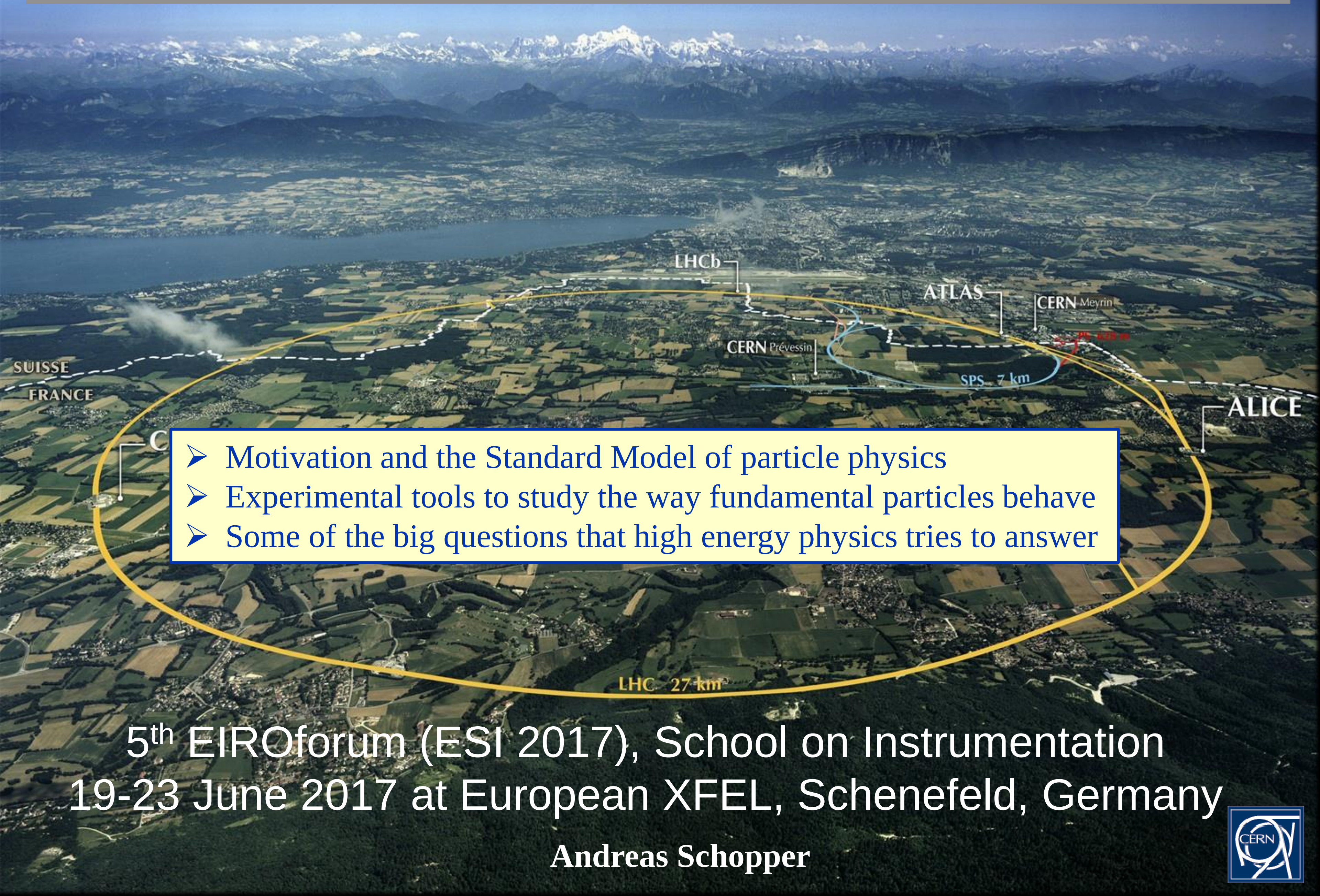
An introduction to High Energy Physics at CERN



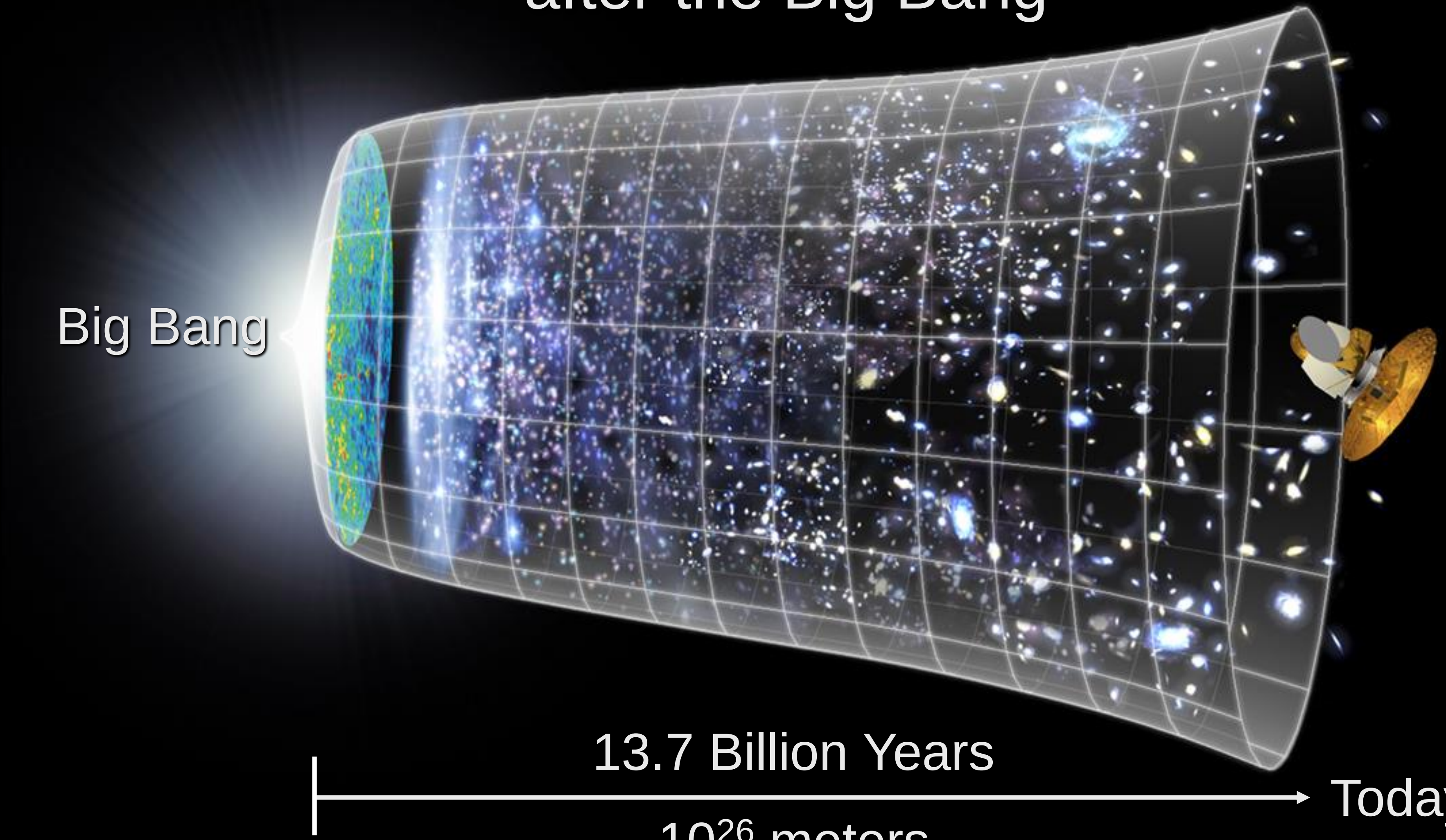
- Motivation and the Standard Model of particle physics
- Experimental tools to study the way fundamental particles behave
- Some of the big questions that high energy physics tries to answer

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

Andreas Schopper

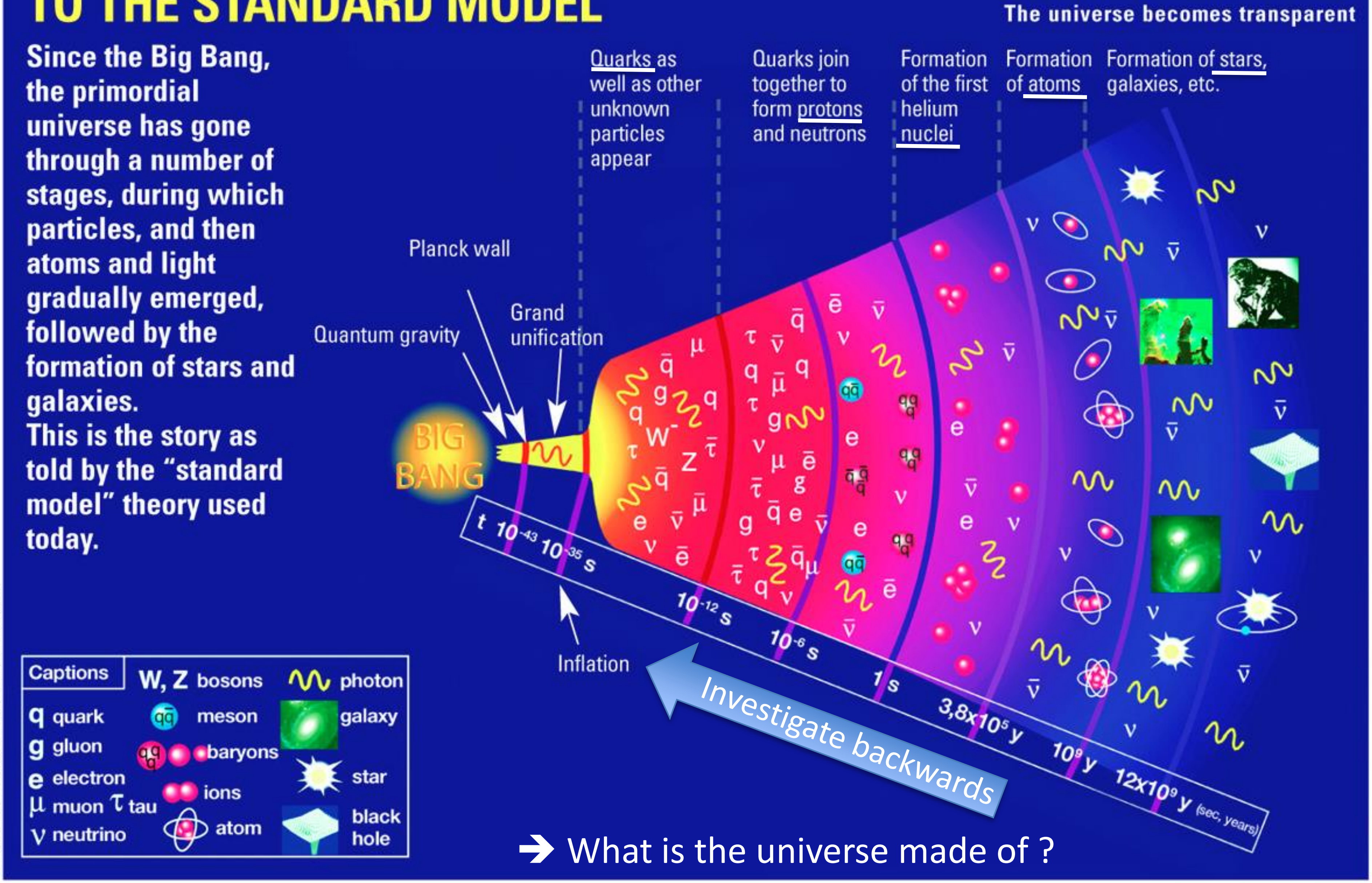
Contribute to the Scientific Challenge

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



THE UNIVERSE ACCORDING TO THE STANDARD MODEL

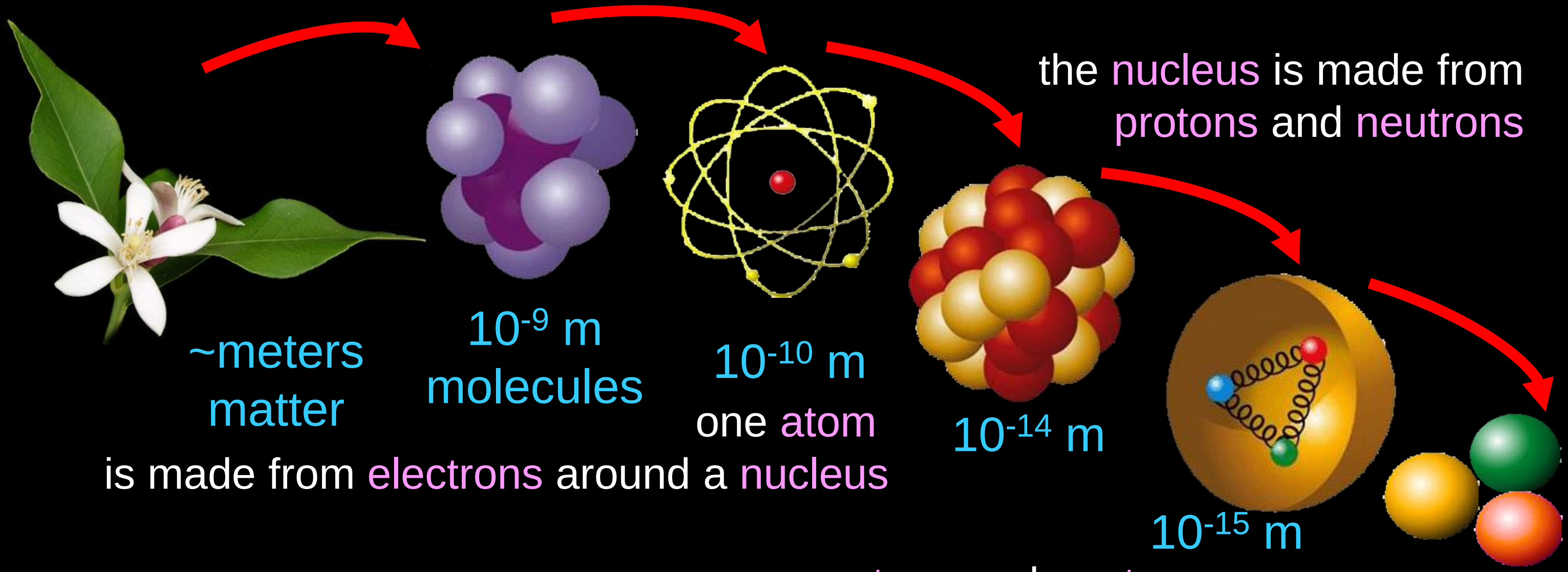
Since the Big Bang, the primordial universe has gone through a number of stages, during which particles, and then atoms and light gradually emerged, followed by the formation of stars and galaxies. This is the story as told by the "standard model" theory used today.



➔ What is the universe made of ?

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

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

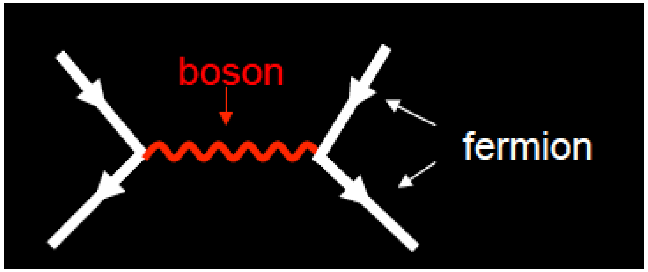
protons and neutrons
contain quarks

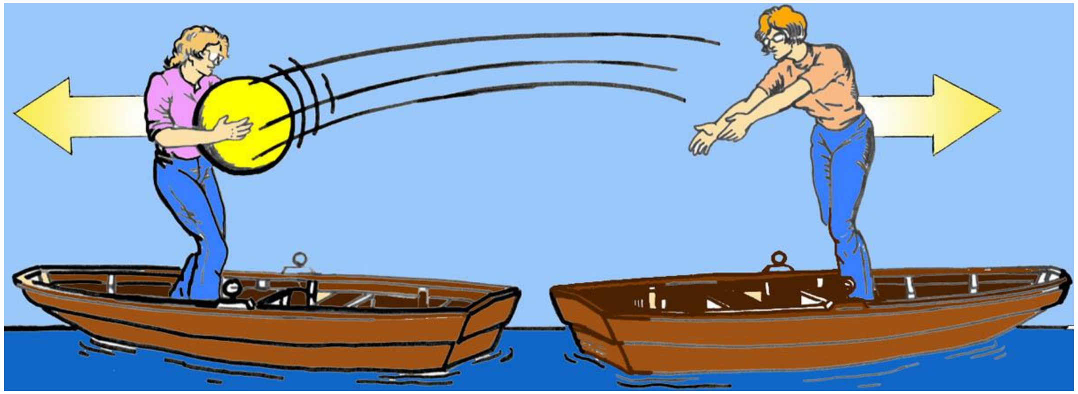
$<10^{-18}$ m
quarks, electrons
(= fermions)

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

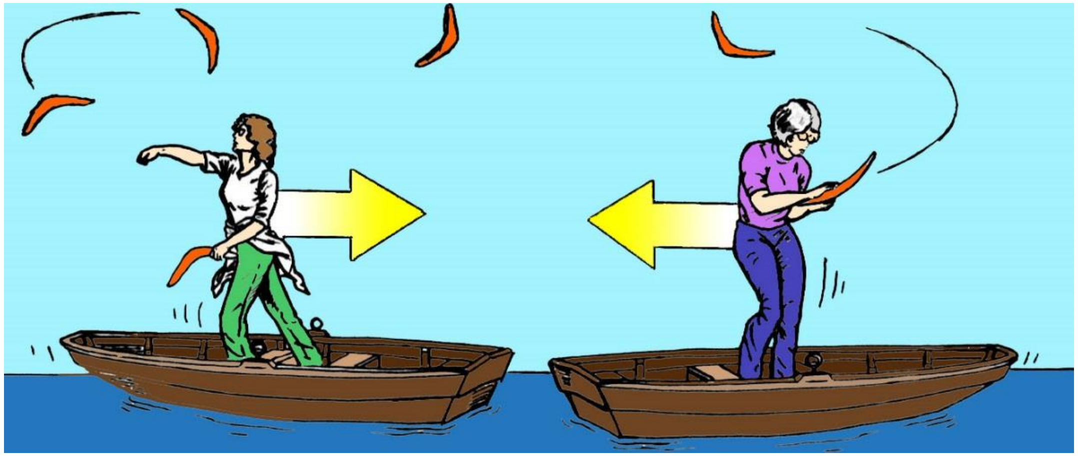
The Fundamental Forces

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



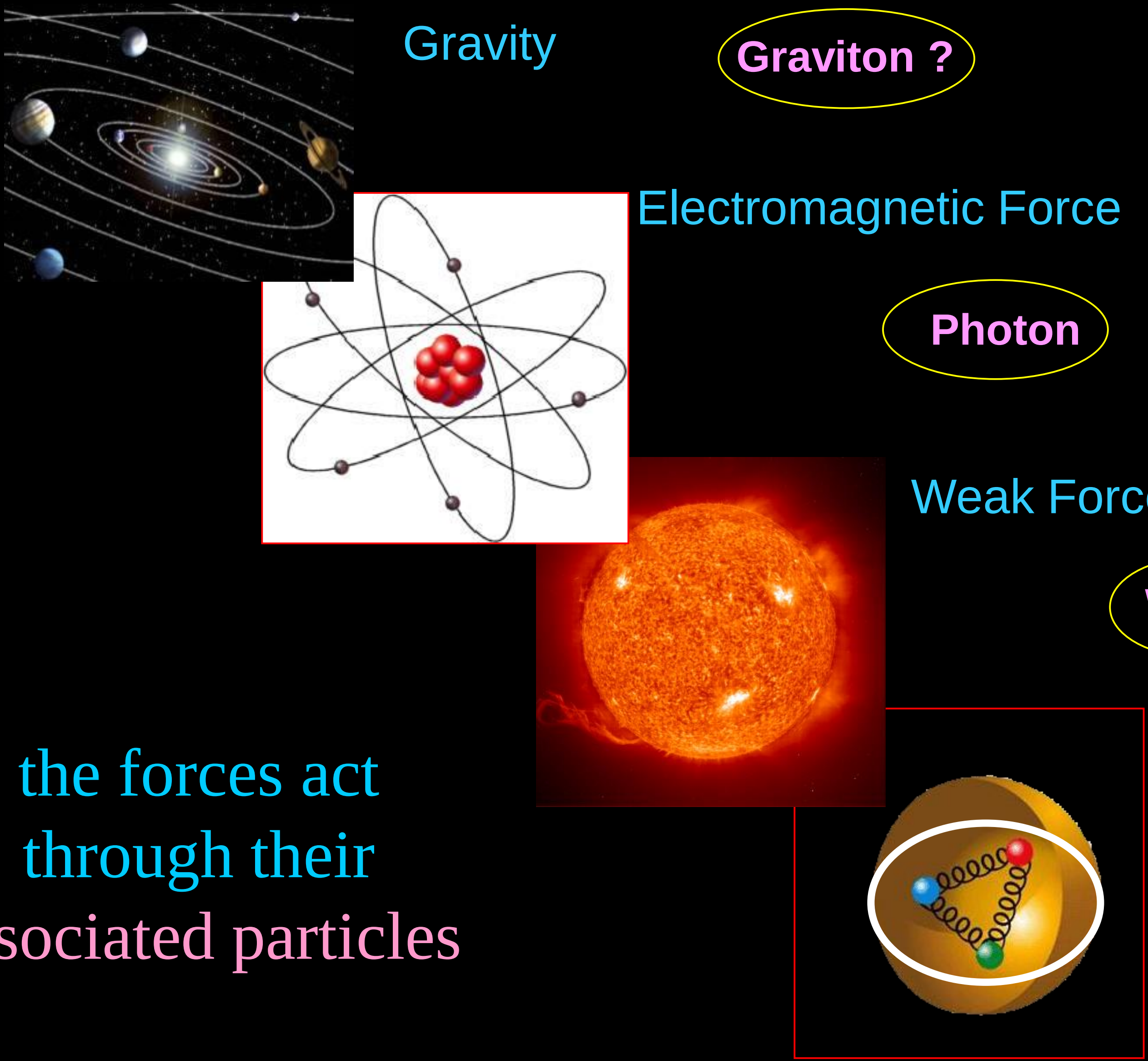


- repulsive



- attractive

The Fundamental Forces



Gravity

Graviton ?

Electromagnetic Force

Photon

Weak Force

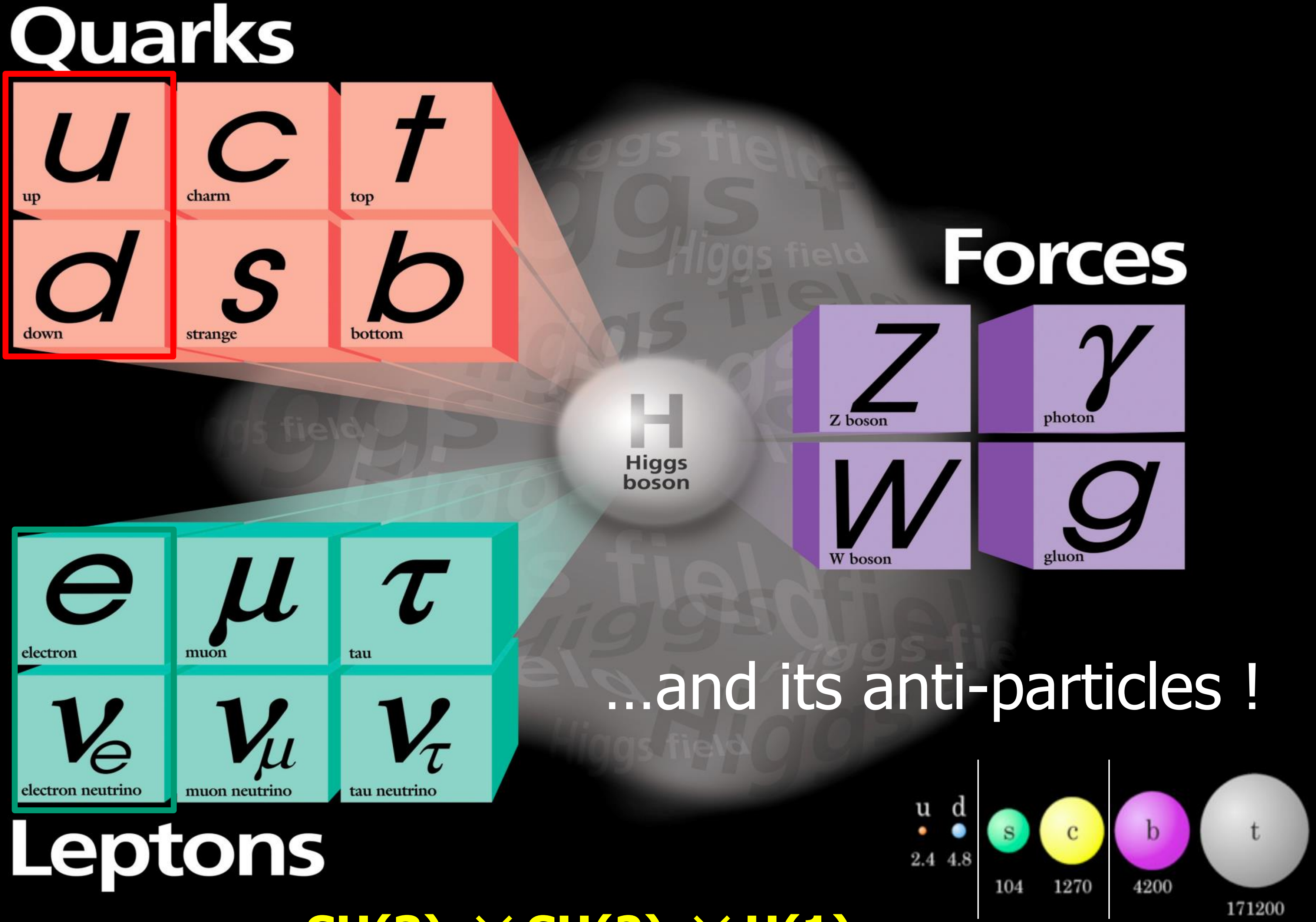
W, Z

Strong Force

Gluon

the forces act
through their
associated particles

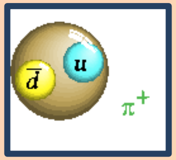
The Standard Model of Particle Physics



…and its anti-particles !

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

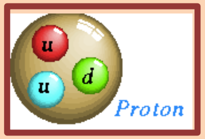
Building the "zoo" of elementary particles



quarks

↓

hadrons



mesons
(1 quark and
1 antiquark)

↓

π±, K±, J/ψ, etc.

baryons
(3 quarks or
3 antiquarks)

↓

p, n, Σ^+, Δ^0, etc.

leptons

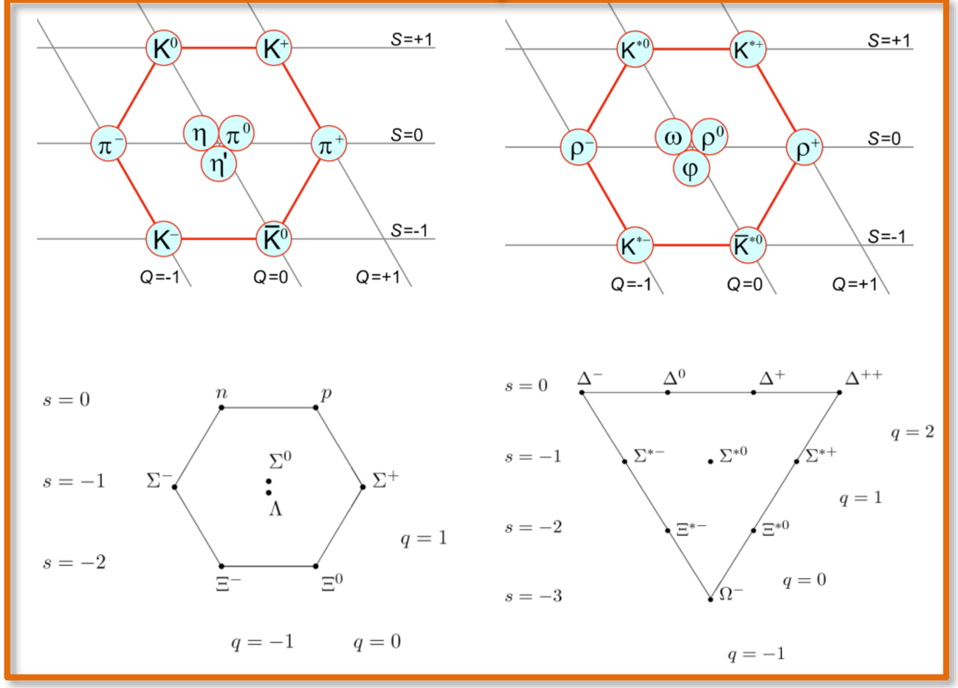
↓

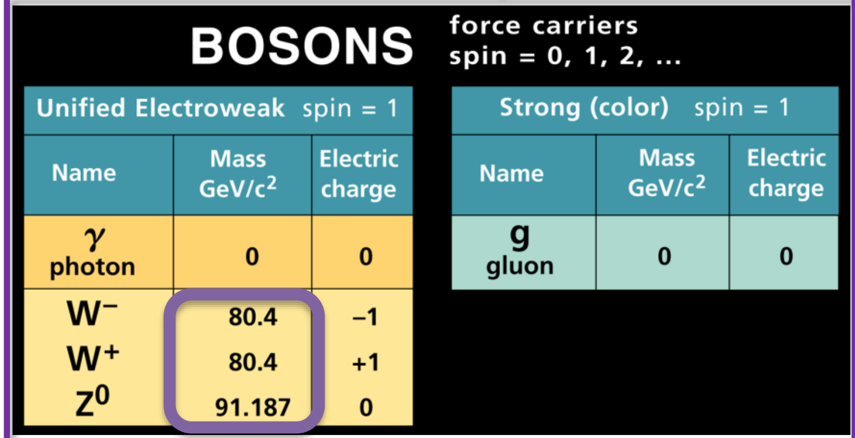
electron,
muon, tau
and neutrinos

bosons

↓

gluon, photon,
Z boson,
W boson





BOSONS

force carriers
spin = 0, 1, 2, …

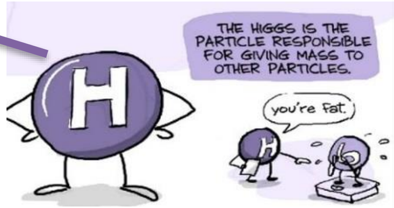
Unified Electroweak spin = 1

Name	Mass GeV/c²	Electric charge
γ photon	0	0
W−	80.4	−1
W+	80.4	+1
Z0	91.187	0

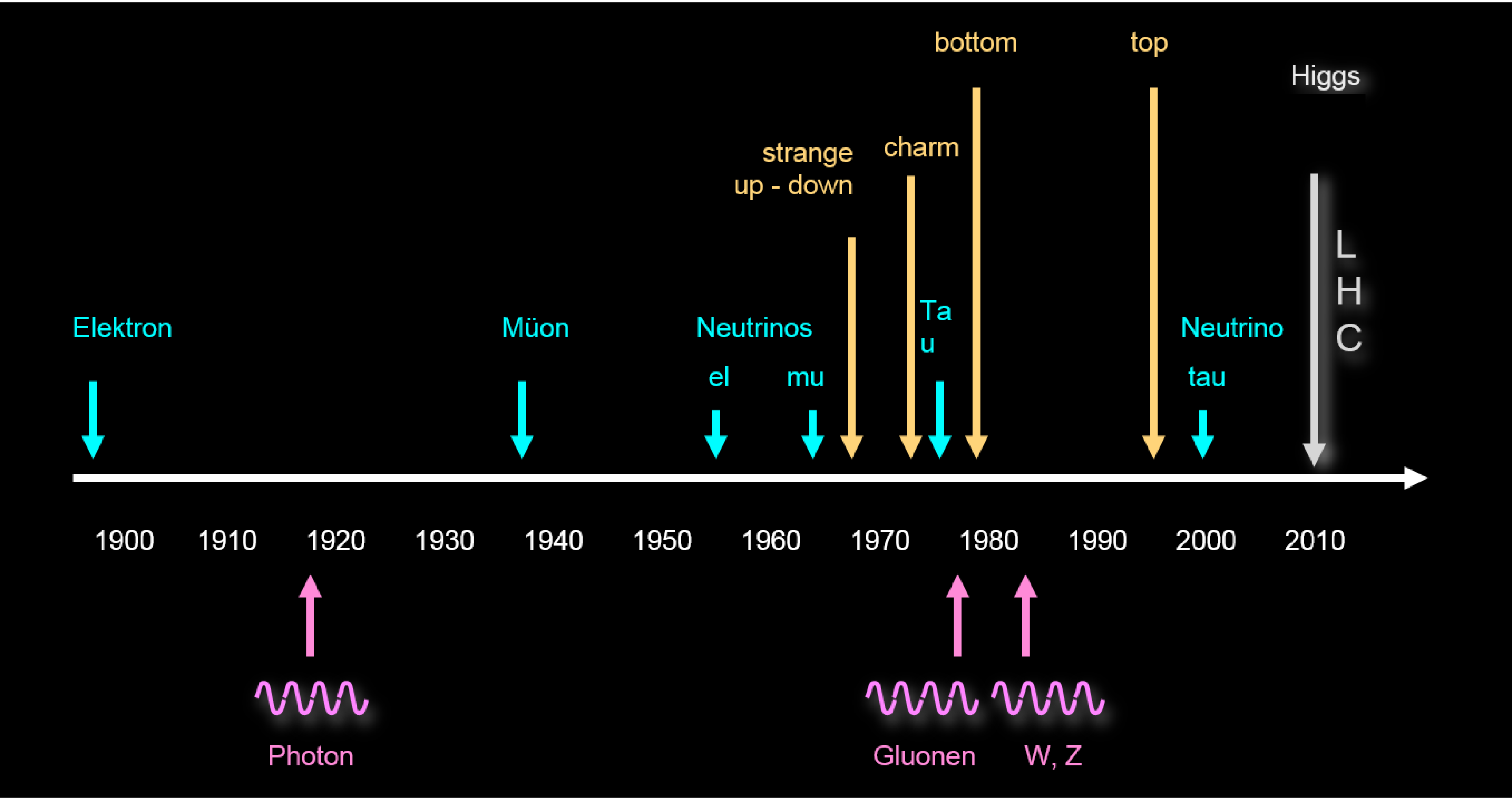
Strong (color) spin = 1

Name	Mass GeV/c²	Electric charge
g gluon	0	0

Massive bosons
require a new potential
in the Standard Model!



Discovery of Standard Model constituents

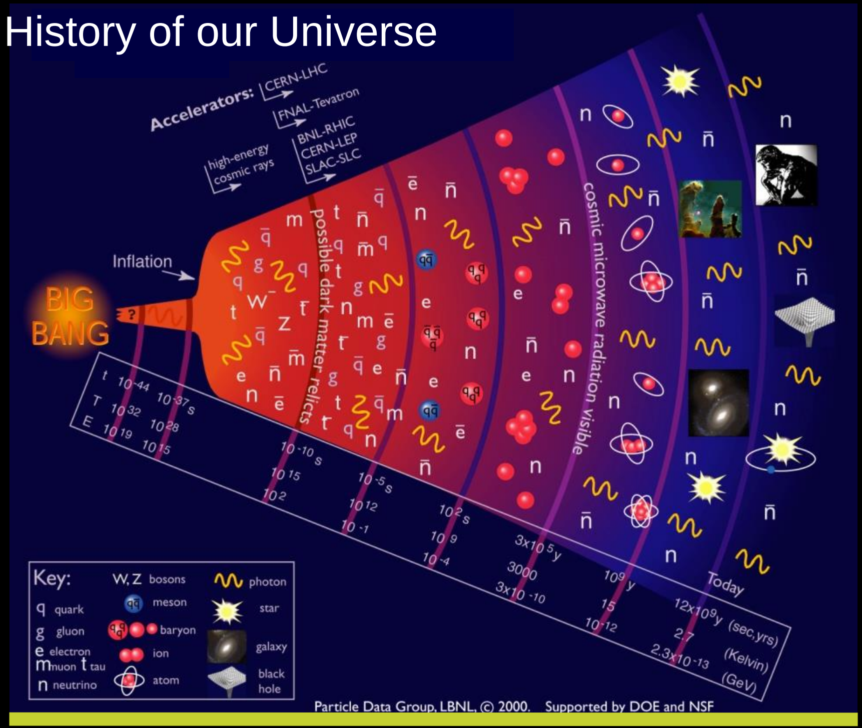


→ The Standard Model is complete !

→ But have we understood everything ?

More Questions ....

BIG BANG


History of our Universe

Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

NOW

The same amount of matter & antimatter was created

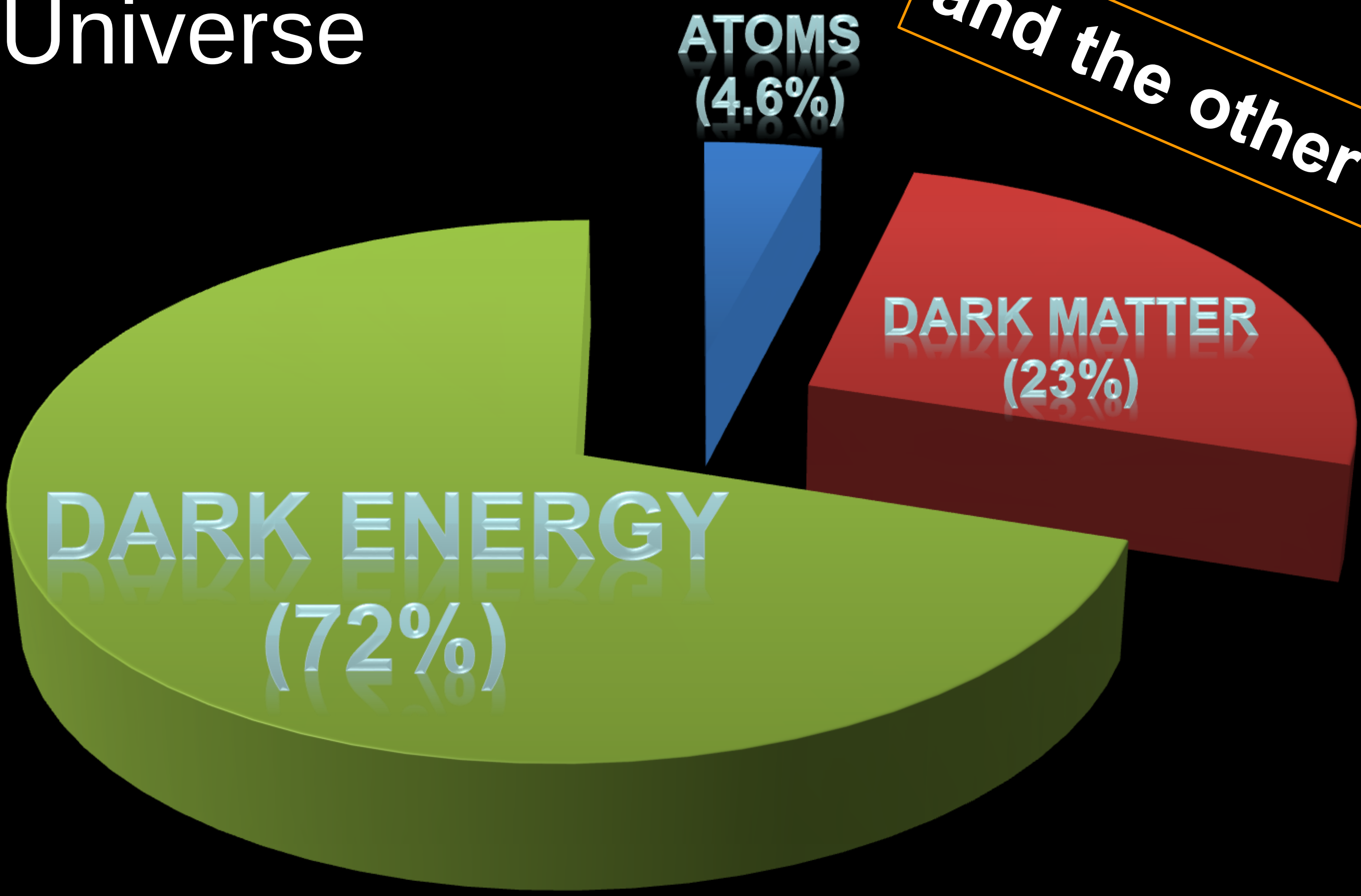
\> > >

Only matter (us) survives

Why?

More Questions ....

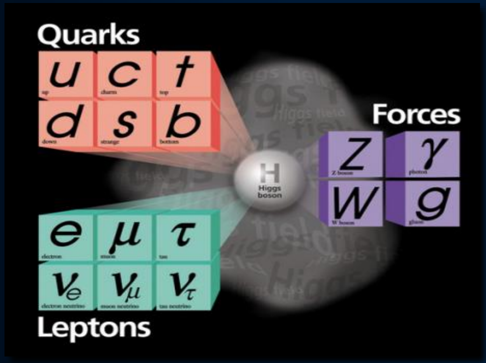
Our Universe



and the other 95%?

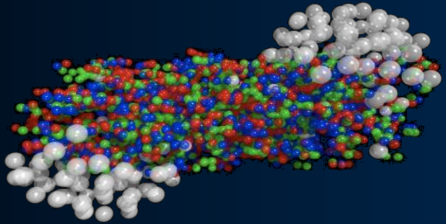
Leaving this stuff for the cosmologists

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?

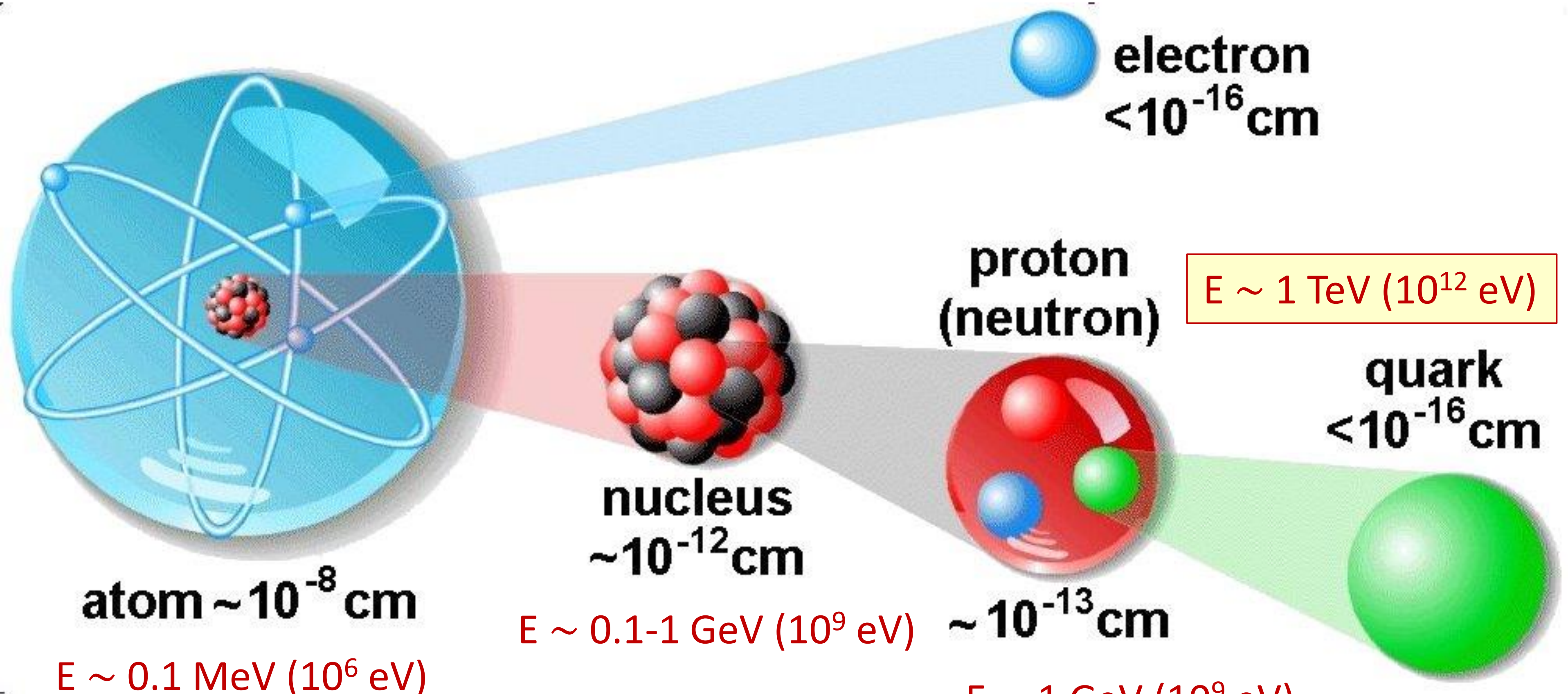
Will we find the particle(s) that make up the mysterious ‘dark matter’ in our Universe?

How do we explore 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 MeV (10^{6} eV)

E ∼ 0.1-1 GeV (10^{9} eV)

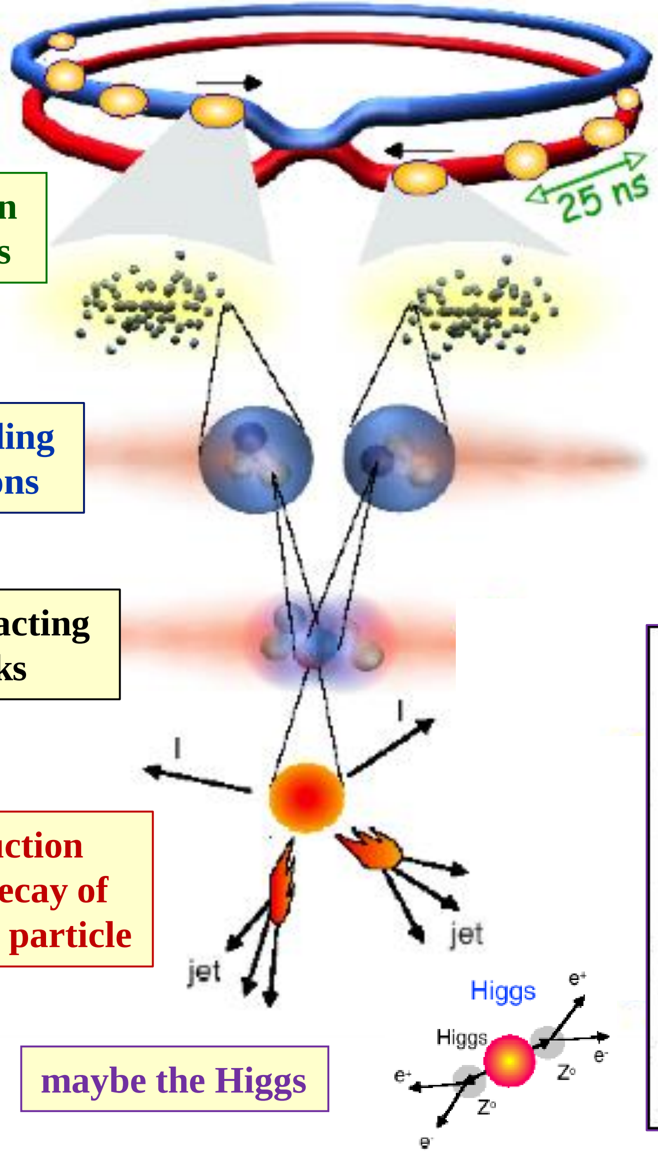
E ∼ 1 GeV (10^{9} eV)

How do we explore such small scales?

13 TeV LHC

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.



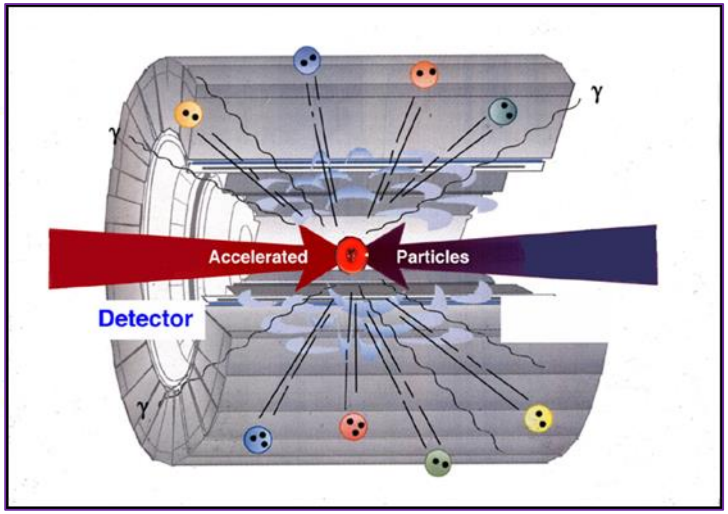
proton beams

colliding protons

interacting quarks

production and decay of a new particle

maybe the Higgs



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

Requirements to such a super-microscope

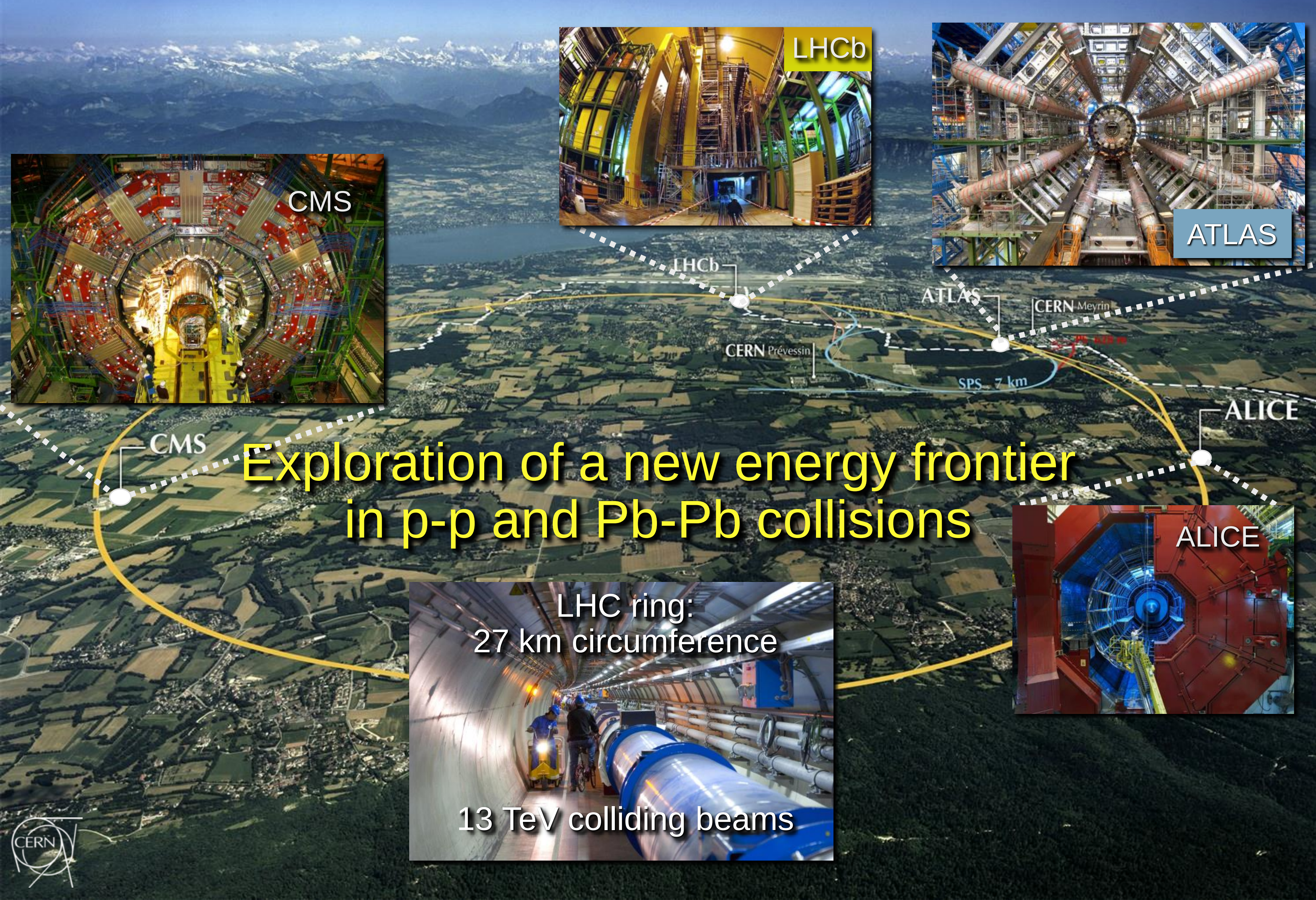
✓ create (new) massive particles → high colliding energy ($E=mc^2$)
✓ detect rare particle decays → high intensity beams and fast-readout detectors
✓ distinguish (new) rare particle decays from (known) abundant particle decays
→ very performant detectors with excellent particle identification

You are looking for this particular particle physicist!

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

Note:
- the world population is $\sim 7.5\cdot 10^{9}$
- 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

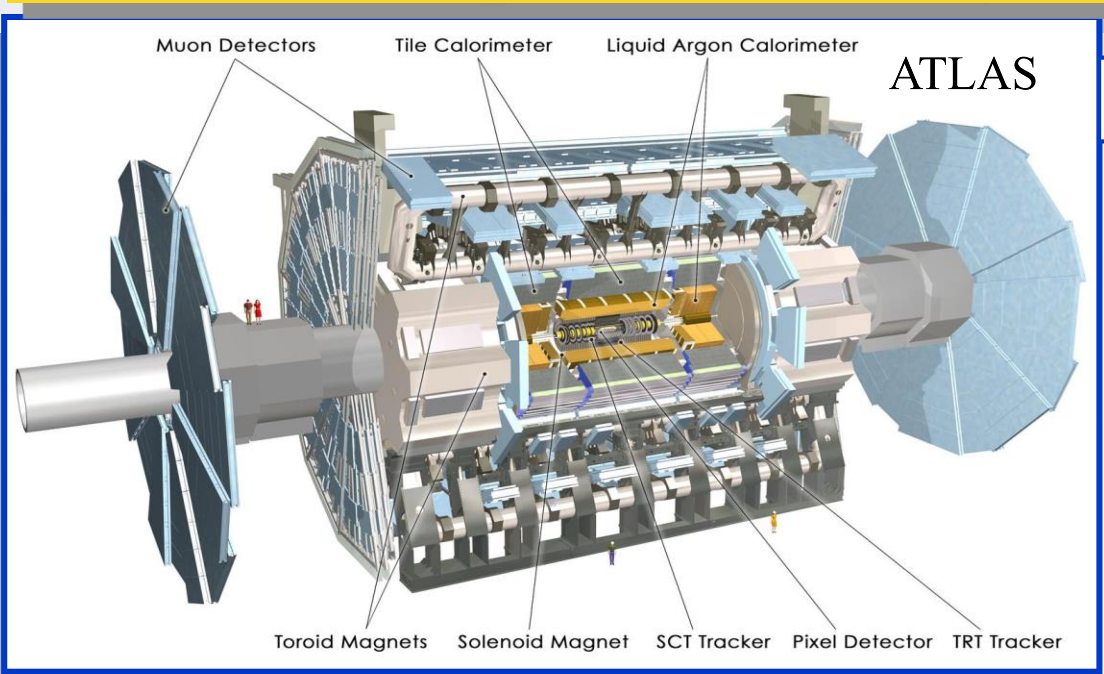


Exploration of a new energy frontier in p-p and Pb-Pb collisions

LHC ring:
27 km circumference

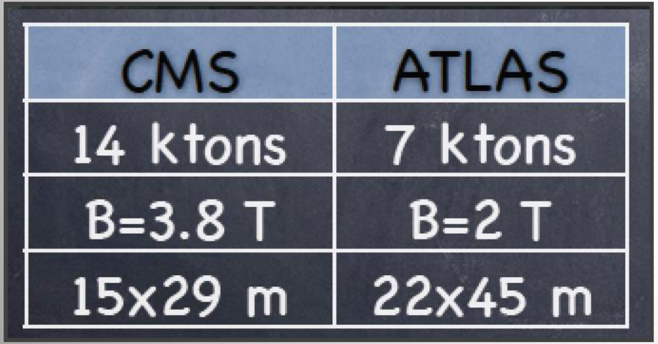
13 TeV colliding beams

General Purpose Detectors (GPD): The Higgs Hunters



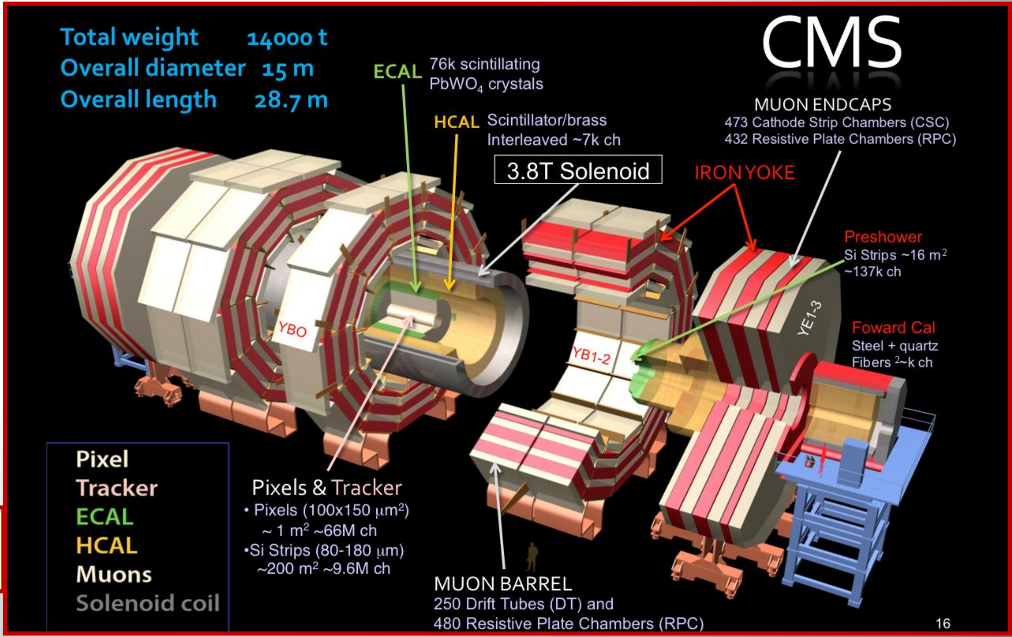
The ATLAS experiment

These experiments use different technologies for their detector components

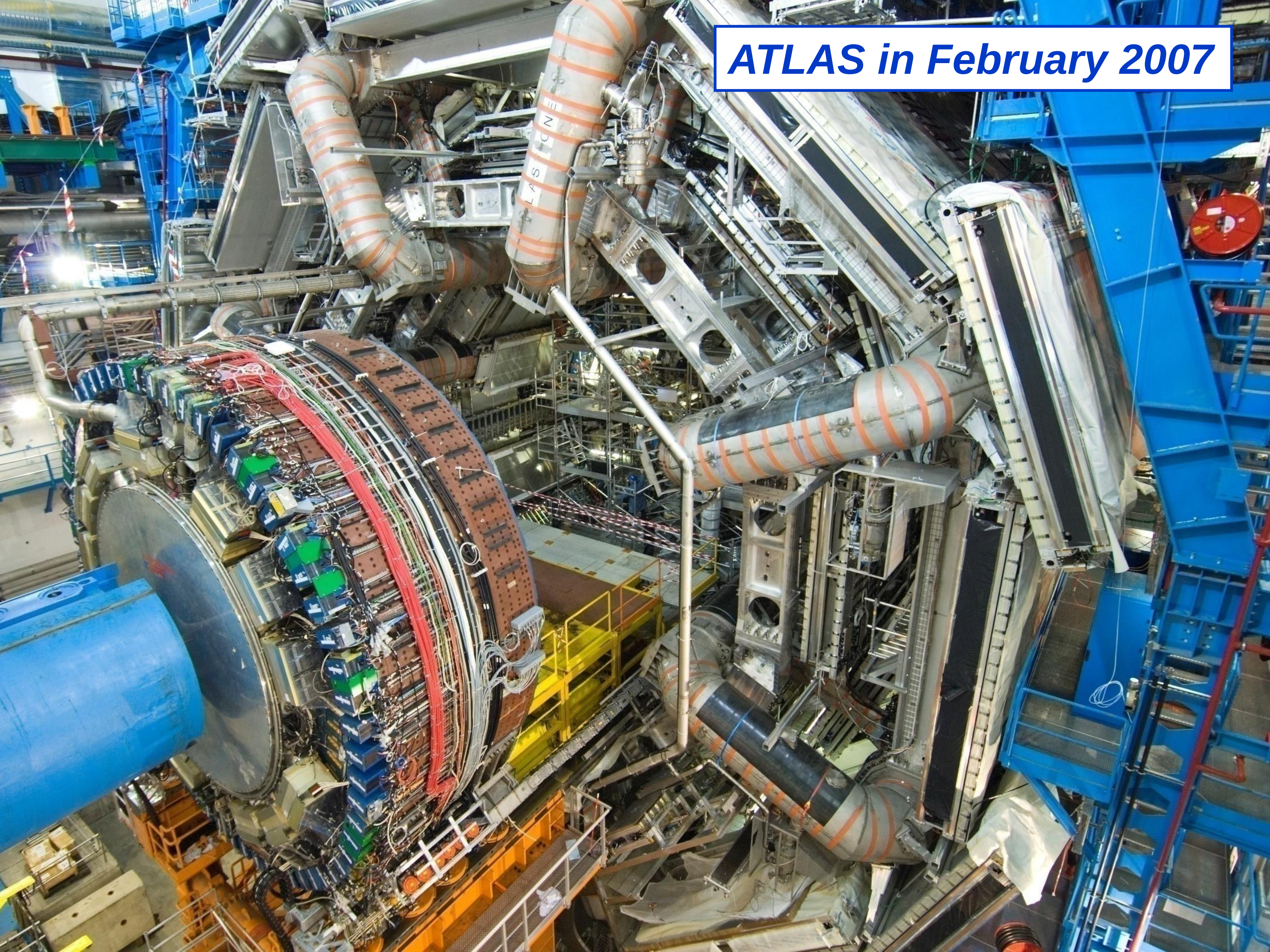


CMS	ATLAS
14 ktons	7 ktons
B=3.8 T	B=2 T
15x29 m	22x45 m

The CMS experiment



ATLAS in February 2007

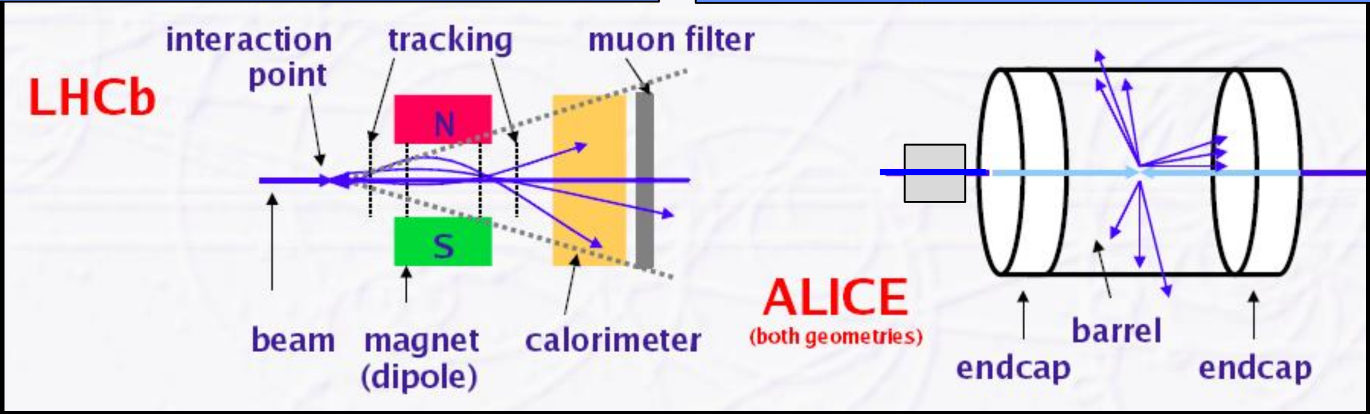


CMS before closure 2008

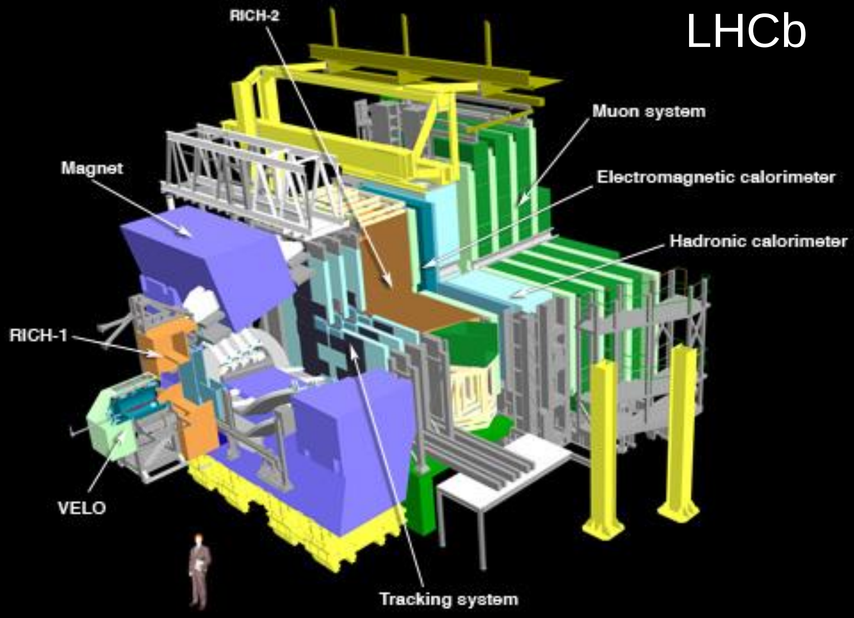
Specialized Detectors: Flavour Physics and Heavy Ions

Forward geometry with special particle identification to detect B meson decays

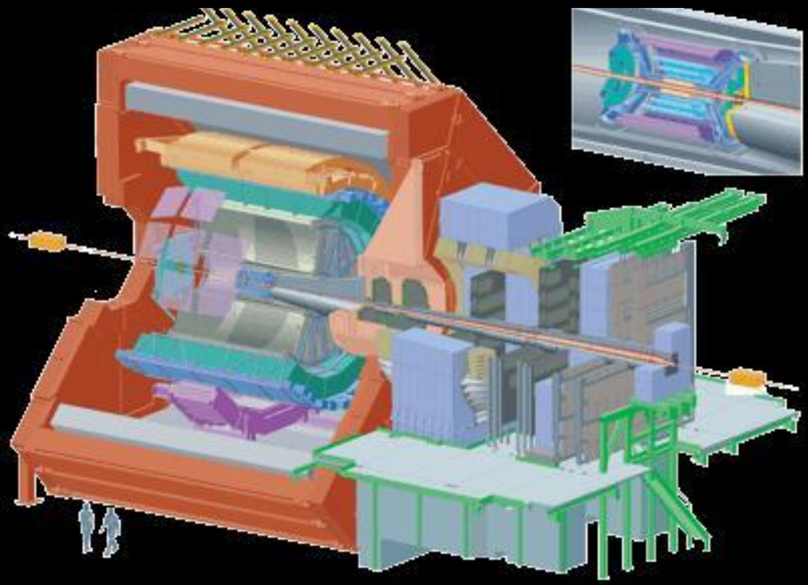
4π geometry with some forward detectors optimised for high multiplicity Pb-Pb collisions



LHCb

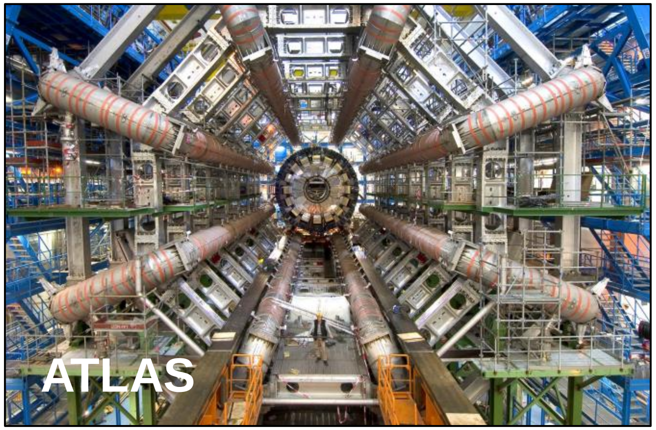


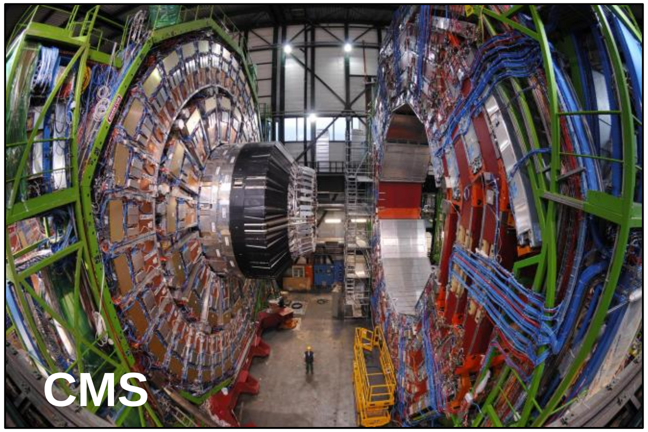
ALICE

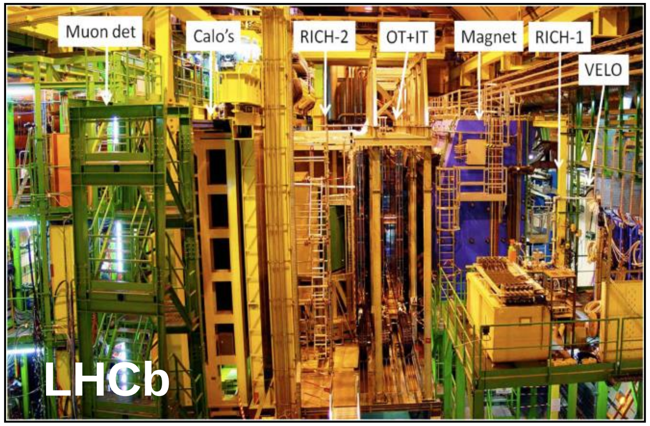


Detector Optimization

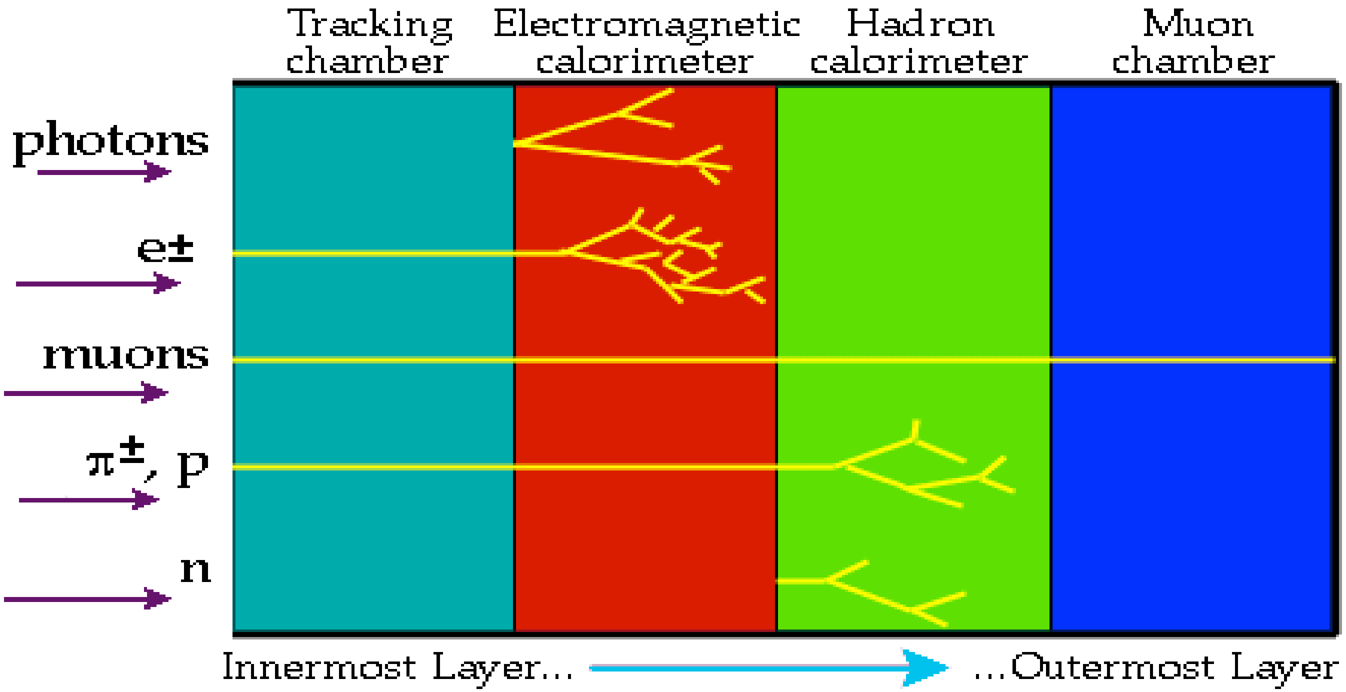
- Which kind of “particle” we have to detect?
- Which “property” of the particle we have to know?
    - ✓position
    - ✓charge
    - ✓energy or momentum
    - ✓mass
    - ✓lifetime
- What is the required resolution?
- What is the required dimension of the detector?
- What is the maximum count rate?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







Particle detection and identification



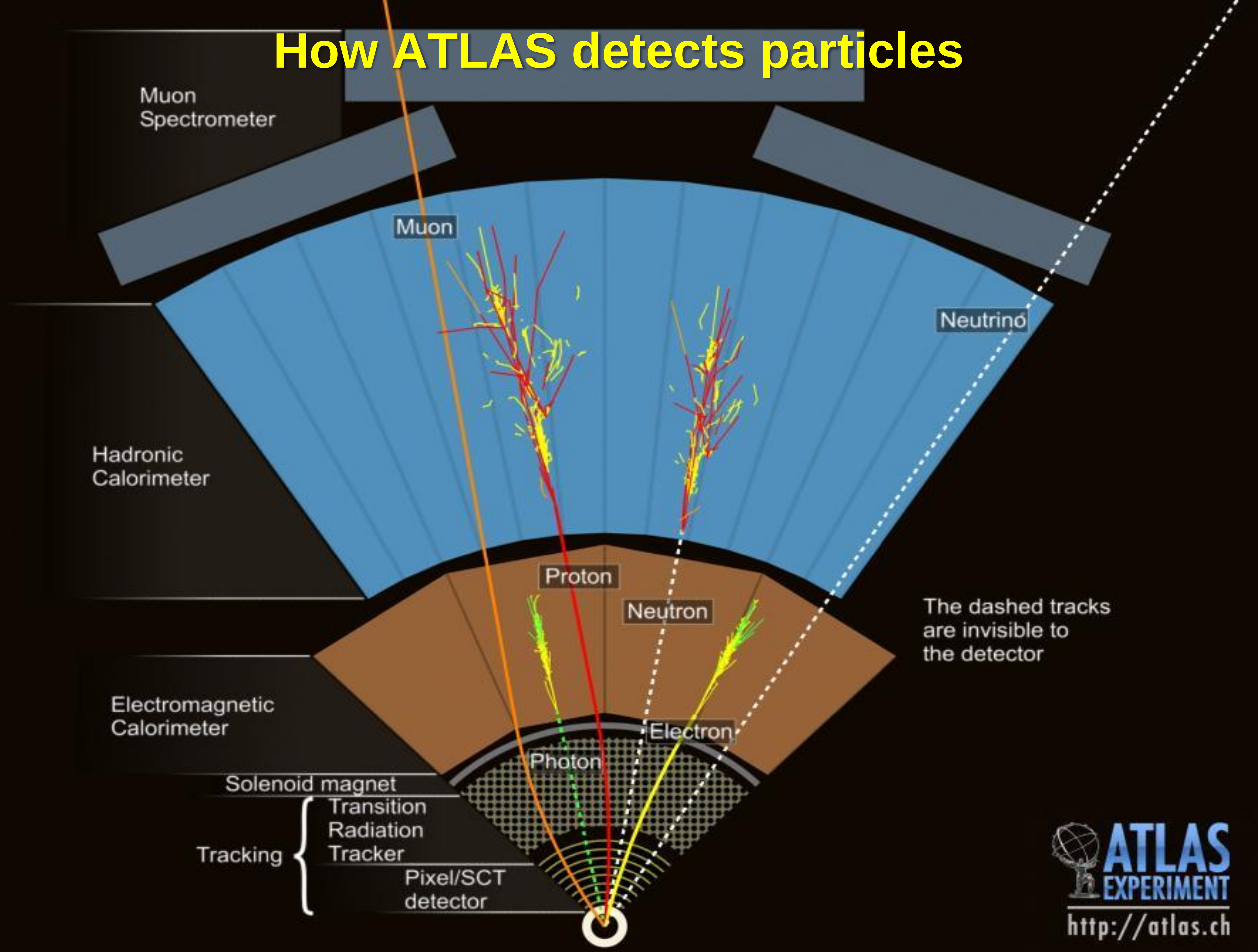
B field &
low density

high radiation
length (X_0)

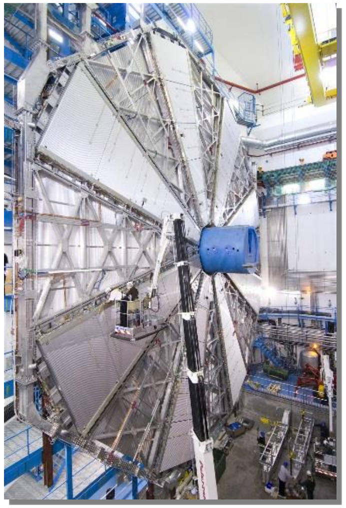
high interaction
length (λ)

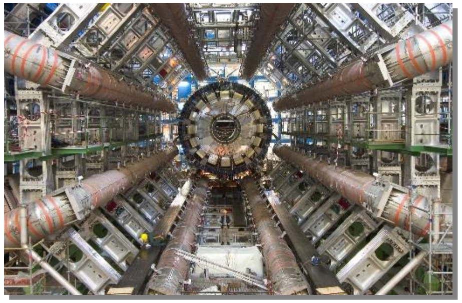
- charged particles leave **tracks** due to ionization
- electrons and photons create an **electromagnetic showers** in dense material
- charged and neutral hadrons create **hadronic showers** in dense material
- neutrinos interact only weakly and therefore do not leave **any signature**

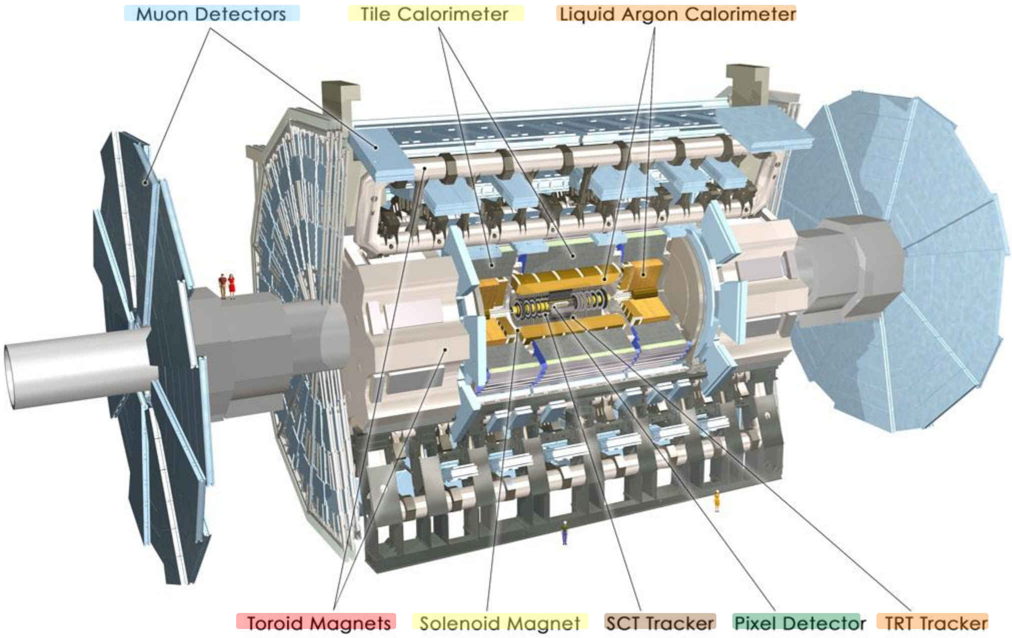
How ATLAS detects particles



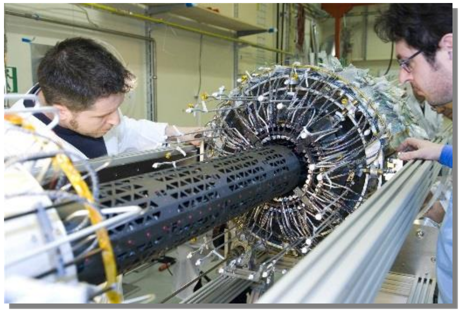
The dashed tracks are invisible to the detector

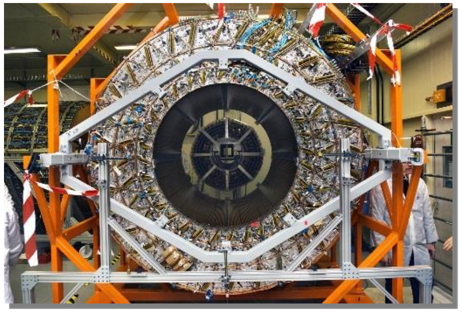




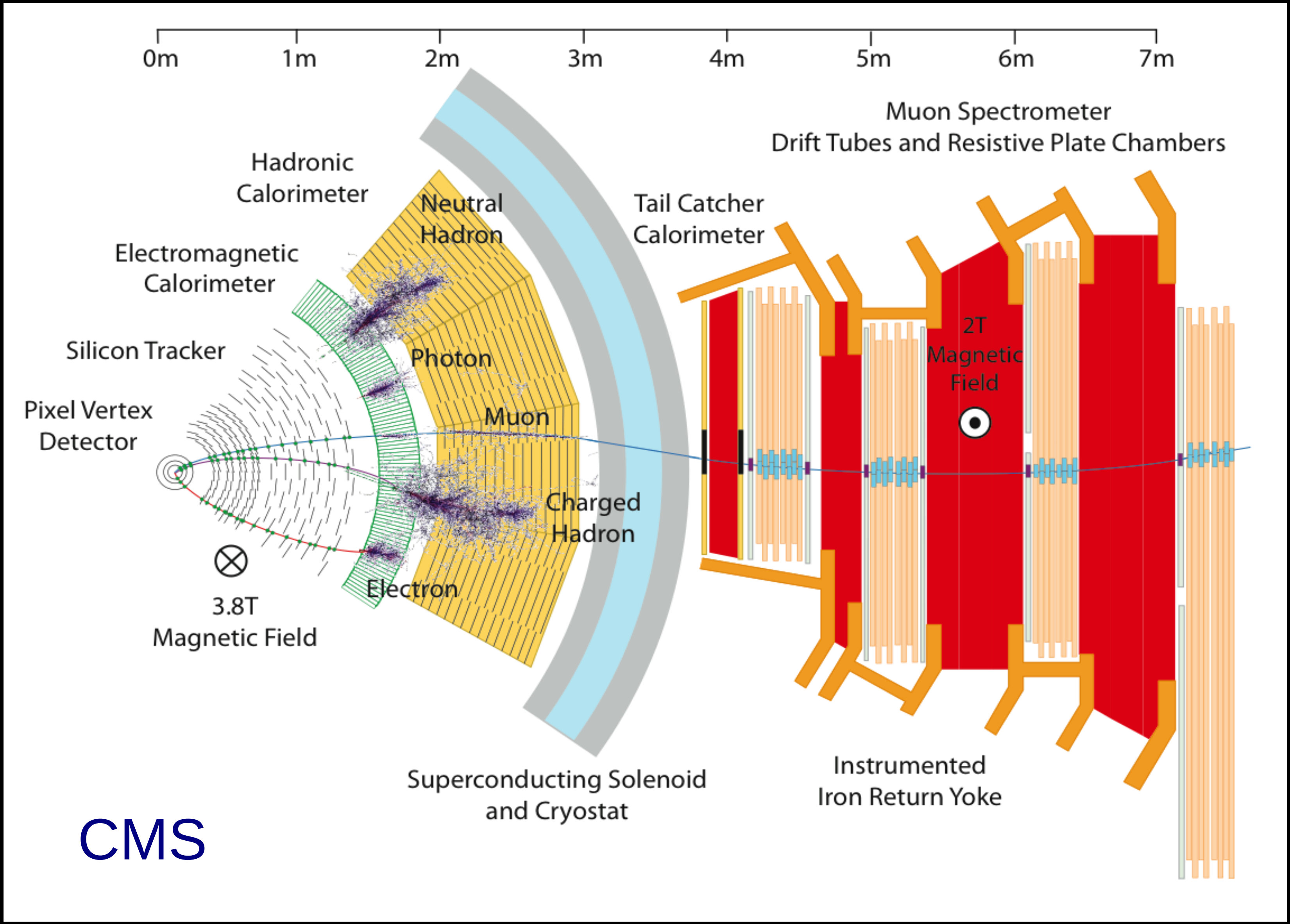

Muon Detectors
Tile Calorimeter
Liquid Argon Calorimeter
Toroid Magnets
Solenoid Magnet
SCT Tracker
Pixel Detector
TRT Tracker

ATLAS

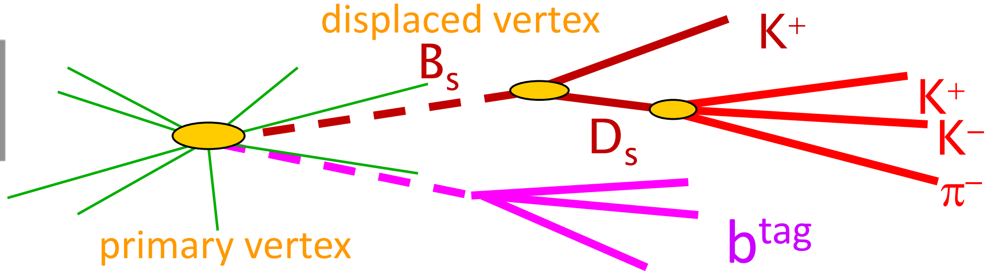




How CMS detects particles

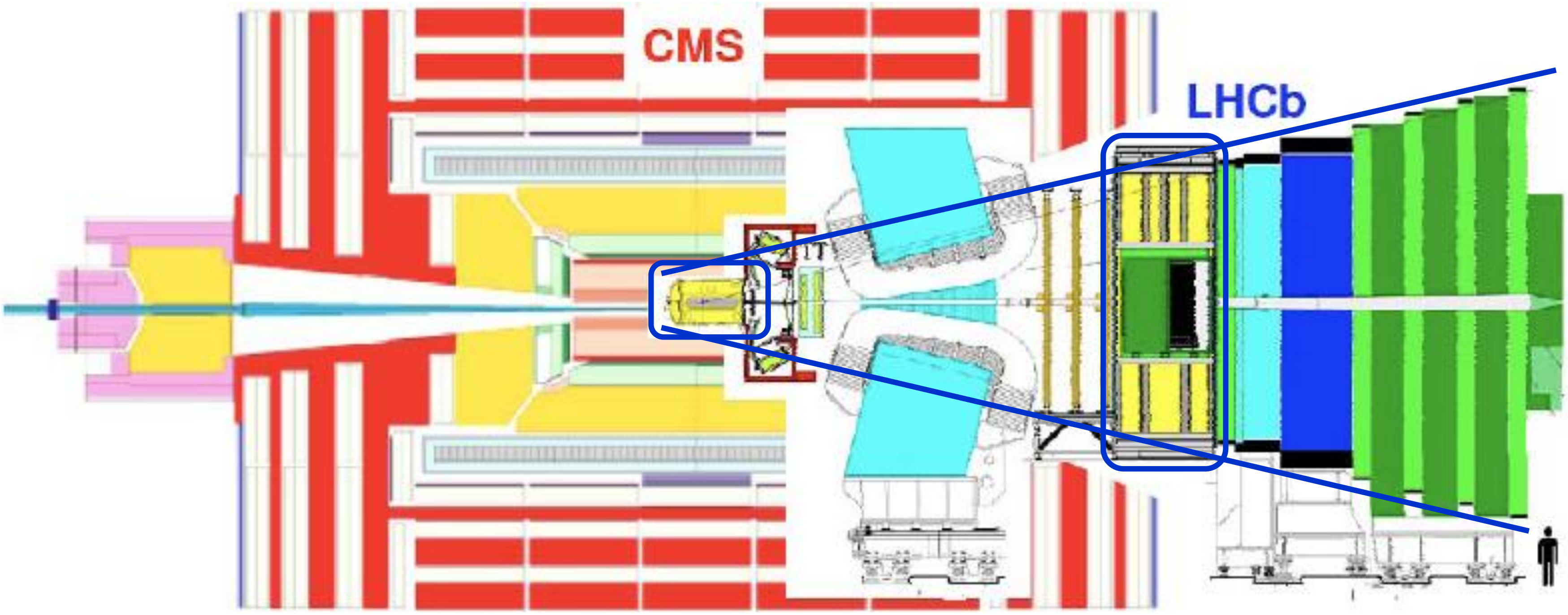


LHCb compared to CMS

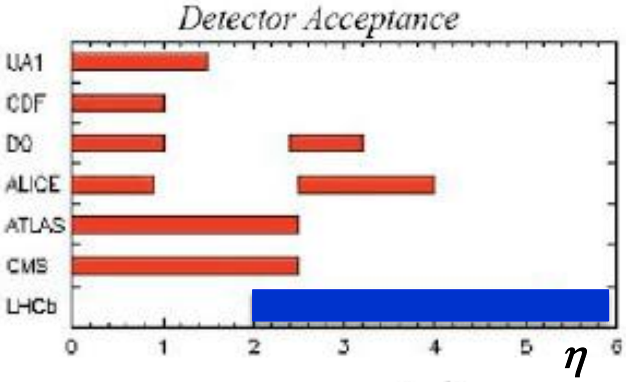


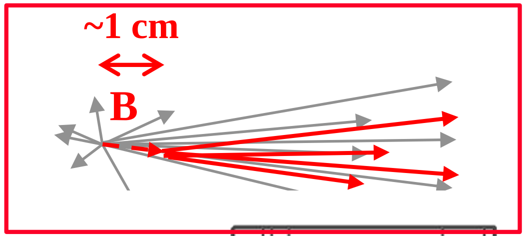
LHCb is specialized to detect mesons containing a b-quark

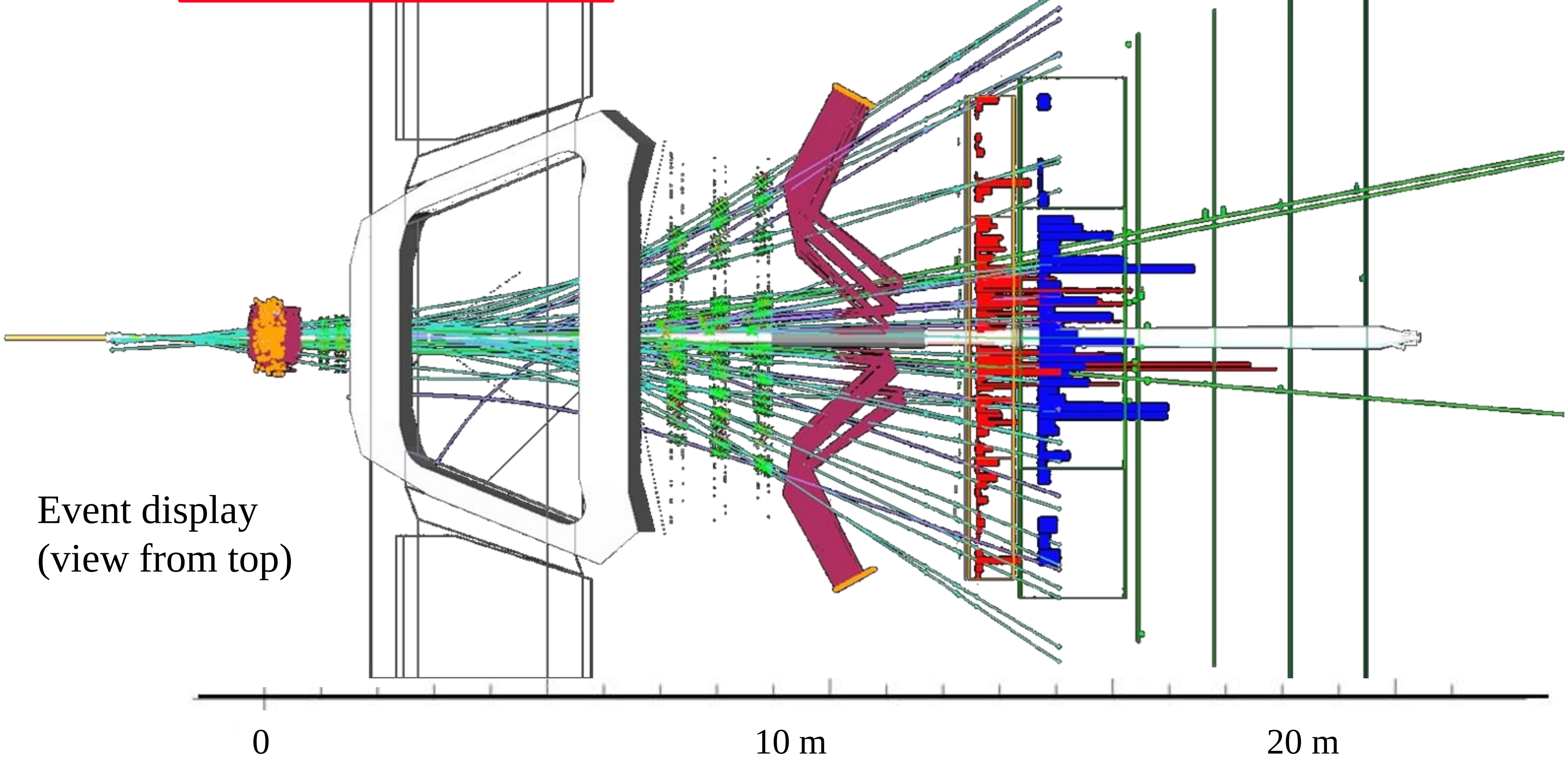
- B-mesons are produced in the forward region → forward geometry
- B-mesons decay after ~1cm in the detector → vertex reconstruction, particle identification



The LHCb Detector optimized for heavy flavour physics

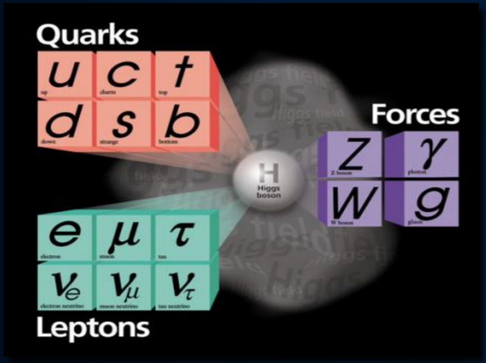






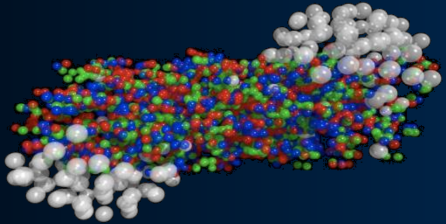
Event display
(view from top)

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?

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The origin of particle masses

log-scale !

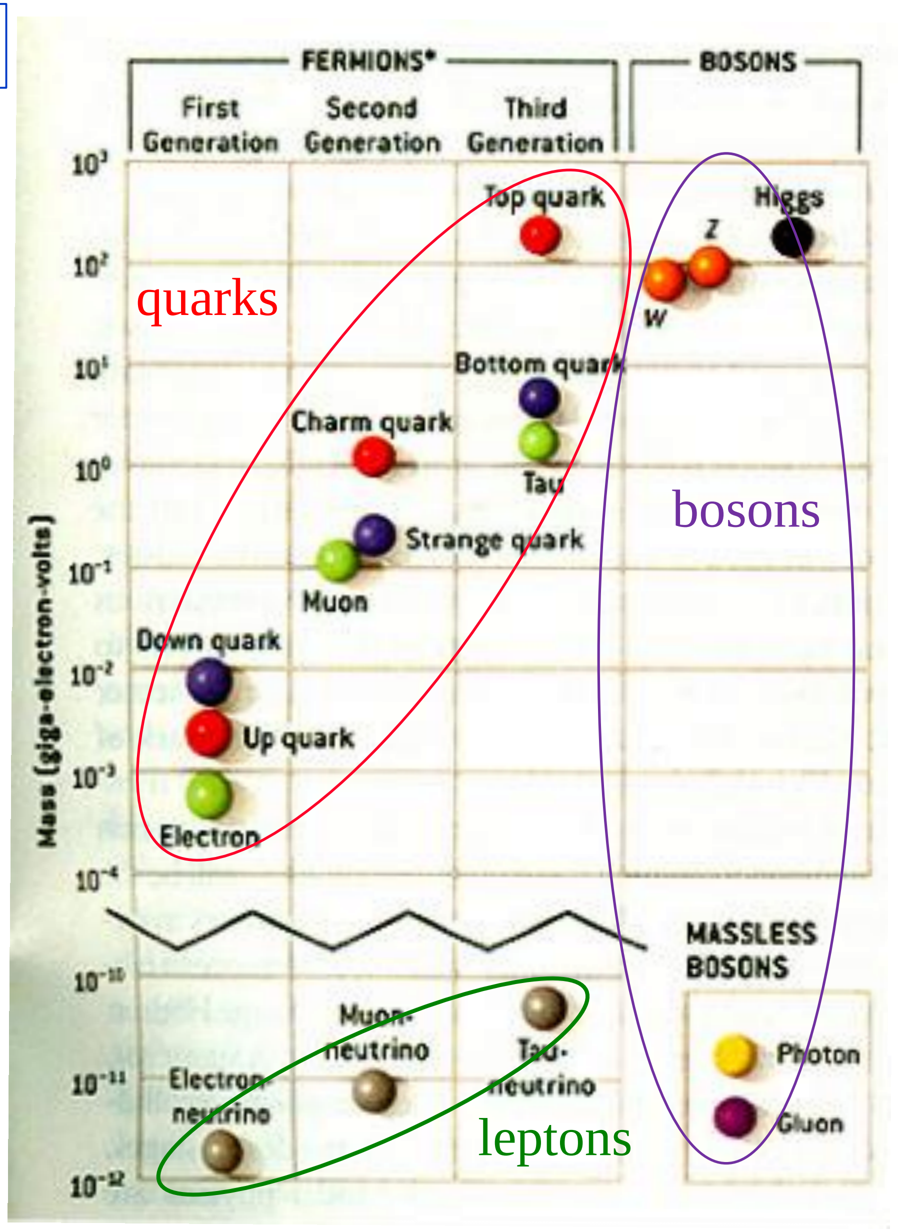
1 TeV

100 GeV

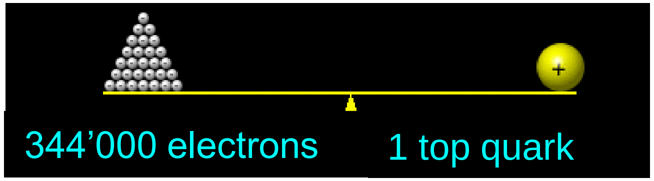
1 GeV

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

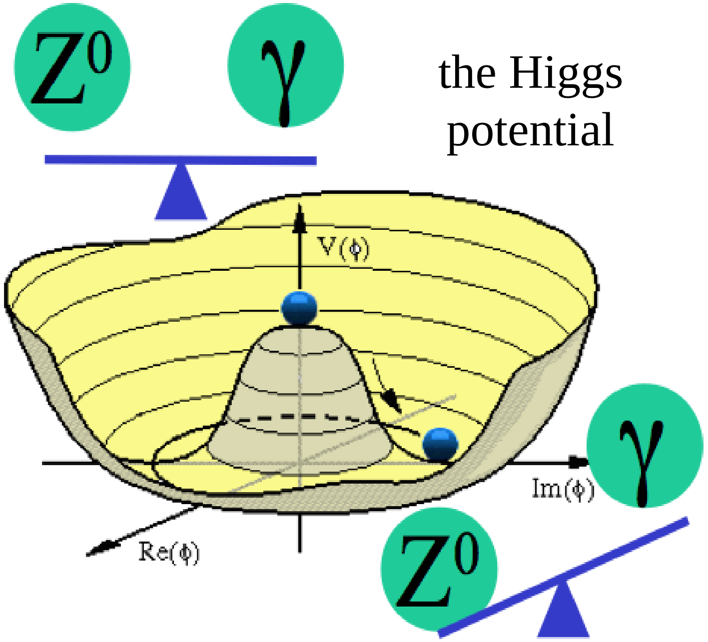
➢ ~ 10^{-11} s after the Big Bang, when **Higgs field** became active, particles acquired masses proportional to the strength of their interactions with this Higgs field

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 ...

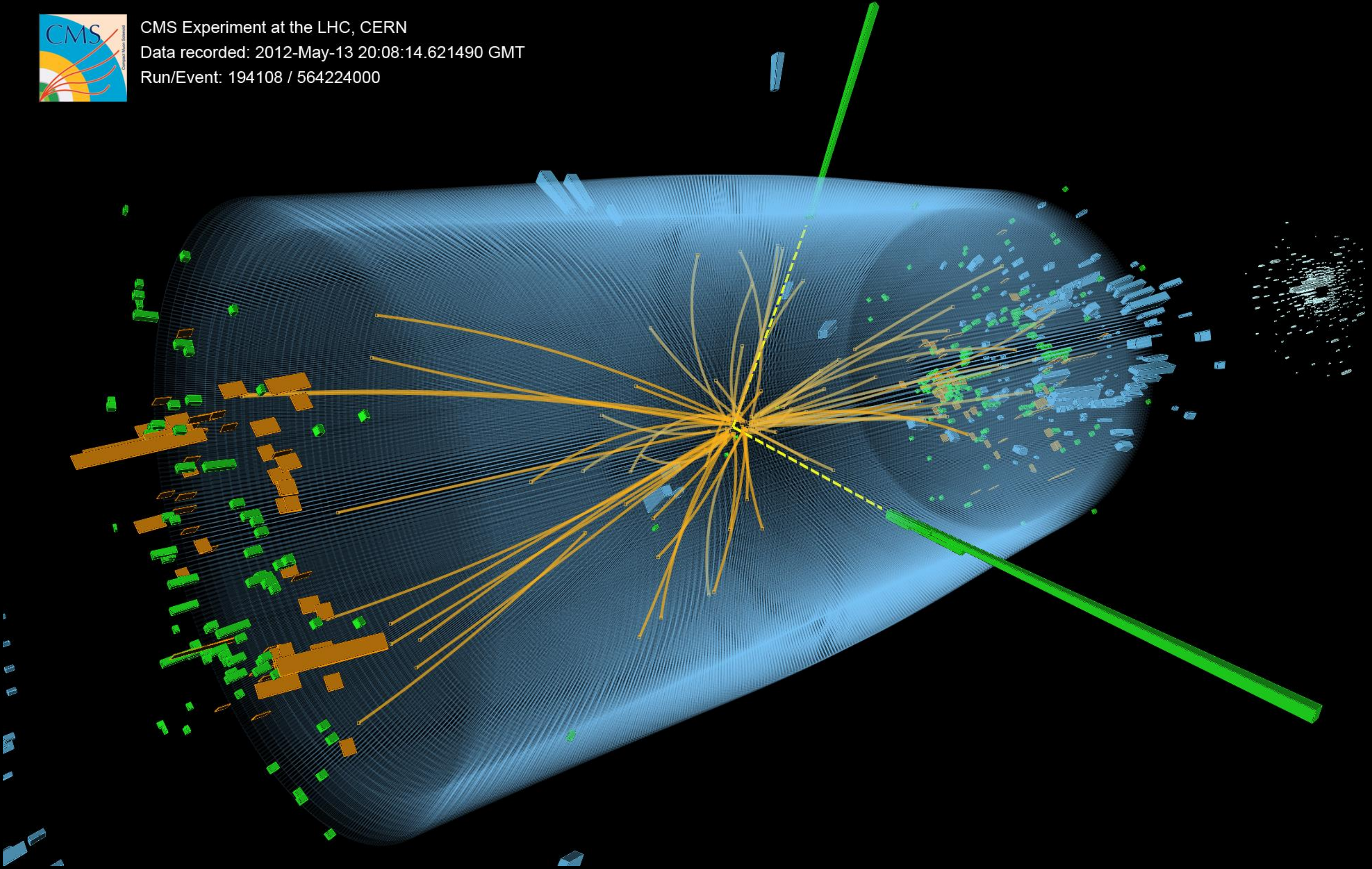
… everybody comes together
and whispers about the news...

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

A Possible H → 2 Photon Decay

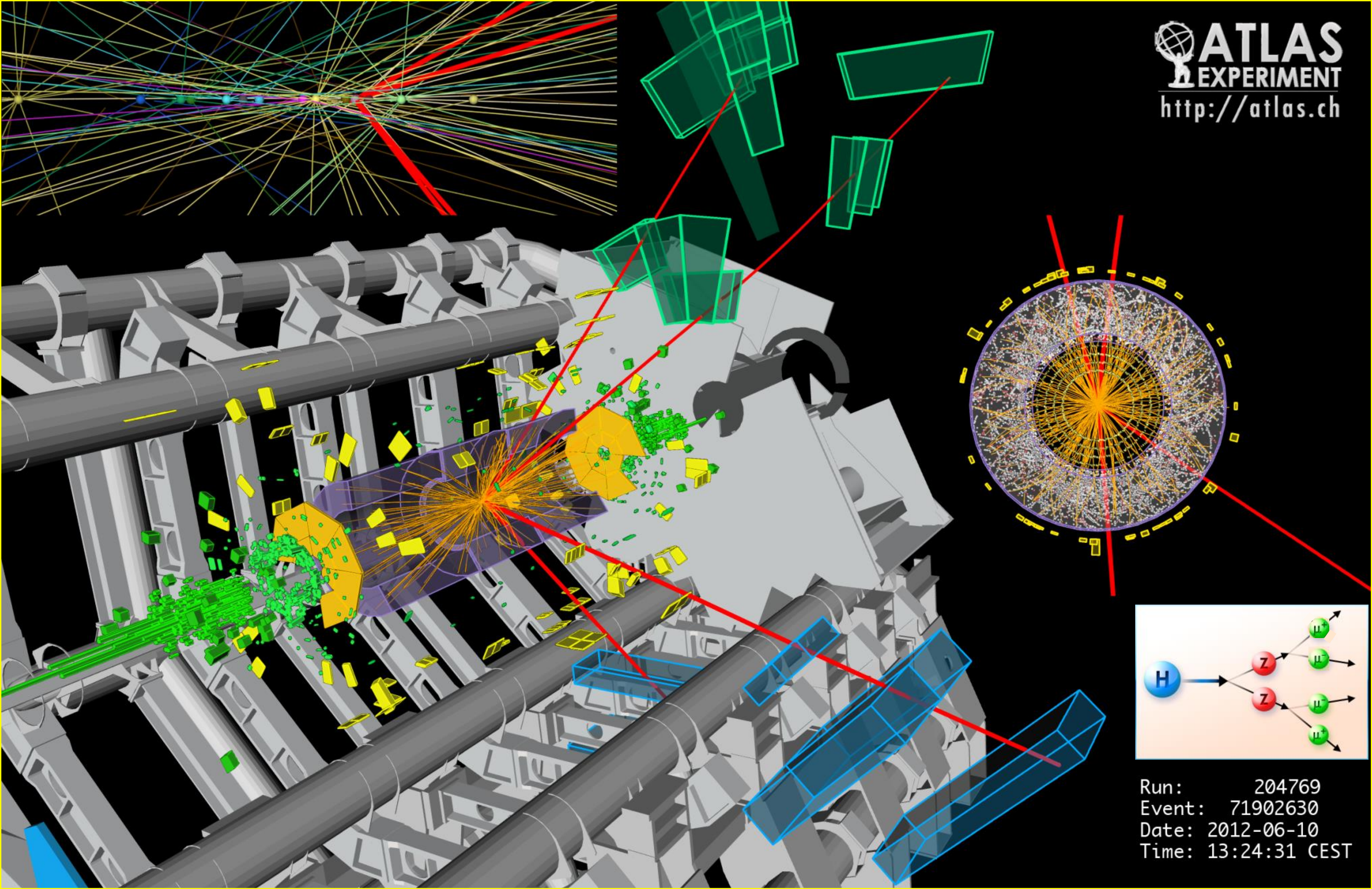
- a Higgs is produced only once in 10^{10} collisions
- it decays to 2 photons only with 0.2% probability

A Possible H → 2 Photon Decay



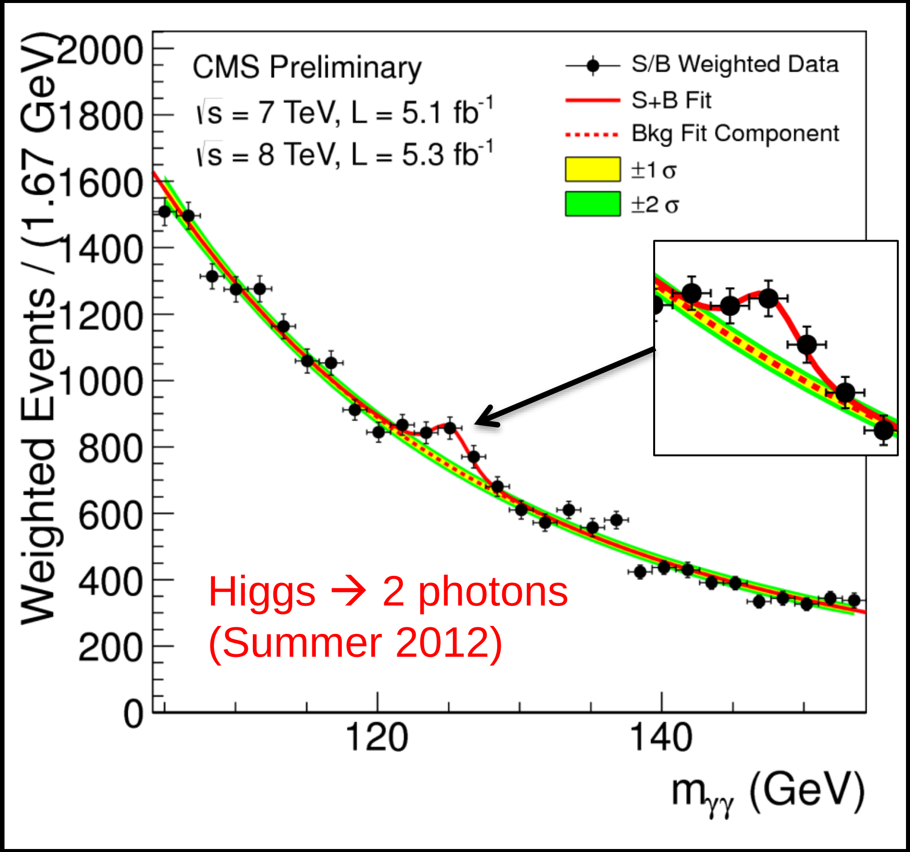
CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000

A Possible H → 4 Muon Decay

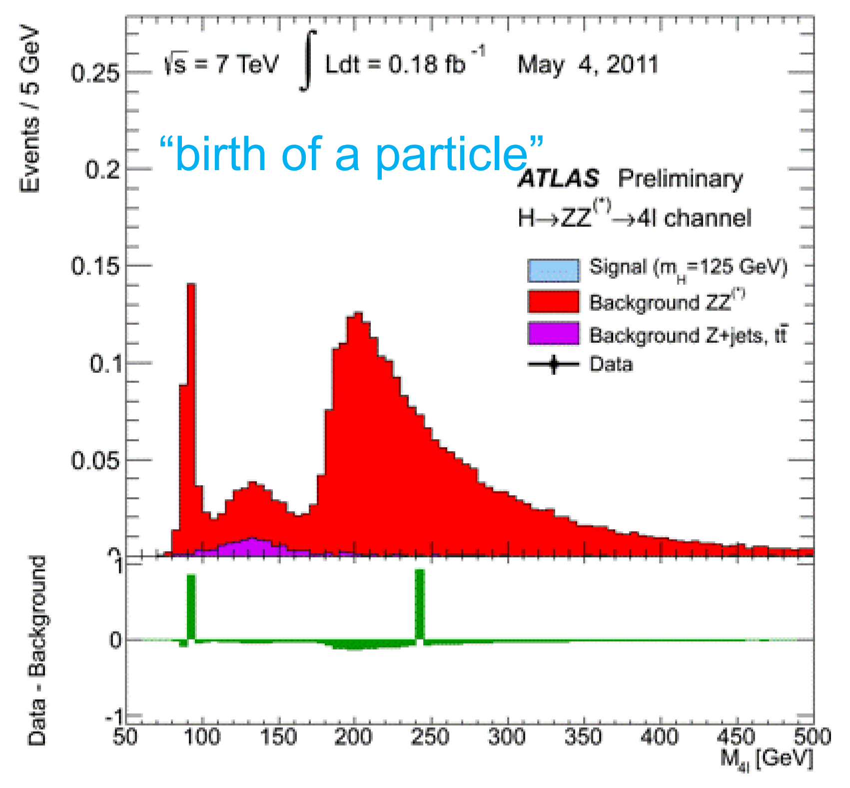


Run: 204769
Event: 71902630
Date: 2012-06-10
Time: 13:24:31 CEST

Identifying the Higgs over Background



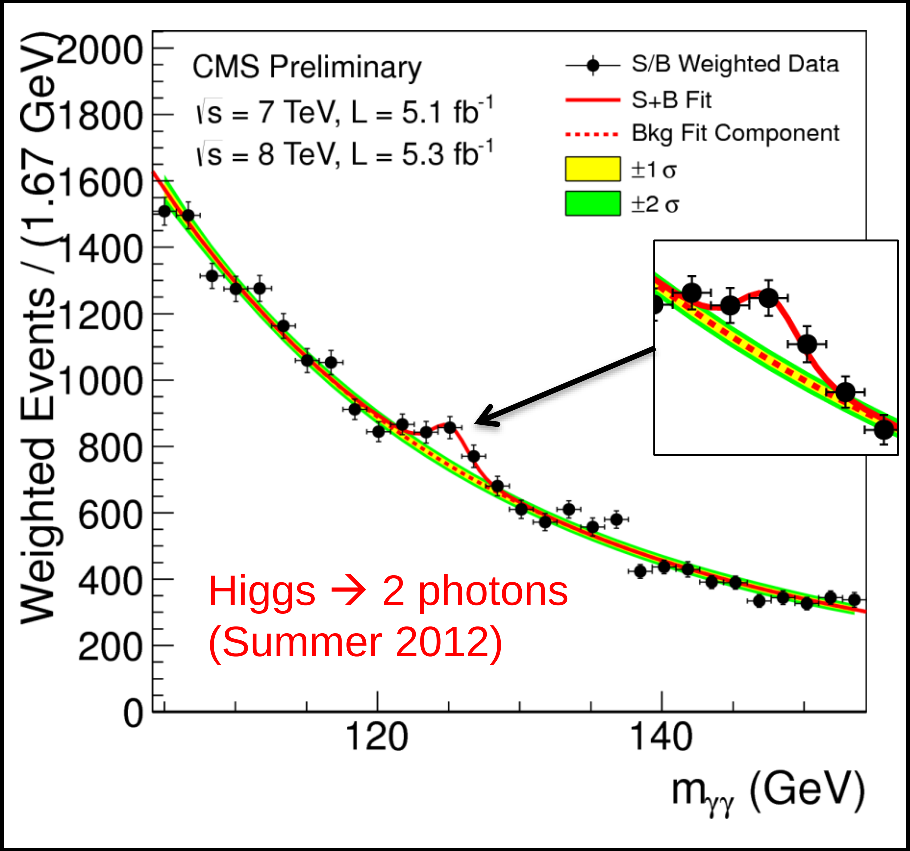
Higgs → 2 photons
(Summer 2012)



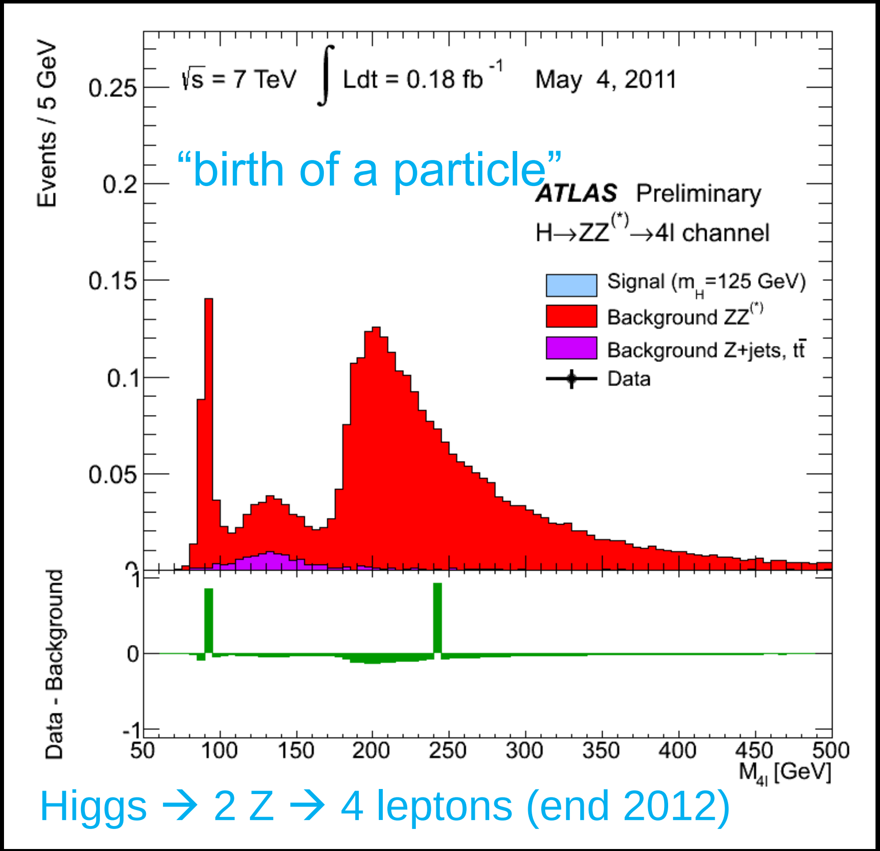
"birth of a particle"

- ✓ 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 photons
(Summer 2012)

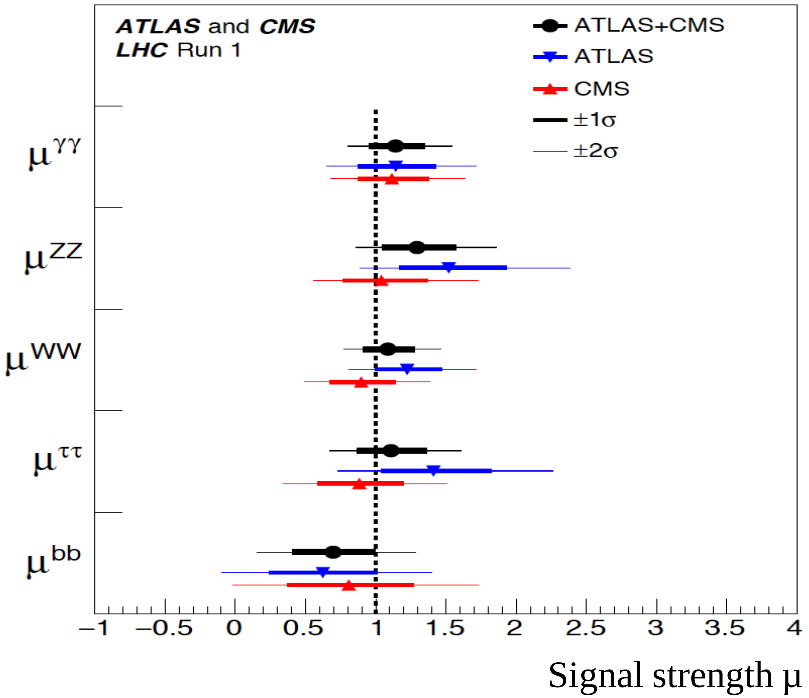


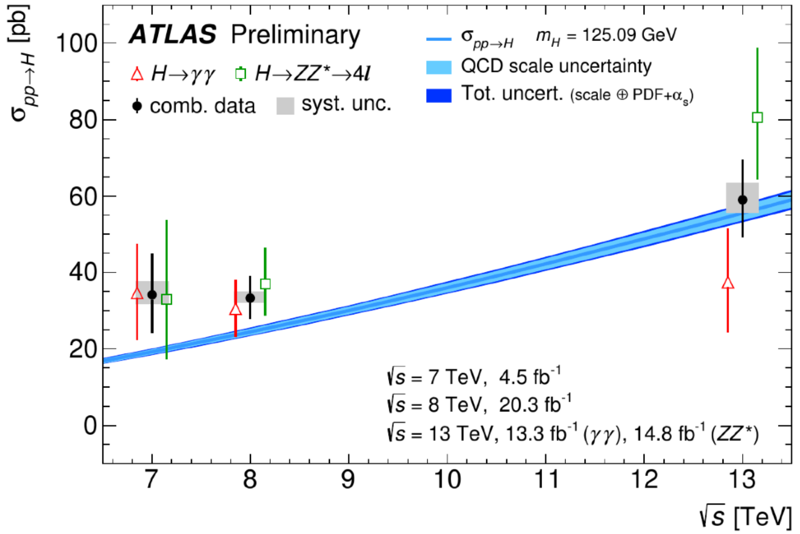
“birth of a particle”

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 ?

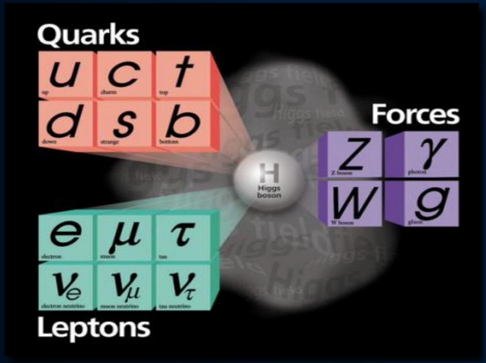




- ✓ **Higgs because:** measured $H\to ZZ\to \ell\ell\ell\ell$, $H\to\gamma\gamma$, $H\to WW\to \ell\nu\ell\nu$ and also less sensitive modes like e.g. $H\to\tau\tau$, etc.
- ✓ **Overall significance of production ~10σ**
- ✓ **We know it's a boson:** Because it decays to two photons
- ✓ **We know it's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

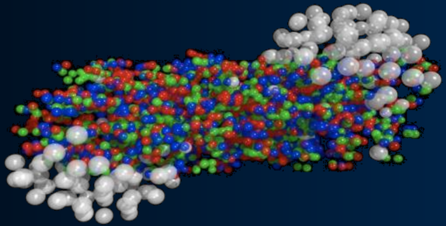
→ it really looks like "THE" SM Higgs!

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



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?



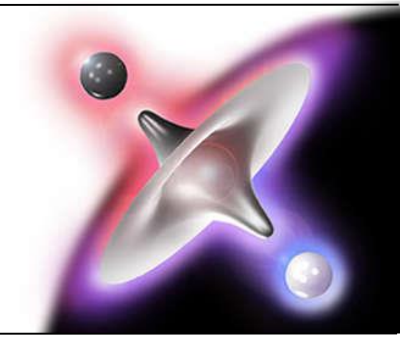
Will we understand the primordial state of matter after the Big Bang before protons and neutrons formed?

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

Antimatter - Matter Asymmetry

$E=mc^2$

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



but the universe is made of *matter* !

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

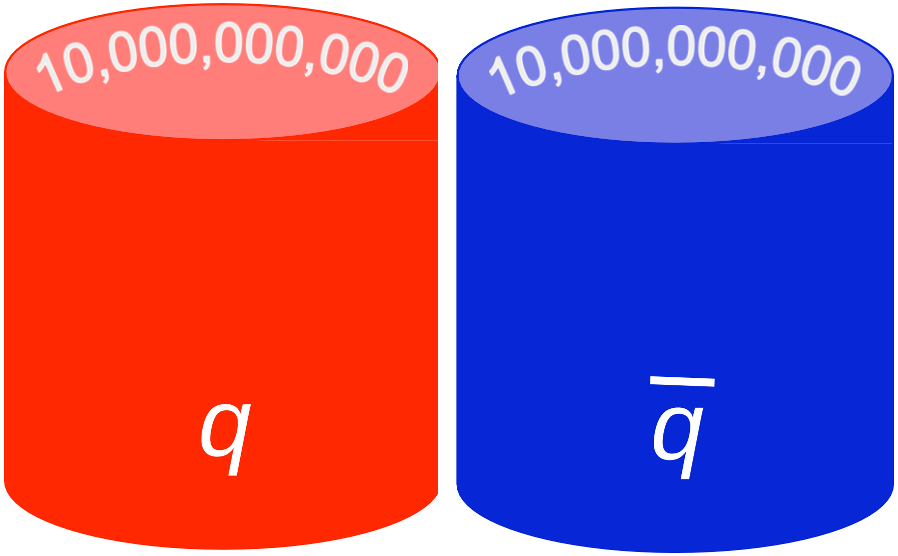
- absence of anti-nuclei amongst cosmic rays in our galaxy
- absence of intense γ−ray emission due to annihilation of distant galaxies in collision with antimatter

where has the *anti-matter* gone ?

Antimatter & the Big Bang

Big Bang:

- Create equal amounts of matter & antimatter



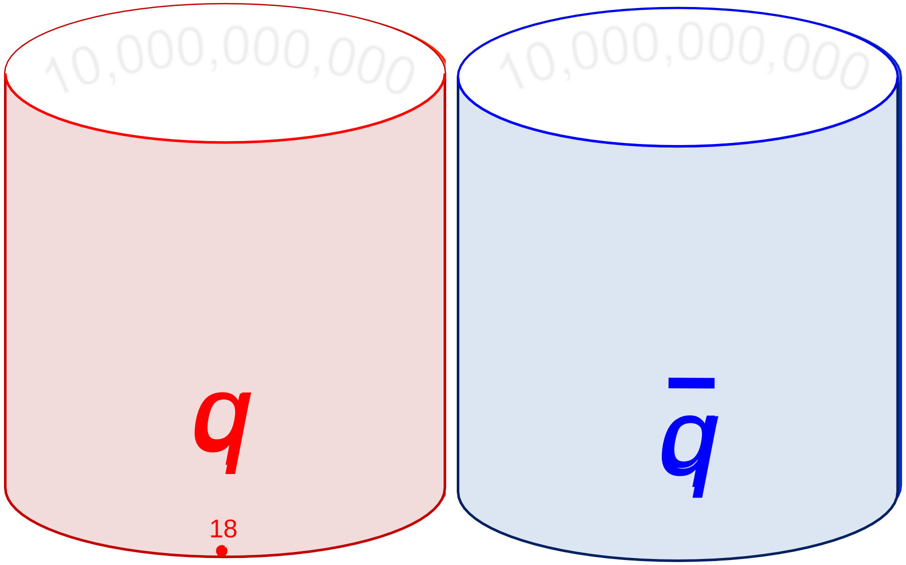
Early universe

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

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



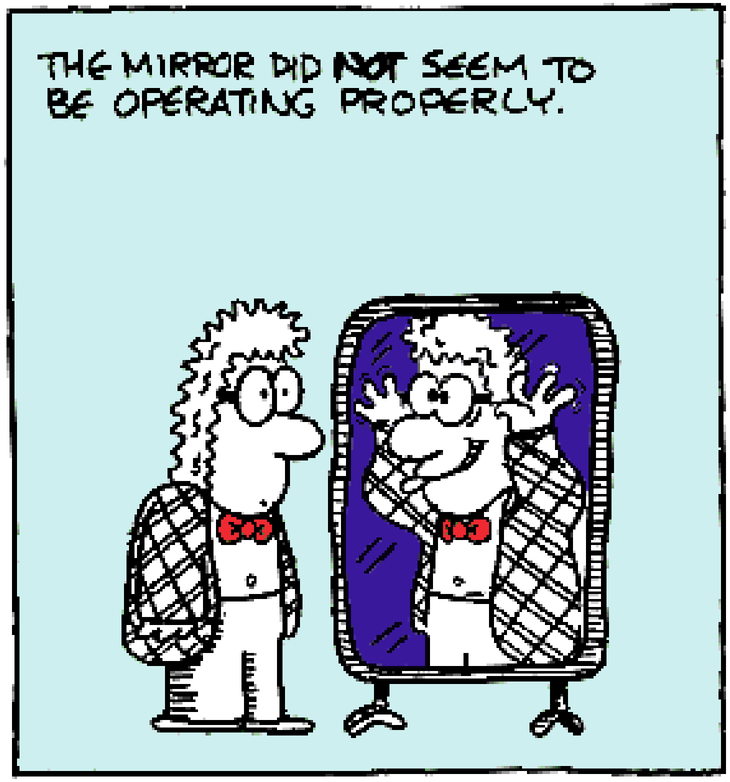
Current universe

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 $K^0 \rightarrow \pi\,\pi$

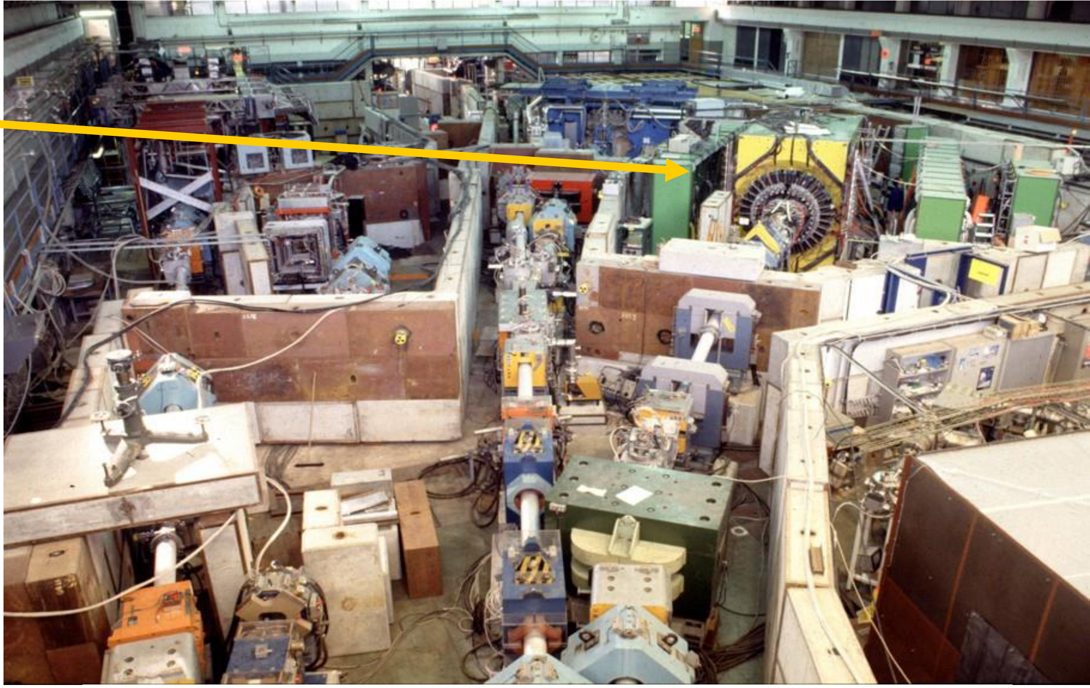
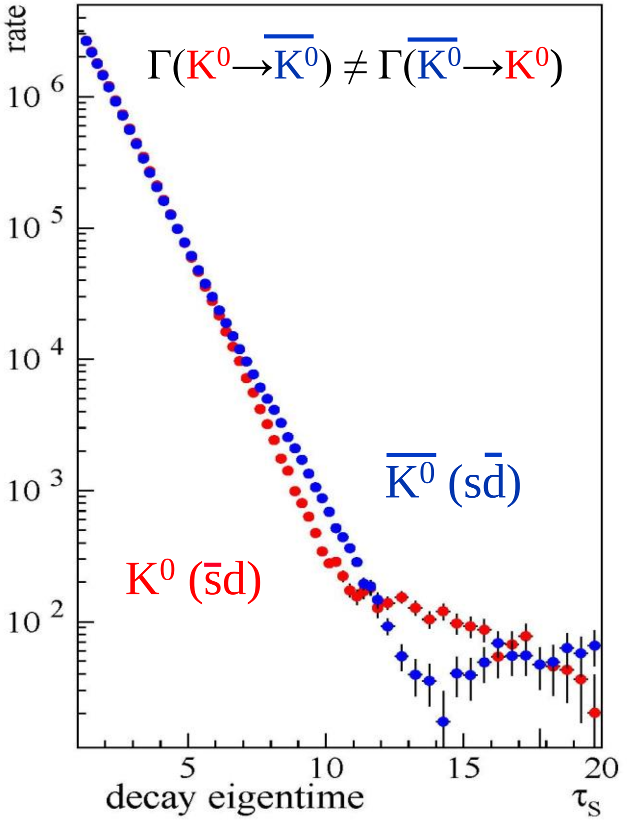
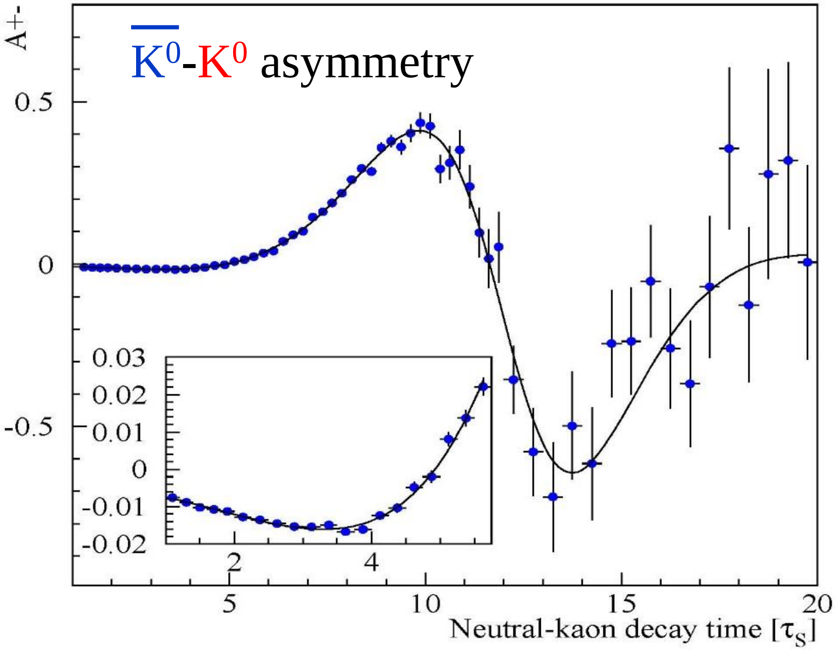


Illustration of CP violation in “mixing” of neutral kaons (1995)

- Kaon = meson of sd-quarks



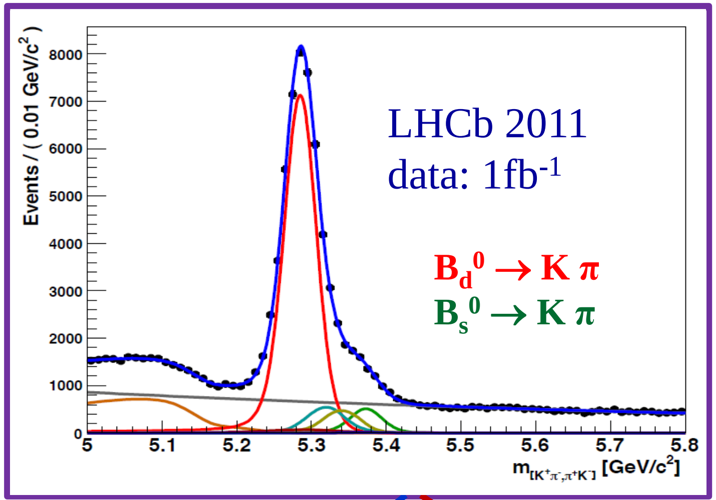
[Phys.Lett. B363 (1995) 243]



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

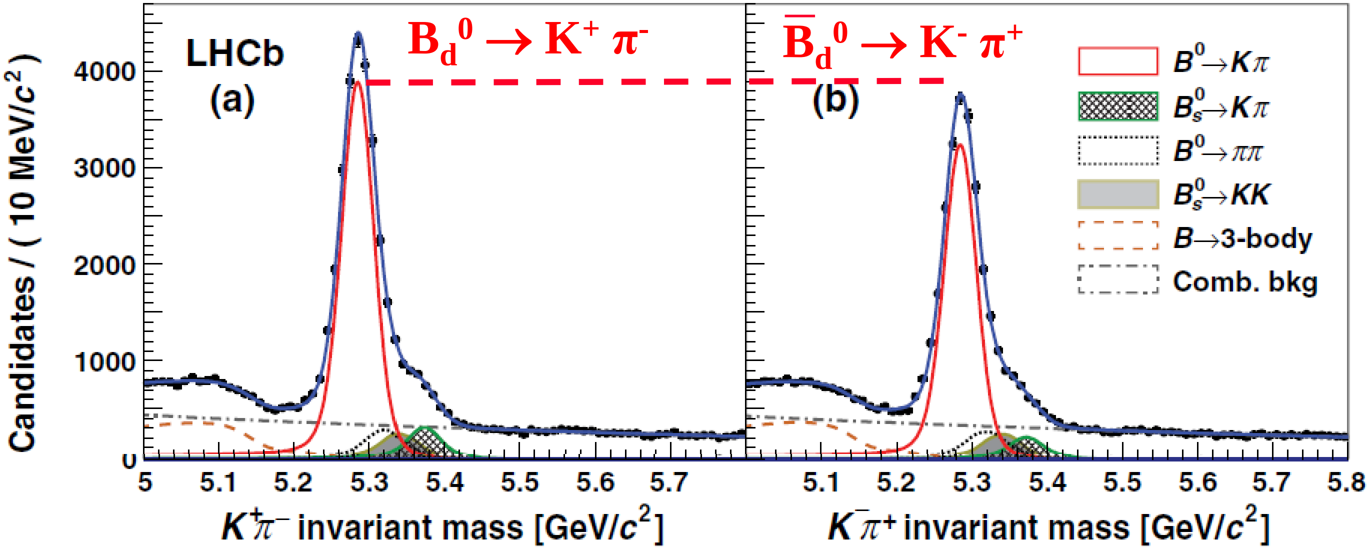
<u>CPV in decay</u>:

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

B_d^0

$\bar{B}_d^0$

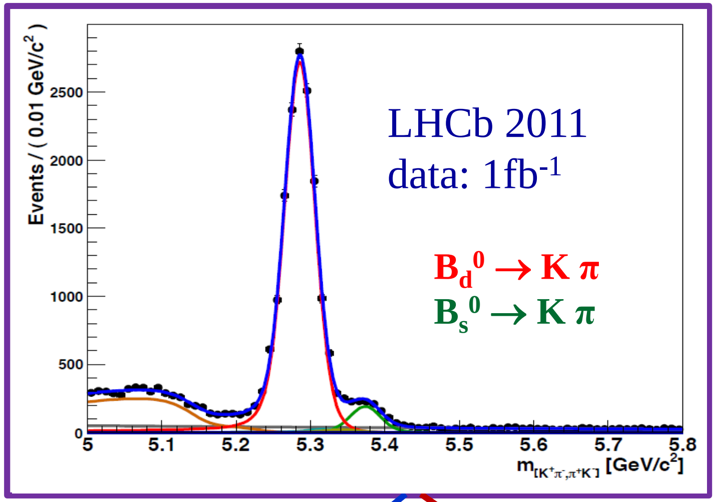
[PRL 110, 221601 (2013)]



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_s^0/B_d^0 **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

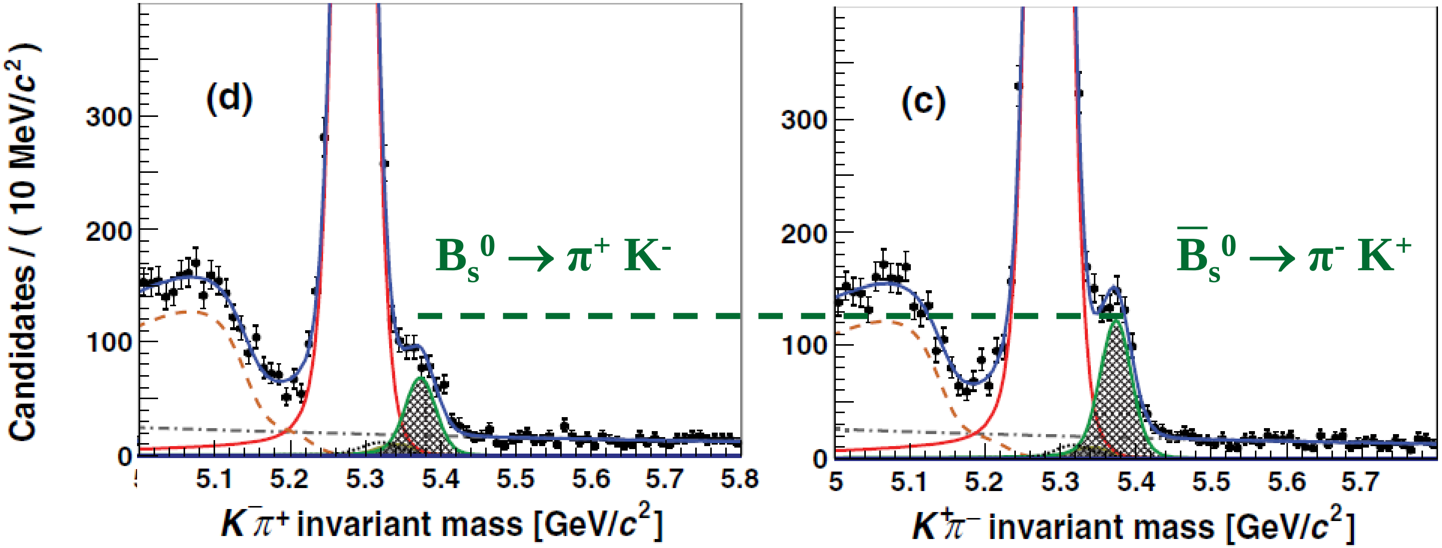
CPV in decay:

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

B_s^0

$\bar{B}_s^0$

[PRL 110, 221601 (2013)]



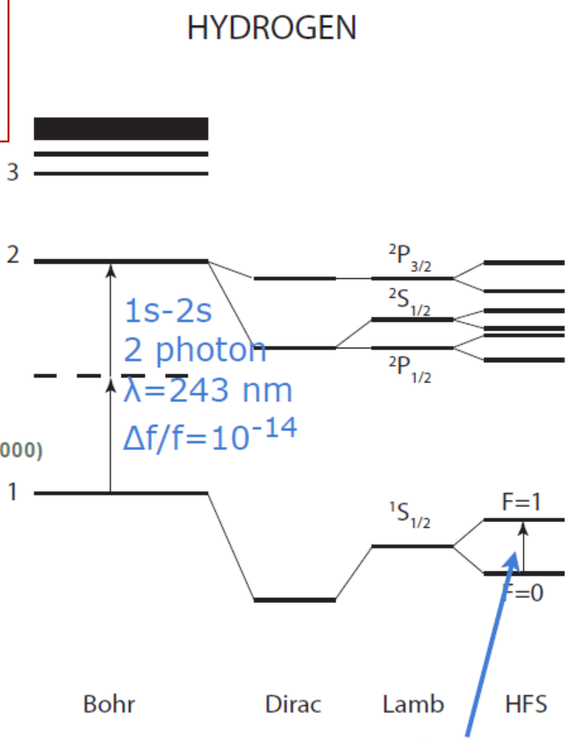
Test of Matter-Antimatter symmetry (CPT) with hydrogen and anti-hydrogen spectroscopy

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

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

Hydrogen

Anti hydrogen

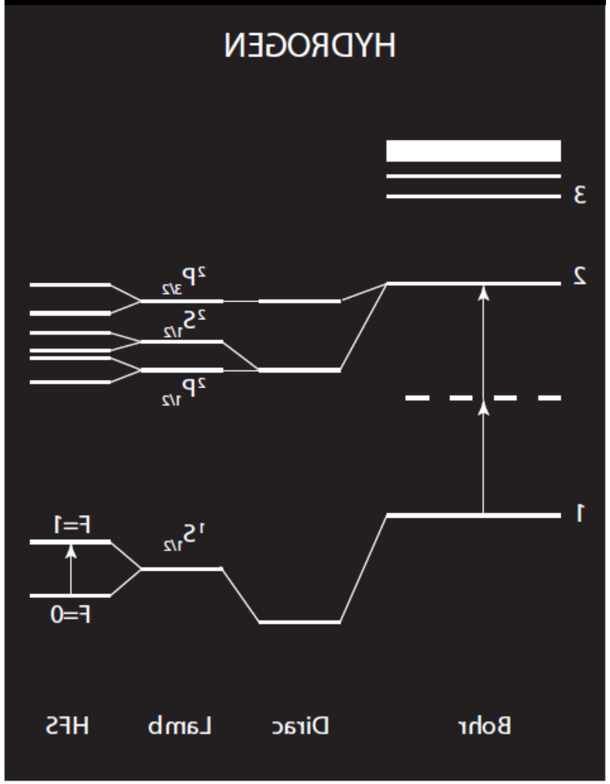


1s-2s
2 photon
$\lambda=243$ nm
$\Delta f/f=10^{-14}$

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

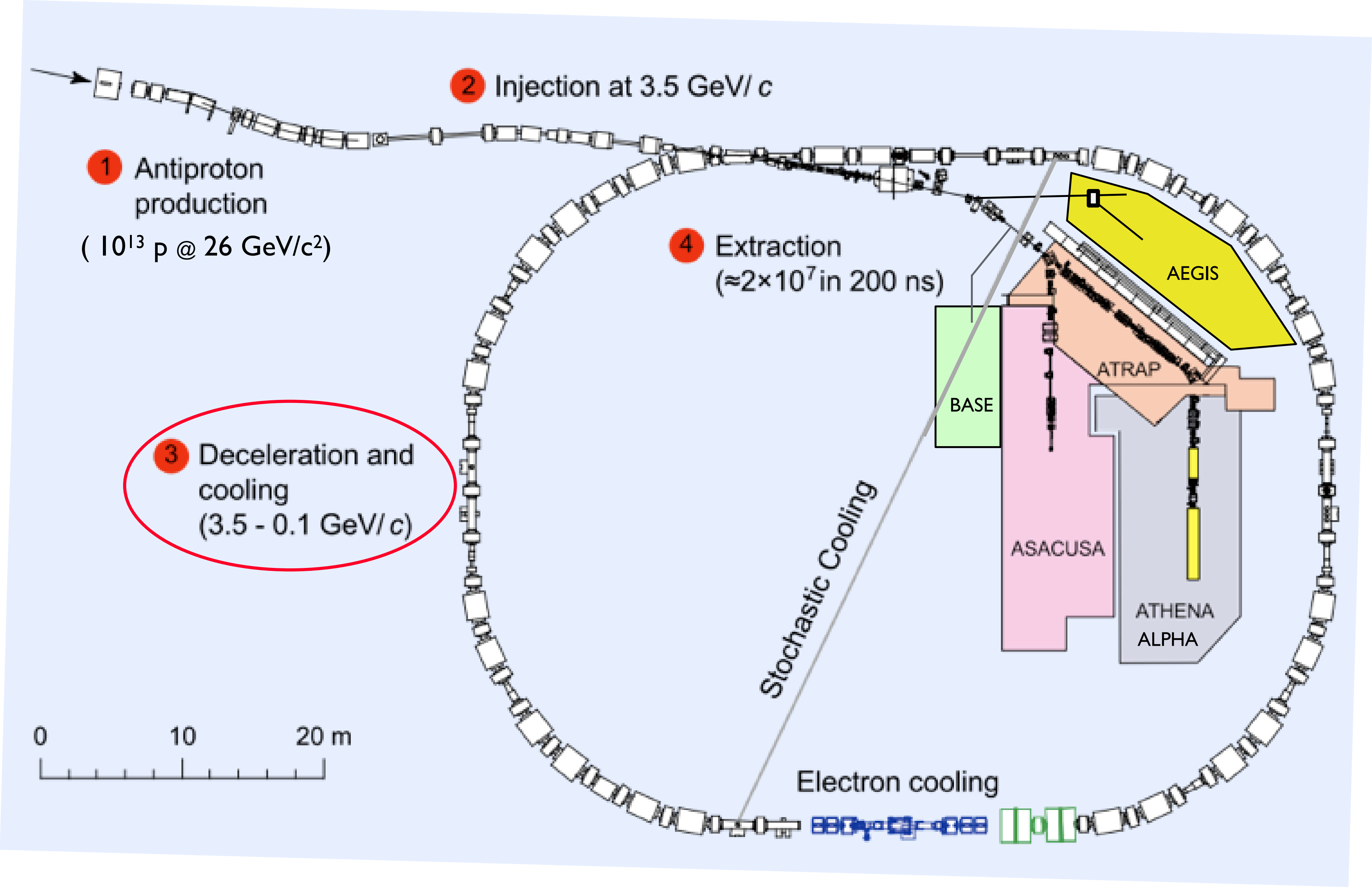
Ground state
hyperfine splitting
f = 1.4 GHz
$\Delta f/f=10^{-12}$

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



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

Antiproton Decelerator



① Antiproton production

(10^{13} p @ 26 GeV/c^2)

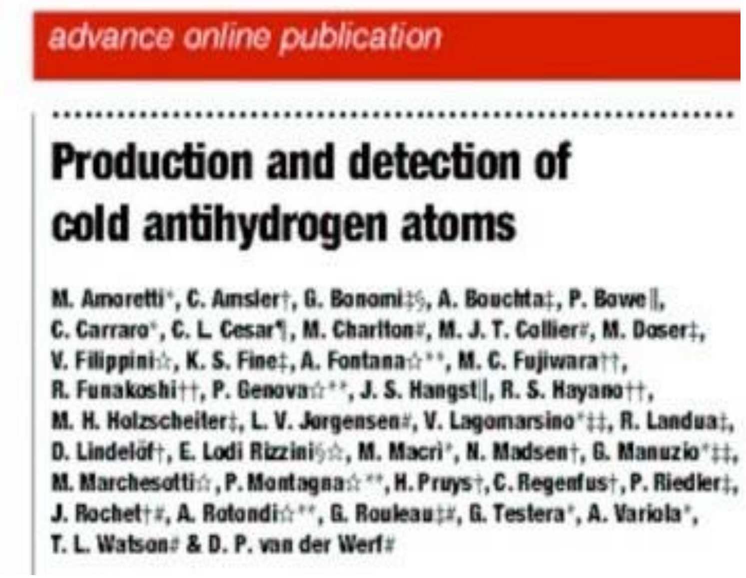
② Injection at 3.5 GeV/ *c*

③ Deceleration and cooling (3.5 - 0.1 GeV/ *c*)

④ Extraction (≈2×10^7 in 200 ns)

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. Macri[*], 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[#]

ATRAP PRL 89 (2002) 213401

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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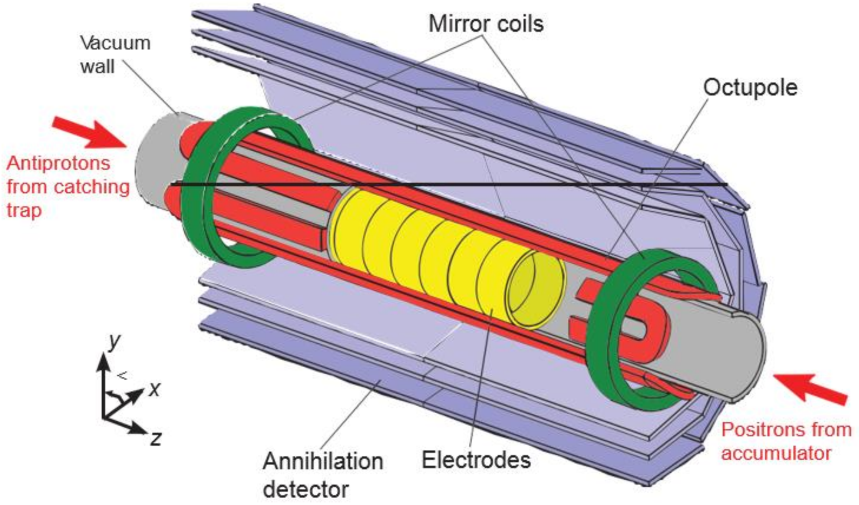
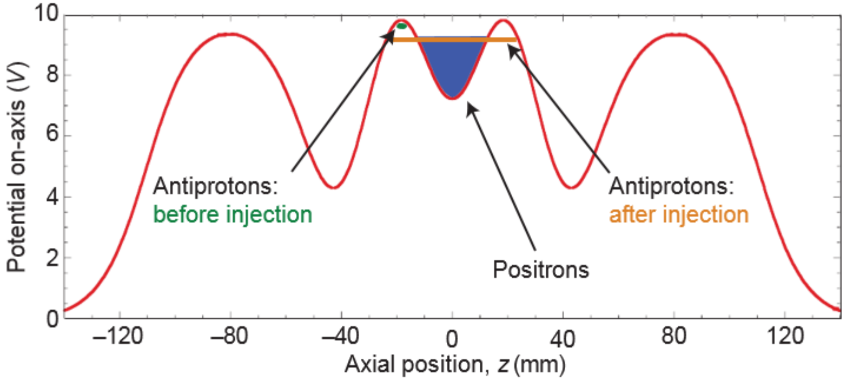
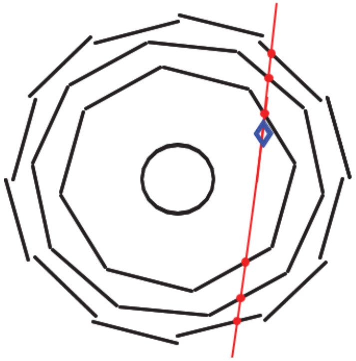
[6]York University, Department of Physics and Astronomy, Toronto, Ontario, Canada M3J 1P3
(Received 11 October 2002; published 31 October 2002)



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



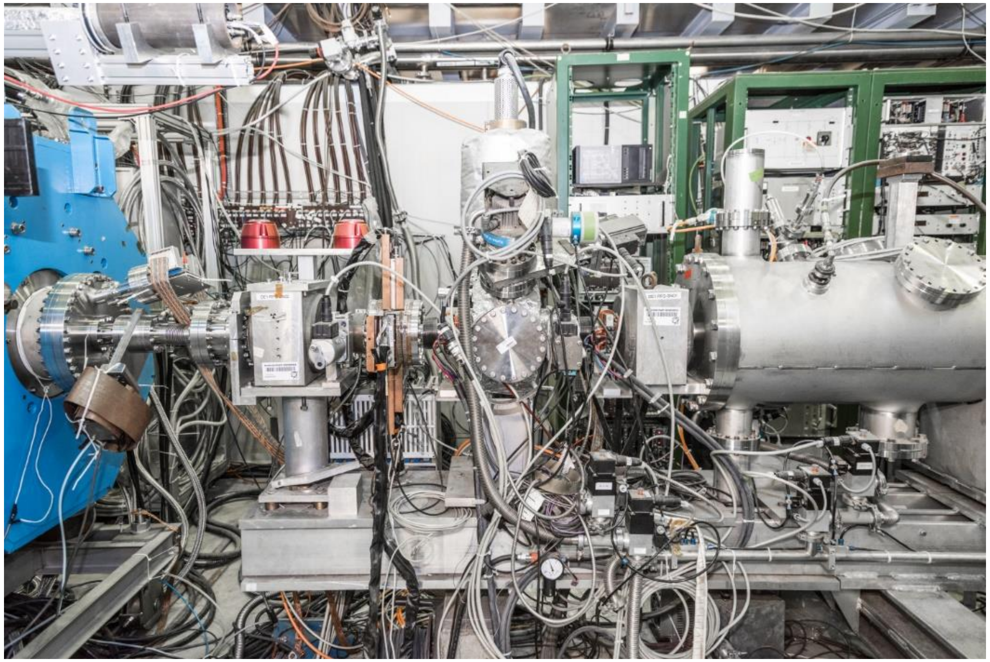


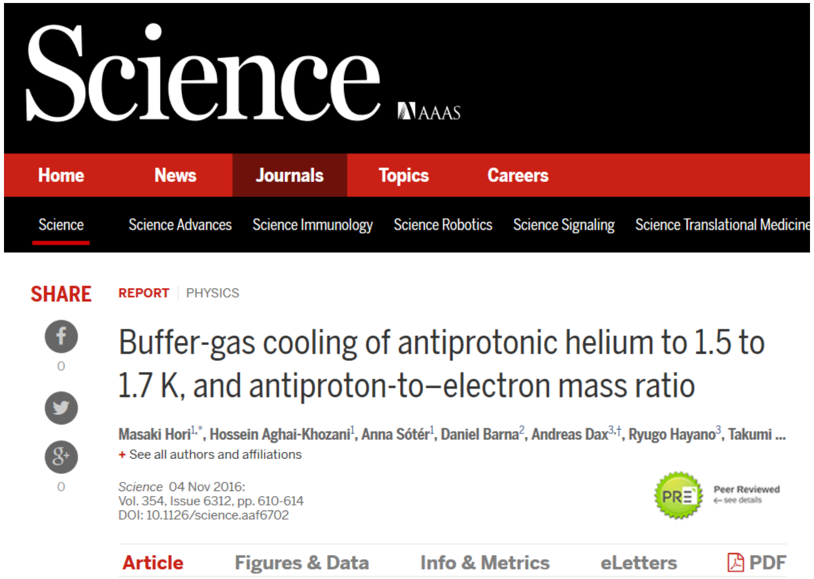
- detect annihilation of anti-hydrogen with silicon-strip detectors

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





REPORT | PHYSICS

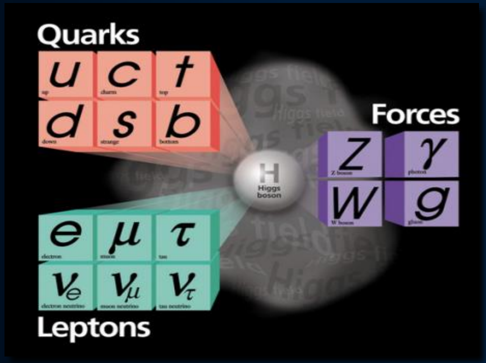
Buffer-gas cooling of antiprotonic helium to 1.5 to 1.7 K, and antiproton-to–electron mass ratio

Masaki Hori[1,*], Hossein Aghai-Khozani[1], Anna Sótér[1], Daniel Barna[2], Andreas Dax[3,†], Ryugo Hayano[3], Takumi ...

+ See all authors and affiliations

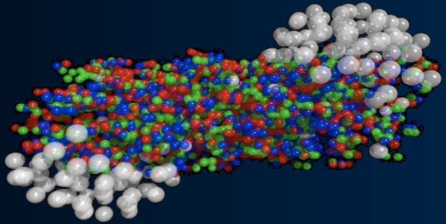
Science 04 Nov 2016:
Vol. 354, Issue 6312, pp. 610-614
DOI: 10.1126/science.aaf6702

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?

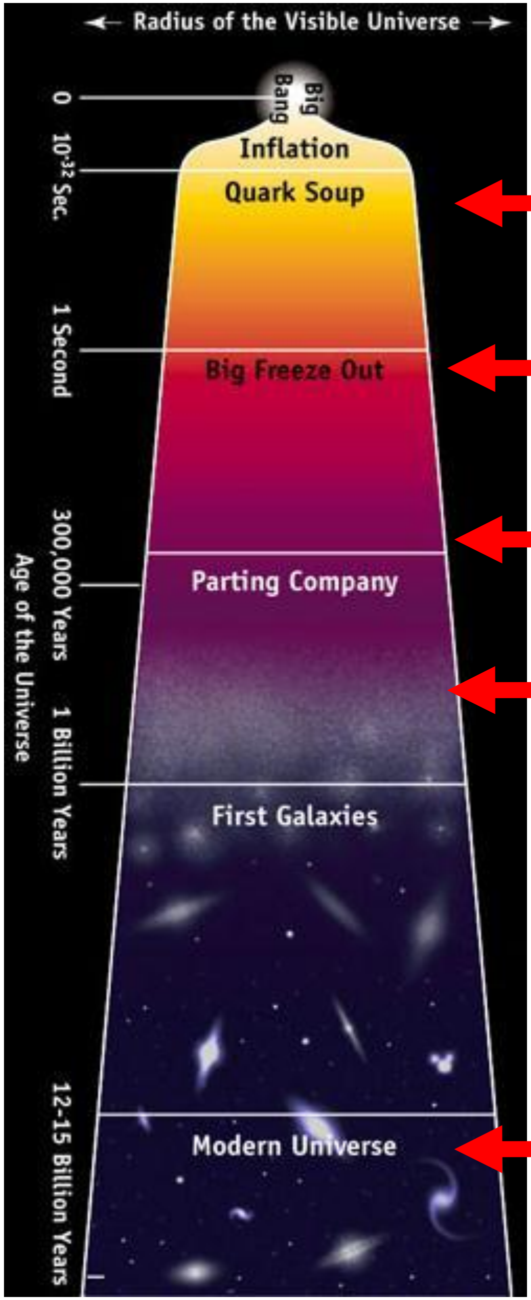
Will we find the reason why antimatter and matter did not completely destroy each other?



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!

Quark Gluon Plasma

Too hot for nuclei to bind

Hadron Gas

Nucleosynthesis builds nuclei up to He

Universe too hot for electrons to bind

E/M Plasma

Today’s Cold Universe

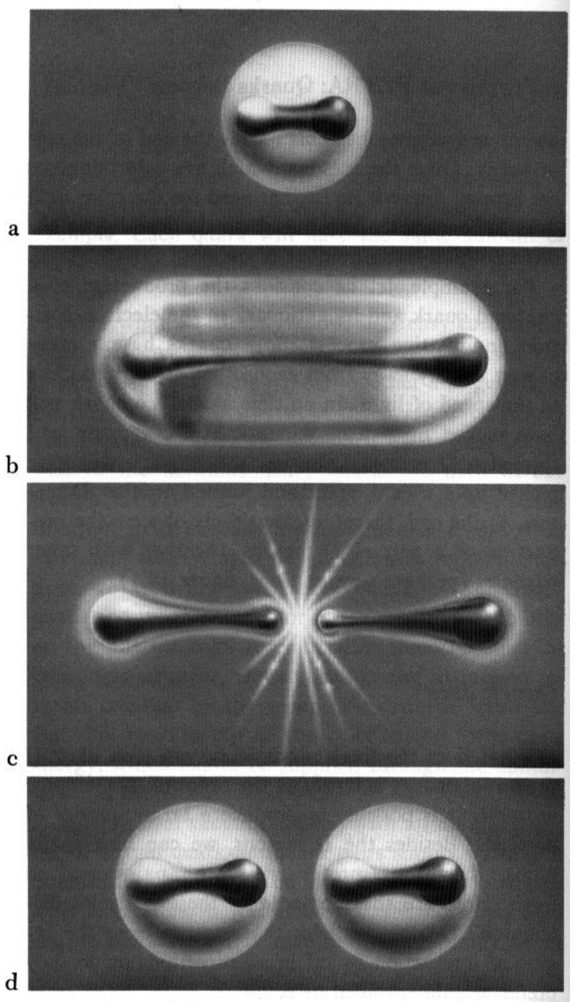
Solid Liquid Gas

How can we create Quark-Gluon Plasma?

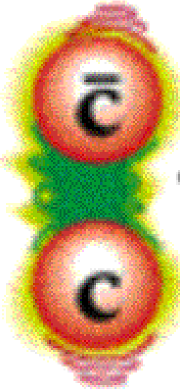
From confinement…

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

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



(Illustration from Fritzsch)



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

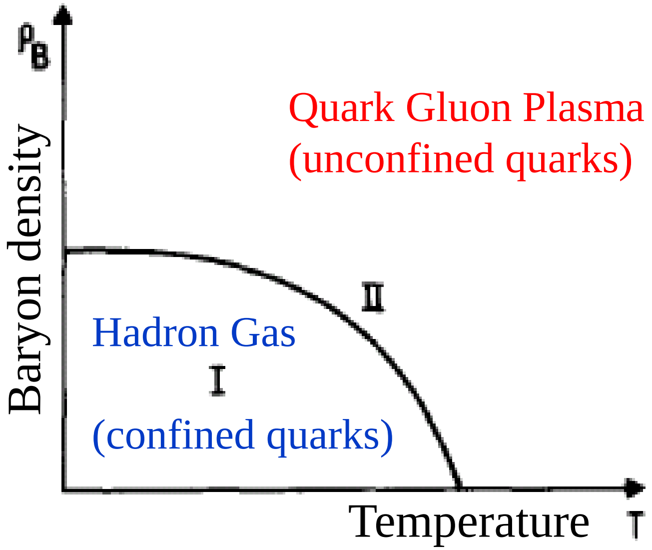
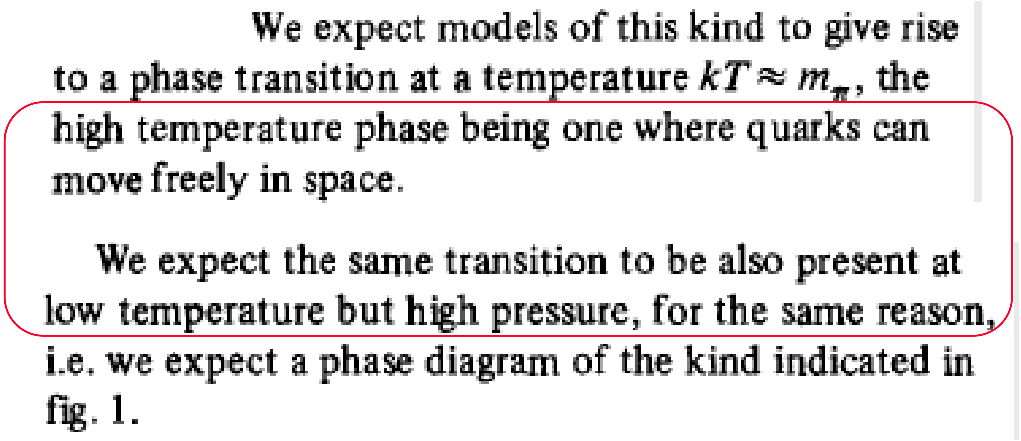


Fig. 1. Schematic phase diagram of hadronic matter. ρ_B is the density of baryonic number. Quarks are confined in phase I and unconfined in phase II.



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.

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

(10^5 times core of sun)

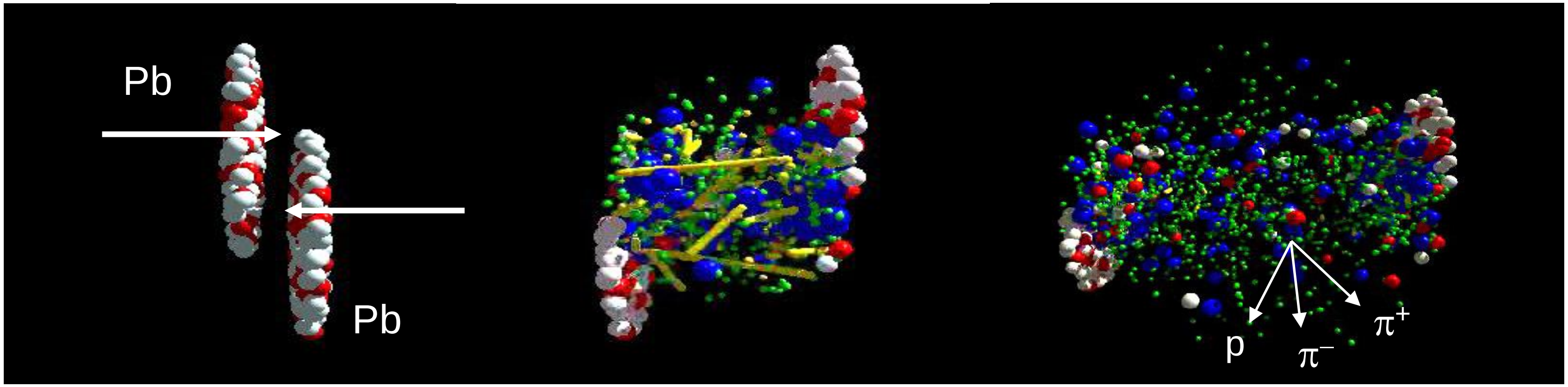
$n_c^B = 0.72\mathrm{fm}^{-3}$

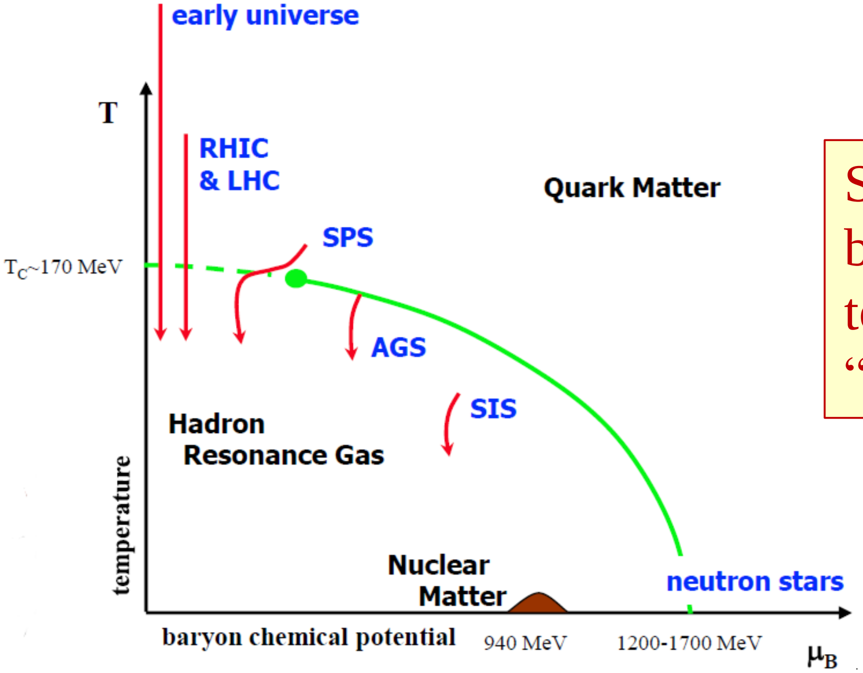
(5 times nucleus)

Phase transition at large T and/or ρ_B

How can we create Quark-Gluon Plasma?

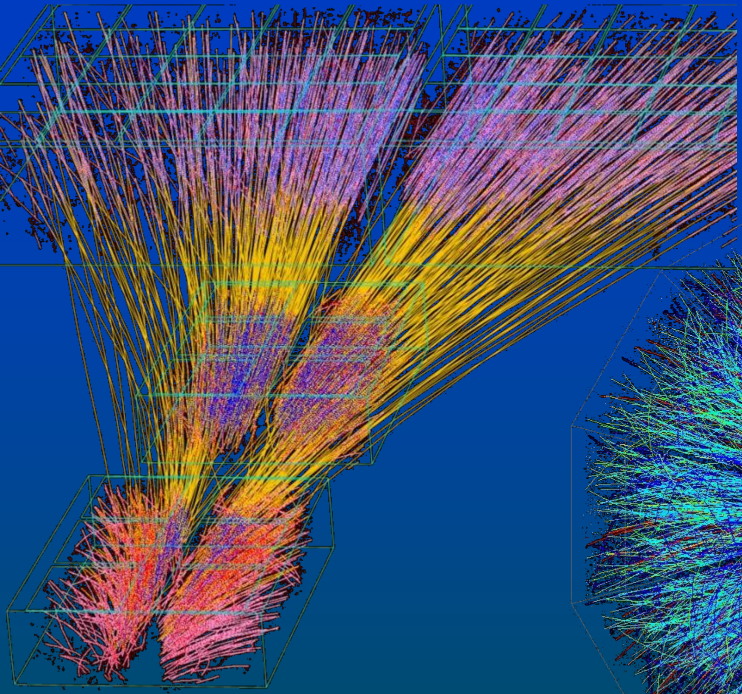
- reproduce the temperature (~10^{16} K) of the Universe a few instants (10^{-11}s) after the Big Bang





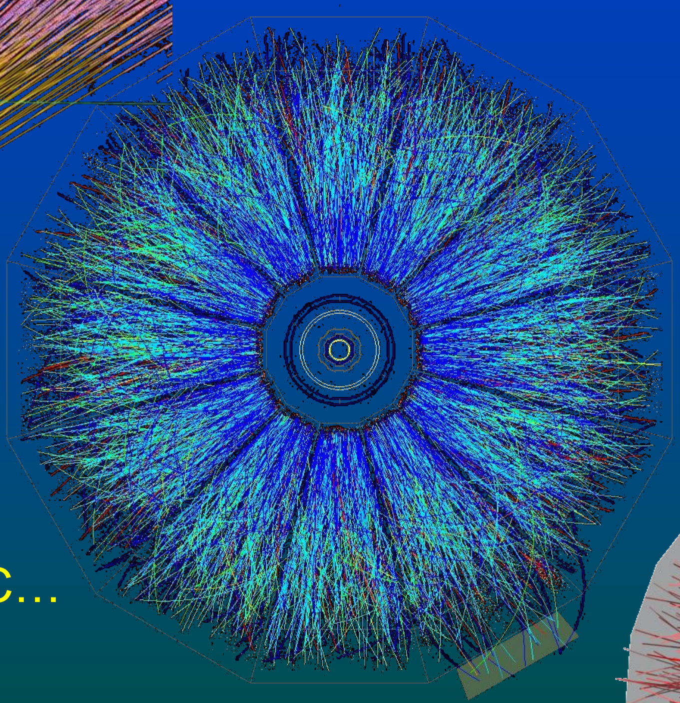
Study experimentally the phase diagram by colliding heavy nuclei (e.g. Pb-Pb) to convert cold nuclear matter into “Quark Matter”

Heavy Ions and Quark-Gluon Plasma…



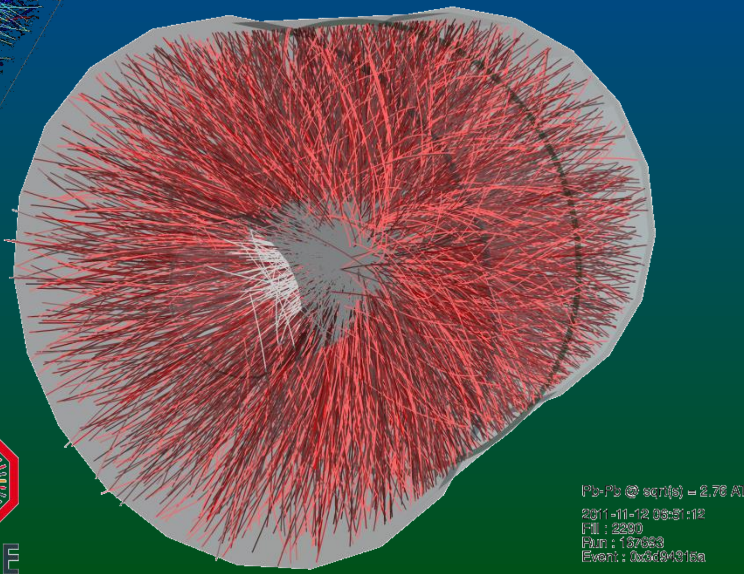
From SPS…

NA49



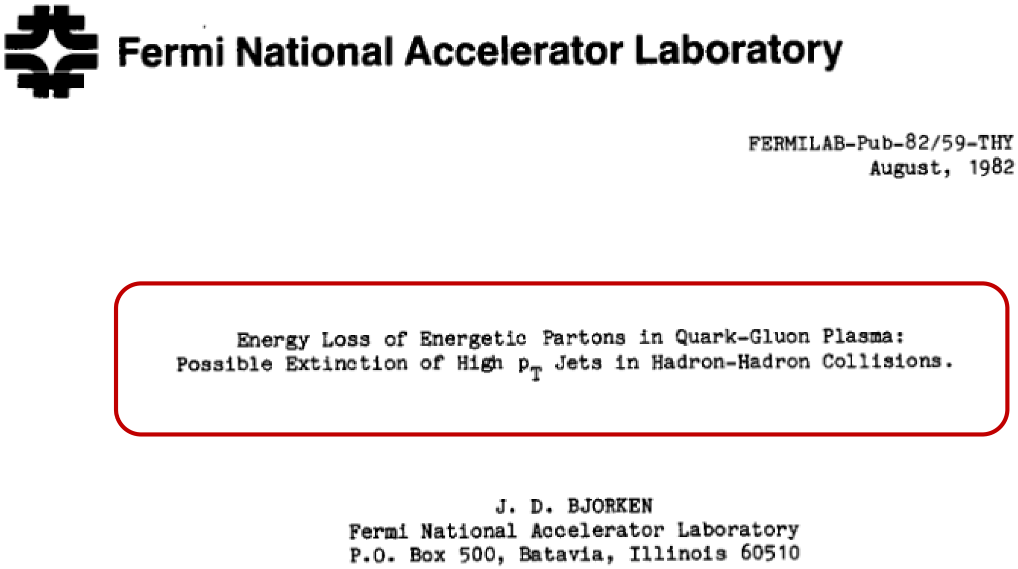
…to RHIC…

STAR



…to LHC!

ALICE
A JOURNEY OF DISCOVERY



Fermi National Accelerator Laboratory

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

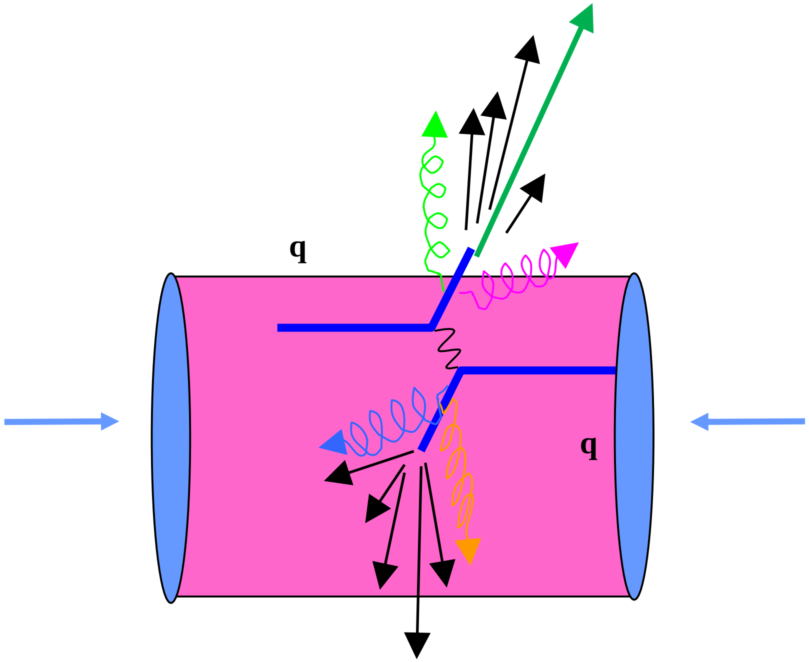
Energy Loss of Energetic Partons in Quark-Gluon Plasma:
Possible Extinction of High p_T Jets in Hadron-Hadron Collisions.

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

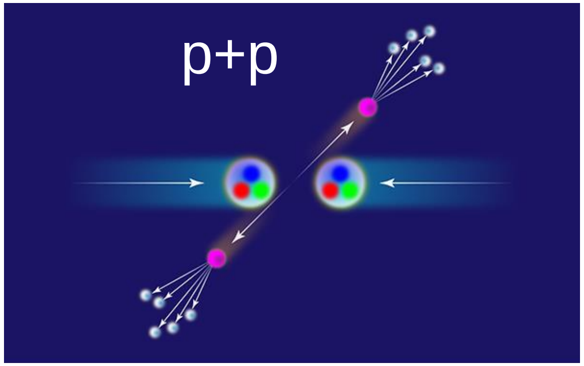
<u>1982</u>:
First idea by Bjorken on "Energy Loss of Energetic Partons in Quark-Gluon Plasma"

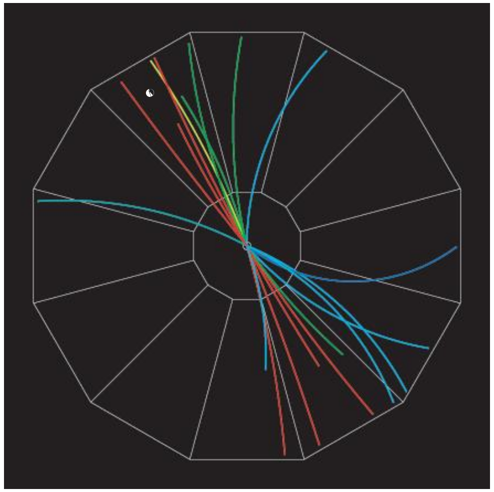
- ✓ High energy quarks and gluons propagating through quark gluon plasma suffer differential energy loss via elastic scattering from quanta in the plasma

- ➢ 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

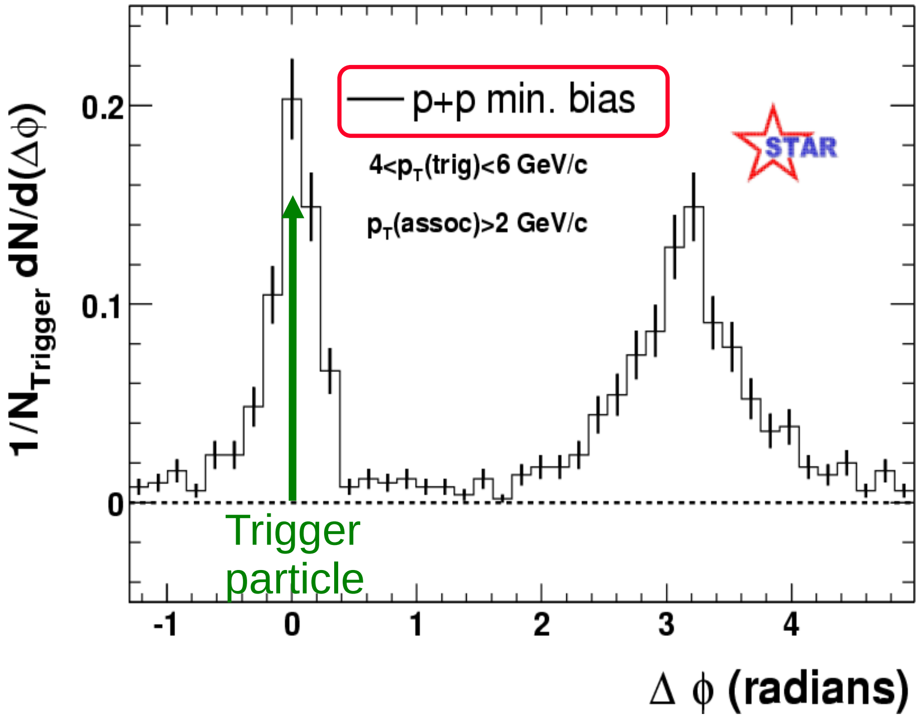


Di-hadron correlations



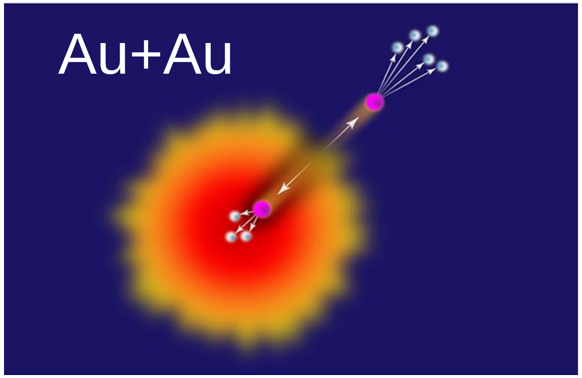


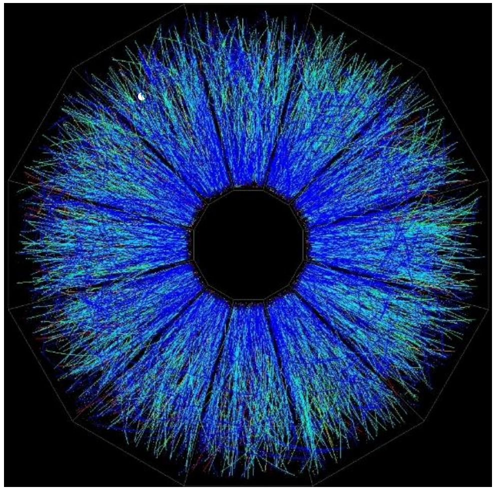
PRL 90 (2003) 082392



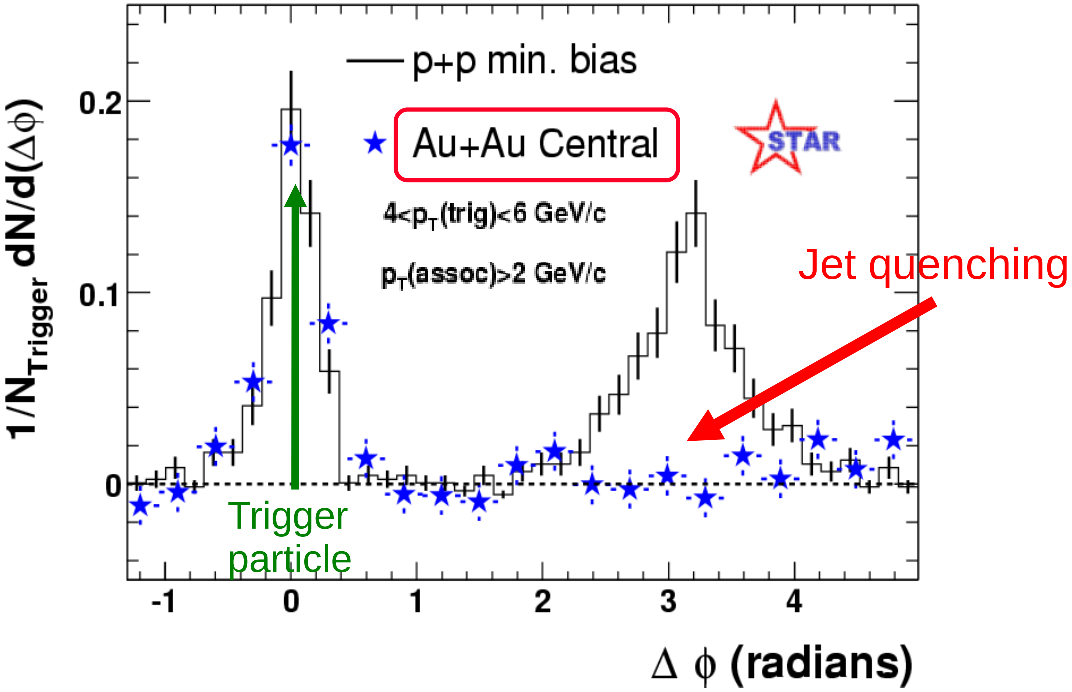
- ✓ study two particle angular correlations relative to high-p_T (trigger) particle:
- ✓ proxy for di-jet measurements
- ➢ in proton-proton collisions no suppression observed

Di-hadron correlations





PRL 90 (2003) 082392

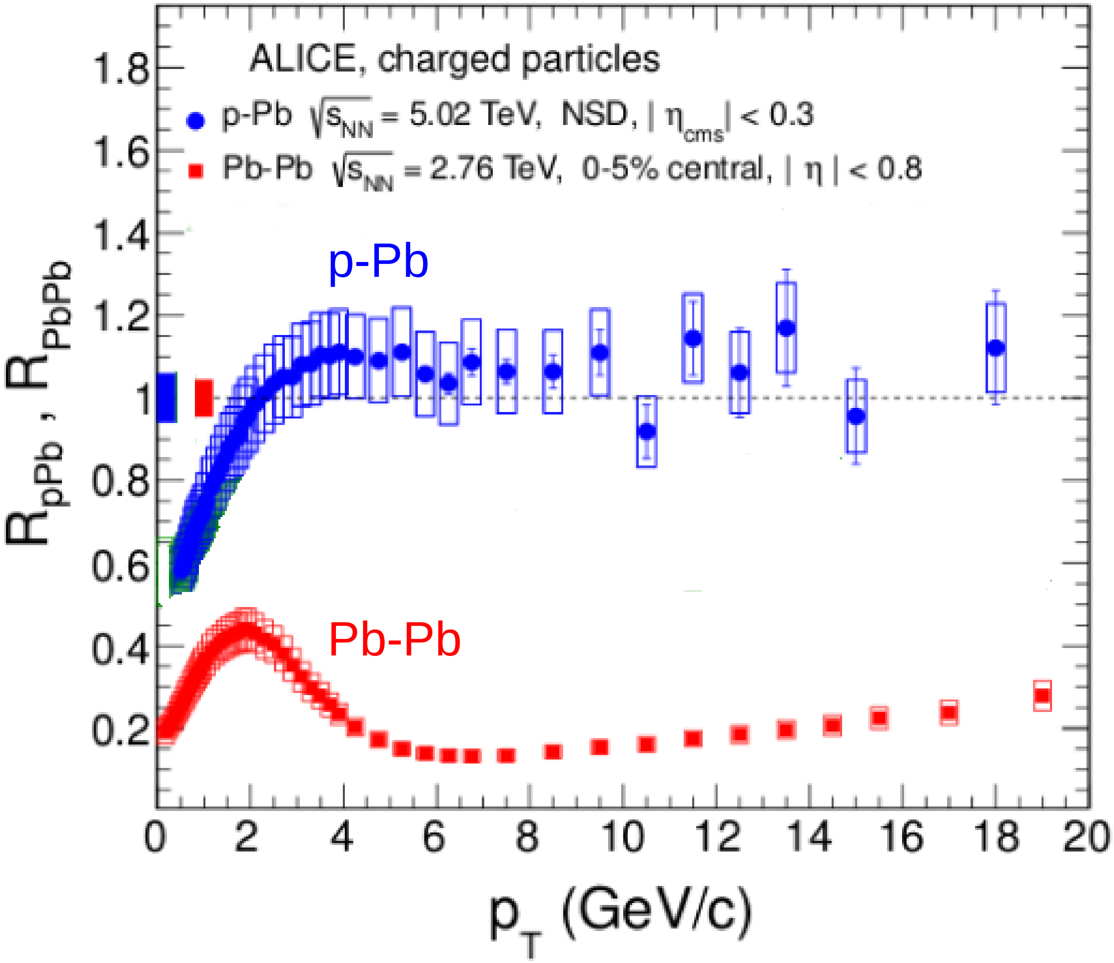


✓ in heavy ion collisions (Au-Au) recoiling jet is strongly suppressed by medium

➢ clear evidence for presence of very high density matter in central ion collisions

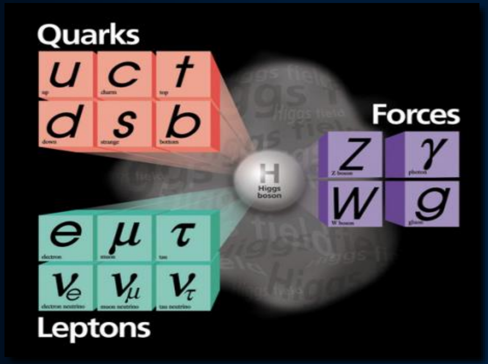
Leading particle suppression at the LHC

ALICE, PRL 110 (2013) 082302



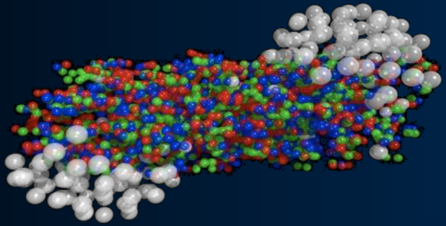
- ✓ strong leading particle suppression also at LHC energies
- ➢ qualitatively similar to the one at RHIC

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



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?

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

Mirror "world" to the Standard Model particles:

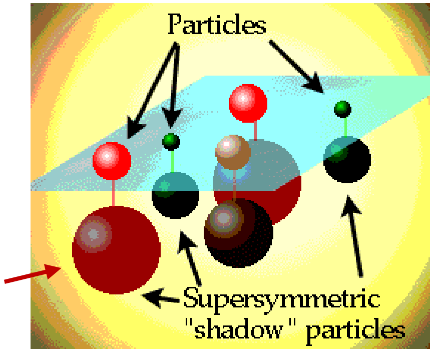
- ➢ for each SM particle a "super-partner" exists that differs only in ½-unit of spin

If lightest SUSY Particle (LSP) is stable:

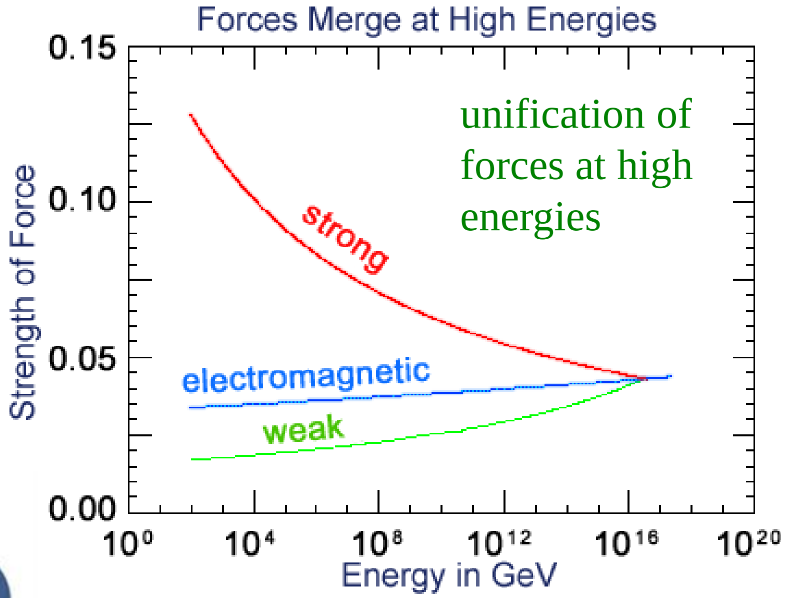
- ➢ offers "natural" dark-matter candidate

Grand Unification of all interactions:

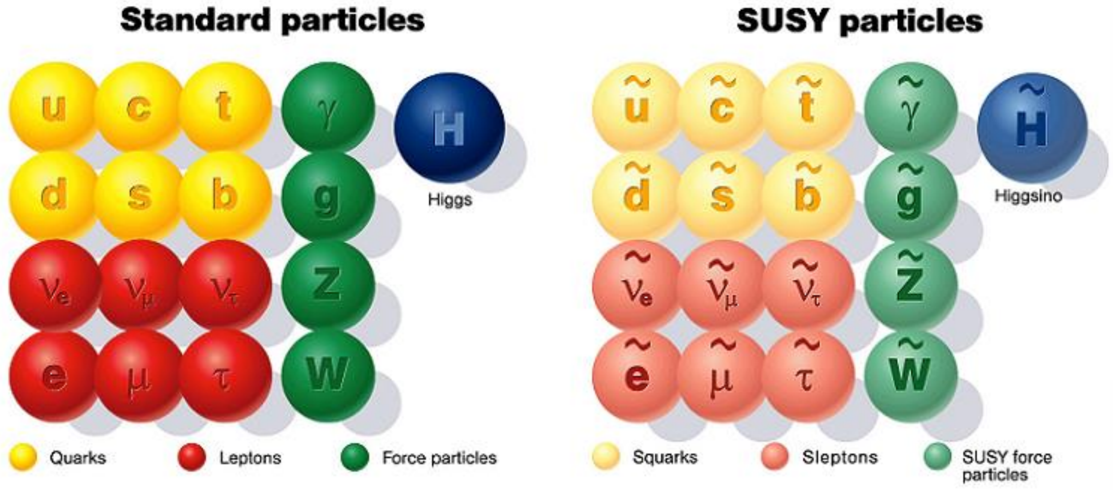
- ➢ equality of strong, weak and electromagnetic couplings at ~10^{16} GeV

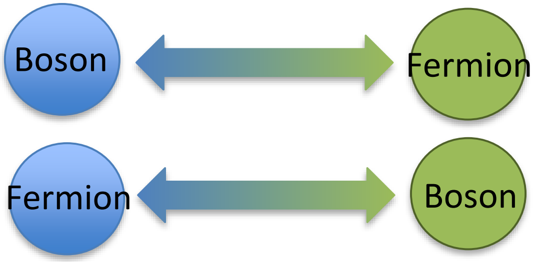


Dark Matter candidate



unification of forces at high energies

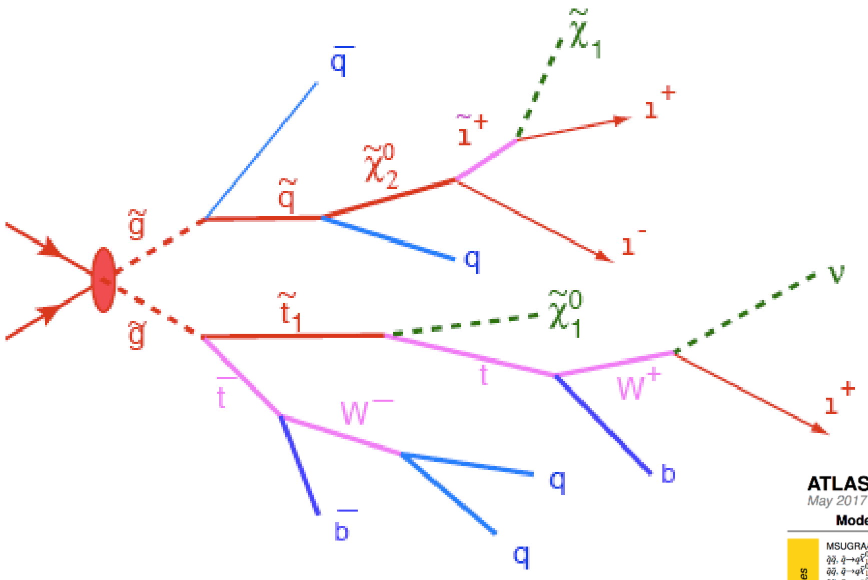




Boson ⟷ Fermion

Fermion ⟷ Boson

Signatures for SUSY

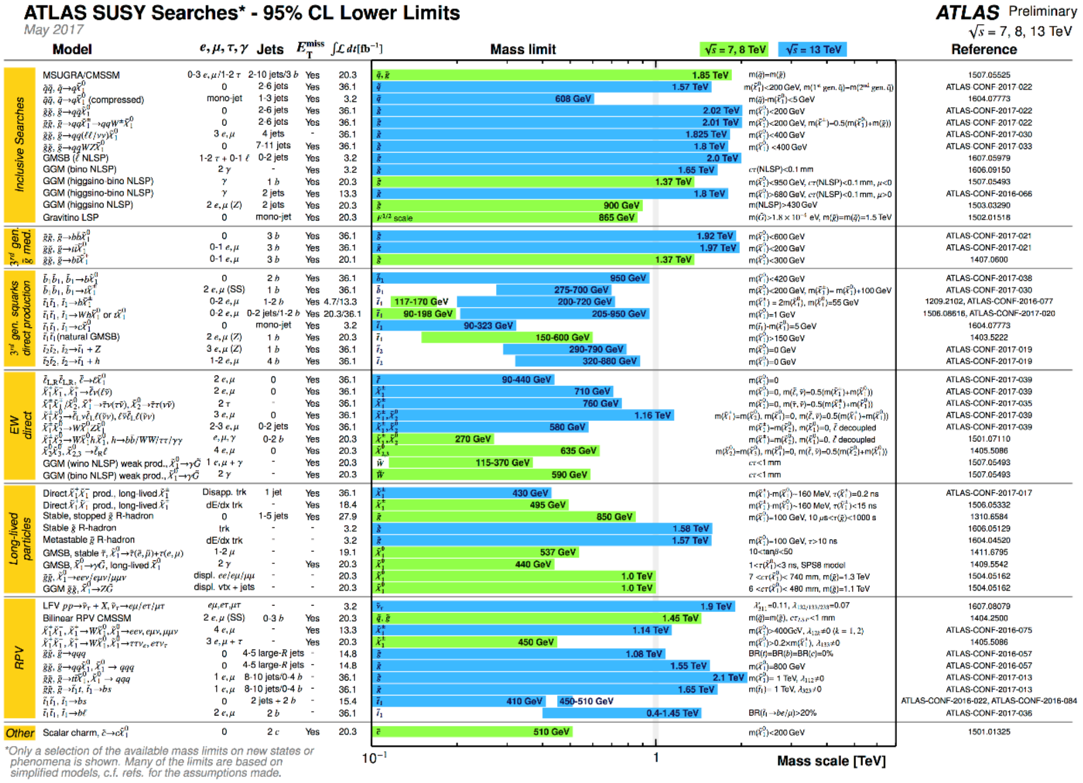


Missing Energy:
- from Lightest SUSY Particle (LSP)

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



ATLAS SUSY Searches* - 95% CL Lower Limits

May 2017

ATLAS Preliminary

$\sqrt{s}$ = 7, 8, 13 TeV

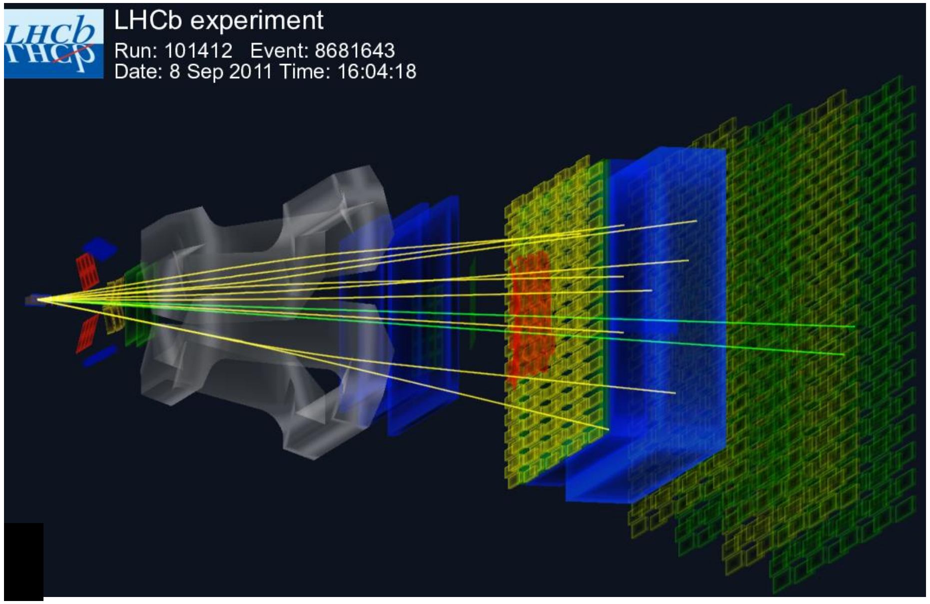
🟩 $\sqrt{s}$ = 7, 8 TeV 🟦 $\sqrt{s}$ = 13 TeV

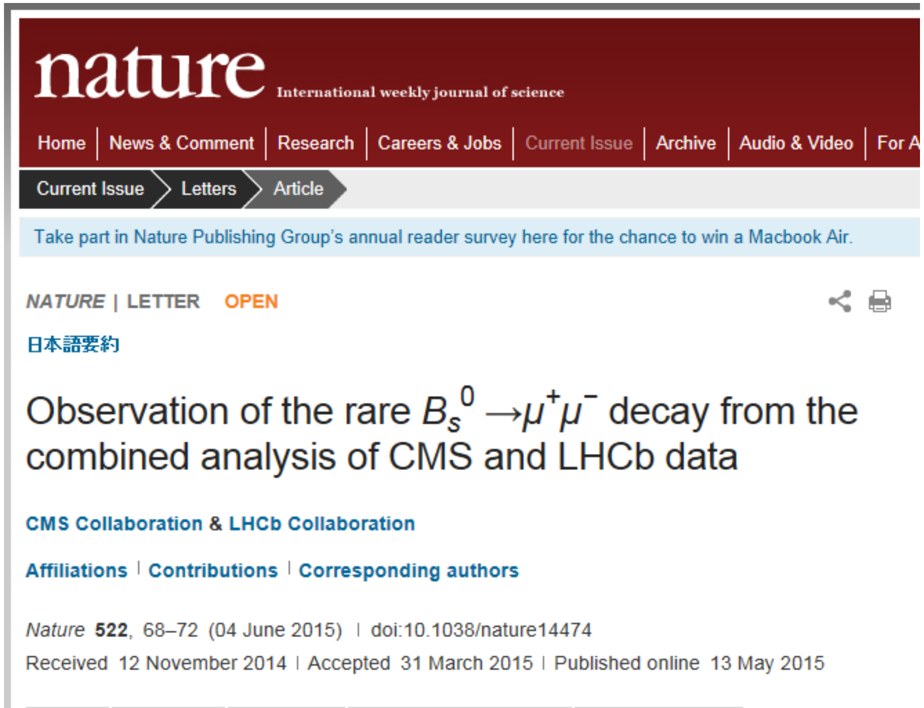
	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$	Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	0-3 e,μ/1-2 τ	2-10 jets/3 b	Yes	20.3	🟩 $\tilde{q}, \tilde{g}$ 1.85 TeV	m($\tilde{q}$)=m($\tilde{g}$)	1507.05525
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	🟦 $\tilde{q}$ 1.57 TeV	m($\tilde{\chi}_1^0$)<200 GeV, m(1st gen. $\tilde{q}$)=m(2nd gen. $\tilde{q}$)	ATLAS-CONF-2017-022
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$ (compressed)	mono-jet	1-3 jets	Yes	3.2	🟦 $\tilde{q}$ 608 GeV	m($\tilde{q}$)-m($\tilde{\chi}_1^0$)<5 GeV	1604.07773
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	🟦 $\tilde{g}$ 2.02 TeV	m($\tilde{\chi}_1^0$)<200 GeV	ATLAS-CONF-2017-022
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}_1^\pm\to qqW^\pm\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	🟦 $\tilde{g}$ 2.01 TeV	m($\tilde{\chi}_1^0$)<200 GeV, m($\tilde{\chi}^\pm$)=0.5(m($\tilde{\chi}_1^0$)+m($\tilde{g}$))	ATLAS-CONF-2017-022
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}(\ell\ell/\nu\nu)\tilde{\chi}_1^0$	3 e,μ	4 jets	-	36.1	🟦 $\tilde{g}$ 1.825 TeV	m($\tilde{\chi}_1^0$)<400 GeV	ATLAS-CONF-2017-030
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}WZ\tilde{\chi}_1^0$	0	7-11 jets	Yes	36.1	🟦 $\tilde{g}$ 1.8 TeV	m($\tilde{\chi}_1^0$) <400 GeV	ATLAS-CONF-2017-033
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	3.2	🟦 $\tilde{g}$ 2.0 TeV		1607.05979
	GGM (bino NLSP)	2 γ	-	Yes	3.2	🟦 $\tilde{g}$ 1.65 TeV	$c\tau$(NLSP)<0.1 mm	1606.09150
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	20.3	🟩 $\tilde{g}$ 1.37 TeV	m($\tilde{\chi}_1^0$)<950 GeV, $c\tau$(NLSP)<0.1 mm, μ<0	1507.05493
	GGM (higgsino-bino NLSP)	γ	2 jets	Yes	13.3	🟦 $\tilde{g}$ 1.8 TeV	m($\tilde{\chi}_1^0$)>680 GeV, $c\tau$(NLSP)<0.1 mm, μ>0	ATLAS-CONF-2016-066
	GGM (higgsino NLSP)	2 e,μ (Z)	2 jets	Yes	20.3	🟩 $\tilde{g}$ 900 GeV	m(NLSP)>430 GeV	1503.03290
	Gravitino LSP	0	mono-jet	Yes	20.3	🟩 $F^{1/2}$ scale 865 GeV	m($\tilde{G}$)>1.8 × 10^{-4} eV, m($\tilde{g}$)=m($\tilde{q}$)=1.5 TeV	1502.01518
3rd gen. $\tilde{g}$ med.	$\tilde{g}\tilde{g}$, $\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	36.1	🟦 $\tilde{g}$ 1.92 TeV	m($\tilde{\chi}_1^0$)<600 GeV	ATLAS-CONF-2017-021
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	Yes	36.1	🟦 $\tilde{g}$ 1.97 TeV	m($\tilde{\chi}_1^0$)<200 GeV	ATLAS-CONF-2017-021
	$\tilde{g}\tilde{g}$, $\tilde{g}\to b\bar{t}\tilde{\chi}_1^+$	0-1 e,μ	3 b	Yes	20.1	🟩 $\tilde{g}$ 1.37 TeV	m($\tilde{\chi}_1^0$)<300 GeV	1407.0600
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}_1^0$	0	2 b	Yes	36.1	🟦 $\tilde{b}_1$ 950 GeV	m($\tilde{\chi}_1^0$)<420 GeV	ATLAS-CONF-2017-038
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to t\tilde{\chi}_1^\pm$	2 e,μ (SS)	1 b	Yes	36.1	🟦 $\tilde{b}_1$ 275-700 GeV	m($\tilde{\chi}_1^0$)<200 GeV, m($\tilde{\chi}_1^\pm$)= m($\tilde{\chi}_1^0$)+100 GeV	ATLAS-CONF-2017-030
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\tilde{\chi}_1^\pm$	0-2 e,μ	1-2 b	Yes	4.7/13.3	$\tilde{t}_1$ 🟩 117-170 GeV 🟦 200-720 GeV	m($\tilde{\chi}_1^\pm$) = 2m($\tilde{\chi}_1^0$), m($\tilde{\chi}_1^0$)=55 GeV	1209.2102, ATLAS-CONF-2016-077
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$	0-2 e,μ	0-2 jets/1-2 b	Yes	20.3/36.1	$\tilde{t}_1$ 🟩 90-198 GeV 🟦 205-950 GeV	m($\tilde{\chi}_1^0$)=1 GeV	1506.08616, ATLAS-CONF-2017-020
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}_1^0$	0	mono-jet	Yes	3.2	🟦 $\tilde{t}_1$ 90-323 GeV	m($\tilde{t}_1$)-m($\tilde{\chi}_1^0$)=5 GeV	1604.07773
	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e,μ (Z)	1 b	Yes	20.3	🟩 $\tilde{t}_1$ 150-600 GeV	m($\tilde{\chi}_1^0$)>150 GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+Z$	3 e,μ (Z)	1 b	Yes	36.1	🟦 $\tilde{t}_2$ 290-790 GeV	m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2017-019
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+h$	1-2 e,μ	4 b	Yes	36.1	🟦 $\tilde{t}_2$ 320-880 GeV	m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2017-019
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e,μ	0	Yes	36.1	🟦 $\tilde{\ell}$ 90-440 GeV	m($\tilde{\chi}_1^0$)=0	ATLAS-CONF-2017-039
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e,μ	0	Yes	36.1	🟦 $\tilde{\chi}_1^\pm$ 710 GeV	m($\tilde{\chi}_1^0$)=0, m($\tilde{\ell}, \tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$))	ATLAS-CONF-2017-039
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp/\tilde{\chi}_2^0$, $\tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$, $\tilde{\chi}_2^0\to\tilde{\tau}\tau(\nu\tilde{\nu})$	2 τ	-	Yes	36.1	🟦 $\tilde{\chi}_1^\pm$ 760 GeV	m($\tilde{\chi}_1^0$)=0, m($\tilde{\tau}, \tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$))	ATLAS-CONF-2017-035
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu)$, $\ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e,μ	0	Yes	36.1	🟦 $\tilde{\chi}_1^\pm,\tilde{\chi}_2^0$ 1.16 TeV	m($\tilde{\chi}_1^\pm$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, m($\tilde{\ell}, \tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$))	ATLAS-CONF-2017-039
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0Z\tilde{\chi}_1^0$	2-3 e,μ	0-2 jets	Yes	36.1	🟦 $\tilde{\chi}_1^\pm,\tilde{\chi}_2^0$ 580 GeV	m($\tilde{\chi}_1^\pm$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, $\tilde{\ell}$ decoupled	ATLAS-CONF-2017-039
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0h\tilde{\chi}_1^0$, $h\to b\bar{b}/WW/\tau\tau/\gamma\gamma$	e,μ,γ	0-2 b	Yes	20.3	🟩 $\tilde{\chi}_1^\pm,\tilde{\chi}_2^0$ 270 GeV	m($\tilde{\chi}_1^\pm$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, $\tilde{\ell}$ decoupled	1501.07110
	$\tilde{\chi}_2^0\tilde{\chi}_3^0$, $\tilde{\chi}_{2,3}^0\to\tilde{\ell}_R\ell$	4 e,μ	0	Yes	20.3	🟩 $\tilde{\chi}_{2,3}^0$ 635 GeV	m($\tilde{\chi}_2^0$)=m($\tilde{\chi}_3^0$), m($\tilde{\chi}_1^0$)=0, m($\tilde{\ell}, \tilde{\nu}$)=0.5(m($\tilde{\chi}_2^0$)+m($\tilde{\chi}_1^0$))	1405.5086
	GGM (wino NLSP) weak prod., $\tilde{\chi}_1^0\to\gamma\tilde{G}$	1 e,μ + γ	-	Yes	20.3	🟩 $\tilde{W}$ 115-370 GeV	$c\tau$<1 mm	1507.05493
	GGM (bino NLSP) weak prod., $\tilde{\chi}_1^0\to\gamma\tilde{G}$	2 γ	-	Yes	20.3	🟩 $\tilde{W}$ 590 GeV	$c\tau$<1 mm	1507.05493
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	Yes	36.1	🟦 $\tilde{\chi}_1^\pm$ 430 GeV	m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)~160 MeV, τ($\tilde{\chi}_1^\pm$)=0.2 ns	ATLAS-CONF-2017-017
	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	dE/dx trk	-	Yes	18.4	🟩 $\tilde{\chi}_1^\pm$ 495 GeV	m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)~160 MeV, τ($\tilde{\chi}_1^\pm$)<15 ns	1506.05332
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	🟩 $\tilde{g}$ 850 GeV	m($\tilde{\chi}_1^0$)=100 GeV, 10 μs<τ($\tilde{g}$)<1000 s	1310.6584
	Stable $\tilde{g}$ R-hadron	trk	-	-	3.2	🟦 $\tilde{g}$ 1.58 TeV		1606.05129
	Metastable $\tilde{g}$ R-hadron	dE/dx trk	-	-	3.2	🟦 $\tilde{g}$ 1.57 TeV	m($\tilde{\chi}_1^0$)=100 GeV, τ>10 ns	1604.04520
	GMSB, stable $\tilde{\tau}$, $\tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	-	-	19.1	🟩 $\tilde{\chi}_1^0$ 537 GeV	10<tanβ<50	1411.6795
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	20.3	🟩 $\tilde{\chi}_1^0$ 440 GeV	1<τ($\tilde{\chi}_1^0$)<3 ns, SPS8 model	1409.5542
	$\tilde{g}\tilde{g}$, $\tilde{\chi}_1^0\to ee\nu/e\mu\nu/\mu\mu\nu$	displ. $ee/e\mu/\mu\mu$	-	-	20.3	🟩 $\tilde{\chi}_1^0$ 1.0 TeV	7 <$c\tau$($\tilde{\chi}_1^0$)< 740 mm, m($\tilde{g}$)=1.3 TeV	1504.05162
	GGM $\tilde{g}\tilde{g}$, $\tilde{\chi}_1^0\to Z\tilde{G}$	displ. vtx + jets	-	-	20.3	🟩 $\tilde{\chi}_1^0$ 1.0 TeV	6 <$c\tau$($\tilde{\chi}_1^0$)< 480 mm, m($\tilde{g}$)=1.1 TeV	1504.05162
RPV	LFV $pp\to\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$	$e\mu,e\tau,\mu\tau$	-	-	3.2	🟦 $\tilde{\nu}_\tau$ 1.9 TeV	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1607.08079
	Bilinear RPV CMSSM	2 e,μ (SS)	0-3 b	Yes	20.3	🟩 $\tilde{q}, \tilde{g}$ 1.45 TeV	m($\tilde{q}$)=m($\tilde{g}$), $c\tau_{LSP}$<1 mm	1404.2500
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to ee\nu, e\mu\nu, \mu\mu\nu$	4 e,μ	-	Yes	13.3	🟦 $\tilde{\chi}_1^\pm$ 1.14 TeV	m($\tilde{\chi}_1^0$)>400GeV, $\lambda_{12k}\neq0$ (k = 1, 2)	ATLAS-CONF-2016-075
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to\tau\tau\nu_e, e\tau\nu_\tau$	3 e,μ + τ	-	Yes	20.3	🟩 $\tilde{\chi}_1^\pm$ 450 GeV	m($\tilde{\chi}_1^0$)>0.2×m($\tilde{\chi}_1^\pm$), $\lambda_{133}\neq0$	1405.5086
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qqq$	0	4-5 large-R jets	-	14.8	🟦 $\tilde{g}$ 1.08 TeV	BR(t)=BR(b)=BR(c)=0%	ATLAS-CONF-2016-057
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to qqq$	0	4-5 large-R jets	-	14.8	🟦 $\tilde{g}$ 1.55 TeV	m($\tilde{\chi}_1^0$)=800 GeV	ATLAS-CONF-2016-057
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to qqq$	1 e,μ	8-10 jets/0-4 b	-	36.1	🟦 $\tilde{g}$ 2.1 TeV	m($\tilde{\chi}_1^0$)= 1 TeV, $\lambda_{112}\neq0$	ATLAS-CONF-2017-013
	$\tilde{g}\tilde{g}$, $\tilde{g}\to\tilde{t}_1t$, $\tilde{t}_1\to bs$	1 e,μ	8-10 jets/0-4 b	-	36.1	🟦 $\tilde{g}$ 1.65 TeV	m($\tilde{t}_1$)= 1 TeV, $\lambda_{323}\neq0$	ATLAS-CONF-2017-013
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to bs$	0	2 jets + 2 b	-	15.4	🟦 $\tilde{t}_1$ 410 GeV 450-510 GeV		ATLAS-CONF-2016-022, ATLAS-CONF-2016-084
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\ell$	2 e,μ	2 b	-	36.1	🟦 $\tilde{t}_1$ 0.4-1.45 TeV	BR($\tilde{t}_1\to be/\mu$)>20%	ATLAS-CONF-2017-036
Other	Scalar charm, $\tilde{c}\to c\tilde{\chi}_1^0$	0	2 c	Yes	20.3	🟩 $\tilde{c}$ 510 GeV	m($\tilde{\chi}_1^0$)<200 GeV	1501.01325

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

Search for Physics Beyond the Standard Model

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





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日本語要約

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

CMS Collaboration & LHCb Collaboration

Affiliations | Contributions | Corresponding authors

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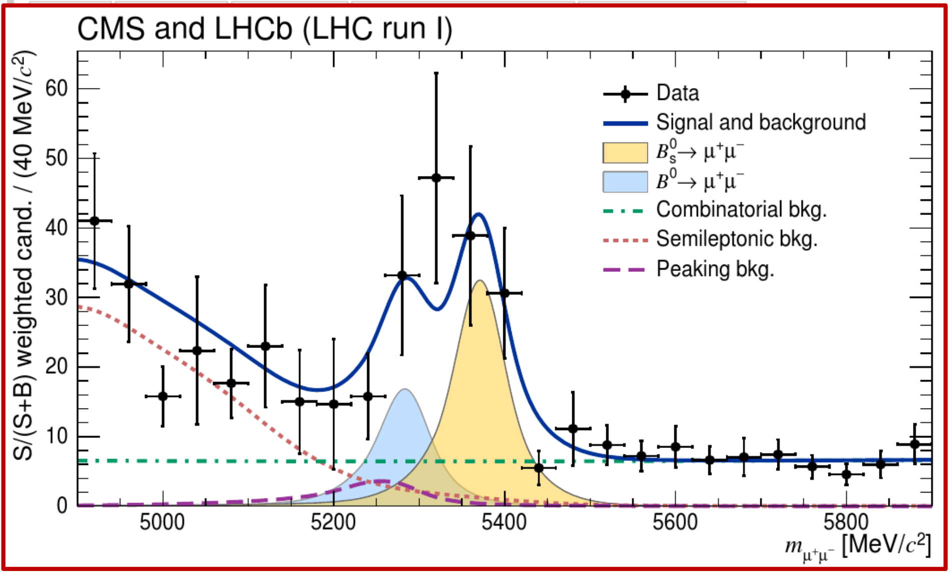


in Standard Model → super-rare decay :

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

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

[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

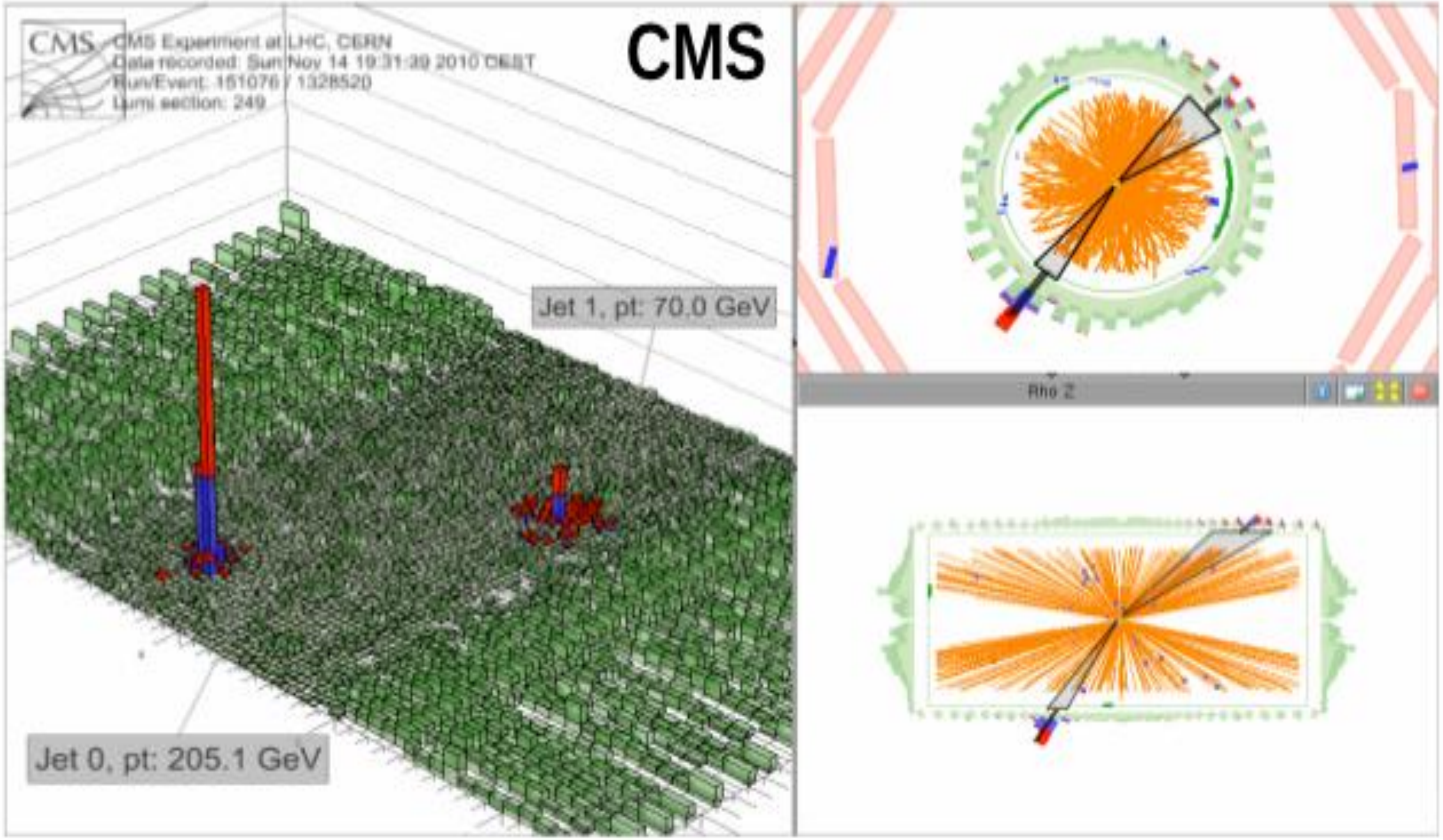
- ✓ After the discovery of the Higgs boson, the Standard Model of particle physics is now "complete"!
- ✓ However, this explains only ~5% of our universe and many questions in understanding the origin of our universe are yet to be resolved.
- ✓ Powerful particle accelerators and sophisticated detectors 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

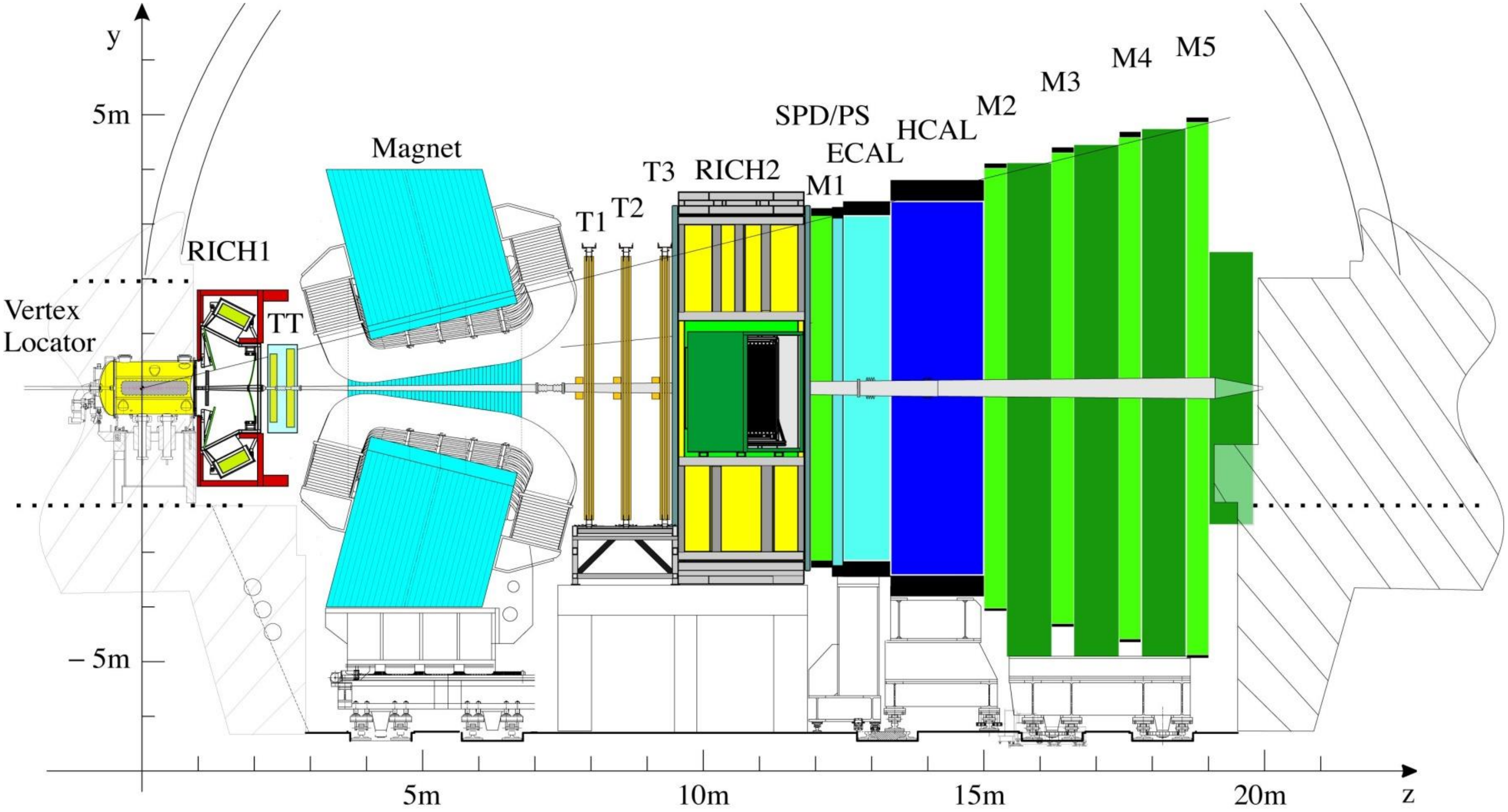
Can even be seen in event displays !!!



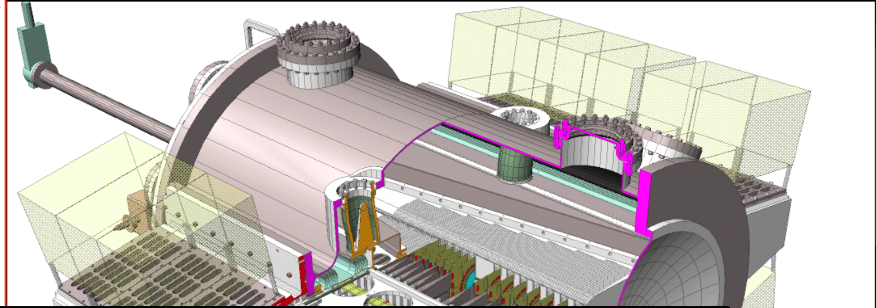
$$A_{\mathrm{J}} = \frac{E_{\mathrm{T1}} - E_{\mathrm{T2}}}{E_{\mathrm{T1}} + E_{\mathrm{T2}}}, \quad \Delta\varphi_{12} > \frac{\pi}{2}$$

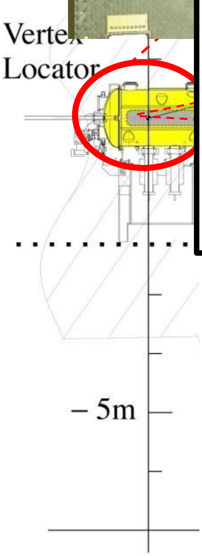
A walk through the LHCb detector

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

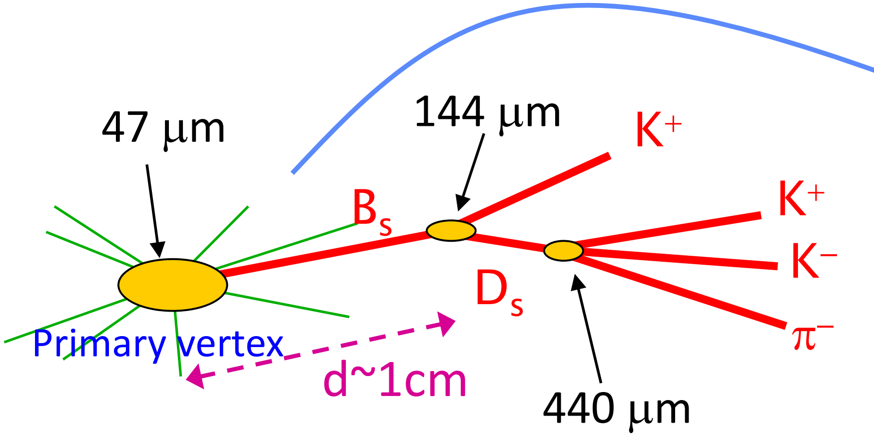


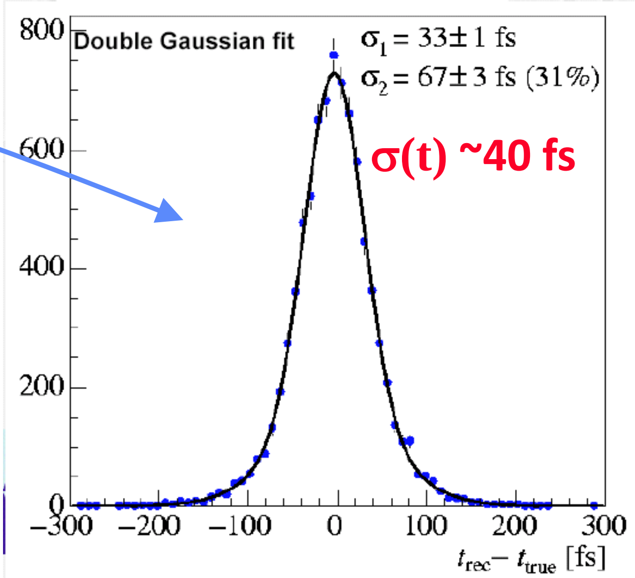
B-Vertex Measurement





Example: $B_s \rightarrow D_s K$



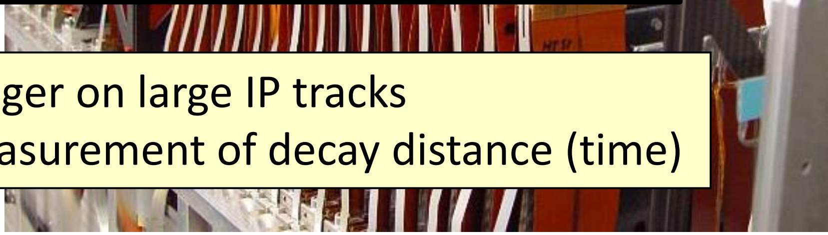


Vertex Locator (Velo)

21 stations of silicon strip detectors (r-ϕ)

~ 8 μm hit resolution

~25 μm IP resolution

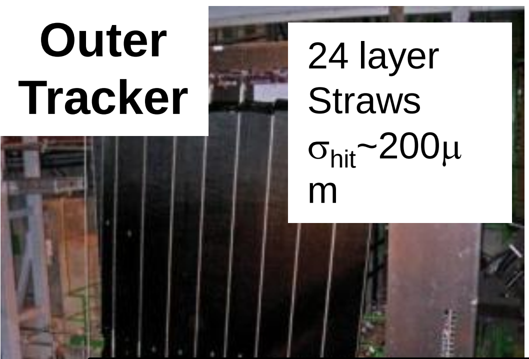


- Trigger on large IP tracks
- Measurement of decay distance (time)

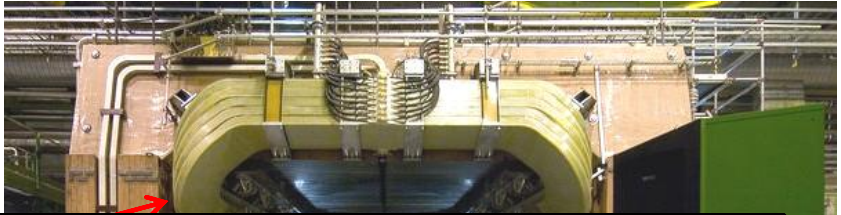
Momentum measurement

Outer Tracker

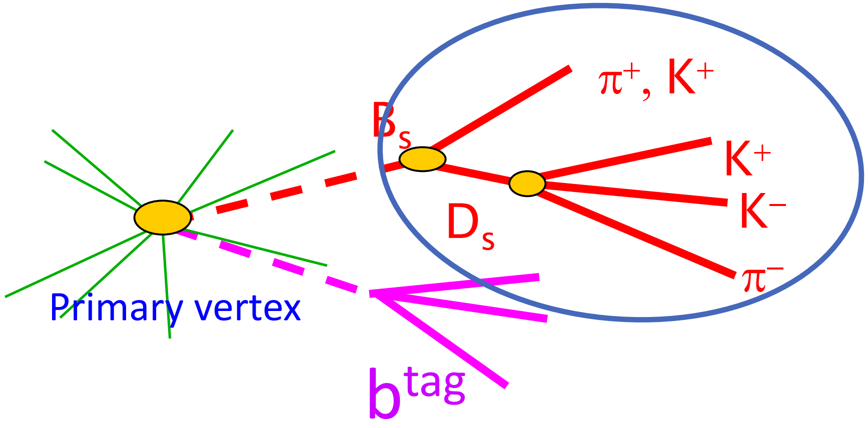
24 layer Straws σ_{hit}~200μm

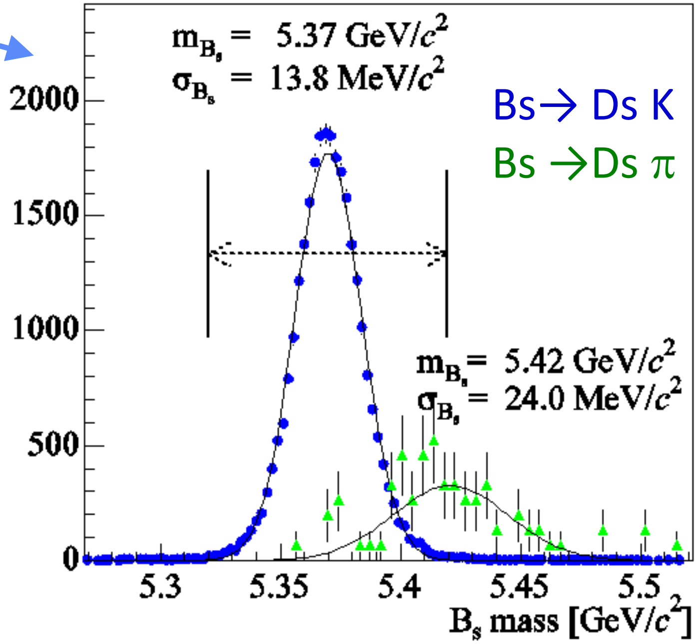


σ_p/p~0.5%

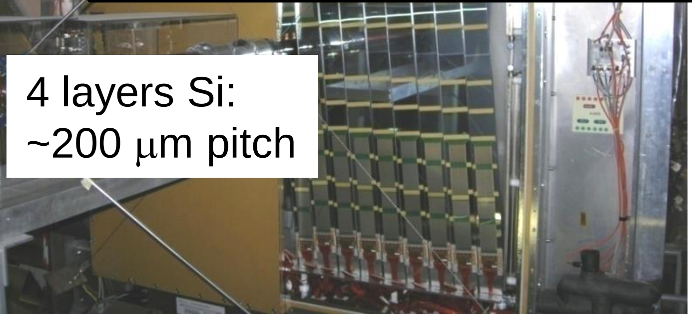


Mass resolution: σ ~ 14 MeV

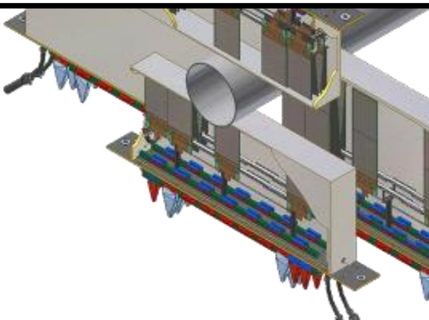


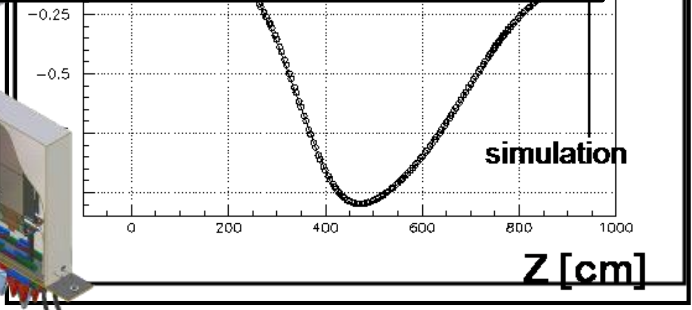


Tri
Tra



4 layers Si:
~200 μm pitch

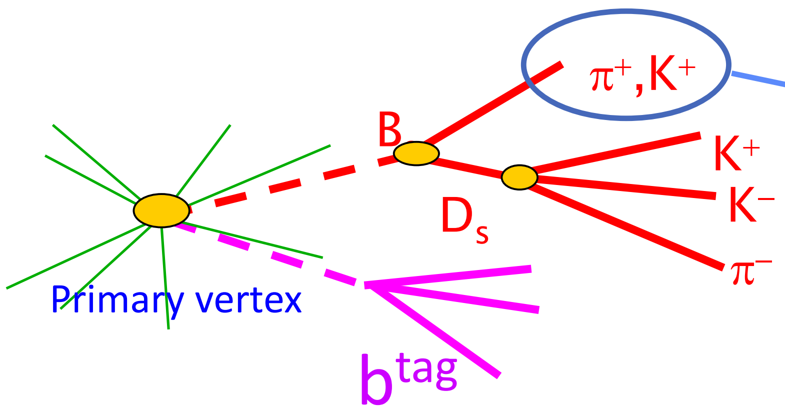




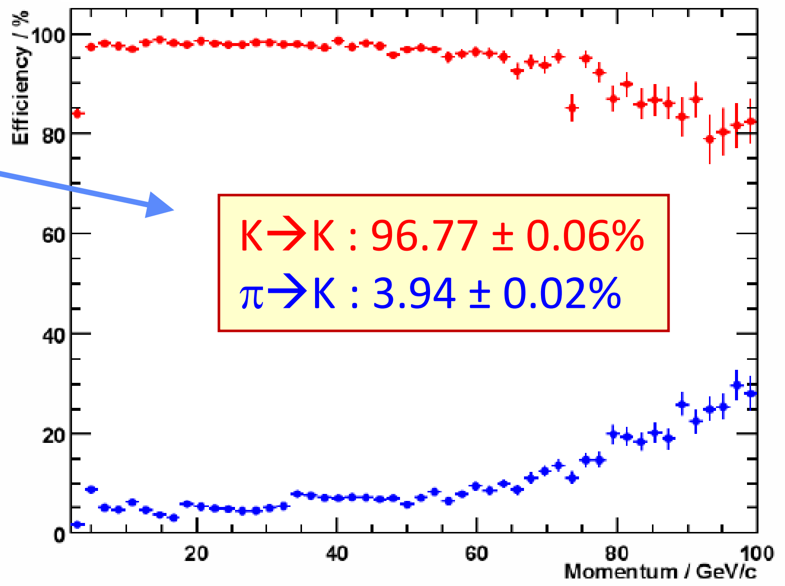
Particle Identification

RICH: K/π identification using Cherenkov light emission angle

$B_s \to D_s K$



Kaon identification performance



K→K : 96.77 ± 0.06%

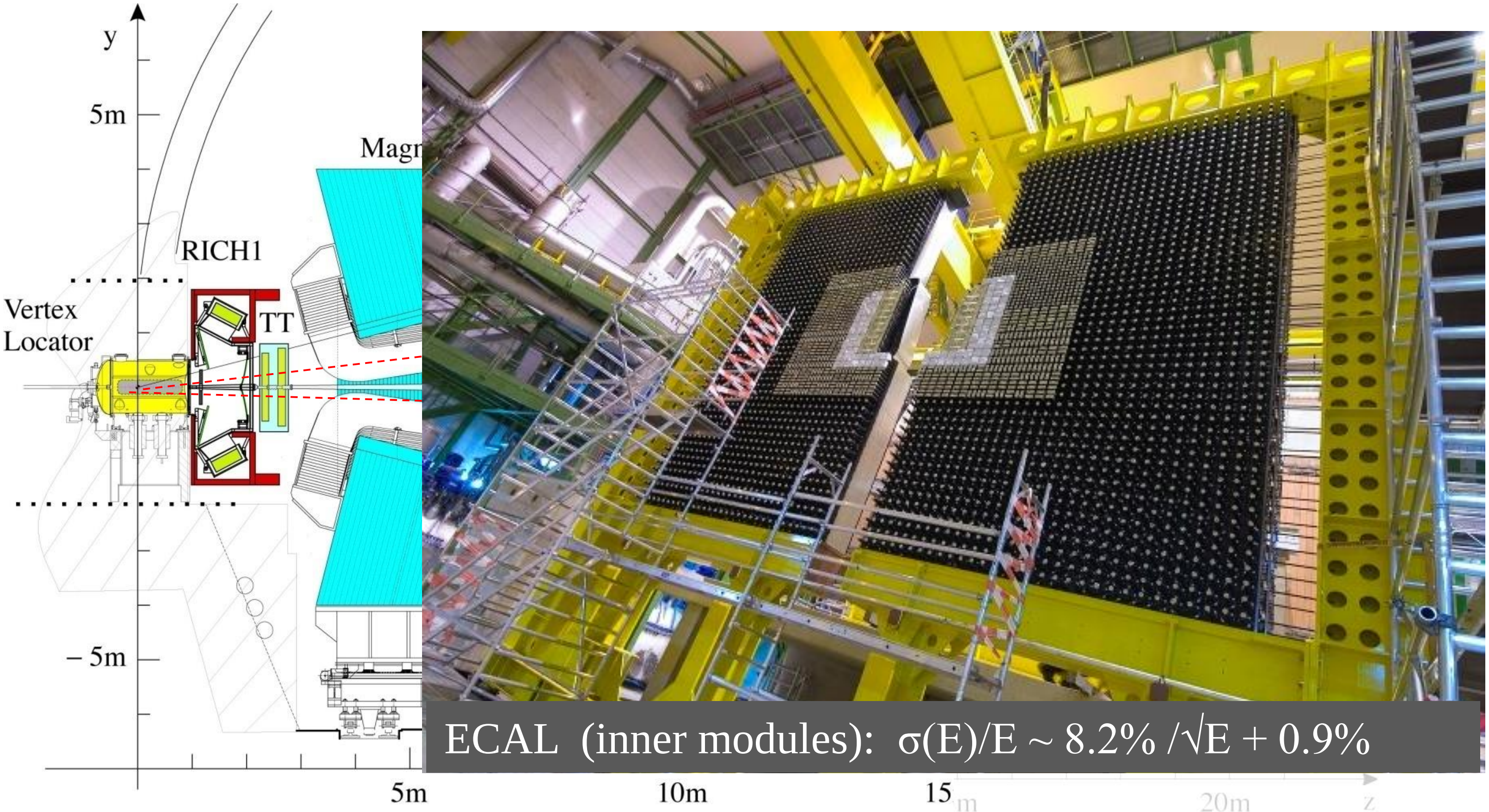
π→K : 3.94 ± 0.02%

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

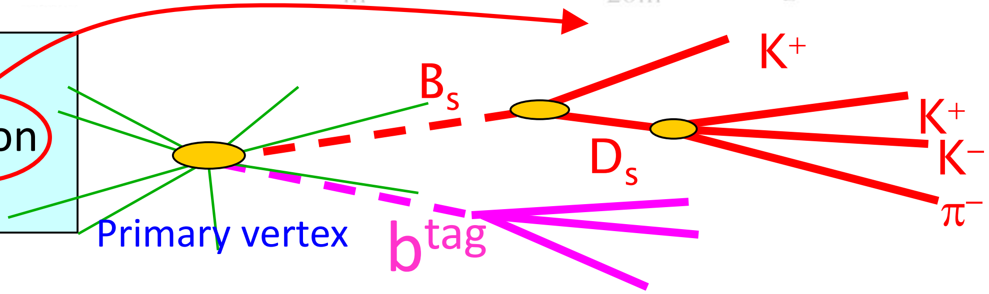
Particle identification and L0 trigger



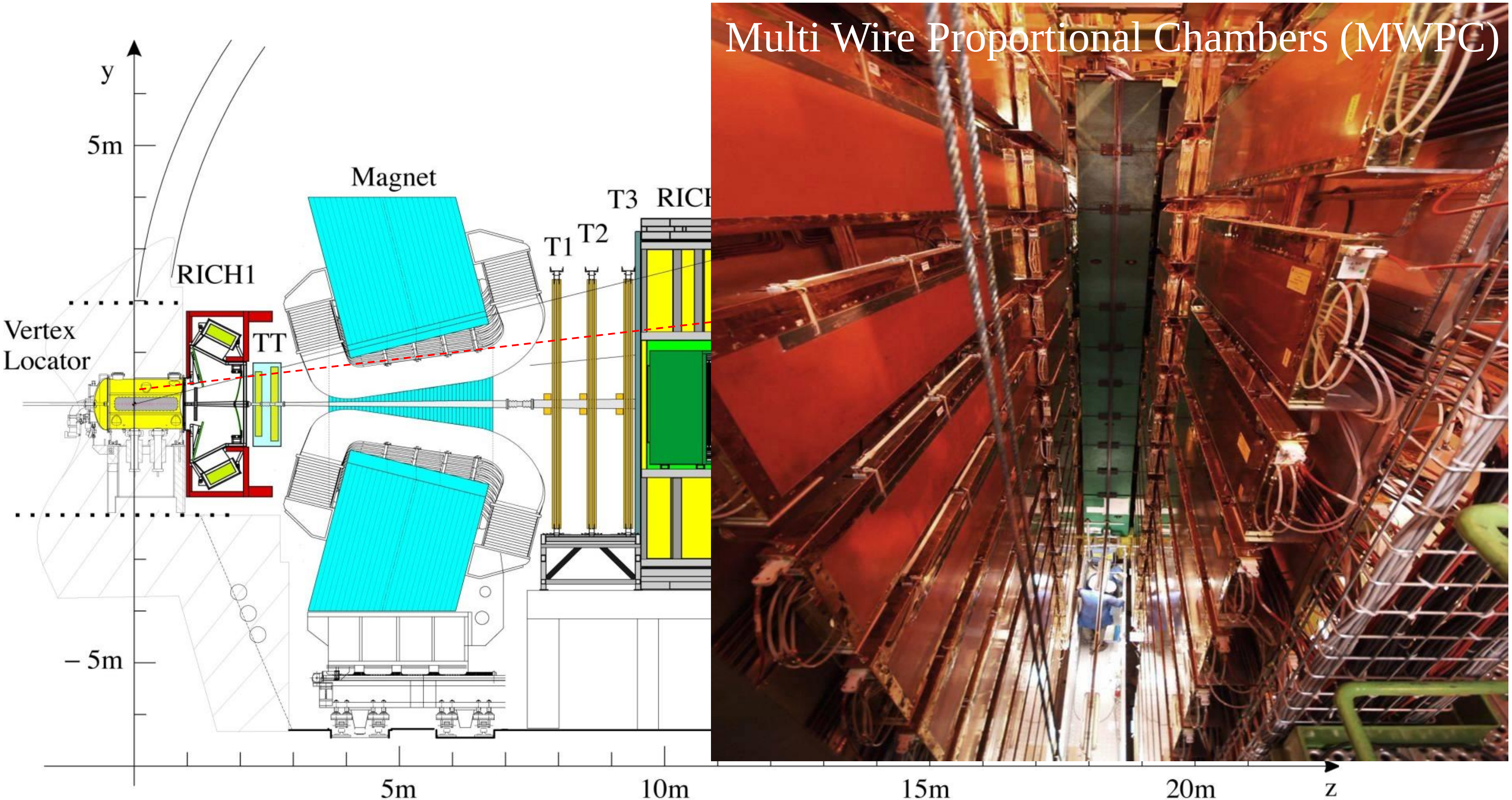
ECAL (inner modules): $\sigma(E)/E \sim 8.2\%/\sqrt{E} + 0.9\%$

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)