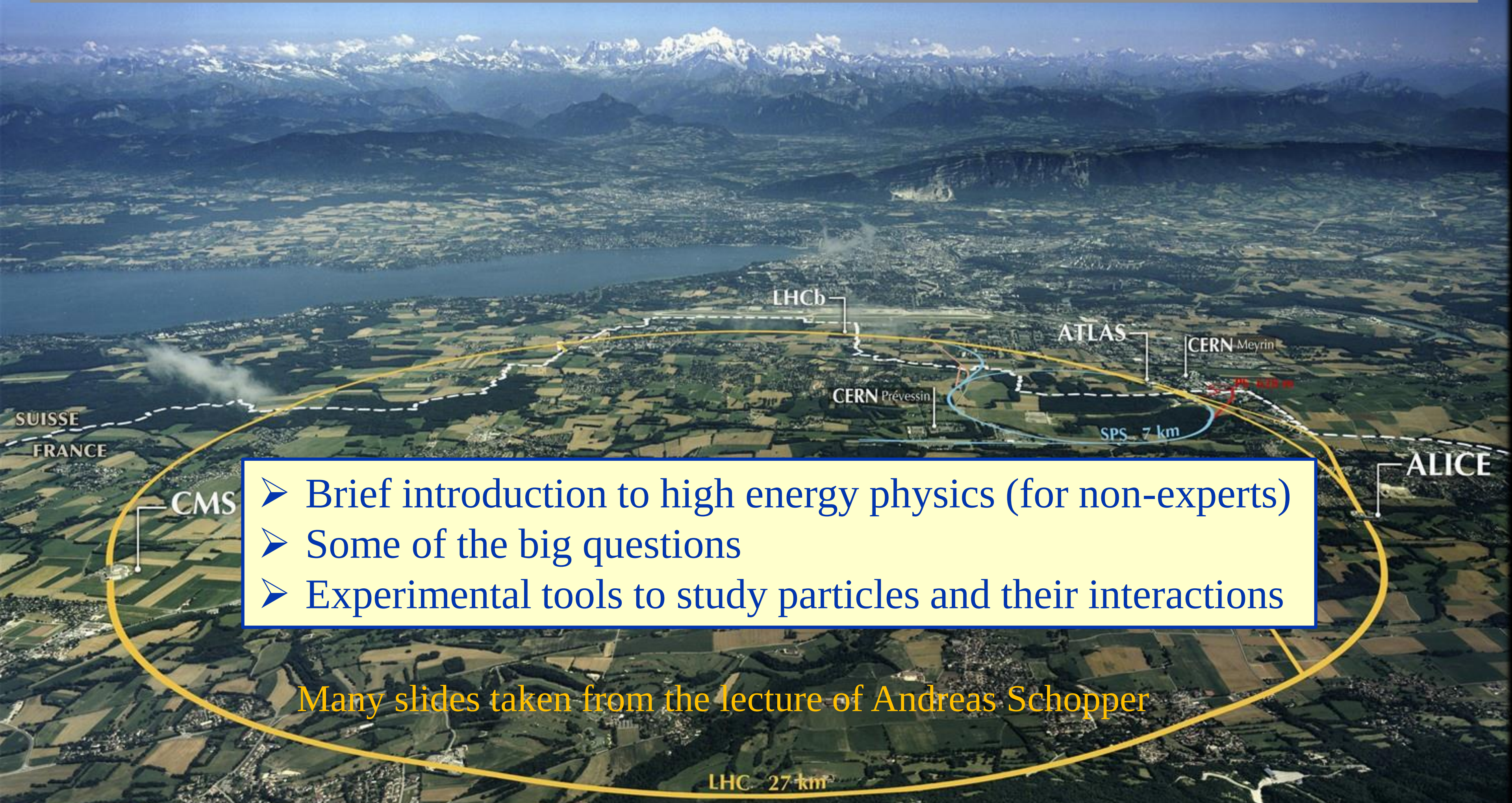
An introduction to High Energy Physics at CERN



- Brief introduction to high energy physics (for non-experts)
- Some of the big questions
- Experimental tools to study particles and their interactions

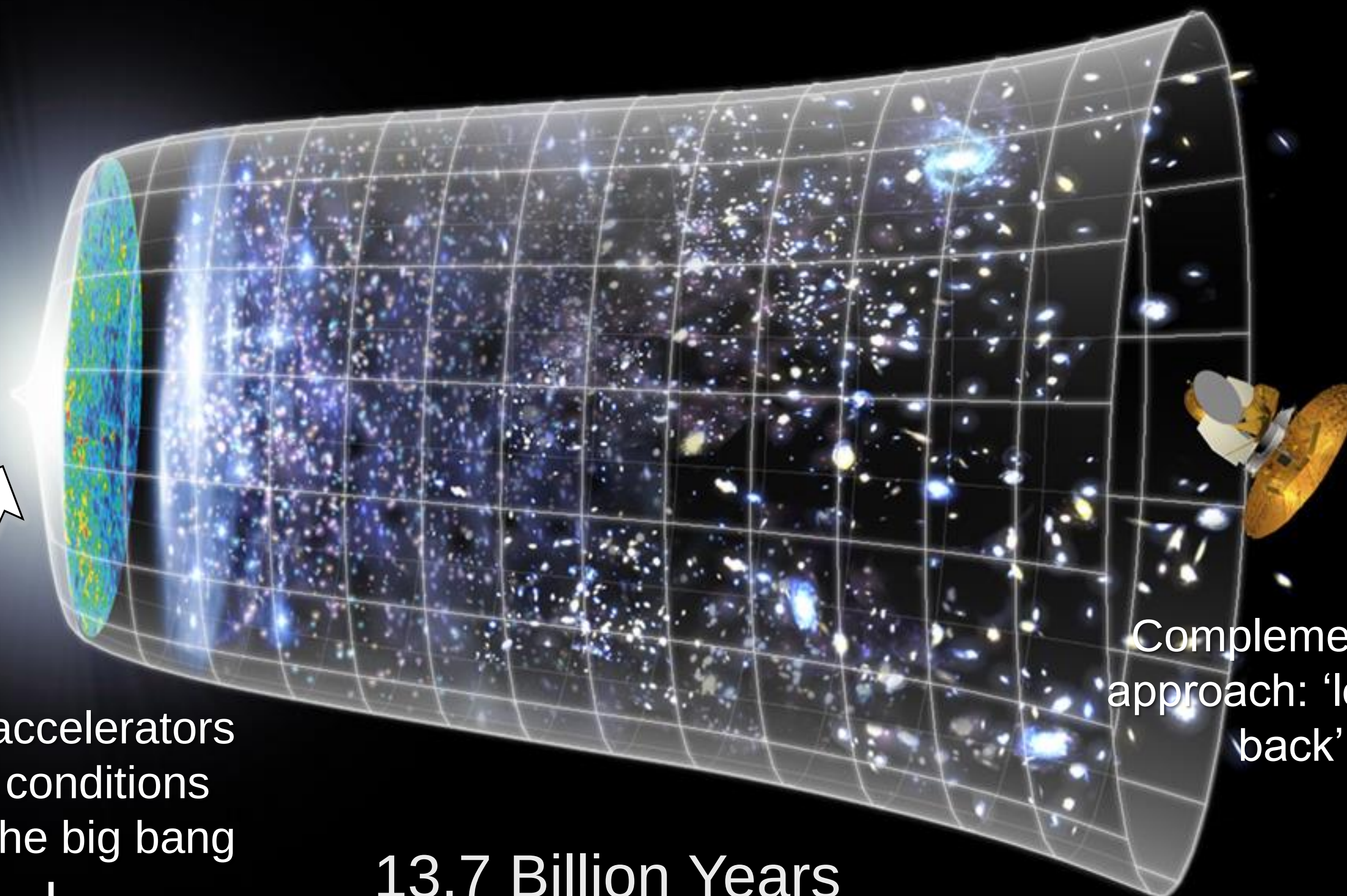
Many slides taken from the lecture of Andreas Schopper

6th EIROforum (ESI 2019) School on Instrumentation
13-17 May 2019 at ESTEC Noordwijk, NL

Christian Joram

Try to understand the very first moments of our Universe after the Big Bang

Big Bang



Use particle accelerators to re-create conditions shortly after the big bang

Complementary approach: ‘looking back’

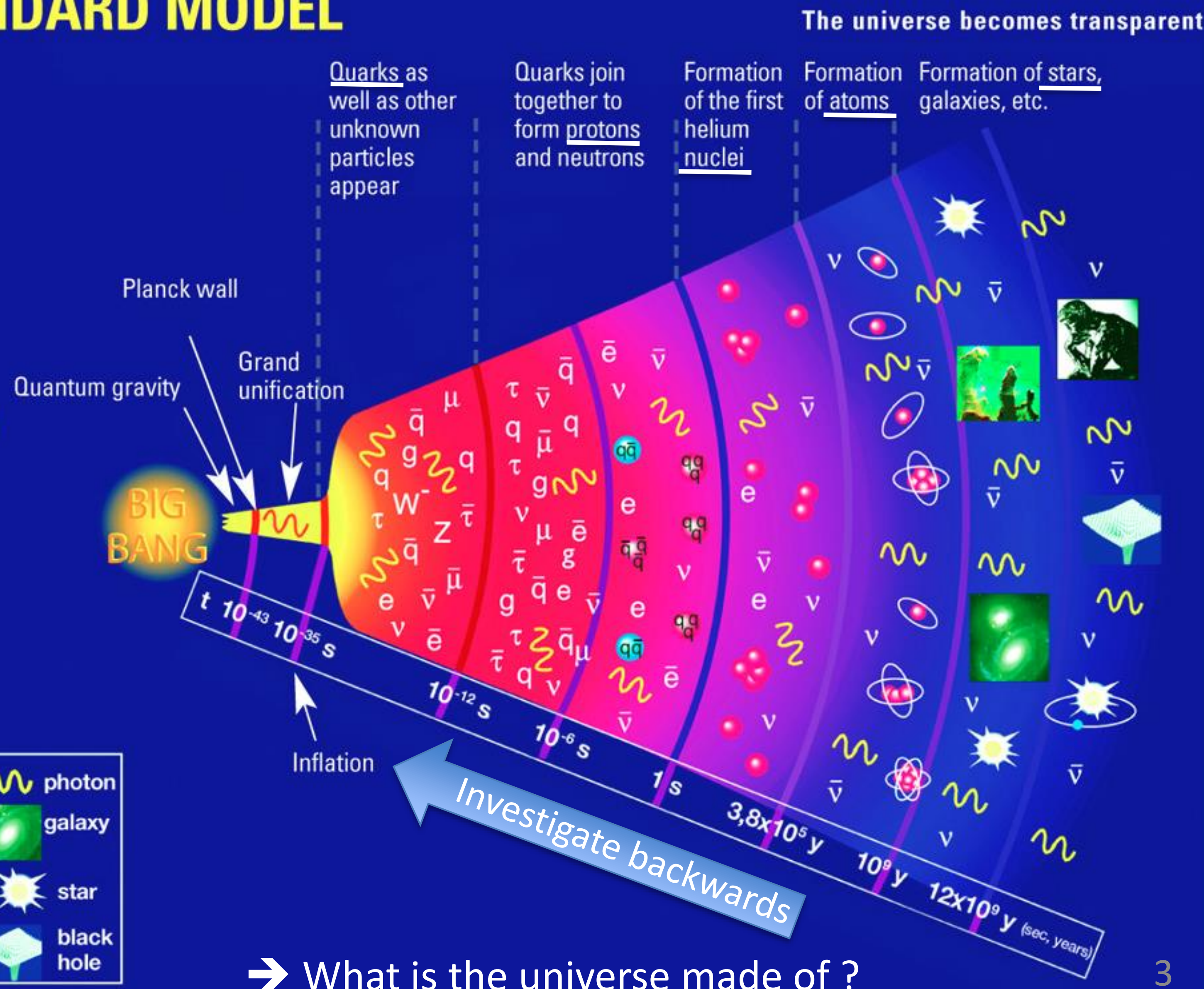
13.7 Billion Years

Today

10^{26} meters

THE UNIVERSE ACCORDING TO THE STANDARD MODEL

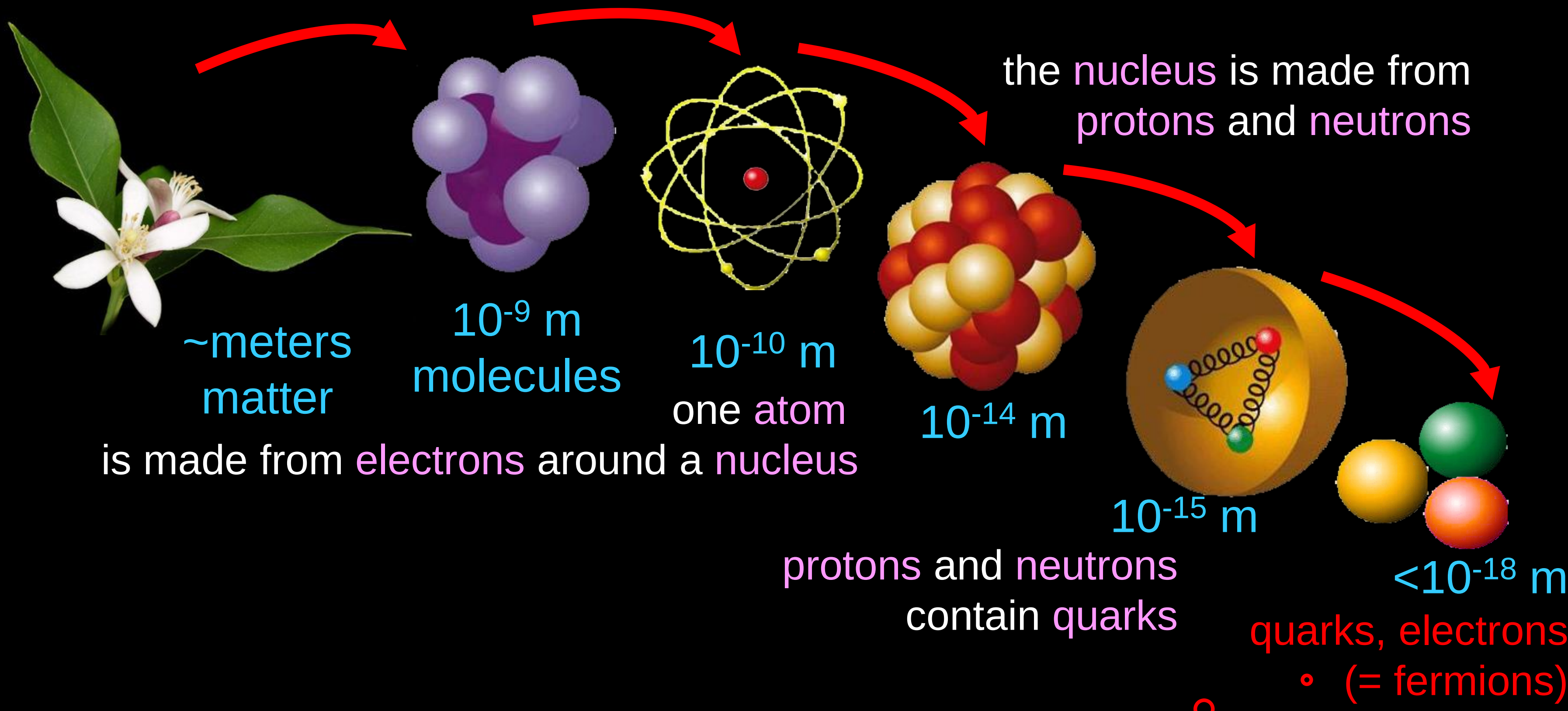
Since the Big Bang, the primordial universe has gone through a number of stages, during which particles, and then atoms and light gradually emerged, followed by the formation of stars and galaxies.
This is the story as told by the "standard model" theory used today.



➔ What is the universe made of ?

young, hot, energetic ⟶ old, cool, less energetic

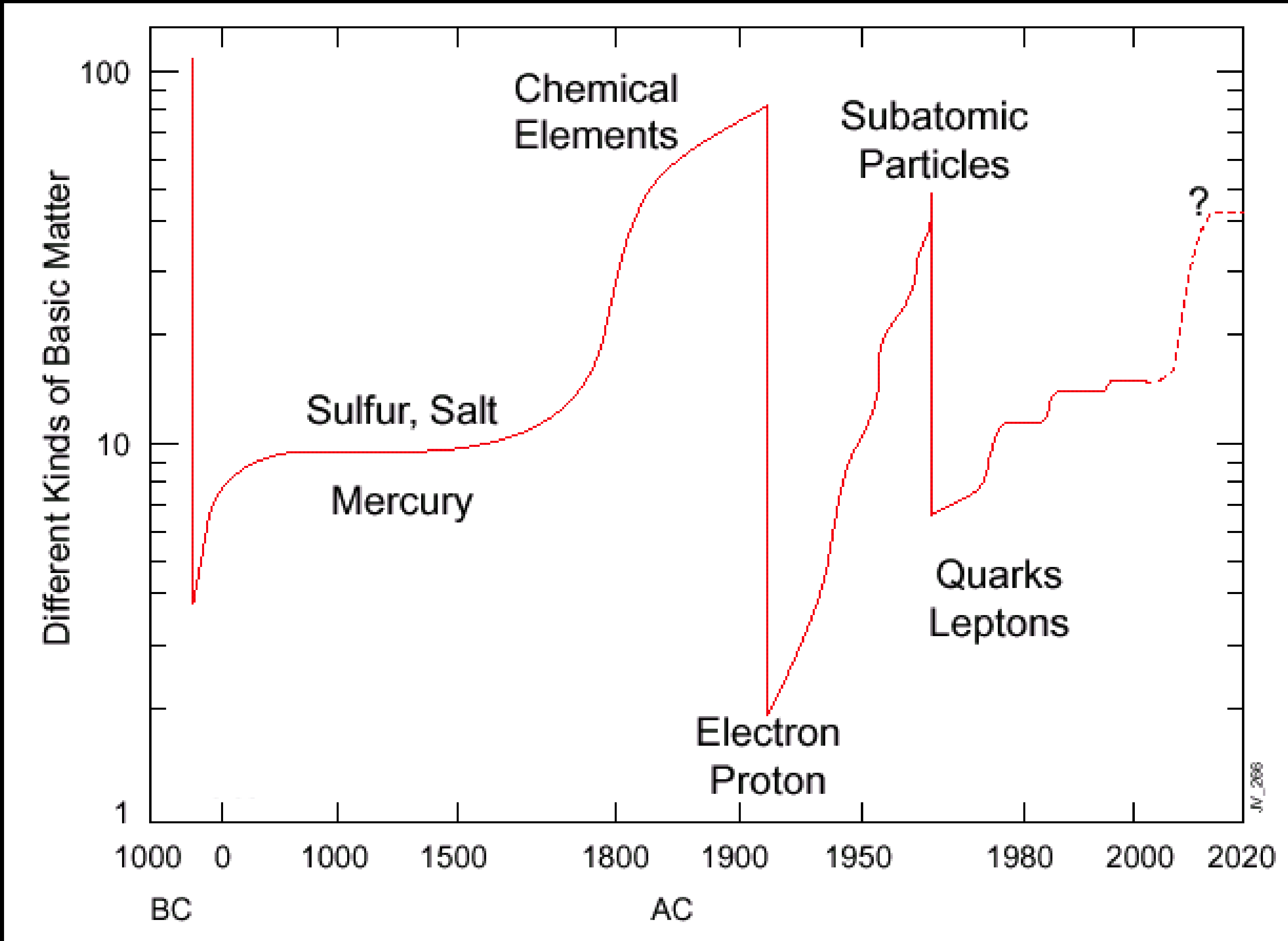
What is ‘normal’ matter made from?



electron, quark < 10^{-18} m = 0.000,000,000,000,000,001 m

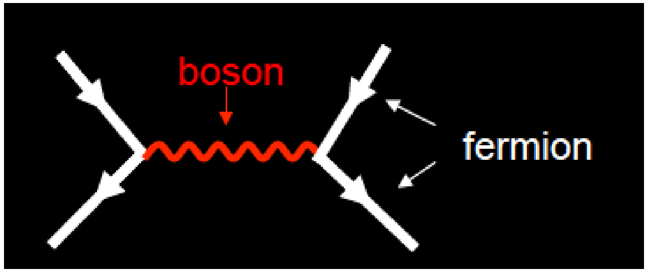
→ fundamental constituents

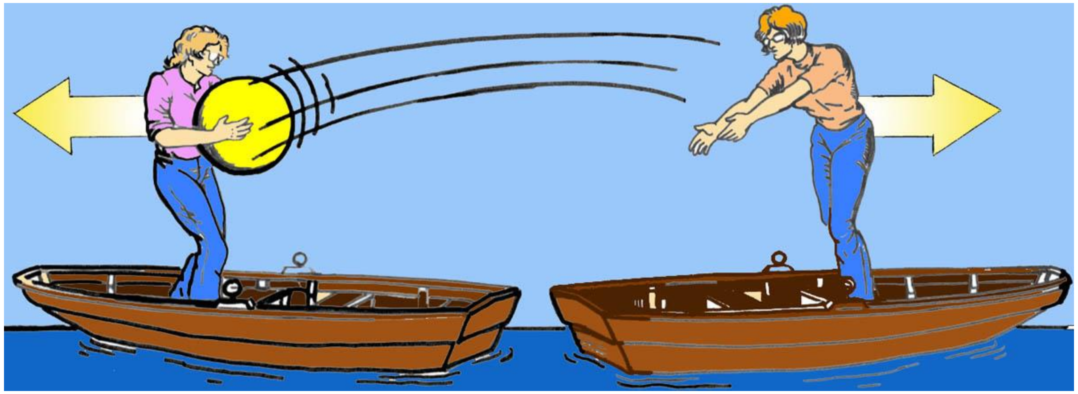
Kinds of matter ➔ Fundamental particles ?



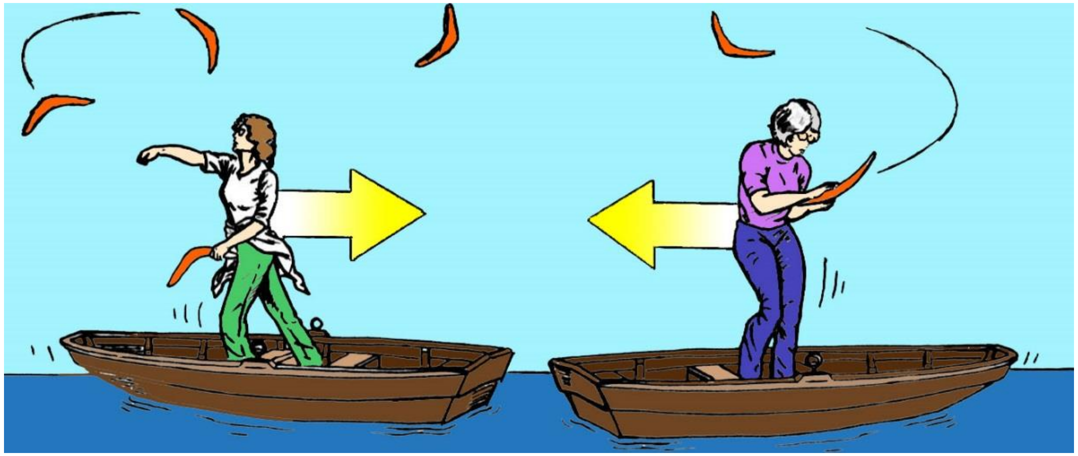
The Fundamental Forces

Forces between **fermions** (spin ½) are mediated by **bosons** (spin 1)





➢ repulsive

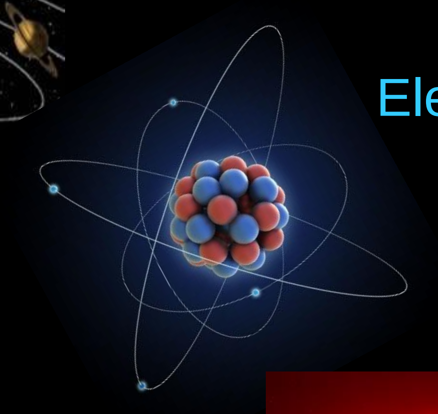


➢ attractive

The Fundamental Forces

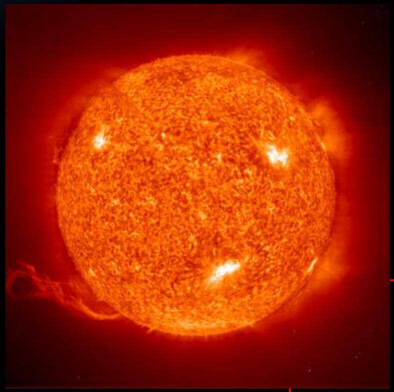
Gravity

Graviton ?



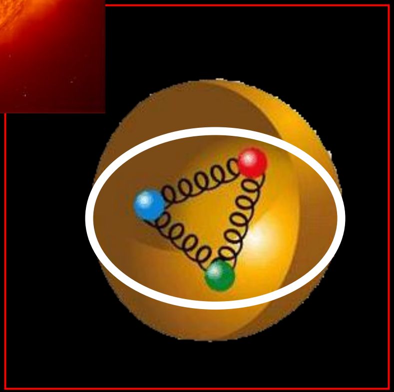
Electromagnetic Force

Photon



Weak Force

W, Z



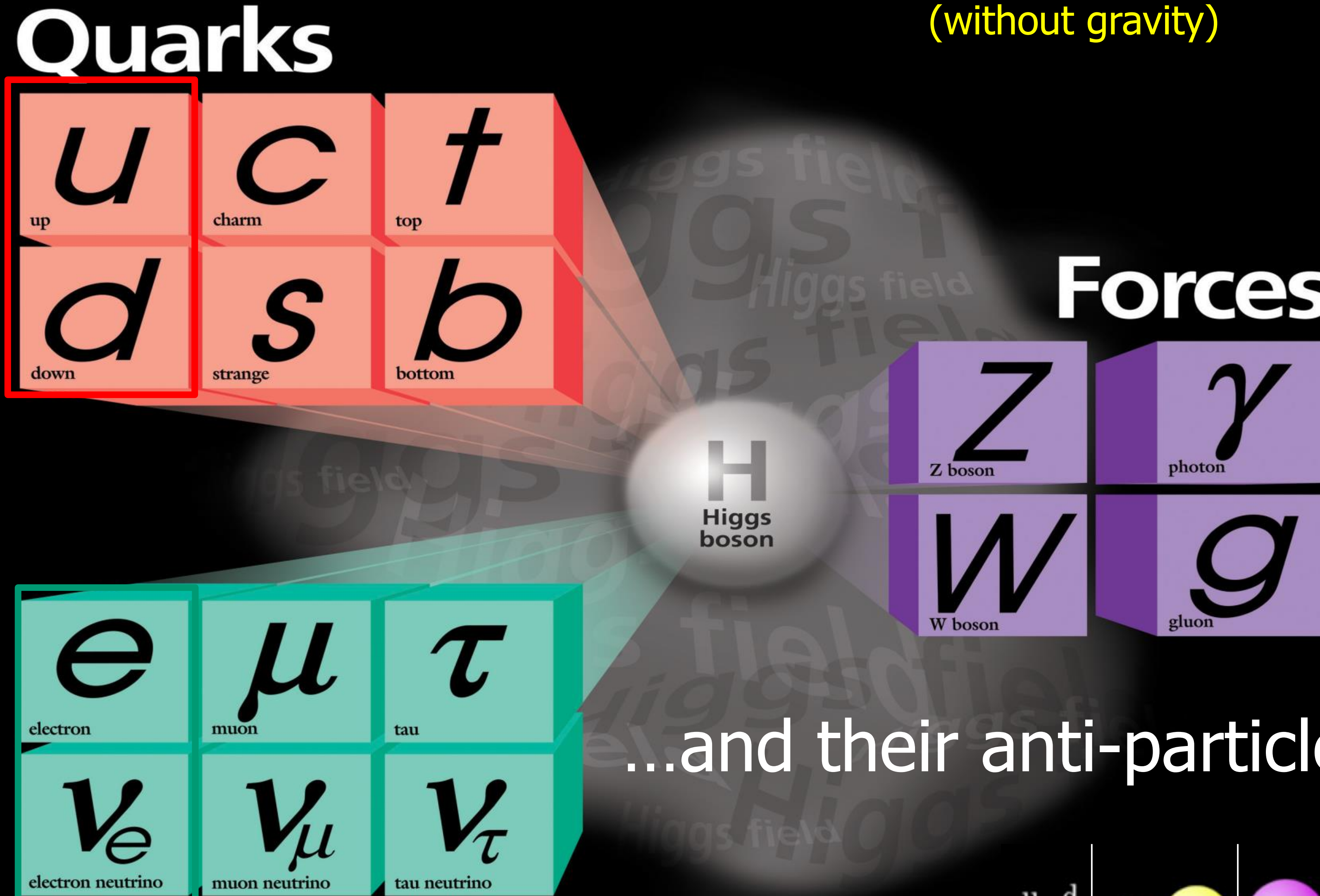
Strong Force

Gluon

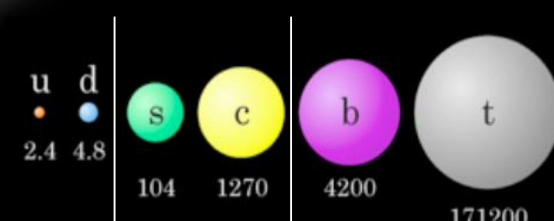
the forces act through their associated particles

The Standard Model of Particle Physics

(without gravity)

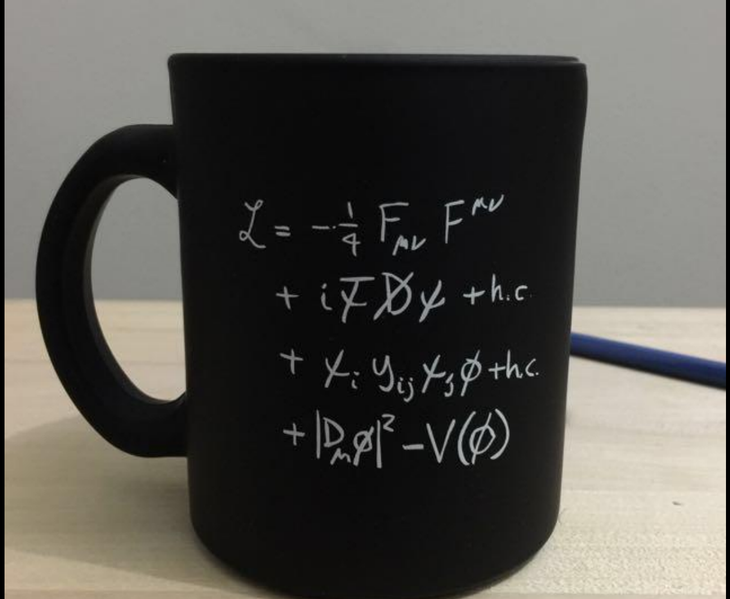


...and their anti-particles !



The Standard Model is much more than an order scheme for elementary particles. It’s the theory of almost everything.

Compact formulation of Standard Model Lagrangian



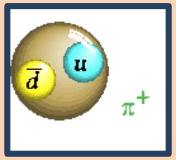
$SU(3)_C \times SU(2)_L \times U(1)_Y$

Unfortunately it has ~20 free parameters which need to be measured.

Neutrinos remain massless!

Parameters of the Standard Model [hide]			
Symbol	Description	Renormalization scheme (point)	Value
m_e	Electron mass		511 keV
m_μ	Muon mass		105.7 MeV
m_τ	Tau mass		1.78 GeV
m_u	Up quark mass	$\mu_{\overline{MS}}$ = 2 GeV	1.9 MeV
m_d	Down quark mass	$\mu_{\overline{MS}}$ = 2 GeV	4.4 MeV
m_s	Strange quark mass	$\mu_{\overline{MS}}$ = 2 GeV	87 MeV
m_c	Charm quark mass	$\mu_{\overline{MS}} = m_c$	1.32 GeV
m_b	Bottom quark mass	$\mu_{\overline{MS}} = m_b$	4.24 GeV
m_t	Top quark mass	On-shell scheme	172.7 GeV
θ_{12}	CKM 12-mixing angle		13.1°
θ_{23}	CKM 23-mixing angle		2.4°
θ_{13}	CKM 13-mixing angle		0.2°
δ	CKM CP-violating Phase		0.995
g_1 or g'	U(1) gauge coupling	$\mu_{\overline{MS}} = m_Z$	0.357
g_2 or g	SU(2) gauge coupling	$\mu_{\overline{MS}} = m_Z$	0.652
g_3 or g_s	SU(3) gauge coupling	$\mu_{\overline{MS}} = m_Z$	1.221
θ_{QCD}	QCD vacuum angle		~0
v	Higgs vacuum expectation value		246 GeV
m_H	Higgs mass		~ 125 GeV ~~(tentative)~~

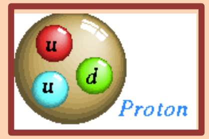
Building the "zoo" of elementary particles



quarks

↓

hadrons



mesons (1 quark and 1 antiquark)	baryons (3 quarks or 3 antiquarks)
$\pi^{\pm}$, $K^{\pm}$, J/ψ, etc.	p, n, Σ^+, Δ^0, etc.

leptons

↓

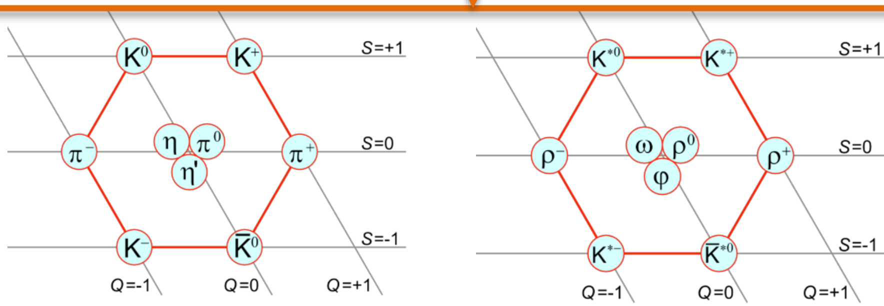
electron, muon, tau and neutrinos

bosons

↓

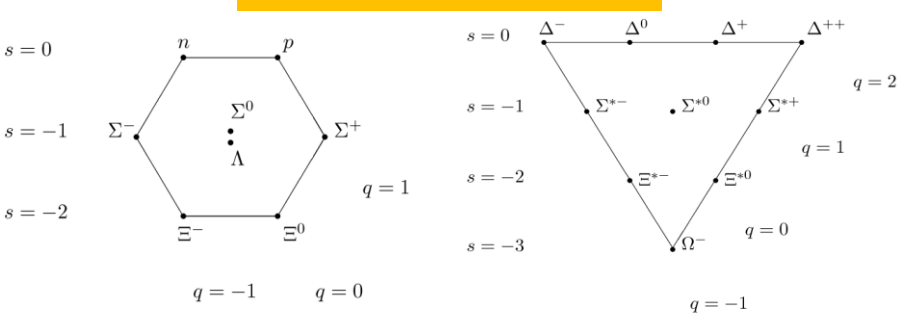
gluon, photon, Z boson, W boson

Mesons



Examples for 3 (u,d,s) quarks:

Baryons



BOSONS

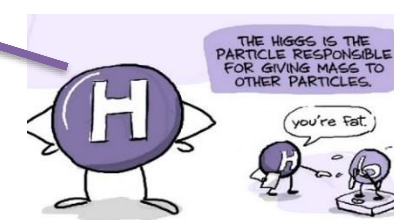
force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1		
Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	−1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1		
Name	Mass GeV/c^2	Electric charge
g gluon	0	0

10

Massive bosons require a new potential in the Standard Model!



The origin of particle masses

log-scale !

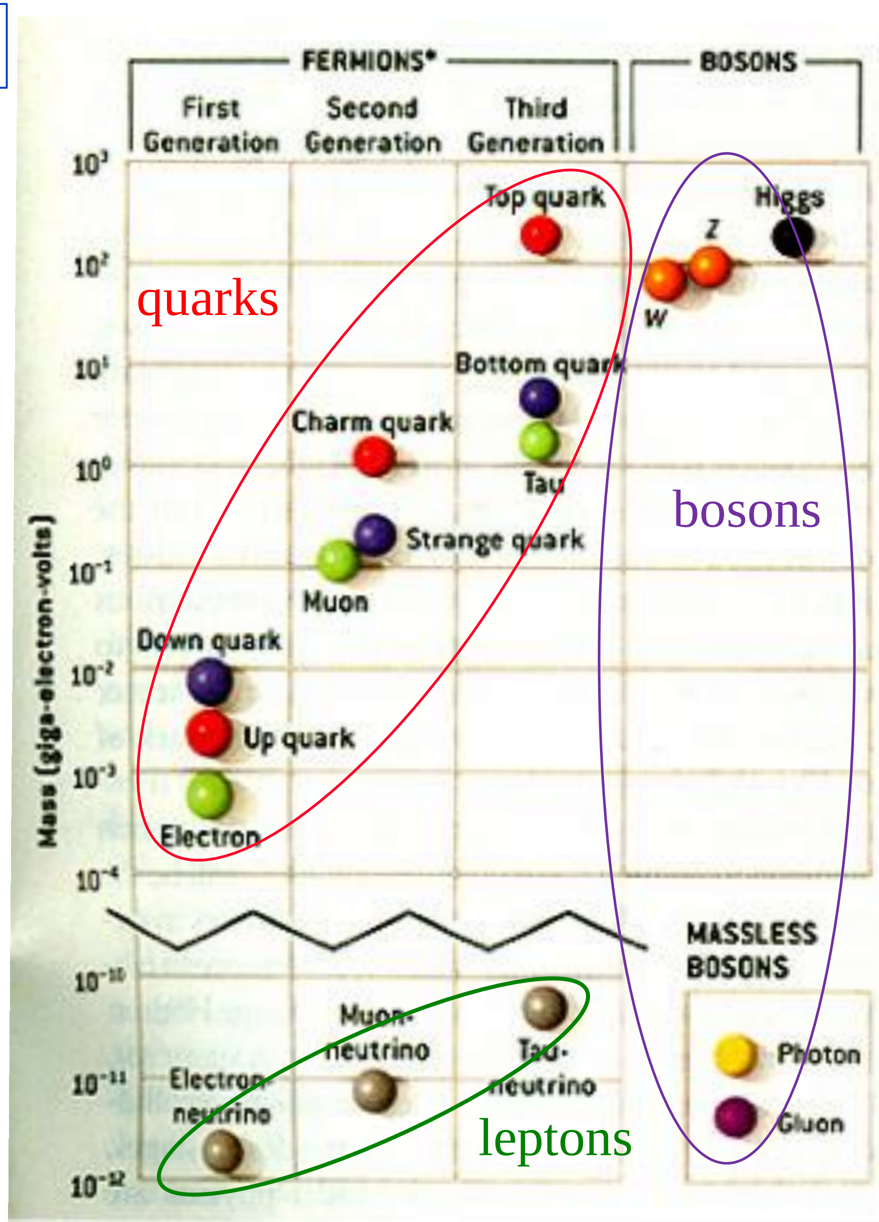
1 TeV

100 GeV

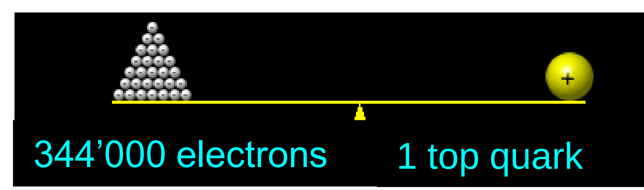
1 GeV

1 MeV

0.01 eV



- ✓ photon is massless (pure energy)
- ✓ W and Z bosons have 100 times the proton mass
- ✓ top quark is the heaviest elementary particle observed
- ✓ mass of top quark ≈ mass of gold atom and ~350’000 times larger than electron mass



➢ WHY ???

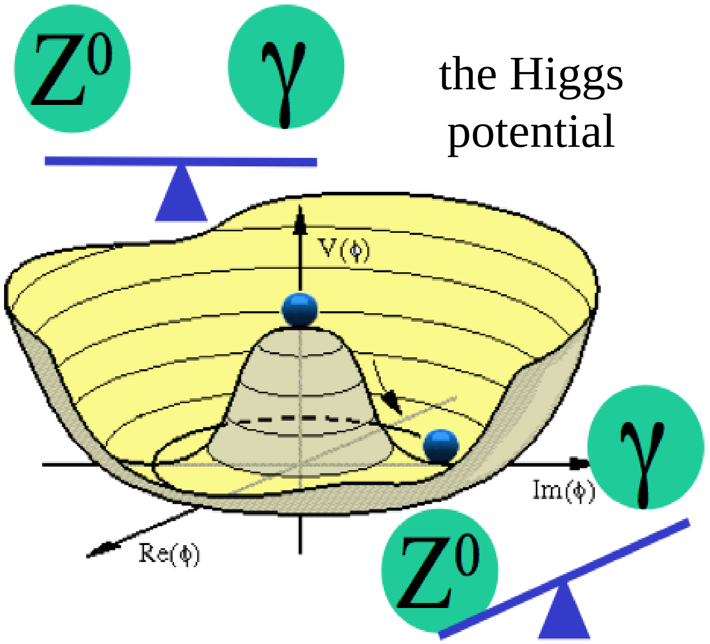
The origin of particle masses

Proposed explanation (by Brout, Englert, Higgs et al., 1964)

- ✓ "Brout-Englert-Higgs mechanism (BEH)" → origin of masses
- ➢ ~ 10^{-11} s after the Big Bang, when **Higgs field** became active, particles acquired masses proportional to the strength of their interactions with this Higgs field

Consequence: existence of a **Higgs boson**

- ✓ the Higgs boson is the quantum of the new postulated field
- ➢ this particle has been searched for > 30 years at accelerators all over the world
- ➢ finally discovered at the LHC



- ➢ spontaneous symmetry breaking

The origin of particle masses

What is so special about the Higgs field ?

- It fills the entire universe uniformly (since the Big Bang)
- It provides every particle with its exact mass (also to the newly created ones)

A party takes place ...

The Higgs field ...

The origin of particle masses

The Higgs Boson

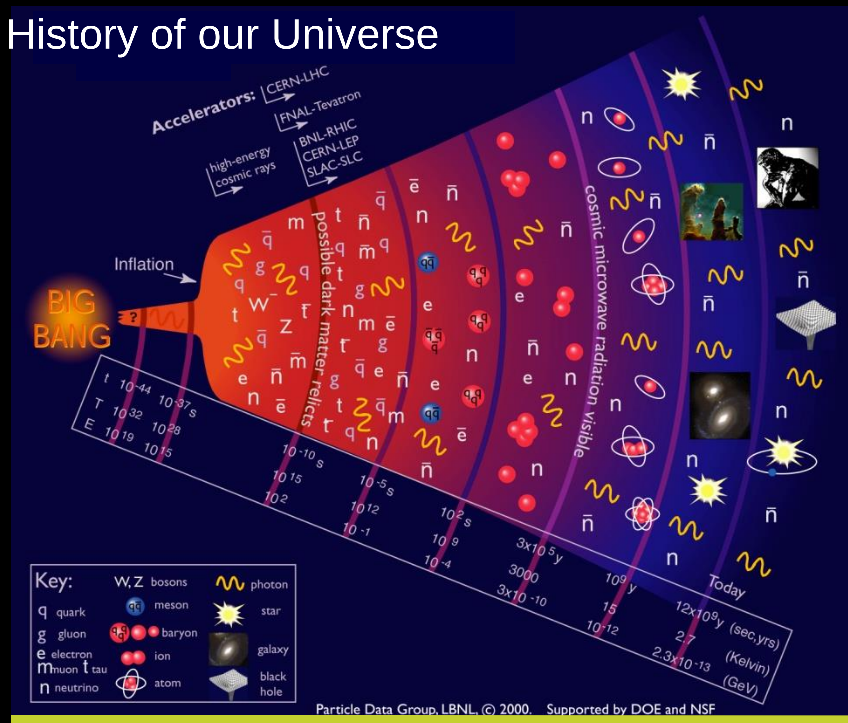
A rumour is being
spread-out at the party ...

The Higgs field ...

More Questions ....

BIG BANG

The same amount of matter & antimatter was created



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Why?

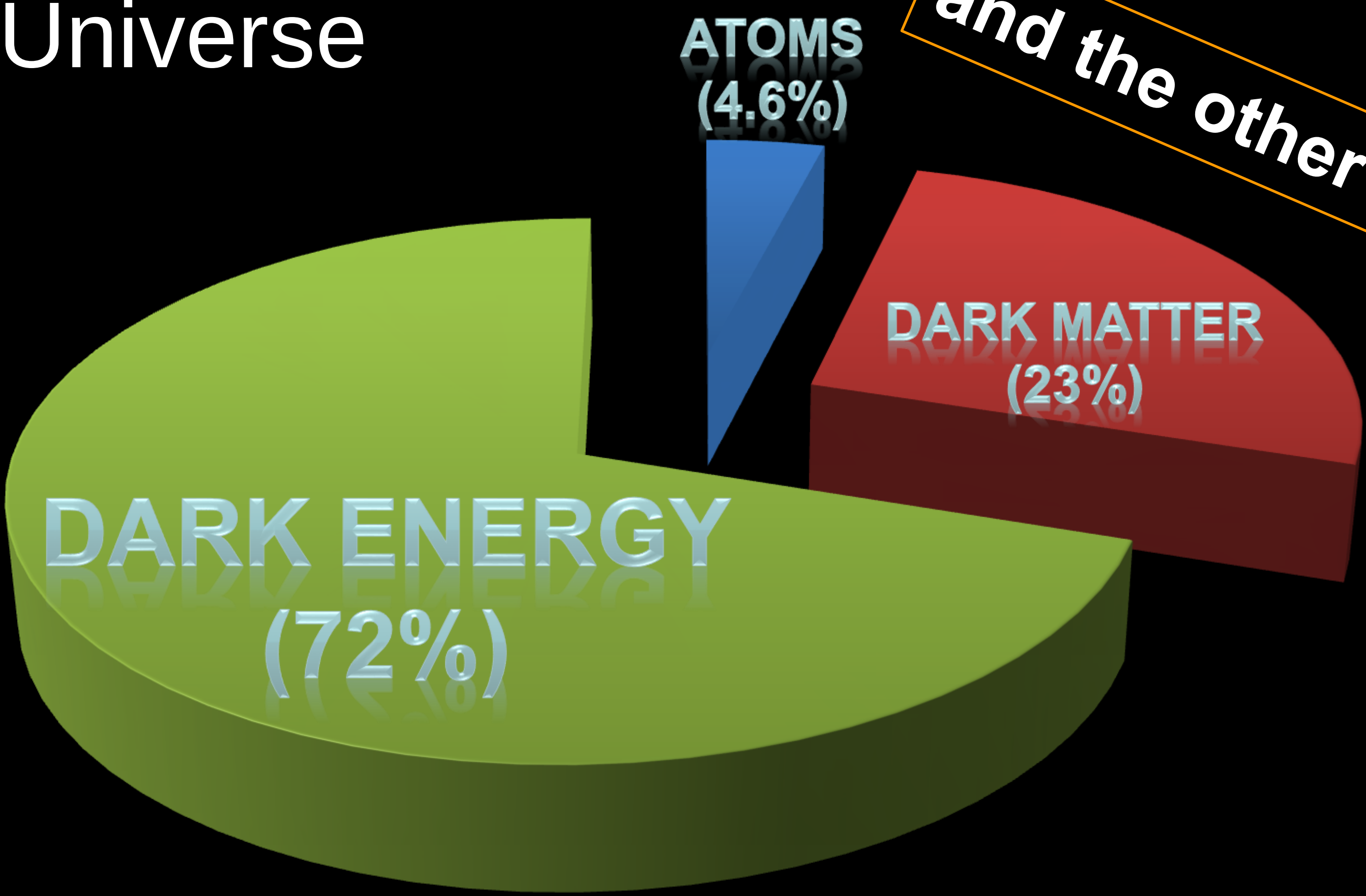
NOW

Only matter (us) survived

$$\frac{N_{baryons}}{N_{photons}} \sim 10^{-9}$$

More Questions ....

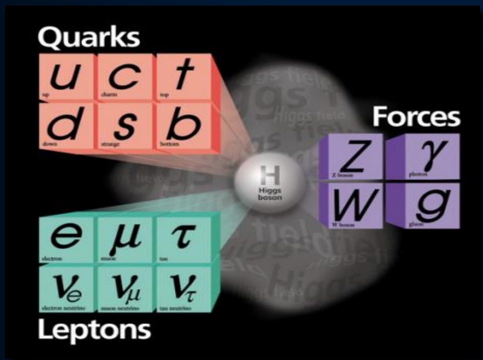
Our Universe



and the other 95%?

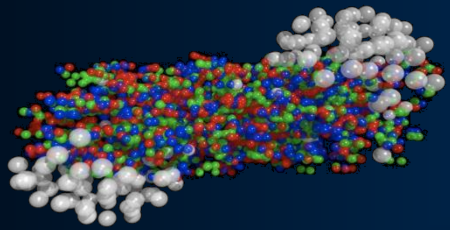
Leaving this stuff for the cosmologists ☺

Experiments at CERN, in particular at the LHC, are designed to answer some of the big questions ...



Have we found “THE” Higgs particle that is responsible for giving mass to all elementary particles?

Will we find the reason why antimatter and matter did not completely destroy each other?



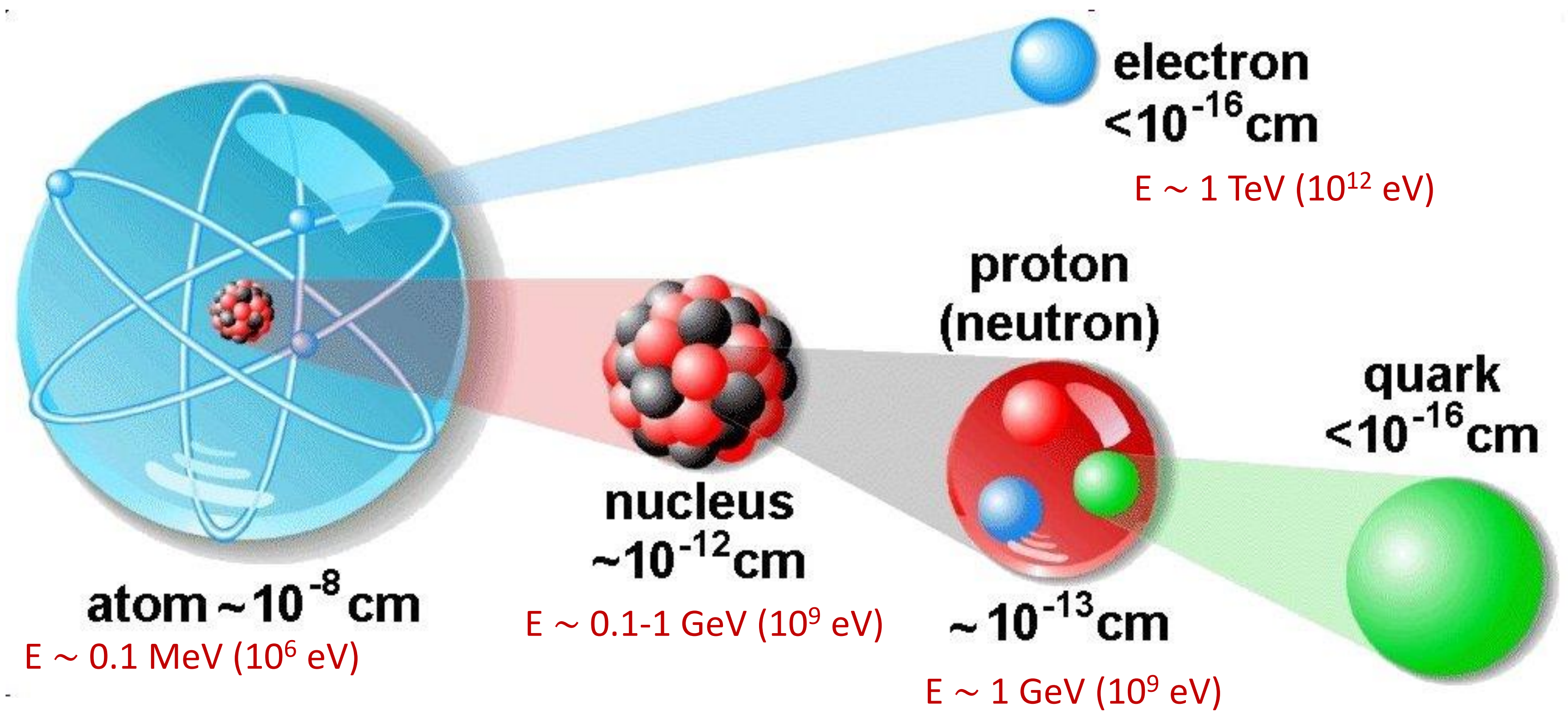
Will we understand the primordial state of matter after the Big Bang before protons and neutrons formed?

Will we find the particle(s) that make up the mysterious ‘dark matter’ in our Universe?

How do we explore small scales or new particles?

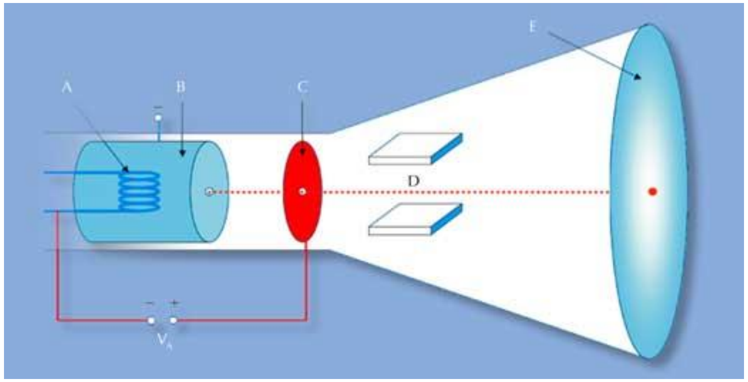
Resolving structures: Use particle beam like light in a microscope. Need very short wavelength, i.e. particles at very high energies **$E = hc/\lambda$**

Creating new particles: collide particles with ‘available’ collision energy corresponding to at least the rest mass of the new particle **$E = mc^2$**

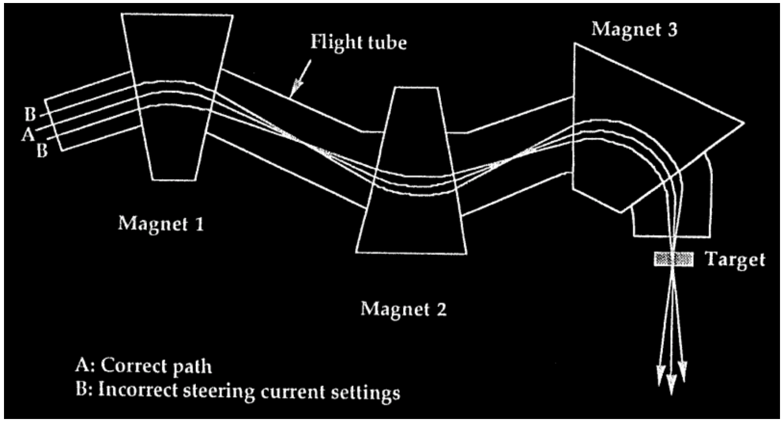


Mini introduction to particle accelerators

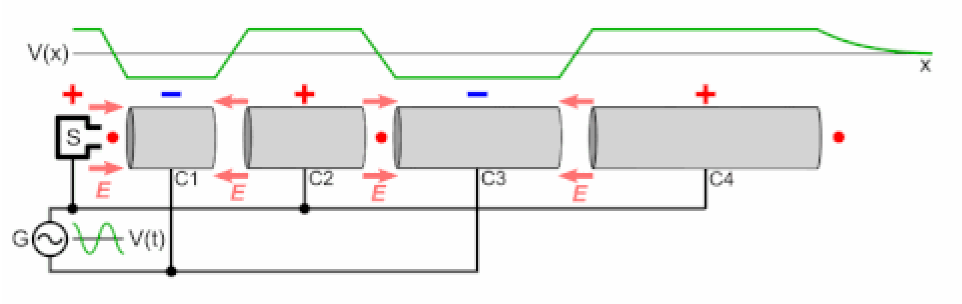
Accelerate (charged) particles in an electric field



Also add some magnets for beam deflection …

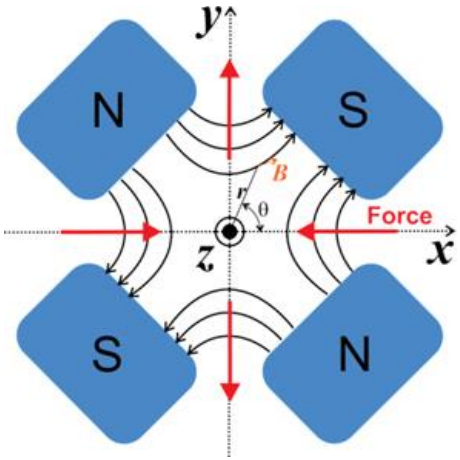


More acceleration ?
Use tubes on alternating potentials.



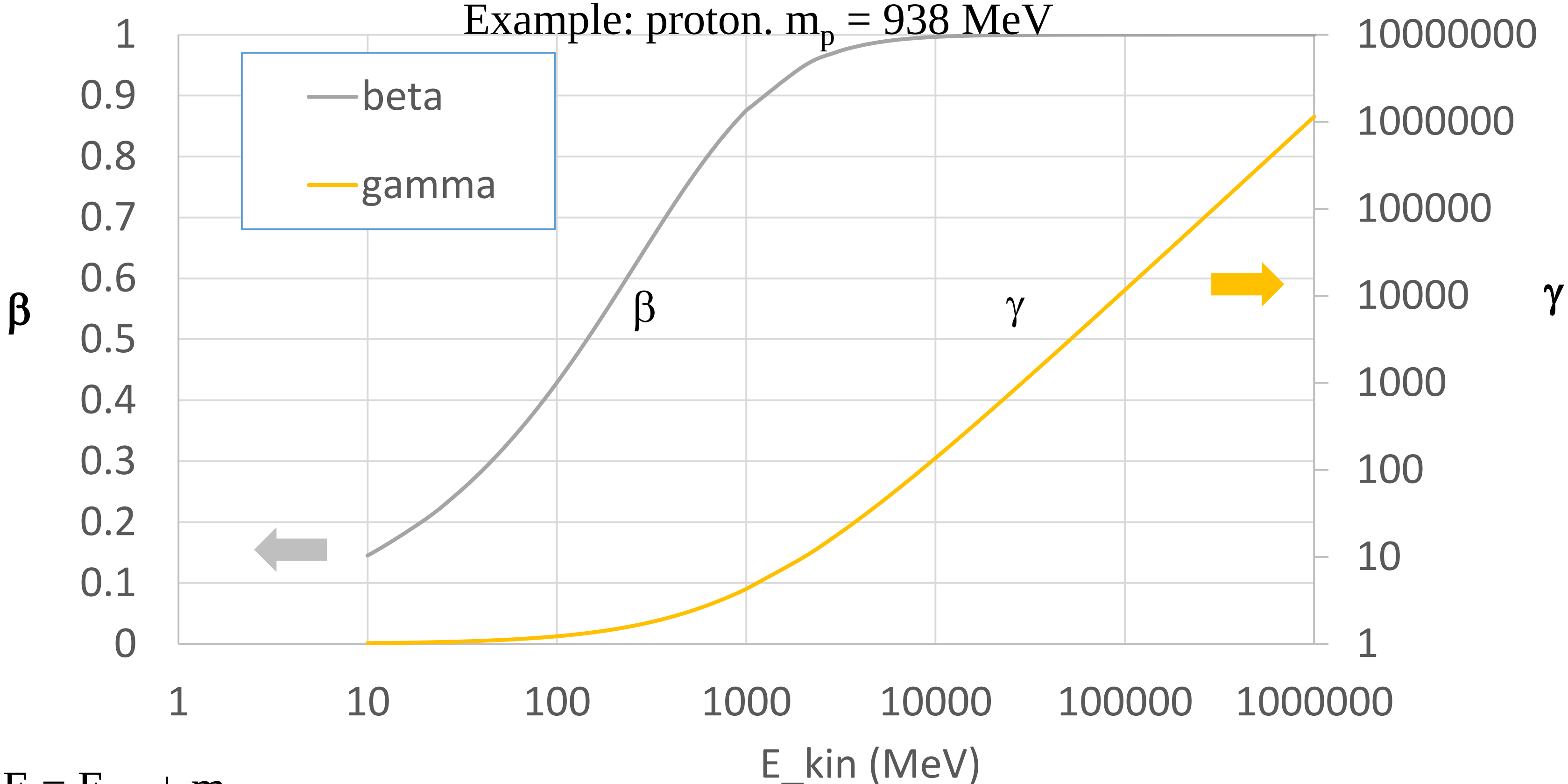
… RF cavities

… and magnetic lenses for focusing



Relativistic Kinematics

Example: proton. m_p = 938 MeV



$E = E_{kin} + m_0$

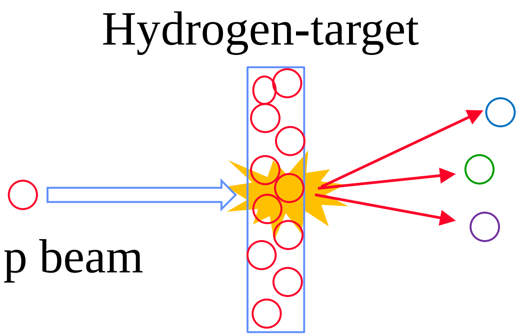
$E^2 = p^2c^2 + m_0{}^2c^4$ $\beta = v/c = pc/E$ $\gamma = 1/(1-\beta^2)$

$E = mc^2 = m_0\gamma c^2$ $\gamma = m/m_0$

Energy accelerates particles <u>towards</u> speed of light (v=c, β = 1) and increases their relativistic mass!

Fixed Target vs Collider

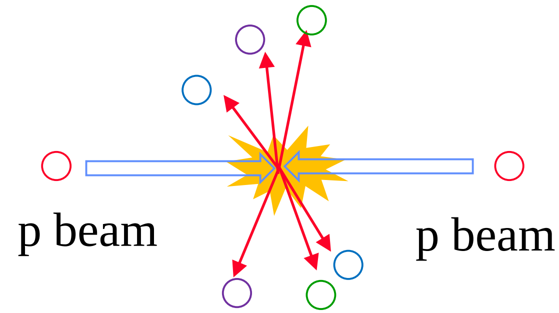
Shooting a beam on a fixed target



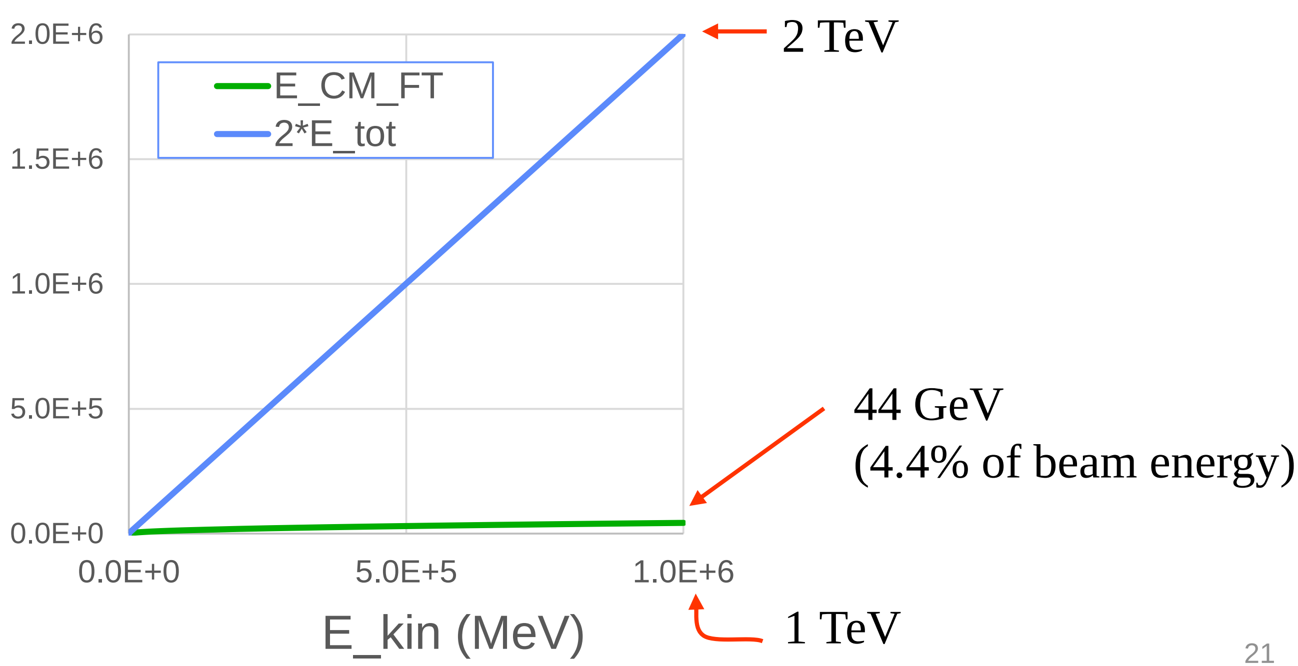
Available energy in the collision:

$$E^* = \sqrt{(2\cdot(E_{kin}+m_p)\cdot m_p)}$$

Colliding two beams

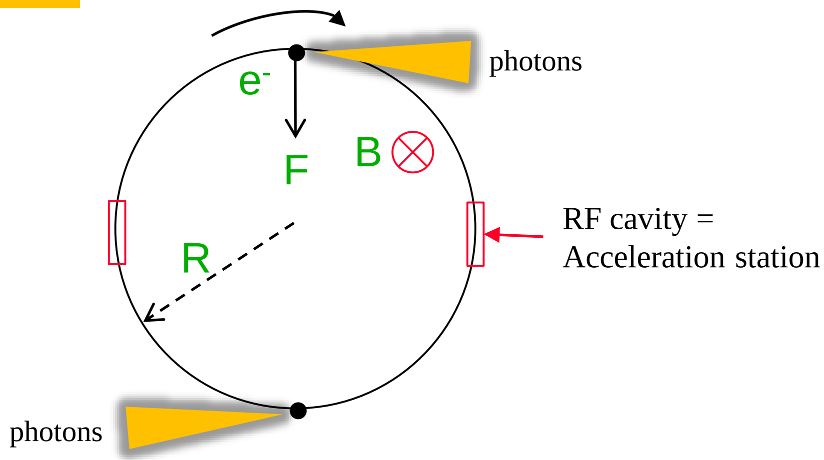


Available energy in the collision: $E^* = 2E_{inc}$



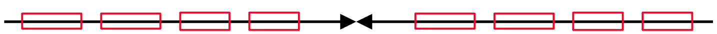
Circular vs Linear Colliders

Circular



- Particles are accelerated in every turn → achieve highest energy
- Need magnetic field to force particles on a circle → permanent acceleration towards the centre.

Linear



- Need to arrange many acceleration stations with very high gradient (many MV/m).
- (Almost) no synchrotron radiation.
- Particles have a single chance to collide → need very precise beam focusing and steering

Emission of synchrotron radiation:

Irradiated power $$P_r = \frac{e^2 c}{6\pi\varepsilon_0}\frac{1}{m^4}\frac{E^4}{R^2}$$

- Serious problems to accelerate e^+ and e^- in a circular machine to >100 GeV.
- Our friends from ESRF, XFEL and EMBL make a living from synchrotron radiation.

How do collisions at the LHC work?

13 TeV LHC, 27 km circumference

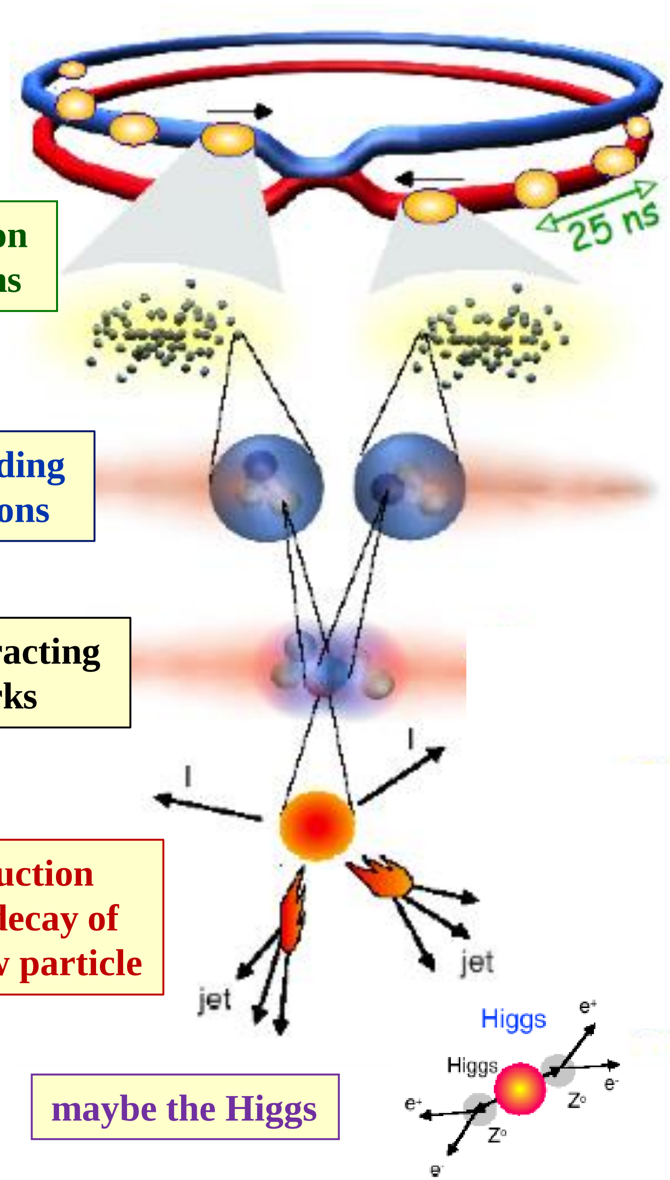
proton beams

colliding protons

interacting quarks

production and decay of a new particle

maybe the Higgs

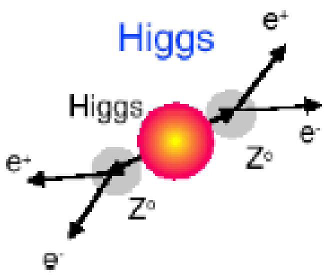


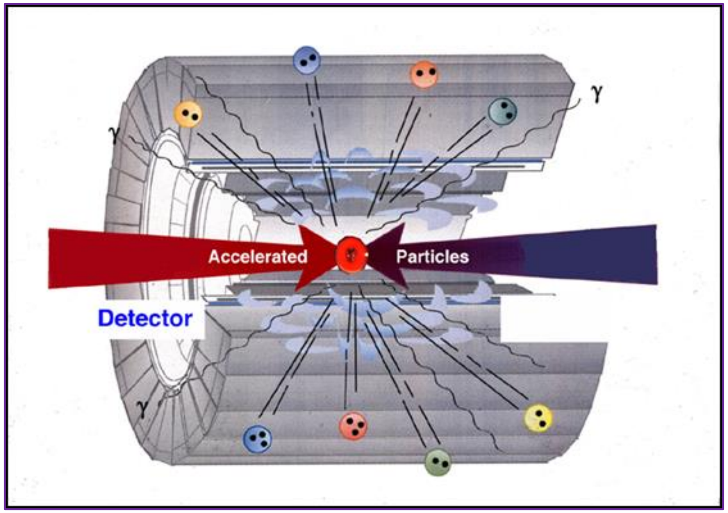
- Two independent proton beams are brought to collision (at specific interaction points)
- Protons are arranged in bunches (~10^{11}). Several pp-collisions per bunch crossing.
- the colliding protons "break" into their fundamental constituents (i.e. quarks)
  → only a fraction of the proton energy is available for the creation of new particles.

  → lots of non-interesting background
- The new particles are generally unstable and decay promptly into lighter (known) particles: electrons, photons, etc.

Invariant mass

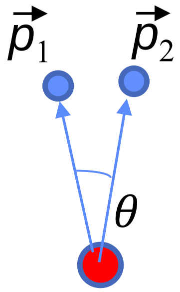
- We can't *see* the new particle itself, but only the end products of its decay.
- In order to reconstruct the reaction mechanism and the properties of the new particles, we want the maximum information about the end products: number, charge, energy, momentum, particle ID !
- End products are detected by high-tech detectors surrounding the collision point





The so-called invariant mass ***M*** of a new particle can be calculated from the energies and momenta of the decay products.

$$(\boldsymbol{M}c^2)^2 = (\sum E_n)^2 - |\sum \vec{p}_n|^2$$



New particle decaying into 2 known particles

Detectors must be ultra-selective

Distinguish (new) rare particle decays from (known) abundant particle decays
→ very performant detectors with excellent particle identification

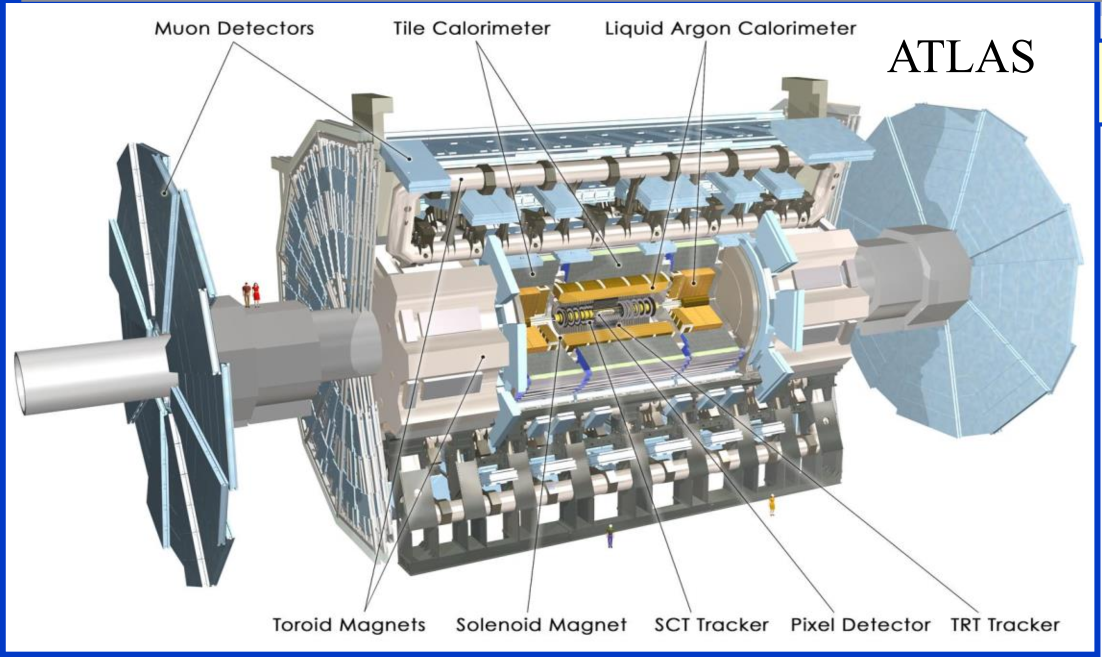
You are looking for this particular particle physicist!

Needs VERY high
- ✓ precision
- ✓ statistics
- ✓ selectivity
- ✓ background suppression

Note:
- ➢ the world population is ~$7.5 \cdot 10^9$
- ➢ typical very rare decay $B(B_s \to \mu\mu) = (3.65 \pm 0.23) \times 10^{-9}$

Enter a New Era in Fundamental Science

General Purpose Detectors (GPD): The Higgs Hunters

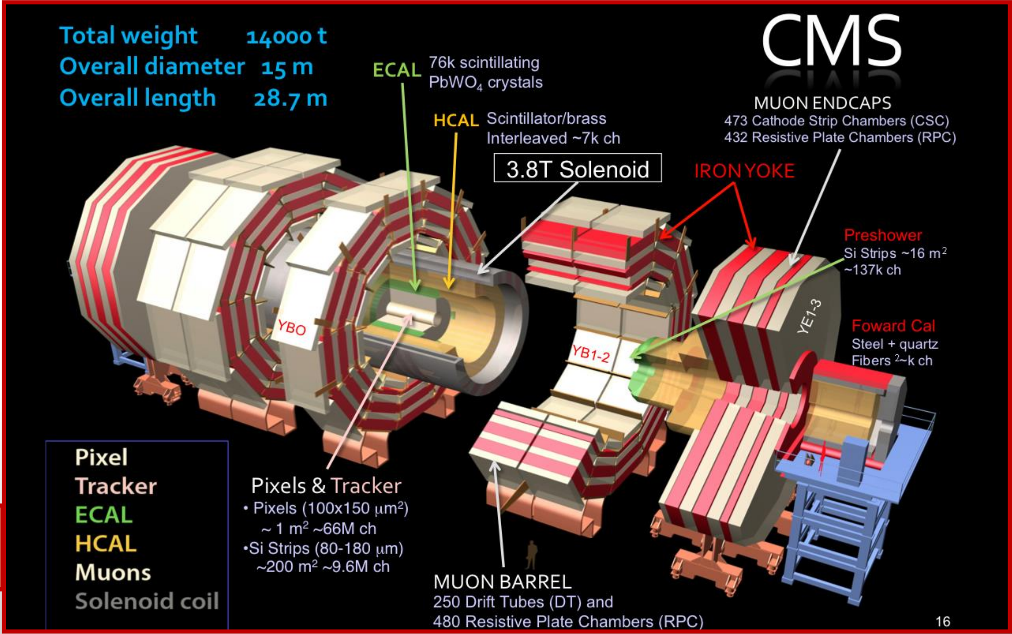


The ATLAS experiment

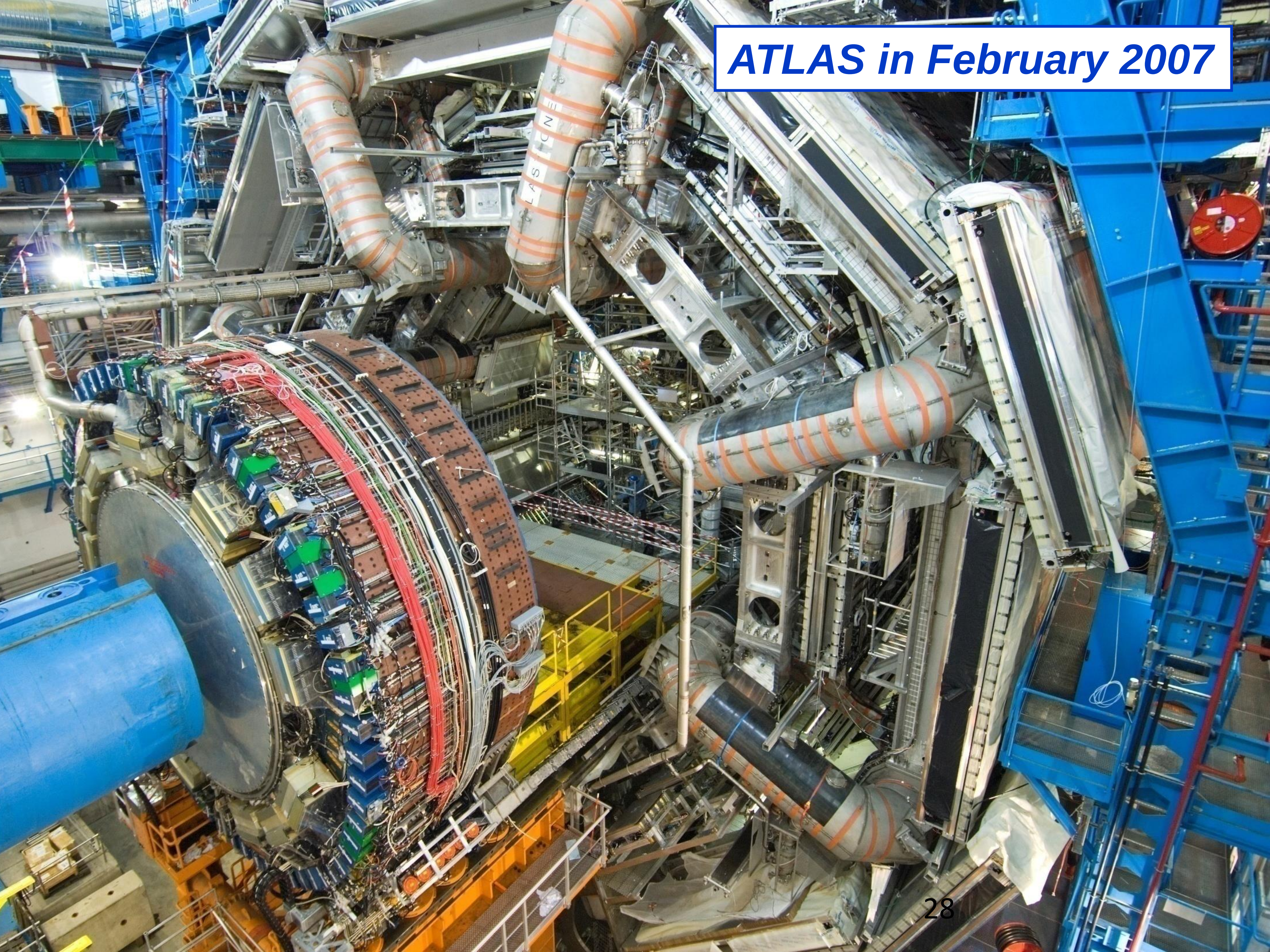
These experiments use different technologies for their detector components

CMS	ATLAS
14 ktons	7 ktons
B=3.8 T	B=2 T
15x29 m	22x45 m

The CMS experiment



ATLAS in February 2007

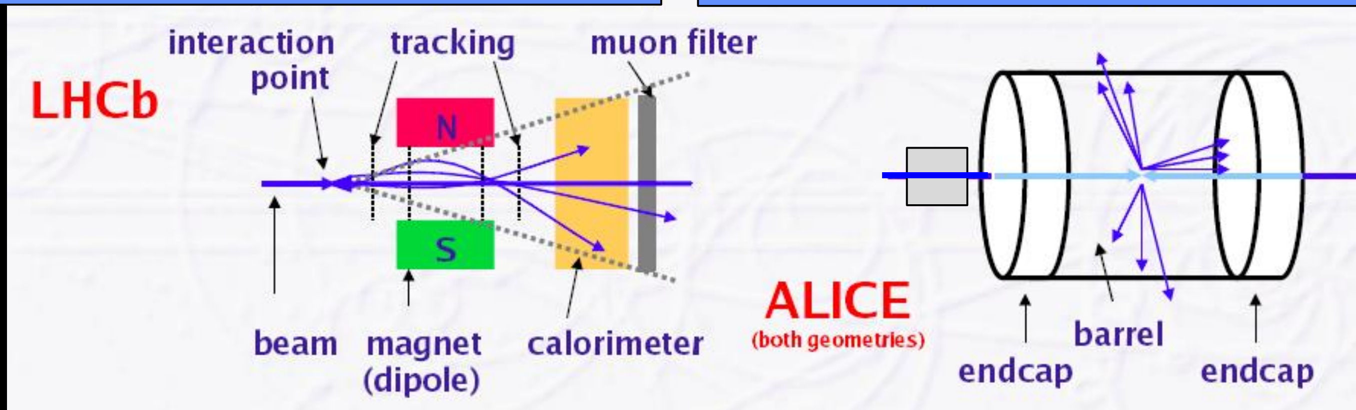


CMS before closure 2008

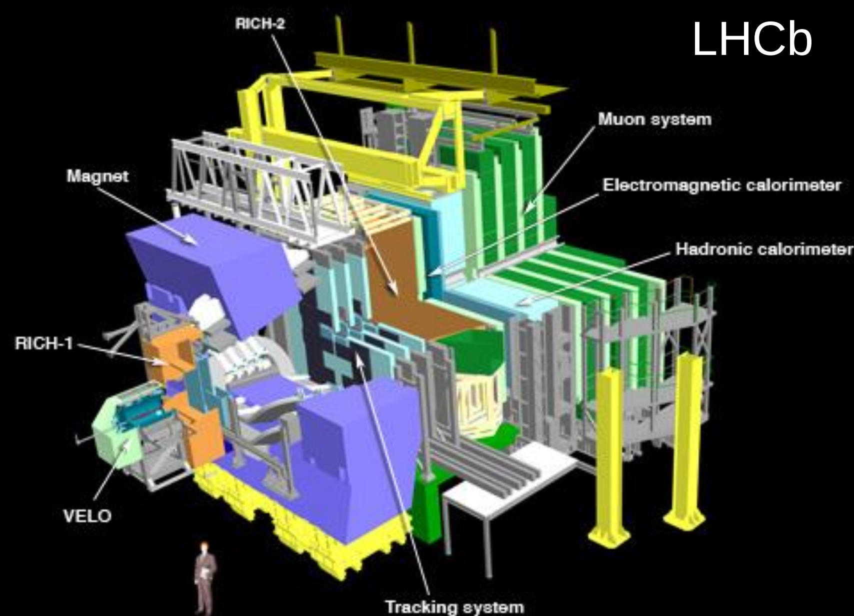
Specialized Detectors: Flavour Physics and Heavy Ions

Forward geometry with special particle identification to detect B meson decays

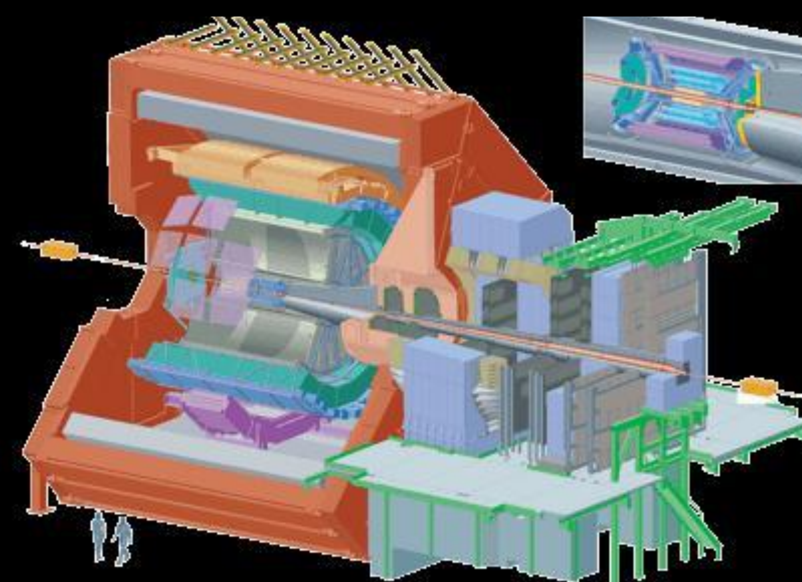
4π geometry with some forward detectors optimised for high multiplicity Pb-Pb collisions



LHCb



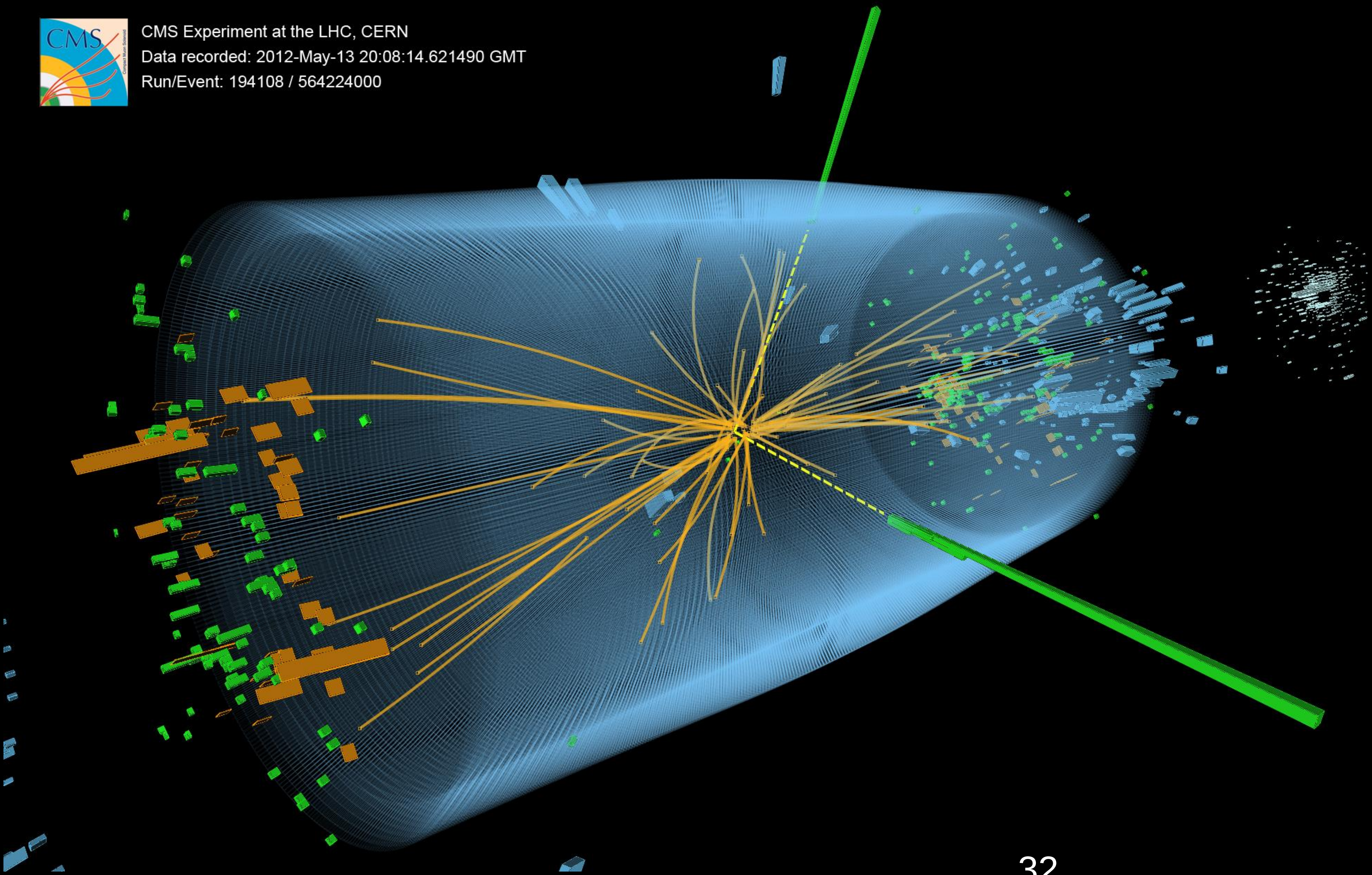
ALICE



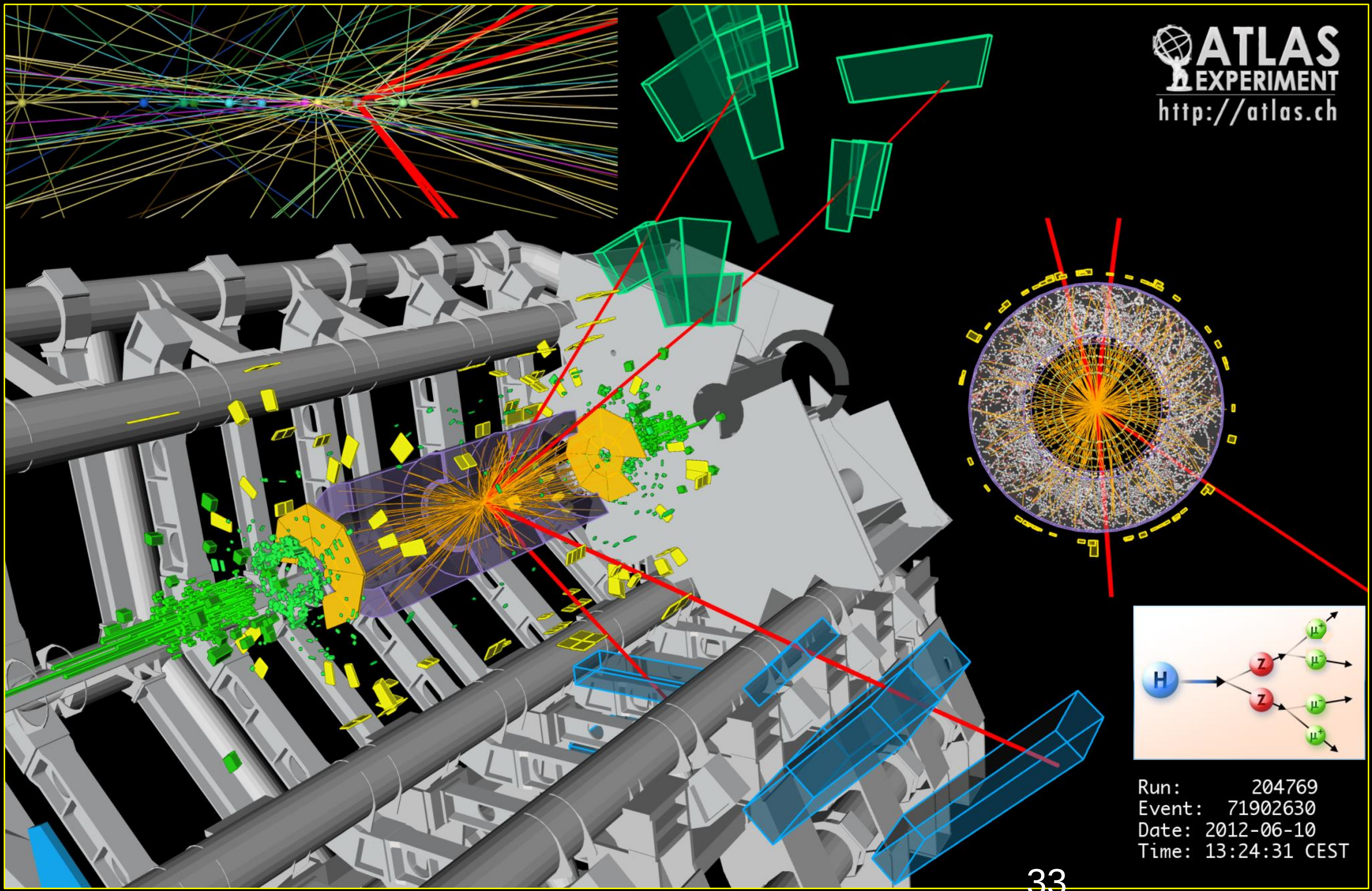
A Possible H → 2 Photon Decay

- a Higgs is produced only once in 10^{10} collisions
- it decays to 2 photons only with 0.2% probability

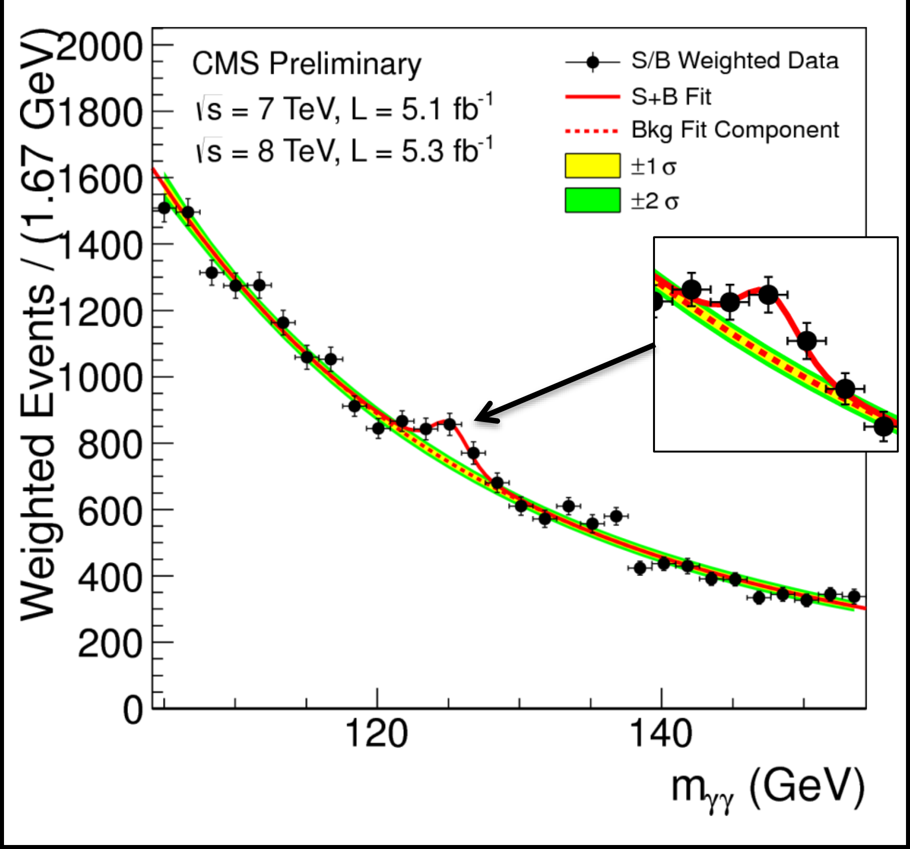
A Possible H → 2 Photon Decay

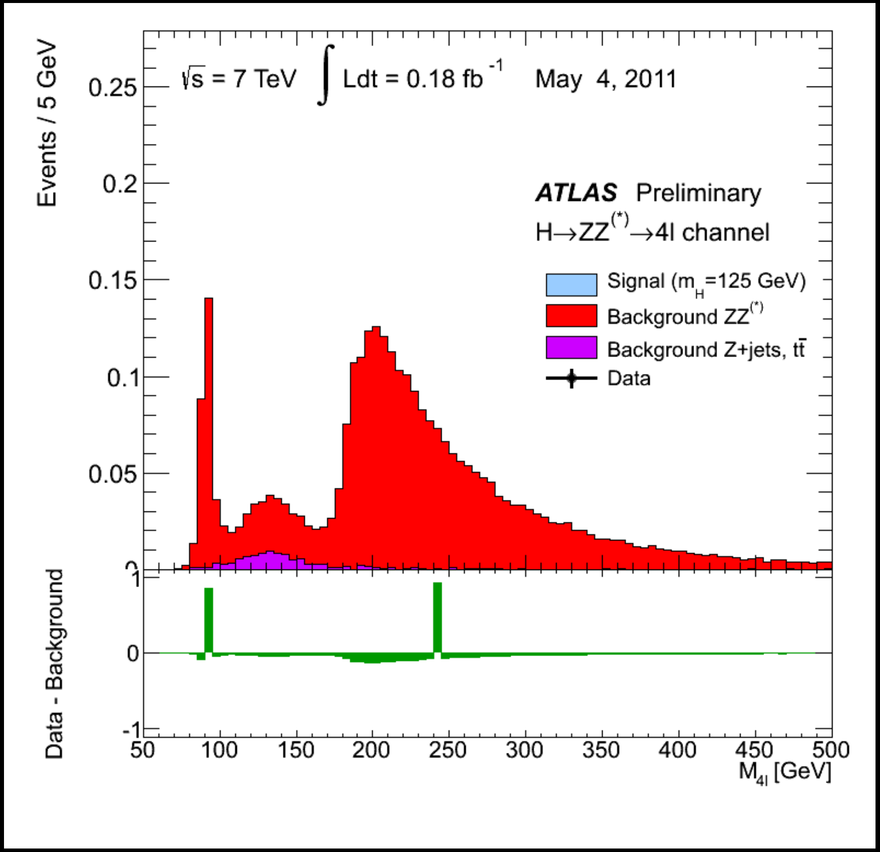


A Possible H → 4 Muon Decay



Identifying the Higgs over background





Higgs → 2 photons (Summer 2012)

Higgs → 2 Z → 4 leptons (end 2012)

✓ Both ATLAS a CMS discover a new particle
- Nobel prize to F. Englert and P. Higgs in 2013

Conclusion

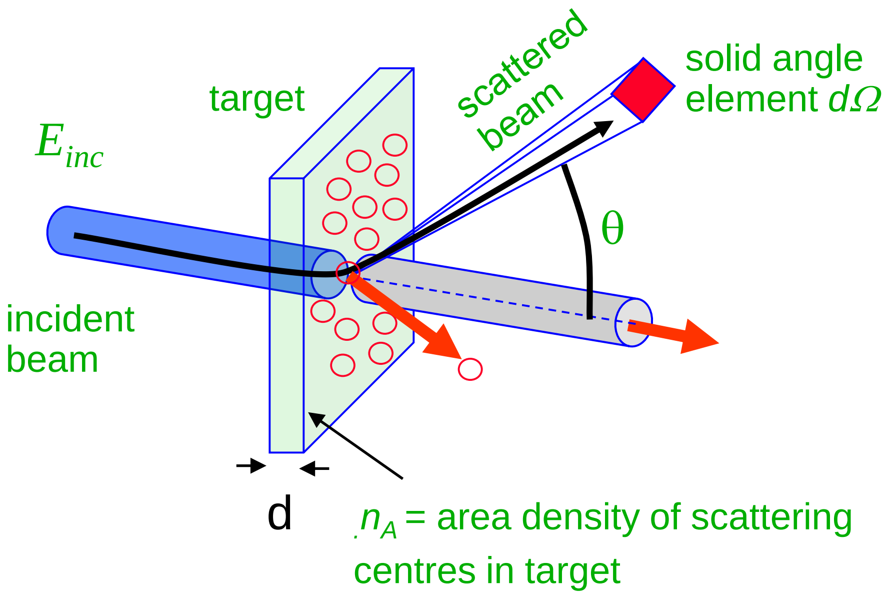
- ✓ After the discovery of the Higgs boson, the Standard Model of particle physics is now "complete"!
- ✓ However, this explains only ~5% of our universe and many questions in understanding the origin of our universe are yet to be resolved.
- ✓ Powerful particle accelerators and sophisticated detectors allow to study some of the most fundamental open questions.
- ✓ So far no significant signal beyond the Standard Model of particle physics has been found.
- ✓ The LHC and the experiments are undergoing very major upgrades (just now 2019-2020) and also around 2024-2025 to increase luminosity and selectivity/precision of the detectors.

> ➢ High energy physics will contribute further to the understanding of our universe by looking for deviations from the Standard Model in a variety of areas. Let's hope that significant deviations will be discovered soon!

Spares

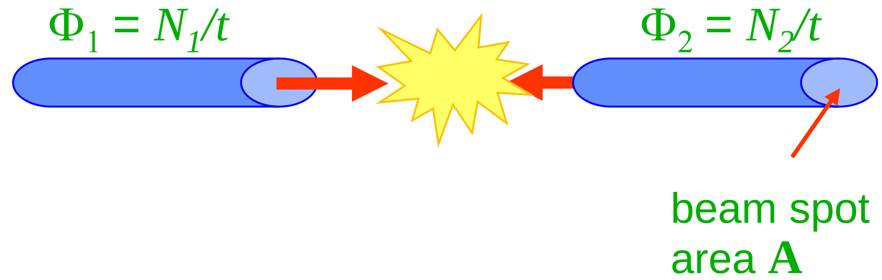
Fixed Target vs Collider

Shooting a beam on a fixed target



$$N_{scat}(\theta) \propto N_{inc} \cdot n_A \cdot d\Omega$$
$$= d\sigma/d\Omega\,(\theta,E) \cdot N_{inc} \cdot n_A \cdot d\Omega$$

Colliding two beams



$$R_{int} \propto \underbrace{N_1 N_2 / (A \cdot t)}_{\text{Luminosity } L\ [\text{cm}^{-2}\ \text{s}^{-1}]} = \sigma \cdot L$$

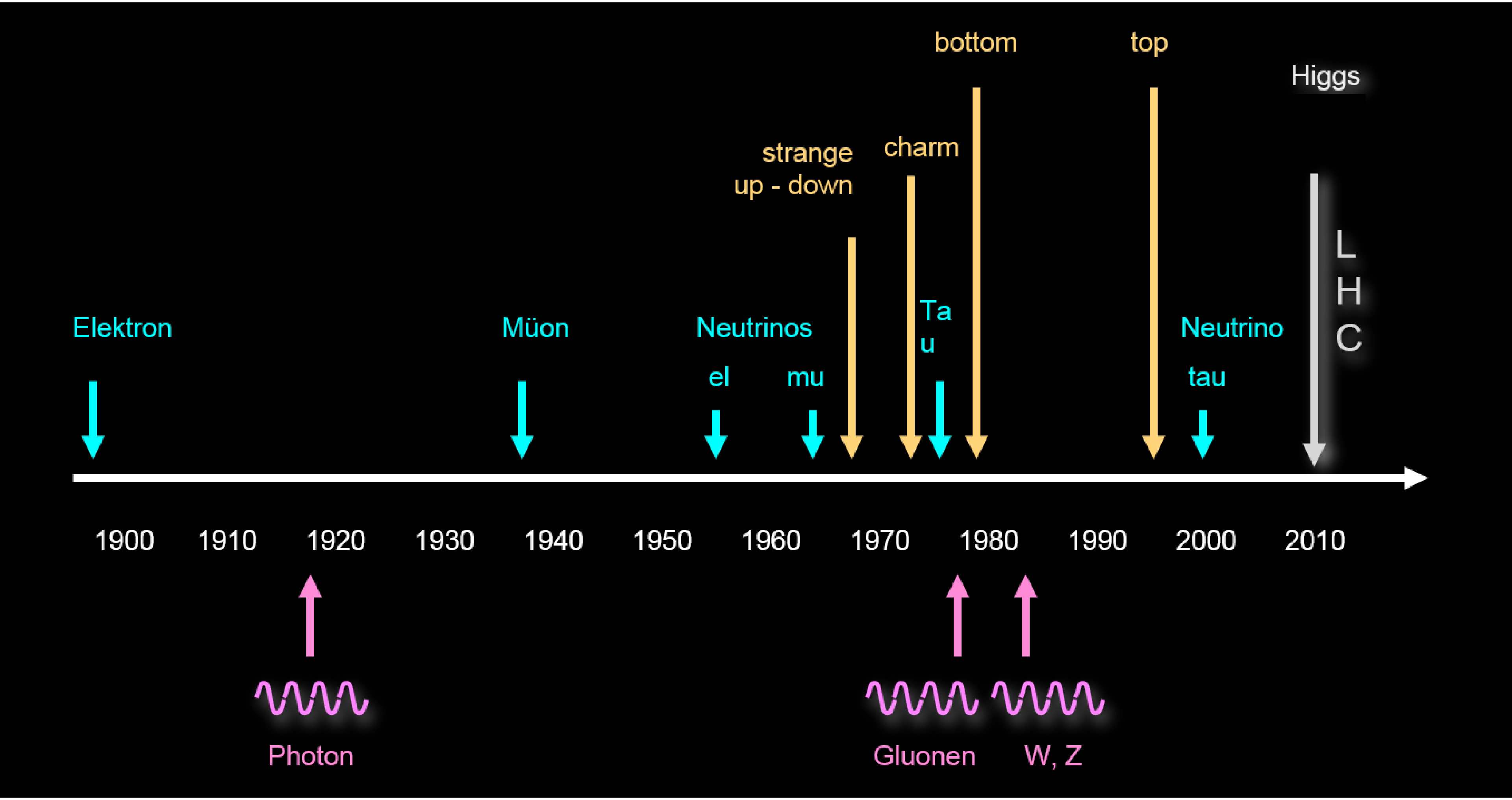
Luminosity L [cm^{-2} s^{-1}]

Property of the accelerator

Cross section $\sigma(E)$

Property of the physics process

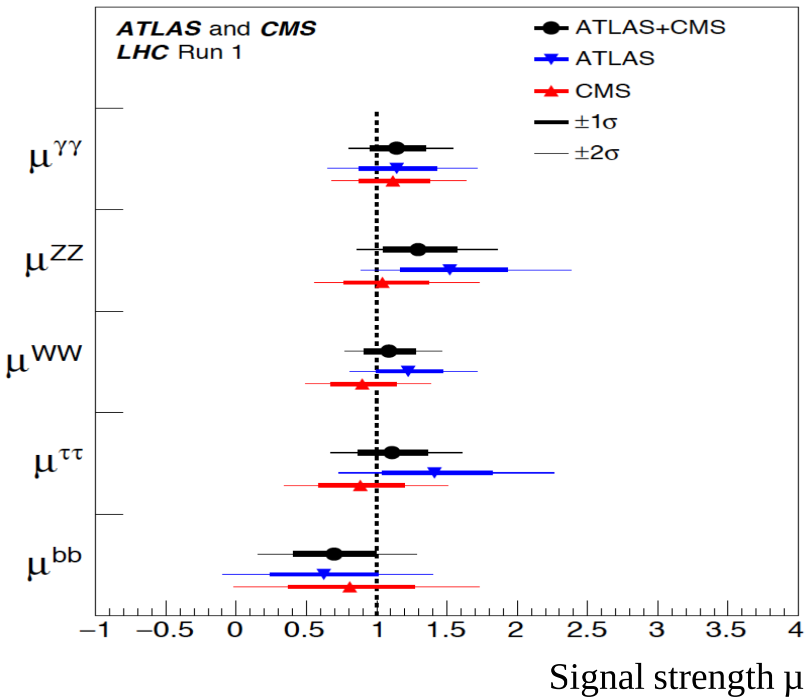
Discovery of Standard Model constituents

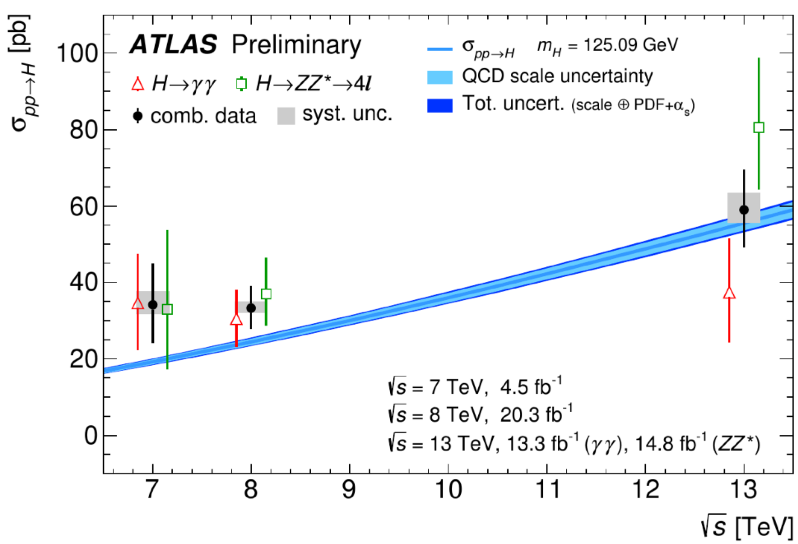


➔ The Standard Model is complete !

➔ But have we understood everything ?

Is this "THE" Standard Model Higgs ?

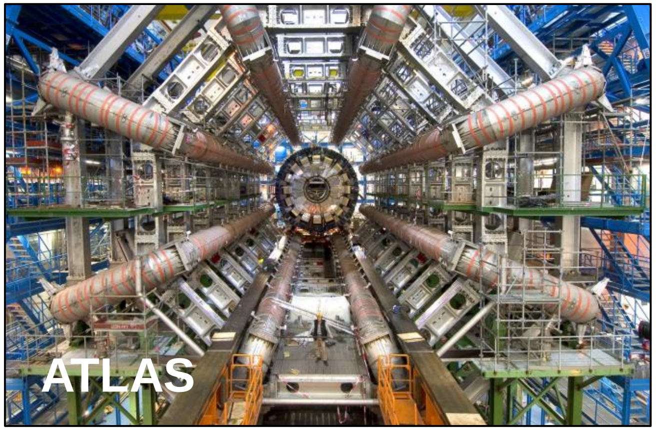


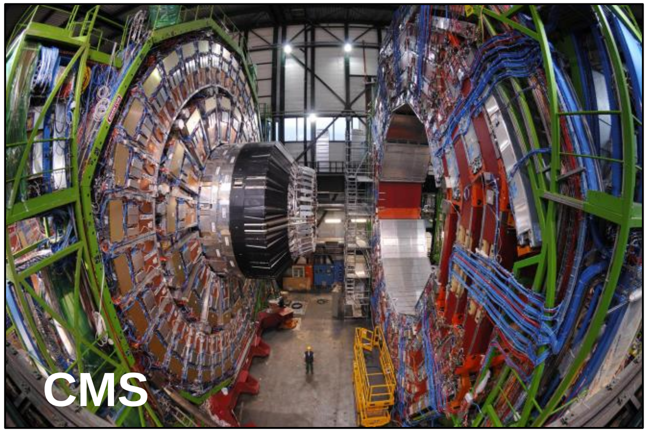


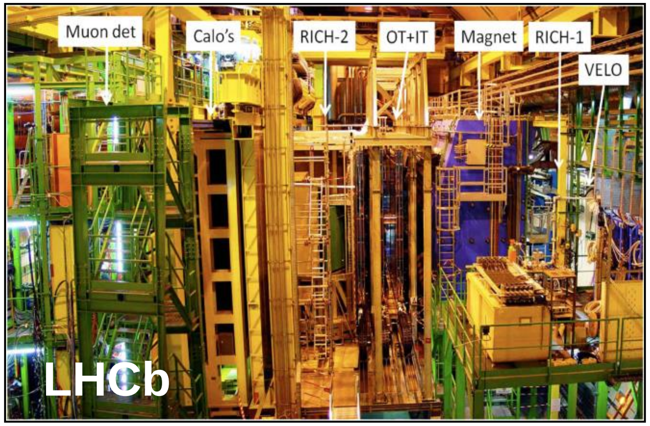
- ✓ **Higgs because:** measured $H \to ZZ \to \ell\ell\ell\ell$, $H \to \gamma\gamma$, $H \to WW \to \ell\nu\ell\nu$ and also less sensitive modes like e.g. $H \to \tau\tau$, etc.
- ✓ **Overall significance of production ~10σ**
- ✓ **We know it's a boson:** Because it decays to two photons
- ✓ **We know it's neutral**
- ✓ We know it has **approximately the right level of σ** x **Br** for all channels studied
- ✓ **It couples to bosons and to fermions** at approximately the right coupling strengths
- ✓ **We have tested various spin hypotheses**: 0^+, 0^-, 1^+, 1^-, 2^+ **0^+ is favoured in all pair-wise comparisons**

→ it really looks like "THE" SM Higgs!

Detector Optimization

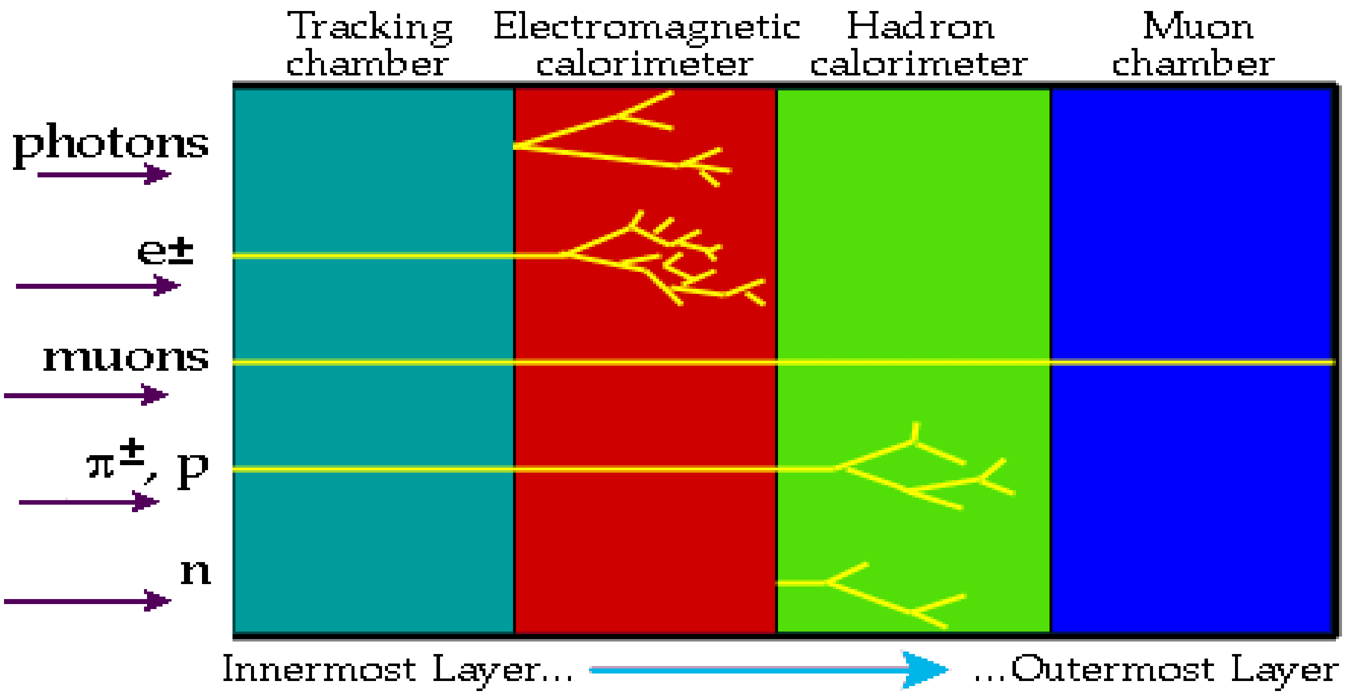






- Which kind of "particle" we have to detect?
- Which "property" of the particle we have to know?
  - ✓ position
  - ✓ charge
  - ✓ energy or momentum
  - ✓ mass
  - ✓ lifetime
- What is the required resolution?
- What is the required dimension of the detector?
- What is the maximum count rate?
- …

Particle detection and identification



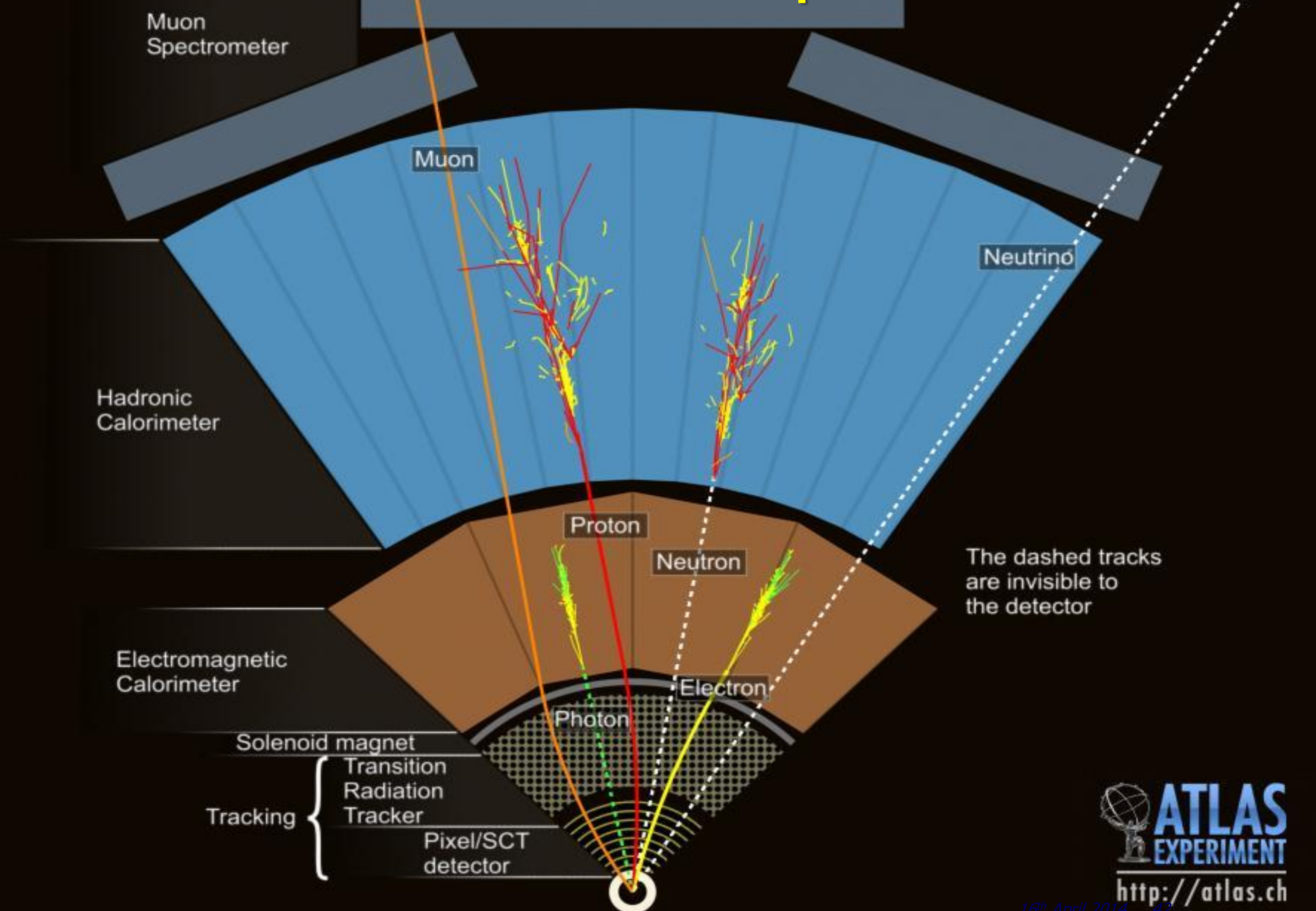
B field & low density

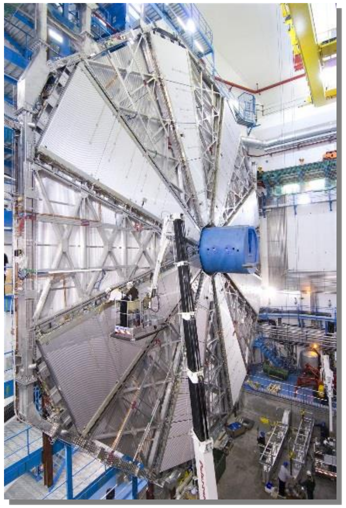
high radiation length (X_0)

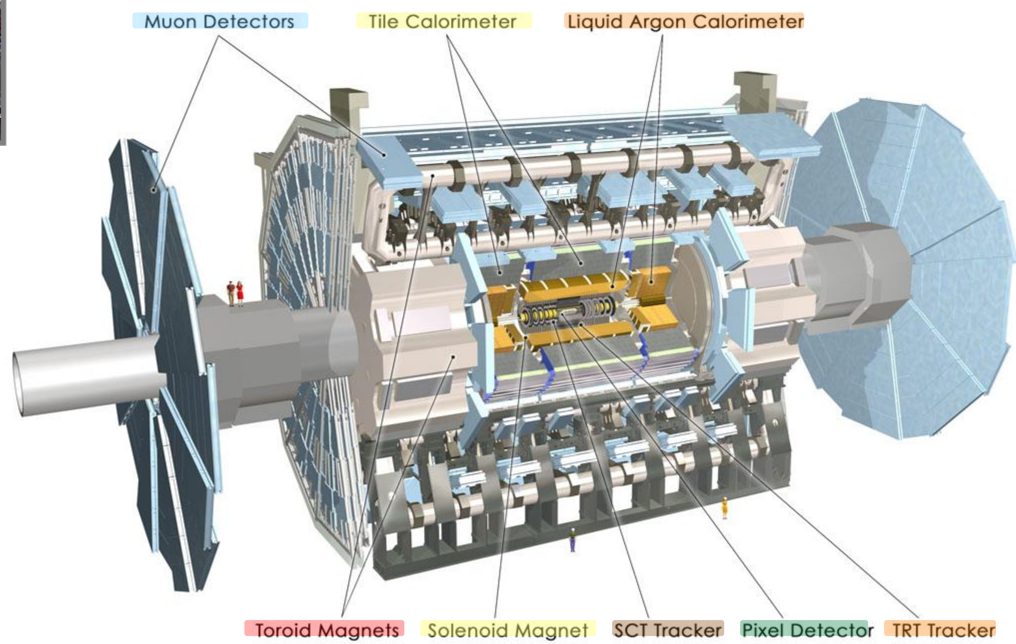
high interaction length (λ)

- charged particles leave **tracks** due to ionization
- electrons and photons create an **electromagnetic showers** in dense material
- charged and neutral hadrons create **hadronic showers** in dense material
- neutrinos interact only weakly and therefore do not leave **any signature**

How ATLAS detects particles

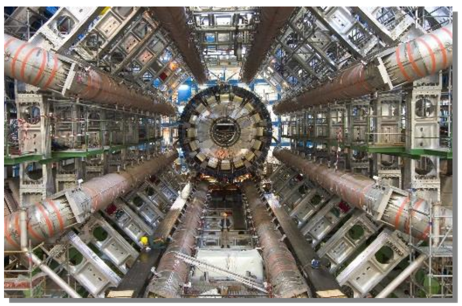


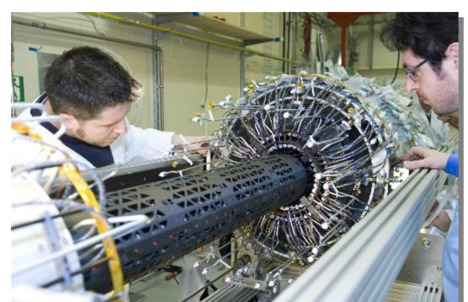


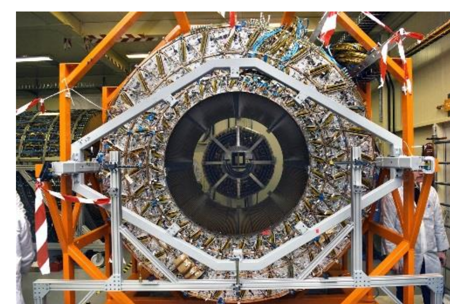


Muon Detectors
Tile Calorimeter
Liquid Argon Calorimeter
Toroid Magnets
Solenoid Magnet
SCT Tracker
Pixel Detector
TRT Tracker

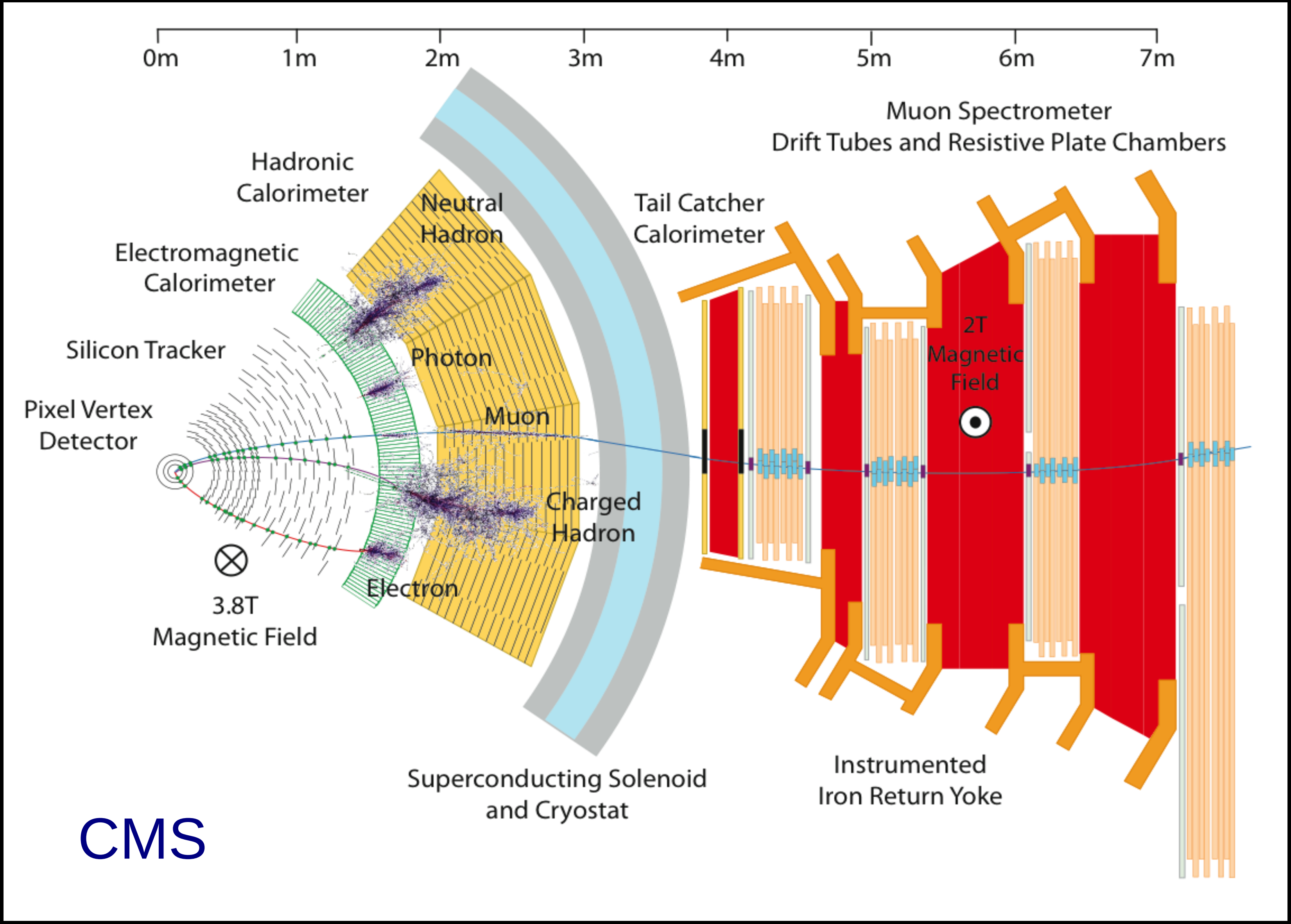
ATLAS







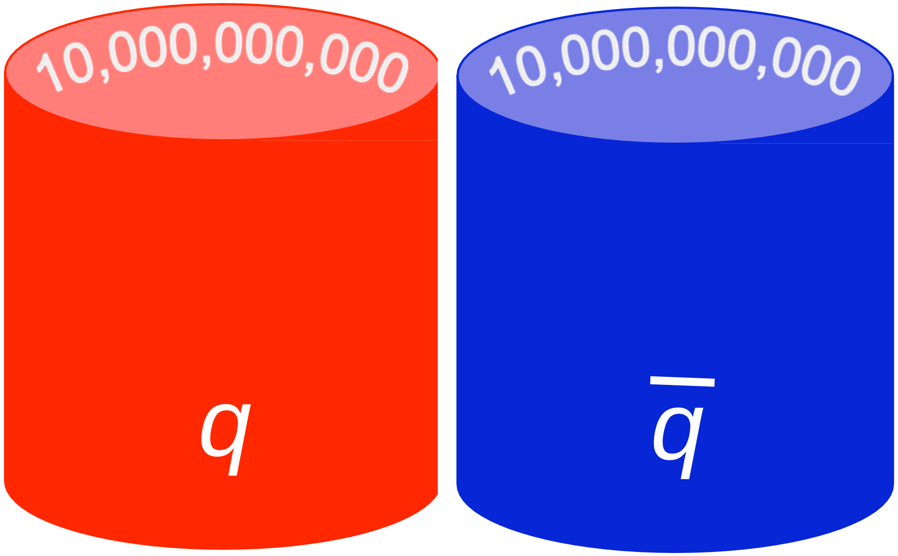
How CMS detects particles



Antimatter & the Big Bang

Big Bang:

- Create equal amounts of matter & antimatter



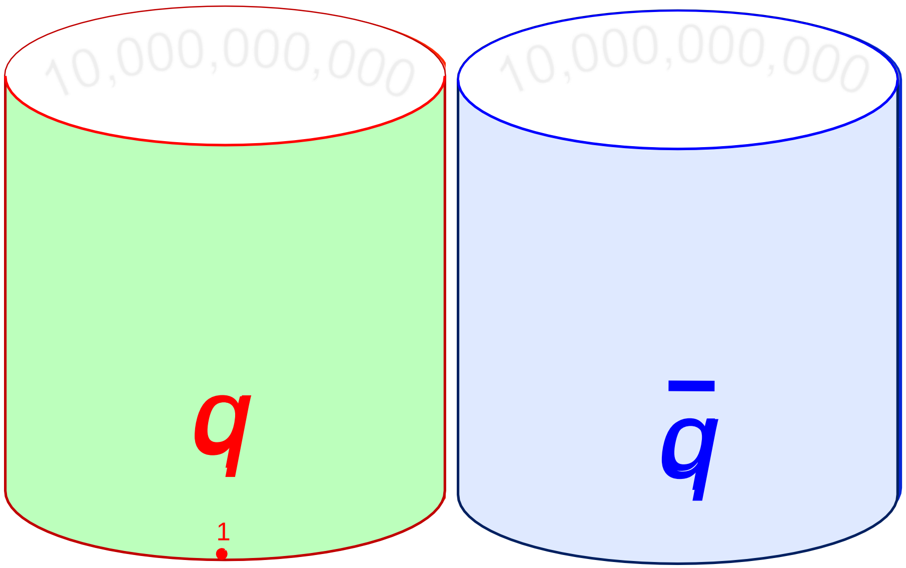
Early universe

Antimatter & the Big Bang

Big Bang:

- Create equal amounts of matter & antimatter
- Somewhere along the way, one (matter) is favored
- Final result: a bit of matter and *lots* of photons

$N_{\text{baryons}} / N_{\text{photons}} \cong 10^{-10}$



Current universe

matter-antimatter asymmetry → *CP* is a broken symmetry !