Introduction to the Standard Model

Summer Student Lecture 2015 – Part II

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DESY

Content

- 0) Introduction
  - What is the Standard Model?
  - Coupling constants, masses and charges
  - Units and scales

- 1) Interactions
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  - Symmetries and conserved quantities
  - Dirac equation
  - Feynman diagrams
  - Cross section measurements

- 2) Quantum electrodynamics: Tests of QED
  - low energy: Magnetic momentum of the electron
  - tests at high energy colliders

Content

- 3) Electroweak interactions
  - Discovery of electroweak bosons
  - Tests of angular distributions
  - Feynman rules
  - Handed-ness of electroweak interactions
  - More tests of the electroweak SM

- 4) Strong Interaction: Quantum-Chromodynamics
  - Quarks and Hadrons
  - QCD at colliders
  - PDFs and parton showers

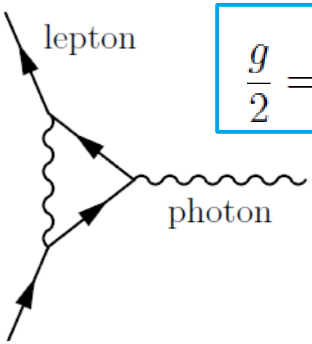
Electromagnetic Interactions: Tests of QED

- Electromagnetism is the “oldest” known fundamental interaction
- Quantum electrodynamics can be tested using
  → **magnetic moment of the electron**
  → at high energy colliders
- Magnetic moment due to rotating charge body → spin of electron

$$\mu = -g\frac{e}{2m}s = -\frac{g}{2}\frac{e}{2m}$$

g-factor is 2: $a \equiv \frac{g-2}{2} = 0$

- Deviations from classical result caused by quantum corrections



$$\boxed{\frac{g}{2} = 1 + C_2\left(\frac{\alpha}{\pi}\right) + C_4\left(\frac{\alpha}{\pi}\right)^2 + C_6\left(\frac{\alpha}{\pi}\right)^3 + C_8\left(\frac{\alpha}{\pi}\right)^4 + C_{10}\left(\frac{\alpha}{\pi}\right)^5 + \cdots + a_{\text{hadronic}} + a_{\text{weak}}}$$

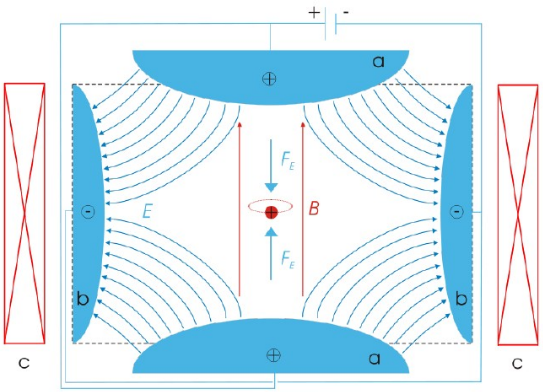
Electromagnetic Interactions: Tests of QED

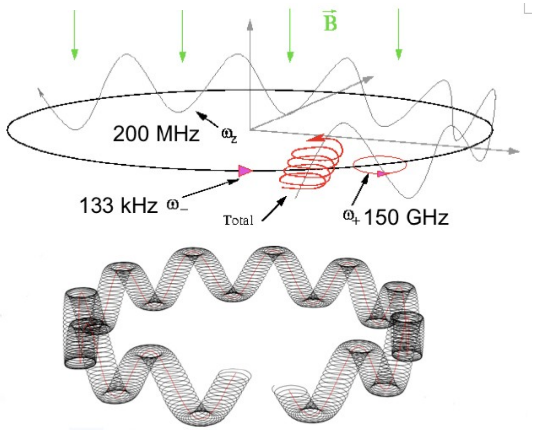
- A non-relativistic electron in a magnetic field has energy levels:

$$E(n, m_s) = \frac{g}{2} h\nu_c m_s + \left(n + \frac{1}{2}\right) h\nu_c \qquad \nu_c = \frac{eB}{2\pi m} \qquad \nu_s = \frac{g}{2}\nu_c = \frac{g}{2}\frac{eB}{2\pi m}$$

- Depend on the cyclotron frequency (ν_c) and on the spin frequency (ν_s)

$$\frac{g}{2} = \frac{\nu_s}{\nu_c} = 1 + \frac{\nu_s - \nu_c}{\nu_c} = 1 + \frac{\nu_a}{\nu_c}$$





$$g/2 = 1.001\ 159\ 652\ 180\ 73\ (28) \quad [0.28\ \text{ppt}]\ (\text{measured})$$
$$g(\alpha)/2 = 1.001\ 159\ 652\ 177\ 60\ (520) \quad [5.2\ \text{ppt}]\ (\text{predicted}).$$

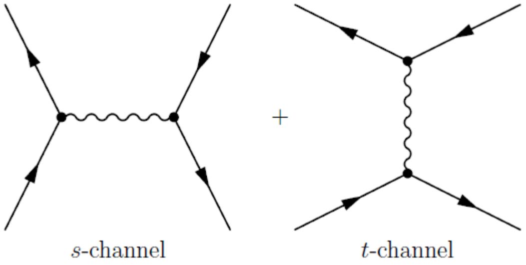
- Muon magnetic moment with larger corrections due to QCD and EWK
- measurement disagrees with SM **by 3.4 standard deviations**

High-energy collider tests of QED

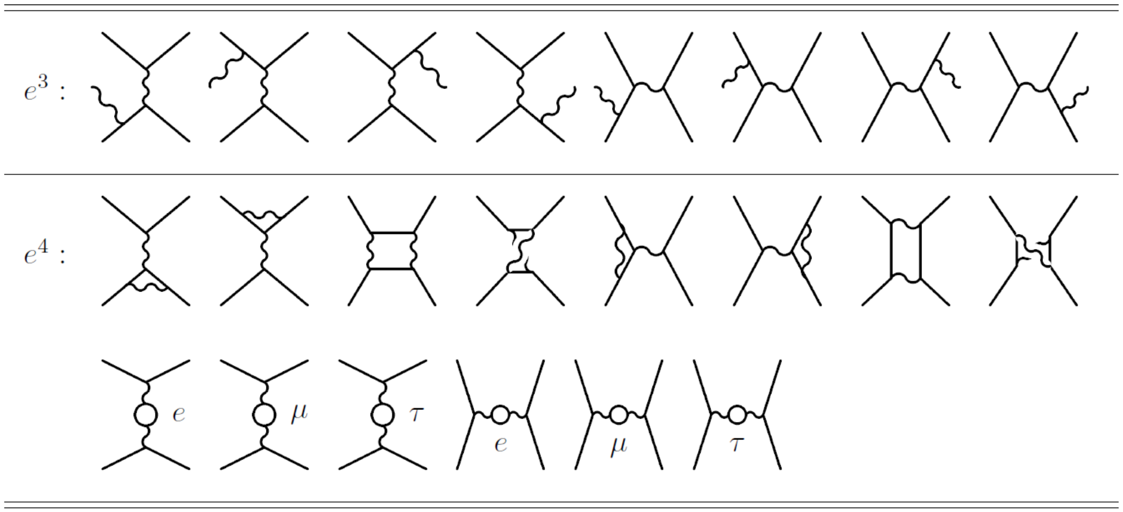
- High-energy colliders probe the following processes:
  - Bhabha scattering : $e^+e^- \to e^+e^-$
  - Lepton pair production : $e^+e^- \to \mu^+\mu^-, \tau^+\tau^-$

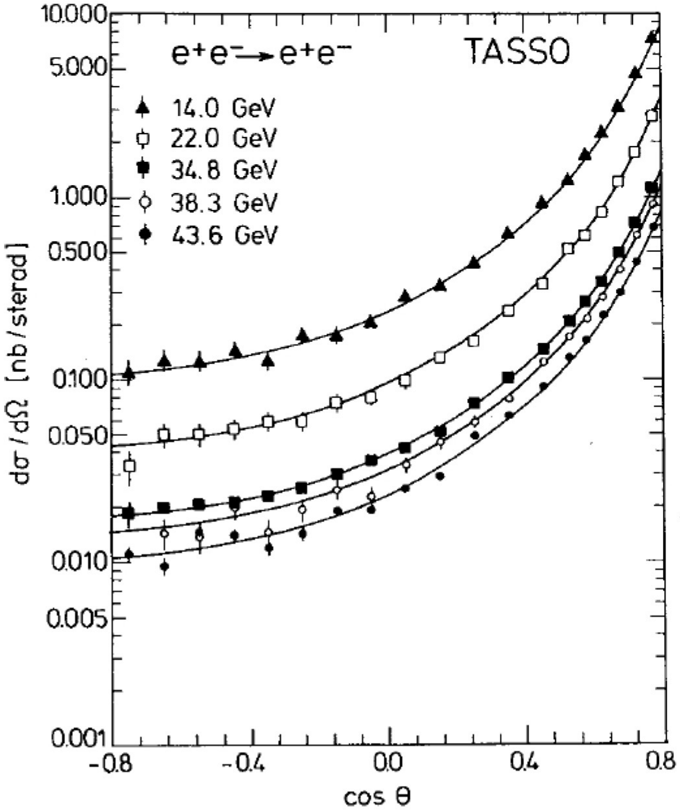
Bhabha scattering: ee → ee

- High-energy colliders probe the following processes:



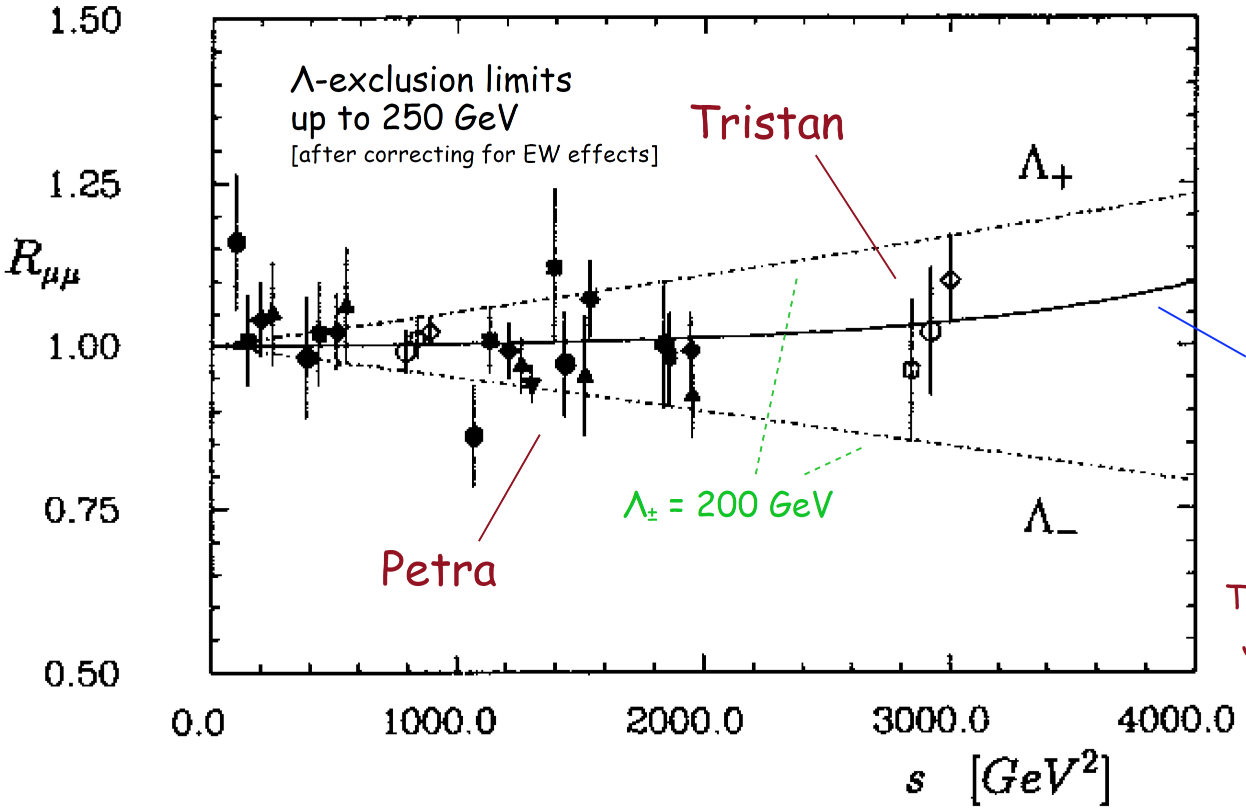
$$\begin{aligned}\frac{d\sigma_0}{d\Omega} &= \frac{\alpha^2}{4s}\left(\underbrace{\frac{t^2+s^2}{u^2}}_{t\text{-channel}} + \underbrace{\frac{2t^2}{us}}_{\text{interference}} + \underbrace{\frac{t^2+u^2}{s^2}}_{s\text{-channel}}\right)\\ &= \frac{\alpha^2}{4s}\left(\frac{3+\cos^2\vartheta}{1-\cos\vartheta}\right)^2 .\end{aligned}$$





Electromagnetic Interactions: Lepton pair production

$$R_{\mu\mu} = \frac{\sigma_{\text{meas}}^{e^+e^-\to\mu^+\mu^-}}{\sigma_{\text{QED}}^{e^+e^-\to\mu^+\mu^-}},$$



Λ-exclusion limits up to 250 GeV [after correcting for EW effects]

Tristan

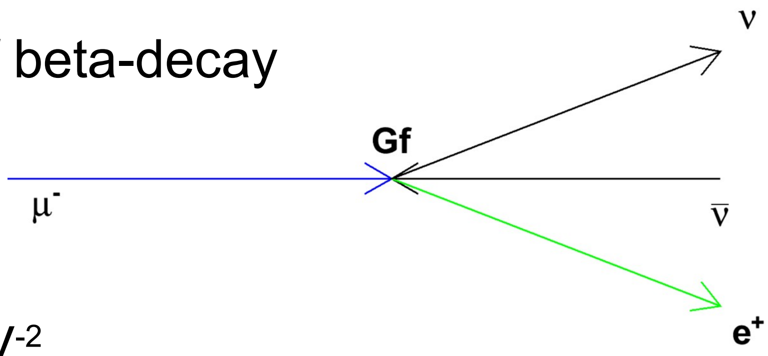
Petra

Z_0

$\Lambda_\pm$ = 200 GeV

Tristan: $\sqrt{s} \approx 55$ GeV

Electroweak interactions



- Fermi theory proposed as explanation of beta-decay
  → four point interaction

- Coupling constant G_F measured
  from lifetime of muon: 1.6637×10^{-5} GeV^{-2}

- Suggested generic four point interaction (a la QED)

$$\mathcal{M} = \frac{G_F}{\sqrt{2}} (\bar{\psi}_p \gamma^\mu \psi_n)(\bar{\psi}_e \gamma_\mu \psi_{\bar{\nu}}), \longleftarrow$$

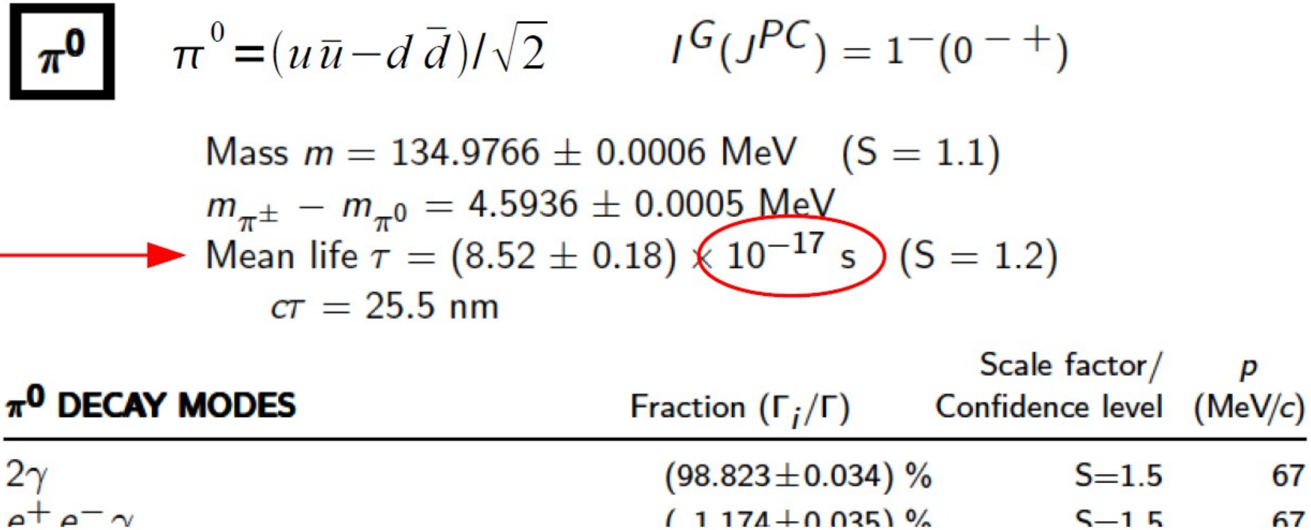
Not quite accurate (see next slides)

- Fermi's theory successfully described decays, few pecularities....

  → Pion and Kaon decays, CP violation: V-A current

  → Ultraviolet behaviour: introduction of massive weak bosons

Handed-ness and hadronic decays: The Pion



$\boxed{\pi^0}$ $\pi^0 = (u\bar{u} - d\bar{d})/\sqrt{2}$ $I^G(J^{PC}) = 1^-(0^{-+})$

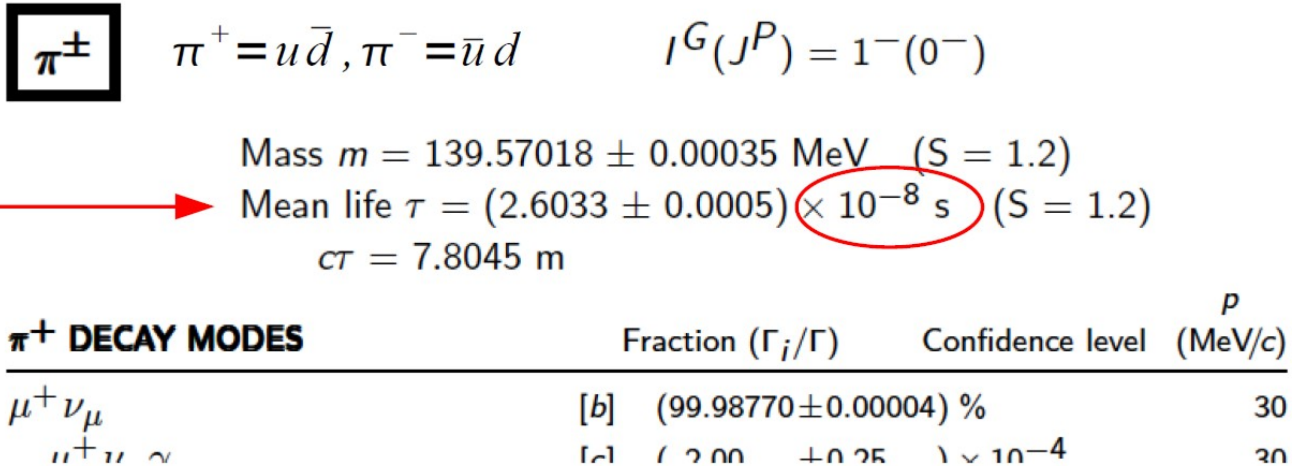
Mass $m = 134.9766 \pm 0.0006$ MeV $(S = 1.1)$

$m_{\pi^\pm} - m_{\pi^0} = 4.5936 \pm 0.0005$ MeV

Mean life $\tau = (8.52 \pm 0.18) \times 10^{-17}$ s $(S = 1.2)$

$c\tau = 25.5$ nm

π^0 DECAY MODES	Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
2γ	(98.823 ± 0.034) %	S=1.5	67
$e^+ e^- \gamma$	(1.174 ± 0.035) %	S=1.5	67



$\boxed{\pi^\pm}$ $\pi^+ = u\bar{d}, \pi^- = \bar{u}d$ $I^G(J^P) = 1^-(0^-)$

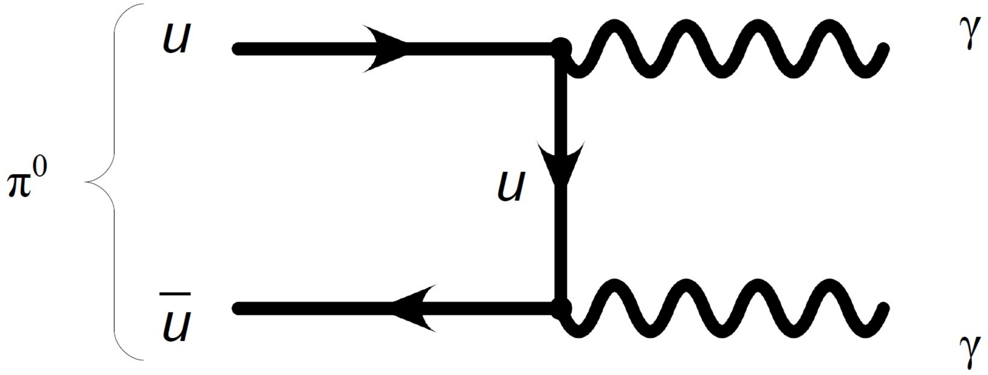
Mass $m = 139.57018 \pm 0.00035$ MeV $(S = 1.2)$

Mean life $\tau = (2.6033 \pm 0.0005) \times 10^{-8}$ s $(S = 1.2)$

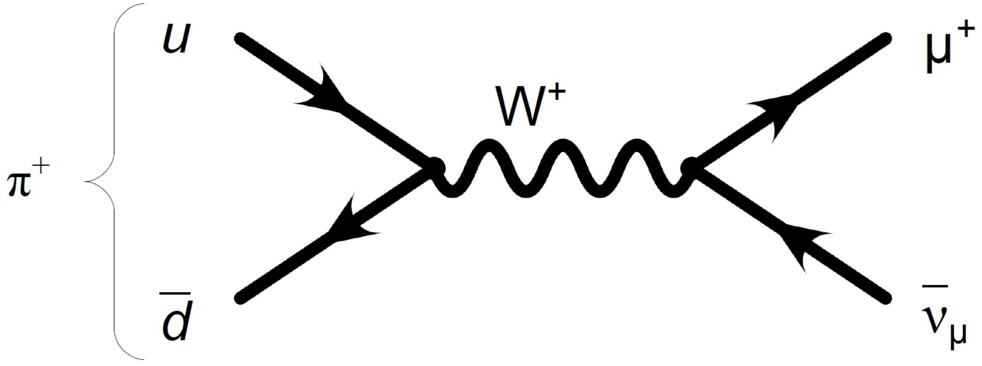
$c\tau = 7.8045$ m

π^+ DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\mu^+ \nu_\mu$	[b]	(99.98770 ± 0.00004) %		30
$\mu^+ \nu_\mu \gamma$	[c]	$(2.00 \pm 0.25) \times 10^{-4}$		30

Handed-ness and hadronic decays: The Pion

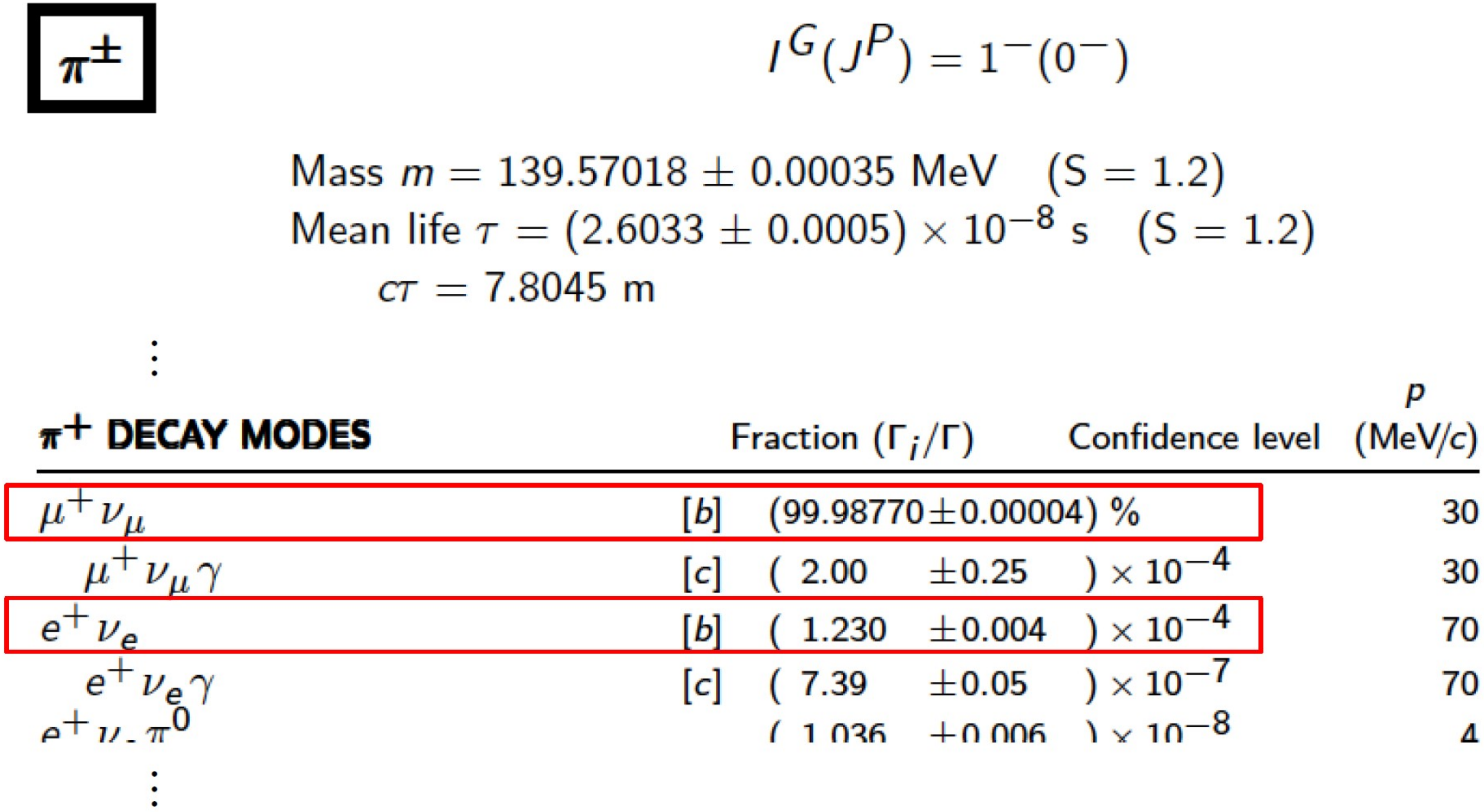


electromagnetic
interaction



weak
interaction

Handed-ness and hadronic decays: The Pion



$\boxed{\pi^{\pm}}$

$$I^G(J^P) = 1^-(0^-)$$

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⋮

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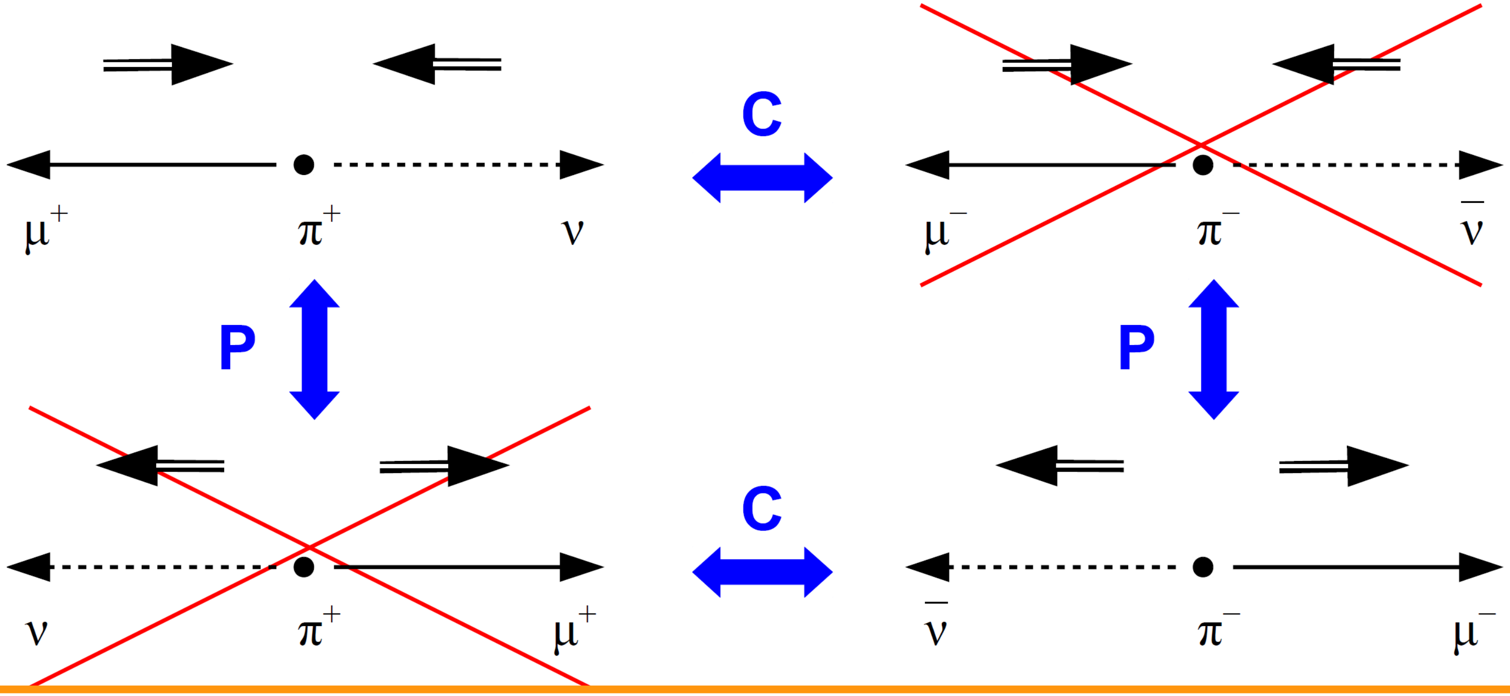
$\mu^+\nu_\mu$	[b]	(99.98770 ± 0.00004) %		30
$\mu^+\nu_\mu\gamma$	[c]	$(2.00 \pm 0.25) \times 10^{-4}$		30
$e^+\nu_e$	[b]	$(1.230 \pm 0.004) \times 10^{-4}$		70
$e^+\nu_e\gamma$	[c]	$(7.39 \pm 0.05) \times 10^{-7}$		70
$e^+\nu_e\pi^0$		$(1.036 \pm 0.006) \times 10^{-8}$		4

⋮

why is the decay to muon and neutrino so much more likely than the decay to electron and neutrino, although the muon is much heavier than the electron?

Handed-ness and hadronic decays: The Pion

- neutrino is left-handed, π has spin 0
  ⇒ charged lepton also has to be left-handed, which is the "wrong" spin
- the heavier the charged lepton, the less suppressed is the wrong helicity, proportional to (1-v/c)

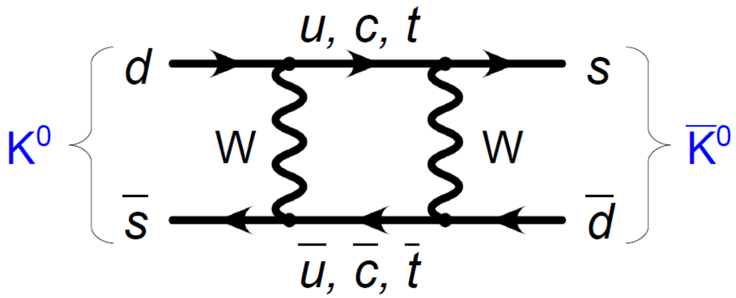


- left-handedness of neutrinos also means that weak interaction violates C, but CP can be conserved (and indeed CP violation is much smaller)

The τ-θ puzzle (1956)

- Same particle K^+ decays into 2 different CP final stat $K^+ \begin{cases} \theta \longrightarrow \pi^+\pi^0 \\ \tau \longrightarrow \pi^+\pi^+\pi^- \end{cases}$
- if you look into the PDG, you will find the following 4 entries:
  - $K^+ = u\bar{s}$, antiparticle: $K^- = \bar{u}s$, $\tau = 1.2 \cdot 10^{-8}$ s ($c\tau = 3.7$ m)
  - $K^0 = d\bar{s}$, antiparticle: $\bar{K}^0 = \bar{d}s$
  - K^0_S, $\tau = 9.0 \cdot 10^{-11}$ s ($c\tau = 2.7$ cm)
  - K^0_L, $\tau = 5.1 \cdot 10^{-8}$ s ($c\tau = 15$ m)
- K^0 and $\bar{K}^0$ are eigenstates of the strong interaction (which conserves strangeness) while K^0_S and K^0_L are eigenstates of the weak interaction
- since kaons decay weakly, only the weak eigenstates have a lifetime
- K^0_S and K^0_L are (nearly) CP eigenstates, the different accessible final states (2π for CP=+1, 3π for CP=−1) lead to the different lifetimes
- K^0 and $\bar{K}^0$ can turn from one into the other:

  “oscillation”



Electroweak interactions

- Description of current changed such that observations could be accounted for:

$\bar{\psi}\psi$	scalar
$\bar{\psi}\gamma^\mu\psi$	vector
$\bar{\psi}\sigma^{\mu\nu}\psi$	tensor
$\bar{\psi}\gamma_5\psi$	pseudoscalar
$\bar{\psi}\gamma^\mu\gamma_5\psi$	pseudovector

$$\mathcal{M} = \frac{G_F}{\sqrt{2}}(\bar{\psi}_p\gamma^\mu\psi_n)(\bar{\psi}_e\gamma_\mu\psi_{\bar{\nu}}), \longrightarrow \boxed{\mathcal{M}(n \to p e^- \bar{\nu}_e) = \frac{G_F}{\sqrt{2}}[\bar{u}_p\gamma^\mu(\mathbb{1}-\gamma_5)u_n][\bar{u}_e\gamma_\mu(\mathbb{1}-\gamma_5)u_{\nu_e}]}$$

- V-A structure selects handedness
- G_F still universal constant
- Desired CP behaviour:

$\Gamma\left(\pi^+ \to \mu_R^+ + \nu_L\right) \neq \Gamma\left(\pi^+ \to \mu_L^+ + \nu_R\right)$	$\not{P}$	✗
$\Gamma\left(\pi^+ \to \mu_R^+ + \nu_L\right) \neq \Gamma\left(\pi^- \to \mu_R^- + \bar{\nu}_L\right)$	$\not{C}$	✗
$\Gamma\left(\pi^+ \to \mu_R^+ + \nu_L\right) = \Gamma\left(\pi^- \to \mu_L^- + \bar{\nu}_R\right)$	CP	✓.

Electroweak interactions

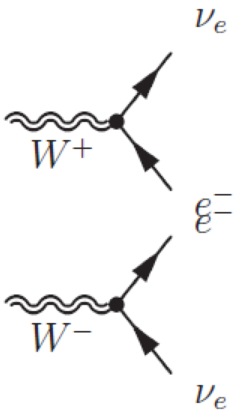
- Problem: Divergences! Fermi theory only valid at low energies

$$\sigma^{e^- + \nu_e \rightarrow e^- \nu_e} = \frac{4G_F^2}{\pi} E_{\mathrm{CM}}^2$$

- 1968: Formulation of electroweak unification (Glashow, Salam, Weinstein) → **massive W/Z bosons + massless γ**

- 1) → Consider W+/W- as doublets of the charge current
- 2) → Postulate SU(2) symmetry: Necessity of *neutral current*

(note: all of the above in analogy to pions and isospin)



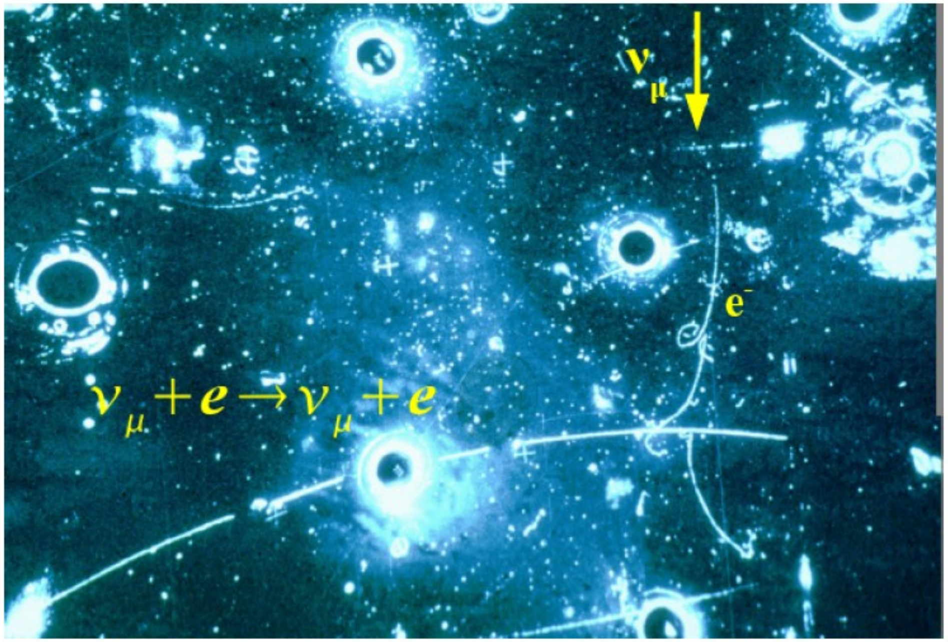
- 3) → Try preserving SU(2) and $U(1)_Q$ symmetry
  Introduce Hypercharge Y_L to preserve $U(1)_Y$

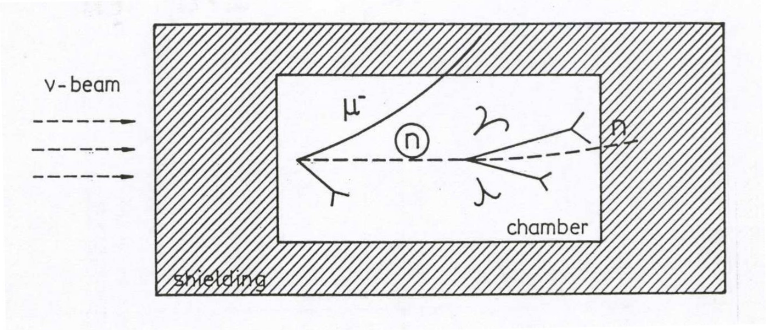
- 4) Arrive at a unified interaction with massive W/Z boson +massless γ

Electroweak interactions

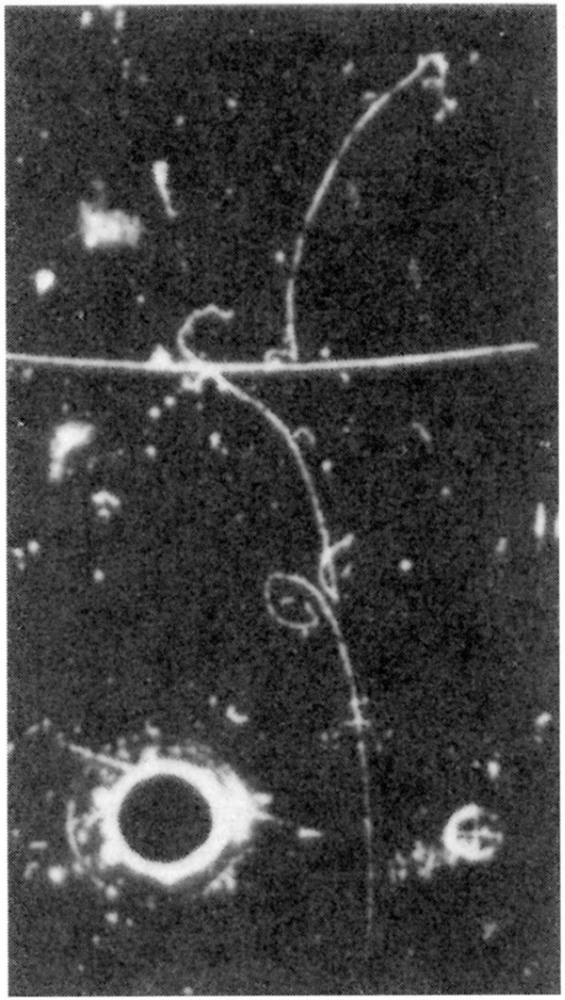
- Neutral current discovered in 1973
  with *Gargamelle* at CERN by observing eν → eν

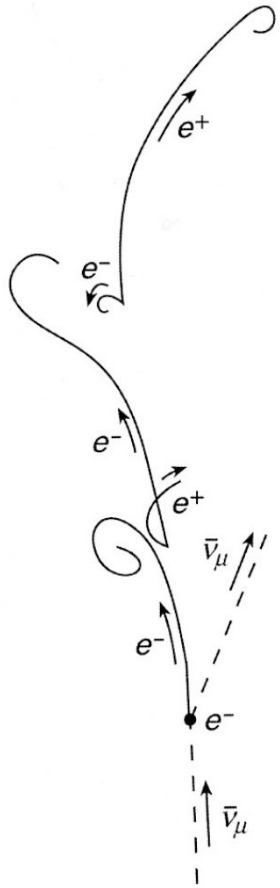
- Before this: no observation / indication of neutral current





Electroweak interactions: Discovery





The first picture of a neutral weak process

$\nu_\mu + e^- \rightarrow \nu_\mu + e^-$.

The neutrino enters from below (leaving no track), and strikes an electron. which moves upwards, emitting two photons (visible via the e+e- pairs from subsequent conversions)

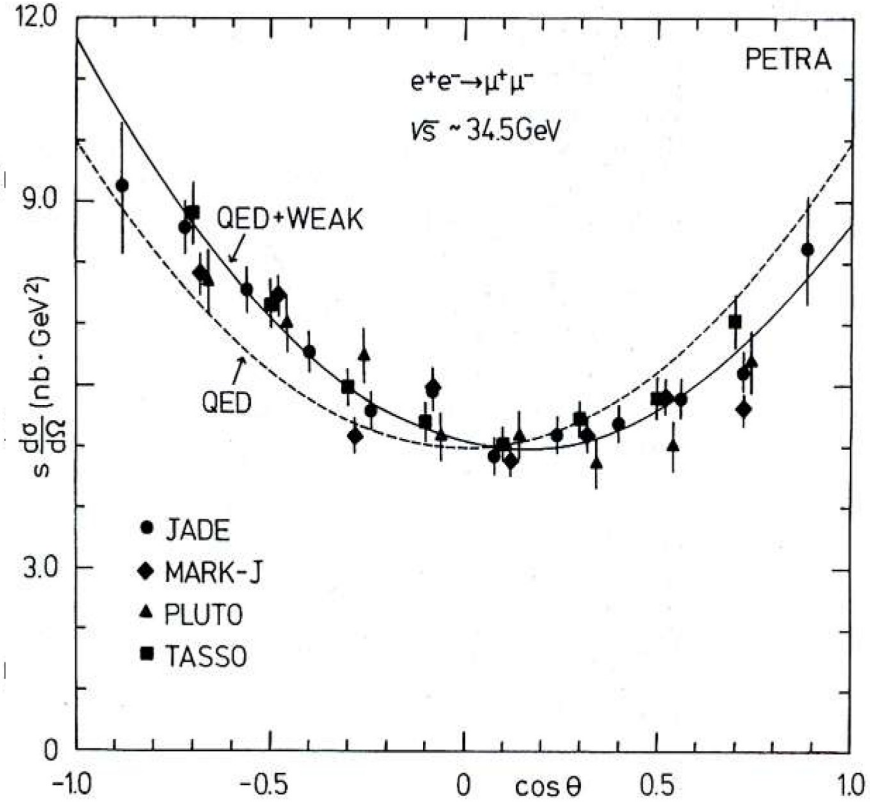
Angular relations in electroweak interactions

- Angular distributions changed by electroweak interactions

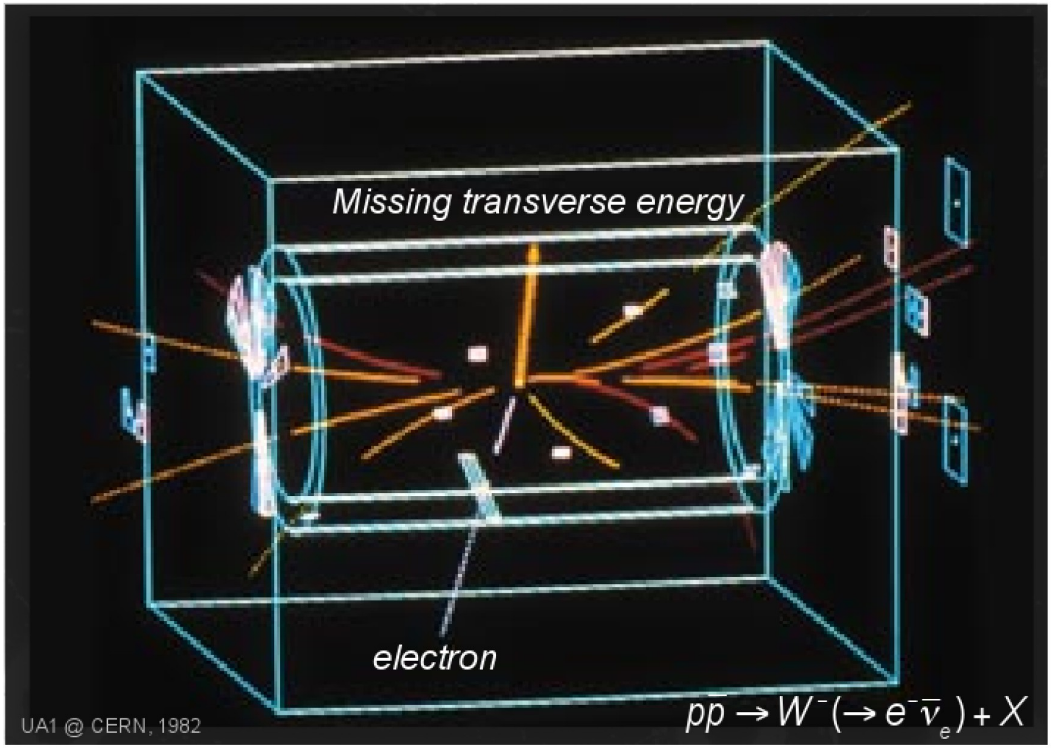
$$\frac{d\sigma_0^{\mathrm{EW}}}{d\Omega} = \frac{\alpha^2}{4s}\left(1+\cos^2\vartheta + A\cos\vartheta\right)$$

- Total cross sections unchanged

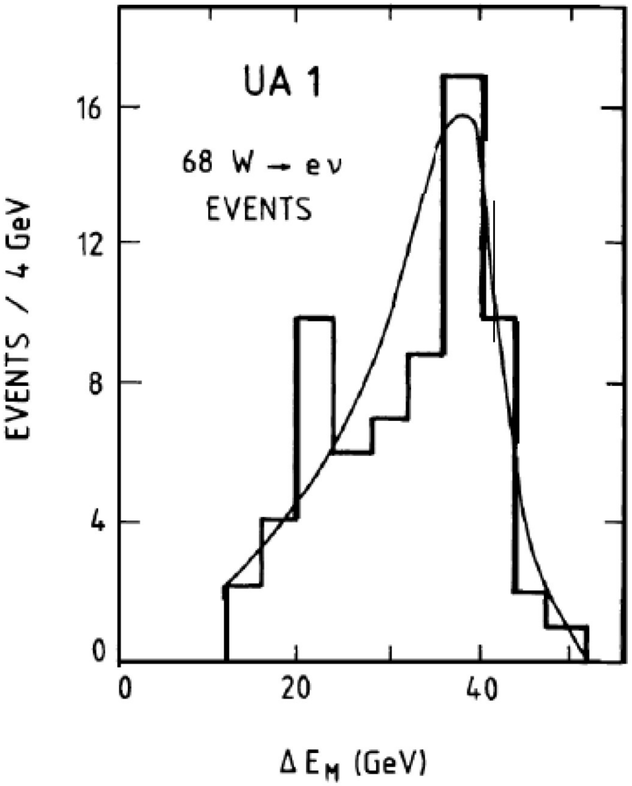
- Reason: V-A structure of neutral current (NC)



Discovery of W boson



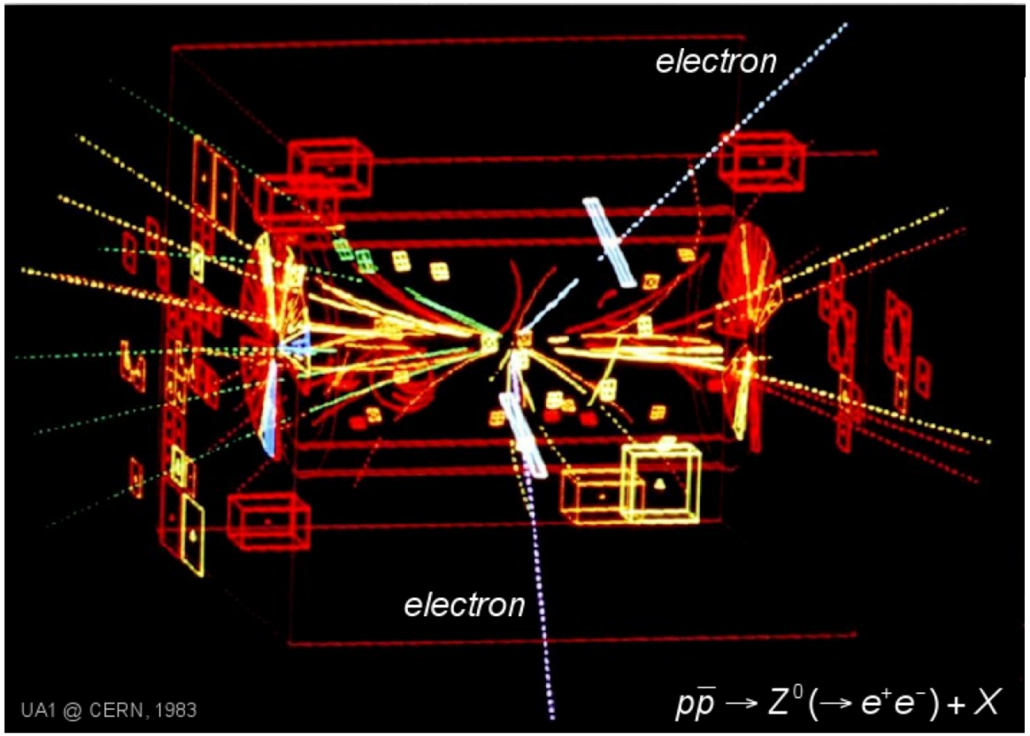
Missing transverse energy in events with $E_e > 15$ GeV

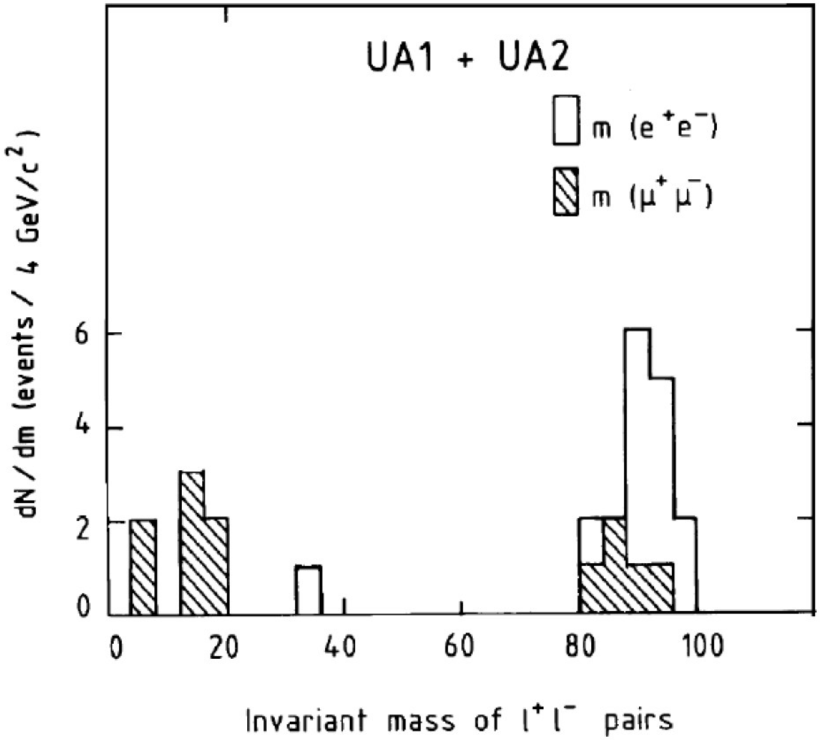


$$m_W = (80.9 \pm 1.5 \pm 2.4)\ \text{GeV}$$

C. Rubbia, Nobel Lecture, 1984

Discovery of Z boson

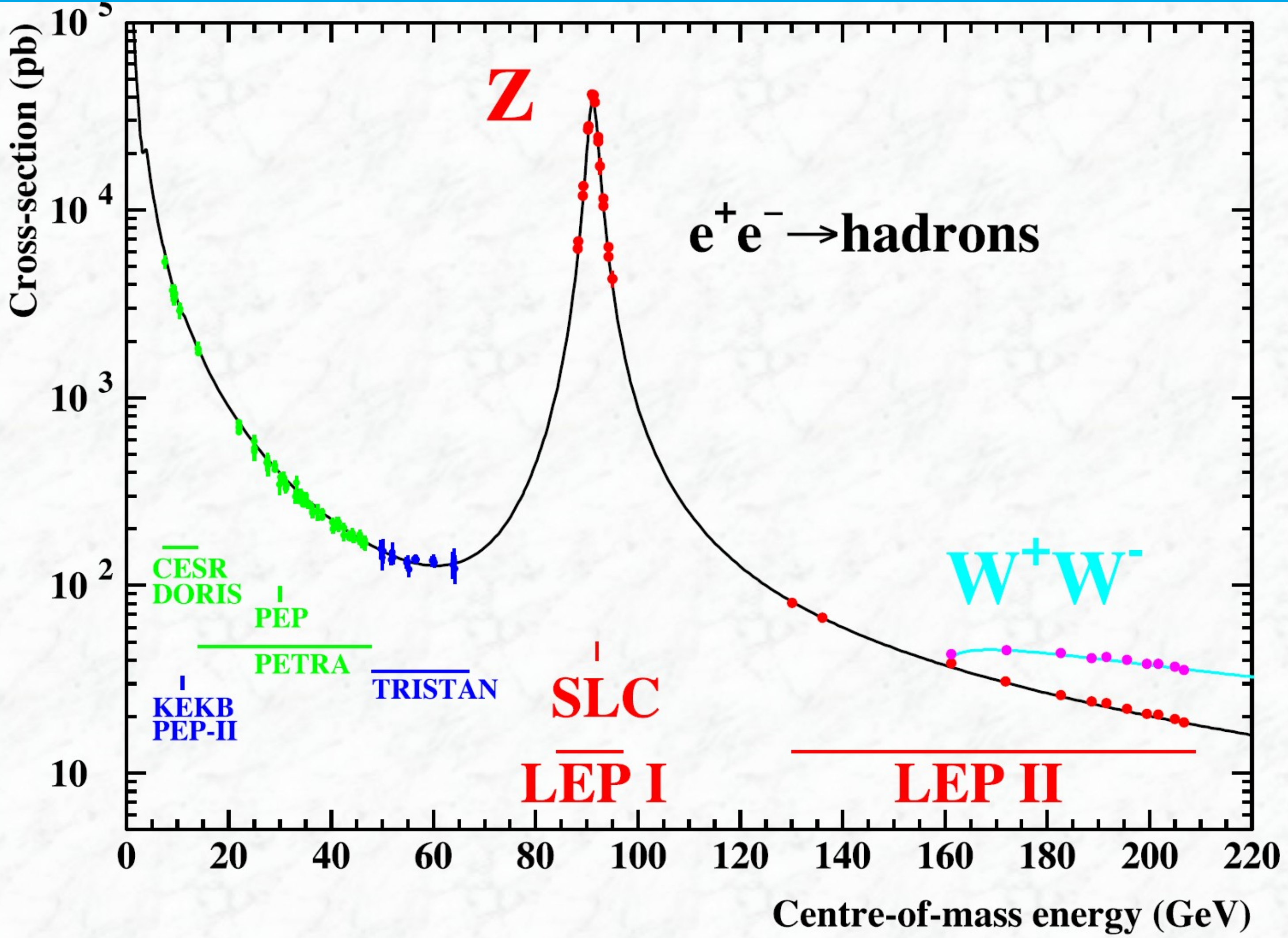




$$m_Z = (95.1 \pm 2.5)\ \mathrm{GeV}$$

- 1983: first signals with 6 W → eν and 4 Z → ee events
- 1984: Nobel prize for C. Rubbia (UA1) and S. van der Meer

Cross section of W/Z production



Precision tests of the Z sector

Tests of the W sector

LEP: Cross section of $e^+e^- \rightarrow \mu^+\mu^-$

$$\frac{d\sigma}{d\cos\theta} = \frac{\pi\alpha^2}{2s}\left[F_\gamma(\cos\theta) + F_{\gamma Z}(\cos\theta)\frac{s(s-M_Z^2)}{(s-M_Z^2)^2+M_Z^2\Gamma_Z^2} + F_Z(\cos\theta)\frac{s^2}{(s-M_Z^2)^2+M_Z^2\Gamma_Z^2}\right]$$

γ $\quad$ γ/Z interference $\quad$ Z

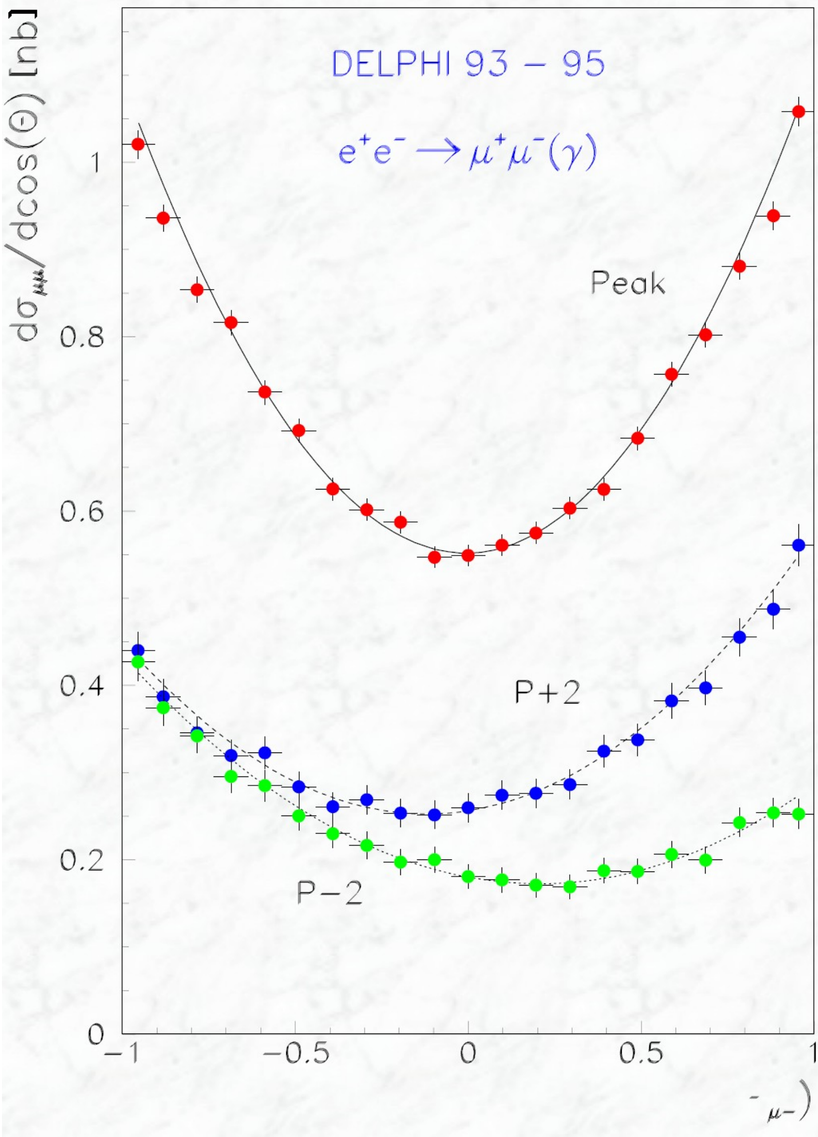
vanishes at $\sqrt{s} \approx M_Z$

$$\begin{aligned}
F_\gamma(\cos\theta) &= Q_e^2 Q_\mu^2(1+\cos^2\theta) = (1+\cos^2\theta) \\
F_{\gamma Z}(\cos\theta) &= \frac{Q_e Q_\mu}{4\sin^2\theta_W\cos^2\theta_W}[2g_V^e g_V^\mu(1+\cos^2\theta) + 4g_A^e g_A^\mu\cos\theta] \\
F_Z(\cos\theta) &= \frac{1}{16\sin^4\theta_W\cos^4\theta_W}[(g_V^{e^2}+g_A^{e^2})(g_V^{\mu^2}+g_A^{\mu^2})(1+\cos^2\theta) + 8g_V^e g_A^e g_V^\mu g_A^\mu\cos\theta]
\end{aligned}$$

$\alpha = \alpha(m_Z)$: running electromagnetic coupling [$\alpha(m_Z) = \alpha/(1-\Delta\alpha)$ with $\Delta\alpha \approx 0.06$]

g_V, g_A = c_V, c_A: effective coupling constants (vector and axial vector)

LEP: Cross section of $e^+e^- \to \mu^+\mu^-$



$$F_\gamma(\cos\theta) = Q_e^2 Q_\mu^2 (1+\cos^2\theta) = (1+\cos^2\theta)$$

$$F_{\gamma Z}(\cos\theta) = \frac{Q_e Q_\mu}{4\sin^2\theta_W \cos^2\theta_W}[2 g_V^e g_V^\mu (1+\cos^2\theta) + 4 g_A^e g_A^\mu \cos\theta]$$

$$F_Z(\cos\theta) = \frac{1}{16\sin^4\theta_W \cos^4\theta_W}[(g_V^{e^2} + g_A^{e^2})(g_V^{\mu^2} + g_A^{\mu^2})(1+\cos^2\theta) +$$

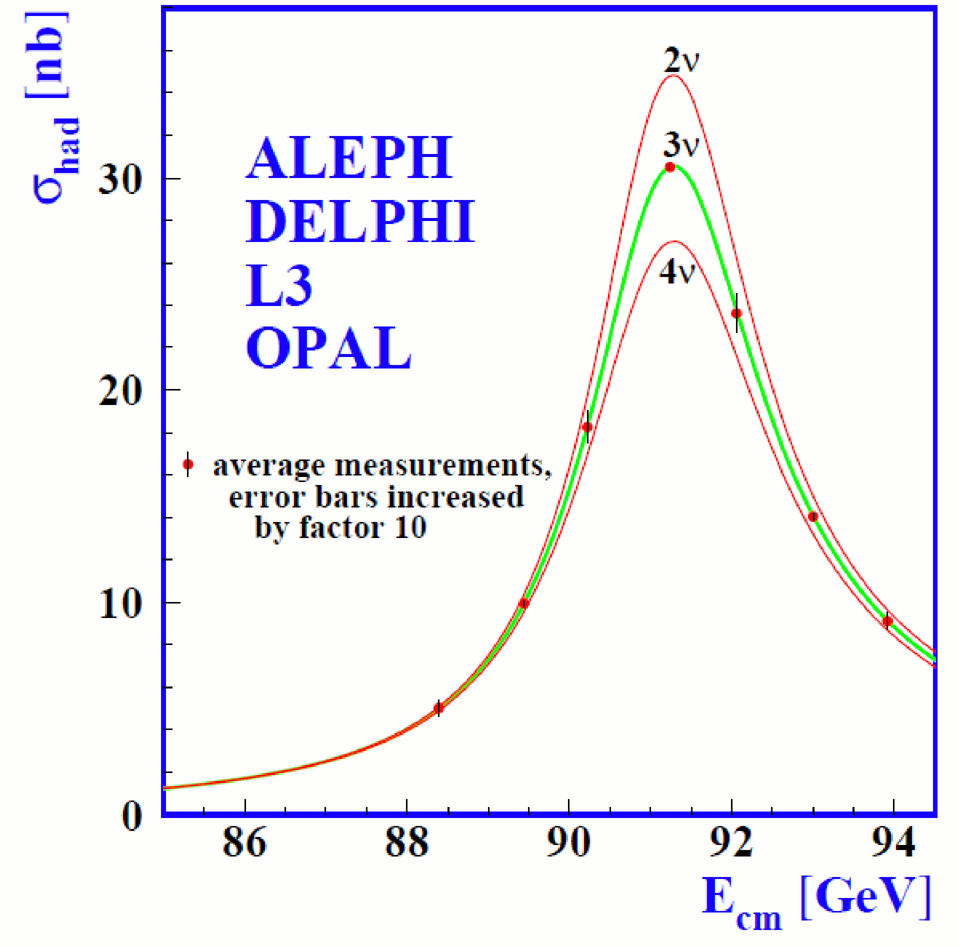
$$8 g_V^e g_A^e g_V^\mu g_A^\mu \cos\theta]$$

Terms ∝ cosθ in dσ/dcosθ
→ asymmetry

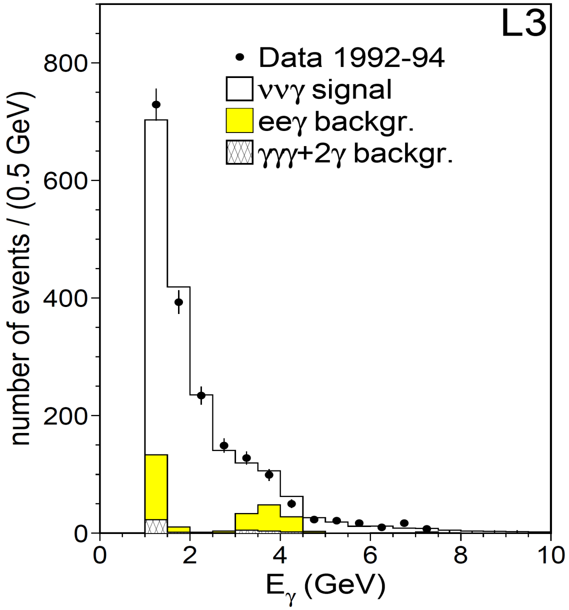
$$\sigma_{F(B)} = \int_{0(-1)}^{1(0)} \frac{d\sigma}{d\cos\theta} d\cos\theta$$

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

LEP: Number of light neutrinos

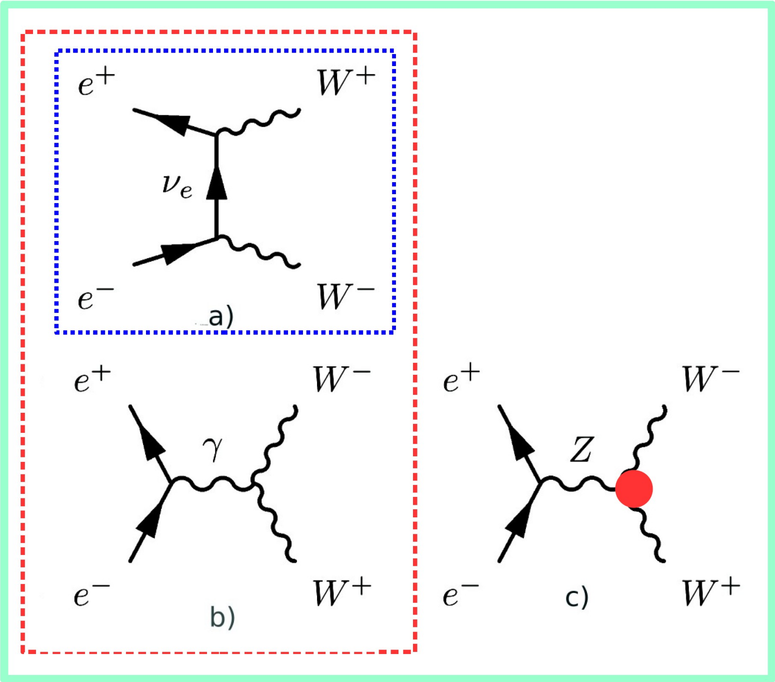


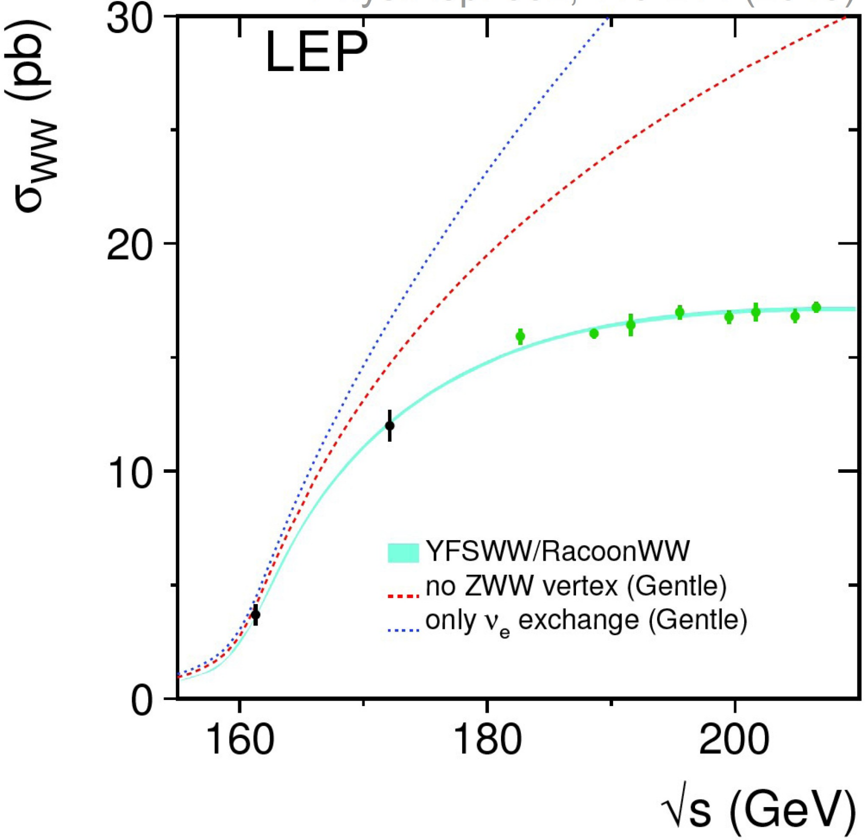
- Data selected using invisible Z decays with photon radiation



LEP: WW production and the TGC vertex

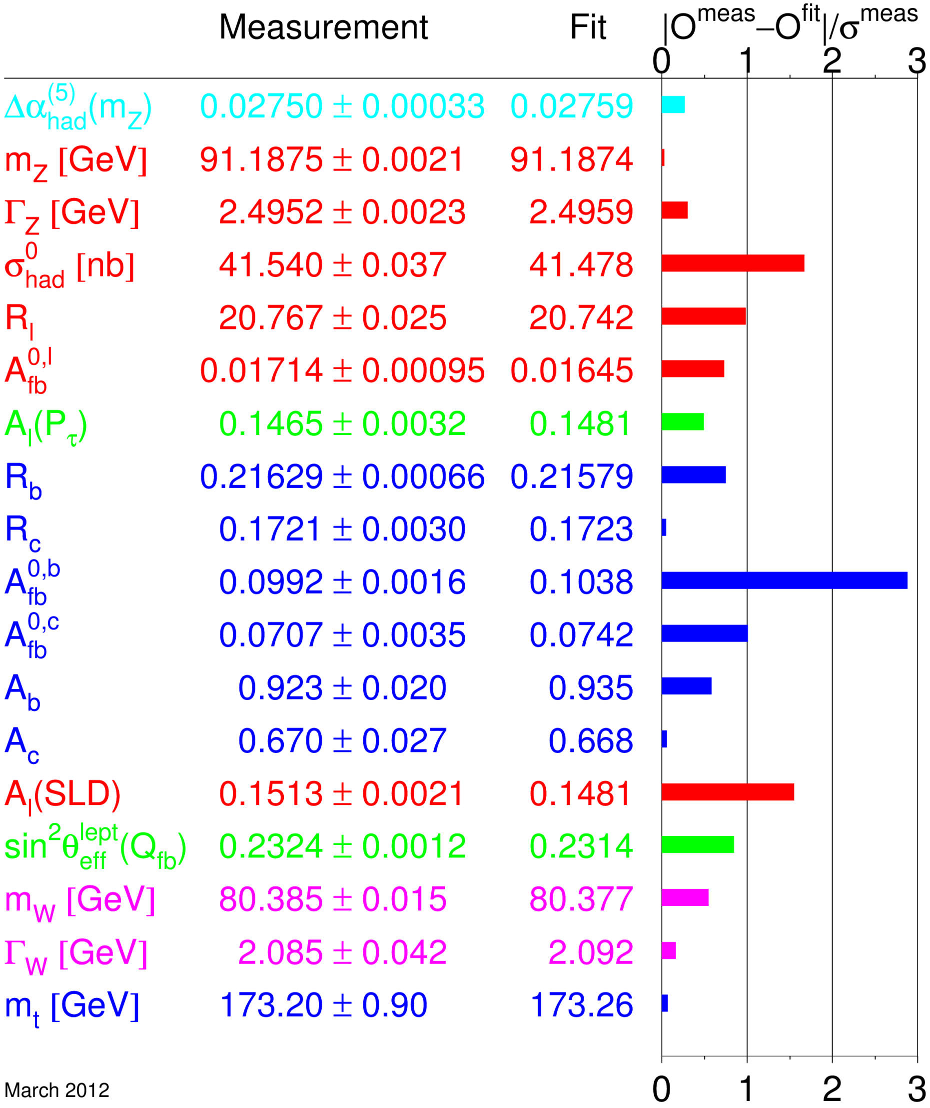
- LEP also proved self-interaction of weak bosons through indirect measurement of triple gauge coupling vertex
- Interference between all three diagrams leads to “safe” energy behavior





Phys.Rep. 532, 119-244 (2013)

LEP: Consistent picture of electroweak parameters



	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02750 ± 0.00033	0.02759
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ_{had}^{0} [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.385 ± 0.015	80.377
Γ_W [GeV]	2.085 ± 0.042	2.092
m_t [GeV]	173.20 ± 0.90	173.26

March 2012

LEP: Quantum corrections and the Higgs

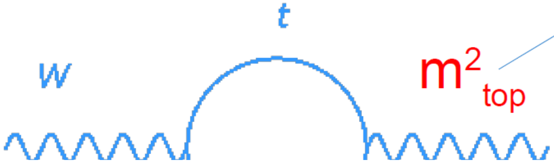
$$m_W = \left(\frac{\pi\,\alpha_{EM}}{\sqrt{2}\,G_F}\right)^{1/2}\frac{1}{\sin\theta_W\,\sqrt{1-\Delta r}}$$

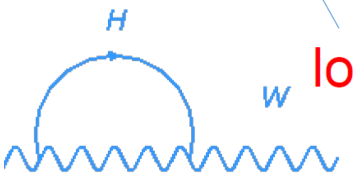
Radiative corrections

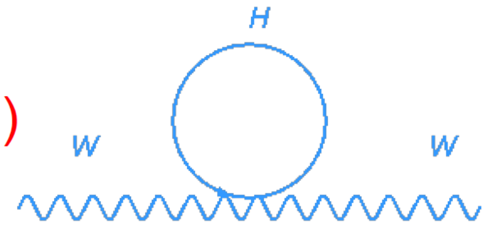
$\Delta r \sim 3\ \%$

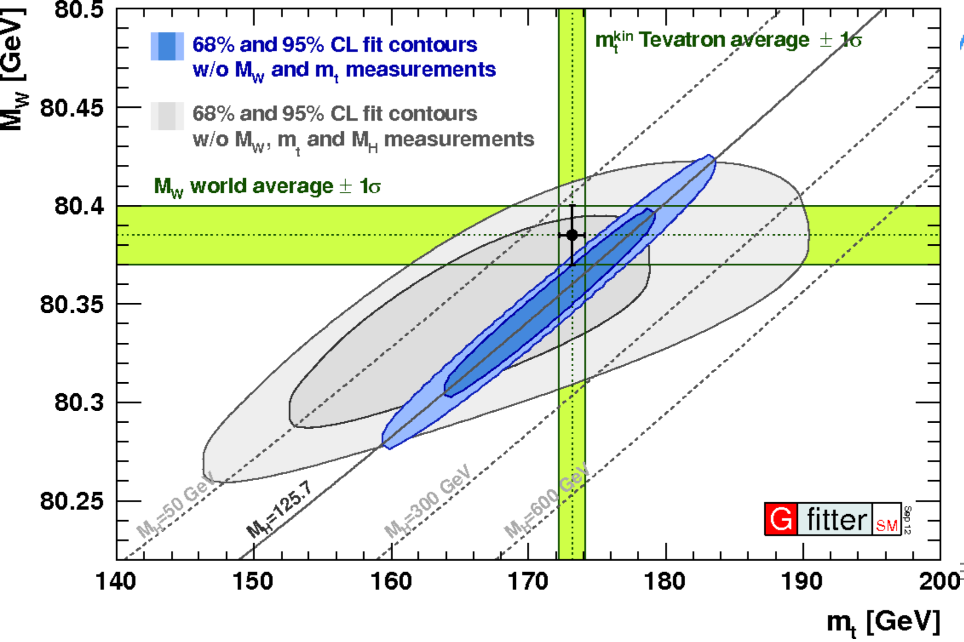
m^2_{top}

$\log(M_H)$

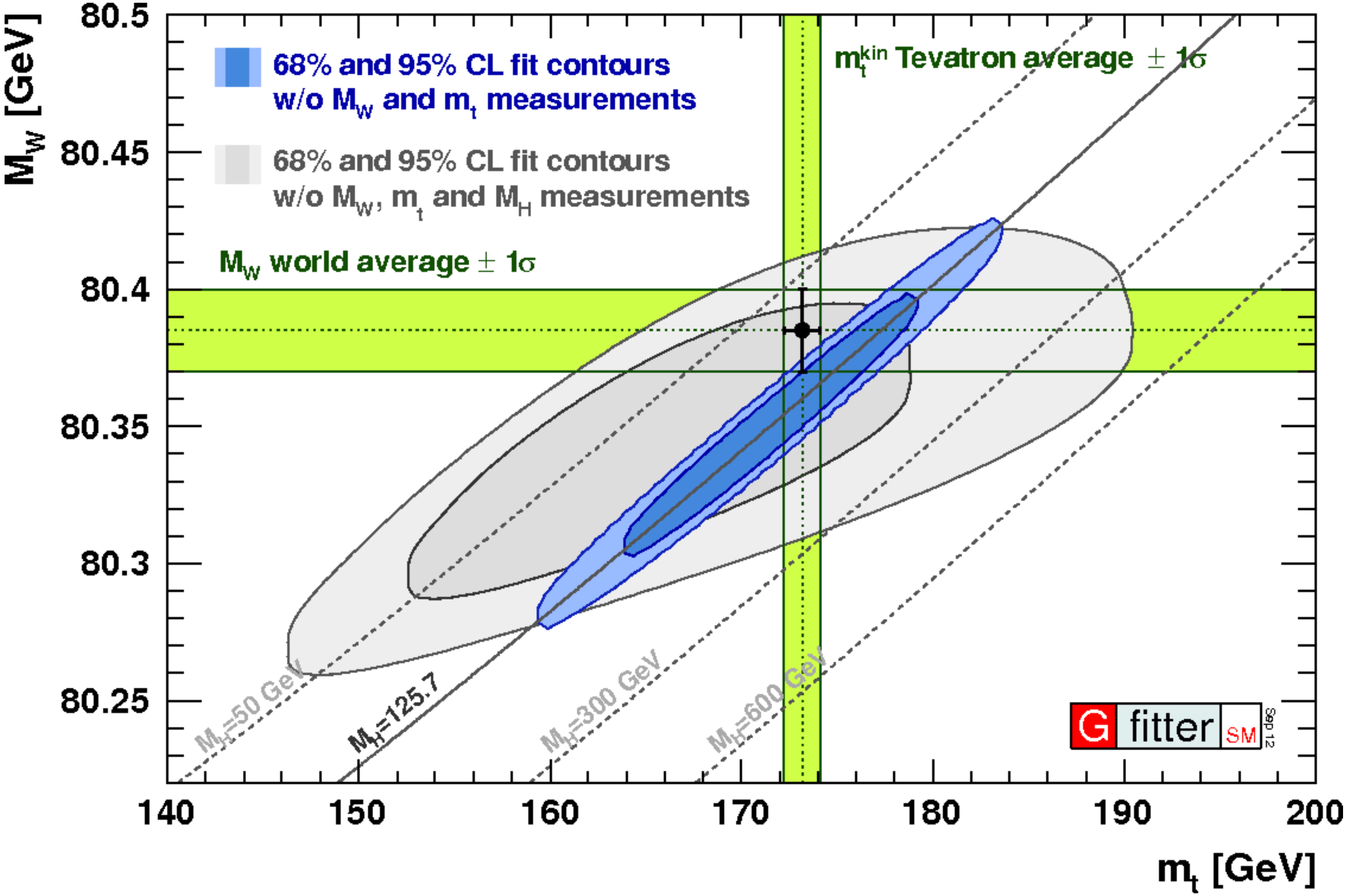




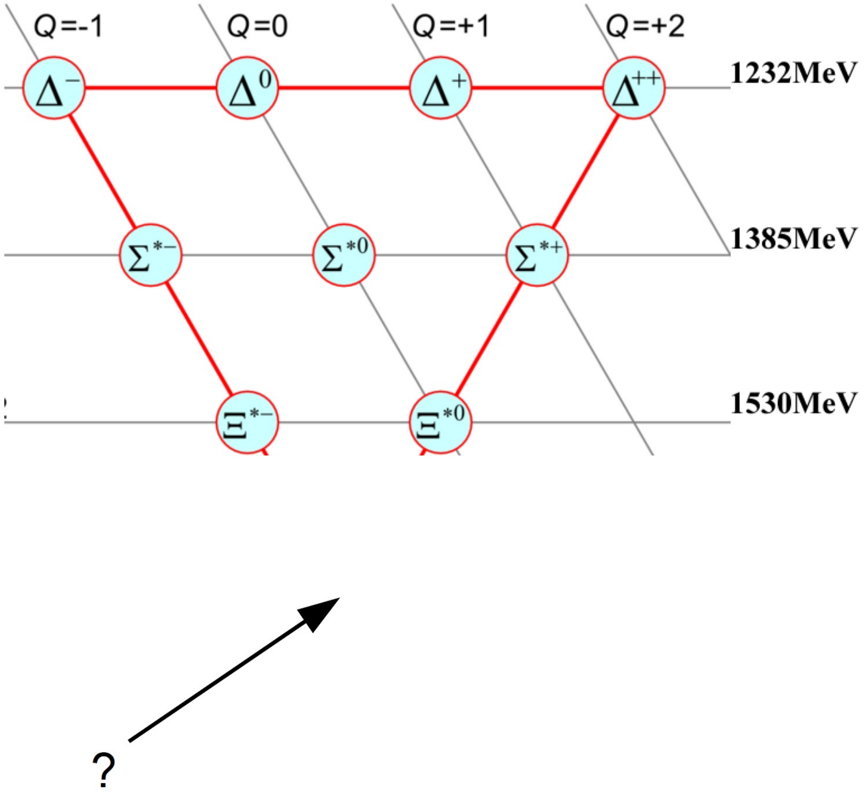




LEP: Quantum corrections and the Higgs



Baryon Decuplet

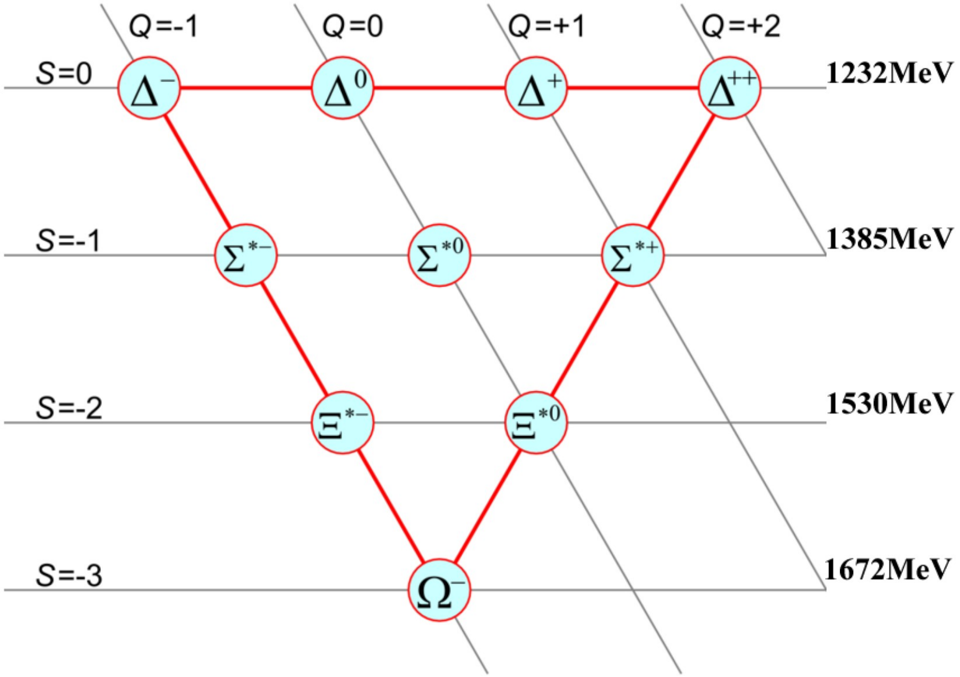


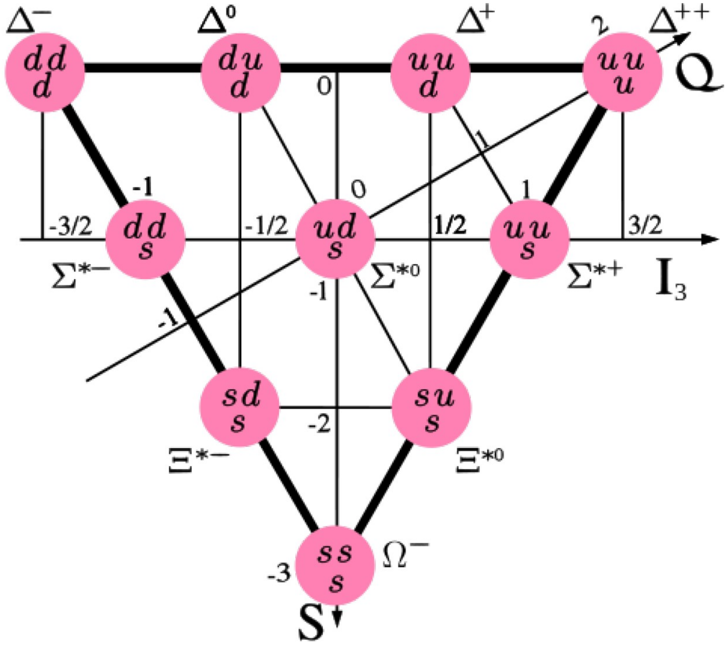
- by the early 1960's many new particles found ("particle zoo")
- try to find ordering principles
- e.g. order all spin-3/2 baryons by mass (or isospin) and charge
- lead to the postulate of quarks
- 1963: prediction of a baryon with isospin 0 at the lower tip

Baryon Decuplet: Omega Discovery

- 1964: Ω^- found, triumph of quark model

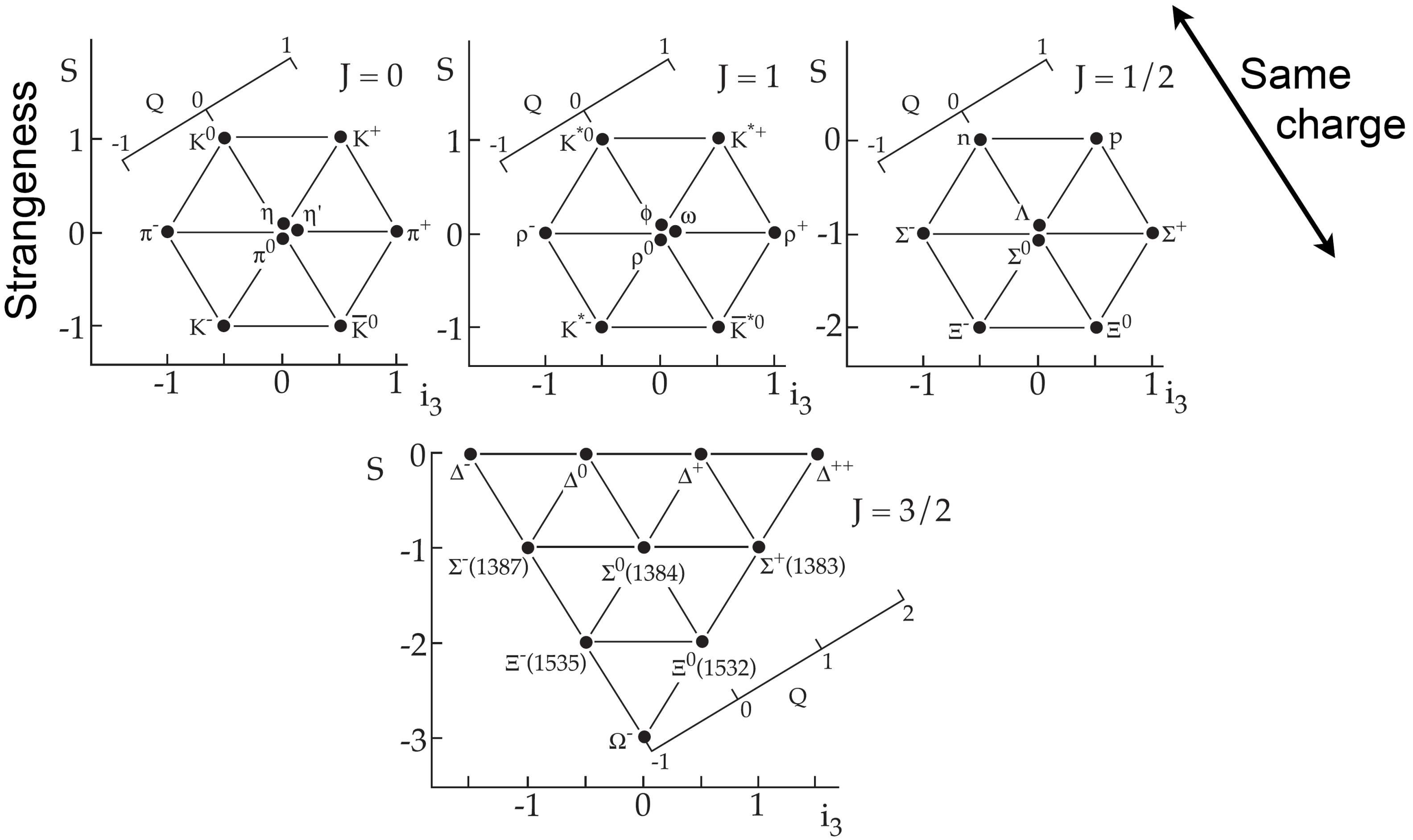
Nobel Prize 1969
for M. Gell-Mann





- “identical” states for all three quarks for Λ^-, Λ^{++} and Ω^- lead to proposal of colour charge

Quarks



Same charge

Strangeness

Isospin third component

LEP: Quantum corrections and the Higgs

Wave function of Δ^{++}: $|\Delta^{++}\rangle = |u,\uparrow\rangle + |u,\uparrow\rangle + |u,\uparrow\rangle$

Symmetric in flavour, spin and space (quarks are in ground state: s-wave)

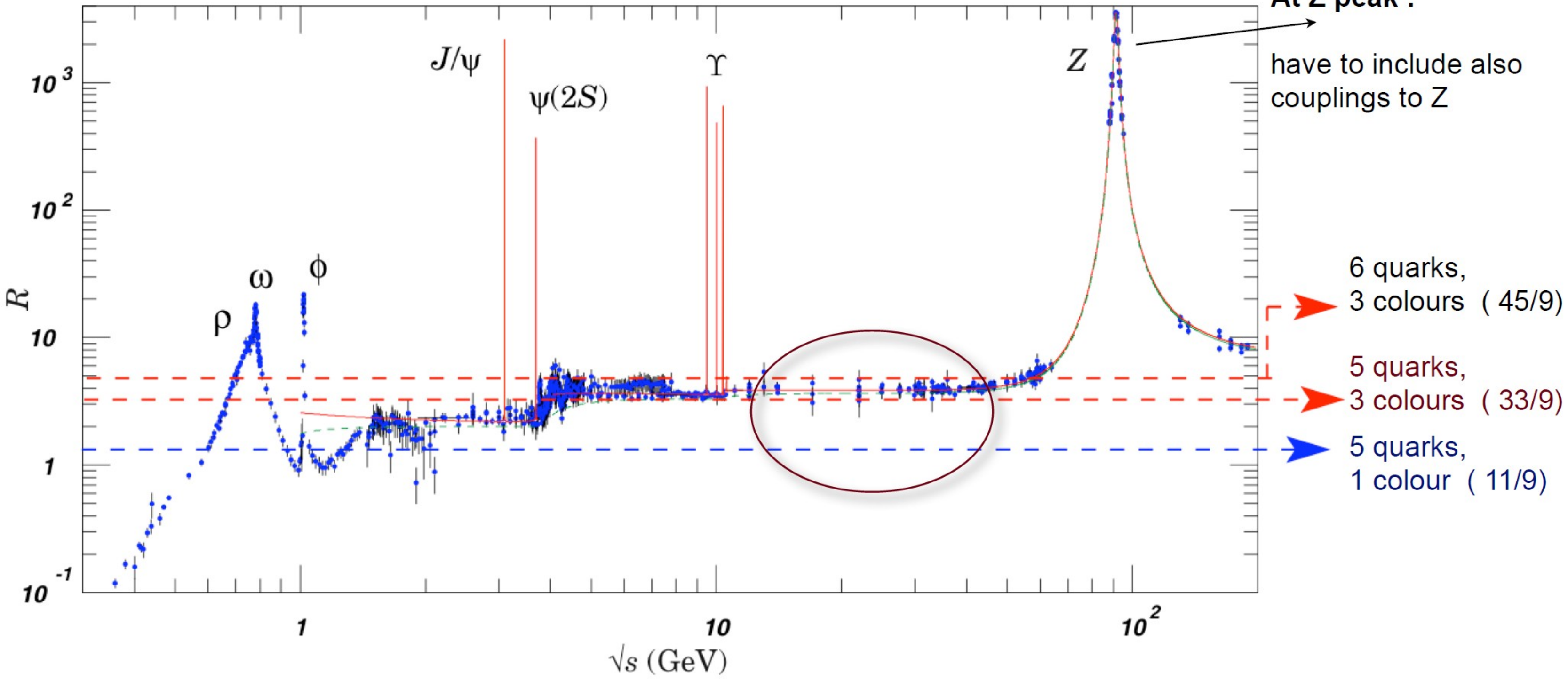
Violates the Pauli Principle!

Solution: one more internal degree of freedom - colour!

$$|\Delta^{++}\rangle = |u,\uparrow,g\rangle + |u,\uparrow,r\rangle + |u,\uparrow,b\rangle$$

Tests of QCD: Hadron pair production

- Prediction for Ratio: $R = \frac{\sigma^{e^+e^-\to \text{hadrons}}}{\sigma^{e^+e^-\to\mu^+\mu^-}} = N_c \sum_q e_q^2$



At Z peak :

have to include also couplings to Z

6 quarks, 3 colours (45/9)

5 quarks, 3 colours (33/9)

5 quarks, 1 colour (11/9)

$$R = N_c \sum_q e_q^2 = N_c \left[\underbrace{\left(\frac{2}{3}\right)^2}_{u} + \underbrace{\left(-\frac{1}{3}\right)^2}_{d} + \underbrace{\left(-\frac{1}{3}\right)^2}_{s} + \underbrace{\left(\frac{2}{3}\right)^2}_{c} + \underbrace{\left(-\frac{1}{3}\right)^2}_{b} \right] = N_c \frac{11}{9}.$$

Scattering experiments

- Transferred momentum:

  $$q = k - k'$$

- Virtuality of exchanged boson:

  $$Q^2 = -q^2 > 0$$

- Squared centre-of-mass energy:

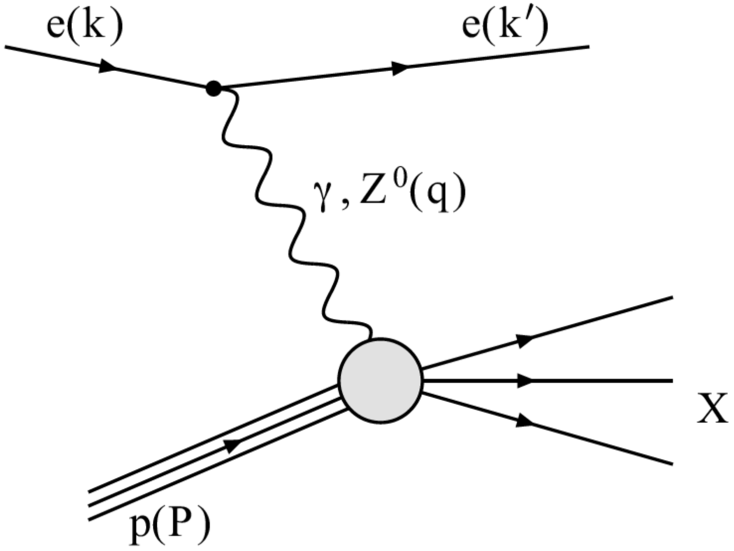
  $$s = (P + k)^2$$

- Squared mass of the hadronic final state:

  $$W^2 = (P + q)^2 = M^2 + 2q \cdot P - Q^2$$

- Inelasticity: $y = \frac{q \cdot P}{k \cdot P}$ with $0 \leq y \leq 1$

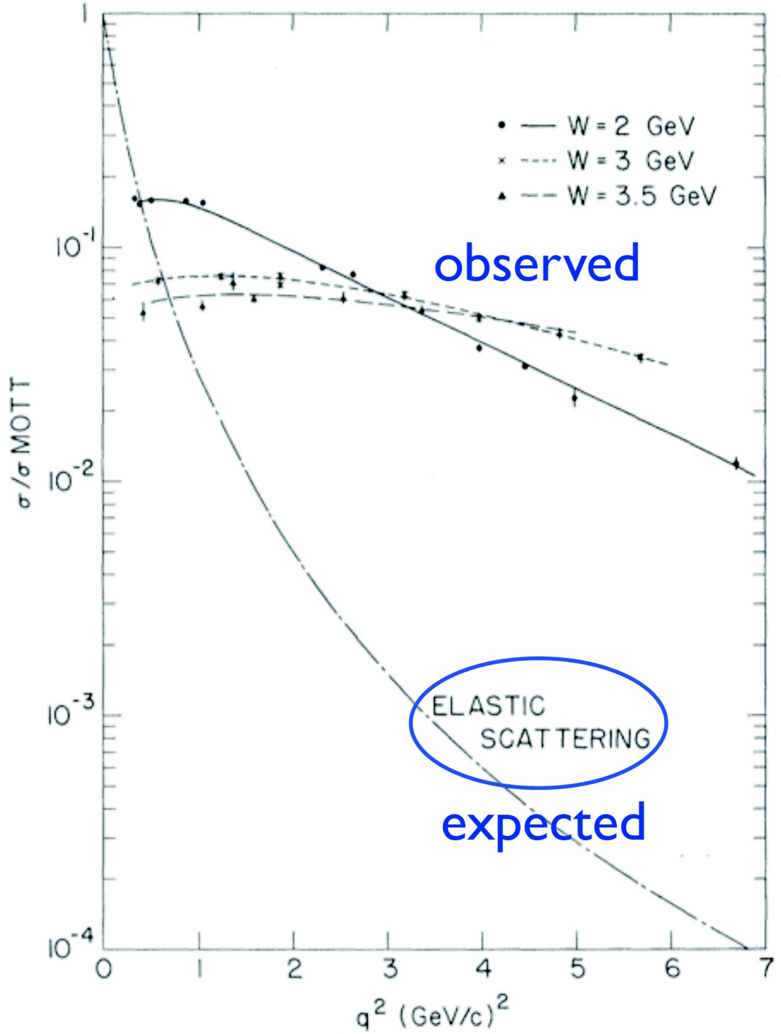
- Scaling variable: $x = \frac{Q^2}{2q \cdot P}$ with $0 \leq x \leq 1$



Deep: $Q^2 \gg M^2$

Inelastic: $W > M$

Scattering experiments



M. Breidenbach *et al.*, Phys. Rev. Lett. 23, 935 (1969)

Early results from SLAC (1969):

$E = 7 - 17.7$ GeV

$\theta = 10°$

Elastic cross section falls off rapidly due to the proton not being point-like

Inelastic: $W > M$

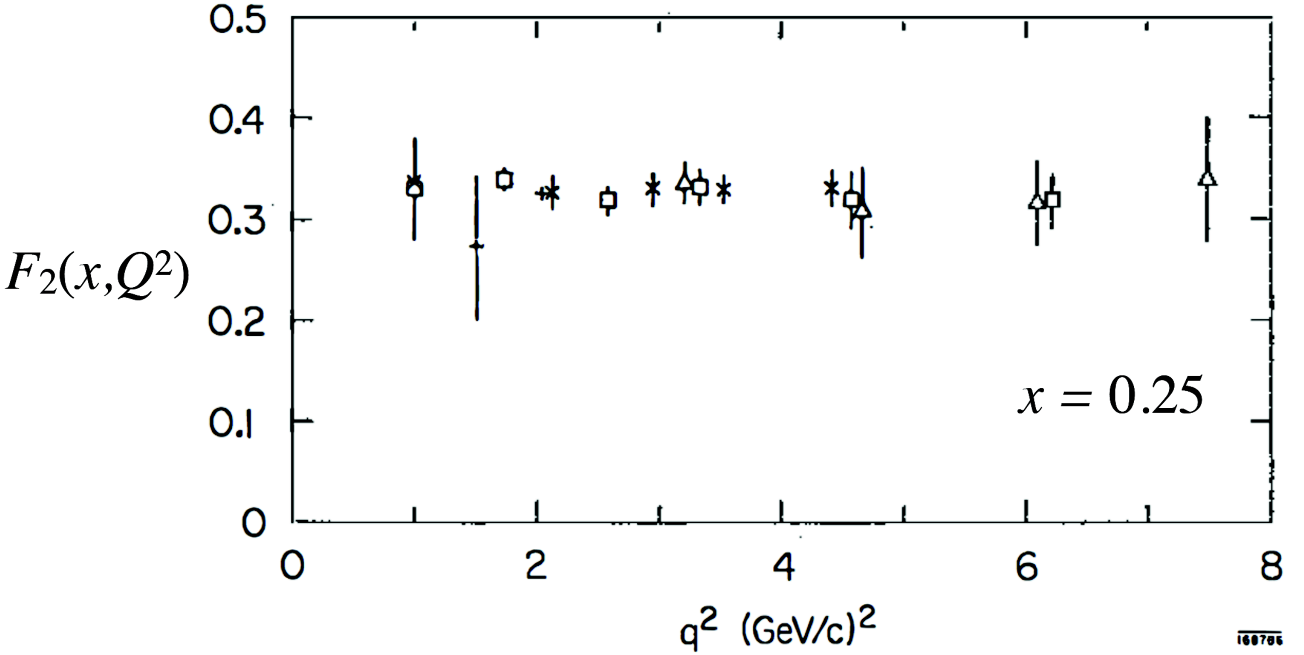
Ratio to Mott cross section nearly flat in Q^2

Q^2 dependence becomes weaker for increasing W

Proton a composite particle!

Scattering experiments

J.T. Friedman, H.W. Kendall, Ann. Rev. Nucl. Sci. 22, 203 (1972)



Scaling!

Independence of the structure functions of Q^2: $F_i(x,Q^2) = F_i(x)$

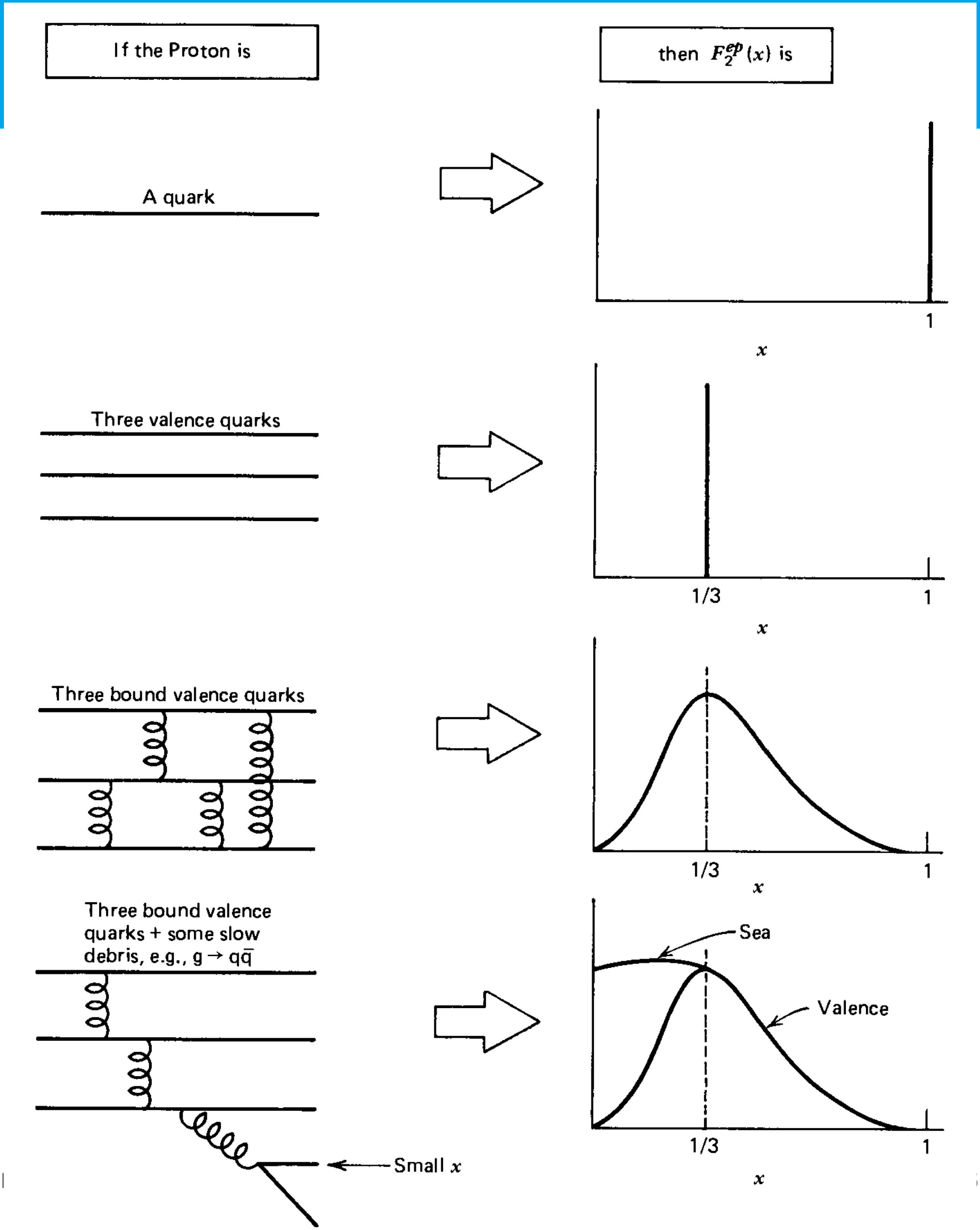
J.D. Bjørken predicted scaling for $Q^2 \to \infty$ as x stays fixed.
Scaling is obtained using Gell-Mann's current algebra in the quark model.

Scattering from point-like constituents of the proton!

“Reality” of Quarks

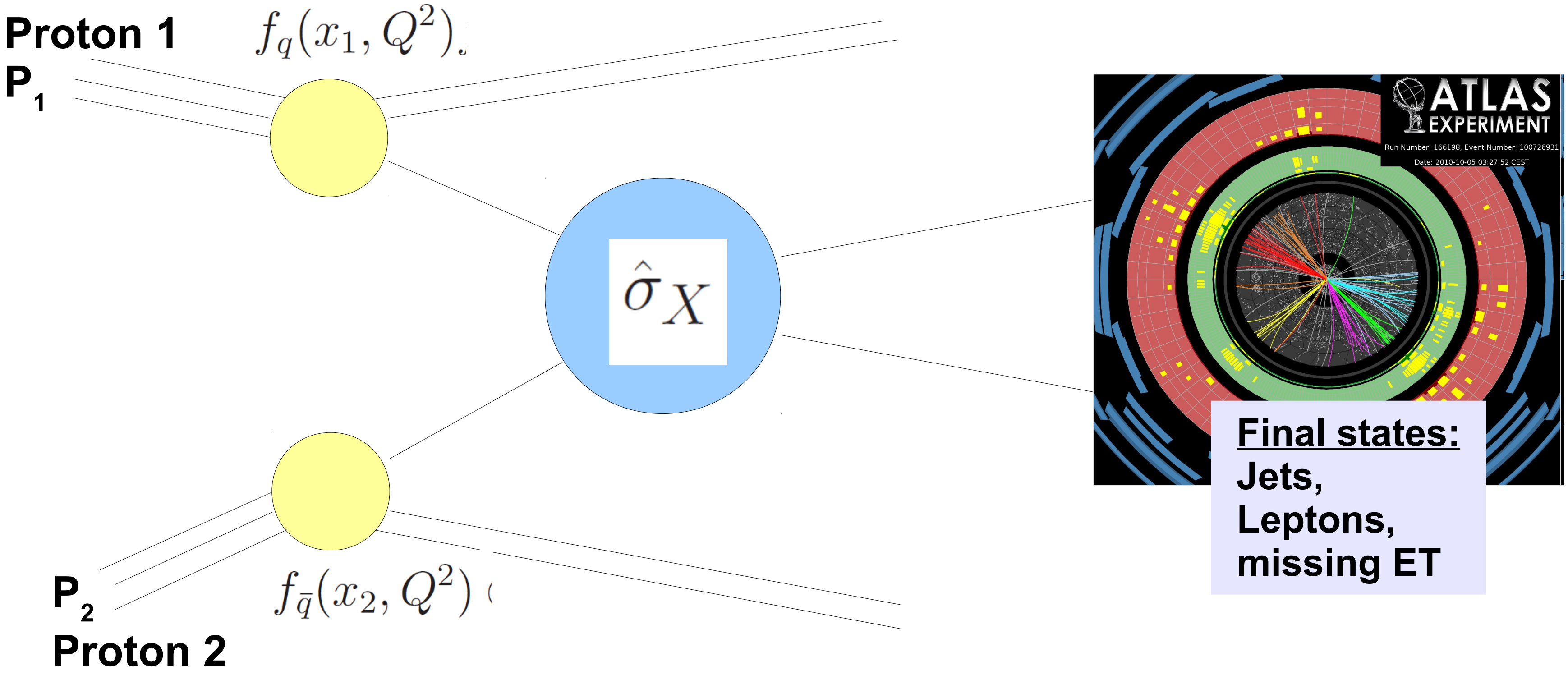
- originally, when proposed in 1964 by Gell-Mann and Zweig, “quarks” were considered by many physicists just a principle for ordering the new-found particle zoo
- if the quarks really correspond to constituents of the hadrons was not clear
- in 1968, deep inelastic electron-proton scattering at SLAC showed that the proton consisted of smaller constituents, then called “partons” by Feynman
- only slowly it was accepted that the partons in the proton correspond to the *u* and *d* quarks

  → Quark-Parton-Model (QPM)


If the Proton is
then $F_2^{ep}(x)$ is
A quark
1
x
Three valence quarks
1/3
1
x
Three bound valence quarks
1/3
1
x
Three bound valence quarks + some slow debris, e.g., g → q$\bar{q}$
Small x
Sea
Valence
1/3
1
x

PDFs at Hadron colliders

$f_q(x_1, Q^2)$ **Probability to find parton with momentum fraction x in proton**



Final states:
Jets,
Leptons,
missing ET

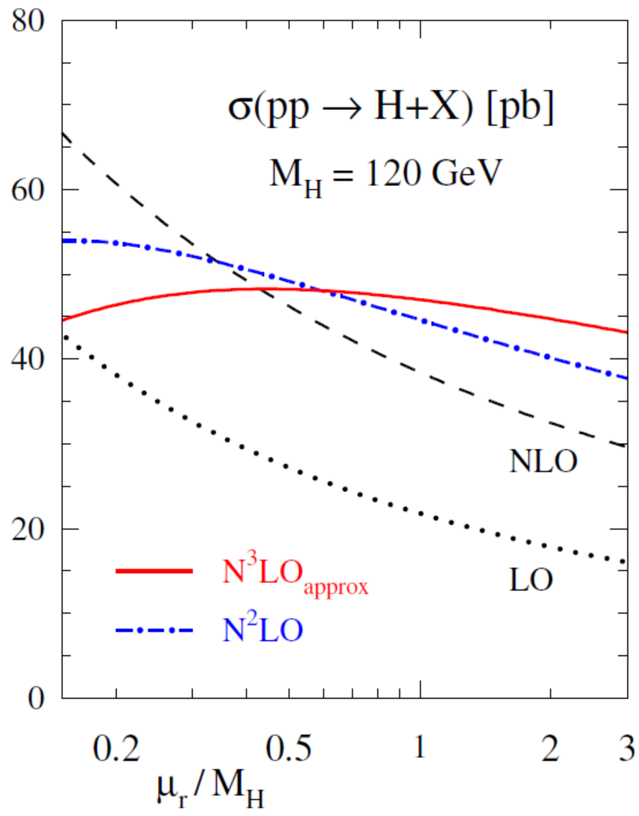
phenomenological part

Analytical part

$$\sigma_{PP\to X} = PDF \otimes \sigma_{\text{hardscatter}} = \sum_q \int dx_1 dx_2 f_q(x_1, Q^2) f_{\bar{q}}(x_2, Q^2) \otimes \hat{\sigma}_{q\bar{q}\to X}(\alpha, Q^2)$$

Analytical part

Moch, Vogt '05

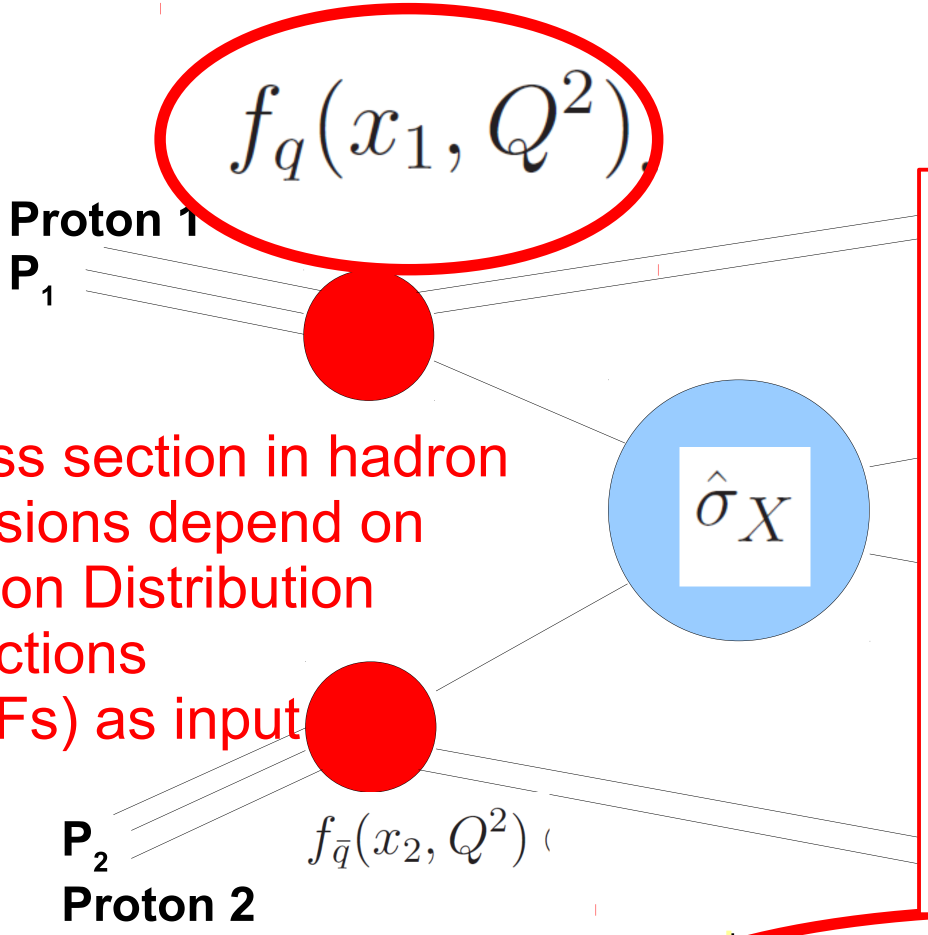


- ➔ Renormalization Scale dependence
- ➔ Factorization Scale dependence
- ➔ Electroweak input-parameter scheme
- ➔ ....

phenomenological part Analytical part

$$\sigma_{PP\to X} = PDF \otimes \sigma_{\text{hardscatter}} = \sum_q \int dx_1 dx_2 f_q(x_1, Q^2) f_{\bar{q}}(x_2, Q^2) \otimes \hat{\sigma}_{q\bar{q}\to X}(\alpha, Q^2)$$

PDFs at Hadron colliders



Cross section in hadron collisions depend on Parton Distribution Functions (PDFs) as input

- → Not calculable from first principles!!!
- → Dependence on input data
- → Fitting scheme
- → PDF parametrization
- → ....

phenomenological part

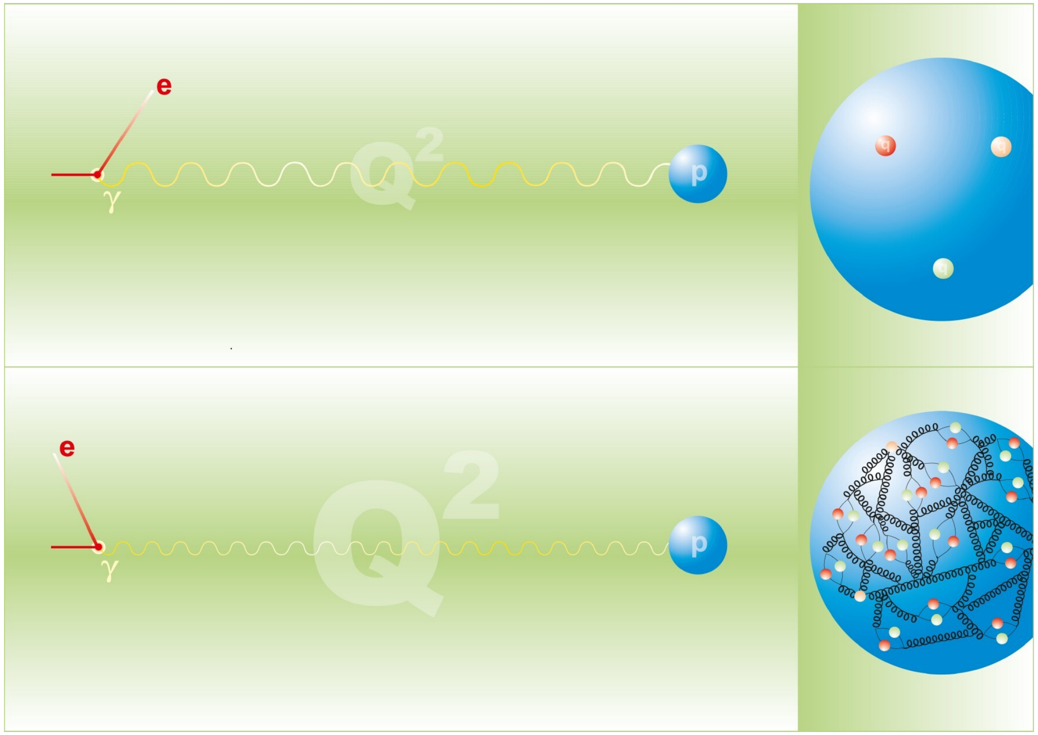
Analytical part

$$\sigma_{PP\to X} = PDF \otimes \sigma_{\text{hardscatter}} = \sum_q \int dx_1 dx_2 f_q(x_1, Q^2) f_{\bar q}(x_2, Q^2) \otimes \hat\sigma_{q\bar q\to X}(\alpha, Q^2)$$

PDFs at Hadron colliders

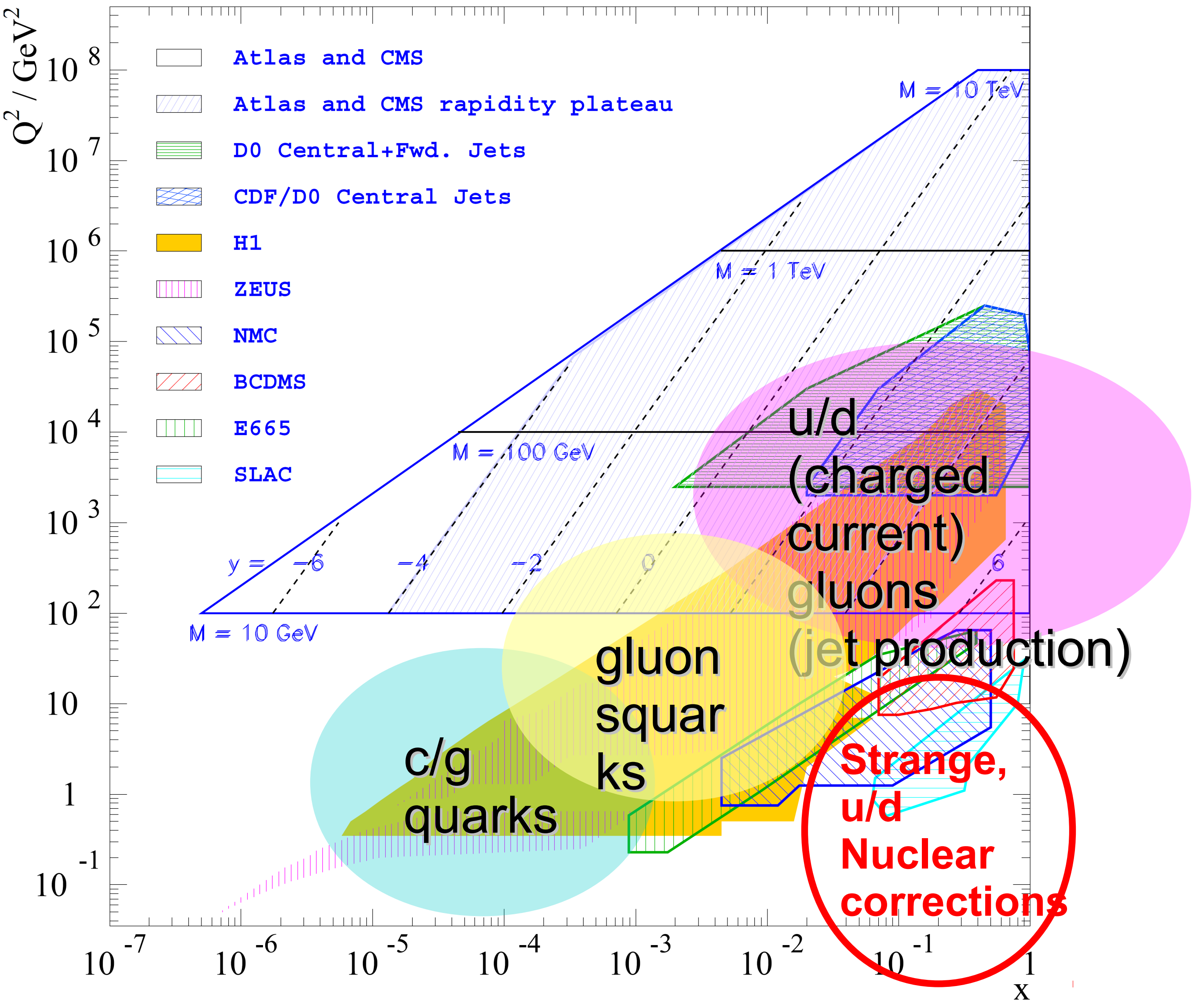
Probability to find a parton q carrying momentum fraction x of the proton momentum to enter a collision at a momentum transfer squared Q^2

$$f_q(x_1, \boxed{Q^2})$$



$$\frac{\Delta E}{\Delta t} \leq \hbar/2$$

Input measurements



u/d (charged current) gluons (jet production)

gluon squarks

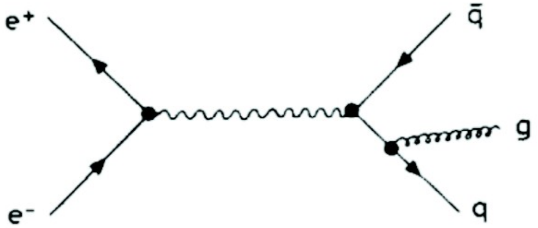
c/g quarks

Strange, u/d Nuclear corrections

The gluon

Three-Jet Events in e^+e^-

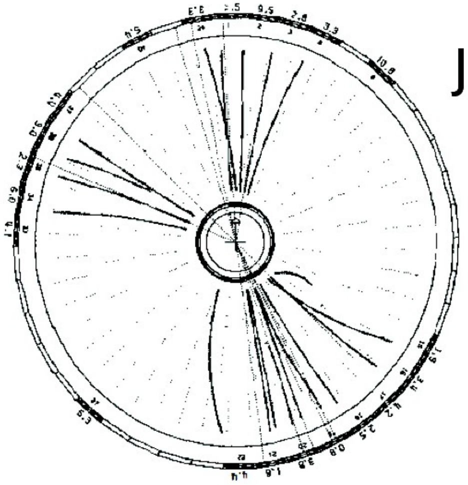
Radiation of a gluon leads to 3-jet structure



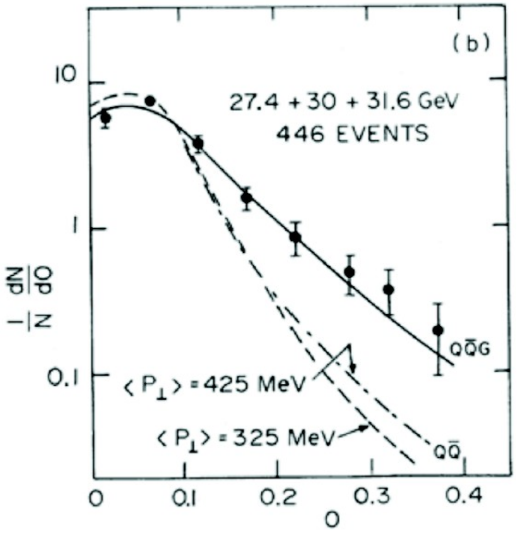
First observed at PETRA (higher CMS energy than at DORIS)

Oblateness: $O = F_{\text{major}} - F_{\text{minor}}$

O is small for 2-jet events and becomes larger for 3-jet events, proportional to the P_T of the radiated gluon



JADE

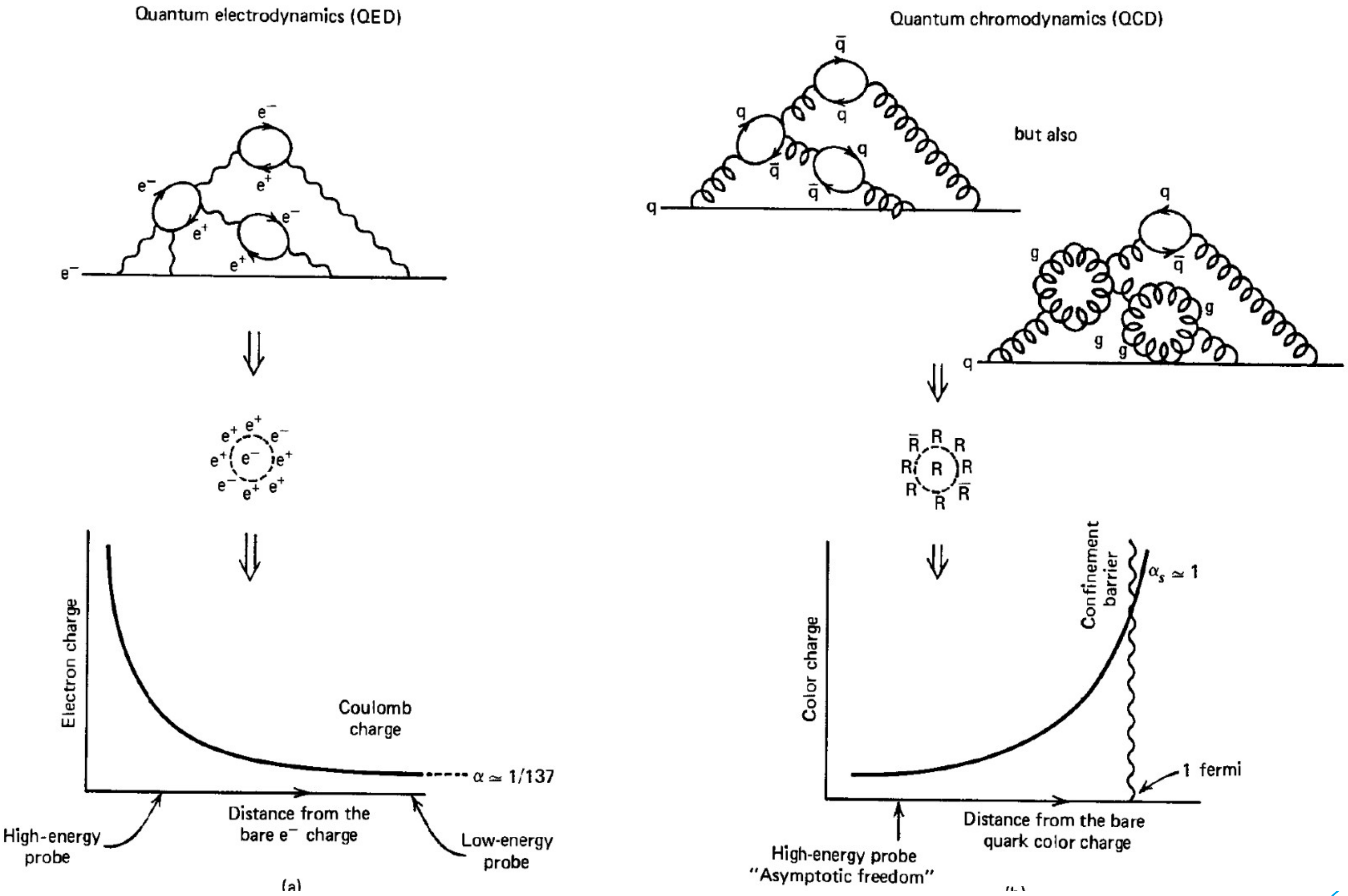


D. P. Barber (Mark-J), Phys.Lett.B89, 139(1979)

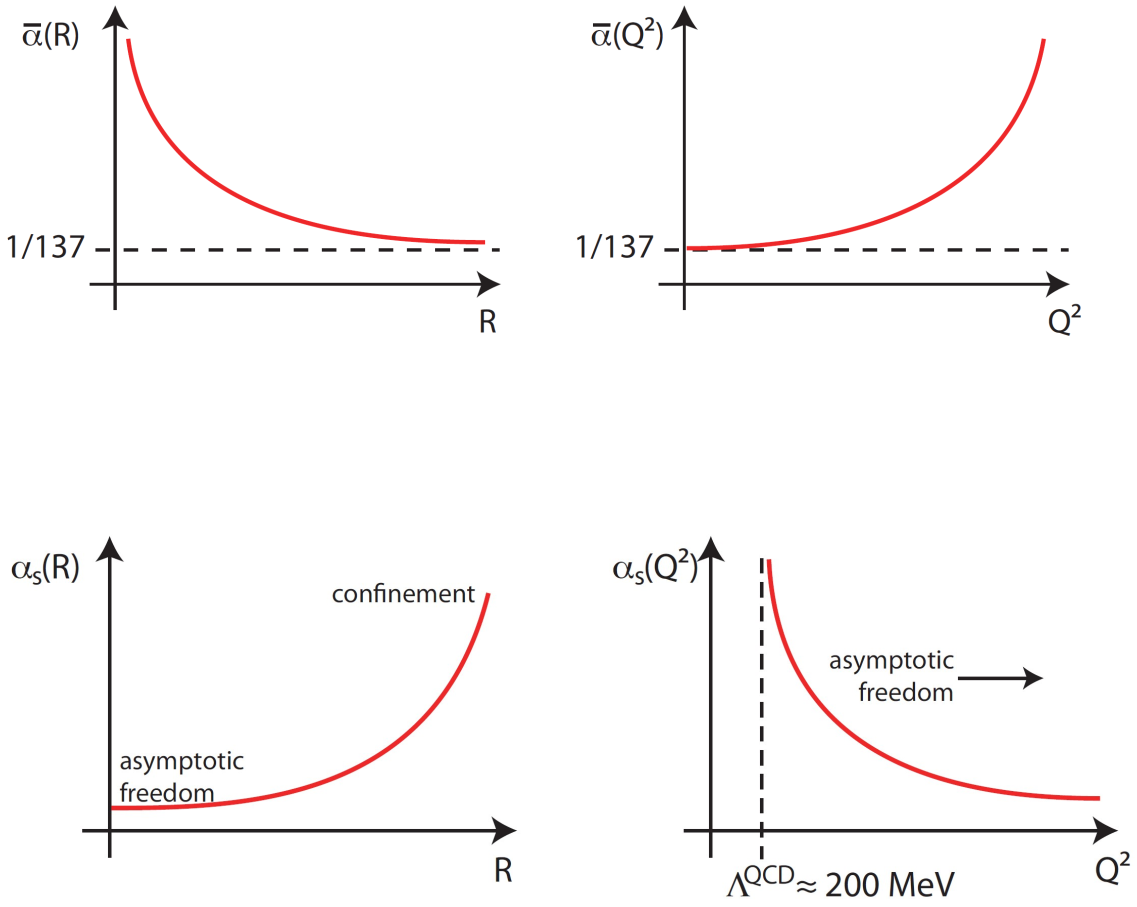
Confinement

1

α



Confinement



The end

- Short introduction
- Some things not covered: The Higgs, flavour physics
- Partly in some of the other lectures....
- Questions?