Quick introduction to particle physics

And some concepts that you will hear about this week

Natural science

Theory — Prediction → **Experiment**

Theory ← Validation — **Experiment**

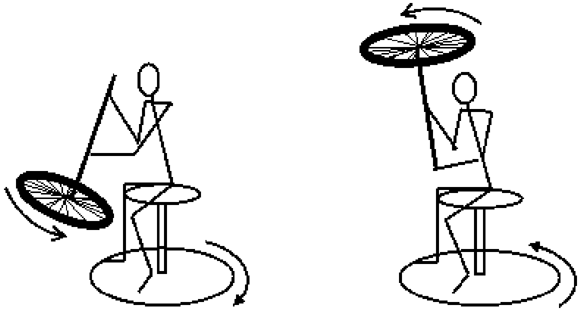
Theory
- Mathematical framework
- Physical system
  - Model
- Calculation methods

Experiment
- Physical system
- Measurements
- Experimental methods

Classical Mechanics

Theory — Prediction → / ← Validation — **Experiment**

- Framework:
  - $F = ma$, or:
  - Lagrangian + Principle of least action (PLA)
  - (Relativistic version)
- Physical system:
  - Interaction between system parts
  - Lagrangian terms (potential)
- Calculation methods:
  - Find $\vec{x}(t)$



Classical electrodynamics

Prediction

Theory **Experiment**

Validation

- Framework:
  - E and B fields
  - Maxwell's diff. equations
  - Field-theory Lagrangian + PLA
- Physical systems:
  - Interaction of fields with matter
  - Lagrangian terms
- Calculation methods:
  - Find $\vec{E}(\vec{r},t)$, $\vec{B}(\vec{r},t)$

Quantum Mechanics (QM)

Theory — Prediction → / ← Validation — **Experiment**

- Framework:
  - Wave function $\psi(\vec{x}, t)$
  - Schroedinger's diff. equation
  - Lagrangian + PLA
- Physical systems:
  - Interaction with environment
  - Lagrangian terms (potential)
- Calculation methods:
  - Find $|\psi(\vec{x}, t)|^2 =$ probability to find the particle in an experiment

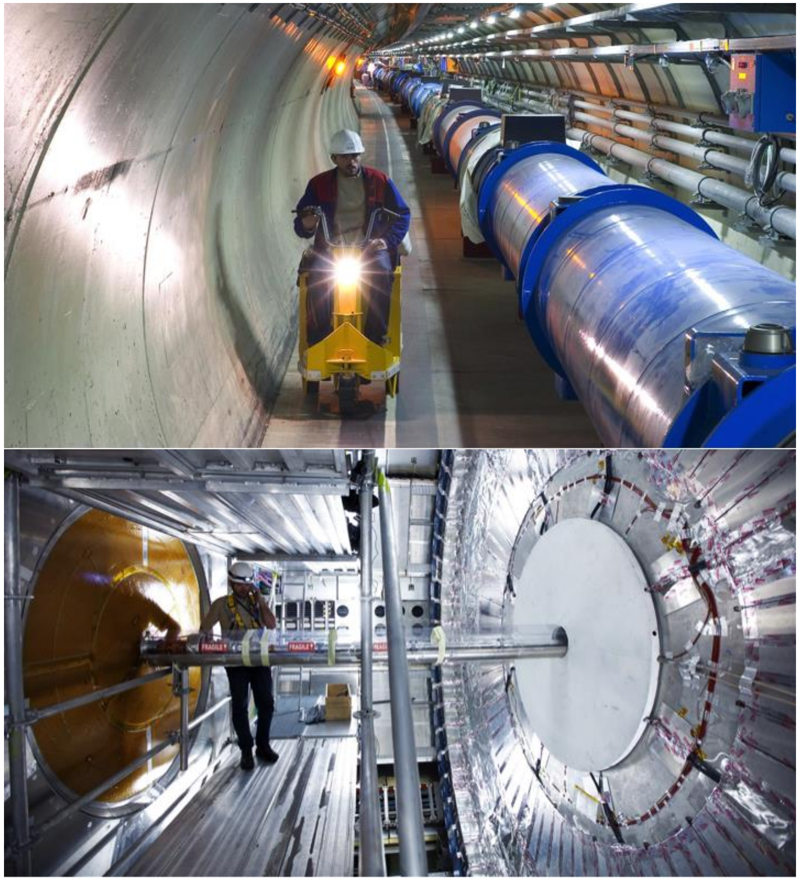
Particle physics (PP)

Prediction →

Theory **Experiment**

← Validation

- Framework:
  - Quantum field theory (QFT): special-relativistic QM
  - Lagrangian + PLA
- Physical systems:
  - Interaction among particles
  - Lagrangian terms
- Calculation methods:
  - Find probability for process:
    - Radioactive decay
    - Particle creation



What is PP all about?

The physical system is

- All the laws of nature
  - All the physical principles
- All the Lagrangian terms that describe
  - All types of particles
  - All possible processes

An experiment is

- A window into part of this physical system

What we know:

The Standard Model (SM)

- The fundamental particles
- The interactions between them
- The (symmetry) principles behind the interactions
- How the particles influenced the evolution of the universe

What we don't know:

New Physics (BSM)

- Open questions
- What L terms are we missing?

When we don’t know something

It’s usually because we can’t access it experimentally

- It happens too rarely
- It happens only under extreme conditions
  - Small systems (QM)
  - High speeds (Relativity)

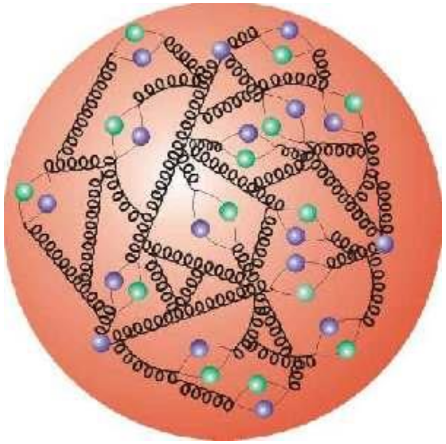
  } Particle physics

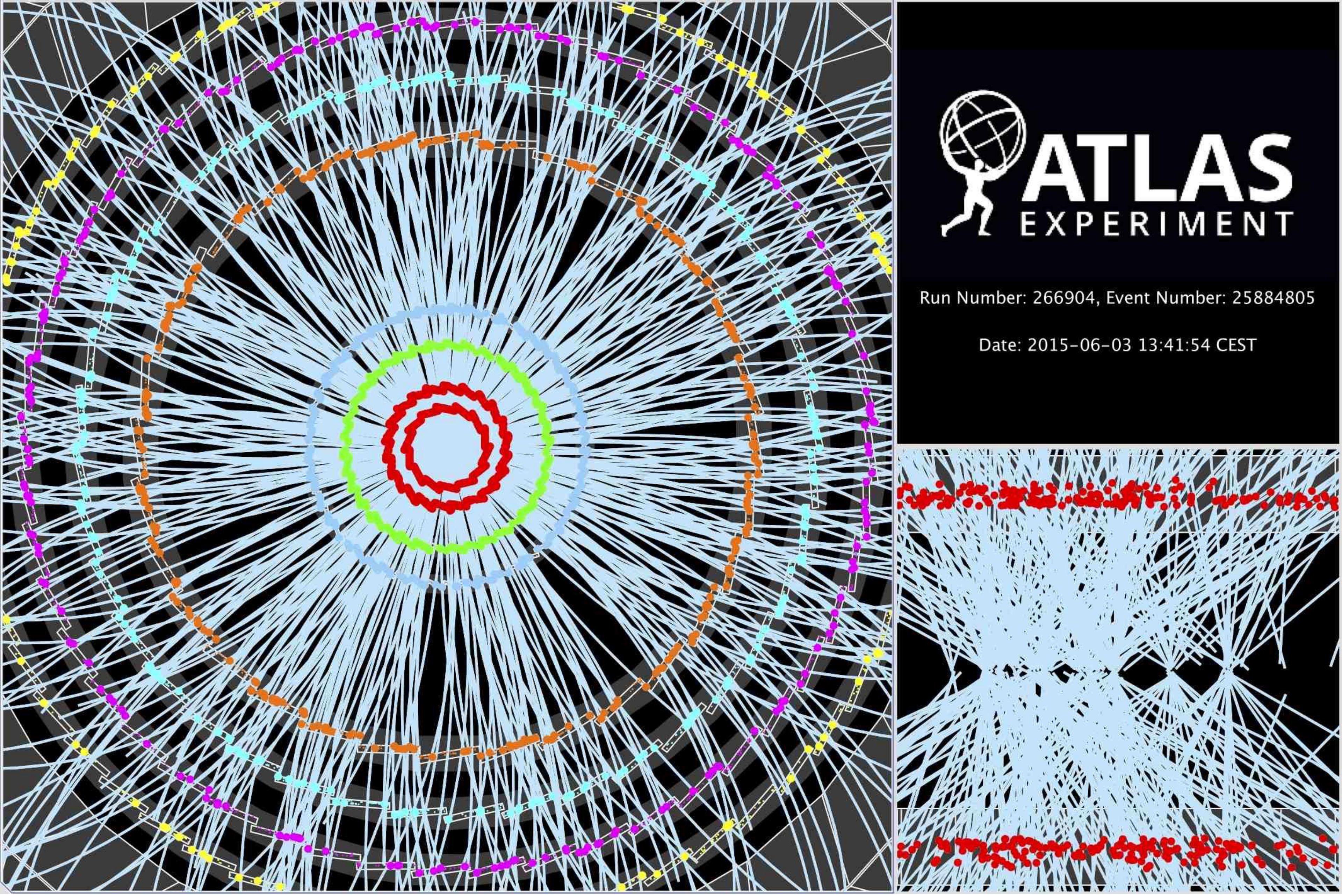
PP pushes the boundaries of what we know, with:

- Particle accelerators and detectors to create and study Nature’s rare events under the most extreme conditions
- Theoretical tools to interpret these experiments

Extreme conditions at LHC: high energy

- LHC (over ~25 minutes) accelerates protons to 6.5 TeV = 6.5×10^{12} ev $\approx 4 \times 10^{-7}$ j
- Protons collide at a CM energy $E = 13$ TeV
- That's the maximal energy available for creation of new particles with mass $m = E/c$
  - The particles generally have momentum, so $E = \sqrt{p^2 + m^2}$
  - The proton is composed of constituents – quarks and gluons, which undergo the fundamental interaction

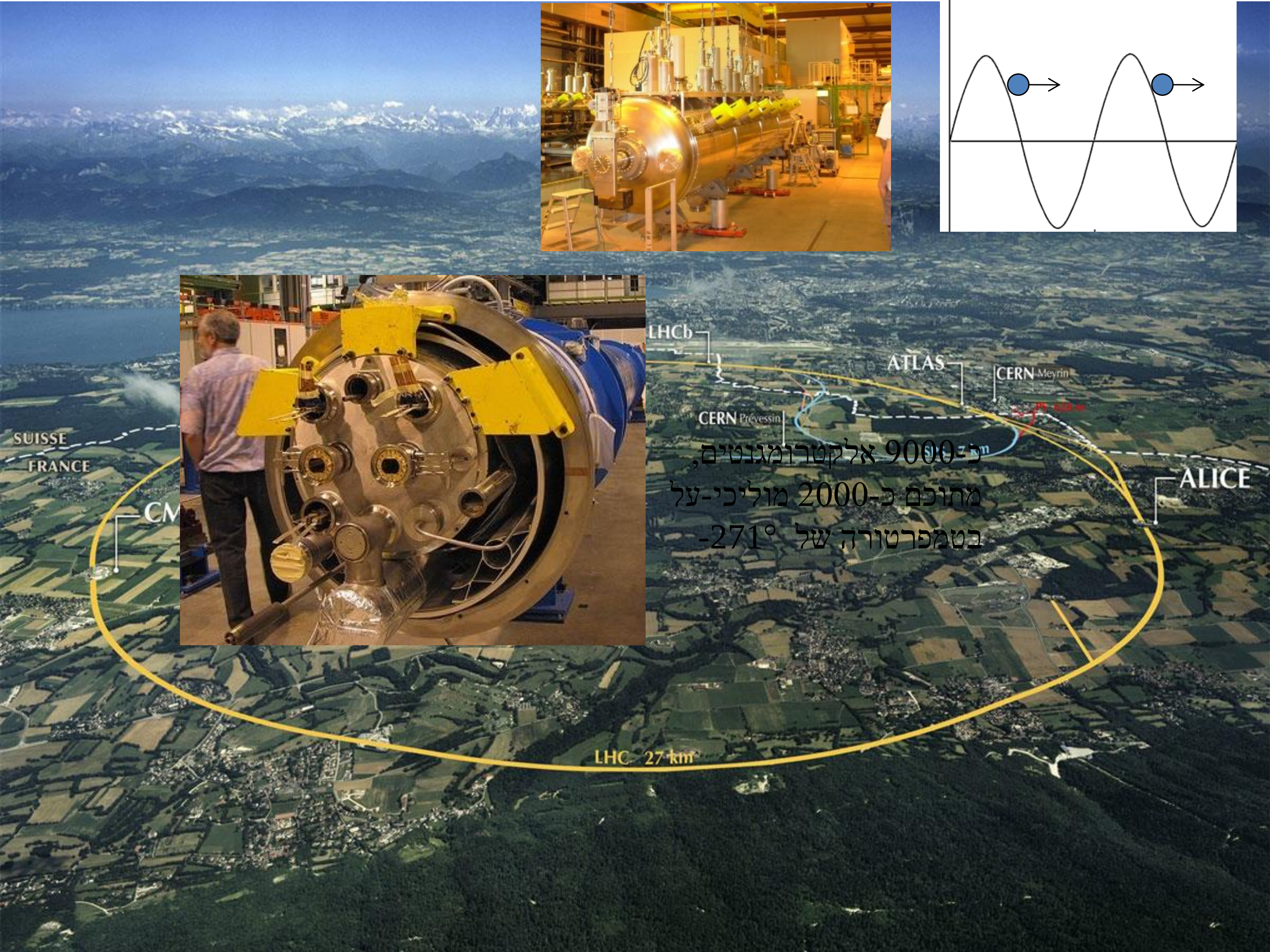




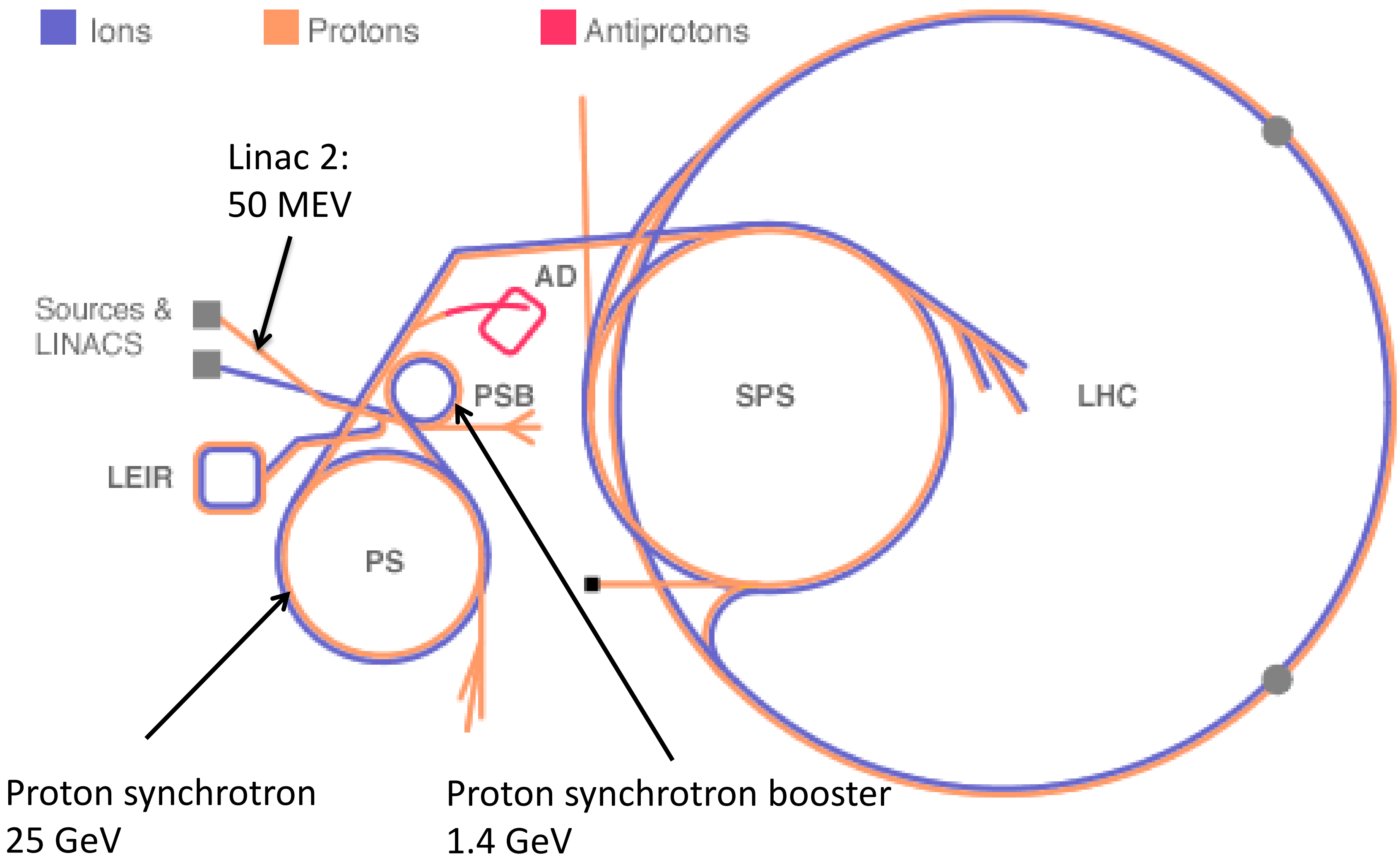
Bunches collide every 25 ns.

At each collisions, dozens of proton-pairs collide, creating new particles

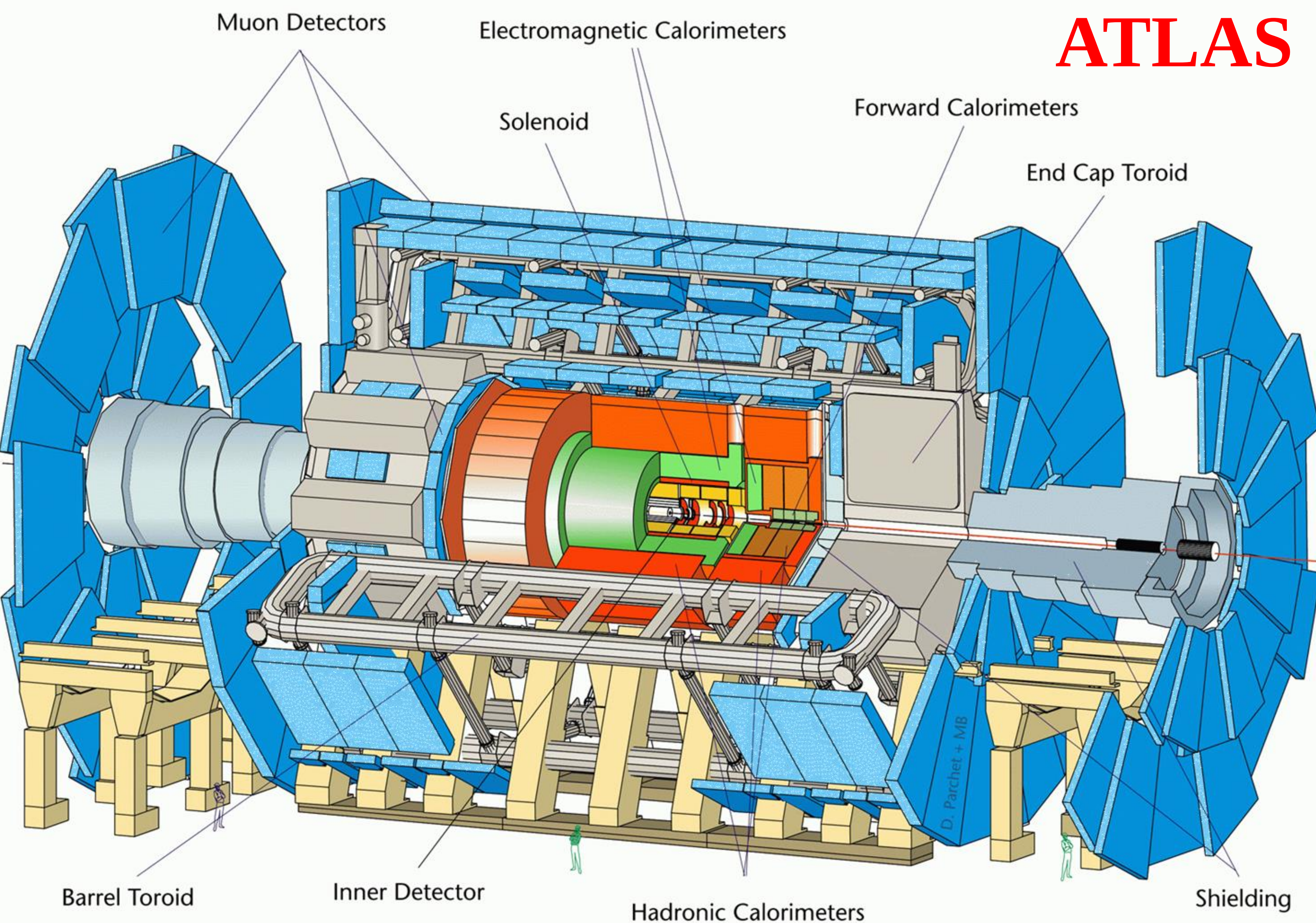

LHCb
ATLAS
CERN Meyrin
CERN Prévessin
SPS 7 km
SUISSE
FRANCE
ALICE
CMS
LHC 27 km



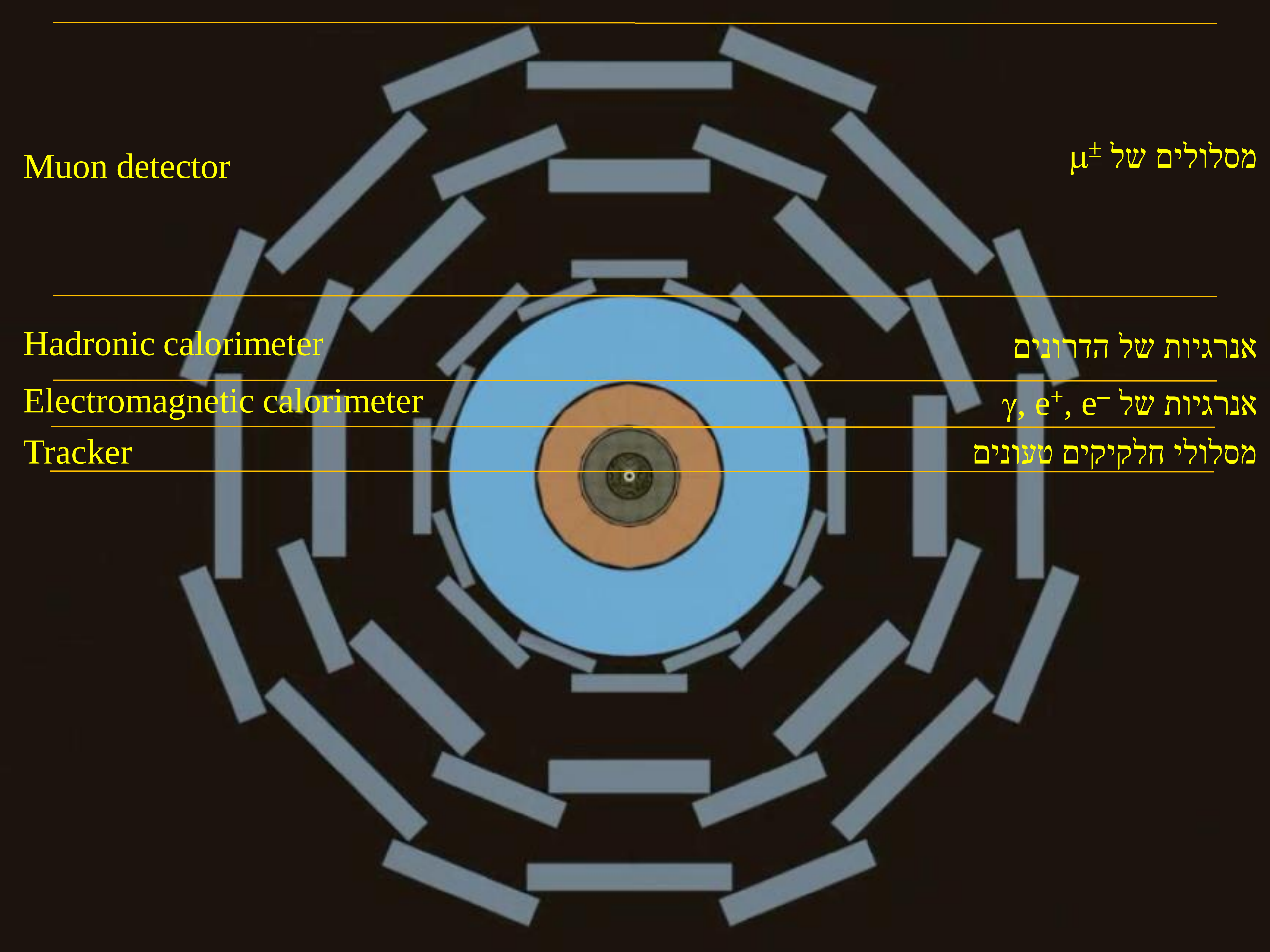
כ-9000 אלקטרומגנטים,
מתוכם כ-2000 מוליכי-על
בטמפרטורה של °271-


Ions
Protons
Antiprotons
Linac 2:
50 MEV
Sources &
LINACS
AD
PSB
SPS
LHC
LEIR
PS
Proton synchrotron
25 GeV
Proton synchrotron booster
1.4 GeV

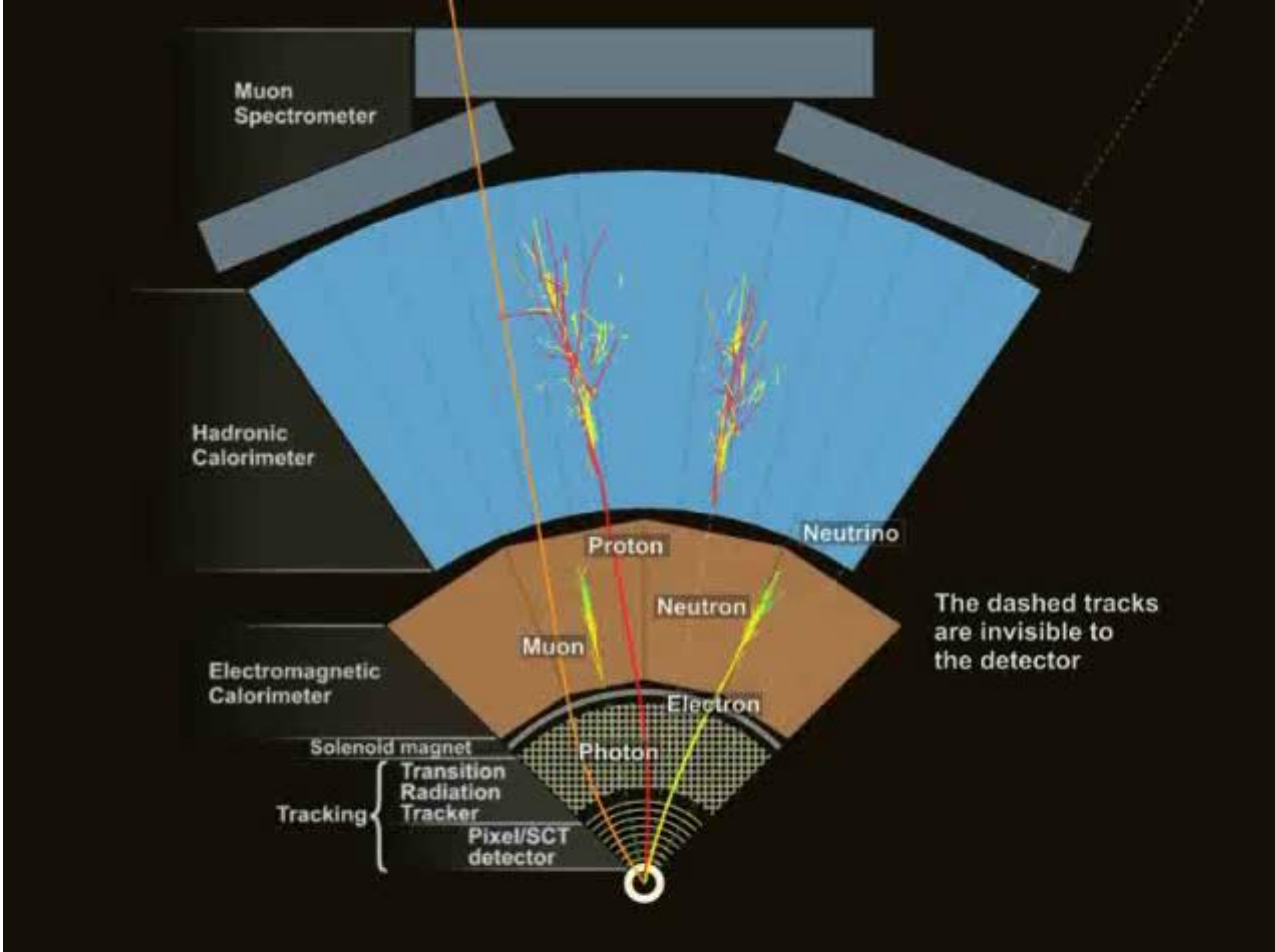
ATLAS



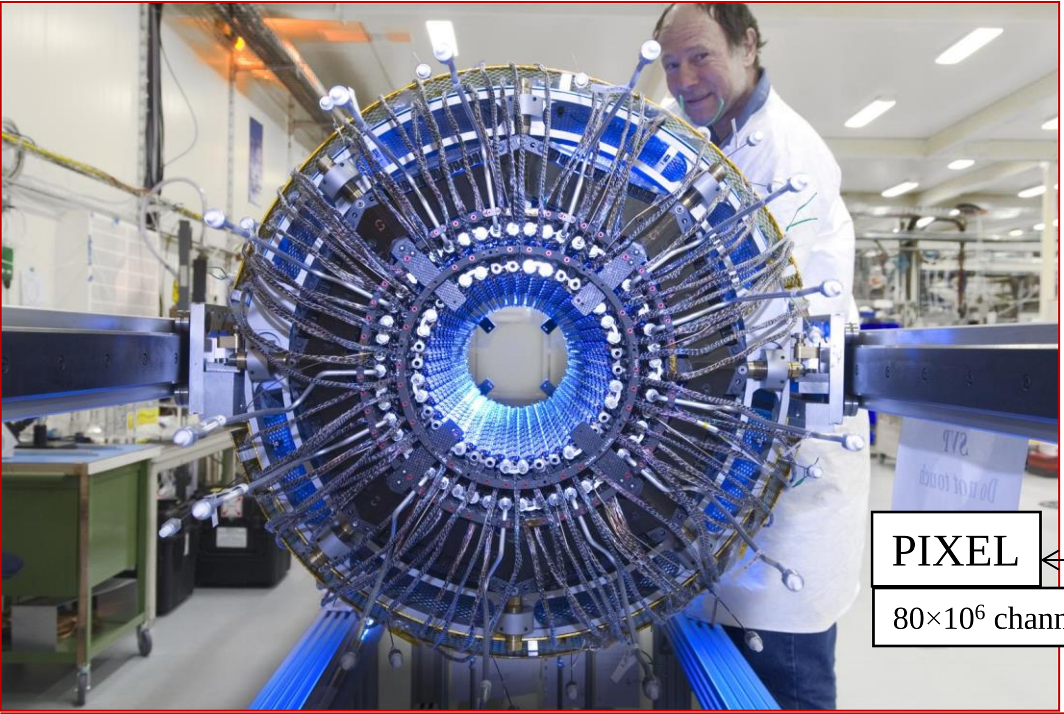
Muon Detectors
Electromagnetic Calorimeters
Solenoid
Forward Calorimeters
End Cap Toroid
Barrel Toroid
Inner Detector
Hadronic Calorimeters
Shielding
D. Parchet + MB

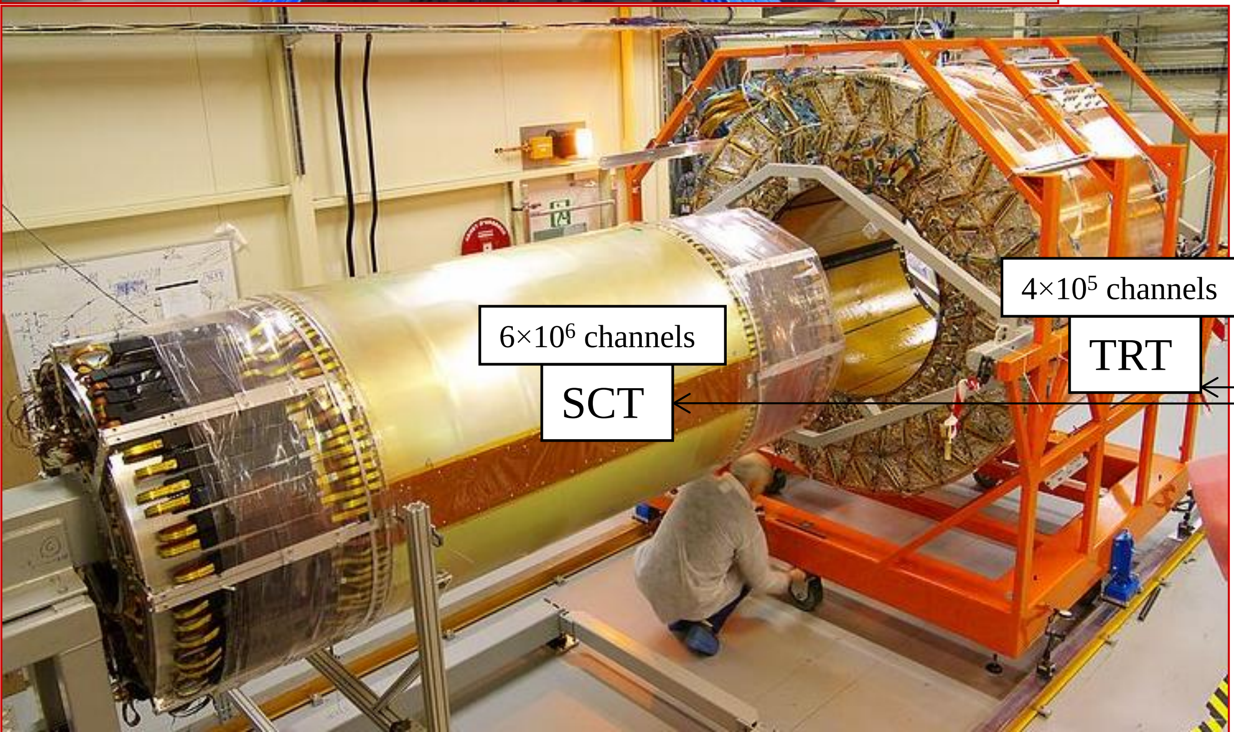


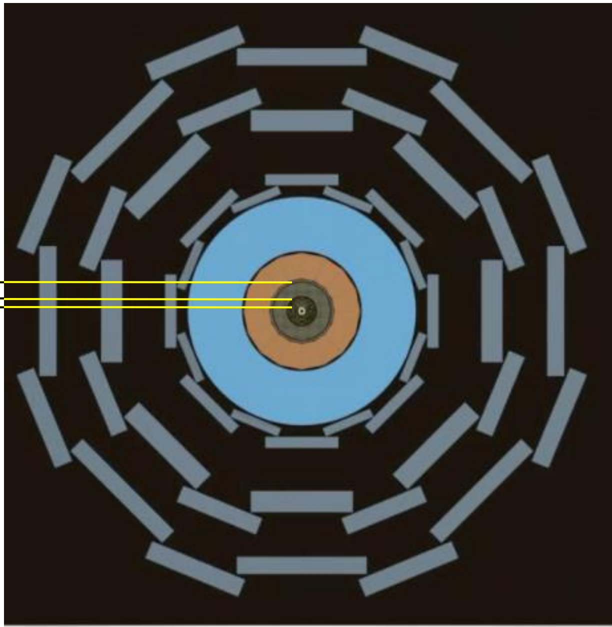
Muon detector
מסלולים של $\mu^{\pm}$
Hadronic calorimeter
אנרגיות של הדרונים
Electromagnetic calorimeter
אנרגיות של γ, e^+, e^-
Tracker
מסלולי חלקיקים טעונים

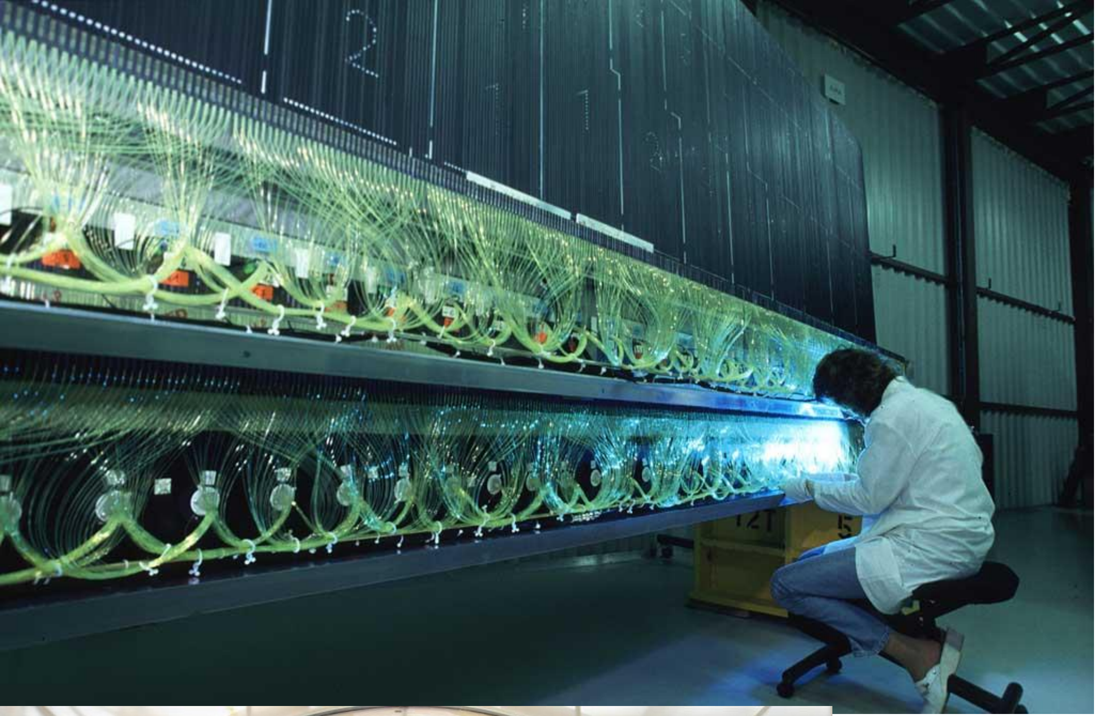

Muon
Spectrometer
Hadronic
Calorimeter
Electromagnetic
Calorimeter
Solenoid magnet
Tracking
Transition
Radiation
Tracker
Pixel/SCT
detector
Proton
Neutrino
Neutron
Muon
Electron
Photon
The dashed tracks
are invisible to
the detector

מדידת מסלול ותנע
של חלקיקים טעונים

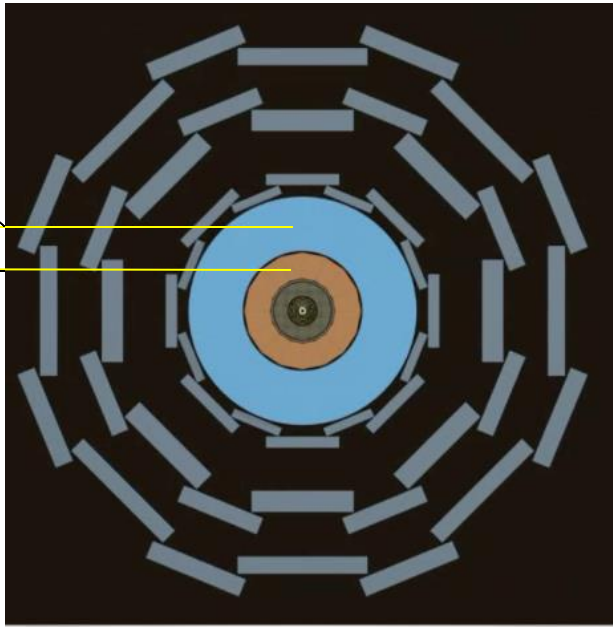






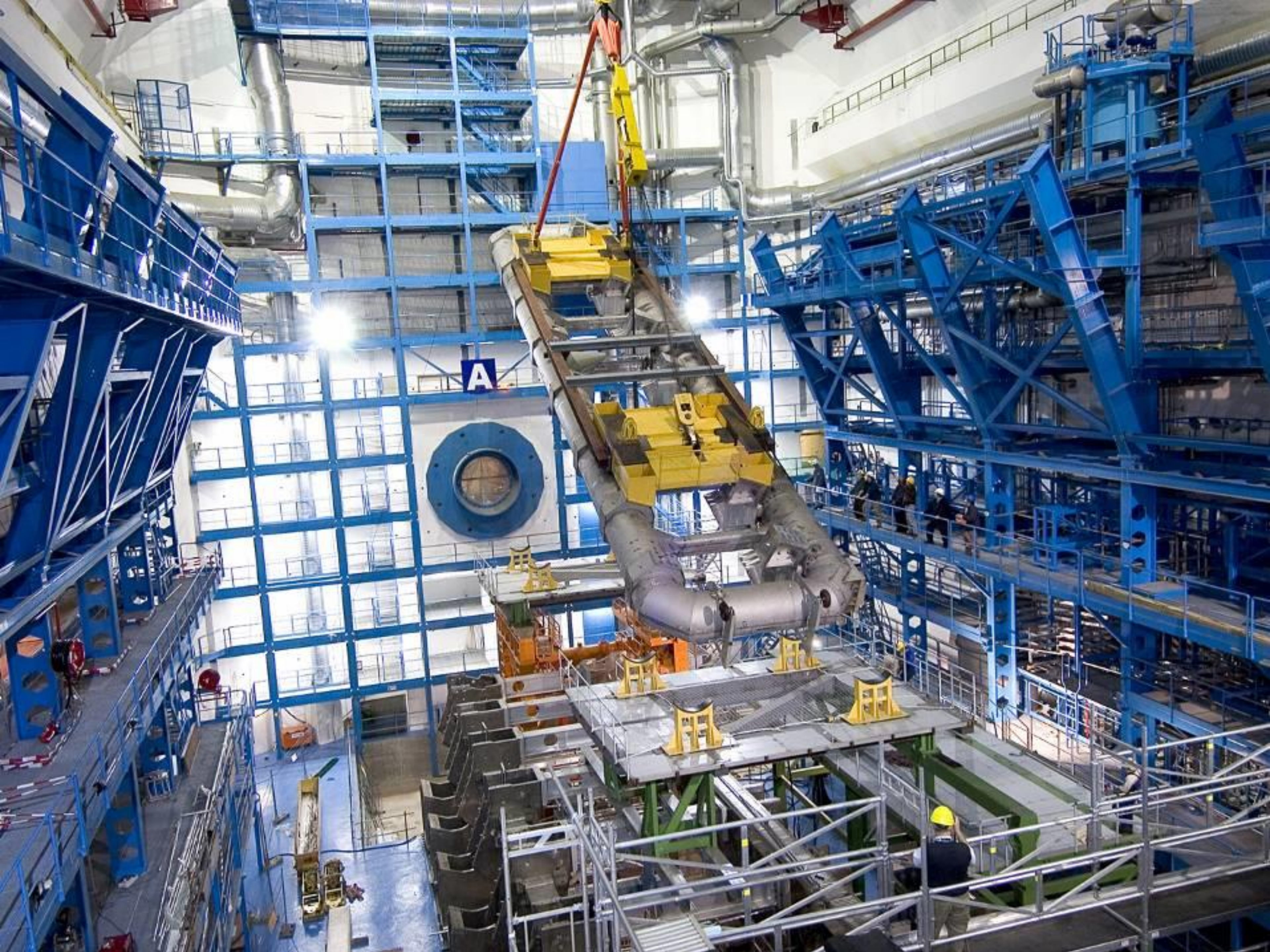


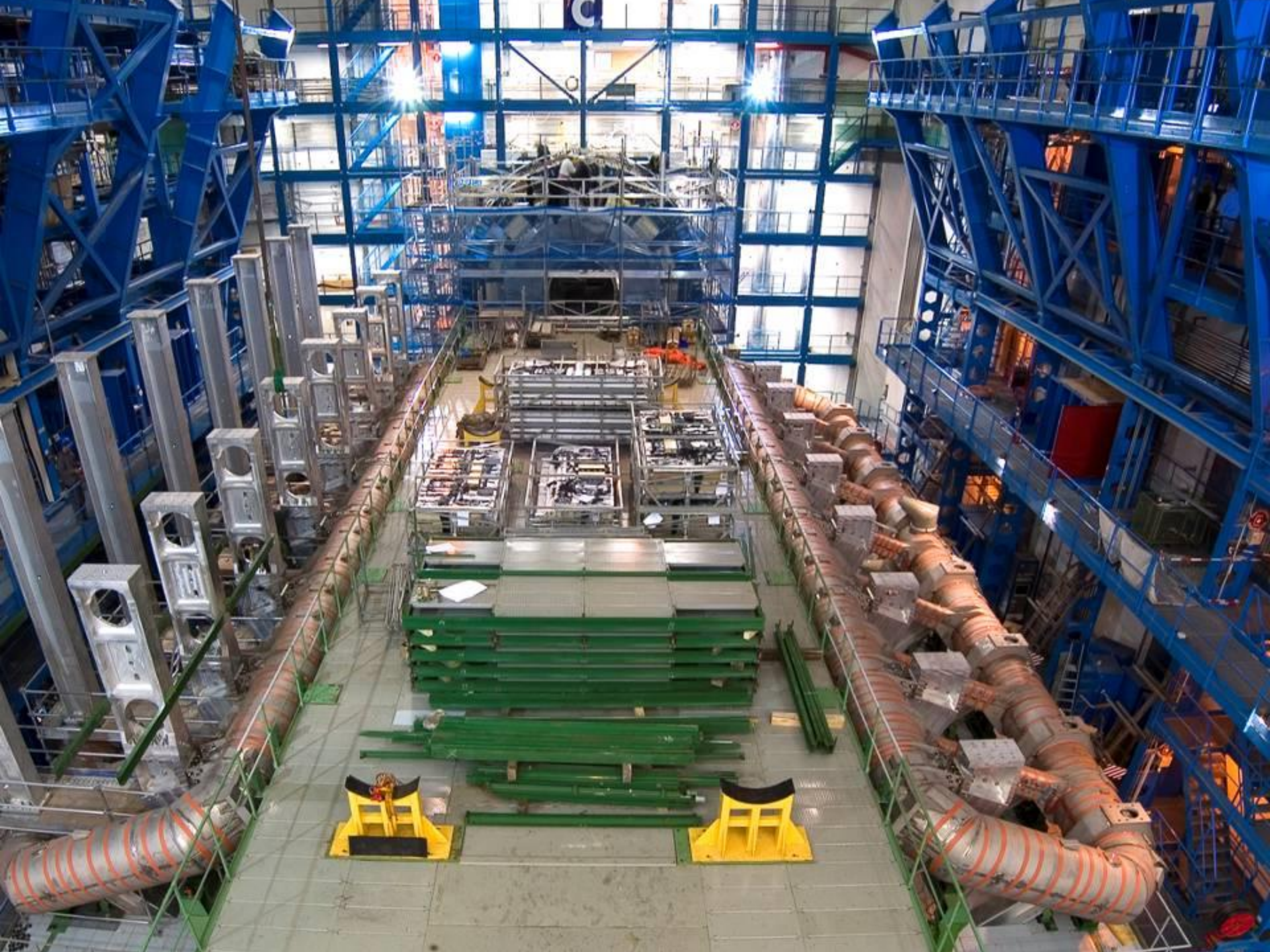
מדידת אנרגיה של הדרונים



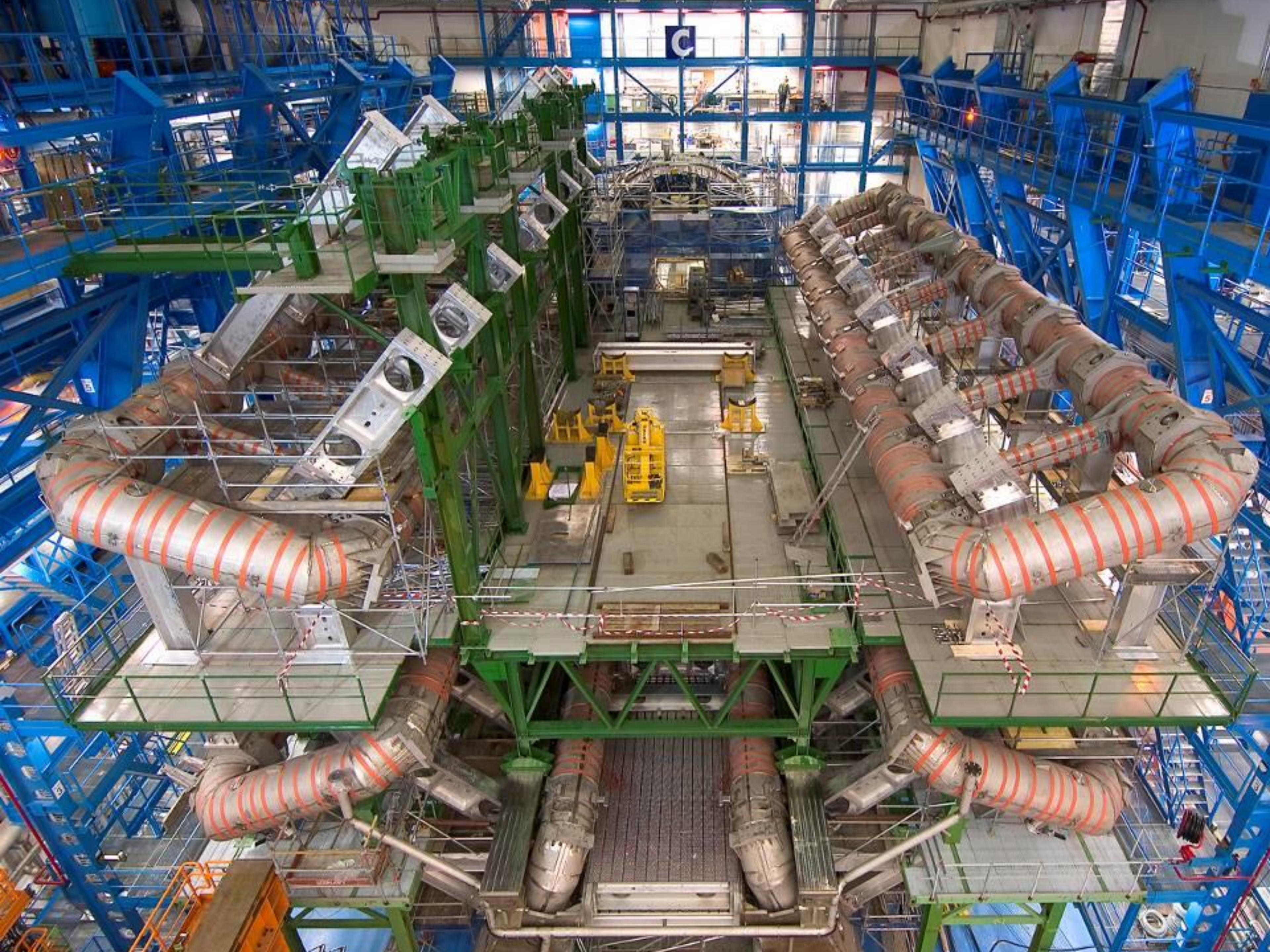
מדידת אנרגיה

של $\gamma, e^{\pm}$


A




C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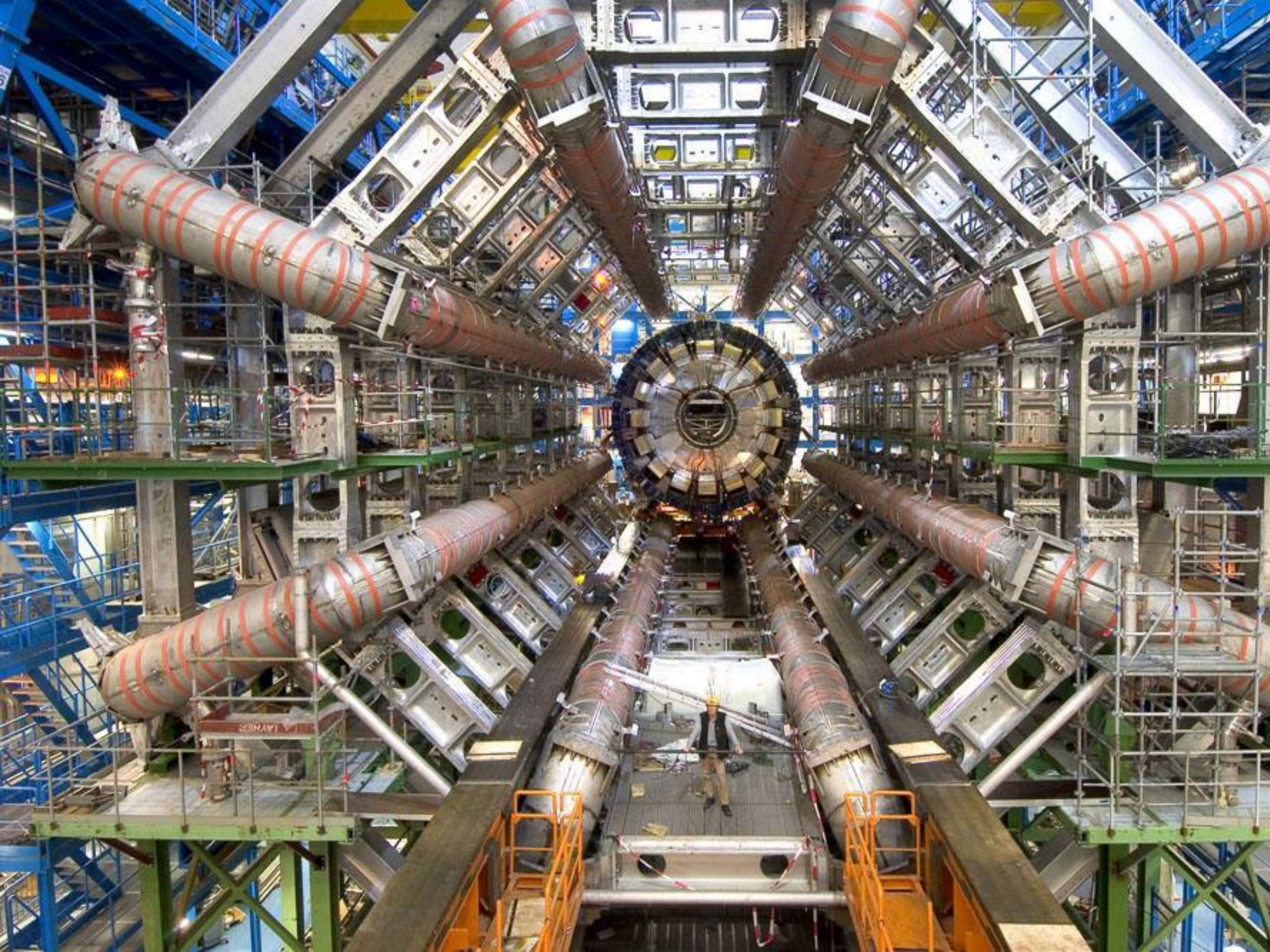
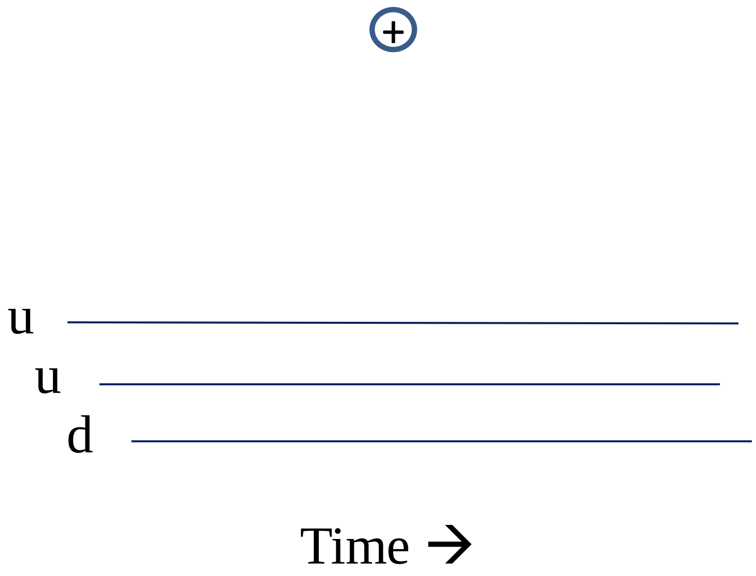


What is a proton?

What is a proton?

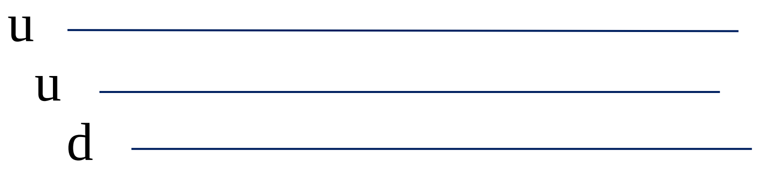


$$Q_u = \frac{2}{3}$$

$$Q_d = -\frac{1}{3}$$

What is a proton?

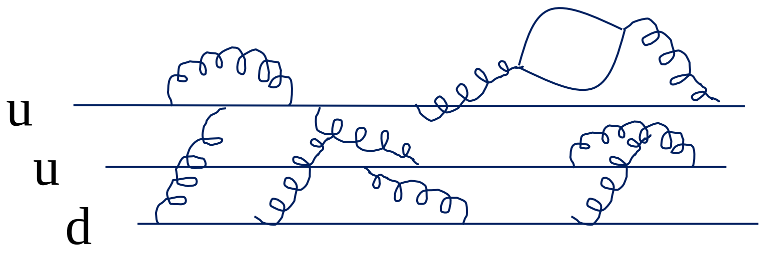
⊕



Time →

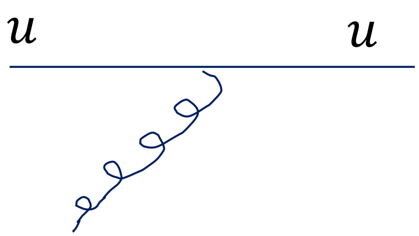
$$Q_u = \frac{2}{3}$$

$$Q_d = -\frac{1}{3}$$

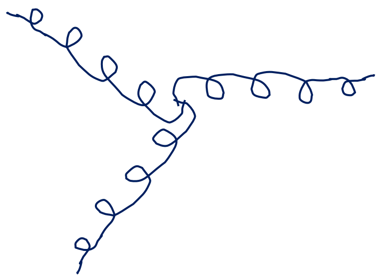


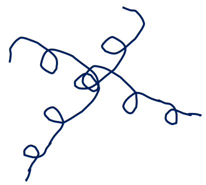
The fundamental vertices of the strong interaction

Initial
sate



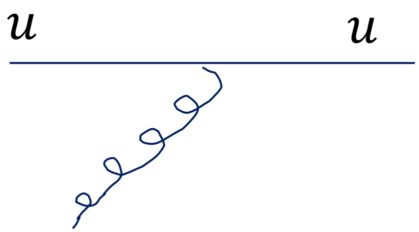
Final
sate



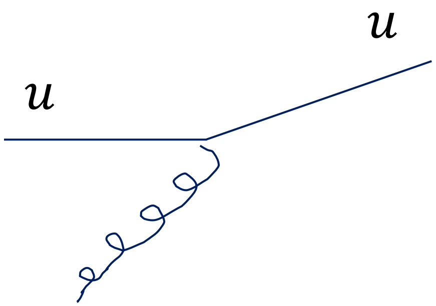


The fundamental vertices of the strong interaction

Initial sate

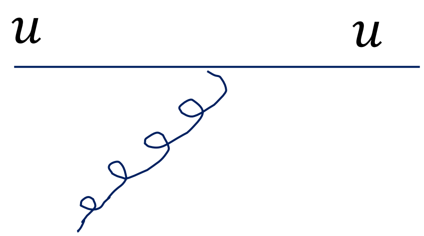


Final sate

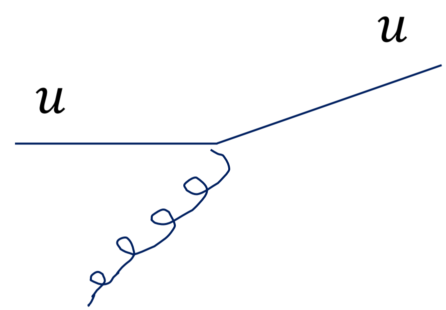


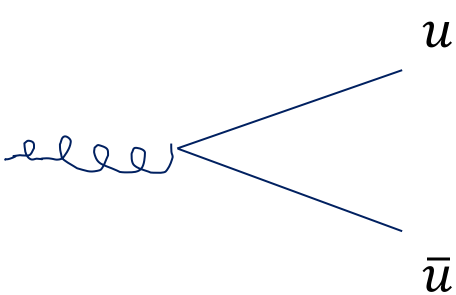
The fundamental vertices of the strong interaction

Initial sate



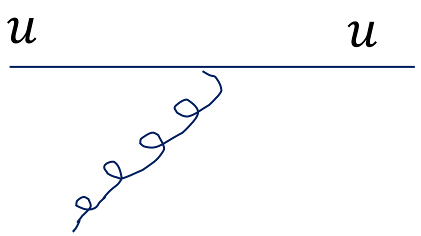
Final sate



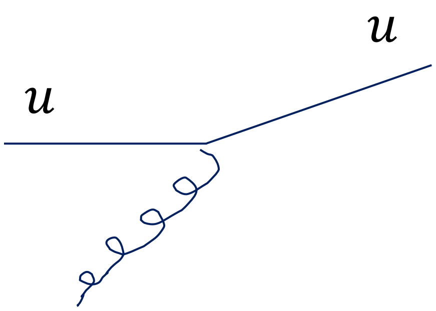


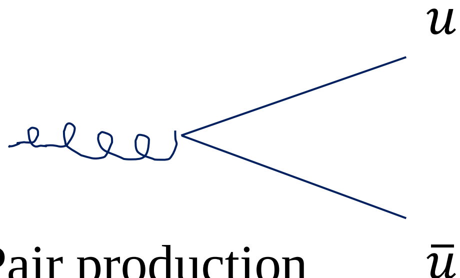
The fundamental vertices of the strong interaction

Initial sate

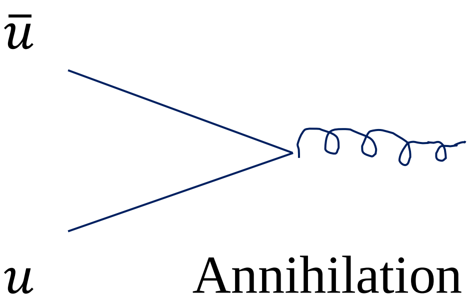


Final sate





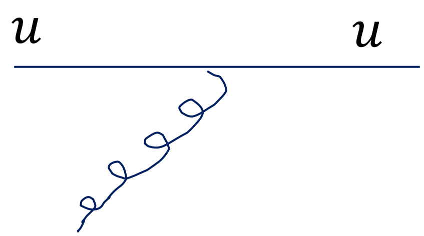
Pair production



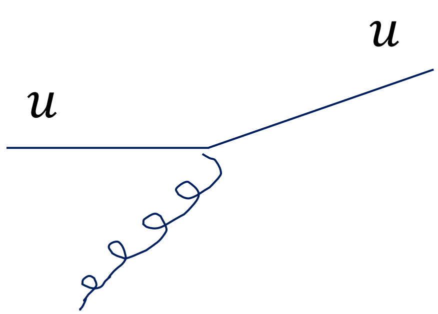
Annihilation

The fundamental vertices of the strong interaction

Initial sate

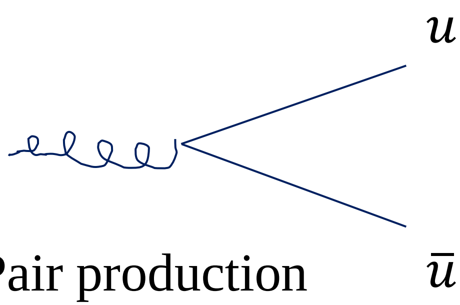


Final sate

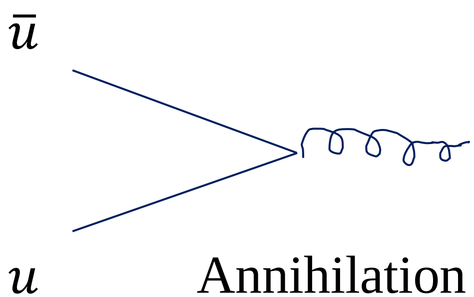


Antiparticles are a necessary concept,

- Since particles can be created and destroyed ($E = mc^2$)
- While there are conserved quantities (e.g., charge)

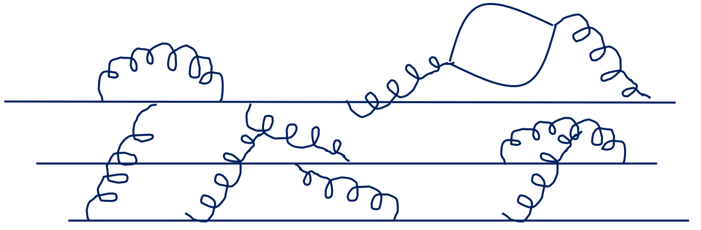


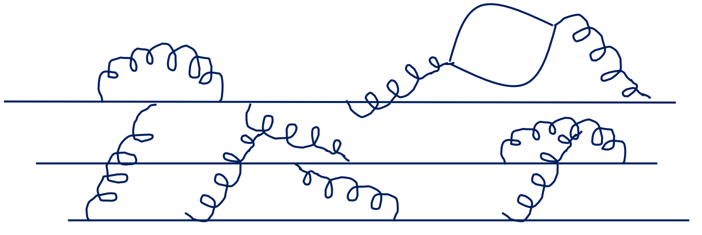
Pair production



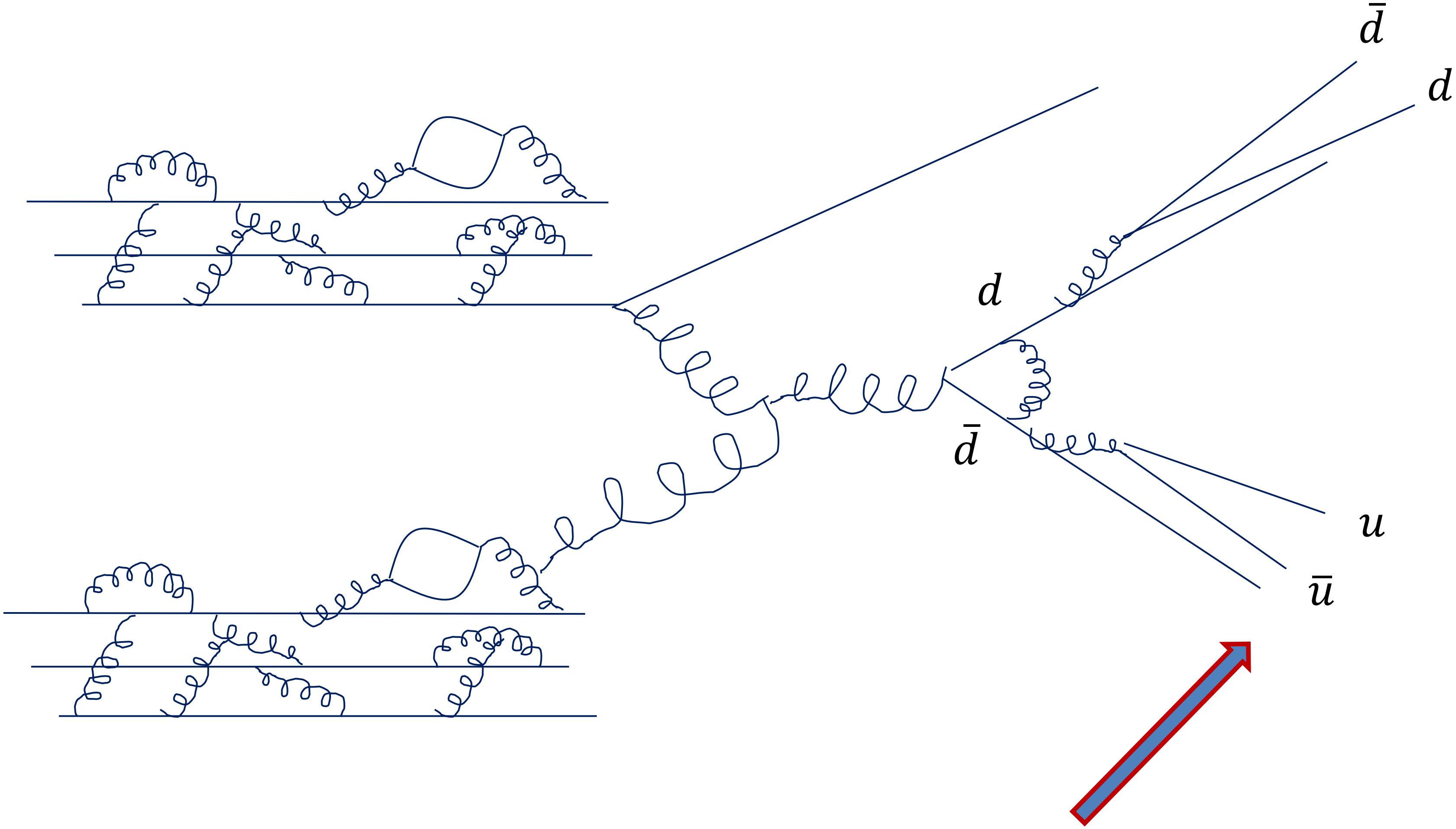
Annihilation

pp collision



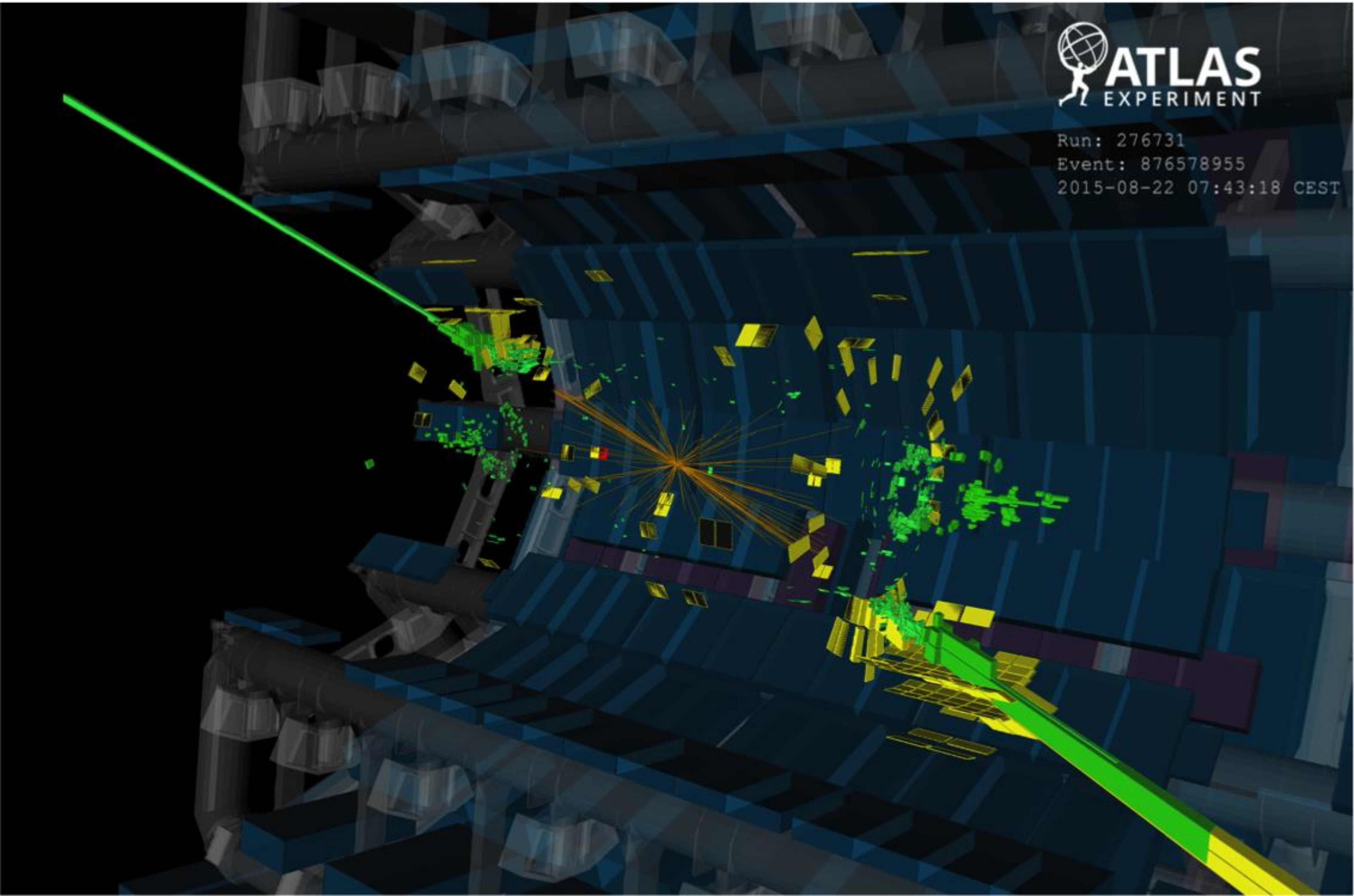


pp collision

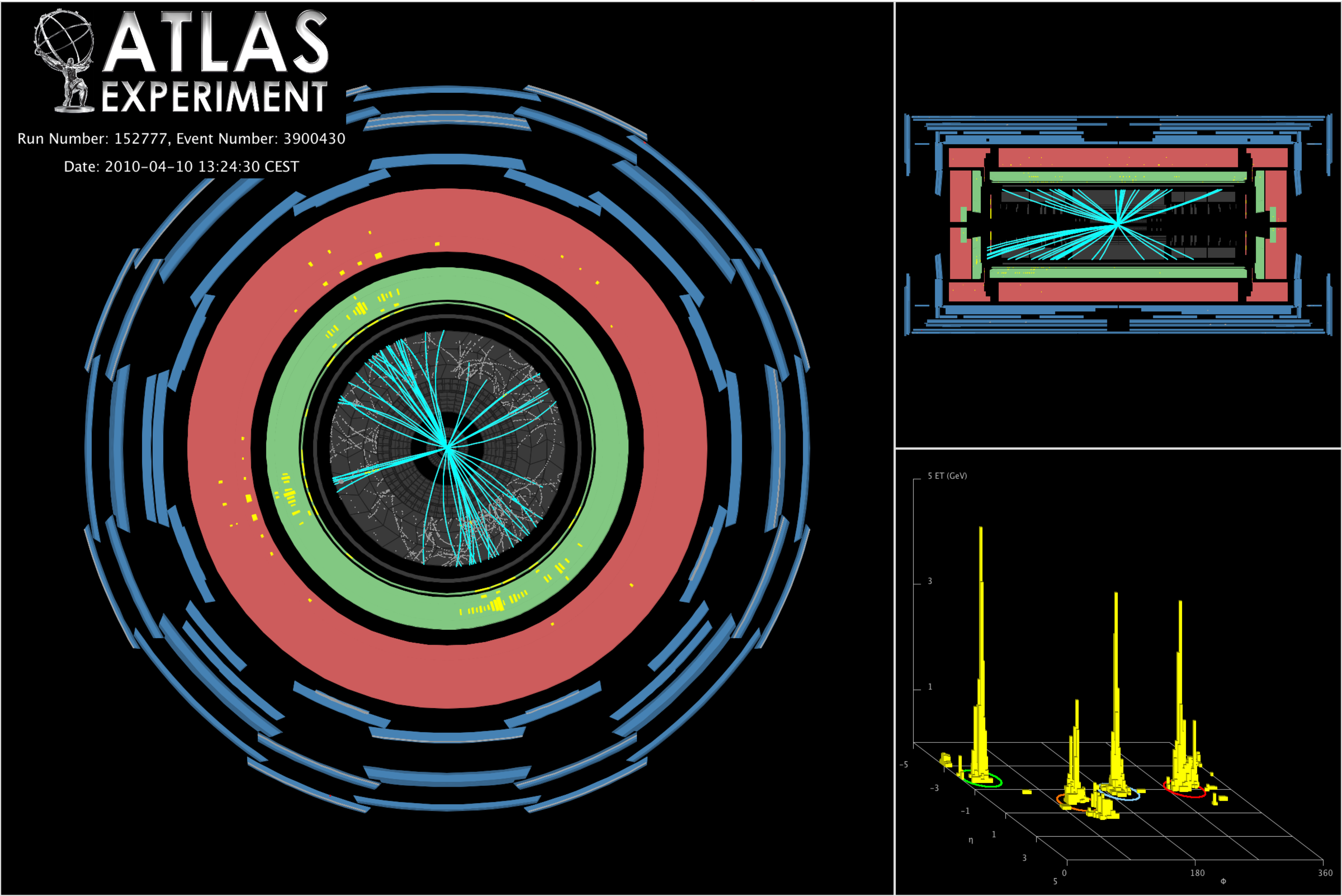


Jets of particles (hadrons)
composed of quarks and antiquarks:
Protons, antiprotons, pions, etc.

Event display: 2 jets



Event display: 4 jets

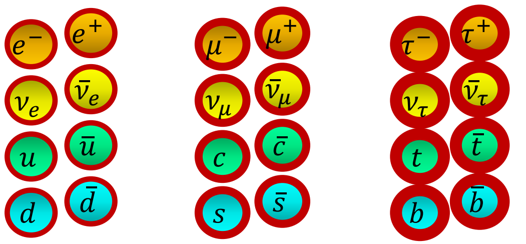


Basic particle properties

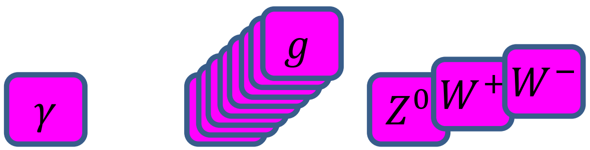
- Mass
  - Always related to energy and momentum: $E^2 = p^2 + m^2$
- Spin
  - Angular momentum that is intrinsic – not due to rotation
  - Allowed values are only $S = n\frac{\hbar}{2}$, where $\hbar \approx 10^{-34}$ Js $\equiv 1$
- Fermions: $S = \frac{1}{2}, \frac{3}{2}, \frac{5}{2}, \ldots$
- Bosons: $S = 0,1,2 \ldots$
  - Scalars: $S = 0$
  - Vector: $S = 1$

The particles of the SM

- Fermions
  - Include “matter” = u, d, e

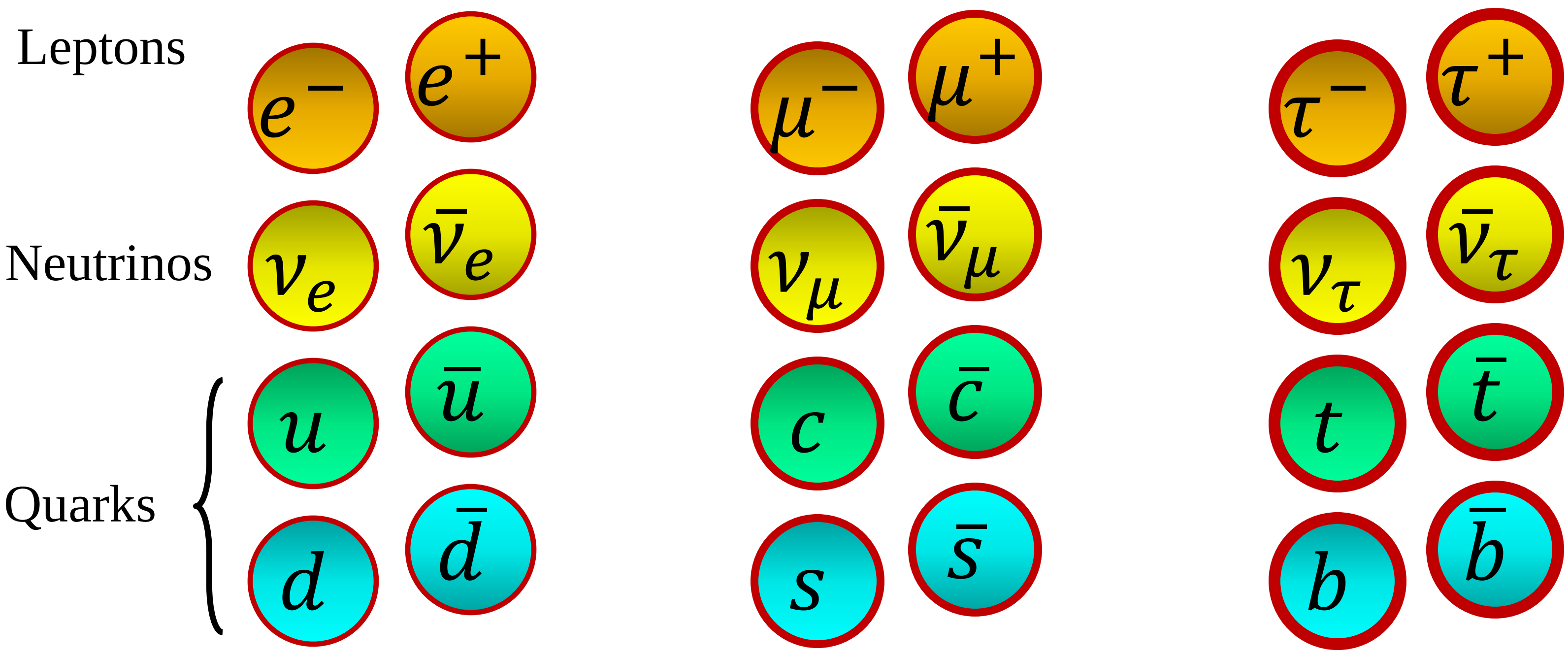


- Gauge bosons (vectors)
  - Mediate the 3 interactions:
  - Photons: electromagnetic
  - Gluons: strong
  - W^+, W^-, Z: weak



- The Higgs boson (scalar)
  - “Byproduct” of the process by which particles obtain mass

The fermions expanded

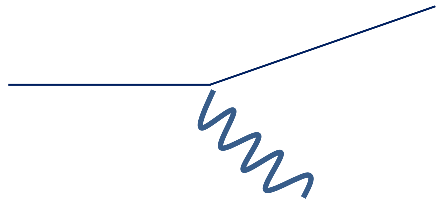


The fundamental vertex of the electromagnetic interaction

ℓ^{-} = charged lepton
q = quark

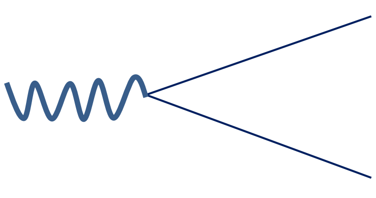
ℓ^{-}, q

ℓ^{-}, q



From this, you know how to make these:

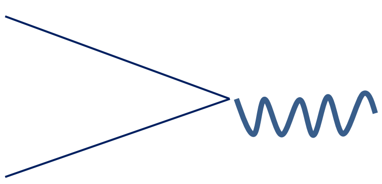
ℓ^{-}, q



Pair production

$\ell^{+}, \bar{q}$

ℓ^{-}, q

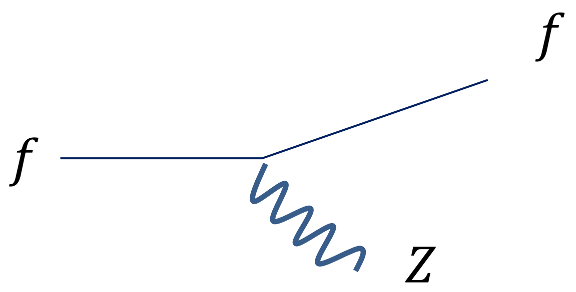


$\ell^{+}, \bar{q}$

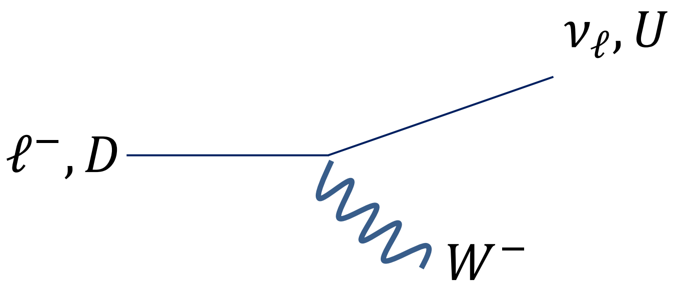
Annihilation

The fundamental vertices of the weak interaction

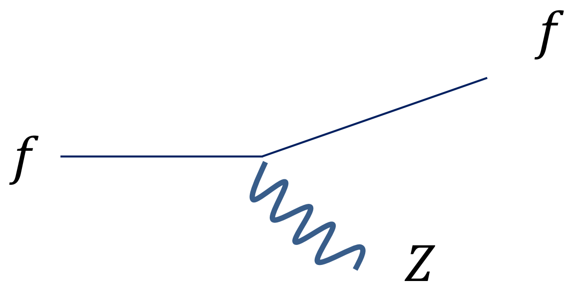
f = fermion



ℓ^- = charged lepton
$D = d, s, b$
$U = u, c, t$



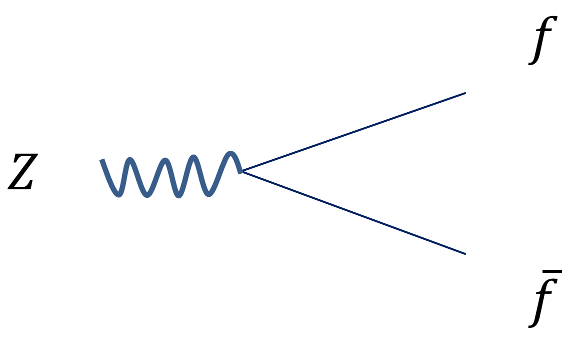
Connecting theory and experiment

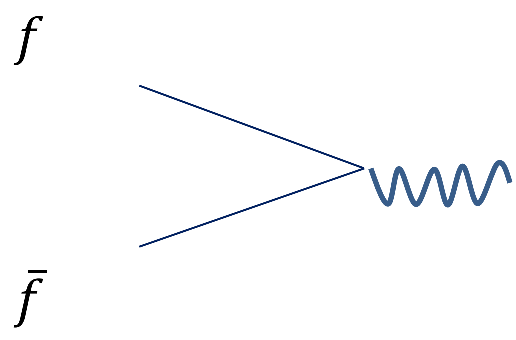


$$g\,\bar{f} Z f$$

coupling strength   fields

From here we can calculate **interaction rates** and compare to experiment, e.g.:





Lifetime, branching fractions

Cross section

What about new physics?

The SM doesn't explain

- Dark matter – which is ~5 times more abundant than normal (baryonic) matter in the universe
- Dark energy, which accelerates the expansion of the universe
- Why the universe contain (almost) no antimatter
- Gravity, and why it is so much weaker than the other forces (the "hierarchy problem")
- The origin of the values of the SM parameters (masses, etc.)
- Why neutrinos are so much lighter than the other fermions

The answers are all within "new physics".

LHC is (a major) part of the program to address these questions.

We will hear more about it this week.