

# Elementary Particle Physics Research

Achim Geiser, DESY Hamburg  
Summer Student Lecture, 18.-20.7.18

Scope of this lecture:

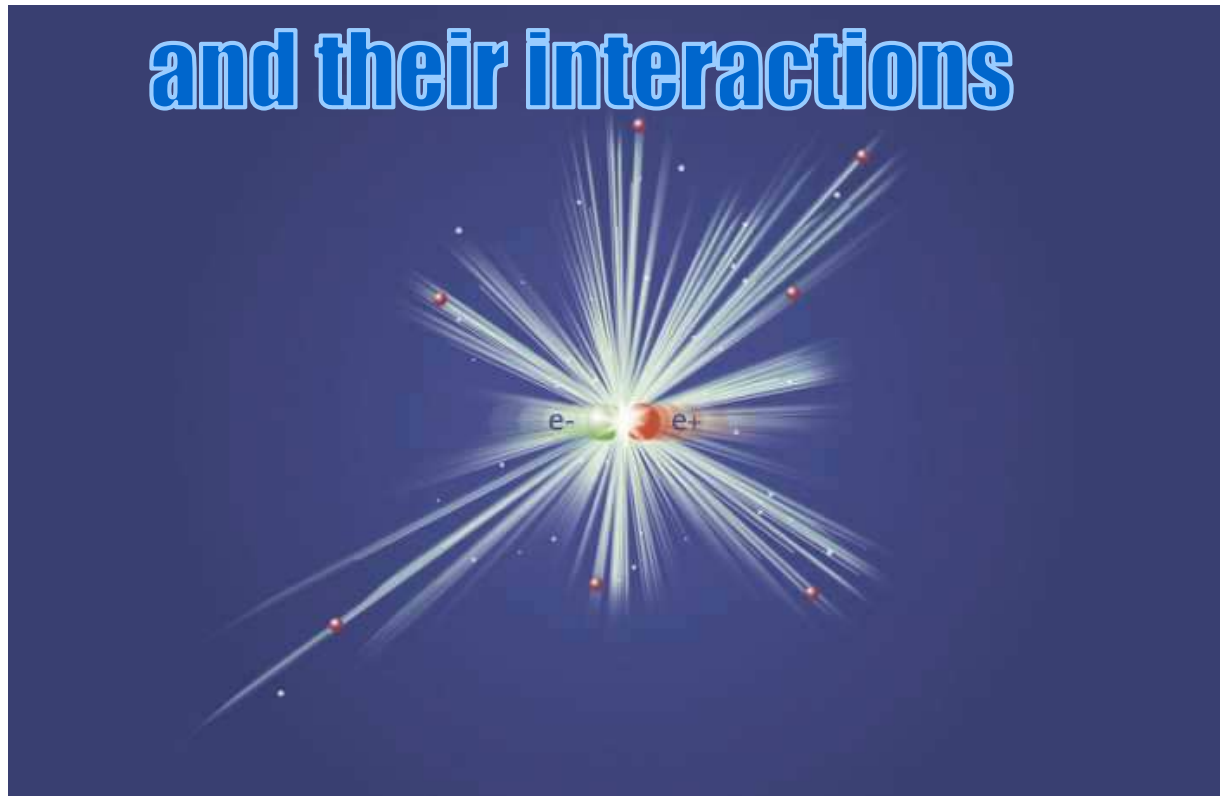
- Introduction to particle physics for non-specialists
  - rather elementary
  - more details -> specialized lectures
  - particle physics in general
  - some emphasis on DESY-related topics



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

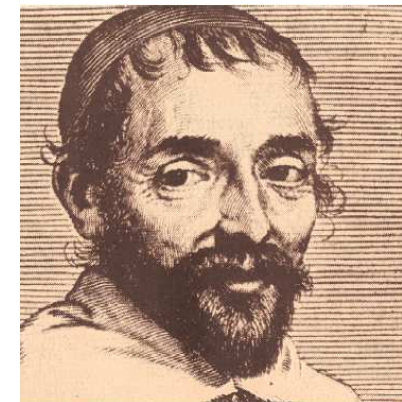
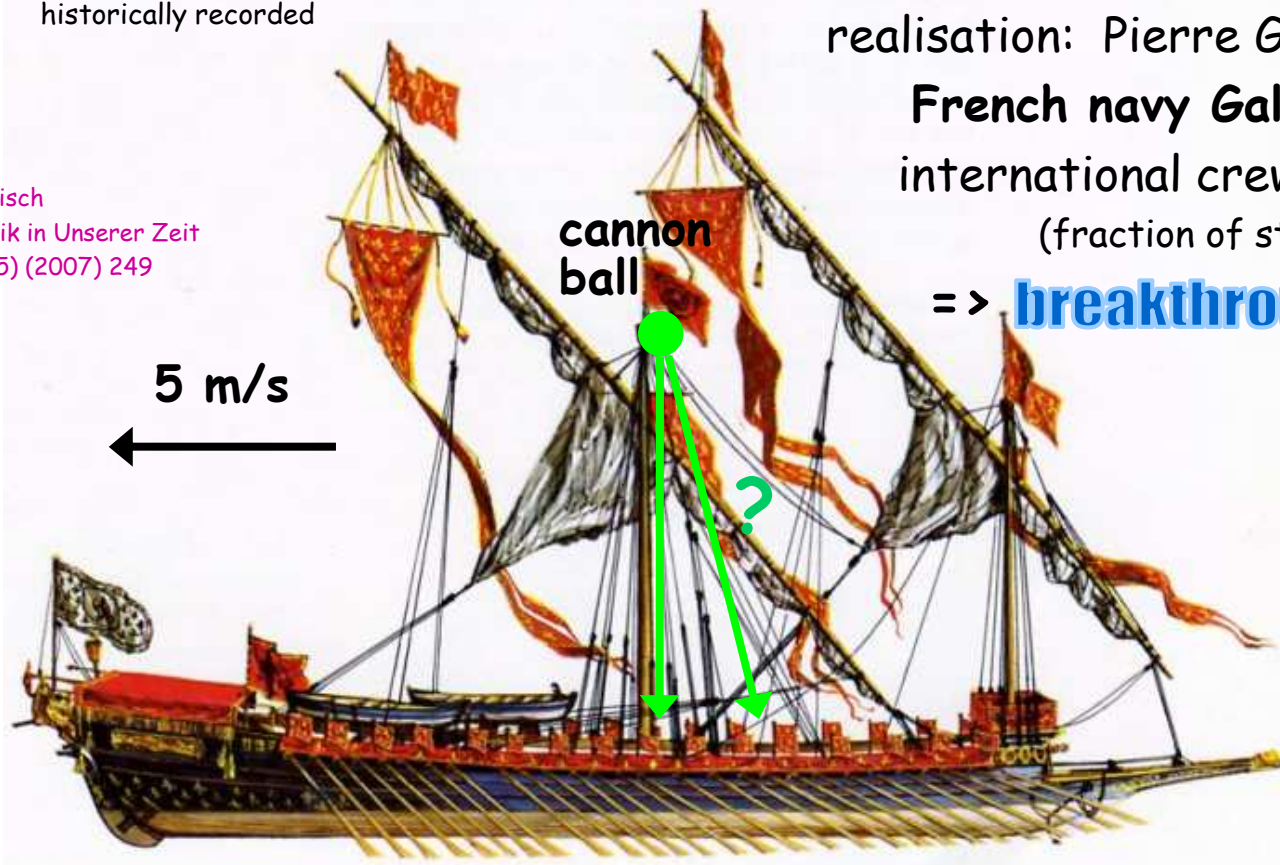
First large scale scientific experiment: proposal: Galilei 1632  
historically recorded

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).

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# 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, ...

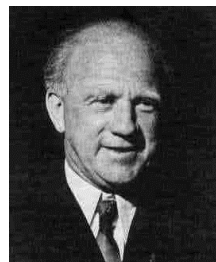
not necessarily located at a specific position,  
(Heisenberg uncertainty principle)

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



Louis  
de Broglie  
(Nobel 1929)

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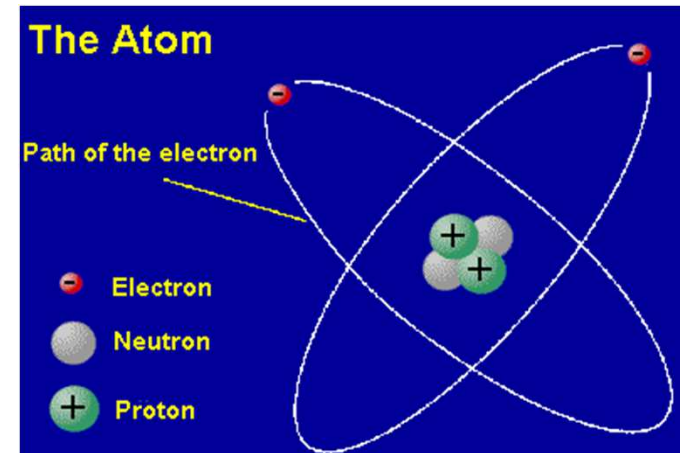


Werner  
Heisenberg  
(Nobel 1932)

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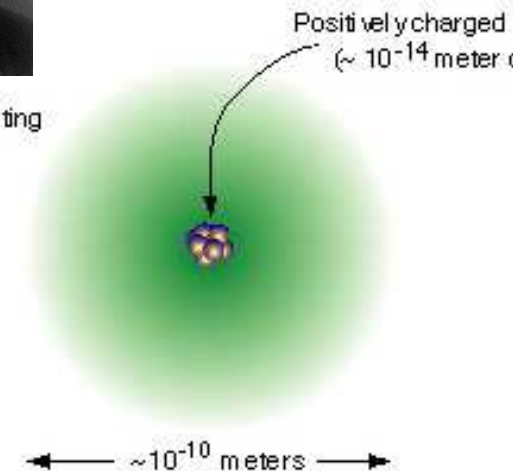


Erwin  
Schrödinger  
(Nobel 1933)



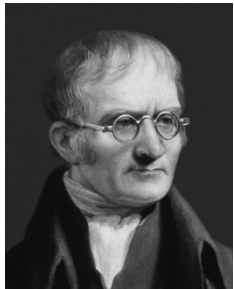
Niels  
Bohr  
(Nobel 1922)

Surrounding orbiting  
electrons (-Z)

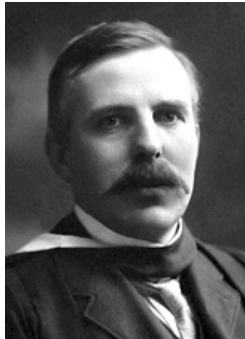


# What is „elementary“?

Greek: atomos = smallest indivisible part

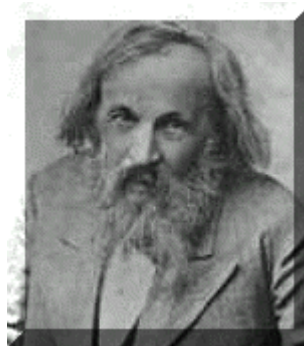


John Dalton  
1803  
(atomic  
model)



Ernest  
Rutherford  
1911  
(nucleus)  
(Nobel 1908)

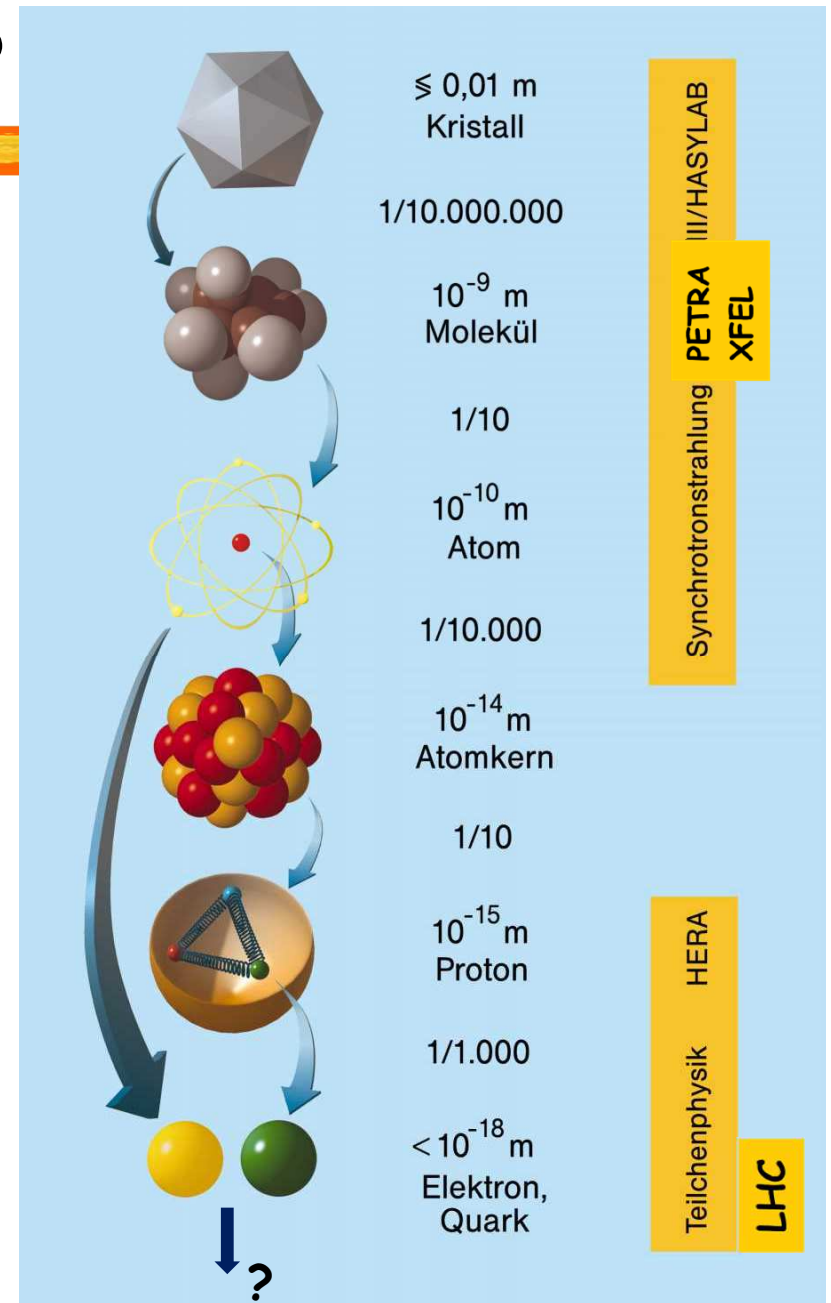
Dmitry  
Ivanowitsch  
Mendeleyev  
1868  
(elements)



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

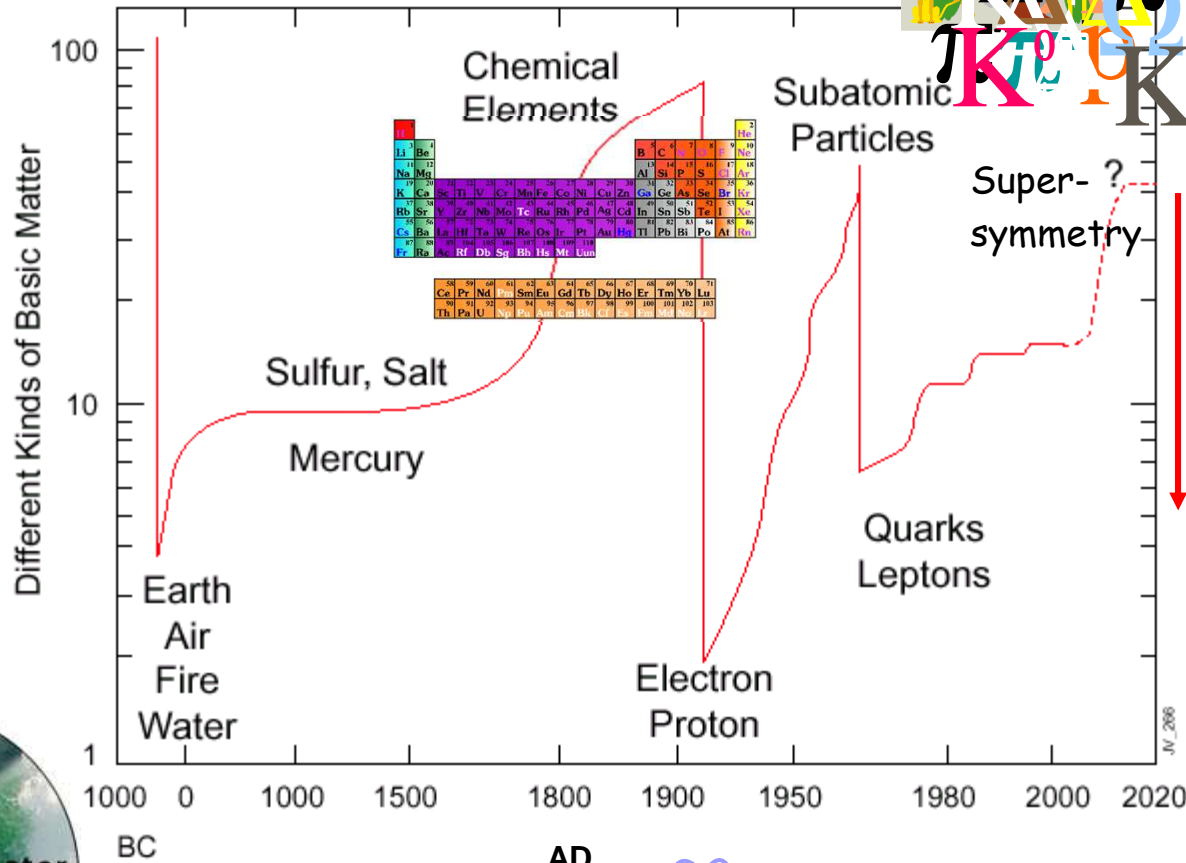


**elementary**  
**= no detectable**  
**substructure**

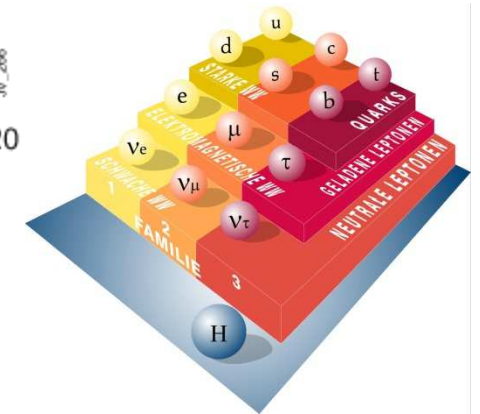
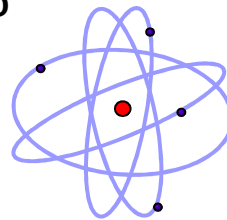


# History of basic building blocks of matter

motivation:  
find  
smallest  
possible  
number



(c) Andy Brice 1998



Quark and  
Lepton  
substructure ??

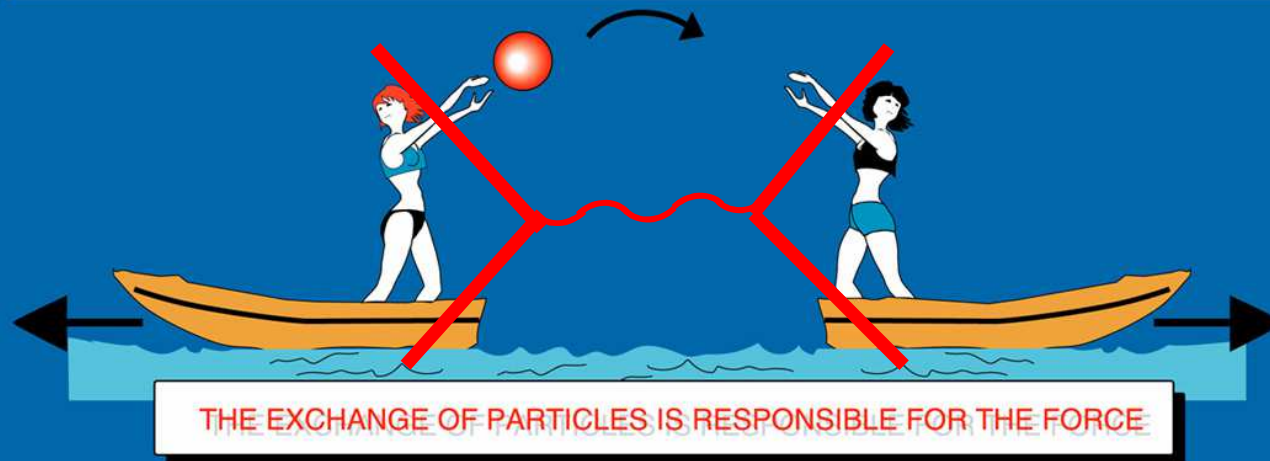
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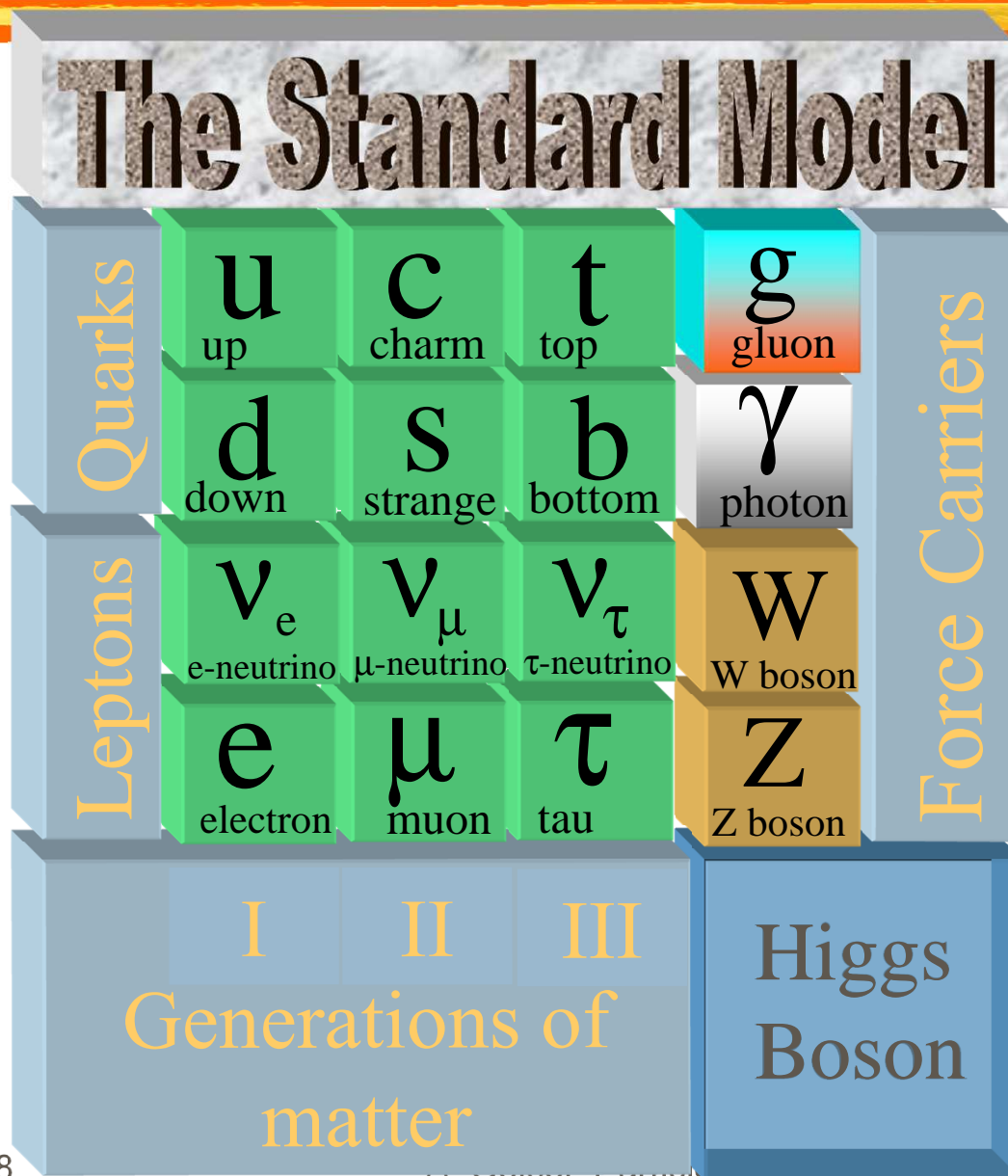
# Which "interactions"?

TYPE	at $\sim 1 \text{ GeV}$ INTENSITY OF FORCES ( DECREASING ORDER )	BINDING PARTICLE ( FIELD QUANTUM )	OCCURS IN :
STRONG NUCLEAR FORCE	$\sim 1$	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

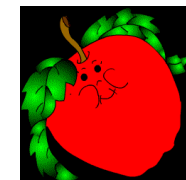




# What we know today



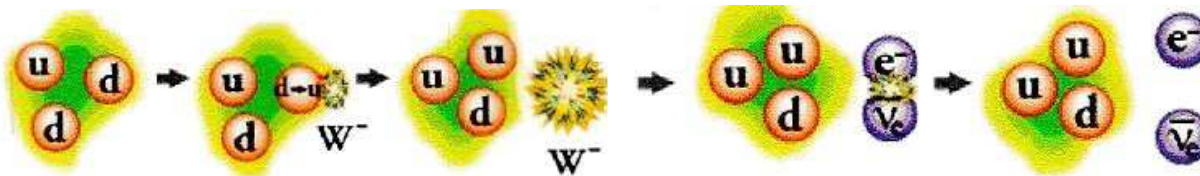
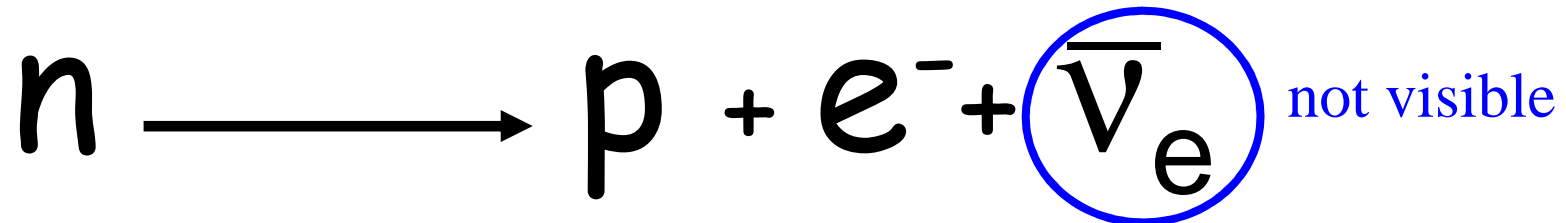
Gravity  
the  
ghost at  
the  
feast





# The Power of Conservation Laws

■ e.g. radioactive neutron decay:



■ Pauli 1930:

Wolfgang  
Pauli  
(Nobel 1945)



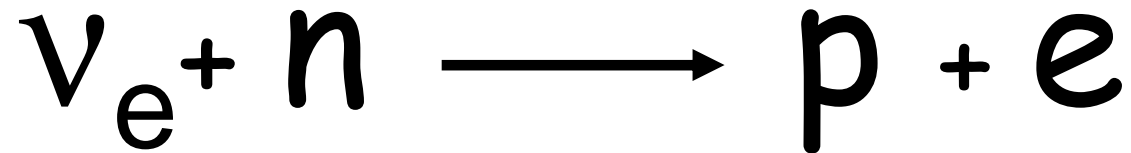
**Neutrino  
must be present  
to account for  
conservation of energy  
and (angular) momentum**



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

# confirmation: neutrino detection

■ e.g. reversed reaction:

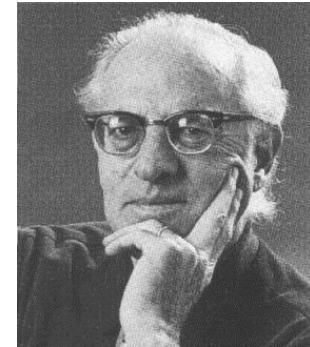


extremely rare!

(absorption length  $\sim 3$  light years Pb)

■ first detection: 1956

Reines and Cowan, neutrinos from nuclear reactor



Frederick Reines

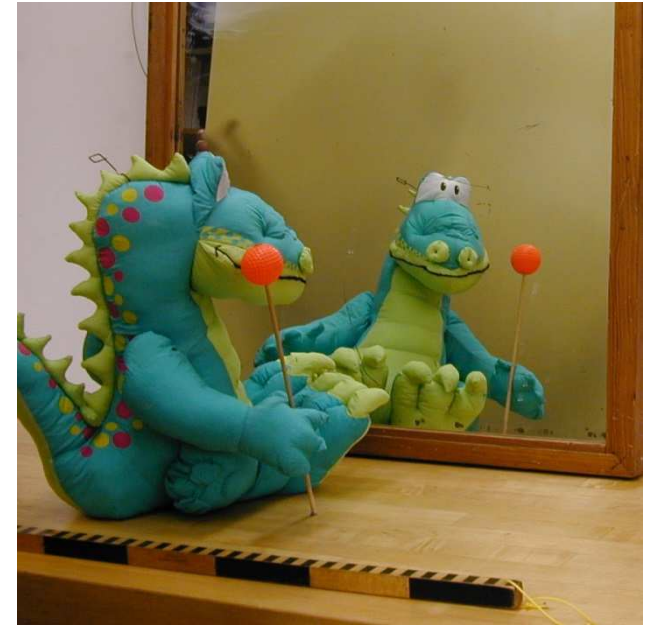
(Nobel 1995)

**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!

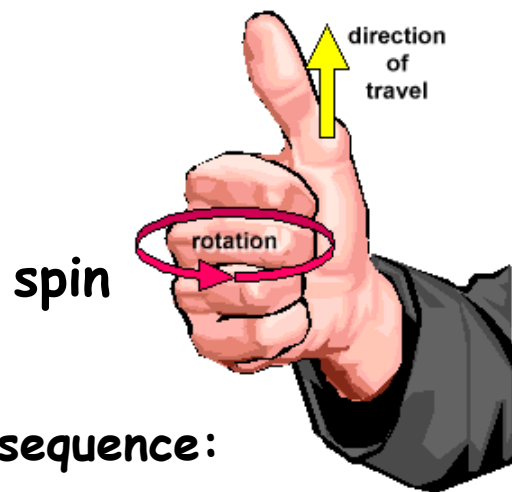


Eugene  
Wigner  
(Nobel 1963)



# The power of symmetries: Parity

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



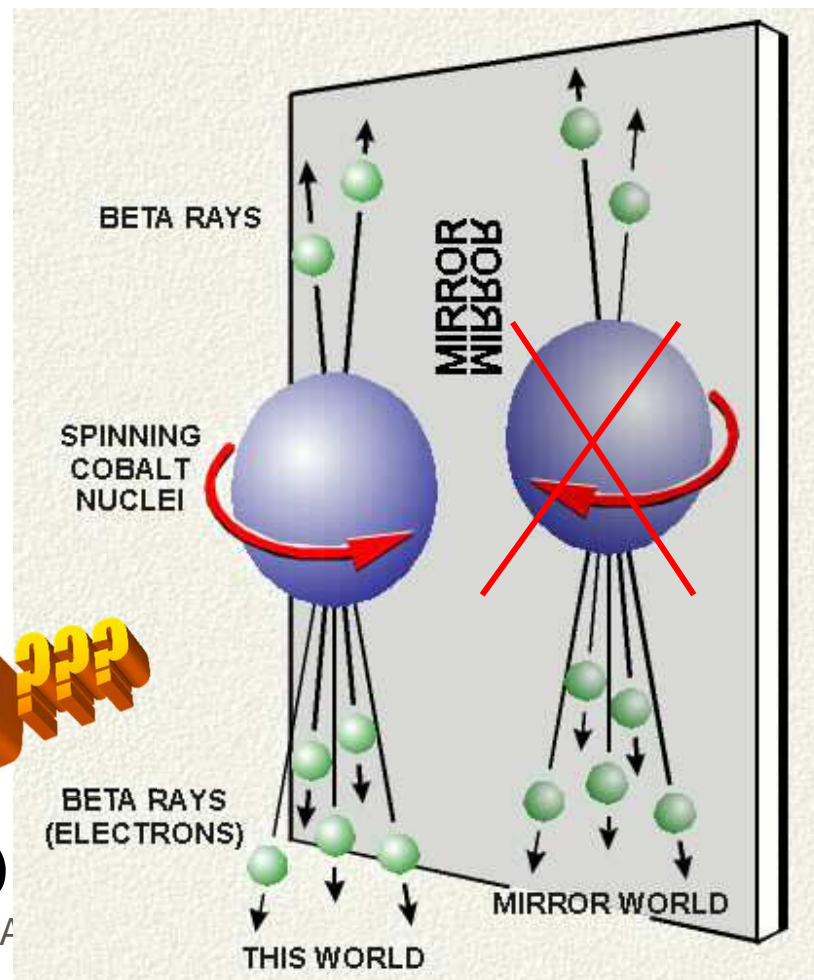
consequence:

**neutrinos are  
always  
lefthanded !**

(antineutrinos righthanded)

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**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

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)

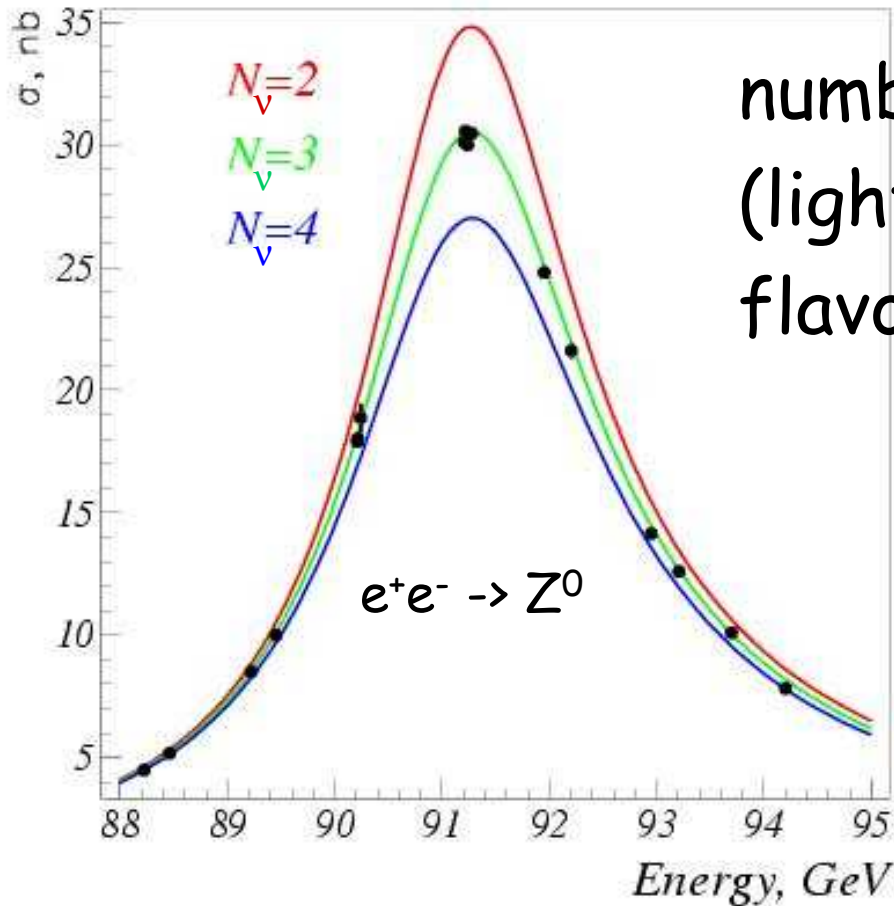
- Lepton number is conserved**

- 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)



Gerardus 't Hooft    Martinus Veltman

(Nobel 1999)

There seem to be  
exactly three  
lepton + quark  
families !

Why ???

# Can we "see" particles?



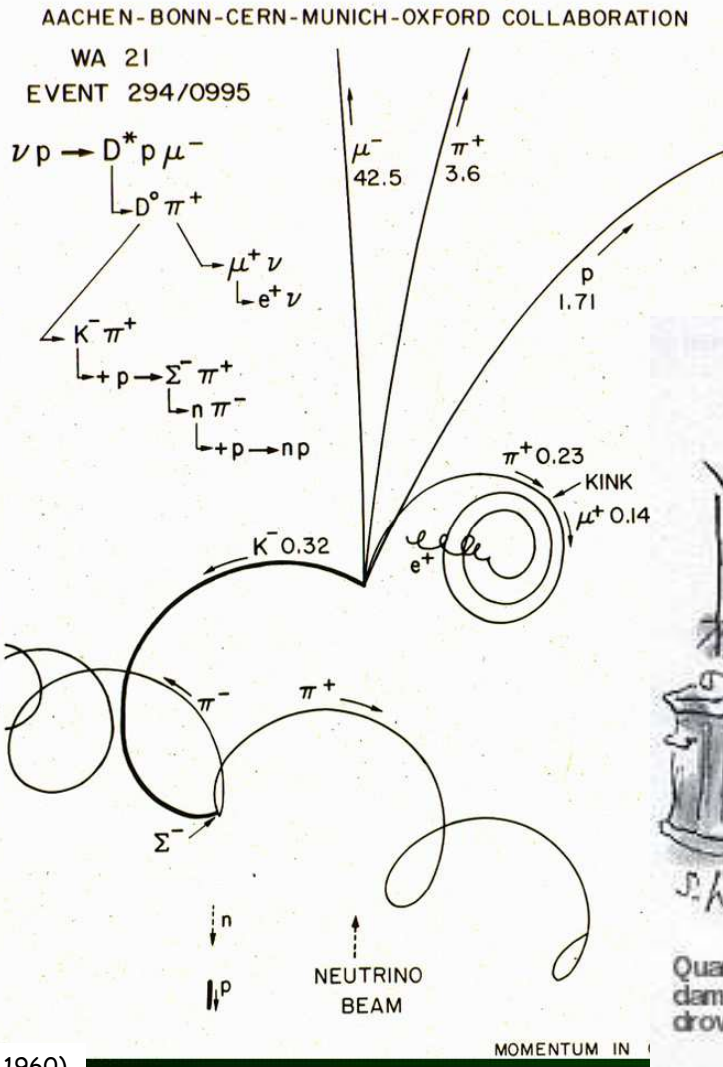
Luis Walter Alvarez (Nobel 1968)

bubble  
chamber  
photo



Donald Arthur Glaser (Nobel 1960)

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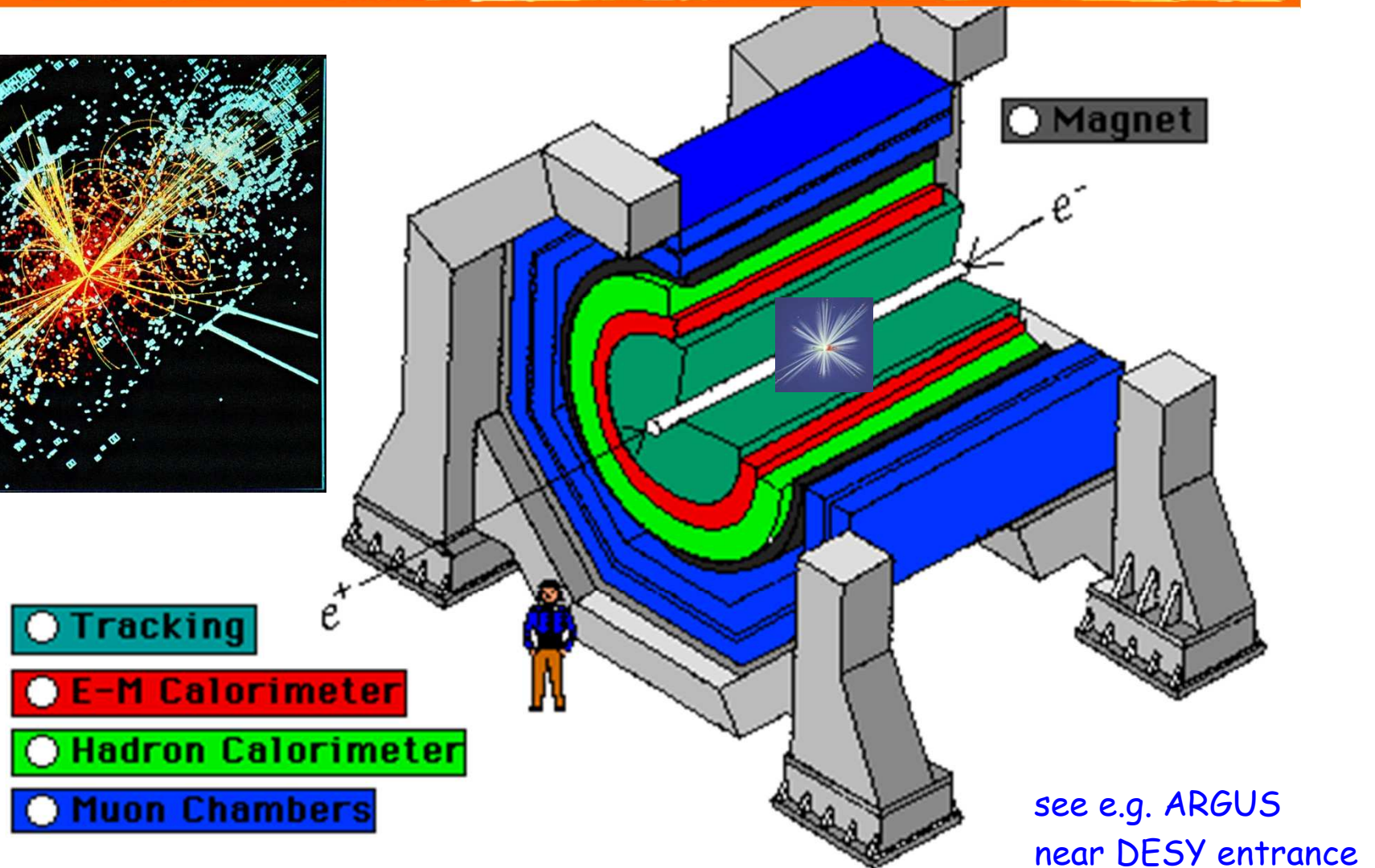
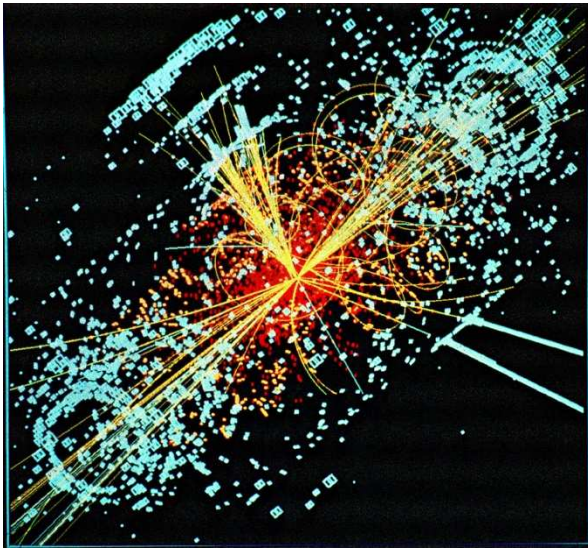
we can!



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

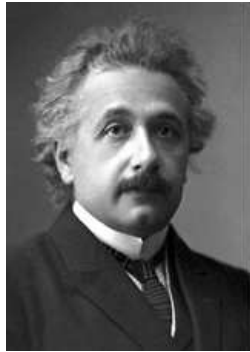




# Why do we need colliders?

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

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

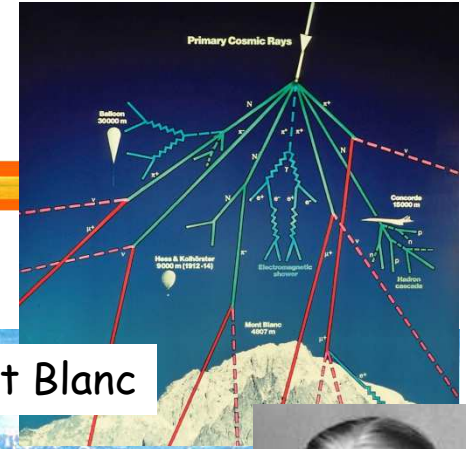


Albert Einstein  
(Nobel 1921)

need high energy  
to discover new  
heavy particles

- colliders =  
microscopes (later)

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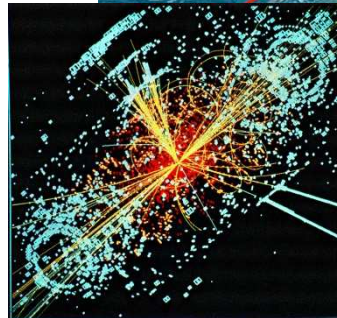


Mont Blanc

V.F. Hess  
(Nobel 1936)



CERN



LEP/LHC



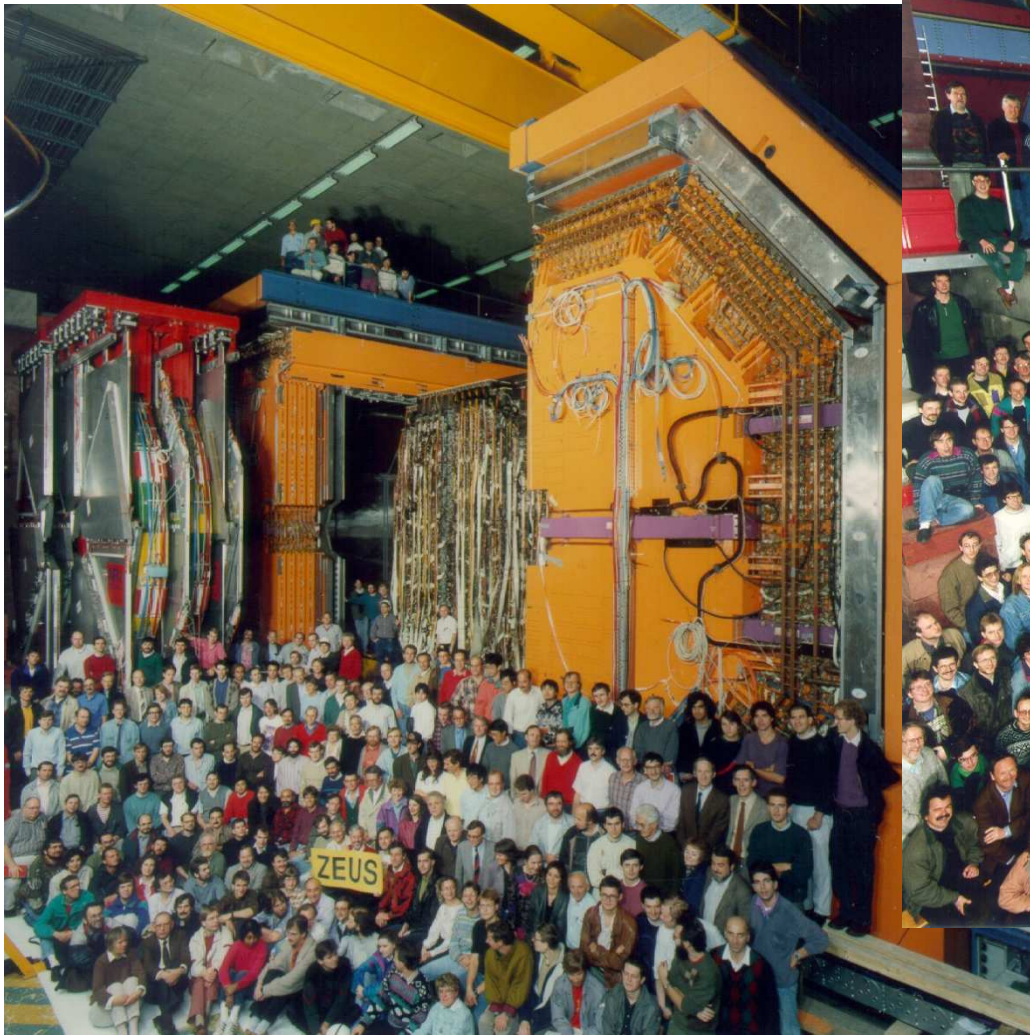
# The HERA ep Collider and Experiments

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





# Particle Physics = People



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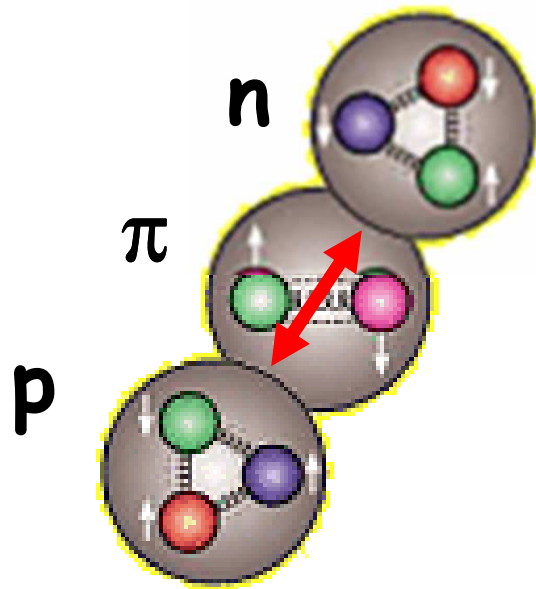
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# Strong Interactions: Quarks and Colour

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



Hideki Yukawa  
(Nobel 1949)



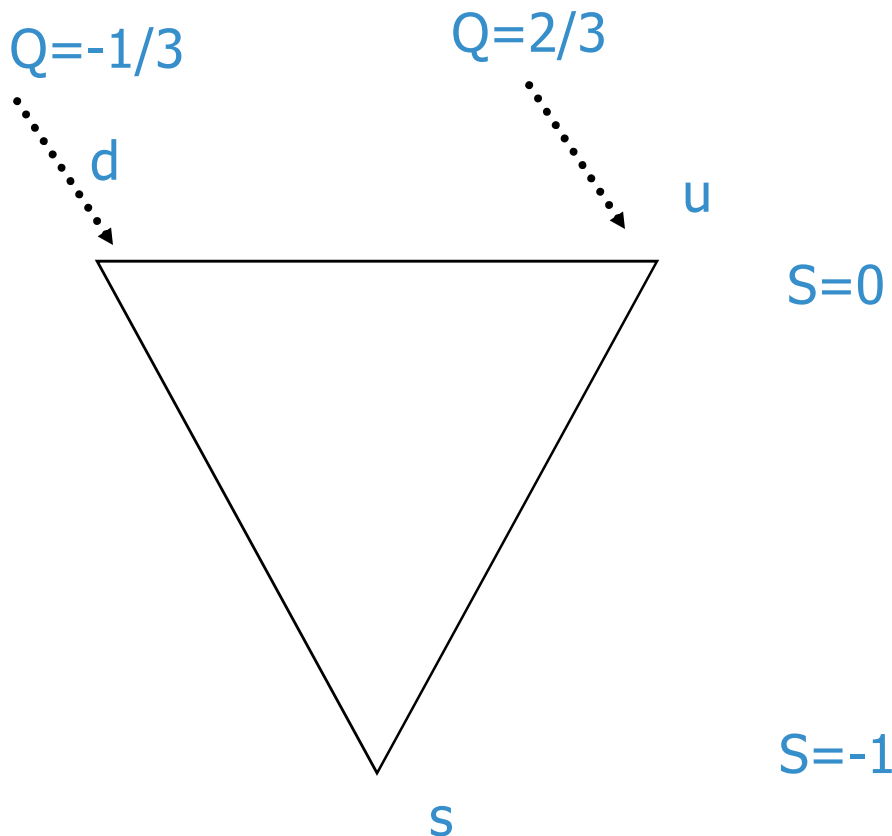
- modern view:  
(Quantum Chromo-Dynamics, QCD)  
exchange of massless gluons  
between quark  
constituents

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



# The Quark Model (1964)

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



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

Murray  
Gell-Mann

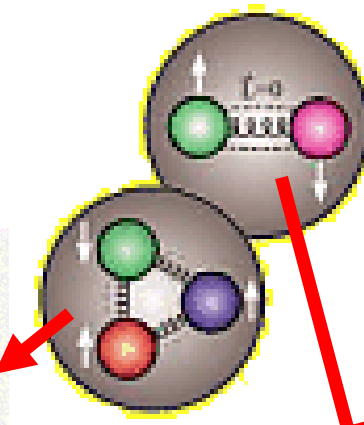
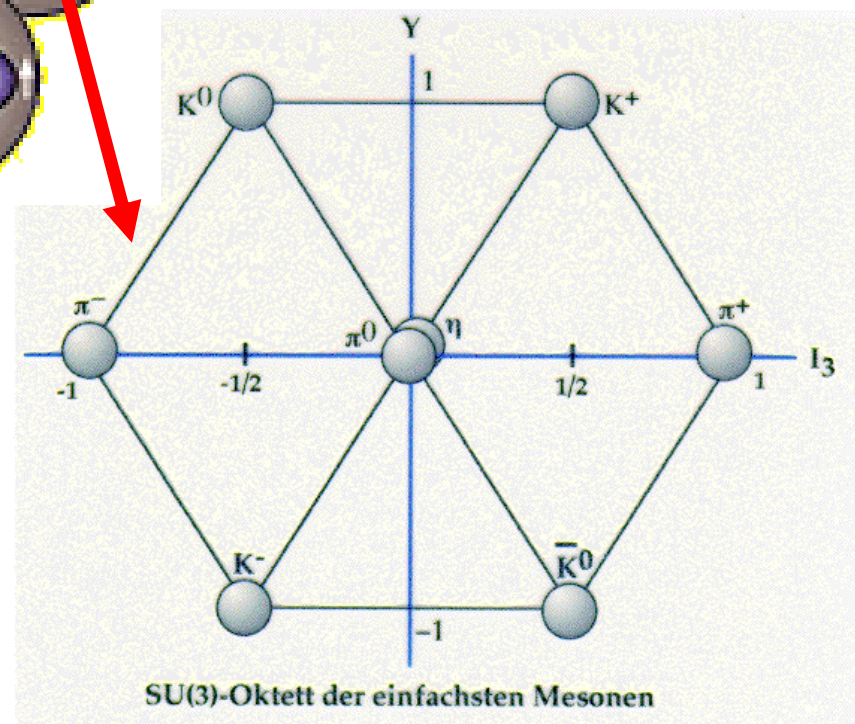
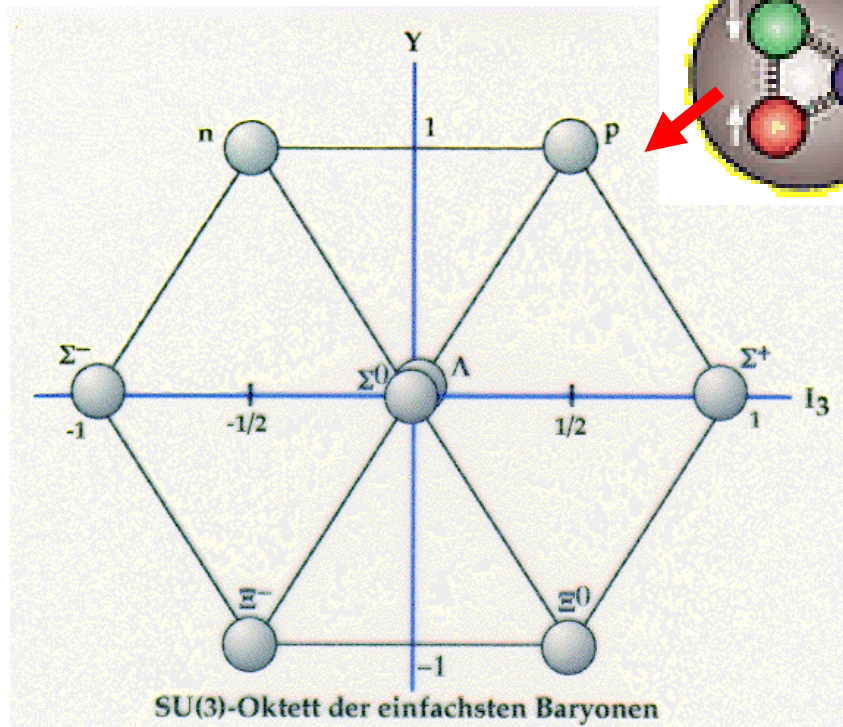
(Nobel 1969)



# The Quark Model

baryons =  $qqq$

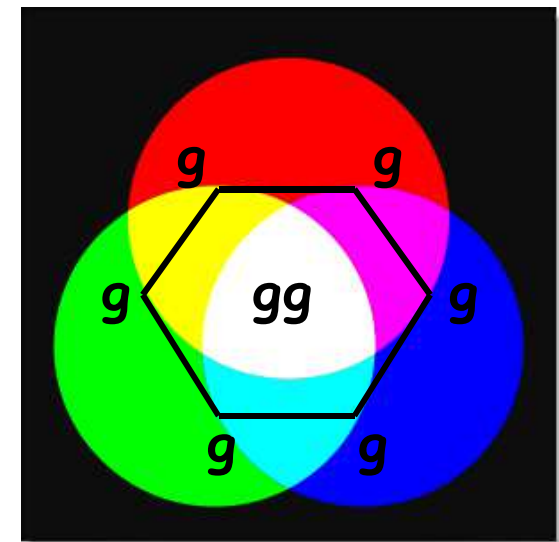
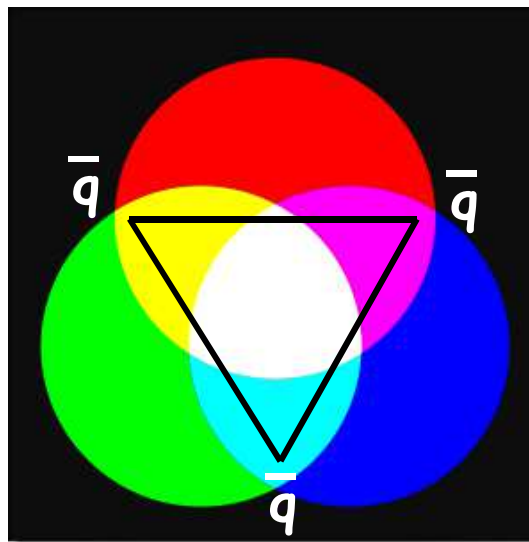
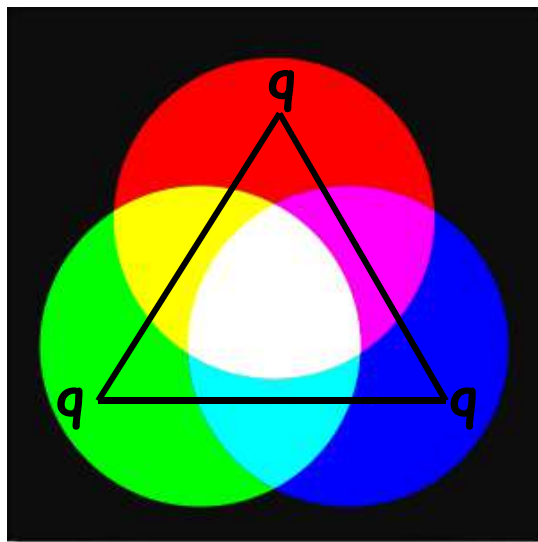
mesons =  $q\bar{q}$



# 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:

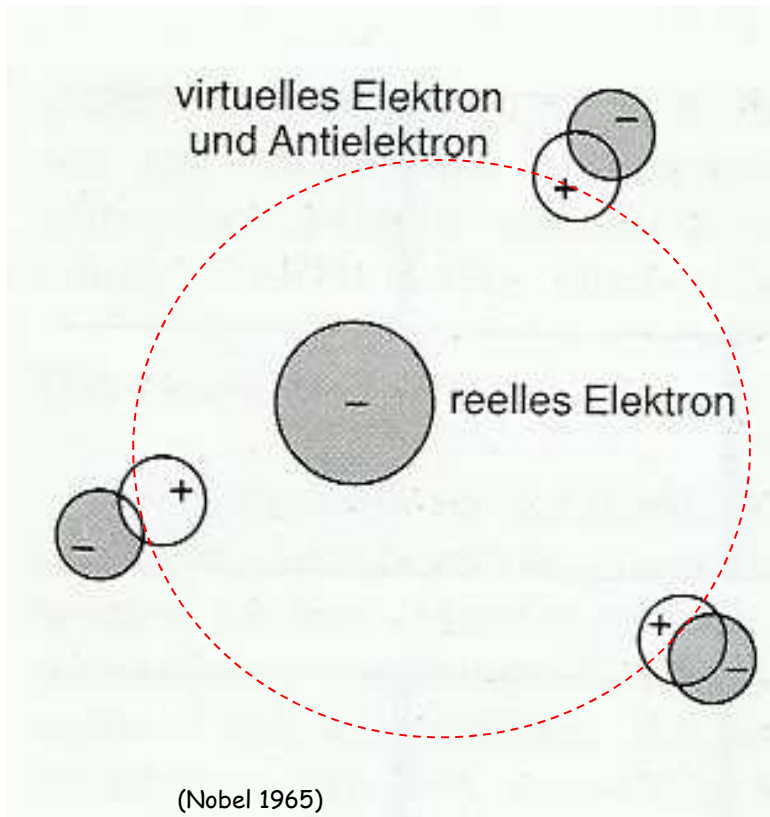
**Colour**



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

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

# Screening of Electric Charge



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Sin-Itoro Tomonaga    Julian Schwinger    Richard P. Feynman

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



1. **Introduction**  
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virtuelles Gluon

reelles Quark

virtuelles Quark und Antiquark

virtuelles Gluon

reelles Quark und Antiquark

g

g'

g''



(Nobel 2004)

Graph illustrating the running of the coupling constants  $\alpha_{\text{QCD}}(Q^2)$  and  $\alpha_{\text{QED}}(Q^2)$  as a function of the inverse squared distance  $1/r^2 \sim E^2, Q^2$ .

The vertical axis is labeled  $\alpha_{\text{qft}}(Q^2)$  and the horizontal axis is labeled  $1/r^2 \sim E^2, Q^2$ .

The curve  $\alpha_{\text{QCD}}(Q^2)$  (solid line) decreases as  $Q^2$  increases, indicating asymptotic freedom. The curve  $\alpha_{\text{QED}}(Q^2)$  (dashed line) increases as  $Q^2$  increases, indicating confinement.

The region where  $\alpha_{\text{QCD}}(Q^2)$  is high is labeled "confinement" (wavy line). The region where  $\alpha_{\text{QED}}(Q^2)$  is high is labeled "asymptotic freedom" (arrow pointing to 0).

# Comparison QED / QCD

electromagnetism

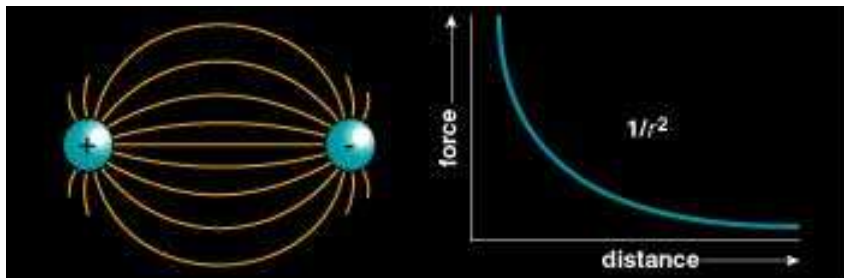
## QED

1 kind of charge ( $q$ )

force mediated by **photons**

photons are neutral

$\alpha$  is nearly constant



strong interactions

## QCD

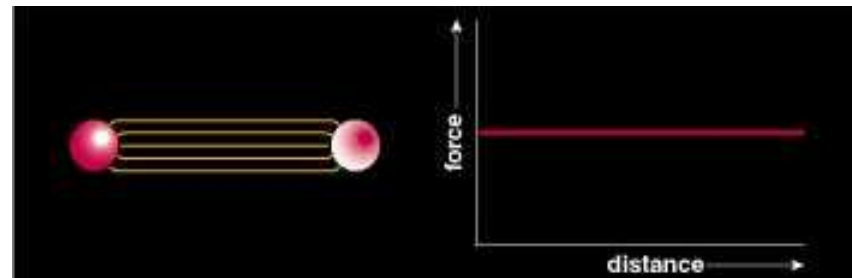
3 kinds of charge ( $r, g, b$ )

force mediated by **gluons**

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

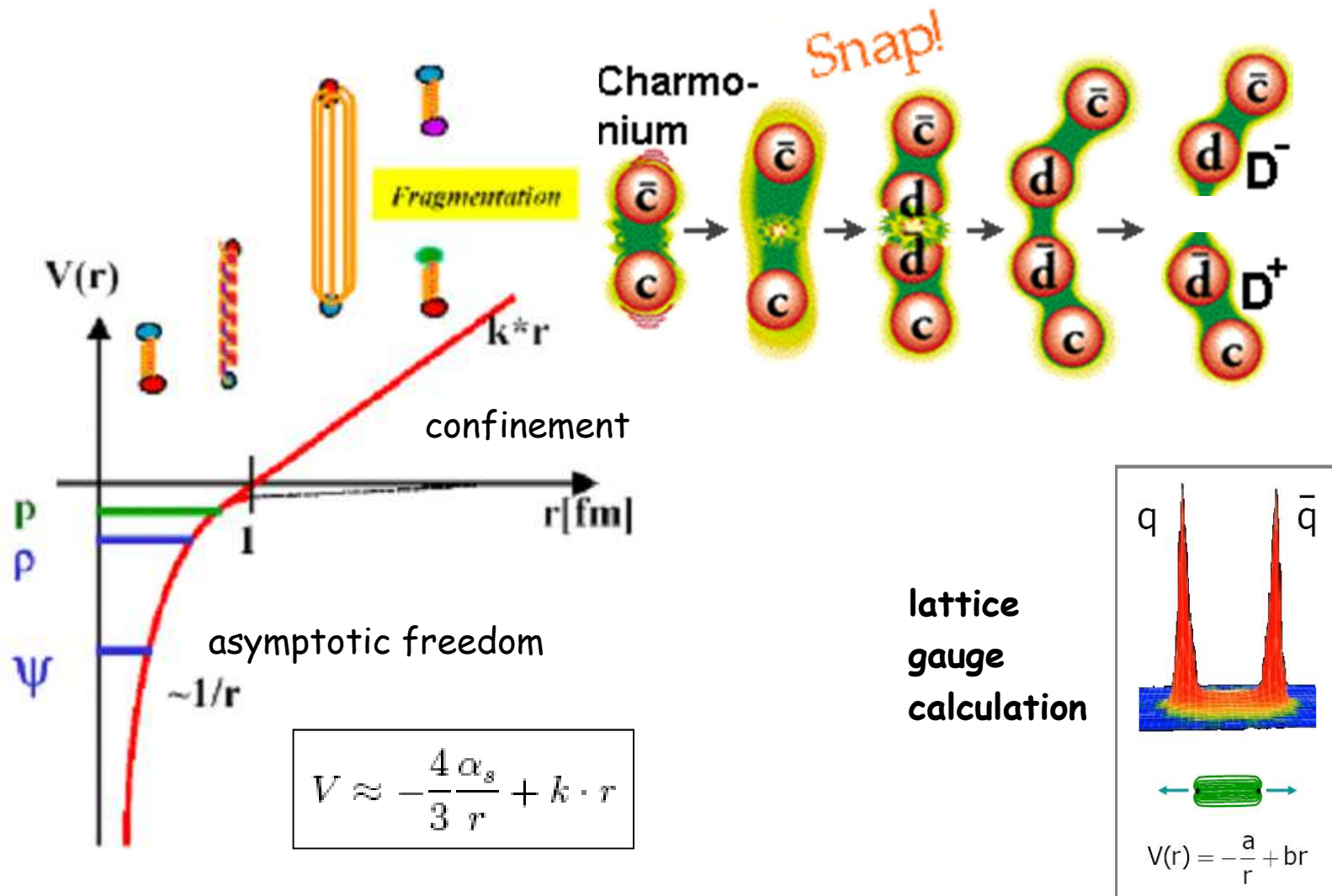
$\alpha_s$  strongly depends on distance

confinement limit:



- The underlying theories are formally almost identical!

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



# Heavy Quark Spectroscopy

Burton  
Richter

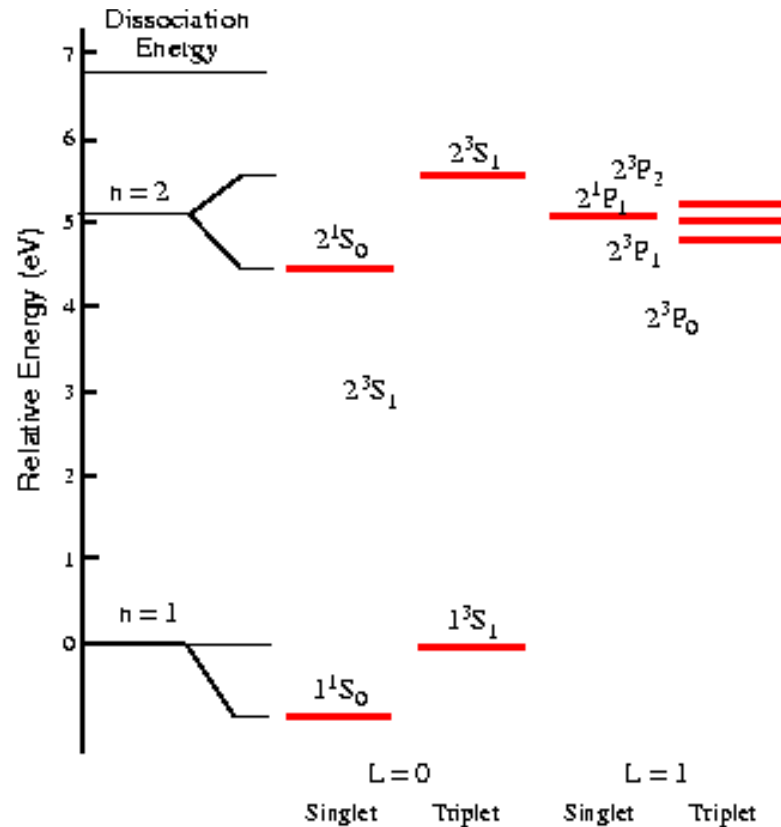


(Nobel  
1976)

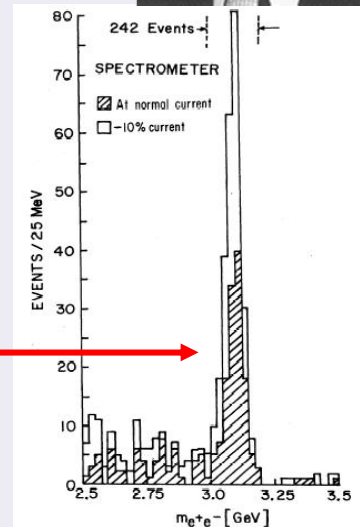
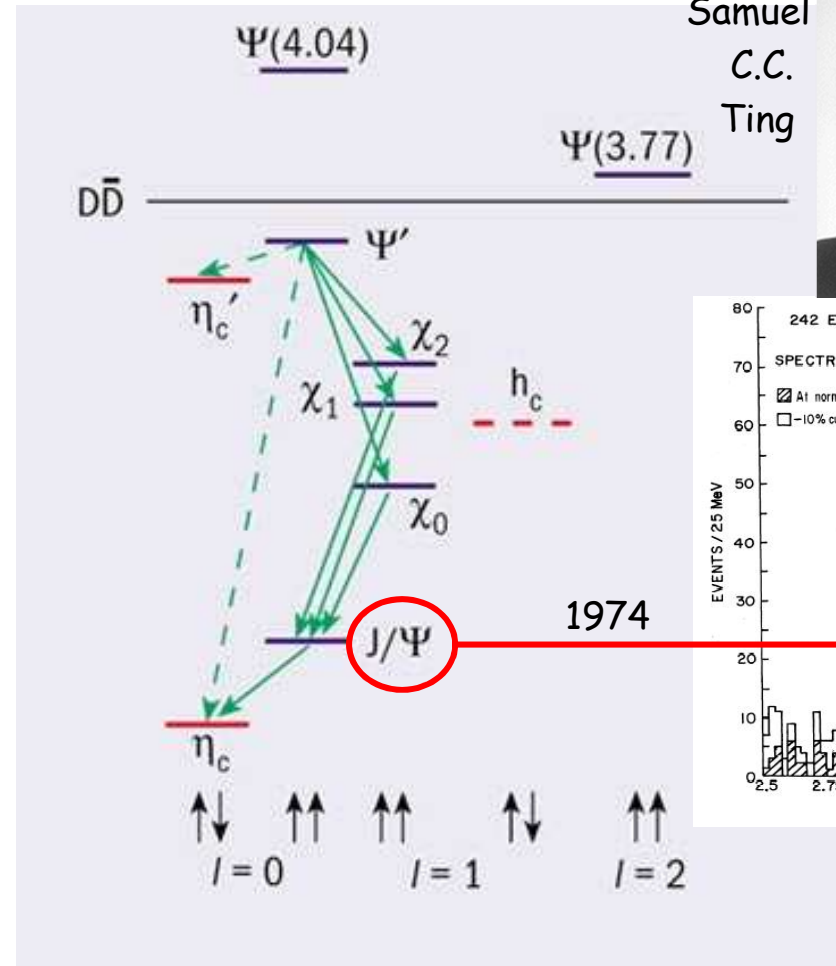
Samuel  
C.C.  
Ting



Positronium = bound  $e^+e^-$  system



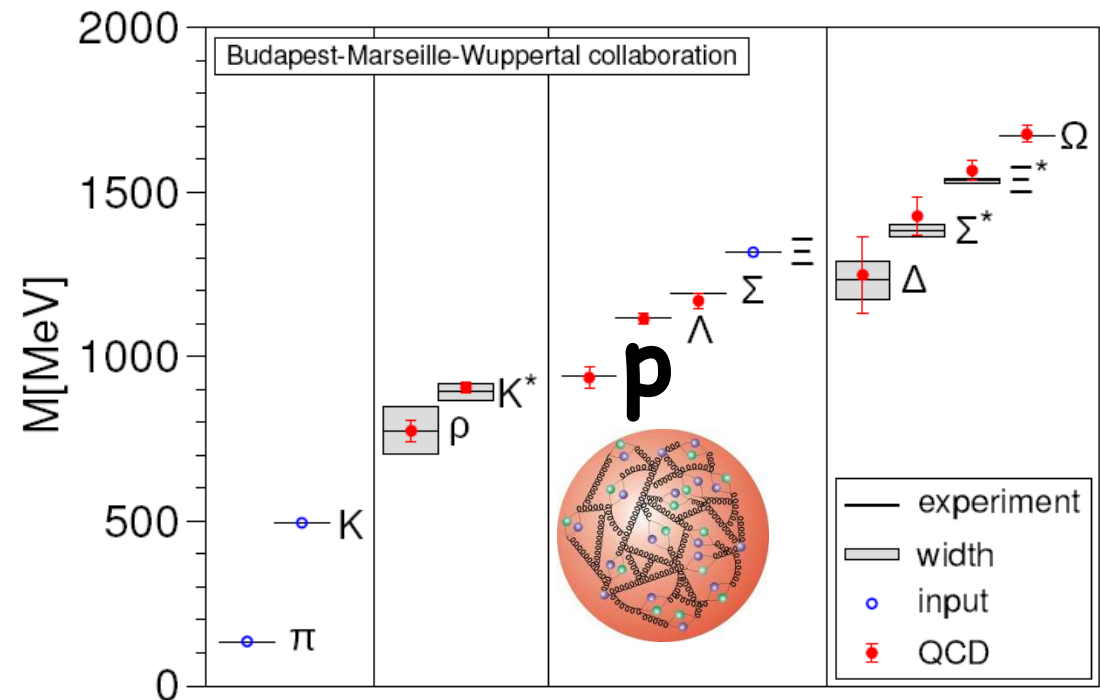
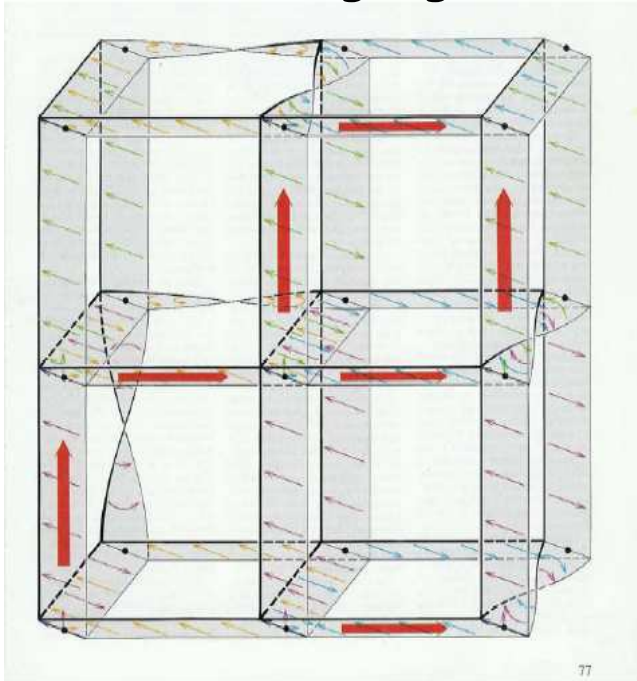
Charmonium = bound system  
of  $c\bar{c}$  quark pair





# 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,**  
⇒ **mass of the visible part of the universe !**

18.-20.7.18

A. Geiser, Particle Physics

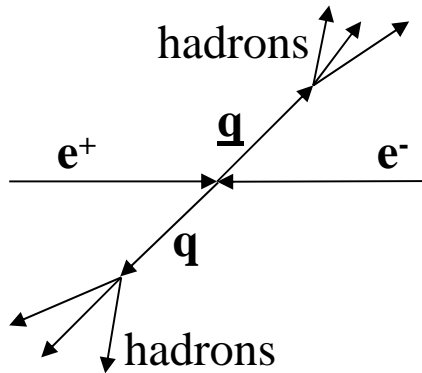


Yoichiro  
Nambu

(Nobel 2008)

# How to detect Quarks and Gluons?

## Jets!



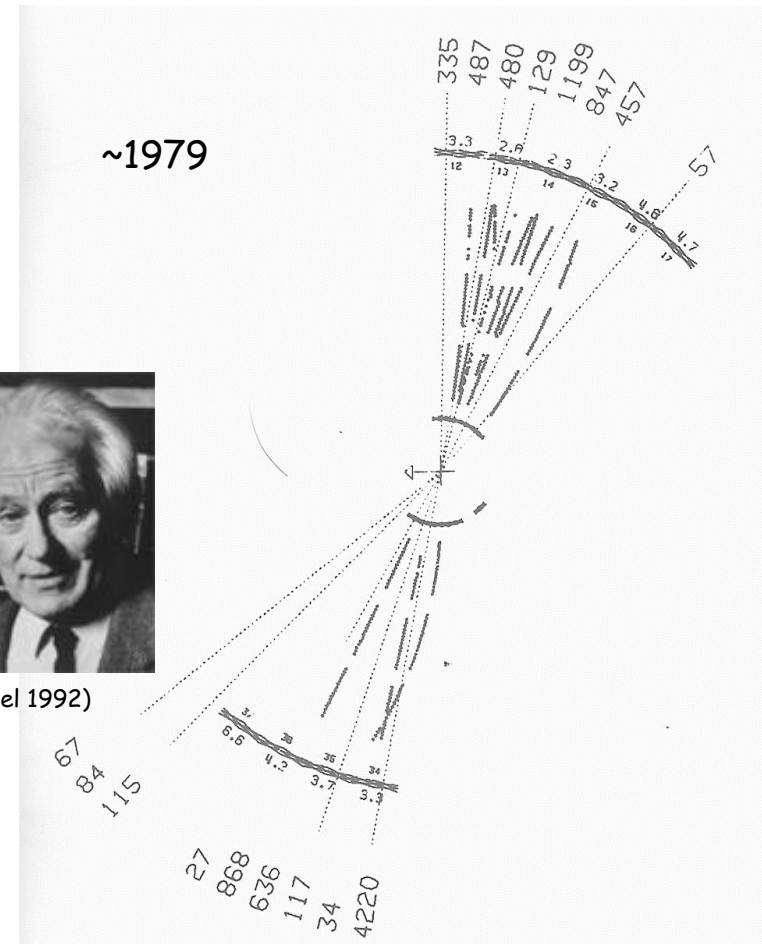
Example of the hadron production in  $e^+e^-$  annihilation in the JADE detector at the PETRA  $e^+e^-$  collider at DESY, Germany.

- $\sqrt{s}$  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.

Georges Charpak

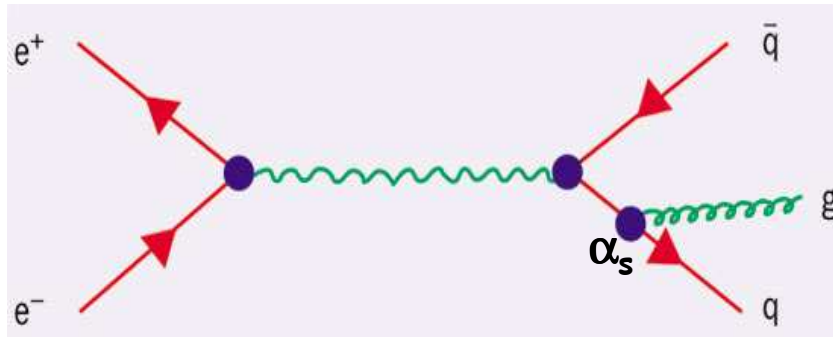


(Nobel 1992)



# Discovery of the Gluon (1979)

PETRA at DESY: look for



Björn Wiik

Paul Söding

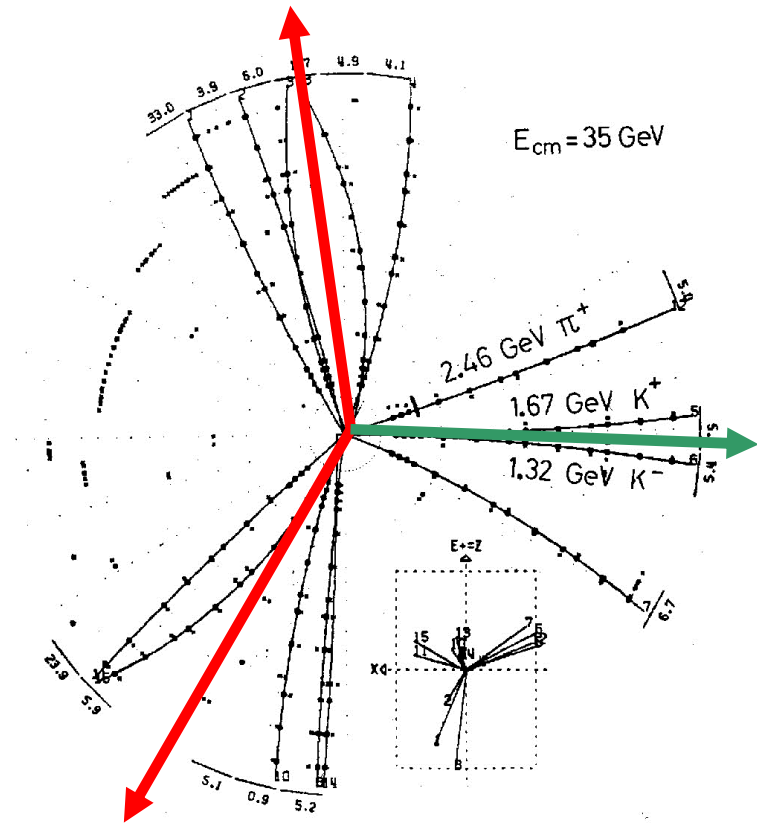


Günter Wolf

Sau Lan Wu

(EPS prize 1995)

18.-20.7.18

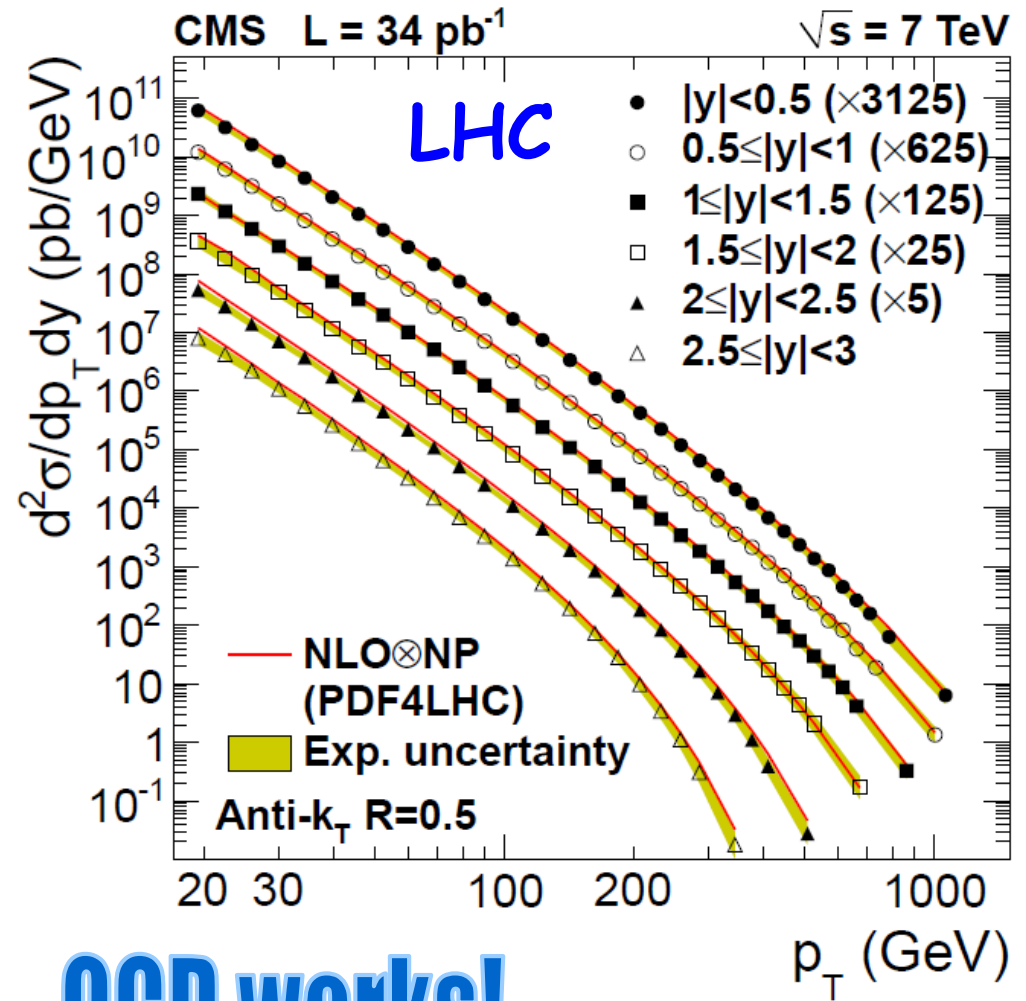
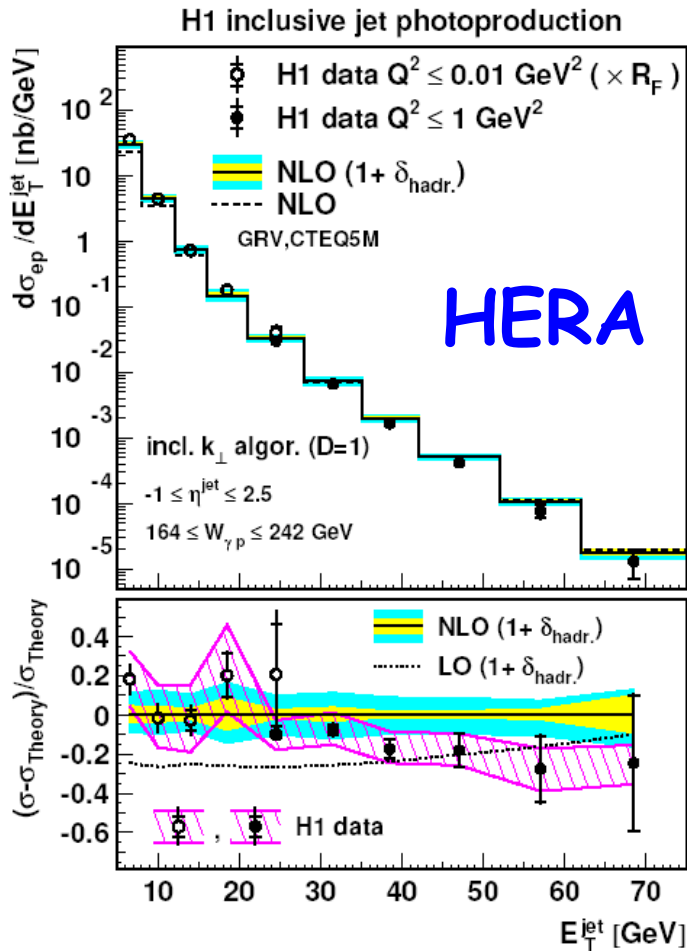


22.9.80

TASSO event picture



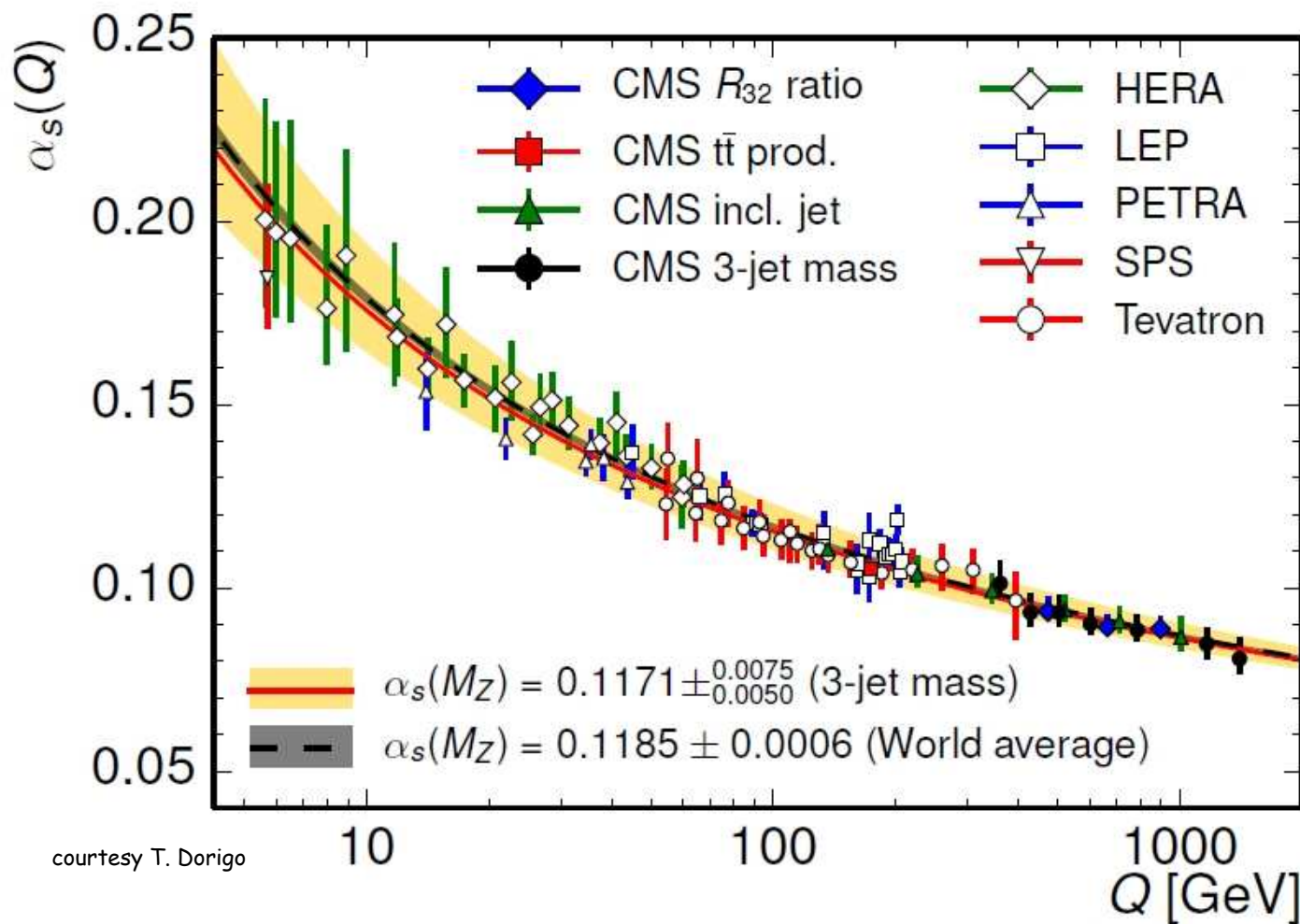
# Jets in ep and pp interactions



**QCD works!**

# Running strong coupling „constant“ $\alpha_s$

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



courtesy T. Dorigo

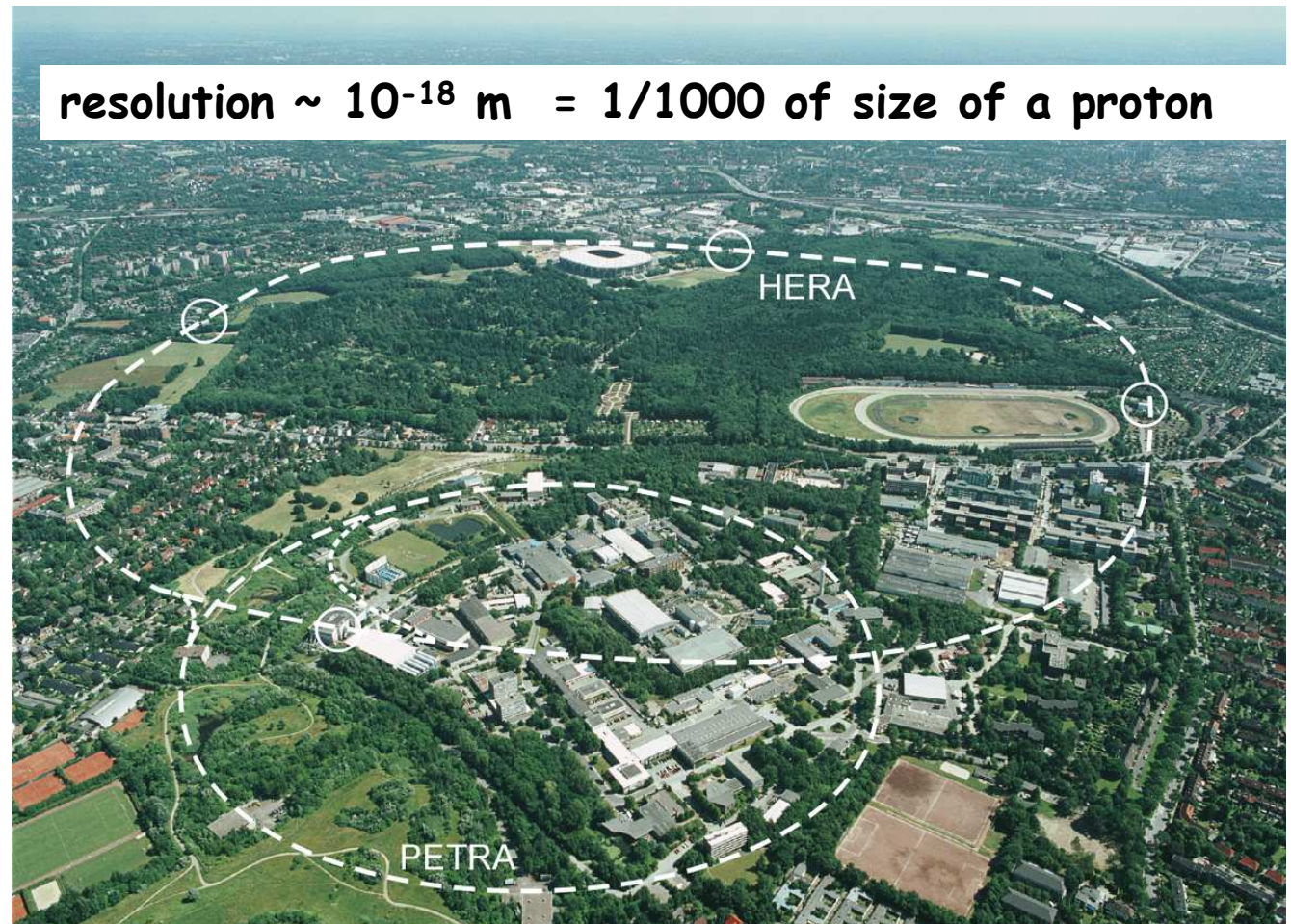
**Yes,  
it runs!**

# How to determine the „size“ of a particle?

microscope:  
low resolution  
-> small instrument

high resolution  
-> large instrument

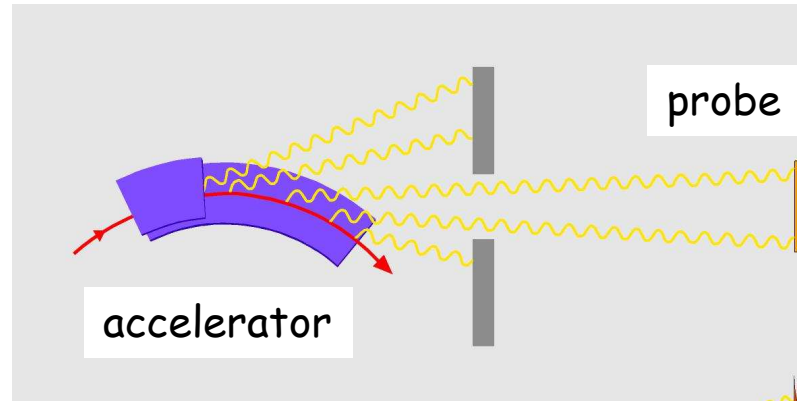
**HERA = giant  
electron  
microscope**



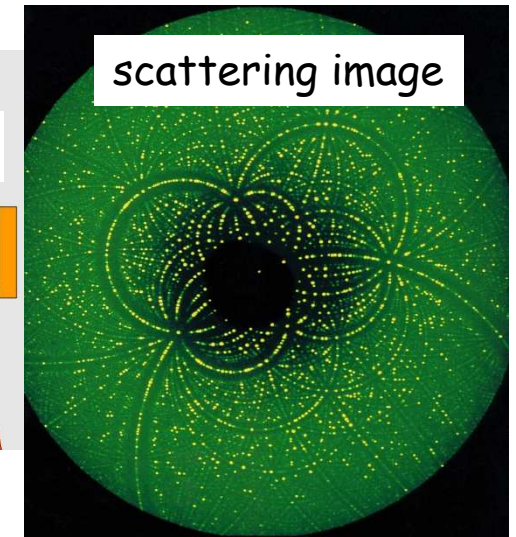


# How to resolve the structure of an object?

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



$E \sim \text{keV}$



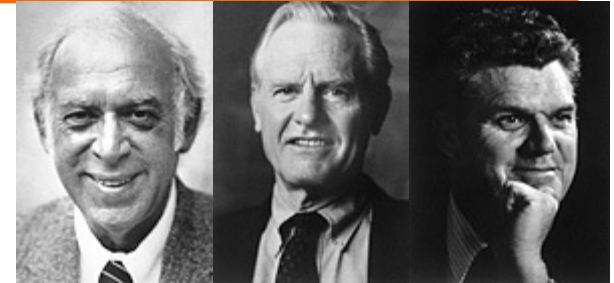
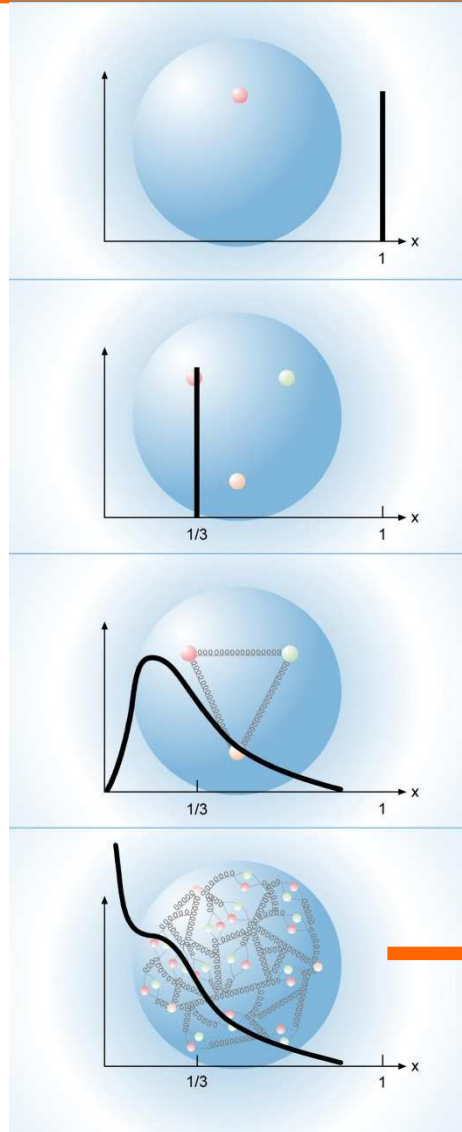
-> structure of  
a biomolecule



Ada Yonath  
(Nobel 2009)

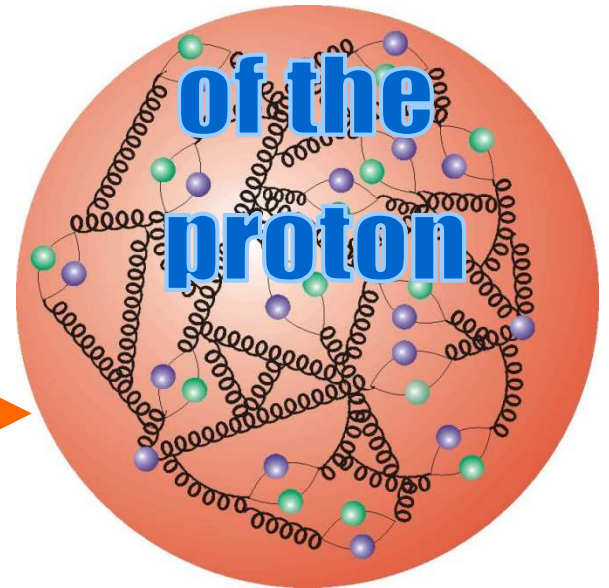
# Resolve the structure of the proton

- $E \sim \text{MeV}$   
resolve whole proton
- static quark model,  
valence quarks  
( $m \sim 350 \text{ MeV}$ )
- $E \sim m_p \sim 1 \text{ GeV}$   
resolve valence quarks  
and their motion
- $E \gg 1 \text{ GeV}$   
resolve quark and gluon  
"sea"



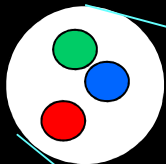
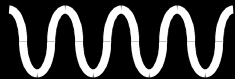
Jerome I. Friedman   Henry W. Kendall   Richard E. Taylor  
(Nobel 1990)

**structure  
of the  
proton**

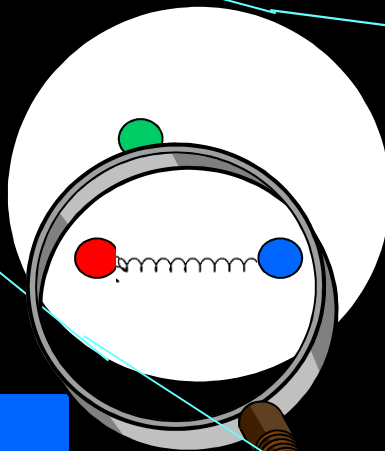


# Inside the proton

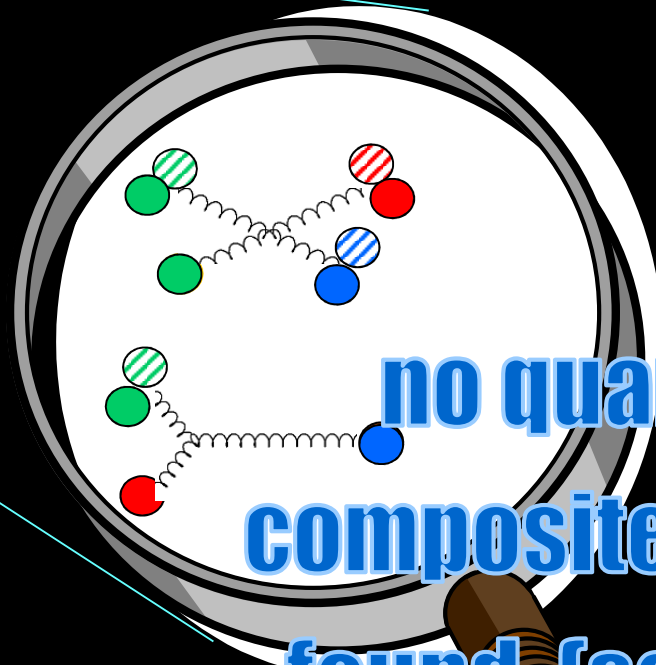
Low  $Q^2$  (large  $\lambda$ )



Medium  $Q^2$  (medium  $\lambda$ )



Large  $Q^2$  (short  $\lambda$ )



no quark  
compositeness  
found (so far)

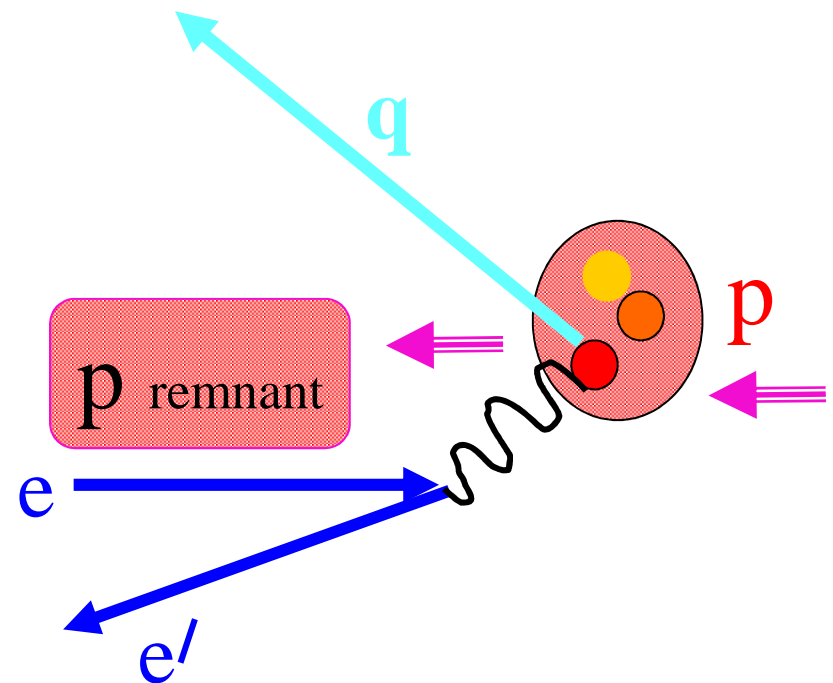
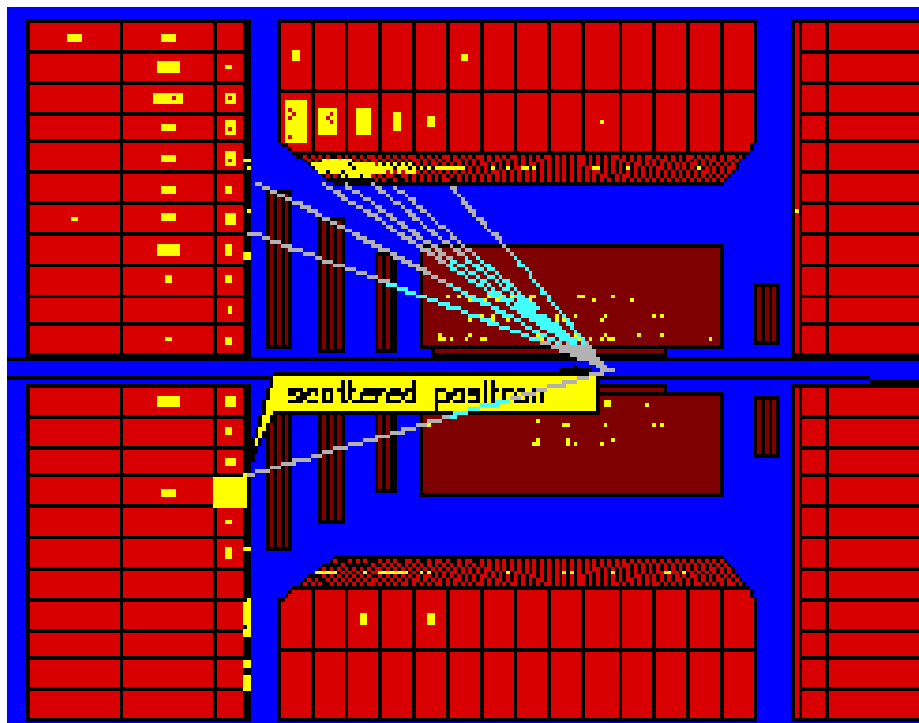
At higher and higher resolutions, the quarks emit gluons, which also emit gluons, which emit quarks, which.....

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

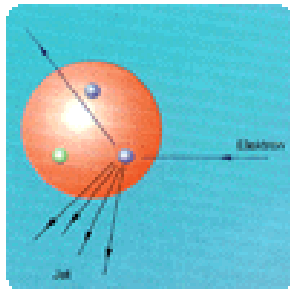
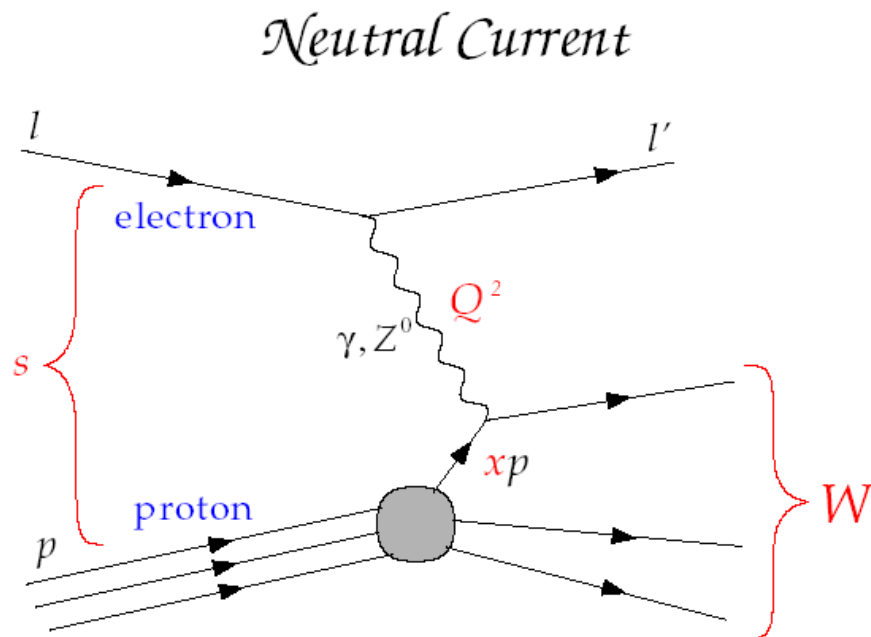
Heisenberg's UP allows gluons, and  $q\bar{q}$  pairs to be produced for a very short time.



# 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)

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

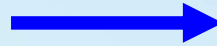
Parton distribution functions (PDF) in pQCD

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

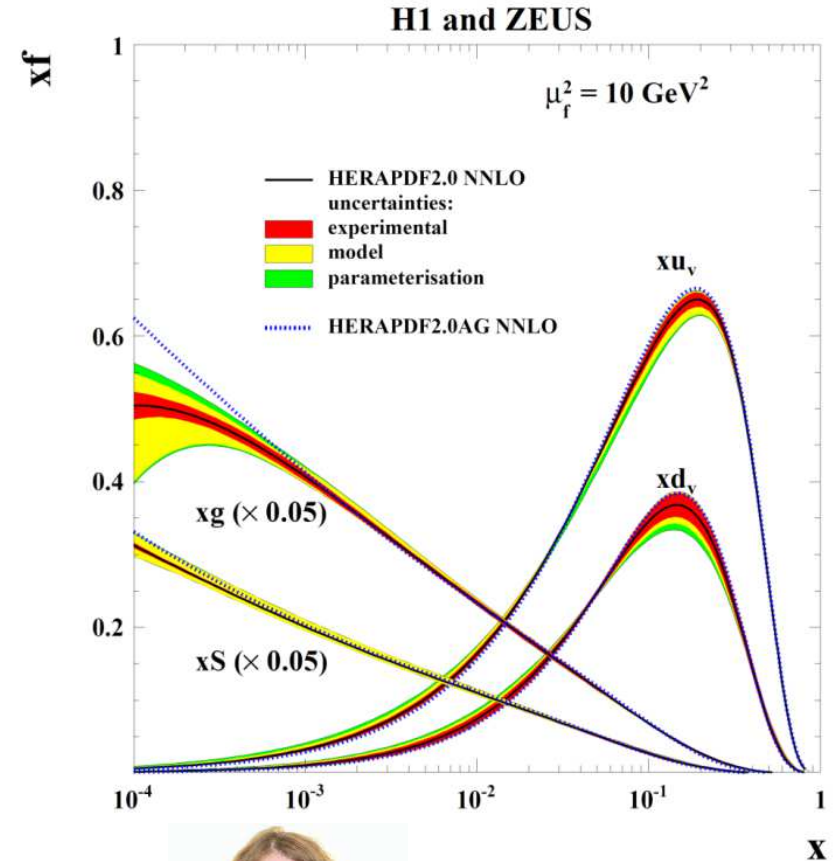
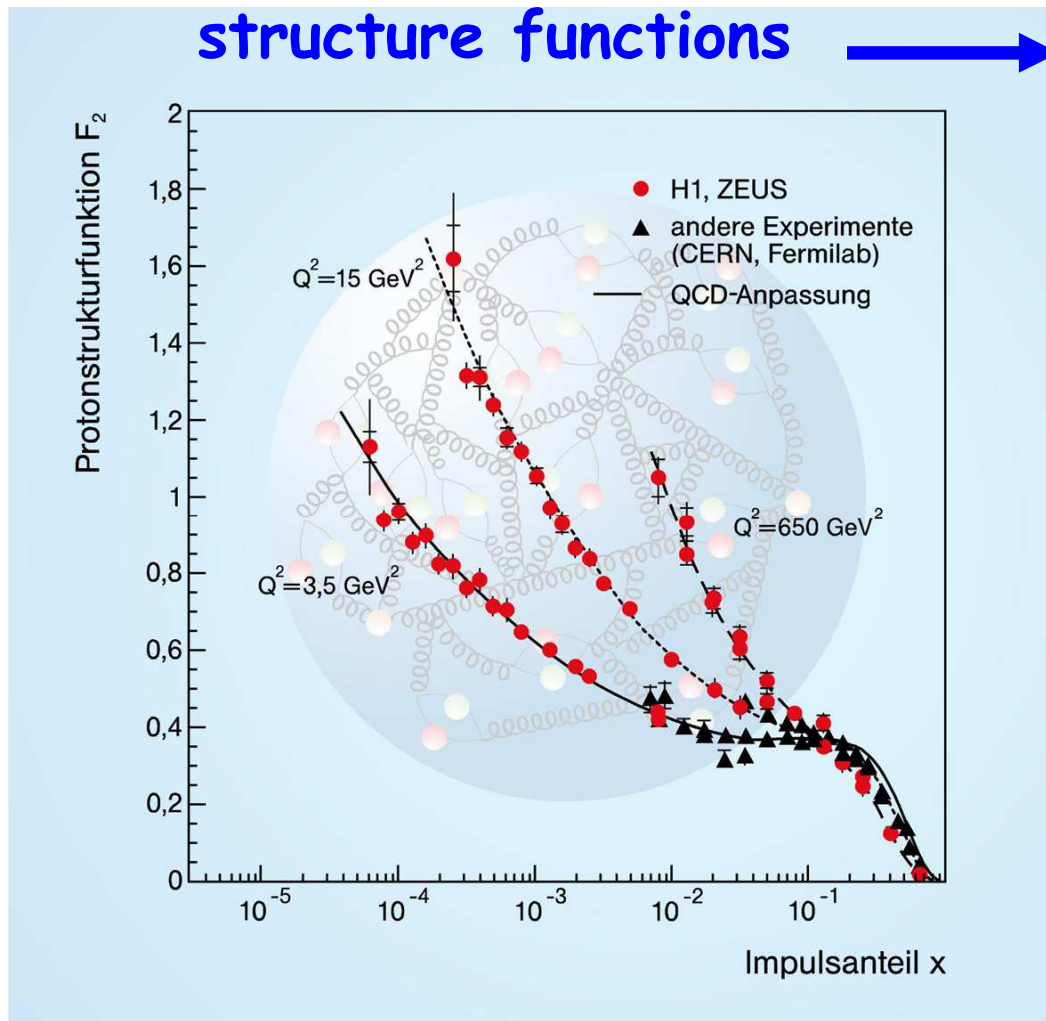
$q_i$  – probability to find quark with flavour  $i$  in proton

# The Proton Structure

structure functions



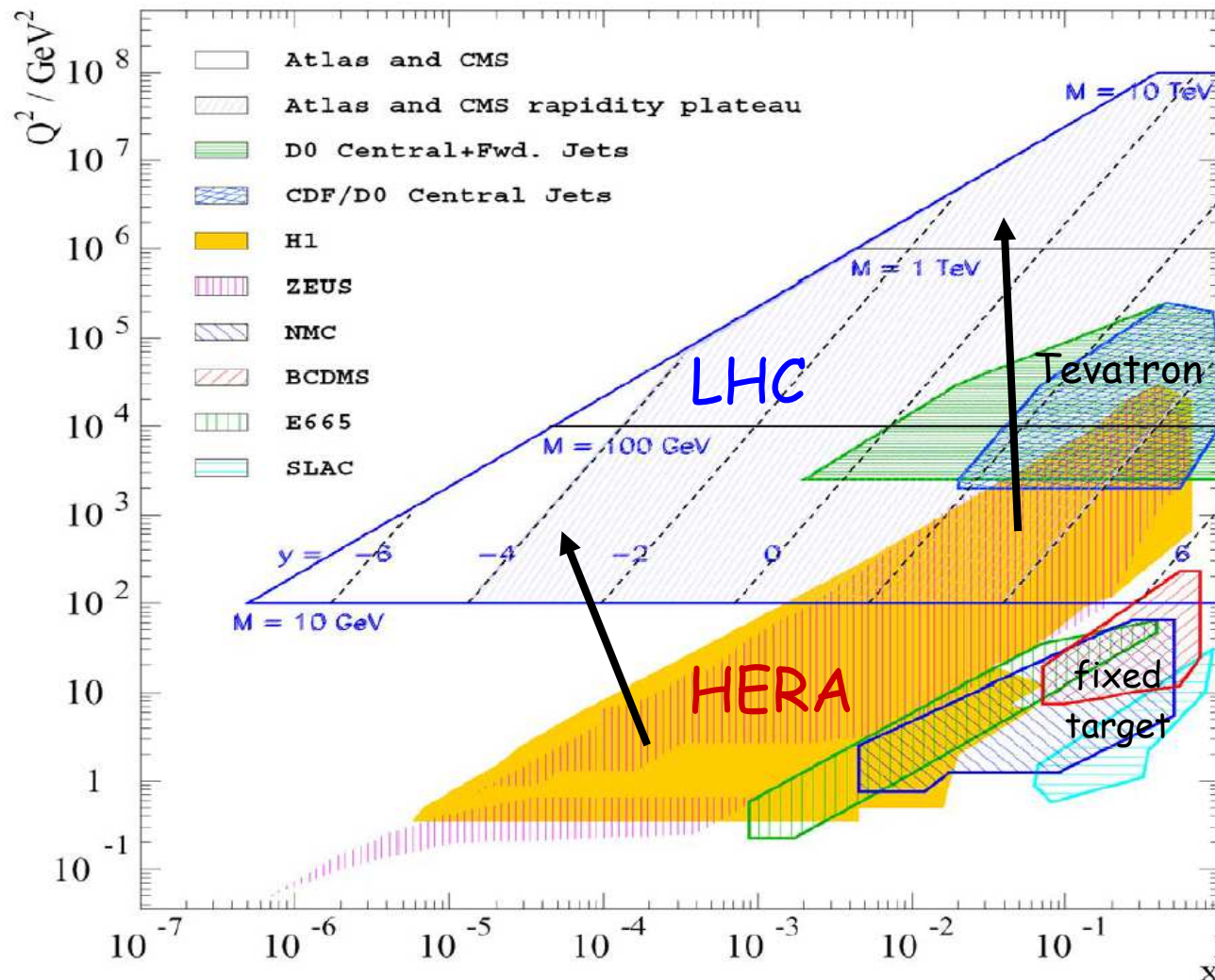
quark and gluon densities



Amanda  
Cooper-Sarkar  
(Chadwick medal 2015)



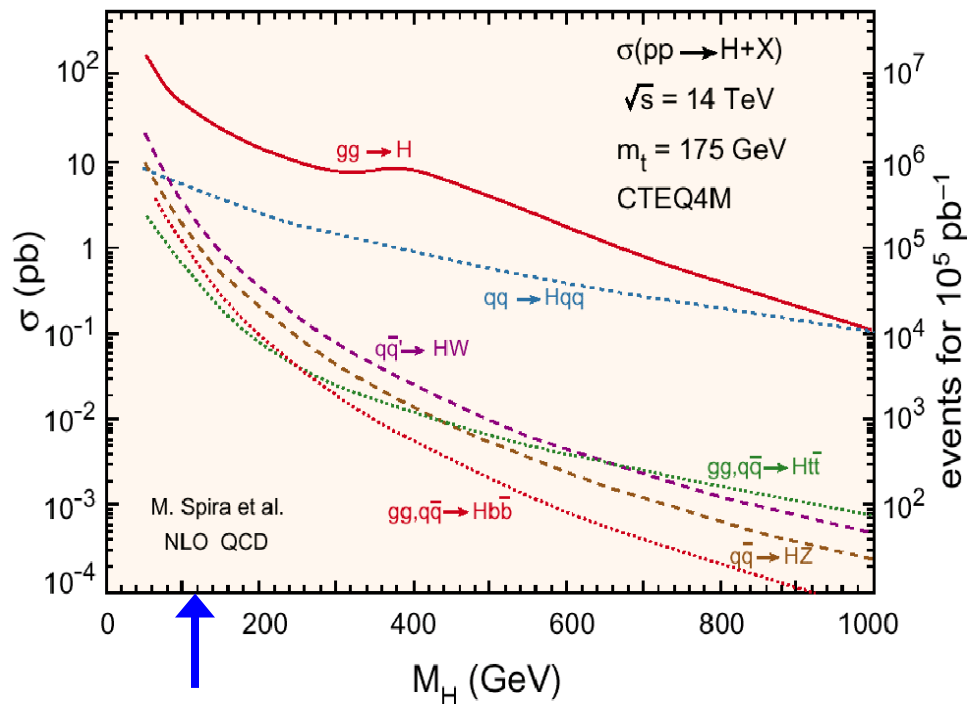
# Kinematic regions: HERA vs. LHC



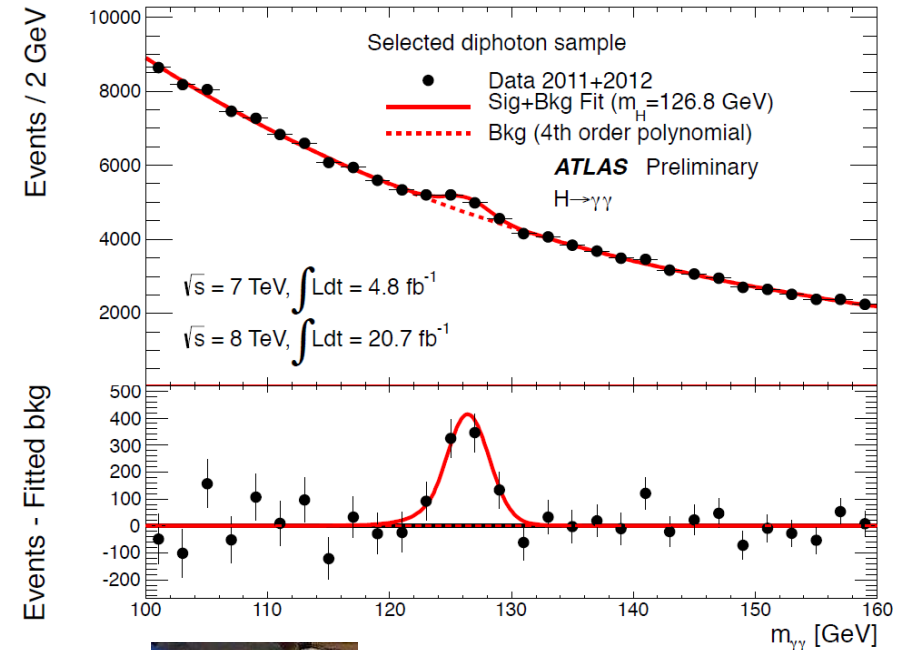
- proton structure measured directly for large part of LHC phase space
- QCD evolution successful  
→ safely extrapolate to higher  $Q^2$

**Input to  
measure-  
ments  
at LHC**

# Example: Higgs cross section at LHC



## $H \rightarrow \gamma\gamma$ in ATLAS



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

Knowledge of gluon and quark distributions essential

# Intermediate summary

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- 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**