Karlsruher Institut für Technologie

Vorlesung:

Teilchenphysik I (Particle Physics I)

Brief History of Particle Physics

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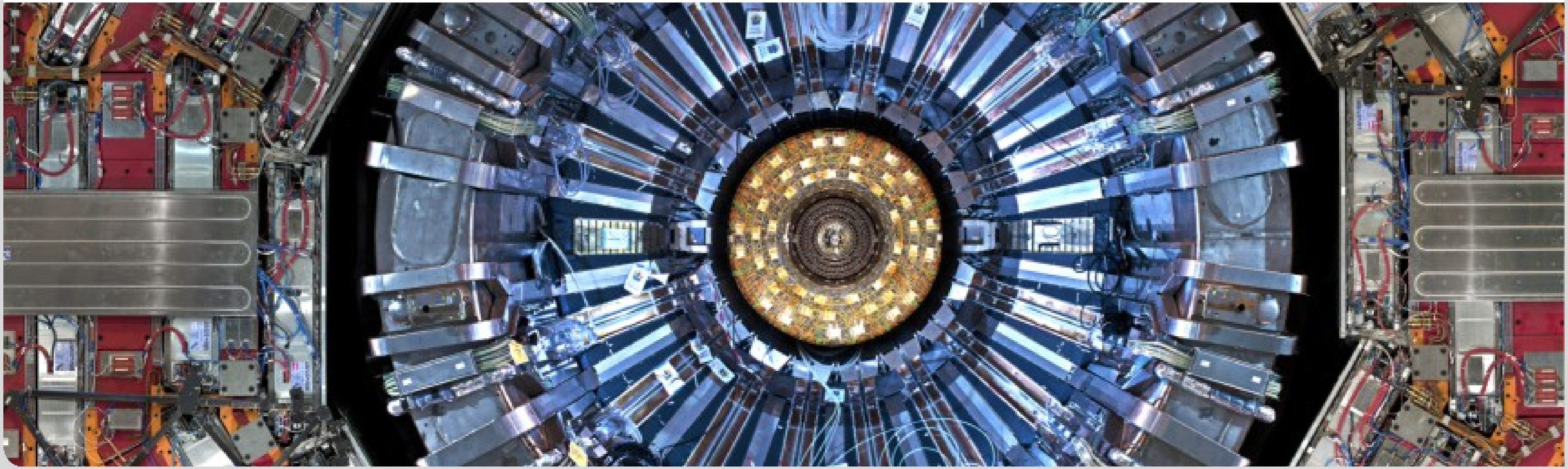
WS20/21



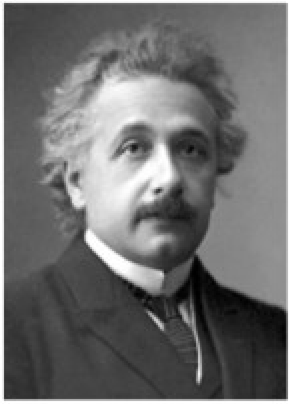
Quantum Mechanics & Special Relativity

- Theoretical foundation of Particle Physics
  - ***Quantum mechanics*** (Heisenberg, Schödinger, Dirac, . . . , 1920s)
  - ***Special relativity*** (Einstein, 1905)
- Modern theories in Particle Physics: relativistic ***quantum field theories*** (QFT)
  - Lorentz invariant
  - Quantised fields (fields $\equiv$ quantum mechanical operators)
  - Physical particle $\equiv$ excitation ("quantum") of fields

Werner Heisenberg

Erwin Schrödinger

Paul A. M. Dirac



Albert Einstein

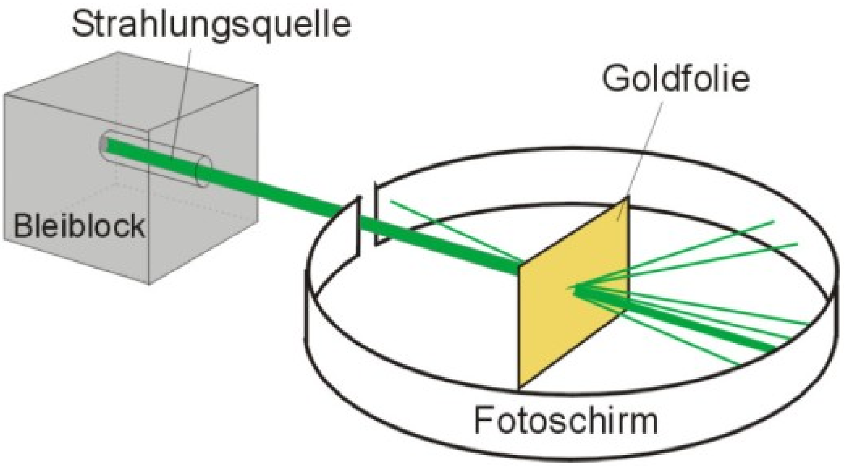
https://www.nobelprize.org/

Nuclear Force

- ***Rutherford experiment***
  (Rutherford, Geiger, Marsdon 1911)
  - Beam of α particles at gold foil
    $\rightarrow$ distribution of scattering angles θ

$$\frac{\mathrm{d}N}{\mathrm{d}\theta} \propto \frac{1}{\sin^4(\theta/2)}$$

  - Angular distribution of Coulomb scattering on compact nucleus
  $\rightarrow$ atom = nucleus + shell
- Chadwick, Bieler (1921)
  - Deviation from $\sin^{-4}(\theta/2)$ behaviour
  $\rightarrow$ new ***nuclear force*** ("strong force")



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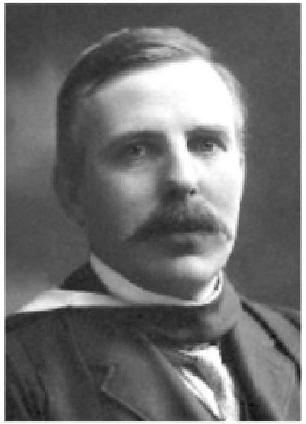


Ernest Rutherford

James Chadwick

https://www.nobelprize.org/

Nuclear Force (2)

- Discovery of the ***neutron***

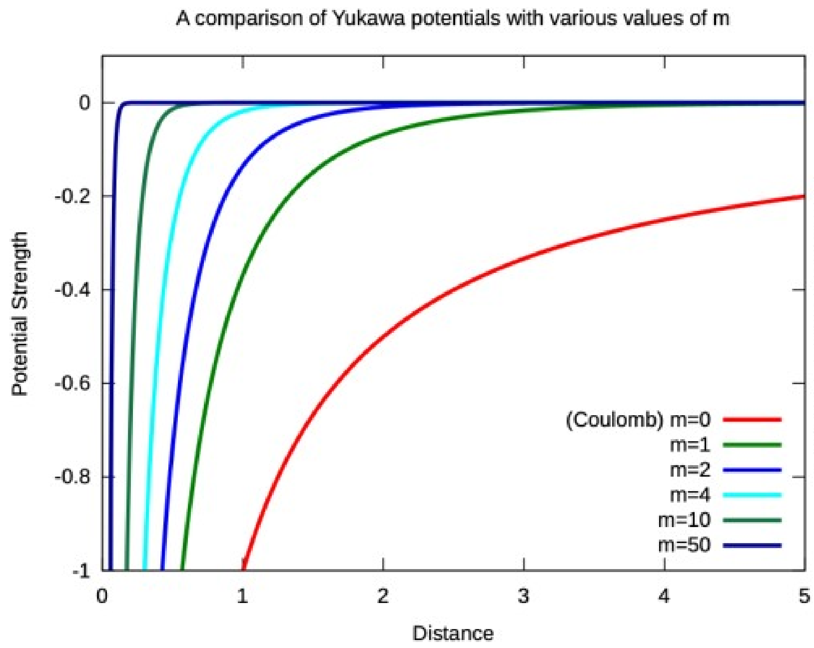
  (Chadwick 1932)
- "***meson***" as exchange particle of the nuclear force (Yukawa 1935)
  - Analogue to the photon in electrodynamics
  - Restricted range λ of nuclear force
  - ***Yukawa potential*** as function of radial distance *r*

$$V(r) \propto -\frac{\exp(-r/\lambda)}{r}\,, \quad \lambda \propto \frac{1}{m}$$

  ('screened Coulomb potential')

  - Experimentally: $\lambda \approx 1\,\mathrm{fm}$

$\rightarrow$ $m_{meson} = \frac{1}{\lambda} = 200\,\mathrm{MeV}$: pions!



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Hideki Yukawa

Strong Isospin

- New concept: ***isospin*** (isotopic spin)
  - Discovery by Heisenberg in 1932 (naming by Wigner in 1937)
  - Proton and neutron: similar properties
  - Experimentally: scattering on mirror nuclei (number of protons and neutrons switched, e. g. $^{3}\mathrm{H} \leftrightarrow {}^{3}\mathrm{He}$, $^{15}\mathrm{N} \leftrightarrow {}^{15}\mathrm{O}$)

$\rightarrow$ ***strong force independent of electric charge***, invariance when exchanging neutrons with protons

- Conclusions
  - If only strong force: proton = neutron = “nucleon”
  - ***Symmetry*** between proton and neutron: (strong) isospin *i*
  - Formal description by group theory: SU(2) group (“flavour SU(2)”, analogue to spin), nucleon as ***isospin doublet***

$$\text{nucleon} = \begin{pmatrix} |p\rangle \\ |n\rangle \end{pmatrix} = \begin{pmatrix} |I = \frac{1}{2}, I_3 = +\frac{1}{2}\rangle \\ |I = \frac{1}{2}, I_3 = -\frac{1}{2}\rangle \end{pmatrix}$$

Strong Isospin (2)

- Extension of isospin concept to further particles
  - For example: pion = ***isospin triplet***

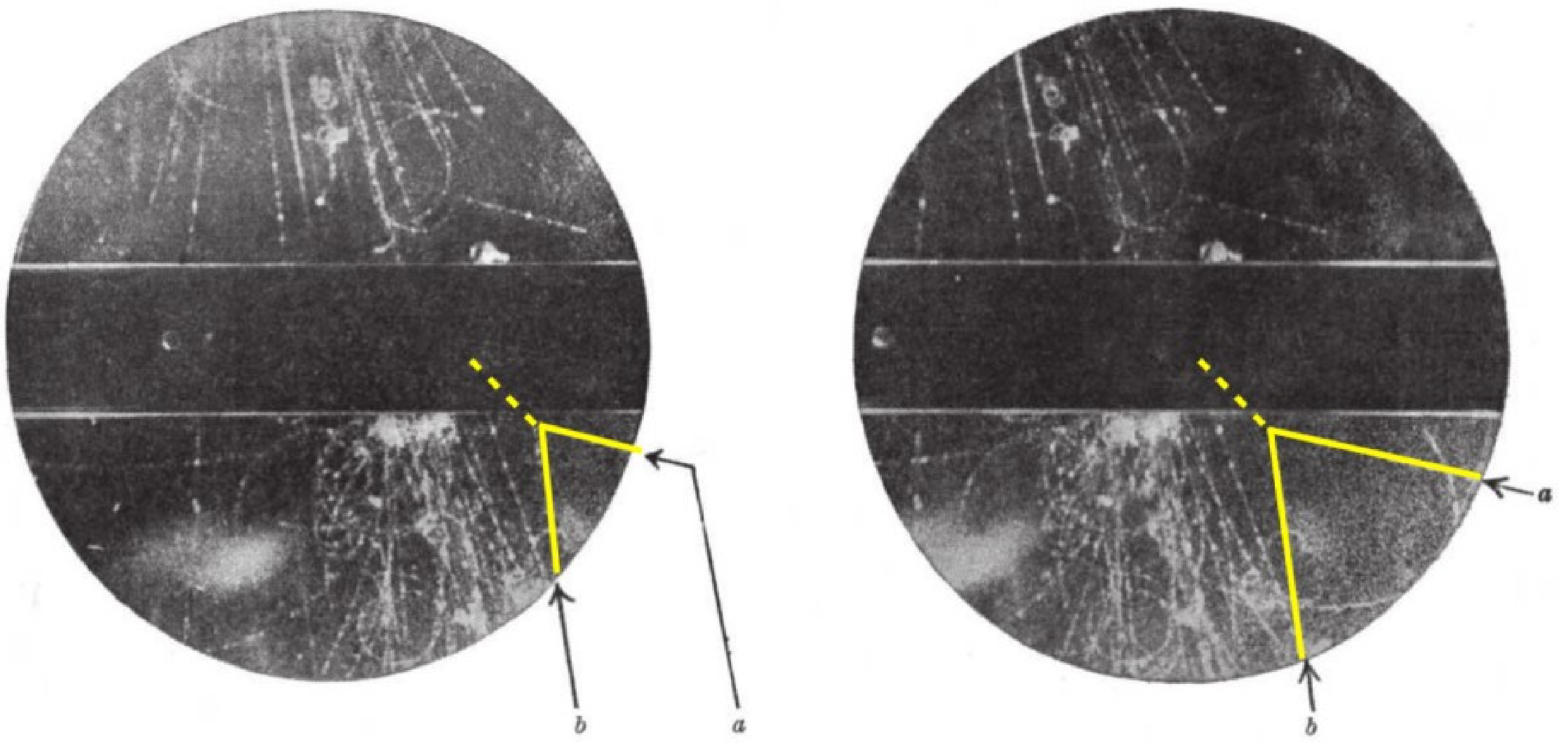
$$\text{pion} = \begin{pmatrix} -|\pi^+\rangle \\ |\pi^0\rangle \\ |\pi^-\rangle \end{pmatrix} = \begin{pmatrix} |I=1, I_3=+1\rangle \\ |I=1, I_3=0\rangle \\ |I=1, I_3=-1\rangle \end{pmatrix}$$

- Observations
  - I_3 related to electric charge Q
  - I_3 different for baryons and mesons
  - Relation to baryon number $\mathcal{B}$
    (reminder: $\mathcal{B} = \frac{1}{3}(\#\text{quarks} - \#\text{antiquarks})$)

$$\boxed{I_3 = Q - \frac{\mathcal{B}}{2}}$$

Discovery of „Strangeness“

- 1940s: ***new “strange” particles*** with long lifetime in cosmic rays
  - Rochester, Butler (1947): cloud-chamber photographs



G. D. Rochester, C. C. Butler, Nature 160 (1947) 855–857

- Signature: “neutral vertex” V^0 in lead tile ($\rightarrow$ naming)
- Modern nomenclature: V^0 decays mostly $K_S^0 \rightarrow \pi^+\pi^-$, $\Lambda_S^0 \rightarrow p\pi^-$

Strangeness (2)

- ***θ-τ puzzle***
  - Observation of two (?) particles with final states of ***different parity***

$$\theta^+ \to \pi^+\pi^0 , \qquad \tau^+ \to \pi^+\pi^0\pi^0$$

  - But: particles have ***same mass and lifetime*** $\to$ same particle
- Solution: new quantum number S = ***strangeness***
  (Gell-Mann, Nishijima 1953)
  - Strangeness conserved in strong and electromagnetic interaction
  - Strangeness not conserved in weak interactions: V^0 long lifetime
  - Different decays of the ***same particle*** $\theta^+ = \tau^+$ (today: $K^+ \to 2\pi/3\pi$)
- Conclusion: ***weak interaction violates parity*** conservation

Strangeness & Flavour SU3

- Group theory: extension of flavour SU(2) to ***flavour SU***(3)
  - Description of all states with two quantum numbers, e.g. I_3, S
  - Often: flavour hypercharge $Y_F = \mathcal{B} + S$
  - Relation to electric charge:

$$\boxed{I_3 = Q - \frac{Y_F}{2} = Q - \frac{1}{2}(\mathcal{B} + S)}$$

Gell-Mann–Nishijima formula

- NB: Generalisation to 6 flavours:

$$Y_F = \mathcal{B} + S + \underbrace{C}_{\text{charm}} + \underbrace{B}_{\text{beauty}} + \underbrace{T}_{\text{truth}}$$

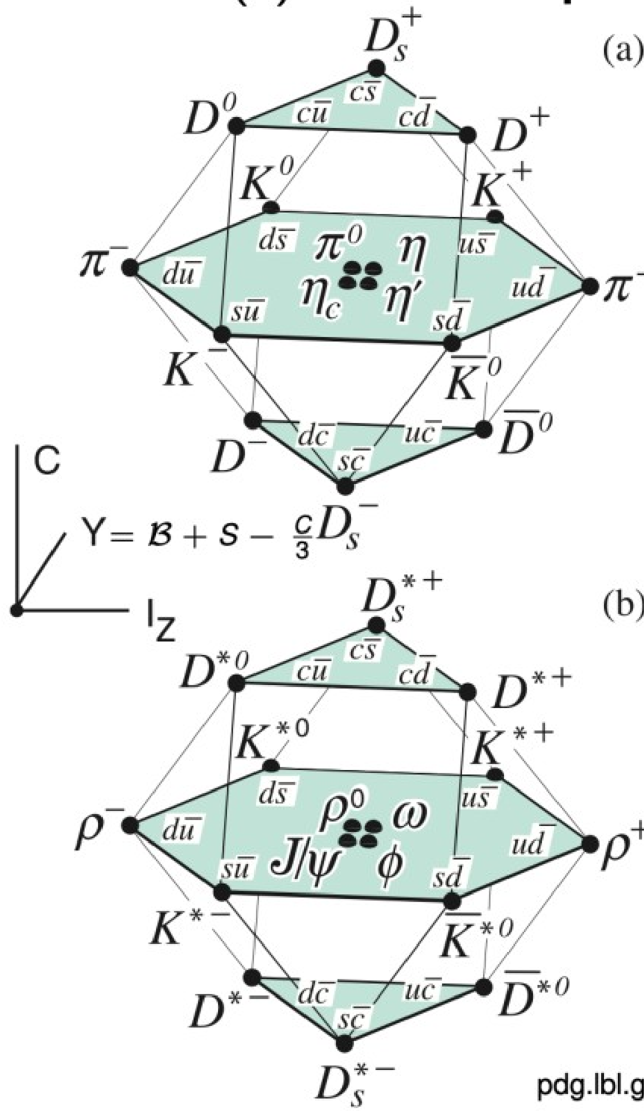
Murray Gell-Mann

Kazuhiko Nishijima

The Quark Model

- 1960s: "***particle zoo***"
  - Discovery of many new "elementary" particles, e. g. η', ρ, ω, K^*, Δ, Σ, Ξ
  - ***Classification scheme*** desired (analogue to Mendelejew's periodic table)
- ***Quarks*** (Gell-Mann 1964) or ***Aces*** (Zweig 1964)
  - Fundamental representation of flavour SU(3): ***3 quarks*** (u=up, d=down, s=strange)
  - Extended to 4 quarks (new: c=charm): flavour SU(4) (badly broken because of large c mass)
  - Illustration: meson and baryon multiplets
  - At first solely mathematical tool, ***no physical reality*** assumed

flavour-SU(4) meson multiplets

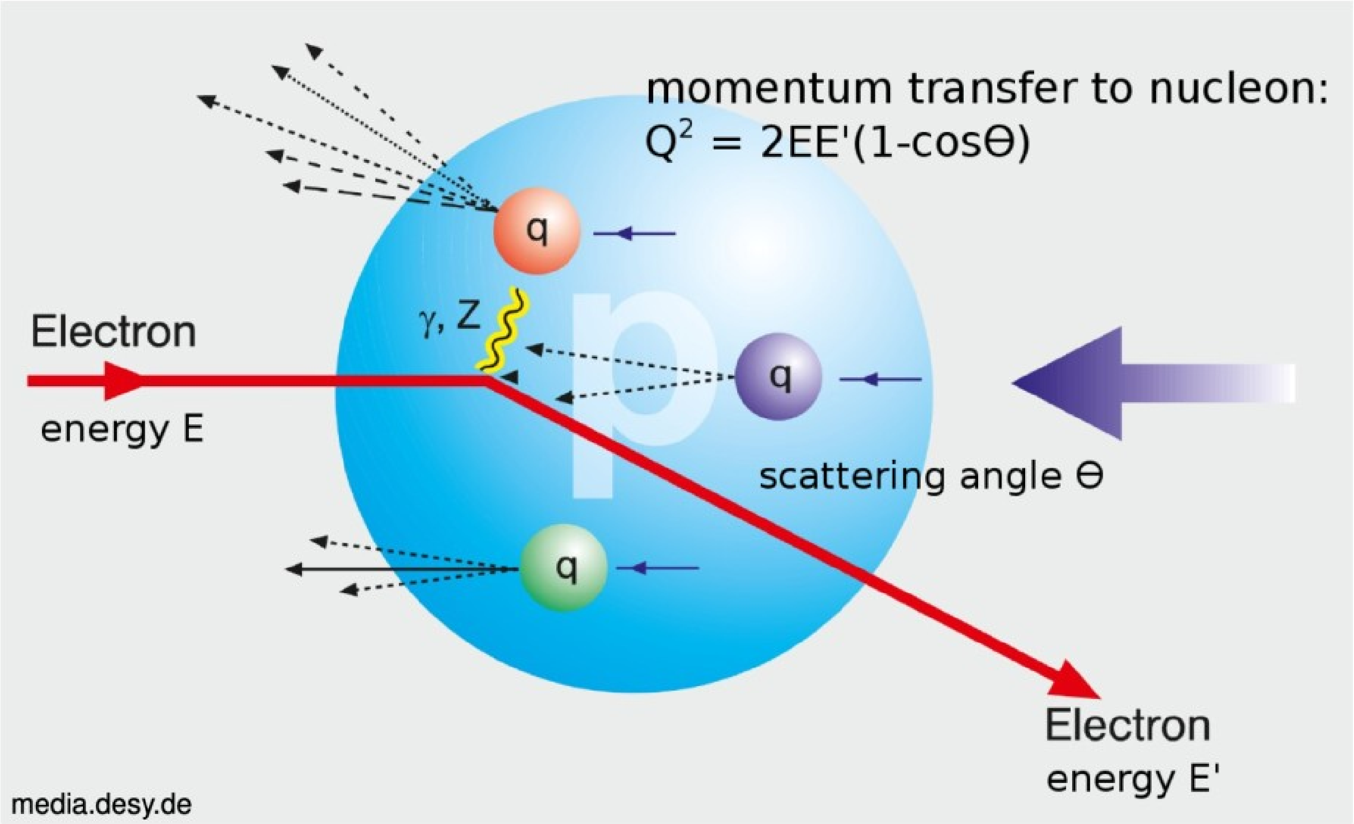


pdg.lbl.gov

Quark-Parton Model

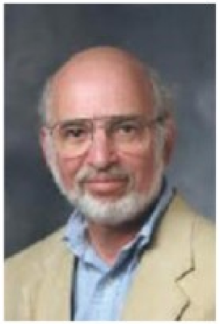
- Stanford Linear Accelerator Center (SLAC), 1960s
  - Scattering experiments: 20 GeV electron beam on fixed target
    deep inelastic scattering (DIS)

→ probes ***nucleon structure*** (form factors, e. g. charge distribution)



Quark-Parton Model (2)

- Discovery: nucleons feature ***substructure***
  (Breidenbach et al., 1969)
- Theoretical interpretation
  - Substructure = "***partons***": point-like spin-$\frac{1}{2}$ particles (Feynman, 1969)
  - Partons = quarks
    (Bjorken, Paschos, 1969)

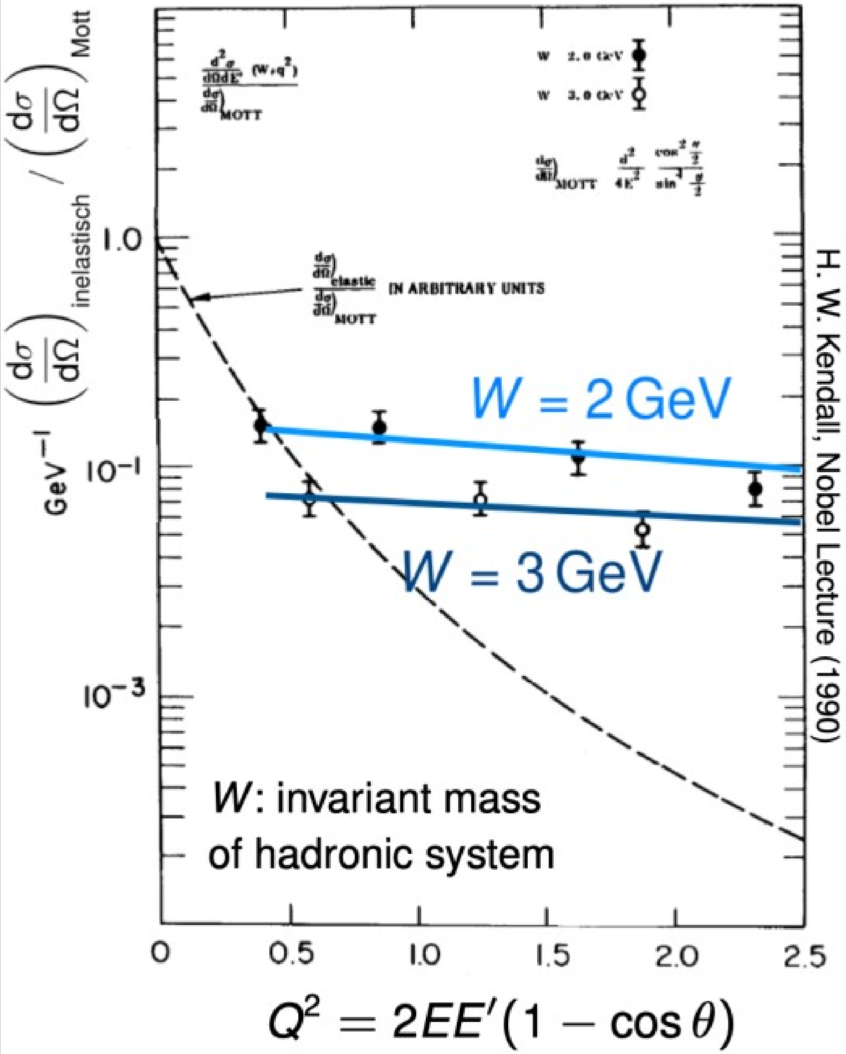


Martin Breidenbach

James D. Bjorken

Emmanuel Paschos

inelastic e – p scattering



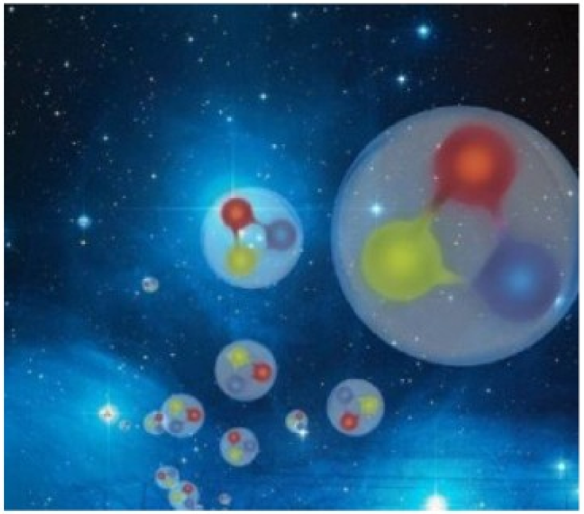
Deviation from Mott scattering shows that proton is not point-like

Quantum Chromodynamics (QCD)

- ***Yang-Mills theory*** (Yang, Mills 1954)
  - ***SU*(n) *gauge theory*** of strong (and weak) interaction
  - Yang-Mills theory predicts massless force carrier (mediator) particles
  - Contradicts observation (nuclear force mediated by pions, dimension of Fermi constant G_F)
- Hints of additional ***internal degree of freedom of quarks***
  - For example, Ω^- baryon with quark content $|sss\rangle$: Ω^- is fermion, but ***symmetric*** position, spin, and flavour wave functions

C. N. Yang (1922 -) and Robert Mills (1927 - 1999) at Stony Brook in 1999.

universe-review.ca

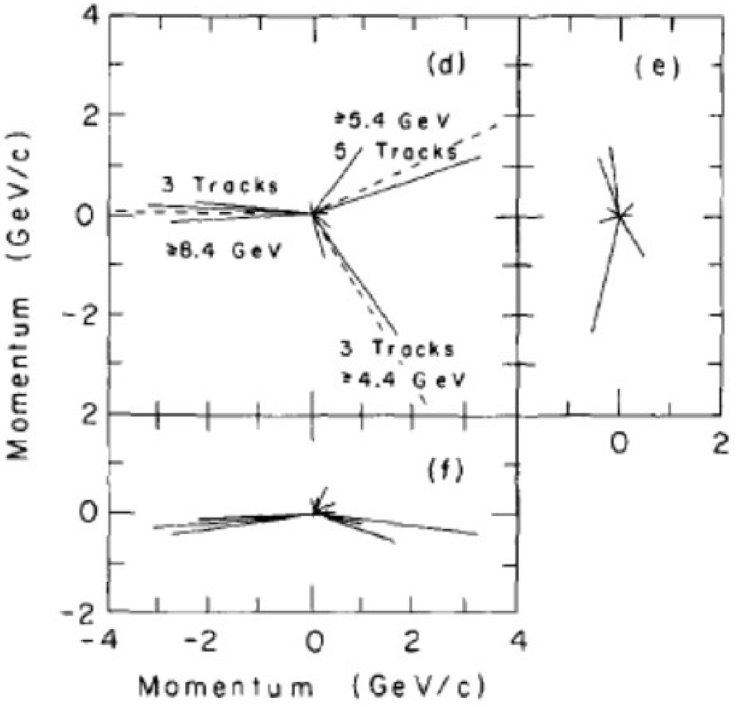


Atom Institut TU Wien

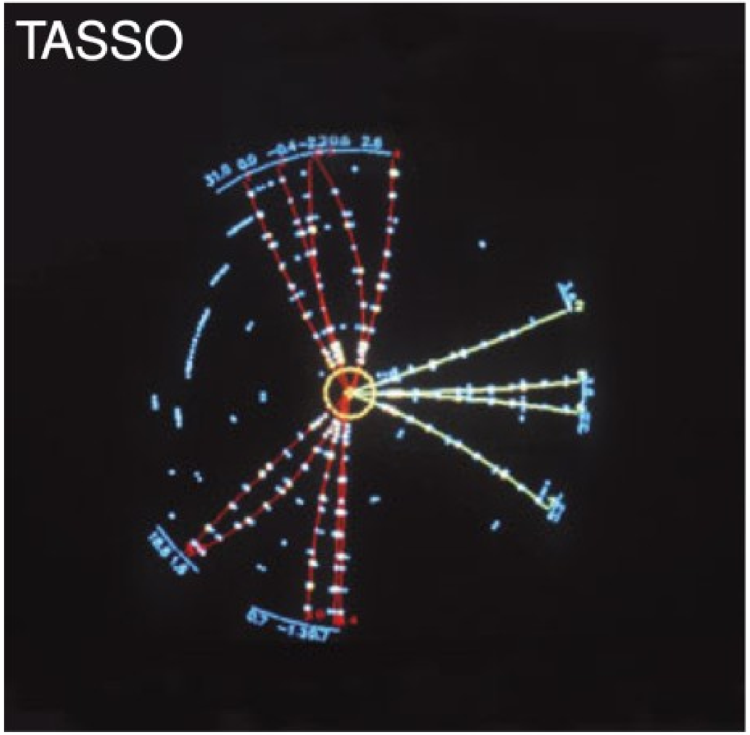
QCD (2)

- ***Colour SU***(3) (Fritzsch, Gell-Mann, Leutwyler 1973)
  - Strong interaction as SU(3) gauge theory for quarks
  - Mediator particles: ***8 massless gluons***
  - Quarks and gluons carry “colour charge”

  → ***Quantum chromodynamics*** (QCD)
- Experimentally: ***3-jet events*** (PETRA, DESY)



Int. J. Mod. Phys. A29 (2014) 31, 1430072



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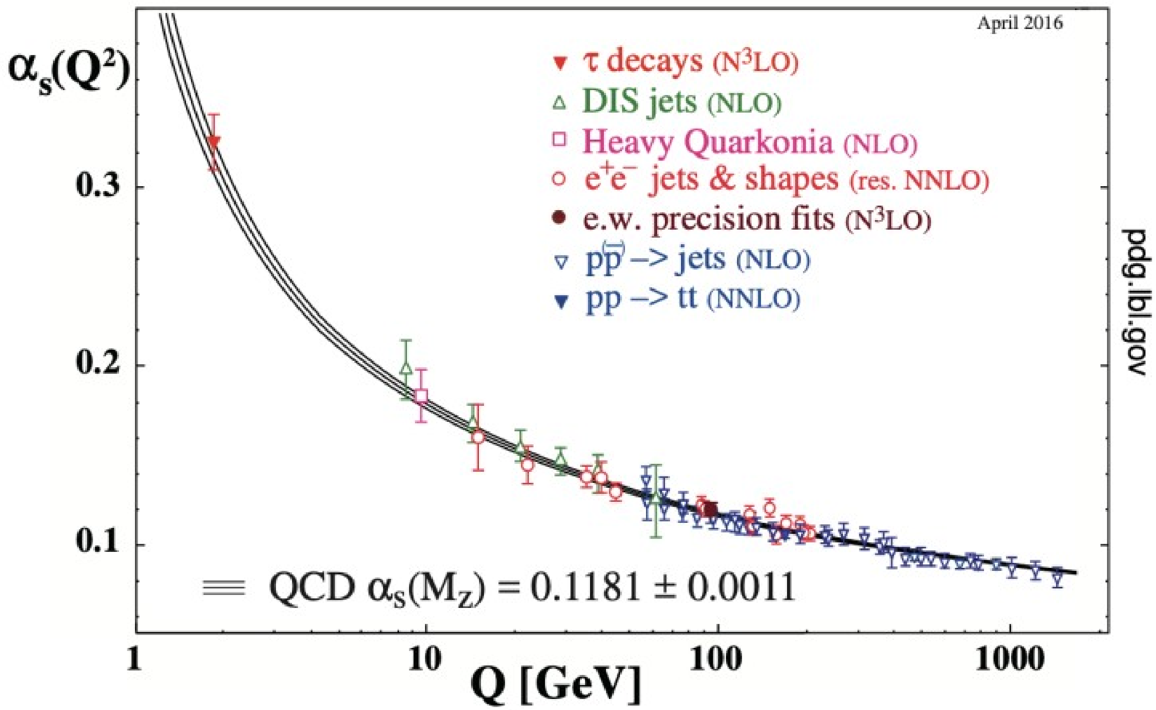
QCD (3)

"running" coupling α_s



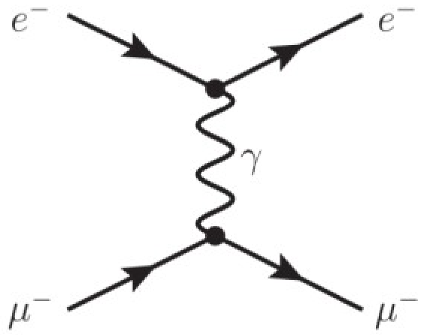
- Remarkable feature: ***asymptotic freedom*** (Gross, Wilczek, Politzer 1973)
  - QCD coupling-strength α_s decreases with larger energy
  - Quarks asymptotically free particles in DIS processes
  - Lower energies: ***confinement***, bound quarks

Weak Interaction

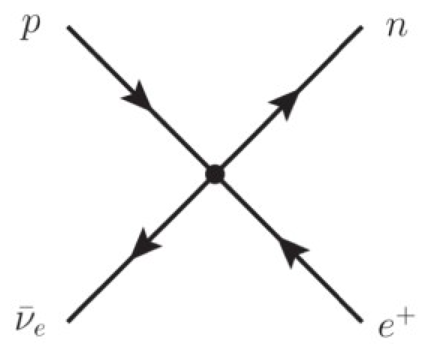
- Interaction known from radioactive β ***decay***:
  $(A, Z) \rightarrow (A, Z+1) + e^-$
  (mass number A, atomic number Z)
  - Two-body decay: electron with fix energy expected $\rightarrow$ ***contradicts*** observation
  - Solution (Pauli 1930): postulation of ***neutrino***
    $(A, Z) \rightarrow (A, Z+1) + e^- + \bar{\nu}_e$

- Theory of weak interaction (Fermi 1934)
  - ***4-vector current*** as in electrodynamics
  - ***Contact interaction*** with coupling constant G_F (Fermi constant)
  - G_F has unit $[\text{energy}]^{-2} \rightarrow$ hint of ***massive mediator*** particle (today: W boson)

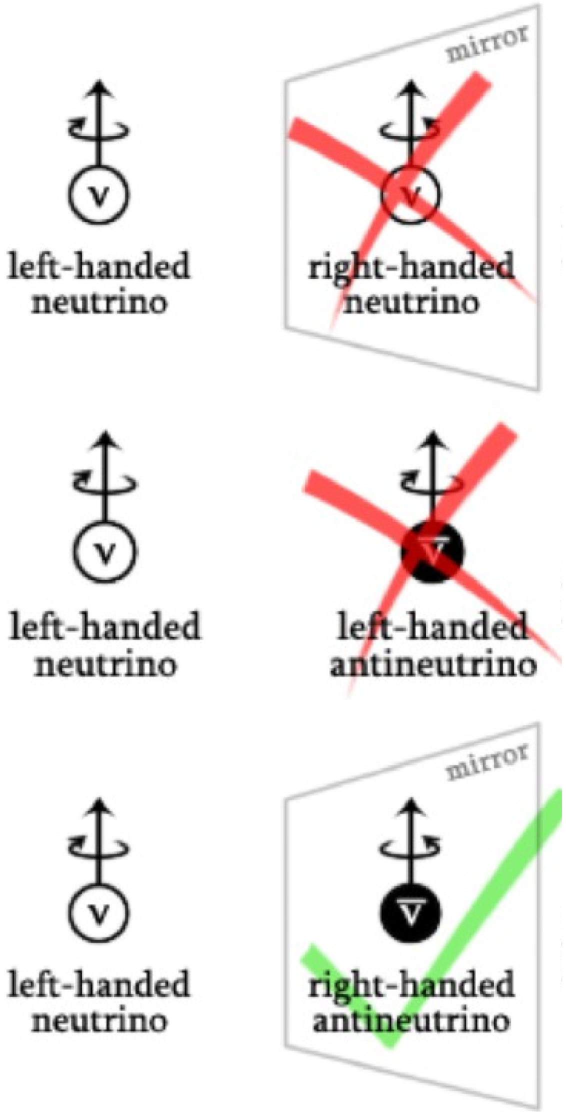
QED-Prozess



Schwacher Prozess



Parity violation in weak interactions



- Discrete symmetries in particle physics:
  - *C* : charge conjugation
  - *P* : parity
  - *T* : time reversal
  - Each ***conserved individually*** in strong and electromagnetic interaction
  - ***Expectation: parity conservation*** in weak interaction

CP-Vialoation

- Experiment by Christenson, Cronin, Fitch, Turlay (1964):
  Decays of neutral *K* mesons ("*K* long")
  CP conserving : $K_L^0 \to \pi^+\pi^-\pi^0$
  CP violating : $K_L^0 \to \pi^+\pi^-$ (2000 times fewer)

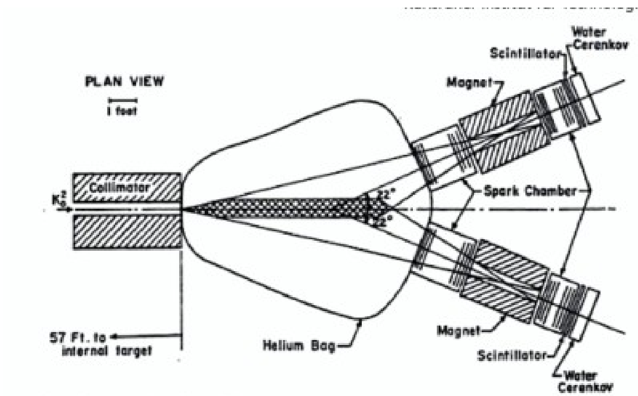


Fig. 9a. Set-up used to detect $K_2 \to \pi^+\pi^-$.

Phys. Rev. Lett. 13, 138 (1964)

Question at the time: - a property of the weak interaction ?
- or a hint to a new „superweak interaction" ?

- ***Cosmological implications*** (Sakharov 1967): any mechanism producing baryon asymmetry $\frac{n_B - n_{\bar{B}}}{n_\gamma} \approx 10^{-9}$ requires
  - baryon number violation
  - C and ***CP violation***
  - Thermal non-equilibrium

  ("Sakharov conditions")

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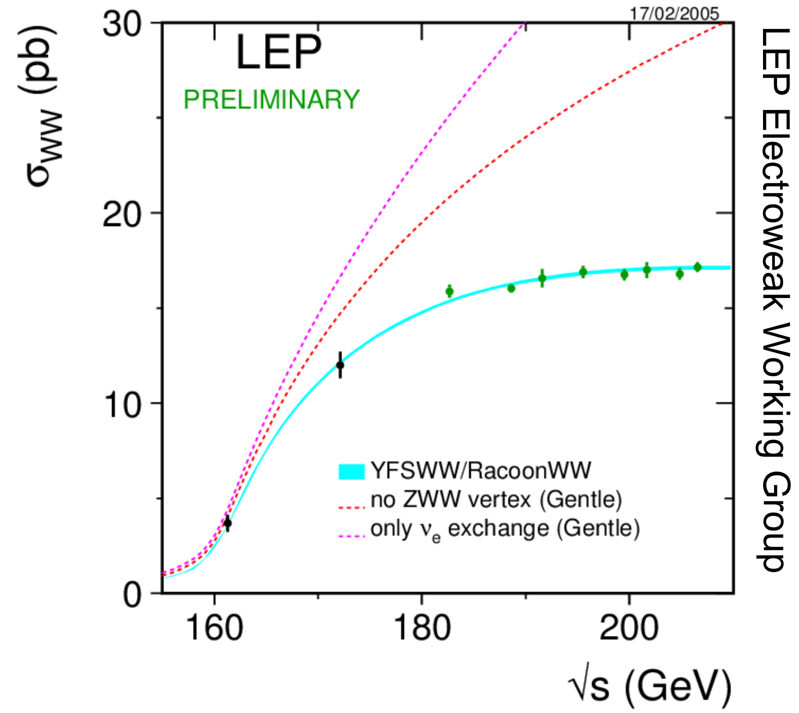
Electroweak Theory

- ***Unitarity violation*** in V-A theory
  - Neutrino-electron scattering cross-section in V-A theory proportional to centre-of-mass energy s, diverges as $s \to \infty$

- Solution: ***unified*** theory of the weak and electromagnetic interactions $\to$ ***Glashow-Salam-Weinberg (GSW) model***
  - Gauge group: $SU(2)_L \times U(1)_Y$ (Glashow 1961)
    $SU(2)_L$: weak-isospin space
    $U(1)_Y$: weak-hypercharge space
  - Same coupling at high energies
  - Prediction of Z boson

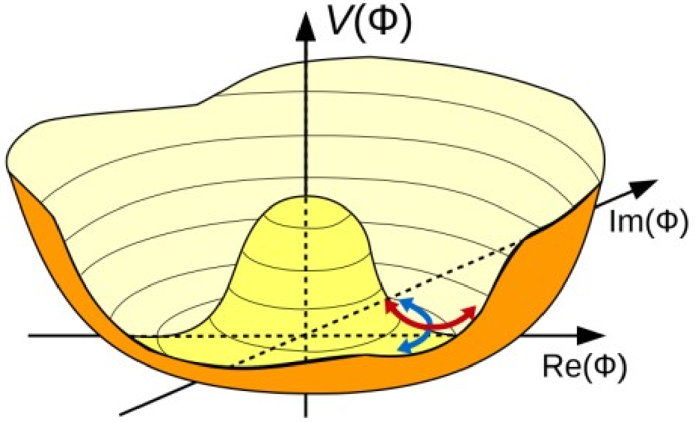
Figure 1: Diagrams of the WW production at LEP2

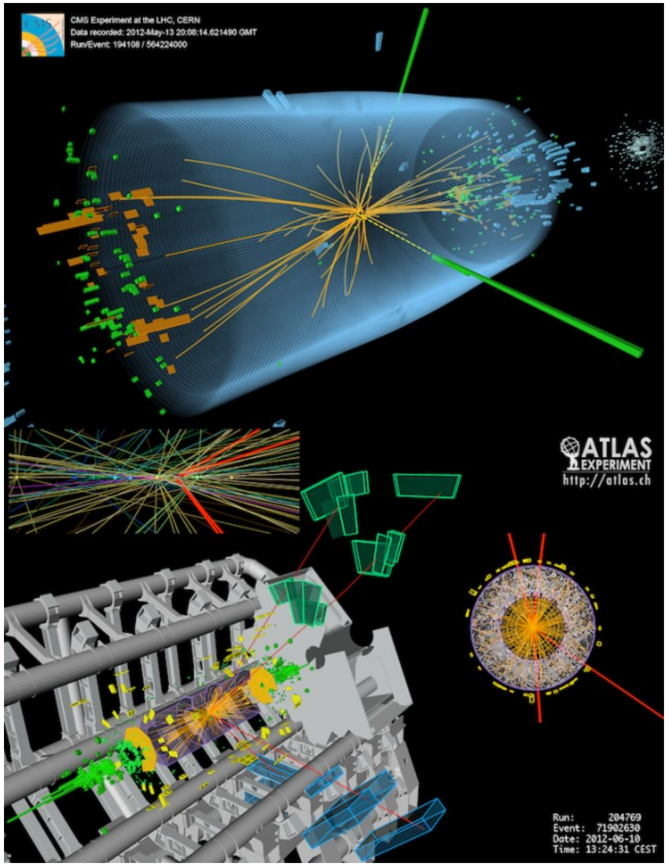


$e^+e^- \to WW$ cross section remains finite with couplings of the GSW Model

Electroweak Theory

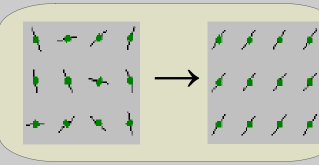
- Higgs mechanism: ***spontaneous symmetry breaking***
  - Independently discovered by several groups: Higgs; Brout, Englert; Goldstone, Jona-Lasinio, Nambu; Guralnik, Hagen, Kibble
  - Application to $SU(2)_L \times U(1)_Y$ symmetry (Salam, Weinberg 1968) $\rightarrow$ allows ***massive*** W/Z ***bosons***, photon remains massless
  - Prediction of a ***Higgs boson*** (excitation of Higgs field)





The Standard-Model of Particle Physics

- consistent theoretical description of fundamental Particles and their interactions **EXCEPTION: Gravity !**
- based on fundamental Symmetries – elegant and beautiful !
- Basic foundations laid in the '60ies – successfully passed all precision tests to date!
- Particle masses through spontaneous symmetry braking **„Higgs-Mechanism“**



related “Higgs Particle“ has long been searched for, found 2012

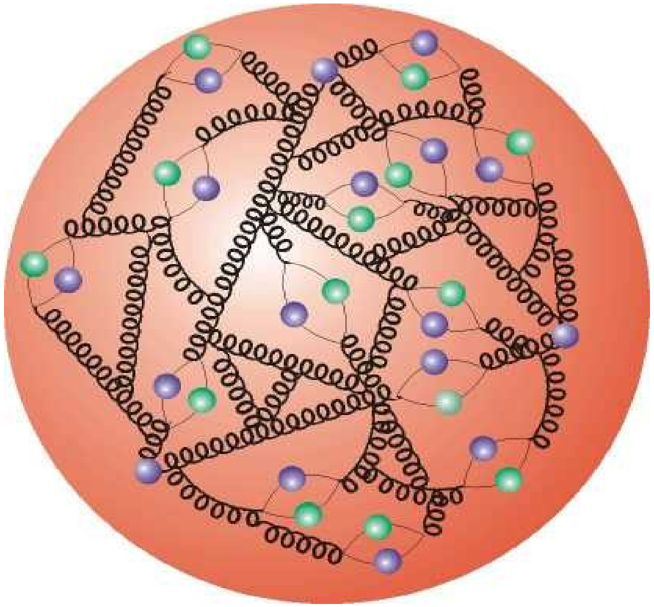
- Many other open questions (Gravity, dark matter & dark energy, ...) require

„new physics“ **beyond the standard model**
(not topic of this lecture ...)

btw: **mass of the proton …**

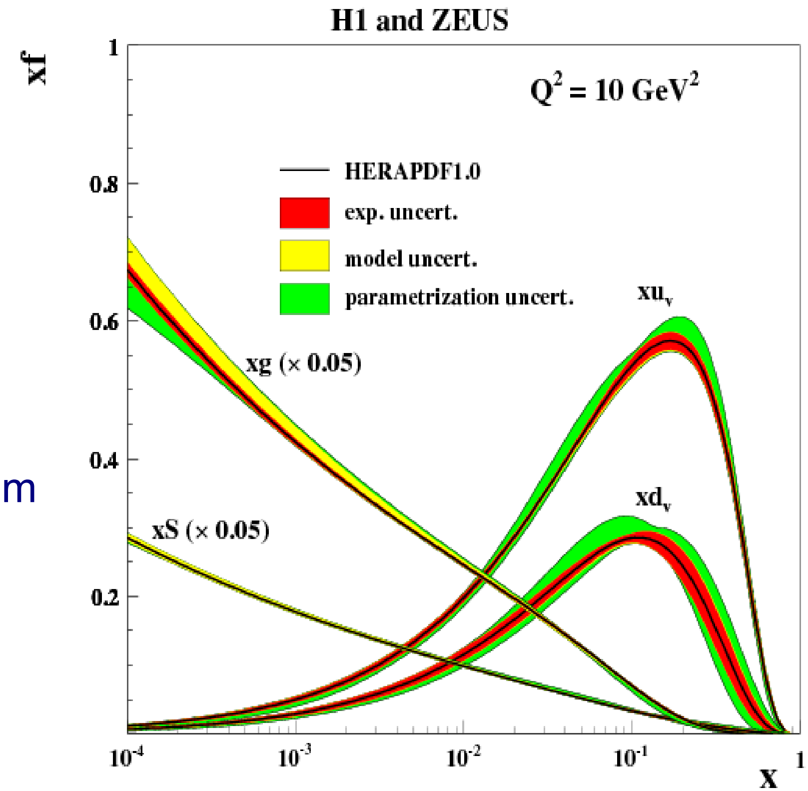
… has a different explanation:

Proton is **not a fundamental** particle,



– valence quarks
– sea quarks
– gluons

bound in volume
of radius ~10^{-15} m



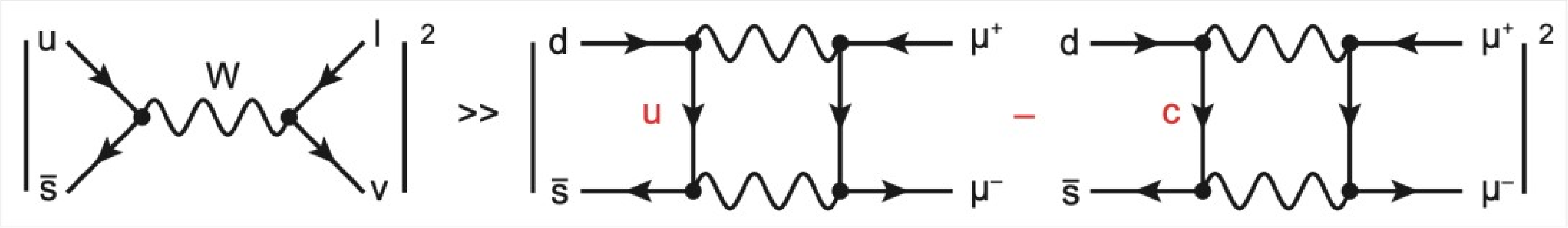
but consists of **quarks and gluons**

proton mass: 938 MeV/c^2 rest mass of valence quarks: ~10 MeV/c^2

Þ only ~ **1% due to valence quark masses, rest is kinetic and binding energy.**

Electroweak Theory – the flavour sector

- ***Quark mixing*** (Cabibbo 1963): $u \to d' = d \cdot \cos\theta_c + s \cdot \sin\theta_c$
  with $\sin\theta_c \approx 0.22$ (Cabibbo angle)
- Application of GSW model to quarks
  - W boson couples to linear combination of d and s quarks
  - ***Eigenstates of weak interaction $\neq$ mass eigenstates***
- ***GIM mechanism*** (Glashow, Iliopoulos, Maiani 1970)
  - Observation: $K^+ \to l\nu$ decays much more frequent than $K^0 \to \mu\mu$
  - GIM prediction: fourth quark c, adding destructively interfering diagram



$$\begin{pmatrix} u \to d' \\ c \to s' \end{pmatrix} = \begin{pmatrix} \cos\theta_c & \sin\theta_c \\ -\sin\theta_c & \cos\theta_c \end{pmatrix} \cdot \begin{pmatrix} d \\ s \end{pmatrix}$$

  - Discovery of $J/\psi = c\bar{c}$ (SLAC, BNL 1974)

Electroweak Theory – the flavour sector

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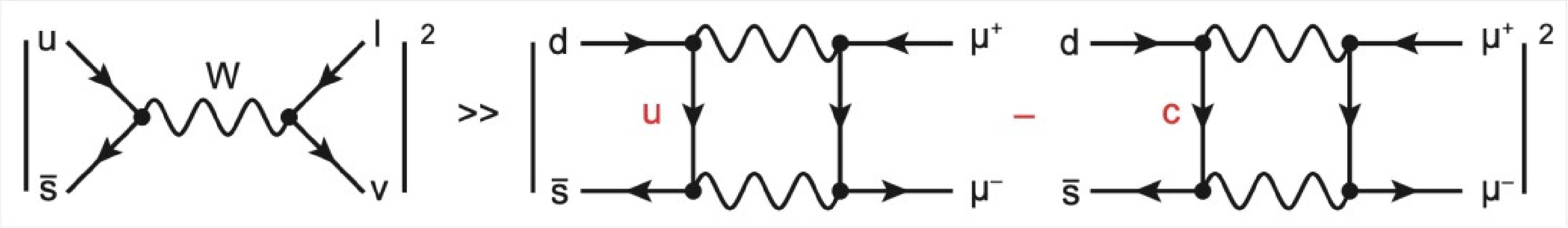

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- Discovery of $J/\psi = c\bar{c}$ (SLAC, BNL 1974)

Electroweak Theory – Quark Mixing

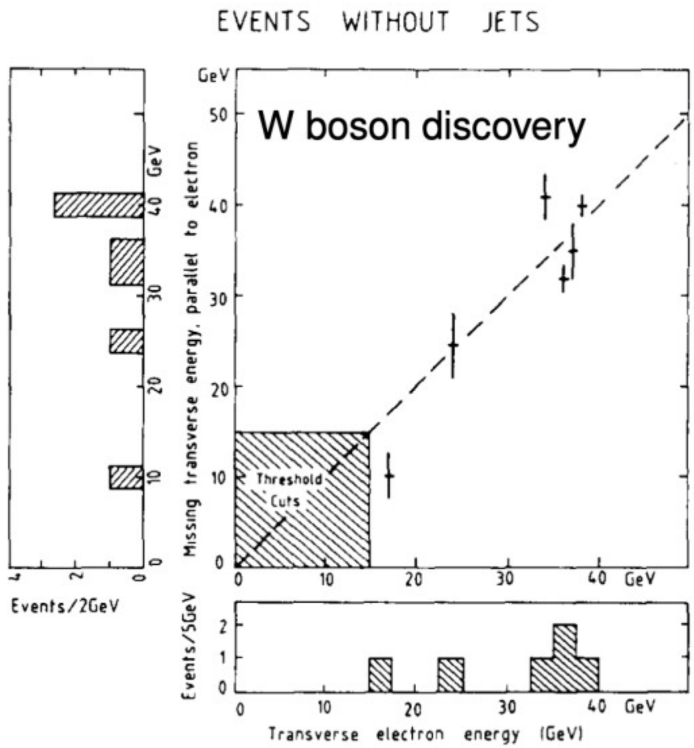
- Kobayashi, Maskawa (1973)
  - CP violation in quark sector only with at least three quark families
  - Mixing via ***Cabibbo-Kobayashi-Maskawa matrix*** (CKM matrix)

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \cdot \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

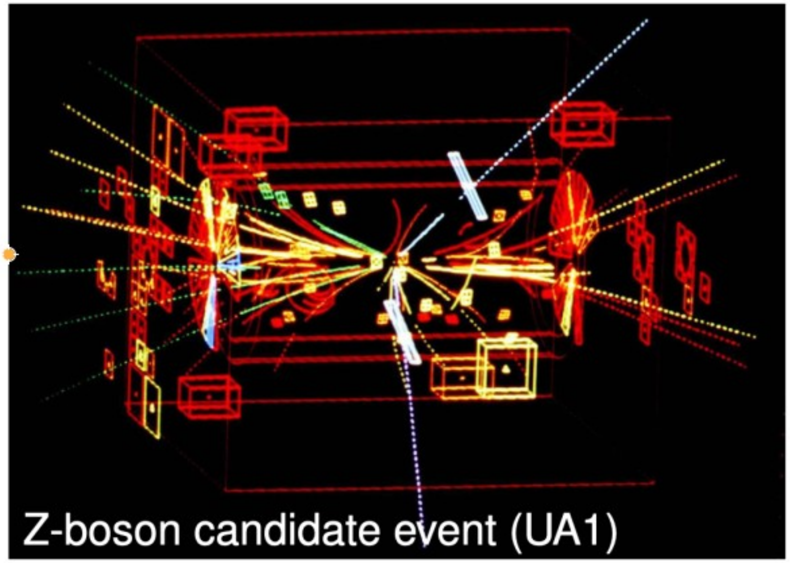
- Discovery of ***third quark and lepton families***
  - τ lepton (Perl et al., 1975)
  - b quark (Lederman et al., 1977)
  - t quark (at Tevatron, 1995)
  - ν_τ (with DONUT experiment, 2000)

EW Theory – Discovery of the gauge Bosons

- Discovery of ***W and Z bosons*** at Sp$\bar{p}$S (CERN, 1983)

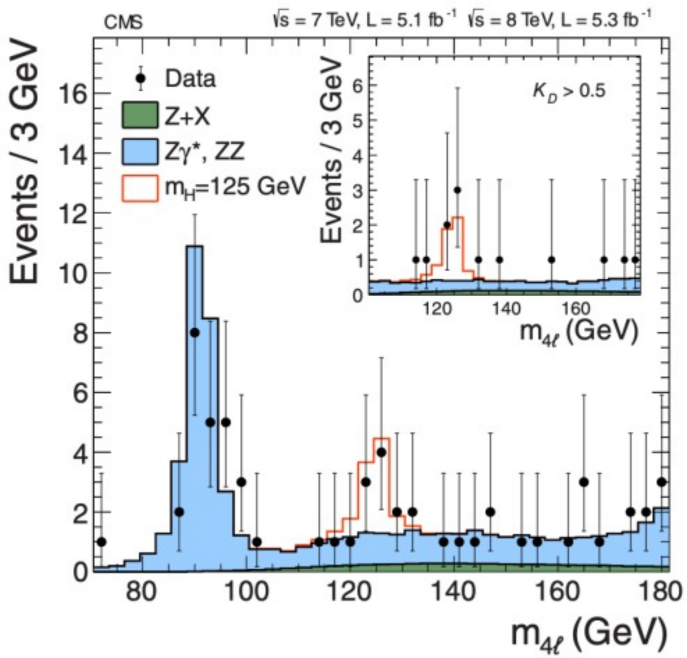


Phys.Lett. 122B (1983) 103-116

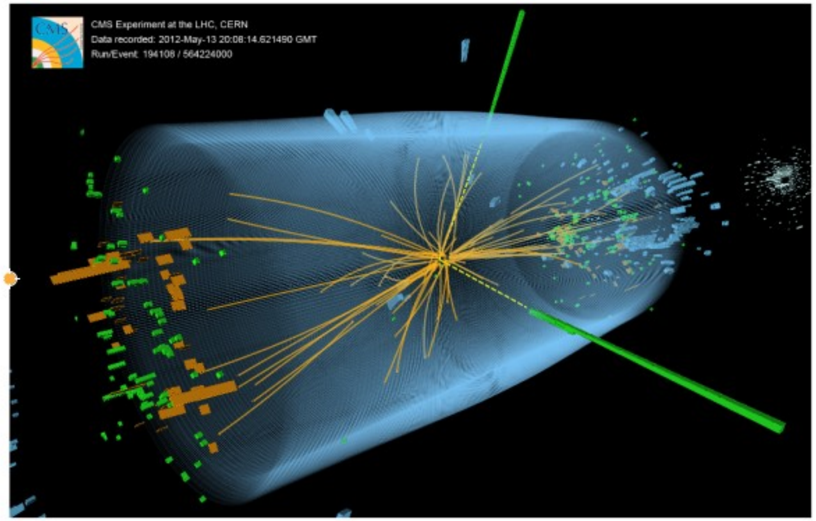


CERN

- Discovery of a (the?) ***Higgs boson*** at LHC (CERN, 2012)



Phys. Lett. B716 (2012) 30-61



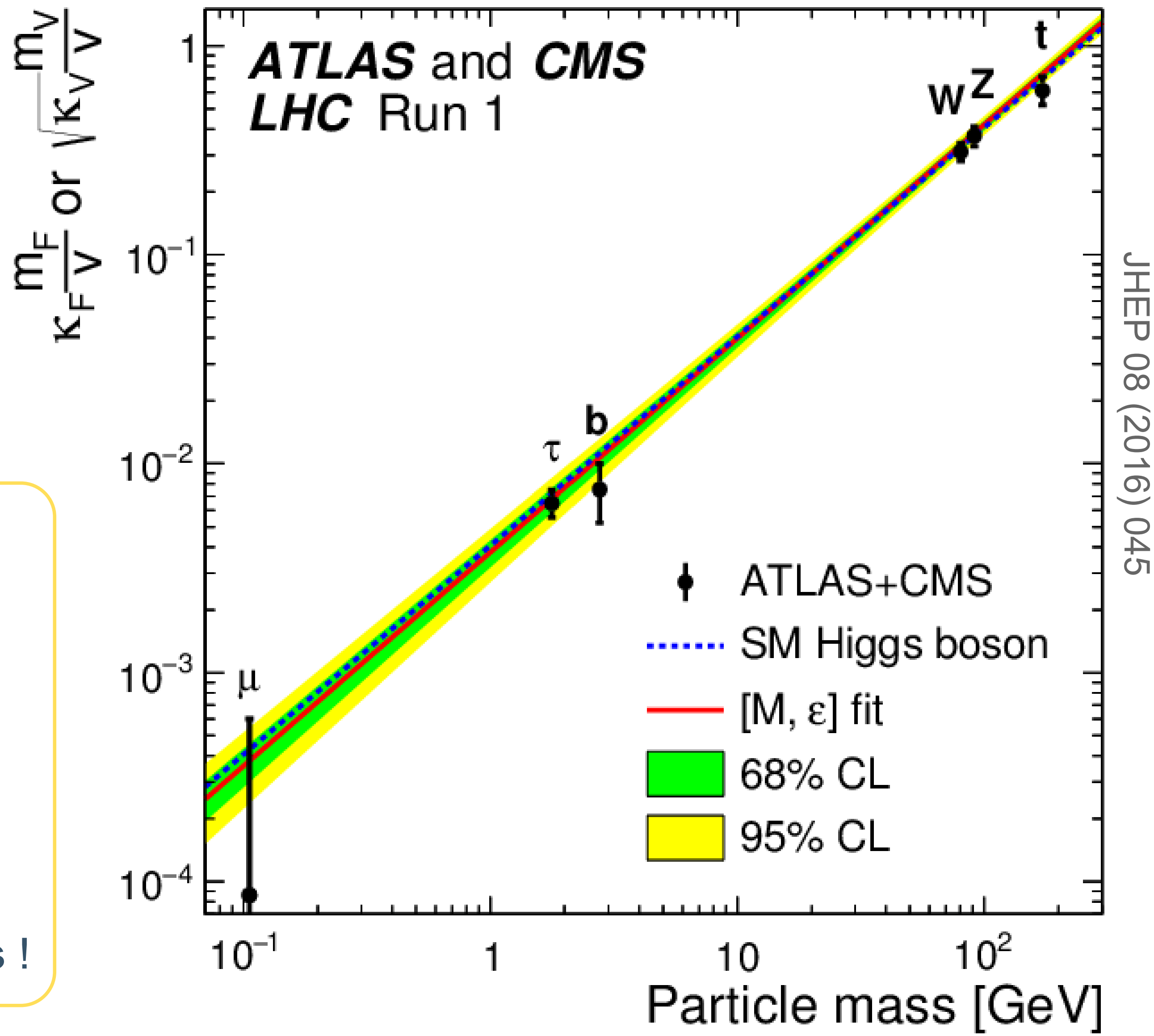
CERN

Higgs-Boson Discovery

- Discovery of „a new particle" announced at CERN on July 4th 2012
- after many more studies called „a Higgs-like particle"
- Today we are sure: it is a (the ?) Higgs boson !

Higgs Couplings to particles

Combination of all measurements at the end of LHC run 1 (2010-2012) :



the new particle is
the only known one
which couples

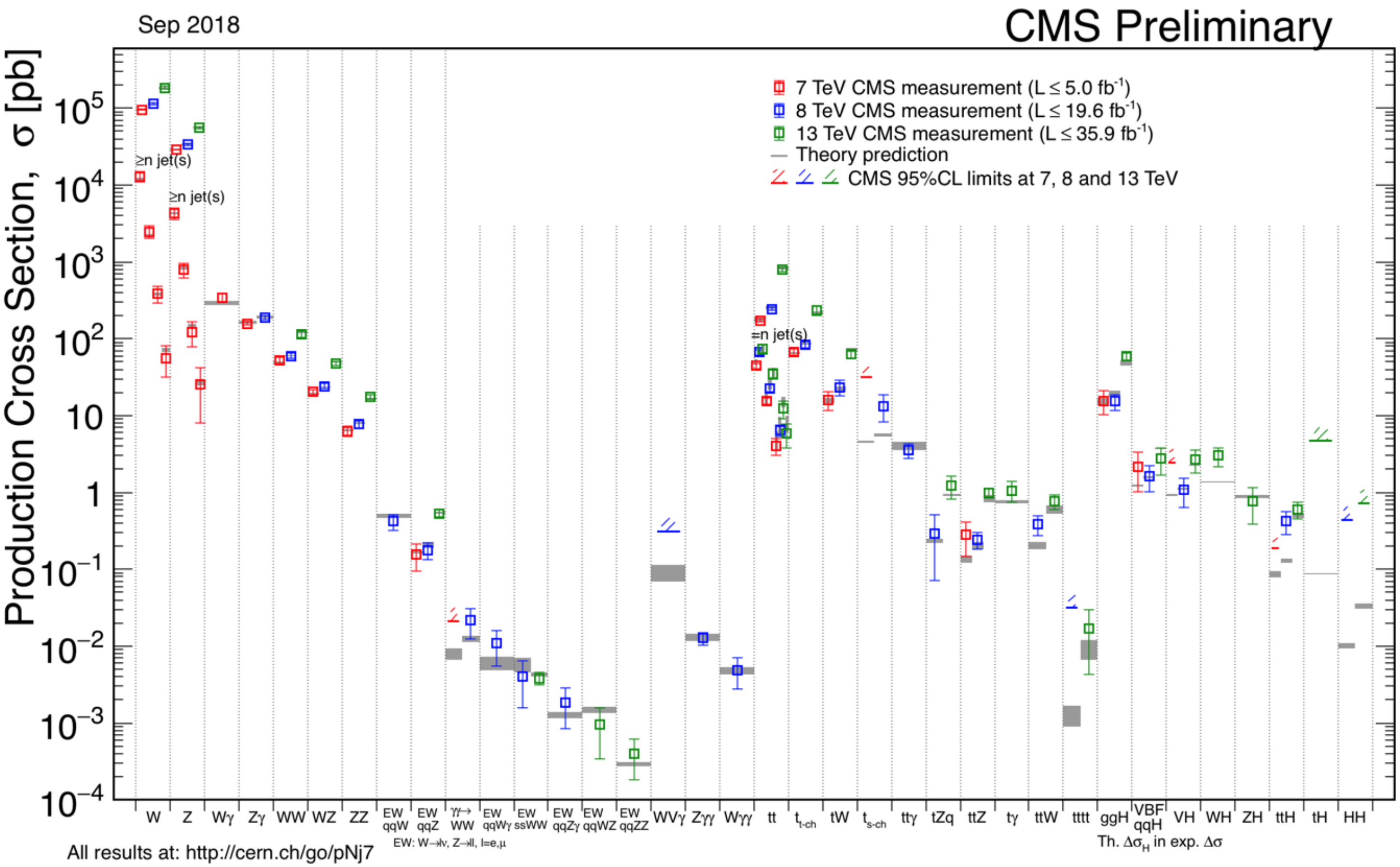
- proportionally to mass
  to fermions
- porportionally to mass²
  to gauge bosons

Like the SM Higgs does !

Current Situation

7 years after the discovery of the Higgs boson

- No new particles have been found
- Many precision measurements consistent with SM predictions



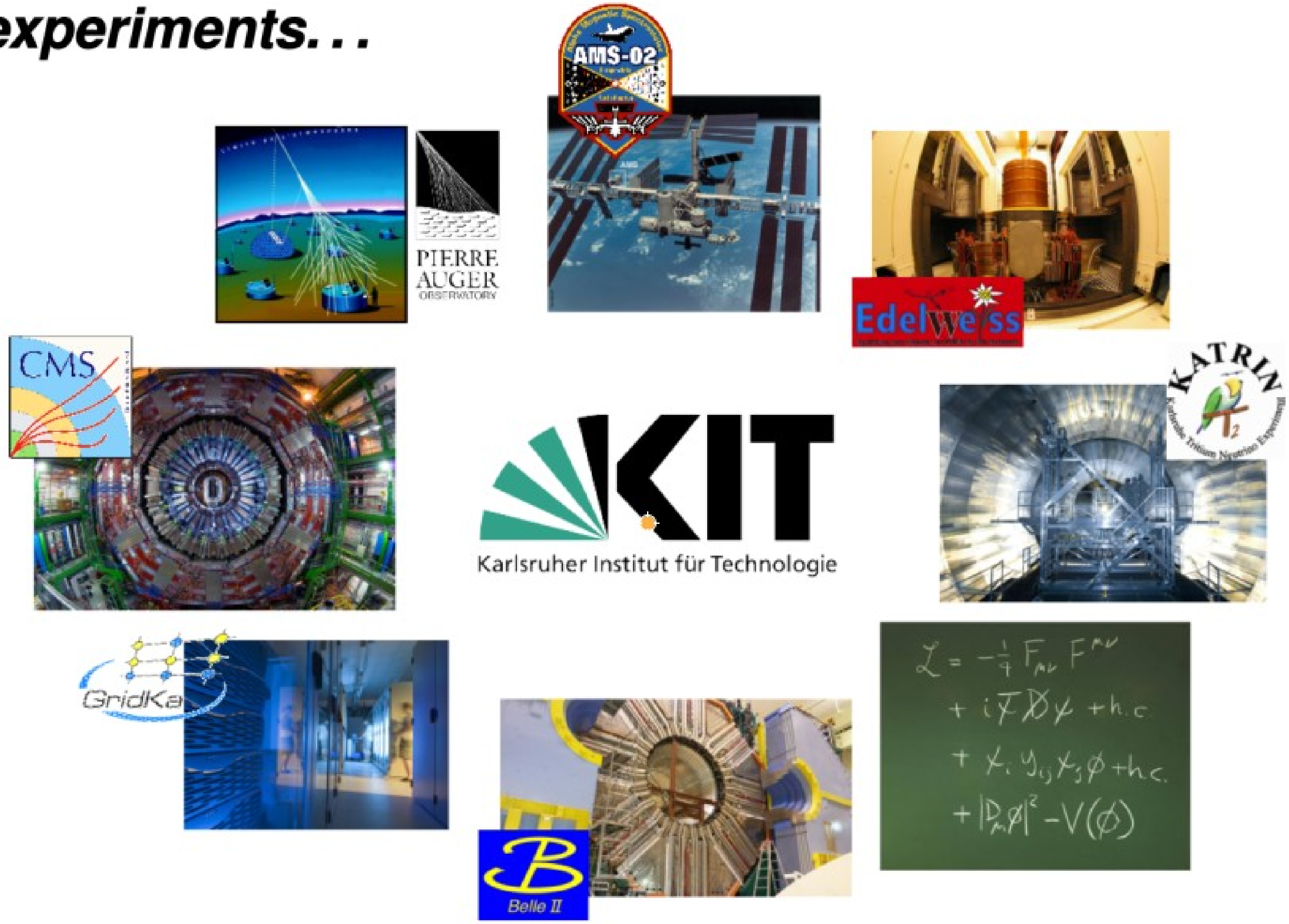
→ **the Standard Model is complete and very healthy !**

Current situation – open questions

- Is the Standard Model complete ?
  we know it cannot be: gravity, dark matter and dark energy not included !
- is it **self-consistent**,
  i. e. can it be extrapolated to higher energy scales ?
- Ist it „**natural**“,
  - Why is the Higgs-boson mass so small ?
  - What is the origin of the mass hierarchy
    (meV for neutrinos to O(100GeV) for W, Z, H, and top quark) ?
- What is the **new physics** beyond the SM ?
  - dark matter and dark energy ?
  - sources of CP-violation ?

Current situation of Particle Physics

We need experiments. . .



… and we have plenty of them at KIT !

Topics of this Lecture

- Units and Conventions
- Detectors and Accelerators
- Standard Model:
  gauge Theories and electroweak theory
- Tests of electroweak theory
- Jets and Quantum Chromodynamics
- Top quark Physics
- Higgs Physics
- Flavour physics
- Neutrino Physics
- Physics beyond the Standard Model
- Future experiments

practical exercises:

Detector Simulation with GEANT

Cross section calculation with madgraph

Hardware Exercises

Analysis project 1:
Top Quark Phyics

Analysis project 2:
SuSy search

Note: there are courses „Particle Physics 2“
- W, Z, H
- Flavour Physics
- Jet and Top quark physics
- Detector Physics
- Modern Methods of Data Analysis
- Accelerator Physics