CMS and LHC run II

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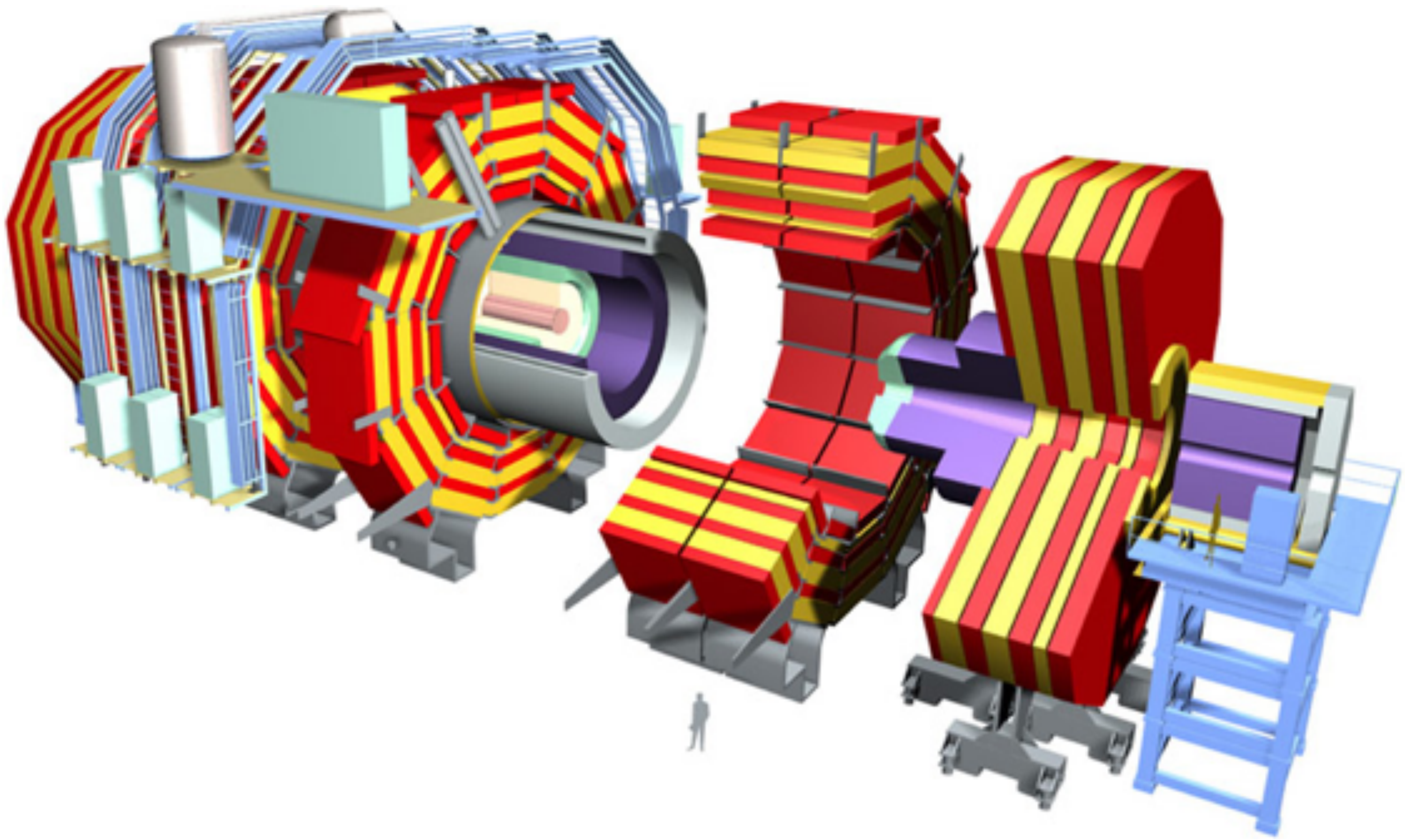
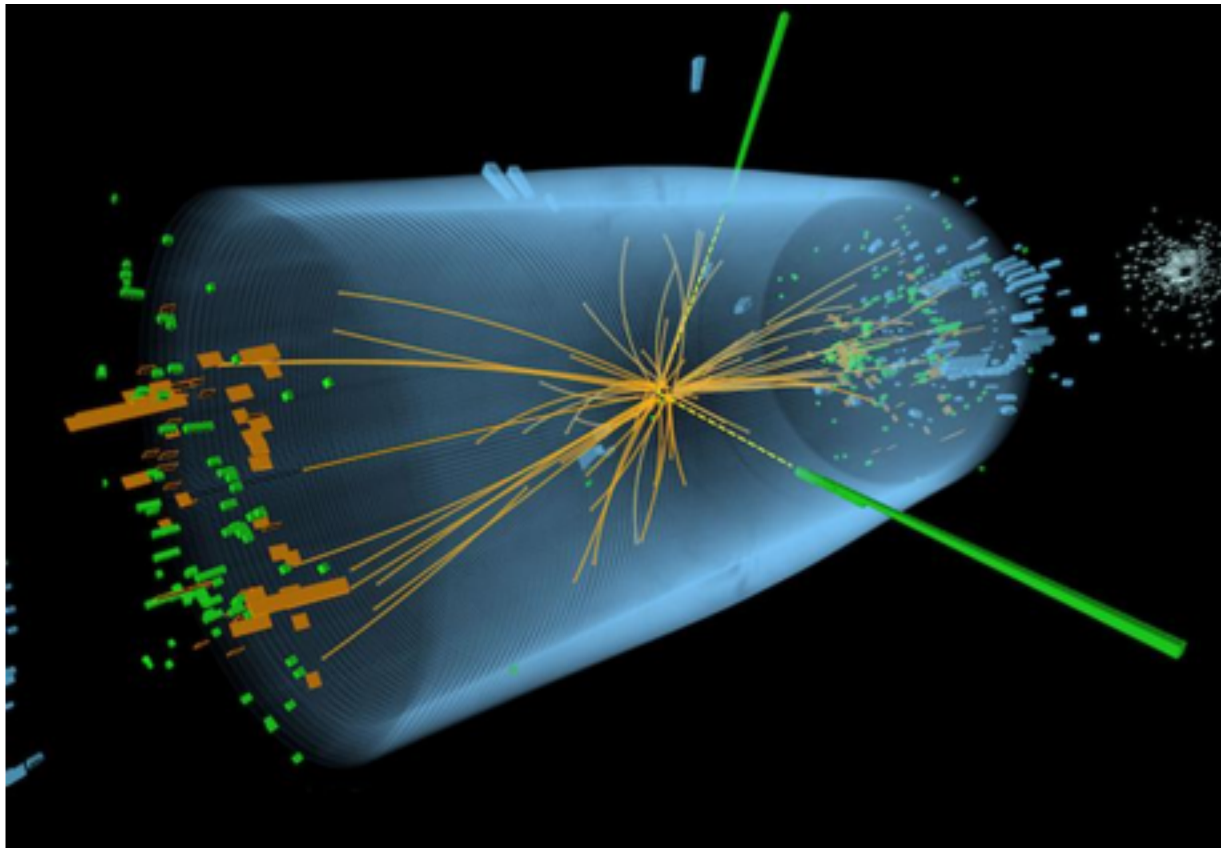
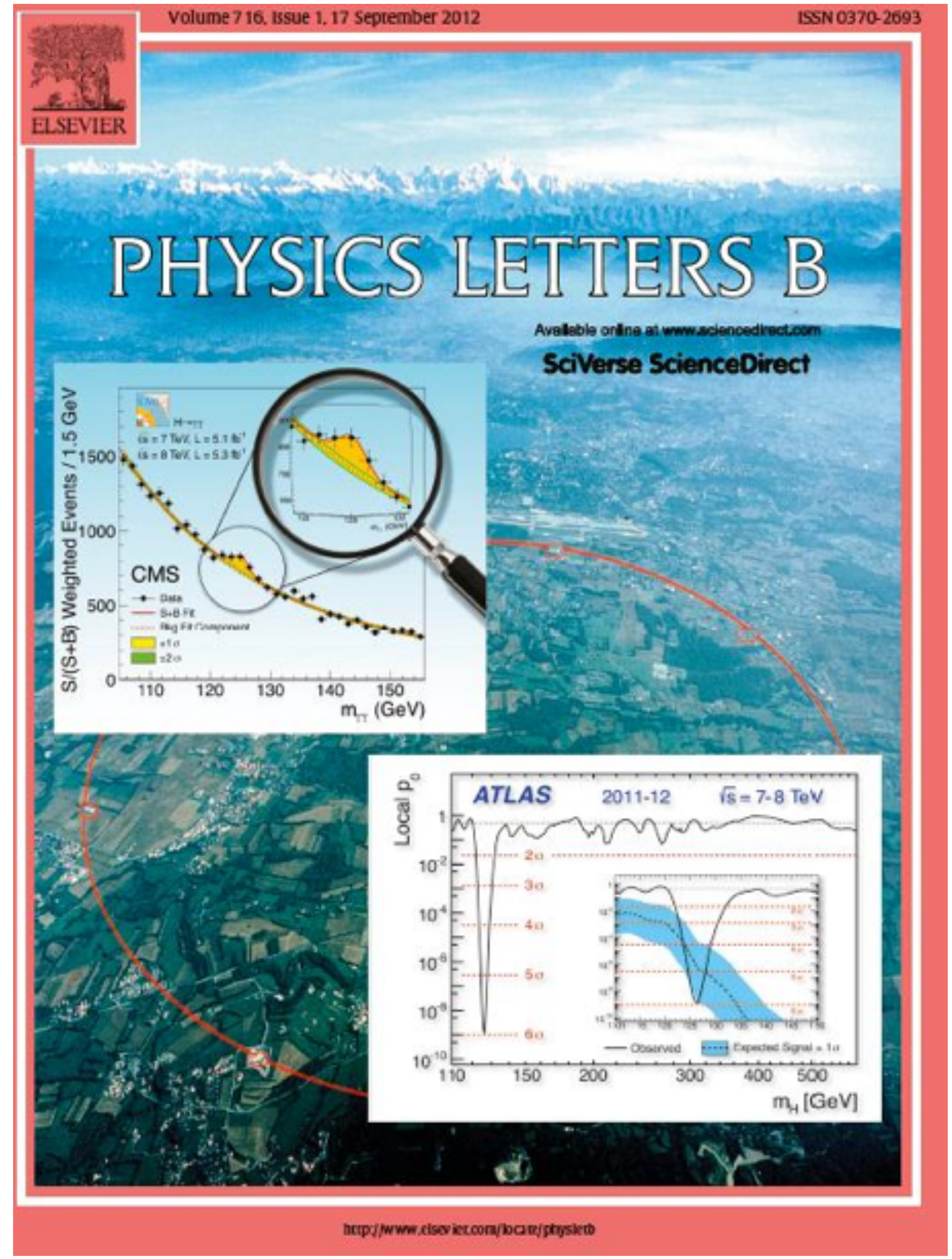
July 6, 2016

- What's left to do at the LHC after the Higgs?
- Focus on CMS and Run II.

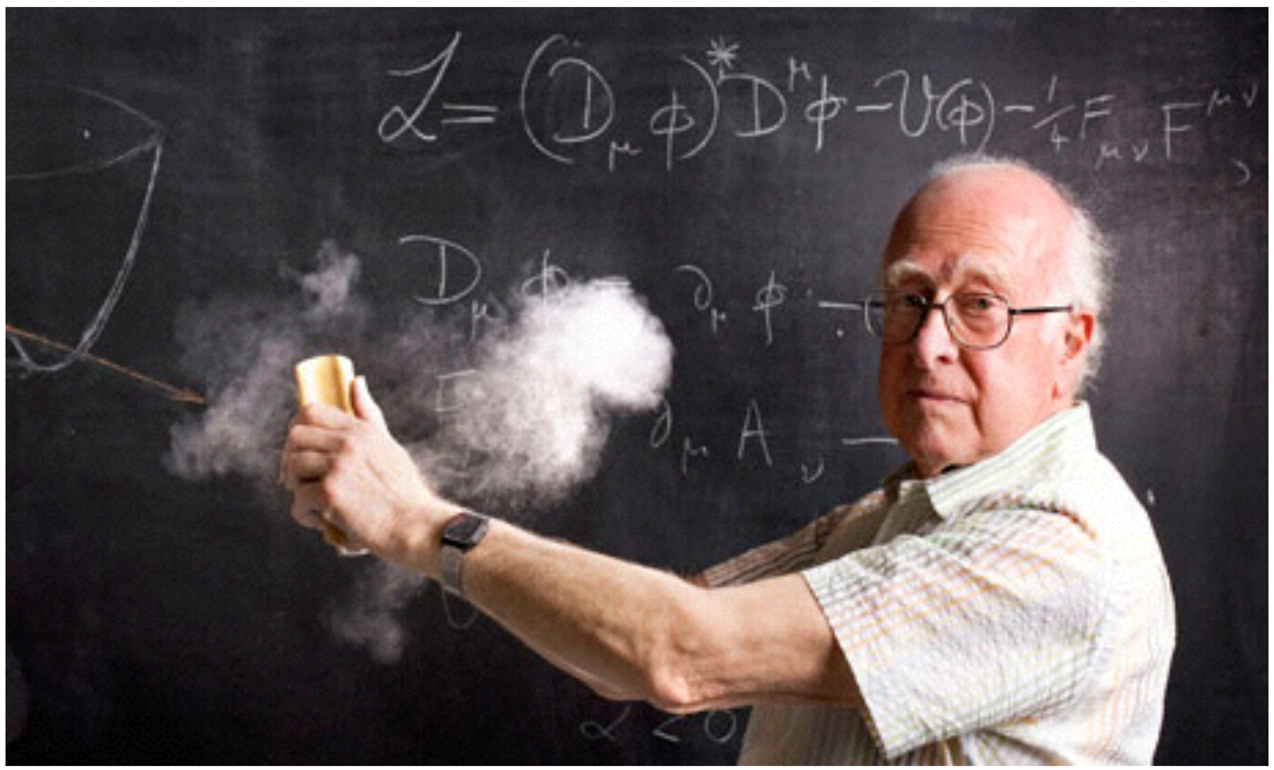


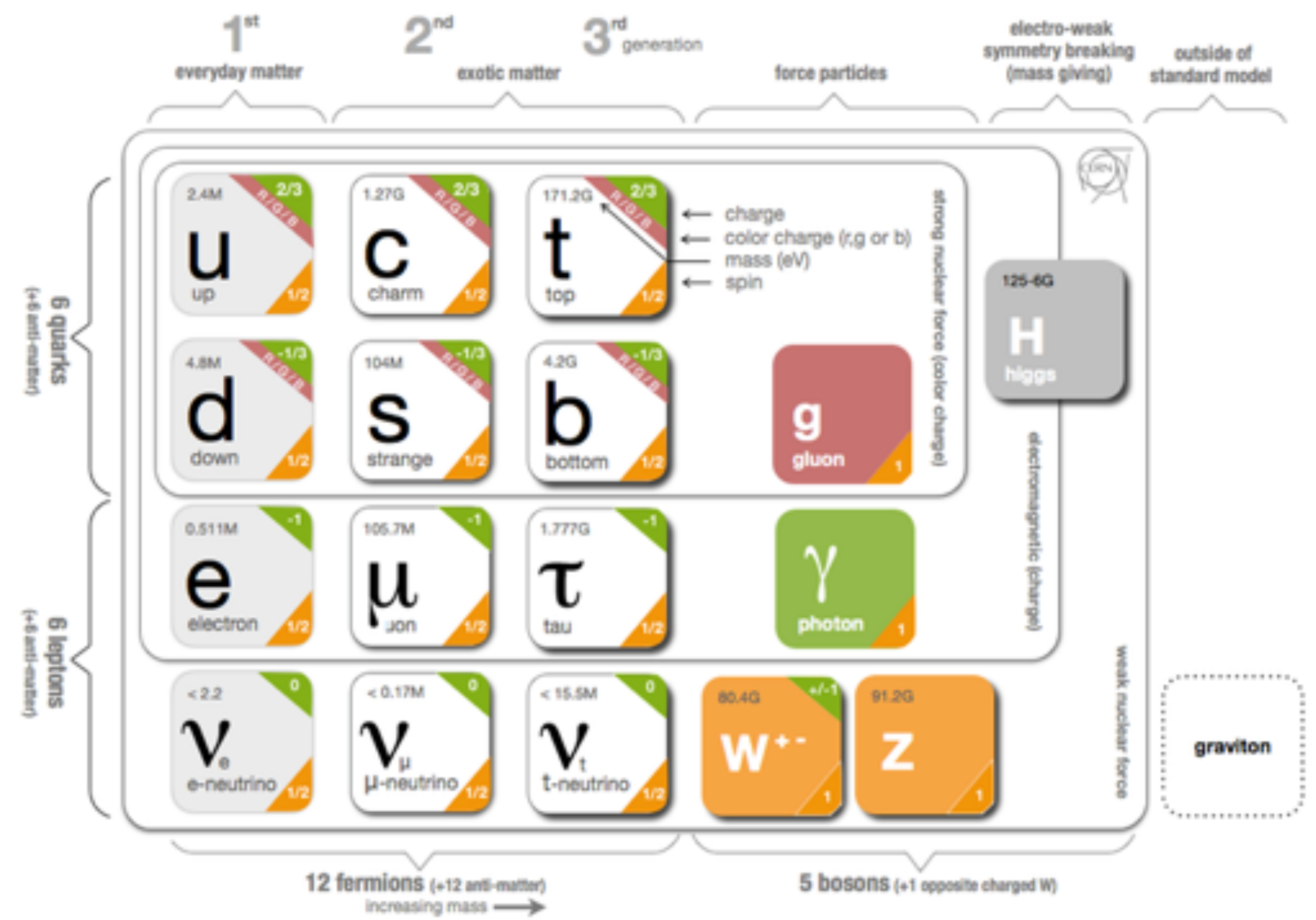


…way back in 2012



With the Higgs discovery in 2012, the Standard Model is complete, right?





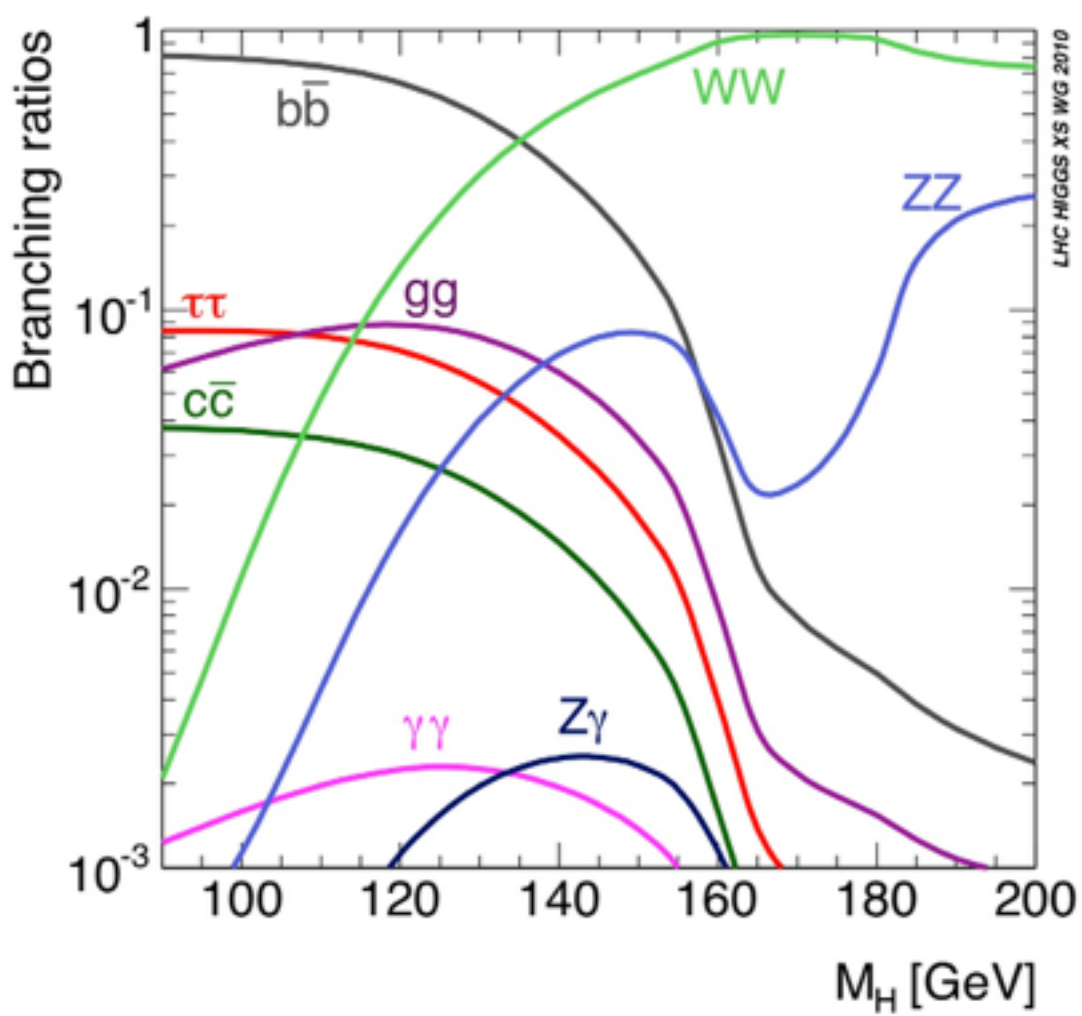
$$M_{\text{Higgs}} = 125.09 \pm 0.24 \text{ GeV} \quad [0.2\%]$$

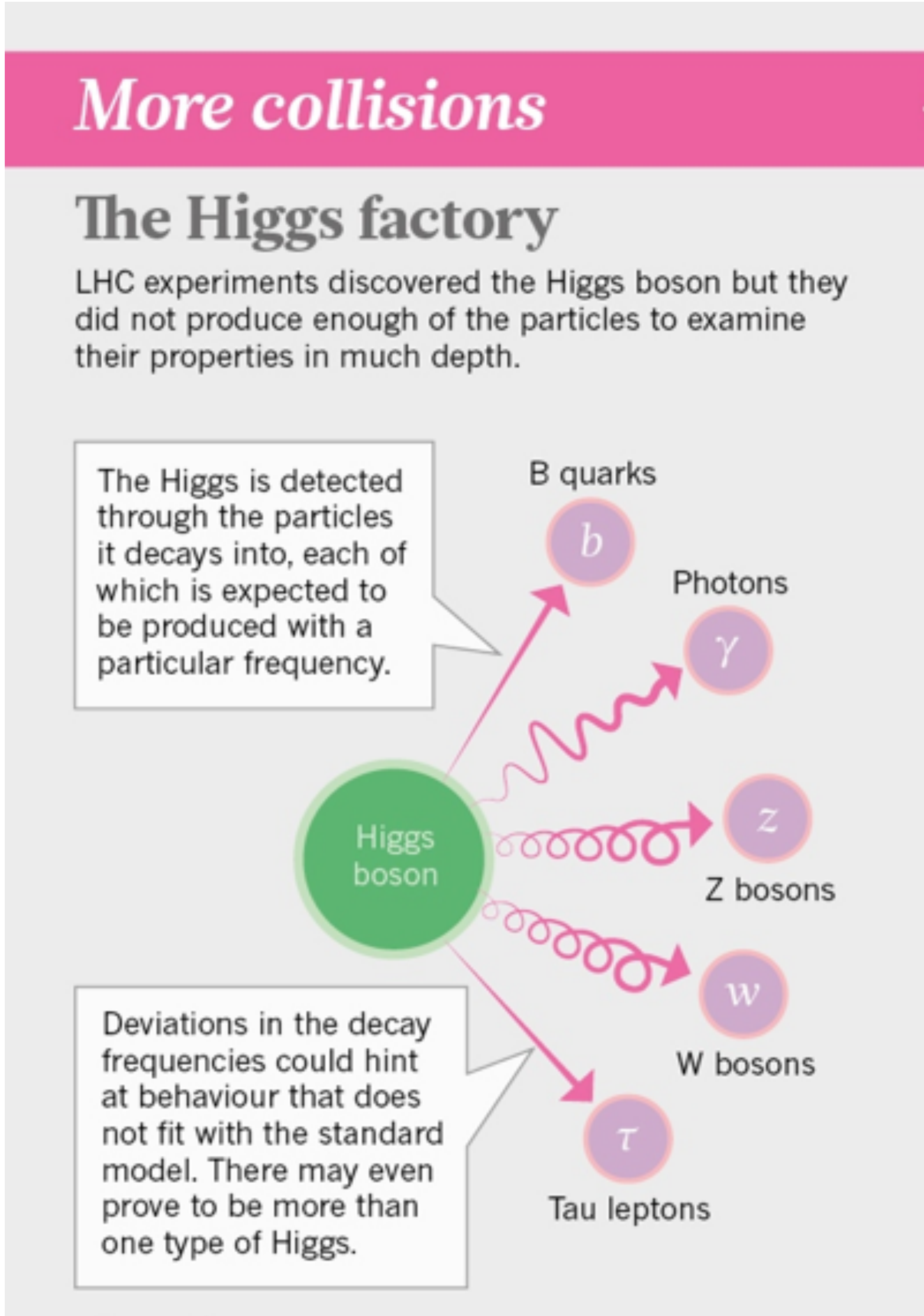
Recent Higgs Physics Preliminary Results

CMS-PAS-HIG-15-003	First results on Higgs to WW at $\sqrt{s} = 13$ TeV		June 2016
CMS-PAS-HIG-16-006	Search for a neutral MSSM Higgs boson decaying into $\tau\tau$ at 13 TeV		June 2016
CMS-PAS-HIG-16-003	Search for the standard model Higgs boson produced through vector boson fusion and decaying to $\mathrm{b\bar{b}}$ with proton-proton collisions at $\sqrt{s} = 13$ TeV		June 2016
CMS-PAS-HIG-16-005	Search for lepton flavour violating decays of the Higgs boson in the μ-τ final state at 13 TeV		June 2016
CMS-HIG-14-032	Search for Higgs boson off-shell production in proton-proton collisions at 7 and 8 TeV and derivation of constraints on its total decay width	Submitted to JHEP	8 May 2016
CMS-PAS-HIG-16-009	Search for invisible decays of a Higgs boson produced via vector boson fusion at $\sqrt{s} = 13$ TeV.		March 2016
CMS-PAS-HIG-16-007	Summary results of high mass BSM Higgs searches using CMS run-I data		March 2016
CMS-PAS-HIG-16-011	Search for resonant Higgs boson pair production in the $\mathrm{b\bar{b}}\ell\nu\ell\nu$ final state at $\sqrt{s} = 13$ TeV		March 2016
CMS-PAS-HIG-15-008	Search for $\mathrm{t\bar{t}H}$ production in multilepton final states at $\sqrt{s} = 13$ TeV		March 2016
CMS-PAS-HIG-16-002	Search for resonant pair production of Higgs bosons decaying to two bottom quark-antiquark pairs in proton-proton collisions at 13 TeV		March 2016
CMS-PAS-HIG-15-005	First results on Higgs to $\gamma\gamma$ at 13 TeV		March 2016
CMS-PAS-HIG-16-010	Search for H to Z(ll)+A(bb) with 2015 data		March 2016
CMS-PAS-HIG-16-014	Search for scalar resonances in the 200-1200 GeV mass range decaying into a Z and a photon in pp collisions at $\sqrt{s} = 8$ TeV		March 2016
CMS-PAS-HIG-16-001	Search for a heavy scalar boson decaying into a pair of Z bosons in the $2\ell 2\nu$ final state		March 2016
CMS-PAS-HIG-15-004	Studies of Higgs boson production in the four-lepton final state at $\sqrt{s} = 13$ TeV		March 2016
CMS-PAS-HIG-16-004	Search for $\mathrm{t\bar{t}H}$ production in the $\mathrm{H} \to \mathrm{b\bar{b}}$ decay channel with $\sqrt{s} = 13$ TeV pp collisions at the CMS experiment		March 2016
CMS-PAS-HIG-15-013	Model independent search for Higgs boson pair production in the $\mathrm{b\bar{b}}\tau^+\tau^-$ final state		March 2016
CMS-PAS-HIG-16-012	Search for non-resonant Higgs boson pair production in the $\mathrm{b\bar{b}}\tau^+\tau^-$ final state		March 2016
CMS-PAS-HIG-16-013	Search for resonant Higgs boson pair production in the $\mathrm{b\bar{b}}\tau^+\tau^-$ final state		March 2016

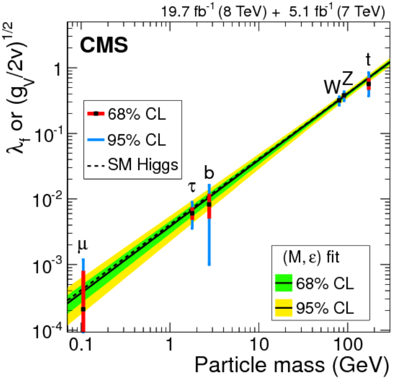
What's left to do?

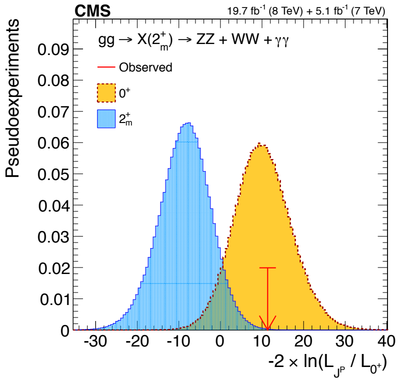
- Is the "Higgs" really the Standard Model "Higgs"?
- This means probing the property of the Higgs to ensure it has:
  - Zero spin
  - Decay channels are as predicted
  - Couples to mass
  - Consistency with higher-energy running.





Higgs properties

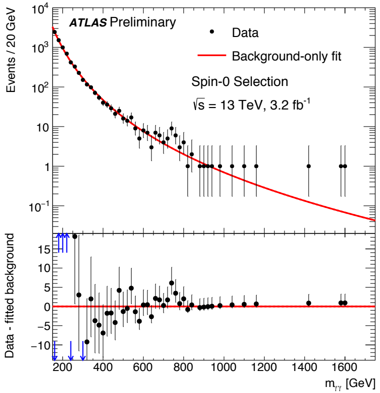




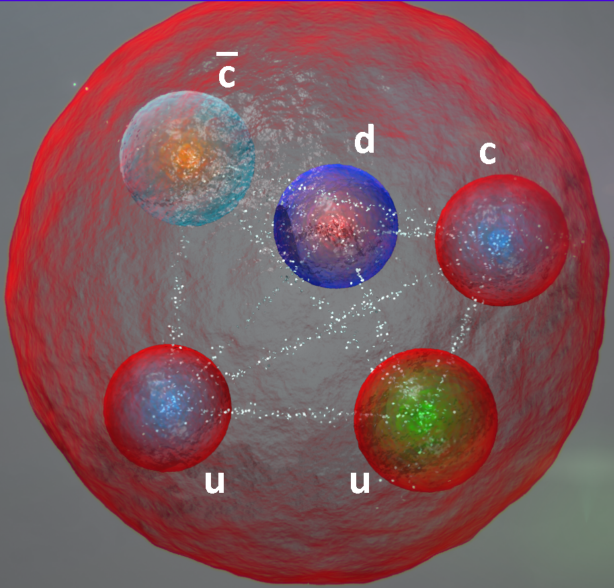
What's left to do?

Search for new physics!

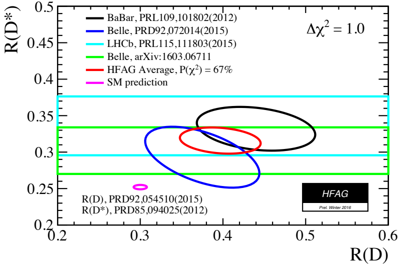
New particle?

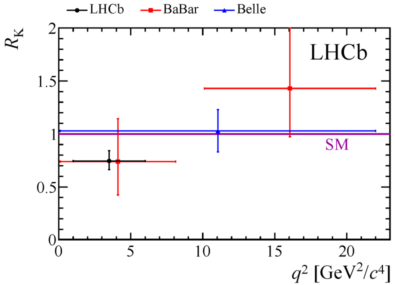


Definitely new particle



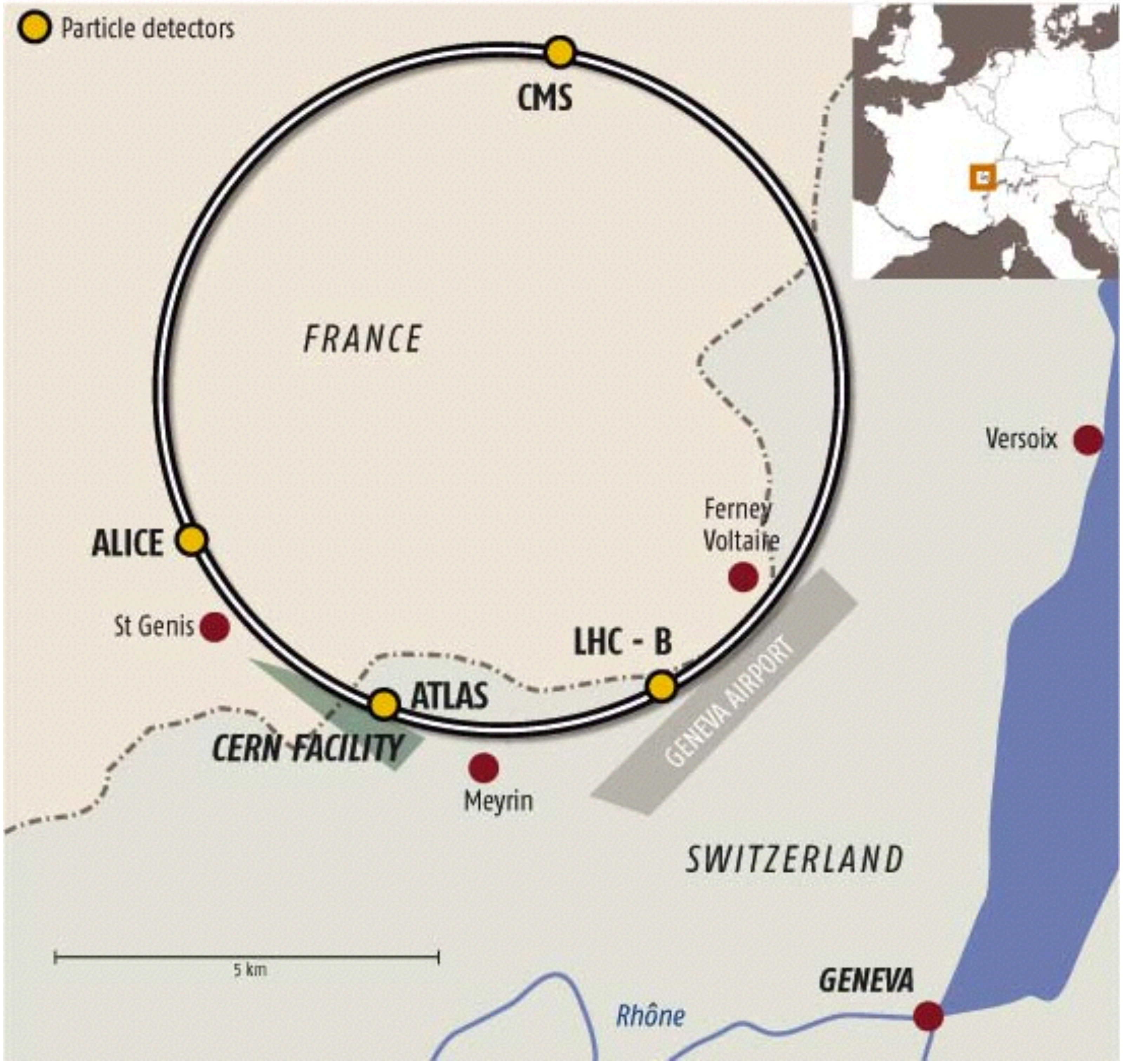
Look at particle decays



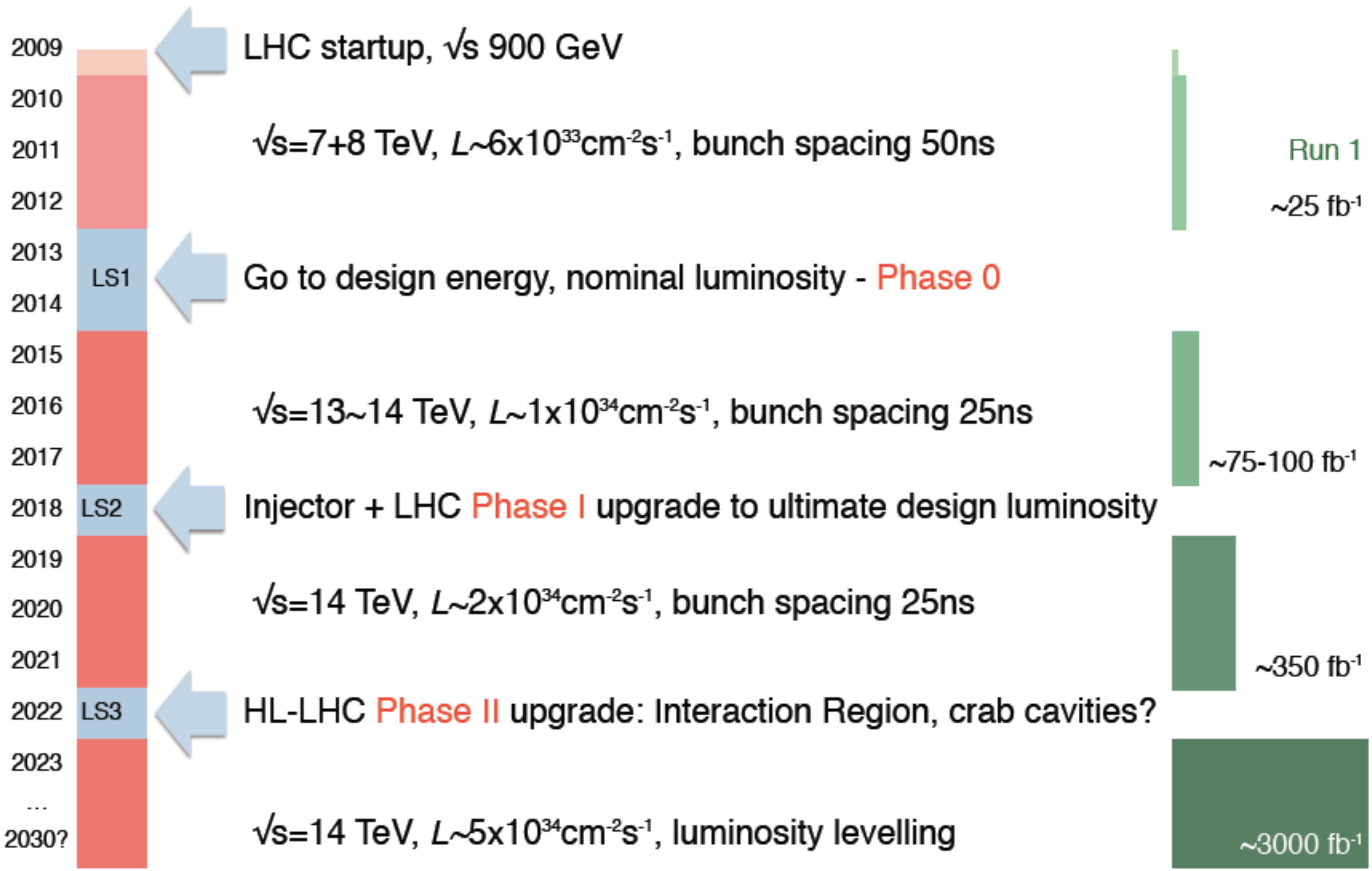


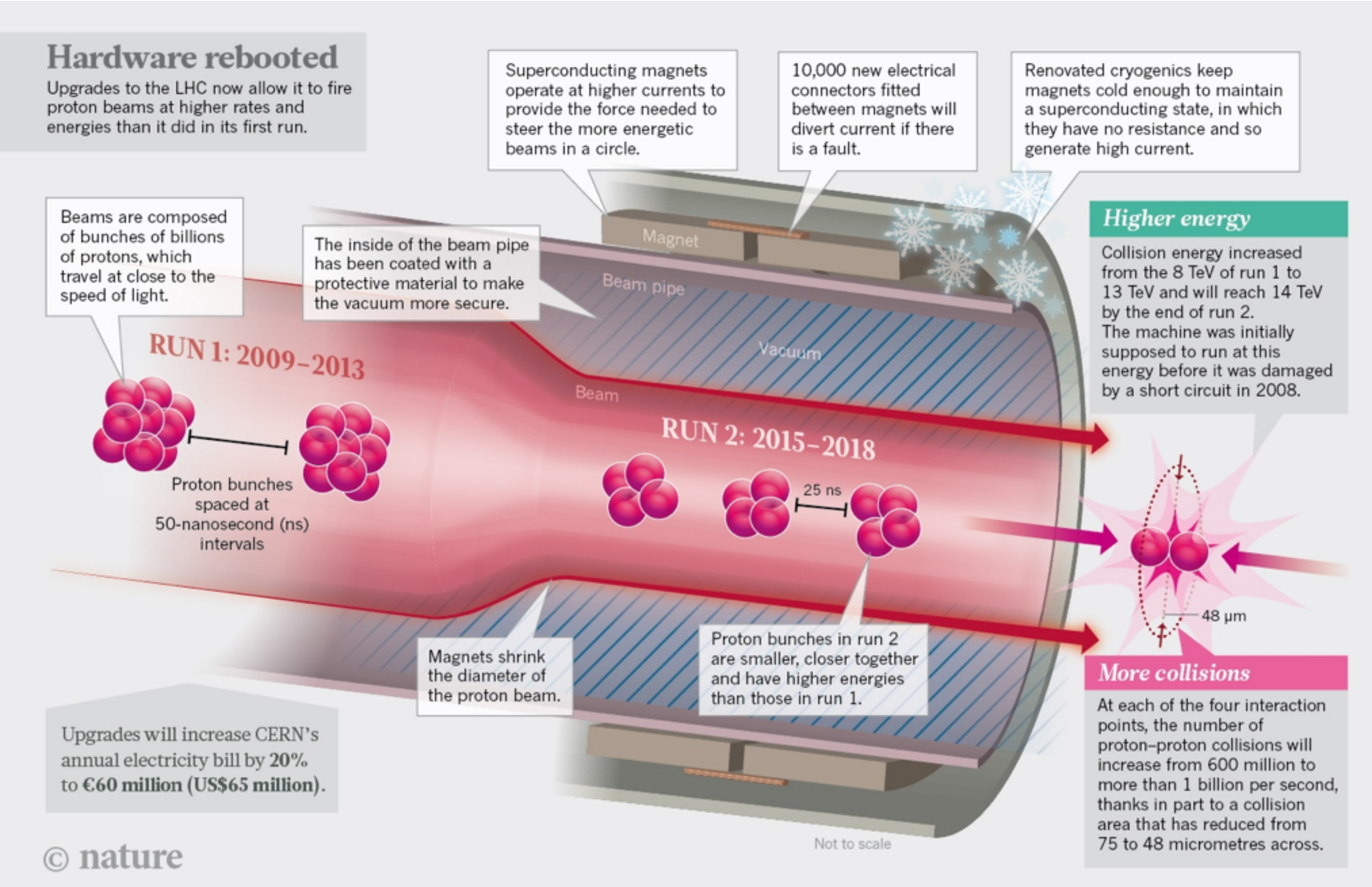
Are there new differences between leptons?

Reminder of LHC setup

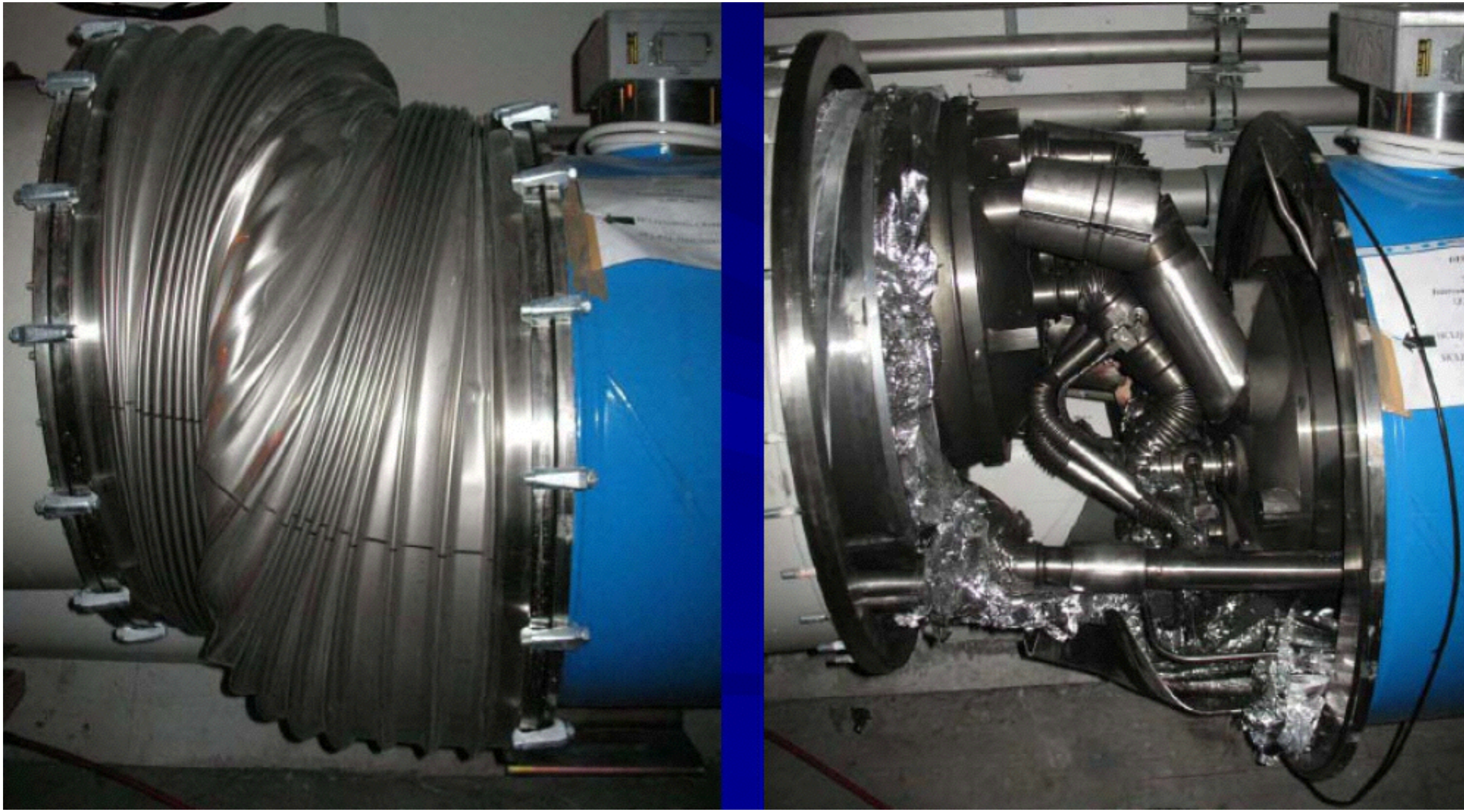


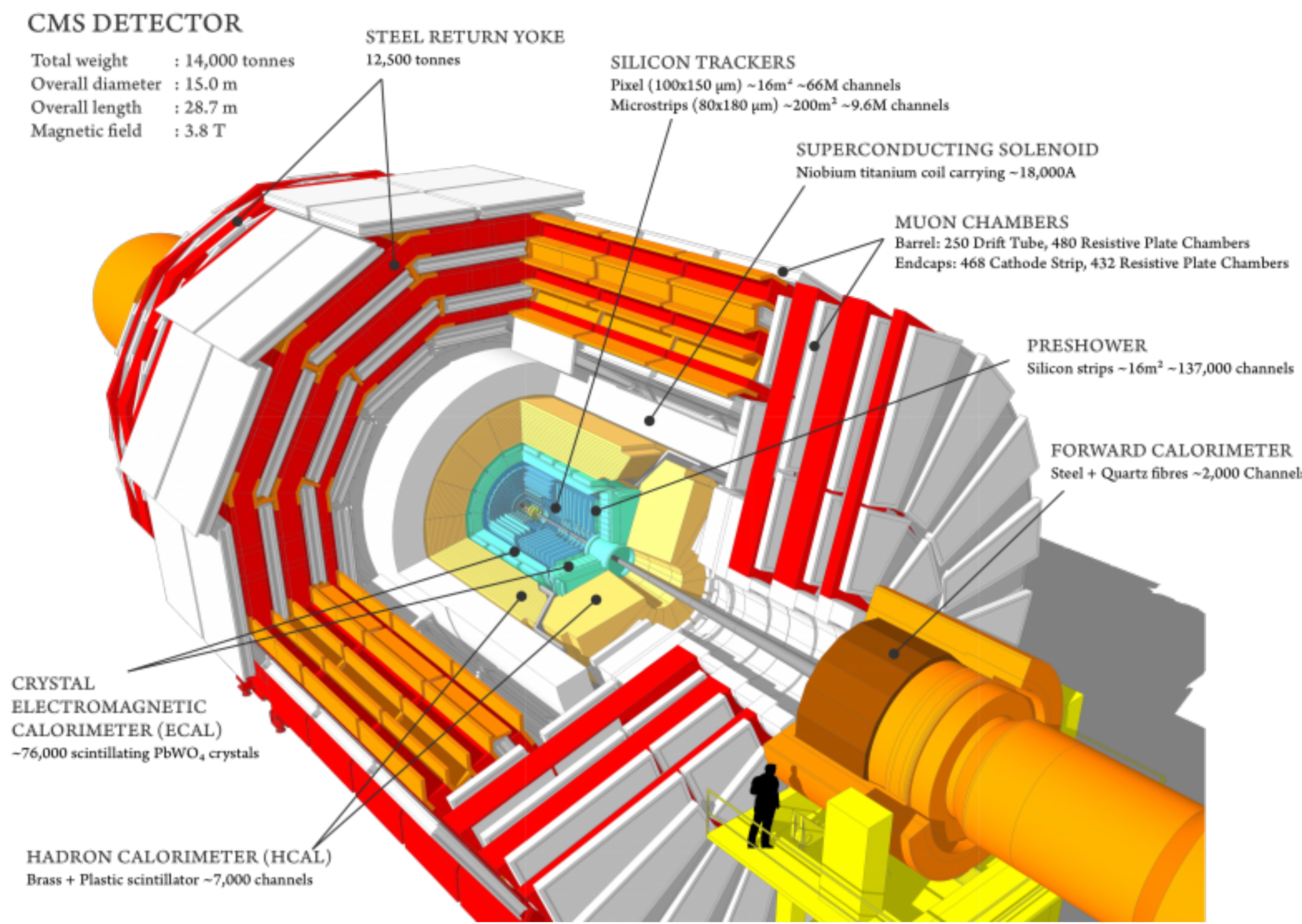
Timeline of LHC running



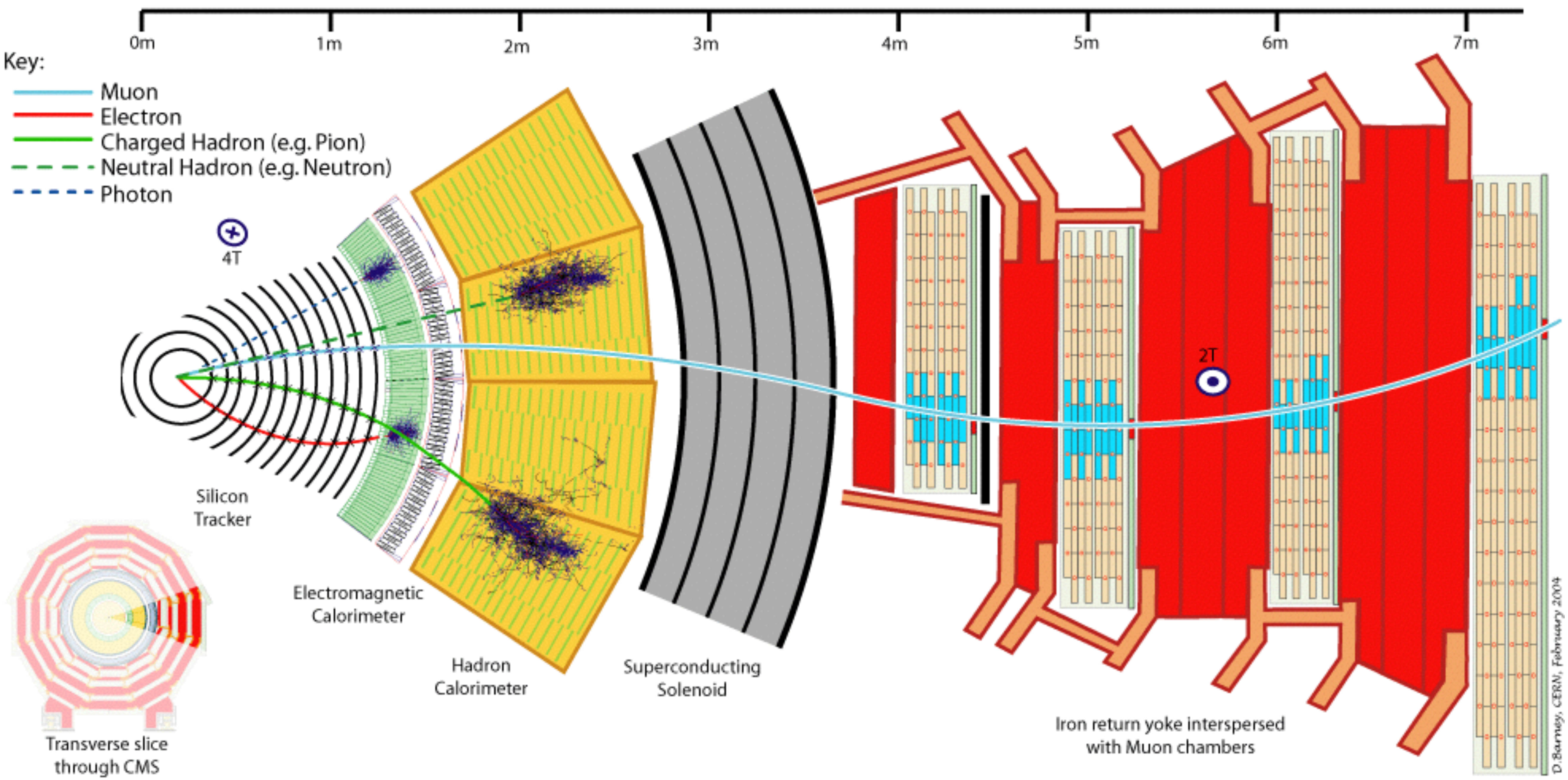

Hardware rebooted
Upgrades to the LHC now allow it to fire proton beams at higher rates and energies than it did in its first run.
Superconducting magnets operate at higher currents to provide the force needed to steer the more energetic beams in a circle.
10,000 new electrical connectors fitted between magnets will divert current if there is a fault.
Renovated cryogenics keep magnets cold enough to maintain a superconducting state, in which they have no resistance and so generate high current.
Beams are composed of bunches of billions of protons, which travel at close to the speed of light.
The inside of the beam pipe has been coated with a protective material to make the vacuum more secure.
Magnet
Beam pipe
Vacuum
Beam
RUN 1: 2009–2013
Proton bunches spaced at 50-nanosecond (ns) intervals
RUN 2: 2015–2018
25 ns
Higher energy
Collision energy increased from the 8 TeV of run 1 to 13 TeV and will reach 14 TeV by the end of run 2.
The machine was initially supposed to run at this energy before it was damaged by a short circuit in 2008.
48 μm
Magnets shrink the diameter of the proton beam.
Proton bunches in run 2 are smaller, closer together and have higher energies than those in run 1.
More collisions
At each of the four interaction points, the number of proton–proton collisions will increase from 600 million to more than 1 billion per second, thanks in part to a collision area that has reduced from 75 to 48 micrometres across.
Upgrades will increase CERN's annual electricity bill by 20% to €60 million (US$65 million).
Not to scale
© nature

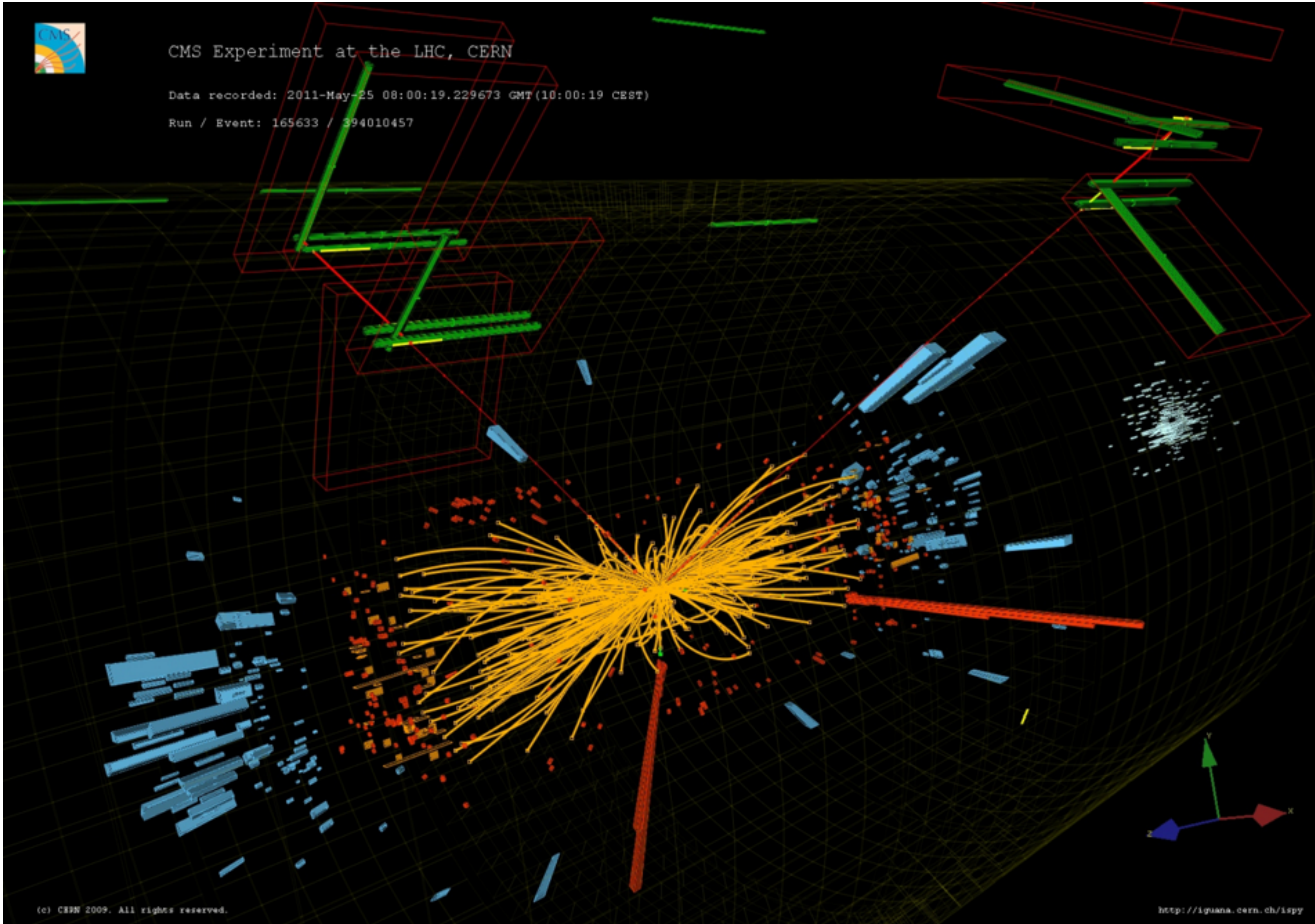
What's so hard about increasing the energy?




CMS DETECTOR
Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T
STEEL RETURN YOKE
12,500 tonnes
SILICON TRACKERS
Pixel (100x150 μm) ~16m² ~66M channels
Microstrips (80x180 μm) ~200m² ~9.6M channels
SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000A
MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers
PRESHOWER
Silicon strips ~16m² ~137,000 channels
FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels
CRYSTAL
ELECTROMAGNETIC
CALORIMETER (ECAL)
~76,000 scintillating $PbWO_4$ crystals
HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels

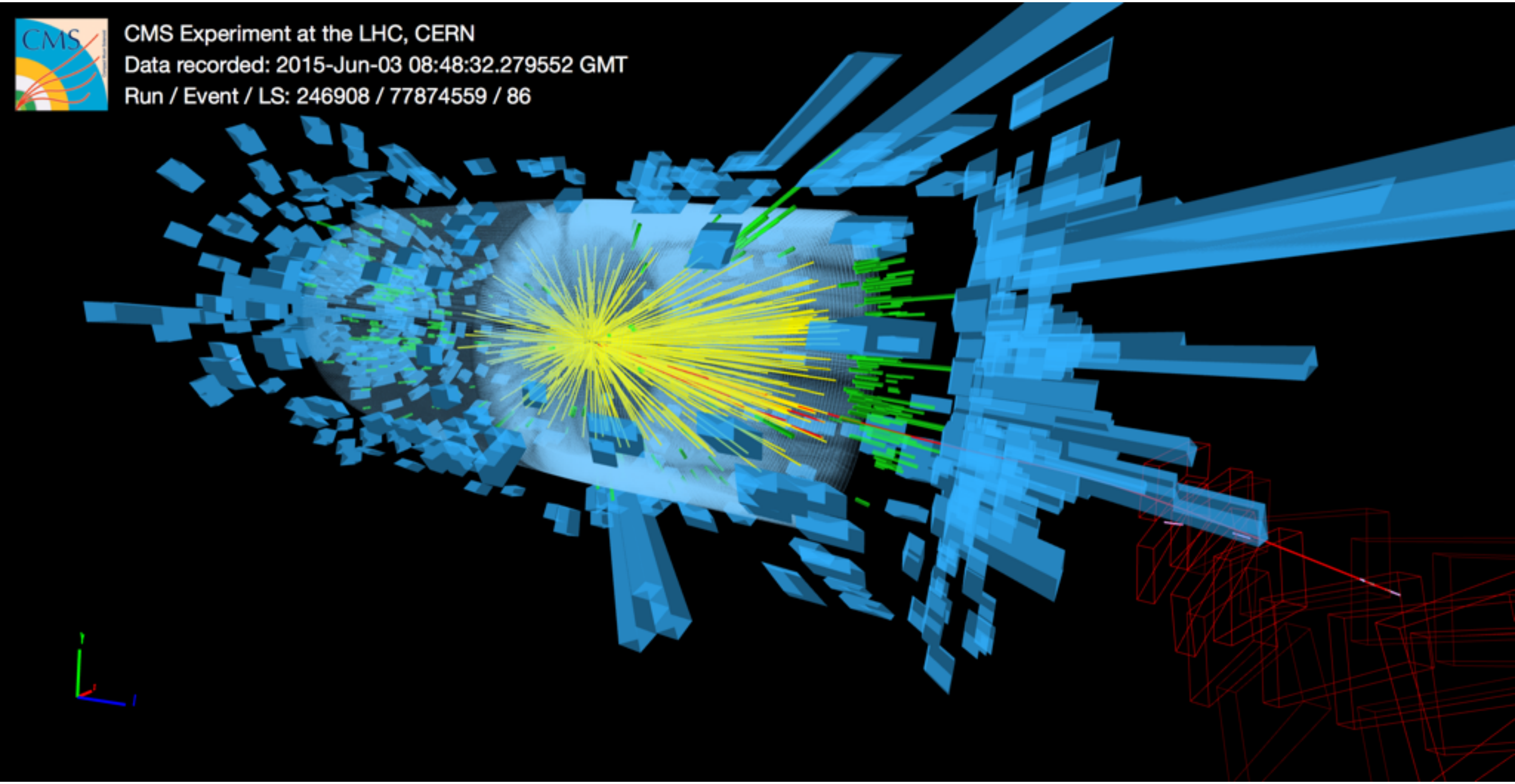
The subsystems of LHC enable Particle Identification



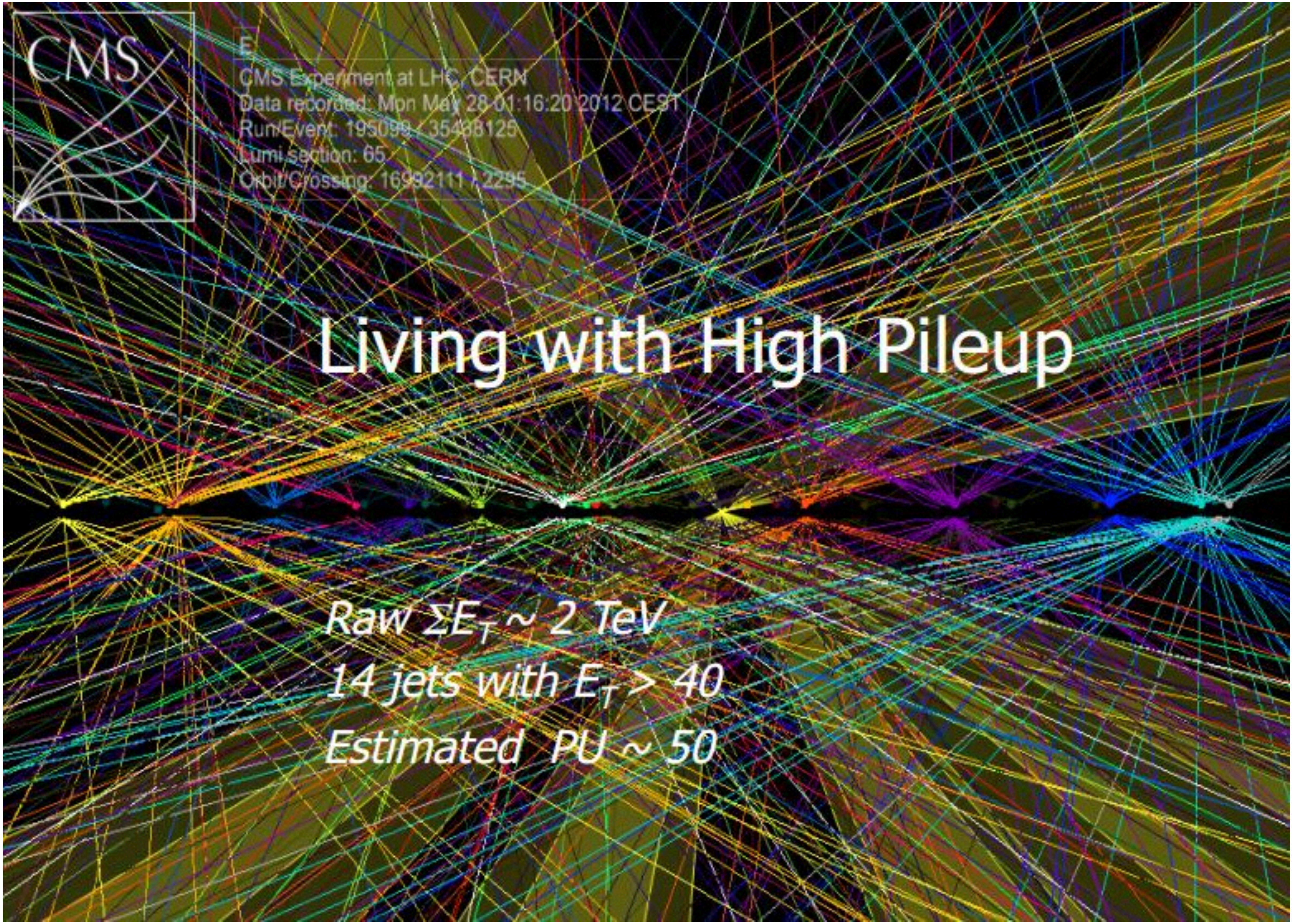


"ZZ" event where one Z decays to 2 electrons (red towers) and one decays to 2 muons (red lines)

CMS collision at 13 TeV

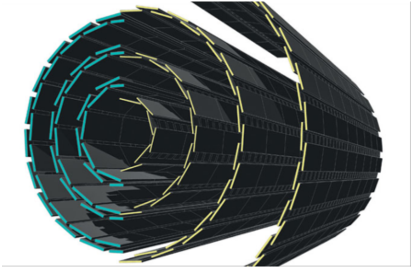


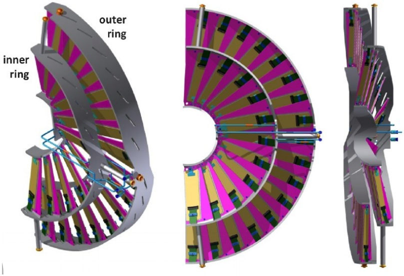
Downsides to more luminosity?



Upgrades

CMS pixels – winter 2016-17



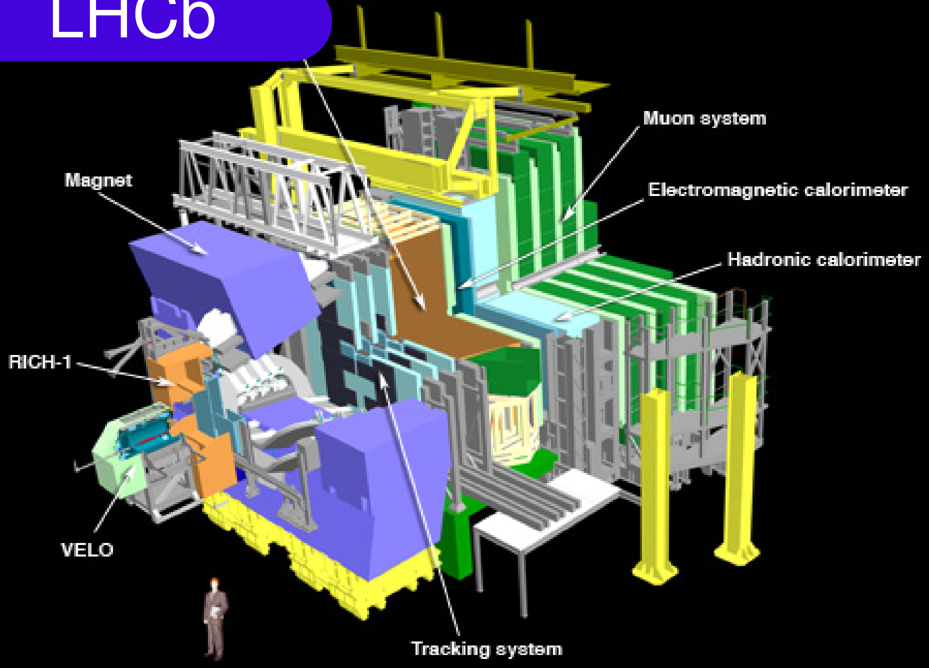


Even bigger upgrades in the future to keep up with HL-LHC

What are we doing at Syracuse?

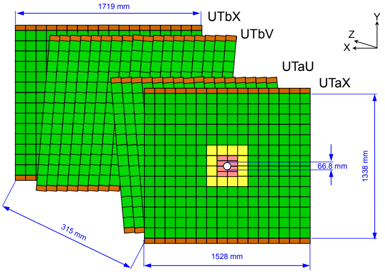
(Besides hopefully discovering new physics on LHCb)

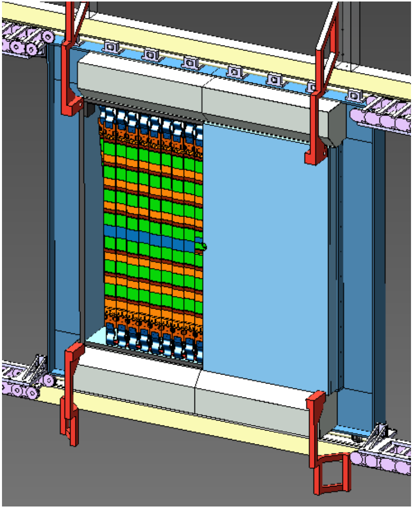
LHCb


Muon system
Electromagnetic calorimeter
Hadronic calorimeter
Magnet
RICH-1
VELO
Tracking system

LHCb UT upgrade

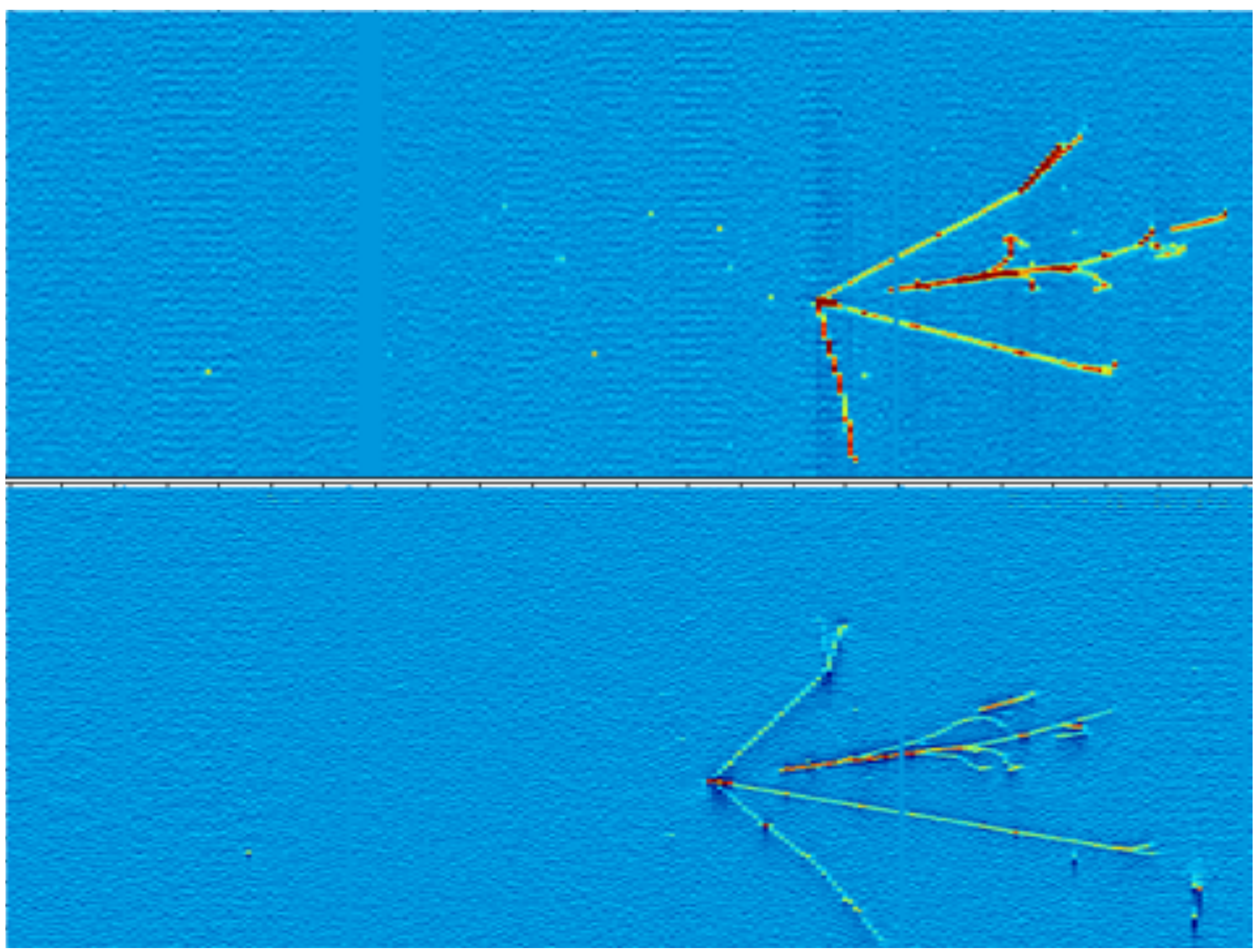
New upstream tracker for 2019

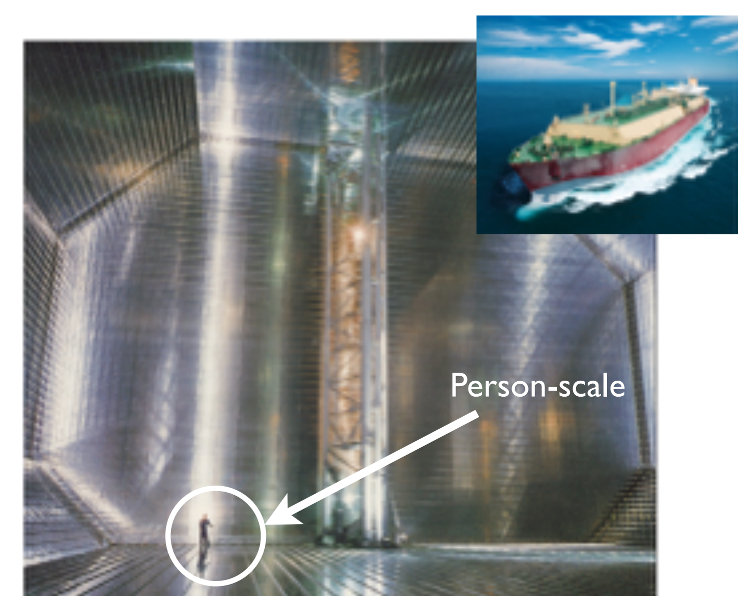




NEUTRINOS

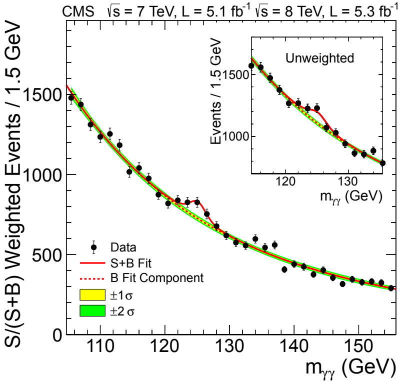
- Neutrinos can oscillate flavors (e.g. muon neutrino can become electron neutrino), and we want to understand all the implications this has for the universe.
- Charge-Parity (CP) symmetry violation in neutrino interactions could explain some of the matter-antimatter asymmetry of the universe.
- To address these questions about neutrinos, very large detectors are being planned for construction deep (~1 mile) underground in a gold mine in South Dakota, receiving a neutrino beam from Fermilab in Chicago.

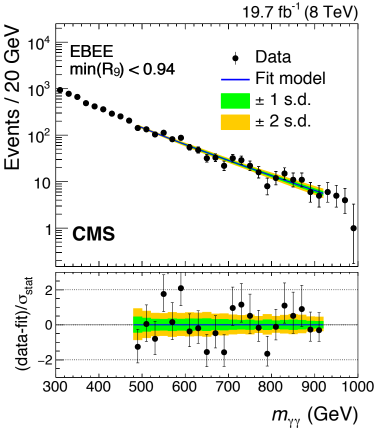


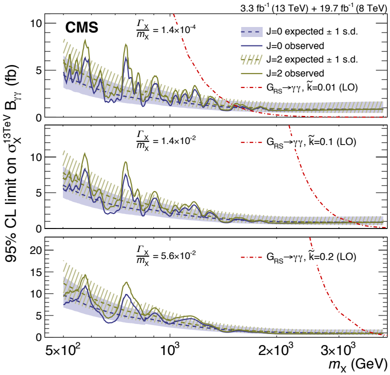


Thank you!
Questions?

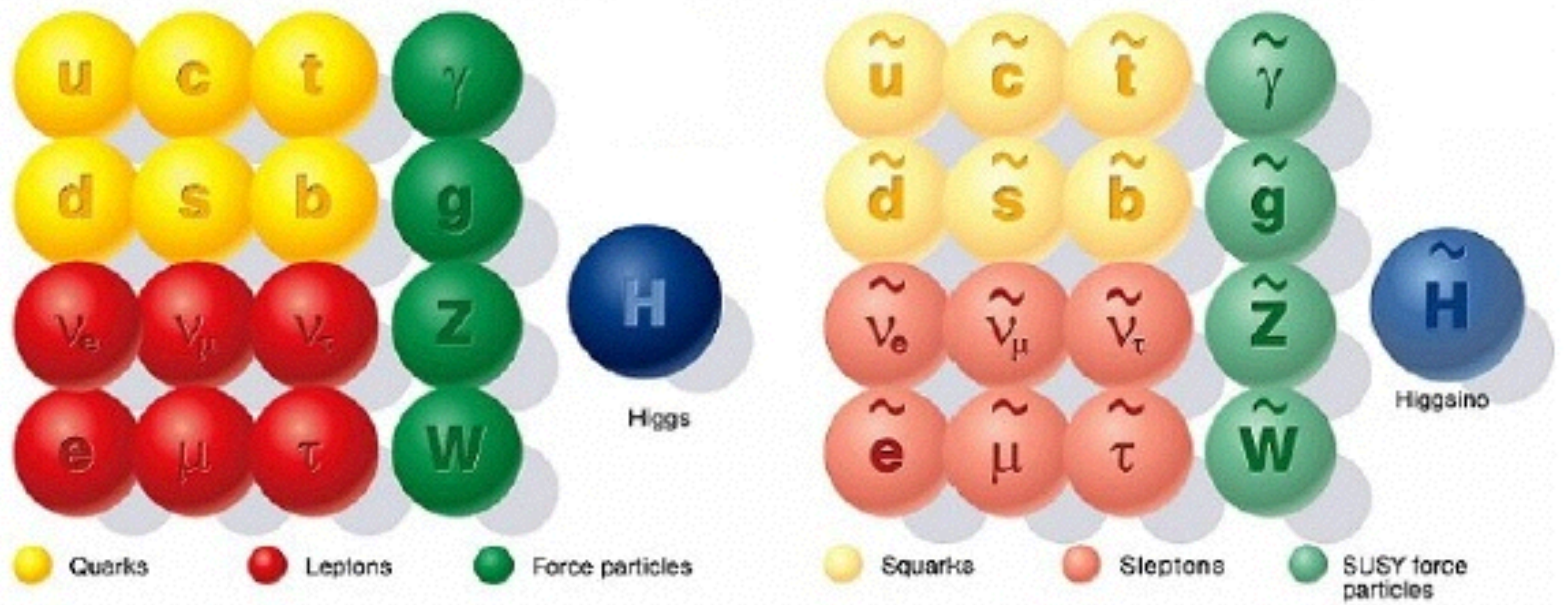
Higgs discovery




19.7 fb-1 (8 TeV)
EBEE
min(R9) < 0.94
Data
Fit model
± 1 s.d.
± 2 s.d.
CMS
Events / 20 GeV
(data-fit)/σstat
mγγ (GeV)


3.3 fb-1 (13 TeV) + 19.7 fb-1 (8 TeV)
CMS
ΓX/mX = 1.4×10-4
J=0 expected ± 1 s.d.
J=0 observed
J=2 expected ± 1 s.d.
J=2 observed
GRS→γγ, k̃=0.01 (LO)
ΓX/mX = 1.4×10-2
GRS→γγ, k̃=0.1 (LO)
ΓX/mX = 5.6×10-2
GRS→γγ, k̃=0.2 (LO)
95% CL limit on σX13TeV Bγγ (fb)
mX (GeV)

SUPERSYMMETRY

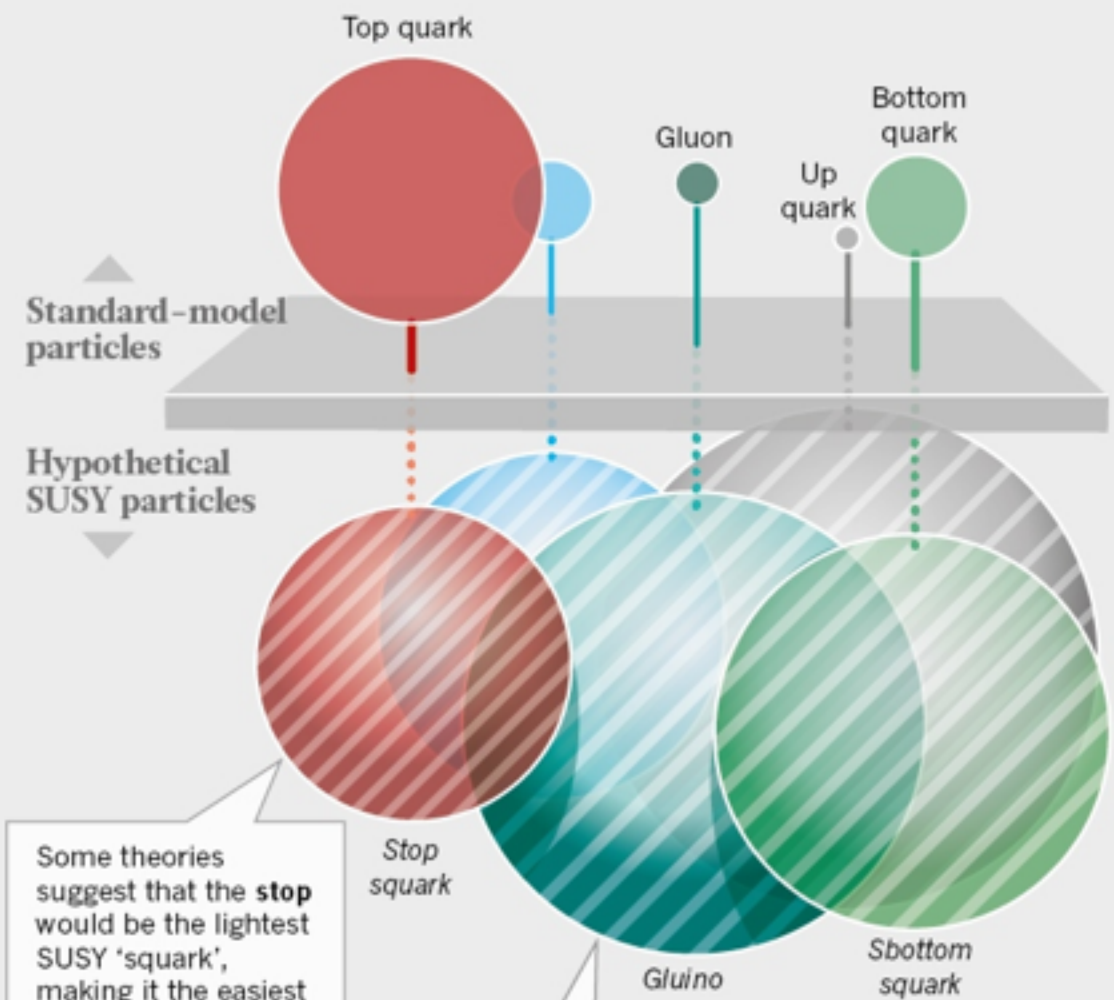


Standard particles **SUSY particles**

Higher energy

Desperately seeking SUSY

Higher energies mean that the LHC can produce heavier particles (because of $E = mc^2$) — and perhaps some of those predicted by the theory of supersymmetry, or SUSY. An extension to the standard model of particle physics, SUSY postulates a giant 'superpartner' for each known particle, and would offer explanations for mysteries such as the nature of dark matter.

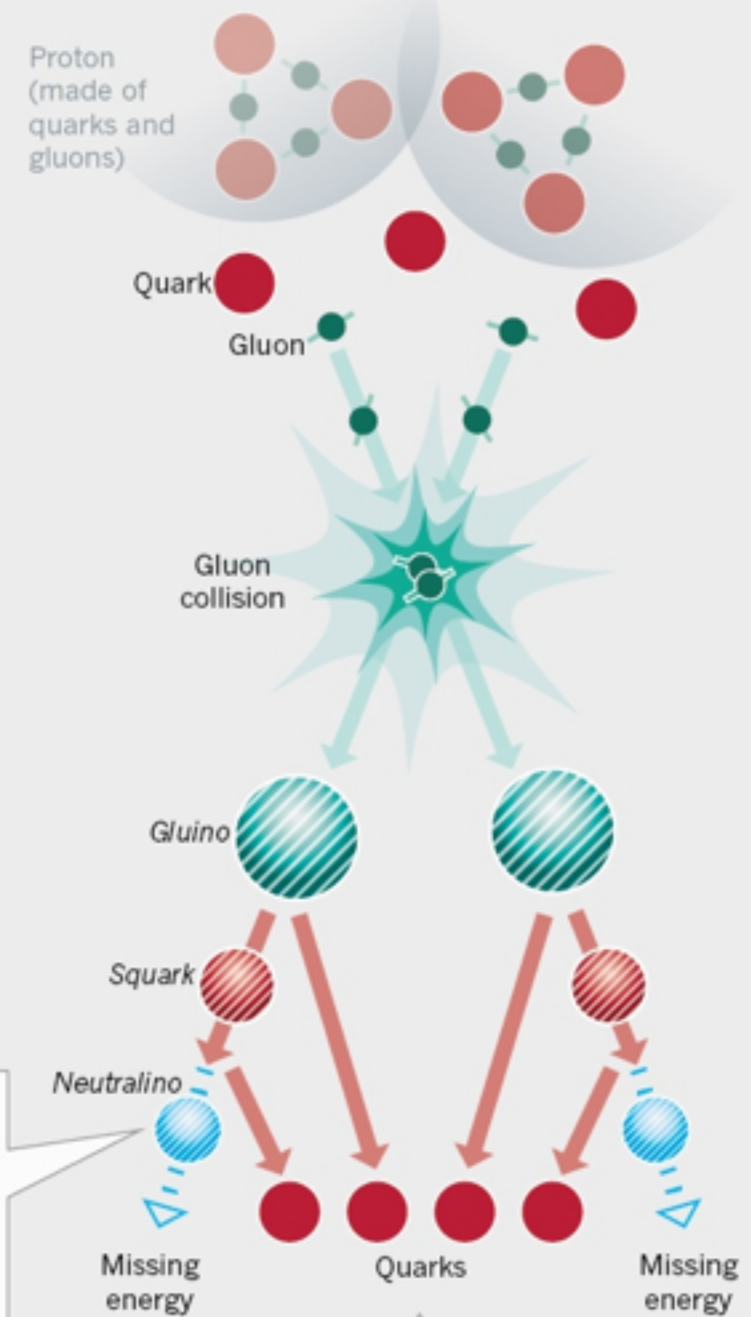


Some theories suggest that the **stop** would be the lightest SUSY 'squark', making it the easiest to detect because it would show up in lower-energy collisions than the others.

The **gluino** is superpartner of the gluon, which carries the strong force that binds the quarks in protons. So both squarks and gluinos should show up more often in proton–proton collisions than should other supersymmetric particles.

Decays decoded

If the LHC makes supersymmetric particles, their lifetimes will be fleeting. But physicists can deduce their presence from the more-stable decay products. In at least one case, such SUSY clues could also be evidence for dark matter.



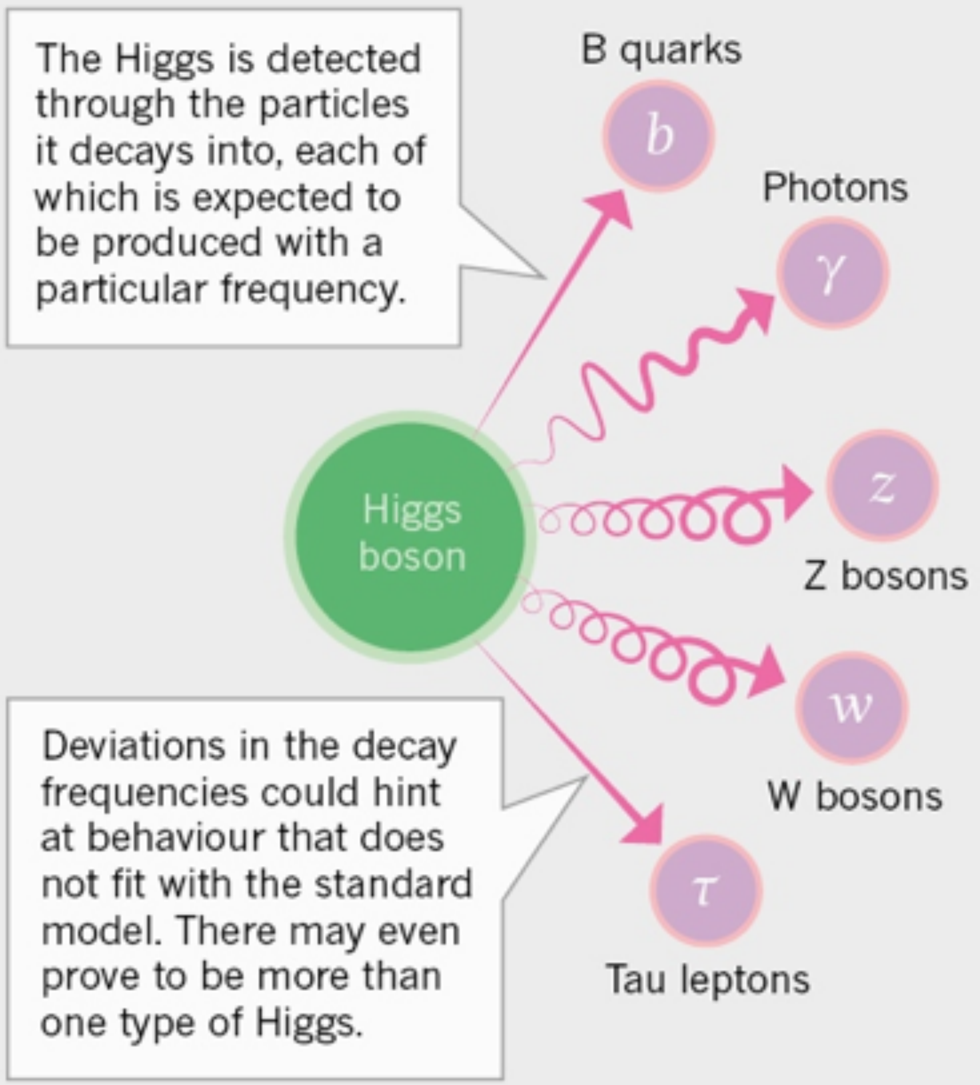
The **neutralino** would have almost no interaction with normal matter — meaning that it would slip through the LHC's detectors — making it a candidate constituent of dark matter.

Physicists will look for these quarks, and see whether their total energy and momentum adds up to that of the two gluons that sparked the collision. Just the right amount of 'missing energy' would suggest the presence of neutralinos — and, by a process of deduction, the other supersymmetric particles in the decay chain.

More collisions

The Higgs factory

LHC experiments discovered the Higgs boson but they did not produce enough of the particles to examine their properties in much depth.



Known unknowns

More collisions will help to resolve some ongoing mysteries. One of these concerns an anomaly in the way a transient particle called a B^+ meson decays.