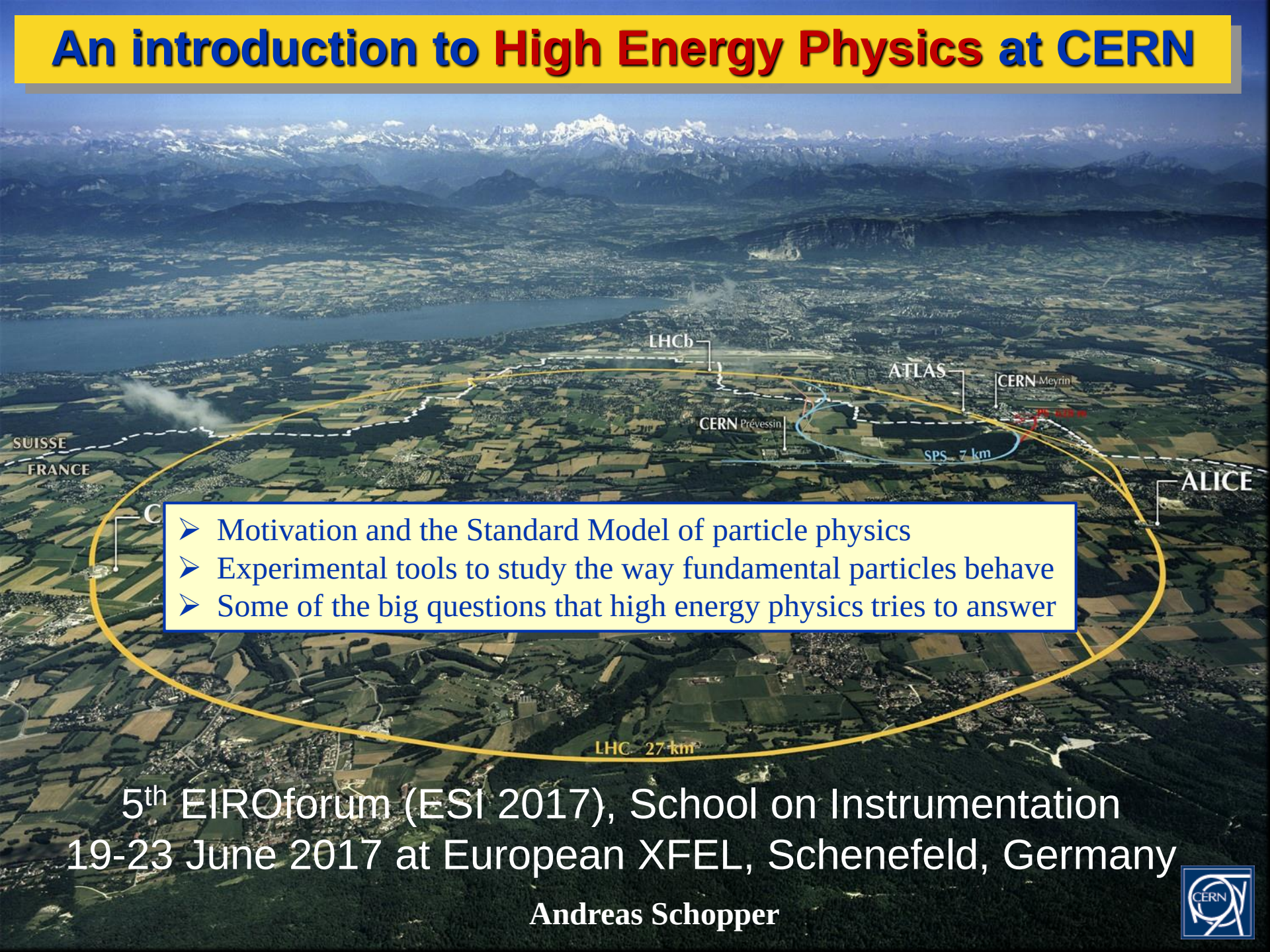
An introduction to High Energy Physics at CERN



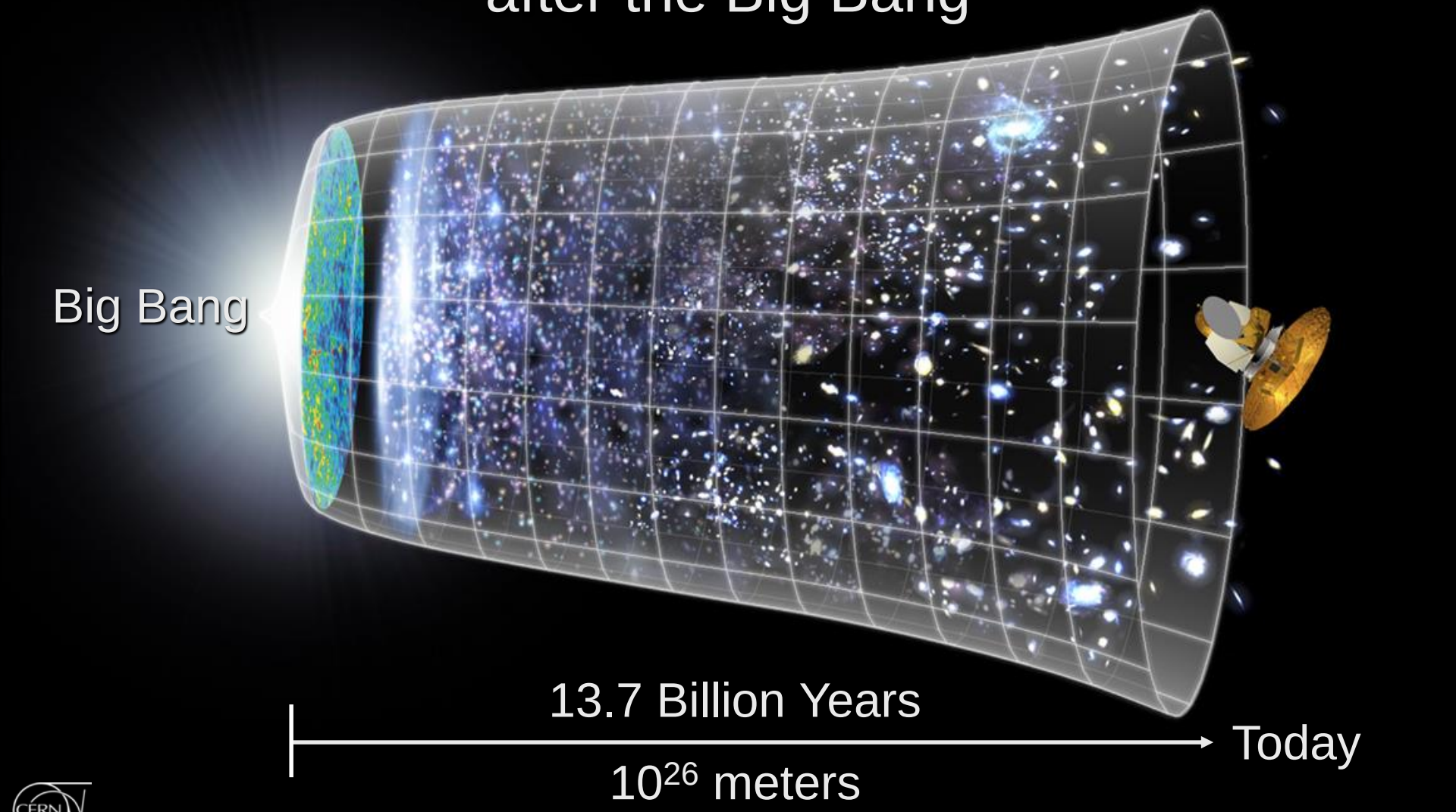
- Motivation and the Standard Model of particle physics
- Experimental tools to study the way fundamental particles behave
- Some of the big questions that high energy physics tries to answer

5th EIROforum (ESI 2017), School on Instrumentation
19-23 June 2017 at European XFEL, Schenefeld, Germany

Andreas Schopper

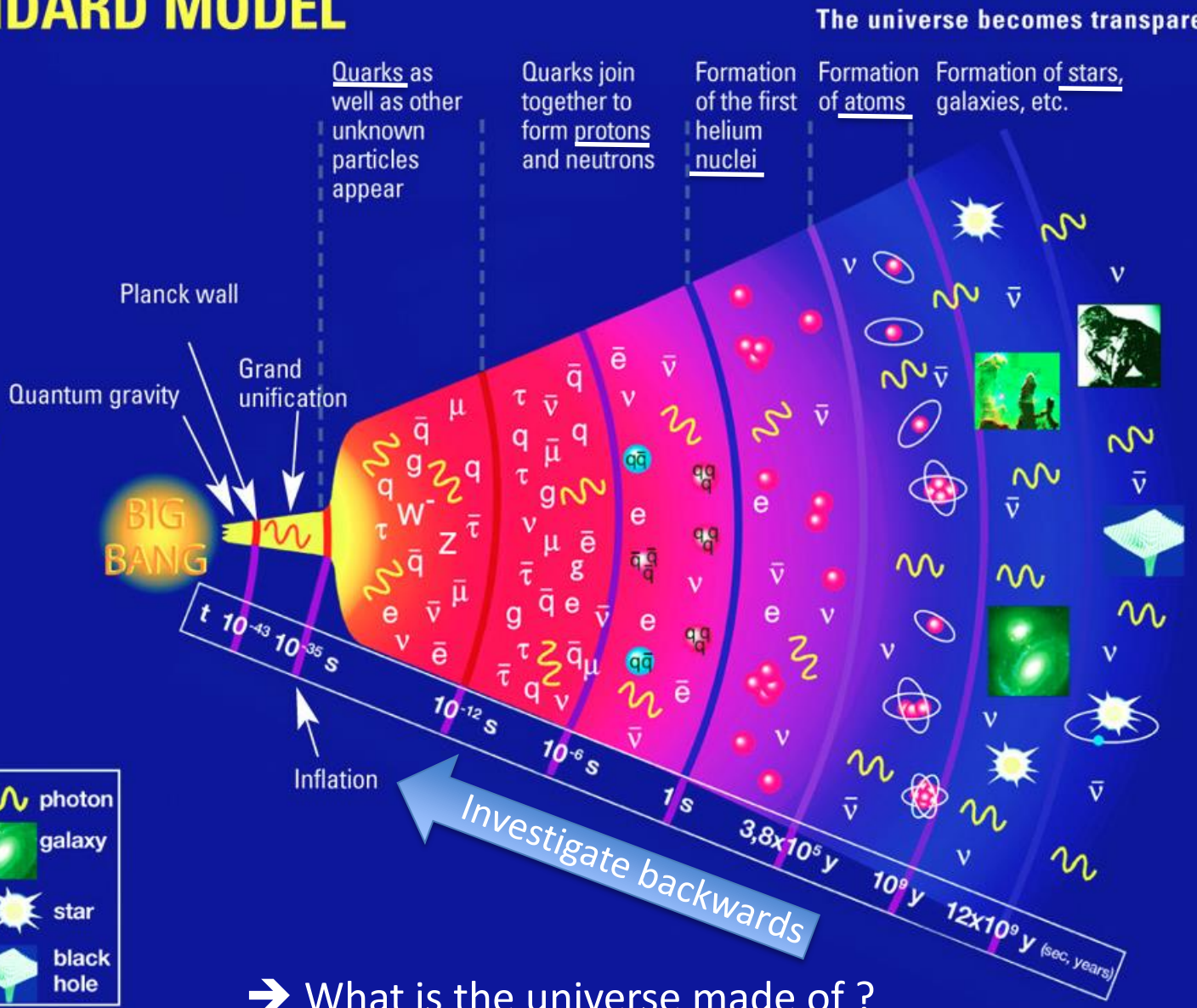
Contribute to the Scientific Challenge

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



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.



Captions

- q quark
- g gluon
- e electron
- μ muon τ tau
- ν neutrino
- W, Z bosons
- qq̄ meson
- qqq baryons
- ions
- atom
- photon
- galaxy
- star
- black hole

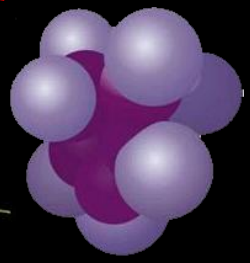
➔ What is the universe made of ?

young, hot, energetic → old, cool, less energetic

© Particle Data Group, LBNL 2008

What is matter made from?

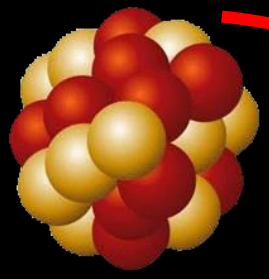
~meters
matter



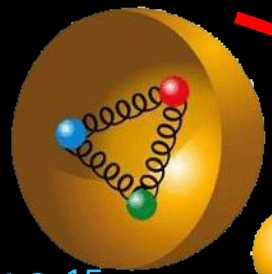
10^{-9} m
molecules

10^{-10} m
one atom
is made from electrons around a nucleus

the nucleus is made from
protons and neutrons



10^{-14} m



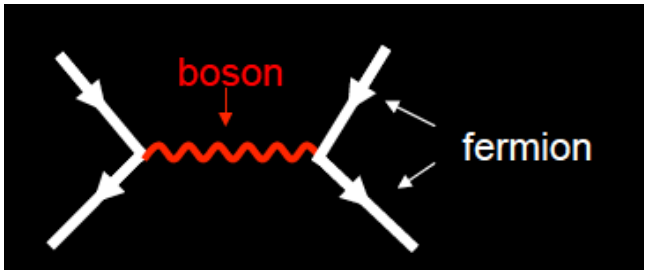
10^{-15} m
protons and neutrons
contain quarks

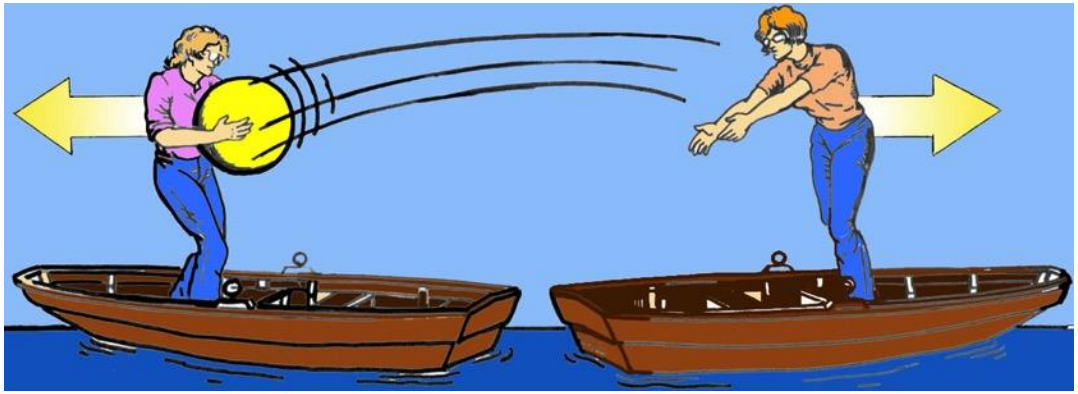
$<10^{-18}$ m
quarks, electrons
• (= fermions)

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

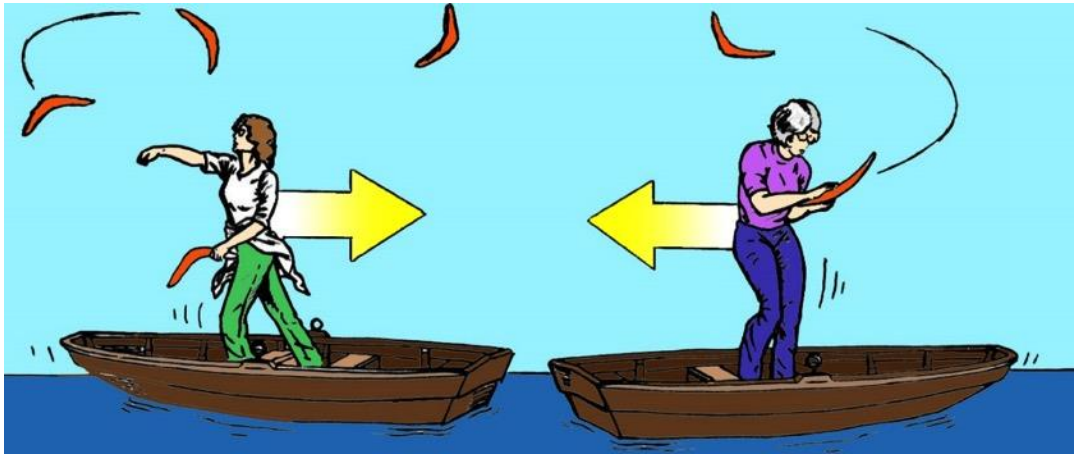
The Fundamental Forces

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





- repulsive

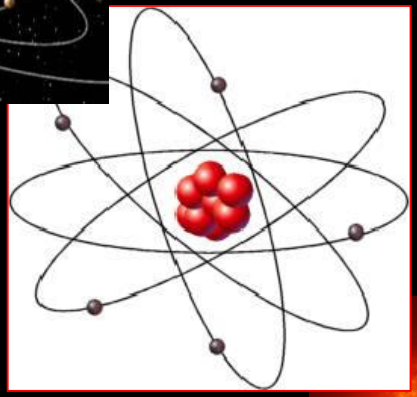


- attractive

The Fundamental Forces

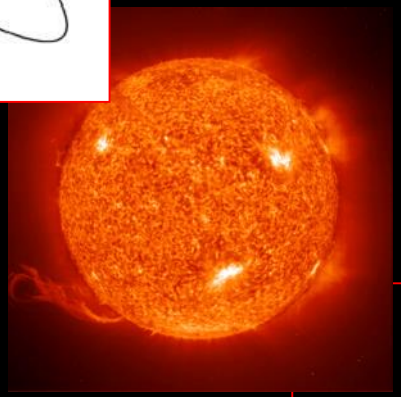
Gravity

Graviton ?



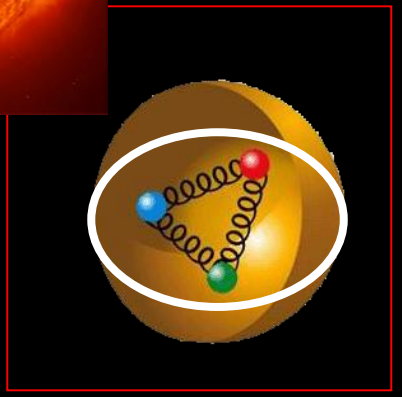
Electromagnetic Force

Photon



Weak Force

W, Z

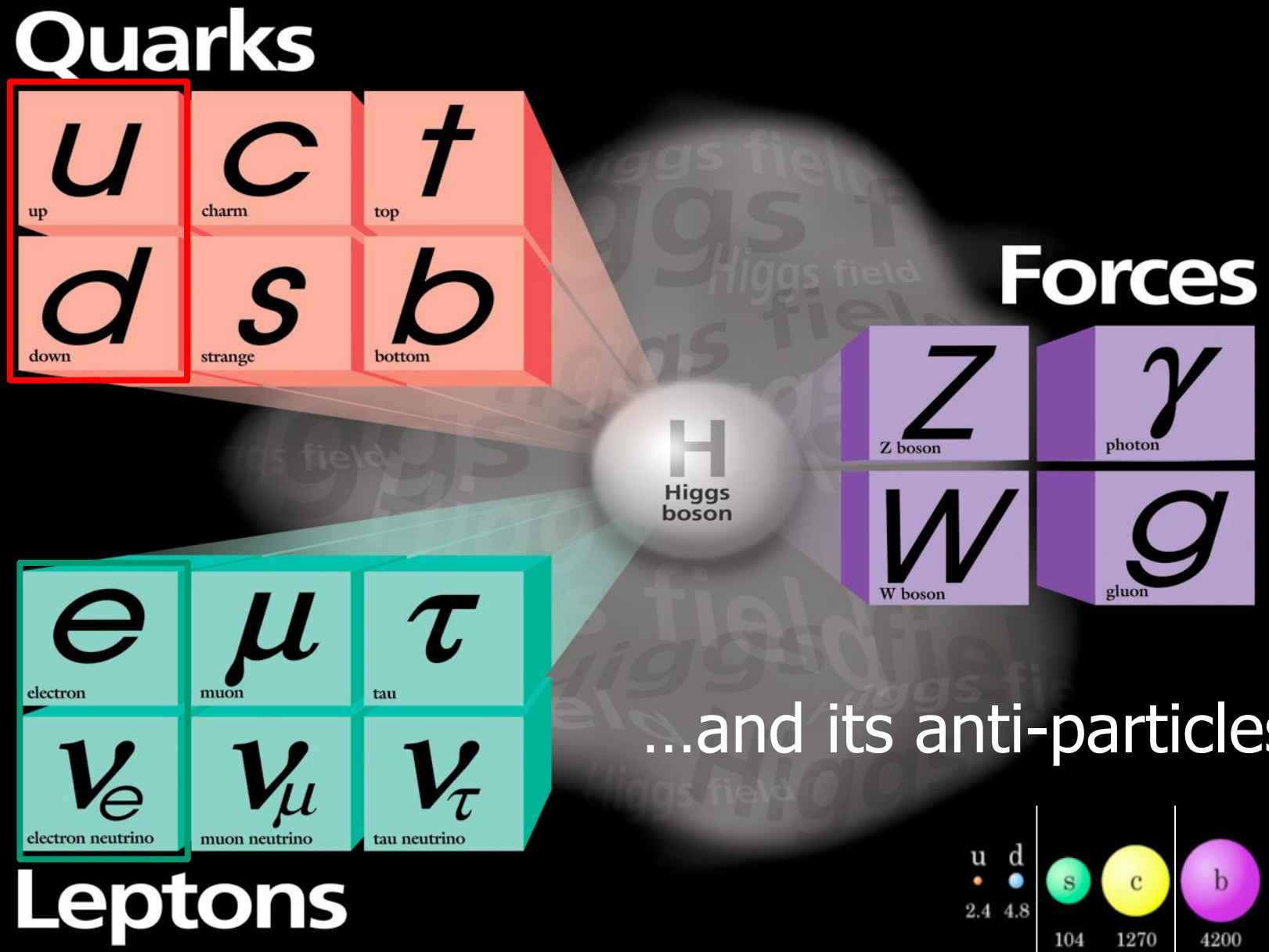


Strong Force

Gluon

the forces act through their associated particles

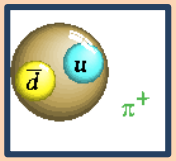
The Standard Model of Particle Physics

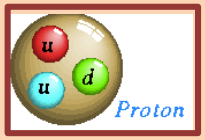


$SU(3)_C \times SU(2)_L \times U(1)_Y$

Building the "zoo" of elementary particles

quarks





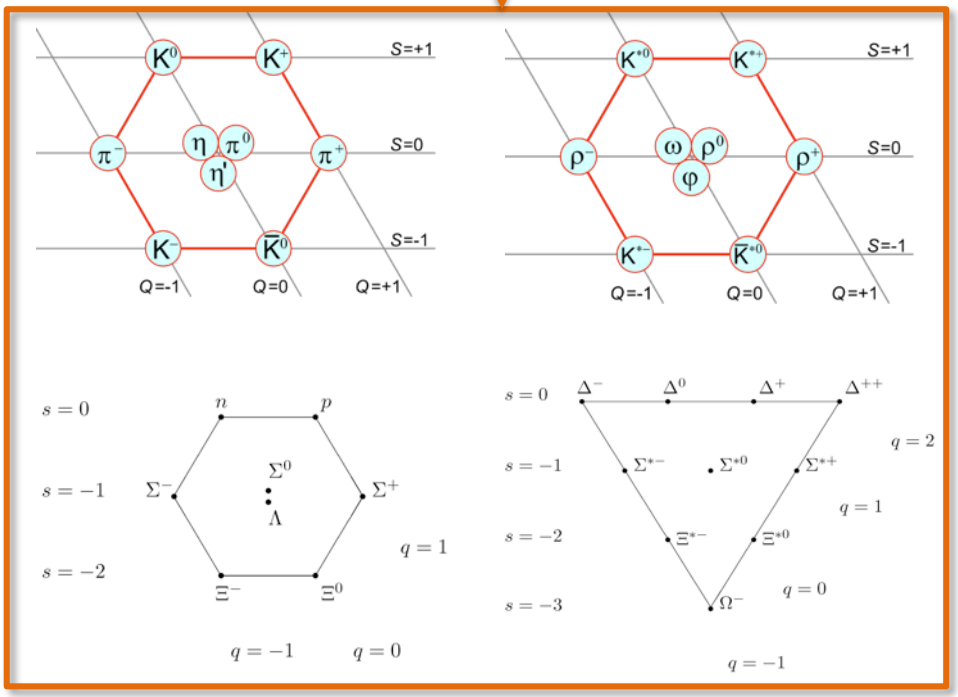
hadrons

mesons (1 quark and 1 antiquark) → $\pi^{\pm}$, $K^{\pm}$, J/ψ, etc.

baryons (3 quarks or 3 antiquarks) → p, n, Σ^+, Δ^0, etc.

leptons → electron, muon, tau and neutrinos

bosons → gluon, photon, Z boson, W boson



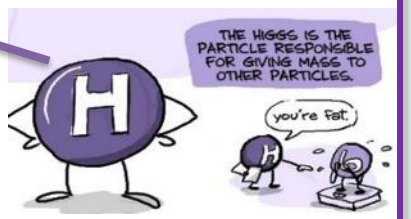
BOSONS

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

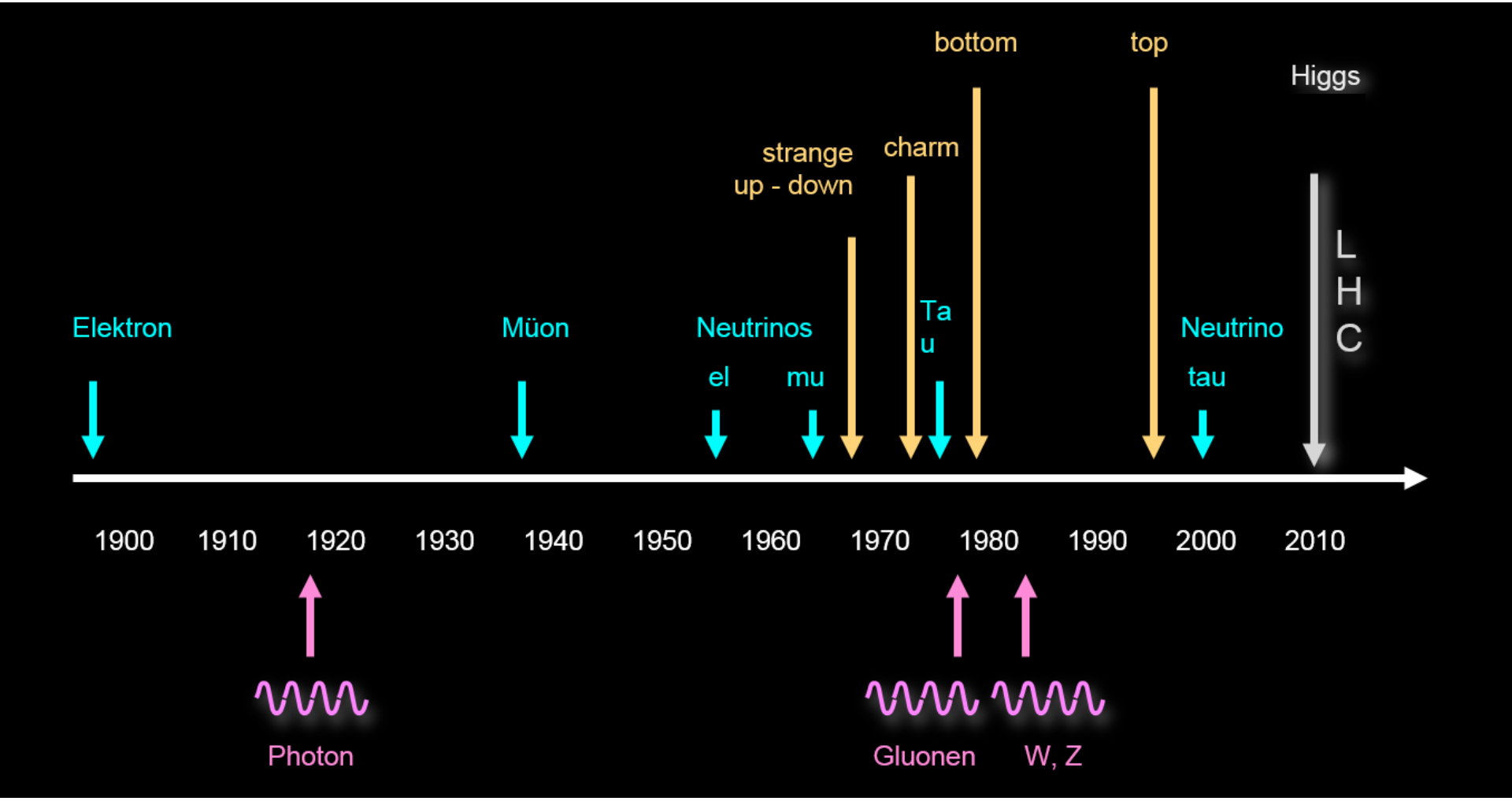
Unified Electroweak spin = 1		
Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	−1
W^+	80.4	+1
Z^0	91.187	0

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

Massive bosons require a new potential in the Standard Model!



Discovery of Standard Model constituents



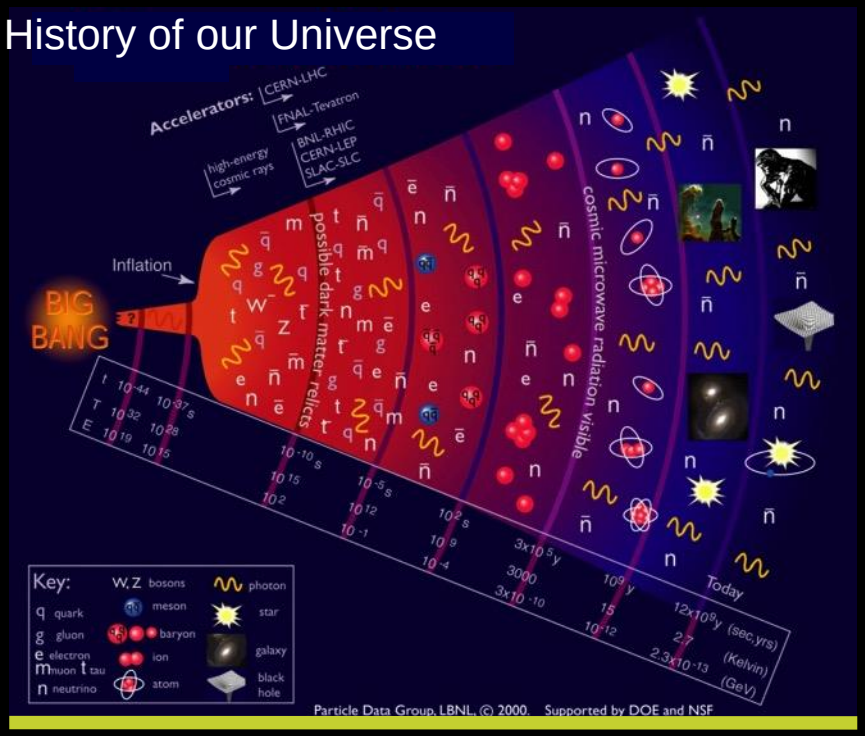
➔ The Standard Model is complete !

➔ But have we understood everything ?

More Questions ....

BIG BANG

The same amount of matter & antimatter was created



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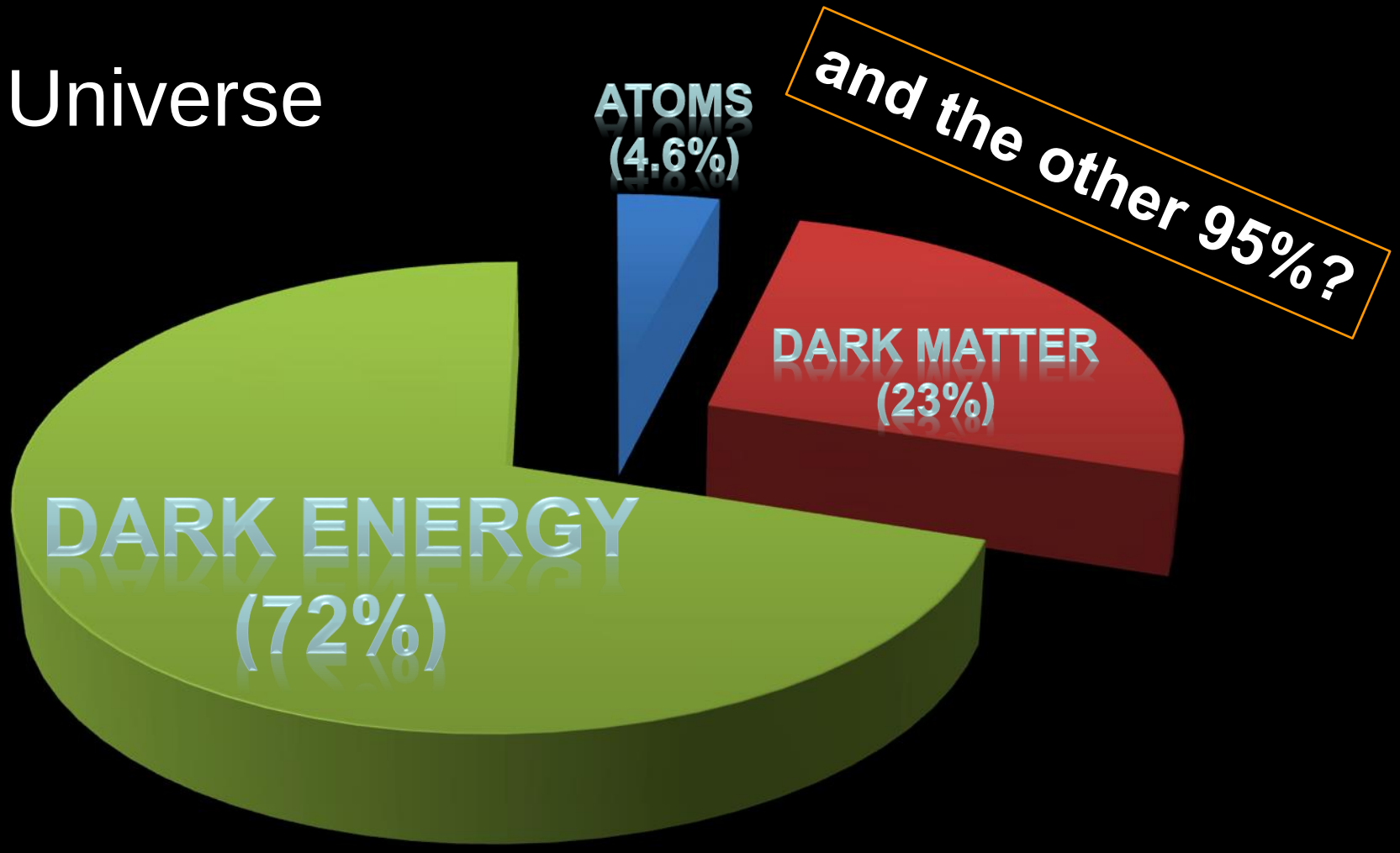
Only matter (us) survives

NOW

Why?

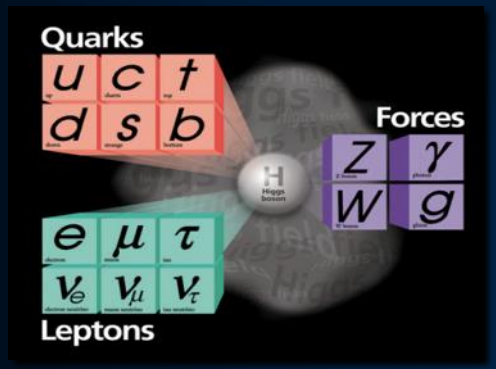
More Questions ....

Our Universe



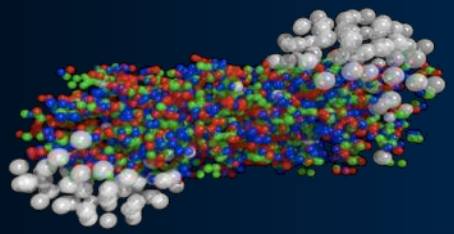
Leaving this stuff for the cosmologists

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?

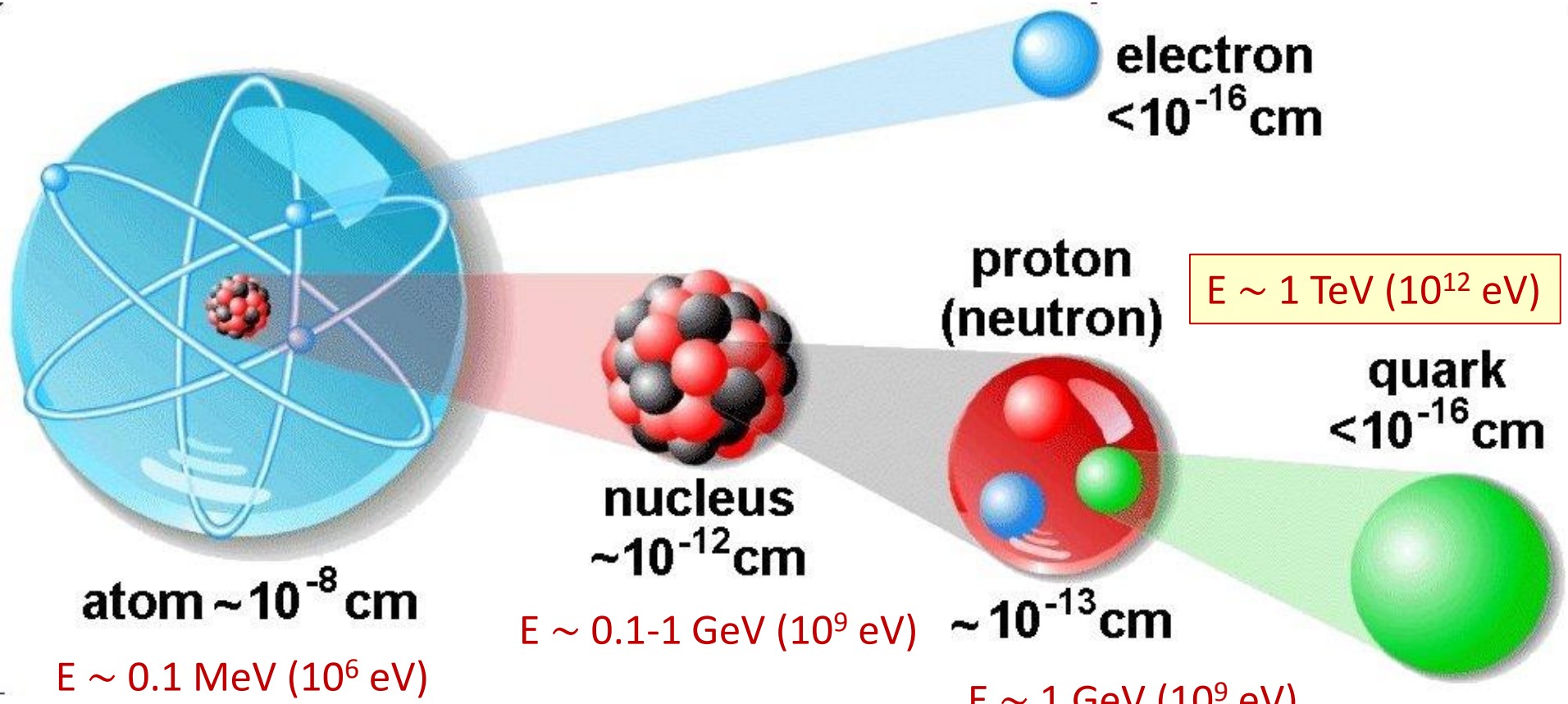
Will we find the particle(s) that make up the mysterious ‘dark matter’ in our Universe?

How do we explore such small scales?

- All visible macroscopic objects of our universe consist of only 3 fundamental particles → up-quark, down-quark & electron !
- How can we study these and the other heavier quarks, leptons & bosons ?

How do we explore such small scales?

Need high energies to probe small distances: **E = hc/λ**



E ~ 1 TeV (10^{12} eV)

E ~ 0.1-1 GeV (10^{9} eV)

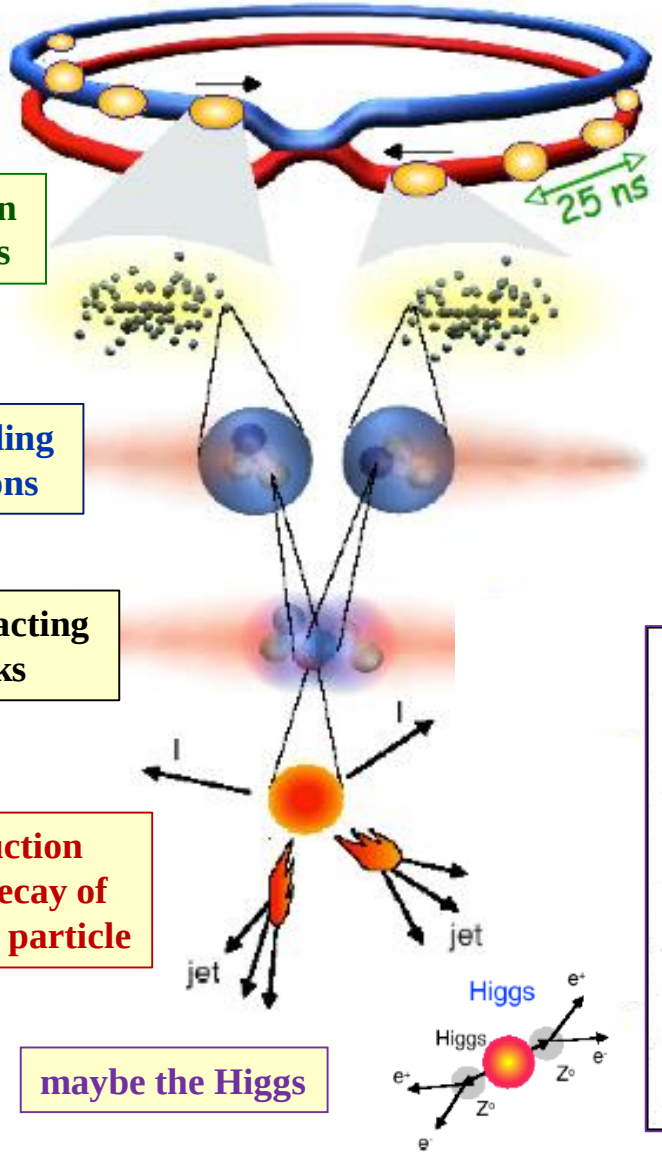
E ~ 0.1 MeV (10^{6} eV)

E ~ 1 GeV (10^{9} eV)

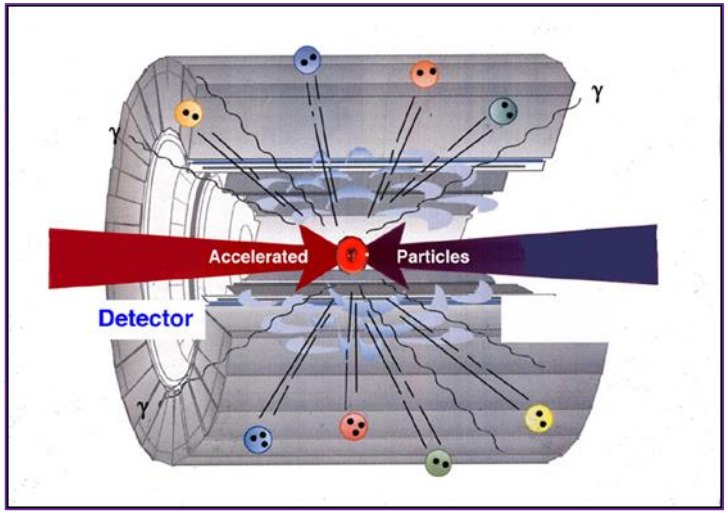
13 TeV LHC

How do we explore such small scales?

The super-microscope



- we accelerate two beams of particles (e.g. protons) close to the speed of light and make them collide
- the colliding protons "break" into their fundamental constituents (i.e. quarks)
- these constituents interact at high energy
- (new) heavy particles can be produced in the collision ($E=mc^2$). The higher the accelerator energy, the heavier the produced particles can be. These particles then decay into lighter (known) particles: electrons, photons, etc.



- collision products detected by high-tech detectors surrounding the collision point

Requirements to such a super-microscope

- ✓ create (new) massive particles → high colliding energy ($E=mc^2$)
- ✓ detect rare particle decays → high intensity beams and fast-readout detectors
- ✓ 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!

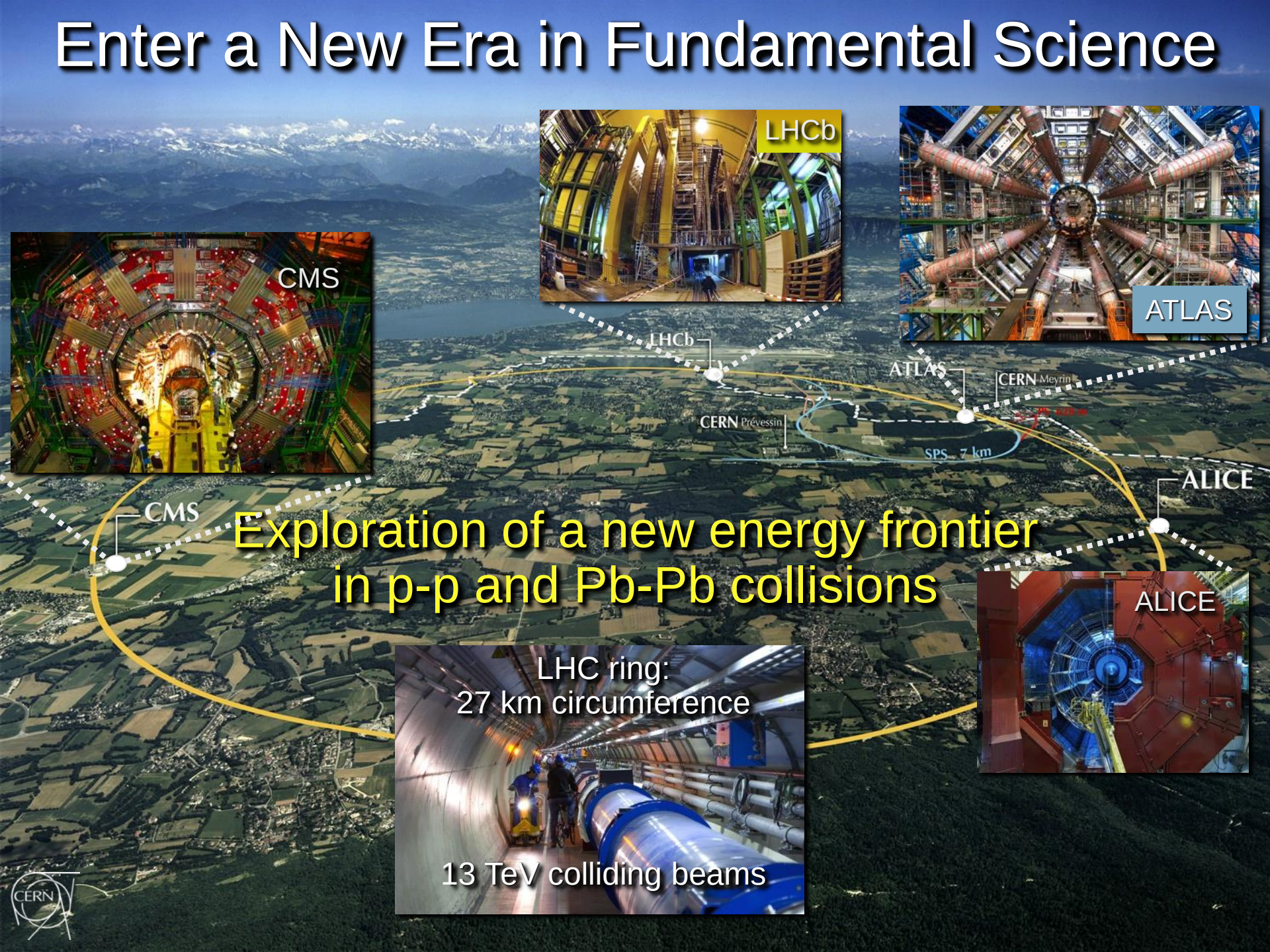
Needs VERY high

- ✓ precision
- ✓ statistics
- ✓ selectivity
- ✓ background suppression

Note:

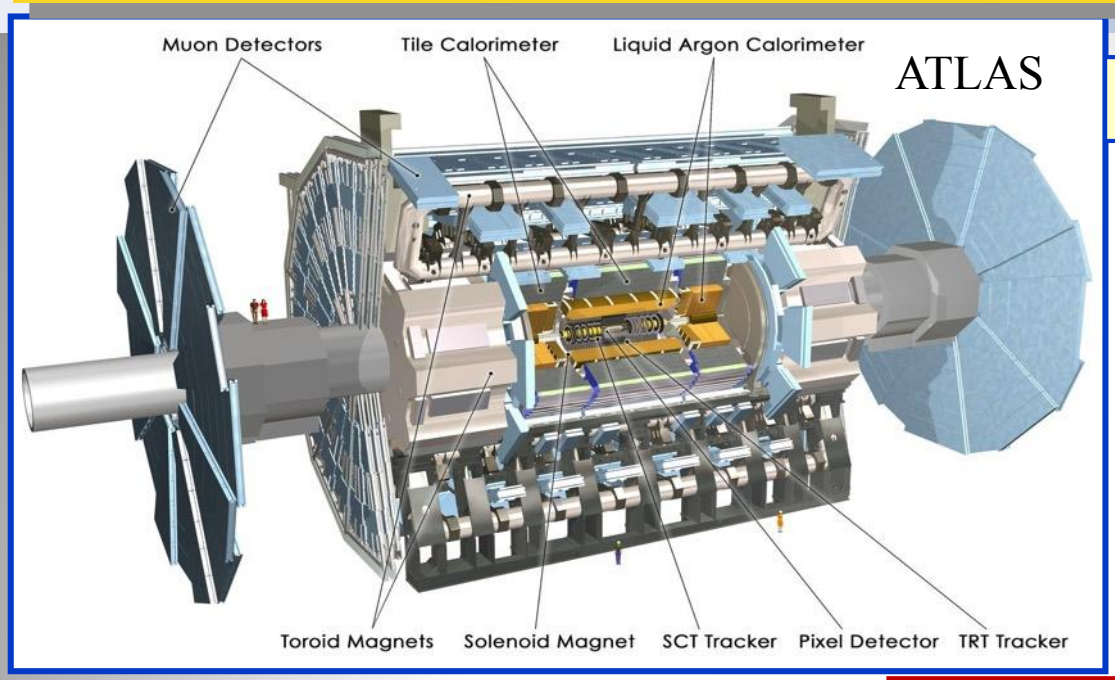
- ➢ the world population is ~$7.5 \cdot 10^9$
- ➢ typical very rare decay $B(B_s \rightarrow \mu\mu) = (3.65 \pm 0.23) \times 10^{-9}$

Enter a New Era in Fundamental Science



Exploration of a new energy frontier
in p-p and Pb-Pb collisions

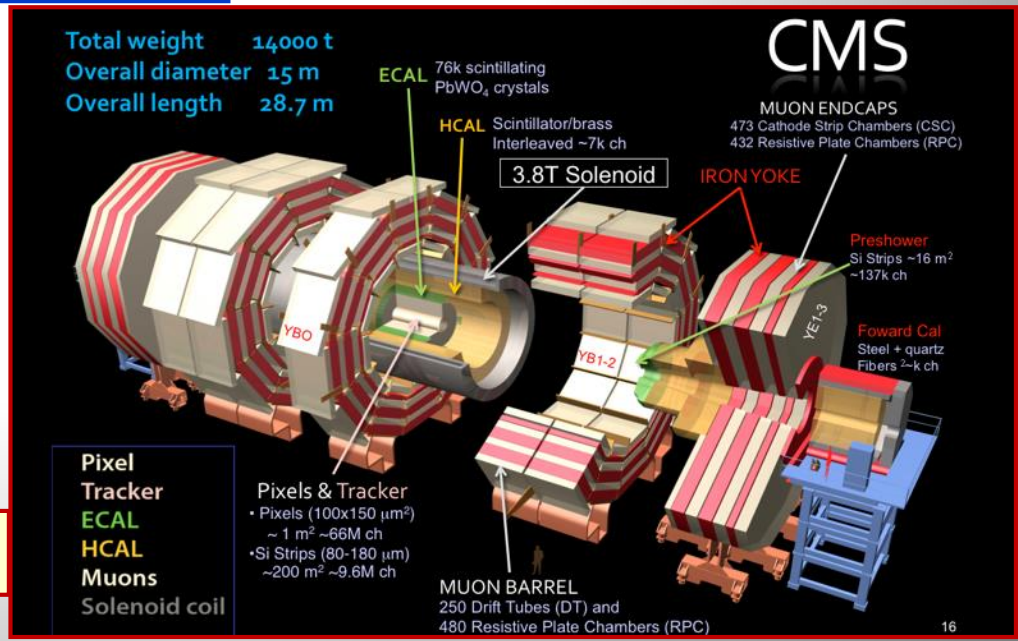
General Purpose Detectors (GPD): The Higgs Hunters



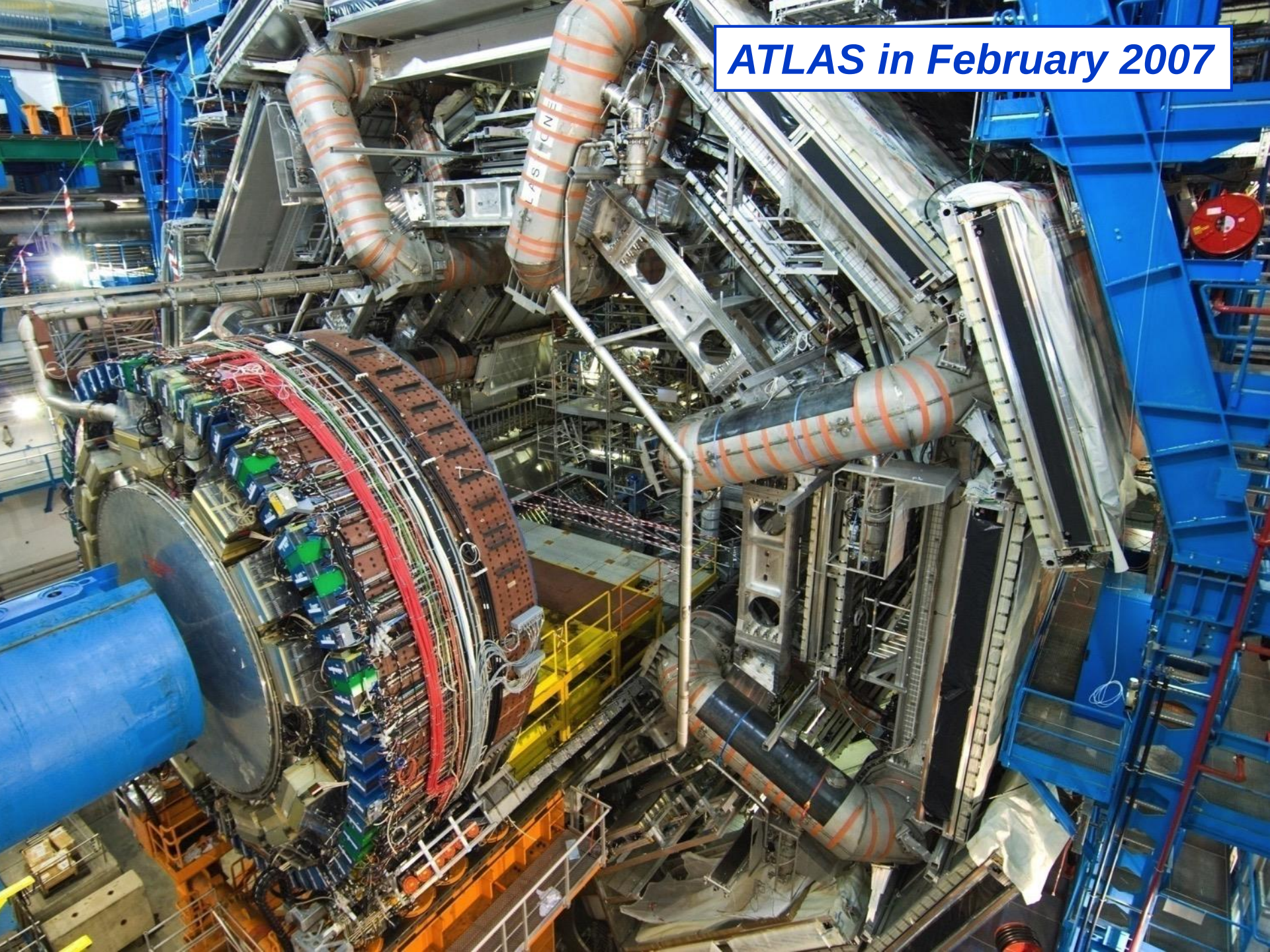
The ATLAS experiment

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

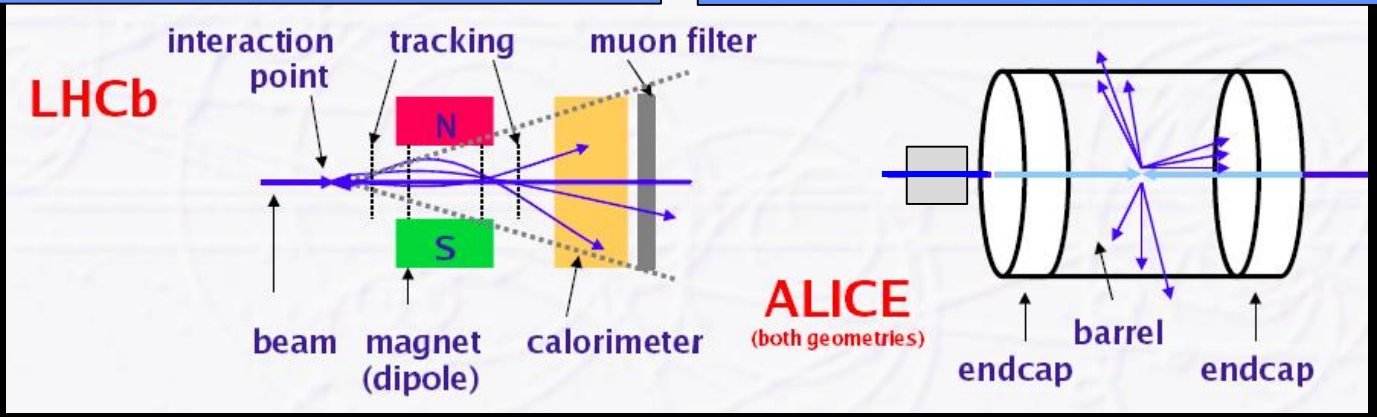

ATLAS in February 2007

CMS before closure 2008
ME-1/1/06
ME-1/1/05
HE-RBX 03
ME-1/1/04
HE-RBX 02
ME-1/1/03
ME-1/1/02
HE-RBX 01
ME-1/1/01
ME-1/1/36
ME-1/1/35
LIFTLUX

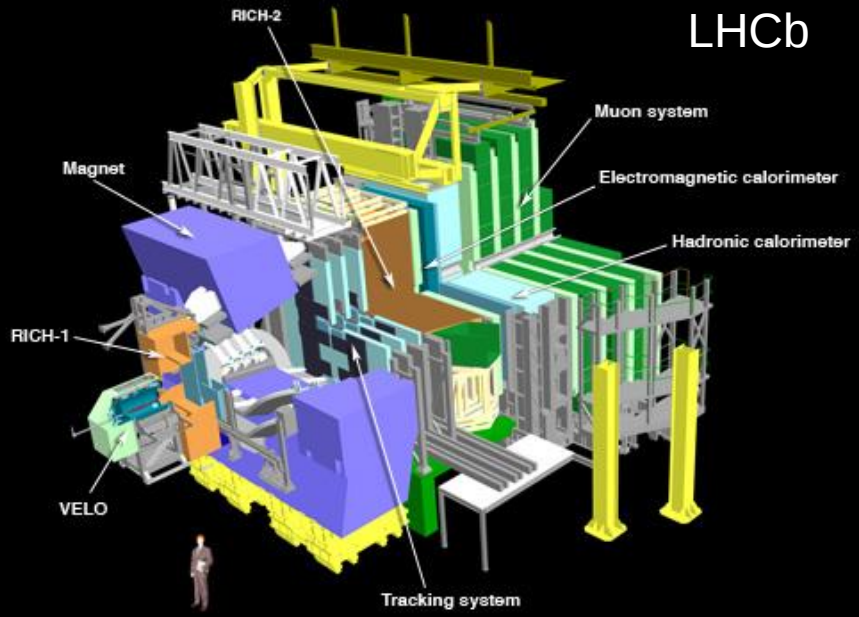
Specialized Detectors: Flavour Physics and Heavy Ions

Forward geometry with special particle identification to detect B meson decays

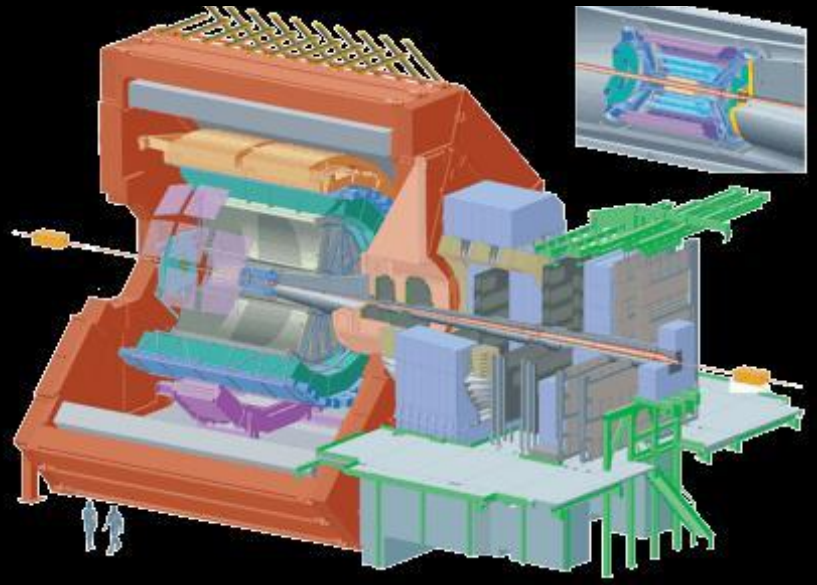
4π geometry with some forward detectors optimised for high multiplicity Pb-Pb collisions



LHCb

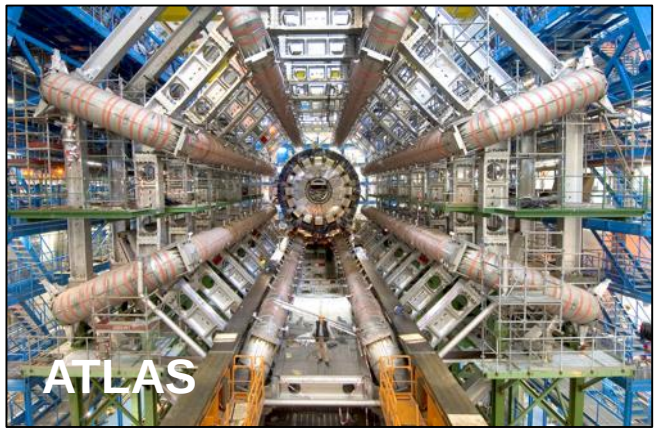


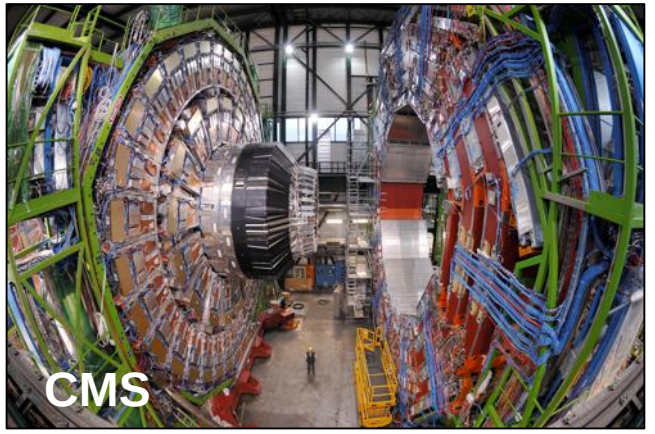
ALICE

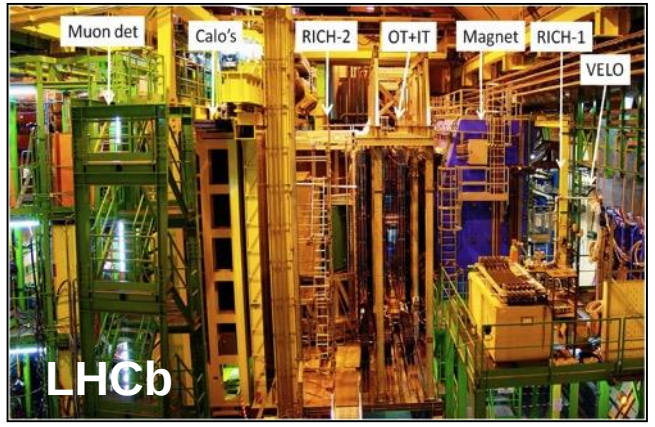


Detector Optimization

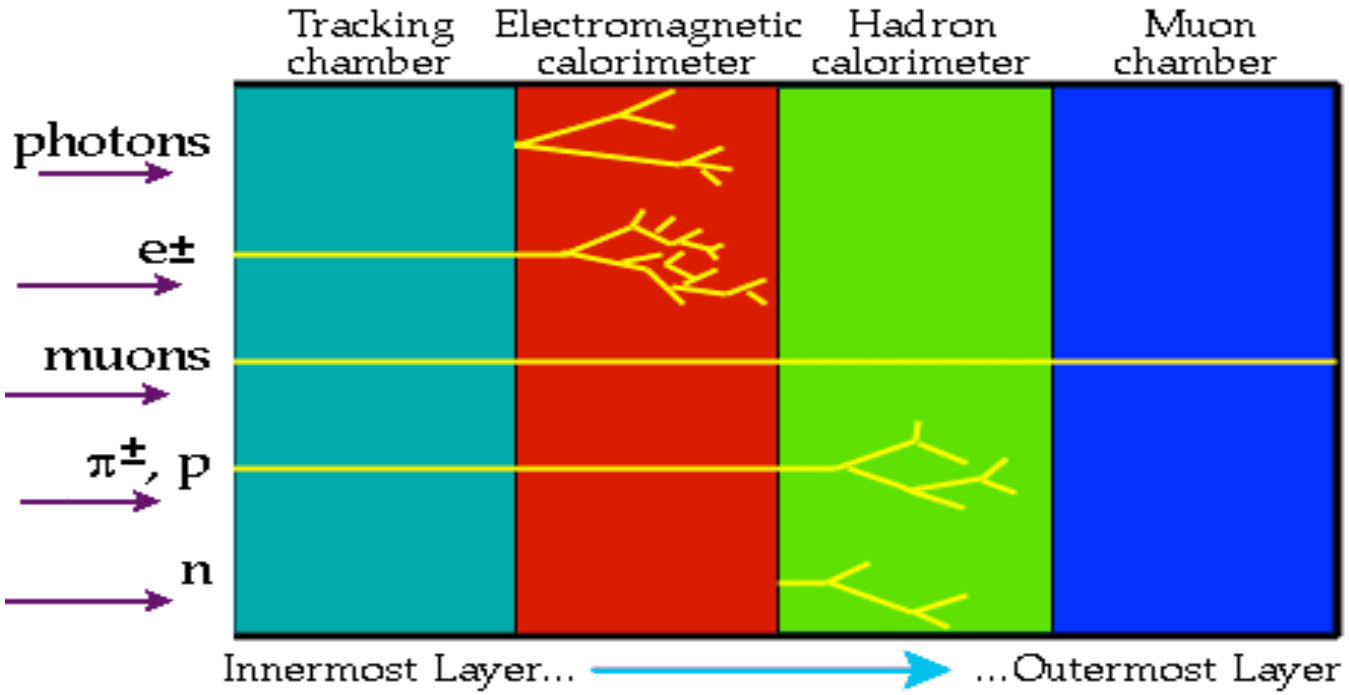
- Which kind of "particle" we have to detect?
- Which "property" of the particle we have to know?
  - ✓position
  - ✓charge
  - ✓energy or momentum
  - ✓mass
  - ✓lifetime
- What is the required resolution?
- What is the required dimension of the detector?
- What is the maximum count rate?
- …





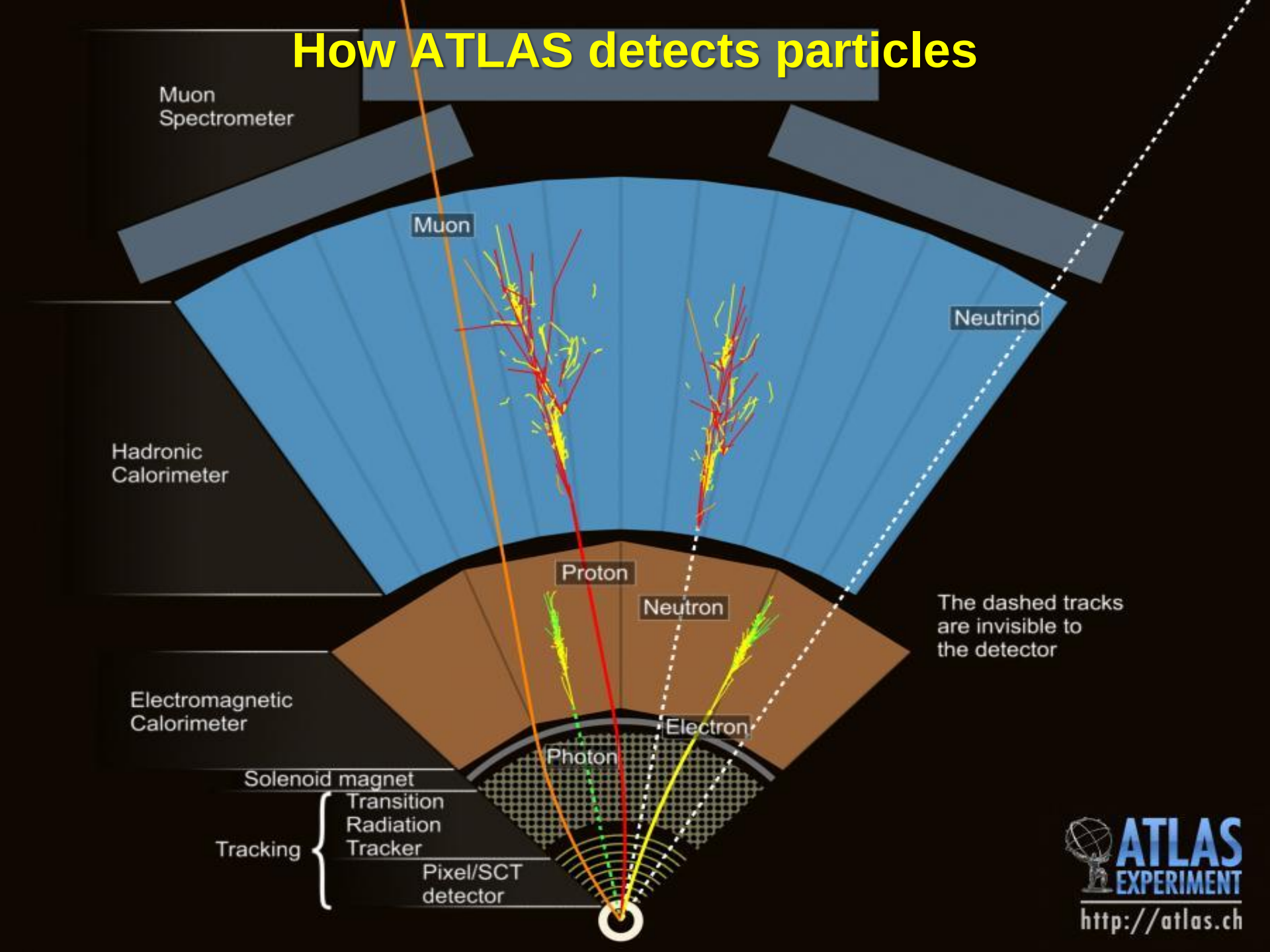


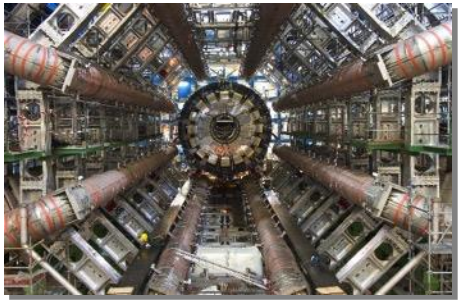
Particle detection and identification

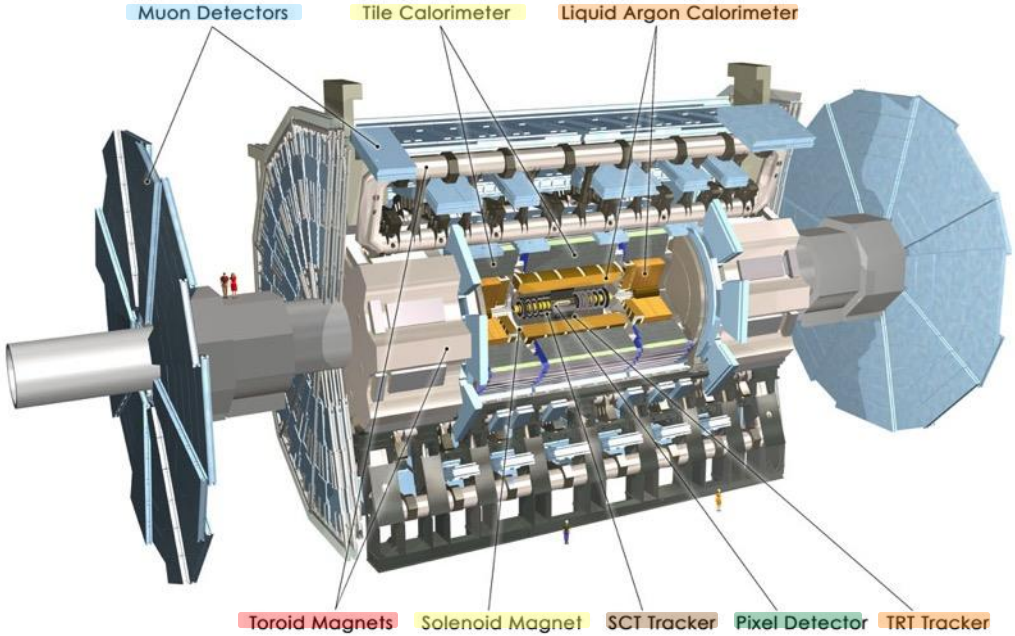


- charged particles leave **tracks** due to ionization
- electrons and photons create an **electromagnetic showers** in dense material
- charged and neutral hadrons create **hadronic showers** in dense material
- neutrinos interact only weakly and therefore do not leave **any signature**

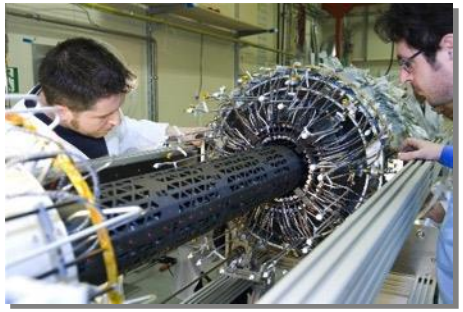
How ATLAS detects particles

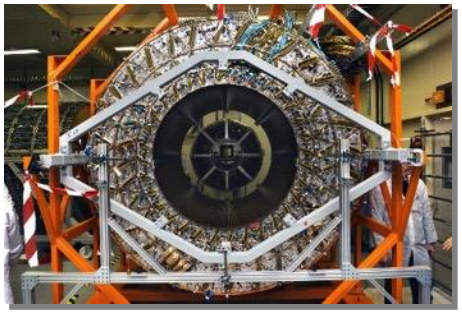




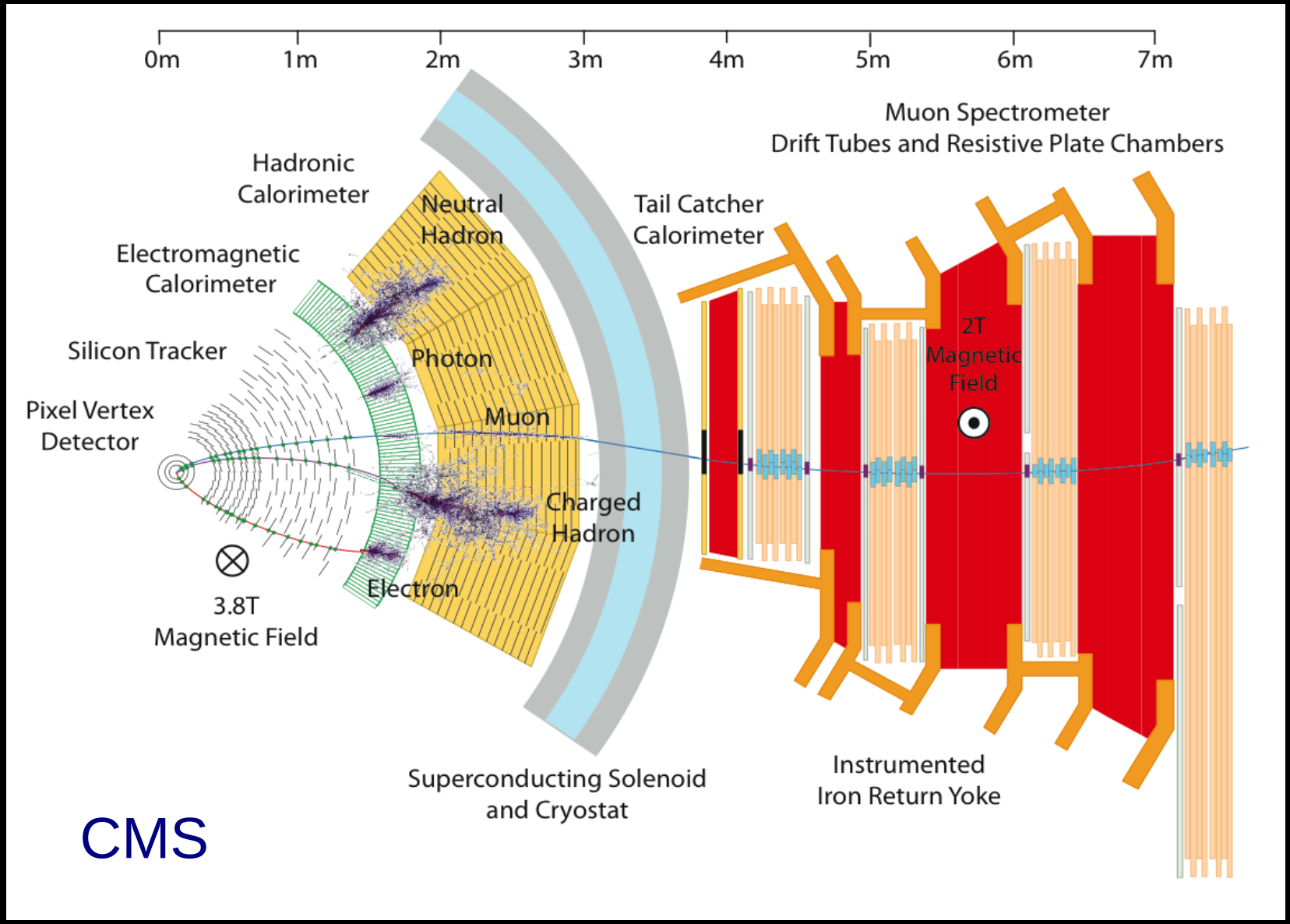

Muon Detectors
Tile Calorimeter
Liquid Argon Calorimeter
Toroid Magnets
Solenoid Magnet
SCT Tracker
Pixel Detector
TRT Tracker

ATLAS

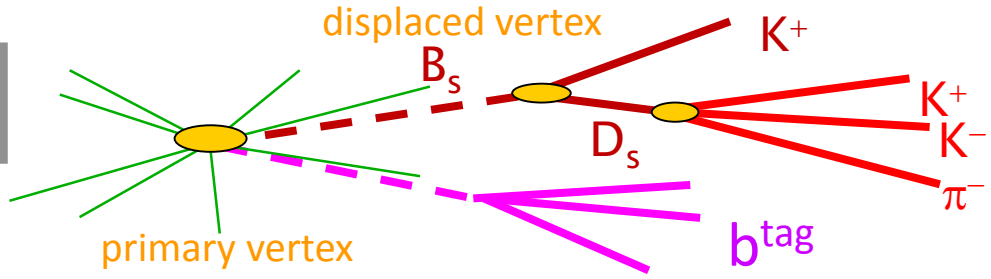




How CMS detects particles

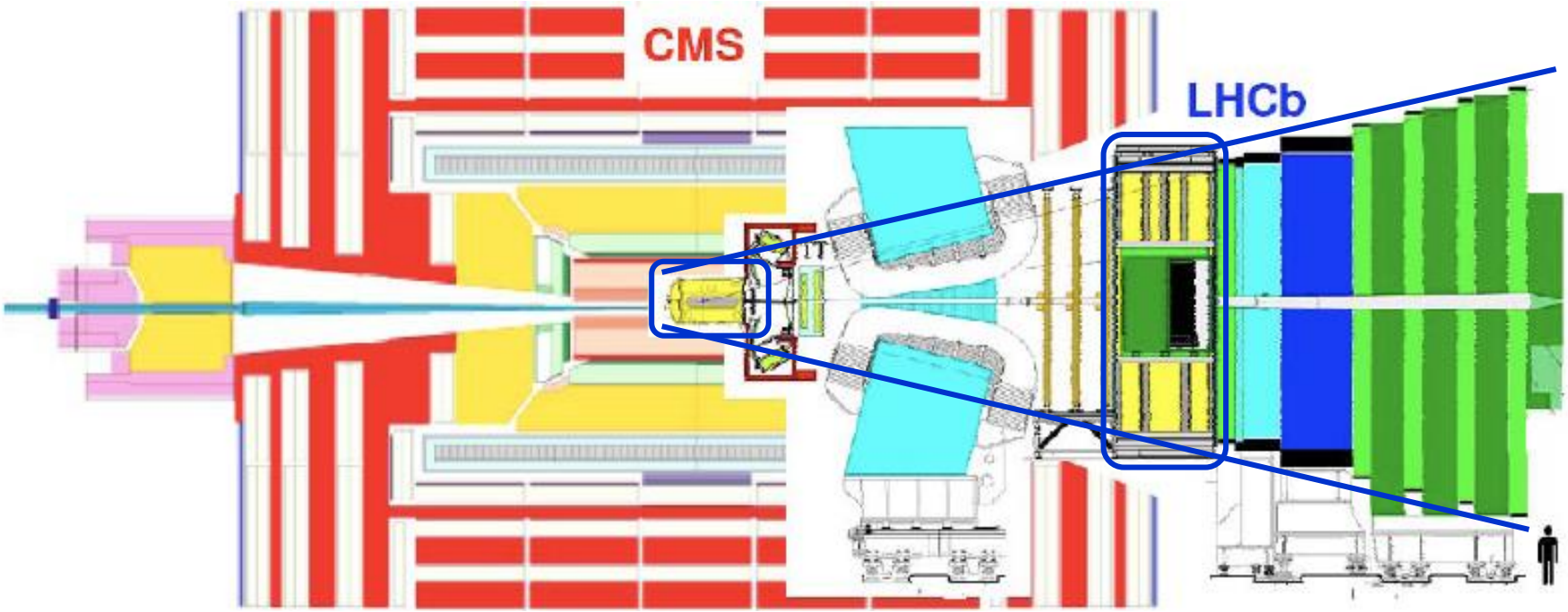


LHCb compared to CMS

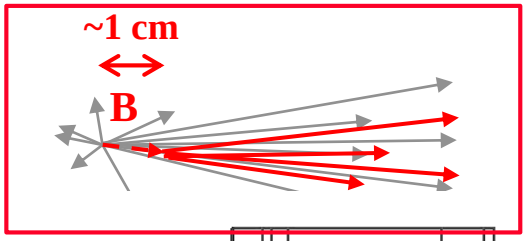


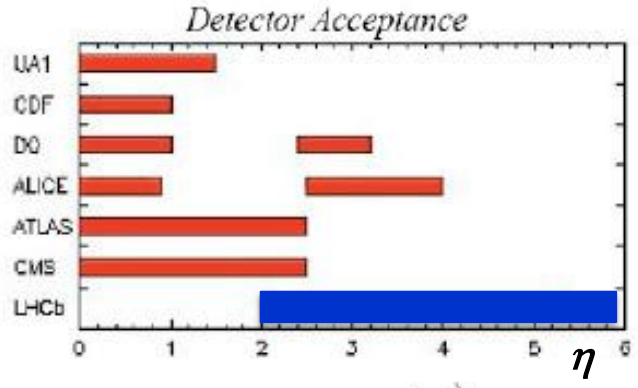
LHCb is specialized to detect mesons containing a b-quark

- B-mesons are produced in the forward region → forward geometry
- B-mesons decay after ~1cm in the detector → vertex reconstruction, particle identification



The LHCb Detector optimized for heavy flavour physics

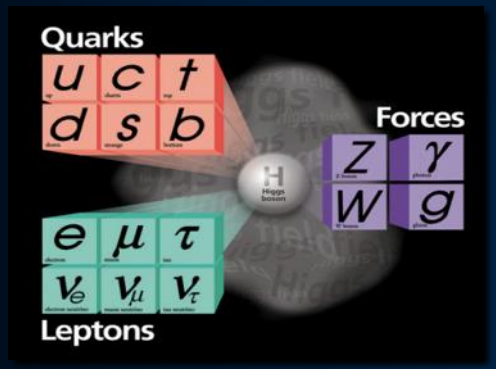




Event display
(view from top)

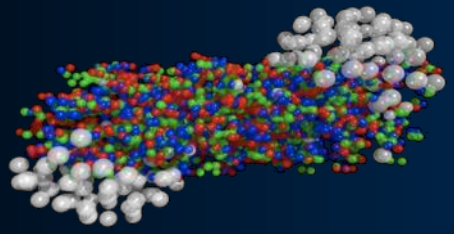
0 10 m 20 m

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?

The origin of particle masses

log-scale !

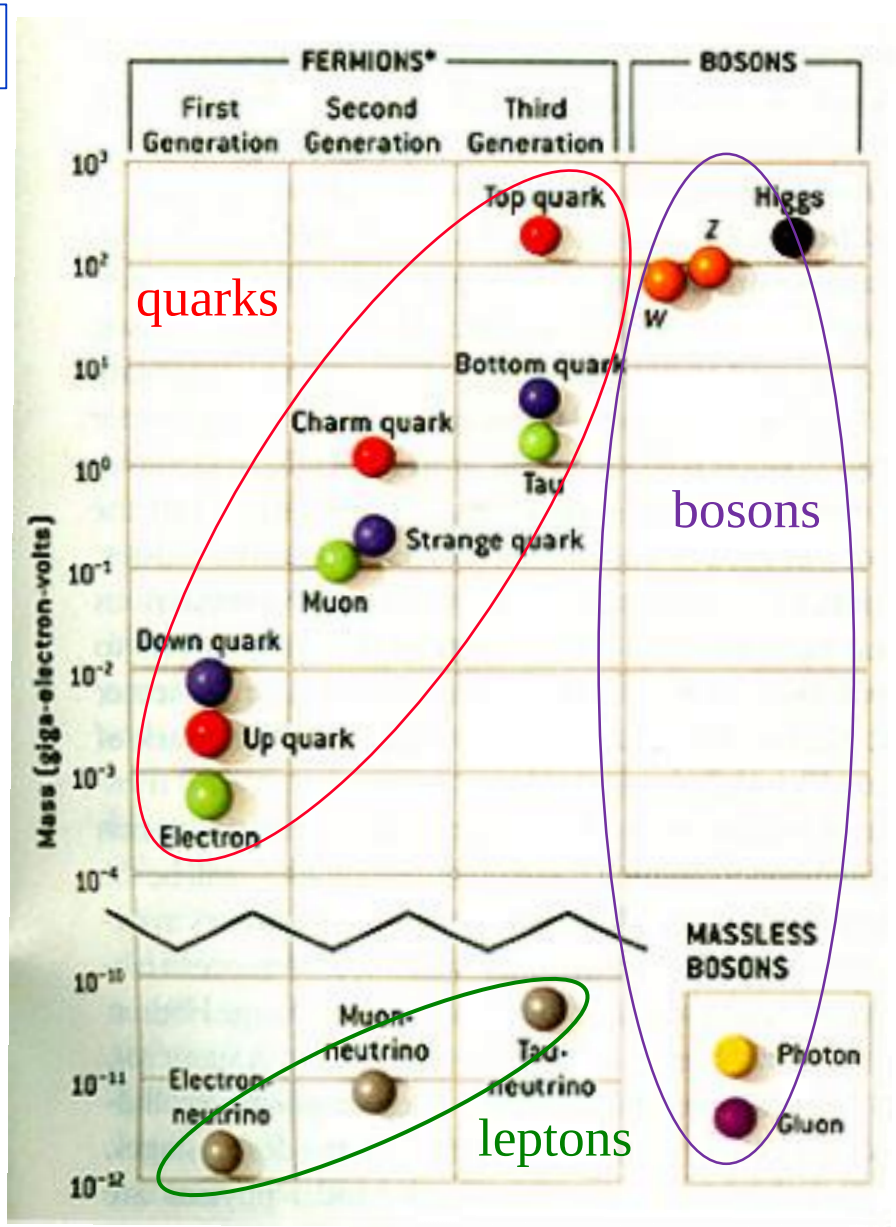
1 TeV

100 GeV

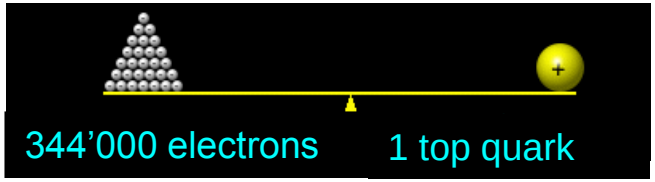
1 GeV

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 ???

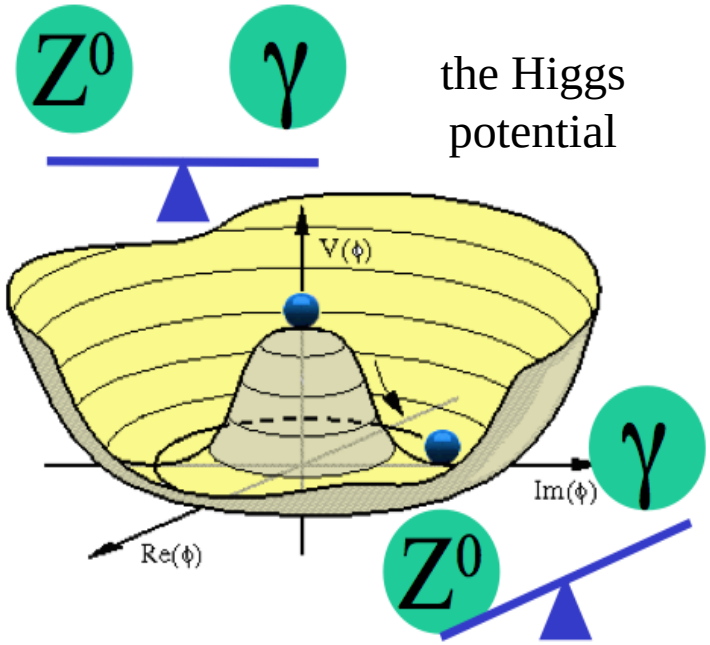
The origin of particle masses

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



the Higgs potential

- ➢ 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 ...

... a famous guest wants to cross the room...

... a new particle is created ...

... he is surrounded by the guests and is slowed-down ...

... the Higgs field makes the particle ”heavy” ...

The origin of particle masses

The Higgs Boson

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

The Higgs field ...

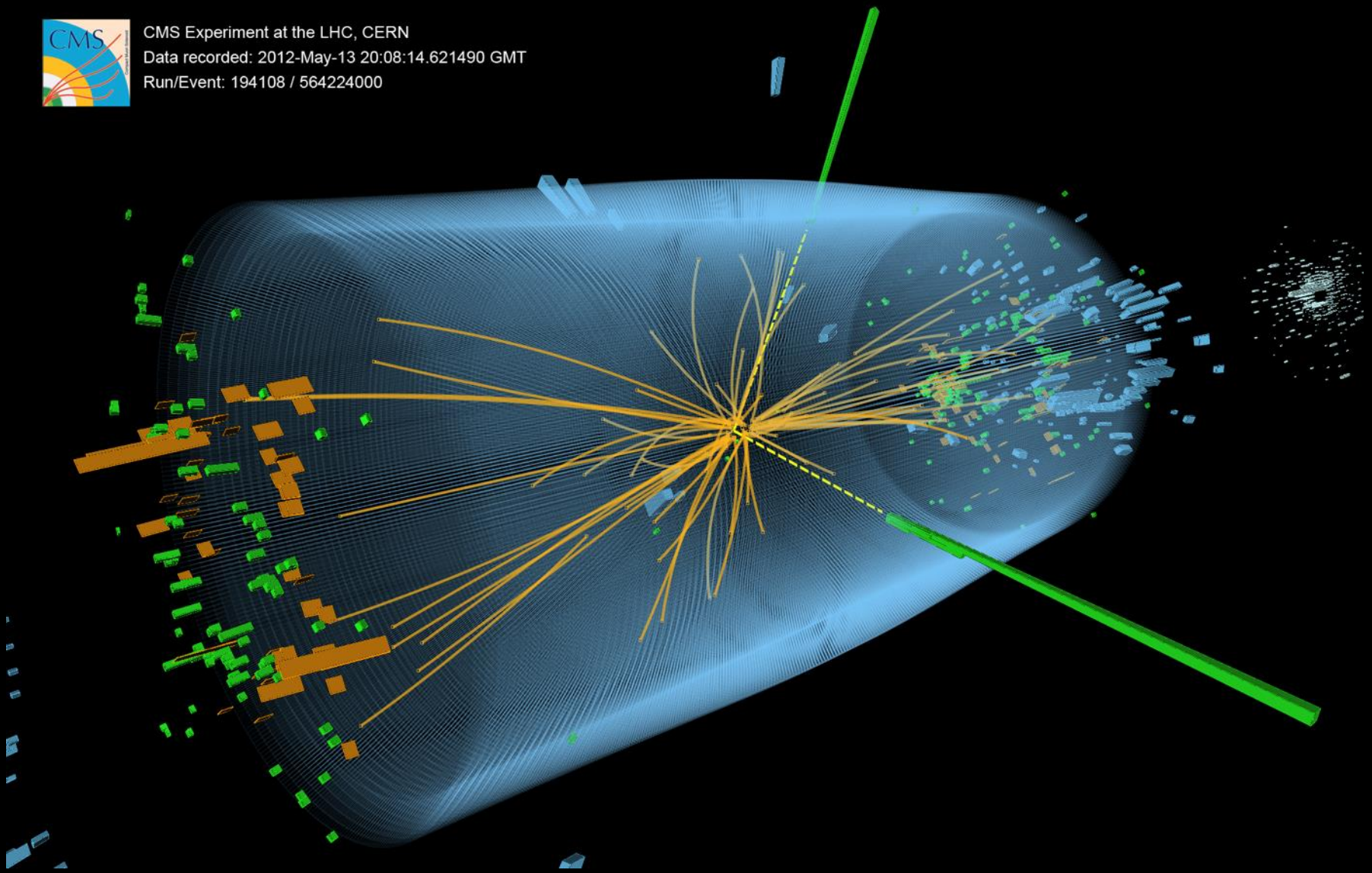
... everybody comes together
and whispers about the news...

... generates its first excitation,
the Higgs particle !

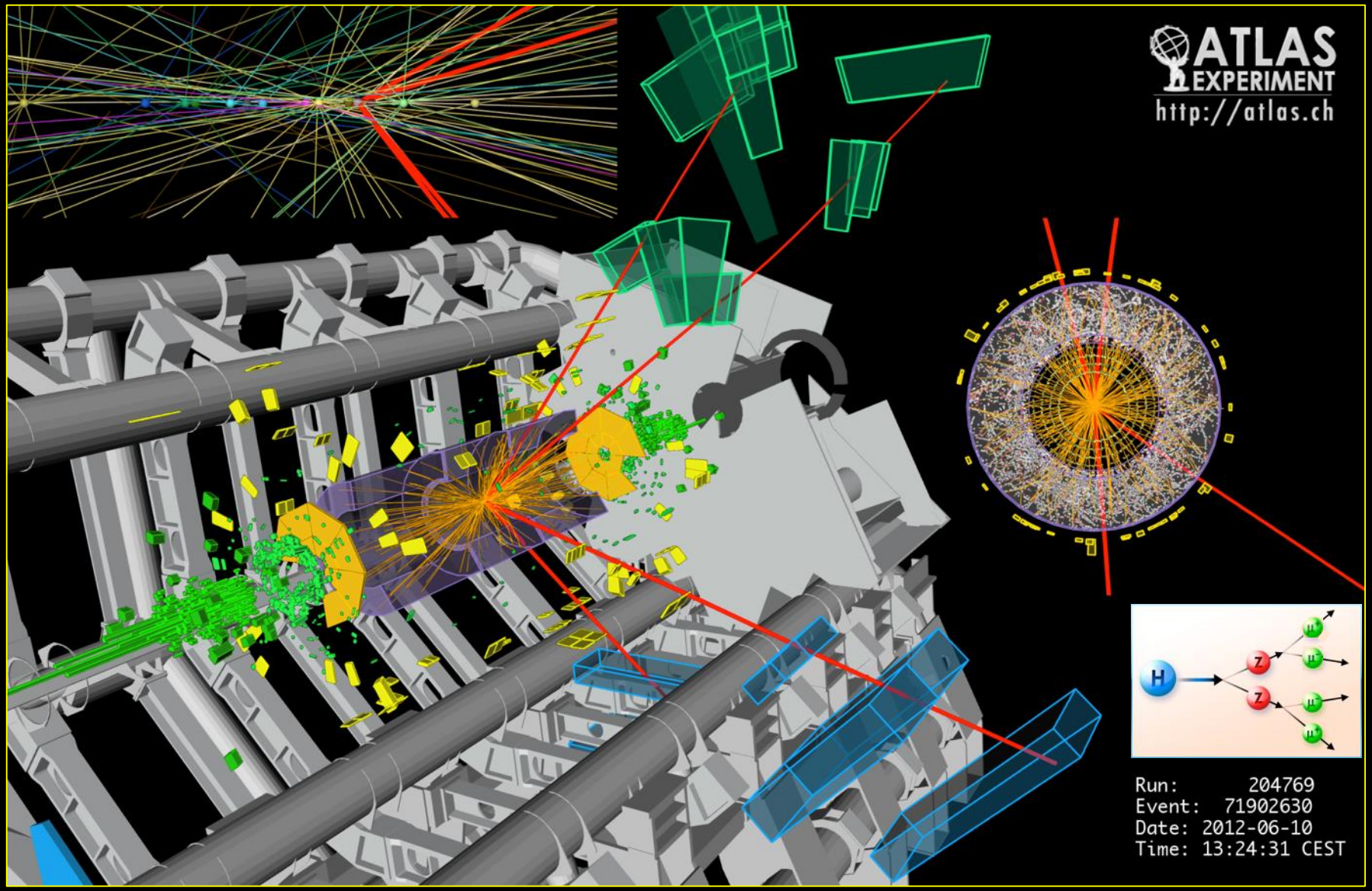
A Possible H → 2 Photon Decay

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

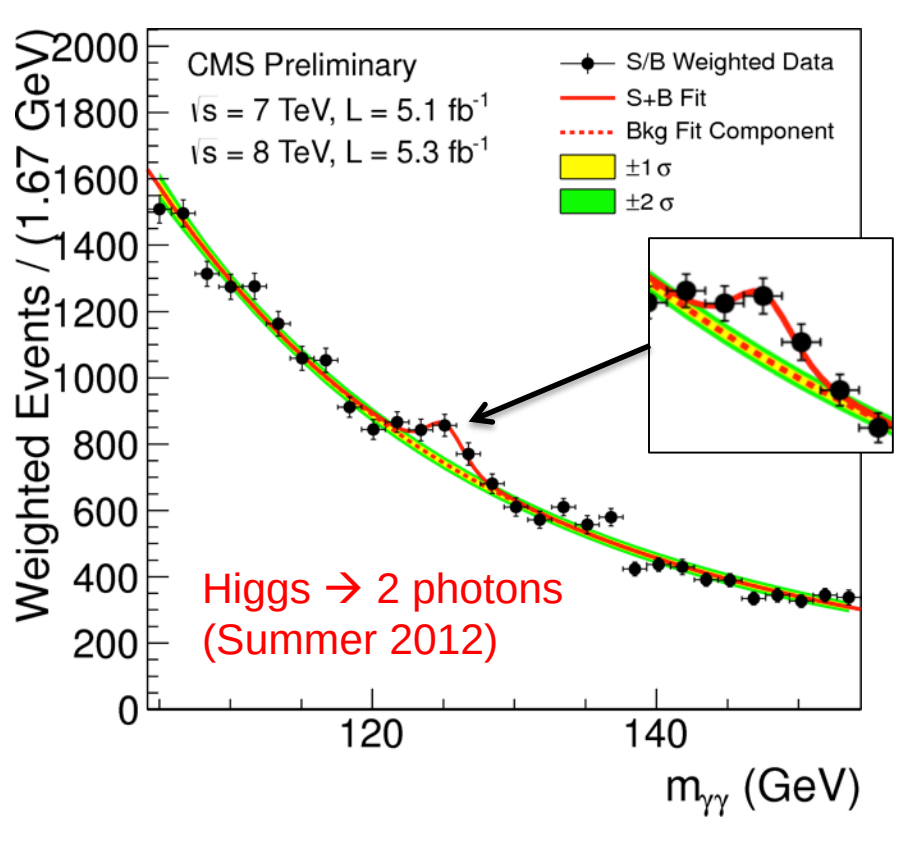
A Possible H → 2 Photon Decay

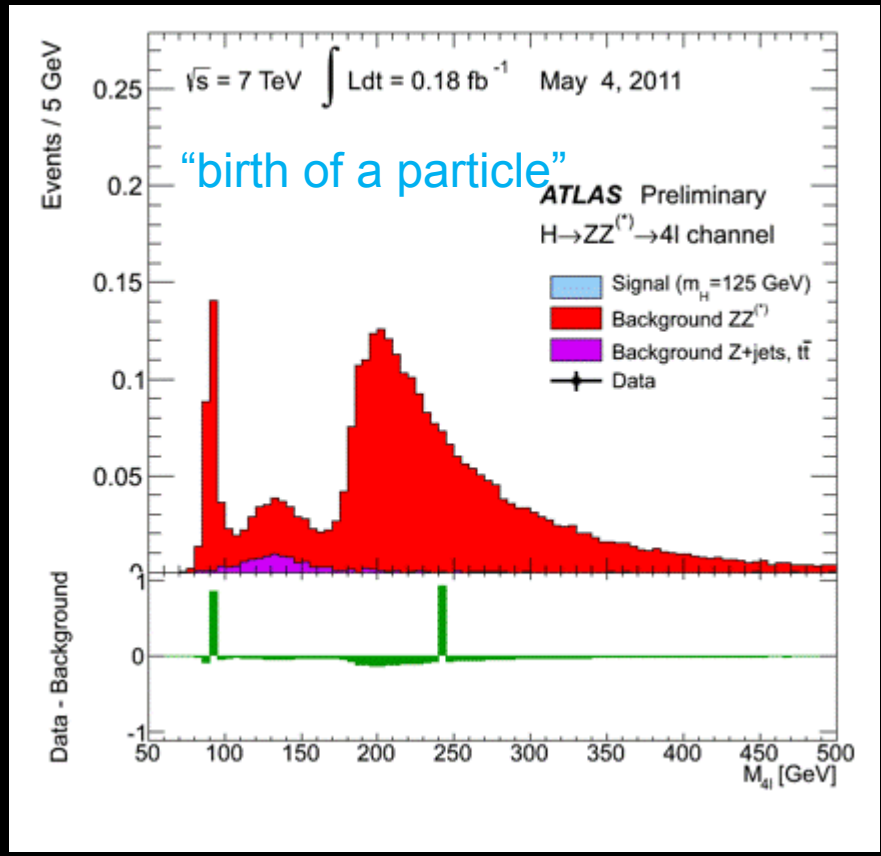


A Possible H → 4 Muon Decay



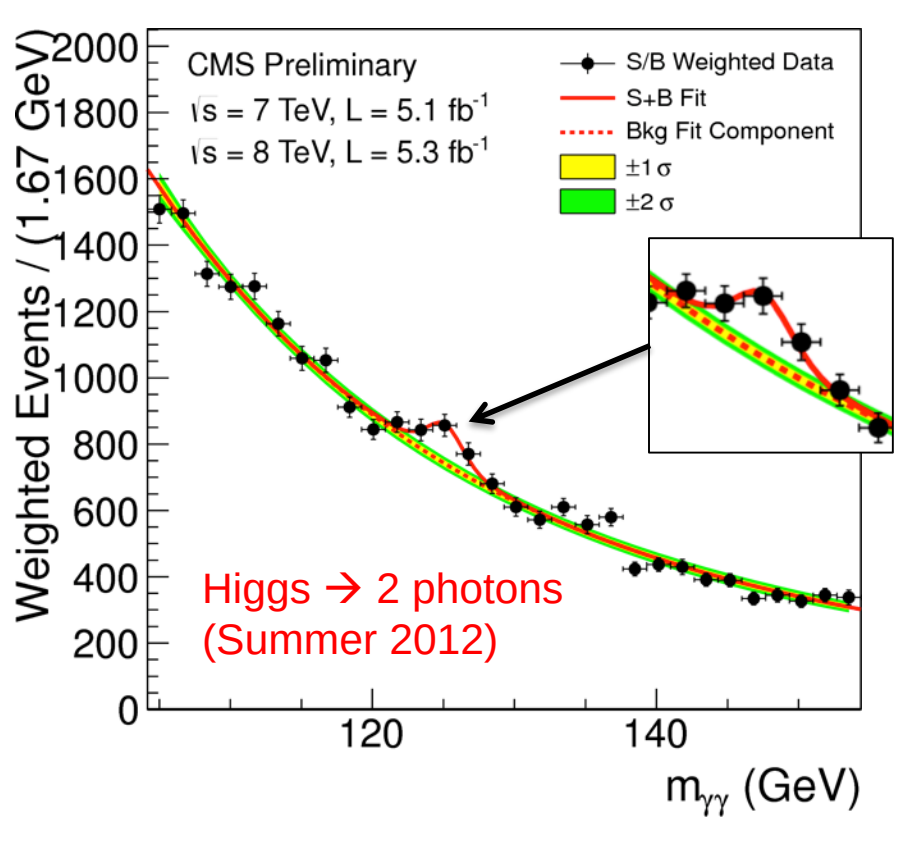
Identifying the Higgs over Background

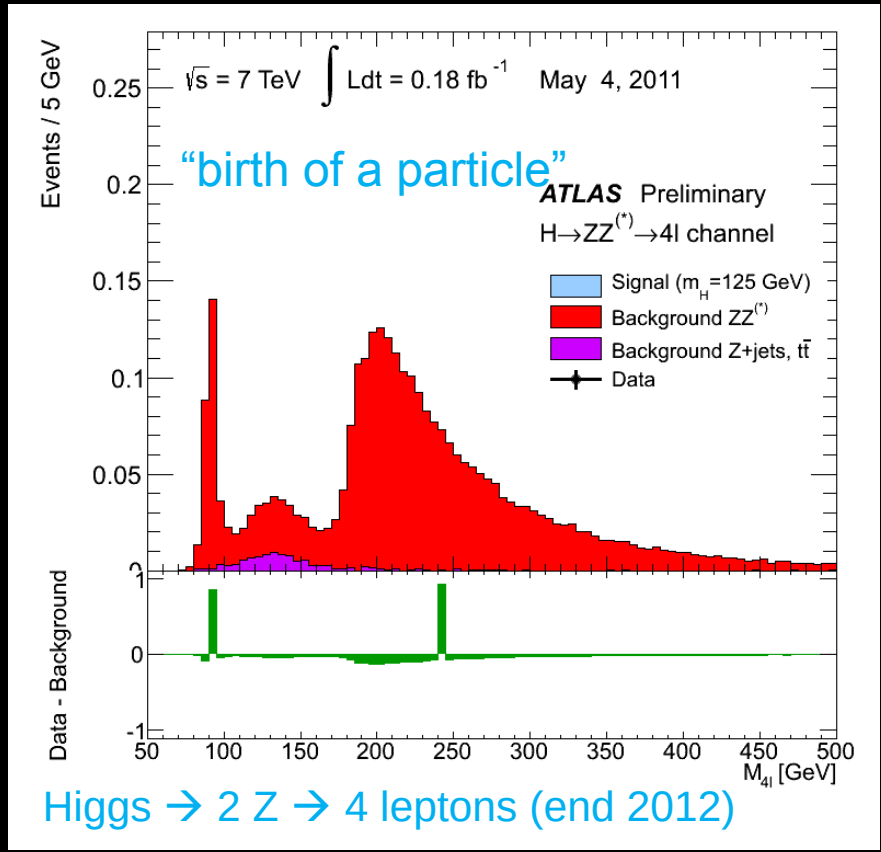




- ✓ Both ATLAS a CMS discover a new particle
  - ➢ The Higgs Boson is the heaviest particle to date
  - ➢ Nobel prize to F. Englert and P. Higgs in 2013

Identifying the Higgs over background

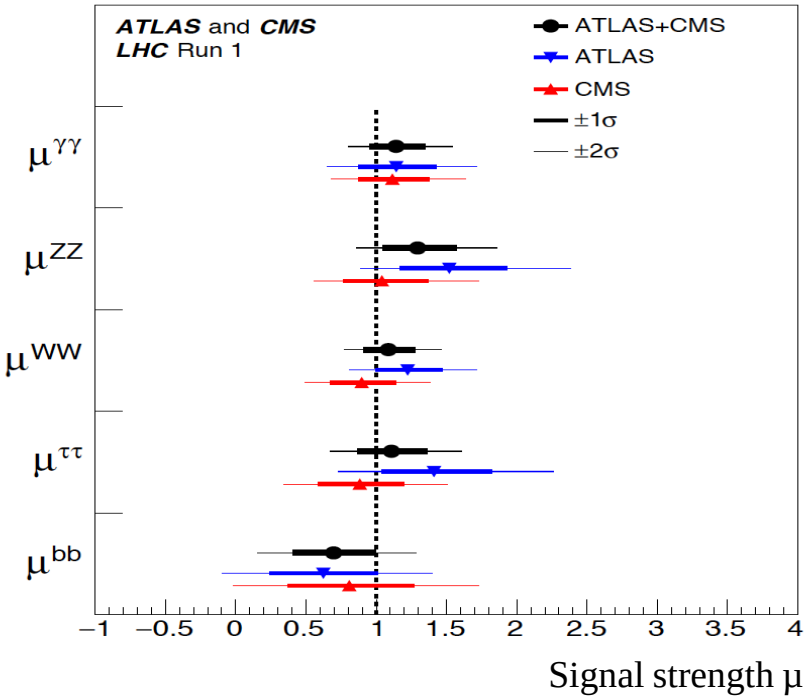


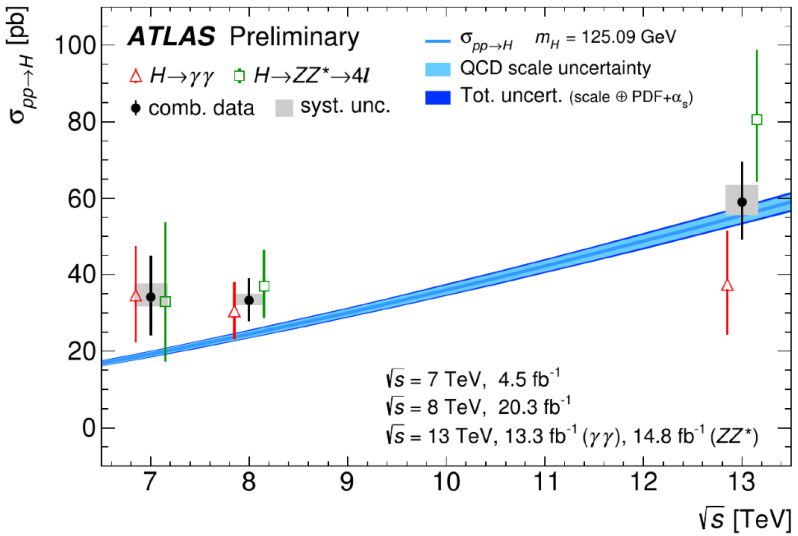


Higgs → 2 Z → 4 leptons (end 2012)

- ✓ Both ATLAS a CMS discover a new particle
  - ➢ The Higgs Boson is the heaviest particle to date
  - ➢ Nobel prize to F. Englert and P. Higgs in 2013

Is this "THE" Standard Model Higgs ?

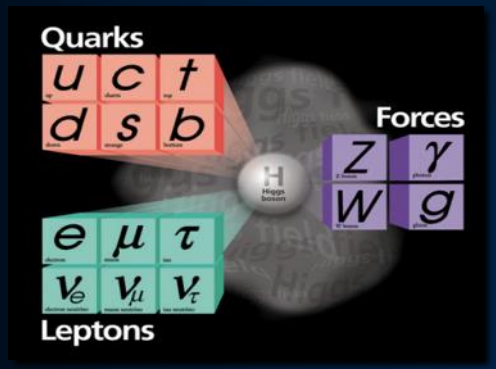




- ✓ **Higgs because:** measured $H \to ZZ \to \ell\ell\ell\ell$, $H \to \gamma\gamma$, $H \to WW \to \ell\nu\ell\nu$ and also less sensitive modes like e.g. $H \to \tau\tau$, etc.
- ✓ **Overall significance of production ~10σ**
- ✓ **We know it's a boson:** Because it decays to two photons
- ✓ **We know 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!

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



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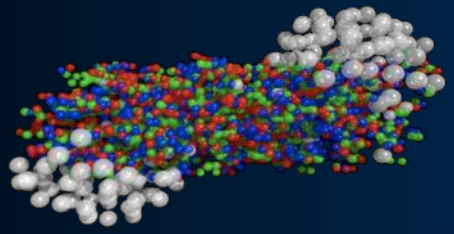


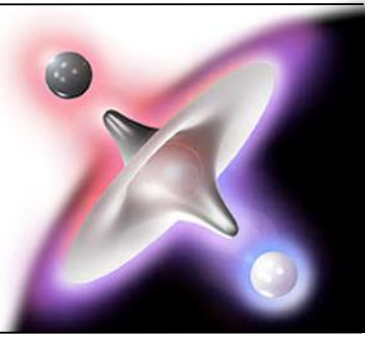
Will we understand the primordial state of matter after the Big Bang before protons and neutrons formed?

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

Antimatter - Matter Asymmetry

$E=mc^2$

In the beginning matter and anti-matter were created in *equal parts*



No evidence for the original, "primordial" cosmic *antimatter*:

- absence of anti-nuclei amongst cosmic rays in our galaxy
- absence of intense γ–ray emission due to annihilation of distant galaxies in collision with antimatter

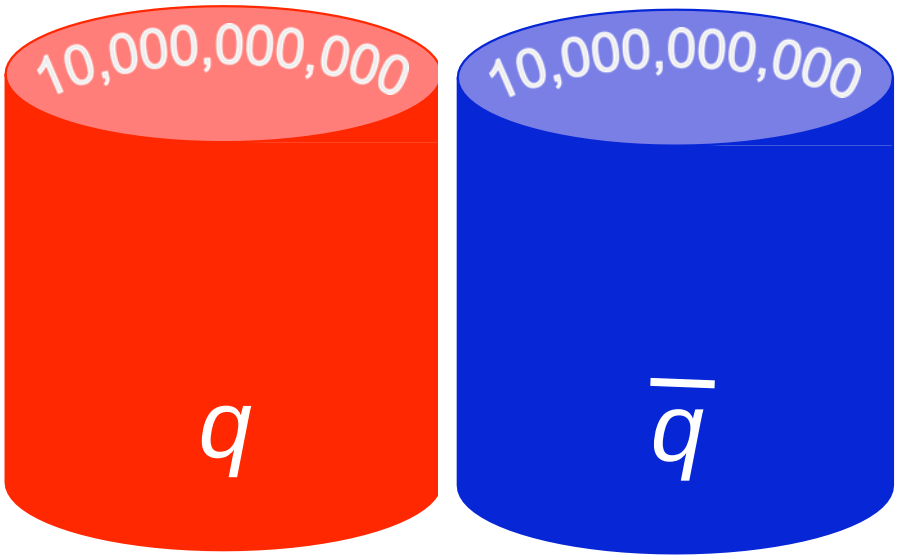
but the universe is made of *matter* !

where has the *anti-matter* gone ?

Antimatter & the Big Bang

Big Bang:

- Create equal amounts of matter & antimatter



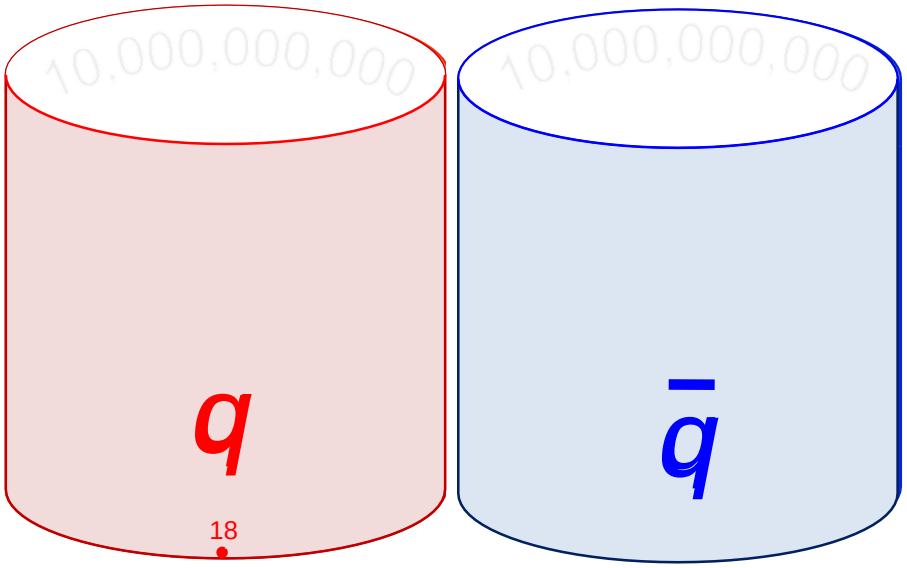
Early universe

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

$N_{baryons} / N_{photons} \cong 6 \cdot 10^{-6}$



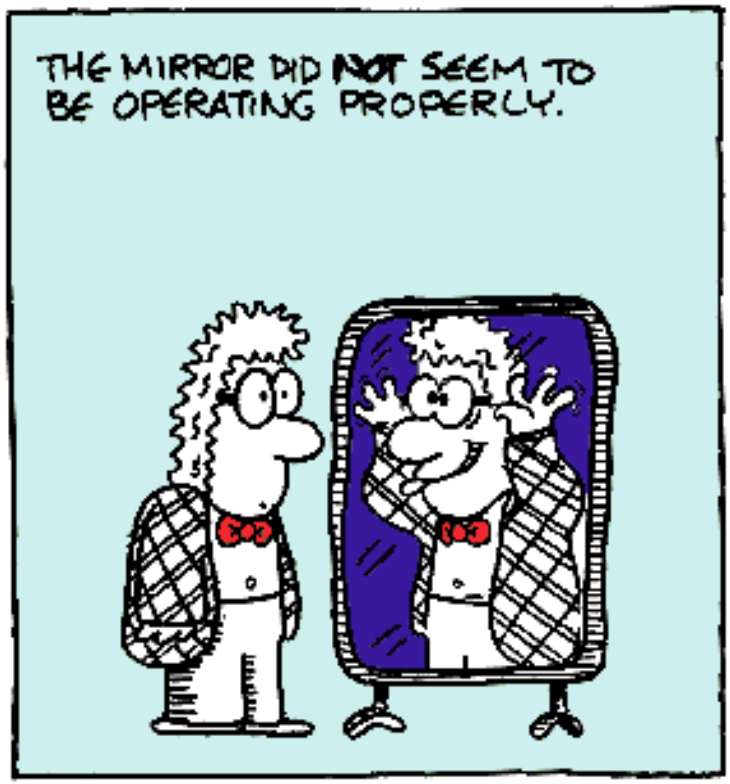
Current universe

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

CP is 'a bit' broken by weak interaction

Discrete symmetries expected to be conserved:
C = charge conjugation symmetry
P = parity (mirror) symmetry
T = time reversal symmetry

CP transforms a particle into its anti-particle (e.g. electron into positron, or proton into anti-proton)



big surprise:
discovery of *CP* violation in 1964 in neutral Kaon decays (Cronin, Fitch Turlay)

Nobel prize 1980:
"This discovery emphasizes, once again, that even almost self evident principles in science cannot be regarded fully valid until they have been critically examined in precise experiments."

However:
Unfortunately, observed *CP* violation *not sufficient* to explain matter anti-matter asymmetry in the universe !

CPLEAR: CP violation in $K^0 \rightarrow \pi\,\pi$

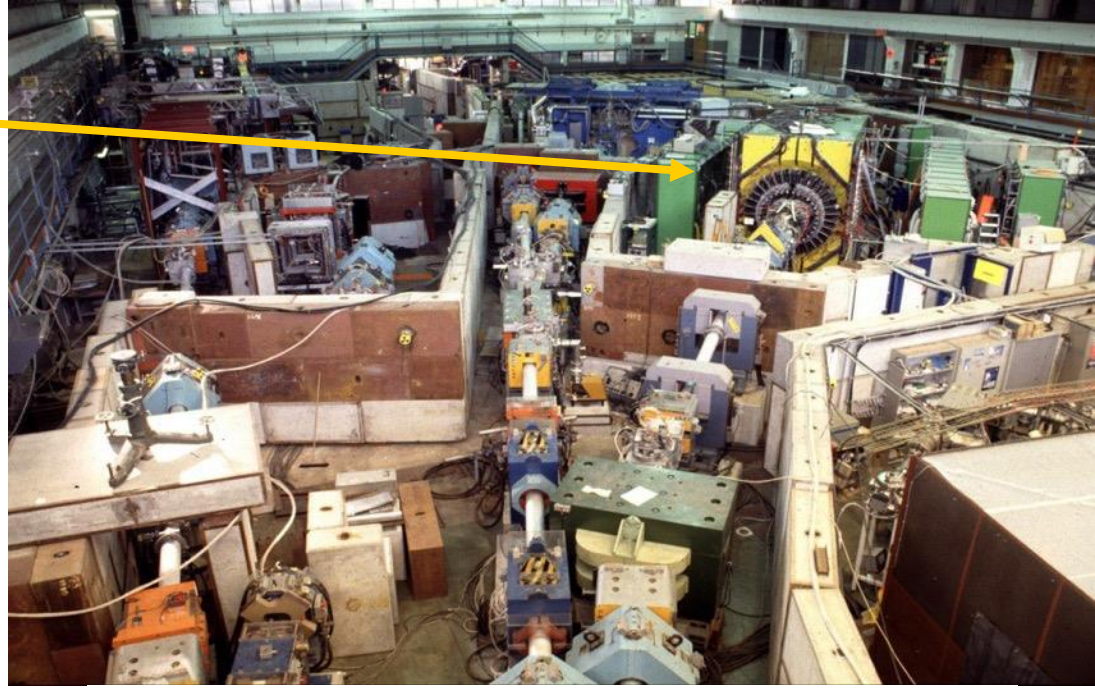
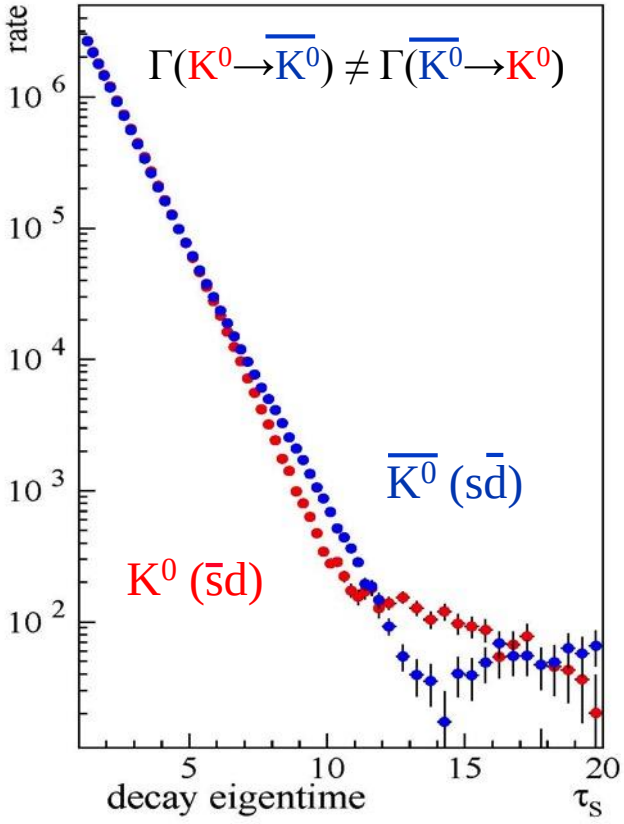
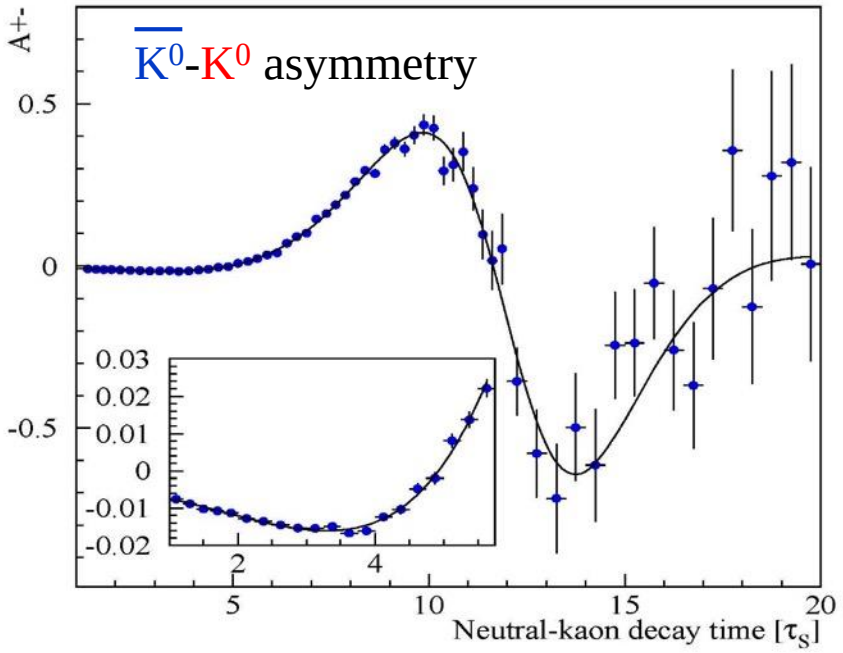


Illustration of CP violation in "mixing" of neutral kaons (1995)

- Kaon = meson of sd-quarks



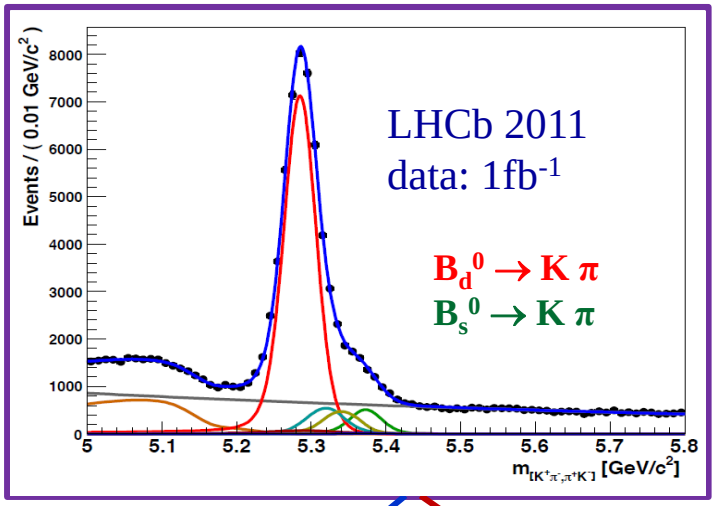
[Phys.Lett. B363 (1995) 243]



LHCb: CP violation in $B^0_d \to K\,\pi$ decays

Illustration of CP violation in decay of neutral Beauty mesons (2013)

- B_d = meson of bd-quarks



$A_{CP}(B_d^0) = (-8.0 \pm 0.7 \pm 0.3)\%$

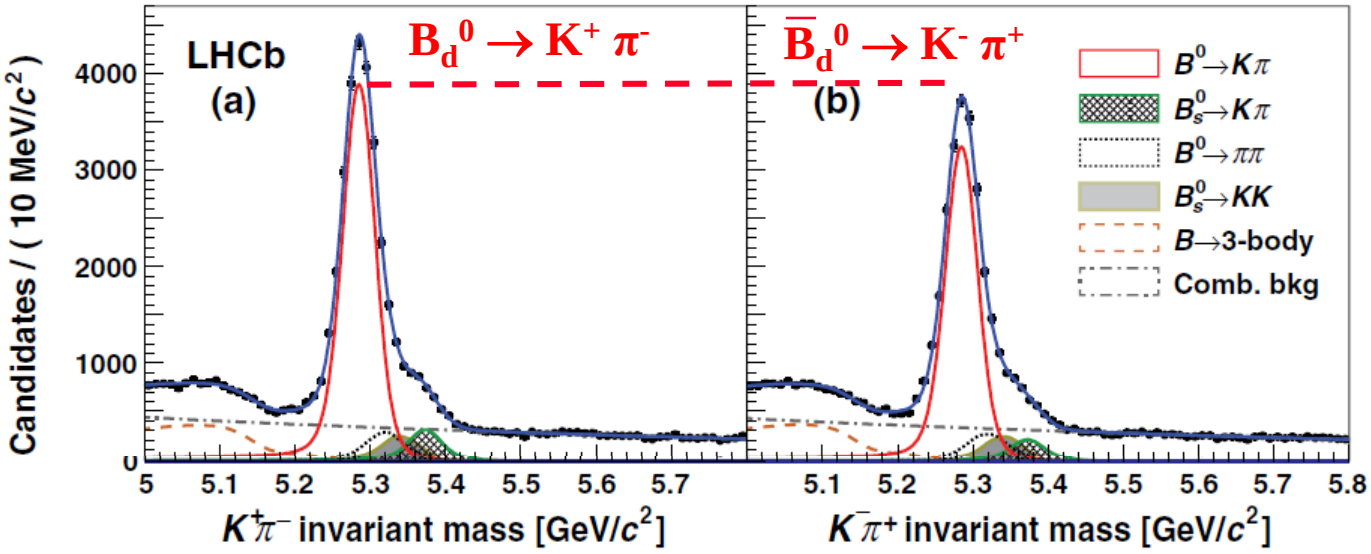
- Most precise (10σ) measurement of direct CPV in B decays

CPV in decay:

$A(B^0 \to f) \neq A(\bar{B}^0 \to \bar{f})$

B_d^0 $\bar{B}_d^0$

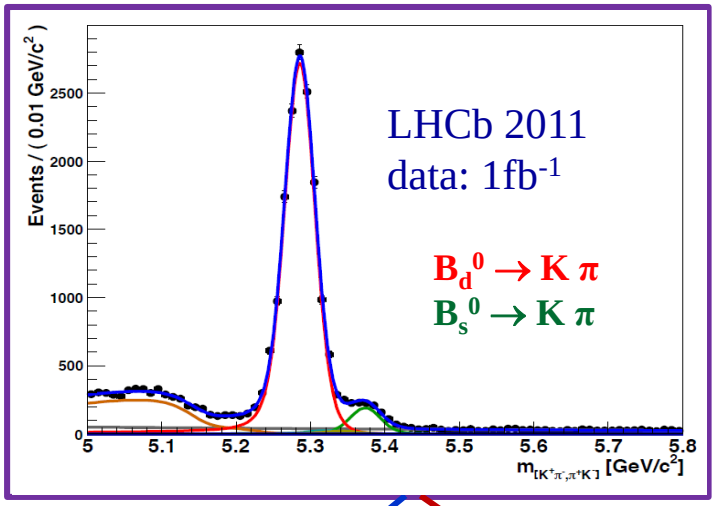
[PRL 110, 221601 (2013)]



LHCb: CP violation in $B^0_s \to K\pi$ decays

Illustration of CP violation in decay of neutral Beauty mesons (2013)

- B_s = meson of bs-quarks



B^0_s yield = (10.7±2.0)%

$A_{CP}(B_s^0) = (27 \pm 4 \pm 1)\%$

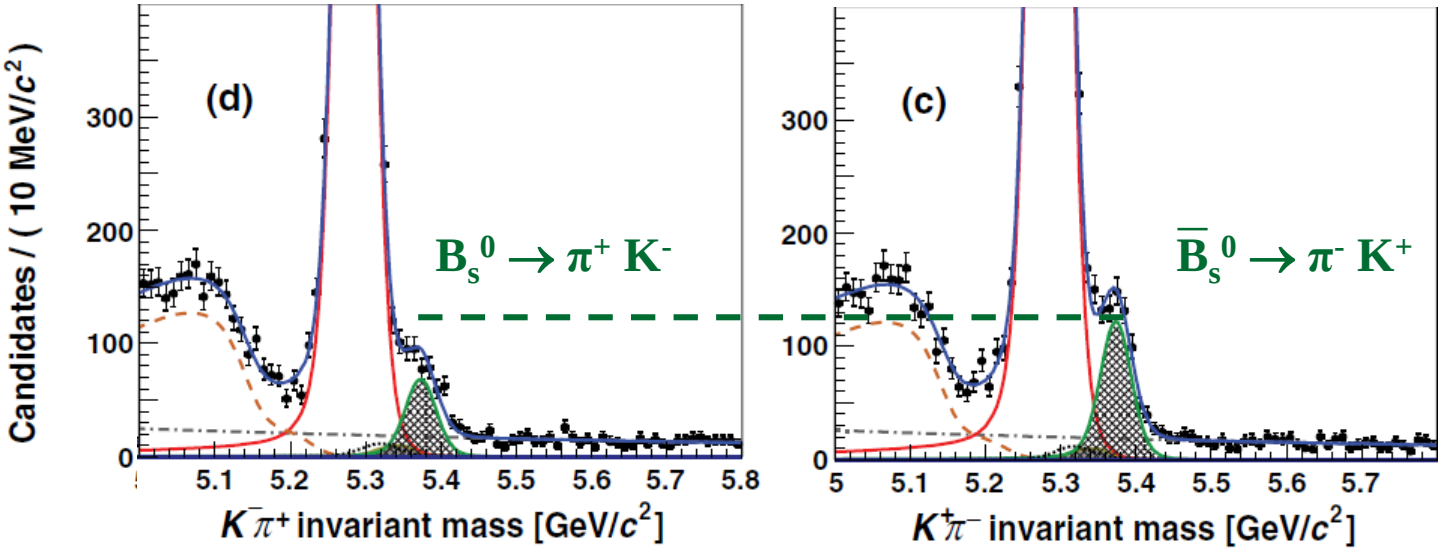
- first observation (6σ) of direct CPV in B_s decays

CPV in decay:

$A(B^0 \to f) \neq A(\bar{B}^0 \to \bar{f})$

B_s^0 $\bar{B}_s^0$

[PRL 110, 221601 (2013)]

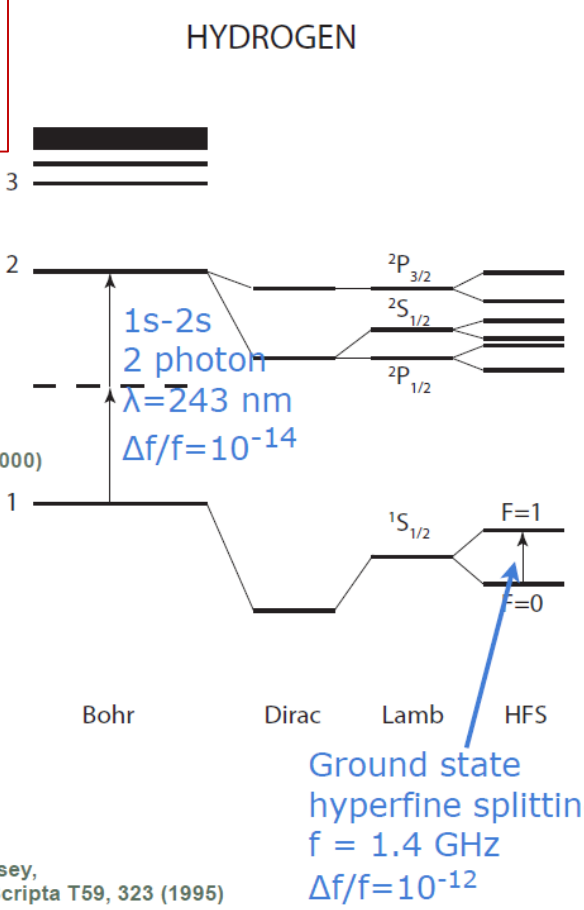


Test of Matter-Antimatter symmetry (CPT) with hydrogen and anti-hydrogen spectroscopy

General principles of relativistic field theory require invariance under the combined transformation CPT

CPT conservation → identical mass and lifetime of particle & anti-particle

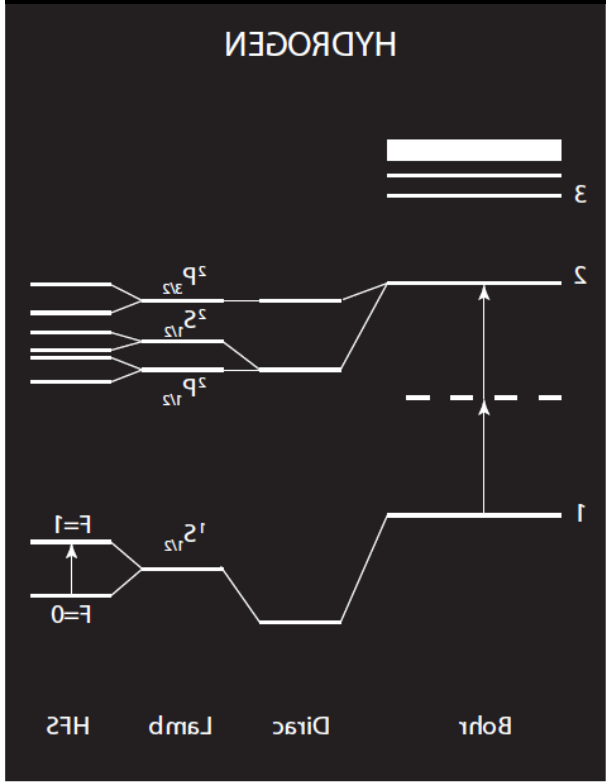
Hydrogen



T. Hänsch et al.,
Phys. Rev. Lett. 84, 5496–5499 (2000)

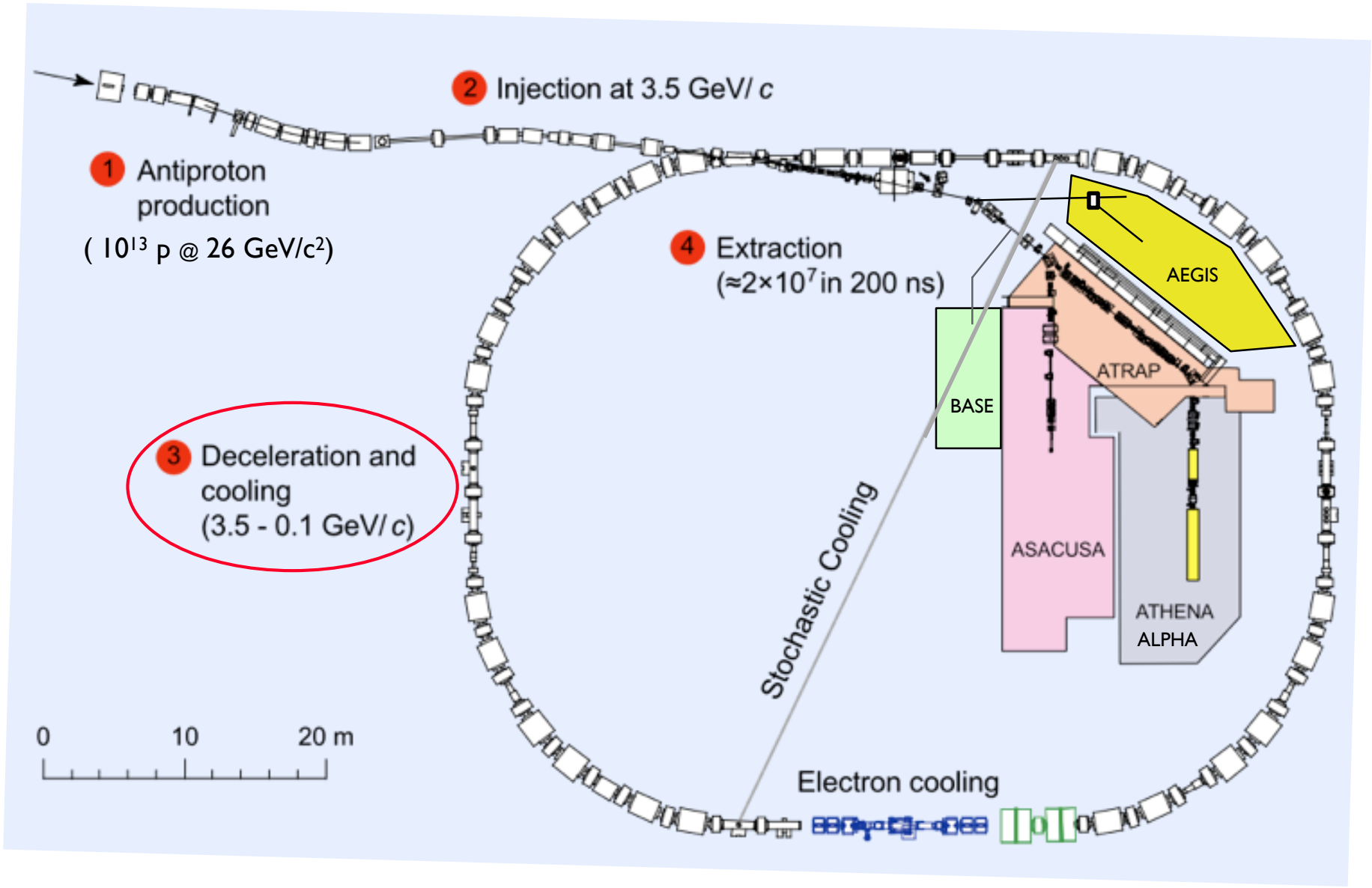
N. F. Ramsey,
Physica Scripta T59, 323 (1995)

Anti hydrogen



Before being able to do spectroscopy, need to produce and "trap" anti-atoms !

Antiproton Decelerator



Production of Anti-Hydrogen

ATHENA Nature 419 (2002) 456

advance online publication

Production and detection of cold antihydrogen atoms

M. Amoretti*, C. Amsler†, G. Bonomi‡§, A. Bouchta‡, P. Bowe‖, C. Carraro*, C. L. Cesar¶, M. Charlton#, M. J. T. Collier#, M. Doser‡, V. Filippini☆, K. S. Fine‡, A. Fontana☆**, M. C. Fujiwara††, R. Funakoshi††, P. Genova☆**, J. S. Hangst‖, R. S. Hayano††, M. H. Holzscheiter‡, L. V. Jorgensen#, V. Lagomarsino*‡‡, R. Landua‡, D. Lindelöf†, E. Lodi Rizzini§☆, M. Macrì*, N. Madsen†, G. Manuzio*‡‡, M. Marchesotti☆, P. Montagna☆**, H. Pruys†, C. Regenfus†, P. Riedler‡, J. Rochet†#, A. Rotondi☆**, G. Rouleau‡#, G. Testera*, A. Variola*, T. L. Watson# & D. P. van der Werf#

VOLUME 89, NUMBER 21 PHYSICAL REVIEW LETTERS 18 NOVEMBER 2002

Background-Free Observation of Cold Antihydrogen with Field-Ionization Analysis of Its States

G. Gabrielse,[1,*] N. S. Bowden,[1] P. Oxley,[1] A. Speck,[1] C. H. Storry,[1] J. N. Tan,[1] M. Wessels,[1] D. Grzonka,[2] W. Oelert,[2] G. Schepers,[2] T. Sefzick,[2] J. Walz,[3] H. Pittner,[4] T. W. Hänsch,[4,5] and E. A. Hessels[6]

(ATRAP Collaboration)

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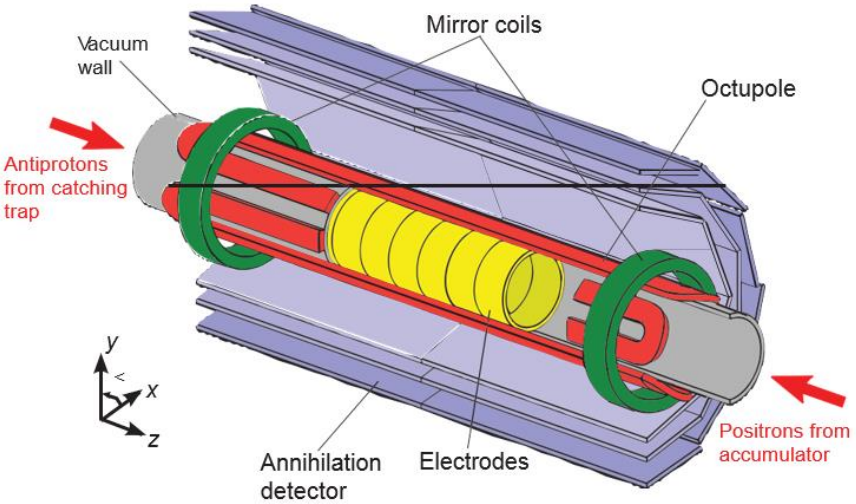
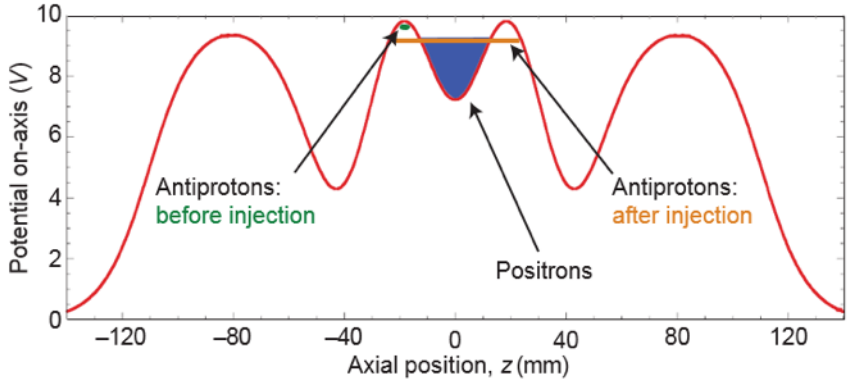
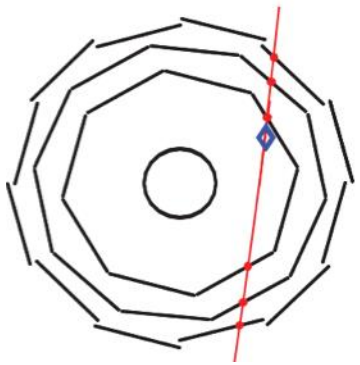


- trap very slow anti-protons and positrons in a "Penning trap" to produce anti-hydrogen



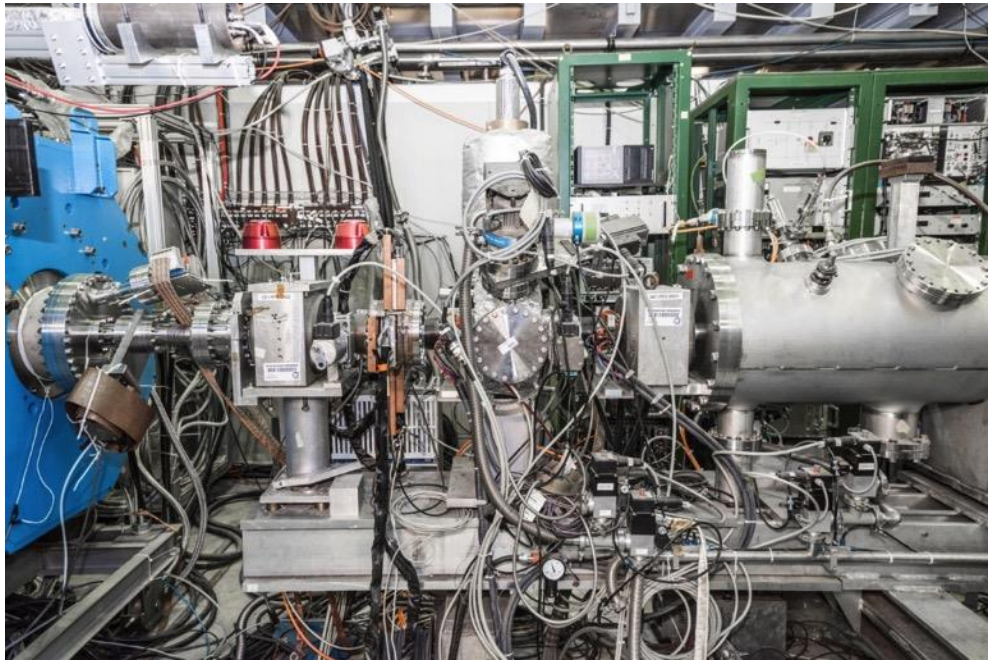


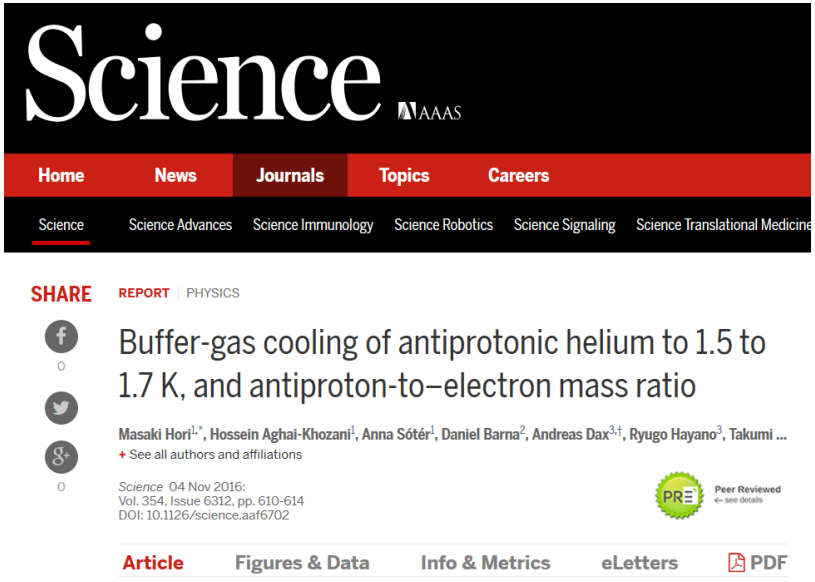
- detect annihilation of anti-hydrogen with silicon-strip detectors

Production of Anti-Protonic Helium

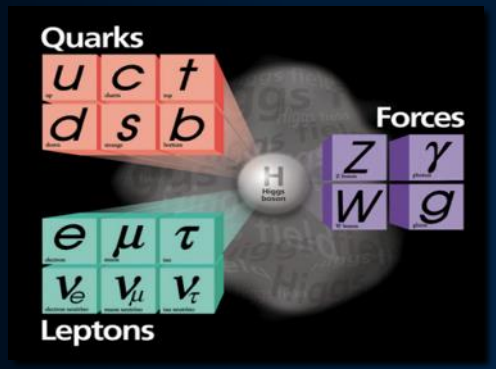
Another method:
Spectroscopy of anti-protonic helium

- mixing antiprotons with helium gas
- in the mixture, ~3% of the antiprotons takes the place of one of the electrons that would normally be orbiting the nucleus
- in 2016 the ASACUSA experiment reported new precision measurement of the mass of the anti-proton relative to that of the electron
- result is based on spectroscopic measurements with about 2 billion anti-protonic helium atoms cooled to extremely cold temperatures of 1.5 to 1.7 degrees above absolute zero improving sensitivity up to factor 10 compared to previous measurements



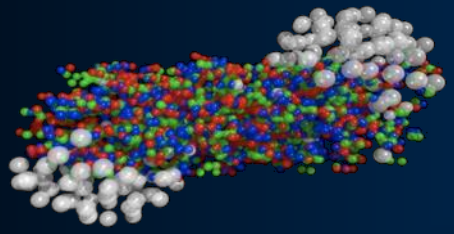


Experiments at CERN, in particular at the LHC, are designed to answer some of the big questions ...



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

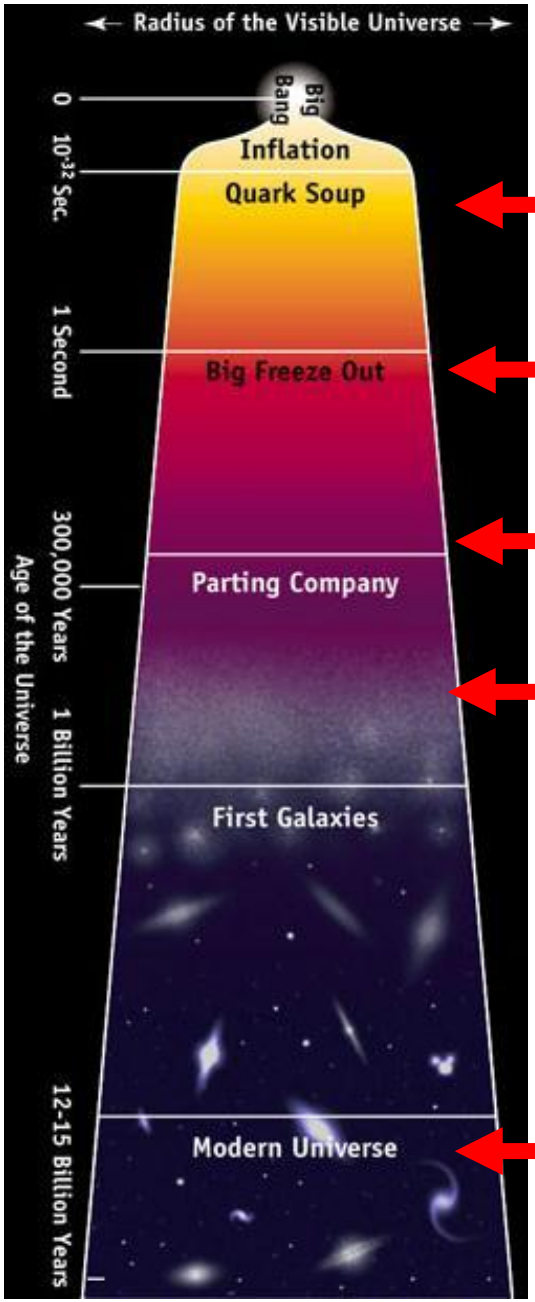
Will we find the reason why antimatter and matter did not completely destroy each other?



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?

Brief history of time



Too hot for quarks to bind!

Too hot for nuclei to bind

Nucleosynthesis builds nuclei up to He

Universe too hot for electrons to bind

Today's Cold Universe

Quark Gluon Plasma

Hadron Gas

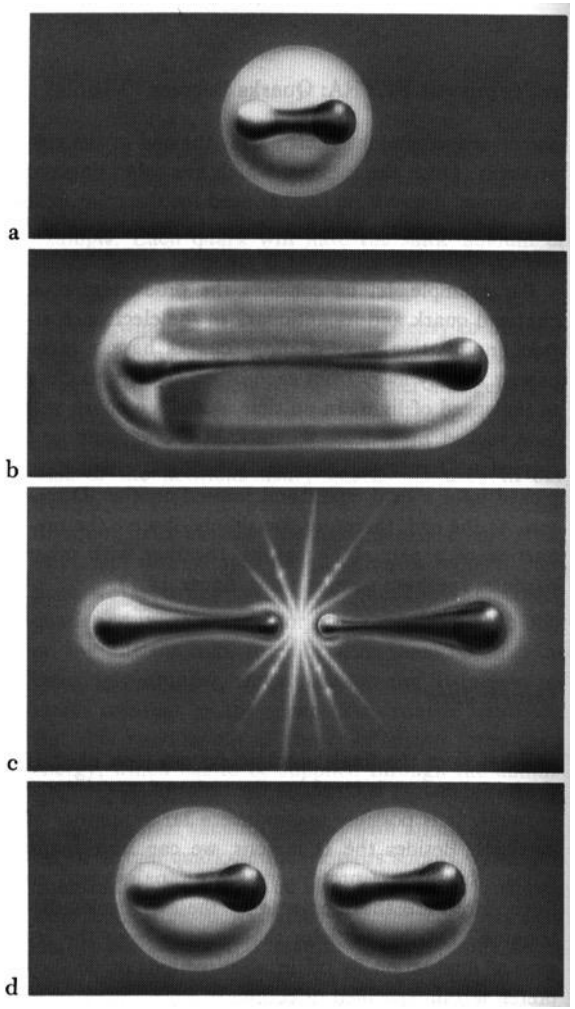
E/M Plasma

Solid Liquid Gas

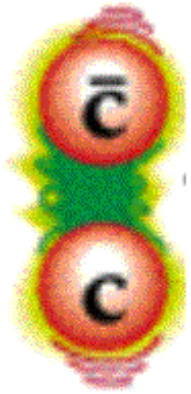
How can we create Quark-Gluon Plasma?

From confinement…

- ✓ contrary to the weak force, the strong force between quarks decreases with shorter distances
- ➢ the strong interaction grows stronger as the distance increases



(Illustration from Fritzsch)



- ✓ at large distances it becomes energetically favourable to convert the increasing energy to a new quark anti-quark pair
- ➢ the quarks are "confined"

How can we create Quark-Gluon Plasma?

…to unconfinement

Since the interactions between quarks and gluons become weaker at small distances, it might be possible, by creating a high density/temperature extended system composed by a large number of quarks and gluons, to create an "unconfined" phase of matter

- First ideas in that sense date back to the '70s :

Cabibbo and Parisi PLB 59B (1975) 67

Collins and Perry, PRL 34 (1975) 1353

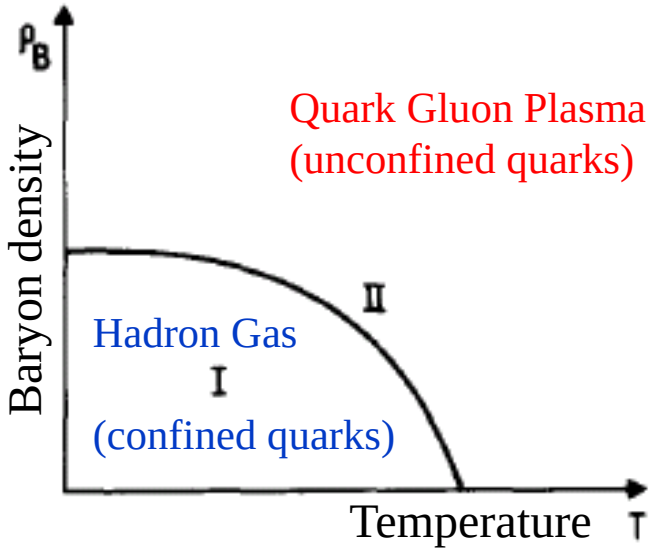


Fig. 1. Schematic phase diagram of hadronic matter. ρ_B is the density of baryonic number. Quarks are confined in phase I and unconfined in phase II.

We expect models of this kind to give rise to a phase transition at a temperature $kT \approx m_\pi$, the high temperature phase being one where quarks can move freely in space.

We expect the same transition to be also present at low temperature but high pressure, for the same reason, i.e. we expect a phase diagram of the kind indicated in fig. 1.

Phase transition at large T and/or ρ_B

note: $T_c \approx 2 \cdot 10^{12}\mathrm{K}$

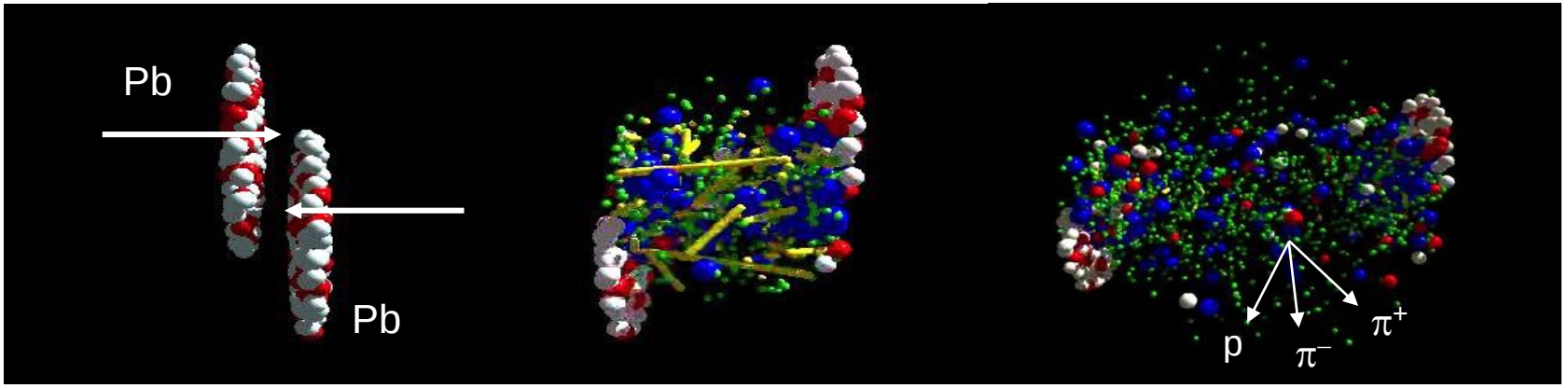
(10^5 times core of sun)

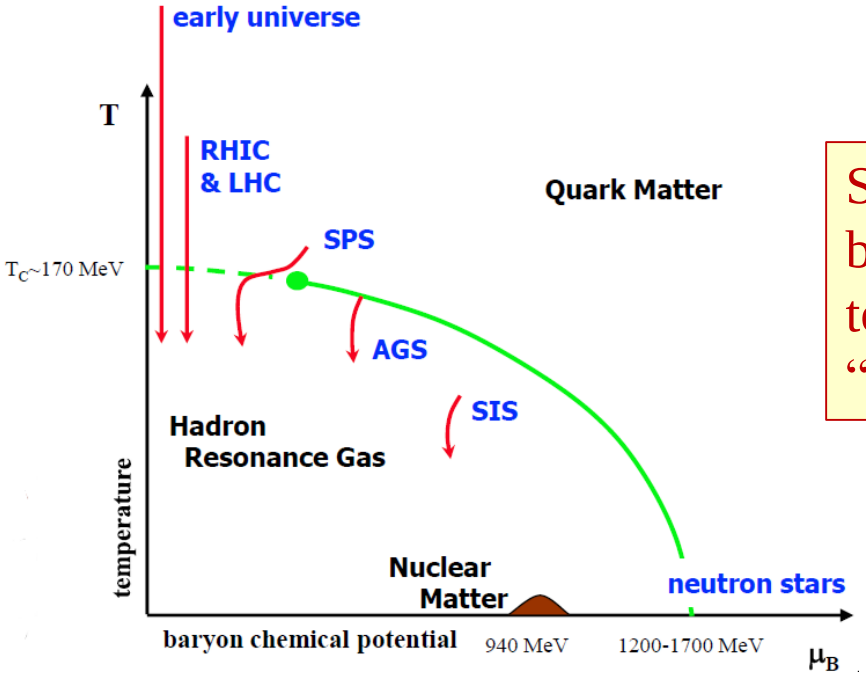
$n_c^B = 0.72\mathrm{fm}^{-3}$

(5 times nucleus)

How can we create Quark-Gluon Plasma?

- reproduce the temperature (~10^{16} K) of the Universe a few instants (10^{-11}s) after the Big Bang



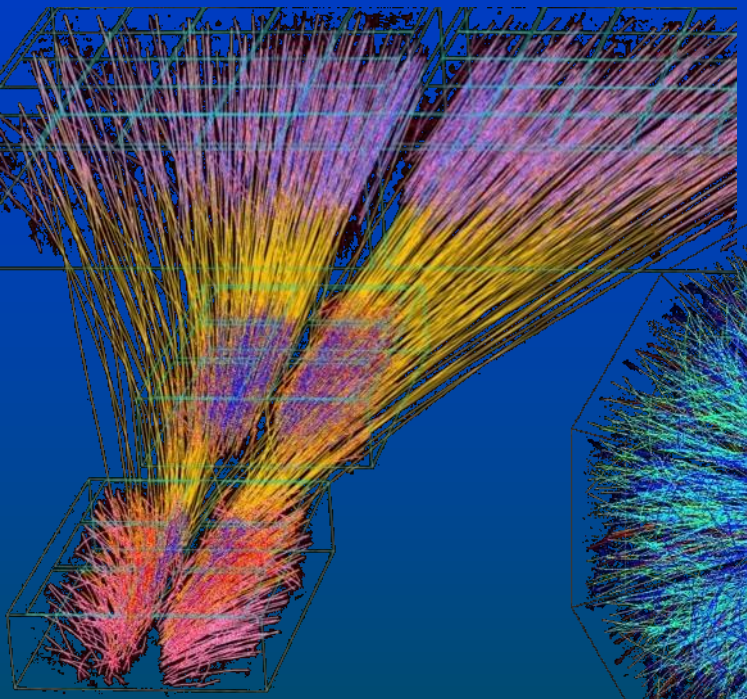


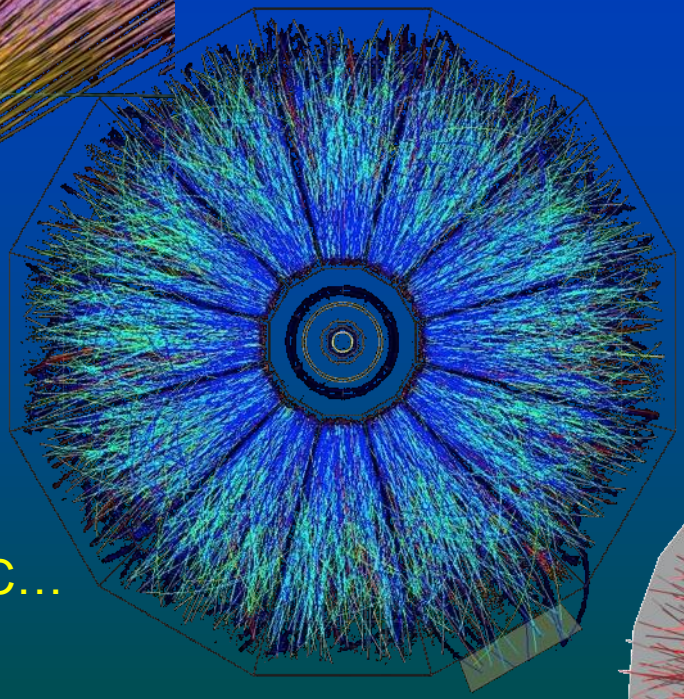
Study experimentally the phase diagram by colliding heavy nuclei (e.g. Pb-Pb) to convert cold nuclear matter into "Quark Matter"

Heavy Ions and Quark-Gluon Plasma…

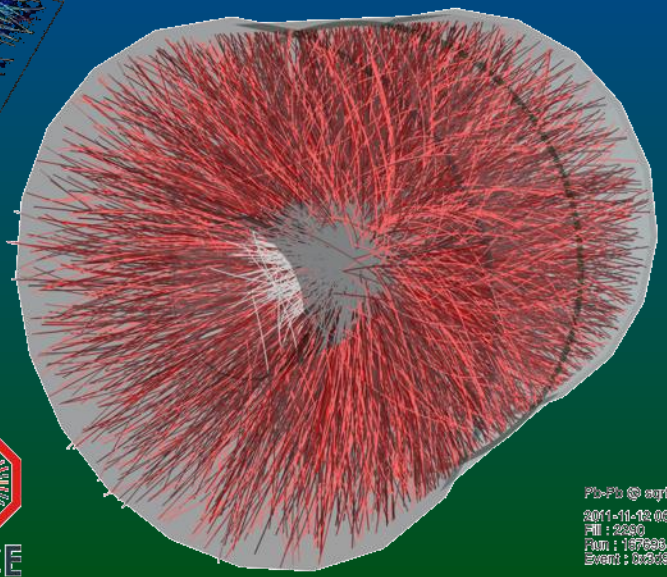
From SPS…

NA49





…to RHIC…



…to LHC!

Fermi National Accelerator Laboratory

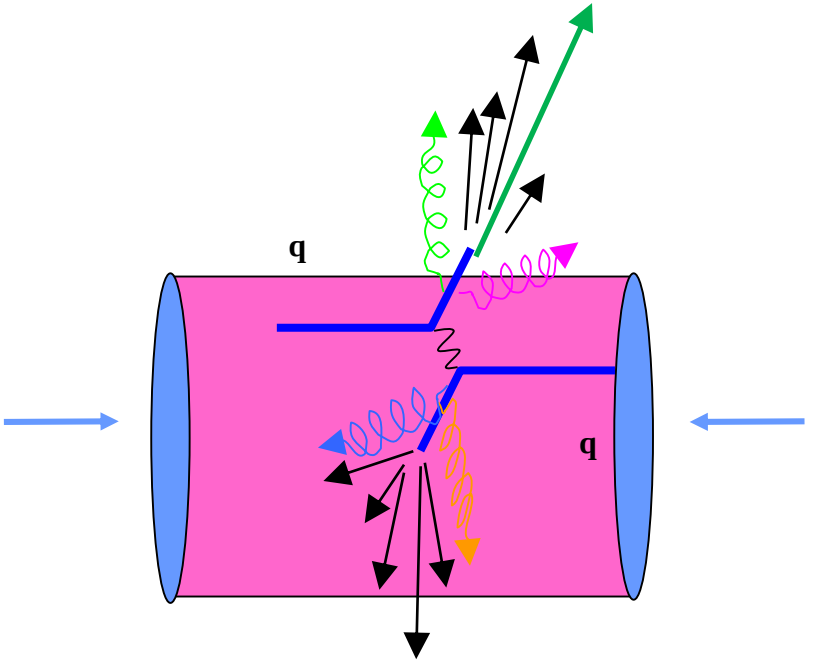
FERMILAB-Pub-82/59-THY
August, 1982

Energy Loss of Energetic Partons in Quark-Gluon Plasma:
Possible Extinction of High p_T Jets in Hadron-Hadron Collisions.

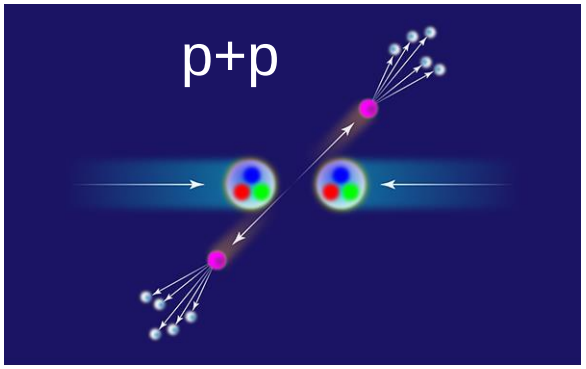
J. D. BJORKEN
Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

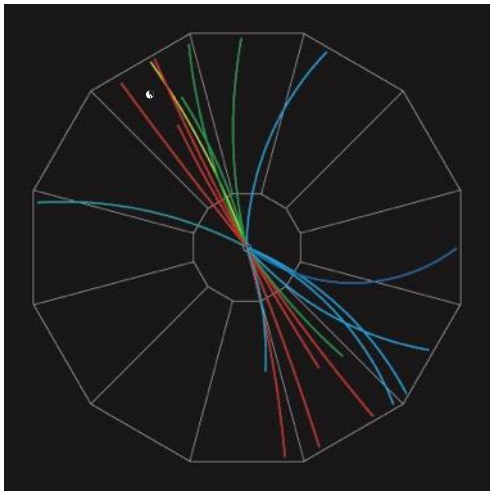
1982:
First idea by Bjorken on "Energy Loss of Energetic Partons in Quark-Gluon Plasma"

- ✓ High energy quarks and gluons propagating through quark gluon plasma suffer differential energy loss via elastic scattering from quanta in the plasma
- ➢ An interesting signature may be events in which the hard collisions occurs near the edge of the overlap region, with one jet escaping without absorption and the other fully absorbed

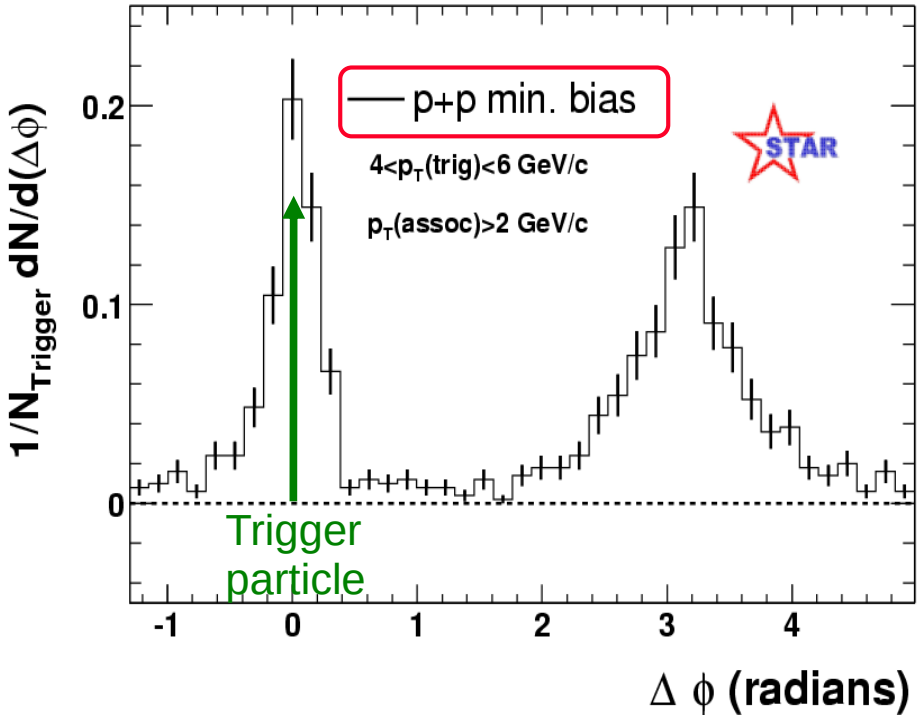


Di-hadron correlations



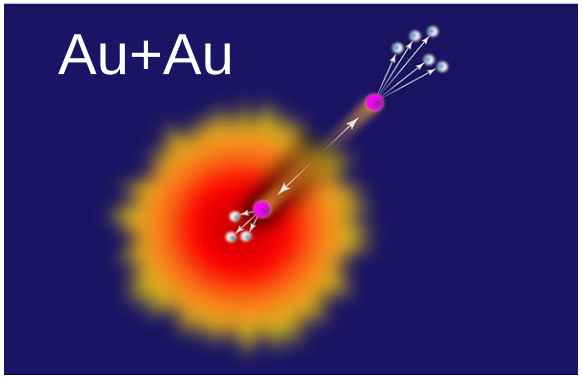


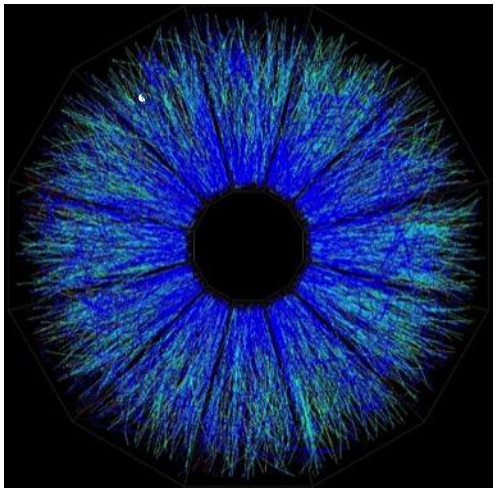
PRL 90 (2003) 082392



- ✓ study two particle angular correlations relative to high-p_T (trigger) particle:
- ✓ proxy for di-jet measurements
- ➢ in proton-proton collisions no suppression observed

Di-hadron correlations





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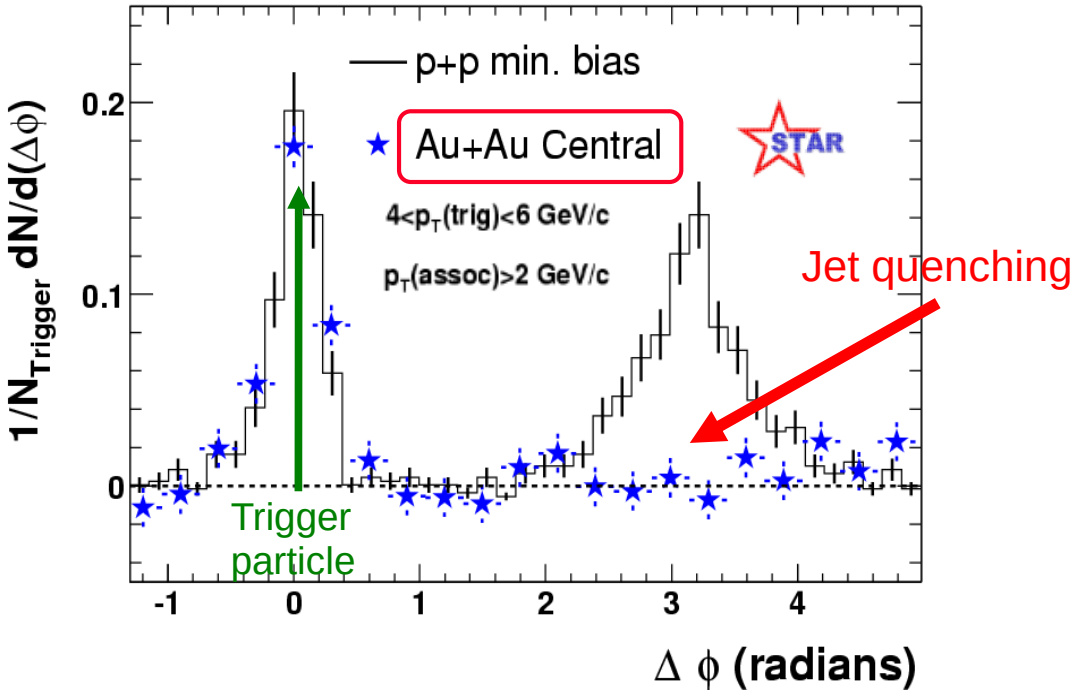
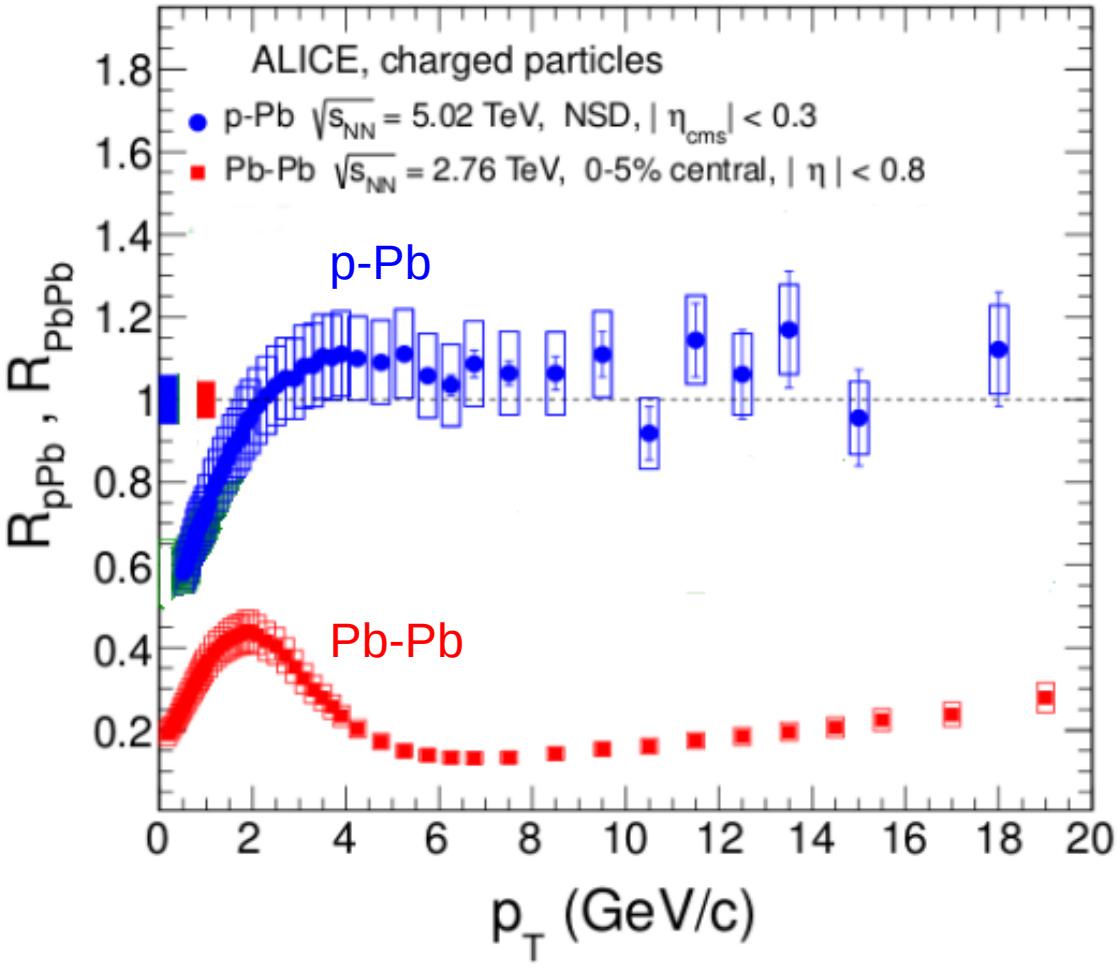


- ✓ in heavy ion collisions (Au-Au) recoiling jet is strongly suppressed by medium
- ➢ clear evidence for presence of very high density matter in central ion collisions

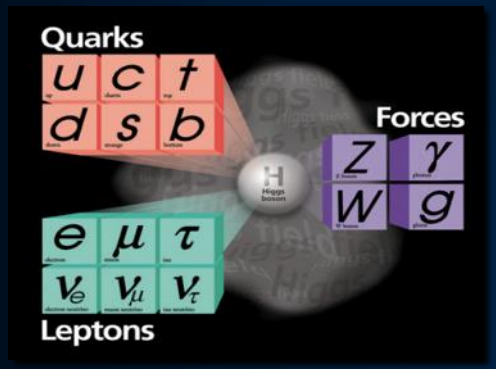
Leading particle suppression at the LHC

ALICE, PRL 110 (2013) 082302



- ✓ strong leading particle suppression also at LHC energies
- ➢ qualitatively similar to the one at RHIC

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



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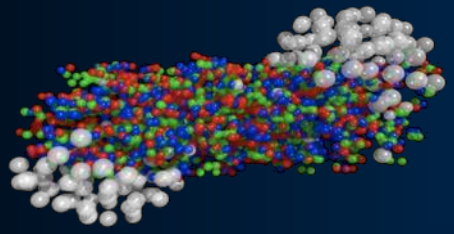

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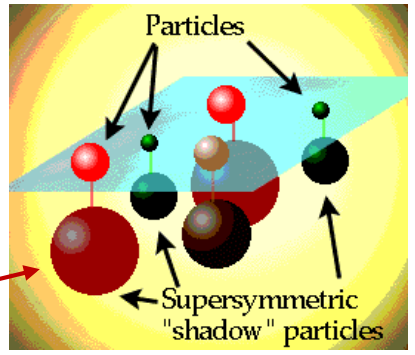
A possible candidate for Dark Matter: Supersymmetric Particles (SUSY)



Dark Matter candidate

Mirror "world" to the Standard Model particles:

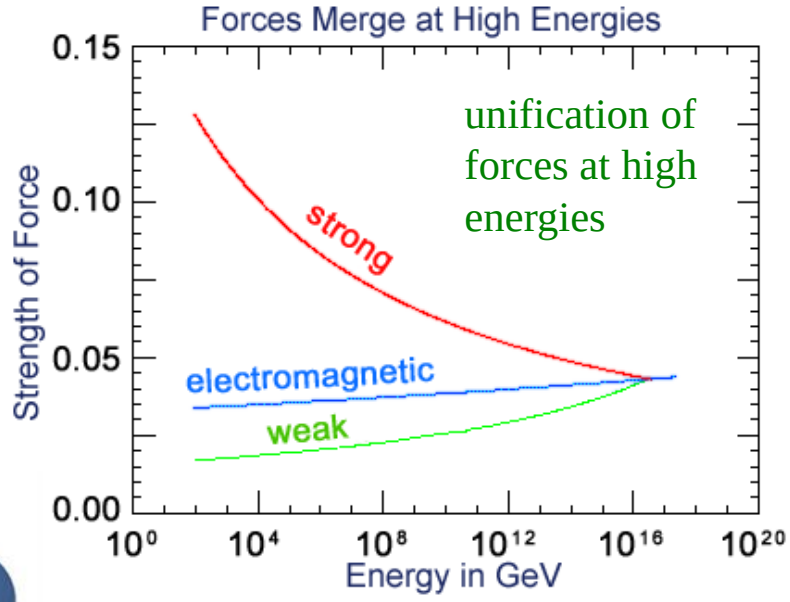
- for each SM particle a "super-partner" exists that differs only in ½-unit of spin

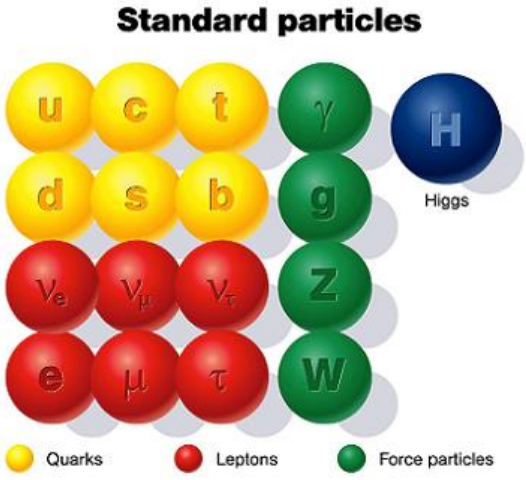
If lightest SUSY Particle (LSP) is stable:

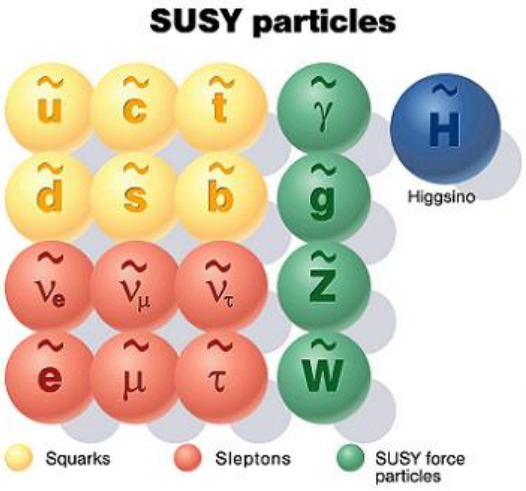
- offers "natural" dark-matter candidate

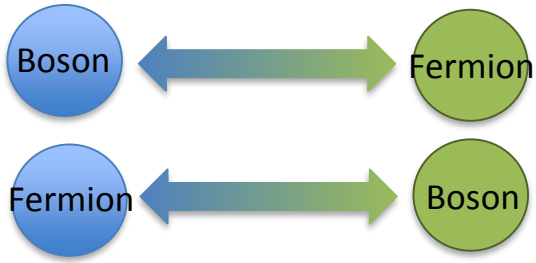
Grand Unification of all interactions:

- equality of strong, weak and electromagnetic couplings at ~10^{16} GeV

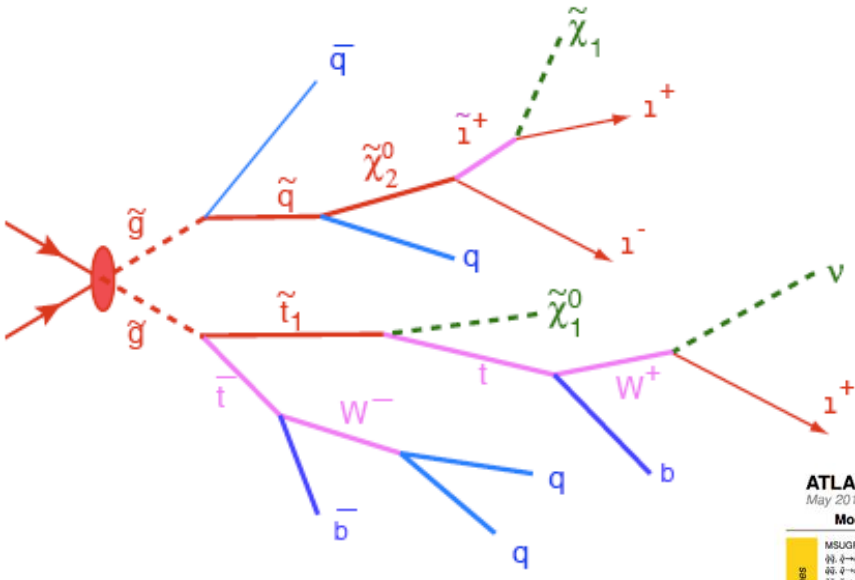








Signatures for SUSY



Missing Energy:

- from Lightest SUSY Particle (LSP)

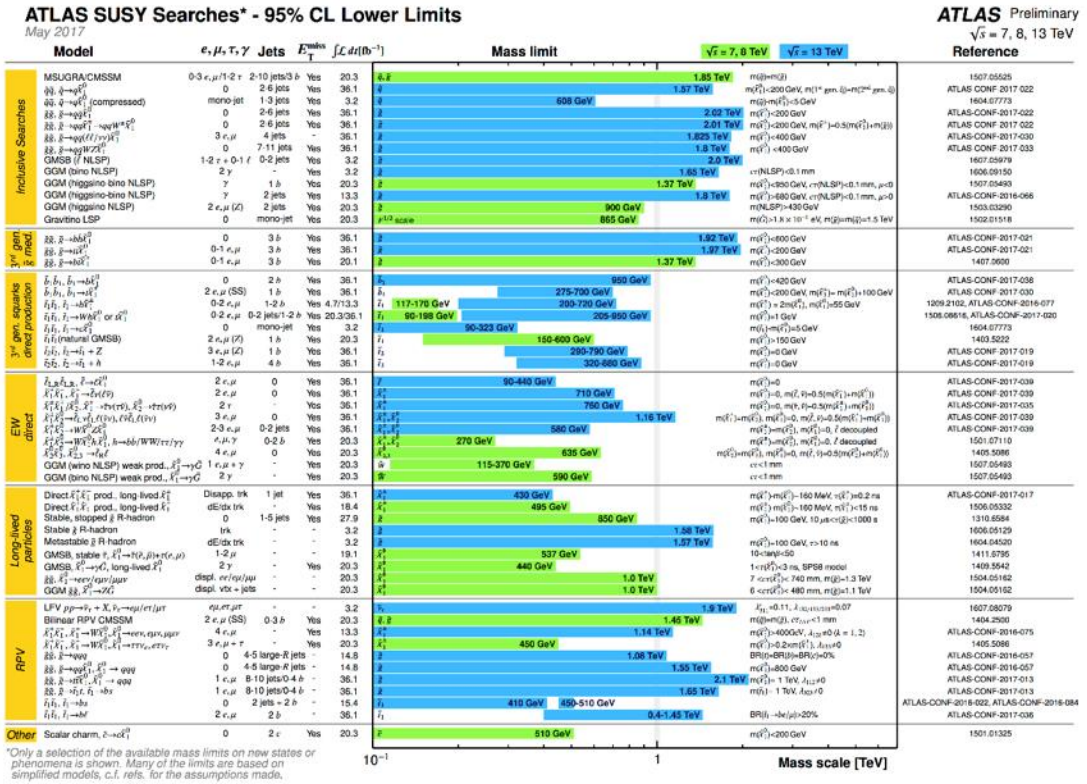
Multi-Jet:

- from cascade decay (gaugino)

Multi-Leptons:

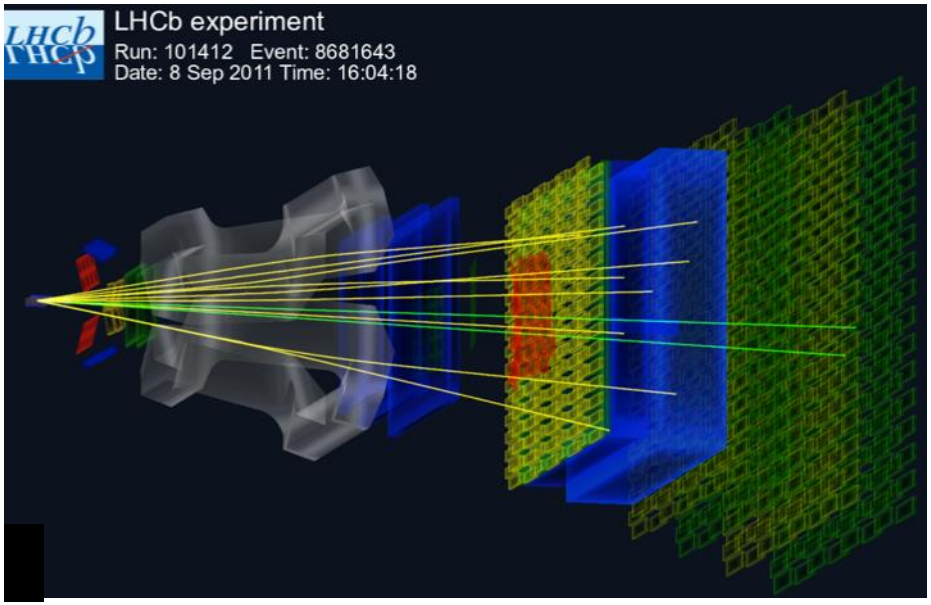
- from decay of charginos/neutralios

- NO sign of supersymmetric particles (so far)
- SUSY is only one of many Grand Unified Theories (GUT)
- NO significant signs of New Physics in general (so far)
- look at any kind of possible deviation from the Standard Model



Search for Physics Beyond the Standard Model

e.g. search for very rare $B_s \rightarrow \mu\,\mu$



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日本語要約

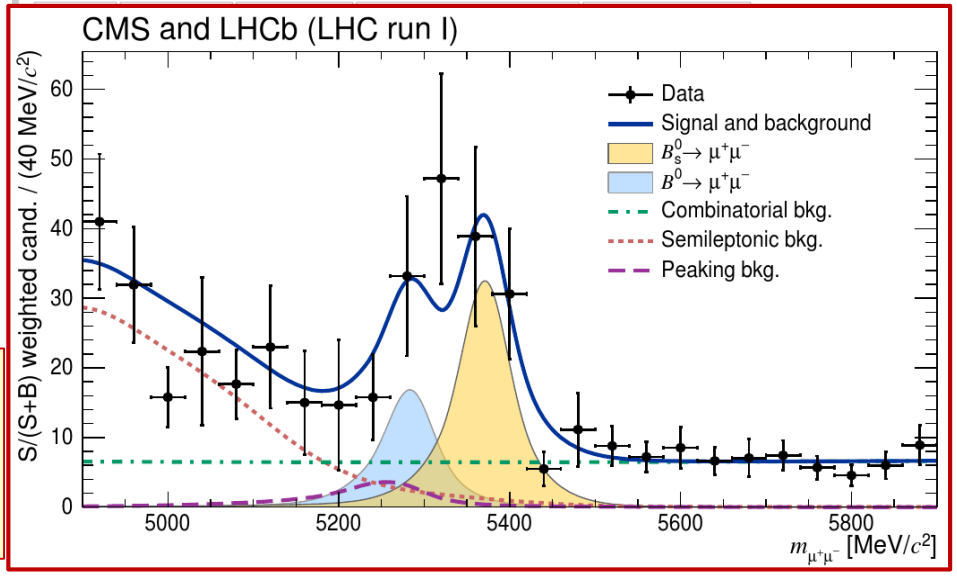
Observation of the rare $B_s^0 \rightarrow \mu^+\mu^-$ decay from the combined analysis of CMS and LHCb data

CMS Collaboration & LHCb Collaboration

Affiliations | Contributions | Corresponding authors

Nature **522**, 68–72 (04 June 2015) | doi:10.1038/nature14474

Received 12 November 2014 | Accepted 31 March 2015 | Published online 13 May 2015



in Standard Model → super-rare decay :

$B(B_d \rightarrow \mu\,\mu) = (1.06 \pm 0.09) \times 10^{-10}$

$B(B_s \rightarrow \mu\,\mu) = (3.65 \pm 0.23) \times 10^{-9}$

[C.Bobeth et al.: arXiv:1311.0903]

- ✓ good probe to test SM to high precision
- ✓ enhancement predicted for SUSY models
- ➢ measurement confirms SM prediction at 5σ!

Conclusion

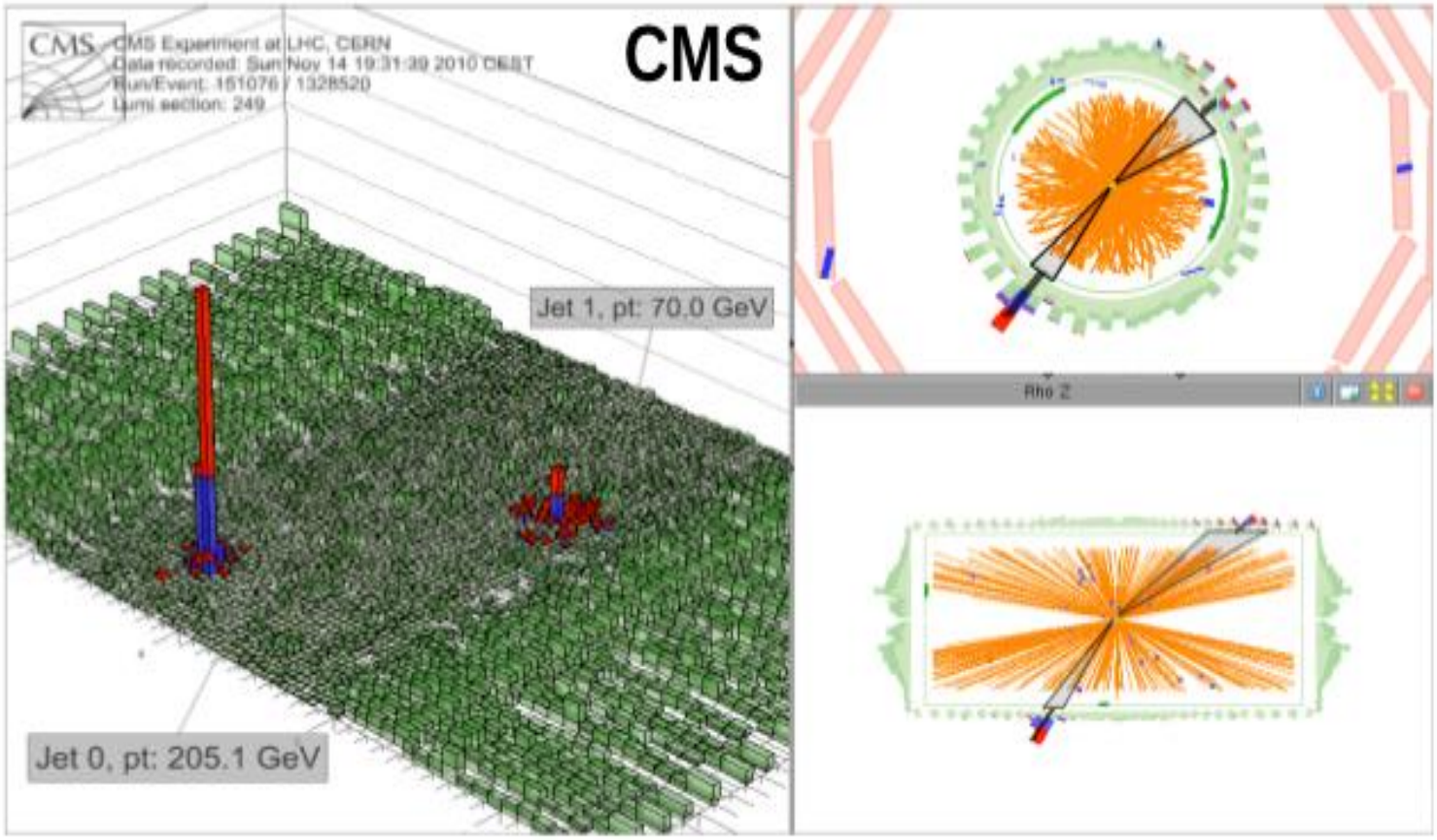
- ✓ After the discovery of the Higgs boson, the Standard Model of particle physics is now "complete"!
- ✓ However, this explains only ~5% of our universe and many questions in understanding the origin of our universe are yet to be resolved.
- ✓ Powerful particle accelerators and sophisticated detectors 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.
- ✓ Since last year LHC is running in a very efficient "production mode" and the experiments are collecting a vast amount of data that will lead to many high precision measurements.

- ➢ 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

Jet quenching in di-jet events

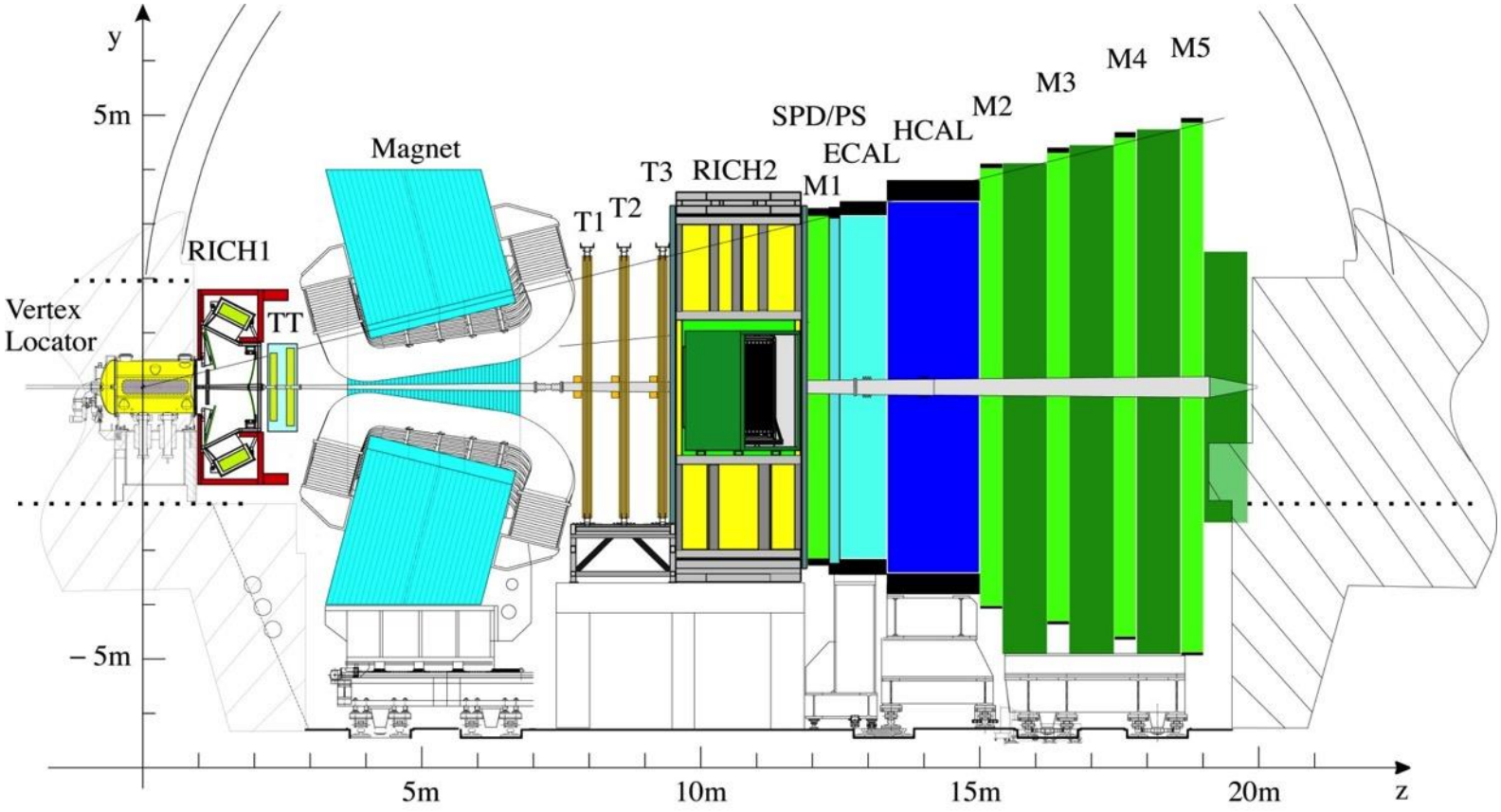
Can even be seen in event displays !!!



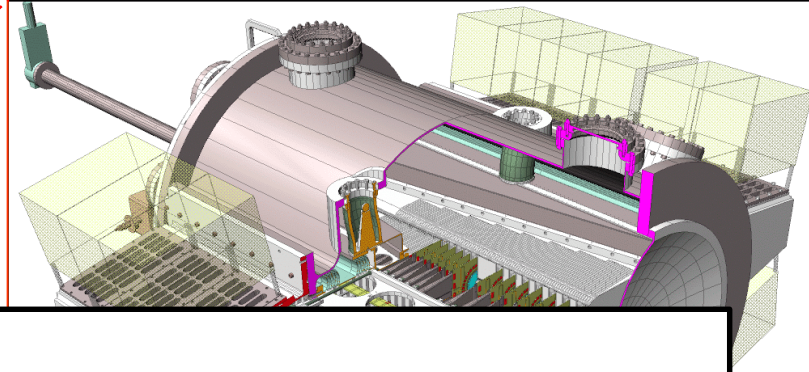
$$A_{\mathrm{J}} = \frac{E_{\mathrm{T1}} - E_{\mathrm{T2}}}{E_{\mathrm{T1}} + E_{\mathrm{T2}}}, \quad \Delta\varphi_{12} > \frac{\pi}{2}$$

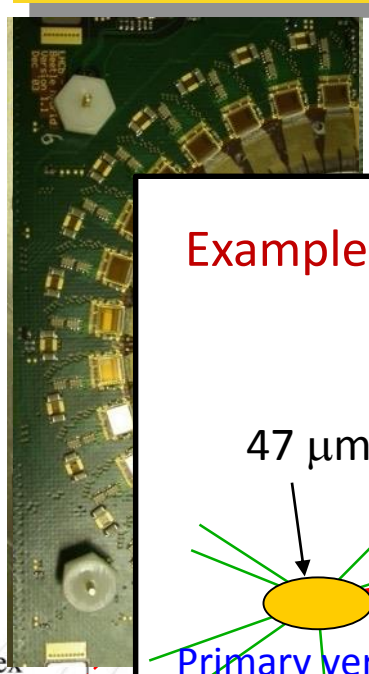
A walk through the LHCb detector

(with the example of a complex decay: $B_s \rightarrow D_s K$)

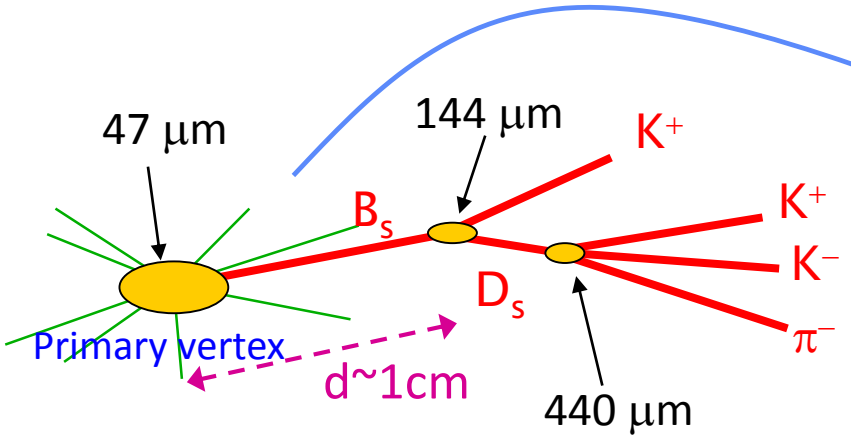


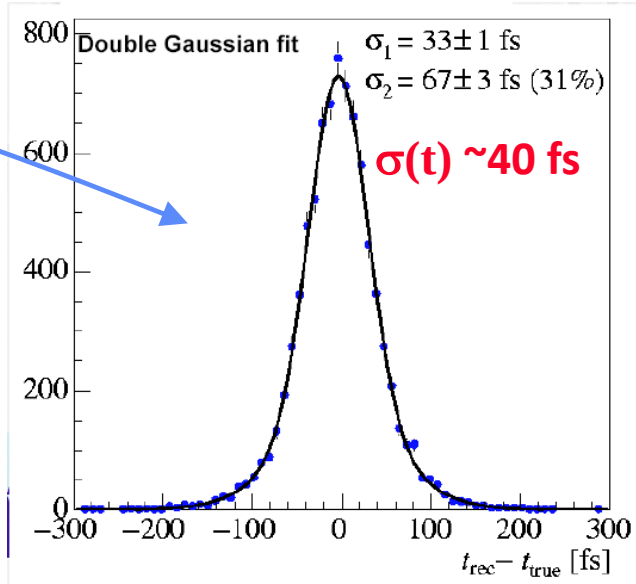
B-Vertex Measurement

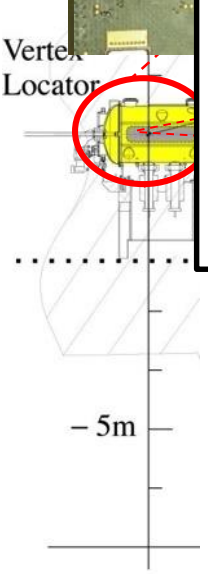




Example: $B_s \rightarrow D_s K$





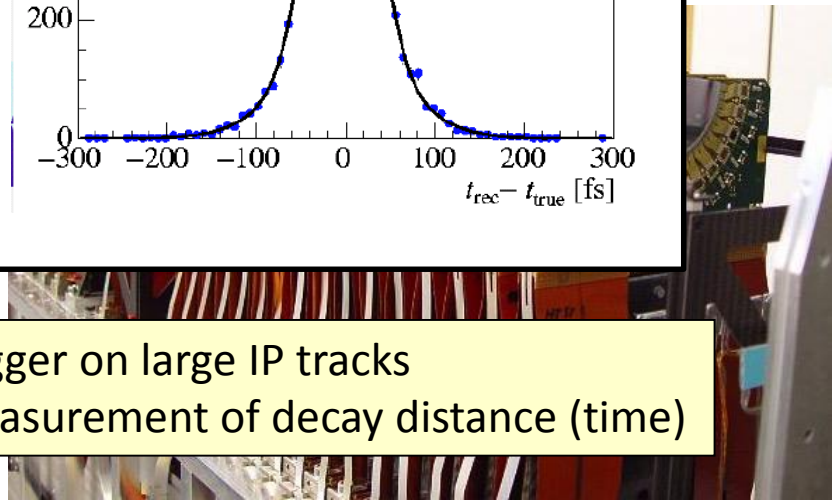


Vertex Locator (Velo)

21 stations of silicon strip detectors (r-ϕ)

~ 8 μm hit resolution

~25 μm IP resolution



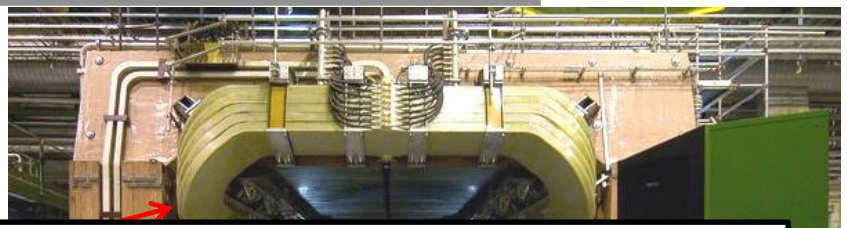
- Trigger on large IP tracks
- Measurement of decay distance (time)

Momentum measurement

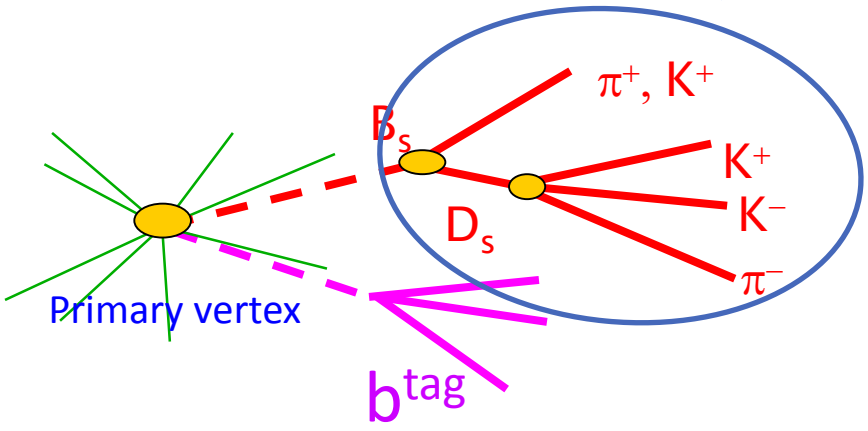
Outer Tracker

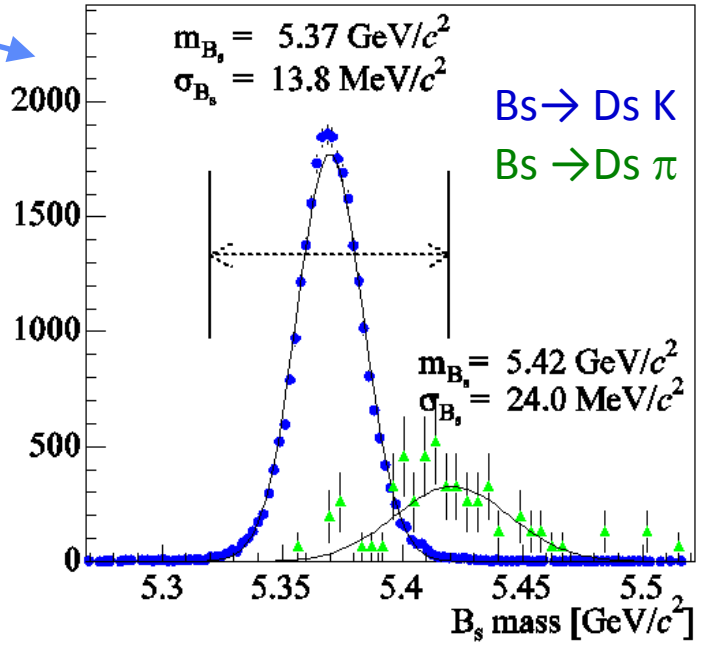
24 layer Straws σ_{hit}~200μm

σ_p/p~0.5%



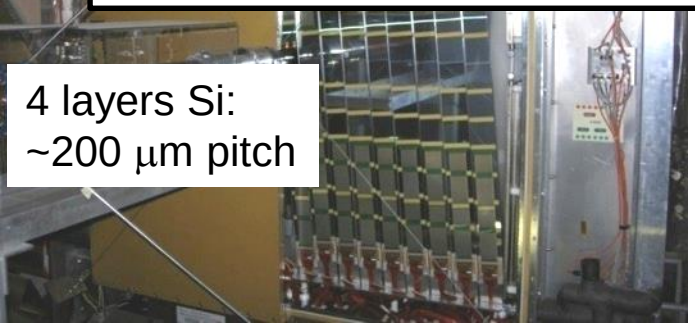
Mass resolution: σ ~ 14 MeV

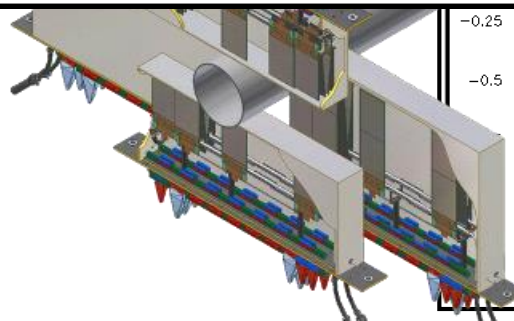


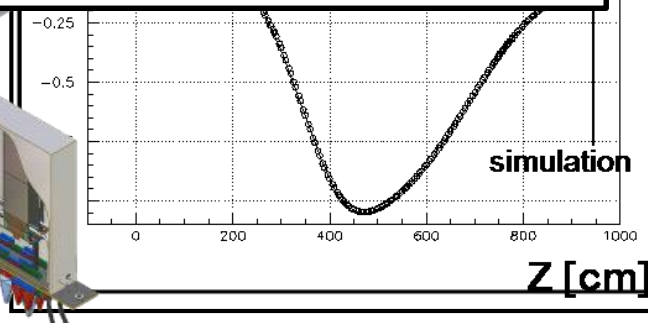


Tri Tra

4 layers Si: ~200 μm pitch

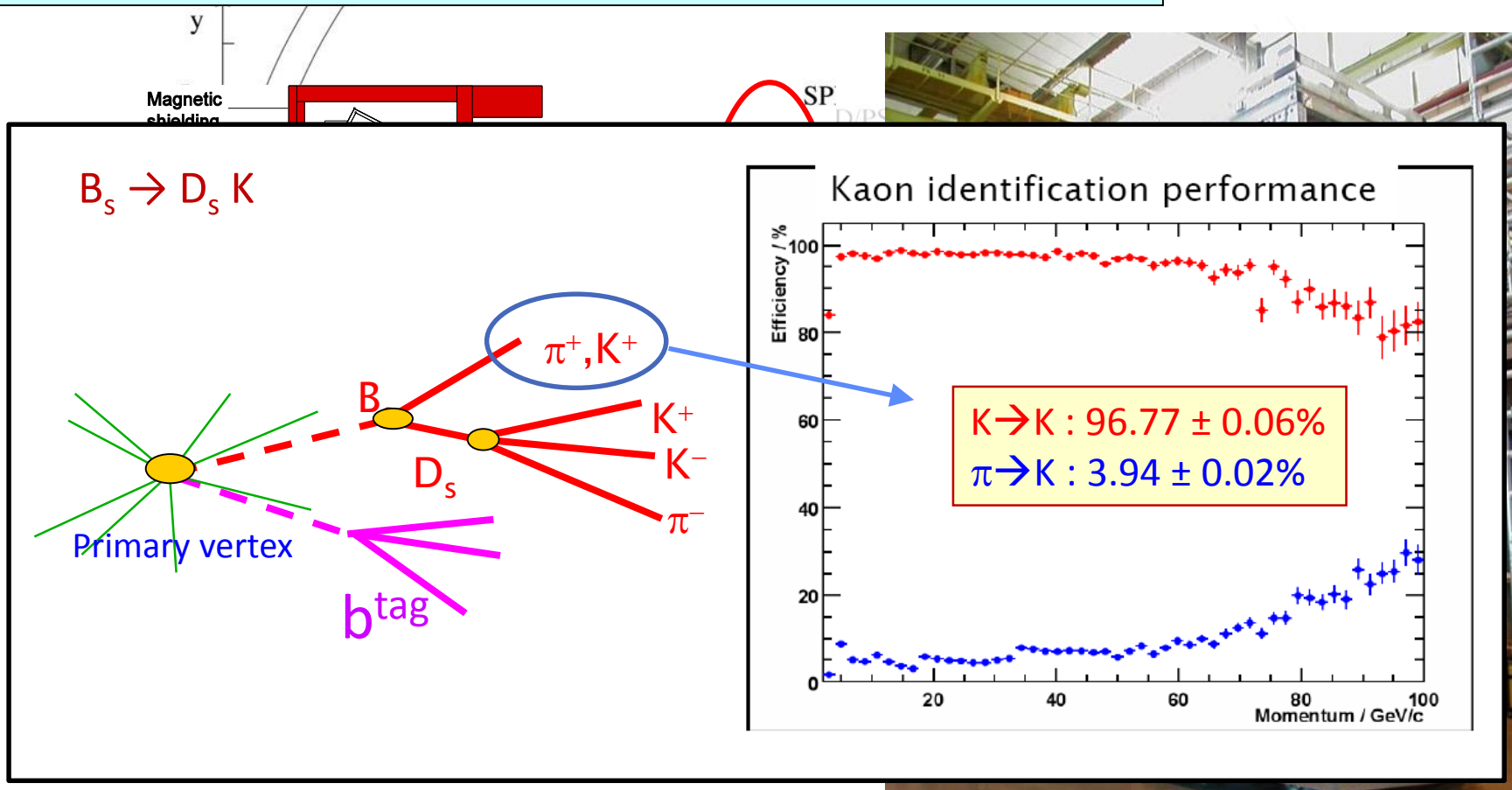


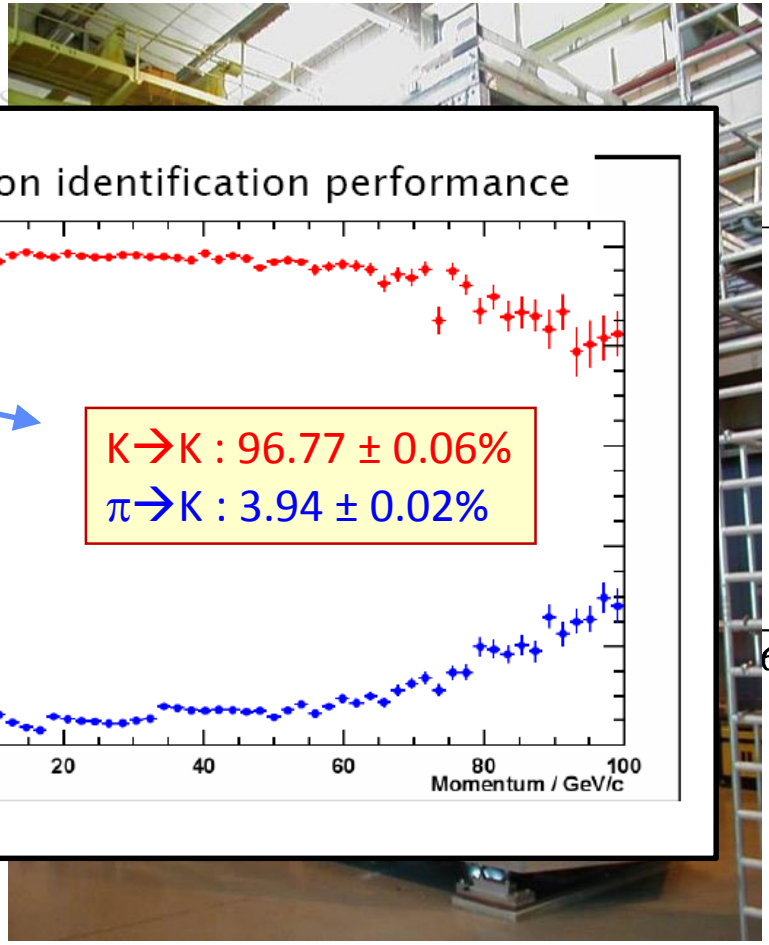




Particle Identification

RICH: K/π identification using Cherenkov light emission angle

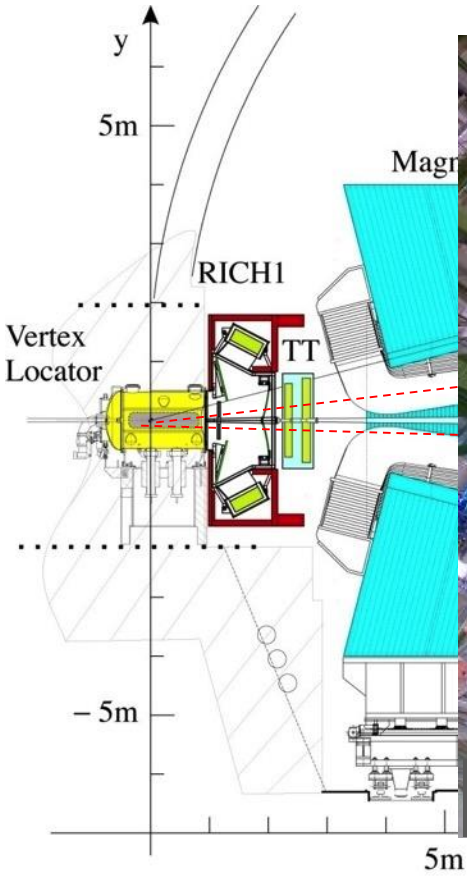


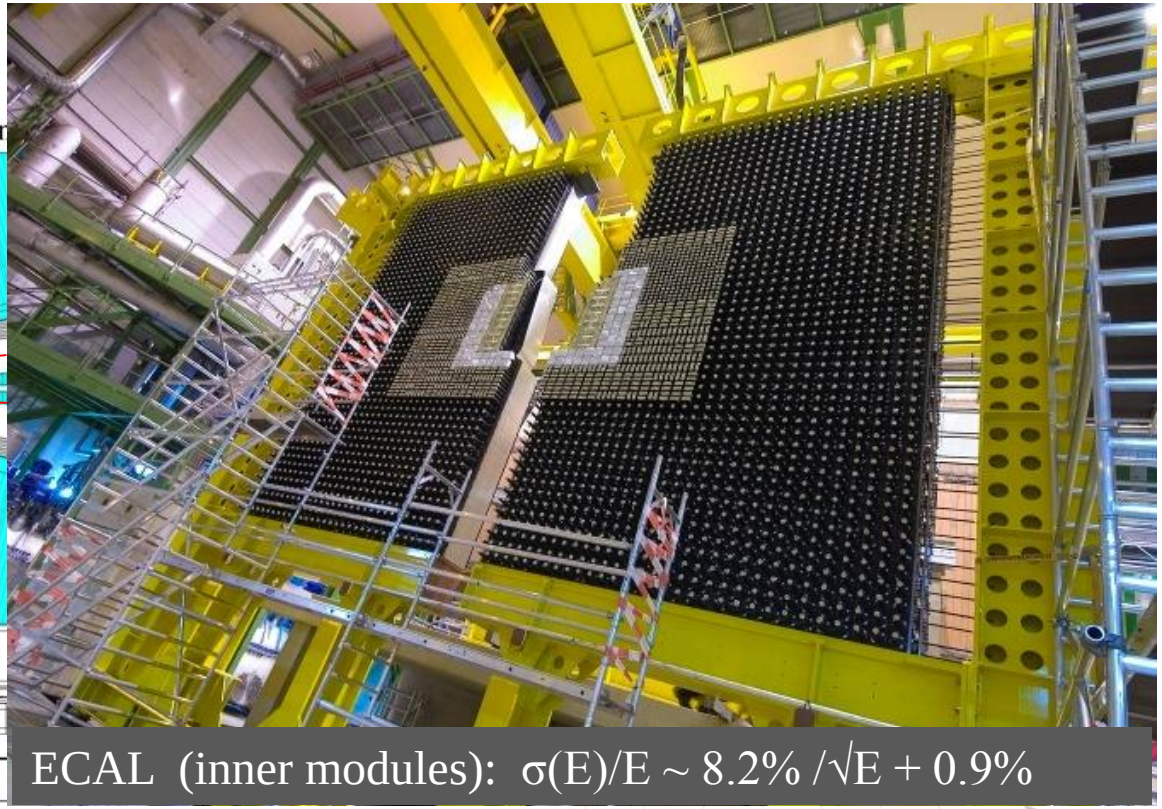


RICH1: 5 cm aerogel n=1.03
4 m^3 C_4F_{10} n=1.0014

RICH2: 100 m^3 CF_4 n=1.0005

Particle identification and L0 trigger

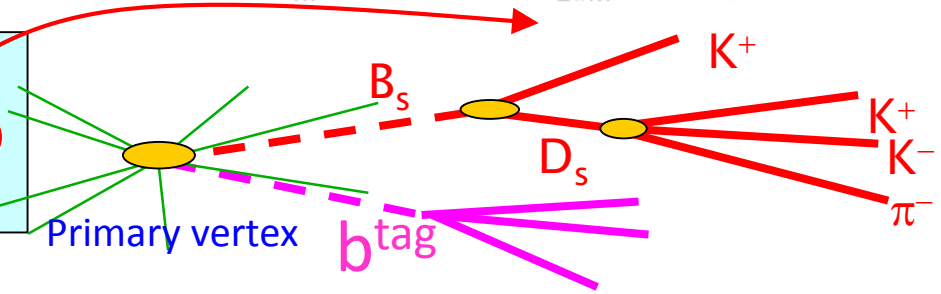




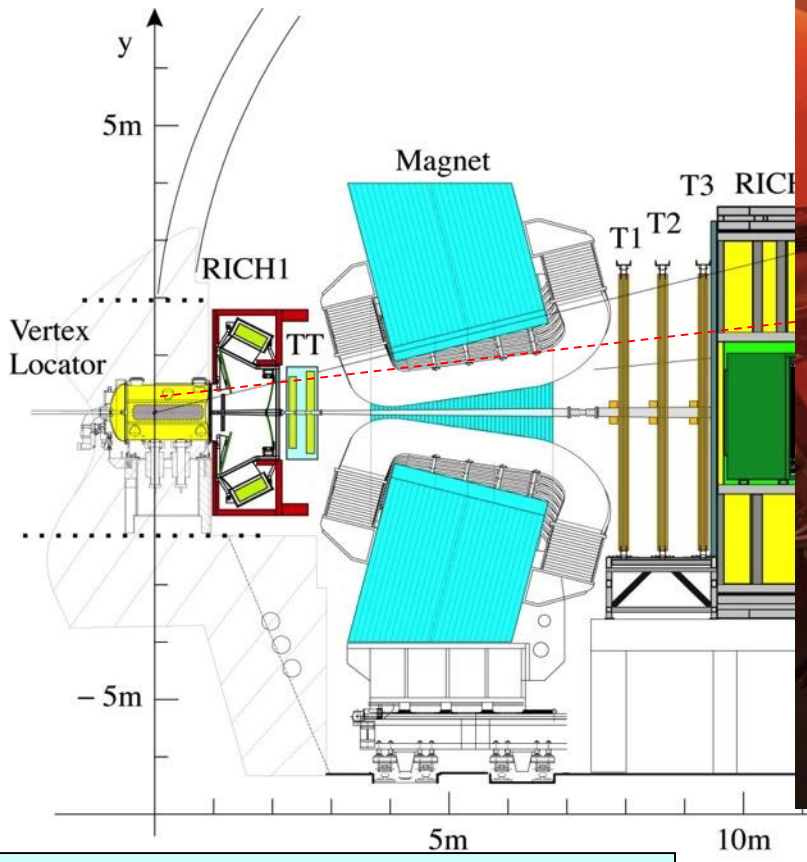
ECAL (inner modules): $\sigma(E)/E \sim 8.2\% /\sqrt{E} + 0.9\%$

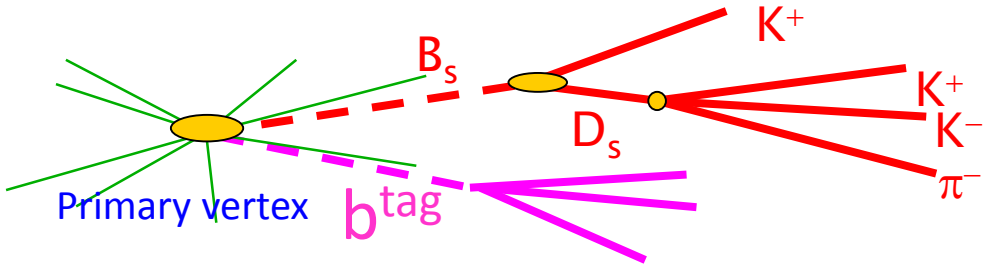
Calorimeter system :

- Level 0 trigger: high E_T electron and hadron
- Identify electrons, hadrons, π^0 ,γ



Particle identification and L0 trigger



Muon system:

- Level 0 trigger: High P_t muons
- Identify muon
  (also important for flavour tagging)