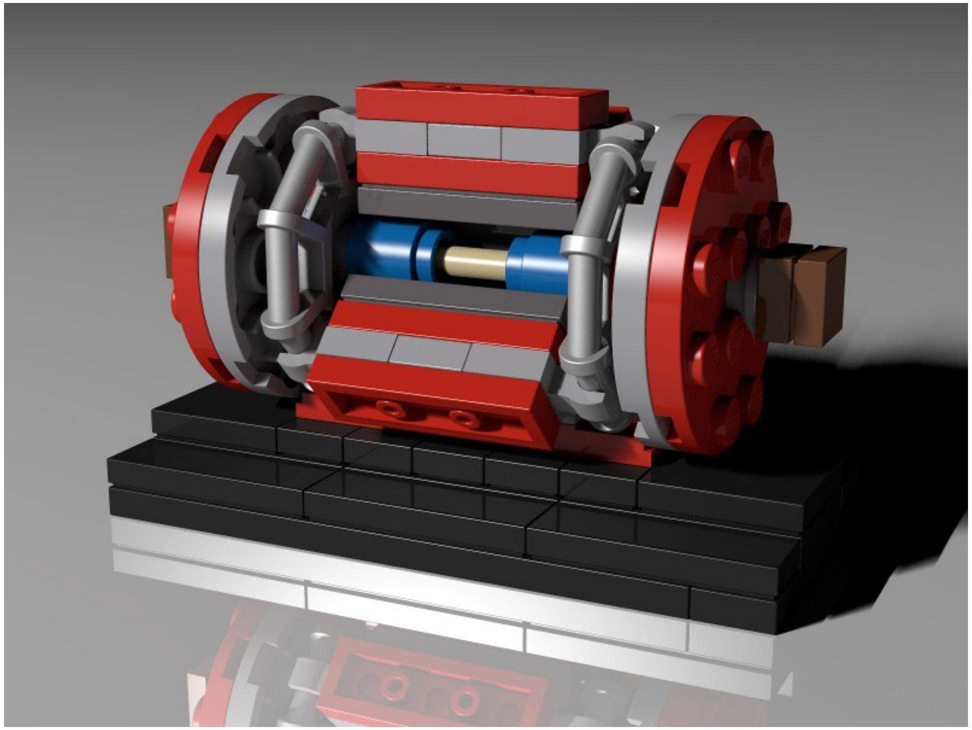
The Compact Muon Solenoid (CMS) Experiment



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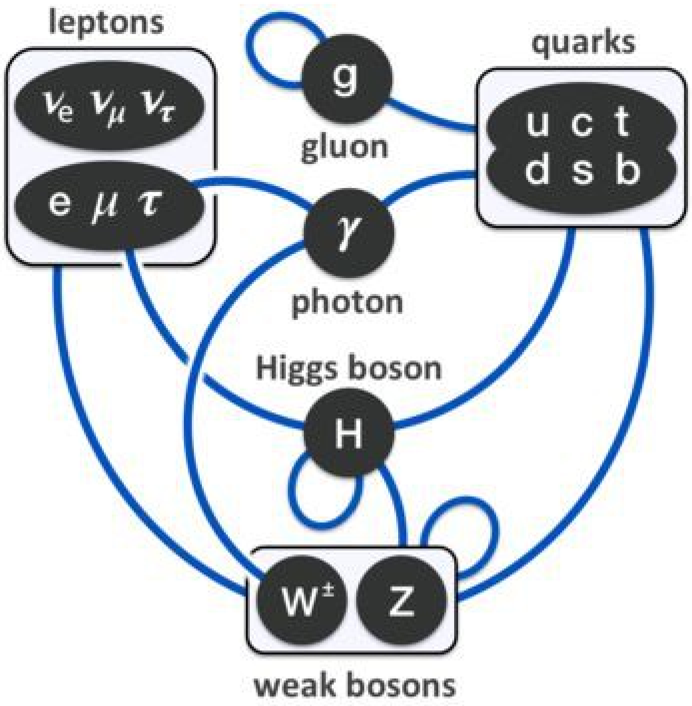
Outline

- Motivations
- LHC and its experiments, in particular CMS
- Digression: some spin-offs
- What LHC and CMS already achieved
- What might be next
- Challenges of complexity

Motivations

Standard Model (SM) in a nutshell

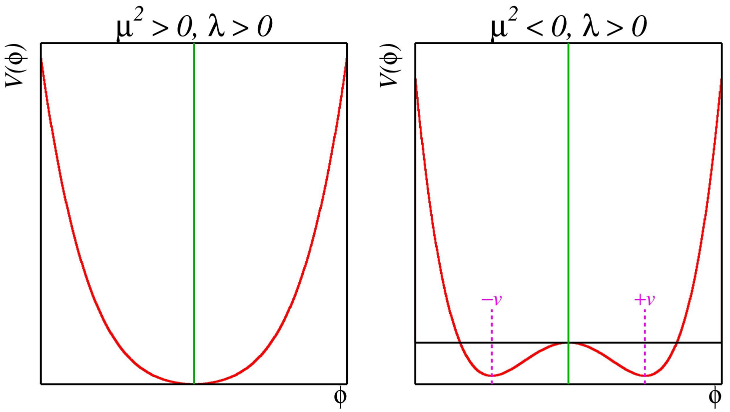


- Forces are carried by bosons: photons (electromagnetism), W/Z (weak force), gluons (strong force), gravitons (gravity)
- Matter is composed of fermions: **quarks** (sensitive to strong force) and **leptons** (neutral to strong force), grouped in 3 generations
- So far very successful *in the lab*, but known to be incomplete

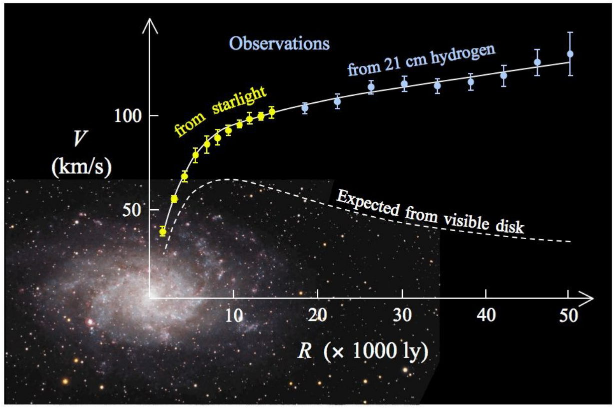
Image source: wikipedia

Some big questions that LHC was designed to address

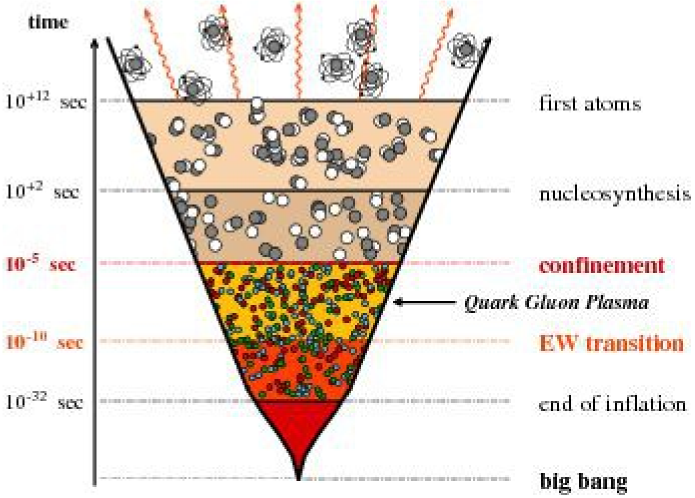
Origin of mass



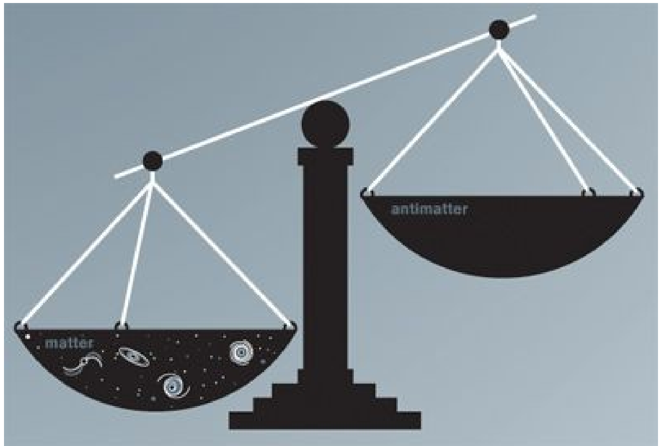
Nature of Dark Matter



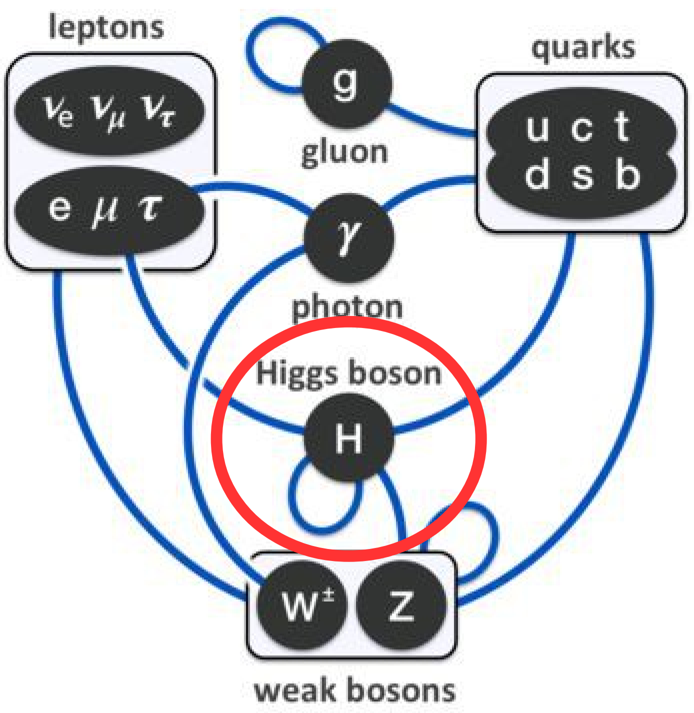
Behaviour of early Universe



Reason for matter / antimatter imbalance

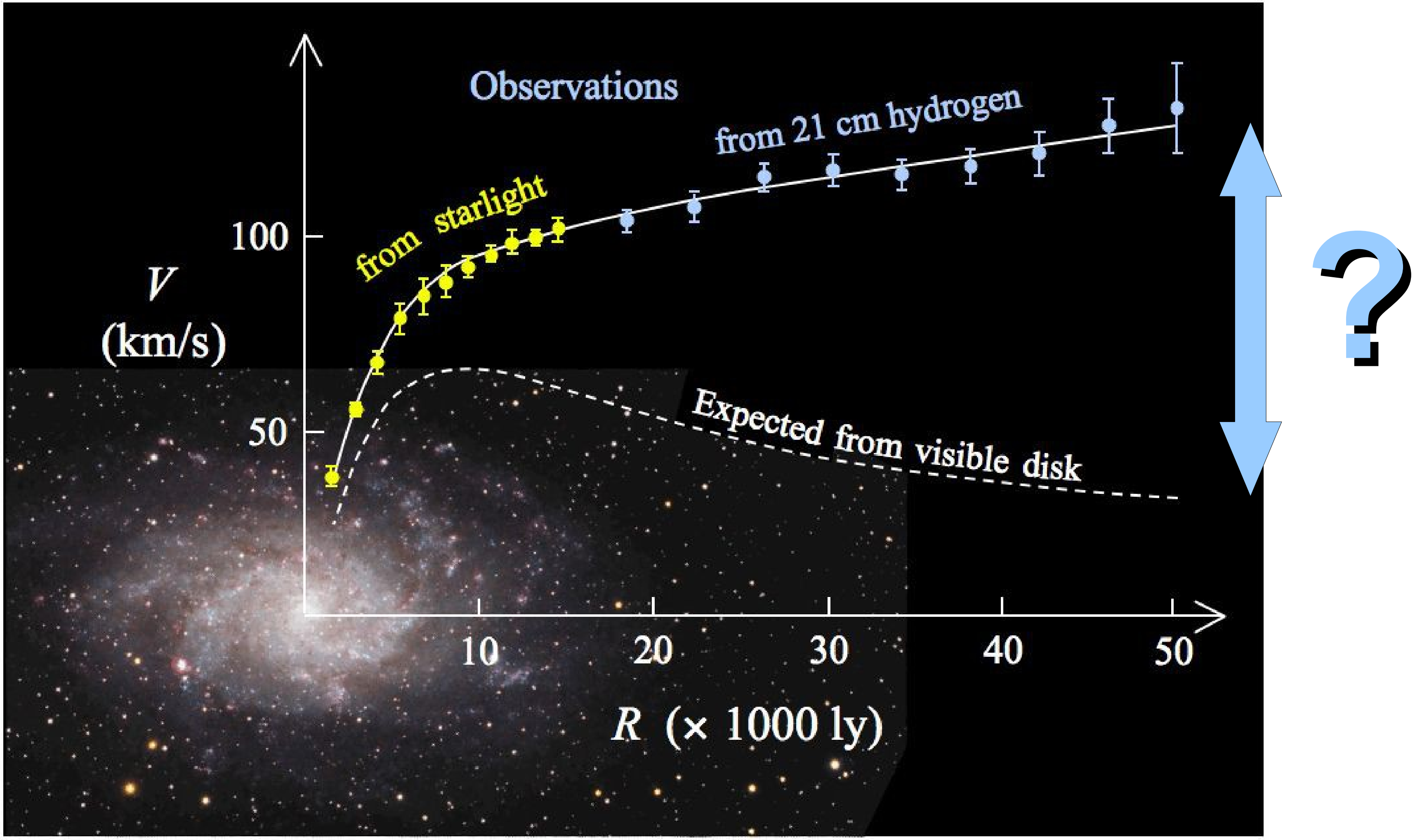


Origin of mass

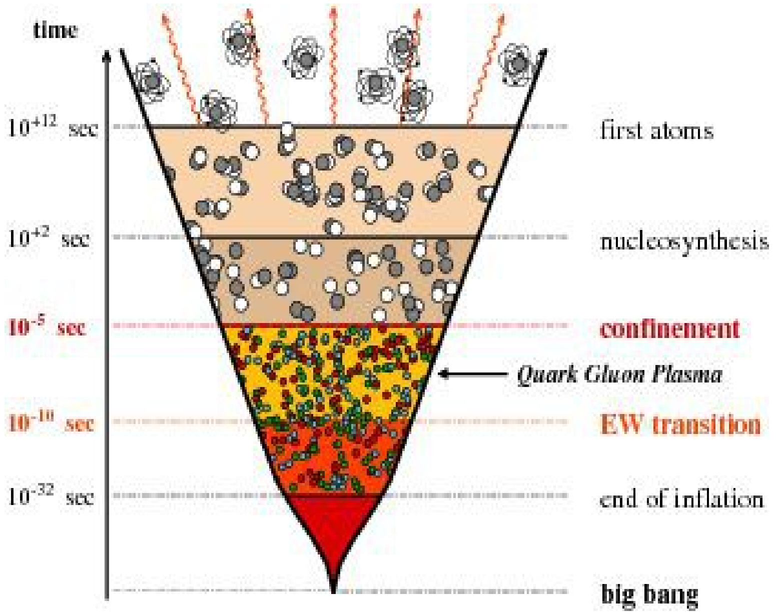


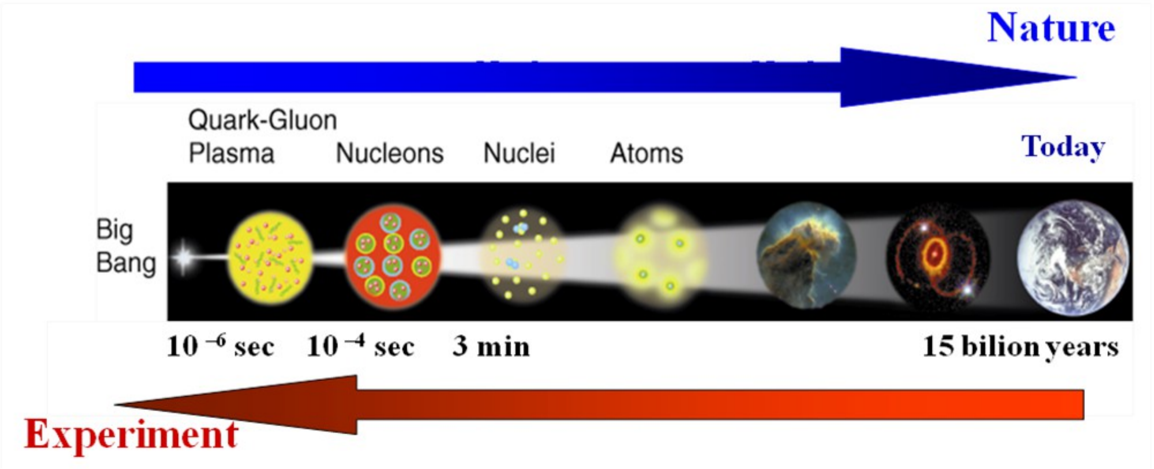
- In the SM, interactions with the **Higgs** field are responsible for elementary particle masses
- Without the Higgs, SM is either mathematically inconsistent (infinities appearing everywhere) or describing only massless particles, contrary to evidence
- The Higgs boson is the cornerstone of the SM, but it escaped detection until 2012

Dark Matter


Observations
from 21 cm hydrogen
from starlight
100
50
V
(km/s)
Expected from visible disk
10
20
30
40
50
R (× 1000 ly)
?

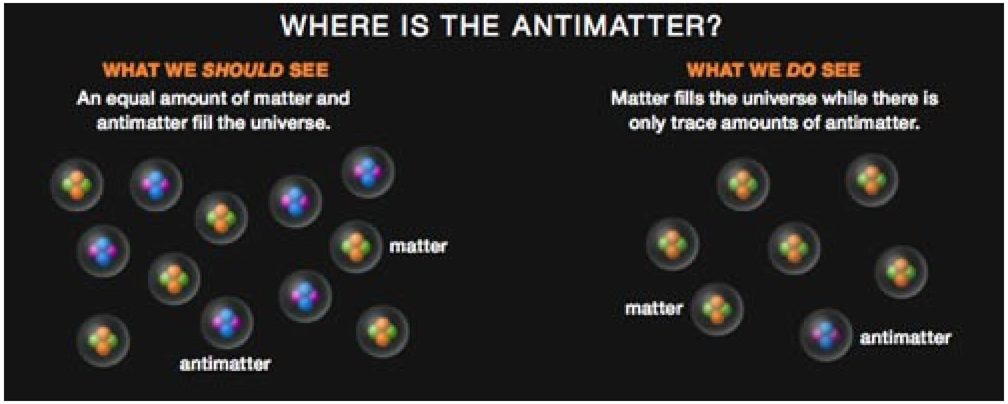
Recreating the early Universe

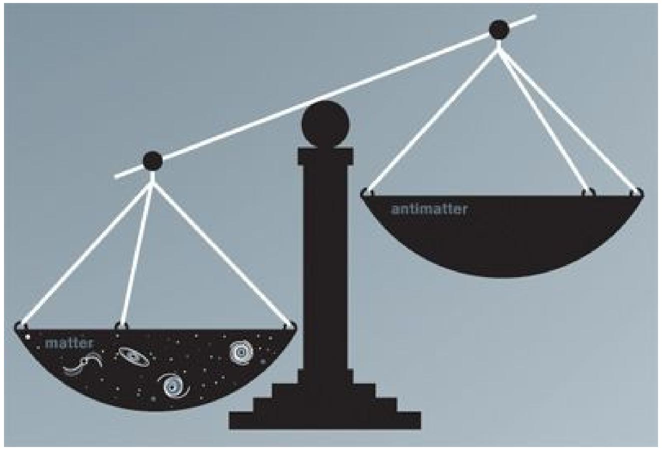




Quark-Gluon Plasma (QGP): a poorly known state of matter that must have existed before the formation of nucleons (i.e. protons, neutrons); we can study it in the lab by colliding very large nuclei at very large energy, forming short-lived QGP droplets

Matter / antimatter imbalance





- As far as we know, the Big Bang should have created equal amounts of particles and antiparticles
- But then all antimatter should have quickly annihilated with matter, and we would not exist
- Some mechanism must have broken the symmetry, either at Big Bang or during the Universe's evolution
- *There is* such a mechanism in the SM (CP violation), but numerically insufficient... we need to look for more

Large Hadron Collider

Source: http://people.physics.tamu.edu/kamon/research/refColliders/LHC/LHC_is_back.html

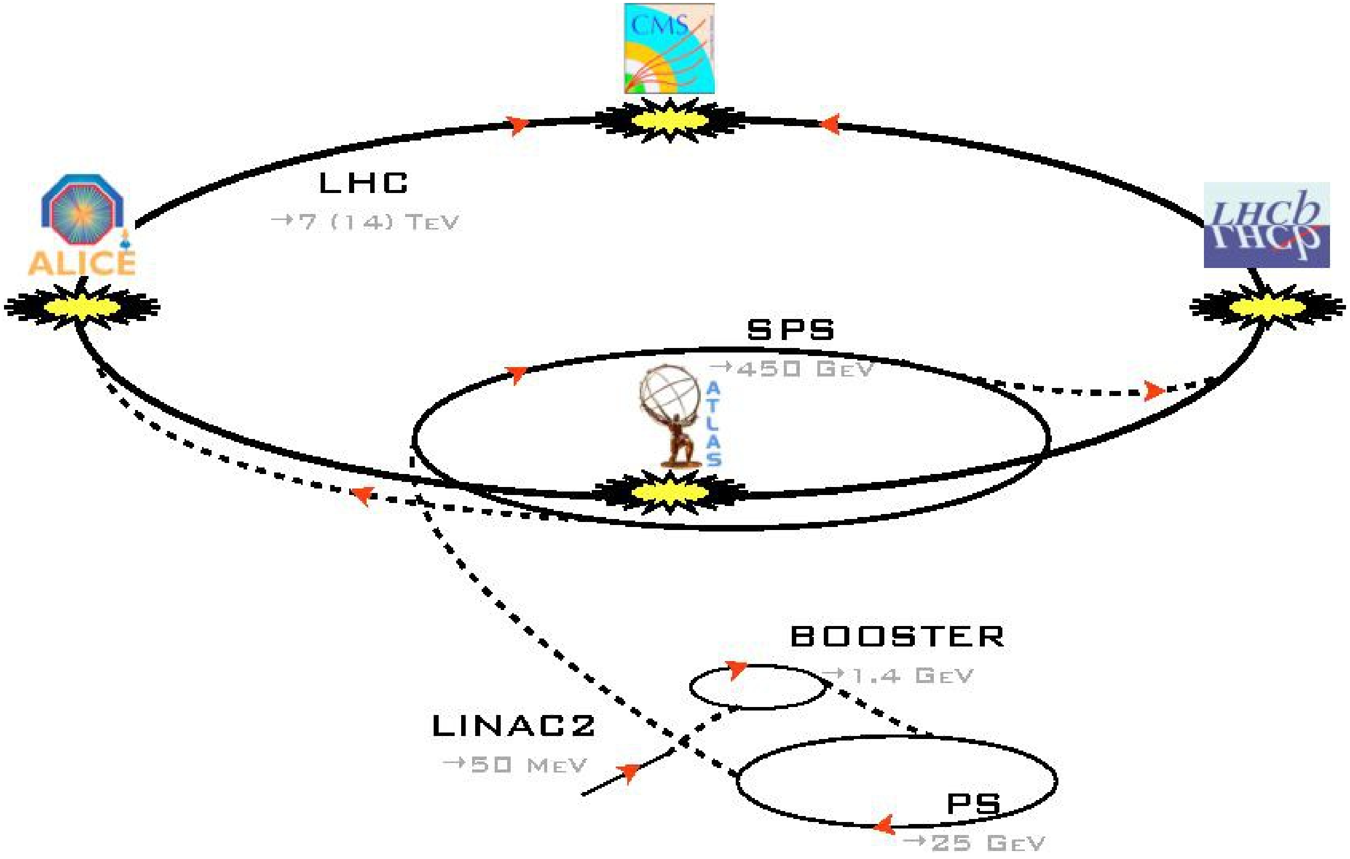
Large Hadron Collider (LHC)

1232 superconducting magnets bend the paths of protons moving at 99.999991% of the speed of light. Each magnet is cooled to -271°C.

Magnetic field = 8.33 Tesla ⇒ proton energy = 14 TeV

From www.symmetrymagazine.org

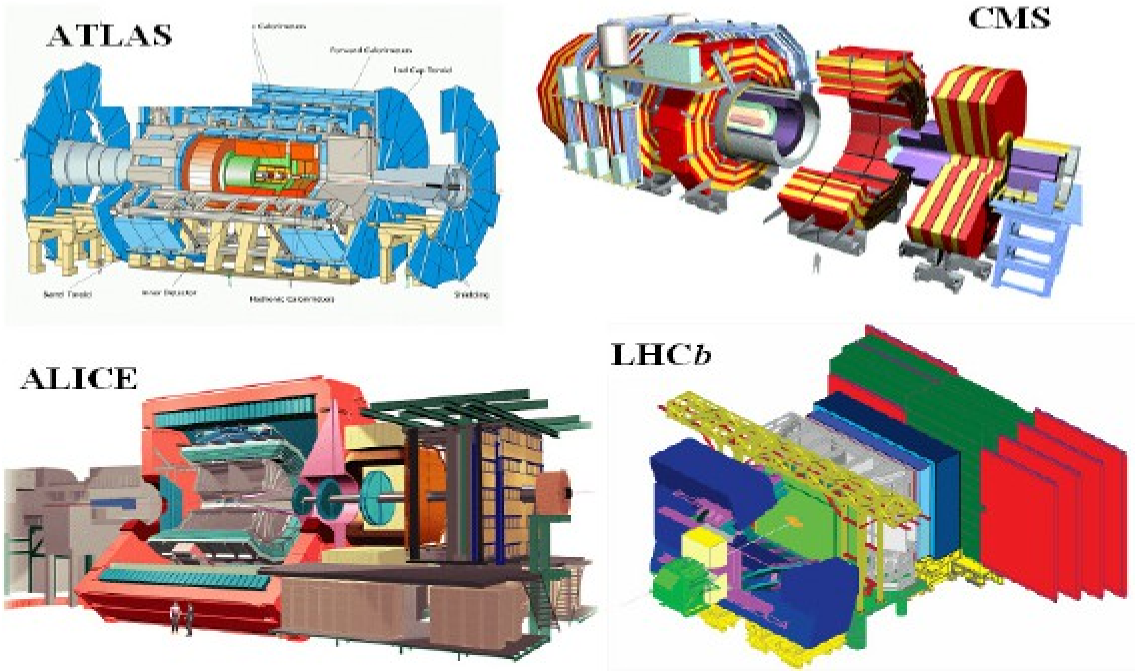
Large Hadron Collider (LHC)



Picture taken from https://inspirehep.net/record/1119569

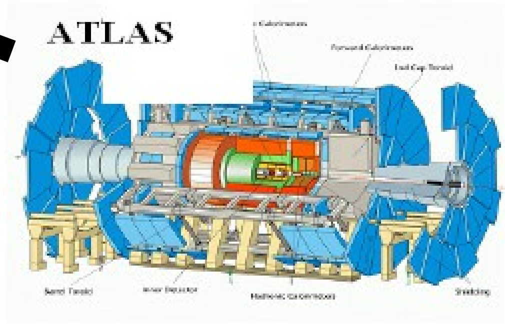
4 collision points surrounded by 4 major experiments
(+ some small ones: LHCf, TOTEM, MoEDAL, FASER, milliQan)
Most operation time is for **pp** collisions; 1 month per year of heavy ion run, mostly **pPb** and **PbPb** collisions

The 4 big LHC experiments

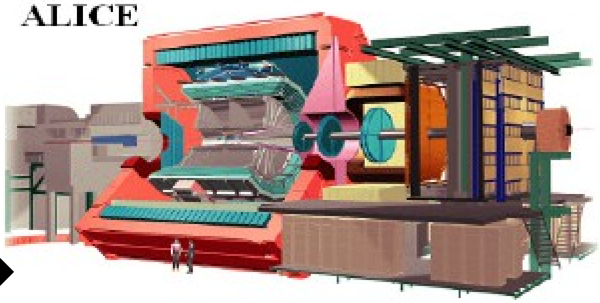


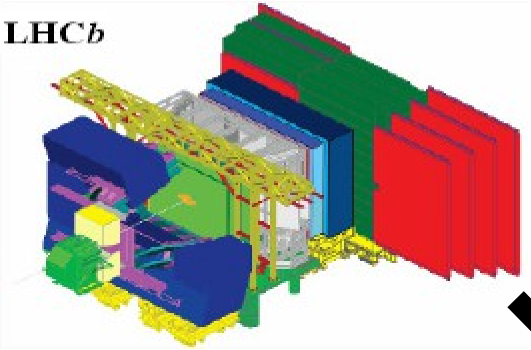
Roughly speaking:

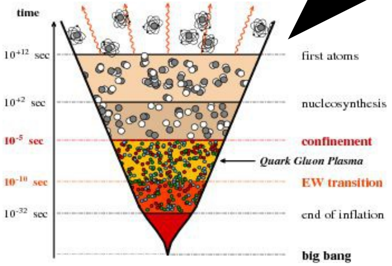
All goals

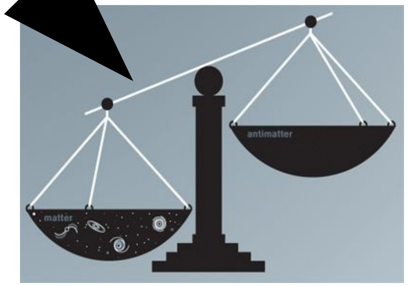


All goals

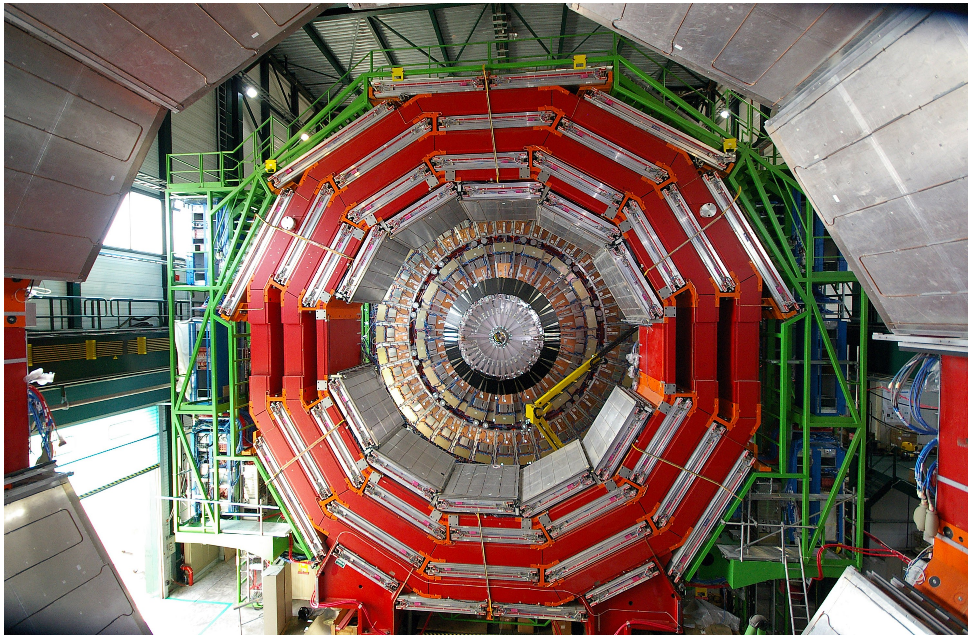




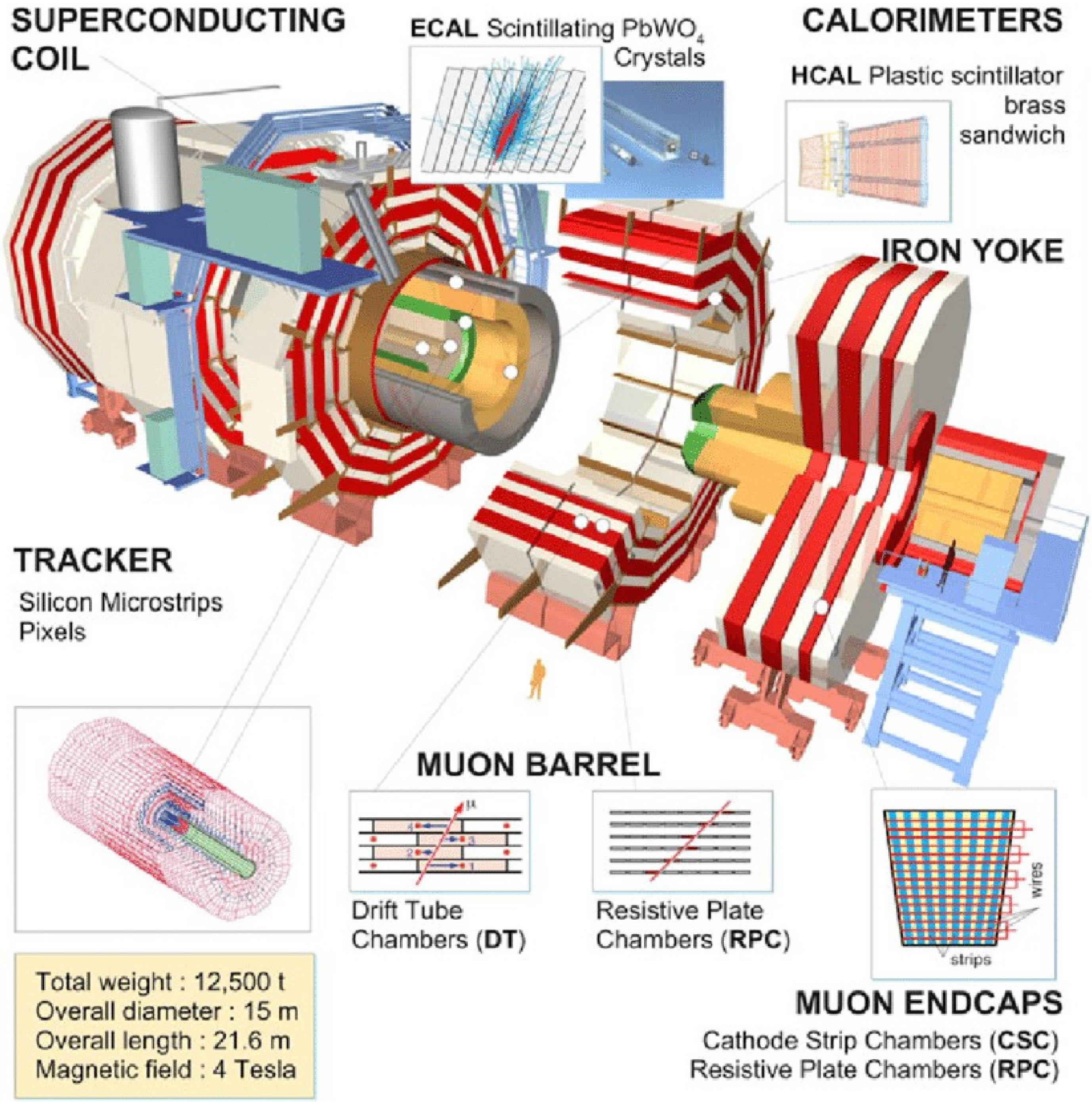




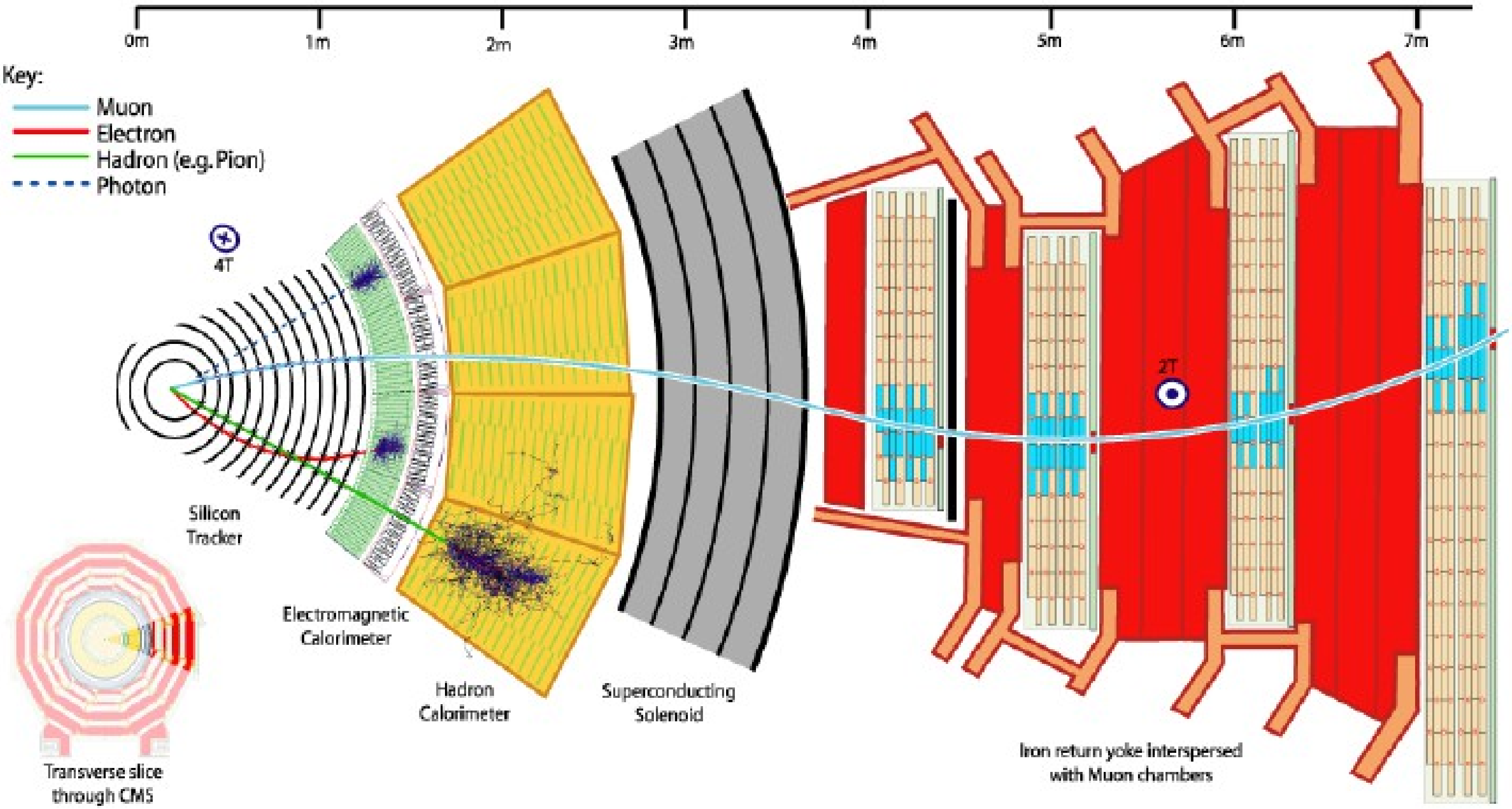
Compact Muon Solenoid (CMS)



From this point on, in my presentation, let me be partisan:
I will provide examples related to CMS, the experiment to
which I belong, although ATLAS is structurally similar, has
the same goals, and got very similar achievements


SUPERCONDUCTING COIL
ECAL Scintillating $PbWO_4$ Crystals
CALORIMETERS
HCAL Plastic scintillator brass sandwich
IRON YOKE
TRACKER
Silicon Microstrips
Pixels
MUON BARREL
μ
1
2
3
4
Drift Tube Chambers (DT)
Resistive Plate Chambers (RPC)
wires
strips
MUON ENDCAPS
Cathode Strip Chambers (CSC)
Resistive Plate Chambers (RPC)
Total weight : 12,500 t
Overall diameter : 15 m
Overall length : 21.6 m
Magnetic field : 4 Tesla

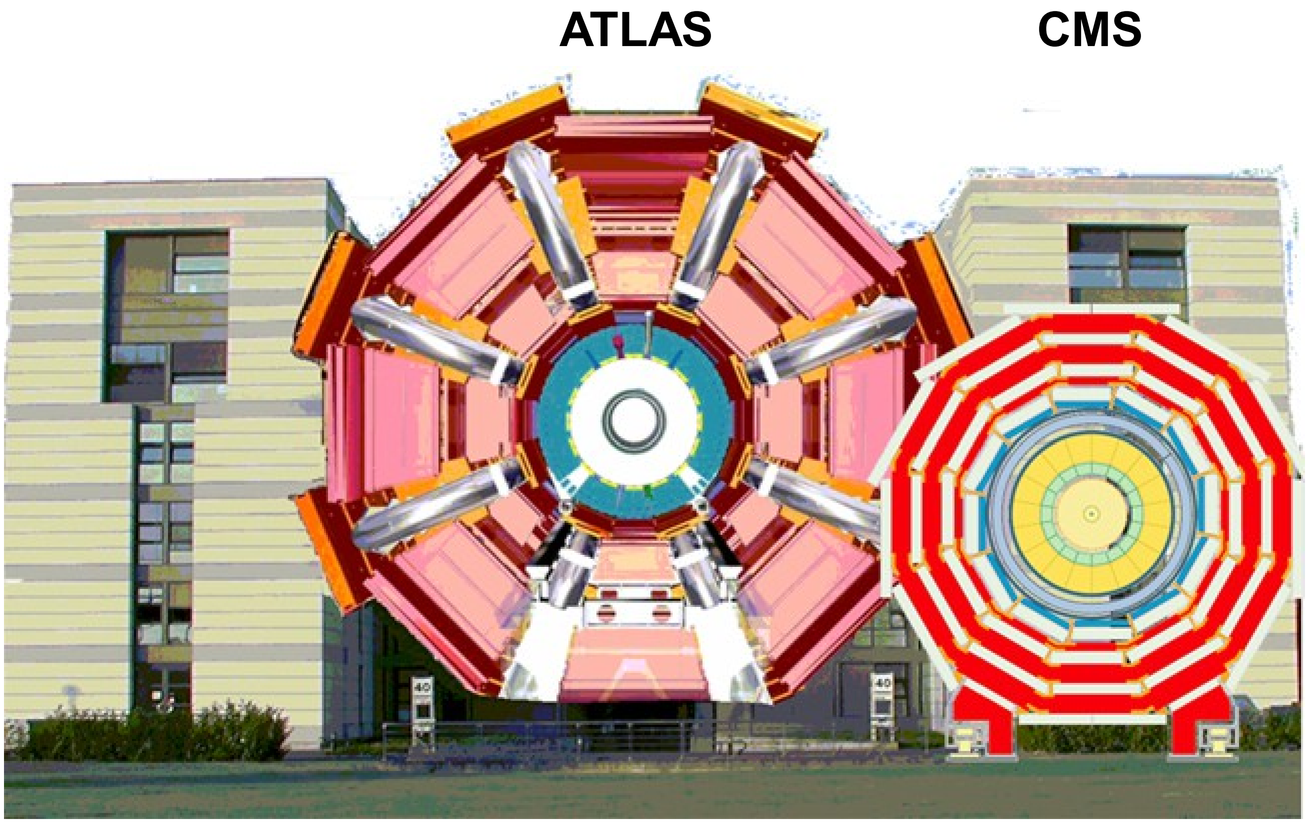
Particle identification



As multipurpose as possible

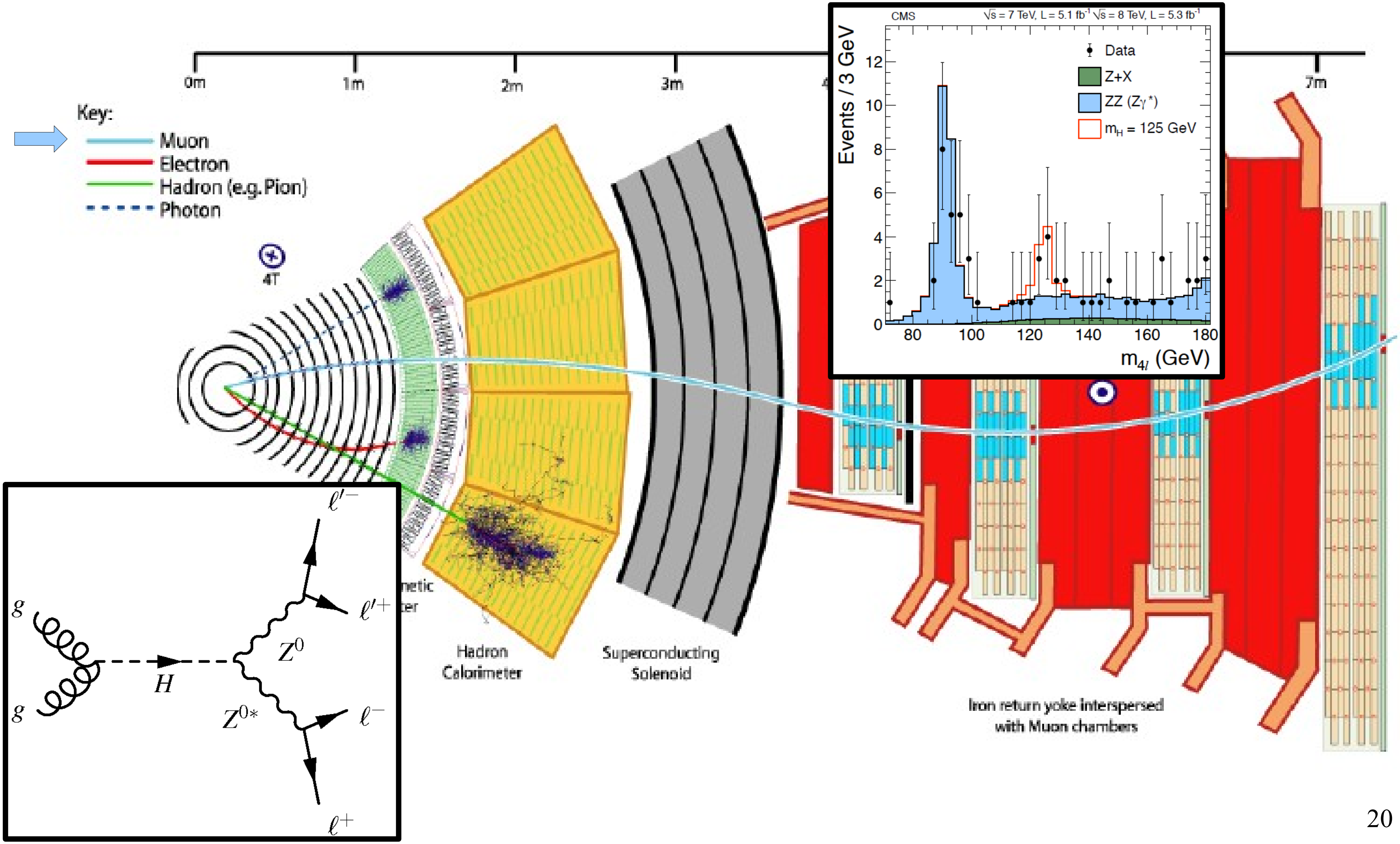
- Because most discoveries in Science actually come by serendipity...

Compact Muon Solenoid (CMS)

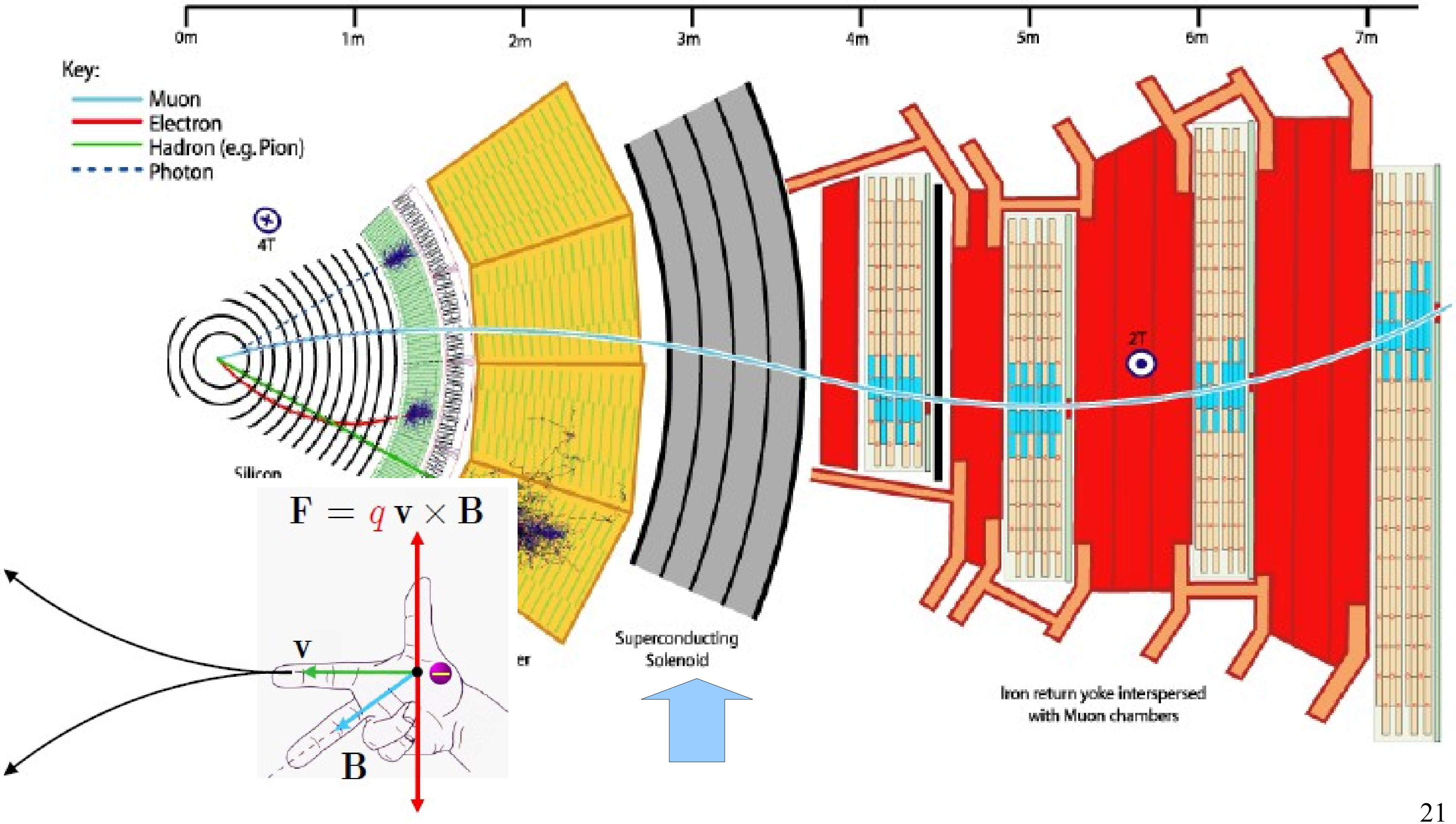


It is compact in relative terms (smaller but heavier than ATLAS), but definitely not small: here compared to a 5-storey building

Compact Muon Solenoid (CMS)



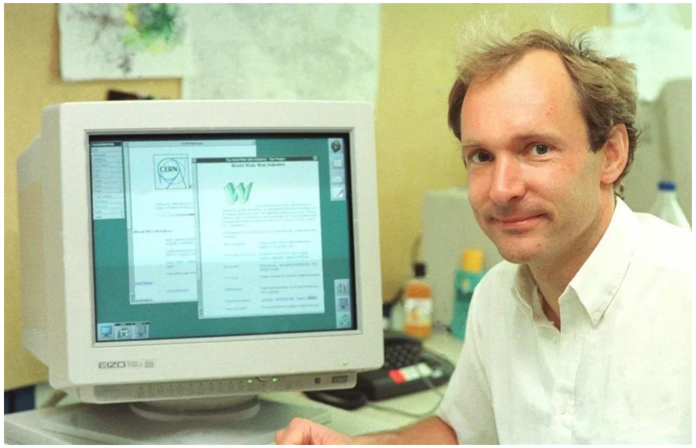
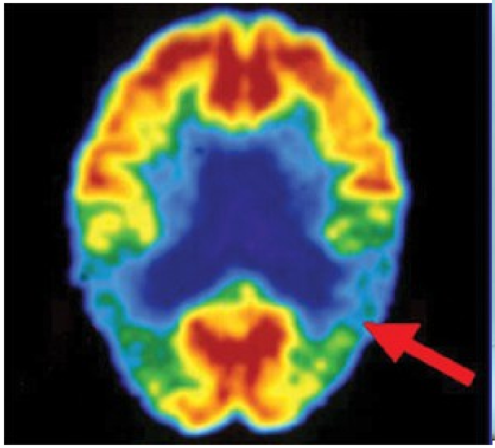
Compact Muon Solenoid (CMS)



$$\mathbf{F} = q\,\mathbf{v} \times \mathbf{B}$$

Digression: some spin-offs

- Several technological spin-offs of particle physics had or may have huge societal impact, for example:
  - The World Wide Web was invented at CERN
  - Positron Emission Tomography (PET)
  - Hadron-therapy: killing cancer cells with particle beams
  - Accelerator-driven nuclear reactors: intrinsically safer (subcritical), also possibility to get rid of nuclear waste


A recent spin-off: "muography"

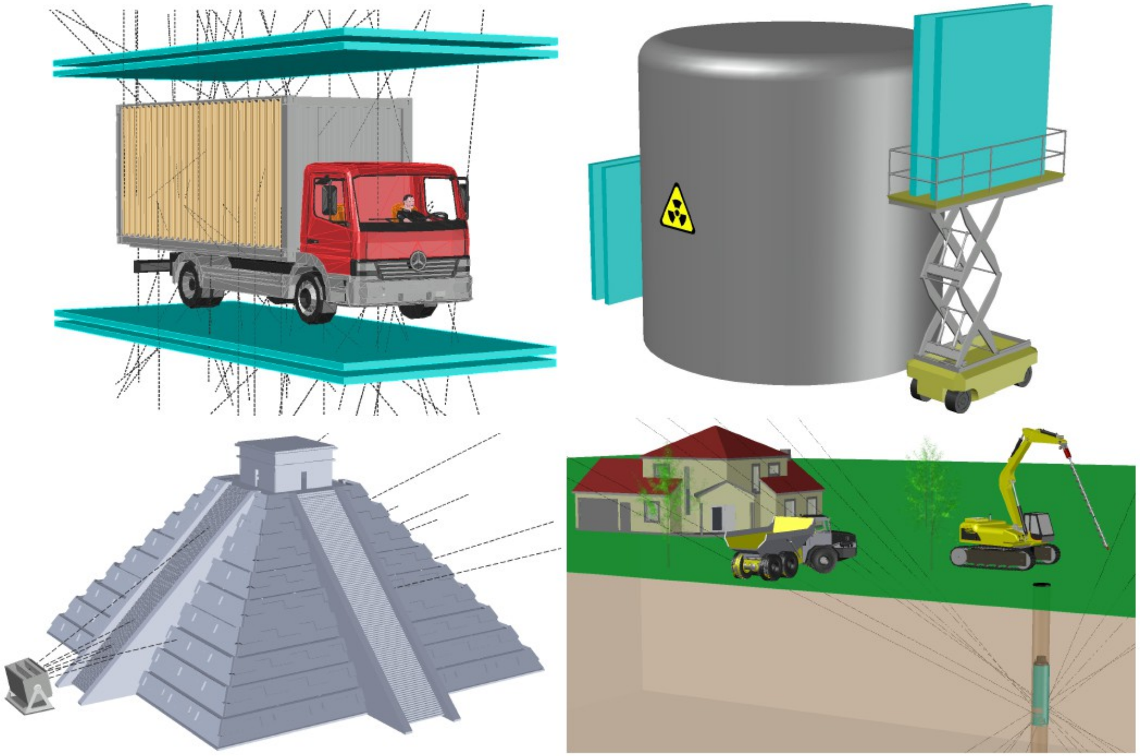
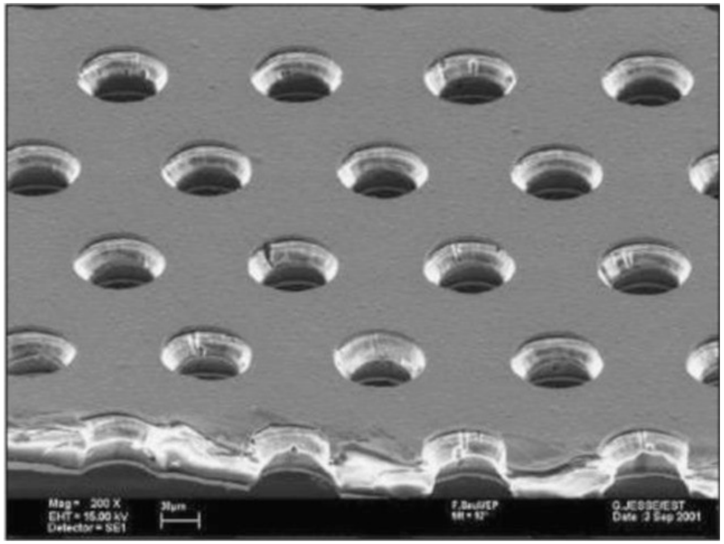


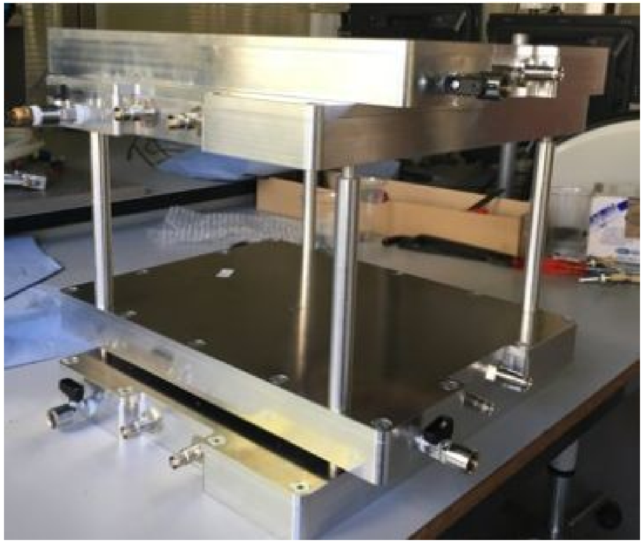
Figure from: L. Bonechi, R. D'Alessandro, A. Giammanco, arXiv:1906.03934 [physics.ins-det], Rev. Phys (2020)

General idea: use the free and abundant flux of cosmic rays (mostly muons) to make radiographies of large objects, adapting muon detectors from particle physics

CMS spin-offs in muography

Remember the emphasis of CMS on muons...





Spare drift tubes from the CMS muon system are used in Legnaro (Italy) to study applications to cargo scanning, nuclear waste control, blast furnaces monitoring, etc.

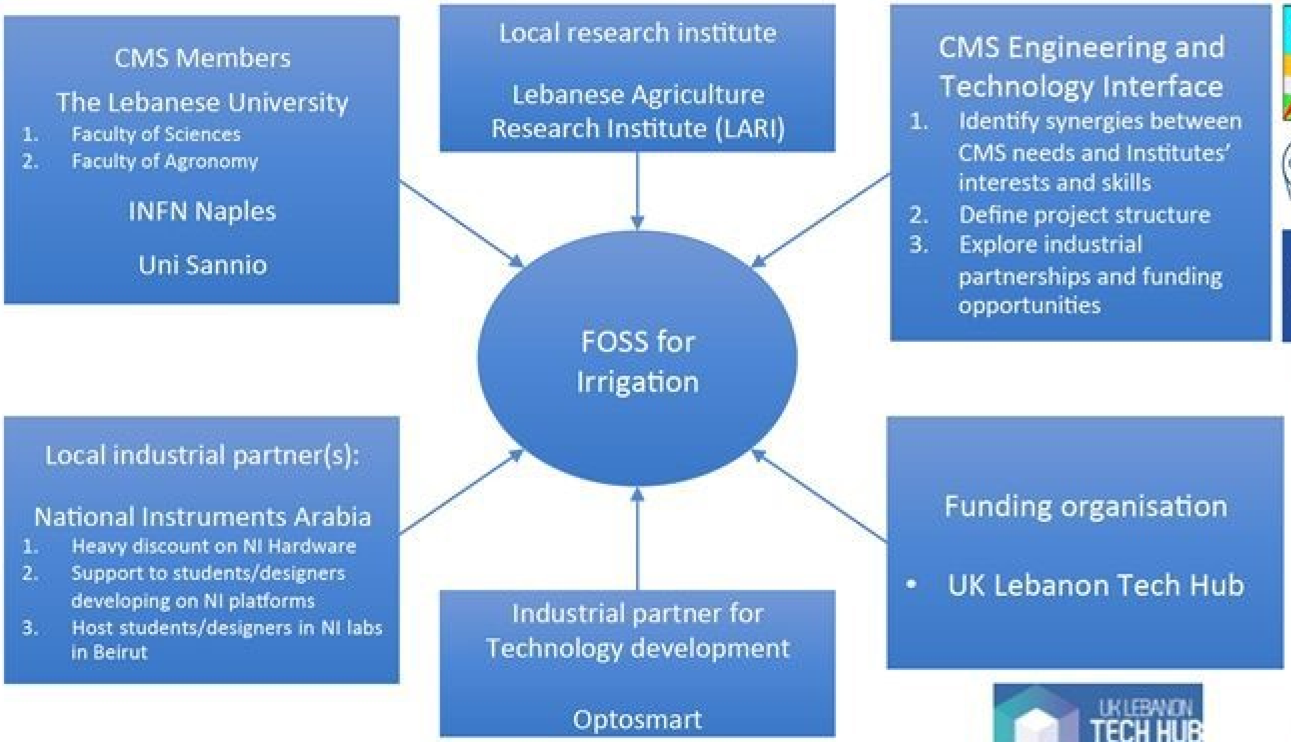
Prototype GEM muon detectors for a CMS upgrade also used in Florida (USA) to investigate muography applications

Reduced version of the CMS resistive plate chambers explored in Louvain-la-Neuve (Belgium) as cheap option for portable muography

CMS spin-off in agriculture

→ Enter **F**ibre **O**ptics **S**ensor **S**ystems for **I**rrigation: FOSS for I

Fibre Optics Sensor Systems for Irrigation



CMS Members

The Lebanese University
1. Faculty of Sciences
2. Faculty of Agronomy

INFN Naples

Uni Sannio

Local research institute

Lebanese Agriculture Research Institute (LARI)

CMS Engineering and Technology Interface
1. Identify synergies between CMS needs and Institutes' interests and skills
2. Define project structure
3. Explore industrial partnerships and funding opportunities

FOSS for Irrigation

Local industrial partner(s):

National Instruments Arabia
1. Heavy discount on NI Hardware
2. Support to students/designers developing on NI platforms
3. Host students/designers in NI labs in Beirut

Industrial partner for Technology development

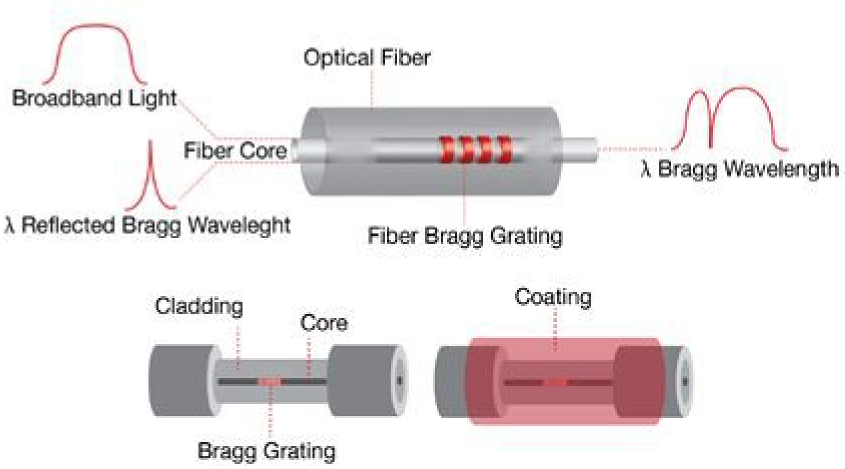
Optosmart

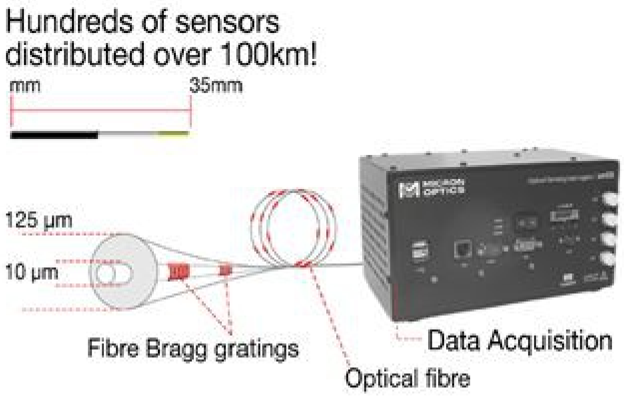
Funding organisation

- UK Lebanon Tech Hub

KT
Accelerating innovation

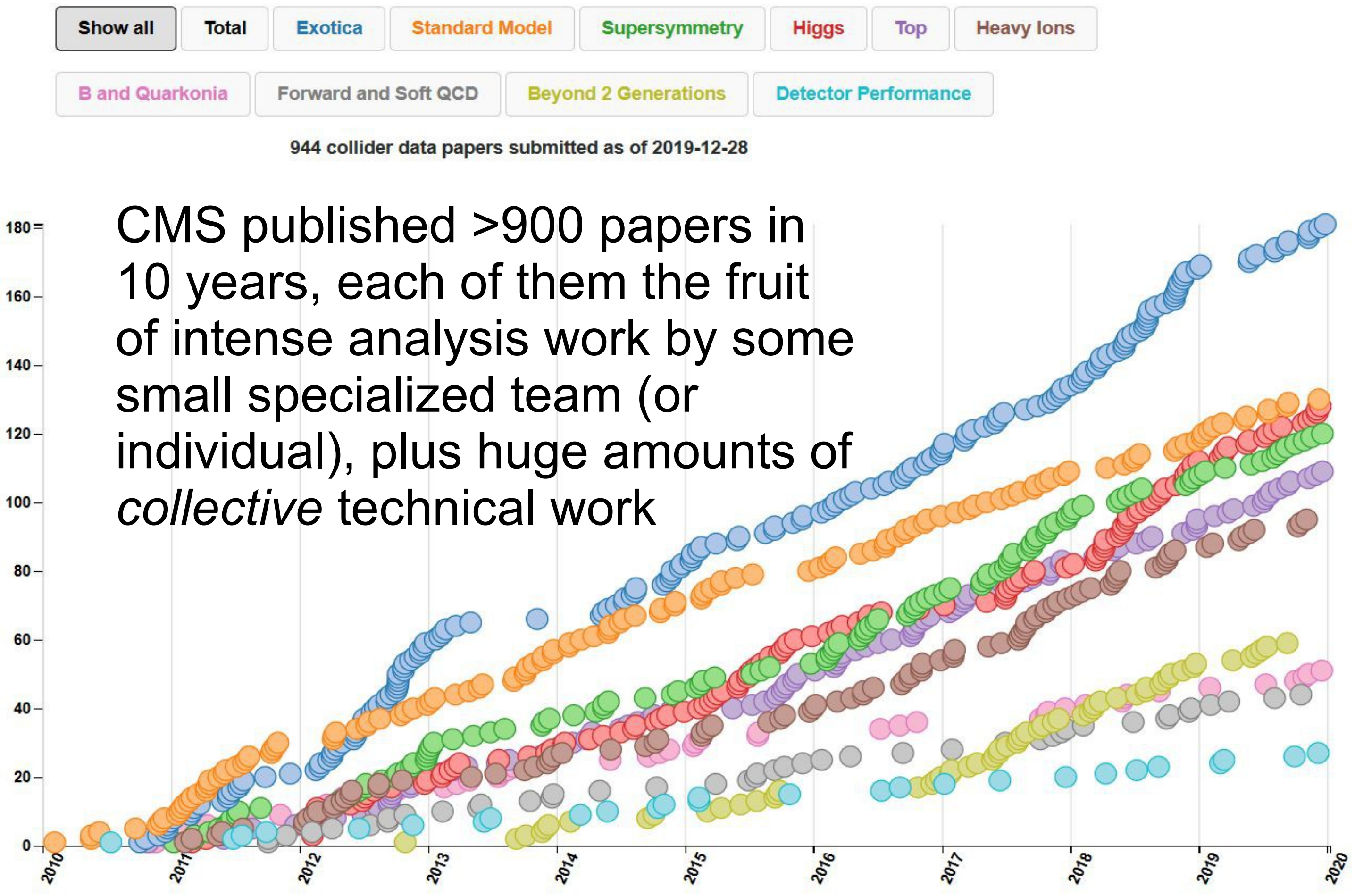
CMS spin-off in agriculture





- Fiber Optics Sensor System (FOSS) has key advantages in terms of robustness (vs extreme temperatures, EM interference, etc.), simplicity of installation, read-out
- Idea: use FOSS to monitor water content in soil → rationalize irrigation → save water
- Operational tens of km when buried at appropriate depth

Now back to fundamental physics

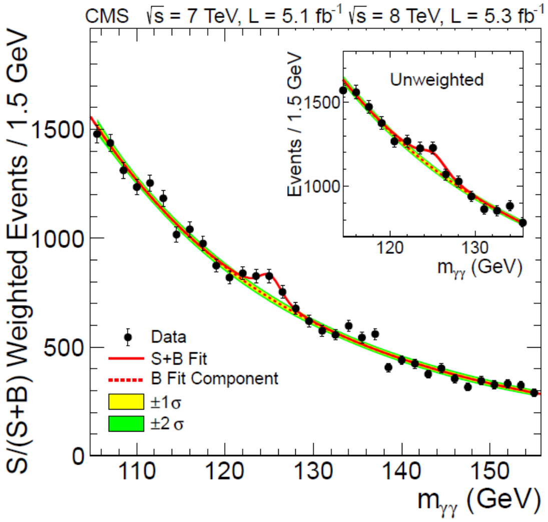


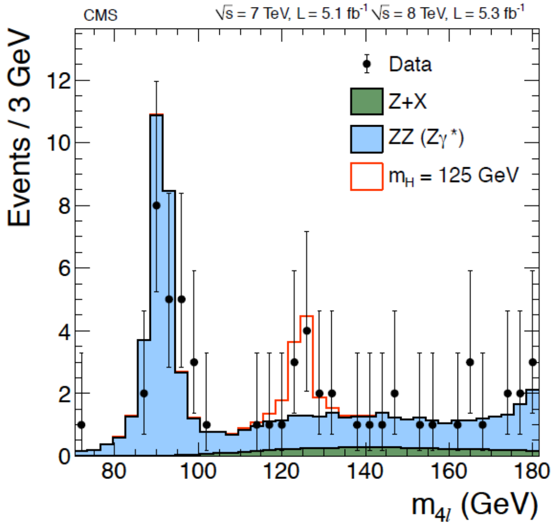
944 collider data papers submitted as of 2019-12-28

CMS published >900 papers in 10 years, each of them the fruit of intense analysis work by some small specialized team (or individual), plus huge amounts of *collective* technical work

First *major* goal achieved...

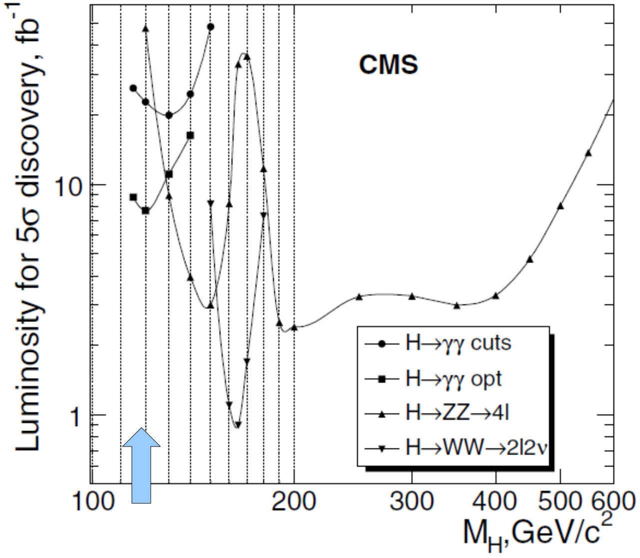
- One particular goal was used as a benchmark to decide LHC's design parameters: giving a YES/NO answer to the question "does the SM Higgs boson exist?"
- Before LHC, we didn't even know at which mass to search
  - Theoretical upper limit: < O(1 TeV)
  - Direct experimental limit: > 110 GeV from LEP experiments (1989-2000)
- We and ATLAS found it at 125 GeV, even before end of Run-1



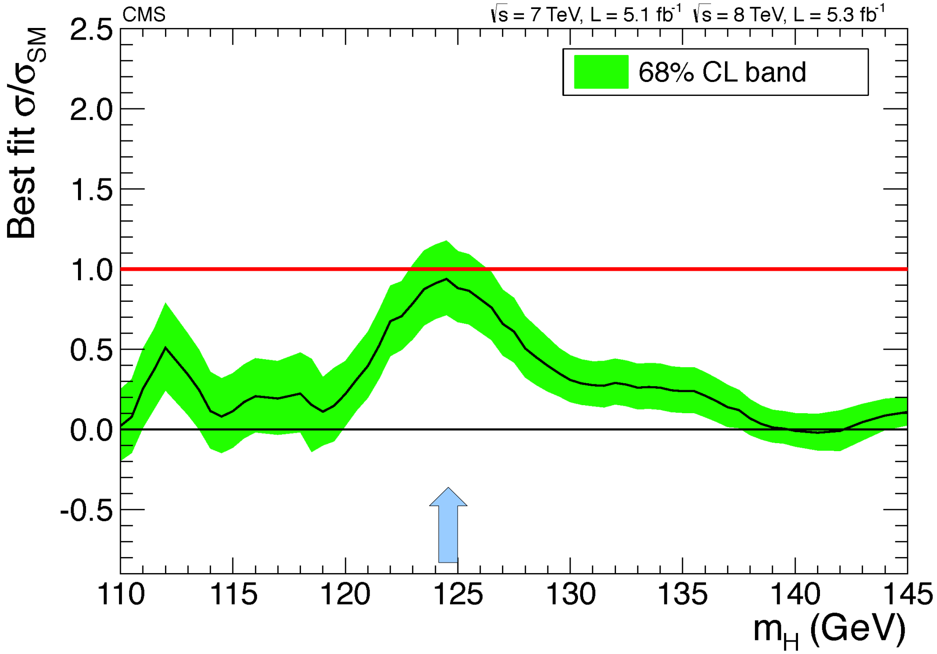


...faster than expected

Simulation-based expectations 3 years before LHC started:



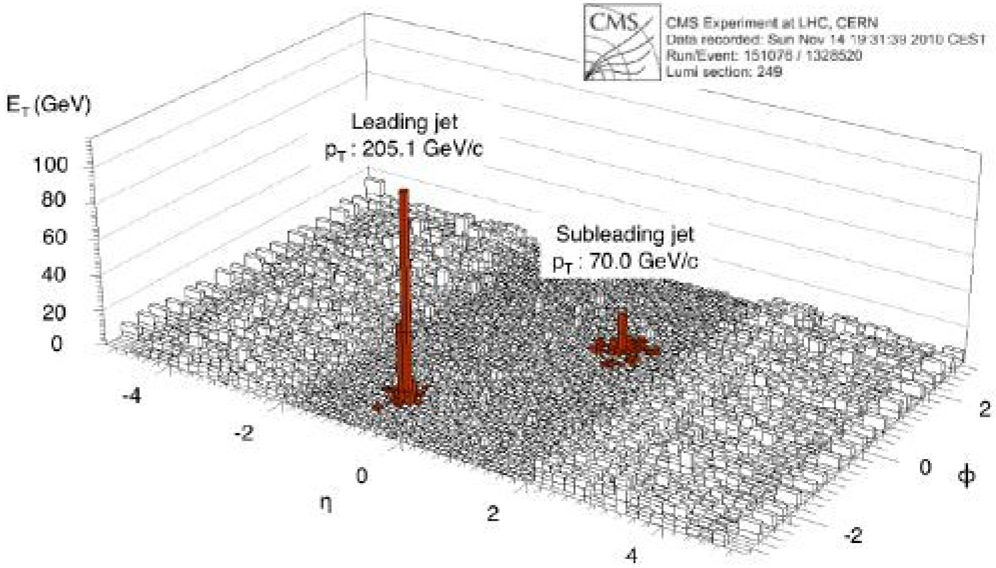
3 years after LHC started:



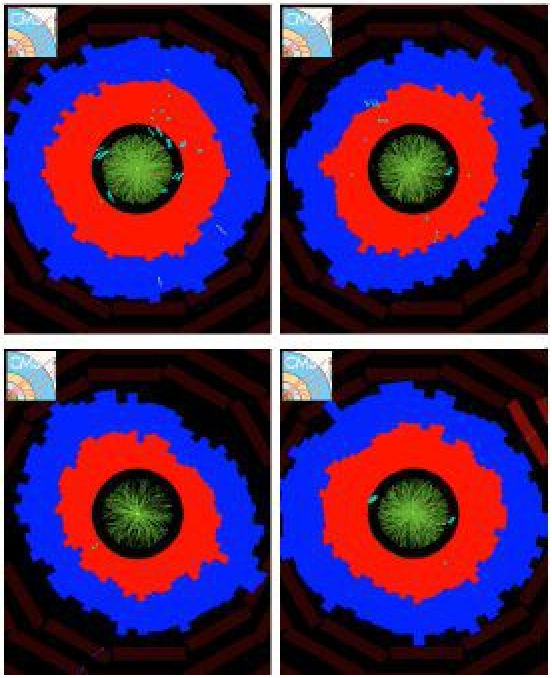
- This required **less data** than expected in simulation studies, in spite of smaller collision energy (7 / 8 TeV vs 14 TeV)
- This over-achievement resulted from advances in data analysis; as I will show tomorrow, LHC physicists are investing huge efforts in pioneering Data Science techniques

Understanding the Quark Gluon Plasma

From: Busza, Rajagopal, van der Schee, Ann.Rev.Nucl.Part.Sci. 68 (2018) 1

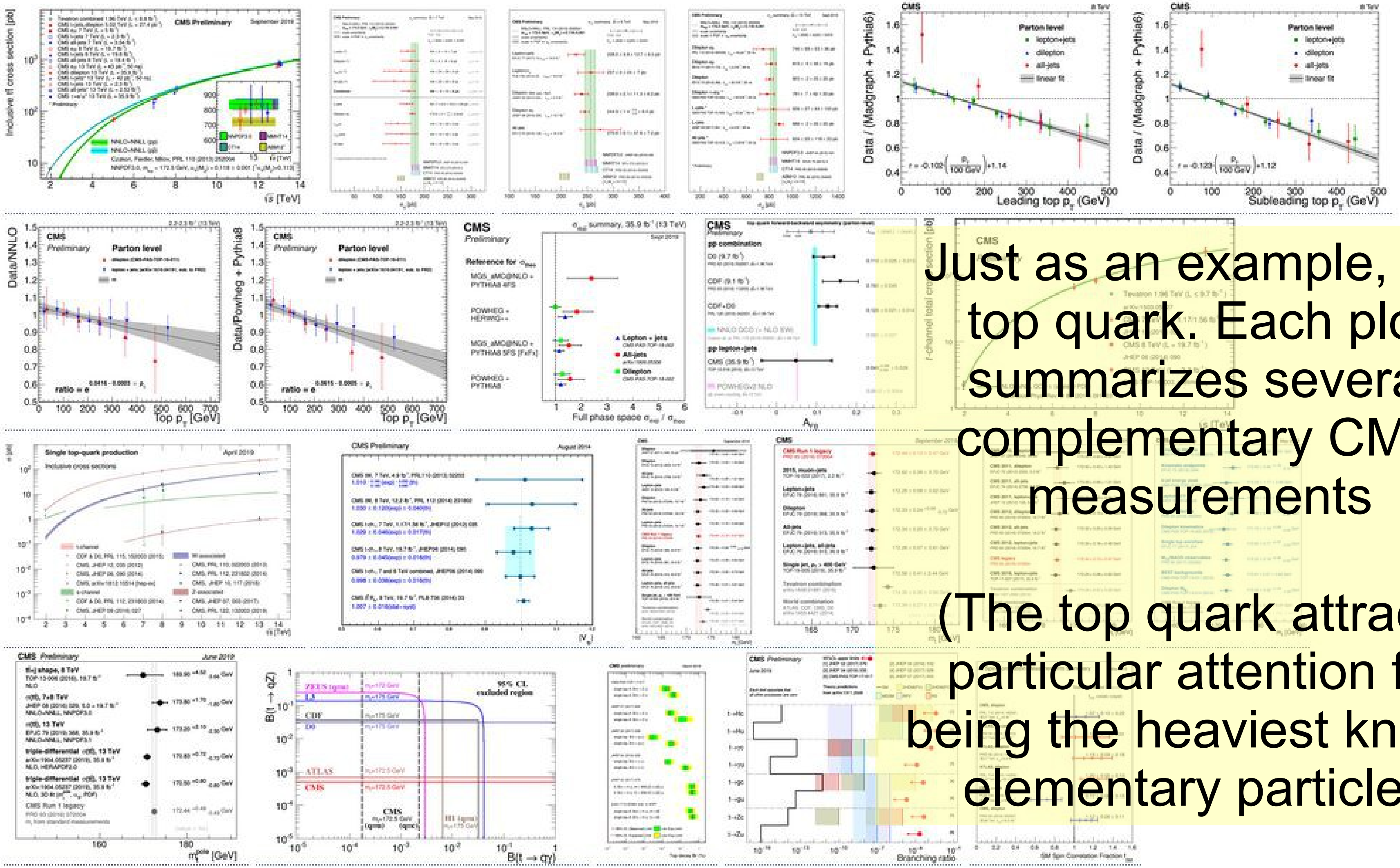


We measured the energy lost by quarks through the QGP



We discovered that the QGP is a liquid

Precise studies of known particles



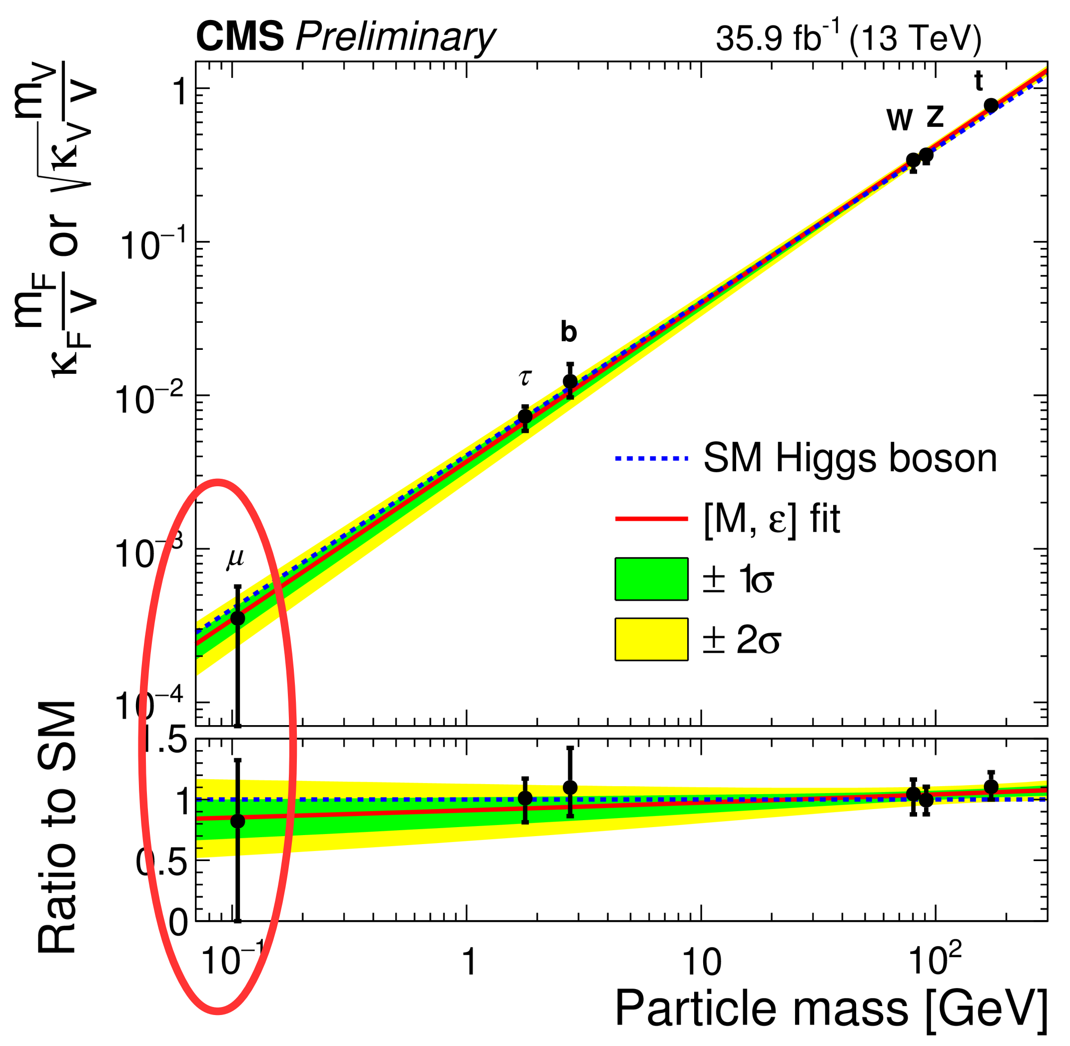
Just as an example, the top quark. Each plot summarizes several complementary CMS measurements

(The top quark attracts particular attention for being the heaviest known elementary particle)

LHC check-list

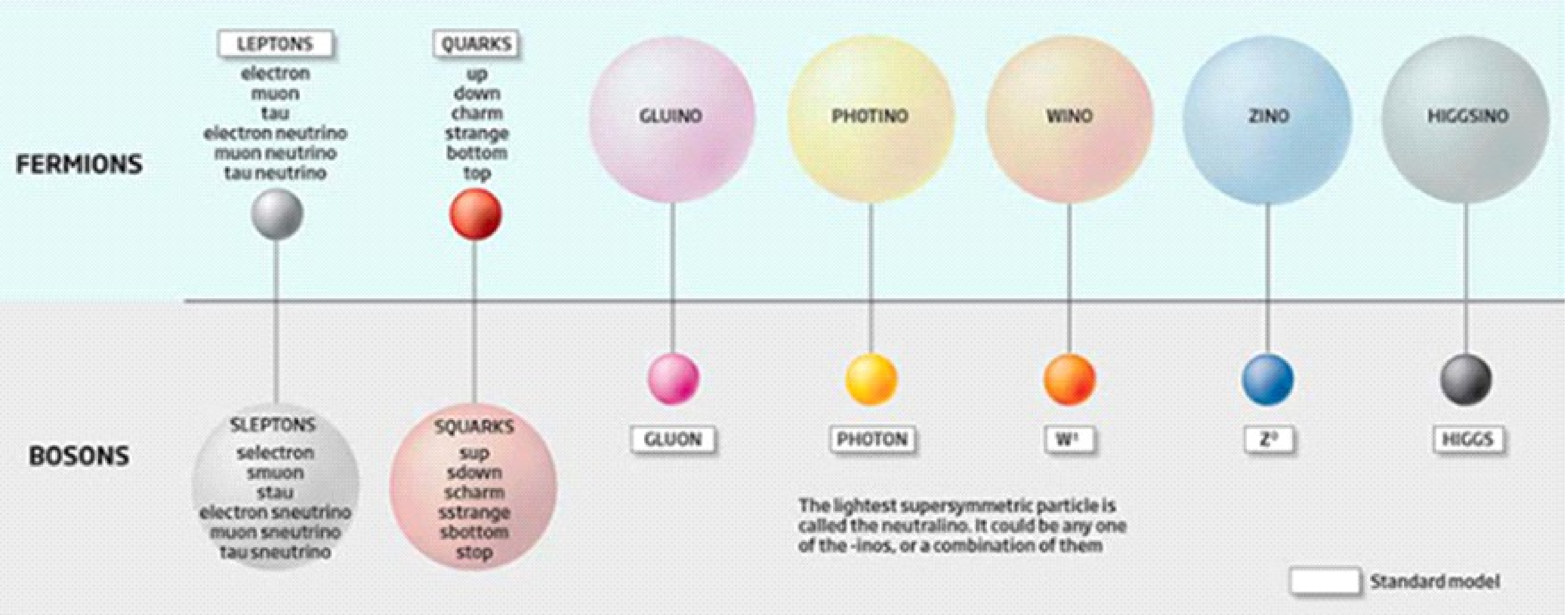
- Confirmation (or not) of the Brout-Englert-Higgs mechanism, i.e., explaining where the mass of elementary particles is coming from
  - Done
- Study the hot medium that filled the early Universe
  - Very advanced
- Precisely measure the properties of the known particles
  - Unprecedented precision achieved almost everywhere
- Check if Dark Matter is made of new particles
  - Trying hard
- Explain the matter/anti-matter imbalance of the Universe
  - Trying hard
- Search for additional particles, forces, dimensions of space
  - Due to LHC data, some of the most promising theories of 2010 are seriously in trouble in 2020 (still alive if "fine tuned" a bit)

Precisely studying how the Higgs creates mass



- Higgs' *raison d'être* in the SM: giving mass to all elementary particles by interacting with them
- Crucial test of the SM: verify if the strength of interaction is indeed compatible with known particle masses
- Confirmed (within error bars) only for a handful of very heavy particles
- Next challenges ahead: test the light ones too

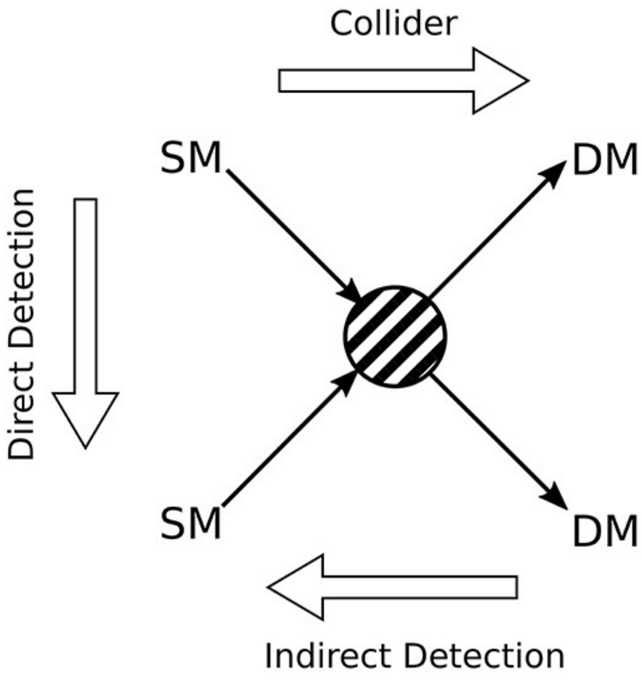
Chasing SuperSymmetry



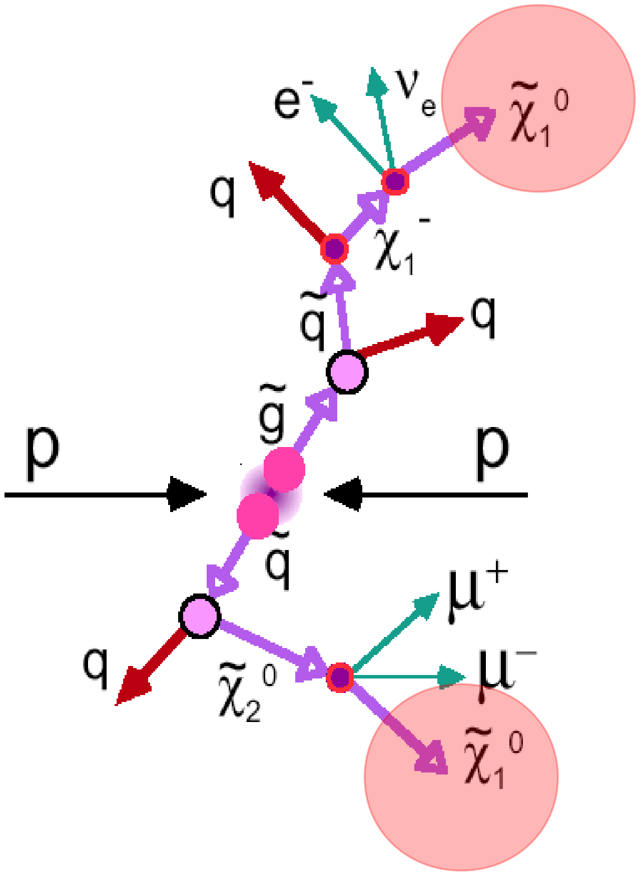
- Arguably the most popular hypothesis to fix the shortcomings of the SM, SuSy postulates a symmetry between fermions (matter particles) and bosons (force carriers)
- This would double the particle zoo; but LHC did not find any, yet

Chasing Dark Matter

General idea:



A collider example predicted by SuSy:



From: S. Giagu, Front. Phys. 7 (2019) 75

How to *see* an *invisible* particle?

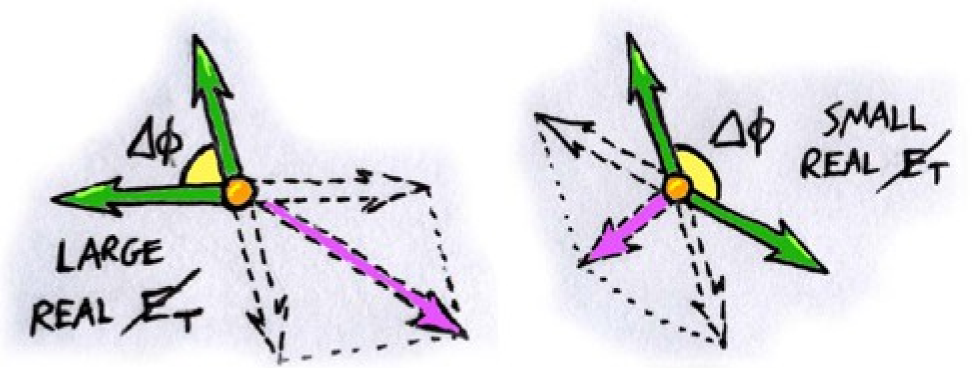
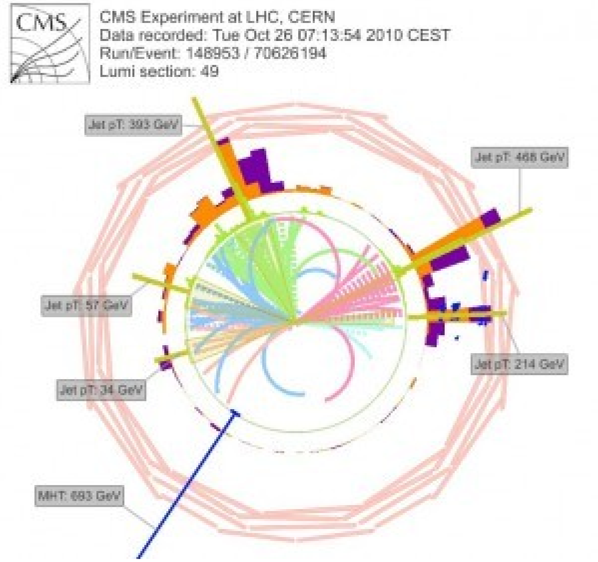
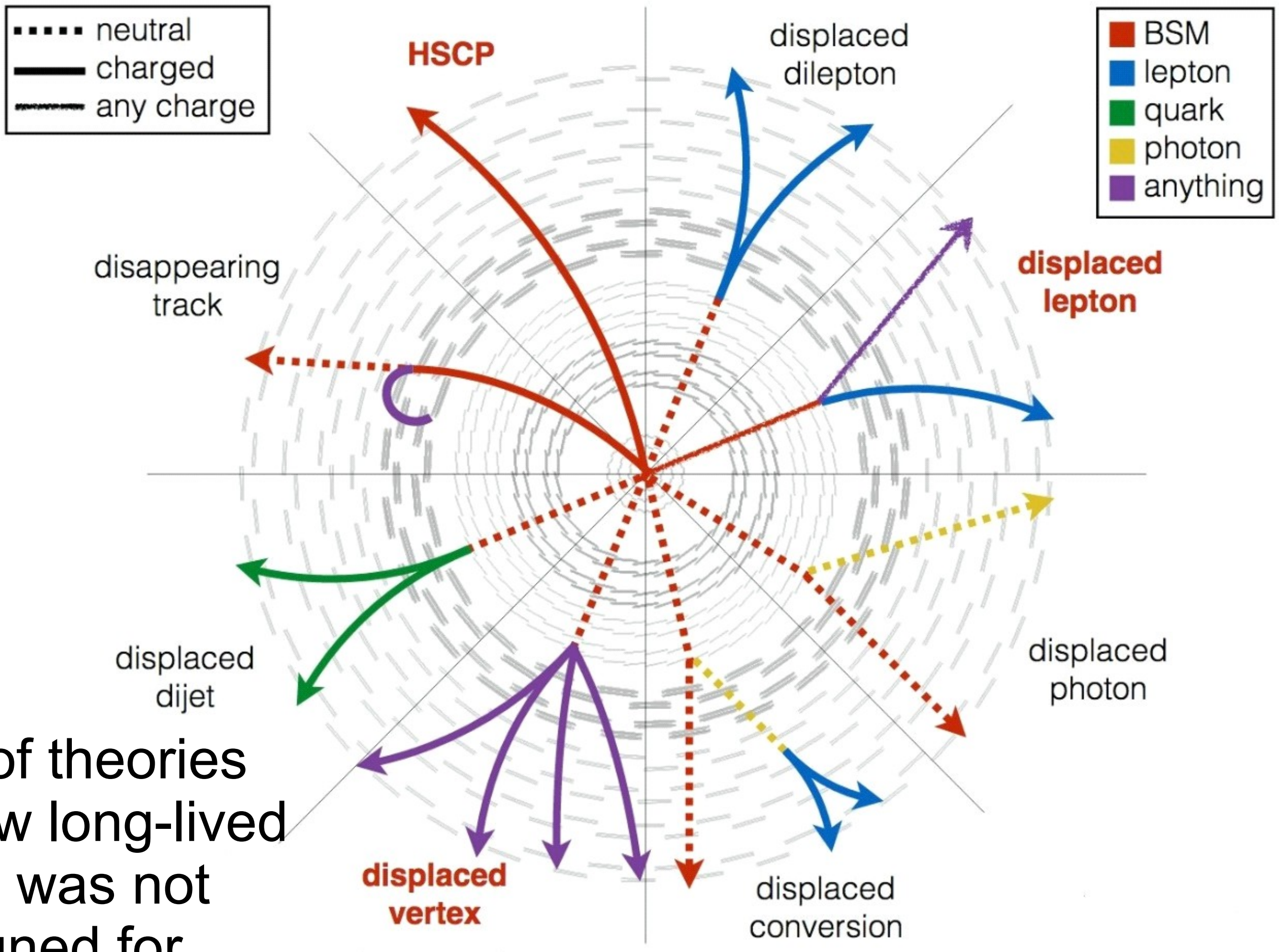


Image from here

Missing momentum (or missing energy) method



Are there new long-lived particles?

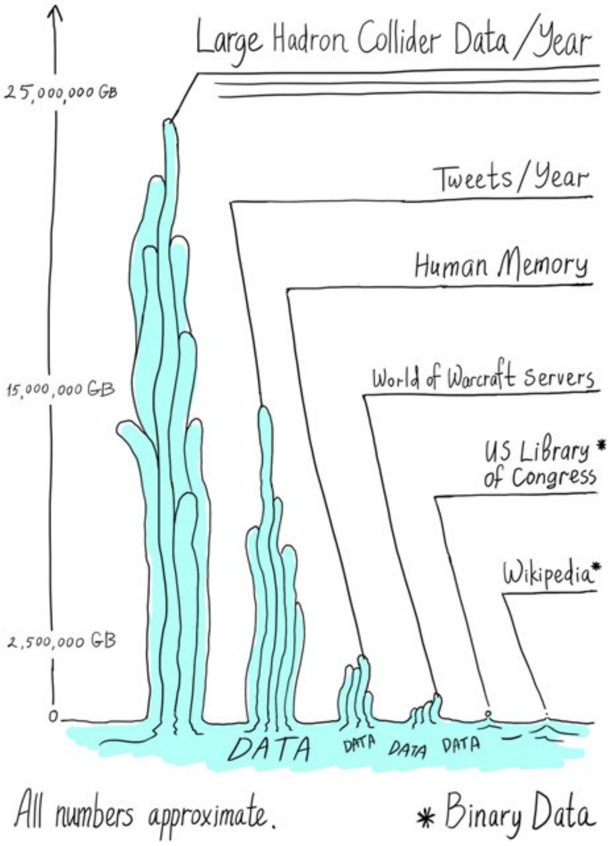


Recent boom of theories that predict new long-lived particles; CMS was not originally designed for that, but proven to be versatile enough!

No stones should be left unturned

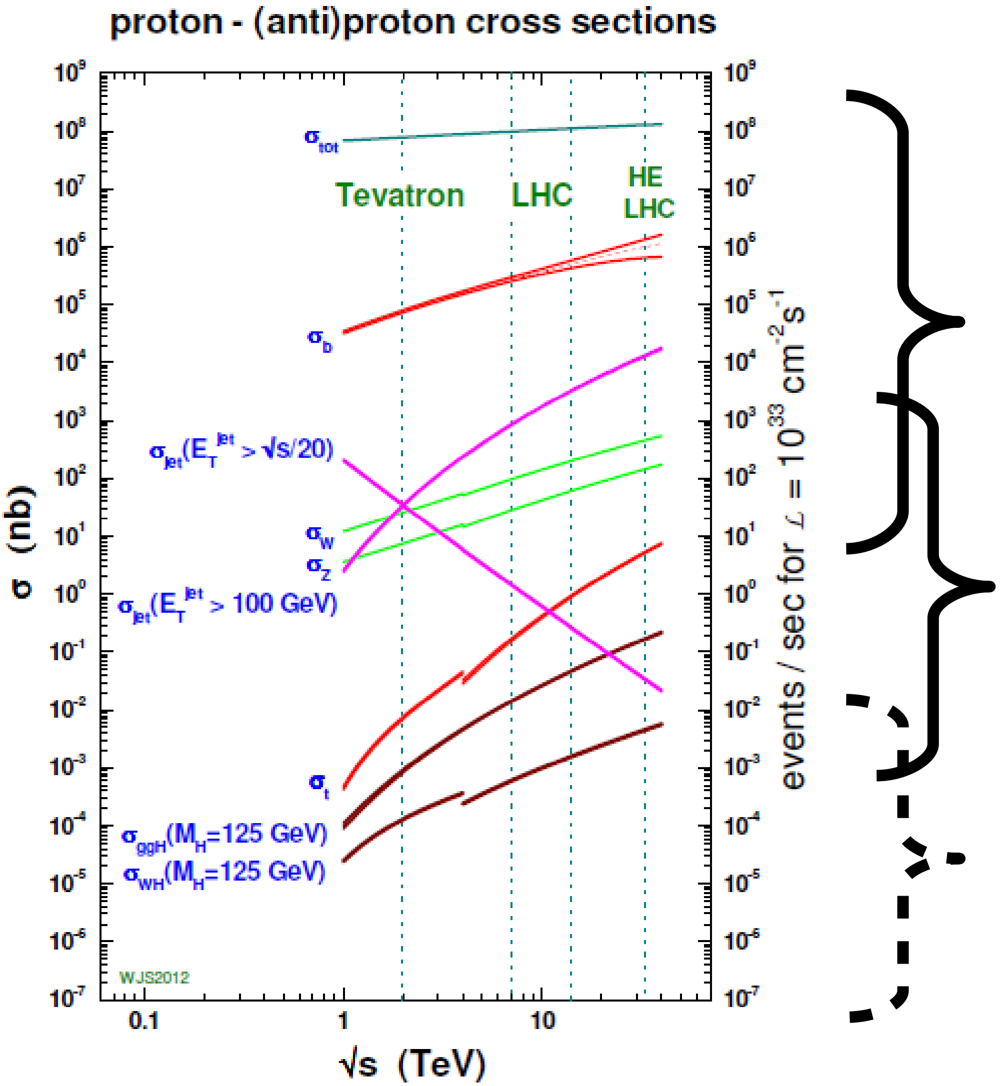
- What if New Physics is in plain sight and we are blinded by theoretical prejudice?
  - Model-independent searches (*anomaly detection*) that cast a very large net are becoming increasingly popular
  - Tomorrow I will discuss some case study
- And outlandish models are getting investigated too
  - Mini black holes could be produced by LHC collisions, and detectable by ATLAS and CMS, according to some alternative theories of gravitation
  - Hidden extra space-time dimensions could have measurable consequences
  - And many more...

Challenges of complexity



Hunting a needle in a haystack

Plot by W.J. Stirling

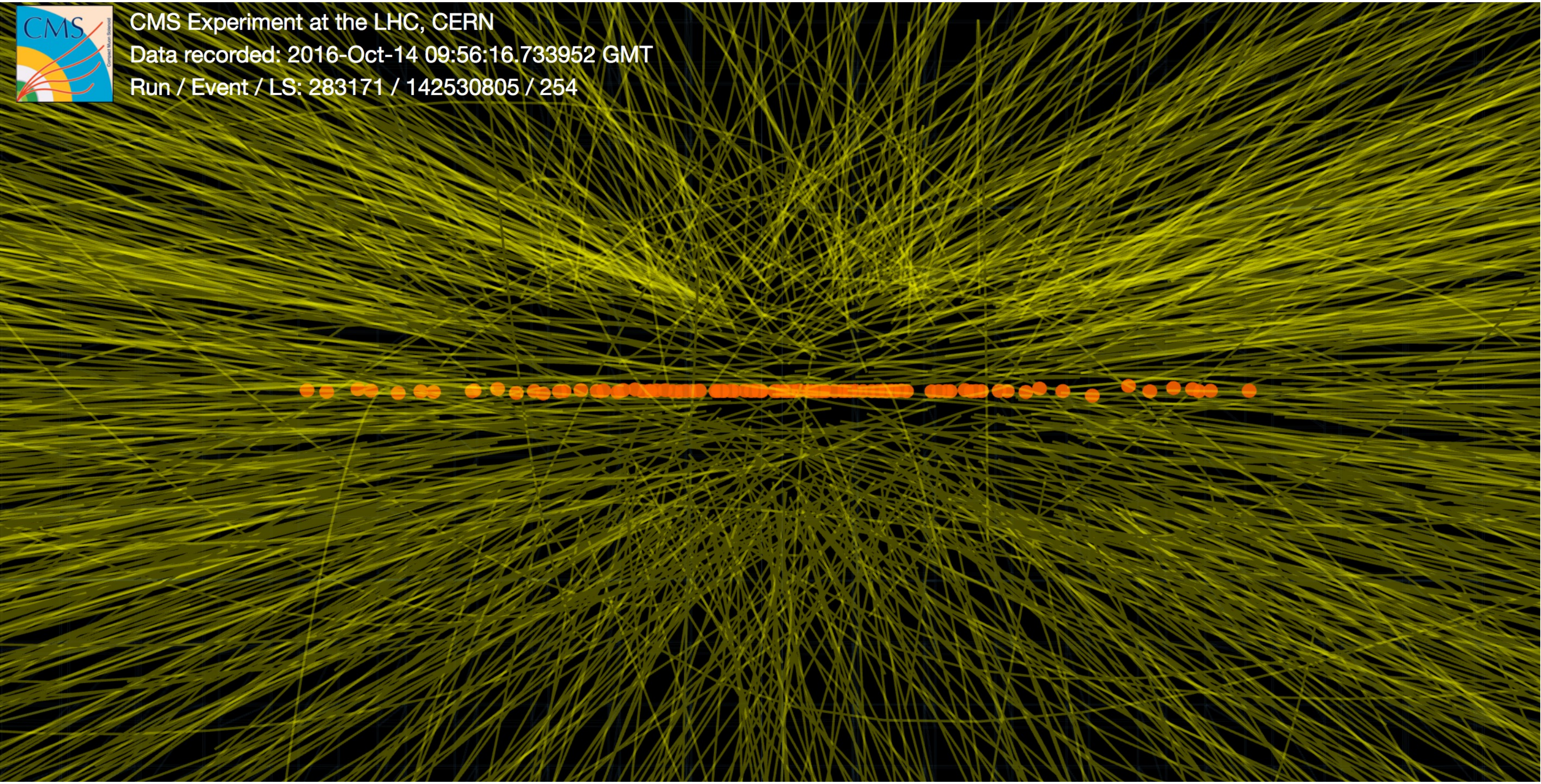


Background

Already known, but interesting

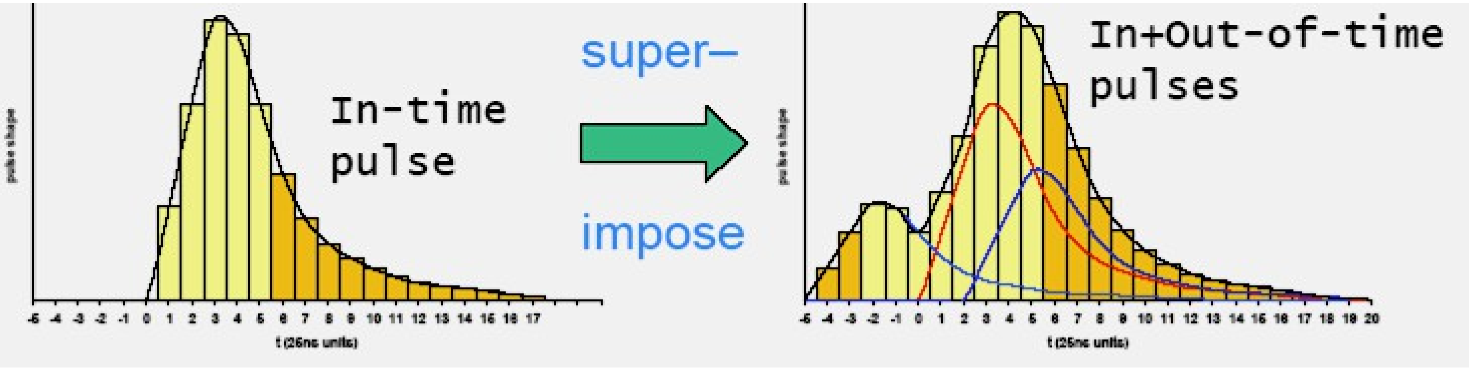
Discoveries (unknown rate, by definition)

There might be a new particle hidden in this mess



A special LHC issue: pile up (PU)

- To achieve large rate of events we need very dense proton bunches (large number of protons, in a small volume)
- In-time PU: several pp interactions during one bunch crossing
- Out-of-time PU: tail of the electronic signal generated by previous bunch crossings

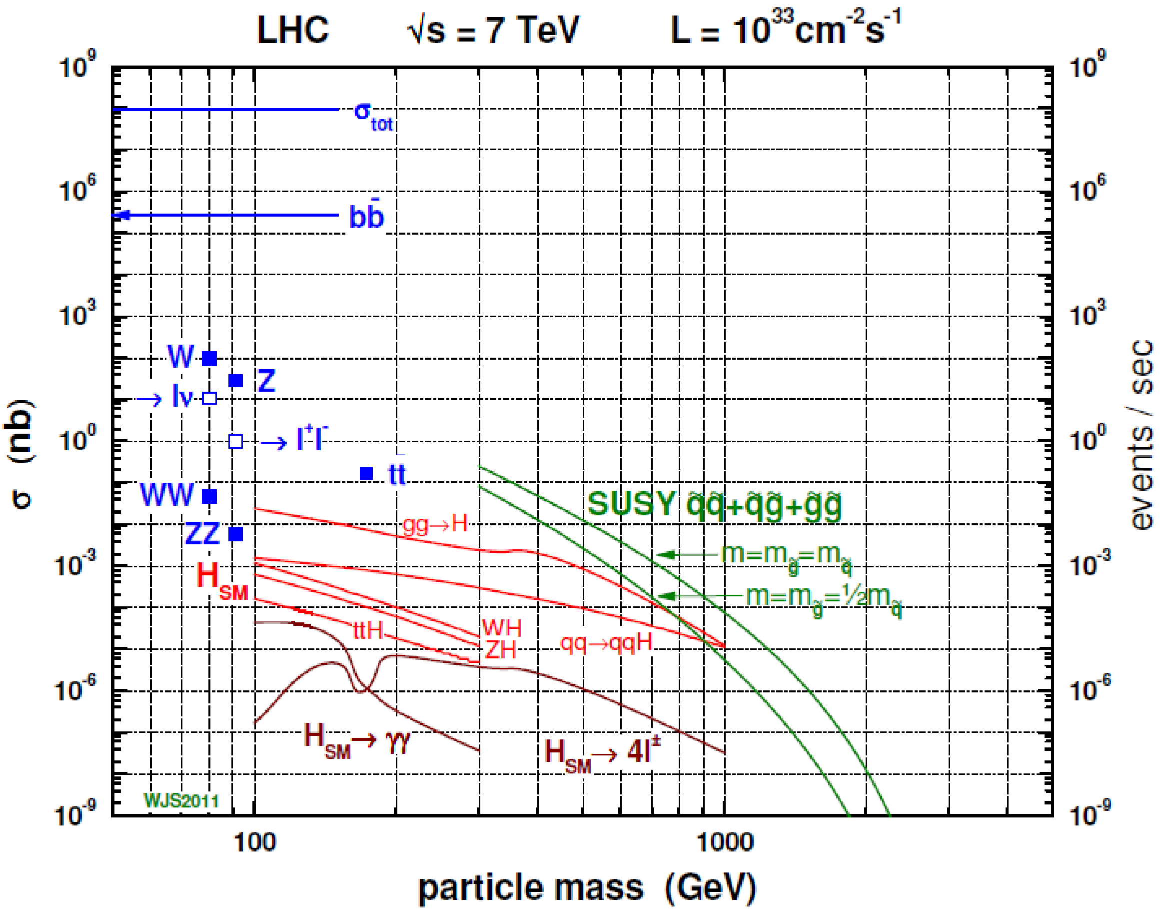


See you tomorrow

- My second talk will be: "Challenges facing CMS data analysis in the 20's"
- Today I talked mostly about Physics, tomorrow mostly about Data Science
- ... but in practice there is no strict boundary between the two disciplines, in the day-by-day work of most LHC physicists

Thanks for your attention!

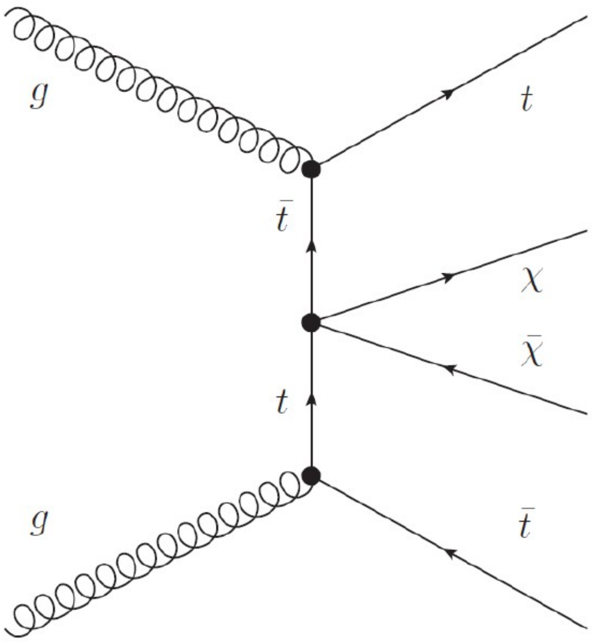
Triggers

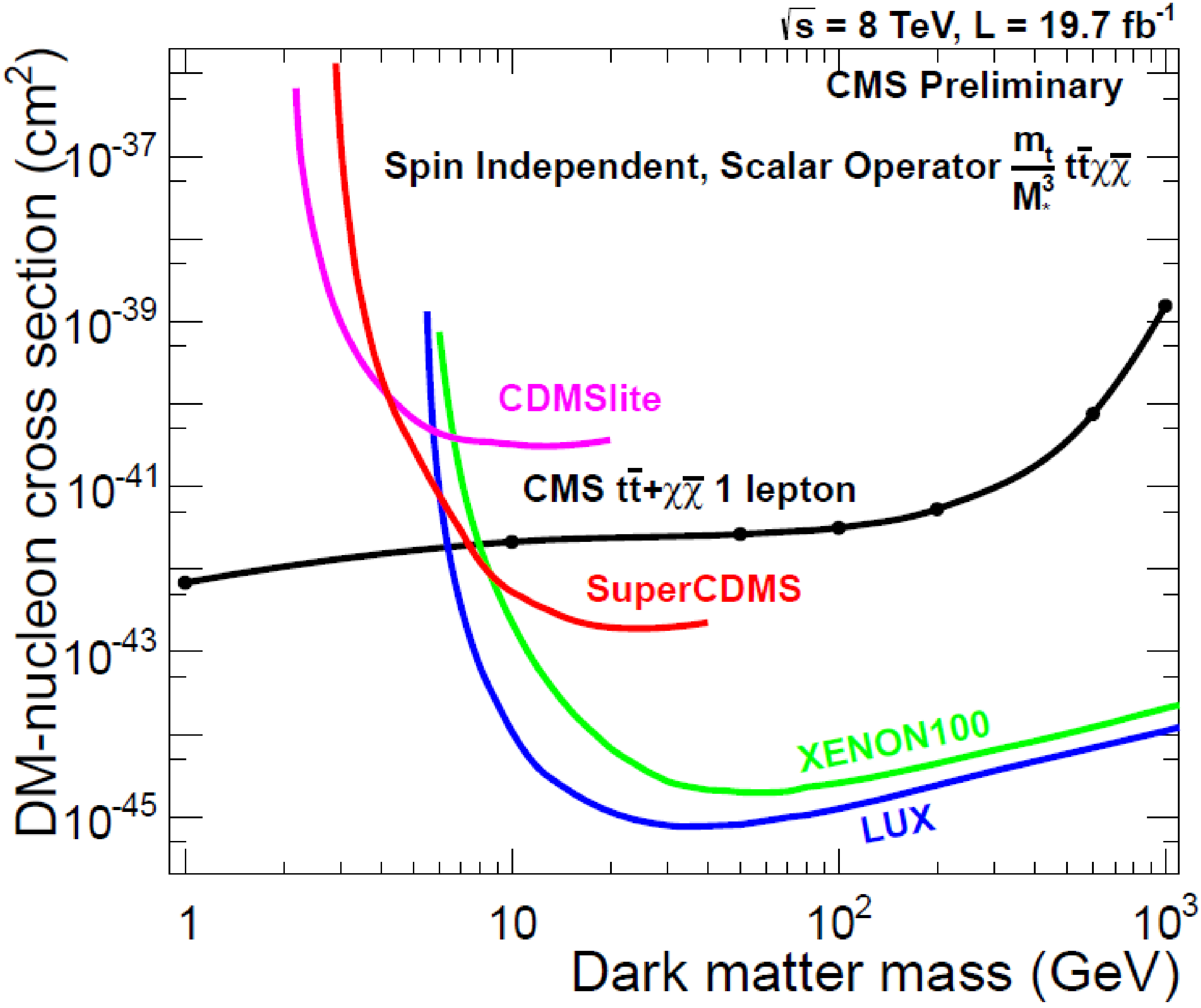


- To generate enough data to ensure Higgs discovery (or exclusion) with Run 1, the LHC has been designed to collide protons every 25 ns (⇒ 40 MHz)
- Multi-purpose detectors have millions of read-out channels ⇒ O(1 MB) per bunch crossing ⇒ O(100 TB/s)
- No technology is currently able to handle this bandwidth
- Solution: reduce the amount of data online by triggering I/O with fast algorithms based on partial information

Dark Matter

- "Dark" because it doesn't emit light
  - Therefore it is invisible to us
  - And it doesn't absorb light either: fully transparent
- It is not a small component: currently estimated as 84% of the mass of the Universe; there are even indications (from gravitational lensing, see later) of the existence of starless galaxies!
- Its composition is still a mystery
- The study of DM is a very intense research field at the boundary between particle physics and astrophysics





LHC searches are complementary to direct detection Dark Matter experiments