Searching for new physics @ Large Hadron Collider: with precision & innovation

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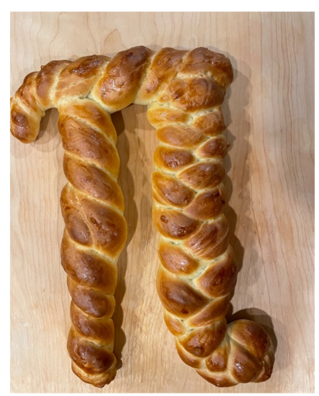
My research:
Standard Model measurements, searches for Beyond the Standard Model particles at the CMS Experiment
Trigger and data-acquisition, Software & Computing

I enjoy:
Working on challenging tasks in a collaborative setting

Beyond research, I am particularly interested in:
Outreach, science communication and improving diversity and inclusion

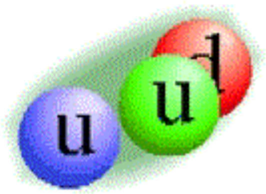
I've got my eyes on:
Learning to cook gourmet meals, playing the piano, spending more time with my family!



The smallest pieces of matter…

- Particle physics is the study of smallest known building blocks of the physical universe -- and the interactions between them.

- The focus is on single particles or small groups of particles, not the billions of atoms or molecules making up an entire planet or star.



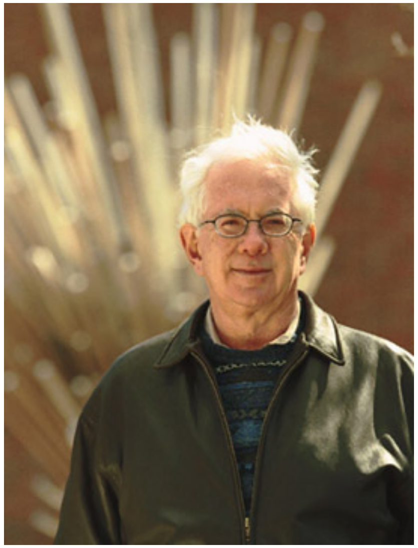
Relativistic Collisions

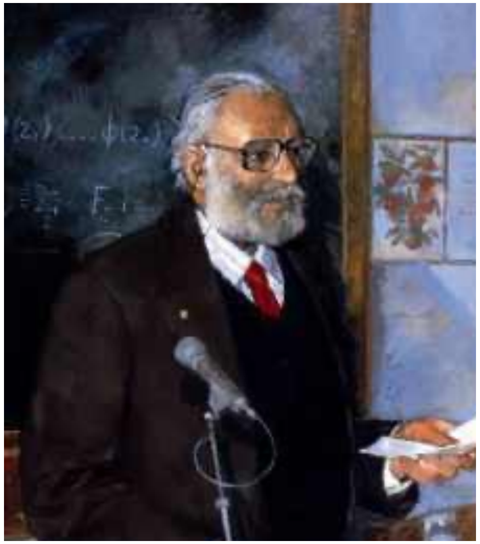
Particle collisions at very high energies produce many particles, some much more massive than initial particles
(unlike in this cartoon, collisions obey specific quantum rules)

Elementary and composite particles studied in great detail over the past 50 years

“Standard Model” of Particles and Forces

- Incorporates:
  - Electroweak theory by Glashow, Weinberg and Salam
  - Quantum Chromo Dynamics – theory of strong interactions





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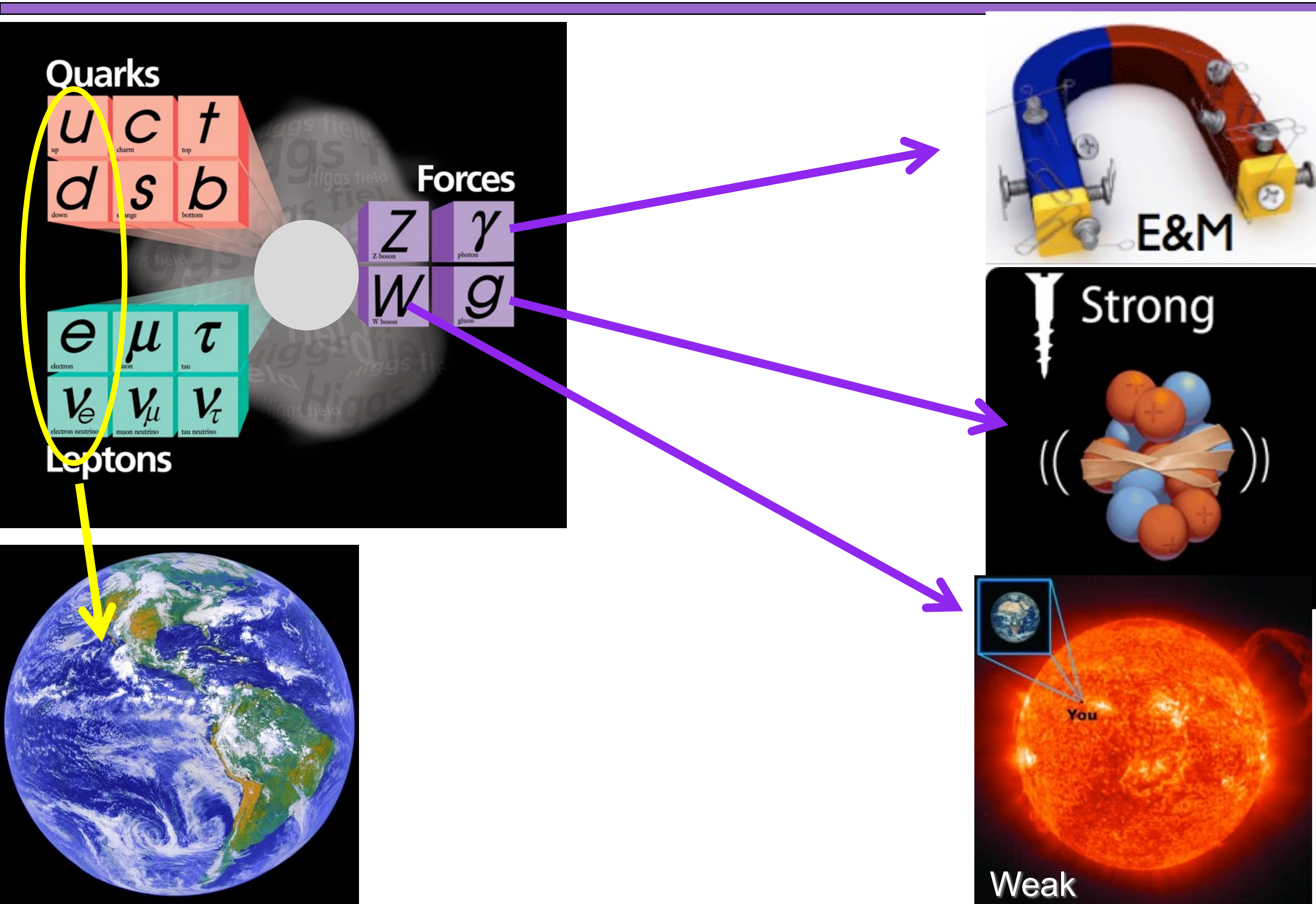
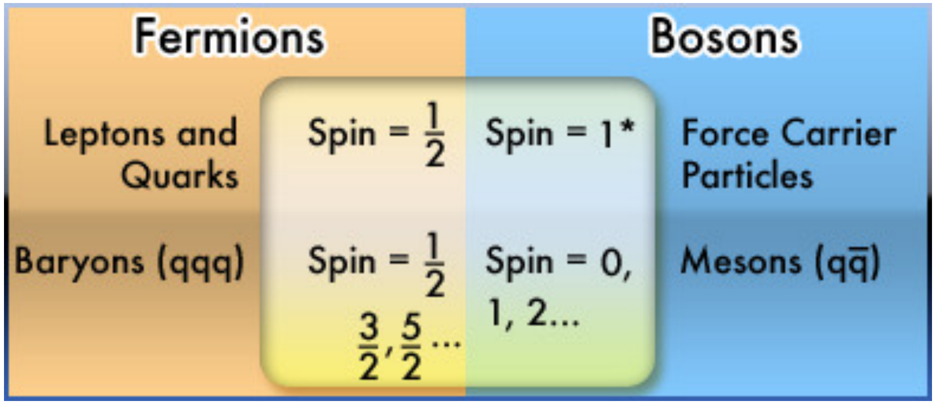
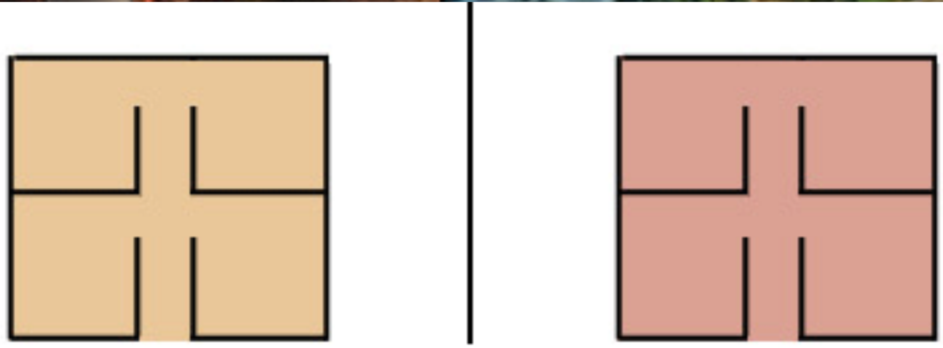


Fermions and Bosons





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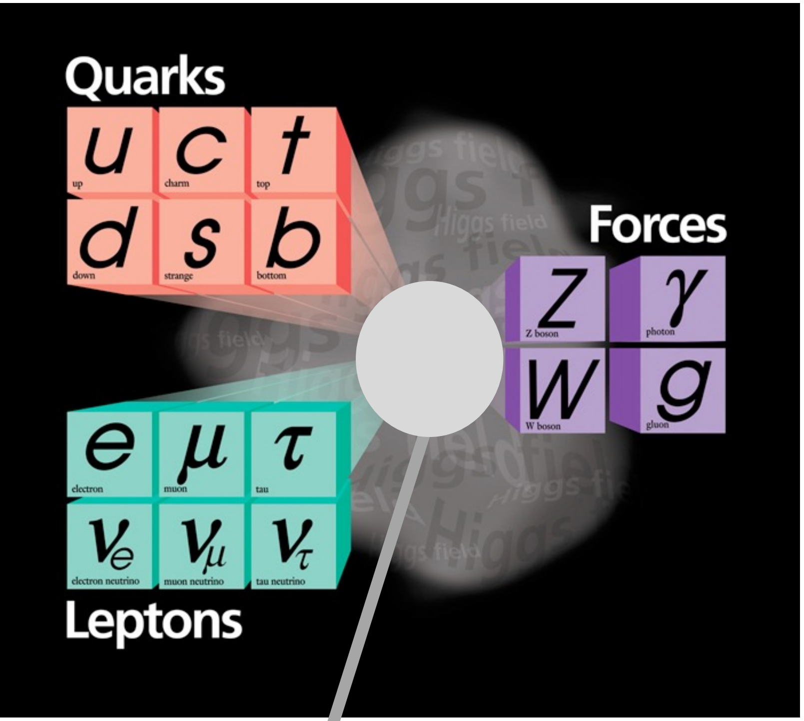
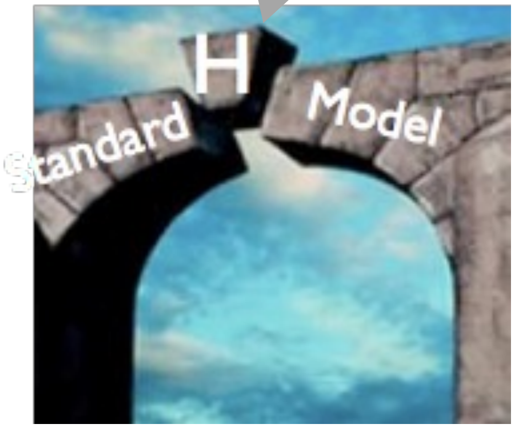
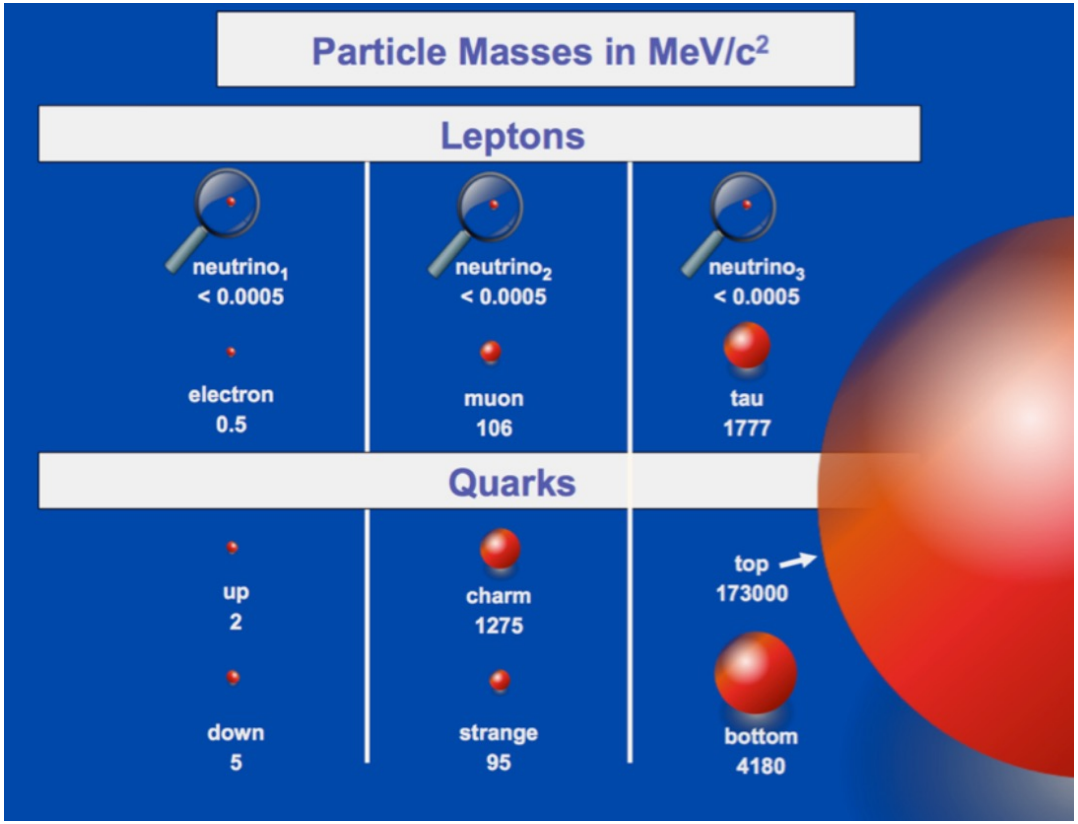




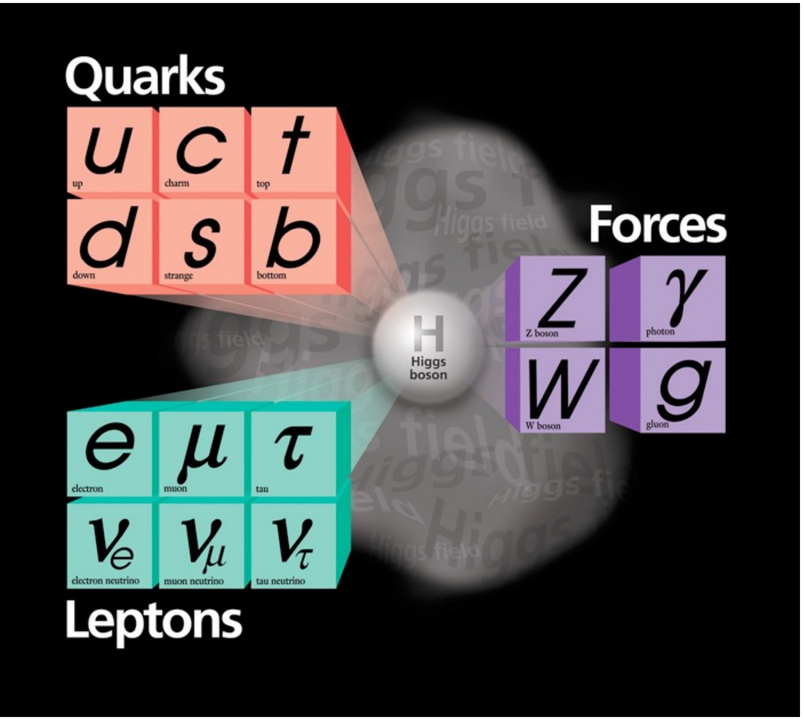
Works beautifully for massless quanta

M_W=80 GeV, M_Z=91 GeV, m_g,m_γ=0



Needs Higgs field for providing mass to the elementary particles

"Standard Model" of Particles and Forces



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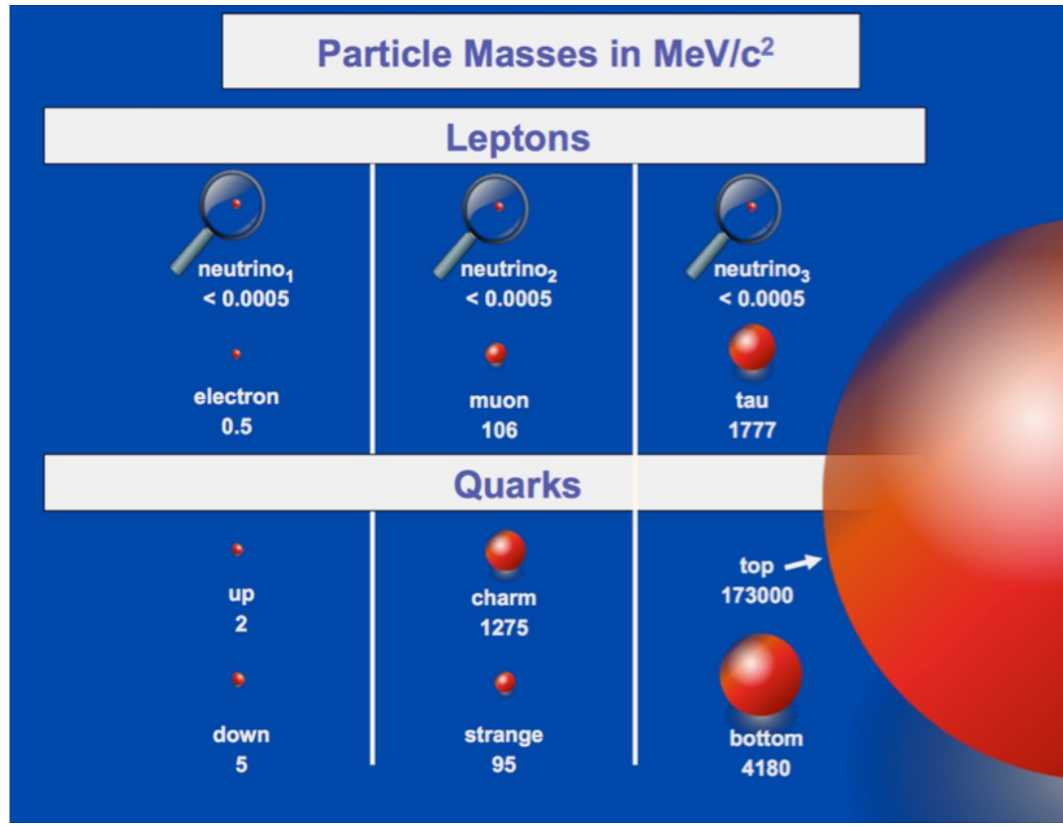


The Standard Model:
Some assembly required.
Gravity not included

Needs Higgs field for providing mass to the elementary particles

Interactions with Higgs Field

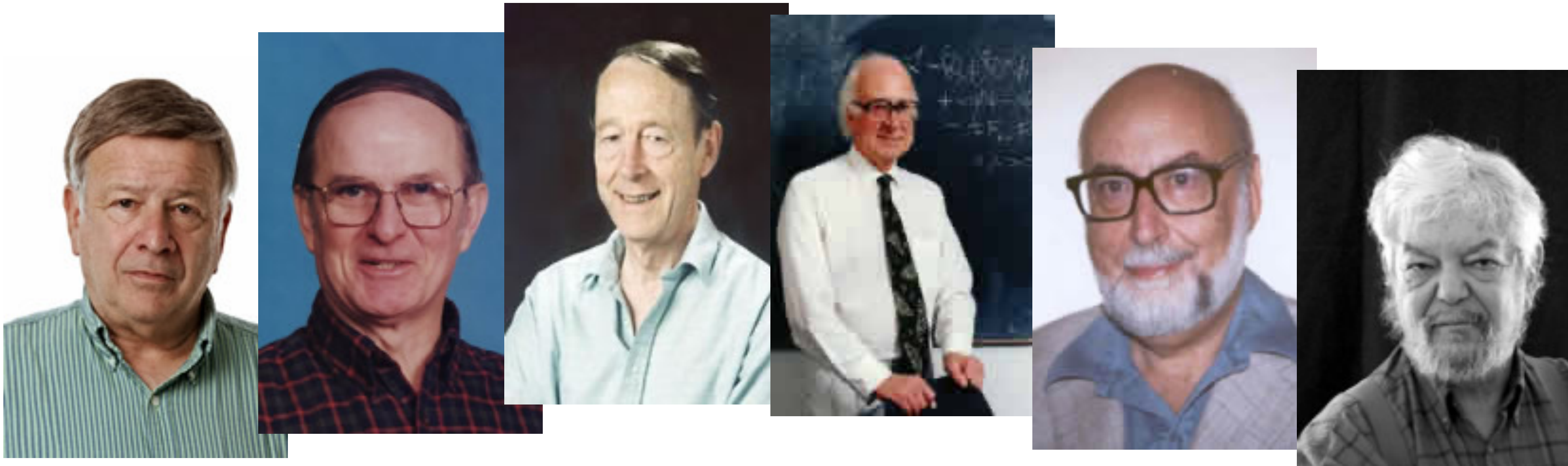
- Which of these falls slower safely?
  - An unopened parachute
  - Fully opened parachute ←

The more interaction with the medium (air) the lower the speed of the drop

Higgs field permeates all space, particles interact with differing strengths with the higgs field. The higher the interaction the larger the particle's mass.

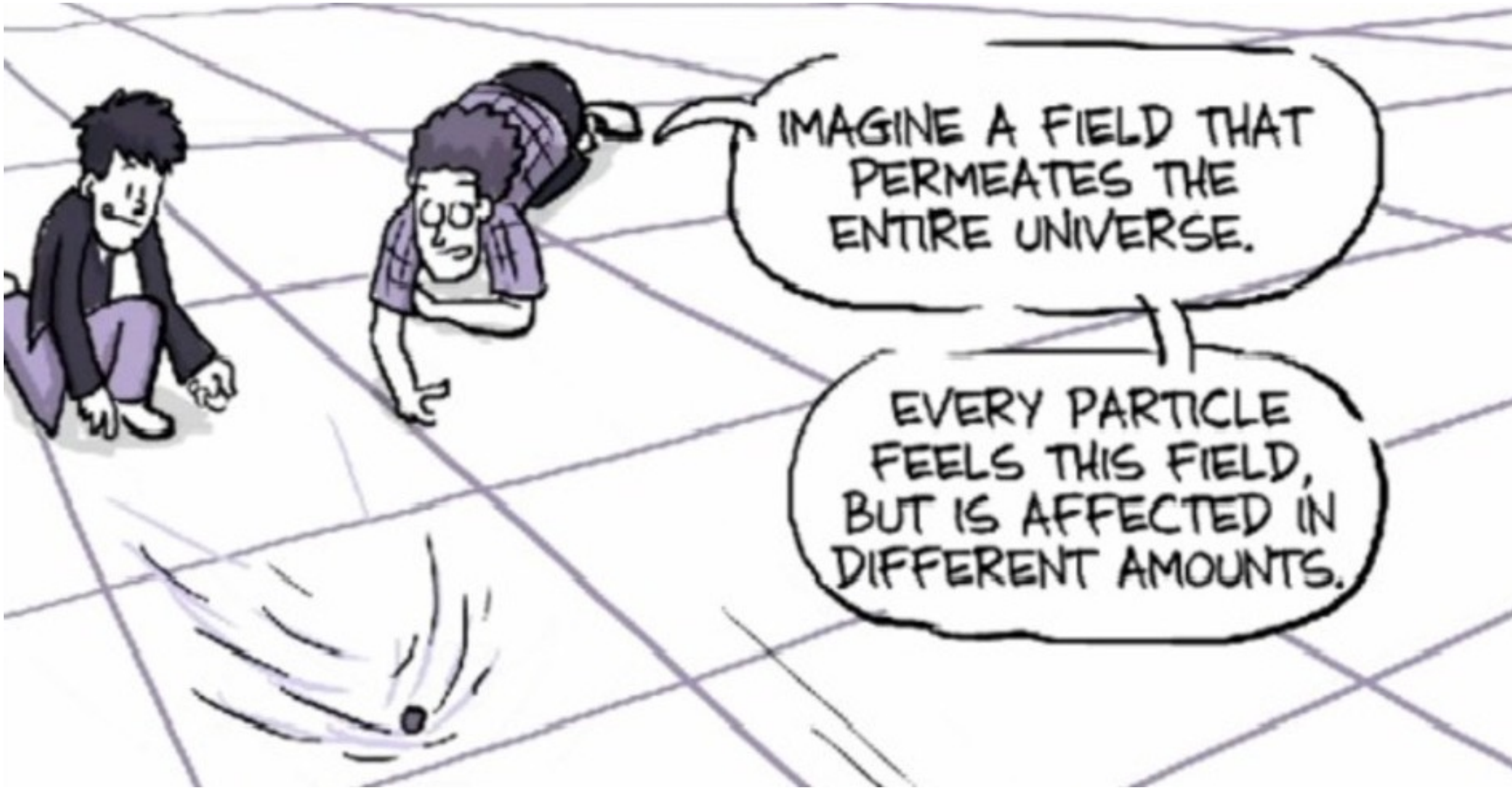
D. Miller / UCL

The Guralnik-Hagen-Kibble-Higgs-Englert-Brout field…



- The mass of particles is generated by interaction with the Higgs field. This was predicted independently by three groups and published in 1964 in the same volume of Physical Review Letters.
  - All three papers were written from different perspectives, and each made a distinct contribution
- Physical Review Letters volume 13 (1964):
  - **Guralnik, Hagen, Kibble**, "Global Conservation Laws and Massless Particles"
  - **Higgs**, "Broken Symmetries and the Masses of Gauge Bosons"
  - **Englert, Brout**, "Broken Symmetry and the Mass of Gauge Vector Mesons"

THEORY: The “Higgs” Field



The more a particle interacts with this *invisible* field, the more mass it gets.

But if this field is invisible, how can we PROVE it exists?

The theory predicts that the field has an associated particle:

The Higgs Boson!

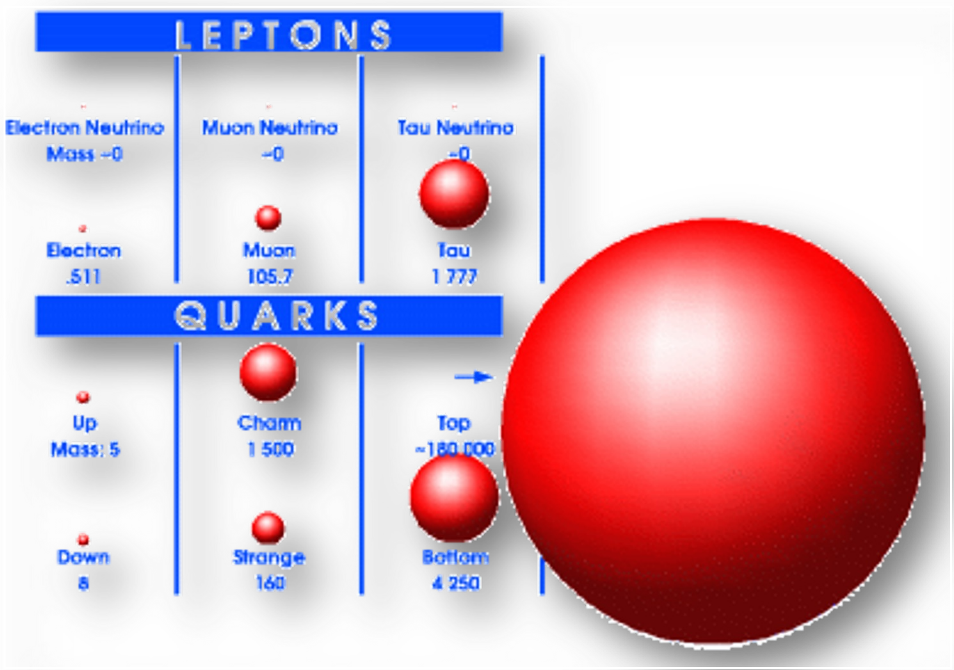
We can try to create the Higgs boson in our experiment!

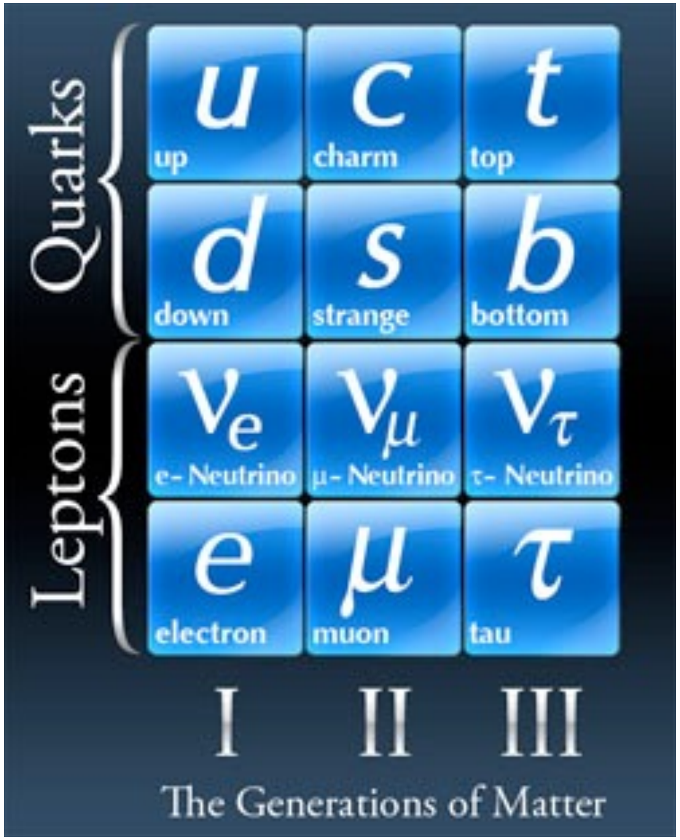
Challenge: the theory does not predict its mass

Other open questions

Why is there a large mass hierarchy in the fermion sector ?

Why are there exactly 3 generations ?





What remains to be answered ?

How can we explain the matter anti-antimatter asymmetry ?

Anti-Tom Hanks

Would look very much like

Tom Hanks

What remains to be answered ?

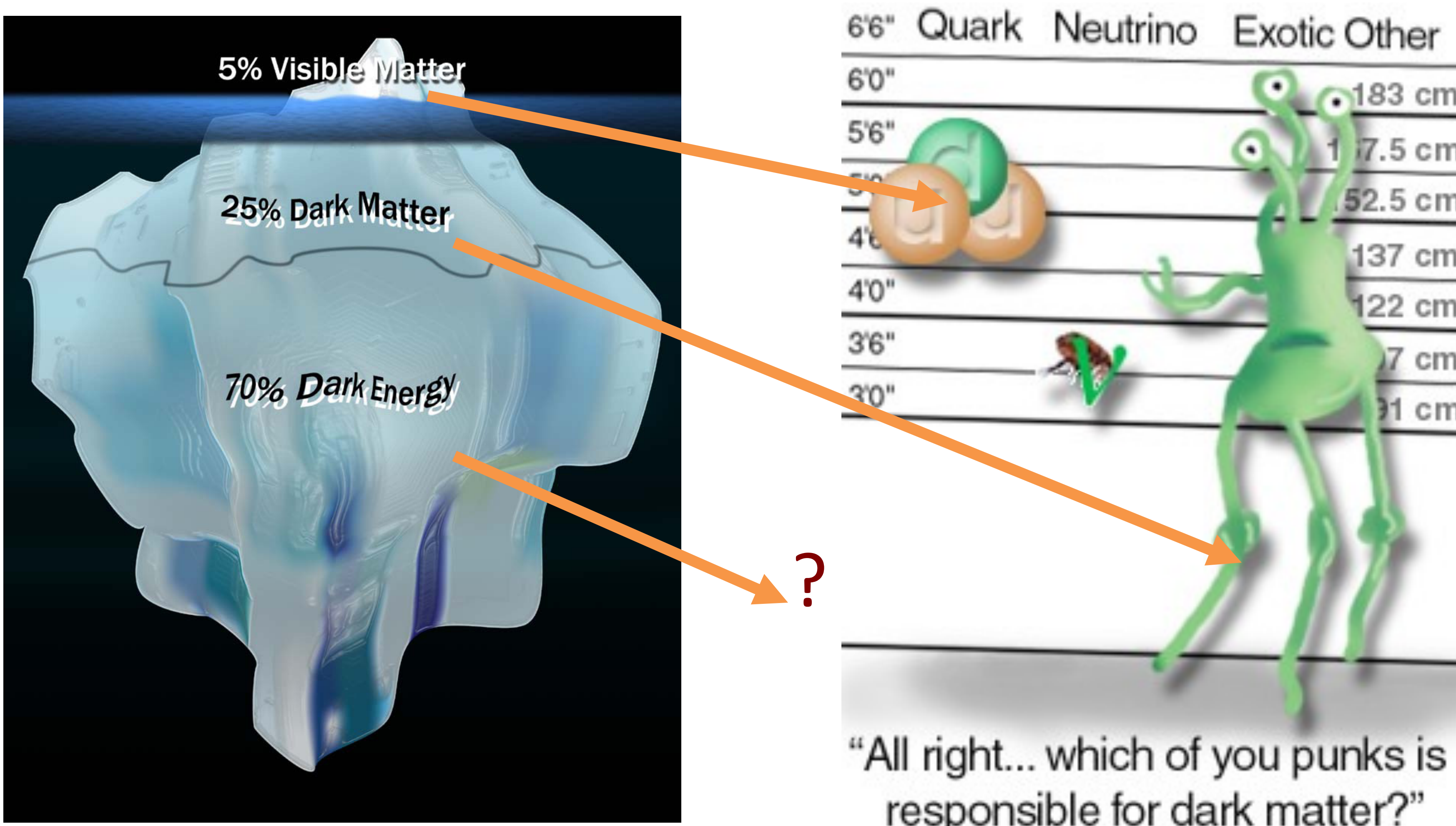
How can we explain the matter anti-antimatter asymmetry ?

But were they to meet…

We are still here

and no naturally occurring antimatter is in sight!

What remains to be answered ?

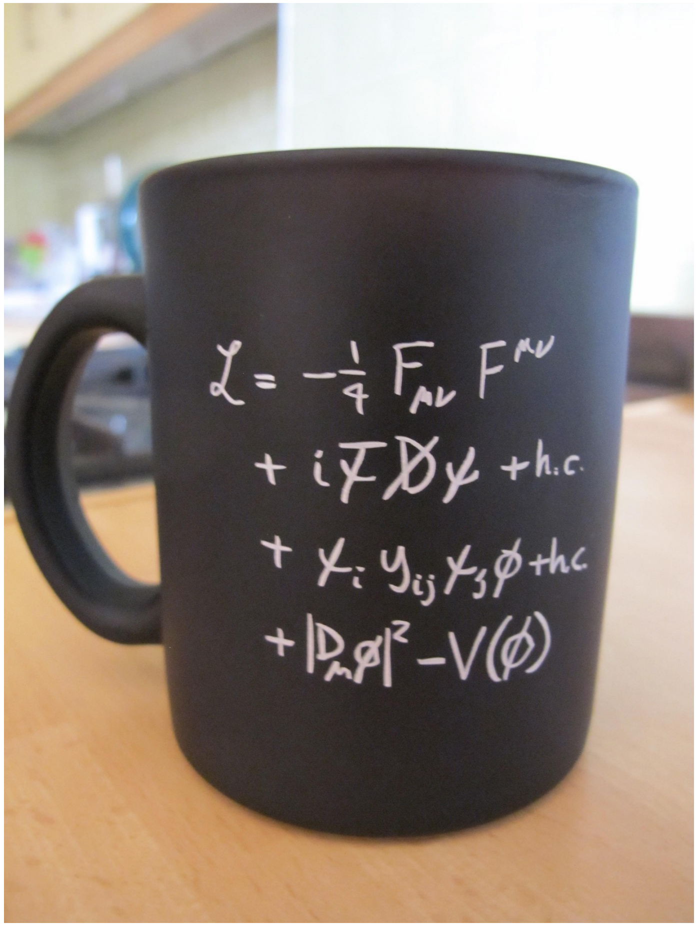


What remains to be answered ?

What is dark matter ?

Are new particles the solution ?

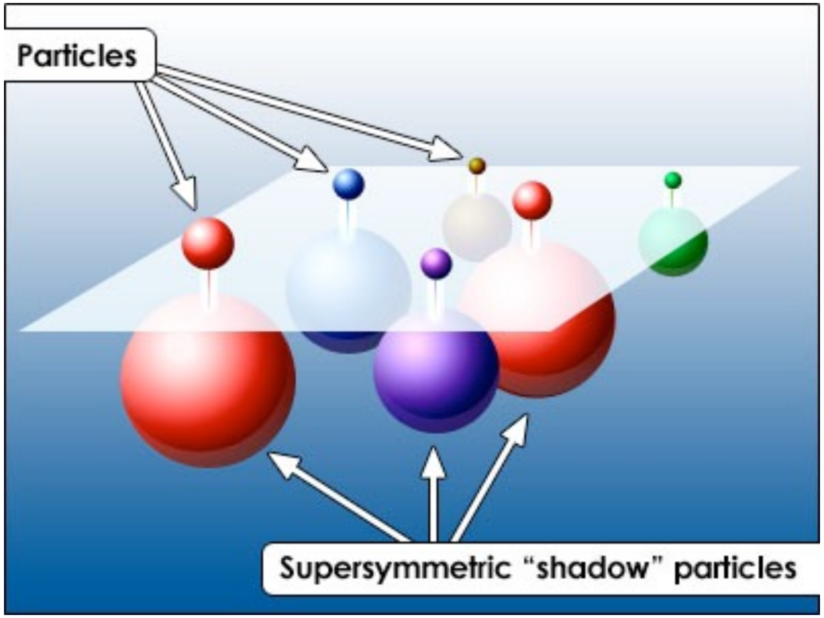
Where is gravity ????



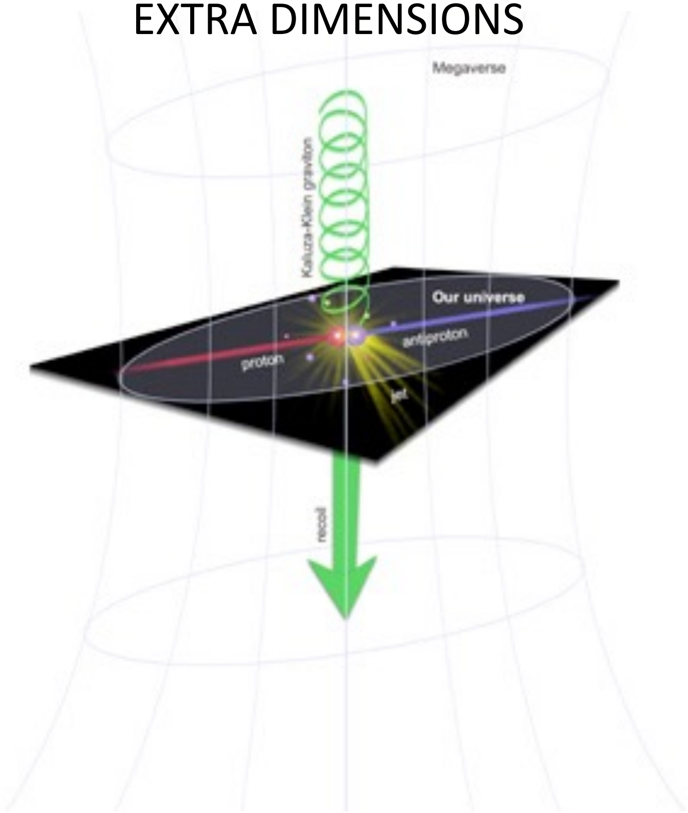
Does the Higgs interact with dark matter ?

Potential Answers

SUPERSYMMETRY



EXTRA DIMENSIONS



And many more…

Hunting for the Exotic

What new physics are we looking for ?

Start by asking these questions in the right way

Look more closely   More Precision, new techniques

Look in new places   Higher Energy, new measurements

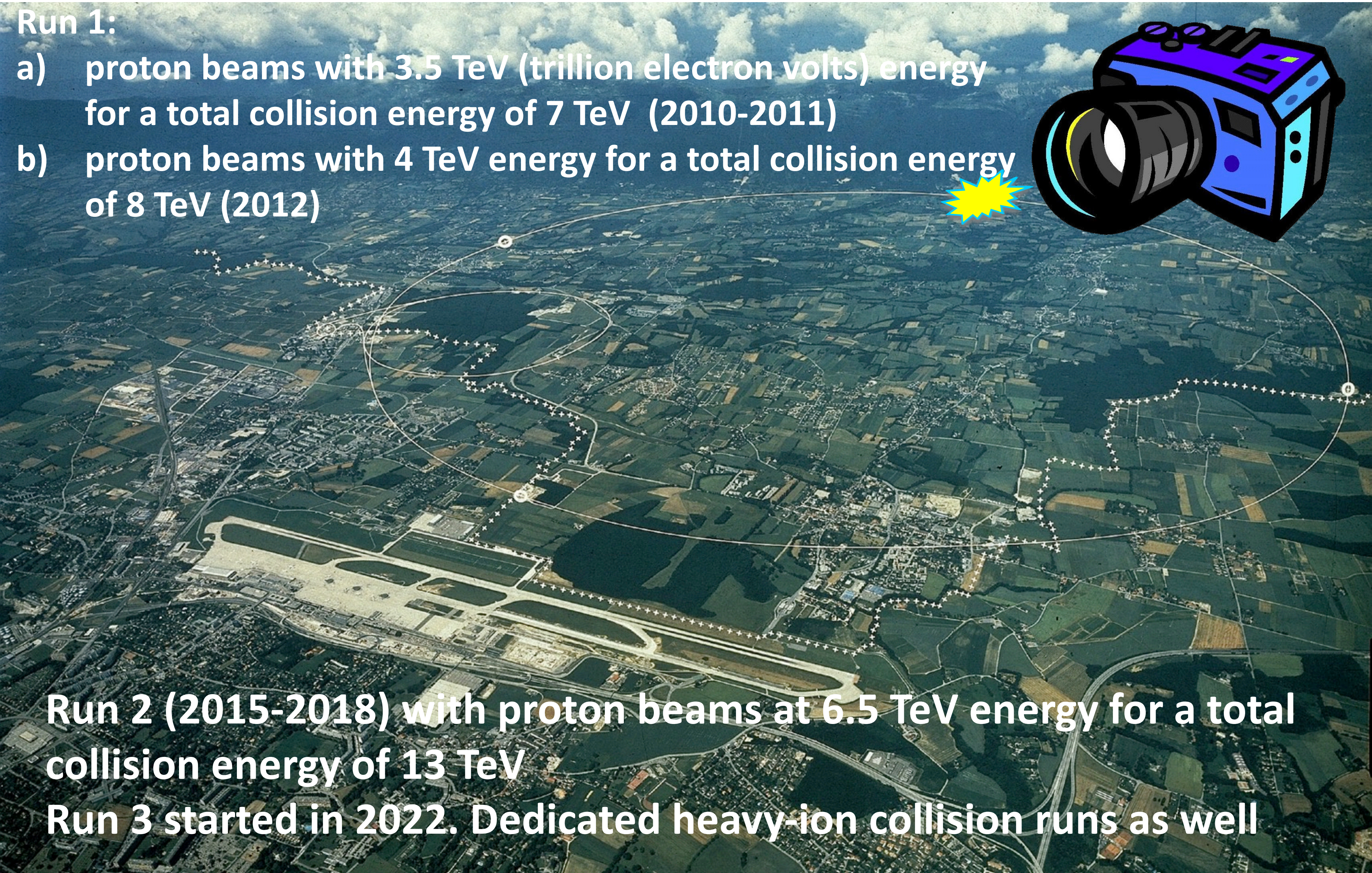
The Energy Frontier….

The Large Hadron Collider…

Run 1:

a) proton beams with 3.5 TeV (trillion electron volts) energy for a total collision energy of 7 TeV (2010-2011)

b) proton beams with 4 TeV energy for a total collision energy of 8 TeV (2012)



Run 2 (2015-2018) with proton beams at 6.5 TeV energy for a total collision energy of 13 TeV

Run 3 started in 2022. Dedicated heavy-ion collision runs as well

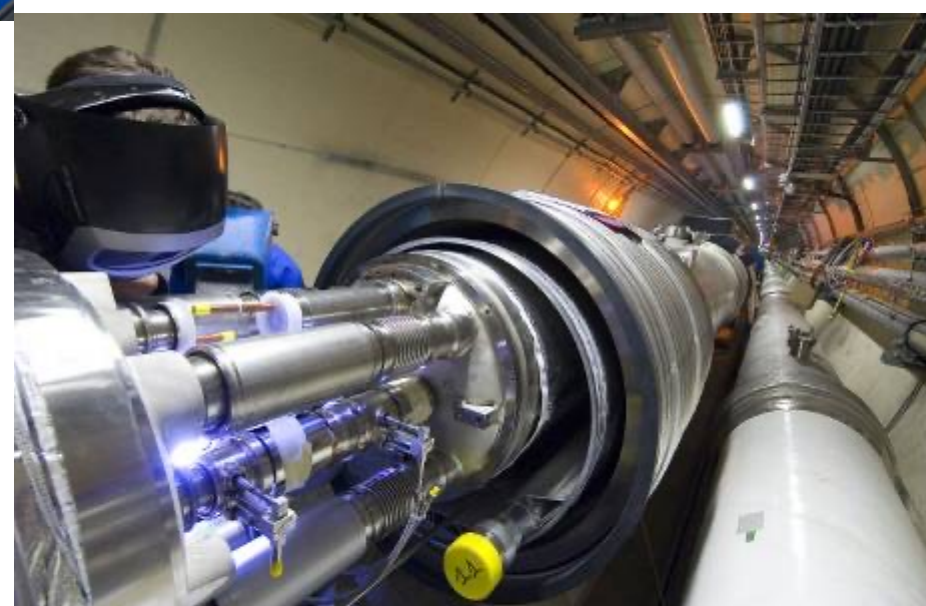
One of the fastest racetracks on the planet…

Several thousand billion protons travelling at 99.9999991% of the speed of light will travel round the 16.8 mile ring over 11000 times a second!

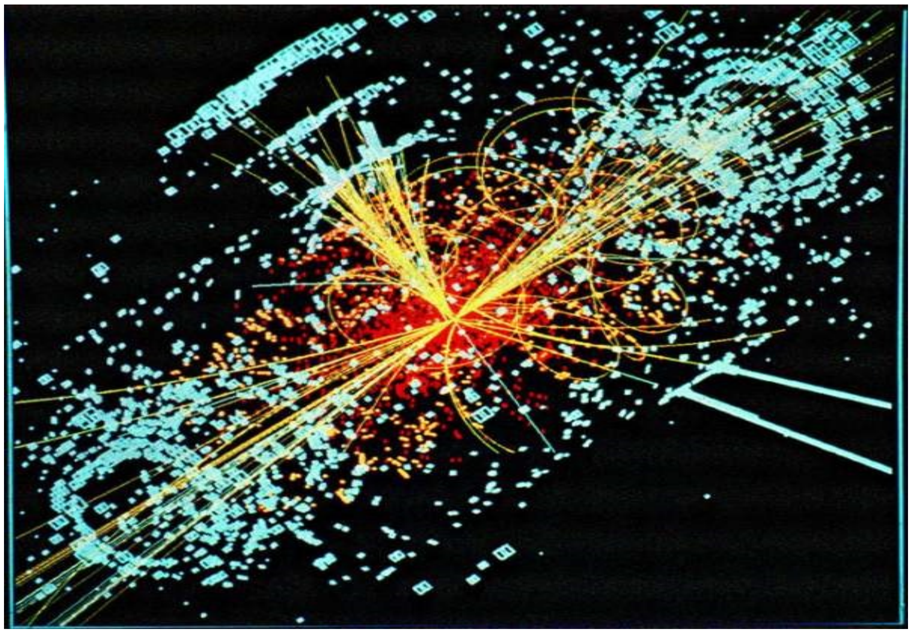
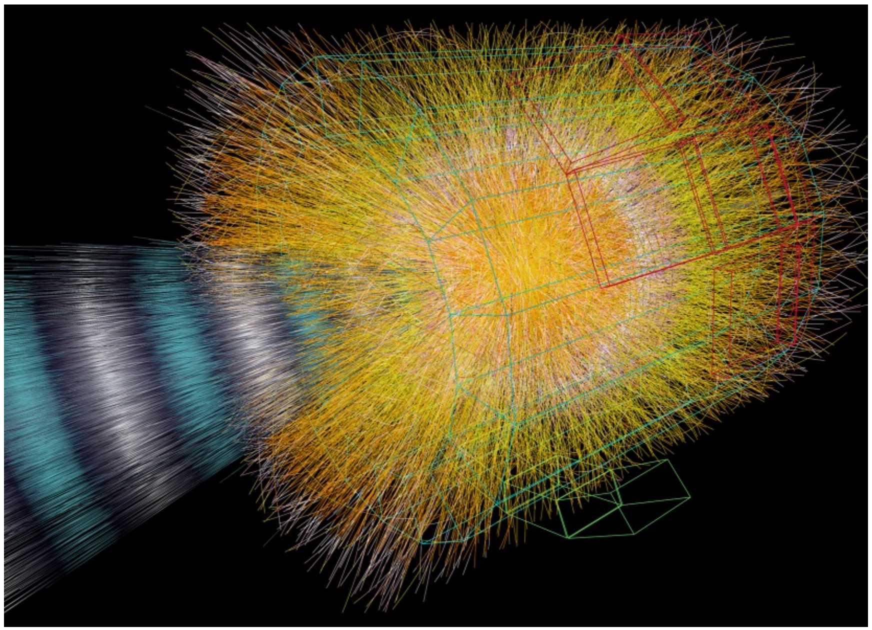
(that’s 670,626,025 mph)

- About 300 ft under ground
- 8.4 T dipole magnets (1232 magnets)
- Cooled to 1.9K with 96 tons of liquid helium
- Energy of beam = 362 MJ

15 kg of chocolate



Where will occur some of the hottest reactions in our galaxy…



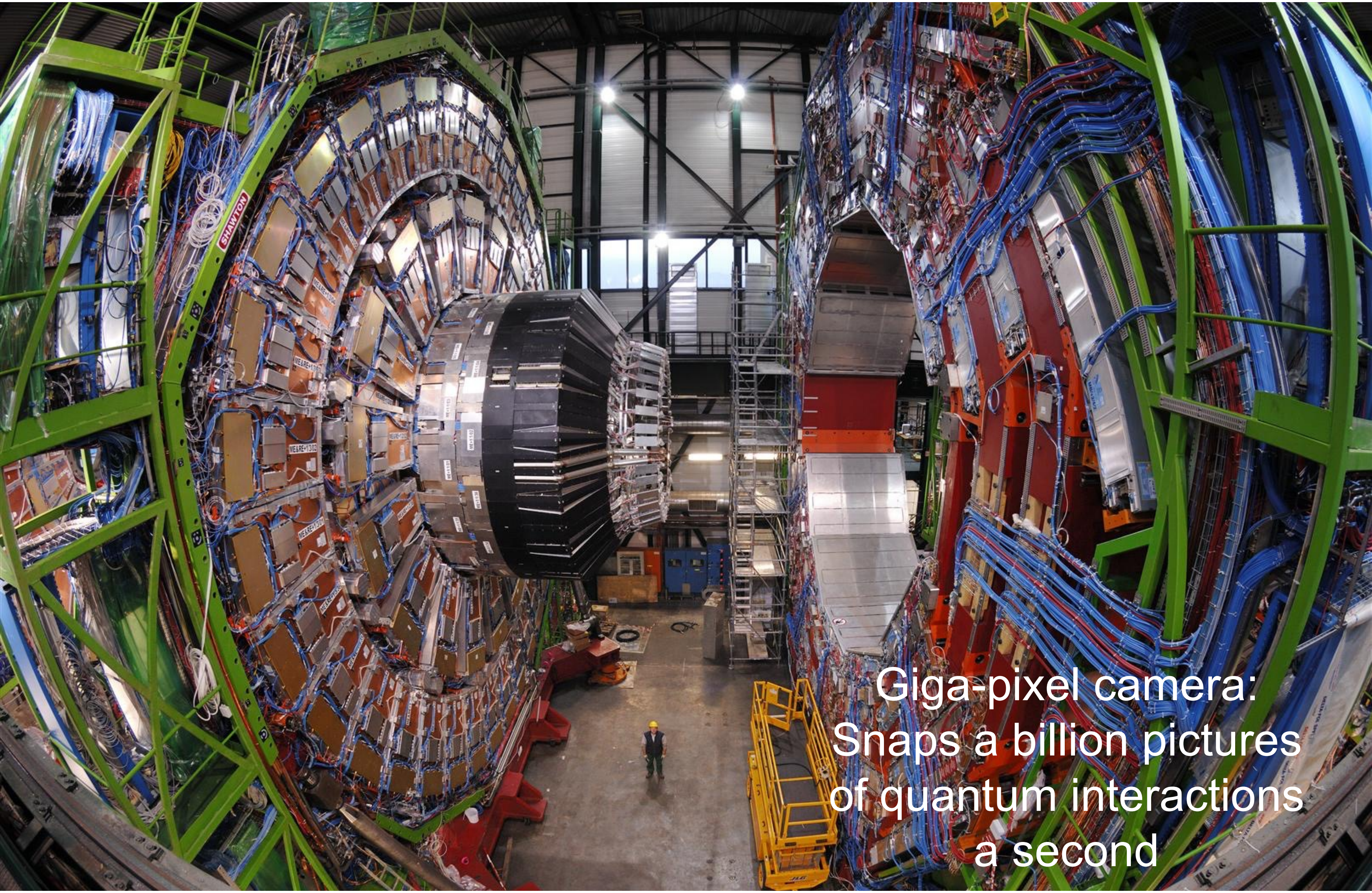
Violent collisions corresponding to temperatures a billion times higher than the core of the sun will be produced.

That is roughly 160,000,000,000,000,000 C to be watched by some of the most complex “eyes” we’ve ever built,

Particle Detectors

allow us to "see" particles

to be watched by some of the most complex "eyes" we've ever built,

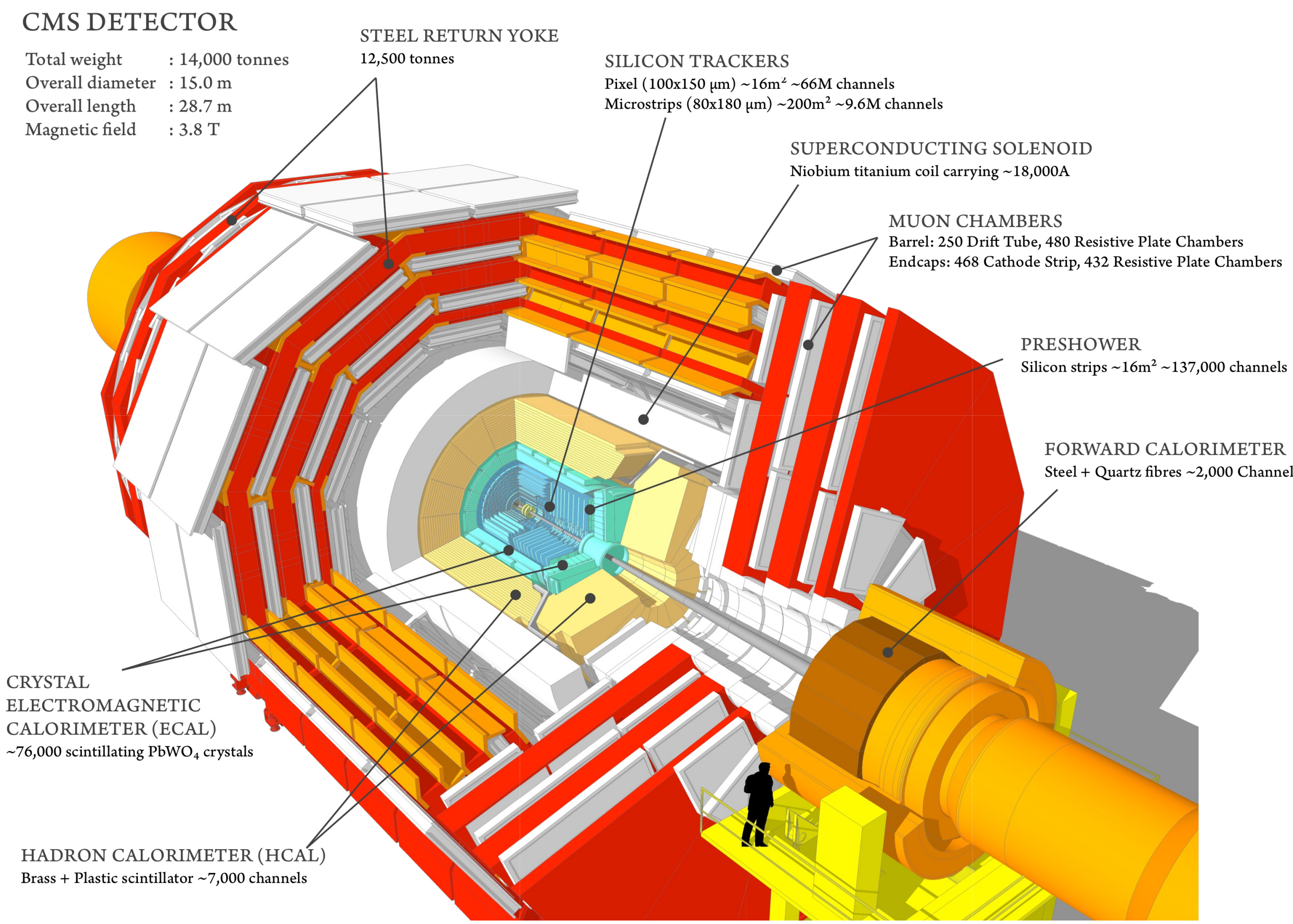



ALICE
CMS
ATLAS
LHCb

The CMS detector

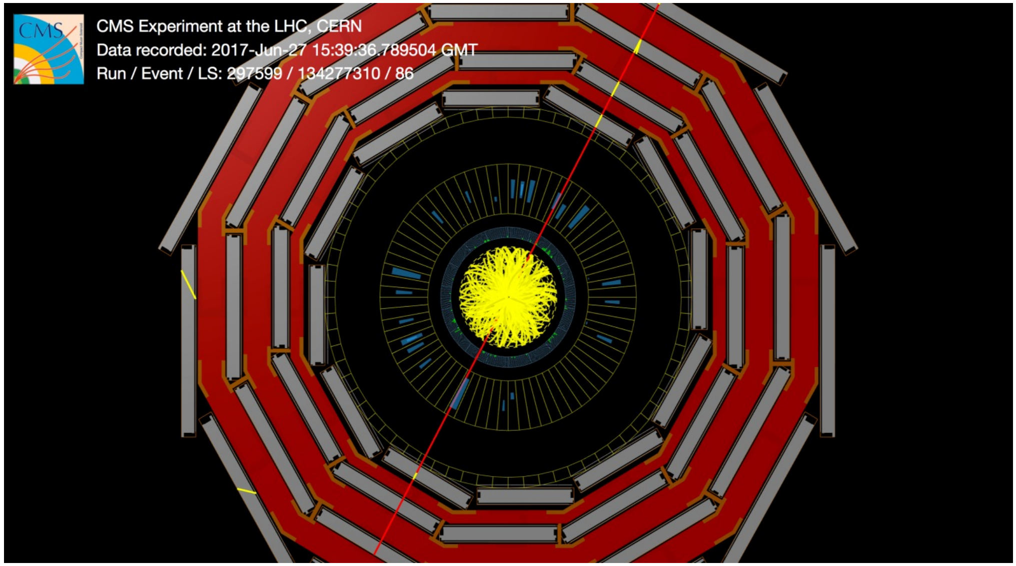
More in Steve Nahn's talk today

- Took ~2000 scientists and engineers more than 20 years to design and build
- Is about 15 metres wide and 21.5 metres long
- Weighs twice as much as the Eiffel Tower – about 14000t
- (~40 large airplanes)



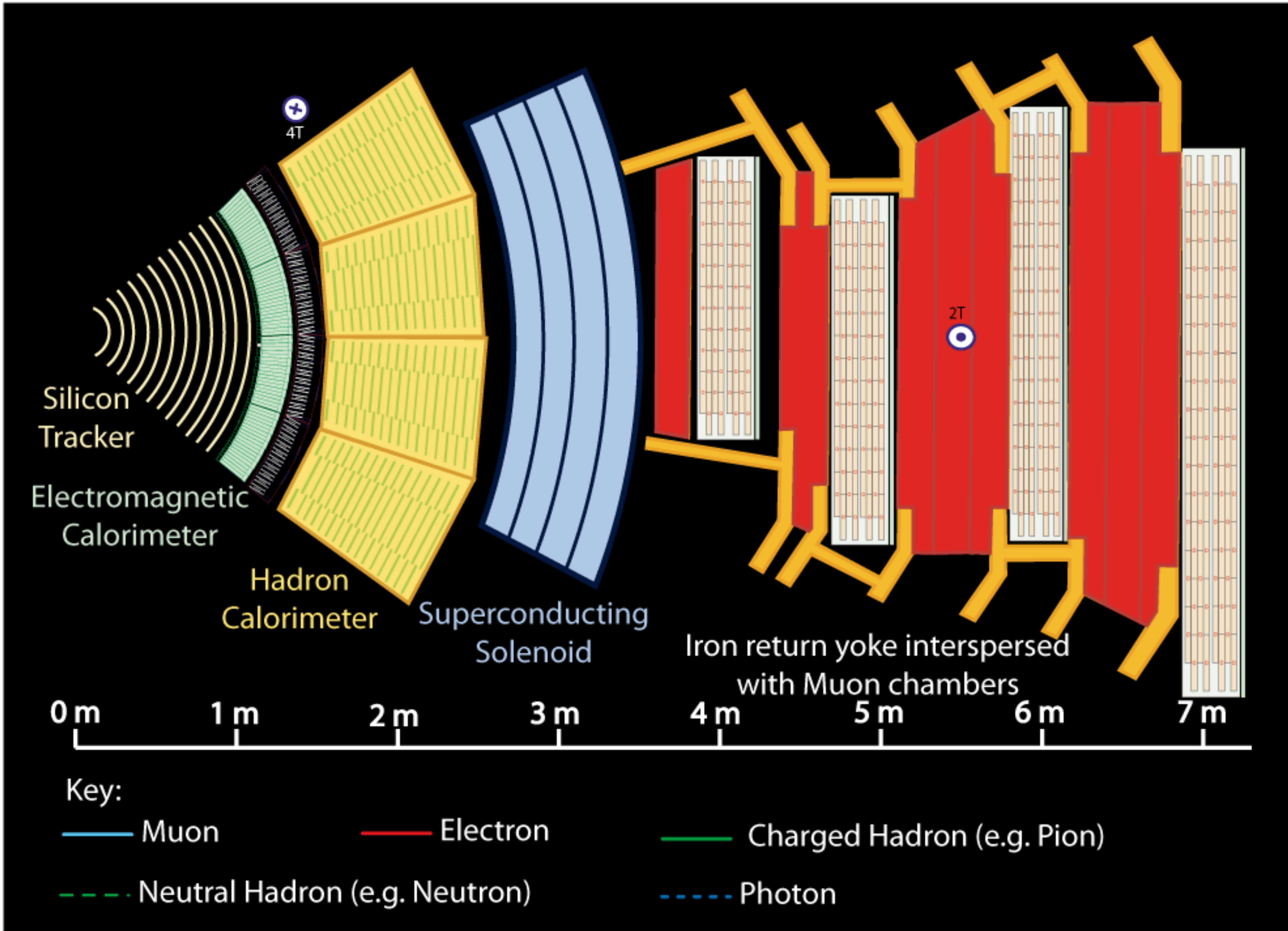
What do we observe with CMS?

- Photons
  - Light quanta
- Electrons
  - Lightest electrically charged lepton
- Muons
  - Heavier cousin of electron (interacts minimally)



- Charged hadrons (π, K, protons)
  - Composite charged particles made of quarks

- Neutral hadrons (neutrons, K_L)
  - Composite neutral particles made of quarks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with Muon chambers
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Key:
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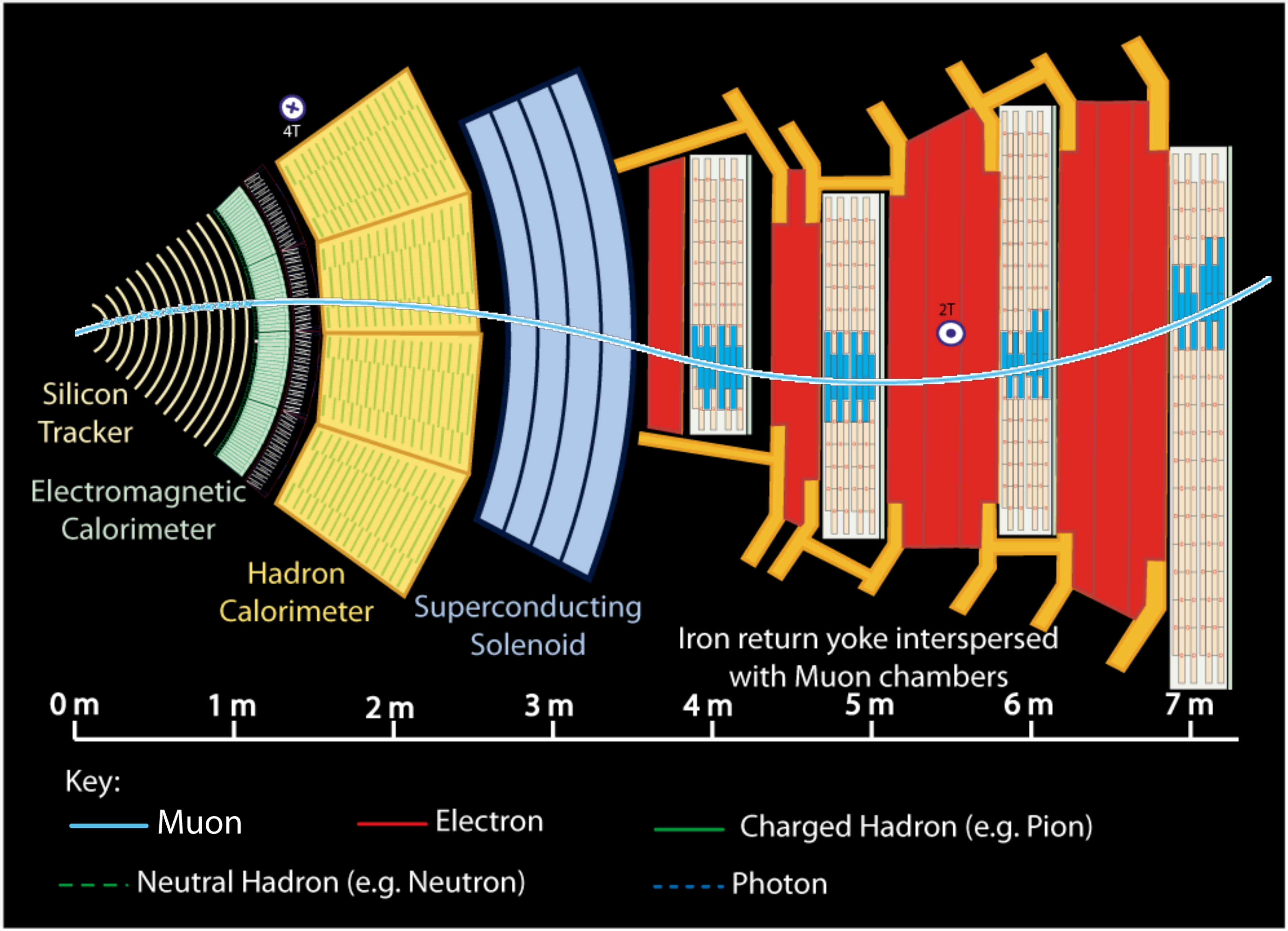
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon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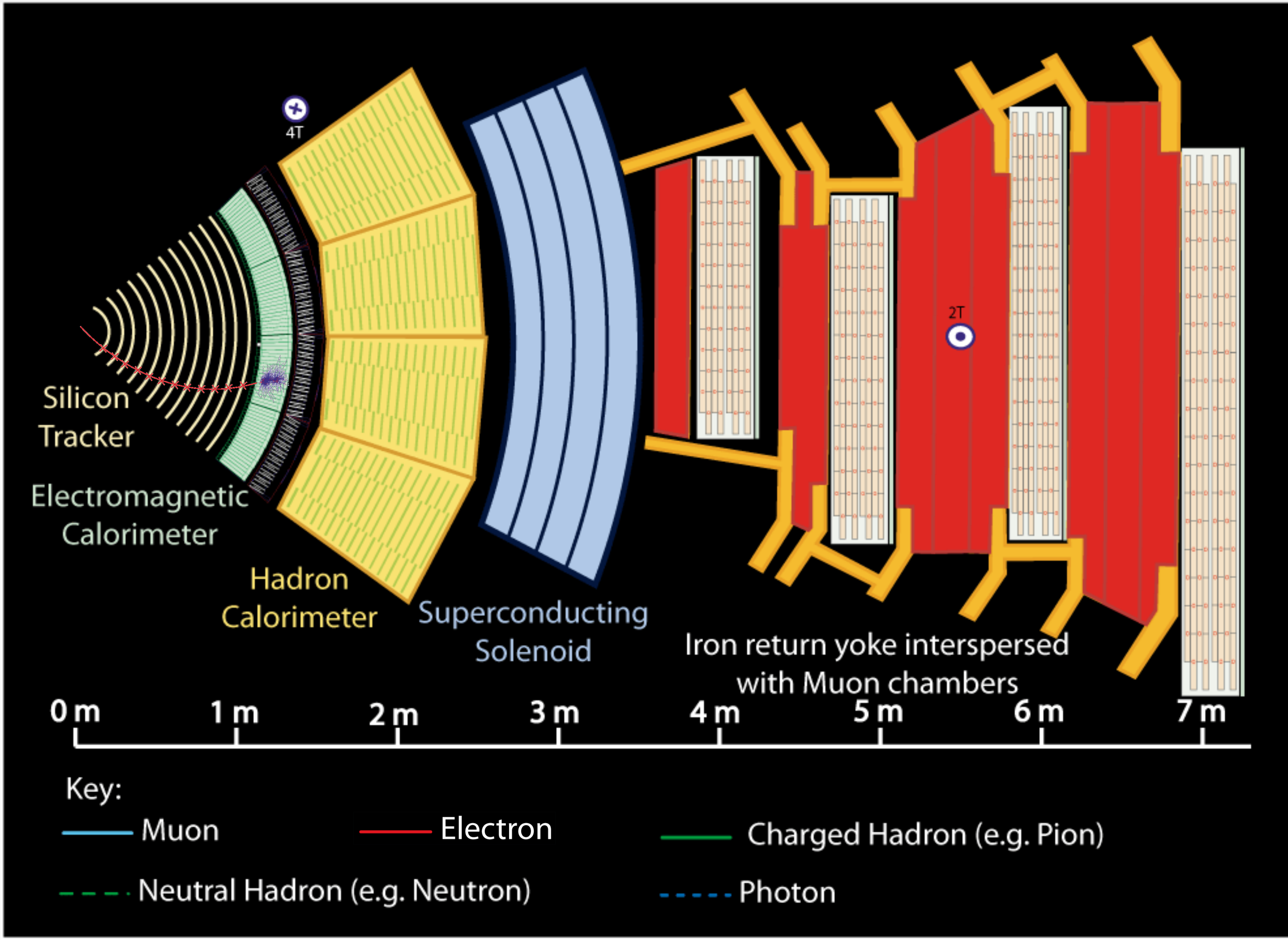
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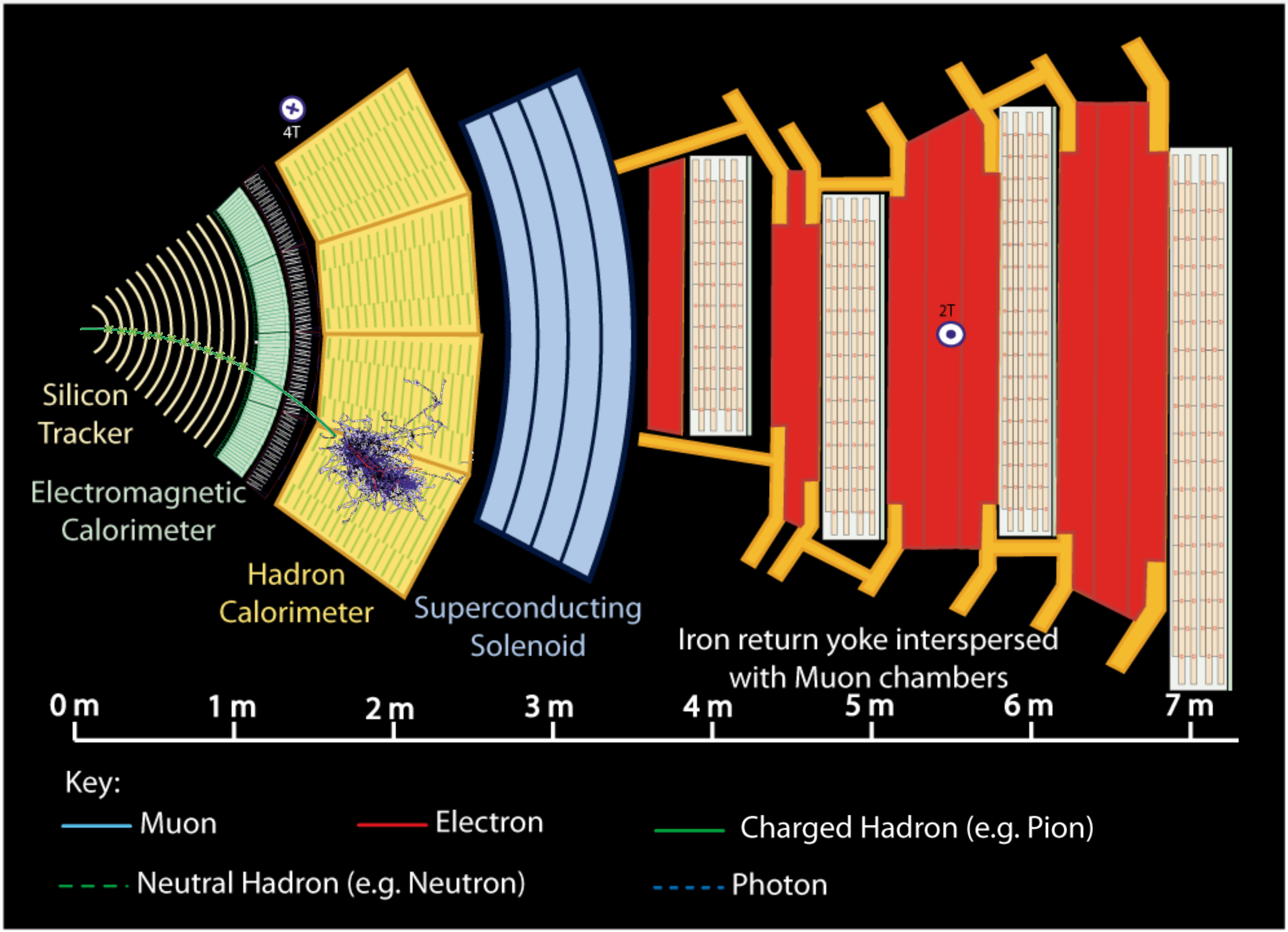
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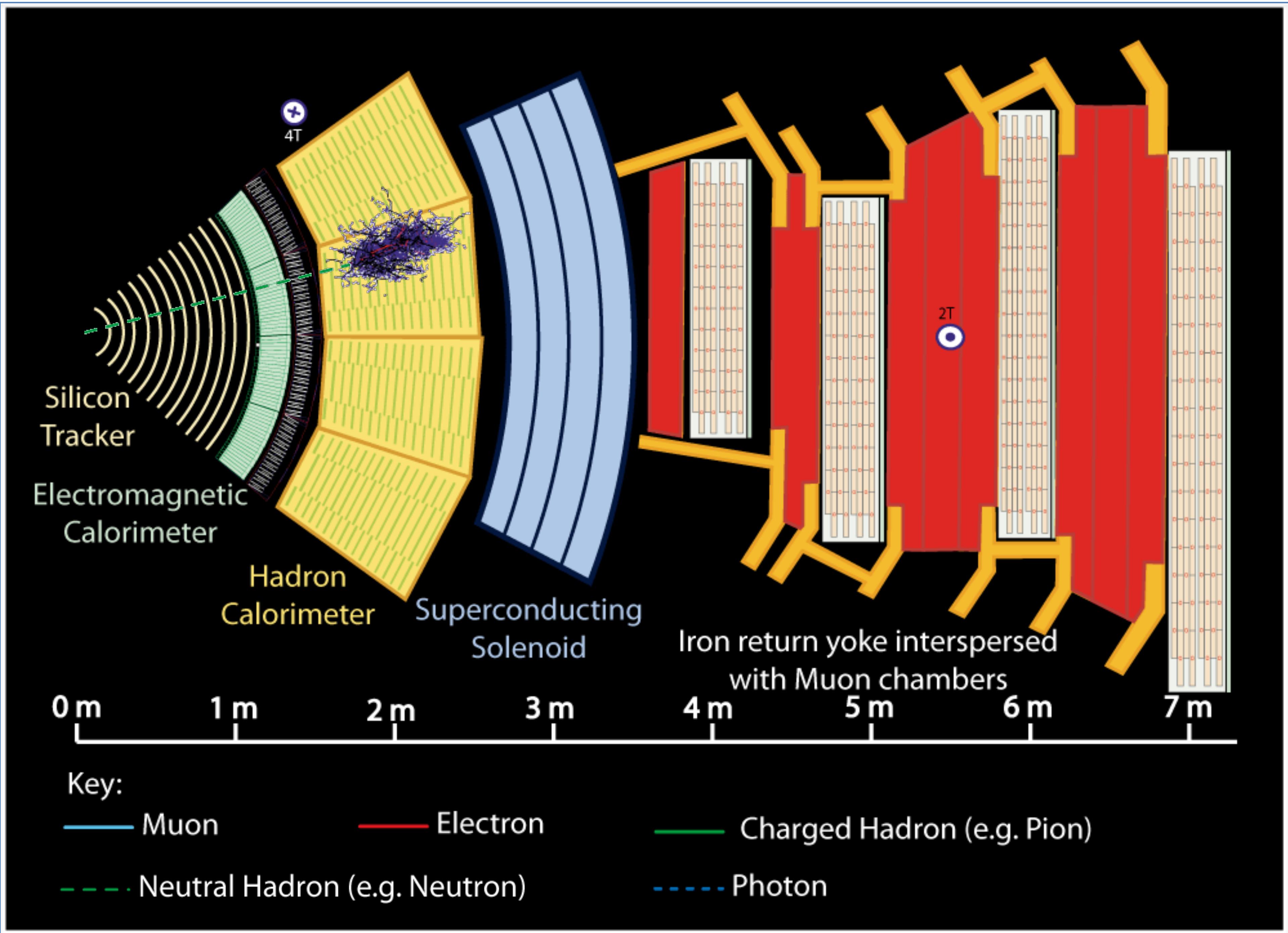
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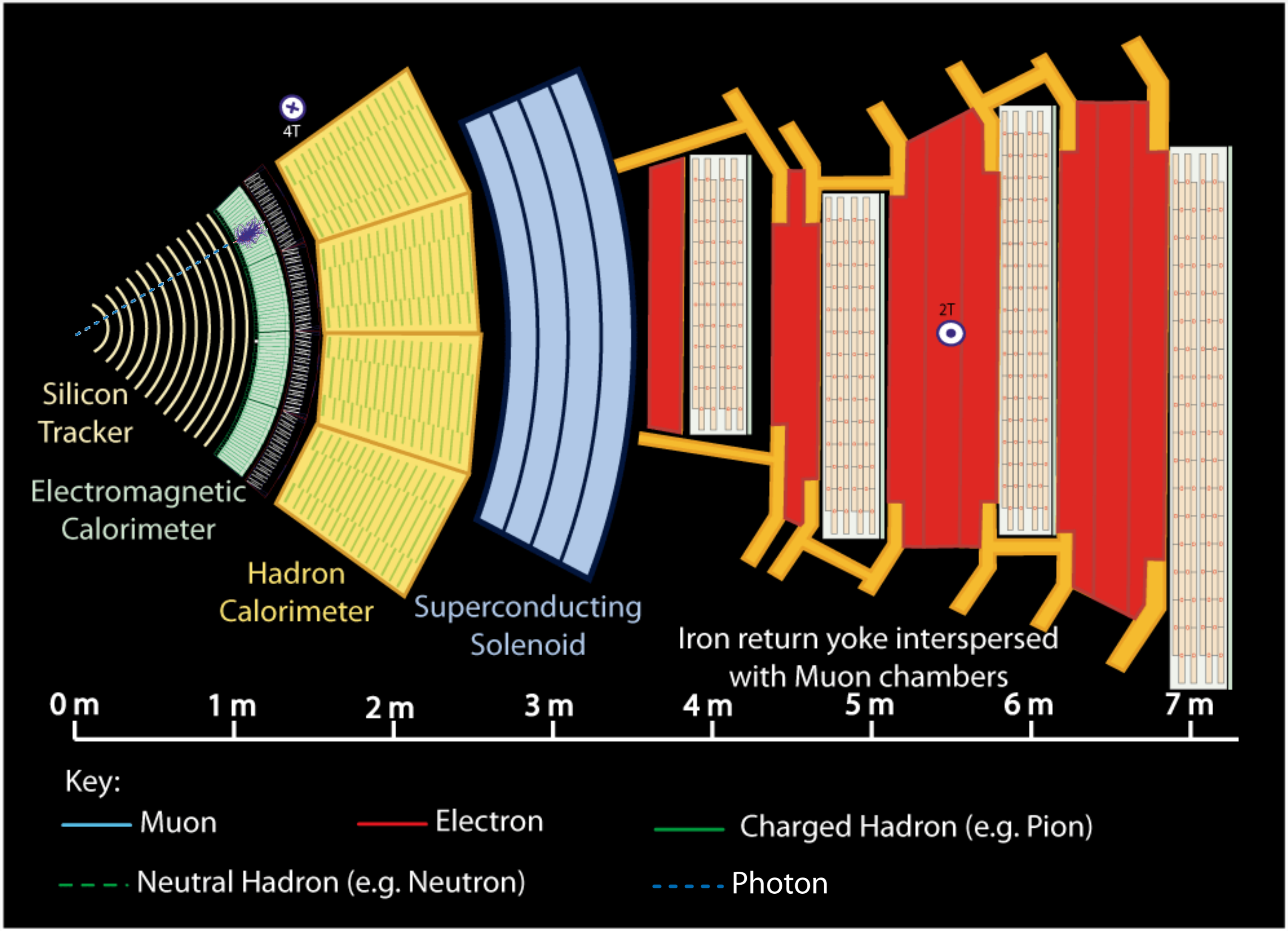
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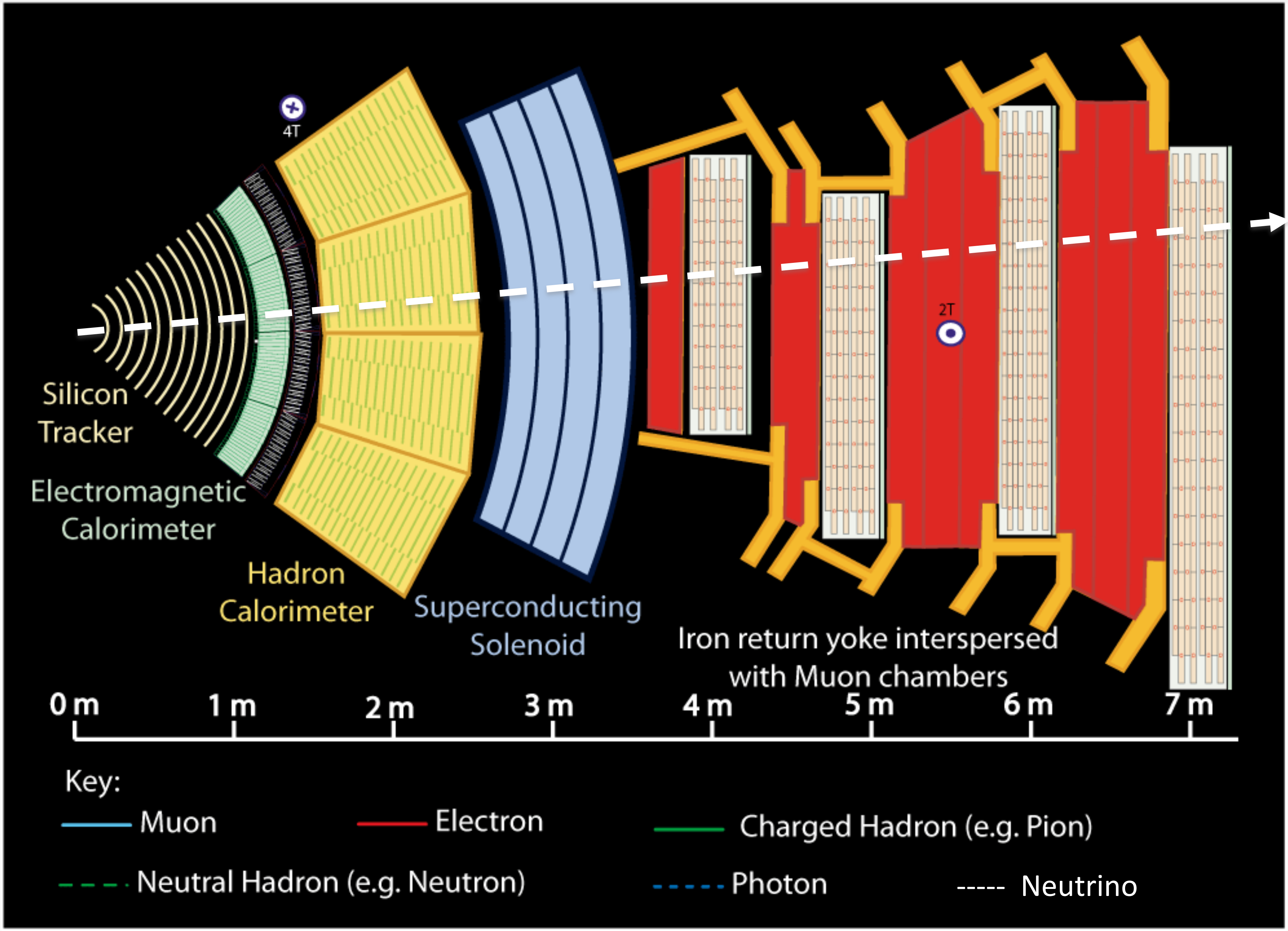

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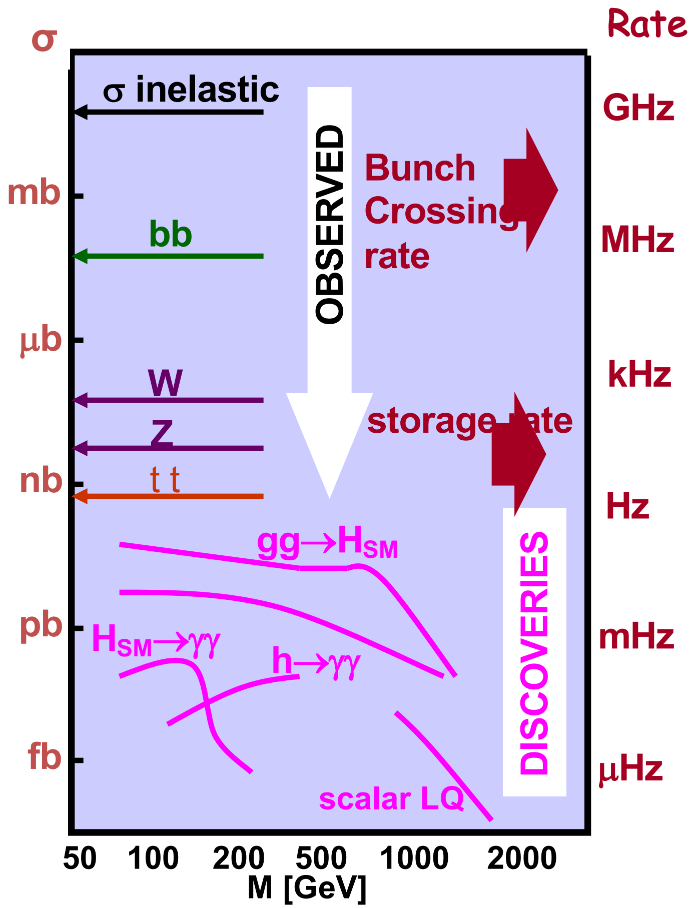
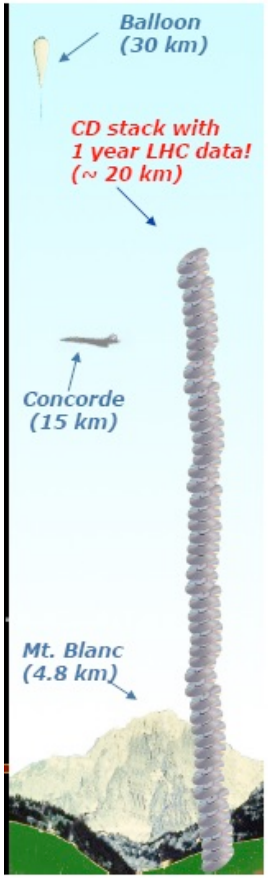
The Challenge at the LHC



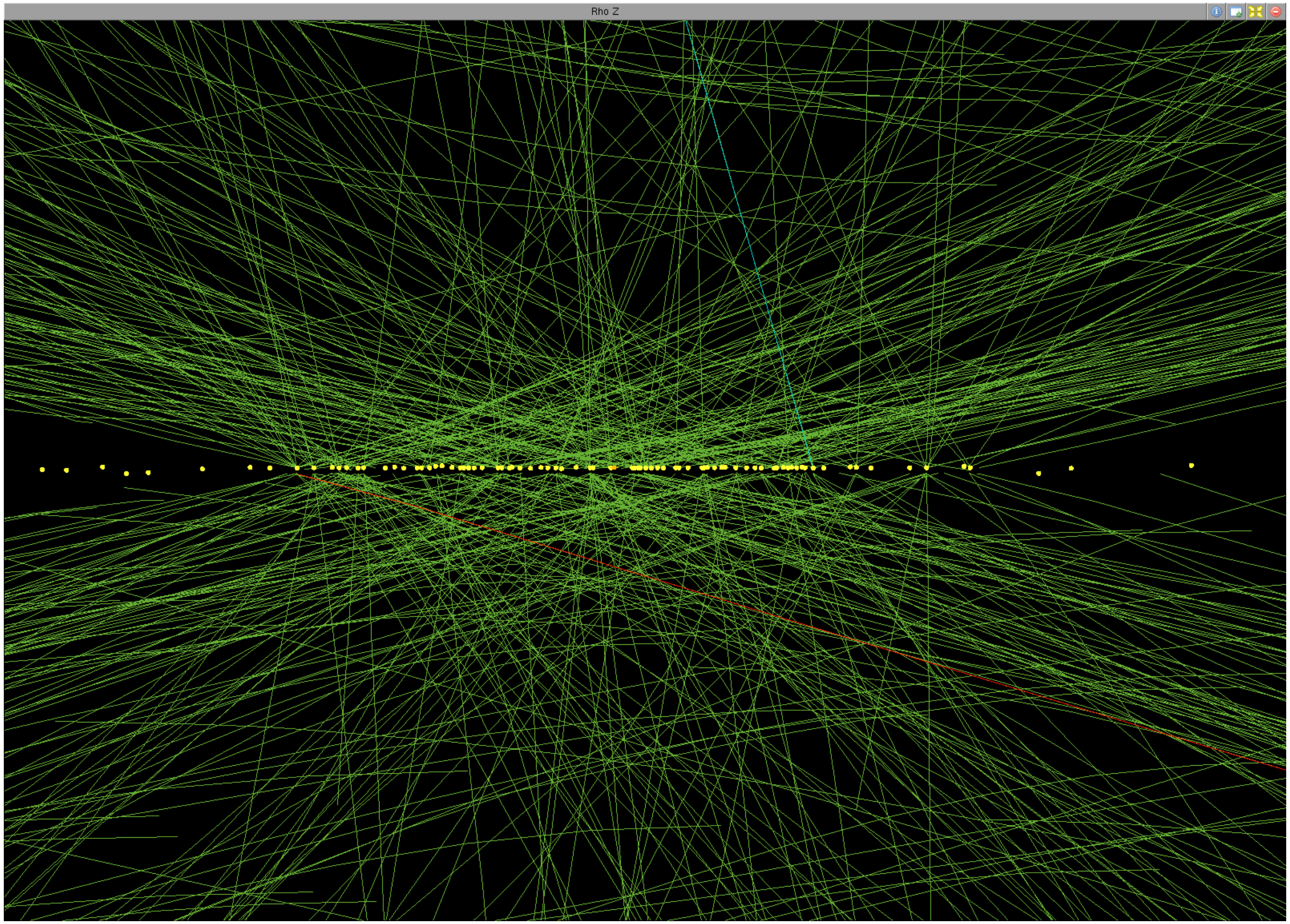
LHC: ~10^9 interactions/s

Bunch crossing frequency: 40MHz
Storage rate ~ 2000 Hz

Discoveries require rare signal extraction in huge data samples of complex detectors – large-scale processing and data management



Pileup



Event from special high pileup run with 78 reconstructed vertices

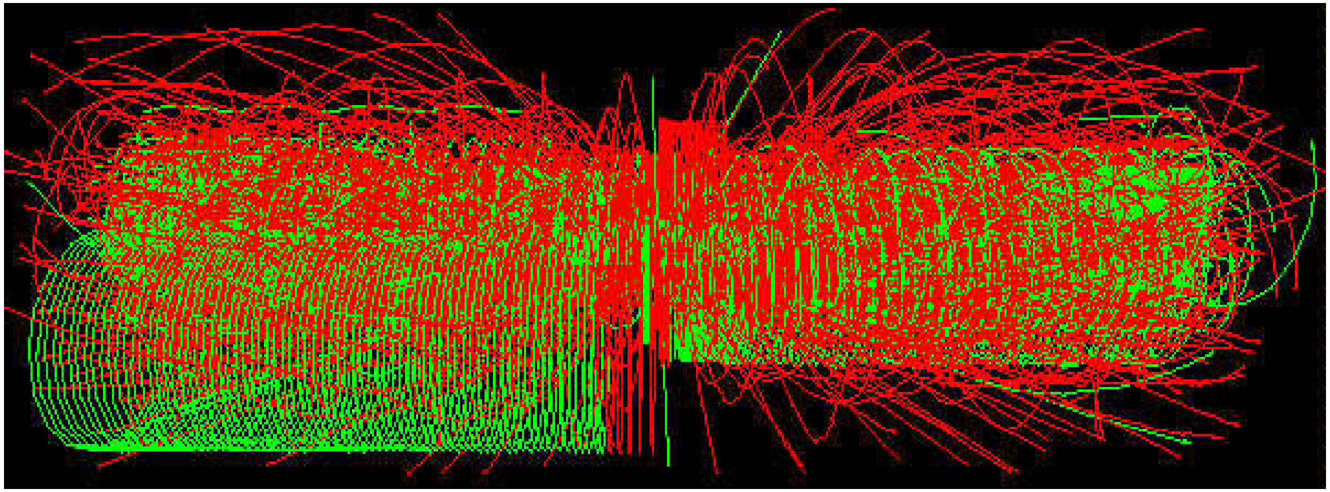
Average pileup in the 2016 run: 25 – 30

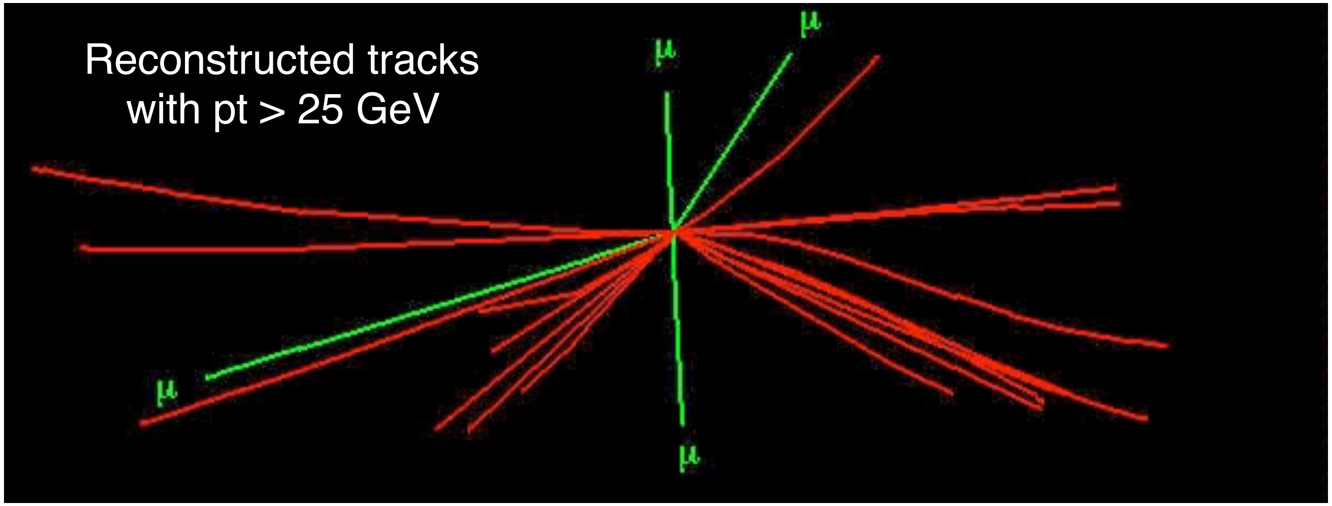
Peak pileup in recent runs exceeded 55!

pp collisions at 14 TeV at 10^{34} $cm^{-2}s^{-1}$

25 minbias events overlap

- H→ZZ (Z→μμ)
- H→ 4 muons: ("golden") signature





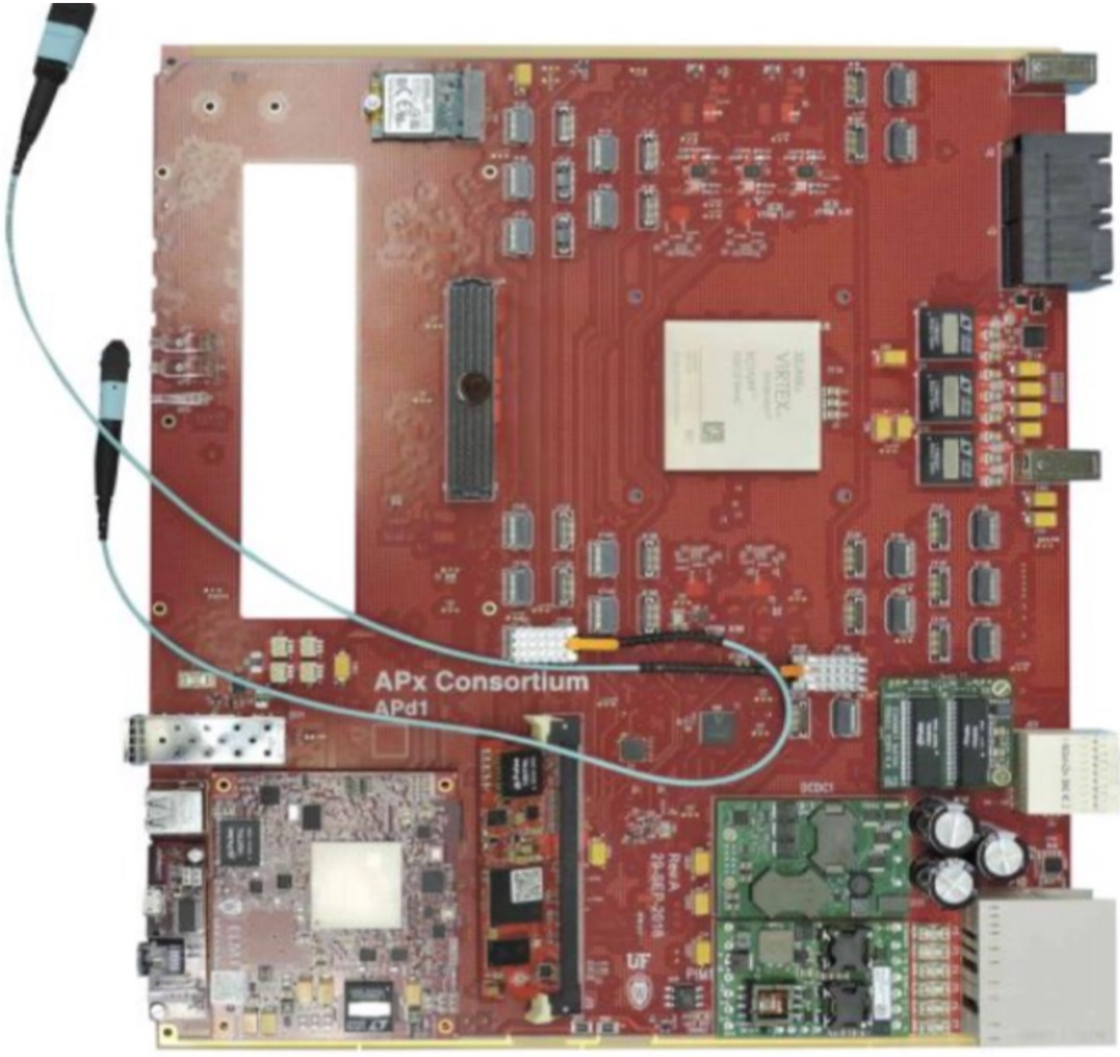
And this (not the H though…) repeats every 25 ns…

The Challenge @ LHC

The Challenge

Where is the needle ?

The Solution

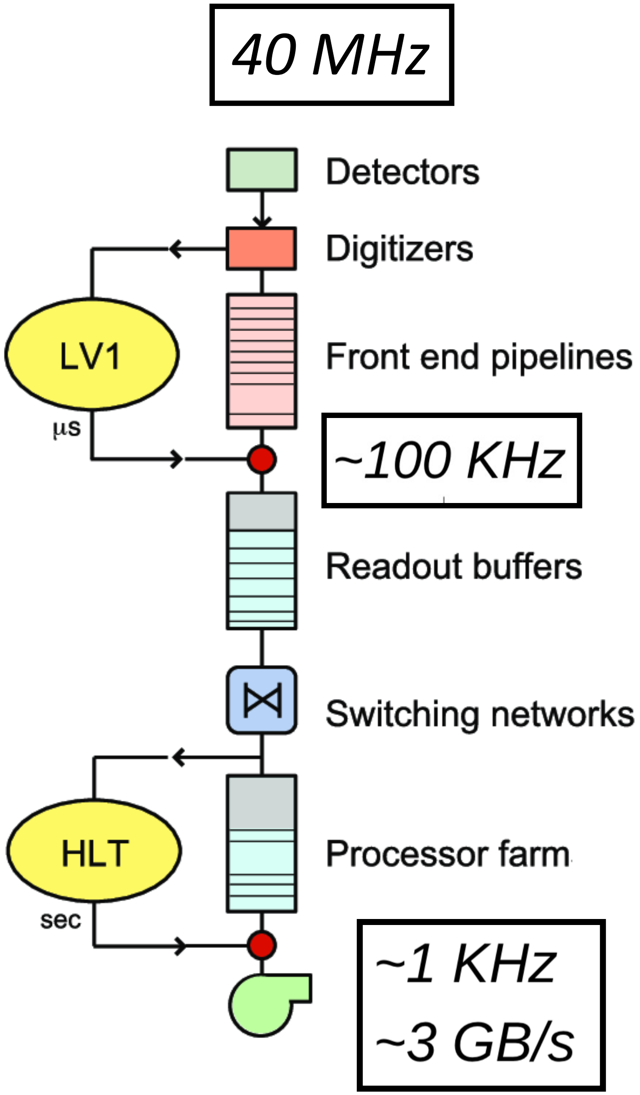


CMS Trigger

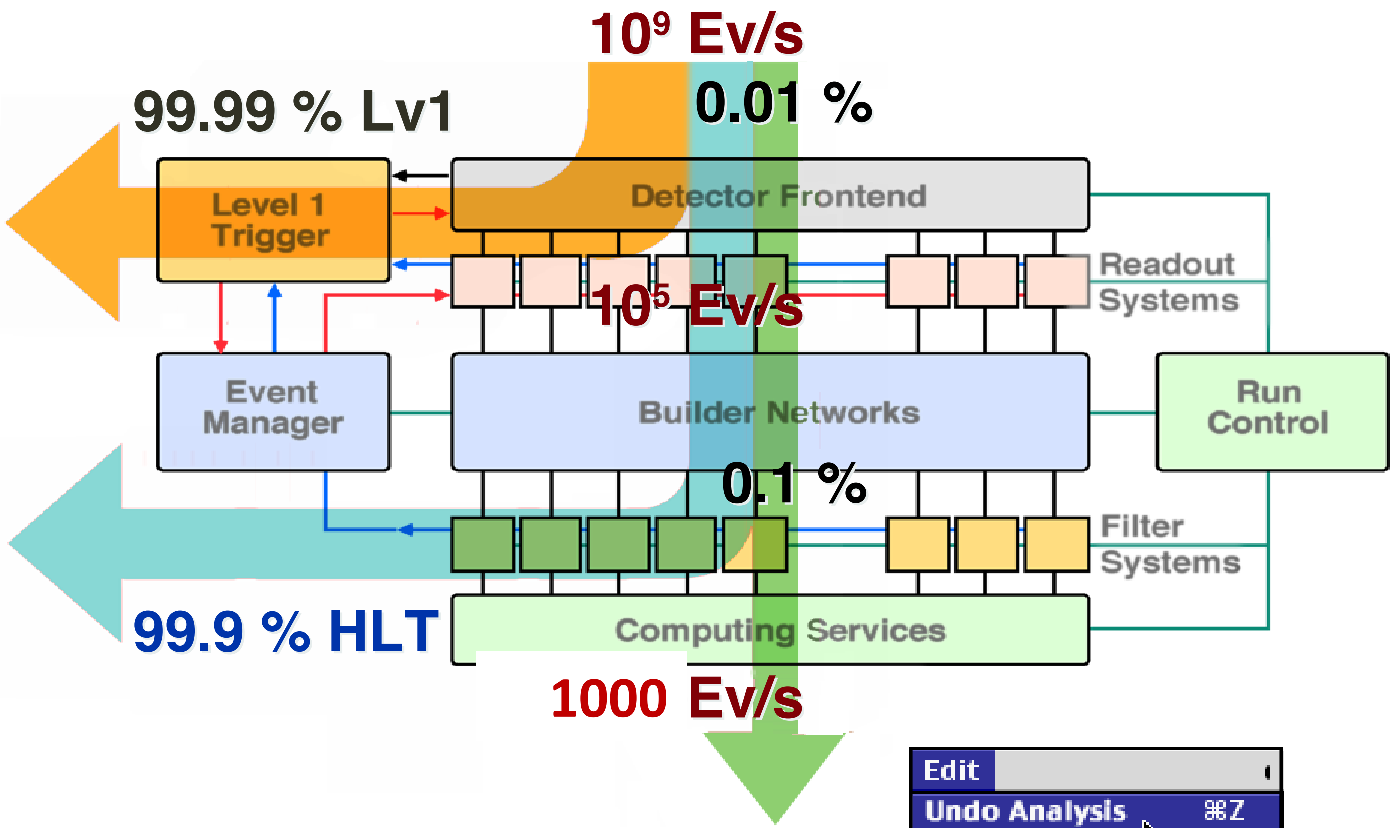
CMS has a 2 level trigger system for selecting interesting collision events

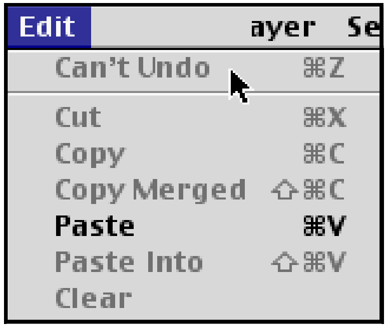
1. Level 1 (L1) trigger: algorithms running on custom electronics boards
   - Coarse calo & muon info, no tracking info.
   - Hard limits on latency (on-detector buffer size) and total accept rate (readout electronics design)

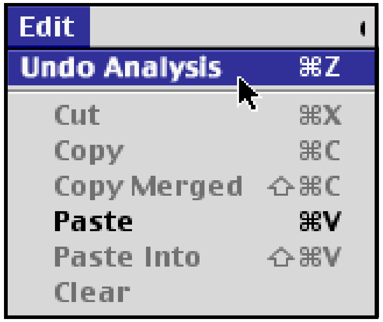
2. High Level Trigger (HLT): algorithms running on commercial CPUs (and GPUs)
   - Hard limit on latency and total bandwidth (transfer data from online file system to storage)
   - *No hard limit on the total rate*



Trigger: tricky business







Will your favorite new physics signal be included in the small fraction of selected events?

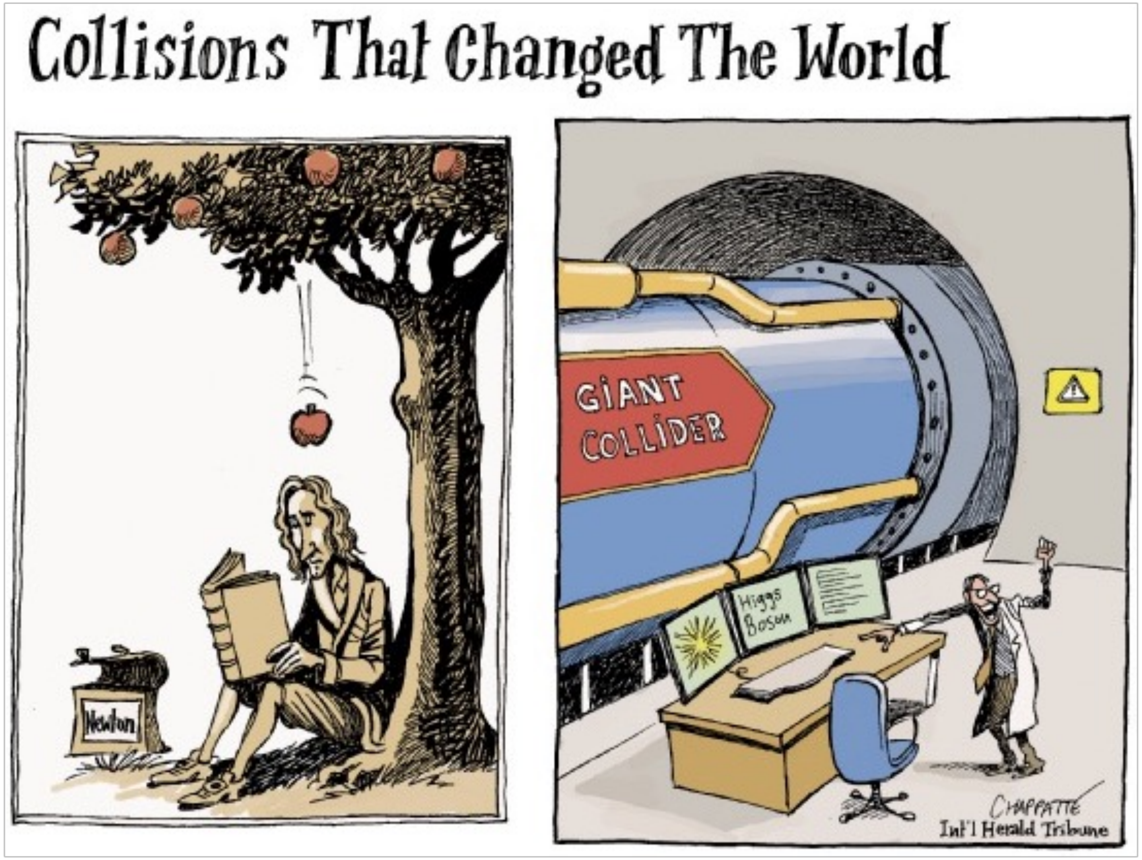
Despite these challenges….

CERN experiments observe particle consistent with long-sought Higgs boson

Geneva, 4 July 2012. At a seminar held at CERN[1] today as a curtain raiser to the year's major particle physics conference, ICHEP2012 in Melbourne, the ATLAS and CMS experiments presented their latest preliminary results in the search for the long sought Higgs particle. Both experiments observe a new particle in the mass region around 125-126 GeV.

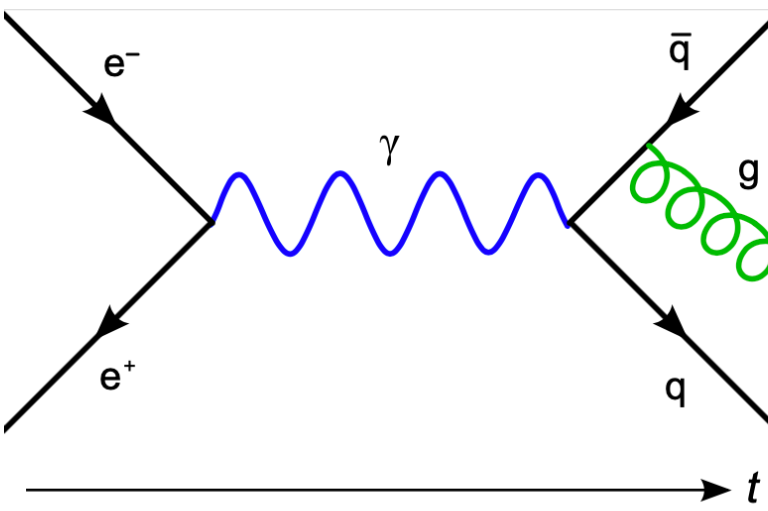
Particle Physics history in the making

The discovery of a SM-like Higgs boson during the LHC Run 1 was a ground-breaking event in physics history



How do you produce a Higgs boson ?

Aside: **Feynman Diagram**



See [video by CMS Collaborator Don Lincoln](#)

Cross sections (σ):
probability that a particular interaction will occur

Unit, by definition: area (cm^2) , commonly "barns", "milli-barns", "pico-barns" etc

Origin: Uranium nucleus – 10^{-24} cm^2
"as big as a barn"

Cross section

$$L = \int \mathcal{L}\, dt$$

Integrated luminosity (dataset)

$$N = L \cdot \sigma$$

Event rate

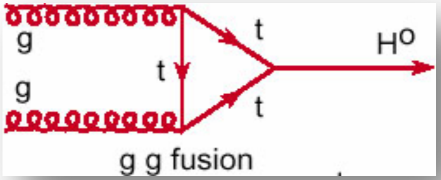
Luminosity (machine)

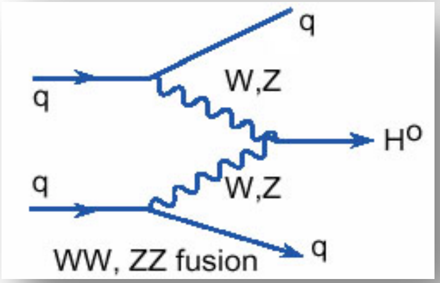
measurement of the **number of collisions** that can be produced in a detector **per cm^2 and per second**

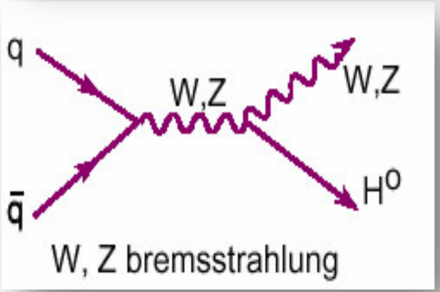
How do you produce a Higgs boson ?

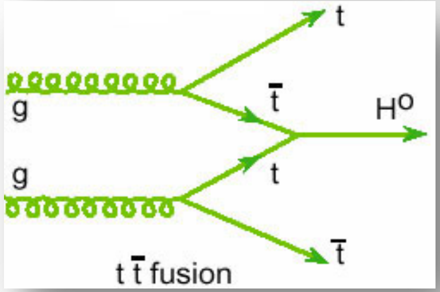
- Dominant production mode: gluon-gluon fusion followed by vector boson fusion (VBF)

- All production modes exploited (gg, VBF, VH, ttH)
  - Latter 3 have smaller **cross-sections** (σ) but better S/B in many cases



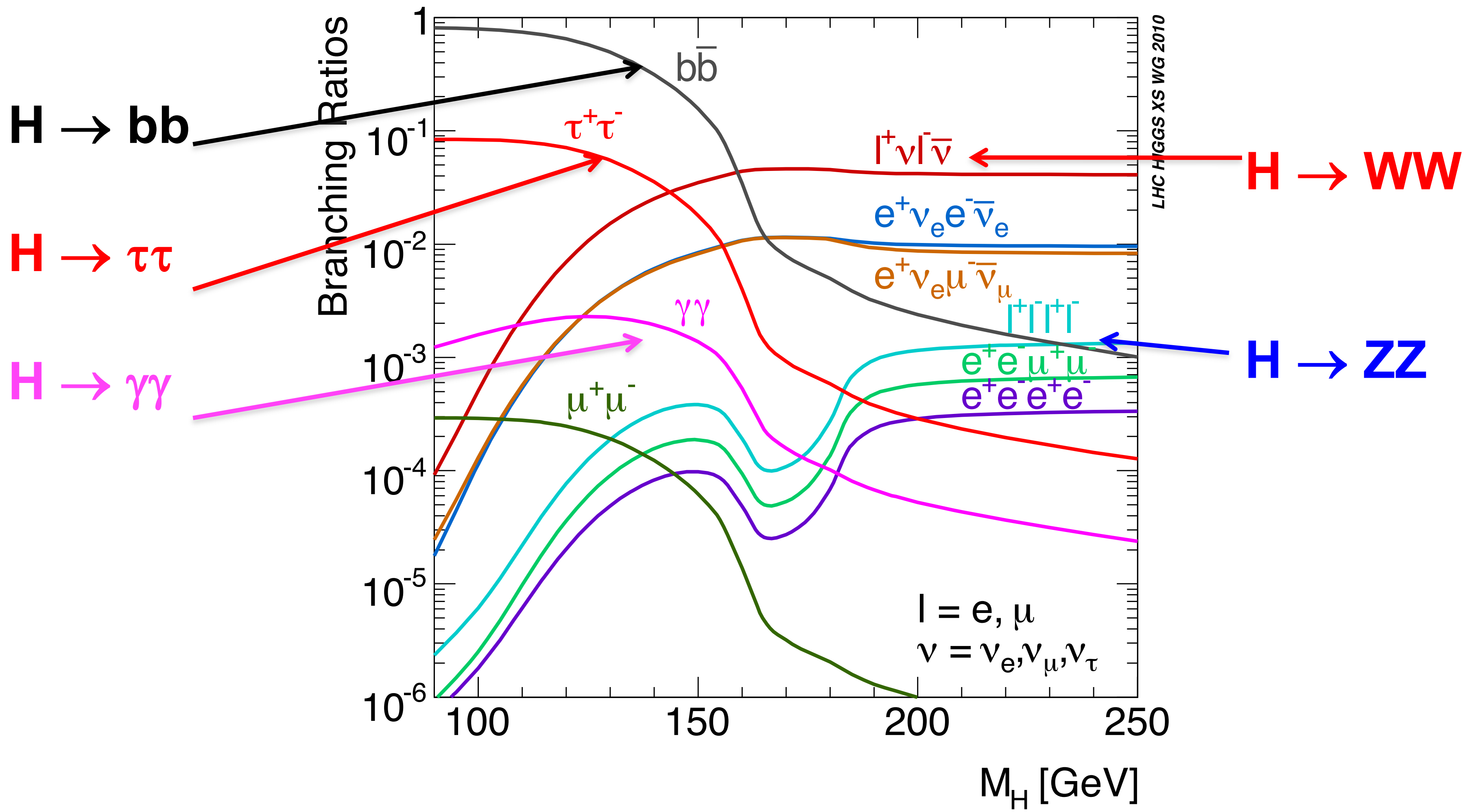






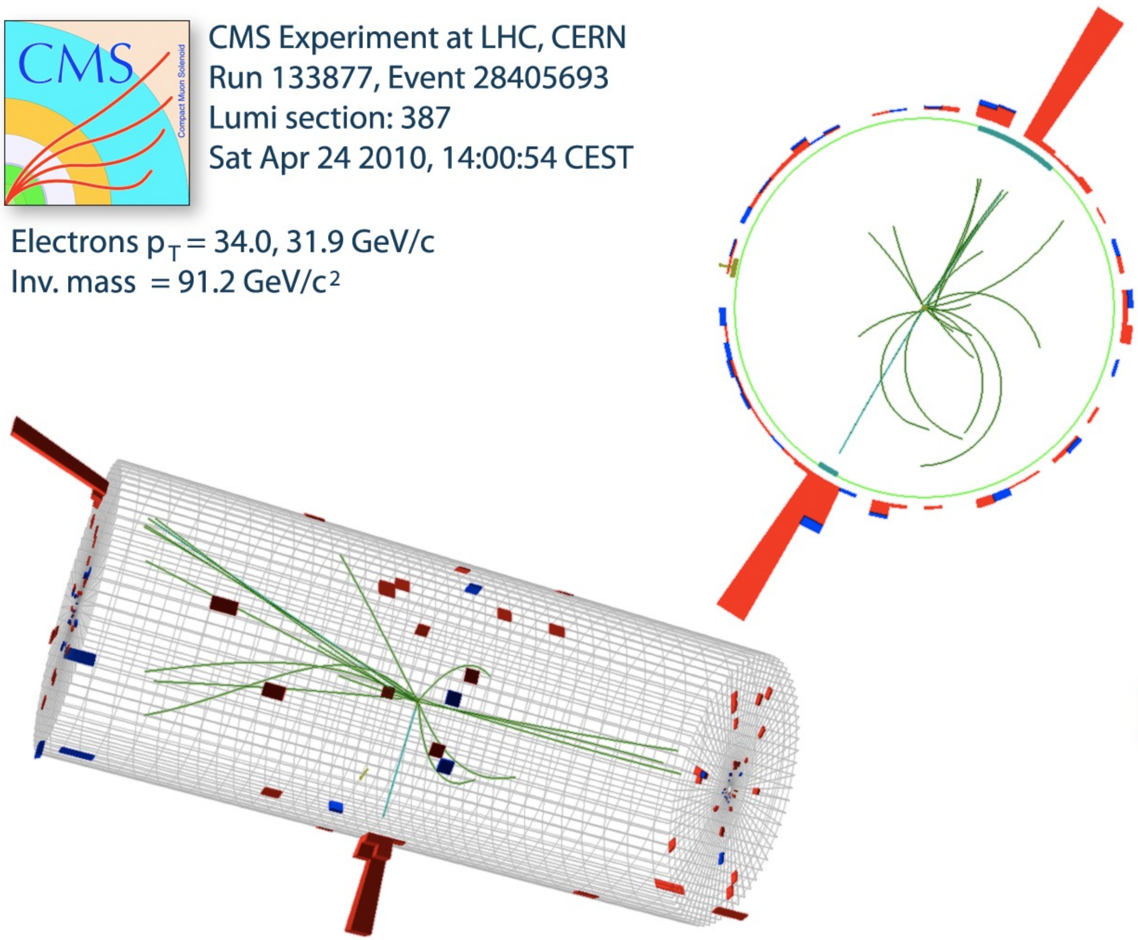
How does a SM Higgs boson decay?

We search for several Higgs decay channels.



How do we reconstruct particles ?

- Most decay close to the interaction point



Event vertex (collision point) is measured using tracks

Note there are several low momentum tracks (underlying event)

Electron (–) and Positron (+) Momentum (P_x, P_y, P_z) measured in tracker
Energy (E) measured in the calorimeter

$$E^2 = (mc^2)^2 + (pc)^2$$

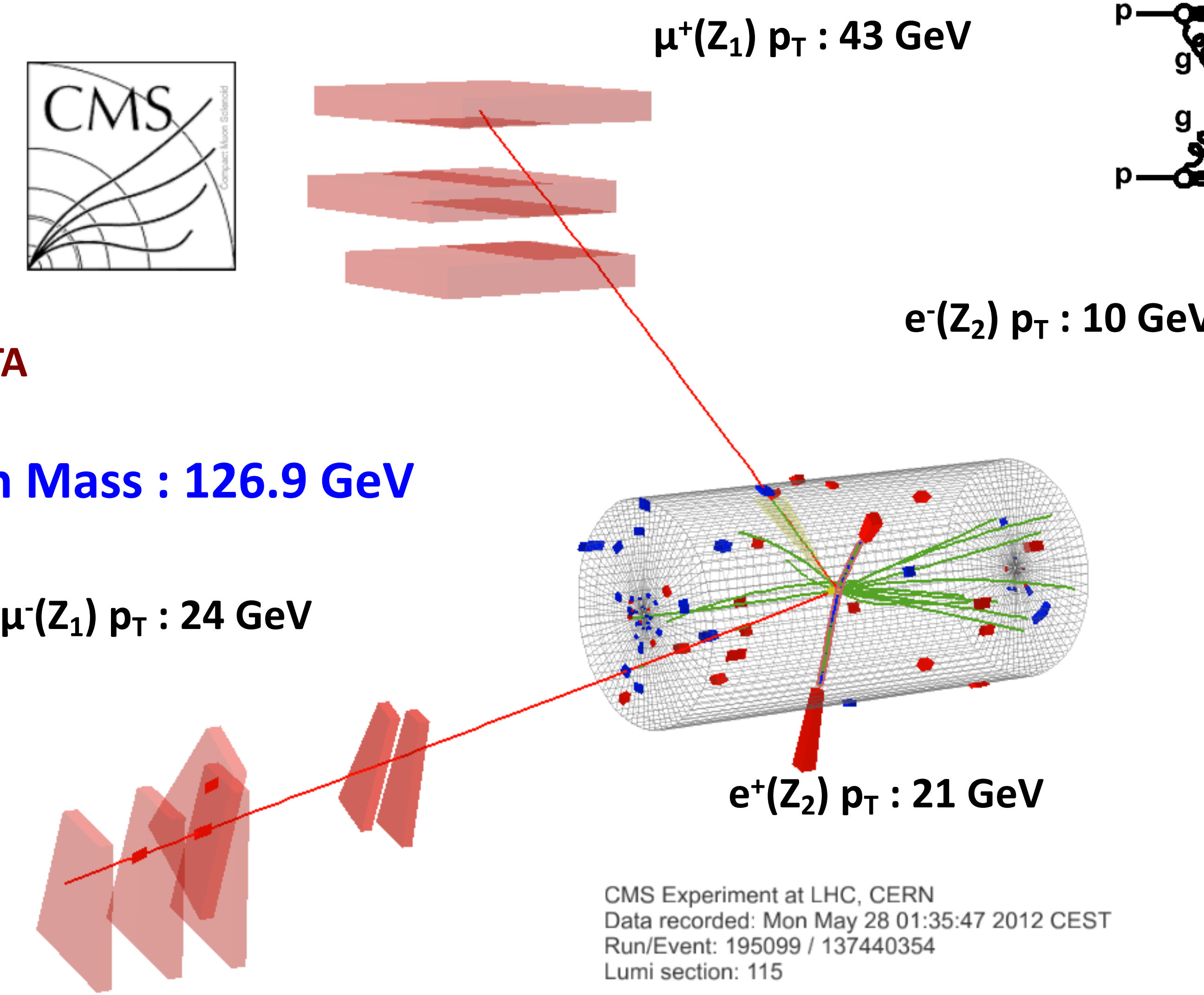
$$pp \rightarrow Z + X \rightarrow e^+e^- + X$$

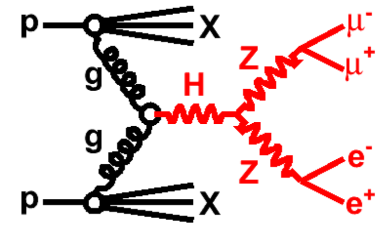
$$Z(91\ \text{GeV})$$

Candidate 4 Lepton Event

8 TeV DATA

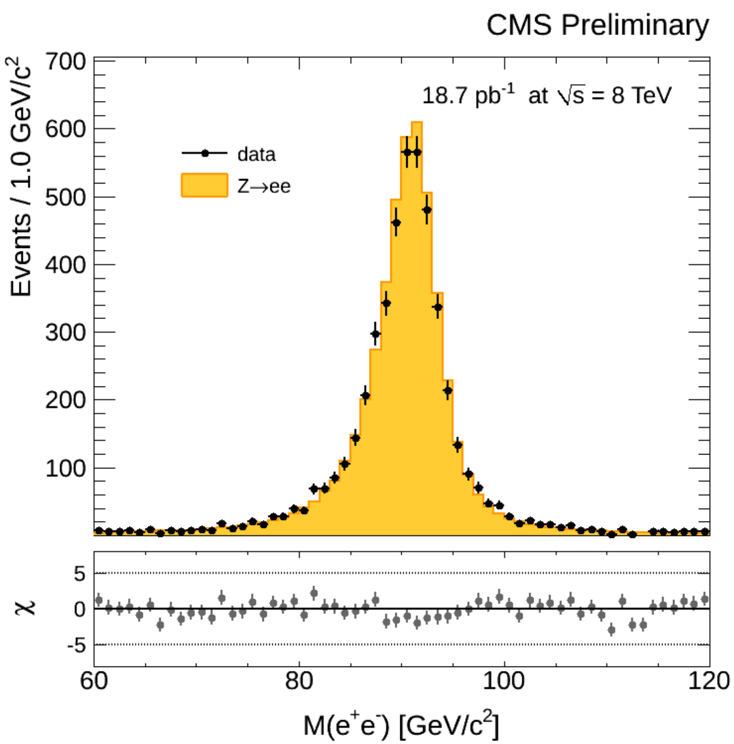
4-lepton Mass : 126.9 GeV



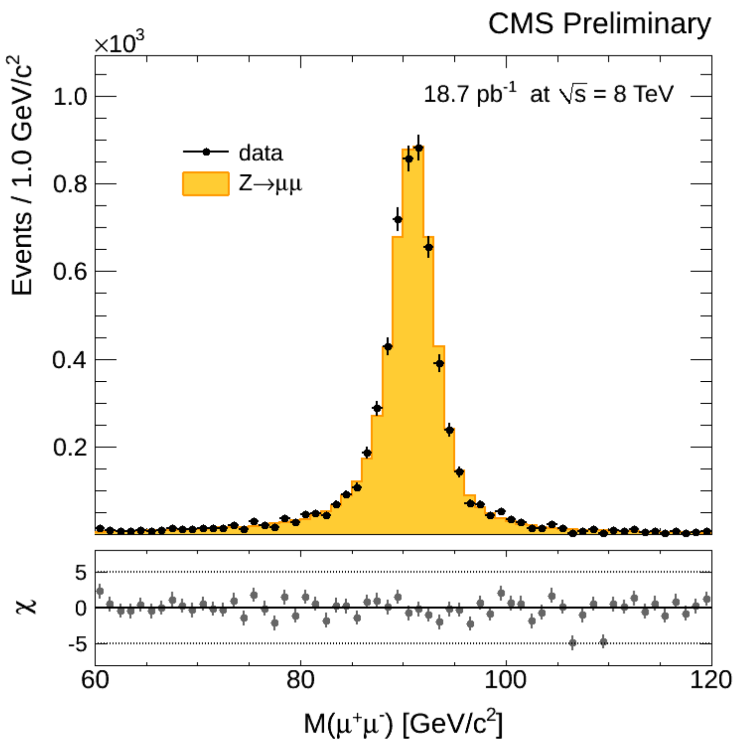


The Z Boson Invariant Mass Peak

- Particles decaying close to the interaction point
  - Histogram of “invariant mass” of the original heavy particle shows a sharp peak at the mass of the Z (91 GeV)



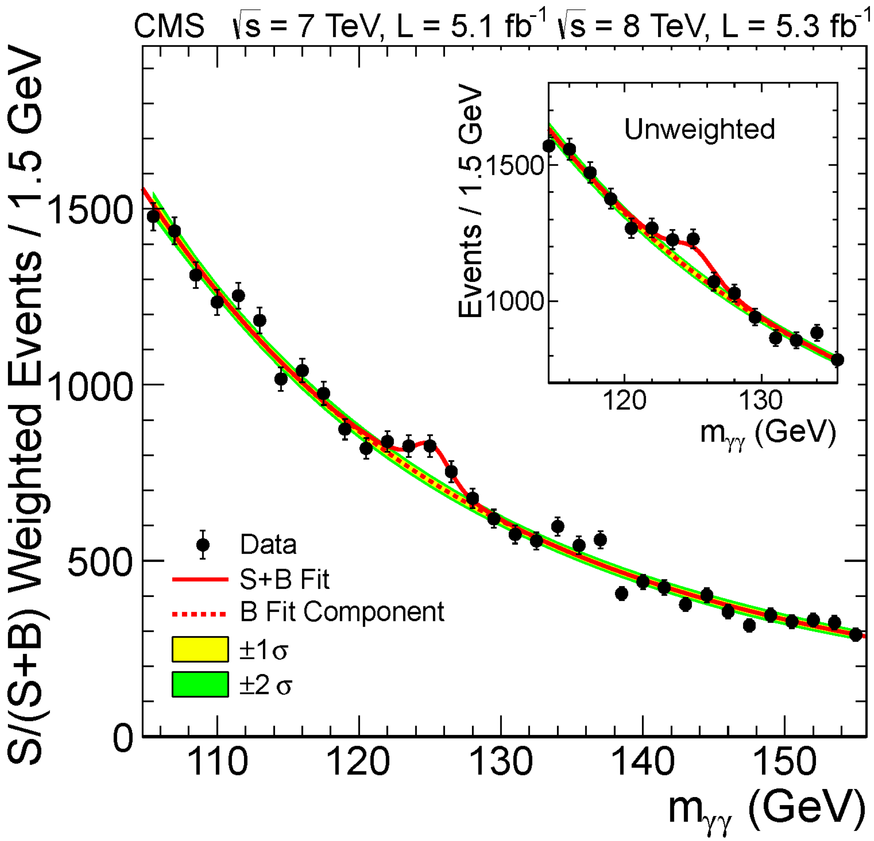
Mass of Electron-Positron Pair

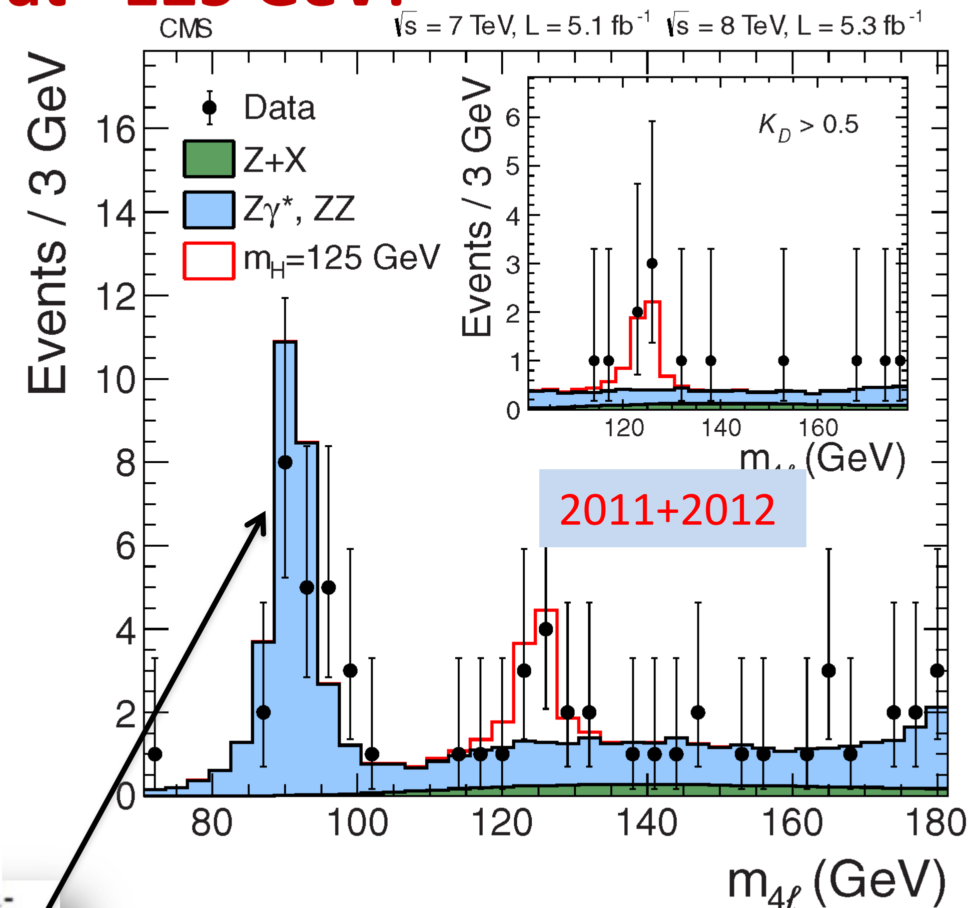


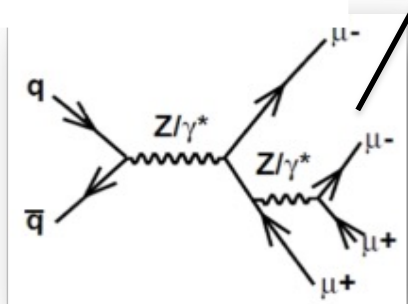
Mass of Muon⁺-Muon⁻ Pair

H→ γγ and H→ ZZ

A clear peak at ~125 GeV!





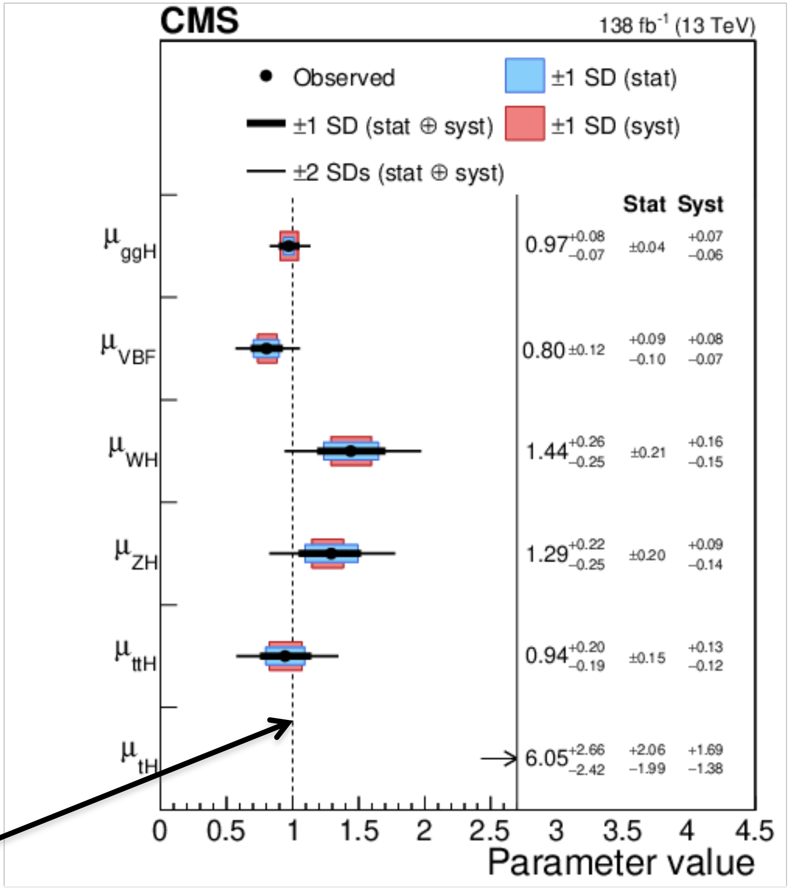


Excellent understanding of the background at all masses

"Greetings Earth-people. We have been monitoring your progress. Now that you have discovered the Higg's boson you are qualified to join the Federation of Advanced Civilisations."

Higgs Production

- Following its discovery, significant effort has been put into characterizing the properties of the Higgs Boson
- Objectives:
  - observe it in as many different ways as possible to measure its properties



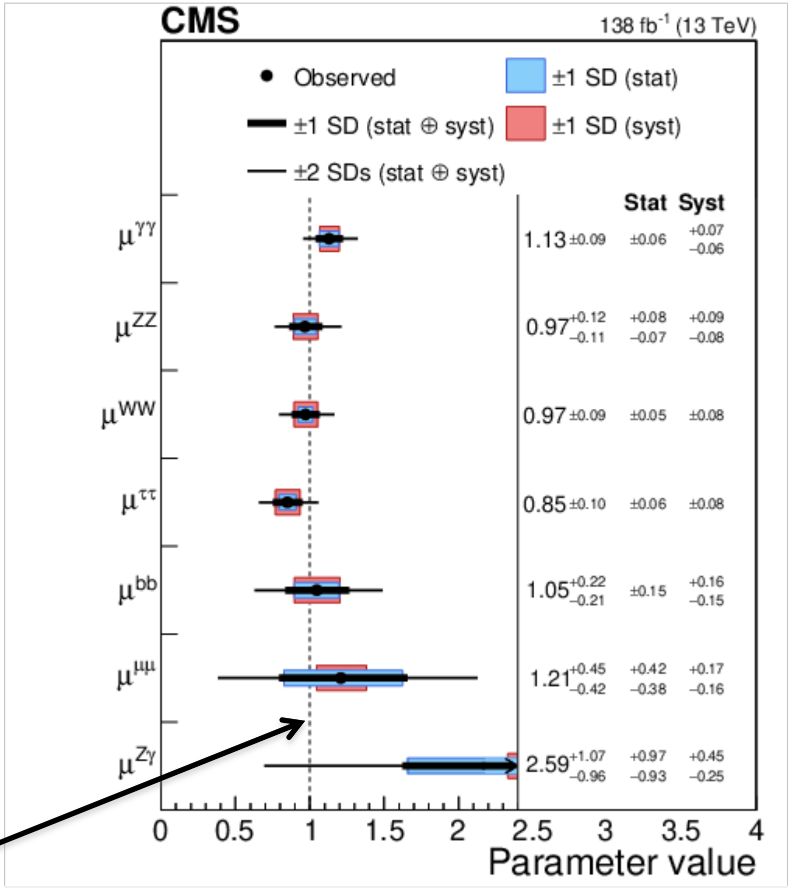
Tests all parts of the theory!

1 is perfect agreement with predictions

μ = measurement/prediction

Higgs Decay

- Following its discovery, significant effort has been put into characterizing the properties of the Higgs Boson
- Objectives:
  – observe it in as many different ways as possible to measure its properties

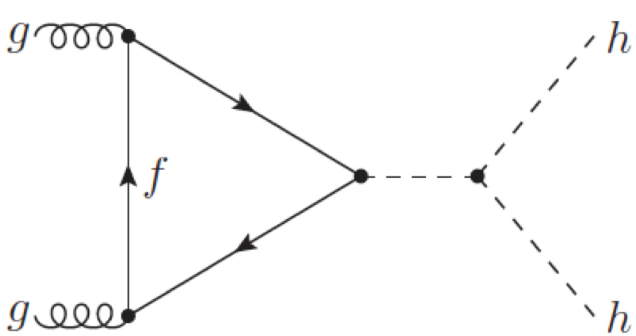


1 is perfect agreement with predictions

Tests all parts of the theory!

Key questions: post-discovery era

- Is it a Higgs boson or the Higgs boson ?
  - Is it elementary or composite ?
  - Does it interact with itself ?
- How does the Higgs couple to light particles (e.g. $h \rightarrow J/\Psi+\gamma$)
- And how does it couple to muons ?
- Why is the Higgs so light ?
- Are there additional Higgs bosons ?
- Are there exotic Higgs decays ?



Where are we today ?

Note 95% of the total LHC data still to come (and be studied)!

Quest for new physics

- Precision measurements of SM processes
  - Understand SM backgrounds, look for deviations or anomalies
- Searches/measurements of rare SM processes
  - Take advantage of the large LHC datasets and look for (significant) enhancement from beyond-the-SM (BSM) particles

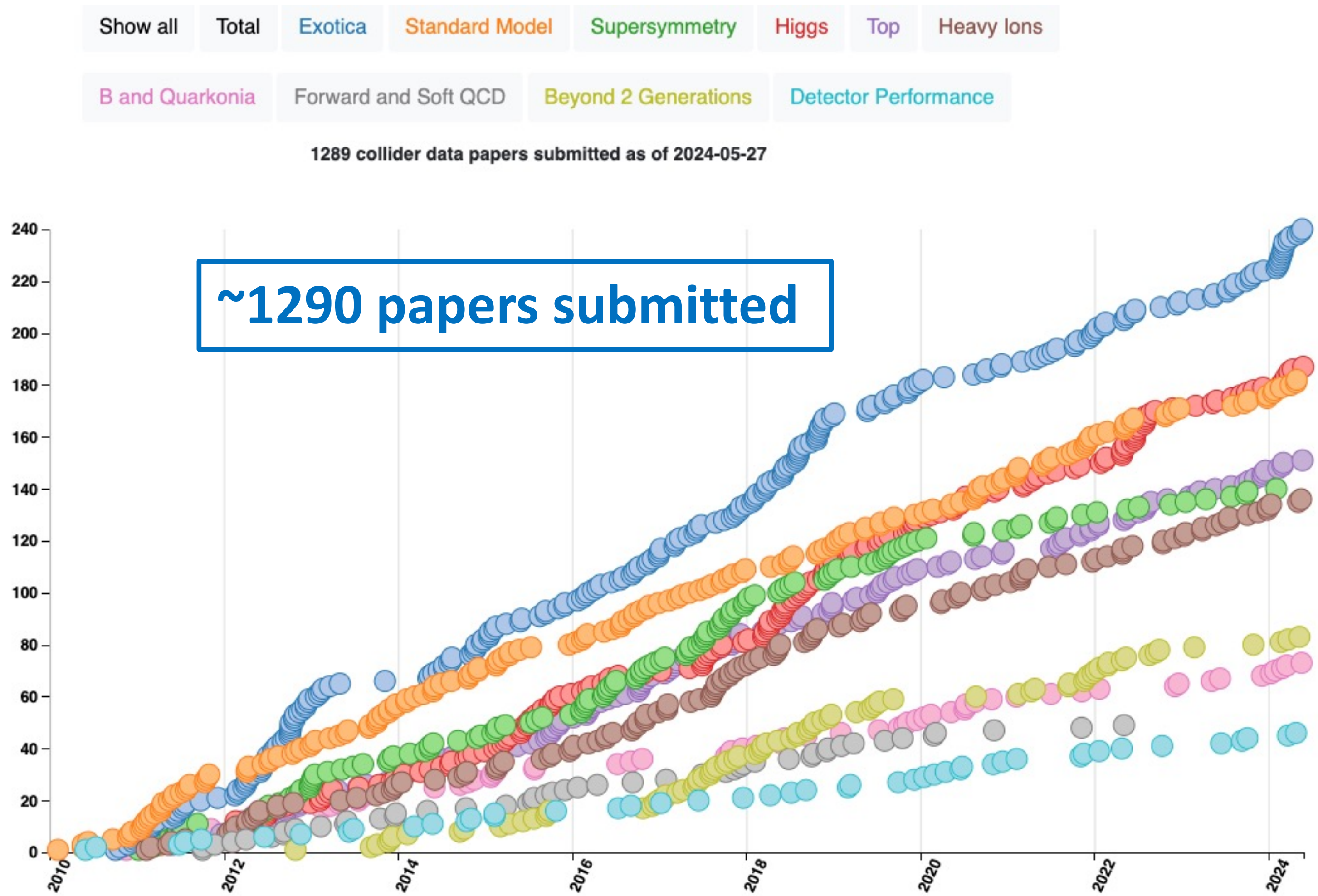
SM as a tool for discovery

- Direct searches for BSM particles
  - Go in new directions with new models, challenging topologies, enlarged parameter space → innovate!

Exploring the unknown

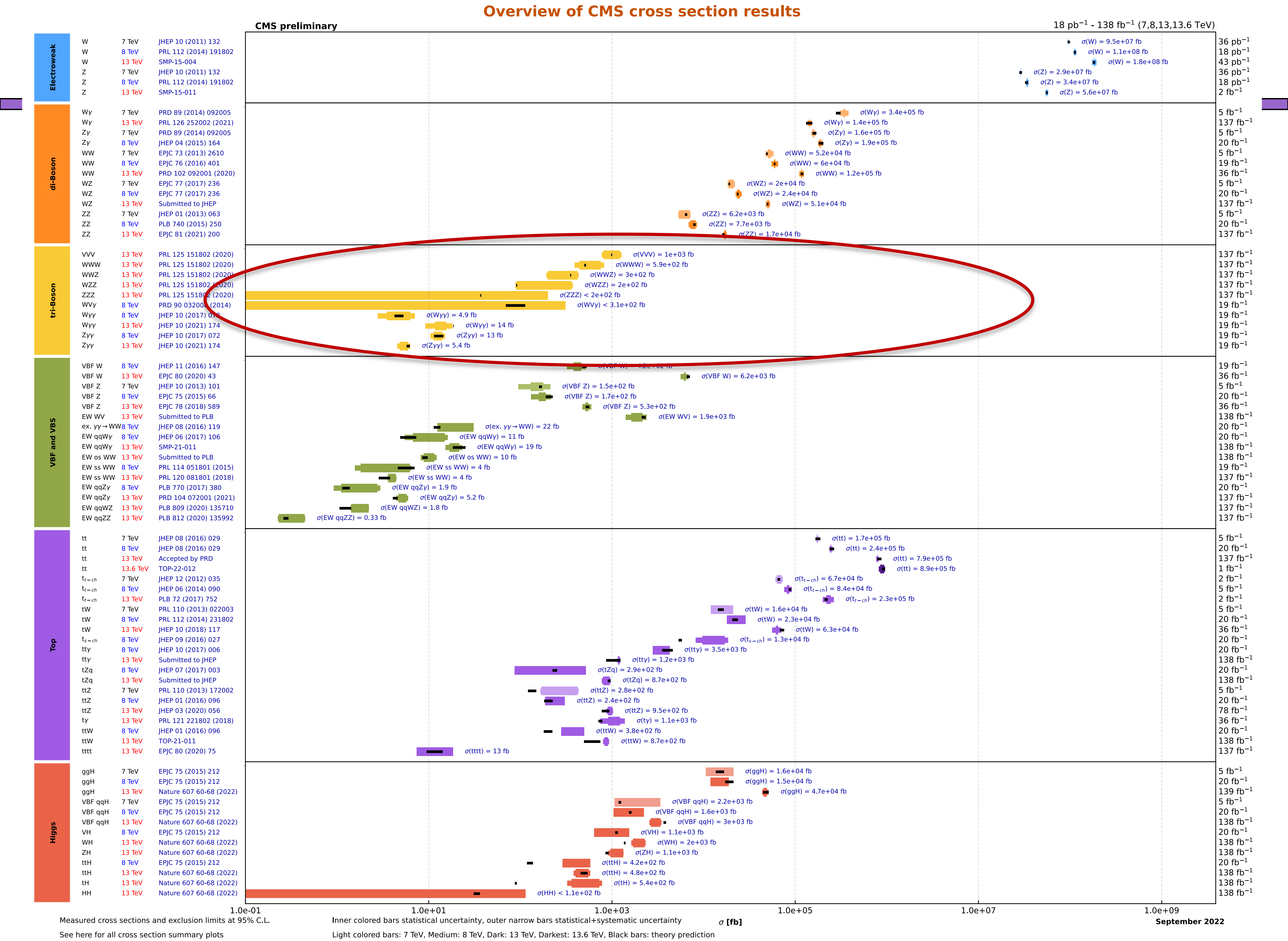
Take advantage of state-of-the-art analysis methods, data mining, machine learning, new technologies, upgraded detectors…

CMS Publications



https://cms-results.web.cern.ch/cms-results/public-results/publications-vs-time/

CMS Physics Briefings: https://cms.cern/tags/physics-briefing

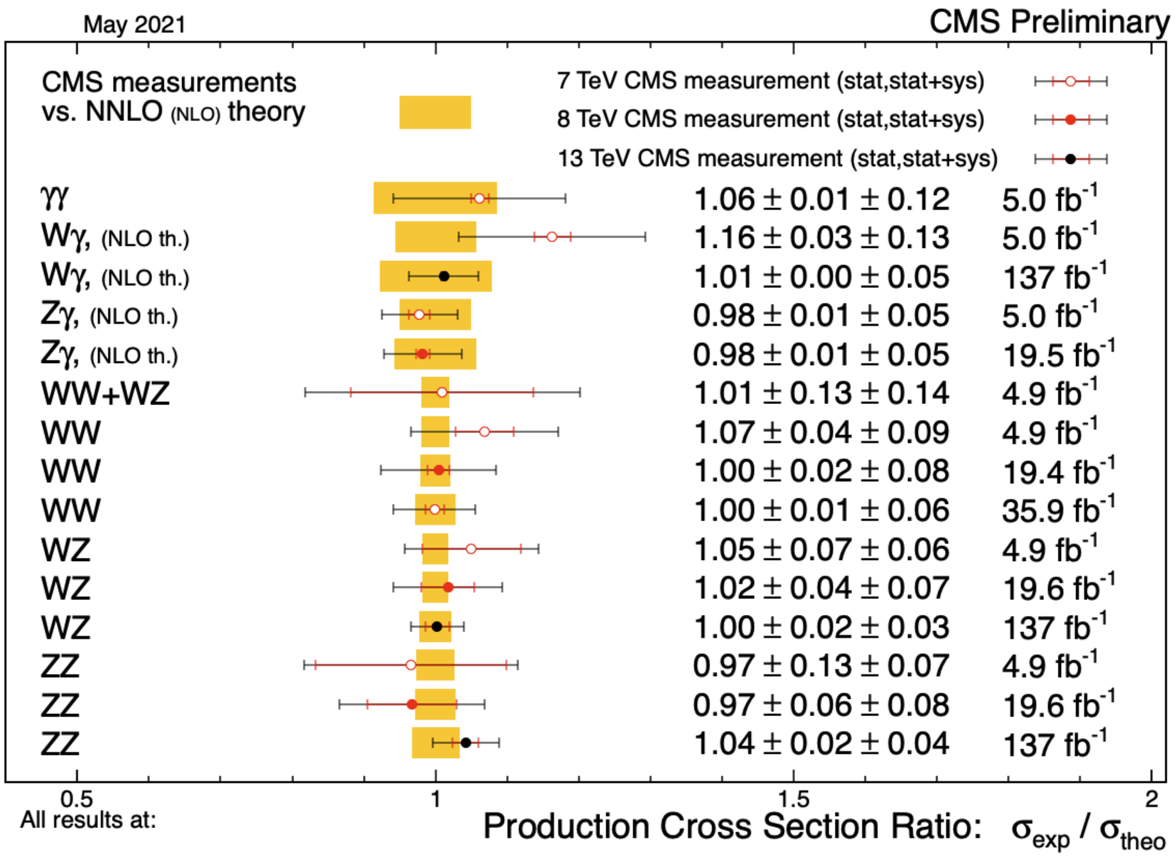

Overview of CMS cross section results
CMS preliminary
18 pb^-1 - 138 fb^-1 (7,8,13,13.6 TeV)
Electroweak
W 7 TeV JHEP 10 (2011) 132 σ(W) = 9.5e+07 fb 36 pb^-1
W 8 TeV PRL 112 (2014) 191802 σ(W) = 1.1e+08 fb 18 pb^-1
W 13 TeV SMP-15-004 σ(W) = 1.8e+08 fb 43 pb^-1
Z 7 TeV JHEP 10 (2011) 132 σ(Z) = 2.9e+07 fb 36 pb^-1
Z 8 TeV PRL 112 (2014) 191802 σ(Z) = 3.4e+07 fb 18 pb^-1
Z 13 TeV SMP-15-011 σ(Z) = 5.6e+07 fb 2 fb^-1
di-Boson
Wγ 7 TeV PRD 89 (2014) 092005 σ(Wγ) = 3.4e+05 fb 5 fb^-1
Wγ 13 TeV PRL 126 252002 (2021) σ(Wγ) = 1.4e+05 fb 137 fb^-1
Zγ 7 TeV PRD 89 (2014) 092005 σ(Zγ) = 1.6e+05 fb 5 fb^-1
Zγ 8 TeV JHEP 04 (2015) 164 σ(Zγ) = 1.9e+05 fb 20 fb^-1
WW 7 TeV EPJC 73 (2013) 2610 σ(WW) = 5.2e+04 fb 5 fb^-1
WW 8 TeV EPJC 76 (2016) 401 σ(WW) = 6e+04 fb 19 fb^-1
WW 13 TeV PRD 102 092001 (2020) σ(WW) = 1.2e+05 fb 36 fb^-1
WZ 7 TeV EPJC 77 (2017) 236 σ(WZ) = 2e+04 fb 5 fb^-1
WZ 8 TeV EPJC 77 (2017) 236 σ(WZ) = 2.4e+04 fb 20 fb^-1
WZ 13 TeV Submitted to JHEP σ(WZ) = 5.1e+04 fb 137 fb^-1
ZZ 7 TeV JHEP 01 (2013) 063 σ(ZZ) = 6.2e+03 fb 5 fb^-1
ZZ 8 TeV PLB 740 (2015) 250 σ(ZZ) = 7.7e+03 fb 20 fb^-1
ZZ 13 TeV EPJC 81 (2021) 200 σ(ZZ) = 1.7e+04 fb 137 fb^-1
tri-Boson
VVV 13 TeV PRL 125 151802 (2020) σ(VVV) = 1e+03 fb 137 fb^-1
WWW 13 TeV PRL 125 151802 (2020) σ(WWW) = 5.9e+02 fb 137 fb^-1
WWZ 13 TeV PRL 125 151802 (2020) σ(WWZ) = 3e+02 fb 137 fb^-1
WZZ 13 TeV PRL 125 151802 (2020) σ(WZZ) = 2e+02 fb 137 fb^-1
ZZZ 13 TeV PRL 125 151802 (2020) σ(ZZZ) < 2e+02 fb 137 fb^-1
Wγ 8 TeV PRD 90 032008 (2014) σ(WVγ) < 3.1e+02 fb 19 fb^-1
Wγγ 8 TeV JHEP 10 (2017) 072 σ(Wγγ) = 4.9 fb 19 fb^-1
Wγγ 13 TeV JHEP 10 (2021) 174 σ(Wγγ) = 14 fb 19 fb^-1
Zγγ 8 TeV JHEP 10 (2017) 072 σ(Zγγ) = 13 fb 19 fb^-1
Zγγ 13 TeV JHEP 10 (2021) 174 σ(Zγγ) = 5.4 fb 19 fb^-1
VBF and VBS
VBF W 8 TeV JHEP 11 (2016) 147 19 fb^-1
VBF W 13 TeV EPJC 80 (2020) 43 σ(VBF W) = 6.2e+03 fb 36 fb^-1
VBF Z 7 TeV JHEP 10 (2013) 101 σ(VBF Z) = 1.5e+02 fb 5 fb^-1
VBF Z 8 TeV EPJC 75 (2015) 66 σ(VBF Z) = 1.7e+02 fb 20 fb^-1
VBF Z 13 TeV EPJC 78 (2018) 589 σ(VBF Z) = 5.3e+02 fb 36 fb^-1
EW WV 13 TeV Submitted to PLB σ(EW WV) = 1.9e+03 fb 138 fb^-1
ex. γγ→WW 8 TeV JHEP 08 (2016) 119 σ(ex. γγ→WW) = 22 fb 20 fb^-1
EW qqWγ 8 TeV JHEP 06 (2017) 106 σ(EW qqWγ) = 11 fb 20 fb^-1
EW qqWγ 13 TeV SMP-21-011 σ(EW qqWγ) = 19 fb 138 fb^-1
EW os WW 13 TeV Submitted to PLB σ(EW os WW) = 10 fb 138 fb^-1
EW ss WW 8 TeV PRL 114 051801 (2015) σ(EW ss WW) = 4 fb 19 fb^-1
EW ss WW 13 TeV PRL 120 081801 (2018) σ(EW ss WW) = 4 fb 137 fb^-1
EW qqZγ 8 TeV PLB 770 (2017) 380 σ(EW qqZγ) = 1.9 fb 20 fb^-1
EW qqZγ 13 TeV PRD 104 072001 (2021) σ(EW qqZγ) = 5.2 fb 137 fb^-1
EW qqWZ 13 TeV PLB 809 (2020) 135710 σ(EW qqWZ) = 1.8 fb 137 fb^-1
EW qqZZ 13 TeV PLB 812 (2020) 135992 σ(EW qqZZ) = 0.33 fb 137 fb^-1
Top
tt 7 TeV JHEP 08 (2016) 029 σ(tt) = 1.7e+05 fb 5 fb^-1
tt 8 TeV JHEP 08 (2016) 029 σ(tt) = 2.4e+05 fb 20 fb^-1
tt 13 TeV Accepted by PRD σ(tt) = 7.9e+05 fb 137 fb^-1
tt 13.6 TeV TOP-22-012 σ(tt) = 8.9e+05 fb 1 fb^-1
t_t−ch 7 TeV JHEP 12 (2012) 035 σ(t_t−ch) = 6.7e+04 fb 2 fb^-1
t_t−ch 8 TeV JHEP 06 (2014) 090 σ(t_t−ch) = 8.4e+04 fb 5 fb^-1
t_t−ch 13 TeV PLB 72 (2017) 752 σ(t_t−ch) = 2.3e+05 fb 2 fb^-1
tW 7 TeV PRL 110 (2013) 022003 σ(tW) = 1.6e+04 fb 5 fb^-1
tW 8 TeV PRL 112 (2014) 231802 σ(tW) = 2.3e+04 fb 20 fb^-1
tW 13 TeV JHEP 10 (2018) 117 σ(tW) = 6.3e+04 fb 36 fb^-1
t_s−ch 8 TeV JHEP 09 (2016) 027 σ(t_s−ch) = 1.3e+04 fb 20 fb^-1
ttγ 8 TeV JHEP 10 (2017) 006 σ(ttγ) = 3.5e+03 fb 20 fb^-1
ttγ 13 TeV Submitted to JHEP σ(ttγ) = 1.2e+03 fb 138 fb^-1
tZq 8 TeV JHEP 07 (2017) 003 σ(tZq) = 2.9e+02 fb 20 fb^-1
tZq 13 TeV Submitted to JHEP σ(tZq) = 8.7e+02 fb 138 fb^-1
ttZ 7 TeV PRL 110 (2013) 172002 σ(ttZ) = 2.8e+02 fb 5 fb^-1
ttZ 8 TeV JHEP 01 (2016) 096 σ(ttZ) = 2.4e+02 fb 20 fb^-1
ttZ 13 TeV JHEP 03 (2020) 056 σ(ttZ) = 9.5e+02 fb 78 fb^-1
tγ 13 TeV PRL 121 221802 (2018) σ(tγ) = 1.1e+03 fb 36 fb^-1
ttW 8 TeV JHEP 01 (2016) 096 σ(ttW) = 3.8e+02 fb 20 fb^-1
ttW 13 TeV TOP-21-011 σ(ttW) = 8.7e+02 fb 138 fb^-1
tttt 13 TeV EPJC 80 (2020) 75 σ(tttt) = 13 fb 137 fb^-1
Higgs
ggH 7 TeV EPJC 75 (2015) 212 σ(ggH) = 1.6e+04 fb 5 fb^-1
ggH 8 TeV EPJC 75 (2015) 212 σ(ggH) = 1.5e+04 fb 20 fb^-1
ggH 13 TeV Nature 607 60-68 (2022) σ(ggH) = 4.7e+04 fb 139 fb^-1
VBF qqH 7 TeV EPJC 75 (2015) 212 σ(VBF qqH) = 2.2e+03 fb 5 fb^-1
VBF qqH 8 TeV EPJC 75 (2015) 212 σ(VBF qqH) = 1.6e+03 fb 20 fb^-1
VBF qqH 13 TeV Nature 607 60-68 (2022) σ(VBF qqH) = 3e+03 fb 138 fb^-1
VH 8 TeV EPJC 75 (2015) 212 σ(VH) = 1.1e+03 fb 20 fb^-1
WH 13 TeV Nature 607 60-68 (2022) σ(WH) = 2e+03 fb 138 fb^-1
ZH 13 TeV Nature 607 60-68 (2022) σ(ZH) = 1.1e+03 fb 138 fb^-1
ttH 8 TeV EPJC 75 (2015) 212 σ(ttH) = 4.2e+02 fb 20 fb^-1
ttH 13 TeV Nature 607 60-68 (2022) σ(ttH) = 4.8e+02 fb 138 fb^-1
tH 13 TeV Nature 607 60-68 (2022) σ(tH) = 5.4e+02 fb 138 fb^-1
HH 13 TeV Nature 607 60-68 (2022) σ(HH) < 1.1e+02 fb 138 fb^-1
1.0e-01 1.0e+01 1.0e+03 1.0e+05 1.0e+07 1.0e+09
σ [fb]
September 2022
Measured cross sections and exclusion limits at 95% C.L.
See here for all cross section summary plots
Inner colored bars statistical uncertainty, outer narrow bars statistical+systematic uncertainty
Light colored bars: 7 TeV, Medium: 8 TeV, Dark: 13 TeV, Darkest: 13.6 TeV, Black bars: theory prediction

Precision measurements of rare processes

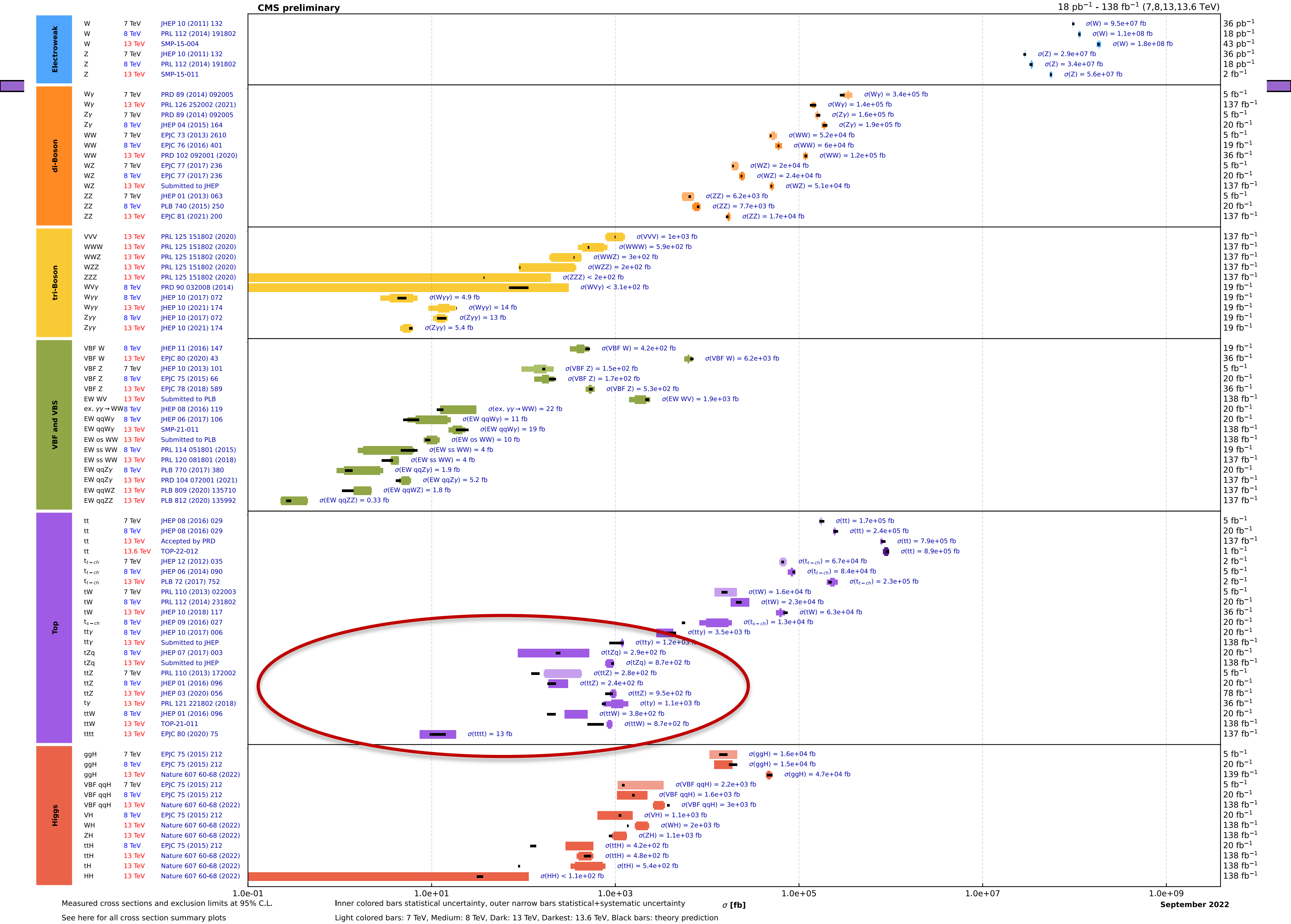
- Large datasets allow us to test the SM in complementary ways
  - multi-differential cross-section measurements
  - First-time sensitivity to rare multi- boson final states and production mechanisms

Starting to be sensitive to higher order theoretical corrections;

Still room for surprises!



Overview of CMS cross section results



Top Quark Physics

Over ~25 years since its discovery, the top quark is still one of the hottest topics…

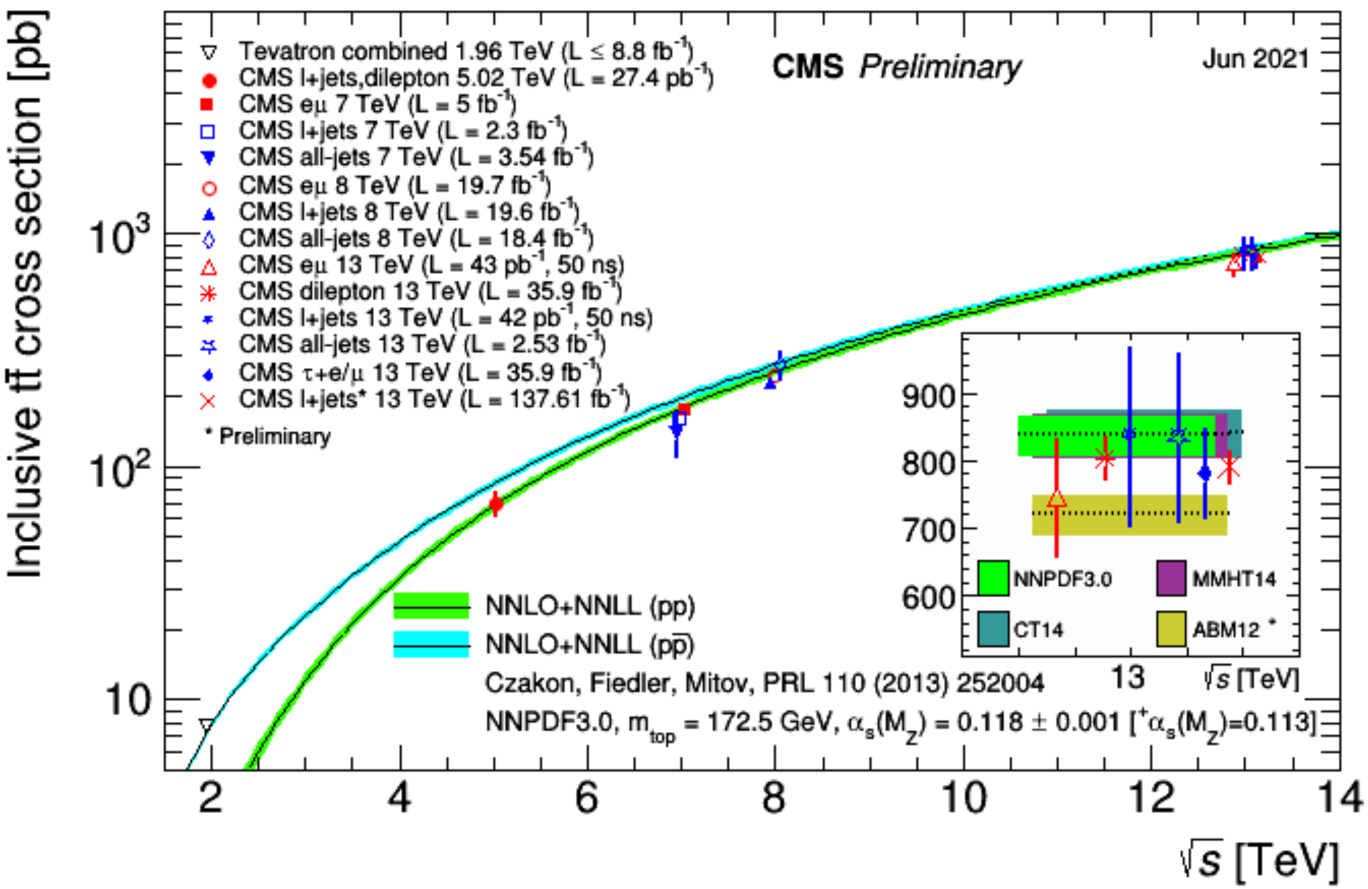
March 2, 1995
Ramsey Auditorium (Fermilab)

DZero experimenters submit their top quark discovery paper to Physical Review Letters

Precision Top Quark Physics

Over ~25 years since its discovery, the top quark is still one of the hottest topics…

LHC: a top quark factory!

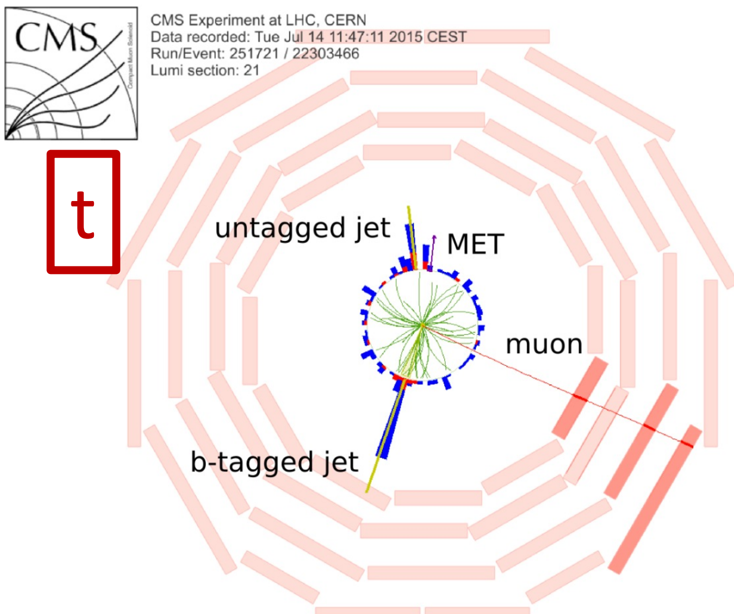


Inclusive cross section well understood;

Agrees with higher order theoretical predictions

Top evolution

t



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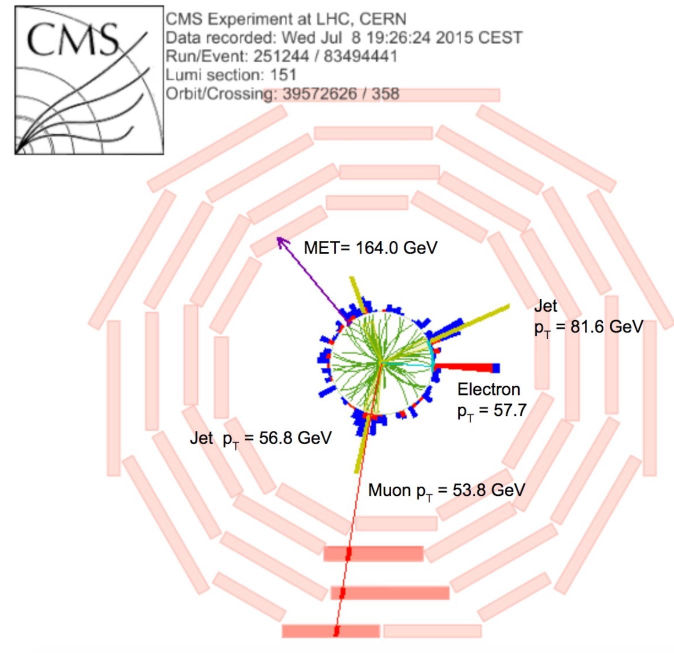
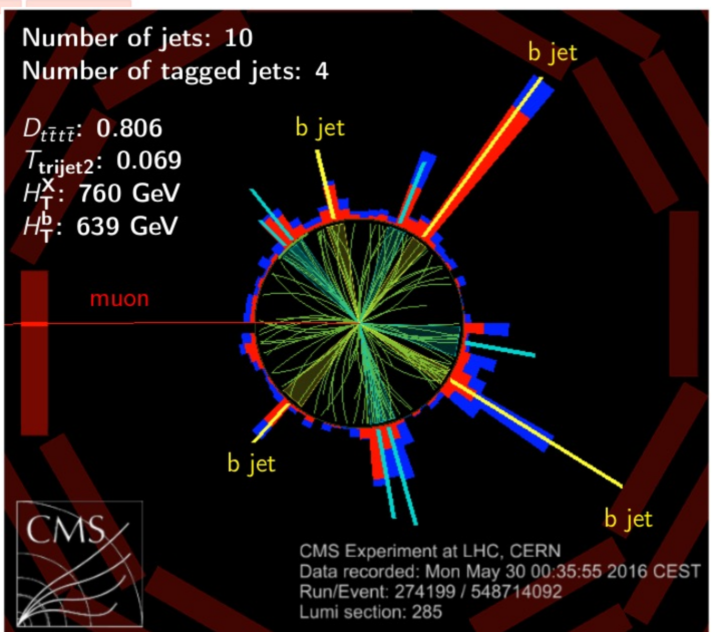


tttt

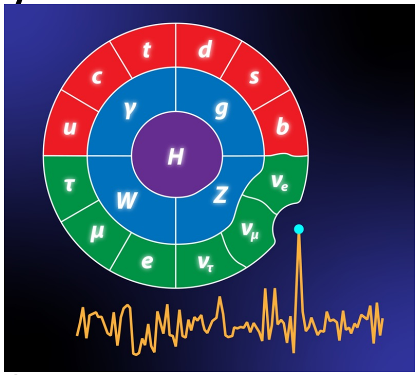


What about ttt production ?

Analysis currently ongoing

Exploring the unknown

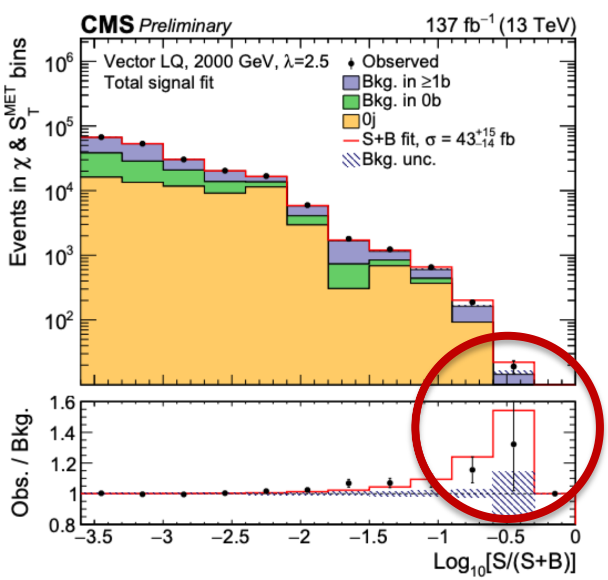
As we look forward to Run 3, I find it useful to group potentially interesting searches into these categories:

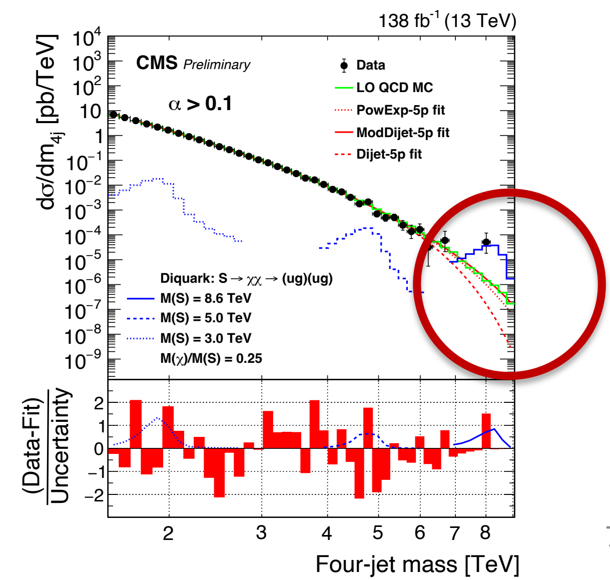


- Anomalies
- **New** channels not yet excluded by other searches
- Searches enabled by **novel** techniques
- Searches enabled by using the detector in **creative** ways
- Unconventional final states

Anomalies

- Extensive program of measurements and searches during Run 2
- Statistical fluctuations are expected to occur
  - given all the different search regions, observables, challenges of background estimation techniques, understanding of systematics etc.
- Some of these “anomalies” have gone away with more data, others persist or appear in the full Run 2 dataset, and others might be due to our incomplete understanding of the SM
  - Imp. to keep an eye on them as we plan analyses for Run 3 and HL-LHC

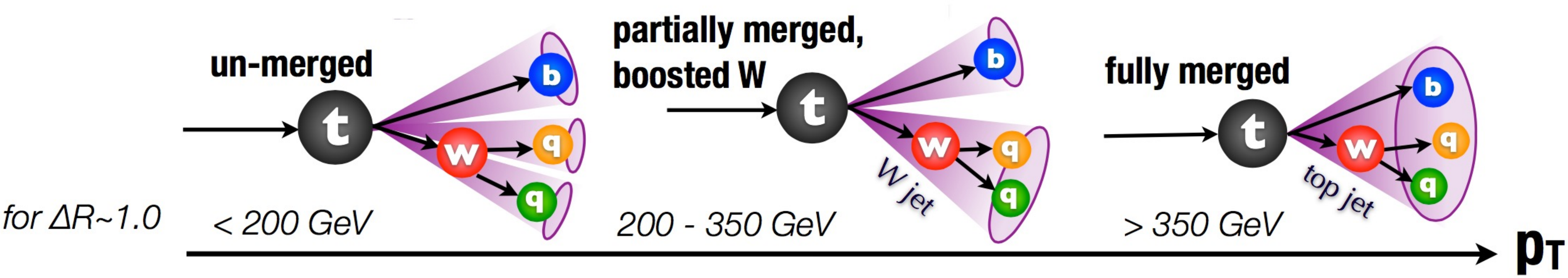




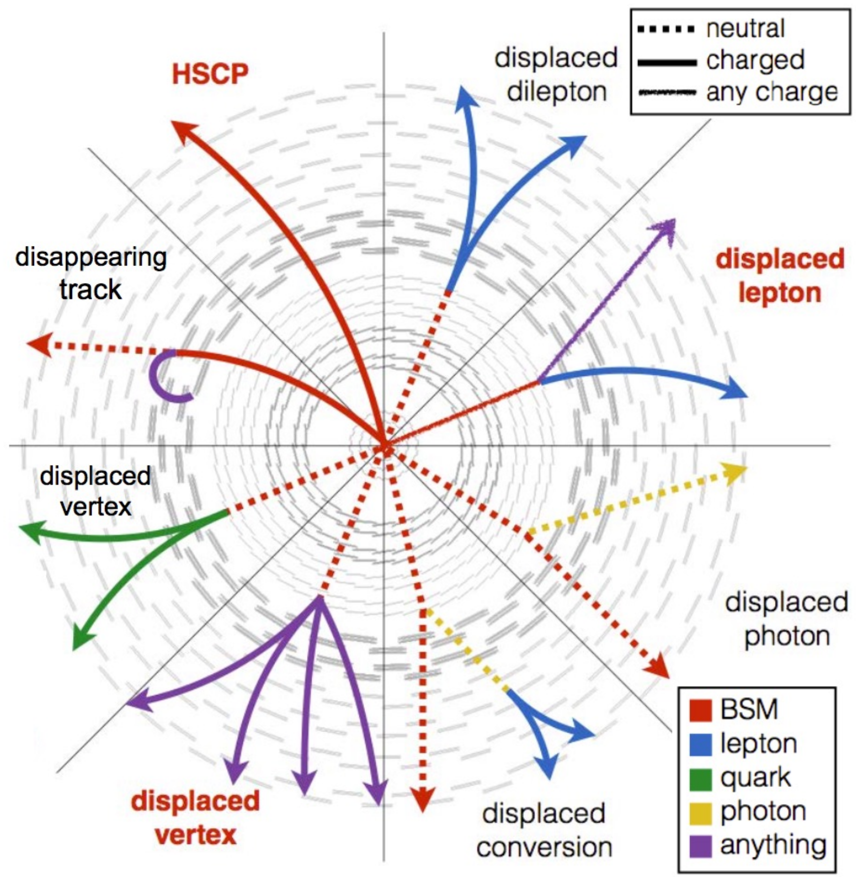
New channels, novel techniques, creative analyses

Rich and diverse search landscape

- Big inclusive searches complemented by dedicated searches that target gaps in coverage
- Incorporate machine learning for Higgs, b, charm, top tagging
- Improve lepton reconstruction/ID for compressed spectra w/ low pT leptons; improve analysis techniques, jet substructure
- Challenging topologies
- Unconventional analyses



Non-conventional final states



Credits: J. Antonelli

New and rich phenomenology:

- Very weakly coupled to SM
- Long-lived particles
- Masses below the EW scale

Searches need to often overcome challenges in trigger, reconstruction & background estimation

Need to deal with unusual backgrounds (e.g. beam-induced backgrounds)

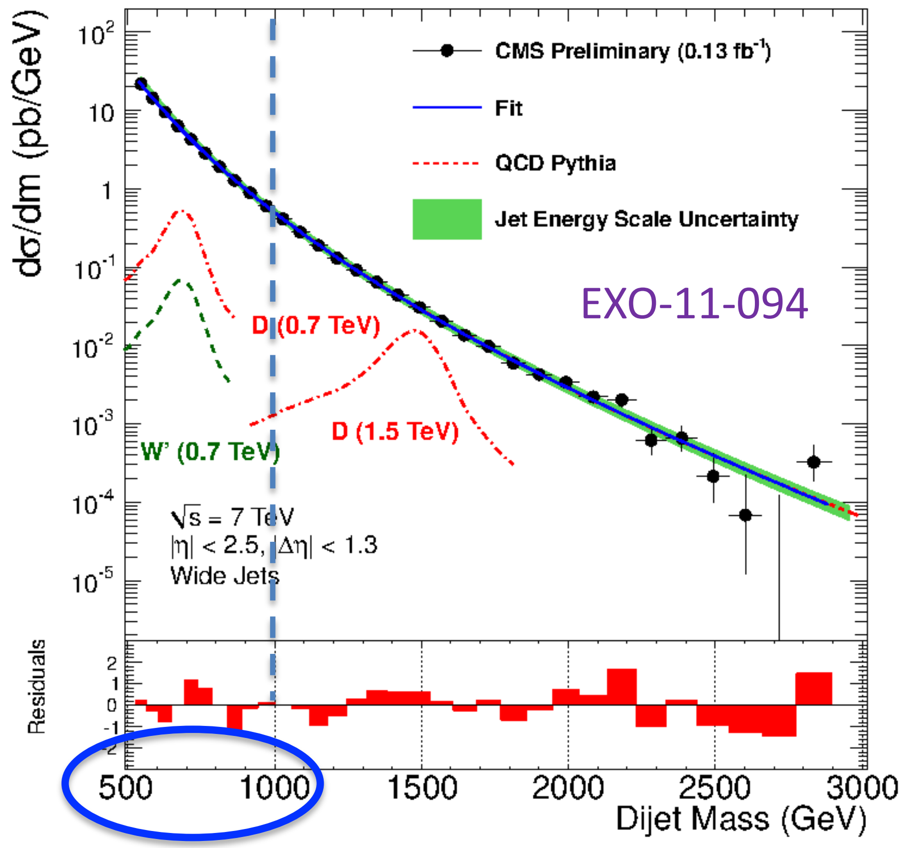
Excellent detector understanding is absolutely critical

Important to take advantage of several topologies and use existing detector in creative ways

"Scouting"

Traditional trigger algorithms usually require high thresholds (e.g. on p_T and mass) to reduce the event rate, and then readout the full event info.

- The limit is the total bandwidth
  - Can reduce the event size to collect events at a higher rate (i.e. lower thresholds)
  - reduction of event size to O(10kB) allows trigger rates of several kHz
- Reconstruct at the HLT stage, keeping limited information (HLT objects)
  - needs adequate calibration @ HLT and validation against full reconstruction



Scouting approach extended the reach below 1 TeV

Summary & Outlook

- The ~14 years of LHC operation has been one amazing ride!
  - Discovery of the Higgs boson
    - Now using the Higgs as a tool for discovery
  - Huge amounts of BSM parameter space ruled out
  - At the same time, innovative strategies for triggering, data-taking and analysis are providing access to previously unexplored territory!
  - Some interesting excesses – being pursued with full Run 2 datasets (and Run 3)

- An exciting time to develop and implement new ideas
  - Go in directions where no one has gone before!

- <u>**95% of the total LHC data still to come (and be studied)!**</u>

- **Come join our quest to answer the unsolved mysteries of nature…**

When questioned during a congressional hearing in 1969 about what the activity carried out at Fermilab was doing for the national defense, Director Robert Wilson replied:

It only has to do with the respect with which we regard one another, the dignity of men, our love of culture….
It has to do with, are we good painters, good sculptors, great poets?

I mean all the things that we really venerate and honor in our country and are patriotic about.

It has nothing to do directly with defending our country except to help make it worth defending.