Lecture:

Standard Model of Particle Physics

(MVHE3)

Heidelberg SS 2013

W.Rodejohann (theorist)

+

A. Schöning (experimentalist)

Dr. Werner Rodejohann

(Max-Planck Institut - Kernphysik)

Goal of this Lecture

- Theoretical and experimental introduction into the Standard Model of Particle Physics.

- Tutorials offer the possibility to discuss open questions and the exercises.

- Content of Lecture:
  - QED (Quantum Electrodynamics)
  - Electroweak Interactions and Unification
  - Electroweak Symmetry Breaking and Higgs Mechanism
  - (Strong Interaction)
  - Flavour Physics

Prerequisites

Requirements:

- **PEP5 (Introduction to Particle Physics, bachelor)**
- **Particle Physics (Module MKEP1, master)**

→ **this course addresses master and graduate students**

Other useful or related lectures:

- Theoretical Statistical Physics
- Quantum Field Theory
- Detector Physics
- Accelerator Physics

Credit Points

According to the Master Handbook the workload is 240 hours corresponding to 8 credit points (ECTS)

Requirements

- Participation at Lectures and Tutorials
- Solve exercises (minimum score 50%)

Organisation

Lectures:

Monday 16h15, Kleiner Hörsaal, Philosophenweg 12
Wednesday 11h15, Kleiner Hörsaal, Philosophenweg 12

Accompanying Tutorials:

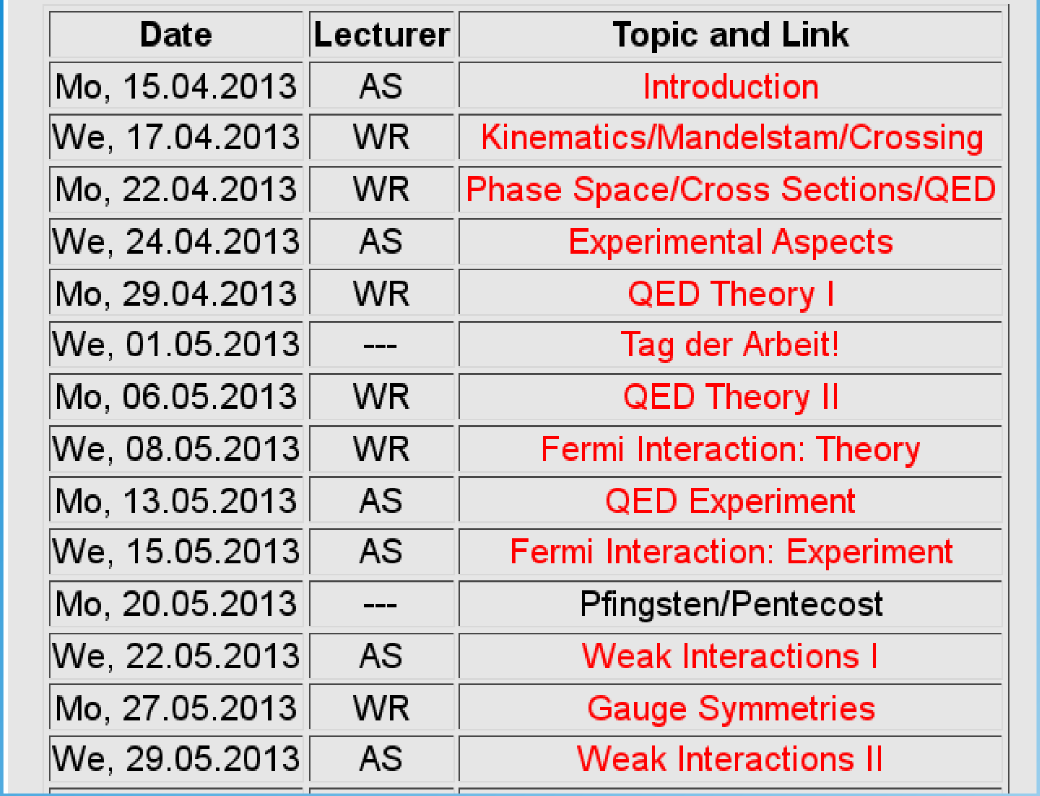
Tuesday (engl./germ.) : 9h15 INF227 SR2.402 (Julian Heeck)
→ first tutorial 30.4.

Thursday (engl.): 14h15 INF227 SR2.402 (He Zhang)
→ first tutorial 2.5.

Handout and return of exercises always **Mondays** after lecture
first exercises handout 22.4.

More Information (e.g. literature) on the Web:
http://www.mpi-hd.mpg.de/manitop/StandardModel/

Lecture Dates

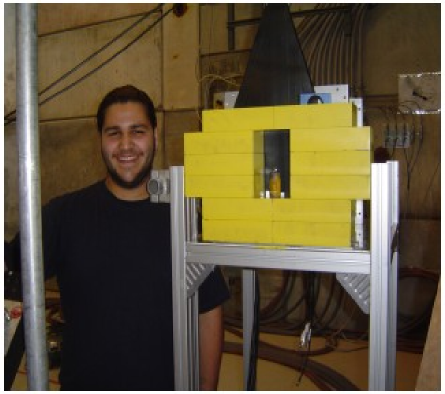



Date	Lecturer	Topic and Link
Mo, 15.04.2013	AS	Introduction
We, 17.04.2013	WR	Kinematics/Mandelstam/Crossing
Mo, 22.04.2013	WR	Phase Space/Cross Sections/QED
We, 24.04.2013	AS	Experimental Aspects
Mo, 29.04.2013	WR	QED Theory I
We, 01.05.2013	---	Tag der Arbeit!
Mo, 06.05.2013	WR	QED Theory II
We, 08.05.2013	WR	Fermi Interaction: Theory
Mo, 13.05.2013	AS	QED Experiment
We, 15.05.2013	AS	Fermi Interaction: Experiment
Mo, 20.05.2013	---	Pfingsten/Pentecost
We, 22.05.2013	AS	Weak Interactions I
Mo, 27.05.2013	WR	Gauge Symmetries
We, 29.05.2013	AS	Weak Interactions II
Mo, 03.06.2013	WR	Gauge Symmetries/Standard Model
We, 05.06.2013	WR	Standard Model/Higgs Mechanism
Mo, 10.06.2013	AS	W- and Z-bosons
We, 12.06.2013	AS	W- and Z-bosons/QCD
Mo, 17.06.2013	WR	Higgs Theory I
We, 19.06.2013	AS	Tests of the SM I
Mo, 24.06.2013	WR	Higgs Theory II
We, 26.07.2013	AS	Tests of the SM II
Mo, 01.07.2013	AS	Tests of the SM III
We, 03.07.2013	AS	Flavor Experiment I
Mo, 08.07.2013	AS	Flavor Experiment II
We, 10.07.2013	WR	Flavor Theory I
Mo, 15.07.2013	WR	Flavor Theory II
We, 17.07.2013	WR	Massive neutrinos
Mo, 22.07.2013	---	Klausurwoche
We, 24.07.2013	---	Klausurwoche

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

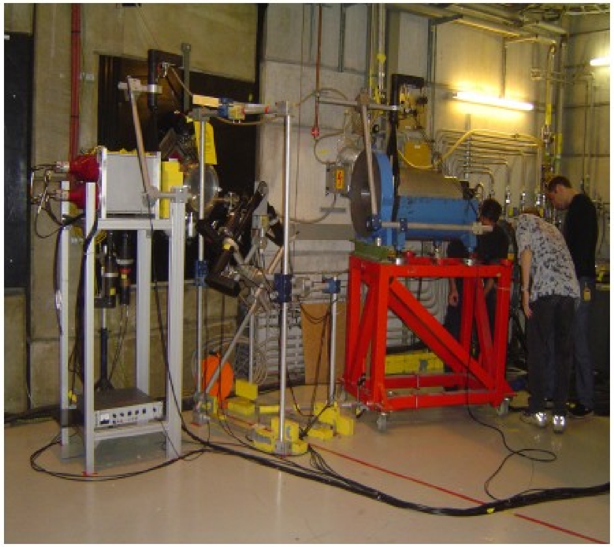
Particle Physics

Particle Physics Practical Course at the Paul Scherrer Institute (PSI, Switzerland) in Summer 2013



Examples from previous measurements:

- Branching Ratio: $B(\pi\to\mu\nu)/B(\pi\to e\nu)$
- Panofski Ratio: $B(\pi p\to n\pi)/B(\pi p\to n\gamma)$
- Lifetimes and decay parameters of muons and pions



Date of next course:

26. August - 13. September 2013

Contact Persons:

A.Schöning: schoning@physi.uni-heidelberg.de
C.Grab : grab@phys.ethz.ch
P.Robmann: peter@physik.uzh.ch

Limited number of places, please register!

This course (MVPSI) is part of the Master Programme at the Faculty of Physics and Astronomy in Heidelberg!

06/02/13 / A.Schöning

PAUL SCHERRER INSTITUT
PSI

ETH Institute for Particle Physics

give FEEDBACK!

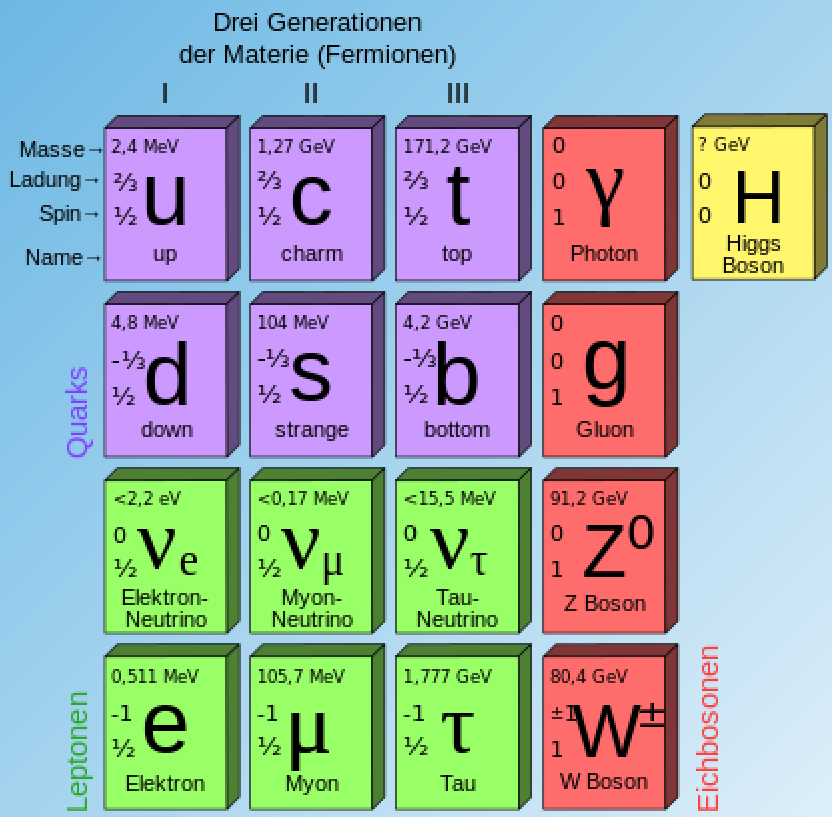
Introduction:

“The Interplay between Theory and Experiment in Particle Physics”

~1930

- electron
- proton
- (neutron)

~50-60 years

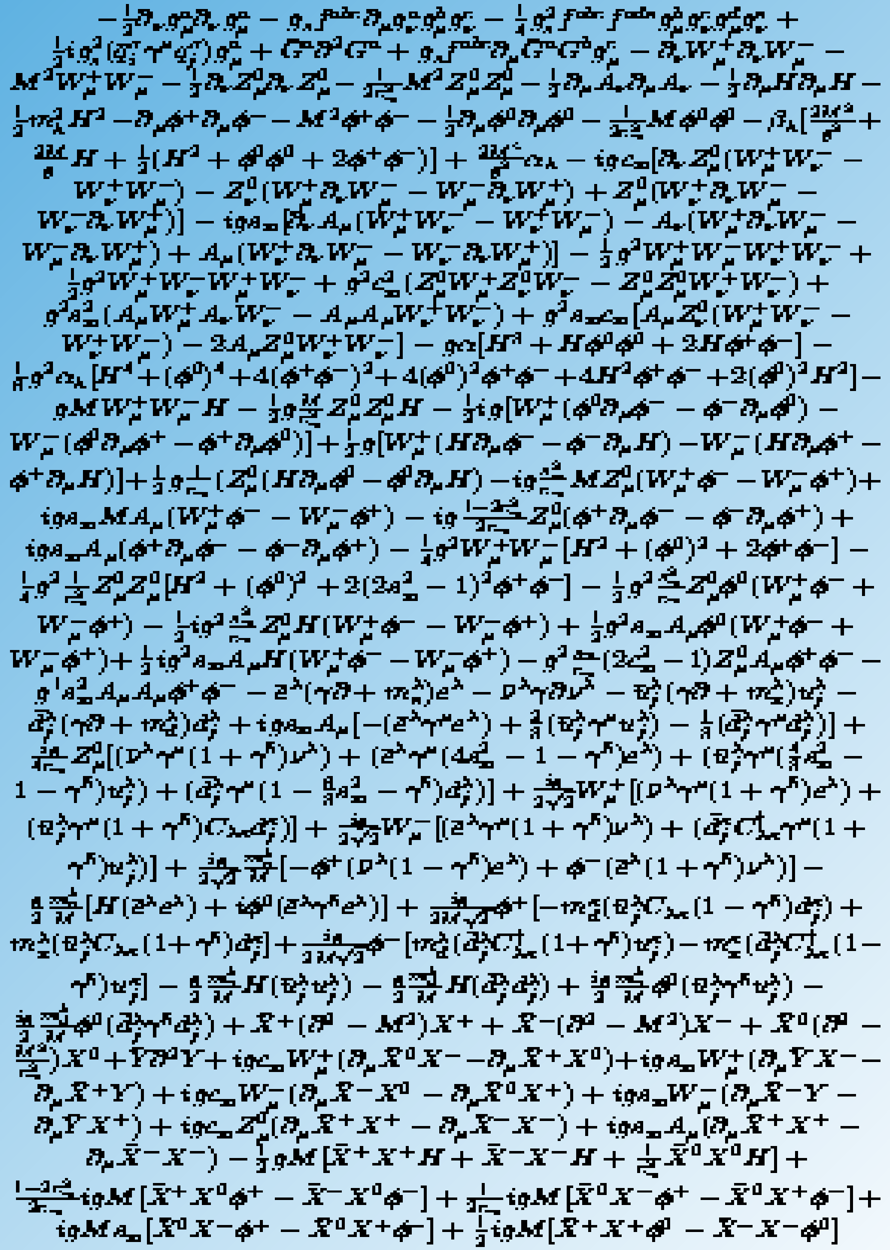


SM Lagrangian

~1930

- electron
- proton
- (neutron)

~50-60 years →



Main Achievements in Theory

- Relativistic Quantum Mechanics (QED, Dirac Equation)
- Relativistic Quantum Field Theory (vacuum polarisation)
- Gauge Theories (renormalisable field theory)
- Electroweak Unification (electromagnetic+weak force)
- Mass Generation and Spontaneous Symmetry Breaking
- Quantum Chromodynamics and understanding of confinement

→ Standard Model of Particle Physics

Important Experimental Discoveries

- Discovery of the muon (particle families)
- Discovery of the pion (strong interaction)
- Discovery of Parity Violation in Weak Interactions
- Discovery of Strangeness and Fermion-Mixing
- Discovery of the Neutrino
- Observation of neutral currents (weak interaction)
- Discovery of massive gauge bosons (W,Z)
- Discovery of the Higgs boson at LHC in 2012

This all goes along with the development of modern particle detectors and accelerators

Interplay Theory-Experiment

Prediction of the Anti-electron (Dirac, 1928)
Discovery of the Positron (Anderson, 1932)

Prediction of mesons (1935)
Discovery of the muon (1936)
Discovery of the pion (1947)

Prediction of the neutrino (Pauli 1930)
Discovery of the electron neutrino (Cowan Reines, 1957)

Prediction of the muon neutrino (1950th)
Discovery of the muon neutrino (Ledermann, Schwartz, Steinberger 1962)

Discovering the particle zoo (1960th)
Development of Quantum Chromodynamics (1968)

Theory of Quark Mixing (1970th)
…...

Anti-Particle Hypothesis

Paul Dirac (1928):

Field equation for a relativistic Quantum Mechanics based on Einsteins special relativity relation:

$$E^2 = m^2 + p^2$$

Dirac equation has solutions for positively and negatively polarised particles and for positive and negative energies:

negative energy: antiparticles!

Later Feynman-Stückelberg interpretation:
antiparticles are particles traveling in reverse time direction

Discovery of the Positron

Carl D. Anderson

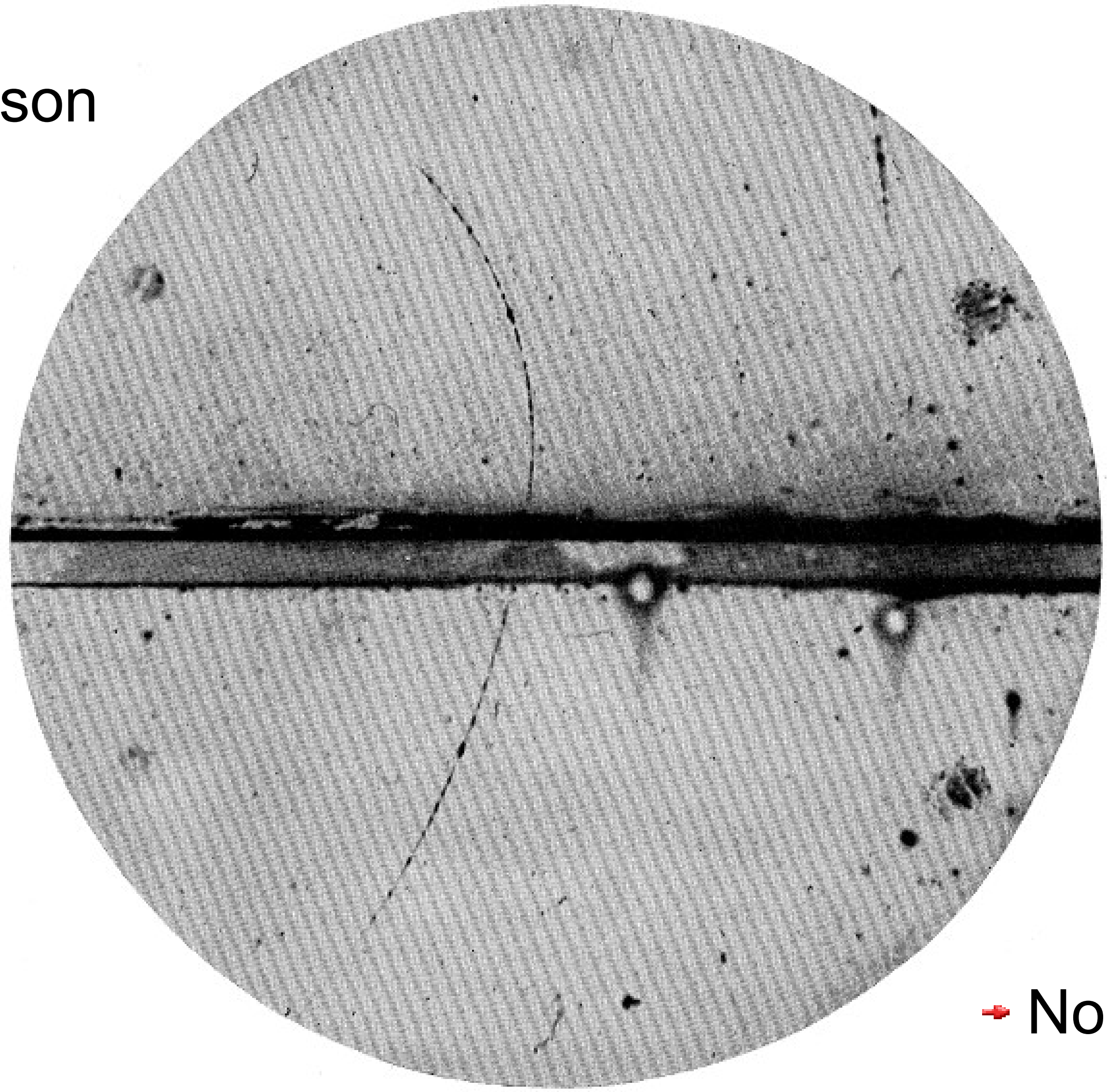


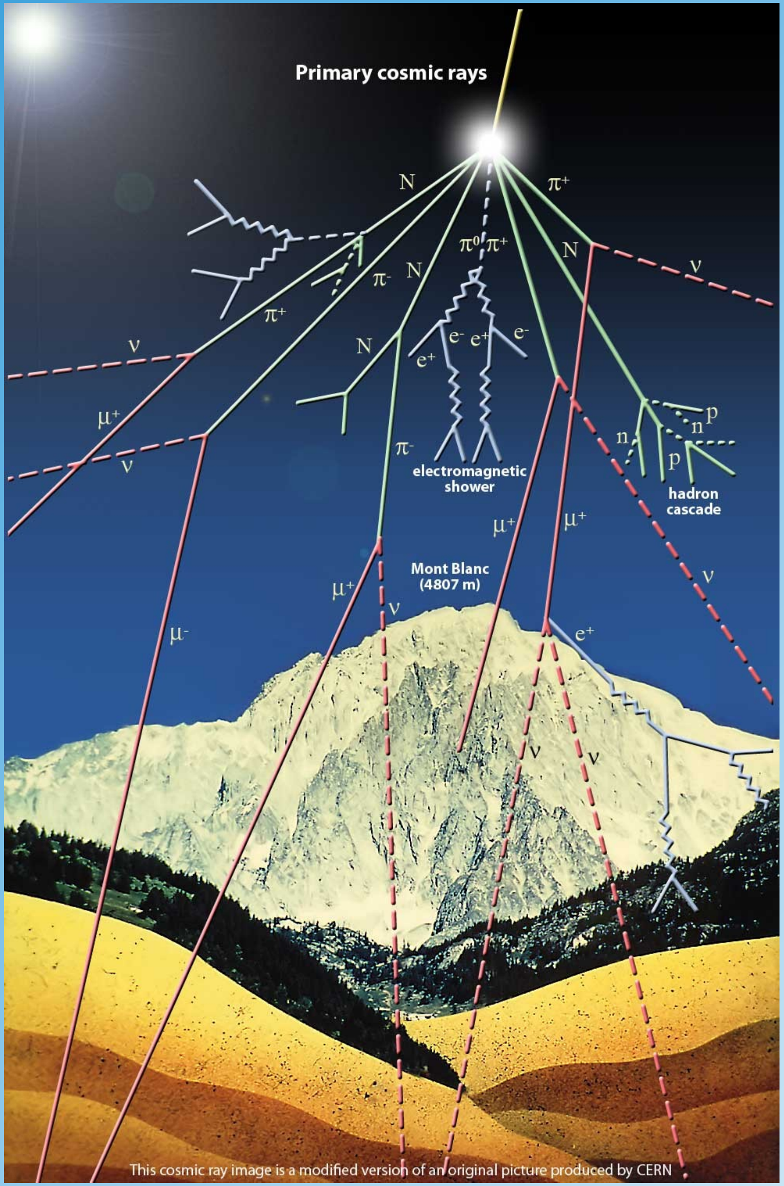
FIG. 1. A 63 million volt positron ($H\rho = 2.1\times10^5$ gauss-cm) passing through a 6 mm lead plate and emerging as a 23 million volt positron ($H\rho = 7.5\times10^4$ gauss-cm). The length of this latter path is at least ten times greater than the possible length of a proton path of this curvature.

- Nobel Prize (1936)

Muon Discovery

Victor Hess
discovery of
cosmic showers

1912



This cosmic ray image is a modified version of an original picture produced by CERN

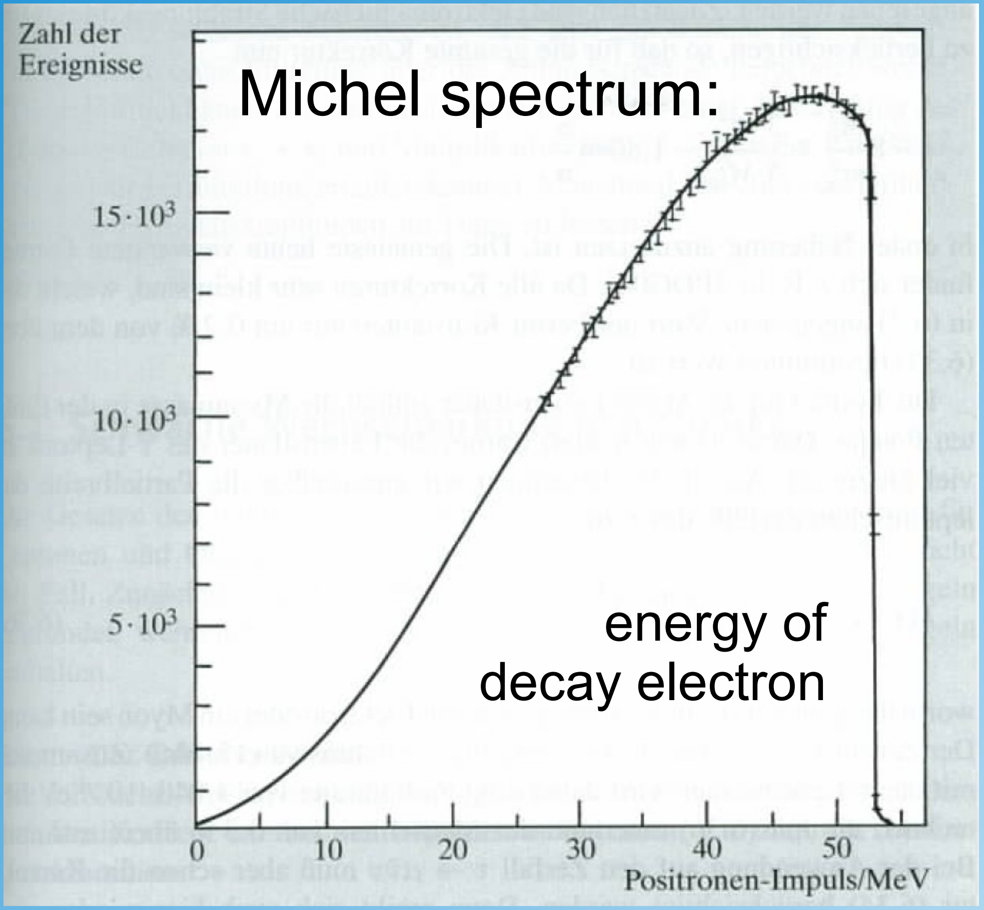
Muon discovery in cosmic rays by

Carl Anderson
+
Seth Nedermeyer

→ Nobel Prize (1936)

Theoretical Interpretation of the muon decay

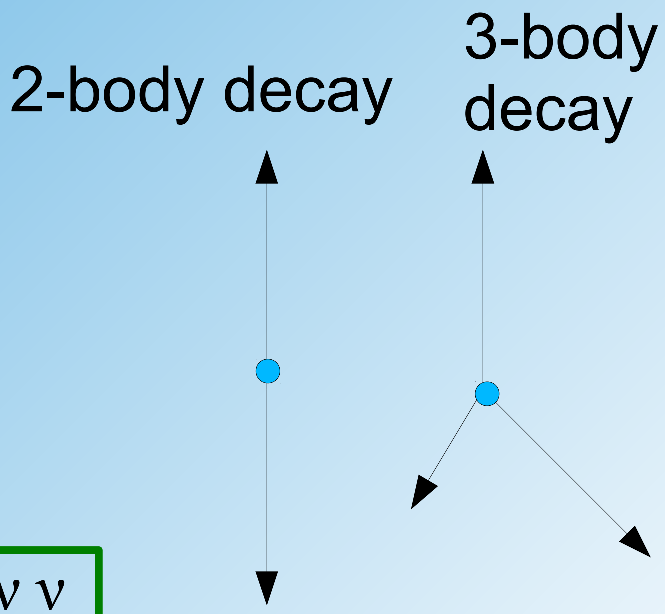
Energy spectrum of electrons from muon decay: $\mu^- \to e^-$??



Michel spectrum:

energy of decay electron

$m_\mu = 105.6$ MeV



2-body decay

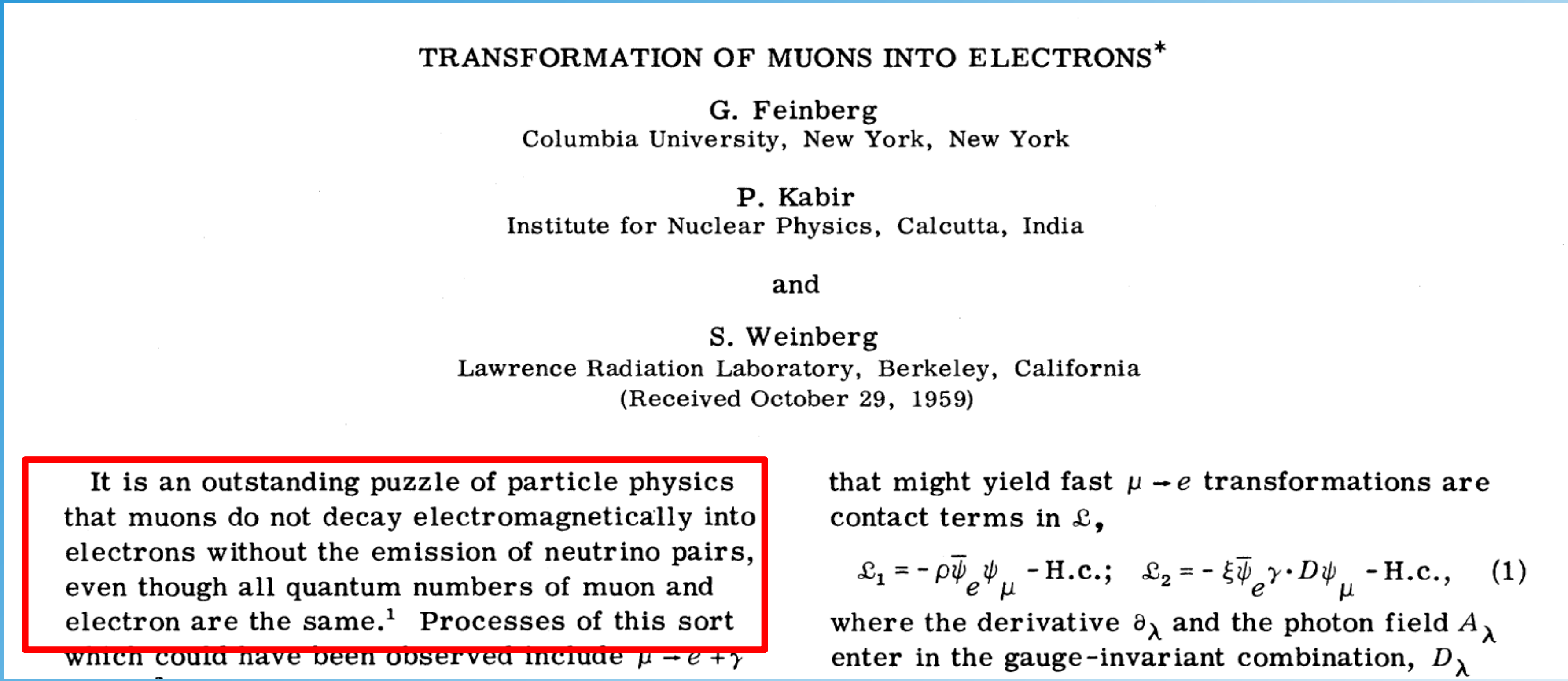
3-body decay

- Two neutrino hypothesis: $\boxed{\mu^- \to e^- \nu \nu}$

Theoretical Interpretation II

Further studies of muon decays showed that e.g. $\mu \rightarrow e\,\gamma$ is forbidden

- the muon is not an excited state of the electron



TRANSFORMATION OF MUONS INTO ELECTRONS*

G. Feinberg
Columbia University, New York, New York

P. Kabir
Institute for Nuclear Physics, Calcutta, India

and

S. Weinberg
Lawrence Radiation Laboratory, Berkeley, California
(Received October 29, 1959)

It is an outstanding puzzle of particle physics that muons do not decay electromagnetically into electrons without the emission of neutrino pairs, even though all quantum numbers of muon and electron are the same.[1] Processes of this sort which could have been observed include $\mu \rightarrow e + \gamma$

that might yield fast $\mu \rightarrow e$ transformations are contact terms in $\mathfrak{L}$,

$$\mathfrak{L}_1 = -\rho\bar{\psi}_e\psi_\mu - \text{H.c.}; \quad \mathfrak{L}_2 = -\xi\bar{\psi}_e\gamma\cdot D\psi_\mu - \text{H.c.}, \qquad (1)$$

where the derivative ∂_λ and the photon field A_λ enter in the gauge-invariant combination, D_λ

- introduction of **Lepton Family Number**

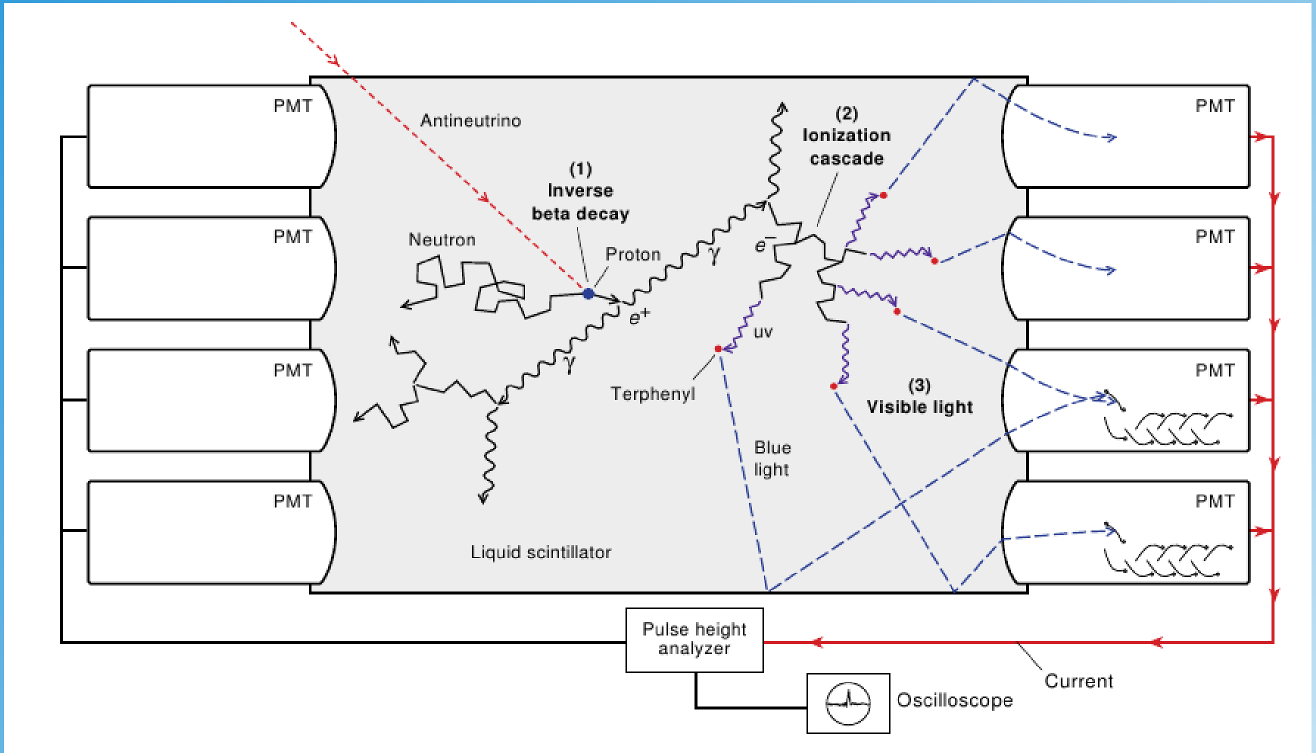
$\mu^- \longrightarrow e^-\,\bar{\nu}_e\,\nu_\mu$ is allowed!

Discovery of the Electron-Neutrino

Discovery of the electron neutrino (Cowan, **Reines**, 1957)

→ Nobel Prize (1995)

Anti-Electron-Neutrino



Discovery of the muon neutrino (**Ledermann,Schwartz,Steinberger** 1962)

→ Nobel Prize (1988)

Prediction of the Pion

H.**Yukawa** predicted 1935 mesons as carriers of the strong force

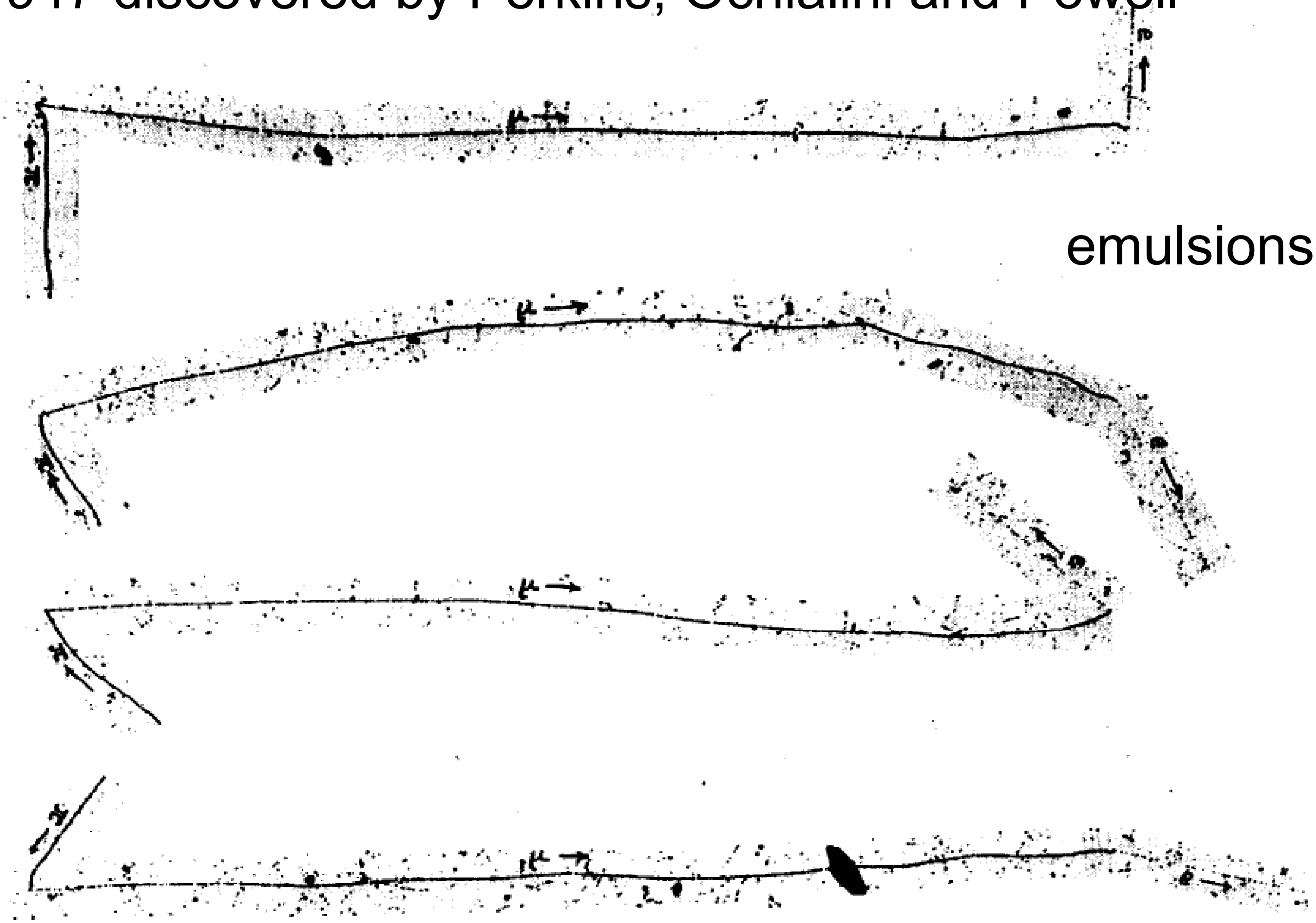
→ Nobel Prize (1949)

meson mass ~ $\hbar c$ / (range of force)

range ~ 1 fm → m_{meson} = 200 MeV

Discovery of the Pion

1947 discovered by Perkins, Ochialini and Powell



emulsions

- Nobel Prize (Powell 1950)

Parity Violation in Weak Interactions

In Quantum Electrodynamics (QED) $\partial_\mu j_V^\mu = 0$ (conservation of currents)

Lorentz Structure of Weak Interactions?

scalar coupling:

$$S = \bar{\psi}\psi$$

pseudoscalar coupling

$$P = \bar{\psi}\gamma^5\psi$$

vector current:

$$j_V^\mu = \bar{\psi}\gamma^\mu\psi$$

axial-vector current:

$$j_A^\mu = \bar{\psi}\gamma^\mu\gamma^5\psi$$

Left-Right Symmetry broken if

$$j_L^\mu = 1/2\left(j_V^\mu - j_A^\mu\right) \neq$$

$$j_R^\mu = 1/2\left(j_V^\mu + j_A^\mu\right)$$

Discovery of Parity Violation in Weak Decays

proposed by **Lee + Yang**

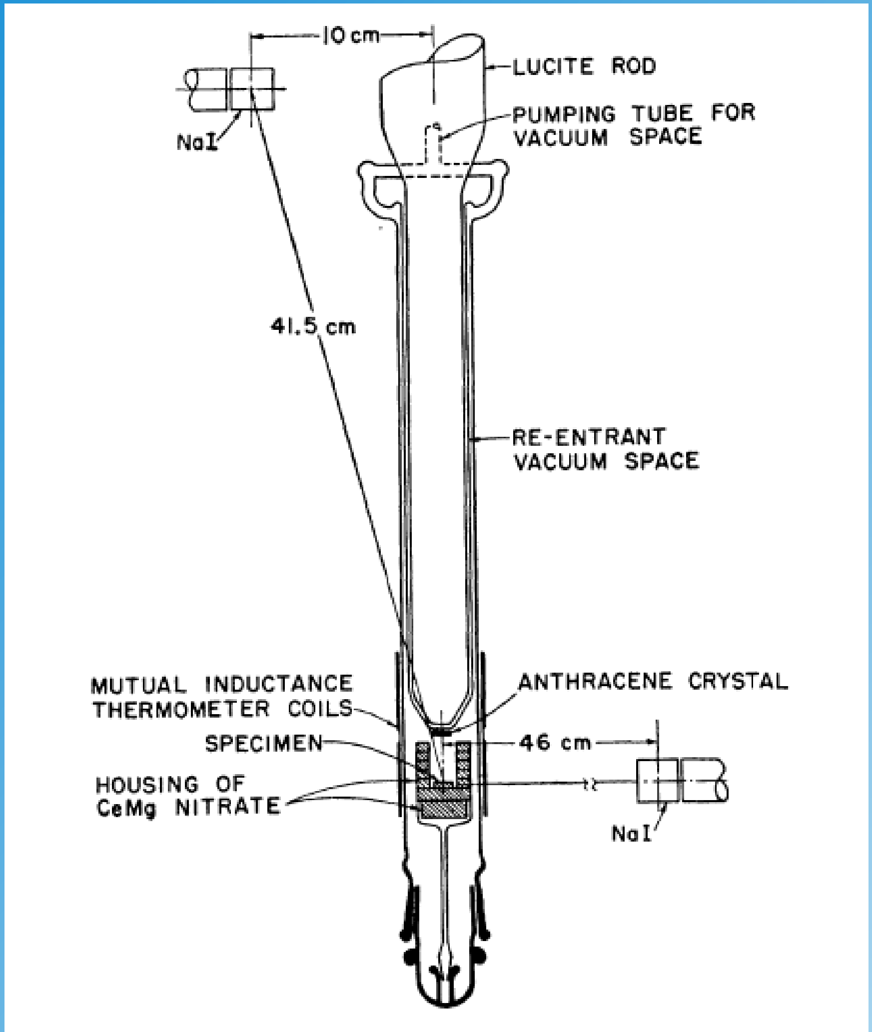
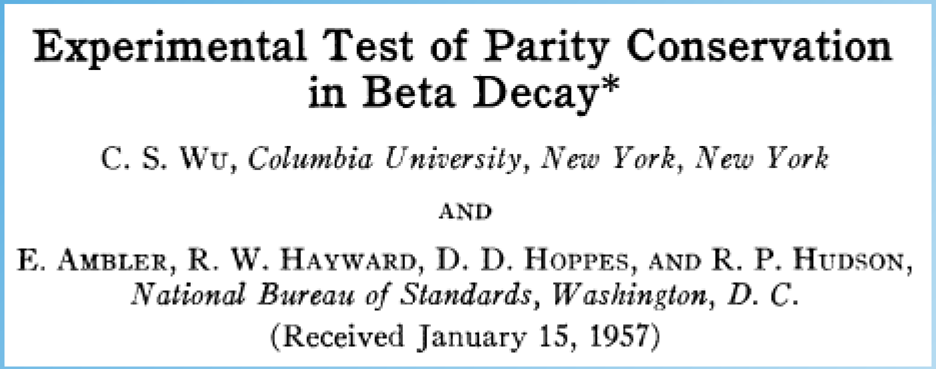


Fig. 1. Schematic drawing of the lower part of the cryostat.



Experimental Test of Parity Conservation in Beta Decay*

C. S. Wu, *Columbia University, New York, New York*

AND

E. Ambler, R. W. Hayward, D. D. Hoppes, and R. P. Hudson, *National Bureau of Standards, Washington, D. C.*

(Received January 15, 1957)

polarised $Co^{60} \rightarrow Ni^{*} e^{-} \nu$

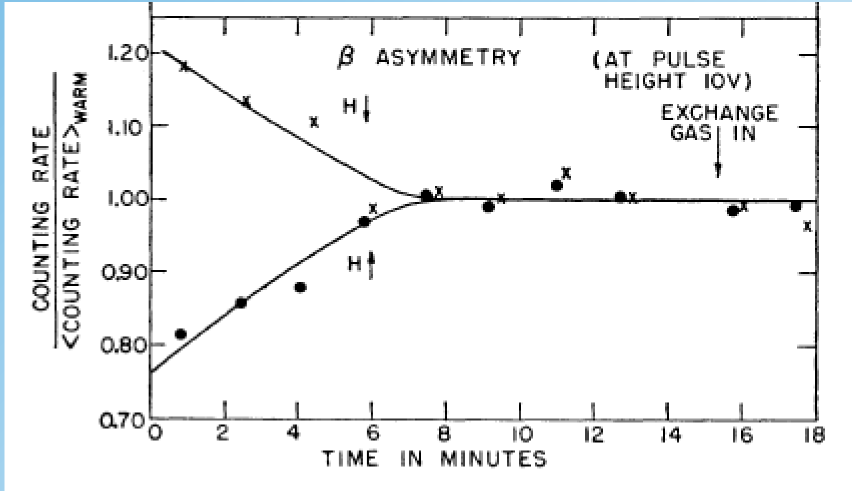
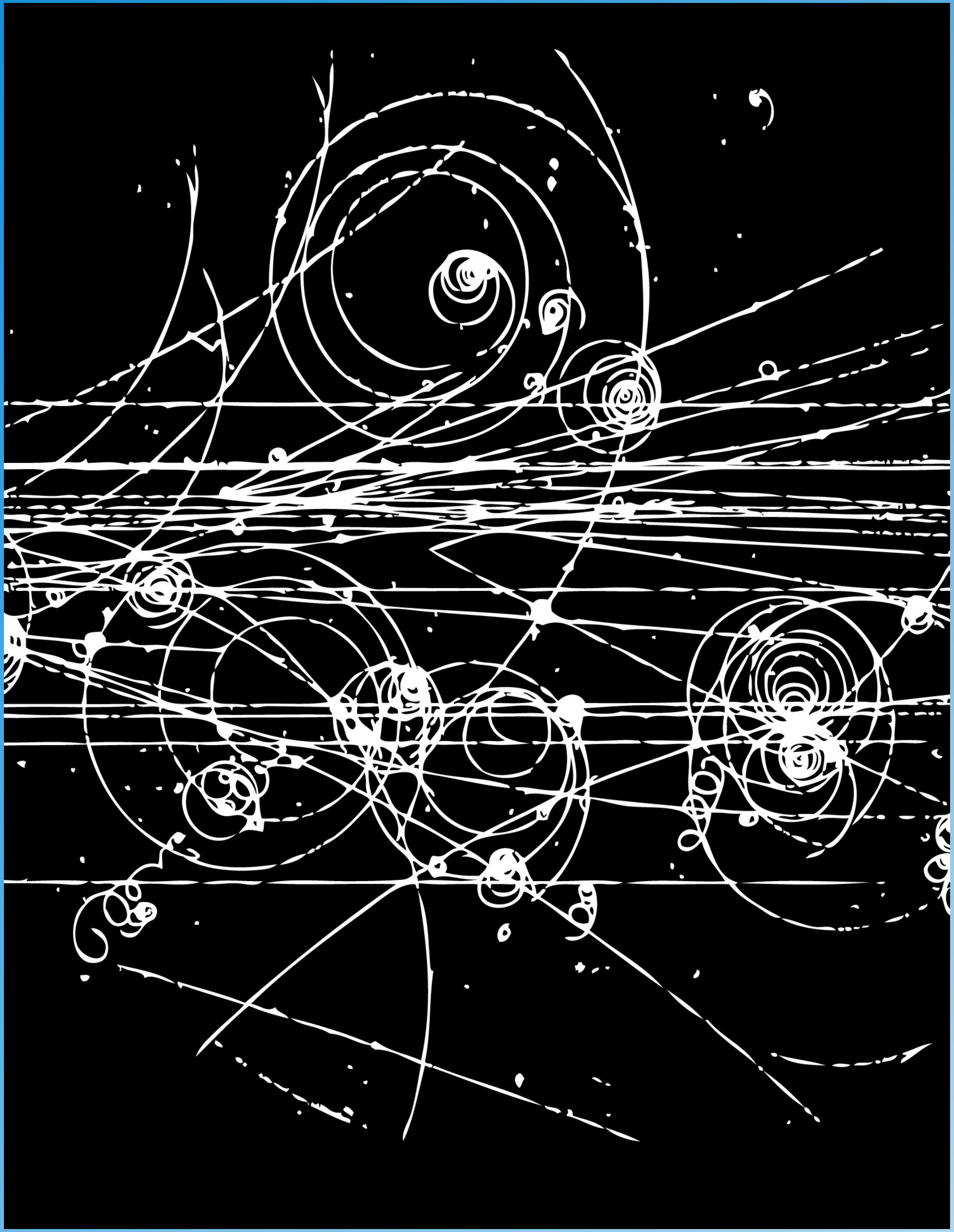


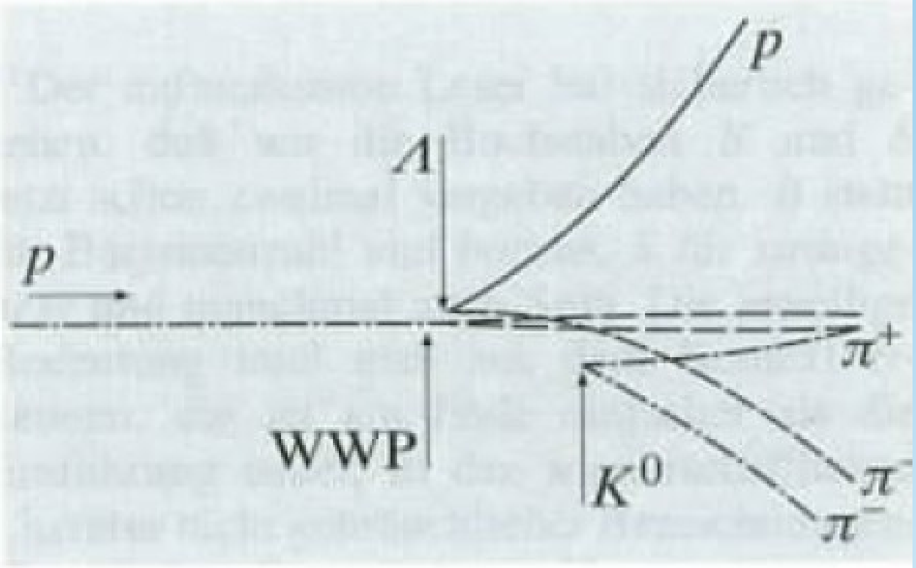
Fig. 2. Gamma anisotropy and beta asymmetry for polarizing field pointing up and pointing down.

- Nobel Prize

(also seen in **muon decay** **Lederman** et al.)

Discovery of the Strangeness Surprise!





“V-particles”

Production of **Kaons** and **Lambda**-Baryons in pp Collisions

Long Lifetime!
neither electromagnetic nor strong force

Prediction of the Charm Quark

How explain non-observation of Flavor Changing Neutral Currents?

$$K \not\to \pi\gamma$$

Add hypothetical c-quark

$$\begin{pmatrix} u \\ d' \end{pmatrix} = \begin{pmatrix} u \\ d\cos\Theta_C + s\sin\Theta_C \end{pmatrix} \qquad \begin{pmatrix} c \\ s' \end{pmatrix} = \begin{pmatrix} c \\ s\cos\Theta_C - d\sin\Theta_C \end{pmatrix}$$

Neutral Current:

$$J_{NC} = \underbrace{\bar{u}\Gamma u + c\Gamma c + (\bar{d}\Gamma d + \bar{s}\Gamma s)\cos^2\Theta_C + (\bar{d}\Gamma d + \bar{s}\Gamma s)\sin^2\Theta_C}_{\Delta S=0}$$

$$+ \underbrace{(\bar{d}\Gamma s + \bar{s}\Gamma d - \bar{d}\Gamma s - \bar{s}\Gamma d)\sin\Theta_C\cos\Theta_C}_{|\Delta S|=1}$$

flavor changing terms cancel out!

GIM suppression (Glashow, Iliopoulos, Maiani)

Observation of the Charm Quark

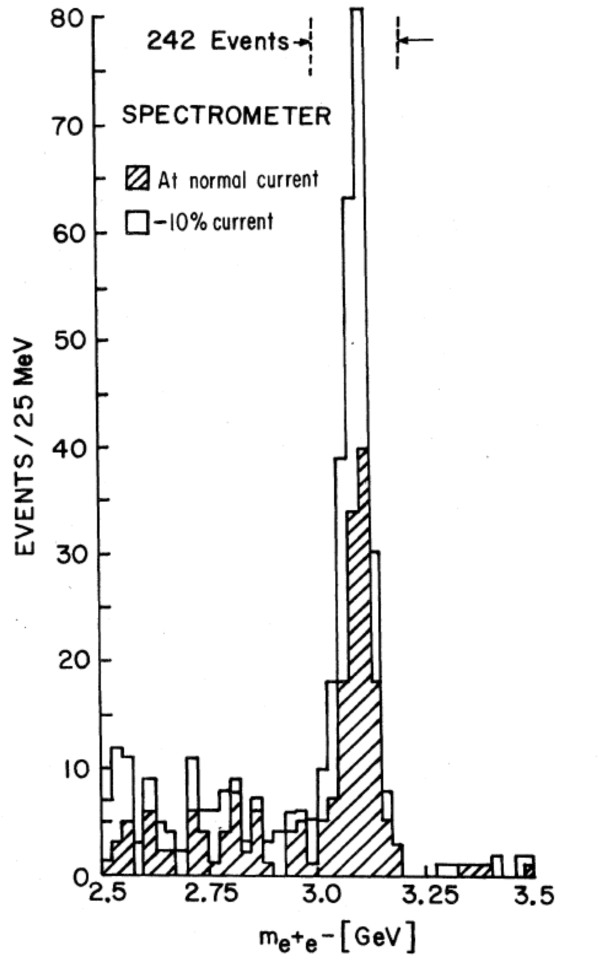


FIG. 2. Mass spectrum showing the existence of *J*. Results from two spectrometer settings are plotted showing that the peak is independent of spectrometer currents. The run at reduced current was taken two months later than the normal run.

$p\,Be \rightarrow X$ J/Psi $\rightarrow X\, e^+ e^-$

BNL: S.**Ting** et al. (1974)

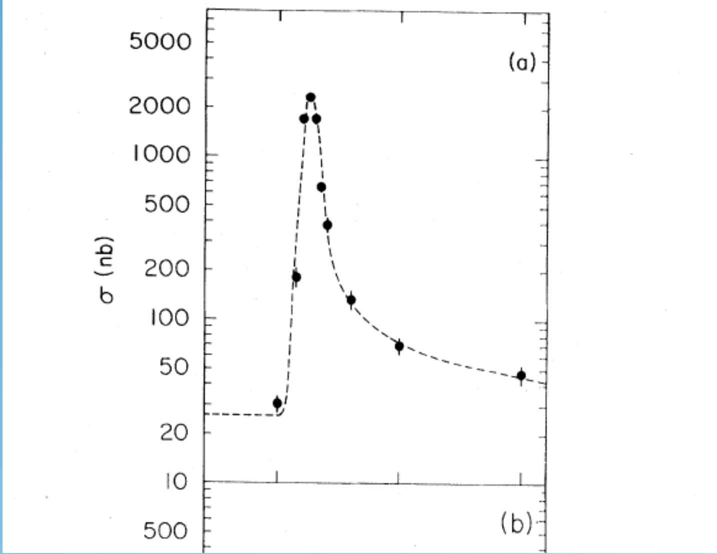


FIG. 1. Cross section versus energy for (a) multi-hadron final states, (b) e^+e^- final states, and (c) $\mu^+\mu^-$, $\pi^+\pi^-$, and K^+K^- final states. The curve in (a) is the expected shape of a δ-function resonance folded with the Gaussian energy spread of the beams and including radiative processes.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

$e^+ e^- \rightarrow$ J/Psi $\rightarrow e^+ e^- (\mu^+,\mu^-),(\pi^+ \pi^-)$

SLAC: B.**Richter** et al. (1974)

- Nobel Prizes

Prediction of the Third Family

Mixing Matrix with three families (**Kobayashi-Maskawa** Matrix):

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

contains CP violation phase

C = charge conjugation particle ↔ anti-particle
P = parity operator

Sakharov: *CP-Violation might explain observed matter-antimatter asymmetry in universe*

➔ third family needed! ➔ Nobel Prize (2008)

Discovery of the Third Family

- Tau Lepton discovered by MARK1 at SPEAR (1974-1976)

electron-muon problem: $e^+ e^- \to e^+ \mu^-$ $e^+ e^- \to e^- \mu^+$

(Reines et al.)

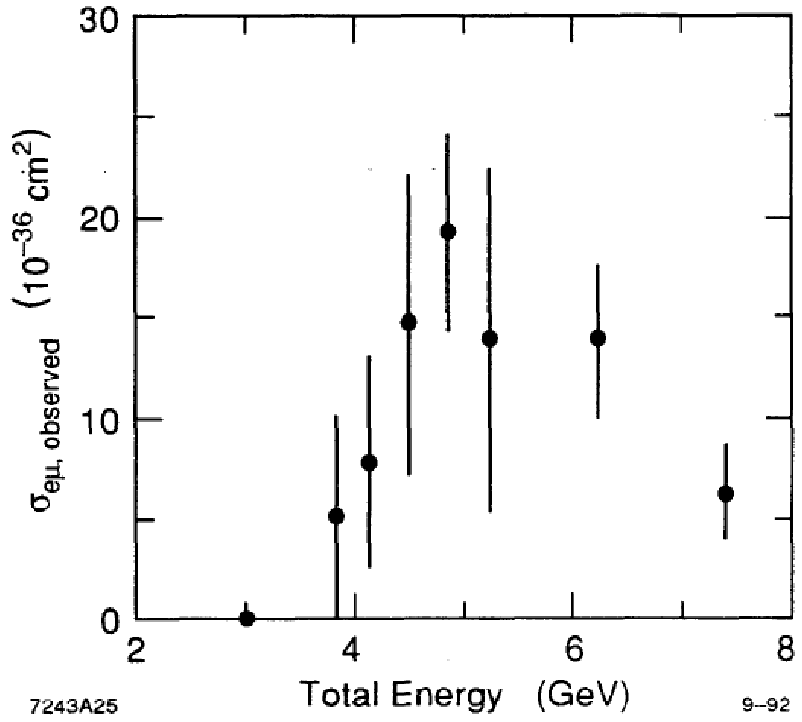


Fig. 4. From Perl *et al.* (1975): the observed cross section for the signature $e\mu$ events from the Mark I experiment at SPEAR. This observed cross section is not corrected for acceptance. There are 86 events with a calculated background of 22 events.

explanation **(M.Perl)**:

$$e^+ e^- \to \tau^+ \tau^-$$

$$\tau \to e \nu \nu$$
$$\tau \to \mu \nu \nu$$

discovery of tau-lepton

- Nobel Prize (1995)

- Discovery of the Bottom-Quark (1977) by M.Ledermann et al. at Fermilab

Prediction of Neutral Currents

Weak Neutral Currents, i.e. exchange of Z particles were predicted by **Abdus Salam**, **Sheldon Glashow** and **Steven Weinberg** 1973 (Standard Model)

➜ Nobel Prize (1979)

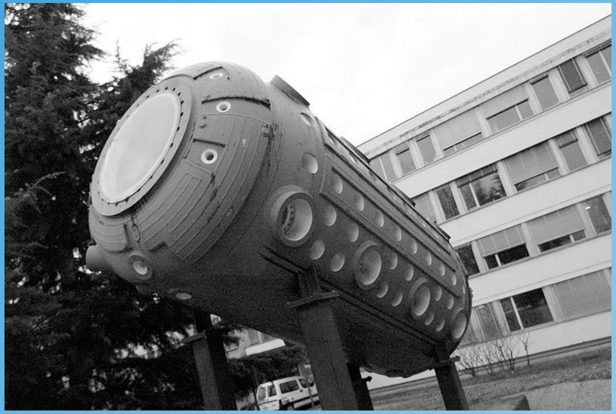
Weak interaction described by SU(2) local gauge symmetry, which contains three fields W_1 , W_2 ,W_3 presented by the physically observable fields $\mathbf{W}^+$ and $\mathbf{W}^-$ and **Z** (neutral gauge boson)

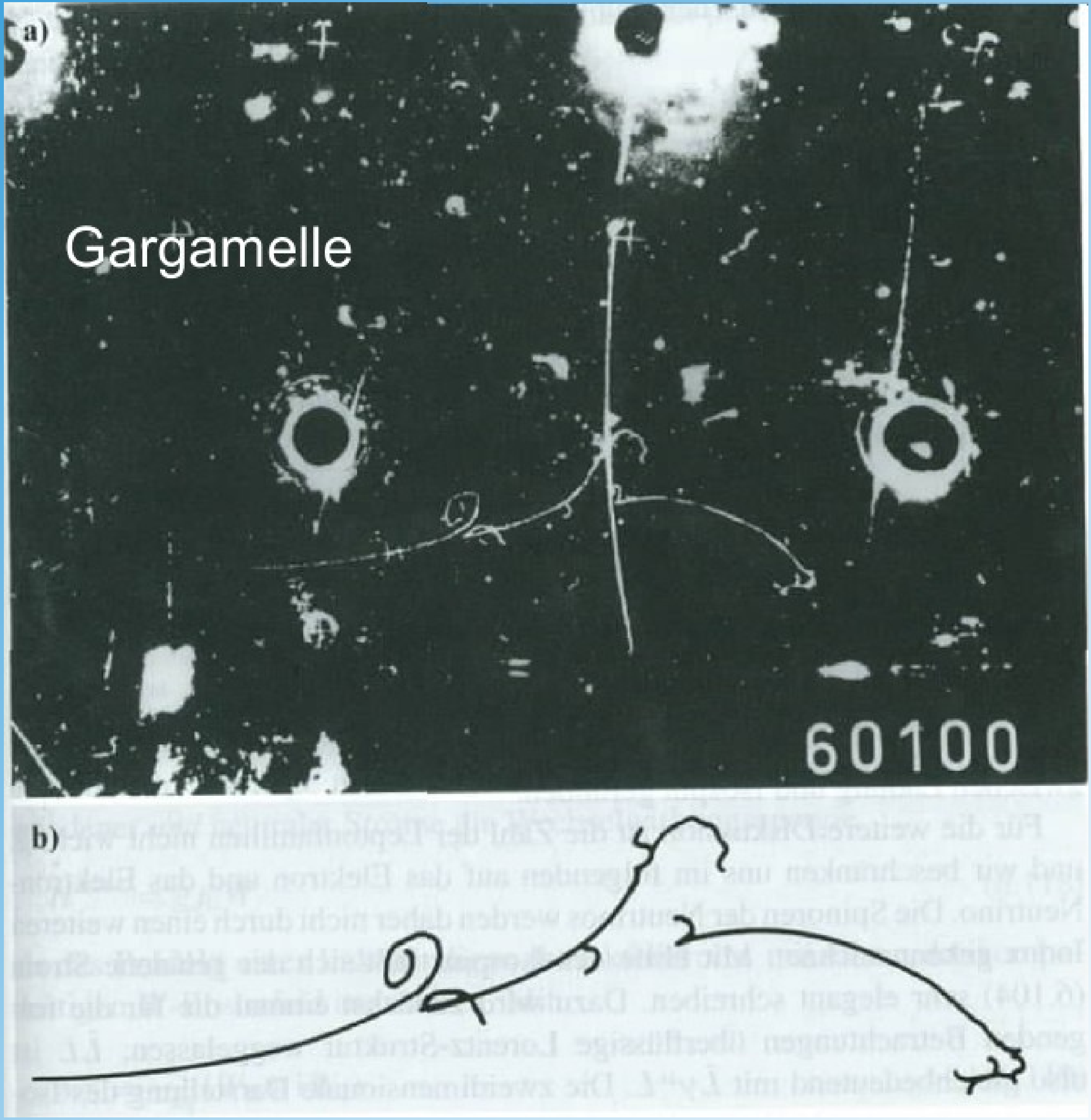
Use neutrinos to test existence of the Z boson

Observation of Neutral Currents

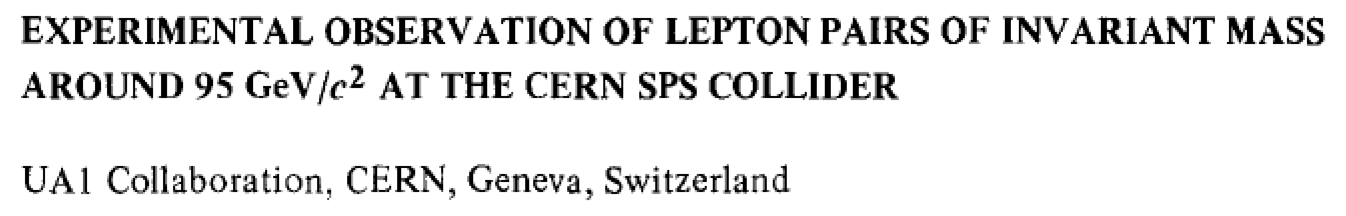
Bubble Chamber
Gargamelle (1974)

$$\bar{\nu}_e e \to \bar{\nu}_e e$$



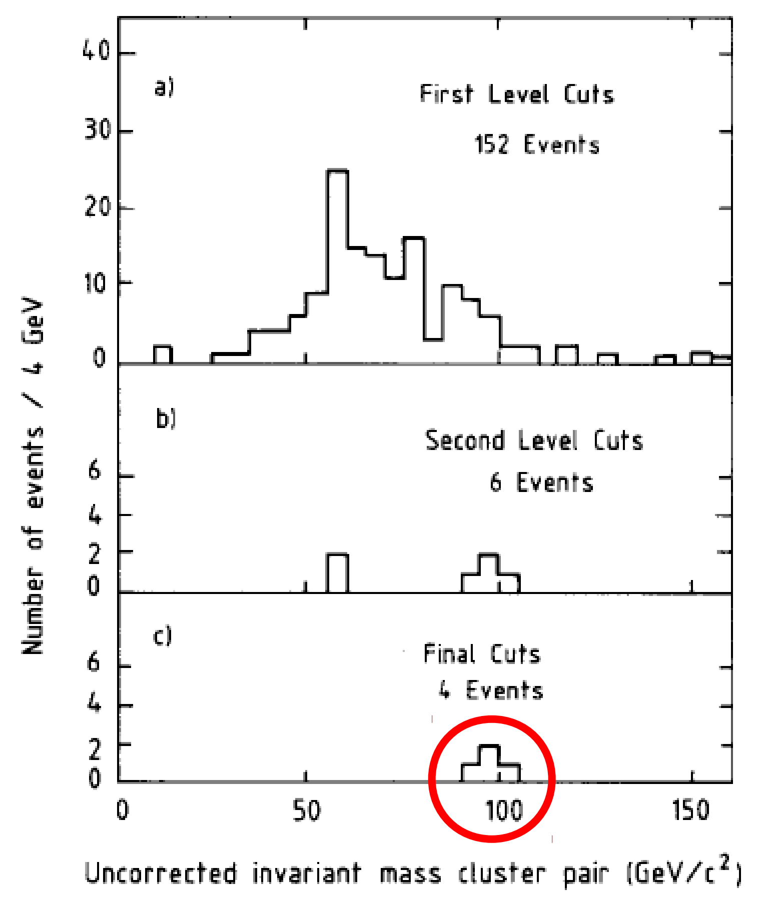


Discovery of Z Gauge Boson



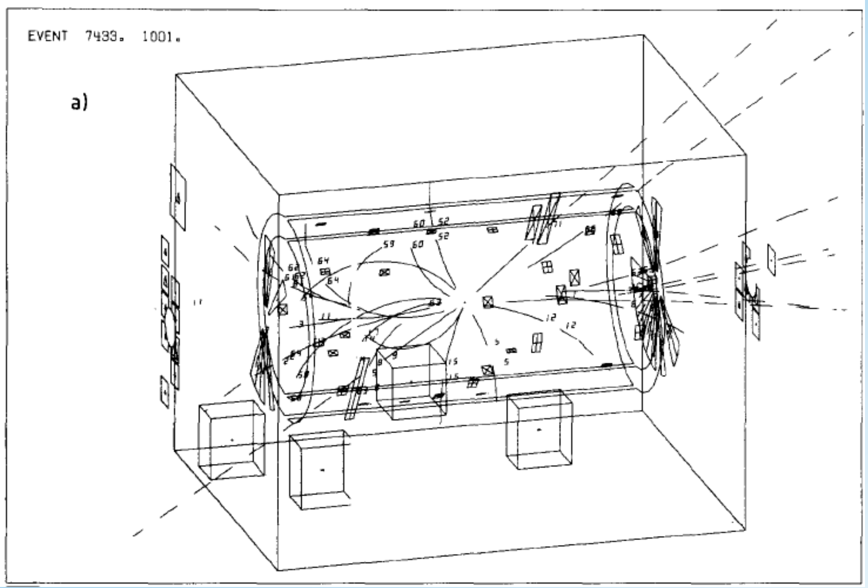
EXPERIMENTAL OBSERVATION OF LEPTON PAIRS OF INVARIANT MASS AROUND 95 GeV/c^2 AT THE CERN SPS COLLIDER

UA1 Collaboration, CERN, Geneva, Switzerland



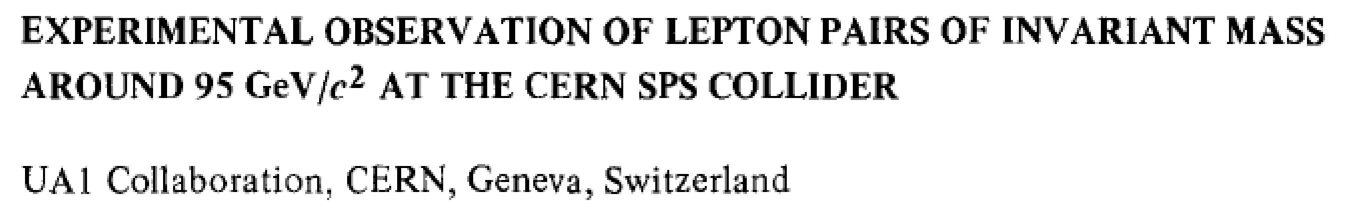
$p\bar{p} \to (Z \to e^+ e^-) X$

Rubia et al. (1983)



- Nobel Prize (1984)

Discovery of Z Gauge Boson



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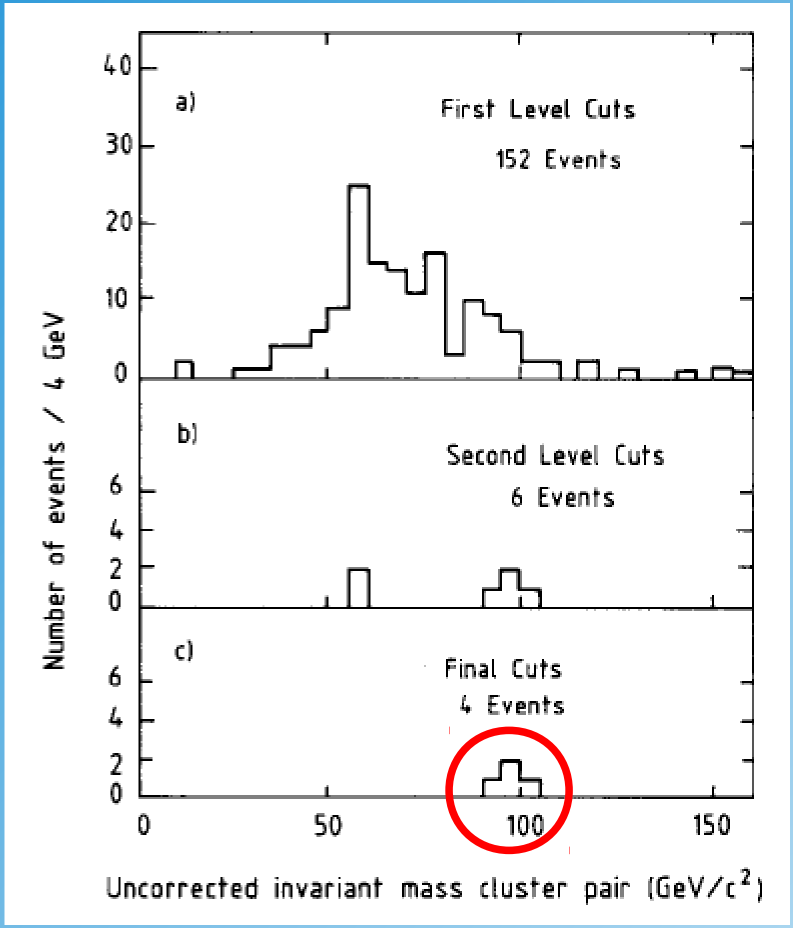
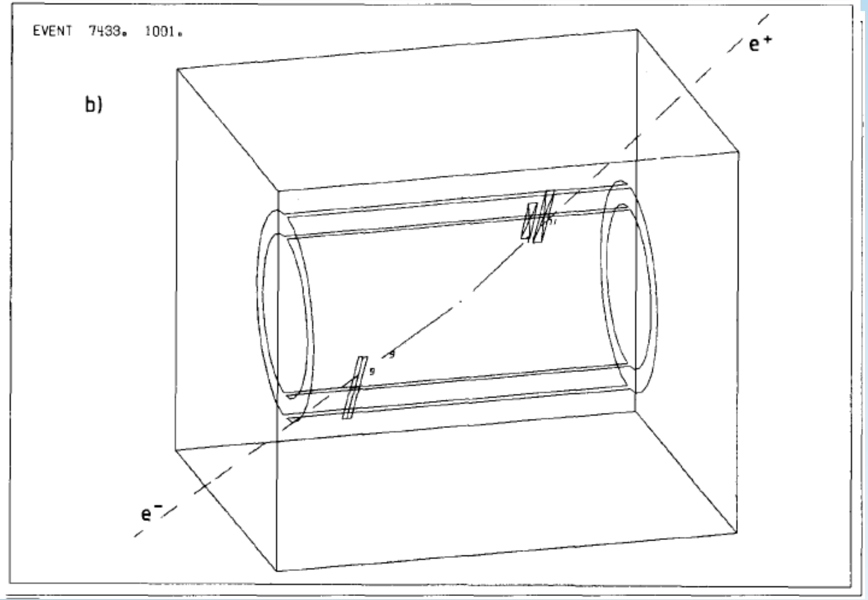


$p\bar{p} \rightarrow (Z \rightarrow e^+ e^-) X$

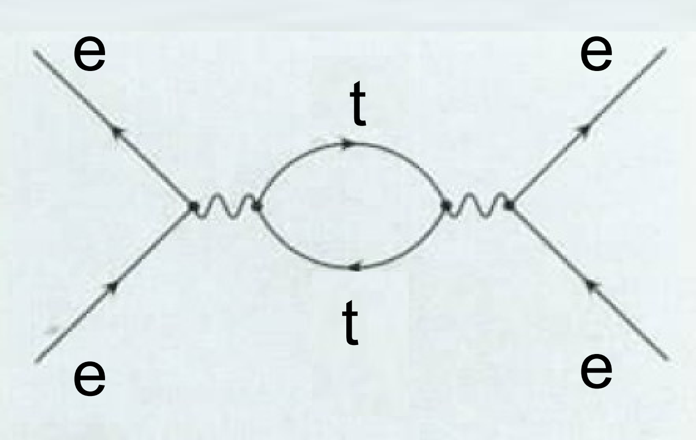
Rubia et al. (1983)



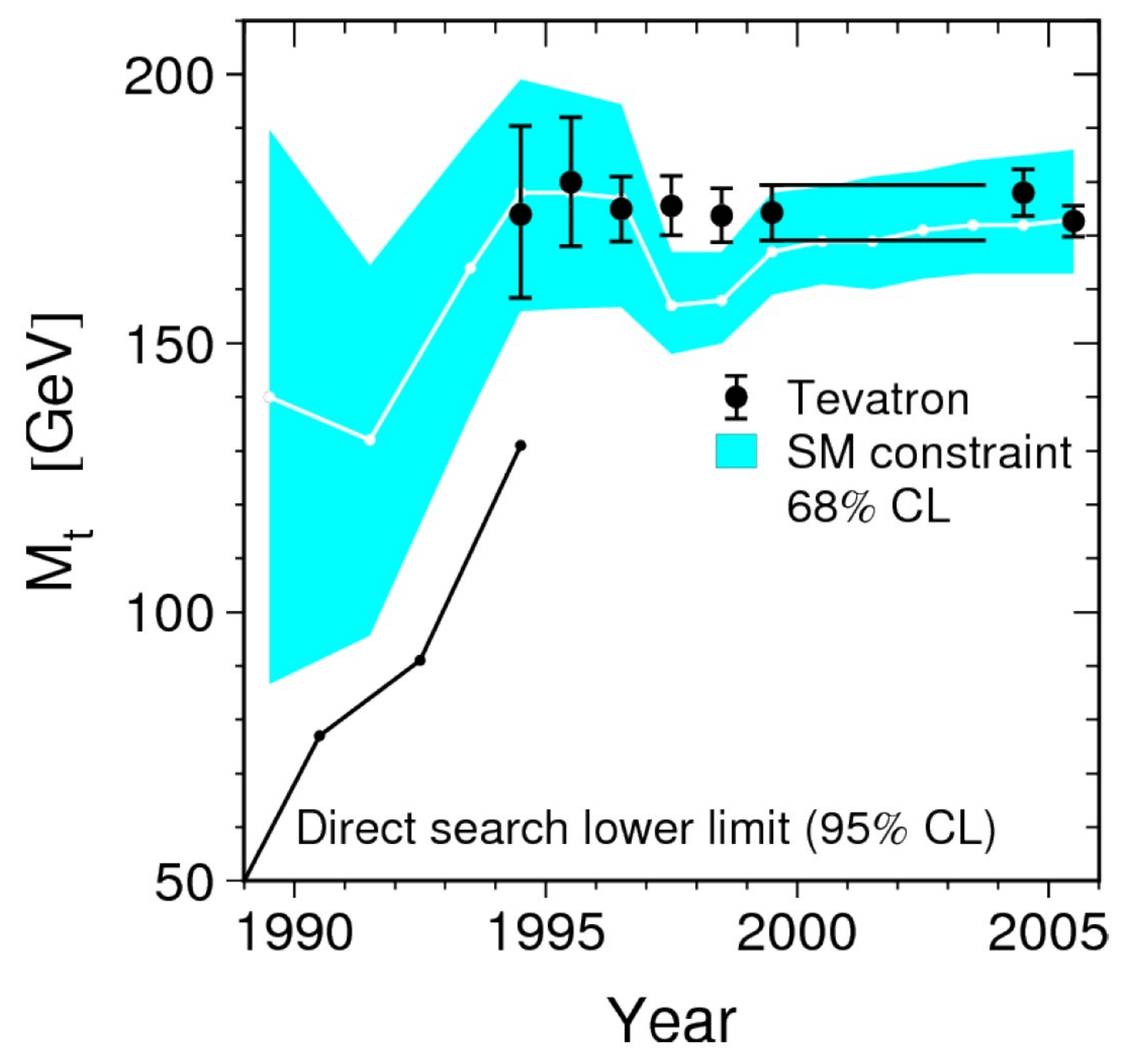
- Nobel Prize (1984)

Prediction of the Top Mass

Radiative Corrections:



$e^+ e^-$ collider LEP, Geneva

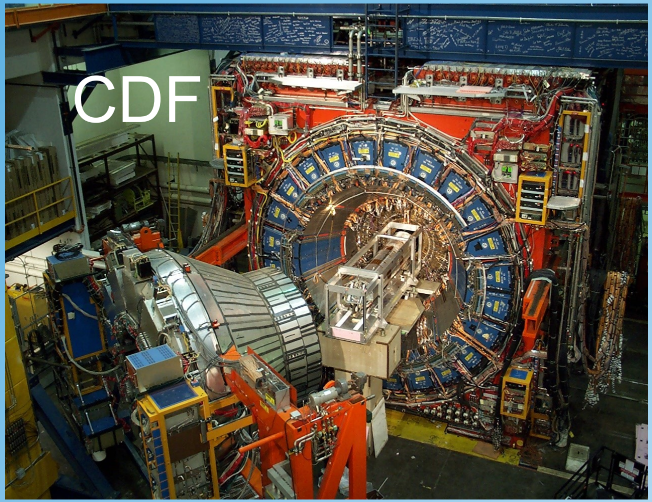


Discovery of the Top-Quark (1995)

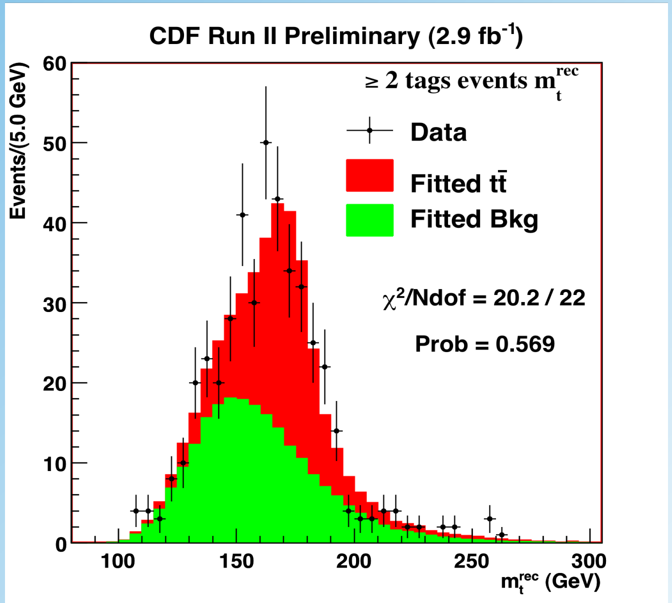
Fermilab, USA

Proton-Antiproton Collider

1 x 1 TeV



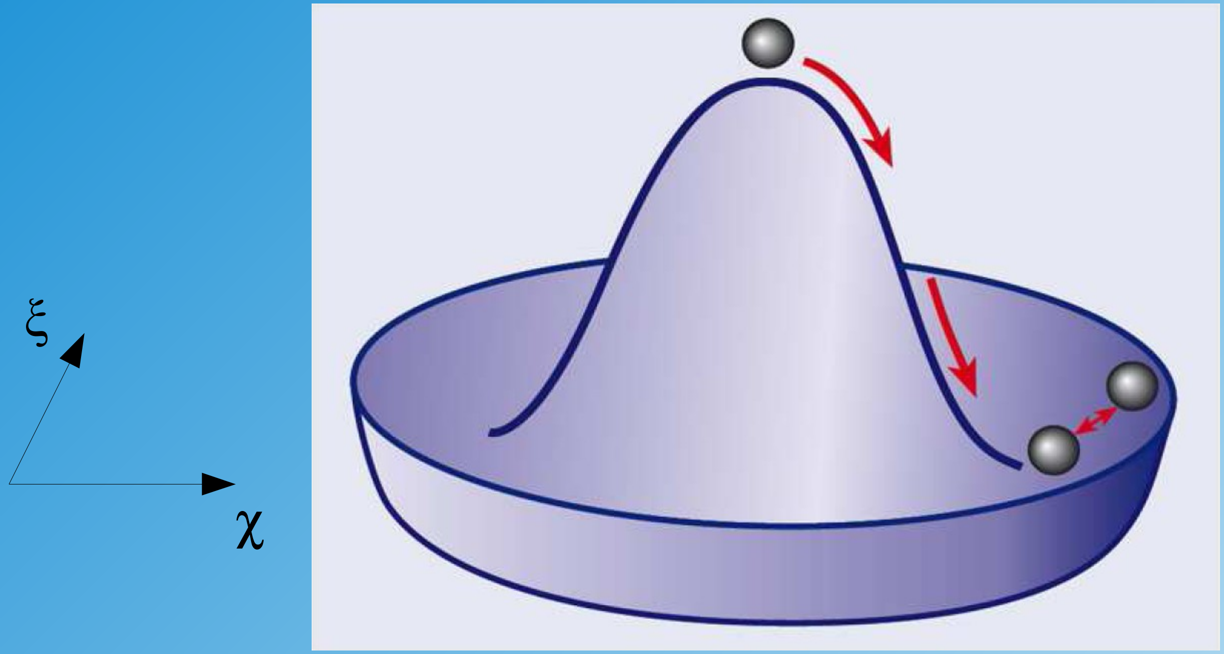
CDF + D0 Detectors



Top-Quark Mass ~172 GeV

Prediction of the Higgs Particle

Introduce new (Higgs-) field to generate mass of fermions and bosons



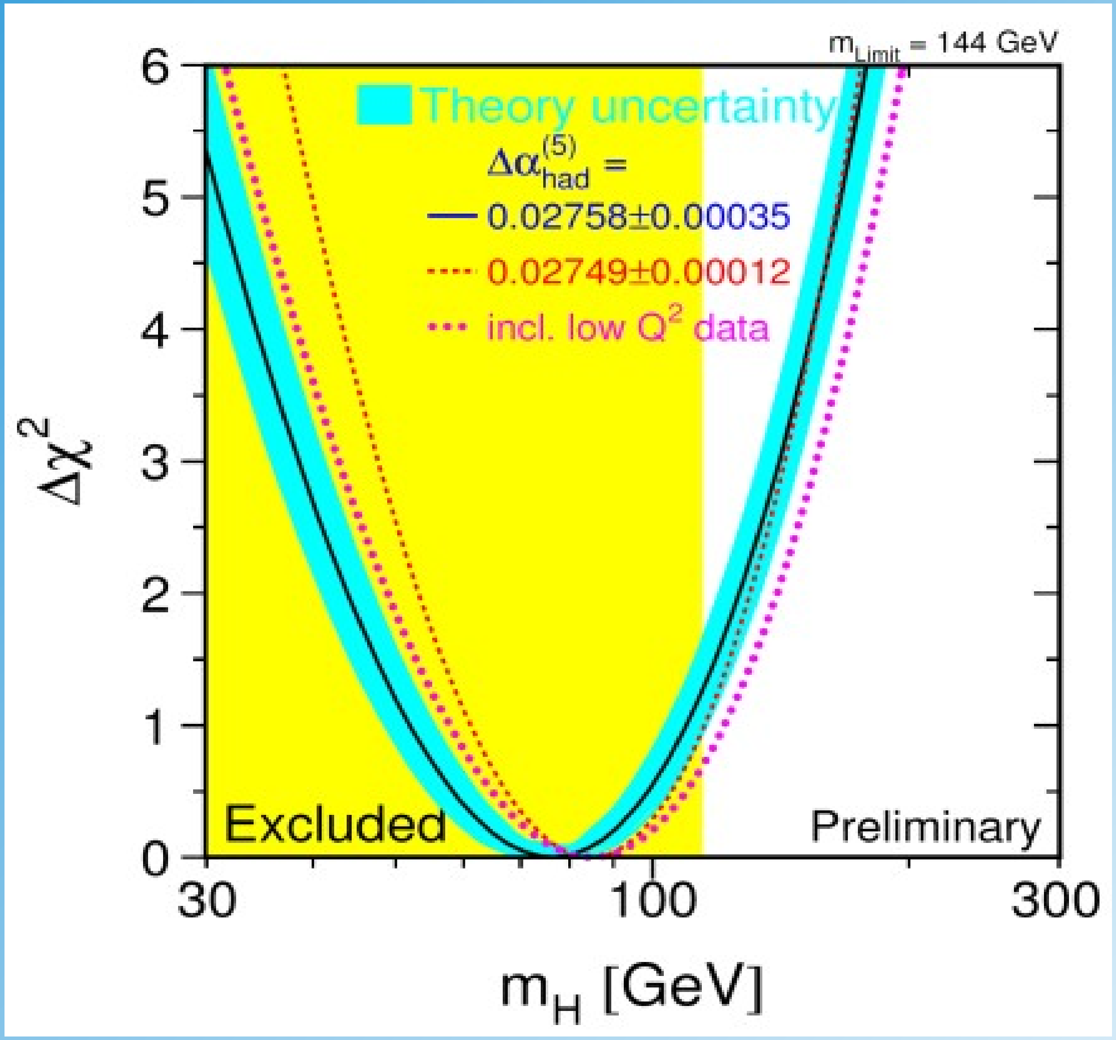
$$\Phi = \varphi_0 + \chi + i\,\xi$$

minimum breaks symmetry:
spontaneous symmetry breaking

$$\Phi \neq 0$$

Prediction of the Higgs Mass

Status after **LEP** and before **Tevatron + LHC**



- yellow region excluded by LEP
- blue chi2 curve from radiative corrections

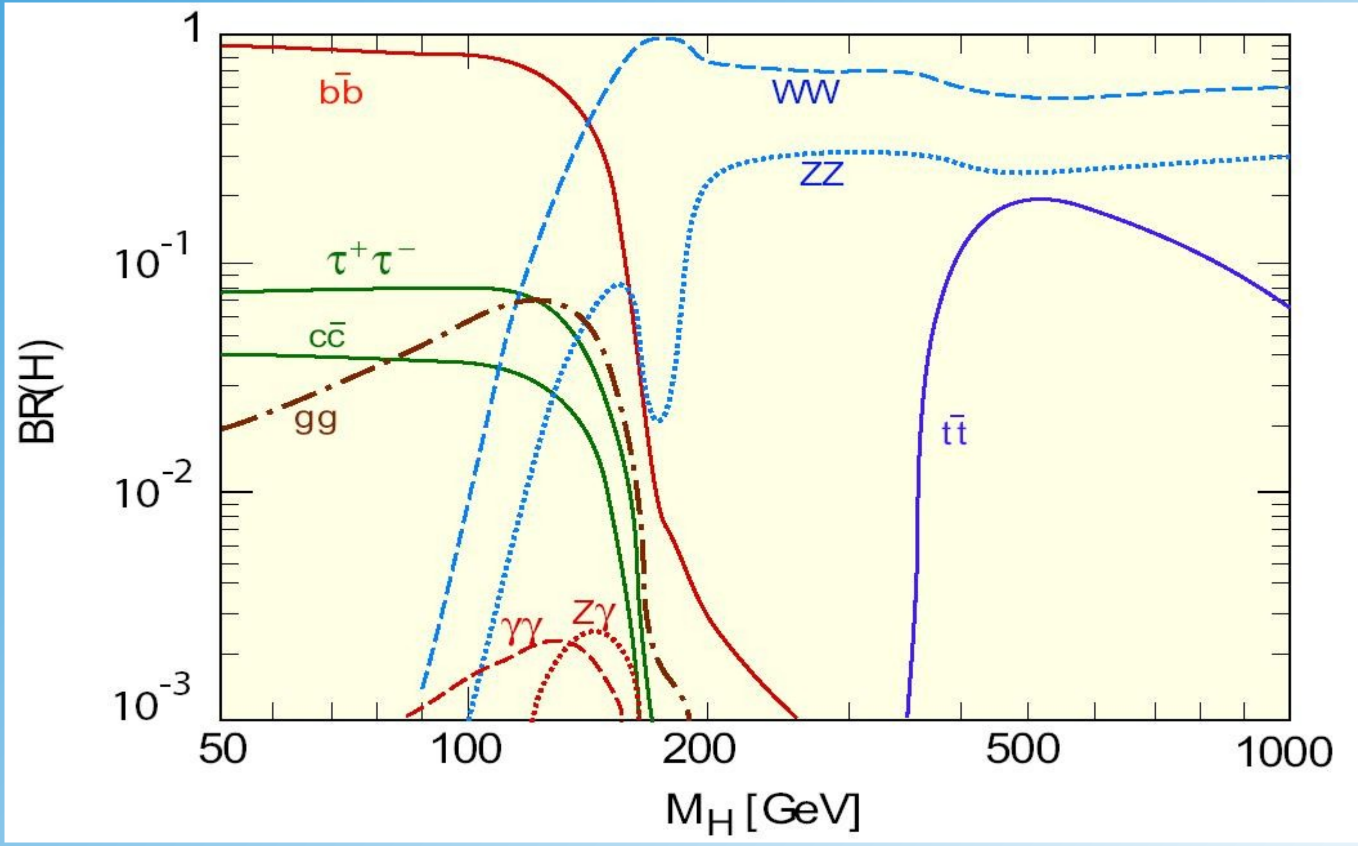
Search for the Higgs Boson

Main Problem:

- SM Higgs Mass is not predicted by theory
- only weakly constrained by precision measurements

Have to look in a large mass range:

Higgs decays:

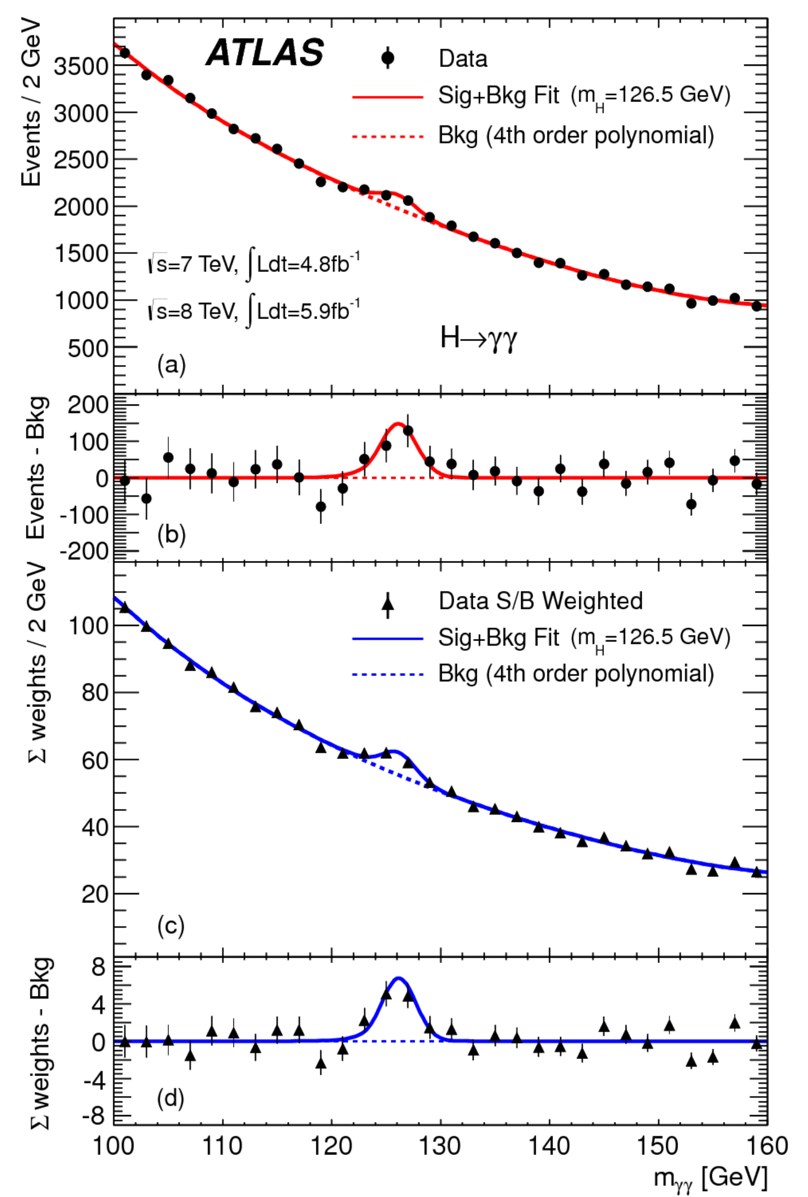


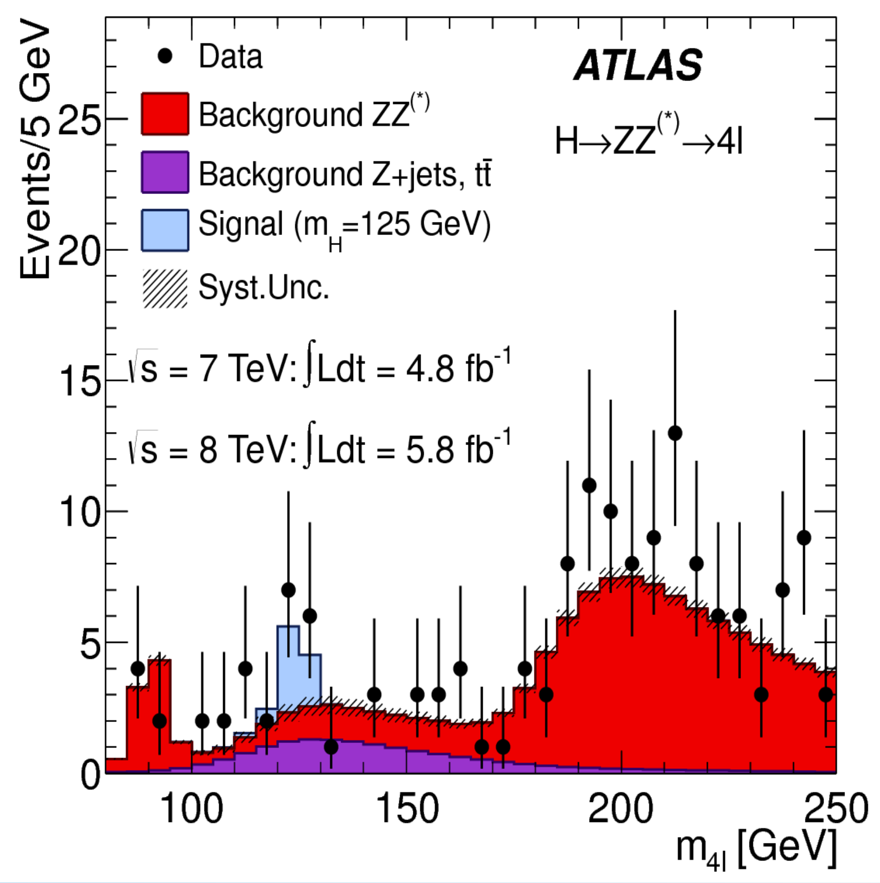
Large Hadron Collider (CERN)

LHC (pp)
7-8 (14) TeV in 2011/12

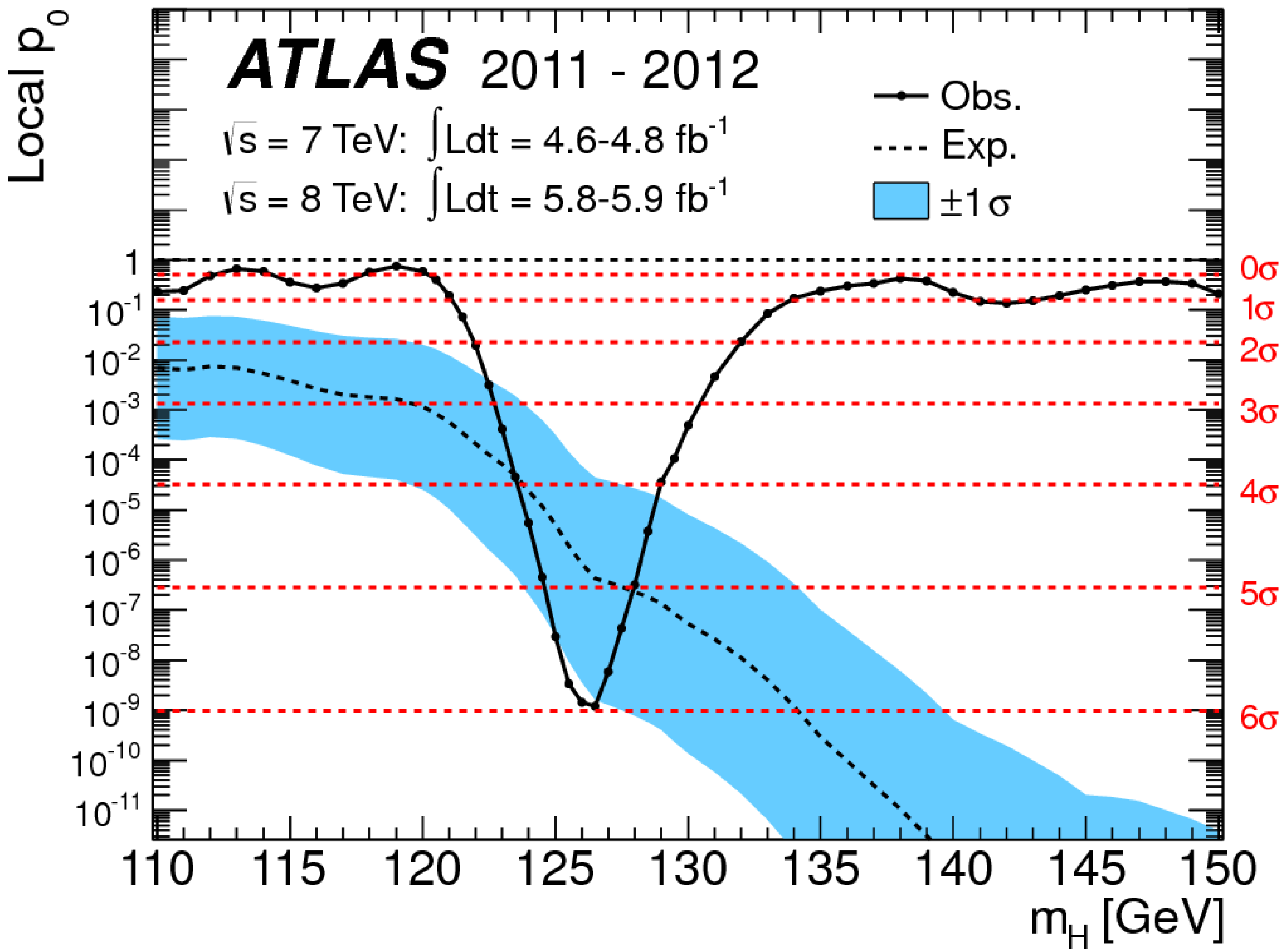
26.7 km circumference!

The Discovery of the Higgs-Boson

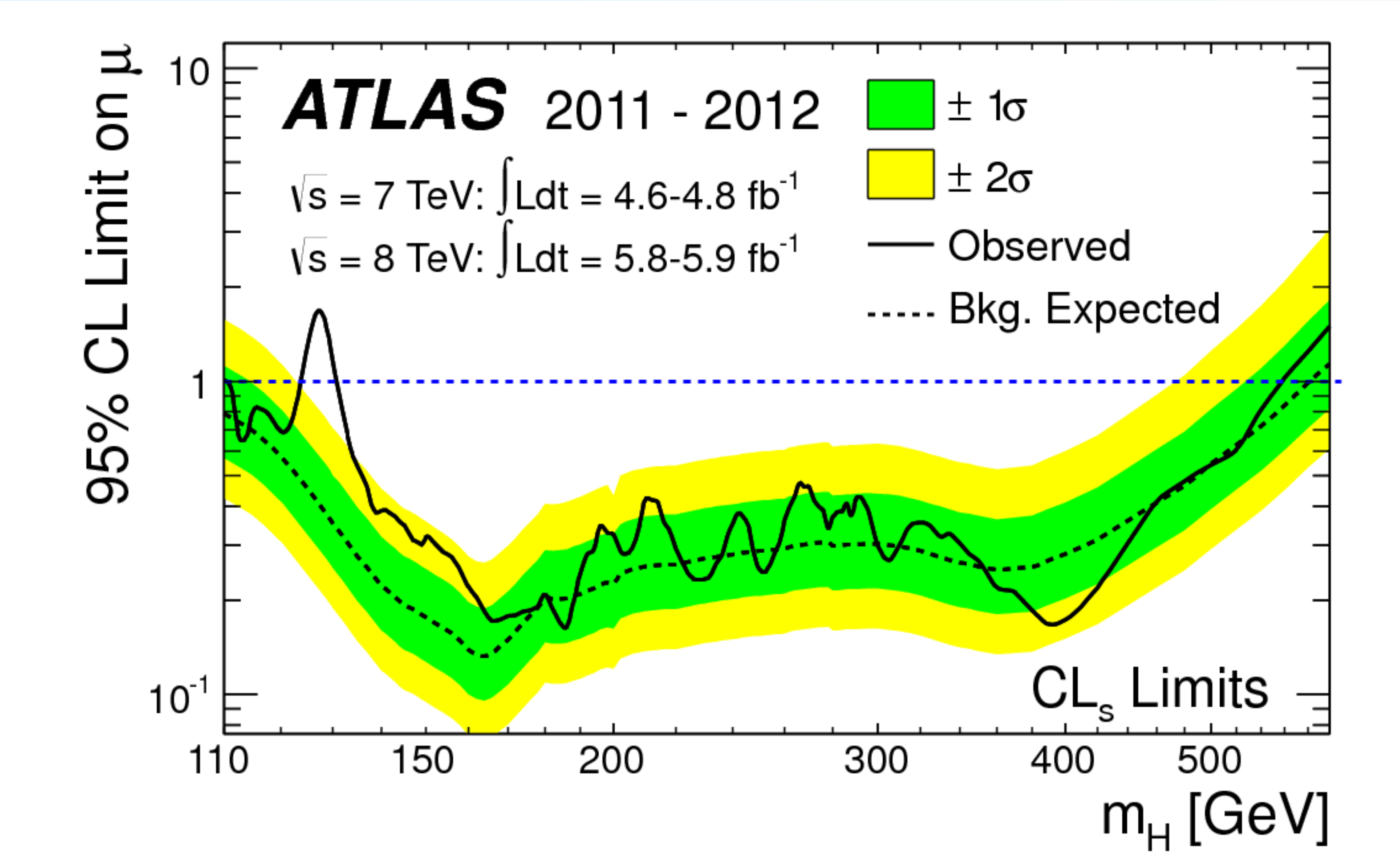




Compatibility of ATLAS data to No-Higgs Hypothesis

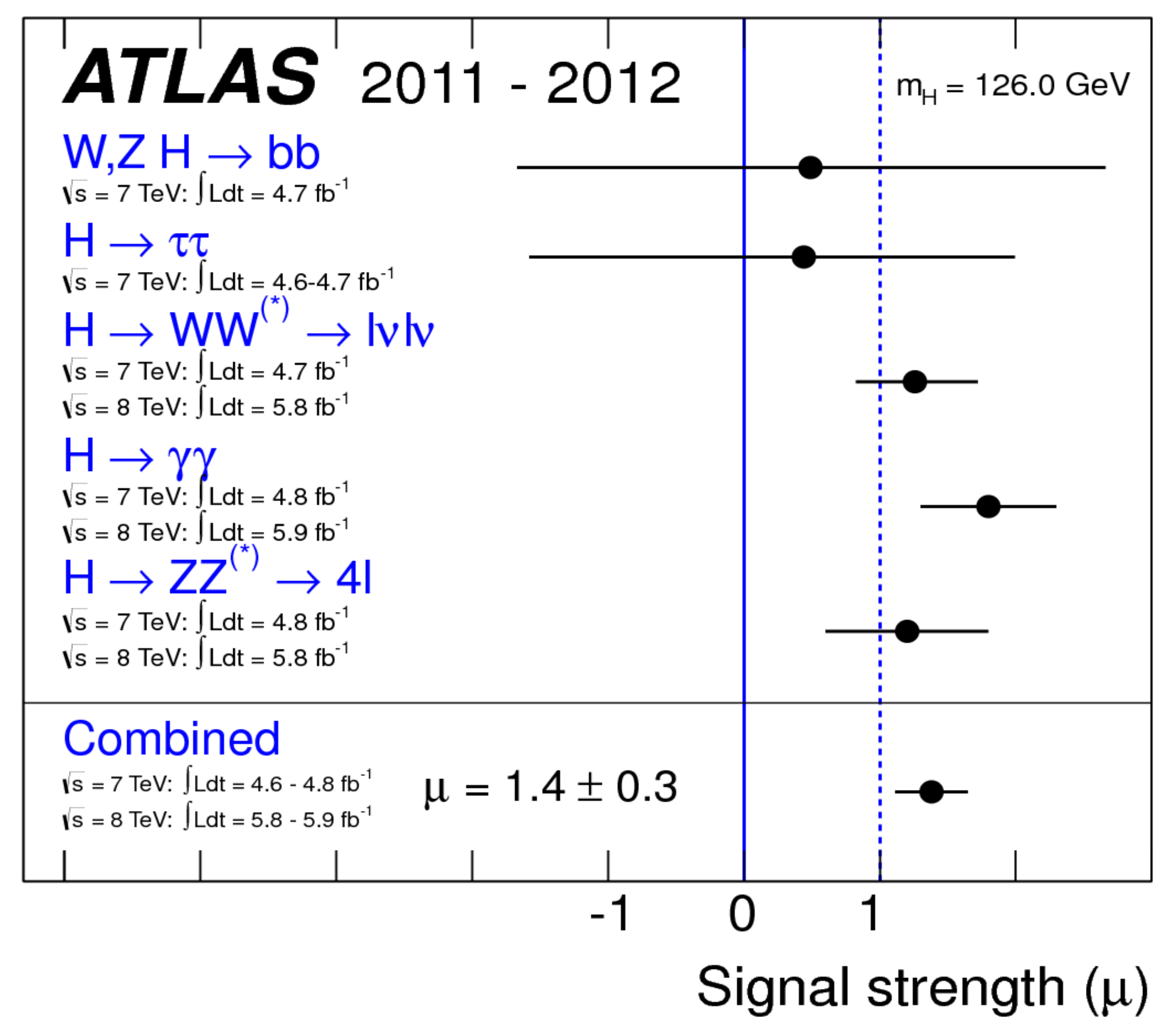


Higgs Exclusion Plot



there is only one SM-Higgs

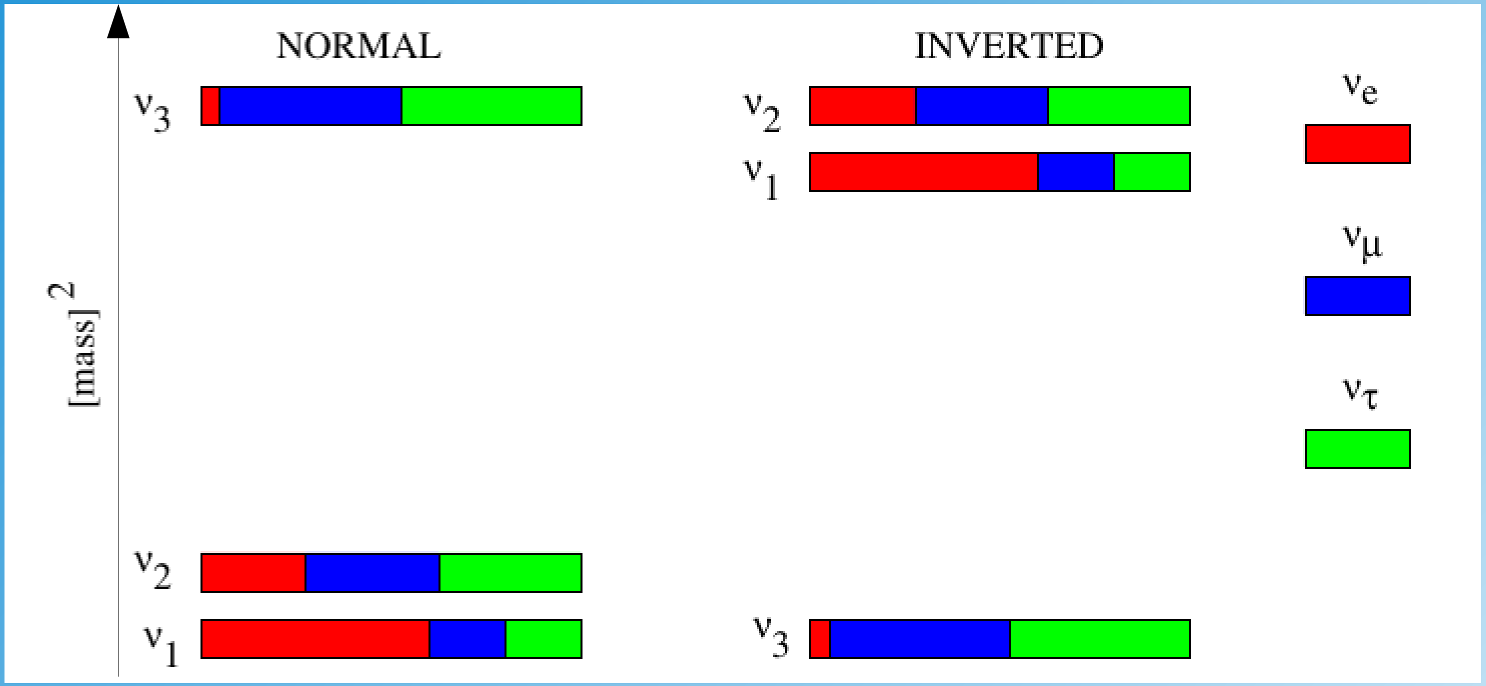
Compilation of Signal Strenghts in Various Decays



July 2012

Really THE SM-Higgs?

The Unknown Mass Hierarchy of Neutrinos

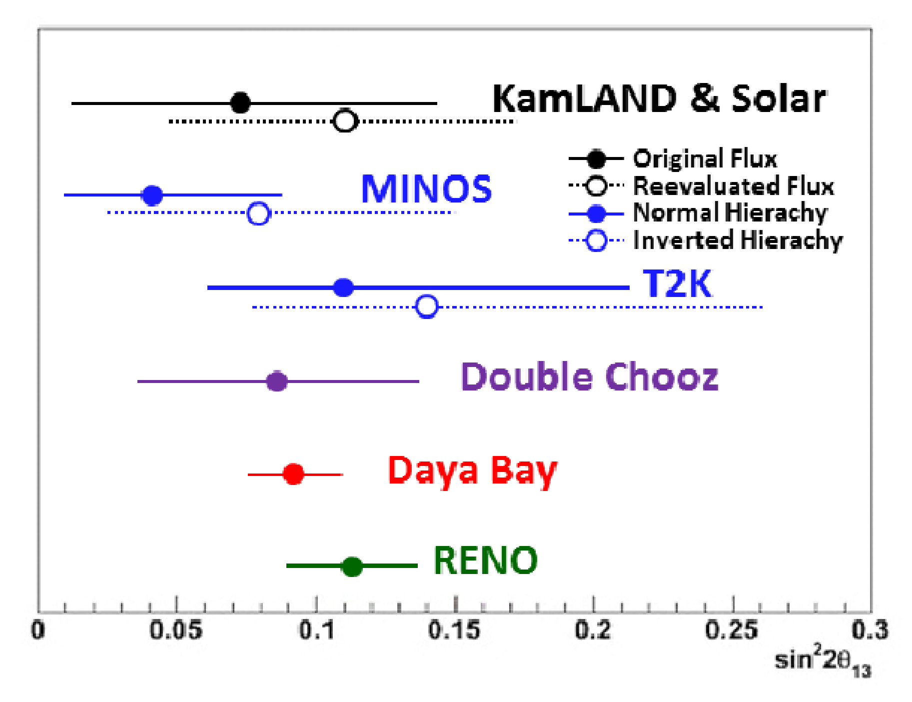


from neutrino oscillation only squared mass differences known!

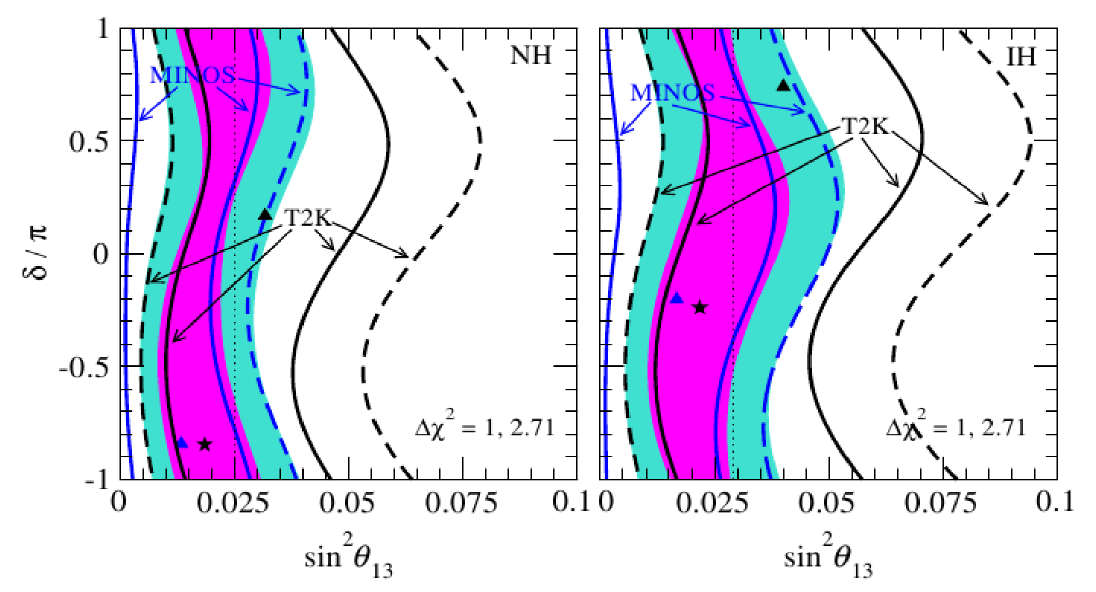
Last Neutrino-Mixing Angle Measured in 2012

Mixing angle Theta$_{13}$

CP-Phase δ



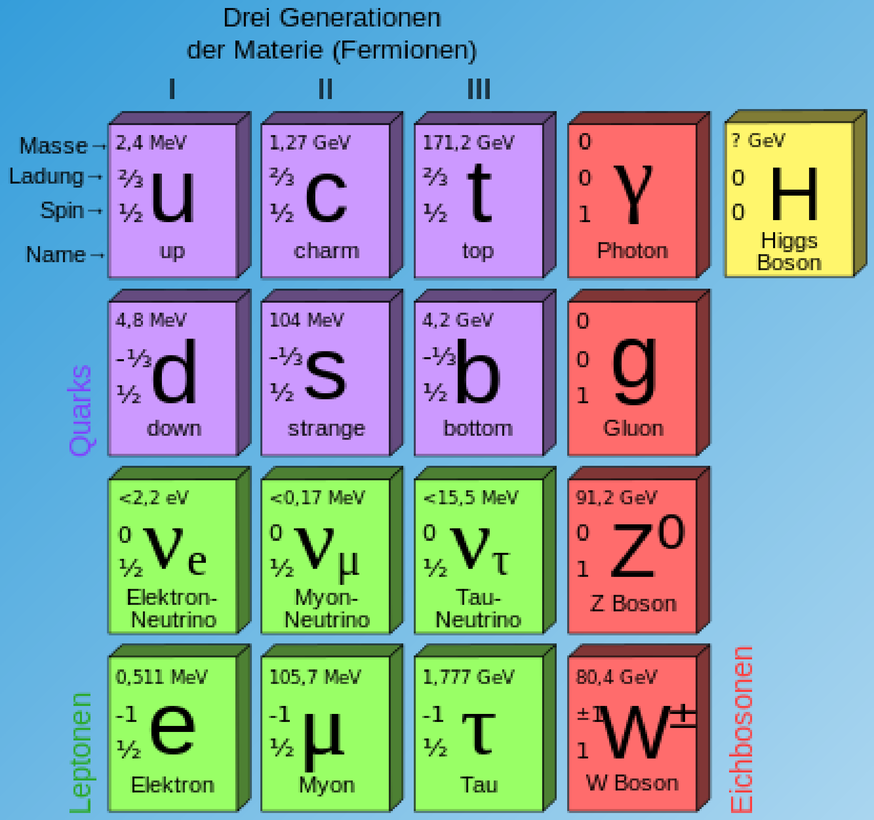
from Y. Nakajima



from T. Schwetz-Mangolt

Missing: CP-Phase δ in lepton matrix (25th parameter of νSM)

Summary



- **Standard Model seems to be fully established**
- **Big triumph of particle physics theory and experiment**

But many fundamental questions not addressed by SM!
(fermion generations, matter-antimatter asymmetry, dark matter, gravitation, ...)