Introduction to Particle Physics

Achim Geiser, DESY Hamburg

DESY summer student program,
23.7.25, part I

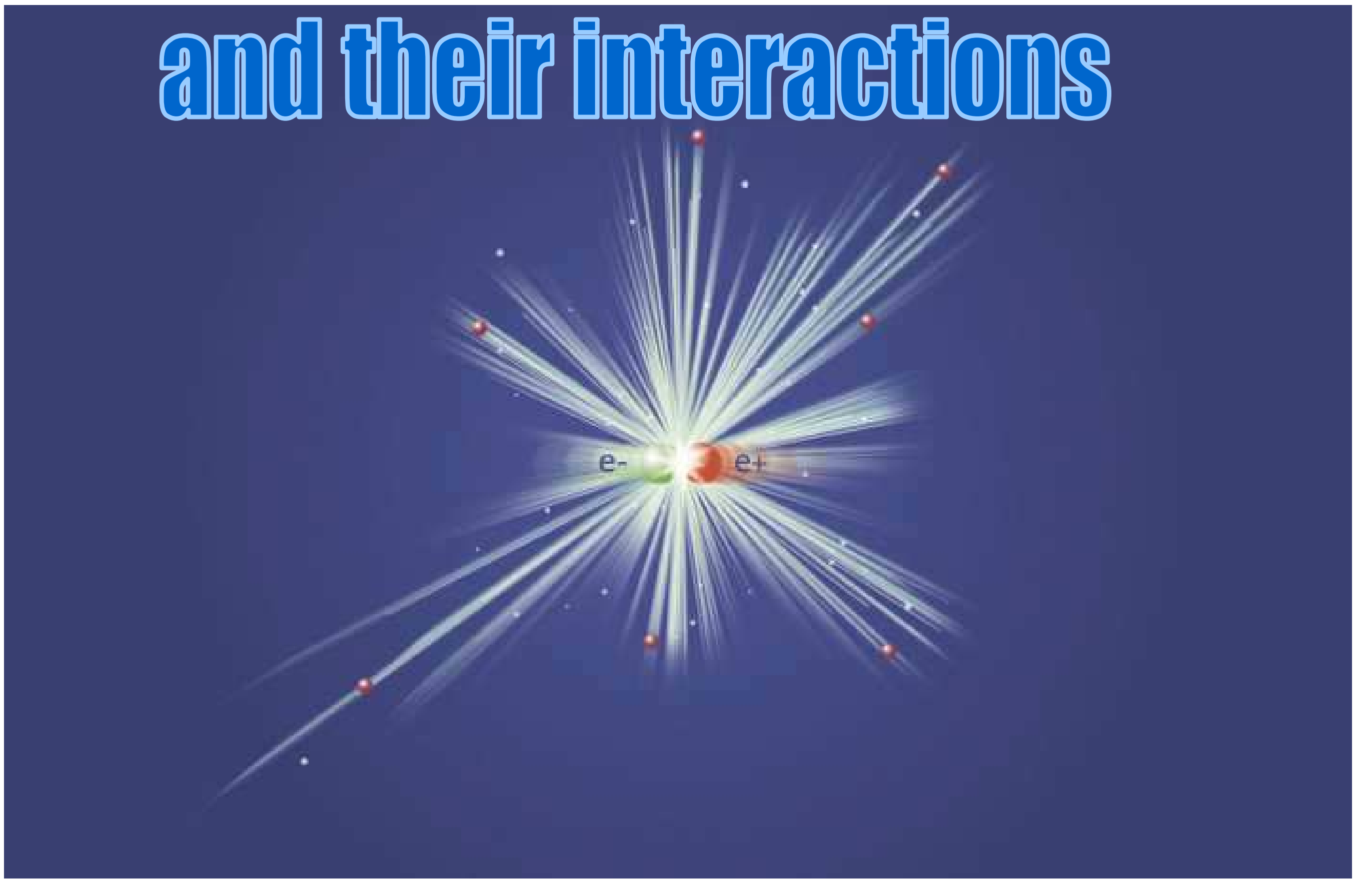
Scope of this lecture:

- 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?

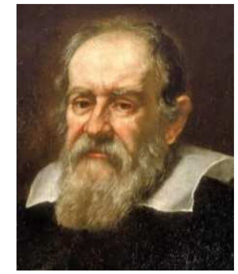
Particle Physics
= science of elementary particles
and their interactions



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

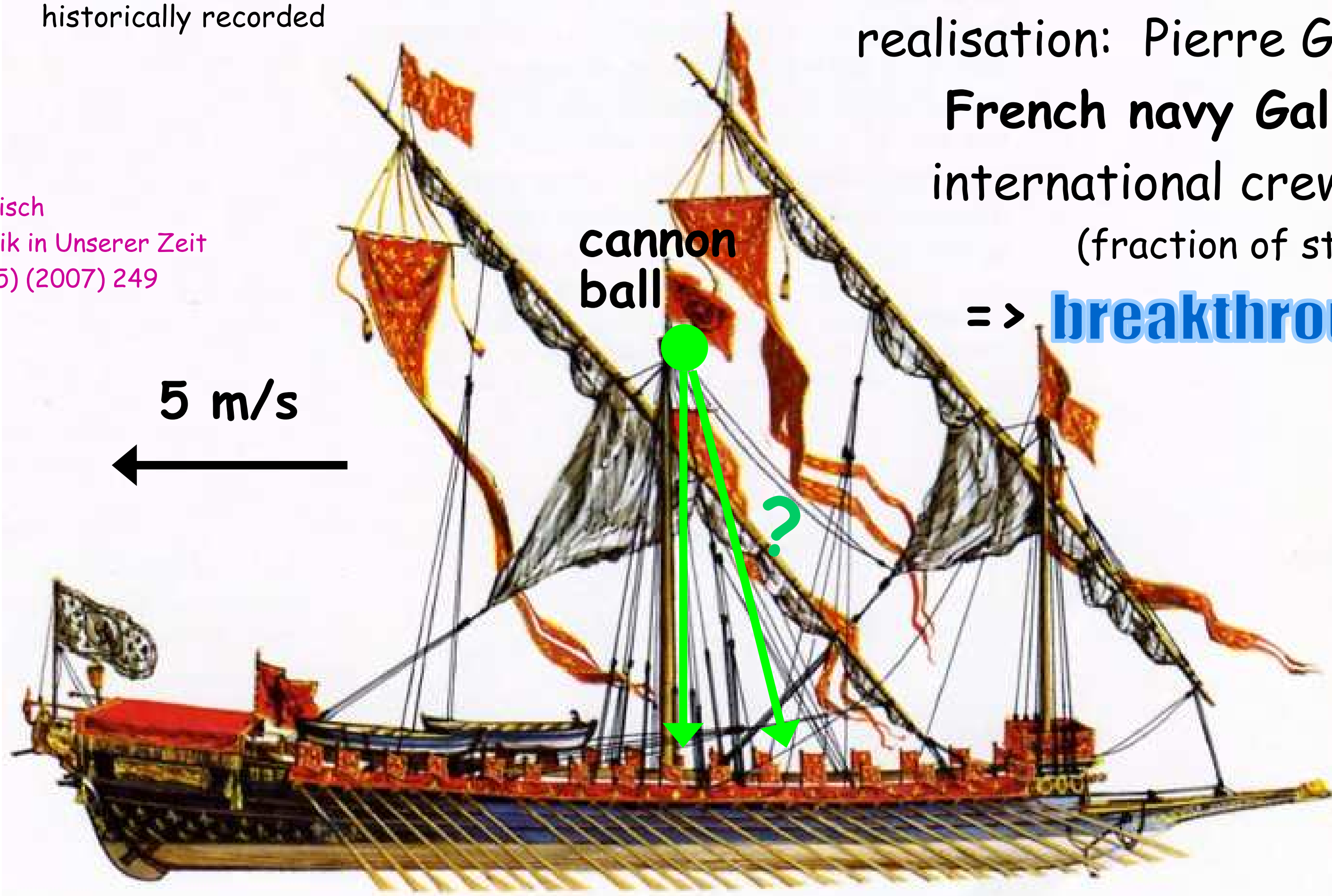
First large scale scientific experiment: proposal: Galilei 1632
^historically recorded

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)

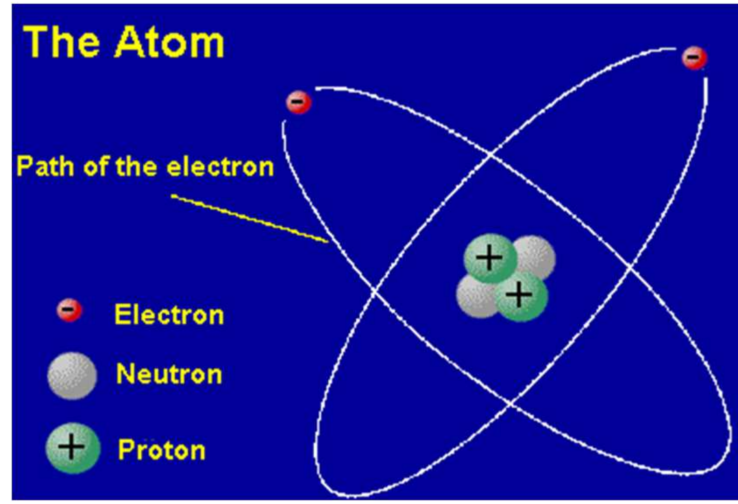
Emilie du Châtelet (1759)

- **Modern view:**

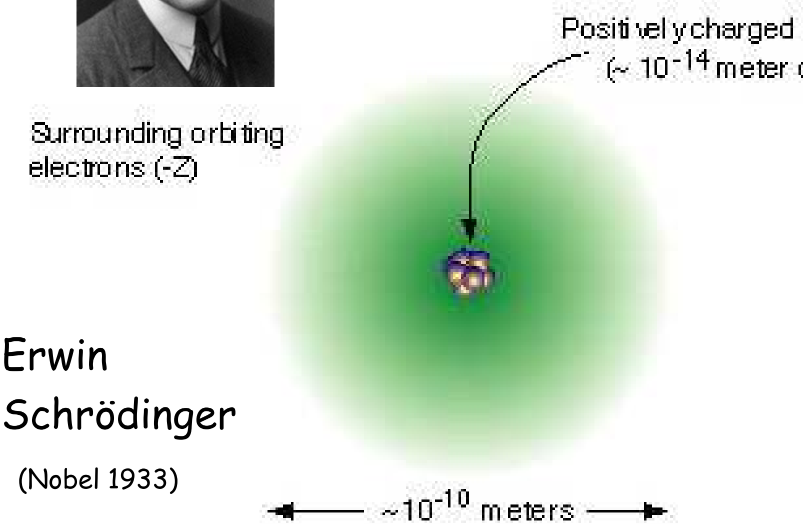
particles = objects with discrete quantum numbers, e.g. charge, mass, ...

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)



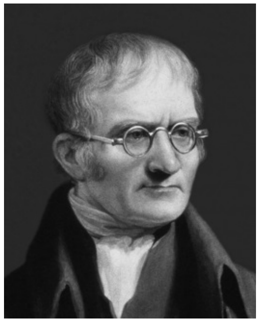
Louis de Broglie (Nobel 1929)

Werner Heisenberg (Nobel 1932)

Erwin Schrödinger (Nobel 1933)

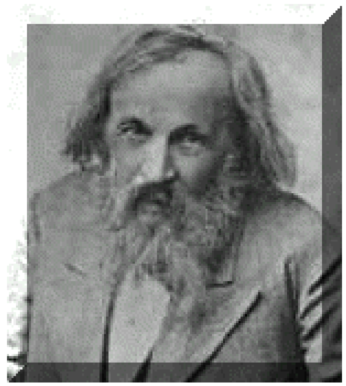
What is „elementary"?

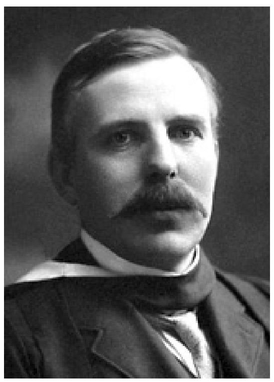
Greek: atomos = smallest indivisible part



John Dalton
1803
(atomic model)

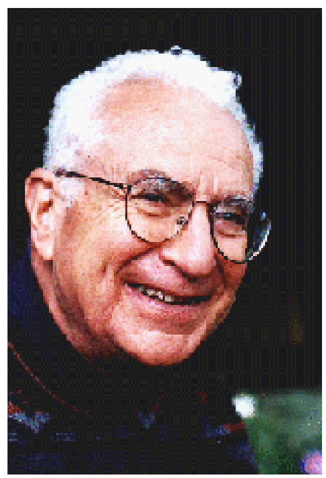
Dmitry Ivanowitsch Mendeleyev
1868
(elements)



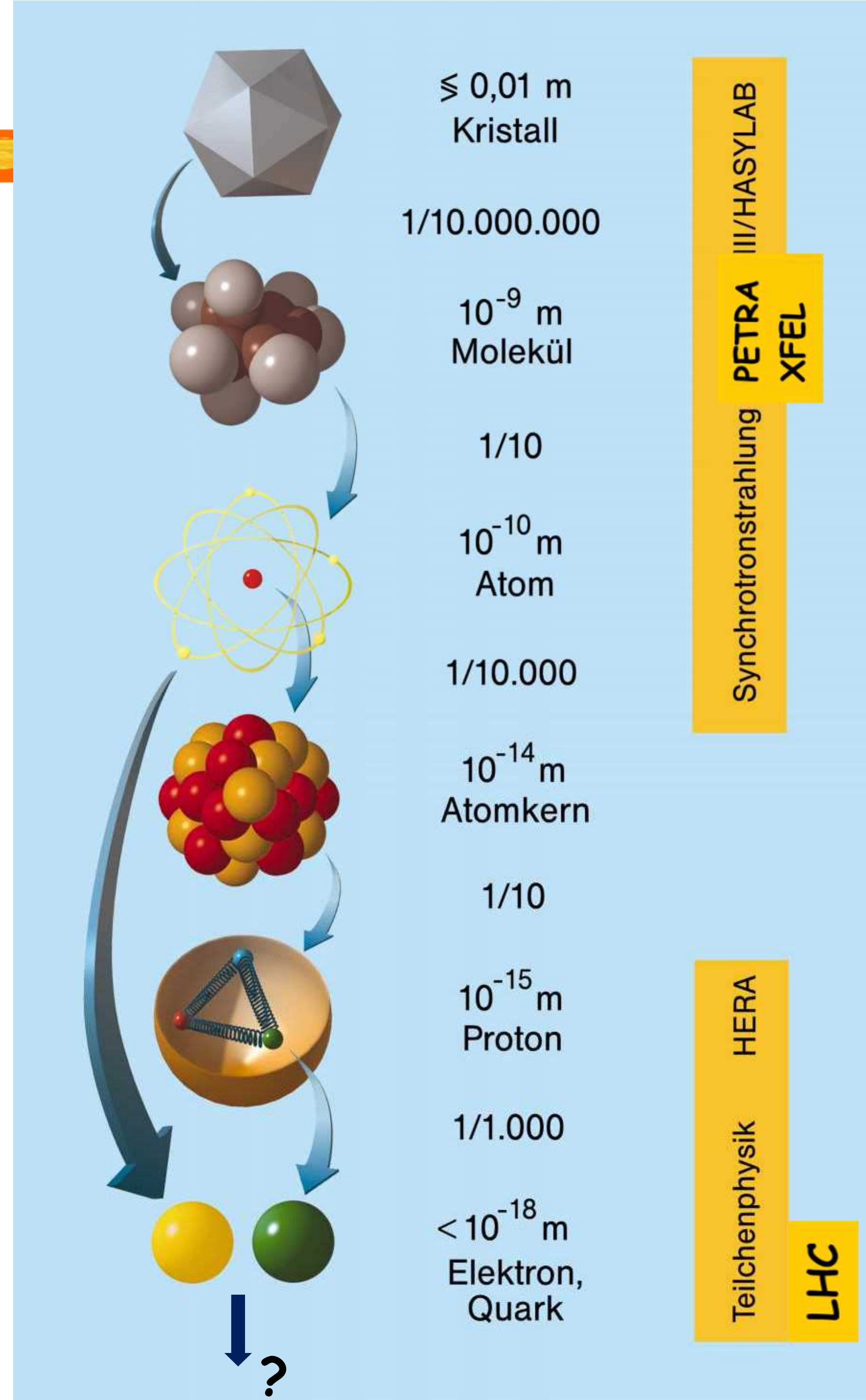


Ernest Rutherford
1911
(nucleus)
(Nobel 1908)

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

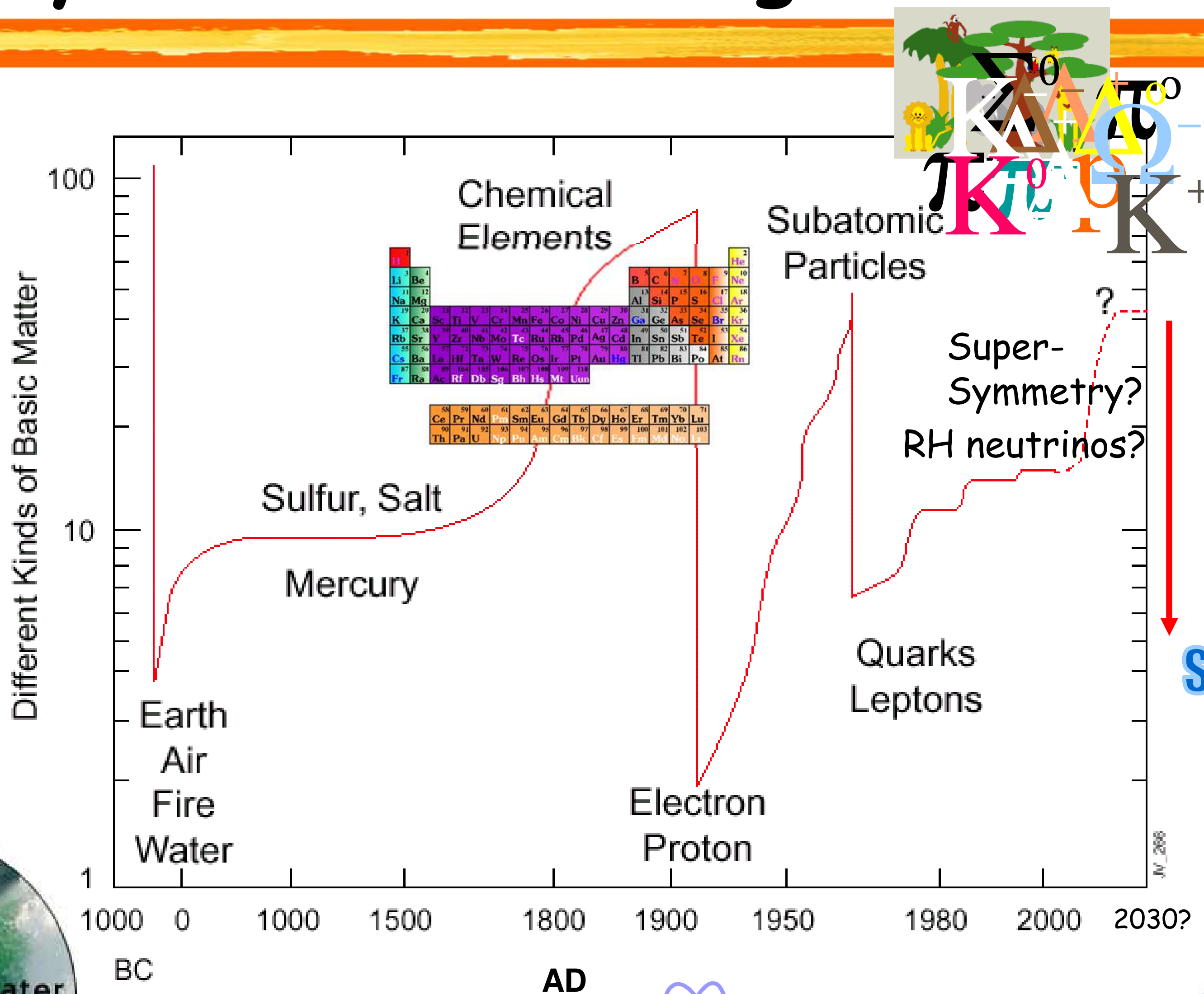


elementary
= no detectable substructure

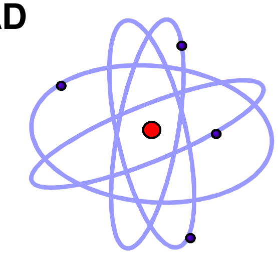


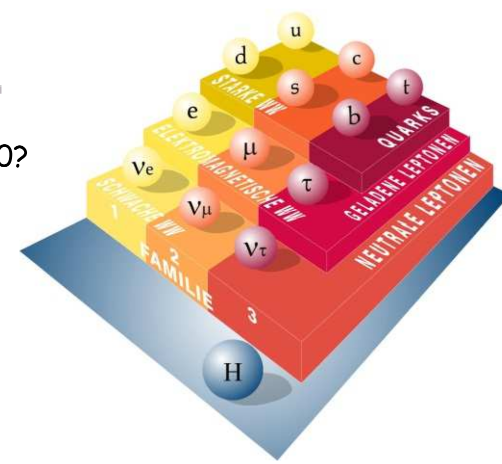
History of basic building blocks of matter

motivation:
find
smallest
possible
number



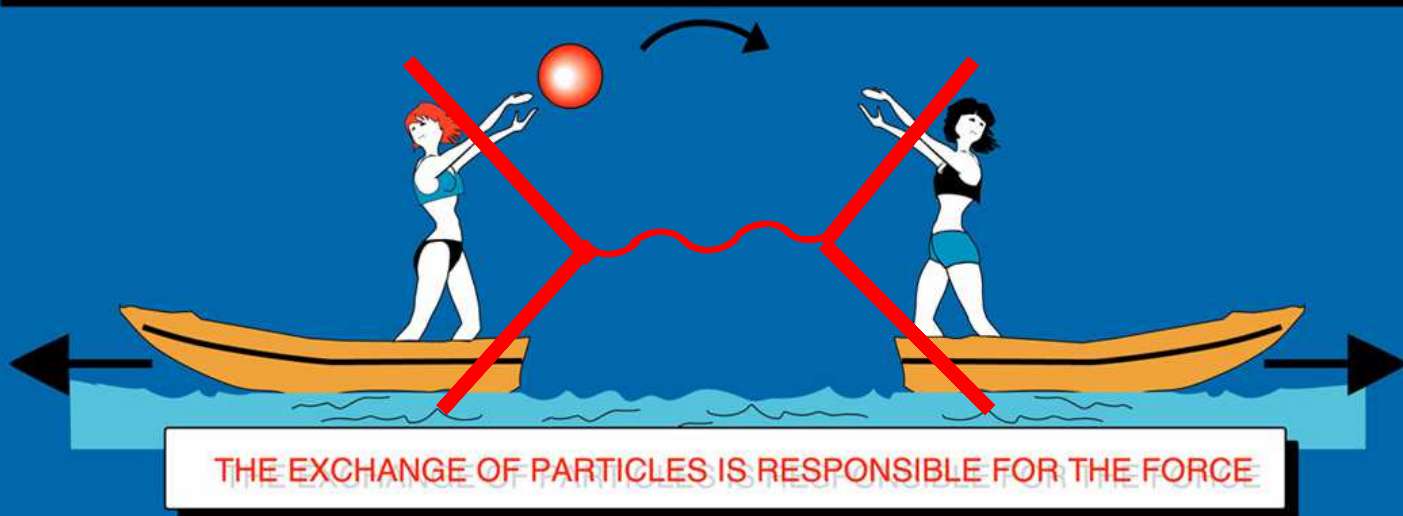
Quark and Lepton substructure ??





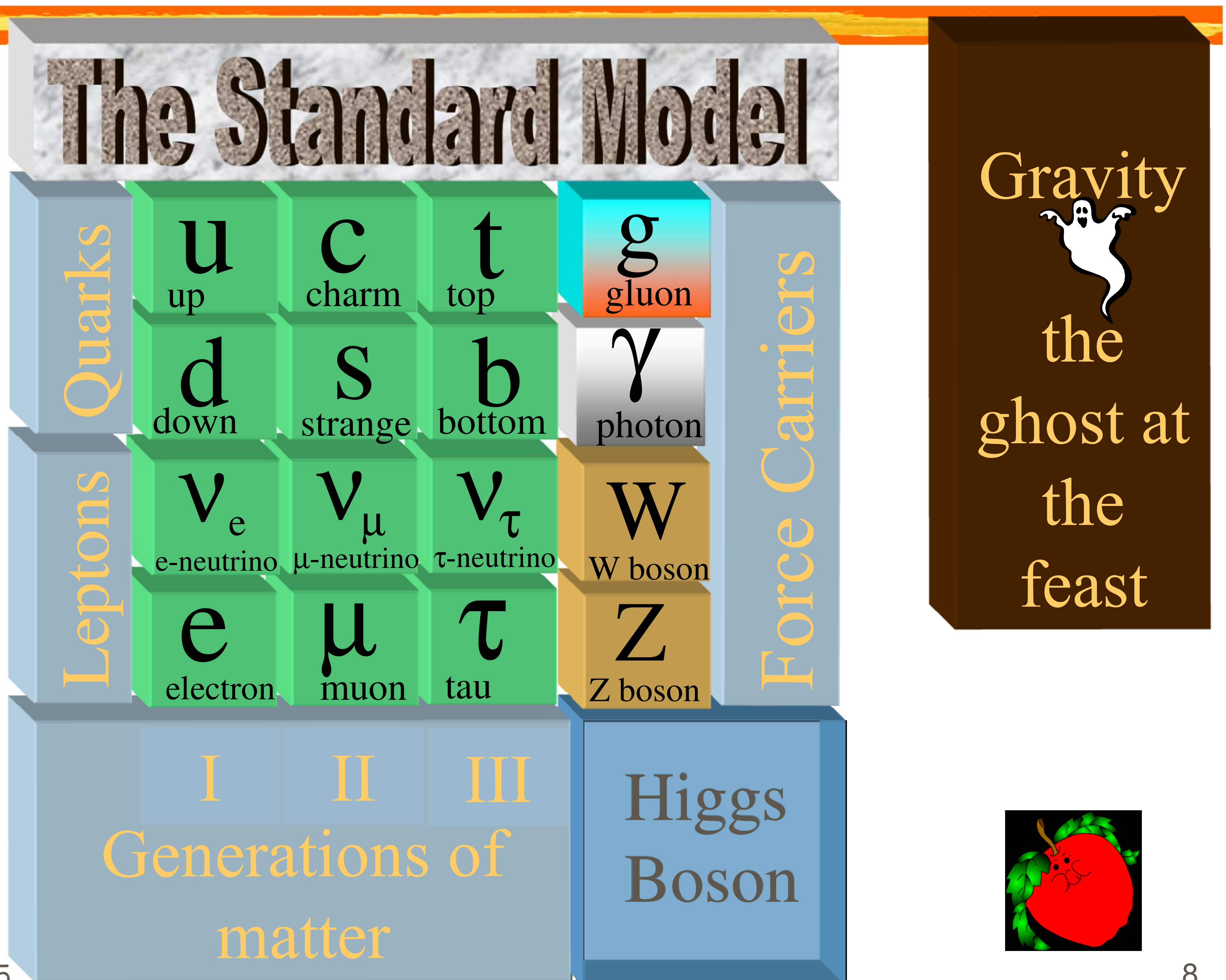
Which “interactions”?

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^0 , W+ , W- (HEAVY)	RADIOACTIVE BETA DESINTEGRATION
GRAVITATION	$\sim 10^{-38}$	GRAVITONS (?)	HEAVENLY BODIES



CERN AC _Z04_ V25/8/1992

What we know today

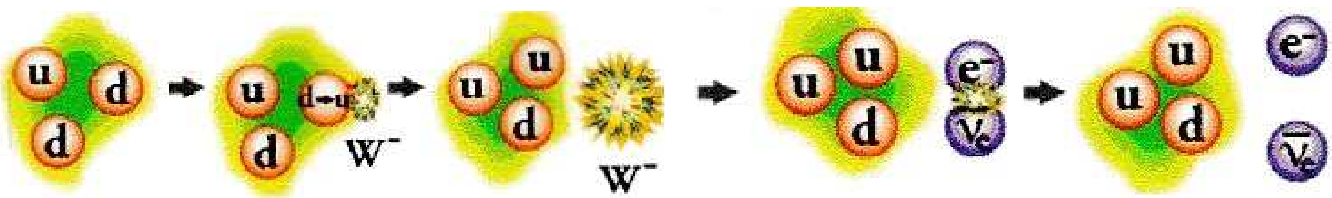


The Power of Conservation Laws

- 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

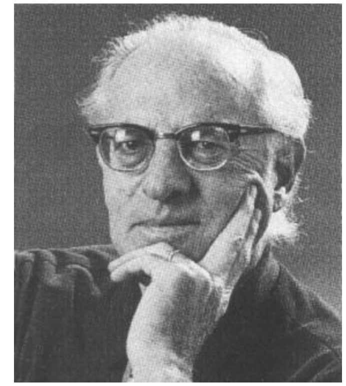
confirmation: neutrino detection

- e.g. reversed reaction:

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

extremely rare!

(absorption length ~ 3 light years Pb)



Frederick Reines

(Nobel 1995)

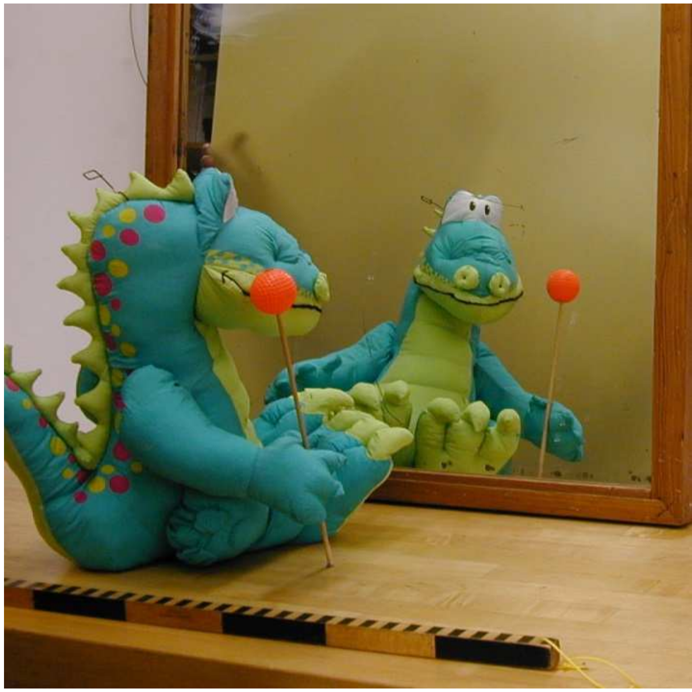
- first detection: 1956

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)

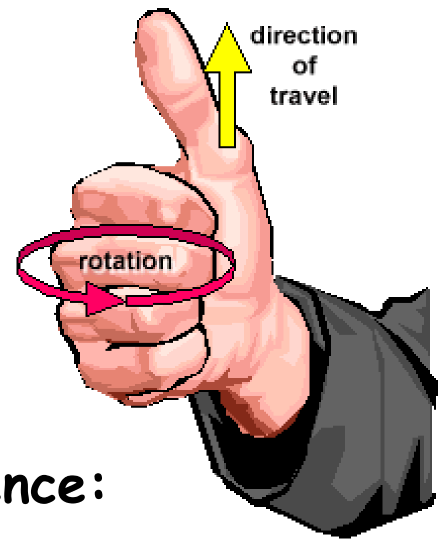
- What about basic interactions?
- Electromagnetic and strong interactions conserve parity!

The power of symmetries: Parity

Lee & Yang 1956: **weak interactions violate Parity**

experimentally verified by Wu et al. 1957:

spin

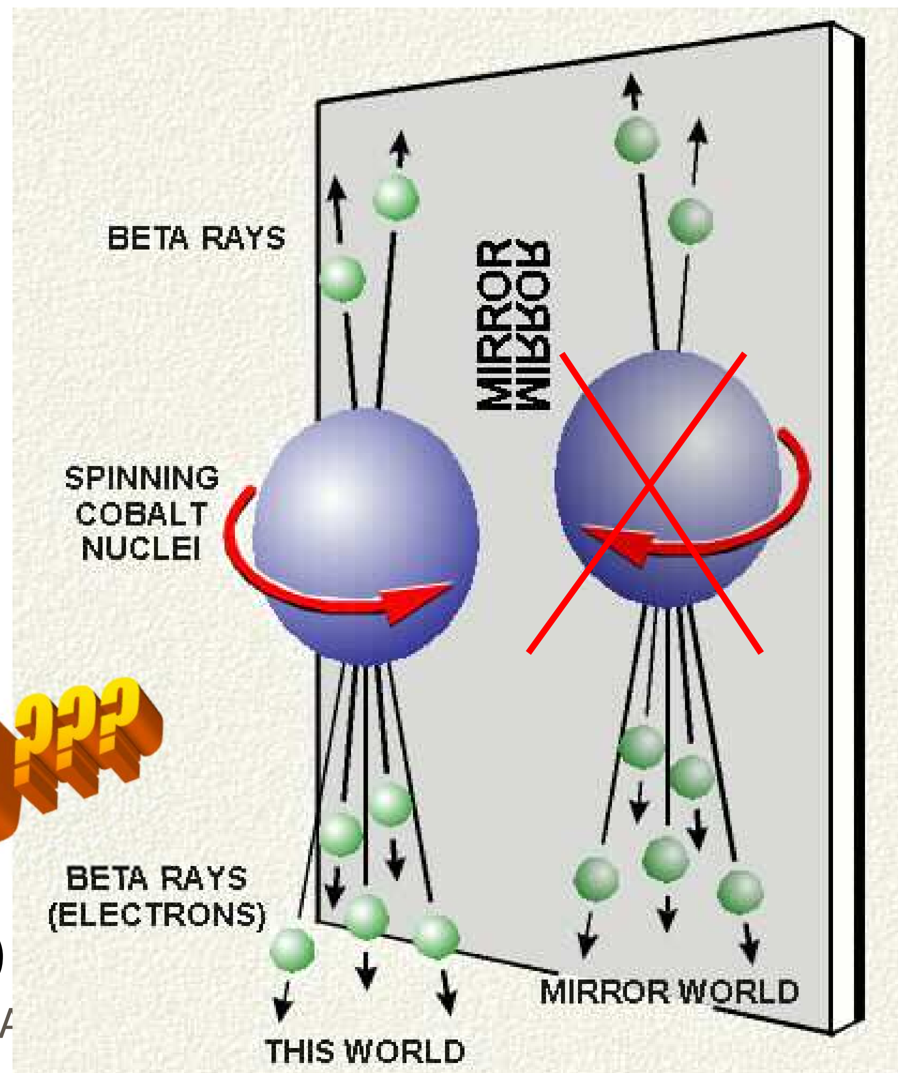


consequence:

neutrinos are always lefthanded !

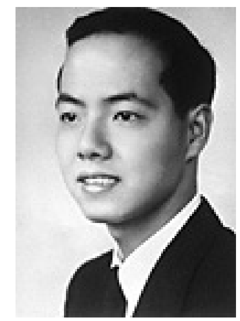
(antineutrinos righthanded)

Why???



Chen Ning Yang

(Nobel 1957)



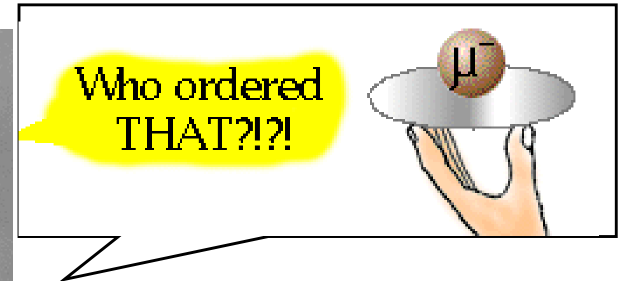
Tsung -Dao Lee

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: $\mu^- \rightarrow \nu_\mu \, e^- \, \bar{\nu}_e$

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**

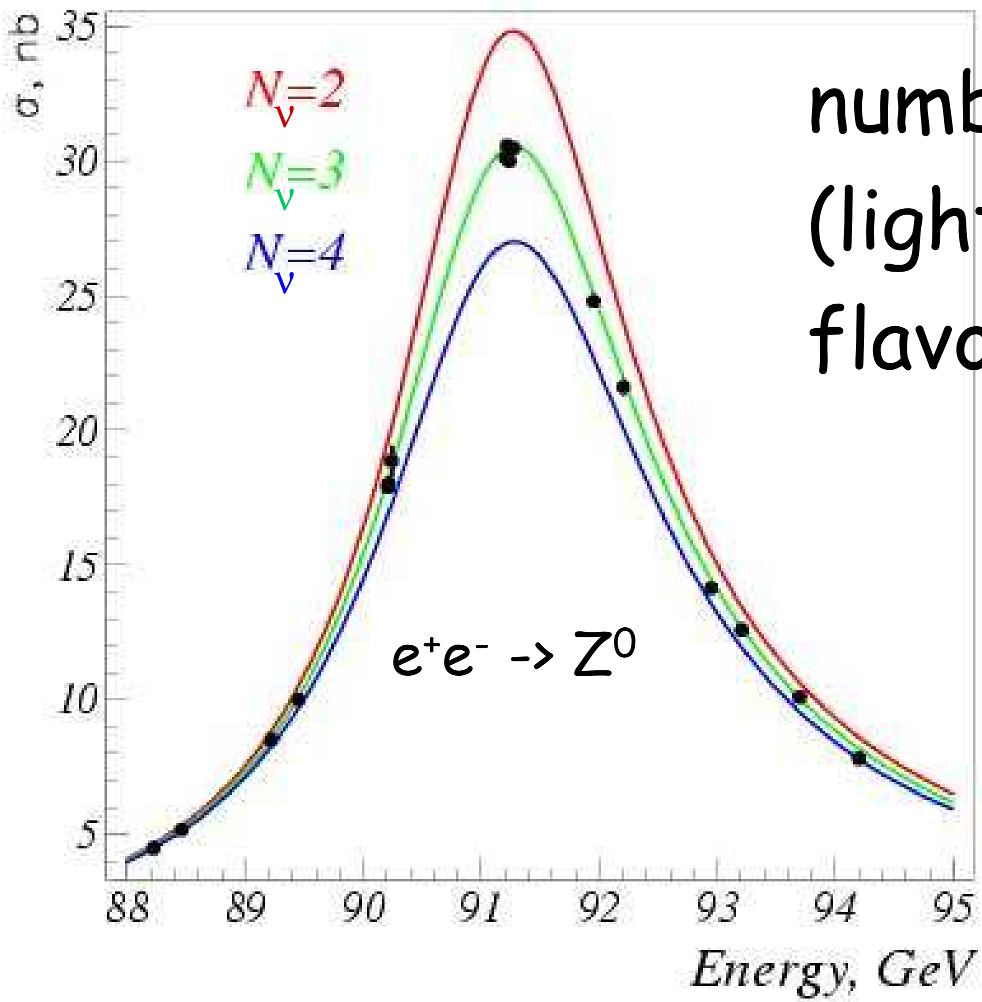
Why???

- 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)



$e^+e^- \to Z^0$

number of (light) neutrino flavours = 3

Gerardus t'Hooft Martinus Veltman

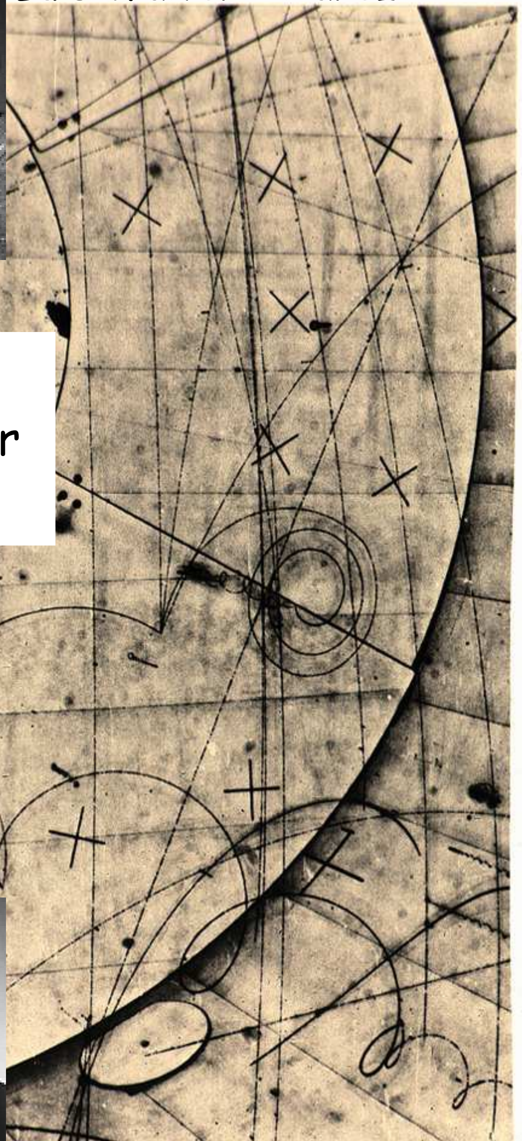
(Nobel 1999)

There seem to be exactly three lepton + quark families !

Why???

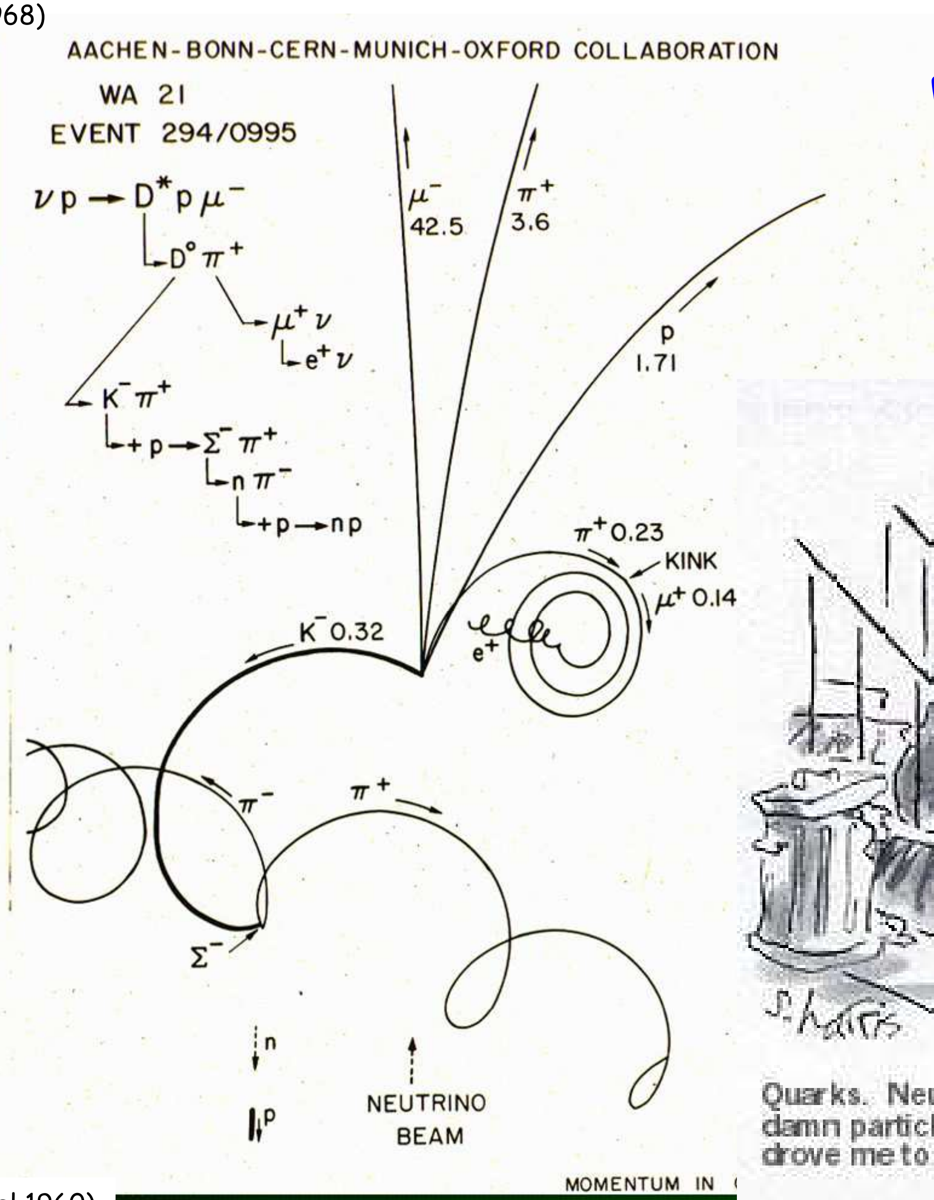
Can we "see" particles?

Luis Walter Alvarez (Nobel 1968)



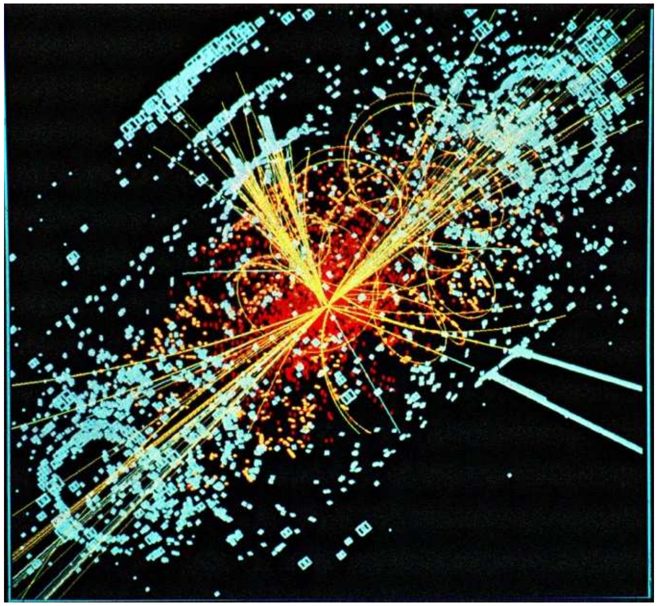
bubble chamber photo

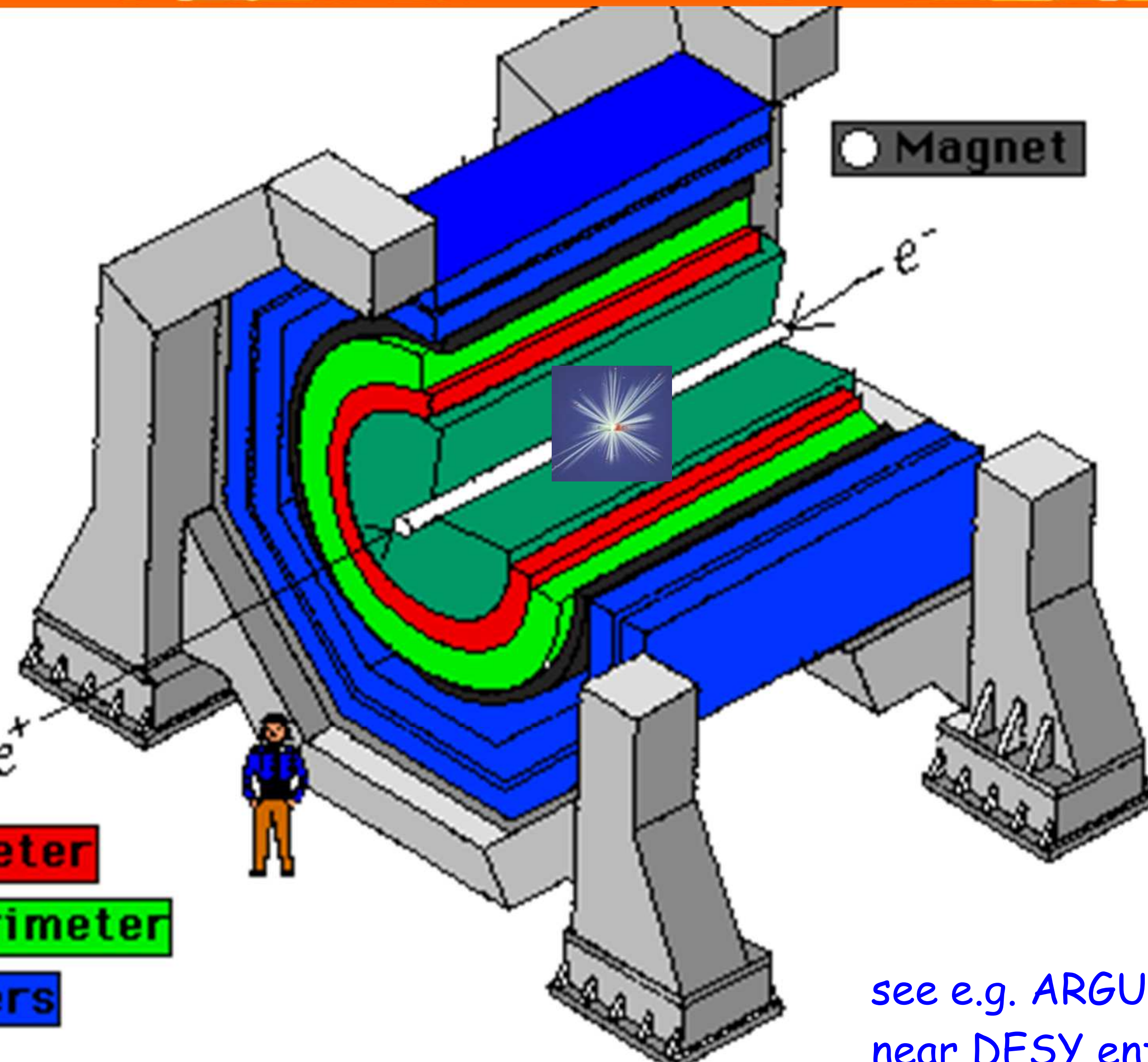
Donald Arthur Glaser (Nobel 1960)



we can!

A typical particle physics detector





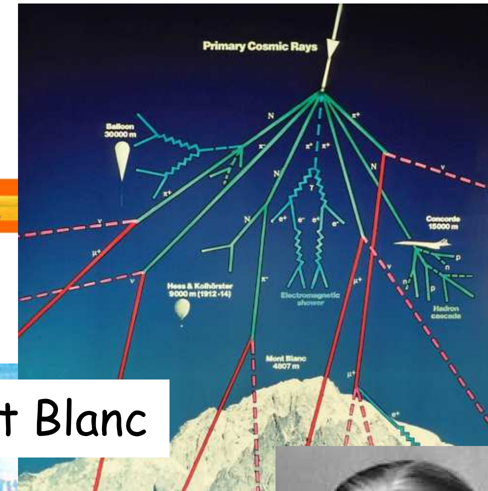
see e.g. ARGUS
near DESY entrance

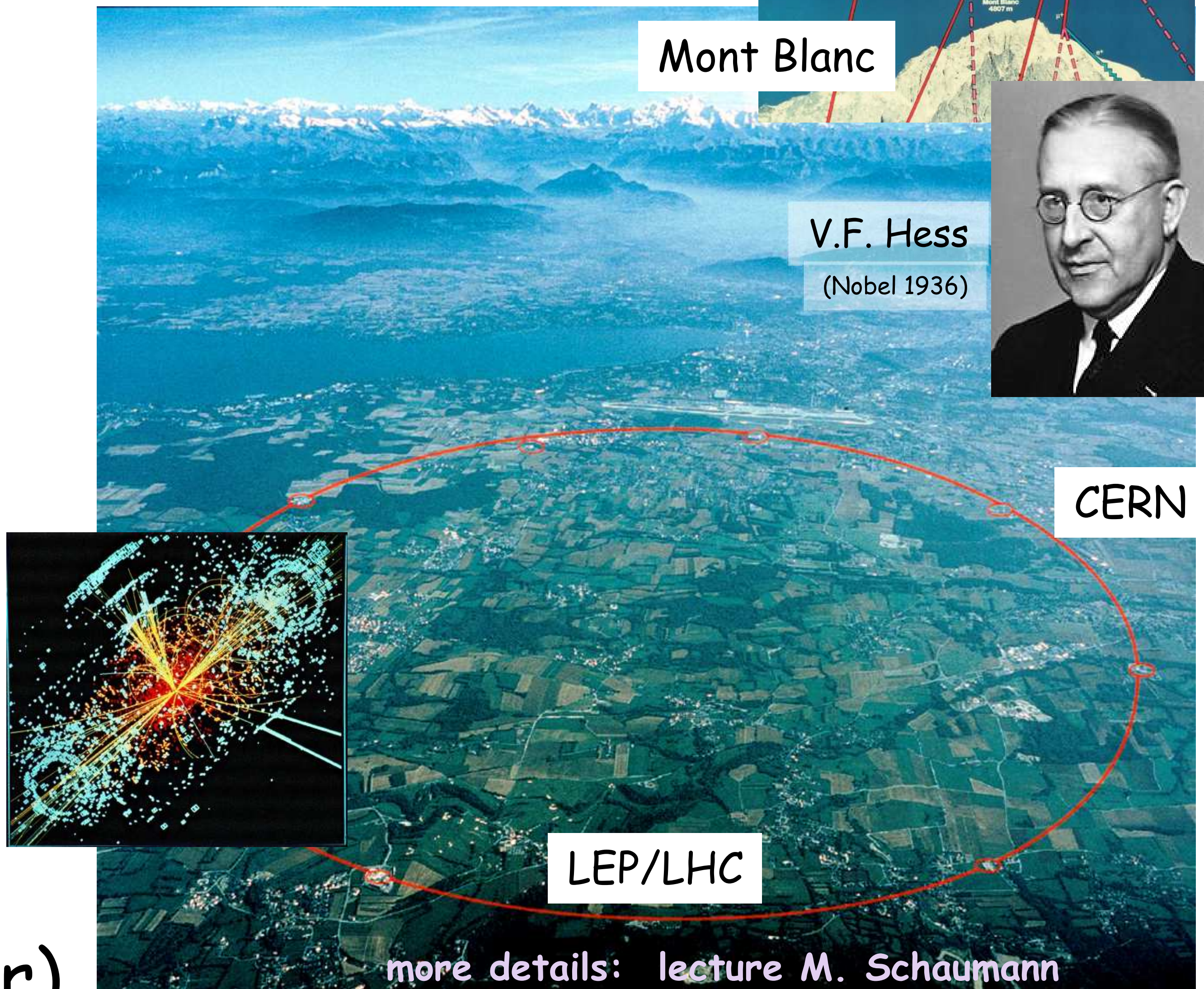
more details: lecture I. Gregor/S.Spannagel

Why do we need colliders?

more details: lecture M. Schaumann

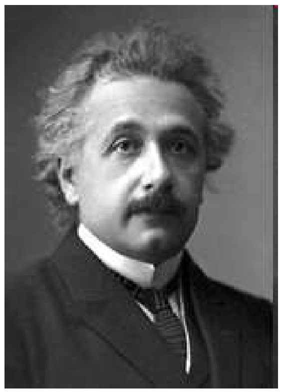
- early discoveries in cosmic rays, but
- need controlled conditions





V.F. Hess
(Nobel 1936)

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



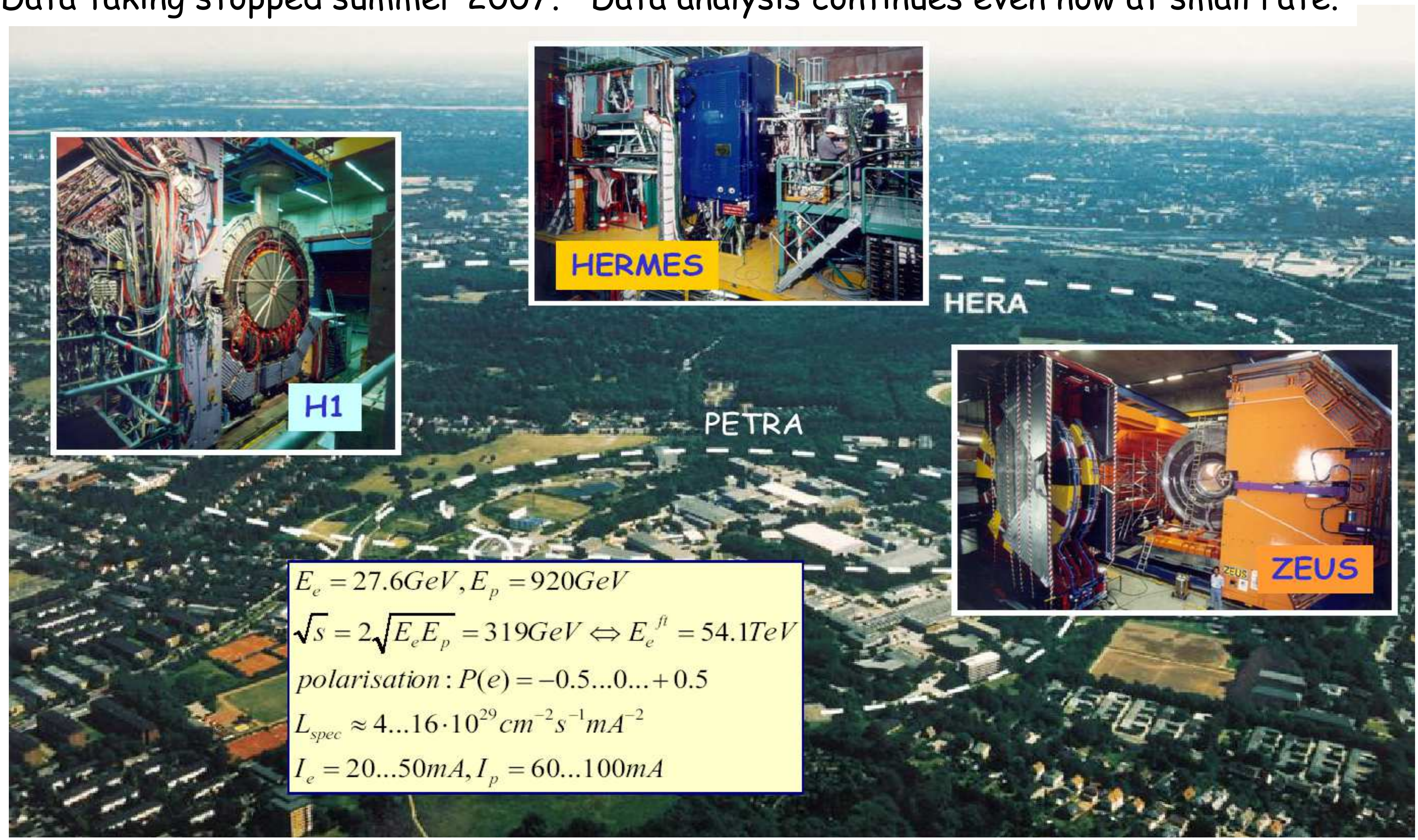
Albert Einstein
(Nobel 1921)

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.



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

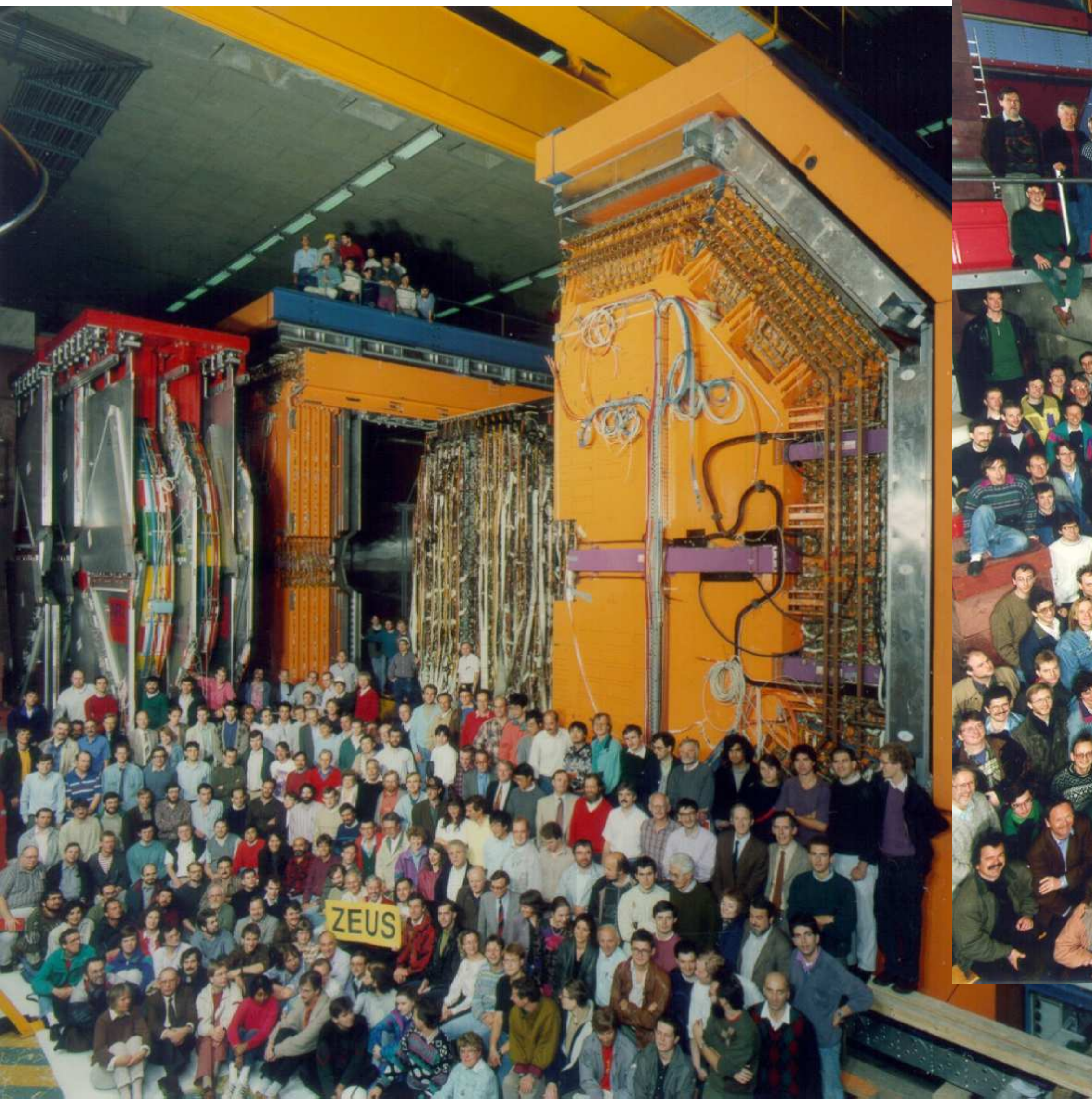
$$\sqrt{s} = 2\sqrt{E_e E_p} = 319 GeV \Leftrightarrow E_e^{ft} = 54.1 TeV$$

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

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

$$I_e = 20 ... 50 mA, I_p = 60 ... 100 mA$$

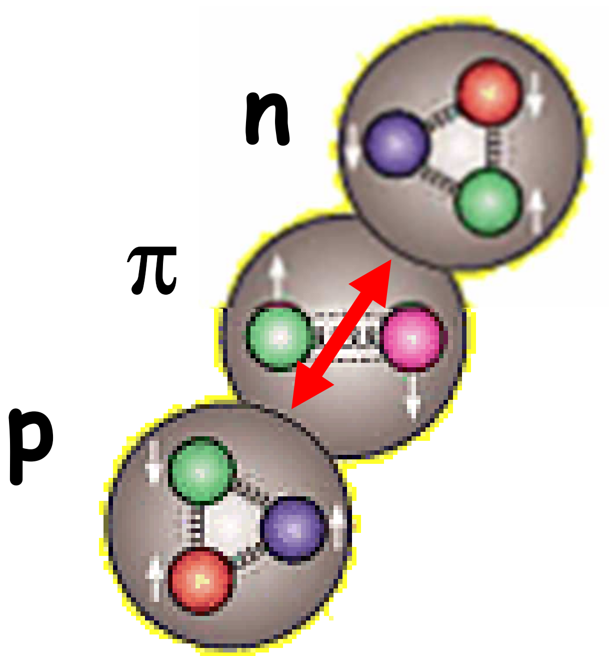
Particle Physics = People



Strong Interactions: Quarks and Colour

Hideki Yukawa
(Nobel 1949)

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



- modern view:

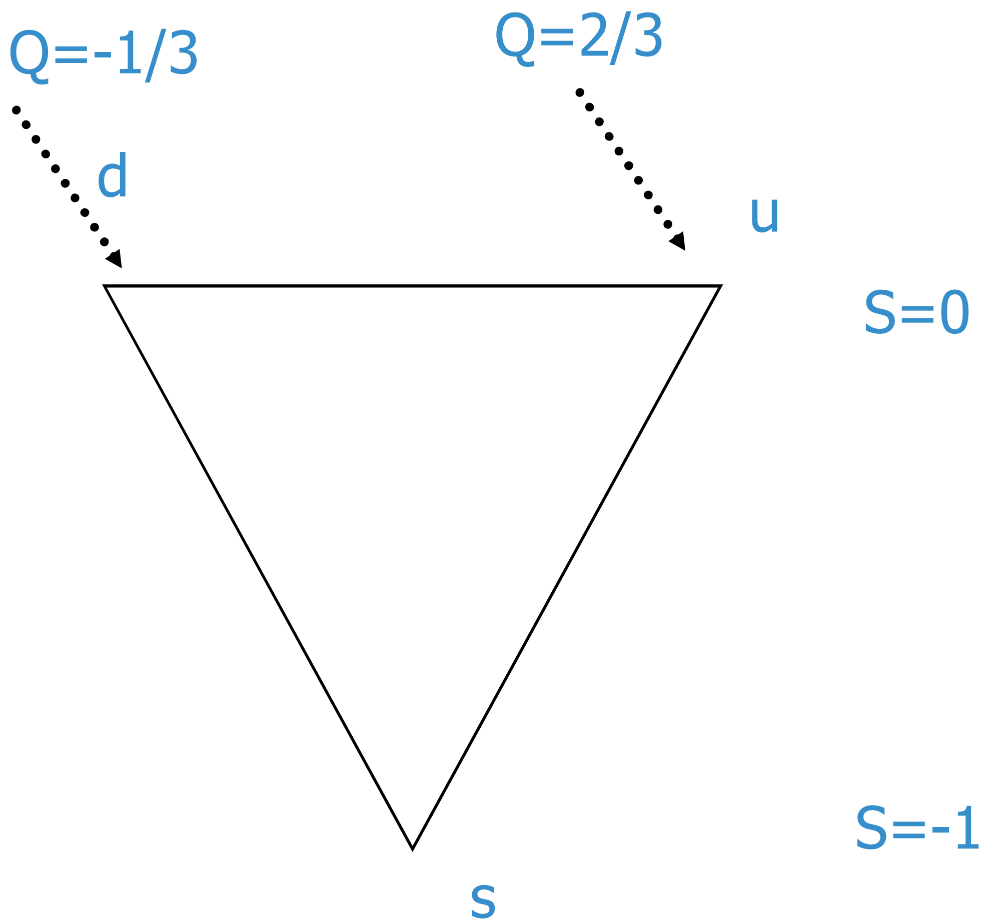
(Quantum Chromo-Dynamics, QCD)
exchange of massless gluons
between quark
constituents

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

The Quark Model (1964)

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

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



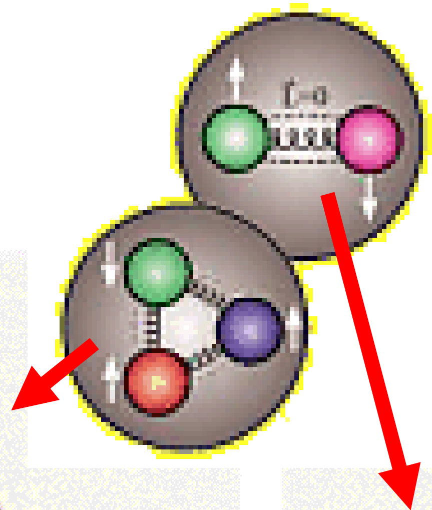
treat almost all known hadrons (protons, neutrons, pions, ...) as objects composed of two or three such quarks (antiquarks)

Murray Gell-Mann

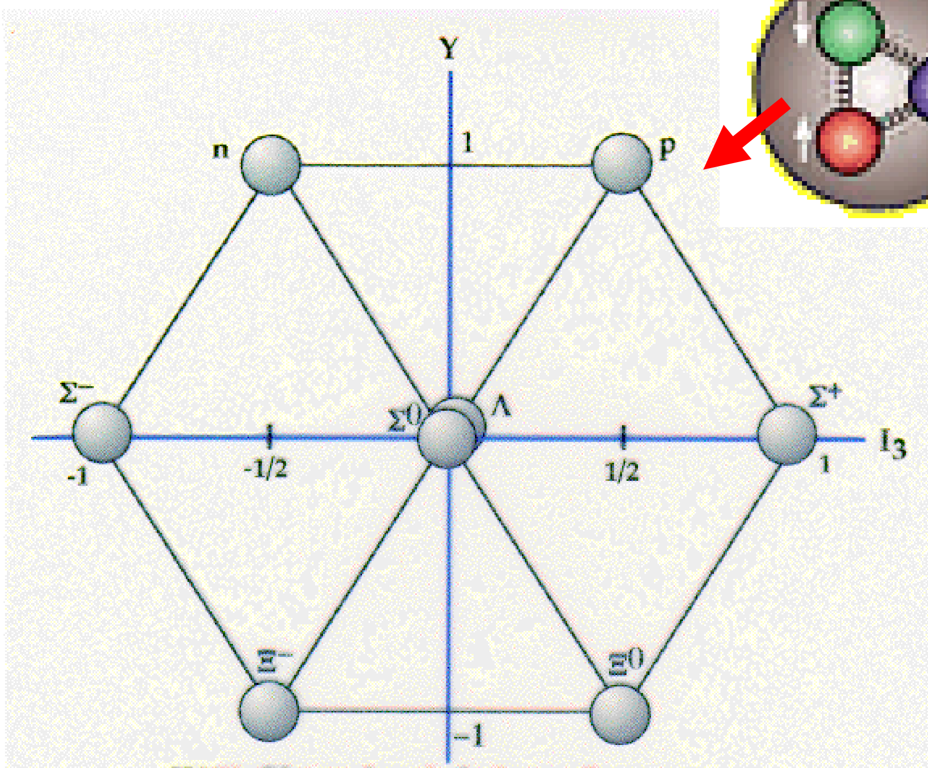
(Nobel 1969)

The Quark Model

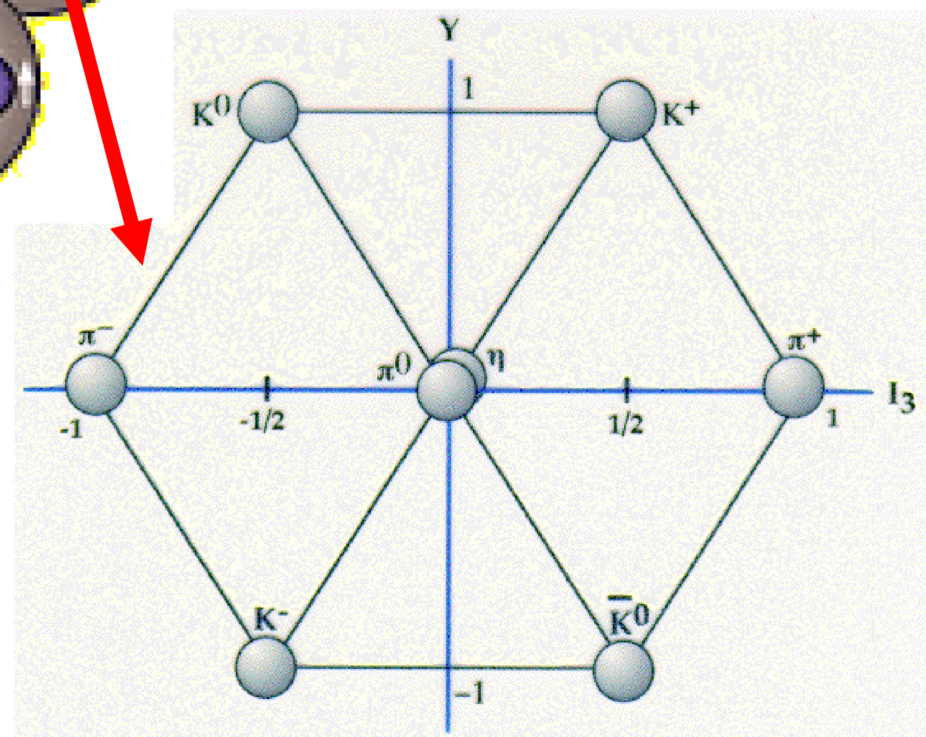
baryons = qqq



mesons = $q\bar{q}$



SU(3)-Oktett der einfachsten Baryonen



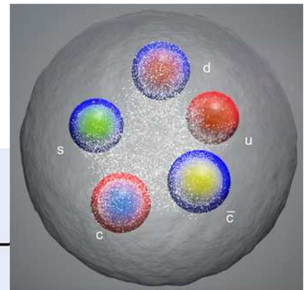
SU(3)-Oktett der einfachsten Mesonen

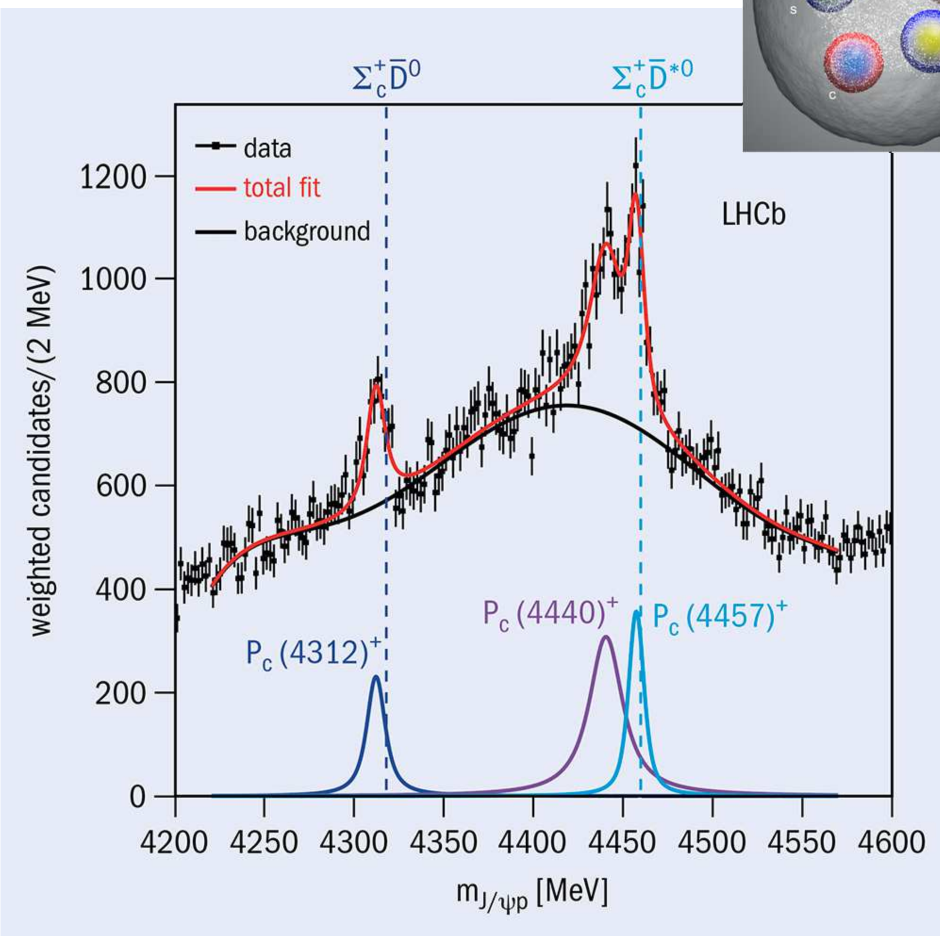
But also (2024)

part of **breakthrough prize 2025** (next lecture)

pentaquark baryons

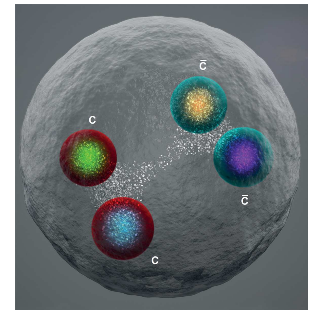
$= qqqq\bar{q}$, e.g $udsc\bar{c}$

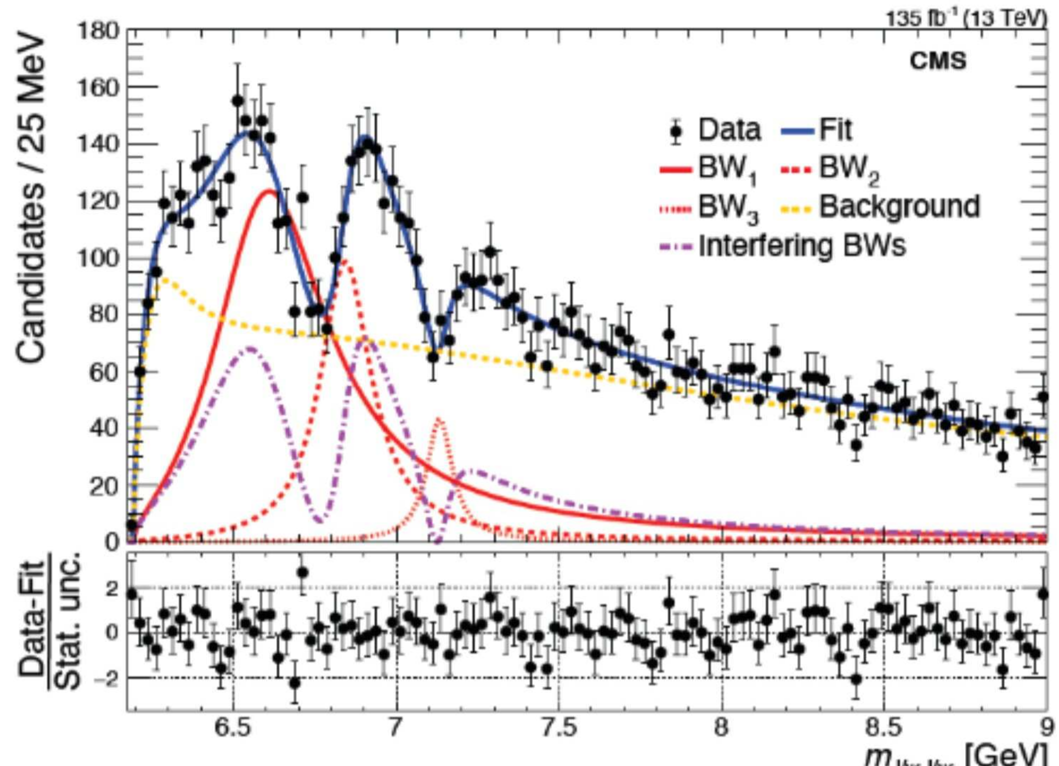




tetraquark mesons

$= q\bar{q}q\bar{q}$, e.g. $c\bar{c}c\bar{c}$

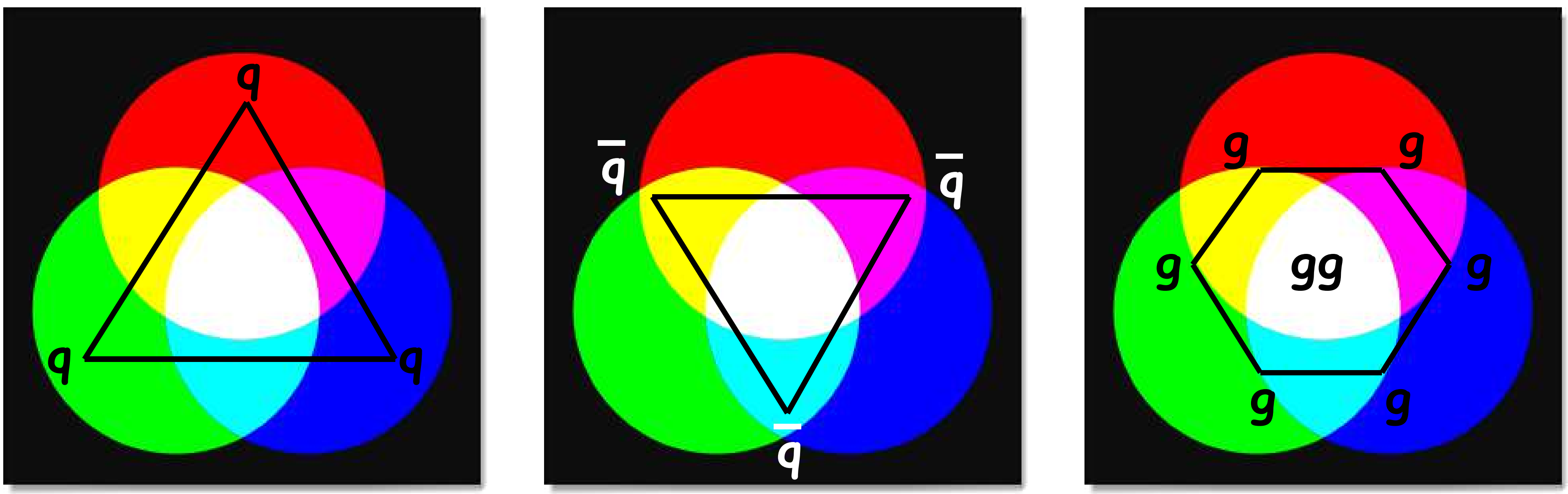




Colour

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

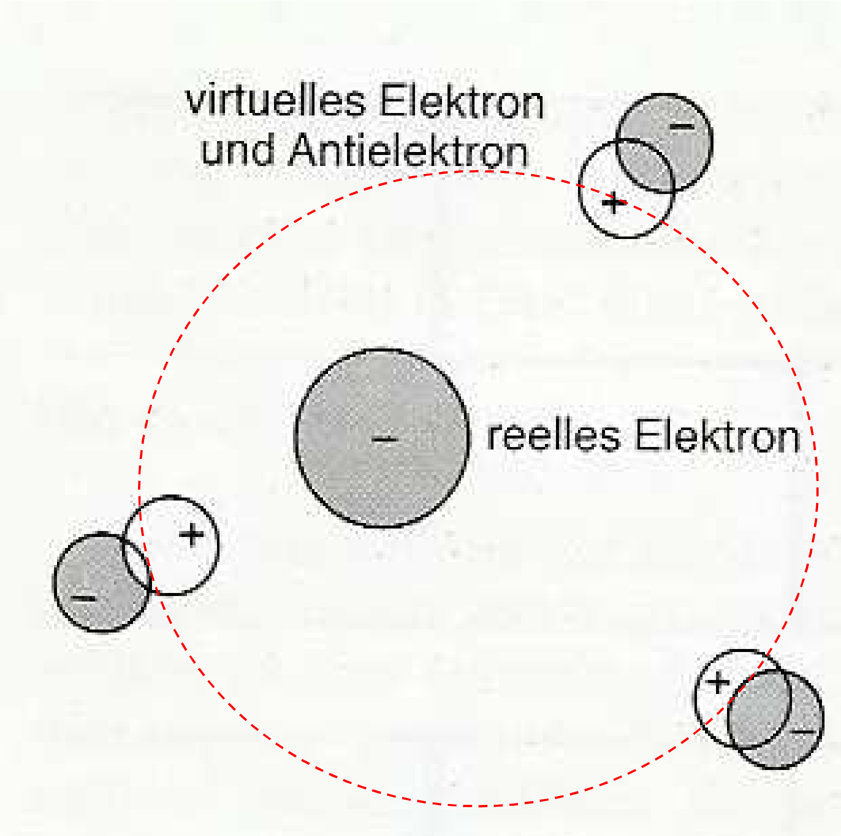
=> introduce new degree of freedom: **Colour**



- 3 coulours -> $SU(3)_{colour}$ (exact symmetry)

$qqq = q\bar{q} = $ white!

Screening of Electric Charge



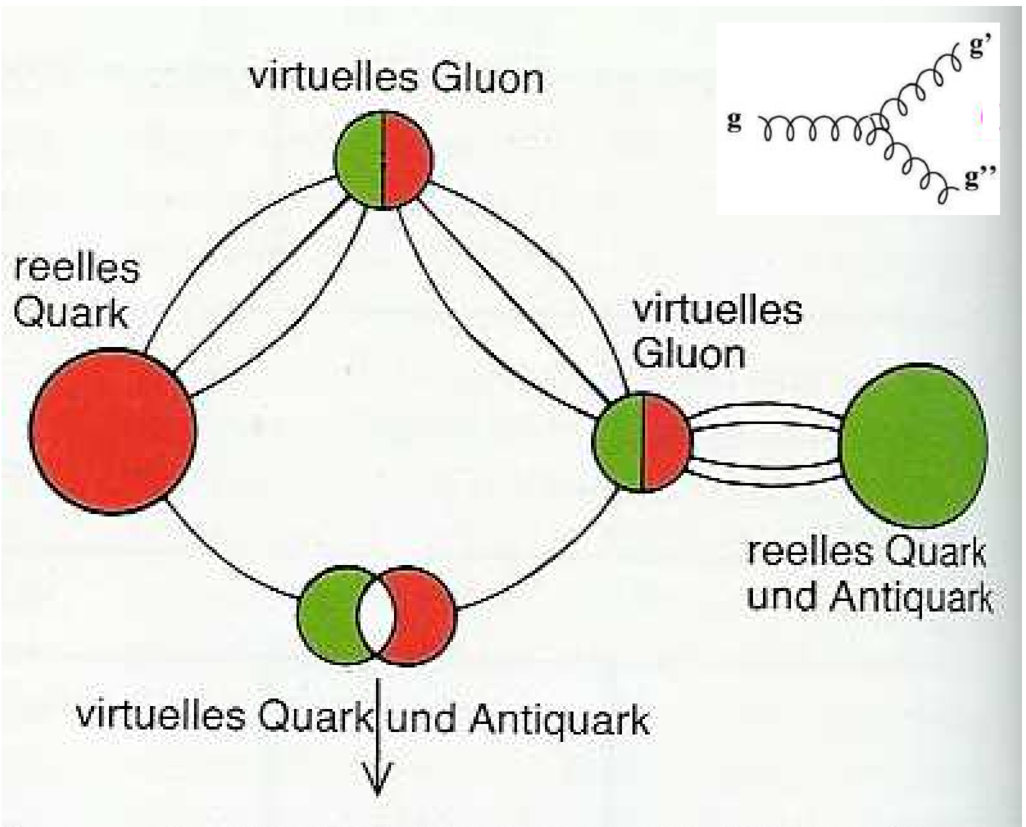
(Nobel 1965)

Sin-Itoro Tomonaga   Julian Schwinger   Richard P. Feynman

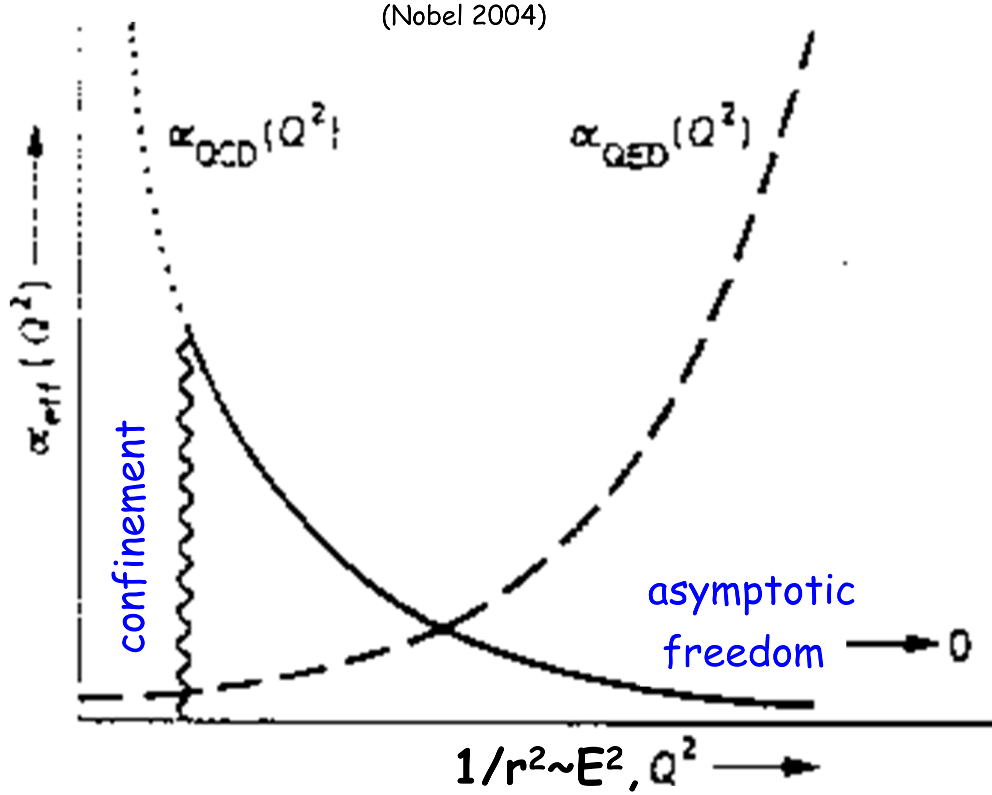
- electric charge polarises vacuum -> virtual electron positron pairs
- positrons partially screen electron charge
- effective charge/force
  - decreases at large distances/low energy (screening)
  - increases at small distance/large energy

Anti-Screening of Coulour Charge!

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

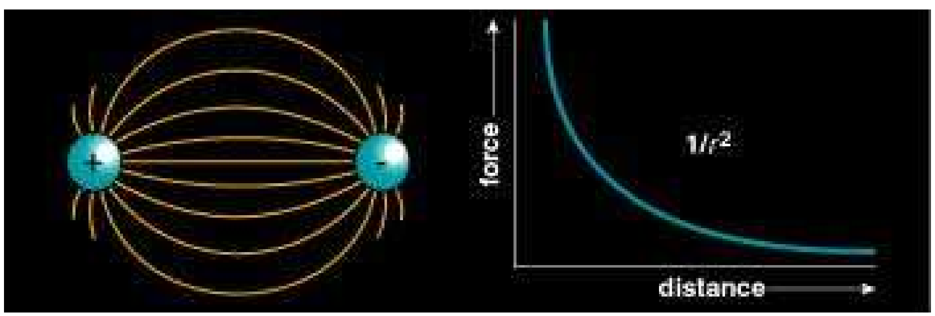


(Nobel 2004)

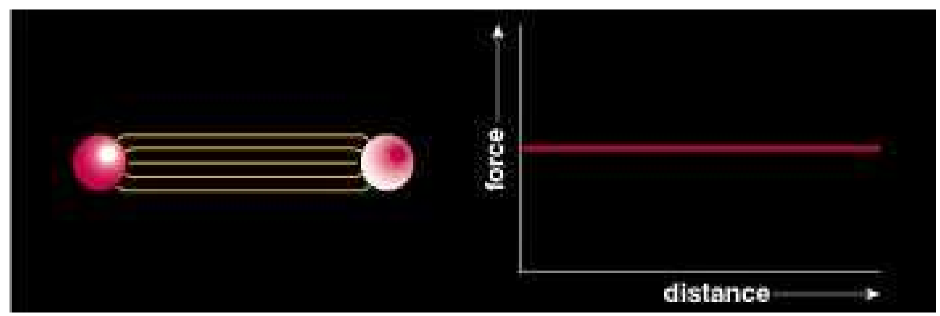


Comparison QED / QCD

electromagnetism	strong interactions
QED	**QCD**
1 kind of charge (q)	3 kinds of charge (r,g,b)
force mediated by **photons**	force mediated by **gluons**
photons are *neutral*	gluons are *charged* (eg. r$\bar{g}$, b$\bar{b}$, g$\bar{b}$)
α is nearly constant	α_s strongly depends on distance



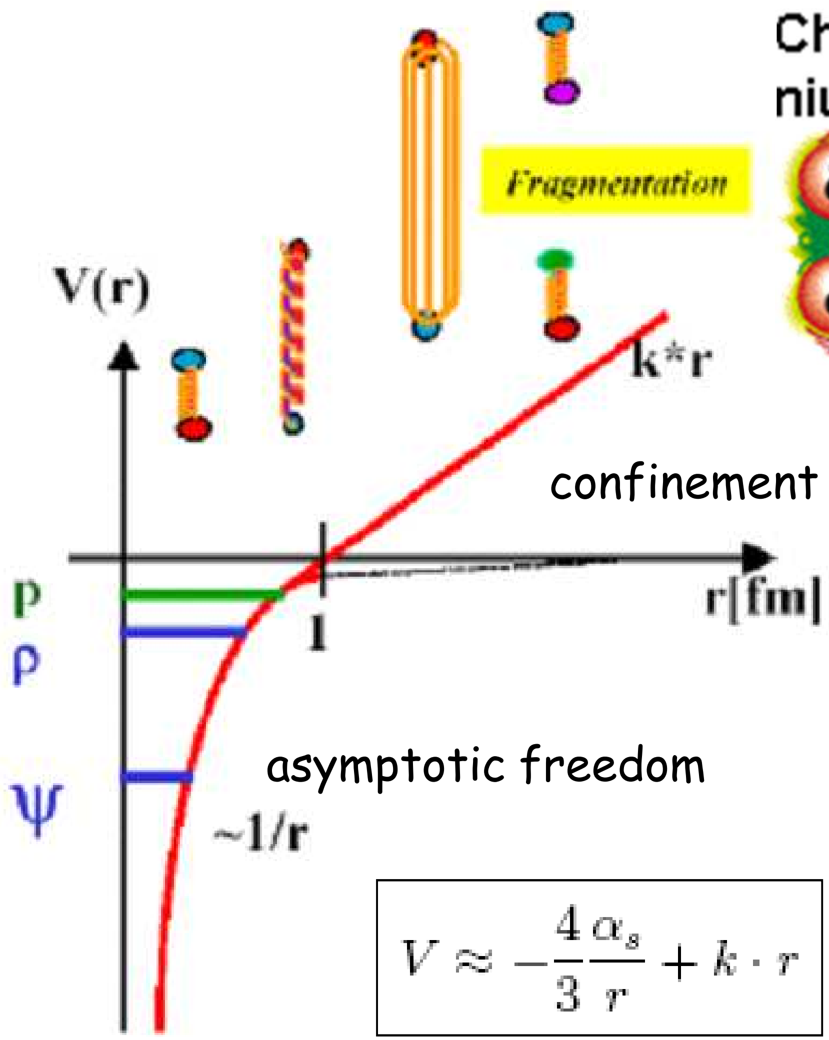
confinement limit:



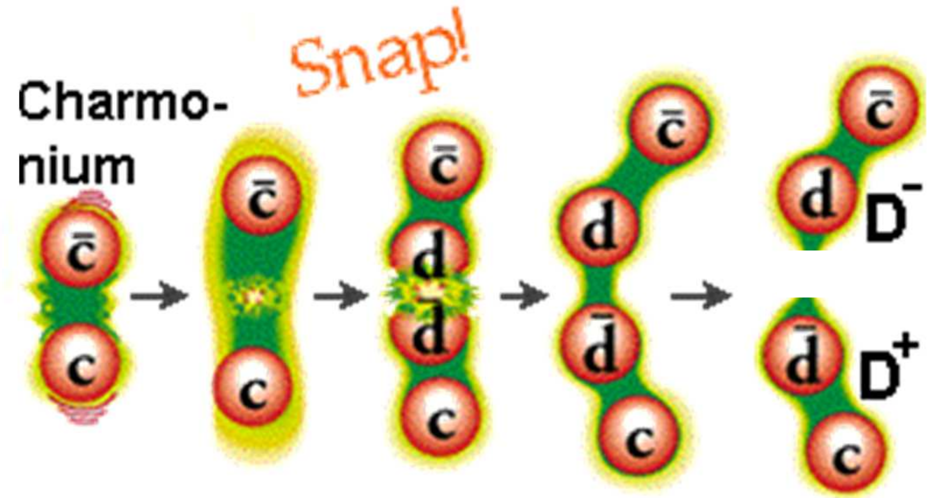
- The underlying theories are formally almost identical!

more details: lecture M. Diehl

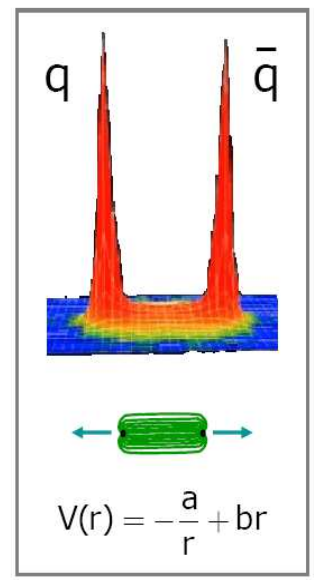
The effective potential for $q\bar{q}$ interactions



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



lattice gauge calculation



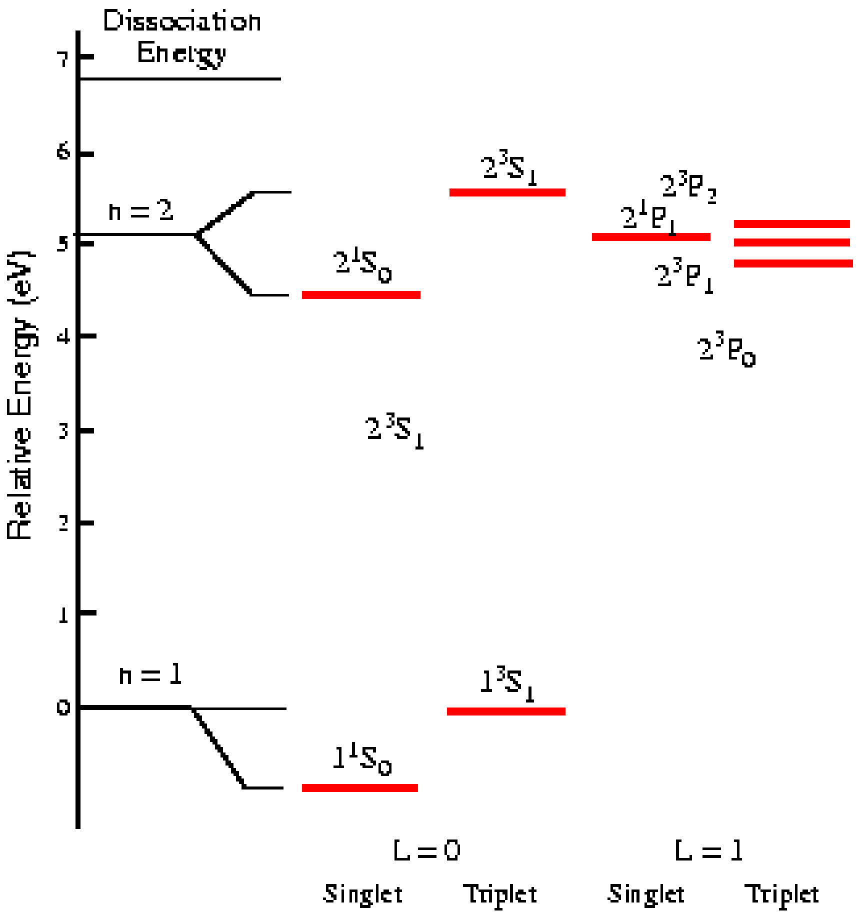
Heavy Quark Spectroscopy

Burton Richter

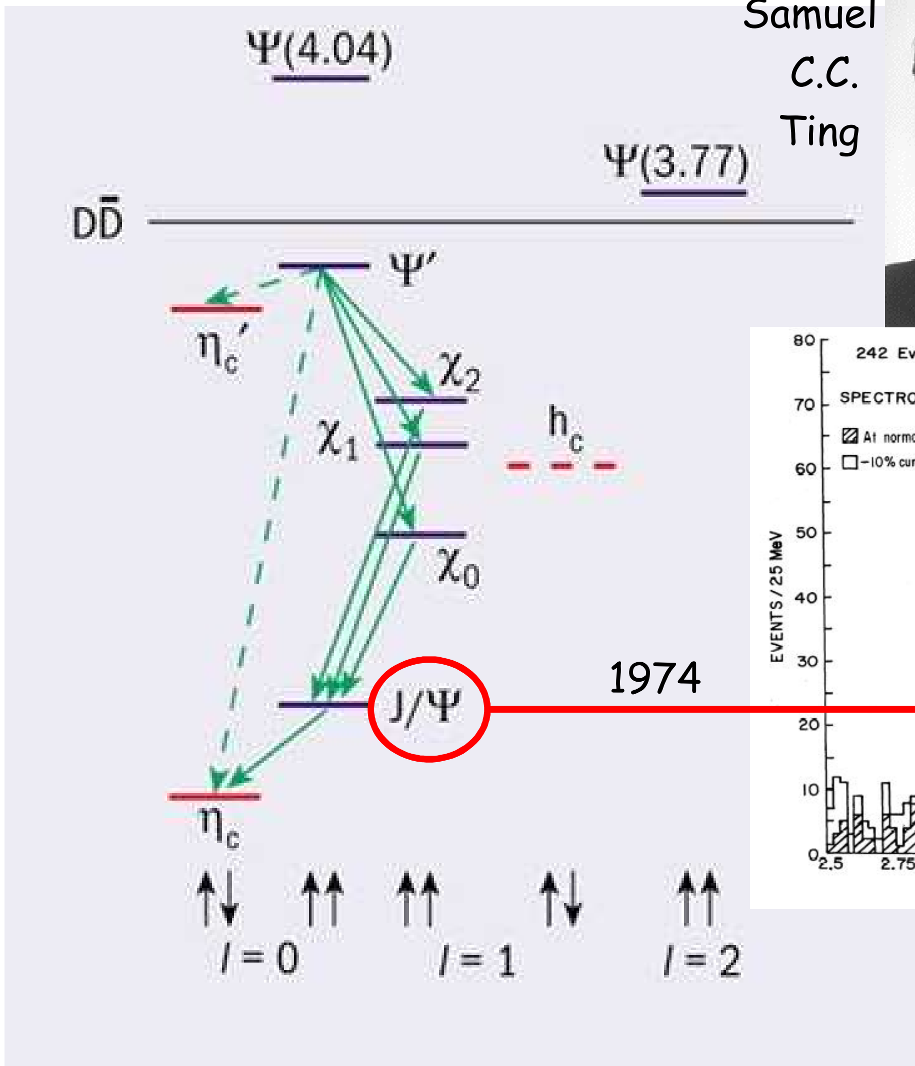
(Nobel 1976)

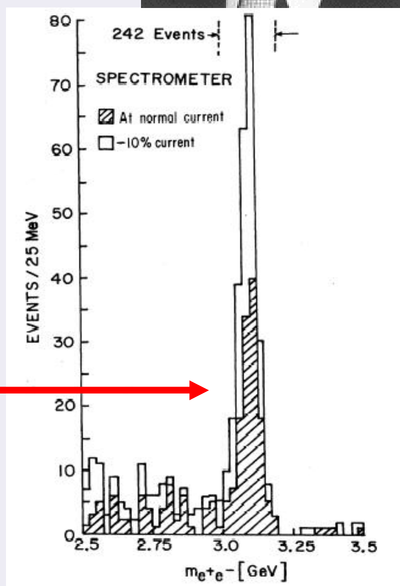
Samuel C.C. Ting

Positronium = bound e^+e^- system



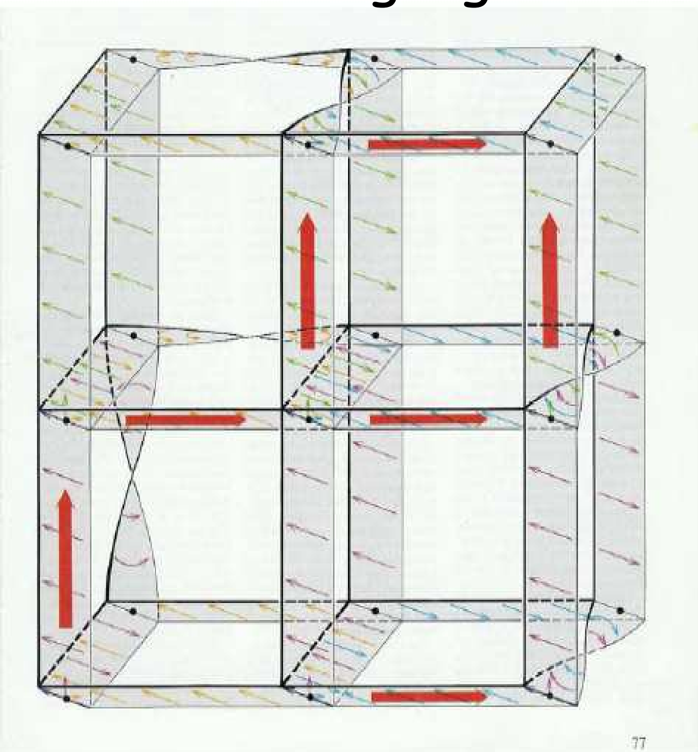
Charmonium = bound system of $c\bar{c}$ quark pair

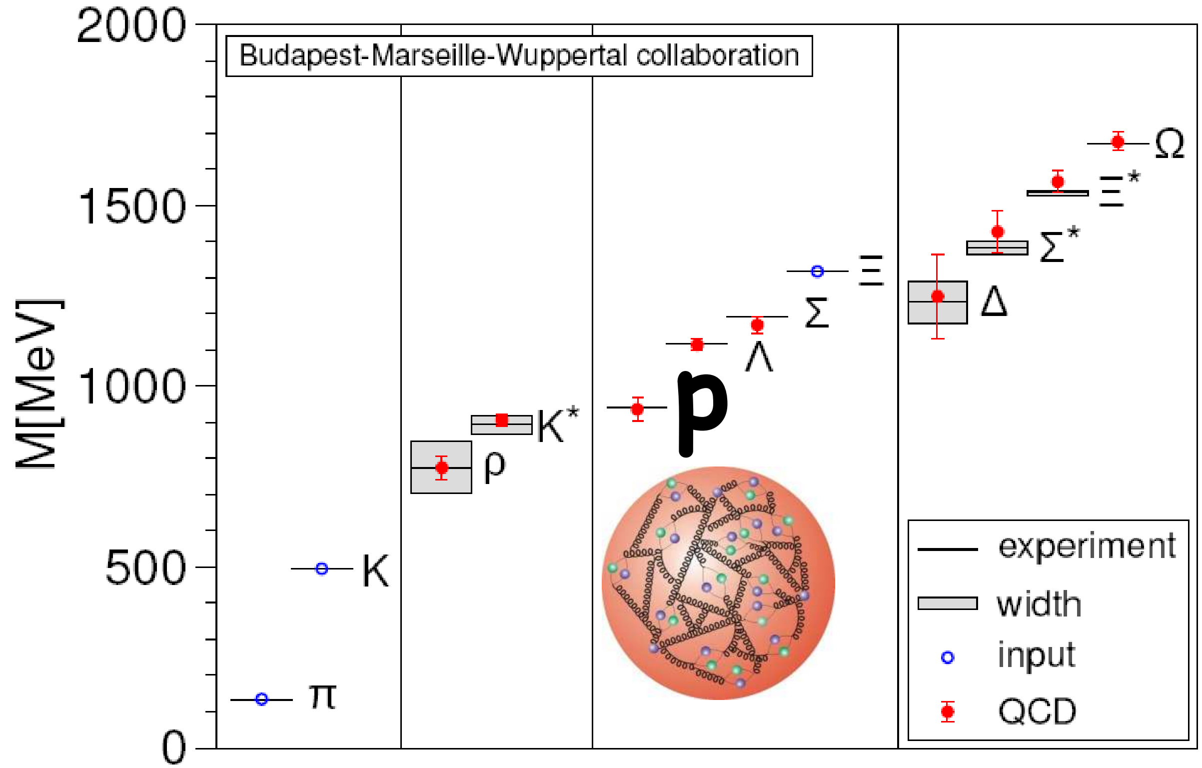




calculation of proton mass in QCD

from lattice gauge theory:





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

⇒ proton mass (~= neutron mass),

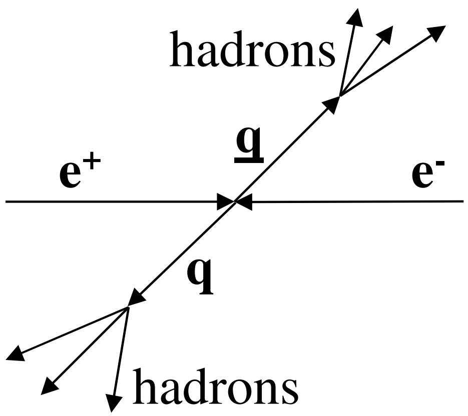
⇒ mass of the visible part of the universe !

Yoichiro Nambu

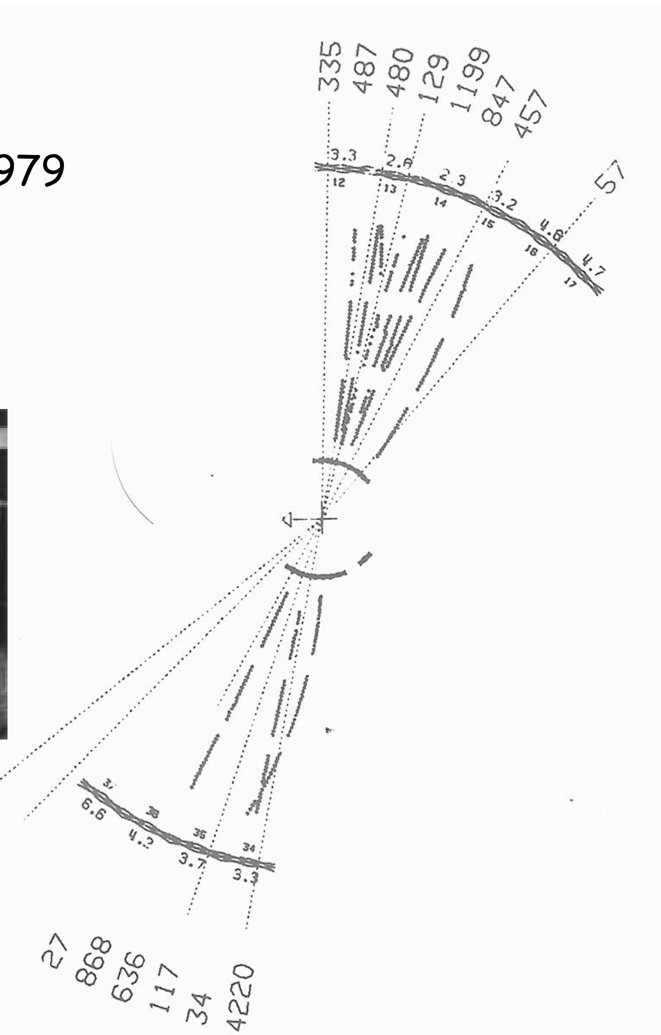
(Nobel 2008)

How to detect Quarks and Gluons?

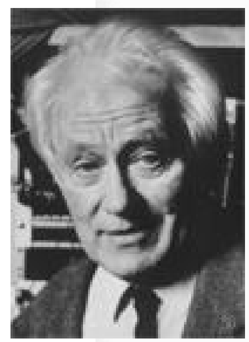
Jets!



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



Georges Charpak

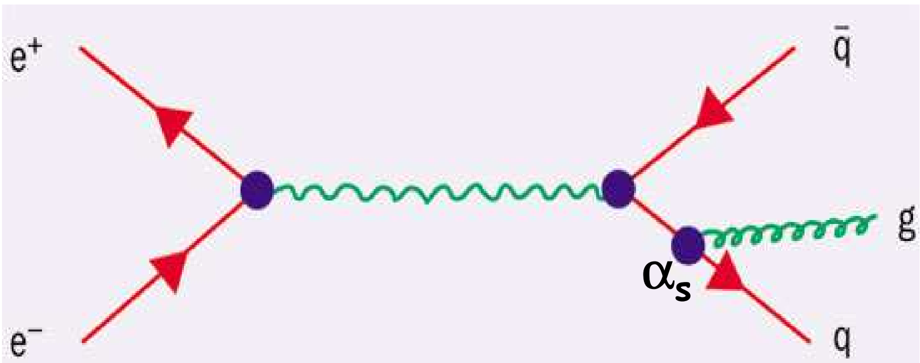


(Nobel 1992)

- $\sqrt{s}$ 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)

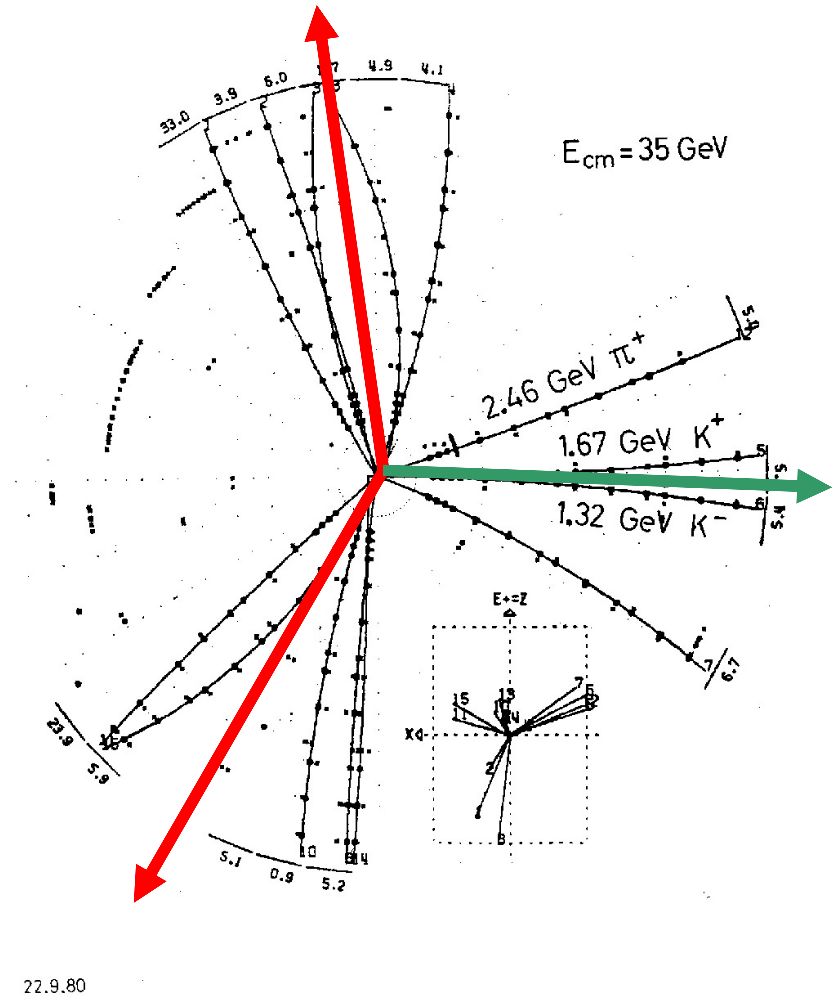
PETRA at DESY: look for



Björn Wiik   Paul Söding

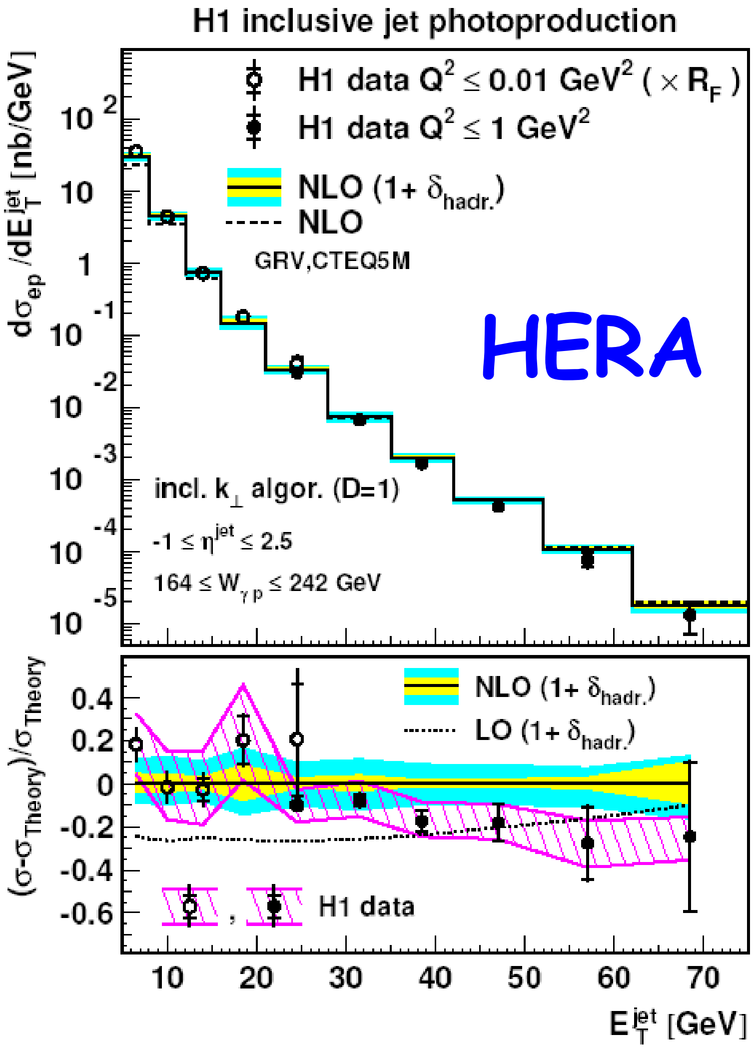
Günter Wolf   Sau Lan Wu

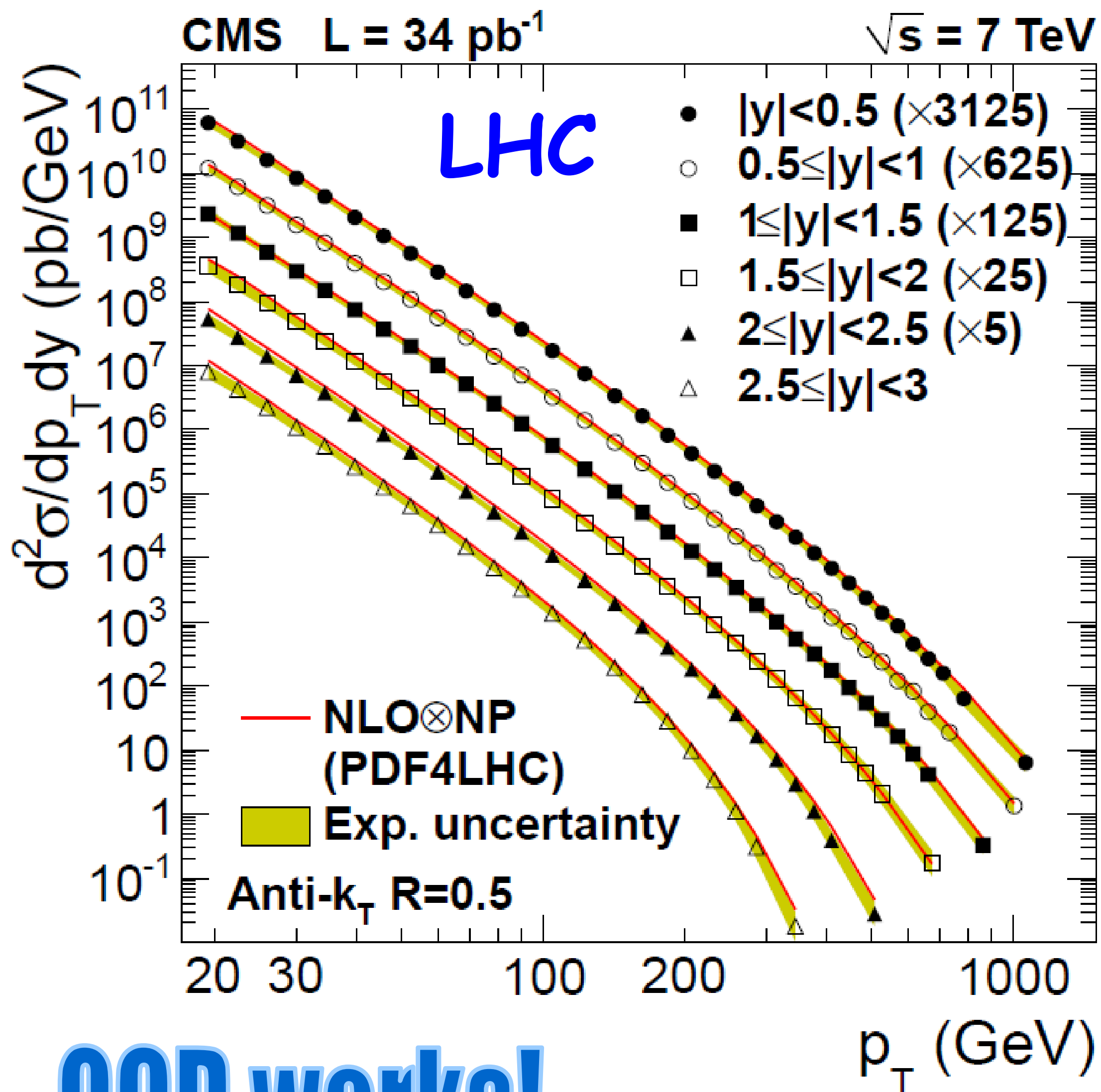
(EPS prize 1995)



TASSO event picture

Jets in ep and pp interactions



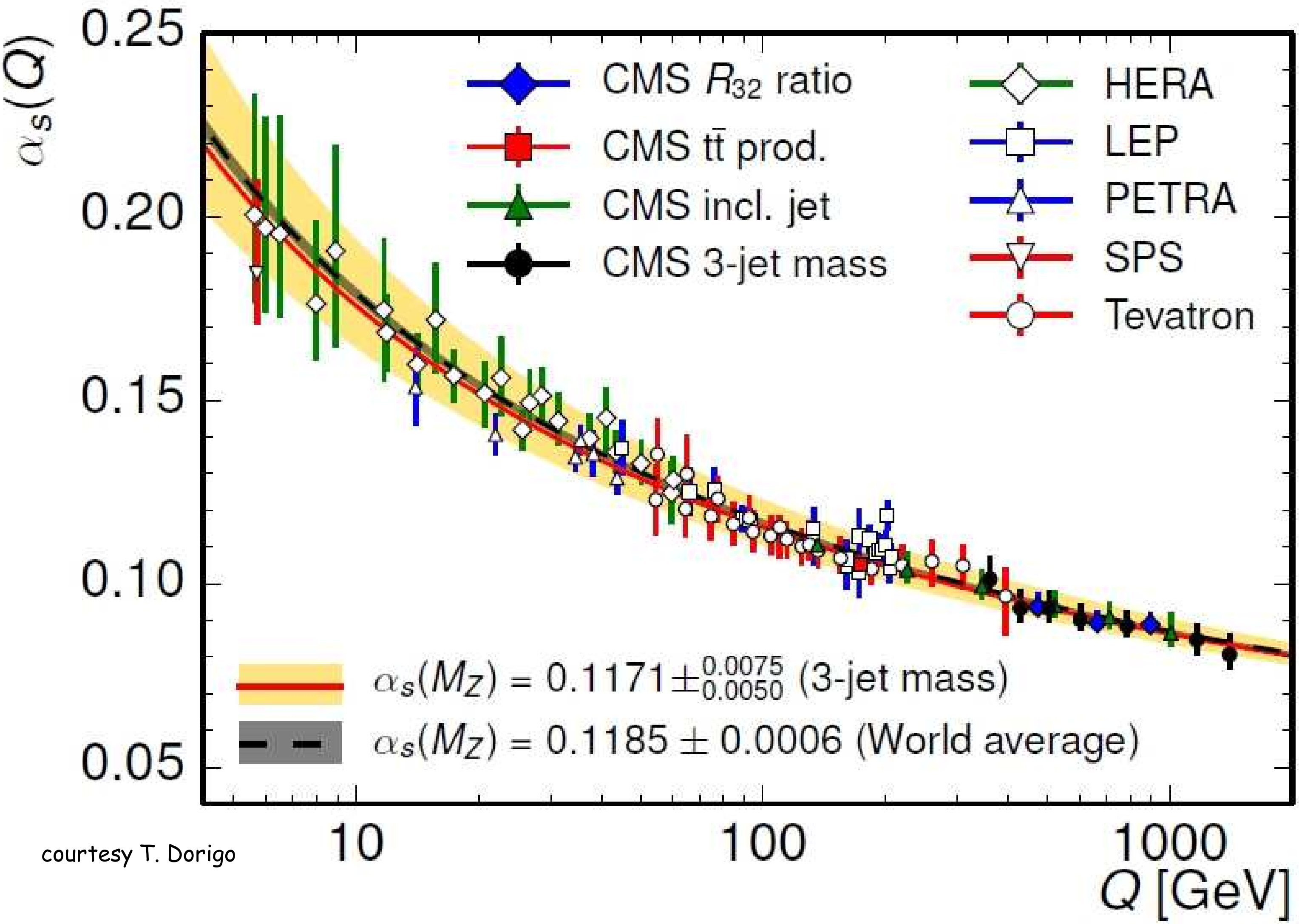


more details: lecture L. Beresford

QCD works!

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

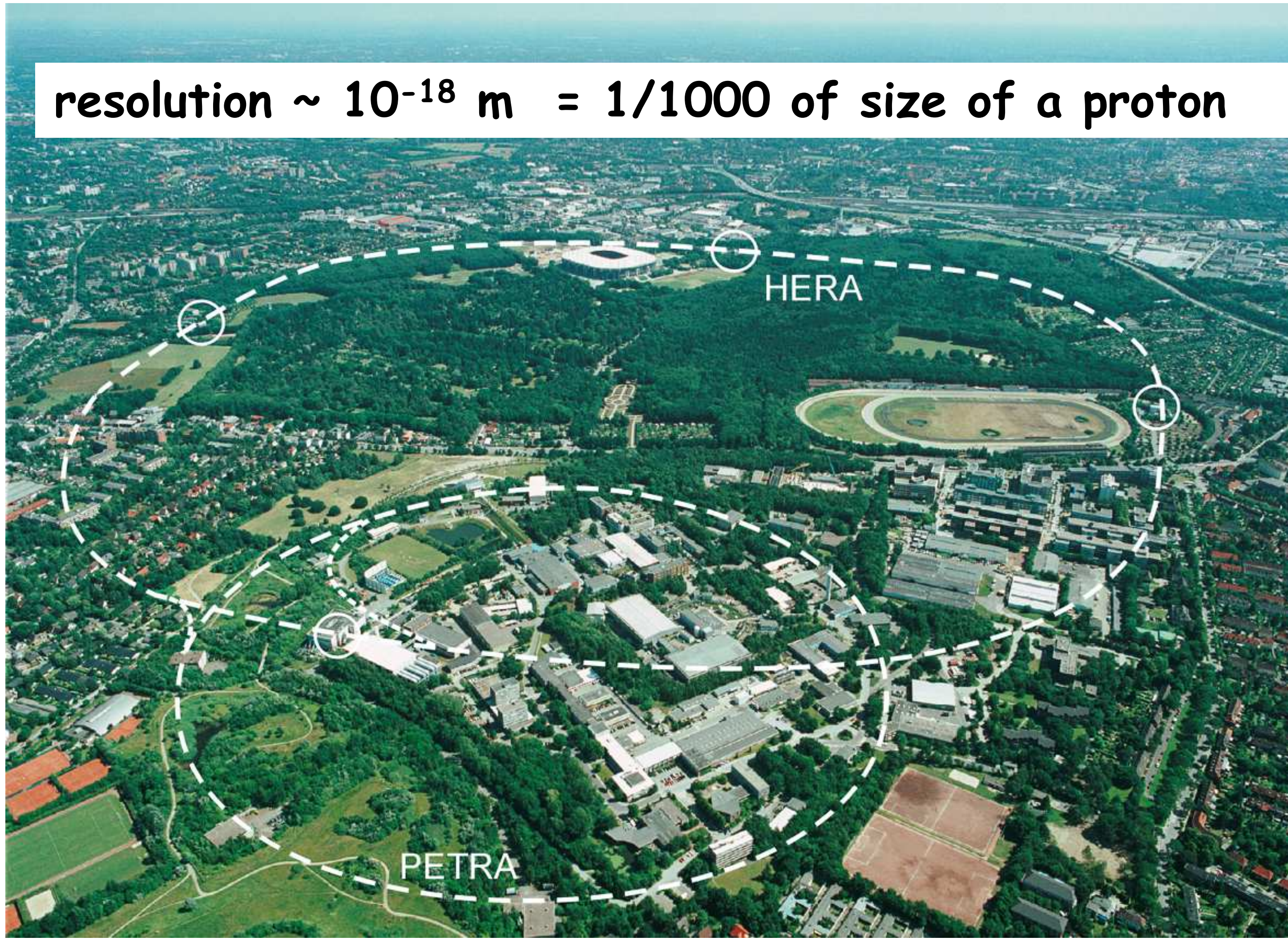
-> small instrument

high resolution

-> large instrument

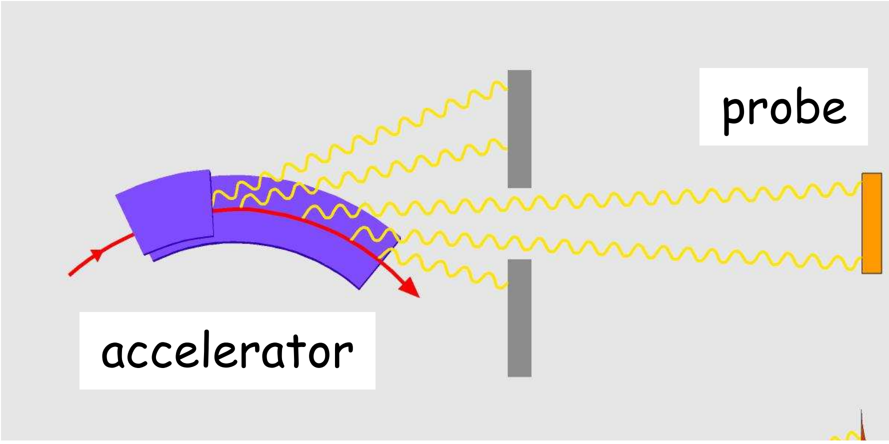
HERA = giant electron microscope

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

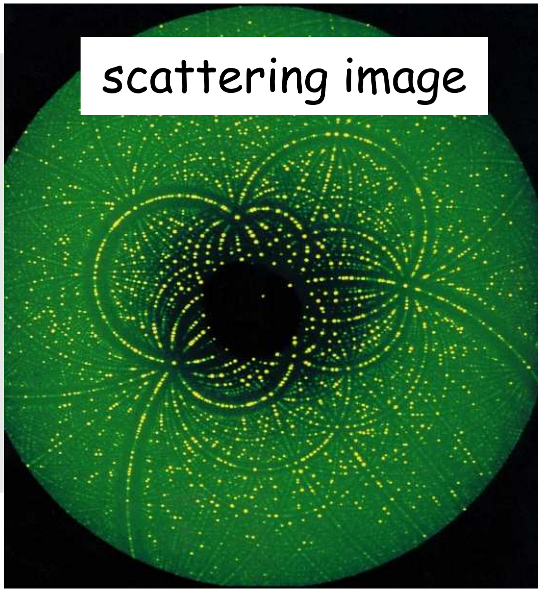


How to resolve the structure of an object?

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



E~ keV



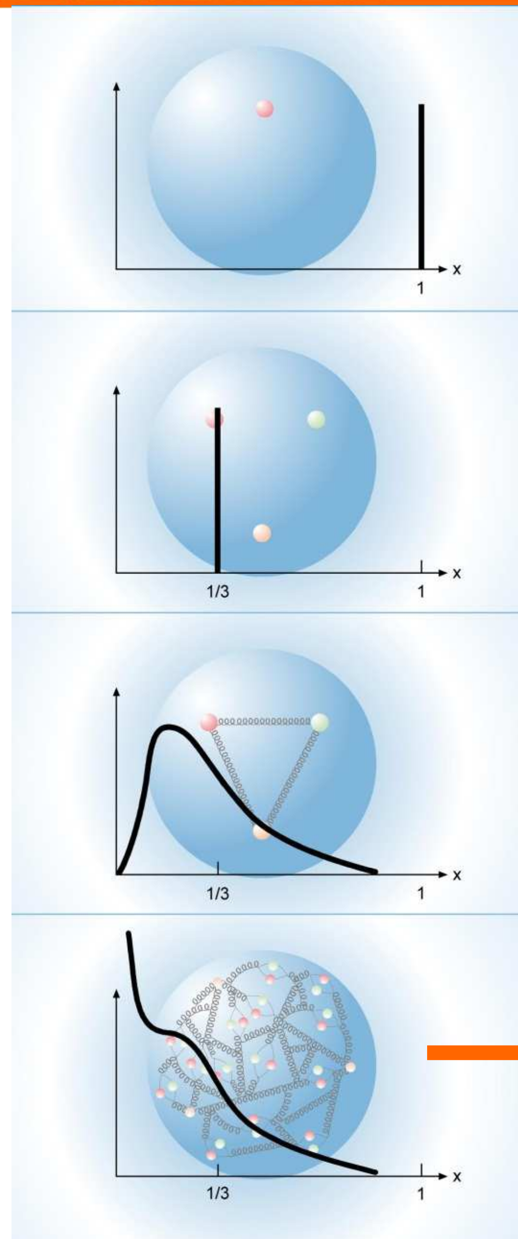
-> structure of
a biomolecule

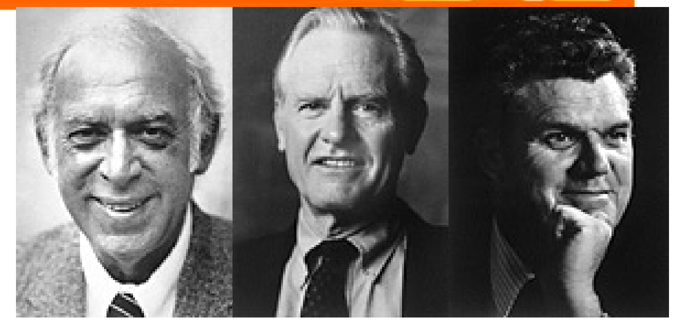
Ada Yonath
(Nobel 2009)

more details: photon lectures

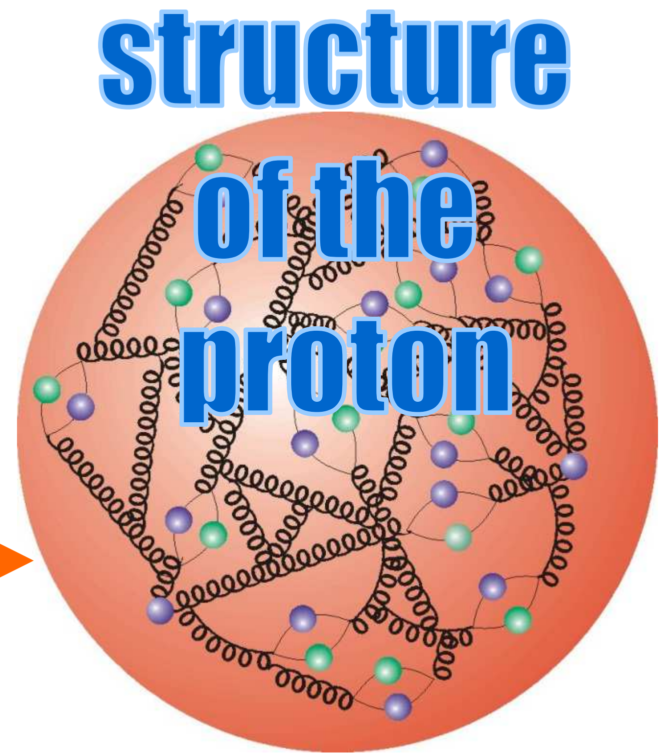
Resolve the structure of the proton

- 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"

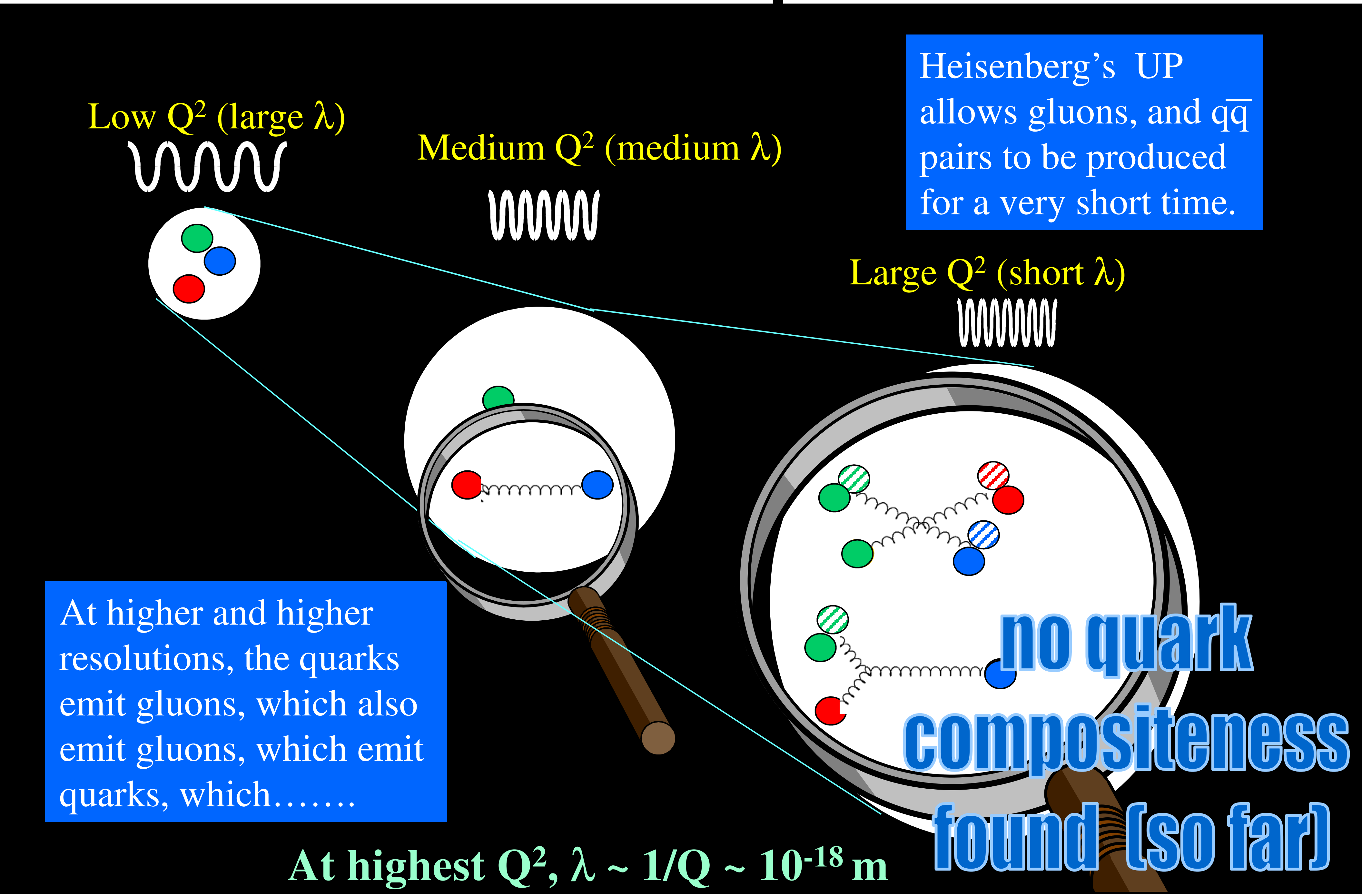




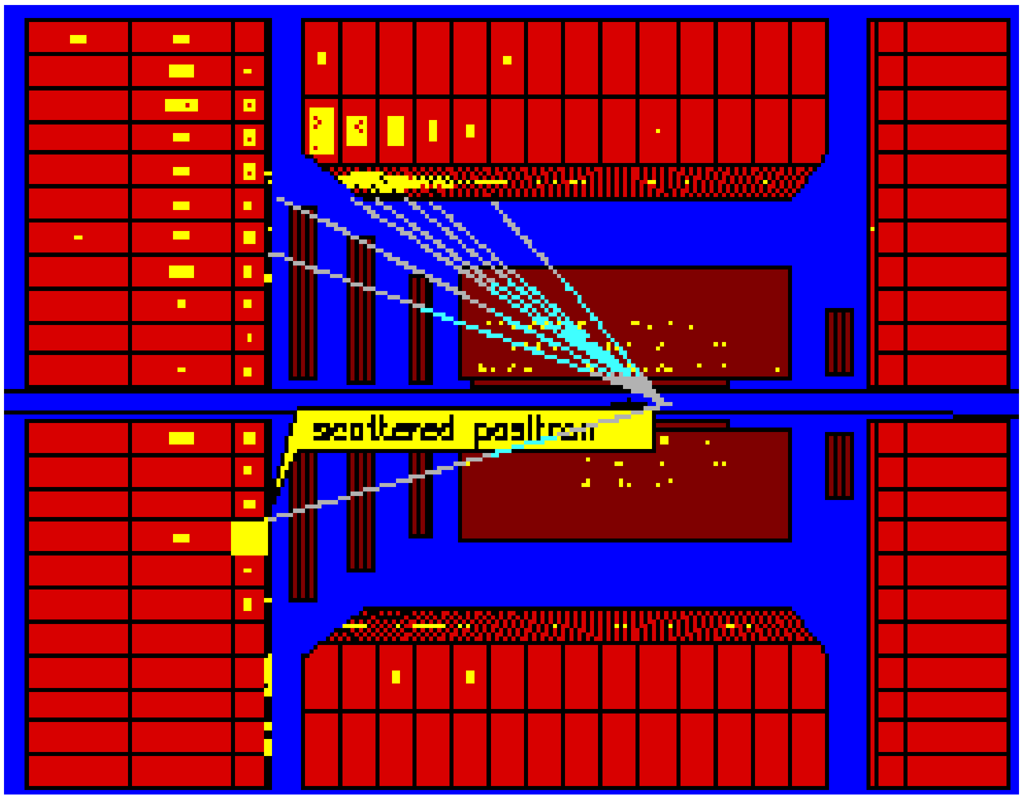
Jerome I. Friedmann Henry W. Kendall Richard E. Taylor
(Nobel 1990)

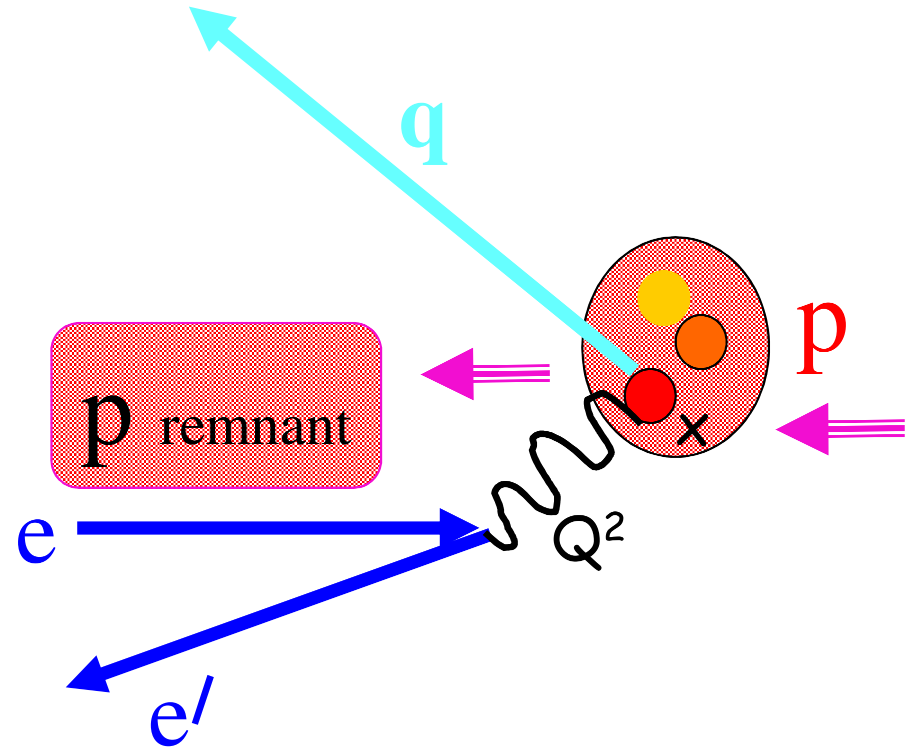


Inside the proton



Deep Inelastic ep Scattering at HERA





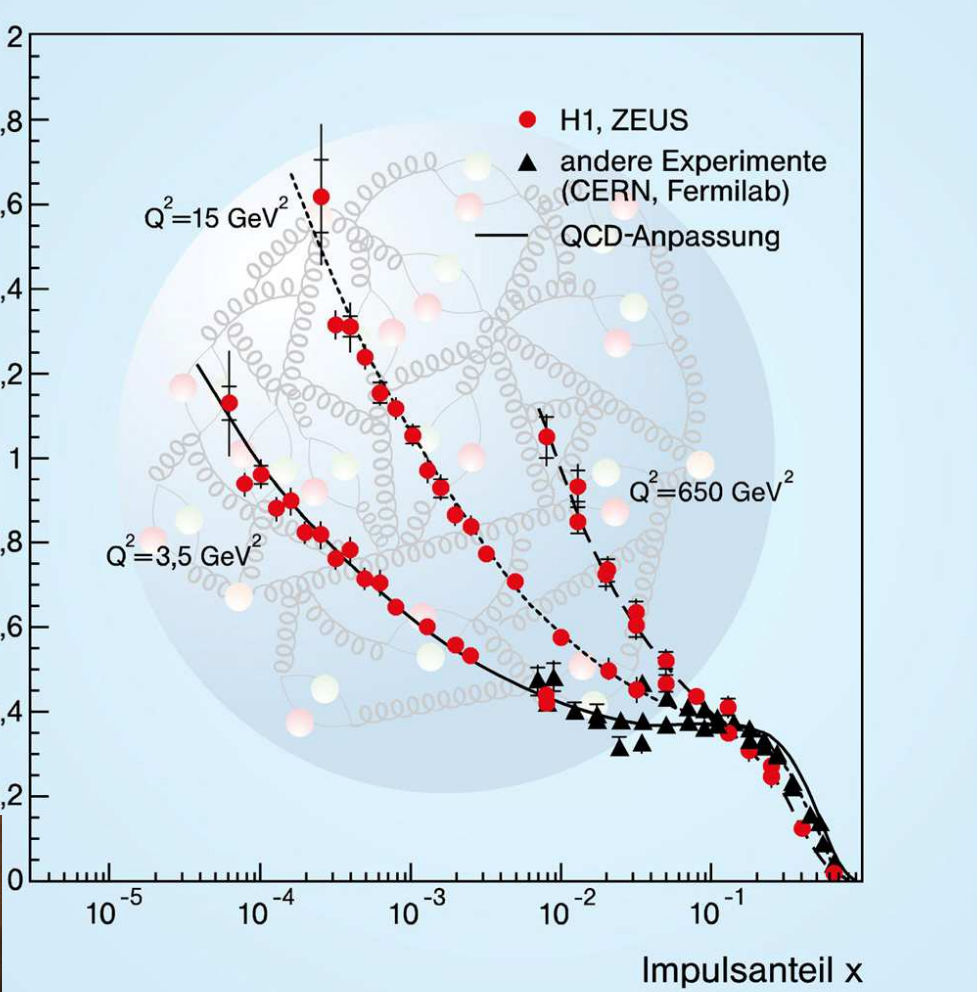
measure
proton structure function $F_2(x,Q^2)$

boson virtuality (resolution scale) Q^2

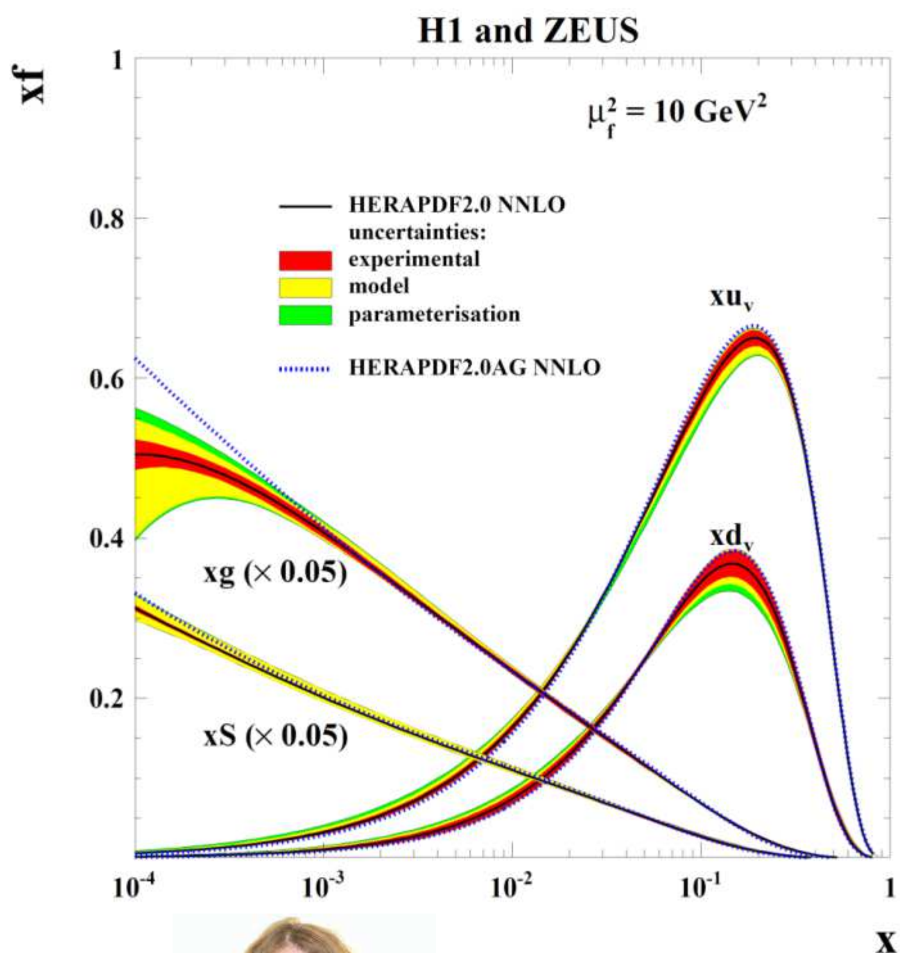
fractional momentum of struck quark x

The Proton Structure

structure functions → quark and gluon densities

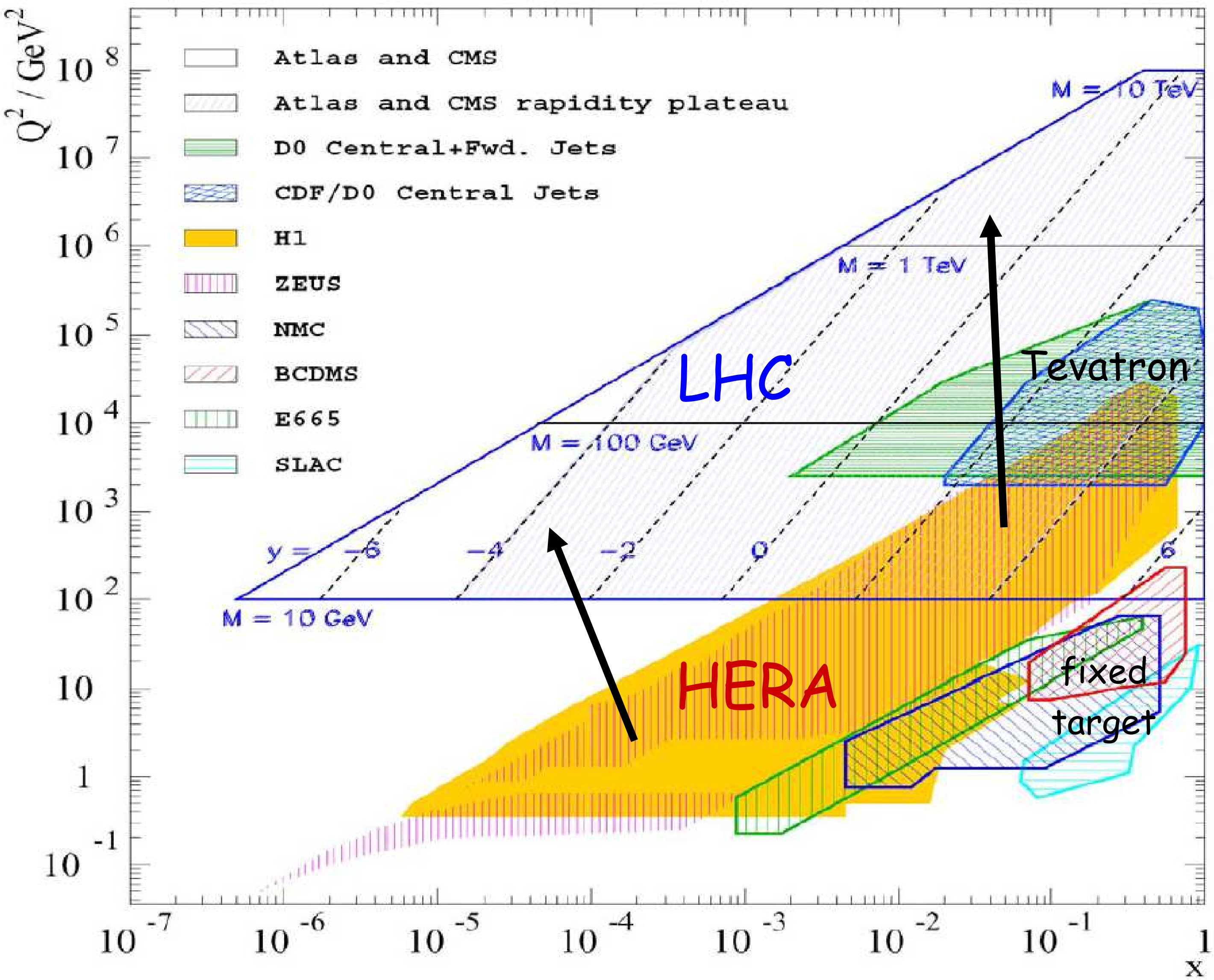


Giorgio Parisi
(Nobel Prize 2021)



Amanda Cooper-Sarkar
(Chadwick medal 2015)

Kinematic regions: HERA vs. LHC

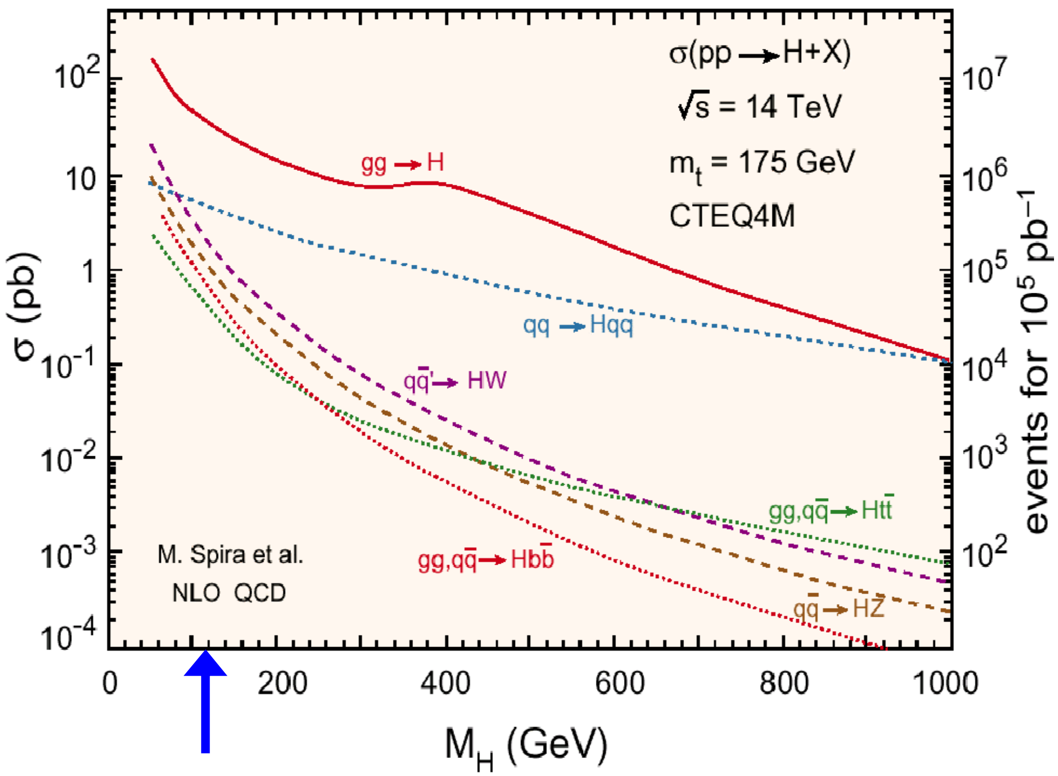


- proton structure measured directly for large part of LHC phase space
- QCD evolution successful

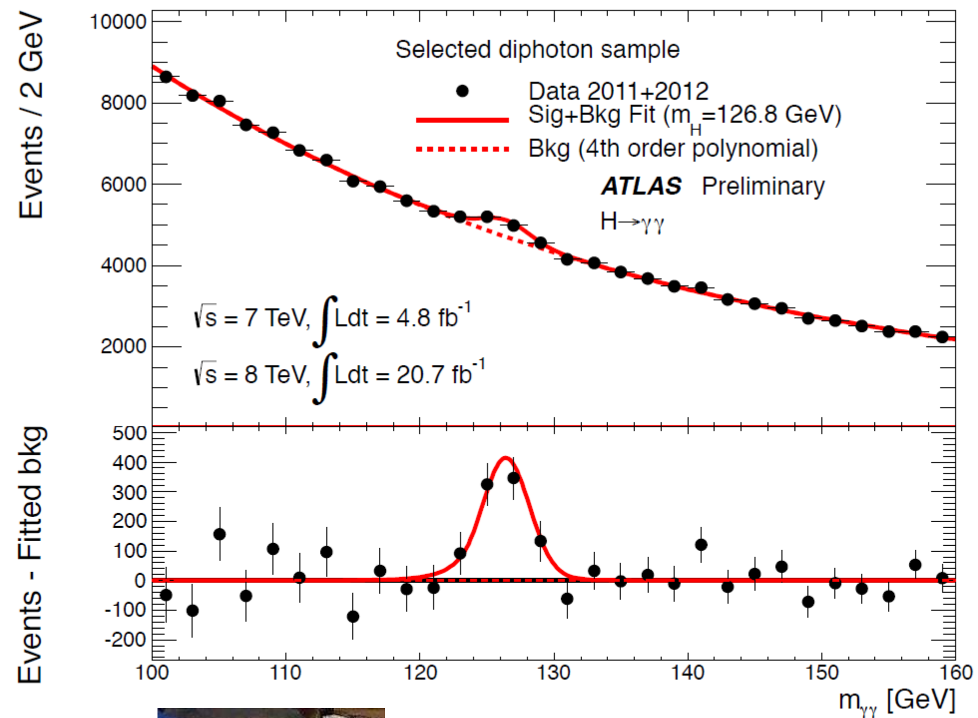
-> safely extrapolate to higher Q^2

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