Particle Physics Lecture

WS 2016/17

Prof. A. Schöning

Physikalisches Institut der Universität Heidelberg

Goal of this Lecture

Introduction to particle physics → master students

Comprehensive overview about particle physics:

- theoretical concepts and fundamental laws
- particle phenomenology
- experiments and experimental methods

Particle Physics Related Courses

<u>Winter term 2016/17:</u>

Particle Physics Colloquium

Tue 17h15 http://www.physi.uni-heidelberg.de/Veranstaltungen/vortraege.php?kol=PC

Lectures:

- **Accelerator Physics**
  lecture + tutorial: Wed 11h15, 16h15 (Schöning)
- **Statistical Methods in Particle Physics**
  lecture + tutorial: Mon 14h00, Mon 16h00 (Brandt)

Master seminars:

- **How to make a discovery: Search strategies at particle colliders**
  Fri 11h15 (Westhoff)
- **Particle tracking and identification at high rates**
  Fri 14h00 (Masciocchi, Schweda)

<u>Summer term 2016:</u>

- Detector Physics, Standard Model I, more seminars, ...

Organisation of PP lecture

Prerequisites:

Knowledge: Quantum Mechanics (Schrödinger Eq.), special relativity
Lectures: Physics I-V, Introduction to Nuclear and Particle Physics

Focus and content of this lecture:

Accelerators, Detectors, Relativisitc Kinematics, Symmetries, Quantum Electrodynamics, Weak Interaction, Quantum Chromodynamics, Standard Model, Beyond the Standard Model, Flavor Physics, Astroparticle Physics

This course is a basis for more specialised lectures:

e.g. HC Physics, Standard Model, Beyond the SM, Supersymmetry

Other useful lectures:

Quantum Field Theory (Mon+Wed, 11h15, Pawlowski)

more information:

http://www.physi.uni-heidelberg.de/~schoning/Vorlesungen/ParticlePhysics/

Tutorials + Requirements

- series of **11 exercises**
- published (web) latest on Wednesday evening
- sheets handed out at Thursday lecture
- to be handed in **Thursday 14h15 at beginning of lecture**
- typically ~4 exercises/sheet (up to three names)
- exercises are checked and corrected
- every student has to present solutions (2 x)
- target: **60% of the maximum score → qualification for examination**
- registration deadline for PP lecture **December 2** (point of no return...)
- written **examination 9.2.2015** (repetition 23.2.2015 if necessary)
- number of credit points = 8 (lecture+tutorial)

Tutorials + Requirements

Dates of tutorials (start this Thursday, October 20):

Mo 11:00 – 13:00, INF 227 / SR 3.402; group 1;
Do 11:15 – 13:00, INF 227 / SR 3.402; group 2;
Do 16:15 – 18:00, INF 226, K1; group 1;
Fr 9:15 – 11:00, INF 226, K2,3; group 4;
Fr 9:15 – 11:00, INF 226, K1; group 5;
Fr 11:15 – 13:00, INF 227 / SR 3.404; group 6;

Registration: https://uebungen.physik.uni-heidelberg.de/v/580

Coordinator: Christoph Anders <anders@physi.uni-heidelberg.de>

Literature on Particle Physics

Ch. Berger: Elementarteilchenphysik, 2014, in German, Springer Verlag, ISBN 978-3-642-41752-8

M. Thompson: Modern Particle Physics, 2013, engl., ISBN-13: 978-1107034266

B.R. Martin, Nuclear and Particle Physics, An Introduction, 2009, Wiley, ISBN 978-0-470-74275-4

Povh, Rith, Scholz and Zetsche, Particles and Nuclei, An Introduction, 2008, Springer Verlag ISBN 978-3-540-79368-7

D.Griffith, Introduction to Elementary Particle Physics, 2008, Wiley, ISBN: 978-3527406012

D.H. Perkins, Introduction to High Energy Physics, 2000, Addison Wesley (older standard book)

P. Schmüser, Feynmann Graphen, 1995, Springer Verlag

Particle Data Group, K.A. Olive et al., Chin. Phys. C, 38, 090001 (2014) and 2015 update [http://pdg.lbl.gov/]

by far not complete. Many, many more books...

Lecture Dates + Topics

Tuesday 14:15-16:00 and Thursday 14:15-16:00

Date	Topic Tuesday	Date	Topic Thursday
18.10.16	Introduction to Particle Physics	20.10.16	Basic Definitions
25.10.16	Accelerators	27.10.16	Particle Interactions with Matter
01.11.16	no lecture (public holiday)	03.11.16	Detectors I
08.11.16	Detectors II	10.11.16	Particle Zoo + Group Theory
15.11.16	Dirac Equation	17.11.16	Spin and Discrete Symmetries
22.11.16	Scattering Matrix and Symmetries	24.11.16	Resonances and Decays I
29.11.16	Resonances and Decays II	01.12.16	Quantum Electrodynamics I
06.12.16	Quantum Electrodynamics II	08.12.16	QED Processes
13.12.16	Nucleon Structure	15.12.16	Structure Functions
20.12.16	QCD and Hadrons I	22.12.16	QCD and Hadrons II
10.01.16	Weak Decays and Interactions I	12.01.16	Weak Decays and Interactions II
17.01.16	Electroweak Physics I	19.01.16	Electroweak Physics II
24.01.16	Standard Model	26.01.16	CKM Matrix
31.01.16	Quark Mixing and CP-Violation	02.02.16	Beyond the Standard Model and Neutrino Physics
07.02.16	no lecture	09.02.16	Examination 14h15
14.02.16	no lecture	16.02.16	no lecture
21.02.16	no lecture	23.02.16	Re-Examination 14h15

Master Thesis in Particle Physics

Nuclear and Heavy Ion Physics:

- Prof. N. Herrmann (CBM)
- Prof. J. Stachel (ALICE)

High Energy Physics:

- Dr. O. Brandt (ATLAS)
- Prof. S. Hansmann Menzemer (LHCb)
- Prof. H.C. Schultz-Coulon (ATLAS,CALICE, MU3E)
- Prof. A. Schöning (ATLAS, MU3E)
- Prof. M. Schmelling (LHCb)
- Prof. U. Uwer (LHCb)

Neutrino Physics:

- Prof. M. Lindner (GERDA,XENON100,...)
- Prof. Ch. Enss, Prof. L. Gestaldo (ECHO, …)

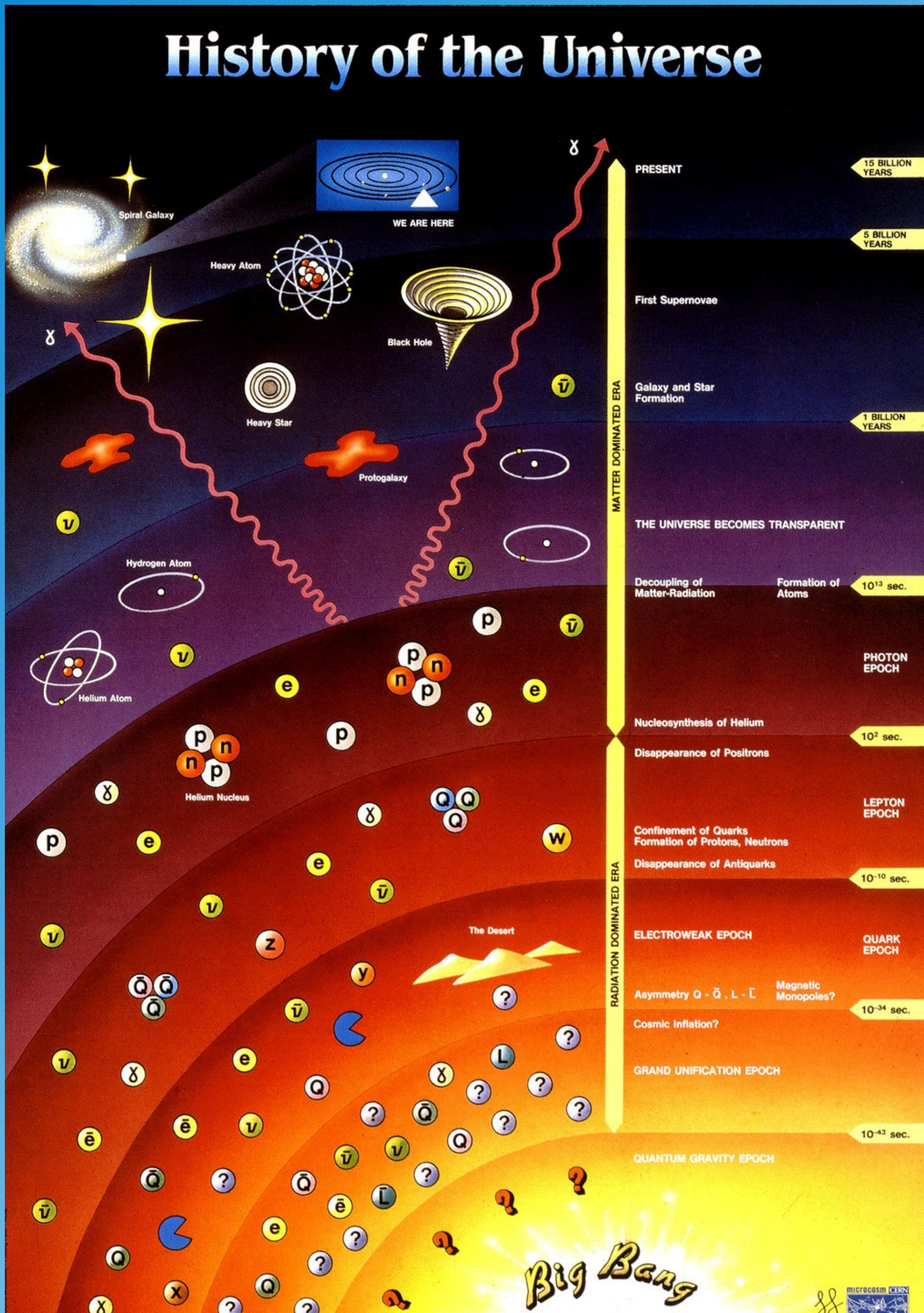
Astroparticle Physics:

- Prof. W. Hoffmann (HESS, CTA)

Theory

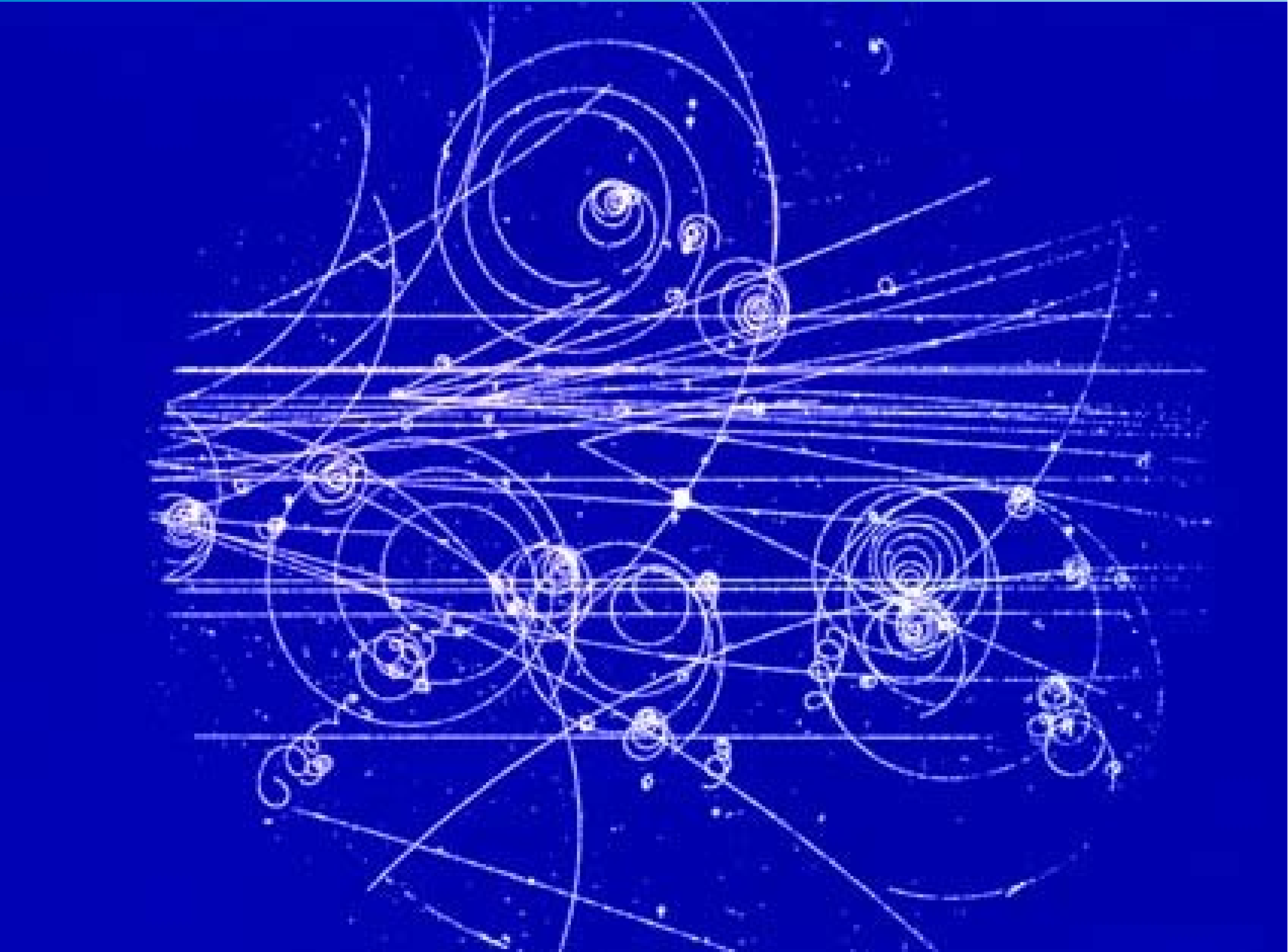
- Prof. J. Jäckel (Beyond the Standard Model)
- Prof. T. Plehn (Beyond the Standard Model+LHC Phenomenology)
- Prof. S. Westhoff (Beyond the Standard Mode+LHC Phenomenology)

Please communicate + give feedback!



era of gravitation

era of particle physics



Introduction

100 years of particle physics...

...more than a success story!

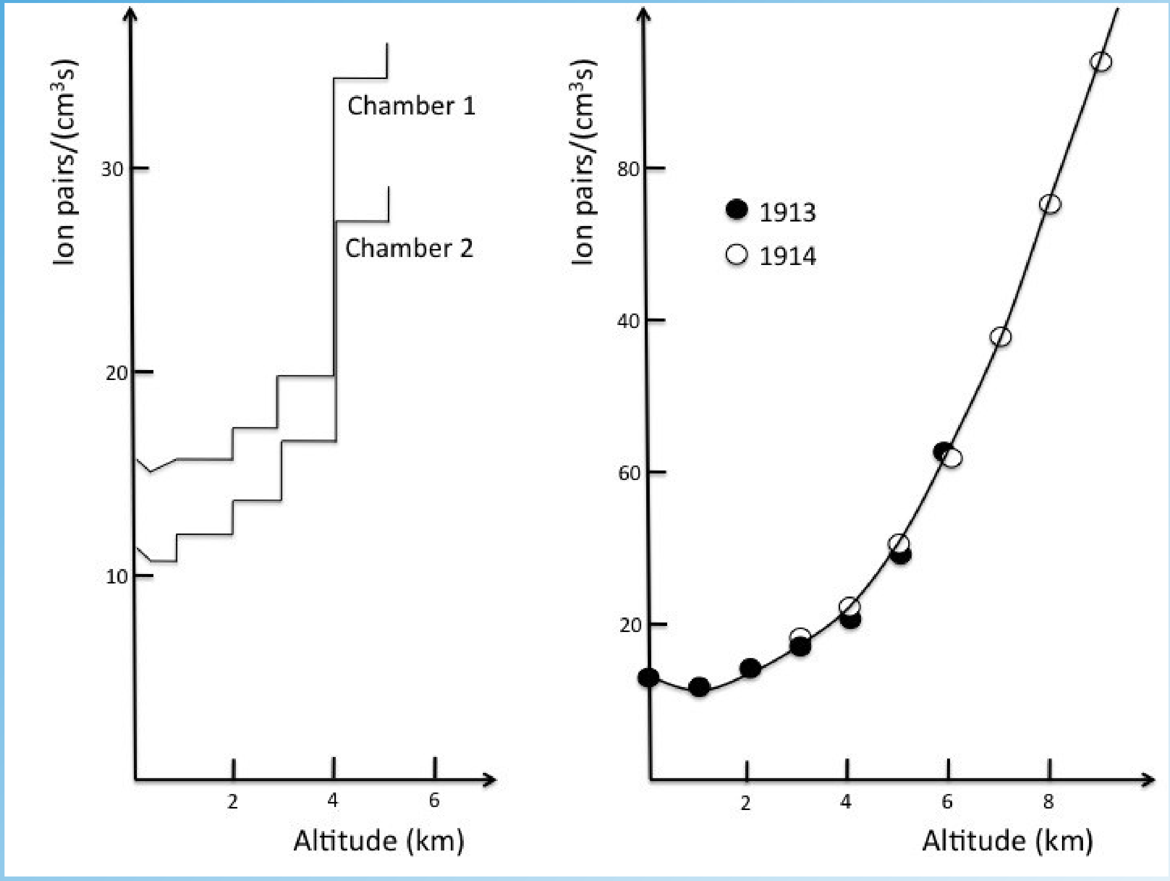
<u>a historical overview</u>

Ionisation Measurement

Victor Hess
discovery of
cosmic showers

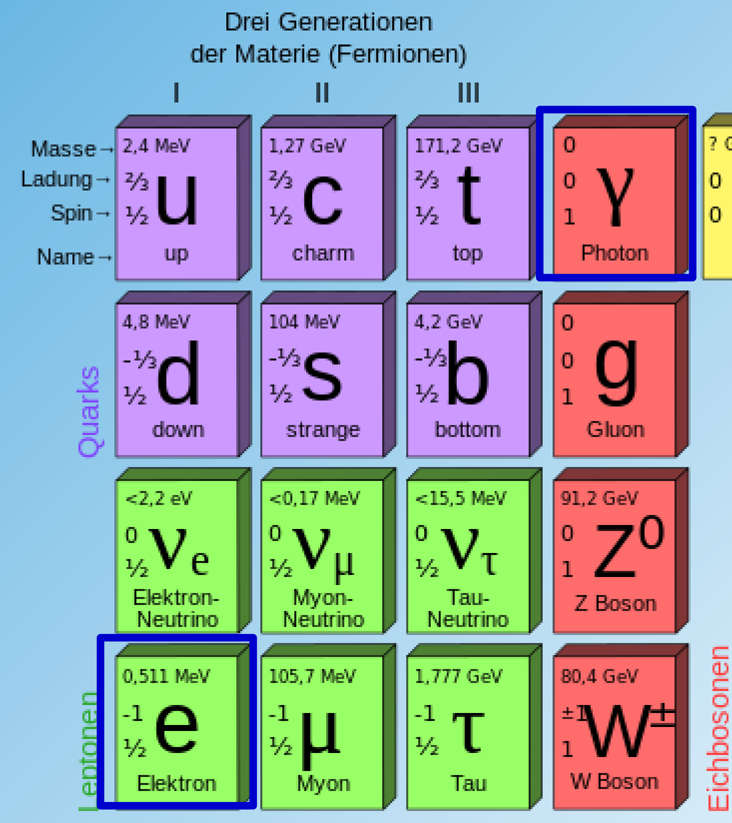
1912

Rate of on pairs:



→ Nobel Prize (1936)

1912 **100 years** → 2012

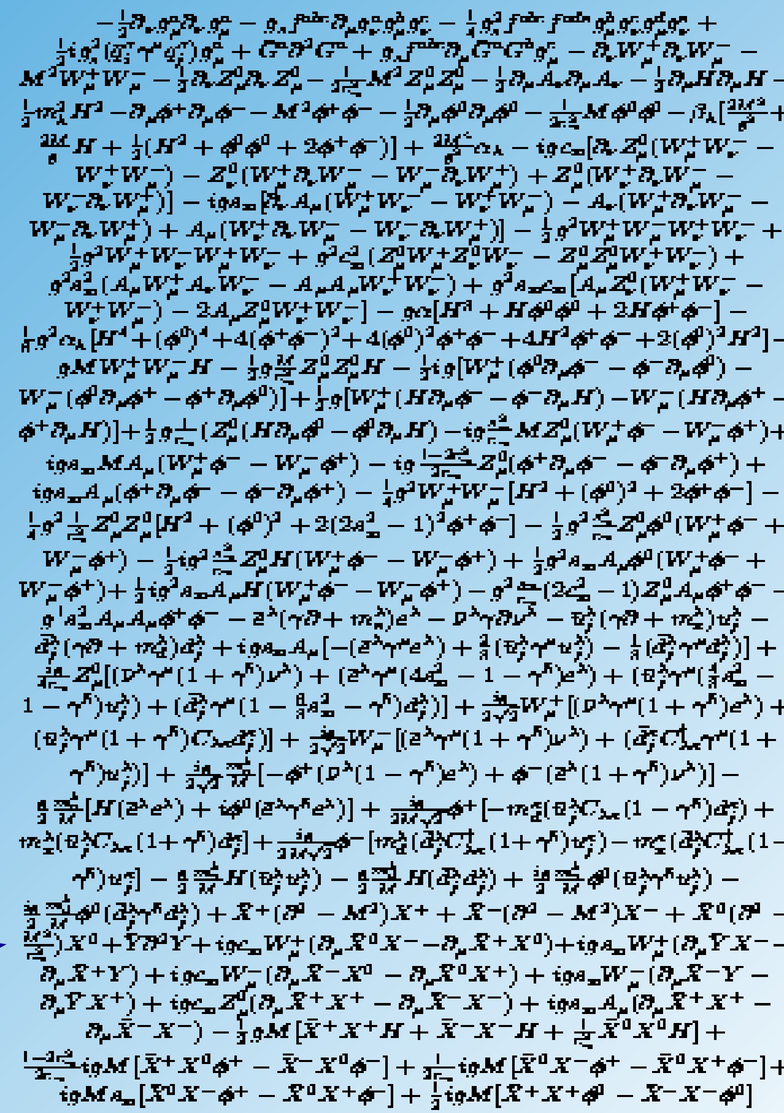


- **electron**
- **photons**
- **nuclei (protons, neutrons)**

1912 → 2012

100 years

- **electron**
- **photons**
- **nuclei (protons, neutrons)**



Standard Model Lagrangian

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 particles with two spin states (fermions) and for positive and "negative" energies:

"negative" energy $\rightarrow$ **antiparticles!**

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

Discovery of the Positron

- first observed by D.Skobeltsyn in cosmic rays using a Wilson cloud chamber (1929)

- C.D. Anderson: study of cosmic rays in a cloud chamber (1932)

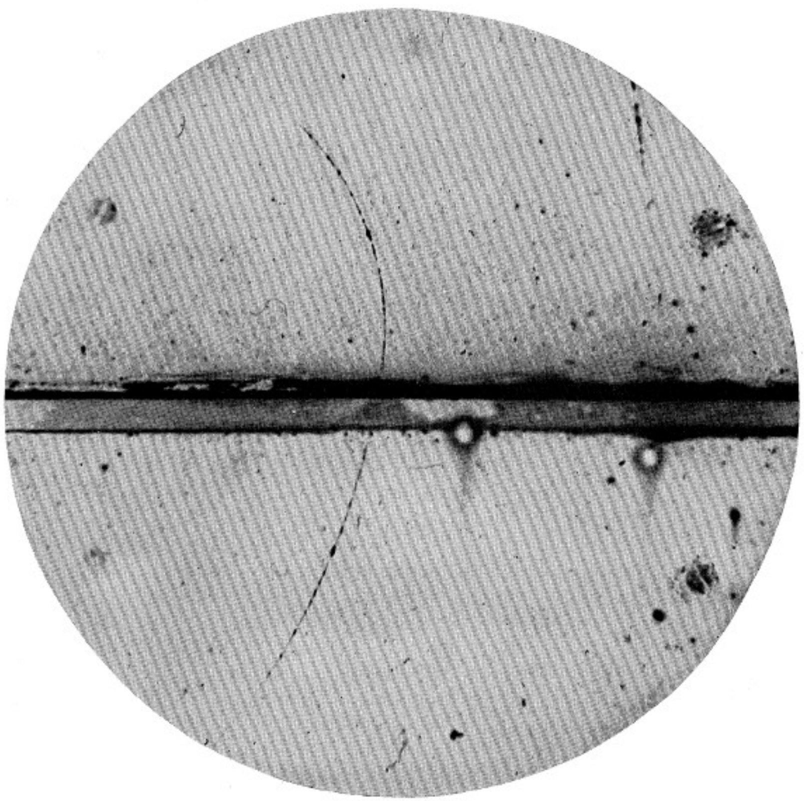


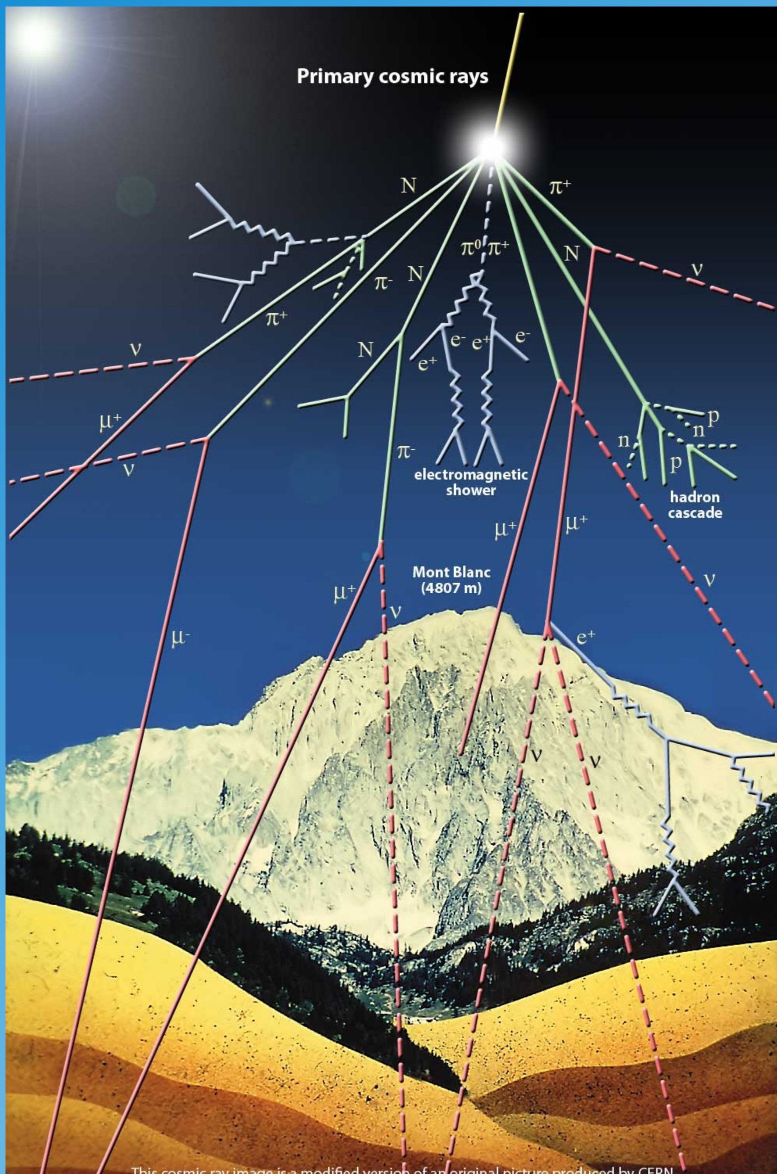
FIG. 1. A 63 million volt positron ($H\rho = 2.1 \times 10^5$ gauss-cm) passing through a 6 mm lead plate and emerging as a 23 million volt positron ($H\rho = 7.5 \times 10^4$ gauss-cm). The length of this latter path is at least ten times greater than the possible length of a proton path of this curvature.

positrons are bent due
to Lorentz force in magnetic field

proof of existence of
anti-particles

Carl D. Anderson
→ Nobel Prize (1936)

Muon Discovery (1936)



Muon discovery in <u>cosmic rays</u> by

Carl Anderson
+
Seth Nedermeyer

mass: **m_μ ~100 MeV**

→ <u>Nobel Prize (1936)</u>

- The myon is the first “exotic” particle
- It was believed to be the meson predicted by Yukawa

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

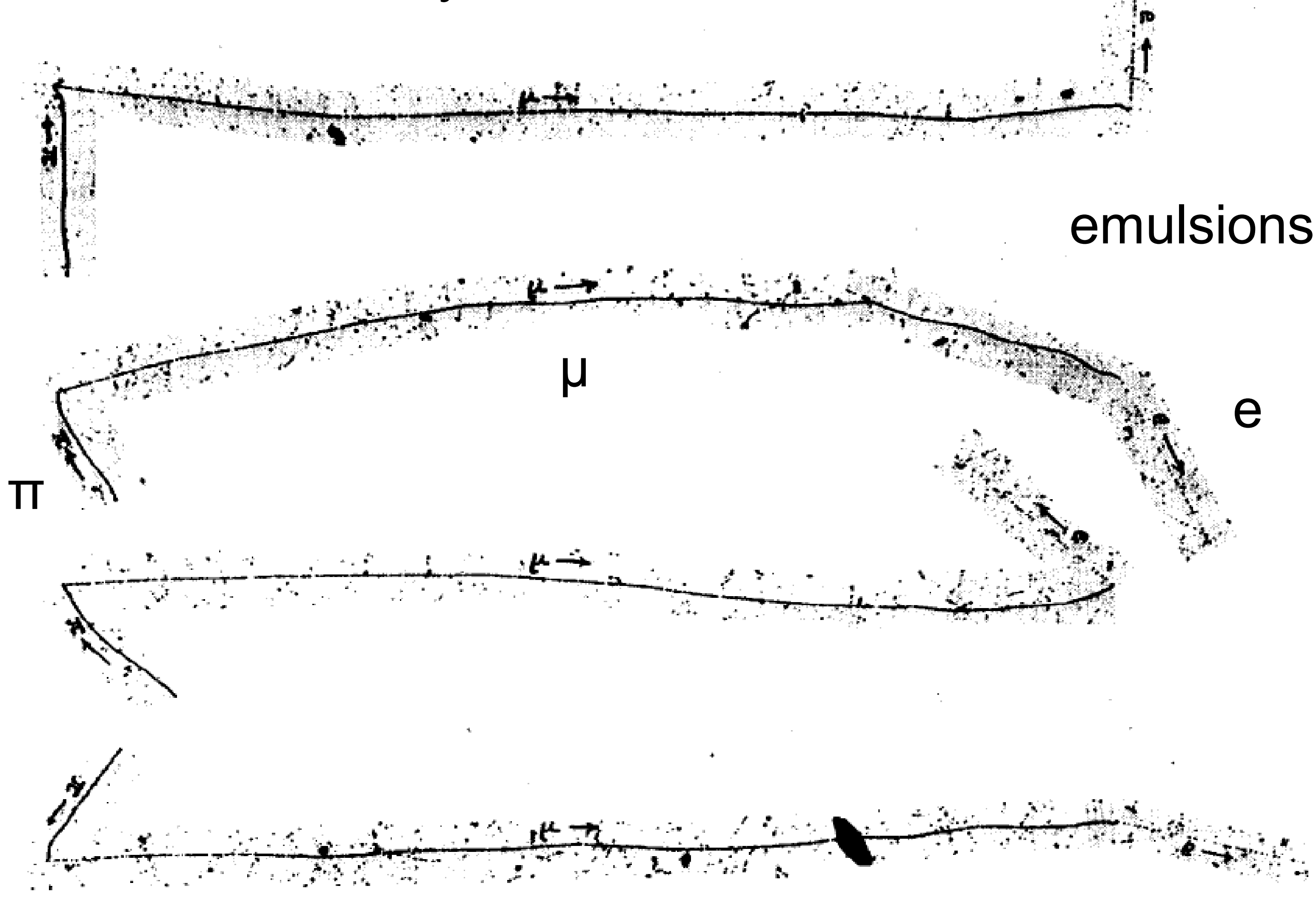
$\hbar c$ = 197.326 MeV fm

note 1: mesons are quark-anti-quark states and not elementary

note 2: meson = “mean, intermediate state”

Discovery of the Pion

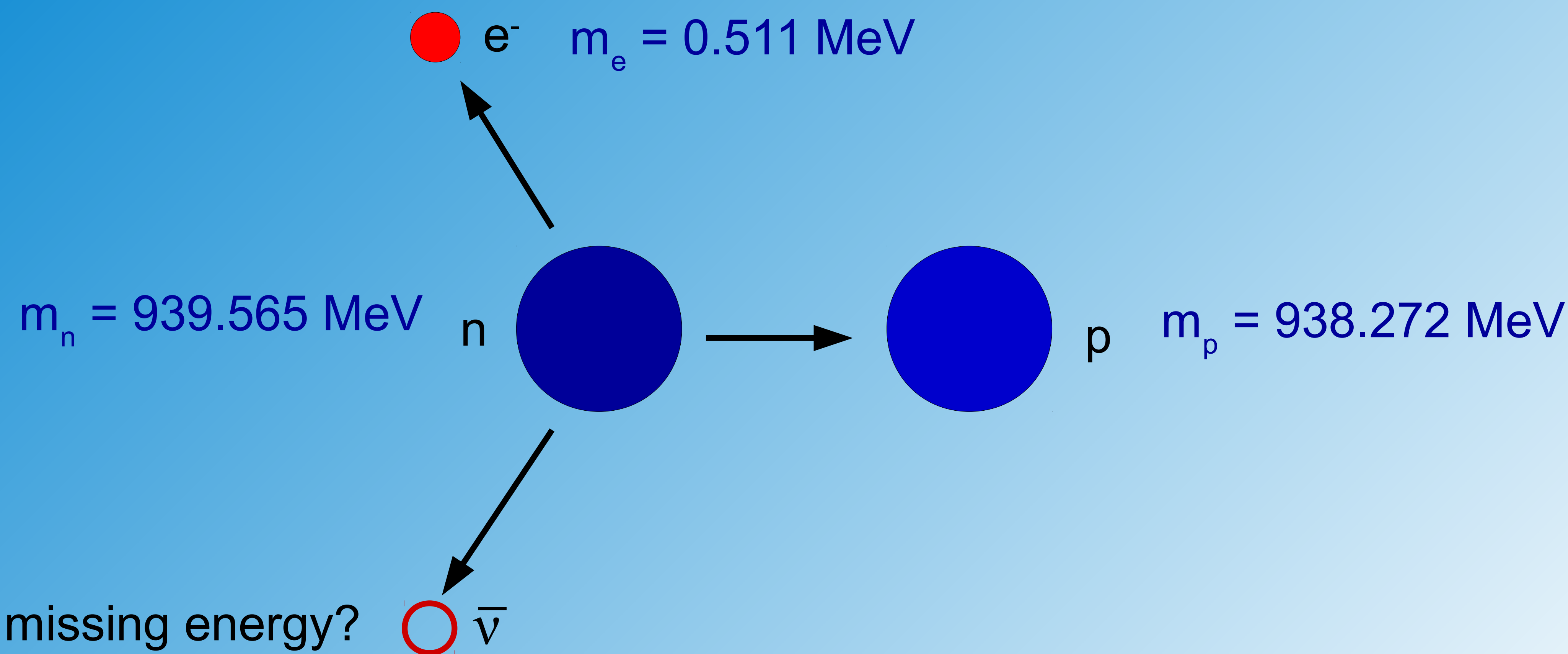
1947 discovered by Perkins, Ochialini and Powell



- Nobel Prize (Powell 1950)

Discovery of Neutrinos

beta decay: $n \rightarrow p\, e^- \bar{\nu}$



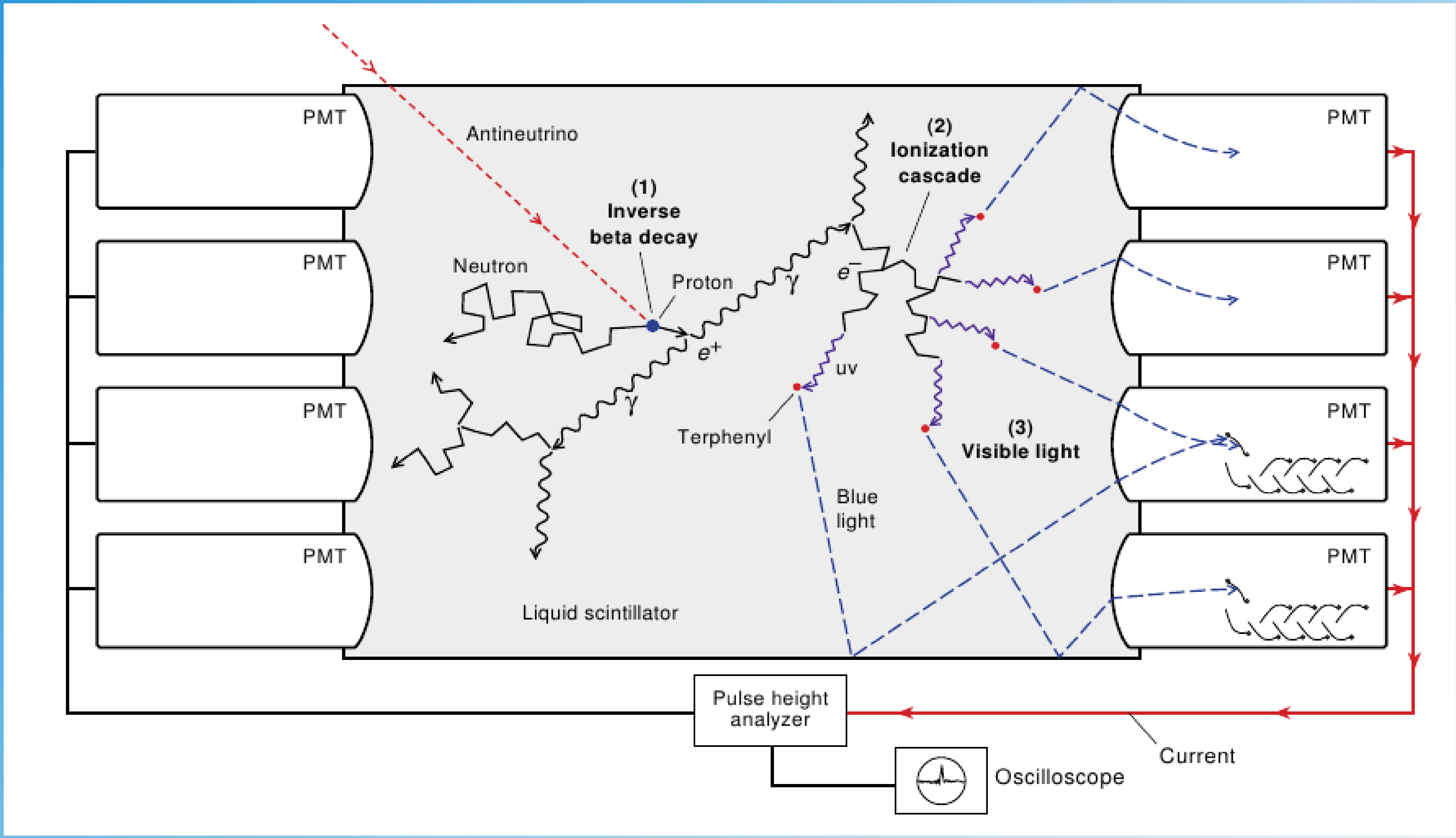
W. Pauli predicted in a letter to E.Fermi the existence of <u>neutrinos</u> (1930)

Discovery of the Electron-Neutrino

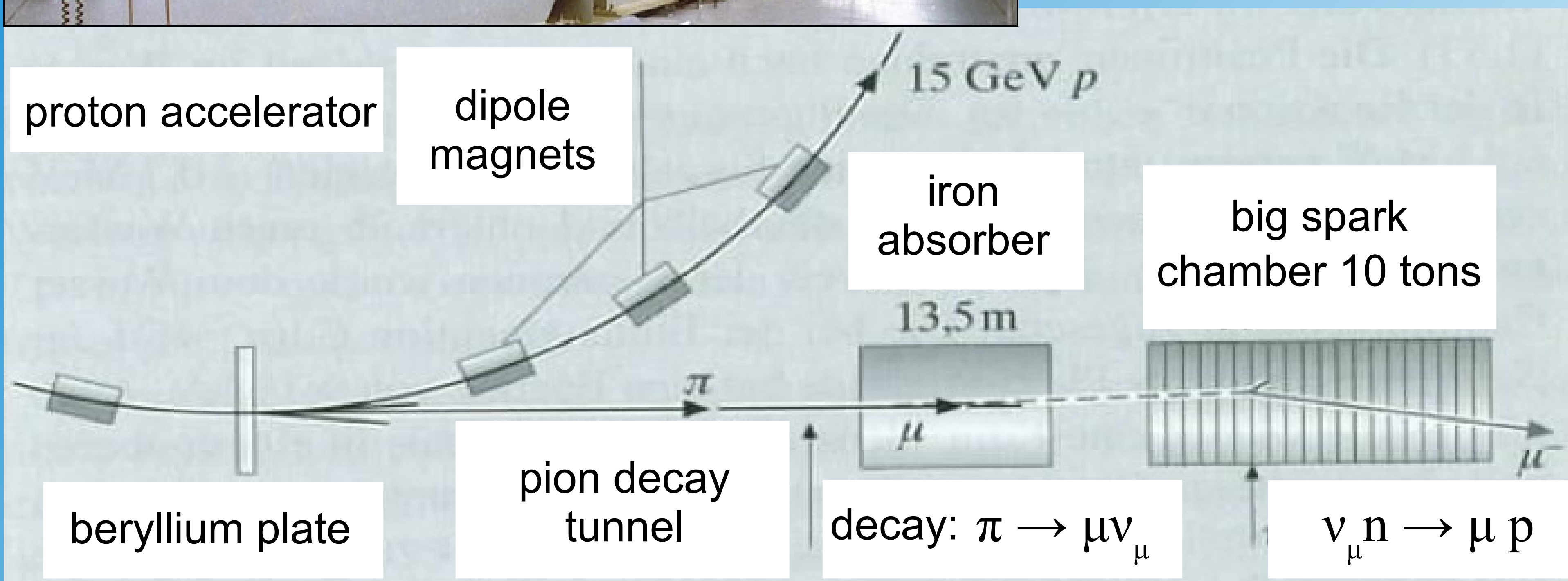
Discovery of the electron neutrino (Cowan, **Reines**, 1957)

→ Nobel Prize (1995)

Anti-Electron-Neutrino



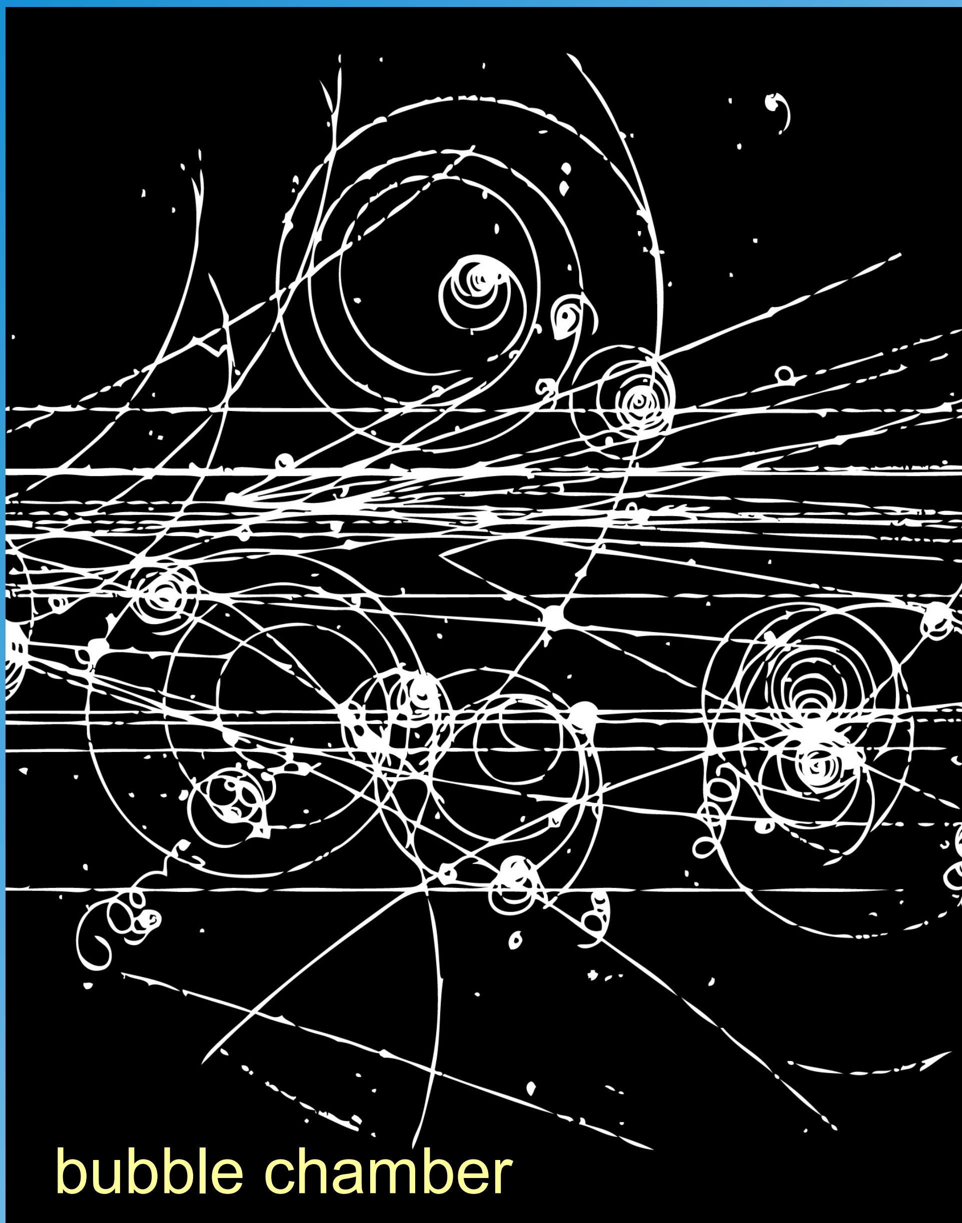
Existence of Muon-Neutrinos

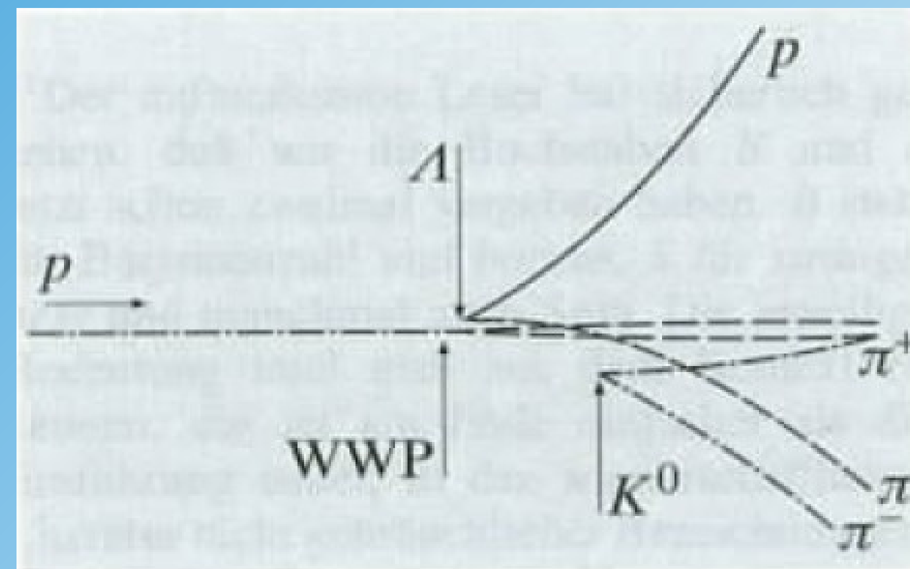


Discovery of the **muon neutrino** (**Ledermann, Schwartz, Steinberger** 1962)

→ Nobel Prize (1988)

Discovery of Strangeness
Surprise!





“V-particles”

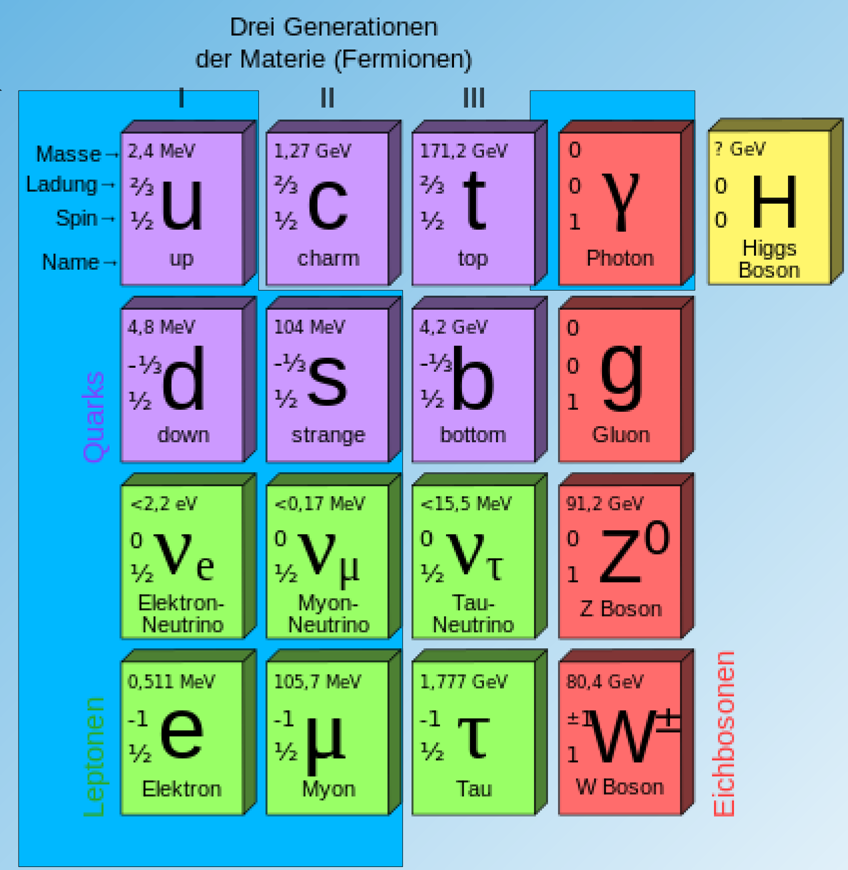
Production of **Kaons** and **Lambda**-Baryons in pp Collisions

Long Lifetime!
neither electromagnetic nor strong force

(1950ties)

Status in 1962
(50 years after Hess' balloon trip)

known fermions



M. Gell-Mann and G. Zweig
hypothised existence of quarks:

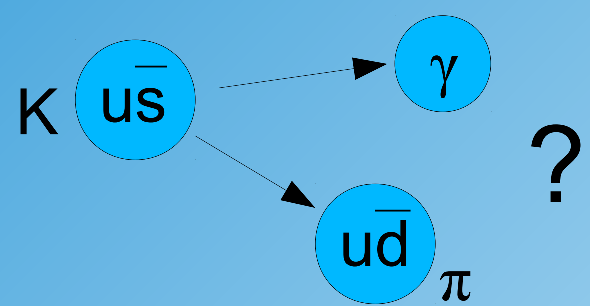
- up-quark
- down-quark
- strange-quark

in the year 1964 → Nobel Prize (1969)

Prediction of the Charm Quark

How explain non-observation of Flavor Changing Neutral Currents?

$$K \not\rightarrow \pi\,\gamma$$



Such a **flavor changing** decay is forbidden if a **fourth quark** exists
(Glashow, Iliopoulos, Maiani)

prediction

Note: Kaon and Pion have similar quantum numbers!

Observation of the Charm Quark

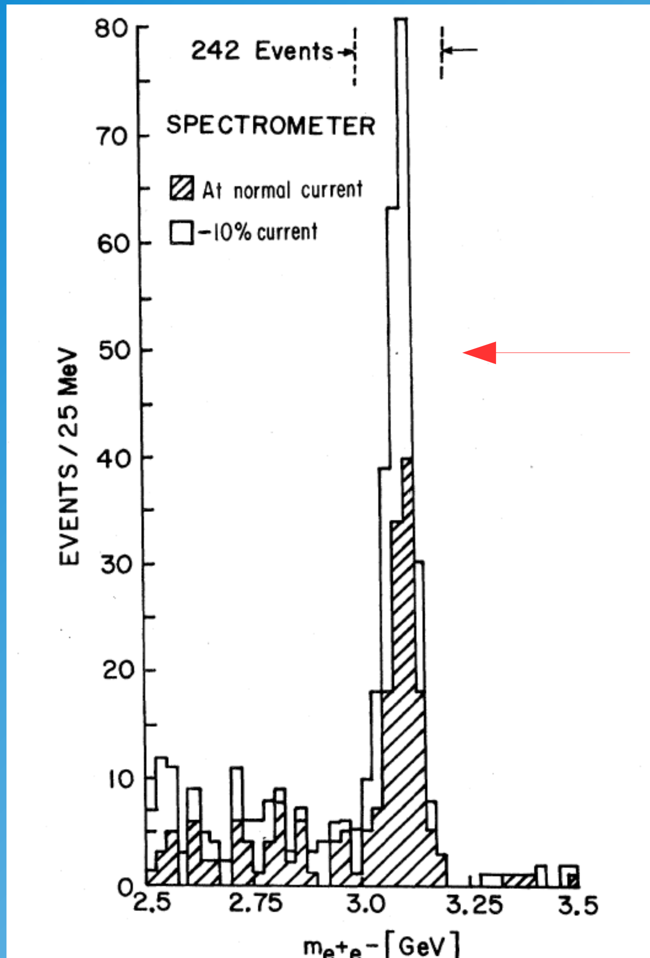


FIG. 2. Mass spectrum showing the existence of J. Results from two spectrometer settings are plotted showing that the peak is independent of spectrometer currents. The run at reduced current was taken two months later than the normal run.

$c\bar{c}$
resonance

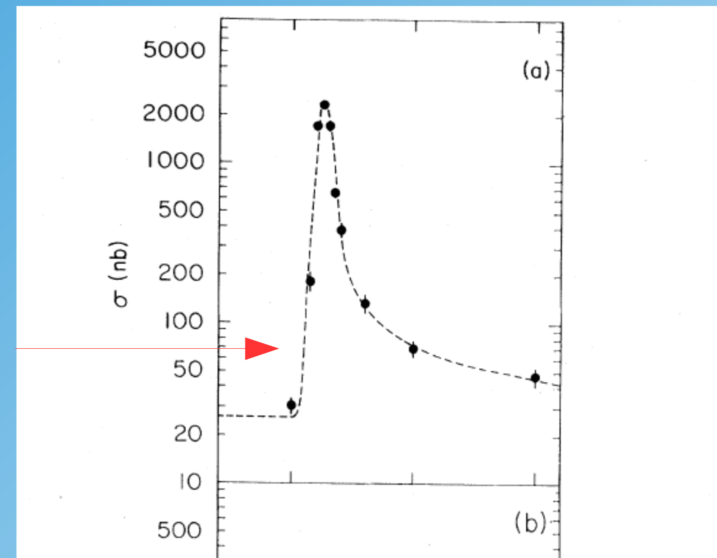


FIG. 1. Cross section versus energy for (a) multi-hadron final states, (b) e^+e^- final states, and (c) $\mu^+\mu^-$, $\pi^+\pi^-$, and K^+K^- final states. The curve in (a) is the expected shape of a δ-function resonance folded with the Gaussian energy spread of the beams and including radiative processes.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

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

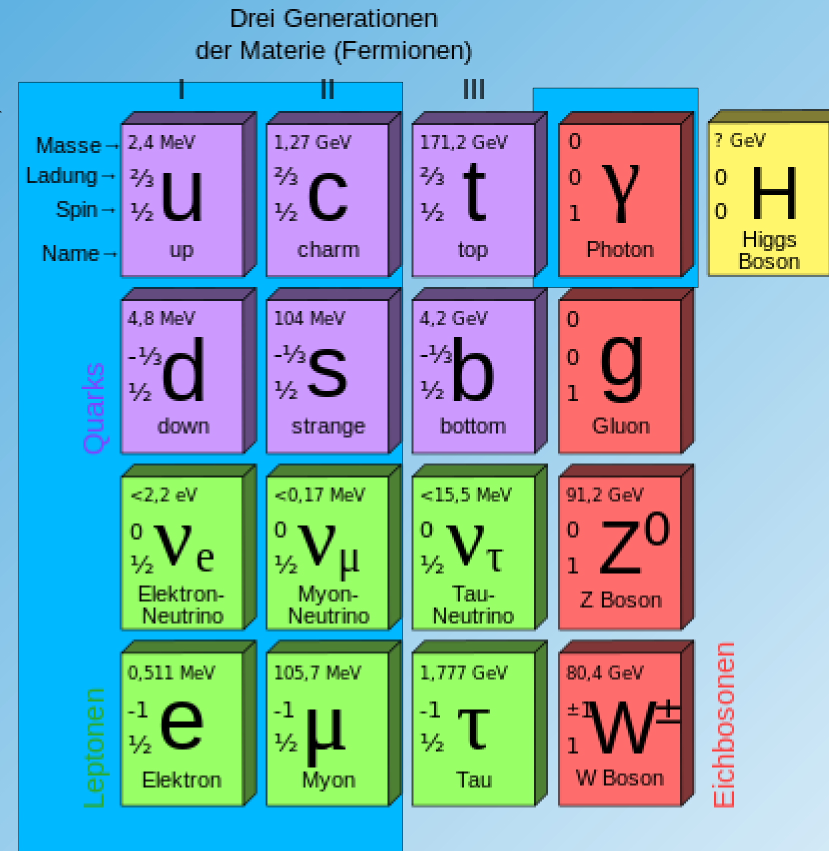
BNL: S.**Ting** et al. (1974)

→ Nobel Prizes 1976

Status in 1975

known fermions

no anti-matter in universe !



Charge and Parity Conservation must be broken!
(2nd A.Sakharovs condition)

→ **third quark family** could explain matter-antimatter asymmetry

Nambu, Kobayashi, Maskawa → Nobel Prize 2008

Note: particle physics and evolution of universe are closely related!

Discovery of the Third Family

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

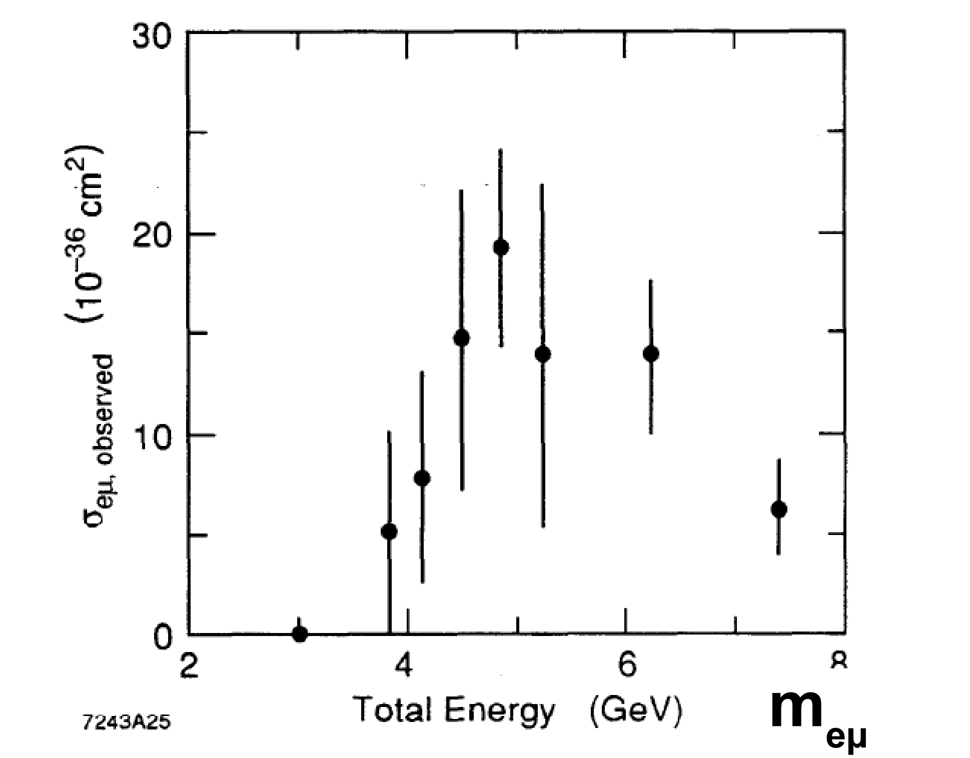


Fig. 4. From Perl *et al.* (1975): the observed cross section for the signature $e\mu$ events from the Mark I experiment at SPEAR. This observed cross section is not corrected for acceptance. There are 86 events with a calculated background of 22 events.

$$e^+ e^- \rightarrow \tau^+ \tau^-$$

$$\tau \rightarrow e \nu \nu$$
$$\tau \rightarrow \mu \nu \nu$$

discovery of tau-lepton

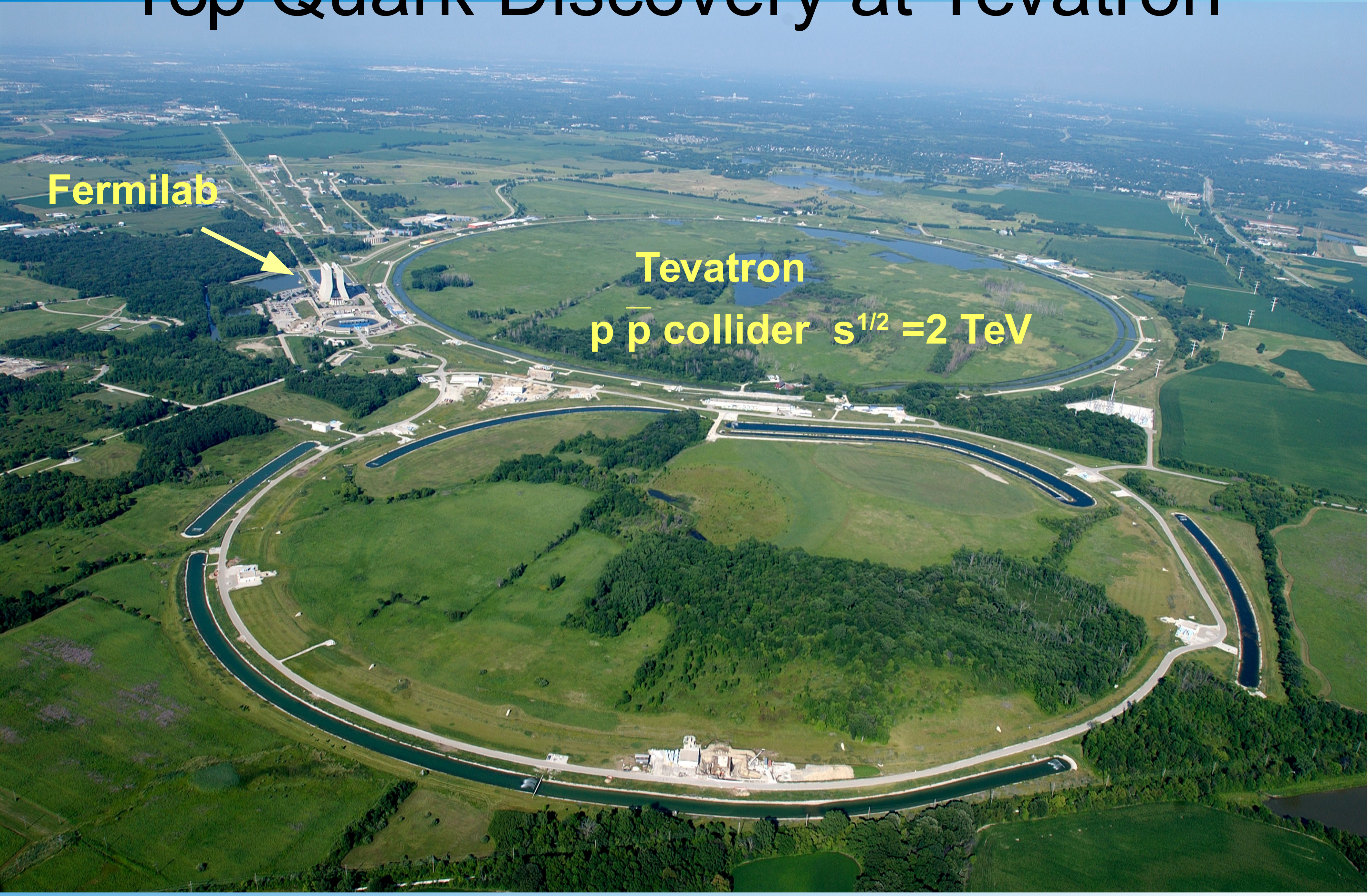
(Reines et al., M.Perl)

➜ Nobel Prize (1995)

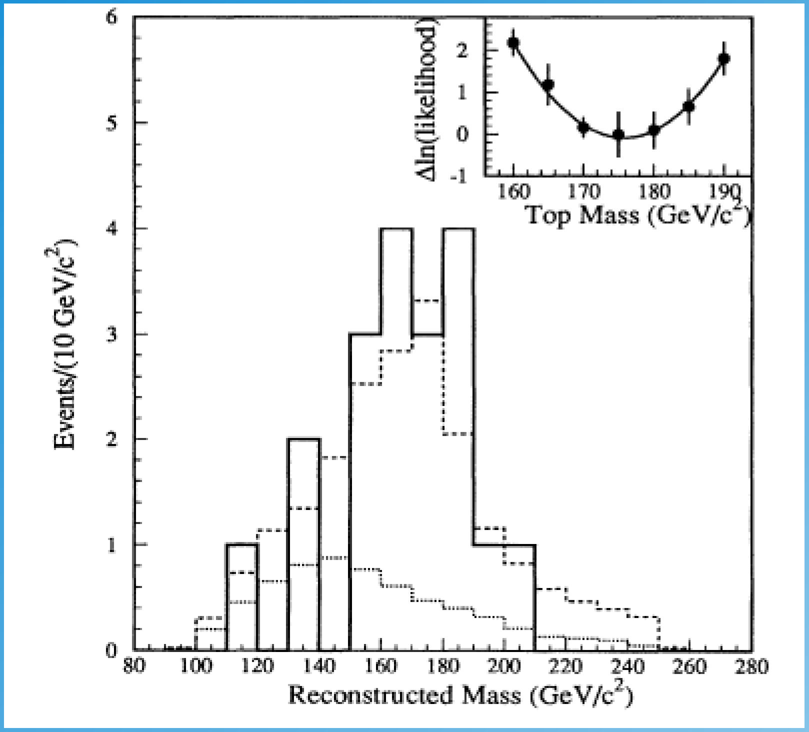
m_τ=1.777 GeV

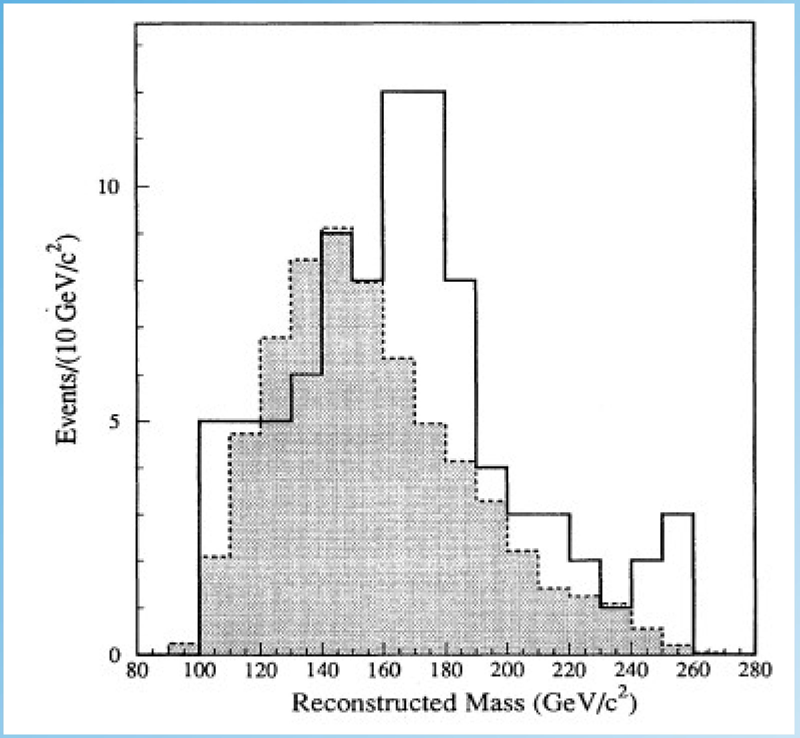
- Discovery of the Bottom-Quark (1977) by M.Ledermann et al. at Fermilab ➜ Nobel Prize (1988)

Top Quark Discovery at Tevatron



Top Quark Discovery in 1995





CDF Collaboration

D0 Collaboration

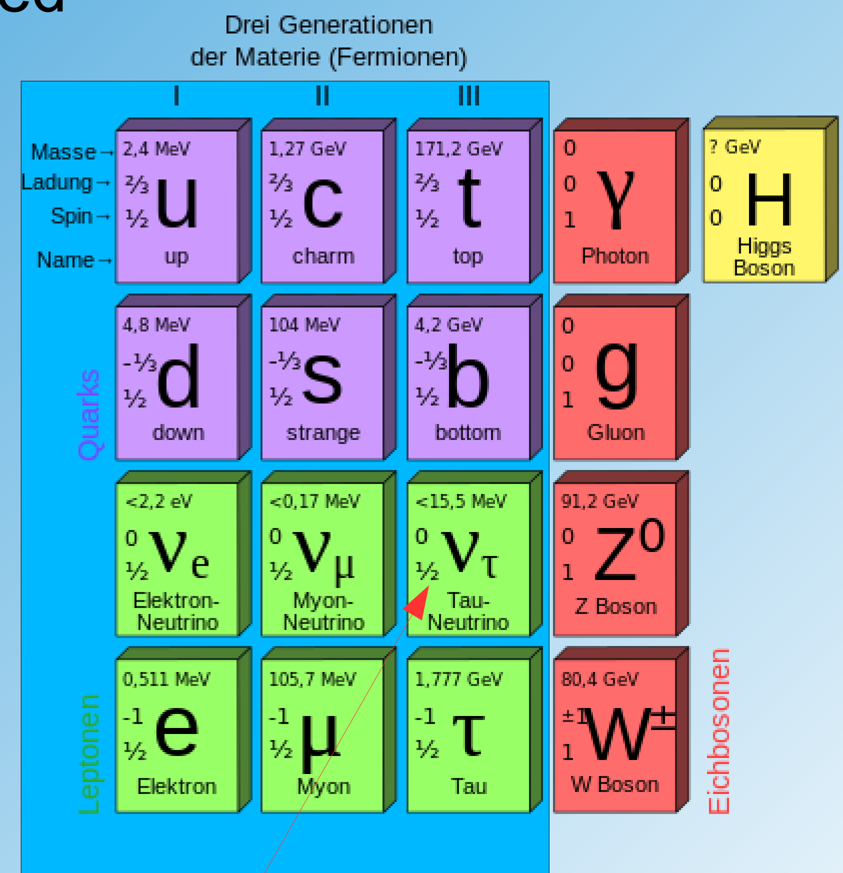
Top-quark mass ~175 GeV

Top production: $p\bar{p} \rightarrow t\bar{t}\,X$

Top decay: $\mathbf{t \rightarrow W\,b}$ and $W \rightarrow q\bar{q}$ or $l\nu$

Status in 2000
(~90 years after Hess balloon trip)

all fermions discovered



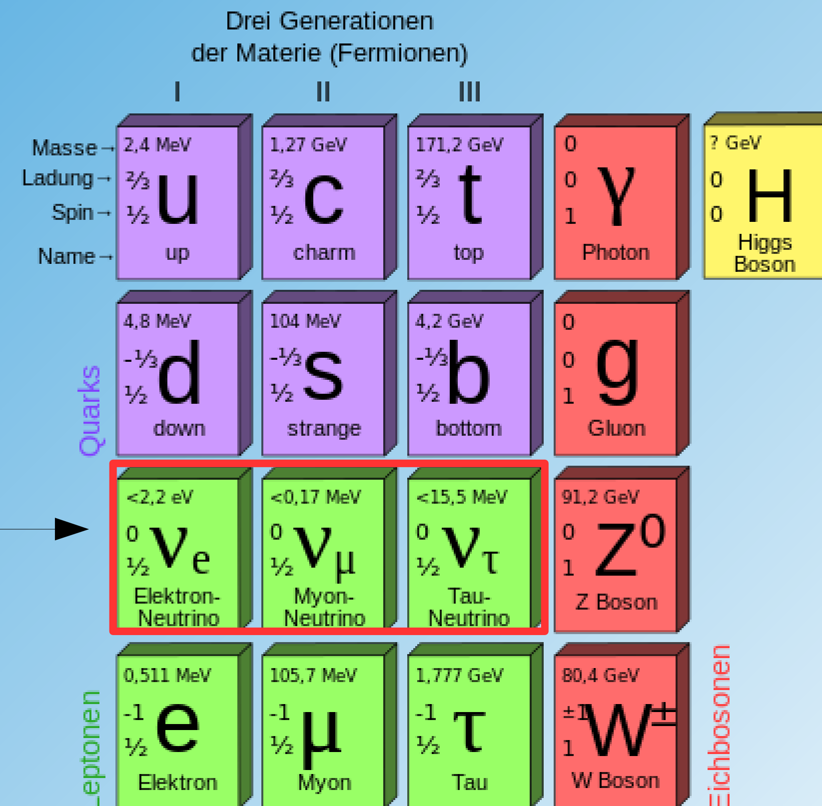
tau neutrino discovered
in 2000 by Donut experiment

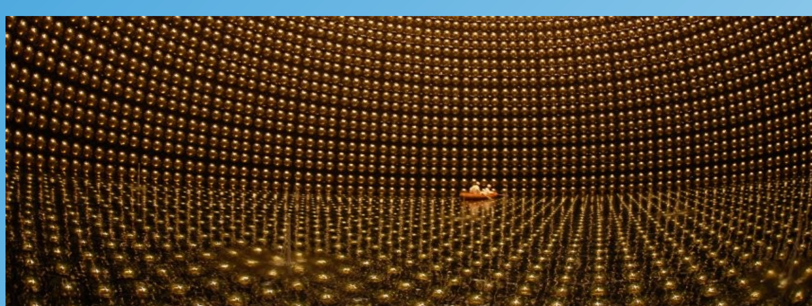
Status in 2002
(90 years after Hess' balloon trip)

Nobel Prize 2015

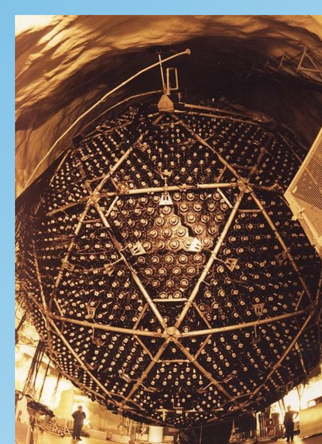
Takaaki Kajita + Arthur B. McDonald

neutrinos have mass!





Super-kamiokande (1998)



SNO experiment (2001/2)

Discovery of Vector Bosons

<u>Photons:</u>

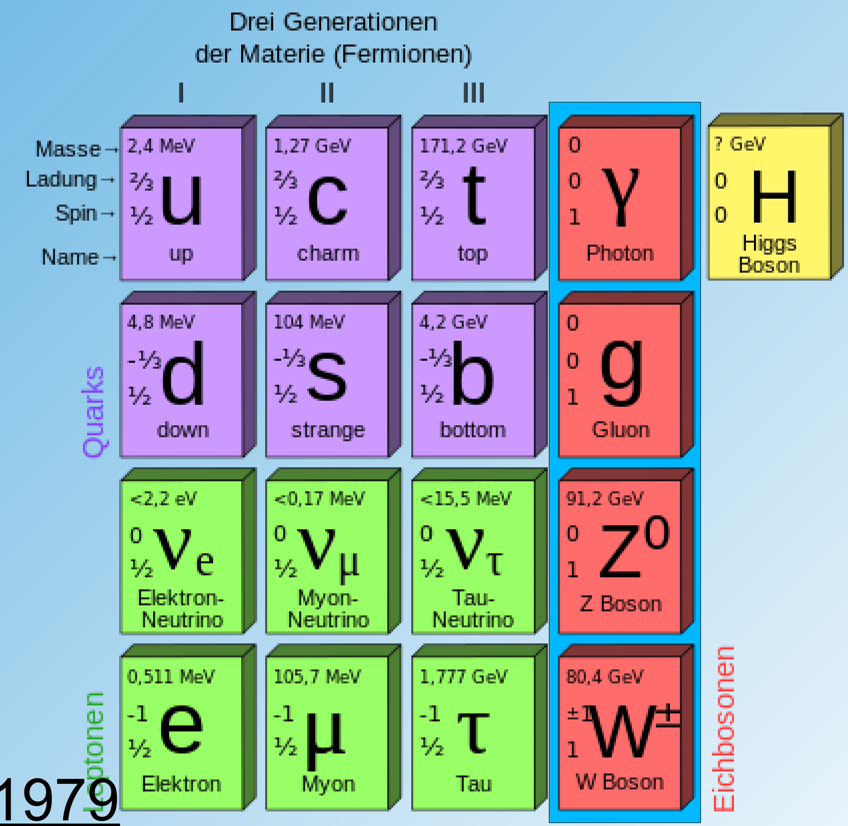
- X-rays (Röntgen 1995) → <u>Nobel Prize</u> 1901
- photo-electric effect (Einstein 1905) → <u>Nobel Prize</u> 1921

<u>Gluons:</u>

- carriers of strong force
- predicted by Gell-Mann *et al.*
- experimentally discovered as jets of hadrons e.g. at PETRA

<u>$W^{\pm}$ bosons:</u>

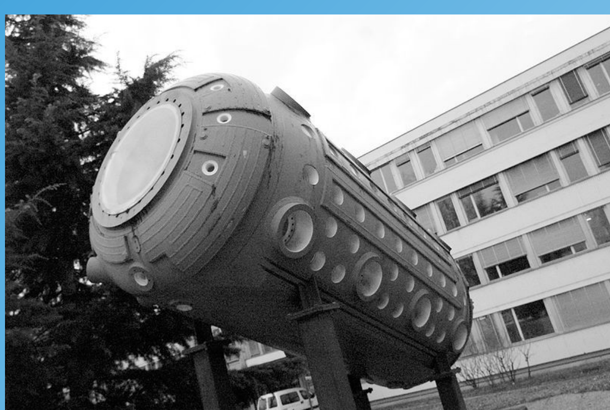
- carriers of weak interactions
- responsible for weak decays.
- building blocks of “Standard Model” Glashow, Salam, Weinberg → <u>Nobel Prize 1979</u>
- W-boson discovered at CERN $Sp\bar{p}S$ in 1983 C.Rubbia and S. van d. Meer → <u>Nobel Prize 1984</u>

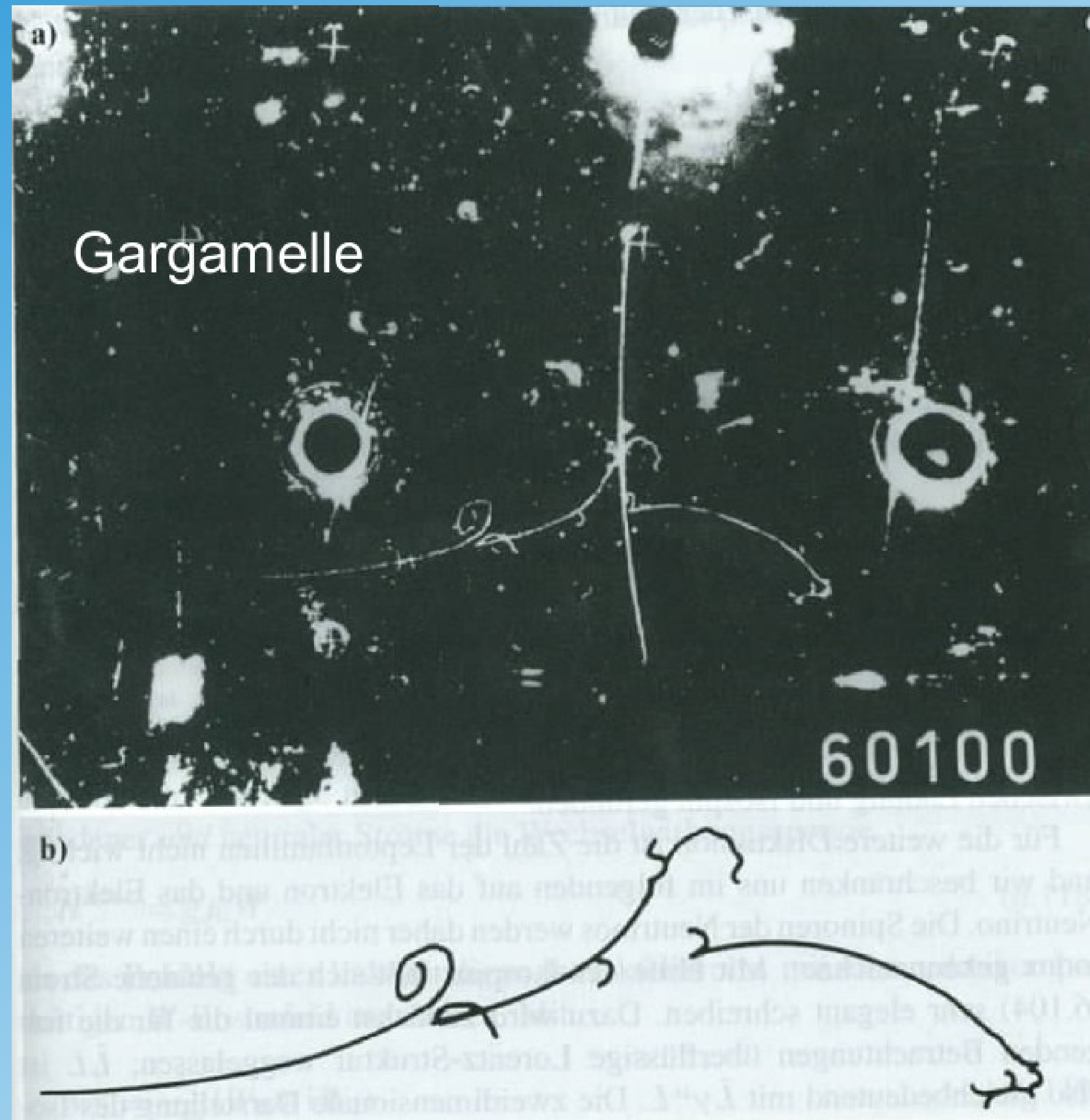


Observation of Neutral Currents

Bubble Chamber
Gargamelle (1974)

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





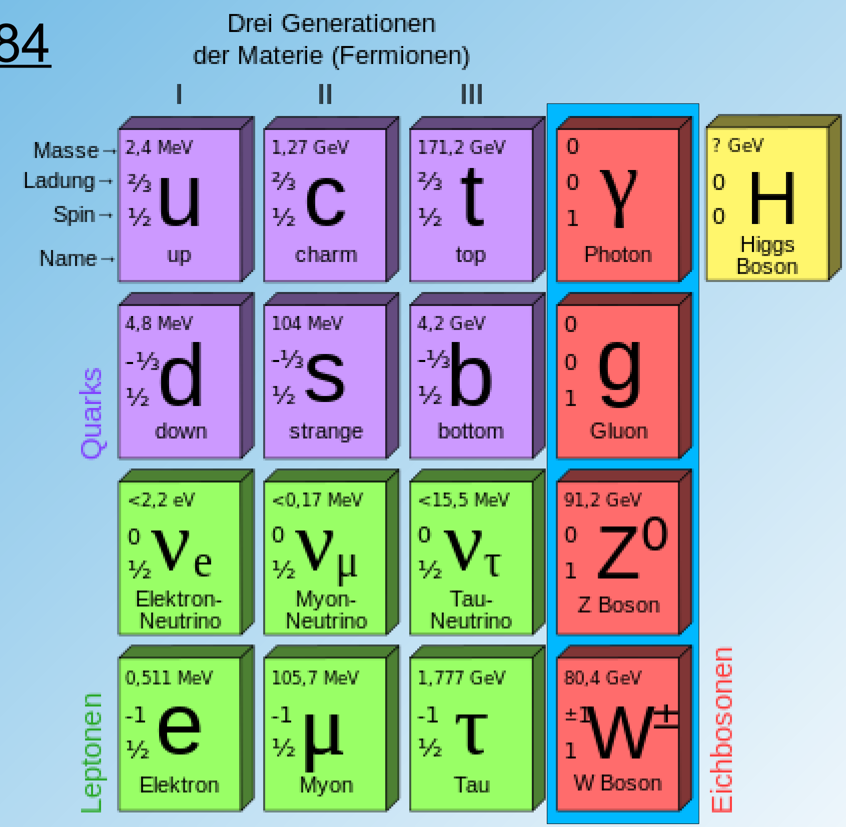
Discovery of Vector Bosons

<u>Z bosons:</u>

- indirectly observed at Gargamelle
- discovered at at CERN $Sp\bar{p}S$ in 1983

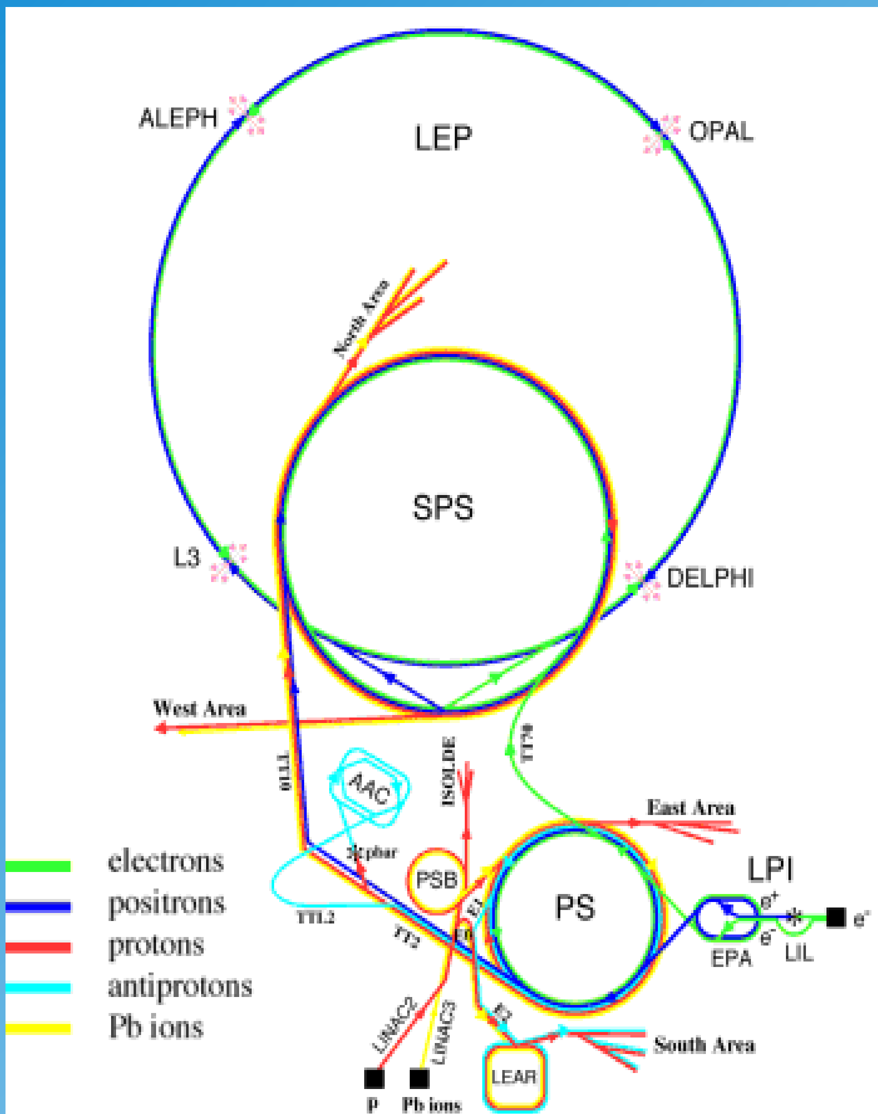
  C.Rubbia and S. van d. Meer → <u>Nobel Prize 1984</u>
- precision studies at LEP accelerator

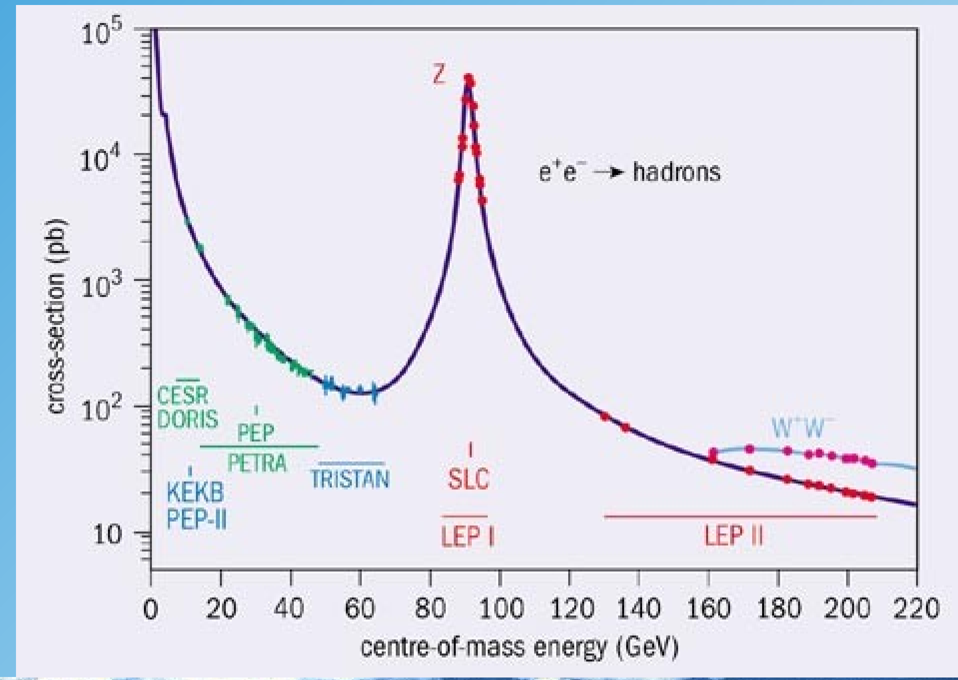
Large Electron Positron (LEP) Collider



Large Electron-Positron Collider CERN

1989-2000 $s^{1/2}$=90-200 GeV





26.7 km circumference

Four experiments:

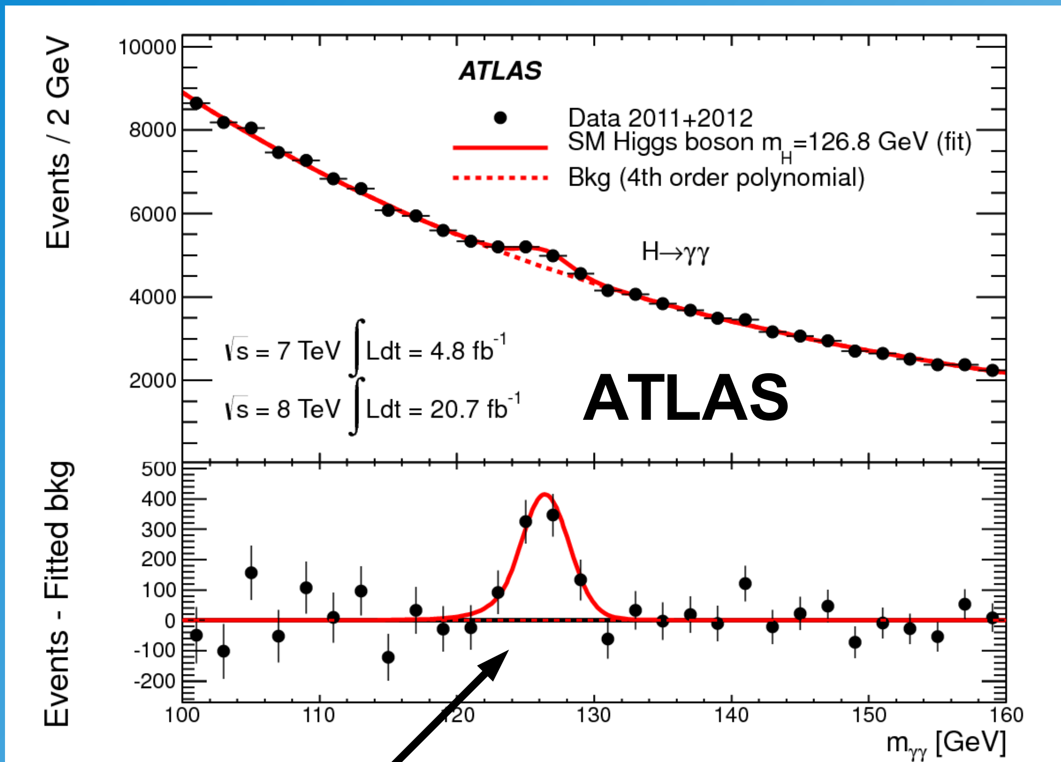
- **ALEPH**
- **DELPHI**
- **L3**
- **OPAL**

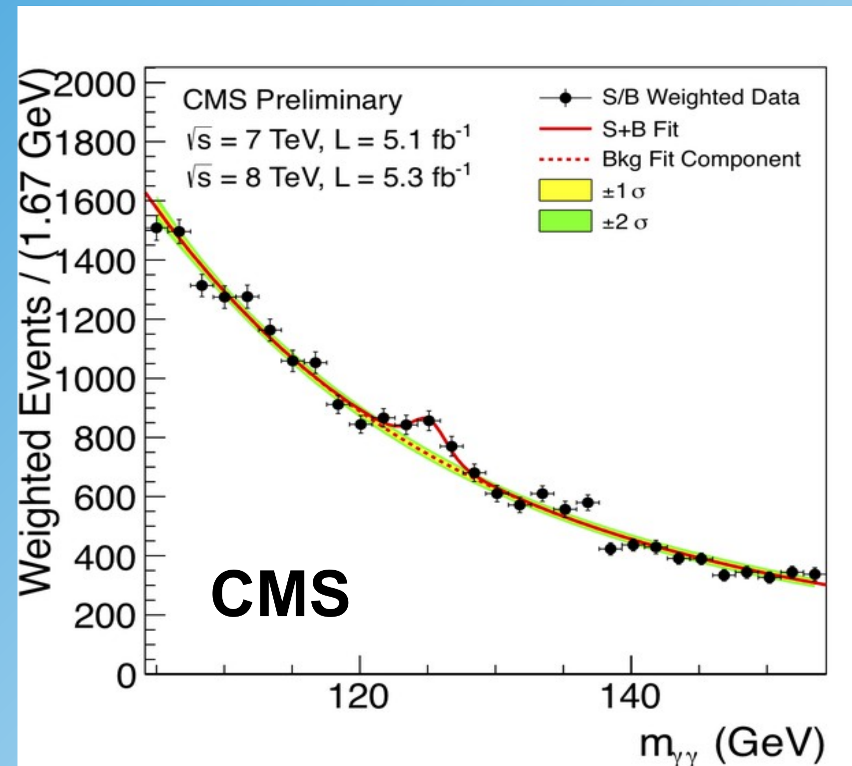
Large Hadron Collider (CERN)

LHC (pp) $s^{1/2} <= 14$ TeV

26.7 km circumference!

The Higgs Boson

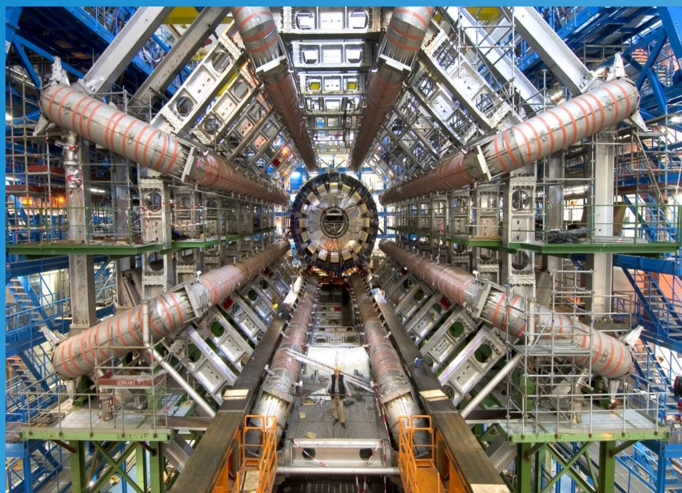




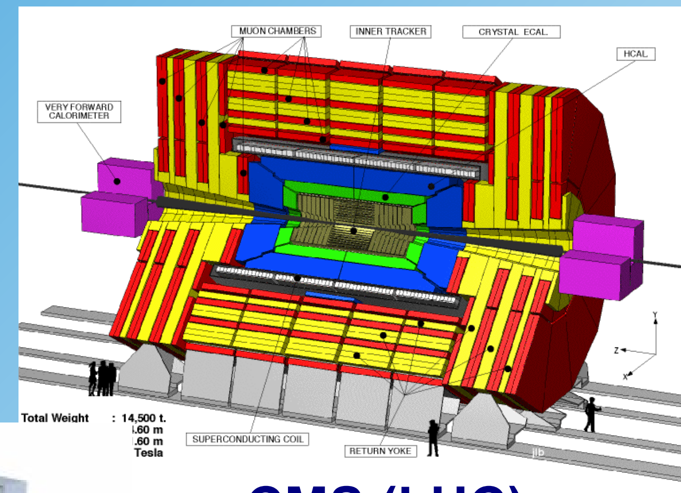
m_H=125 GeV

Nobel Prize 2013
- F.Englert
- P.Higgs

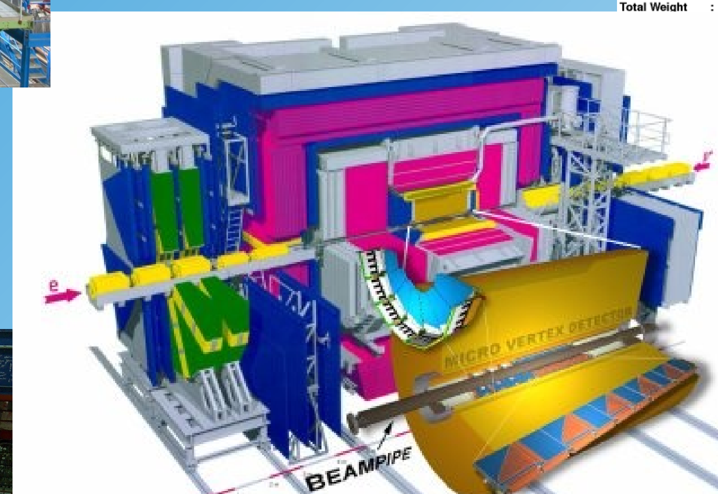
Experimental Tools



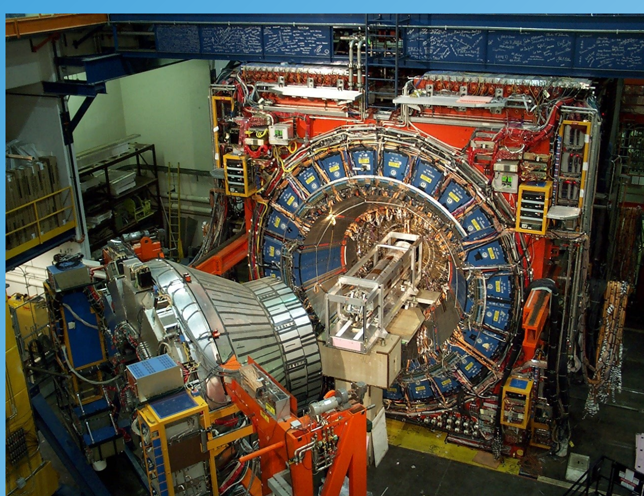
ATLAS (LHC)



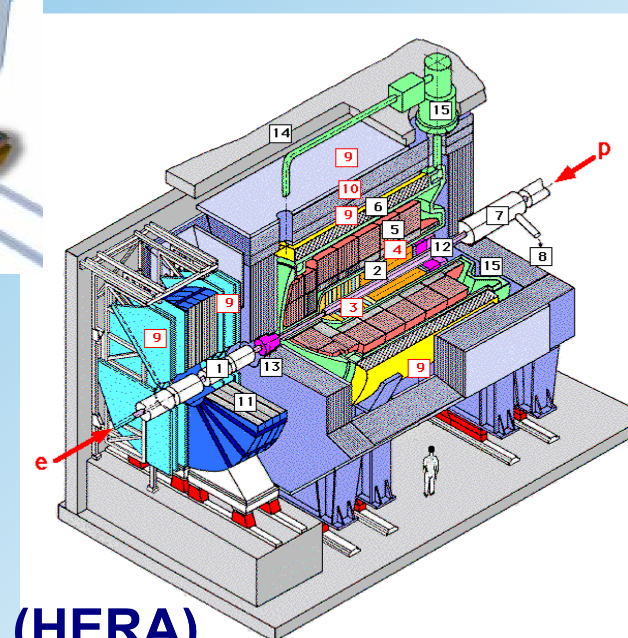
CMS (LHC)



ZEUS (HERA)

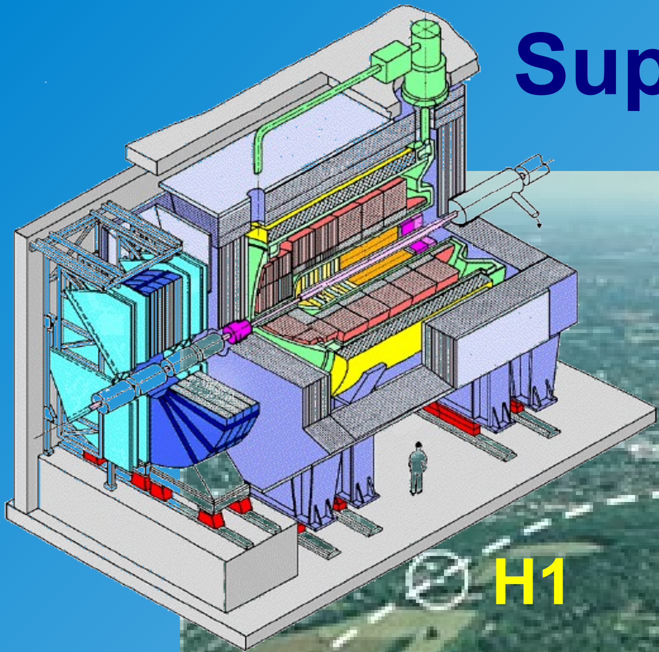


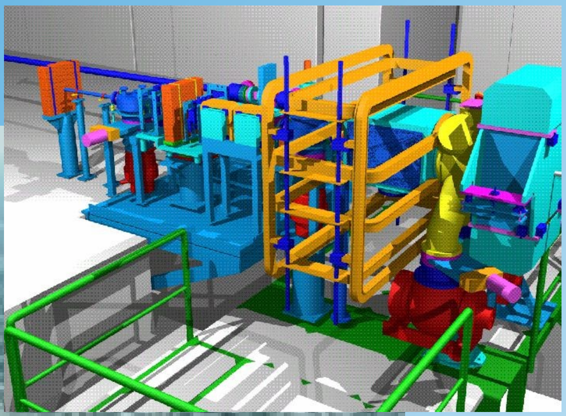
CDF (Tevatron)



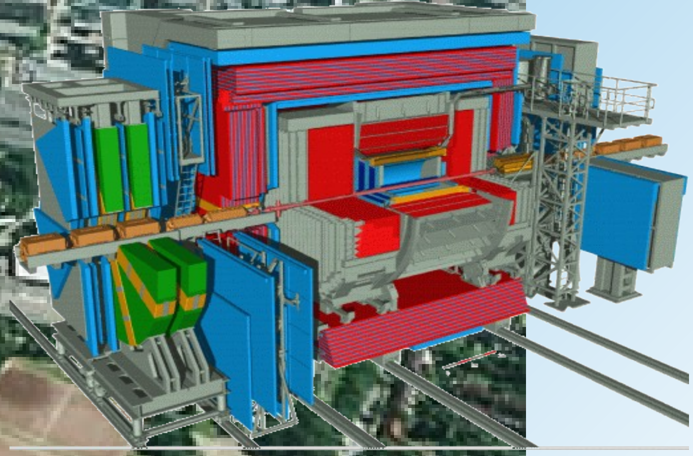
H1 (HERA)

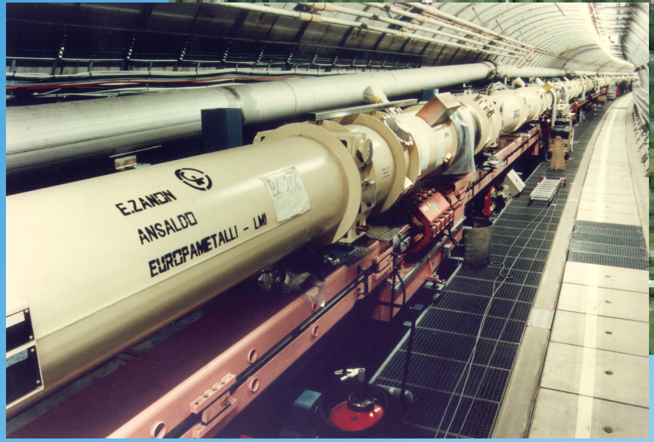
Supermikroskop HERA





920 GeV Protonen
x
26.7 GeV Elektronen

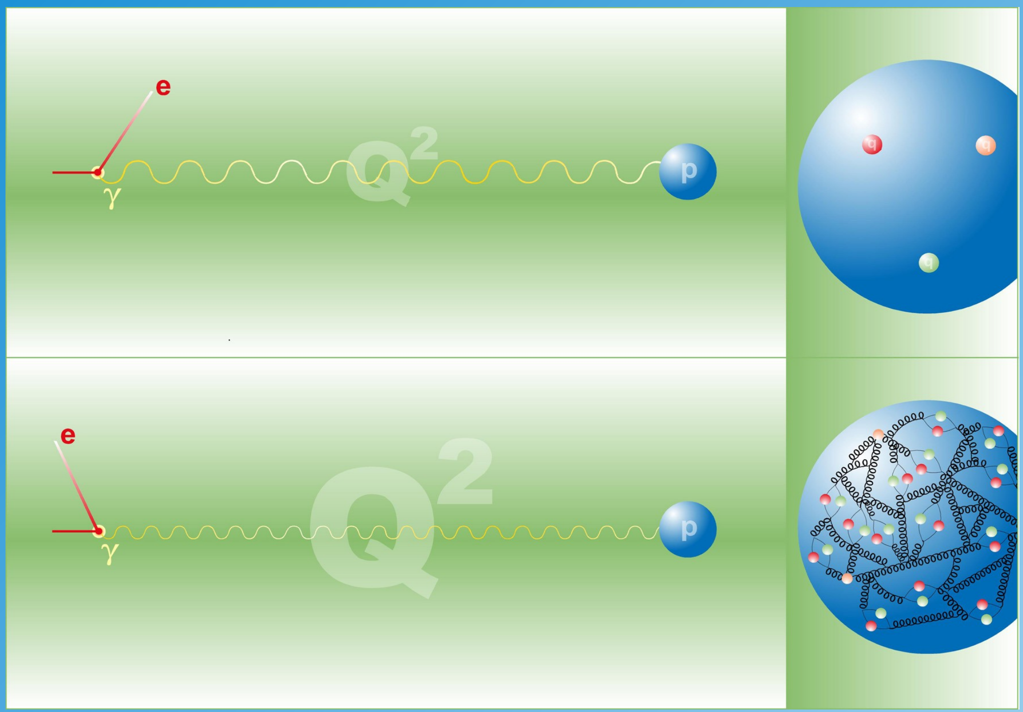


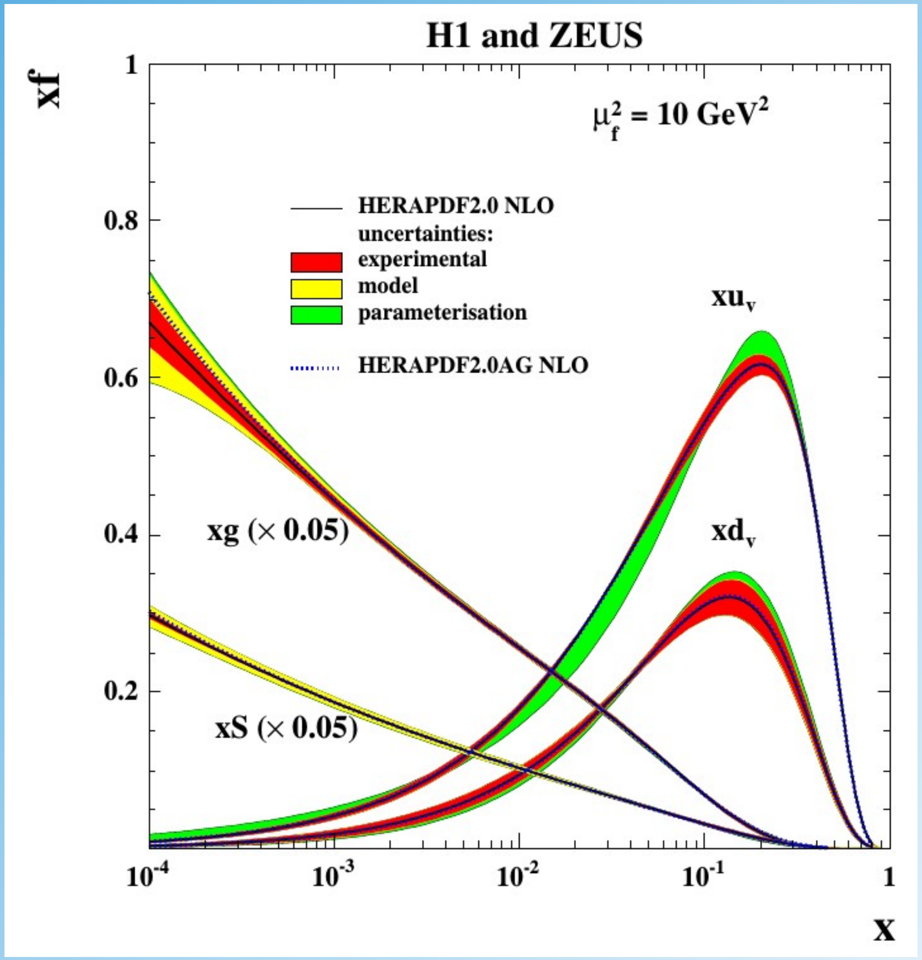


(1992-2007 Hamburg)

Study of the Proton Structure

Recent results on proton structure



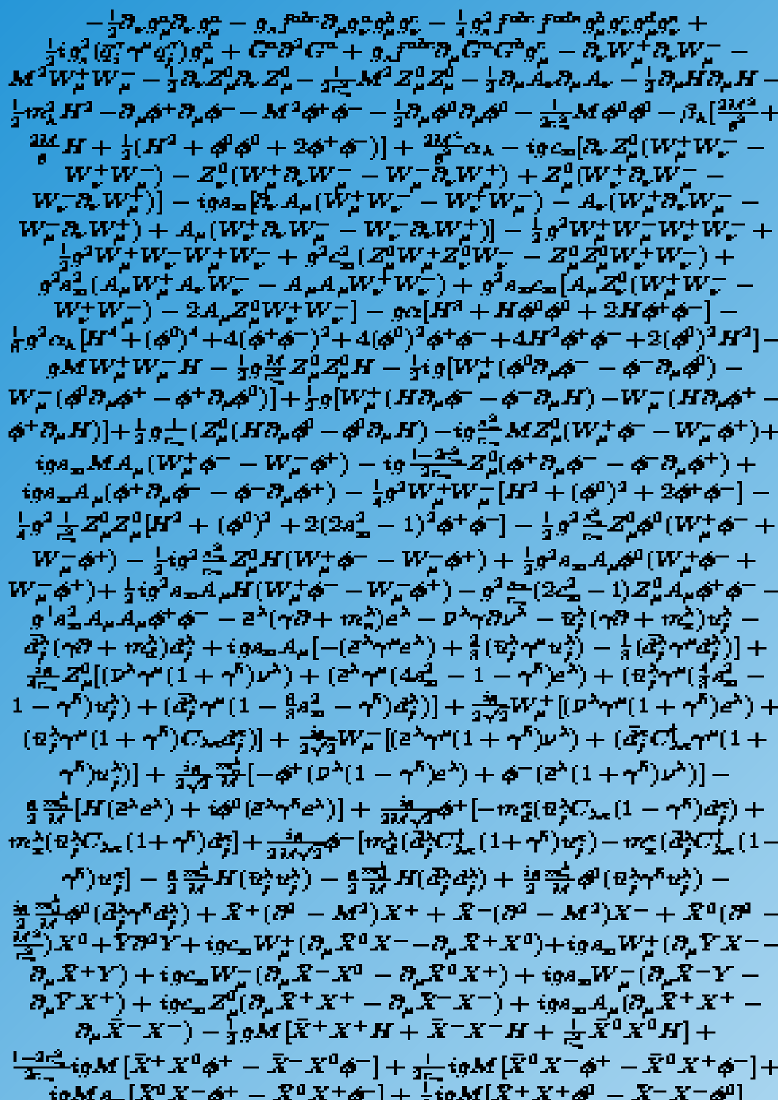


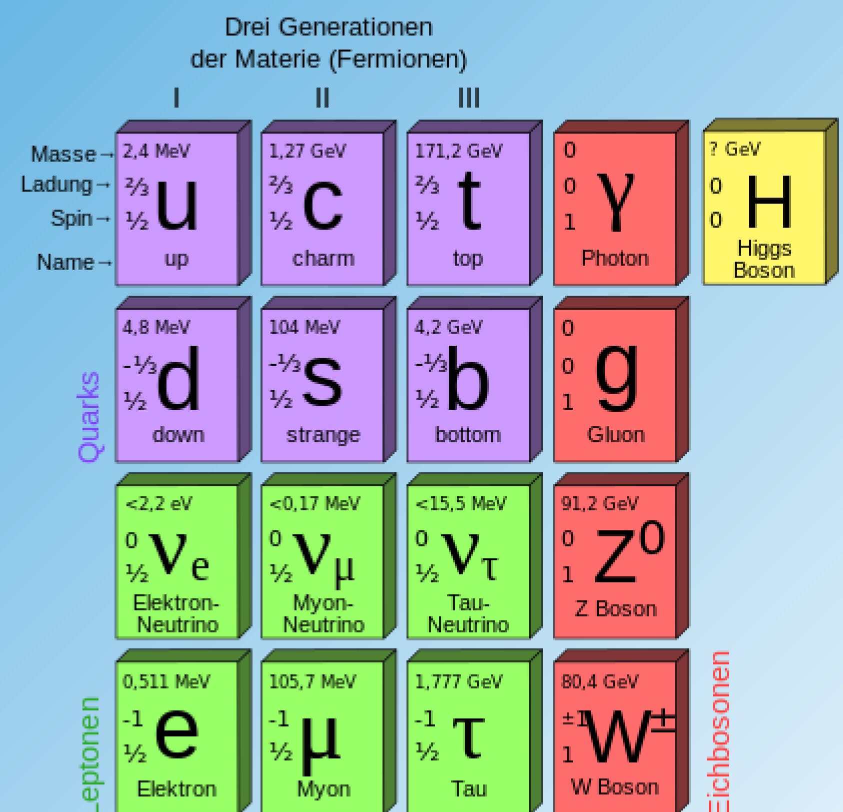
H1 + ZEUS experiments (2015)

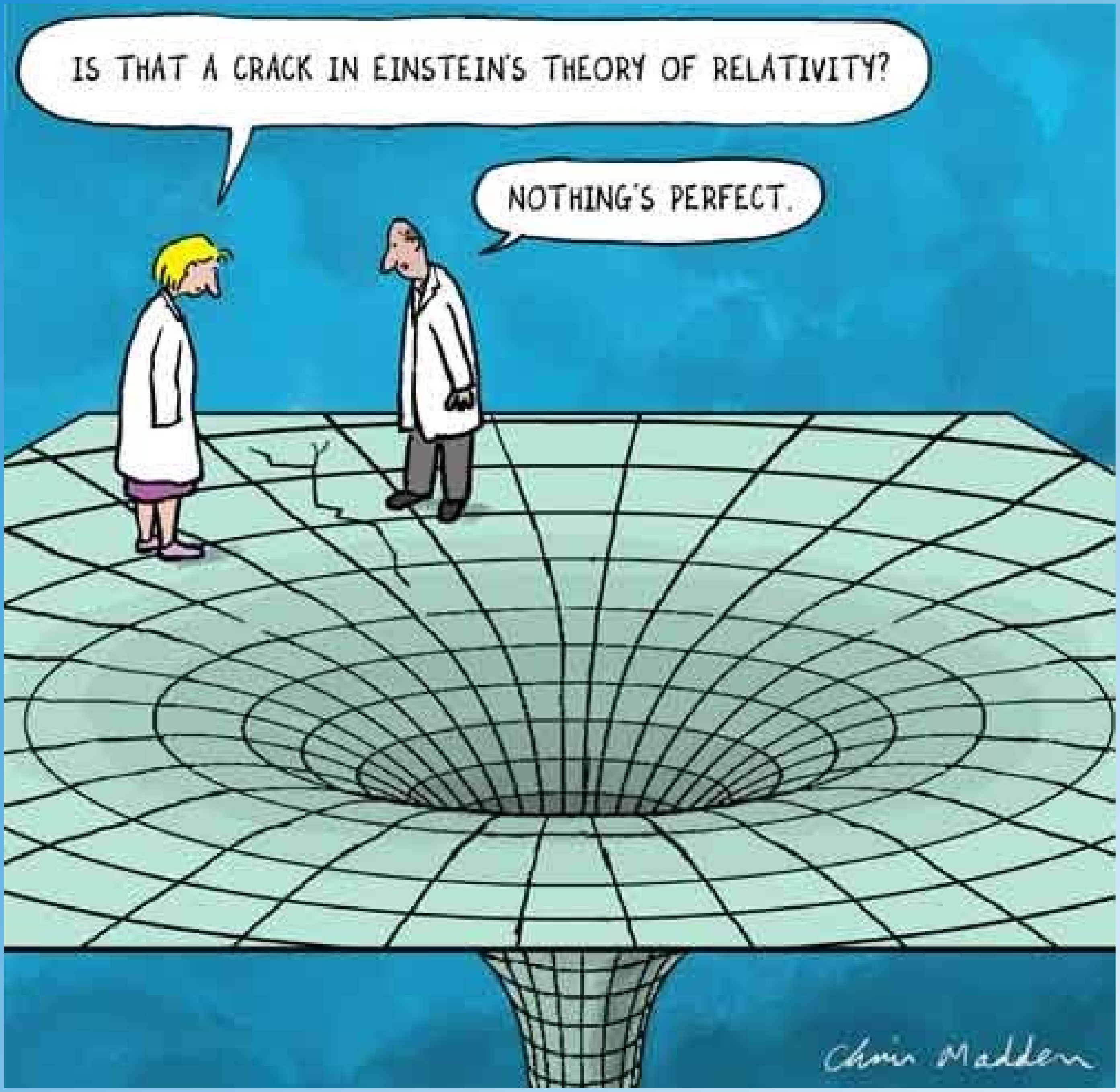
→ very precise determination of the proton structure

→ important for LHC and other (future) experiments

The Standard Model (Theory)

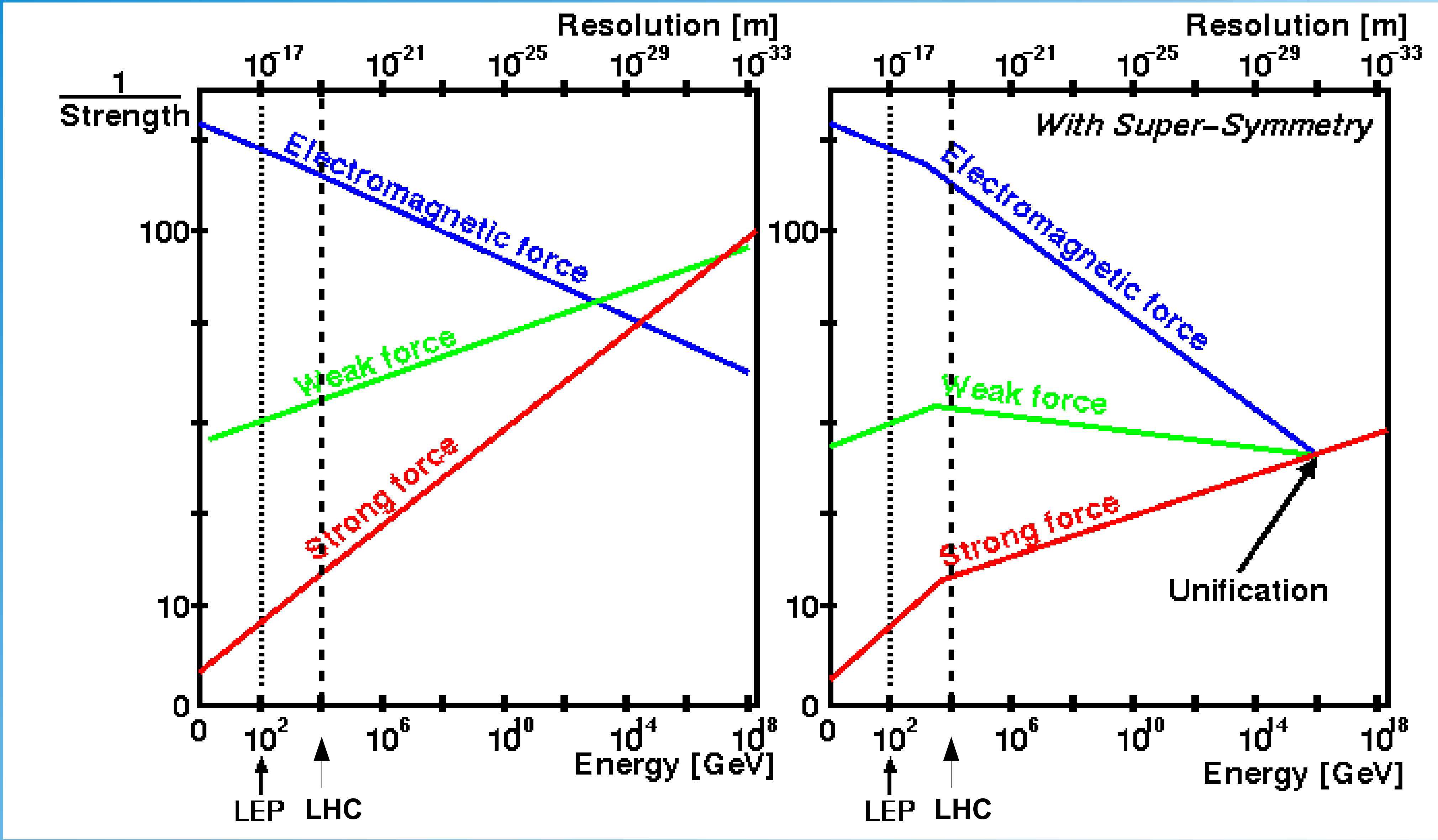




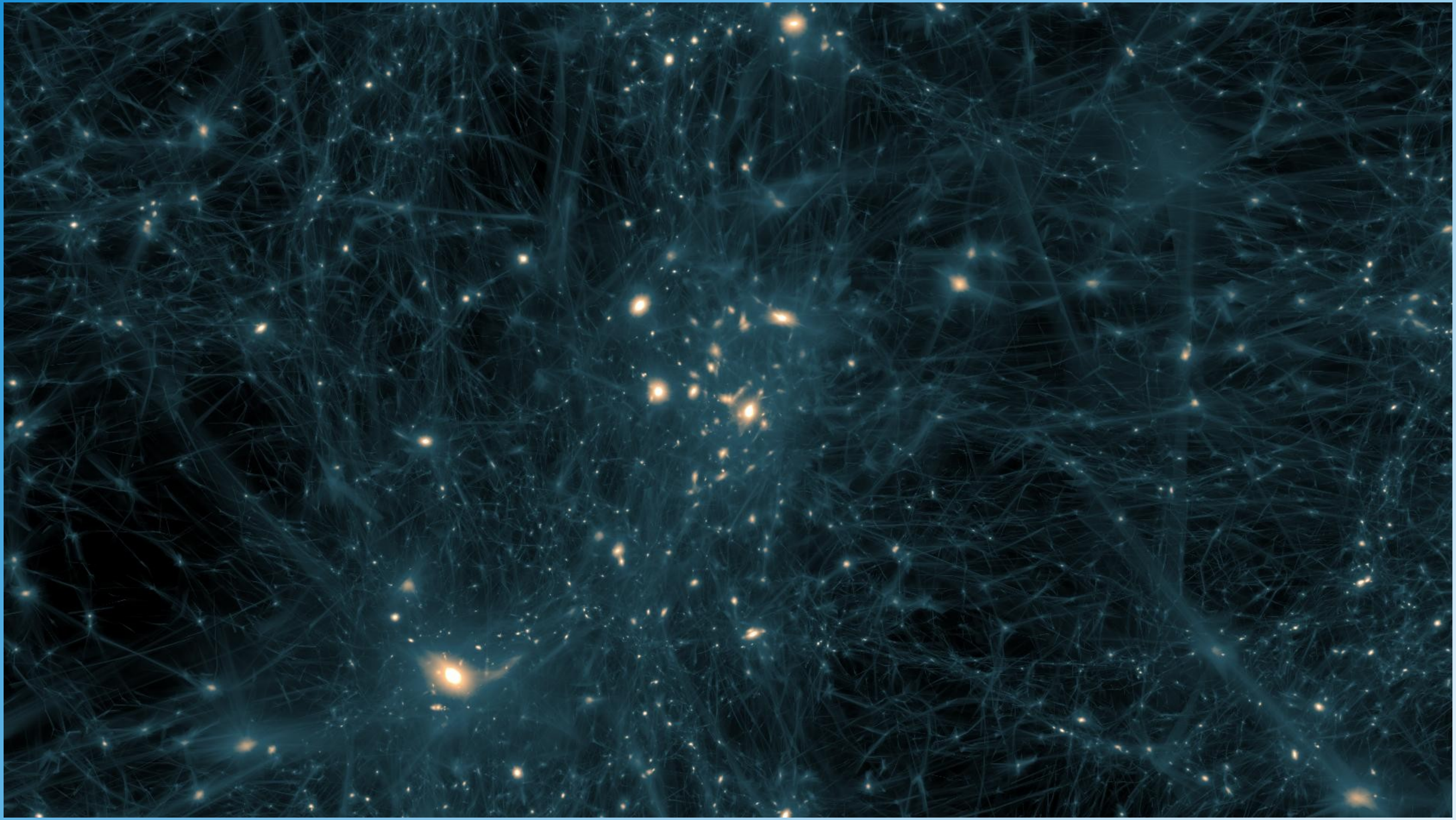

IS THAT A CRACK IN EINSTEIN'S THEORY OF RELATIVITY?
NOTHING'S PERFECT.
Chris Madden

Theoretical Problems of the SM

Grand Unification ???



Dark Matter



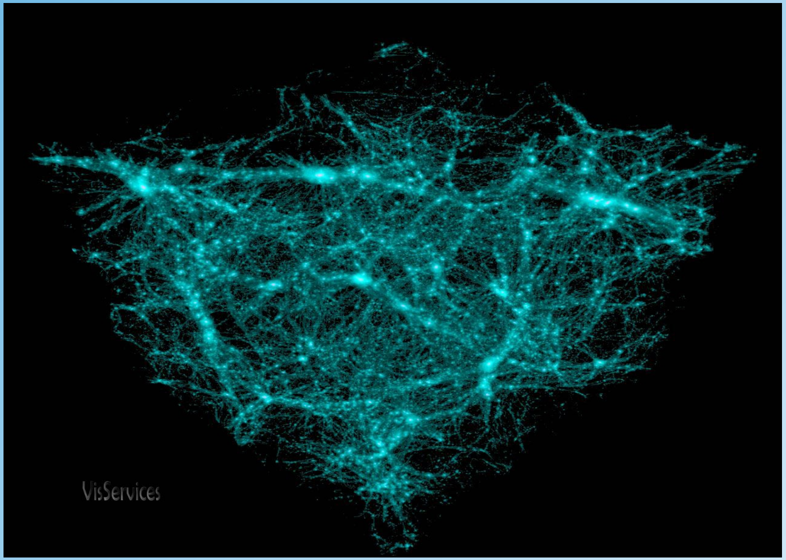
dark matter in filaments between galaxies (simulation)

[R.Kaehler et al. (KIPAC)]

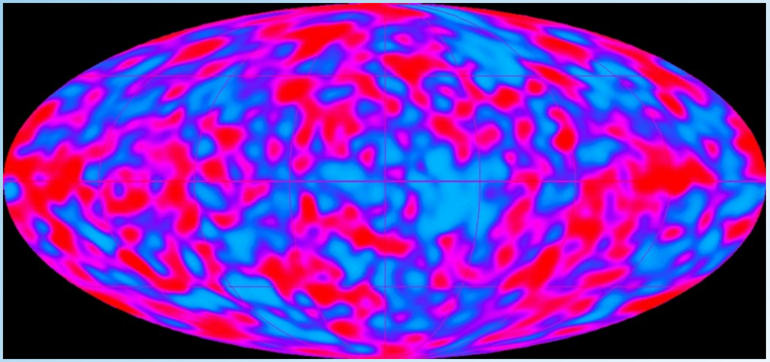
The SM and Astro- Particle Physics

Matter-Antimatter Asymmetry in Universe

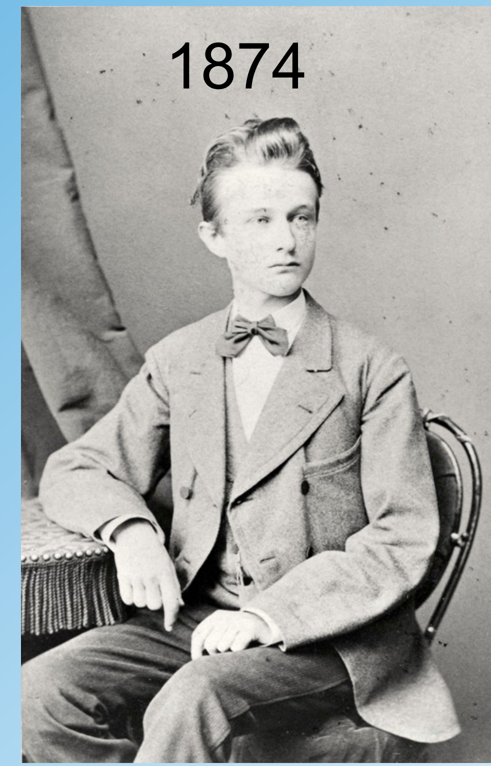
$$\frac{N(B)}{N(\gamma)} \approx 10^{-9}$$



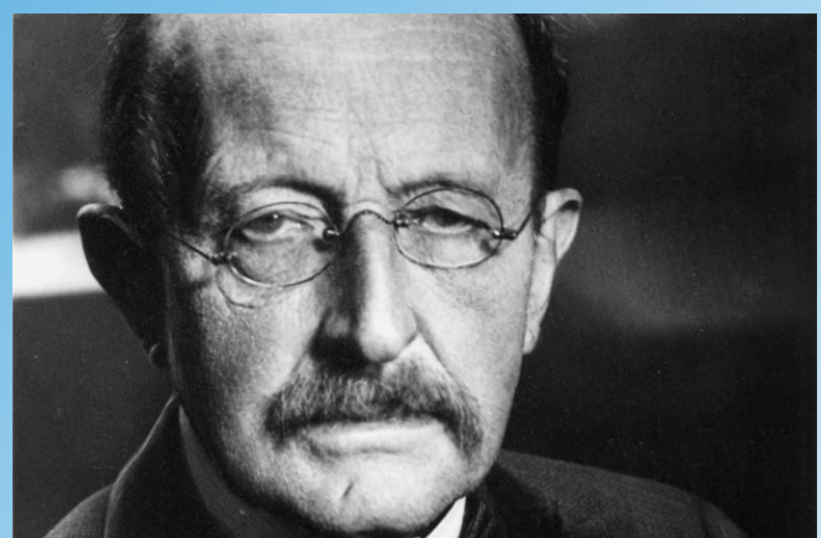
- Dark Matter Problem (only 1% of the mass is visible in the universe)
- Formation of galaxies and structures in the universe
- Dark energy (from microwave back-ground anisotropy)
- Nucleosynthesis constraints
- Big-Bang



"in this field (physics), almost everything is already discovered, and all that remains is to fill a few unimportant holes." (1874)



Philipp von Jolly
(1809 – 1884,
physicist and
mathematician)
Prof. in Heidelberg
and Munich
and Planck's teacher



Max Planck:
1858-1947