Next big thing(s) in high energy physics

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Outline

Questions we try to address

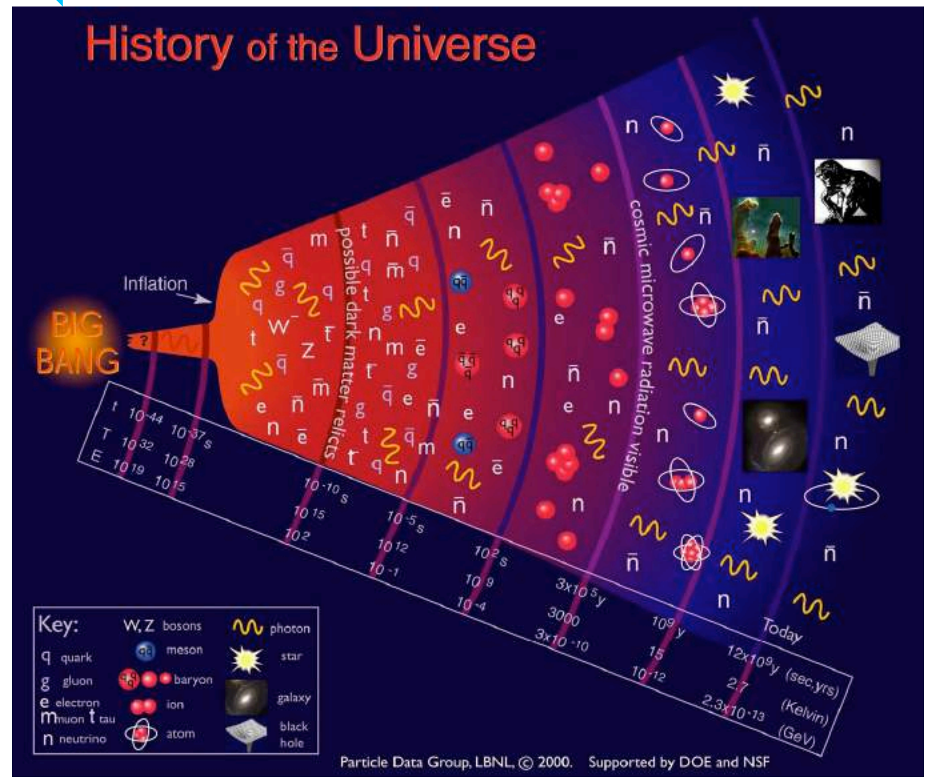
① Where do we stand?

② What are we doing now?

③ Why do we want go beyond?

④ When would it be done?

⑤ How will we do it?



Where to start from?

Ancient philosophy

- Universe is made of five elements: air, earth, fire, water and space
- Greek and other civilizations also had similar concepts

Periodic table

Modern chemistry

Group→ ↓Period	1	2		3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																		2 He
2	3 Li	4 Be												5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg												13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca		21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr		39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	*	71 Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	**	103 Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og
			*	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb		
			**	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No		

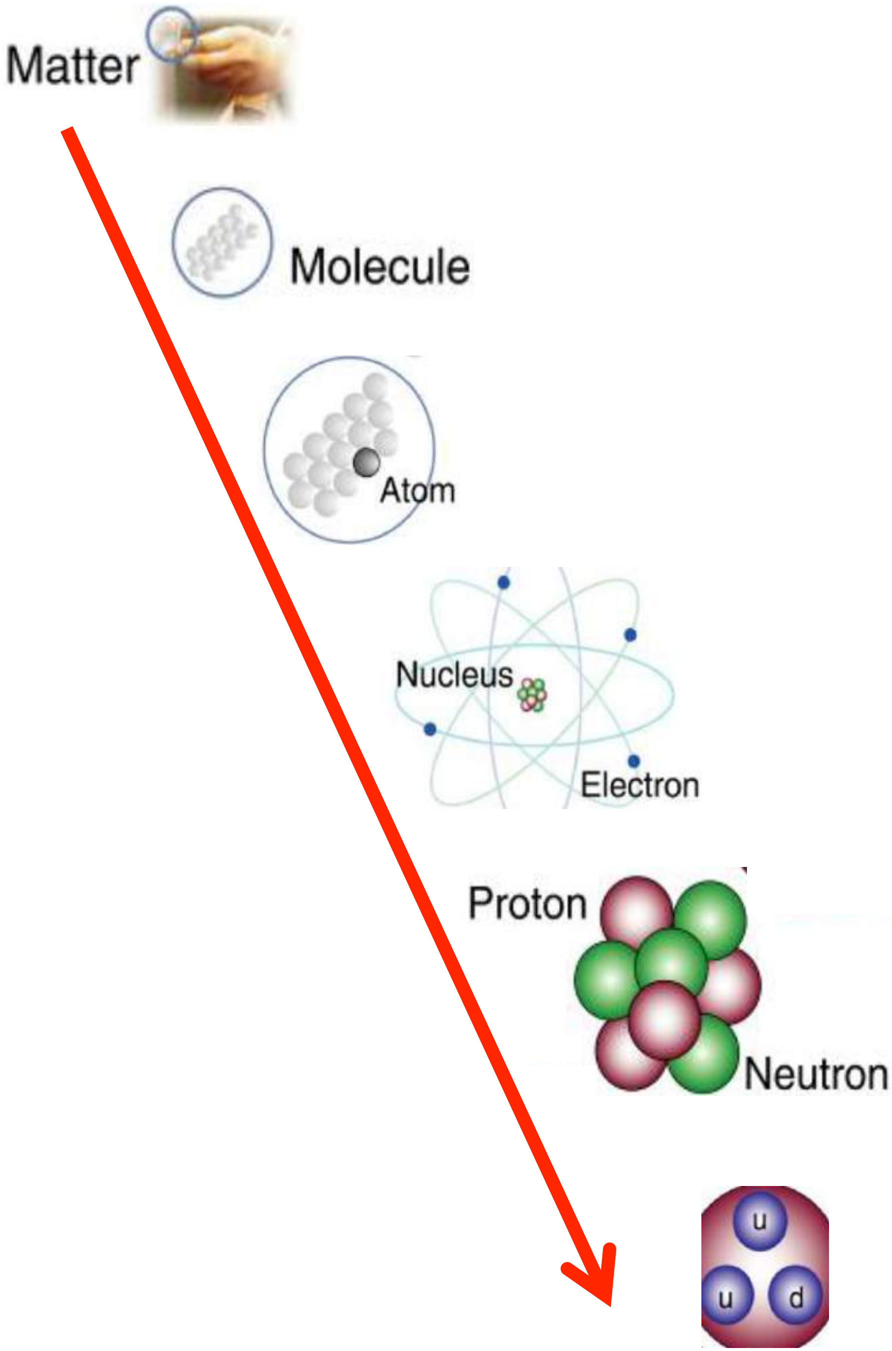
A marriage of theory and experiment

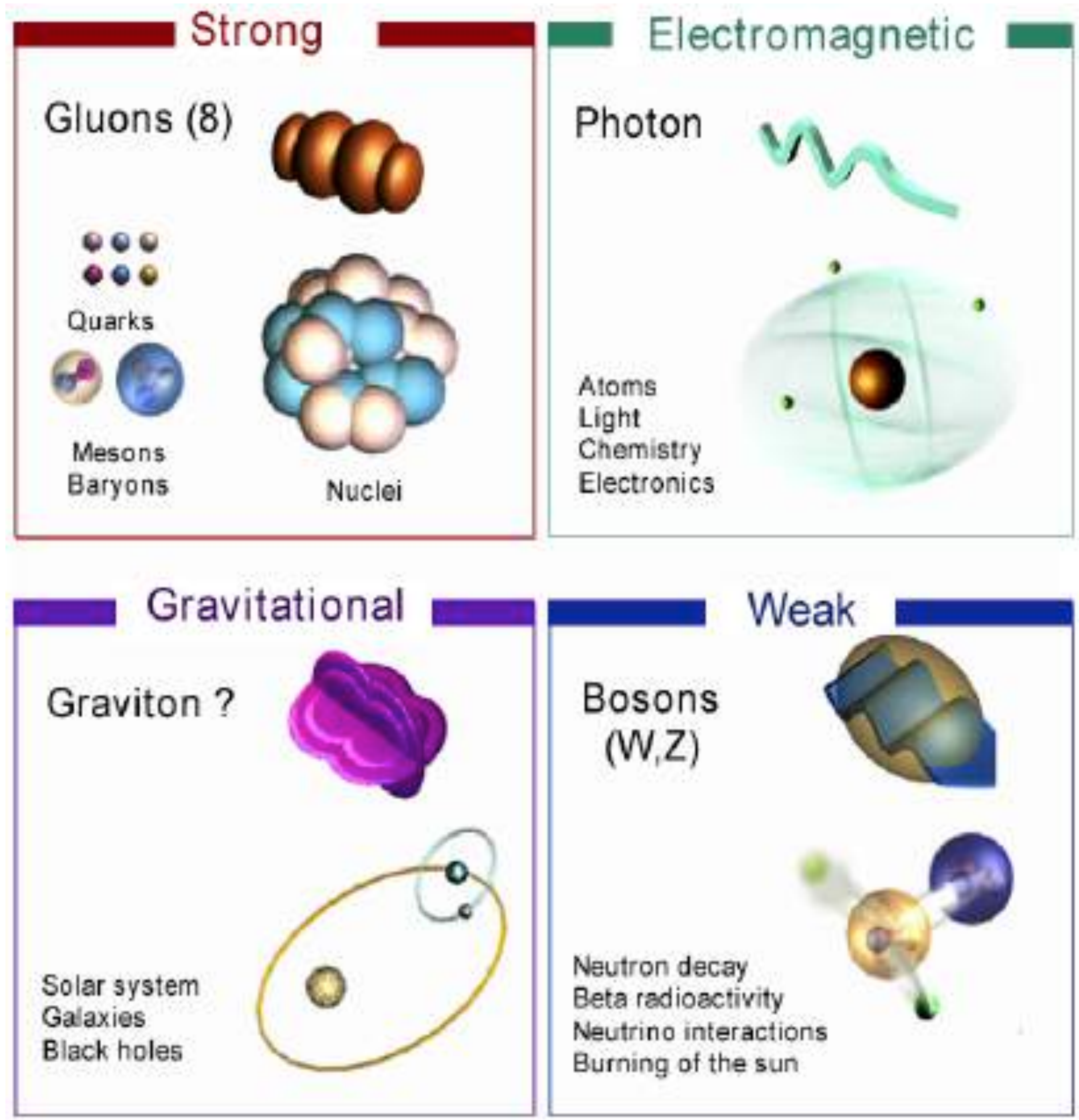
Particle physics

- Two basic questions:
  - ① What are the elementary elementary building blocks of matter?
  - ② What are the forces that control their behaviour at the most fundamental level?

- Three key steps:
  - ① Prepare and make energetic particles interact ➔ accelerator
  - ② Study the products and properties of the results of this interaction by measuring energy, direction and type of products as accurately as possible ➔ detector
  - ③ Back-trace (‘reconstruct’) what happened during the collision ➔ physics analysis

Where do we stand?





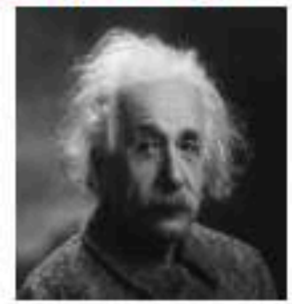
- Quarks and leptons are basic building blocks and interact among themselves via exchange of gluons, photon, W and Z bosons

Why need high-energy accelerators?

High energies allow us to

i) Study the young universe ($E= kT$)
Revisit the earlier moments of our ancestral universe
(look further back in time ➔"powerful telescopes")

Boltzmann



Einstein

de Broglie

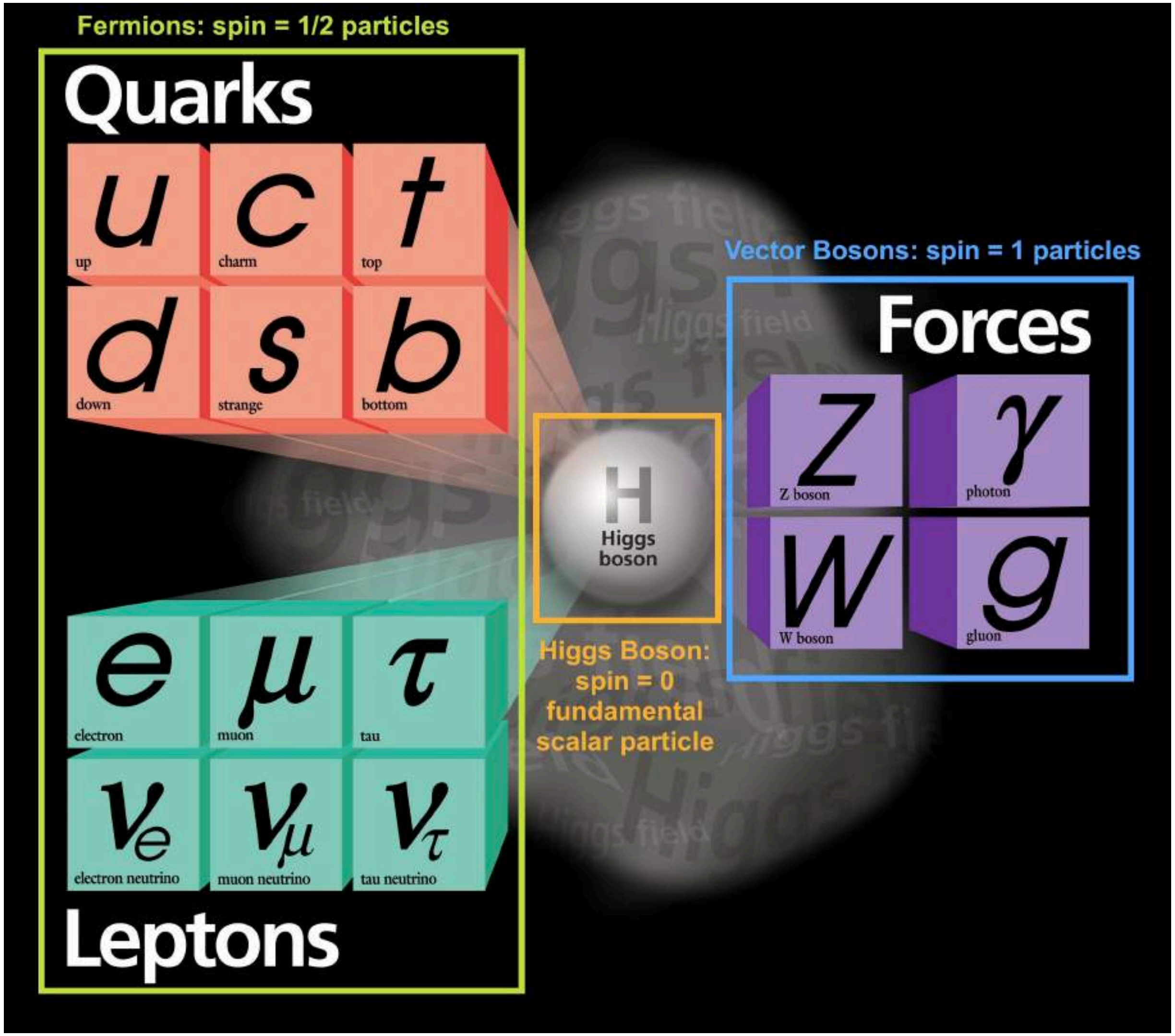
ii) Discover new particles with high(er) mass ($E = mc^2$)

iii) Look deeper into Nature ($E \alpha 1/size$),
(look deeper ➔"powerful microscopes")

Observe phenomena and particles normally no longer observable in our everyday experience.

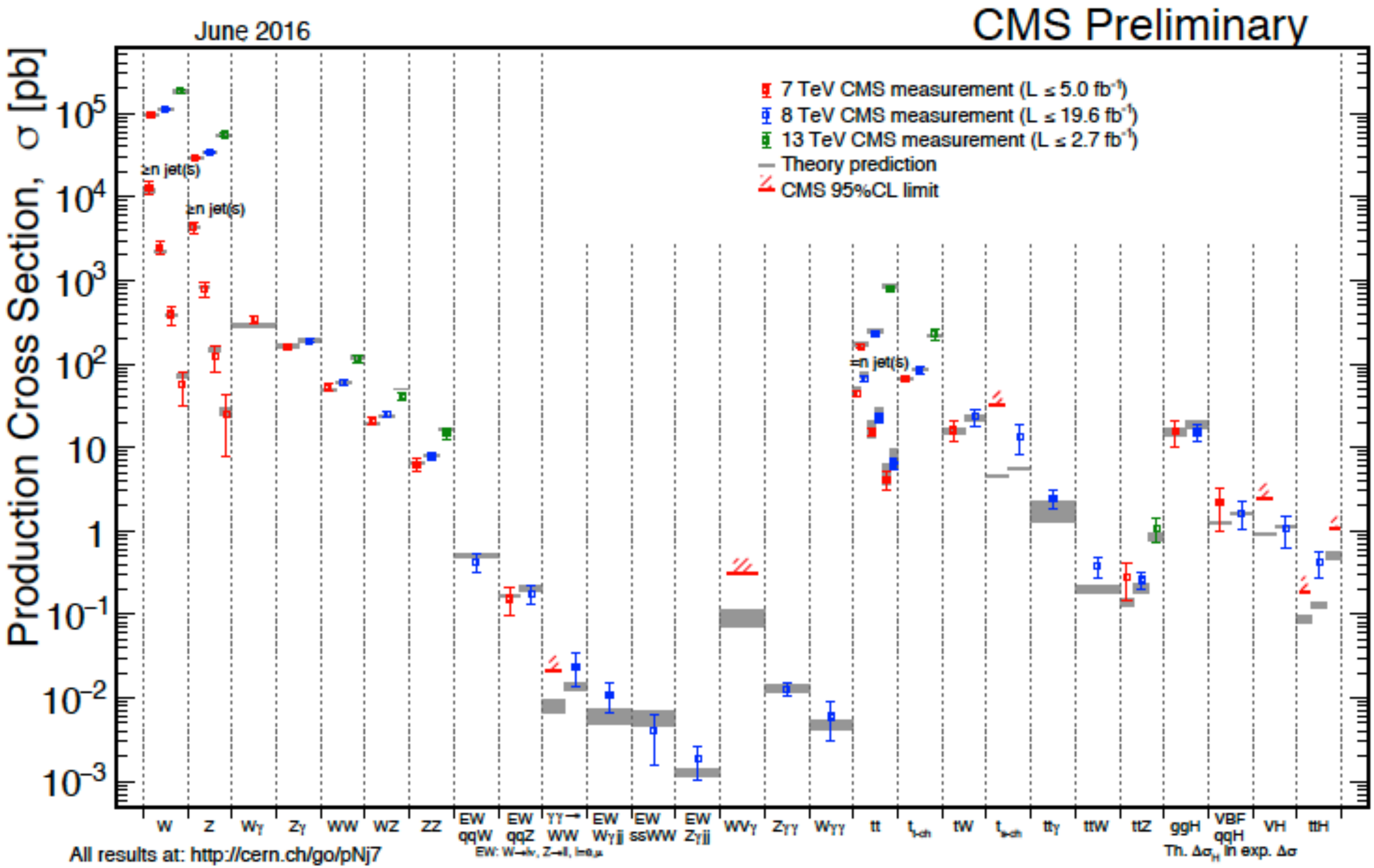
➢ All in a 'controlled manner' inside the laboratory

A modern periodic table?



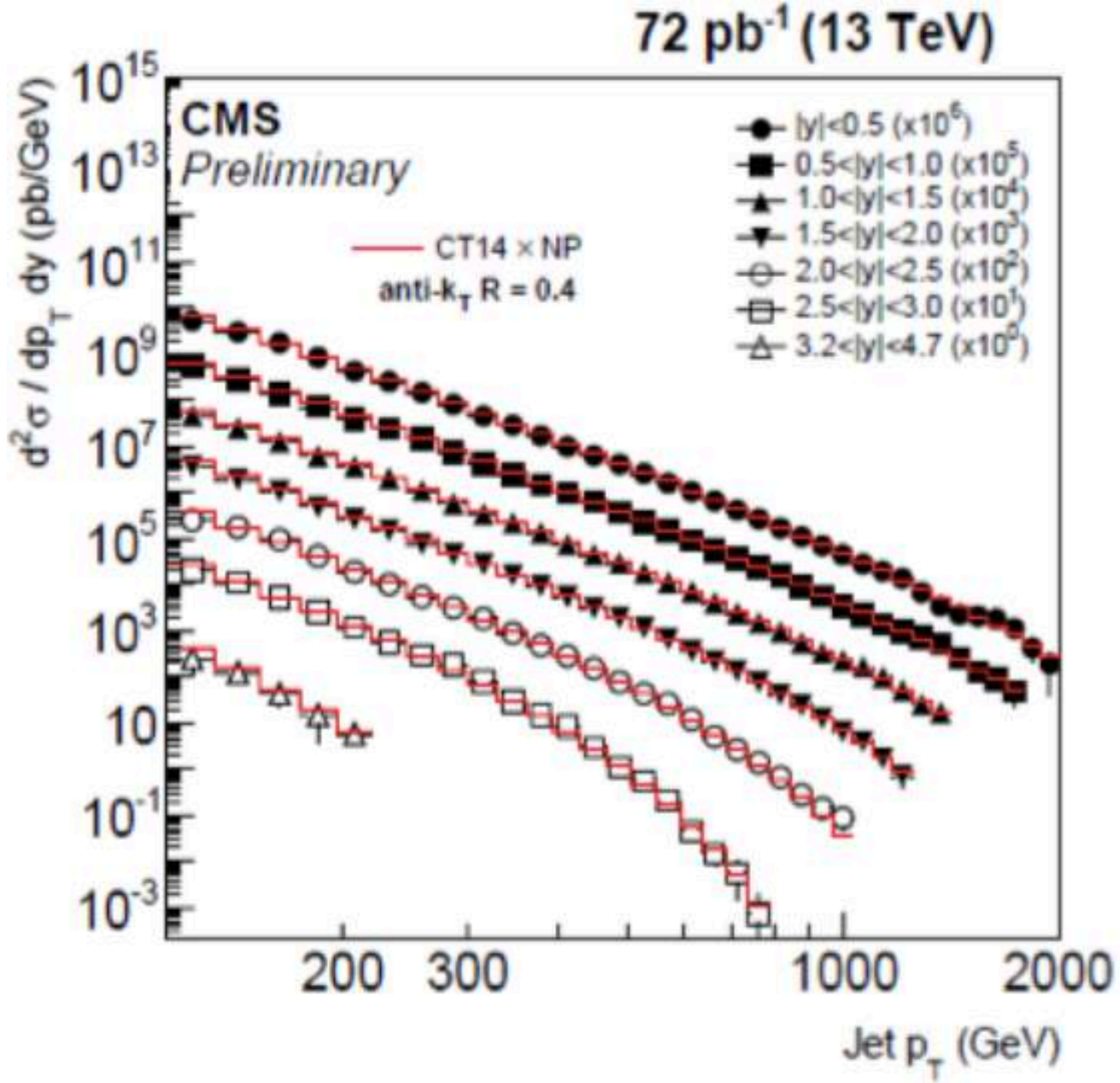
- Combining quantum mechanics (physics of small) and relativity (physics of fast) along with plethora of particles discovered ➔ Standard Model of particle physics

How good is the SM?



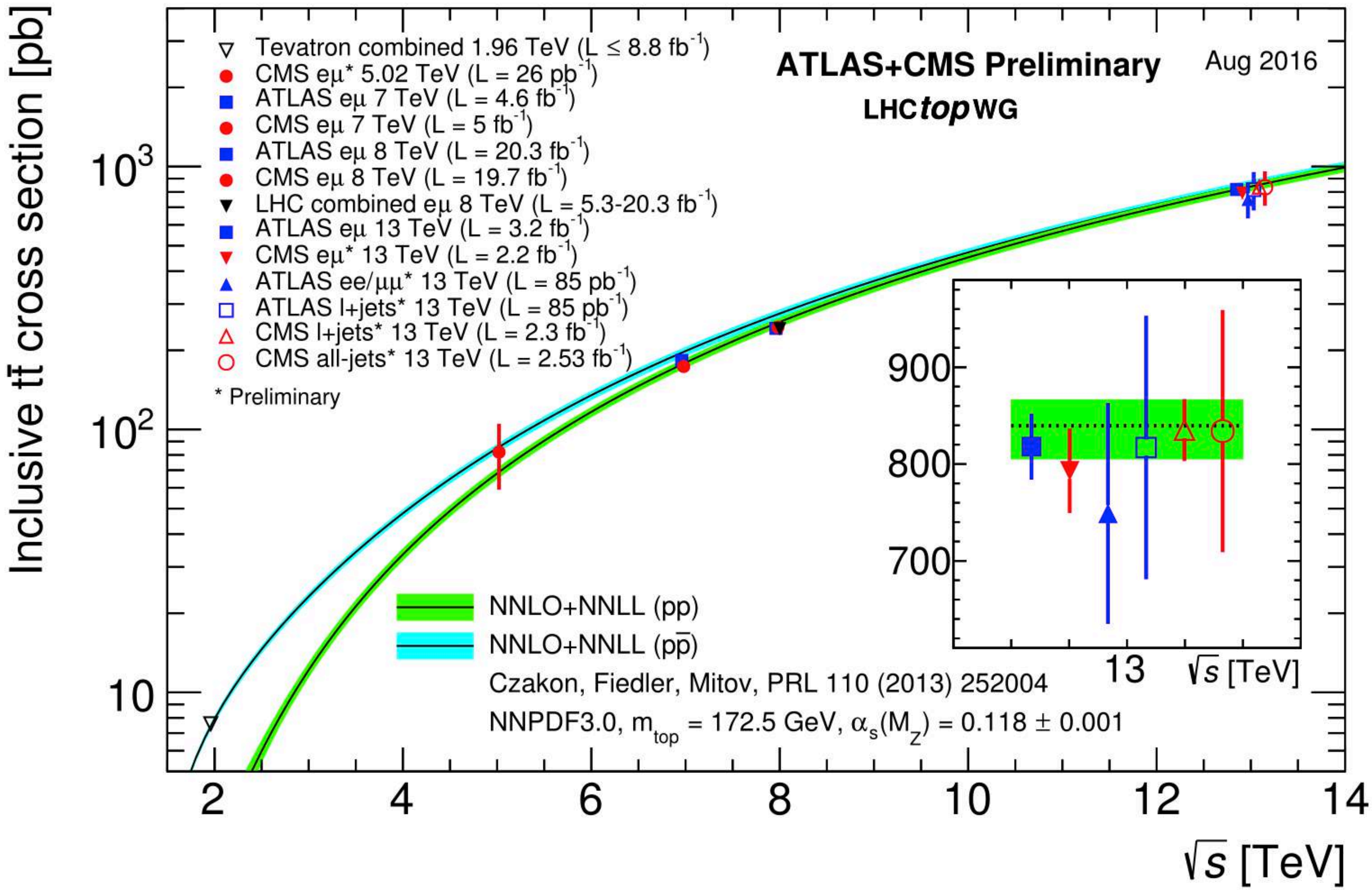
❑ Successful in describing physical phenomena over a broad scale

Second example...



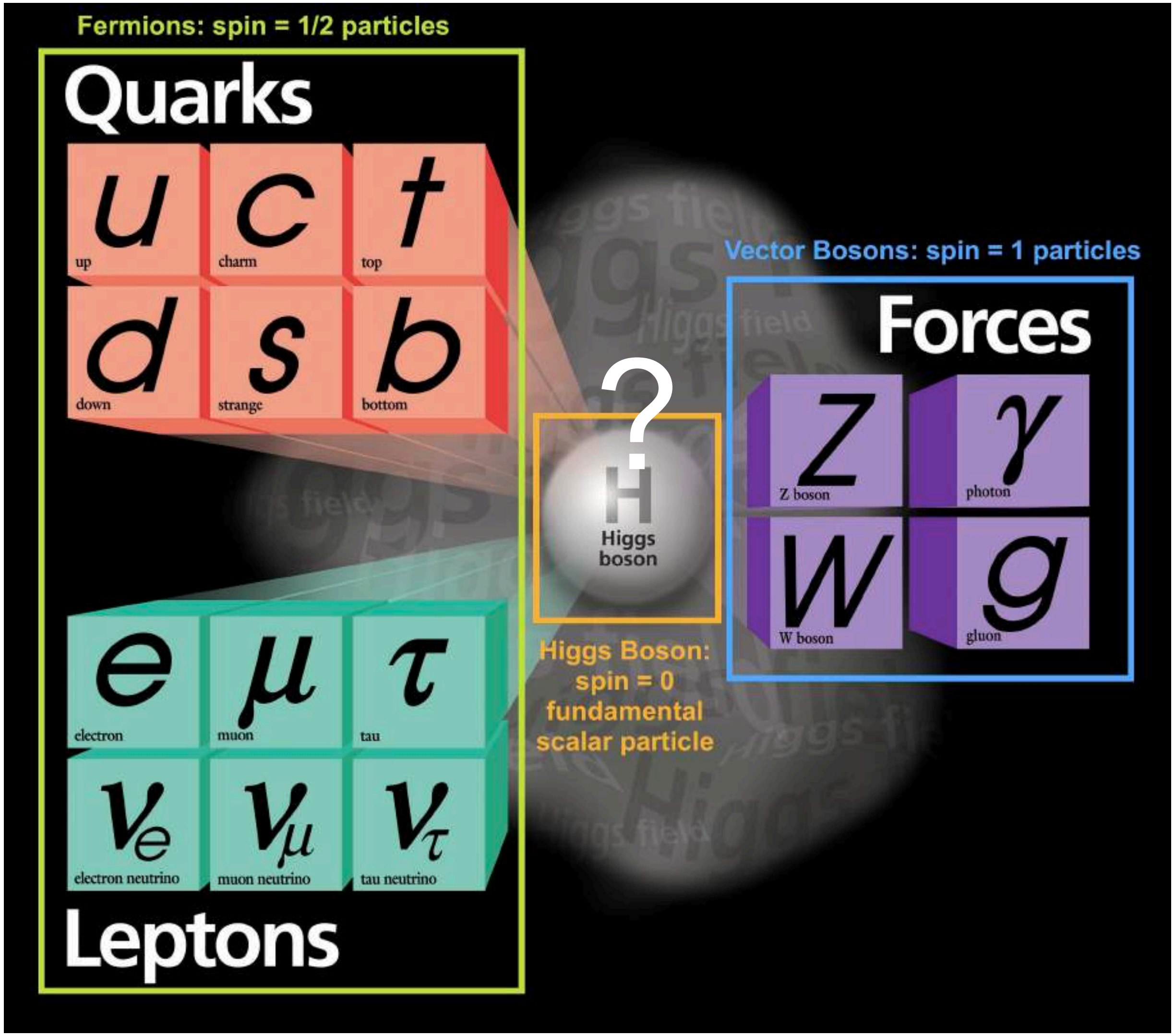
- Successfully describes the physics of quarks and gluons at the highest energy achieved in the laboratory!

Third example...



- ❑ Well describes physics of the top quark, the heaviest known elementary particle

One key ingredient missing till recently...



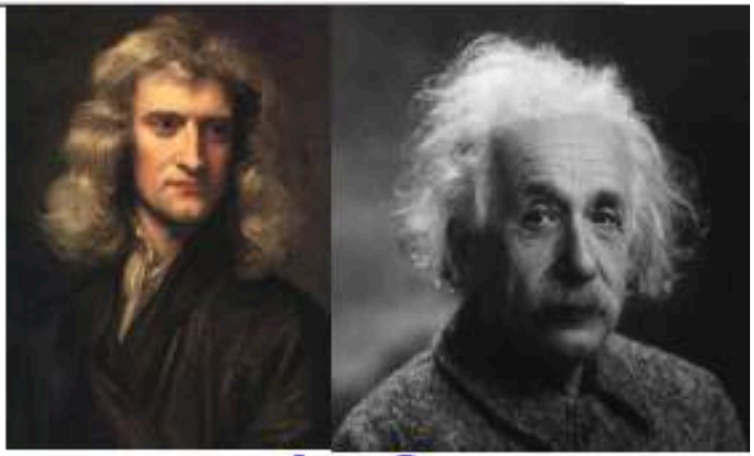
- ❑ Before 2012 its most basic mechanics, that of granting mass to elementary particles, was still missing ➔ spin-0 Higgs boson

Revolution of July 4, 2012...

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs

"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle,
by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

So, why it such a big deal?



To Newton: F= ma, w = mg
To Einstein: $E = mc^2$
Mass curves space-time

All of this is correct.
But how do fundamental objects become massive?
Simplest theory – all fundamental particles are massless !!

A bold intellectual conjecture (1964): a field pervades our entire universe. Particles interacting with this field acquire mass, the stronger the interaction the larger the mass

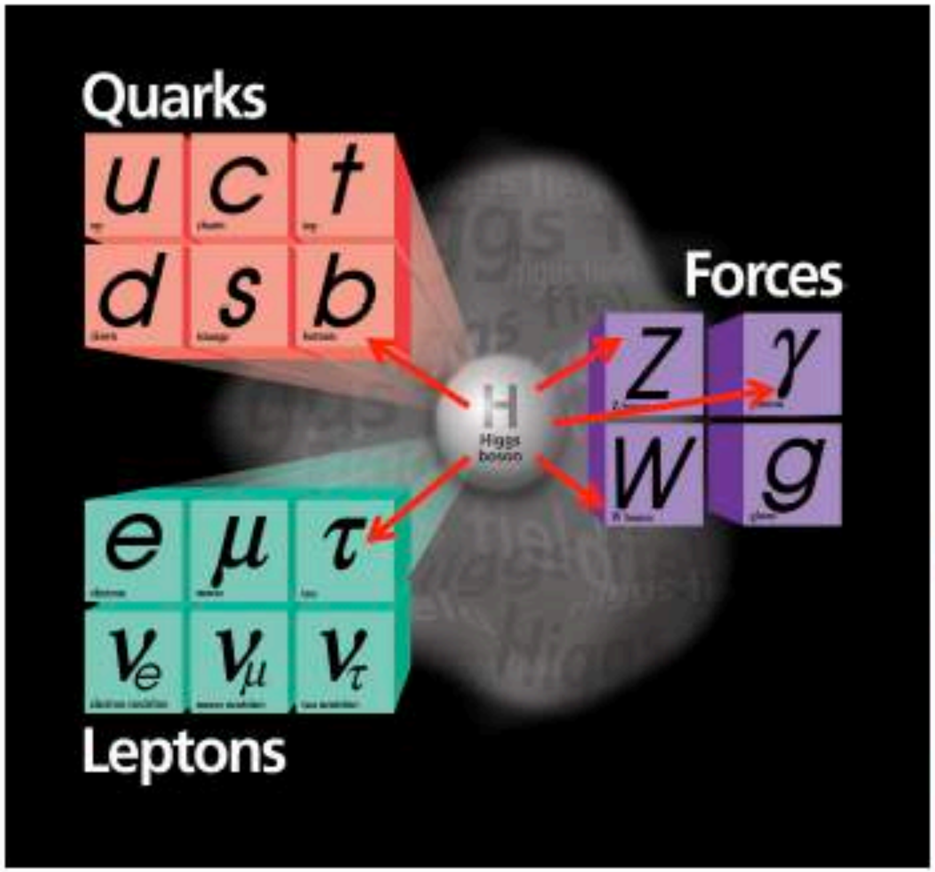
The field is a quantum field – its quantum is the Higgs boson. Finding the Higgs boson establishes the existence of this field.

- No Higgs boson, no masses for elementary particles, no formation of atoms and molecules...

Homework for experimentalists at LHC

The SM Higgs boson leaves very characteristic fingerprints in our detectors

In its couplings, decay rates and angular distributions of final products



Higgs lifetime (125 GeV): 10^{-22} s

So decay immediately

Will only see decay products

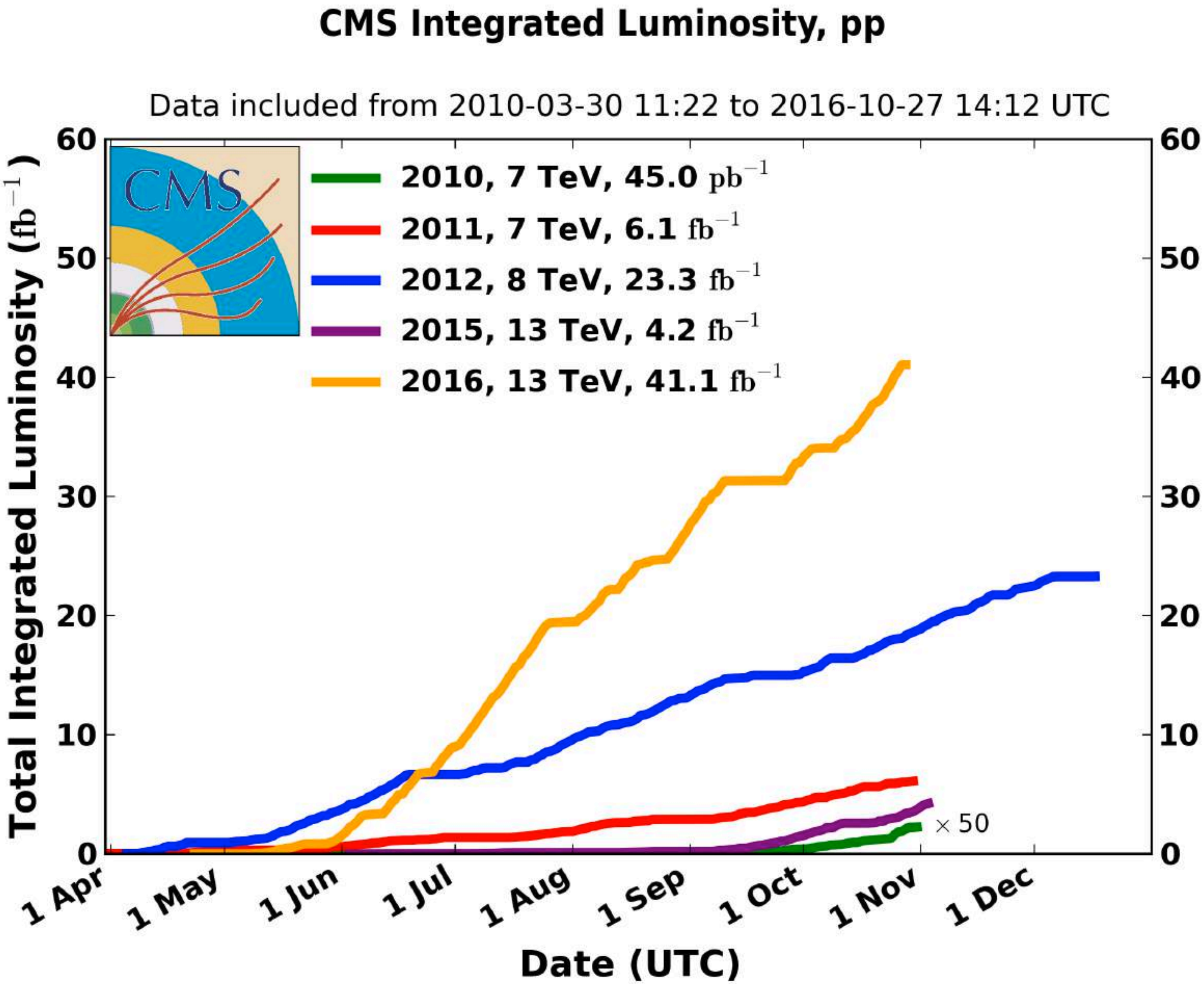
Higgs couples to mass:

Coupling to fermions (quarks and leptons)

$H \to b\bar{b}$,	$H \to \tau^+\tau^-$	$H \to \gamma\gamma$	$H \to ZZ, H$
~55 %	~10%	~2/mille	~3%

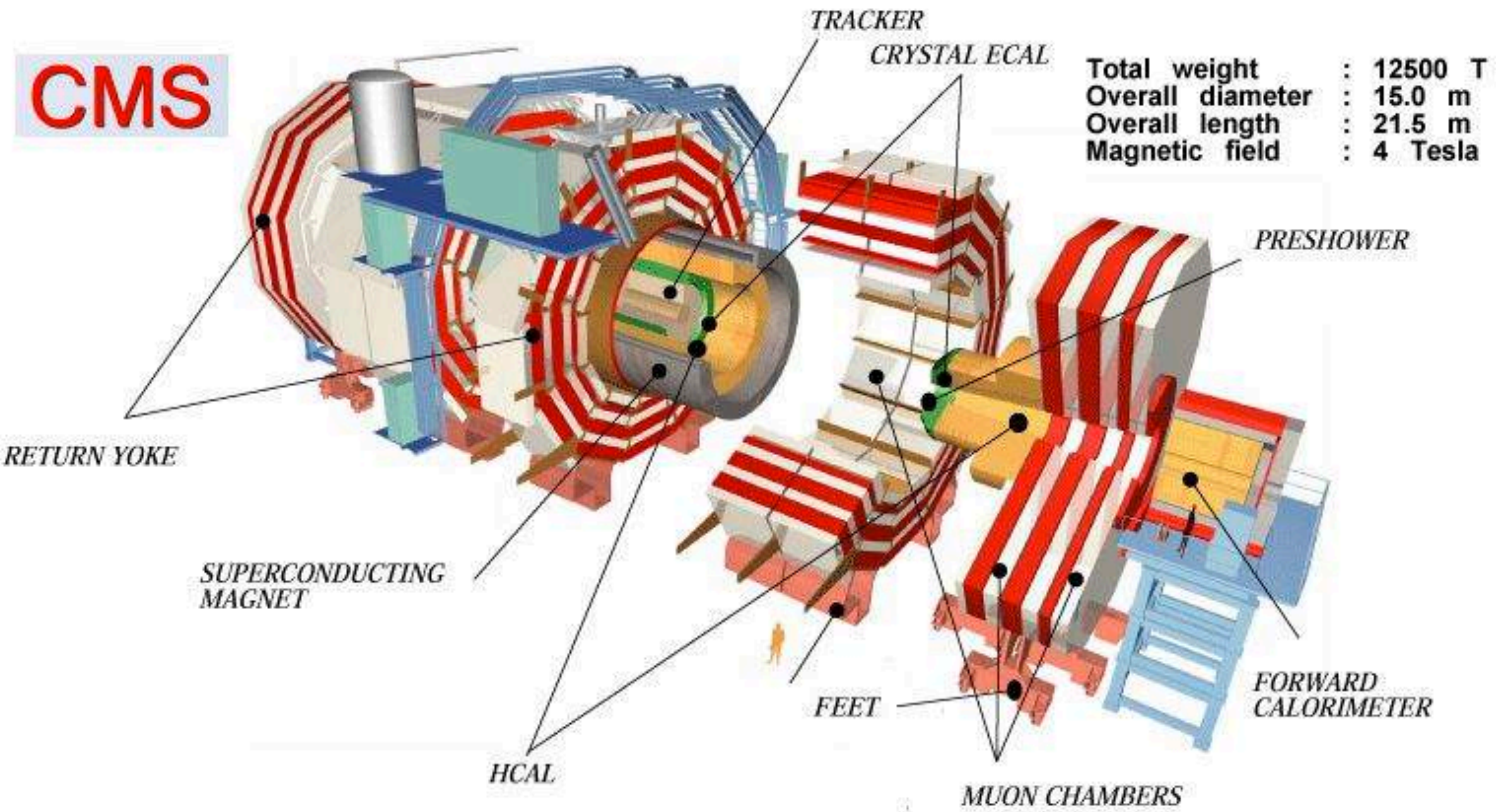
at a mass of ~125 GeV
many decay modes are detectable
Makes it easier to establish whether or not it is a SM Higgs boson

Most important thing for us...



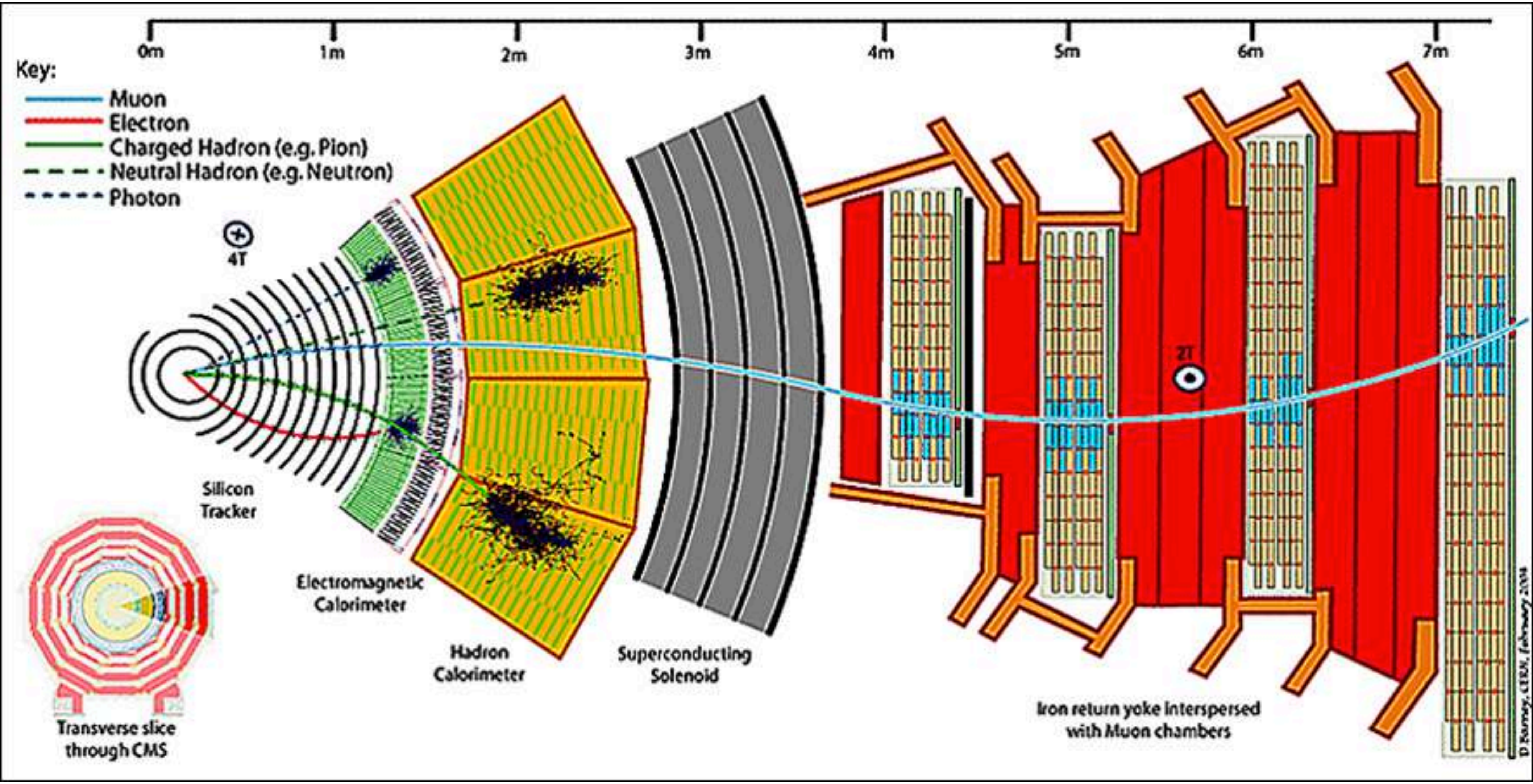
- Luminosity is the key as we probe more and more rare phenomena viz. Higgs

A gigantic multi-million pixel camera...



- India built the outer hadron calorimeter (outside magnet coil) in the central part and silicon preshower for the endcaps

Why do we need such a complex device?

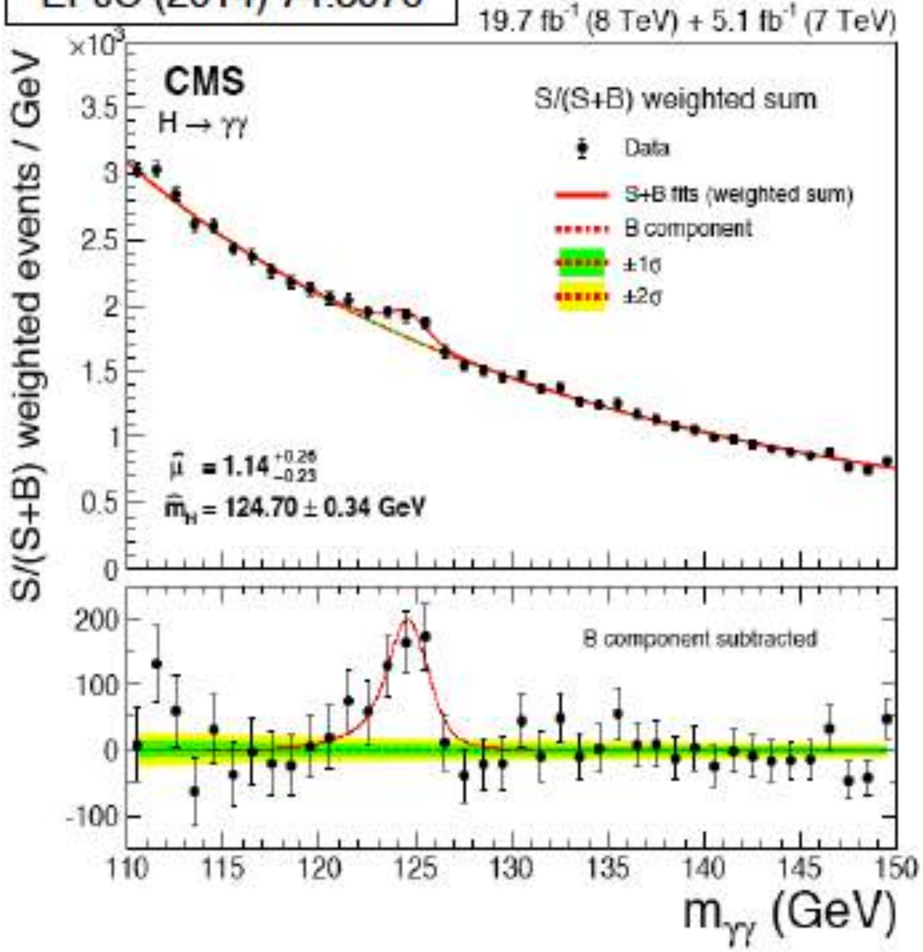


- ❑ Each of the detector components has a role to play in the space-time odyssey

How did we see ‘it’ for the first time?

H→ 2γ Channel

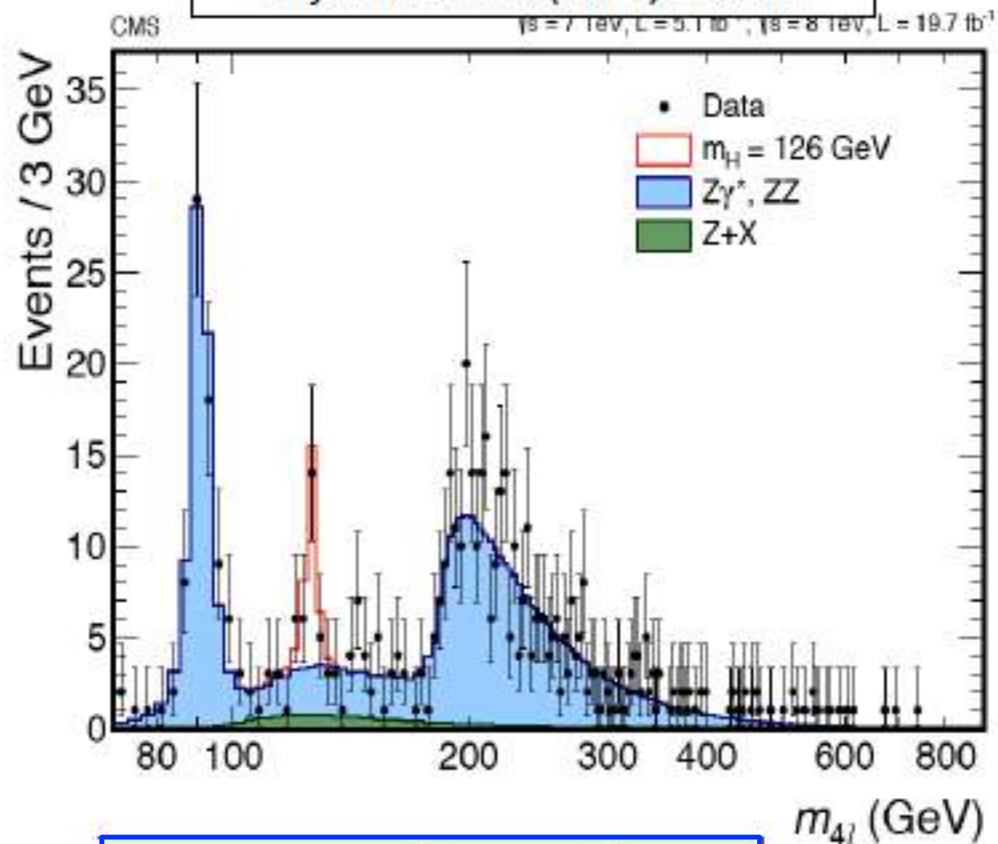
EPJC (2014) 74:3076



Similar results from ATLAS

H→Z→4*l* Channel

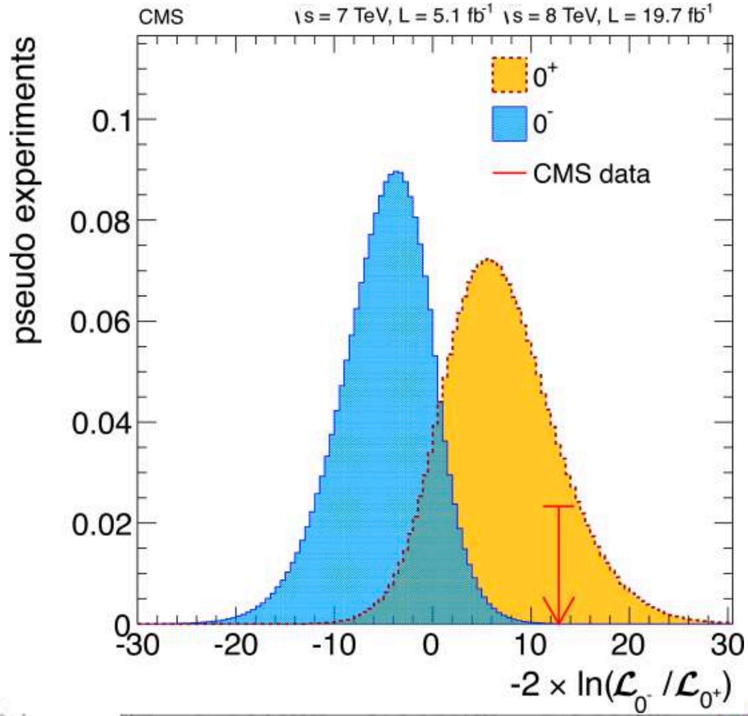
Phys. Rev. D89 (2014) 092007

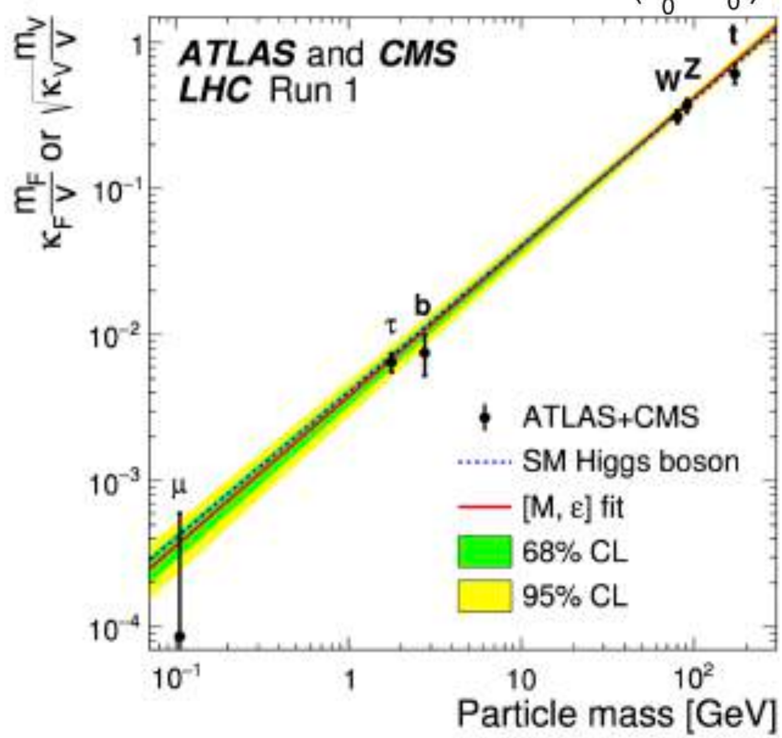


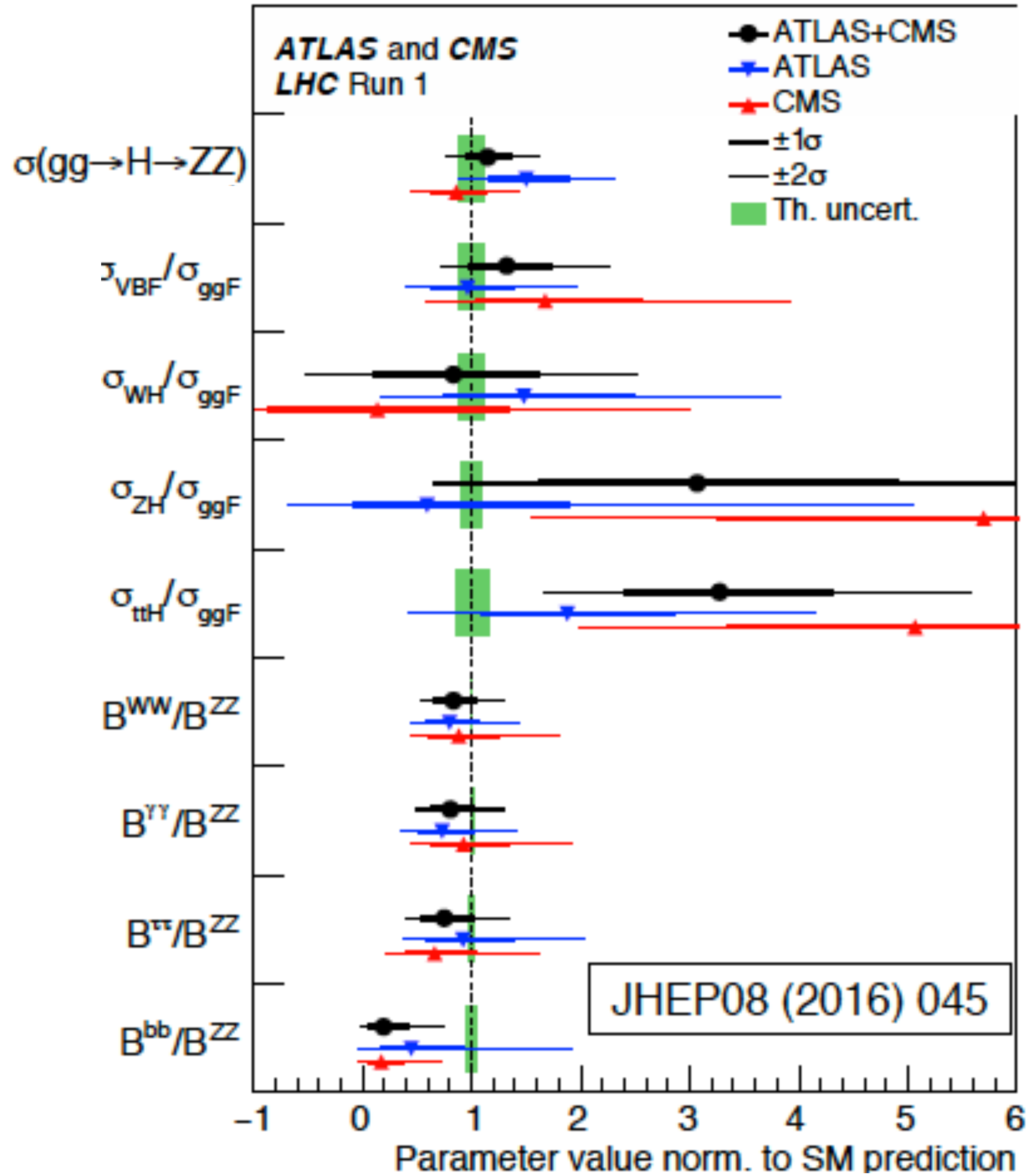
Significance	Exp	Obs
H→ 2γ	5.3 σ	5.6 σ
H→Z→4*l*	6.3 σ	6.5 σ

- ❑ All components of the detector, especially tracker and ECAL, played their role in this epochal discovery

How sure are we it is the ‘SM’ one?



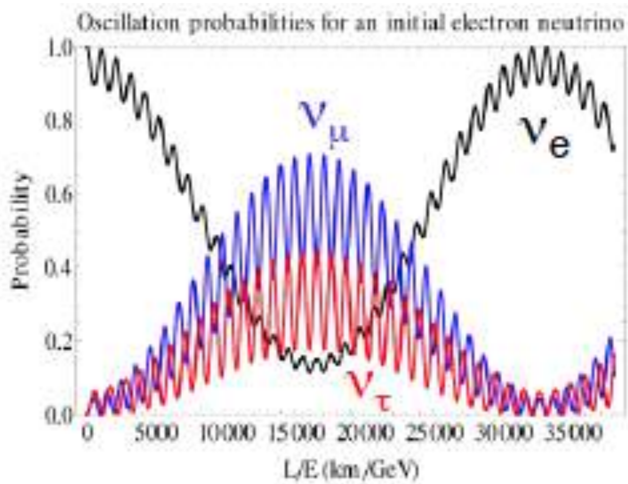




With the SM being complete, should we close the shop?

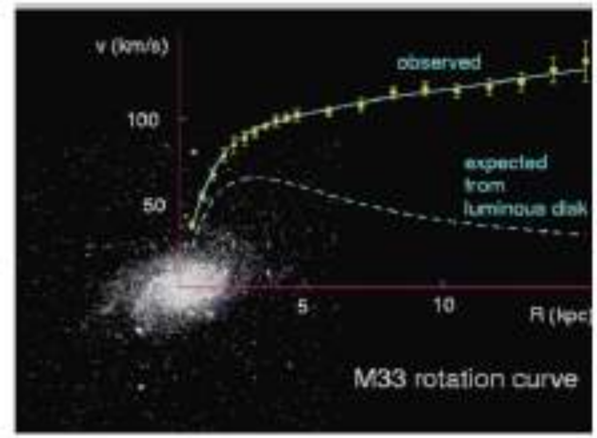
There are lots that the SM is silent about...

Neutrino mass (oscillations)



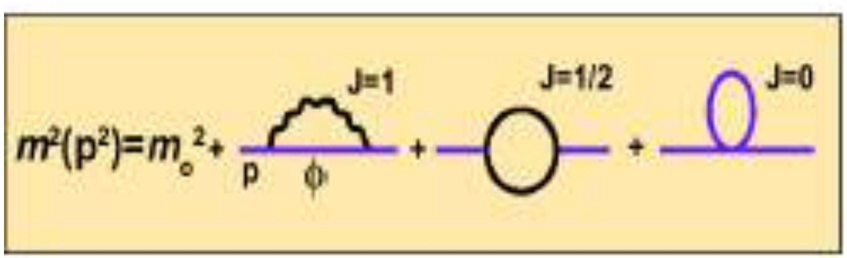
2015

Dark Matter



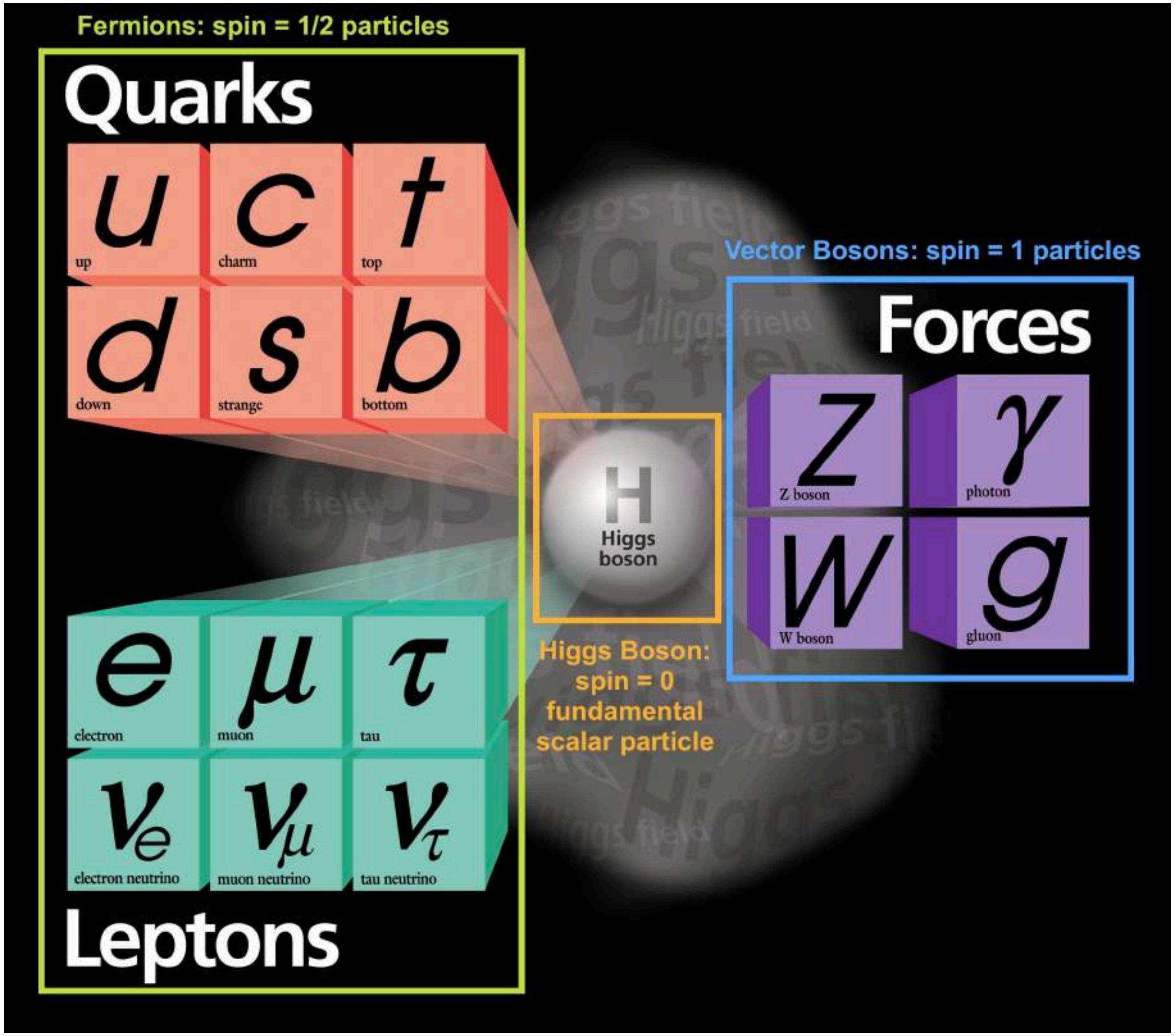
Matter-antimatter asymmetry

The lightness of the Higgs boson?



- In addition to these grandiose questions, there are many questions within the SM

The SM is an enigma...

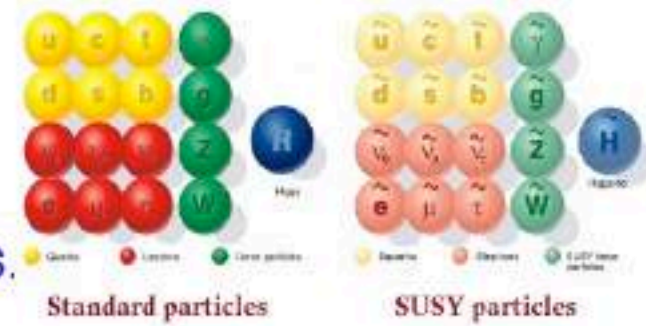


① Why there are only three family?

② Why such a great disparity of mass?

③ ...

Out theory friends have been very active...



Supersymmetry (SUSY)

Intimately relates matter particles and force particles.

SUSY predicts the existence of a partner for every known SM particle with spin differing by half a unit and 5 Higgs bosons!

The lightest particle of this species is a candidate for dark matter
Would address the issue of the "lightness" of the Higgs boson.

Superstring Theory

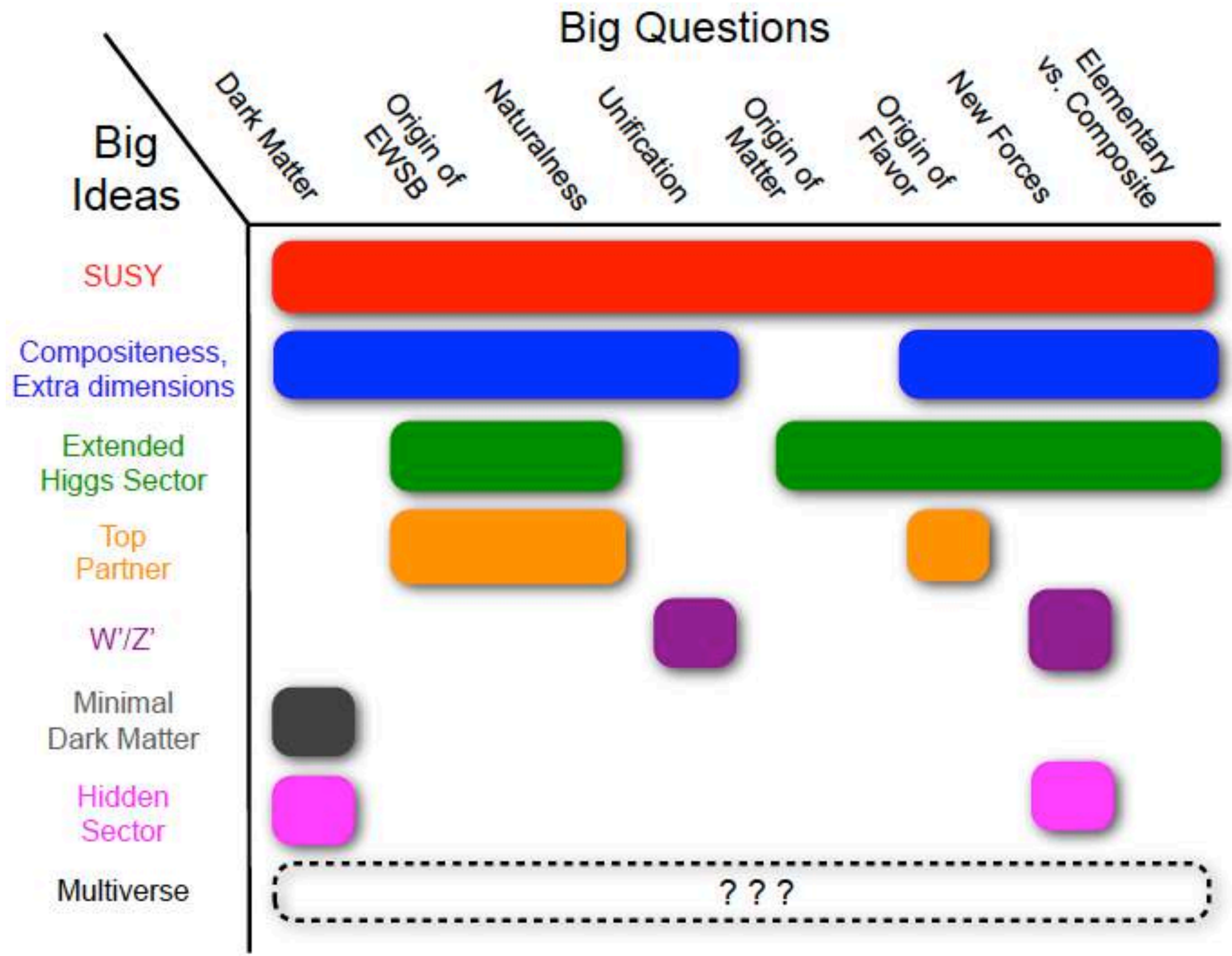
Can gravity be unified with the other forces? Supersymmetry helps.

Extra Dimensions

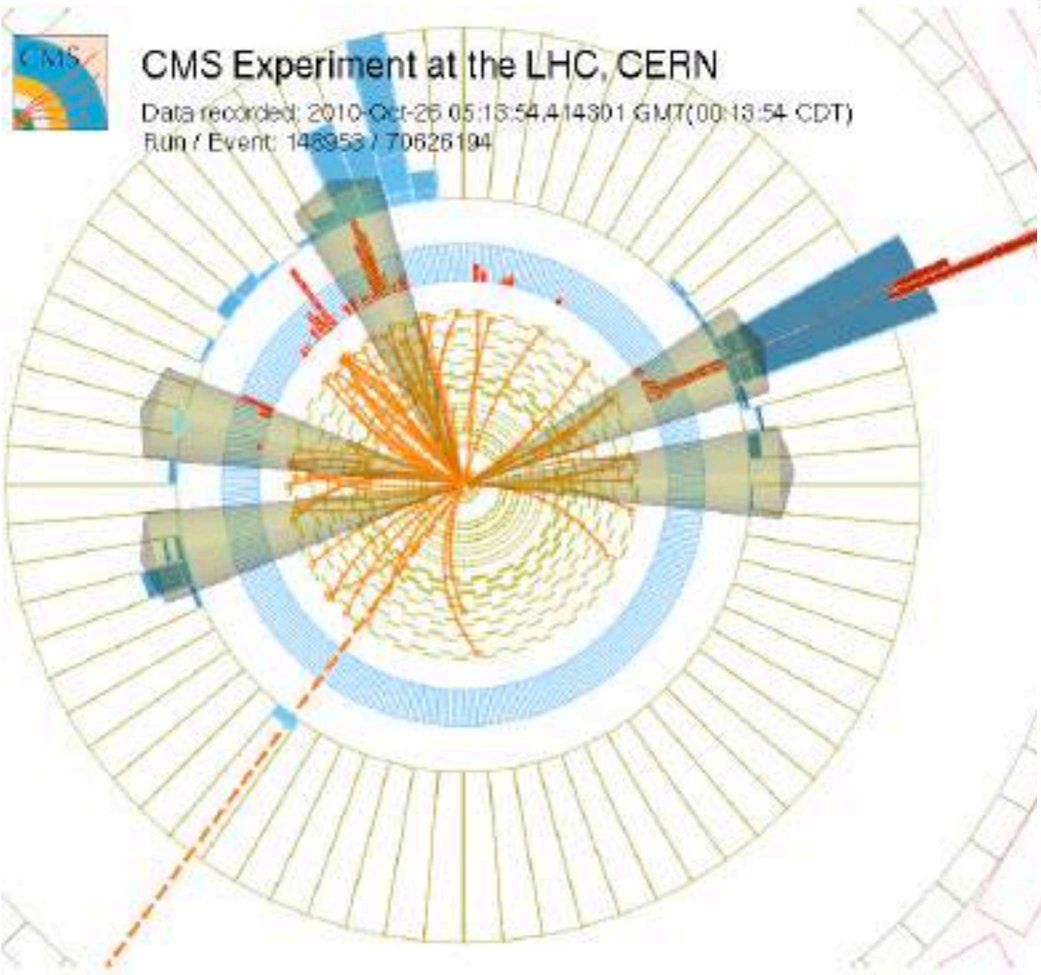
Number of space-time dimensions determines the observed form of a force
Tell-tale signs are new heavy Z-like particles.

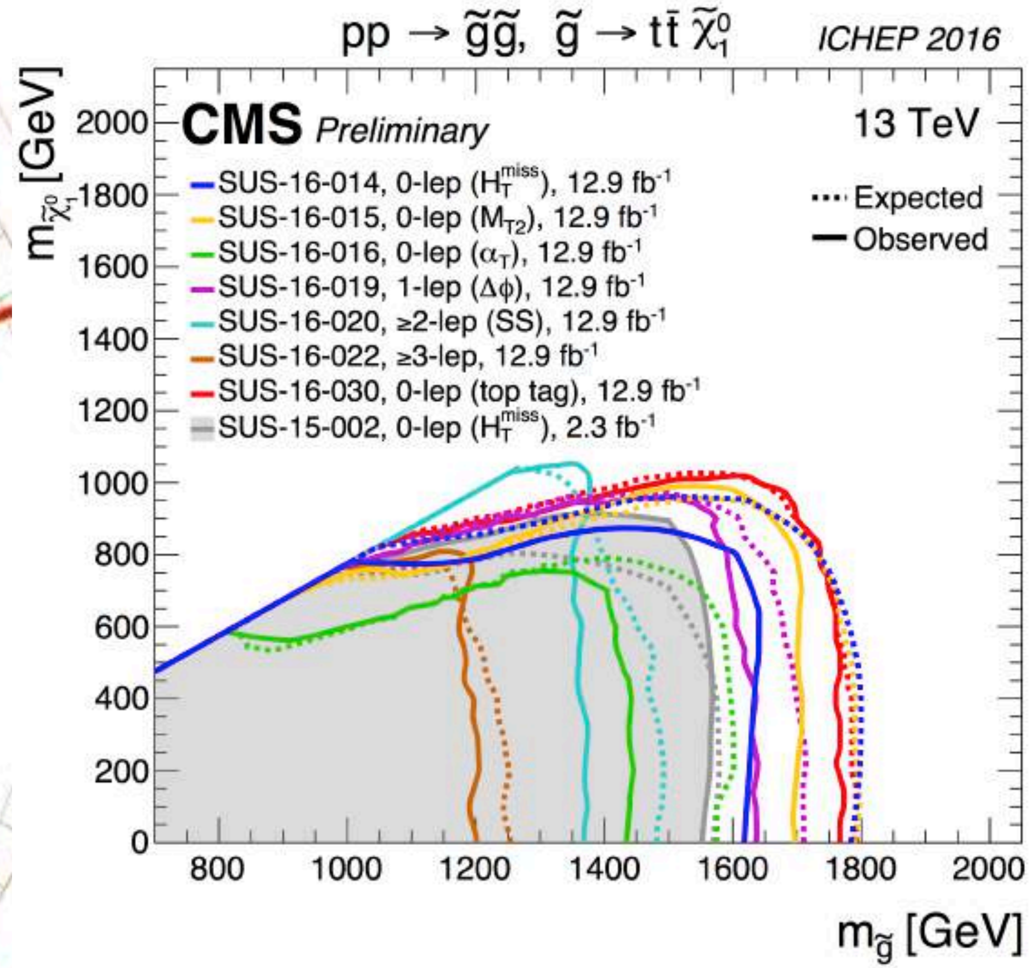
- In addition to these favourite ones there are many others in the market...

Big questions to big ideas...



The most favourite one has no luck...



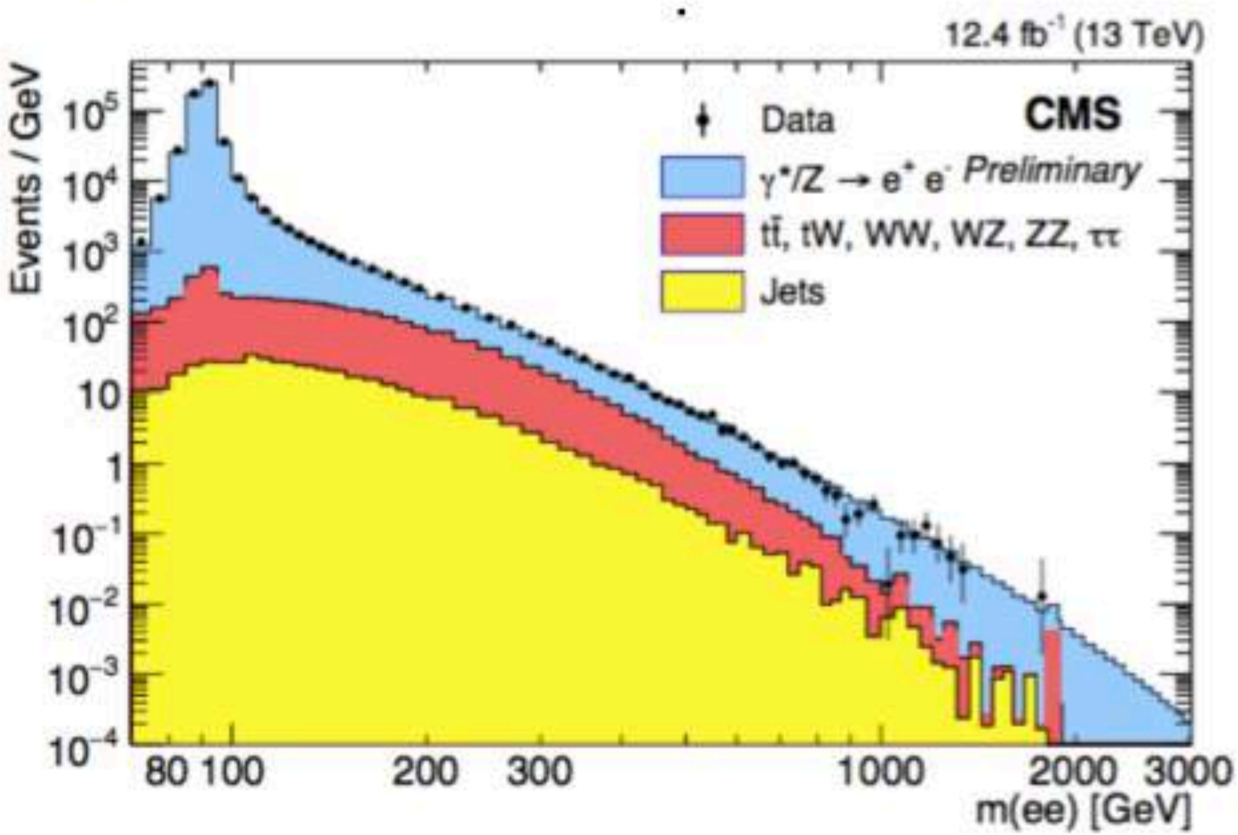


No evidence for Supersymmetry has been found so far.

- In addition to these favourite ones there are many others in the market...

A simple plot tells hundred things

Searches for compositeness (do the particles of the SM have structure?), extra dimensions (some of these theories predict heavy resonances observable at the LHC), new heavy gauge bosons, leptoquarks (quark and lepton bound states), excited fermions, black holes, dark matter particles, and more.



CMS: ee and μμ

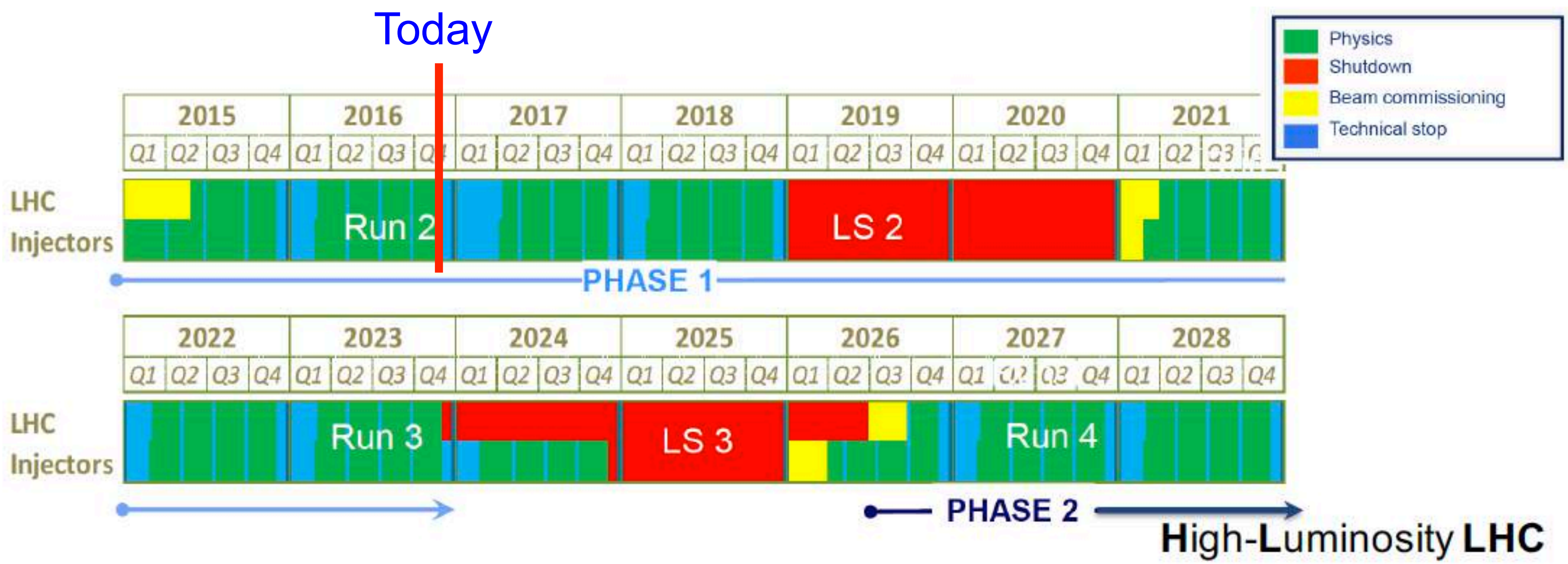
at 95% CL

$M(Z'_{SSM}) > 2.90$ TeV

$M(Z'_{\Psi}) > 2.57$ TeV

- Just by studying the invariant mass spectrum of the di-electron system we can probe many BSM models

Looking ahead...



Topmost Priority – exploitation of the full potential of the LHC
High luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design

1. Conduct detailed studies of the properties of the found Higgs boson.
LHC → HL-LHC - a Higgs factory! 100M produced with $3ab^{-1}$
How much does it contribute to restoring unitarity in VBF (closure test of SM), exotic decays, rare decays (e.g. $H\rightarrow\mu\mu$)

2. Search for new physics: resonances, supersymmetry, exotica, yet unknown. If new physics found in Phase 1, associated particle(s) will be heavy. Then conduct detailed studies in HL-LHC

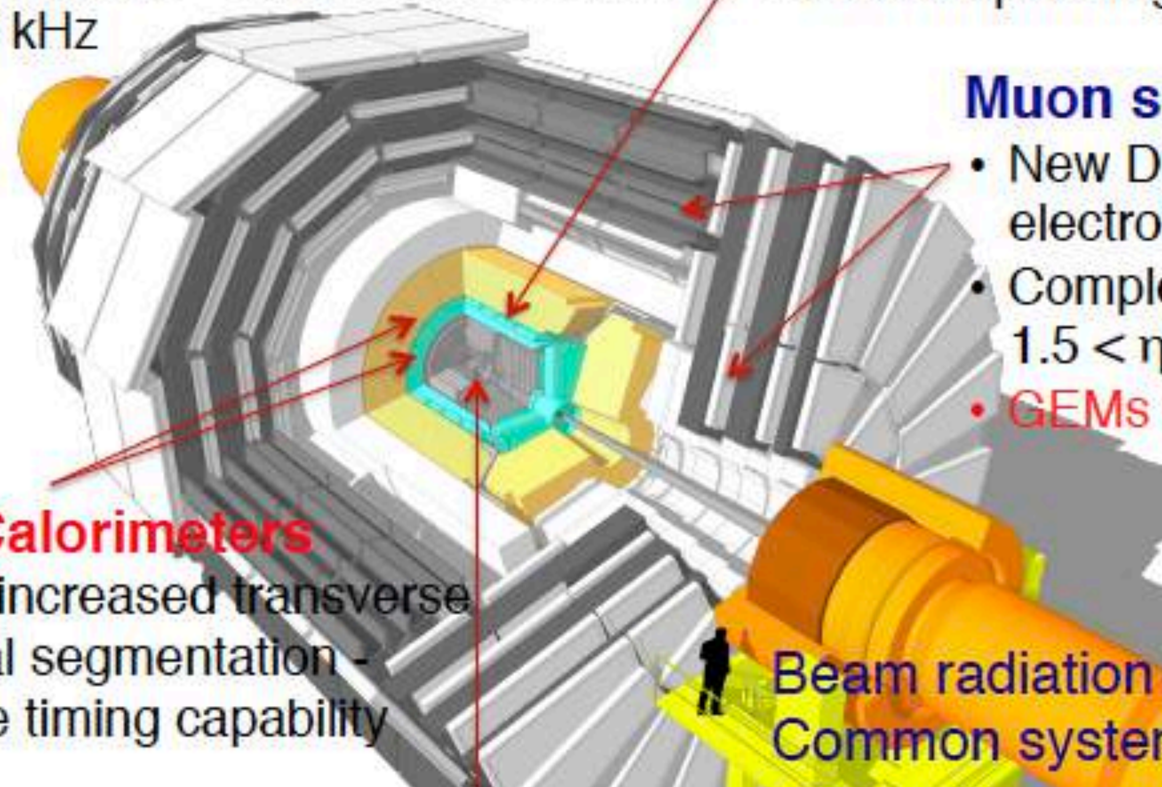
3. Look for deviations from the standard model – precision SM measurements (e.g. tens of millions of top pairs produced/yr)

How would the upgraded CMS look like?

Trigger/HLT/DAQ
- Track information in Trigger (hardware)
- Trigger latency 12.5 μs - output rate 750 kHz
- HLT output 7.5 kHz

Barrel EM calorimeter
- New FE/BE electronics
- Lower operating temperature (8°C)

Muon systems
- New DT & CSC FE/BE electronics
- Complete RPC coverage $1.5 < \eta < 2.4$
- GEMs GE1/1, GE2/1, ME0



New Endcap Calorimeters
- Rad. tolerant - increased transverse and longitudinal segmentation - intrinsic precise timing capability

Beam radiation and luminosity
Common systems &infrastructure

New Tracker
- Rad. tolerant - increased granularity - lighter
- 40 MHz selective readout ($p_T \geq 2$ GeV) in Outer Tracker for Trigger
- Extended coverage to $\eta \approx 3.8$

India: 7th largest nation within CMS

- Indian institutes:
  - Mumbai (TIFR, BARC, IIT), Chennai (IIT), Delhi (DU), Chandigarh (PU), Kolkata (SINP), Bhubaneswar (NISER, IIT, IOP), Bangalore (IISc), Pune (IISER), Shoolini, Visva Bharti
- Detector construction:
  - Outer hadron calorimeter (full responsibility)
  - Si preshower (millistrip sensors made at BEL, Bangalore)
- Operation & data recording: HO, HCAL and outer tracker
- Physics:
  - Higgs, SUSY, BSM searches, QCD, B-physics
- Computing:
  - Tier-2 at TIFR (dedicated 10Gbps connection to CERN)
  - Core software development
- Upgrades:
  - Phase 1: RPC, GEM and HCAL electronics
  - Phase 2: Si microstip tracker, HGCAL, GEM

Summary and Outlook

- **Over the last 50 years, the "construction" of the Standard Model (SM) represents a towering intellectual achievement of humankind.**
- **This has allowed us to trace in much detail the evolution of our universe onwards from moments after the Big Bang.**

- **At the LHC we have discovered the keystone of the SM – the Higgs boson** – it appears to be the one predicted by the SM. It now will be studied in great detail.
- **No evidence has yet been found for physics BSM.**
- **We are just at the start of the exploration of the Terascale.**

- **What further discoveries await us?**
- Several of the open questions today are just as profound as those a century ago. LHC is the foremost place to look for new physics.

- **Discoveries in fundamental science invariably lead to paradigm shifting technologies**

➢ Data will likely drive the science...

For this particular audience...

- We can go up to 100 TeV energy, with a substantial improvement in the superconducting magnet technology

- That to, for proton-proton (or at best muon-muon) collisions

- Beyond that, the conventional acceleration mechanism won't work ➔ look for alternative

- Laser-plasma based mechanism fits the bill well, of course, noting that we need both high energy as well as high luminosity