Some of the experimental origins of the Electroweak Theory

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MIT

August 18, 2006

"Experimental origin of EW theory."

Jackson, Treiman & Wilde (1)

Prelude: Feynman & Gell-Mann (1)

Pleasanton article (2)

Beginning: [illegible] (2)

Neutrino helicity

Revolution [illegible]: J/ψ SLAC (1)+(2)

BNL (2)

Elucidation: Neutral currents (1)

Gargamelle (1)

Prescotts (2)

Discovery: [illegible] W/Z (1)

UA1 (2)

Interlude: E287 (2)

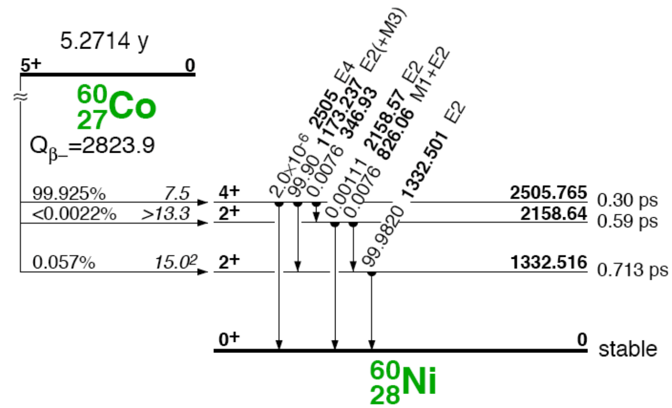
Precision: LEP I/Tevatron/SLD (2)

WuTeV (3)

Future: LEP II WW, Higgs (2) (24)

Prelude: Parity violation in β decay

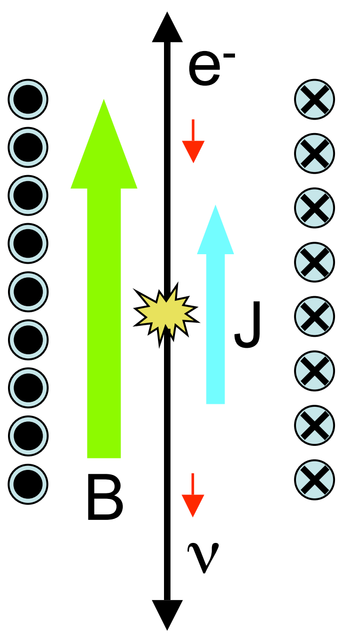
Observing PV requires the measurement of a pseudoscalar observable:



$$\langle A \rangle = \psi^* A \psi = a$$

$$\psi' = P\psi \text{ and } P^{-1}\mathrm{AP} = \text{-A}$$

$$\psi^{*\prime} A\psi = \psi^* P^{-1} A P \psi = -\psi^* A \psi = -a$$



Measure:

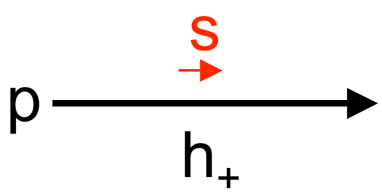
$$\langle A \rangle = \frac{\vec{J} \bullet \vec{p}}{|\vec{J}||\vec{p}|}$$

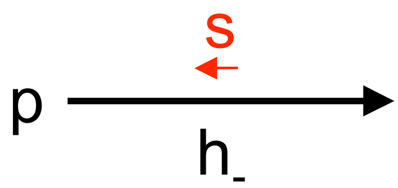
Wu & Ambler, 1956

Telegdi & Friedman

Garwin & Lederman

Helicity of the neutrino





Polarization: average projection of spin along momentum

$P=N(h_+)-N(h_-)/N$

In the weak interaction (beta decay), electrons are emitted with $P_{e-}=-v/c=-\beta$ (left handed), positrons have $P_{e+}=v/c=\beta$ (right handed). Measured by Koks & Van Klinken using Mott polarimetery.

What about neutrinos? Recently observed by Reines (1953), known to have low mass. Determination of their helicity a crucial first test of the model.

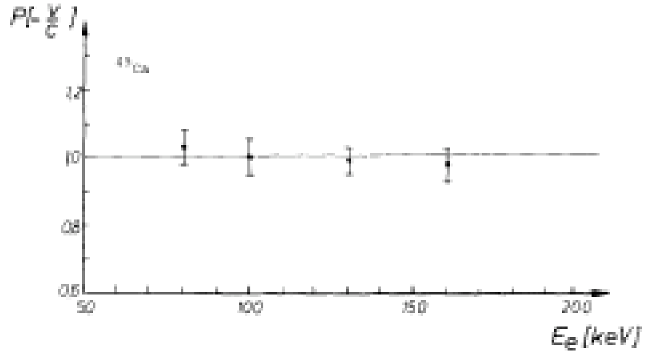


Fig. 3. Experimental results of polarization measurements for ^{45}Ca. Polarization P is given in units of $-v/c$

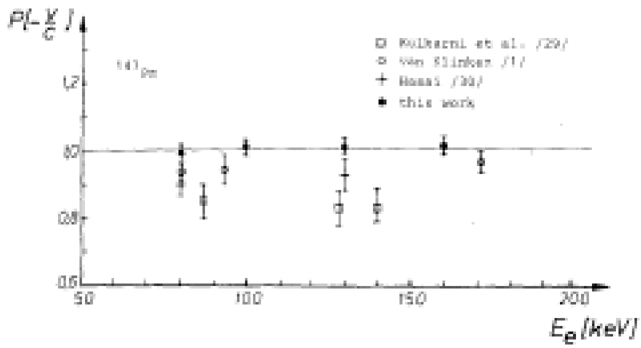


Fig. 4. Experimental results of polarization measurements for ^{147}Pm. Polarization P is given in units of $-v/c$. Also shown are the experimental results of other groups

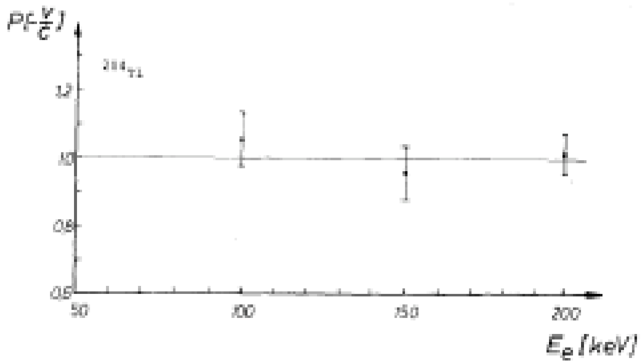


Fig. 5. Experimental results of polarization measurements of ^{204}Tl. Polarization P is given in units of $-v/c$

Koks & Van Klinken, 1976

Aside on discovery of the neutrino:

Detection of the Free Neutrino*

F. Reines and C. L. Cowan, Jr.
Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico
(Received July 9, 1953; revised manuscript received September 14, 1953)

An experiment[1] has been performed to detect the free neutrino. It appears probable that this aim has been accomplished although further confirmatory work is in progress. The cross section for the reaction employed,

$$\nu_- + p \rightarrow n + \beta^+, \tag{1}$$

has been calculated[2,3] from beta-decay theory to be given by the expression,

$$\sigma = \left(\frac{G^2}{2\pi}\right)\left(\frac{\hbar}{mc}\right)^2\left(\frac{p}{mc}\right)^2\left(\frac{1}{v/c}\right), \tag{2}$$

Difference due to the pile: 0.41 ± 0.20 delayed count/min.

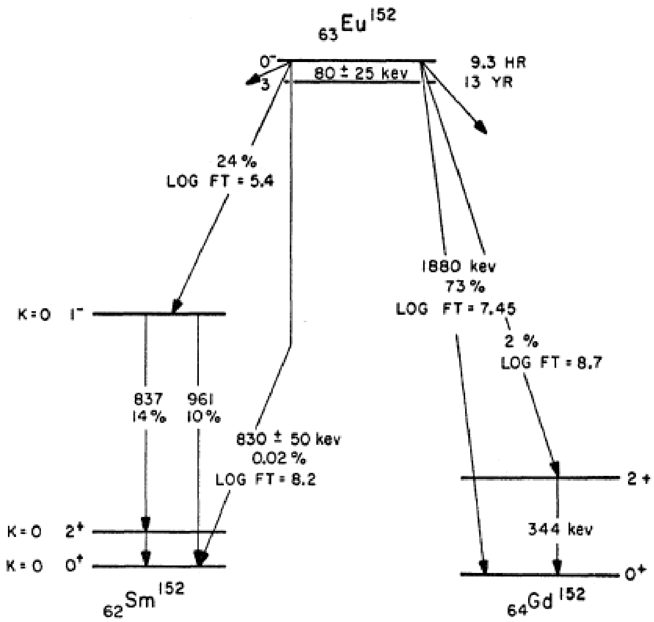
This difference is to be compared with the predicted $\sim\frac{1}{3}$ count/min due to neutrinos, using an effective cross section of $\sim 6\times10^{-20}$ barn for the process. It is to be remarked that a small channel

PHYSICAL REVIEW VOLUME 113, NUMBER 1 JANUARY 1, 1959

Free Antineutrino Absorption Cross Section. II. Expected Cross Section from Measurements of Fission Fragment Electron Spectrum*

R. E. Carter, F. Reines, J. J. Wagner, and M. E. Wyman†
Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico
(Received September 8, 1958)

A measurement of the electron spectrum from the thermal neutron fission of U^{235} is described. From this spectrum the antineutrino spectrum is calculated, and on the basis of the two-component theory of the antineutrino a predicted average cross section for the absorption of antineutrinos by protons is $(6.1\pm1)\times10^{-43}$ cm²/fission. This agrees with the measured cross section of $(6.7\pm1.5)\times10^{-43}$ cm²/fission. The four-component theory of the antineutrino would have predicted $(3.05\pm0.5)\times10^{-43}$ cm²/fission.



7% electron polarization in iron magnet, scatters *L* and *R* photons at different rates

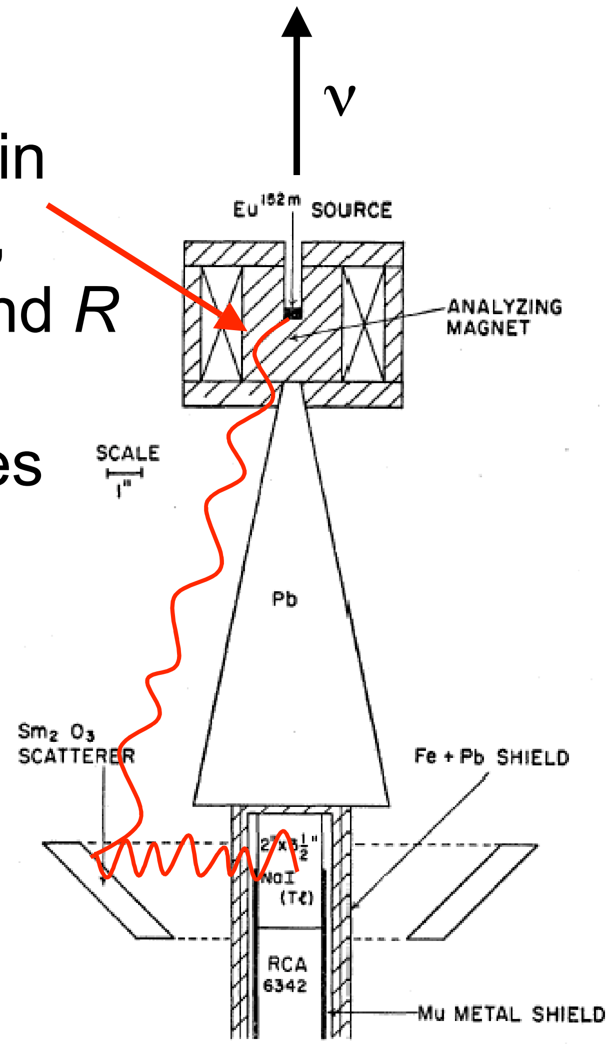
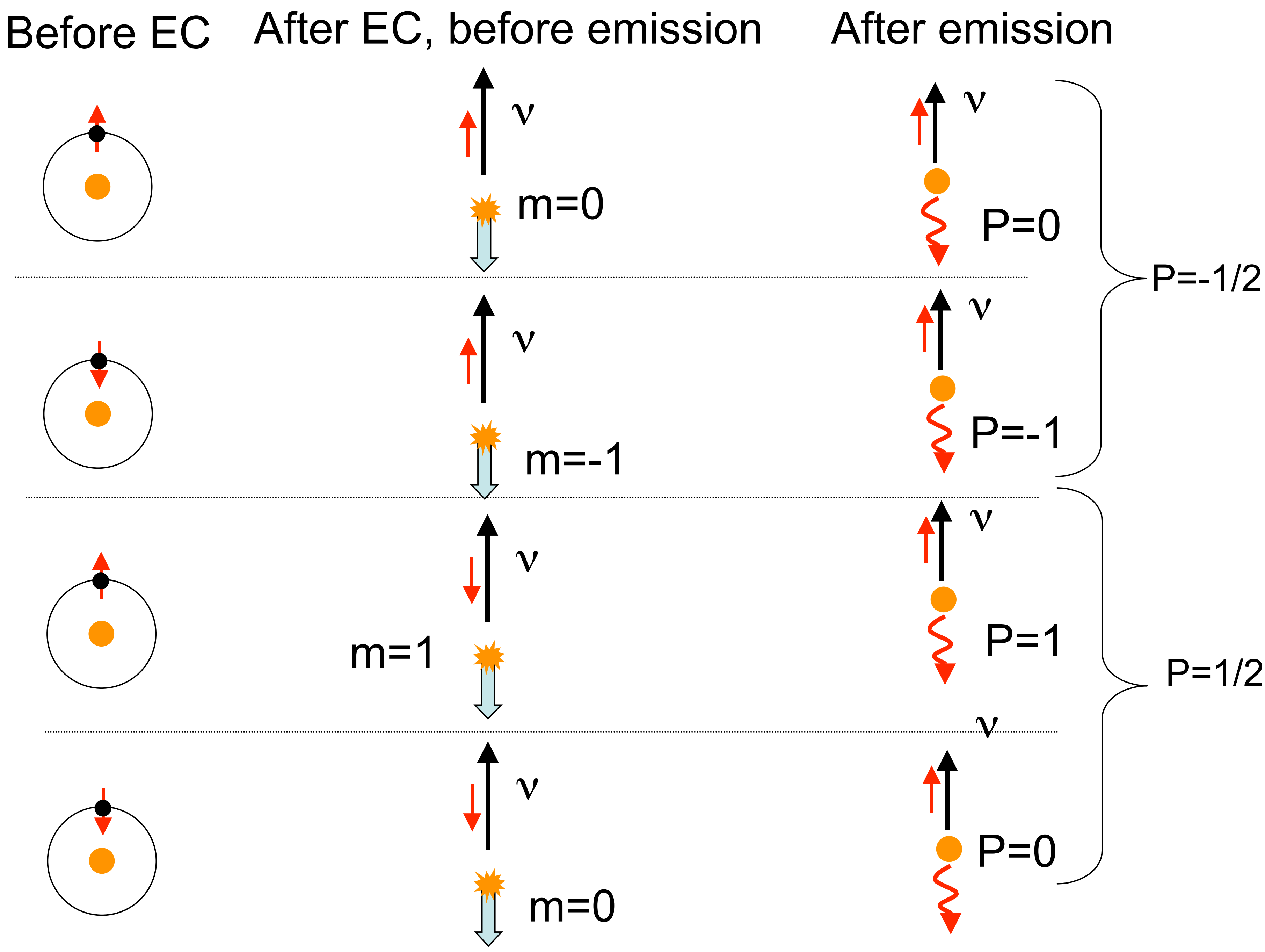


Fig. 1. Experimental arrangement for analyzing circular polarization of resonant scattered γ-rays. Weight of Sm_2O_3 scatterer: 1850 grams.

$$e^- + {}^{152}Eu \rightarrow {}^{152}Sm^* + \nu$$
$$\hookrightarrow {}^{152}Sm + \gamma$$

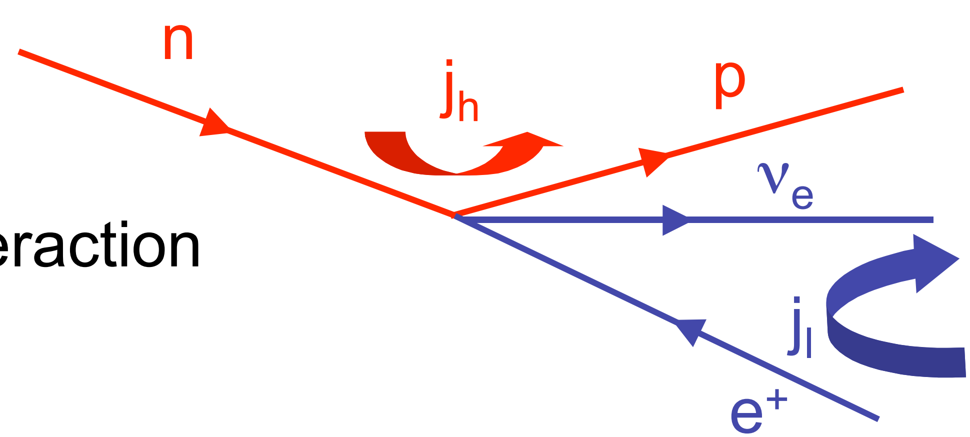
$^{152}Sm^*$ recoils after emission of neutrino, use resonant scattering to select decays in which the neutrino goes up.

Neutrino is left handed, supports V-A.



Before EC
After EC, before emission
After emission
ν
m=0
P=0
ν
m=-1
P=-1
P=-1/2
ν
m=1
P=1
P=1/2
ν
m=0
P=0

Beginnings:



Fermi: current-current interaction

$$j_l(x) = \overline{\psi}_f(x) O \psi_i(x)$$

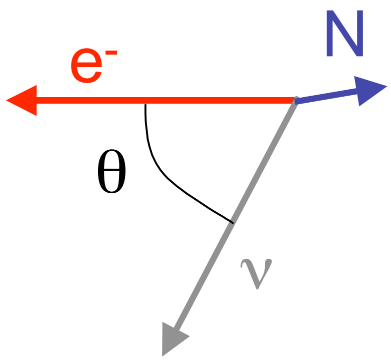
Jackson-Trieman-Wyld (1956): 5 x 2 x 2=20 parameters

$$\begin{aligned} H_{\text{int}} = & (\bar{\psi}_p\psi_n)(C_S\bar{\psi}_e\psi_\nu + C_S'\bar{\psi}_e\gamma_5\psi_\nu) \\ & + (\bar{\psi}_p\gamma_\mu\psi_n)(C_V\bar{\psi}_e\gamma_\mu\psi_\nu + C_V'\bar{\psi}_e\gamma_\mu\gamma_5\psi_\nu) \\ & + \tfrac{1}{2}(\bar{\psi}_p\sigma_{\lambda\mu}\psi_n)(C_T\bar{\psi}_e\sigma_{\lambda\mu}\psi_\nu + C_T'\bar{\psi}_e\sigma_{\lambda\mu}\gamma_5\psi_\nu) \\ & - (\bar{\psi}_p\gamma_\mu\gamma_5\psi_n)(C_A\bar{\psi}_e\gamma_\mu\gamma_5\psi_\nu + C_A'\bar{\psi}_e\gamma_\mu\psi_\nu) \\ & + (\bar{\psi}_p\gamma_5\psi_n)(C_P\bar{\psi}_e\gamma_5\psi_\nu + C_P'\bar{\psi}_e\psi_\nu) \qquad (1) \\ & + \text{Hermitian conjugate,} \end{aligned}$$

O=1	Scalar
γ^5	Pseudoscalar
γ^μ	Vector
$\gamma^\mu\gamma^5$	Axial vector
$\sigma_{\mu\nu}$	Tensor

Huge number of parameters and early confusion (S+T favored), but largely resolved in about five years (V-A). NB: SUSY only has a factor of five more parameters.

Establishing V-A (or T+S)



Best complementary observable to electron polarization is e-ν opening angle, but, need to know neutrino momentum and energy.

$$P(\mathbf{p},\mathbf{q})dW\,d\Omega = D_0 F(Z,W) L_0(Z,W) pWq^2 \times\left(1+\frac{\beta}{W}+\alpha\frac{p}{W}\cos\theta\right)dW\,d\Omega,$$

α=-1/3 for V-A

$$3\xi\alpha = |C_T|^2+|C_T'|^2-|C_A|^2-|C_A'|^2 \pm\frac{2e^2Zm}{\hbar cp}\,\mathrm{Im}\,(C_T C_A^* + C_T' C_A'^*),$$

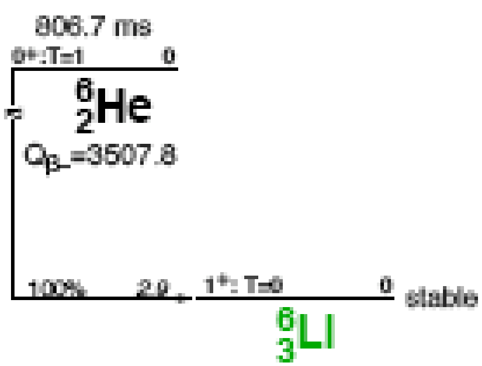
where

$$\xi = |C_T|^2+|C_T'|^2+|C_A|^2+|C_A'|^2.$$

It turns out cosθ is highly correlated with nucleus recoil (<1 keV) energy, so measuring the nuclear recoil spectrum is almost as good.

Johnson, Pleasonton and Carlson, PR 132(1149) 1963.

Use light nucleus (highest recoil energy) with magnetic and electrostatic analyzers, followed by accelerating voltage and electron multiplier to identify Li ion.



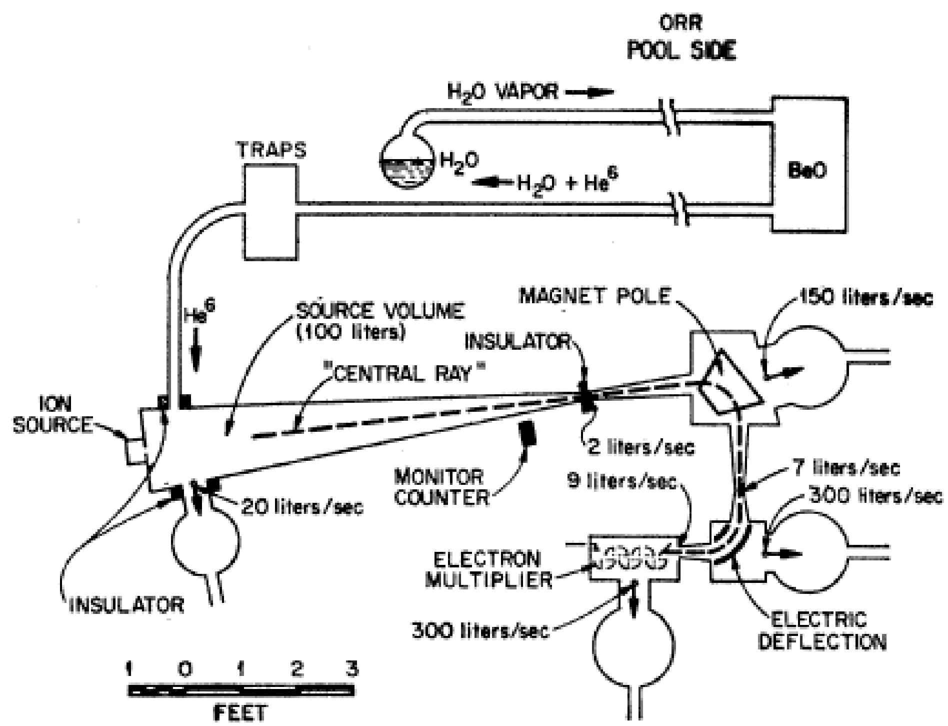


FIG. 2. Experimental apparatus. The He^6 produced in a reactor by the $Be^9(n,\alpha)He^6$ reaction is carried by a continuous stream of water vapor to the laboratory where the vapor is removed and the He^6 is left to decay in the conical source volume. A proportional counter monitors the source activity. Recoil Li^6 ions undergo magnetic and electrostatic analysis and are detected by a secondary electron multiplier. Three stages of differential pumping reduce the background of atoms which decay near the detector.

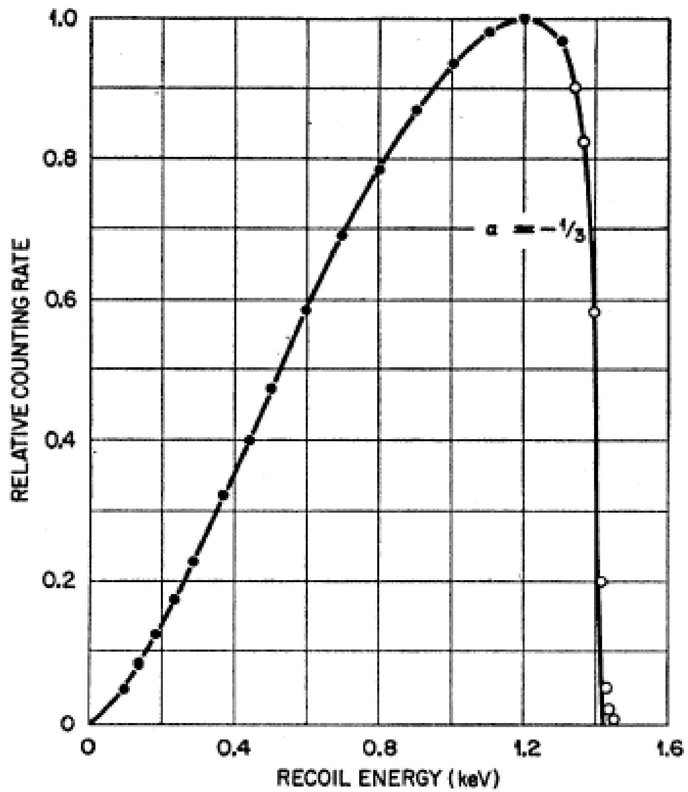
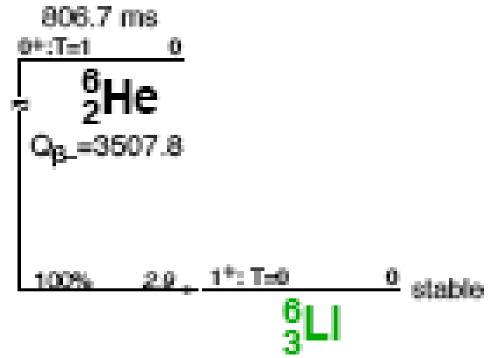
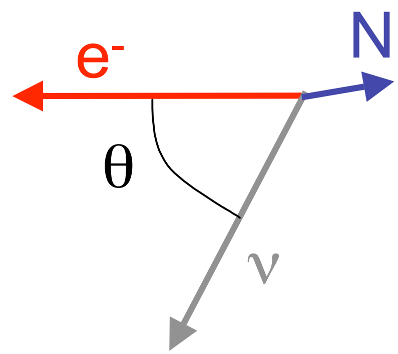


FIG. 6. Spectrum of singly charged Li^6 ions as a function of the average recoil energy of the ions transmitted by the analyzers. Ions were accelerated to about twice their recoil energy before analysis. Data indicated by solid dots are from four observations of the spectrum which form set No. 10 of data in Table I. Data indicated by open circles near the end point were obtained separately. The only significant correction that has been made is for background; other corrections in the analysis are not discernible on a linear plot. Uncertainties from counting statistics are less than the point sizes. The theoretical curve is plotted for $\alpha = -\frac{1}{3}$ with the normalization constant and the end-point W_0 chosen to give a good fit of theory to experiment.



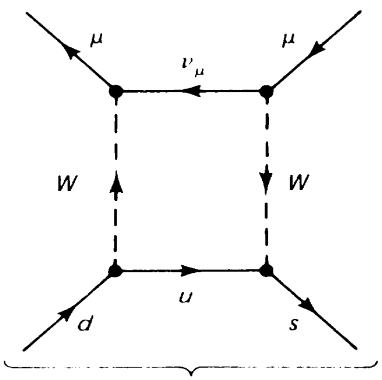


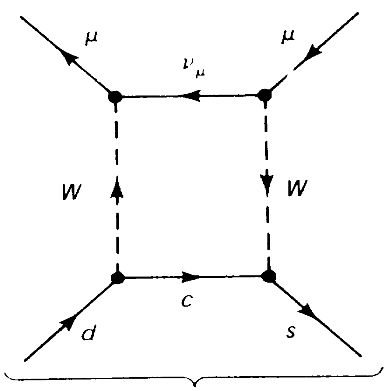
Recoil energy larger for smaller opening angle.

α=-0.3343±0.0030

Revolution: J/ψ

Early 1970's, accumulating evidence that something was not right: $K^o \rightarrow \mu^+\mu^-$ and "R crisis"





Calculation of this process alone gives a branching fraction of 0.1%, 6×10^{-9} measured.

GIM mechanism uses a fourth q=2/3 quark to largely cancel, giving low

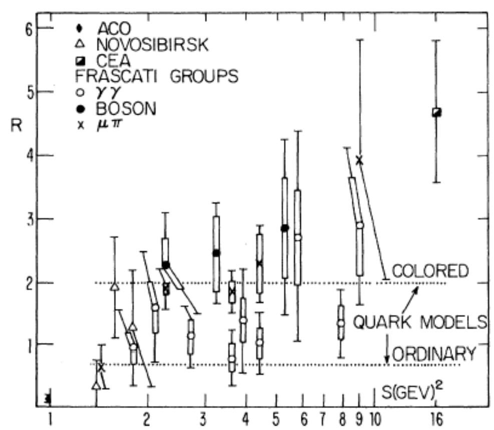
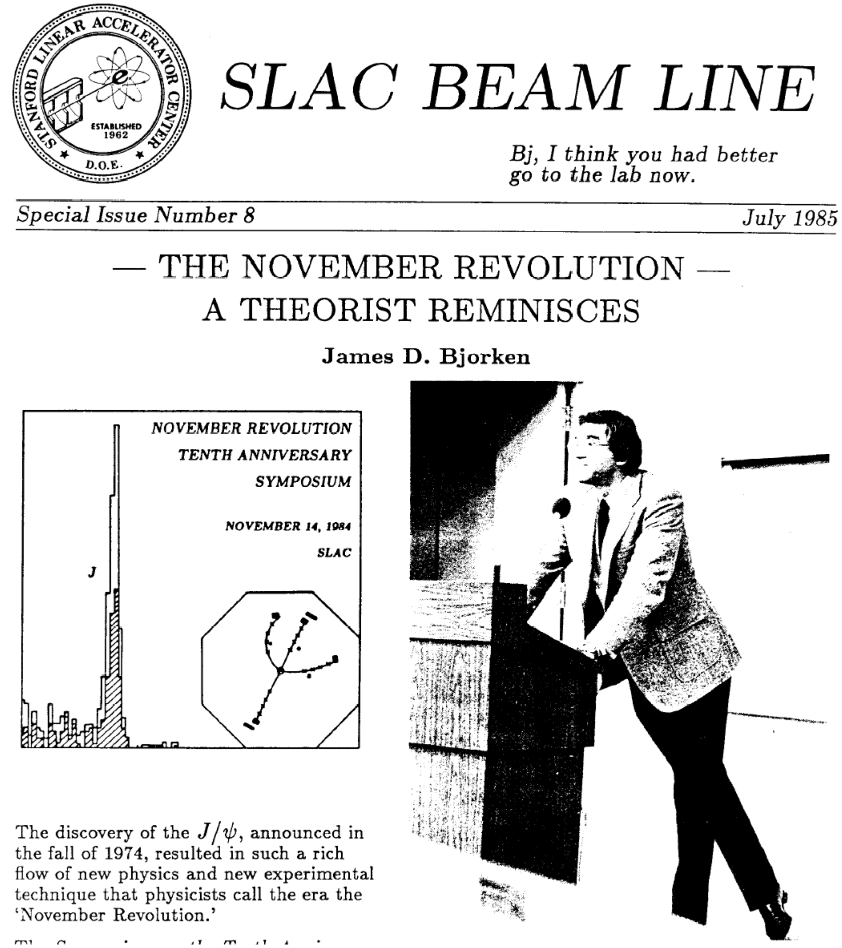


FIG. 2. $R=\sigma(e^+e^- \rightarrow$ multibody hadrons$)/\sigma(e^+e^- \rightarrow \mu^+\mu^-)$ versus the square of the center-of-mass energy s in GeV^2. The dotted lines give the asymptotic predictions of parton models assuming ordinary and colored quarks.

$$R = \frac{\sigma\left(e^+e^- \rightarrow hadrons\right)}{\sigma\left(e^+e^- \rightarrow \mu^+\mu^-\right)} = \sum q^2 \quad = \frac{2}{3} \text{ below charm threshold}$$

$$= 2 \text{ above charm threshold}$$

nuclear democracy
current algebra
Regge poles
bootstrap
dispersion theory
field algebra
field-current identities
vector dominance
chiral dynamics
Melosh transformation
$SU(6)_W$
$U(12)$
light cone current algebra
Mandelstam representation
Veneziano formula
Kallen-Lehmann representation
strings
flavor groups
LSZ
Wightman axioms


SLAC BEAM LINE

Bj, I think you had better go to the lab now.

Special Issue Number 8 — *July 1985*

— THE NOVEMBER REVOLUTION —
A THEORIST REMINISCES

James D. Bjorken

The discovery of the J/ψ, announced in the fall of 1974, resulted in such a rich flow of new physics and new experimental technique that physicists call the era the 'November Revolution.'

There was no "standard model" before the Standard Model.

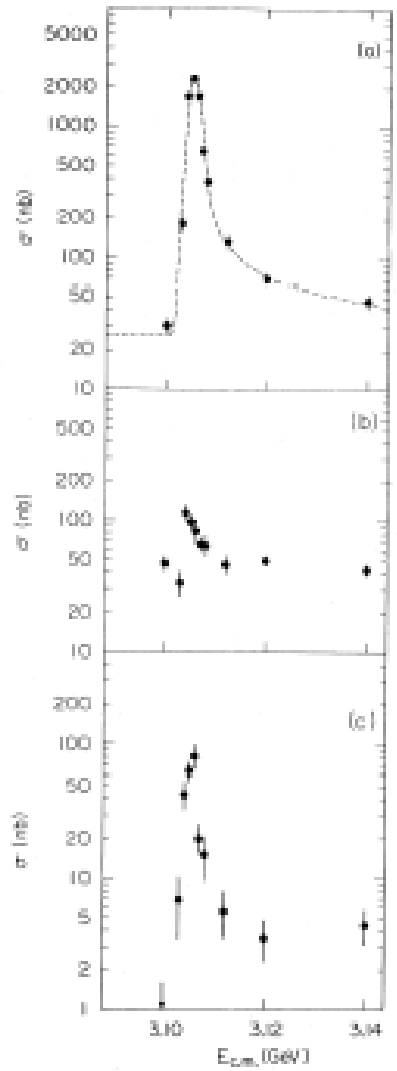
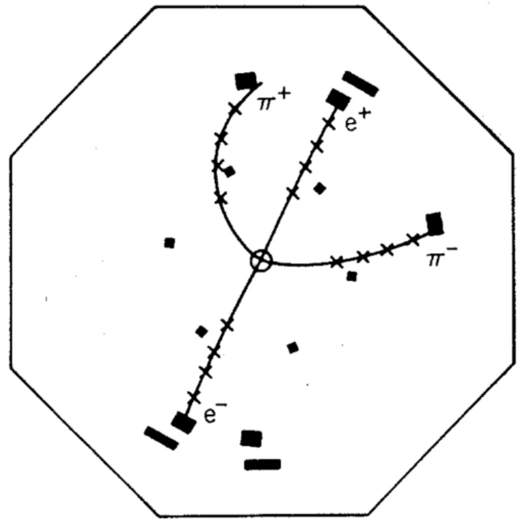


FIG. 1. Cross section versus energy for (a) multi-hadron final states, (b) e^+e^- final states, and (c) $\mu^+\mu^-$, $\pi^+\pi^-$, and K^+K^- final states. The curve in (a) is the expected shape of a δ-function resonance folded with the Gaussian energy spread of the beams and including radiative processes. 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.



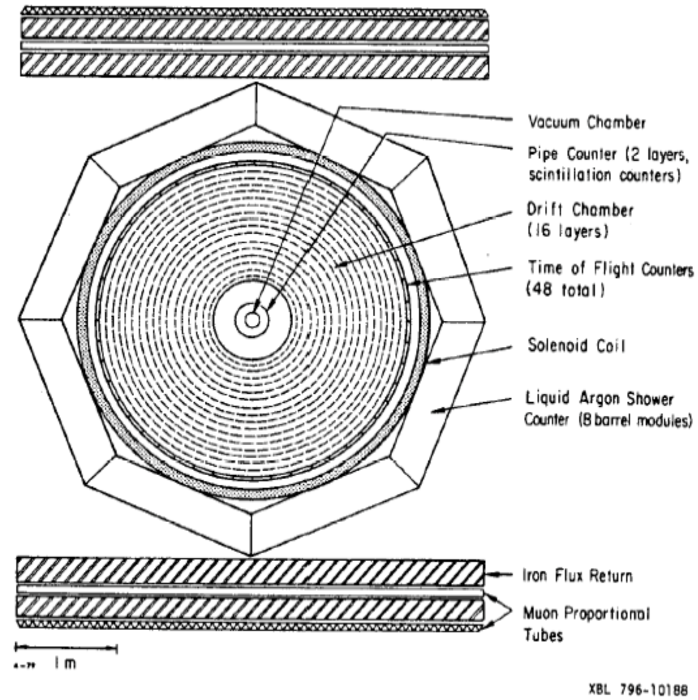


Figure 2

Sharp resonance at 3.1 GeV

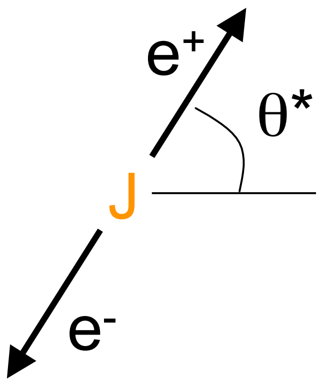
$$e^+e^- \rightarrow \psi \rightarrow \pi^+\pi^-e^+e^-$$

Mark Ia at SPEAR

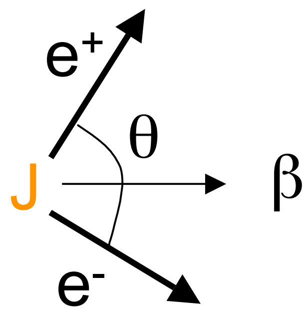
Brookhaven Experiment (Twin arm spectrometer)

$$p(26\ \text{GeV}) + Be \rightarrow J + X$$

$$J \rightarrow e^+e^- \qquad m^2 = E_1E_2(1-\cos\theta)$$



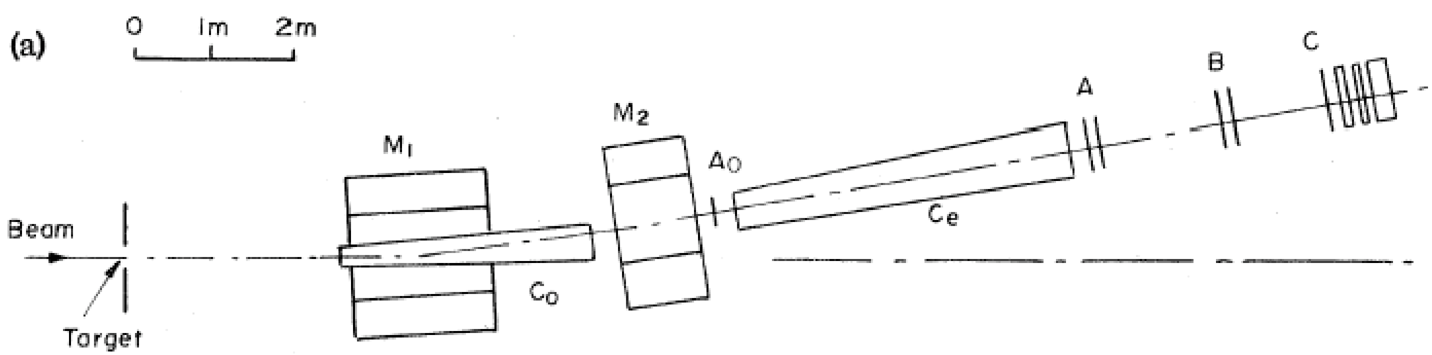
Rest frame



Lab frame

$$\cos\theta = \frac{\beta^2\gamma^2\sin^2\theta^* - 1}{\sin^4\theta^* + 4\beta\gamma^2\sin^2\theta^*\cos\theta^* - \gamma^4\left(\beta^2 - \cos^2\theta^*\right)^2}$$

$$-1 \qquad \text{as } \beta \rightarrow 1$$



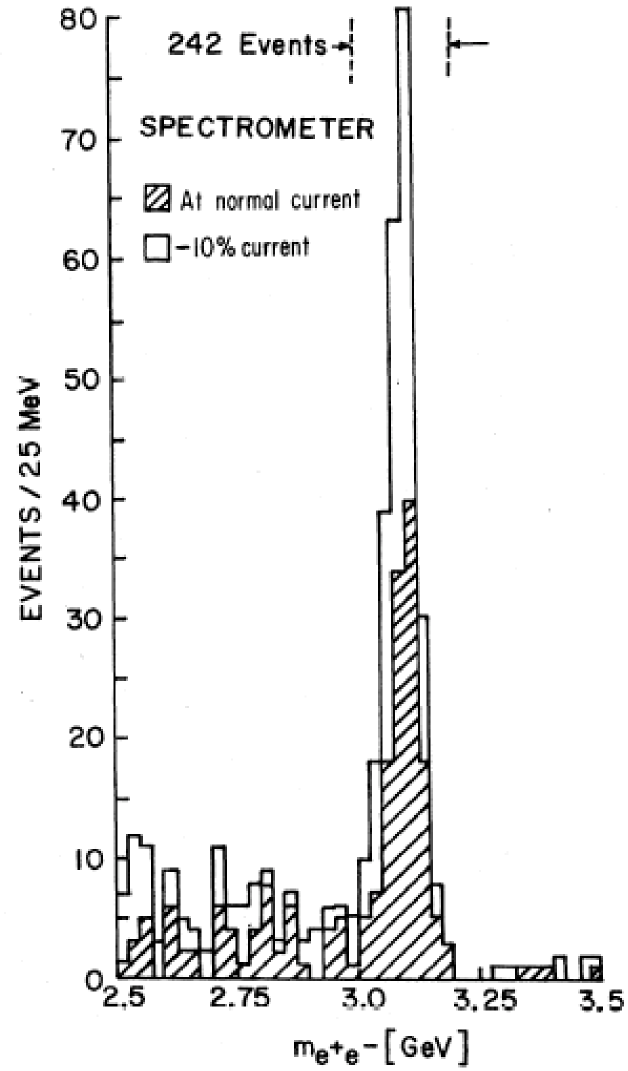


FIG. 2. Mass spectrum showing the existence of J. Results from two spectrometer settings are plotted showing that the peak is independent of spectrometer currents. The run at reduced current was taken two months later than the normal run.

Both Mark I and the BNL experiment observed J/ψ. Mark I went on to observe ψ',τ, etc. BNL, a twin arm spectrometer, was limited in acceptance that data collection at higher masses would have been problematic.

Elucidation: neutral currents

GIM solved K^o decay with a model containing 4 quarks, 2 charged and 2 neutral leptons and one charge gauge boson. But:

	W^-	$\sin^2\theta_W$		W^-	$g = e\sin\theta_W$
A^o	B^o	$\Rightarrow$	γ	Z^o	Neutral triplet has different
	W^+			W^+	couplings for L and R

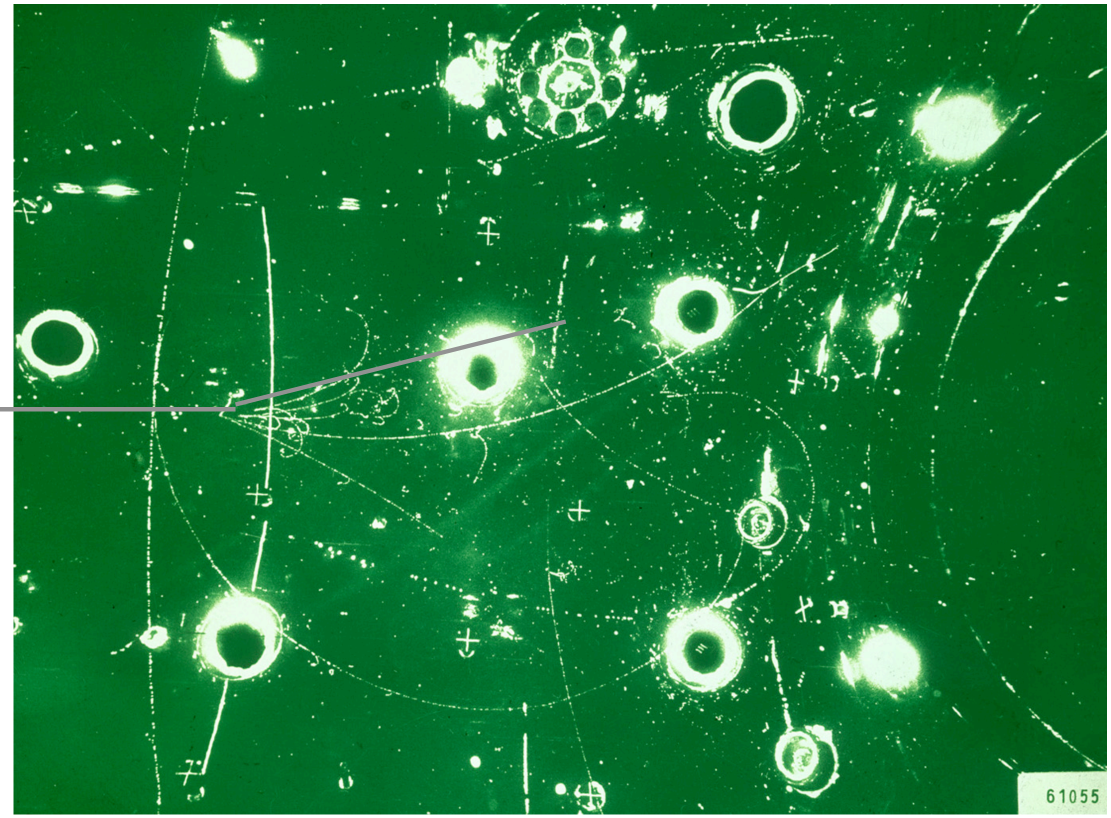
Are weak bosons a triplet? If so, neutral member makes reactions like

$$\nu + e^- \rightarrow \nu + e^-$$

$$\nu + N \rightarrow \nu + \text{hadrons}$$

possible. Also, these interactions would not conserve parity.

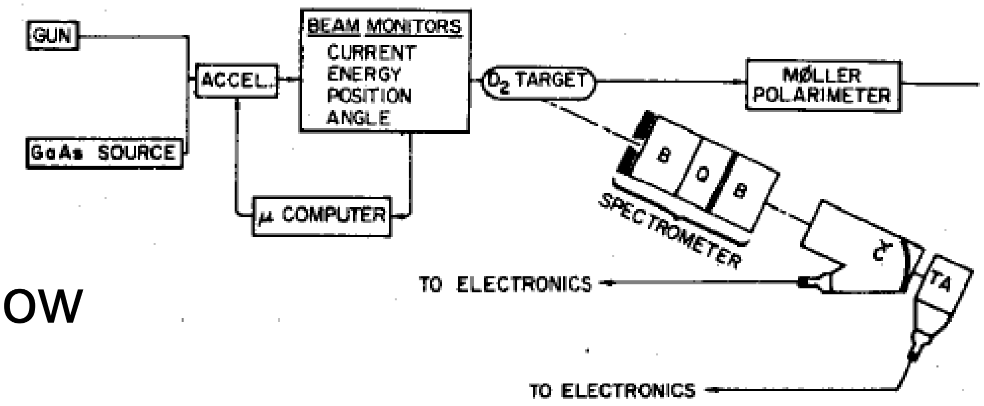
Gargamelle bubble chamber



50-100GeV ν

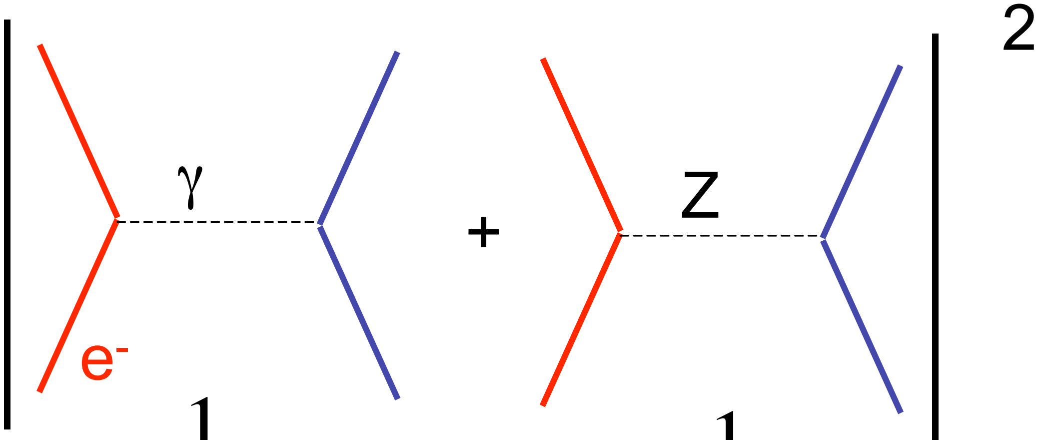
CERN WBB

SLAC Polarized electron scattering



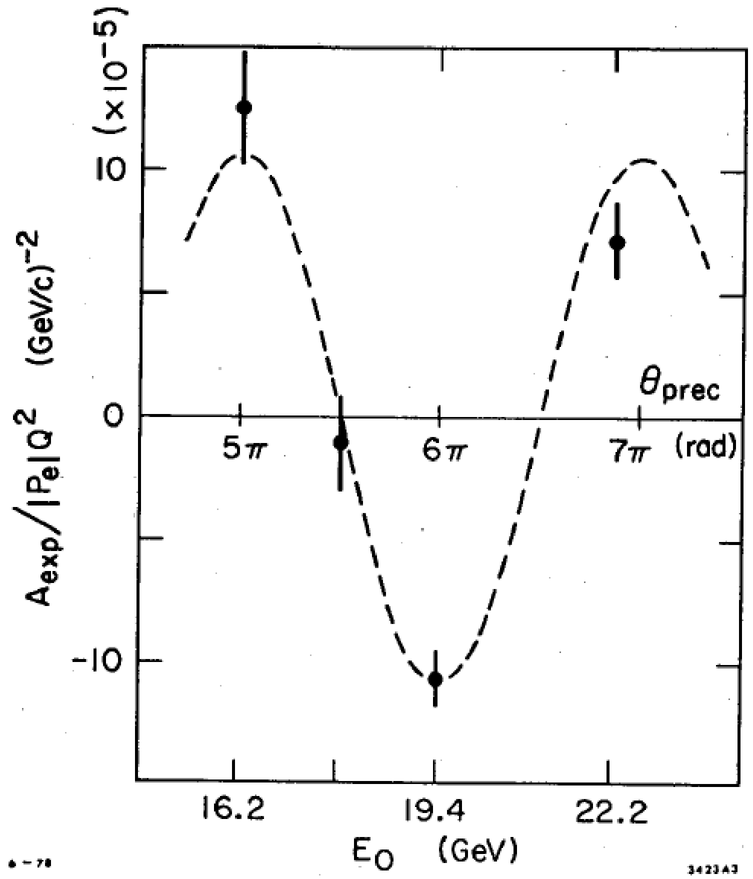
With e^-(pol)+D→e^-+X can show neutral currents interactions violate parity

$\sigma \propto$



$$\frac{1}{Q^2} \qquad \frac{1}{M^2}$$

$$\sigma(h) \propto \frac{A}{Q^4} + \frac{B(h)}{Q^2 M^2} + \frac{C(h)}{M^4}$$



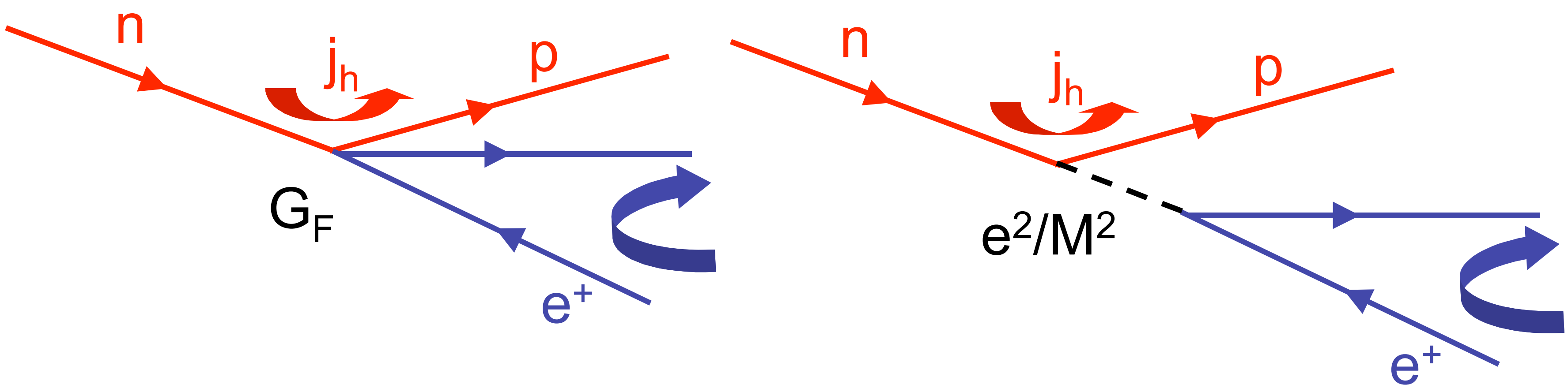
Leading *h* dependent term goes like $Q^2/M^2 \sim 10^{-5}$.

Measure

$$A = \frac{N(h+) - N(h-)}{N(h+) + N(h-)}$$

Polarization varies with E_{beam} (precession in magnetic beam transport). Decisive observation of expected parity violation in neutral current interactions.

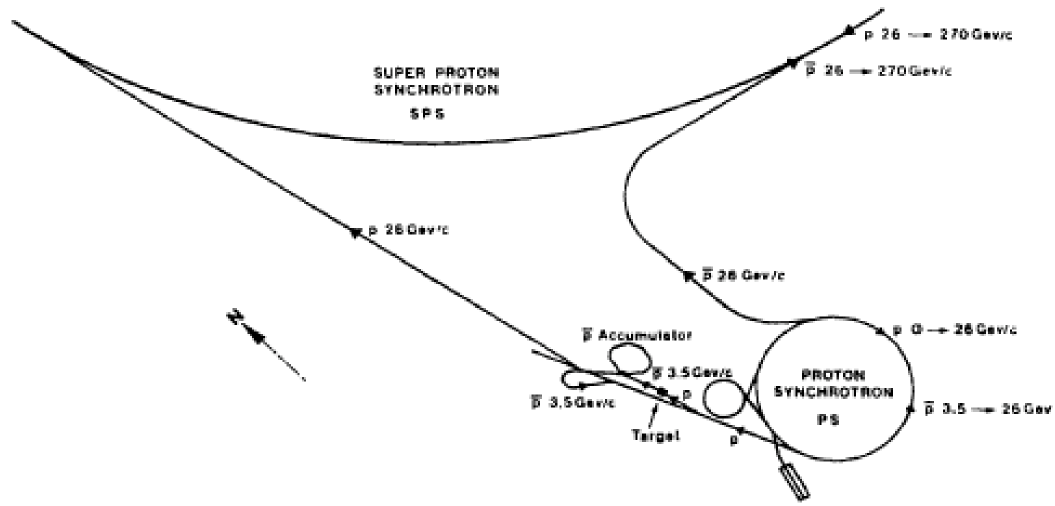
Discovery: W and Z

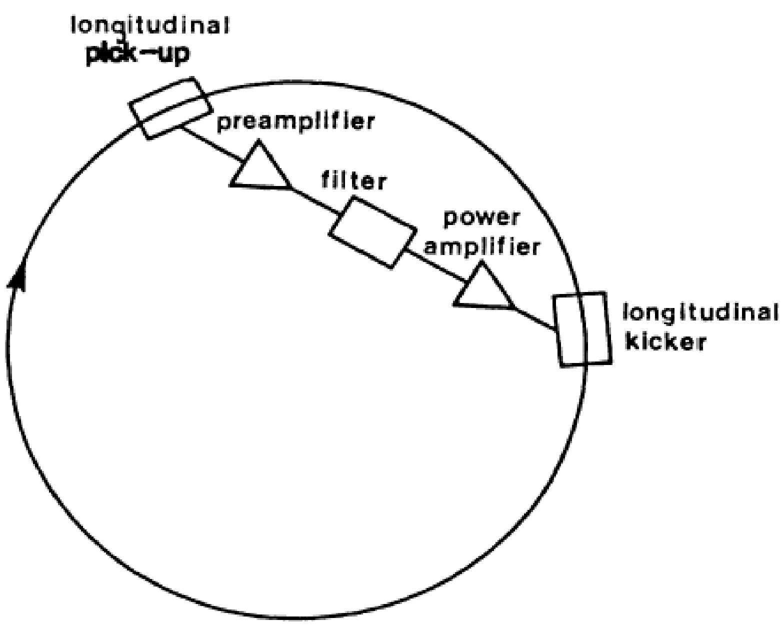


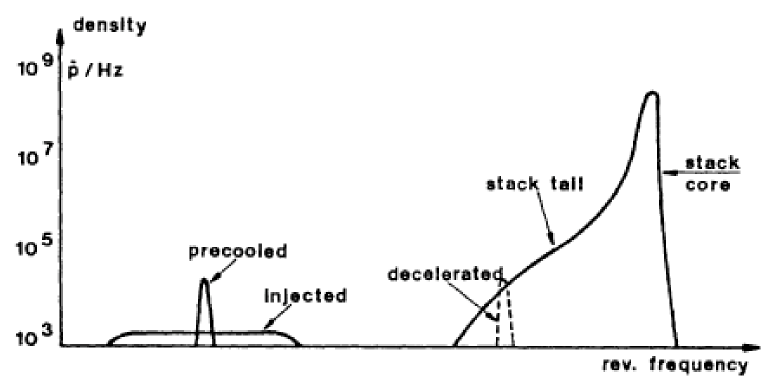
Expect vector bosons to have masses around 100 GeV. CERN started Large Electron Positron collider in 1974 with the aim of direct production. In 1977, the idea of using proton-antiproton collisions was vigorously pushed by Rubbia and Cline.

Could detectors be built to sort out jets, e-pairs and muon pairs in $p\bar{p}$ collisions? Could a collider store sufficient $\bar{p}$'s to achieve enough luminosity to make W's and Z's?

Luminosity problem was solved by van der Meer using stochastic cooling of antiprotons produced in high energy p-Cu collisions.

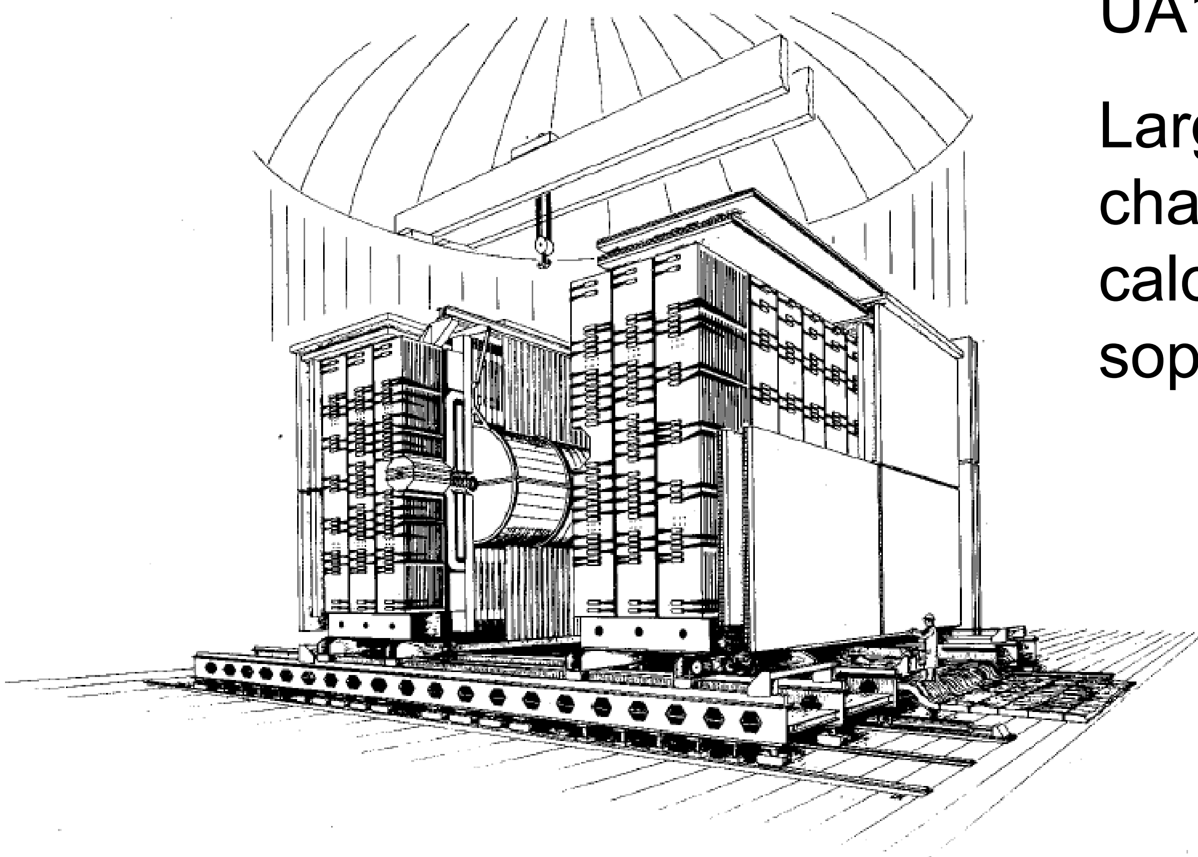






UA1

Large central tracking chamber, hermetic calorimeter and sophisticated trigger



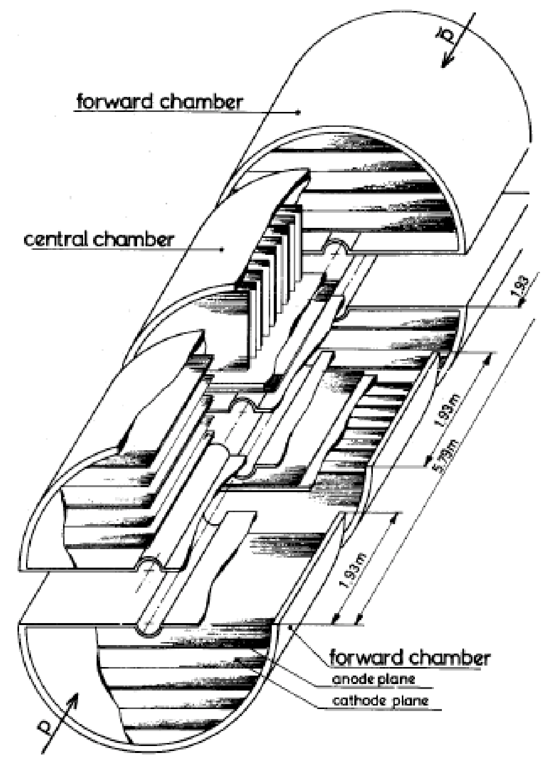
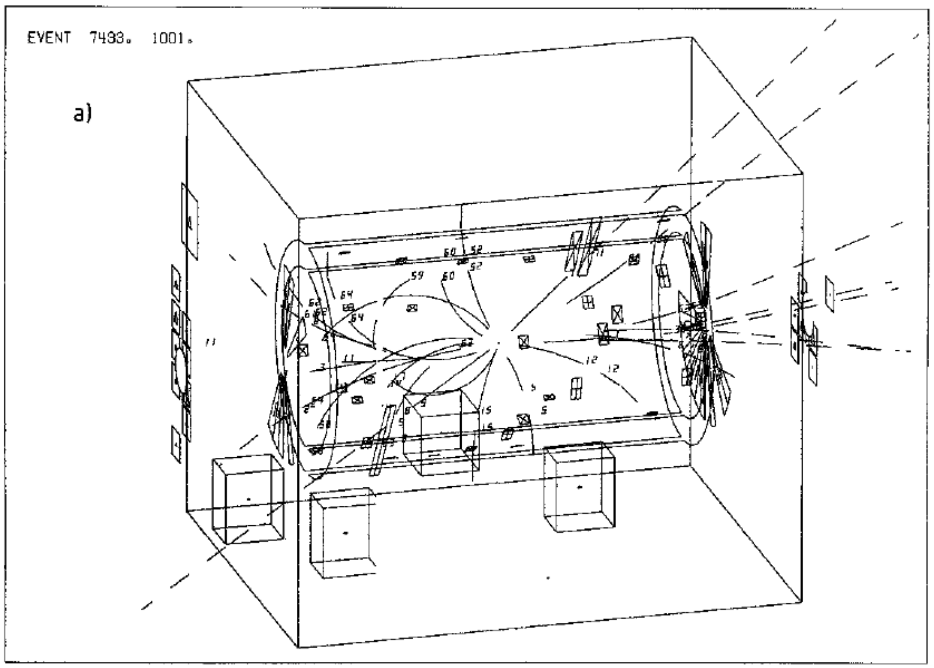
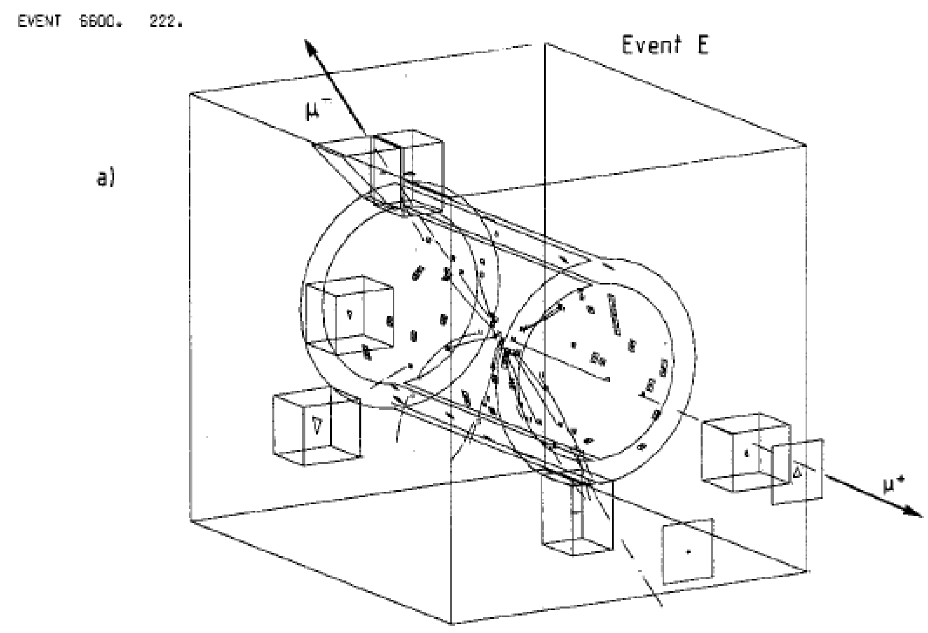
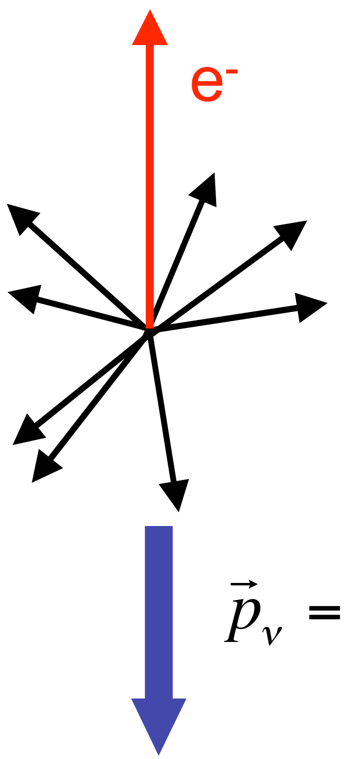


Fig. 2


EVENT 7433. 1001.
a)


EVENT 6600. 222.
Event E
a)
μ⁻
μ⁺

W observation



$$\vec{p}_\nu = - \sum_{i=\text{everything else}} \vec{p}_i$$

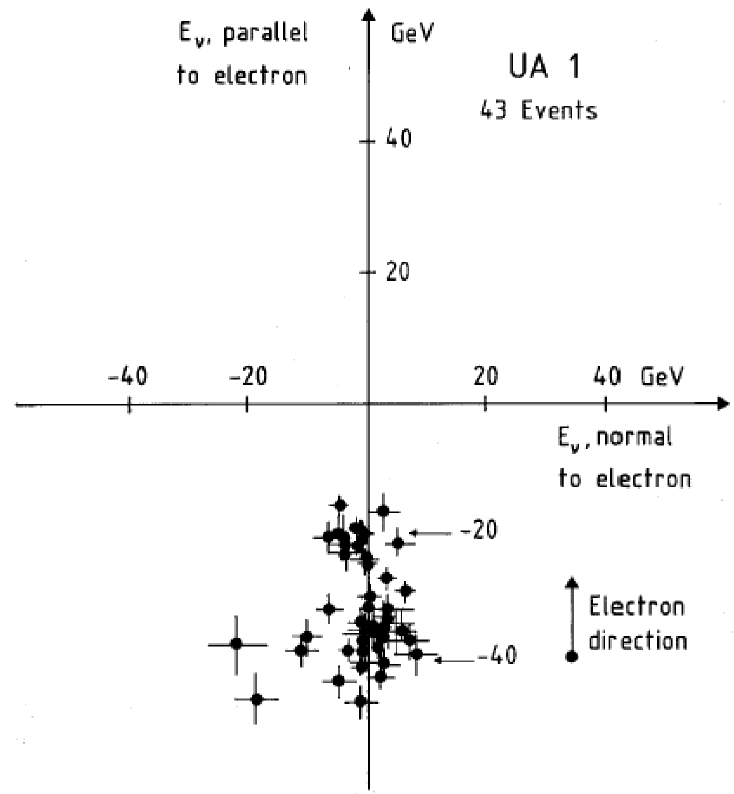
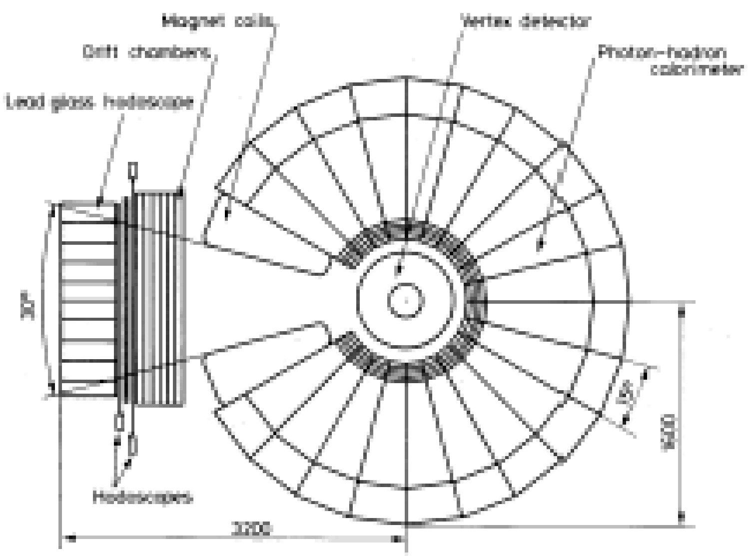
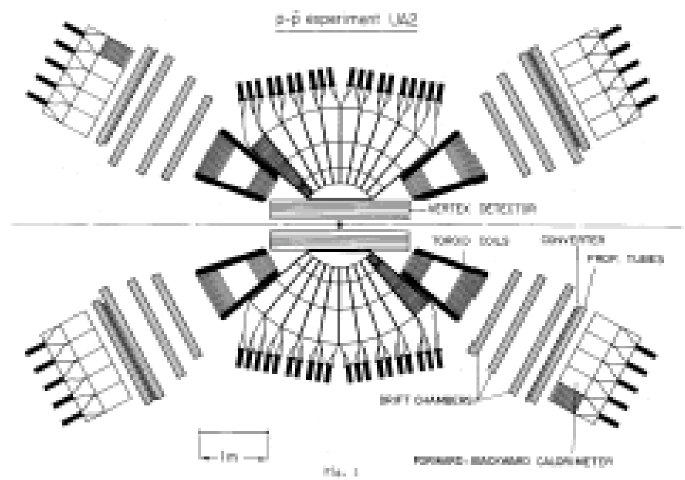
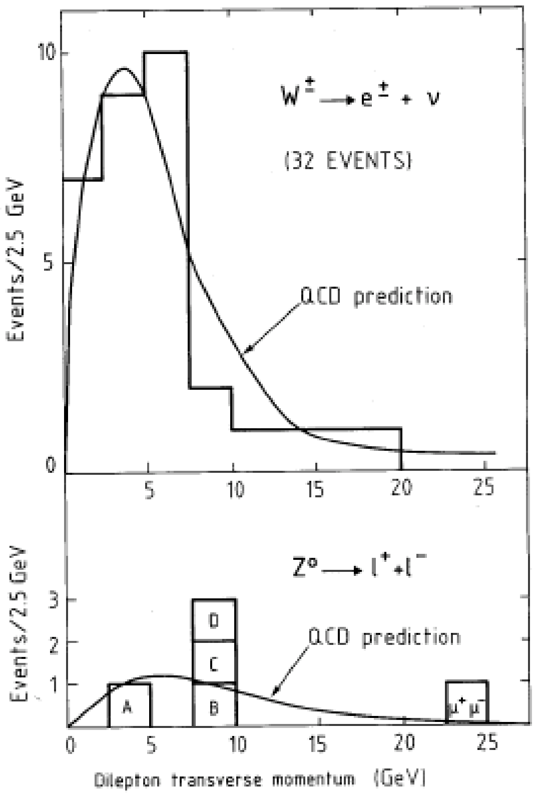


Fig. 3a

UA2

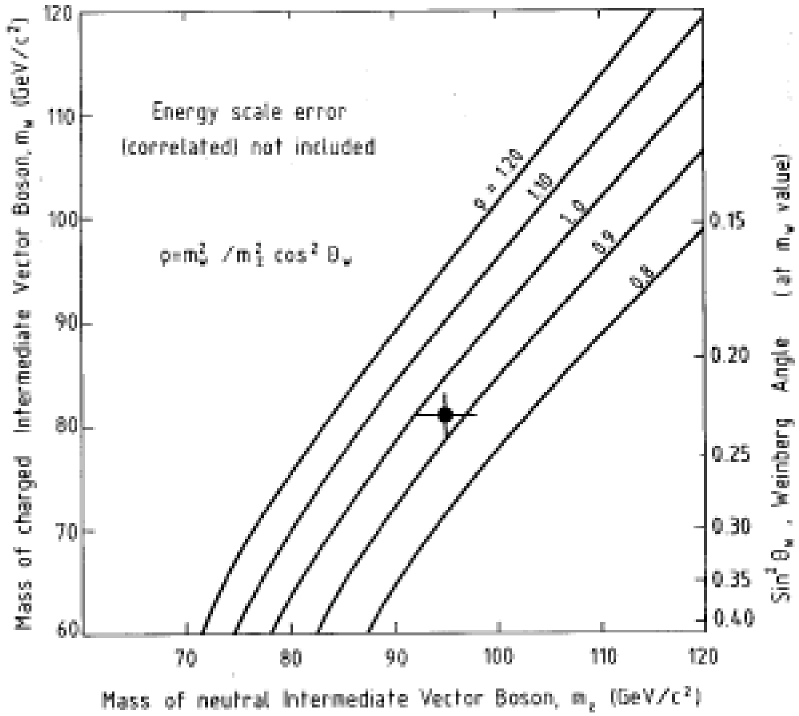

Magnet coils
Drift chambers
Lead glass hodoscope
Vertex detector
Photon–hadron calorimeter
30°
Hodoscopes
3200
9600
135°


p-p̄ experiment UA2
VERTEX DETECTOR
TOROID COILS
CONVERTER
PROP. TUBES
DRIFT CHAMBERS
1m
FORWARD-BACKWARD CALORIMETER



W± → e± + ν
(32 EVENTS)
QCD prediction
Events/2.5 GeV
Z° → l⁺+l⁻
A
B
C
D
μ⁺μ⁻
Dilepton transverse momentum (GeV)

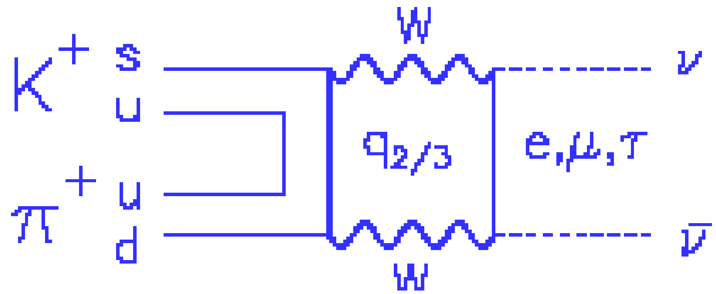
Fig. 7



Energy scale error
(correlated) not included
ρ=m²_W / m²_Z cos² θ_W
ρ = 1.20
1.10
1.0
0.9
0.8
Mass of charged Intermediate Vector Boson, m_W (GeV/c²)
Mass of neutral Intermediate Vector Boson, m_Z (GeV/c²)
Sin² θ_W , Weinberg Angle (at m_W value)

Interlude: E787

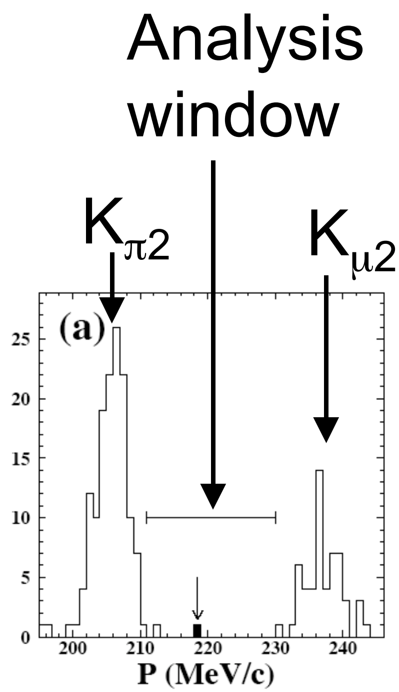
In EW theory, $K^+ \rightarrow \pi^+ \nu \nu$ is sensitive to m_t, V_{td} via a box diagram. The expected branching fraction was ~10^{-8}.

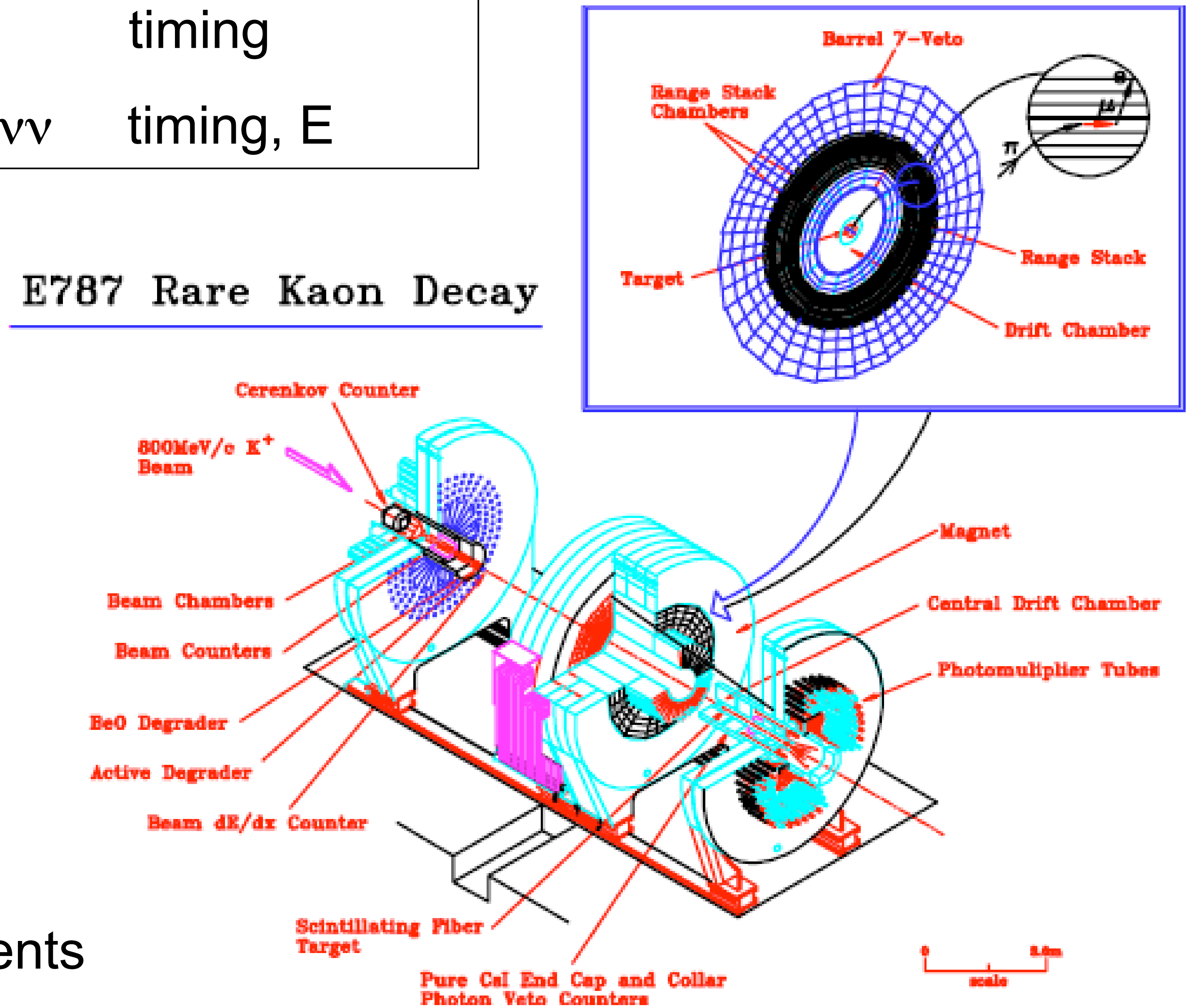


More deeply than measuring $|V_{td}|$, measurement of this decay opened sensitivity of many extensions to the EW theory. A key point in most of the strong interaction effects could be measured from $K^+ \rightarrow \pi^o e^+ \nu$, leaving a total theory error of about 7%.

Rule of thumb: with a single measurement, 90% rejection is easy, 99% very hard and 99.9% almost impossible. For $K^+ \rightarrow \pi^+ \nu \nu$, six discrminants were used.

$K^+ \to \pi^+ \nu\nu$	P, R, timing
$\to \mu^+ \nu$	timing
$\to e^+ \nu\nu$	timing, E





Background:
0.15±0.03 events

Observed 5×10^{12} K^+ decays in two years of running at AGS.

Observed *two* candidate events.

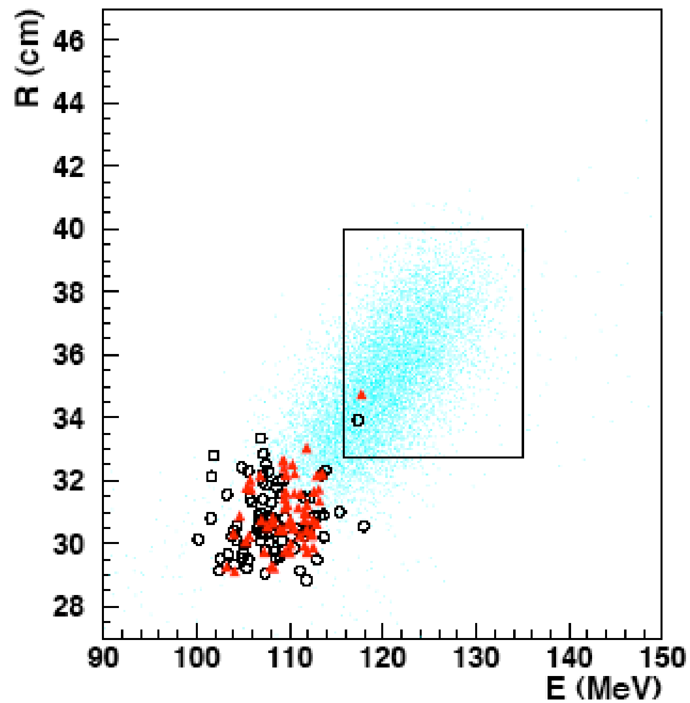


FIG. 2: Range vs. energy plot of the final sample. The circles are for the 1998 data and the triangles are for the 1995-97 data set. The group of events around $E = 108$ MeV is due to the $K_{\pi 2}$ background. The simulated distribution of expected events from $K^+ \to \pi^+ \nu\bar{\nu}$ is indicated by dots.

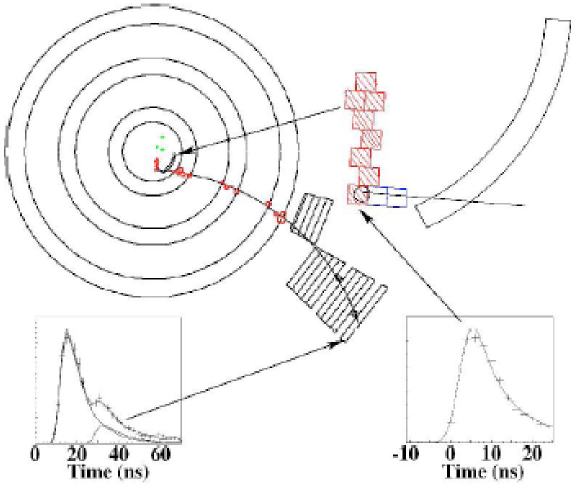
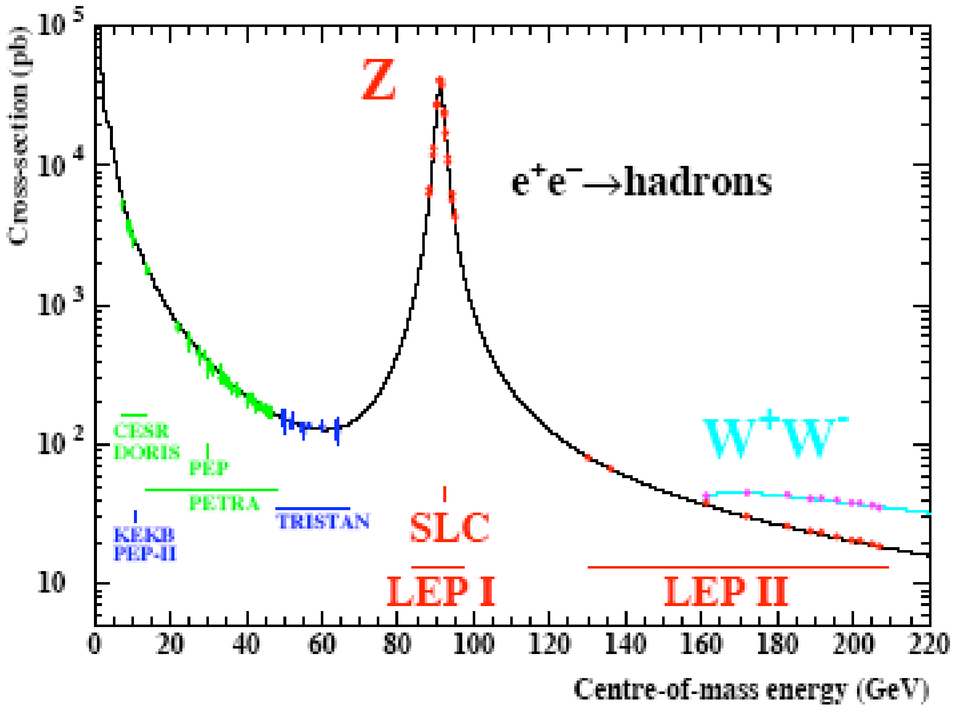


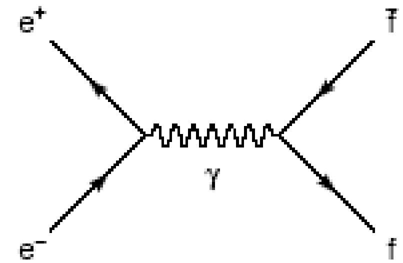
FIG. 1: Display of candidate Event C. On the top left is the end view of the detector showing the track in the target, the drift chamber, and the range stack. On the top right is a blow-up of the track in the target, where the hatched squares represent target fibers hit by the K^+ and the open squares indicate those hit by the π^+; a trigger scintillator that was hit is also shown. The lower right hand box shows the digitized signal in the target fiber where the kaon stopped indicating no additional activity. The pulse was sampled every 2 ns (crosses) and the solid line is a fit. The lower left hand box shows the digitized $\pi \to \mu$ decay signal in the scintillator where the pion stopped. The curves are fits for the first, second and combined pulses.

$$B(K^+ \to \pi^+ \nu\bar{\nu}) = 1.57^{+1.75}_{-0.82} \times 10^{-10}.$$

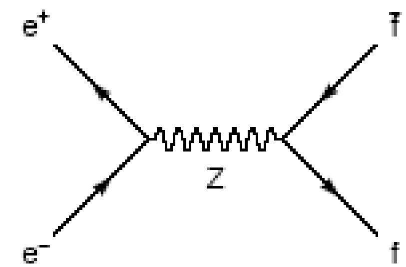
$$0.007 < |V_{td}| < 0.030$$

Precision: LEP I/SLD



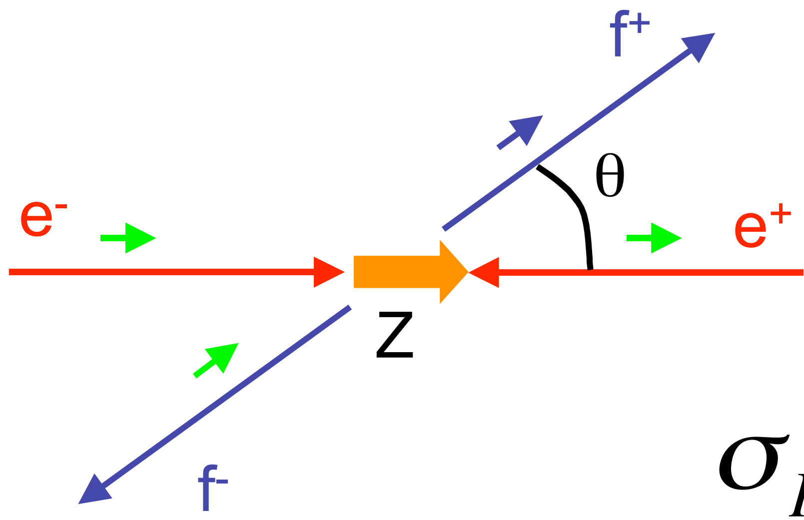


$\propto 1/Q^2$



$\propto 1/\Gamma^2$

Direct access to measurement of neutral current couplings, M_z, Γ_z



Can calculate angular distributions using quantum mechanical rotation of spin 1 system. For example:

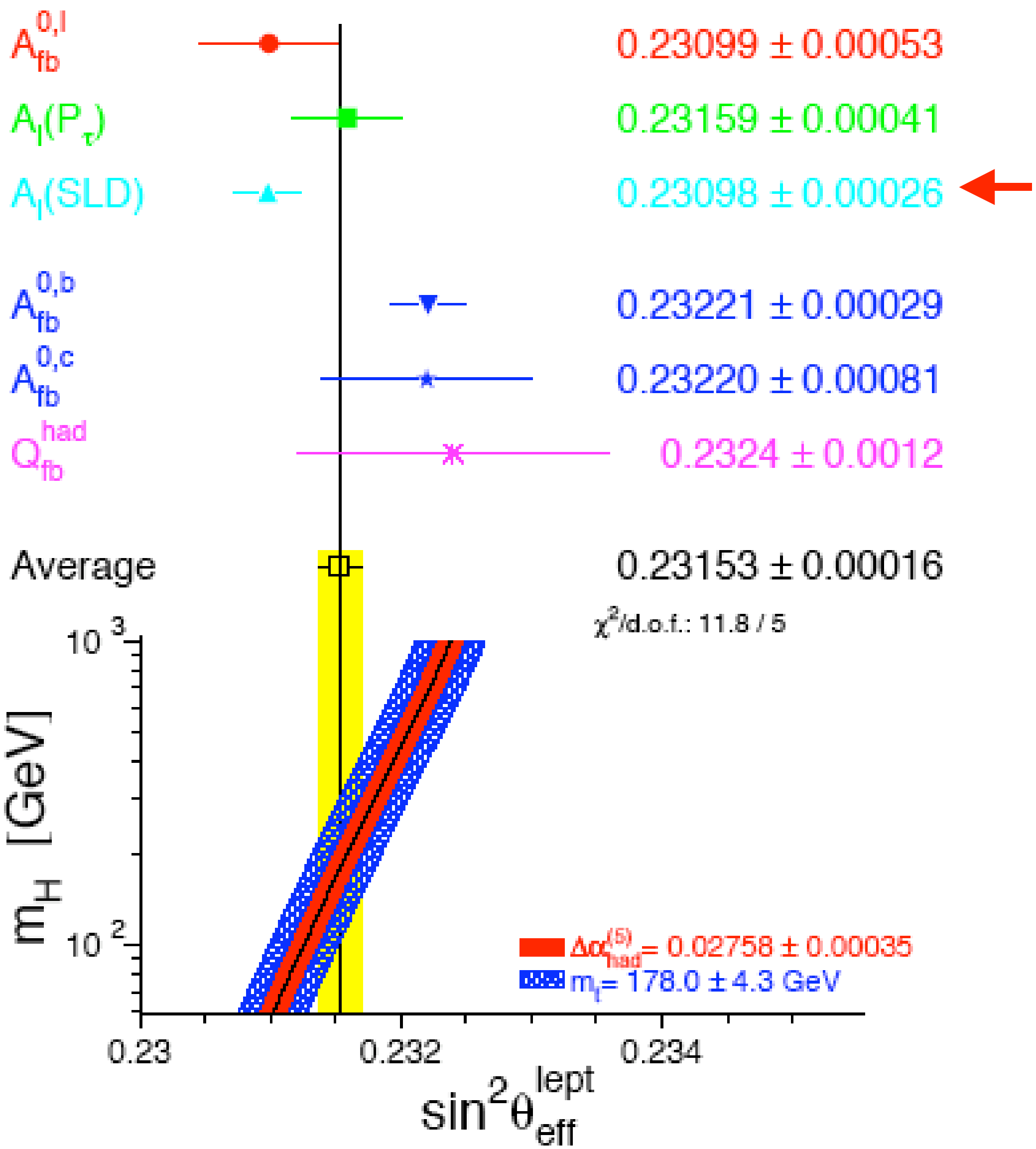
$$\sigma_{RL} \propto g_R g_L (1 + \cos\theta)$$

For unpolarized beams, average over initial, sum over final spin states:

$$\sigma = (\sigma_{LL} + \sigma_{LR} + \sigma_{RL} + \sigma_{RR})/2$$

$$g_L = -\sqrt{\rho}\left(T_3 - q\sin^2\theta_W\right)$$
$$g_R = -\sqrt{\rho}\,q\sin^2\theta_W$$

Direct access to mixing angle which is related to m_H via quantum corrections.



All the measurements except

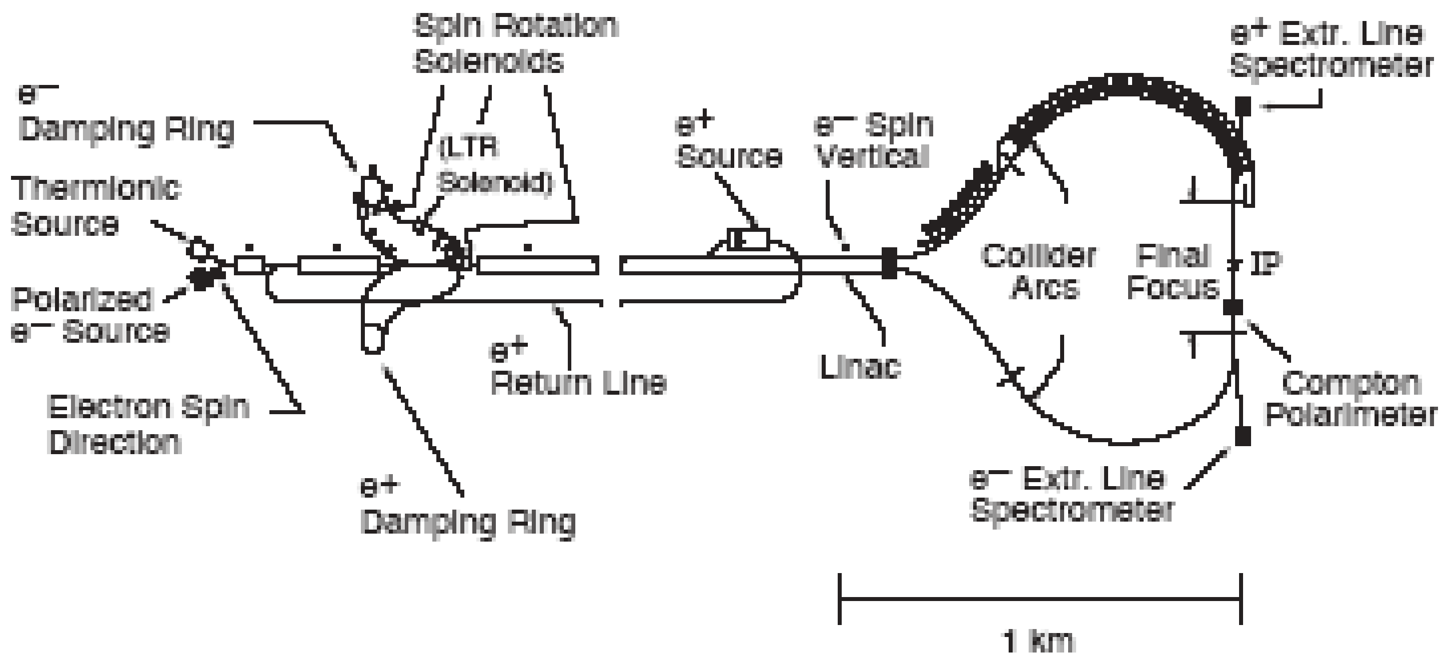
this one

Come from 4 experiments at LEP with 6M Z decays *each*. Why is SLD so damn good with less than 0.5M Z decays?

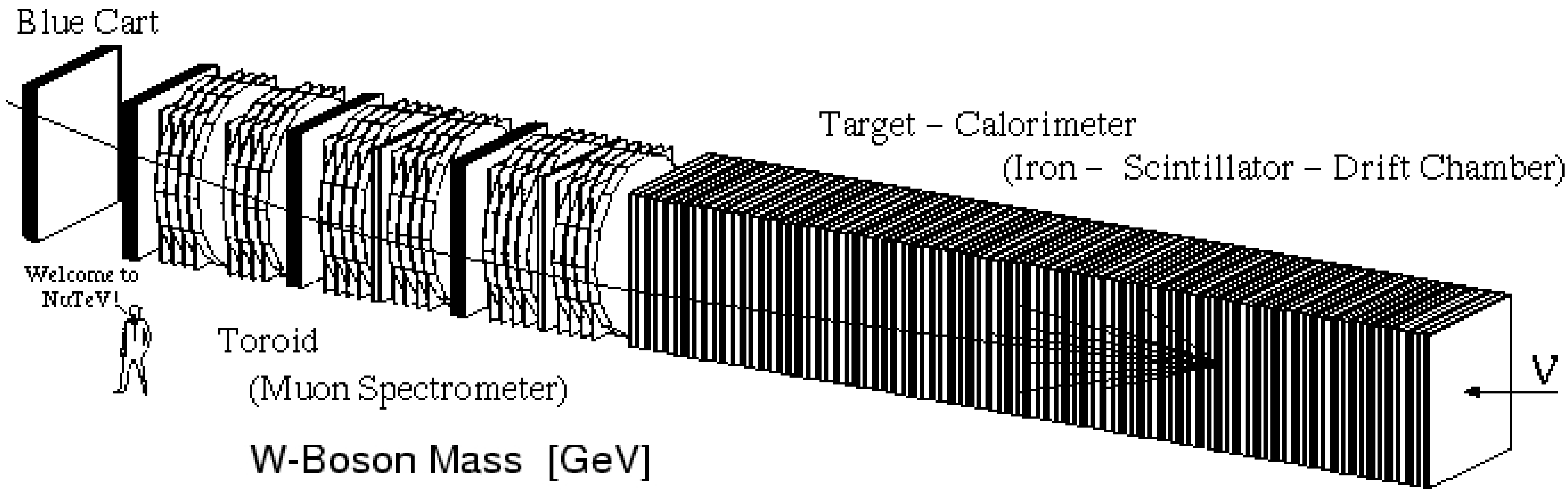
Polarization! SLD has the ability of polarize the electron beam and simply measure

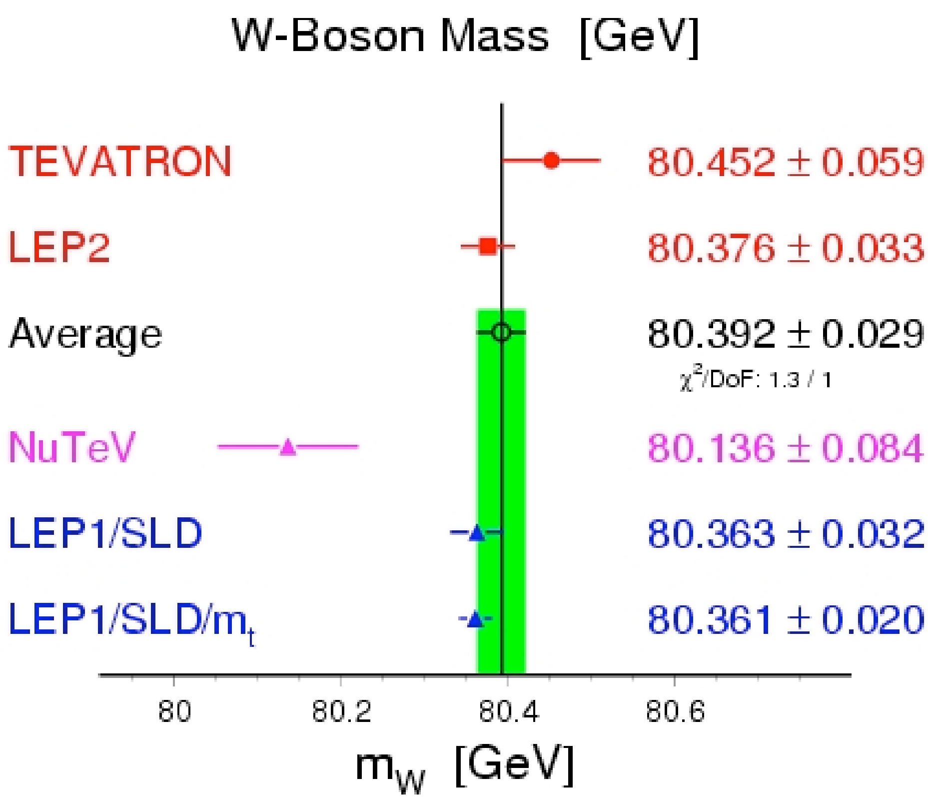
$A_{LR}=(N_R-N_L)/(N_R-N_L)P_e=(g_R{}^2-g_L{}^2)/(g_R{}^2+g_L{}^2)P_e=(1-4\sin^2\theta_W)/P_e$

Moral: a polarized beam is worth a factor of 100 in luminosity.



Critical: must measure the beam polarization to 0.1%





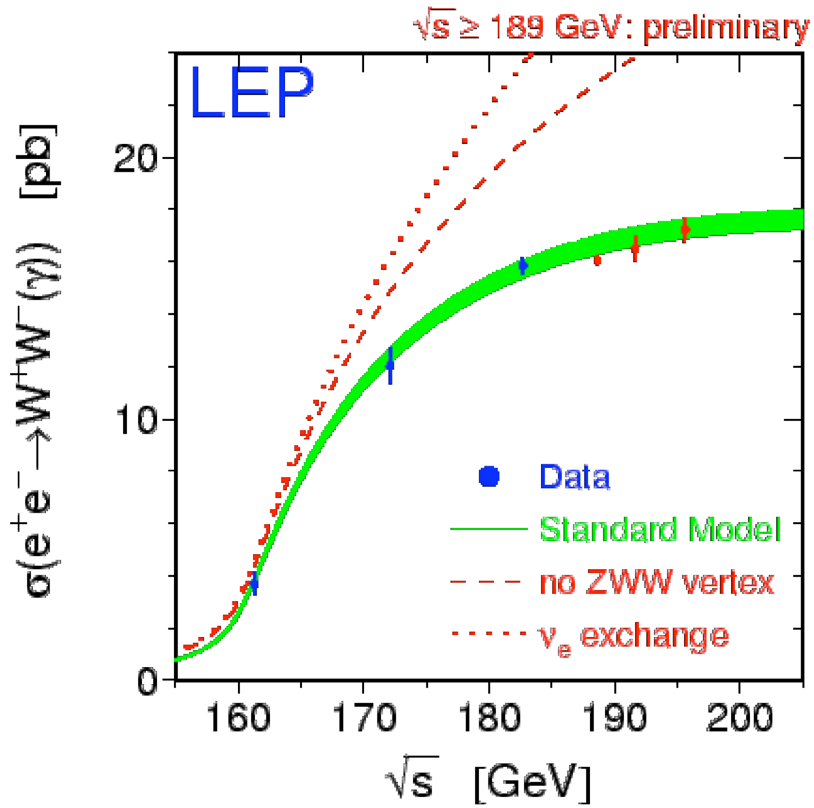
Neutrino scattering experiment NuTeV measures g_L^2 for muon neutrino about 3 σ too small. Only new physics model (Loinaz et al., 2003) predicts violation of universality at 0.3%…

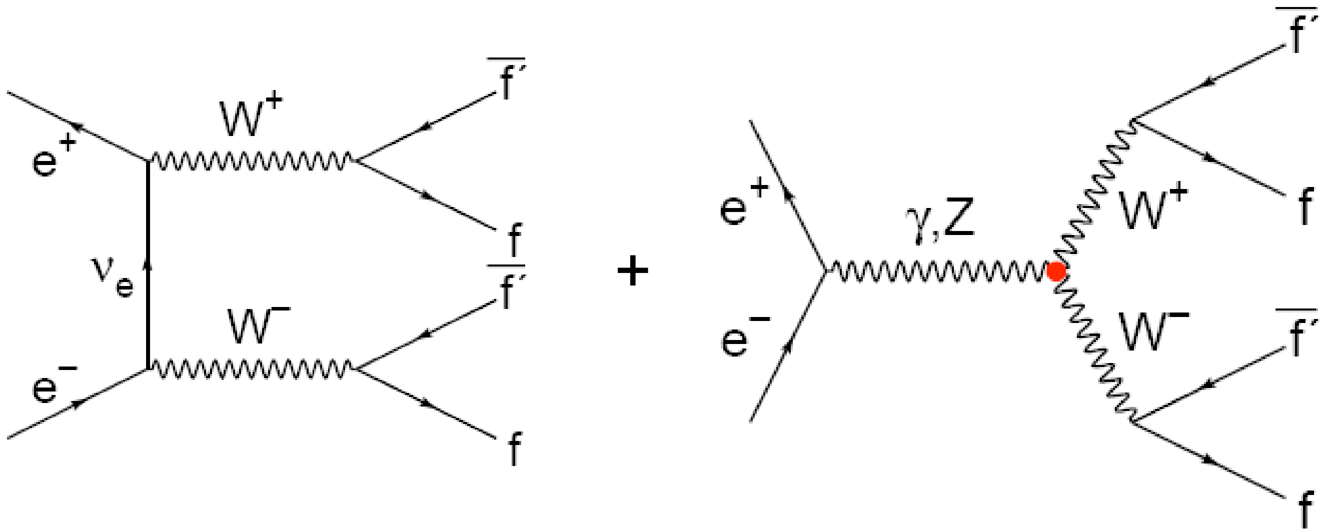
…and 500 GeV Higgs!

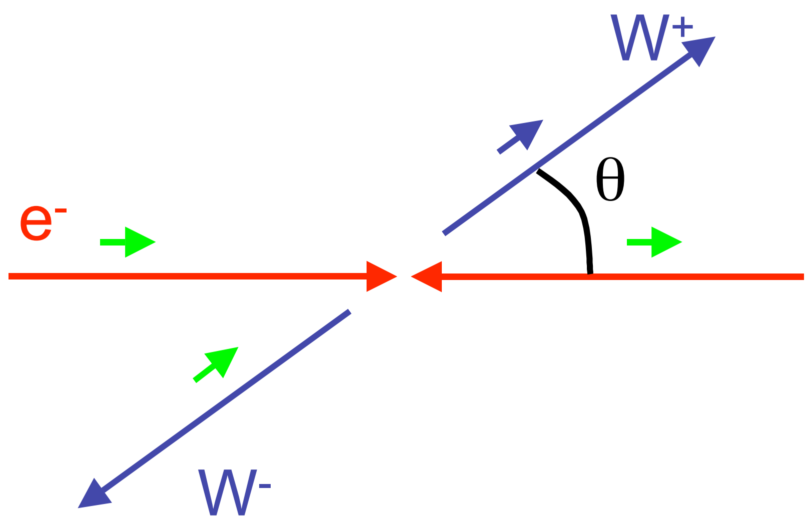
Precision: it is not so clear that everything hangs together…

Future: LEP II

Ecm=161-208 GeV in 1996-1999: $e^+e^- \rightarrow W^+W^-$



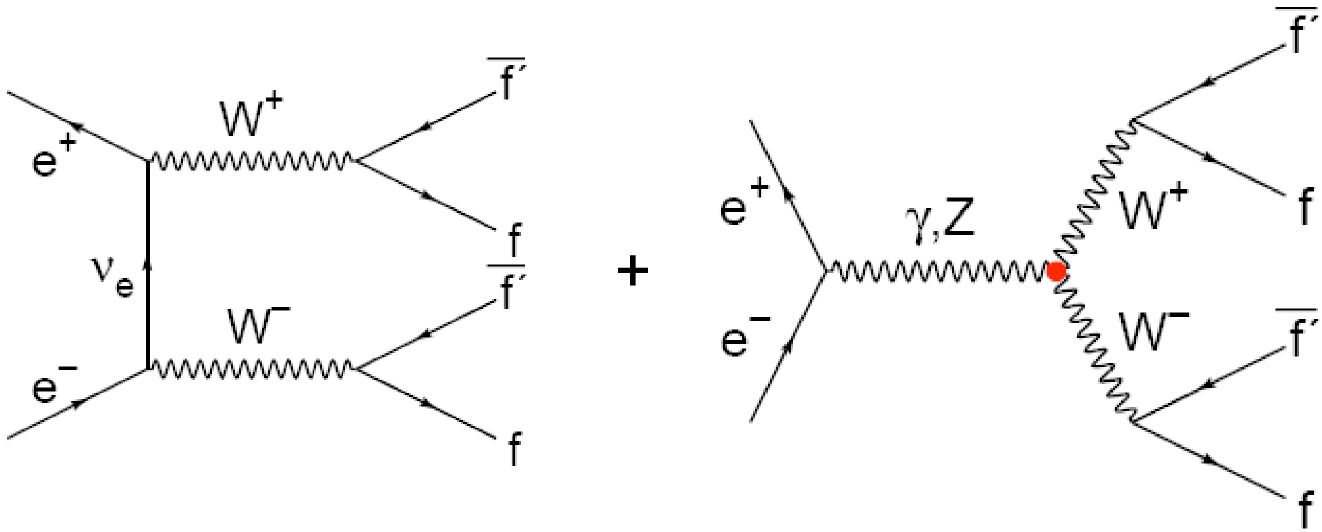


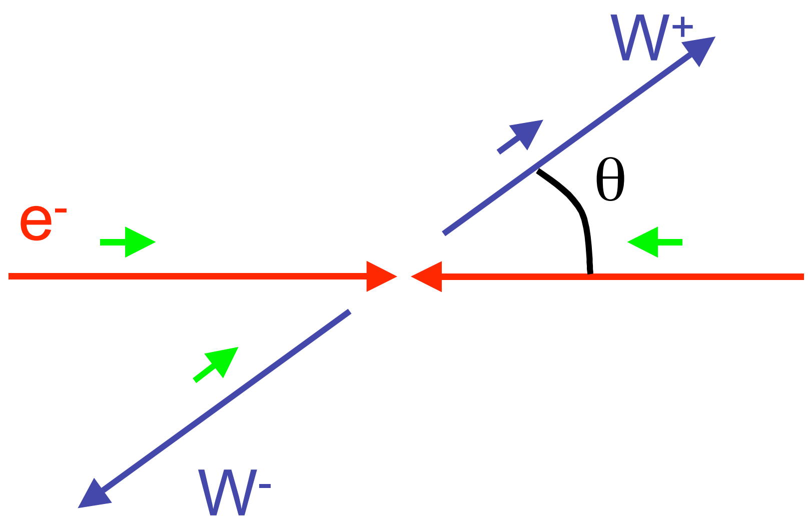


$\rightarrow \sigma_o \cos\theta$ as $E_{beam} \rightarrow \infty$

Unitary okay!

J=1, $m_J = \pm 1$



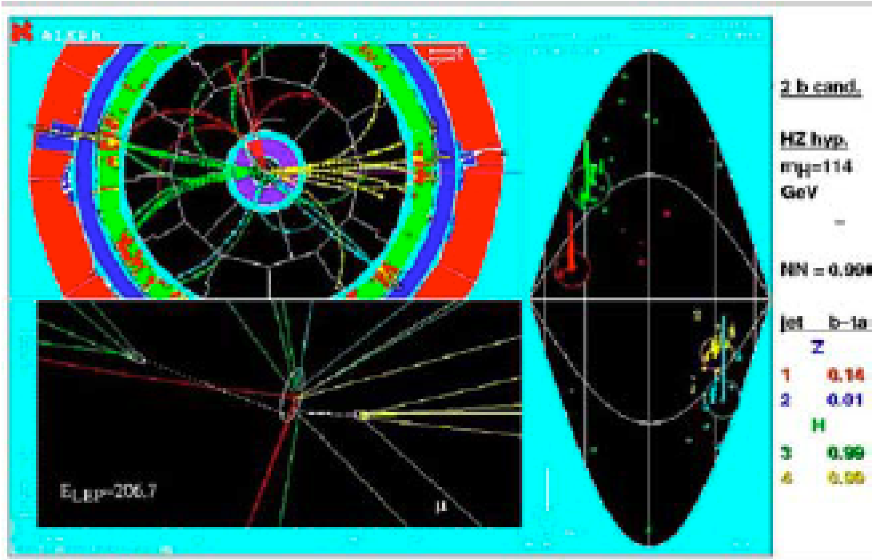


J=1,0, m_J=0

Angular distribution isotropic, "wrong helicity state"∝m/E

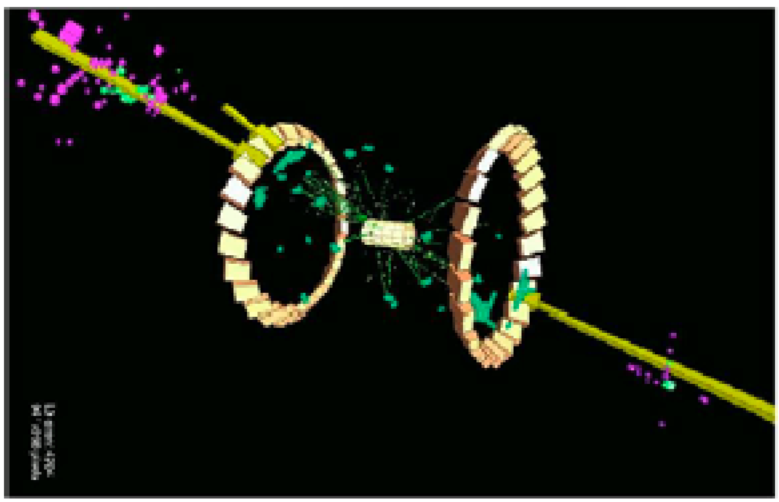
→need a scalar interaction with a coupling proportional to mass

Higgs fills this role.



Right at the end:

+3 events (all at ALEPH)

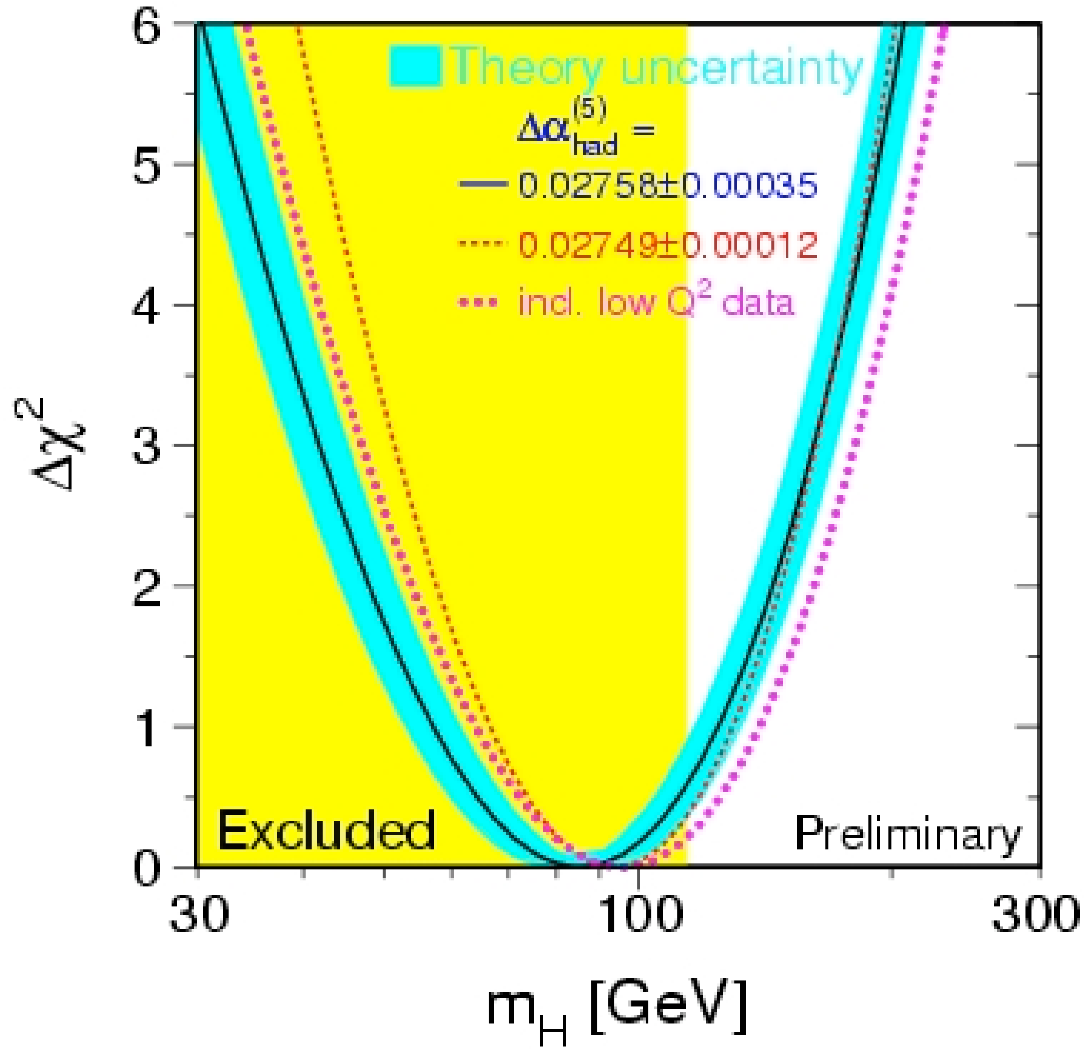


1 event at L3

2.8 σ effect

mass~115 GeV

2000-CERN elected to end LEP, now up to the Tevatron.



Now its up to you at the Tevatron or LHC.

While preparing these slides, I listened to the panel discussion, which I thought was very valuable and informed. I will pass on two pieces of advice which I have found valuable:

“Do the most interesting thing you can find to do.” Mark Wiedenbeck, 1983

“Don’t waste time on idiots.” Sam Ting, 1994.