

Elementary Particle Physics Research

Achim Geiser, DESY Hamburg

Summer Student Lecture, 19.-21.7.17

Scope of this lecture:

■ Introduction to particle physics for non-specialists

- rather elementary
- more details -> specialized lectures
- particle physics in general
- some emphasis on DESY-related topics



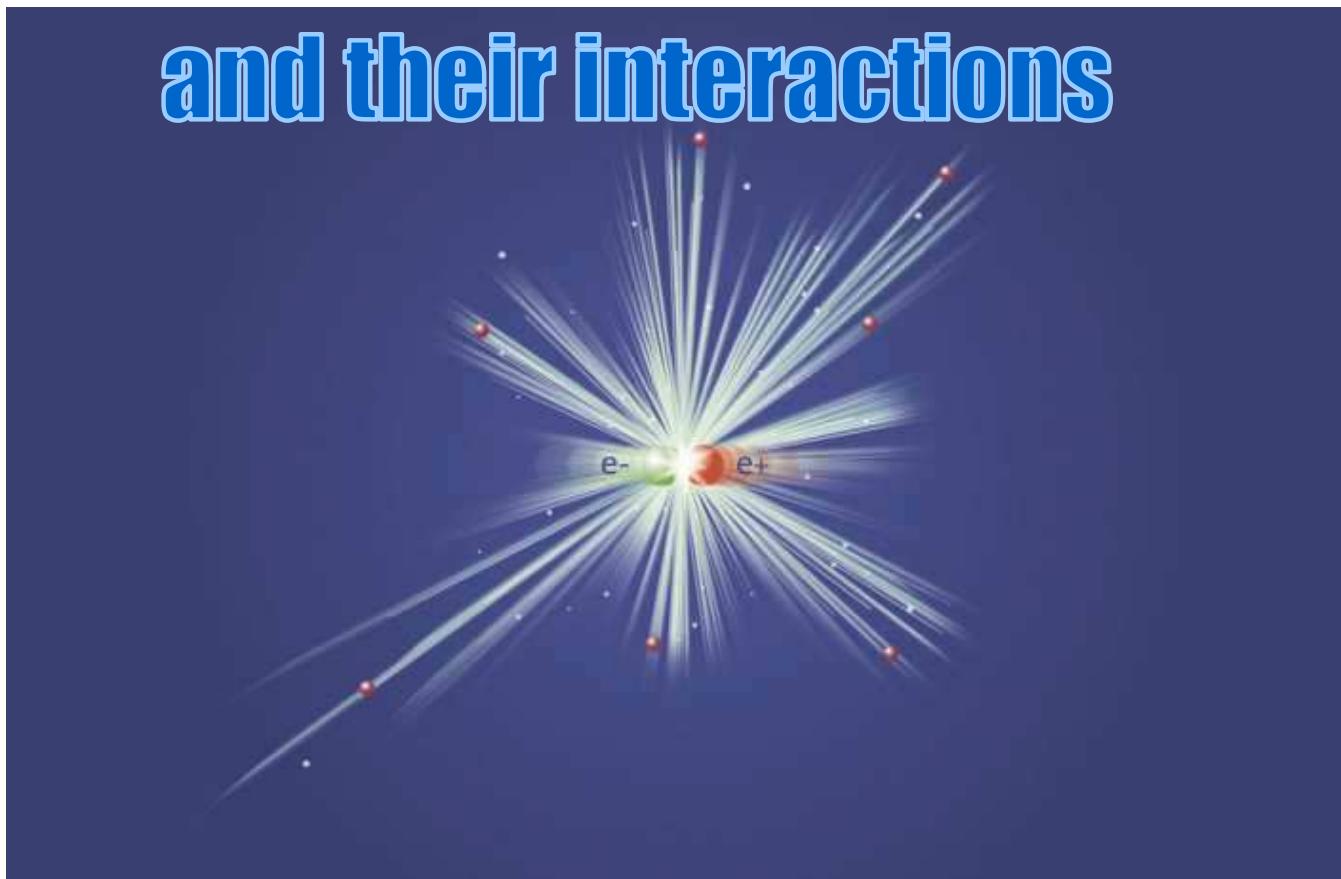
thanks to B. Foster for some
of the nicest slides/animations
other sources:
www.desy.de and [CERN](http://cern.ch)

What is Particle Physics?

Particle Physics

= science of elementary particles

and their interactions

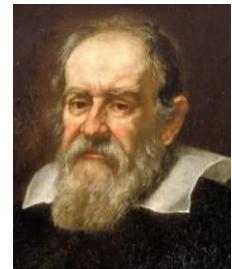


What is "science"?

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.

First large scale scientific experiment:
historically recorded

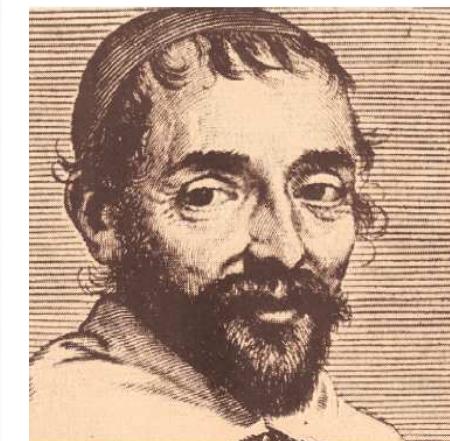
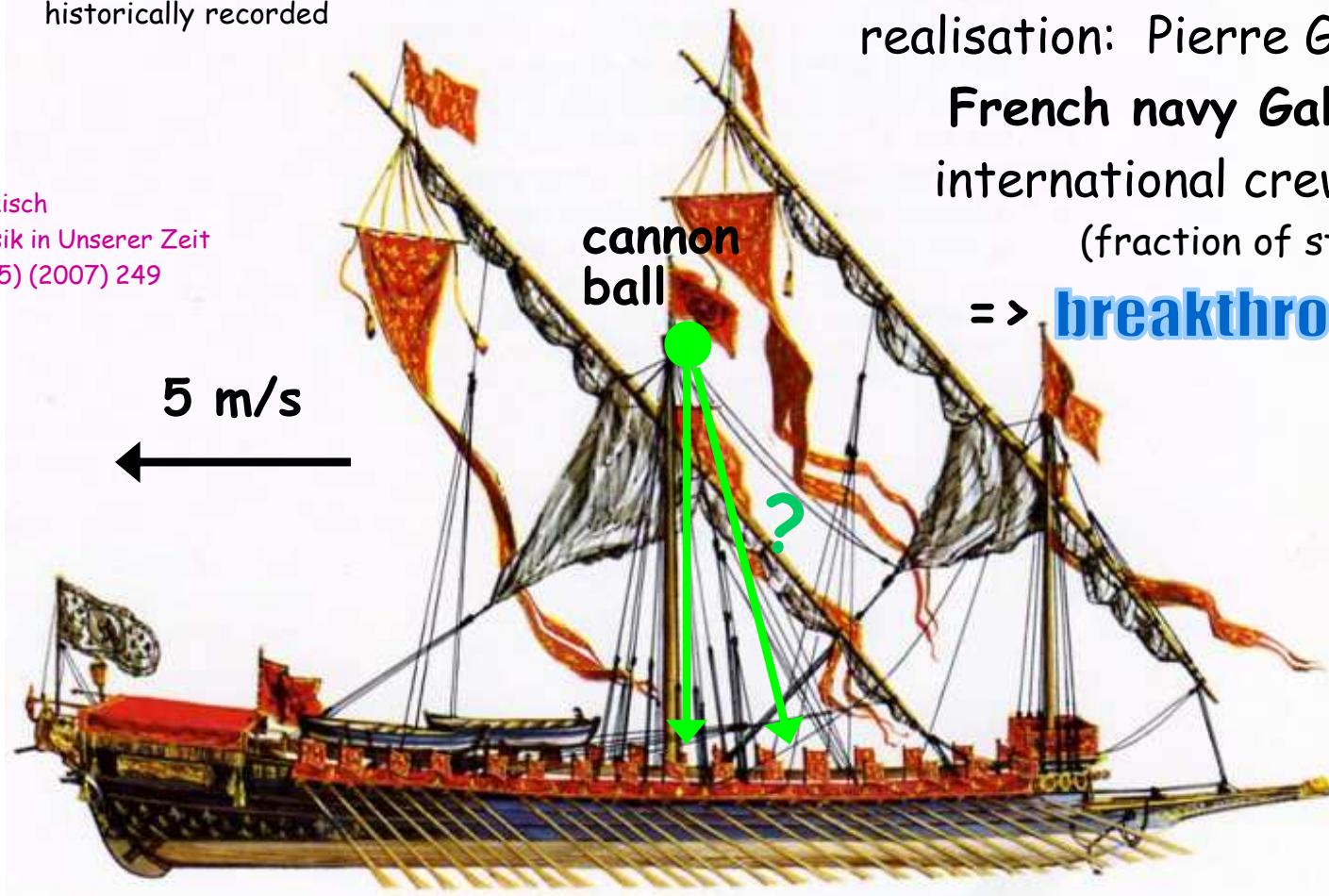


Galileo Galilei

proposal: Galilei 1632

realisation: Pierre Gassendi 1640

French navy Galley with
international crew of ~100 people
(fraction of students not reported)
=> breakthrough of inertial theory



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)



Louis
de Broglie
(Nobel 1929)



Werner
Heisenberg
(Nobel 1932)



Erwin
Schrödinger
(Nobel 1933)

The Atom

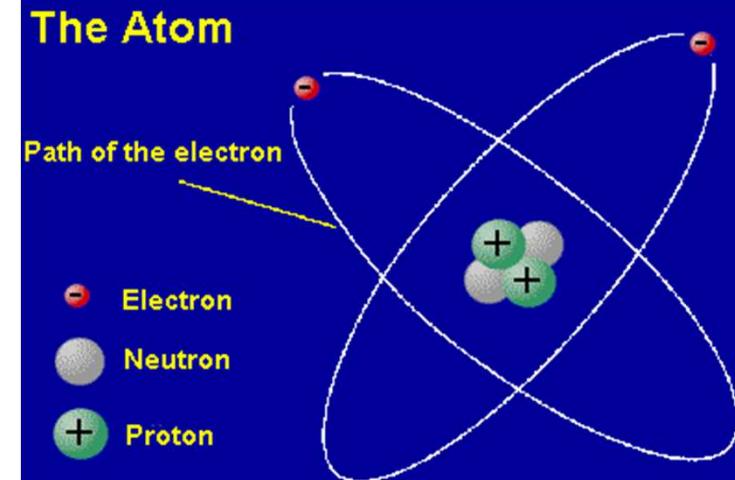
Path of the electron

- Electron
- Neutron
- Proton

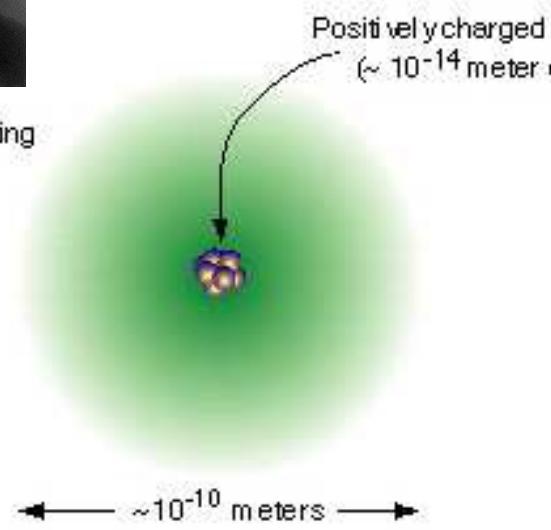


Niels
Bohr
(Nobel 1922)

Surrounding orbiting electrons ($-Z$)



Positively charged
($\sim 10^{-14}$ meter)

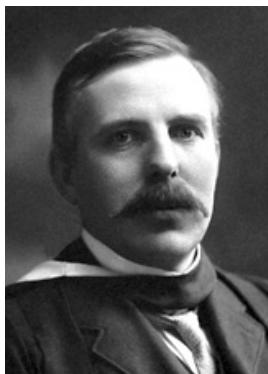


What is „elementary“?

Greek: atomos = smallest indivisible part



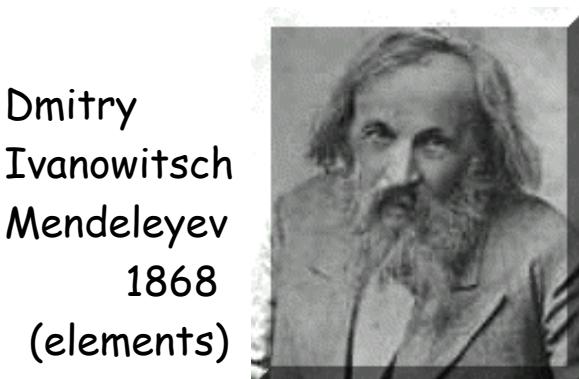
John Dalton
1803
(atomic model)



Ernest Rutherford
1911
(nucleus)
(Nobel 1908)

elementary
= no detectable
substructure

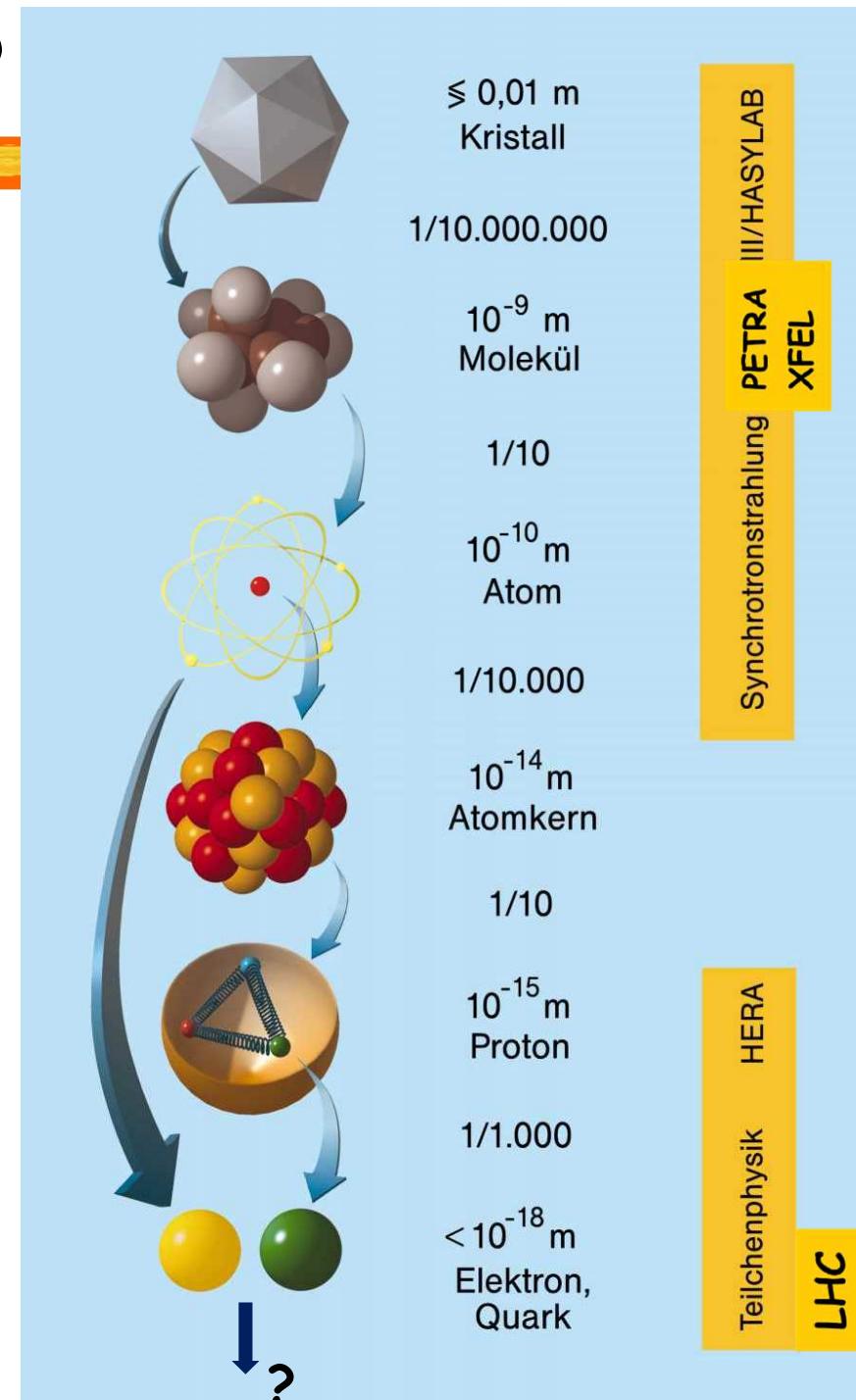
19.-21.7.17



Dmitry Ivanowitsch Mendeleyev
1868
(elements)



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

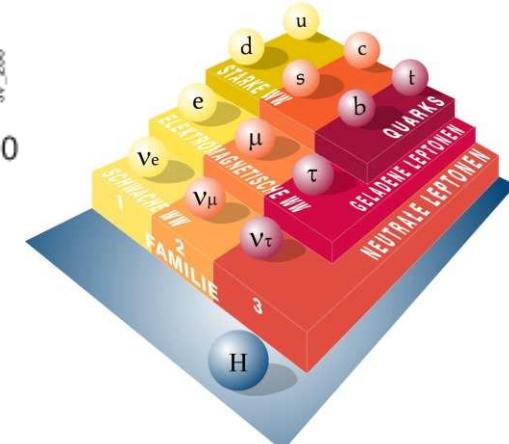
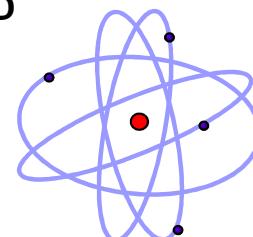
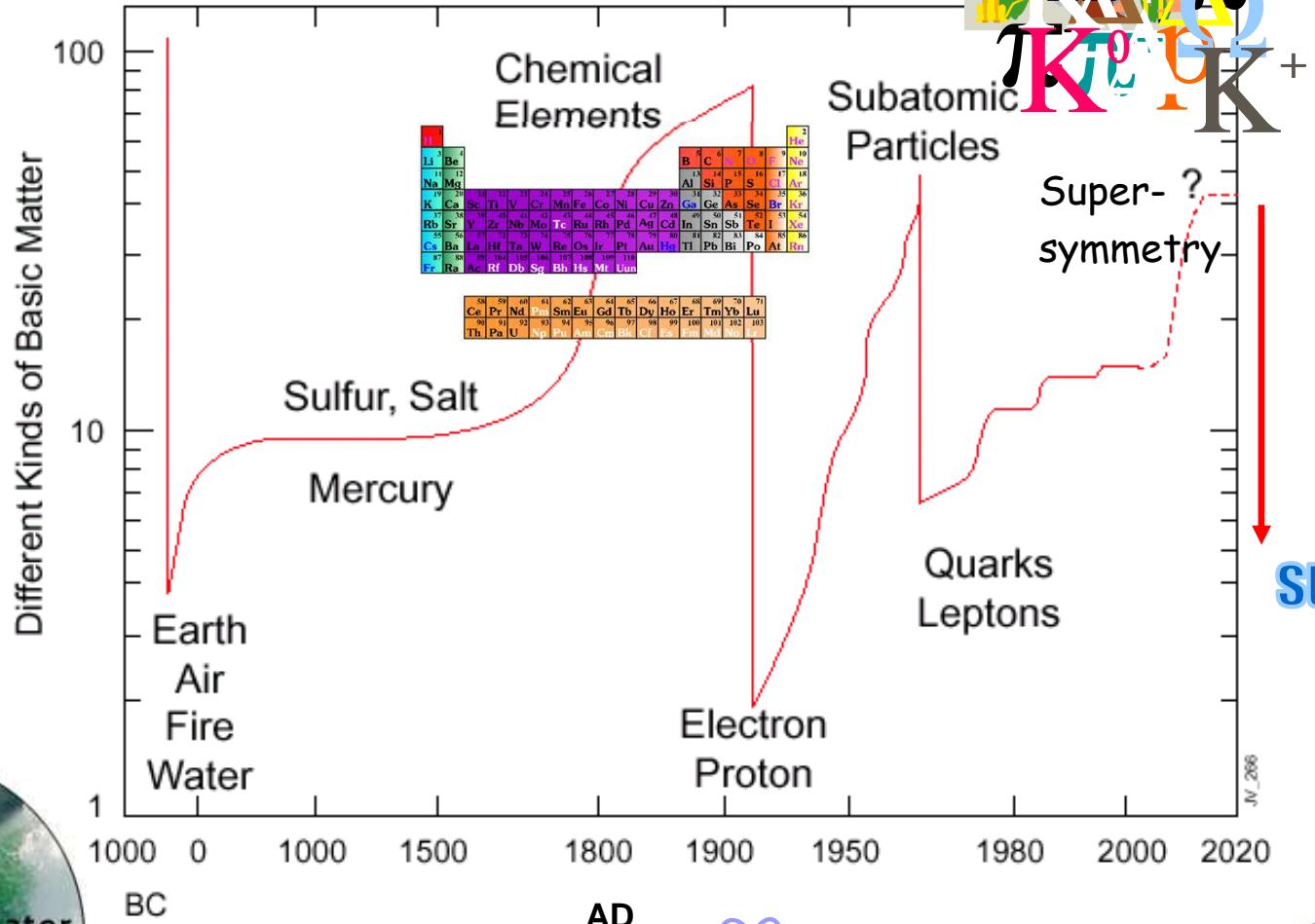


A. Geiser, Particle Physics

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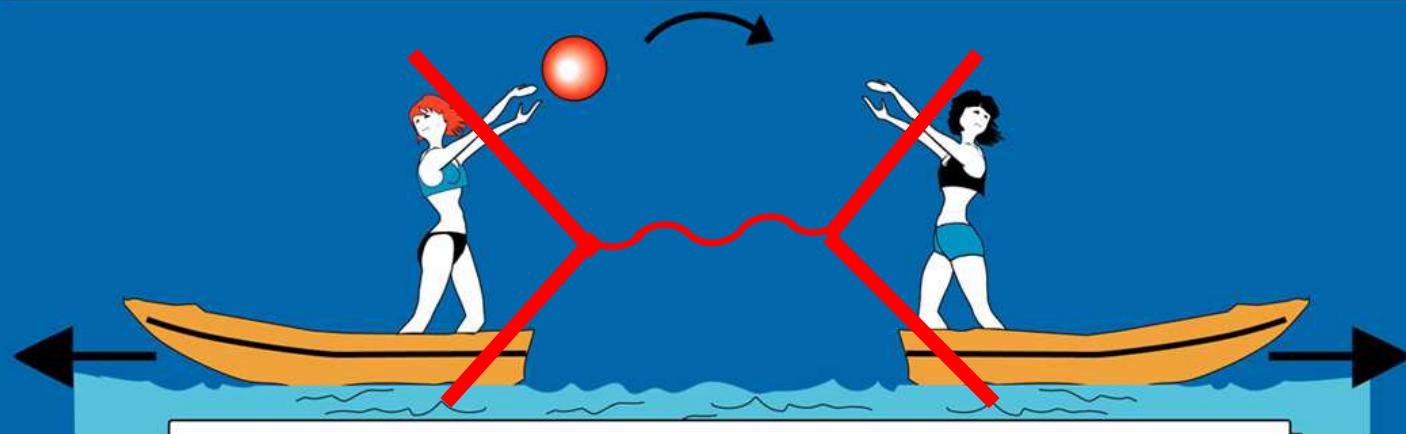
History of basic building blocks of matter

motivation:
find
smallest
possible
number

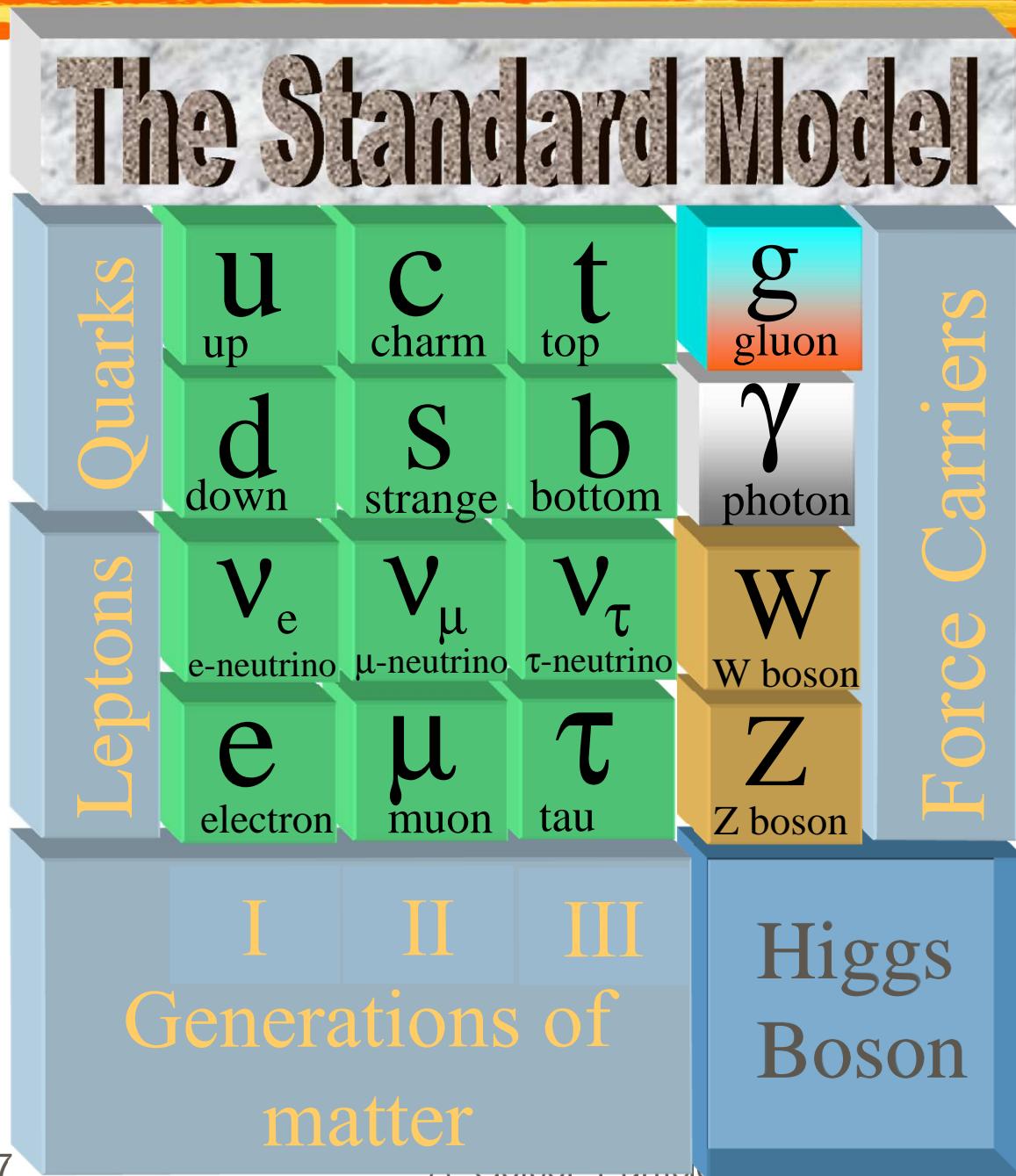


Which “interactions”?

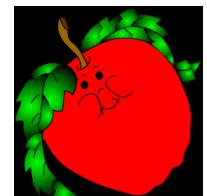
TYPE	at ~ 1 GeV INTENSITY OF FORCES (DECREASING ORDER)	BINDING PARTICLE (FIELD QUANTUM)	OCCURS IN :
STRONG NUCLEAR FORCE	~ 1	GLUONS (NO MASS)	ATOMIC NUCLEUS
ELECTRO -MAGNETIC FORCE	$\sim 10^{-2}$	PHOTONS (NO MASS)	ATOMIC SHELL ELECTROTECHNIQUE
WEAK NUCLEAR FORCE	$\sim 10^{-5}$	BOSONS Z^0 , W^+ , W^- (HEAVY)	RADIOACTIVE BETA DESINTEGRATION
GRAVITATION	$\sim 10^{-38}$	GRAVITONS (?)	HEAVENLY BODIES



What we know today

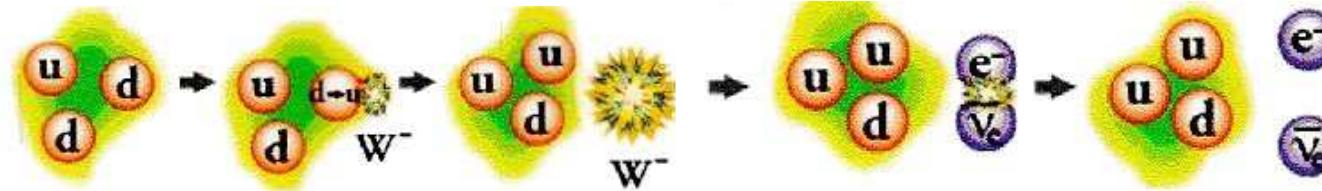
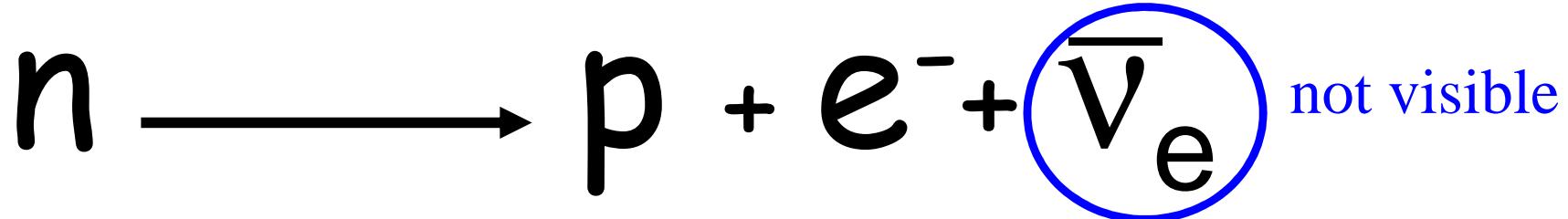


Gravity
the
ghost at
the
feast



The Power of Conservation Laws

■ e.g. radioactive neutron decay:



■ Pauli 1930:



Wolfgang
Pauli
(Nobel 1945)

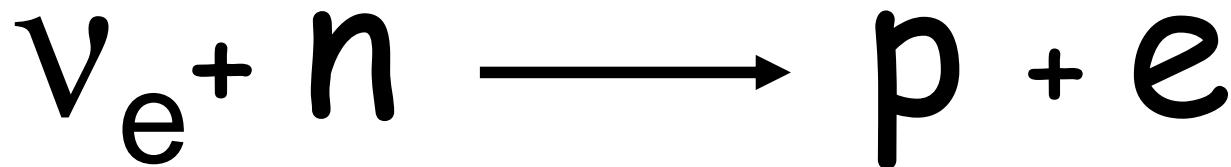
**Neutrino
must be present
to account for
conservation of energy
and (angular) momentum**



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

confirmation: neutrino detection

- e.g. reversed reaction:

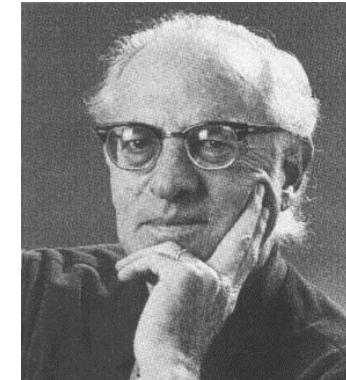


extremely rare!

(absorption length ~ 3 light years Pb)

- first detection: 1956

Reines and Cowan, neutrinos from nuclear reactor



Frederick Reines

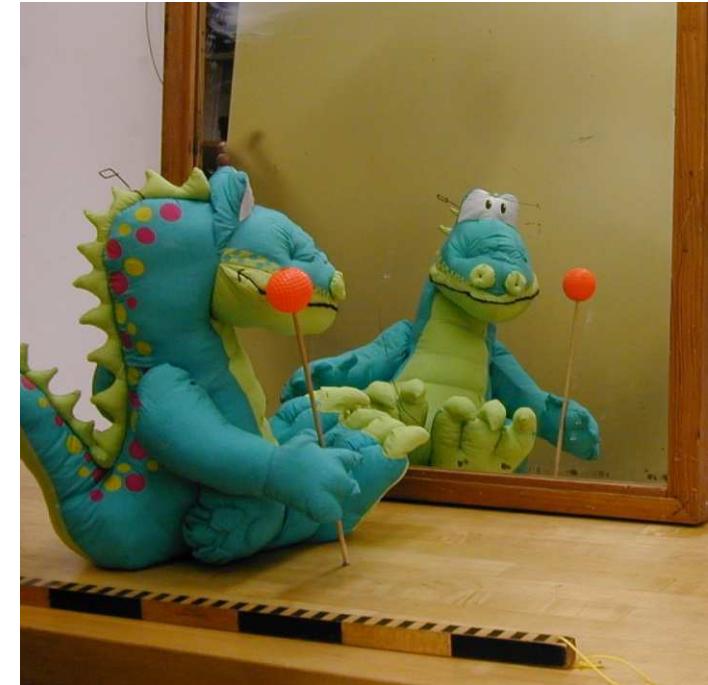
(Nobel 1995)

**Conservation laws remain valid
down to microscopic scales!**

The power of symmetries: Parity

Parity = Mirror Symmetry

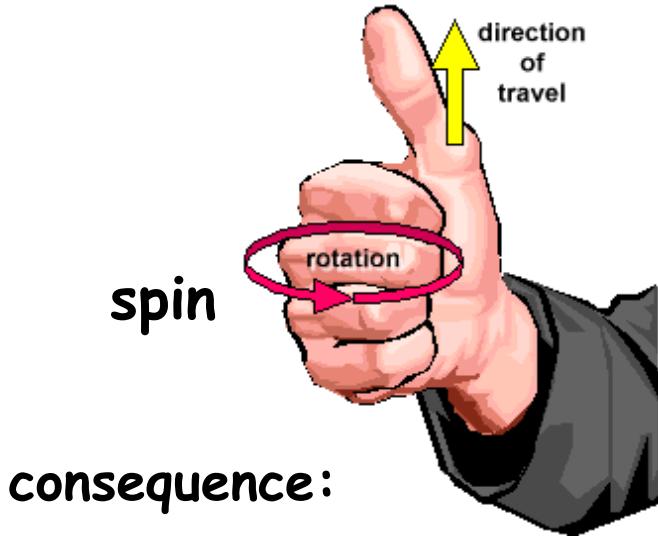
- Will physical processes look the same when viewed through a mirror?
- In everyday day life:
violation of parity symmetry is common
„natural“: our heart is on the left
„spontaneous“: cars drive on the right
(on the continent)
- What about basic interactions?
- Electromagnetic and strong interactions conserve parity!



Eugene
Wigner
(Nobel 1963)

The power of symmetries: Parity

Lee & Yang 1956: **weak interactions violate Parity**
experimentally verified by Wu et al. 1957:

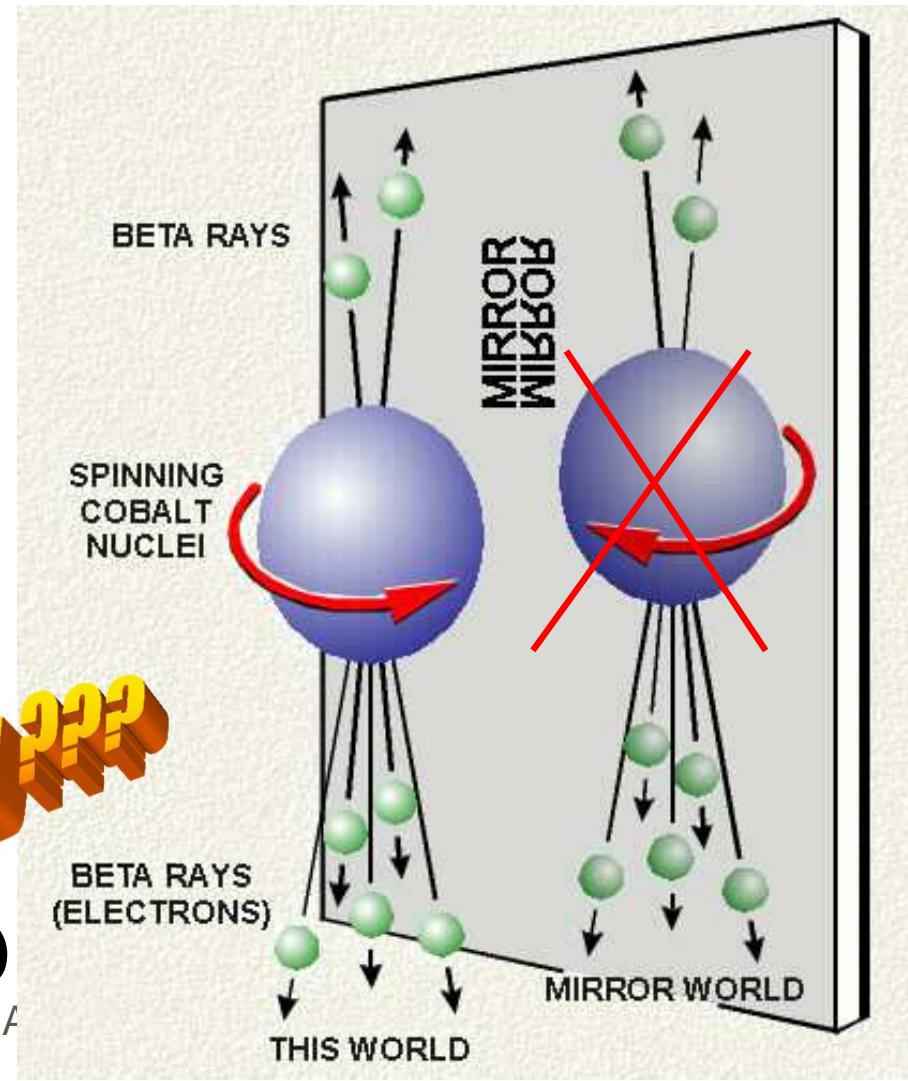


consequence:

**neutrinos are
always
lefthanded !**

Why ???

(antineutrinos righthanded)



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

■ 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**

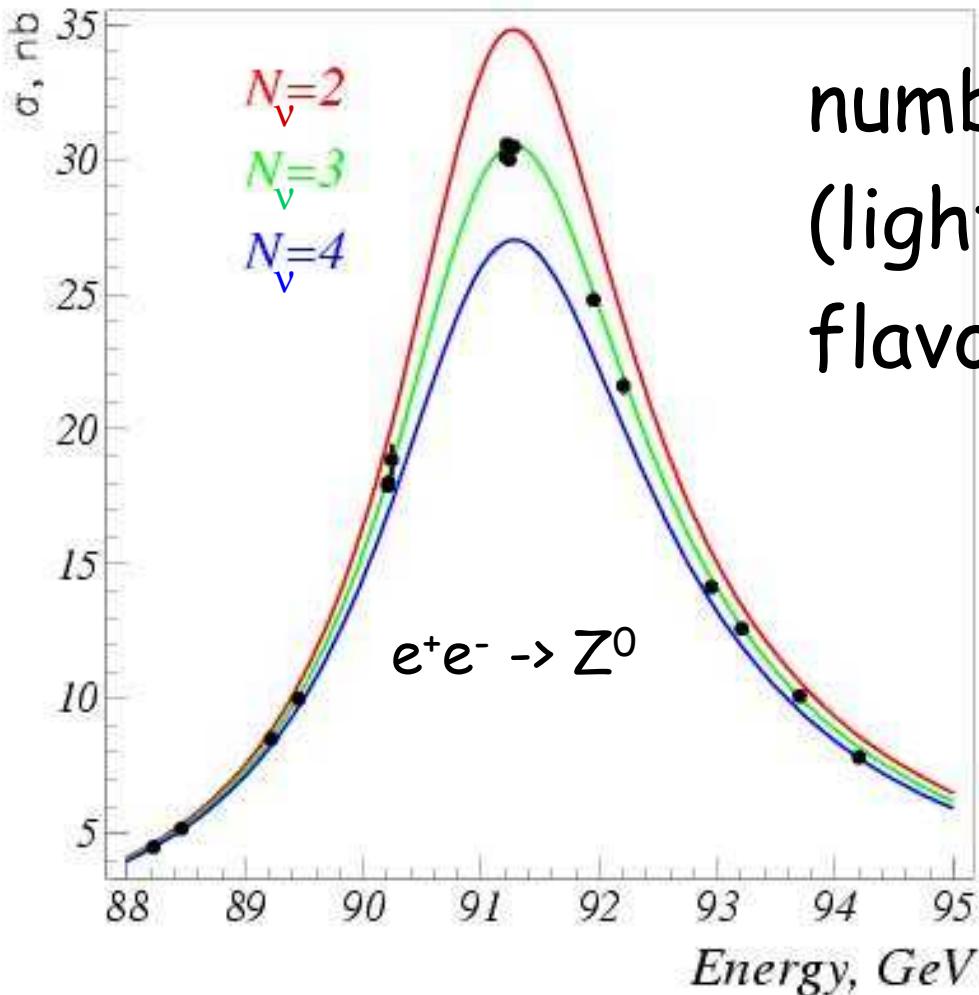
■ There is a distinct neutrino for each charged lepton

Why ???

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



(Nobel 1999)

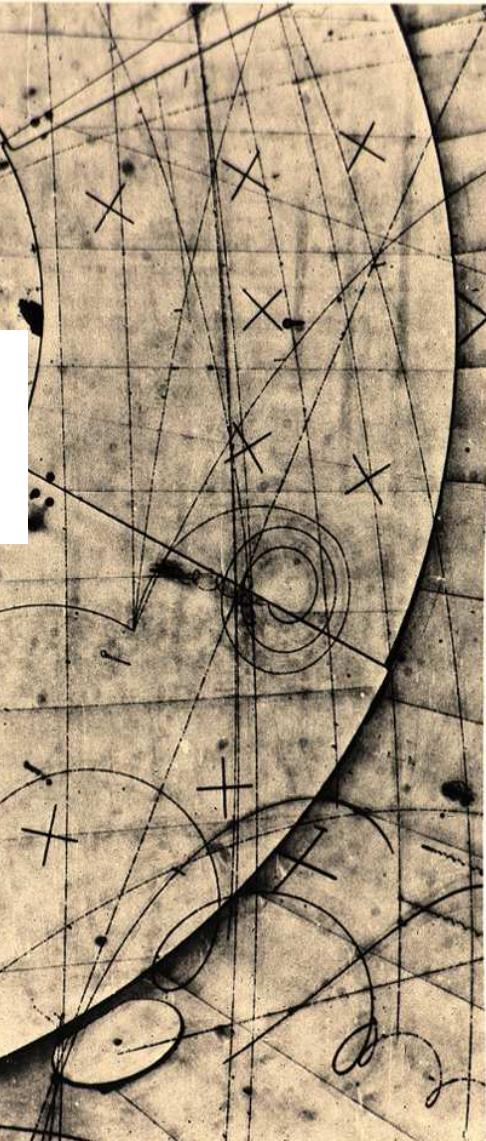
There seem to be
exactly three
lepton + quark
families!

Why ????

Can we “see” particles?



Luis Walter Alvarez (Nobel 1968)



bubble
chamber
photo

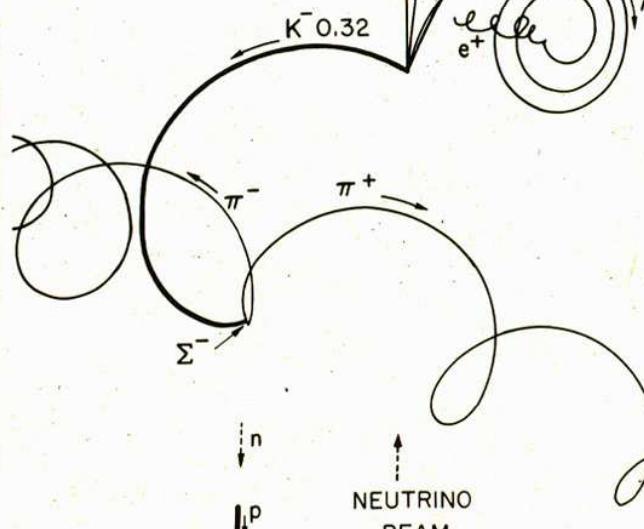


Donald Arthur Glaser (Nobel 1960)

AACHEN-BONN-CERN-MUNICH-OXFORD COLLABORATION

WA 21
EVENT 294/0995

$$\nu p \rightarrow D^* p \mu^- \rightarrow D^0 \pi^+ \rightarrow K^- \pi^+ \rightarrow p \rightarrow \Sigma^- \pi^+ \rightarrow n \pi^- \rightarrow p \rightarrow np$$



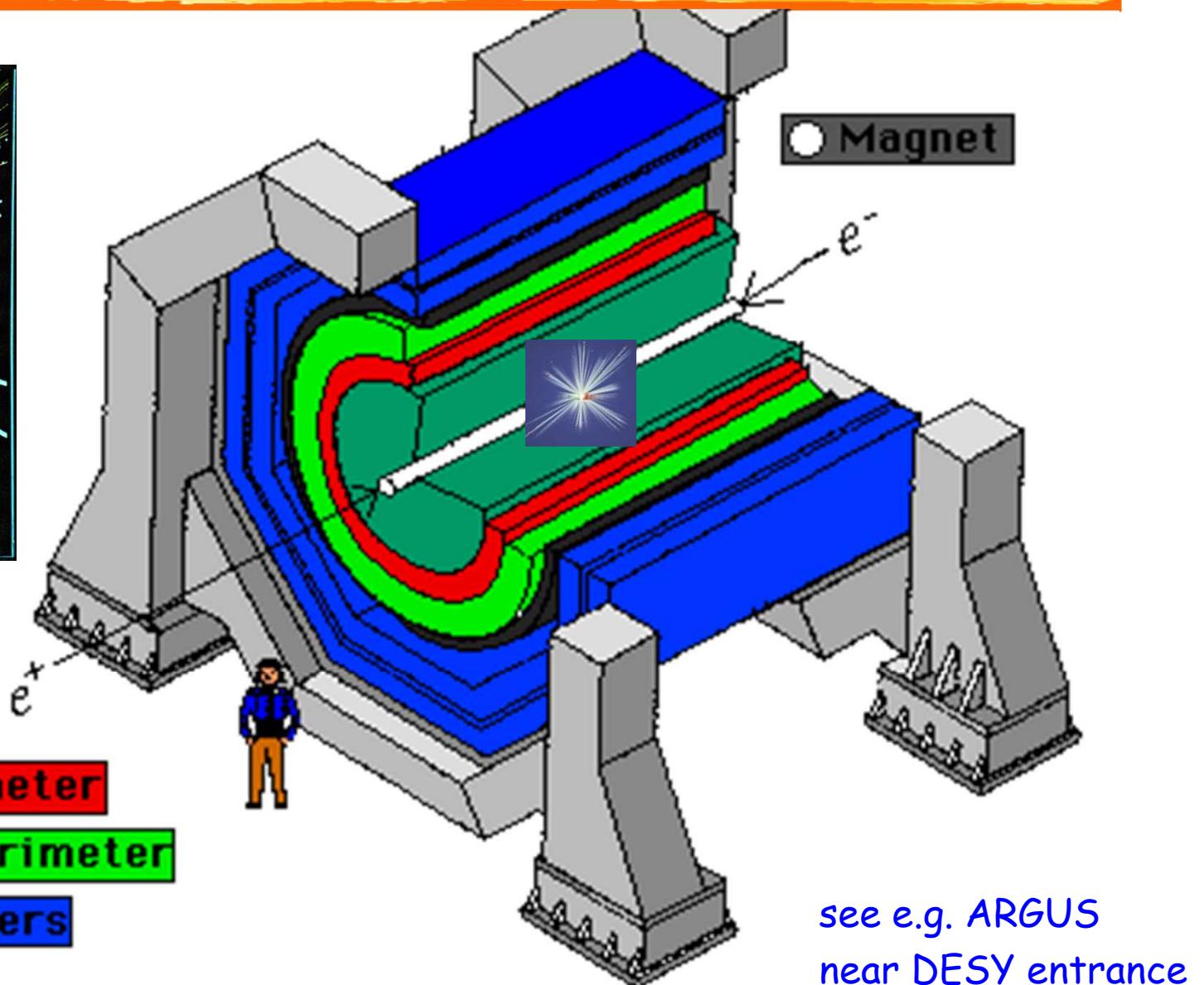
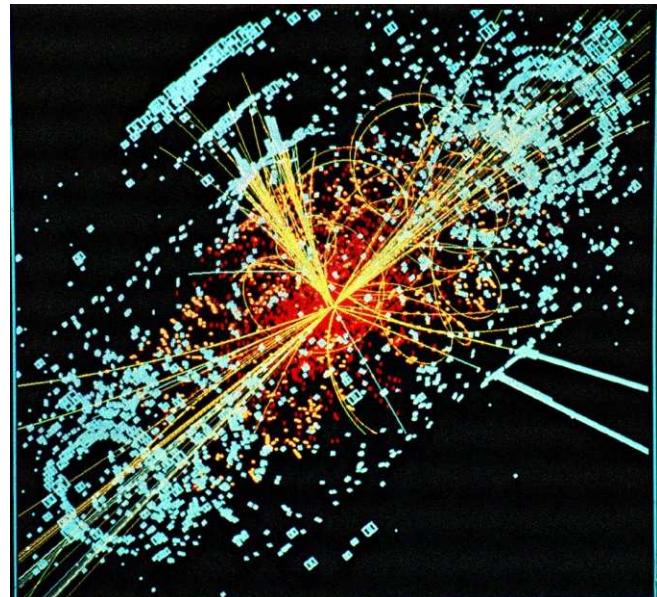
MOMENTUM IN

we can!

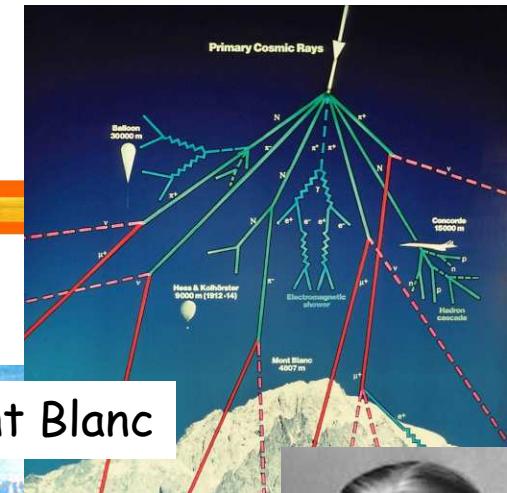


Quarks. Neutrinos. Mesons. All those
damn particles you can't see. That's what
drove me to drink. But now I can see them.

A typical particle physics detector

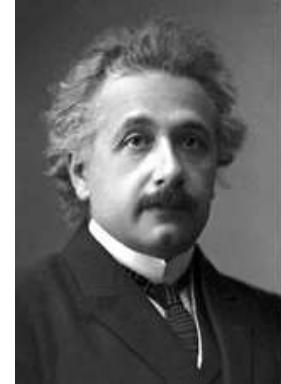


Why do we need colliders?



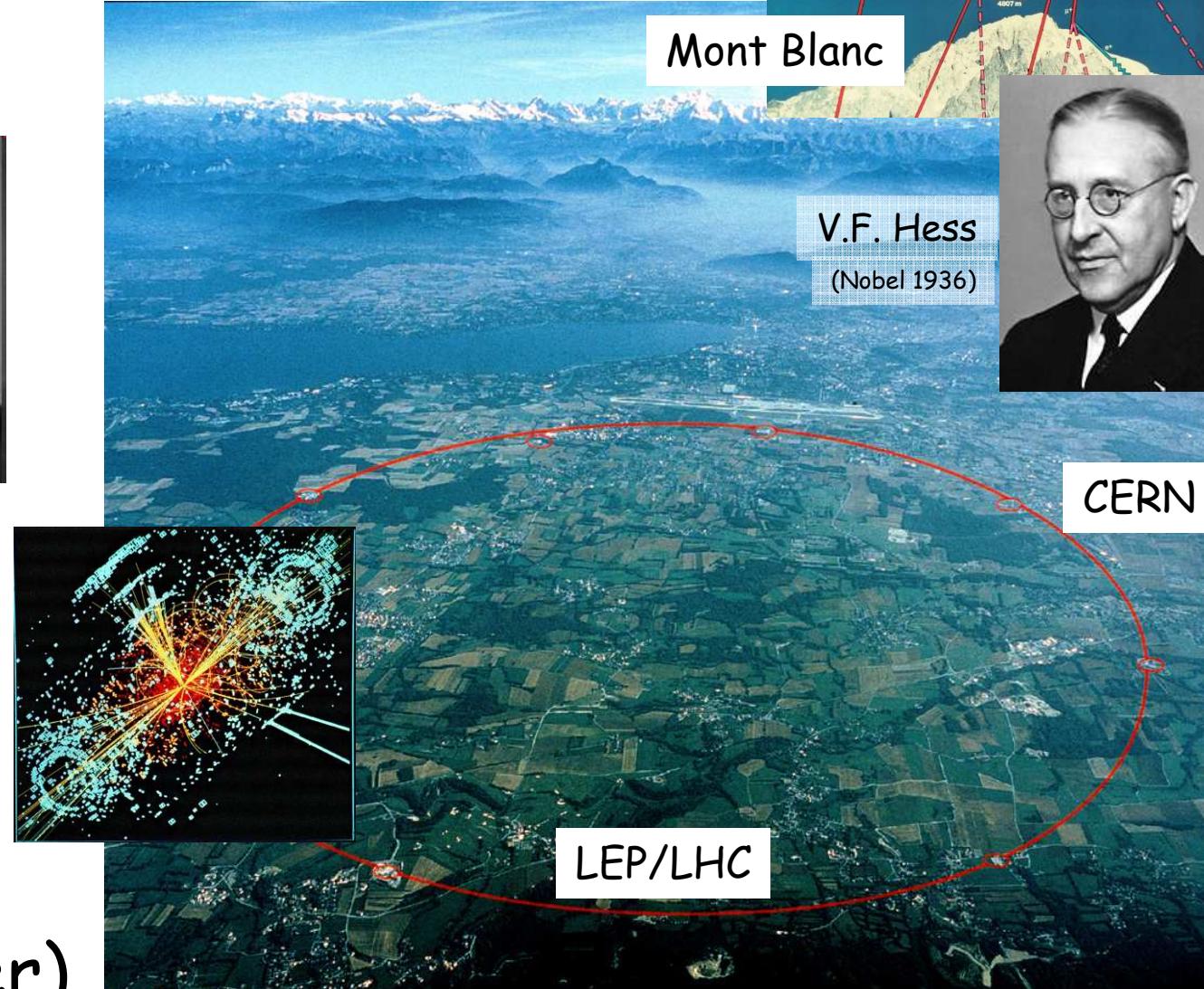
- early discoveries in cosmic rays, but
- need controlled conditions

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



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 at small rate.



Particle Physics = People

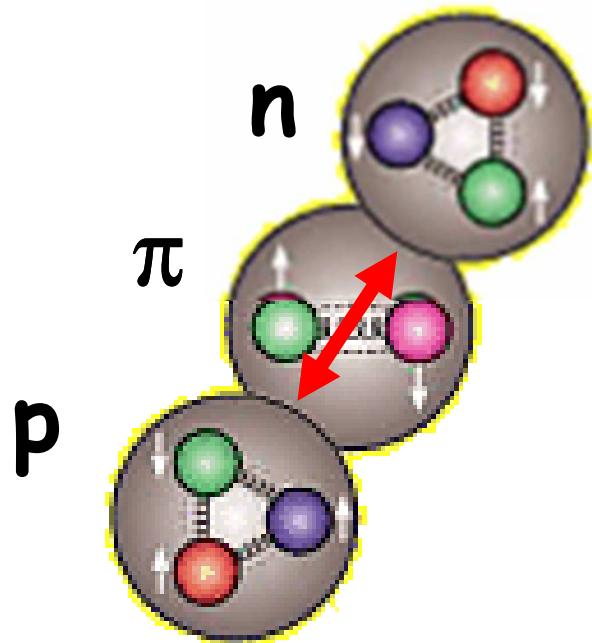


Strong Interactions: Quarks and Colour

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



Hideki Yukawa
(Nobel 1949)

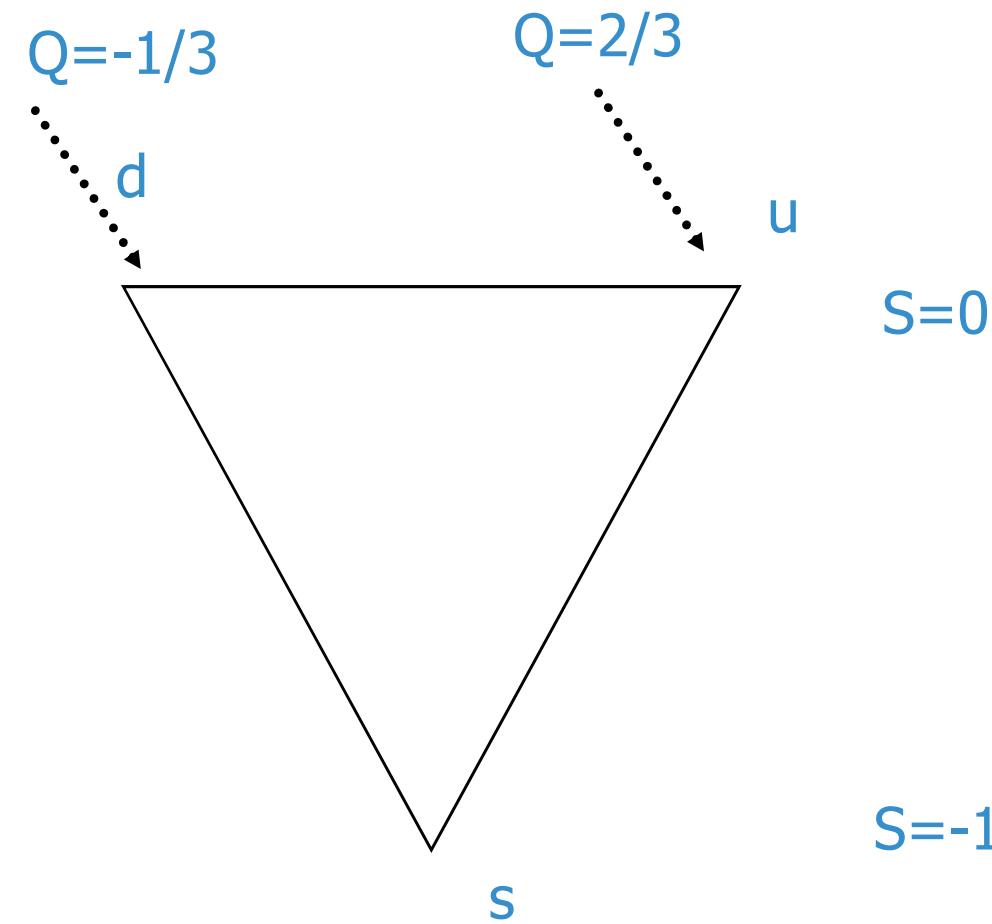


- modern view:
(Quantum Chromo-Dynamics, QCD)
exchange of massless gluons
between quark
constituents

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

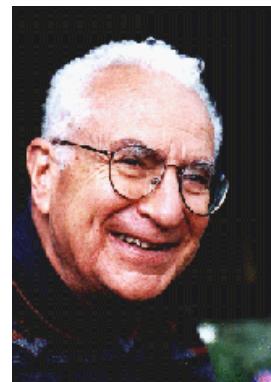
The Quark Model (1964)

arrange quarks (known at that time) into flavour-triplet
 $\Rightarrow \text{SU}(3)_{\text{flavour}}$ symmetry



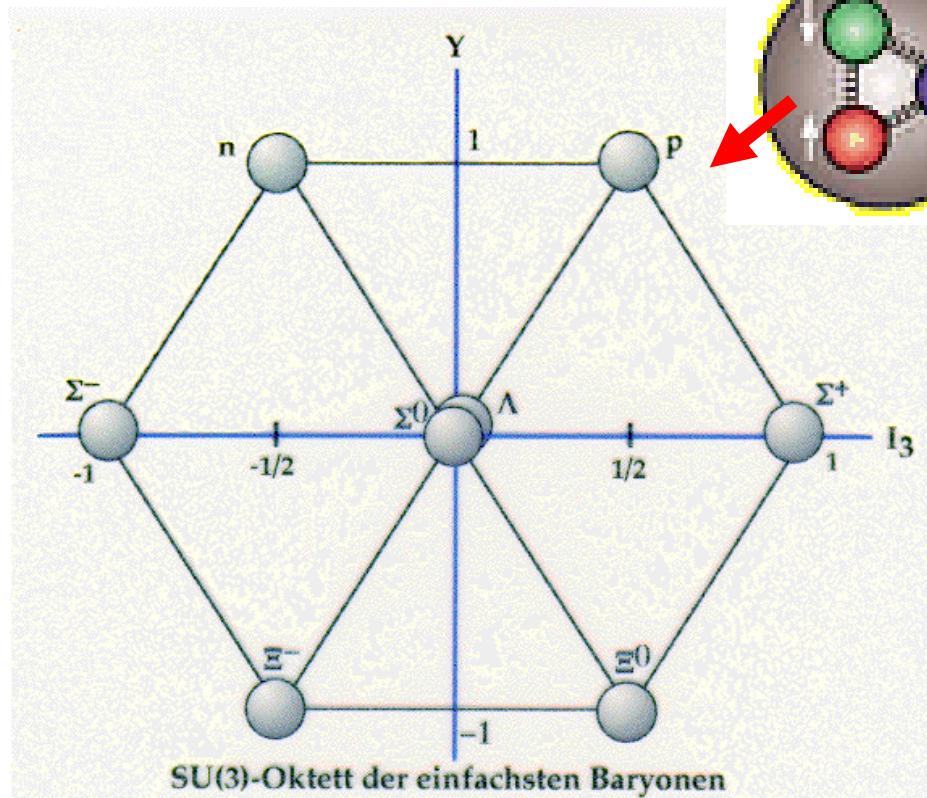
treat all known hadrons
(protons, neutrons, pions, ...)
as objects composed of
two or three such
quarks (antiquarks)

Murray
Gell-Mann
(Nobel 1969)

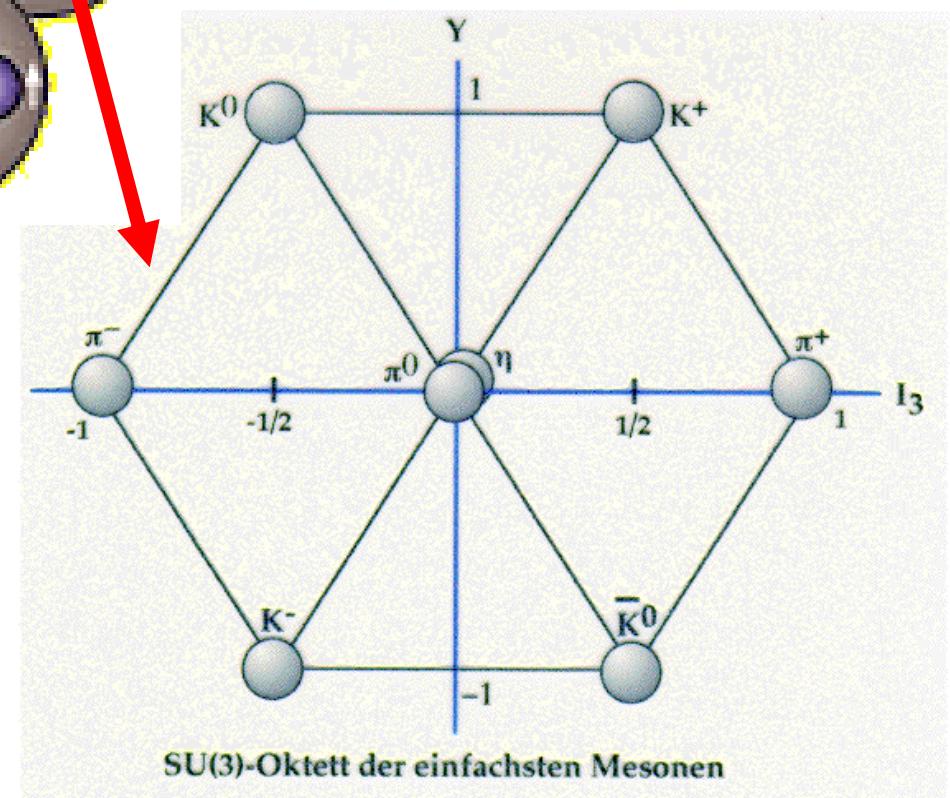


The Quark Model

baryons = qqq



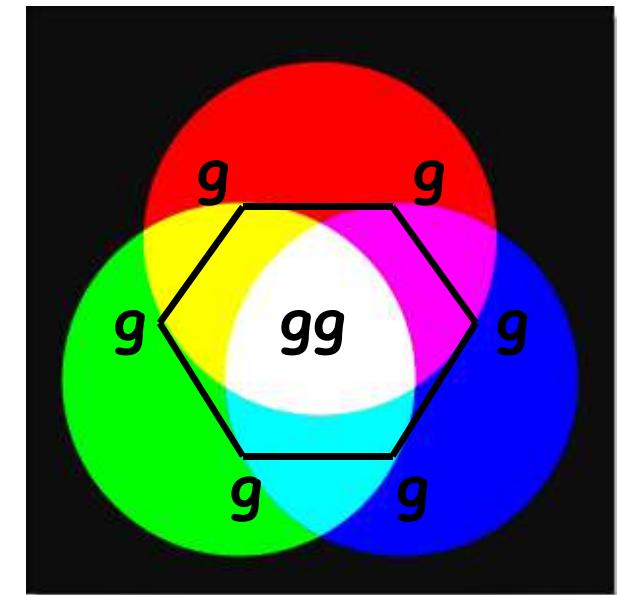
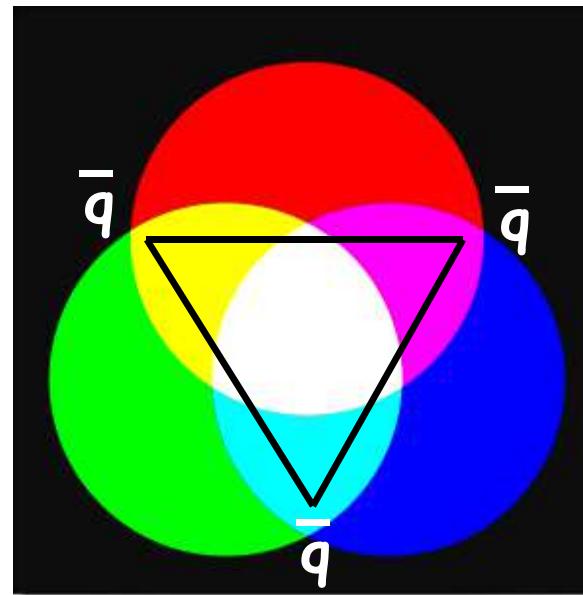
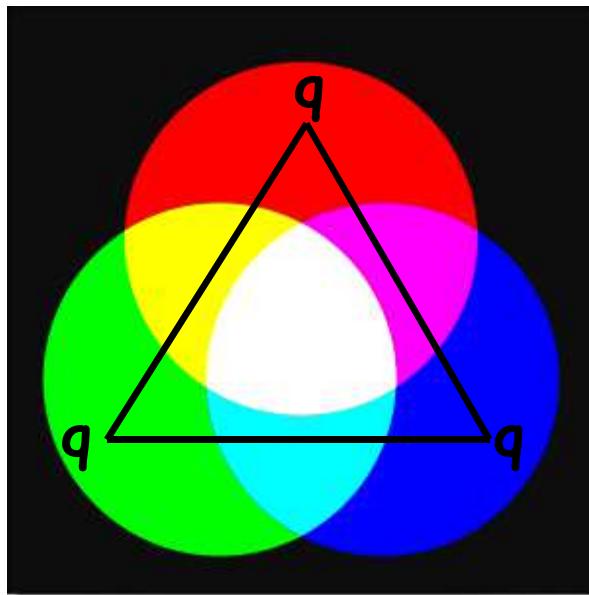
mesons = $q\bar{q}$



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:

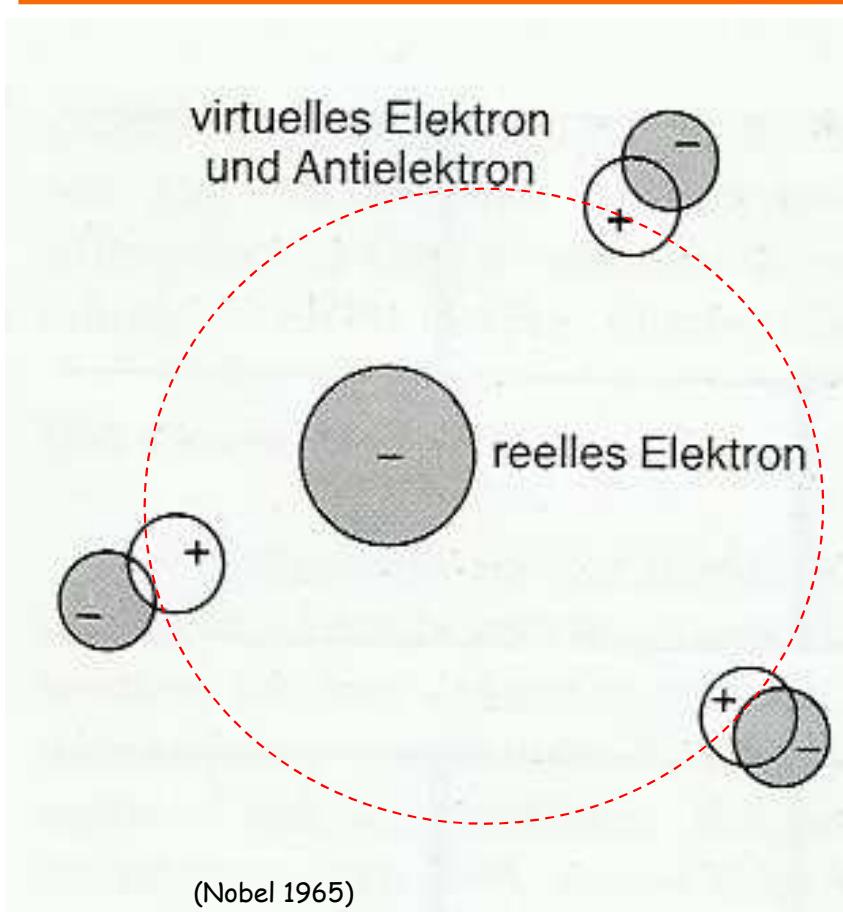
Colour



■ 3 colours $\rightarrow \text{SU}(3)_{\text{colour}}$
(exact symmetry)

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

Screening of Electric Charge



19.7.17
19.7.17

Julian
Schwinger

Richard P.
Feynman

A. Geiser, Particle Physics

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- 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

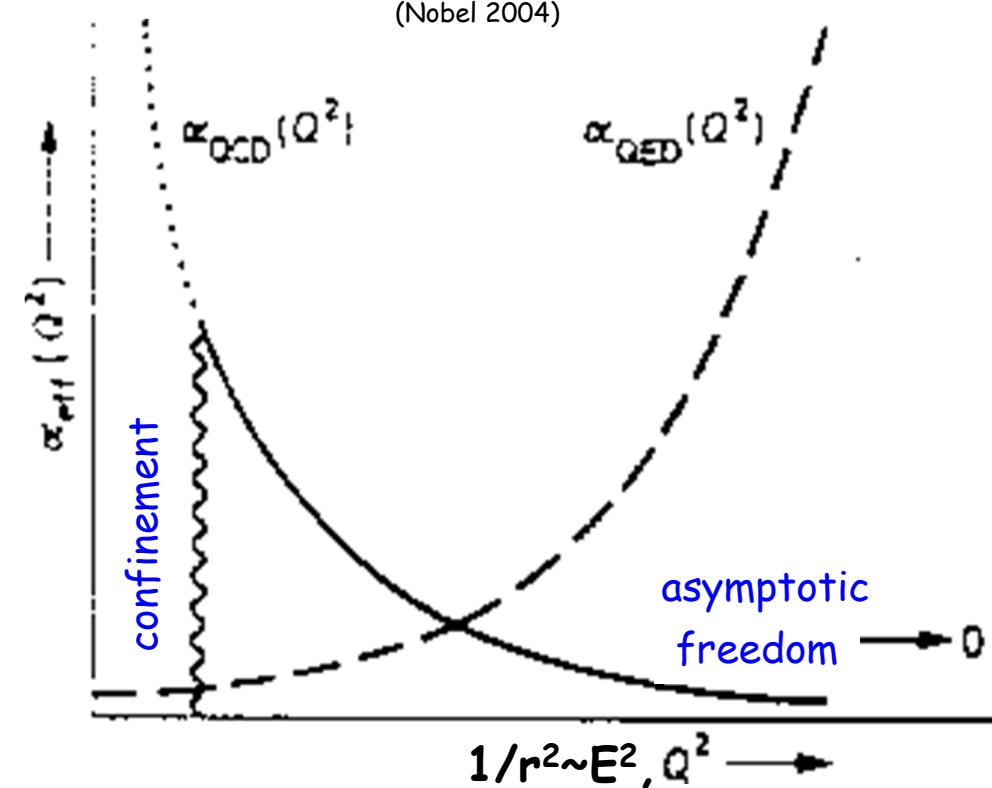
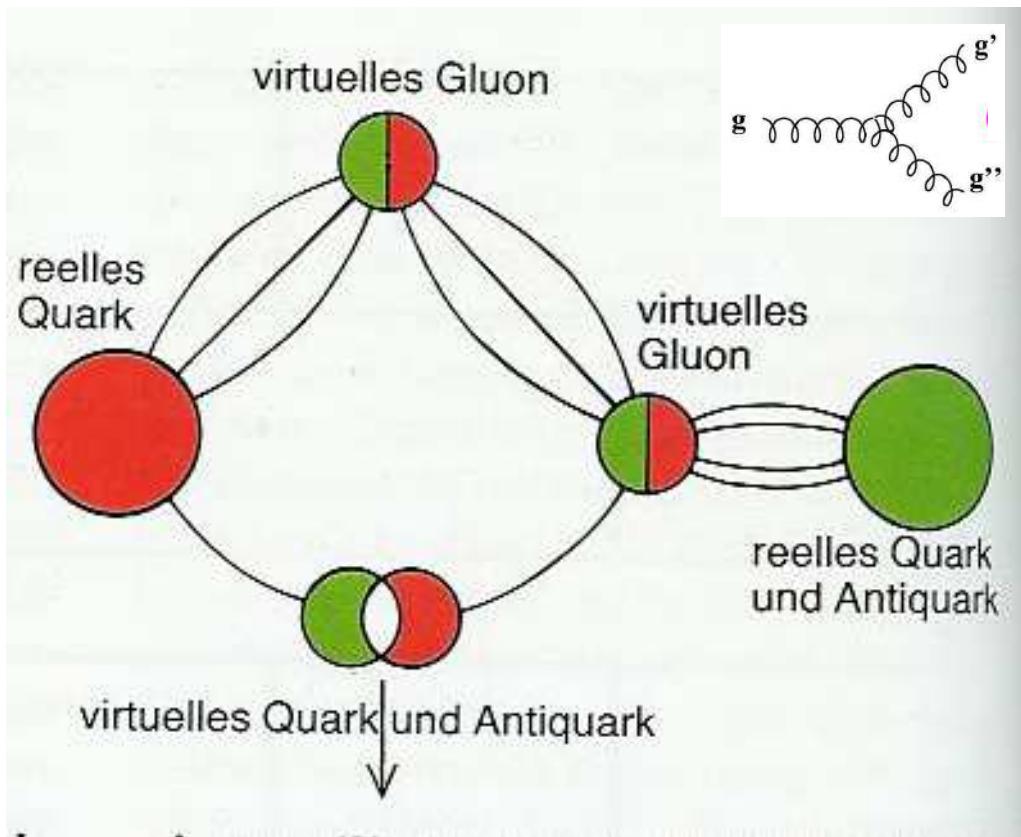
Anti-Screening of Colour Charge!

quark-antiquark pairs \rightarrow screening
gluons carry colour \rightarrow gg pairs
 \rightarrow anti-screening!



David J. Gross H. David Politzer Frank Wilczek

(Nobel 2004)

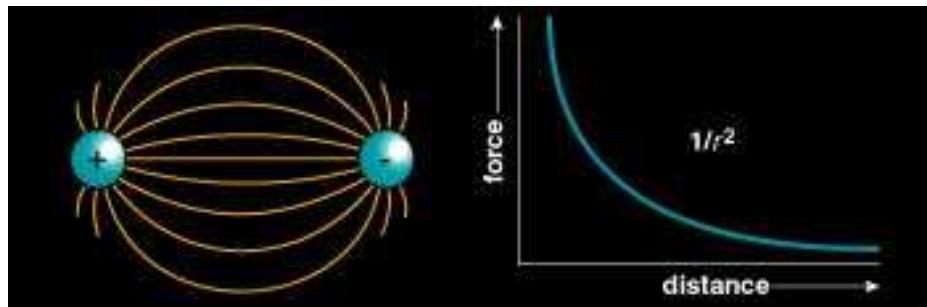


Comparison QED / QCD

electromagnetism

QED

1 kind of charge (q)
force mediated by **photons**
photons are *neutral*
 α is nearly constant

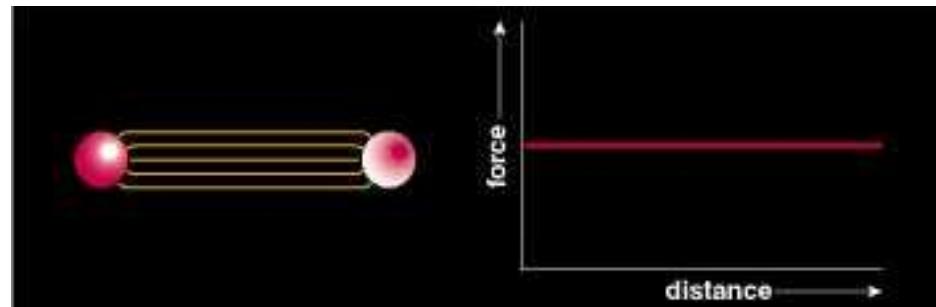


strong interactions

QCD

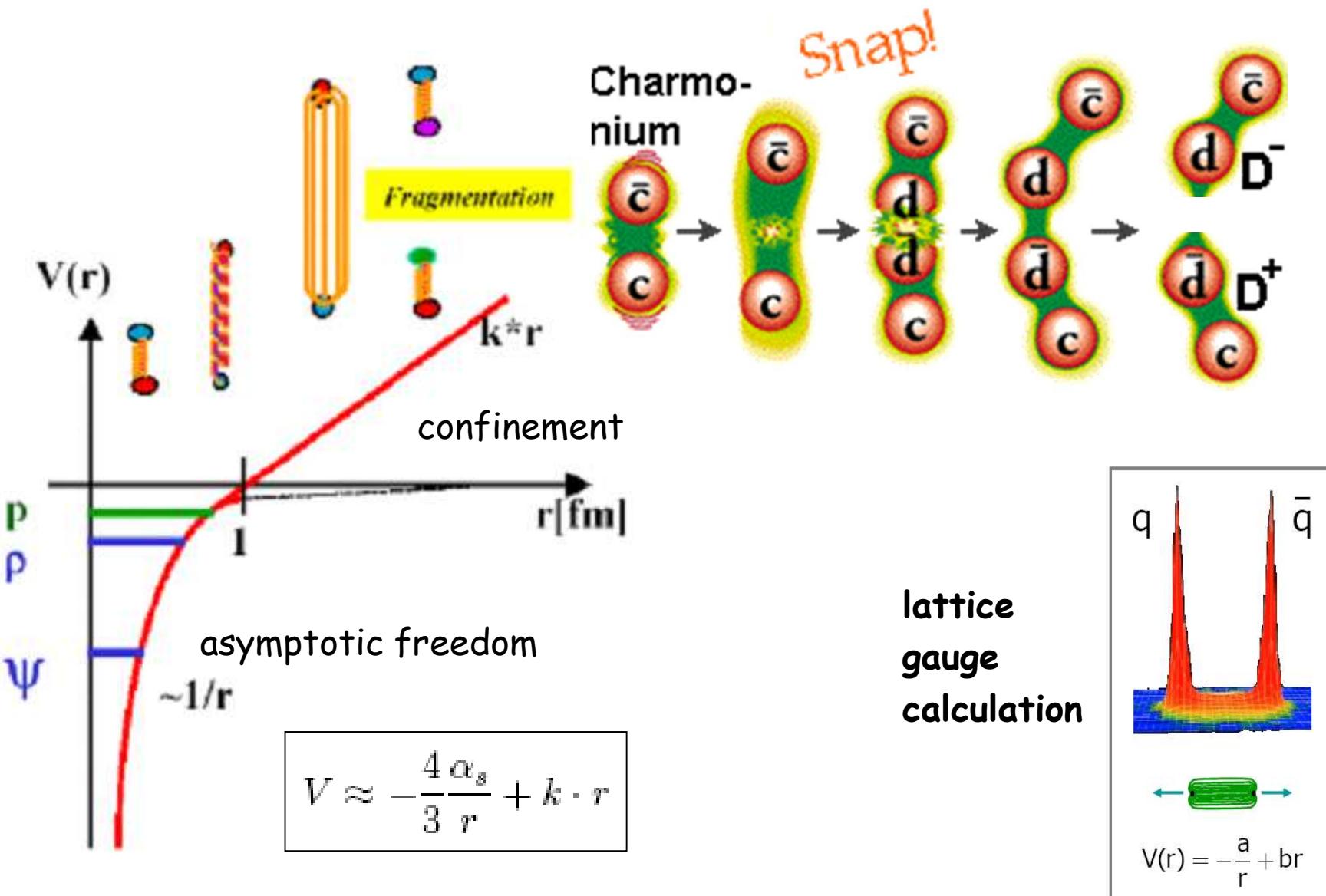
3 kinds of charge (r, g, b)
force mediated by **gluons**
gluons are *charged* (eg. rg , bb , gb)
 α_s strongly depends on distance

confinement limit:



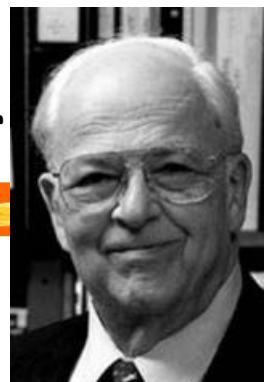
- The underlying theories are formally almost identical!

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

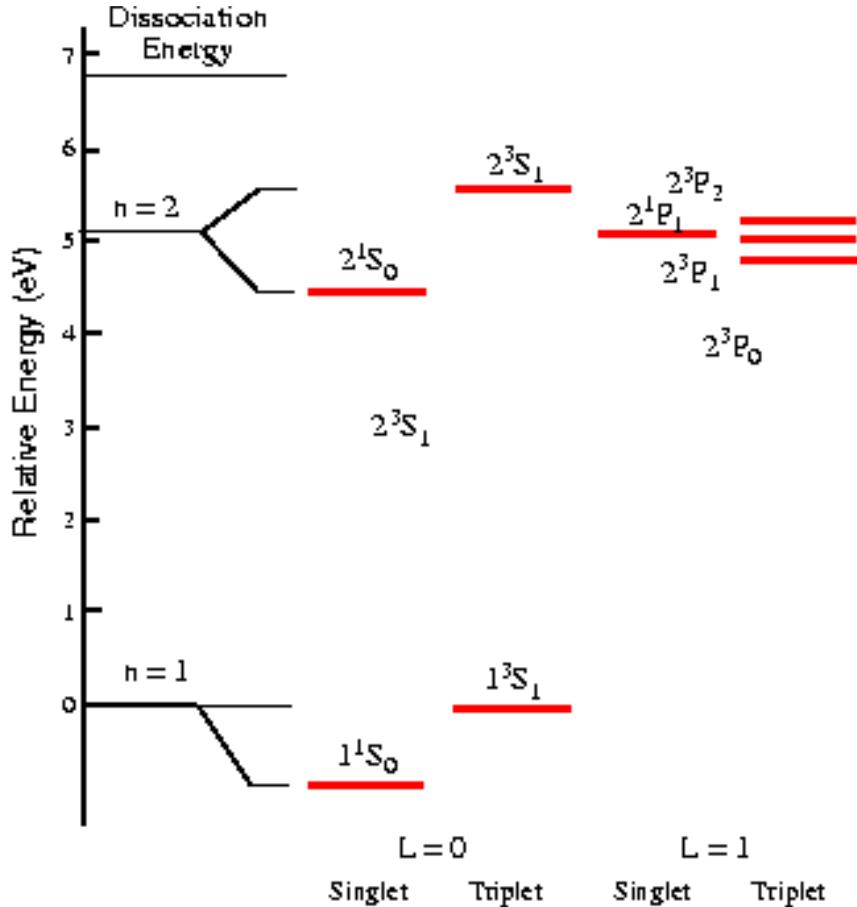


Heavy Quark Spectroscopy

Burton
Richter



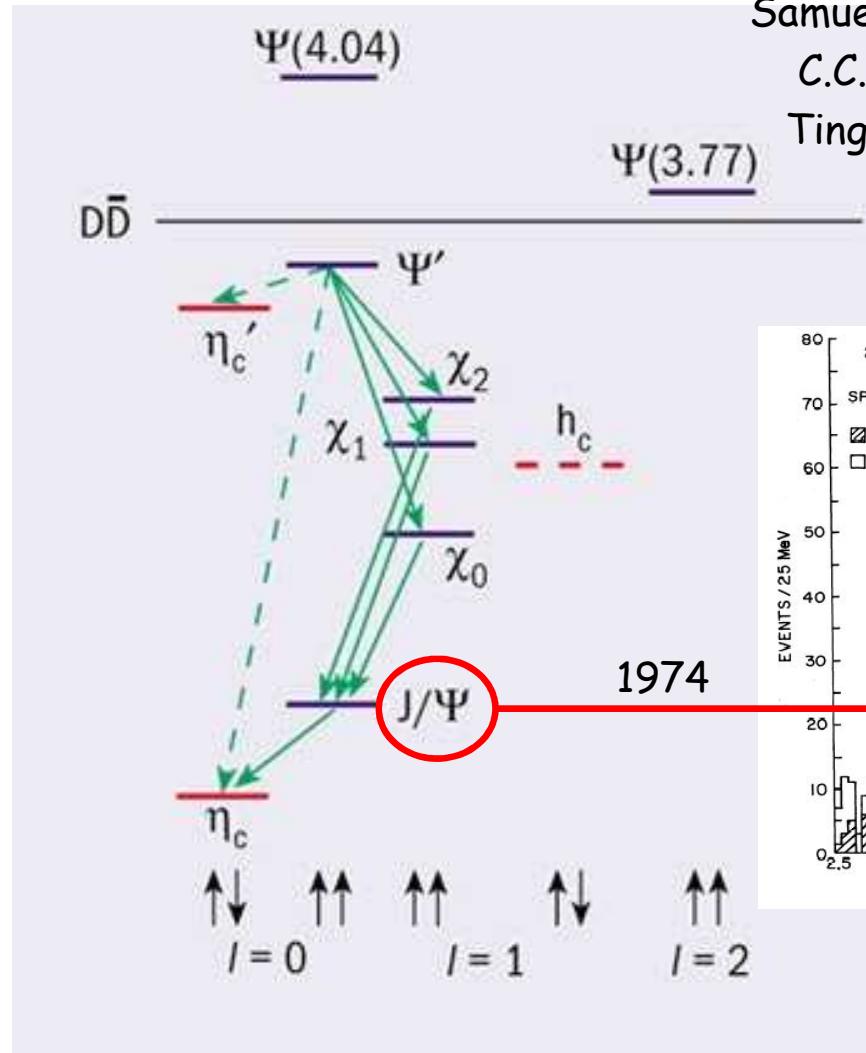
Positronium = bound e^+e^- system



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

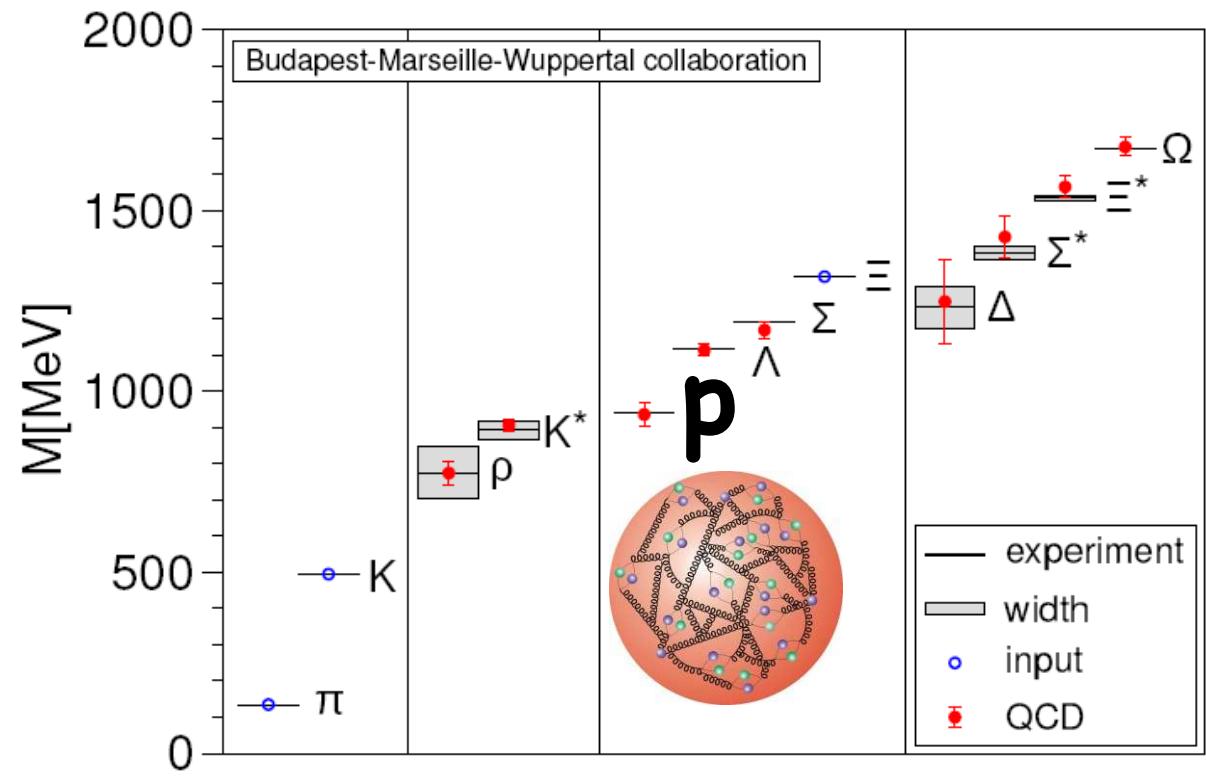
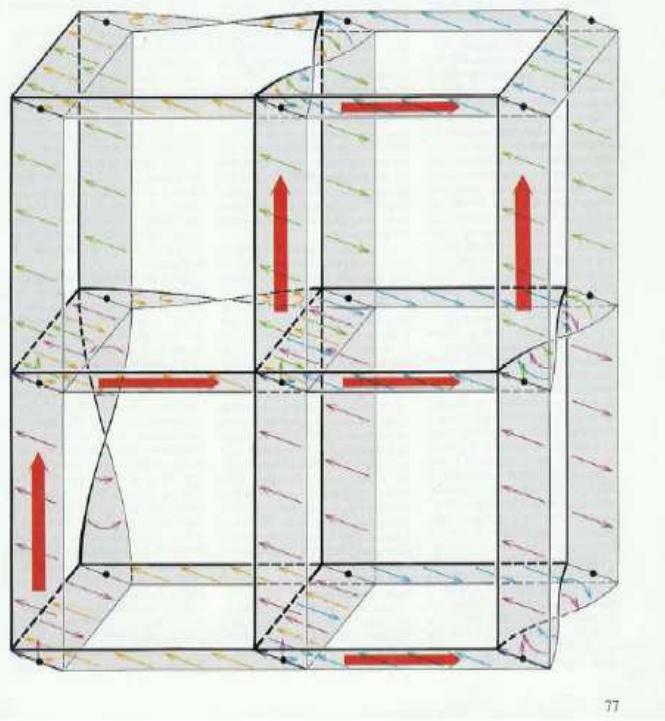
(Nobel
1976)

Samuel
C.C.
Ting



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,
⇒ mass of the visible part of the universe !

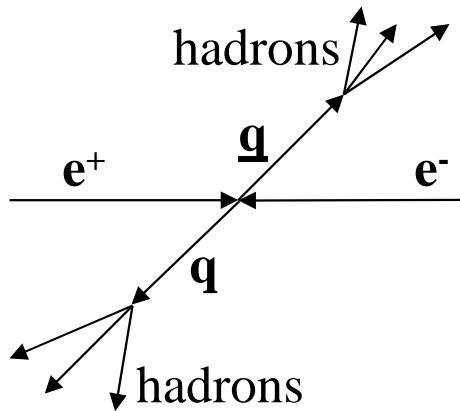


Yoichiro
Nambu

(Nobel 2008)

How to detect Quarks and Gluons?

Jets!



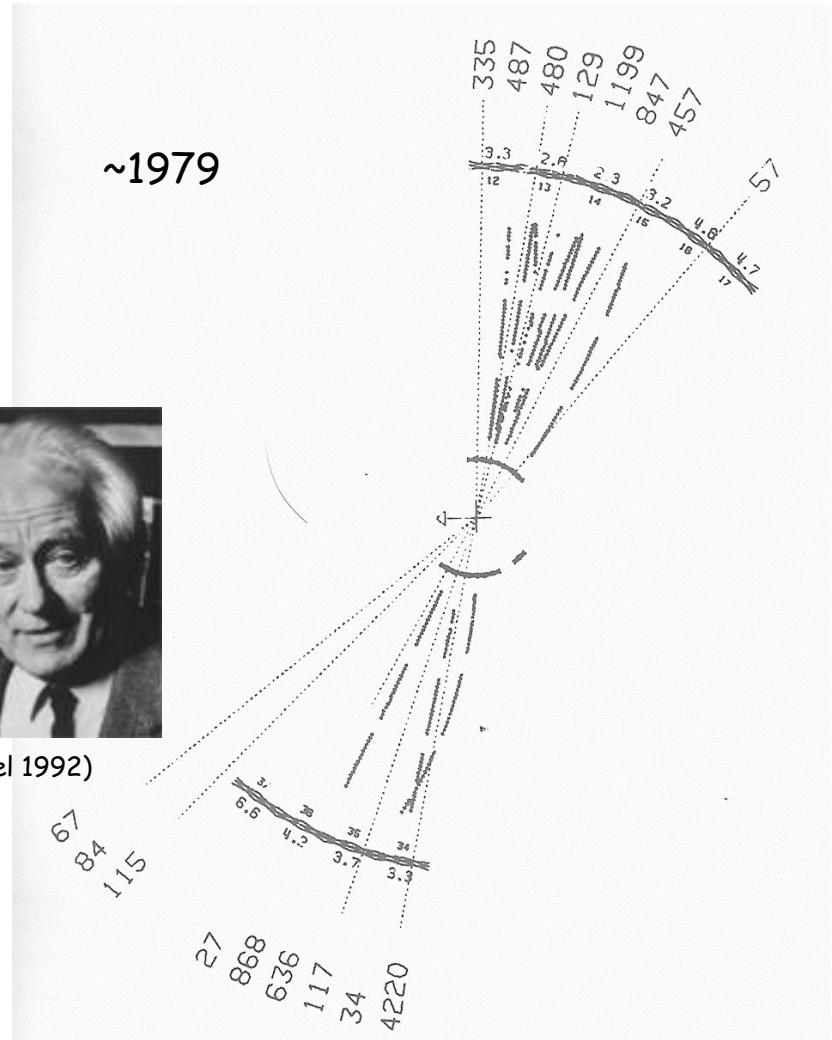
Example of the hadron production in e^+e^- annihilation in the JADE detector at the PETRA e^+e^- collider at DESY, Germany.

- cms 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.

Georges Charpak

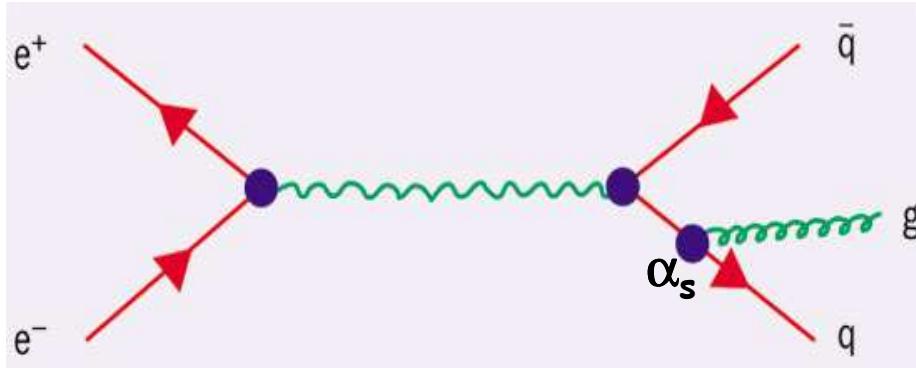


(Nobel 1992)



Discovery of the Gluon (1979)

PETRA at DESY: look for



Björn Wiik

Paul Söding



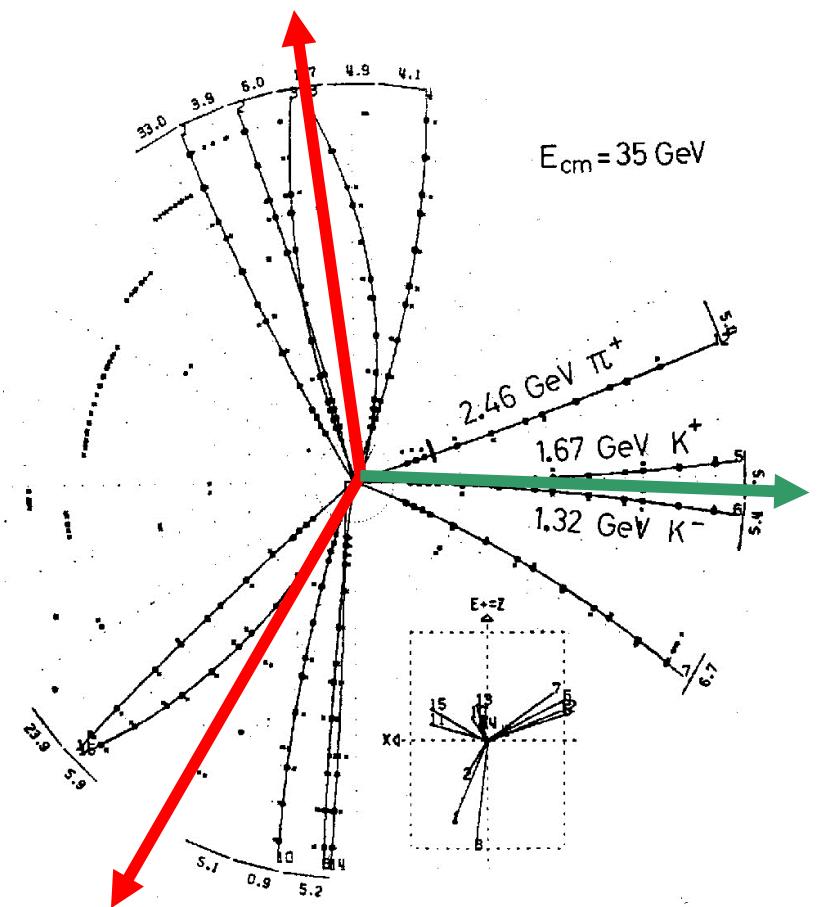
Günter Wolf

(EPS prize 1995)

19.-21.7.17

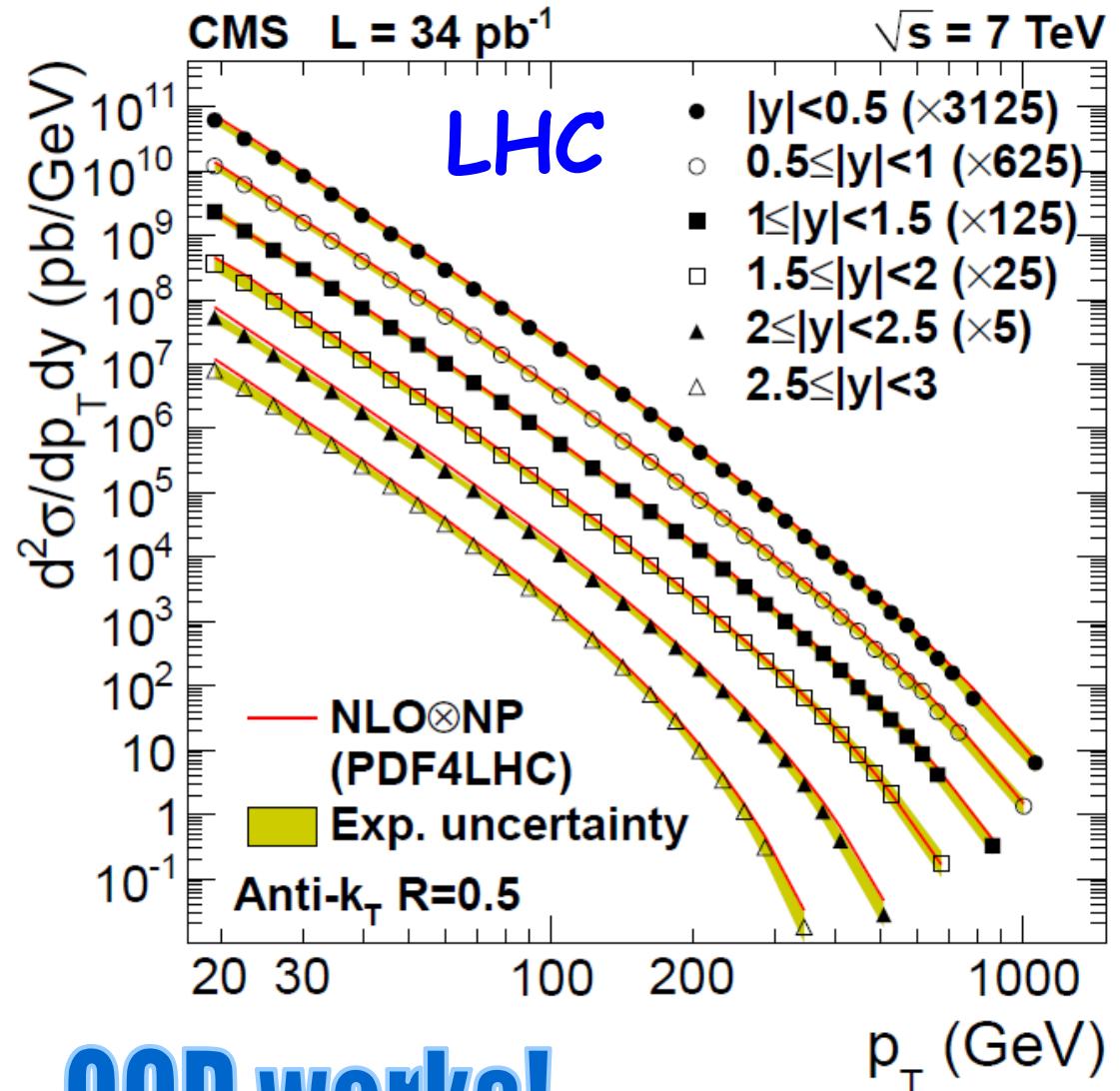
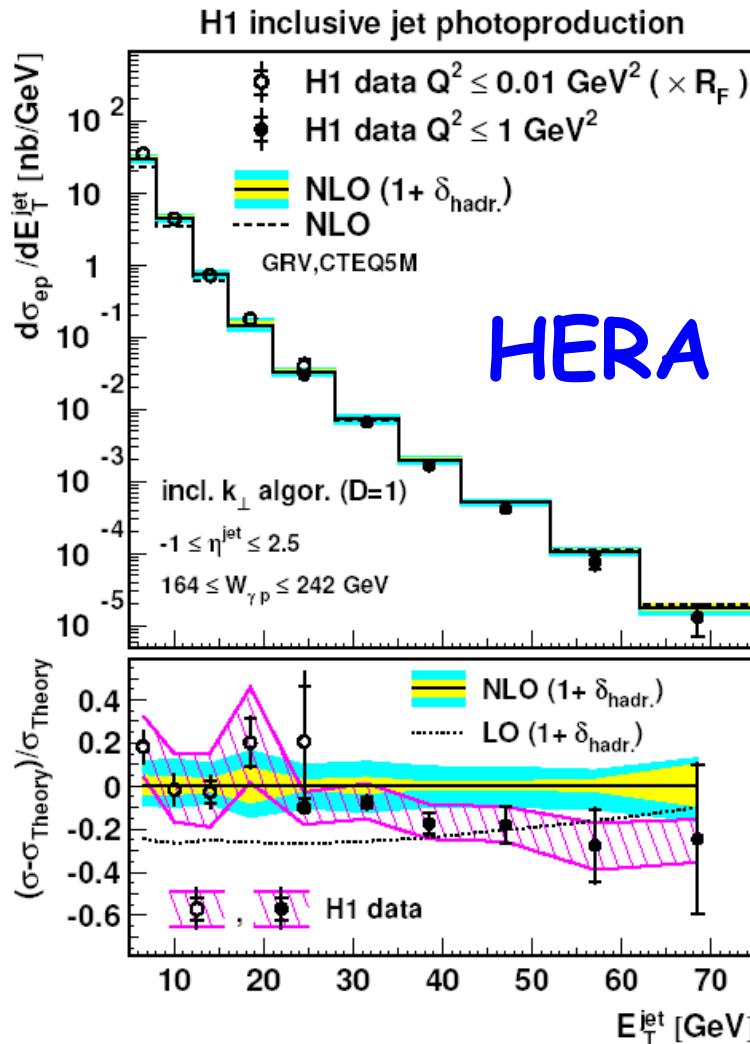
Sau Lan Wu

A. Geiser, Particle Physics



TASSO event picture

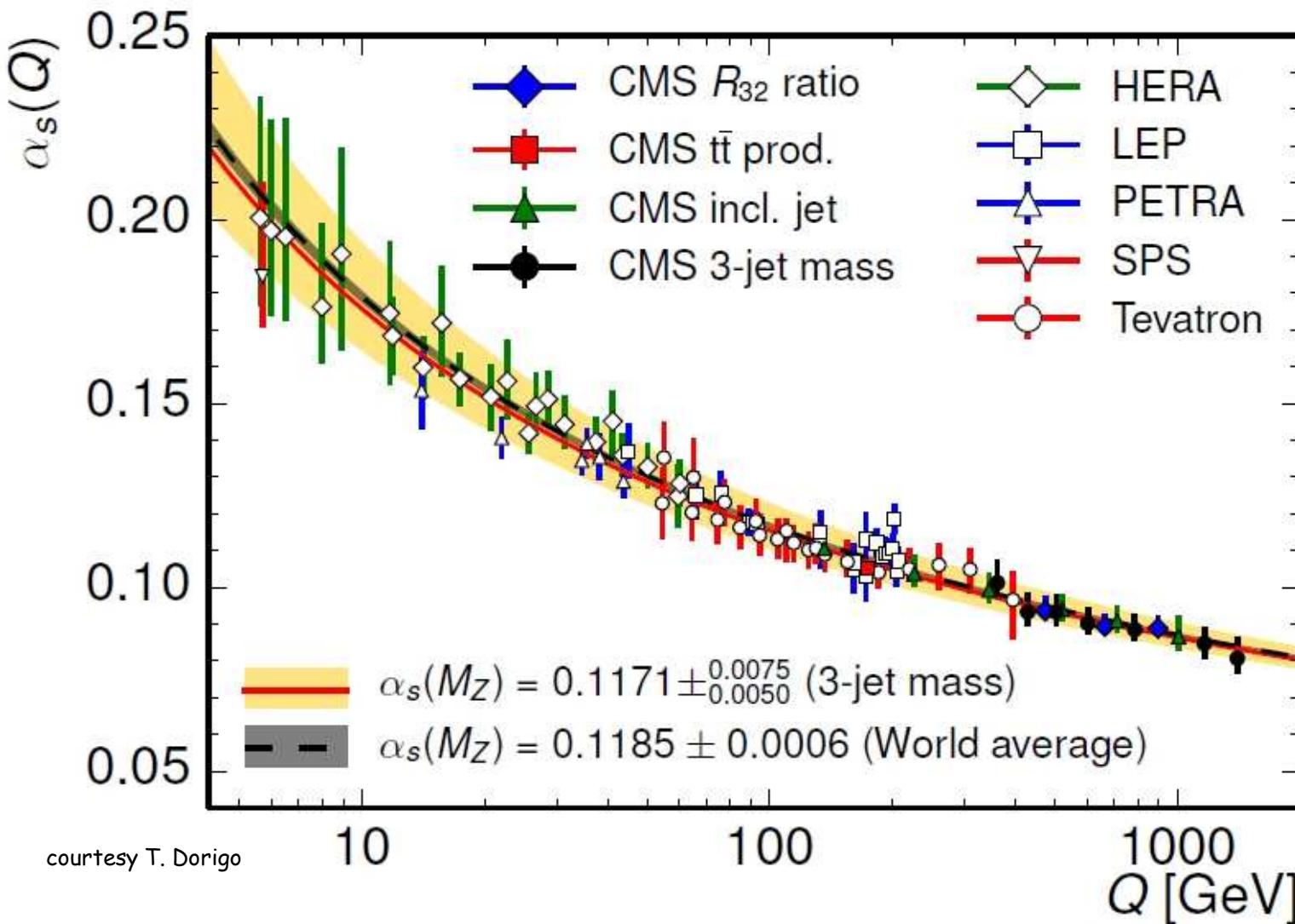
Jets in ep and pp interactions



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

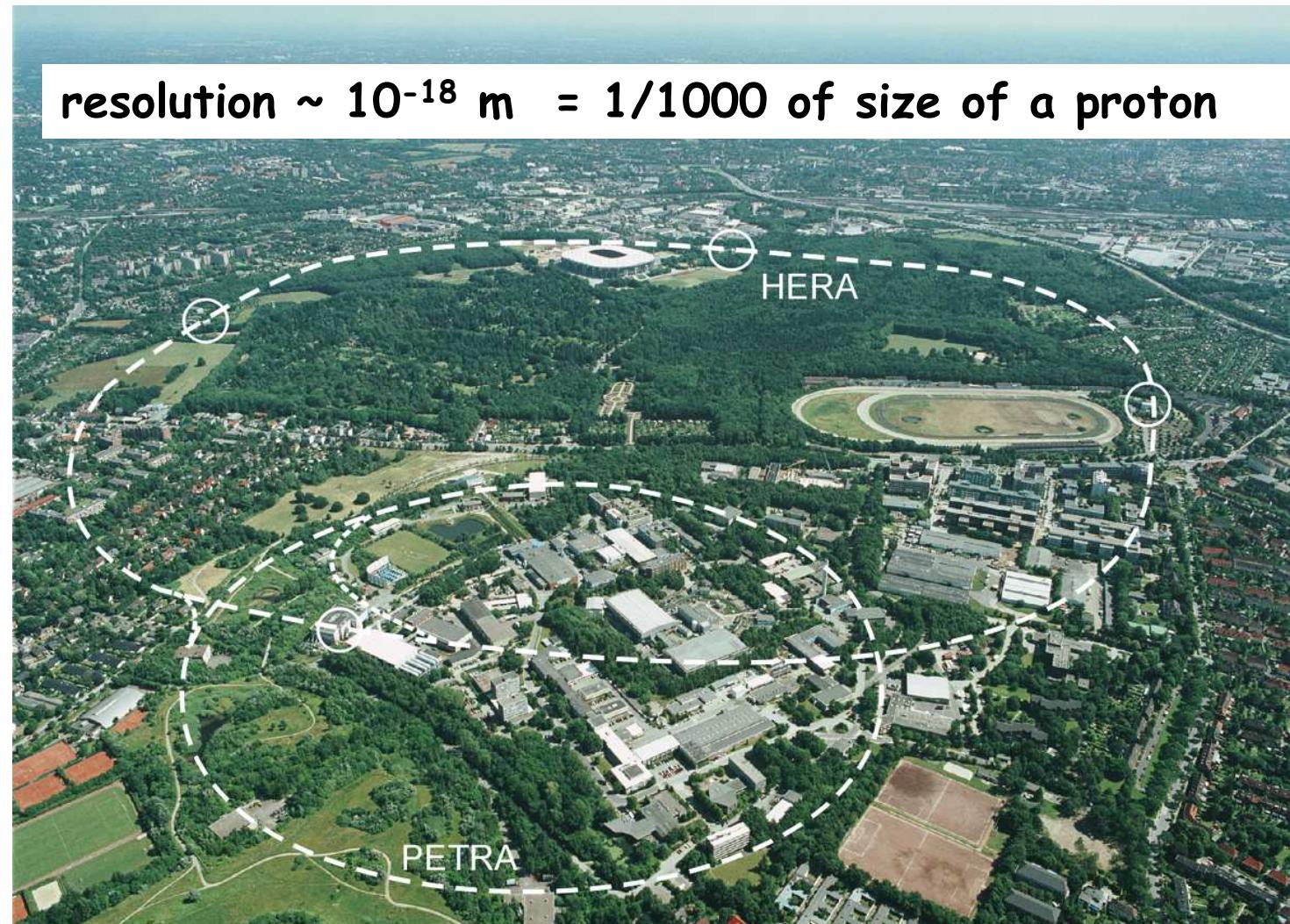
Yes,
it runs!

How to determine the „size“ of a particle?

microscope:
low resolution
-> small instrument

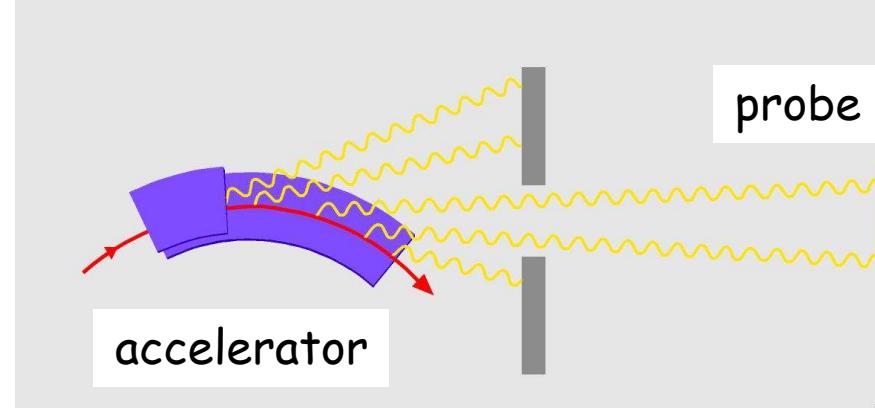
high resolution
-> large instrument

**HERA = giant
electron
microscope**

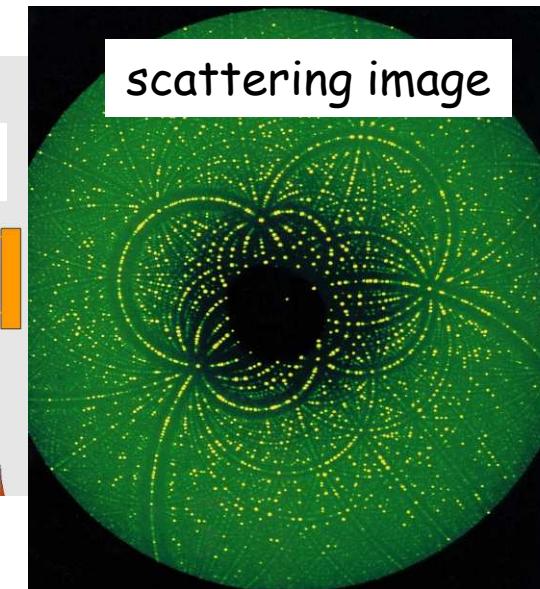


How to resolve the structure of an object?

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



$E \sim \text{keV}$



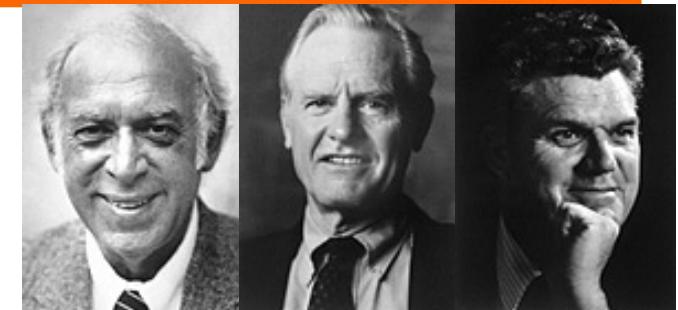
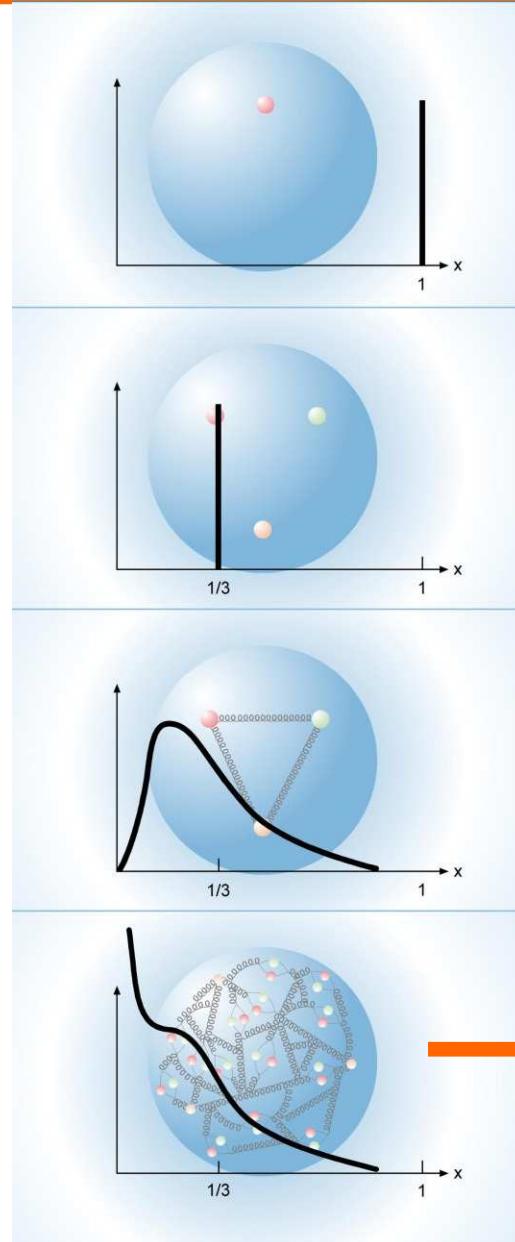
-> structure of
a biomolecule



Ada Yonath
(Nobel 2009)

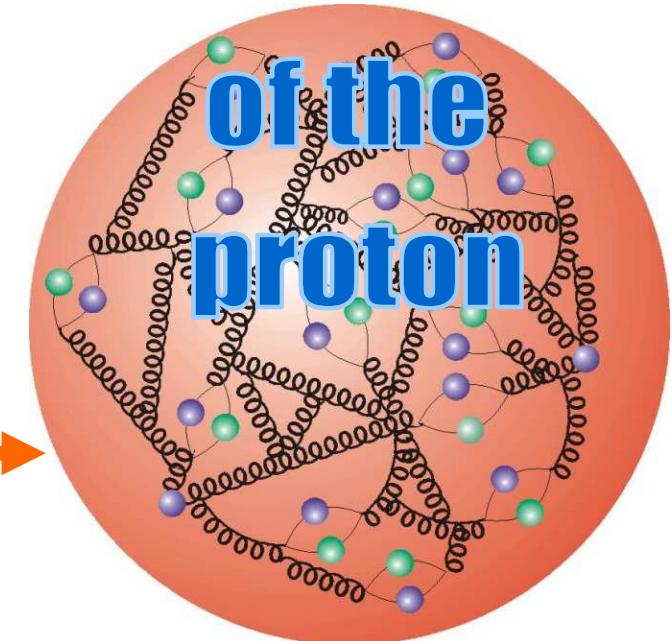
Resolve the structure of the proton

- E ~ MeV
resolve whole proton
- static quark model,
valence quarks
($m \sim 350$ MeV)
- E ~ $m_p \sim 1$ GeV
resolve valence quarks
and their motion
- E >> 1 GeV
resolve quark and gluon
“sea”



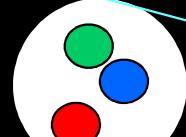
Jerome I. Friedmann Henry W. Kendall Richard E.
Kendall Taylor
(Nobel 1990)

structure



Inside the proton

Low Q^2 (large λ)

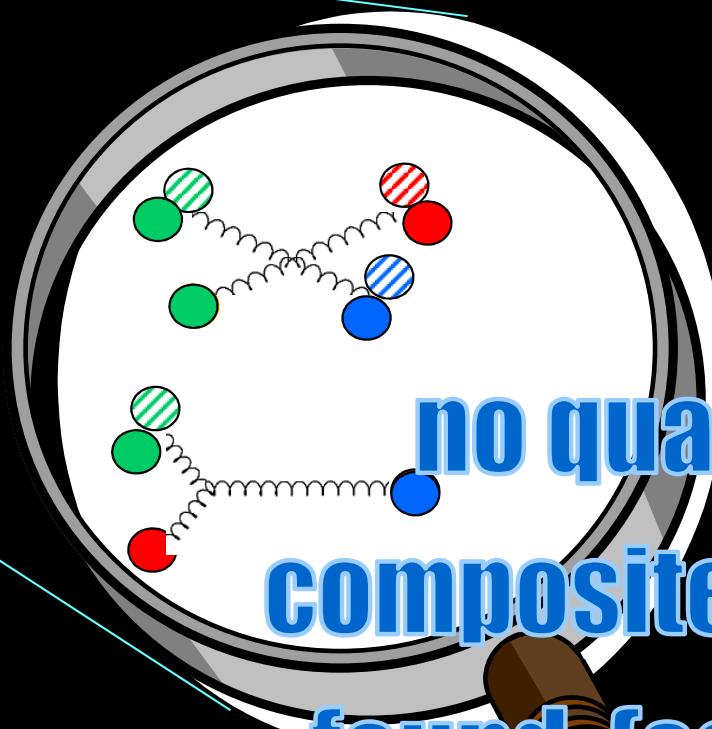


Medium Q^2 (medium λ)



Heisenberg's UP allows gluons, and $q\bar{q}$ pairs to be produced for a very short time.

Large Q^2 (short λ)

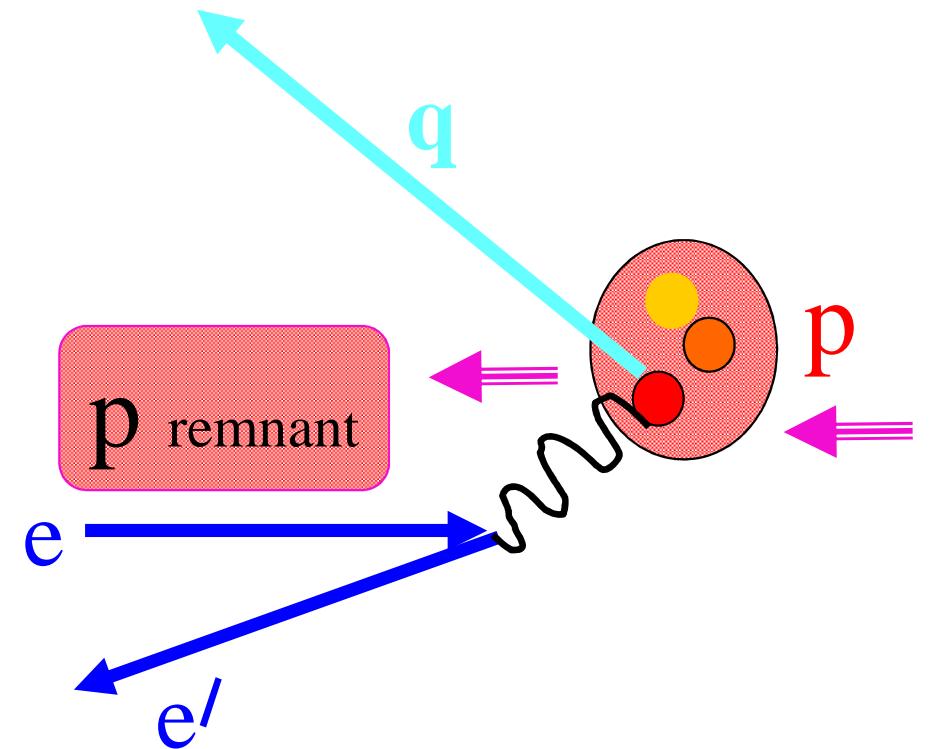
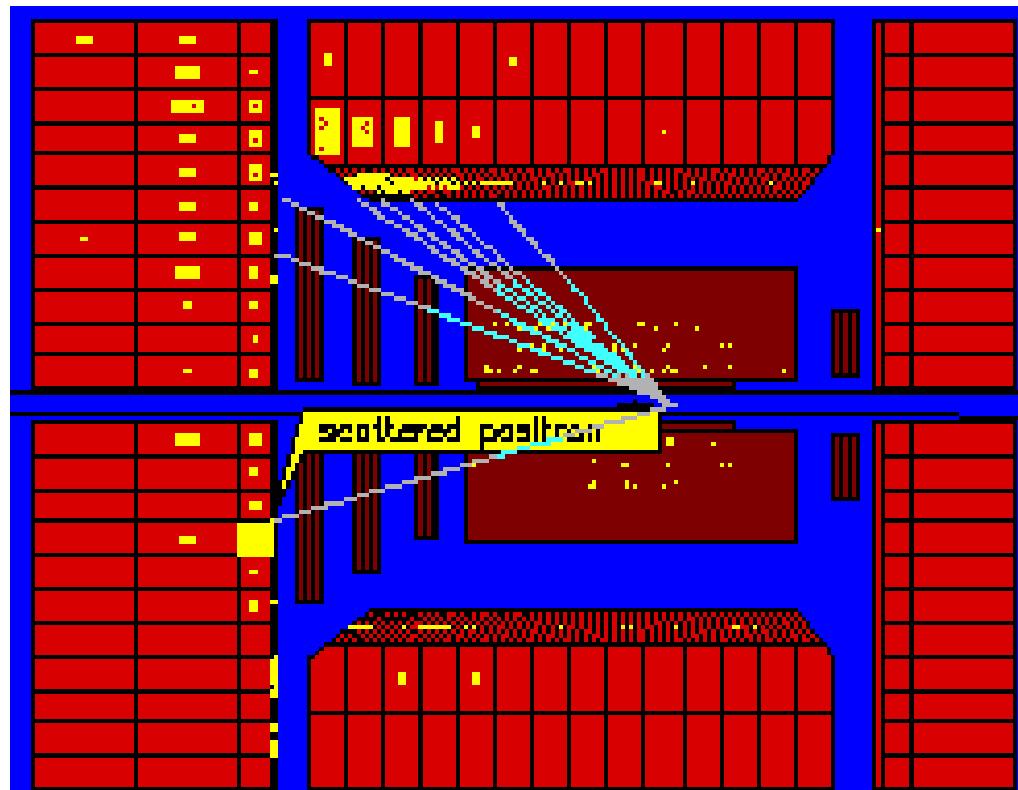


At higher and higher resolutions, the quarks emit gluons, which also emit gluons, which emit quarks, which.....

At highest Q^2 , $\lambda \sim 1/Q \sim 10^{-18} \text{ m}$

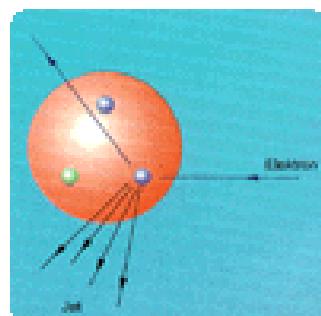
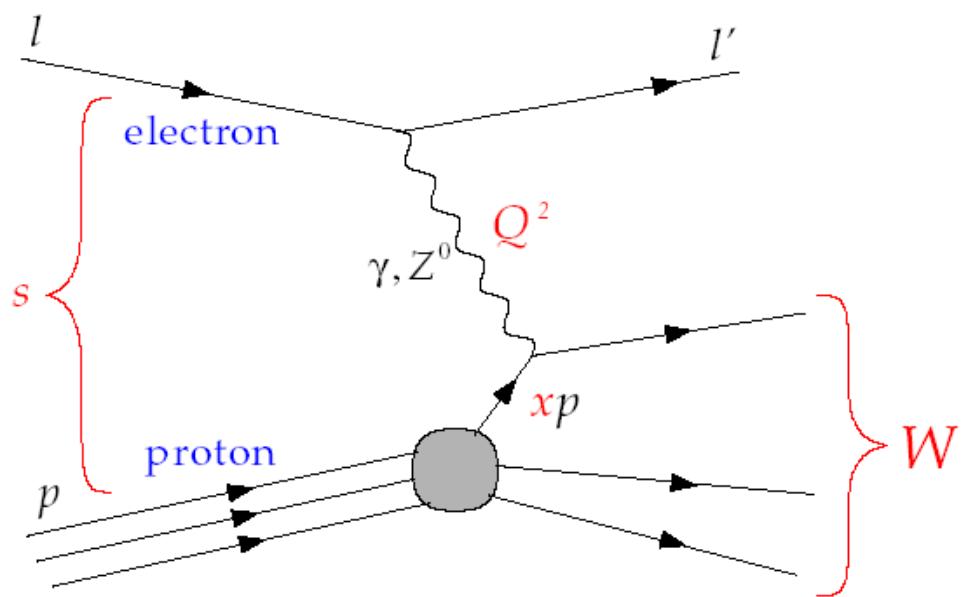
**no quark
compositeness
found (so far)**

Deep Inelastic ep Scattering at HERA



Deep Inelastic Scattering (DIS)

Neutral Current



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

boson virtuality
(resolution scale)

fractional momentum
of struck quark (in QPM)

$$Q^2 = -(l - l')^2$$

$$x = \frac{Q^2}{2p \cdot q}$$

Parton distribution functions (PDF) in pQCD

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

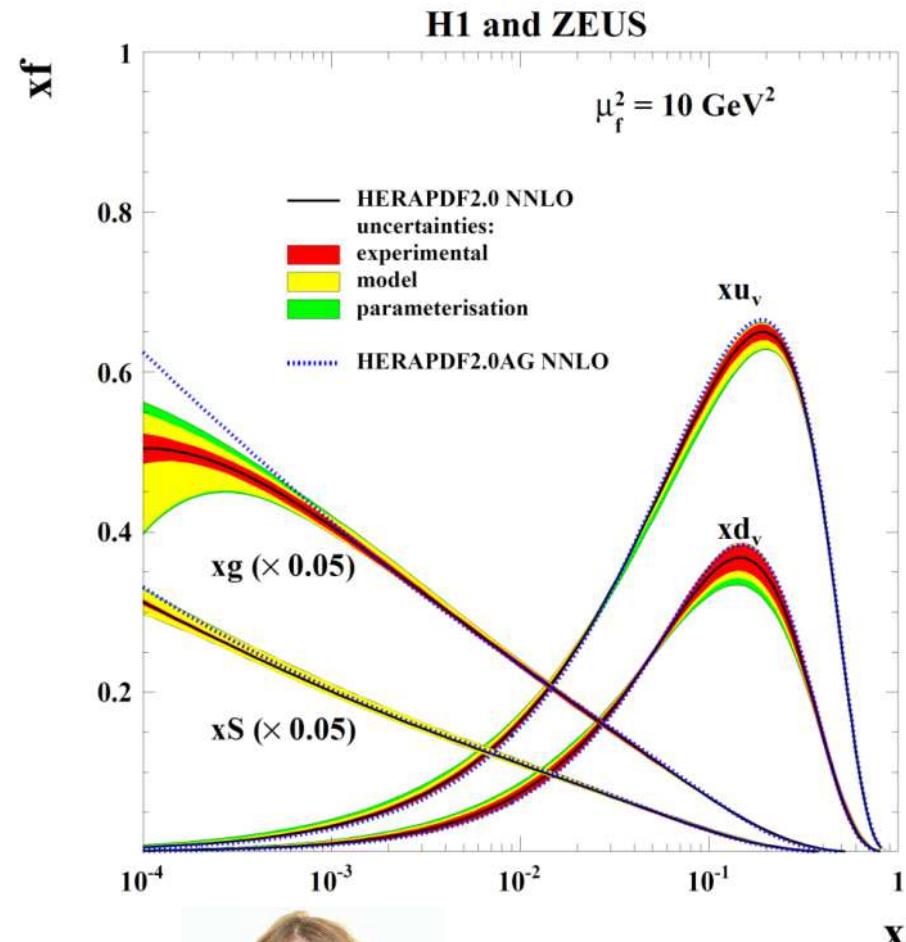
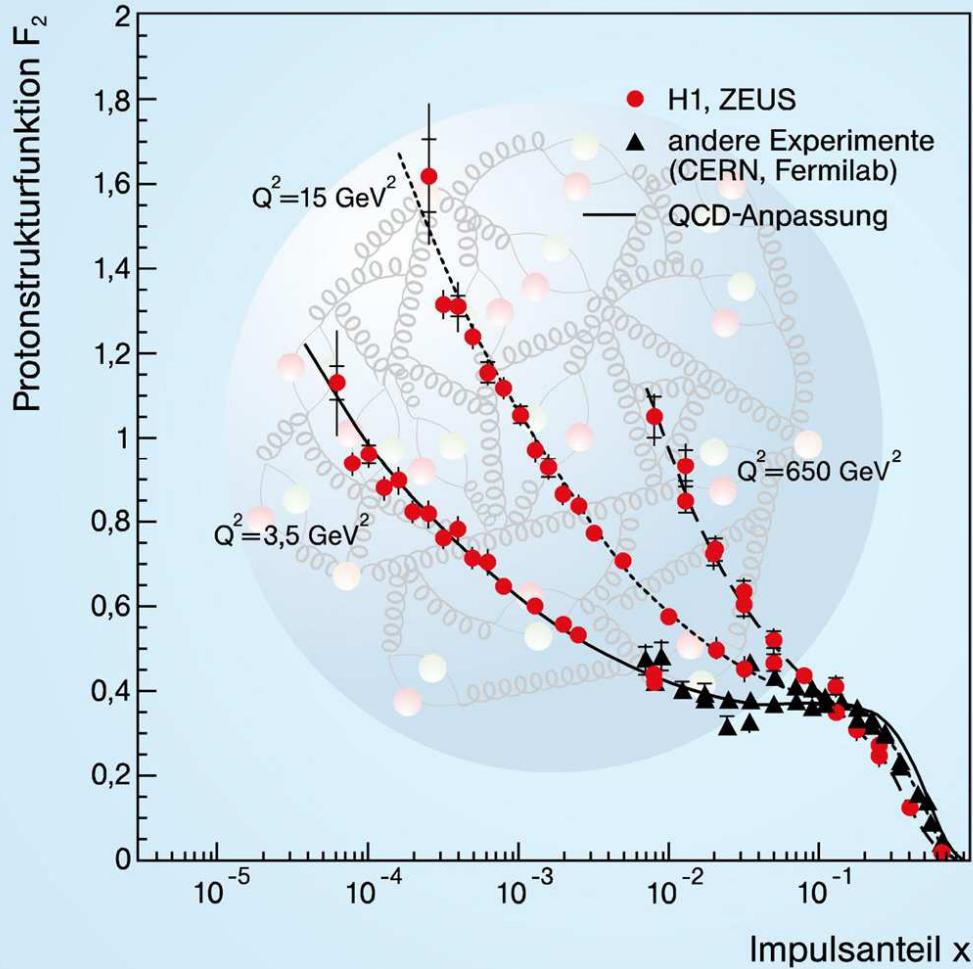
q_i – probability to find quark with flavour i in proton

The Proton Structure

structure functions

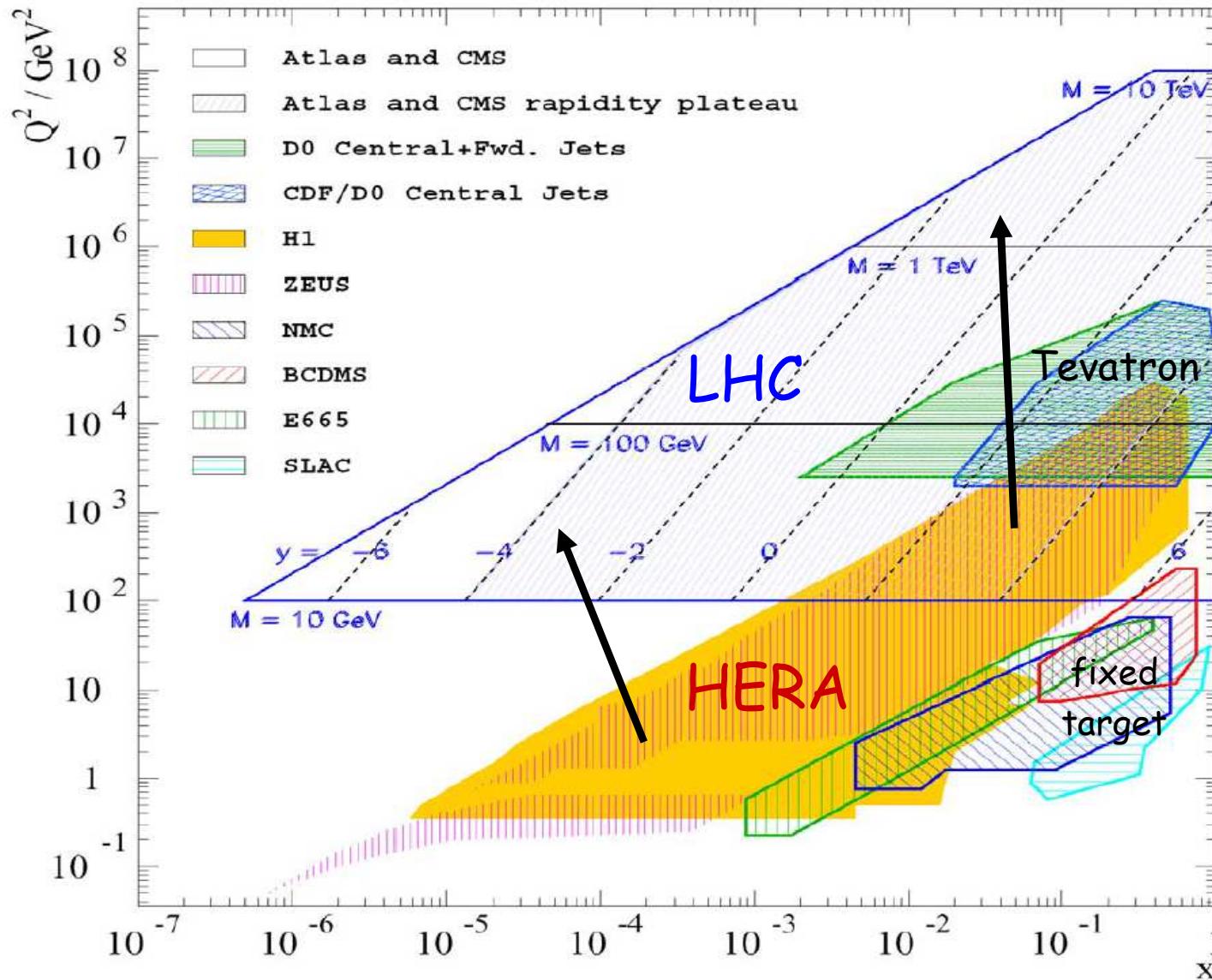


quark and gluon densities



Amanda
Cooper-Sarkar
(Chadwick medal 2015)

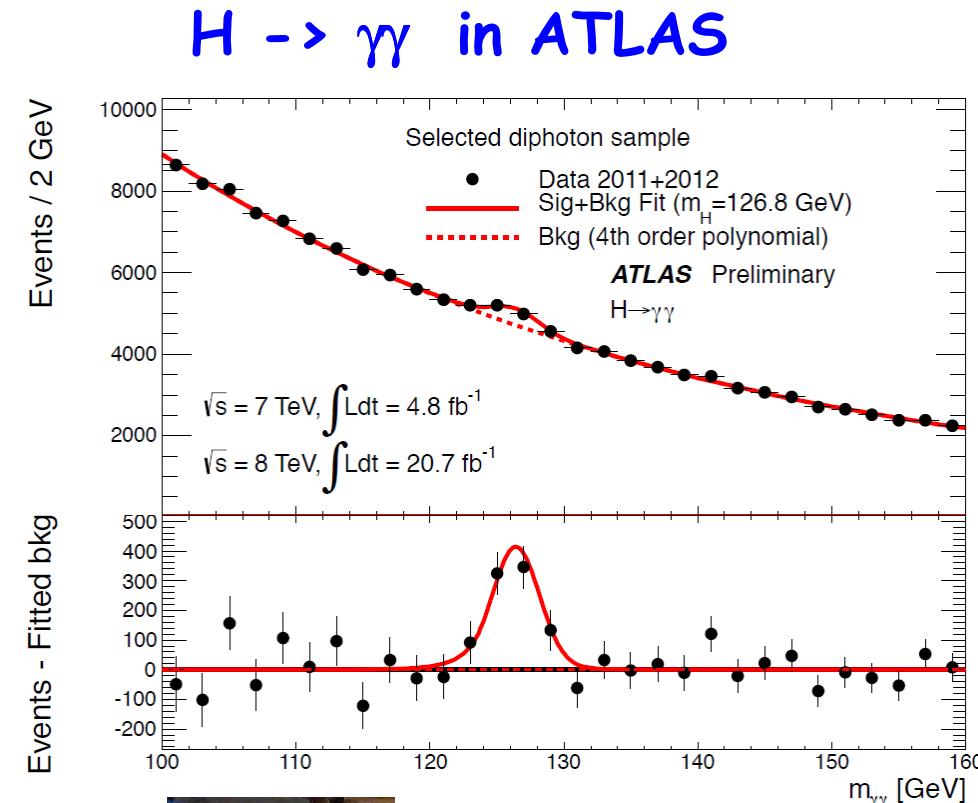
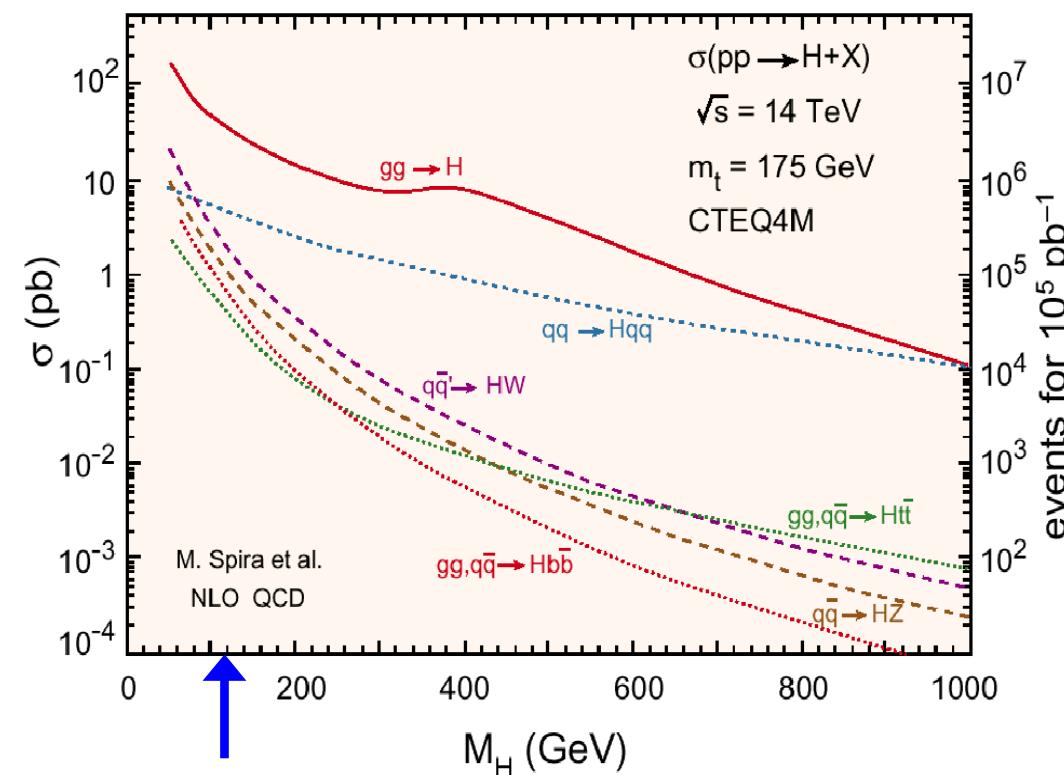
Kinematic regions: HERA vs. LHC



- 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



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