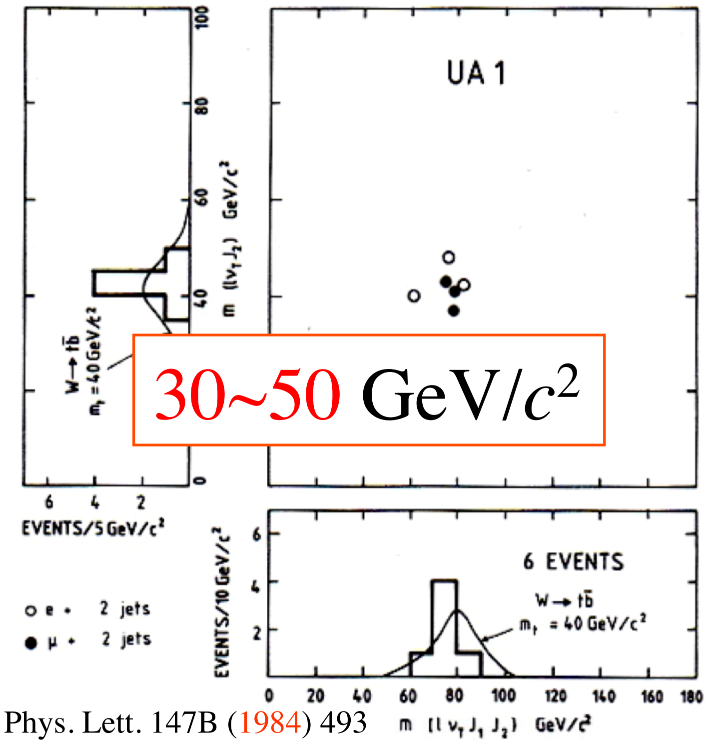
$pp \to W + X$

jet

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

$\hookrightarrow b l \nu$

jet



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Phys. Lett. 147B (1984) 493

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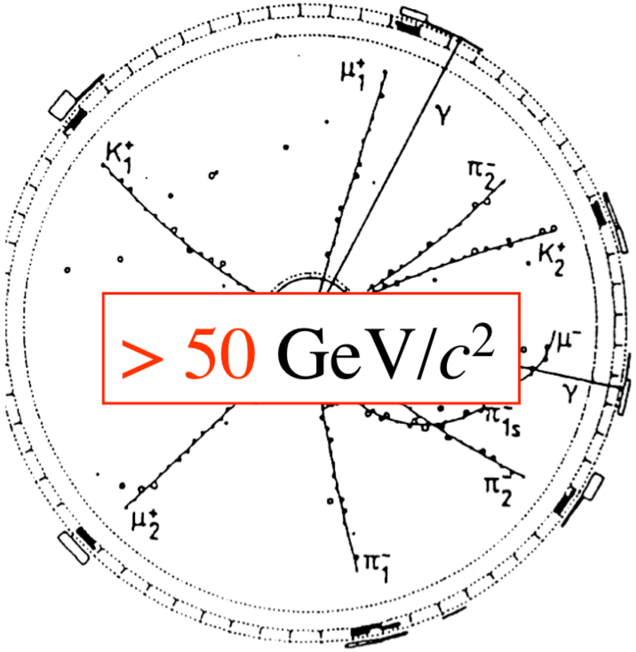
$\to \ell^+ \ell^+$ or $\ell^- \ell^-$

24.8±7.6±3.8

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



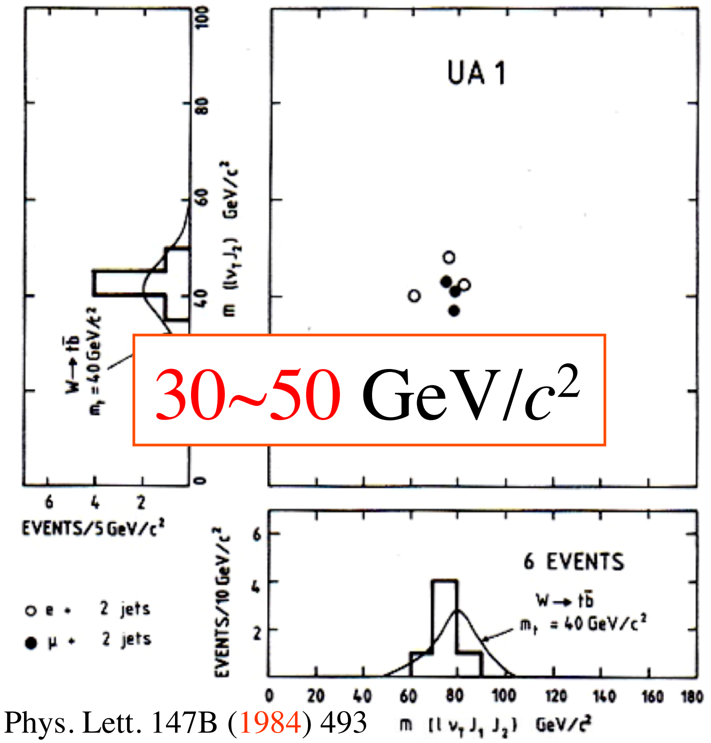
> 50 GeV/c^2

Phys. Lett. B 192 (1987) 245

History of m_t

UA1, 1984

$p\bar{p} \to W + X$
$\nearrow$ jet
$W^+ \to t\,\bar{b}$
$\llcorner\!\to b l \nu$
$\searrow$ jet



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Phys. Lett. 147B (1984) 493

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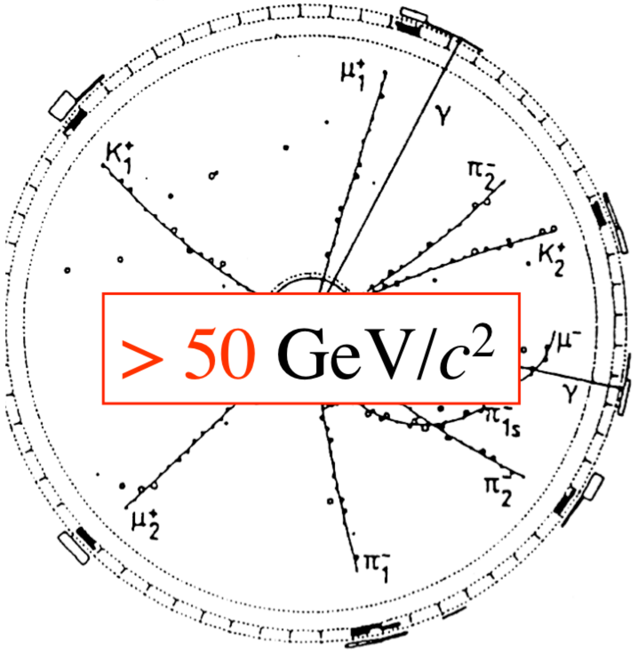

> 50 GeV/c^2

Phys. Lett. B 192 (1987) 245

LEP
electroweak fit
150~210 GeV/c^2

1995
CDF
$175\pm8\pm10$ GeV/c^2
D0
$199^{+19}_{-21}\pm22$ GeV/c^2

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CPV ⇒ third family

Δm_B ⇒ top mass

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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

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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

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), 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 $K^0_{t=0} \rightarrow \overline{K}^0(t)$

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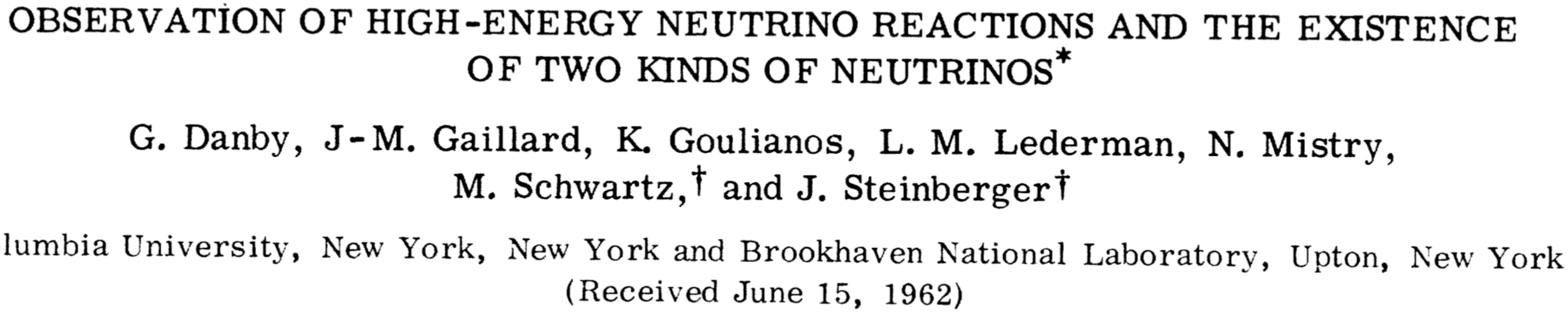
Discovery of ν_μ: BNL spark chamber experiment

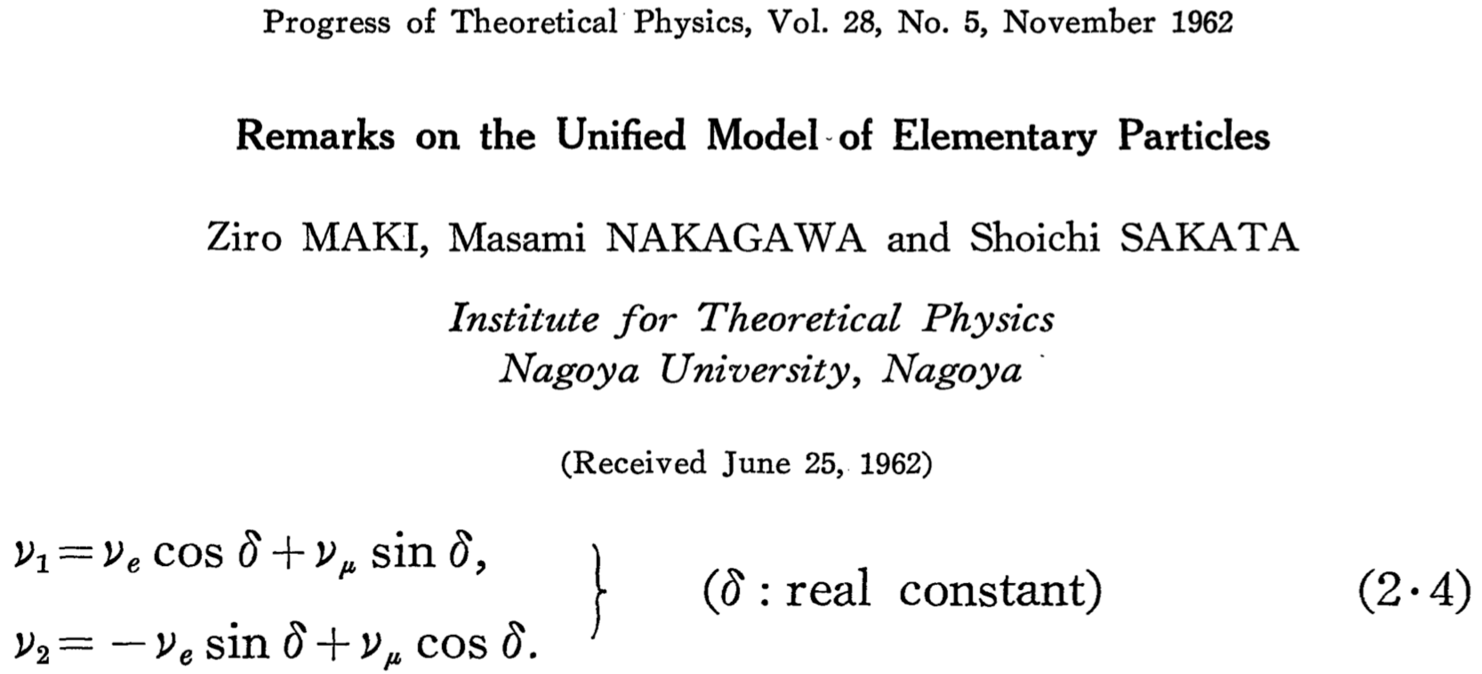


OBSERVATION OF HIGH-ENERGY NEUTRINO REACTIONS AND THE EXISTENCE OF TWO KINDS OF NEUTRINOS*

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)

$$\left.\begin{aligned} \nu_1 &= \nu_e \cos\delta + \nu_\mu \sin\delta, \\ \nu_2 &= -\nu_e \sin\delta + \nu_\mu \cos\delta. \end{aligned}\right\} \quad (\delta : \text{real constant}) \qquad (2\cdot4)$$

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

Flavour Physics

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CPV ⇒ third family

Δm_B ⇒ 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

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Δm_B	⇒ top mass
ν mixing pattern	

ν oscillations now seen by, Davis, KAMIOKANDE, IMB, SNO
MACRO, KamLAND, T2K, MINOS, and finally OPERA

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 ⇒ third family

Δm_B ⇒ top mass

ν mixing pattern ⇒ may be heavy neutrinos?

⇒ may Majorana component?

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

Meson 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.

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

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.)

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

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

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. $H_\mathrm{w} << H_\mathrm{s} + H_\mathrm{em}$), $a(t)$ 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.

Can you prove this?

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

NB: The following relations could be useful…

$$CP|P\rangle = e^{i\varphi}|\overline{P}\rangle,\ CP|\overline{P}\rangle = e^{-i\varphi}|P\rangle$$

$$T|P\rangle = e^{i\vartheta}|P\rangle,\ T|\overline{P}\rangle = e^{i\overline{\vartheta}}|\overline{P}\rangle$$

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

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

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

Can you prove this?

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 Can you prove this?

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

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

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

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

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

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

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

$$\left|P_\pm\right\rangle = \frac{1}{\sqrt{1+|\zeta|^2}}\underbrace{\left(\left|P\right\rangle \pm \zeta\left|\overline{P}\right\rangle\right)}_{\text{quantum mechanics state mixing}}$$

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

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

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

Can you prove this?

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

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 $\overline{\mathrm{P}}$ 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

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

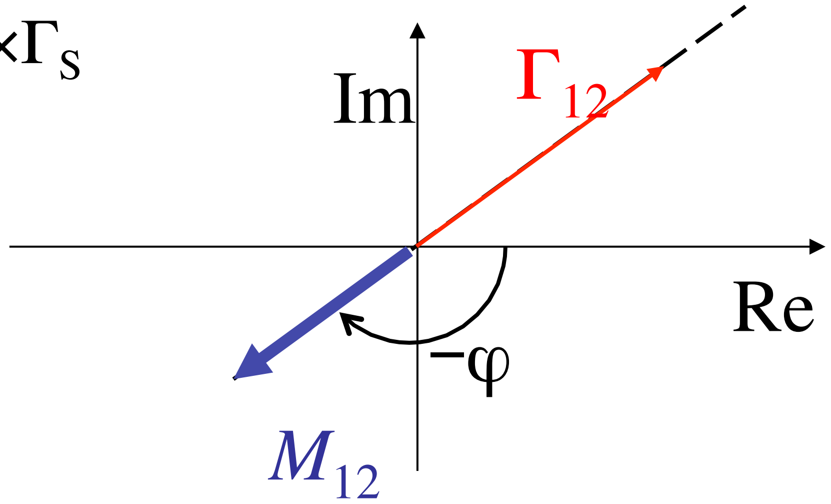
K^0 system: mass eigenstates are K_L and K_S

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:

$$x = 0.776,\ y < 0.09$$

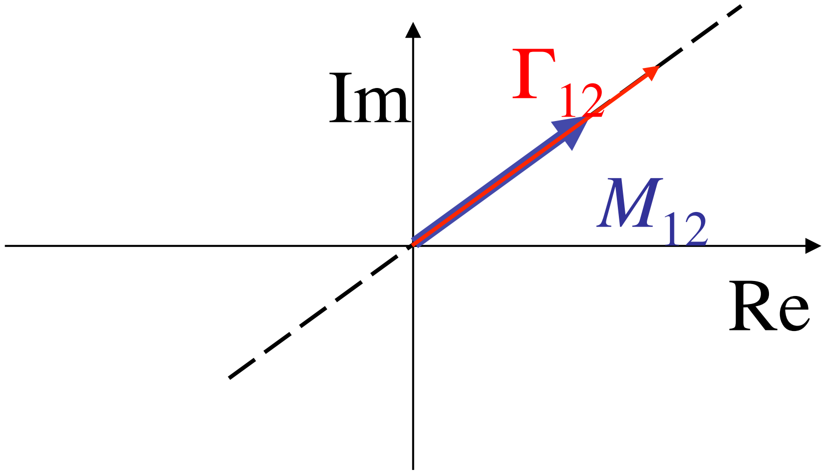
Recall

$$CP|P\rangle = e^{i\varphi}|\overline{P}\rangle,\ CP|\overline{P}\rangle = e^{-i\varphi}|P\rangle$$

Bs system:

$$x = 25.5,\ y = 0.06$$

For your information



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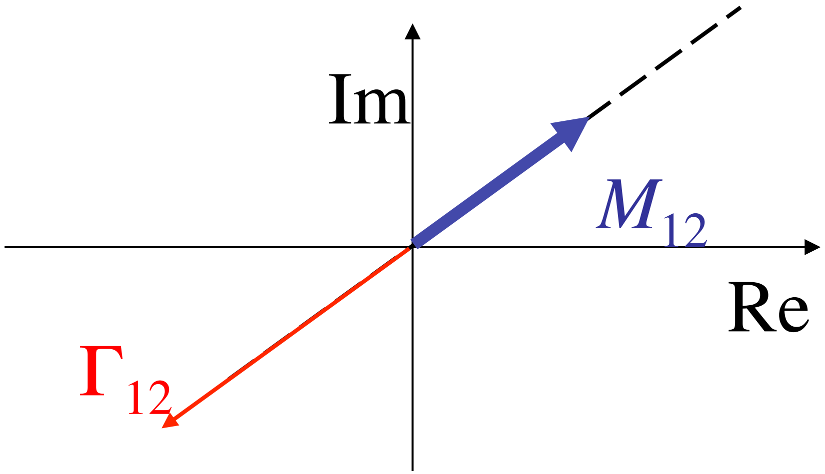
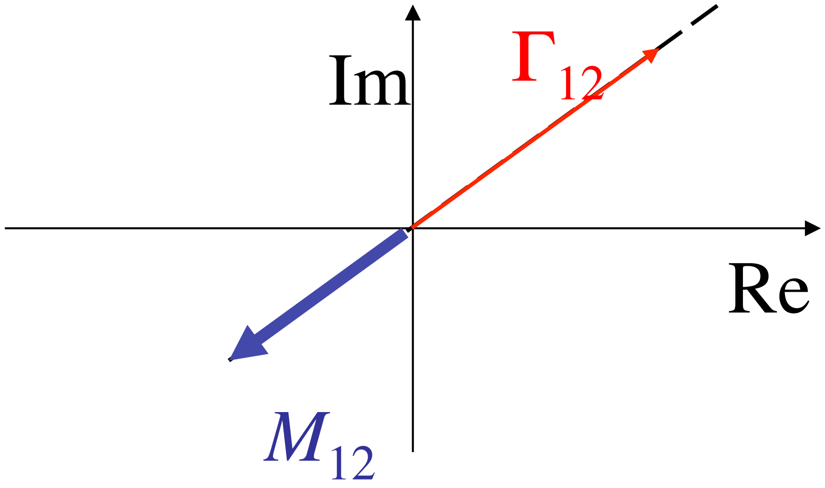
and decay faster



CP=+1 state is heavier
and decay slower



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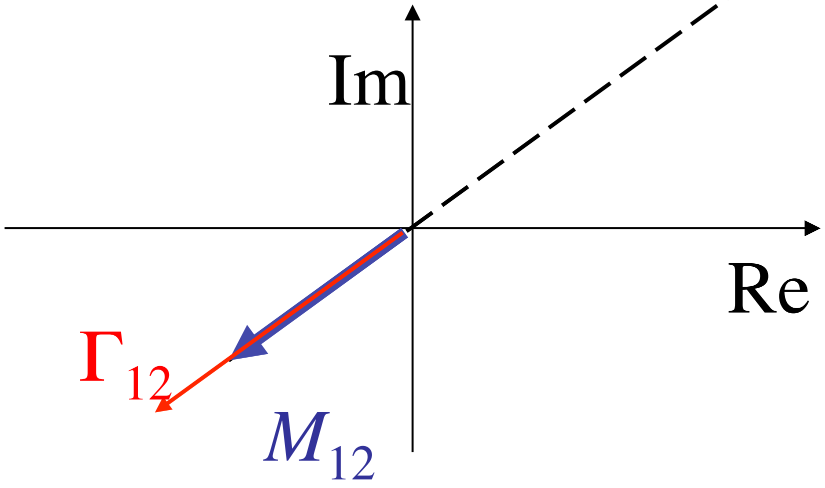

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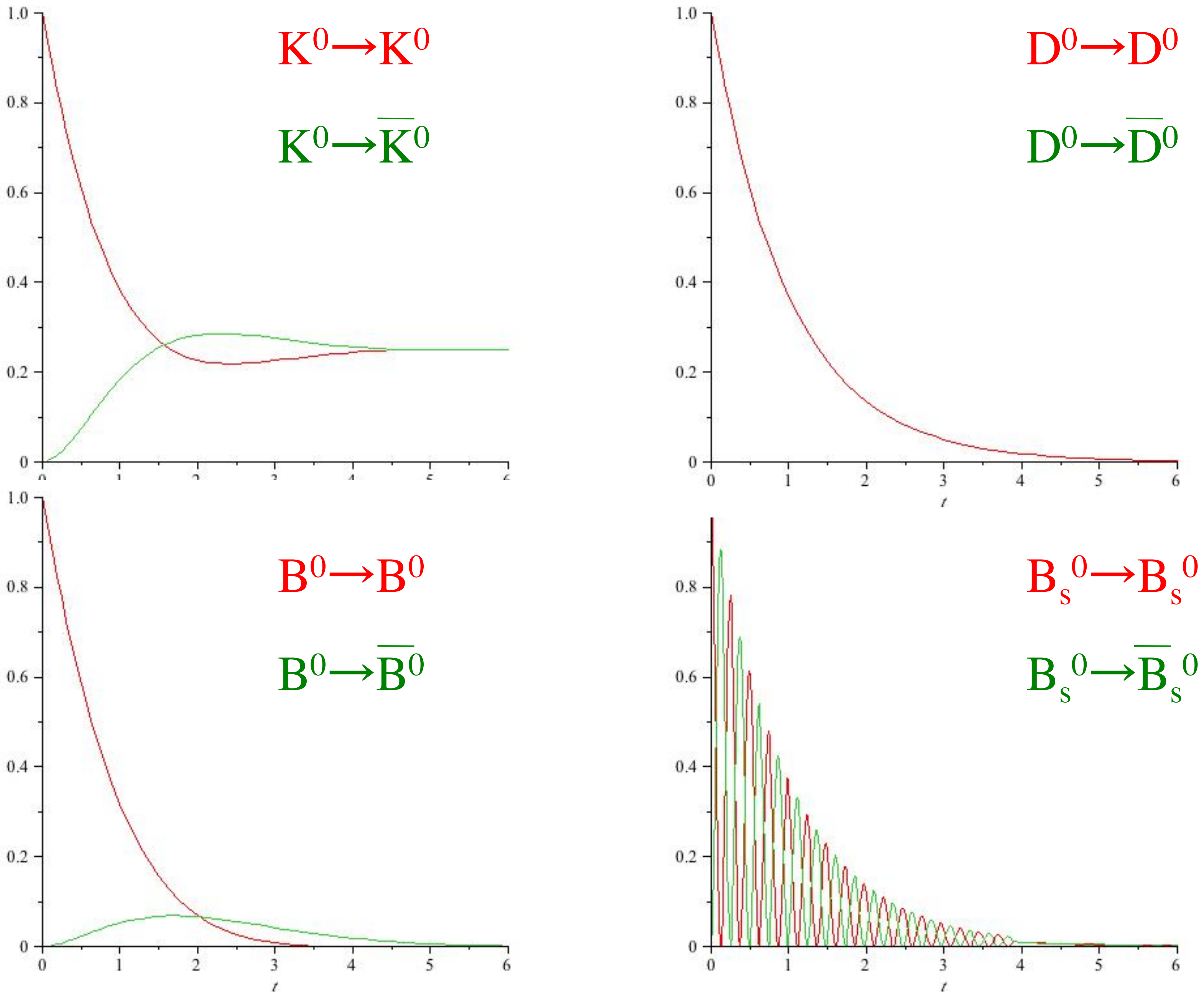

$K^0 \to K^0$
$K^0 \to \overline{K}^0$
$D^0 \to D^0$
$D^0 \to \overline{D}^0$
$B^0 \to B^0$
$B^0 \to \overline{B}^0$
$B_s^0 \to B_s^0$
$B_s^0 \to \overline{B}_s^0$
1.0
0.8
0.6
0.4
0.2
0
0
1
2
3
4
5
6
t

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: $A_{\mathrm{T}}(t)$

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

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

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

$A_{\mathrm{T}}(t) \neq 0 \Rightarrow$ 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 $t = 0$: $\mathrm{p\bar{p}}$ annihilation at rest

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

$\mathrm{S} = 0$ $\qquad$ $\mathrm{S} = 0$

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

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

Accompanying charged kaons indicate the flavour of neutral kaons.

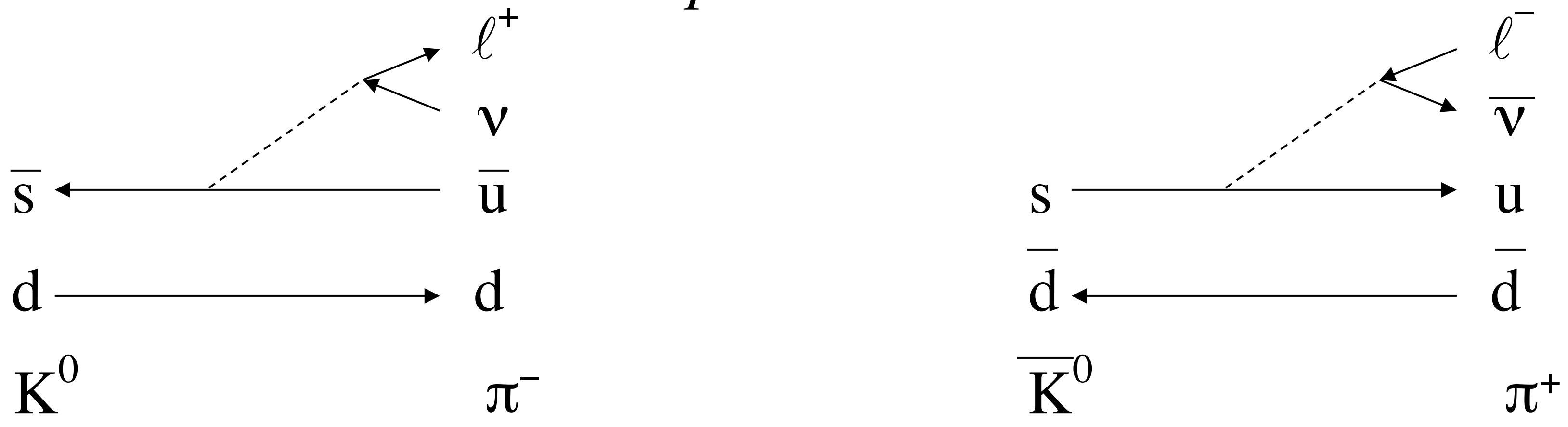
$$\boxed{\mathrm{K}^+\pi^- \rightarrow \mathrm{\bar{K}}^0,\ \mathrm{K}^-\pi^+ \rightarrow \mathrm{K}^0}$$

Identification of the final states:

Semileptonic decays are used to directly measure this…

i.e. flavour specific decay modes

$\Delta q = \Delta s$ rule



K^0: $q = 0$, $s = +1$ → π^-: $q = -1$, $s = 0$

$\Delta q = -1$

$\Delta s = -1$

$\bar{K}^0$: $q = 0$, $s = -1$ → π^+: $q = +1$, $s = 0$

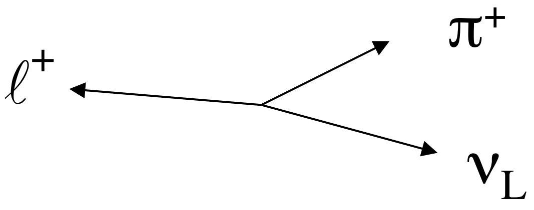
$\Delta q = +1$

$\Delta s = +1$

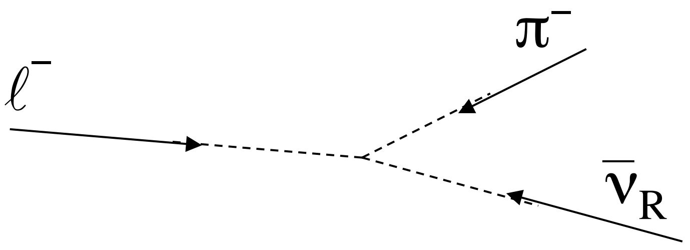
final states are specific to the flavour,

i.e. the particle and the anti-particle

(no hadronic decay mode available for the neutral kaons)



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



$$\Big\Downarrow \quad \text{CPT}$$

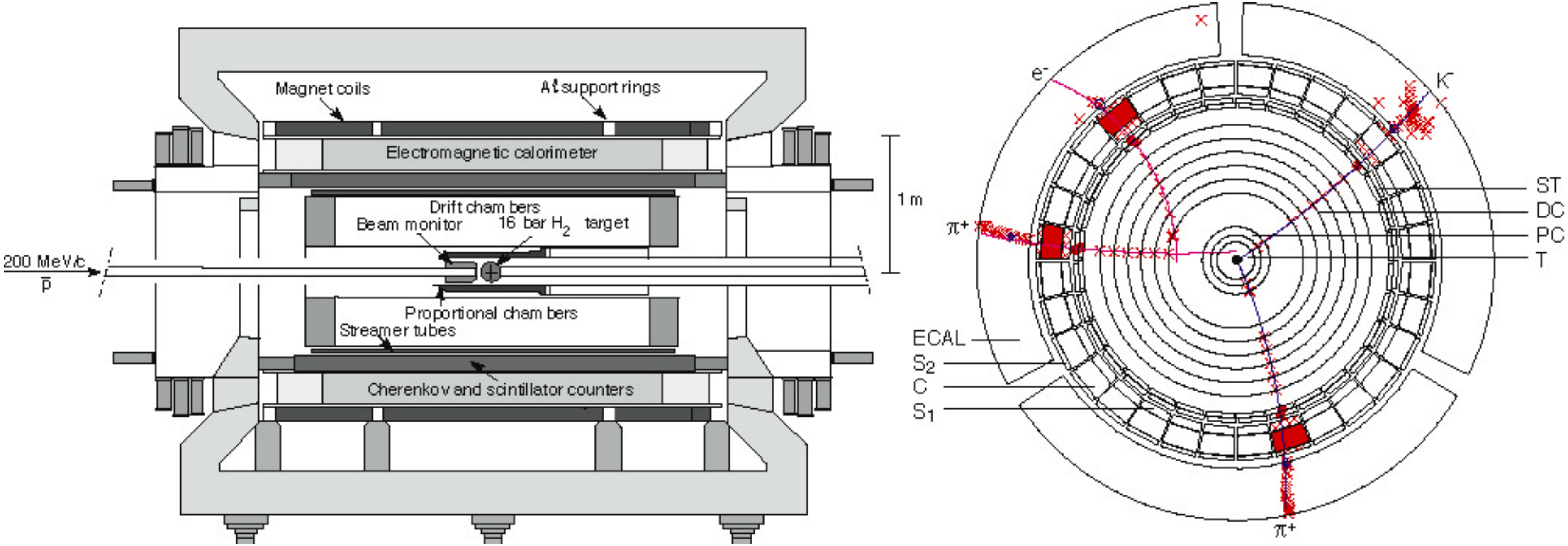
$$\int_{\text{phase space}} d\Omega\Big|_{\text{in}} \Big\langle \ell^-(-p_1)\overline{\upsilon}_R(-p_2)\pi^+(-p_3)\Big|H_W\Big|\overline{K}^0\Big\rangle\Big|^2$$

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

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

Since the interactions between the final states are weak,

CPLEAR experiment

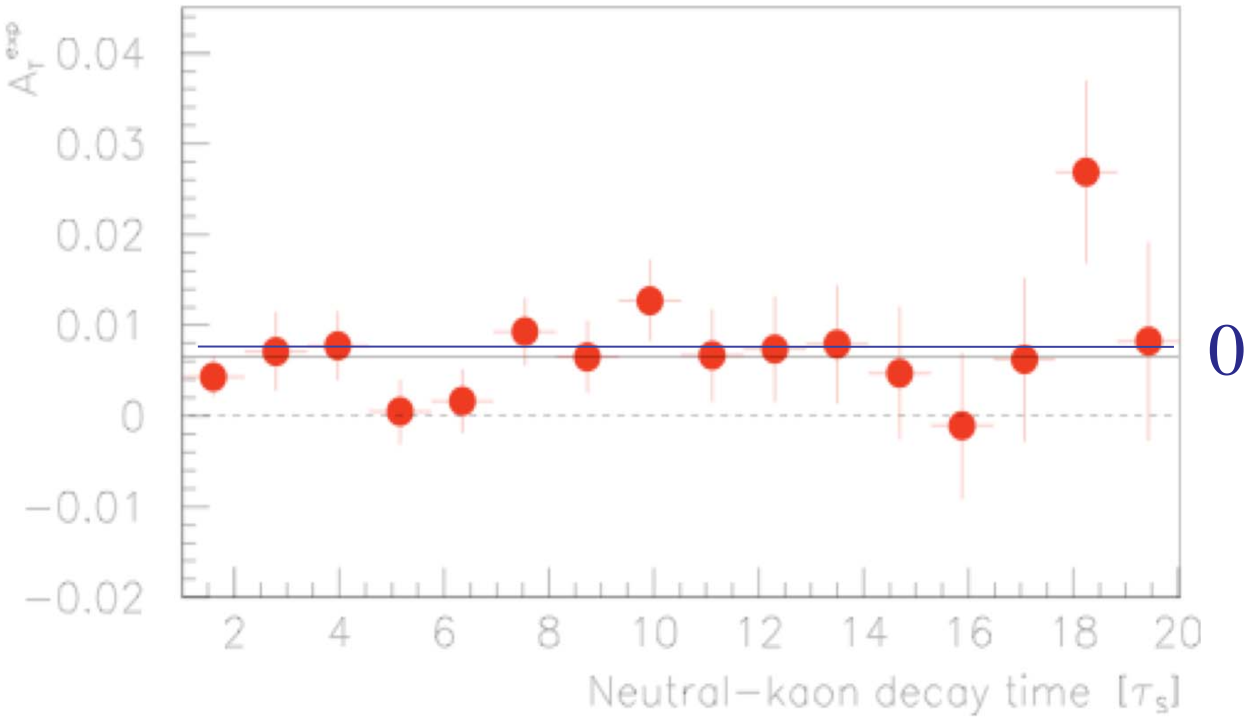


$$p\bar{p} \Rightarrow K^- \pi^+ K^0$$

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

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

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



$$A_T = (6.6 \pm 1.6) \times 10^{-3}$$

$$A_T(t) = \frac{1 - |\zeta|^4}{1 + |\zeta|^4} \xrightarrow{\qquad\qquad} |\zeta| = 0.9967 \pm 0.0008 \neq 1$$

Small $\cancel{CP}$ and $\cancel{T}$ 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. $\mathrm{Im}(M_{12}/\Gamma_{12}) << 1$

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

⇒ even with CP violation

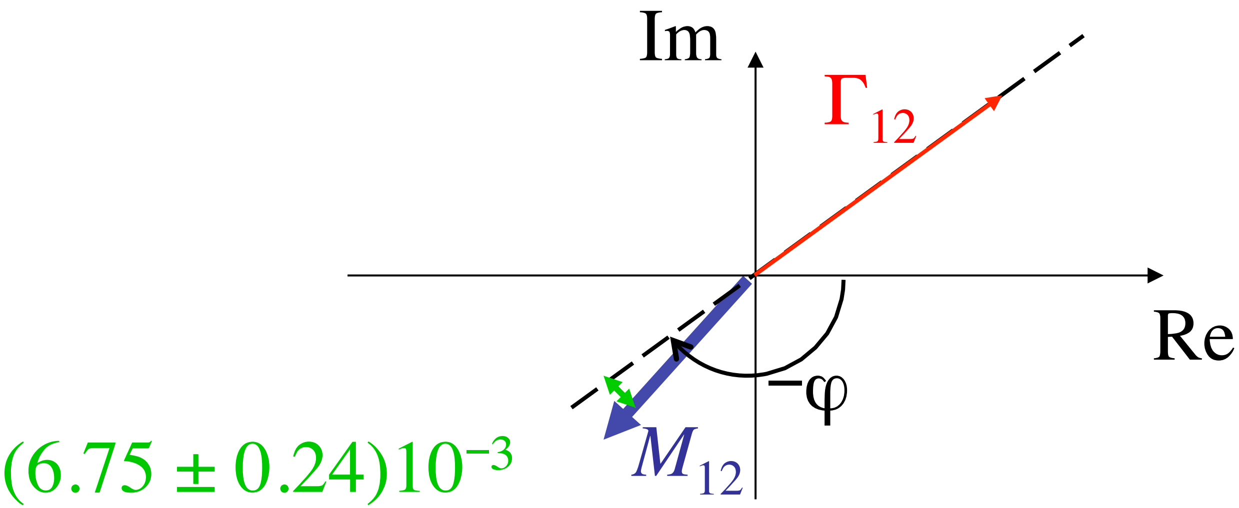
$|\Delta m| = 2|M_{12}|$ and $|\Delta \Gamma| = 2|\Gamma_{12}|$ are still good for the neutral kaons.

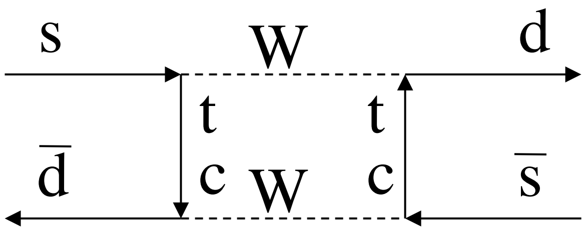
Can you prove this?

NB:

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

For your Information





Base of the CP violation in the oscillations

In the CKM scheme: $\boxed{\Gamma_{12} \propto V_{us}V_{ud}^{*}e^{-i\varphi}}$

$$\boxed{\begin{aligned} M_{12} &= \frac{G_{\mathrm{F}}^2}{12\pi^2} f_{\mathrm{K}}^2 B_{\mathrm{K}} m_{\mathrm{K}} m_{\mathrm{W}}^2 \\ &\quad \times\left[\lambda_c^2 \eta_1 S_0(x_{\mathrm{c}}) + \lambda_t^2 \eta_2 S_0(x_{\mathrm{t}}) + \lambda_c \lambda_t \eta_3 S_0(x_{\mathrm{c}}, x_{\mathrm{t}})\right] e^{i(\pi-\varphi)} \end{aligned}}$$

$$\lambda_c = V_{cs}V_{cd}^{*},\ \lambda_t = V_{ts}V_{td}^{*}$$

$$x_{\mathrm{c}}=(m_{\mathrm{c}}/m_{\mathrm{W}})^2,\ x_{\mathrm{t}}=(m_{\mathrm{t}}/m_{\mathrm{W}})^2$$

$$\left.\begin{aligned} \eta_1 &= 1.38 \pm 0.20 \\ \eta_2 &= 0.57 \pm 0.01 \\ \eta_3 &= 0.47 \pm 0.04 \end{aligned}\right\} \text{QCD corrections}$$

Most general case…

Time dependent decay rates for a final state f.

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

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

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

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

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

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

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

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

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

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

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 $\pi^+\pi^-\pi^0$):

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

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 CP eigenstates,

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

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

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

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

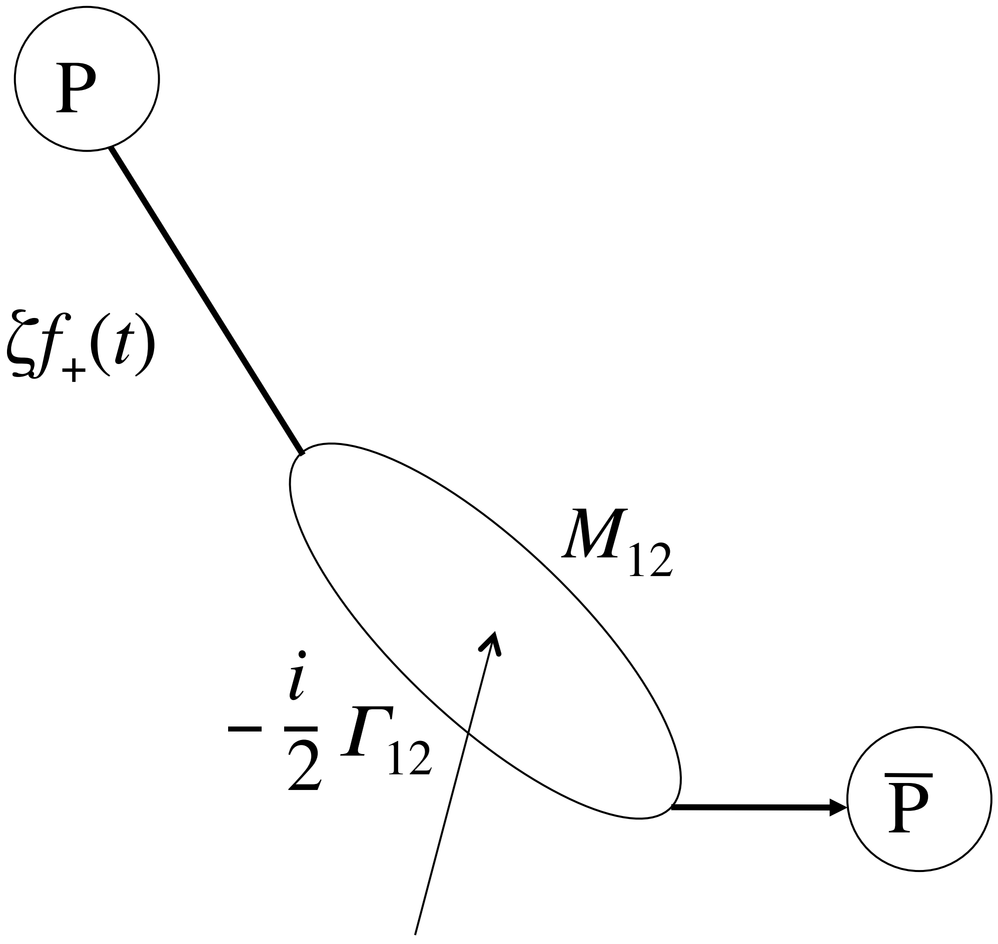
Initially $\overline{\mathrm{P}}$
$$\overline{R}_{\mathrm{f}^{\mathrm{CP}}}(\tau) = \frac{\left|A_{\mathrm{f}^{\mathrm{CP}}}\right|^2}{2|\zeta|^2} e^{-\tau}\left\{ I_+^{\mathrm{f}^{\mathrm{CP}}}(\tau) - I_-^{\mathrm{f}^{\mathrm{CP}}}(\tau) \right\}$$

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

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

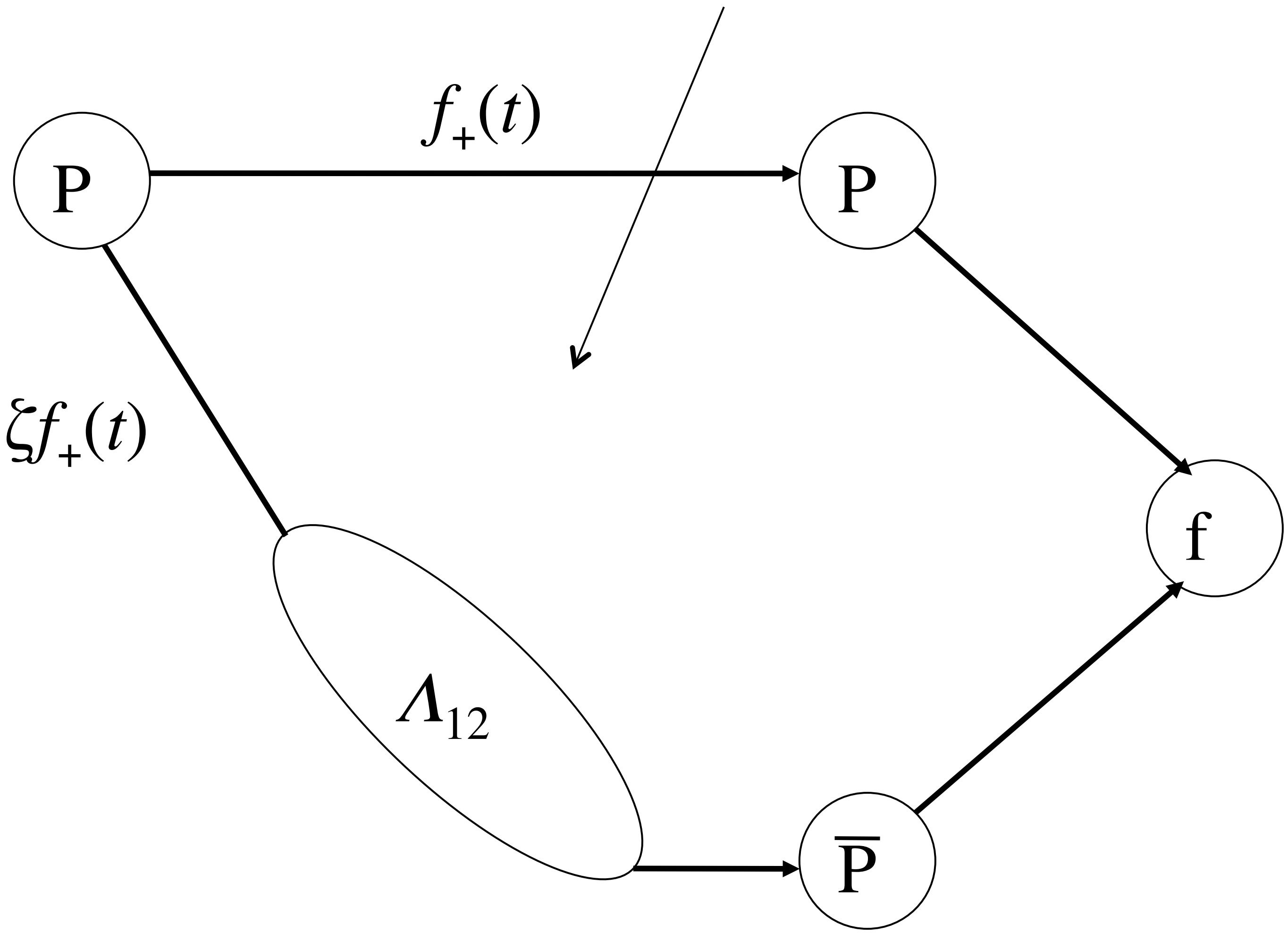
B$_\mathrm{d}$: $y \approx 0$, i.e. cosh = 1 and sinh = 0, CPV in oscillations ignored, $|\zeta| = 1$

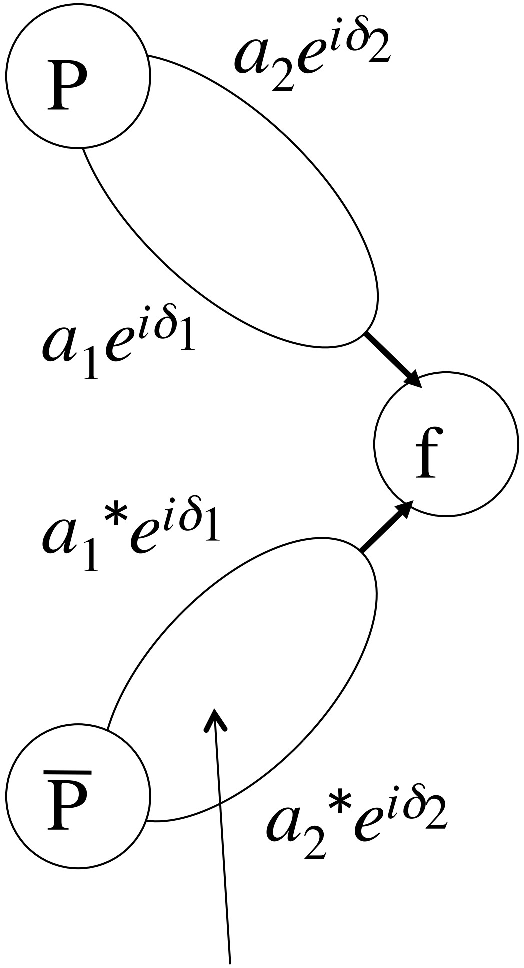
B$_\mathrm{s}$: $y < 1$ but not ignored, CPV in oscillations usually ignored, $|\zeta| = 1$



CPV in the oscillation

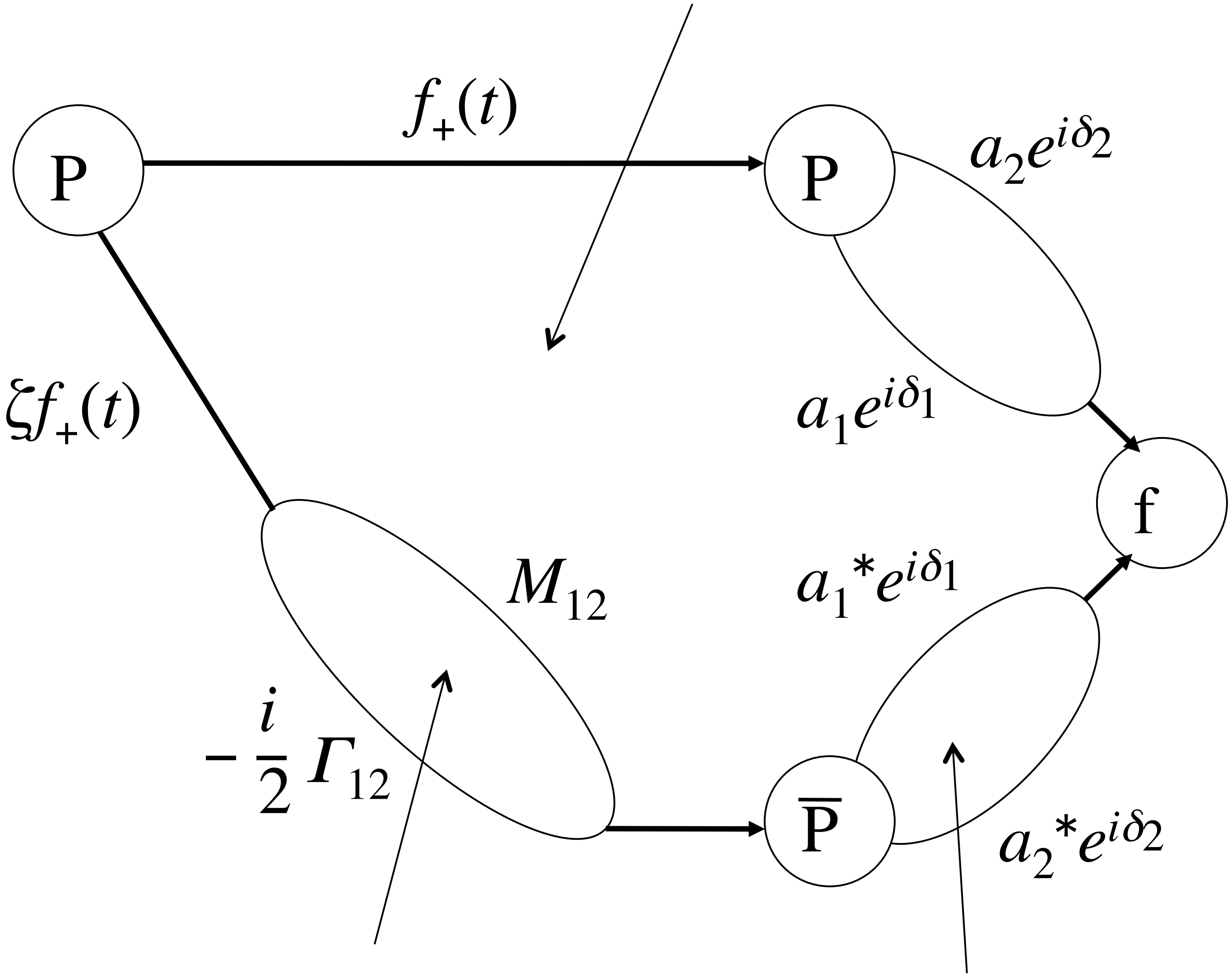
CPV in oscillation-decay inter play




P
$a_2 e^{i\delta_2}$
$a_1 e^{i\delta_1}$
f
$a_1^* e^{i\delta_1}$
$\overline{\mathrm{P}}$
$a_2^* e^{i\delta_2}$

CPV in decay

CPV in oscillation-decay inter play



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
plus some contribution from CDF and D0

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"

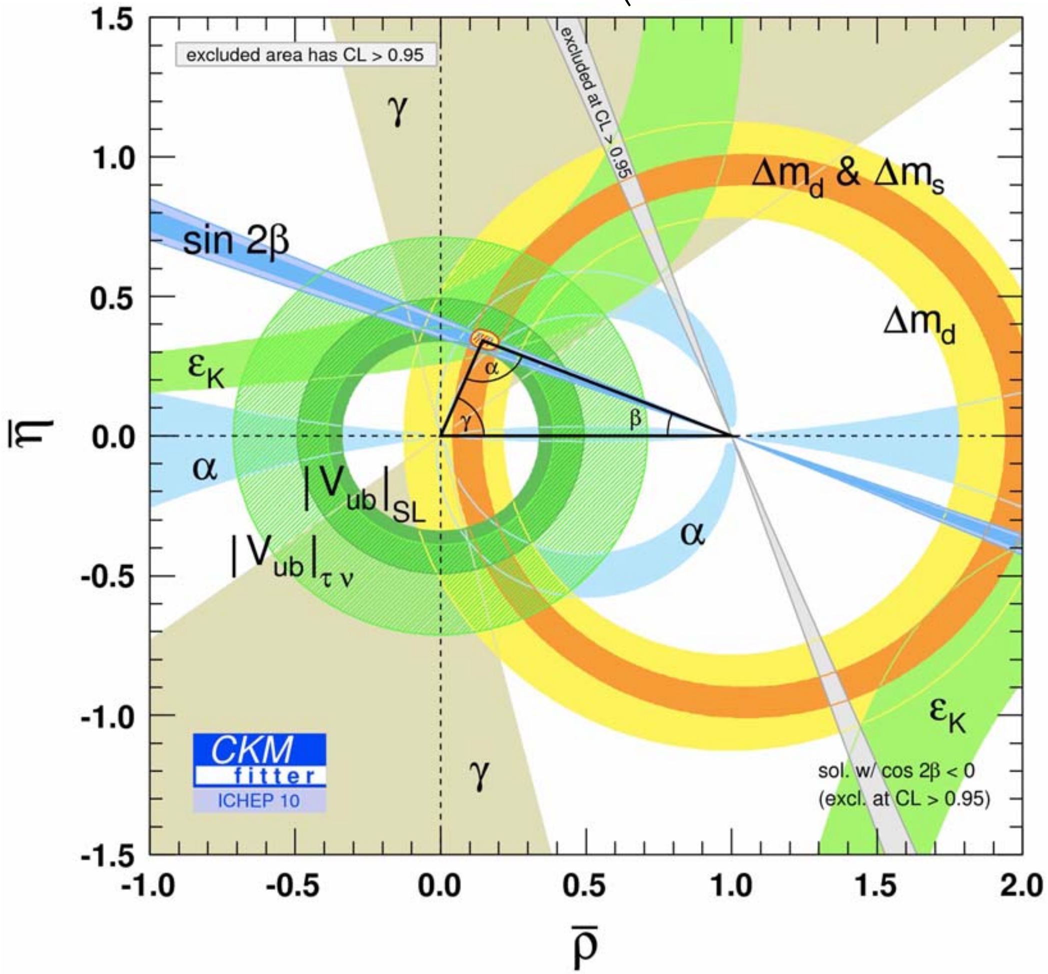
CERN: Beatrice FNAL:E866/E789/E772, E771
b cross section measurements (with large error bars)
→ simply not enough b's and too small $\sigma_b/\sigma_{\text{inelastic}}$

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 $B_s \to J/\psi\phi$ and B-$\bar{B}$ oscillations

Agreement with the SM

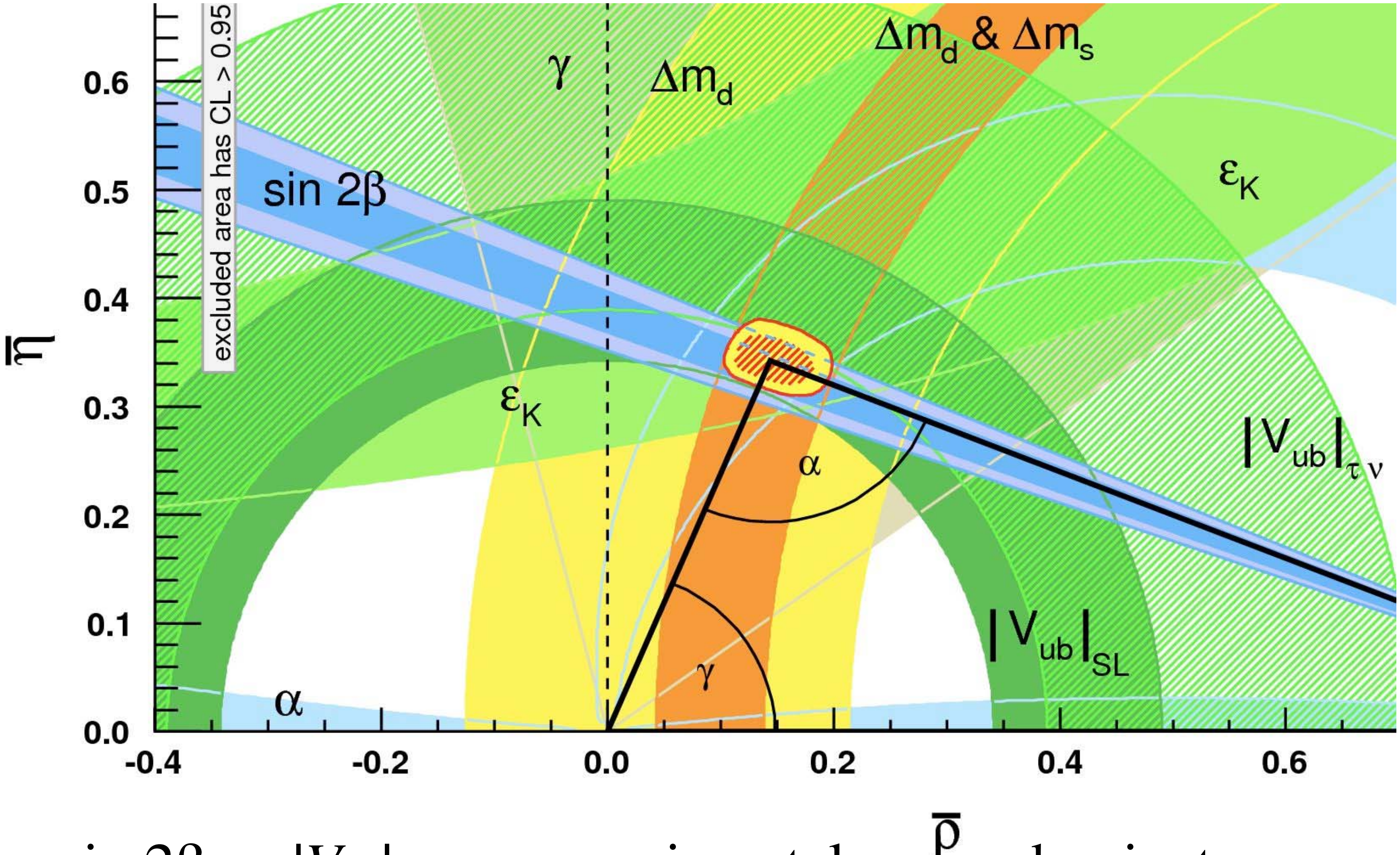
$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{\mathrm{ud}} & V_{\mathrm{us}} & V_{\mathrm{ub}} \\ V_{\mathrm{cd}} & V_{\mathrm{cs}} & V_{\mathrm{cb}} \\ V_{\mathrm{td}} & V_{\mathrm{ts}} & V_{\mathrm{tb}} \end{pmatrix} \approx \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda - iA^2\lambda^5\eta & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\hat{\rho}-i\hat{\eta}) & -A\lambda^2 - iA\lambda^4\eta & 1 \end{pmatrix}$$



Unique (ρ, η) solution

Data look consistent

Expanded view…



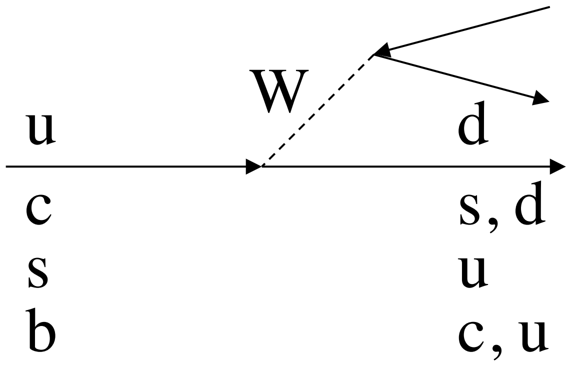
sin 2β, γ, $|V_{ub}|_{\tau\nu}$, α: experimental errors dominate

$|V_{ub}|_{SL}$, Δm, ε_K: soft QCD errors dominate: help!!!!

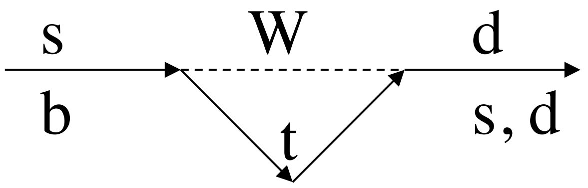
Then…

Standard Model diagrams

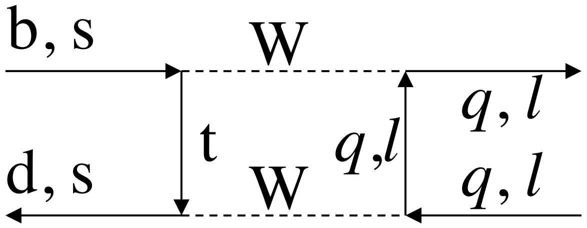
Tree level decays



Penguin level decays

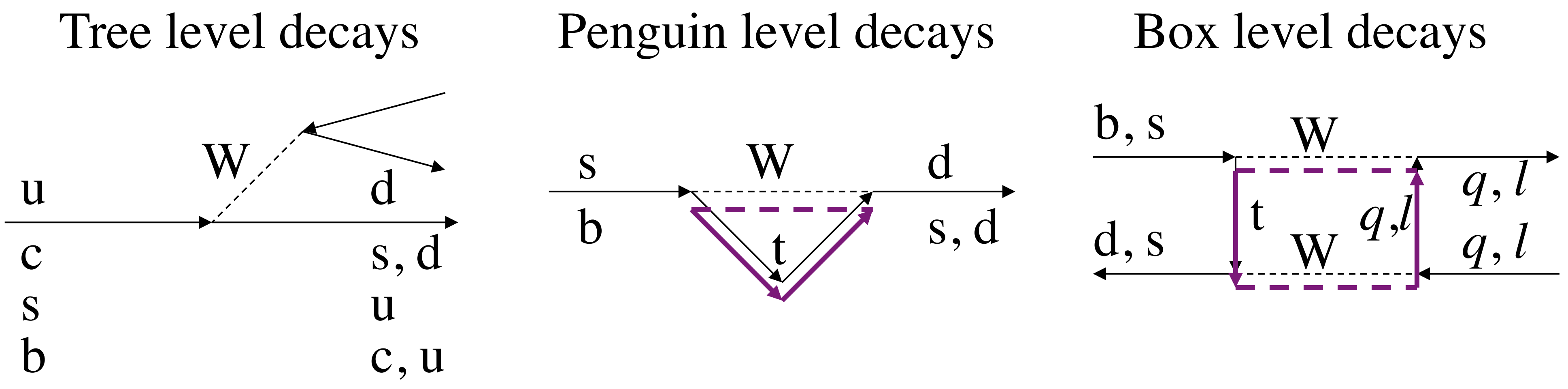


Box level decays



Then…

Standard Model diagrams + new physics



unchanged

+ new particles

Phases
Lorentz structure
Absolute values

} of the amplitude modified

Since I will talk about LHCb…

- Change of the phases:
  Larger CPV
  in B-B oscillations, $B_s \to J/\psi\phi$, $B_s \to \phi\phi$, …
- Change of the Lorentz structure:
  - Different angular distribution of the vectorial final states, e.g. $\mu^\pm$ forward-backward asymmetry in $B_d \to K^{*0}\mu^+\mu^-$, etc.
  - Photon polarization in the radiative decays, e.g. CPV in $B_s \to \phi\gamma$, $e^\pm$ forward-backward asymmetry in $B_d \to K^{*0}e^+e^-$, etc.
- Change of the magnitude
  Larger branching fractions for rare decay
  $B_s \to \mu^+\mu^-$ (recall $K_L \to \mu^+\mu^-$)

Status now

- BBABR 433 fb^{-1} $\Upsilon(4S)$ = ~500 M $B\bar{B}$
  Belle: 720 fb^{-1} $\Upsilon(4S)$ = ~800 M $B\bar{B}$

Final statistics

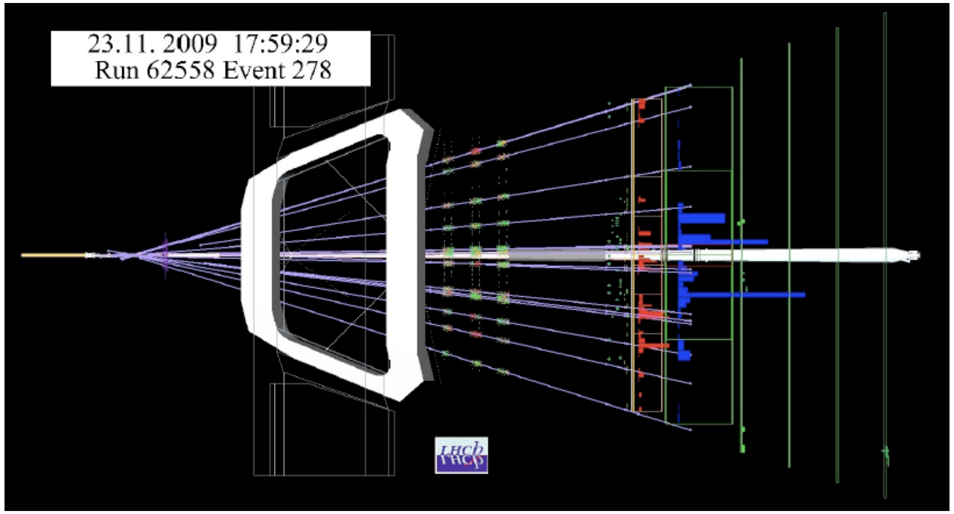
- Tevatron
  CDF and D0 continue to take data
  ~7 fb^{-1}/experiment collected
  ~10 fb^{-1}/experiment or more by the end of data taking?

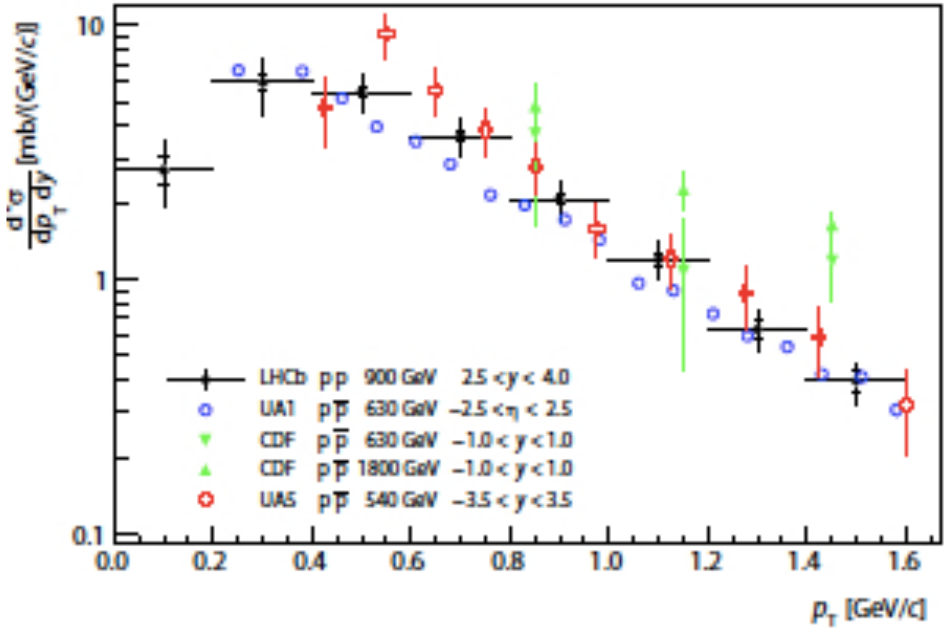
LHC running, LHCb collecting data

- November 2009, $\sqrt{s}$ = 900 GeV collisions took place

23^{rd} November 2009

- First collisions took place at LHC
- 2009 run: $\int L\,\mathrm{d}t \approx 7\ \mu\mathrm{b}^{-1}$, at $\sqrt{s} = 900$ GeV





One of the first event

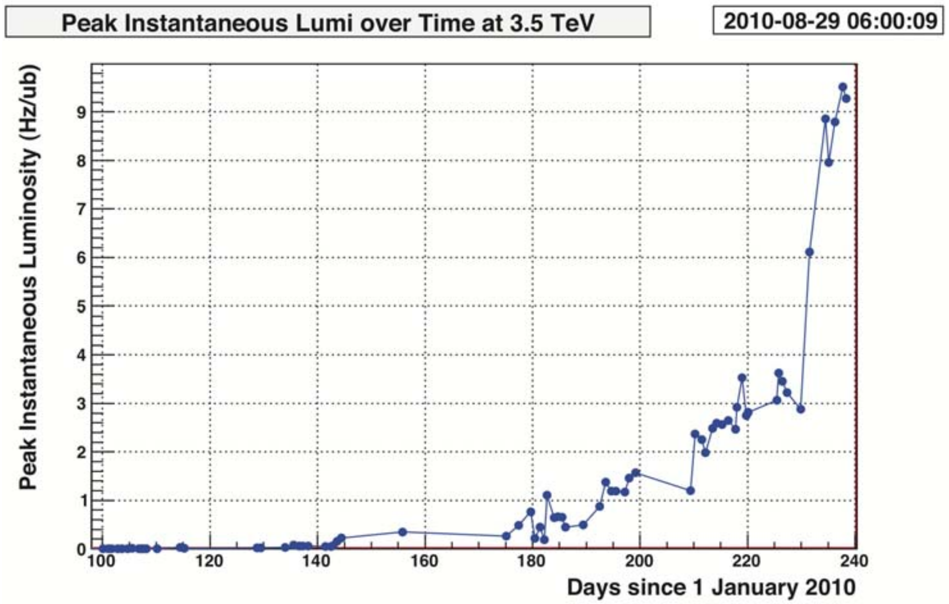
$K_S{}^0$ cross sections
to be published in PLB

LHC running, LHCb collecting data

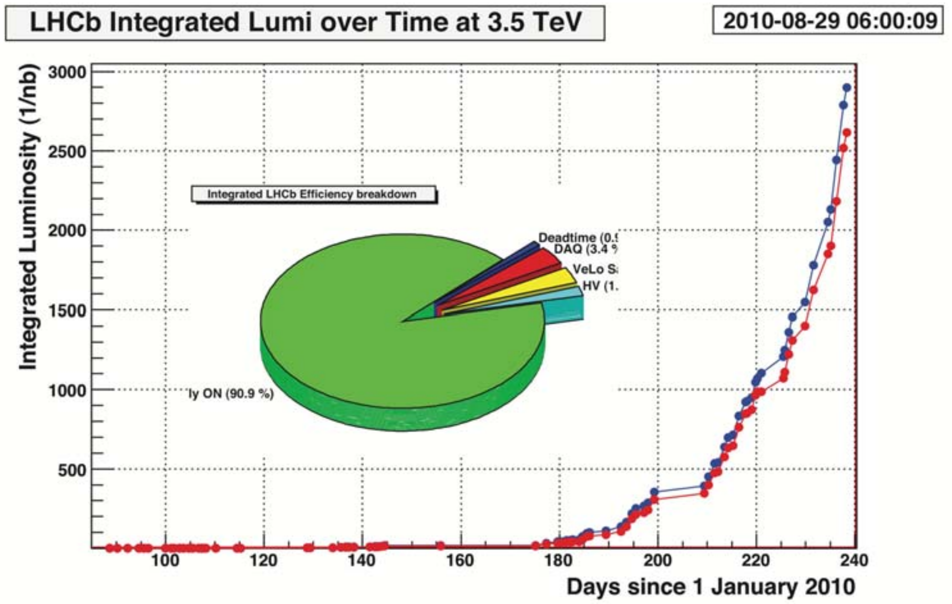
- November 2009, √s = 900 GeV collisions took place
- Since March 2010, running at √s = 7 TeV

Impressive progress in *L*

Peak luminosity
already ~$10^{31}\mathrm{cm}^{-2}\mathrm{s}^{-1}$



Integrated luminosity
already ~3 pb^{-1}



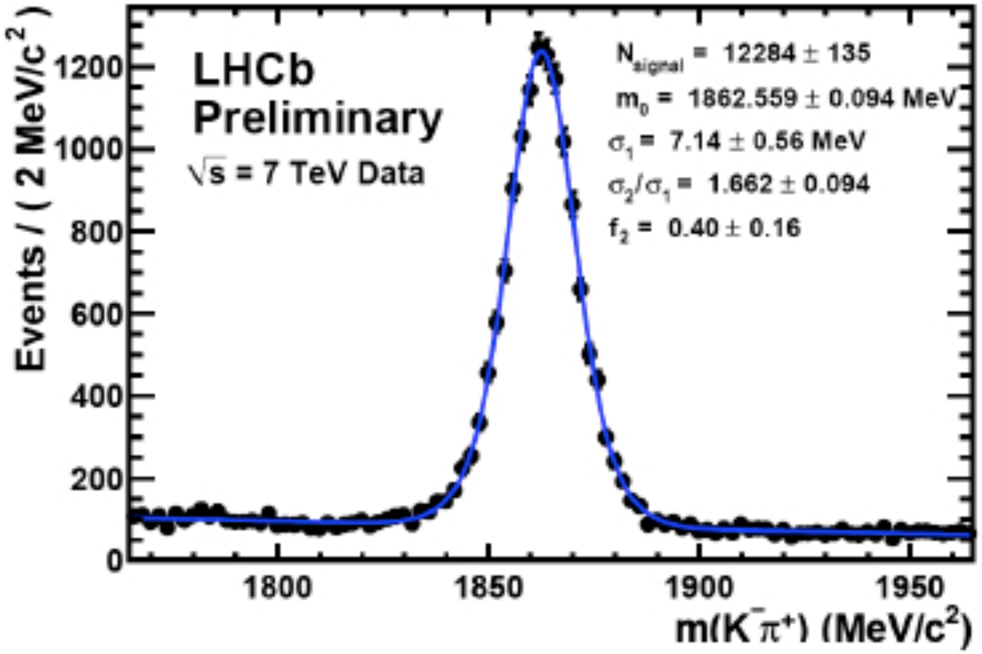
LHC running, LHCb collecting data

- November 2009, √s = 900 GeV collisions took place
- Since March 2010, running at √s = 7 TeV
  - $n_{\text{p-bunch}} \approx 10^{11}$ ⇔ already nominal value
  - $\beta^* = 3.5$ m ⇔ nominal 0.55 m for 10^{34} cm^{-2}s^{-1}
  - $n_{\text{bunch}} = 46$ ⇔ nominal = 2808
  - $L = 1\times10^{31}$ cm^{-2}s^{-1} ⇔ nominal = 10^{34} cm^{-2}s^{-1}
  - Experiments >90% DAQ efficiencies

LHCb $\sigma_{b\bar{b}}$ measurements

b detection from $b \to D^0(K^-\pi^+)\mu^-X$

Inclusive D:

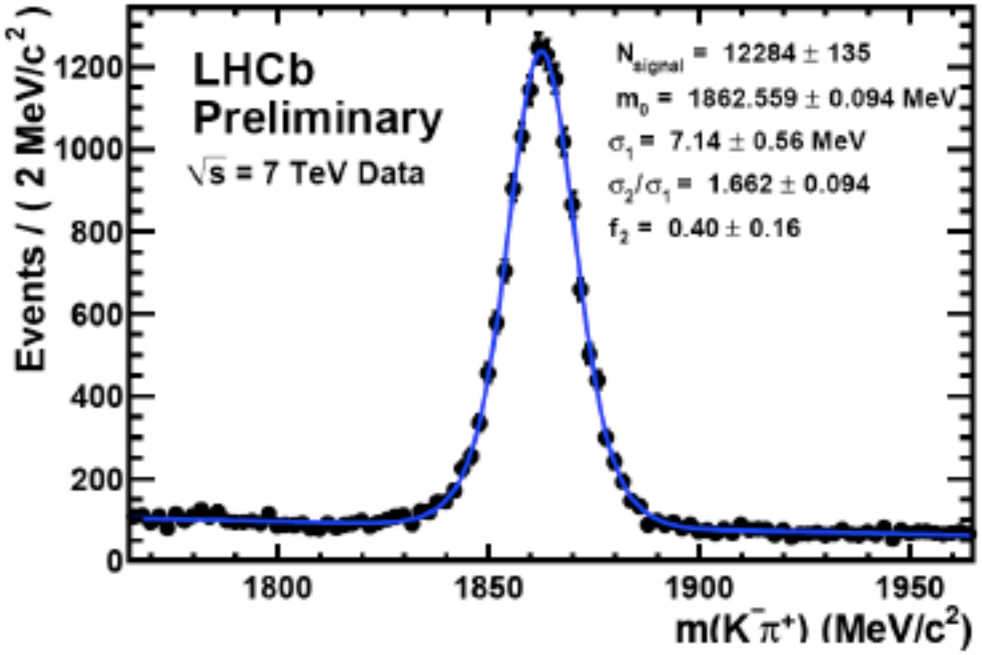


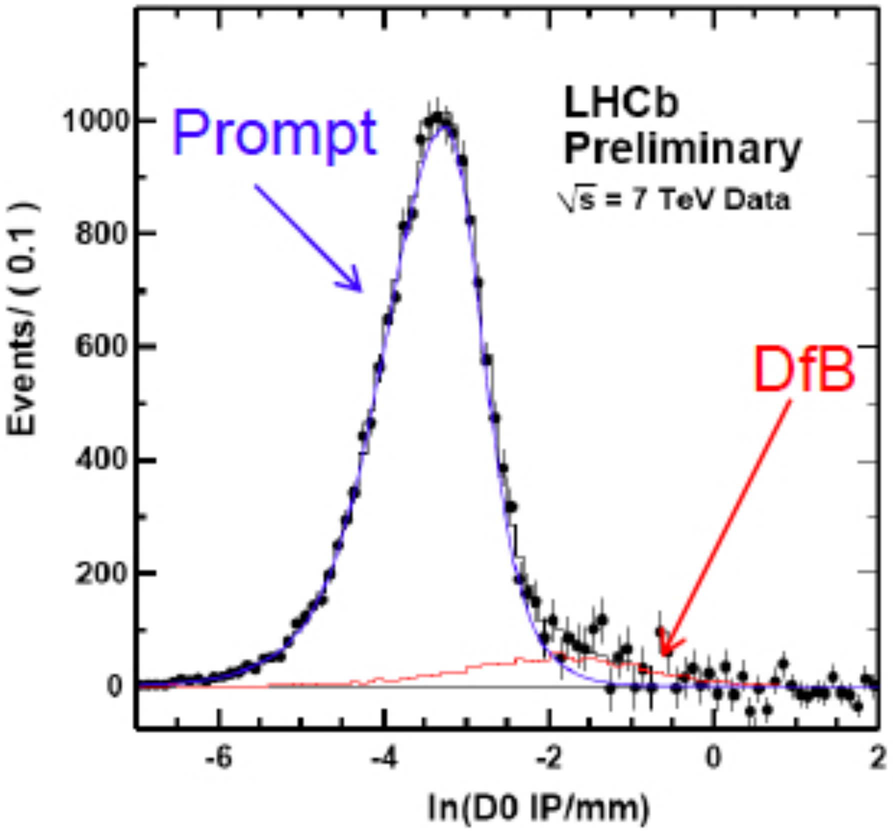
Clean D signal with hadron PID

LHCb $\sigma_{b\bar{b}}$ measurements

b detection from $b \to D^0(K^-\pi^+)\mu^- X$

Inclusive D:
dominated by the prompt production





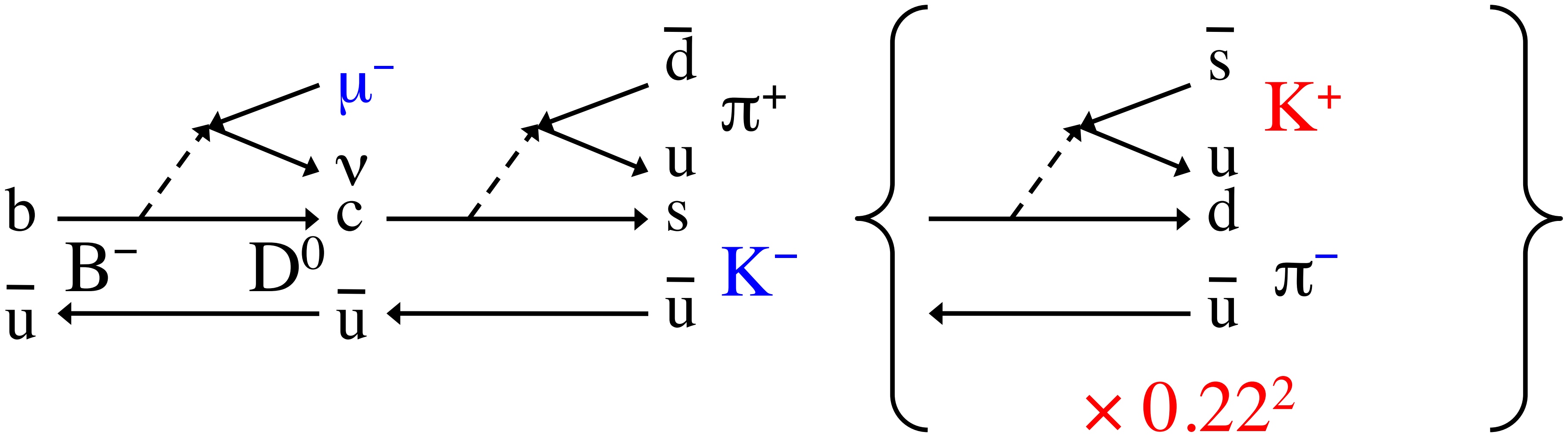
IP(D from b→D) > IP (prompt D)

LHCb $\sigma_{b\bar{b}}$ measurements

b detection from $b \rightarrow D^0(K^-\pi^+)\mu^- X$

Adding μ with a right sign enhances D from b:

e.g. $B^- \rightarrow D^0(\rightarrow K^-\pi^+)\mu^- X$ [$B^- \rightarrow D^0(\rightarrow K^+\pi^-)\mu^- X$ only through DCSD]



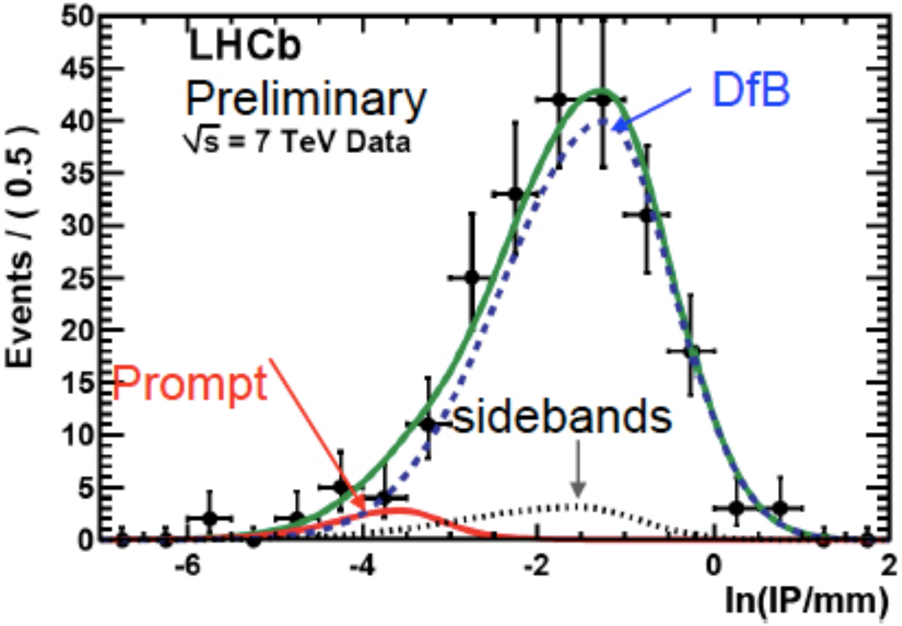
LHCb $\sigma_{b\bar{b}}$ measurements

b detection from $b \rightarrow D^0(K^-\pi^+)\mu^-X$

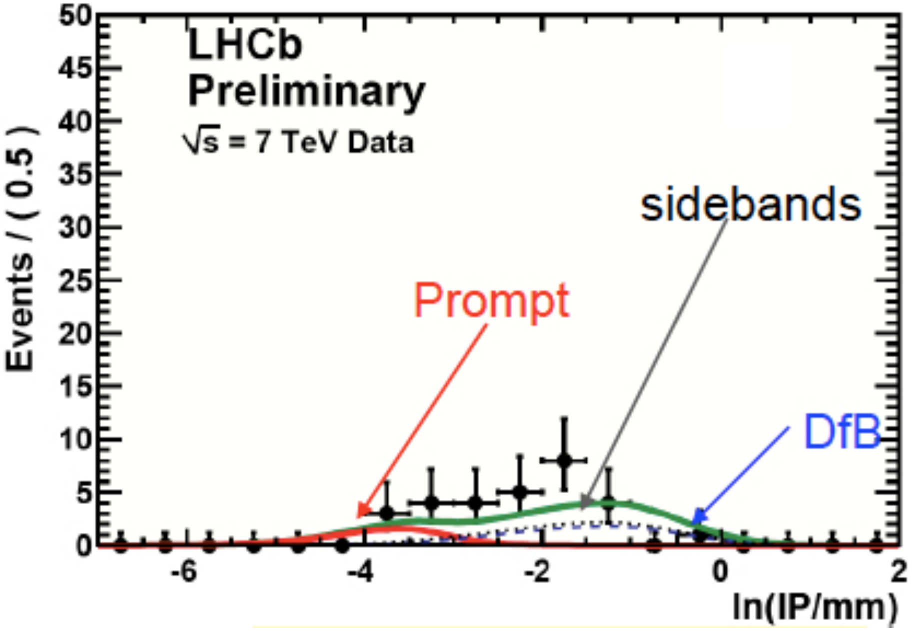
Adding μ with a right sign enhances D from b:

e.g. $B^- \rightarrow D^0(\rightarrow K^-\pi^+)\mu^-X$ [$B^- \rightarrow D^0(\rightarrow K^+\pi^-)\mu^-X$ only through DCSD]

with right sign muons



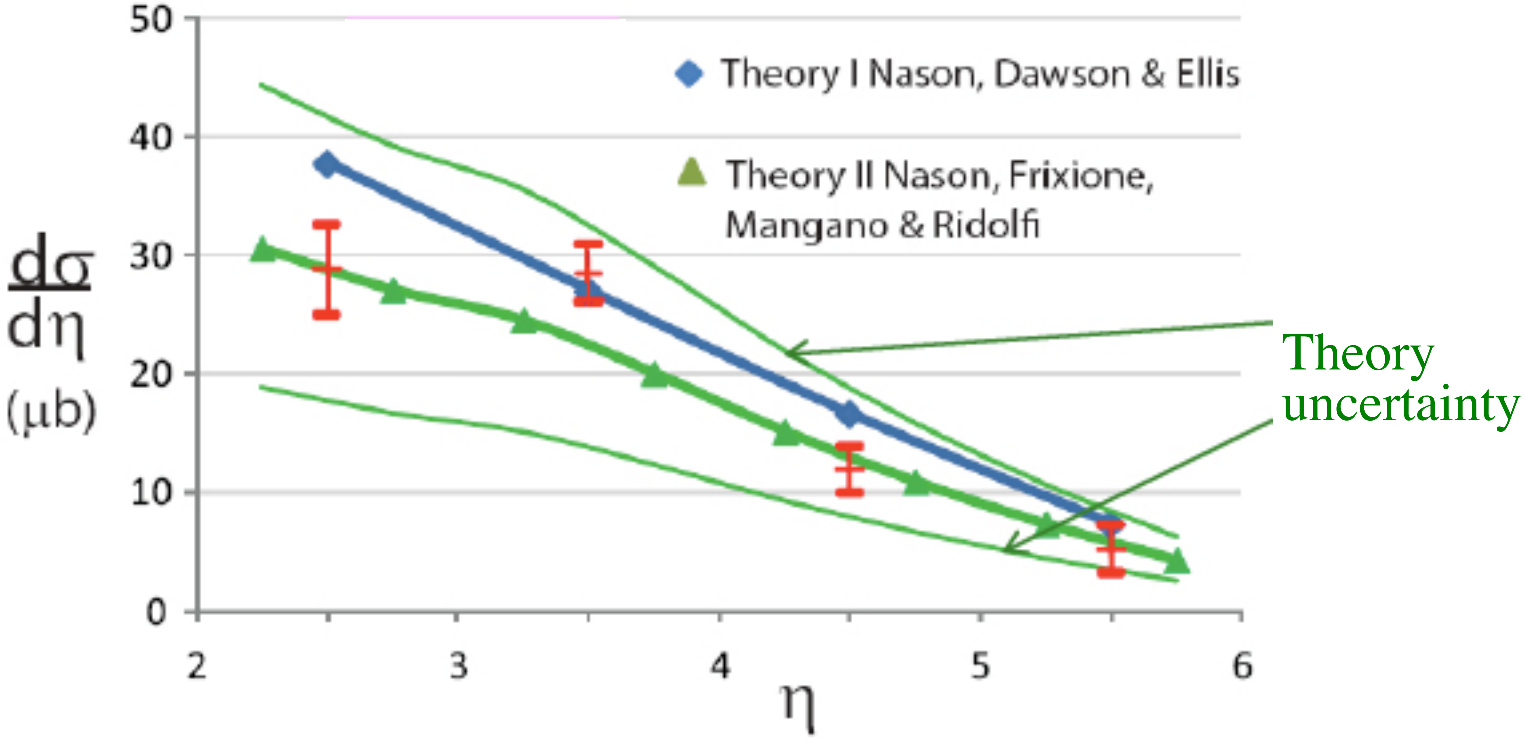
with wrong sign muons



LHCb $\sigma_{b\bar{b}}$ measurements

b detection from $b \rightarrow D^0(K^-\pi^+)\mu^- X$

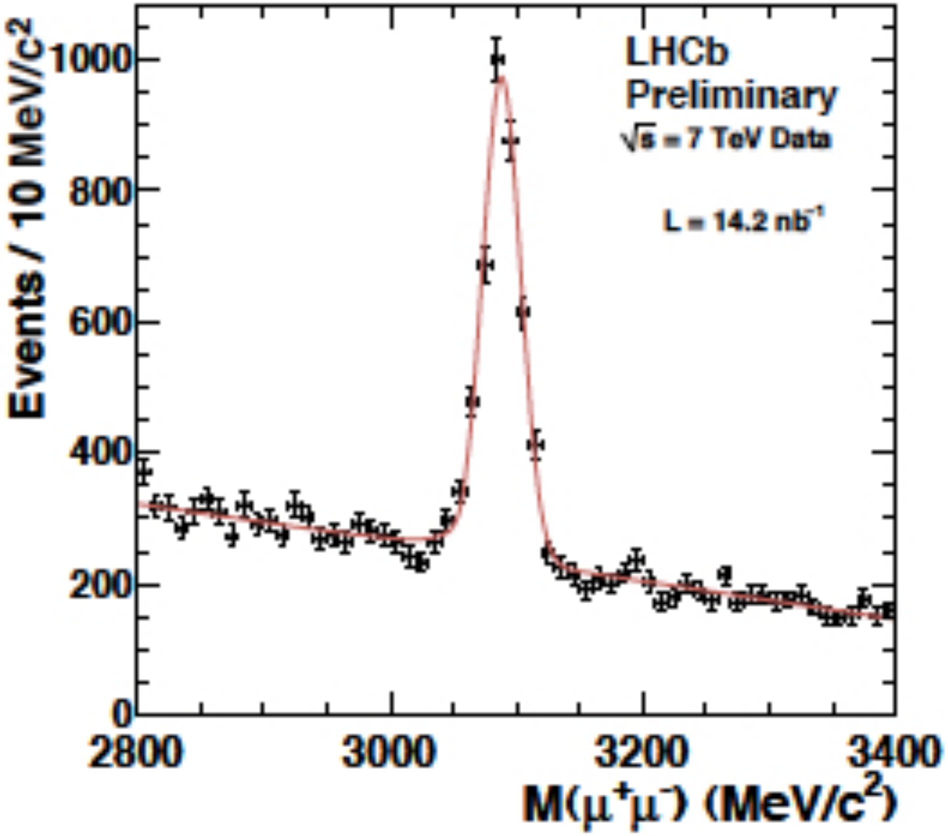
$\int L\, dt = 25\ \text{nb}^{-1}$ data



Theory uncertainty

LHCb $\sigma_{b\bar{b}}$ measurements

b detection from b→J/ψX

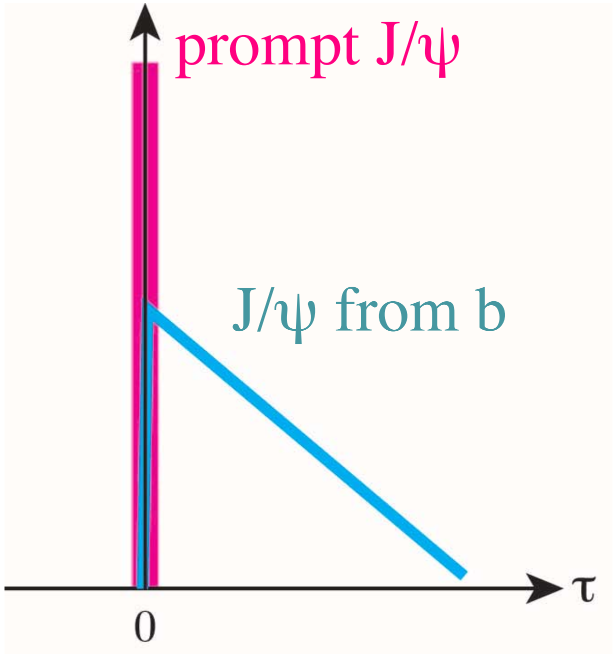


Clean $\mu^+\mu^-$ mass distribution
with $\int L\,dt = 14\ \mathrm{nb}^{-1}$ data

LHCb $\sigma_{b\bar{b}}$ measurements

b detection from b→J/ψX

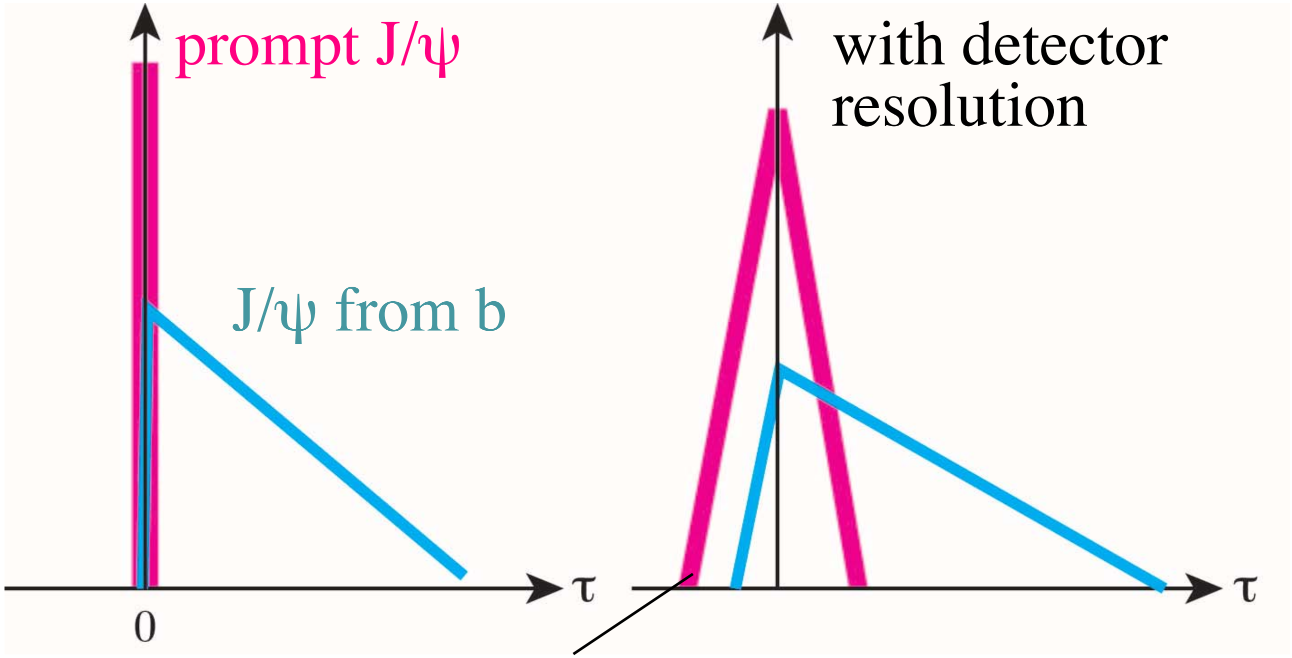
proper time distribution of J/ψ



LHCb $\sigma_{b\bar{b}}$ measurements

b detection from $b \to J/\psi X$

proper time distribution of J/ψ

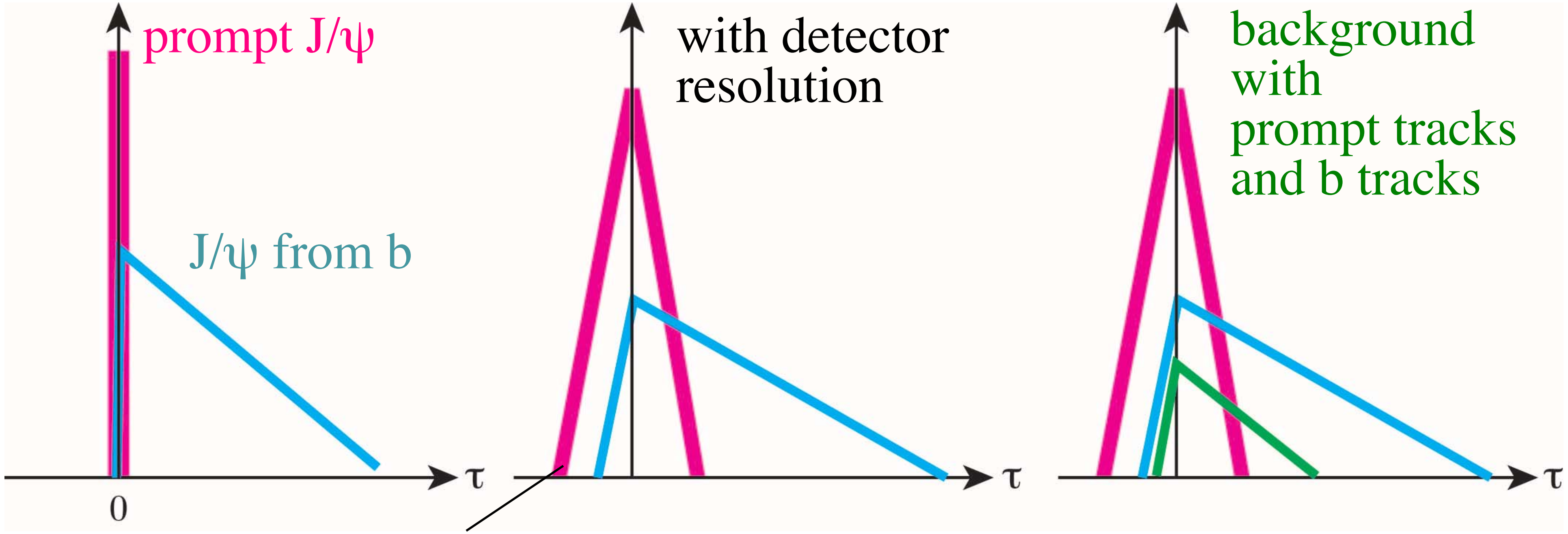


negative proper time important for studying resolution

LHCb $\sigma_{b\bar{b}}$ measurements

b detection from b→J/ψX

proper time distribution of J/ψ



prompt J/ψ

J/ψ from b

with detector resolution

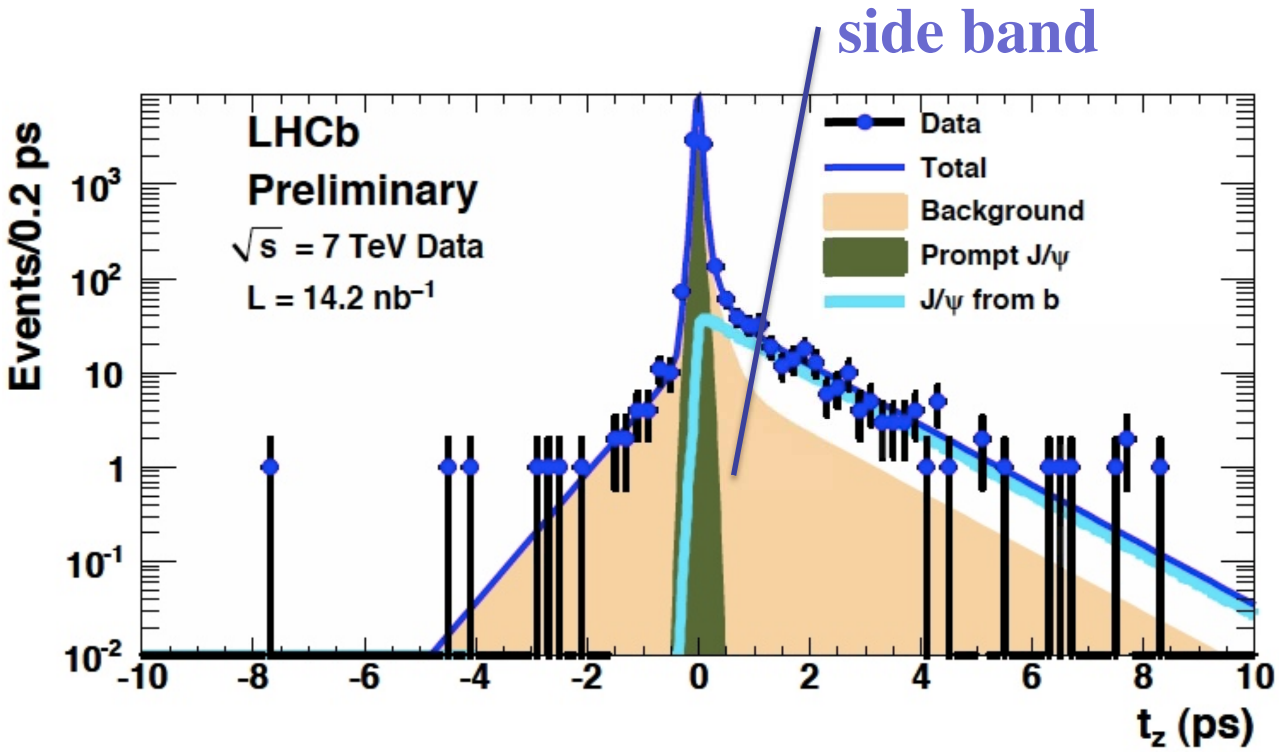
combinatorial background with prompt tracks and b tracks

negative proper time important for studying resolution

LHCb $\sigma_{b\bar{b}}$ measurements

b detection from $b \rightarrow J/\psi X$

Proper time distribution with $\int L\,dt = 14\ \text{nb}^{-1}$ data

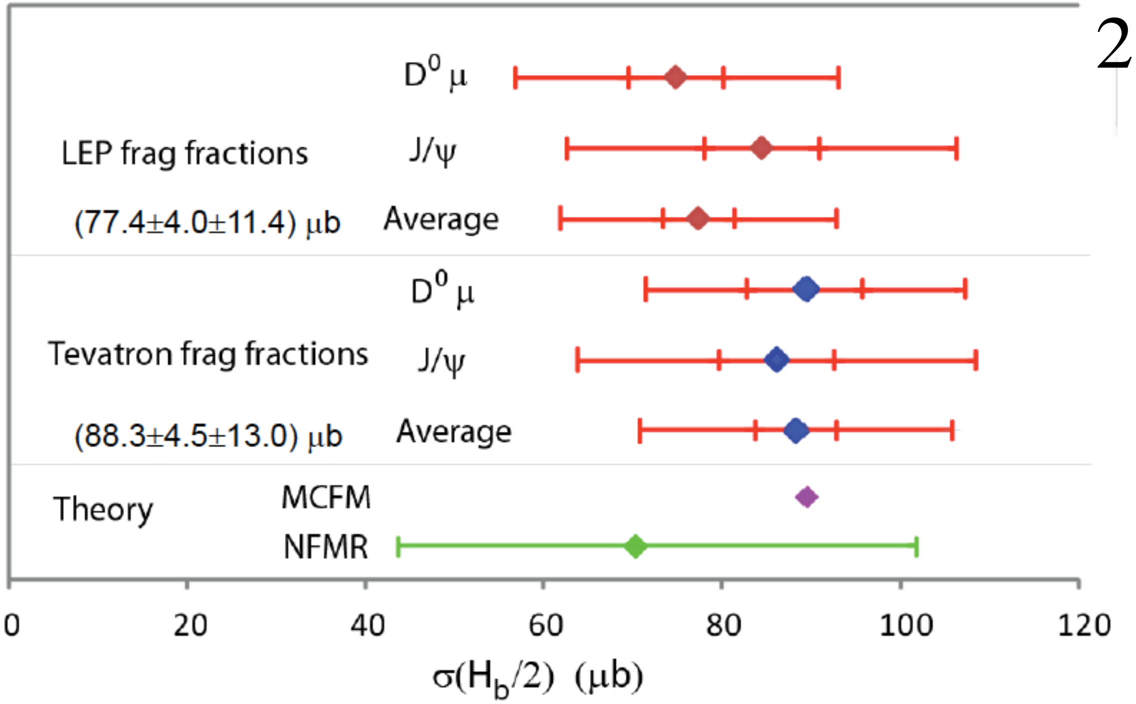


side band

J/ψ with a long
proper time
due to b-hadron
decays

LHCb $\sigma_{b\bar{b}}$ measurements

LHCb $\sigma_{b\bar{b}}$ from b→$D^0\mu X$ and →$J/\psi X$



$2<\eta<6$

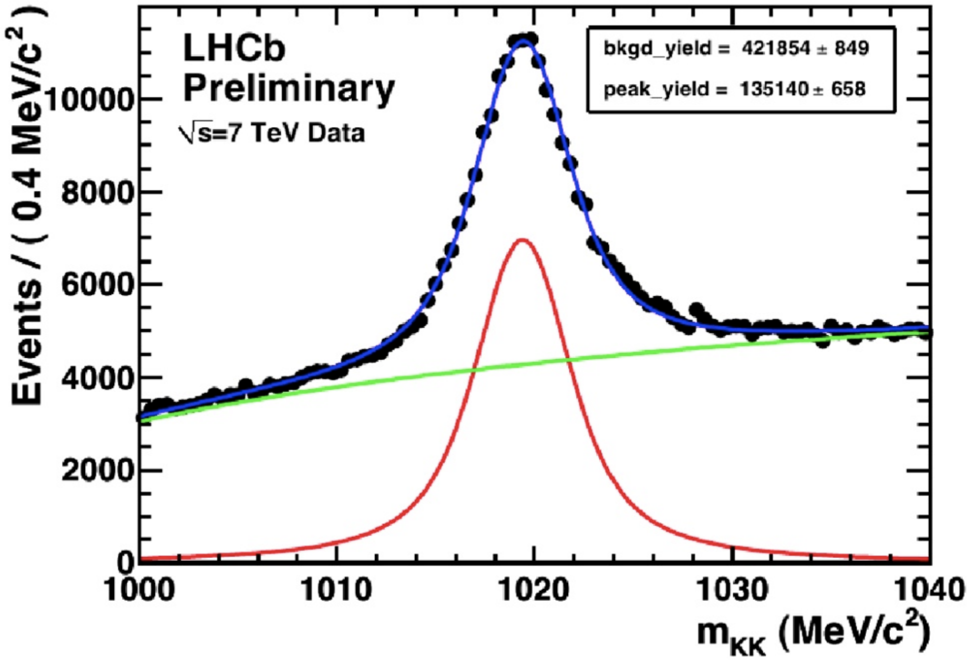
σ_{bb} in $4\pi = 292 \pm 15 \pm 43$ μb (with LEP $B_u/B_d/B_s/\Lambda_b$)

→agree with the Pythia used for the performance studies

LHC running, LHCb collecting data

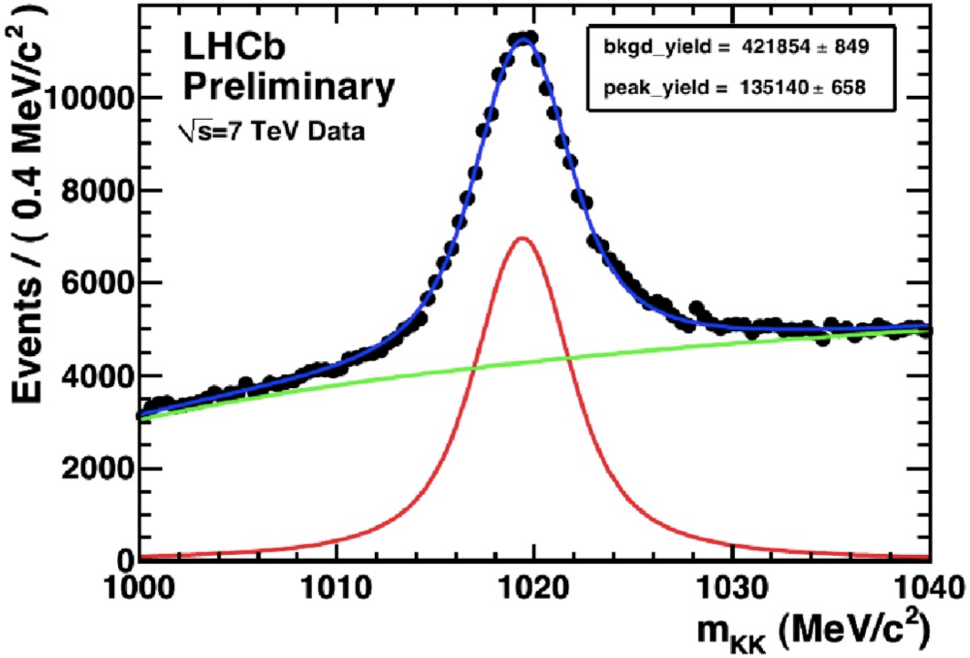
- November 2009, $\sqrt{s}$ = 900 GeV collisions took place
- Since March 2010, running at $\sqrt{s}$ = 7 TeV
  - $n_{\text{p-bunch}} \approx 10^{11}$ ⇔ already nominal value
  - $\beta^* = 3.5$ m ⇔ nominal 0.55 m for 10^{34} cm^{-2}s^{-1}
  - $n_{\text{bunch}} = 46$ ⇔ nominal = 2808
  - $L = 1\times10^{31}$ cm^{-2}s^{-1} ⇔ nominal = 10^{34} cm^{-2}s^{-1}
  - Experiments >90% DAQ efficiencies
  - Current plan for this year
    $n_{\text{bunch}} = 46$ steadily increased to 384
    $L \approx 10^{31}$ cm^{-2}s^{-1} ⇒ 10^{32} cm^{-2}s^{-1} (~0.2 pb^{-1}/10h fill)
- 2011: $\int L\,dt = 1$ fb^{-1} goal to be achieved by running with a slight improvement (~2 in the luminosity) by further decreasing β^* and/or increasing the number of bunches.

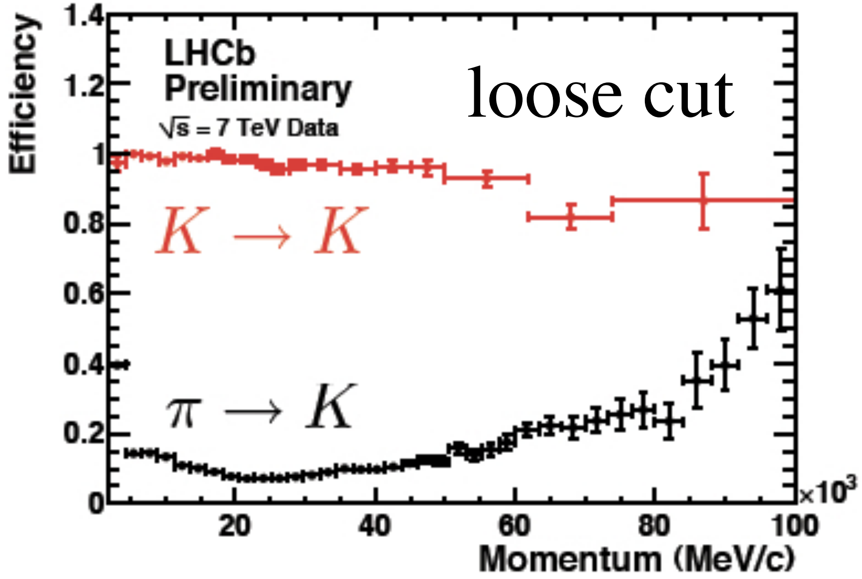
LHCb how about $B_s \rightarrow J/\psi\phi$?

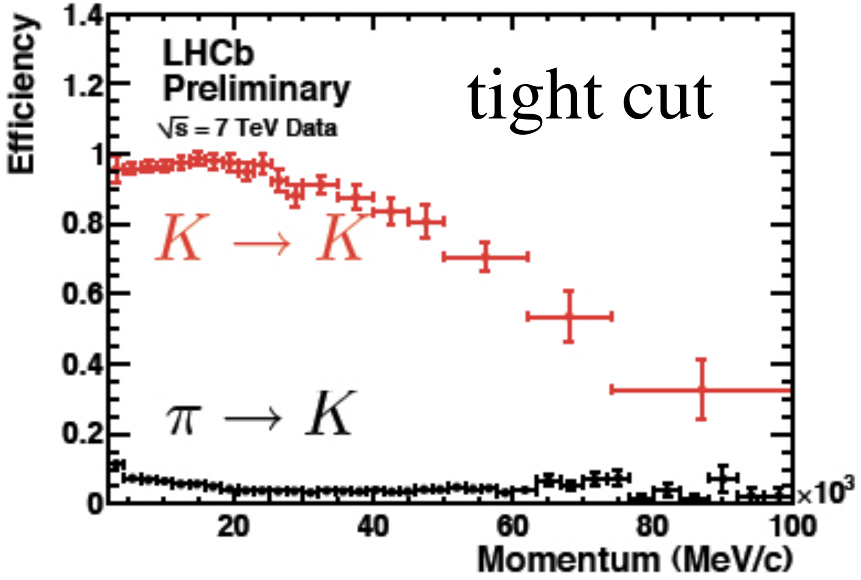


Nice ϕ with kaon identification

LHCb how about $B_s \rightarrow J/\psi\phi$?





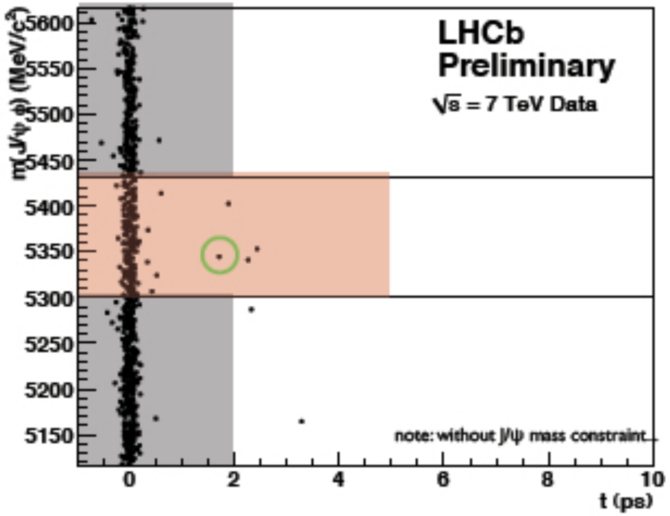


Nice ϕ with kaon identification

ϕ is also used to calibrate PID
with one kaon identified
NB: flavour-tag with kaons

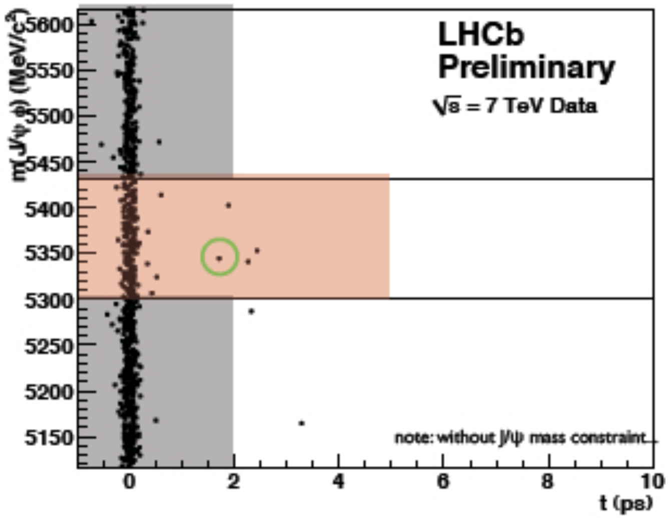
LHCb how about $B_s \to J/\psi\phi$?

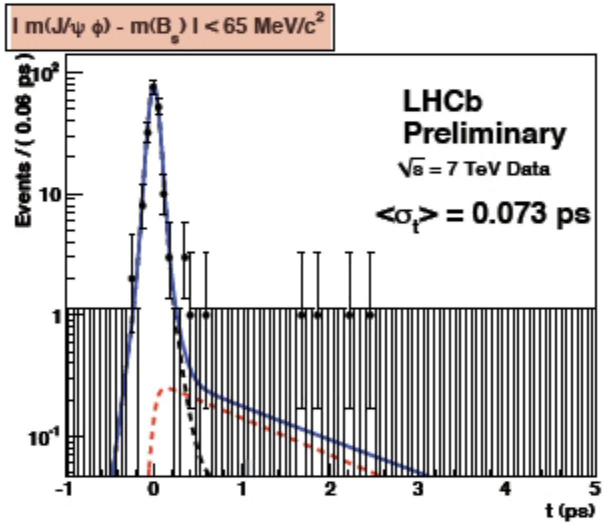
$B_s \to J/\psi\phi$ candidates with $\int L\, dt = 140\ nb^{-1}$ data

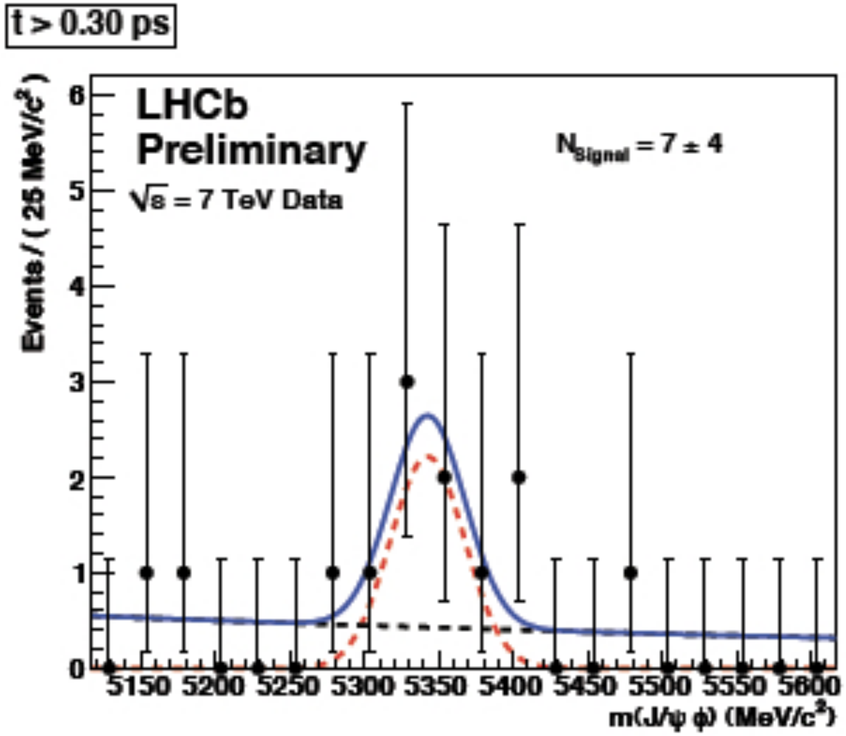


LHCb how about $B_s \rightarrow J/\psi\phi$?

$B_s \rightarrow J/\psi\phi$ candidates with $\int L\,dt = 140\ \mathrm{nb}^{-1}$ data



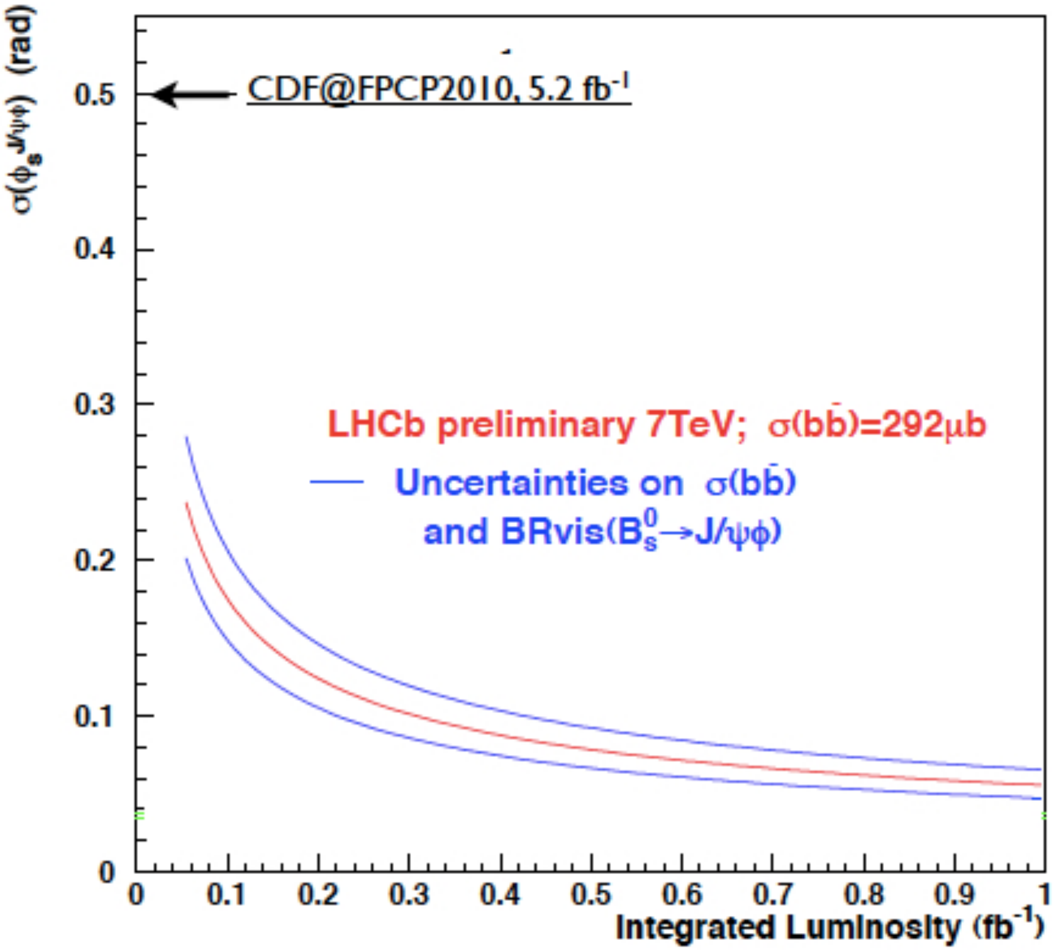




Yield agrees with the MC performance expectation of ~7

LHCb how about $B_s \rightarrow J/\psi\phi$?

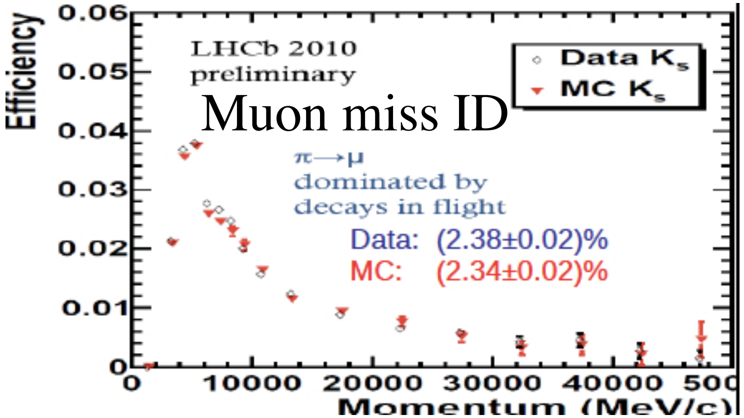
1σ error for CPV in $B_s \rightarrow J/\psi\phi$

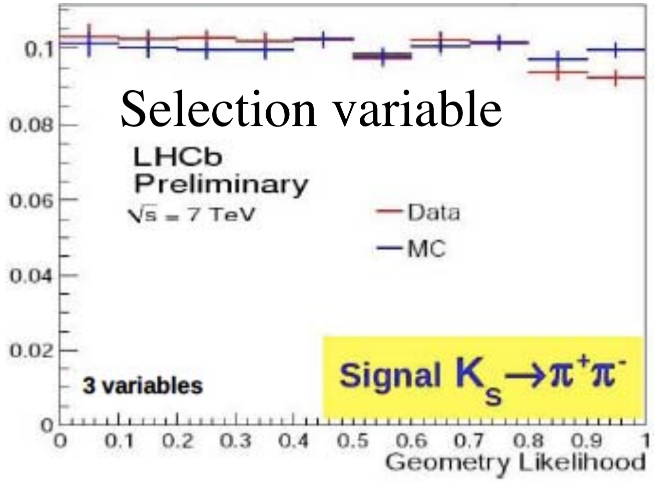


1 fb^{-1} of data expected by the end of 2011

LHCb how about $B_s \rightarrow \mu^+\mu^-$?

Of course we see currently no serious background, but can validate analysis method with data by comparing with MC; → They agree well!





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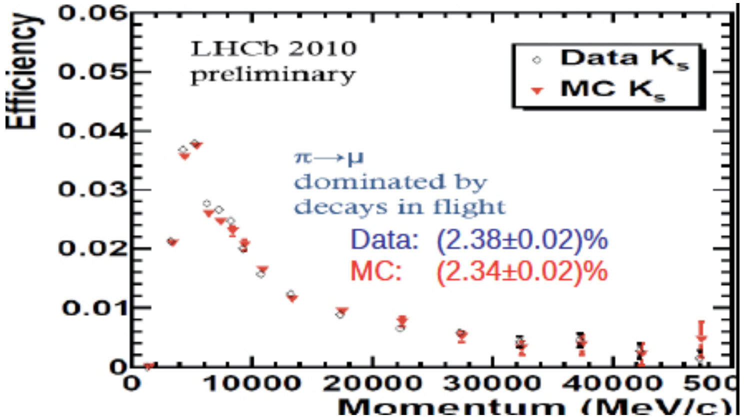
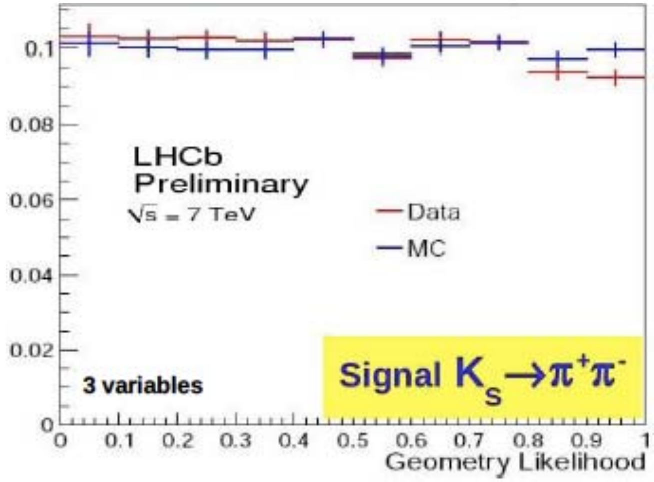
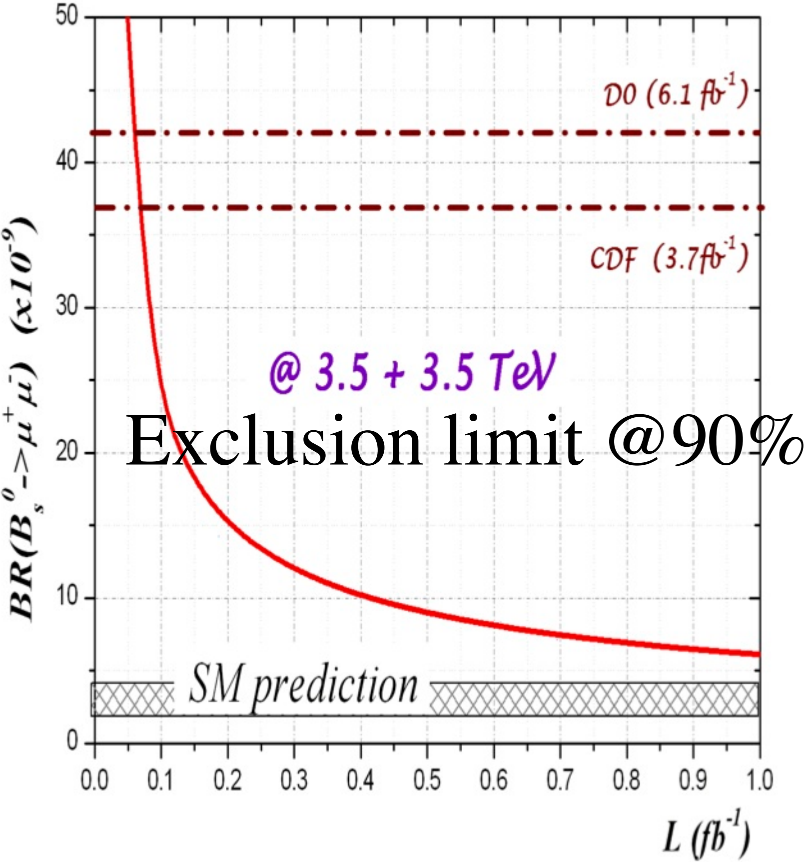




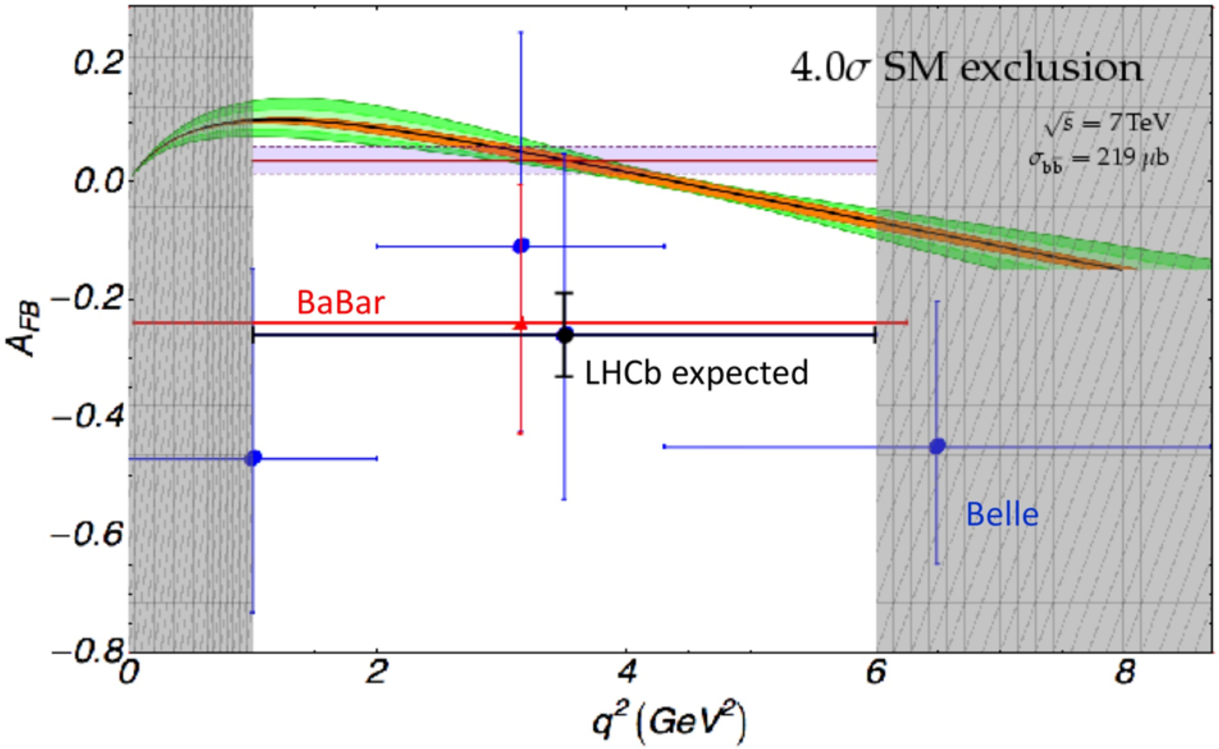


Exclusion limit @90% C.L.

1 fb^{-1} of data expected by the end of 2011

LHCb how about $B_d \to K^{*0}\mu^+\mu^-$?

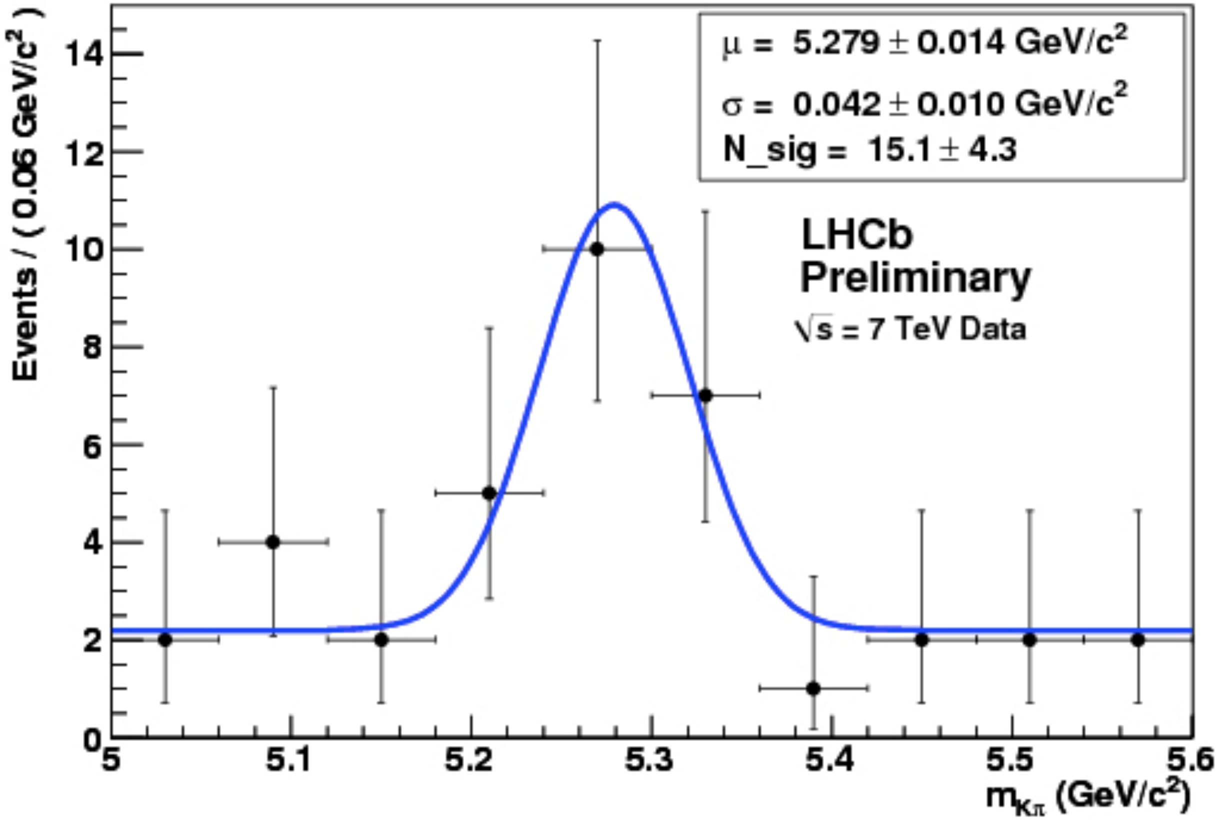
With 1 fb^{-1} LHCb expects 1200 events



If the current BABAR and Belle results are correct, LHCb could exclude SM prediction with 4σ significance

LHCb how about B→hh?

$B_d \rightarrow K^{\pm}\pi^{\mp}$ candidates with $\int L\, dt = 122\ \mathrm{nb}^{-1}$ data



PID, IP, vertex, p_T cuts

Agrees with the MC performance expectation of ~16

With 1 fb-1 data, >100k events!

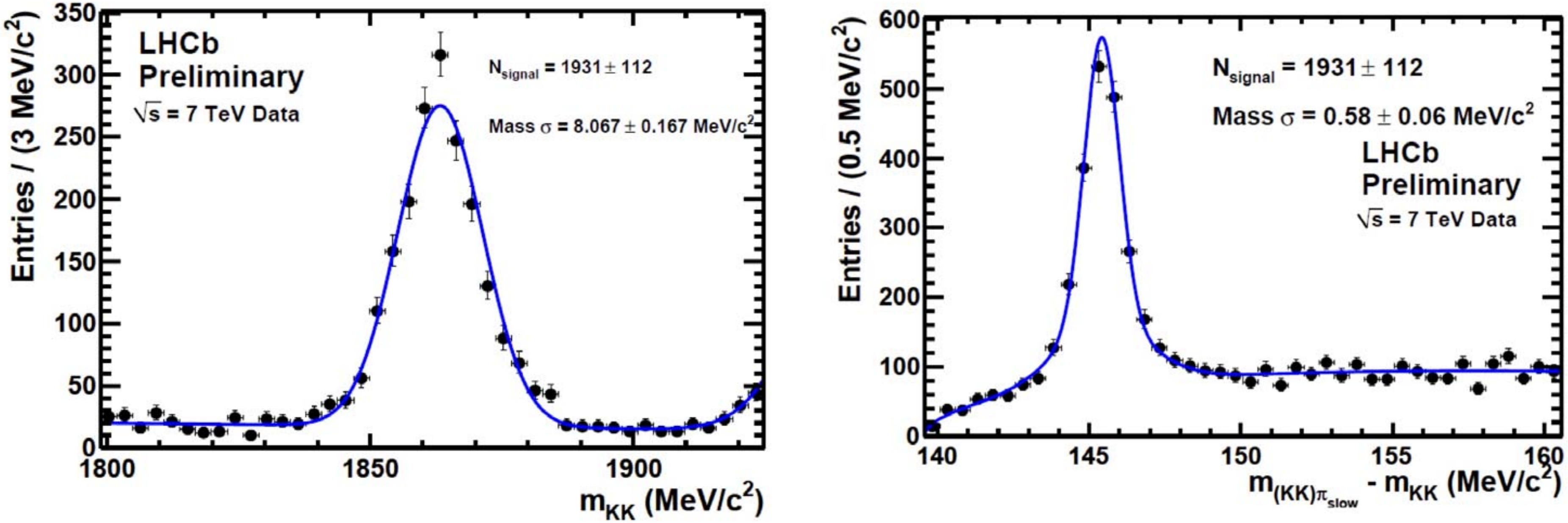
similar improvements for all the other B→hh modes

LHCb how about charm physics?

Huge number of charms can be detected with LHCb

Initial flavour tagged D^0 decays:

$D^{*+} \rightarrow D^0\pi^+$, $D^0 \rightarrow K^+K^-$ with 124 nb^{-1} data



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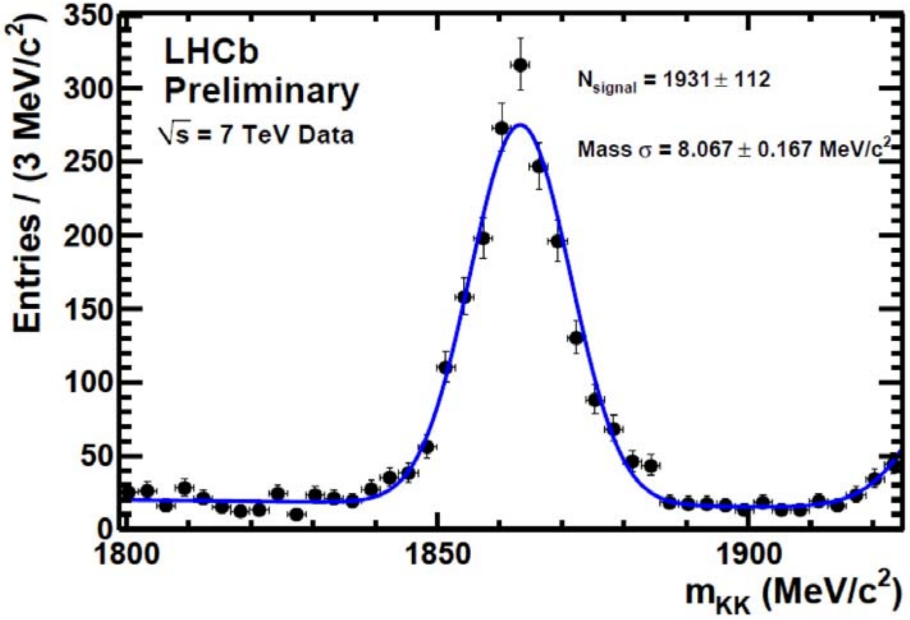

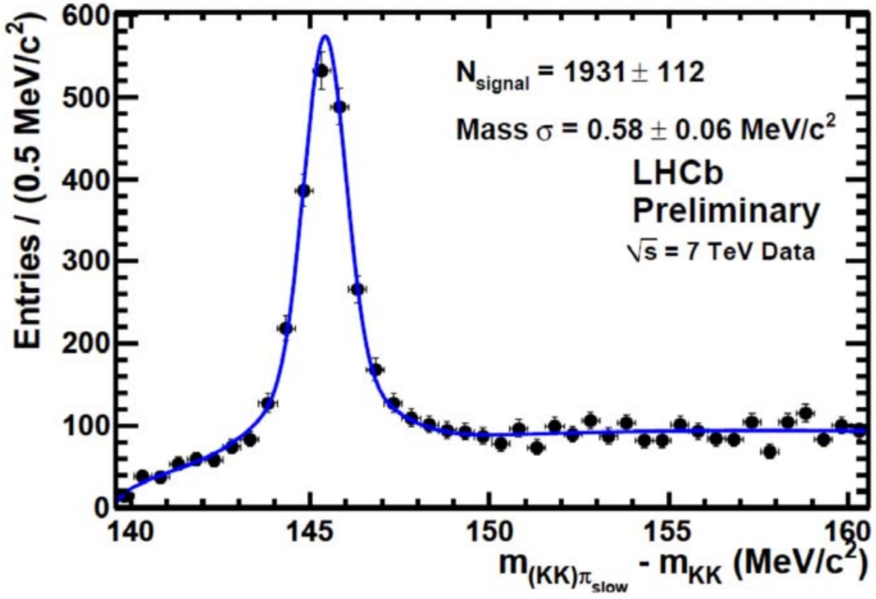

Huge statistics to study CPV from the decay time distribution between D^0 and $\overline{D}^0 \rightarrow K^+K^-$, well before reaching 1 fb^{-1} (~15×10^6 events)

BABAR
~300k events

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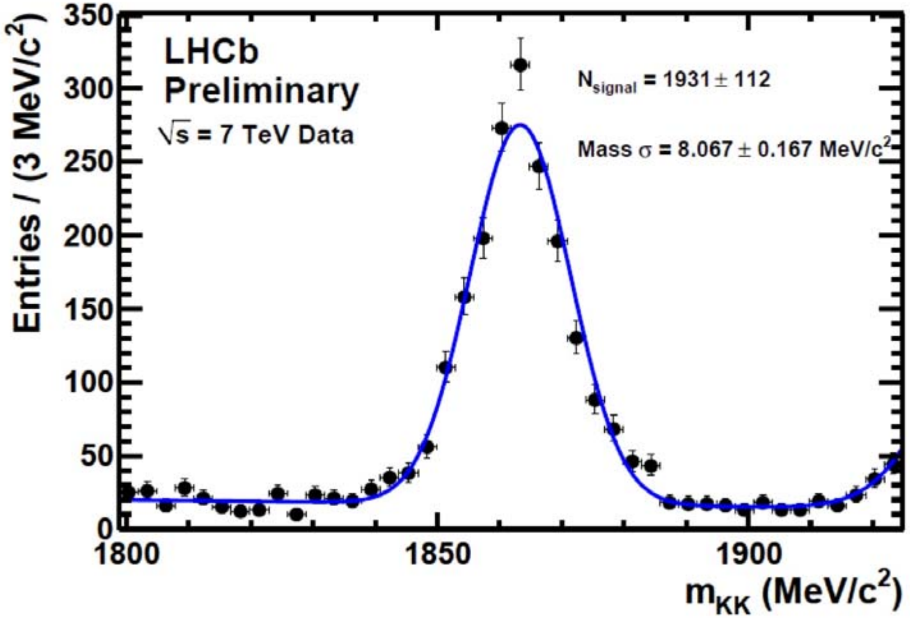
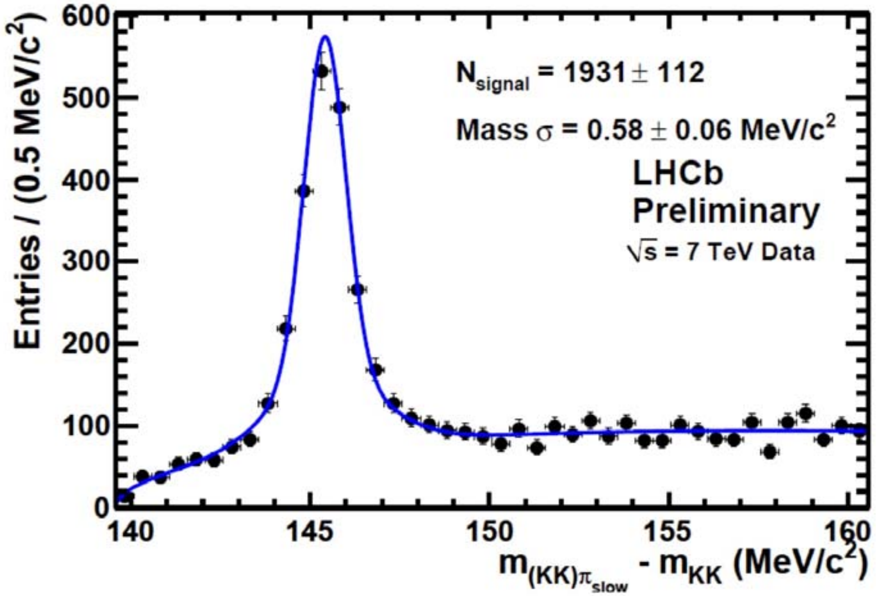


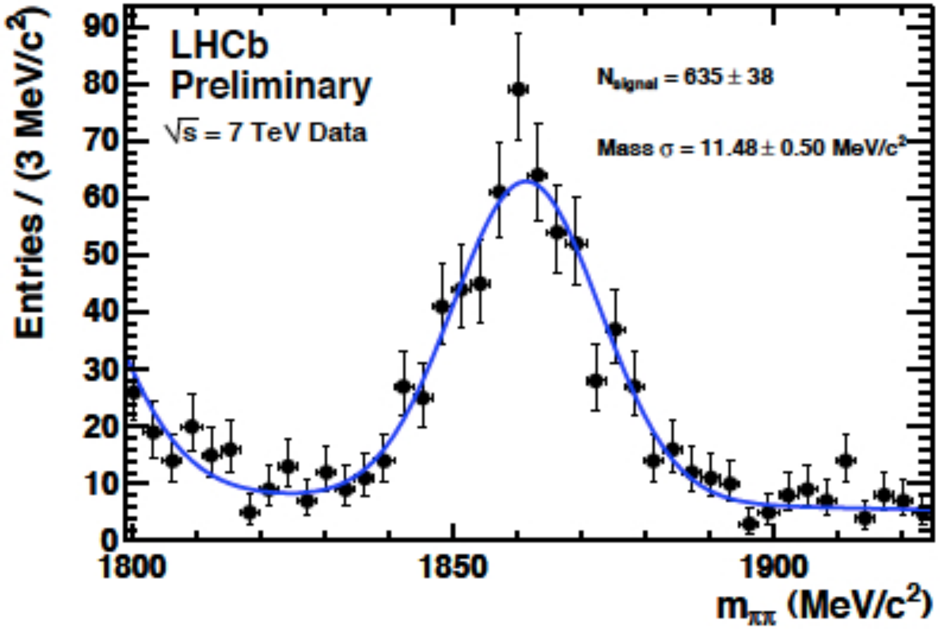


Huge statistics to study CPV: comparing the decay time distribution between $D^0 \rightarrow \pi^+K^-$ and $D^0 \rightarrow K^+K^-$, comparing the D^0 and $D^0 \rightarrow K^+K^-$, well before reaching 1 fb^{-1} ($\sim 15 \times 10^6$ events)

LHCb how about charm physics?

Huge number of charms can be detected with LHCb

Other interesting D^0 decays: with 124 nb^{-1} data



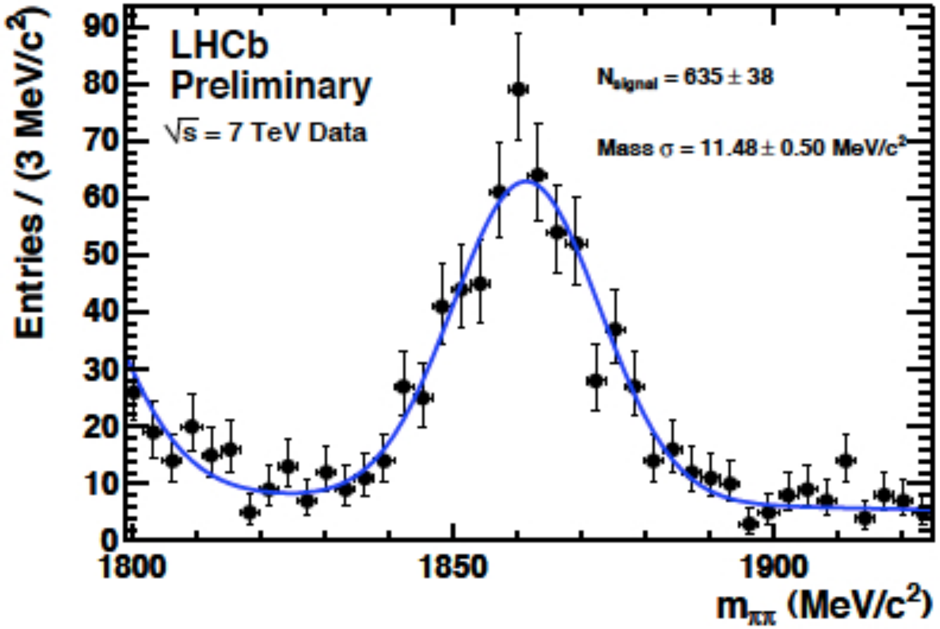
Initial flavour tagged
$D \rightarrow \pi^+\pi^-$

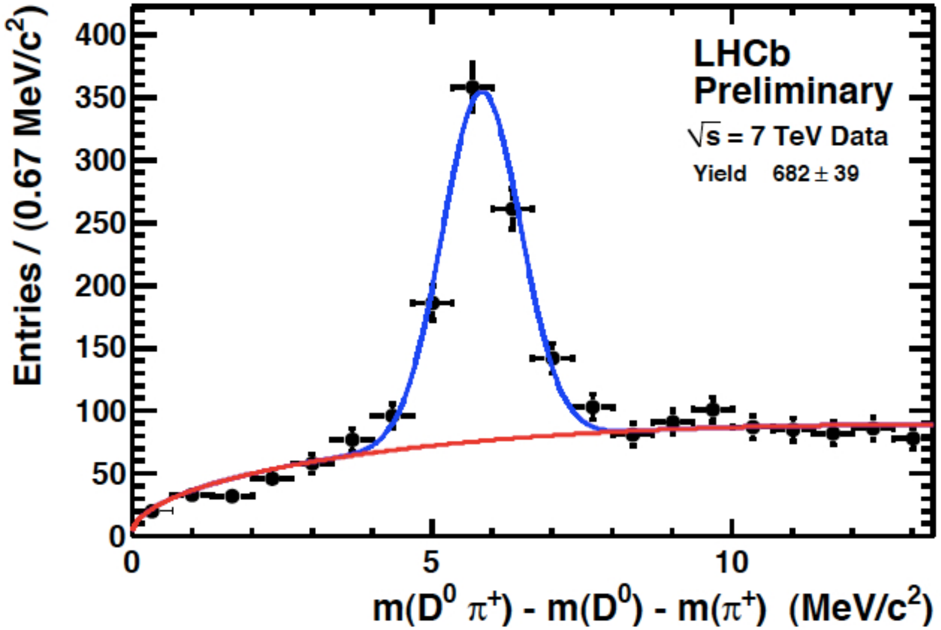
CPV study with
~5×10^6 events (1 fb^{-1})

LHCb how about charm physics?

Huge number of charms can be detected with LHCb

Other interesting D^0 decays: with 124 nb^{-1} data





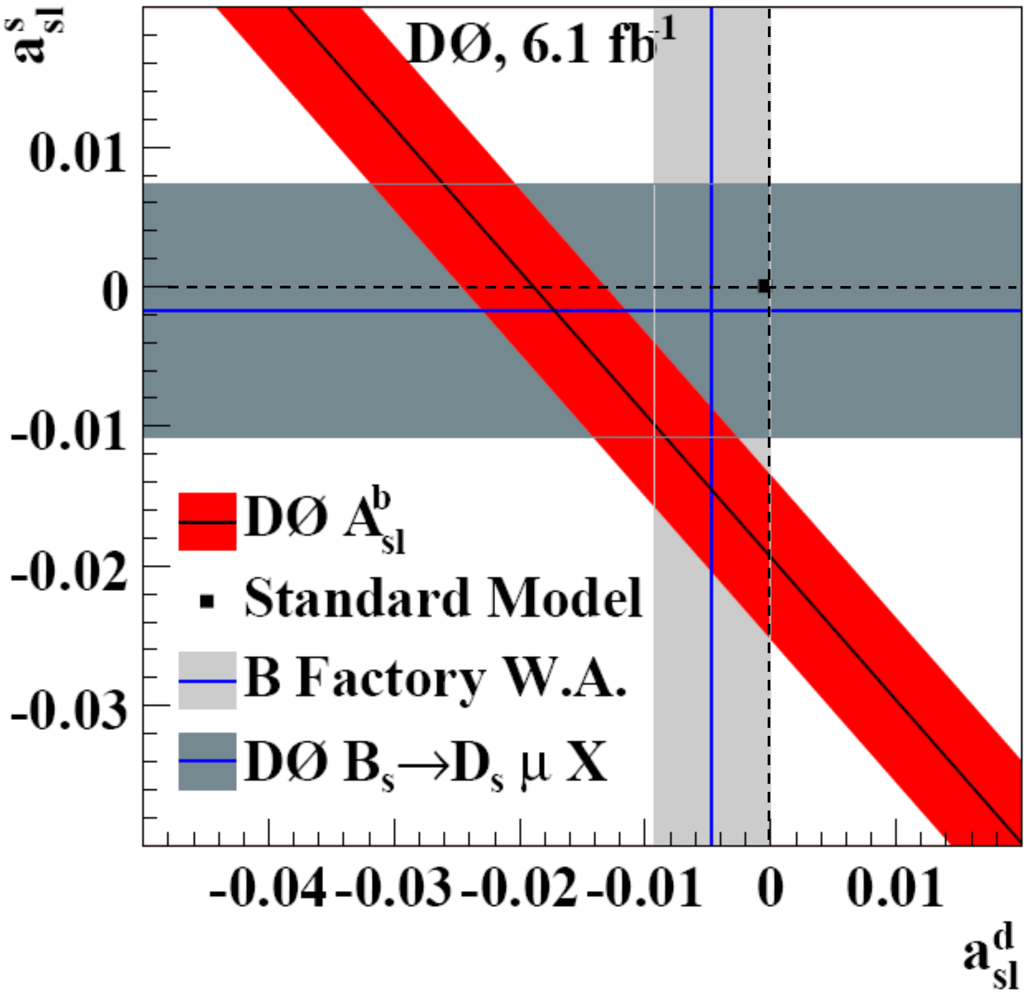
Initial flavour tagged
$D \to \pi^+\pi^-$

Initial flavour tagged
$D \to K_S\pi^+\pi^-$

CPV study with
~5×10^6 events (1 fb^{-1})

Bench mark for γ_{CKM} with
B→DK Dalitz method

Current situation with a^s_{SL}?



LHCb how about a^{s}_{SL}?

How to deal with
-possible B_s^0 / $\overline{B}_s^0$ production asymmetry in pp $2<\eta<6$
-controlling detection and background asymmetries to $< 10^{-3}$

LHCb how about a^s_{SL}?

How to deal with
-possible $B_s^0 / \overline{B}_s^0$ production asymmetry in pp $2<\eta<6$
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Inclusive muon pairs difficult to control systematic errors…

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Inclusive muon pairs difficult to control systematic errors…

Time dependent B_s decay asymmetry
$D_s^+(K^+K^-\pi^+)\pi^-$ vs $D_s^-(K^+K^-\pi^+)\pi^+$
production or detection asymmetry from data

LHCb how about a^{s}_{SL}?

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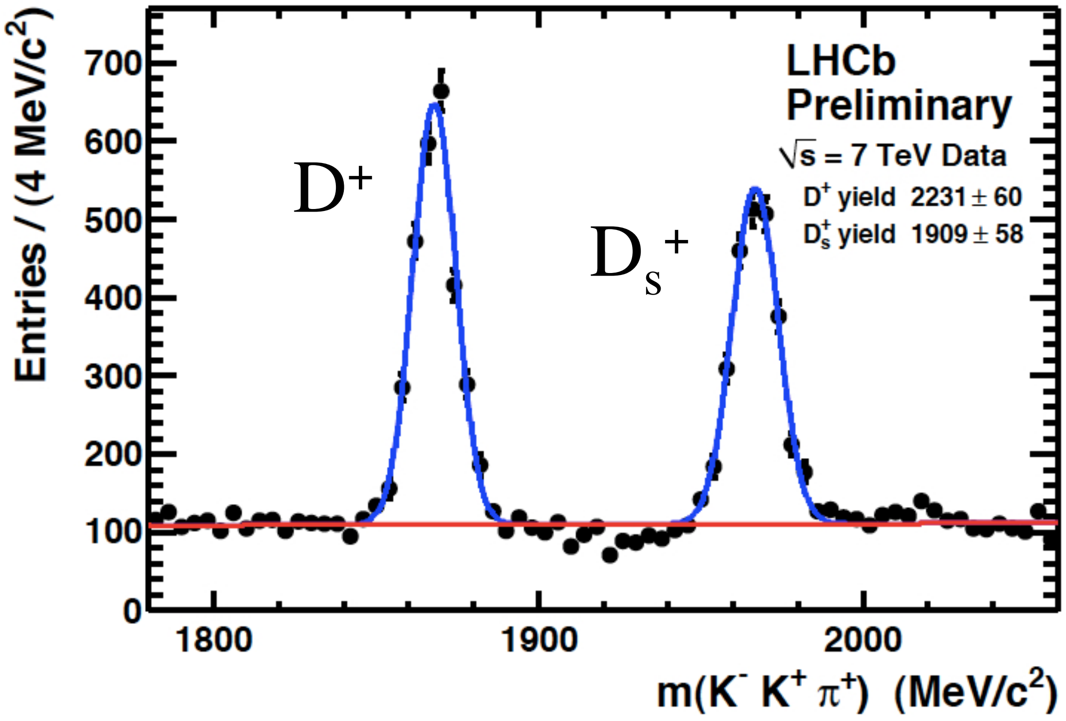
Inclusive muon pairs difficult to control systematic errors…

Time dependent B_s decay asymmetry
$D_s^+(K^+K^-\pi^+)\pi^-$ vs $D_s^-(K^+K^-\pi^+)\pi^+$
production or detection asymmetry from data

B_d and B_s time depended CP asymmetries from the same final ftates: i.e.
$B_d \rightarrow D^+(K^+K^-\pi^+)\mu^-X$ - c.c. and $B_s \rightarrow D_s^+(K^+K^-\pi^+)\mu^-X$ - c.c.
difference depends only on $a^{s}_{SL} - a^{d}_{SL}$

LHCb how about a^s_{SL}?

$D^+ \rightarrow K^+K^-\pi^+$ and $D_s^+ \rightarrow K^+K^-\pi^+$ with 124 nb^{-1} data



LHCb how about a^{s}_{SL}?

$D^+ \rightarrow K^+K^-\pi^+$ and $D_s^+ \rightarrow K^+K^-\pi^+$
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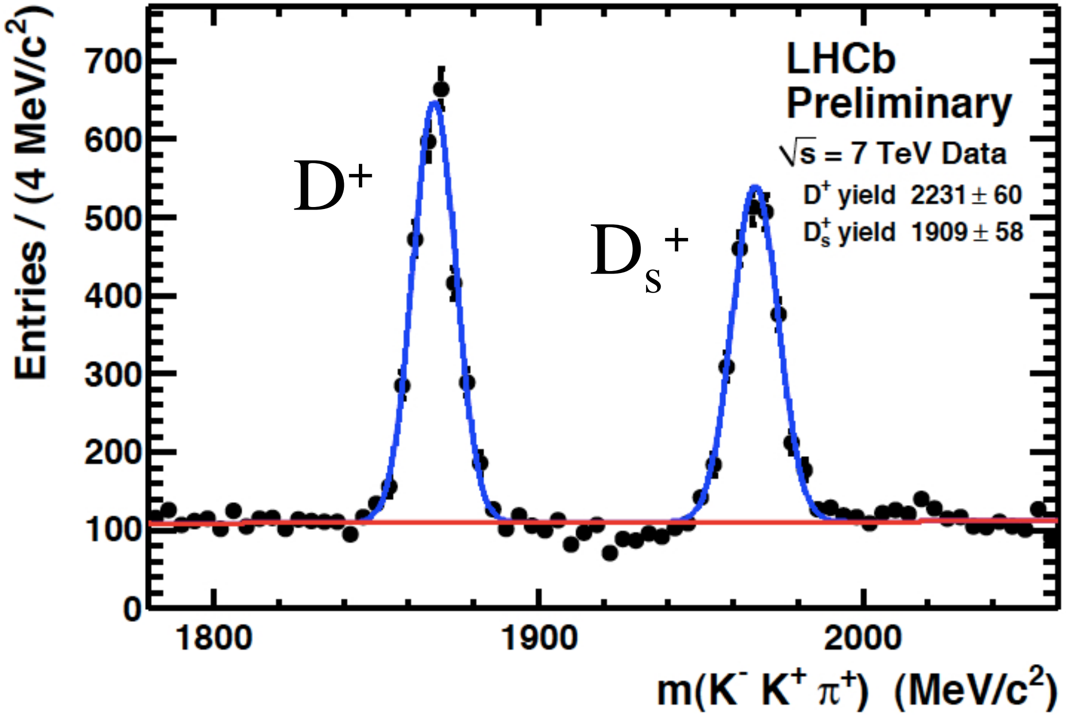


Expected statistical errors on

$$\Delta_{SL} \equiv a^{s}_{SL} - a^{d}_{SL}$$

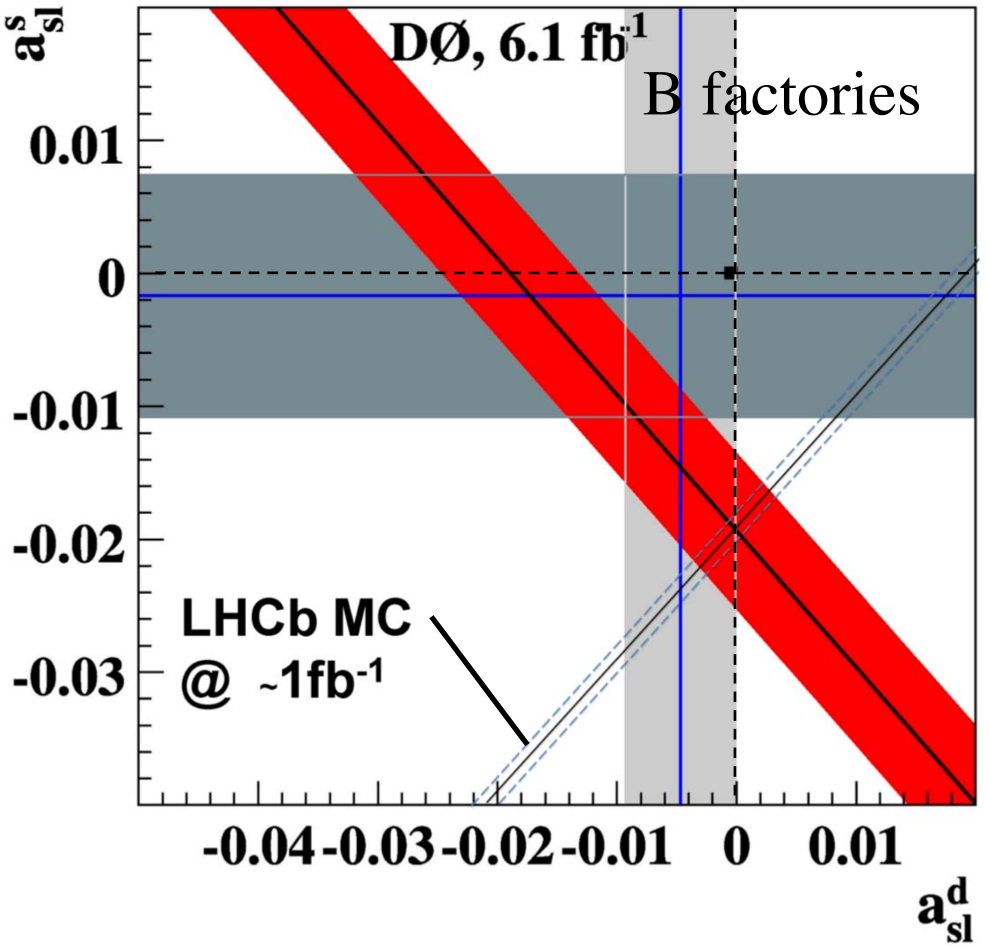
$$6.3\times10^{-4}$$

with 1 fb^{-1} of data

Systematic errors still to be investigated

LHCb how about a^s_{SL}?

LHCb expected performance with 1 fb^{-1} data
assuming Δ_{SL}(LHCb measured) = A^b_{SL}(D0 now)



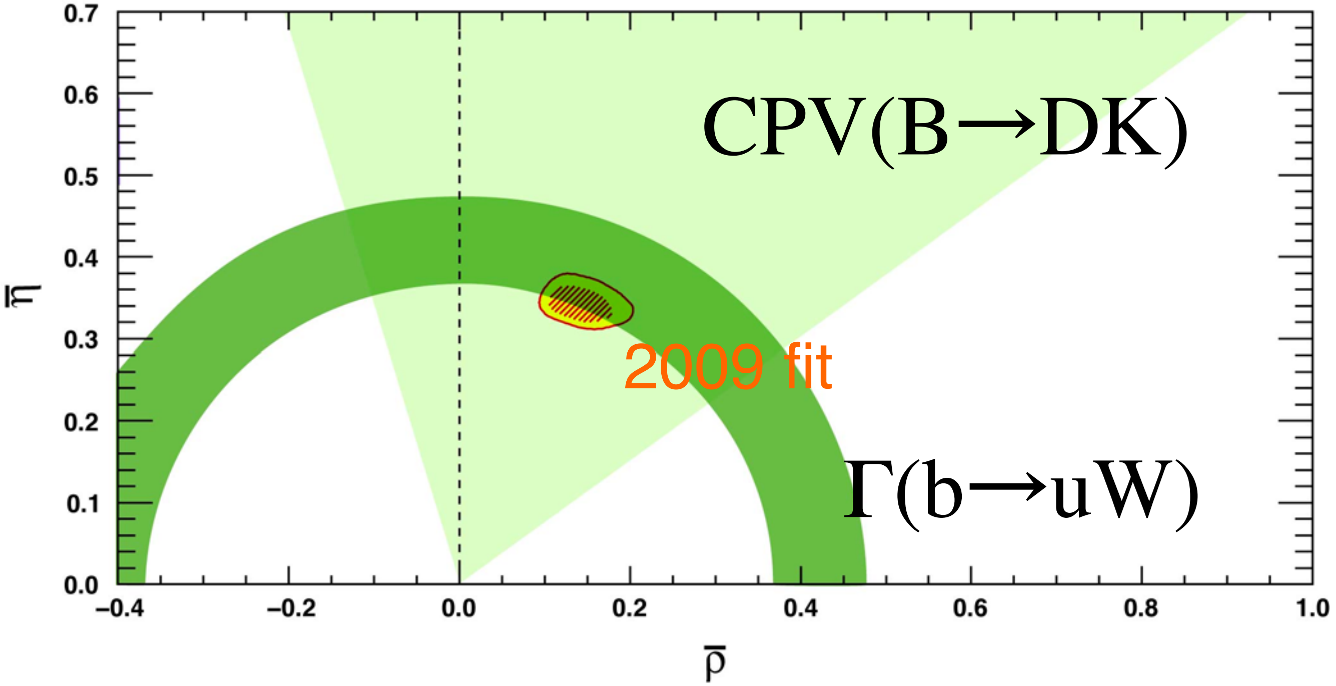
Conclusions

- Impressive track records of flavour physics for probing energy scale far beyond the direct reach:
- Major contribution from flavour physics for establishing the Standard Model. Most recent major contributions have been made by BABAR, Belle, CDF and D0. (CLEOc, BES, …)
- Current remarkable agreement with the Standard Model already indicates either,
  - New Physics is >> *O*(1 TeV) or
  - New Physics has very similar flavour structure to that of SM
- "Large" contribution from New Physics still not excluded in the B_s sector

Conclusions

- LHCb starts to take data at $\sqrt{s} = 7$ TeV with expected perfoamance
- LHC luminosity is expected to reach $\sim 10^{32}$, i.e. the designed luminosity for LHCb, and collect 1 fb^{-1} of data by the end of 2011: significant results can be expected from LHCb for
  $B_s \to J/\psi\phi$, $\to \mu^+\mu^-$,
  $B_s \to J/\psi K^{*0}$, CPV in charm, and others
- In 2013, LHC will start at $\sqrt{s} = 14$ TeV; LHCb, γ_{CKM}, photon polarization in $b \to s\gamma$, and others.

Now


0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
$\bar{\eta}$
−0.4
−0.2
0.0
0.2
0.4
0.6
0.8
1.0
$\bar{\rho}$
CPV(B→DK)
2009 fit
Γ(b→uW)

May be a surprise!

LHCb with 10 fb^{-1}