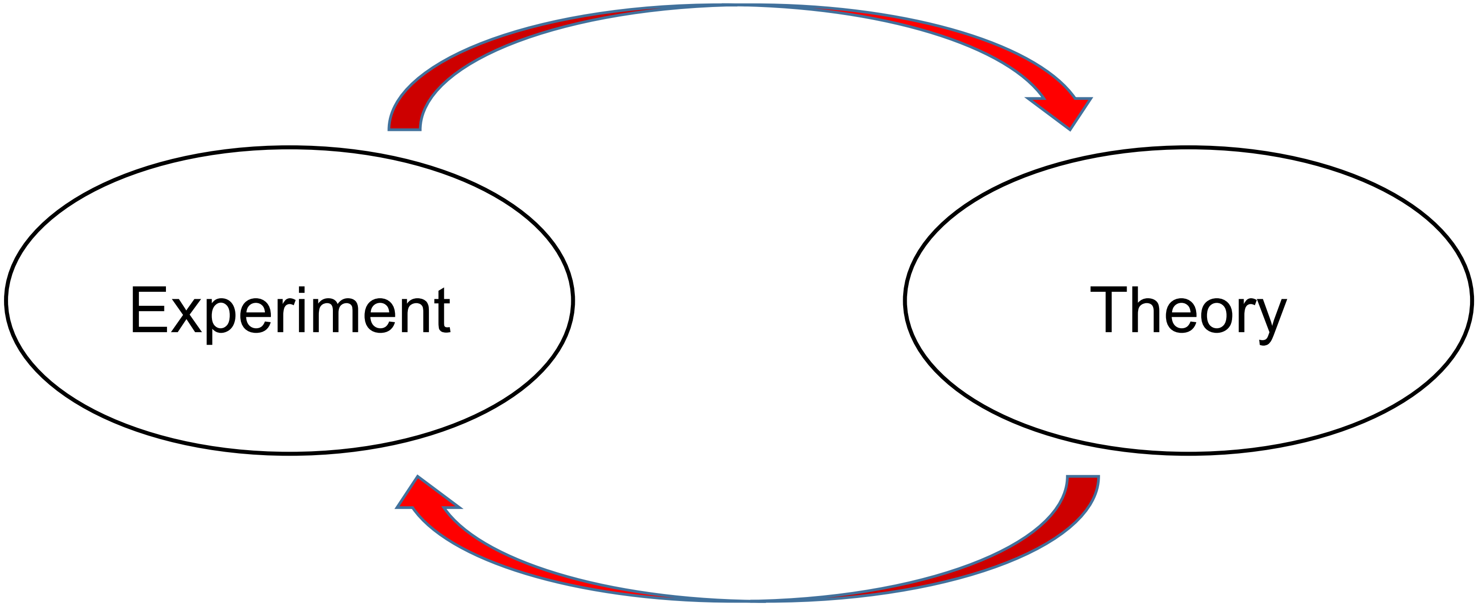
Experimental Foundations of the Standard Model



Experiment

Theory

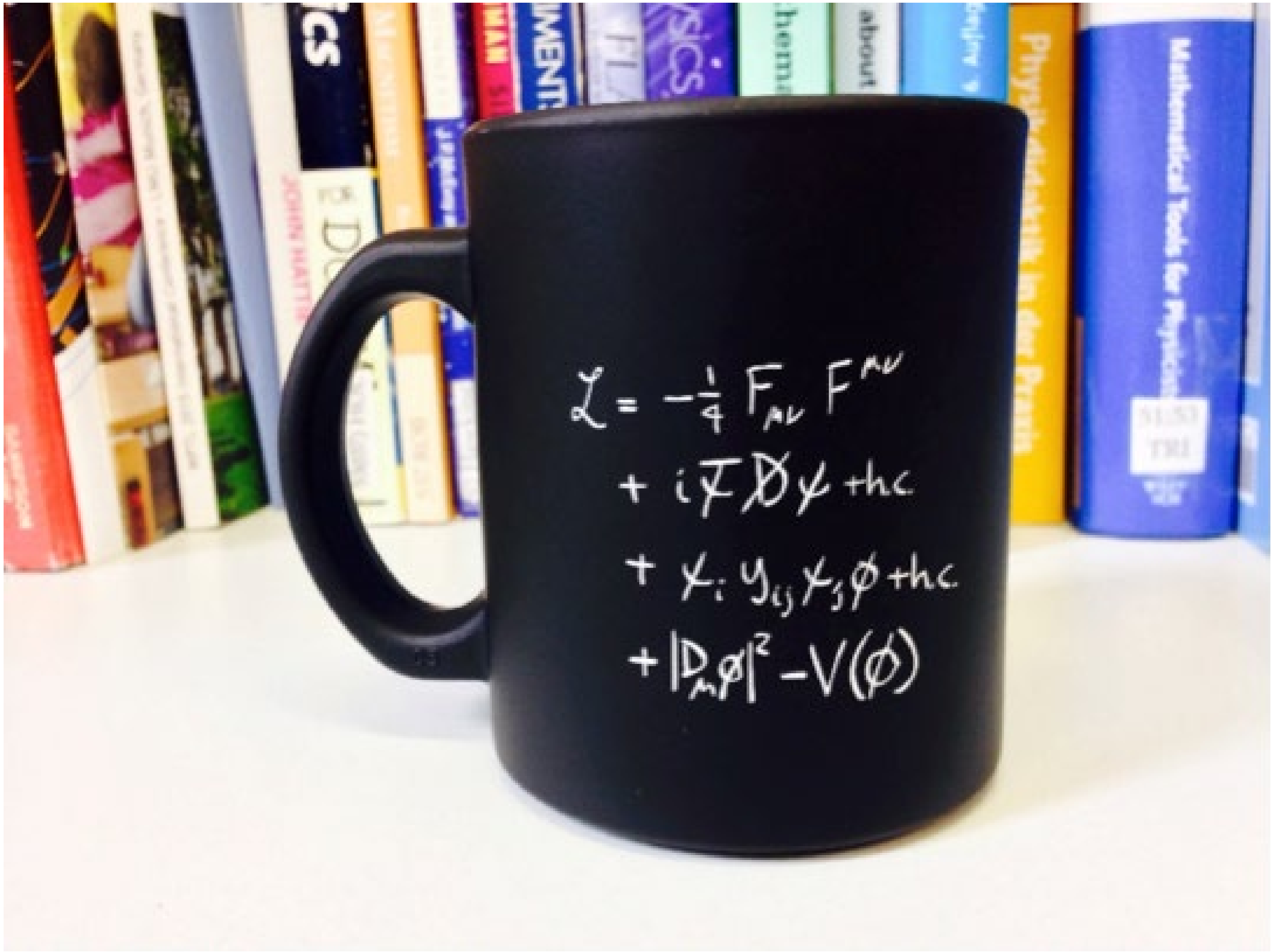
Standard Model is a quantum field theory. It describes the fundamental building blocks for matter and their interactions.

Today, I will give a "historical overview" of experimental results shaping our todays understanding of the particle world*).

(→ 22 Nobel prizes)

Some of the results will be discussed in more detail in the course of the lecture, others are subject of PEP4, MKEP1.

Standard Model as Souvenir for CERN visitors

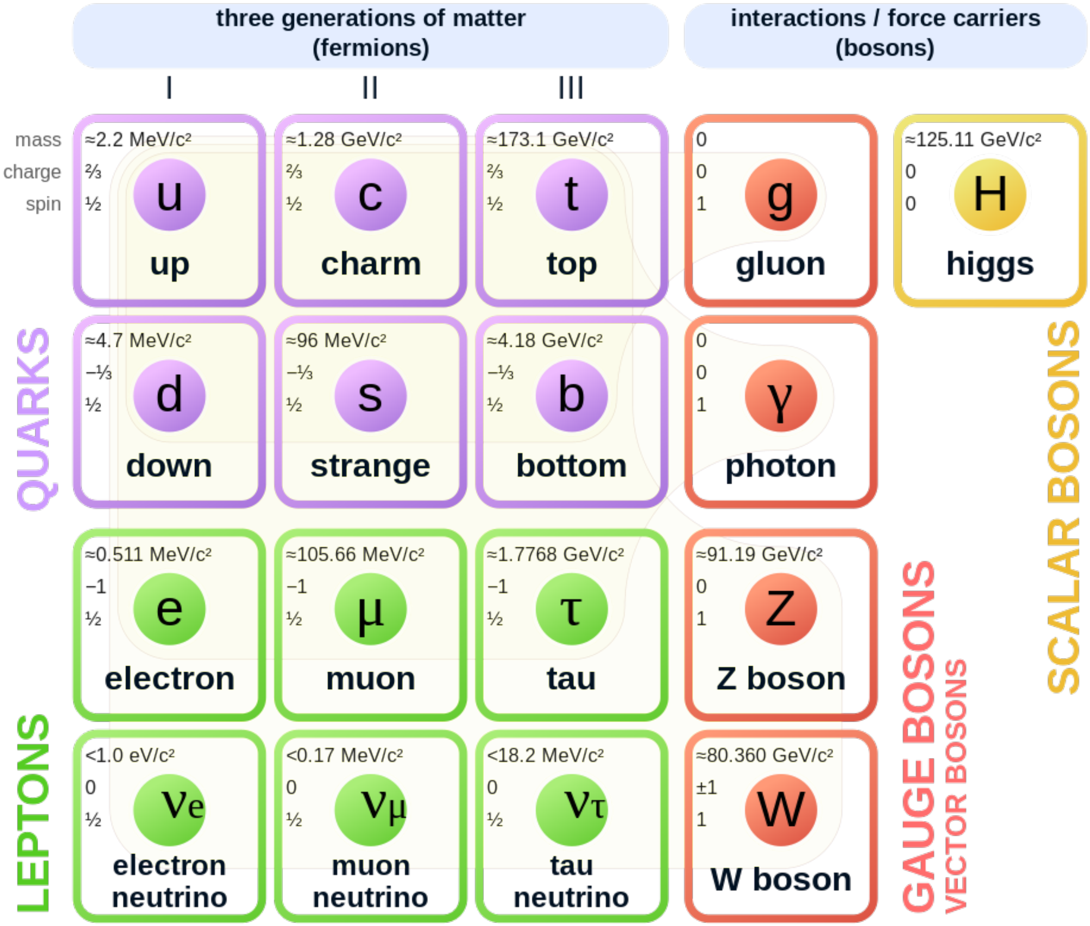


The Standard Model Lagrangian on a mug available in the CERN shop (Image: CERN)

“Standard Model” as found in many Master Theses

Wikipedia

Standard Model of Elementary Particles



3 generations of fermion:
3 × Lepton doublets
3 × Quark doublets

Vector bosons:
Photon
$W^{\pm}$, Z
8 Gluons

Higgs boson

<u>Parameters of SM (18):</u>
9 fermion masses ($m_{\nu i}=0$)
4 quark mixing parameters
3 couplings, 1 mixing angle
Higgs mass

1 coupling, $\sin^2\theta_w \Leftrightarrow M_w M_Z$

From the Atom to Quantum-Electrodynamic (QED)

P. A. M. Dirac (1925++): *(Nobel prize 1933)*
Relativistic wave equation for the electron.
Prediction of a particle w/ charge opposite to that of the electron.

(Dirac originally identified it with the proton. Oppenheimer and others showed that mass should be equal to m_e – thus different from proton).

C. D. Anderson (1932): *(Nobel prize 1936)*
Discovery of the positron in cosmic rays (see next slide)

→ experimental situation (beginning 1940):
e^-, e^+, γ (quantized: photo effect)

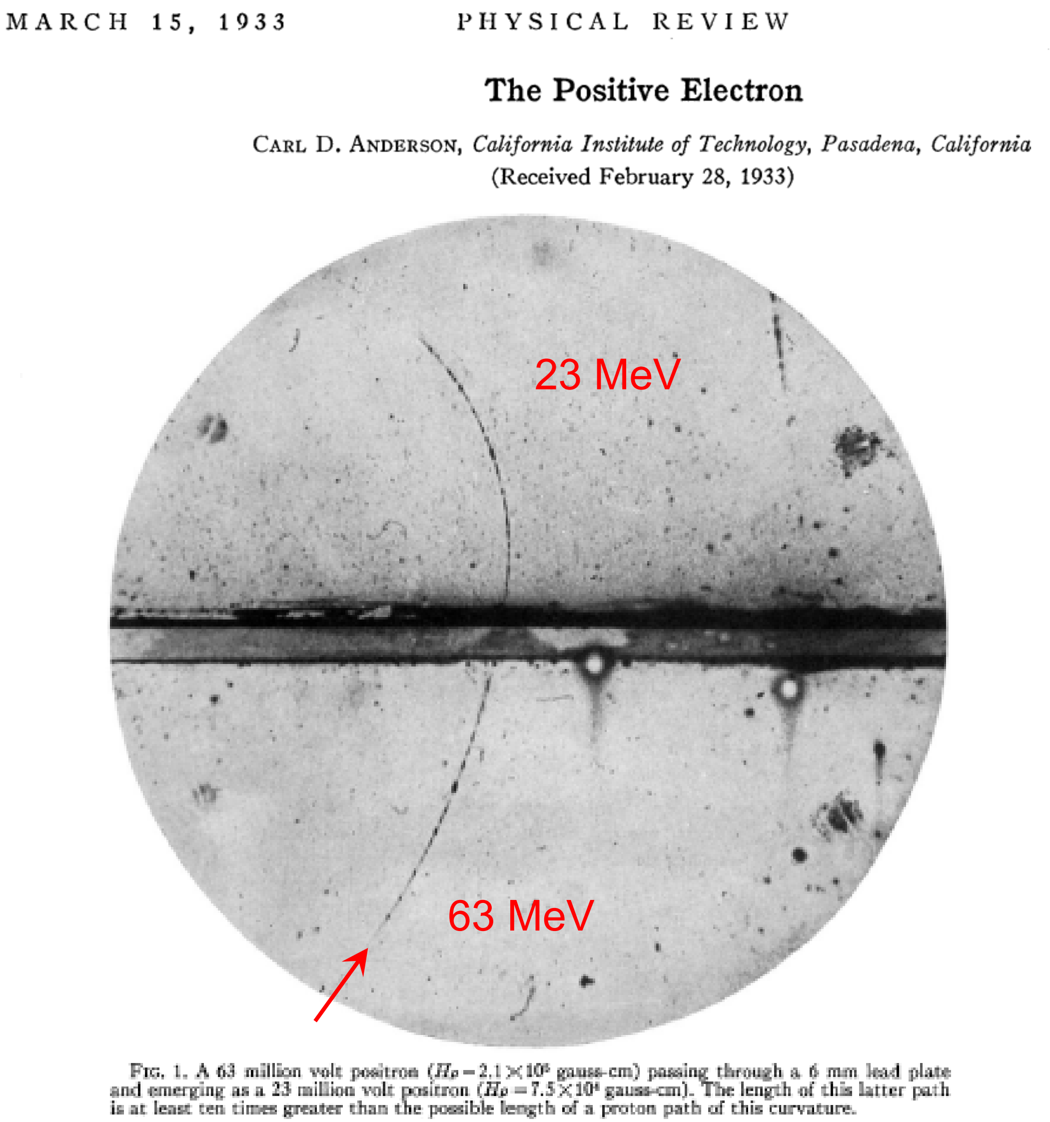
From Dirac Theory:
There must be corrections in which electromagnetic interaction acted more than the minimal number of times.

(Nobel prize 1955)

Observation of Lamb-Shift (1947): 2S½ , 2P½ splitting (Dirac: degenerated)
Formulation of QED (Feynman, Schwinger, Tomonaga) *(Nobel prize 1965)*

Discovery of Positron (C.D. Anderson 1934)

(Nobel prize 1936)



MARCH 15, 1933 PHYSICAL REVIEW

The Positive Electron

CARL D. ANDERSON, *California Institute of Technology, Pasadena, California*

(Received February 28, 1933)

FIG. 1. A 63 million volt positron ($H\rho = 2.1 \times 10^5$ gauss-cm) passing through a 6 mm lead plate and emerging as a 23 million volt positron ($H\rho = 7.5 \times 10^4$ gauss-cm). The length of this latter path is at least ten times greater than the possible length of a proton path of this curvature.

Particle source: cosmic rays

(Nobel prize for C. Wilson, 1927)

Detector: cloud chamber + photo
(inside magnetic field)

- Bending → positive particle
- Path length after absorber too long for proton

⬇

New, light positive particle:
positron

QED and its predictions: Electron Magnetic Moment

Electron magnetic moment in Dirac-Theory:

$$\mu_e = g_e \frac{e}{2m_e} \qquad \text{and} \qquad g_e = 2$$

P. Kusch and H. M. Foley (1947)

Study of Zeeman splitting of Ga atom: electron g-factor was about 0.2% larger than the value 2 predicted by the Dirac equation.

J. Schwinger (1948) *(Nobel prize 1965)*

Showed that deviation can be explained as the effect of radiative correction. His 2nd order calculation revealed:

$$g_e = 2(1+\frac{\alpha}{\pi}) = 2.0023$$

see T. Kinoshita, Study of Electron G-2 From 1947 To Present

DOI 10.1103/BAPS.2014.APRIL.Y10

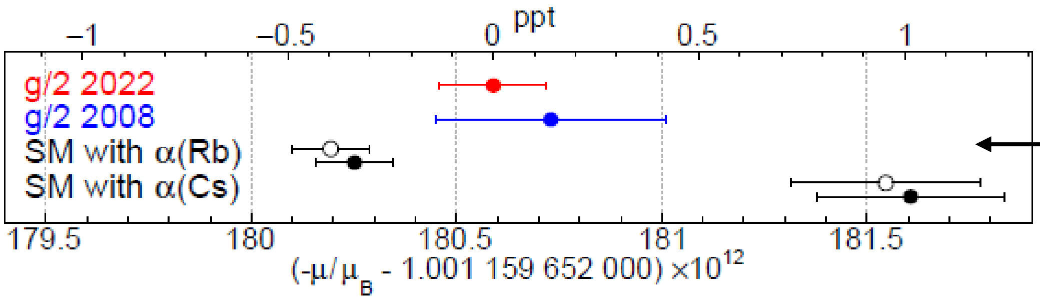
Electron Magnetic Moment

after 75 years of continuous work

Anomalous moment: $\frac{g_e}{2} = 1 + a_e$

G. Gabrielse et al., PRL Phys. 130, 071801 (2023)

$$g/2 = 1.001\,159\,652\,180\,59\,(13)\;[0.13\;\text{ppt}]$$



most recent (2020)

Theoretical prediction (Kinoshita et al.)

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

Numerically evaluated

Triumph of QED and of experimental physics

Particle Zoo: More Leptons and Hadrons

Discovery of neutron (J. Chadwick, 1932): $^{9}\mathrm{Be} + {}^{4}\mathrm{He}\ (\alpha) \rightarrow {}^{12}\mathrm{C} + \boxed{{}^{1}\mathrm{n}}$.

(Nobel prize 1935)

"New neural" radiation w/ mass close to proton
(from recoil energy of bombarded atoms)

→ isospin symmetry of proton an neutron (W. Pauli)

(saturated vapor)

Study of Cosmic Rays (w/ cloud chambers or photo sensitive emulsions)

Path length (stopping) can be used to estimate particle energy/mass:
dE/dx (Bethe-Bloch) for "heavy charged particles" (non electrons).

Discovery of muon (Neddermeyer & Anderson, Street & Stevenson, 1937)

Penetrating component of cosmic rays:

- particle with unit charge, w/ large mass – much larger than electron **but** lower than proton, exists w/ positive an negative charges.
- Mass ~130 m_e (x1.6 too low)

"μ-meson" (meson – medium mass)

Pion discovery

D. H. Perkins (1947):

A slow negative particle that came to rest in an atom, most likely a light atom like carbon, nitrogen, or oxygen. After the particle was absorbed by the nucleus, the nucleus was blasted apart and three fragments were observed in the emulsion.

Consistent w/ exchange particle of nuclear force predicted by H. Yukawa *(Nobel prize 1949)* but inconsistent with the muon found earlier.

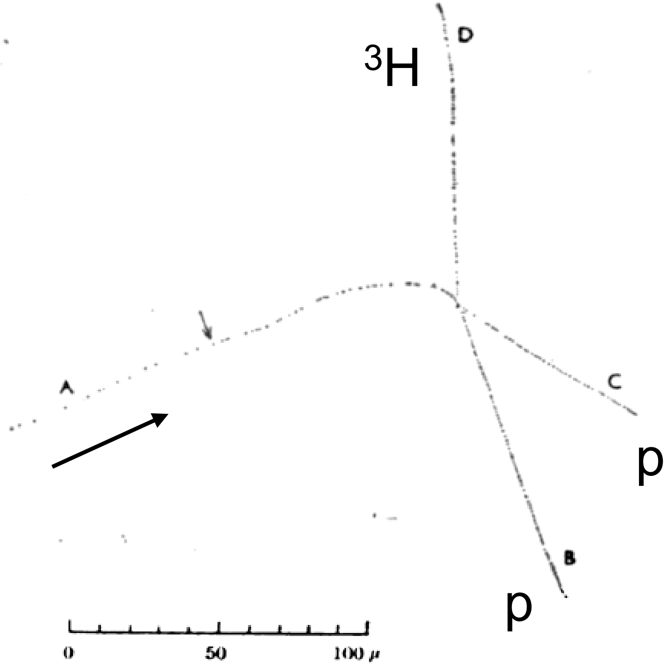
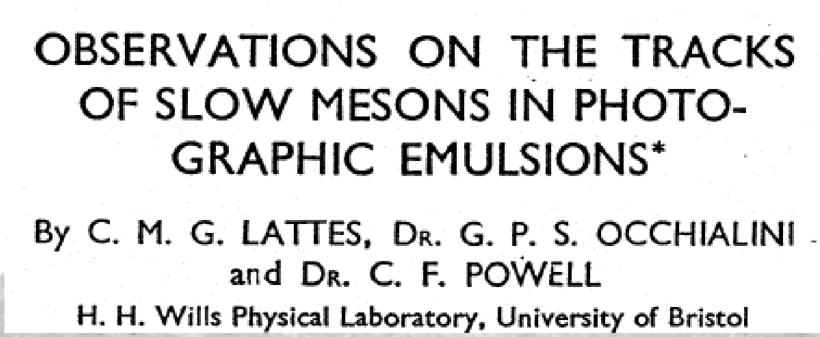


Fig. 1 *b*. TRACE OF COMPLETE STAR ON SCREEN OF PROJECTION MICROSCOPE, SHOWING PROJECTION OF THE TRACKS IN THE PLANE OF THE EMULSION. TRACE *A* CANNOT BE TRACED WITH CERTAINTY BEYOND THE ARROW

C. F. Powell et al. (1947) *(Nobel prize 1950 also for photo emulsion)*

Existence of two different type of “mesons” with different masses.
One type decayed into the other type: π-mesons.

(paper also introduced the names μ- and π-meson – proposed by Lattes)



OBSERVATIONS ON THE TRACKS OF SLOW MESONS IN PHOTOGRAPHIC EMULSIONS*

By C. M. G. LATTES, Dr. G. P. S. OCCHIALINI and Dr. C. F. POWELL
H. H. Wills Physical Laboratory, University of Bristol

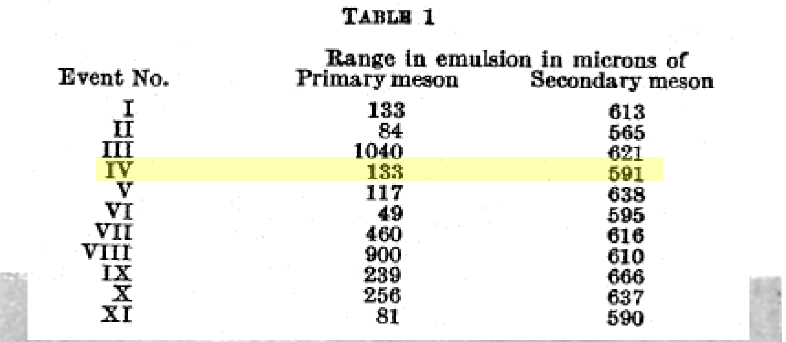
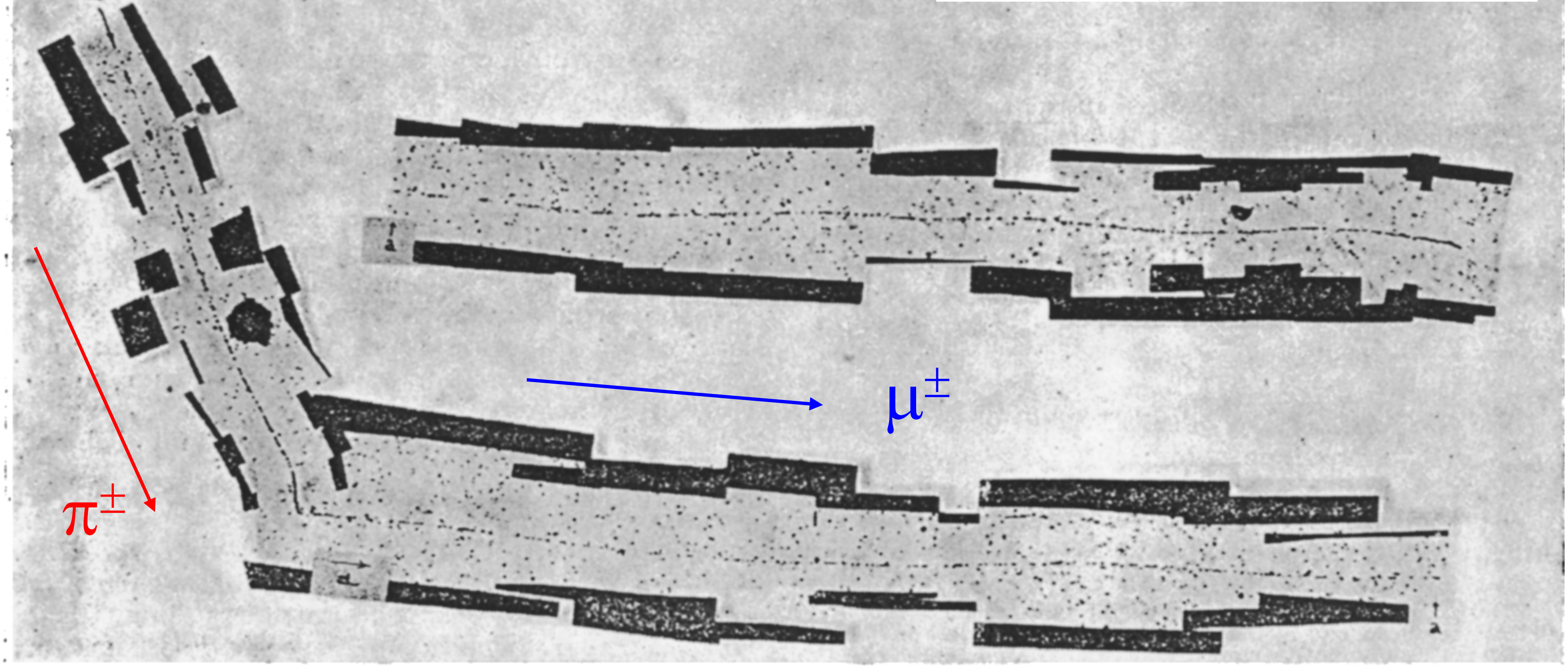


TABLE 1

Event No.	Range in emulsion in microns of Primary meson	Range in emulsion in microns of Secondary meson
I	133	613
II	84	565
III	1040	621
IV	133	591
V	117	638
VI	49	595
VII	460	616
VIII	900	610
IX	239	666
X	256	637
XI	81	590



$$\pi^\pm \longrightarrow \mu^\pm + \nu$$

Approx. same path length of μ's indicates a 2-body decay with an undetected neutrino.
β-decay: μ is just an heavier electron!

Isospin symmetry and the π^0

π-mesons feel the nuclear force (see Perkins observation): Hadrons

Muons (“μ-mesons”) are heavier electrons: Leptons

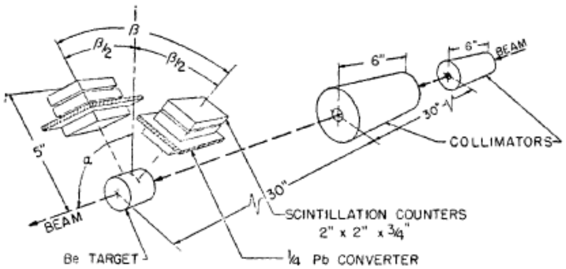
We shouldn’t use “meson” for the leptons
(some people still do – very confusing)

Cosmic showers also contain a soft electromagnetic component, and it was suggested that this component could be due to neutral partners of the $\pi^{\pm}$ assuming isospin symmetry and I = 1 for the π-meson.

Discovery of the $\pi^0 \to \gamma\gamma$

Carlson, Hooper, King (1950) – using cosmic rays.

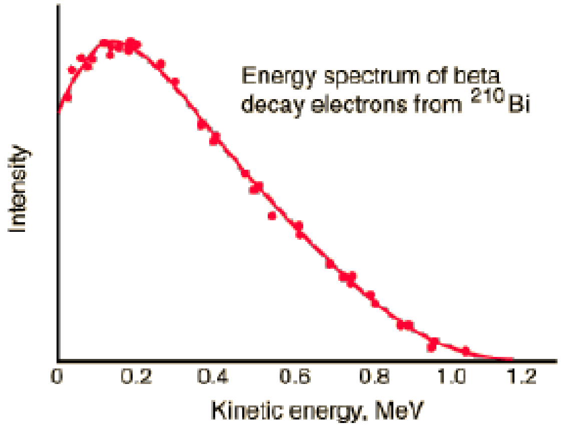
Steinberger, Panofsky, Steller (1950) - using the electron synchrotron at Berkley – beam was able to generate x-ray beam of 330 MeV.



Used 2 crystall scintillators in coincidence: $\pi^0 \to \gamma\, \gamma$

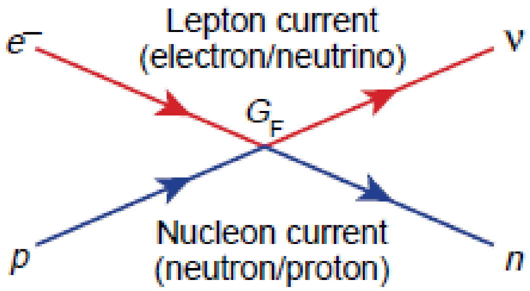
Neutrinos

W. Pauli introduced the neutrino (very light, neutral, spin ½ particle) to explain the observed β-spectrum and the angular momentum conservation in nuclear beta decays.



Experimental energy spectrum for decay electrons from 210Bi,
From G. J. Neary, Proc. Phys. Soc. (London), A175, 71 (1940).

Fermi's theory of Nuclear β-decay:



- Current-current contact interaction
- Fermi's Golden Rule

→ predict the β-spectrum.

Neutrino difficult to detect as it only interacts weakly.

Project “Poltergeist”: Detection of antineutrinos

(Nobel prize 1995)

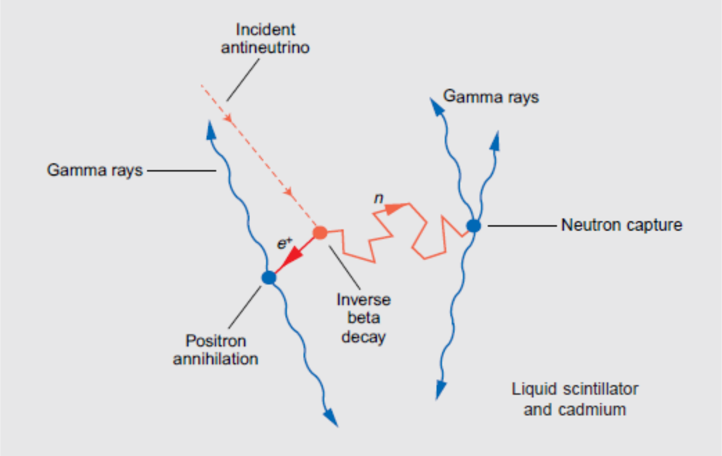
F. Reines and C.L Cowan (1956, LANL)

Reactor antineutrinos (inverse β decay:

$$\bar{\nu}_e + p \rightarrow n + e^+ \longrightarrow +e^- \rightarrow \gamma\gamma$$

Neutron detection:

$$n + {}^{113}Cd \rightarrow {}^{114}Cd + \gamma$$



Techniques: PMTs & coincidence

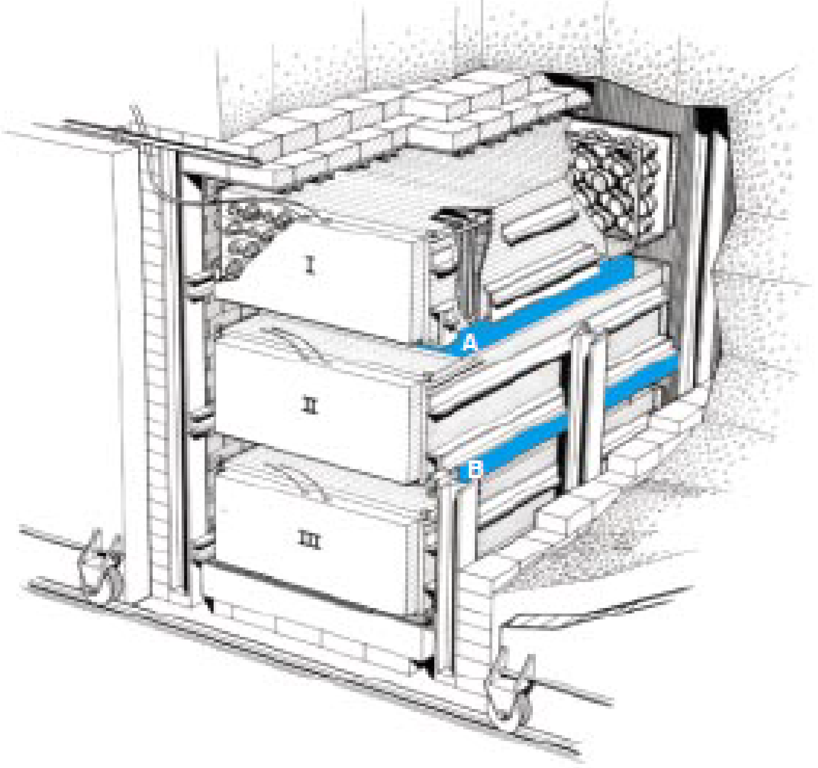


Figure 4. The Savannah River Neutrino Detector—A New Design
The neutrino detector is illustrated here inside its lead shield. Each of two large, flat plastic tanks (pictured in light blue and labeled A and B) was filled with 200 liters of water. The protons in the water provided the target for inverse beta decay; cadmium chloride dissolved in the water provided the cadmium nuclei that would capture the neutrons. The target tanks were sandwiched between three scintillation detectors (I, II, and III). Each detector contained 1,400 liters of liquid scintillator that was viewed by 110 photomultiplier tubes. Without its shield, the assembled detector weighed about 10 tons.

https://permalink.lanl.gov/object/tr?what=info:lanl-repo/lareport/LA-UR-97-2534-02

Discovery of Muon-Neutrino and Lepton Number

Schwartz, Lederman, and Steinberger (1962) *(Nobel prize 1988)*

AGS (BNL) proton beam of 15 GeV:
p (15 GeV) → Be-Target → π, K → $\mu\nu$

Use spark-chambers to record neutrino induced events

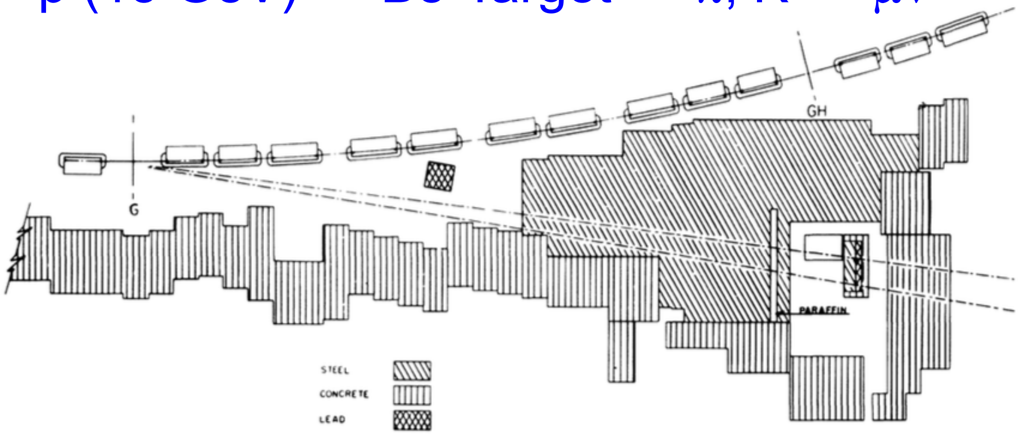
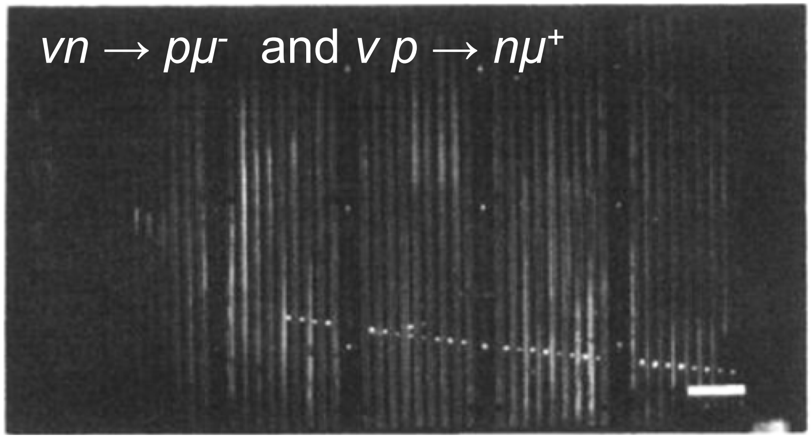


FIG. 1. Plan view of AGS neutrino experiment.



$\nu n \rightarrow p\mu^-$ and $\nu p \rightarrow n\mu^+$

“electron events” strongly suppressed.

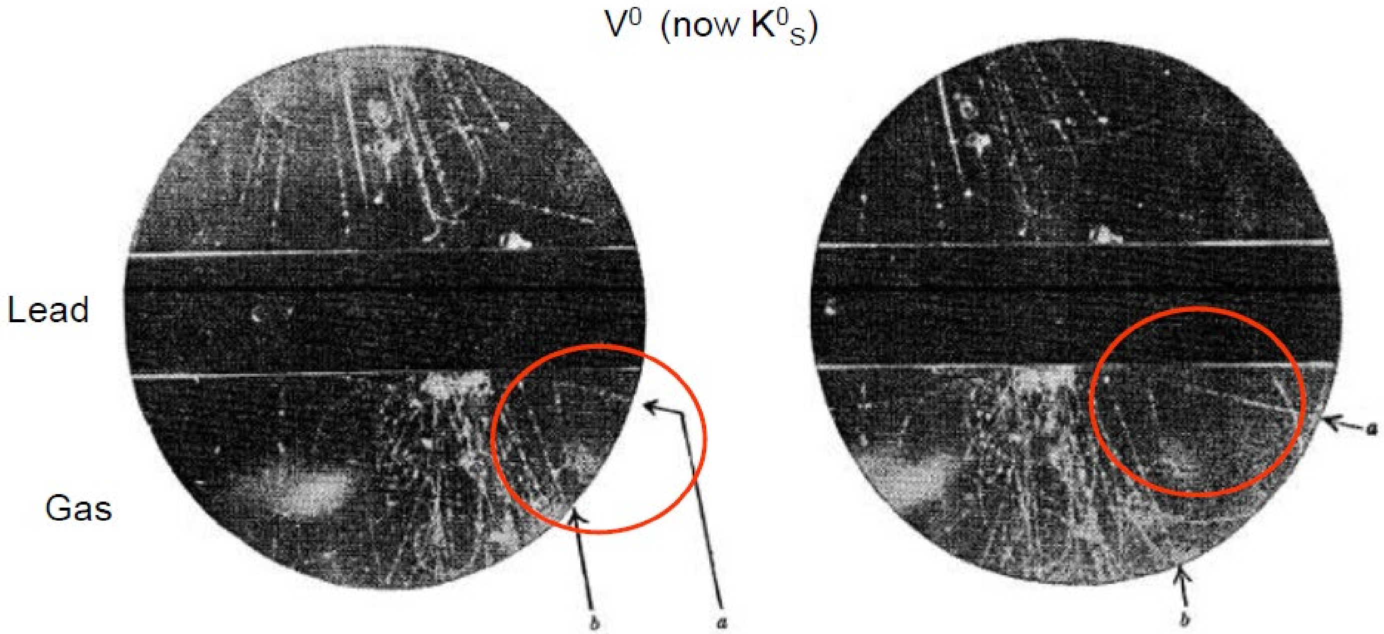
Conclusion:
two neutrinos, ν_μ and ν_e, and two conserved quantum numbers, muon number (+1 for μ^- and ν_μ) and electron number (+1 for e^- and ν_e).

AGS = alternating gradient synchrotron

Discovery of strange particles

1947: Rochester & Butler

Discovery of the V_0 (K_s) particle in a cosmic ray shower provoked by a lead target in a cloud chamber: observation of long-lived neutral particles, decaying into 2 tracks with a "very striking" character (V-shape).



Rochester & Butler, 1947 in a cloud chamber exposed to **cosmic rays**
" Forked tracks of a very striking character "

Peculiar behavior → new quantum number S (strangeness).

Strangeness

A large number of subsequent cosmic ray experiments lead to the discovery of further “unstable particles” with typical lifetimes of $10^{-9} \ldots 10^{-10}$ s.

At that time it was not clear which of the observed particles are the same particles but diff. decay chains and which are really different particles.

BUT “strangeness” conserved in strong And violated in weak interaction.

Old Name	New Name
τ	$K_{\pi 3}$: $K^+ \to \pi^+ \pi^+ \pi^-$
V_1^0	$\Lambda^0 \to p \pi^-$
V_2^0 (θ^0)	$K^0_S \to \pi^+ \pi^-$
κ	$K_{\mu 2}$: $K^+ \to \mu^+ \nu$
	$K_{\mu 3}$: $K^+ \to \mu^+ \pi^0 \nu$
χ (θ^+)	$K_{\pi 2}$: $K^+ \to \pi^+ \pi^0$
V^+, Λ^+	$\Sigma^+ \to p \pi^0$, $n \pi^+$

Most famous example: θ / τ puzzle

θ and τ particle known to have the same mass, however as they decayed to final states with different parity they were believed to be different particles:

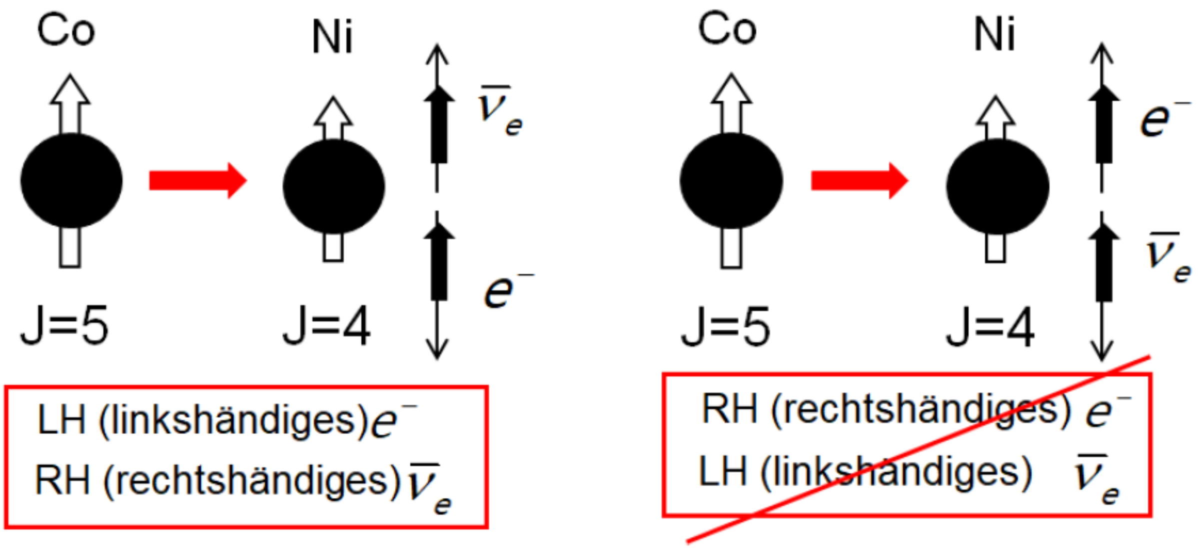
$$\tau^+ \to 3\pi \quad \text{Parity } P = -1 \qquad \theta^+ \to 2\pi \quad P = +1$$

Parity violation in weak interaction

(Nobel prize 1957)

T.D. Lee and C.N. Yang proposed (1956) that τ^+ and θ^+ are the same particle and that parity P is violated in weak decays. Shortly after this proposal parity violation was confirmed experimentally by C.S. Wu (1957):

Electrons of polarized Co are emitted preferentially opposite to Co spin.



LH (linkshändiges) e^-
RH (rechtshändiges) $\bar{\nu}_e$

~~RH (rechtshändiges) e^-~~
~~LH (linkshändiges) $\bar{\nu}_e$~~

M. Goldhaber (1957): Helicity of neutrinos is left-handed.

Lepton currents in Fermi's theory have V-A structure.

Electroweak Standard Model (QFT)

Fermi's theory of weak interactions w/ V-A currents and contact interaction was rather successful: Short range of the of weak interaction suggested very heavy exchange bosons.

C. N. Yang, R. Mills (1954): Theory of massless interacting vector particles. This theory could accommodate particles like the photon, *W*+, and *W*− that would interact with one another, but it required them to be massless.

P. Higgs (1964), R. Brout & F. Englert (1964) : Theory initially containing a massless photon and two scalar particles could turn into a theory with a massive vector particle and one scalar. This "Higgs mechanism" was a key ingredient in the final model. *(Nobel prize 2013: Higgs, Englert)*

However: a model with only (massive) W-bosons would violate unitarity at very high energies → theory with only W-bosons incomplete.

S. Glashow (1959), A. Salam (1959), S. Weinberg (1967) : *(Nobel prize 1979)*
Electroweak theory predicting in addition to the charged currents also weak neutral current interactions: massive $W^{\pm}$, **Z^0** and massless γ

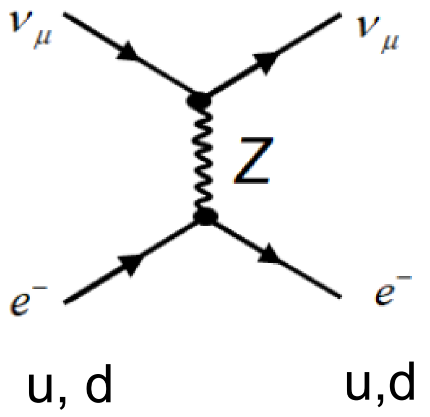
(Nobel prize 1999)

G. t'Hooft, M. J. G. Veltman (1971): Renormalisability of non-abelian QFTs.

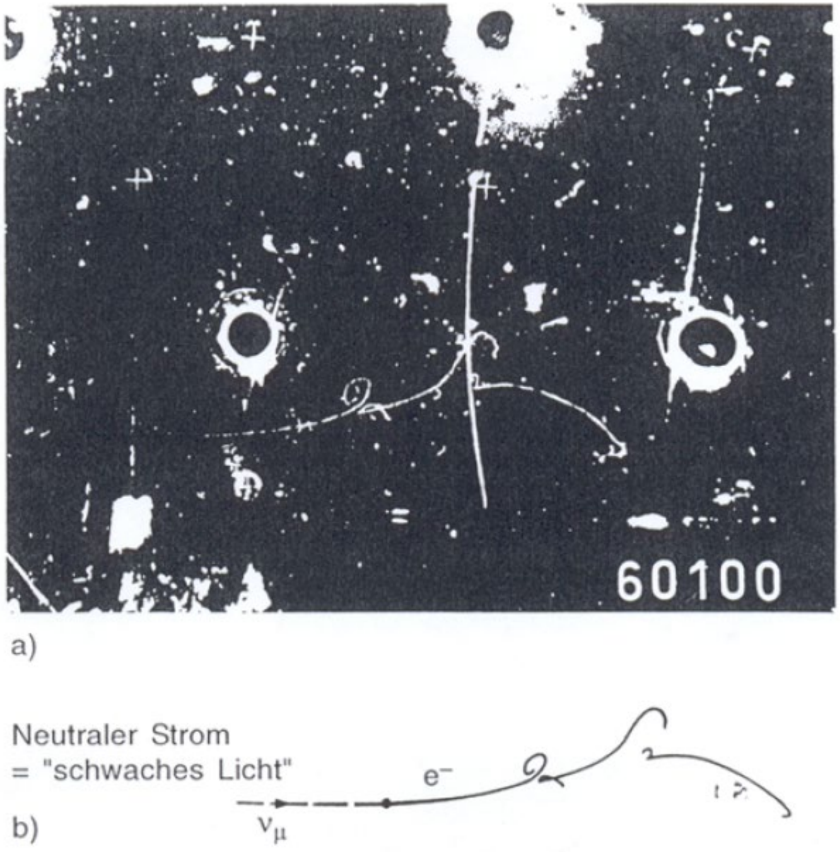
Discovery of Neutral Currents (Z-exchange)

Phys. Lett. 46B (1973)

Muon neutrino beam directed on the CERN Gargamelle bubble chamber (1.5t Freon): 83000 ν_μ and 207000 anti- ν_μ pictures analyzed to search for:



"no muon"



Most famous but only electron event.

Most of the events were hadronic events – ration NC/CC events:

$$(NC/CC)_\nu = 0.21 \pm 0.03$$

$$(NC/CC)_{\bar{\nu}} = 0.45 \pm 0.09$$

⇒

$$\sin^2\theta_w = 0.3 \ldots 0.4$$

Gargamelle Bubble Chamber

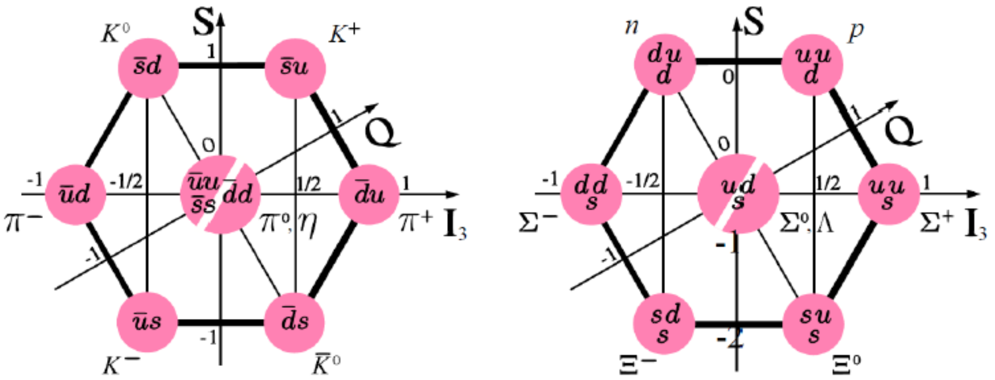
Particle content: Quarks

Ordering of hadrons using isospin and strangeness suggested static quark model:

(Gell-Mann 1964, Zweig 1964)

(Nobel prize 1979)

SU(3) symmetry



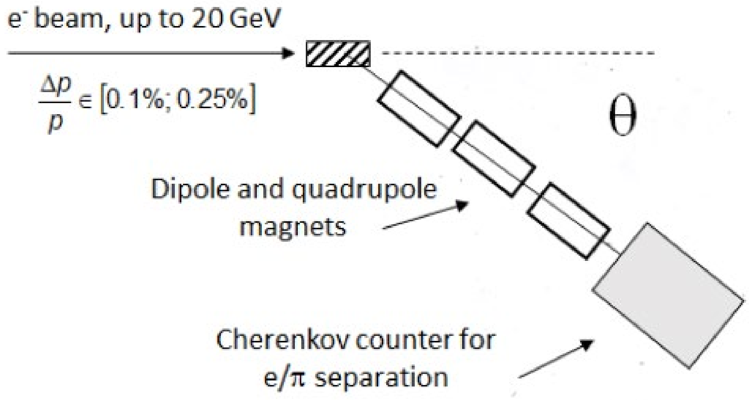
u, d, s quarks

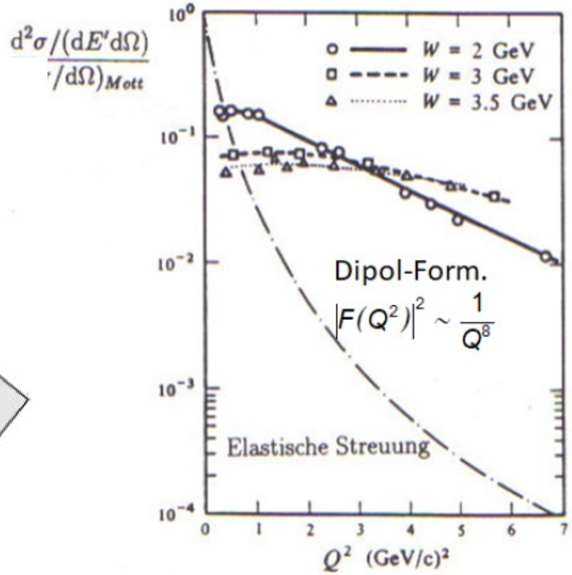
Parton Model (Bjorken, Fenyman): point-like spin ½ constituents of proton.

Gluons carry 50% of proton 4-momentum

Deep-inelastic e-proton scattering:

(Stanford 3.2 km Linac: 20 GeV)





SLAC-MIT: J. Friedman, H. Kendall ,R. Taylor (1969)

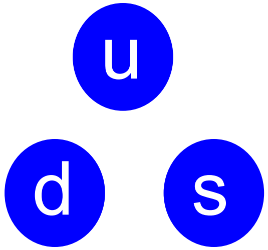
(Nobel prize 1990)

Fundamental particles at beginning of 1970s

Leptons:

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}$$

Quarks:

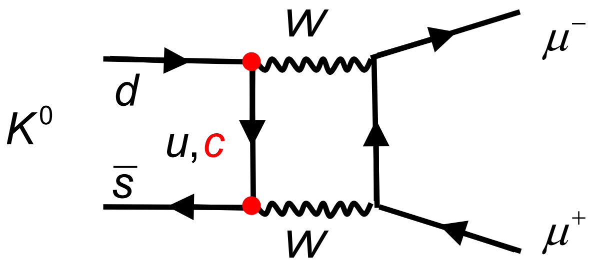


$$\overbrace{\begin{pmatrix} u \\ \cos\theta_c \cdot d + \sin\theta_c \cdot s \end{pmatrix}}^{\text{Mixing suggested by Cabibbo (1963)}}$$

Glashow, Iliopoulos, Maiani (1970)

$$\mathcal{B}\left(K_L^0 \to \mu^+\mu^-\right) \simeq \left(6.84 \pm 0.11\right) \cdot 10^{-9}$$

Proposed 4th quark (u-type) to explain small BR:



M. Kobayashi, T. Masukawa (1973) *(Nobel prize 2008)*

To explain CP violation there must be at least 3 generations of quarks.

CP violation was observed in 1964 in the decay of neutral K0s (J. Cronin, V. Fitch). Until 2001, it was the only system w/ CPV. *(Nobel prize 1980)*

For 3 generations (i.e. w/ 6 quarks) the mixing matrix exhibits 3 mixing angles and a non-trivial phase → CPV

November Revolution 1974 – Discovery of 4th quark

B. Richter et al. at SLAC:

$@3.1\,\text{GeV}: e^+e^- \rightarrow e^+e^-$

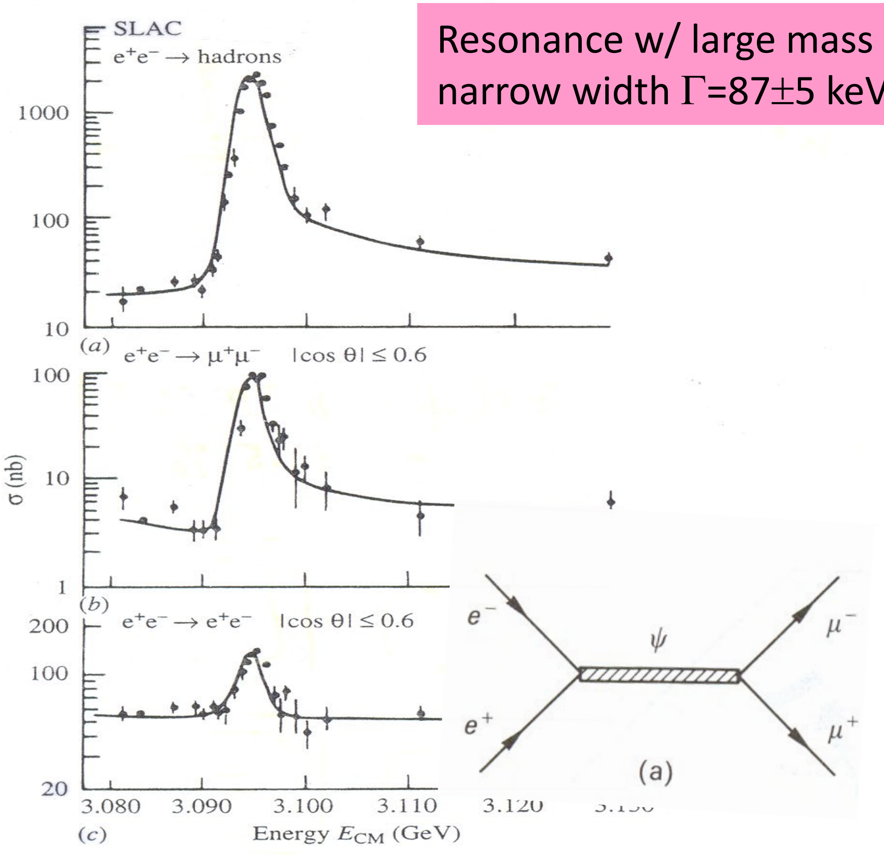
S.C.C. Ting et al. at BNL:

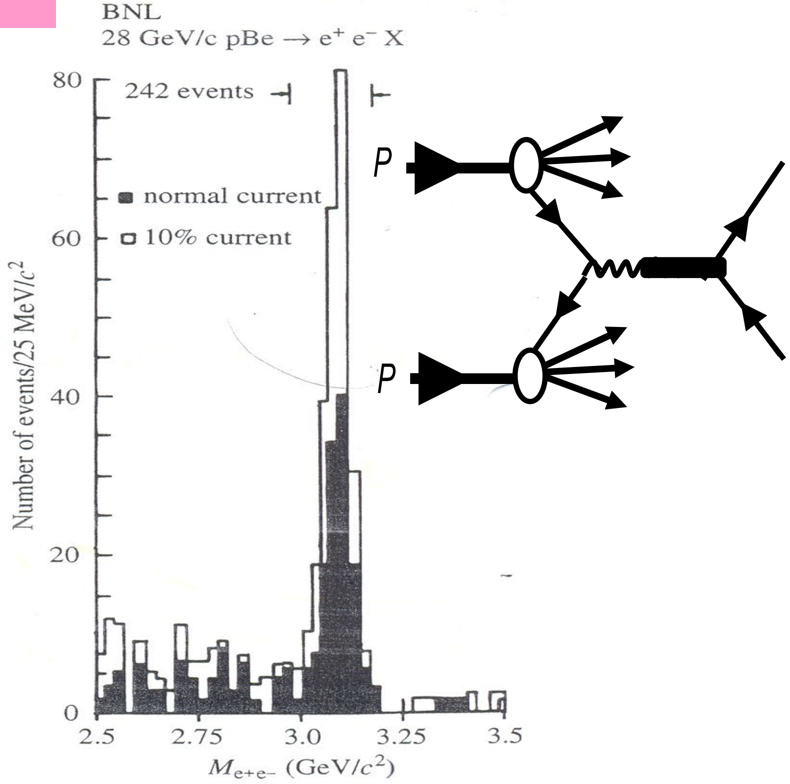
$p(28\,\text{GeV}) + Be \rightarrow e^+e^-X$

AGS

Resonance w/ large mass
narrow width Γ=87±5 keV

Not original paper





Both experiments discovered a very sharp and heavy resonance: bound state of new $q\bar{q}$ ($c\bar{c}$)

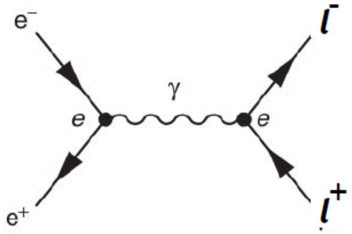
(Nobel prize 1976)

3rd Generation

(Nobel prize 1995)

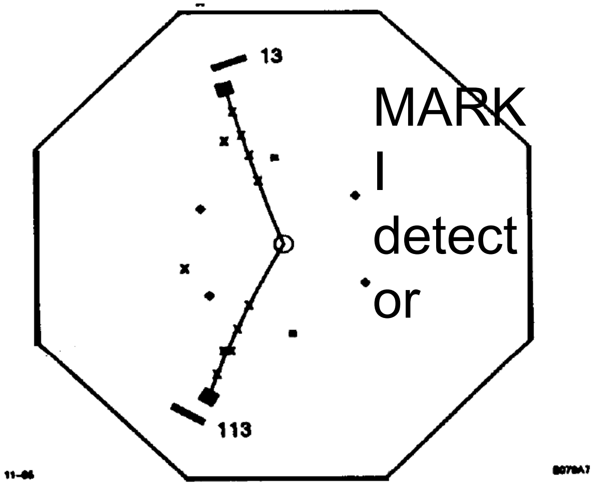
Discovery of the τ-lepton Perl et al. (1975)

SLAC SPEAR e^+e^- storage ring



$$\ell^- \to \nu_\ell + e^- + \bar{\nu}_e$$

$$\ell^- \to \nu_\ell + \mu^- + \bar{\nu}_\mu$$



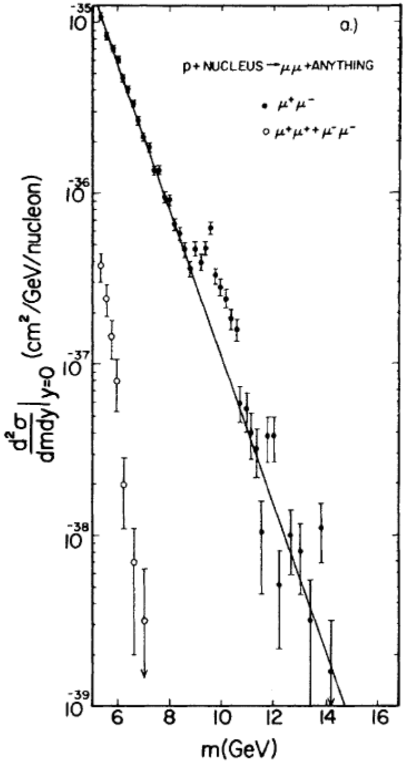
MARK I detector

In 1975: 24 eμ events…

Discovery of b-quark: ϒ-resonance at 9.46 GeV

$$p(400\,\text{GeV}) + Cu \to \underbrace{\mu^+\mu^-}_{\Upsilon-\text{resonance}} + X$$

L.M. Ledermann et al.
(Fermilab) 1977



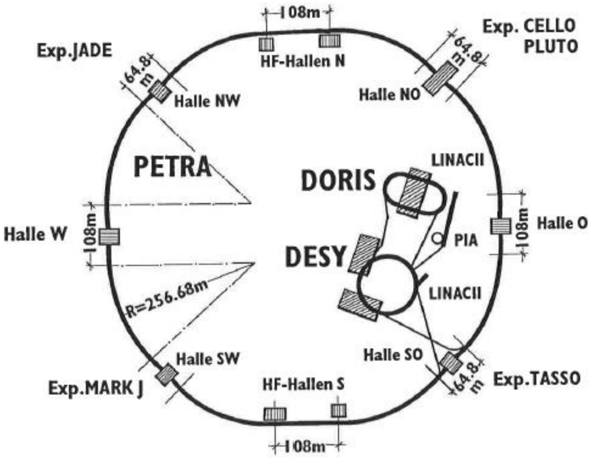
Confirmed by DESY in e^+e^- (PLUTO, DASP II)

Beside top-quark – matter content complete in 1977.

Gluon Discovery

Up until 1979, the only gauge particle that has been observed experimentally is the photon.

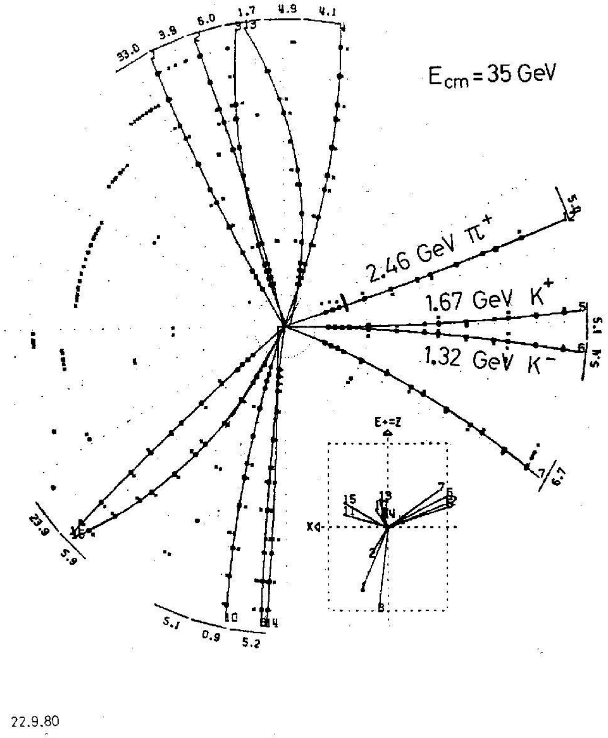
Massless gluons have been predicted by Yang & Mills – due to the non-abelian character of the theory the gluon is predicted to exhibit a self-coupling (contrary to the photon)

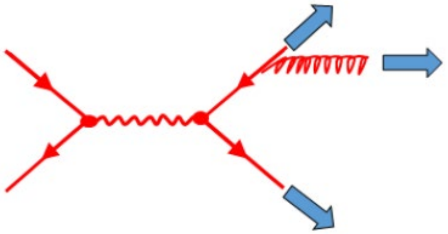


PETRA (Positron-Electron-Ring-Accelerator): e^+e^- accelerator/storage ring, started in 1978
In 1979 $\sqrt{s}$ was increased to 27 GeV.

Detectors:
CELLO/PLUTO, JADE, MARK-J, TASSO:
studied e^+e^- annihilation (ee →ee, $\mu\mu$, $\tau\tau$, qq)

3-Jet events as signature for gluon emission:



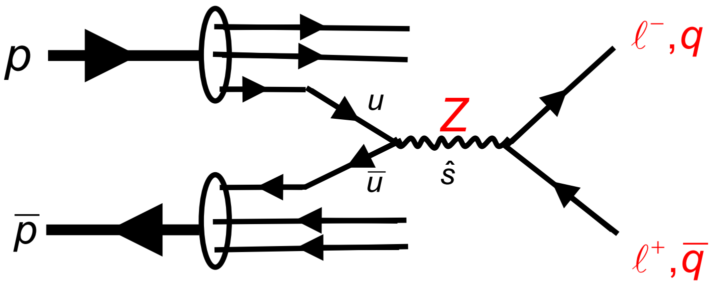


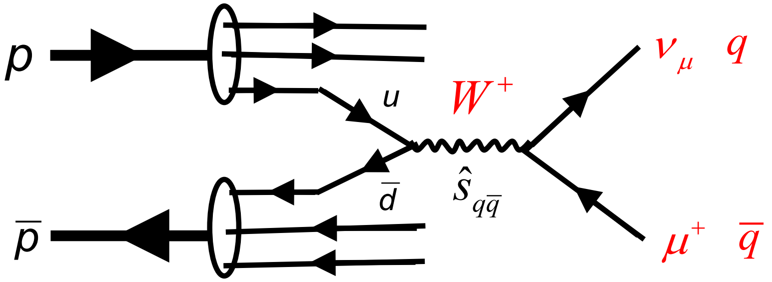
3-Jet event, TASSO 1979

Exchange bosons of weak interaction

Idea (C. Rubbia): Use CERN’s Super-Proton-Synchrotron to store protons and anti-protons at the same time → pp collisions at

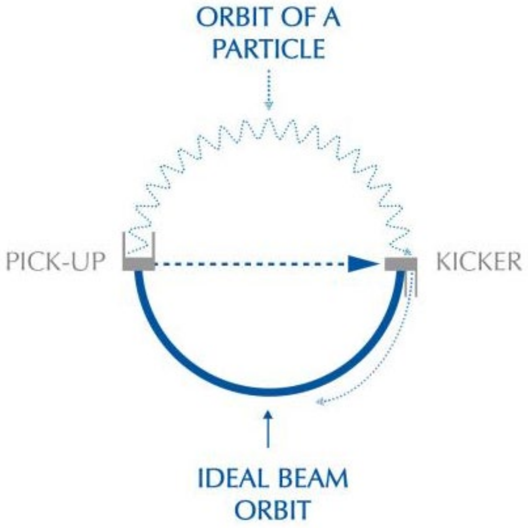
$$p\overline{p} \to Z \to f\overline{f} + X \qquad\qquad p\overline{p} \to W \to \ell\,\overline{\nu}_\ell + X$$



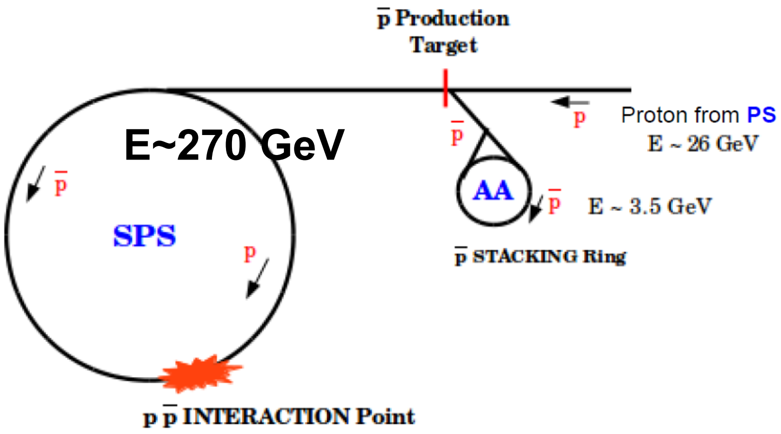


Critical to achieve acceptable anti-proton densities: phase space “cooling”

S. Van de Meer: “stochastic cooling”



Sp$\bar{p}$S and the UA1 detector



$\bar{p}$ Production Target

Proton from PS
E ~ 26 GeV

E~270 GeV

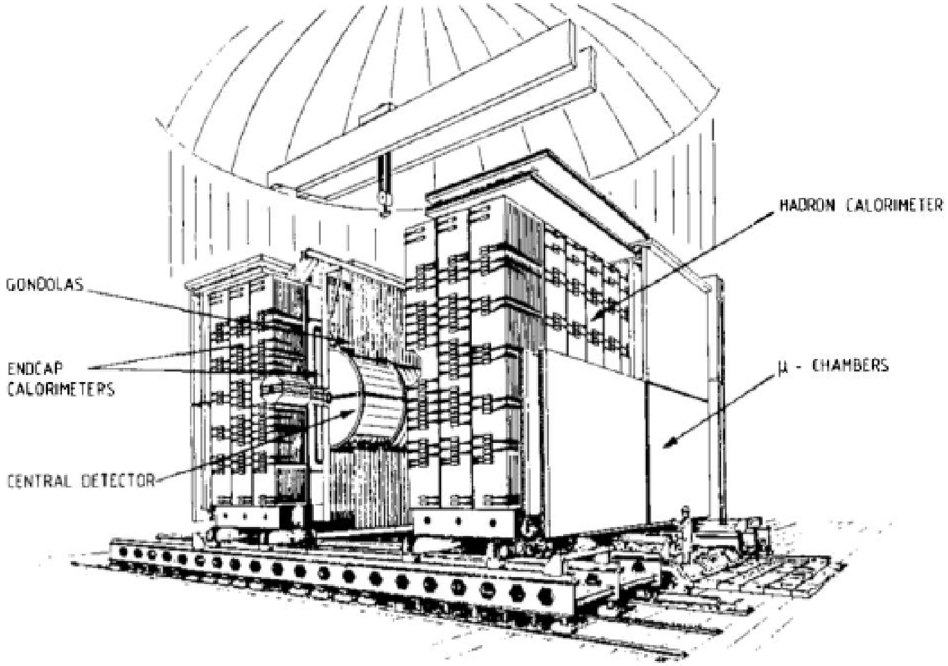
SPS

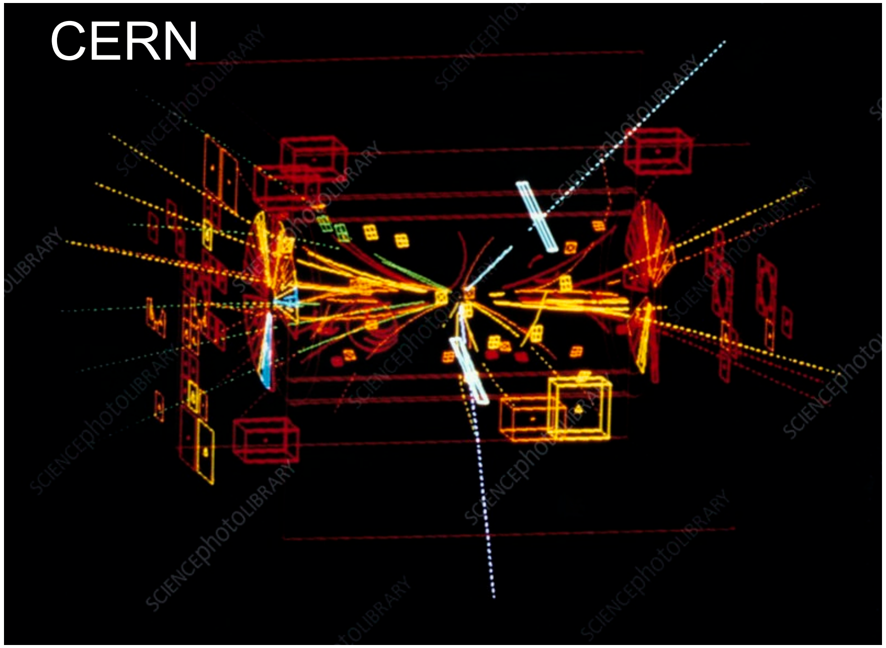
AA

E ~ 3.5 GeV

$\bar{p}$ STACKING Ring

p $\bar{p}$ INTERACTION Point

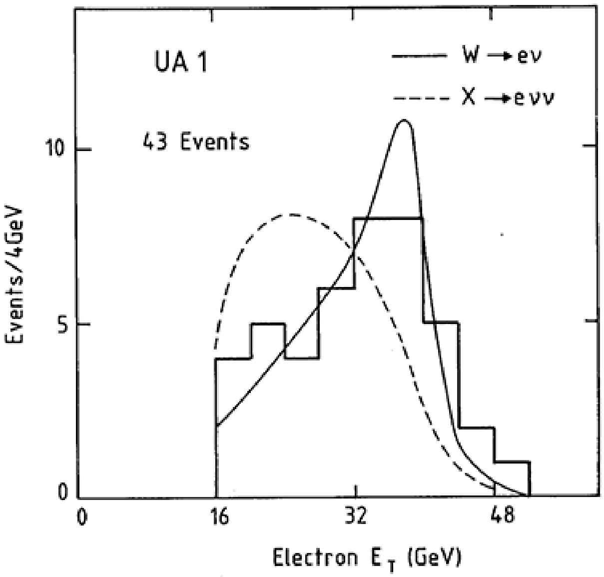


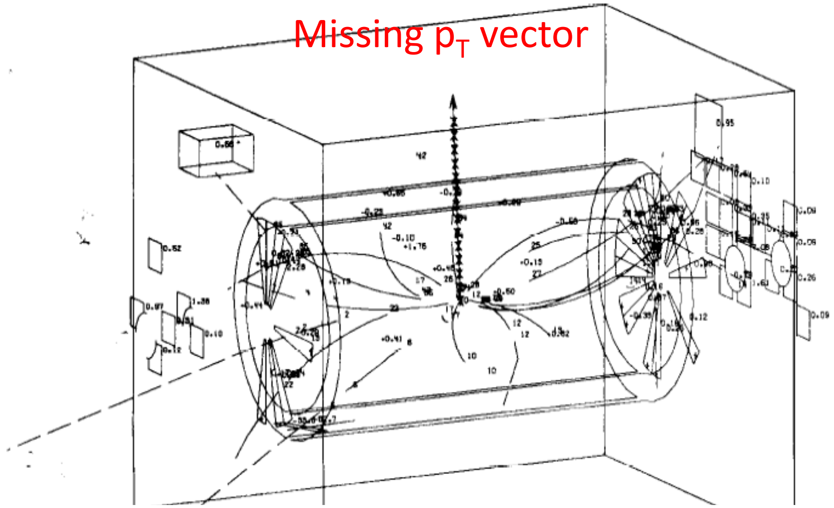


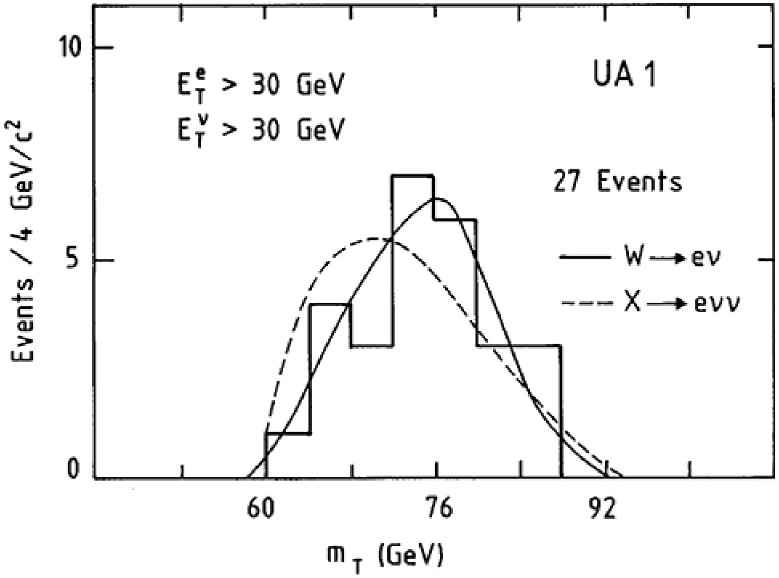
Discovery of W-Boson (Jan 1983)

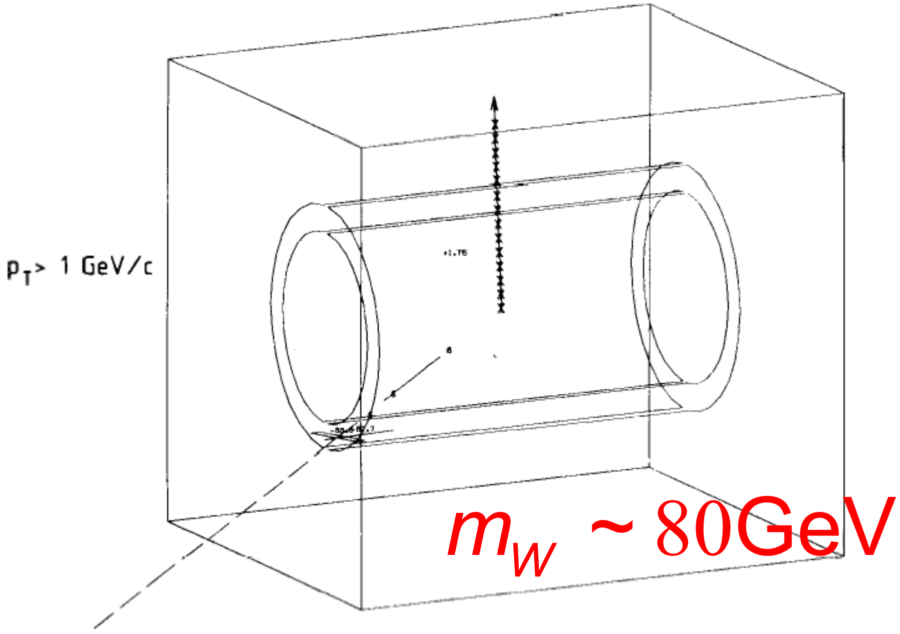
(Nobel prize for C. Rubbia and S. v.der Meer, 1984)

$W \rightarrow e\,\bar{\nu}$







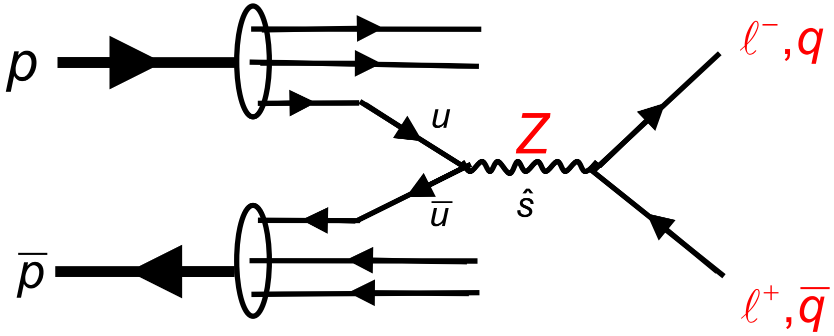


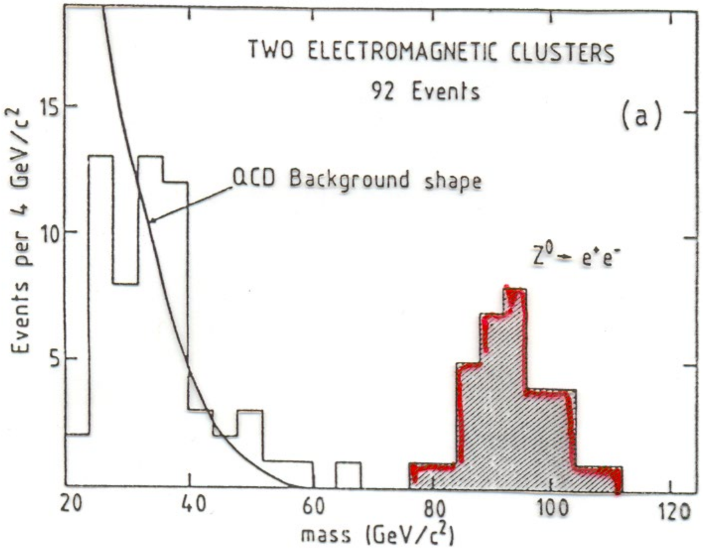
$m_W \sim 80\mathrm{GeV}$

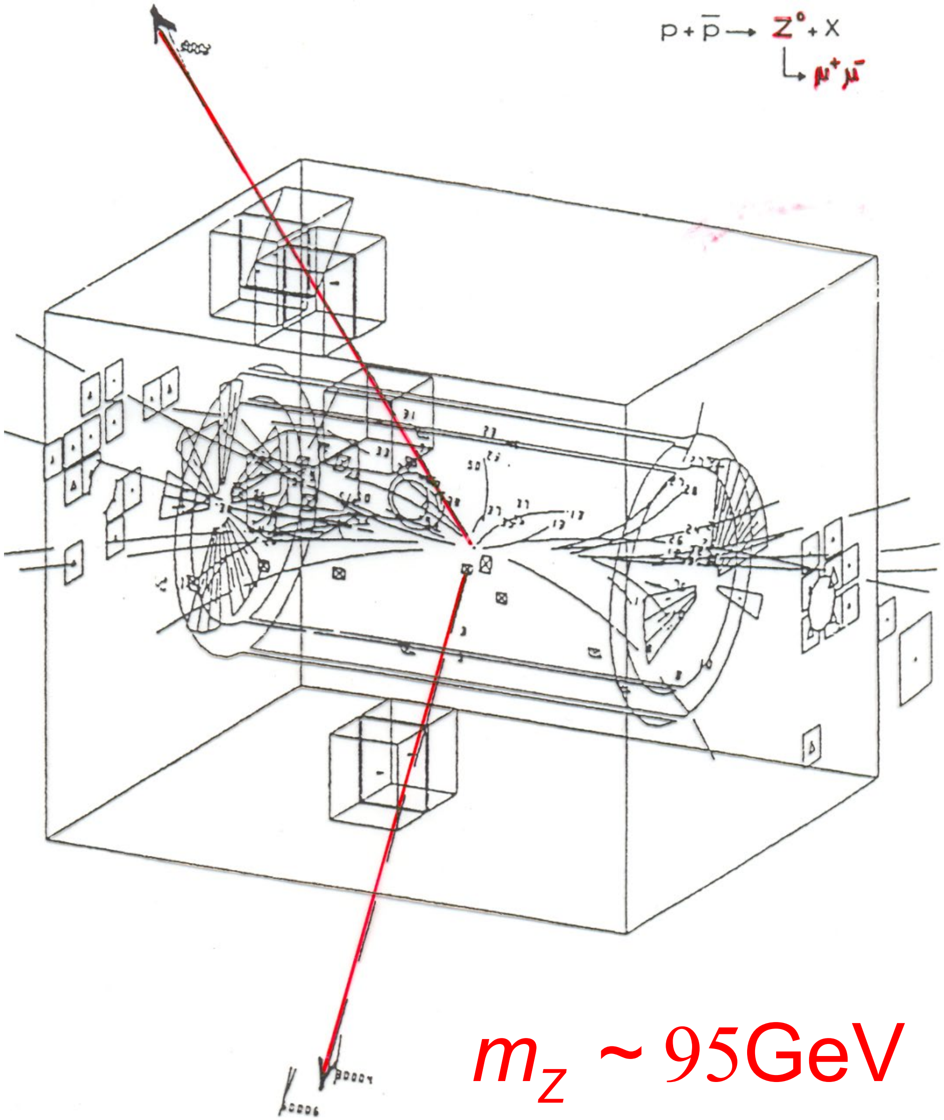
Fig. 16b. The same as picture (a), except that now only particles with $p_T > 1$ GeV/c and calorimeters with $E_T > 1$ GeV are shown.

Discovery of Z-Boson (Jun 1983)

(Nobel prize for C. Rubbia and S. v der Meer, 1984)



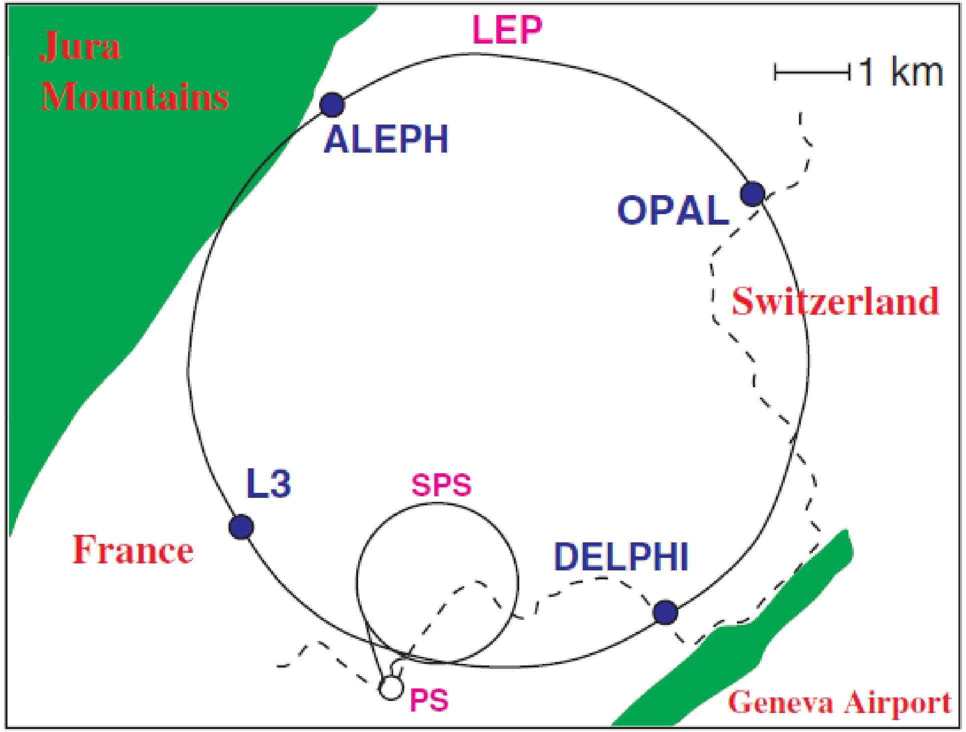




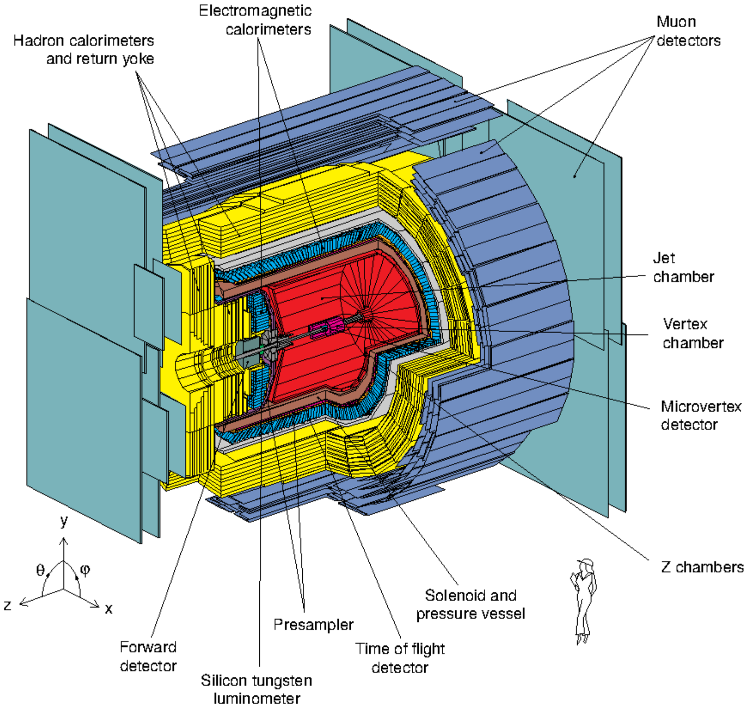
$m_Z \sim 95\text{GeV}$

Precision Tests of Standard Model

LEP = Large-Electron Positron Collider



4 detectors – example: OPAL



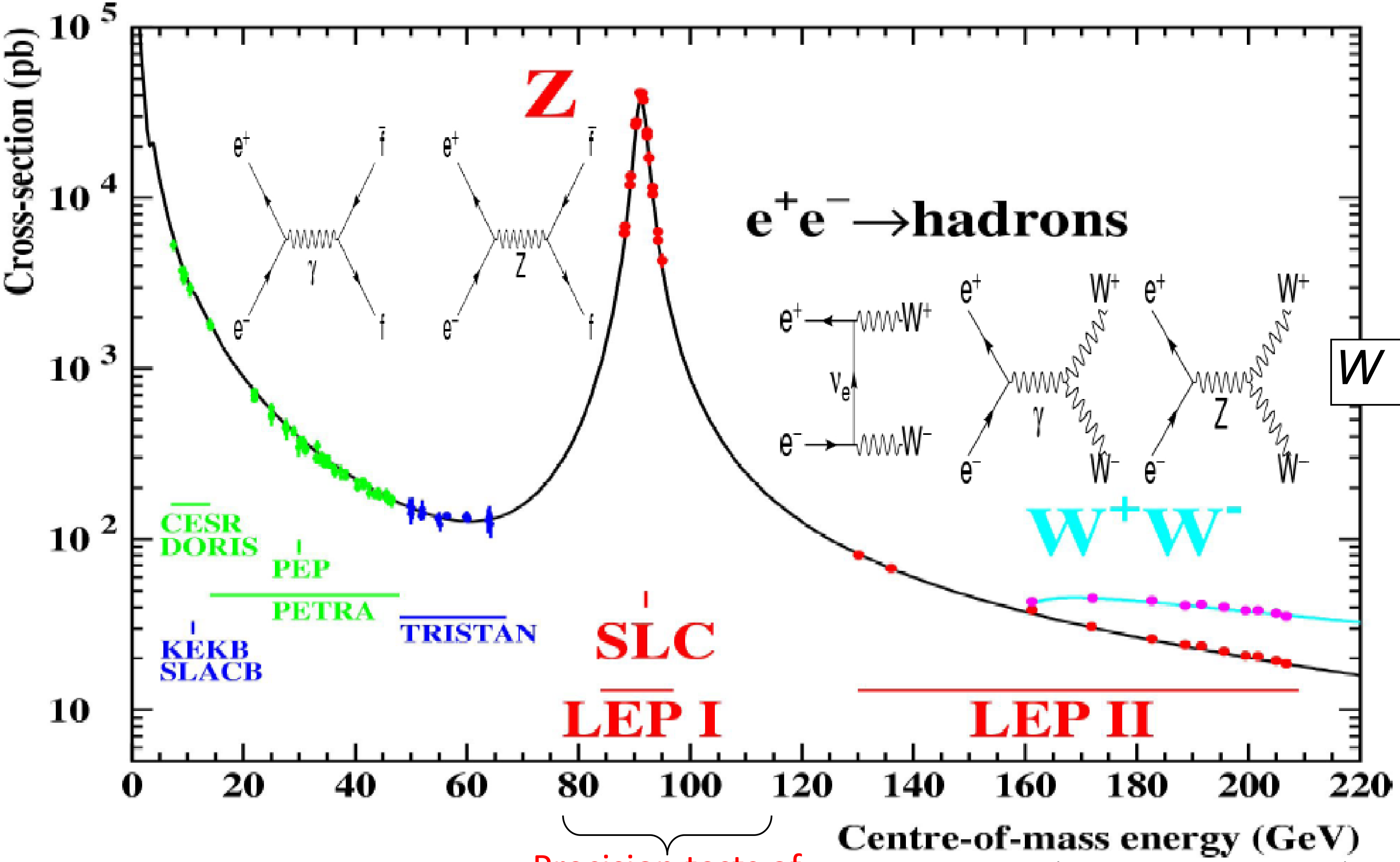
LEP1: ee @ √s ~ 91 GeV (Z-pole)

LEP2: ee @ 160 GeV < √s < 200 GeV

(above WW-threshold)

In total about ~18 M Z-boson decays have been recorded by the 4 detectors

LEP Operation at Z-pole and above WW-threshold

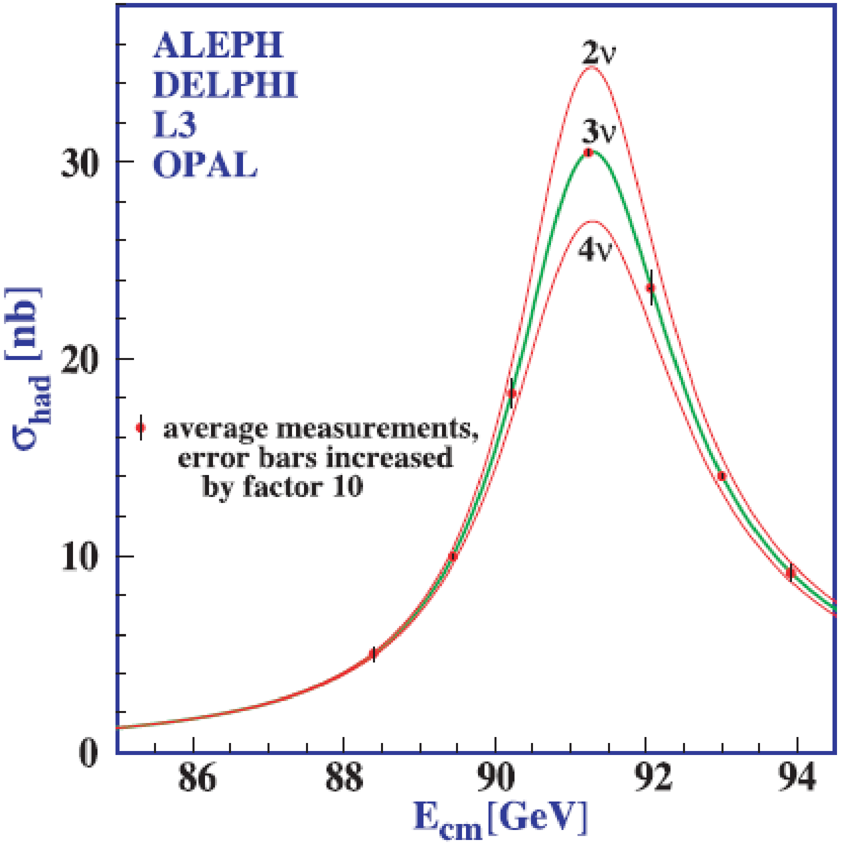


$\boxed{W \to q\bar{q}}$

Precision tests of the Z sector

Tests of the W sector

Precision Measurement of Z Parameters



$$\sigma(s) = 12\pi \frac{\Gamma_e \Gamma_f}{M_Z^2} \cdot \frac{s}{(s - M_Z^2)^2 + M_Z^2 \Gamma_Z^2}$$

M_Z = 91.1876 ± 0.0021 GeV ±23 ppm (*)

Γ_Z = 2.4952 ± 0.0023 GeV ±0.09 %

Γ_{had} = 1.7458 ± 0.0027 GeV

Γ_e = 0.08392 ± 0.00012 GeV

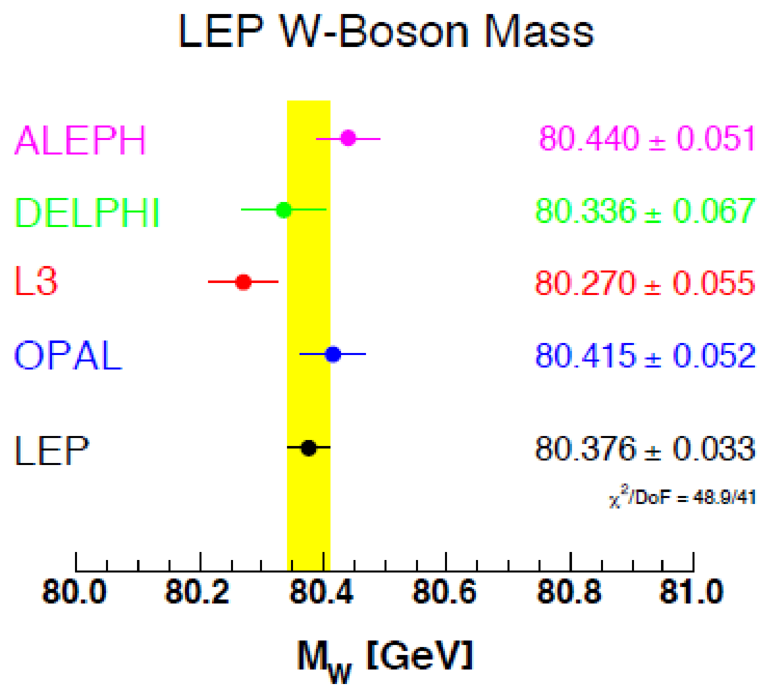
Γ_μ = 0.08399 ± 0.00018 GeV

Γ_τ = 0.08408 ± 0.00022 GeV

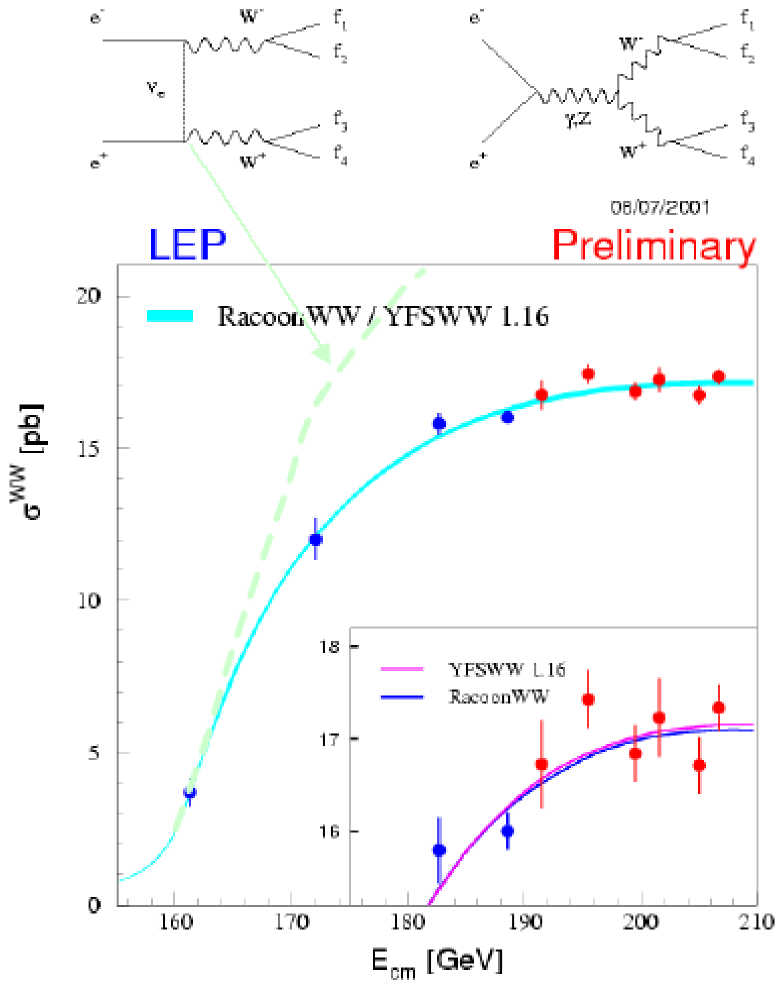
*) error of the LEP energy determination:
±1.7 MeV (19 ppm)

Number of light neutrino generations: 3

W-Mass Measurement



[LEP EWWG arXiv:1302.3415]



Cross section measurement
confirms the triple boson coupling

Electroweak-Radiative Corrections

$$\sin^2\theta_w = 1 - \frac{M_W^2}{M_Z^2} \qquad \sin\theta_w = \frac{e}{g}$$

Lowest order SM predictions

$$\rho = \frac{m_W^2}{m_Z^2\cos^2\theta_W} = 1 \quad \Longrightarrow \quad \bar{\rho} = 1 + \Delta\rho$$

$$\sin^2\theta_W = 1 - \frac{m_W^2}{m_Z^2} \quad \Longrightarrow \quad \sin^2\theta_{\text{eff}} = (1+\Delta\kappa)\sin^2\theta_W$$

$$m_W^2 = \frac{\pi\alpha}{\sqrt{2}\sin^2\theta_W G_F} \quad \Longrightarrow \quad m_W^2 = \frac{\pi\alpha}{\sqrt{2}\sin^2\theta_W G_F}(1+\Delta r)$$

$$\alpha(0) \quad \Longrightarrow \quad \alpha(m_Z^2) = \frac{\alpha(0)}{1-\Delta\alpha}$$

with : $\Delta\alpha = \Delta\alpha_{\text{lept}} + \Delta\alpha_{\text{top}} + \Delta\alpha_{\text{had}}^{(5)}$

Including radiative corrections

$\sin^2\theta_w$

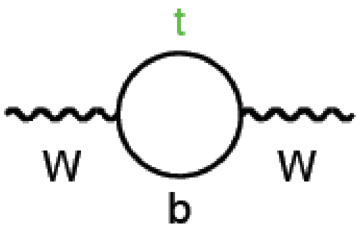
g_A, g_V

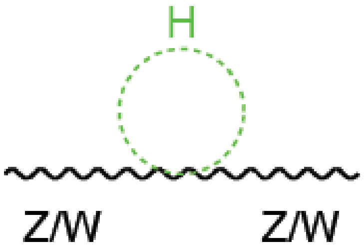
⟹

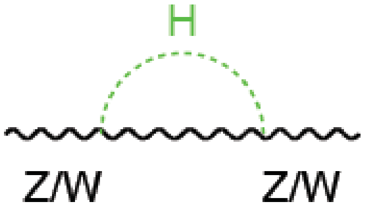
$$\Delta\rho, \Delta\kappa, \Delta r = f\left(m_t^2, \log(m_H), \ldots\right)$$

$\sin^2\theta_{eff}$

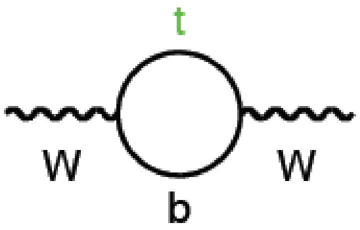
$\overline{g}_A, \overline{g}_V$

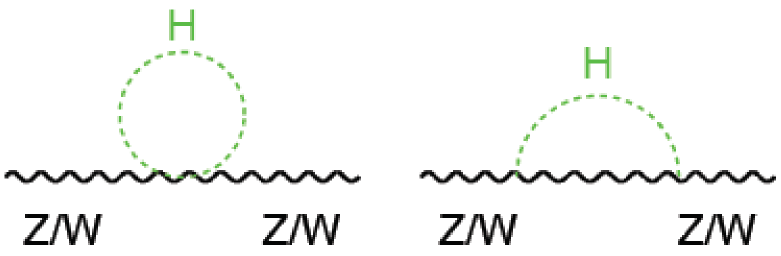


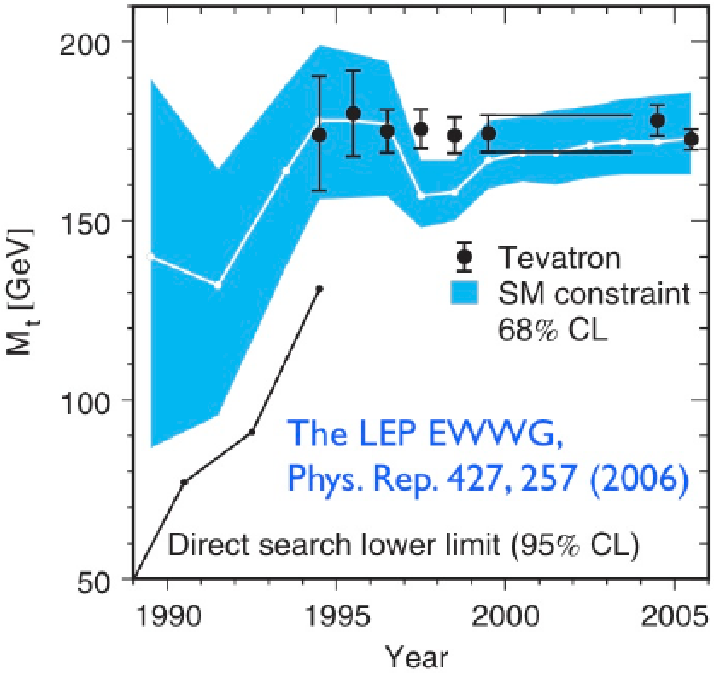


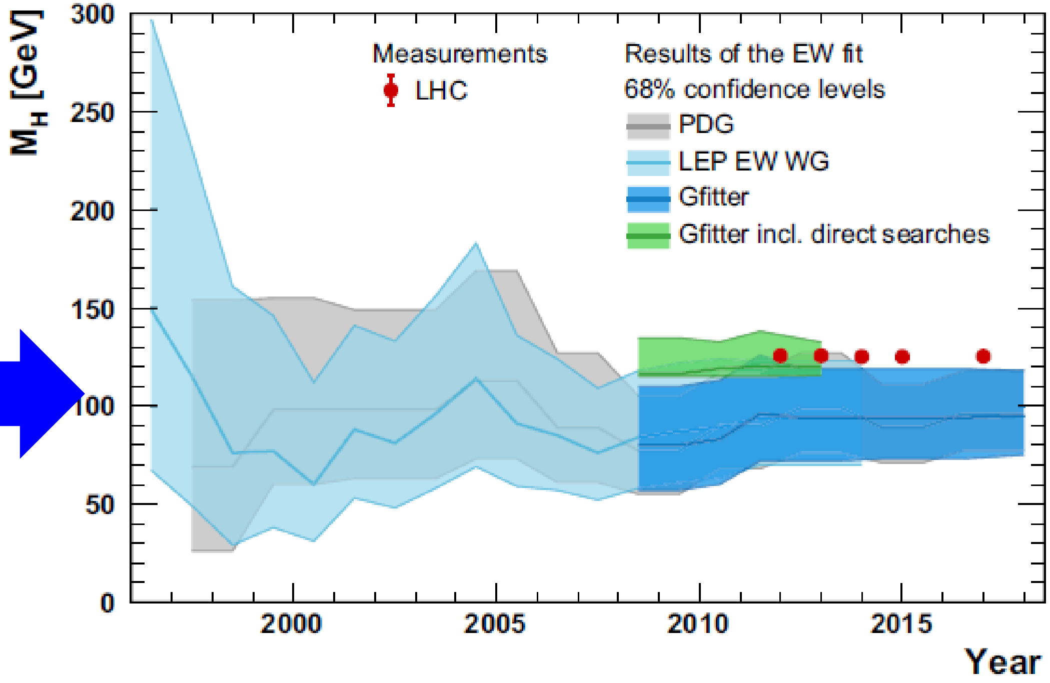


Top-Quark Mass and Higgs Mass prediction





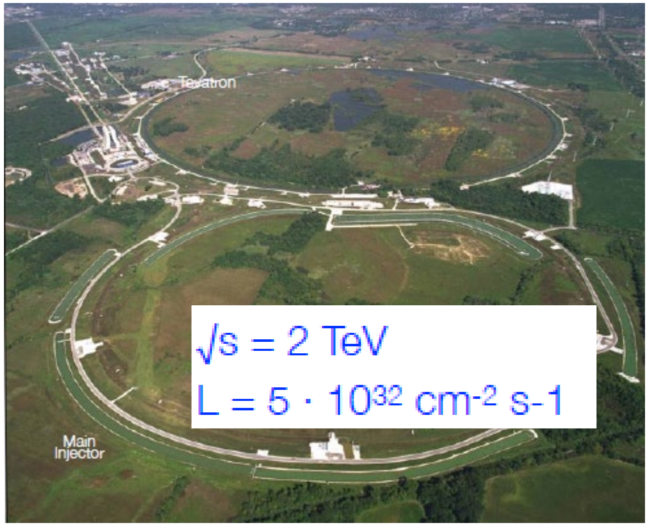




Top Quark was discovered in 1995 by the CDF / D0 experiments (TEVATRON)

Electroweak precision data predicted a very light (~100 GeV) Higgs.

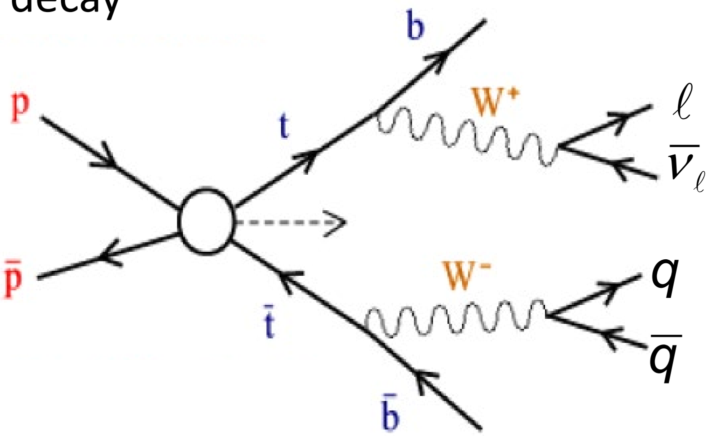
Top Discovery at TEVATRON



$\sqrt{s} = 2$ TeV

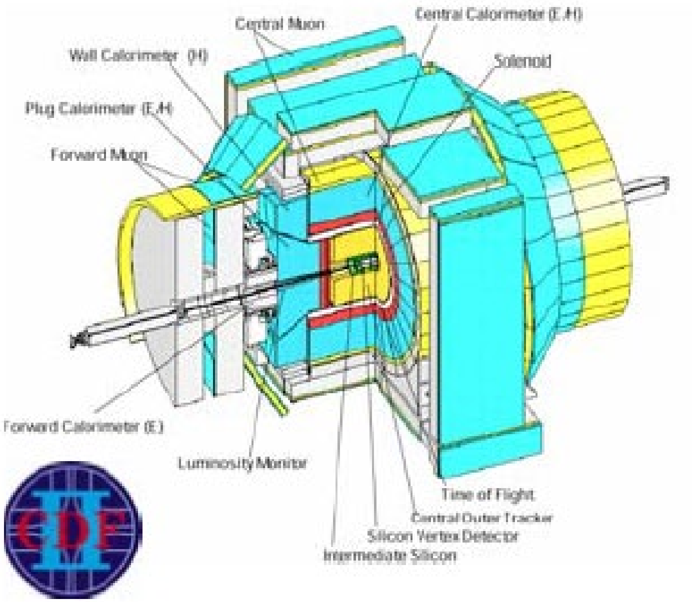
$L = 5 \cdot 10^{32}$ cm^{-2} s-1

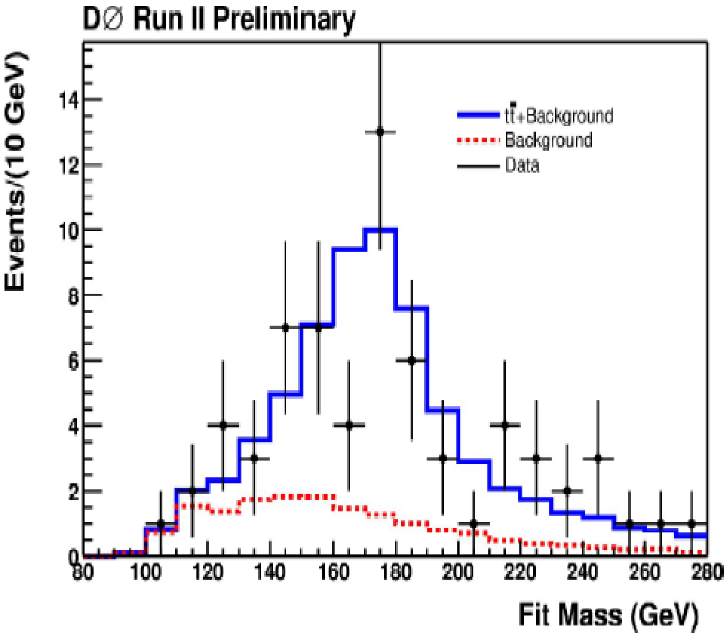
Top decay



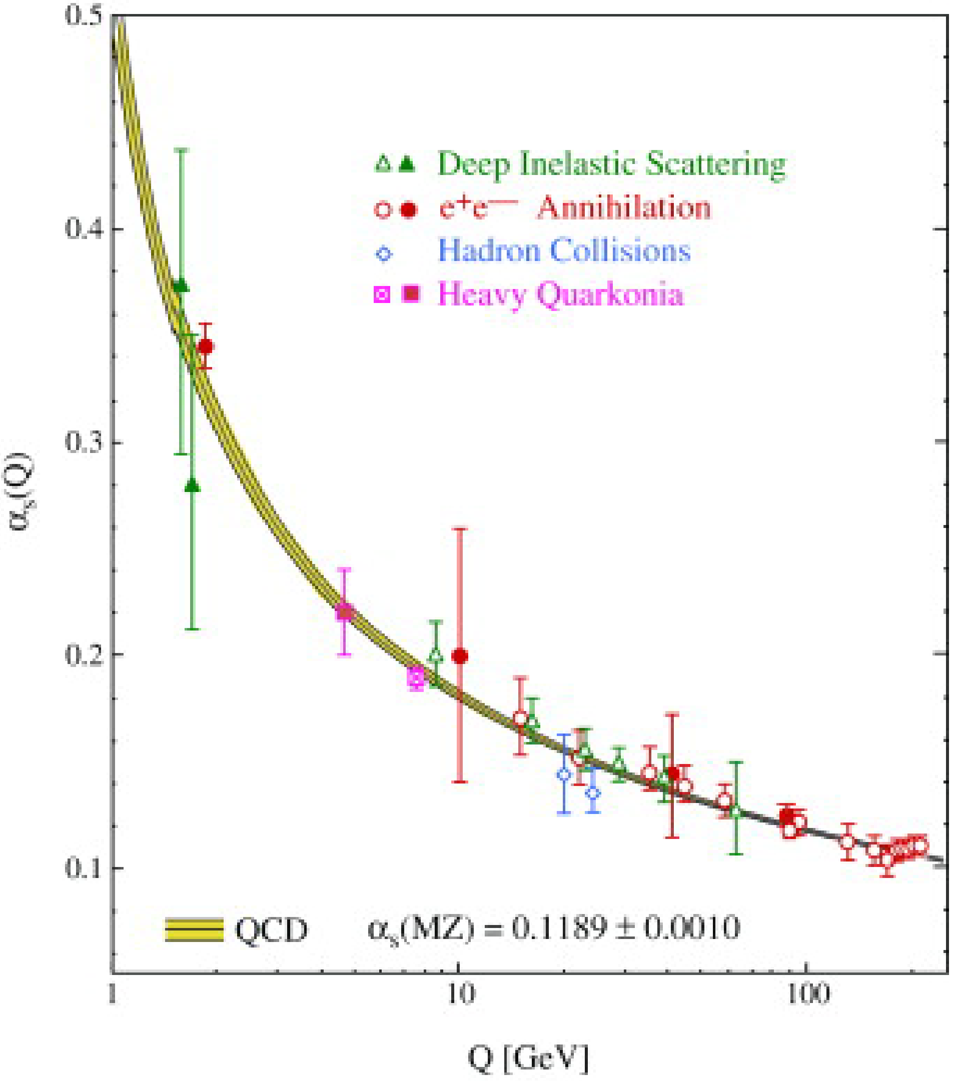
Channel used for mass reconstruction:

$$m_t = m_{inv}(b - jet, W \to jet + jet)$$





Measurement of strong coupling constant

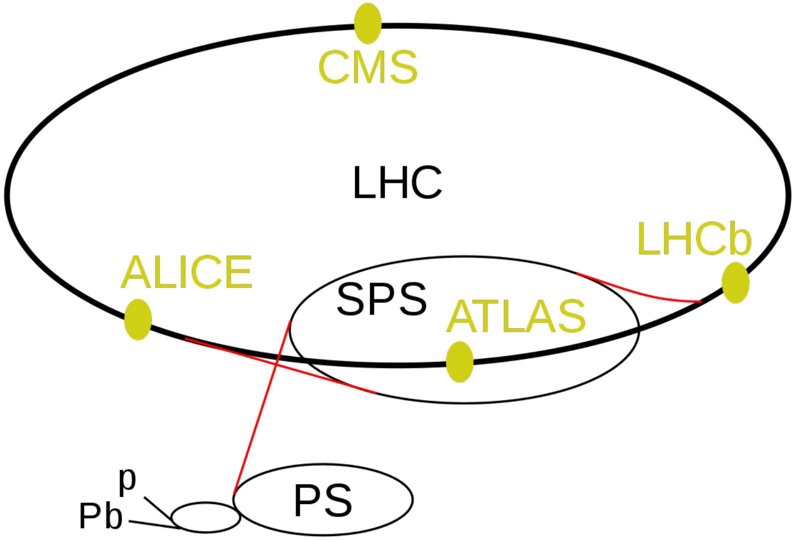


… and test of asymptotic freedom

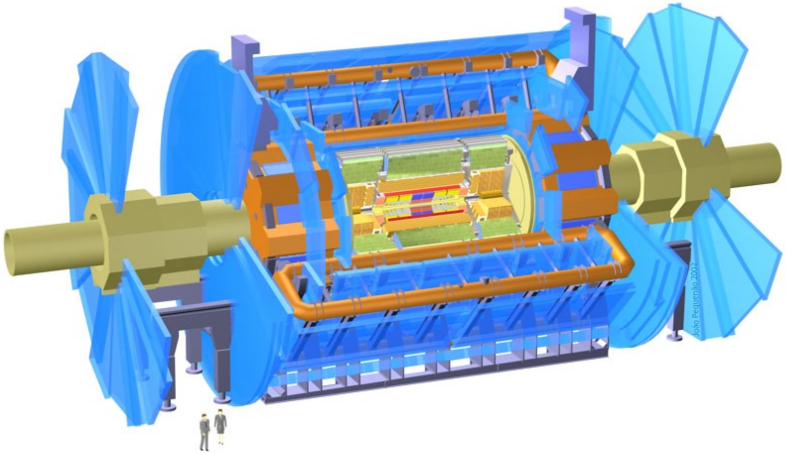
[S.Bethge (2007) https://doi.org/10.1016/j.ppnp.2006.06.001](https://doi.org/10.1016/j.ppnp.2006.06.001)

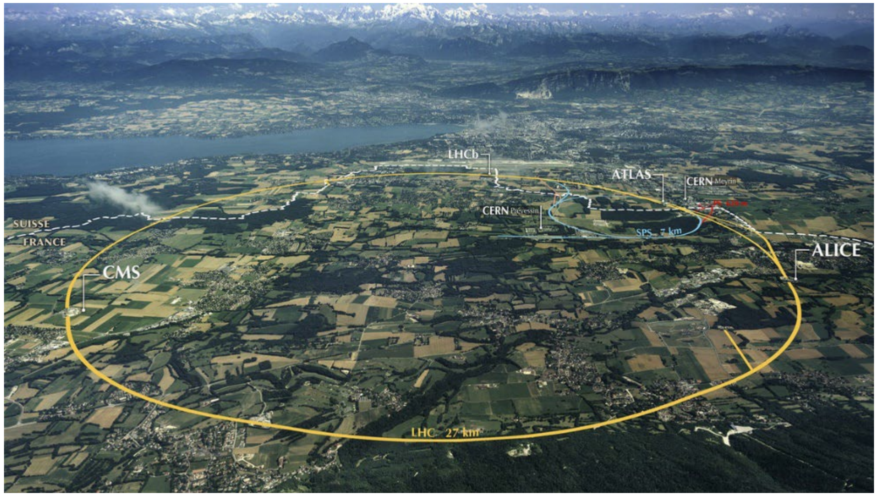
Nobel prize 2004 for “asymptotic freedom” of QCD: D. Gross, D. Politzer F. Wilczek

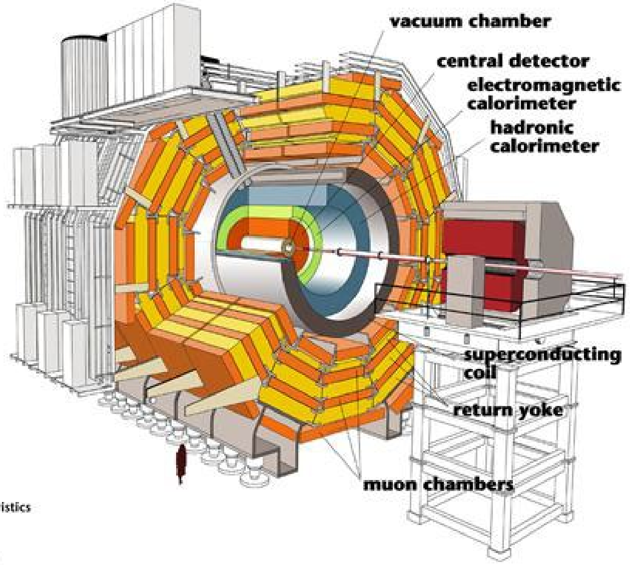
Large Hadron Collider



ATLAS
EXPERIMENT





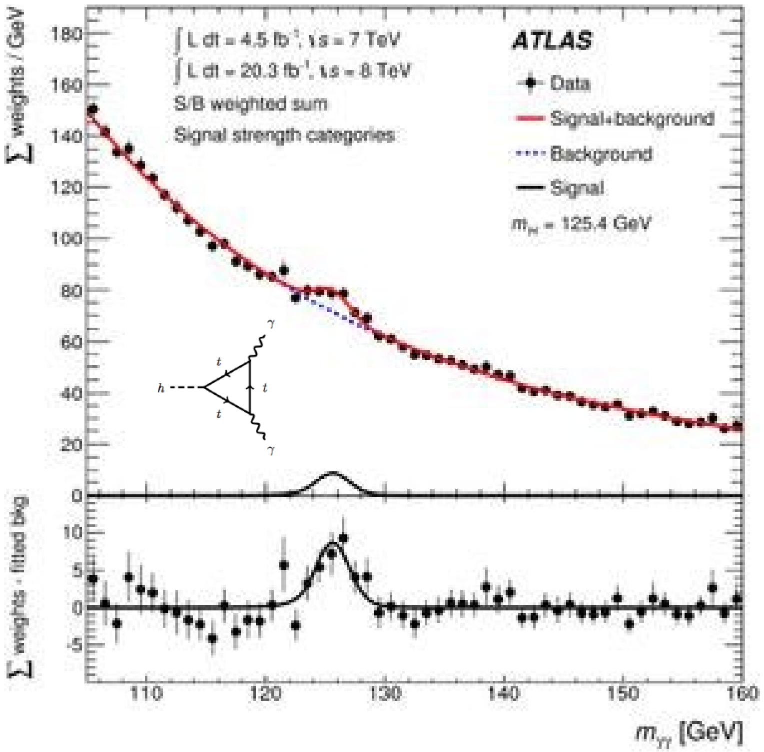


Detector characteristics

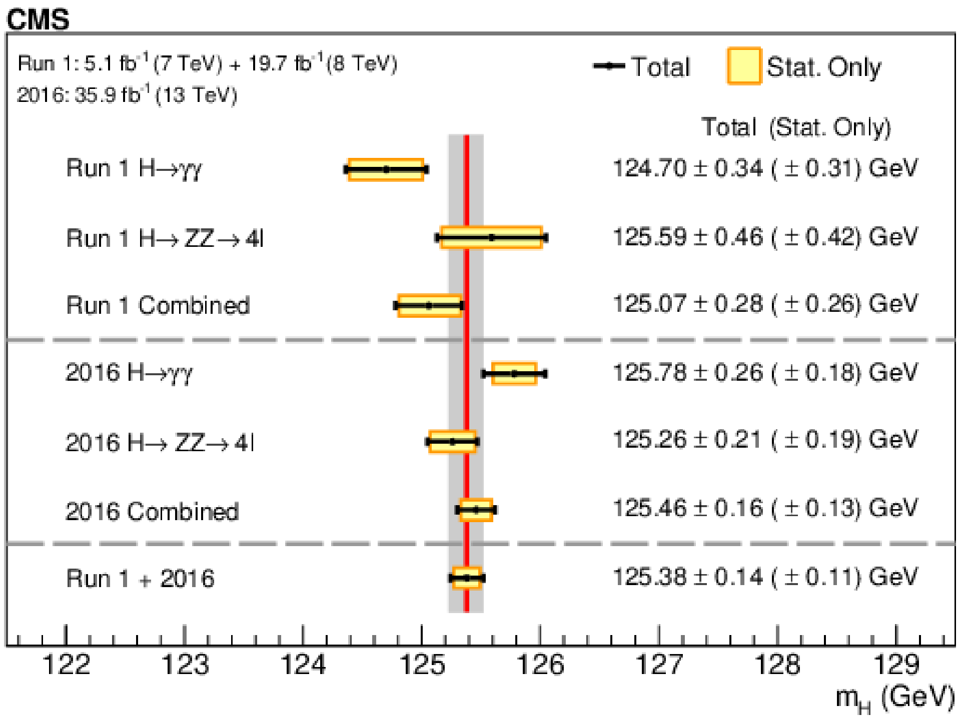
Width: 22m
Diameter: 15m
Weight: 14'500t

Discovery of the Higgs

Phys. Rev. D 90 (2014) 112015.

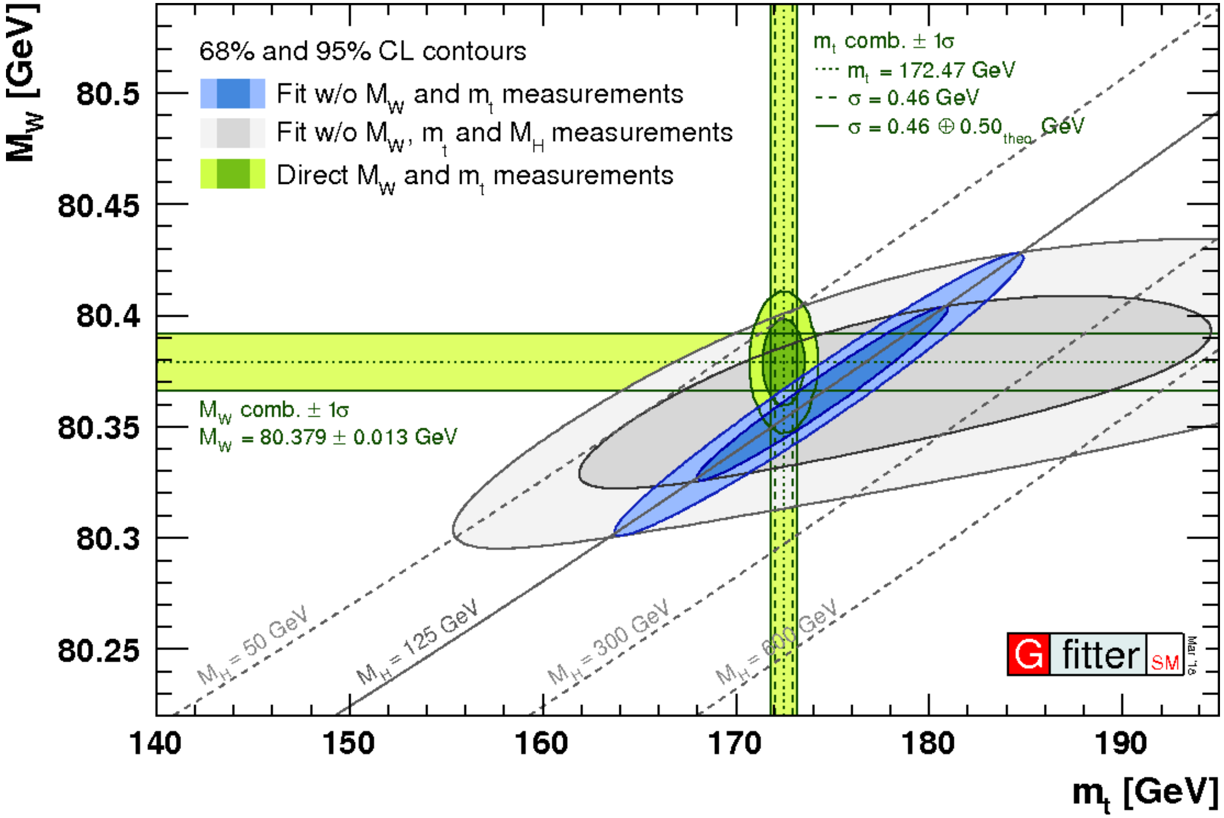


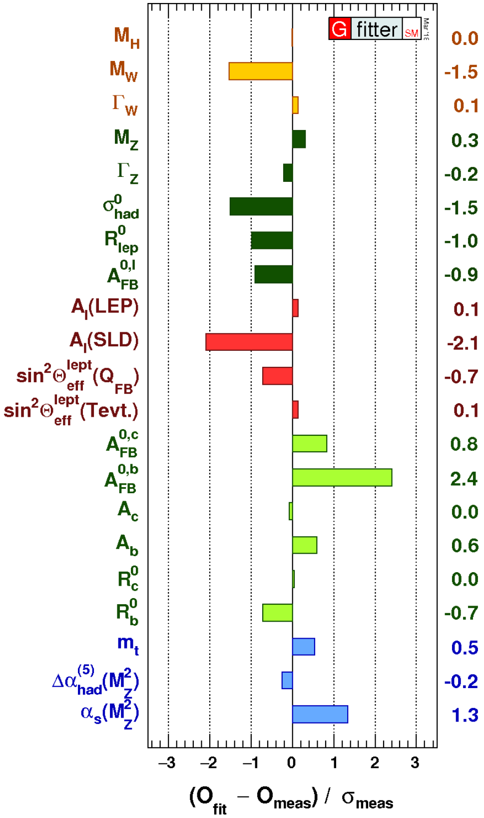
arXiv:2002.06398



Test of Electroweak Standard Model

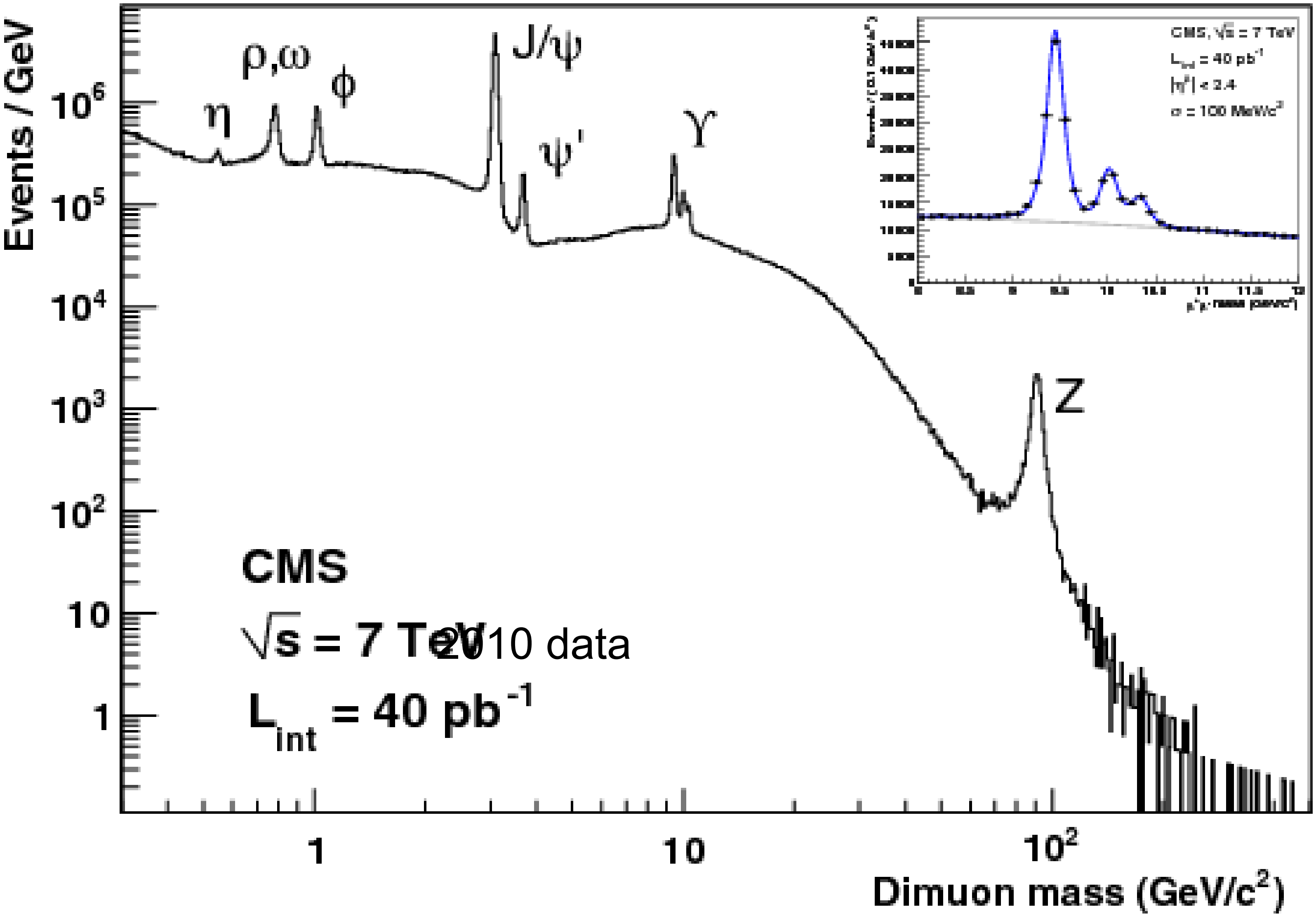
https://project-gfitter.web.cern.ch/project-gfitter/





Rather impressive agreement between direct and indirect measurements.

Standard Model in one view: pp → $\mu^+\mu^-$



2010 data

CMS Collab. arXiv:1206.4071v2

In the LHC high-lumi era these kind of plots can be generated quasi online.

Conclusion

Our understanding of the sub-atomic / particle world is the result of a very close interplay between theory and experiment.

Technological progress on the experimental side was essential push our knowledge boundaries:

- Advances of accelerator technology allowed to go to higher energies and higher luminosities.
- Sophisticated detection techniques leading to complex detector system with several hundred millions of channels allow to reconstruct complicated final states.

Reference for this lecture:
R. N. Cahn, G. Goldhaber: The Experimental Foundations of Particle Physics

Accelerators and their impact on Particle Physics

(selection)

e-accelerators

Year	Energy	Name / Laboratoy	Physics
1951	22 MeV	Betatron / Illinois	Electron Nucleus scattering
1953	225 MeV	Linac /Stanford	Nucleus form factors
1955	500 MeV	Linac Stanford	Proton form factor
1966	20 GeV	2 miles Linac / Stanford	Partons & Scaling

e^+e^- colliders

1961	225 MeV	AdA / Frascati	1st particle-antiparticle collider
1972	4 GeV	SPEAR / Stanford	ψ-Meson, τ
1978	46 GeV	PETRA / DESY	Gluon
1989	100 GeV	LEP / CERN	Precision Z and W parameter

p/A-accelerators A = ion

Year	Energy	Name / Laboratoy	Physics
1953	3.3 GeV	Cosmotron / BNL	Kaon & meson production
1955	6.2 GeV	Bevatron / Berkley (weak)	Antiproton
1960	30 GeV	AGS / BNL (strong focus)	CPV, Ω, J/ψ, Muon neutrino
1976	570 GeV	SPS / CERN	See SppS

pp ($p\bar{p}$) AA colliders

1983	540 GeV	ppbar: SppS / CERN	W, Z Boson
1986	1.8 TeV	ppbar: Tevatron / Femilab	Top
2009	13.6 TeV	LHC / CERN	Higgs