Introduction to Particle Physics

Achim Geiser, DESY Hamburg

DESY summer student program,
20.-22.7.21, part I

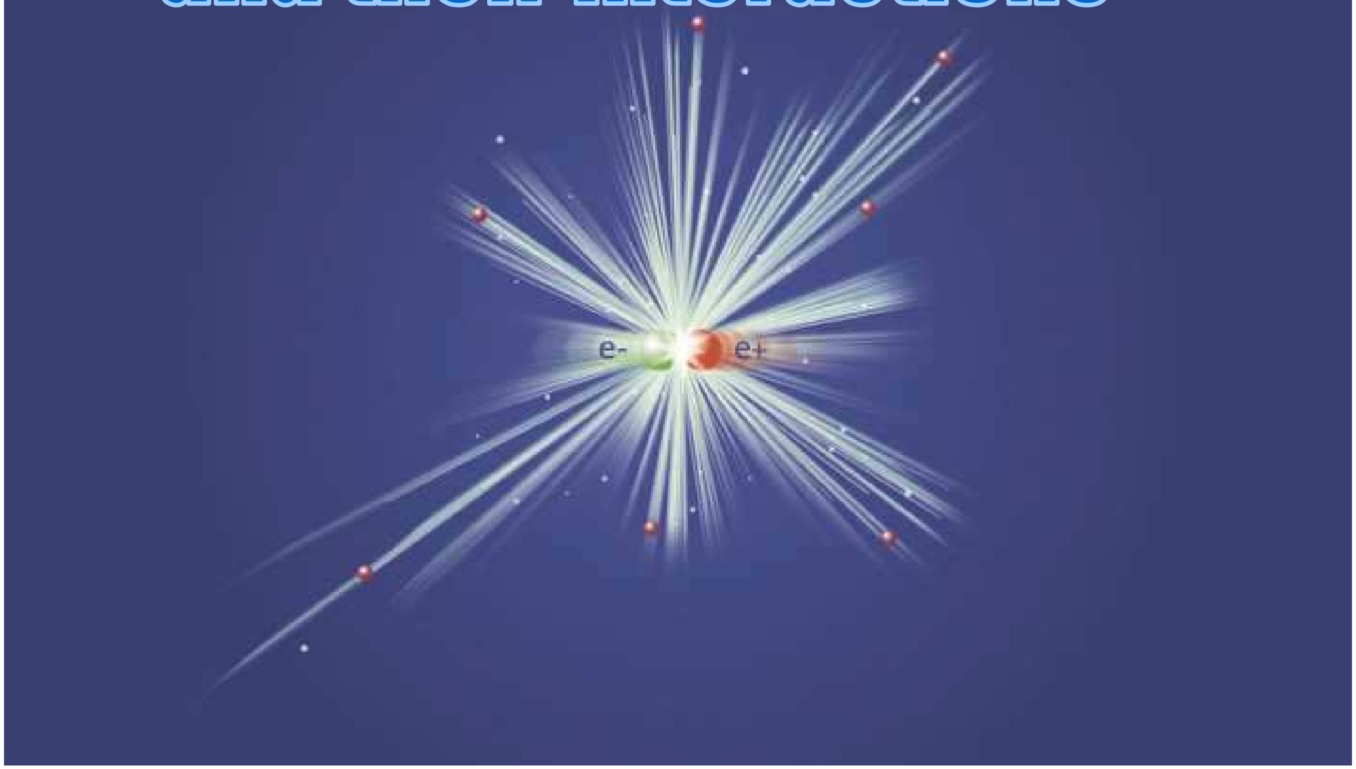
Scope of this lecture:

- **Introduction to particle physics for novices**
  - **rather elementary**
  - **more details -> specialized lectures**
  - **particle physics in general**
  - **some emphasis on DESY-related topics**

thanks to B. Foster for some of the nicest slides/animations
other sources:
www pages of DESY and CERN

What is Particle Physics?

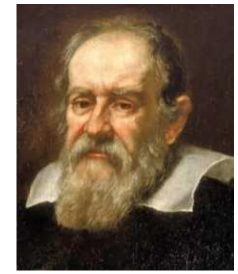
Particle Physics
= science of elementary particles
and their interactions



What is “science”?

Wikipedia.org:

Science (from Latin *scientia*, meaning "knowledge") is a systematic enterprise that builds and organizes knowledge in the form of **testable** explanations and predictions about the universe.



Galileo Galilei

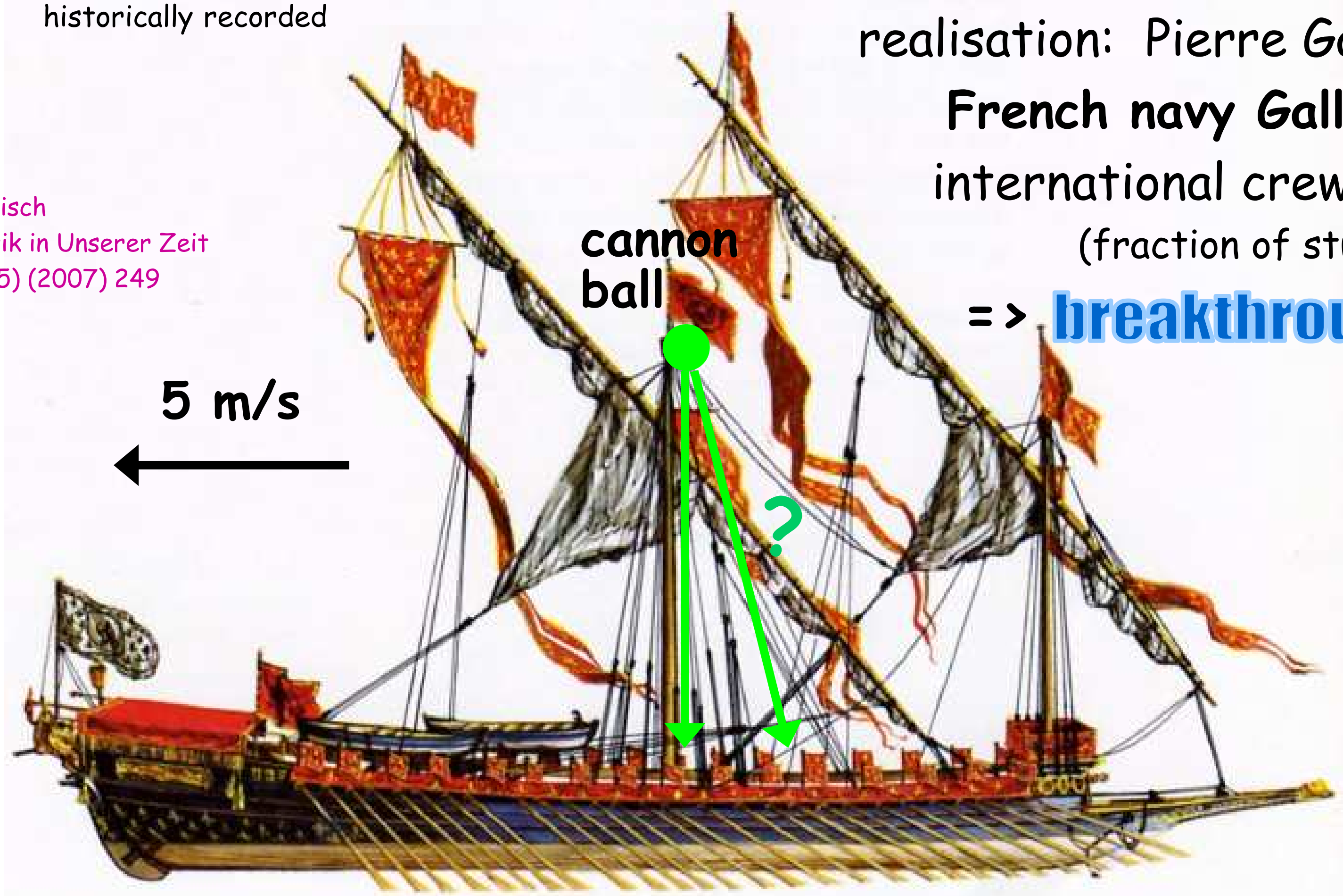
First ^ large scale scientific experiment: proposal: Galilei 1632
historically recorded

realisation: Pierre Gassendi 1640

French navy Galley with international crew of ~100 people
(fraction of students not reported)

=> **breakthrough of inertial theory**

M. Risch
Physik in Unserer Zeit
38 (5) (2007) 249



Pierre Gassendi (1592 – 1655).

What is a „particle“?

- **Classical view: particles = discrete objects.**

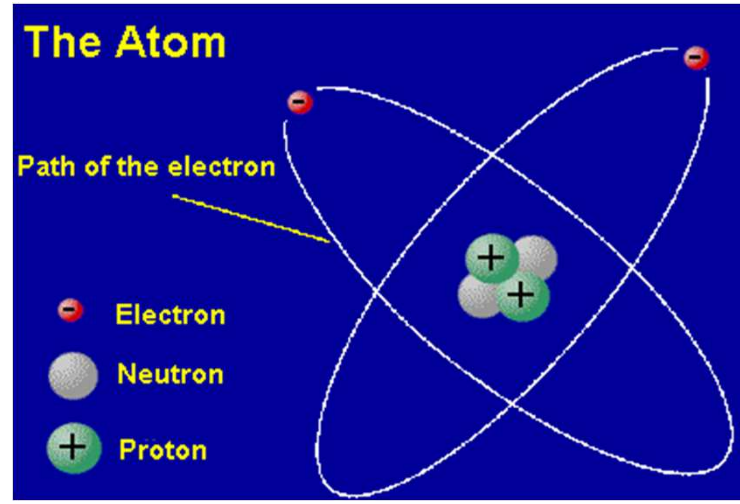
Mass concentrated into finite space with definite boundaries.

Particles exist at a specific location.

-> Newtonian mechanics

Isaac Newton (Principia 1687)

Emilie du Châtelet (1759)



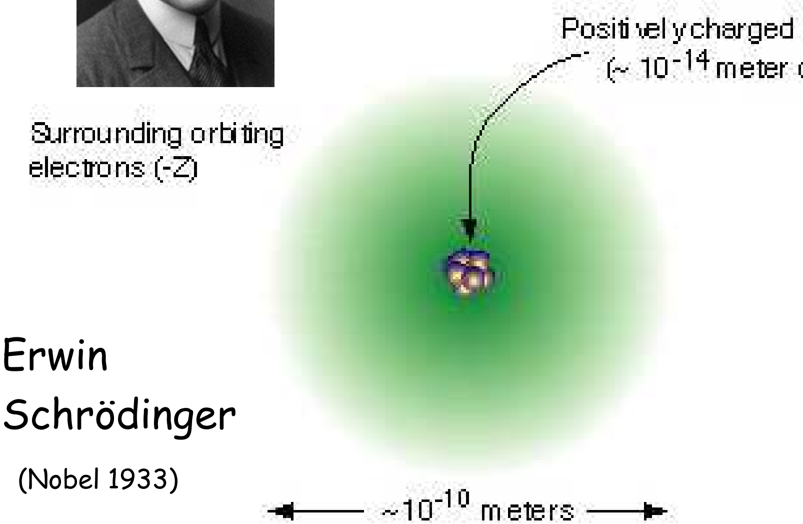
- **Modern view:**

particles = objects with discrete quantum numbers, e.g. charge, mass, ...

not necessarily located at a specific position (Heisenberg uncertainty principle),

can also be represented by wave functions (quantum mechanics, particle/wave duality).

Niels Bohr (Nobel 1922)



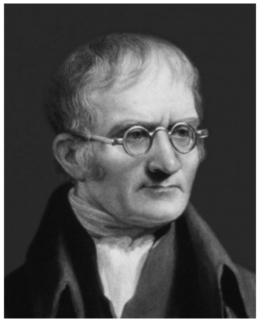
Louis de Broglie (Nobel 1929)

Werner Heisenberg (Nobel 1932)

Erwin Schrödinger (Nobel 1933)

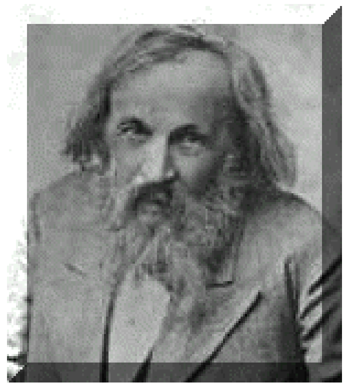
What is „elementary“?

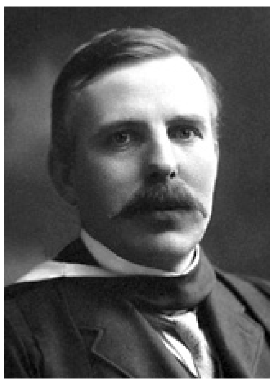
Greek: atomos = smallest indivisible part



John Dalton
1803
(atomic model)

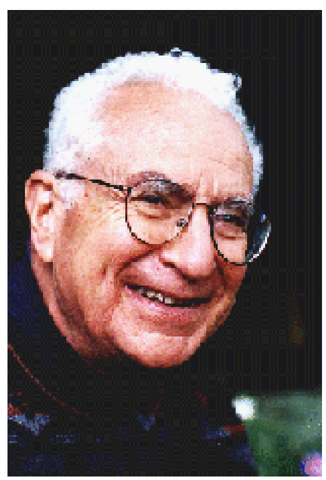
Dmitry Ivanowitsch Mendeleyev
1868
(elements)



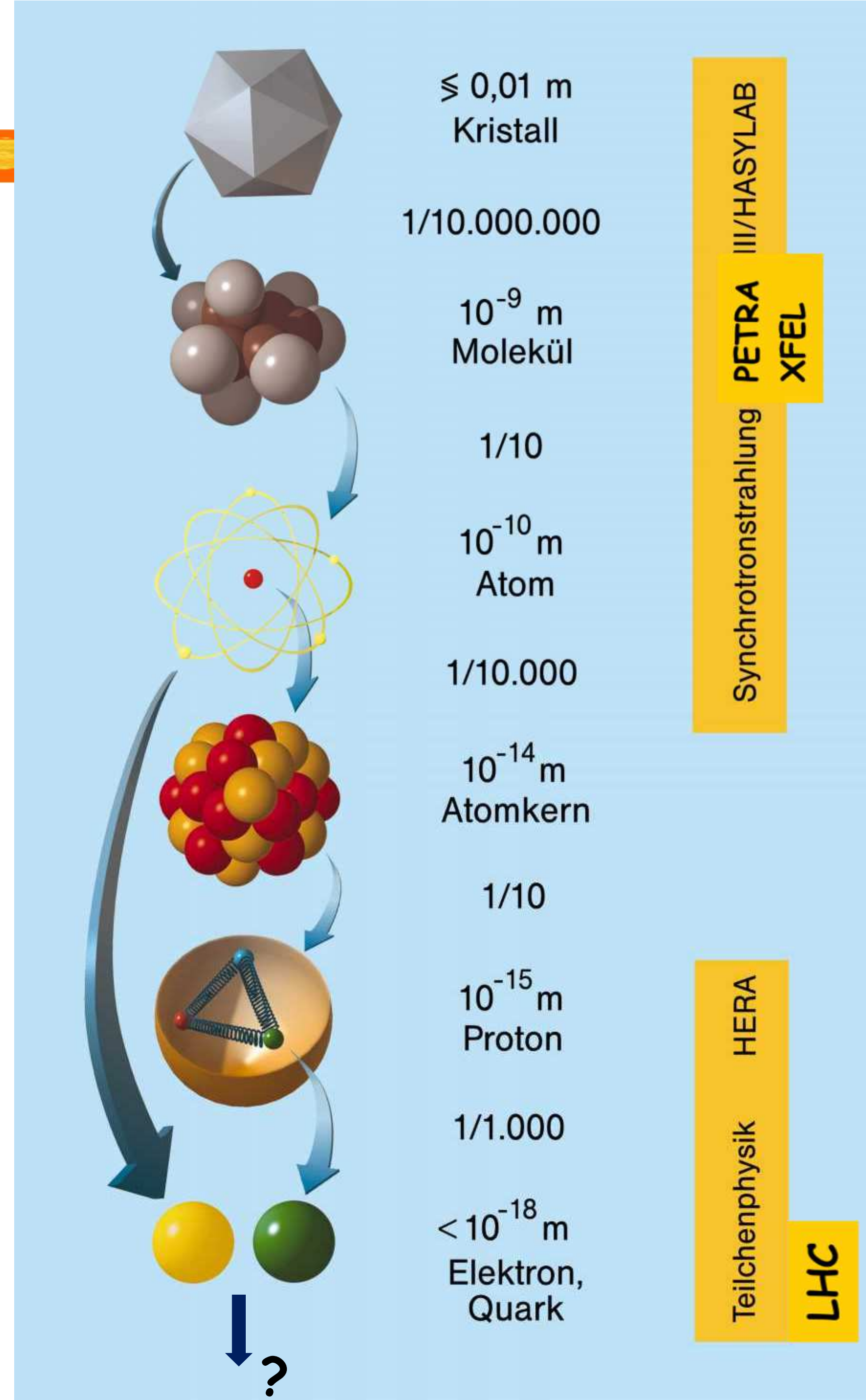


Ernest Rutherford
1911
(nucleus)
(Nobel 1908)

Murray Gell-Mann
1962
(quarks)
(Nobel 1969)

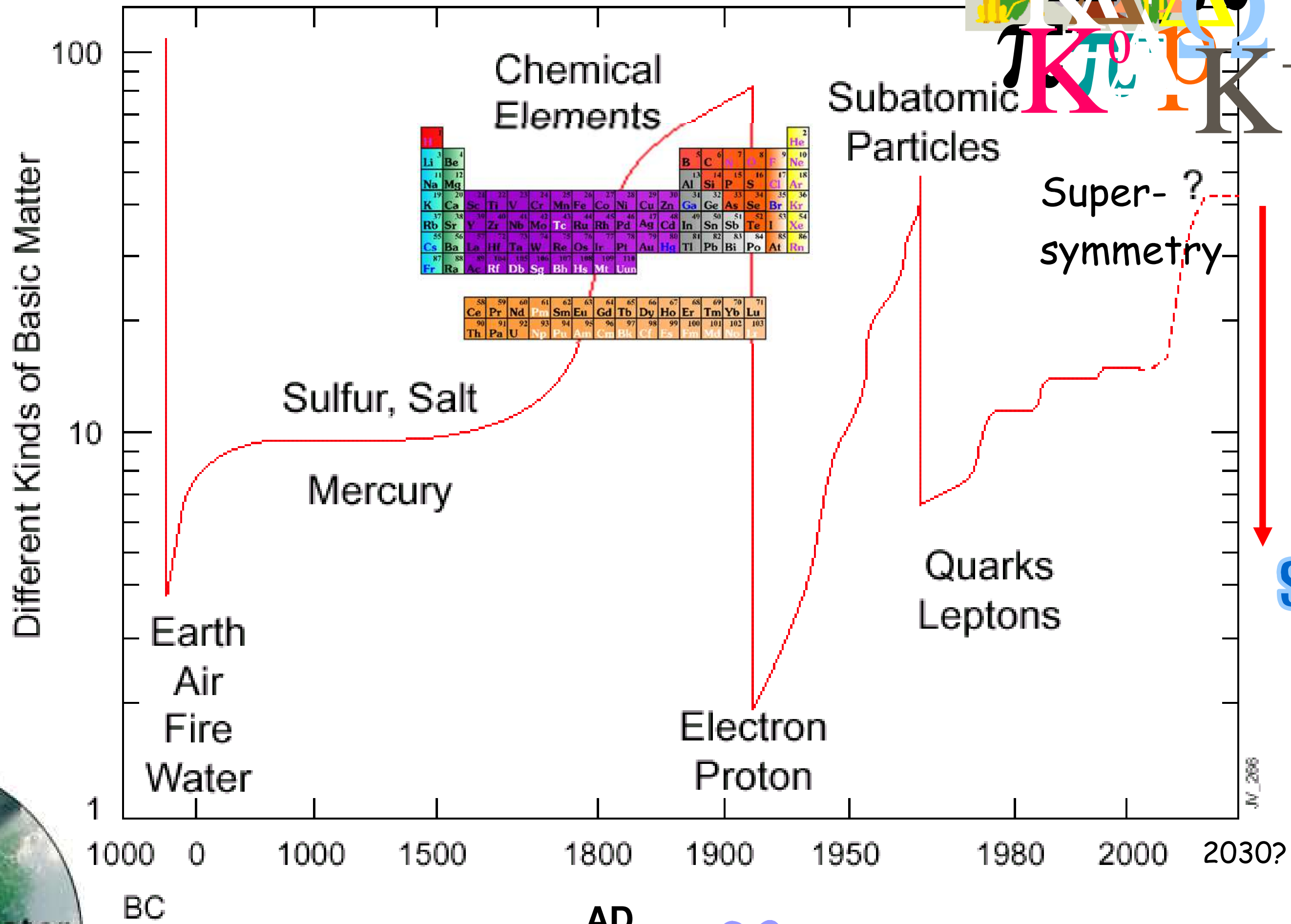


elementary
= no detectable substructure

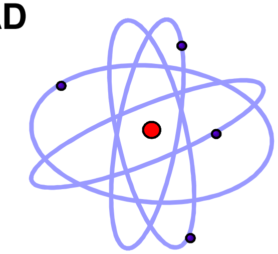


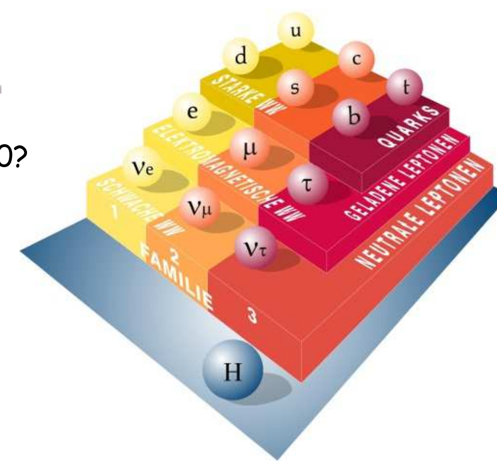
History of basic building blocks of matter

motivation:
find
smallest
possible
number



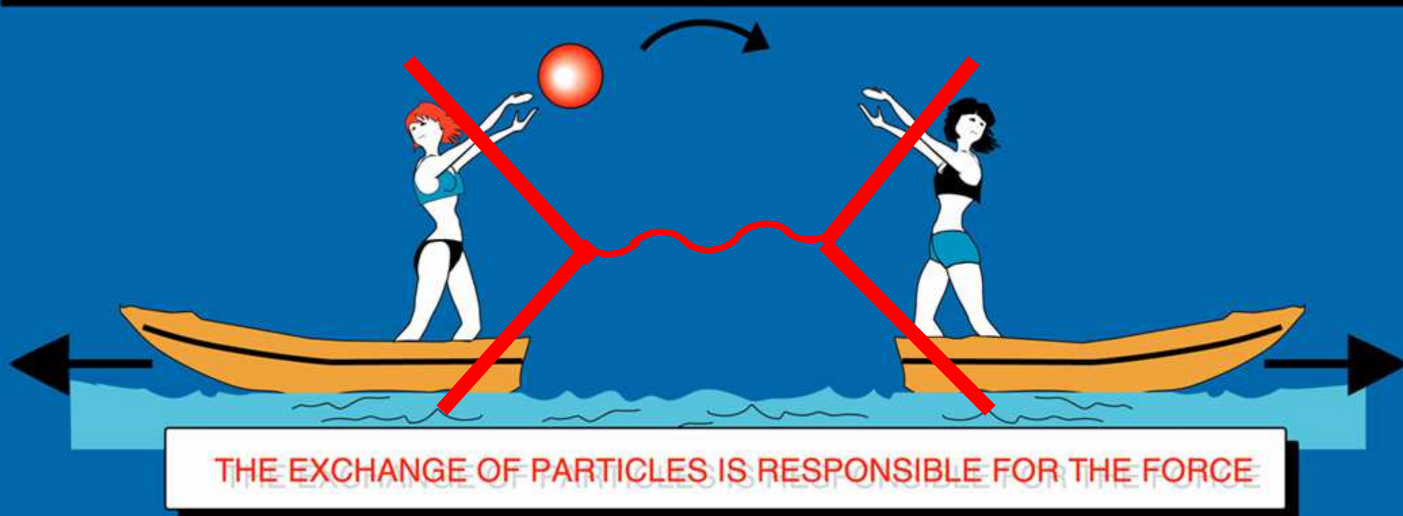
Quark and Lepton substructure ??





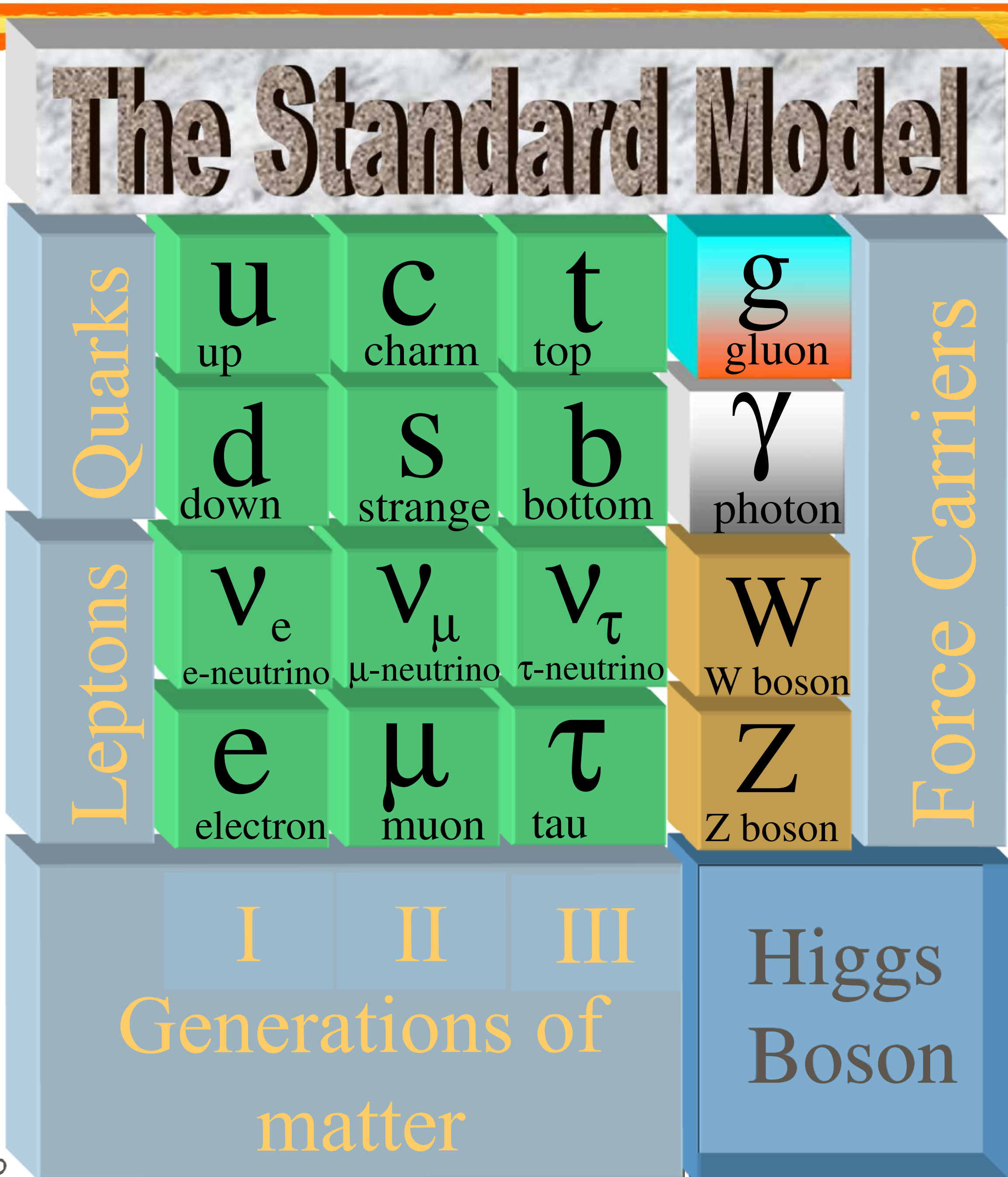
Which "interactions"?

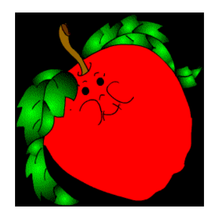
TYPE	at ~ 1 GeV INTENSITY OF FORCES (DECREASING ORDER)	BINDING PARTICLE (FIELD QUANTUM)	OCCURS IN :
STRONG NUCLEAR FORCE	~ 1	GLUONS (NO MASS)	ATOMIC NUCLEUS
ELECTRO -MAGNETIC FORCE	$\sim 10^{-2}$	PHOTONS (NO MASS)	ATOMIC SHELL ELECTROTECHNIQUE
WEAK NUCLEAR FORCE	$\sim 10^{-5}$	BOSONS Z^o, $W+$, $W-$ (HEAVY)	RADIOACTIVE BETA DESINTEGRATION
GRAVITATION	$\sim 10^{-38}$	GRAVITONS (?)	HEAVENLY BODIES



CERN AC _Z04_ V25/8/1992

What we know today

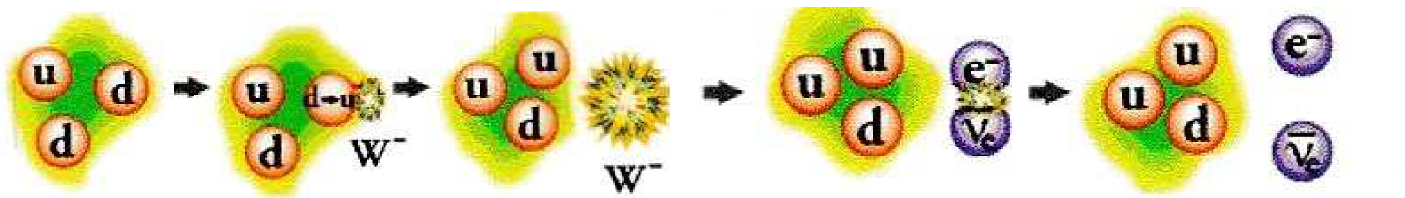




The Power of Conservation Laws

- e.g. radioactive neutron decay:

$$n \longrightarrow p + e^- + \bar{\nu}_e$$ not visible



- Pauli 1930:

Wolfgang Pauli

(Nobel 1945)

Neutrino (ν)
must be present
to account for
conservation of energy
and (angular) momentum

Emmy Noether 1919:
E,p,L conservation related to homogeneity of time+space and isotropy of space

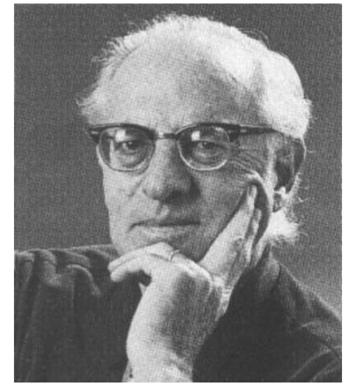
confirmation: neutrino detection

- e.g. reversed reaction:

$$\nu_e + n \longrightarrow p + e$$

extremely rare!

(absorption length ~ 3 light years Pb)



Frederick Reines

(Nobel 1995)

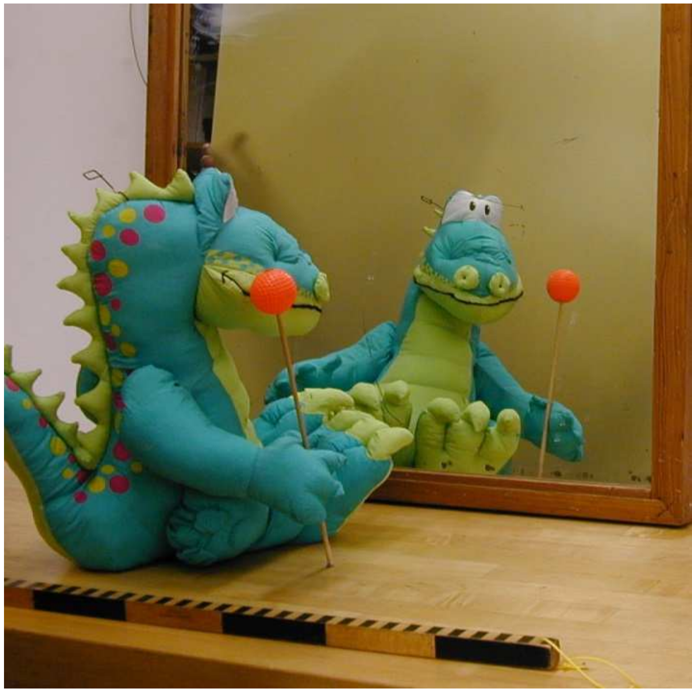
- first detection: 1956

Reines and Cowan, neutrinos from nuclear reactor

Conservation laws remain valid down to microscopic scales!

The power of symmetries: Parity

Parity = Mirror Symmetry



- Will physical processes look the same when viewed through a mirror?

- In everyday life:

violation of parity symmetry is common

„natural": our heart is on the left

„spontaneous": cars drive on the right (on the continent)

Eugene Wigner (Nobel 1963)

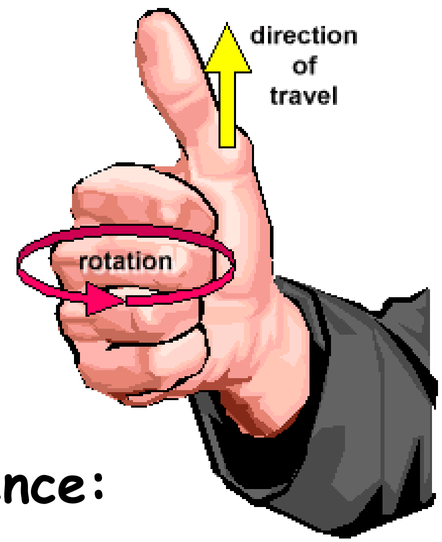
- What about basic interactions?
- Electromagnetic and strong interactions conserve parity!

The power of symmetries: Parity

Lee & Yang 1956: weak interactions violate Parity

experimentally verified by Wu et al. 1957:

spin

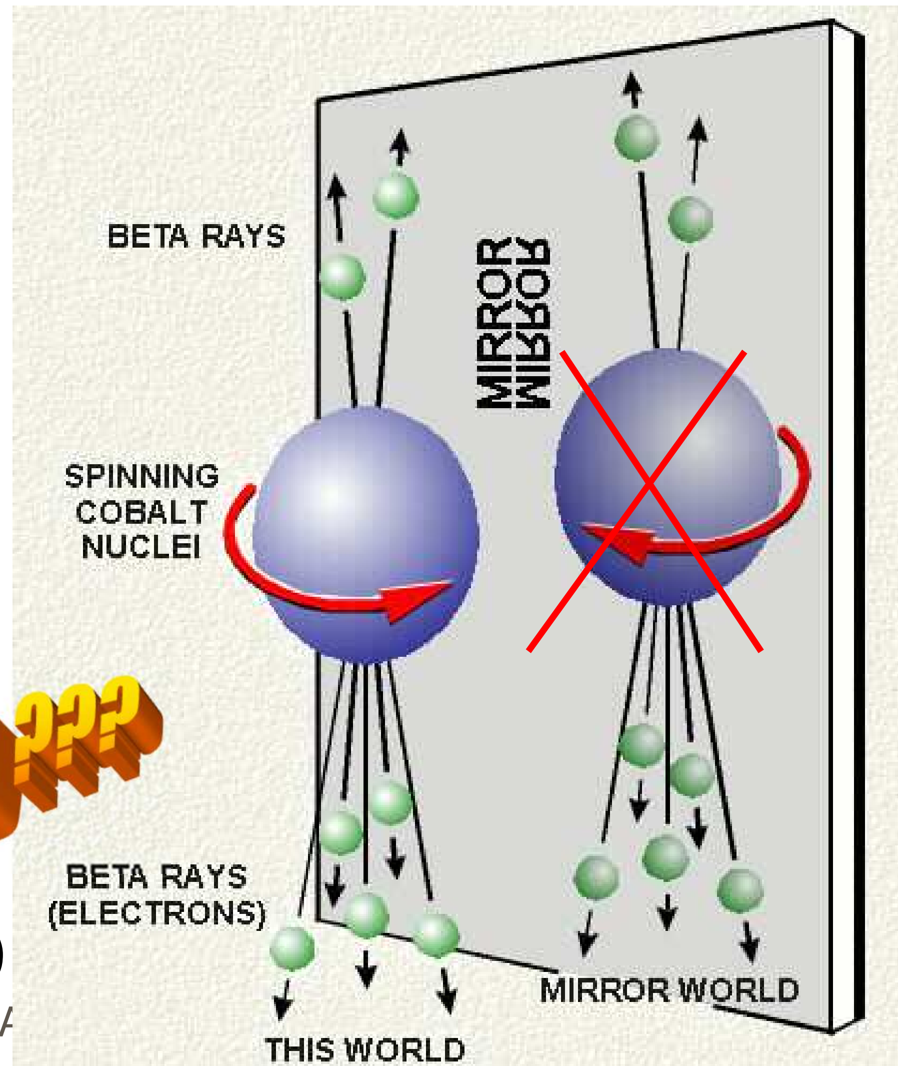


consequence:

neutrinos are always lefthanded !

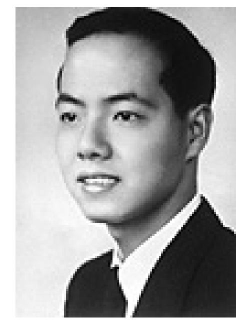
(antineutrinos righthanded)

Why???



Chen Ning Yang

(Nobel 1957)



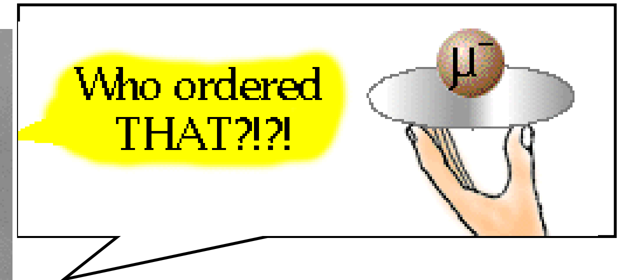
Tsung-Dao Lee

Chieng Shiung Wu

The Power of Quantum Numbers

- 1948: discovery of muon
- same quantum numbers as electron, except mass

I.I. Rabi
(Nobel 1944)



(Nobel 1988)

Leon M. Ledermann Melvin Schwartz Jack Steinberger

- muon decay: $\mu^- \to \nu_\mu \, e^- \, \bar{\nu}_e$

conservation of

	μ^-	ν_μ	e^-	$\bar{\nu}_e$		
electric charge	-1	0	-1	0		
lepton number:	1	1	1	-1	$\nu \neq \bar{\nu}$	(1955)
„muon number“:	1	1	0	0	$\nu_\mu \neq \nu_e$	(1962)

- **Lepton number is conserved**

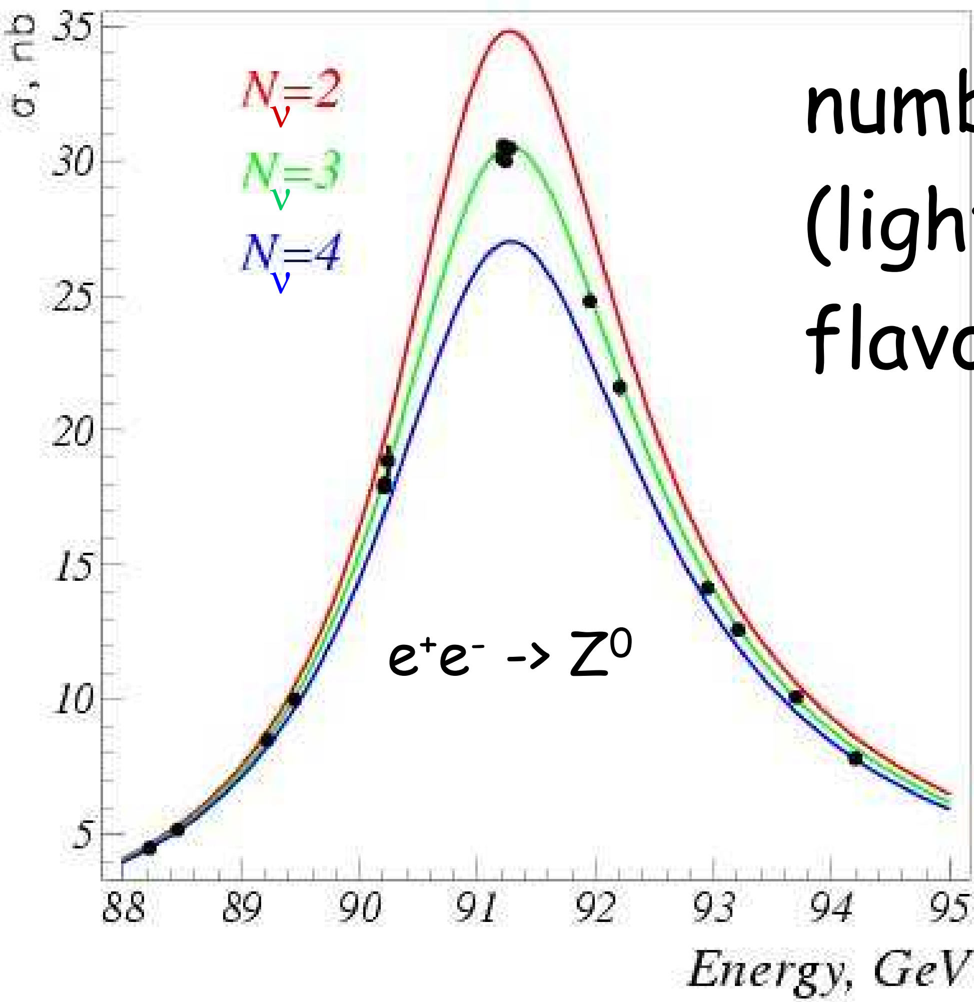
Why???

- There is a distinct neutrino for each charged lepton

The Power of Precision

- Precision measurements of shape and height of Z^0 resonance at LEP I

(CERN 1990's)



number of (light) neutrino flavours = 3

Gerardus t'Hooft

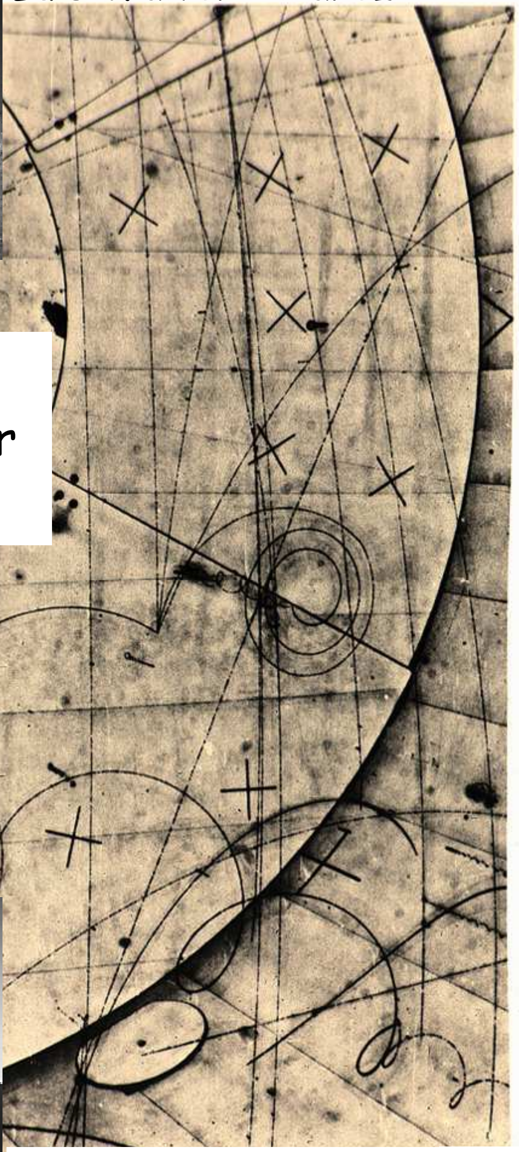
Martinus Veltman

(Nobel 1999)

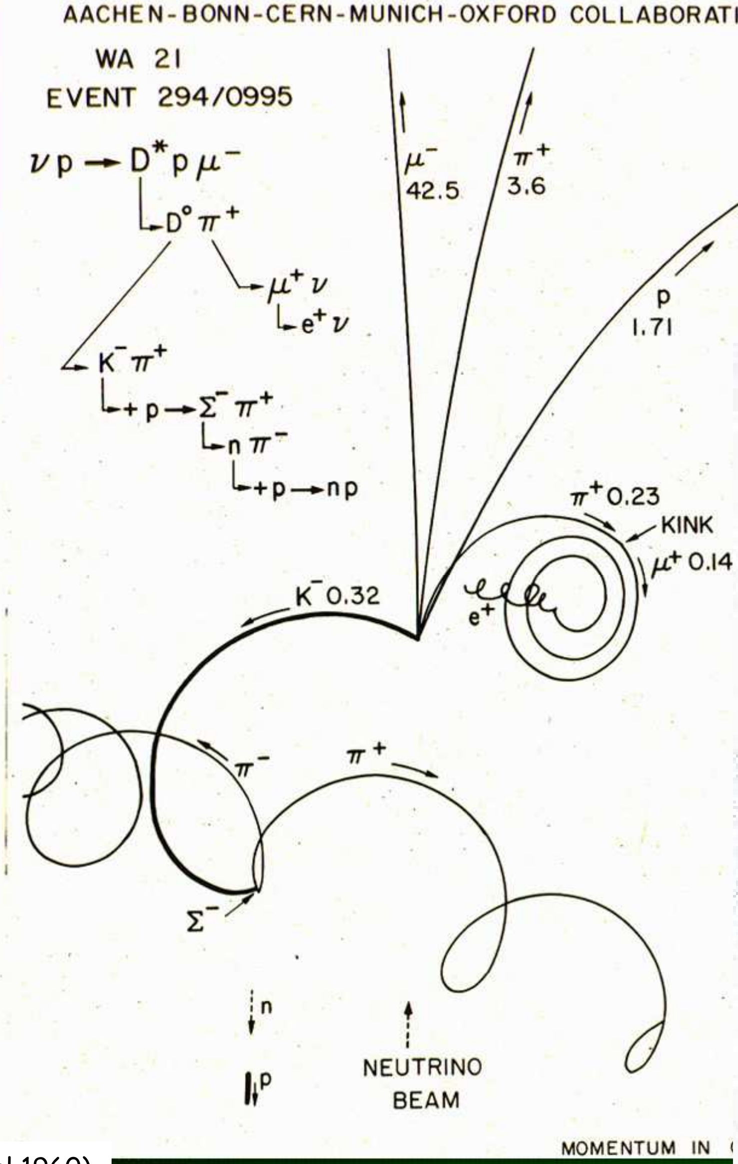
There seem to be exactly three lepton + quark families !

Can we "see" particles?

Luis Walter Alvarez (Nobel 1968)



bubble chamber photo

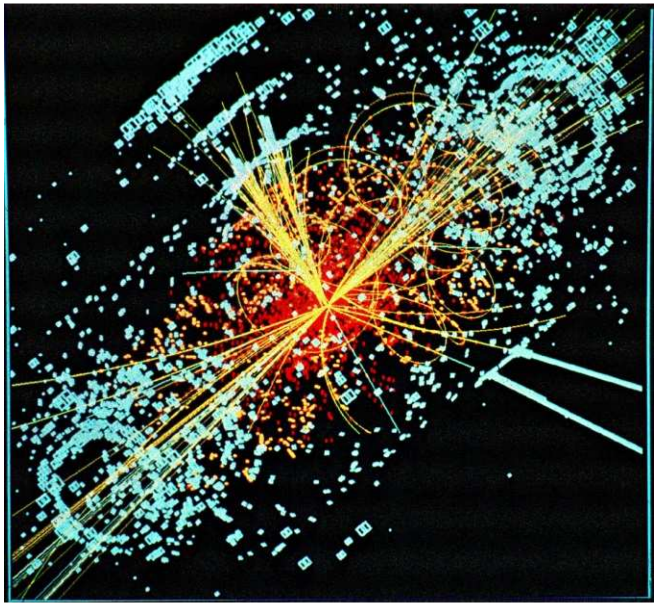


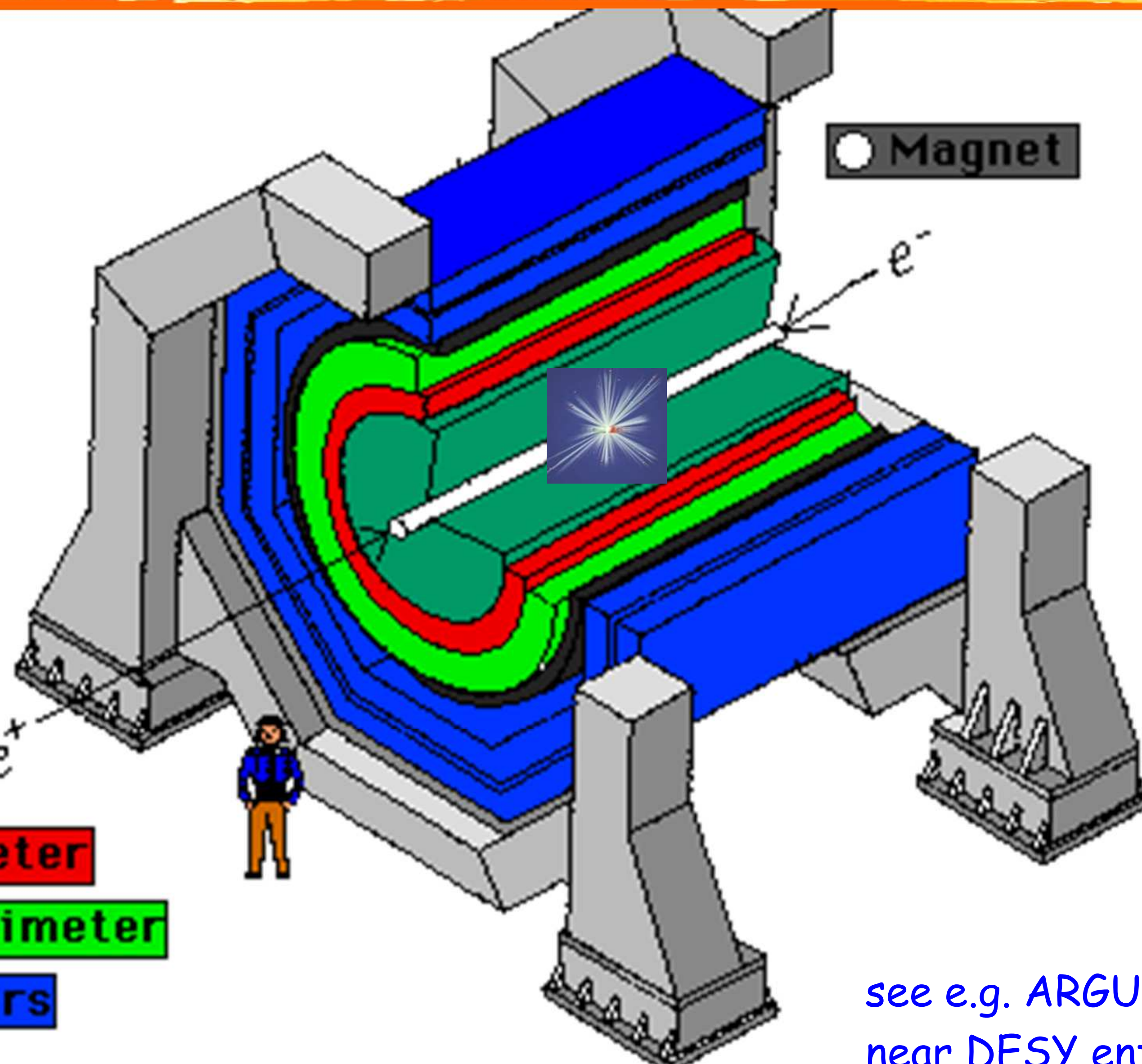
we can!

Quarks. Neutrinos. Mesons. All those damn particles you can't see. That's what drove me to drink. But now I can see them.

Donald Arthur Glaser (Nobel 1960)

A typical particle physics detector



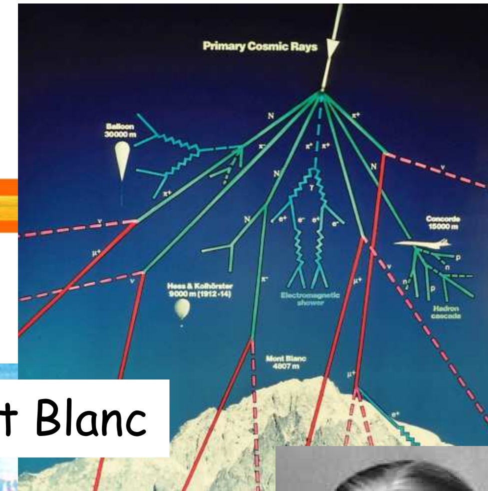


see e.g. ARGUS
near DESY entrance

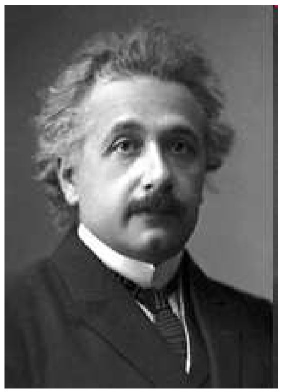
more details: lecture I. Gregor

Why do we need colliders?

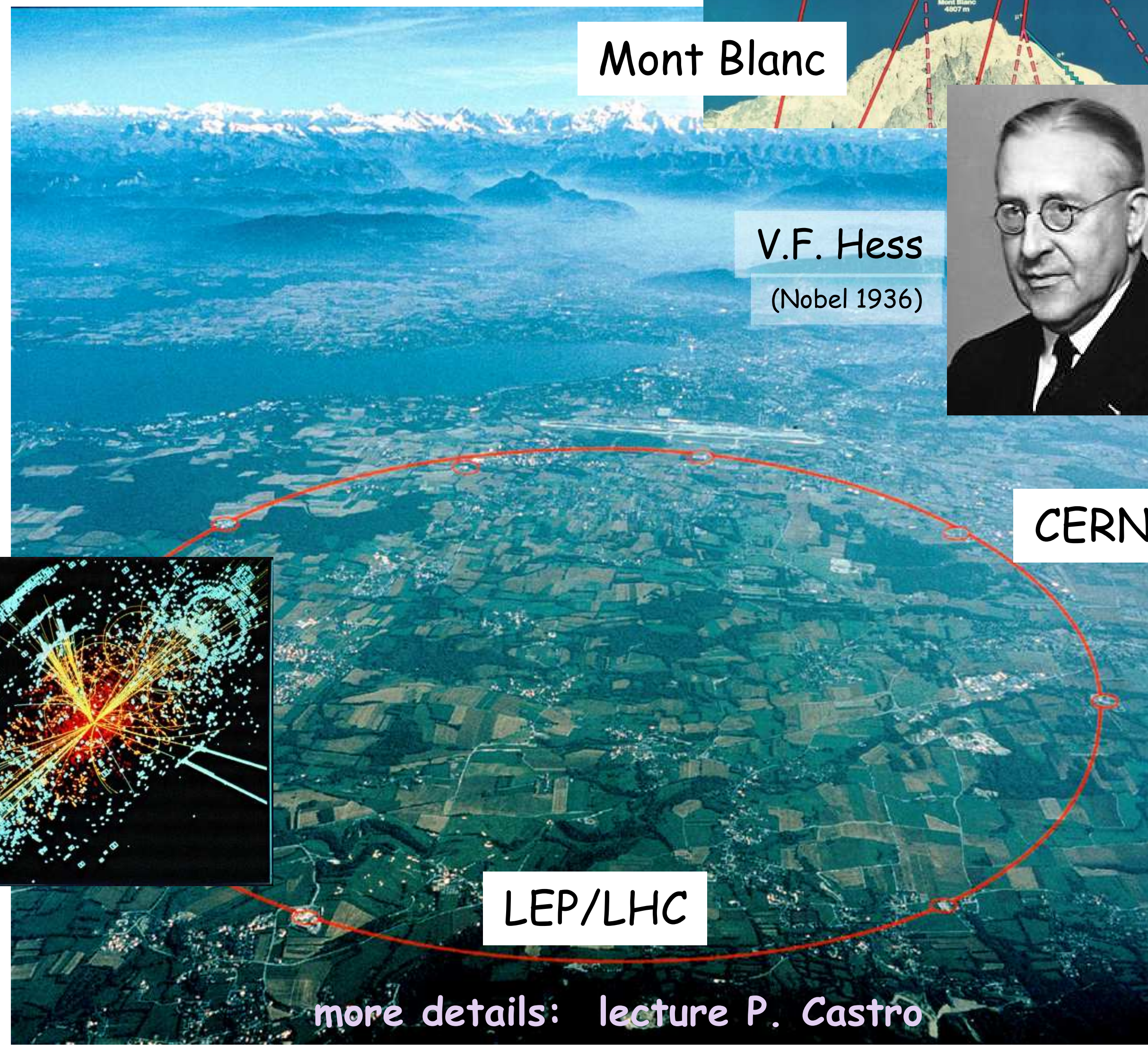
- early discoveries in cosmic rays, but
- need controlled conditions



$$m = \frac{E}{c^2}$$



Albert Einstein
(Nobel 1921)



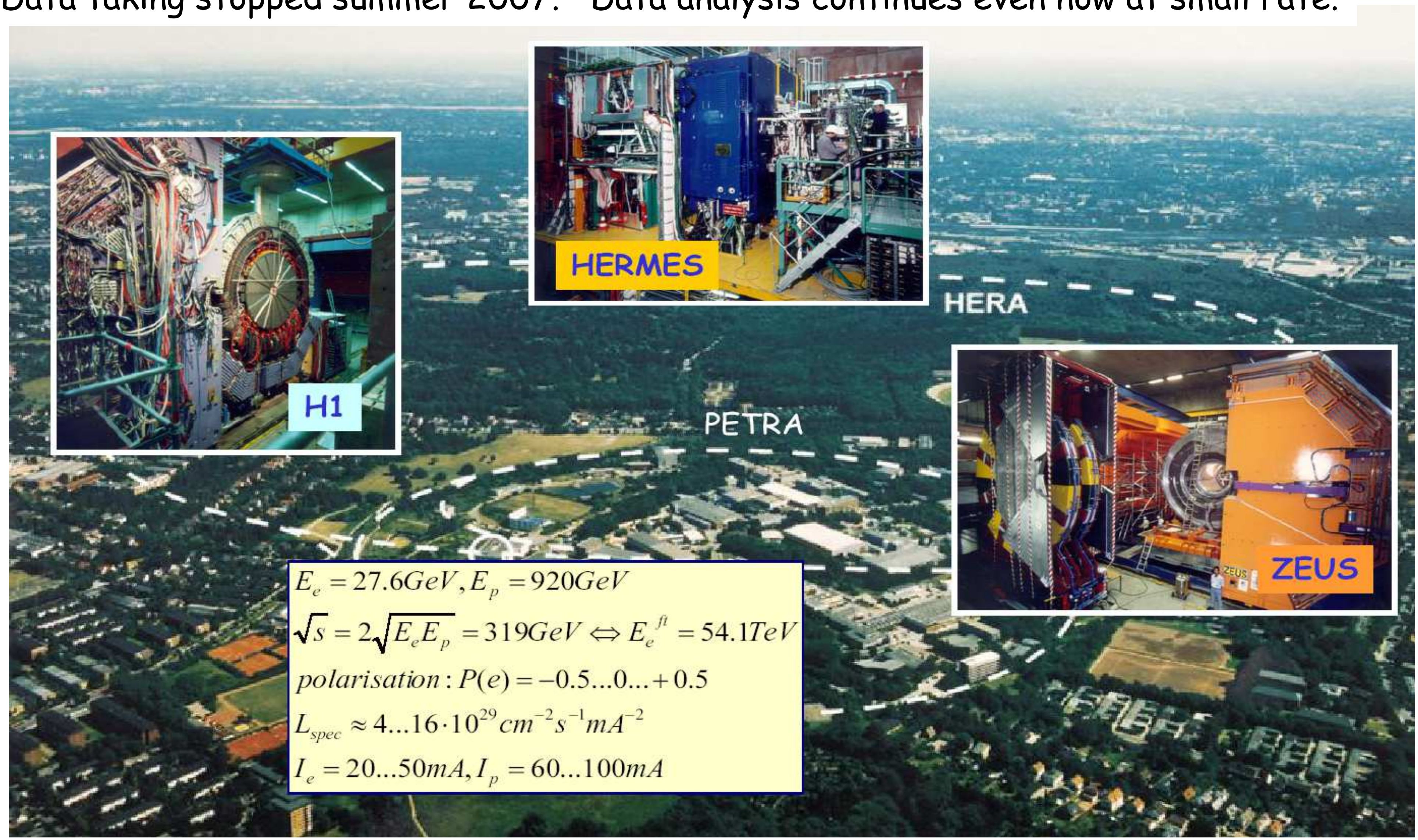
V.F. Hess
(Nobel 1936)

need high energy to discover new heavy particles

- colliders = microscopes (later)

The HERA ep Collider and Experiments

Data taking stopped summer 2007.   Data analysis continues even now at small rate.



$$E_e = 27.6\,GeV, E_p = 920\,GeV$$

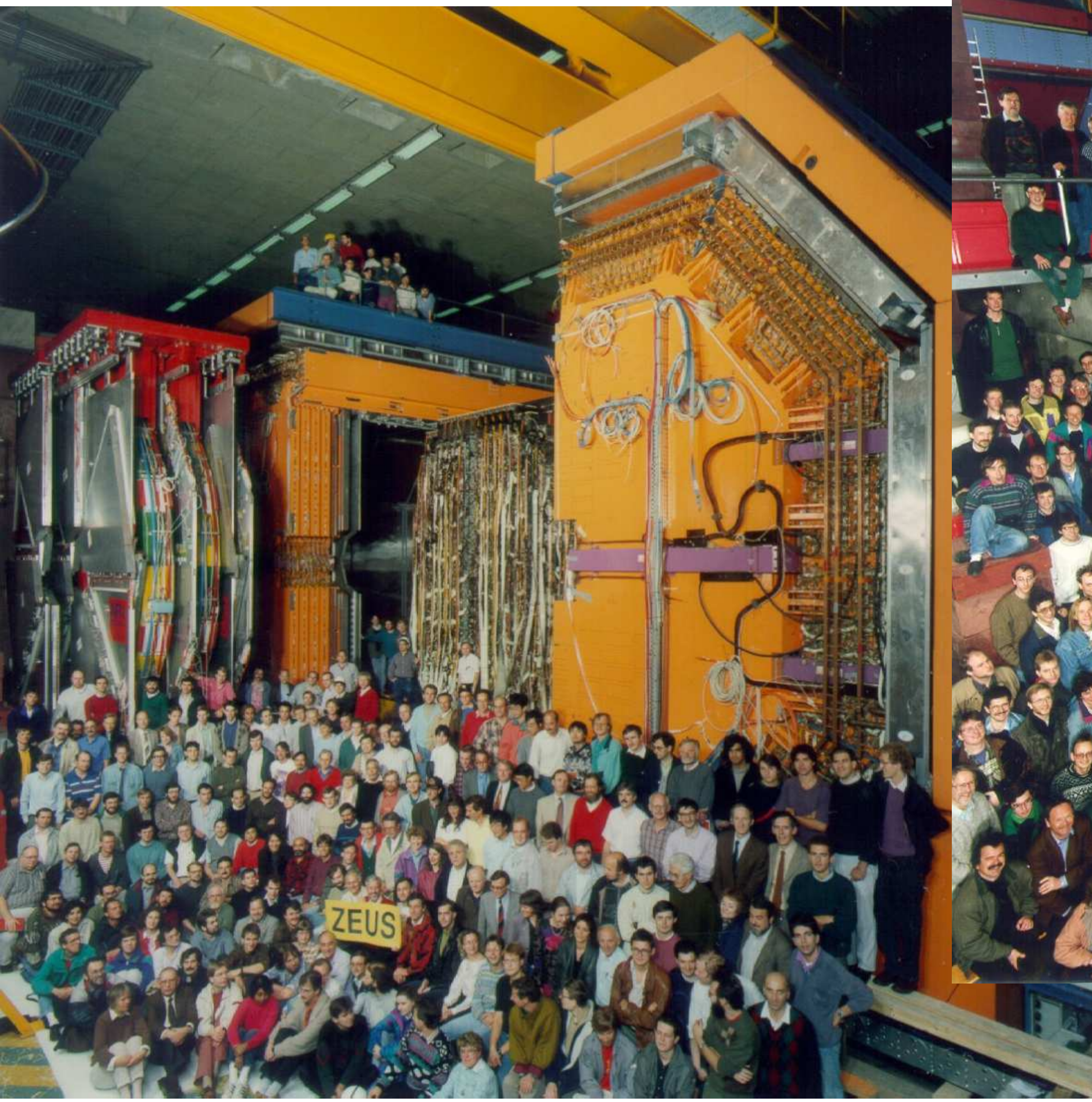
$$\sqrt{s} = 2\sqrt{E_e E_p} = 319\,GeV \Leftrightarrow E_e^{ft} = 54.1\,TeV$$

$$polarisation: P(e) = -0.5 \ldots 0 \ldots +0.5$$

$$L_{spec} \approx 4 \ldots 16 \cdot 10^{29}\,cm^{-2} s^{-1} mA^{-2}$$

$$I_e = 20 \ldots 50\,mA, I_p = 60 \ldots 100\,mA$$

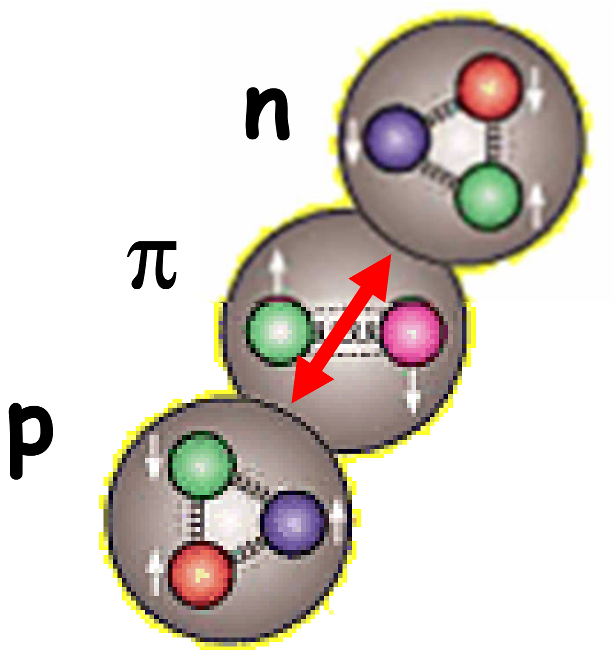
Particle Physics = People



Strong Interactions: Quarks and Colour

- strong force in nuclear interactions
  = „exchange of massive pions" between nucleons
  = residual Van der Waals-like interaction

Hideki Yukawa
(Nobel 1949)



- modern view:

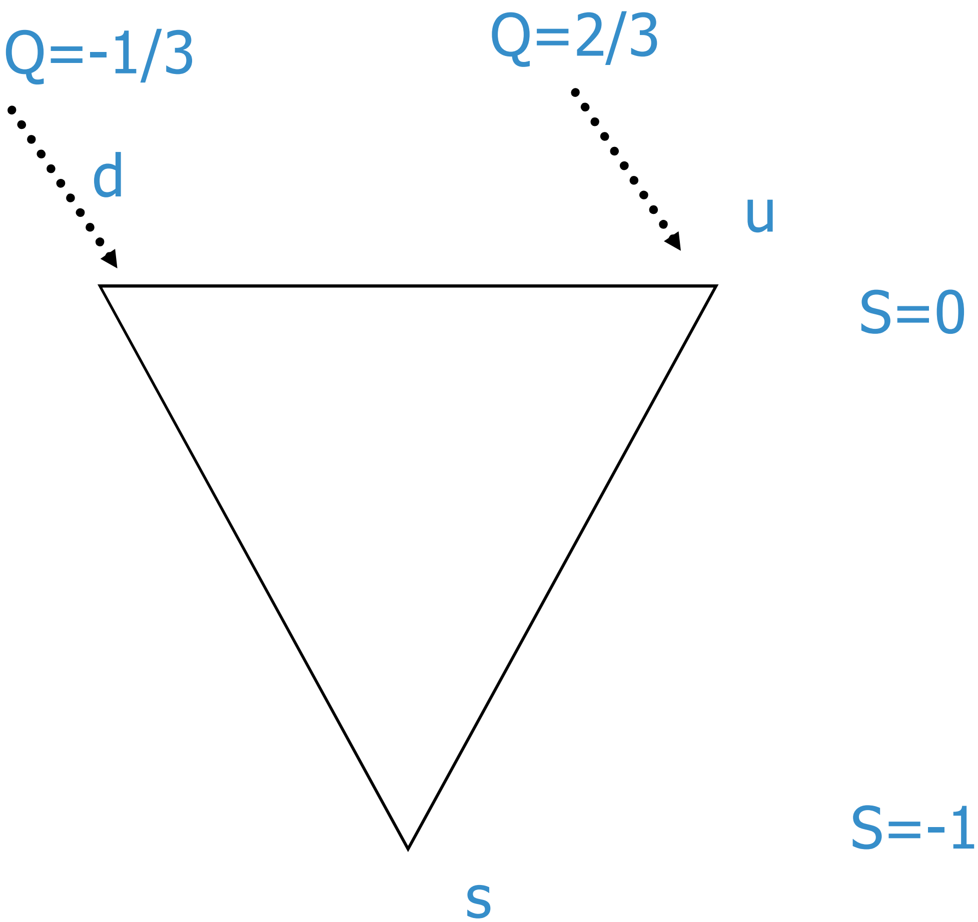
(Quantum Chromo-Dynamics, QCD)
exchange of massless gluons
between quark
constituents

„similar" to electromagnetism
(Quantum Electro-Dynamics, QED)

The Quark Model (1964)

arrange quarks (known at that time) into flavour-triplet

=> $SU(3)_{flavour}$ symmetry



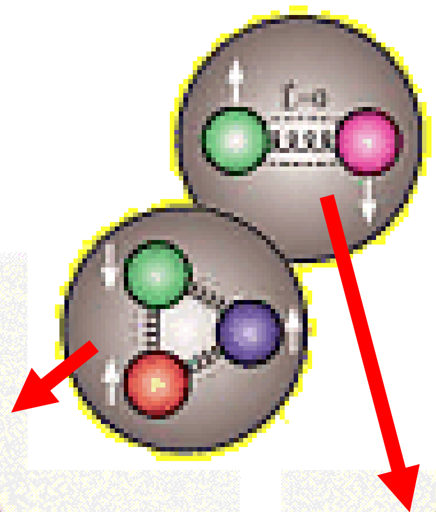
treat almost all known hadrons (protons, neutrons, pions, ...) as objects composed of two or three such quarks (antiquarks)

Murray Gell-Mann

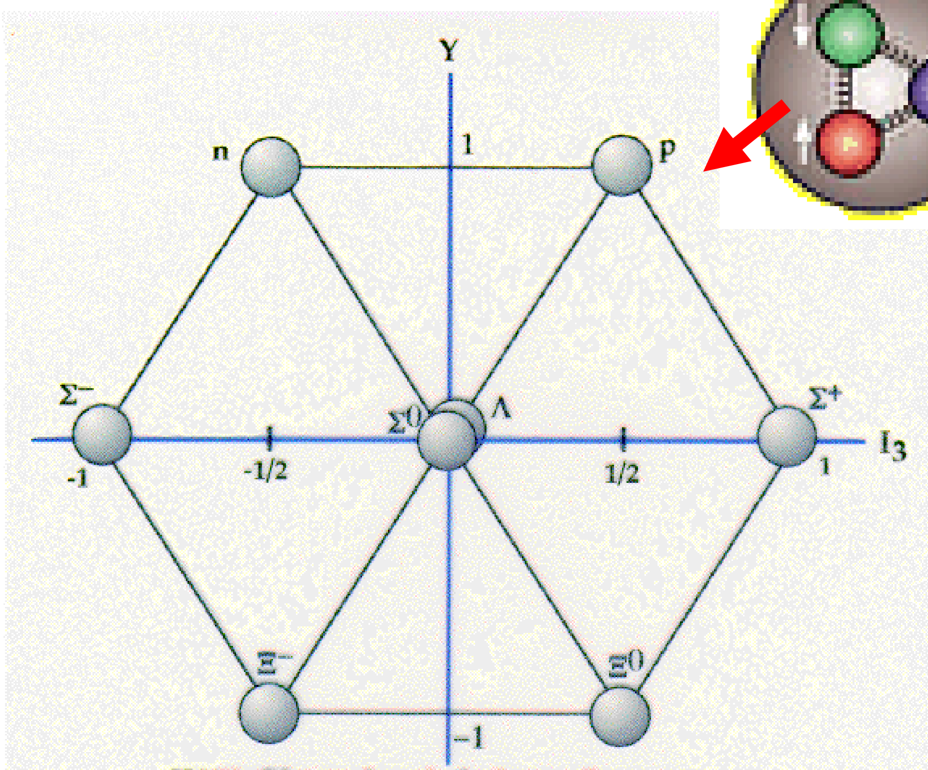
(Nobel 1969)

The Quark Model

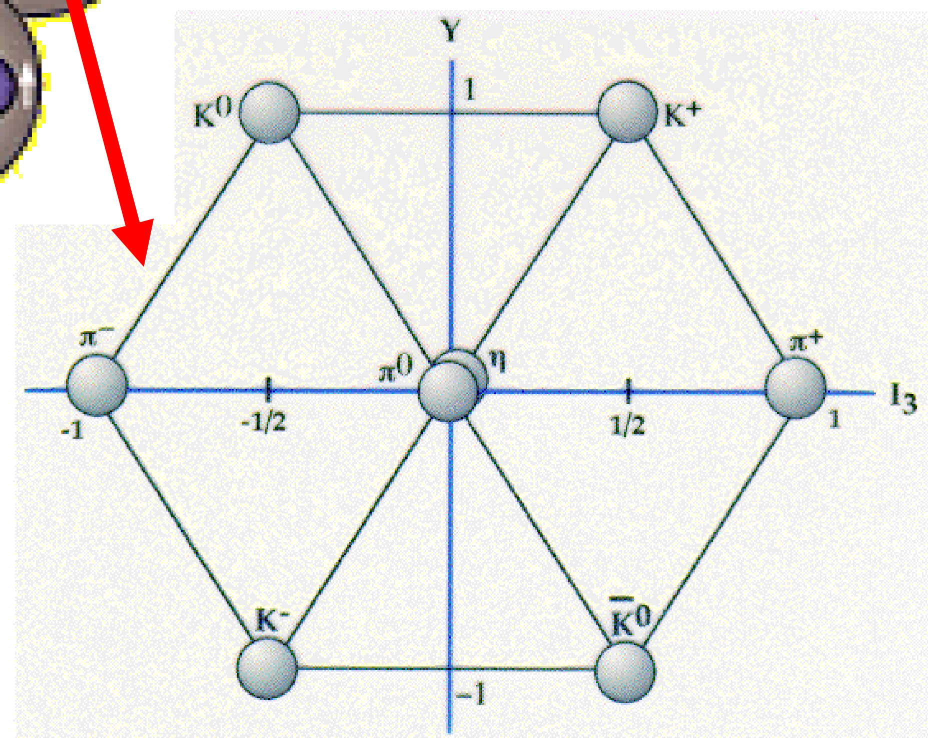
baryons = qqq



mesons = $q\bar{q}$



SU(3)-Oktett der einfachsten Baryonen

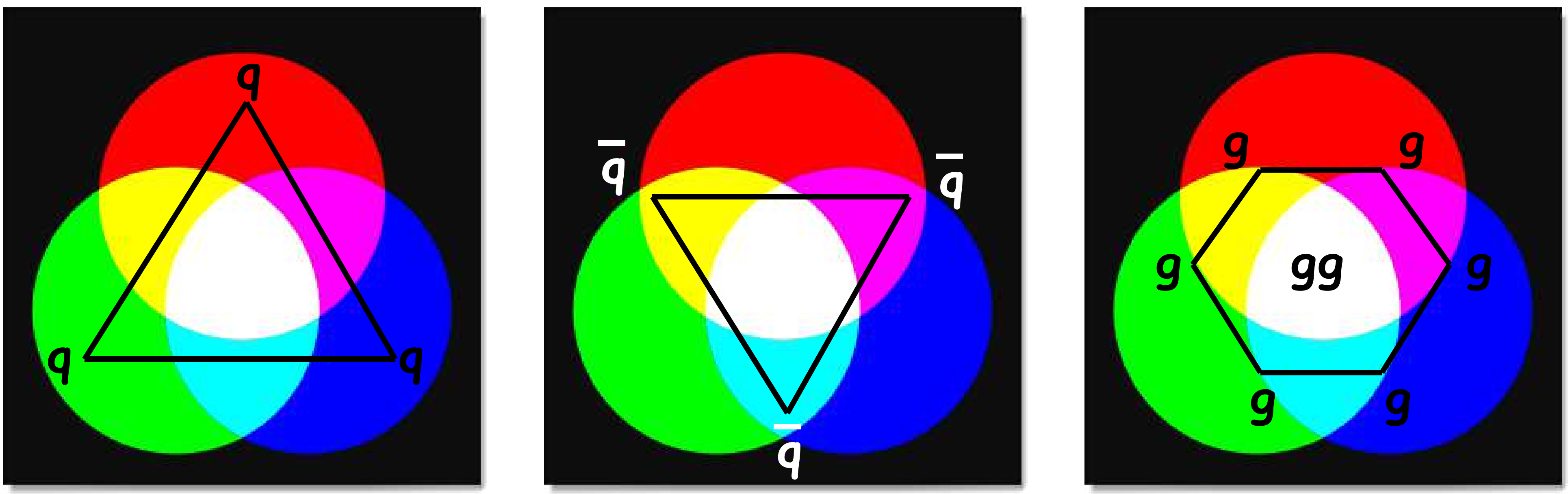


SU(3)-Oktett der einfachsten Mesonen

Colour

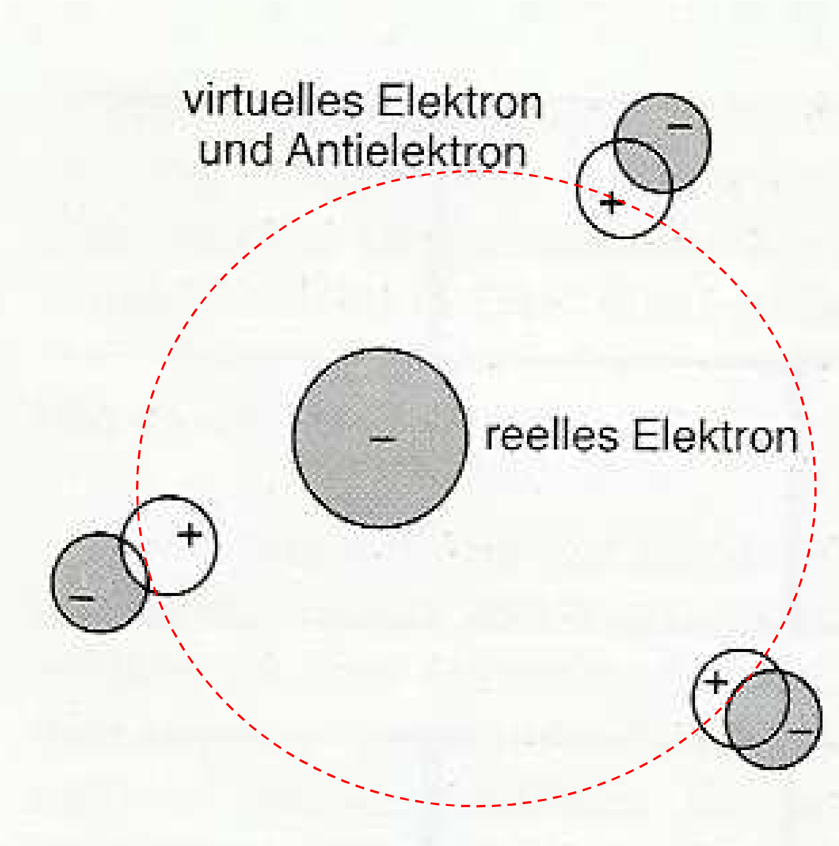
Quark model very successful, but seems to violate quantum numbers (Fermi statistics), e.g. $|\Delta^{++}\rangle = |uuu\rangle|\uparrow\uparrow\uparrow\rangle$

=> introduce new degree of freedom: **Colour**



- 3 coulours -> $SU(3)_{colour}$ (exact symmetry) $qqq = q\bar{q} =$ white!

Screening of Electric Charge



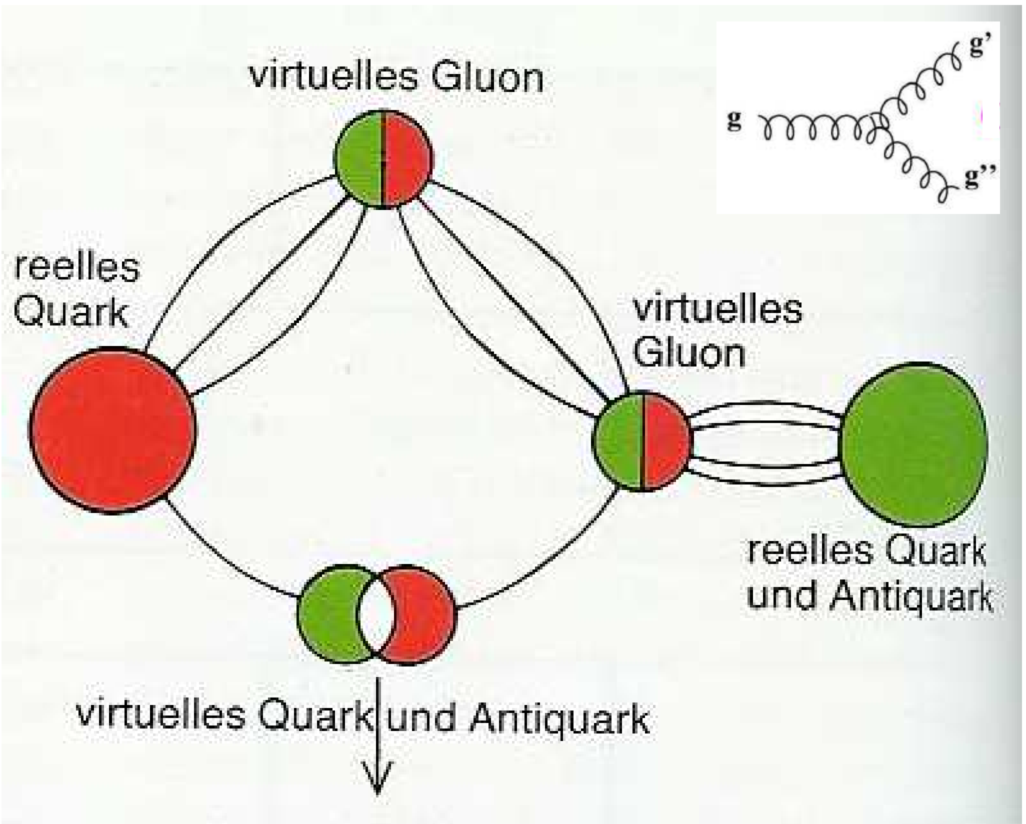
(Nobel 1965)

Sin-Itoro Tomonaga | Julian Schwinger | Richard P. Feynman

- electric charge polarises vacuum -> virtual electron positron pairs
- positrons partially screen electron charge
- effective charge/force
  - decreases at large distances/low energy (screening)
  - increases at small distance/large energy

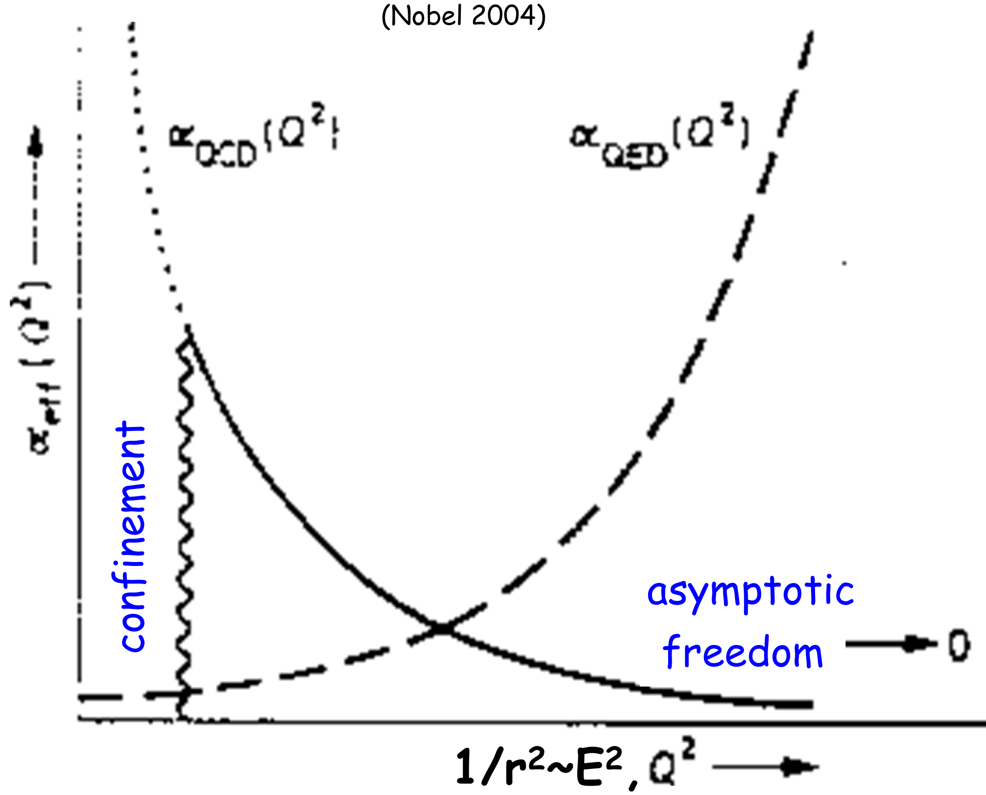
Anti-Screening of Coulour Charge!

quark-antiquark pairs -> screening
gluons carry colour -> gg pairs
-> anti-screening!



David J. Gross   H. David Politzer   Frank Wilczek

(Nobel 2004)



Comparison QED / QCD

electromagnetism | strong interactions

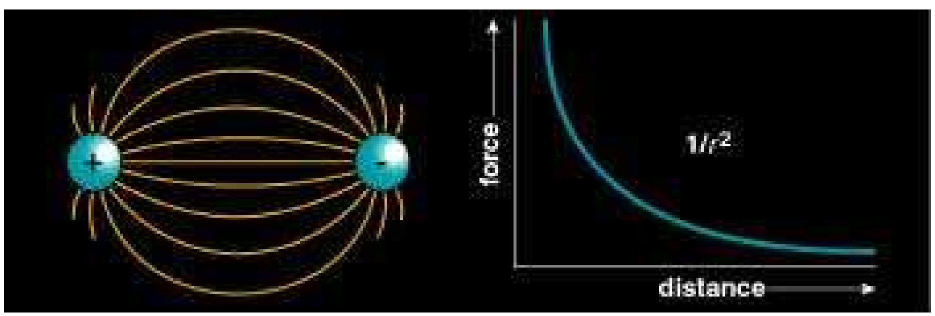
QED

1 kind of charge (q)

force mediated by **photons**

photons are *neutral*

α is nearly constant



QCD

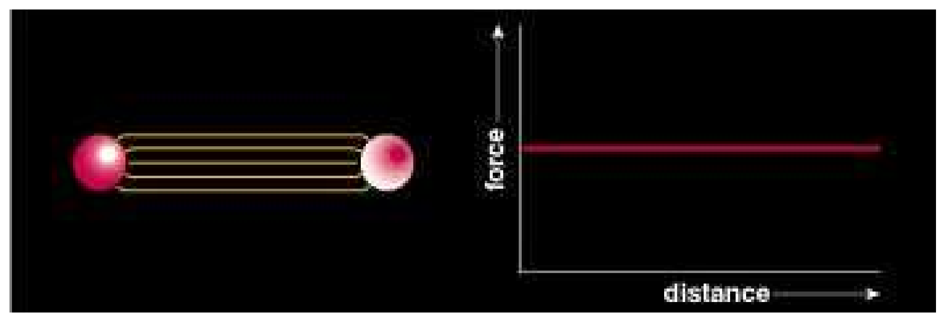
3 kinds of charge (r,g,b)

force mediated by **gluons**

gluons are *charged* (eg. rg, bb, gb)

α_s strongly depends on distance

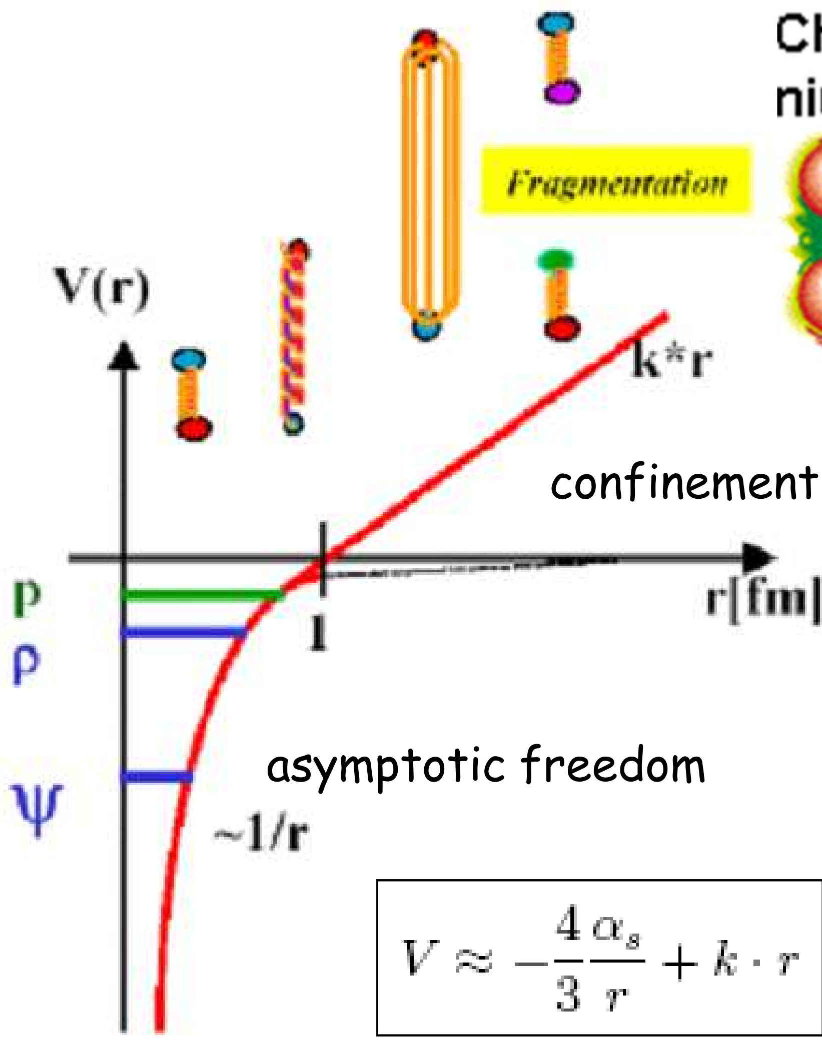
confinement limit:



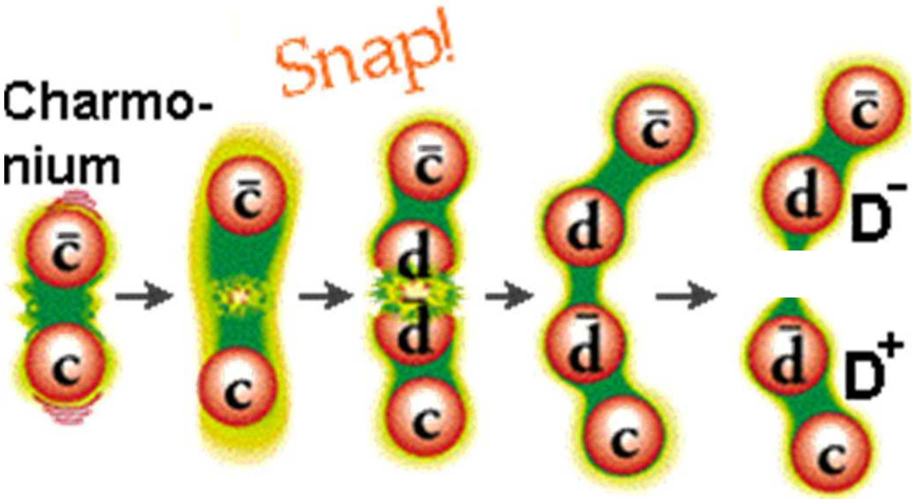
- The underlying theories are formally almost identical!

more details: lecture M. Diehl

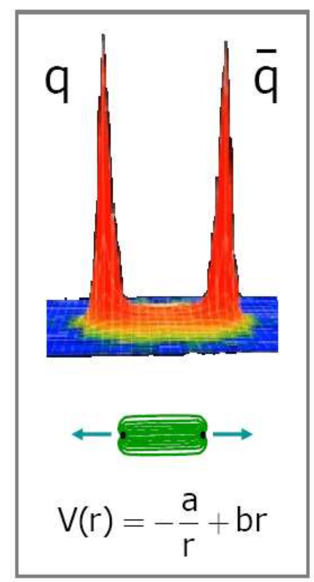
The effective potential for $q\bar{q}$ interactions



$$V \approx -\frac{4}{3}\frac{\alpha_s}{r} + k \cdot r$$

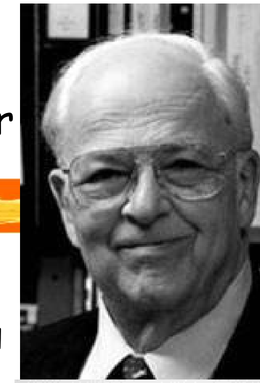


lattice
gauge
calculation



Heavy Quark Spectroscopy

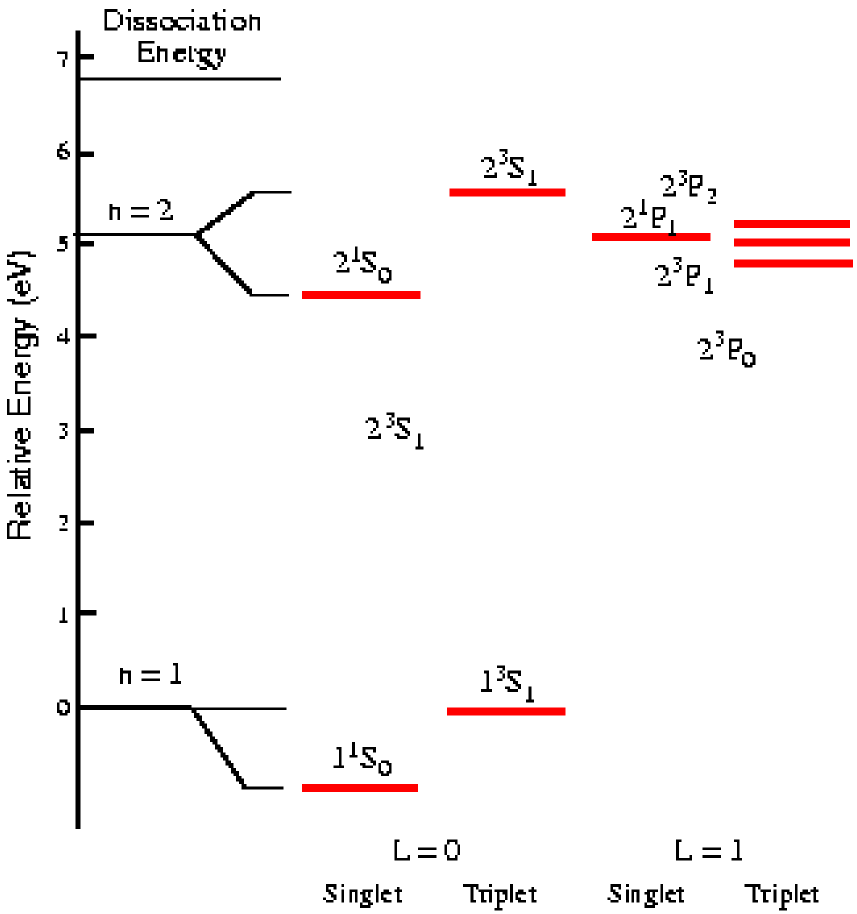
Burton Richter



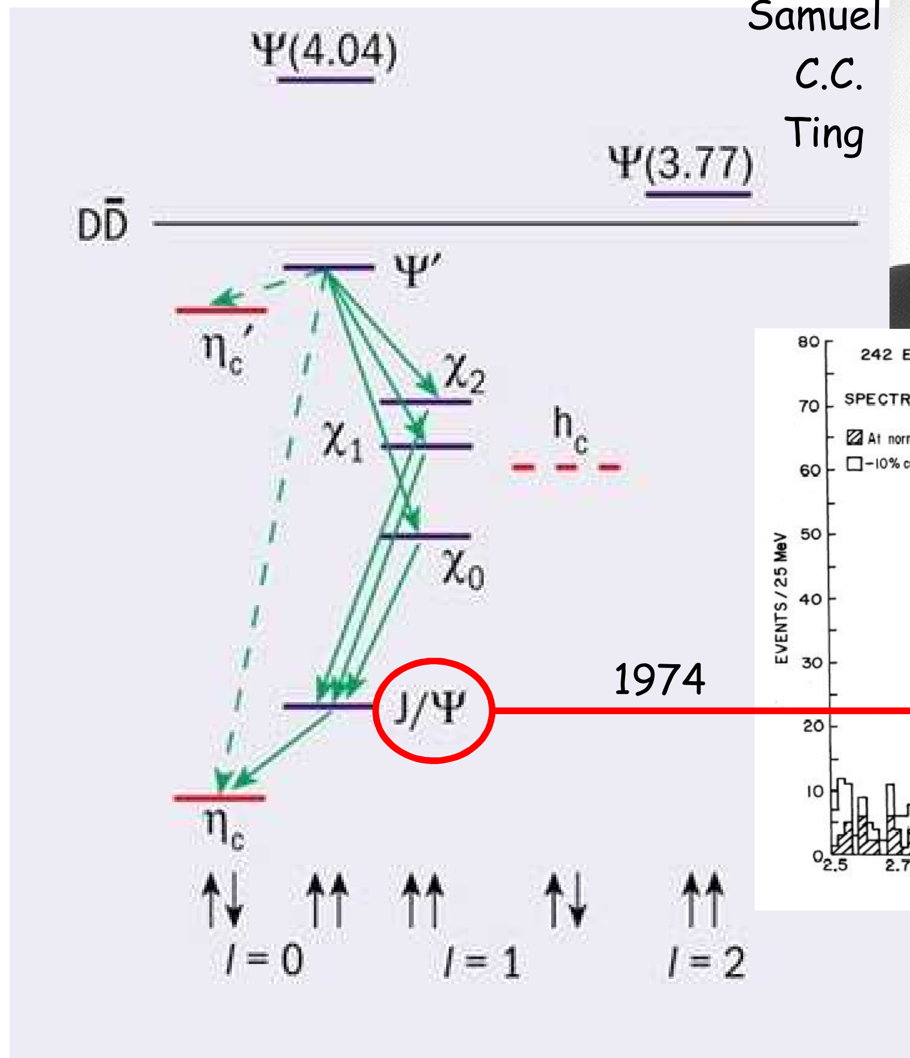
(Nobel 1976)

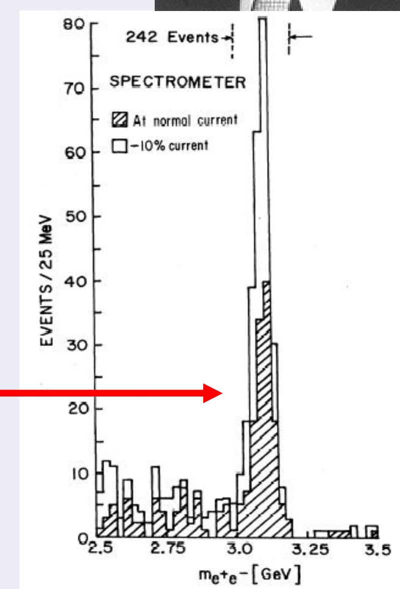
Samuel C.C. Ting

Positronium = bound e^+e^- system



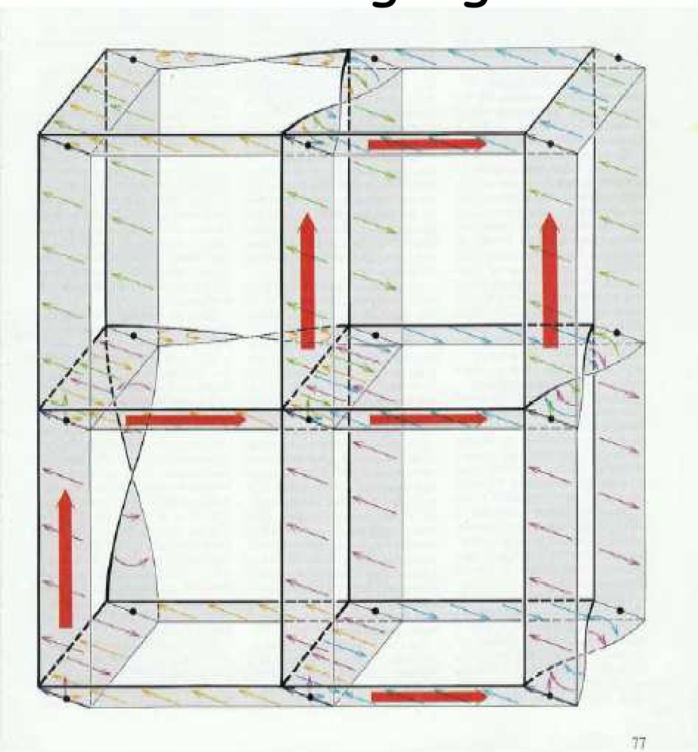
Charmonium = bound system of $c\bar{c}$ quark pair

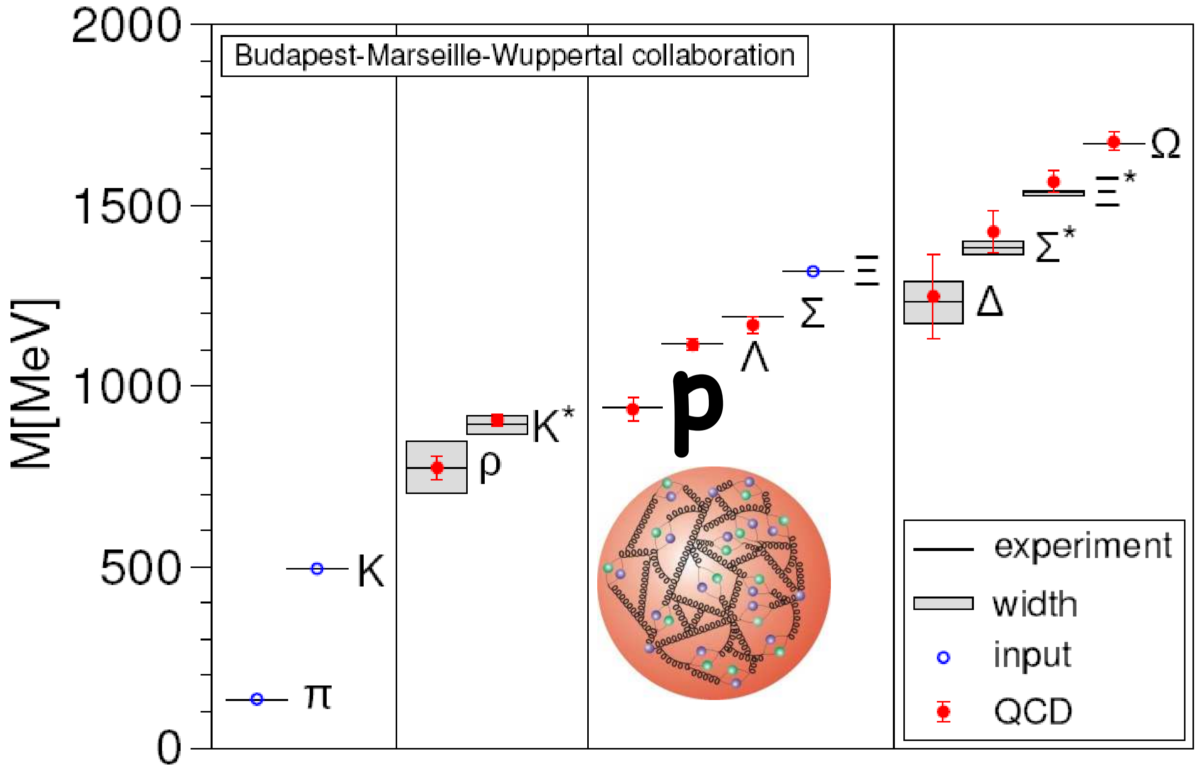




calculation of proton mass in QCD

from lattice gauge theory:





spontaneous breakdown of "chiral symmetry" (left-right-symmetry) yields QCD "vacuum" expectation value

⇒ proton mass (~= neutron mass),

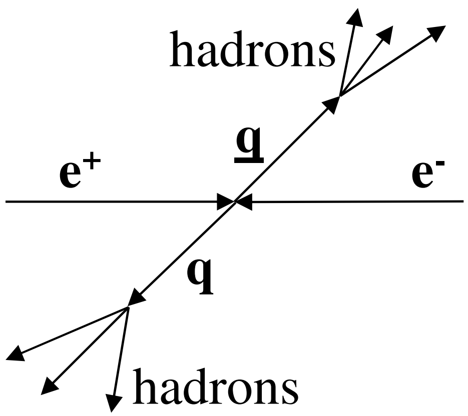
⇒ mass of the visible part of the universe !

Yoichiro Nambu

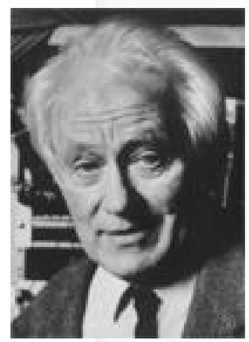
(Nobel 2008)

How to detect Quarks and Gluons?

Jets!

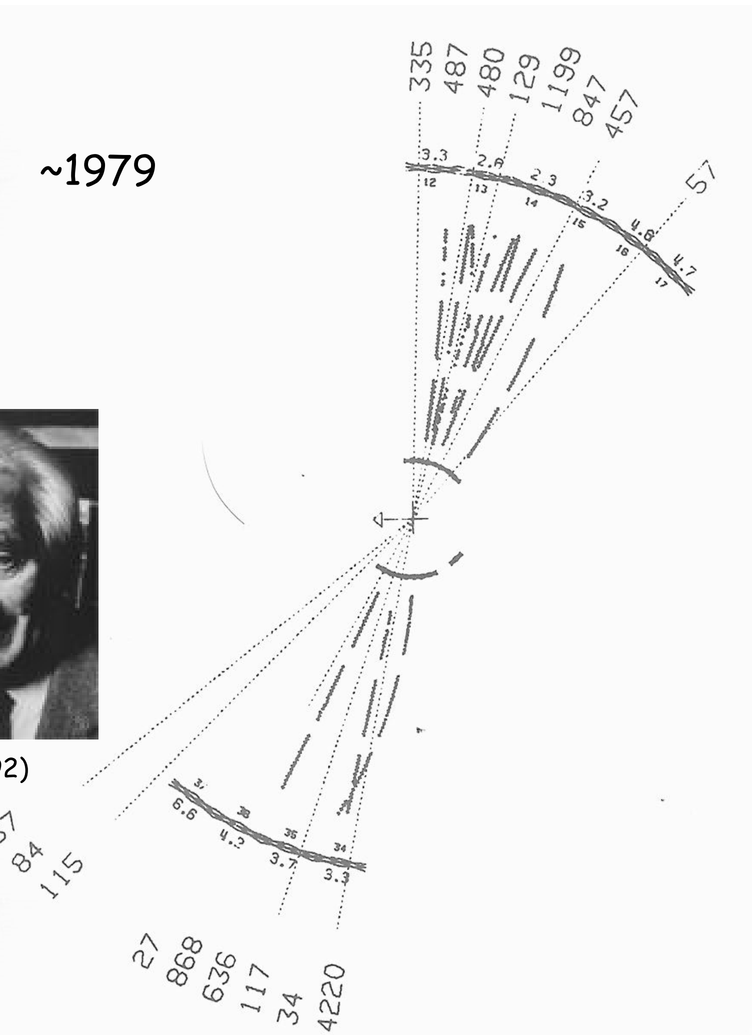


Example of the hadron production in e^+e^- annihilation in the JADE detector at the PETRA e^+e^- collider at DESY, Germany.



Georges Charpak

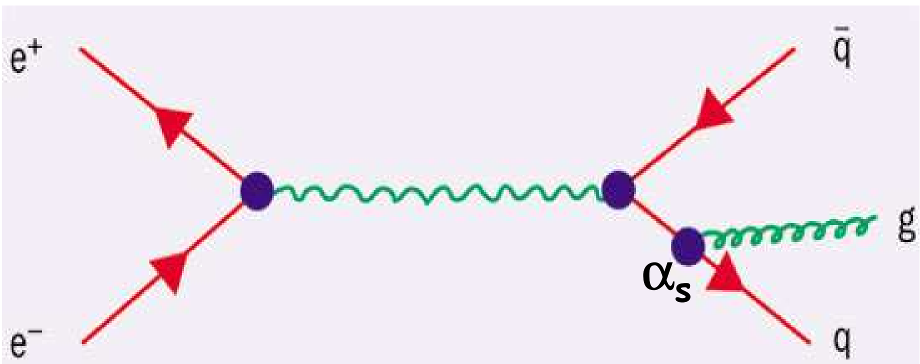
(Nobel 1992)



- $\sqrt{s}$ energy 30 GeV.
- Lines of crosses - reconstructed trajectories in drift chambers (gas ionisation detectors).
- Photons - dotted lines - detected by lead-glass Cerenkov counters.
- Two opposite jets.

Discovery of the Gluon (1979)

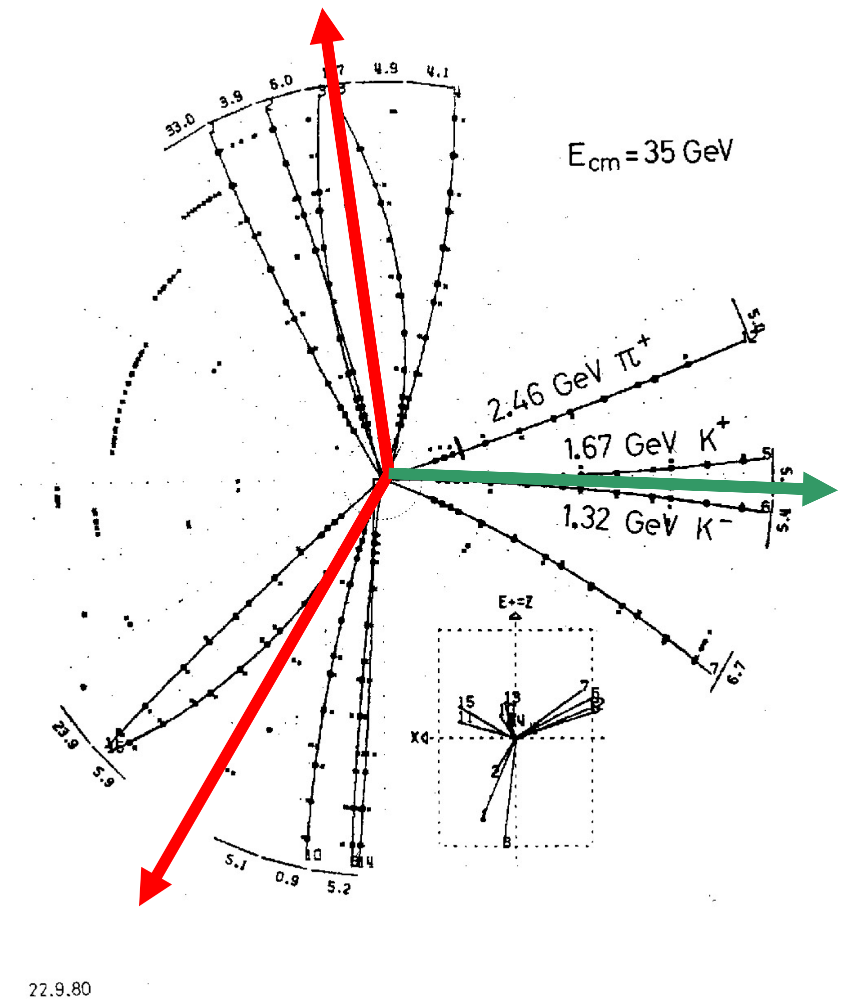
PETRA at DESY: look for



Björn Wiik Paul Söding

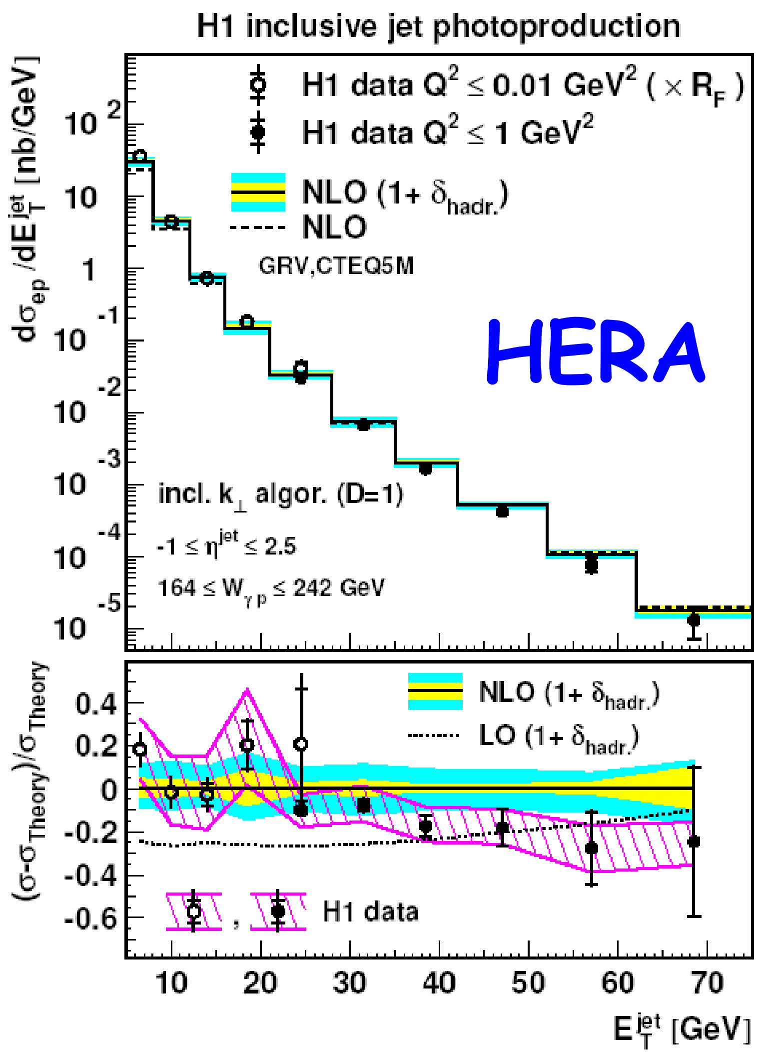
Günter Wolf Sau Lan Wu

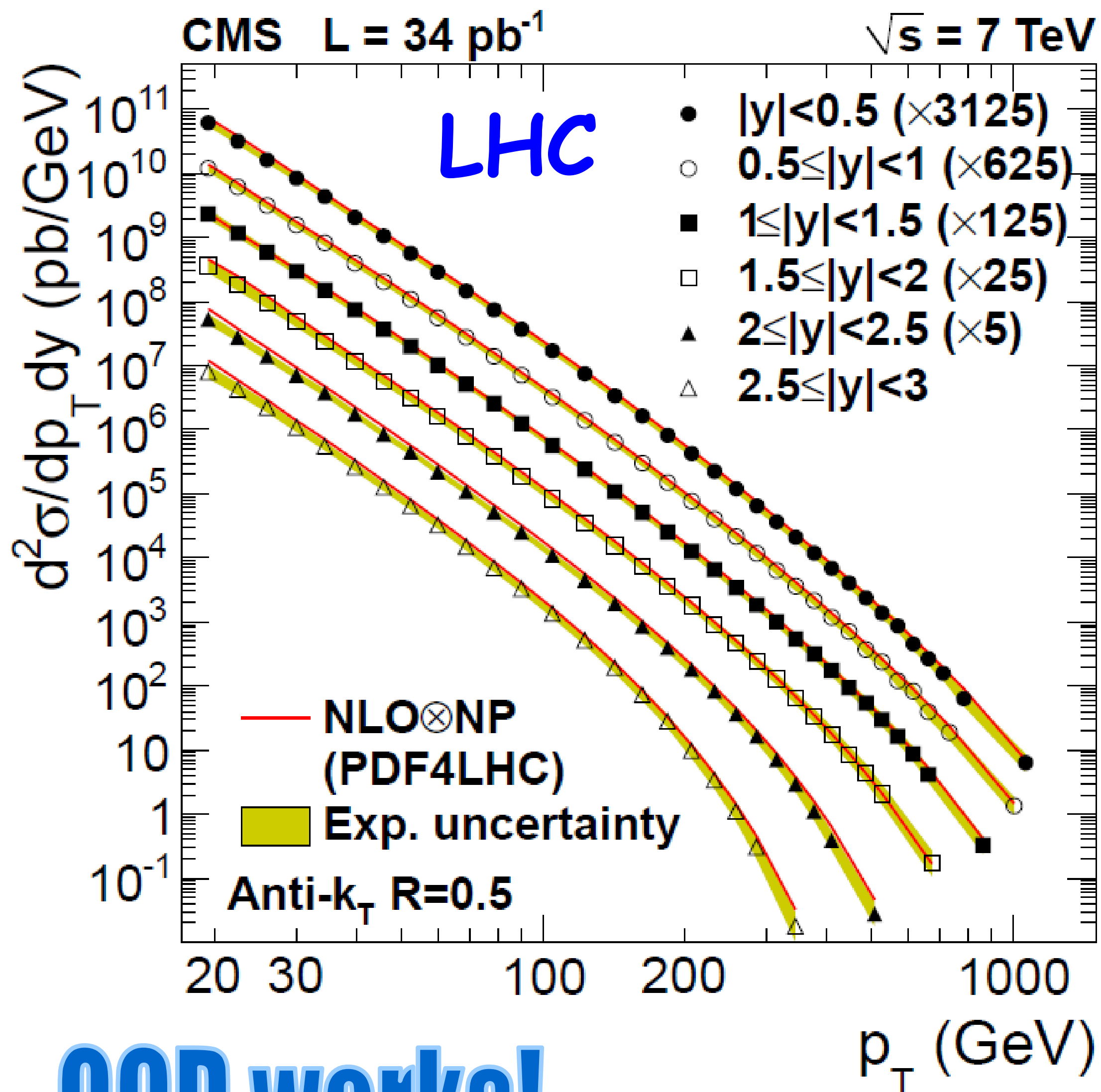
(EPS prize 1995)



TASSO event picture

Jets in ep and pp interactions



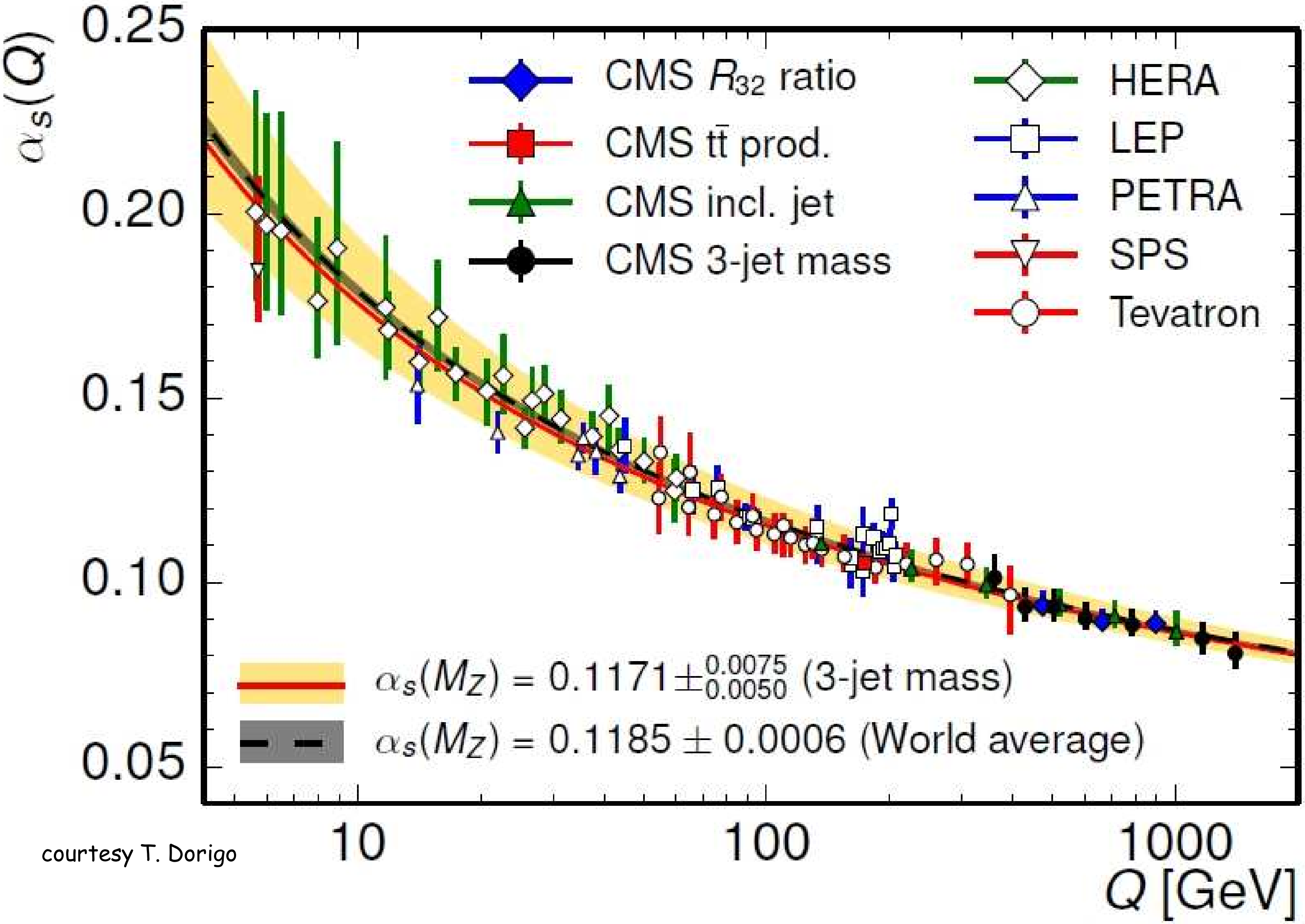


QCD works!

more details: lecture C. Seitz

Running strong coupling „constant“ α_s

e.g. from jet production at e^+e^-, ep, and pp at DESY, Fermilab and CERN



courtesy T. Dorigo

Yes, it runs!

How to determine the „size“ of a particle?

microscope:

low resolution

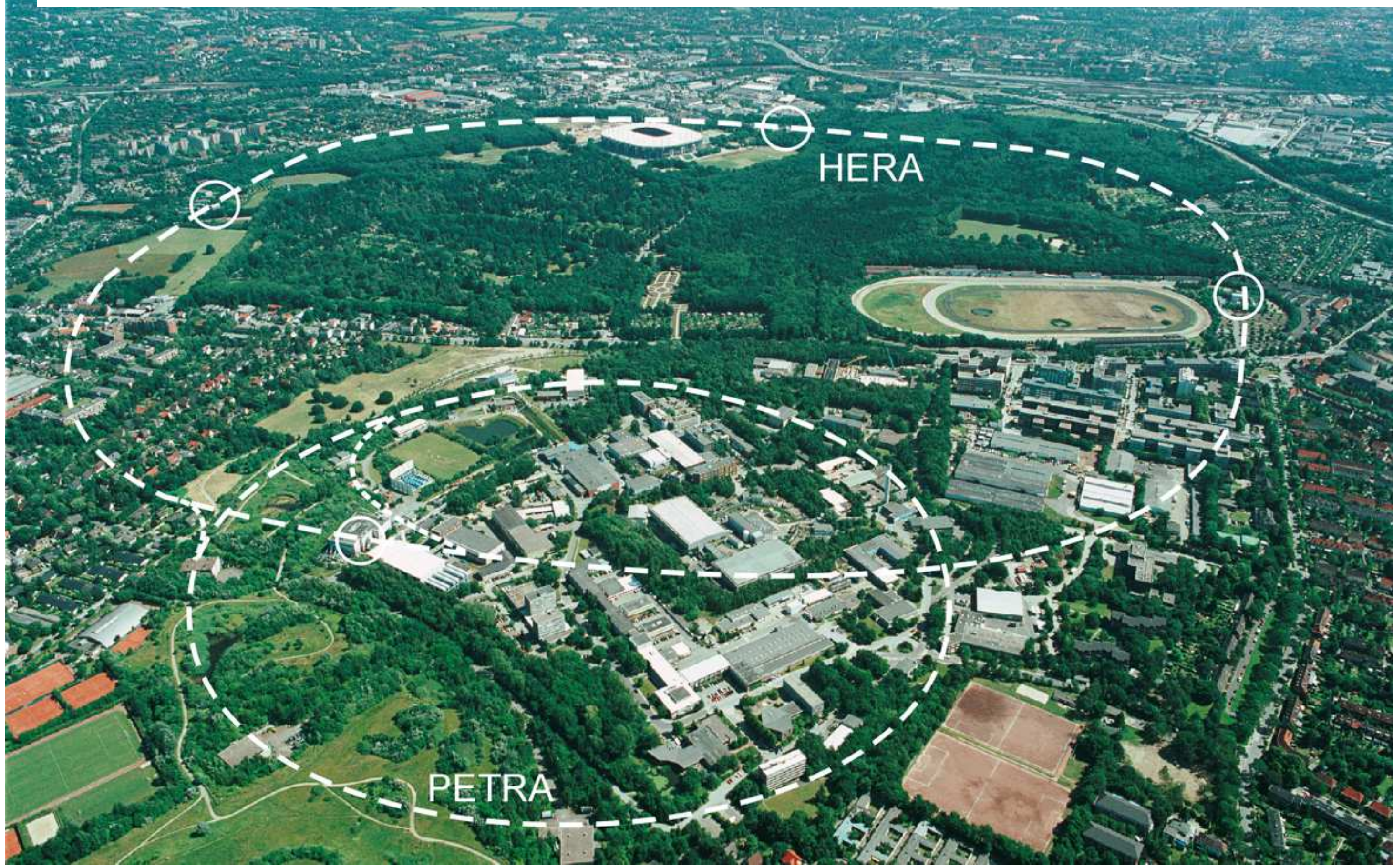
-> small instrument

high resolution

-> large instrument

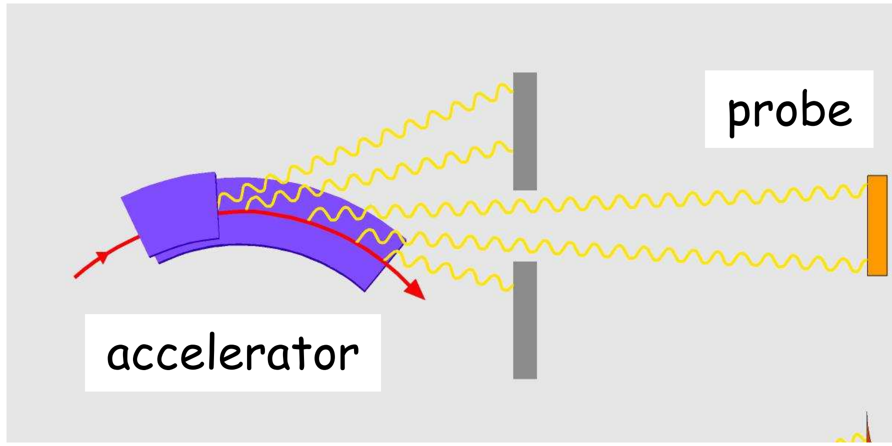
HERA = giant electron microscope

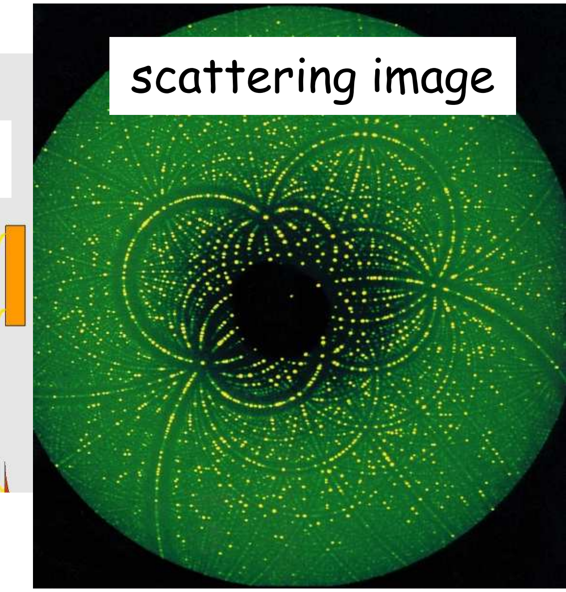
resolution ~ 10^{-18} m = 1/1000 of size of a proton



How to resolve the structure of an object?

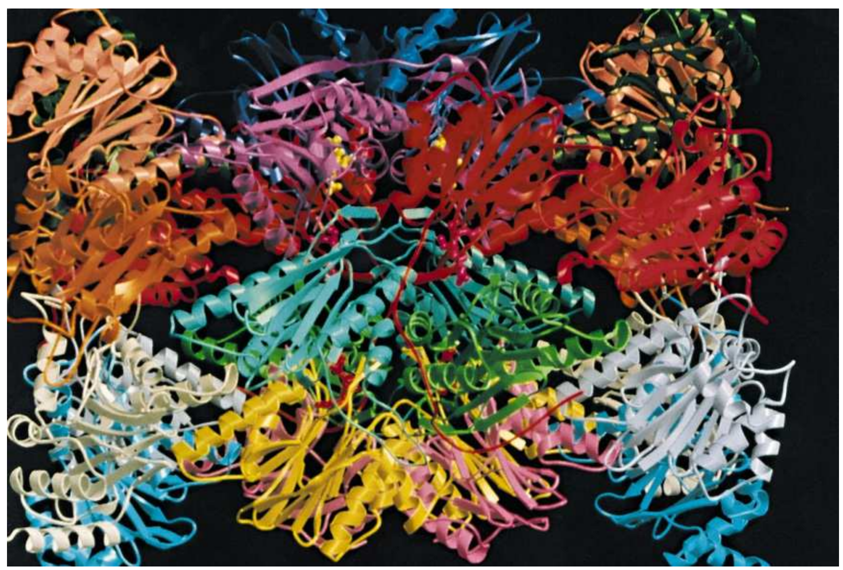
e.g. X-rays
(Hasylab,
FLASH,
PETRA III,IV
XFEL)





E~ keV

-> structure of
a biomolecule



Ada Yonath
(Nobel 2009)

more details: photon lectures

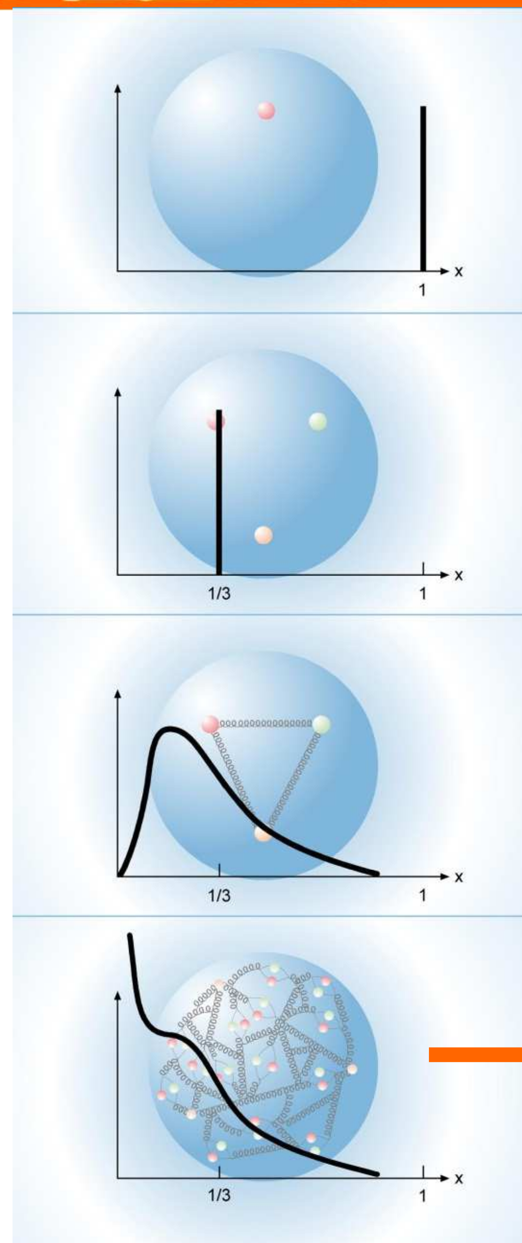
Resolve the structure of the proton

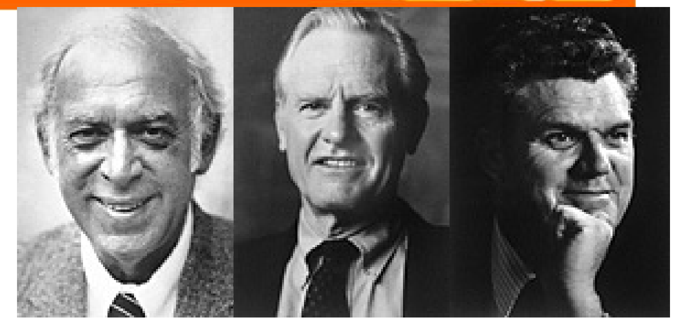
- E ~ MeV
  resolve whole proton

- static quark model,
  valence quarks
  (m ~ 350 MeV)

- E ~ m_p ~ 1 GeV
  resolve valence quarks
  and their motion

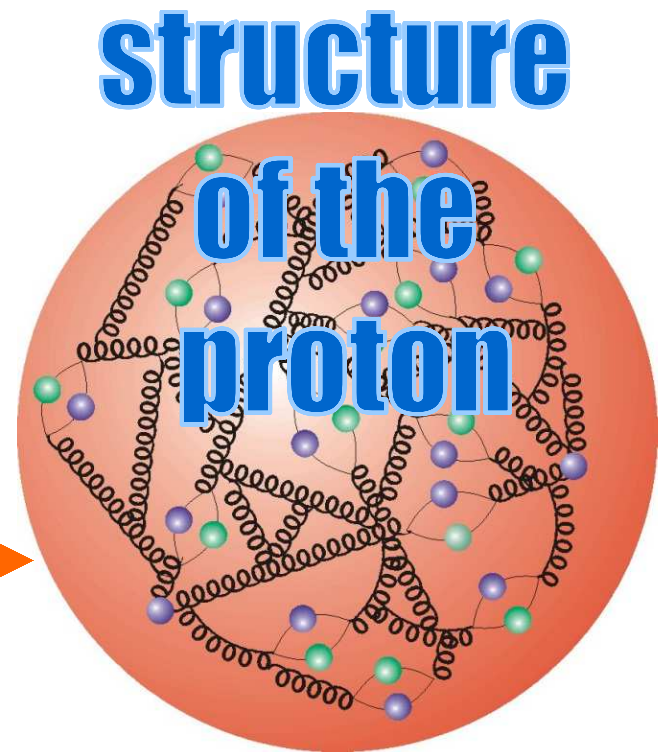
- E >> 1 GeV
  resolve quark and gluon
  "sea"



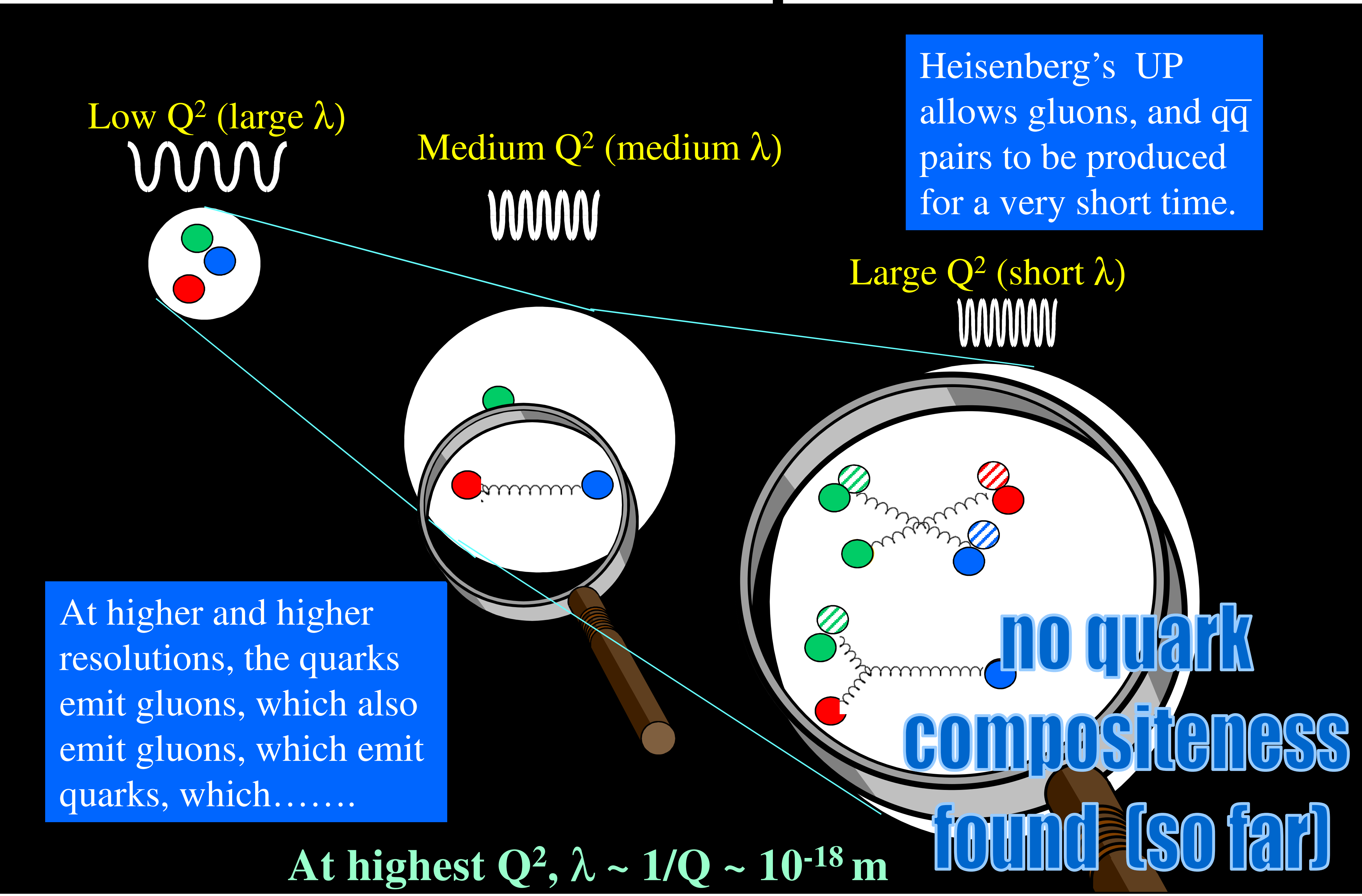


Jerome I. Friedmann   Henry W. Kendall   Richard E. Taylor

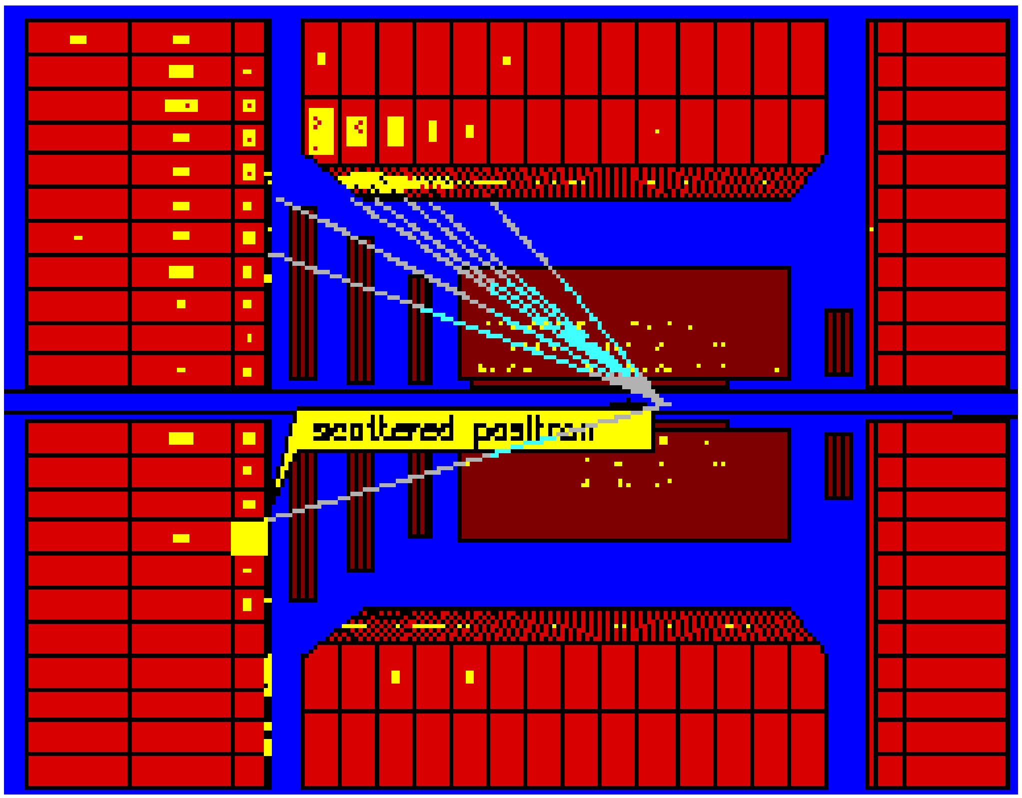
(Nobel 1990)

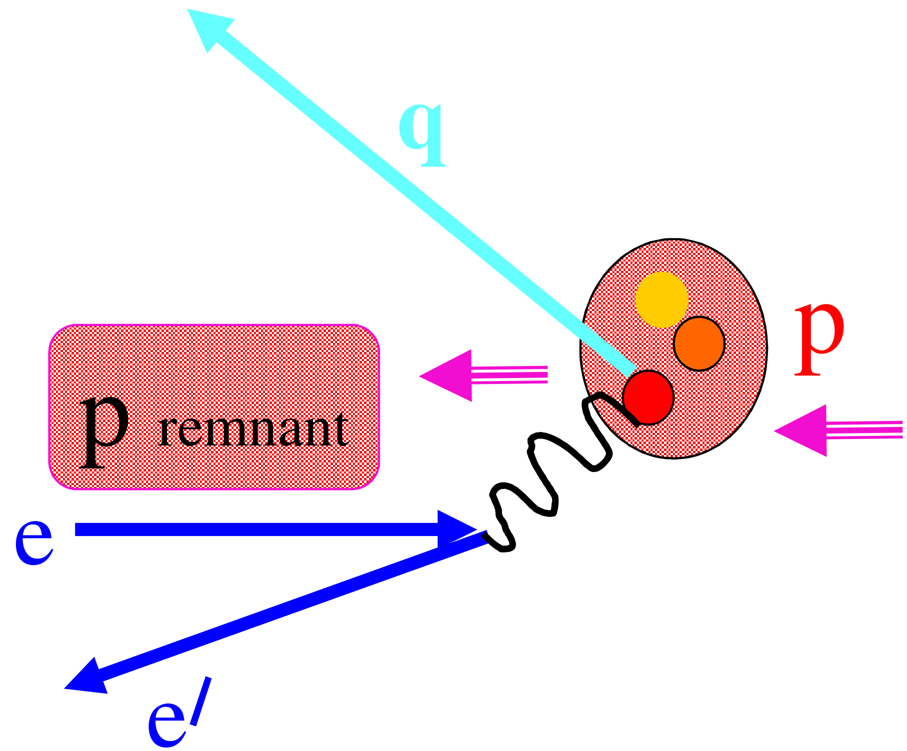


Inside the proton

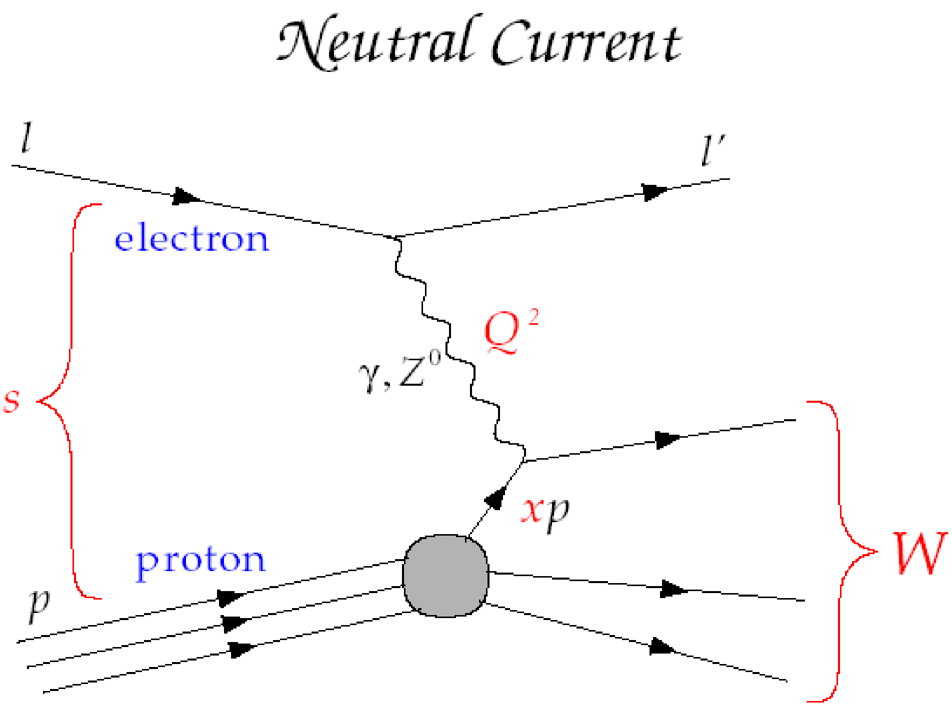


Deep Inelastic ep Scattering at HERA





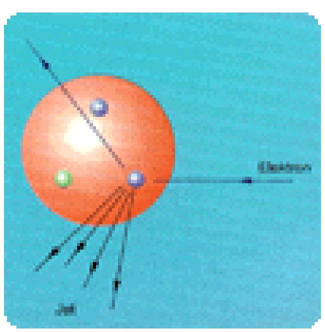
Deep Inelastic Scattering (DIS)



► 2 degrees of freedom at fixed cms energy $s = (l + p)^2$

boson virtuality (resolution scale) $Q^2 = -(l - l')^2 = -q^2$

fractional momentum of struck quark (in QPM) $x = \frac{Q^2}{2p \cdot q}$



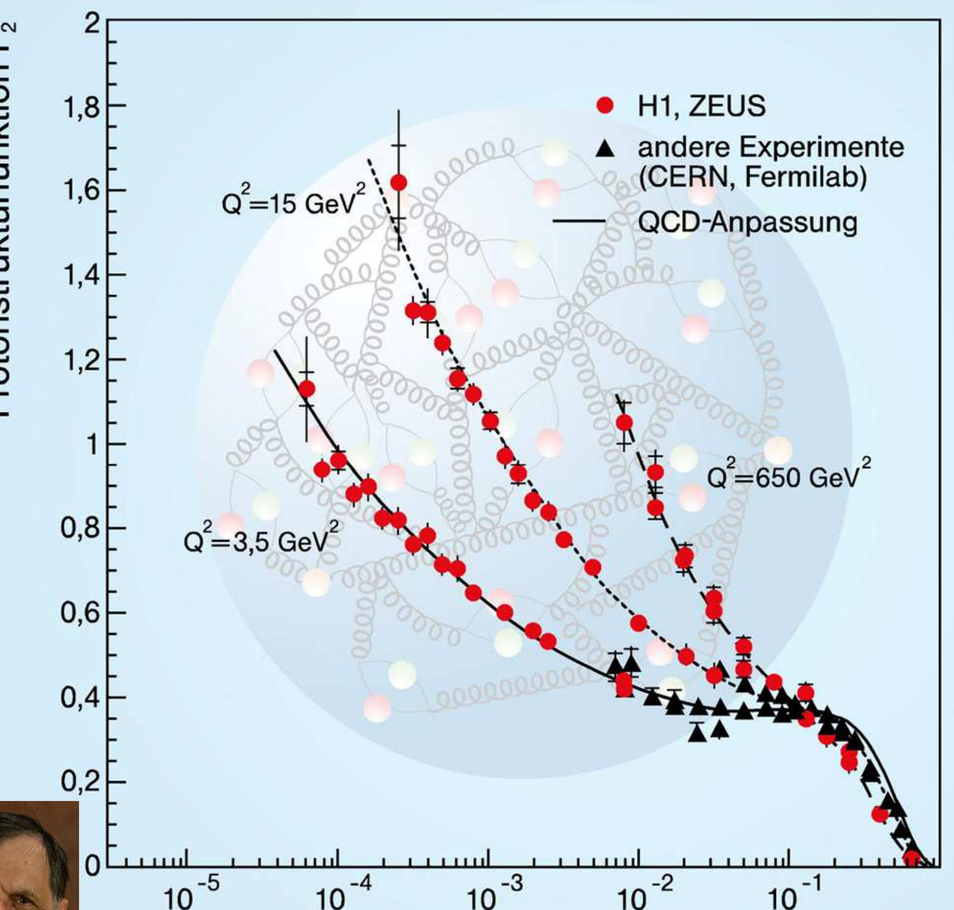
Parton distribution functions (PDF) in pQCD

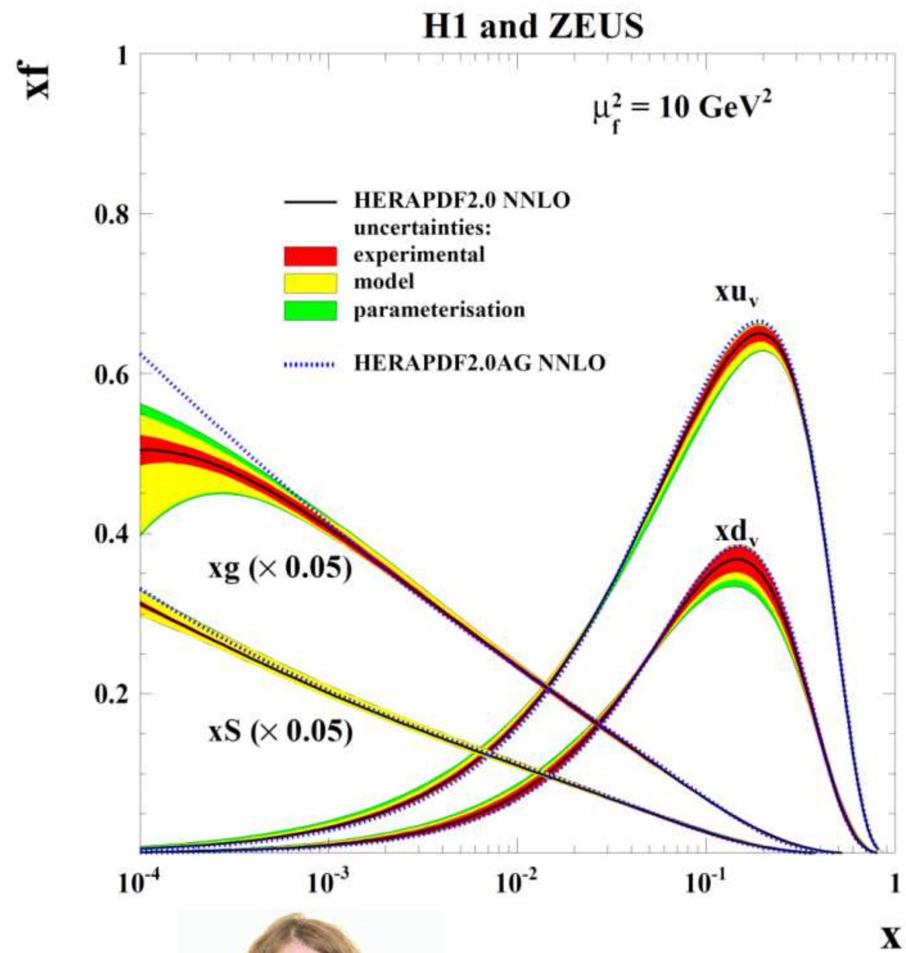
$$F_2^{em}(x, Q^2) = x \sum_i e_i^2 [q_i(x, Q^2) + \bar{q}_i(x, Q^2)]$$

q_i – probability to find quark with flavour i in proton

The Proton Structure

structure functions → quark and gluon densities

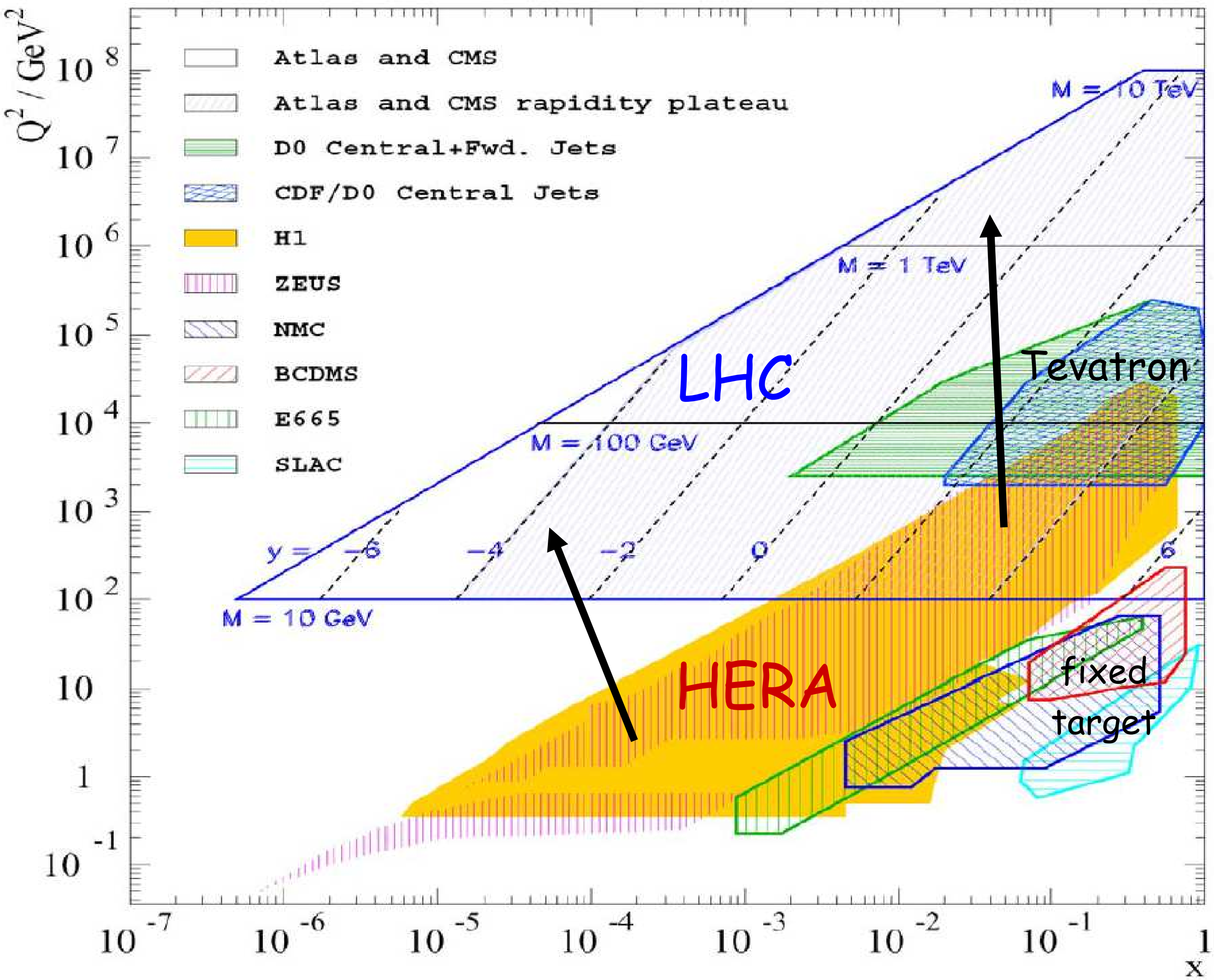




Giorgio Parisi
(Nobel Prize 2021)

Amanda Cooper-Sarkar
(Chadwick medal 2015)

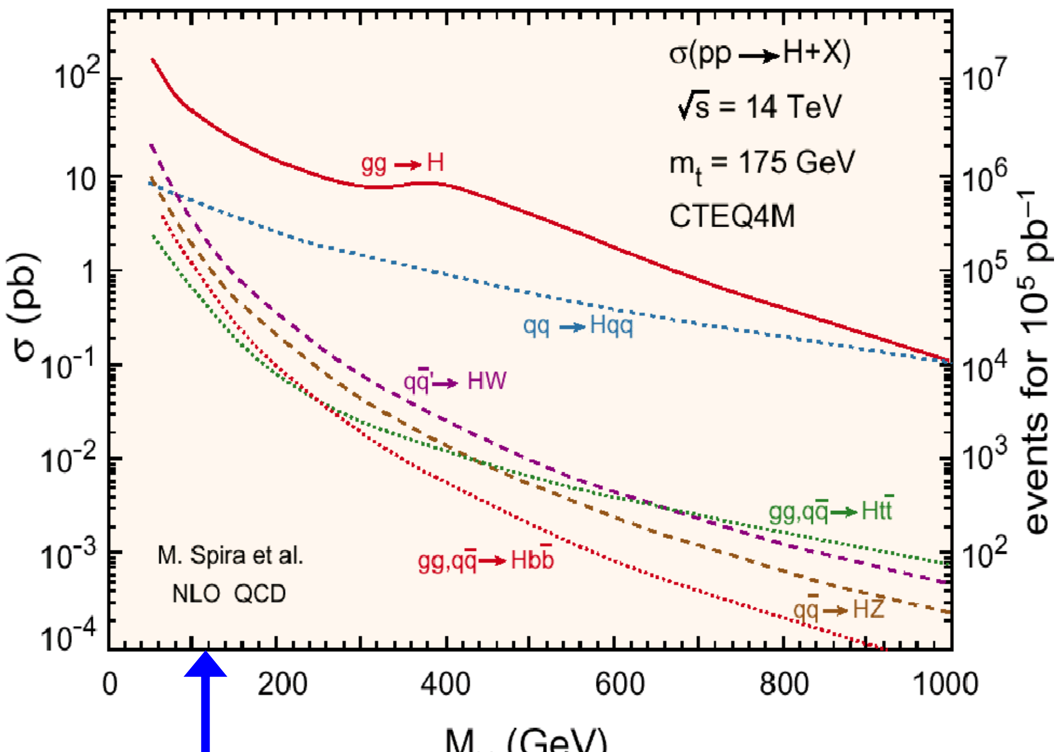
Kinematic regions: HERA vs. LHC



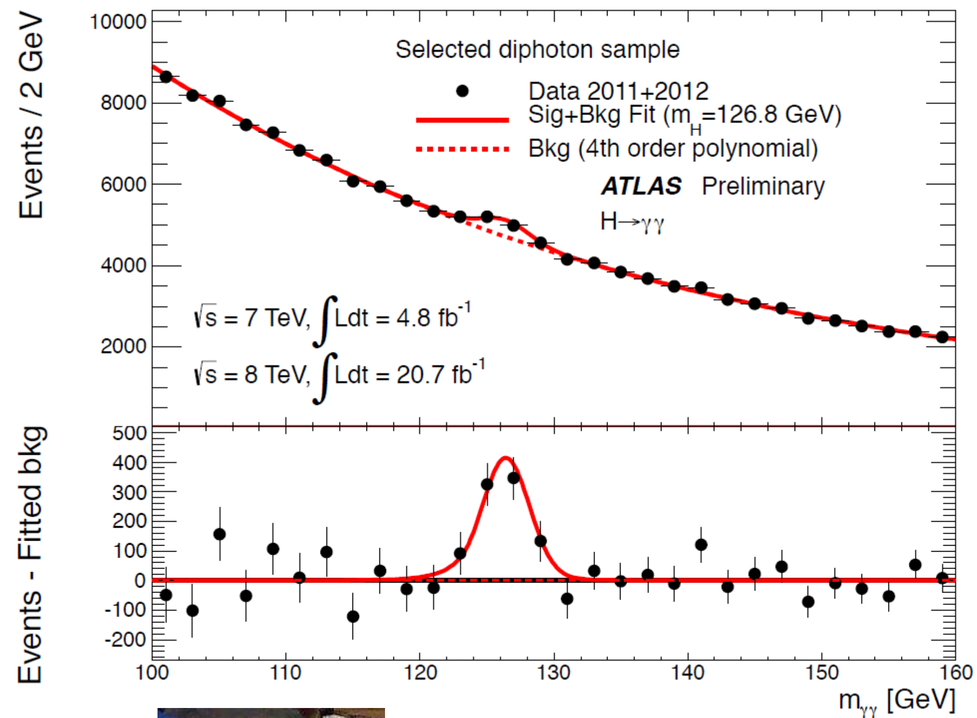
- proton structure measured directly for large part of LHC phase space
- QCD evolution successful
  -> safely extrapolate to higher Q^2

Input to measure-ments at LHC

Example: Higgs cross section at LHC



H -> γγ in ATLAS



Kerstin Tackmann

(DPG Hertha Sponer prize 2013,
IUPAP Young Particle Physicist Prize 2014)

Knowledge of gluon and quark distributions essential

Intermediate summary

- Particle physics: Symmetries and conservation laws are important
- many exciting results at DESY, CERN and elsewhere!
- HERA closed down, but particle physics at DESY (e.g. participation in LHC) alive and well
- next: weak interactions, Higgs,
  neutrinos, cosmology,
  future of particle physics