Elementary Particle Physics Research

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Summer Student Lecture, 29./30.7.08

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

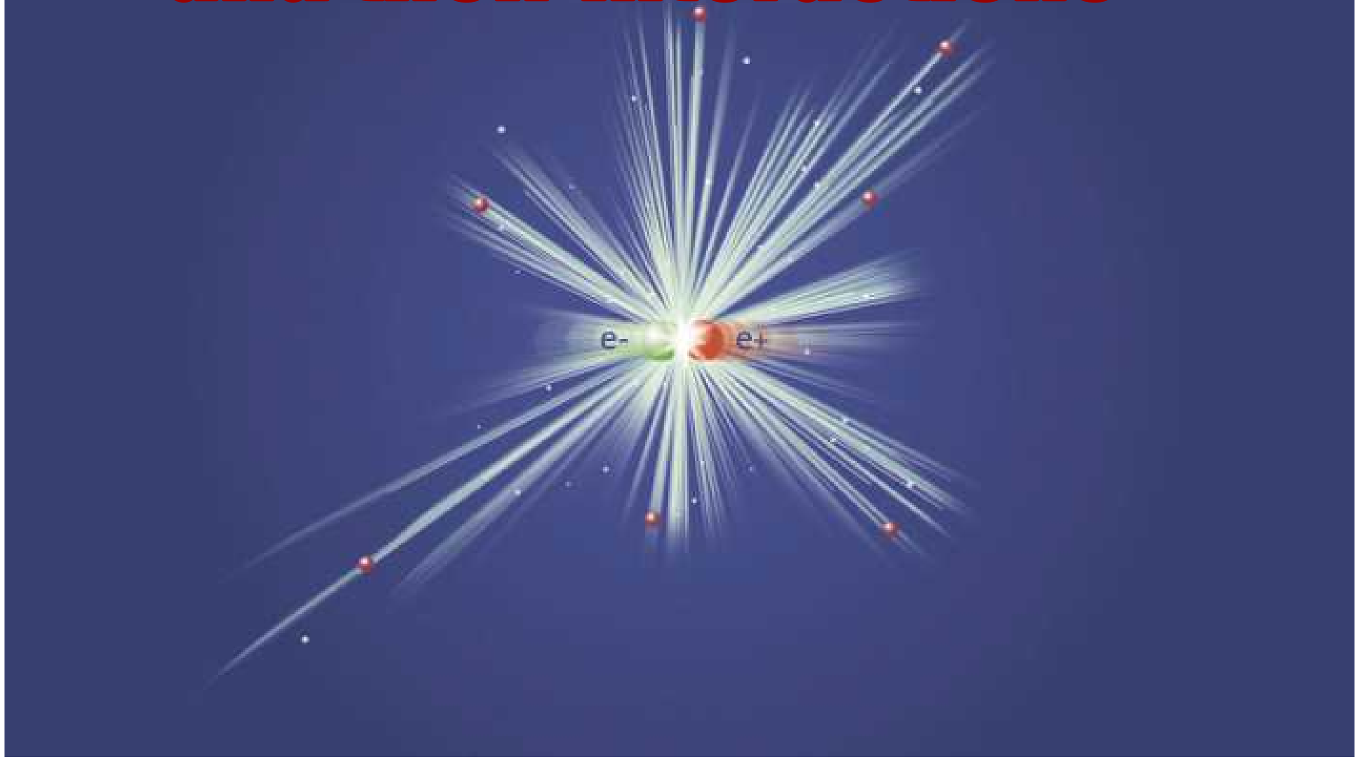
thanks to B. Foster for some of the nicest slides/animations
other sources:
www pages of DESY and CERN

What is Particle Physics?

Particle Physics

= science of elementary particles

and their interactions



What is a „particle"?

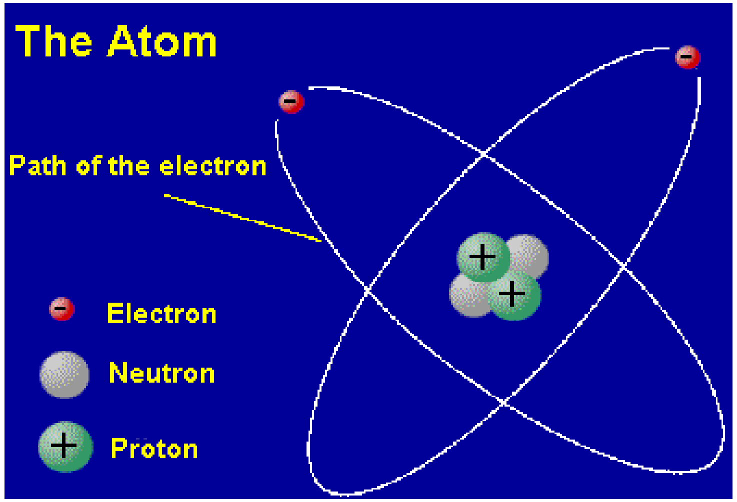
- **Classical view: particles = discrete objects.**

energy concentrated into finite space with definite boundaries.

Particles exist at a specific location.

-> Newtonian mechanics

Isaac Newton



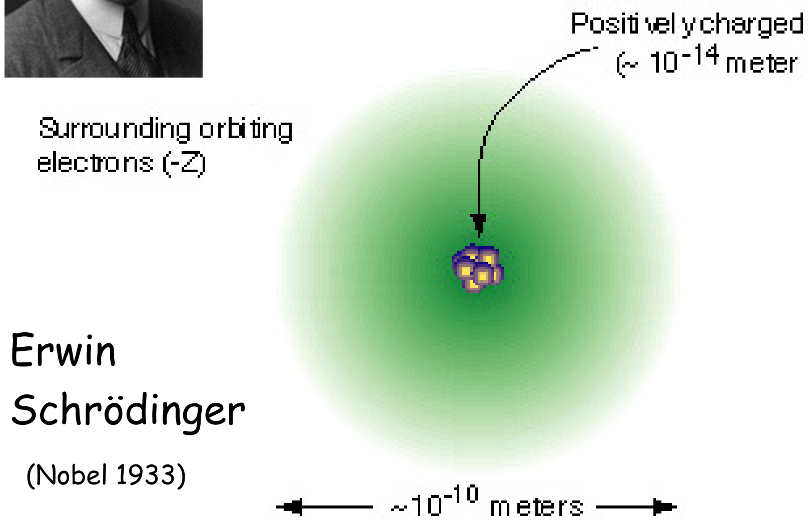
- **Modern view:**

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)

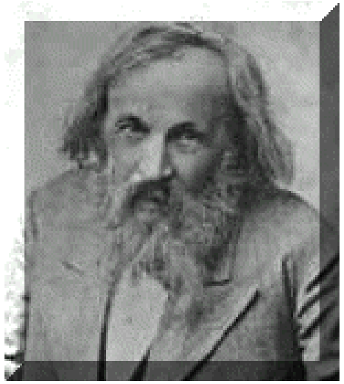
Werner Heisenberg
(Nobel 1932)

Erwin Schrödinger
(Nobel 1933)

What is „elementary“?

Greek: atomos = smallest indivisible part

Dmitry
Ivanowitsch
Mendeleyev
1868
(elements)



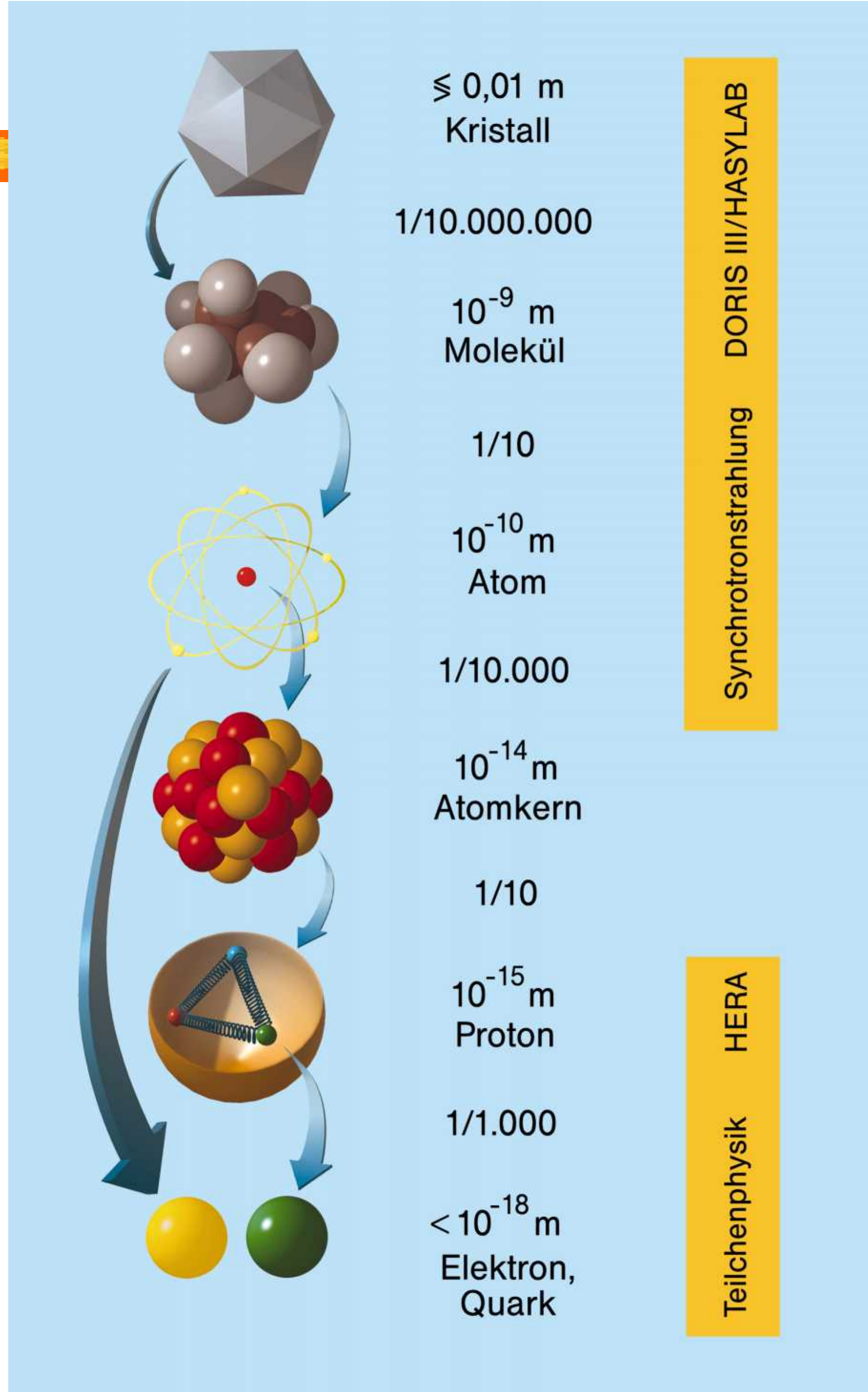
Ernest
Rutherford
1911
(nucleus)

(Nobel 1908)

Murray
Gell-Mann
1962
(quarks)

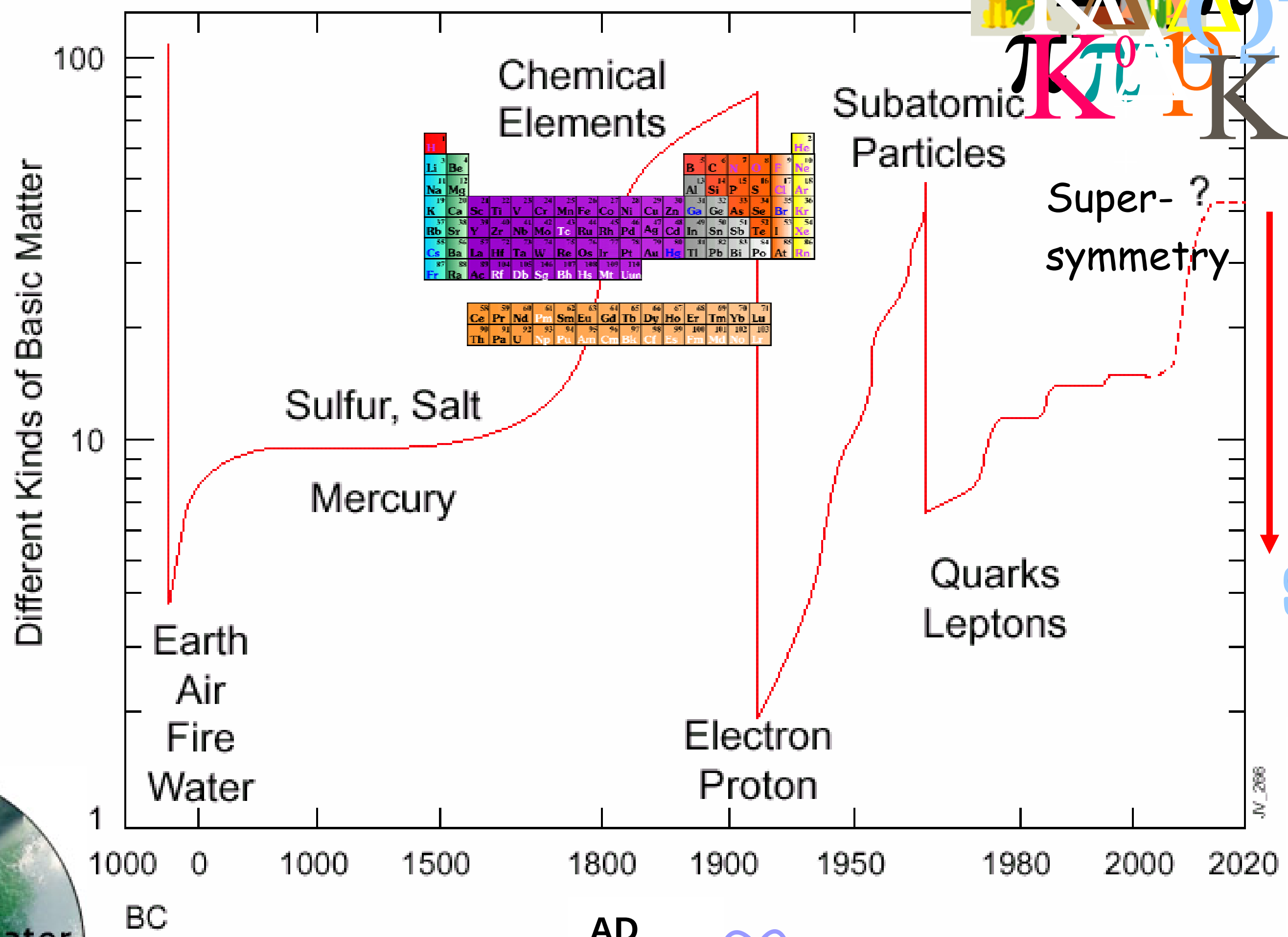
(Nobel 1969)

elementary
= no detectable substructure

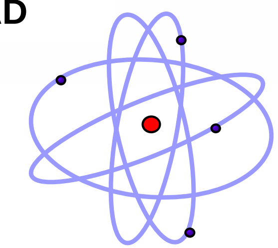


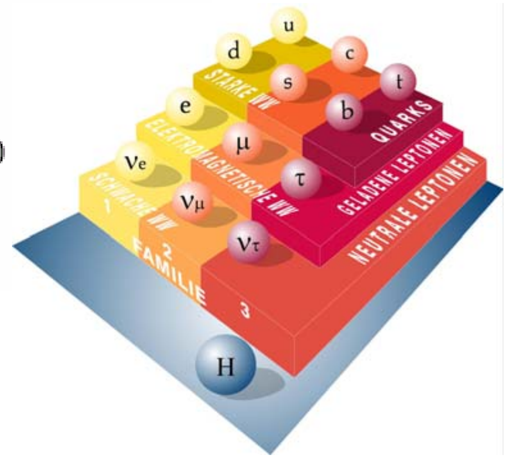
History of basic building blocks of matter

motivation: find smallest possible number

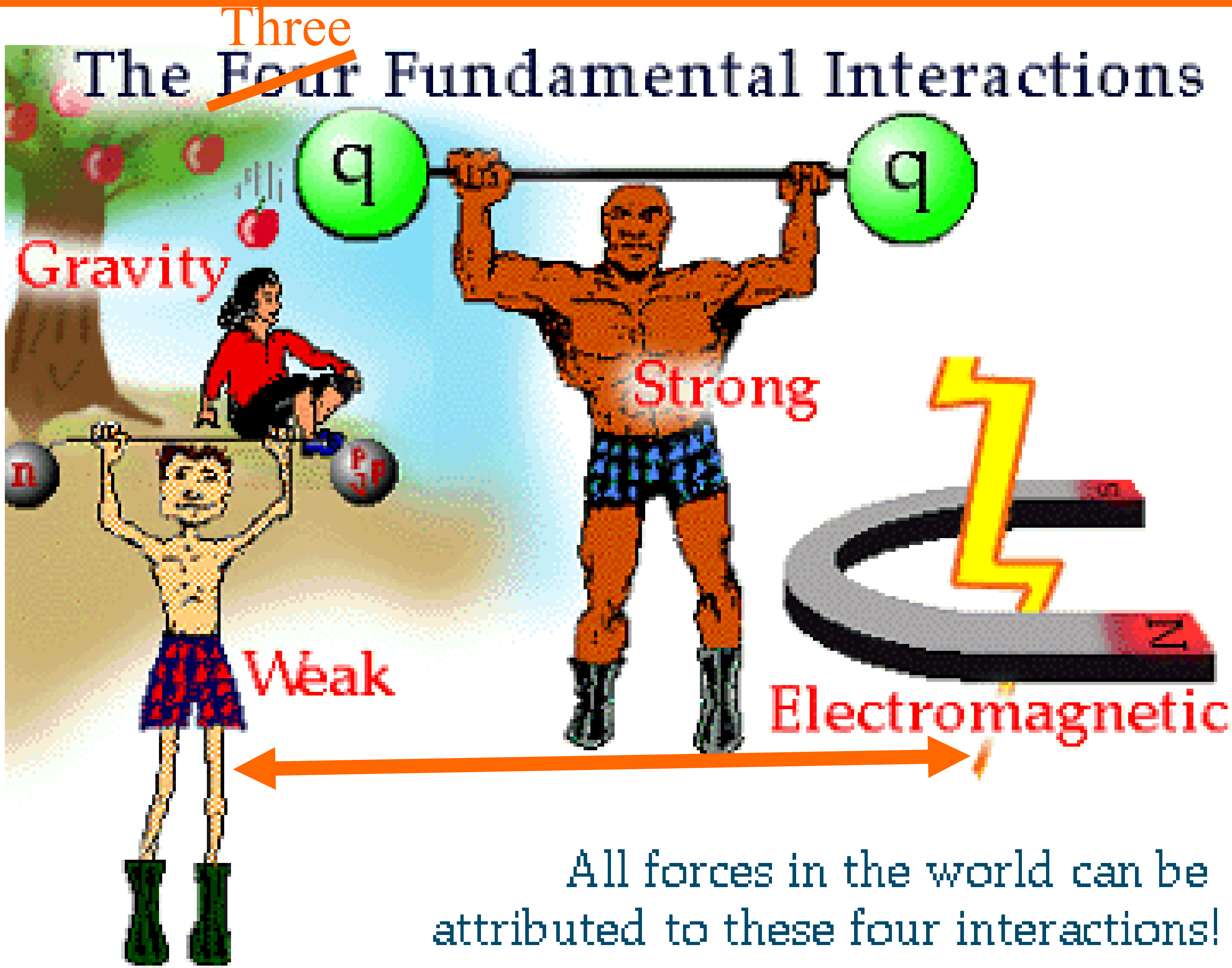


Quark and Lepton substructure ??



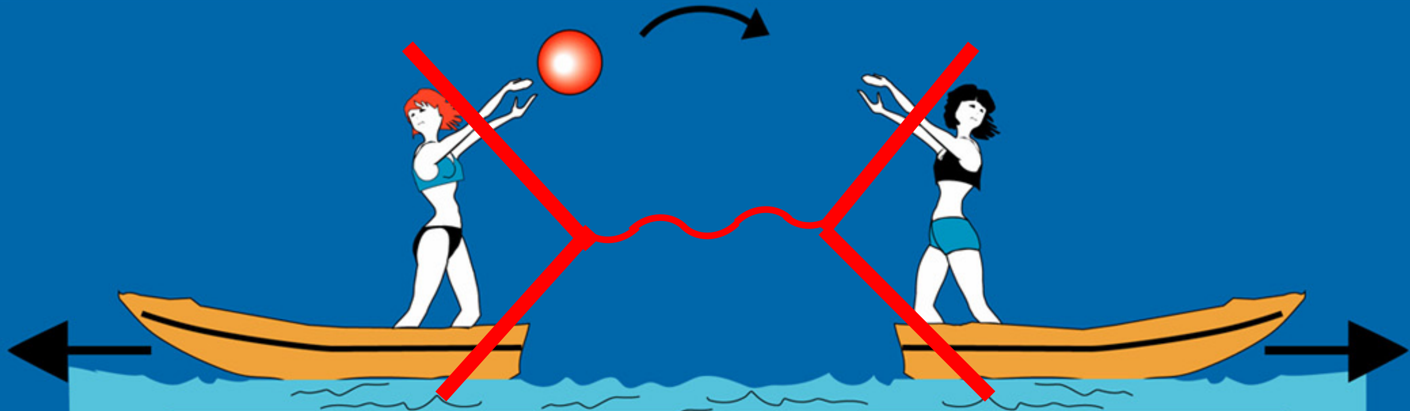


Which Interactions?



The Forces in Nature

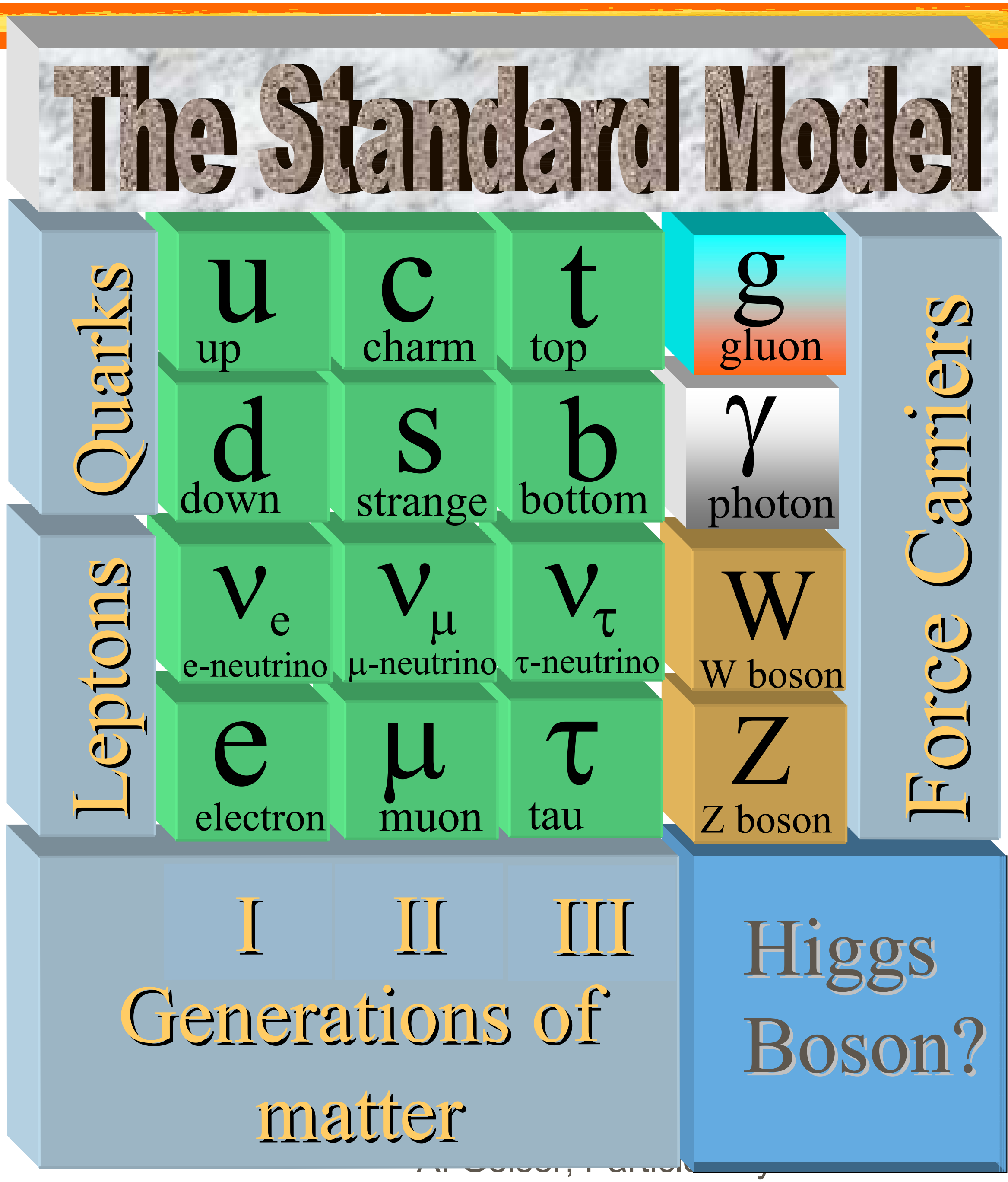
TYPE	at ~ 1 GeV INTENSITY OF FORCES (DECREASING ORDER)	BINDING PARTICLE (FIELD QUANTUM)	OCCURS IN :
STRONG NUCLEAR FORCE	~ 1	GLUONS (NO MASS)	ATOMIC NUCLEUS
ELECTRO -MAGNETIC FORCE	$\sim 10^{-3}$	PHOTONS (NO MASS)	ATOMIC SHELL ELECTROTECHNIQUE
WEAK NUCLEAR FORCE	$\sim 10^{-5}$	BOSONS Z^0 , W+ , W- (HEAVY)	RADIOACTIVE BETA DESINTEGRATION
GRAVITATION	$\sim 10^{-38}$	GRAVITONS (?)	HEAVENLY BODIES

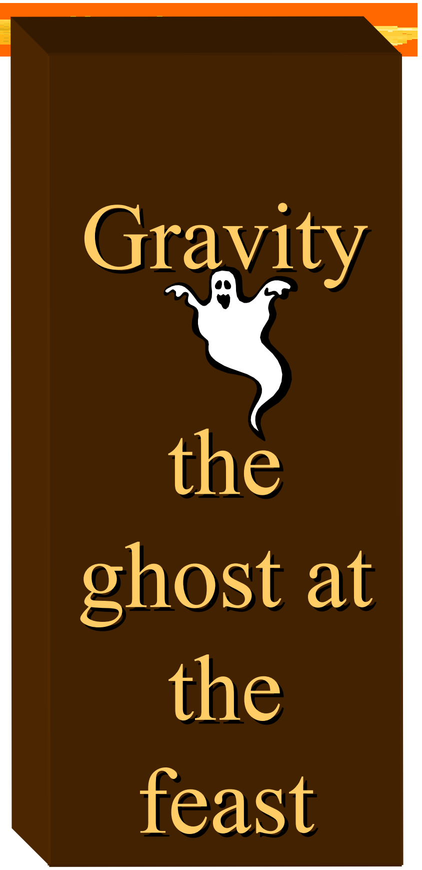


THE EXCHANGE OF PARTICLES IS RESPONSIBLE FOR THE FORCE

CERN AC _Z04_ V25/8/1992

What we know today



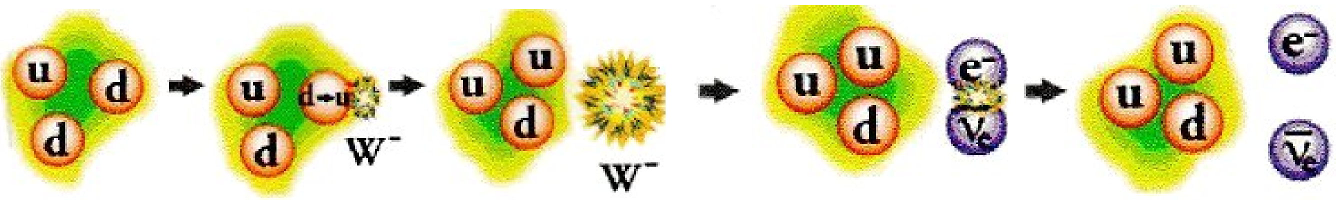


The Power of Conservation Laws

- e.g. radioactive neutron decay:

$$n \longrightarrow p + e^- + \bar{\nu}_e$$

not visible



- Pauli 1930:

Wolfgang Pauli

(Nobel 1945)

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

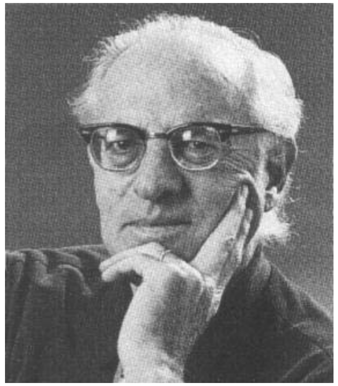
confirmation: neutrino detection

- e.g. reversed reaction:

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

extremely rare!

(absorption length ~ 3 light years Pb)



Frederick Reines

(Nobel 1995)

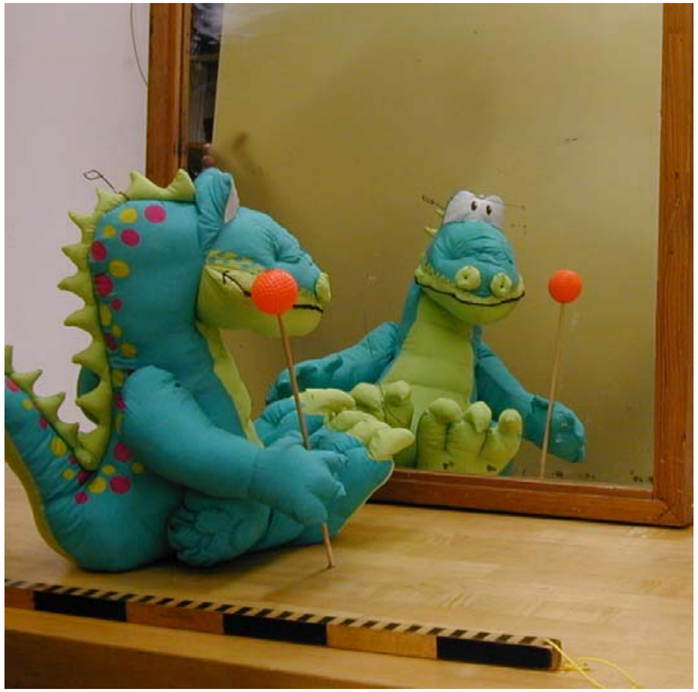
- first detection: 1956 (!)

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 day 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)

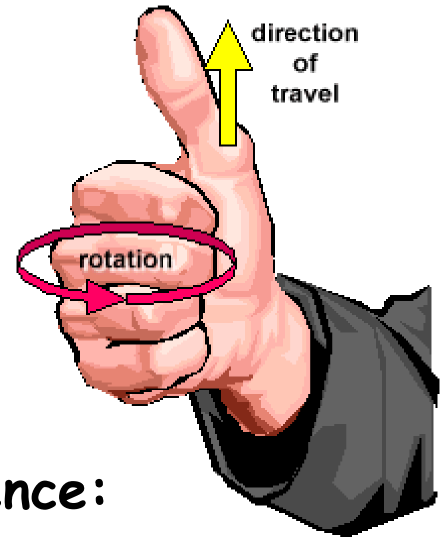
- What about basic interactions?
- Electromagnetic and strong interactions conserve parity!

The power of symmetries: Parity

Lee & Yang 1956: weak interactions violate Parity

experimentally verified by Wu et al. 1957:

spin

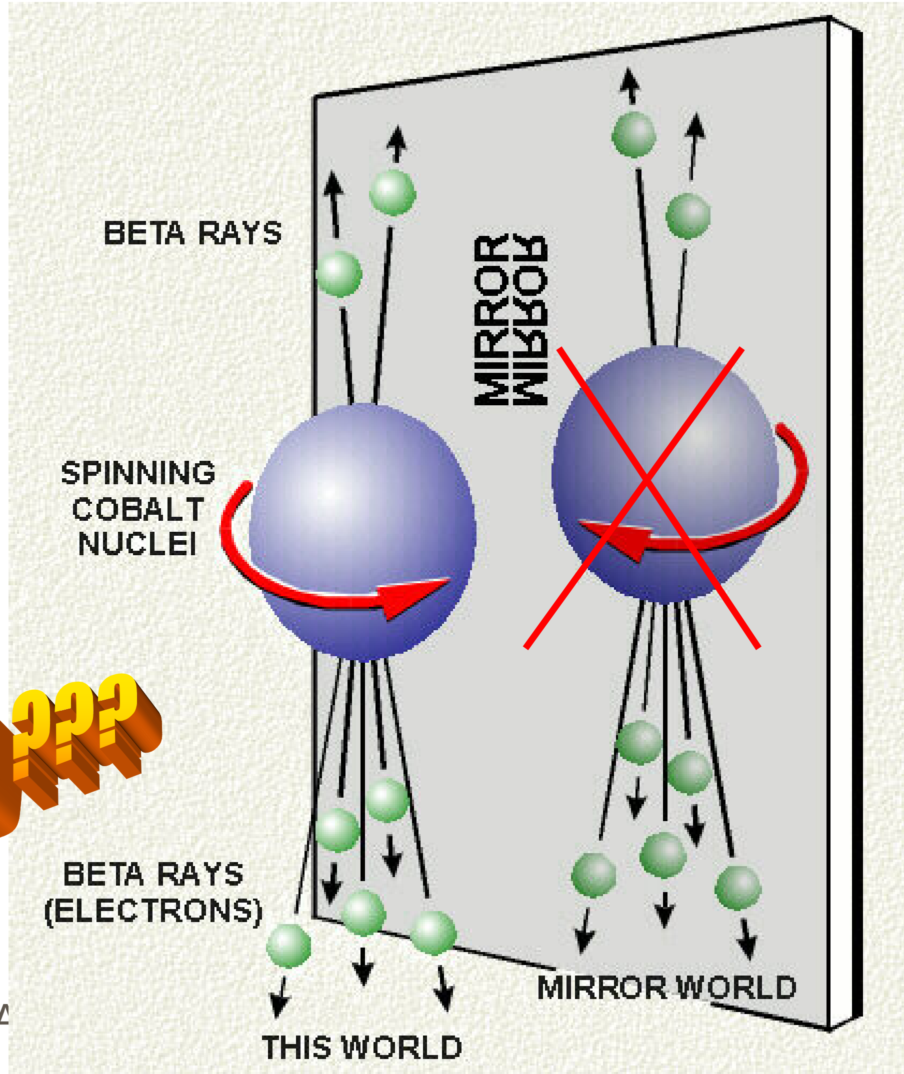


consequence:

neutrinos are always lefthanded !

(antineutrinos righthanded)

Why ???



Chen Ning Yang

(Nobel 1957)

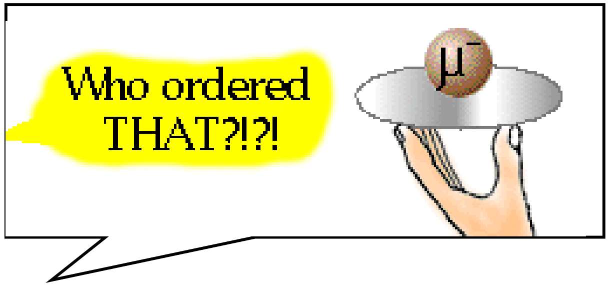
Tsung -Dao Lee

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**

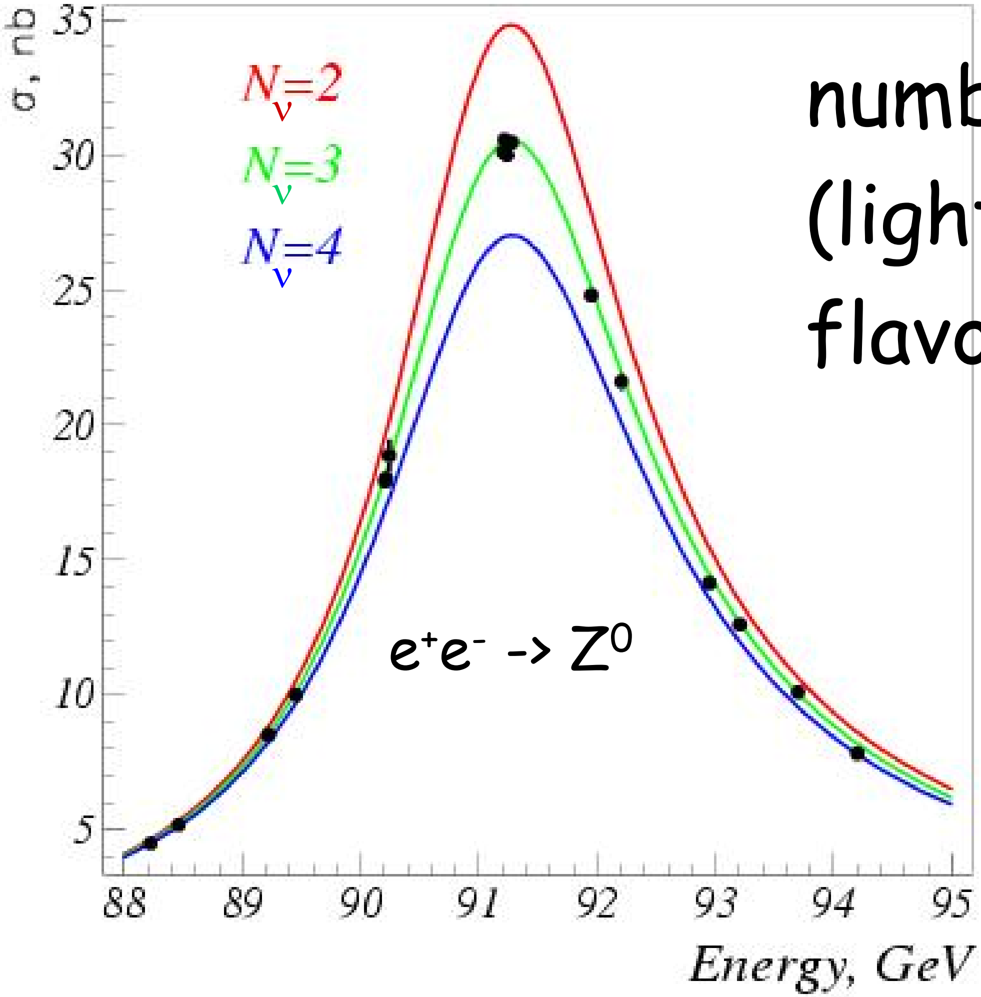
Why ???

- There is a distinct neutrino for each charged lepton

The Power of Precision

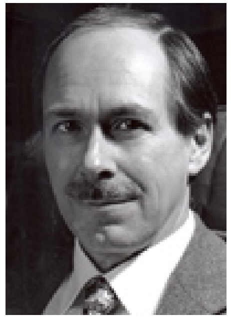
- Precision measurements of shape and height of Z^0 resonance at LEP I

(CERN 1990's)

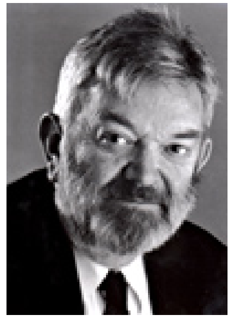


$e^+e^- \to Z^0$

number of (light) neutrino flavours = 3



Gerardus t'Hooft



Martinus Veltman

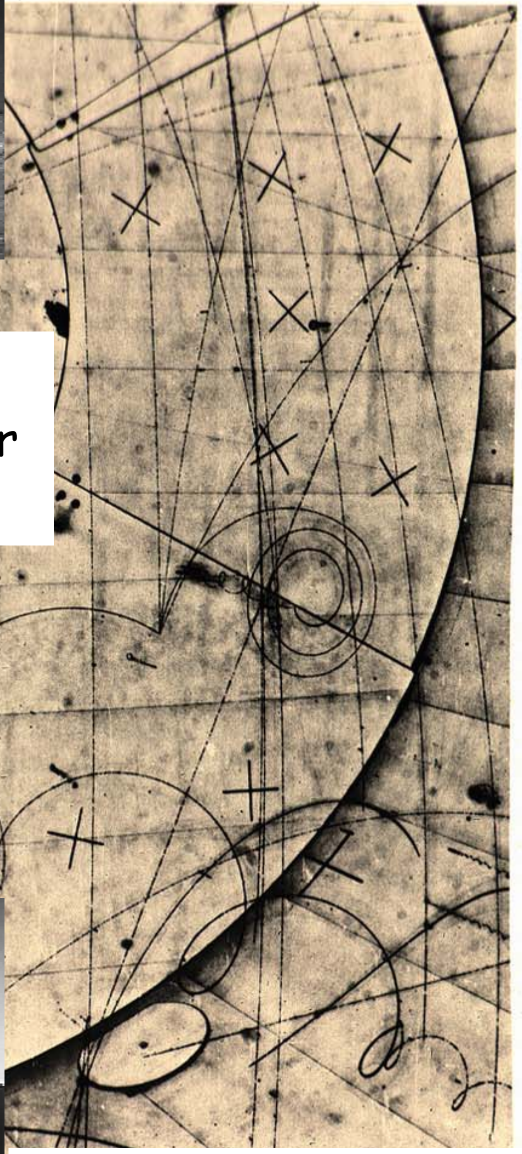
(Nobel 1999)

There seem to be exactly three lepton + quark families !

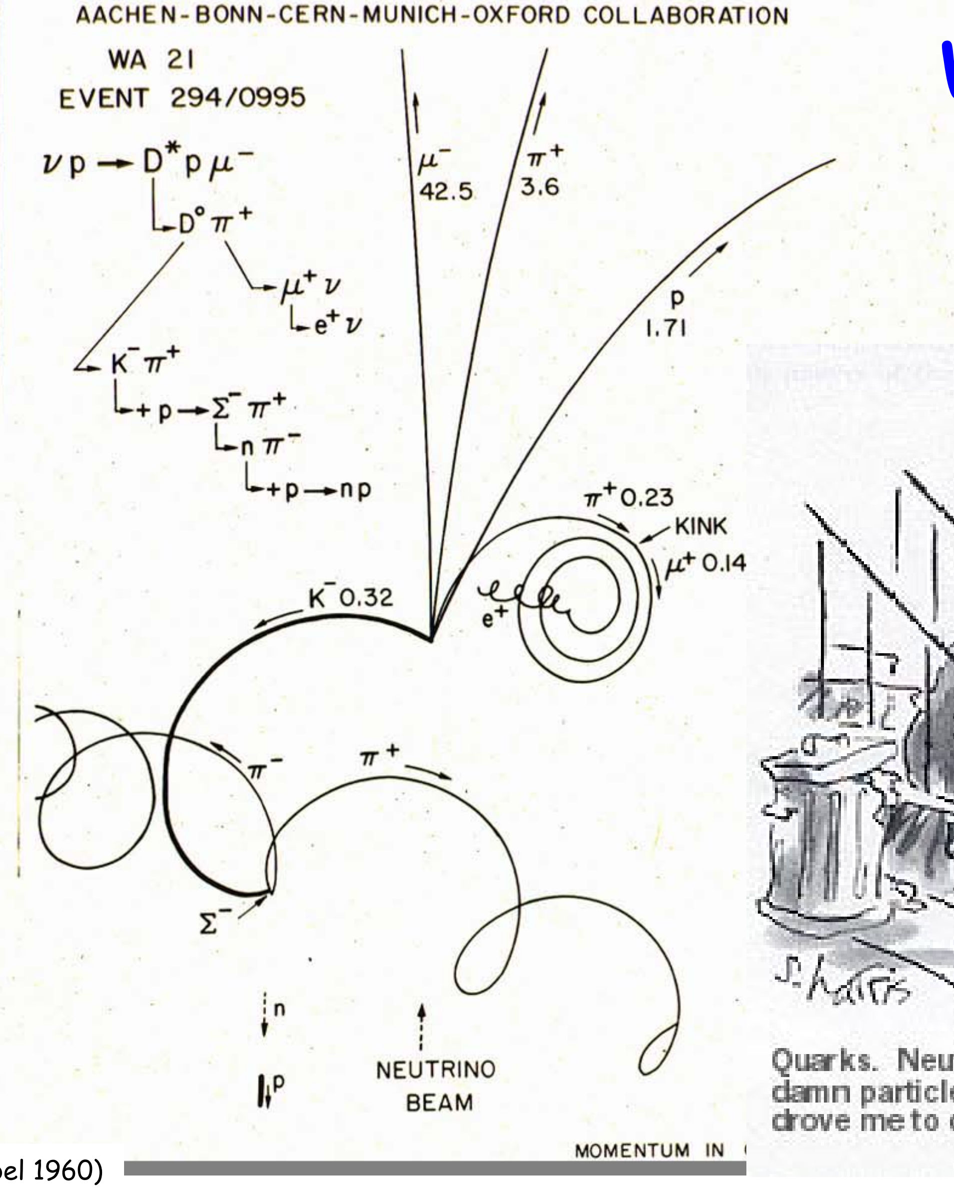
Why ???

Can we “see” particles?

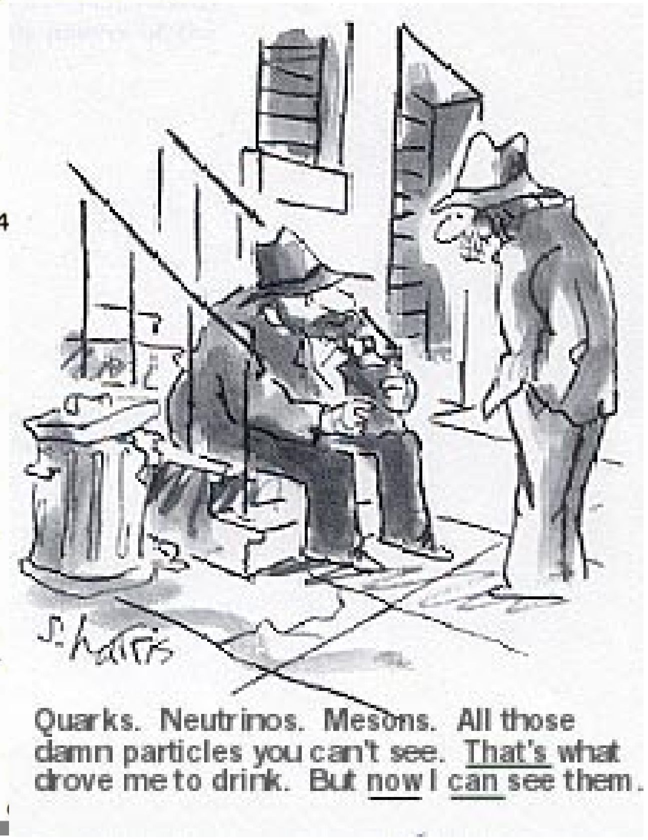
Luis Walter Alvarez (Nobel 1968)



bubble chamber photo

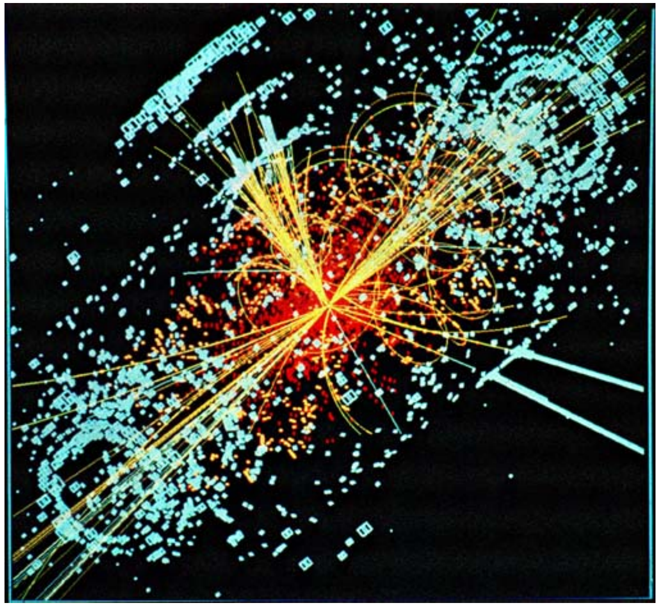


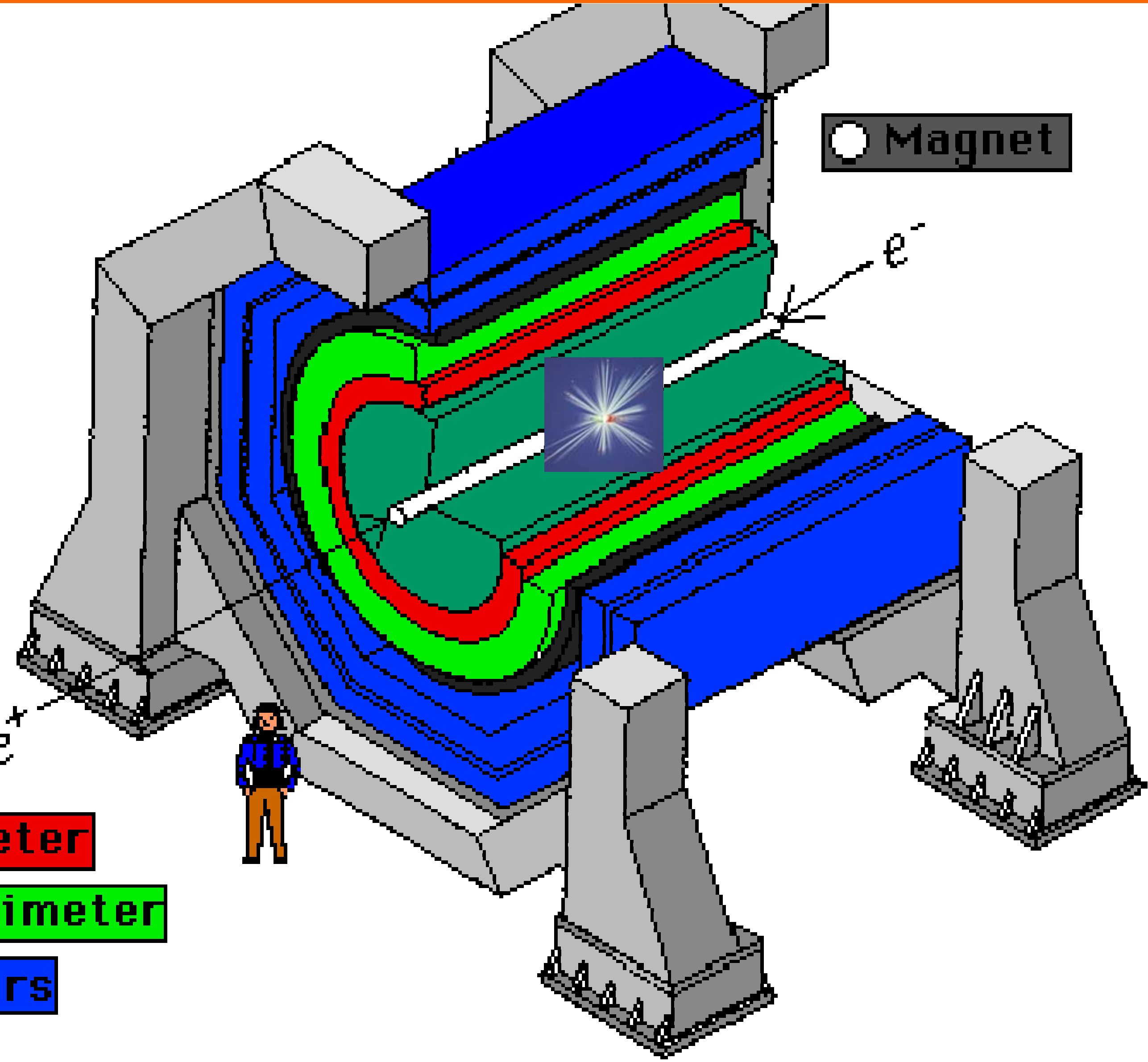
we can!



Donald Arthur Glaser (Nobel 1960)

A generic modern particle detector



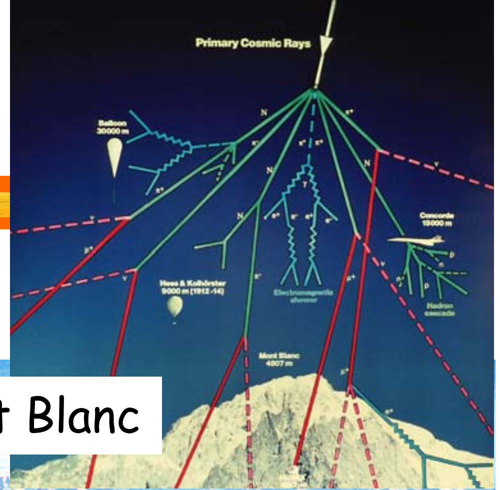


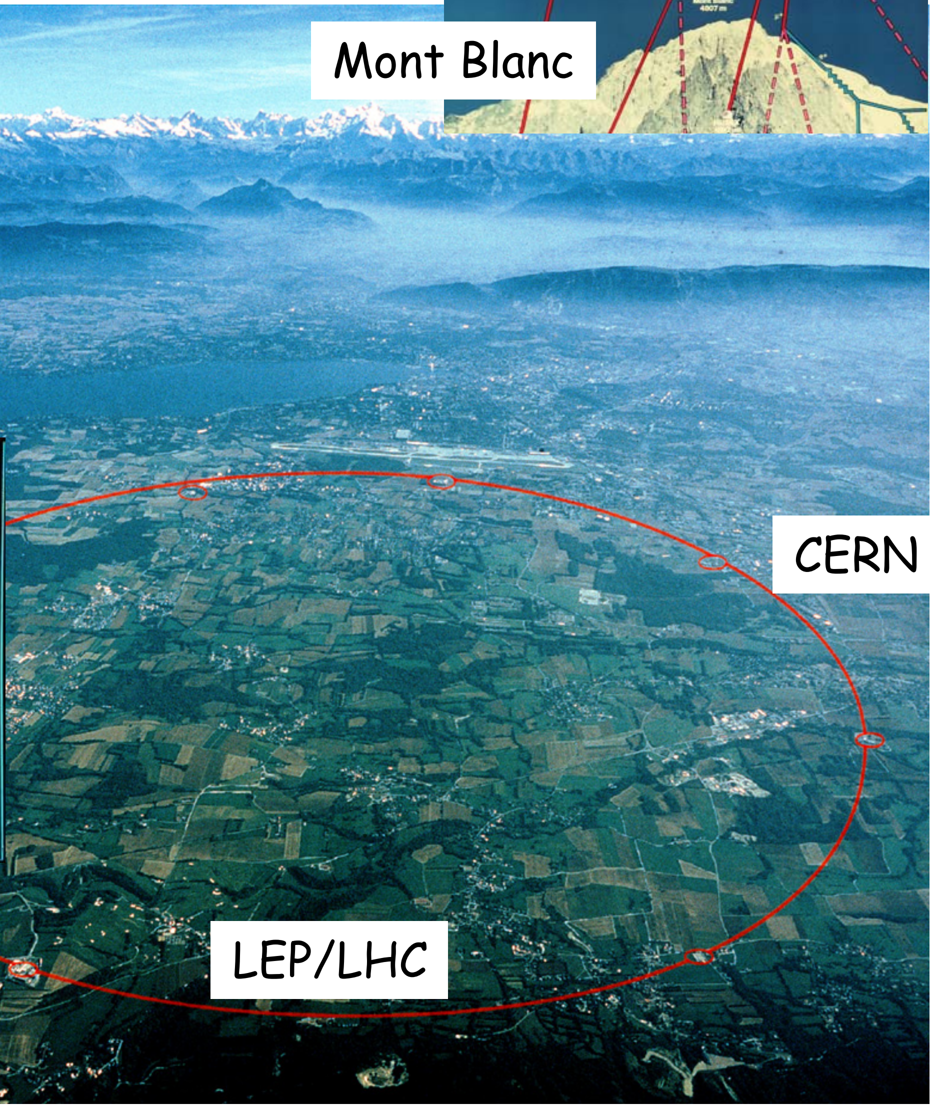
Why do we need colliders?

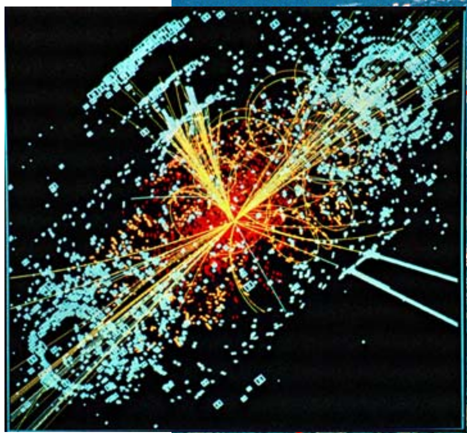
- early discoveries in cosmic rays, but
- need controlled conditions
- $$m = \frac{E}{c^2}$$

need high energy to discover new heavy particles

- colliders = microscopes (later)

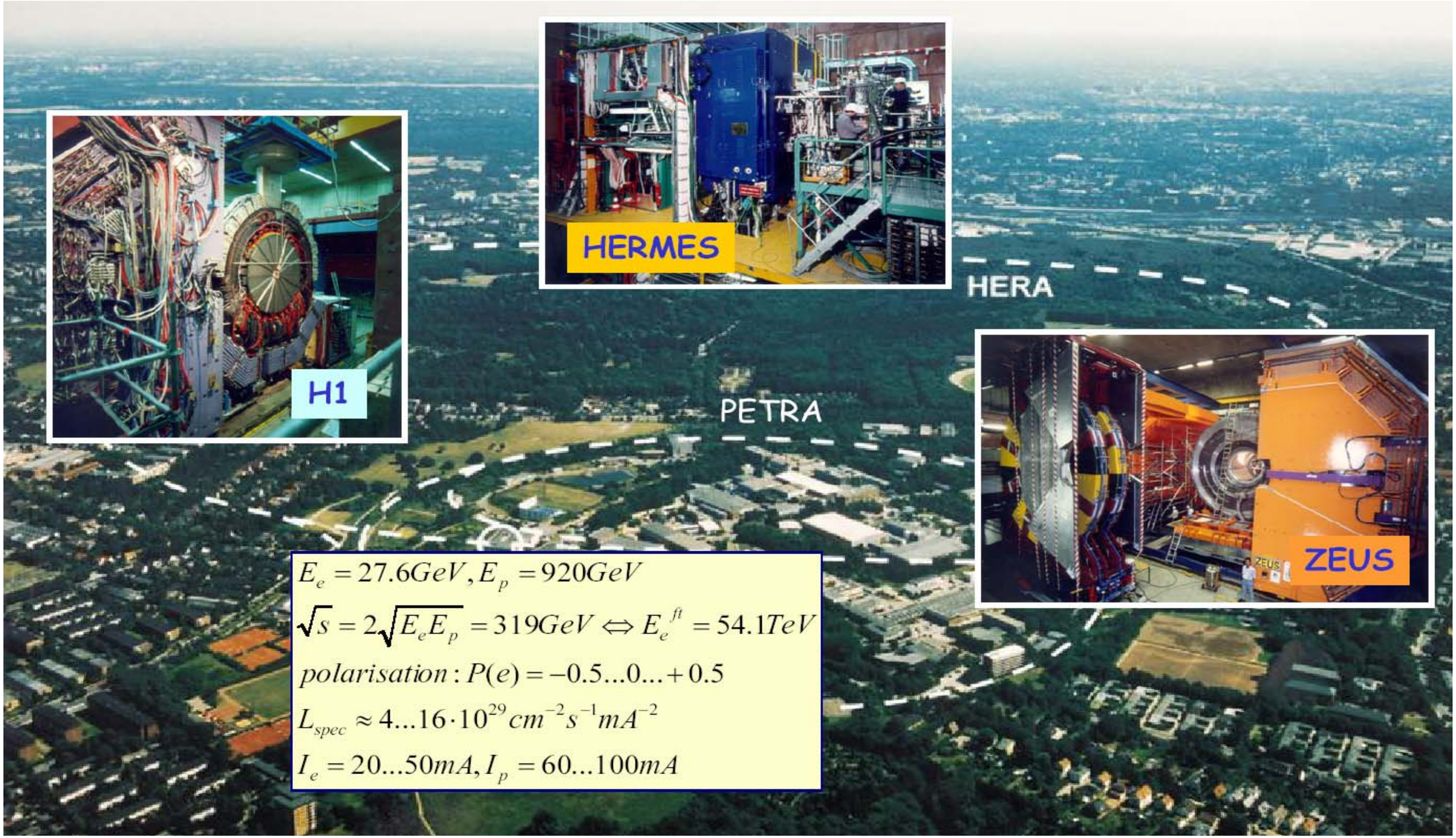






The HERA ep Collider and Experiments

Data taking stopped summer 2007.   Data analysis ongoing.   Visits this Thursday/Friday.



$E_e = 27.6 GeV, E_p = 920 GeV$

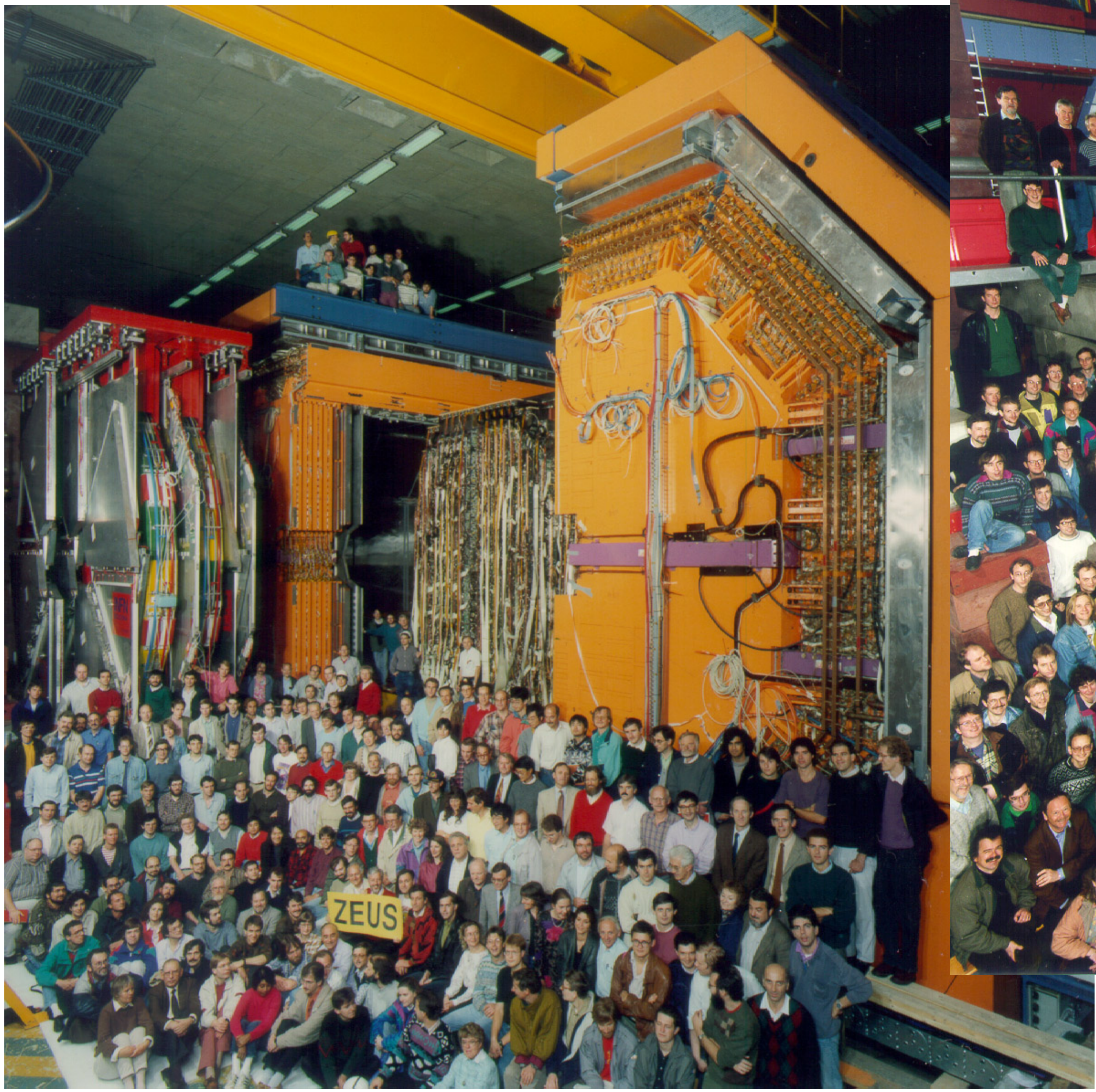
$\sqrt{s} = 2\sqrt{E_e E_p} = 319 GeV \Leftrightarrow E_e^{ft} = 54.1 TeV$

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

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

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

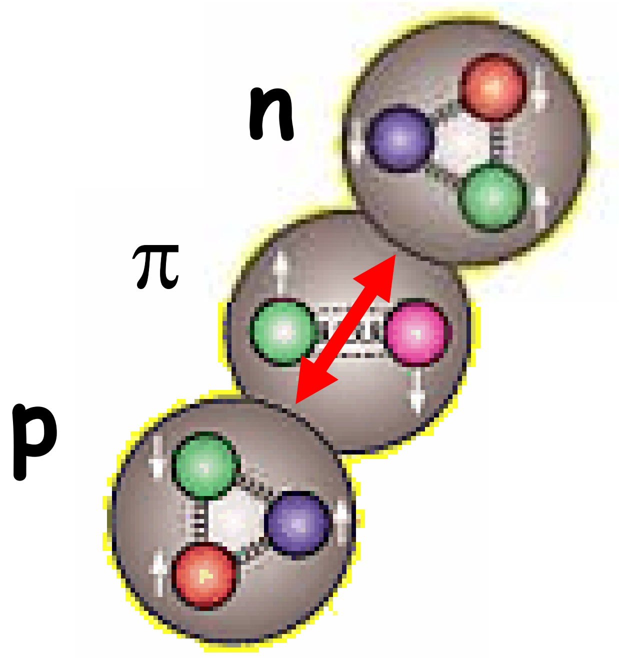
Particle Physics = People



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:

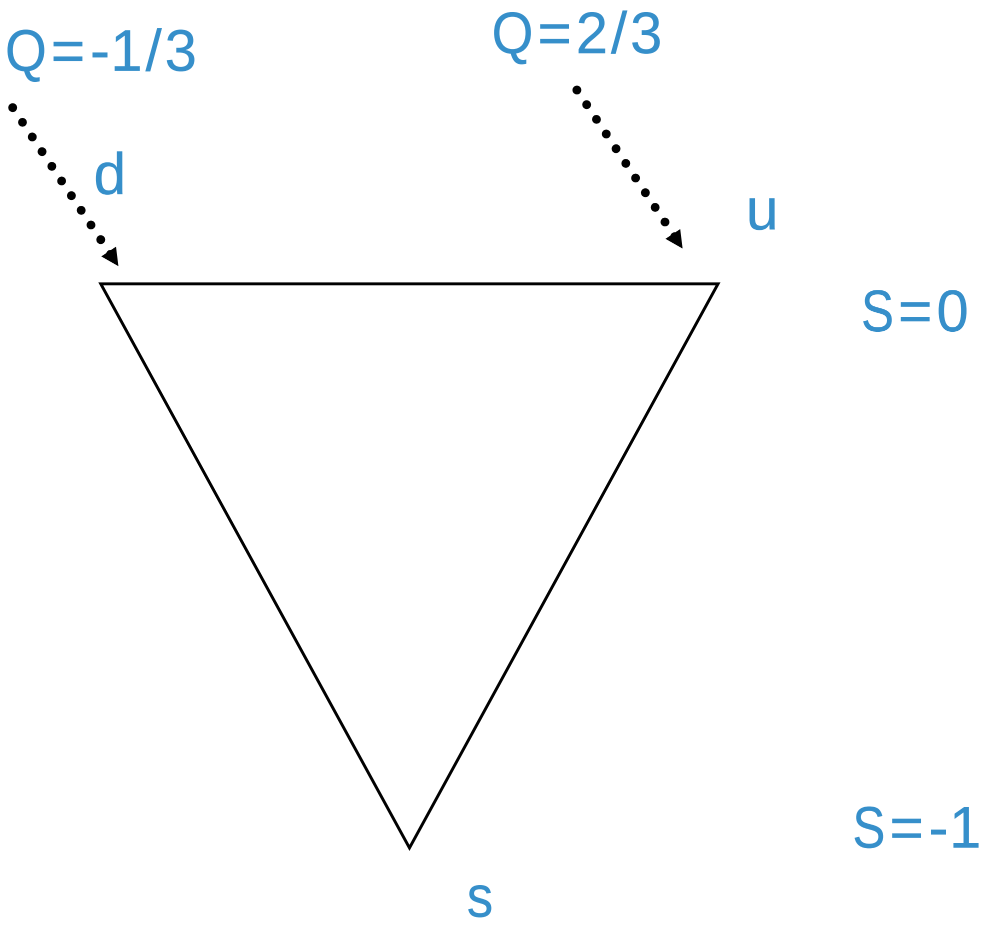
(Quantum Chromo-Dynamics, QCD)
exchange of massless gluons
between quark
constituents

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

The Quark Model (1964)

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

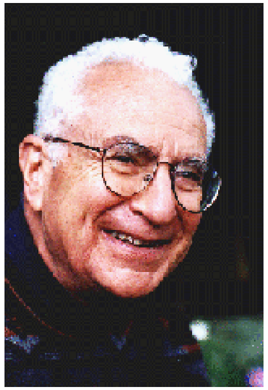
=> $SU(3)_{flavour}$ symmetry



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

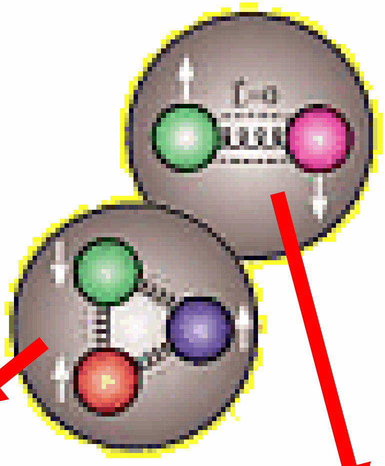
Murray Gell-Mann

(Nobel 1969)

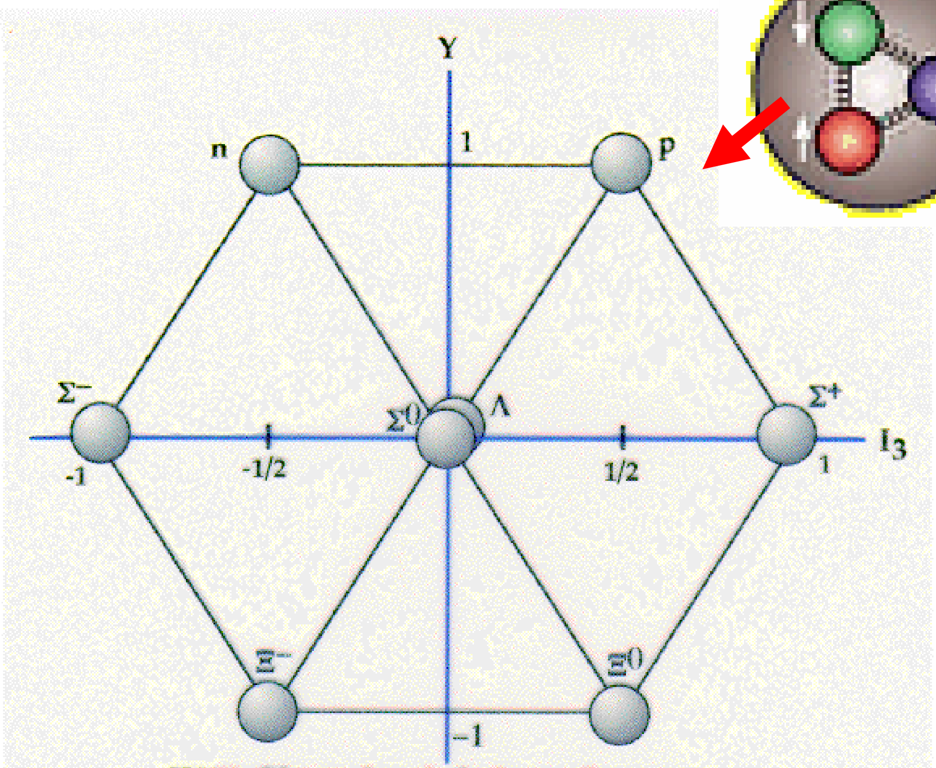


The Quark Model

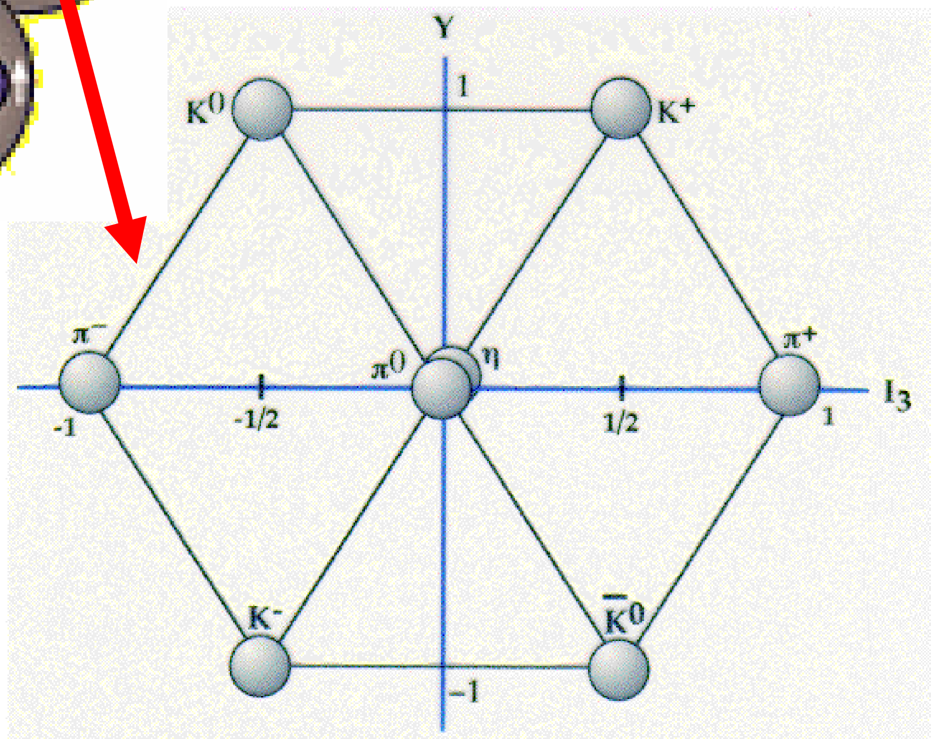
baryons = qqq



mesons = $q\bar{q}$



SU(3)-Oktett der einfachsten Baryonen

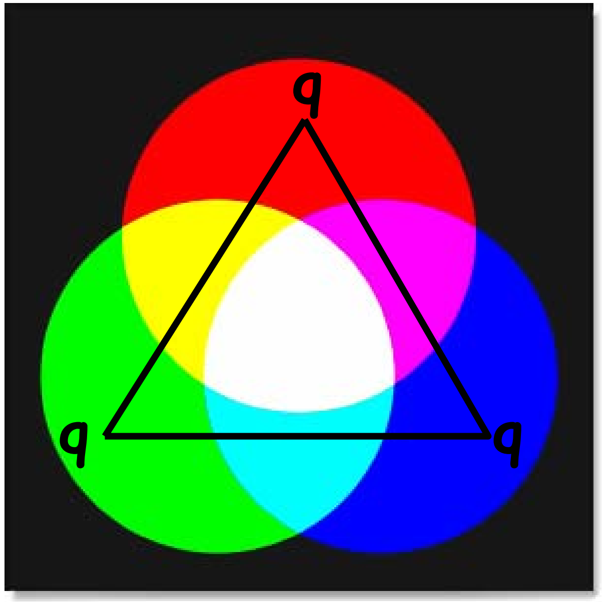


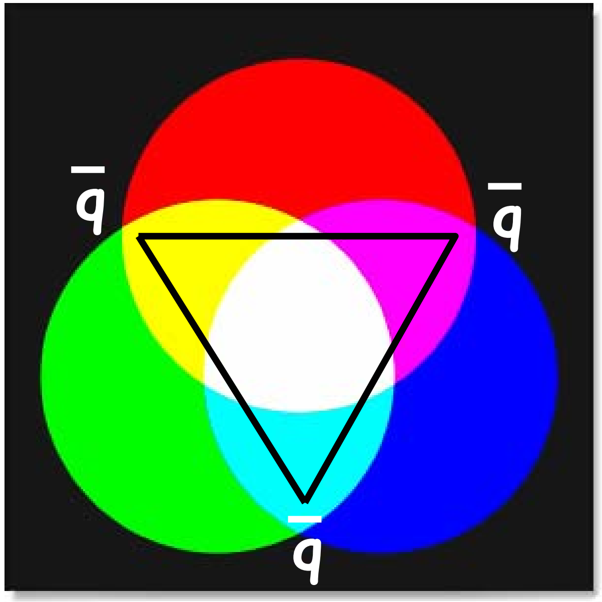
SU(3)-Oktett der einfachsten Mesonen

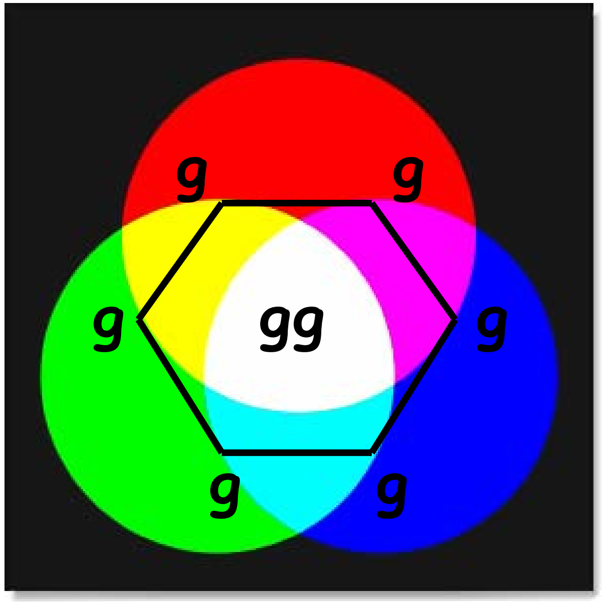
Colour

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**

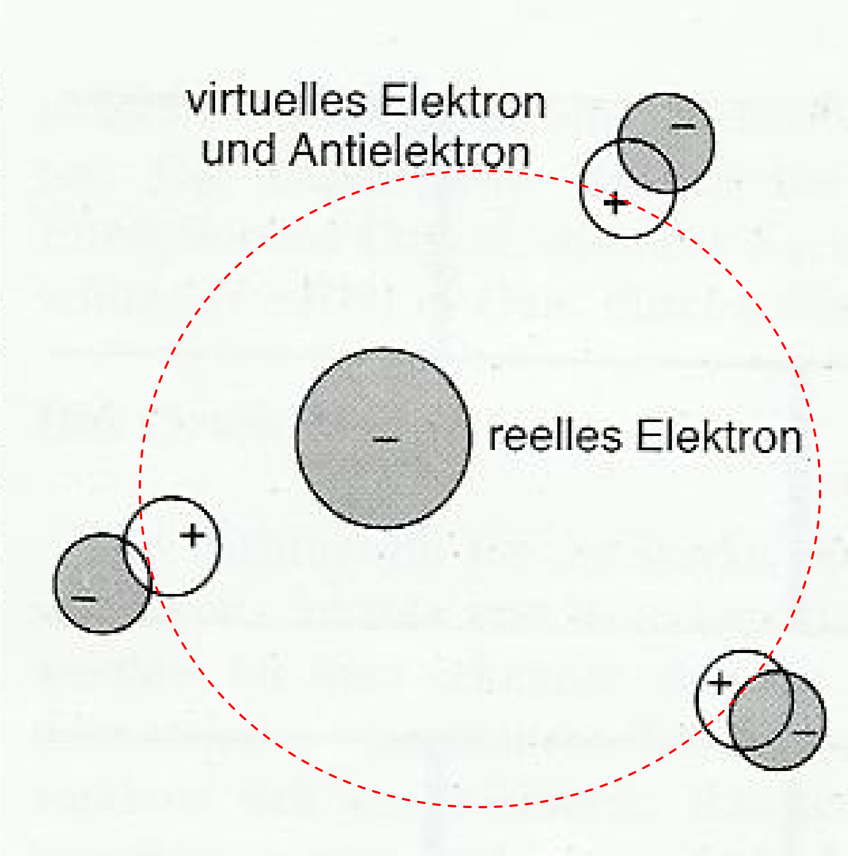






- 3 coulours -> $SU(3)_{colour}$ $qqq = q\bar{q}$ = white!

Screening of Electric Charge



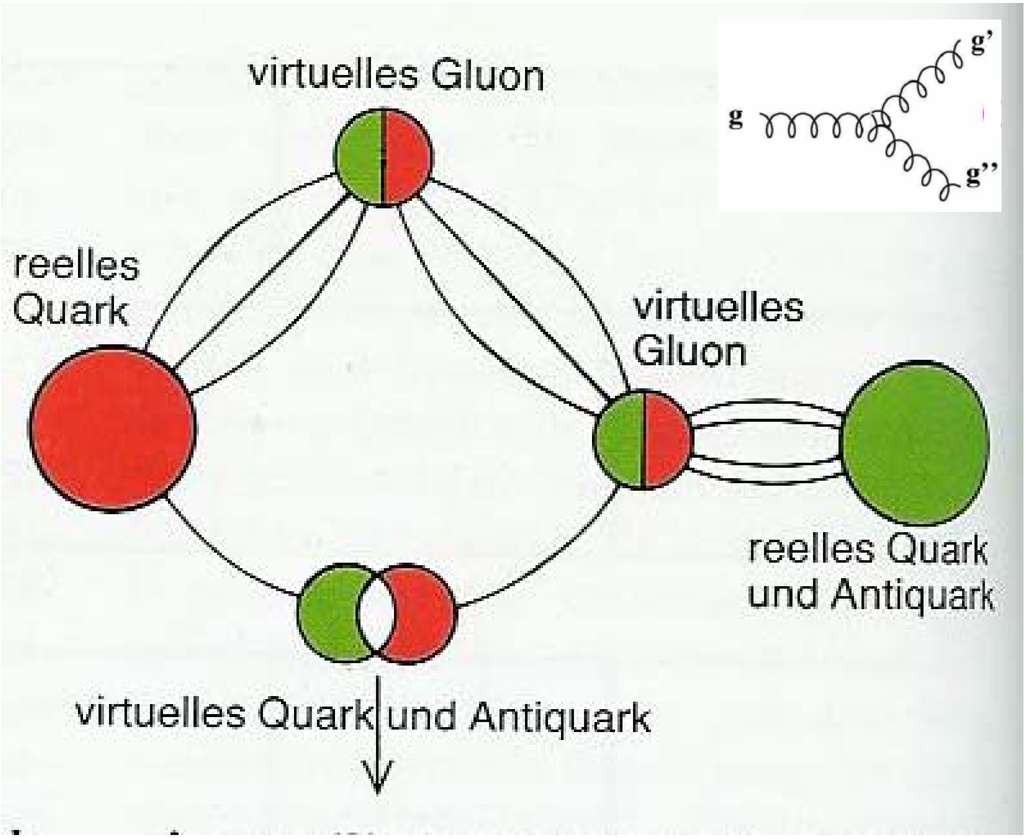
(Nobel 1965)

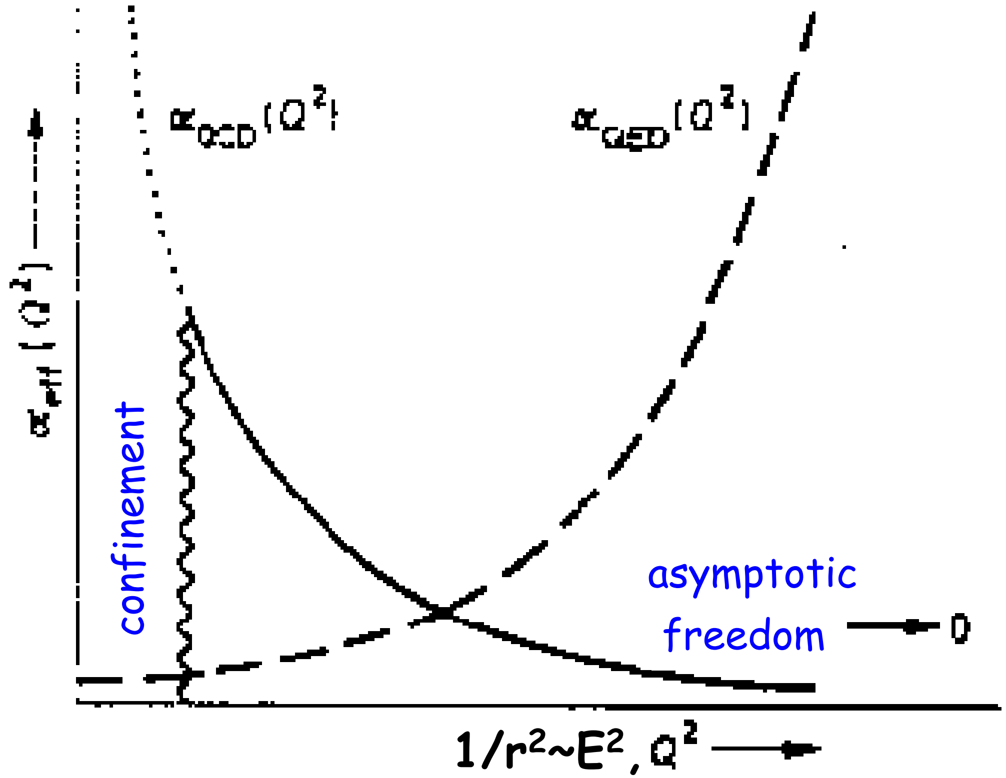
Sin-Itoro Tomonaga   Julian Schwinger   Richard P. Feynman

- 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!

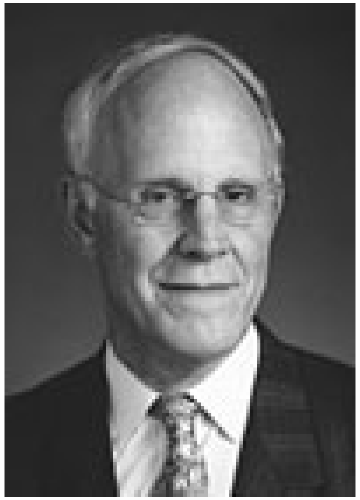
- quark-antiquark pairs -> screening
- gluons carry colour -> gg pairs -> anti-screening!





The Nobel Prize in Physics 2004

"for the discovery of asymptotic freedom in the theory of the strong interaction"



David J. Gross

1/3 of the prize

USA

Kavli Institute for Theoretical Physics, University of California
Santa Barbara, CA, USA

b. 1941

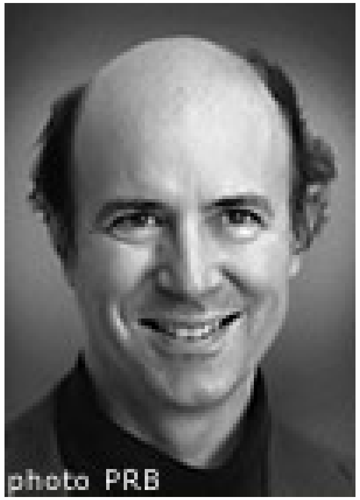
H. David Politzer

1/3 of the prize

USA

California Institute of Technology (Caltech)
Pasadena, CA, USA

b. 1949



Frank Wilczek

1/3 of the prize

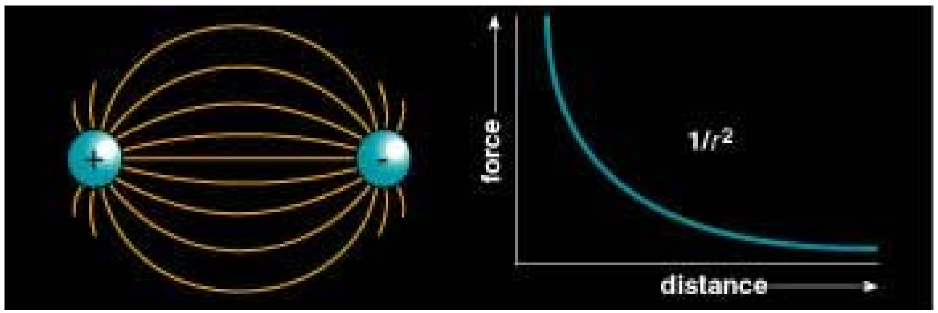
USA

Massachusetts Institute of Technology (MIT)
Cambridge, MA, USA

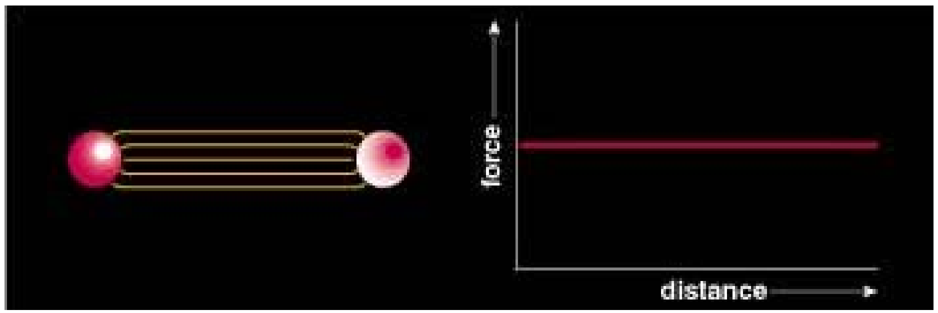
b. 1951

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$\underline{g}$, b$\underline{b}$, g$\underline{b}$)
α is nearly constant	α_s strongly depends on distance

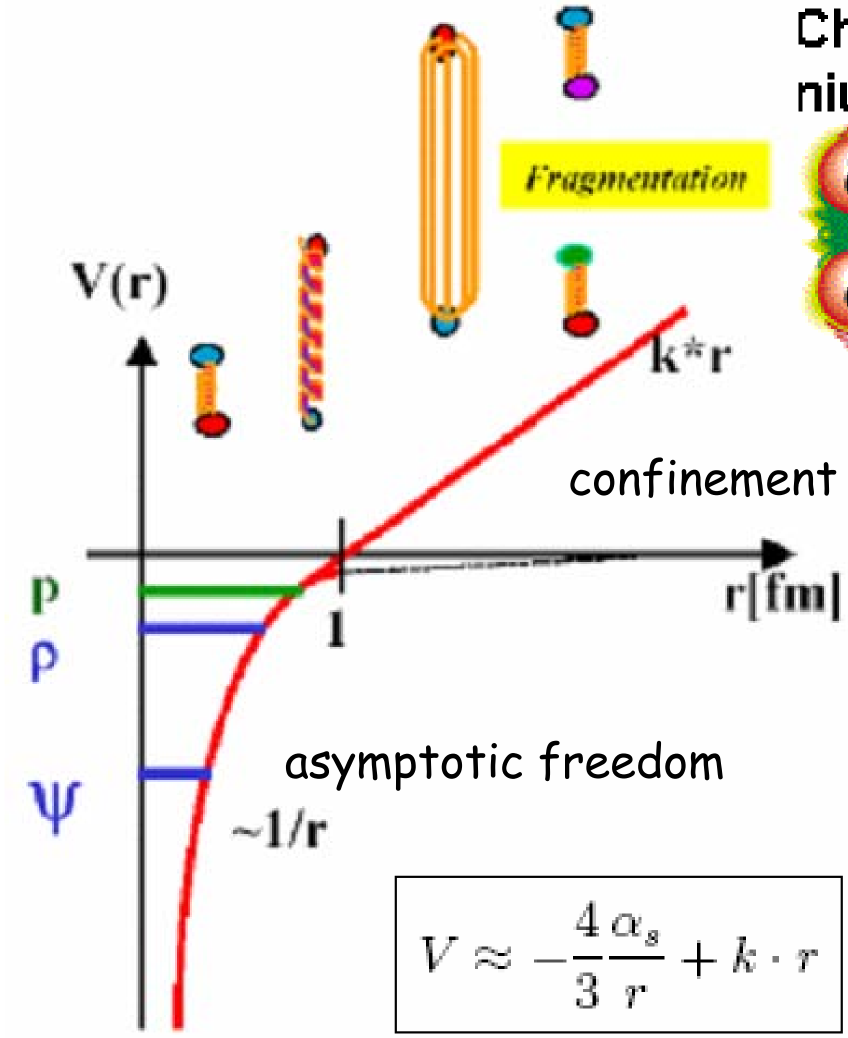


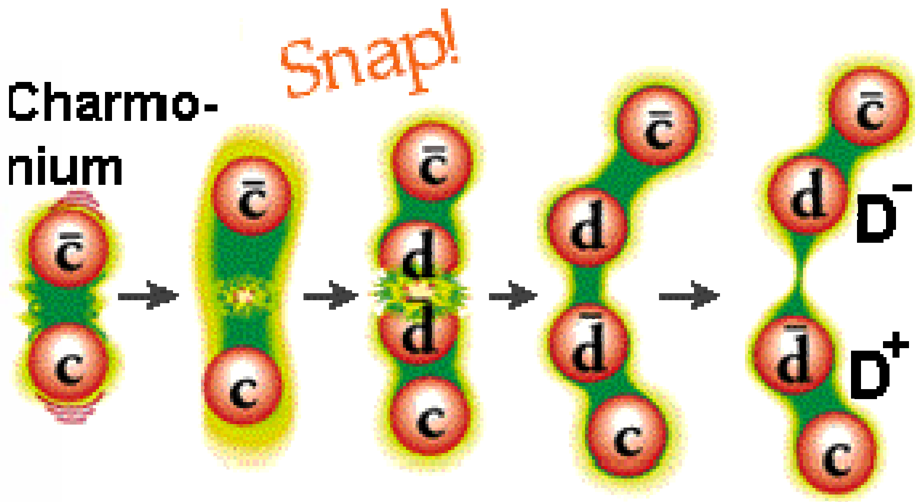
confinement limit:



- The underlying theories are formally almost identical!

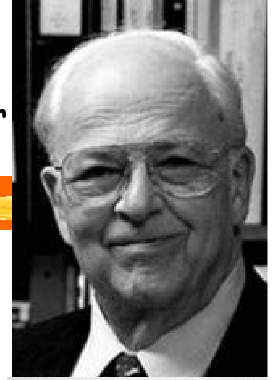
The effective potential for $q\bar{q}$ interactions





Heavy Quark Spectroscopy

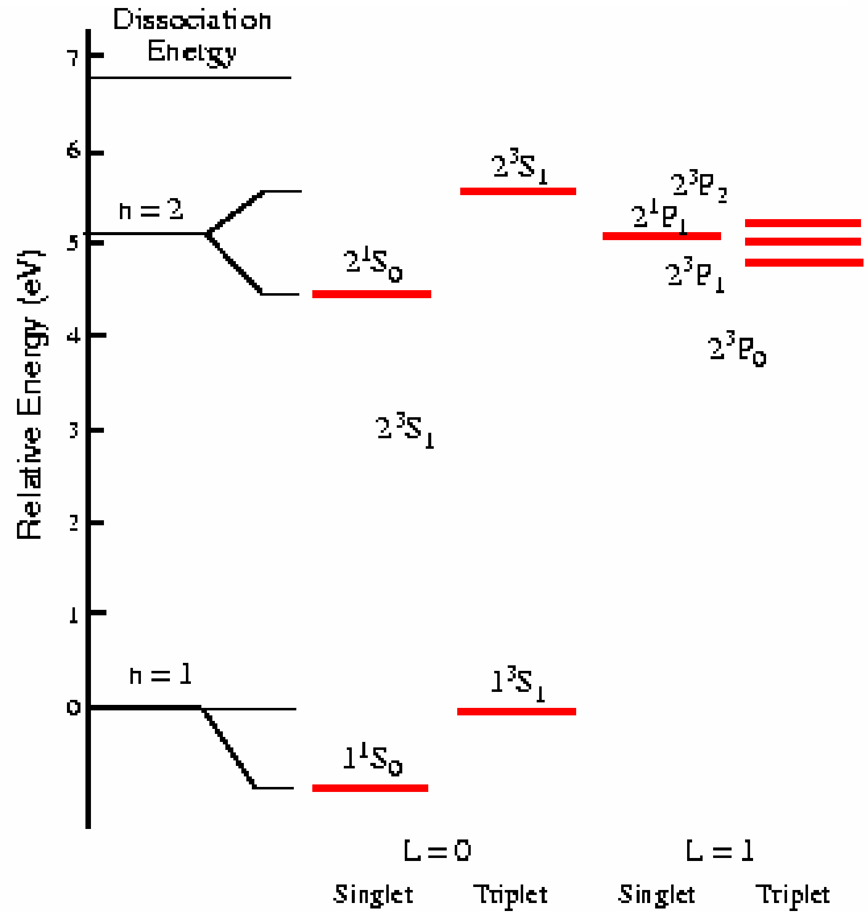
Burton Richter



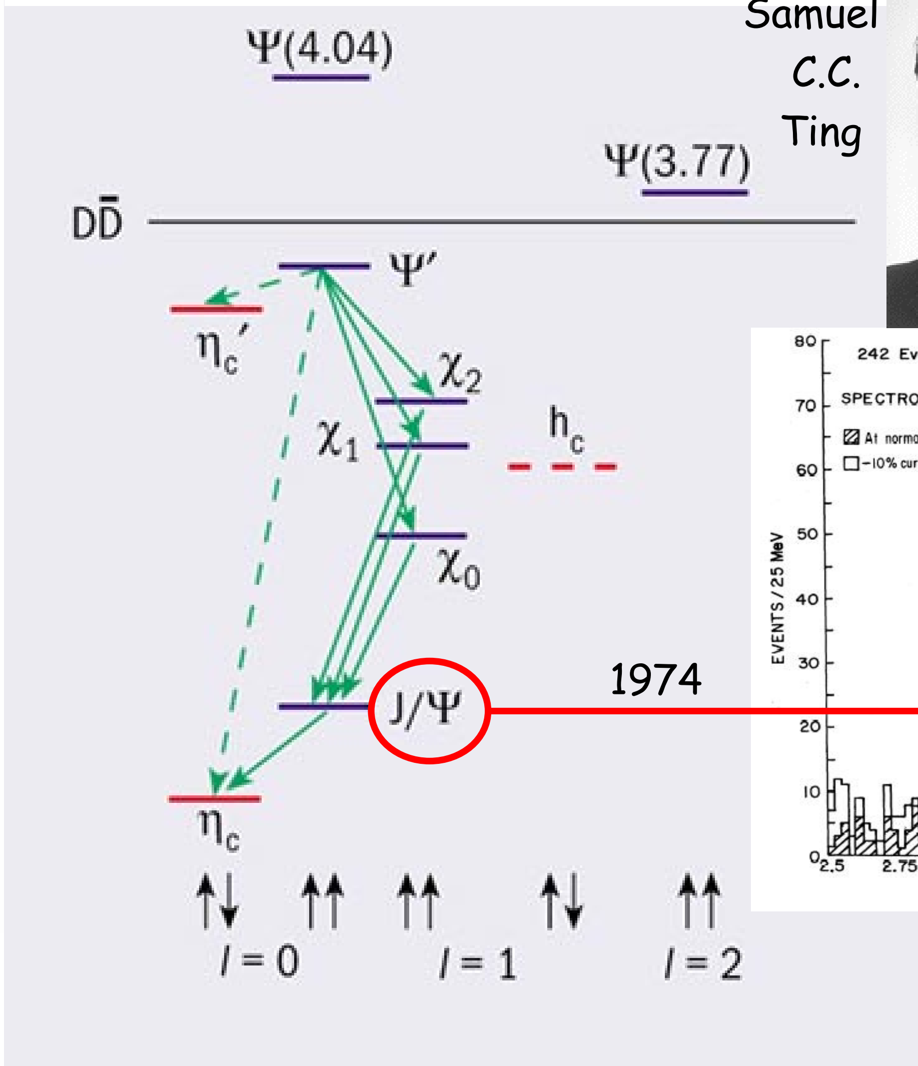
(Nobel 1976)

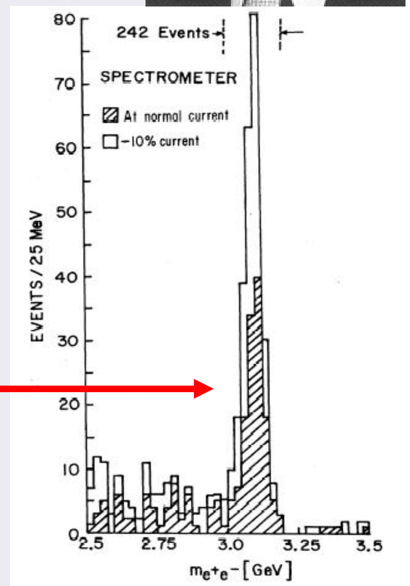
Samuel C.C. Ting

Positronium = bound e^+e^- system



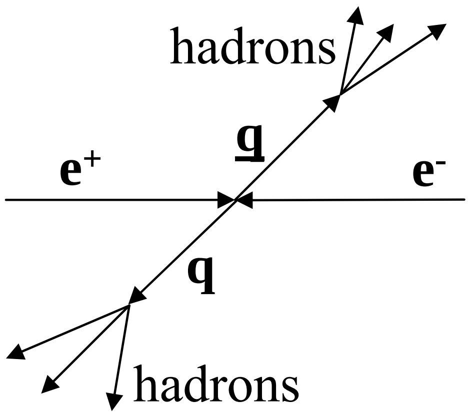
Charmonium = bound system of $c\bar{c}$ quark pair



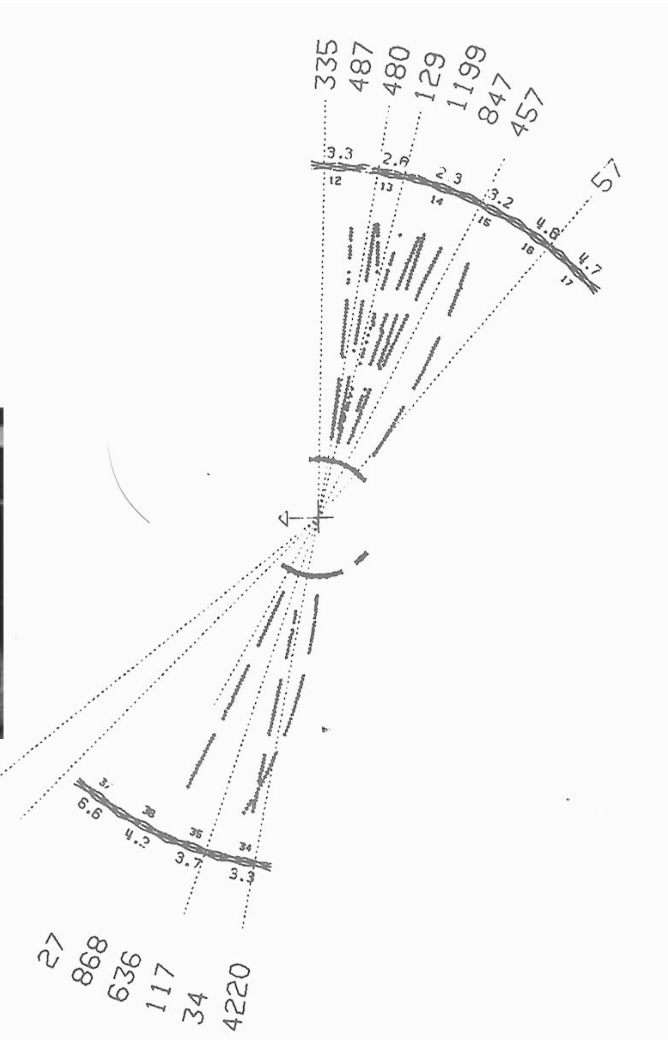


How to detect Quarks and Gluons?

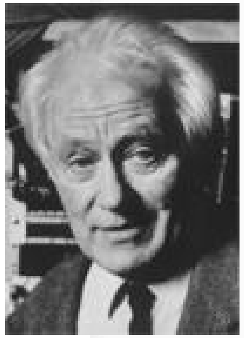
Jets!



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



Georges Charpak

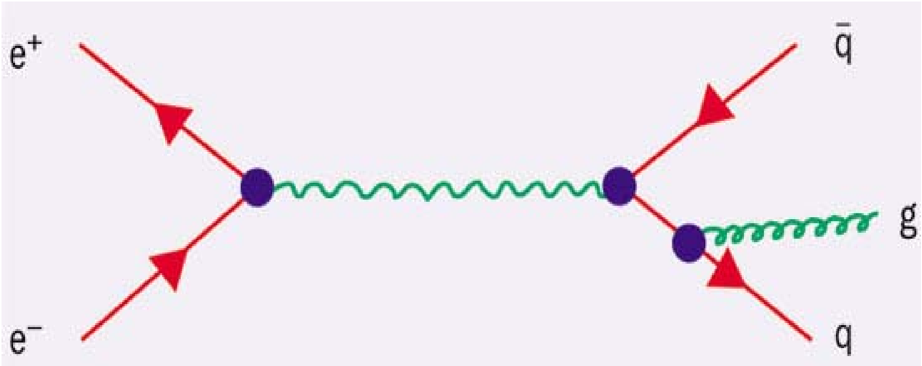


(Nobel 1992)

- 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.

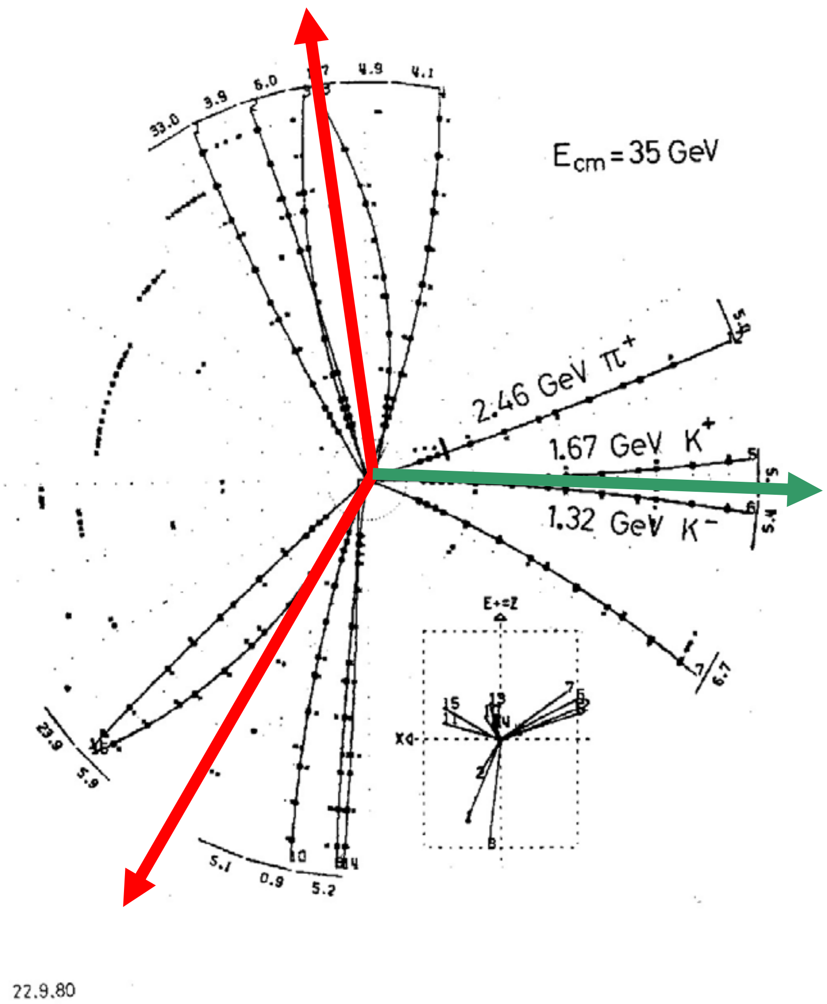
Discovery of the Gluon (1979)

PETRA at DESY: look for



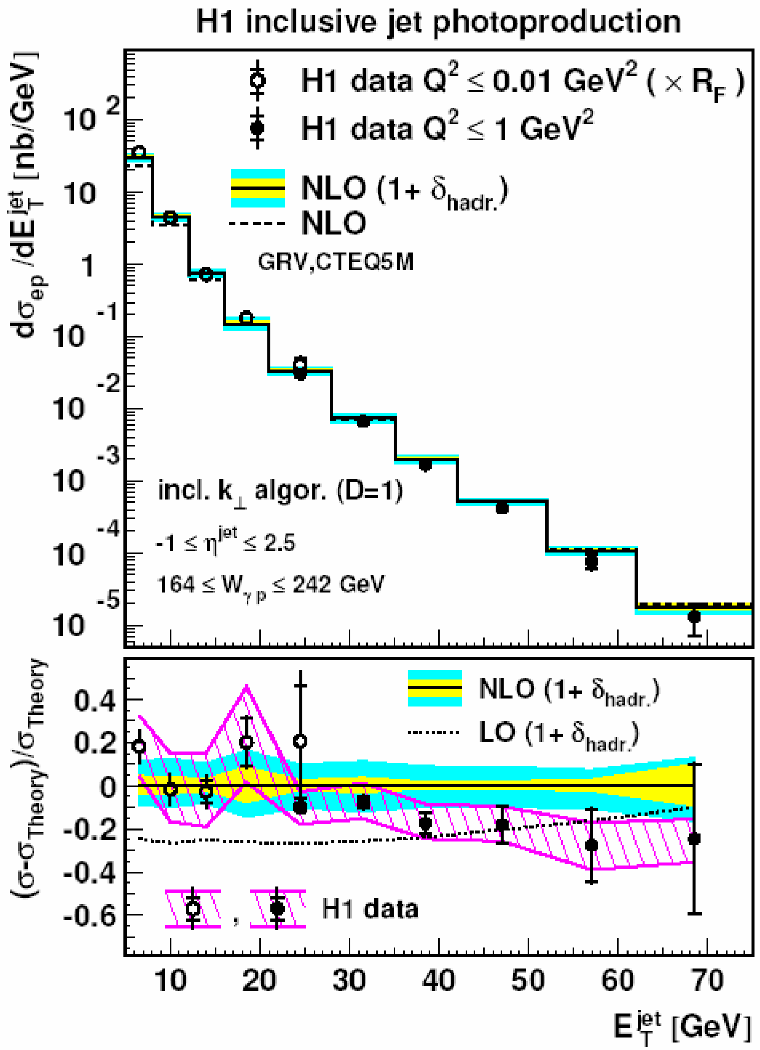
Björn Wiik Paul Söding

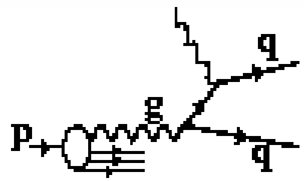
Günter Wolf Sau Lan Wu

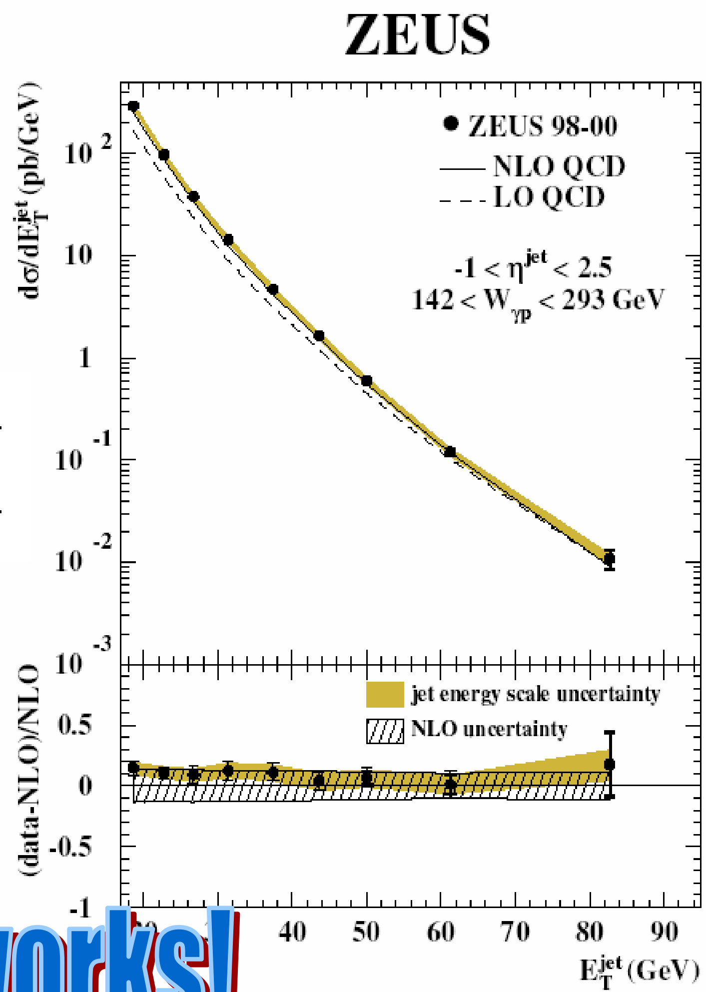


TASSO event picture

Jets in ep interactions (HERA)





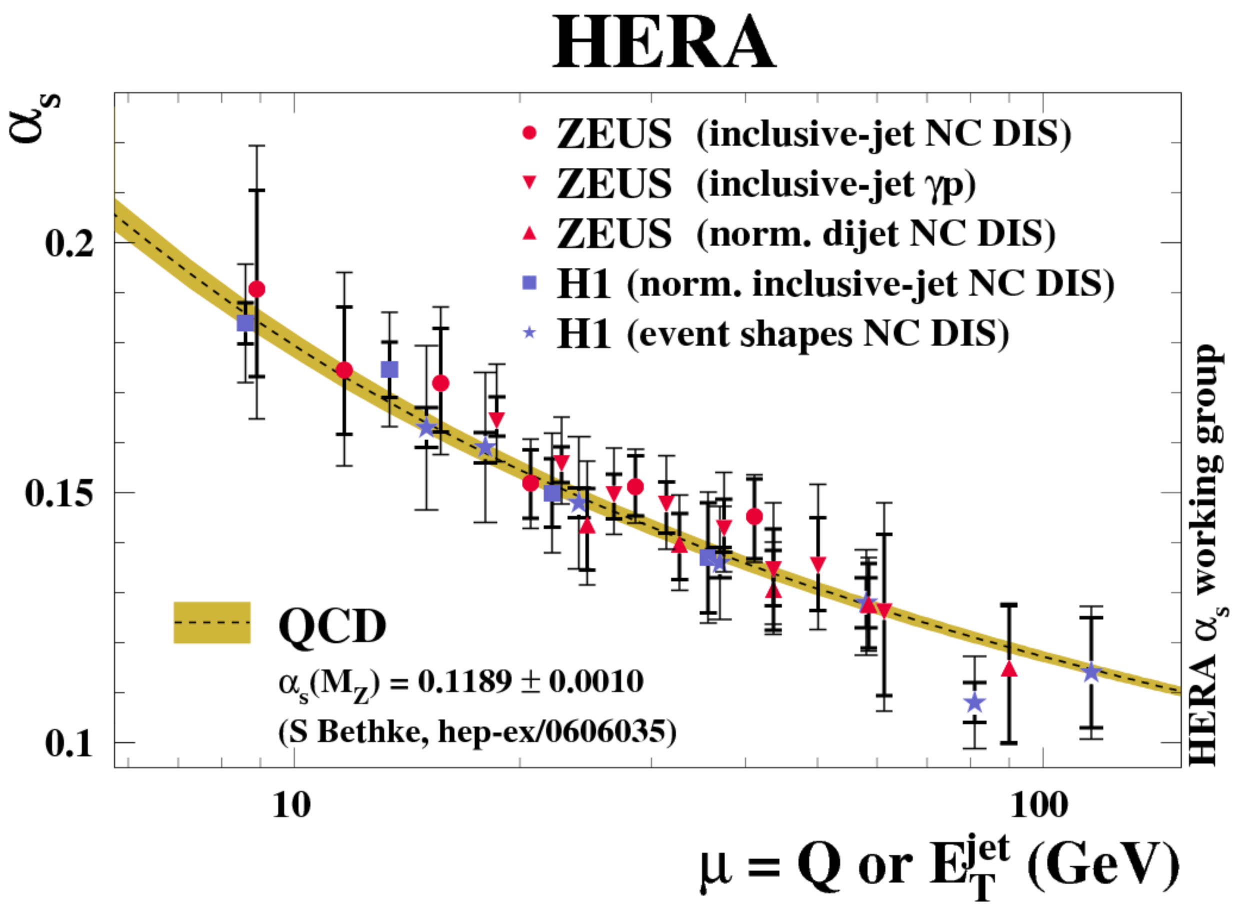


QCD works!

Good agreement with NLO over six orders of magnitude, dominant uncertainty due to theory

Running coupling α_s from jet production

HERA

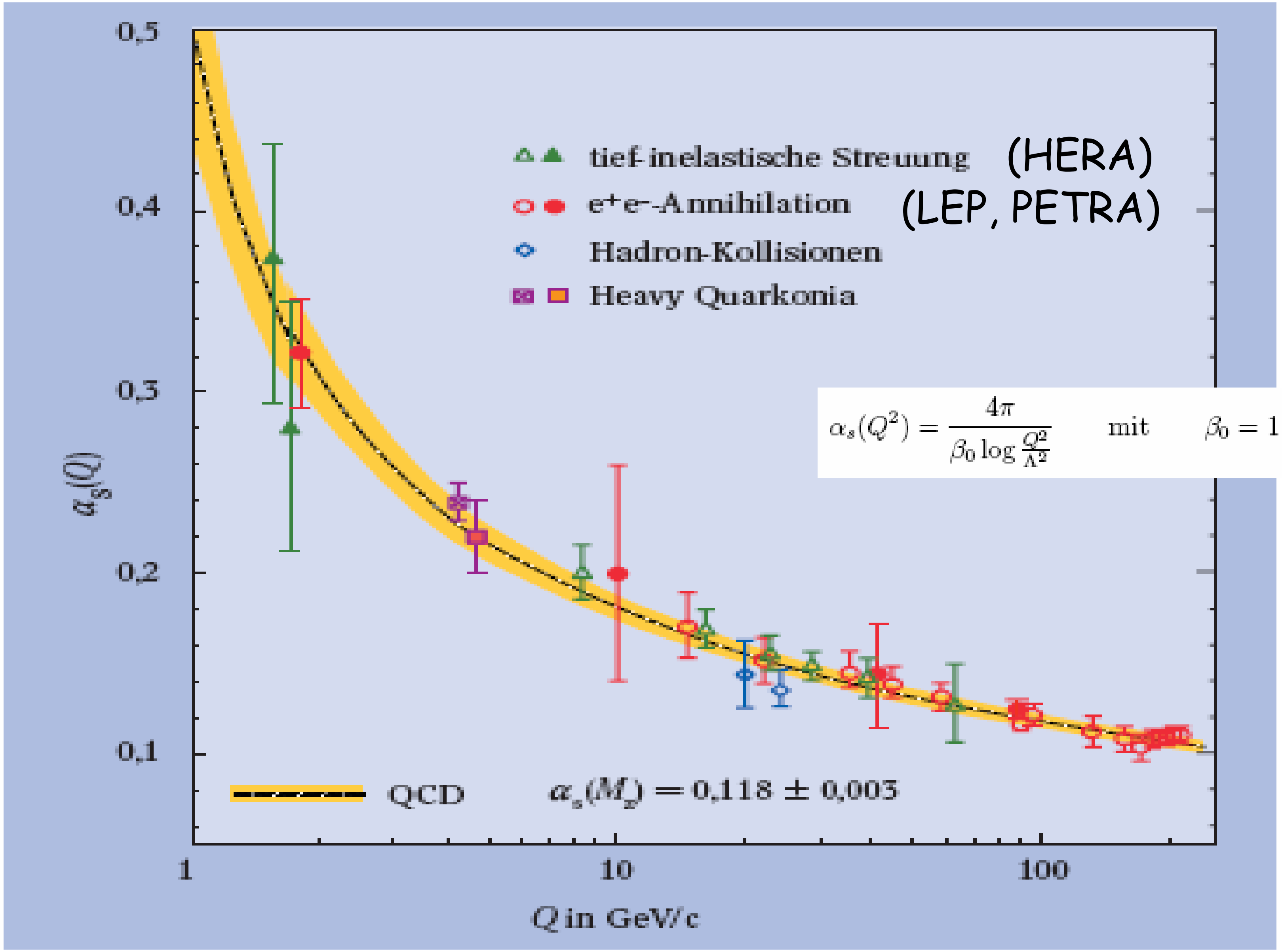


(E,Q ~ 1/r)

Good agreement with expected running of α_S

Consistent and competitive measurement of α_S between HERA and LEP

Running coupling α_s from other measurements



$$\alpha_s(Q^2) = \frac{4\pi}{\beta_0 \log \frac{Q^2}{\Lambda^2}} \quad \text{mit} \quad \beta_0 = 11 - \frac{2}{3} n_f$$

HERA = currently best place to study QCD!

How to determine the „size“ of a particle?

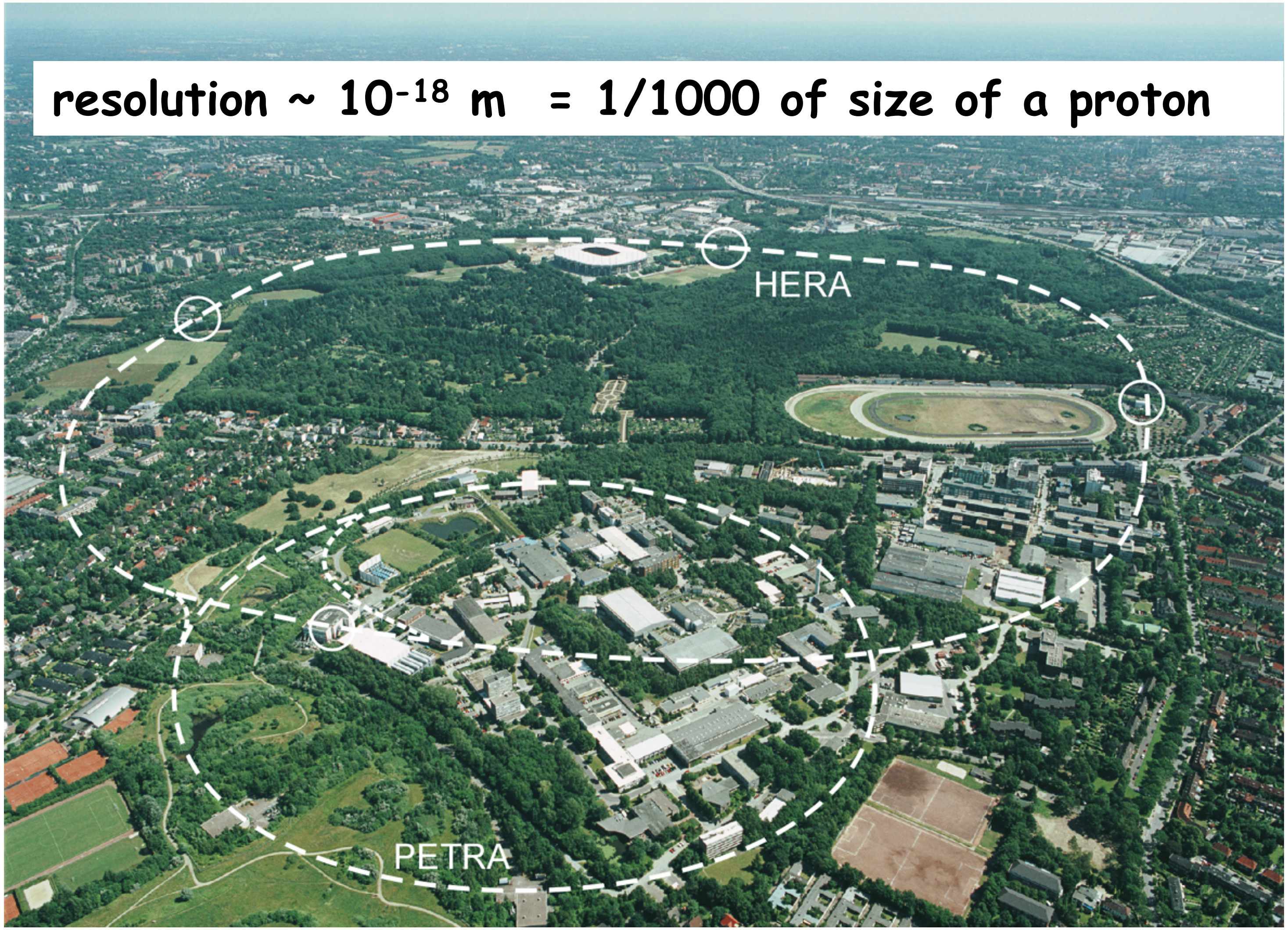
microscope:

low resolution

-> small instrument

high resolution

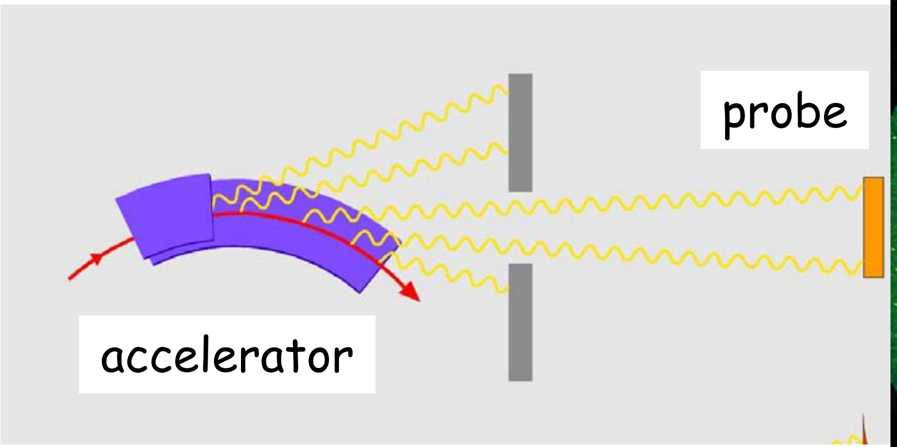
-> large instrument

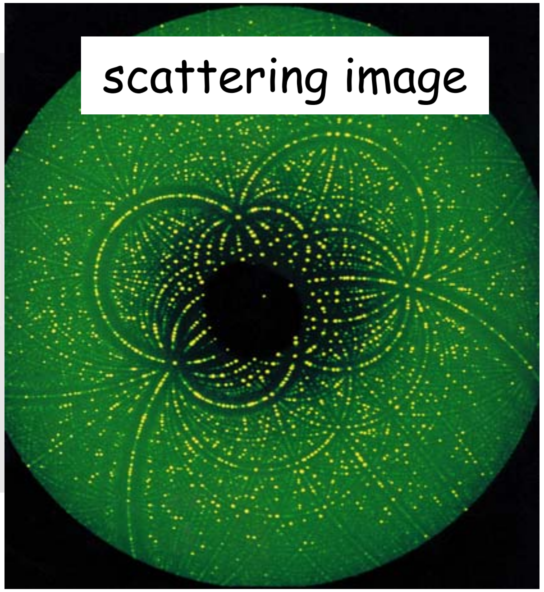


HERA = giant electron microscope

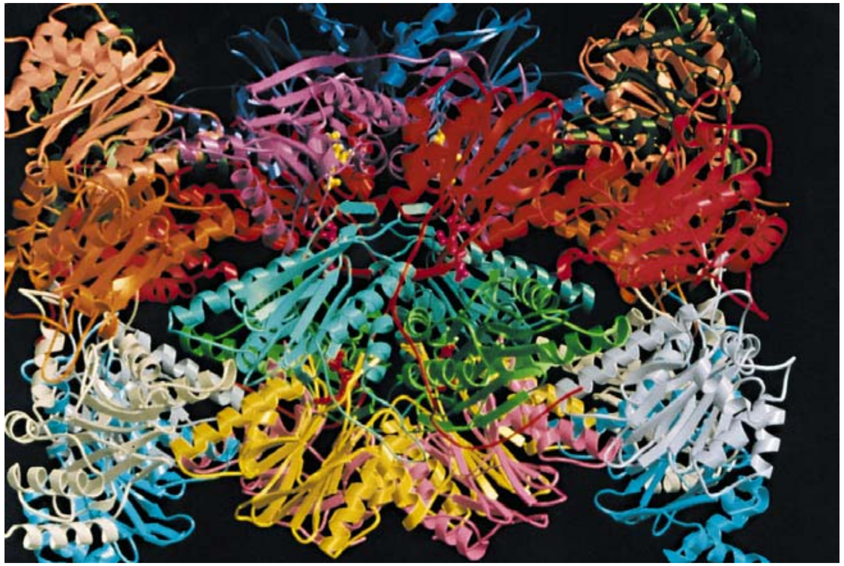
How to resolve the structure of an object?

e.g. X-rays
(Hasylab,
FLASH)
E~ keV



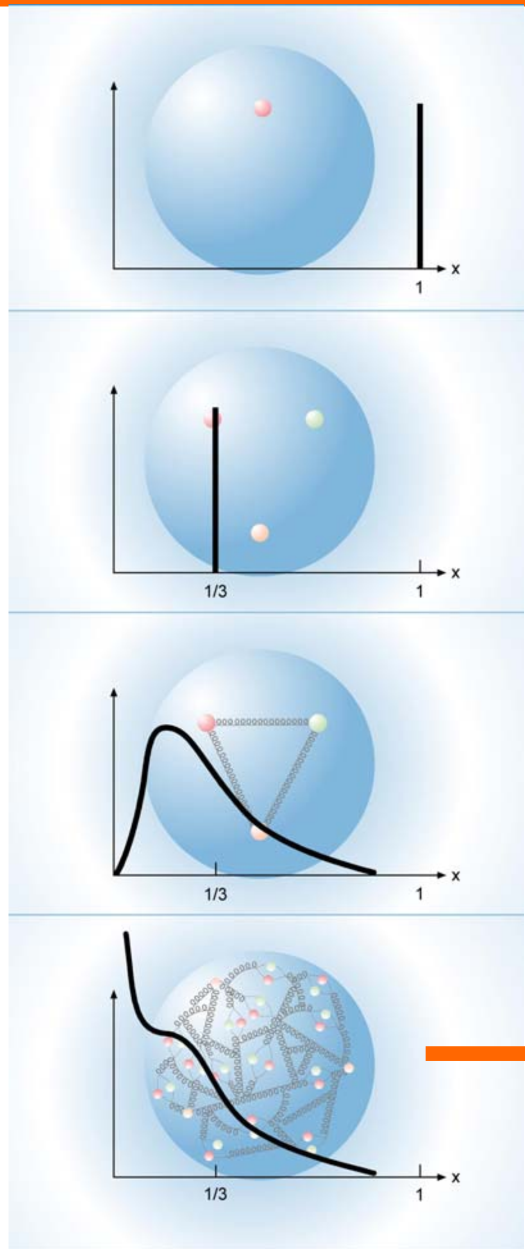


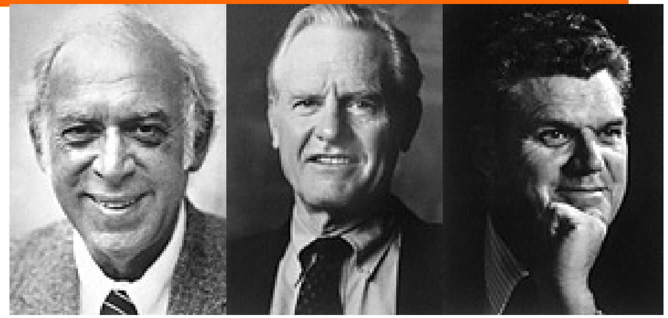
-> structure of
a biomolecule



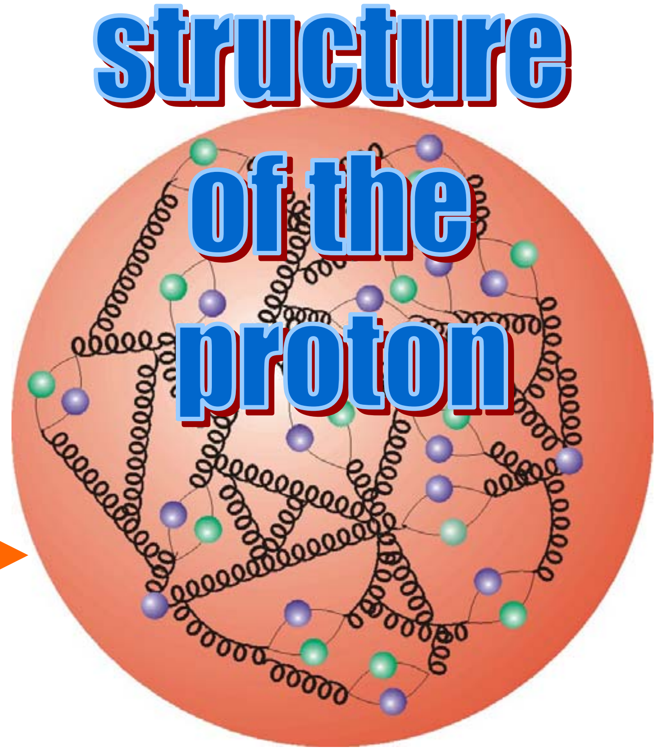
Resolve the structure of the proton

- 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"

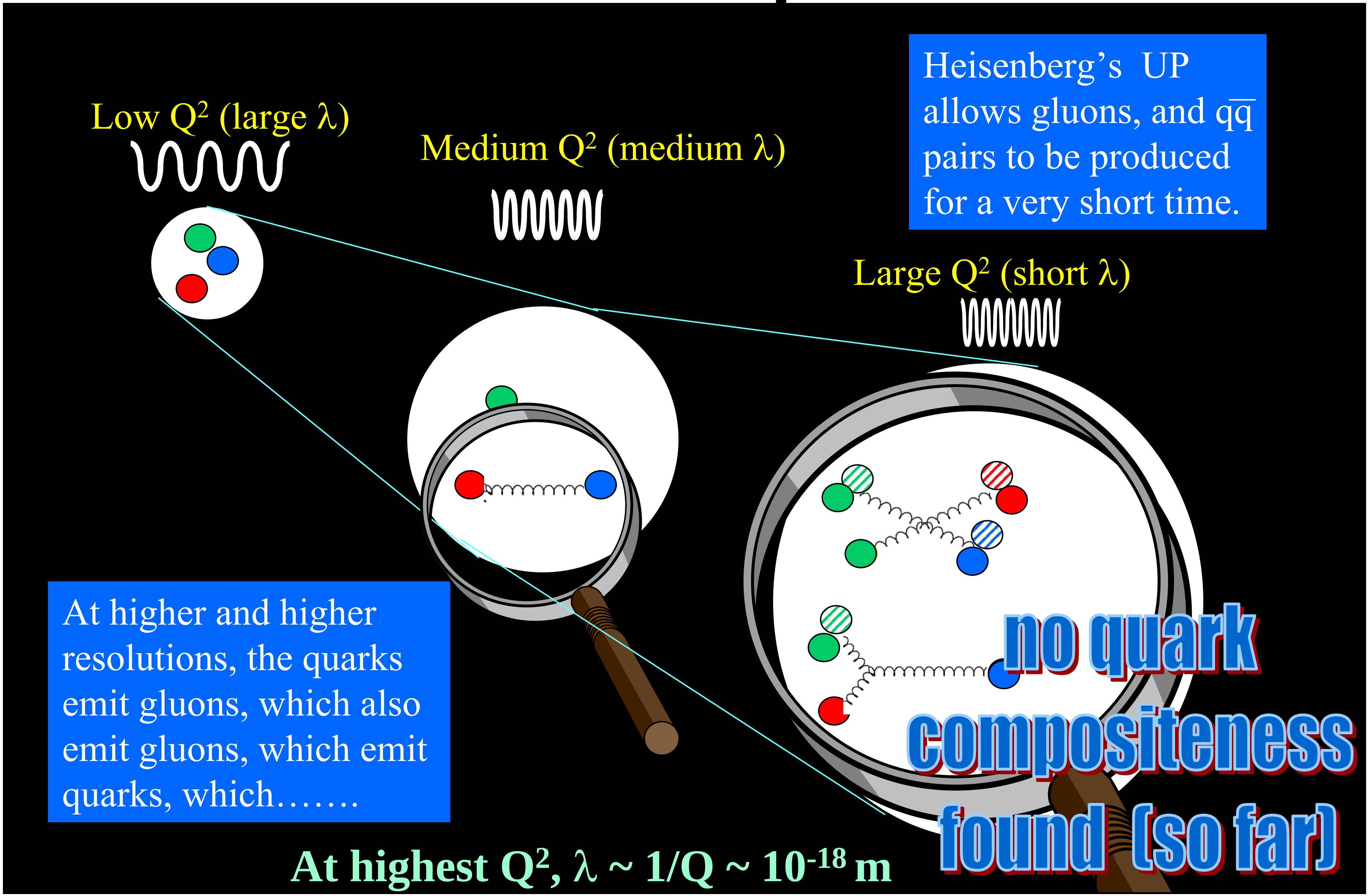




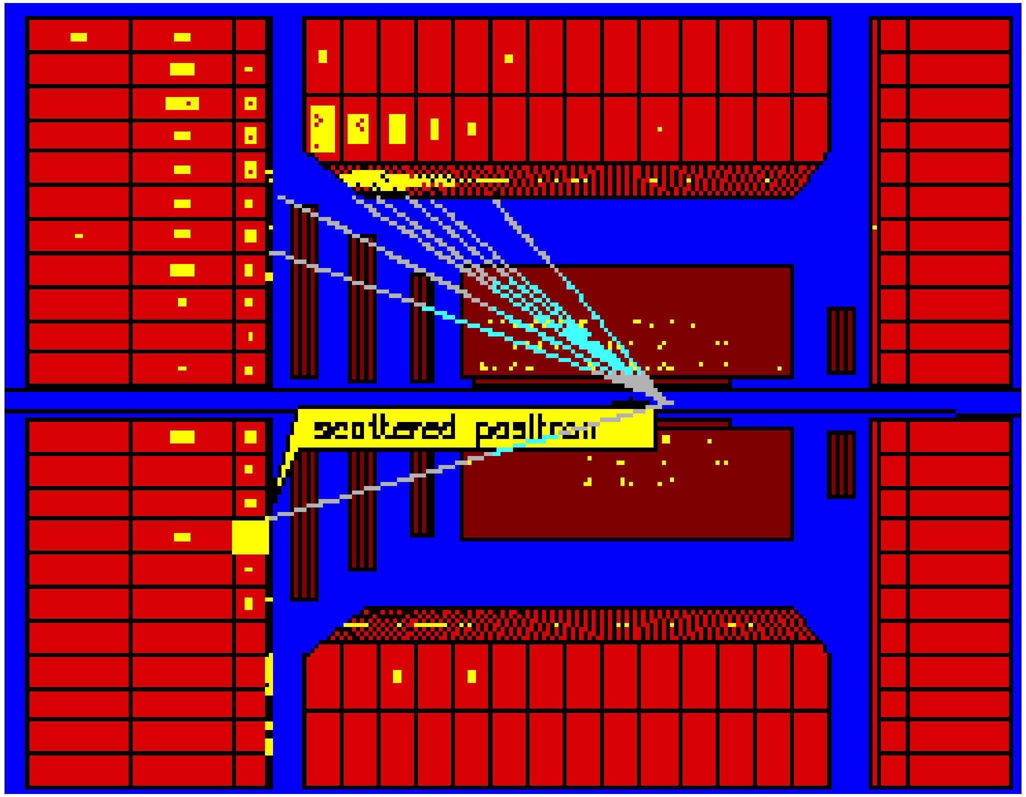
Jerome I. Friedmann, Henry W. Kendall, Richard E. Taylor
(Nobel 1990)

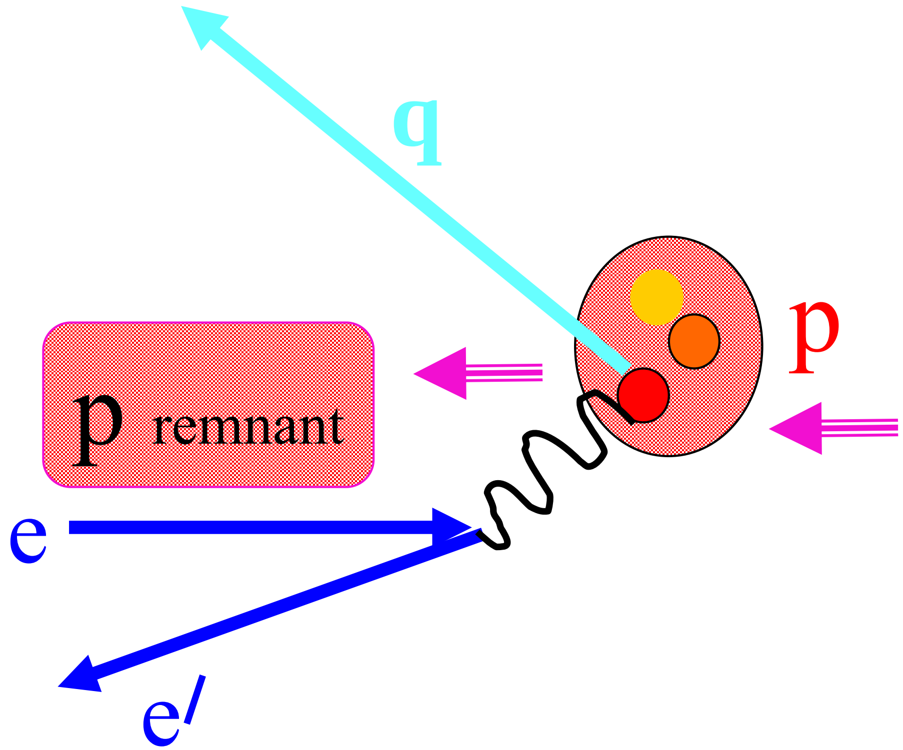


Inside the proton

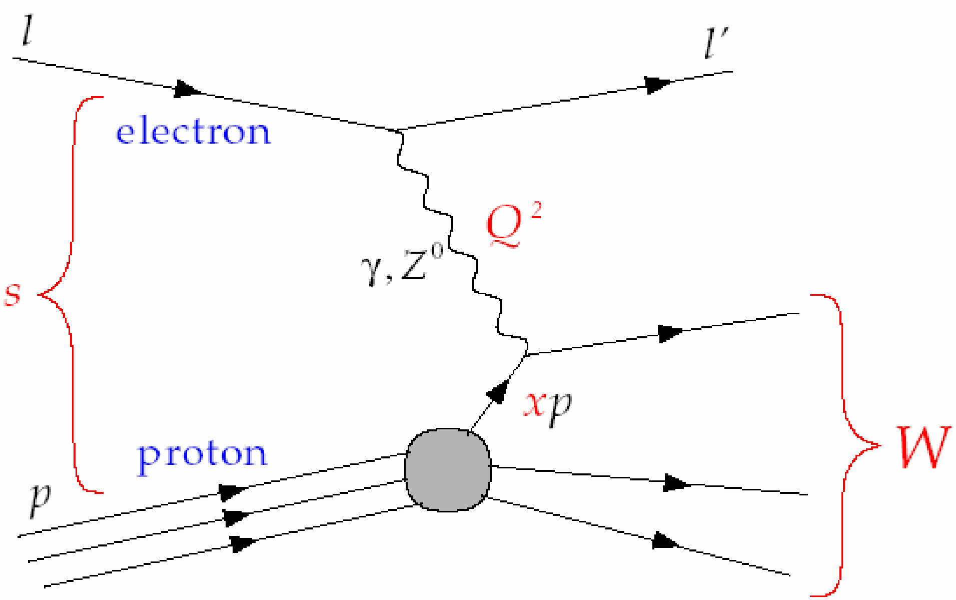


Deep Inelastic ep Scattering at HERA





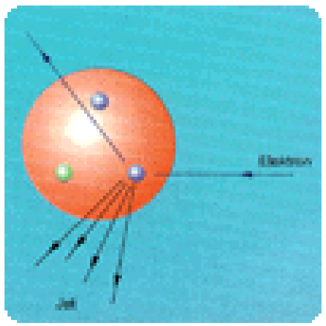
Deep Inelastic Scattering (DIS)



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

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

fractional momentum of struck quark $x = \dfrac{Q^2}{2p \cdot q}$



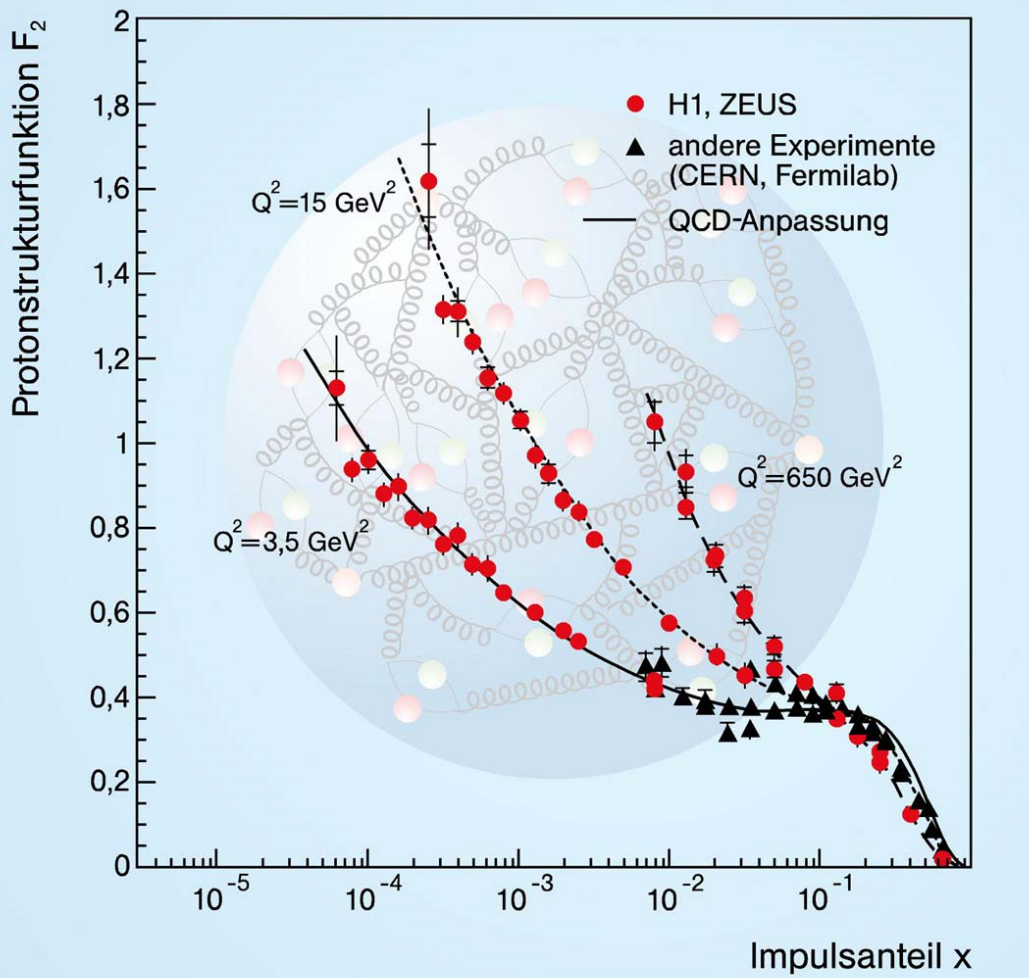
Parton distribution functions (PDF) in pQCD

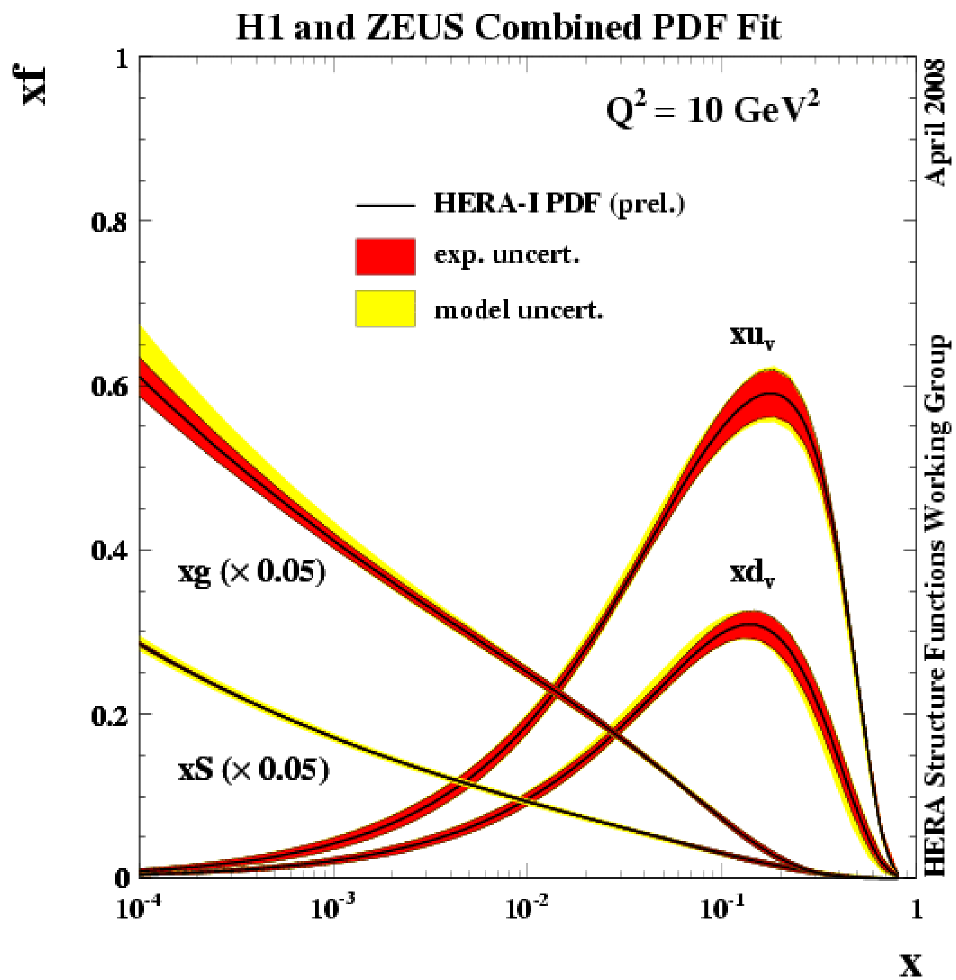
$$F_2^{em}(x, Q^2) = x \sum_i e_i^2 [q_i(x, Q^2) + \bar{q}_i(x, Q^2)]$$

q_i – probability to find quark with flavour i in proton

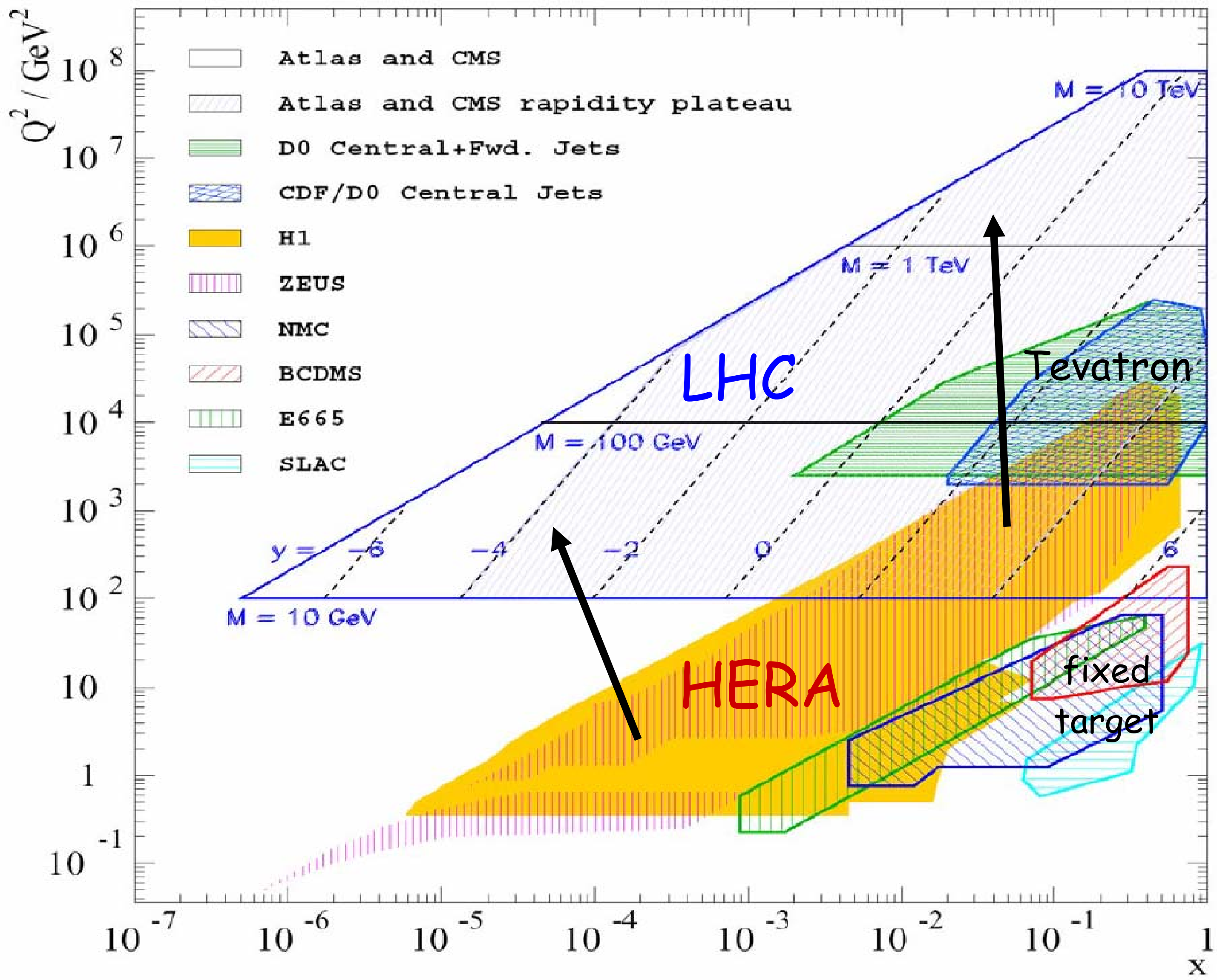
The Proton Structure

structure functions → quark and gluon densities





Kinematic regions: HERA vs. LHC

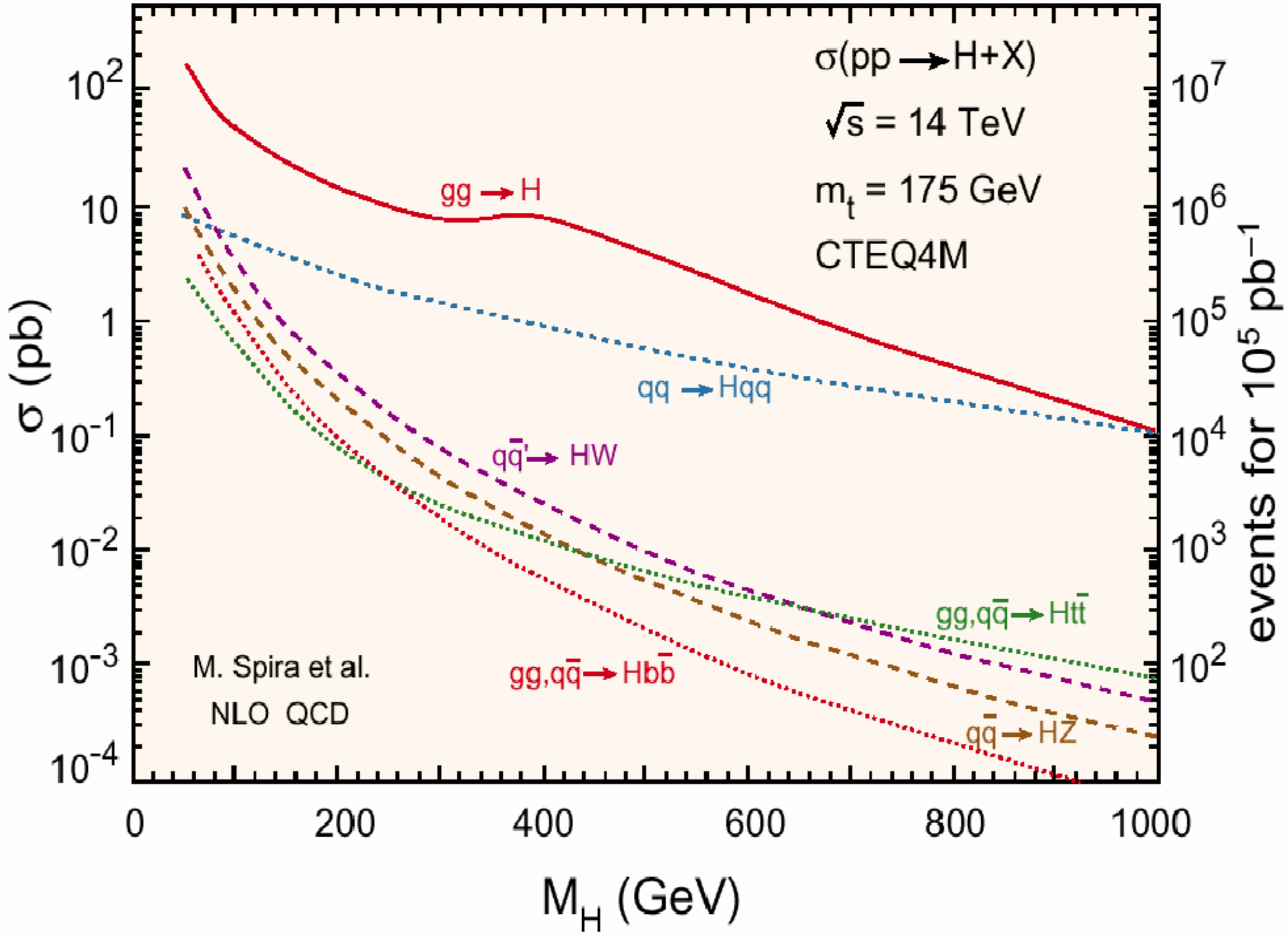


- proton structure measured directly for large part of LHC phase space
- QCD evolution successful

-> safely extrapolate to high Q^2 or low x

Input to measure-ments at LHC

Example: Higgs cross section at LHC



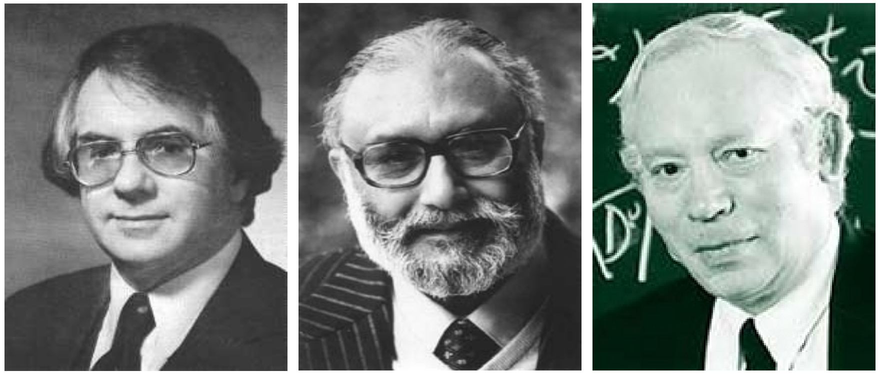
Knowledge of gluon and quark distributions essential

Intermediate summary

- Particle physics: Symmetries and conservation laws are important
- many exciting results at DESY and elsewhere! e.g. quarks, gluons, protons
- HERA closed down, but particle physics at DESY continues
- tomorrow: weak interactions, Higgs,
  (neutrinos), cosmology,
  future of particle physics

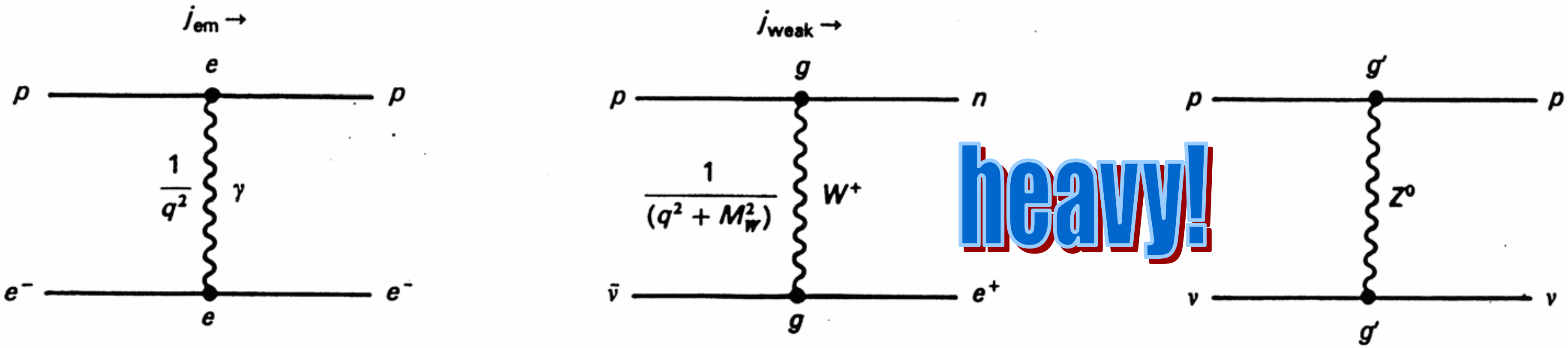
Weak Interactions

The Theory of GLASHOW, SALAM and WEINBERG ~ 1959-1968



(Nobel 1979)

Theory of the unified weak and electromagnetic interaction, transmitted by exchange of "intermediate vector bosons"



(a) Electromagnetic scattering

(b) Weak scattering (charged current)

(c) Weak scattering (neutral current)

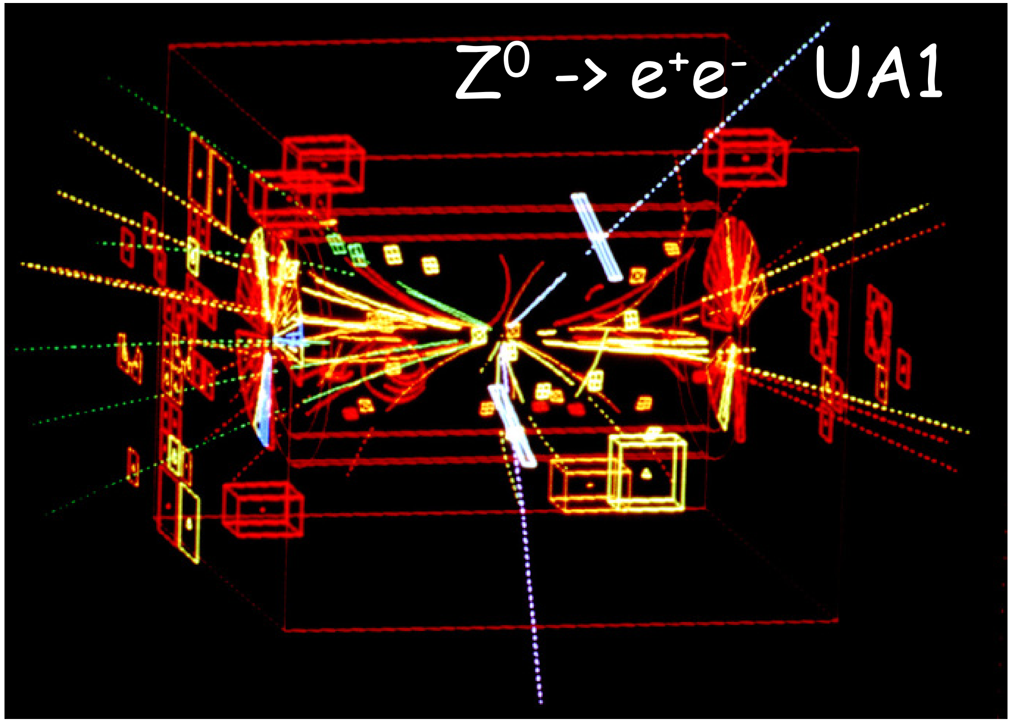
Discovery of the W and Z (1983)

- To produce the heavy W and Z bosons (m ~ 80-90 GeV) need high energy collider!
- 1978-80: conversion of SPS proton accelerator at CERN into proton-antiproton collider
  challenge: make antiproton beam!
- success!
  -> first W and Z produced 1982/83

(Nobel 1984)

Carlo Rubbia

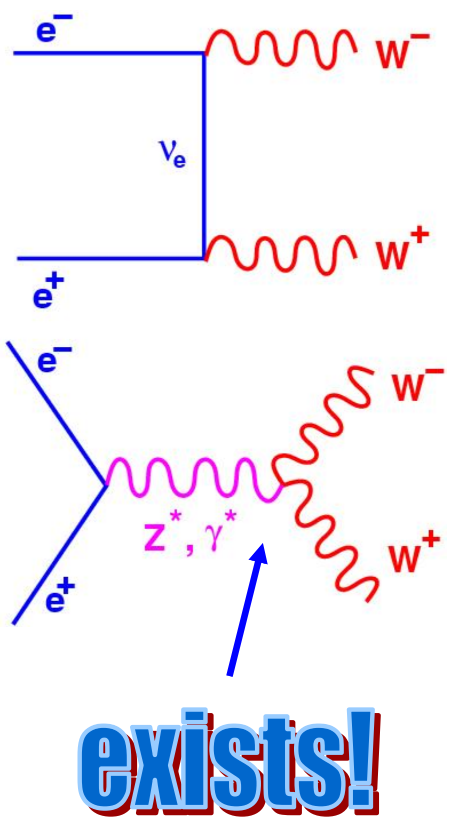
Simon van der Meer

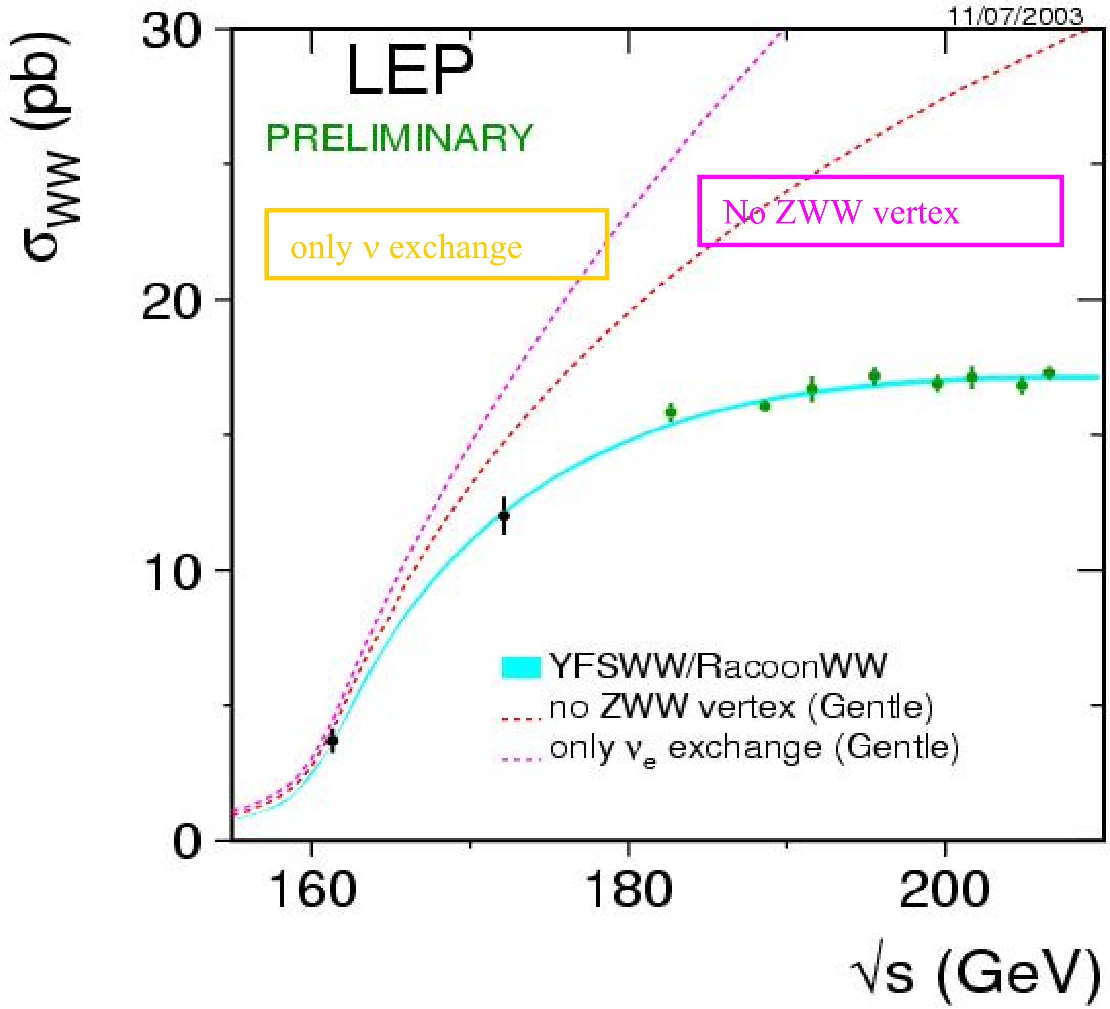


Three Boson Coupling @ LEP

W/Z bosons carry electroweak charge (like gluons)

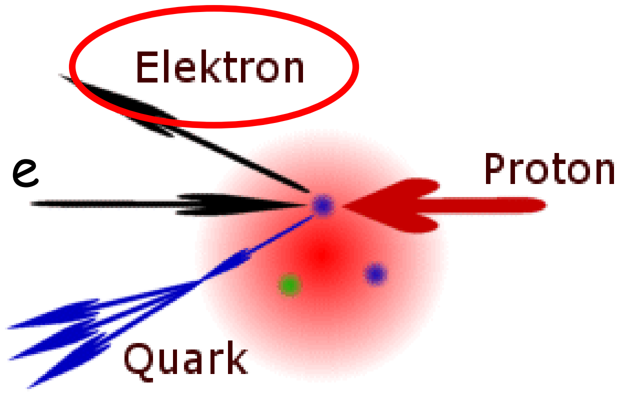
-> measure rate of W pair production at LEP II

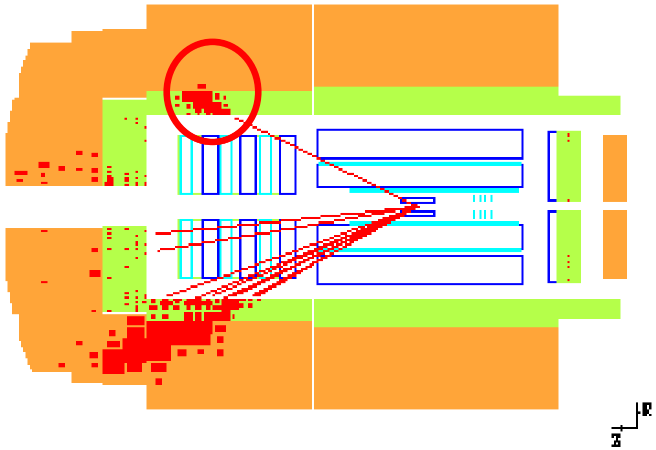


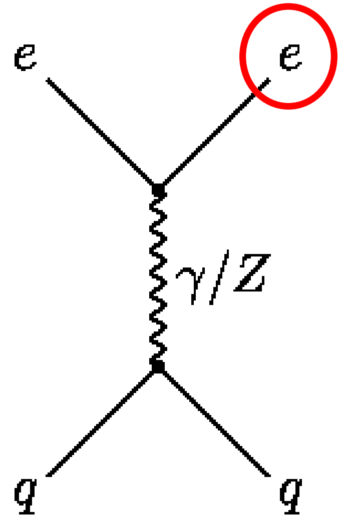


Electroweak Physics at HERA

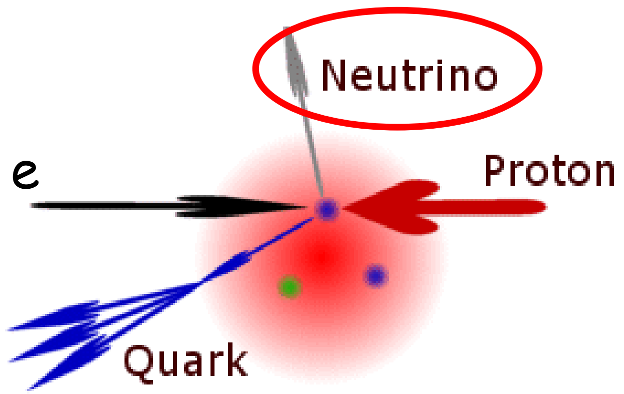
Neutral Current (NC) interactions

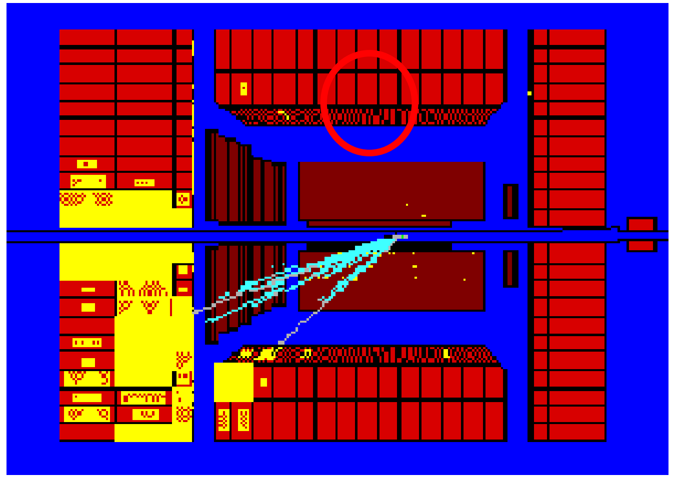


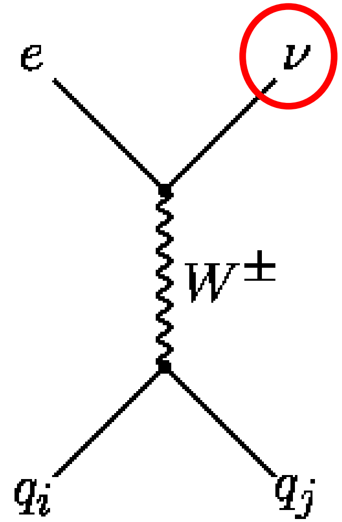




Charged Current (CC) interactions



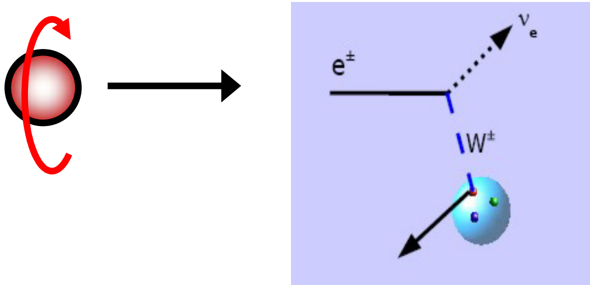




Weak interactions are "left-handed"

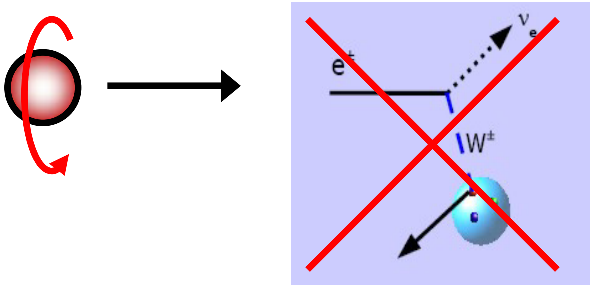
- lefthanded electrons interact (CC)

e^-



- righthanded electrons do not!

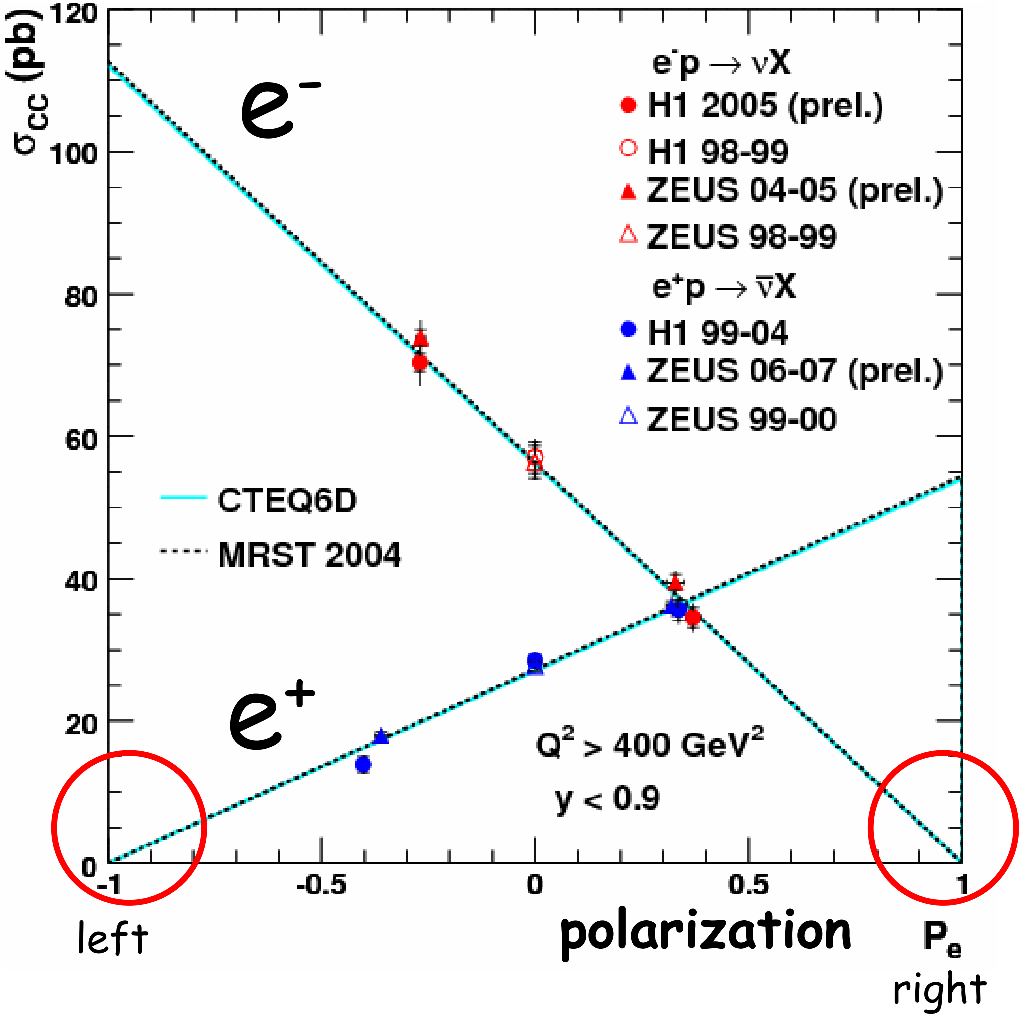
e^-



- cross section linearly proportional to polarization

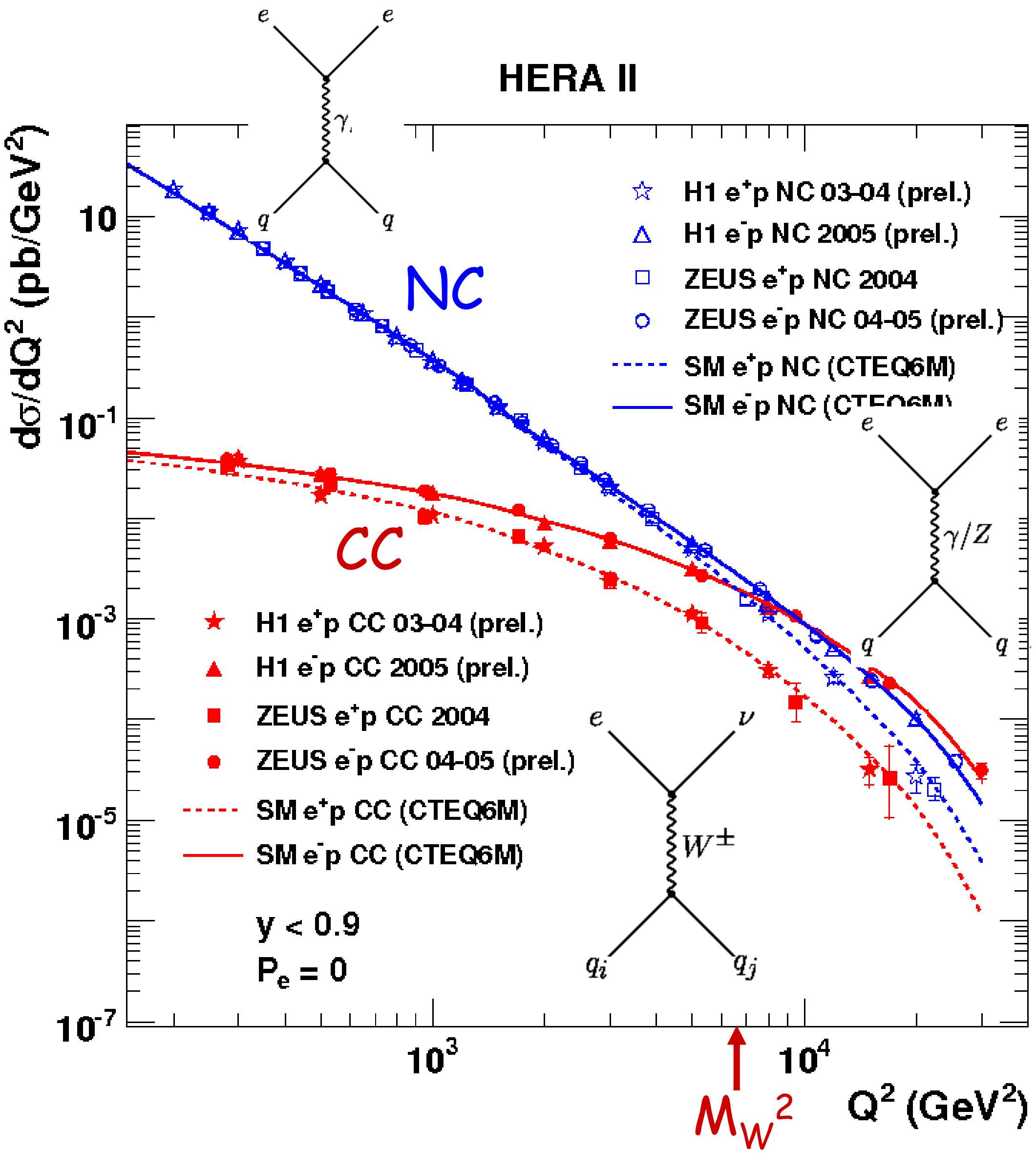
$$\boxed{\sigma^{e^{\pm}p}_{polCC} = (1 \pm P_e) \cdot \sigma^{e^{\pm}p}_{unpolCC}}$$

Polarized CC Cross Sections



It works!

Electroweak Unification

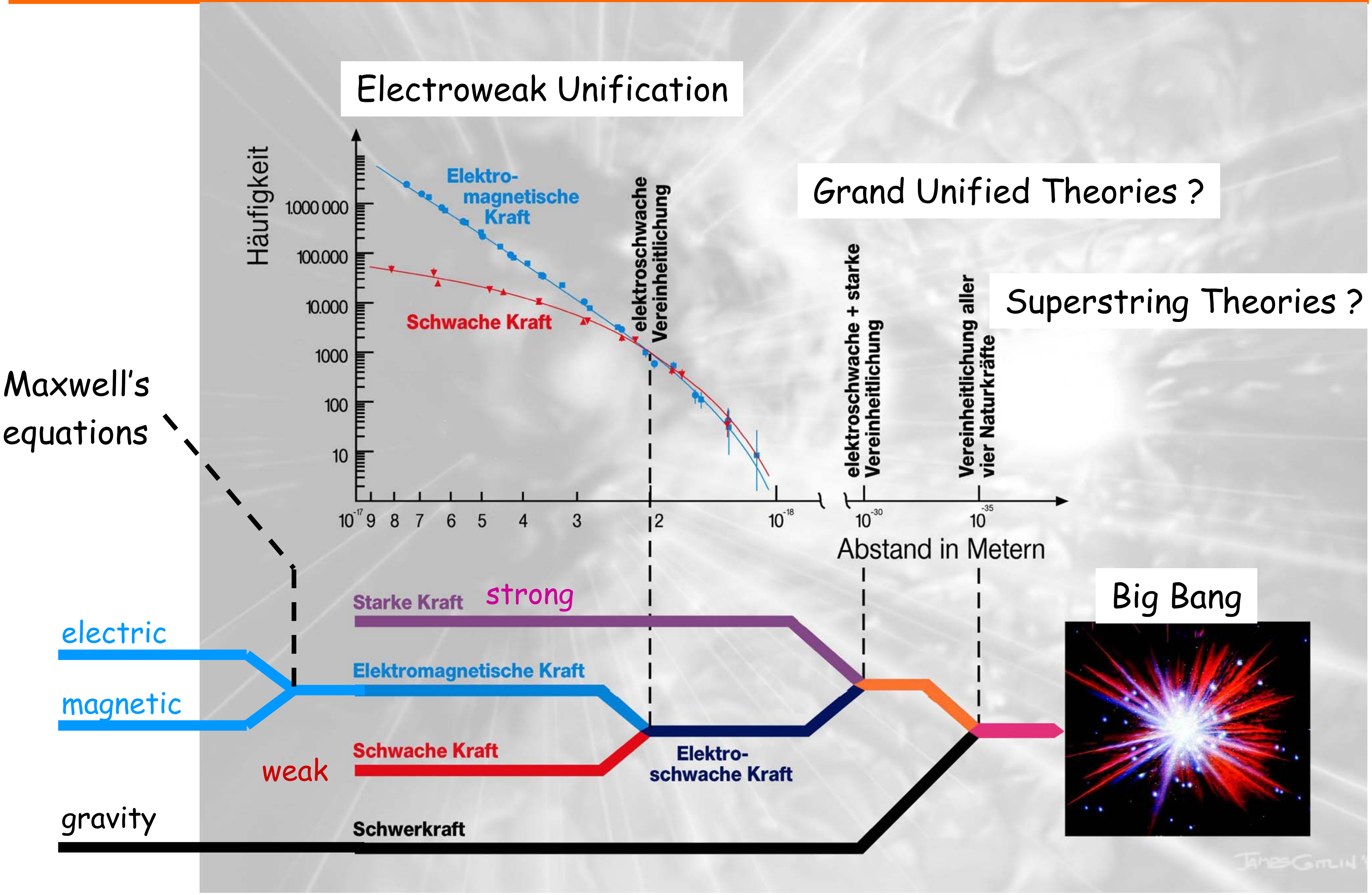


Strength of weak and electromagentic forces become similar at scale $Q^2 \sim M_W^2$

$$\frac{d^2\sigma_{NC}}{dQ^2\,dx} \sim \alpha^2 \quad \frac{1}{Q^4} \quad \frac{1}{x}\Phi_{NC}(x,Q^2)$$

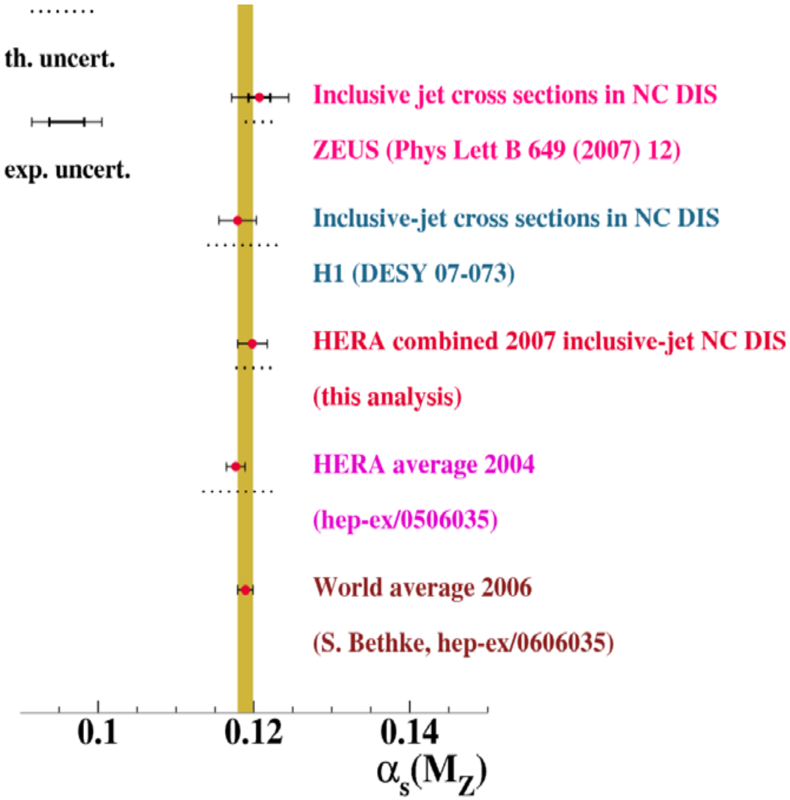
$$\frac{d^2\sigma_{CC}}{dQ^2\,dx} \sim G_F^2 \left(\frac{M_W^2}{M_W^2+Q^2}\right)^2 \frac{1}{x}\Phi_{CC}(x,Q^2)$$

The Quest for Unification of Forces

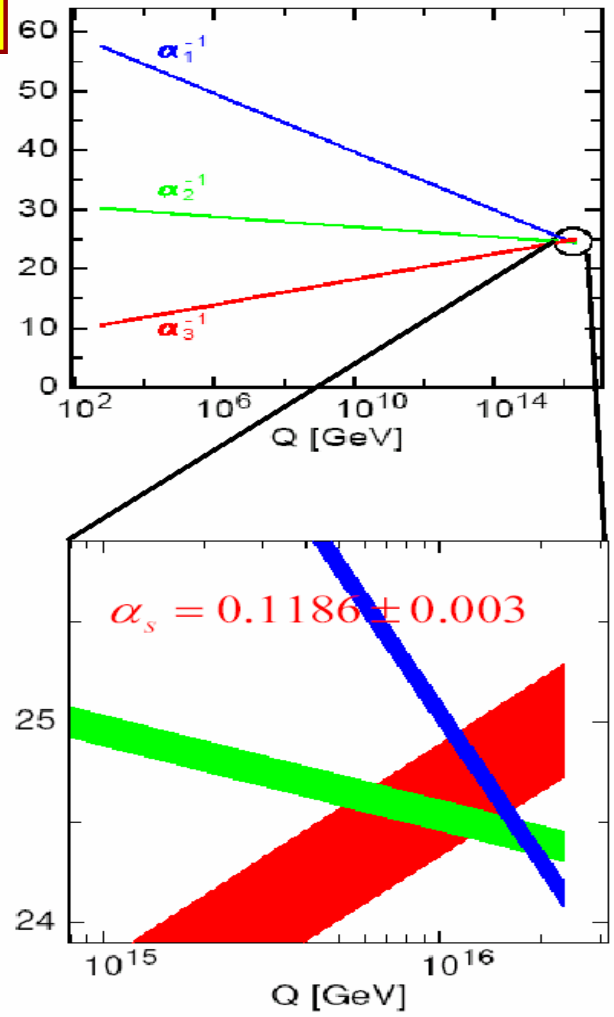


α_s from HERA and Grand Unification

HERA prel.:
$\alpha_S(M_Z) = 0.1198 \pm 0.0019(\mathrm{exp}) \pm 0.0026(\mathrm{th})$



with SUSY (see later):



hep-ph/0407067 B.Allanach ... P.Zerwas

world average: $\alpha_S(M_Z) = 0.1176 \pm 0.0020$
NNLO, MSbar PDG 2006

Antimatter

P.A.M. Dirac

(Nobel 1933)

relativistic Schrödinger equation
(Dirac equation)
two solutions:

one with positive, one with negative energy

Dirac: interpret negative solution as **antiparticle**

1932 antielectrons (positrons) found in conversion of energy into matter

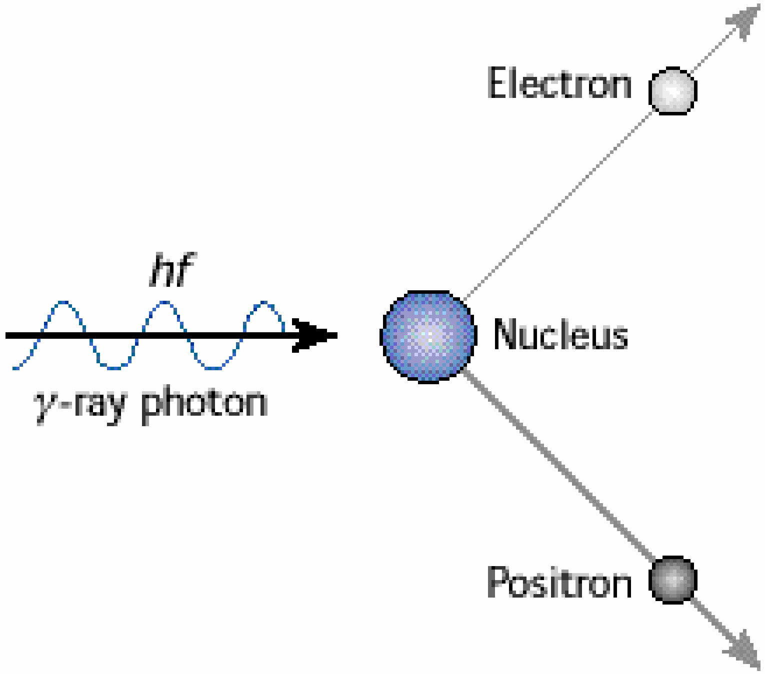
1995 antihydrogen consisting of antiprotons and positrons produced at CERN

In principle: antiworld can be built from antimatter
In practice: produced only in accelerators and in cosmic rays

Why???

Pair Production

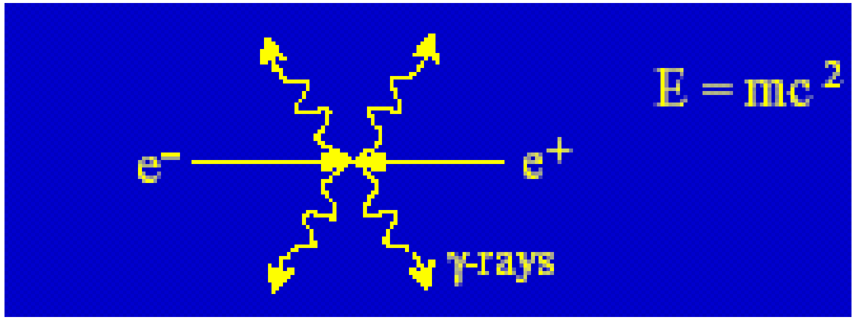
e.g. $$\gamma \rightarrow e^{+} + e^{-}$$

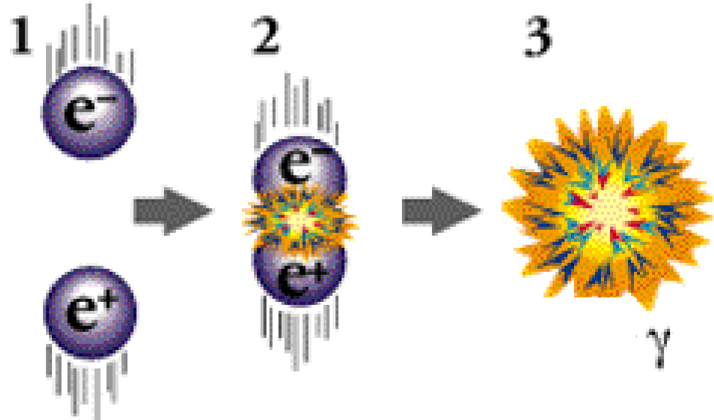


Equal amounts of matter and antimatter are produced when radiation is converted to matter

Annihilation

$$e^{+} + e^{-} \rightarrow 2hf$$

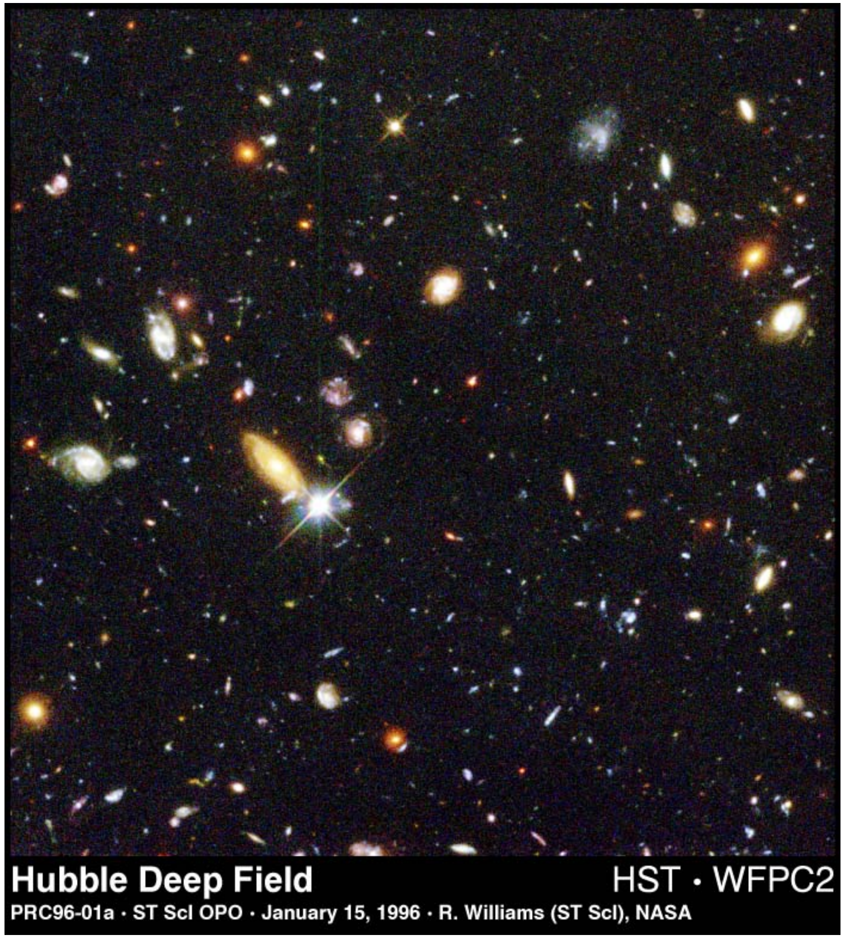


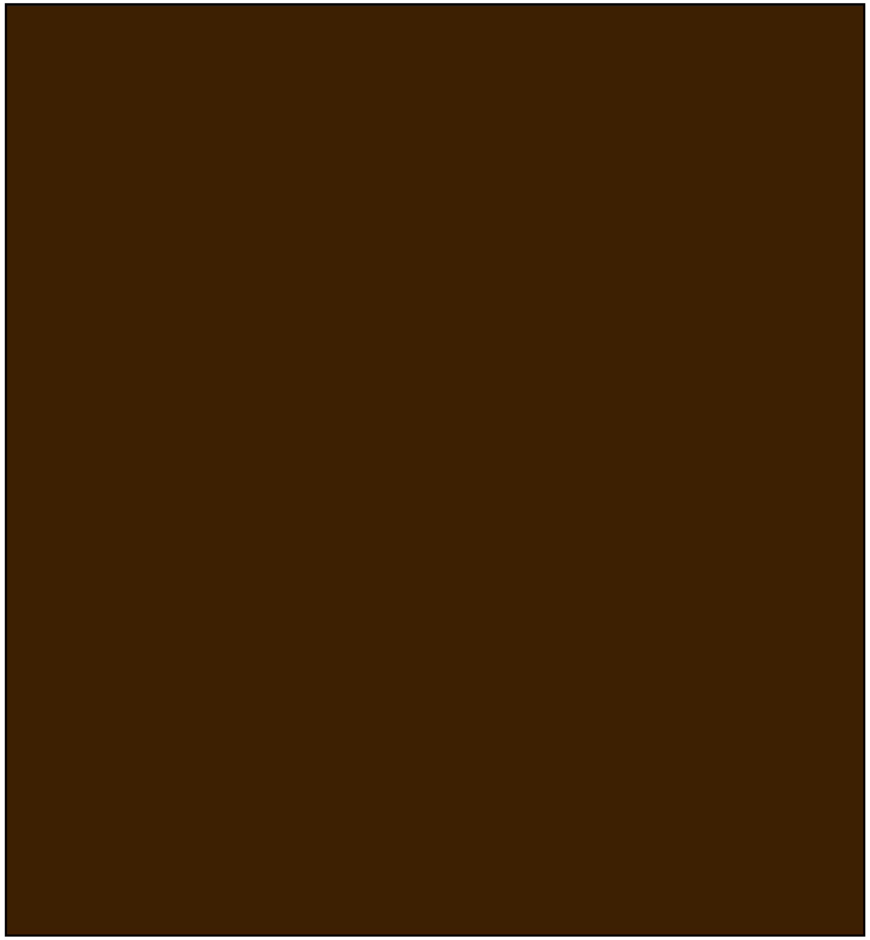


Antimatter can be produced.
It annihilates with matter to produce radiation

The Matter Antimatter Puzzle

Why does the Universe look like this not that?



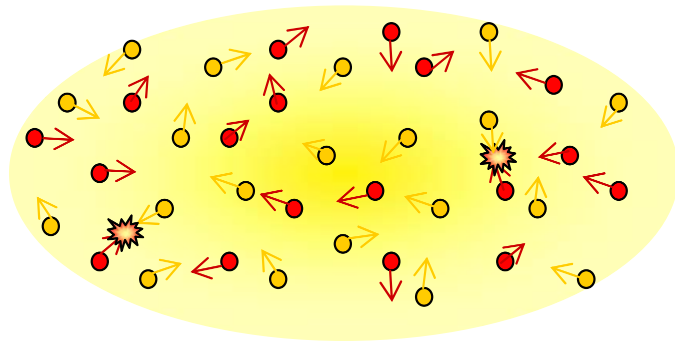


As far as we can see in universe, no large-scale antimatter.

-> need CP violation!

The Matter Antimatter Puzzle

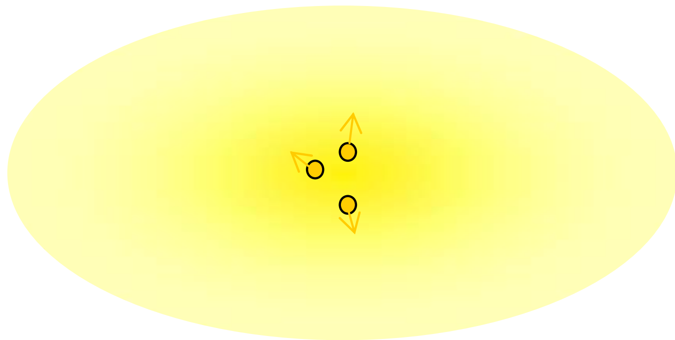
Early Universe



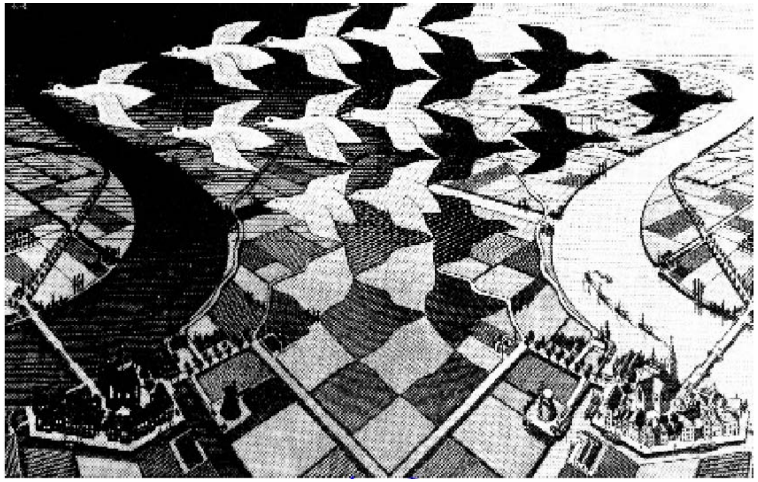
-> particles, anti-particles and photons in thermal equilibrium
– colliding, annihilating, being re-created etc.

Slight difference in fundamental interactions between matter and antimatter ("CP violation") ?
-> matter slightly more likely to survive

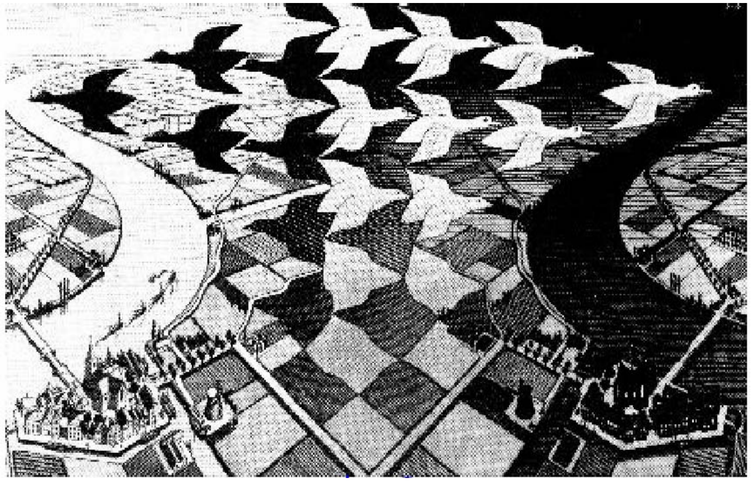
Ratio of baryons (e.g. p, n) to photons today tells us about this asymmetry – it is about $1:10^9$



CP symmetry

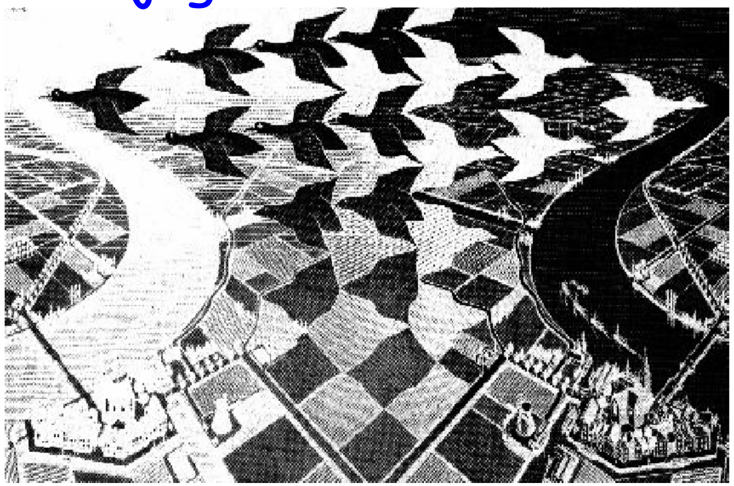


Parity
(reflection)

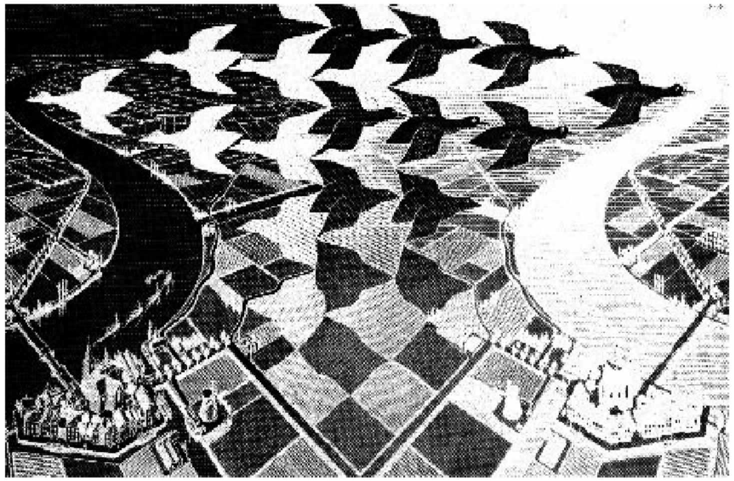


Charge Conjugation (black → white)

C

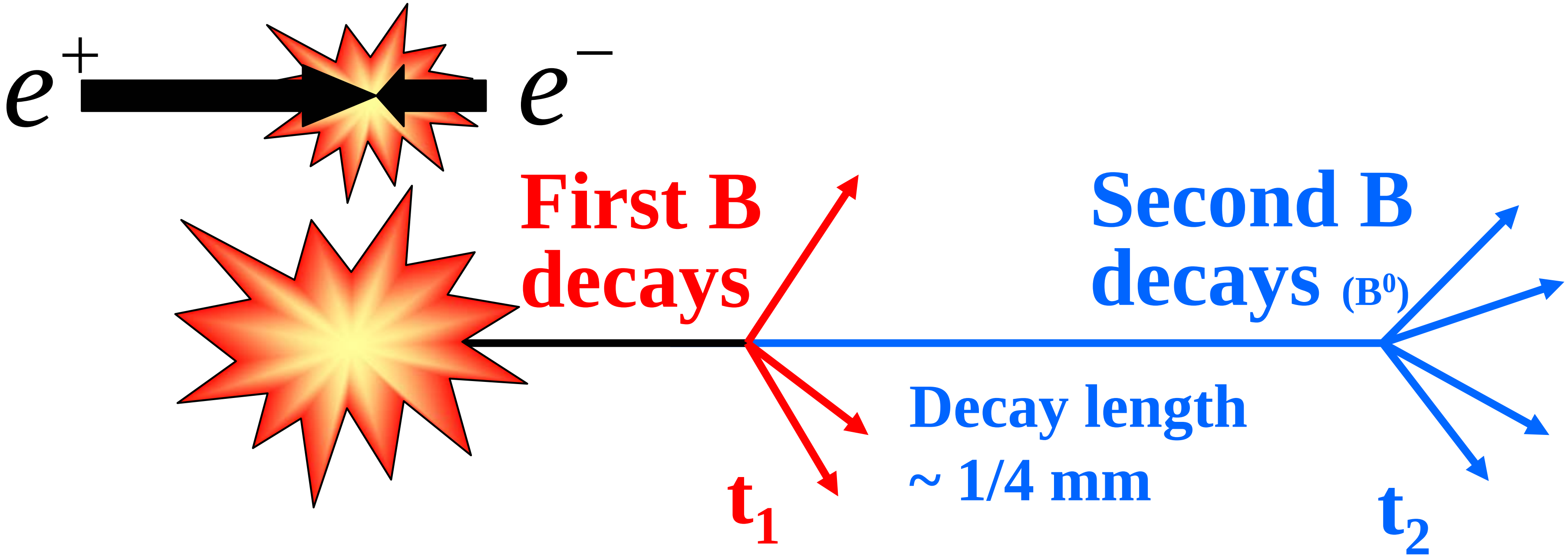


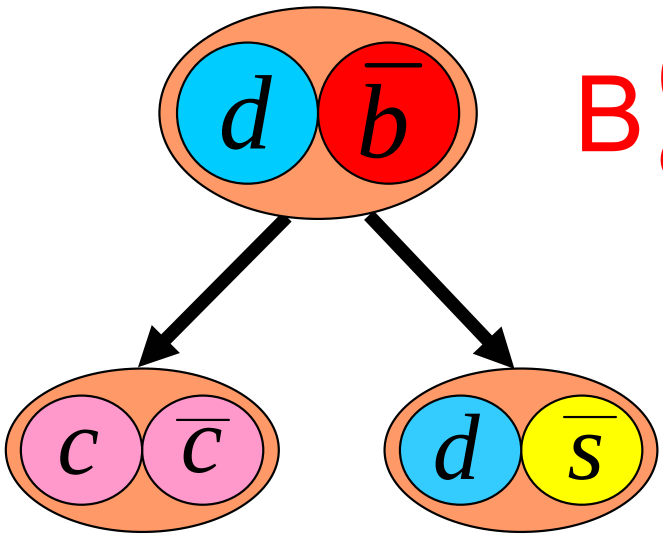
P



Like weak interaction, symmetric under CP (at first sight!)
Can there be small deviations from this symmetry?

CP violation in B meson decays





B_d^0 (or $\overline{B}_d^0$)

$$Asymmetry(t) = \frac{\overline{B}^0 - B^0}{\overline{B}^0 + B^0}$$

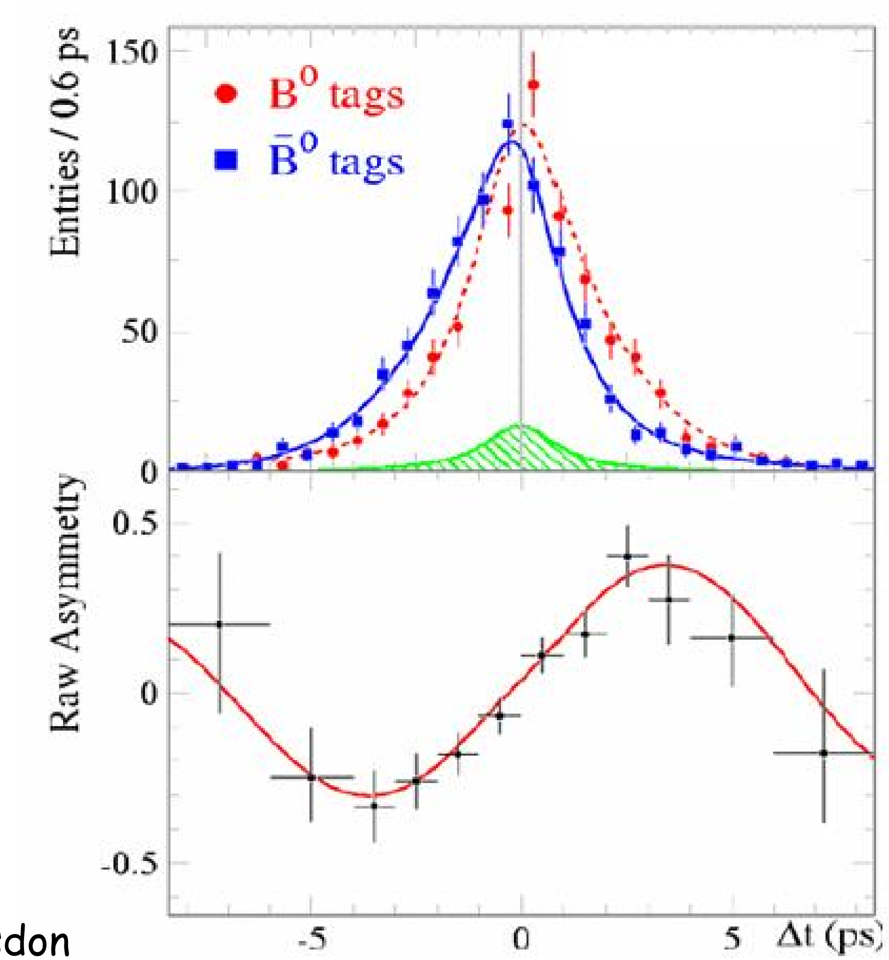
Simply count decays as function of t!

CP violation in B meson decays

Example: recent measurement from BaBar at SLAC

(also Belle at KEK)

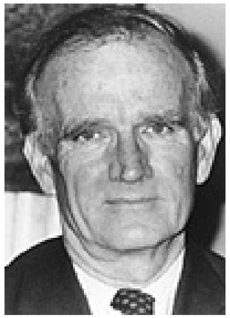
B and anti-B are indeed different



Weak Interactions violate CP!

(also found earlier for K decays:)

James Watson Cronin



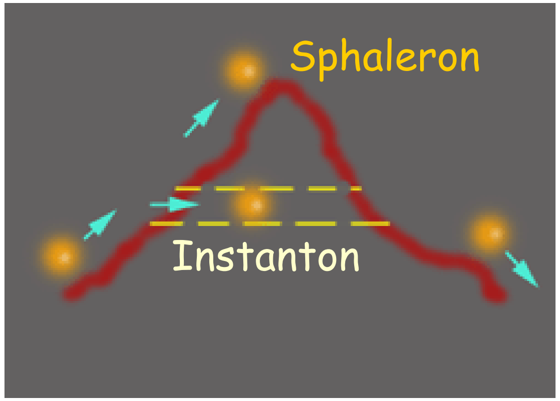
Val Logsdon Fitch

(Nobel 1980)

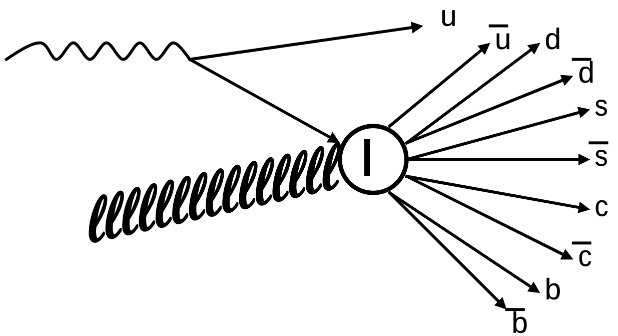
data taking stopped. Belle/Super-Belle continuing.

contribution to the antimatter puzzle from HERA?

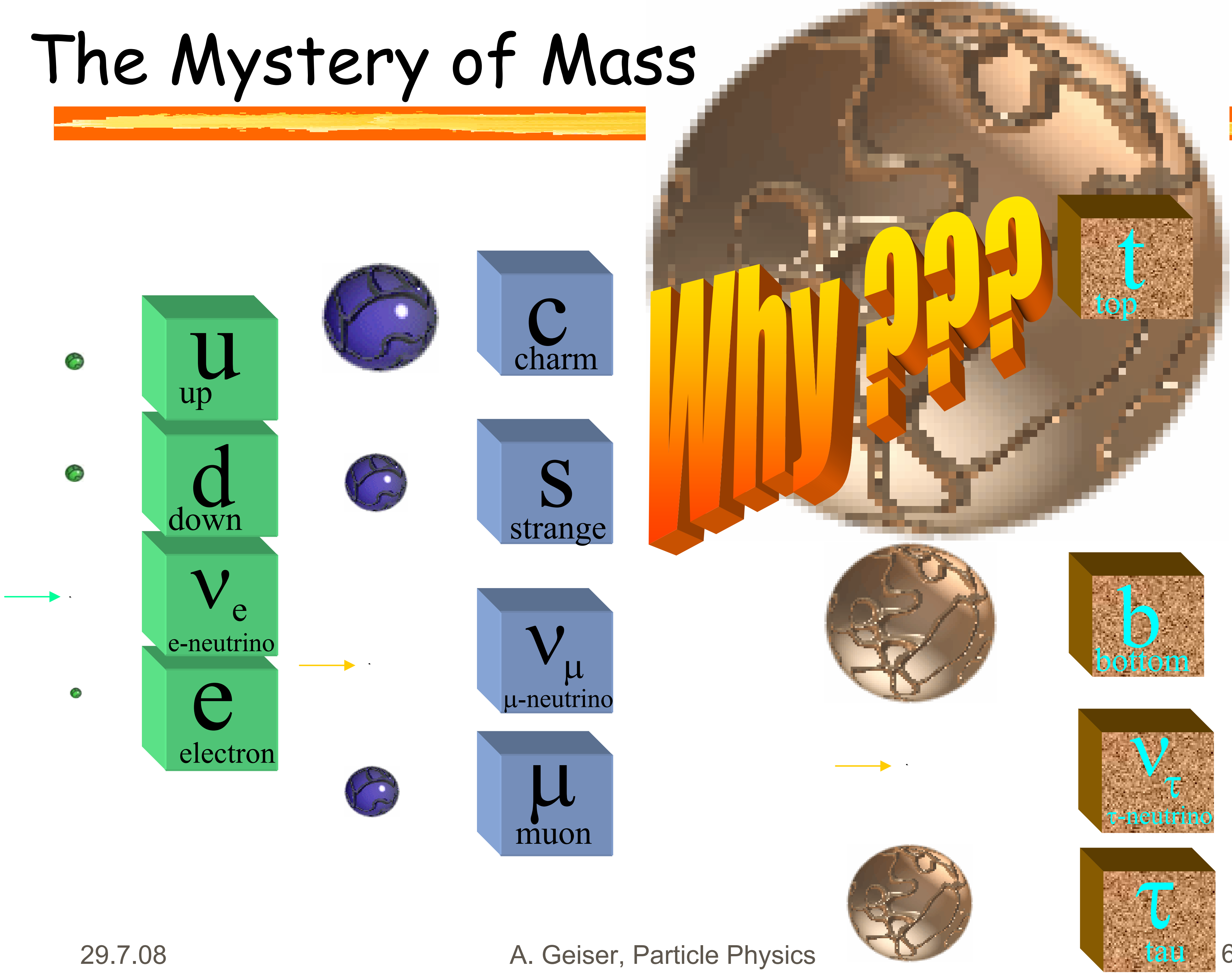
- CP violation measured so far not strong enough to explain matter-antimatter asymmetry
- way out: CP violation in neutrino oscillations (see C. Hagner) and/or strong lepton number asymmetry in early universe (see A. Lindner).
- Standard Model predicts baryon and lepton number violation through so-called „sphaleron" process: converts 3 leptons into 3 baryons!



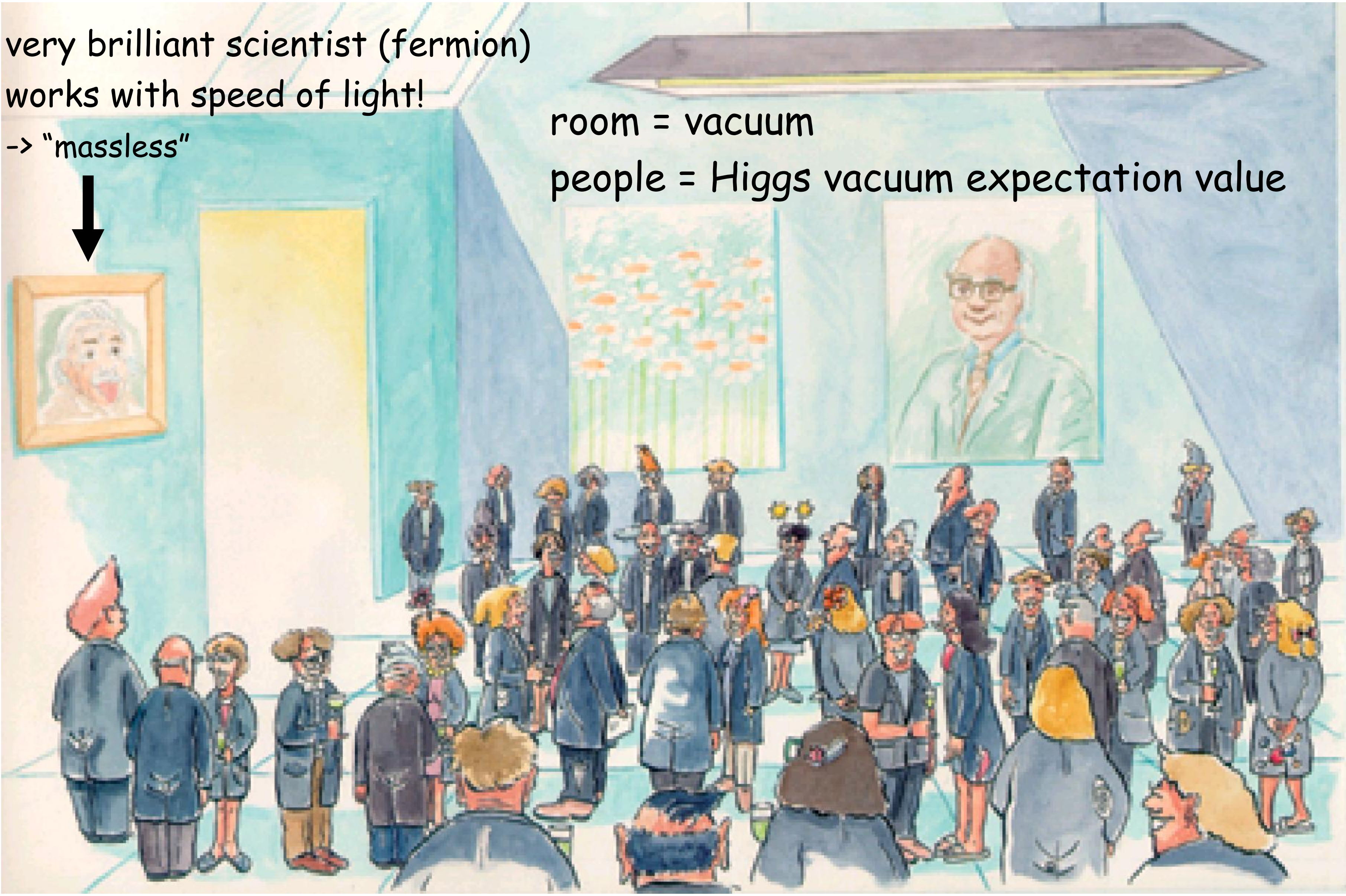
- rare process at very high energy -> not observable so far
- related process: QCD „instantons"
- in principle observable at HERA!
- still searching ...



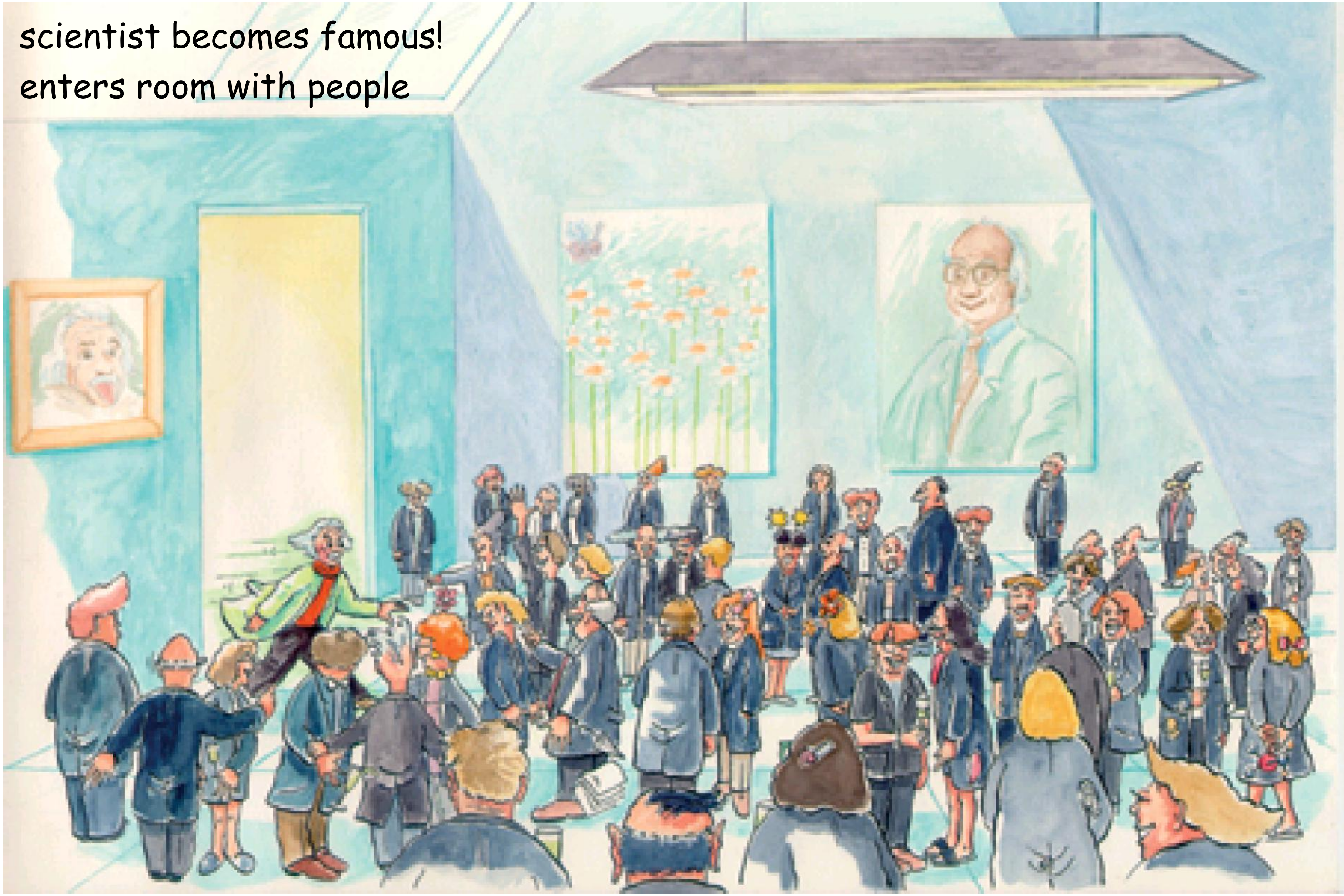
The Mystery of Mass



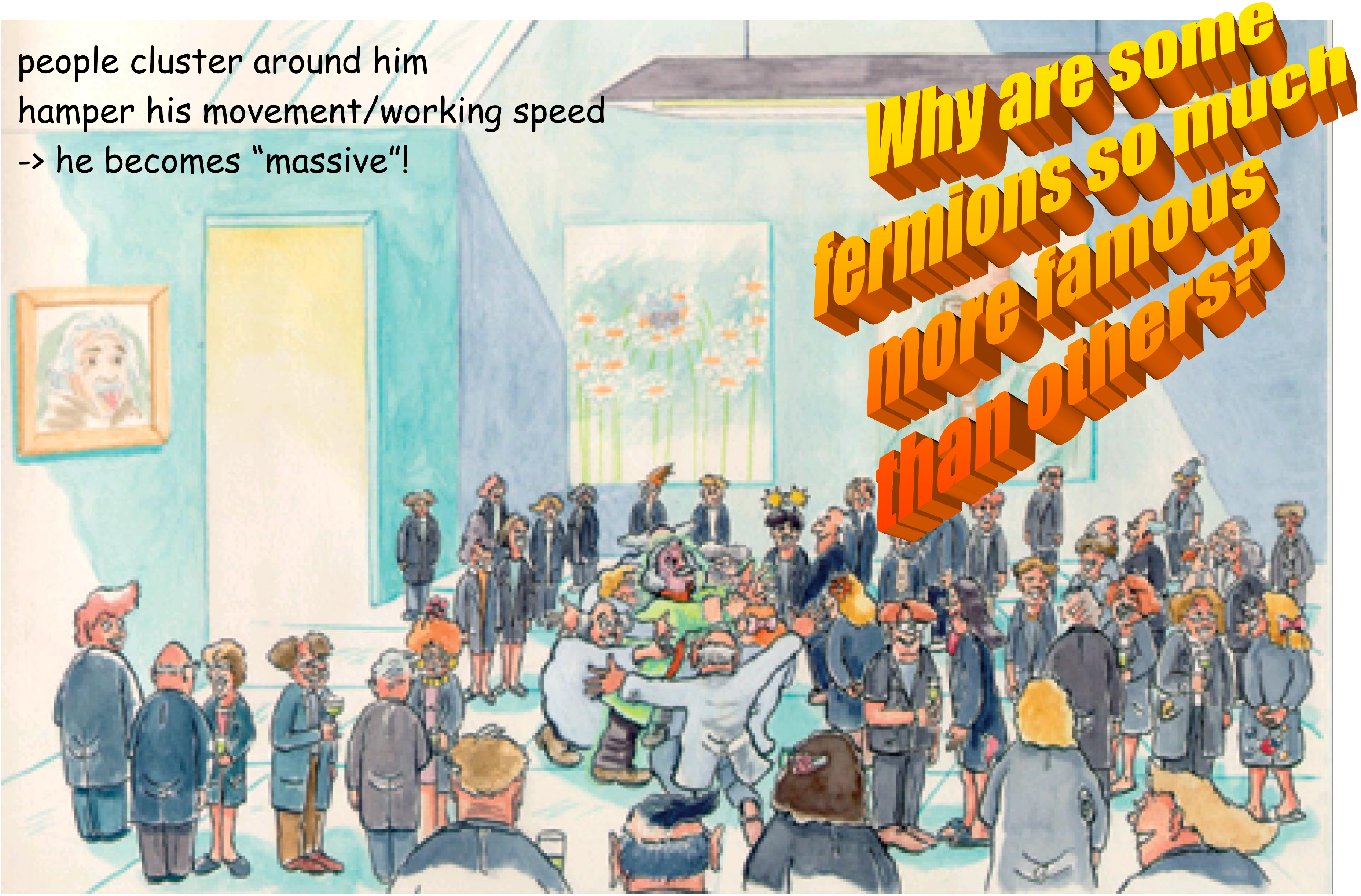
Fermion Mass from Higgs field?



Fermion Mass from Higgs field?

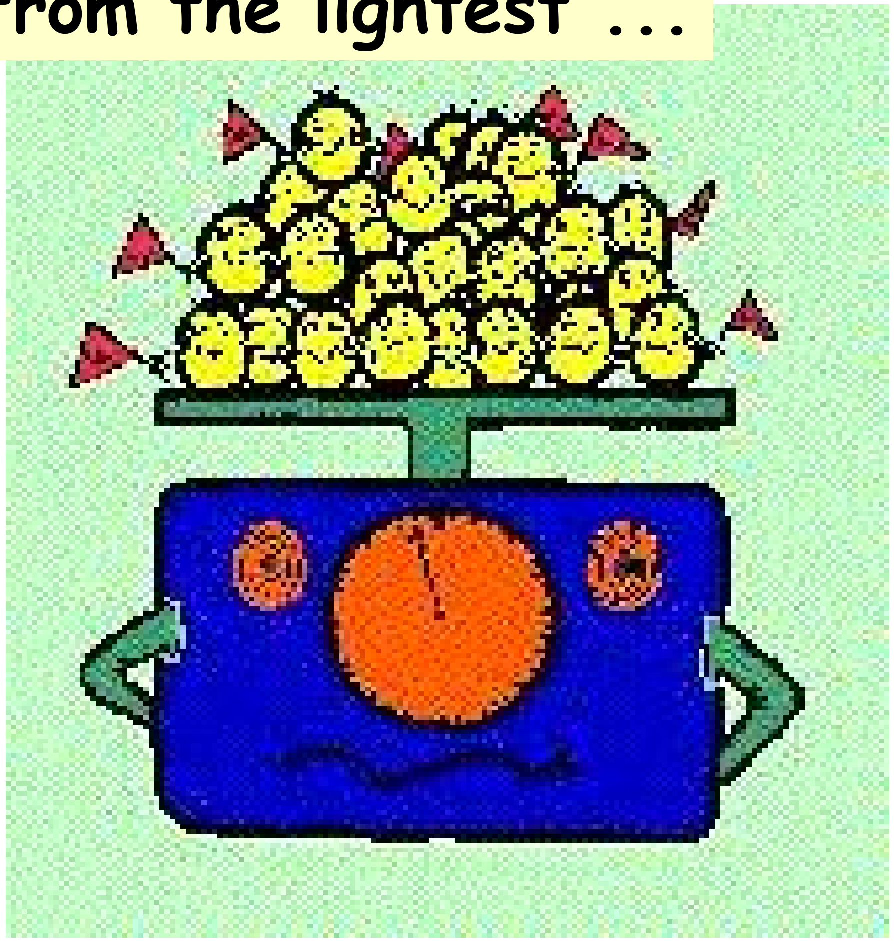


Fermion Mass from Higgs field?



How much do Neutrinos weigh?

from the lightest ...



Standard Model has $m_\nu = 0$

-> **evidence for $m_\nu \neq 0$**
forces

extension of Standard Model

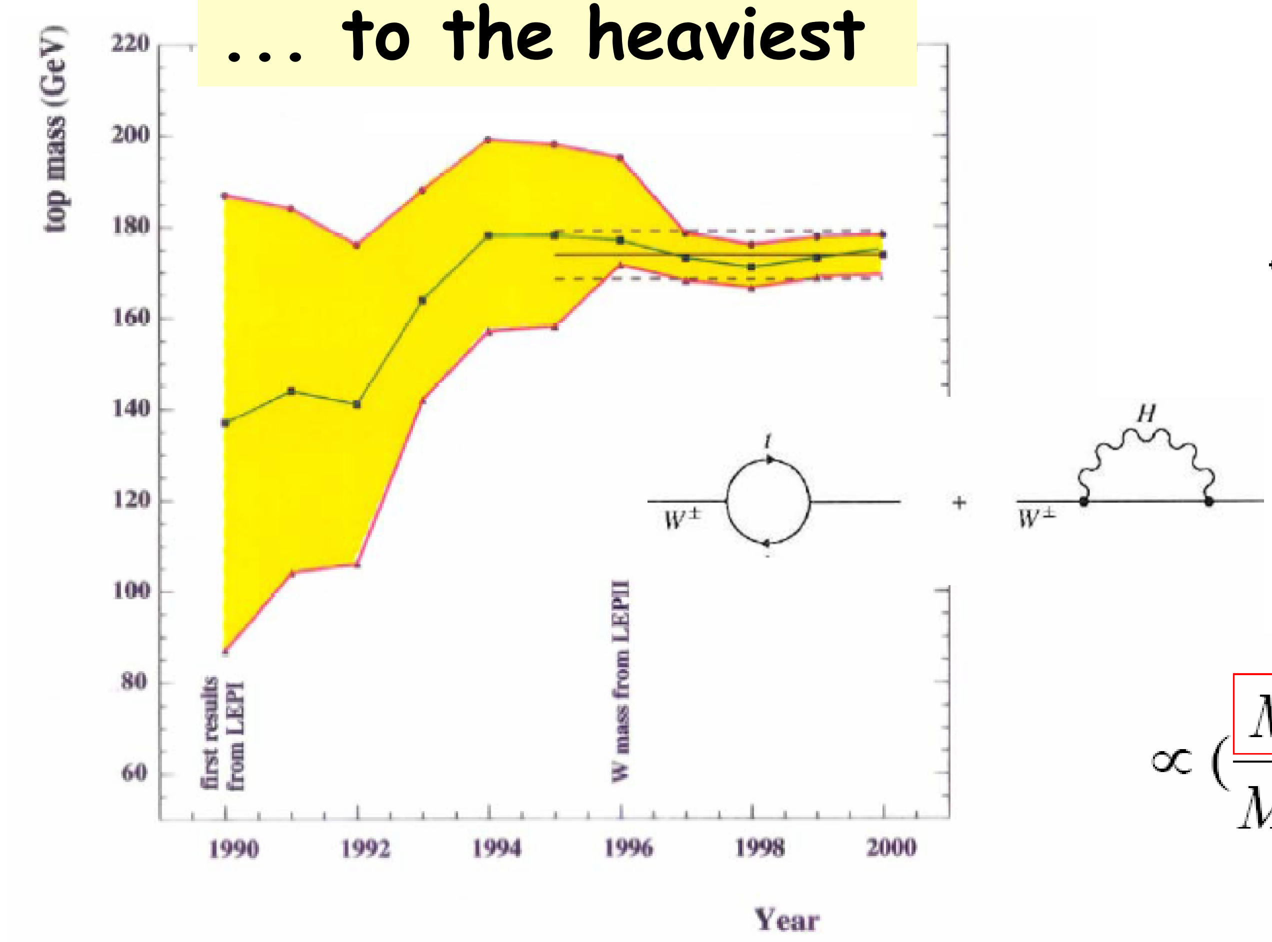
Why ???

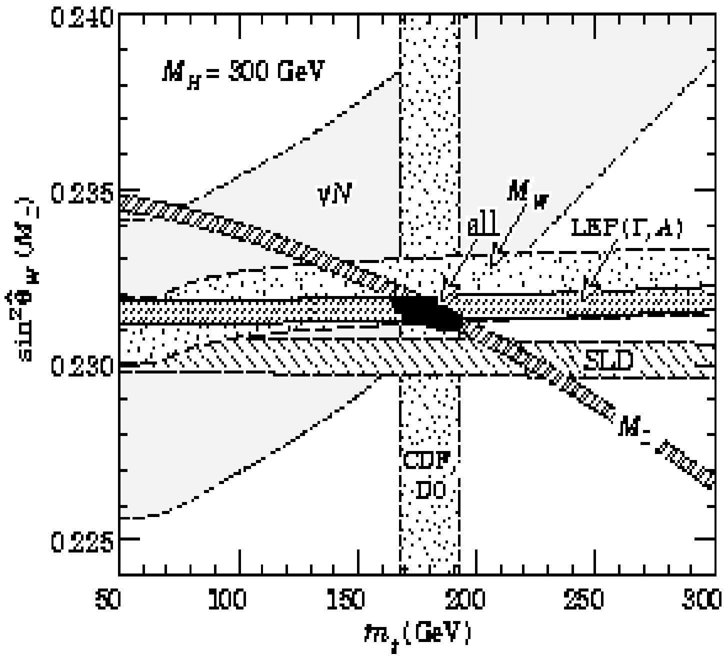
see lectures C. Hagner! (last week)

The quest for the top quark

Electroweak precision measurements at LEP/CERN
sensitive to top quark mass and Higgs mass (indirect effects)

... to the heaviest

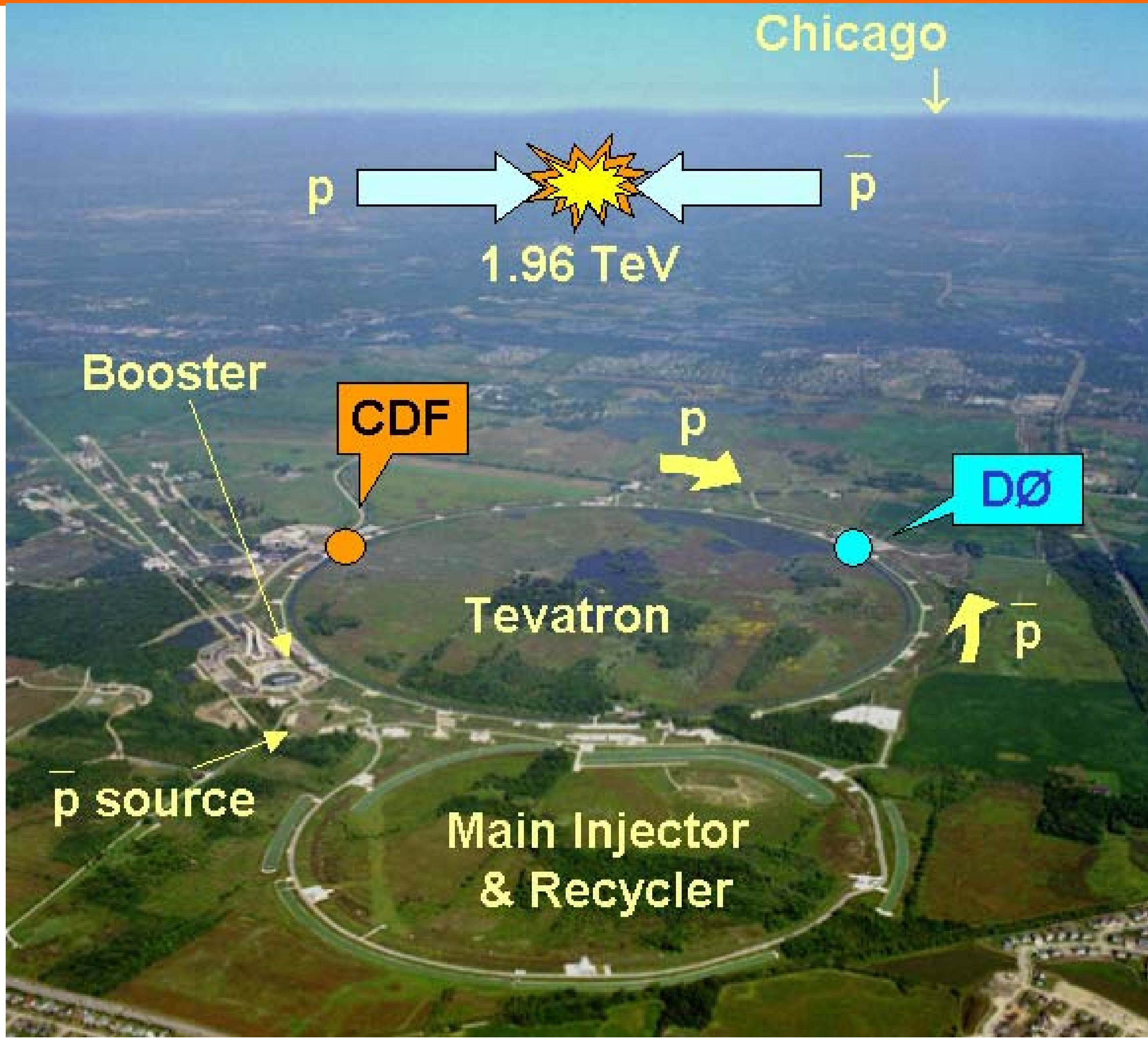




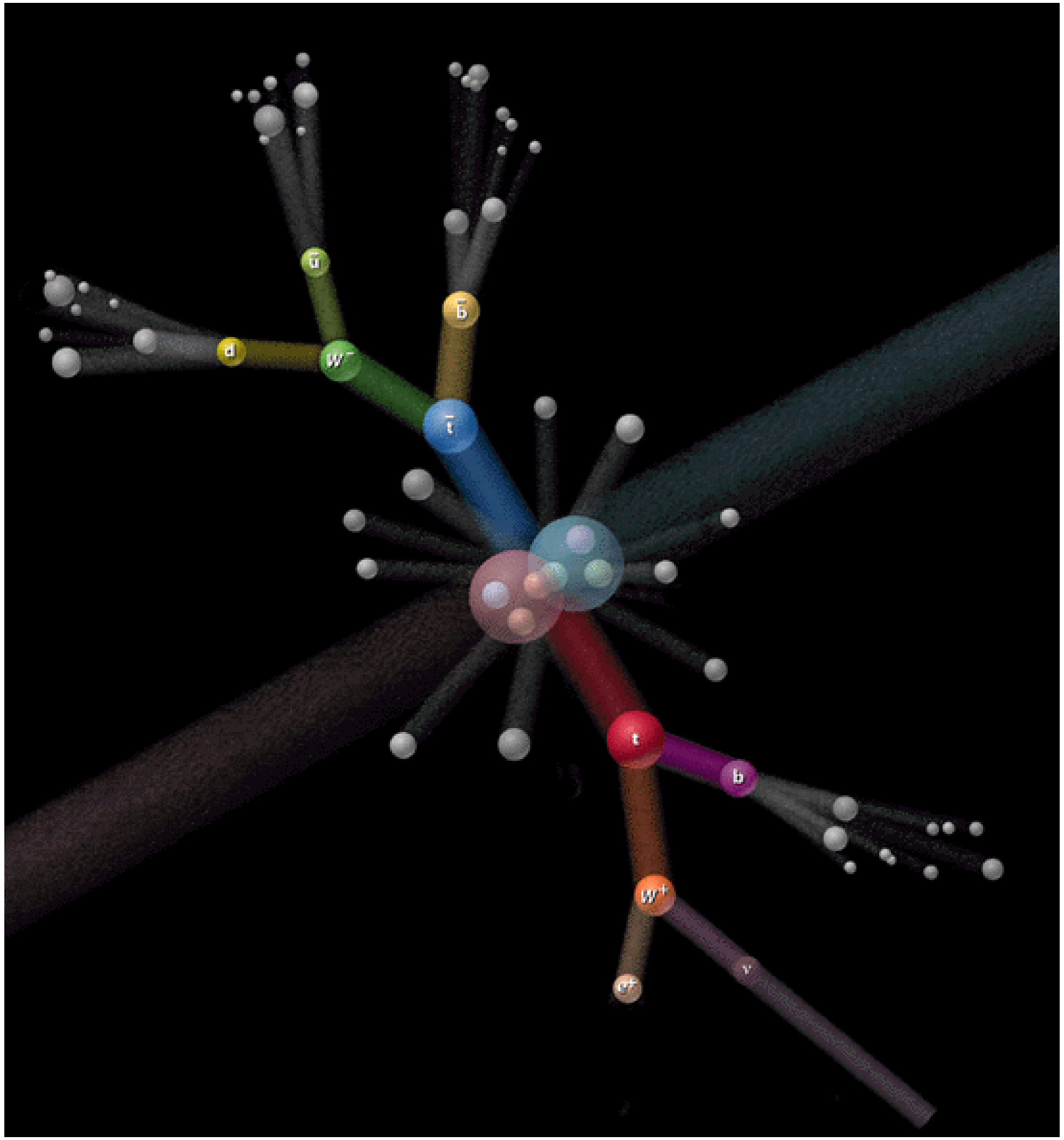
$$\propto \left(\frac{\boxed{M_t}}{M_W}\right)^2, \ln\left(\frac{\boxed{M_h}}{M_W}\right)$$

-> M_t ~ 170 GeV

The Tevatron (Fermilab)



Top quark discovery (Fermilab 1995)



Top quark actually found where expected!

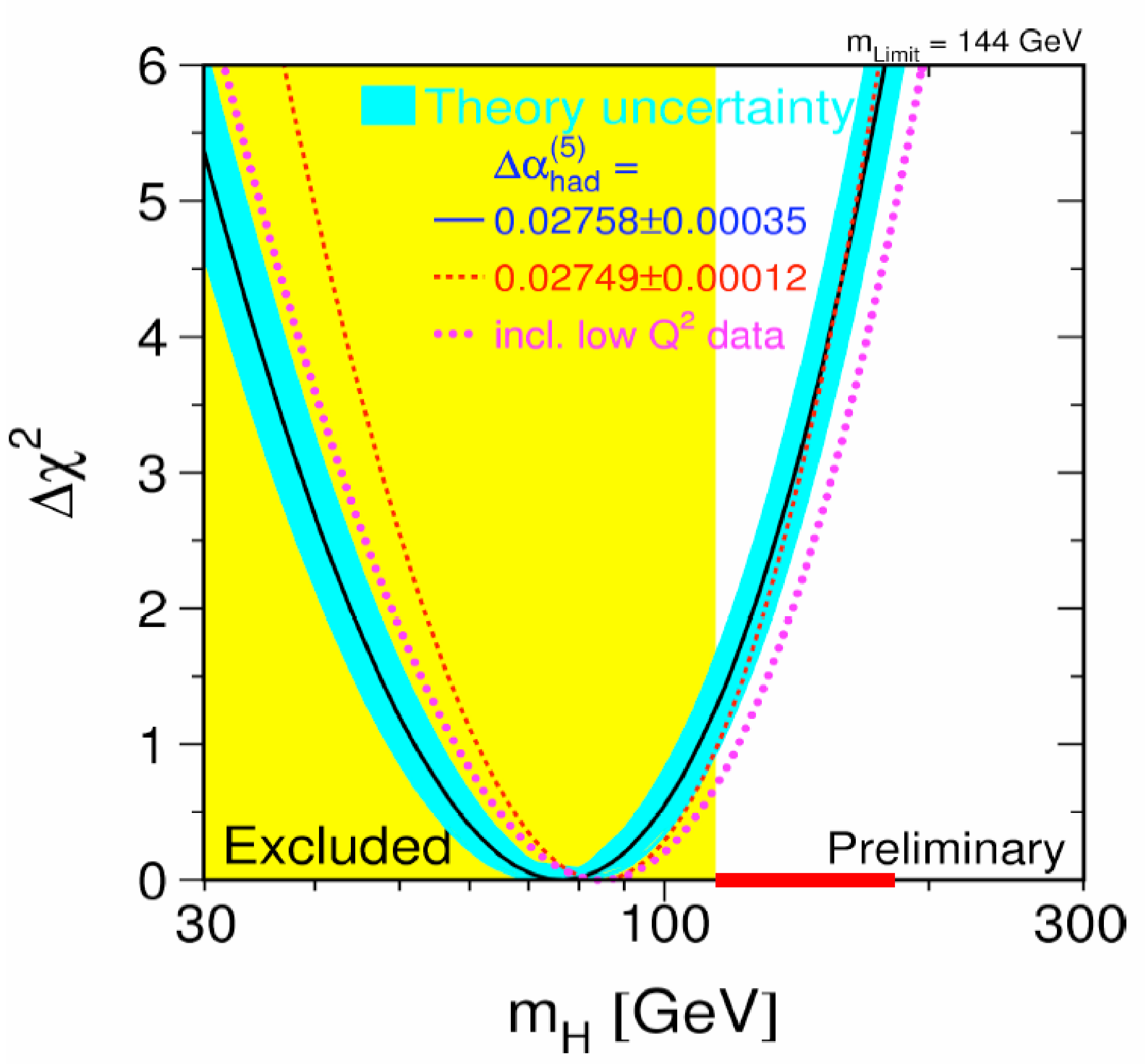
Tevatron at Fermilab (CDF + D0)

recent mass value: (EPS07)

$$M_{top} = 170.9 \pm 1{,}8\ \mathrm{GeV}/c^2$$

it works!

Precision @ LEP and Higgs



insert measured top mass into precision measurements at LEP -> now sensitive to Higgs mass (last undetected particle of Standard Model!)

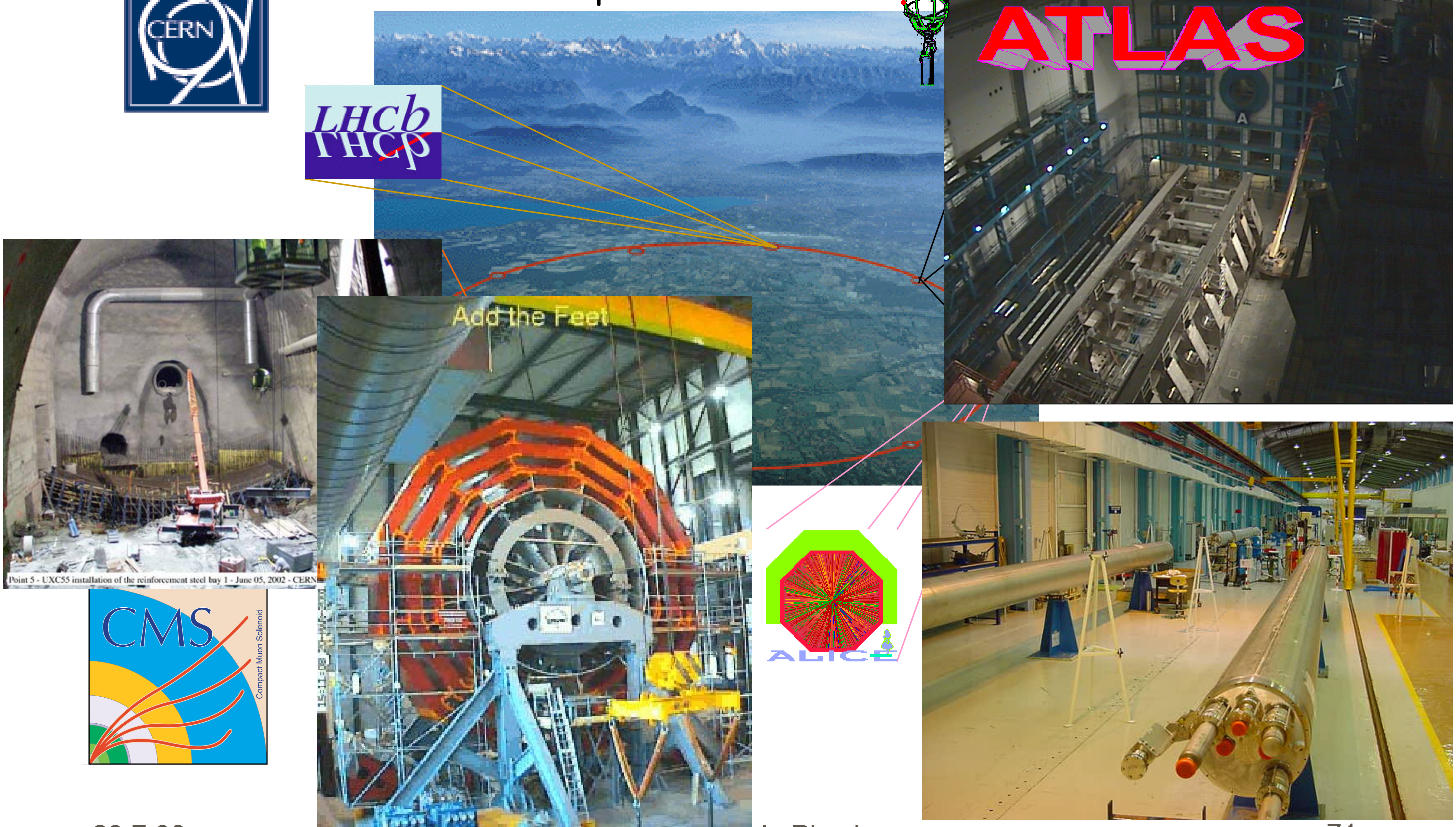
m_H < 182 GeV at 95% CL

current direct lower limit:

m_H > 114 GeV at 95% CL

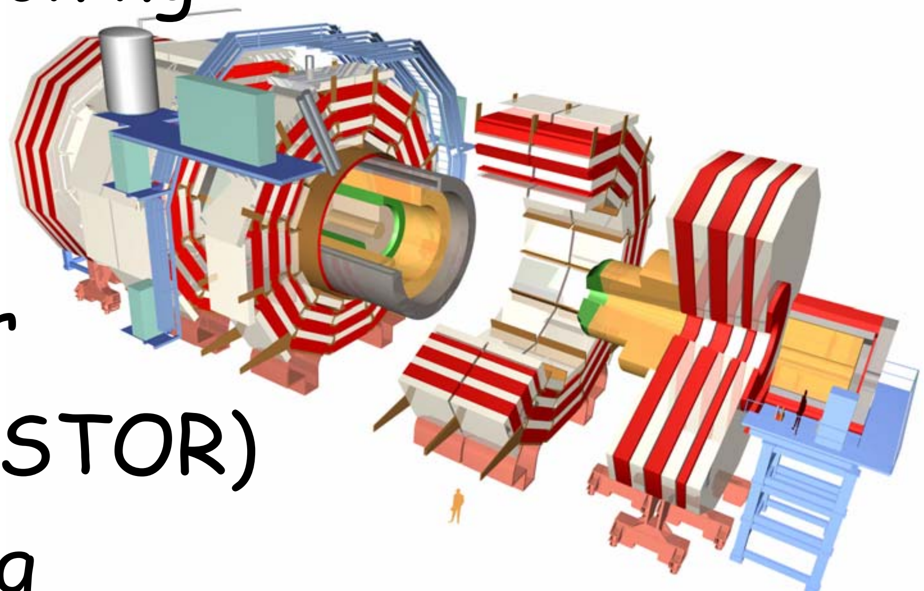
The LHC Project

scheduled startup: October 2008 !



The DESY CMS group

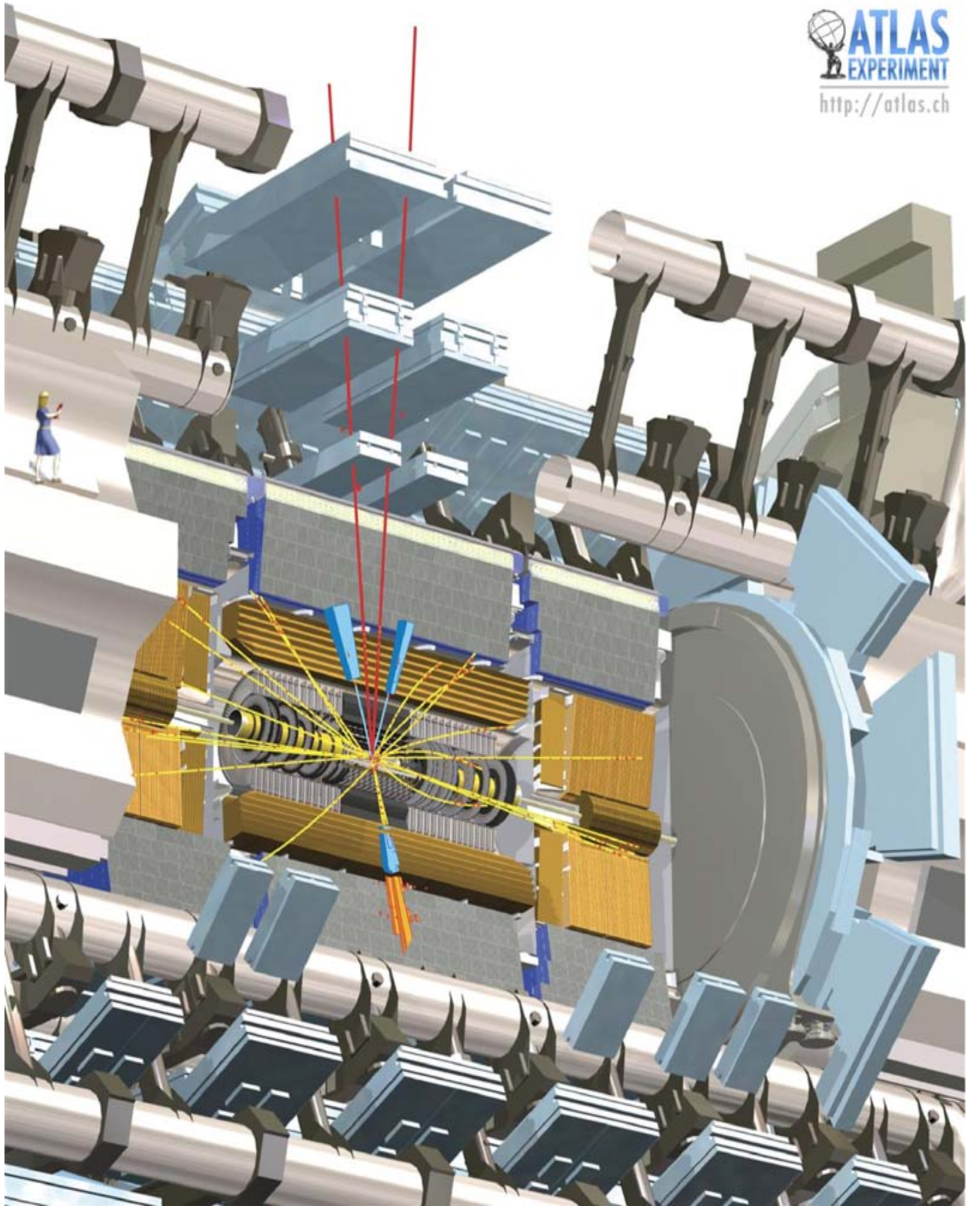
- Installation & Commissioning
- Computing
- High Level Trigger
- Beam Condition Monitor
- Forward detectors (CASTOR)
- Data Quality Monitoring
- Physics
  - Standard Model
  - Forward Physics
  - Top + Higgs



CMS remote center at DESY

The DESY ATLAS group

- High level trigger
- Computing
- Lumi monitor (ALFA)
- sLHC upgrade
- Physics:
  - Standard Model
  - Top quarks
  - Supersymmetry



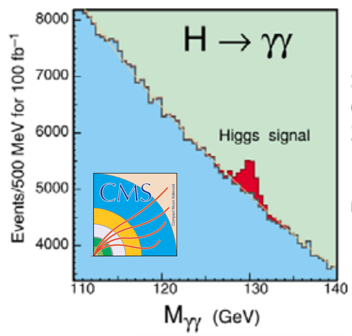
LHC startup exhibition

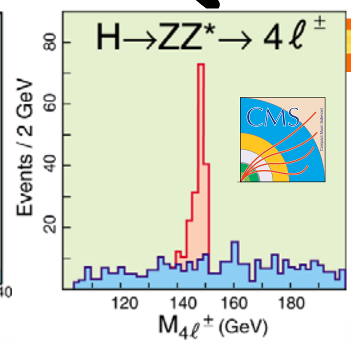
for the general public

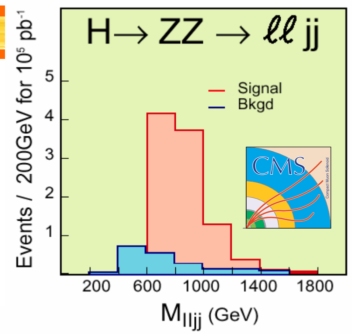
Berlin, U-Bahnhof Bundestag,

15.10-16.11. 2008

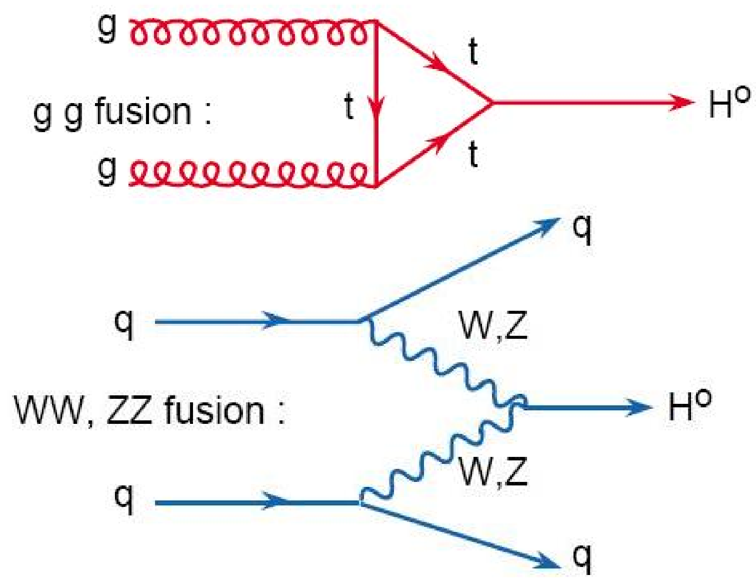
The Quest for the Higgs at LHC

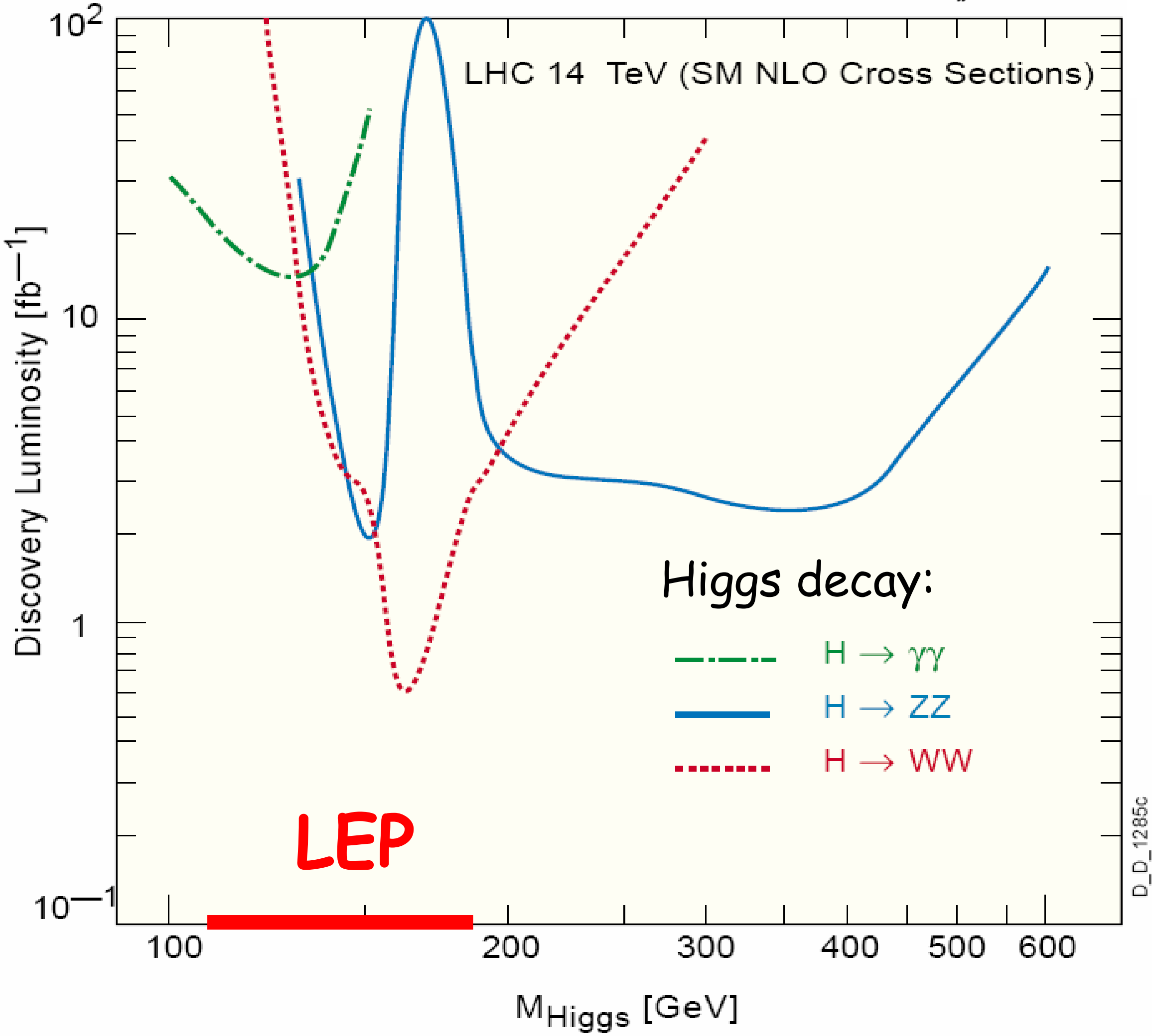






Higgs production:

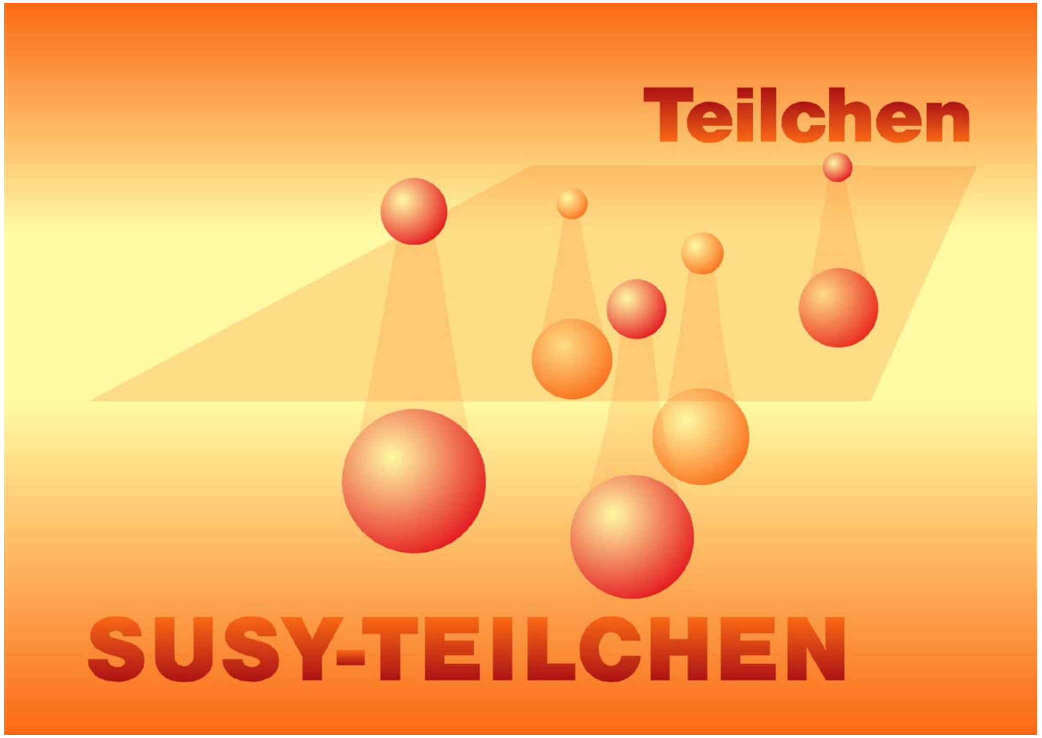




depending on mass, Higgs might be found within first year of LHC physics operation!

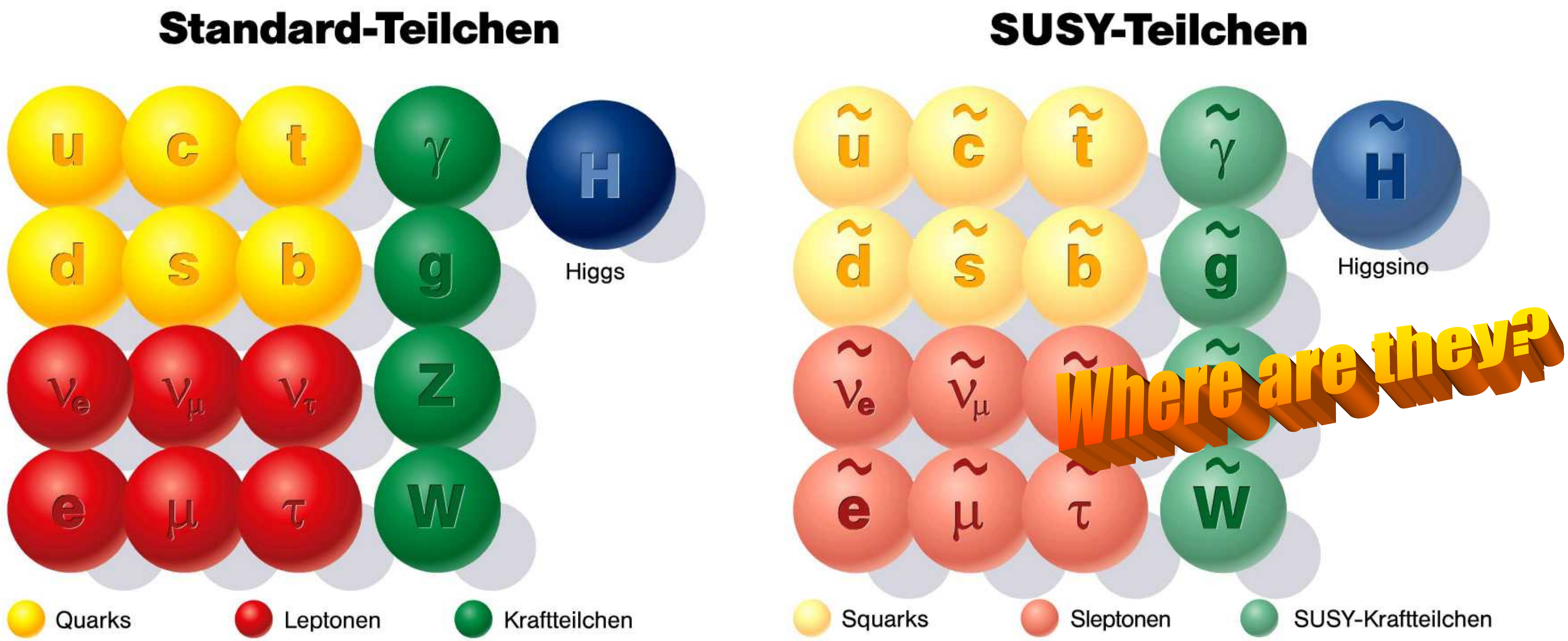
Supersymmetry

- A way to solve theoretical problems with Unification of Forces: Supersymmetry
- For each existing particle, introduce similar particle, with spin different by 1/2 unit



Supersymmetry

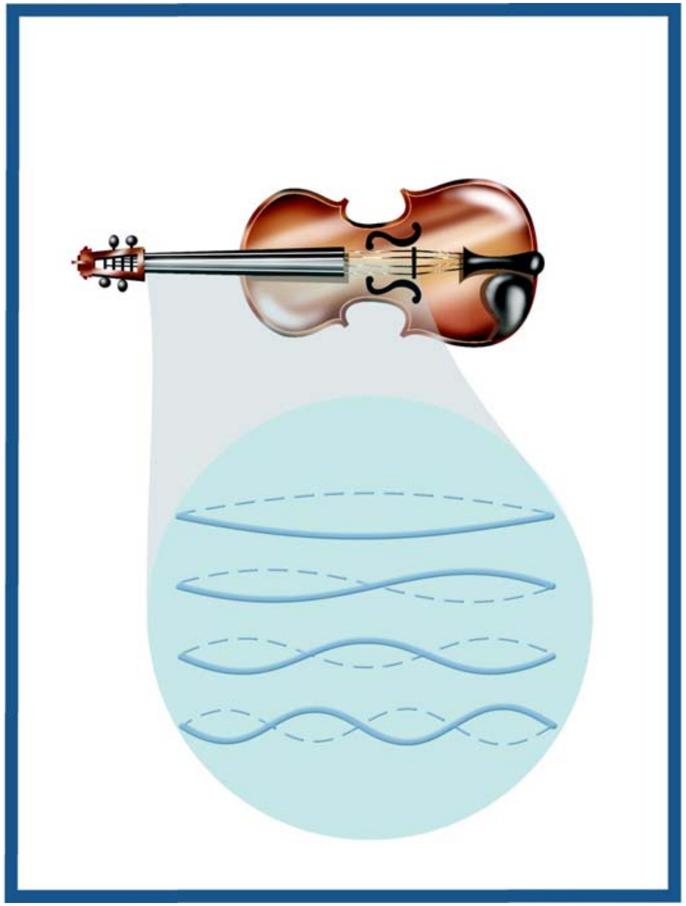
- double number of particles:

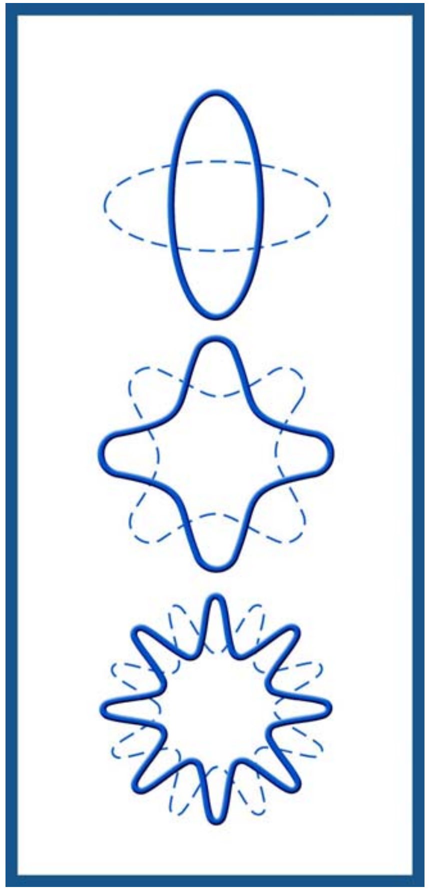


- not seen at LEP, HERA, Tevatron ... -> must be heavy!
- **hope to see them at LHC !**

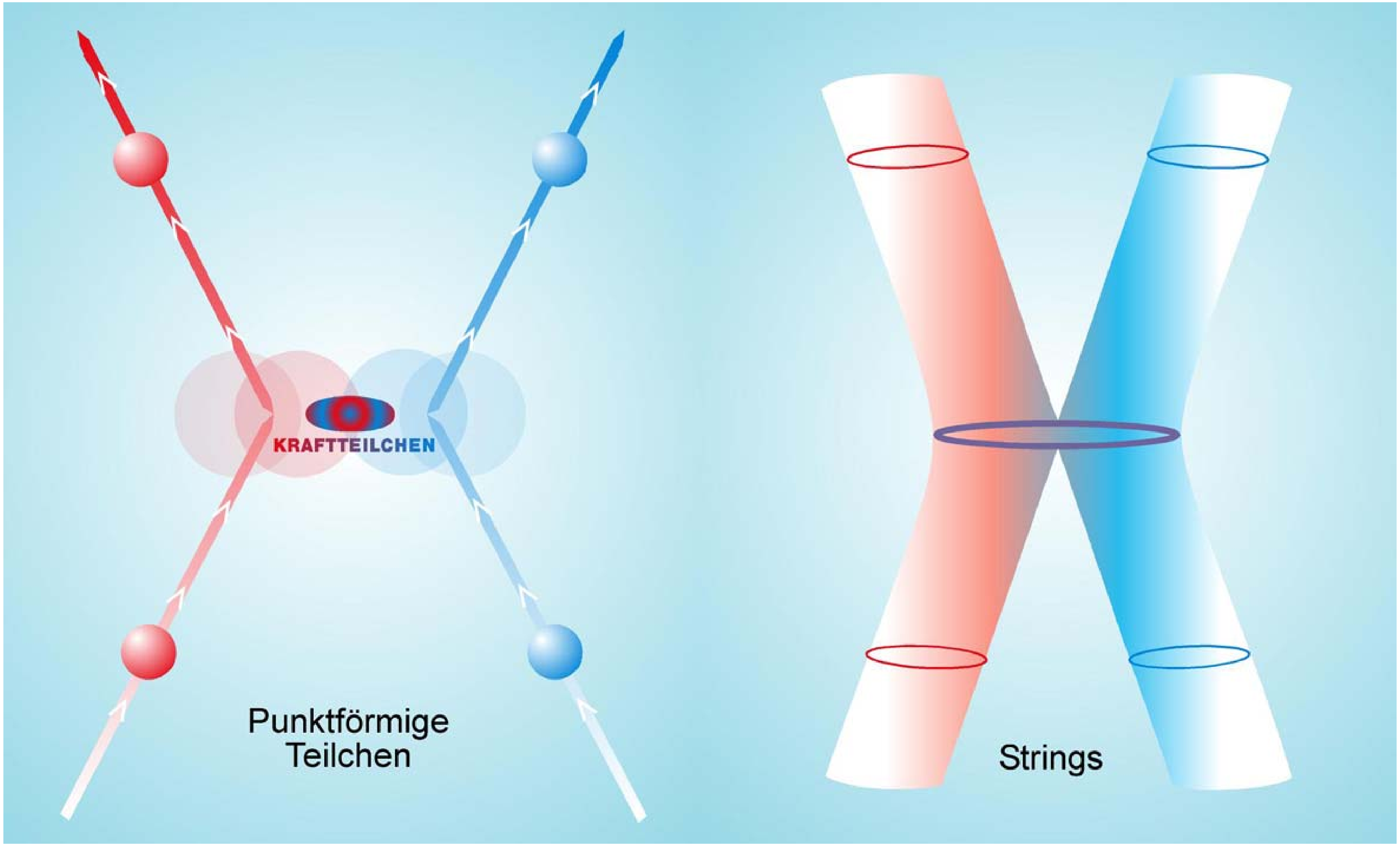
Unification and Superstrings

To include gravity in unification of forces, need Superstrings (Supersymmetric strings)



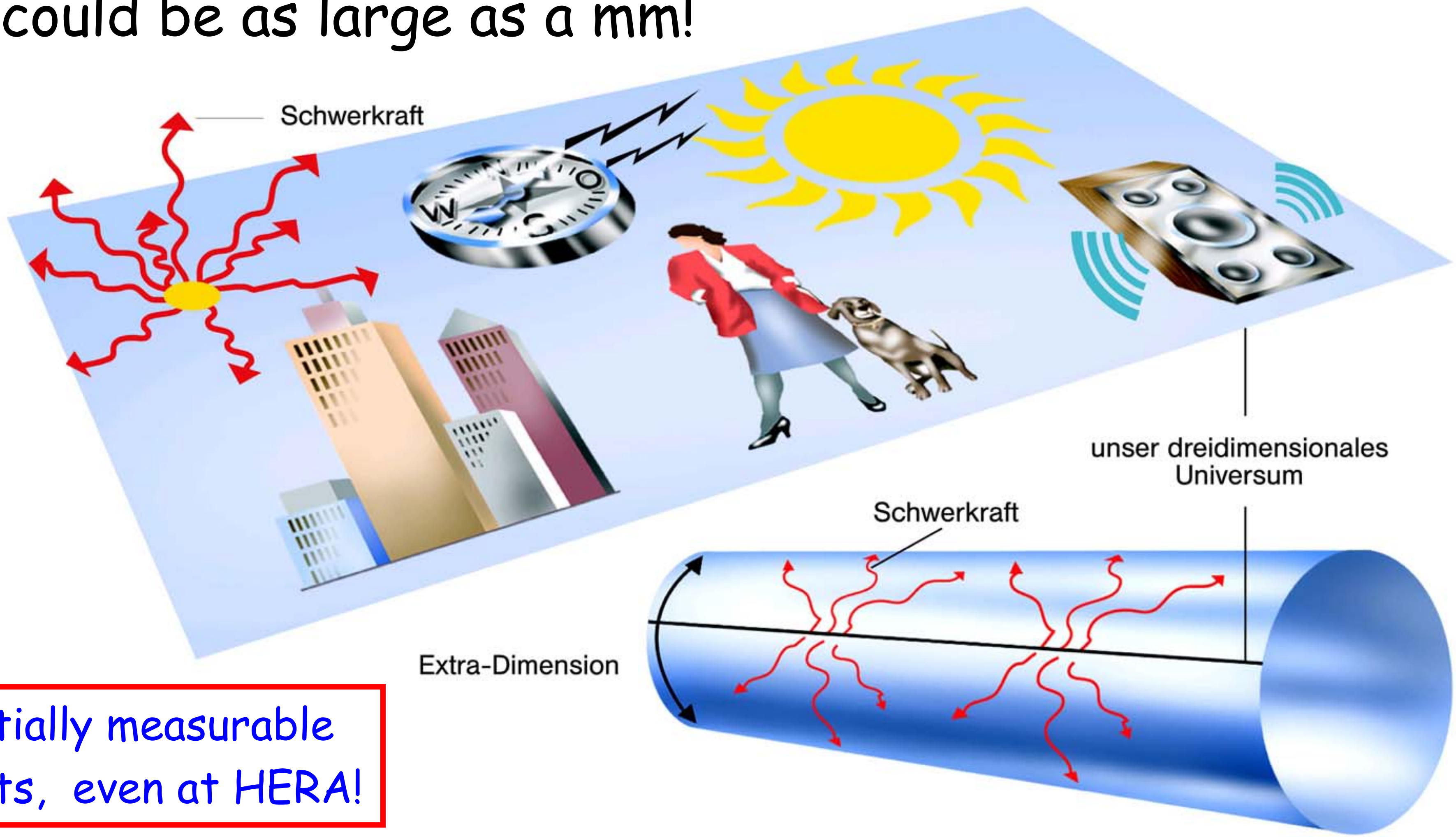


Superstring interaction



Extra Dimensions?

- Superstrings require more than 3+1 dimensions
- additional "extra" dimensions -> "curled up"
  - could be as large as a mm!



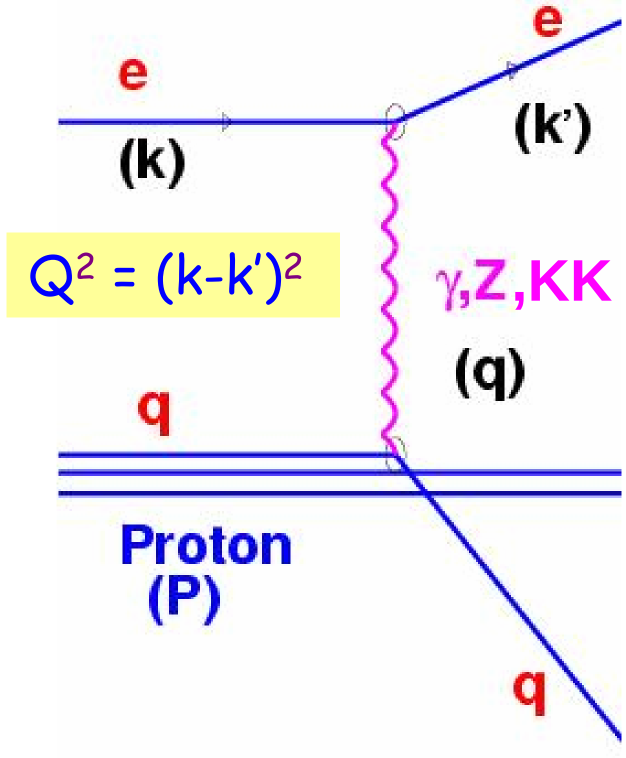
potentially measurable effects, even at HERA!

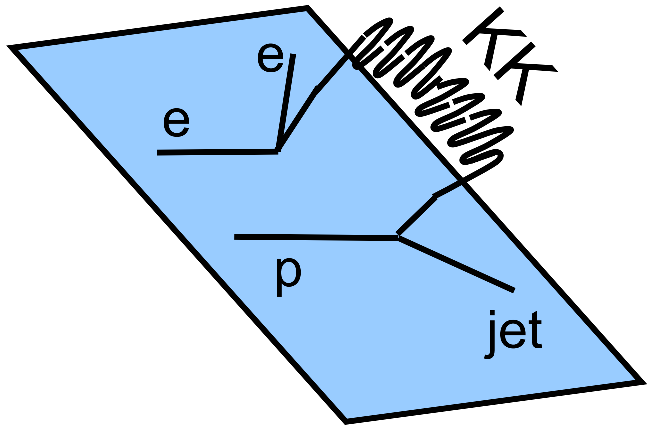
Large extra dimensions: virtual graviton exchange

Virtual graviton exchange in t-channel interferes with Deep Inelastic Scattering (DIS)

Exchange of Kaluza-Klein tower (KK) affects Q^2 distribution at high Q^2

Compare $d\sigma/dQ^2$ to what is expected from SM





Large extra dimensions: virtual graviton exchange

Zeus	$s^{1/2}$(GeV)	L_{int}(pb^{-1})
$e^+ p$	301/319	112
$e^- p$	319	16

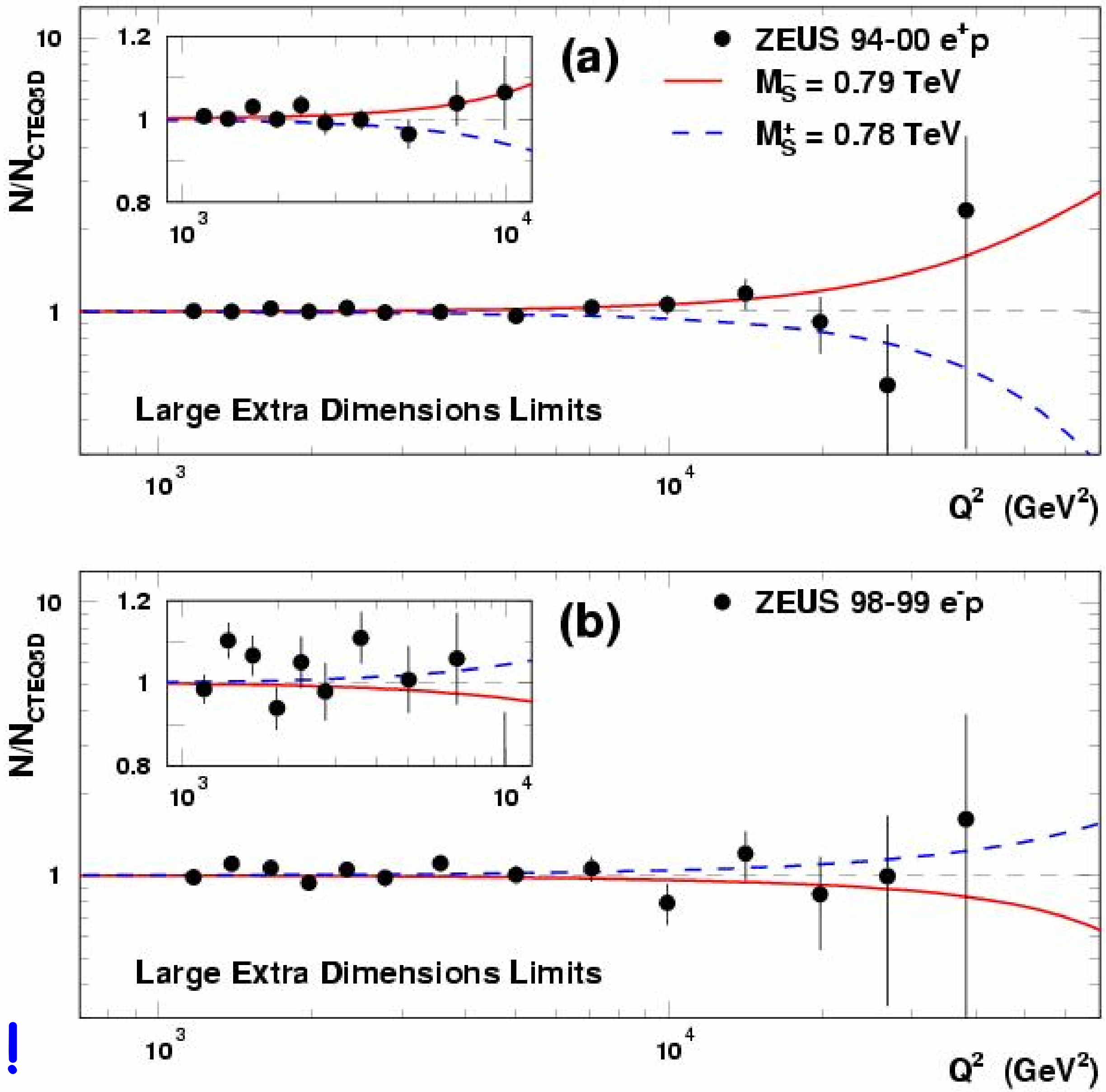
$d\sigma/dQ^2$ used in binned likelihood

=> 95% CL limits on M_S (TeV)

$\lambda = -1 : M_S > 0.79$ TeV

$\lambda = +1 : M_S > 0.78$ TeV

continue search at LHC !



The case for an e+e- Linear Collider

for more see lectures K. Buesser

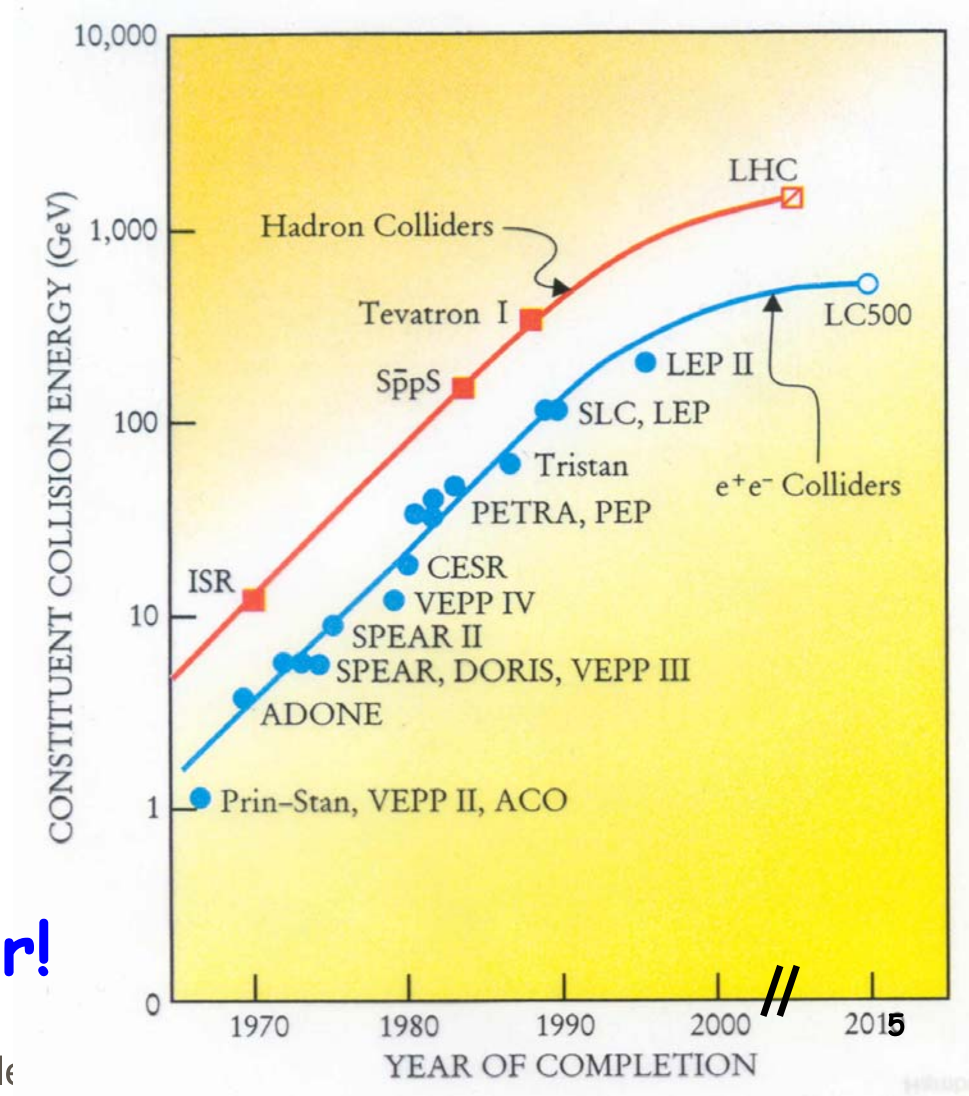
- Historically, hadron (proton) and electron colliders have yielded great symbiosis:

- hadron colliders: discoveries at highest energies

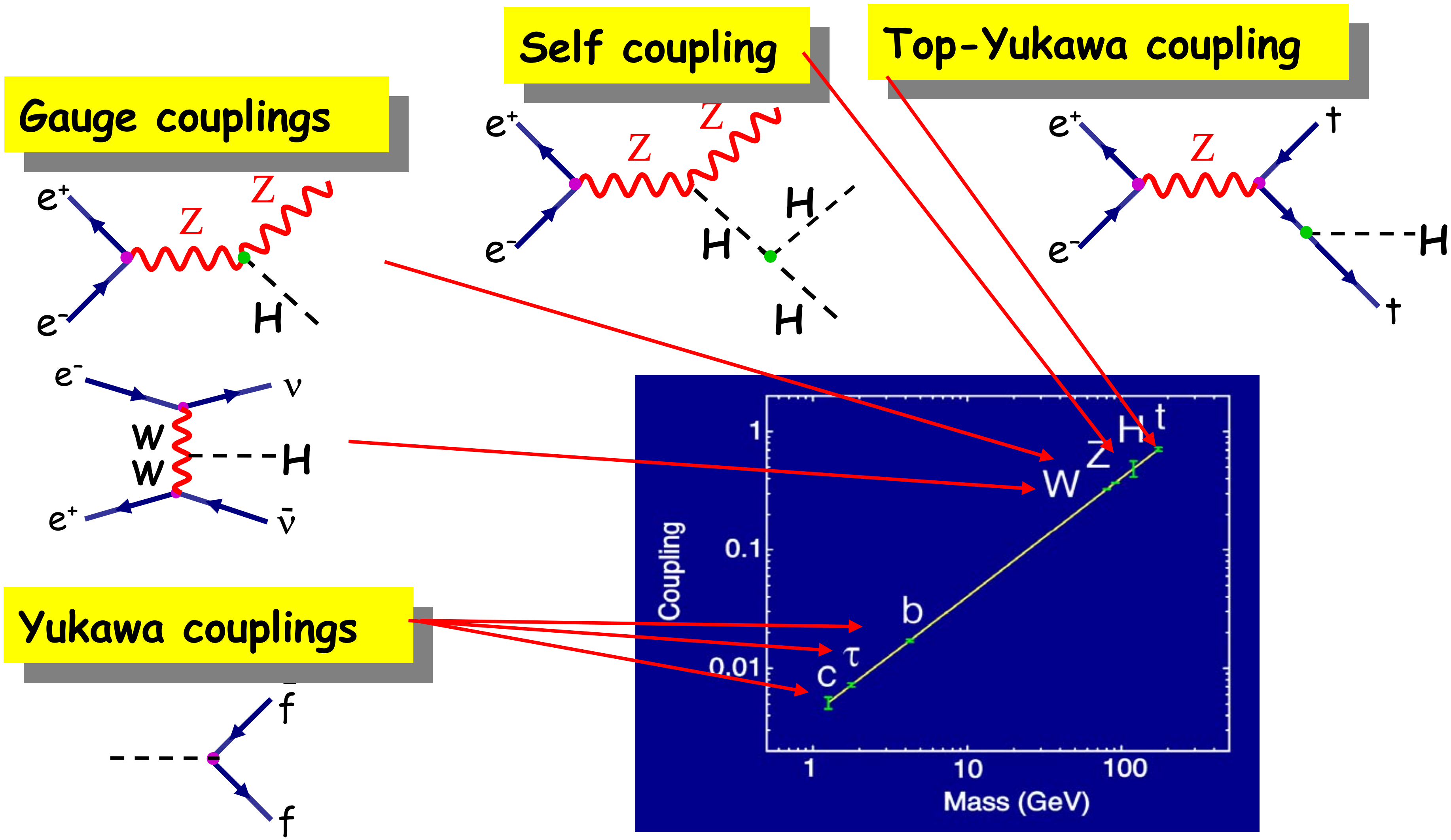
- electron colliders: discoveries and precision measurements

- latest example: Tevatron/LEP (top)

=> International Linear Collider!



Example: Higgs Physics at the ILC

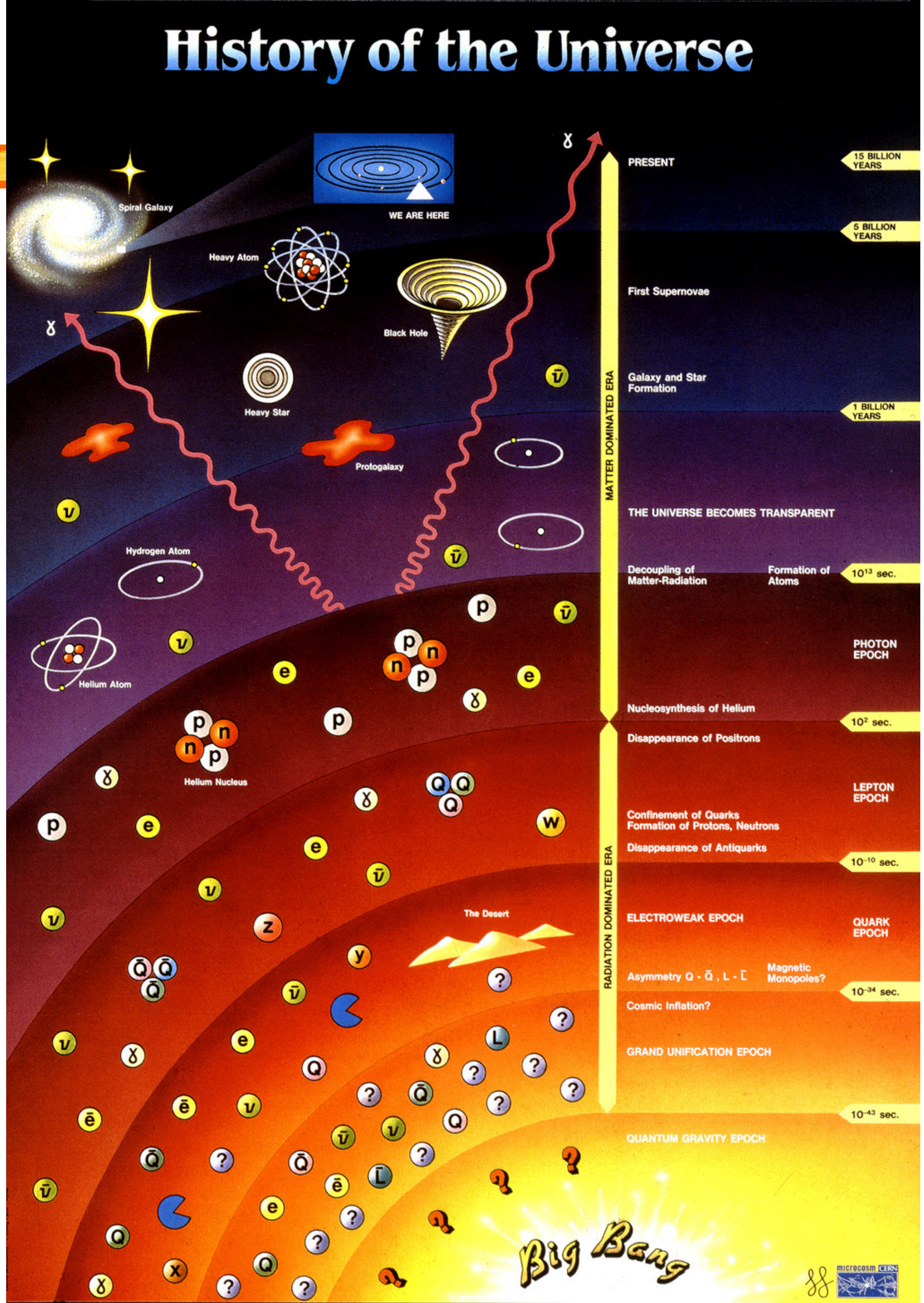


all measurable with high precision!

Cosmology

Direct link between Particle Physics and Cosmology

increasing energy
-> going further
backwards in time
in the universe
-> getting closer to
the Big Bang



The Big Bang

Galaxy formation

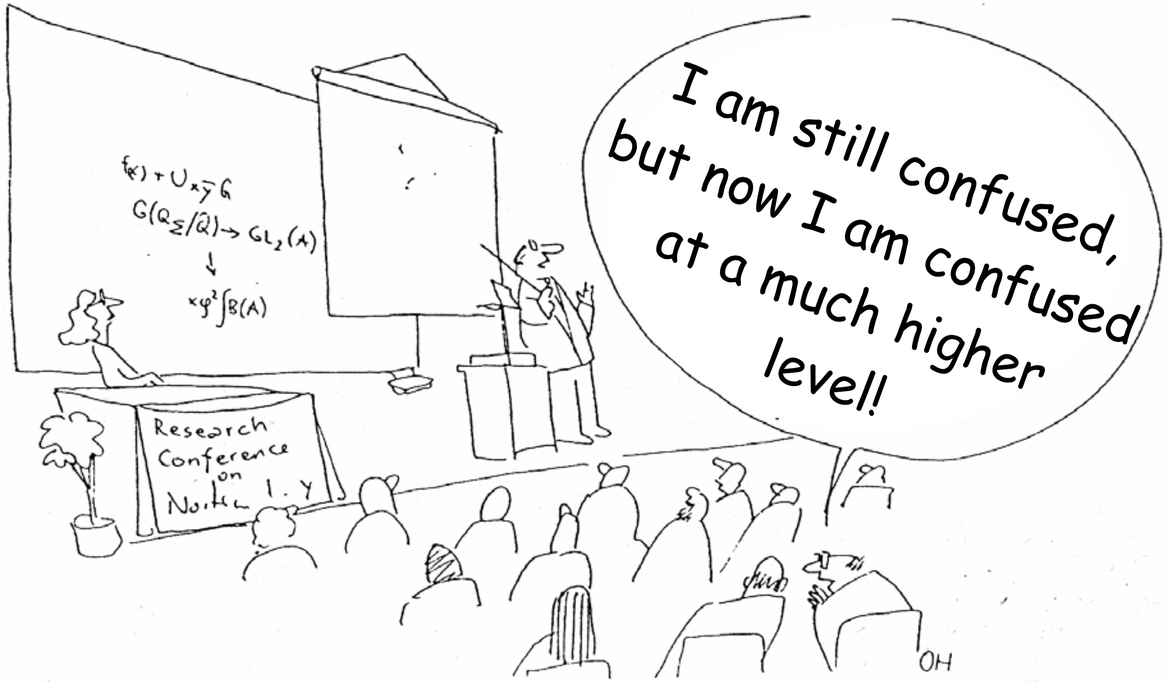
1000 M years

Galaxies begin to form

Urknall

Elementary Particle Physics is exciting!

- We already know a lot, but many open issues



- Exciting new insights expected for the coming decade!

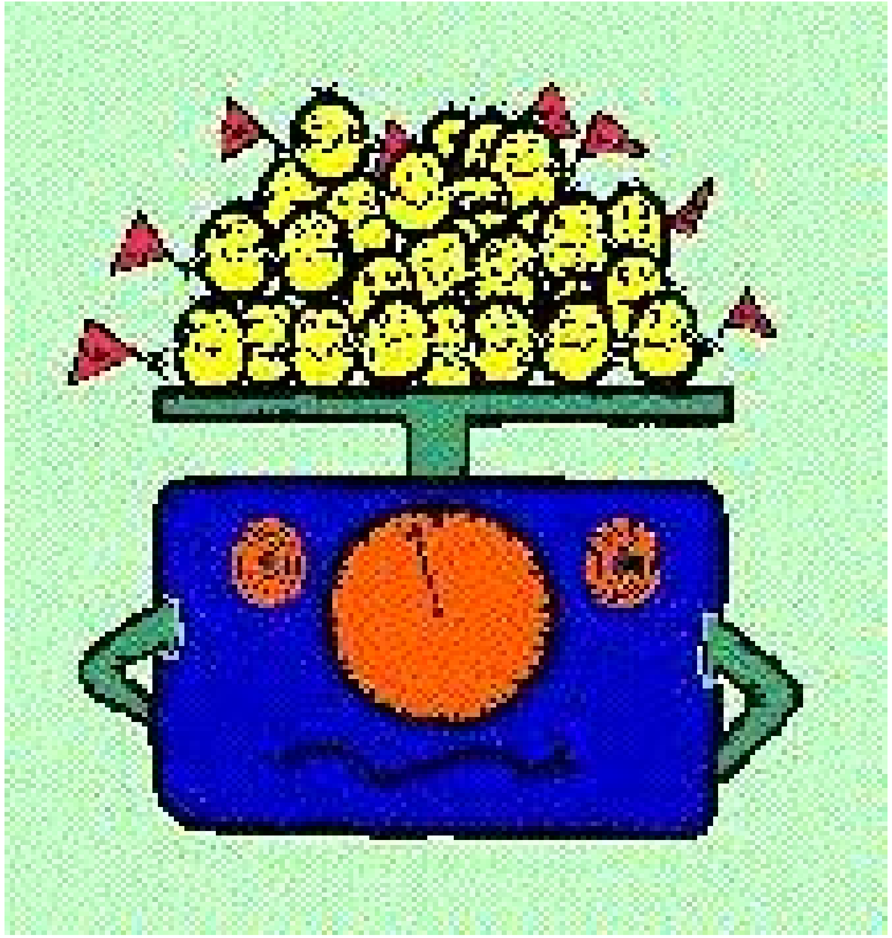
Join the Fun!

Backup Slides

Why ILC?

- If LHC finds Higgs
  ILC will study its detailed properties
- If LHC does not find Higgs
  -> Problem with Standard Model, only ILC can study why (precision measurements)
- If LHC finds SUperSYmmetery
  ILC will study SUSY particles, and potentially find/distentangle many more
- If LHC does not find SUperSYmmetry
  ILC might provide indirect evidence (precision measurements)
- + potential unexpected discoveries ...
  Compositeness, Large Extra Dimensions, indirect effects from Superstrings, ...

How much do Neutrinos weigh?



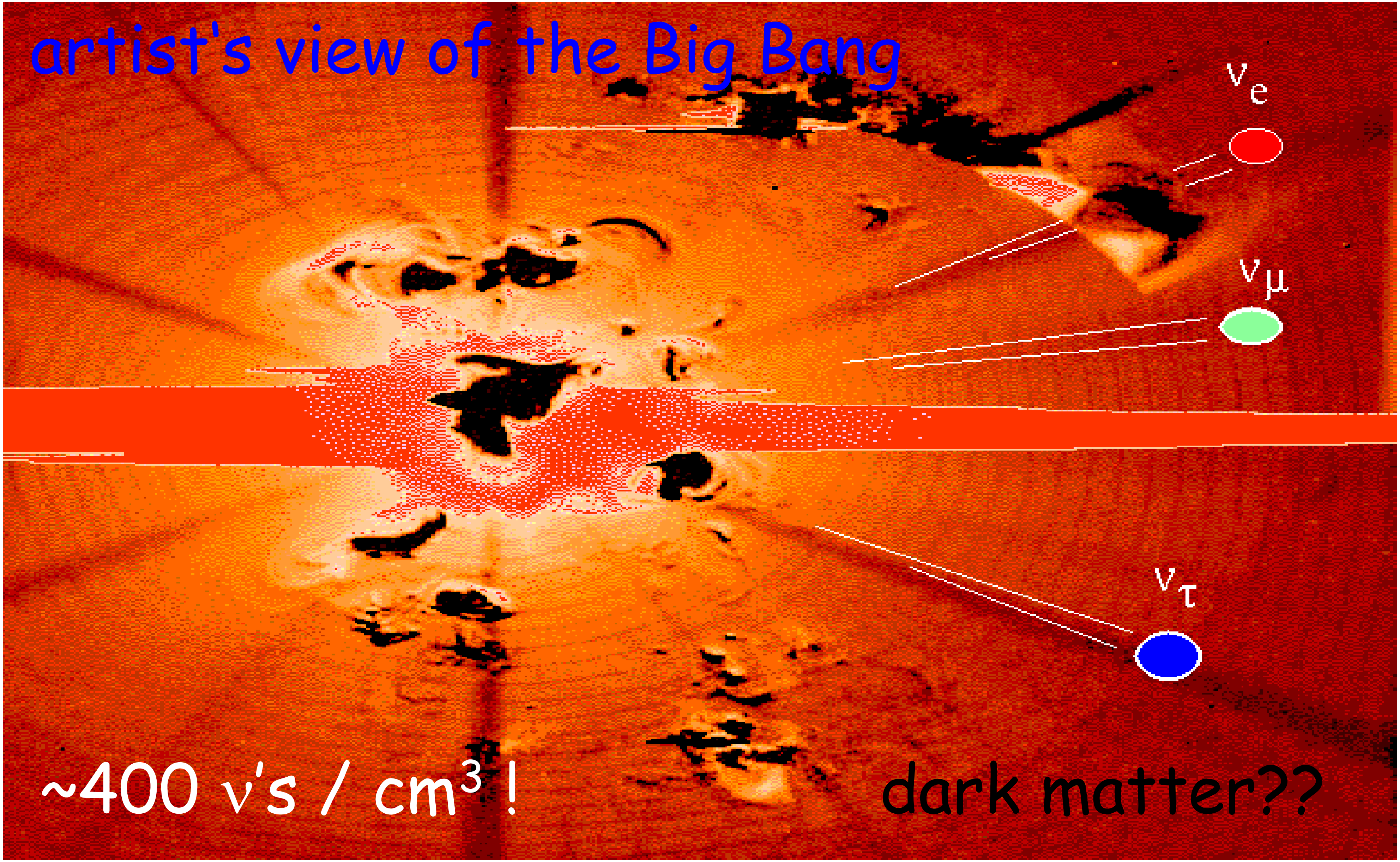
Standard Model has $m_\nu = 0$

-> evidence for $m_\nu \neq 0$
forces

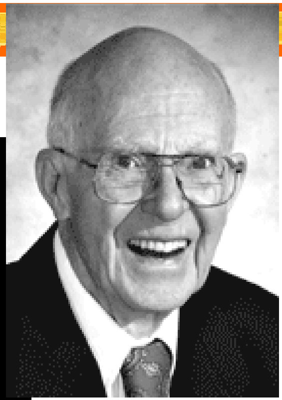
extension of Standard Model

nothing ? or almost nothing?

Neutrinos in Cosmology



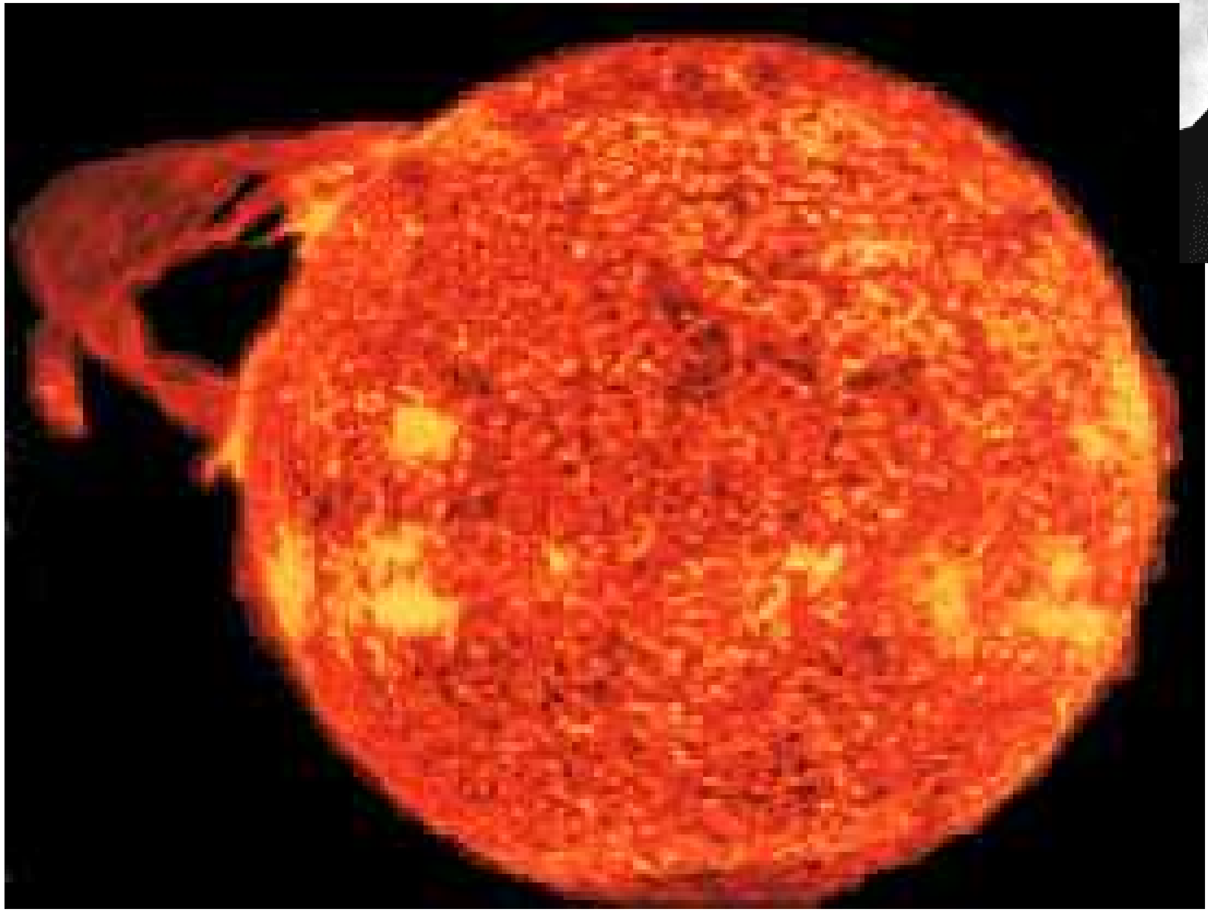
Neutrinos from the Sun



Raymond Davis Jr

(Nobel 2002)

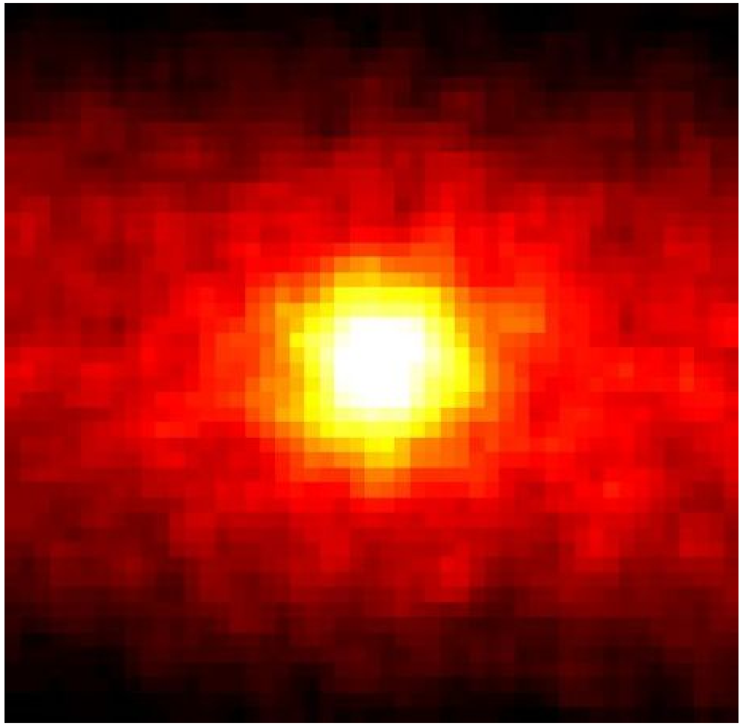
Masatoshi Koshiba



$\sim 7 \times 10^{10}$ ν's / cm^2 s

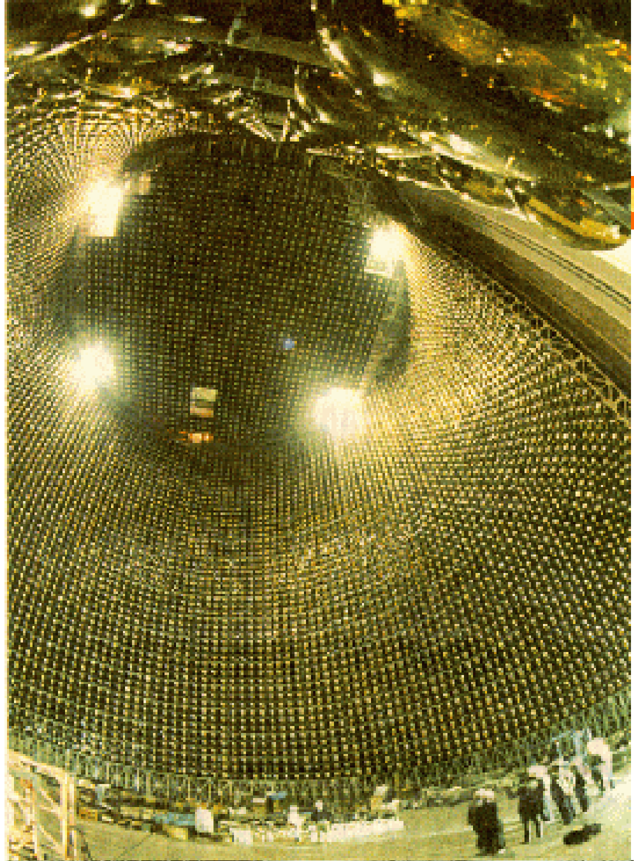
measure ~ half predicted!?

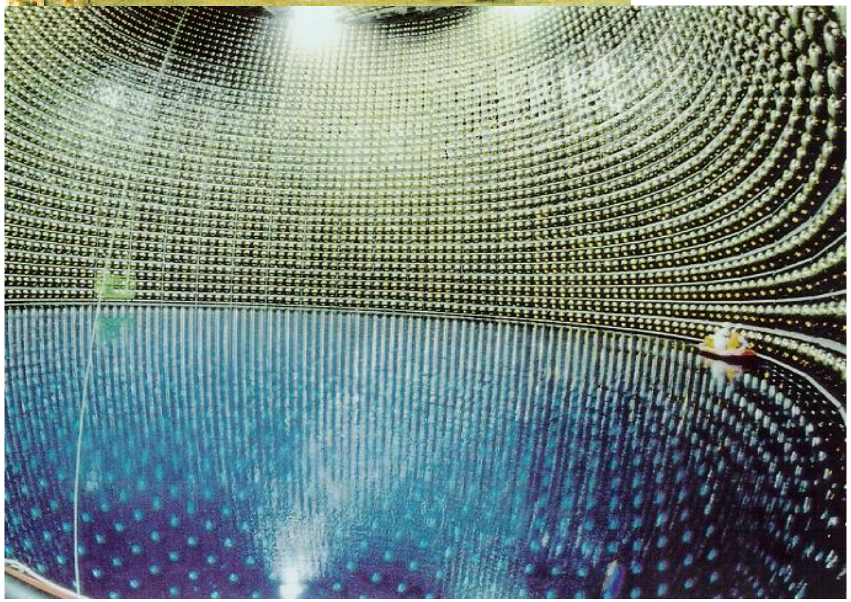
The sun in neutrino "light" (Super-Kamiokande)



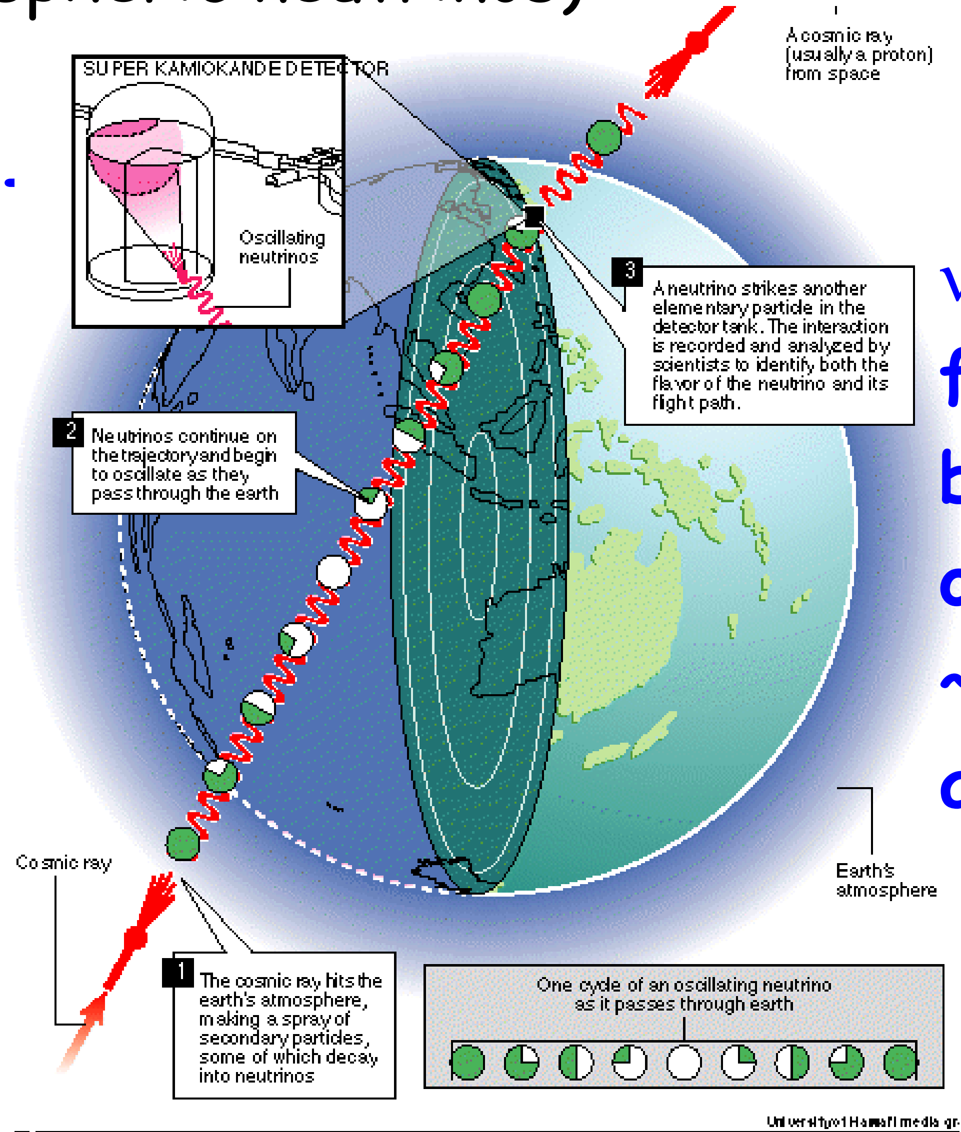
Neutrinos from Cosmic Rays

(atmospheric neutrinos)





Super Kamio-kande



ν rate from below only ~half of above ??

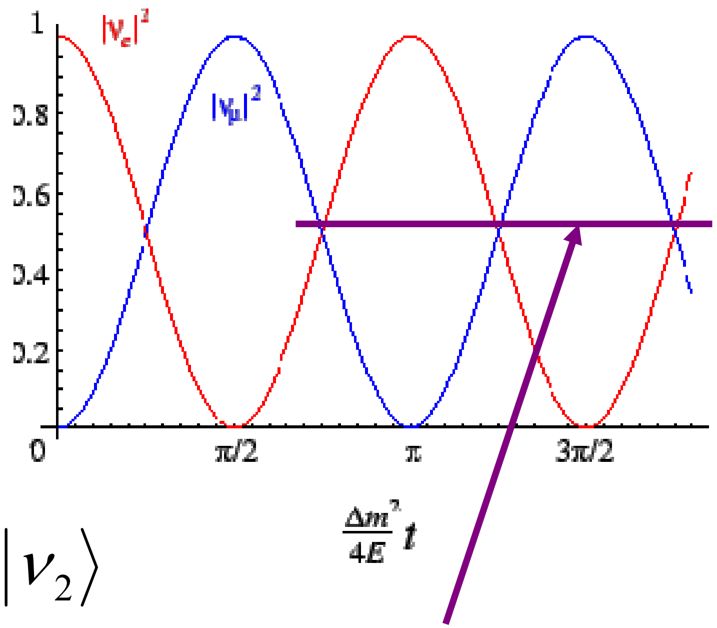
Solution: Neutrino Oscillations

simplified case: two neutrino flavours, simple quantum mechanics

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

flavour eigenstates

mass eigenstates



time evolution:

$$|\nu_e(t)\rangle = \cos\theta \cdot \exp(-iE_1 t)|\nu_1\rangle + \sin\theta \cdot \exp(-iE_2 t)|\nu_2\rangle$$

average ~ 50%

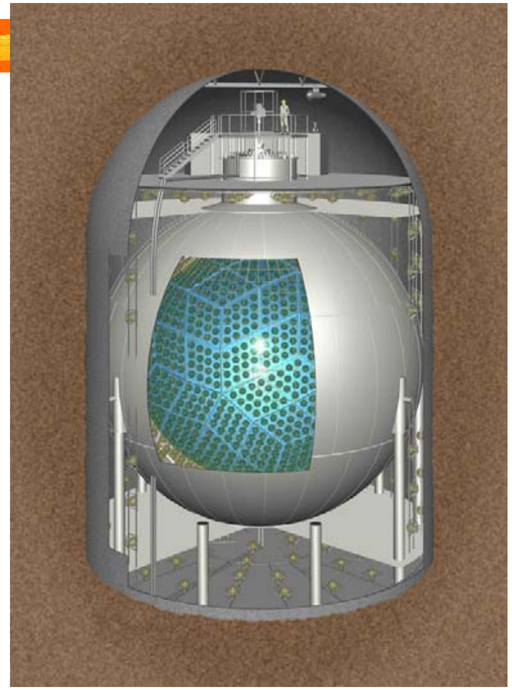
if $m_1 \neq m_2$ -> $E_1 \neq E_2$ -> **oscillations !**

$$P_{\nu_e \to \nu_\mu} = \sin^2 2\theta \cdot \sin^2\left(\frac{1.27 \cdot L(\mathrm{m}) \cdot \Delta m^2 (\mathrm{eV}^2)}{E_\nu (\mathrm{MeV})} \right)$$

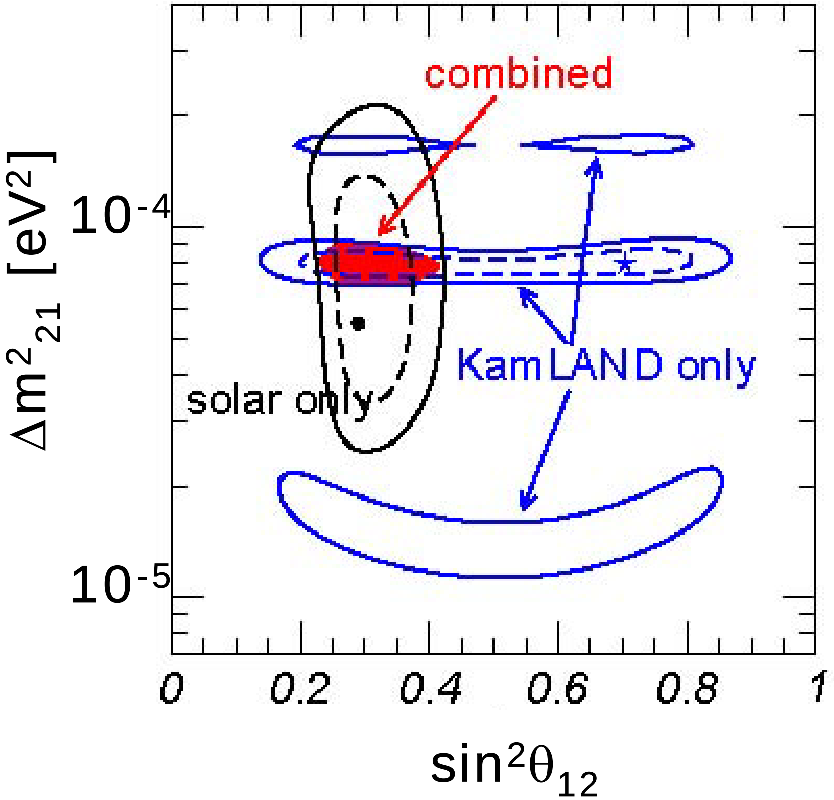
Solution for "Solar" Neutrinos

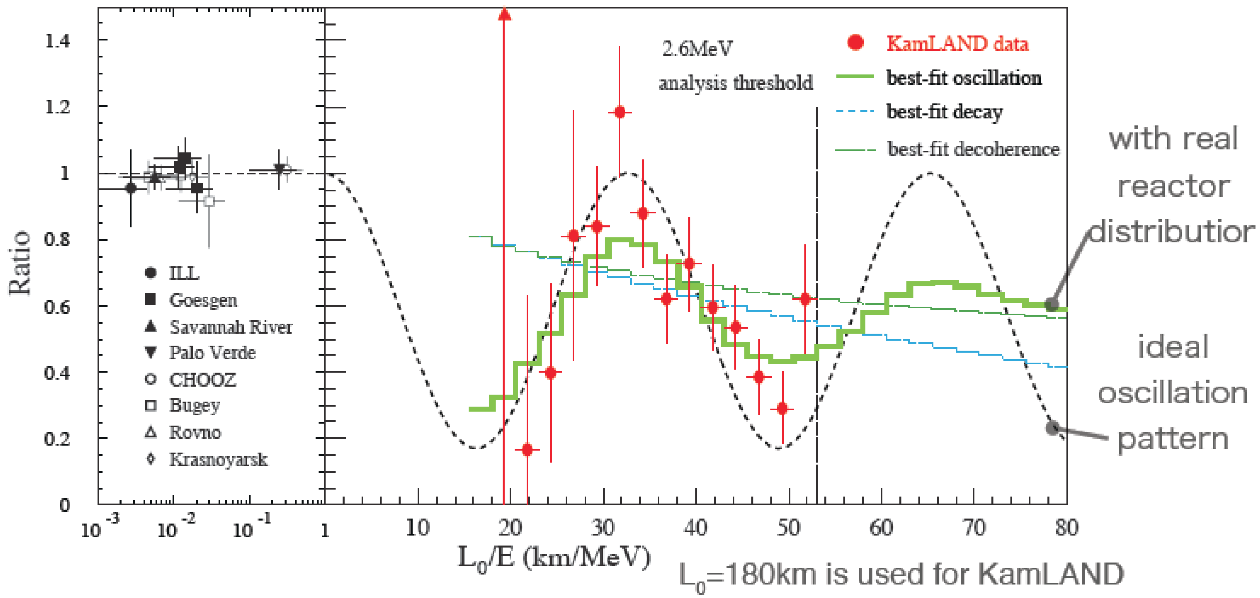
SNO,
Solar Neutrino
Observatory

$$\nu_e \longrightarrow \nu_x$$

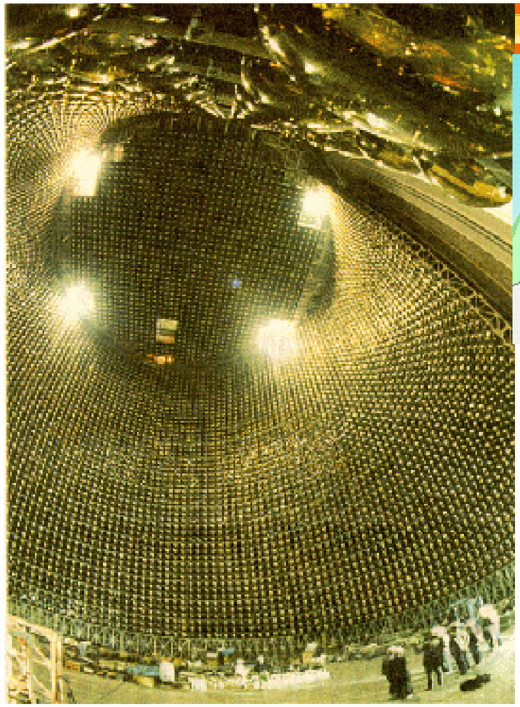


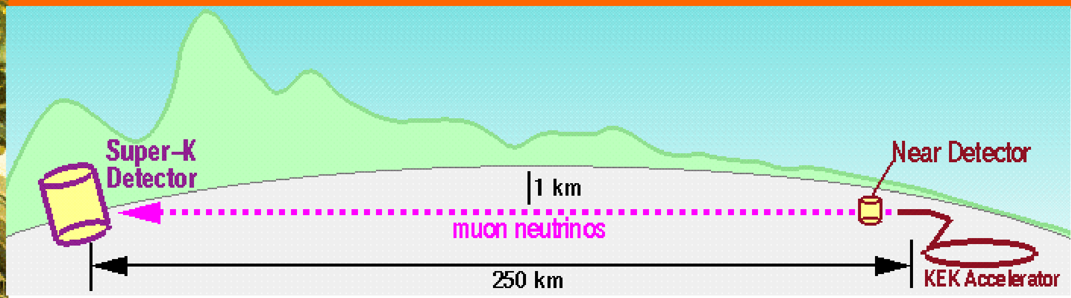
KamLand,
Reactor Neutrino
Experiment

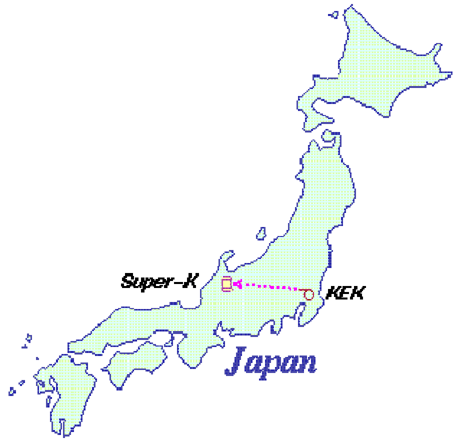




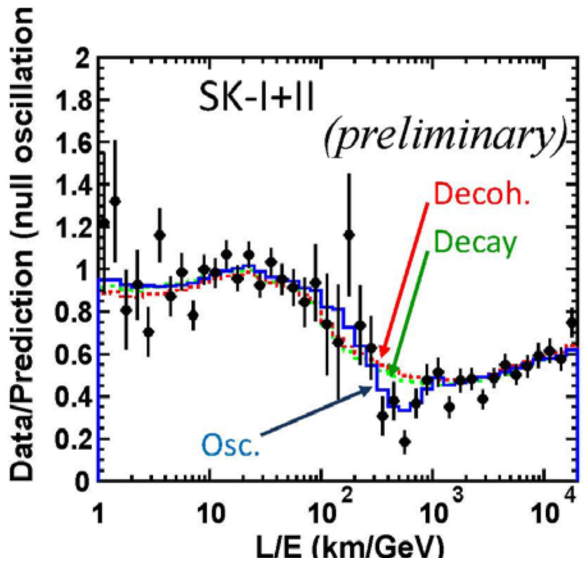
Solution for "Atmospheric" Neutrinos

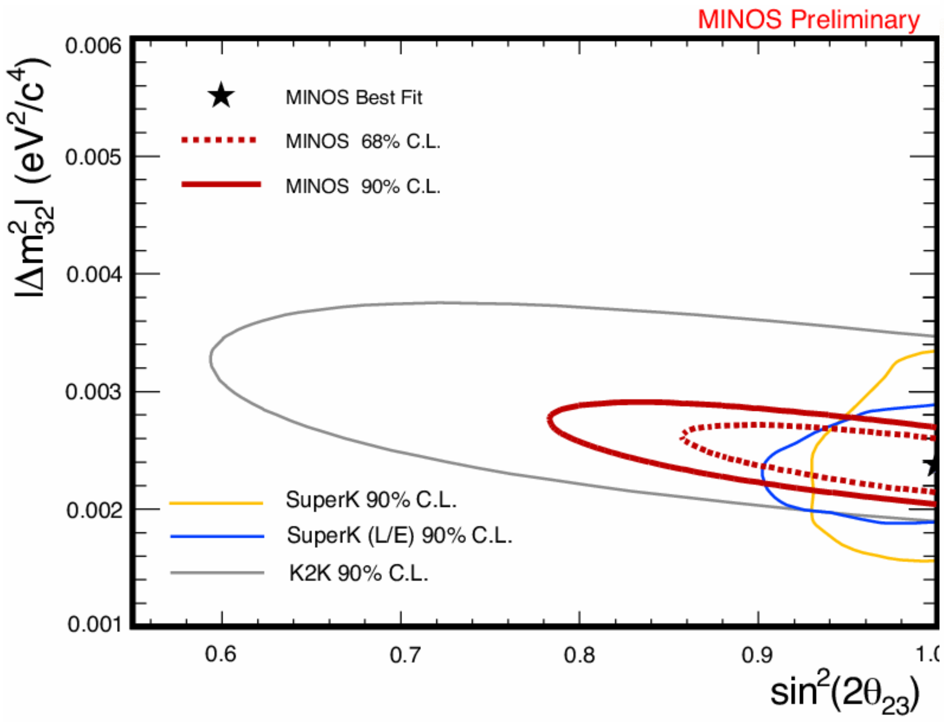






$$\boxed{\nu_\mu \longrightarrow \nu_x}$$





MINOS/Fermilab

Conclusions for Neutrinos

Neutrino oscillations established

-> **Neutrinos have mass!**

-> **Extend Standard Model**

How? -> see lecture C. Hagner

Neutrino Mixing is large! **Surprise!**

Important consequences e.g. for CP violation

Helmholtz-Alliance and Tier-2