Why does the Universe exist?

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Charterhouse

Fundamental Physics

Aim: **Understand the world** - not: make money!
But: Understanding costs a lot of money

Fundamental Physics in 2016

Special Relativity
Quantum Theory -> Particle Physics (Microcosm)

$$i\hbar\frac{\partial\Psi}{\partial t} = \left(-\frac{\hbar^2}{2m}\vec{\nabla}^2 + V(\vec{x})\right)\Psi$$

SCHROEDINGER EQUATION

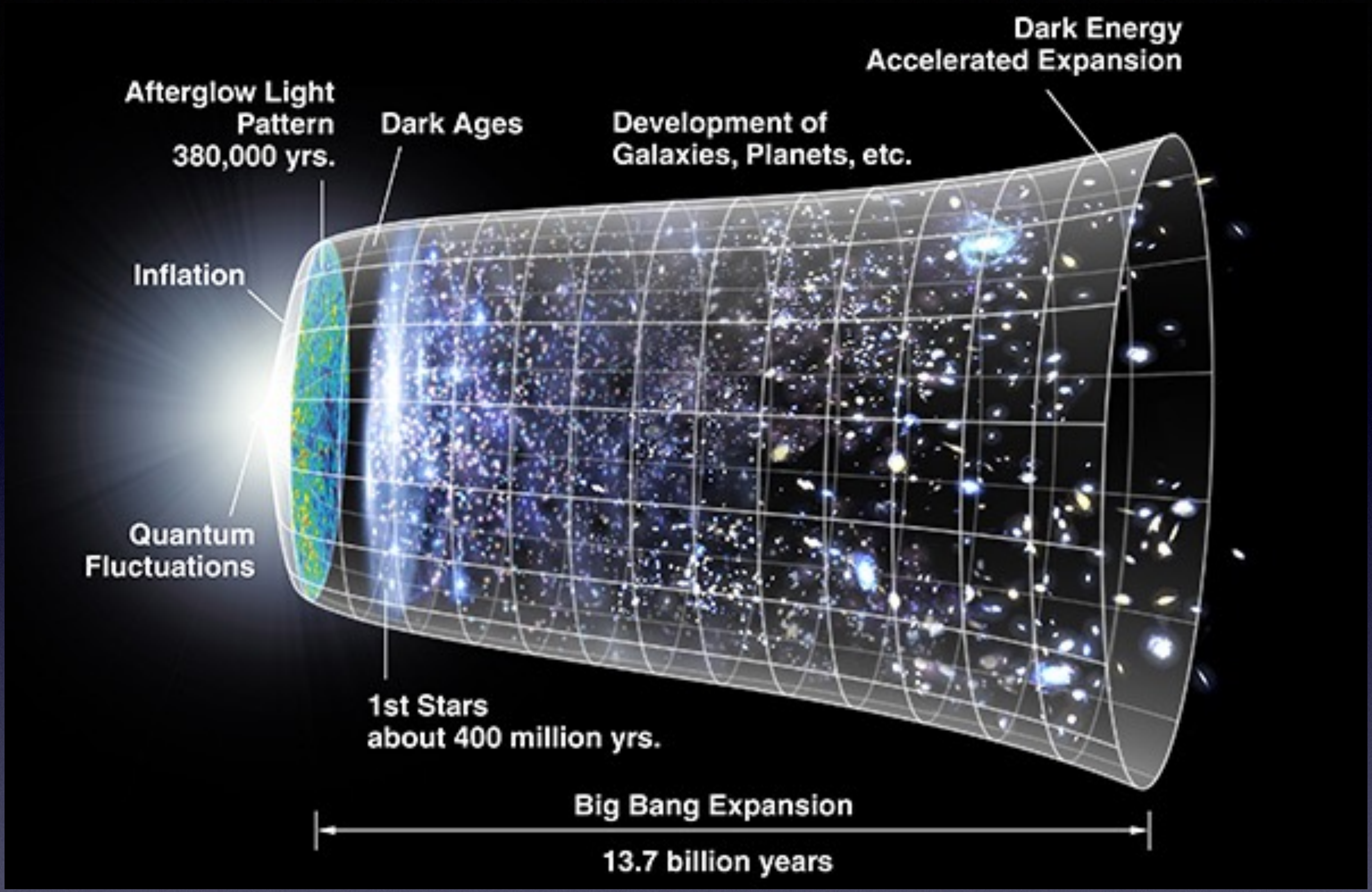
General Relativity -> Astrophysics (Macrocosm)

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu}$$

EINSTEIN EQUATION

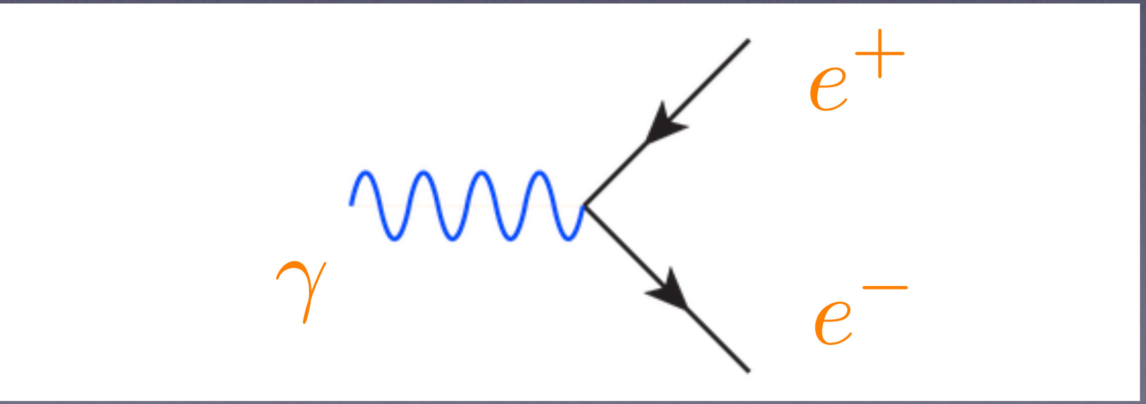
Is there any overlap of these two fields?

Big Bang: huge amount of energy



Quantum Theory + EINSTEIN: $E = mc^2$

Energy can be transformed into an exactly equal amount of matter and anti-matter



But: the Universe is only full of matter

50% of the galaxies matter and 50% anti-matter?
No

Asymmetric initial conditions?
(for whatever reason the universe had only matter in the beginning and no anti-matter)
No

Sakharov 1964:

“A matter asymmetry can be created from symmetric initial conditions if the **fundamental laws of nature** have the following properties:

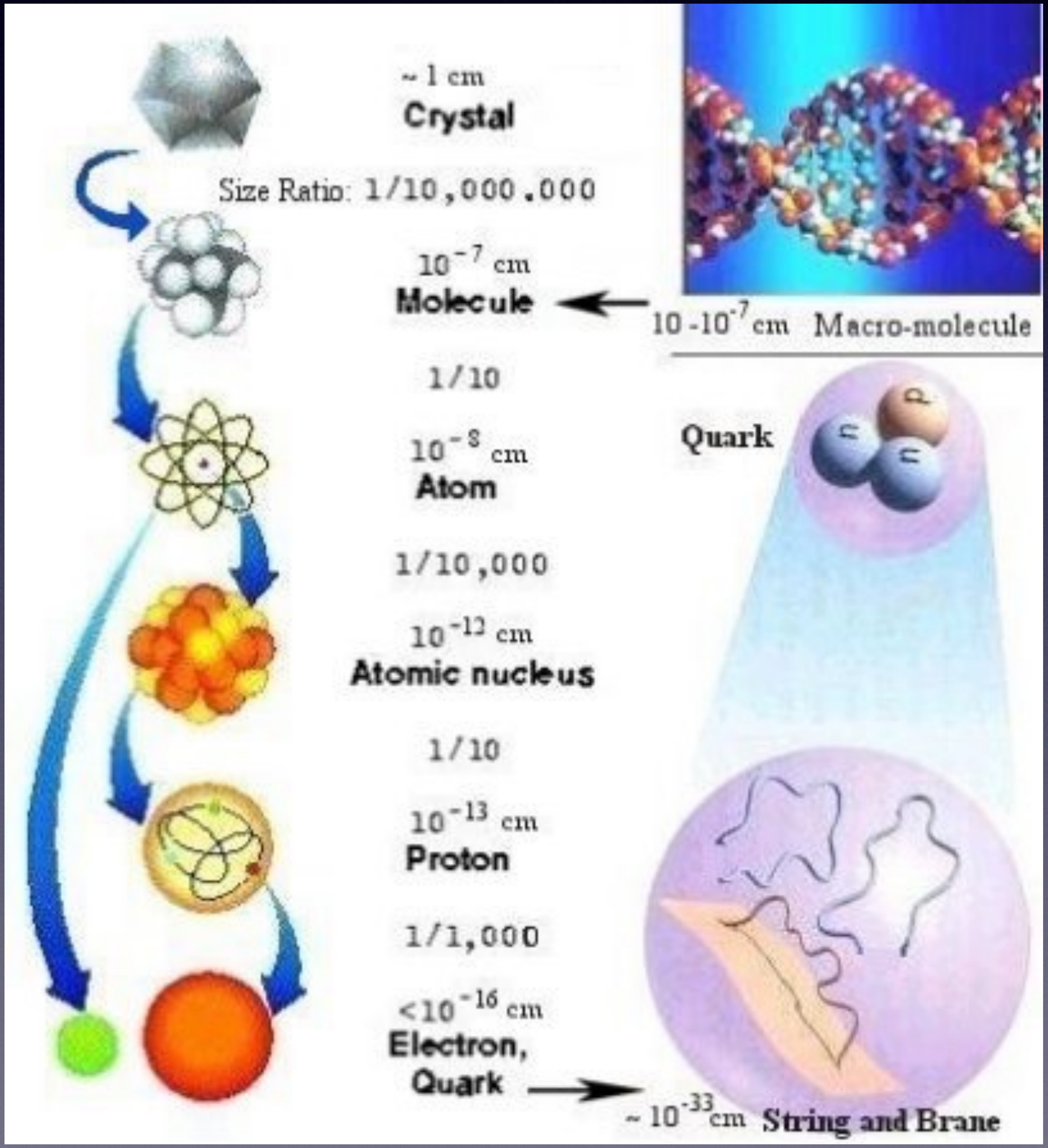
- **CP symmetry** is violated
- **Baryon number** is violated
- There was a phase **away from the thermal equilibrium** “

Now we have to understand several concepts:

- **Fundamental laws of nature**
- **CP Symmetry**
- **Baryon number**
- **Thermal equilibrium**

The fundamental laws of nature

What is our world made of?

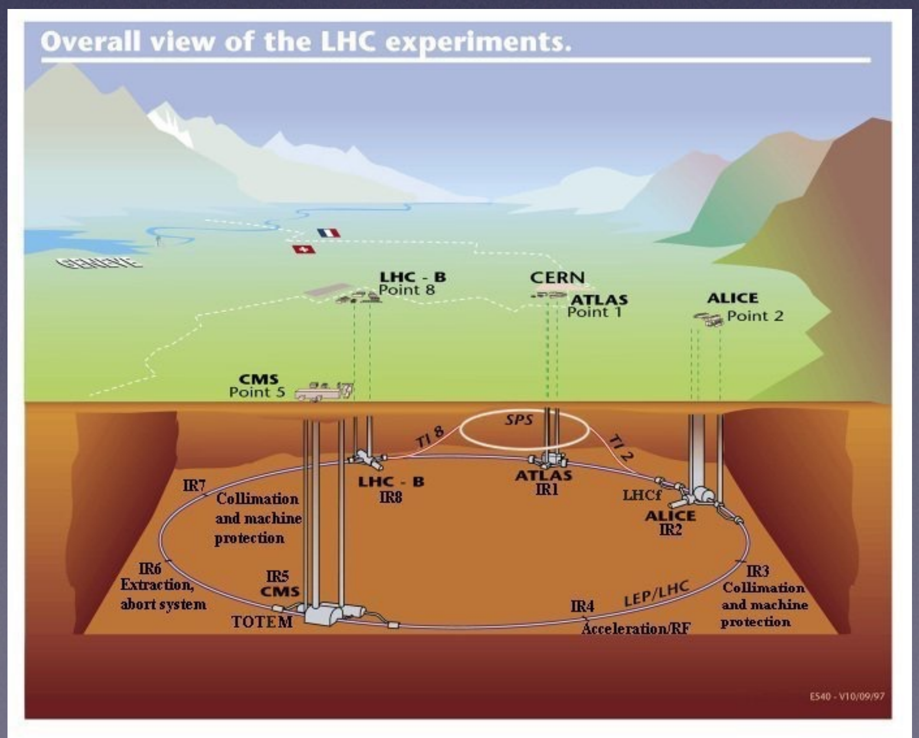


How do we get knowledge about the microcosm?

Microscope
down to $5 \cdot 10^{-7}\mathrm{m}$

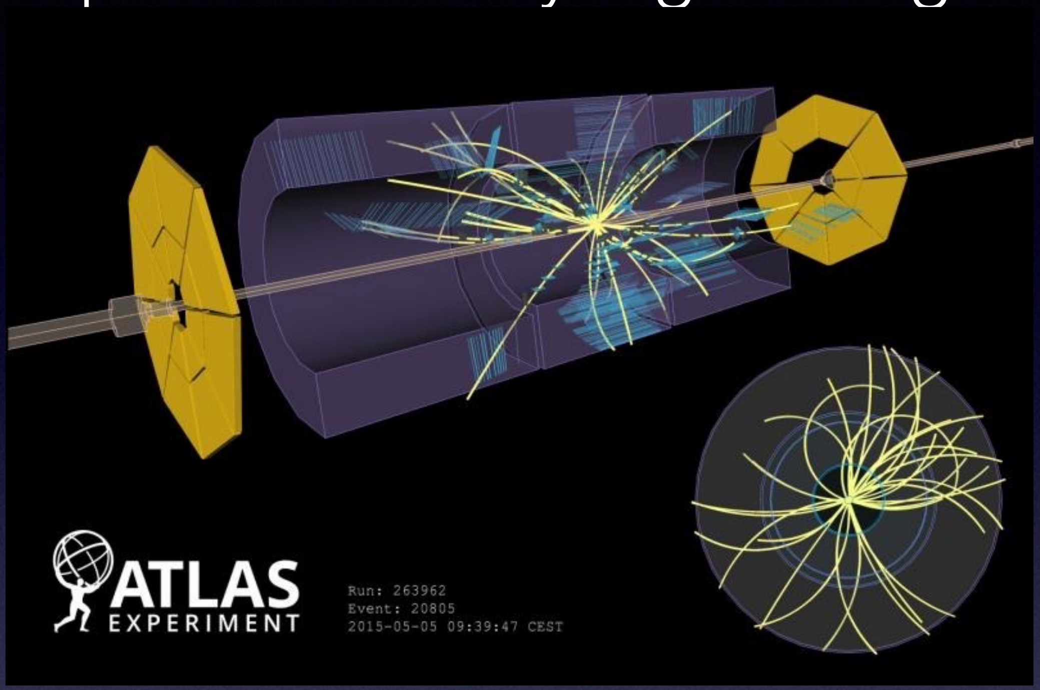
Electron Microscope
down to $5 \cdot 10^{-10}\mathrm{m}$

Particle Accelerator
down to $5 \cdot 10^{-19}\mathrm{m}$



The Large Hadron Collider

The LHC collides protons at very high energies to create new particles



- Energies/masses are measured in Electron Volts

$$m_{\text{Proton}} \approx 1\text{GeV} = 10^{9}\text{eV} \approx 10^{-27}kg$$

- Protons have an energy of 6.5+6.5=13 TeV
- The collider has a circumference of 27 km
- More than 10 000 scientists from 100 countries
- tens of Petabyte per year
- 4 big detectors: **ATLAS**, **CMS**, **ALICE** and **LHCb**

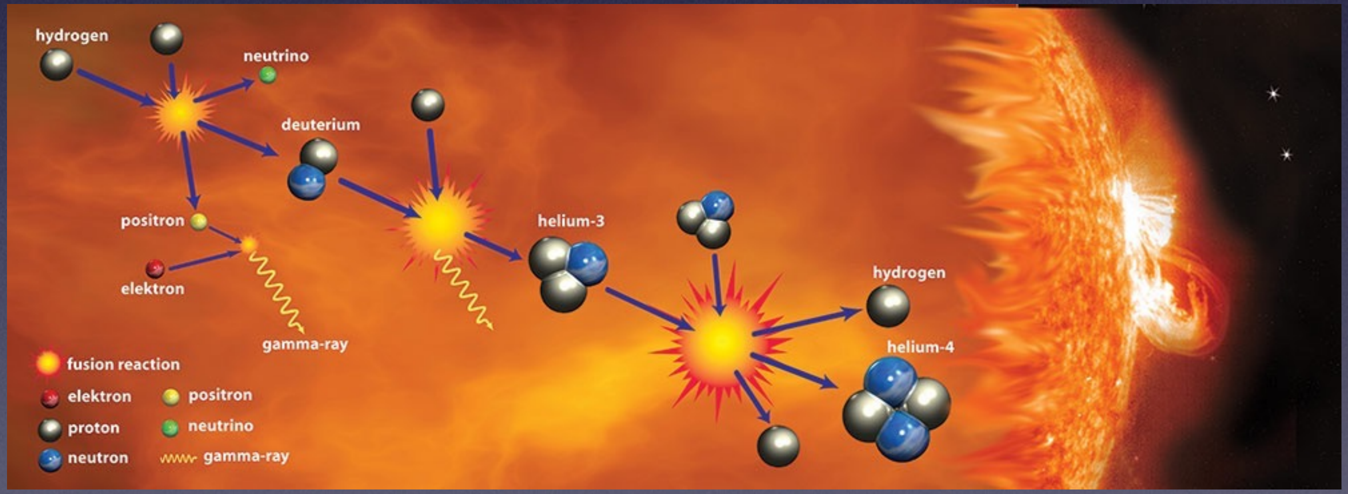
The fundamental laws of nature:

We have the following **interactions** in nature:

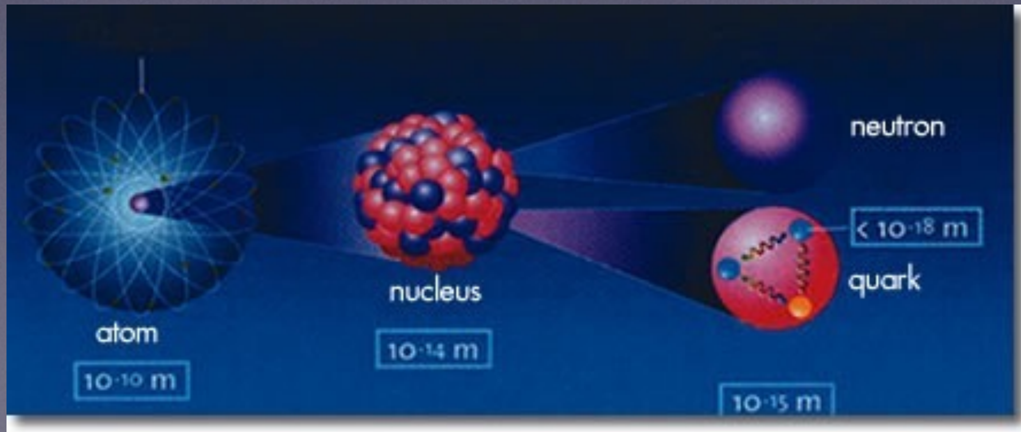
- **Gravity:** *lets apples fall from trees*

- **Electro-magnetic interaction:** *thunder and lightning, electricity*

- **Weak interaction:** *energy production in the sun*



- **Strong interaction:** *binds nucleons to nuclei and quarks to nucleons*



The fundamental laws of nature

The Standard Model (SM) of Particle Physics:

Matter constituents: Fermions with spin 1/2

Quarks | Leptons

$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix} \qquad \begin{pmatrix} \nu_e \\ e^- \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix} \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}$$

Interactions: Bosons with spin 1 (gauge bosons)

Photon	γ	m=0
Weak bosons	$W^{\pm}, Z^0$	m=80 Gev, 91 GeV
Gluons	g	m=0

Creation of Mass: Boson with spin 0

Higgsparticle H

Elementary reactions

Strong interaction binds quarks and gluons to nucleons:

$$p = |uud\rangle + |uud + g + q\bar{q}\rangle + \ldots$$

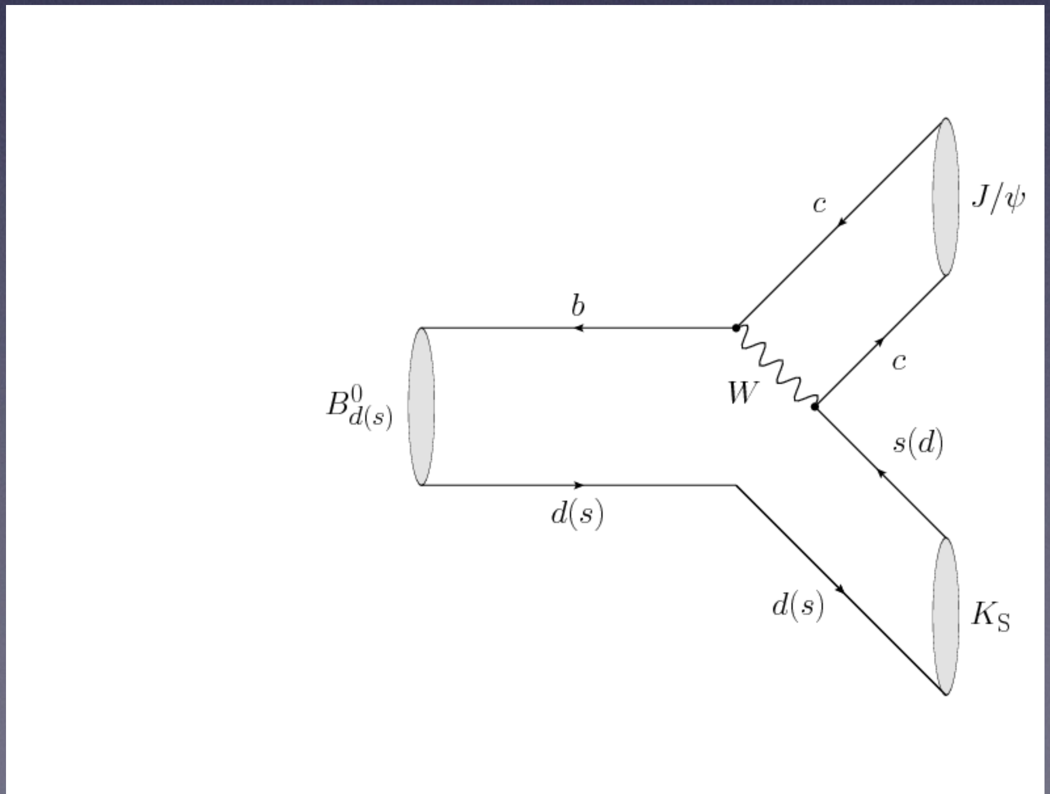
Weak interaction produces energy in the sun

$$4\,p \rightarrow^4_2 He + 2e^+ + 2\nu_e$$

A B-meson decays

$$B_d \rightarrow J/\psi + K_s$$

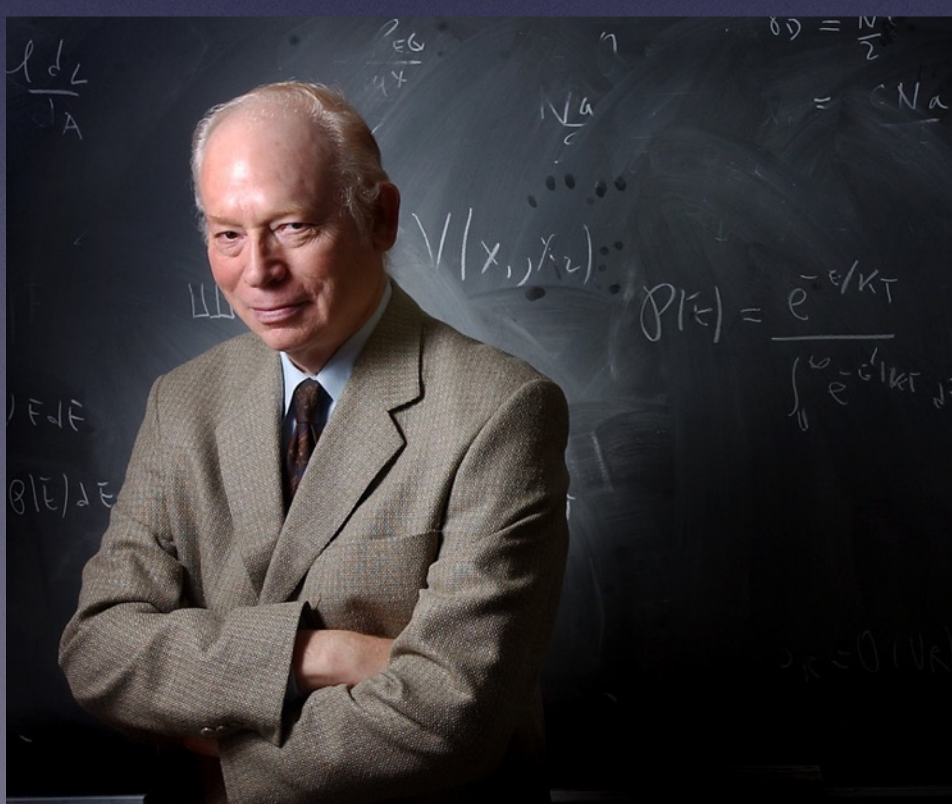
$$|\bar{b}d\rangle \rightarrow |\bar{c}c\rangle + |\bar{s}d\rangle$$



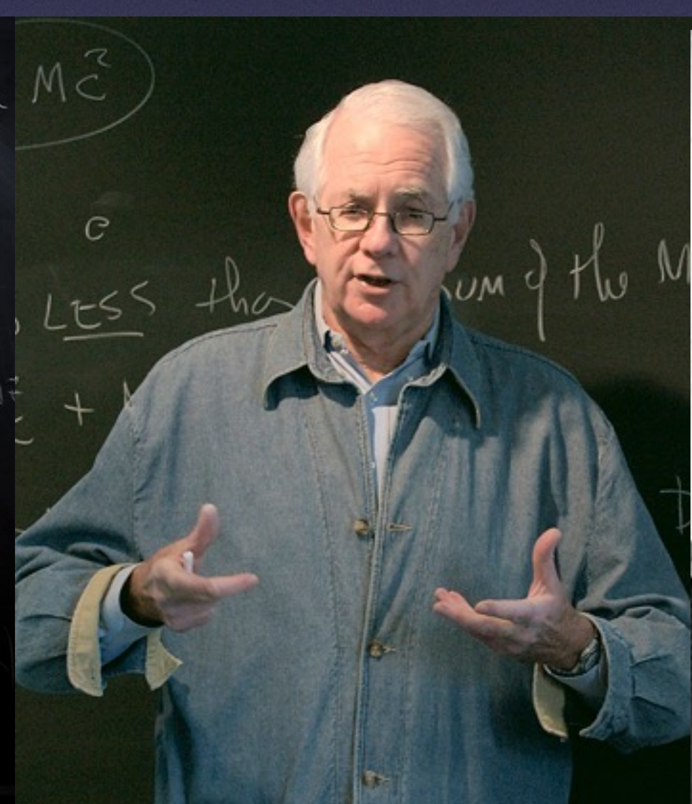
The standard model of particle physics

$$\mathcal{L} = \bar{\Psi} i \not{D} \Psi - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} + y \bar{\Psi} \phi \Psi + D_\mu \phi D^\mu \phi - V(\phi)$$

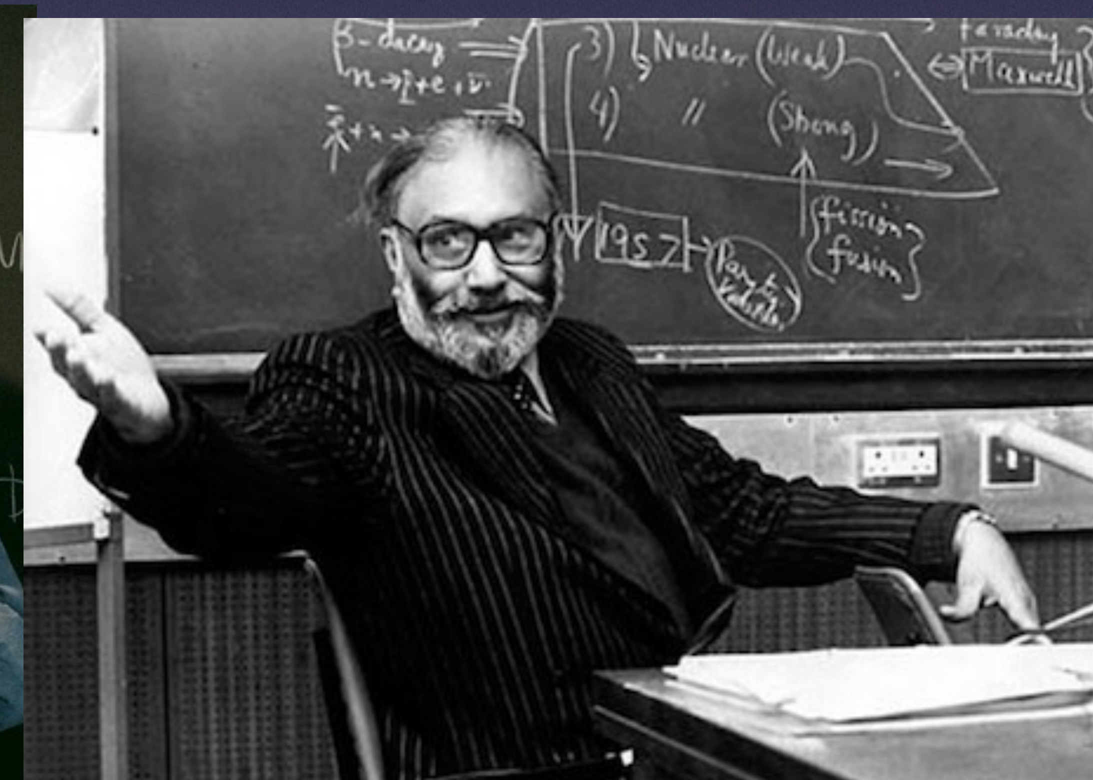
STEVEN WEINBERG



SHELDON GLASHOW



ABDUS SALAM



Symmetries rule

It turns out (experiment) that the SM is ruled by symmetries

- **Lorentz-symmetry:** The symmetry based on the assumption, that the speed of light is constant. This gives certain requirements on space-time.
- **Gauge symmetry:** This is a symmetry that acts on an internal quantum mechanical space and not the usual space-time.

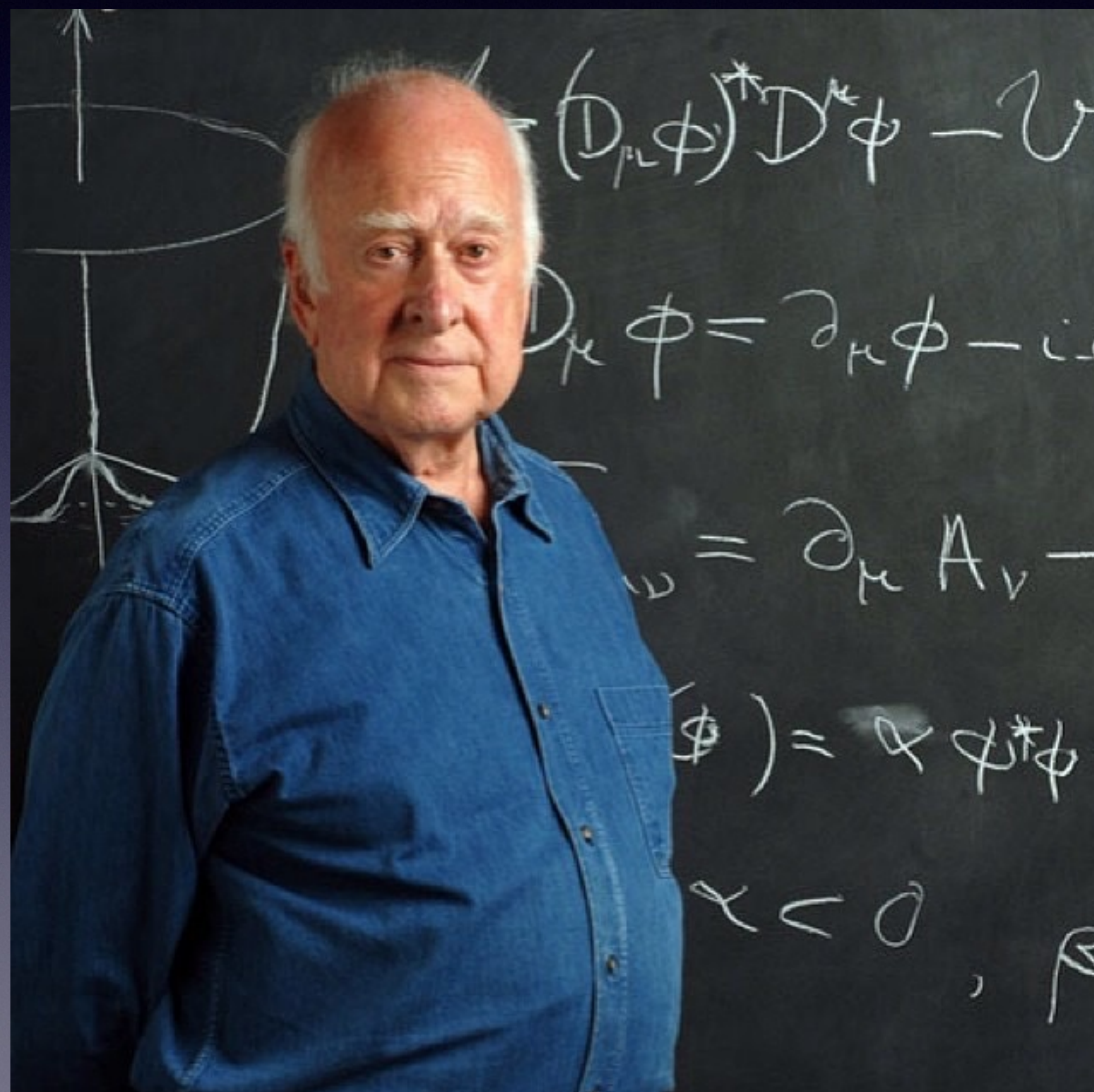
Demanding Lorentz-symmetry and a certain gauge symmetry, one can immediately write down the SM, which describes hundreds of experiments at the per mille level!

Tests of the SM: Nobel Prizes

1965 Tomonaga, Schwinger, Feynman: **QED**
1968 Alvarez: **Experiment**
1969 Gell-Mann: **Quark model**
1976 Richter, Ting: **Charm-quark**
1979 Weinberg, Salam, Glashow: **Standard Model**
1980 Cronin, Fitch: **CP violation in Kaons**
1984 Rubbia, van der Meer: **W+-, Z**
1988 Lederman, Schwartz, Steinberger: **Muon neutrino**
1990 Friedman, Kendall, Taylor: **Quarks**
1992 Charpak: **Particle Detectors**
1995 Perl, Reines: **Tauon and electron neutrino**
1999 t'Hooft, Veltman: **Gauge symmetries**
2002 Davies, Koshiba: **Neutrino oscillations (solar)**
2004 Gross, Politzer, Wilczek: **Asymptotic freedom**
2008 Nambu, Kobayashi, Maskawa: **CP violation in the SM**
2013 Englert, Higgs: **Higgsmechanism**
2015 Kajita, Mc Donald: **Neutrino oscillations (athmospheric)**

The final missing piece

The Higgs boson



Why do we need a Higgs?

Gauge symmetries seem to be **necessary for the theoretical consistency** of the SM - else predictions can yield infinity ('t Hooft, Veltman in 1971)!

Gauge symmetry requires massless gauge bosons (as photon and gluon), but the weak bosons are massive

????

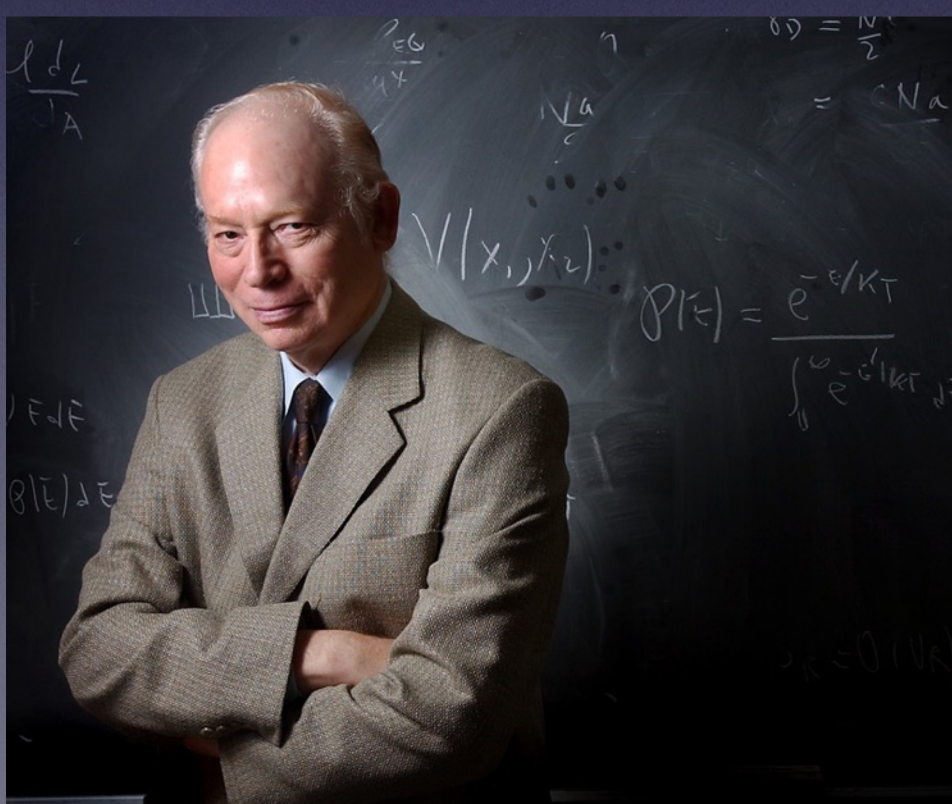
Solution: Trick invented in 1964 by Brout, Englert; Higgs; Guralnik, Hagen, Kibble

Combine massive bosons with gauge symmetry
Price to pay: postulate a new unobserved particle, the Higgs boson - observed in 2012!!

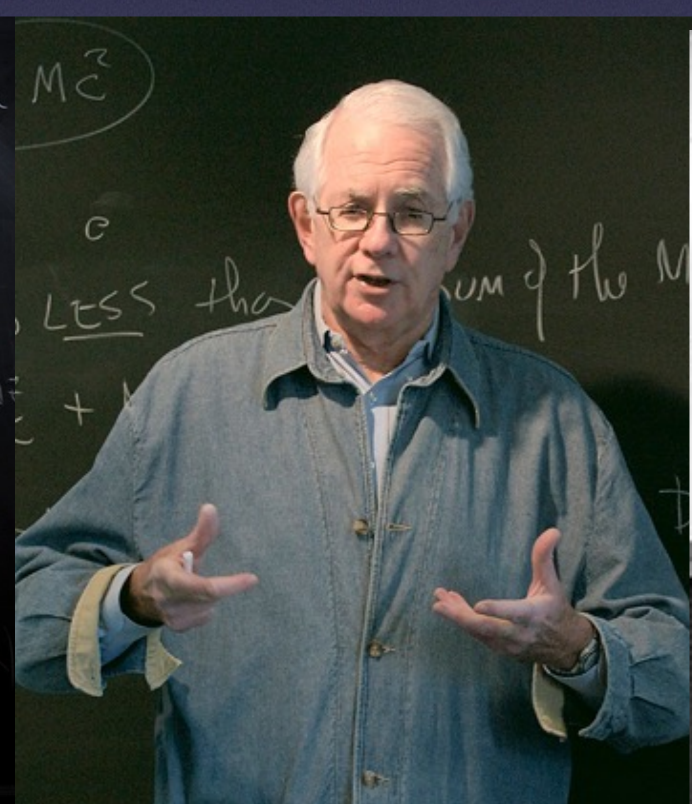
The standard model of particle physics

$$\mathcal{L} = \bar{\Psi} i \not{D} \Psi - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} + y \bar{\Psi} \phi \Psi + D_\mu \phi D^\mu \phi - V(\phi)$$

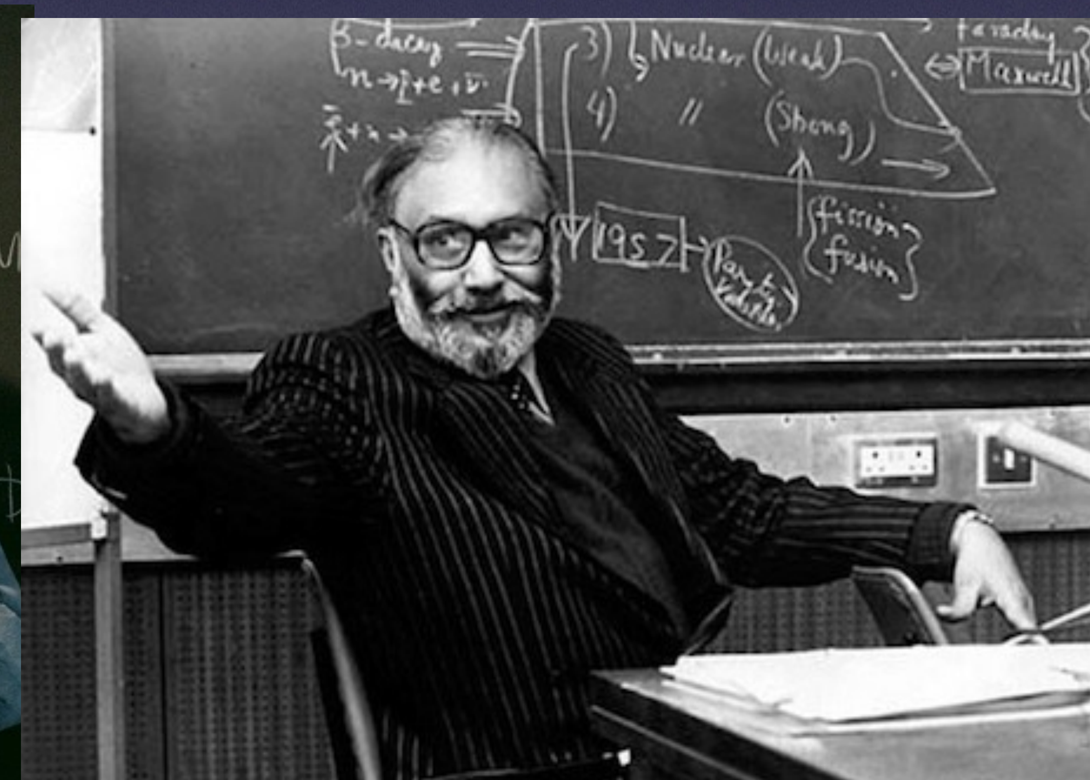
Steven Weinberg



Sheldon Glashow



Abdus Salam



Coming back to our problem

Creation of matter: **fundamental laws must violate CP:**

Does the Standard Model include CP violation?

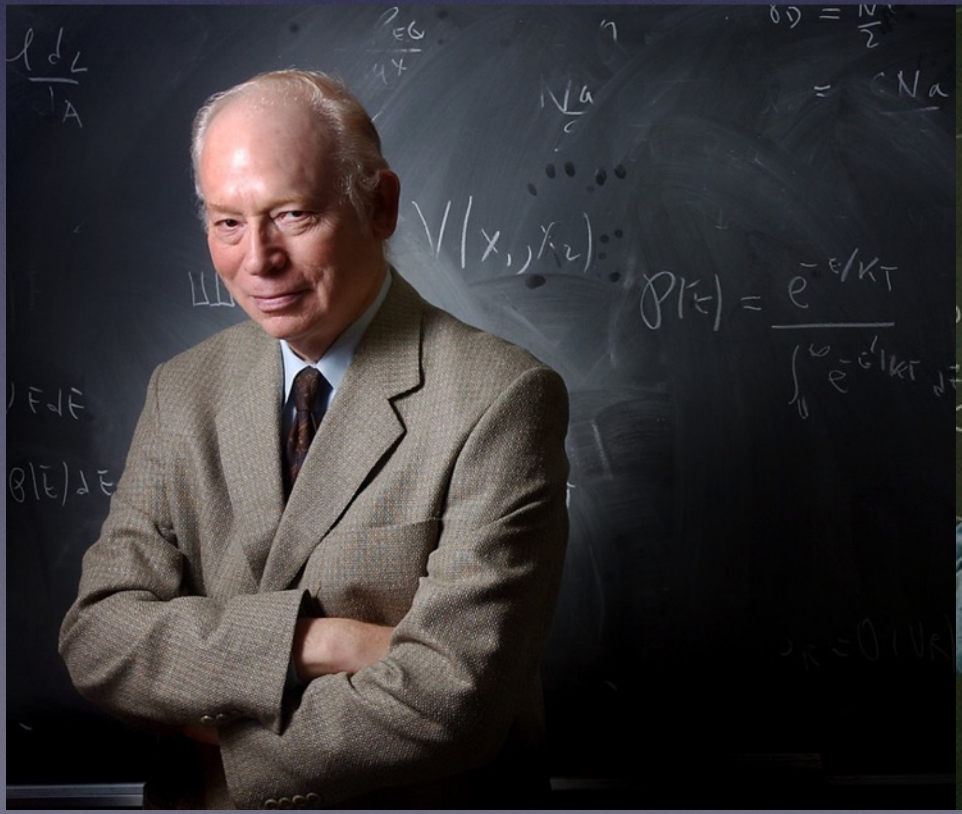
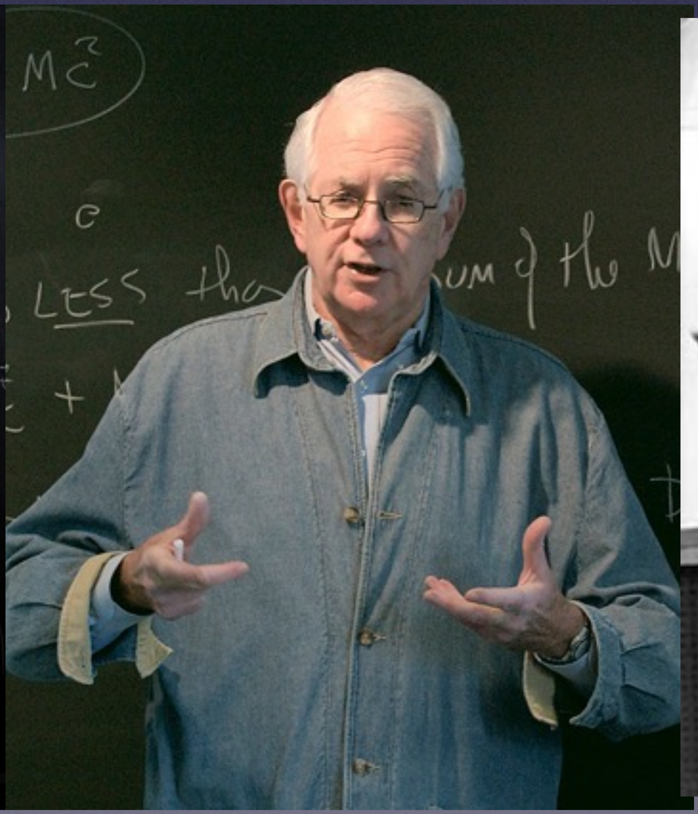
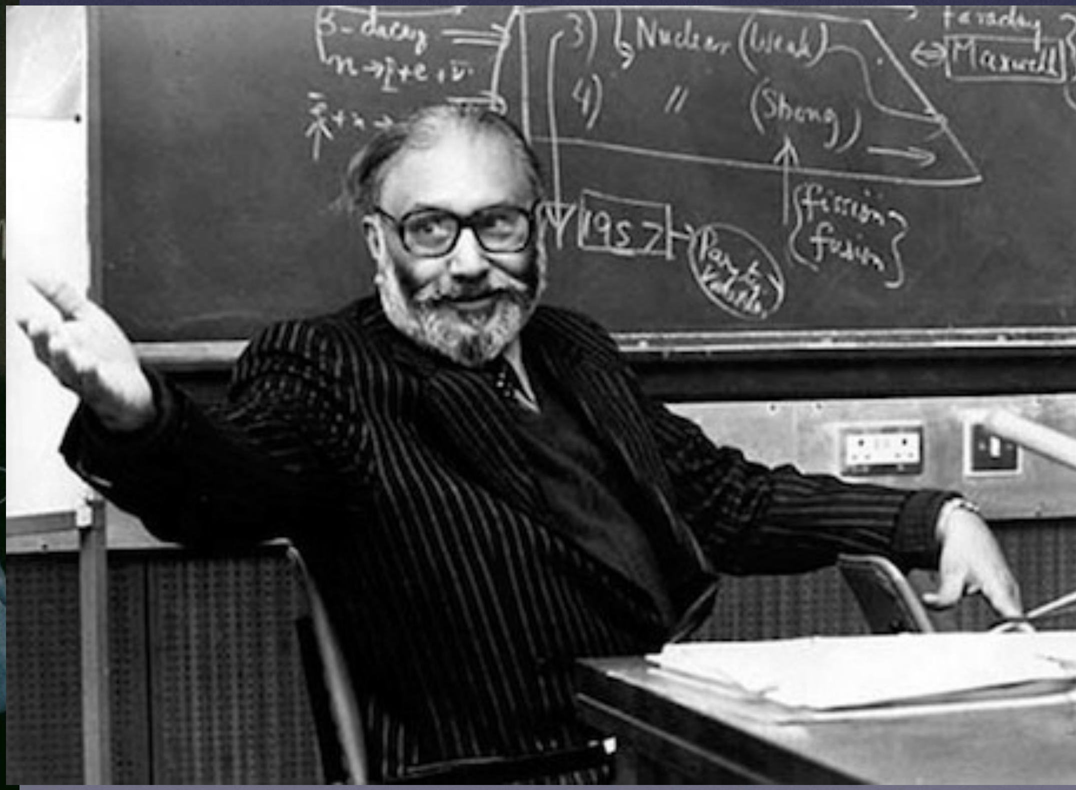
- **What is CP?** A combined symmetry: C is charge conjugation and P is parity, i.e. a mirror reflection.
- **What is CP violation?** An effect that is not invariant under CP; naive: left is different from right!
- **Is it observed in nature?** Yes: 1964 as a tiny effect in Kaon decays and from 1999 on as a large effect in B meson decays.
- **Is it included in the Standard Model?** Yes! Fermion masses are also produced with the Higgs, via Yukawa.

Modern Searches for CP violation = **Flavour Physics**

The standard model of particle physics

$$\mathcal{L} = \bar{\Psi} i \not{D} \Psi - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} + y \bar{\Psi} \phi \Psi + D_\mu \phi D^\mu \phi - V(\phi)$$

STEVEN WEINBERG | SHELDON GLASHOW | ABDUS SALAM

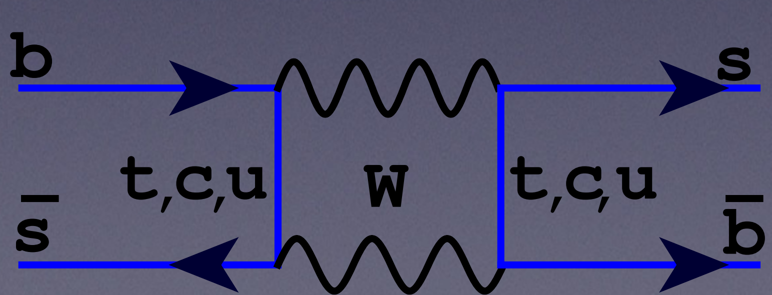
Flavour Physics

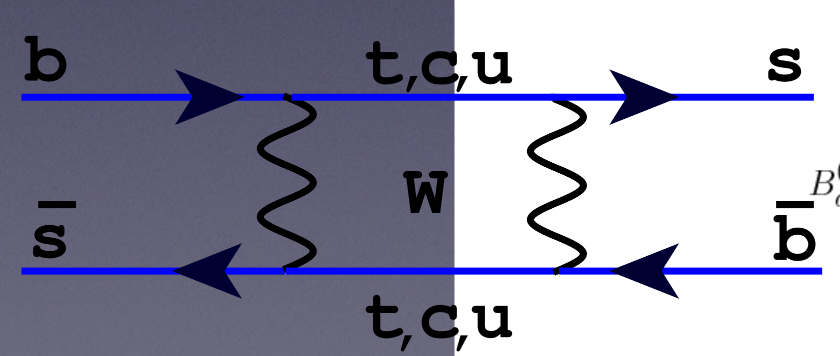
The study of decays of mesons (q + anti-q)

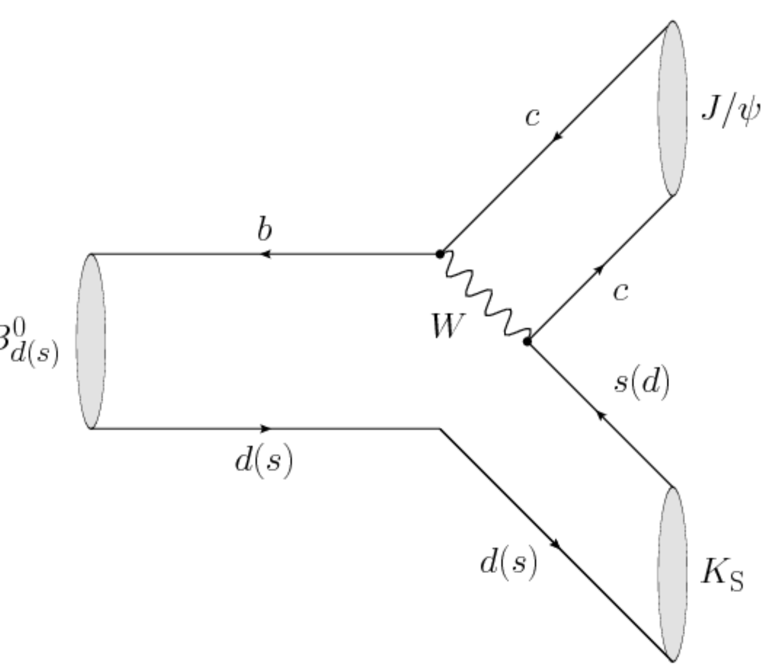
- Kaons = strange quark: **CP violation at per mille level**

- B-mesons = bottom/beauty quark:
  CP violation up to 50%

Build dedicated experiments to study B-mesons:
LHCb, **BaBAR** (SLAC, USA), **Belle** (KEK, Japan)

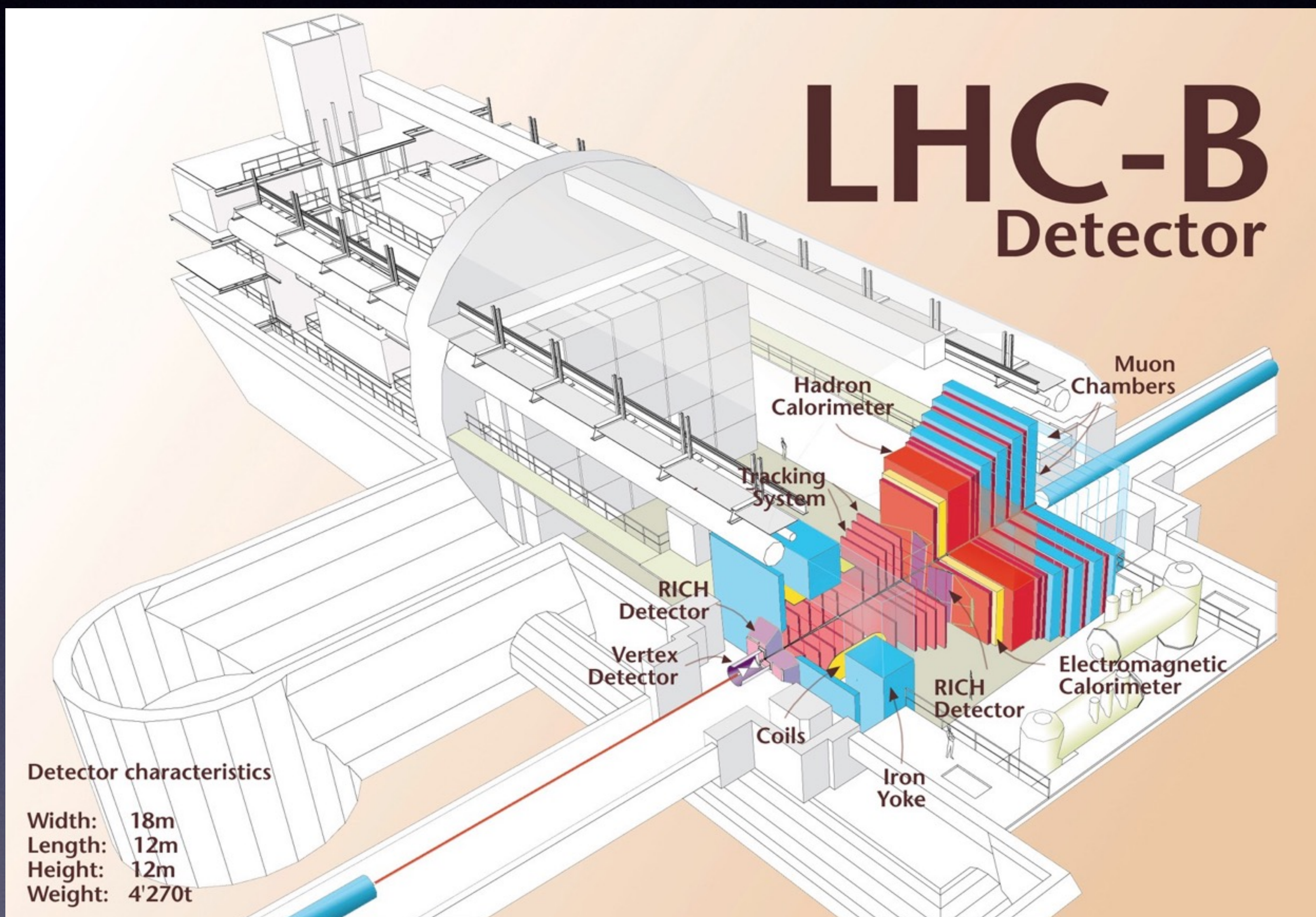


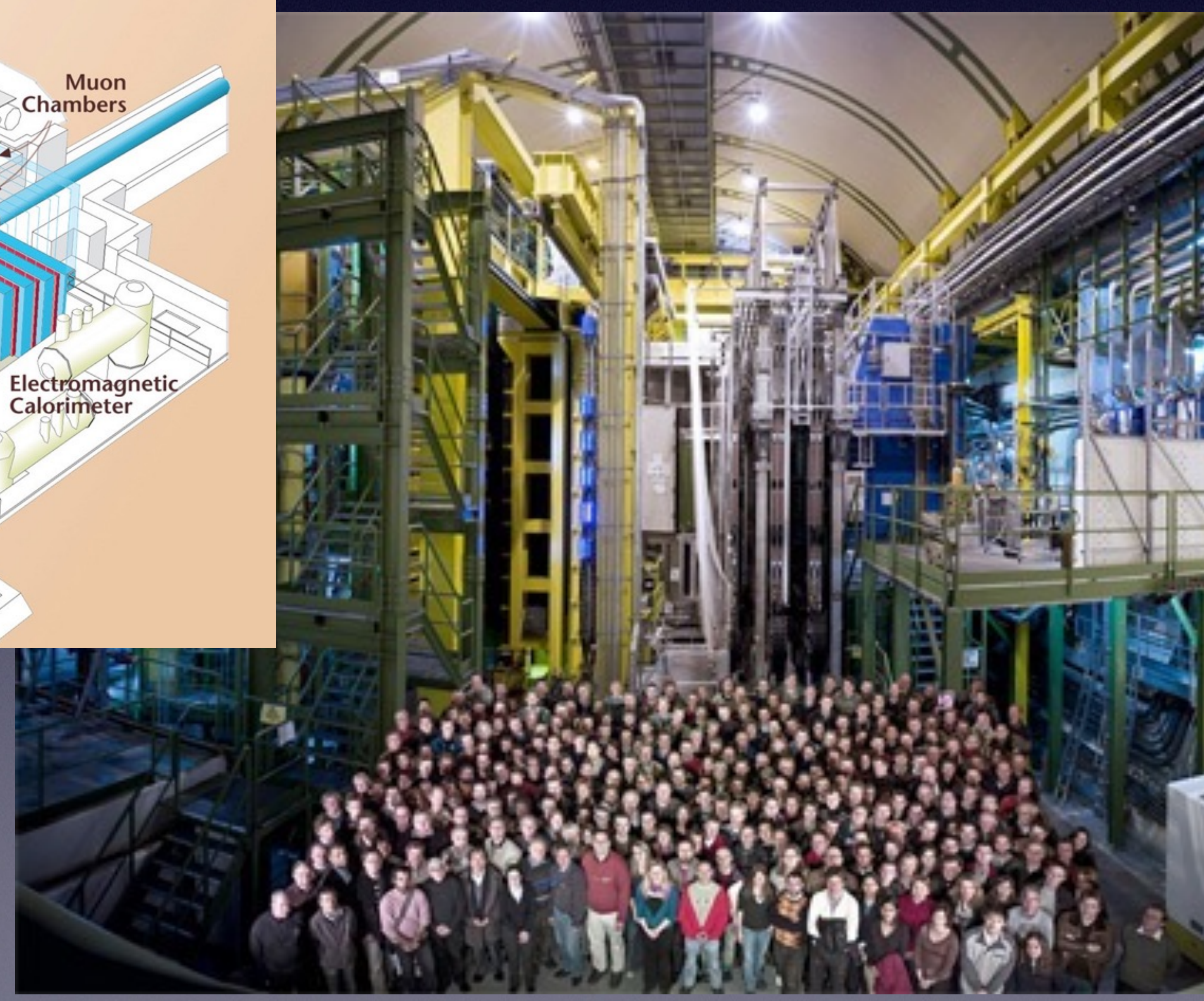




Flavour Physics

dedicated experiment at LHC: LHCb

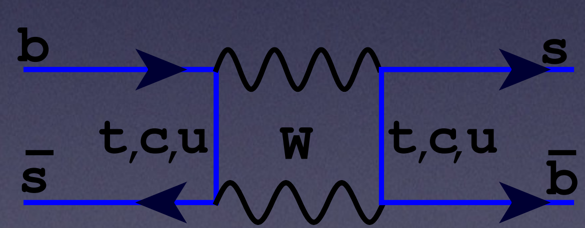


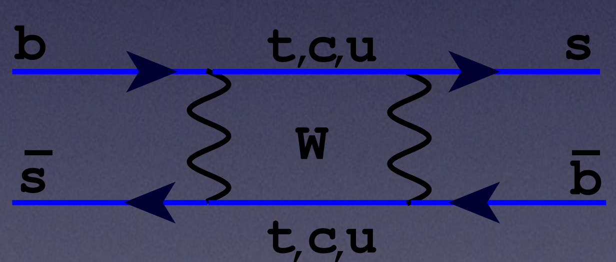


Flavour Physics

- **Measure SM parameters:** many decays of B mesons depend strongly on fundamental SM parameters, like quark masses, CKM couplings (= CPV parameters). These parameters are needed to make precise theory predictions

- **Study CP violation:** The quark sector is the only part so far, where CP violation has been discovered





- **Search for new physics:**
 Compare very precise measurements with very precise predictions and try to find deviations that might hint to physics beyond the SM.

Unsolved Problems

We have an extremely successful theory to describe the microcosmos

- Based on few, simple (symmetry) principles
- All predicted particle have been observed
- Predictions have been observed at the per mille level

BUT

- The **amount of CP violation in the SM is not sufficient**
- The SM does not include **dark matter**

Search for extensions of the SM

- **Theory guided model building:**

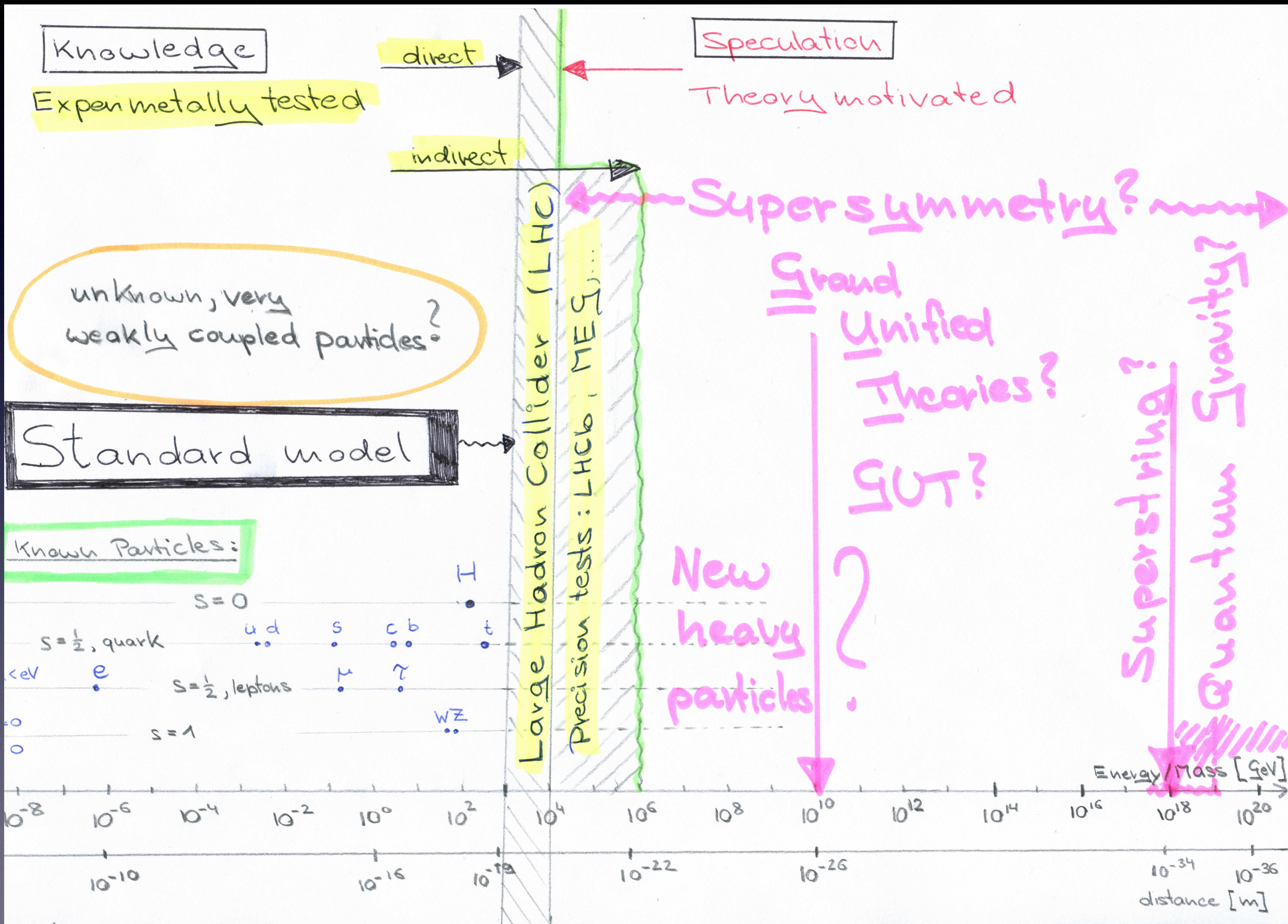
are there only three generations of fermions (**SM4**)
is there only one Higgs (**2HDM**),
is there a symmetry between bosons and fermions (**Supersymmetry**)
is there a single unifying gauge symmetry(**GUT**),...

- **Direct searches:** build bigger accelerators to to create heavier particles

- **Indirect searches:** compare high precision experiments with precise calculations

$$f^{\mathrm{Exp}} = f^{\mathrm{SM}}(m_b, \ldots) + f^{\mathrm{NP}}(m_X, \ldots)$$

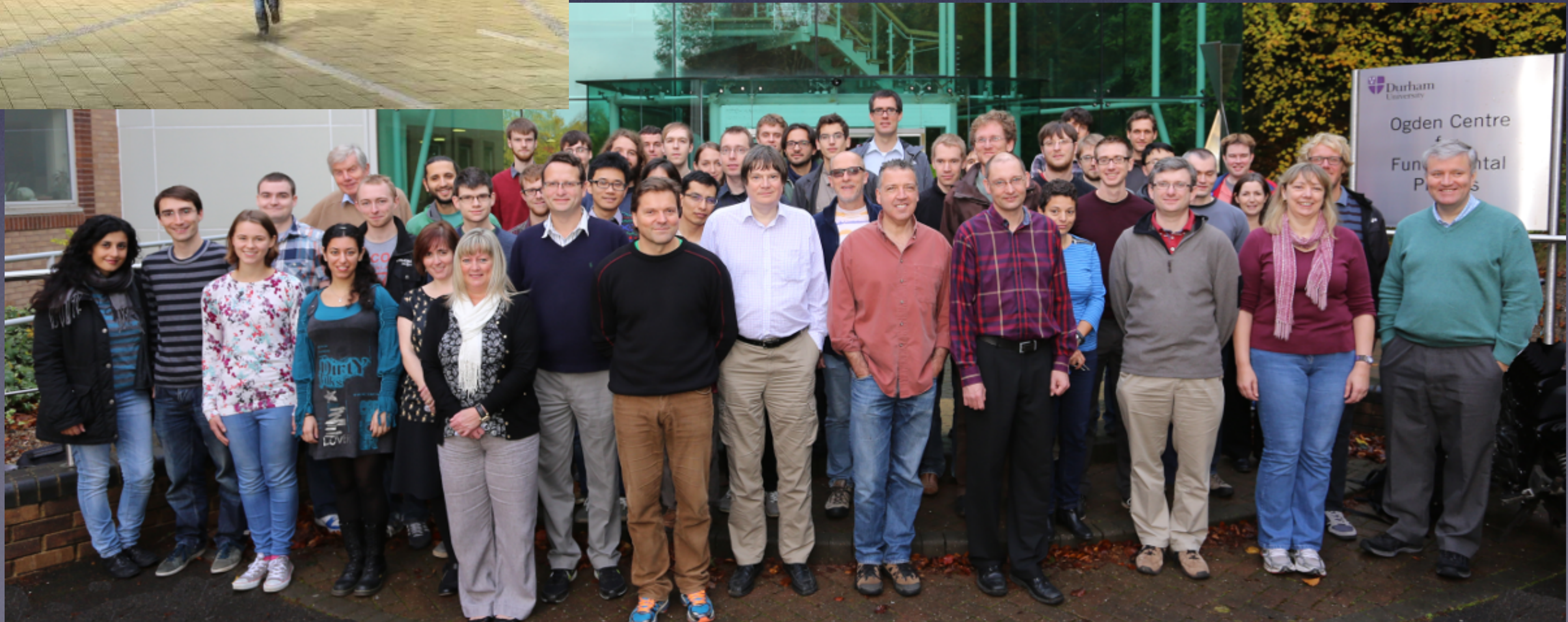
Knowledge vs. speculation



IPPP in Durham

Institute for Particle Physics **Phenomenology**
(Combination of experiment and theoretical ideas)

IPPP: about 80 members
biggest research centre for PPP in the UK,
one of the biggest in the world
(CERN, Fermilab, SLAC)



Summer students or internships

Every year we have up to 10 students
(secondary school up to 4th year at university)
from all over the world
who do a summer internship with us.

Duration: 1 to 10 weeks

Contact: alexander.lenz@durham.ac.uk