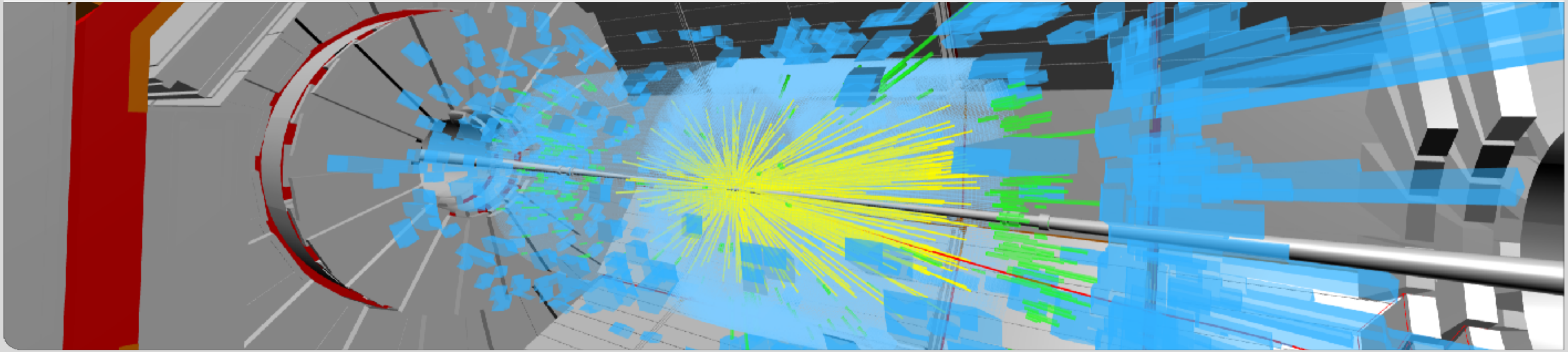
# Overview of Particle Physics

*7th ENHEP School on High Energy Physics*
*Ain Shams University, Cairo, January 26–31, 2019*

Ulrich Husemann, Institute of Experimental Particle Physics, Karlsruhe Institute of Technology



# Outline

Introduction

Foundations of Particle Physics

The Standard Model of Particle Physics

Particle Physics Today

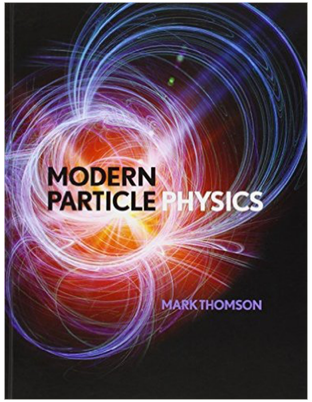
# What Is Particle Physics?

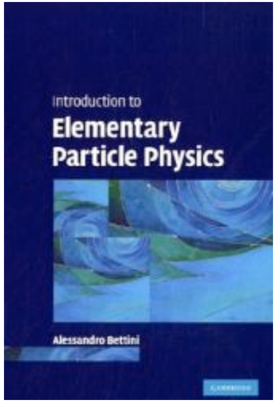
Karlsruhe Institute of Technology

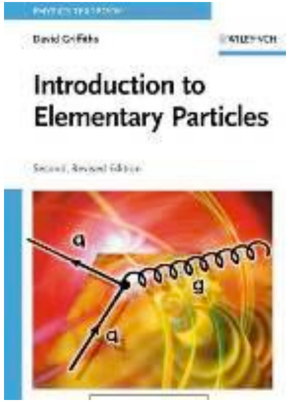
- We have theories at hand for the **largest** and the **smallest**:
  - **Standard model** of **particle physics**: six quarks and six leptons
  - **Standard model** of **cosmology**: cold dark matter, dark energy, …
  - Guiding principle: start from **symmetries**
- Particle physics means **experiments** – with and without accelerators:
  - Highest **energy**: cosmic rays, Large Hadron Collider, …
  - Highest **precision**: B factories, measurement of neutrino masses and mixing, Dark Matter searches, …
  - Advanced **technology**: detectors, statistical data analysis, …

# Recommended Reading

- **Experimental textbooks:**
  - M. Thomson: *Modern Particle Physics,* Cambridge UP (2013)
  - D. Griffith: *Introduction to Elementary Particles*, Wiley (2008)
  - A. Bettini: *Introduction to Elementary Particle Physics*, Cambridge UP (2008)
  - R. Cahn, G. Goldhaber: *The Experimental Foundations of Particle Physics,* Cambridge UP (2009)



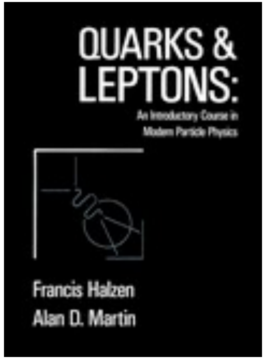



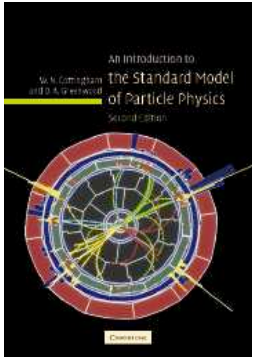



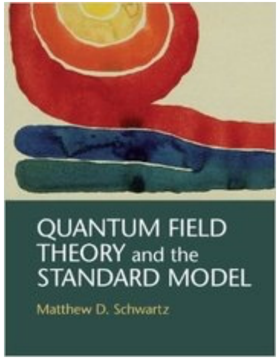

Karlsruhe Institute of Technology

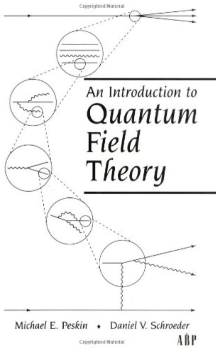
# Recommended Reading

- **Theory textbooks:**
  - F. Halzen, A. D. Martin:
    *Quarks & Leptons*, Wiley (1984)
  - W. N. Cottingham, D. A. Greenwood:
    *An Introduction to the Standard Model of Particle Physics*, Cambridge UP (2007)
  - M. D. Schwartz: *Quantum Field Theory and the Standard Model*, Cambridge UP (2013)
  - M. E. Peskin, D. V. Schroeder:
    *An Introduction to Quantum Field Theory*, Westview (1995)



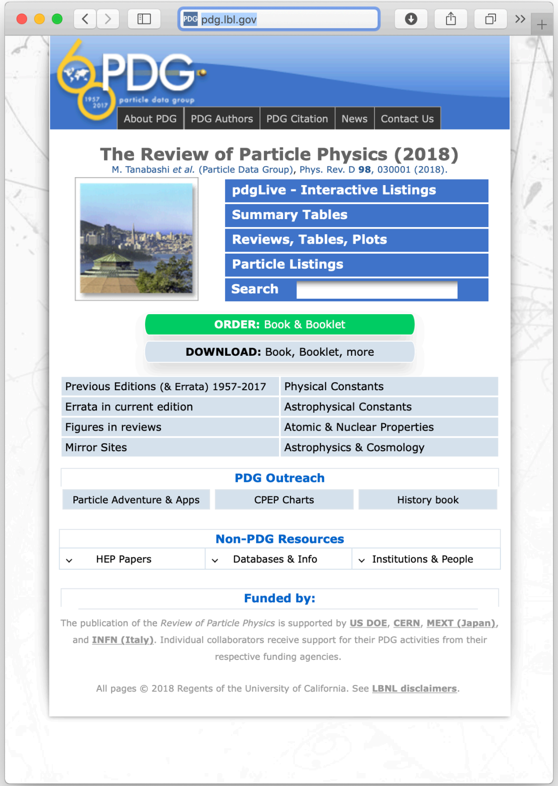



# Looking up Particle Properties

Karlsruhe Institute of Technology

- The **Review of Particle Physics**:
  - PDG – the “holy book” of particle physics: particle properties, overview articles for experts
  - Current printed version: M. Tanabashi et al., Phys. Rev. D 98, 030001 (2018).
  - Online version: http://pdglive.lbl.gov/





Ulrich Husemann
Institute of Experimental Particle Physics

# Online Literature Search


- **arXiv** (http://arxiv.org):
  - Preprints of very many scientific publications
  - Topics: physics, mathematics, computer science, system biology, finance mathematics, statistics, …


- **INSPIRE** (http://inspirehep.net):
  - Specialized literature search for particle physics
  - arXiv and other preprints, published articles
  - Authors: affiliations, publication statistics, …



Ulrich Husemann
Institute of Experimental Particle Physics

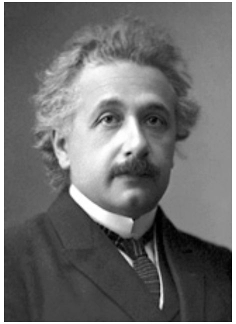
Historical Overview, Part I

# FOUNDATIONS OF PARTICLE PHYSICS


Ulrich Husemann
Institute of Experimental Particle Physics

# Quantum Mechanics & Special Relativity

- Theoretical foundations of particle physics:
  - **Quantum mechanics**
    (Heisenberg, Schrödinger, Dirac, …, 1920s)
  - **Special relativity** (Einstein, 1905)
- Modern theories of particle physics:
  relativistic **quantum field theory** (QFT)
  - Lorentz invariance
  - Quantized fields (i.e. fields = QM operators)
  - Physical particles = excitations (quanta) of fields


Albert Einstein


Erwin Schrödinger


Paul A. M. Dirac


Werner Heisenberg

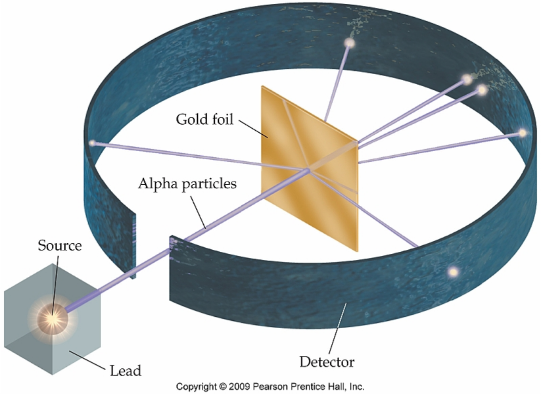
nobelprize.org

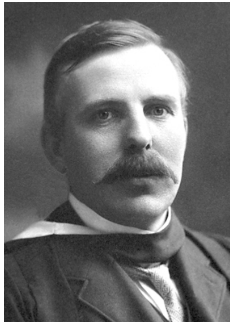
# Nuclear Force

- **Rutherford experiment** (Rutherford, Geiger, Marsdon, 1911):
  - Beam of $\alpha$ particles directed at thin gold foil → measure distribution of scattering angles $\theta$

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

  - Result: scattering angle distribution compatible with Coulomb scattering at compact nucleus → **atom = nucleus + shell**
- Chadwick, Bieler (1921): deviation from $\sin^{-4}(\theta/2)$ behavior→ new **nuclear force** ("strong force")





Ernest Rutherford


James Chadwick

nobelprize.org

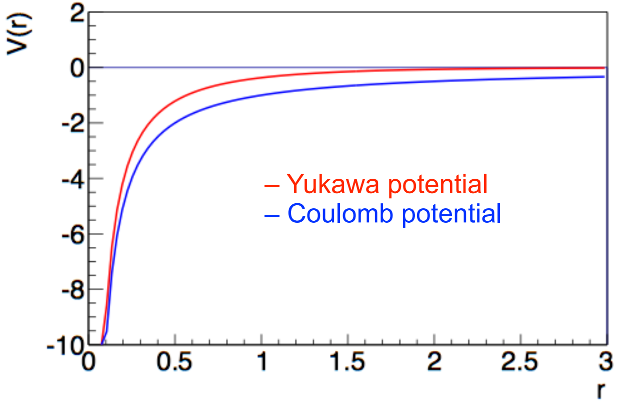
# Nuclear Force

- Discovery of the **neutron** (Chadwick, 1932)
- **Mesons** as messengers of nuclear force (Yukawa, 1935)
  - Analogous to photon in electrodynamics
  - Limited range of nuclear force $\lambda$: Yukawa potential = exponentially damped Coulomb potential

$$V(r) \sim -\frac{exp[-r/\lambda]}{r}$$

  - Experimentally: $\lambda \cong 1$ fm
    $\rightarrow m_{\text{meson}} \cong 200$ MeV: pions!

Hideki Yukawa





Ulrich Husemann
Institute of Experimental Particle Physics

# Isospin

- New internal degree of freedom for nuclei: **isospin** (short for: “isotopic spin”) (Discovery: Heisenberg 1932, name “isospin” coined by Wigner 1937)
  - Proton/neutron: **similar** properties (if charge is ignored)
  - Experiment: scattering off mirror nuclei (number of protons/neutrons exchanged, e.g. $^3$H $\leftrightarrow$ $^3$He, $^{15}$N $\leftrightarrow$ $^{15}$O) $\rightarrow$ strong force **independent** of electric charge
- New view on the strong force:
  - If there was only the strong force: proton = neutron = “nucleon” $\rightarrow$ **symmetry** between protons and neutrons: (strong) isospin $I$
  - Mathematical description: **group theory** – $SU(2)$ group (like for spin), nucleon as **isospin doublet**:

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

# Isospin

Karlsruhe Institute of Technology

- Isospin concept can be extended to further particle classes:
  - Example: **pion** = isospin **triplet**

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

- Compare third component $I_3$ of isospin for nucleons and pions:
  - $I_3$ depends on charge $Q$ (in $e$) – different for mesons and baryons
  - Connection to baryon number $B$ (reminder: $B$ = (#quarks – #antiquarks)/3):

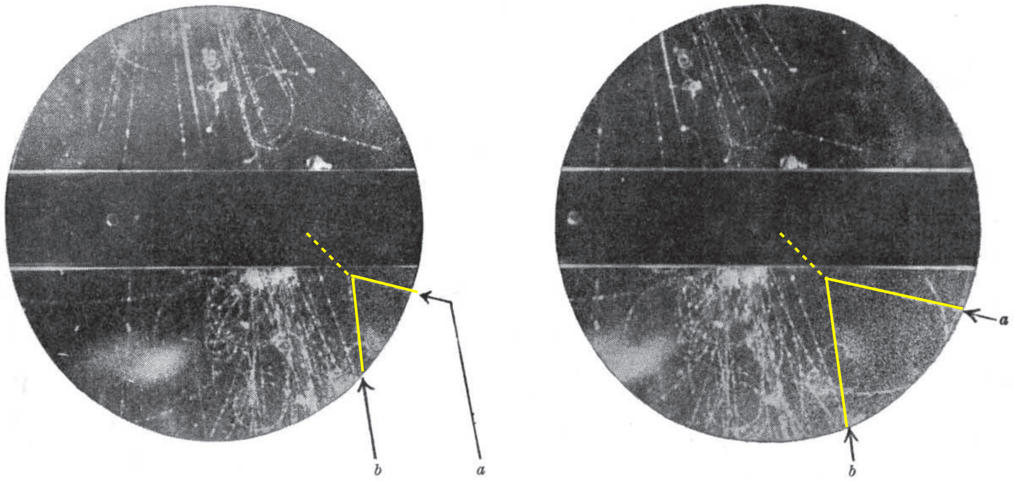
$$I_3 = Q - \frac{B}{2}$$


Ulrich Husemann
Institute of Experimental Particle Physics

# Strangeness

Karlsruhe Institute of Technology

- 1940s: new “strange” particles in cosmic rays (Rochester, Butler, 1947)
  - Experimental technique: stereoscopic **bubble chamber pictures**
  - Signature: ***V*⁰** (“neutral vertex”) created in lead block
  - Today: $V^0$ decays are mainly $K_S^0 \to \pi^+\pi^-$, $\Lambda^0 \to p\pi^-$




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

# Strangeness & Parity

Karlsruhe Institute of Technology

- Theta-tau puzzle:
  - Observation: “two" particle decays with **different final state parity**

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

  - But: both particles have the **same mass and lifetimes** → same particle?

$$m_{\theta^+} = m_{\tau^+},\ \tau_{\theta^+} = \tau_{\tau^+}$$

- Solution: new quantum number $S$ = **strangeness** (Gell-Mann; Nakano, Nishijima, 1953)
- Indeed: two different decays of the **same** particle $K^+ \to 2\pi/3\pi$ , in today’s language:
  - Strangeness **conserved** in $K^+$ production (strong interaction)
  - Strangeness **violated** in $K^+$ decay (weak interaction)
  - Another important consequence: **weak interaction violates parity**

# From Strangeness to Flavor

Karlsruhe Institute of Technology

- Group theory: from isospin $SU(2)$ to **flavor $SU(2)$**
  - Describe states with two quantum numbers, e.g. $I_3$ and $S$
  - Alternative choice: $I_3$ and (flavor) hypercharge $Y_F = B + S$
  - Relation to electric charge: **Gell-Mann–Nishijima formula**

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

  - Generalized to today's **six flavors**: $Y_F = B + S + C + \mathscr{B} + T$

| | |
|---|---|
| $C$ | = charm |
| $\mathscr{B}$ | = bottomness (also: beauty) |
| $T$ | = topness (also: truth) |

nobelprize.org

Murray Gell-Mann

Kazuhiko_Nishijima.jpg

Kazuhiko Nishijima

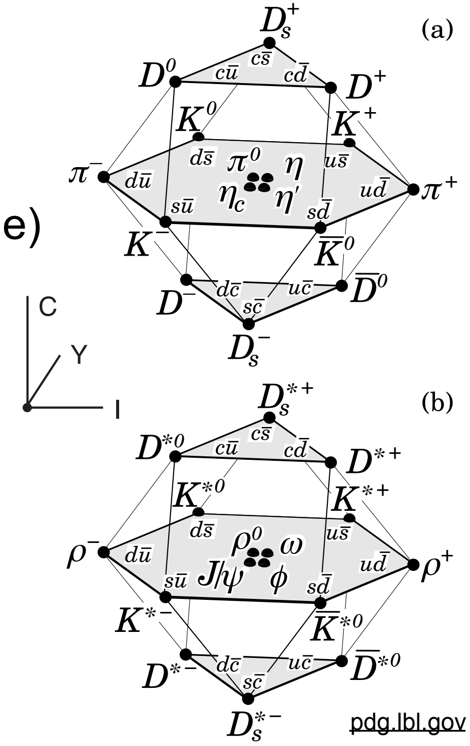
# Quark Model

- 1960s: **particle zoo**
  - Many further “elementary” particles discovered, e.g.

$$\eta', \rho, \omega, K^* \Delta, \Sigma, \Xi$$

  - Missing: **classification** scheme (cf. Mendeleev’s periodic table)
- **Quarks** (Gell-Mann, 1964) and **Aces** (Zweig, 1964)
  - Fundamental representation of flavor $SU(3)$: **three quarks** ($u$ = up, $d$ = down, $s$ = strange)
  - Baryon and meson multiplets as further representations of flavor $SU(3)$
  - Straightforward extension to four quarks: flavor $SU(4)$
  - Initially: purely mathematical tool, **no physical reality**

**Meson Multiplets**

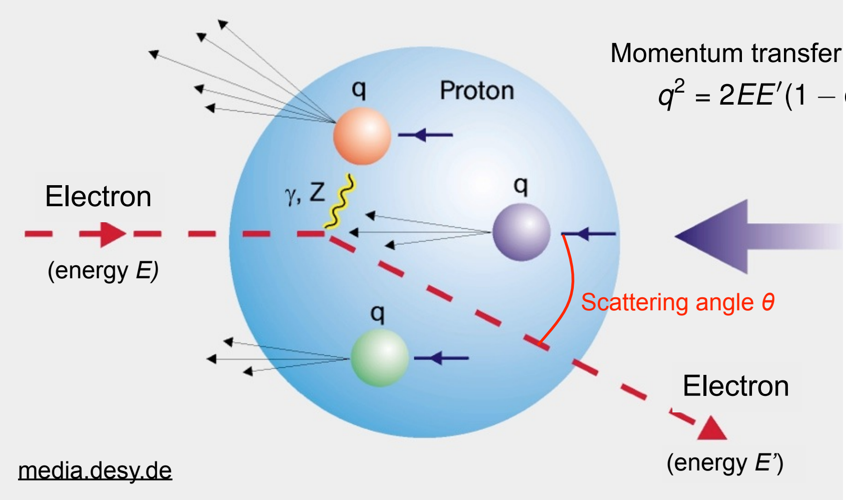



pdg.lbl.gov


Ulrich Husemann
Institute of Experimental Particle Physics

# Quark-Parton Model

- Stanford Linear Accelerator Center (SLAC), 1960s:
  - Scattering experiment: 20-GeV electron beam on fixed target → **nucleon structure** (expressed through form factors, e.g. for charge distribution)
  - Process: **deep inelastic scattering** (DIS)

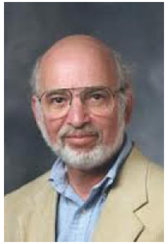




Ulrich Husemann
Institute of Experimental Particle Physics

# Quark-Parton Model

- Discovery of nucleon **substructure** (Breidenbach et al., 1969)
- Theoretical interpretation:
  - Substructure = “**partons**” – pointlike spin-1/2 particles (Feynman, 1969)
  - These partons can be identified with quarks (Bjorken, Paschos, 1969)



ppa.slac.stanford.edu

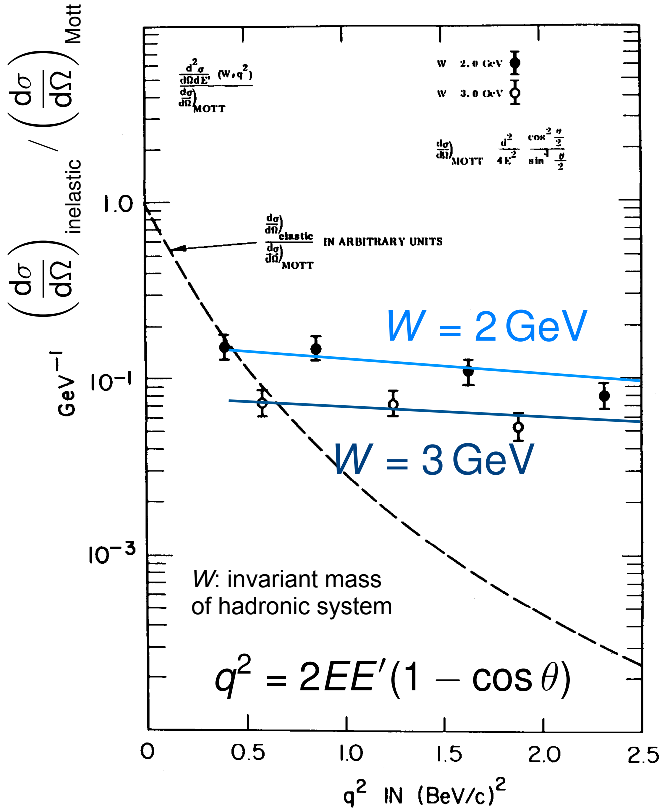
Martin Breidenbach

www.fnal.gov

James D. Bjorken

www.hep.princeton.edu

Emmanuel Paschos




H. W. Kendall, Nobel Lecture 1990

# Quantum Chromodynamics

- **Yang-Mills theory** (Yang, Mills, 1954):
  - Use gauge symmetries to construct theories of of strong & weak interactions (symmetry group: ***SU*(*N*)**)
  - Prediction: **massless** mediators (= force carriers)
  - But: **massive pions** as mediators of nuclear force, Fermi coupling constant $G_F$ of weak interactions **not dimensionless** → contradiction to theory

Chen Ning Yang, Robert L. Mills (1999)

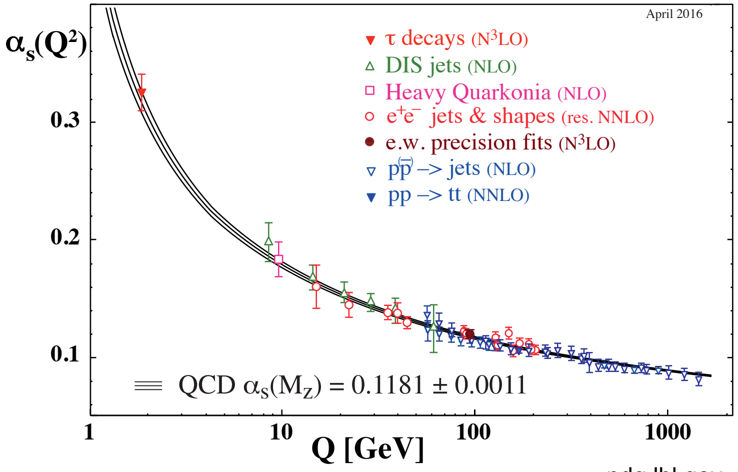
www-rnc.lbl.gov

- Hints of unknown **new internal degree of freedom** for quarks:
  - Example: $\Omega^-$ baryon has quark content $|sss\rangle$
  - $\Omega^-$ is a **fermion**, but wave functions in position, spin, and flavor space **symmetric** → wave function **antisymmetric** in new degree of freedom: **"color"**

# Quantum Chromodynamics

- **Color-*SU*(3)** (Fritzsch, Gell-Mann, Leutwyler, 1973):
  - Strong interaction described as *SU*(3) gauge theory for quarks
  - Mediators ("force carriers"): **8 gluons**
  - Quarks and gluons carry "color charge" → quantum **chromo**dynamics (QCD)

Energy Dependence of QCD Coupling




pdg.lbl.gov

- **Asymptotic freedom** (Gross, Wilczek, Politzer, 1973): QCD coupling $\alpha_S$ gets weaker with increasing energy
  - Quarks approximately free particles in DIS
  - Low energies: **confinement** → no free quarks

# Weak Interactions

- Process known from radioactive beta decay (*A:* mass number, *Z:* atomic number)

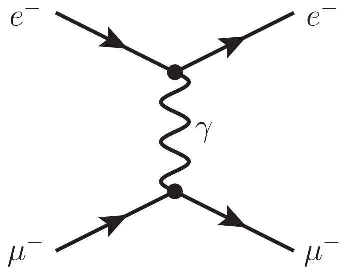
$$(A, Z) \rightarrow (A, Z+1) + e^-$$

  - Apparent two-body decay: expect fixed electron energy
    → contradicts observation
  - Solution (Pauli, 1930): **neutrino postulate**

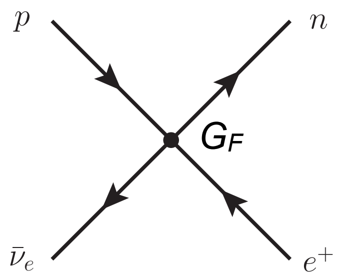
    $$(A, Z) \rightarrow (A, Z+1) + e^- + \bar{\nu}_e$$

- Fermi's theory of **weak interactions**:
  - **Vector currents** (like in electrodynamics)
  - **Contact interactions** with Fermi coupling constant $G_F$
  - Dimension of $G_F$: $[\text{energy}]^{-2}$
    → hint of massive mediator particle (today: W boson)

**QED Process**




**Weak Process**





Ulrich Husemann
Institute of Experimental Particle Physics

# Parity Violation in Weak Interactions

- **Discrete symmetries** of particle physics:
  *C* (charge conjugation), *P* (parity), and *T* (time reversal)
  - Each **conserved individually** in strong and electromagnetic interactions
  - Expectation: **parity conservation** also for weak interactions
- Starting from theta-tau puzzle (see above):
  - Lee/Yang: suggestion of **parity violation** in weak interactions (1956)
  - Parity violation first observed in Wu experiment (1957)
  - Goldhaber, Grodzins, Sunyar experiment (1958): massless neutrinos are left-handed → **maximal** parity violation → weak interactions only act on left-handed particles
- Improved theory of weak interactions: ***V–A* theory** (Feynman, Gell-Mann; Sudarshan, Marshak, 1958) → weak current = “vector minus axial vector” current

# CP Violation

- Search for CP violation in neutral K meson ("K long") decays (Christenson, Cronin, Fitch, Turlay, 1964):
  - CP conserving: $K_L^0 \to \pi^+\pi^-\pi^0$
  - CP violating: $K_L^0 \to \pi^+\pi^-$ (2000 times smaller)
  - Weak interaction also violates **combined CP symmetry**
- Cosmological implications of CP violation: each explanation of the baryon asymmetry $\frac{n_B - n_{\overline{B}}}{n_\gamma} \approx 10^{-9}$ in the universe requires (Sakharov, 1967):
  - Thermal non-equilibrium
  - **CP violation**
  - Baryon number violation

Historical Overview, Part II

# THE STANDARD MODEL OF PARTICLE PHYSICS


Ulrich Husemann
Institute of Experimental Particle Physics

# Electroweak Theory

Karlsruhe Institute of Technology

- **Unitarity problem** in *V–A* theory:
  - Cross section for neutrino-electron scattering prediction by *V–A* theory proportional to *s* (center-of-mass energy squared), **infinitely large** for $s \to \infty$
  - Solution: **unified** theory of weak and electromagnetic interactions
    → **Glashow-Salam-Weinberg model** (GSW)
  - Gauge group (Glashow, 1961): $SU(2) \times U(1)$
    $SU(2)$: weak isospin
    $U(1)$: weak hypercharge


S.L. Glashow


A. Salam

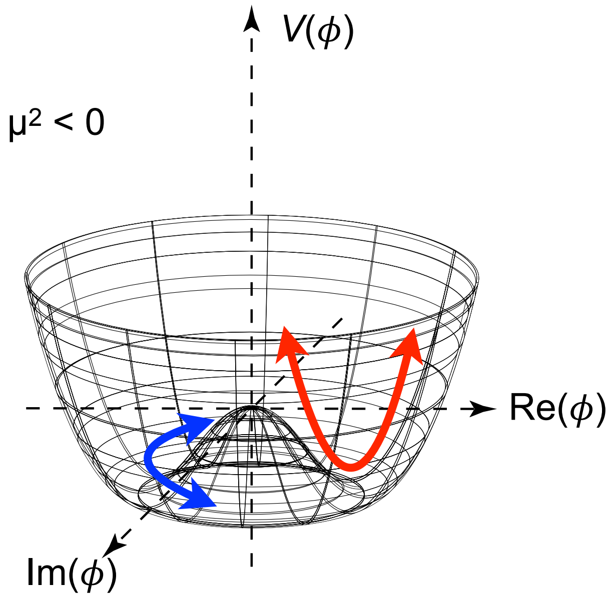

S. Weinberg

nobelprize.org

# Electroweak Theory

- (Brout-Englert-)Higgs mechanism: **spontaneous symmetry breaking** (SSB) through Higgs potential $V(\phi)$
  - SSB: ground state of a theory does not preserve symmetry of Lagrangian
  - Discovered independently by several groups: Higgs; Brout, Englert; Goldstone, Jona-Lasinio, Nambu; Guralnik, Hagen, Kibble (1960s)
  - Application of Higgs mechanism on $SU(2)\times U(1)$ theory (Salam, Weinberg, 1968)
    → **massive** $W$ und $Z$ bosons, **massless** photon
    → prediction of a **Higgs boson**

**2D Analogy of Higgs Potential**

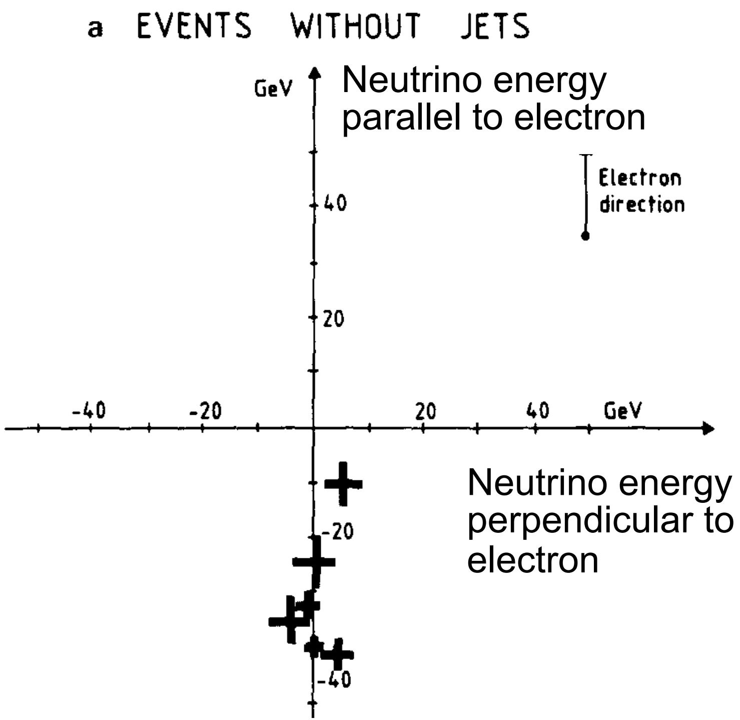




Ulrich Husemann
Institute of Experimental Particle Physics

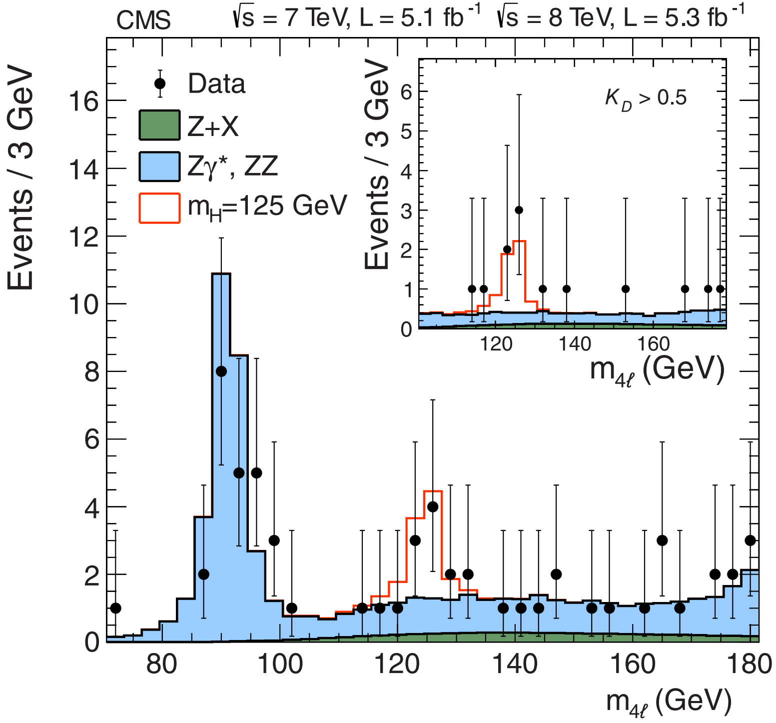
# Discoveries

## *W* and *Z* Boson Discovery (Sp$\bar{p}$S, CERN, 1983)




Phys. Lett. B122 (1983) 103

## Higgs Boson Discovery (LHC, CERN, 2012)




Phys. Lett. B 716 (2012) 30



Ulrich Husemann
Institute of Experimental Particle Physics

# Quark Mixing and Flavor Physics

Karlsruhe Institute of Technology

- Application of GSW model to quarks:
  - Eigenstates of weak interactions (= particles interacting with the *W* boson) ≠ mass eigenstates (= physical particles)
  - *W* boson couples to **linear combination** of mass eigenstates *d* and *s*

$$u \to d' = d\cos\theta_C + s\sin\theta_C$$

  $\rightarrow$ quark "mixing" with $\theta_C$ "Cabibbo angle", sin $\theta_C \cong 0.22$ (Cabibbo, 1963)

- **GIM mechanism** (Glashow, Iliopoulos, Maiani, 1970):
  - Observation: decay $K^+ \to \ell\nu$ much more likely than $K^0 \to \mu\mu$
  - GIM: $K^0 \to \mu\mu$ suppressed due to quantum corrections from **fourth quark c**
  - **Discovery of the *J/ψ*** = bound $c\bar{c}$ state (SLAC, BNL, 1974)


Ulrich Husemann
Institute of Experimental Particle Physics

# Quark Mixing and Flavor Physics

Karlsruhe Institute of Technology

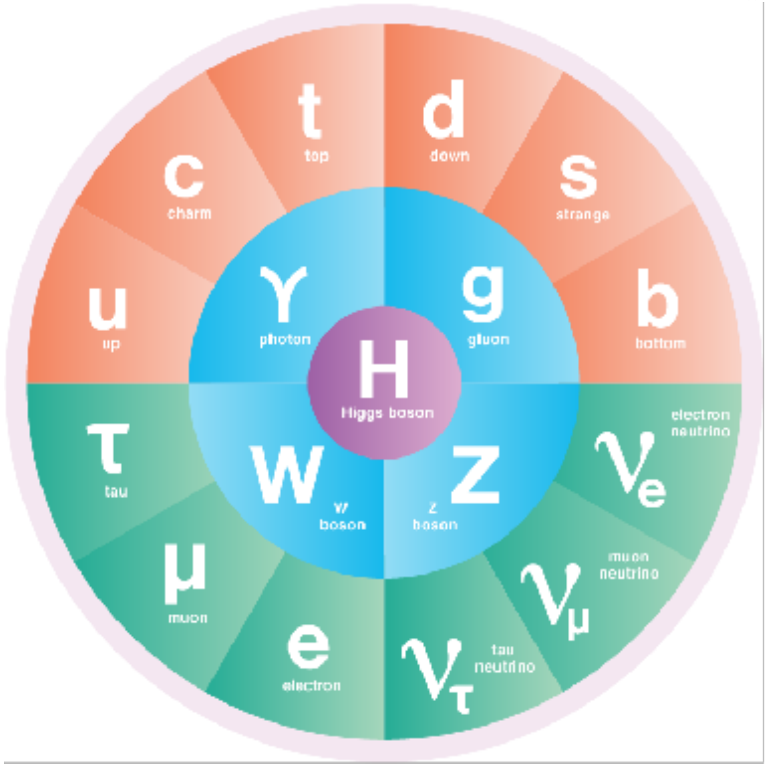
- Quark mixing as source of **CP violation**:
  - Only with **at least three quark generations** (Kobayashi, Maskawa, 1973)
  - Mathematical description: (complex, unitary) **Cabibbo-Kobayashi-Maskawa (CKM) mixing matrix**

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

- Discovery of **third generation quarks and leptons**:
  - Leptons: $\tau$ lepton (Perl et al., 1975), $\nu_\tau$ (DONUT, 2000)
  - Quarks: bottom quark (Lederman et al., 1977), top quark (Tevatron, 1995)

# Standard Model of Particle Physics

- **Particle content**: 6 quarks + 6 leptons (+ antiparticles)
- **Interactions** (mediated by gauge bosons): **electroweak** interaction (= unified electromagnetic and weak interaction), **strong** interaction




symmetrymagazine.org


Ulrich Husemann
Institute of Experimental Particle Physics

# Beyond the Standard Model?

- Higgs-boson discovery: **standard model completed** with mechanism for spontaneous symmetry breaking
- Many **open questions** remain:
  - Does the standard model work also at **(much) higher energy scales**?
  - Is the standard model **“natural”?** Or: Why is the **Higgs-boson mass so small**, despite huge quantum corrections? Do we care if it is not?
  - What lies **beyond** the standard model? (explanations missing for: neutrino mass, dark matter, dark energy, …)

C. Grupen after C. Flammarion, L'atmosphère (1888)

# PARTICLE PHYSICS TODAY


Ulrich Husemann
Institute of Experimental Particle Physics

# High-$p_T$ Collider Physics

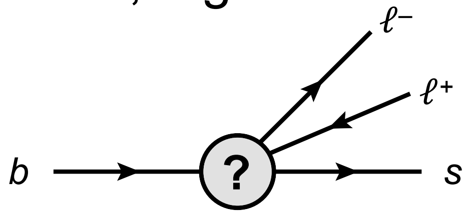
## Current flagship: Large Hadron Collider

- World's largest and most powerful particle accelerator
  27 km circumference, approx. 100 m underground
- Protons accelerated to up to 7 TeV
- Four large multi-purpose experiments:
  ATLAS, CMS, ALICE, LHCb
- Broad physics program: standard model and beyond
- Main topic of this school → more in upcoming lectures

Bildquelle: CERN

# High-Precision Flavor Physics

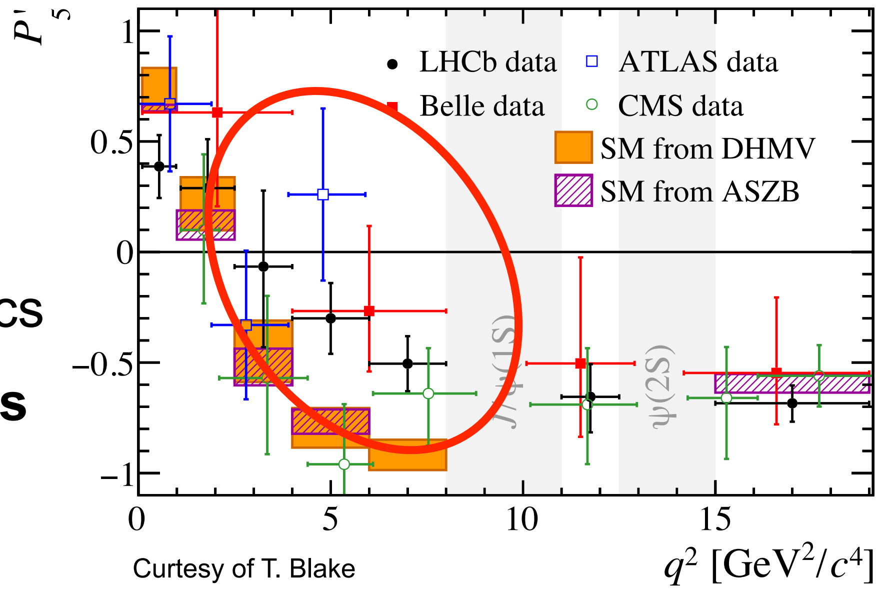
- Search for new physics in **quantum corrections**, e.g.




→ probe **indirect effects** to much higher scales than in high-$p_T$ physics

- Only significant **source of tensions** with the SM so far, e.g. muon anomalous momentum (“g–2”), rare *B*-meson decays

Angular observable in decay B → K*ℓℓ



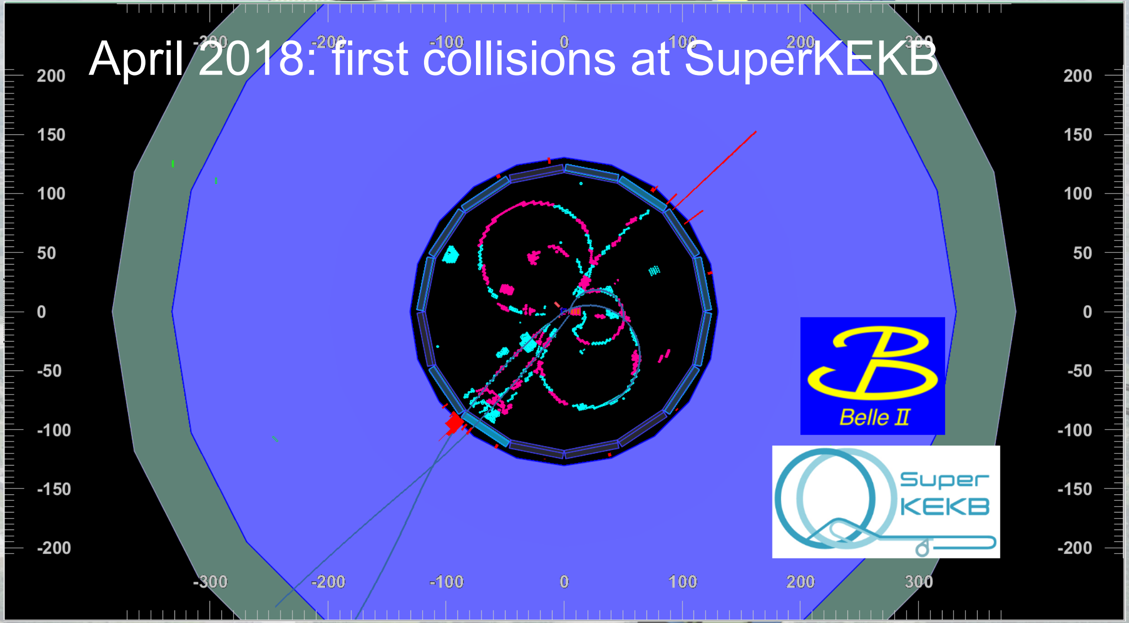

Curtesy of T. Blake


Ulrich Husemann
Institute of Experimental Particle Physics

# Super B Factory: KEKB and Belle II

Picture courtesy of KEK

- Experiment at asym-metric $e^+e^-$ collider at $\sqrt{s} \approx 10.5$ GeV
- Pushing the **precision frontier**: 50 $ab^{-1}$ of integrated luminosity expected
- Physics program: **CP violation** and **rare decays** in heavy quarks



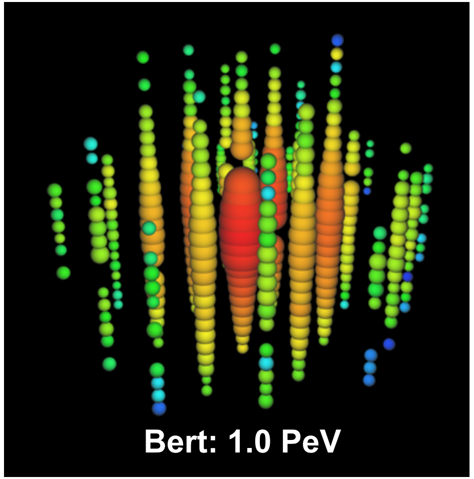


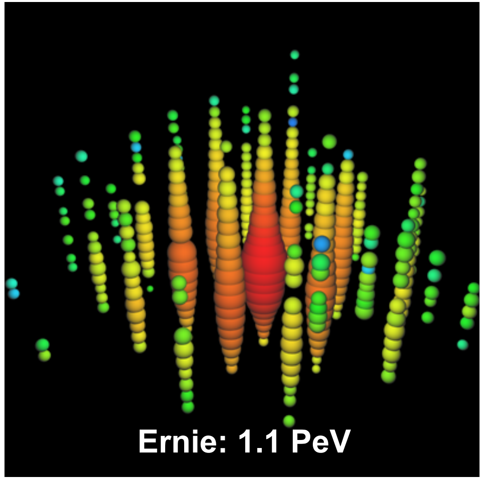
Ulrich Husemann
Institute of Experimental Particle Physics

# Neutrino Physics: Some Recent Results

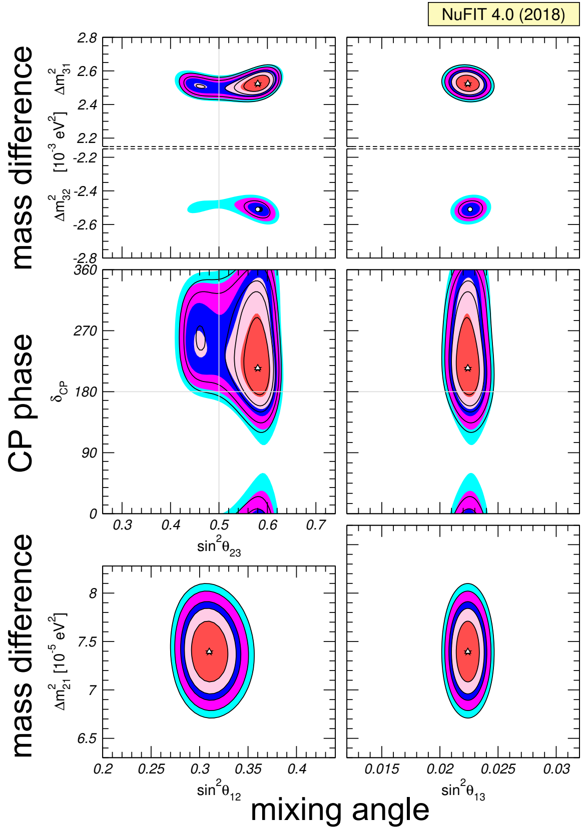
Karlsruhe Institute of Technology

- Neutrino oscillations: **non-zero mass** (many experiments)
- Universe contains sources of **PeV neutrinos** (IceCube, South Pole)




icecube.wisc.edu



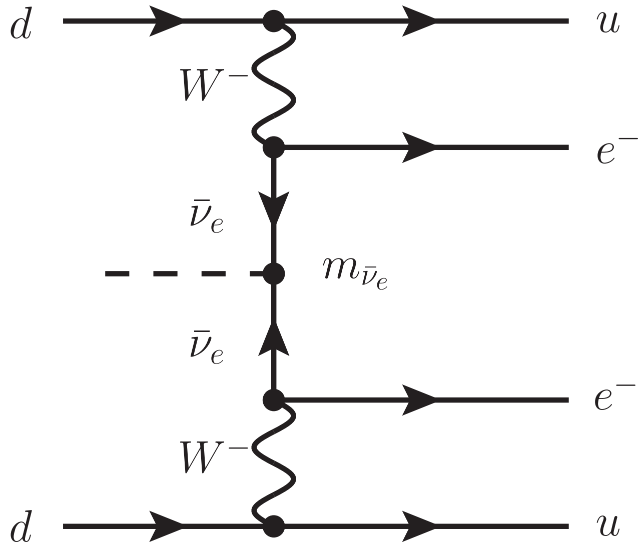

nu-fit.org




Ulrich Husemann
Institute of Experimental Particle Physics

# Neutrino Physics: Open Questions

- **Dirac of Majorana** particle?
  → neutrinoless double-beta decay ($0\nu\beta\beta$)





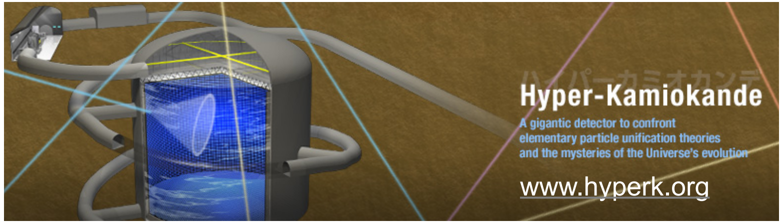
Ulrich Husemann
Institute of Experimental Particle Physics

# Neutrino Physics: Open Questions

Karlsruhe Institute of Technology

- **Dirac of Majorana** particle?
  → neutrinoless double-beta decay ($0\nu\beta\beta$)
- **CP violation** in the lepton sector?
  → accelerator & reactor neutrino beams

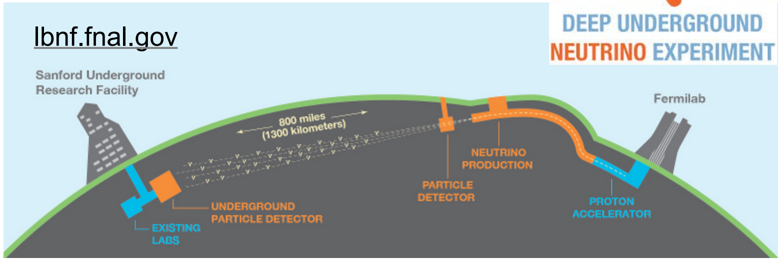
**Japanese Project: Hyper-Kamiokande**




→ J-PARC $\nu$ beam, water Cherenkov detector

**US Project: DUNE**

DEEP UNDERGROUND NEUTRINO EXPERIMENT




→ Fermilab $\nu$ beam, liquid-argon detector

# Neutrino Physics: Open Questions

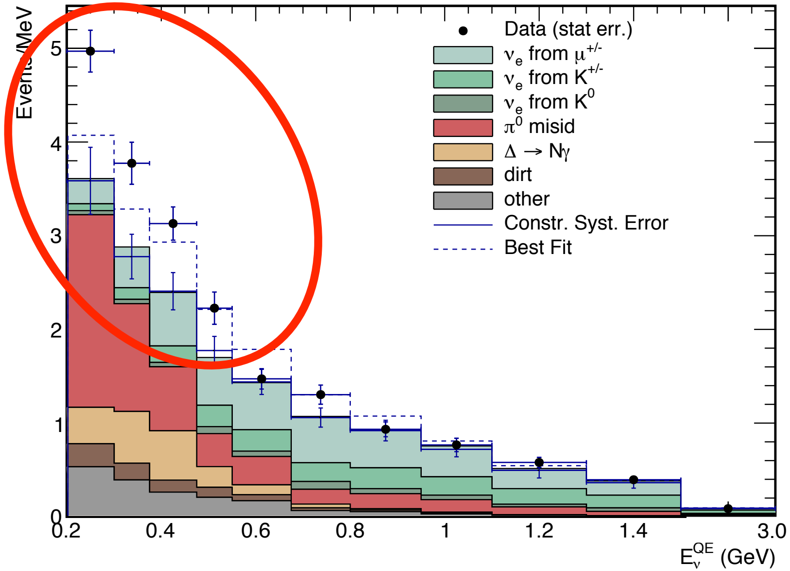
- **Dirac of Majorana** particle?
  → neutrinoless double-beta decay ($0\nu\beta\beta$)
- **CP violation** in the lepton sector?
  → accelerator & reactor neutrino beams
- Absolute **mass scale** (& hierarchy) ?
  → KATRIN (+ $0\nu\beta\beta$ + cosmology)


katrin.kit.edu

# Neutrino Physics: Open Questions

- **Dirac of Majorana** particle?
  → neutrinoless double-beta decay ($0\nu\beta\beta$)
- **CP violation** in the lepton sector?
  → accelerator & reactor neutrino beams
- Absolute **mass scale** (& hierarchy) ?
  → KATRIN (+ $0\nu\beta\beta$ + cosmology)
- Additional **sterile** neutrinos?
  **Non-standard model** interactions?
  → small deviations in experiments

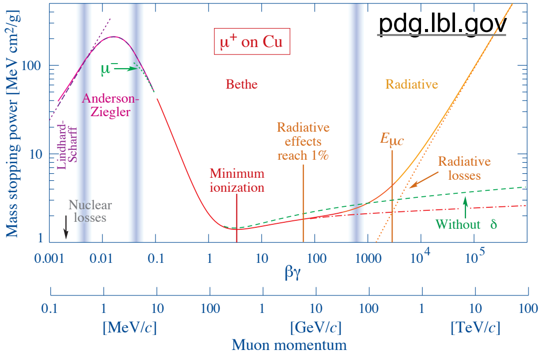
**LSND/MiniBooNE Anomaly**



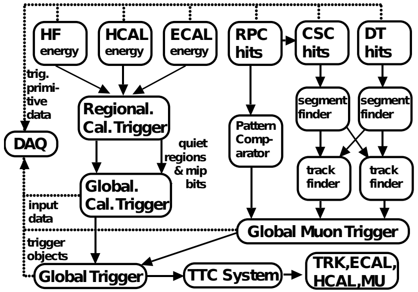

Phys. Rev. Lett. 121 (2018) 221801

# All That Technology…

## Energy Loss in Matter

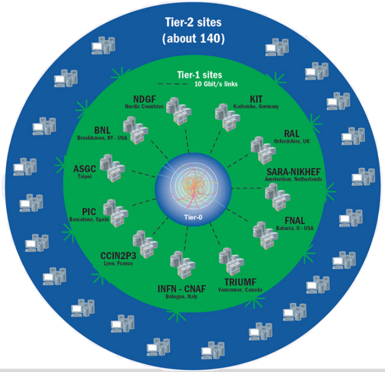



## CMS L1 Trigger Overview



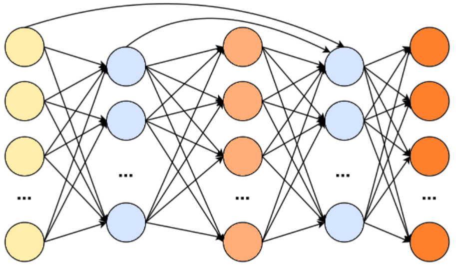

JINST 12 (2017) P01020

## WLCG Computing Model




cerncourier.com

## Deep Neural Network Architecture



M. Rieger

- **Instrumentation**:
  - Accelerators and detectors (→ Dobrzynski, Colaleo)
  - Trigger & readout electronics
- **Computing**:
  - Offline data processing
  - Data analysis (→ Prosper, UH)


Ulrich Husemann
Institute of Experimental Particle Physics

# Summary

- Particle physics:
  **what is our universe made of** on the fundamental level?
- Solid foundation of particle physics
  → well established **standard model of particle physics**
- Particle physics today: **highly specialized** sub-fields
  (e.g. high-$p_T$ collider physics, flavor physics, neutrino physics)
- There's so much more … enjoy the school


Ulrich Husemann
Institute of Experimental Particle Physics