Flavour Physics

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1 April 2014

Outline

- Lecture 2
  - predictions of CKM theory
    - unitarity triangles
    - discoveries of charm, bottom and top
  - mixing
    - neutral meson mixing
    - categories of CP violation
    - time-reversal invariance
  - kaon physics
    - direct CP violation
  - charm physics

CKM Matrix / KM mechanism

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

- 3x3 matrix of complex numbers $\Rightarrow$ 18 parameters
- Unitary $\Rightarrow$ 9 parameters
- Quark fields absorb unobservable phases $\Rightarrow$ 4 parameters
  - 3 mixing angles and 1 phase (V_{CKM} complex)

CKM Matrix : parametrizations

- 3 mixing angles and 1 phase

Standard (PDG) parametrization; Chau & Keung PRL 53 (1984) 1802

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

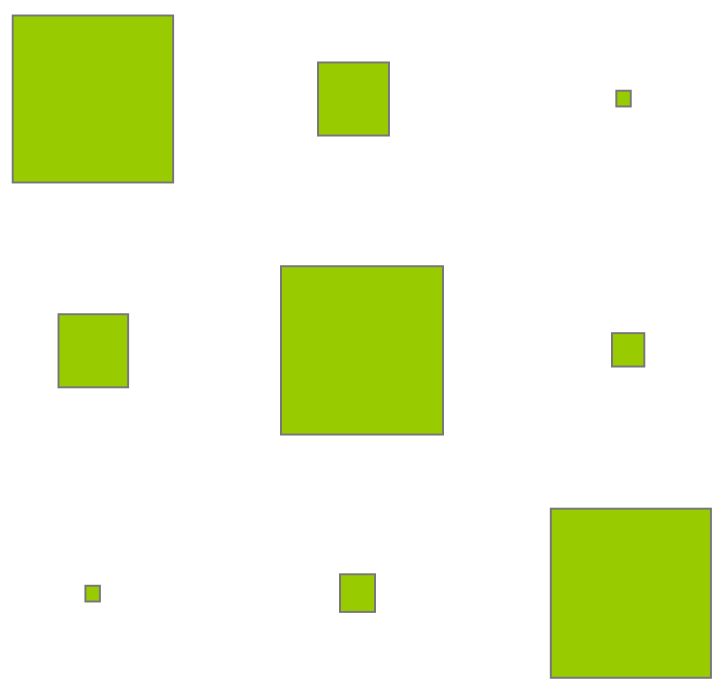
$s_{12} \sim 0.2$ $s_{23} \sim 0.04$ $s_{13} \sim 0.004$

- Exploit hierarchy – Wolfenstein parametrization
  - expansion parameter $\lambda \sim \sin\theta \sim 0.22$

$$V = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}\left(\lambda^4\right)$$

Hierarchy in quark mixing

$$V = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}\left(\lambda^4\right)$$



Unitarity

$$V^\dagger V = 1$$

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 \qquad V_{ud}V_{us}^* + V_{cd}V_{cs}^* + V_{td}V_{ts}^* = 0$$

$$|V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2 = 1 \qquad V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

$$|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2 = 1 \qquad V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0$$

$$|V_{ud}|^2 + |V_{cd}|^2 + |V_{td}|^2 = 1 \qquad V_{ud}V_{cd}^* + V_{us}V_{cs}^* + V_{ub}V_{cb}^* = 0$$

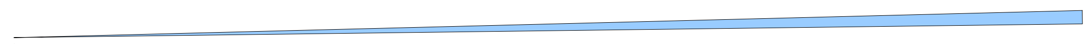
$$|V_{us}|^2 + |V_{cs}|^2 + |V_{ts}|^2 = 1 \qquad V_{ud}V_{td}^* + V_{us}V_{ts}^* + V_{ub}V_{tb}^* = 0$$

$$|V_{ub}|^2 + |V_{cb}|^2 + |V_{tb}|^2 = 1 \qquad V_{cd}V_{td}^* + V_{cs}V_{ts}^* + V_{cb}V_{tb}^* = 0$$

Unitarity triangles

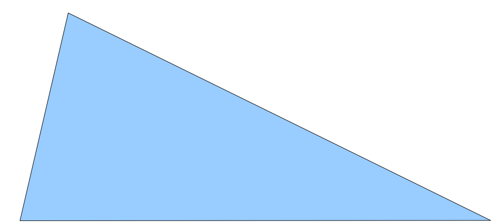
$$V_{ud}V_{us}^* + V_{cd}V_{cs}^* + V_{td}V_{ts}^* = 0$$

$$\lambda \qquad \lambda \qquad \lambda^5$$



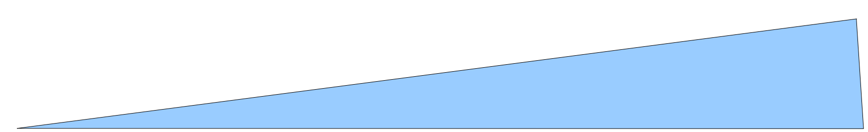
$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

$$\lambda^3 \qquad \lambda^3 \qquad \lambda^3$$



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

$$\lambda^4 \qquad \lambda^2 \qquad \lambda^2$$



See also Harrison, Dallison, Scott, PLB 680, 328 (2009)

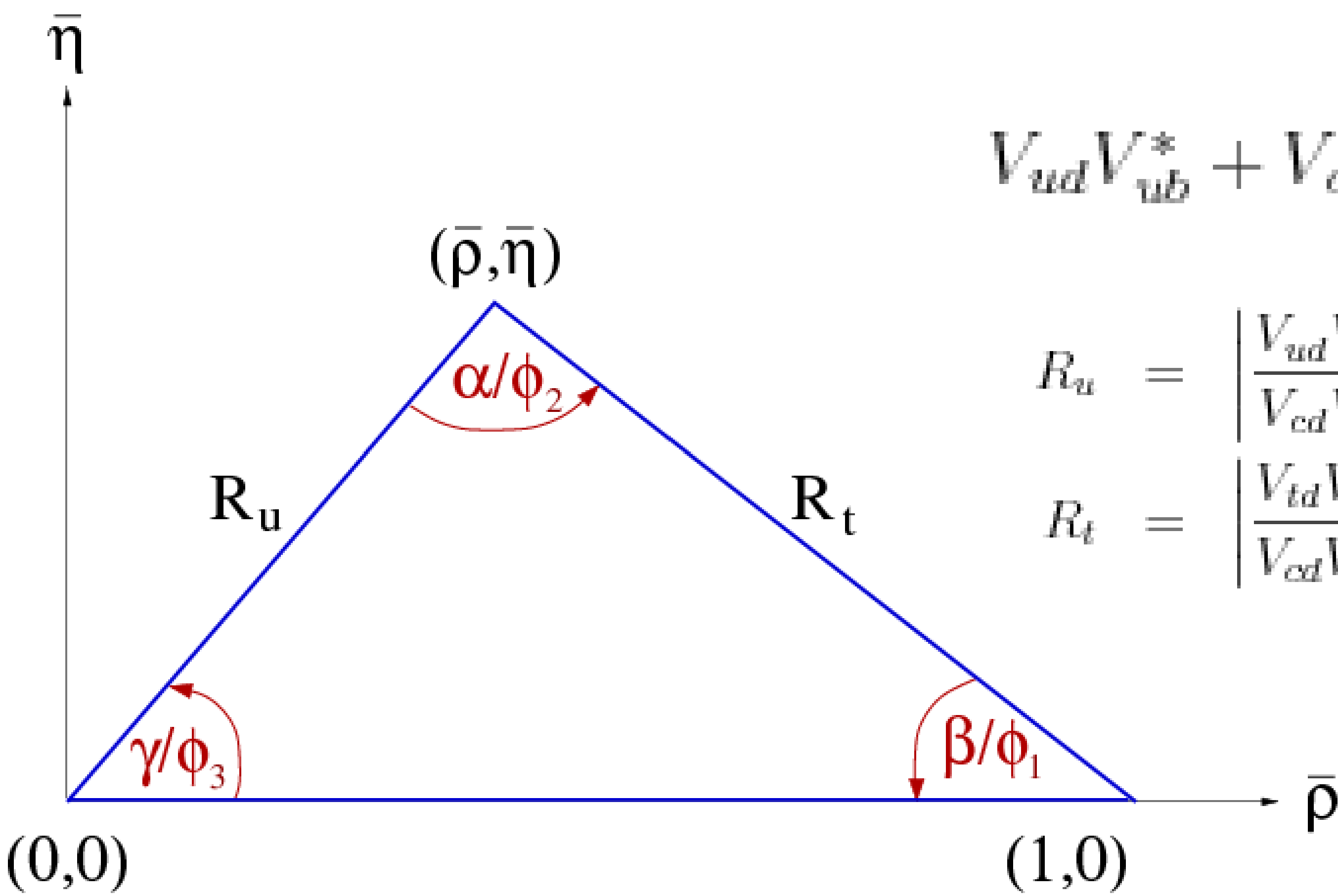
DISCLAIMER : THESE ARE NOT TO SCALE!

Jarlskog

- All unitarity triangles have the same area
  - $A = J/2$
  - J is the Jarlskog invariant
  - $J = c_{12}\ c_{23}\ c_{13}^2\ s_{12}\ s_{23}\ s_{13} \sin\delta \sim 4\ 10^{-5}$
    - invariant measure of CP violation in the quark sector
  - $|J| = \mathrm{Im}(\ V_{ij}\ V_{kl}\ V_{kj}^*\ V_{il}^*)$, for any choice of ijkl ($i \neq k$; $j \neq l$)
  - J related to commutator of mass matrices
    - $[M,M'] = iC \quad \det(C) = -2\ F\ F'\ J$
    - $F = (m_t - m_c)(m_t - m_u)(m_c - m_u)$
    - $F' = (m_b - m_s)(m_b - m_d)(m_s - m_d)$

The Unitarity Triangle

- Convenient method to illustrate (dis-)agreement of observables with CKM prediction



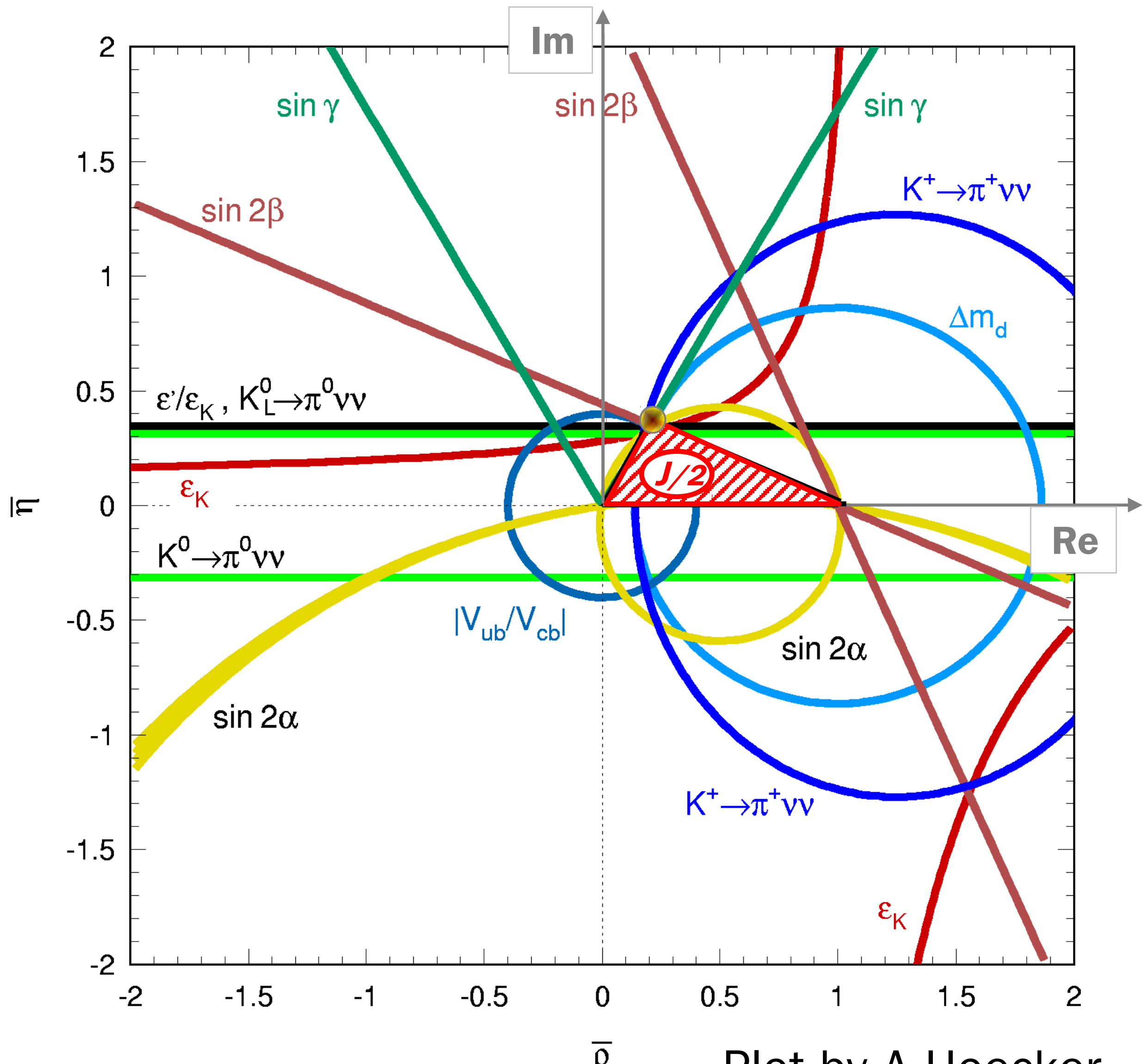
$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0,$$

$$R_u = \left|\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right| = \sqrt{\bar{\rho}^2 + \bar{\eta}^2},$$

$$R_t = \left|\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*}\right| = \sqrt{(1-\bar{\rho})^2 + \bar{\eta}^2}.$$

Predictive nature of KM mechanism

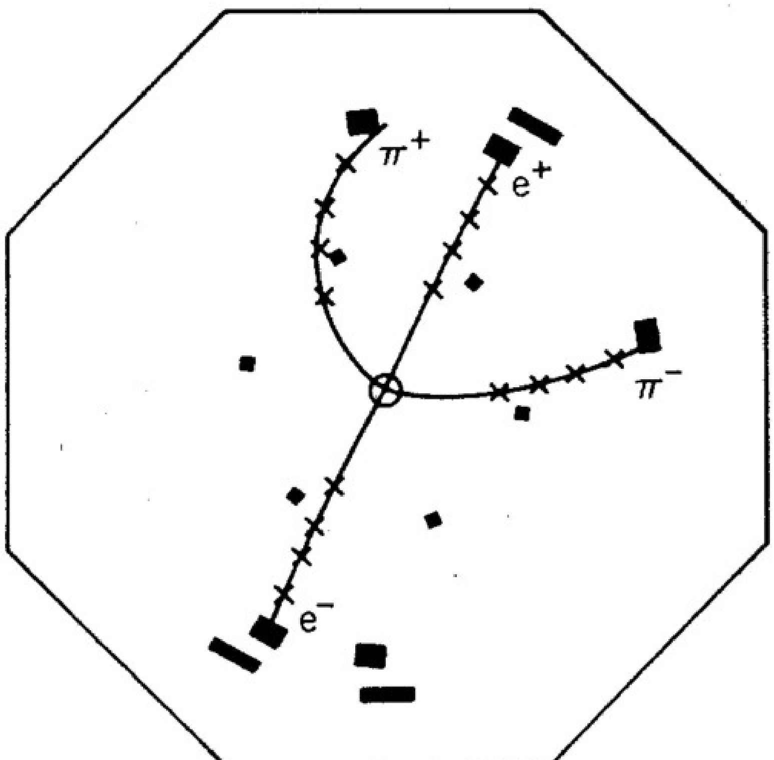
All measurements must agree

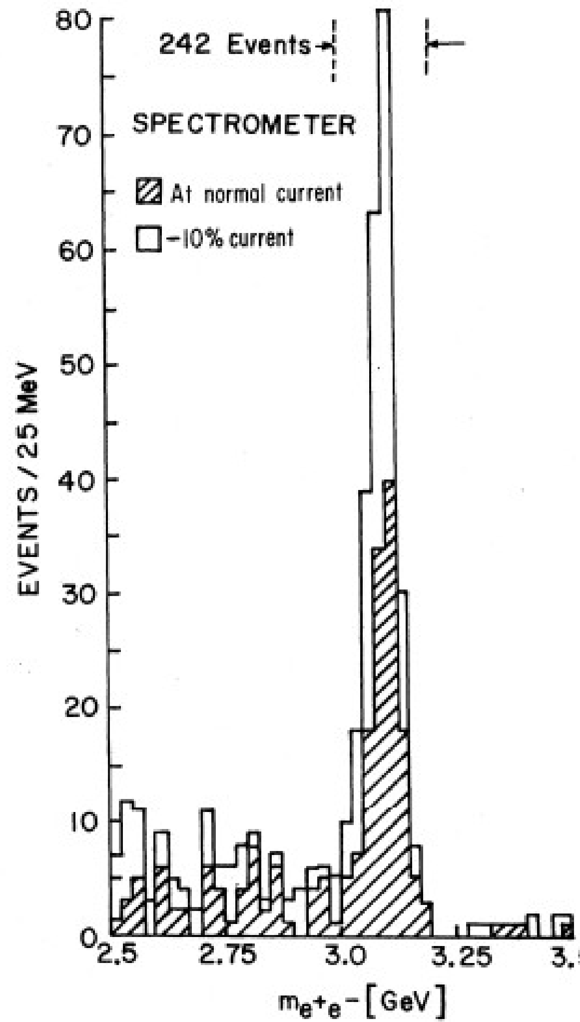


Plot by A.Hoecker

Discovery of charm

- J/ψ discovery, Nov. 1974 ("November revolution")
  - J : Samuel Ting, BNL
  - ψ : Burton Richter, SLAC





Discovery of J/ψ

- 2 observations & 1 confirmation in the same edition of Physical Review Letters

EDITORIAL

Publication of a New Discovery

This issue of Physical Review Letters must certainly be one of the most unusual in our history, with not just one but three extremely stimulating reports of a new discovery. Undoubtedly, the activity which will be aroused will be enormous and we happily join the rest of the physics community in congratulating those involved.

At the same time we would like to point out that the events of the past weeks placed some considerable stress not only on our office staff but also on our editorial policy regarding prior publication. We are grateful to the authors who were willing to meet our desires to defer publication announcements until the journal issue appeared. When, however, upon consulting our advisors we became aware of the truly unusual extent to which the entire high energy physics community was involved, we concurred that the news justified early public release. We hope that this decision will not be used as a precedent in future controversies concerning our stated editorial policies but will instead be taken as an indication that we are willing to bend these policies so as to be of service to the physics community.

J. A. Krumhansl

George L. Trigg

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
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and

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(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 $p + \mathrm{Be} \rightarrow e^+ + e^- + x$ by measuring the e^+e^- mass spectrum with a precise pair spectrometer at the Brookhaven National Laboratory's 30-GeV alternating-gradient synchrotron.

Discovery of charmonium (J)
Brookhaven National Laboratory
$p + \mathrm{Be} \rightarrow e^+ e^- X$

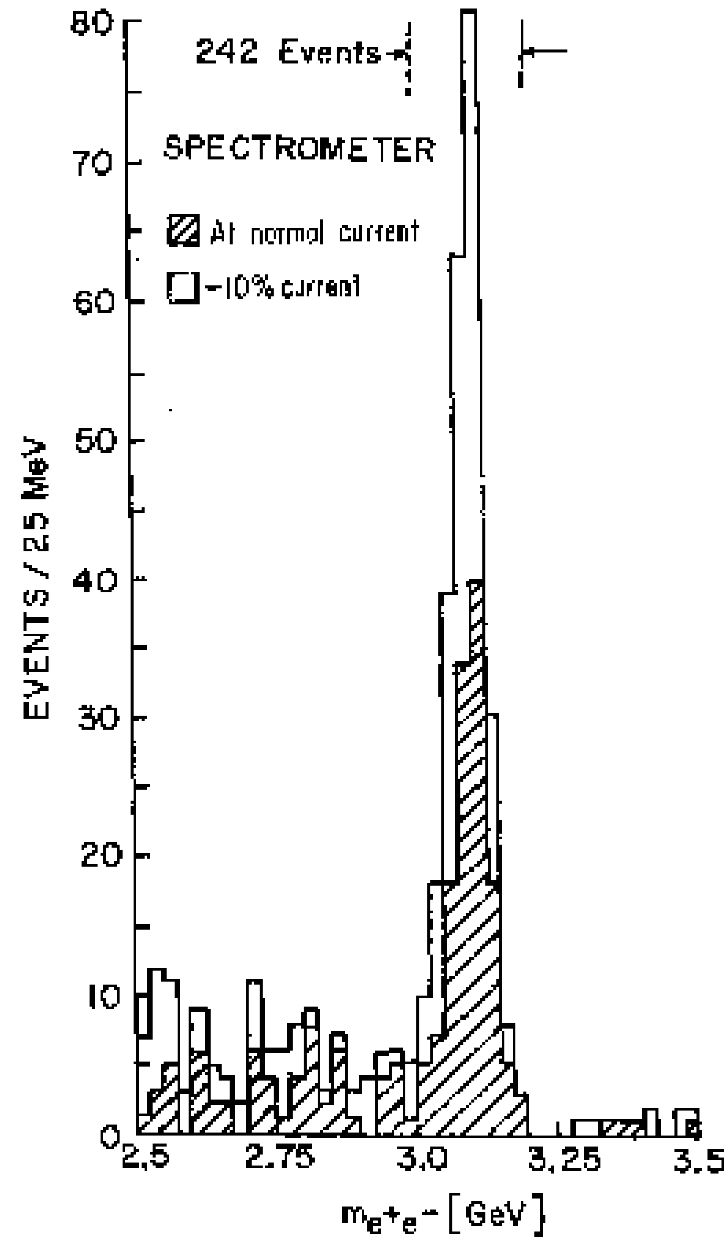

FIG. 2. Mass spectrum showing the existence of J. Results from two spectrometer settings are plotted showing that the peak is independent of spectrometer currents. The run at reduced current was taken two months later than the normal run.

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

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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.

Discovery of charmonium (ψ)
Stanford Linear Accelerator Center
$e^+e^- \to$ hadrons, e^+e^- , $\mu^+\mu^-$

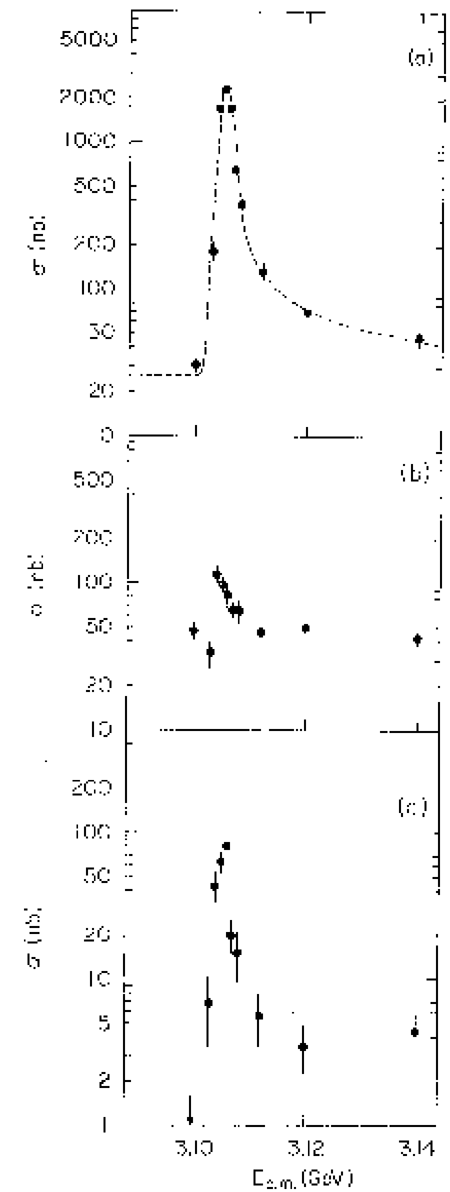

FIG. 1. Cross section versus energy for (a) multi-hadron final states, (b) e^+e^- final states, and (c) $\mu^+\mu^-$, $\pi^+\pi^-$, and K^+K^- final states. The curve in (a) is the expected shape of a δ-function resonance folded with the Gaussian energy spread of the beams and including radiative processes. The cross sections shown in (b) and (c) are integrated over the detector acceptance. The total hadron cross section, (a), has been corrected for detection efficiency.

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. Paoluzi, I. Peruzzi, G. Piano Mortari, 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. Calvetti, 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-GeV particle.

Confirmation of charmonium (J/ψ)
Laboratori Nazionale di Frascati
$e^+e^- \rightarrow$ hadrons, e^+e^- , $\mu^+\mu^-$

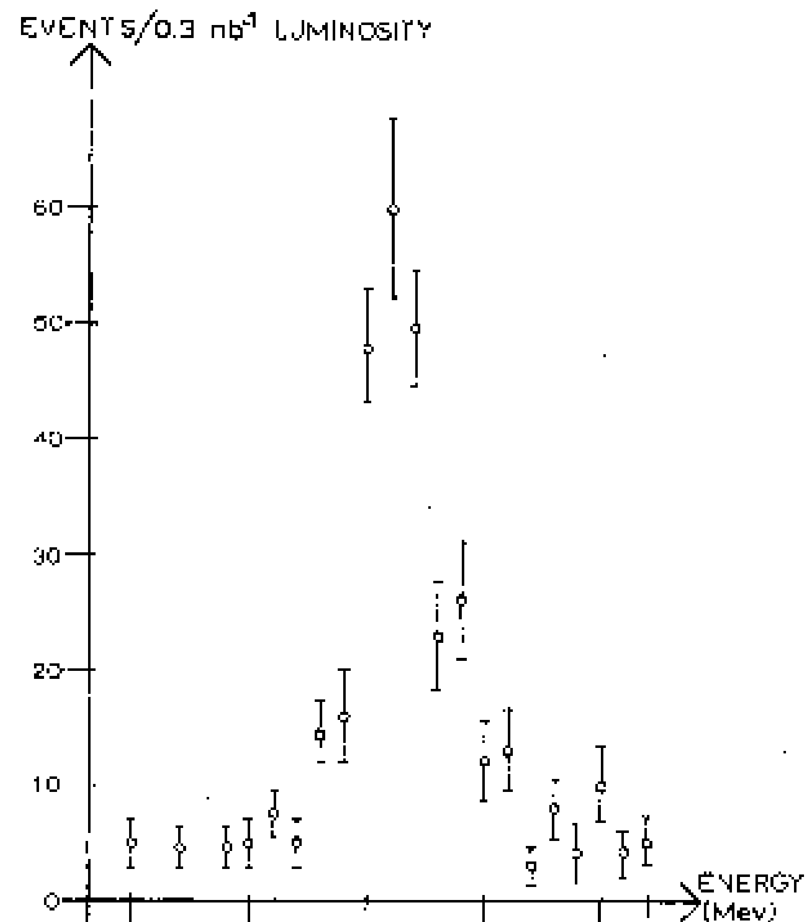

FIG. 1. Result from the Gamma-Gamma Group, total of 446 events. The number of events per 0.3 nb^{-1} luminosity is plotted versus the total c.m. energy of the machine.

Flavour physics machines

- Previous examples illustrate the two main tools used to study quark flavour physics
  - hadron machines
    - symmetric colliders
    - fixed target
  - electron-positron machines
    - symmetric colliders
    - asymmetric colliders
- Very roughly, the former are good for discoveries of particles, while the latter are good for precision studies of those particles

Observation of a Dimuon Resonance at 9.5 GeV in 400-GeV Proton-Nucleus Collisions

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(Received 1 July 1977)

Accepted without review at the request of Edwin L. Goldwasser under policy announced 26 April 1976

Dimuon production is studied in 400-GeV proton-nucleus collisions. A strong enhancement is observed at 9.5 GeV mass in a sample of 9000 dimuon events with a mass $m_{\mu^+\mu^-} > 5$ GeV.

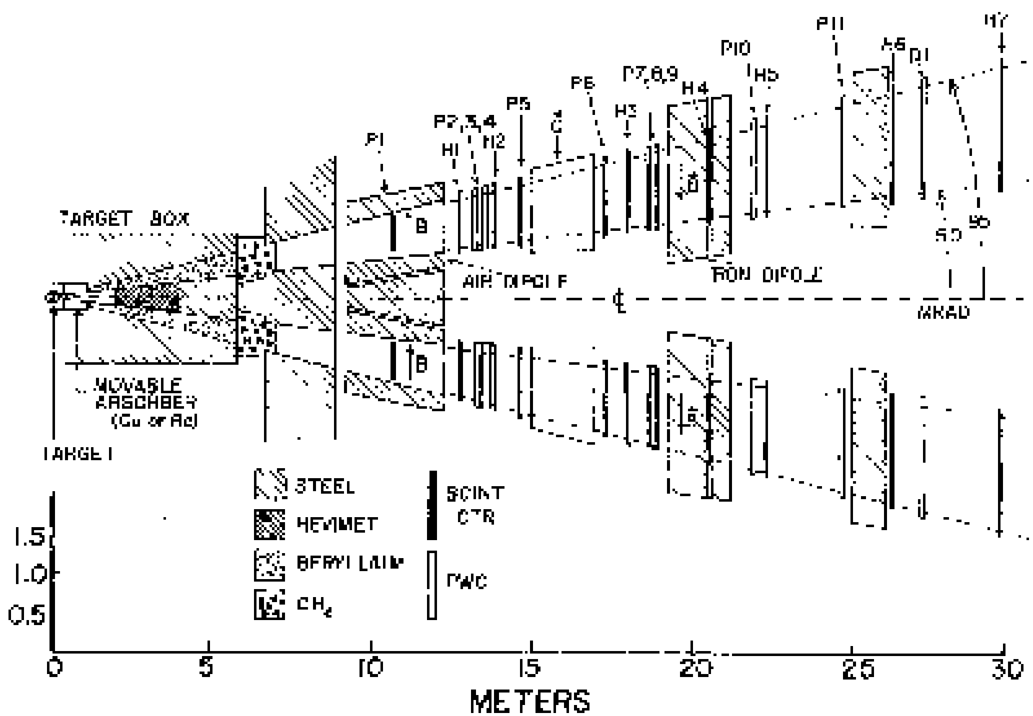

FIG. 1. Plan view of the apparatus. Each spectrometer arm includes eleven PWC's P1–P11, seven scintillation counter hodoscopes H1–H7, a drift chamber D1 and a gas-filled threshold Čerenkov counter Č. Each arm is up/down symmetric and hence accepts both positive and negative muons.

Discovery of bottomonium (Υ)
Fermilab National Accelerator Laboratory
$p + \{Cu,Pt\} \rightarrow \mu^+ \mu^- X$

Discovery of bottomonium (Υ)
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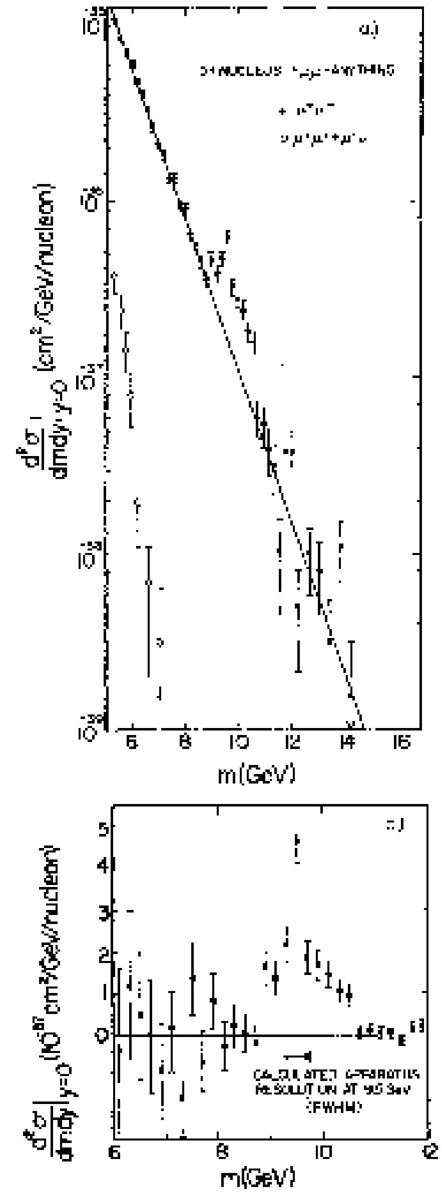

FIG. 3. (a) Measured dimuon production cross sections as a function of the invariant mass of the muon pair. The solid line is the continuum fit outlined in the text. The equal-sign–dimuon cross section is also shown. (b) The same cross sections as in (a) with the smooth exponential continuum fit subtracted in order to reveal the 8–10-GeV region in more detail.

Discovery of bottomonium (Υ)
Fermilab National Accelerator Laboratory
$p + \{Cu,Pt\} \rightarrow \mu^+ \mu^- X$

VOLUME 39, NUMBER 20 PHYSICAL REVIEW LETTERS 14 NOVEMBER 1977

Observation of Structure in the Υ Region

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The properties of the dimuon enhancement seen in 400-GeV proton-nucleus collisions have been clarified by a threefold increase in data. We find two peaks whose widths are consistent with our resolution: $M_1 = 9.4$ GeV with $B\,d\sigma/dy|_{y=0} = 1.8 \times 10^{-37}$ cm^2/nucleon and $M_2 = 10.0$ GeV with $B\,d\sigma/dy|_{y=0} = 0.7 \times 10^{-37}$ cm^2/nucleon. Evidence for the possible existence of a third peak near 10.4 GeV is discussed as are the comparisons with the properties of a $q\bar{q}$ system, where q is a new heavy quark.

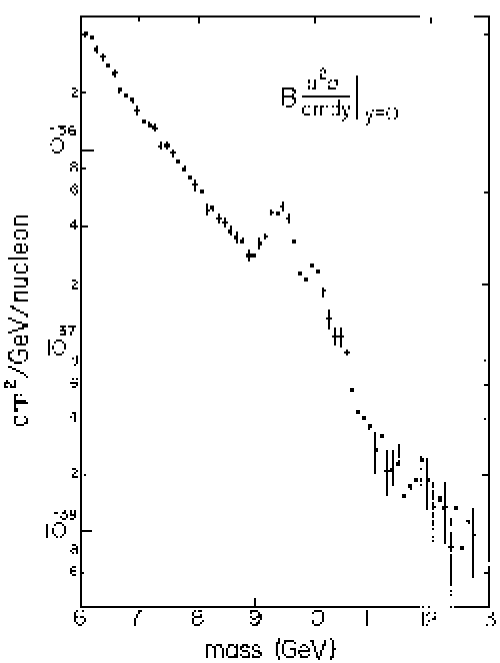

FIG. 1. Dimuon spectrum above 6 GeV.

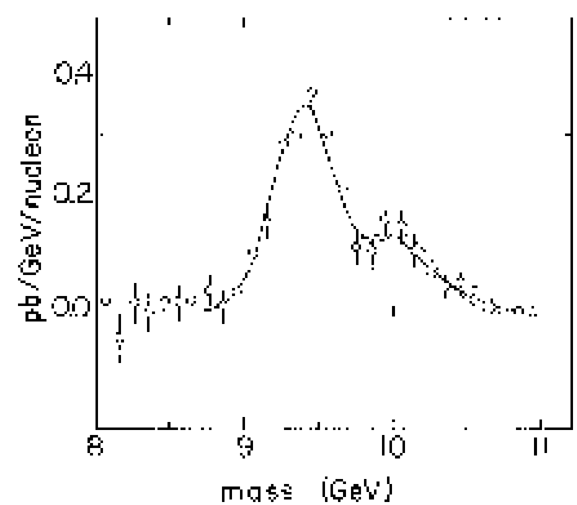

FIG. 2. Excess of the data over the continuum fit of Eq. (1). Errors shown are statistical only. The solid curve is the three-peak fit; the dashed curve is the two-peak fit.

Discovery of Υ(4S)
Cornell University
e^+e^- collisions

VOLUME 45, NUMBER 4 PHYSICAL REVIEW LETTERS 28 JULY 1980

Observation of a Fourth Upsilon State in e^+e^- Annihilations

D. Andrews, K. Berkelman, R. Cabenda, D. G. Cassel, J. W. DeWire, R. Ehrlich, T. Ferguson, T. Gentile, M. G. D. Gilchriese, B. Gittelman, D. L. Hartill, D. Herrup, M. Herzlinger, D. L. Kreinick, N. B. Mistry, E. Nordberg, R. Perchonok, R. Plunkett, K. A. Shinsky, R. H. Siemann, A. Silverman, P. C. Stein, S. Stone, R. Talman, H. G. Thonemann, and D. Weber
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(Received 18 April 1980)

A fourth state in the upsilon energy region has been seen in e^+e^- collisions at the Cornell Electron Storage Ring. A resonance is observed with a mass 1112 ± 5 MeV above the lowest upsilon state. The 9.6-MeV rms width is greater than the 4.6-MeV energy resolution of the e^+e^- beams. The observed characteristics of the new state make it a likely candidate for the 4S state of the $b\bar{b}$ system, lying above the threshold for the production of B mesons.

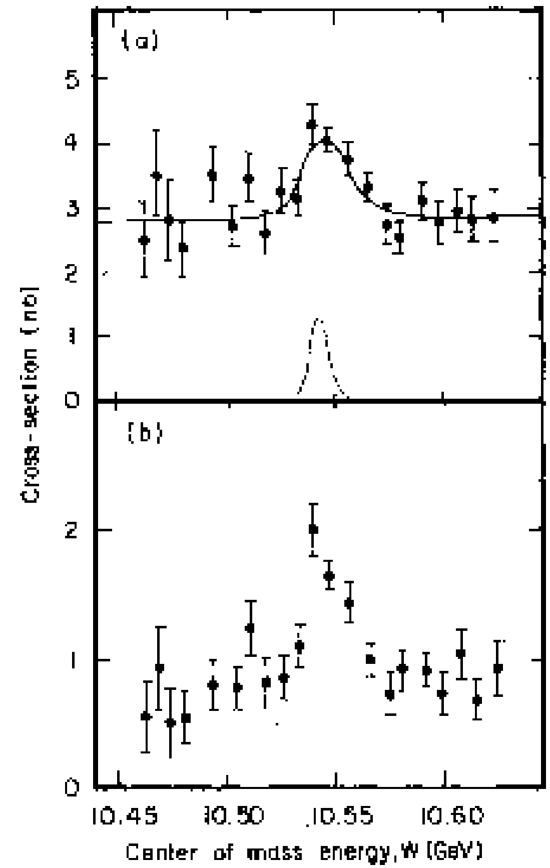

FIG. 1. Hadronic cross sections corrected for acceptance, as a function of center-of-mass energy, W. There is an additional overall systematic error of $\pm 15\%$, arising mainly from the uncertainty in the detector acceptance. (a) Total hadronic cross section. The curve is a radiatively corrected Gaussian fit to the resonance above a smooth continuum varying as W^{-2}. The dashed curve indicates the beam energy resolution. (b) Partial cross section for events with $R_2 < 0.3$. (See text.)

Quarkonia & mesons

- J/ψ identified as $J^{PC} = 1^{--}$ charmonium ($c\underline{c}$)
  - produced in e^+e^- collisions
  - decays to e^+e^-, $\mu^+\mu^-$, etc. (clean signatures)
  - narrow: width ~ 90 keV
- Charmonia above $D\underline{D}$ threshold are wide
  - no OZI suppression
  - discovery of the D^0 ($c\underline{u}$), D^+ ($c\underline{d}$), D_s^+ ($c\underline{s}$), ... mesons
- Charmonia with other quantum numbers take a bit longer to discover
  - η_c (0^{-+}), $\chi_{c\{0,1,2\}}$ ($\{0,1,2\}^{++}$), and more (still active area)

Quarkonia & mesons

- Υ identified as $J^{PC} = 1^{-}$ bottomonium ($b\underline{b}$)
  - narrow: width ~ 50 keV
- Bottomonia above $B\underline{B}$ threshold are wide
  - no OZI suppression
  - discovery of the B^0 ($d\underline{b}$), B^+ ($u\underline{b}$), B_s^0 ($s\underline{b}$), ... mesons
  - Υ(4S) ~ 100% decay to $B^0\underline{B}^0$, B^+B^-
- Bottomonia with other quantum numbers take a bit longer to discover
  - η_b (0^{-+}) discovered recently (PRL 101, 071801 (2008))
  - $\chi_{b\{0,1,2\}}$ ($\{0,1,2\}^{++}$), and more (still active area)

WARNING: NOT ALL "DISCOVERIES" ARE REAL

Observation of High-Mass Dilepton Pairs in Hadron Collisions at 400 GeV

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(Received 28 January 1976)

We report preliminary results on the production of electron-positron pairs in the mass range 2.5 to 20 GeV in 400-GeV p-Be interactions. 27 high-mass events are observed in the mass range 5.5–10.0 GeV corresponding to $\sigma = (1.2 \pm 0.5) \times 10^{-35}$ cm² per nucleon. Clustering of 12 of these events between 5.8 and 6.2 GeV suggests that the data contain a new resonance at 6 GeV.

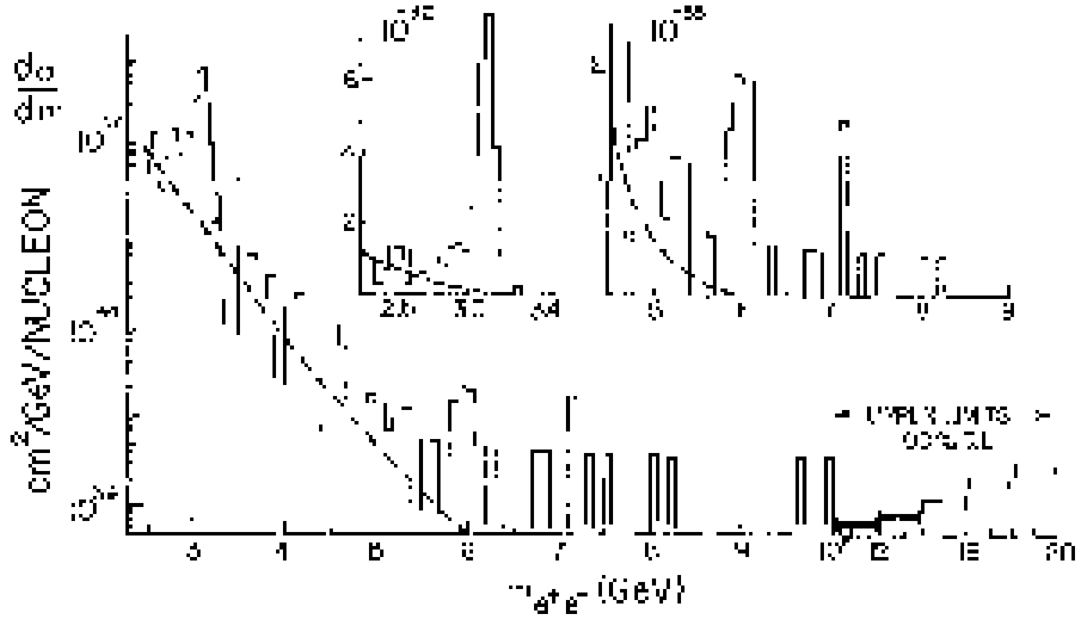


FIG. 2. Electron-positron mass spectrum: $d\sigma/dm$ per nucleon versus the effective mass. A linear A dependence is assumed. Note bin-width changes.

WARNING: NOT ALL "DISCOVERIES" ARE REAL

Discovery of the top quark

- The top quark decays too quickly to hadronise
  - no ($t\underline{t}$) “toponium” resonance (no top mesons at all)
- top pairs produced from g in hadronic collisions
  - $t\underline{t} \rightarrow W^+bW^-\underline{b}$
    - W^{+-} can give high p_t leptons
    - b quarks have displaced vertices
  - single top production ($W^+ \rightarrow t\underline{b}$) also possible
    - first observed in 2009 (CDF/D0), now giving good measurement of $|V_{tb}|$ (CMS arXiv:1403.7366)
      - $|V_{tb}| = 0.998 \pm 0.038$ (exp.) ± 0.016 (theo.)

Discovery of the top quark

CDF collaboration
PRL 74, 2626 (1995)

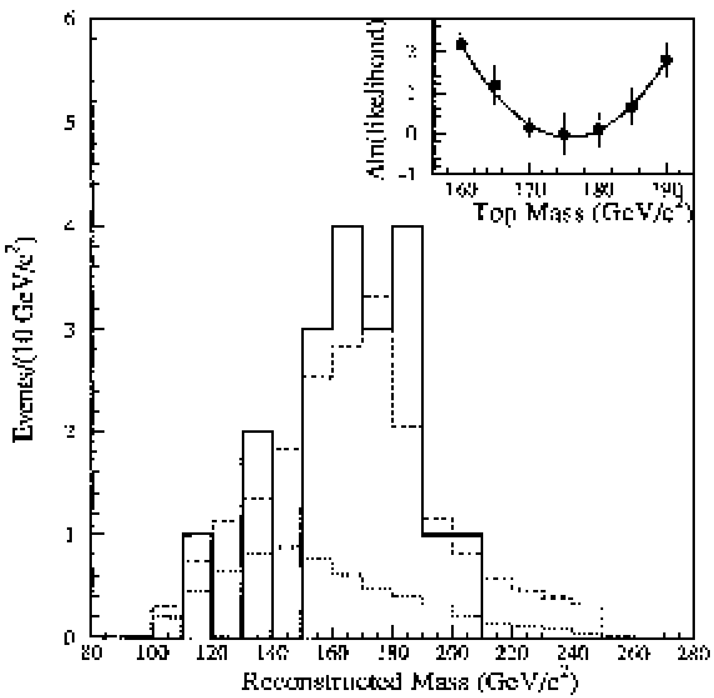


FIG. 3. Reconstructed mass distribution for the b-tagged $W+\geq 4$-jet events (solid). Also shown are the background shape (dotted) and the sum of background plus $t\bar{t}$ Monte Carlo simulations for $M_{top} = 175$ GeV/c^2 (dashed), with the background constrained to the calculated value, $6.9^{+2.5}_{-1.9}$ events. The inset shows the likelihood fit used to determine the top mass.

D0 collaboration
PRL 74, 2632 (1995)

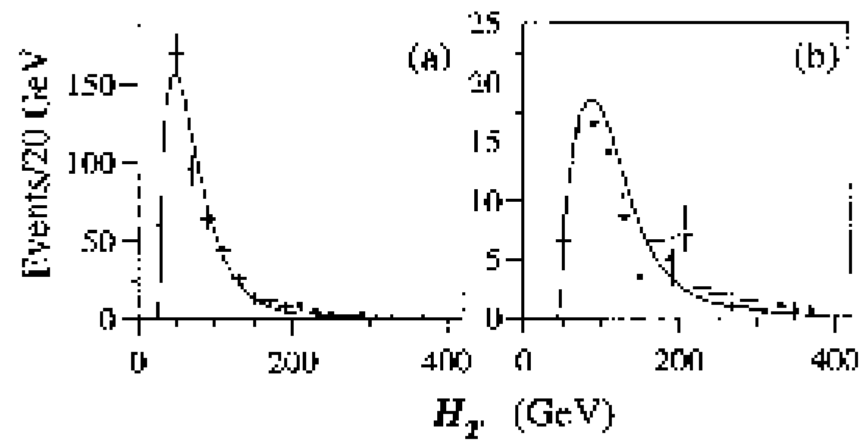
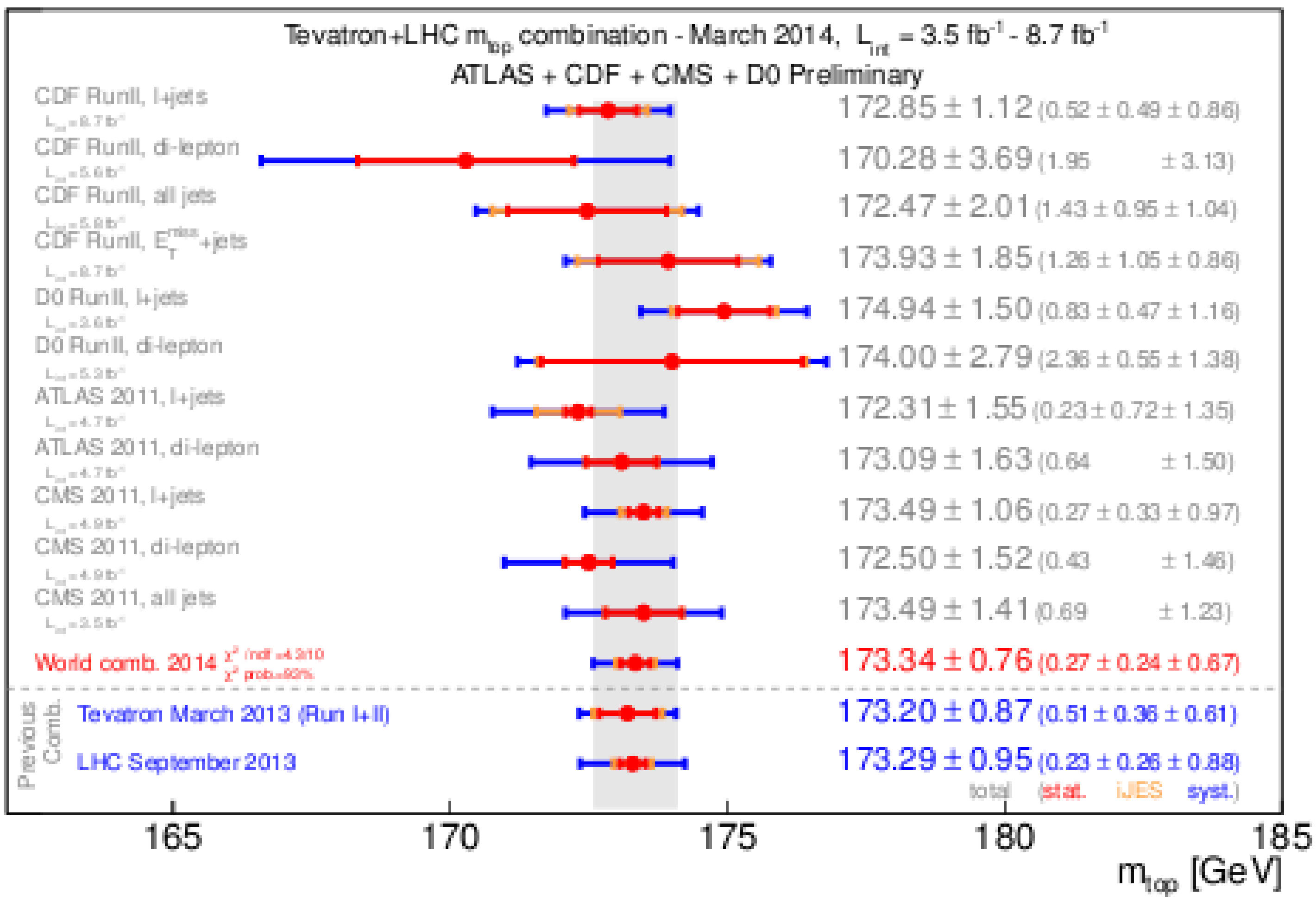


FIG. 2. Observed H_T distributions (points) compared to the distributions expected from background (line) for $\not{E}_T >$ 25 GeV/c and (a) $n = \geq 2$ jets and (b) $n \geq 3$ jets.

Current m_t World Average



ATLAS + CDF + CMS + D0
arXiv:1403.4427 [hep-ex]

Mixing

- Various mixings
  - quark mixing (CKM)
  - flavour SU(2)
  - flavour SU(3)
  - neutral meson mixing

Mixing in flavour SU(2) – isospin

- Four meson combinations of u & d quarks
  - $u\underline{d}$, $\underline{u}d$, $u\underline{u}$, $d\underline{d}$
- Under SU(2) symmetry
  - π^0 is member of isospin triplet
  - η is isosinglet
  - $\pi^0 = (u\underline{u} - d\underline{d})/\sqrt{2}$ $\quad$ $\eta = (u\underline{u} + d\underline{d})/\sqrt{2}$
- $m(\pi^0) \sim 0.135$ GeV $\quad$ $m(\eta) \sim 0.550$ GeV

Mixing in flavour SU(3)

- Now 3 quarks: u,d,s
- SU(3) symmetry → octuplet & singlet
  - $\pi^0 = (u\underline{u} - d\underline{d})/\sqrt{2}$
  - $\eta_1 = (u\underline{u} + d\underline{d} + s\underline{s})/\sqrt{3}$ $\eta_8 = (u\underline{u} + d\underline{d} - 2s\underline{s})/\sqrt{6}$
- Physical states η,η' are further mixtures
  - $\eta = \eta_1 \cos\theta_P + \eta_8 \sin\theta_P$
  - $\eta' = -\eta_1 \sin\theta_P + \eta_8 \cos\theta_P$
- Pseudoscalar mixing angle θ_P determined from masses or from partial widths

CPT theorem

- So far, considering mixing of particles with no flavour quantum numbers
- Now move to neutral kaons:
  - K^0 ($\underline{s}d$) & $\underline{K}^0$ ($s\underline{d}$)
- CPT theorem → particle & antiparticle have
  - equal and opposite charges
  - identical masses
  - identical lifetimes
- Mixed states (eg. K_S & K_L) can have Δm, $\Delta\Gamma \neq 0$

Time evolution

- Consider arbitrary mixture: a|K^0> + b|$\underline{K}^0$> governed by time-dependent Schrodinger eqn.

$$i\frac{\partial}{\partial t}\begin{pmatrix} a \\ b \end{pmatrix} = H\begin{pmatrix} a \\ b \end{pmatrix} = \left(M - \frac{i}{2}\Gamma\right)\begin{pmatrix} a \\ b \end{pmatrix}$$

- H is Hamiltonian; M and Γ are 2x2 Hermitian matrices
- CPT theorem: $M_{11} = M_{22}$ & $\Gamma_{11} = \Gamma_{22}$

Time evolution

- Physical states : eigenstates of effective Hamiltonian

$$|K_{S,L}> = p|K^0> \pm q|\underline{K}^0>$$

- Eigenvalues

$$\lambda_{S,L} = m_{S,L} - \tfrac{1}{2}i\Gamma_{S,L} = (M_{11} - \tfrac{1}{2}i\Gamma_{11}) \pm (q/p)(M_{12} - \tfrac{1}{2}i\Gamma_{12})$$

$$\Delta m = m_L - m_S \qquad \Delta\Gamma = \Gamma_S - \Gamma_L$$

$$(\Delta m)^2 - \tfrac{1}{4}(\Delta\Gamma)^2 = 4(|M_{12}|^2 + \tfrac{1}{4}|\Gamma_{12}|^2)$$

$$\Delta m\Delta\Gamma = 4\mathrm{Re}(M_{12}\Gamma_{12}^*)$$

$$q/p = -(\Delta m - \tfrac{1}{2}i\Delta\Gamma)/2(M_{12} - \tfrac{1}{2}i\Gamma_{12})$$

$$= -2(M_{12}^* - \tfrac{1}{2}i\Gamma_{12}^*)/(M_{12} - \tfrac{1}{2}i\Gamma_{12})$$

What do we expect?

- mixing occurs via box diagrams
- SM predictions for
  - neutral kaon system
  - neutral D meson system
  - B_d^0 system
  - B_s^0 system

What do we observe?

TG, arXiv:1306.4588

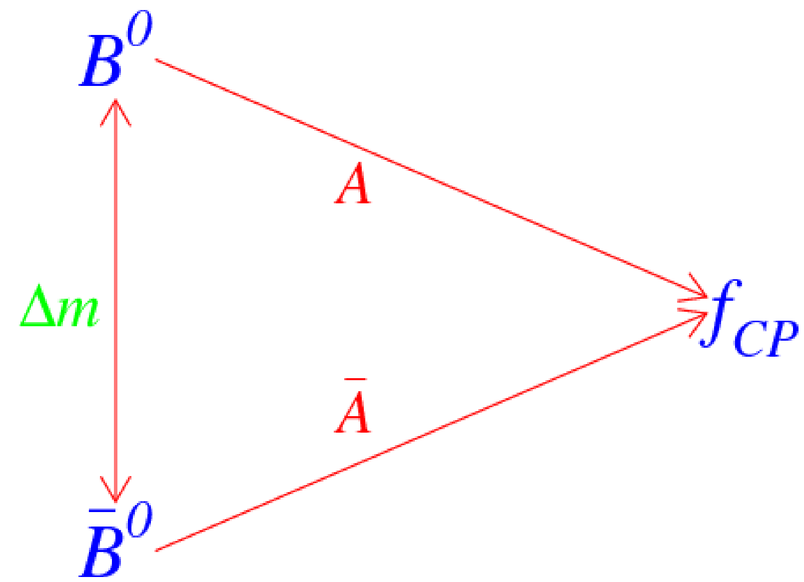
	Δm ($x = \Delta m/\Gamma$)	$\Delta\Gamma$ ($y = \Delta\Gamma/(2\Gamma)$))	$\lvert q/p\rvert$ ($a_{sl} \approx 1 - \lvert q/p\rvert^2$)
K^0	large	$\sim$ maximal	small
	~ 500	~ 1	$(3.32 \pm 0.06) \times 10^{-3}$
D^0	small	small	small
	$(0.63 \pm 0.19)\%$	$(0.75 \pm 0.12)\%$	$0.52^{+0.19}_{-0.24}$
B^0	medium	small	small
	0.770 ± 0.008	0.008 ± 0.009	-0.0003 ± 0.0021
B_s^0	large	medium	small
	26.49 ± 0.29	0.075 ± 0.010	-0.0109 ± 0.0040

significant recent progress (numbers already out-of-date)

some recent progress and more anticipated

Categories of CP violation

- Consider decay of neutral particle to a CP eigenstate



$$\lambda_{CP} = \frac{q}{p}\frac{\overline{A}}{A}$$

$$|\frac{q}{p}| \neq 1$$

CP violation in mixing

$$|\frac{\overline{A}}{A}| \neq 1$$

CP violation in decay (direct CPV)

$$\Im\left(\frac{q}{p}\frac{\overline{A}}{A}\right) \neq 0$$

CP violation in interference between mixing and decay

CP violation in mixing

- Observed first in K_L decays in 1964
  - $K_L \rightarrow \pi^+\pi^-$
  - $K_L \rightarrow \pi^0\pi^0$
  - $\delta_L(\mu) = (\Gamma(K_L \rightarrow \pi^-\mu^+\nu) - \Gamma(K_L \rightarrow \pi^+\mu^-\nu))/SUM$
  - $\delta_L(e) = (\Gamma(K_L \rightarrow \pi^-e^+\nu) - \Gamma(K_L \rightarrow \pi^+e^-\nu))/SUM$
- Due to CPT theorem, CP violation = T violation
- Is it possible to observe T violation directly?

CPLEAR experiment

$$A_T = \frac{P\left(\overline{K^0} \to K^0\right) - P\left(K^0 \to \overline{K^0}\right)}{P\left(\overline{K^0} \to K^0\right) + P\left(K^0 \to \overline{K^0}\right)}$$

- Tag strangeness of initial kaon using charge of associated kaon from production

$$p\underline{p} \to K^+\underline{K}^0\pi^- \;/\; K^-K^0\pi^+$$

- Tag strangeness of neutral kaon from charge of lepton in semileptonic decay ($\Delta S = \Delta Q$ rule)

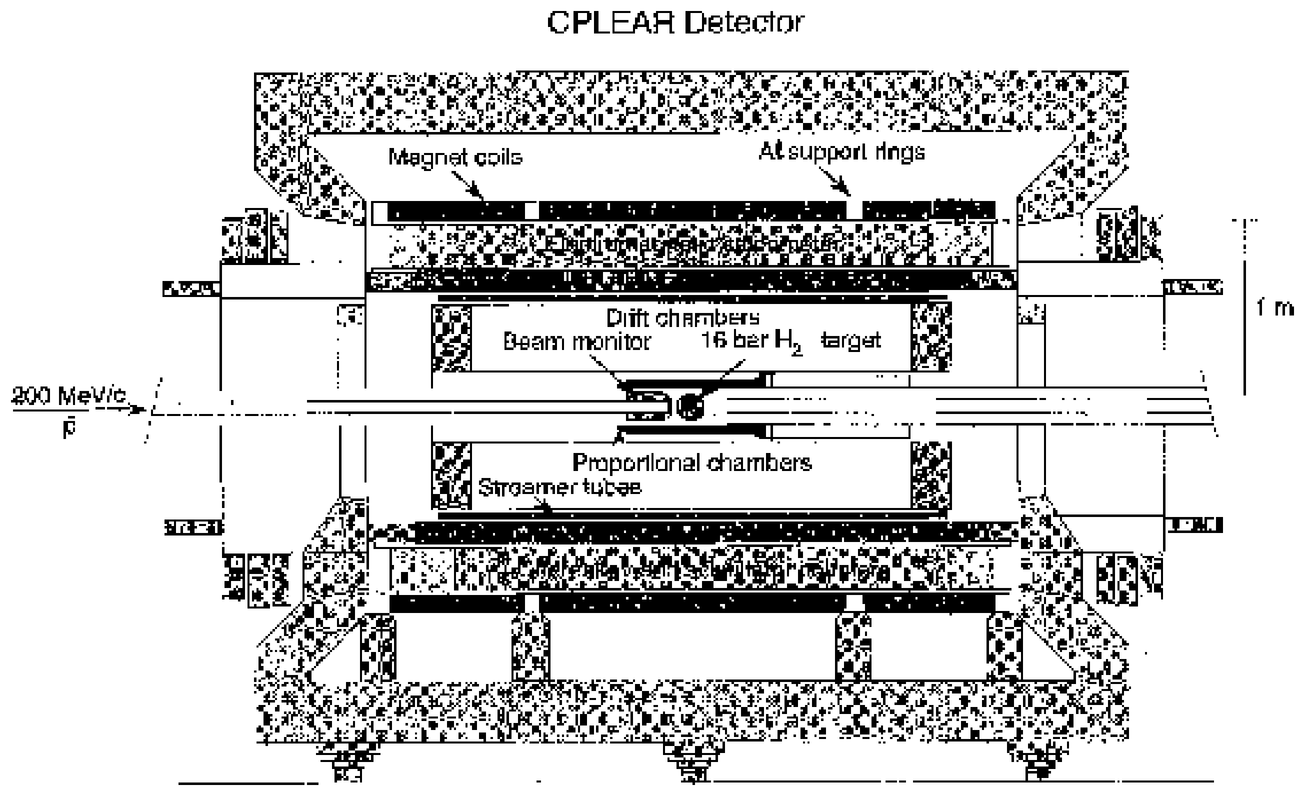


Fig. 1. The general layout of the CPLEAR experiment.

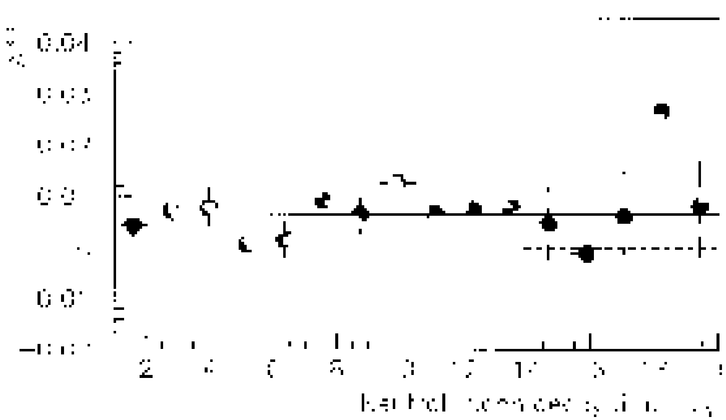
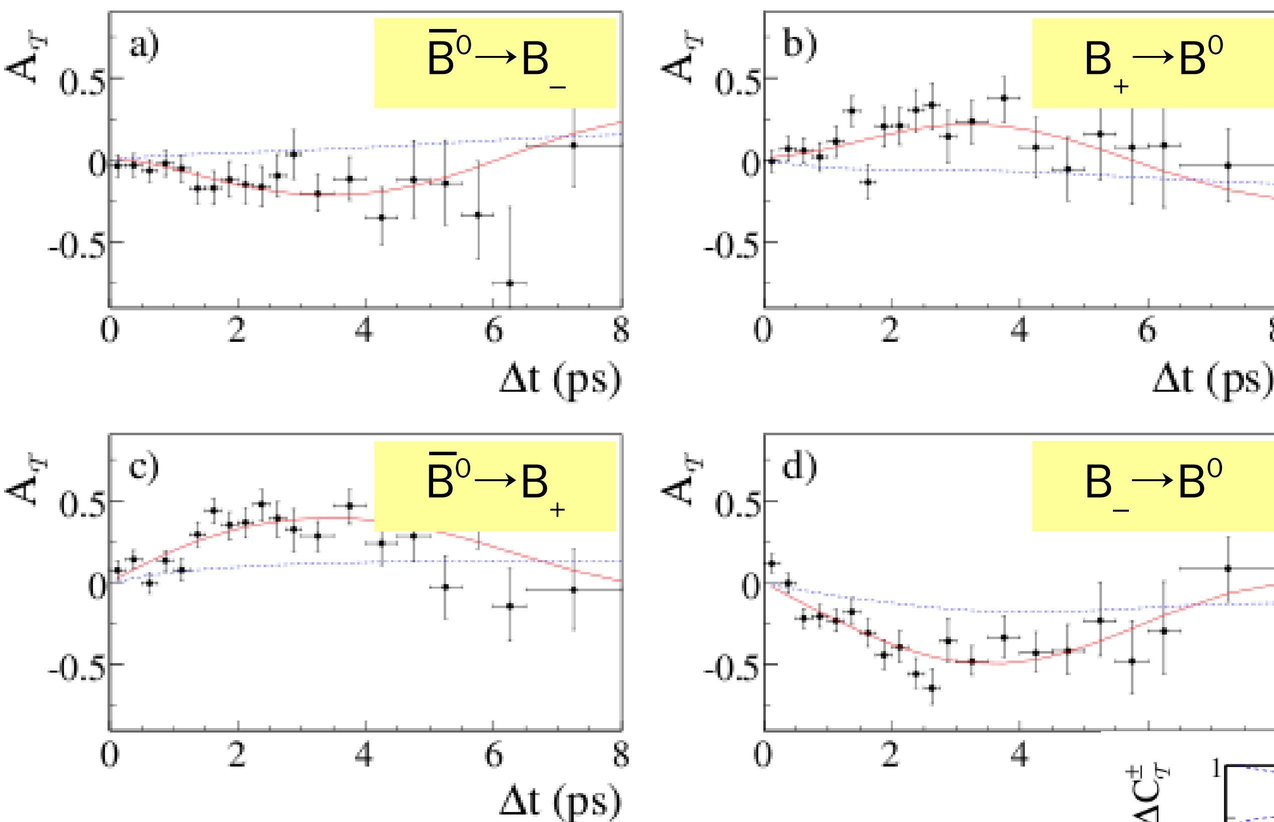


Fig. 1. The asymmetry A_T^{exp} versus the neutral-kaon decay time (in units of τ_S). The solid line represents the fitted average $\langle A_T^{exp} \rangle$.

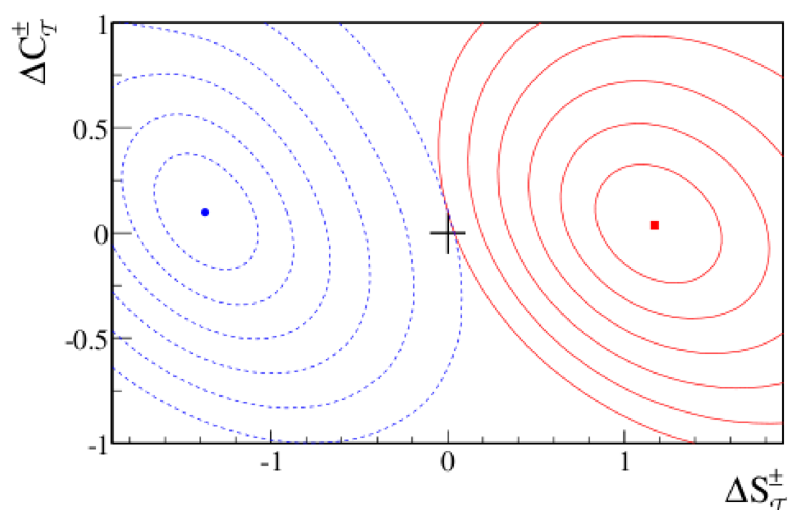
T violation in the B system



BaBar
PRL 109 (2012) 211801

Generalisation of usual sin(2β) analysis allowing for separate CP, T and CPT violating terms

No significant sign of CPT violation in any test



e.g. $A_T(\overline{B}^0 \to B_-)$ between (l^- tag, $J/\psi K_S$, $\Delta t>0$)

and (l^+ tag, $J/\psi K_L$, $\Delta t<0$)

$\sim \frac{1}{2}(\Delta S_T^+ \sin(\Delta m_d \Delta t) + \Delta C_T^+ \cos(\Delta m_d \Delta t))$

Comment on T violation

- We can never run experiments backwards in time, so we never really compare a process with its T conjugate
- Nonetheless, certain observables are sensitive to T violation
  - electric dipole moments
  - transverse polarizations in semileptonic decay
  - triple product correlations in $P \rightarrow VV$ decays
- CPT conservation : T violation = CP violation

Direct CP violation in neutral kaons

- Superweak models (Wolfenstein, 1964) predict CP violation occurs only in mixing
- KM mechanism: CPV in decay also possible
  - eg. $A(K_2 \to \pi^+\pi^-) \neq 0$
- Experimental test:
  - if CPV in $K_L \to \pi^+\pi^-$ ≠ CPV in $K_L \to \pi^0\pi^0$ ↔ CPV cannot be in mixing only

  $R = (K_L \to \pi^0\pi^0)/(K_S \to \pi^0\pi^0)/(K_L \to \pi^+\pi^-)/(K_S \to \pi^+\pi^-)$

  $R = 1 - 6\,\mathrm{Re}(\epsilon'/\epsilon)$

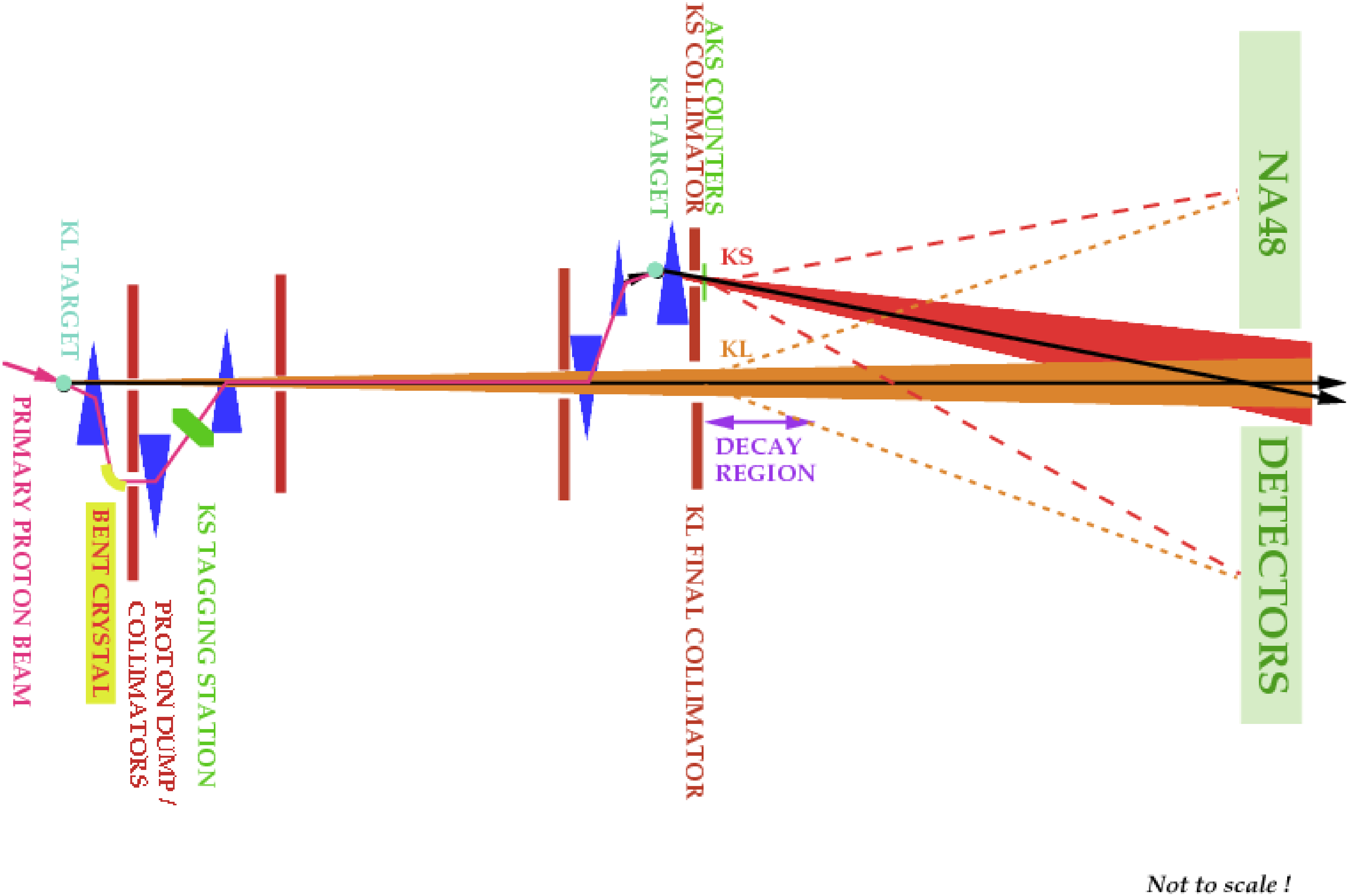
Measurement of Re(ϵ'/ϵ)

- Long running saga to establish Re(ϵ'/ϵ) $\neq 0$
  - NA31 (CERN) : $(23.0 \pm 6.5) \times 10^{-4}$
  - E731 (FNAL) : $(7.4 \pm 5.9) \times 10^{-4}$
- Next generation of experiments to confirm or refute the effect at level of 2×10^{-4}
  - NA48 (CERN) & KTeV (FNAL)
- Final results from NA48 in 2002, KTeV in 2008

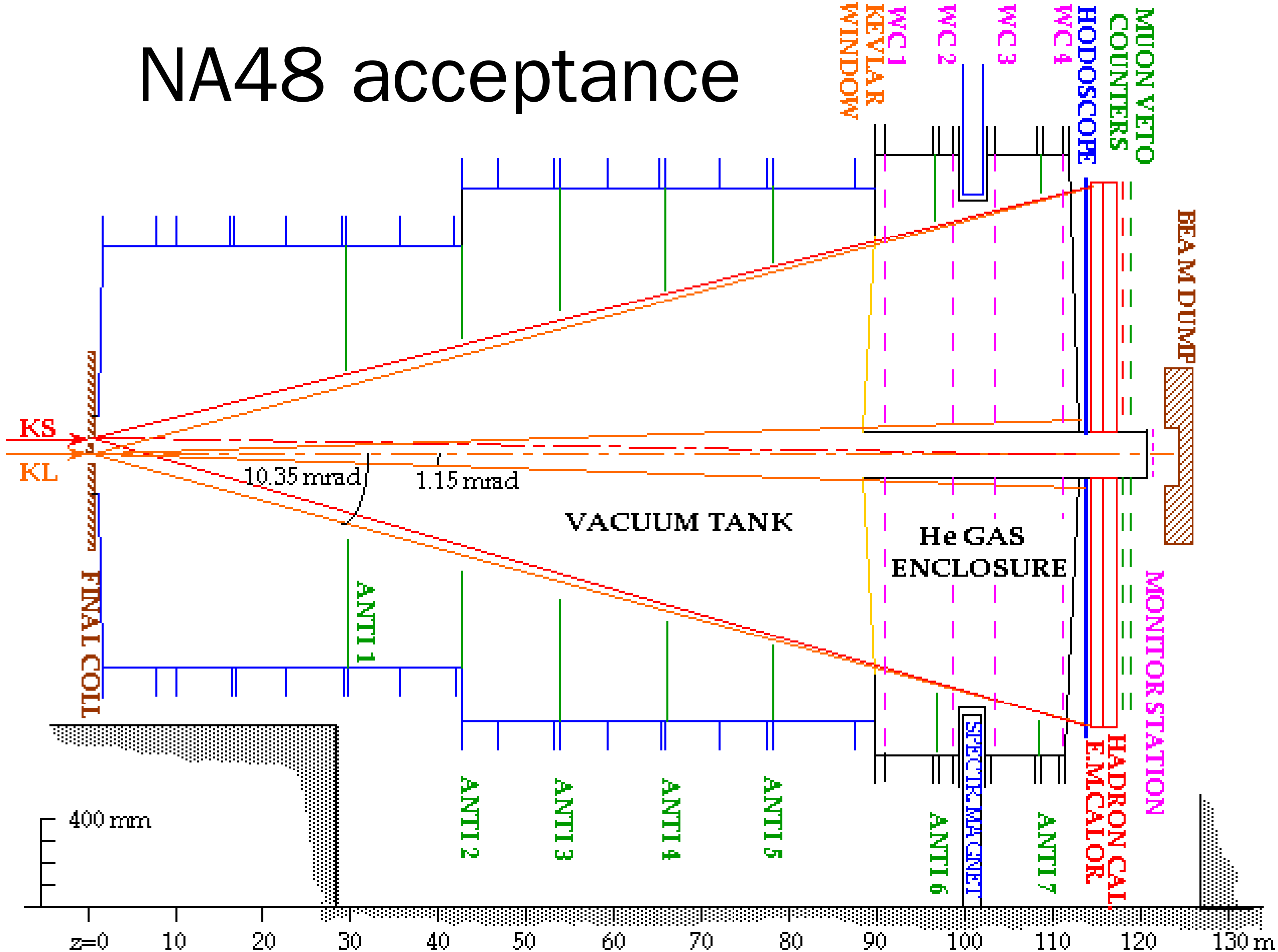
NA48 technique

- Precise measurement – need control of systematic errors
  - use simultaneous K_L and K_S beams
  - take data in all four modes together
  - make acceptance as similar as possible
  - perform analysis in bins on kaon energy
    - correct for differences in K_L and K_S energy spectra
  - weight K_L events according to K_S decay distribution

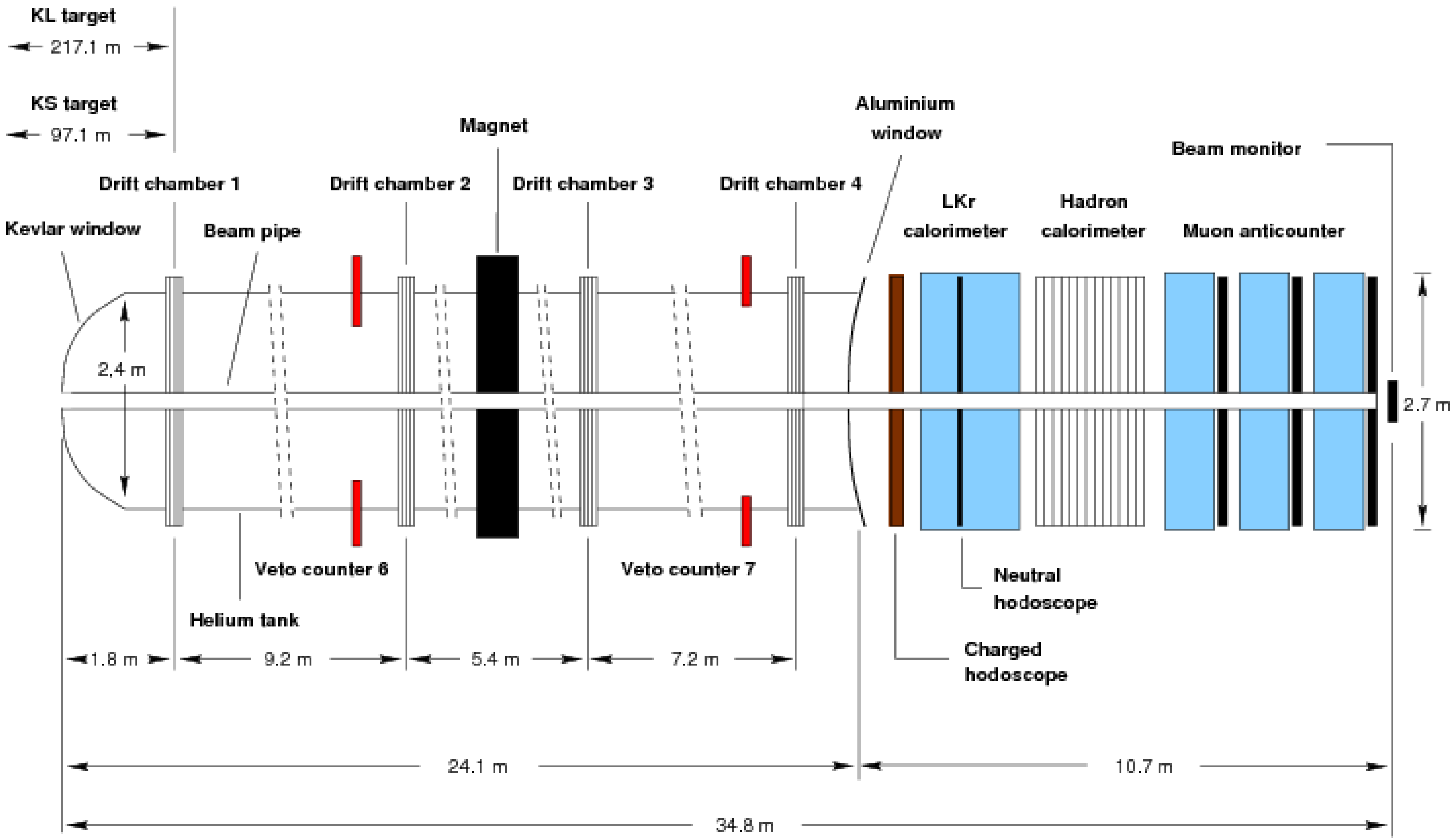
NA48 beams


KL TARGET
PRIMARY PROTON BEAM
BENT CRYSTAL
COLLIMATORS
PROTON DUMP /
KS TAGGING STATION
KS TARGET
KS COLLIMATOR
AKS COUNTERS
KS
KL
DECAY REGION
KL FINAL COLLIMATOR
NA48
DETECTORS
Not to scale !

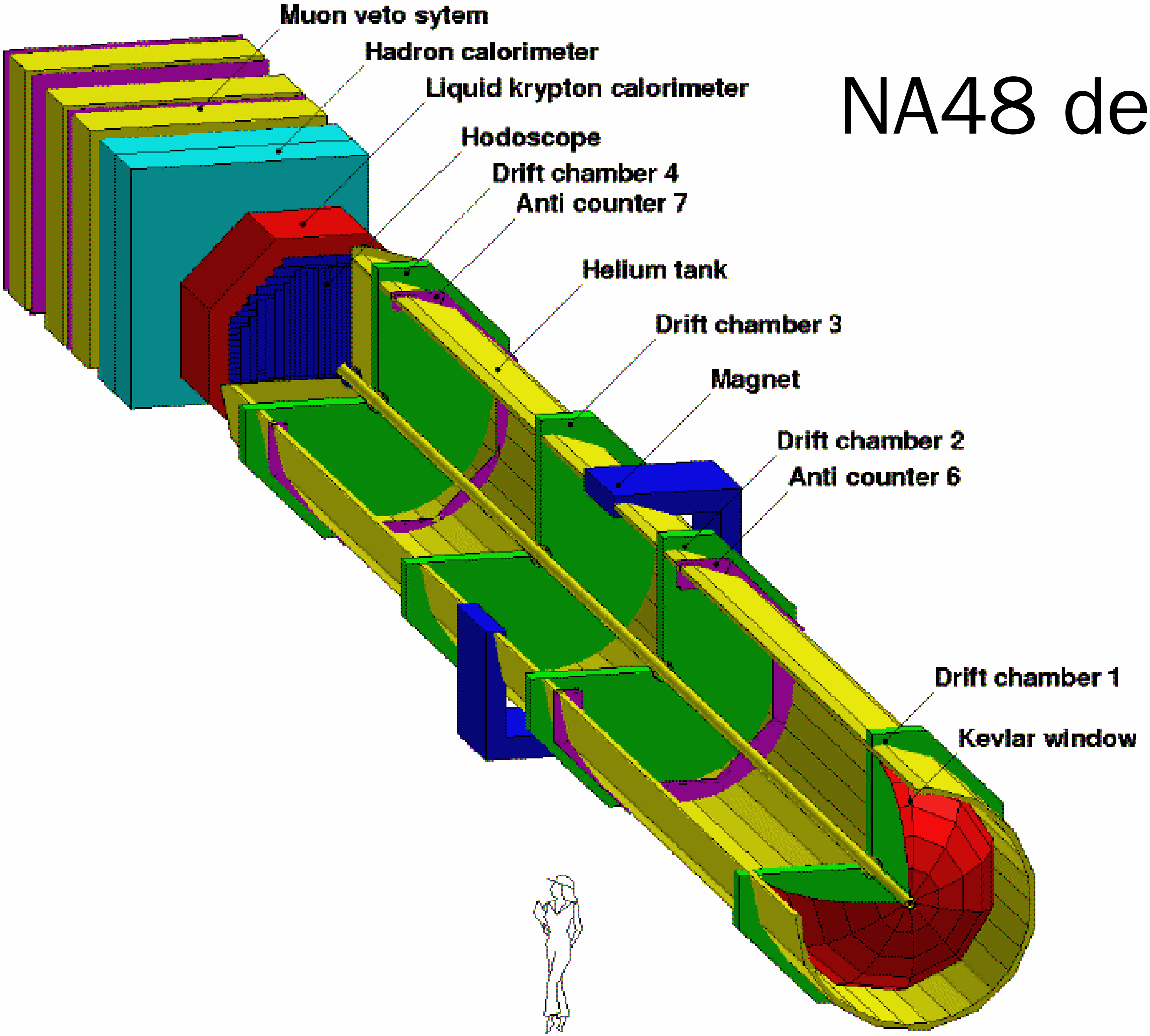
NA48 acceptance



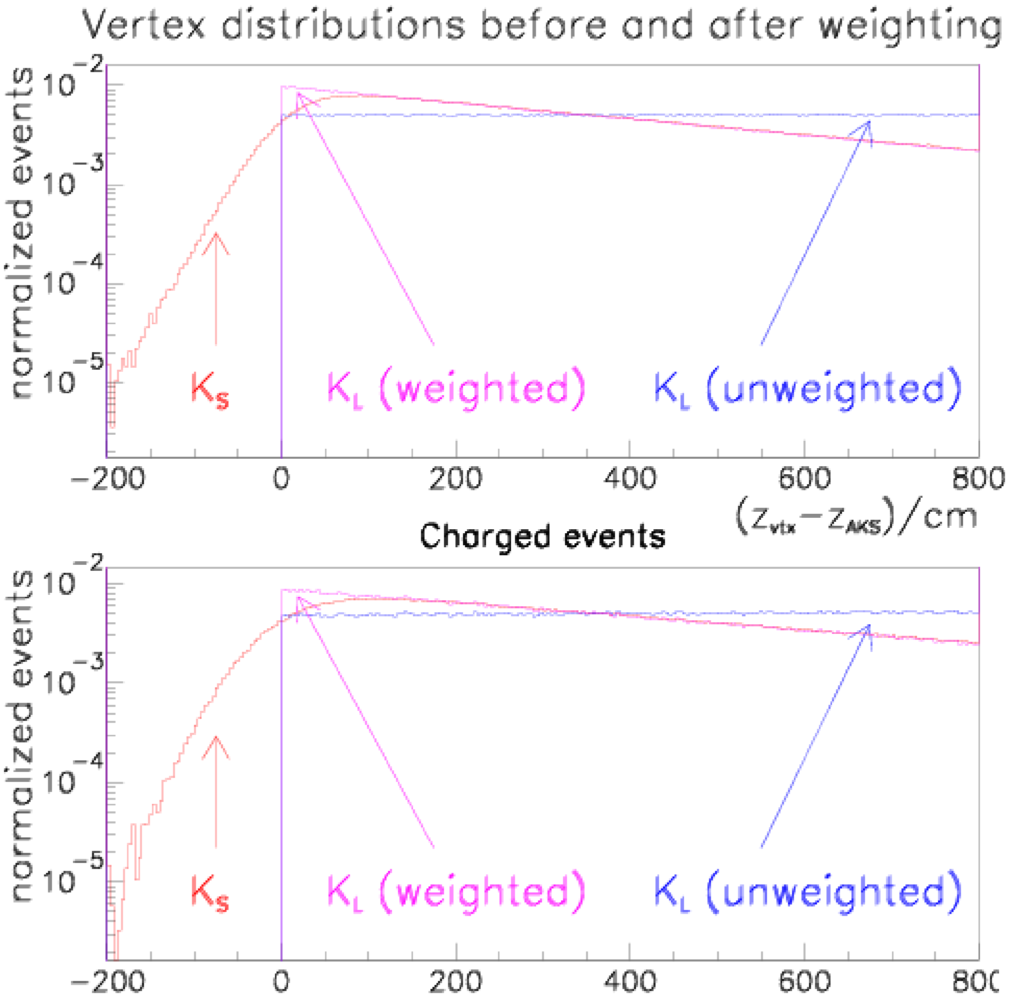
NA48 detector

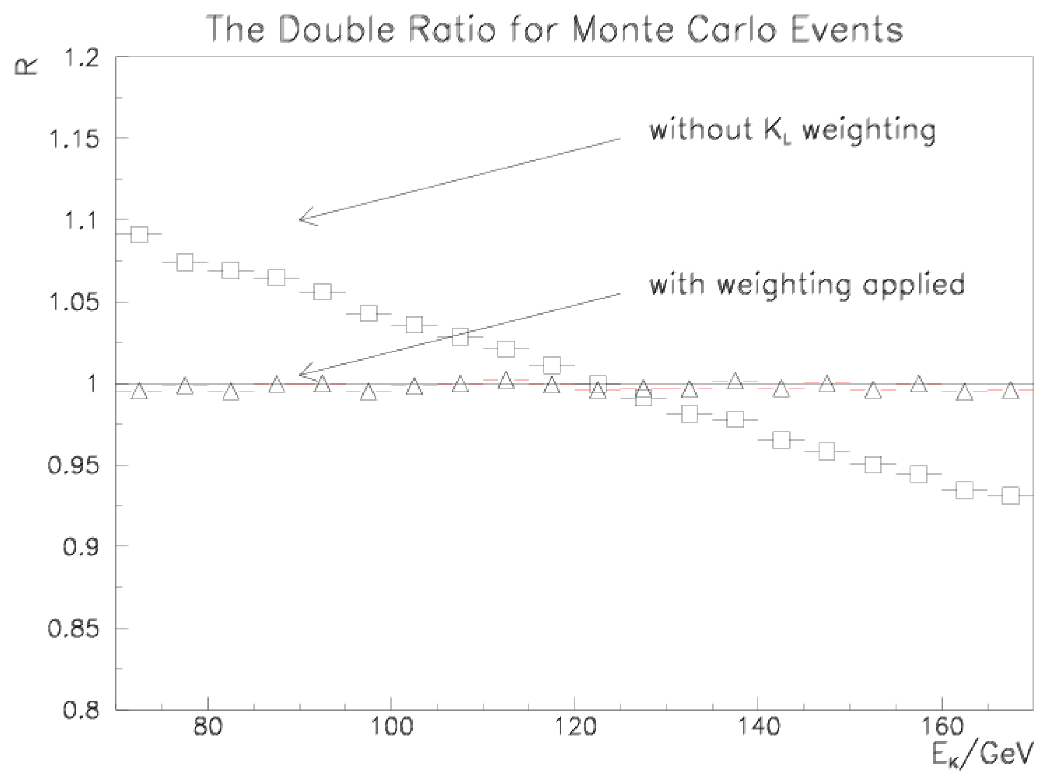


NA48 detector



NA48 – K_L weighting



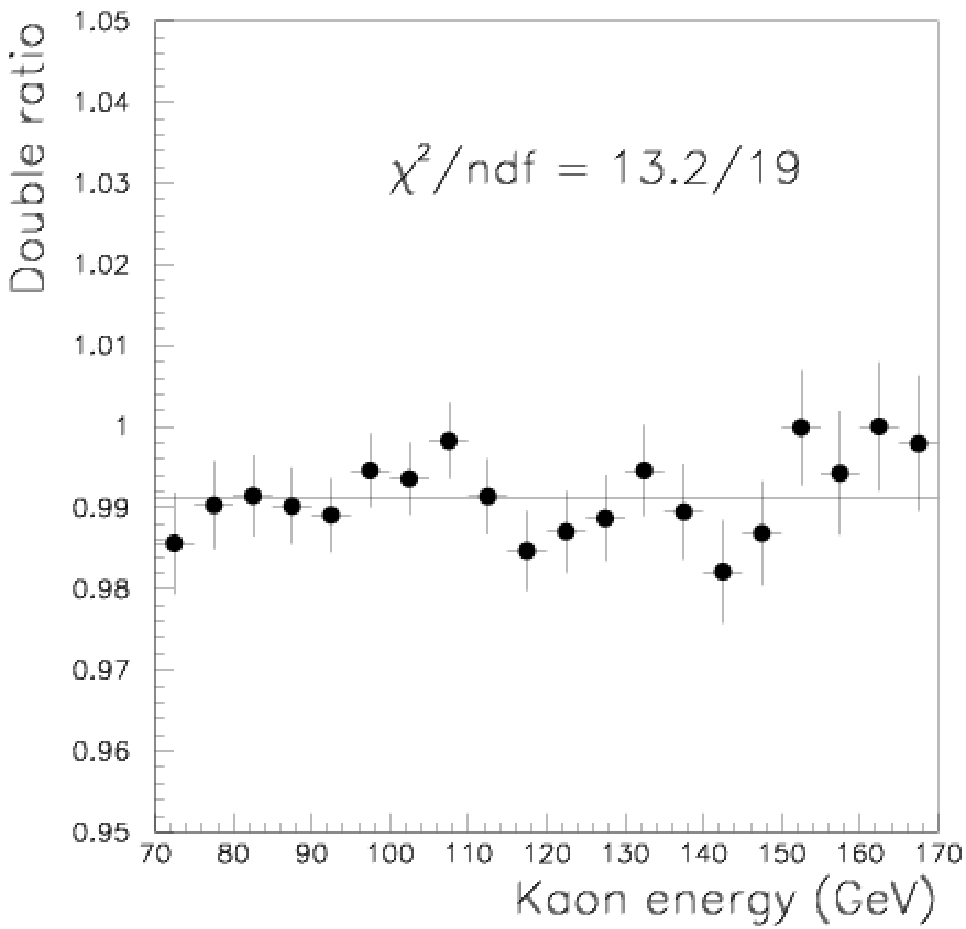


Increase in statistical error $\sim 40\%$

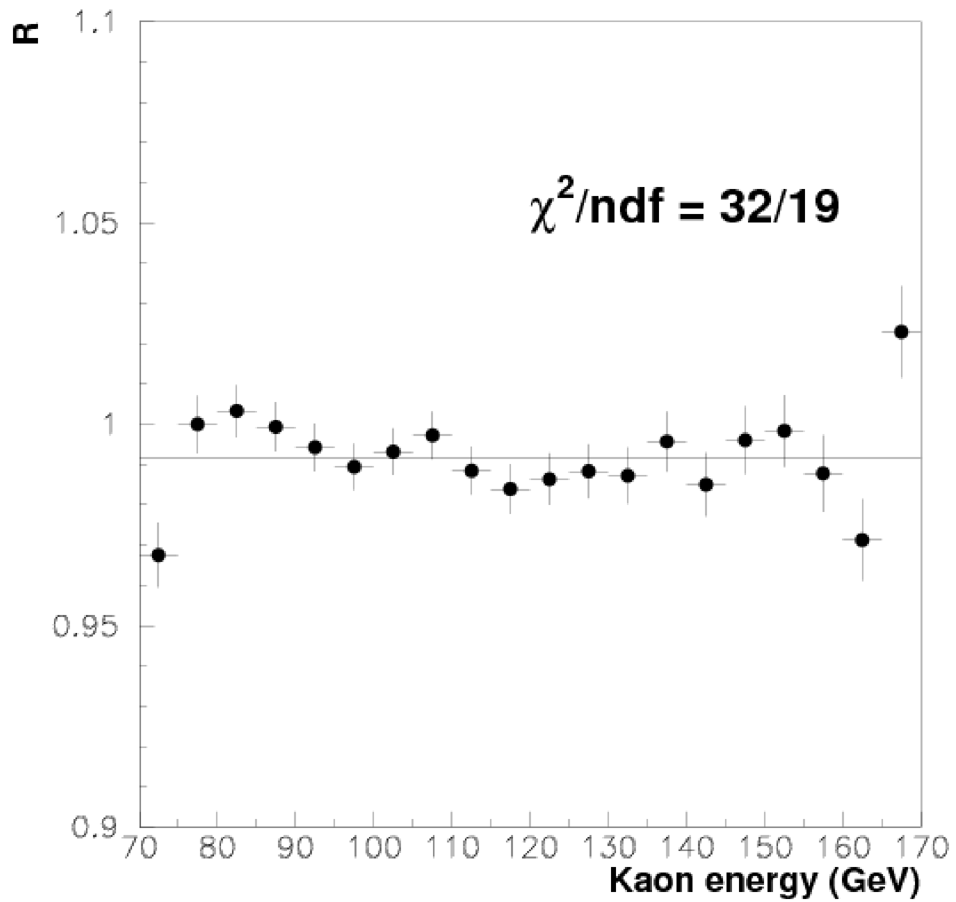
NA48 result

$$\mathrm{Re}(\epsilon'/\epsilon) = (14.7 \pm 2.2) \times 10^{-4}$$

1997-1999 data set



2001 data set



Re(ϵ'/ϵ) World Average