Lecture:

Standard Model of Particle Physics

(MVHE3)

Heidelberg SS 2012

W.Rodejohann (theorist)

+

A. Schöning (experimentalist)

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(Physikalisches Institut - Heidelberg)

Goal of this Lecture

- Theoretical and experimental introduction into the Standard Model of Particle Physics.
- The lectures are therefore given by a theoretician and an experimentalist.
- Tutorials offer the possibility to discuss open questions and the exercises.
- Content:
  - QED (Quantum Electrodynamics)
  - Electroweak Interactions and Unification
  - Electroweak Symmetrybreaking and Higgs
  - (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 11h15, Großer Hörsaal, Philosophenweg 12
Wednesday 11h15, Großer Hörsaal, Philosophenweg 12

Accompanying Tutorials:

Tuesday (engl) : 9h15 Albert-Überle Str. 3-5 SR1 (Julian Heeck)
Thursday (german): 14h15 Philisoph. kl. Hörsaal (Dominik Neuenfeld)

Handout and return of exercises always Mondays after lecture

More Information (e.g. literature) on the Web:

http://www.mpi-hd.mpg.de/manitop/StandardModel/

Lecture Dates

Date	Lecturer	Topic and Link
Mo, 16.04.2012	AS	Introduction
We, 18.04.2012	WR	Kinematics; Mandelstam variables
Mo, 23.04.2012	WR	Crossing; Cross sections
We, 25.04.2012	WR	Feynman rules; QED
Mo, 30.04.2012	WR	QED: basic processes
We, 02.05.2012	AS	QED: tests
Mo, 07.05.2012	WR	QED: theoretical issues
We, 09.05.2012	AS	QED: tests
Mo, 14.05.2012	WR	Fermi theory: theory
We, 16.05.2012	AS	Fermi theory: experiment
Mo, 21.05.2012	AS	Weak interactions
We, 23.05.2012	AS	Weak interactions
Mo, 28.05.2012	---	Pfingsten/Pentecost

Lecture Dates

Mo, 28.05.2012	---	Pfingsten/Pentecost
We, 30.05.2012	WR	Gauge symmetries
Mo, 04.06.2012	WR	Gauge symmetries; SU(3) x SU(2) x U(1)
We, 06.06.2012	WR	SU(3) x SU(2) x U(1); Higgs mechanism
Mo, 11.06.2012	AS	Neutral currents, W- and Z-bosons
We, 13.06.2012	AS	Neutral currents, W- and Z-bosons
Mo, 18.06.2012	WR	Theoretical Higgs constraints
We, 20.06.2012	AS	Tests of the SM
Mo, 25.06.2012	AS	Tests of the SM
We, 27.06.2012	AS	Tests of the SM
Mo, 02.07.2012	WR	Flavor: Theory
We, 04.07.2012	WR	Flavor: Theory
Mo, 09.07.2012	AS	Flavor: Experiment
We, 11.07.2012	AS	Flavor: Experiment
Mo, 16.07.2012	WR	Massive neutrinos
We, 18.07.2012	---	---
Mo, 23.07.2012	---	Klausurwoche

give FEEDBACK!

Introduction:

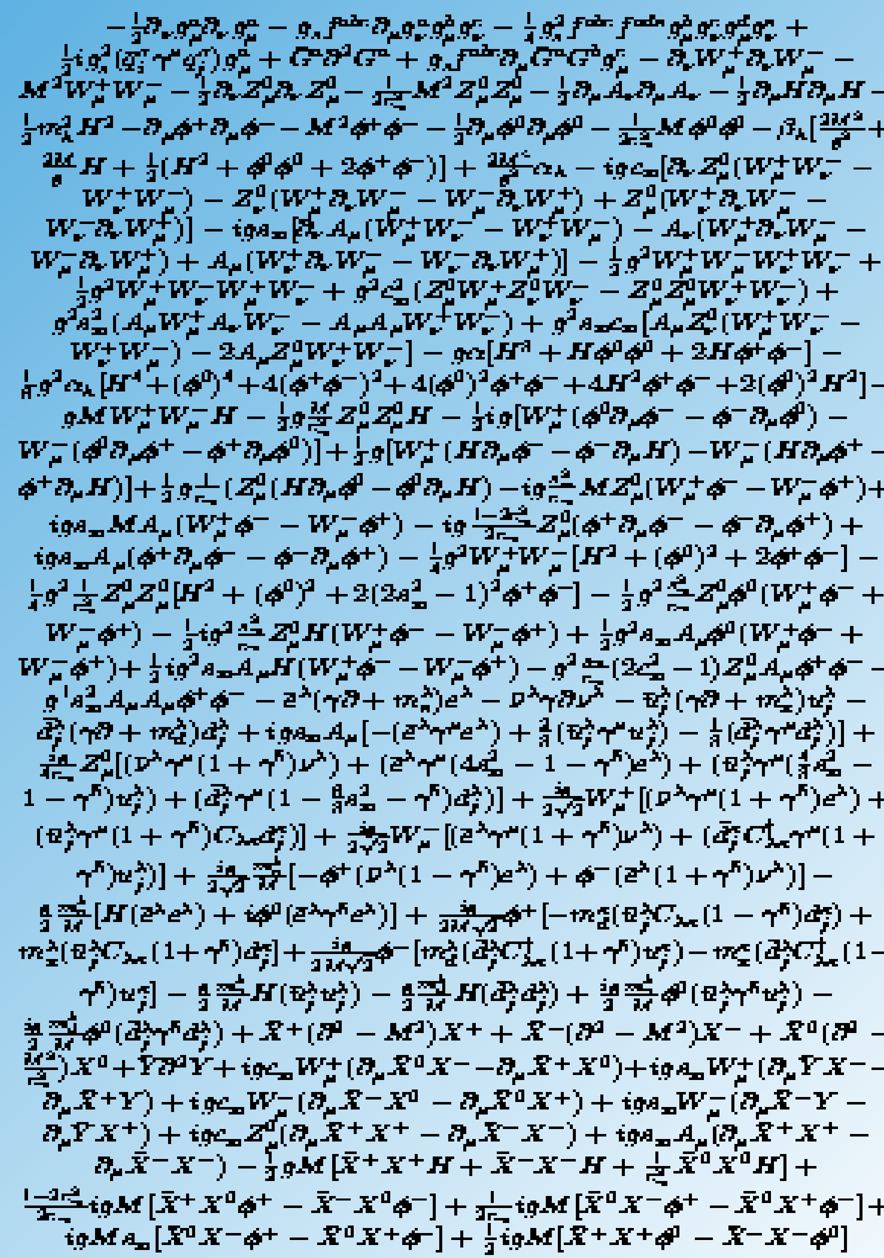
The Interplay between Theory and Experiment in Particle Physics

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

Early History

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

Prediction of mesons (1935)
Discovery of the muon (1936, **surprise!**)
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, **surprise!**)
Development of Quantum Chromodynamics (1968)
Theory of Quark Mixing (1970th)
…...

Anti-Particle Hypothesis

Paul Dirac (1928):

find field equations for a relativistic Quantum Mechanics
based on Einsteins special relativity relation:

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

Diracs 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

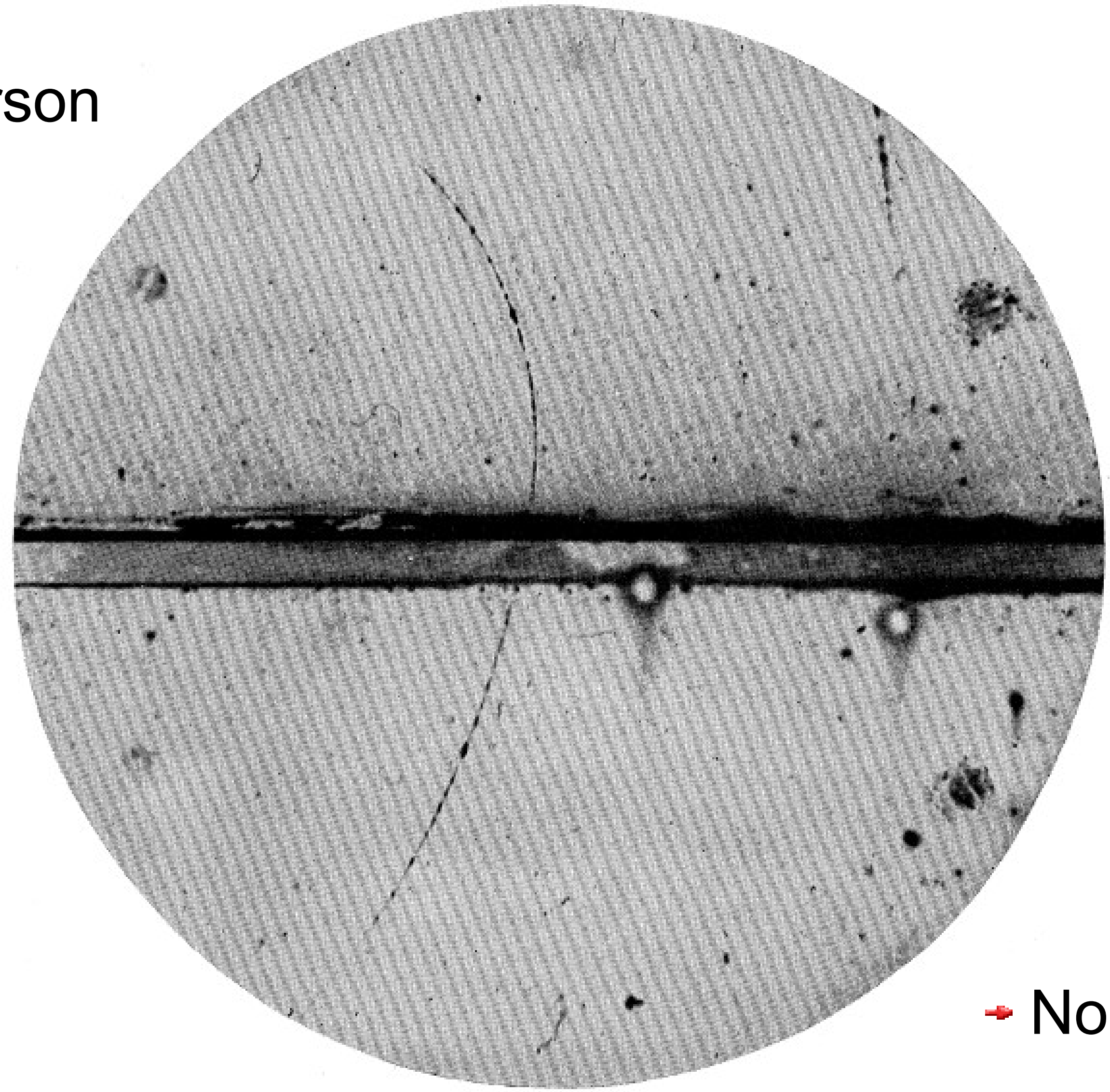


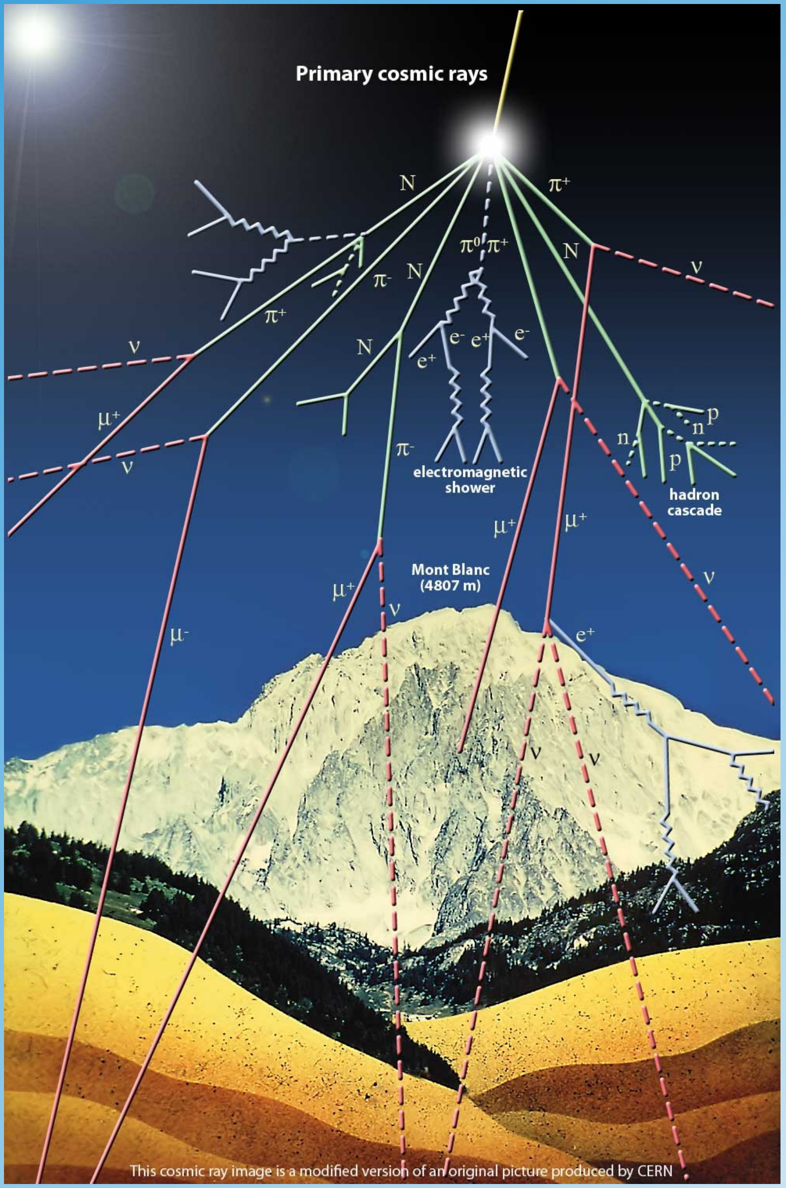
FIG. 1. A 63 million volt positron ($H\rho = 2.1 \times 10^5$ gauss-cm) passing through a 6 mm lead plate and emerging as a 23 million volt positron ($H\rho = 7.5 \times 10^4$ gauss-cm). The length of this latter path is at least ten times greater than the possible length of a proton path of this curvature.

➡ Nobel Prize (1936)

Muon Discovery

Victor Hess
discovery of
cosmic showers

1912



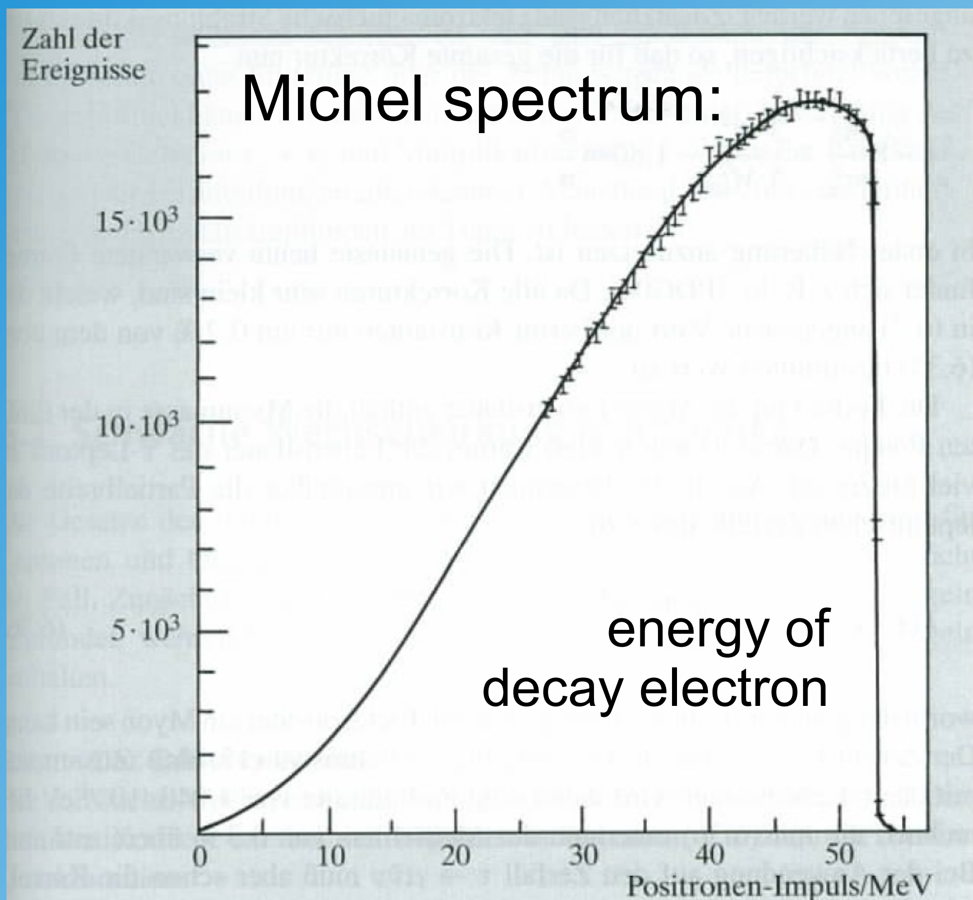
Muon discovery in cosmic rays by

Carl Anderson
+
Seth Nedermeyer

→ Nobel Prize (1936)

Theoretical Interpretation of the muon decay

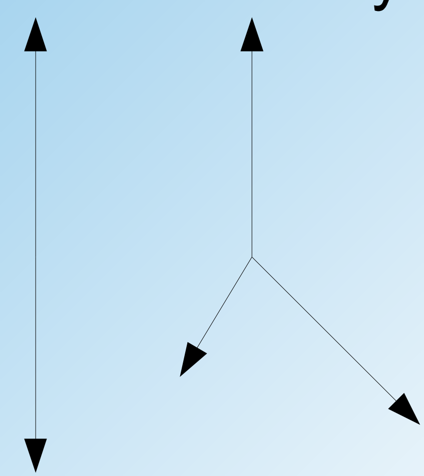
Energy spectrum of electrons from muon decay: $\mu^- \rightarrow e^-$??



m_μ =105.6 MeV

2-body decay

3-body decay



- Two neutrino hypothesis: $\mu^- \rightarrow e^- \nu \nu$

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**

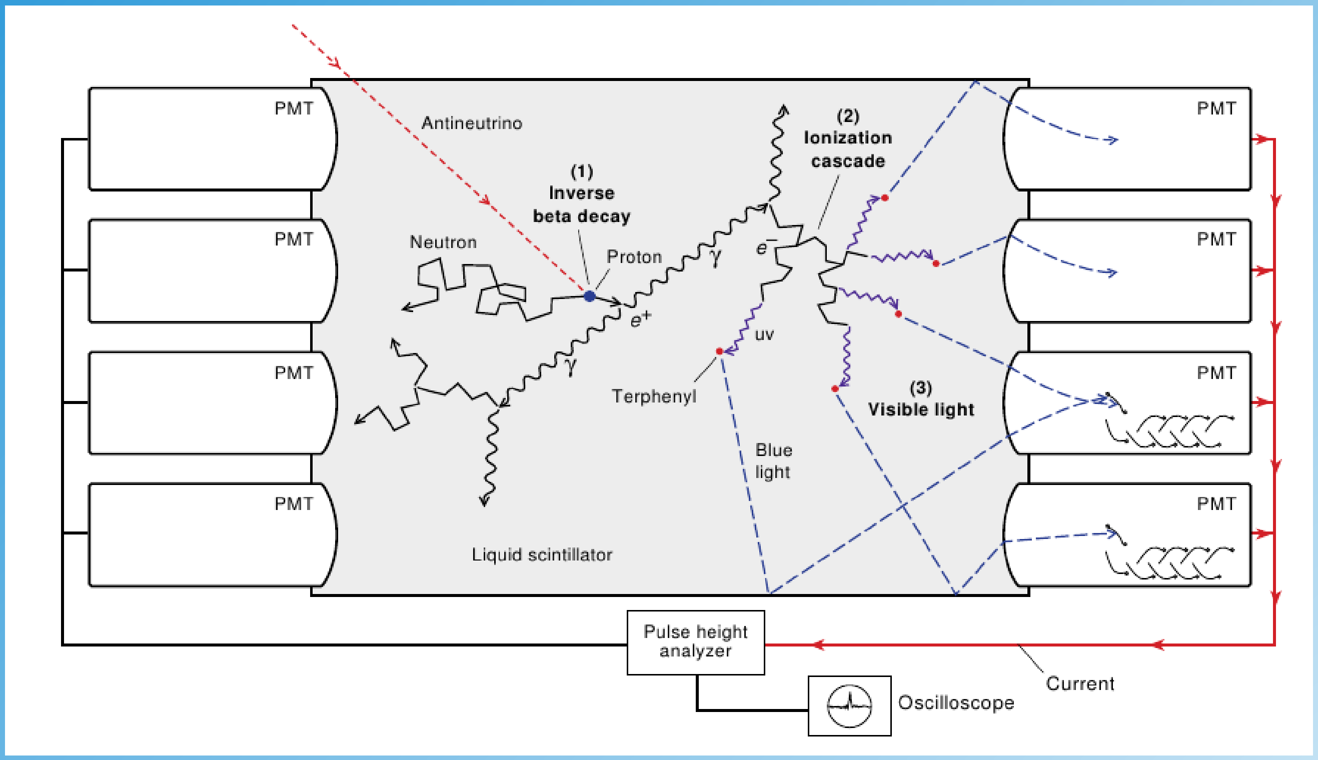
$\mu^- \rightarrow e^-\,\bar{\nu}_e\,\nu_\mu$ is allowed!

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

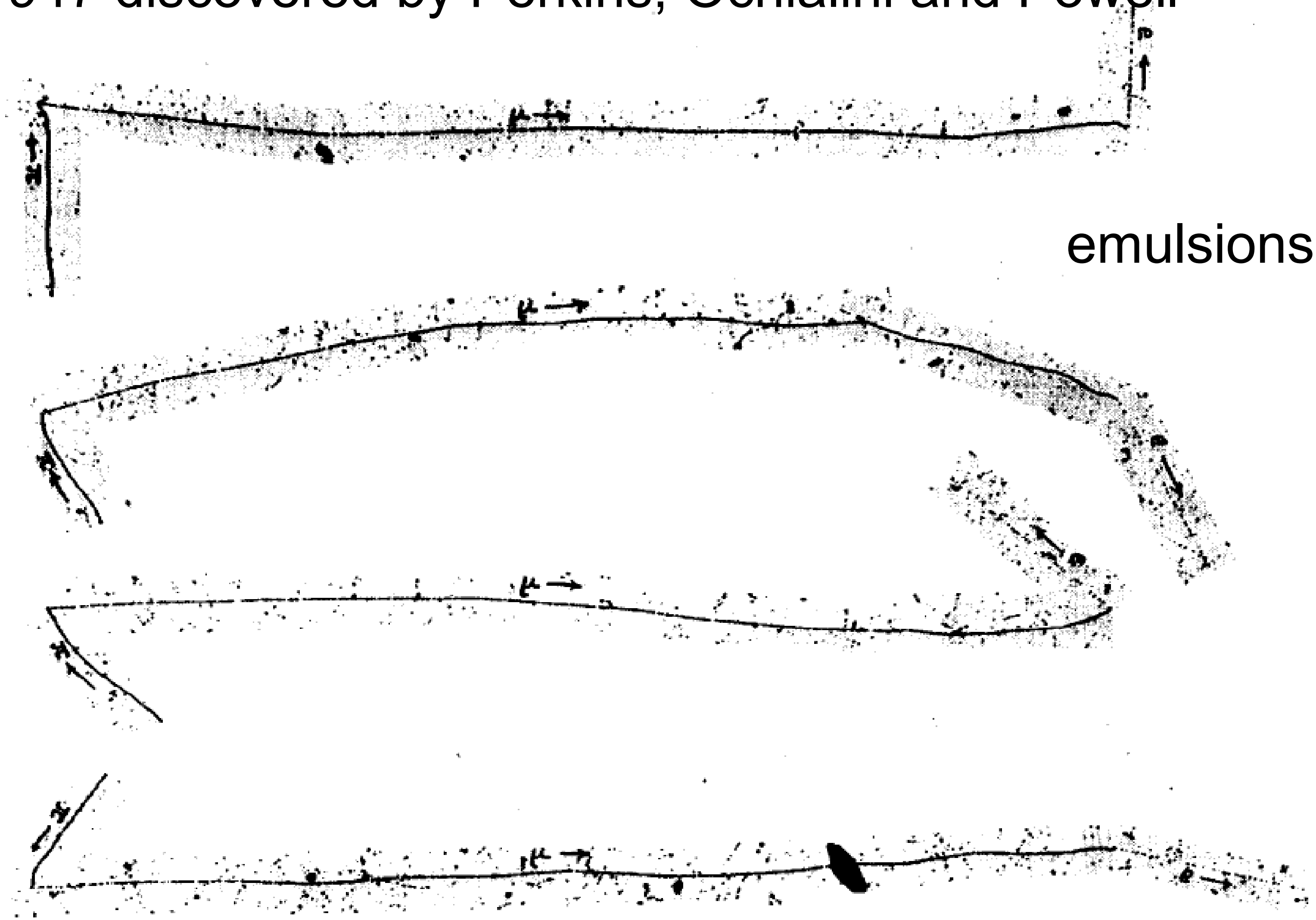
meson mass ~ ħc / (range of force)

range ~ 1 fm → m_{meson} = 200 MeV

→ Nobel Prize (1949)

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) $\partial_\mu j^\mu_V = 0$ (conservation of currents)

Lorentz Structure of Weak Interactions?

scalar coupling:

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

pseudoscalar coupling

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

vector current:

$$j^\mu_V = \bar{\psi}\gamma^\mu\psi$$

axial-vector current:

$$j^\mu_A = \bar{\psi}\gamma^\mu\gamma^5\psi$$

Left-Right Symmetry Broken if

$$j^\mu_L = 1/2\left(j^\mu_V - j^\mu_A\right) \neq$$

$$j^\mu_R = 1/2\left(j^\mu_V + j^\mu_A\right)$$

Discovery of Parity Violation in Weak Decays

proposed by **Lee + Yang**

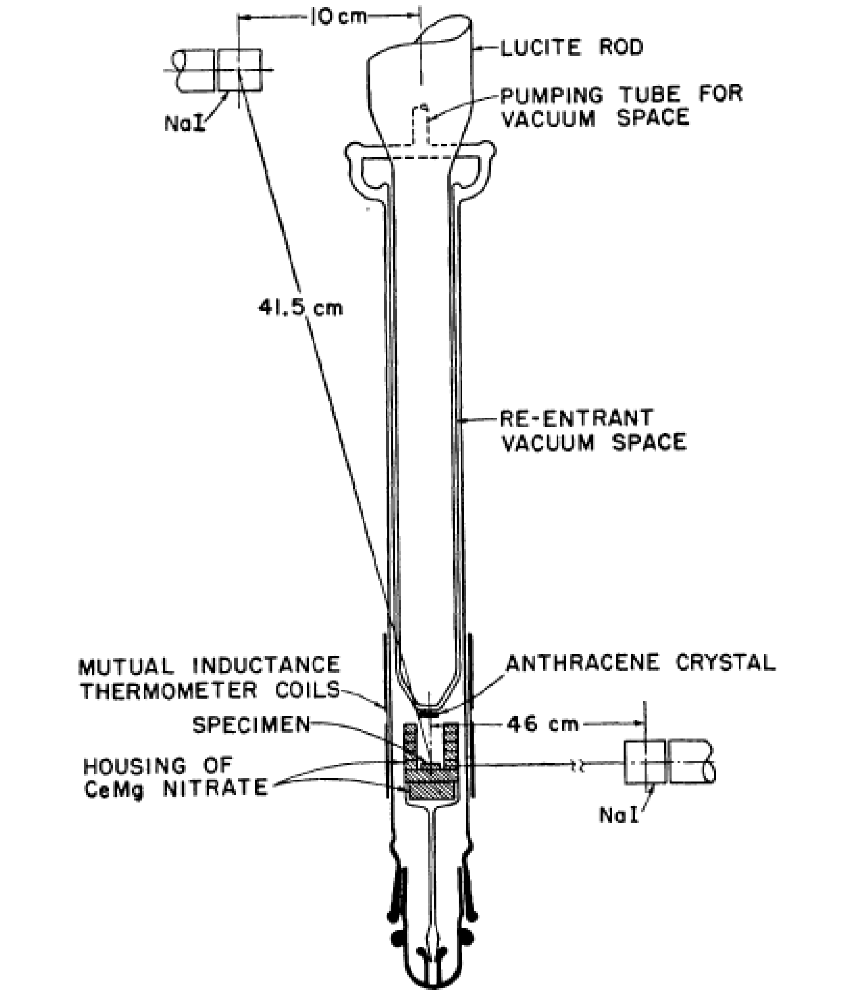


FIG. 1. Schematic drawing of the lower part of the cryostat.

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

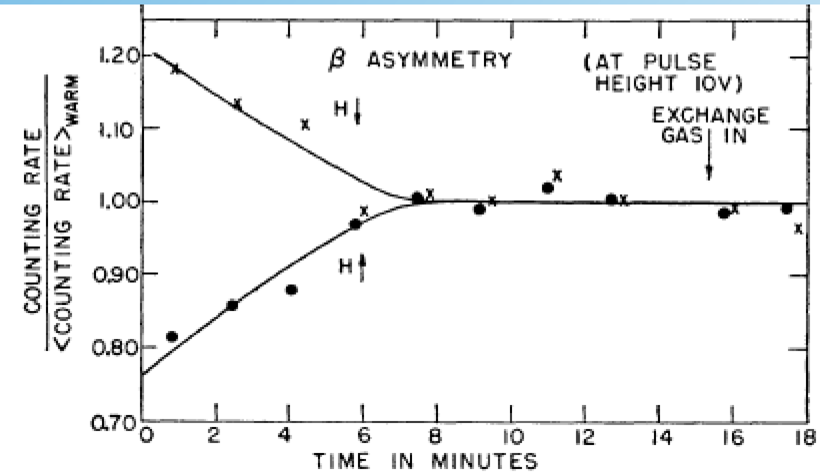
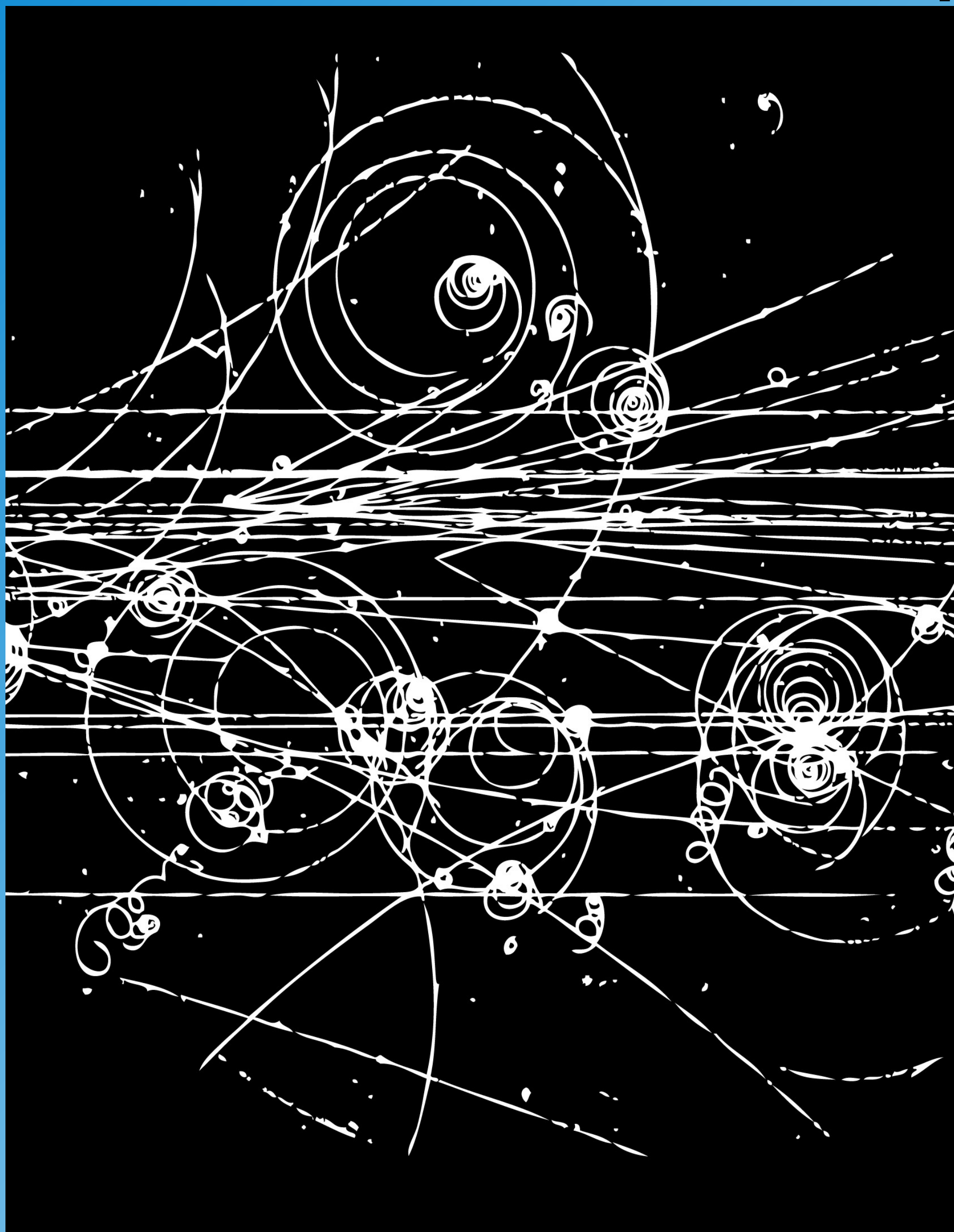


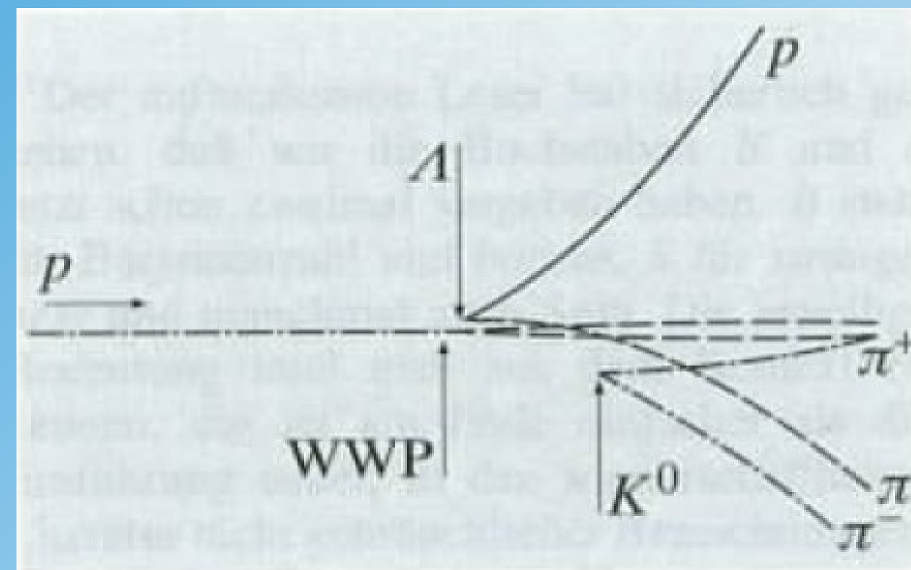
FIG. 2. Gamma anisotropy and beta asymmetry for polarizing field pointing up and pointing down.

- 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

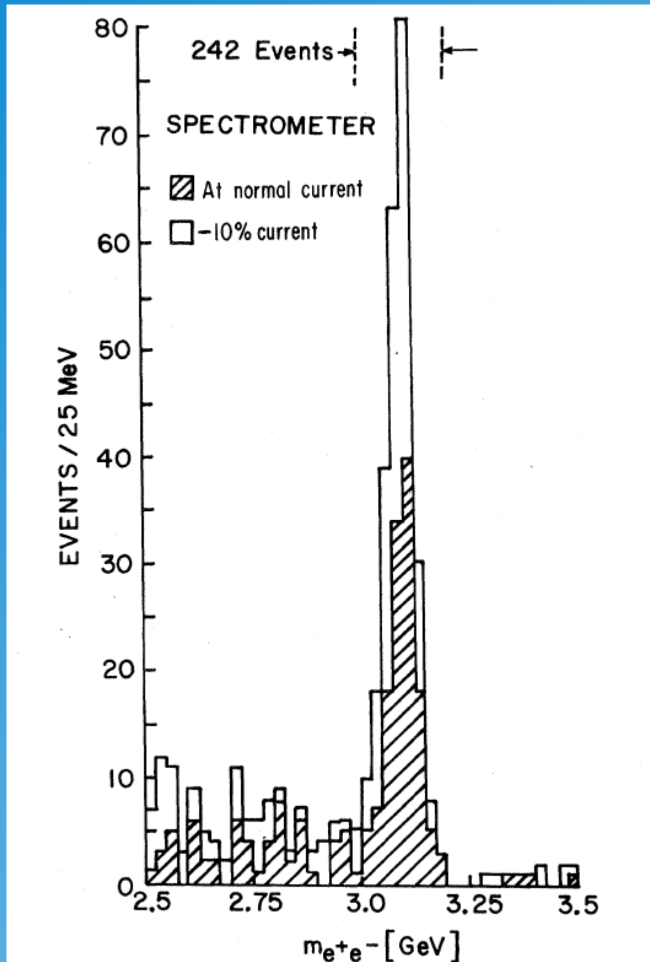


FIG. 2. Mass spectrum showing the existence of *J*. Results from two spectrometer settings are plotted showing that the peak is independent of spectrometer currents. The run at reduced current was taken two months later than the normal run.

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

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

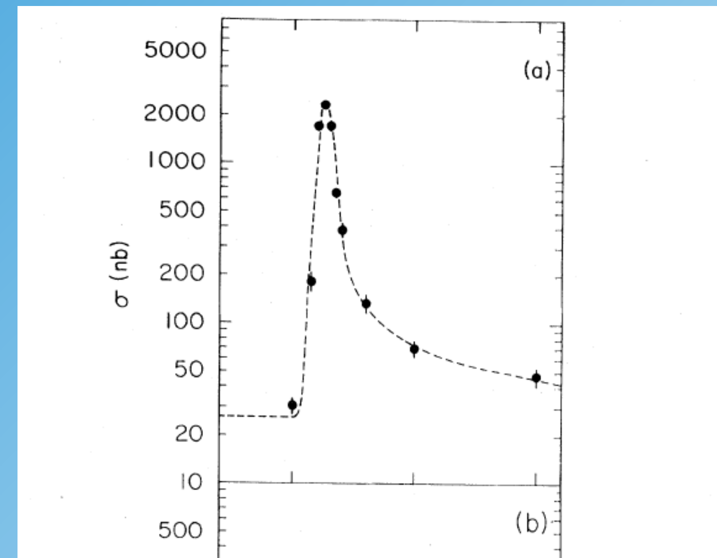


FIG. 1. Cross section versus energy for (a) multi-hadron final states, (b) e^+e^- final states, and (c) $\mu^+\mu^-$, $\pi^+\pi^-$, and K^+K^- final states. The curve in (a) is the expected shape of a δ-function resonance folded with the Gaussian energy spread of the beams and including radiative processes.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

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: $e^+ e^- \to e^+ \mu^-$ $\quad e^+ e^- \to e^- \mu^+$

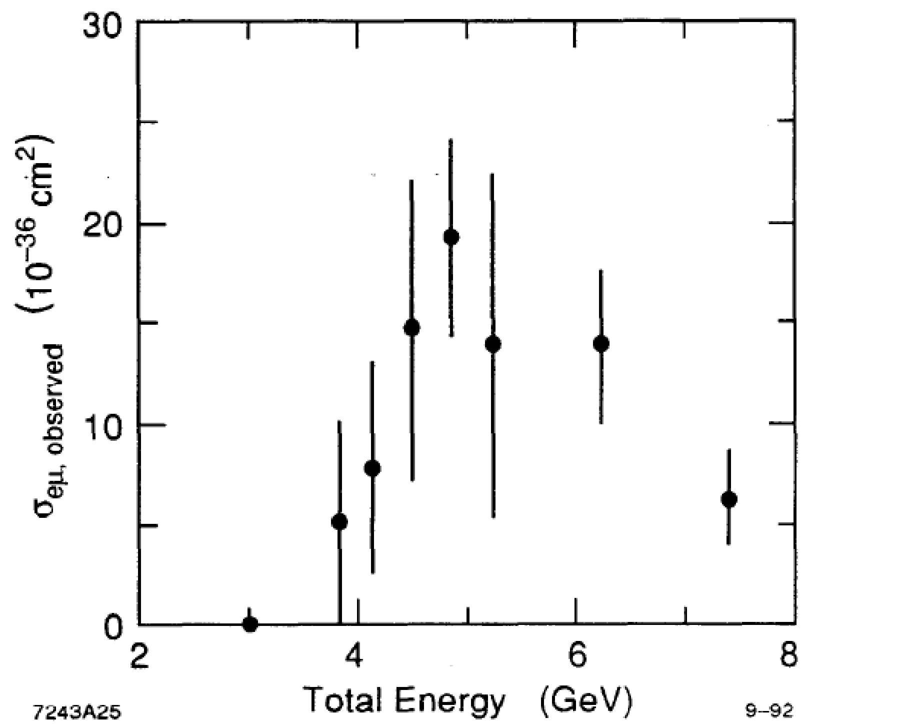


Fig. 4. From Perl *et al.* (1975): the observed cross section for the signature $e\mu$ events from the Mark I experiment at SPEAR. This observed cross section is not corrected for acceptance. There are 86 events with a calculated background of 22 events.

(Reines et al.)

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)

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)

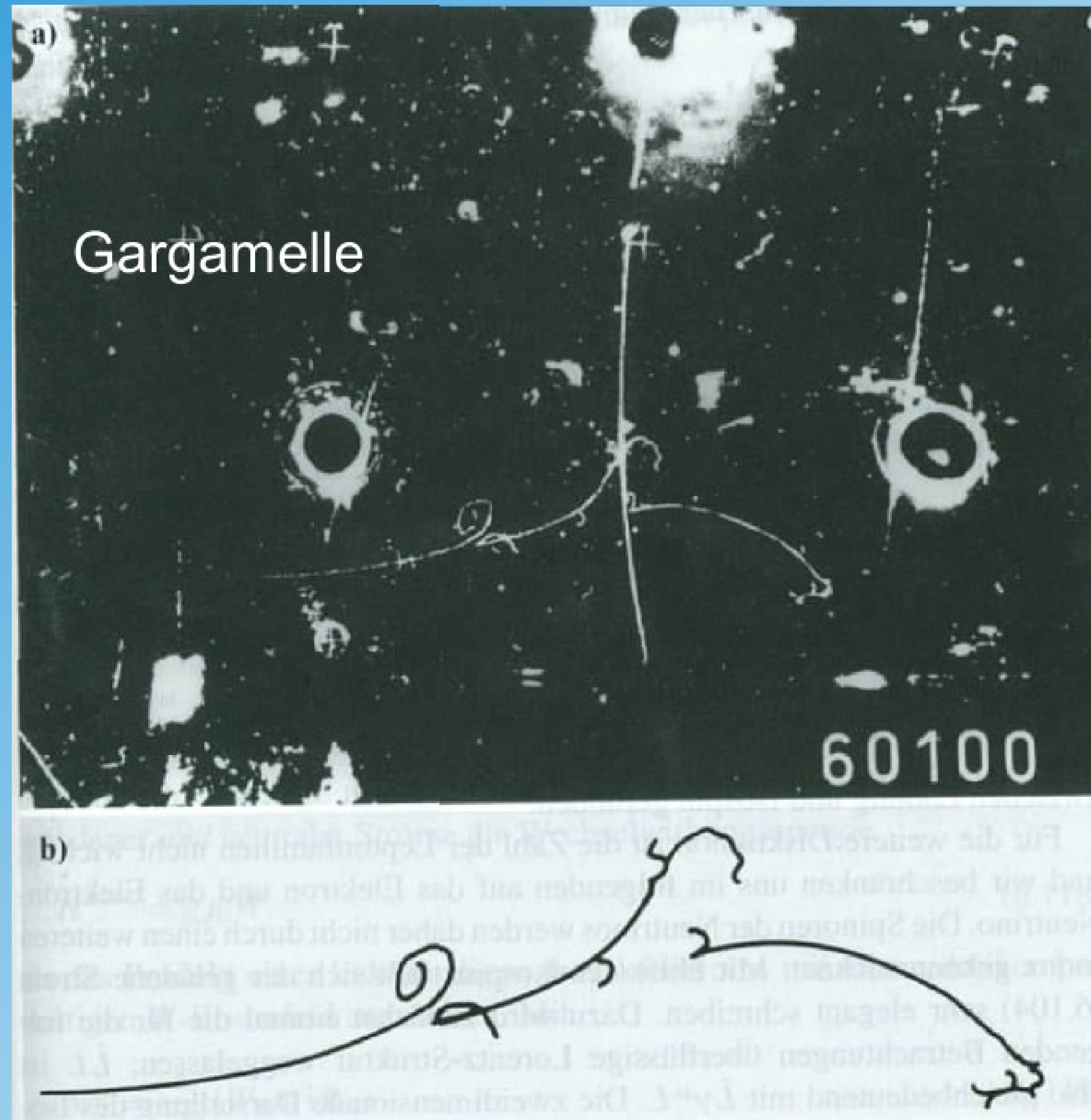
Use neutrinos to test existence of the Z boson

→ Nobel Prize (1979)

Observation of Neutral Currents

Bubble Chamber
Gargamelle (1974)

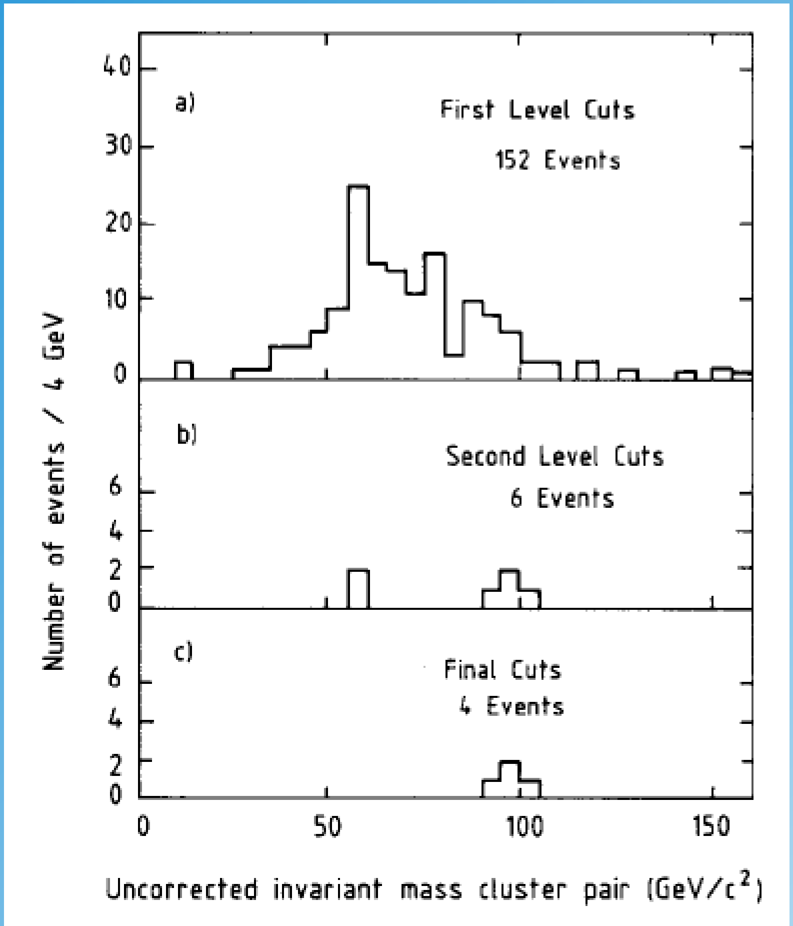
$$\nu_e e \rightarrow \nu_e e$$



Discovery of Z Gauge Boson

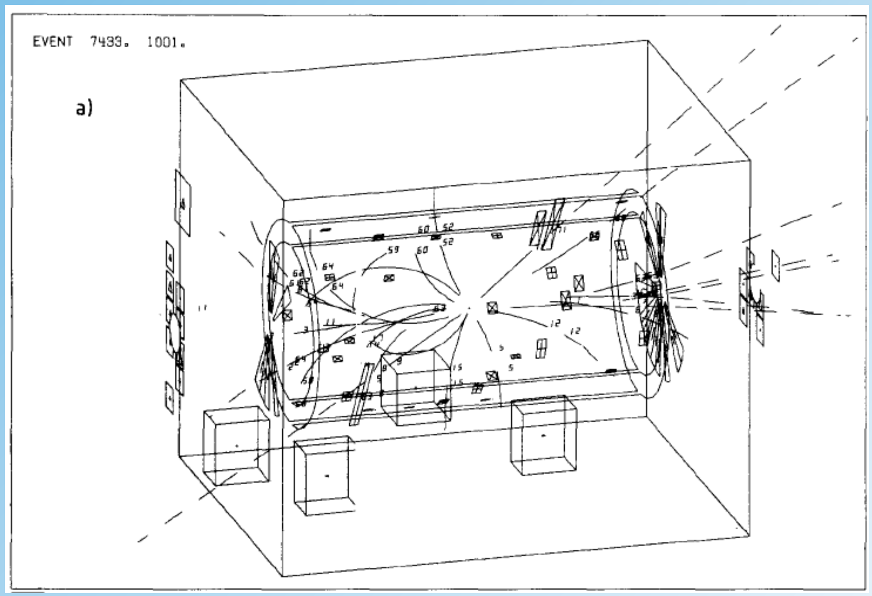
EXPERIMENTAL OBSERVATION OF LEPTON PAIRS OF INVARIANT MASS AROUND 95 GeV/c^2 AT THE CERN SPS COLLIDER

UA1 Collaboration, CERN, Geneva, Switzerland



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

Rubia et al. (1983)



➜ Nobel Prize (1984)

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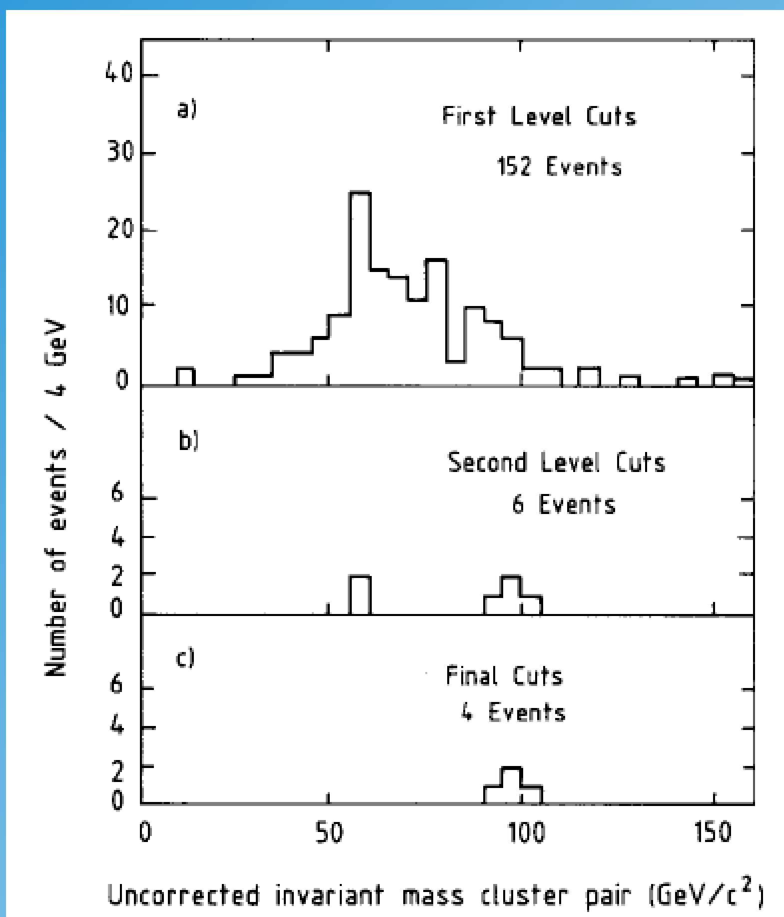

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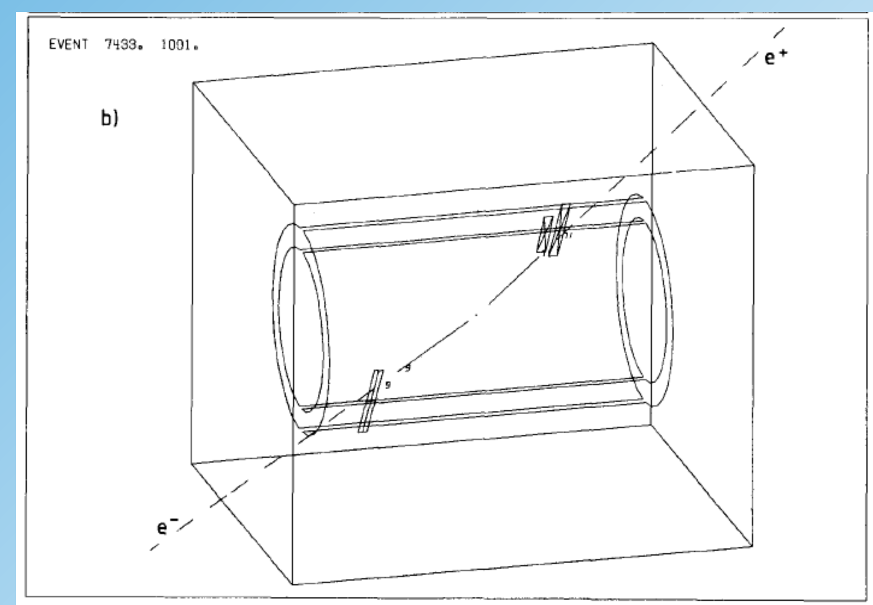
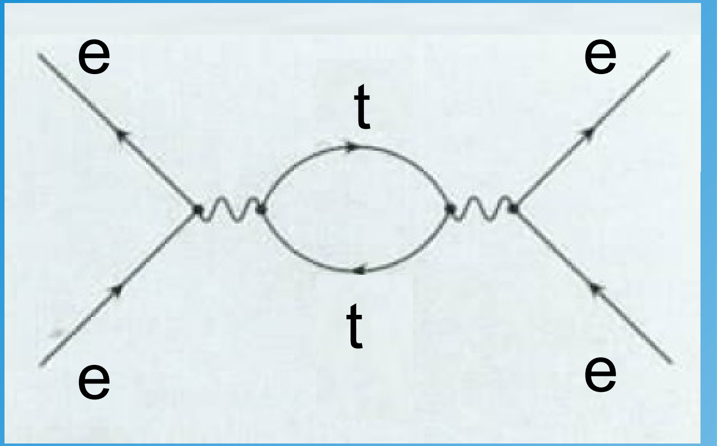


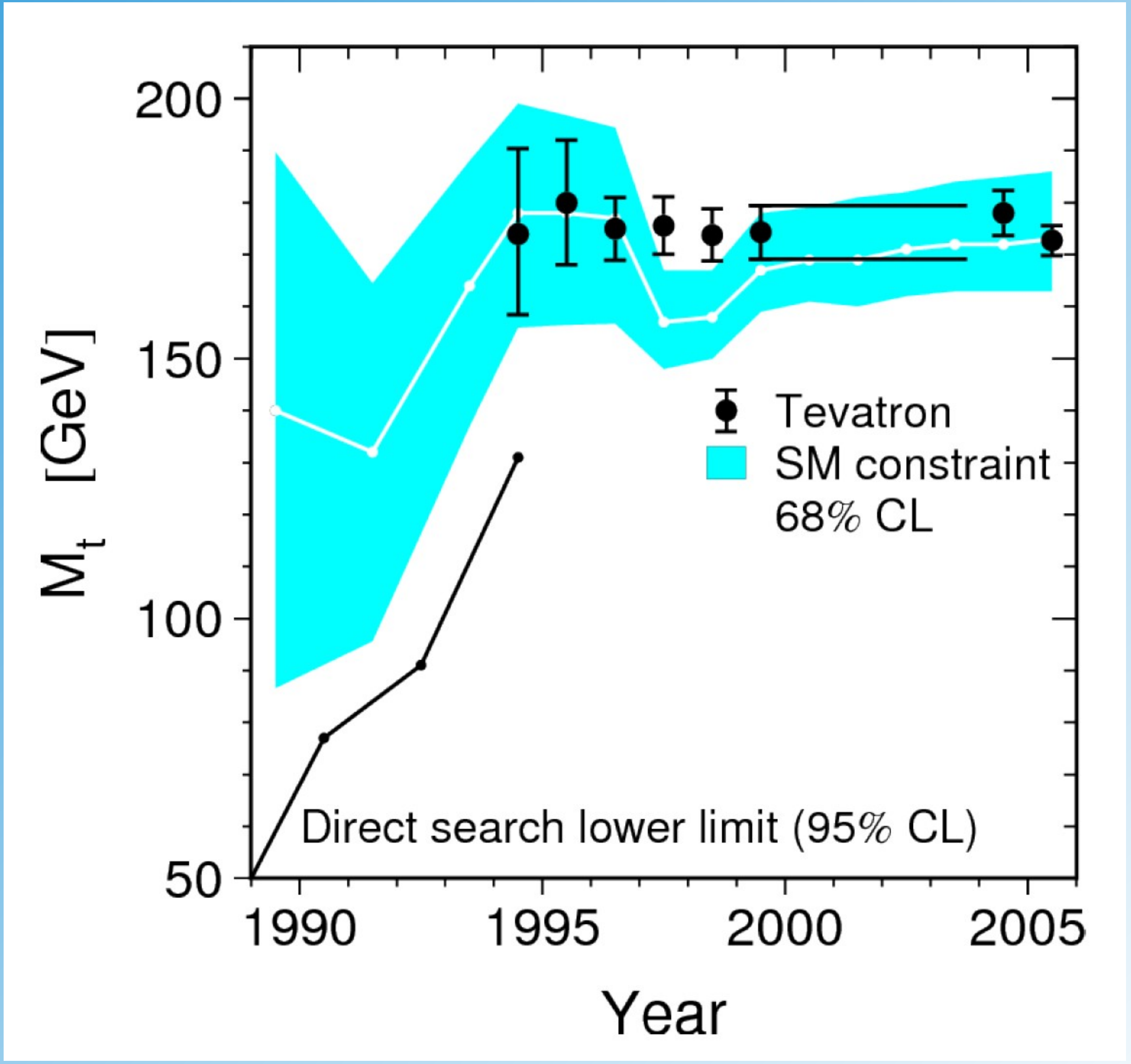
- Nobel Prize (1984)

Prediction of the Top Mass

Radiative Corrections:



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

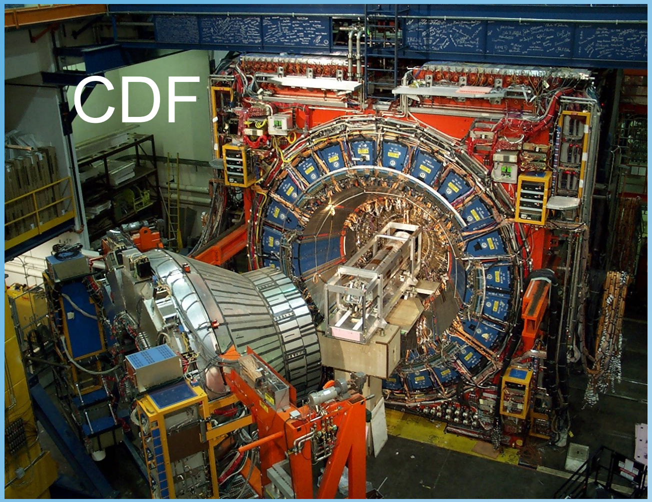


Discovery of the Top-Quark (1995)

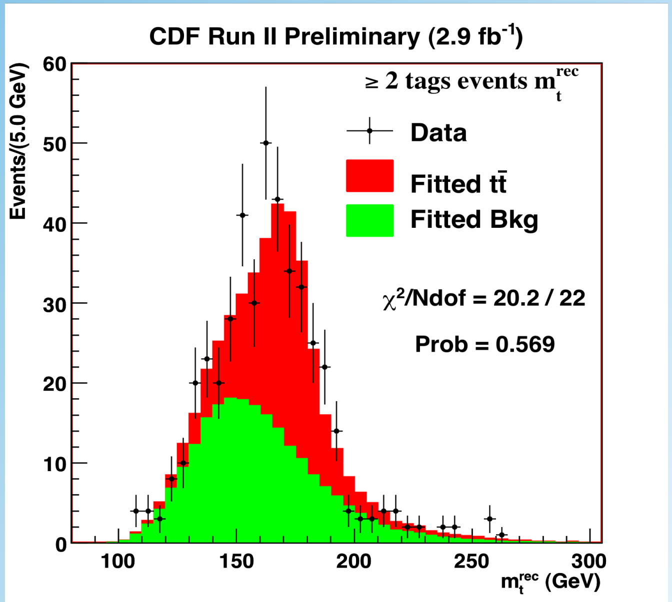
Fermilab, USA

Proton-Antiproton Collider

1 x 1 TeV



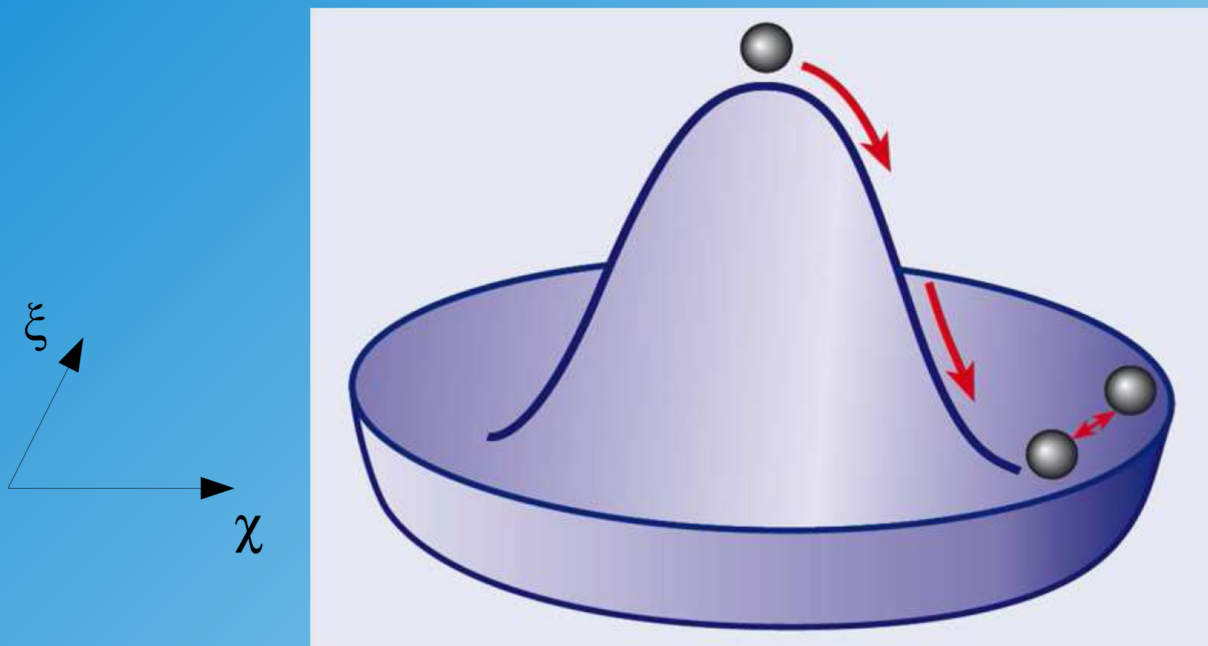
CDF + D0 Detectors



Top-Quark Mass ~172 GeV

Prediction of the Higgs Particle

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



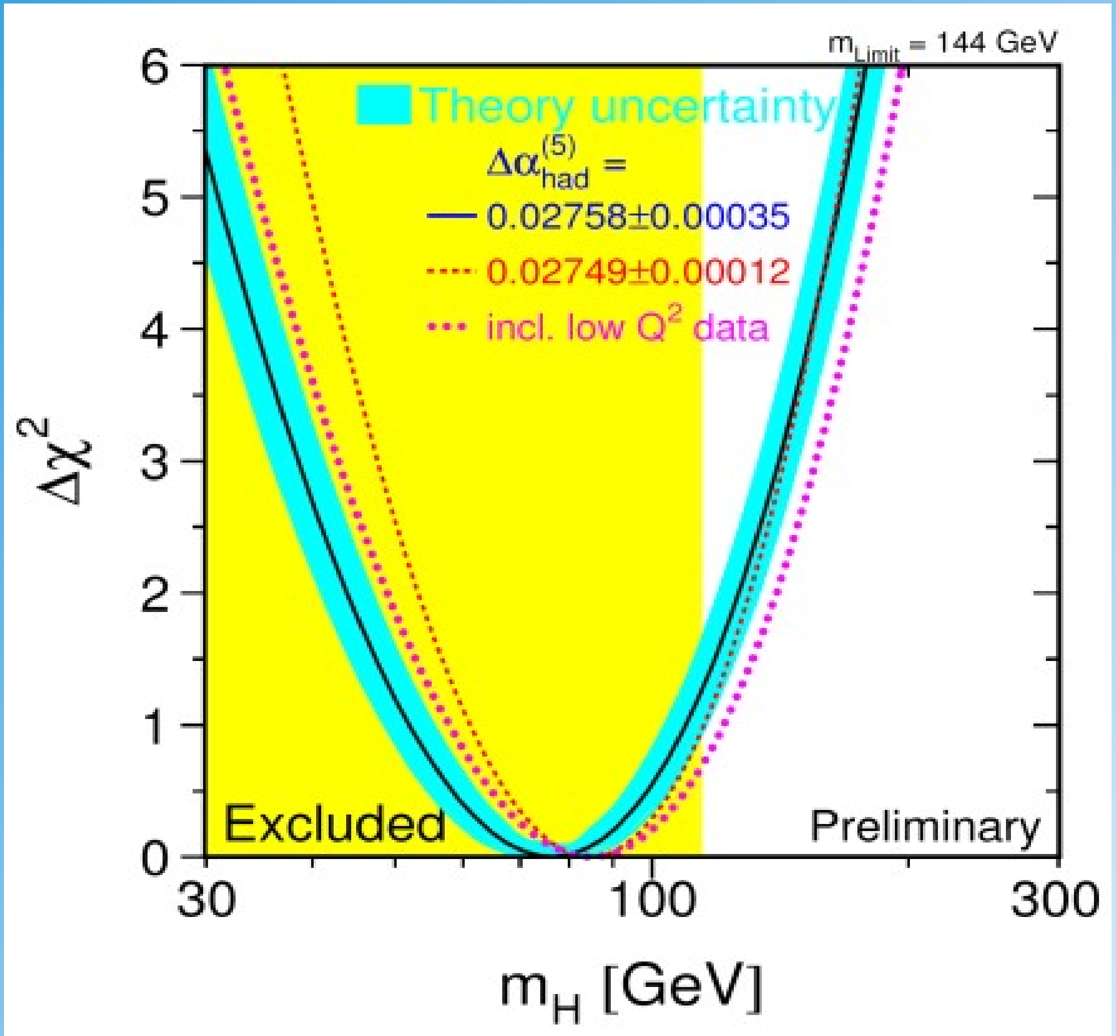
$$\Phi = \phi_0 + \chi + i\,\xi$$

minimum breaks symmetry:
spontaneous symmetry breaking

$$\Phi \neq 0$$

Prediction of the Higgs Mass

Status before Tevatron + LHC



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

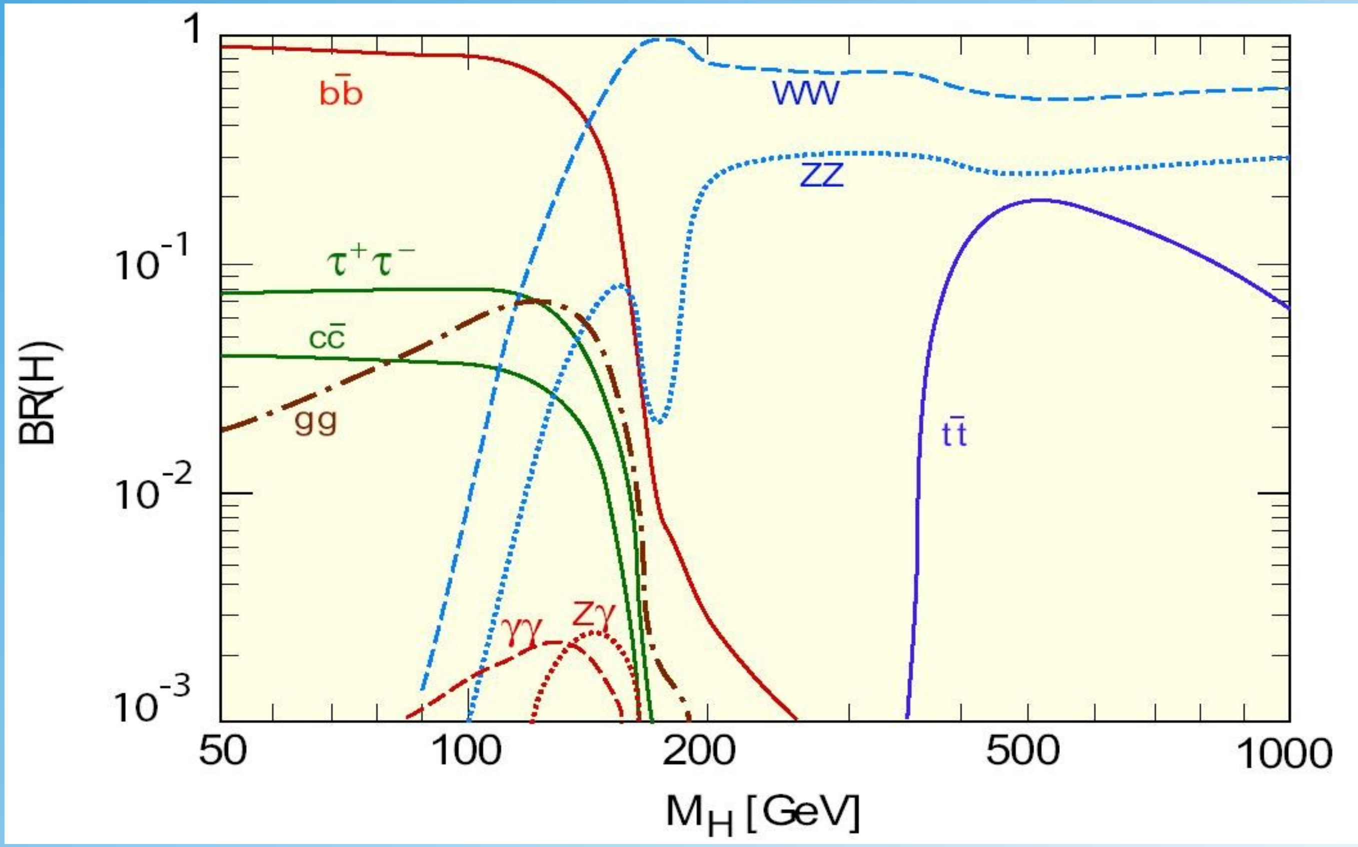
Search for the Higgs Boson

Main Problem:

Higgs Mass is unknown and only weakly constrained by precision measurements

Look in a large mass range:

Higgs decays:

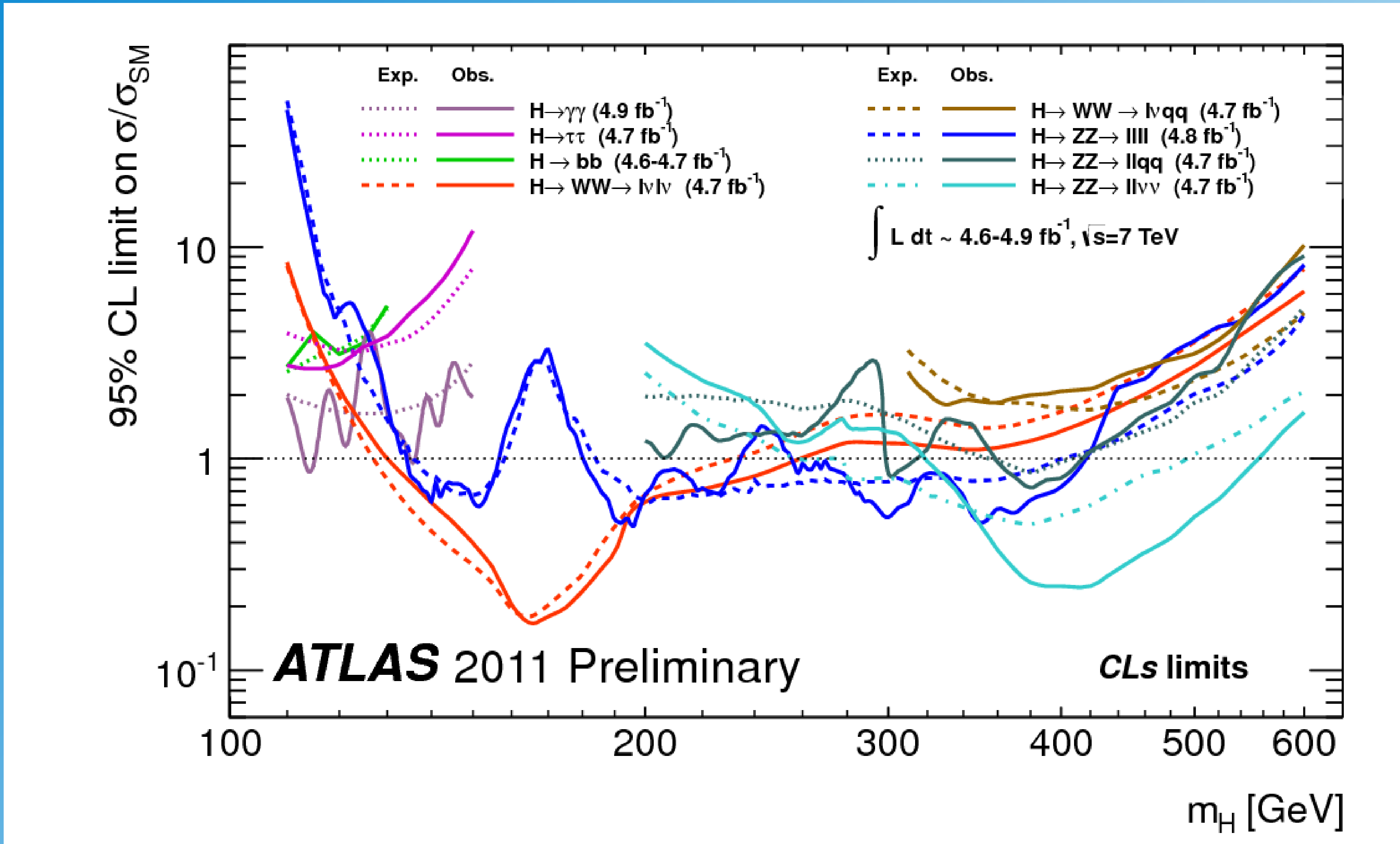


Large Hadron Collider (CERN)

LHC (pp) 7-8 (14) TeV

26.7 km circumference!

Preliminary Results of Search



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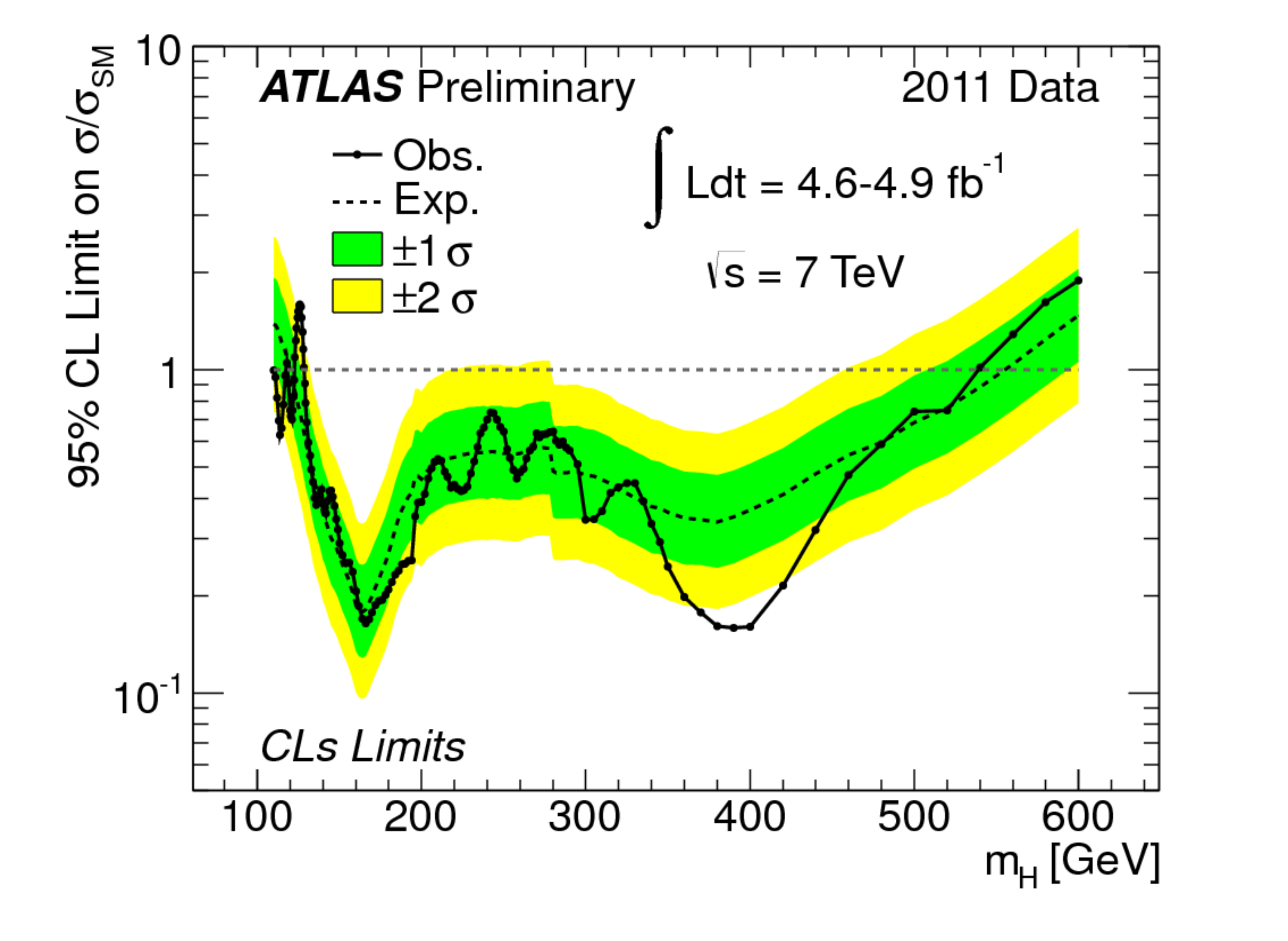
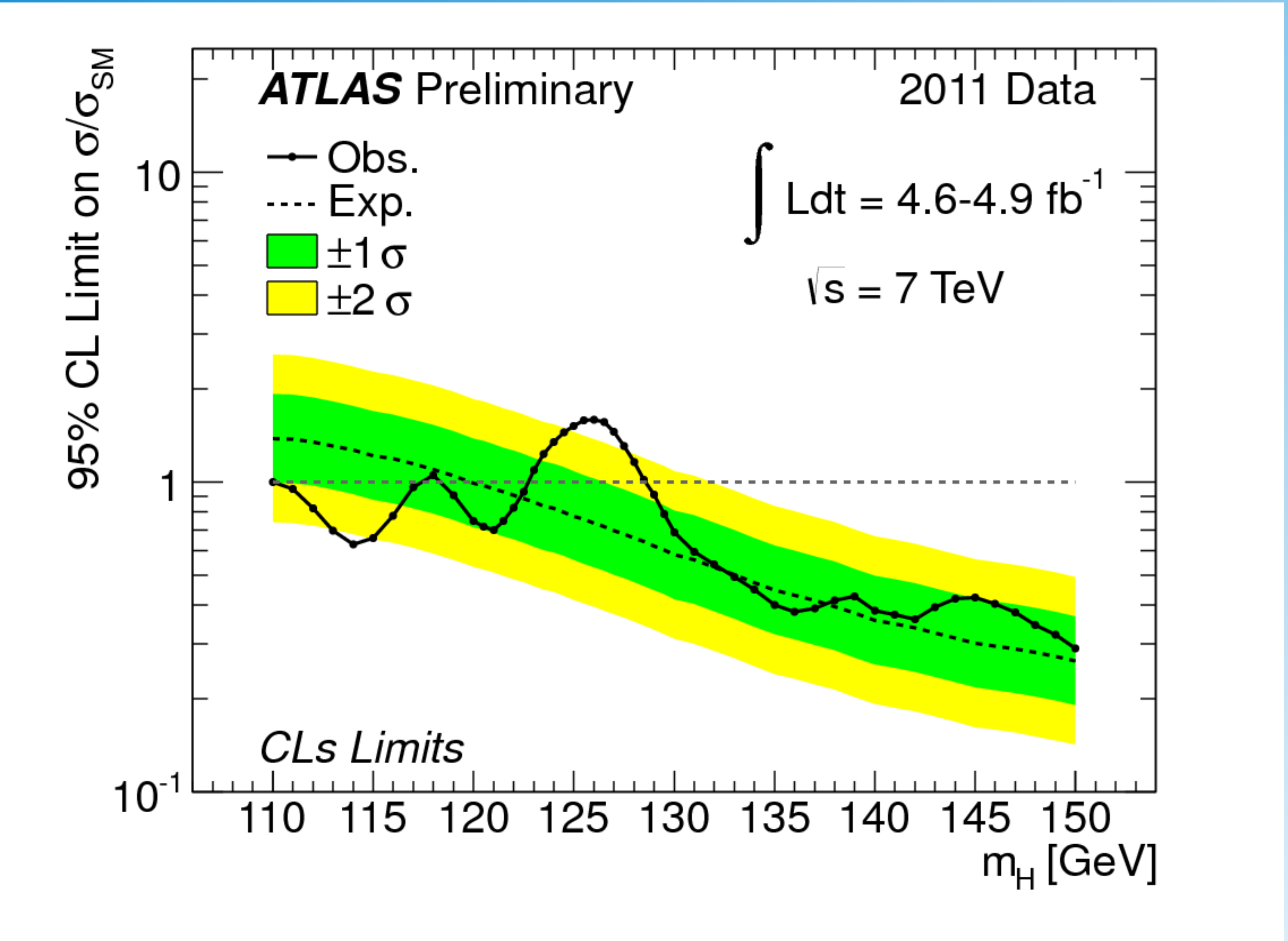


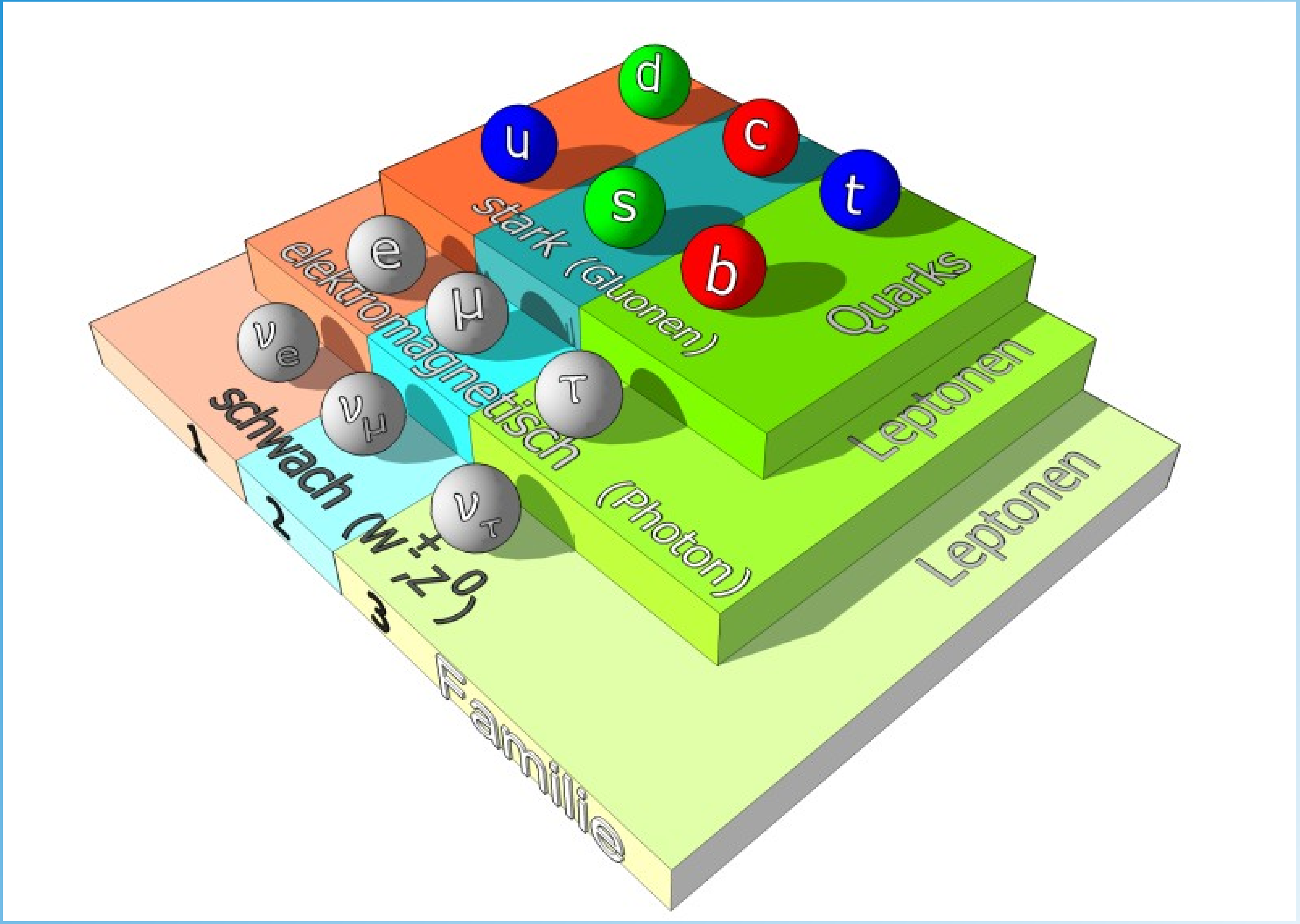
Preliminary Results of Search



only small window at m~125 GeV allowed!

running period in 2012 (already started) will be decisive!

Summary



d
u
c
s
t
b
stark (Gluonen)
Quarks
e
μ
elektromagnetisch
ν_e
ν_μ
τ
Leptonen
schwach
1
2
3
ν_τ
$(W^\pm, Z^0)$
(Photon)
Leptonen
Familie