PARTICLE PHYSICS, THE LHC AND CERN, TRIGGERING

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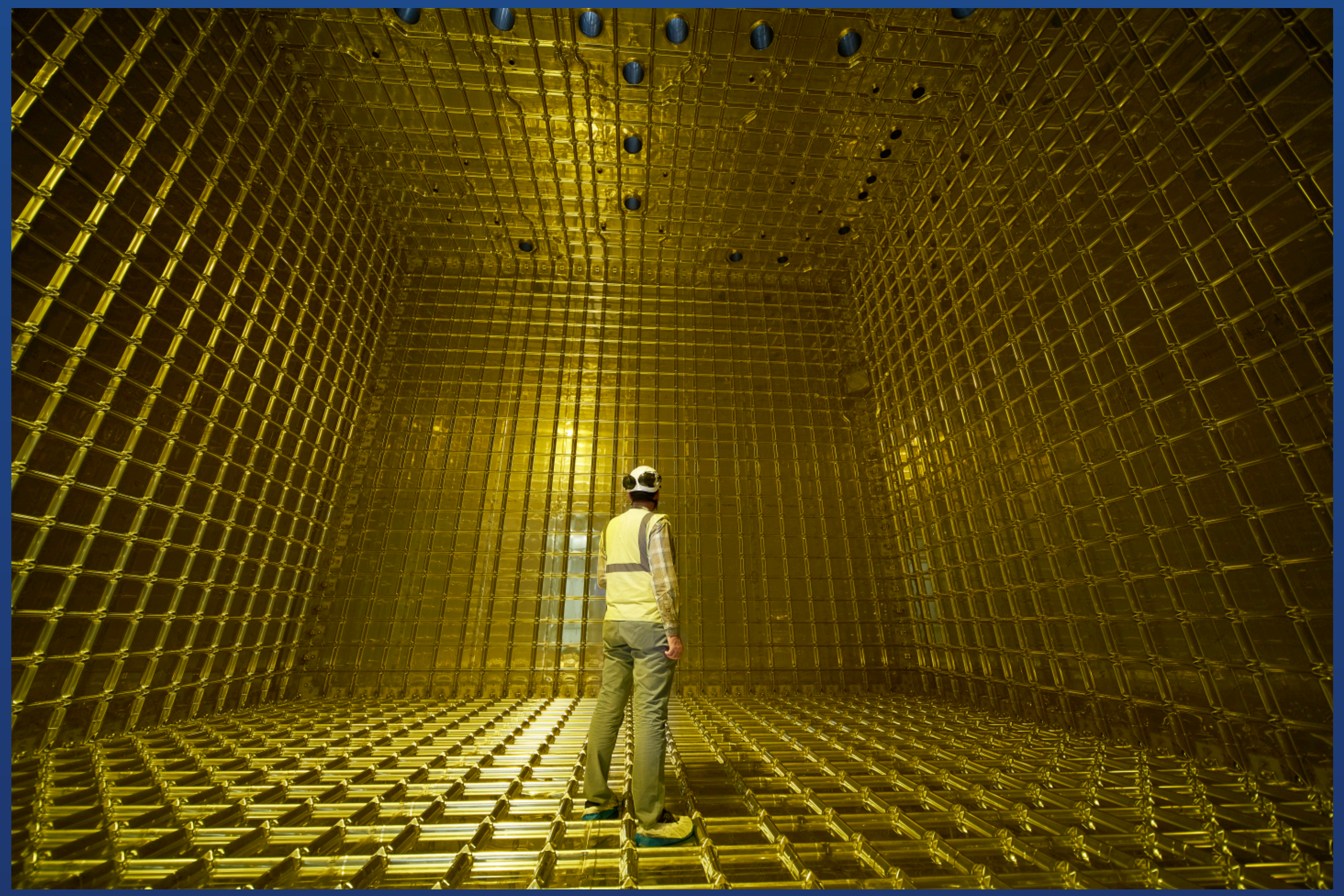
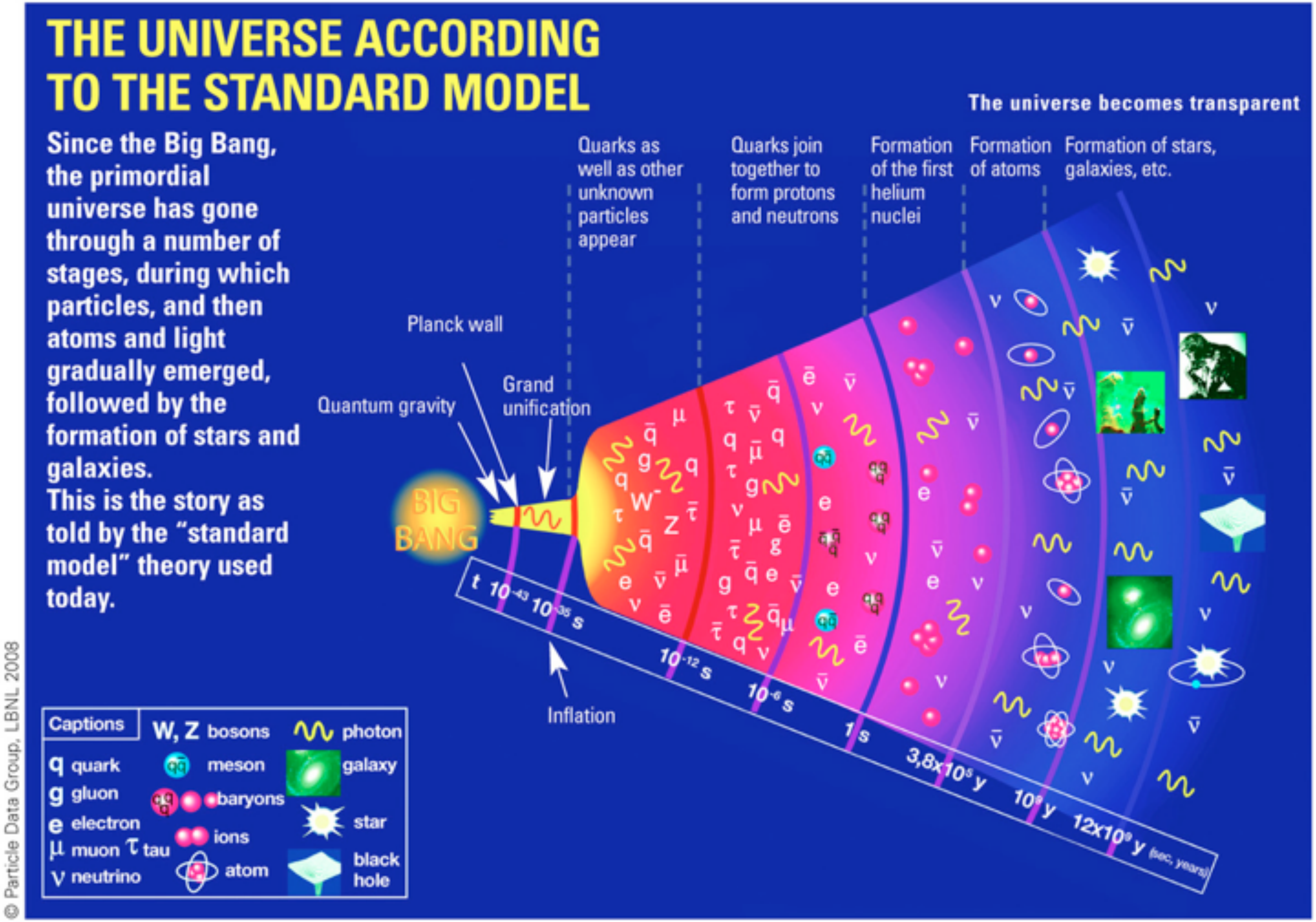


OUTLINE

- What is Particle Physics?
- The Large Hadron Collider and CMS
- Triggering
- Future

WHAT IS PARTICLE PHYSICS?


THE UNIVERSE ACCORDING TO THE STANDARD MODEL
Since the Big Bang, the primordial universe has gone through a number of stages, during which particles, and then atoms and light gradually emerged, followed by the formation of stars and galaxies.
This is the story as told by the "standard model" theory used today.
The universe becomes transparent
Quarks as well as other unknown particles appear
Quarks join together to form protons and neutrons
Formation of the first helium nuclei
Formation of atoms
Formation of stars, galaxies, etc.
Planck wall
Quantum gravity
Grand unification
Inflation
BIG BANG
t 10^{-43} 10^{-35} s
10^{-12} s
10^{-6} s
1 s
$3,8\times10^{5}$ y
10^{9} y
12×10^{9} y (sec, years)
Captions
W, Z bosons
photon
q quark
meson
galaxy
g gluon
baryons
e electron
star
ions
μ muon τ tau
black hole
ν neutrino
atom
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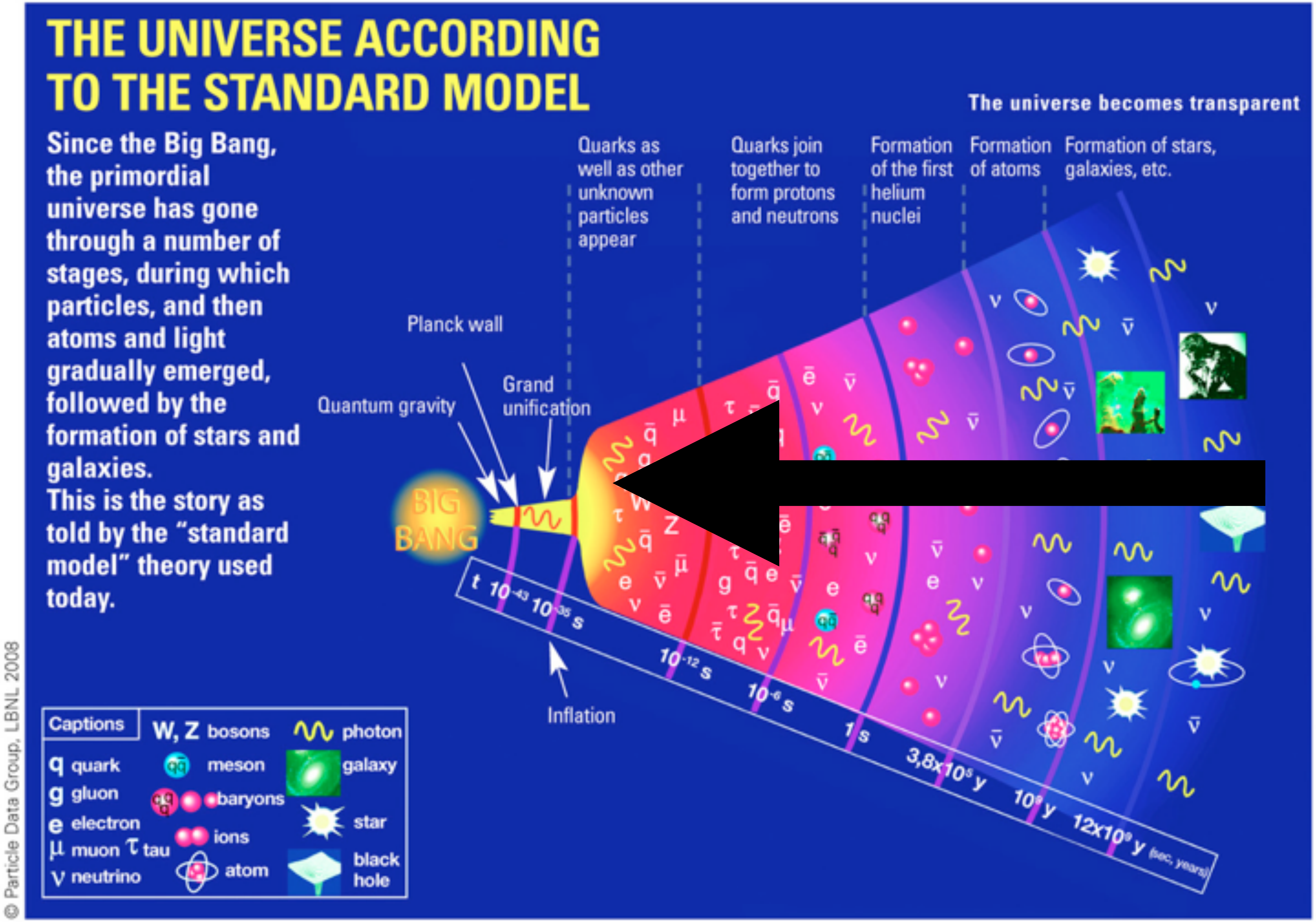
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t 10⁻⁴³ 10⁻³⁵ s
10⁻¹² s
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Captions
q quark
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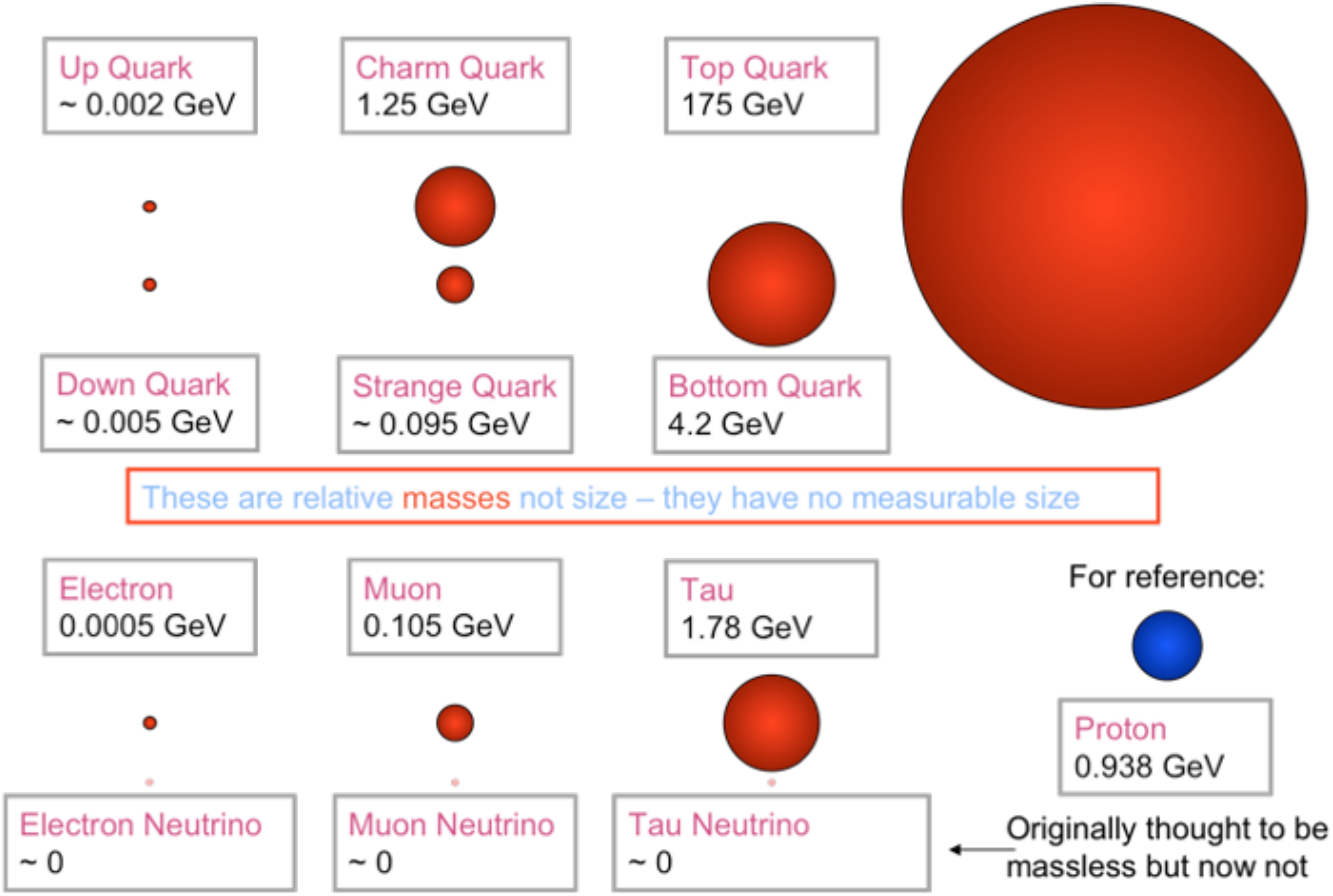
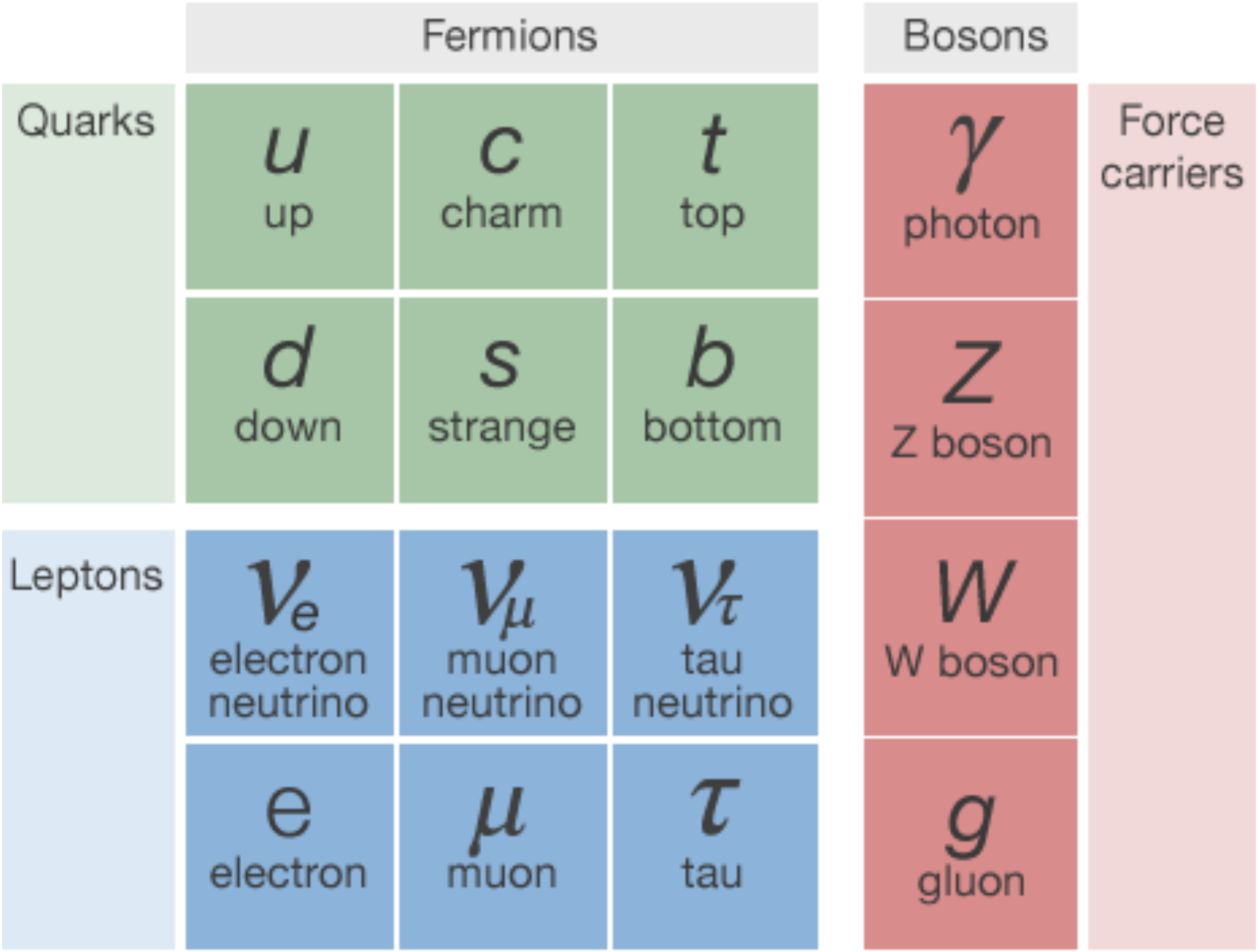
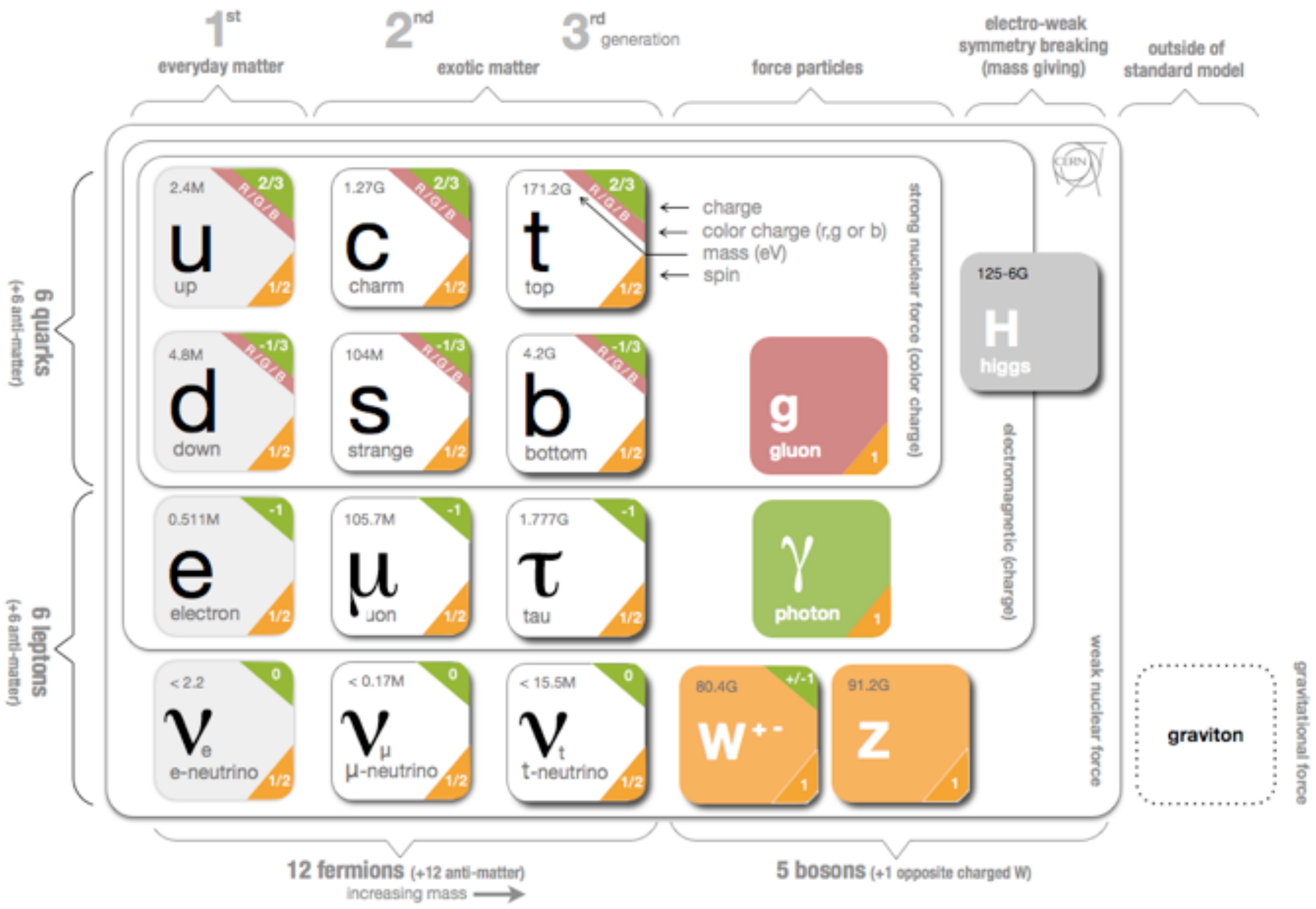

Up Quark
~ 0.002 GeV
Charm Quark
1.25 GeV
Top Quark
175 GeV
Down Quark
~ 0.005 GeV
Strange Quark
~ 0.095 GeV
Bottom Quark
4.2 GeV
These are relative masses not size – they have no measurable size
Electron
0.0005 GeV
Muon
0.105 GeV
Tau
1.78 GeV
For reference:
Proton
0.938 GeV
Electron Neutrino
~ 0
Muon Neutrino
~ 0
Tau Neutrino
~ 0
Originally thought to be massless but now not


Fermions
Bosons
Quarks
u
up
c
charm
t
top
d
down
s
strange
b
bottom
Leptons
ν_e
electron neutrino
ν_μ
muon neutrino
ν_τ
tau neutrino
e
electron
μ
muon
τ
tau
γ
photon
Z
Z boson
W
W boson
g
gluon
Force carriers

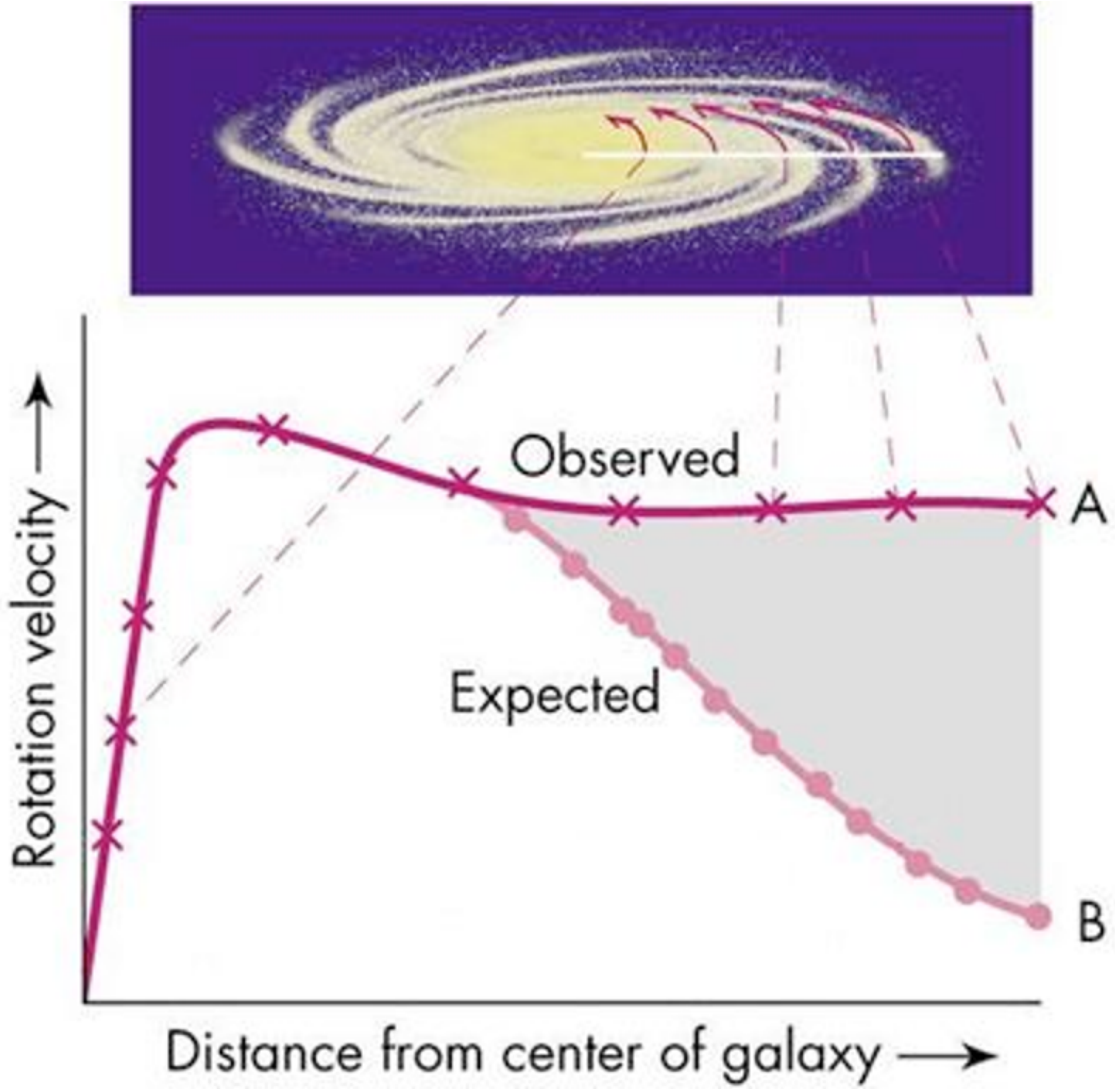
Whats missing?

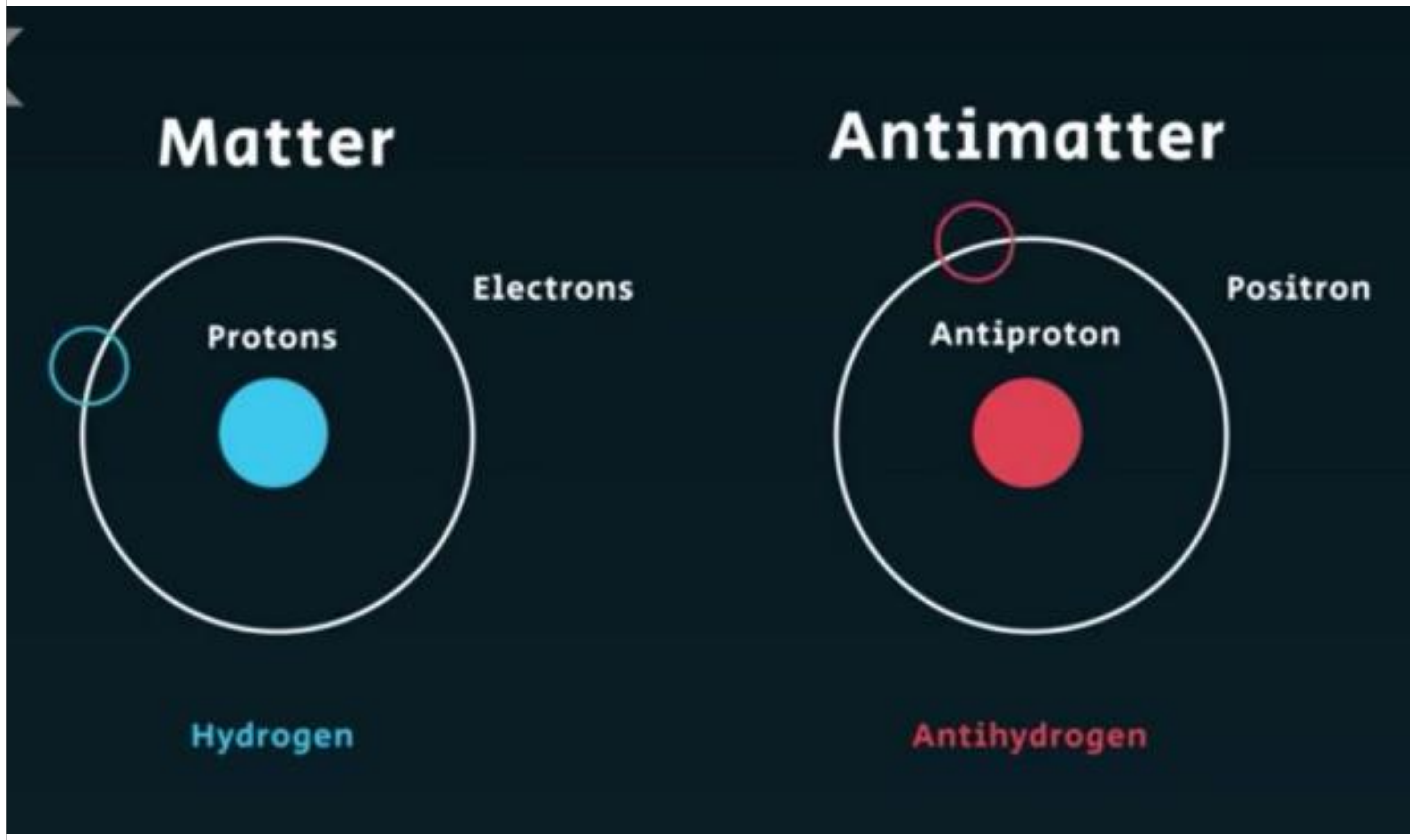


1st everyday matter
2nd exotic matter
3rd generation
force particles
electro-weak symmetry breaking (mass giving)
outside of standard model
6 quarks (+6 anti-matter)
6 leptons (+6 anti-matter)
2.4M u up 2/3 R/G/B 1/2
1.27G c charm 2/3 R/G/B 1/2
171.2G t top 2/3 R/G/B 1/2
charge
color charge (r,g or b)
mass (eV)
spin
4.8M d down -1/3 R/G/B 1/2
104M s strange -1/3 R/G/B 1/2
4.2G b bottom -1/3 R/G/B 1/2
g gluon 1
strong nuclear force (color charge)
125-6G H higgs
0.511M e electron -1 1/2
105.7M μ uon -1 1/2
1.777G τ tau -1 1/2
γ photon 1
electromagnetic (charge)
< 2.2 ν e-neutrino 0 1/2
< 0.17M ν μ-neutrino 0 1/2
< 15.5M ν t-neutrino 0 1/2
80.4G W+- +/-1 1
91.2G Z 1
weak nuclear force
graviton
gravitational force
12 fermions (+12 anti-matter)
increasing mass
5 bosons (+1 opposite charged W)

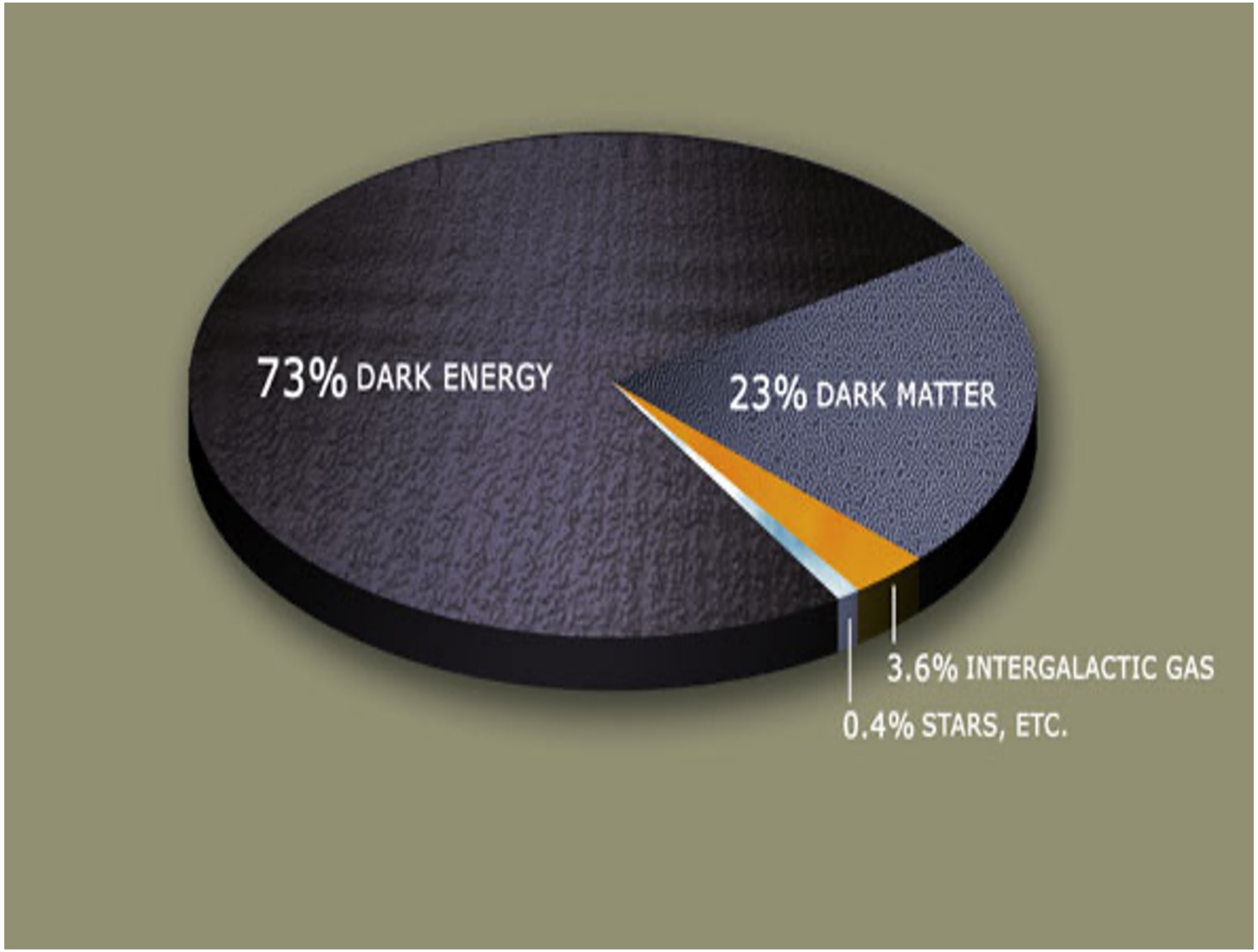
So the standard model is great right??

yes but its not perfect!

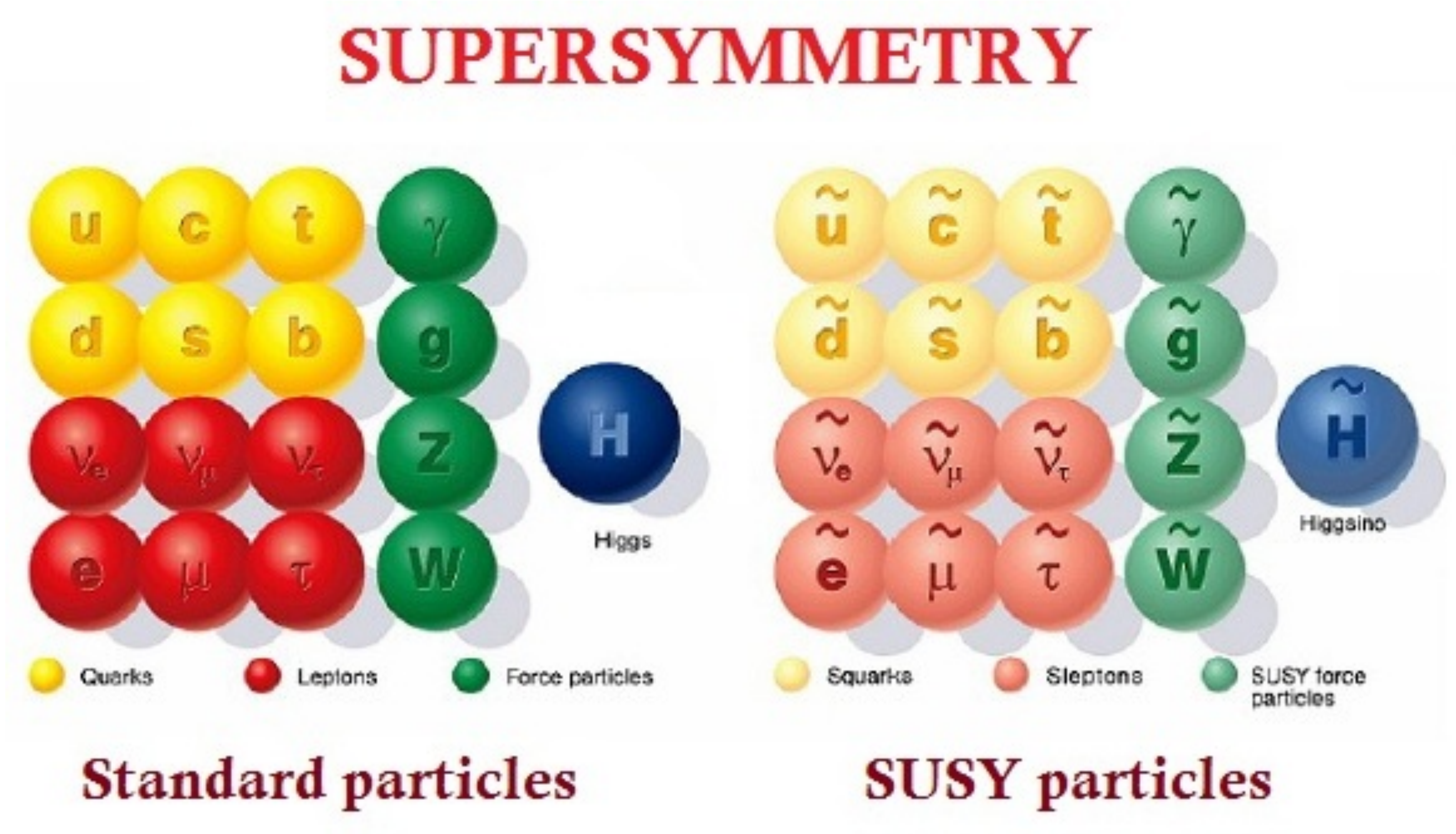




What is the Universe made of?



Beyond the Standard Model…

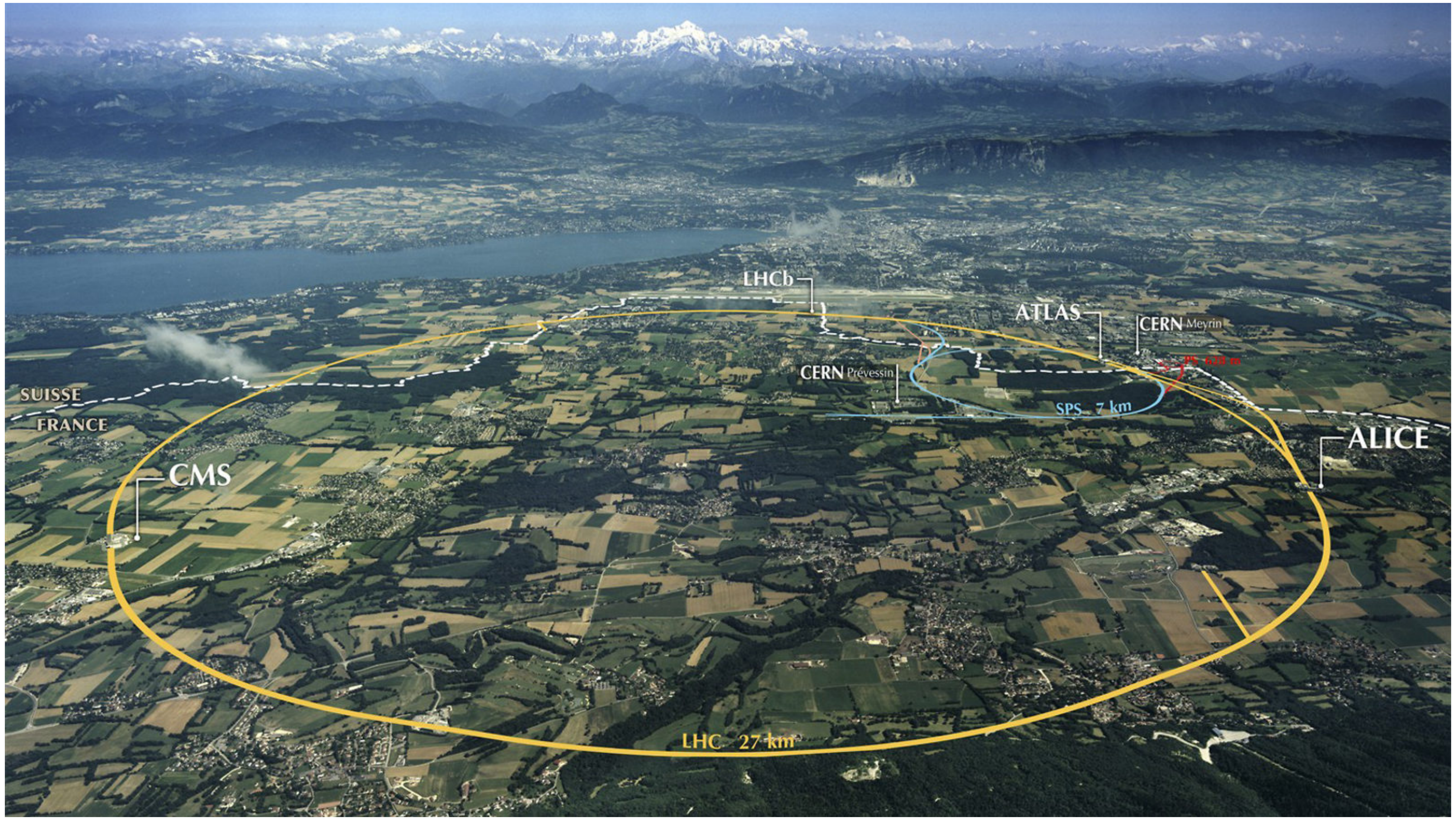


- Supersymmetry
  - Fermions↔bosons
  - New spectrum of particles
  - Could explain dark matter

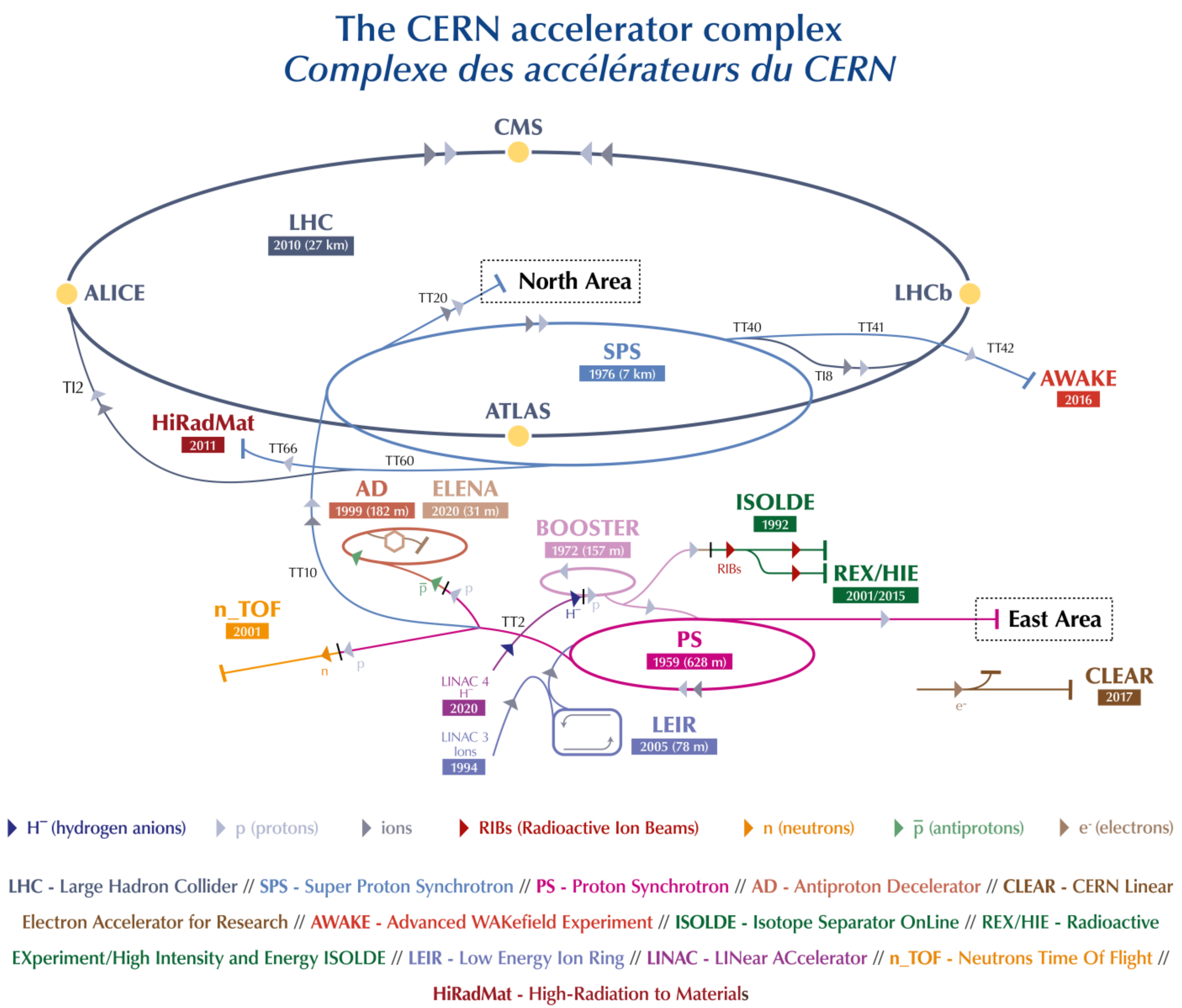
What do we do to
answer these questions?

LHC @ CERN

- 27km tunnel, 100m underground
- proton-proton collisions @7,8,13 TeV
- Four major experiments: CMS, ATLAS, LHCb, ALICE
- collisions every 25ns, 40 MHz collision rate



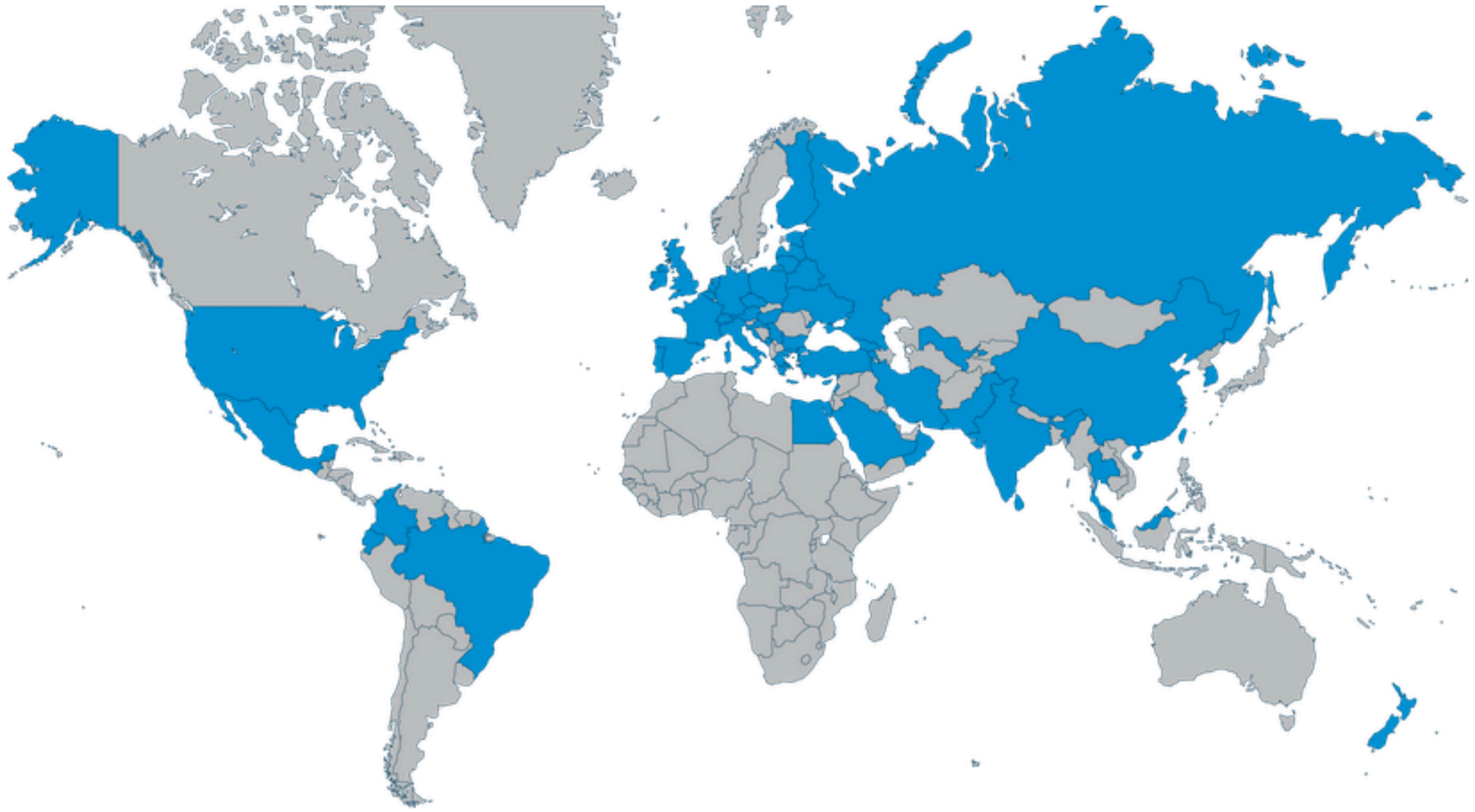
CAN'T GO FROM 0 TO HIGH ENERGY IN ONE RING!



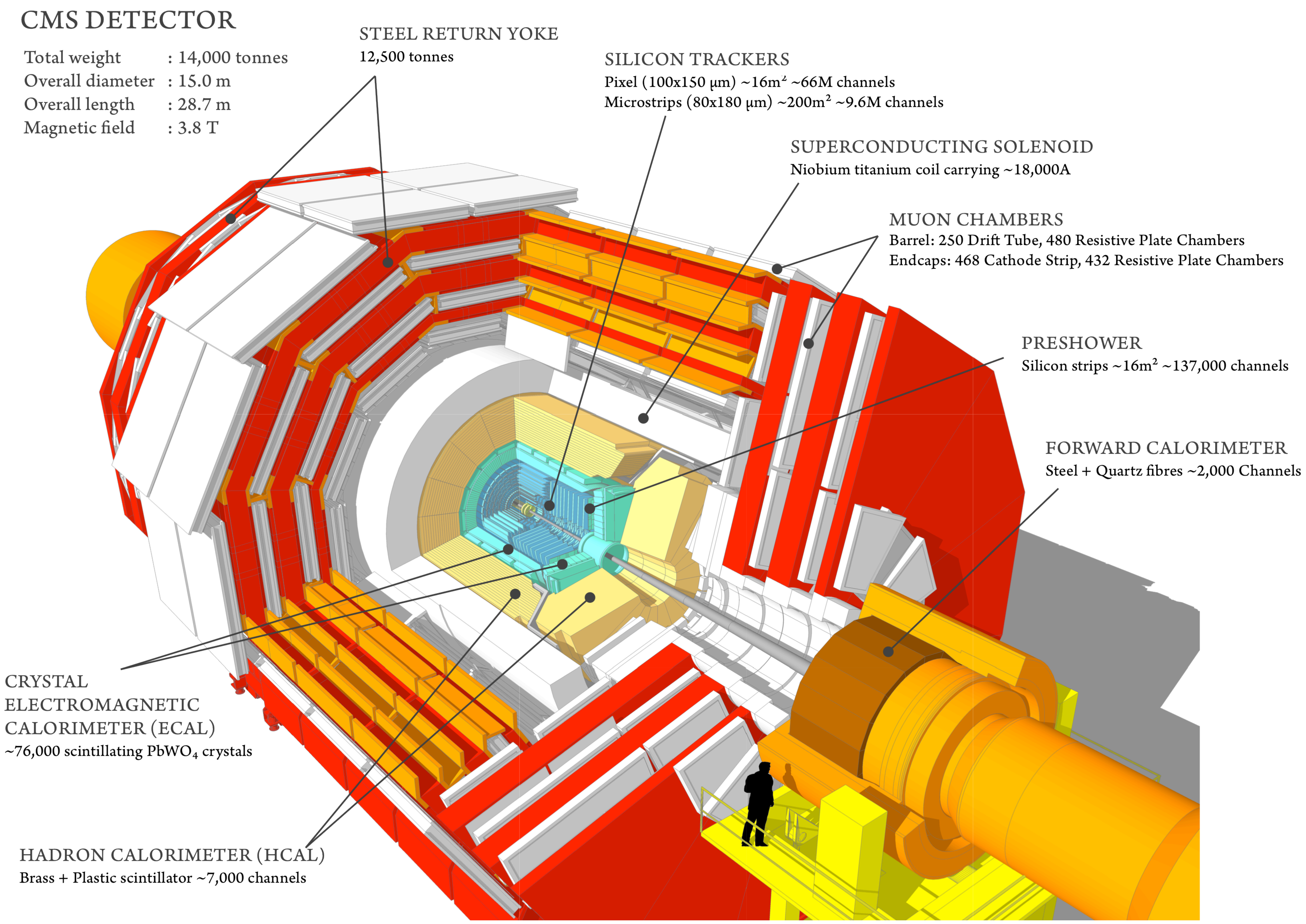
CMS = COMPACT(!)
MUON SOLENOID

CMS COLLABORATION

2942	1065	281	229	51
PHYSICISTS (1036 STUDENTS)	ENGINEERS	TECHNICIANS	INSTITUTES	COUNTRIES & REGIONS

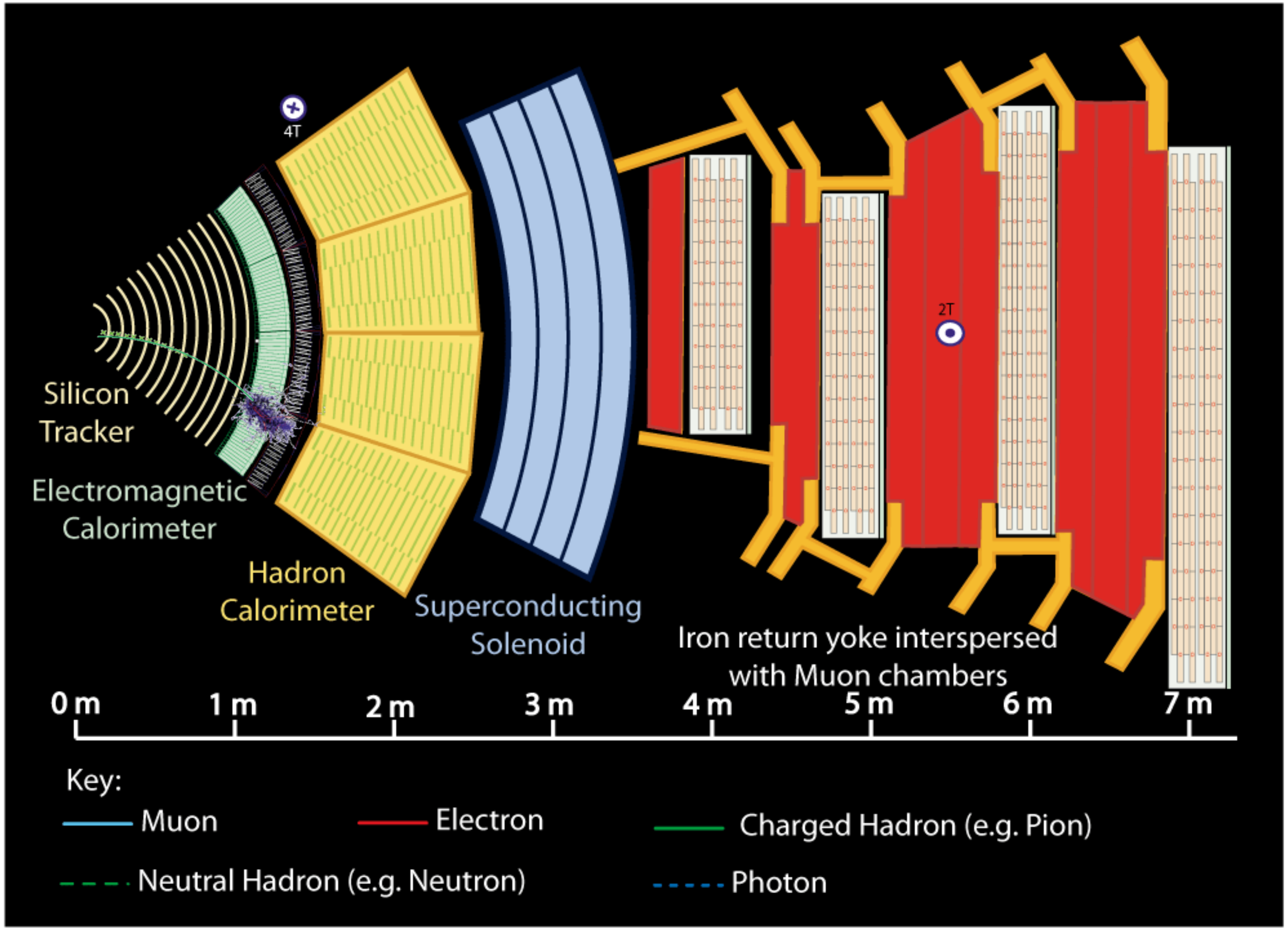


CMS @ LHC



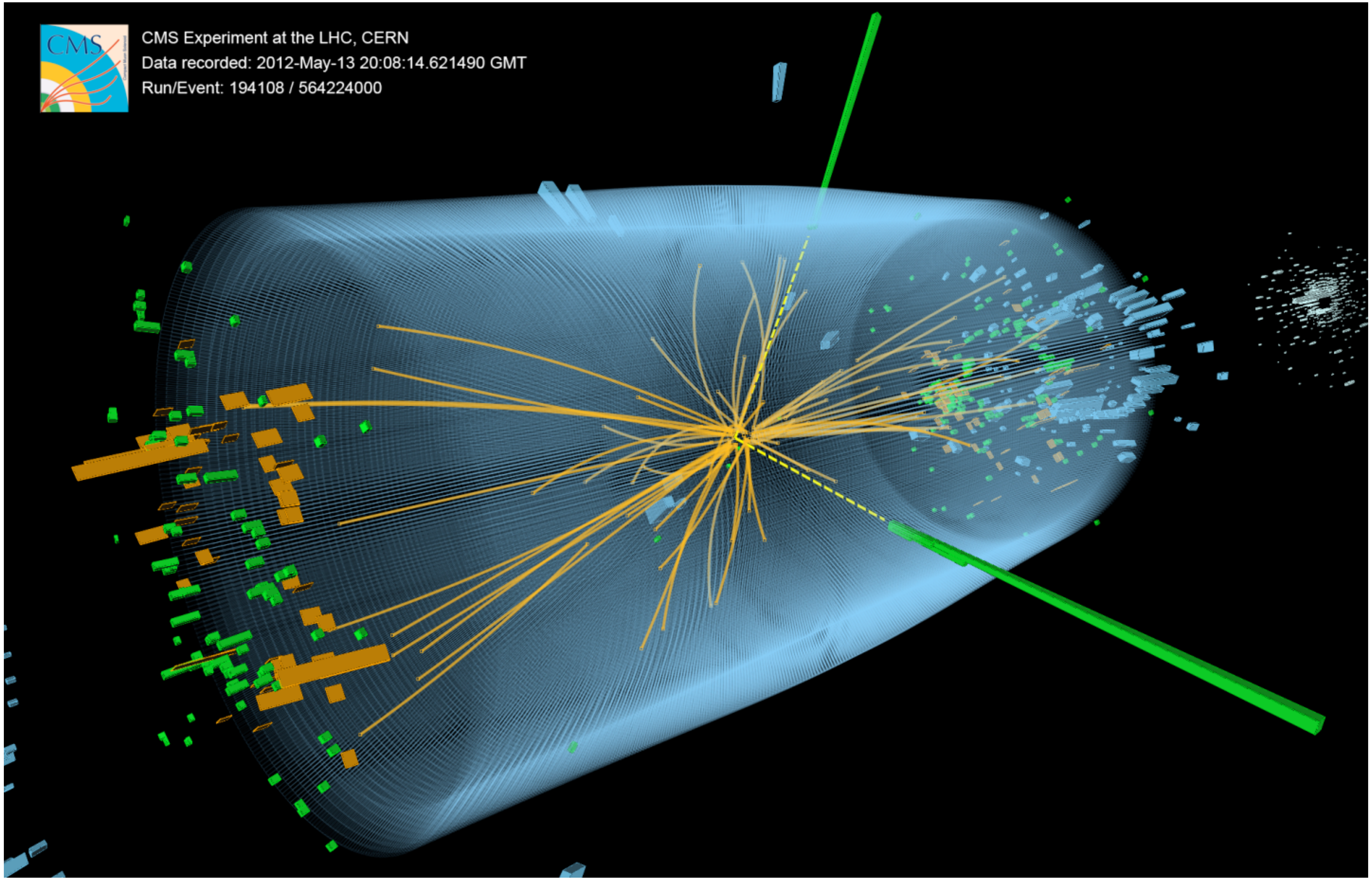
CMS DETECTOR
Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T
STEEL RETURN YOKE
12,500 tonnes
SILICON TRACKERS
Pixel (100x150 μm) ~16m² ~66M channels
Microstrips (80x180 μm) ~200m² ~9.6M channels
SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~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

CMS @ LHC



4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon

CMS @ LHC


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

WHAT IS A TRIGGER?

WHAT IS A TRIGGER?

WHAT IS A TRIGGER?

Looking for the specks of gold hidden in the water

WHAT IS A TRIGGER?

WHAT IS A TRIGGER?

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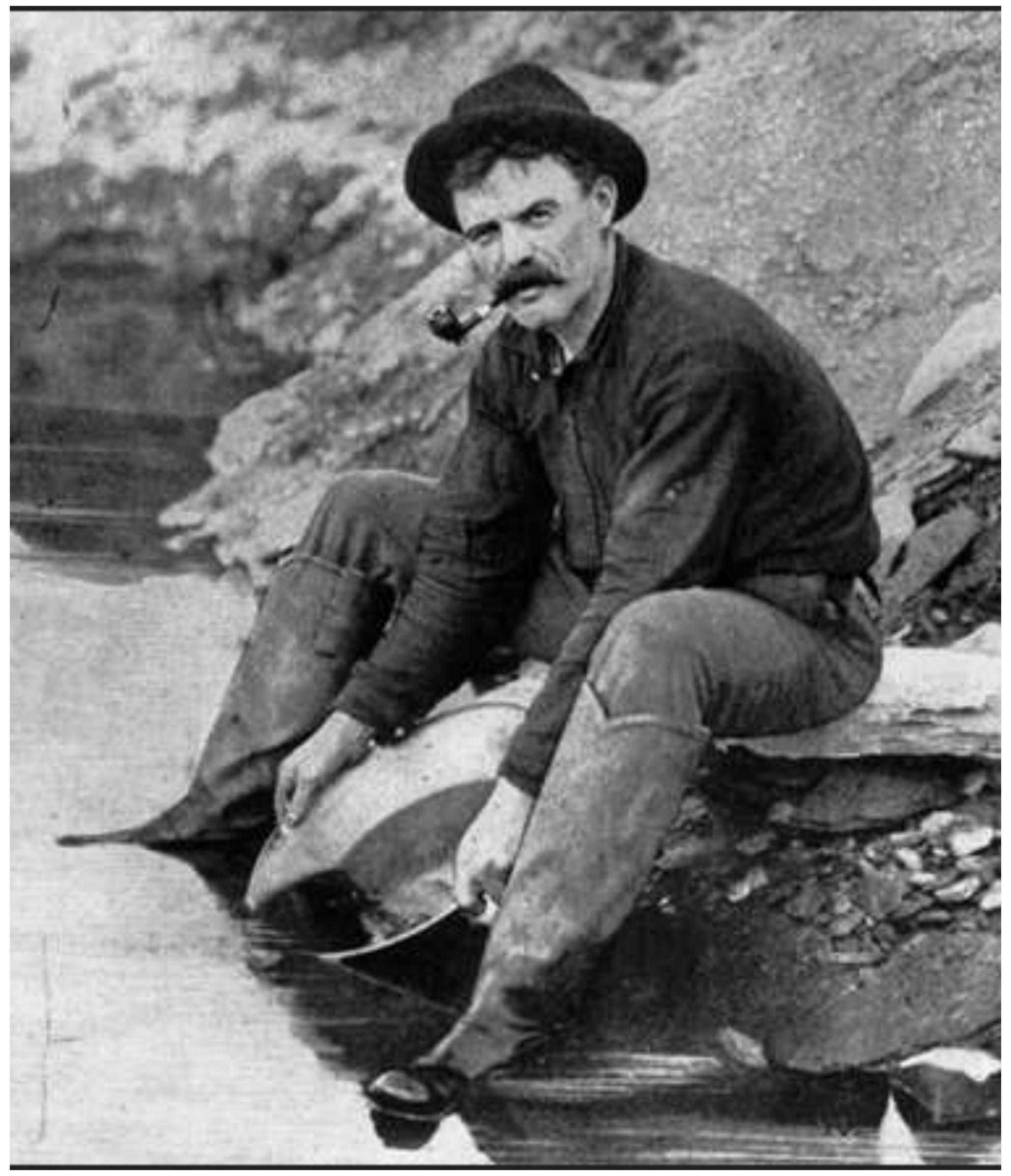

WHY DO WE NEED A TRIGGER?

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To answer this question we first need to understand another concept:

DAQ = DATA ACQUISITION

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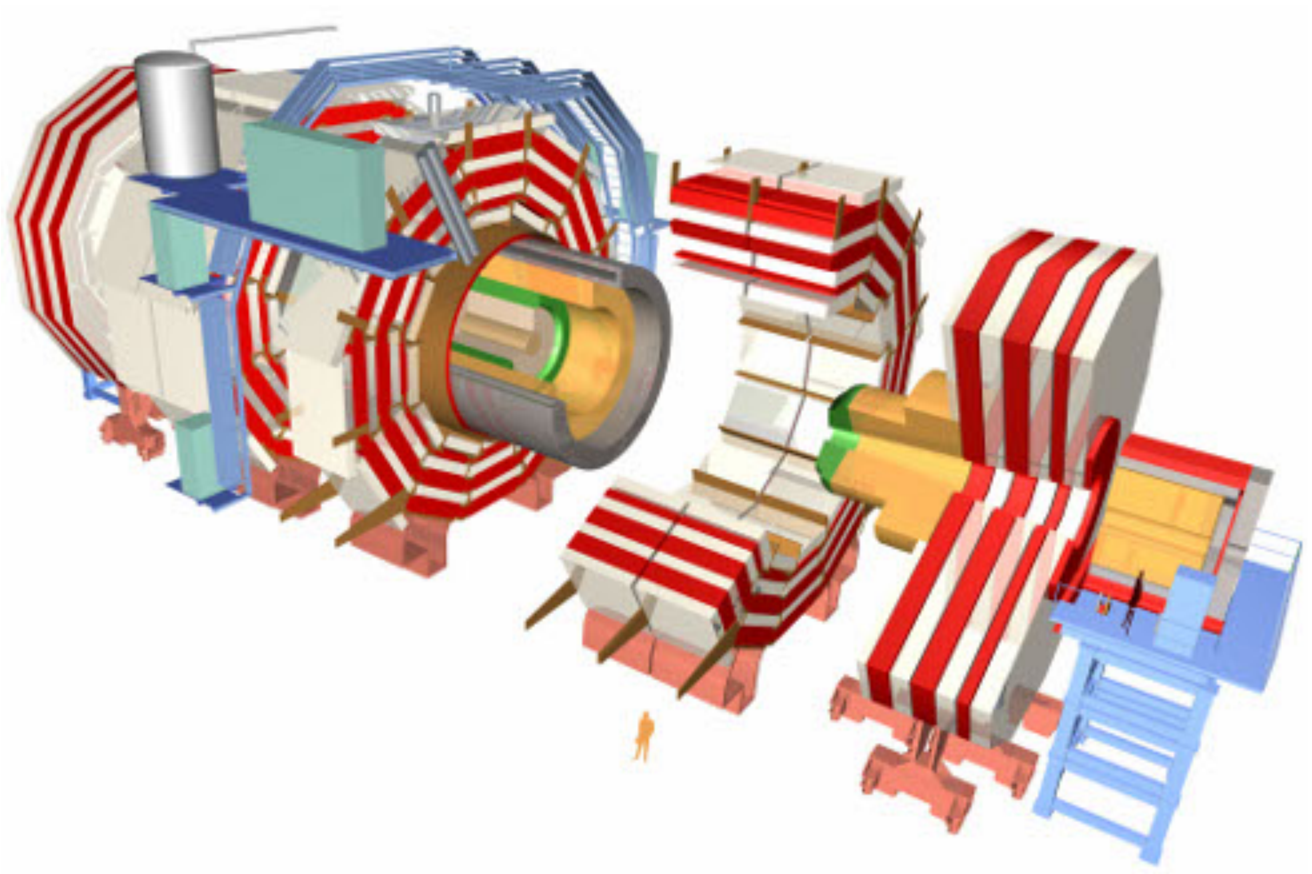
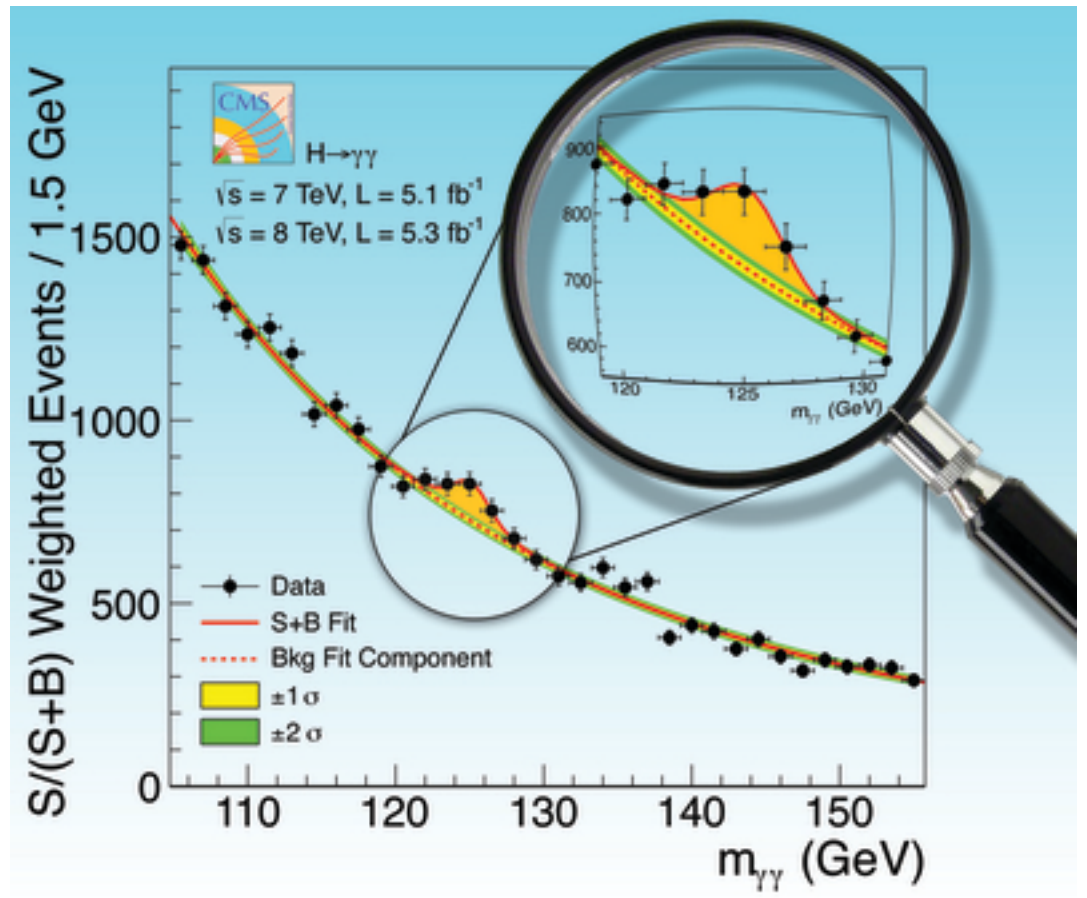


?



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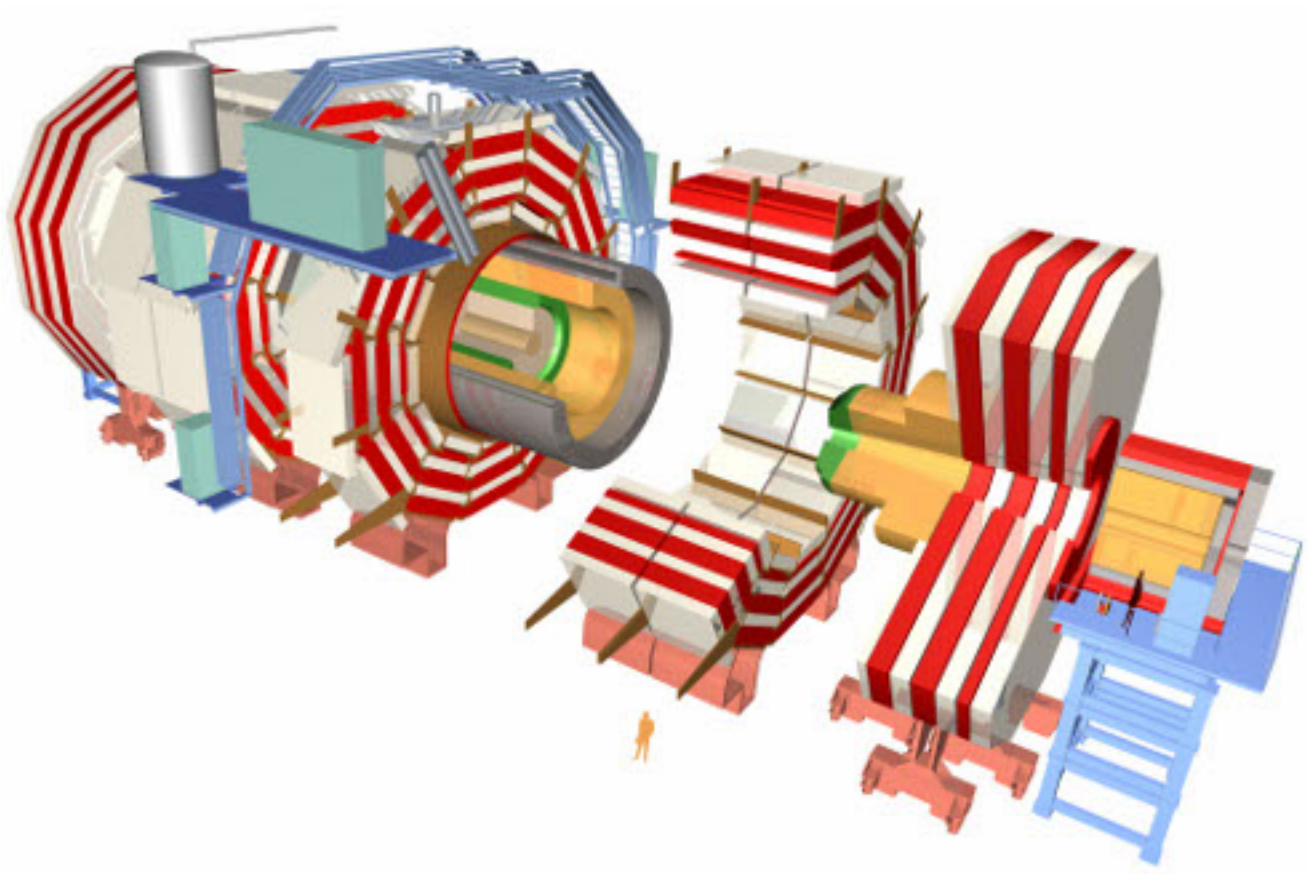
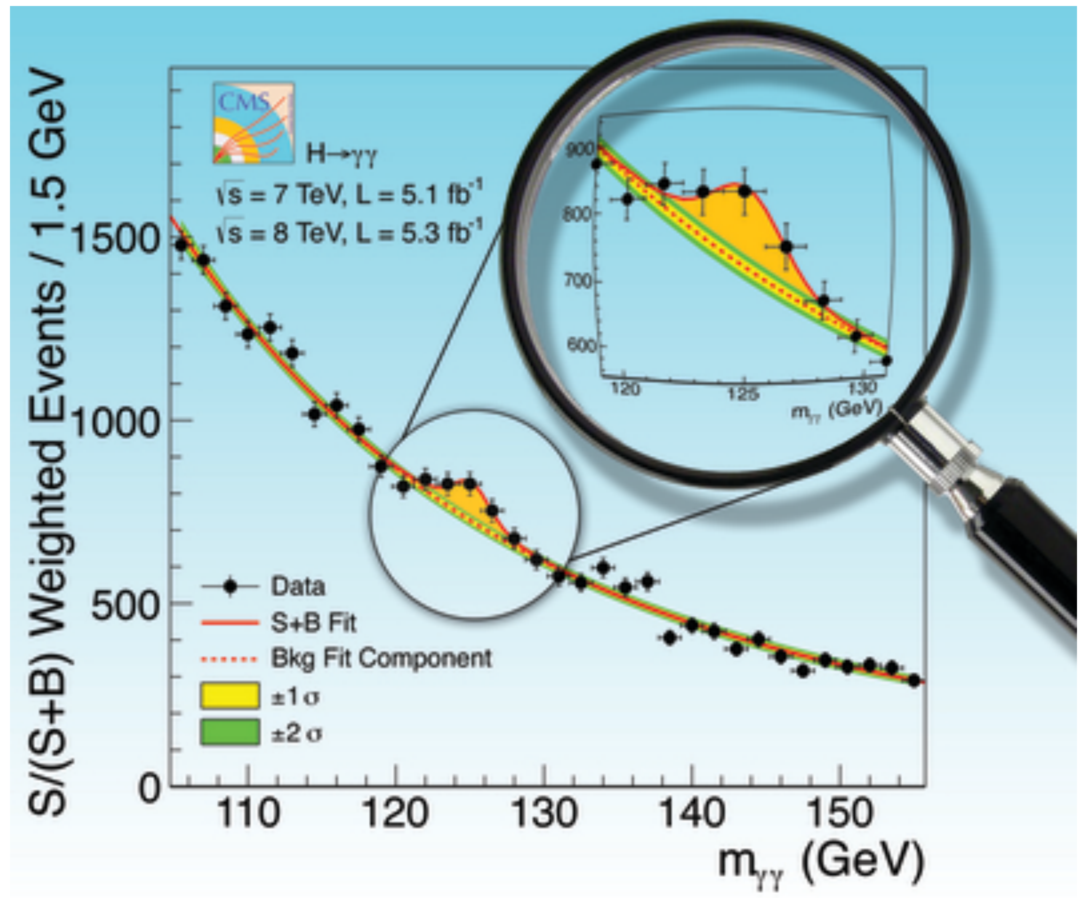


DAQ

data acquistion



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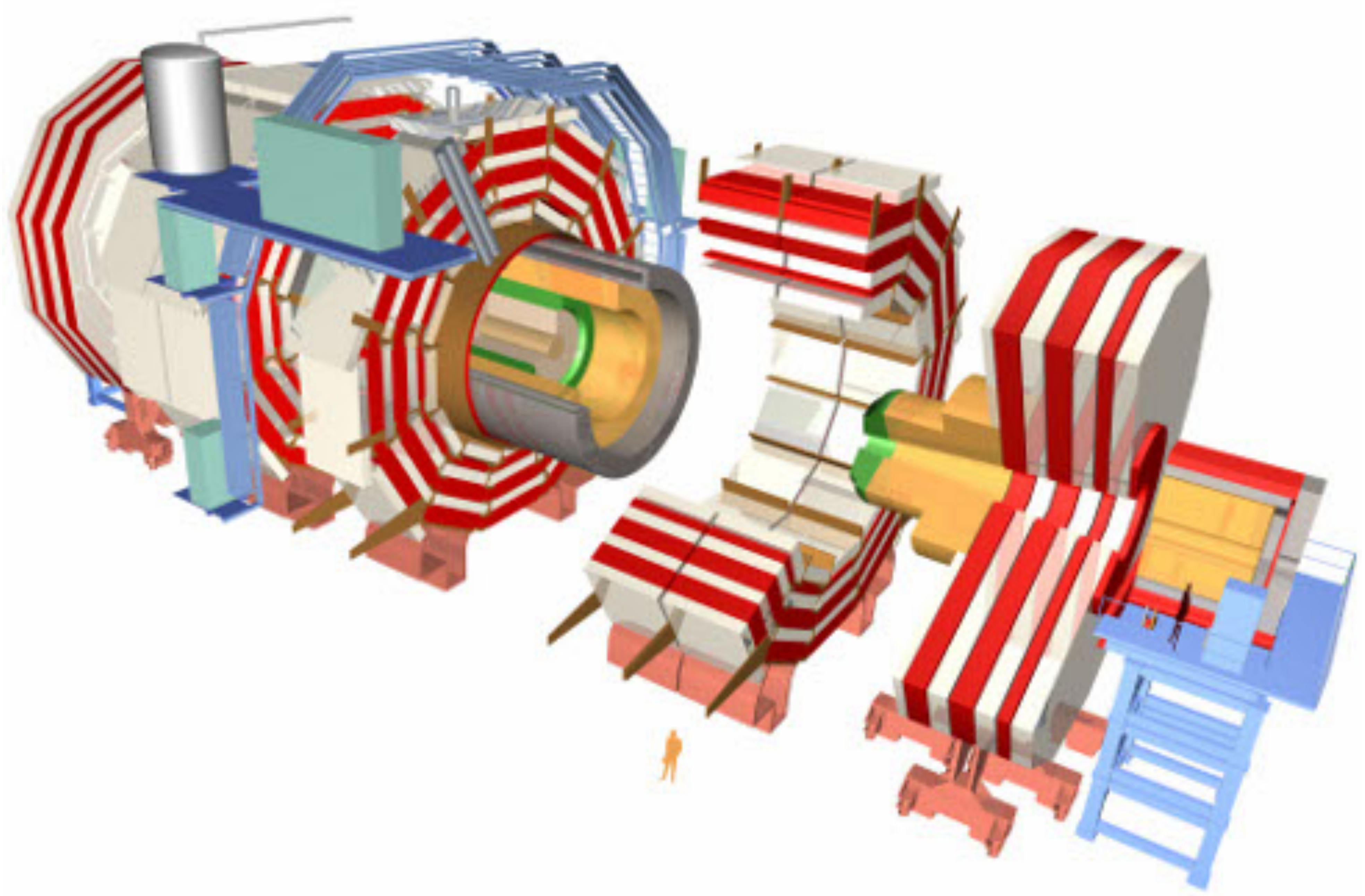

~100 million channels

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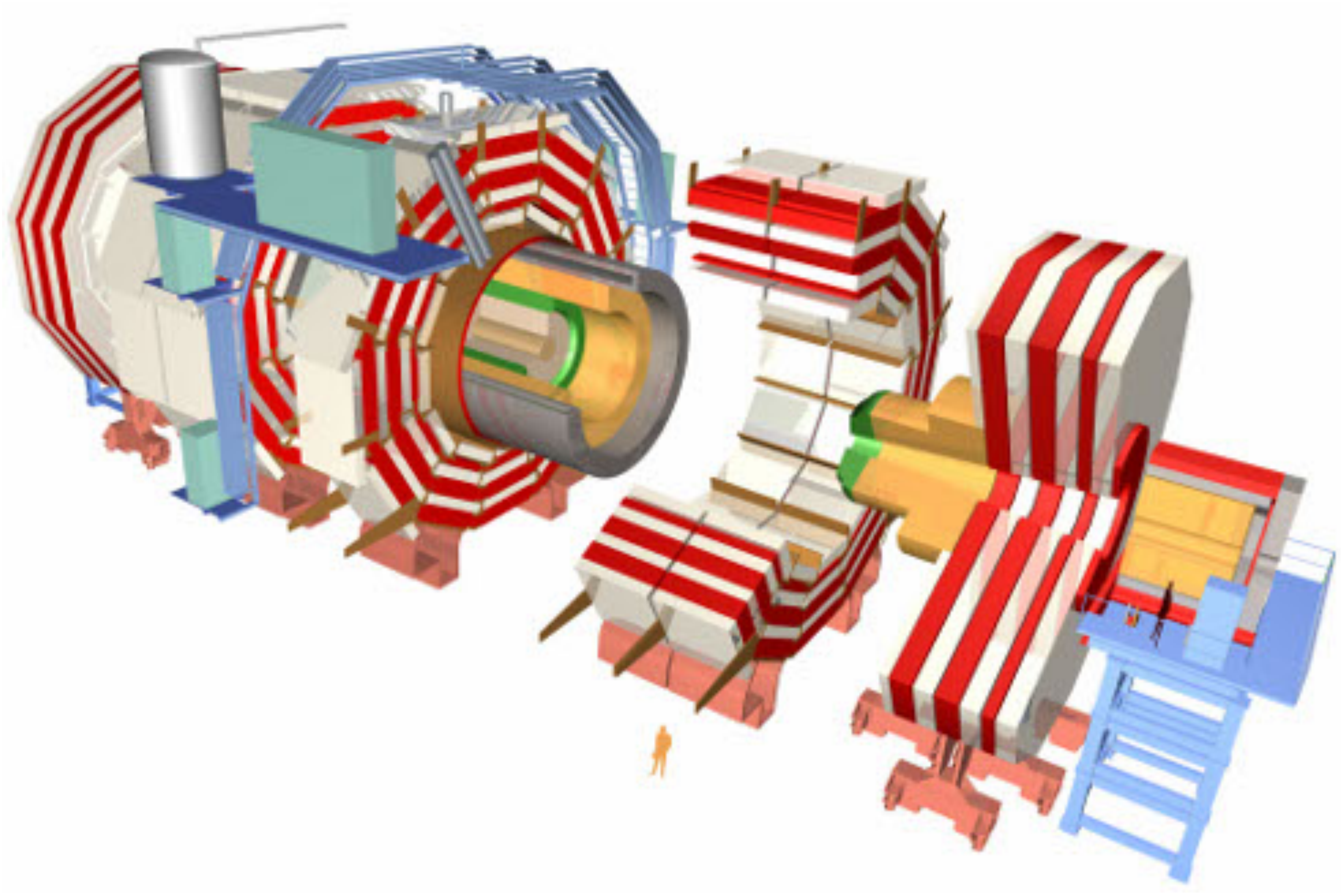

~100 million channels

~1MB per event

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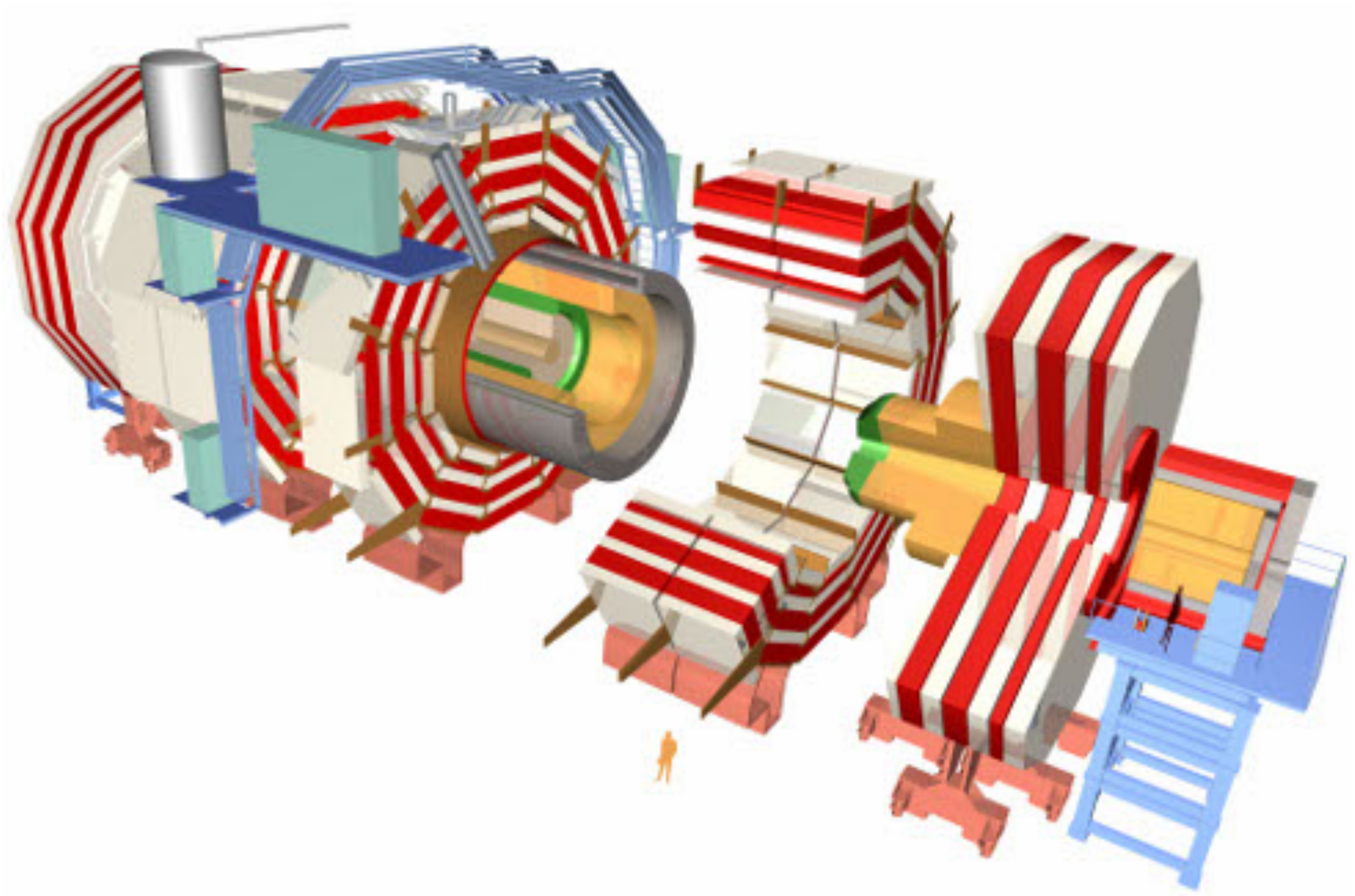
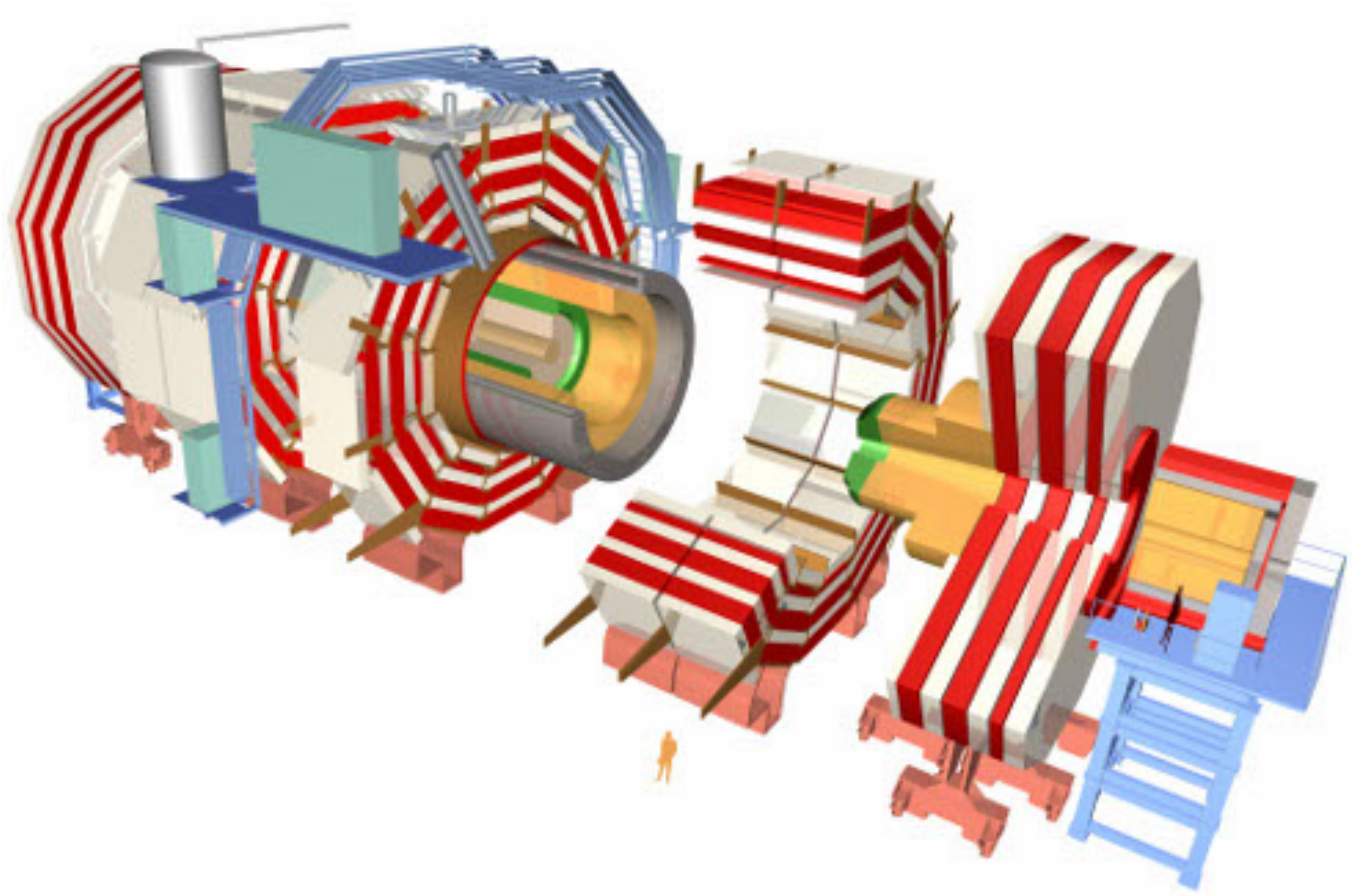


~100 million channels

~1MB per event

40 million collisions per second

WHY DO WE NEED A TRIGGER?



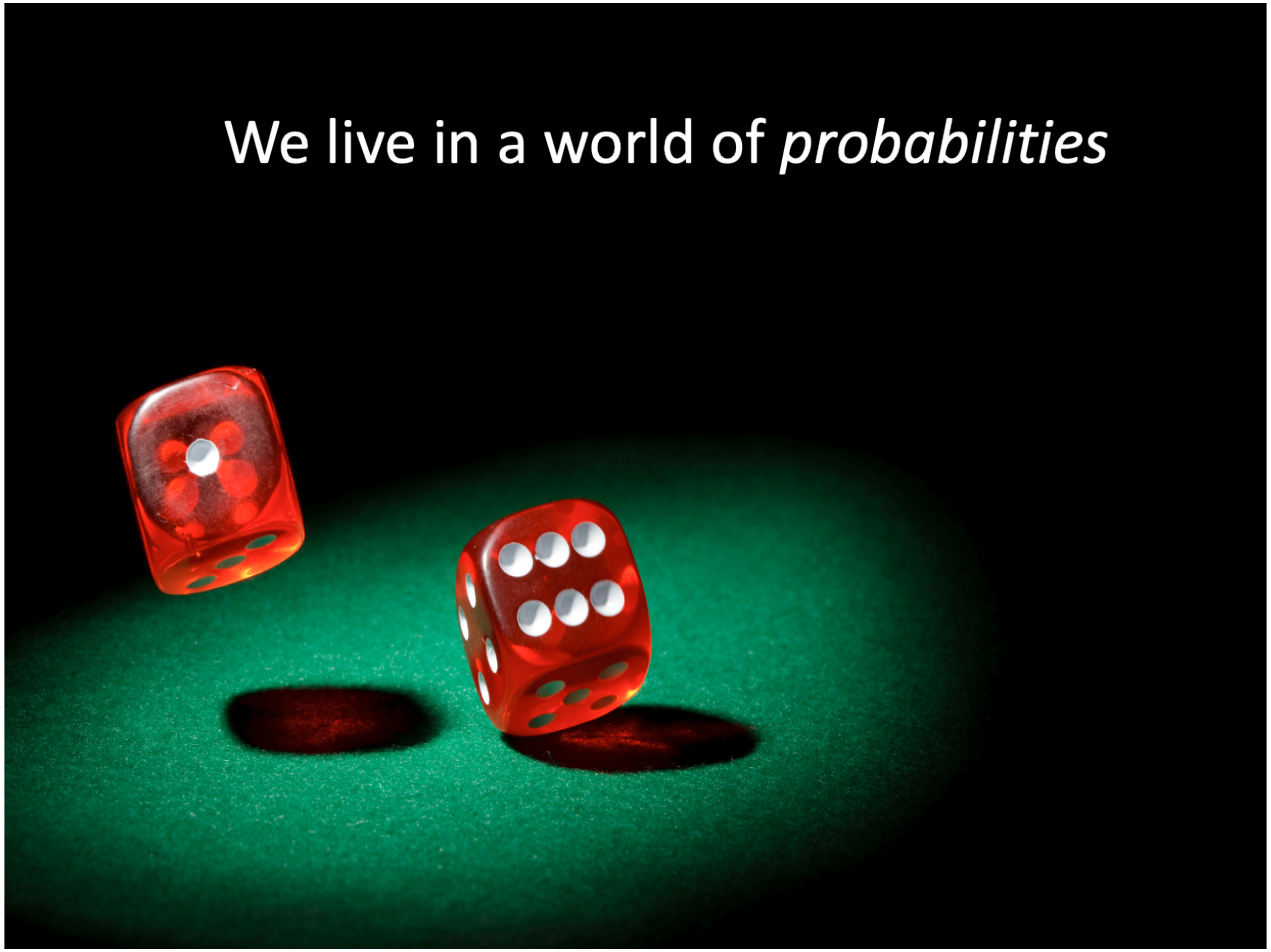
~100 million channels

~1MB per event

40 million collisions per second

40 TB/s!!!!

WHY DO WE NEED SO MUCH DATA?



WHY DO WE NEED A TRIGGER?

PROBLEM

Data volume is much too high - has to be reduced! (We can record ~1.5GB/s)

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PROBLEM

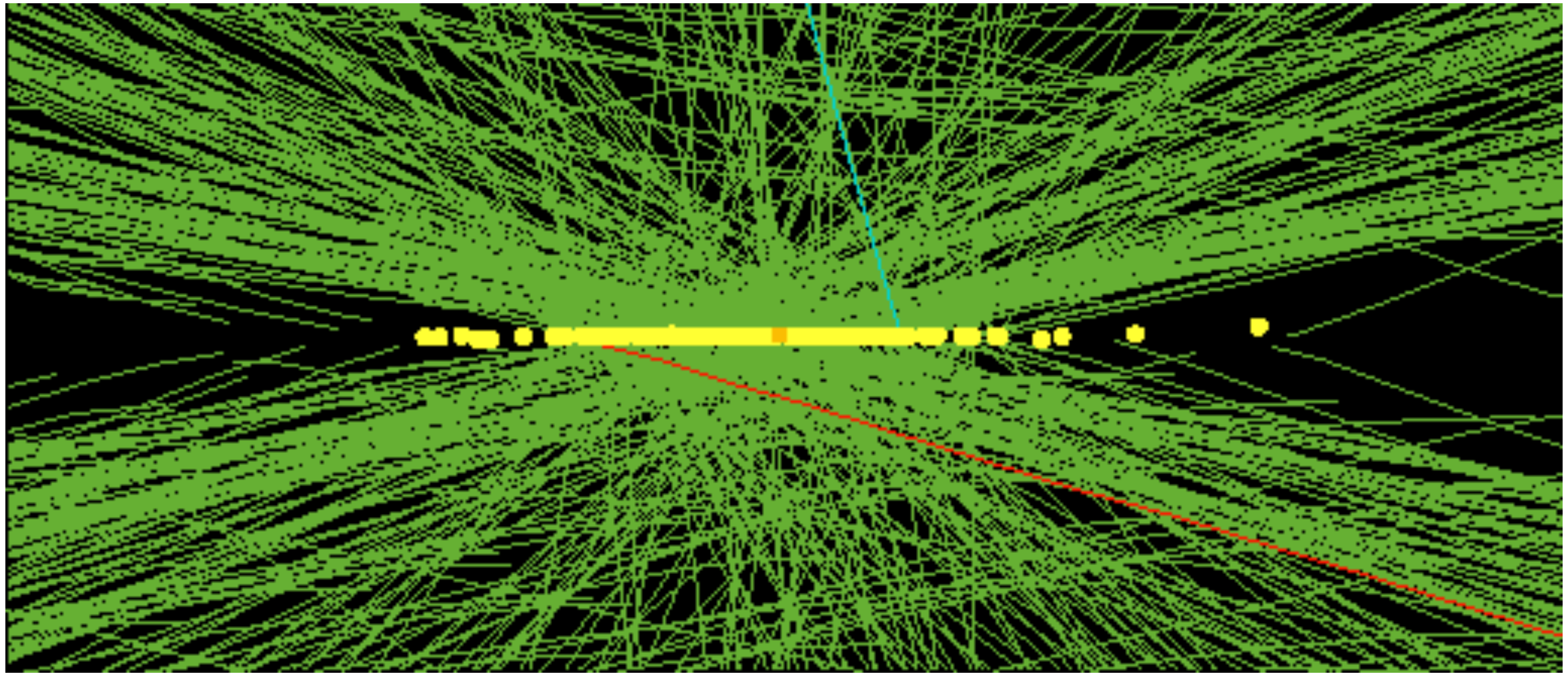
Data volume is much too high - has to be reduced! (We can record ~1.5GB/s)

SOLUTION

Store "interesting" physics only

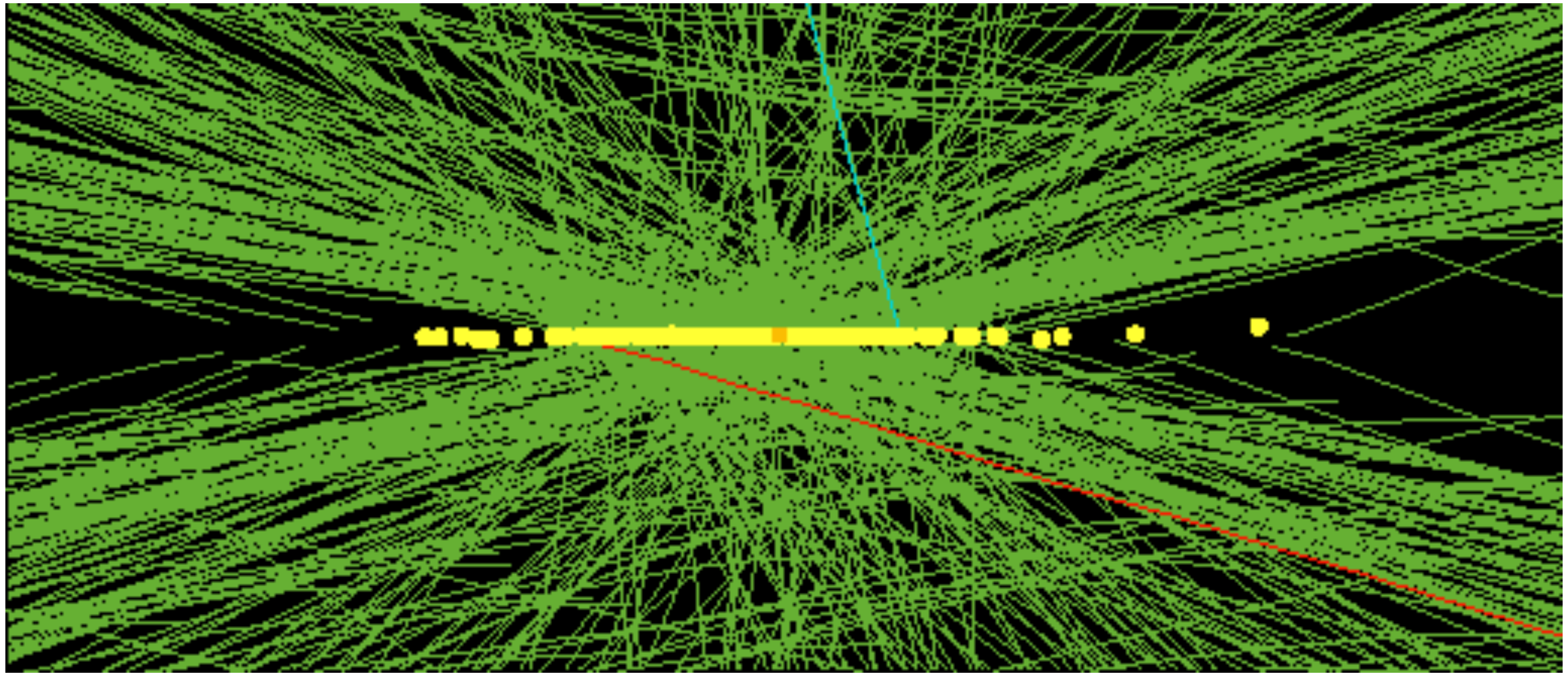
EASIER SAID THAN DONE…

EASIER SAID THAN DONE...



how long do we have to make the yes/no decison?

EASIER SAID THAN DONE...



0.000003 of a second!!!

BASIC REQUIREMENTS OF TRIGGER SYSTEM

1 Real time processing

The trigger system has to decide in a very short space of time (us) whether to keep the event or discard it. It has to take a 'quick look' and then make a decision.

2 High rejection factor

Can conceivably store O(1000Hz) of data, so need to able to discard 10e5 events.

3 High efficiency for interesting events

Must be able to design algorithms that identify specific interesting signatures

4 Flexibility

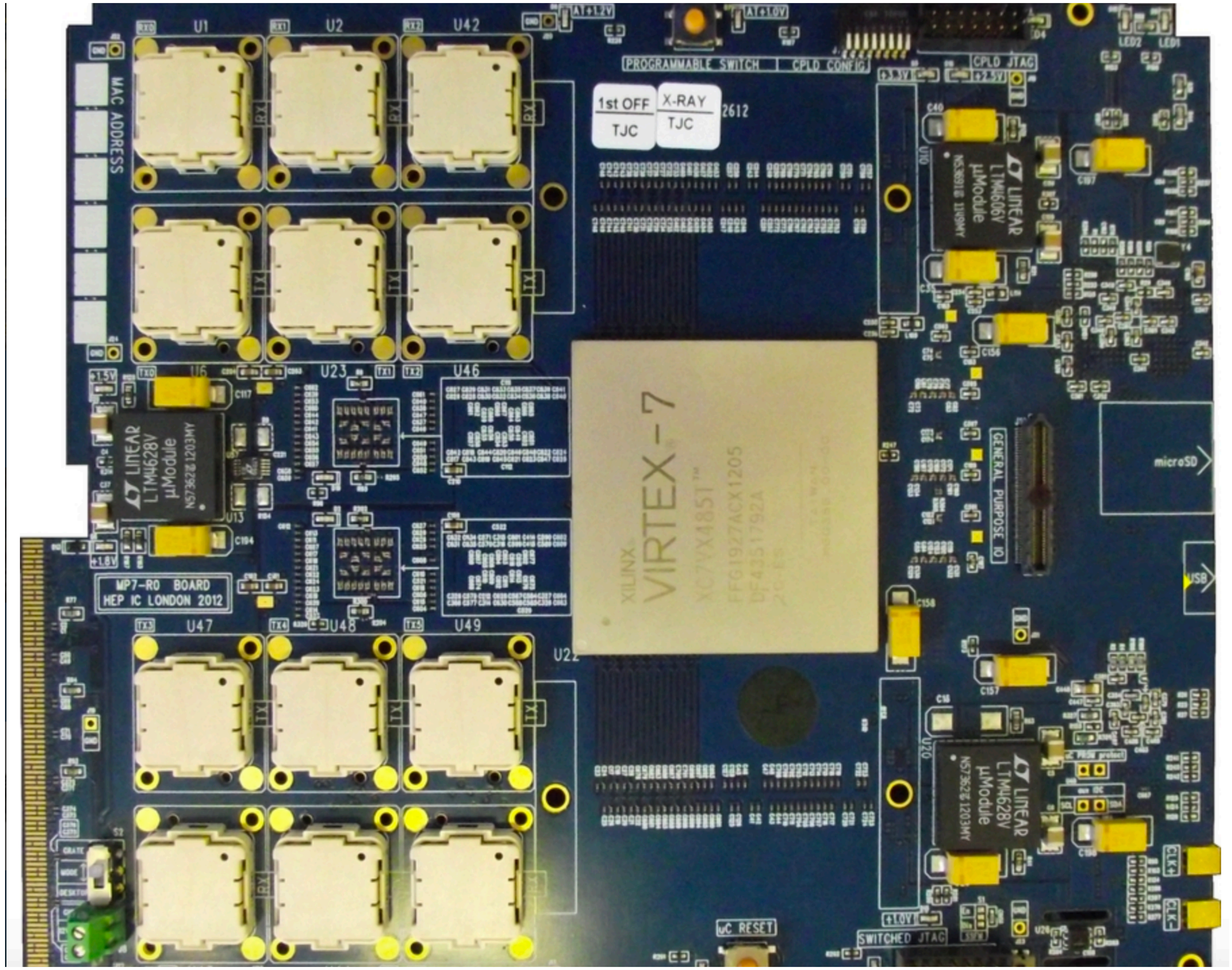
Physics needs might evolve,and LHC conditions could change - so must be able to make changes relatively easily.

5 Affordability

Can't blow the experiment budget on the Trigger! Need to make a reliable system within limited budget.

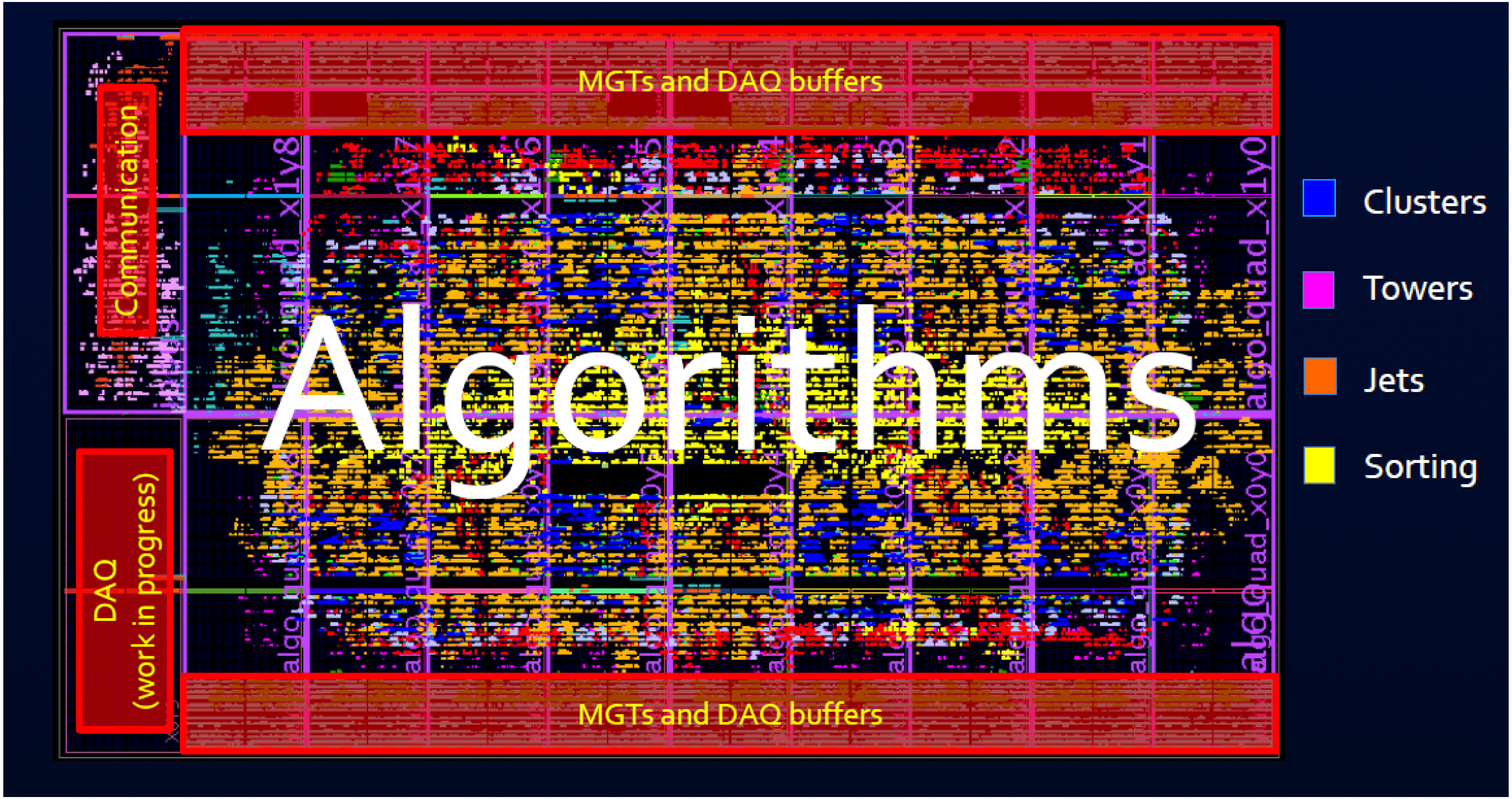
HOW?

HOW?



MAC ADDRESS
U1
U2
U42
PROGRAMMABLE SWITCH
CPLD CONFIG
CPLD JTAG
1st OFF
TJC
X-RAY
TJC
2612
U6
U23
U46
LINEAR
LTM4628V
µModule
MP7-R0 BOARD
HEP IC LONDON 2012
U47
U48
U49
U22
XILINX
VIRTEX-7
GENERAL PURPOSE IO
microSD
USB
uC RESET
SWITCHED JTAG

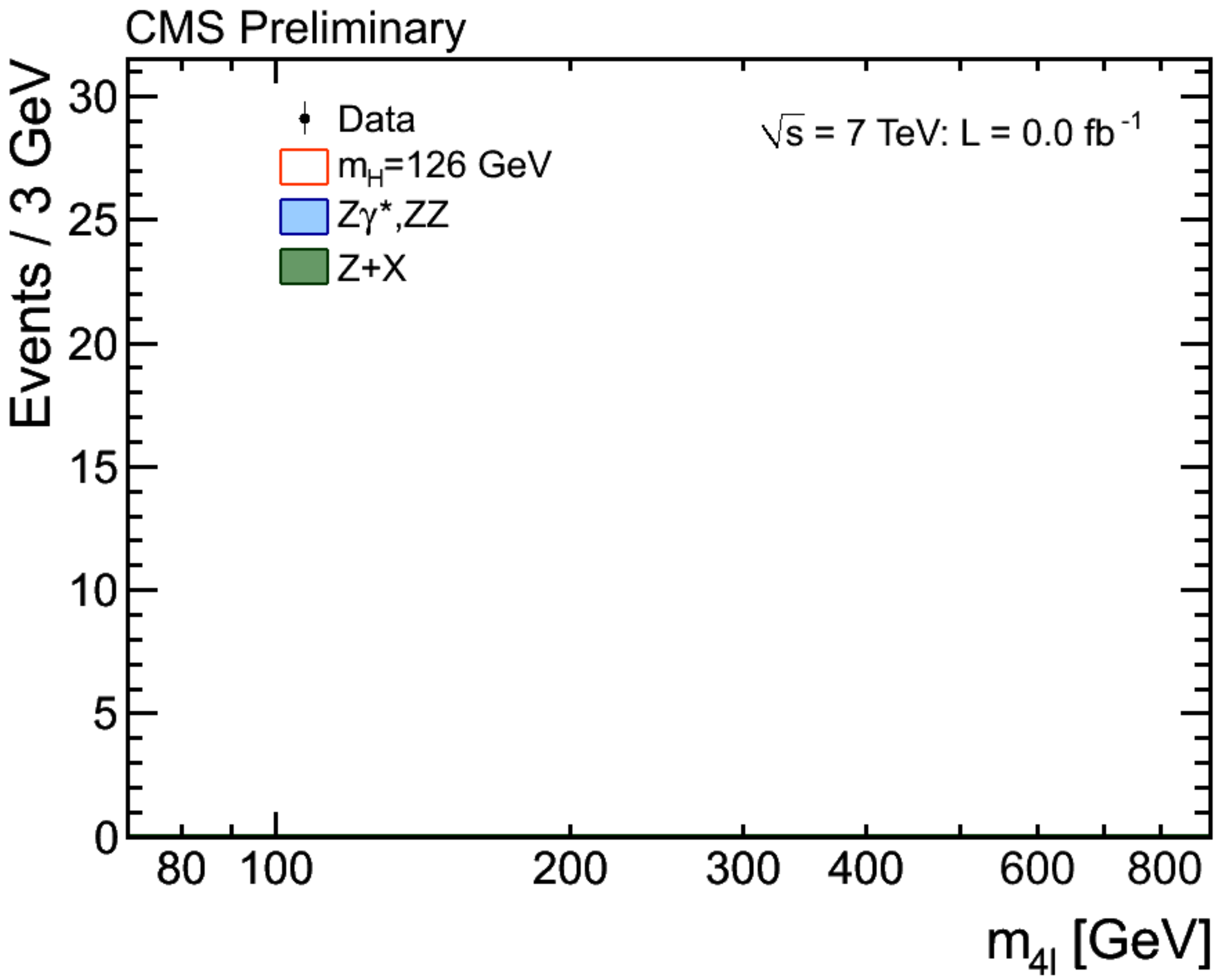
WHAT GOES IN THE CHIPS?



PERFORMING AN "ANALYSIS"

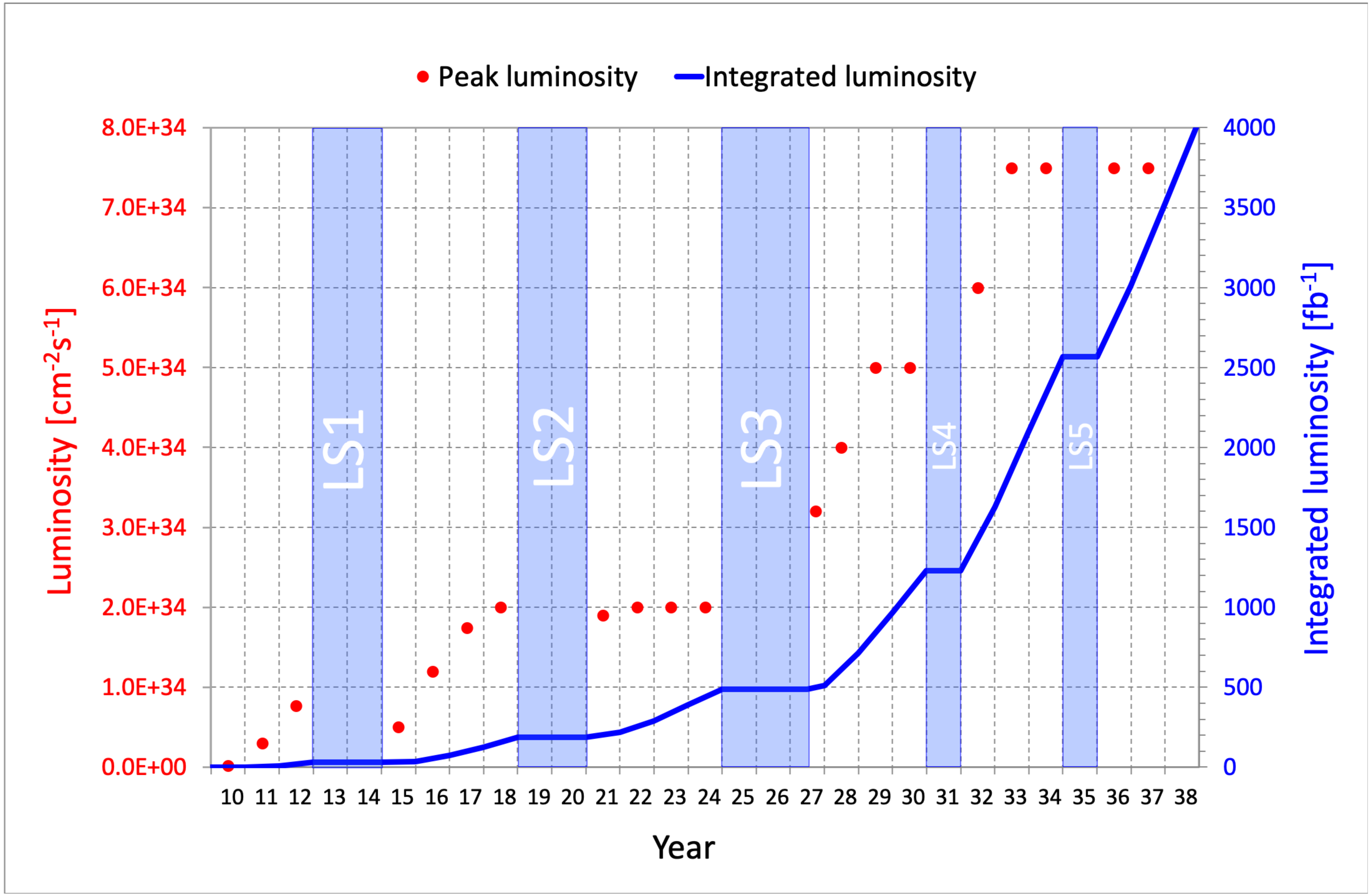
PERFORMING AN ANALYSIS

- Triggering
- Selecting events
- Predicting background – <u>uncertainties</u>
- After very careful checking of all the above, open the box….


CMS Preliminary
Data
m_H=126 GeV
Zγ*,ZZ
Z+X
√s = 7 TeV: L = 0.0 fb^-1
Events / 3 GeV
0
5
10
15
20
25
30
80
100
200
300
400
600
800
m_4l [GeV]

THINGS TO COME…
HIGH-LUMINOSITY LHC

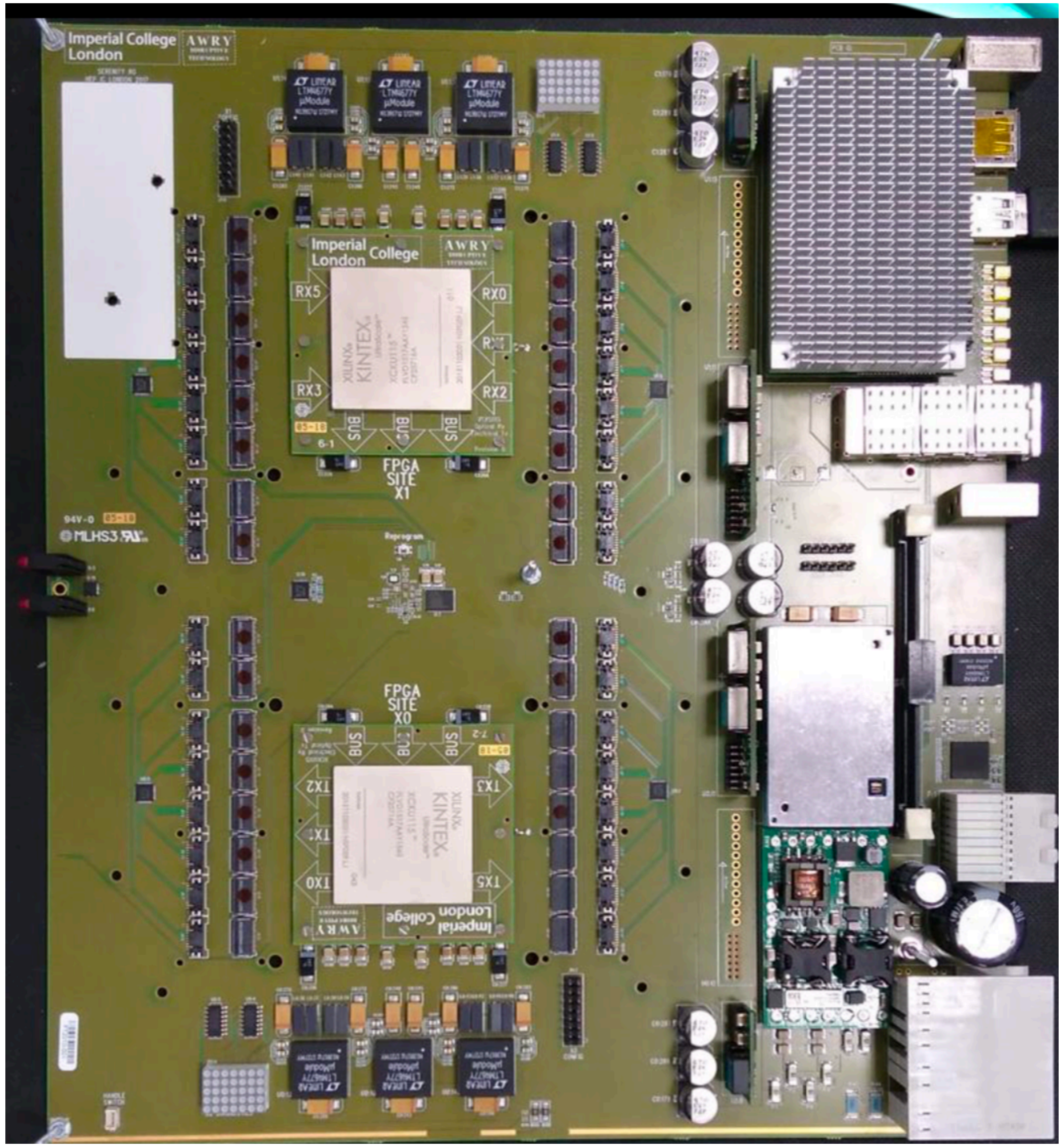
SCHEDULE



ONLY TAKEN 5% OF EXPECTED TOTAL DATA SET

NEW TECHNOLOGY REQUIRED

- Moving to larger form factor
- Having FPGAs on daughter cards provides flexibility to adapt boards to the purpose
- Maintain idea of generic stream processing boards.



AND NEW IDEAS…

CTL1 → **CTL2** → **CTL2** → **GT**

Particle Flow reconstruction

1. Calorimeter and track information processed for reconstructed PF candidates.

Histogramming algorithm

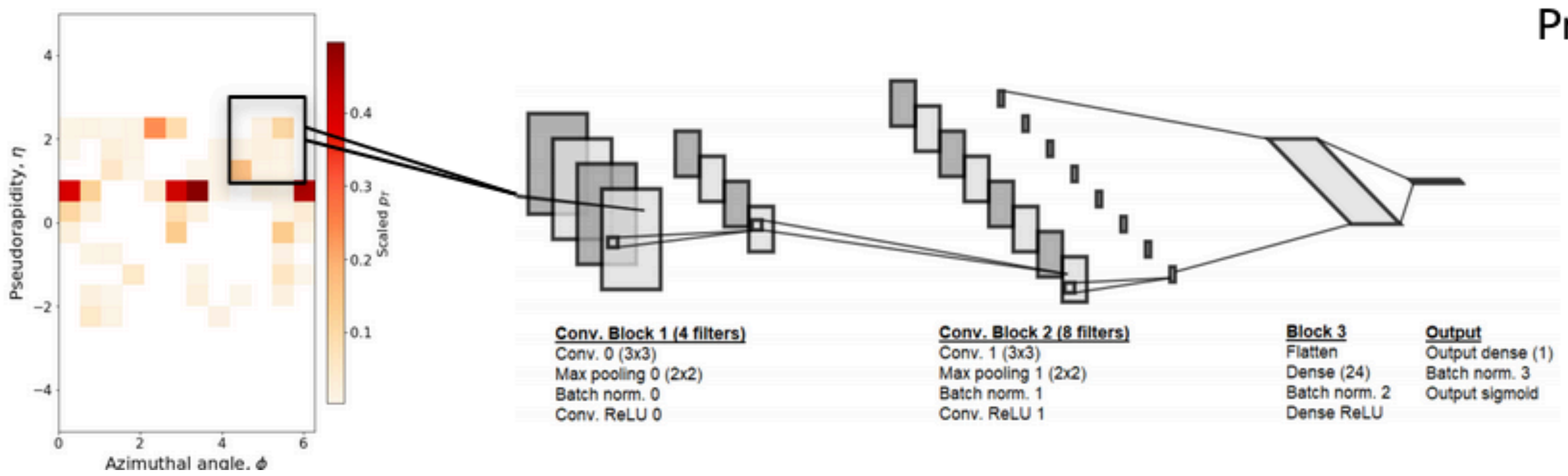
2. Histogramming algorithm on reconstructed PUPPI candidate three-vector (eta, phi, pT) to create "image"

Classification

3. Obtain probability distribution output by "raw-image" classifier.

Global Trigger input

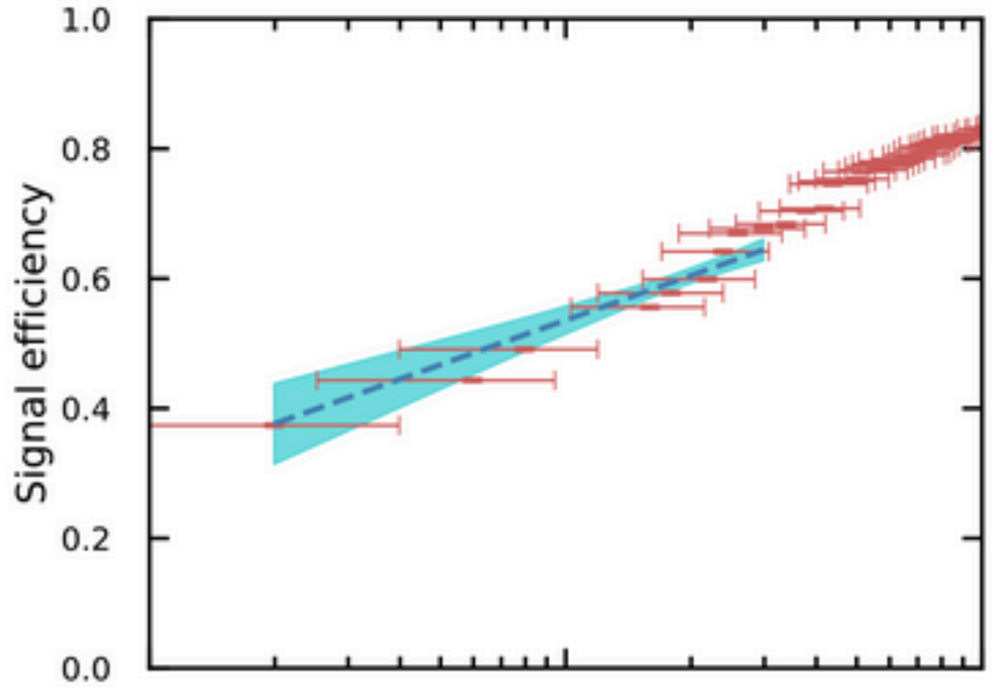
4. Deliver set of event-ID bits to GT, to be added to the global trigger menu.



Previously reported: *

➔ 50-60% HH → bbbb signal efficiency for a designated 10 KHz trigger rate of minBias background.

➔ Implemented on Serenity board



SLIDE FROM M.GLOWACKI

HIGH LEVEL SYNTHESIS

- Traditionally the programming of FPGAs was done by electronics engineers - within particle physics their recruitment and retention was difficult, and they were frequently single points of failure within the project

- HLS was devised to allow C (++) code to be written and then automatically translated into appropriate HDL (hardware design languages)

- Allows a much larger pool of people to contribute to algorithm design - CMS making use of this for upgrade

hls4ml

`hls4ml` is a Python package for machine learning inference in FPGAs. We create firmware implementations of machine learning algorithms using high level synthesis language (HLS). We translate traditional open-source machine learning package models into HLS that can be configured for your use-case!

TRIGGERING= DATA SELECTION

- We use telecommunications standard hardware for our trigger system
- Continuing to rethink our problem as a problem encountered across domains
  - medical imaging
  - high-speed networking
  - data reduction
- Machine learning increasingly being used to tackle these problems

SUMMARY

- Particle Physics studies the fundamental constituents of the Universe and the way they interact
- Hadron Collider facilities (like the LHC) provide a vast amount of data, but we are searching for rare decays - fast real-time analysis required to select.
- The advent of HLS and Machine Learning are new tools which are changing the way we develop algorithms and hopefully will lead to big discoveries in the coming years!
- Triggering is a data selection/data reduction problem with many applications outside of Physics - interdisciplinary studies are a focal point of research currently.

THANK YOU!