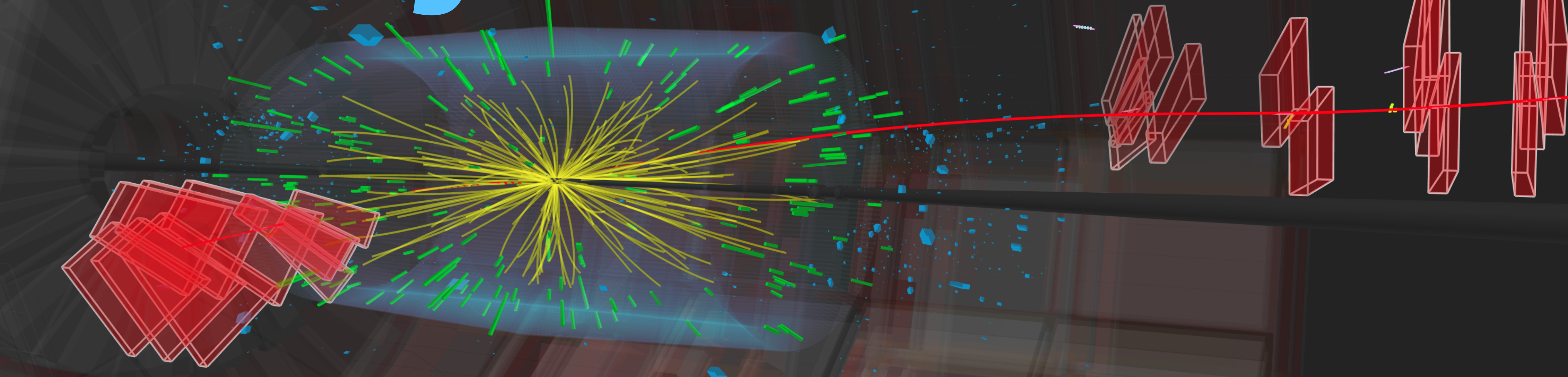
CMS Experiment at the LHC, CERN
Data recorded: 2022-Jul-05 14:48:56.743936 GMT
Run / Event / LS: 355100 / 51596902 / 53

Physics @ LHC



Probing the Standard Model & beyond

Nuno Leonardo

LIP & IST, nuno@cern.ch

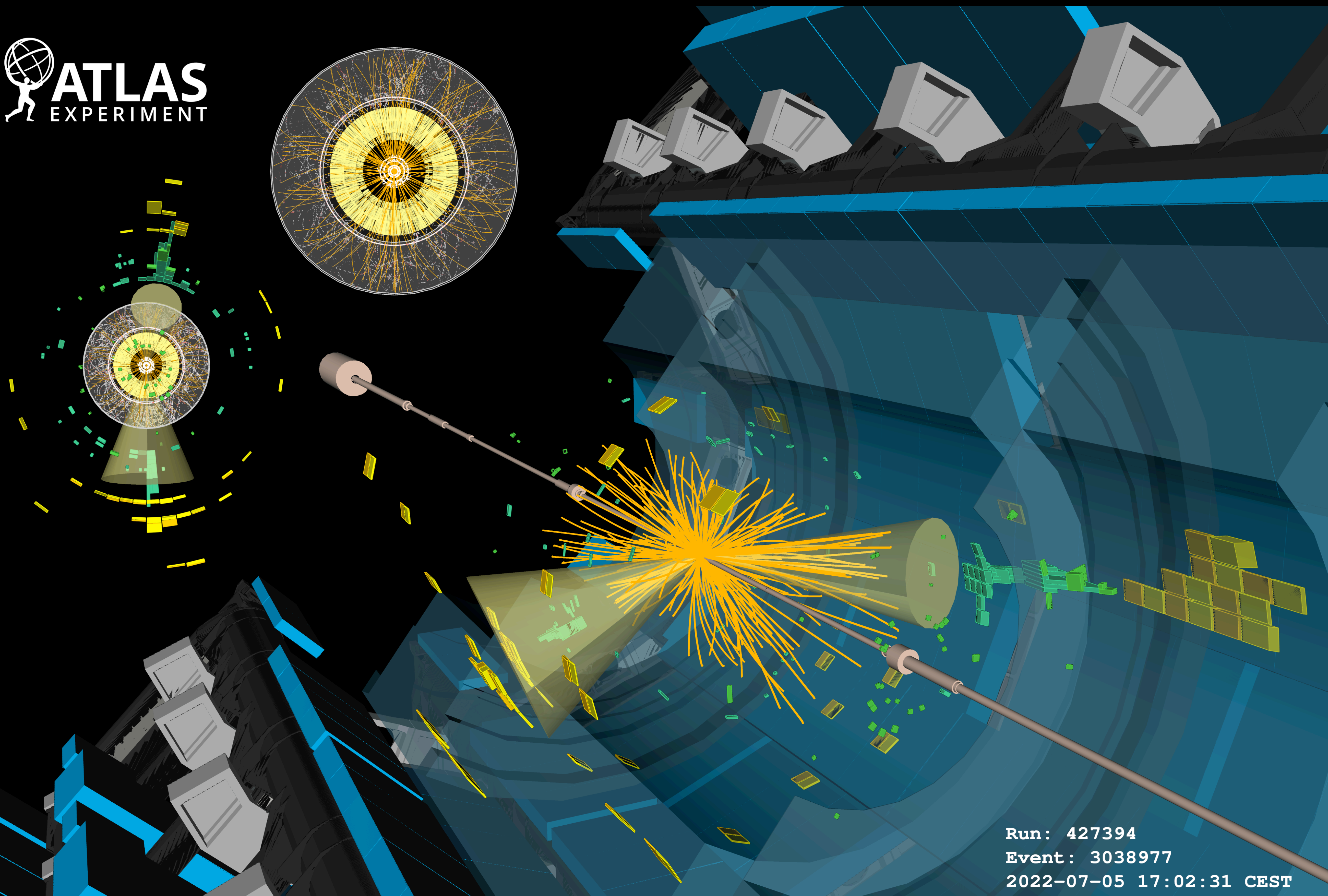
LIP Internship Lecture, July 8th, 2023

2023 INTERNSHIP PROGRAM
COIMBRA LISBOA MINHO

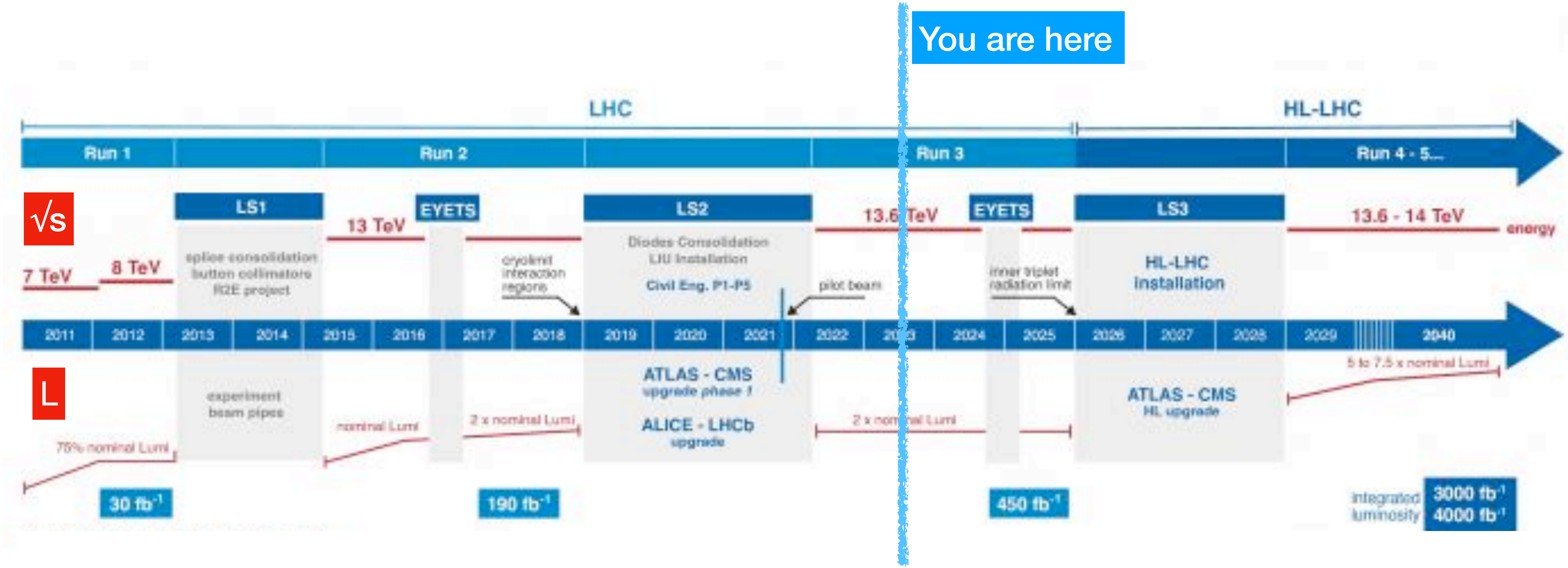
LIP

fct Fundação para a Ciência e a Tecnologia

LHC: Run 3 has started! (2022-2025, ongoing)

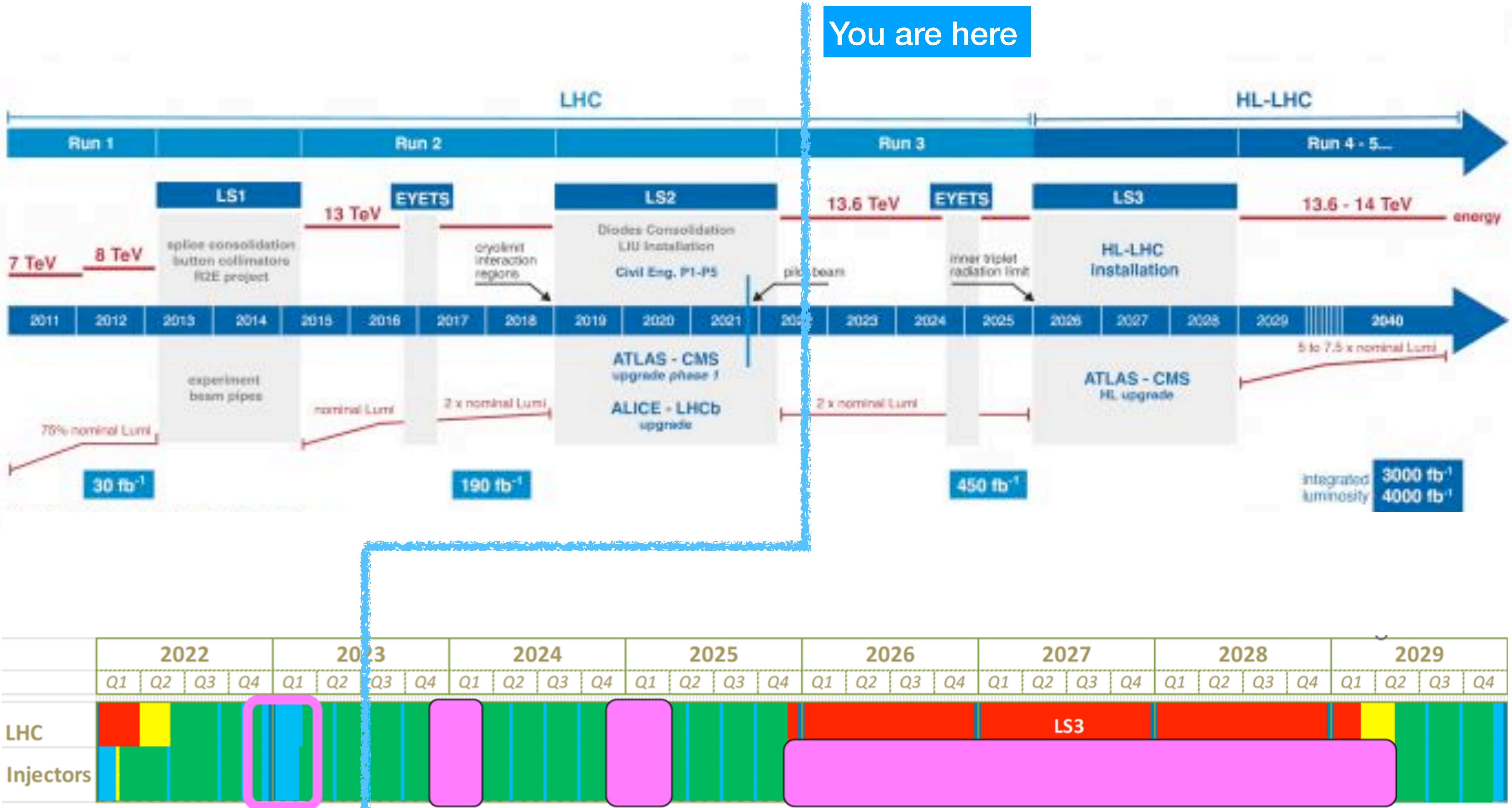


LHC schedule



- The LHC has been operating for over a **decade**, two more to go
- Two main parameters determine the physics reach
  - Collision **energy** (√s) — just attained another record (13.6 TeV)
  - **Luminosity** (L) — related to the collision rate
- both have been increasing, but the forthcoming jump will be in lumi!

LHC schedule



Run 3 : 2022 — 2025

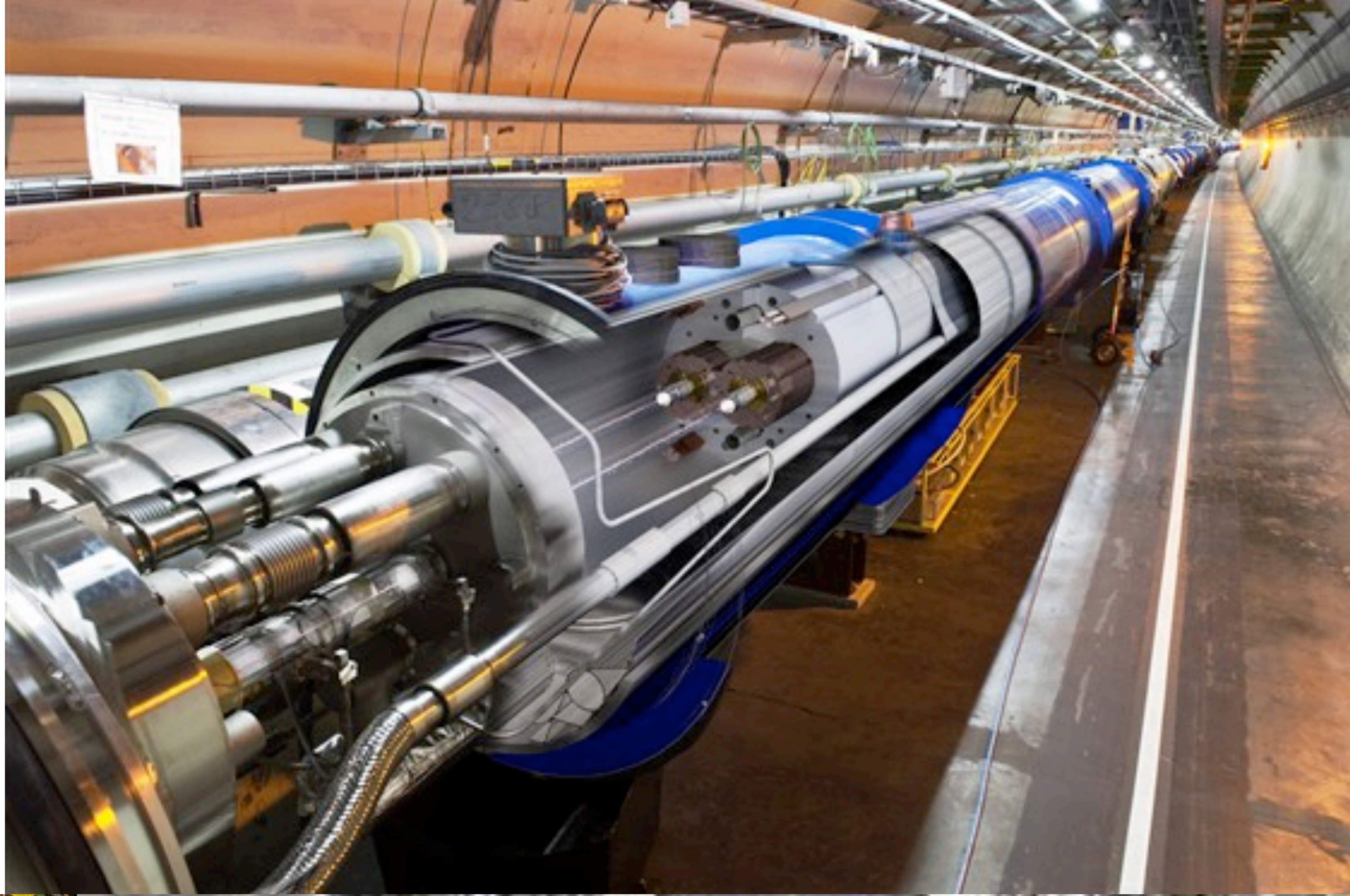
A *new* LHC: **HL-LHC**, 2026 — 2040

The LHC is the **world-leading** particle accelerator & collider

Delivering **unprecedented** energies and intensities

The LHC detectors are the most **sophisticated** scientific tools yet

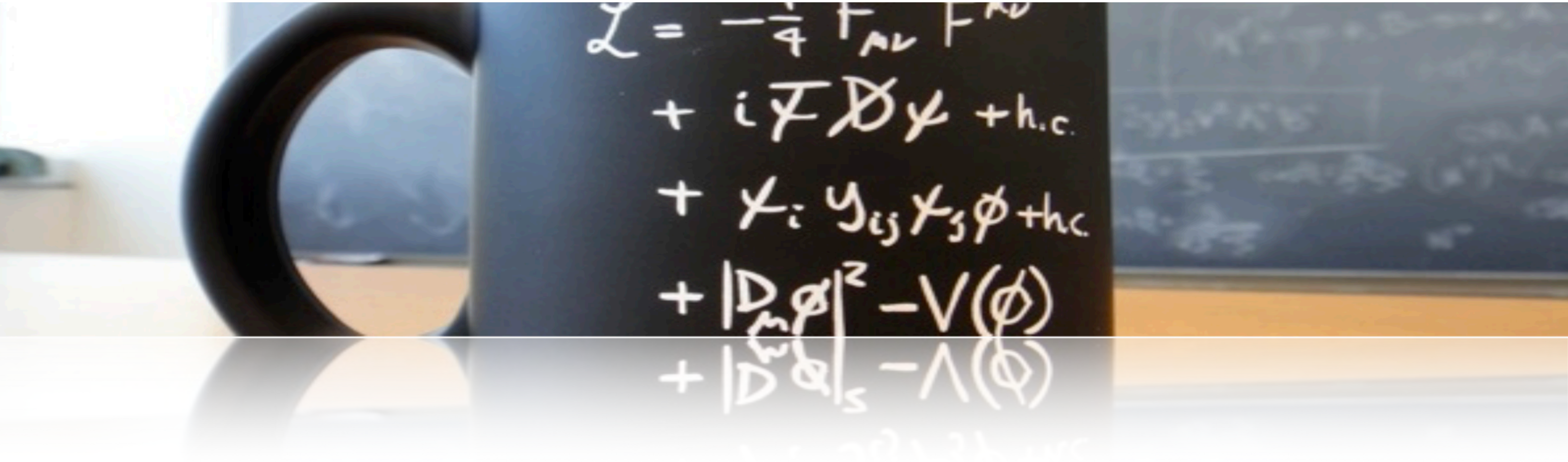
Machine and detectors not static, systematically improved/**upgraded**



Lecture overview

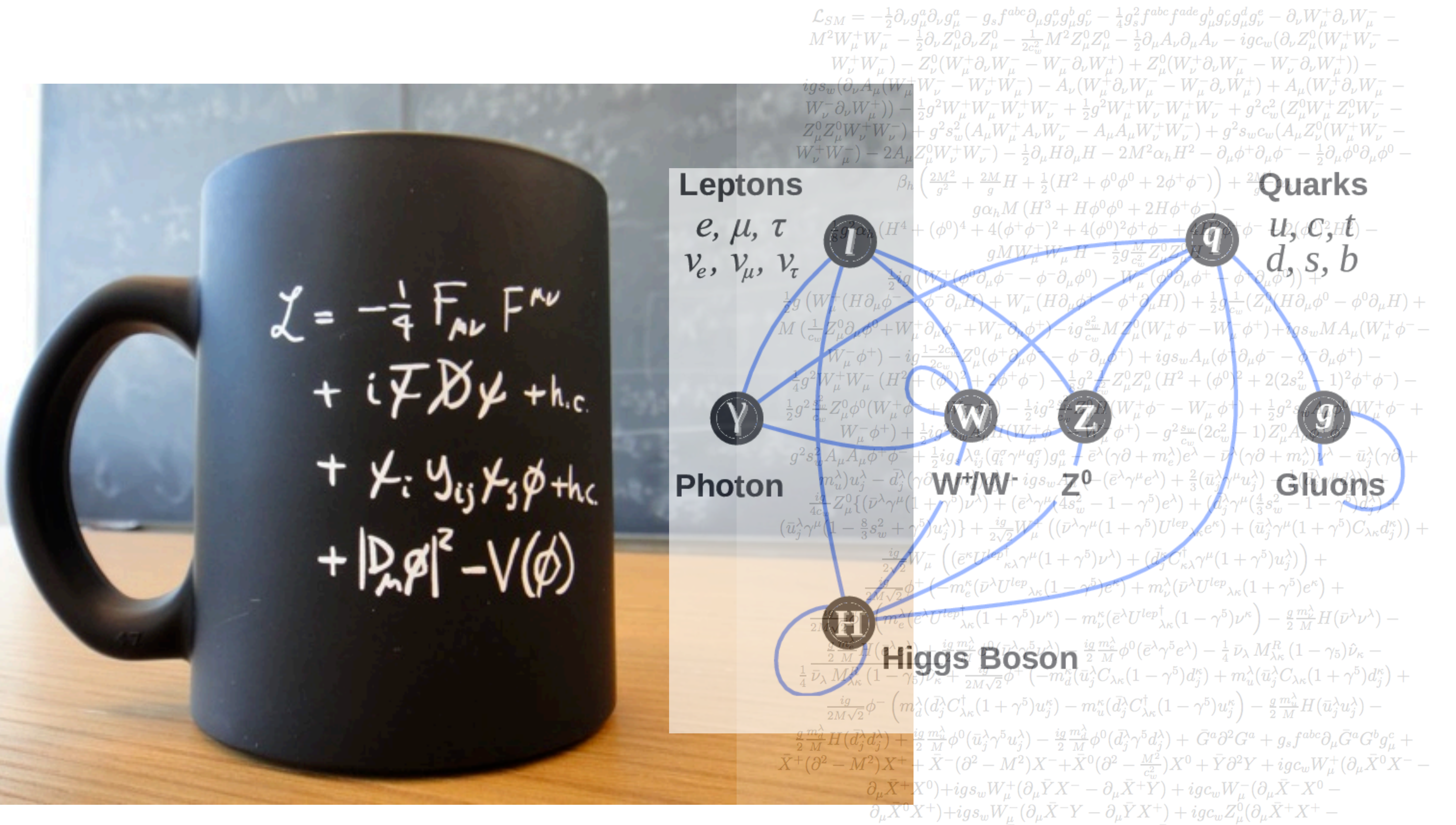
- The physics case
  - Particle physics, the standard model, and beyond
  - Precision SM measurements,
    discover new & rare processes
- The accelerator
  - Energy, luminosity, accelerating, bending, focusing
- The detectors
  - ATLAS, CMS, Trigger, Data flow
  - the newest experiments @LHC
- Going beyond the SM
  - Direct and indirect searches (& anomalies)

Physics



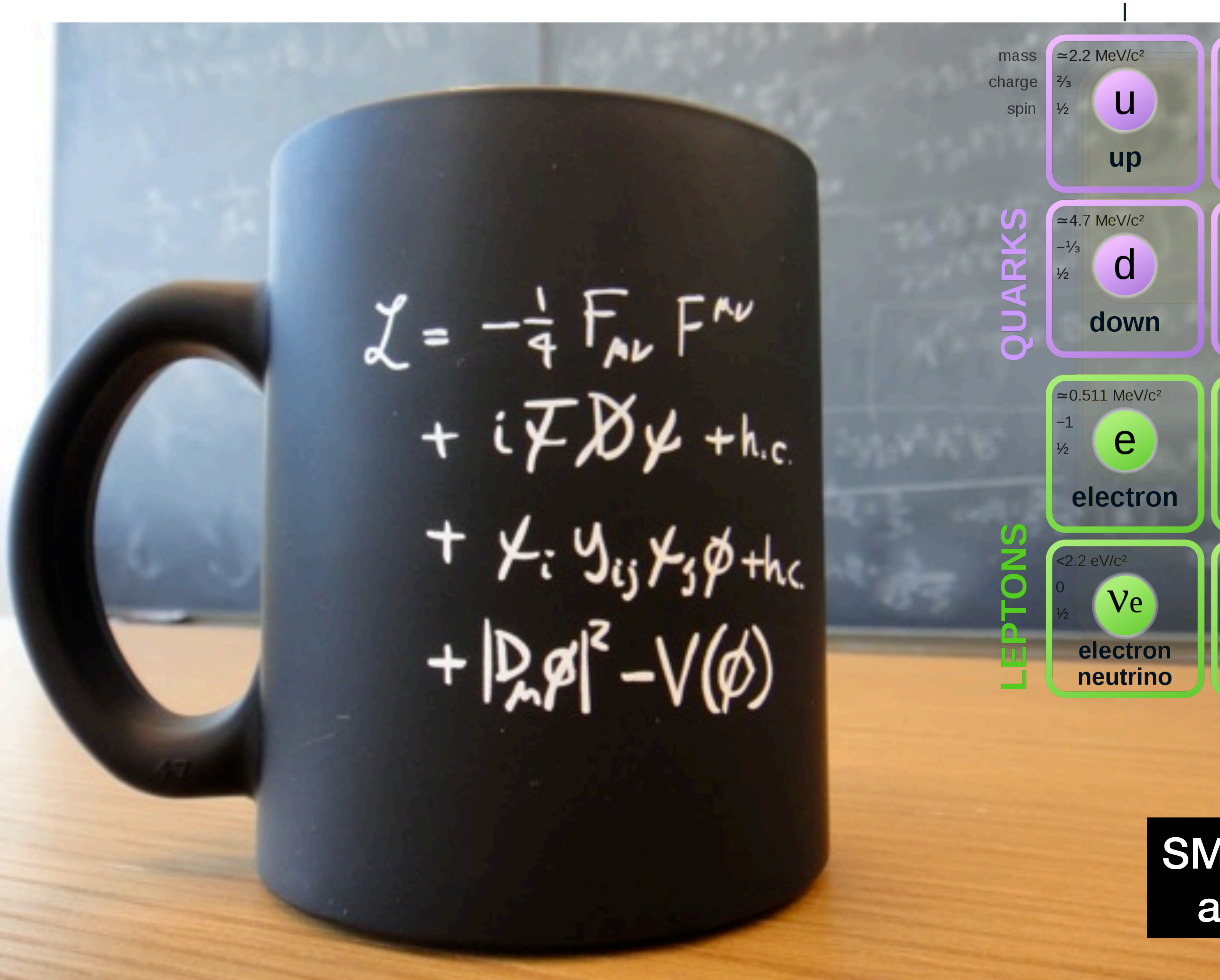
- **Particle Physics** is the study of
  - **Matter** — the fundamental constituents of the universe — i.e. the elementary particles
  - **Force** — the fundamental forces of nature — i.e. the interaction between the elementary particles
- The **Standard Model** embodies our current understanding
  - Forces between particles due to exchange of particles
  - SM built from systematic interaction between theory *and* experiment
  - SM accommodates all observed particles, and it is impressively consistent with *all* $^{(*)}$ current experimental data!
  - But *just a model,* e.g. many unpredicted parameters
  - Not the *ultimate theory* (whatever that might be), there are many mysteries — to be resolved by *probing nature* with *experiment*

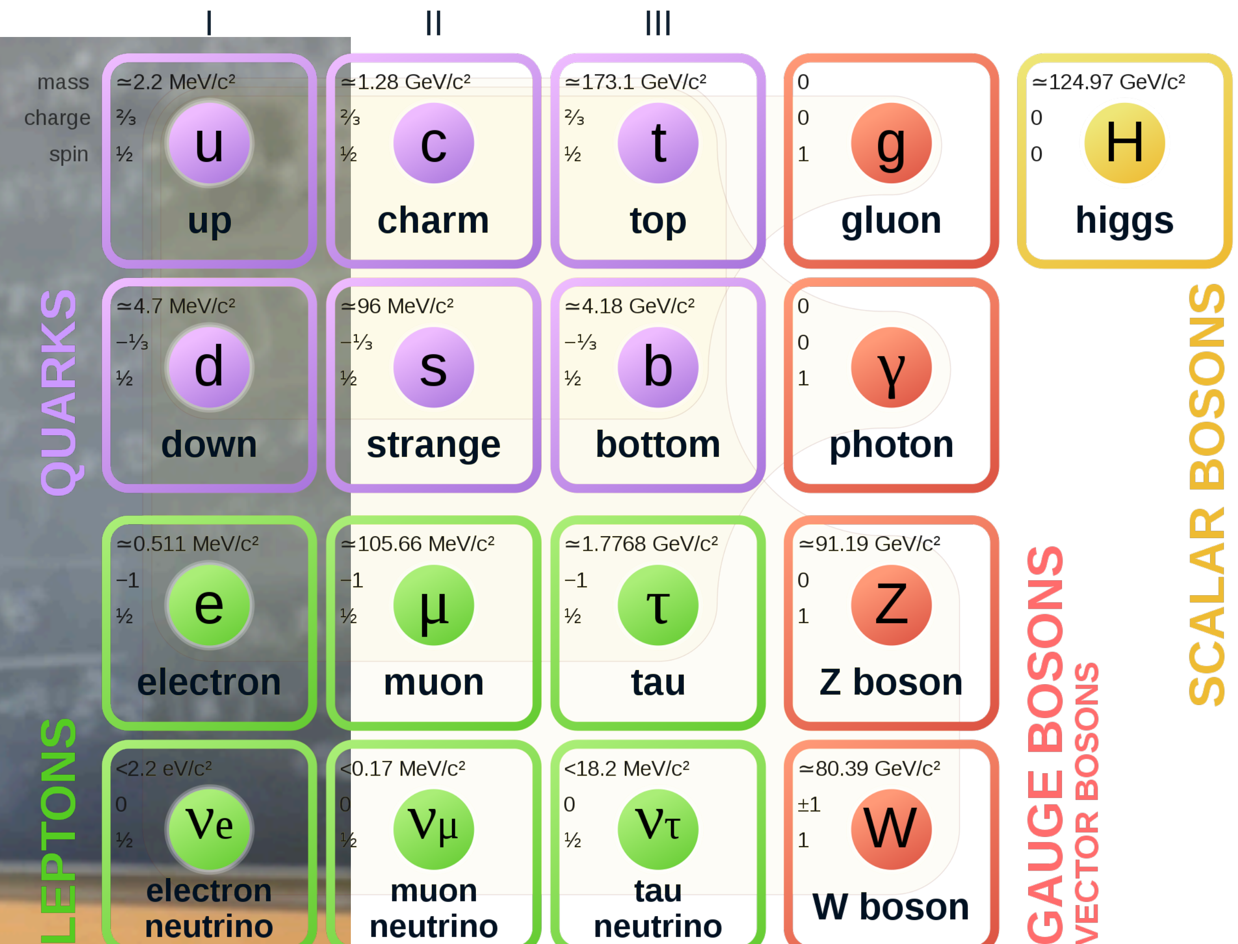
The Standard Model of Particle Physics



SM = Quantum field theory + Experimental measurement & discovery

The Standard Model of Particle Physics

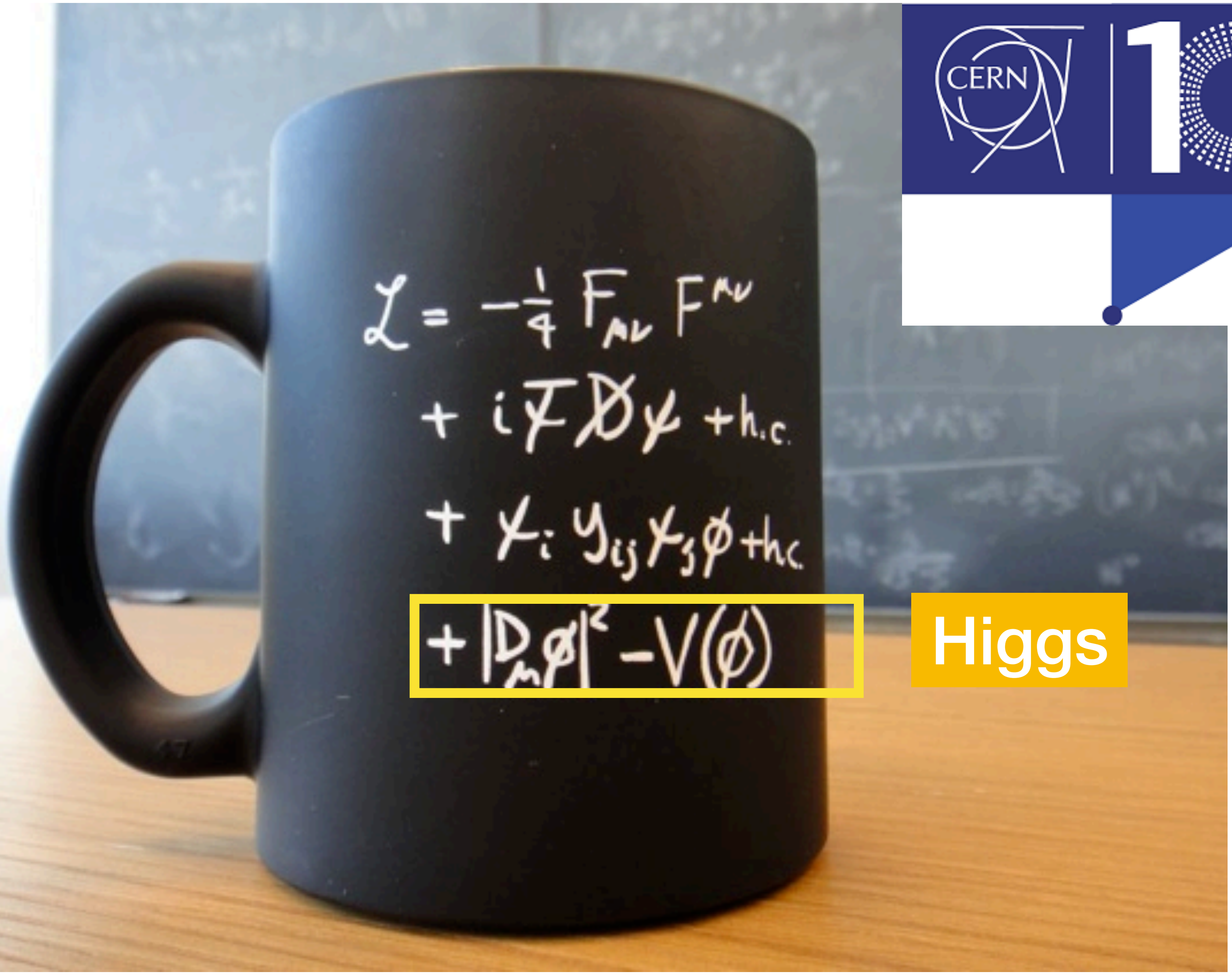




SM **predictions** can be **tested** against experimental data

One of the great achievements of 20th century science.

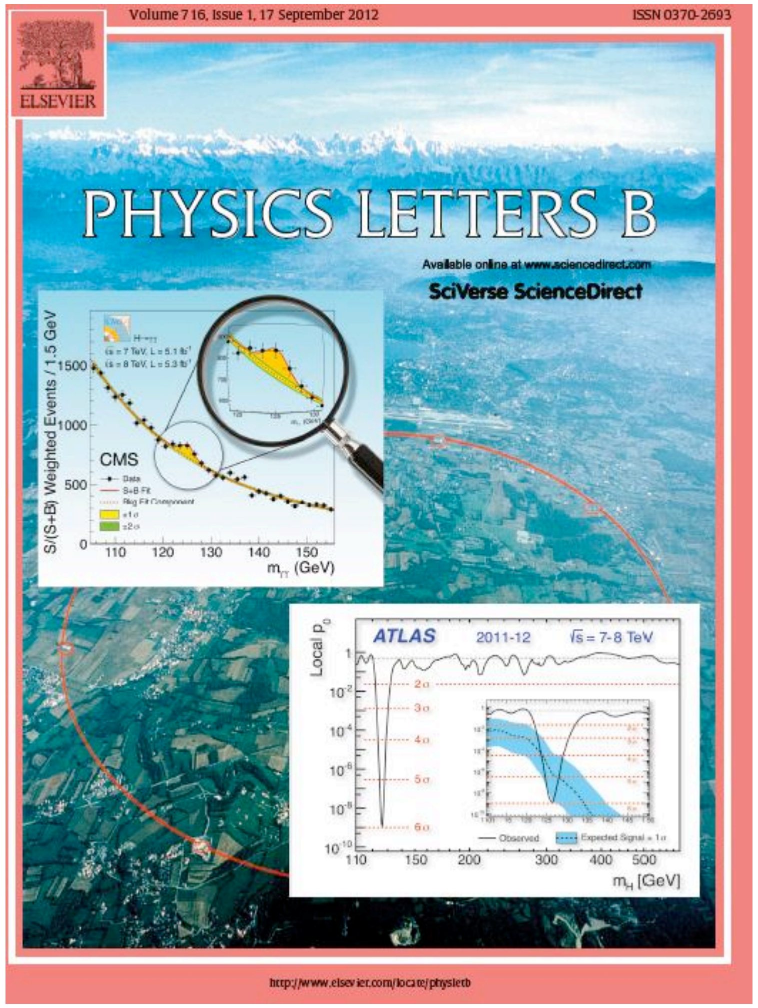
The Higgs boson



Higgs

CERN 10 years HIGGS boson discovery

≈124.97 GeV/c²
0
0
H
higgs



The Higgs boson turns 11 years old

The Higgs boson, ten years after its discovery

The landmark discovery of the Higgs boson at the Large Hadron Collider exactly ten years ago, and the progress made since then to determine its properties, have allowed physicists to make tremendous steps forward in our understanding of the universe

4 JULY, 2022

Read the celebratory CMS & ATLAS papers

Research Articles

A detailed map of Higgs boson interactions by the ATLAS experiment ten years after the discovery

Ten years after the discovery of the Higgs boson, the ATLAS experiment at CERN probes its kinematic properties with a significantly larger dataset from 2015–2018 and provides further insights on its interaction with other known particles.

The ATLAS Collaboration

Article | Open Access | 4 Jul 2022 | Nature

A portrait of the Higgs boson by the CMS experiment ten years after the discovery

The most up-to-date combination of results on the properties of the Higgs boson is reported, which indicate that its properties are consistent with the standard model predictions, within the precision achieved to date.

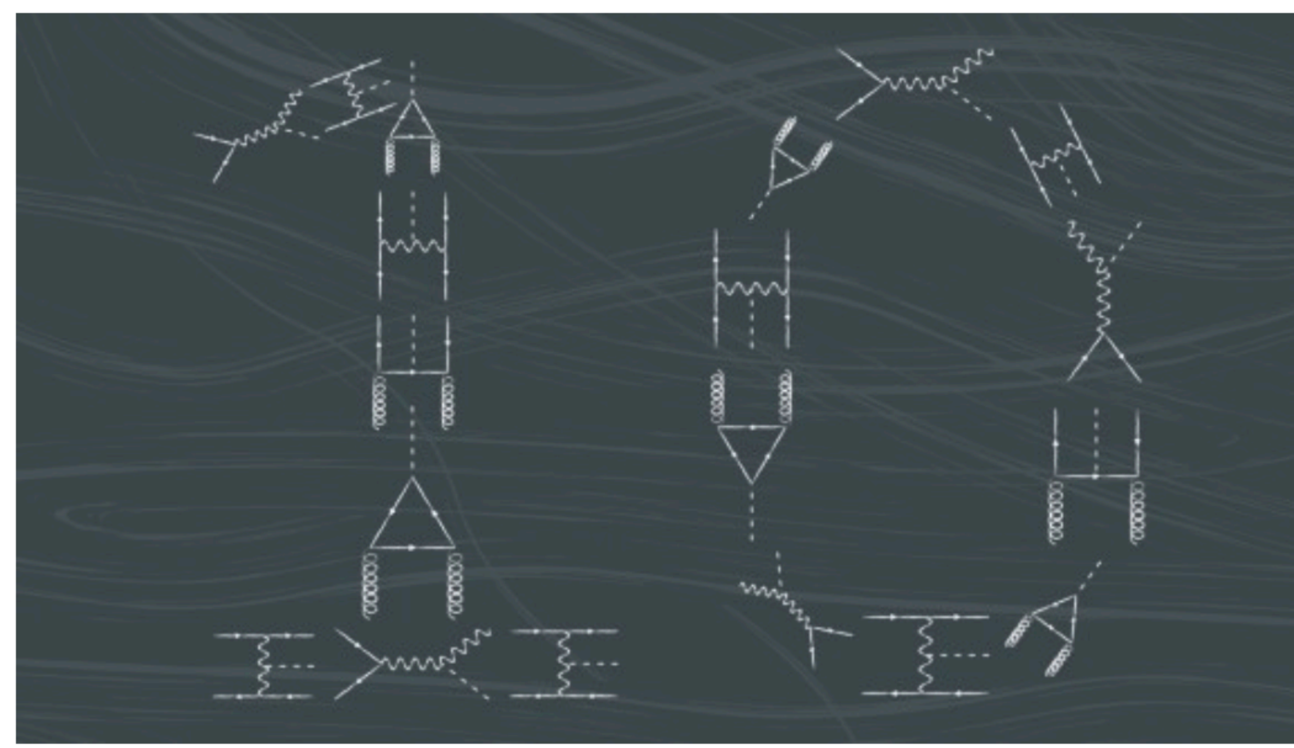
The CMS Collaboration

Article | Open Access | 4 Jul 2022 | Nature

Collection | **04 July 2022**

The Higgs boson discovery turns ten

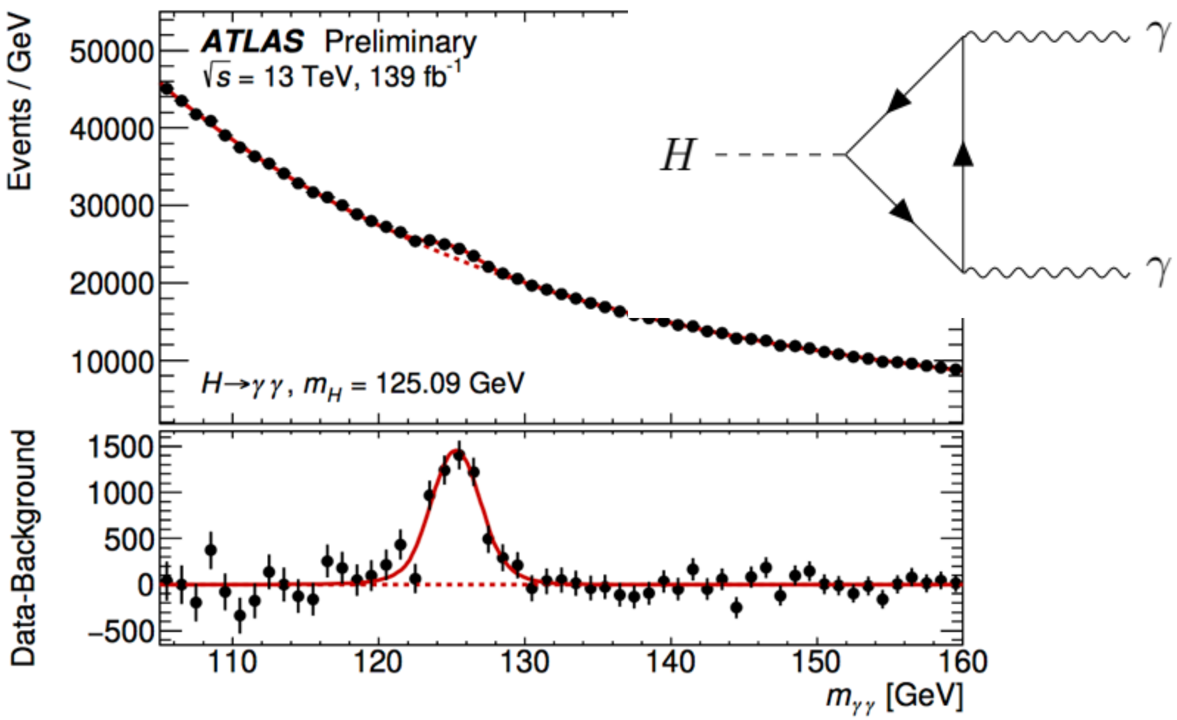
The discovery of the Higgs boson was announced ten years ago on the 4th of July 2012 — an event that substantially advanced our understanding of the origin of elementary particles' masses. In this collection of articles from *Nature, Nature Physics* and *Nature Reviews Physics* we celebrate this groundbreaking discovery and reflect on what we have learned about the Higgs boson over the intervening years.

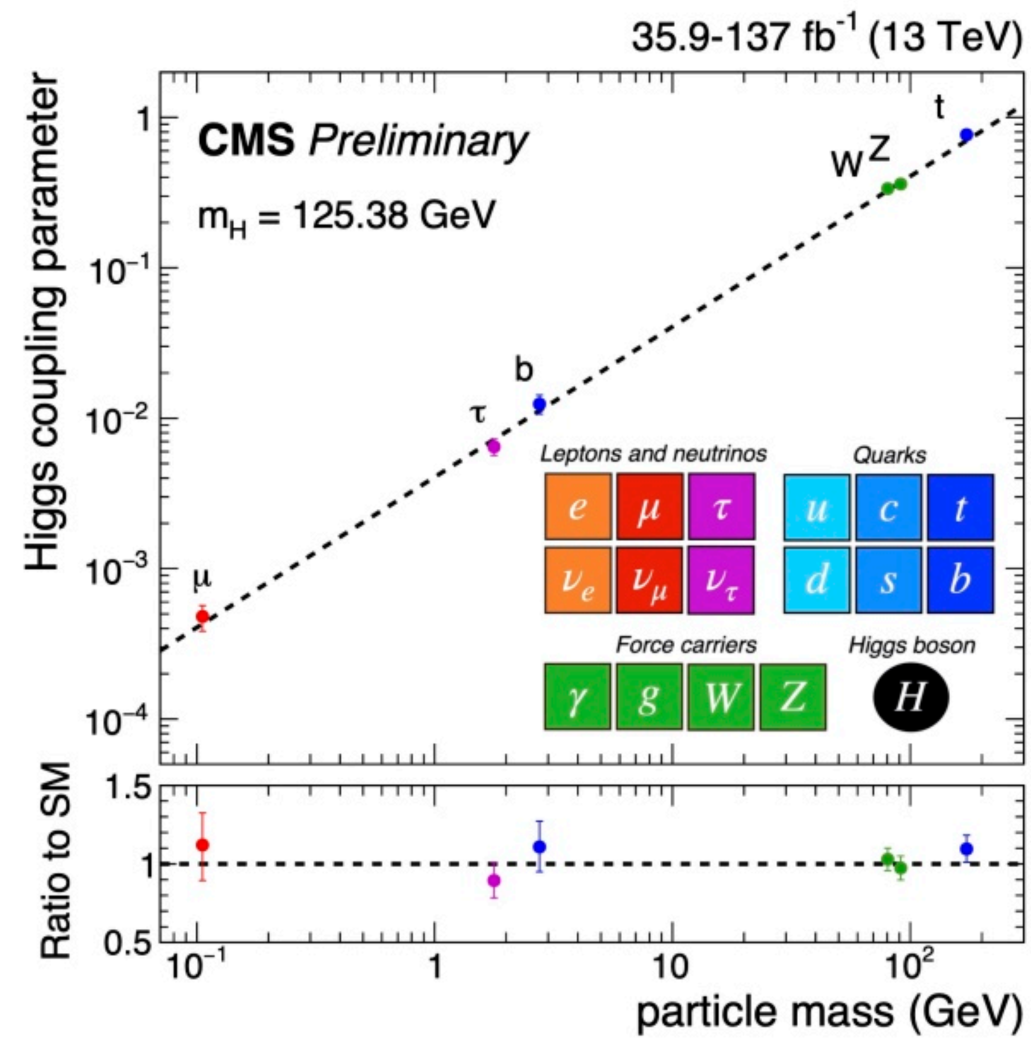


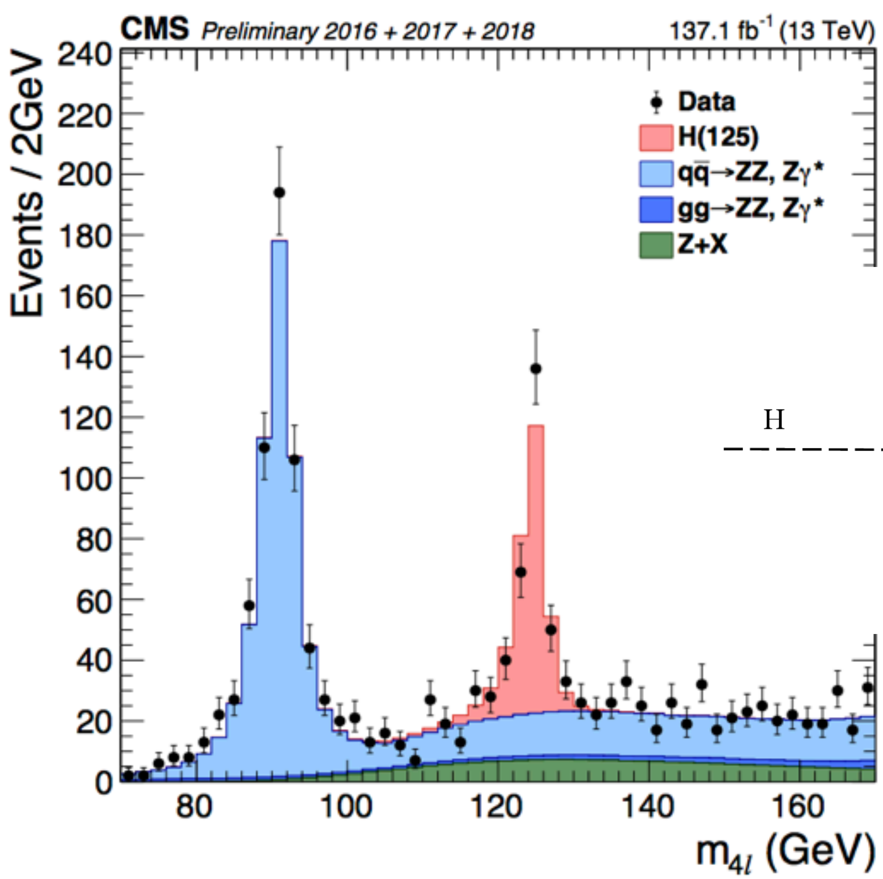
https://home.cern/news/press-release/physics/higgs-boson-ten-years-after-its-discovery

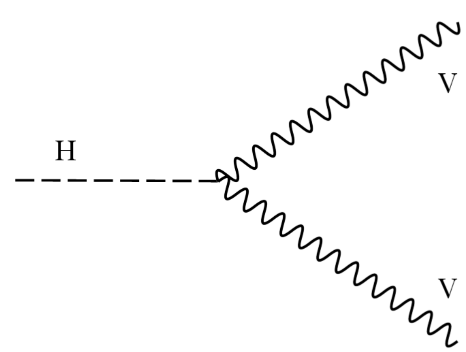
https://www.nature.com/collections/gbfhieacie

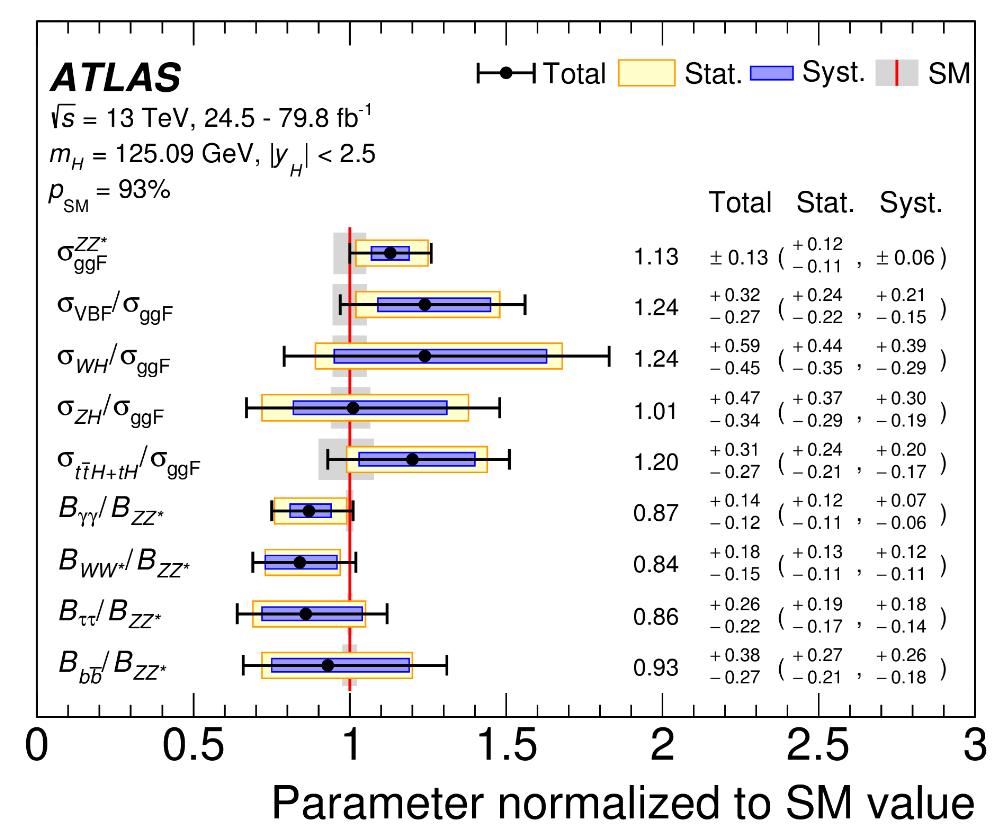
Status of the scalar





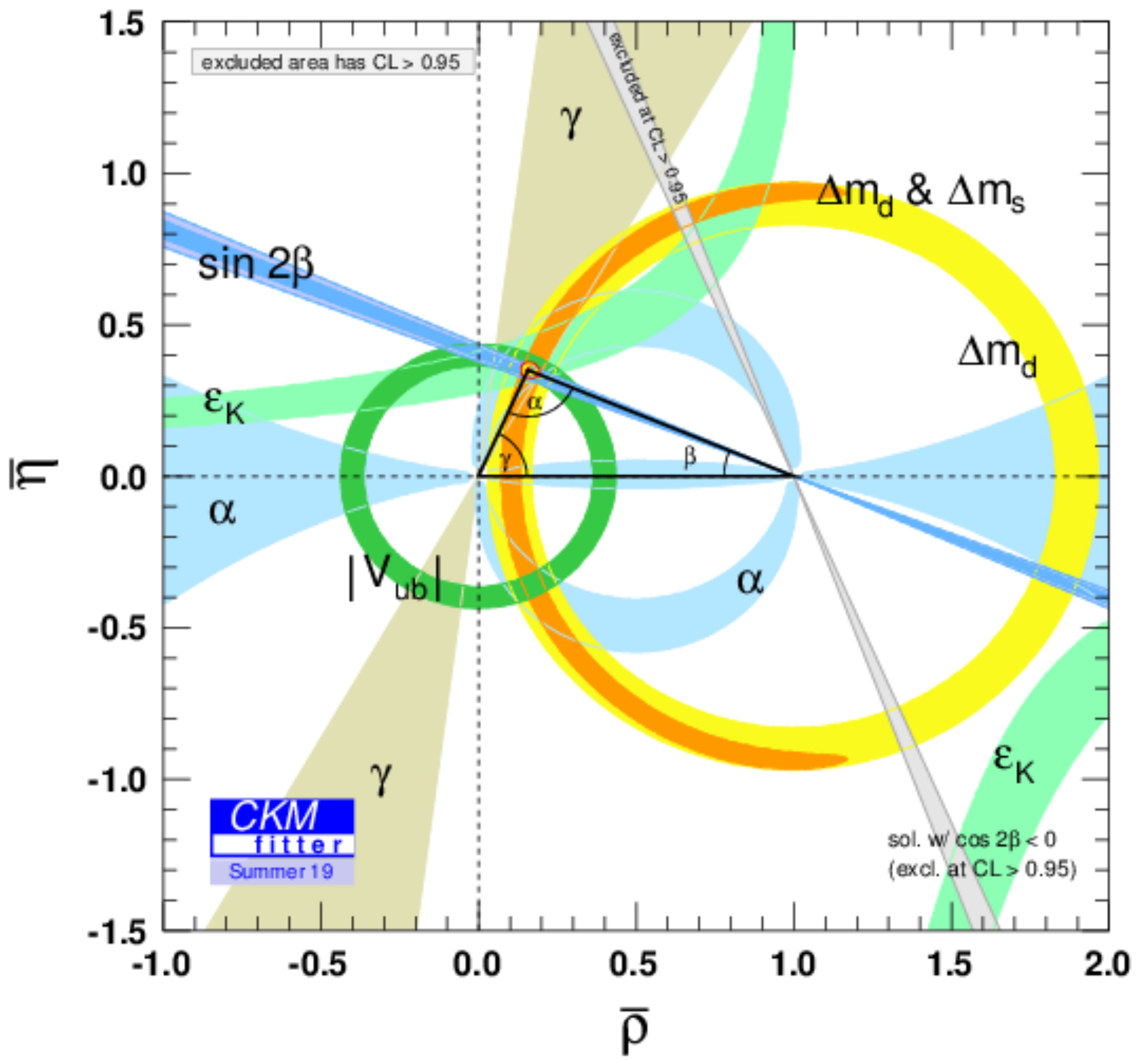




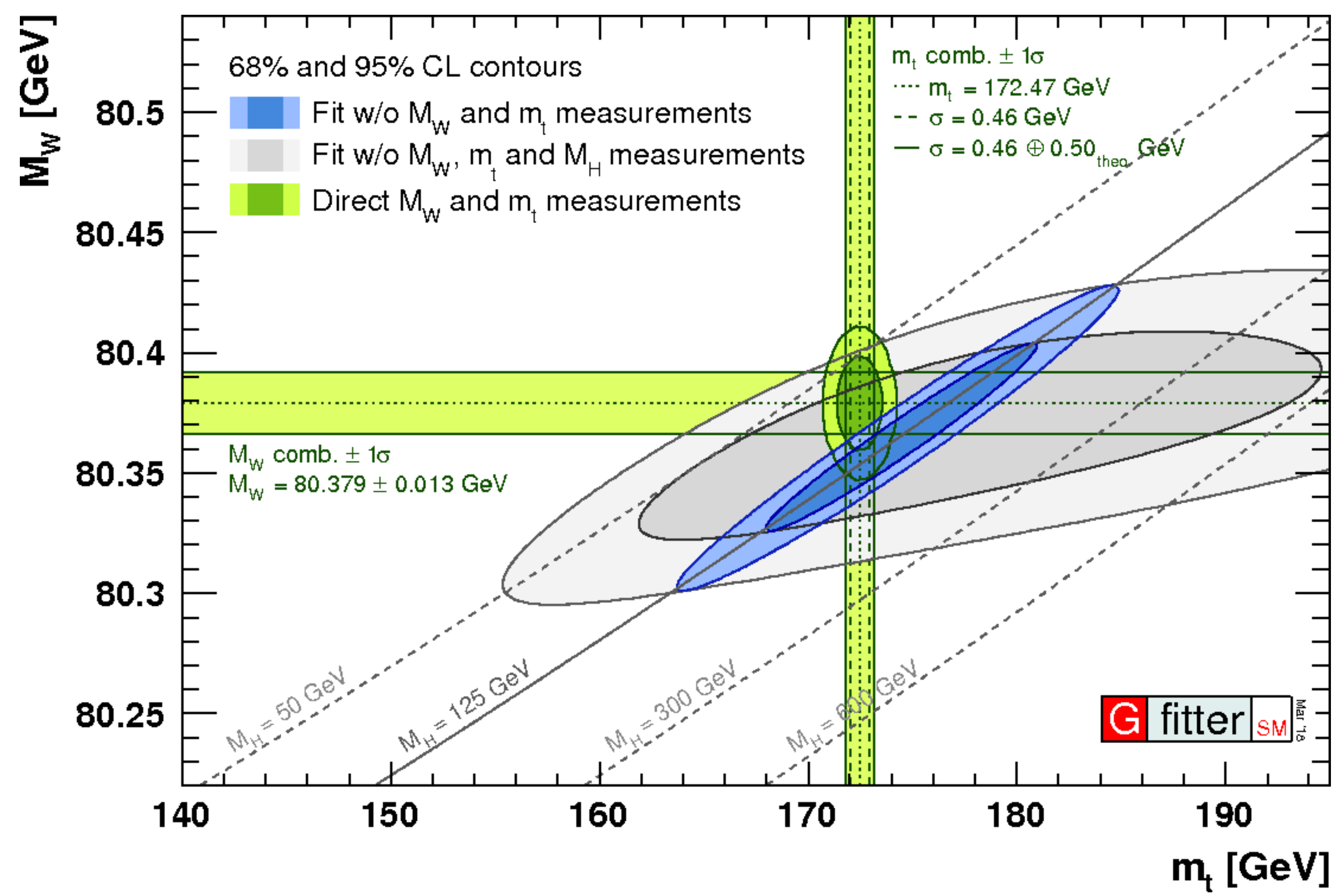


The Standard Model: precision measurements

quarks



H vs W vs t

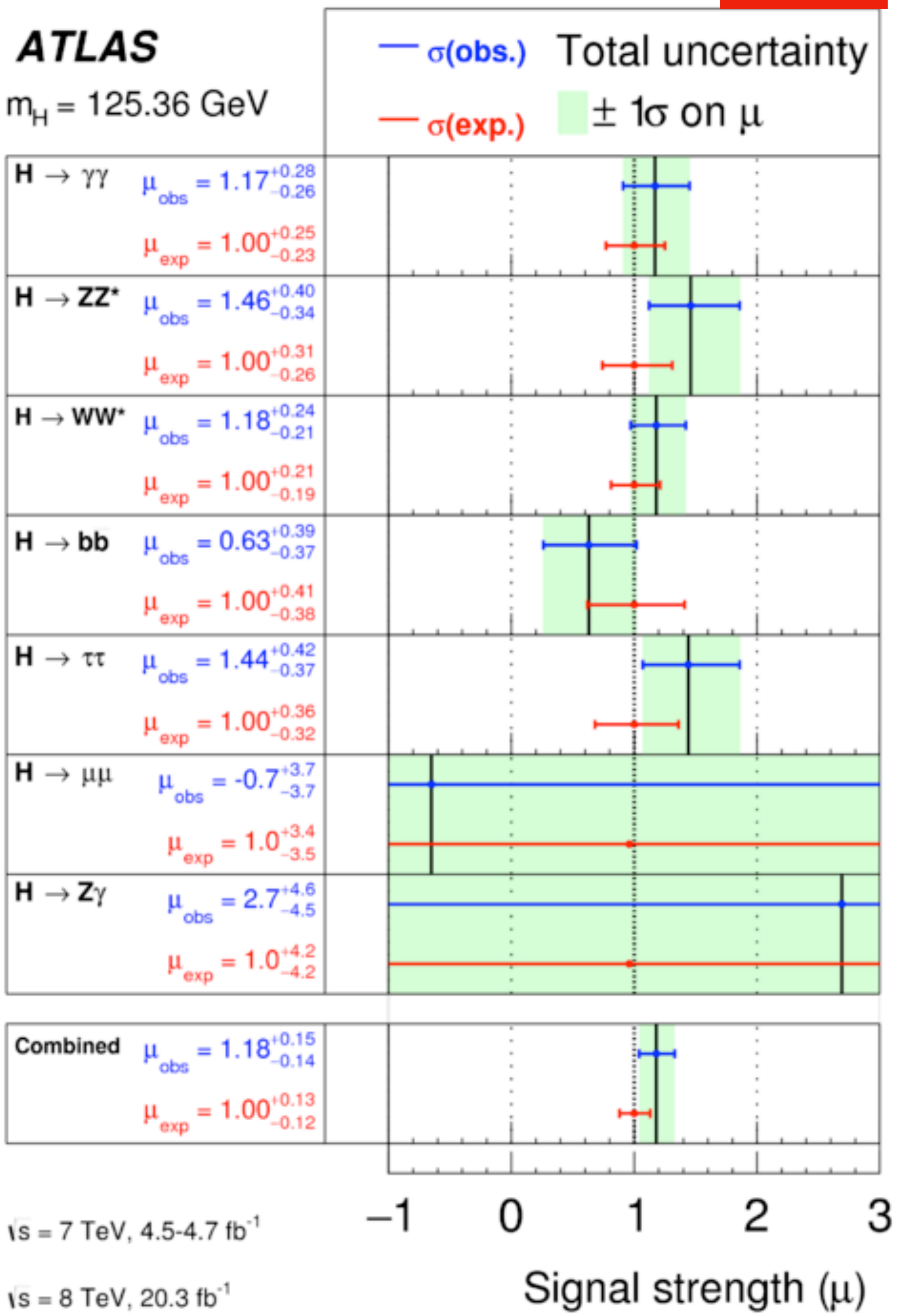


The SM describes all (*) experimental data !

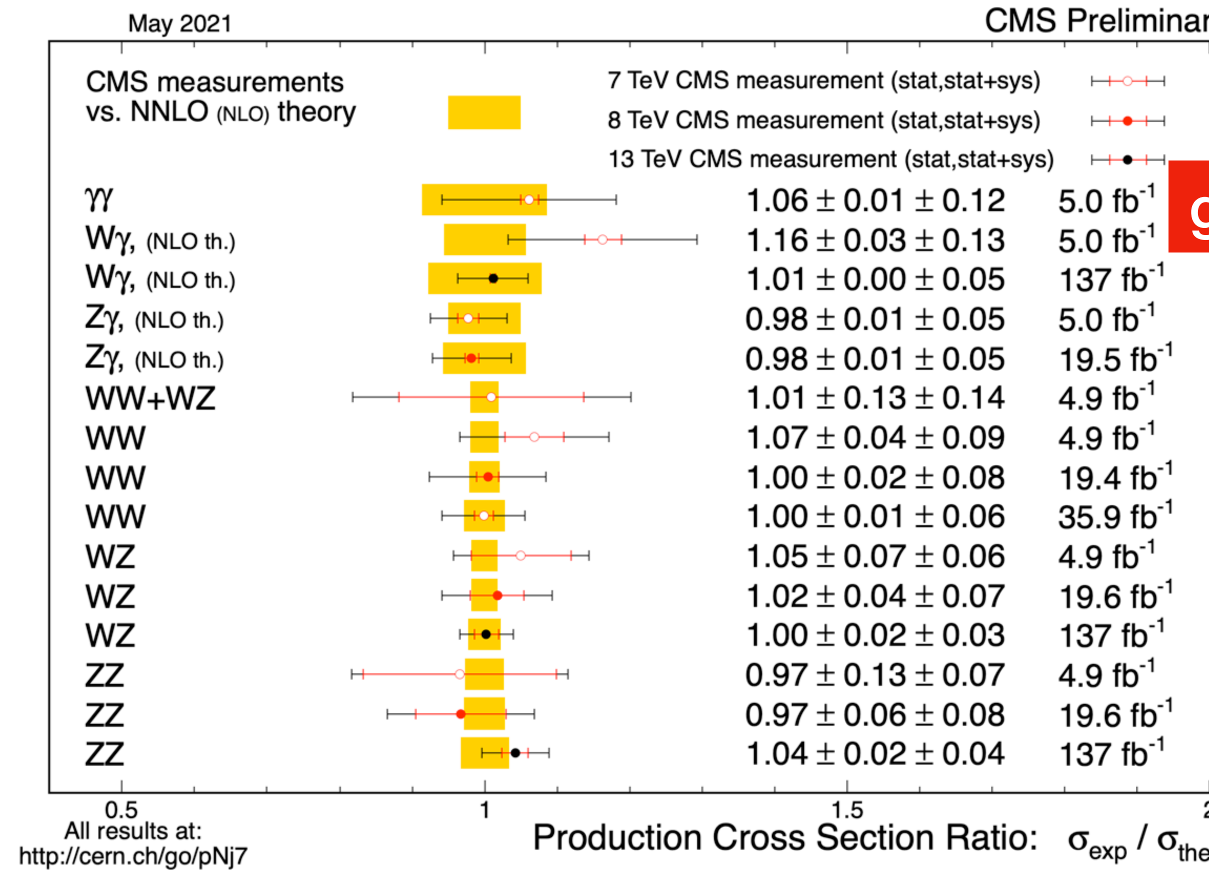
SM = Precision

data vs theory

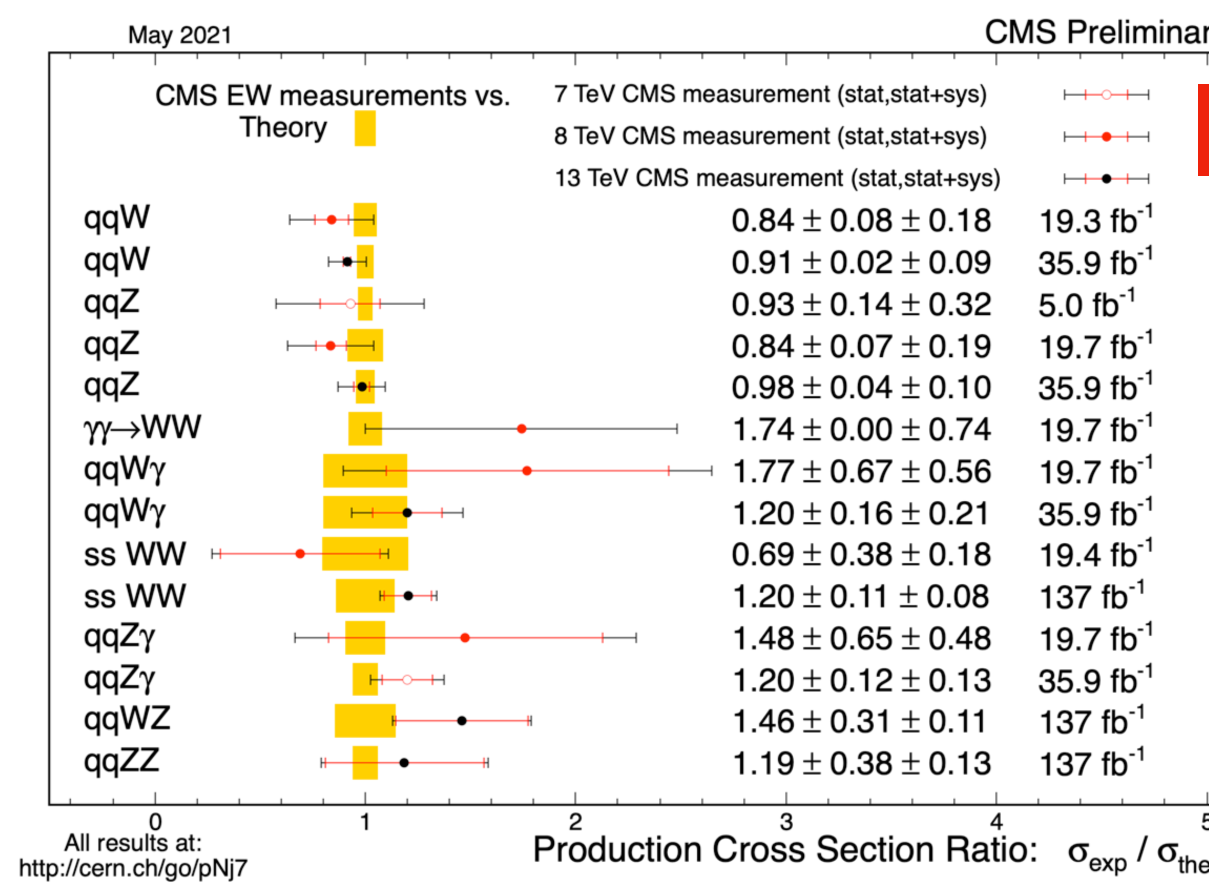
higgs



gauge



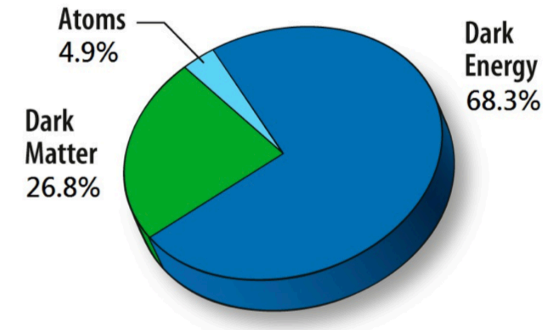
ewk

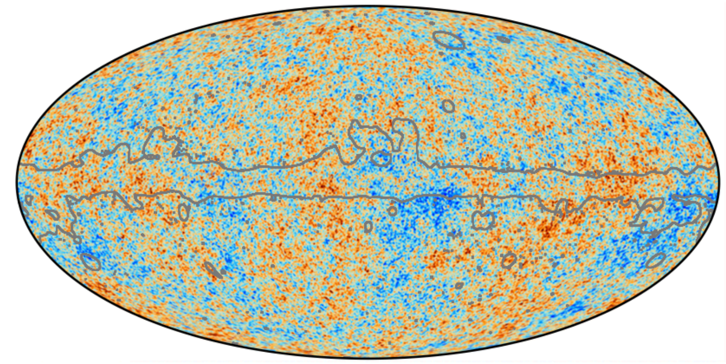


μ = data/SM

Why the need to go beyond the SM?

SM + gravity ≠ cosmos

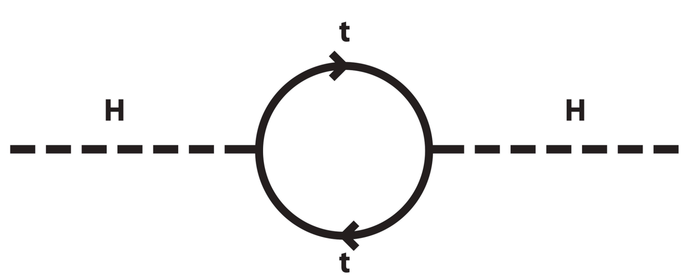




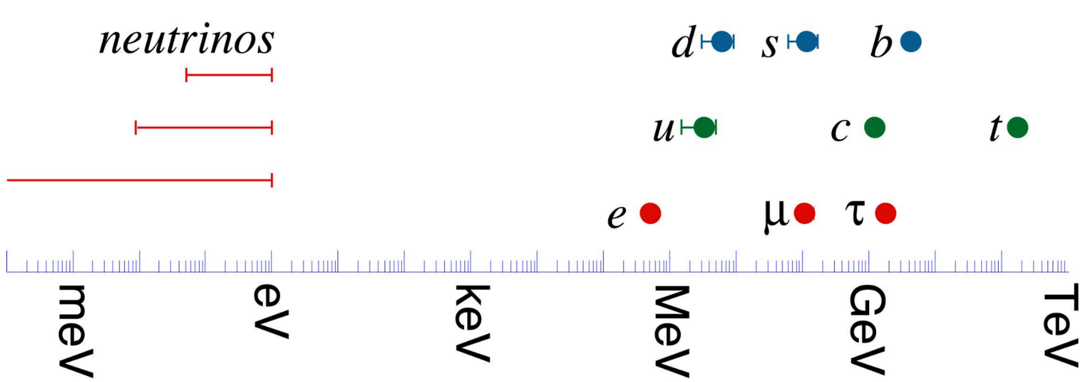
<u>Dados</u> que *decididamente* não conseguimos explicar:

assimetria matéria-antimatéria (CPV?...) — matéria escura (WIMPs, ALPs, ...?) — inflação (inflatão?)

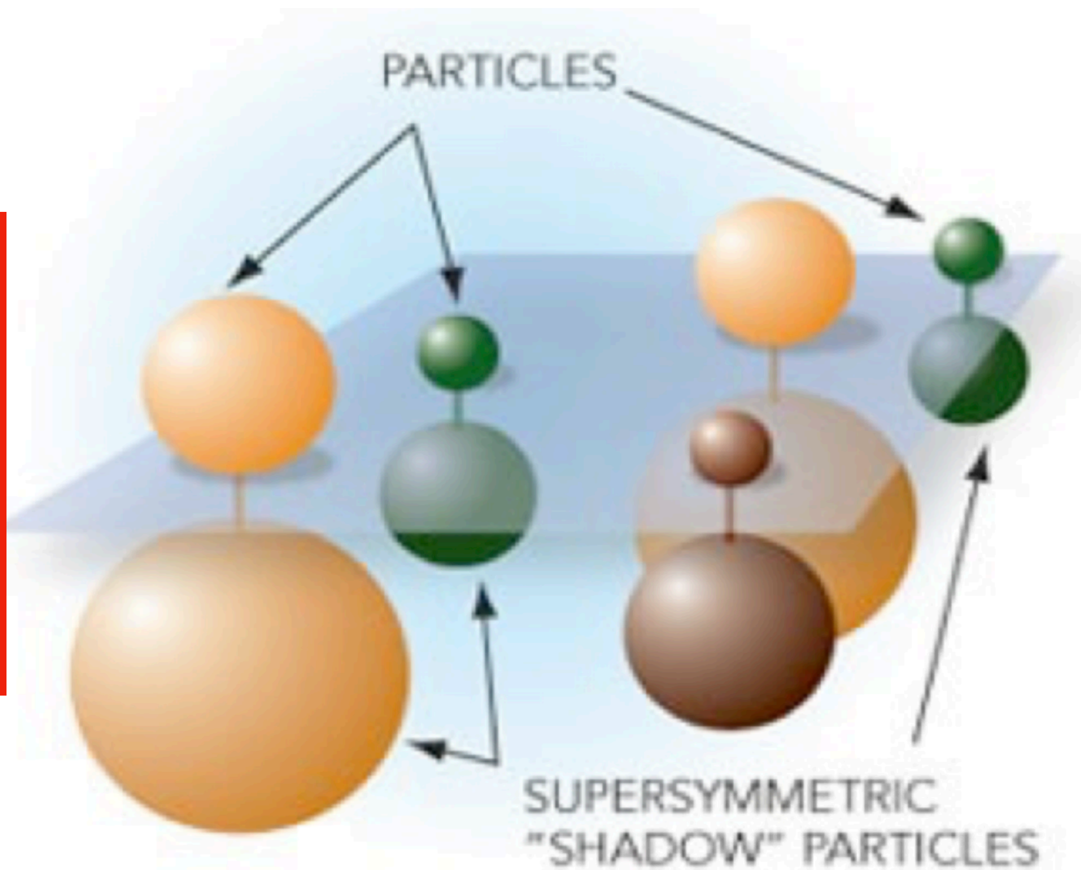
- **Hierarquia electrofraca**
- Fraca/Gravidade ~10^{24}
- EWK << Planck (Deserto?)
- Instabilidade da massa do Higgs
- Fine tuning
- Naturalness

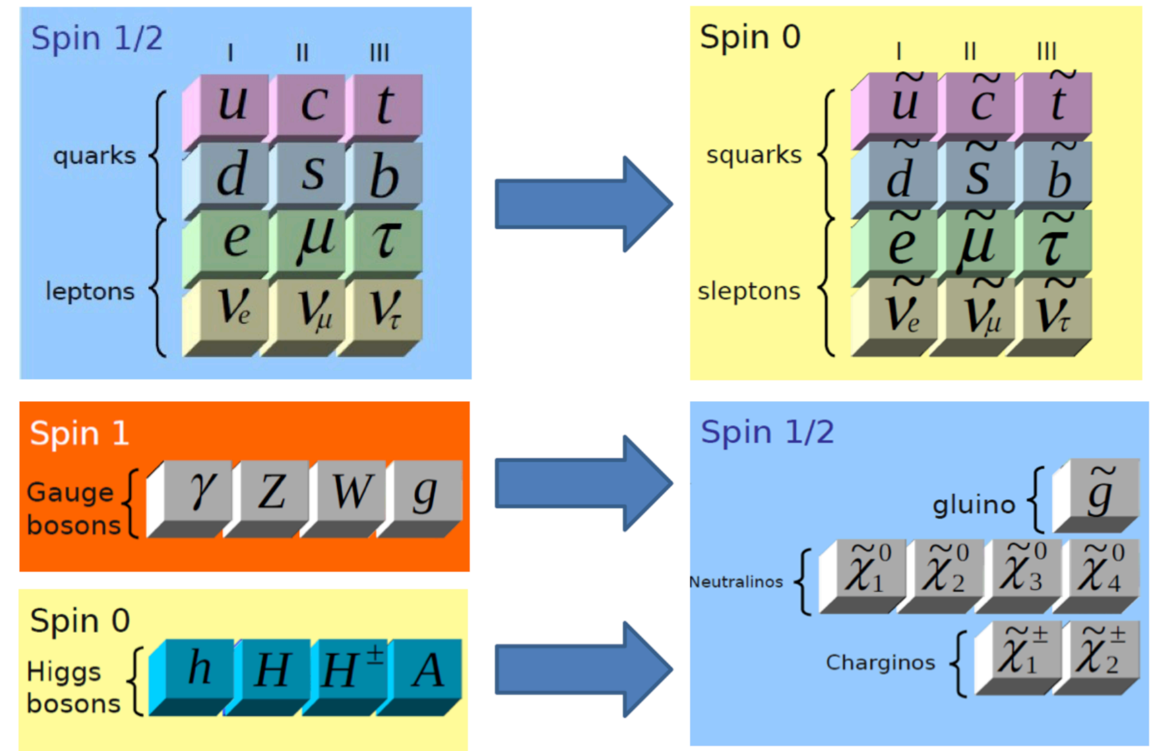


- **Hierarquia de sabor**
- Porquê tantos parâmetros (19+)?
- Porquê 3 famílias ('Who ordered that?')
- Porquê $\theta_{QCD}<10^{-9}$ (Strong CP problem)
- Porquê hierarquias enormes nas massas e acoplamentos dos fermiões?

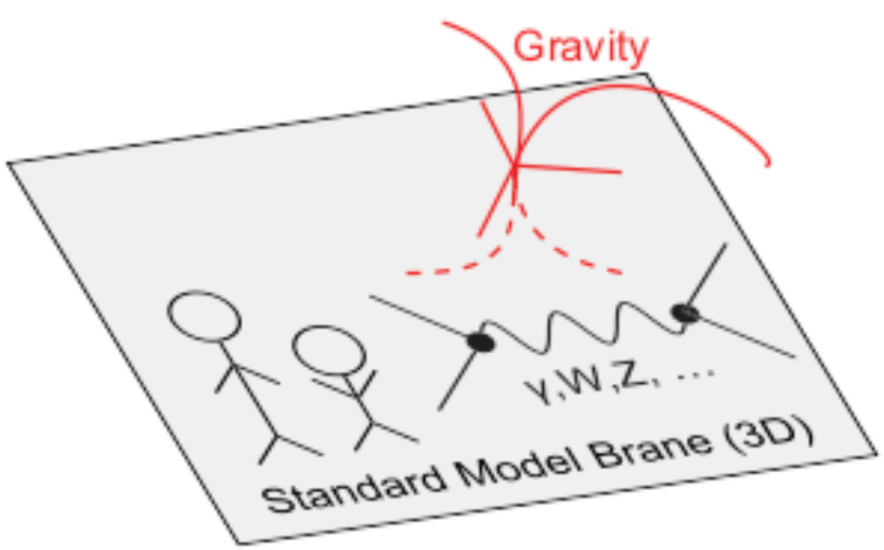


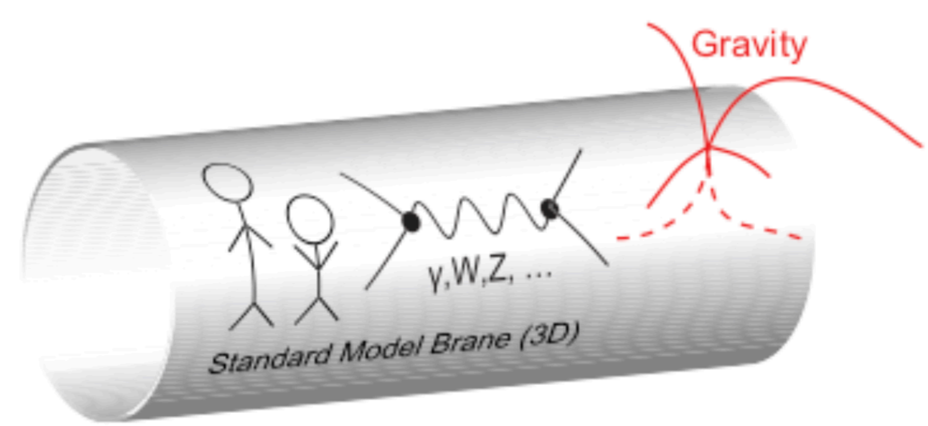
Supersymmetry?



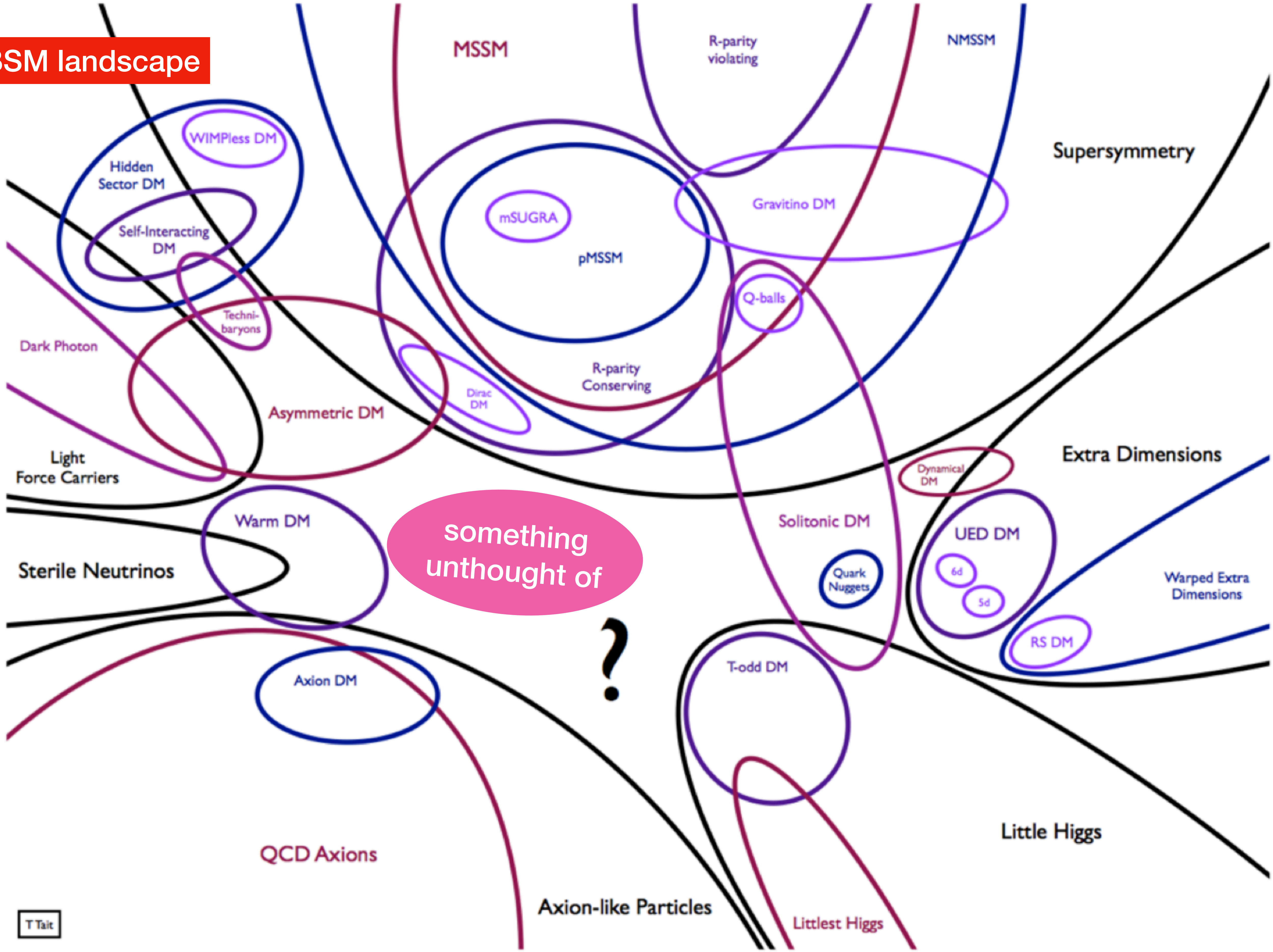


Extra Dimensions?

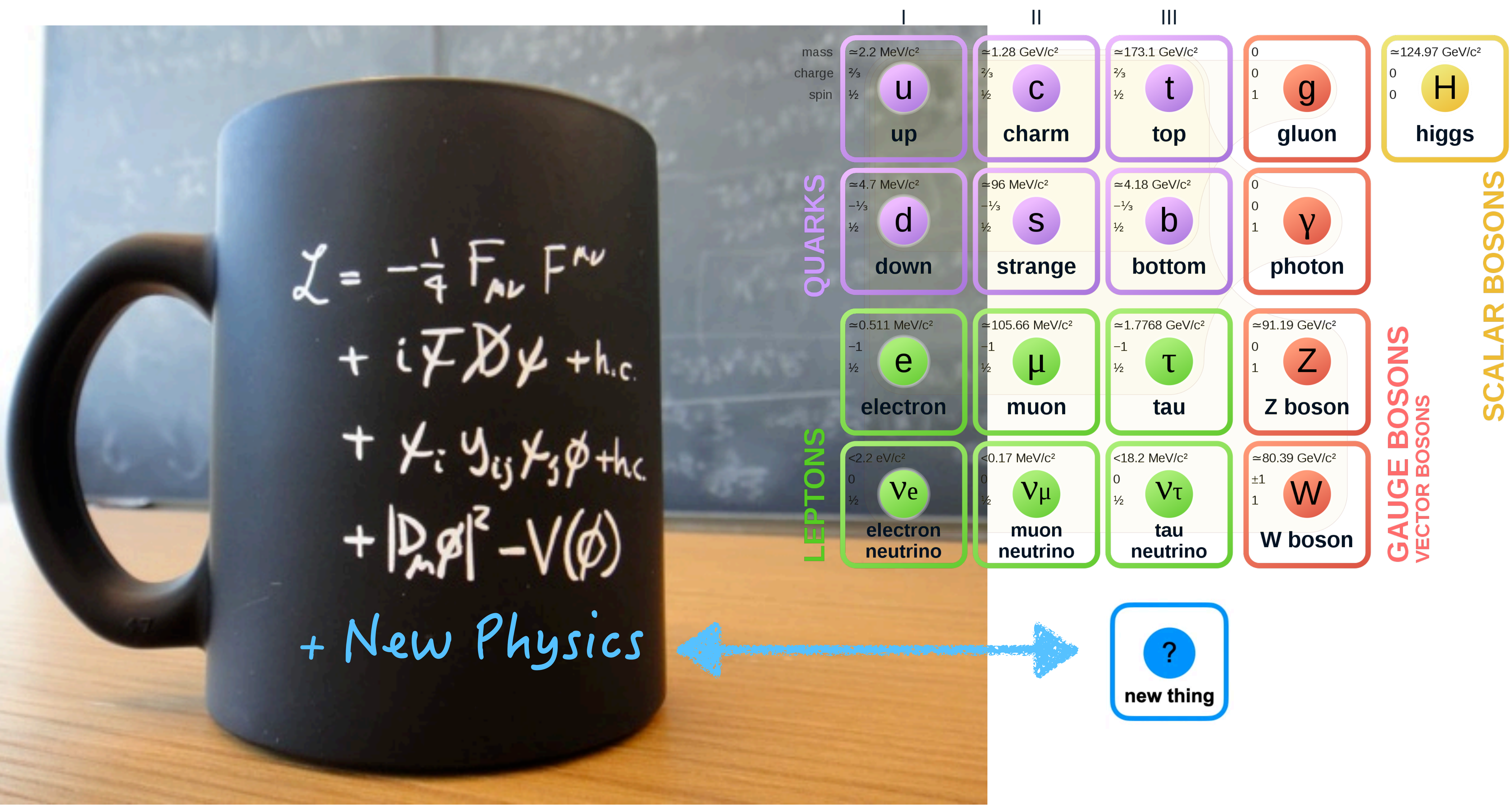




BSM landscape



Going beyond the Standard Model



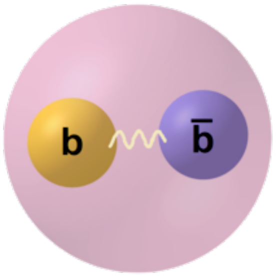
Physics goals at the LHC?

- Test the Standard Model (SM)
  - Precision measurements + rare processes
- Find physics beyond the Standard Model (BSM)
  - Direct and indirect searches for new particles

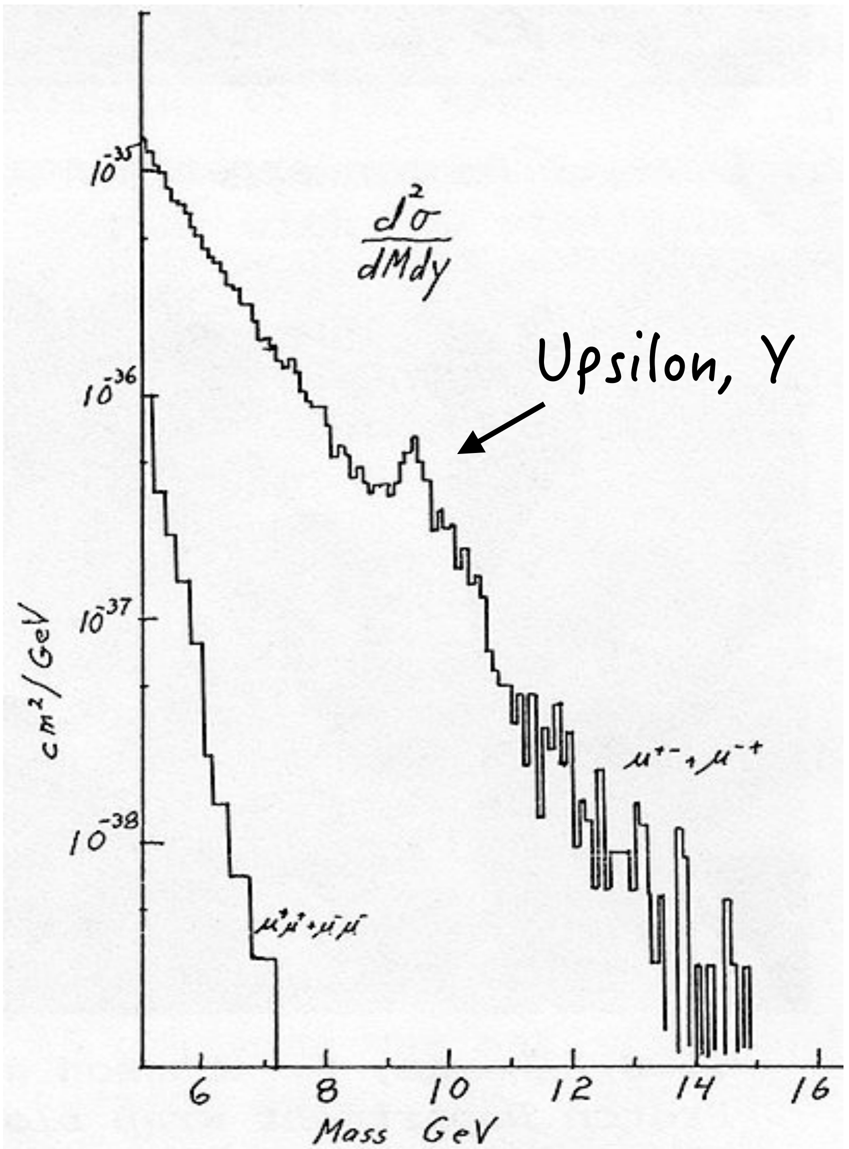
Produce
BSM particles
in the collisions
+
detect their
decay
products

Infer
presence of
BSM particles
through their effect
on properties
of SM
particles

the SM discovery



1977

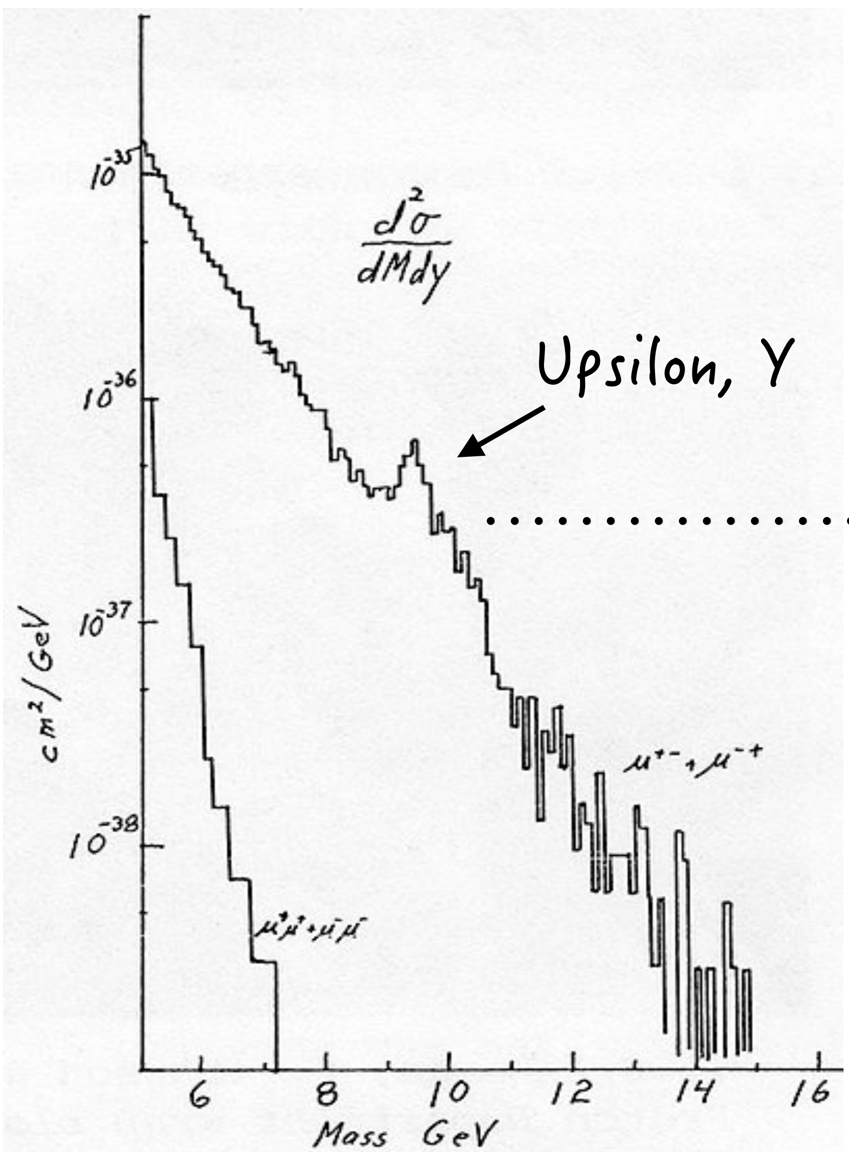


the discovery of the
b quark

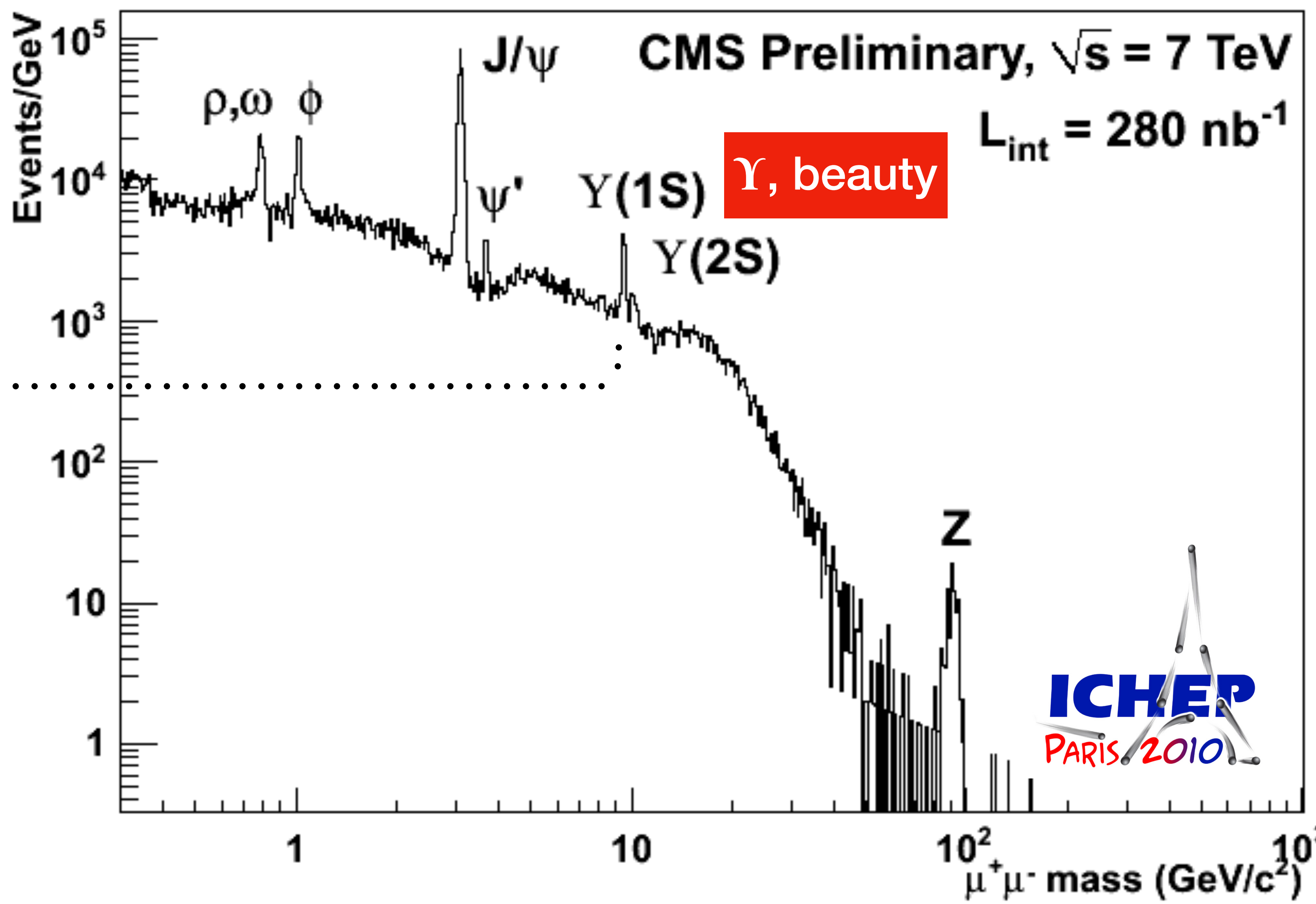
Υ, beauty

the SM *re*-discovery @ *LHC*

1977

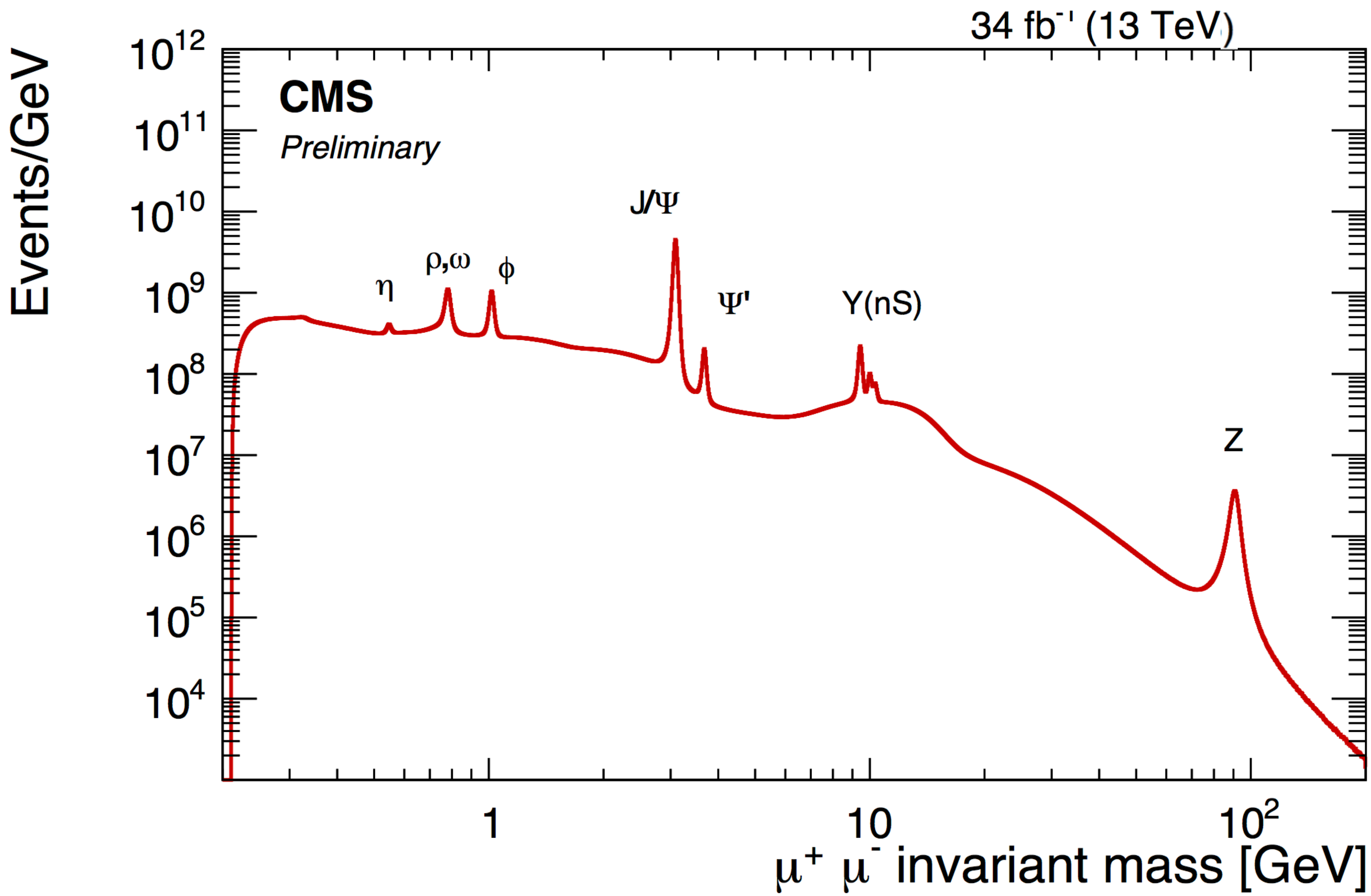


2010



the discovery of the
b quark

the SM *re*-discovery @ *LHC*

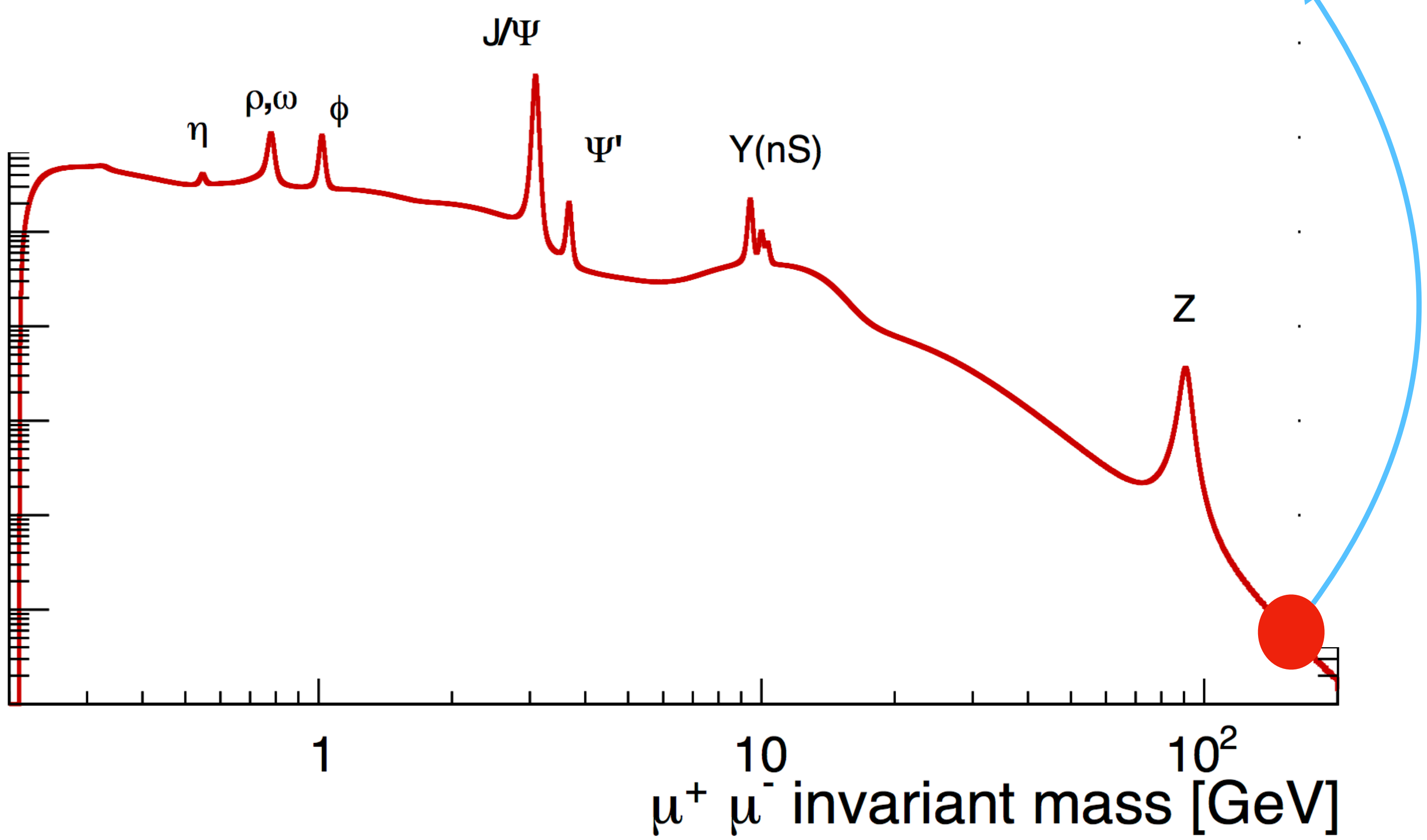


➡ Thursday's Data Analysis Tutorial

Decades worth of particle physics discovery … in a single plot!

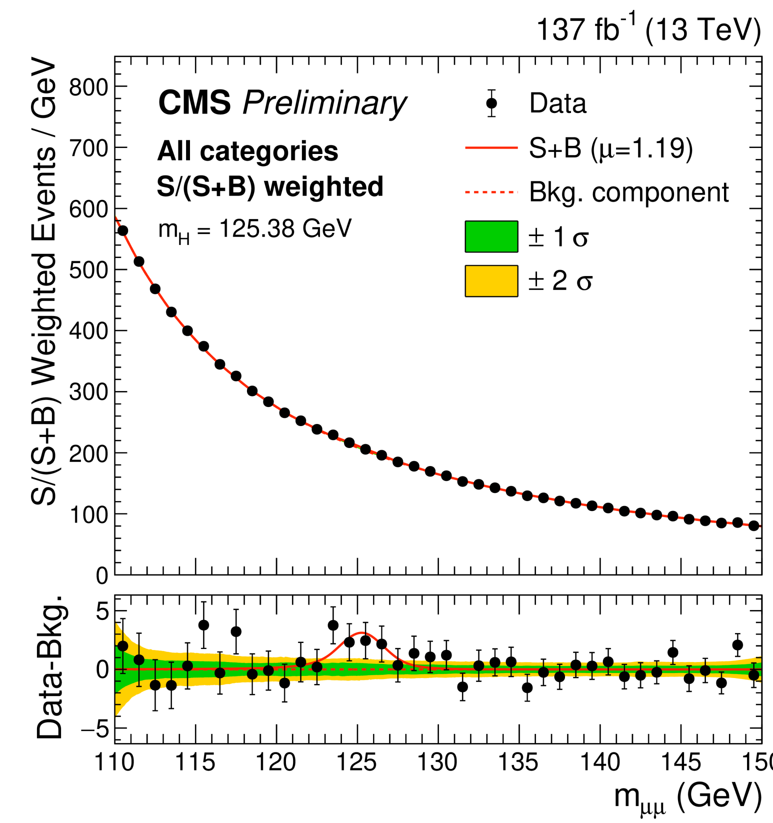
New particles discovered at LHC?

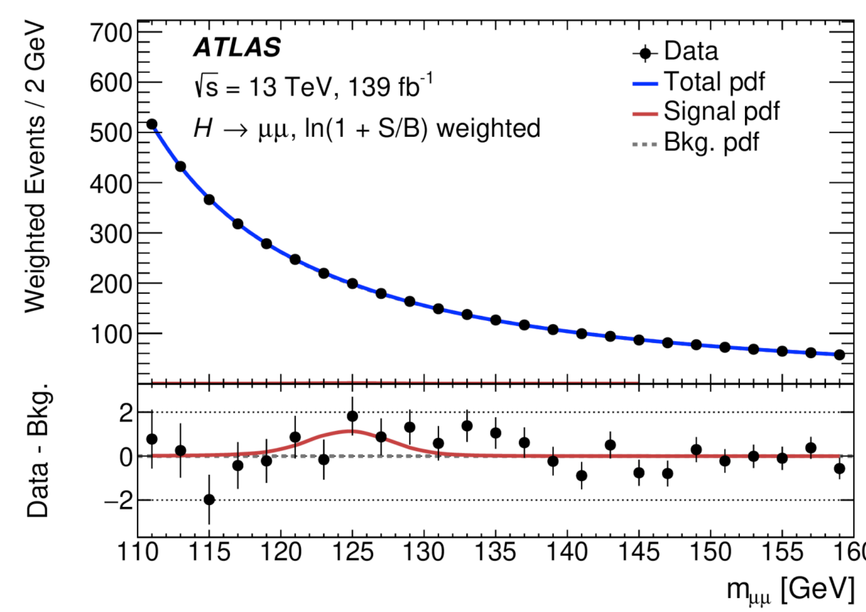
New particles discovered at LHC?



evidence for

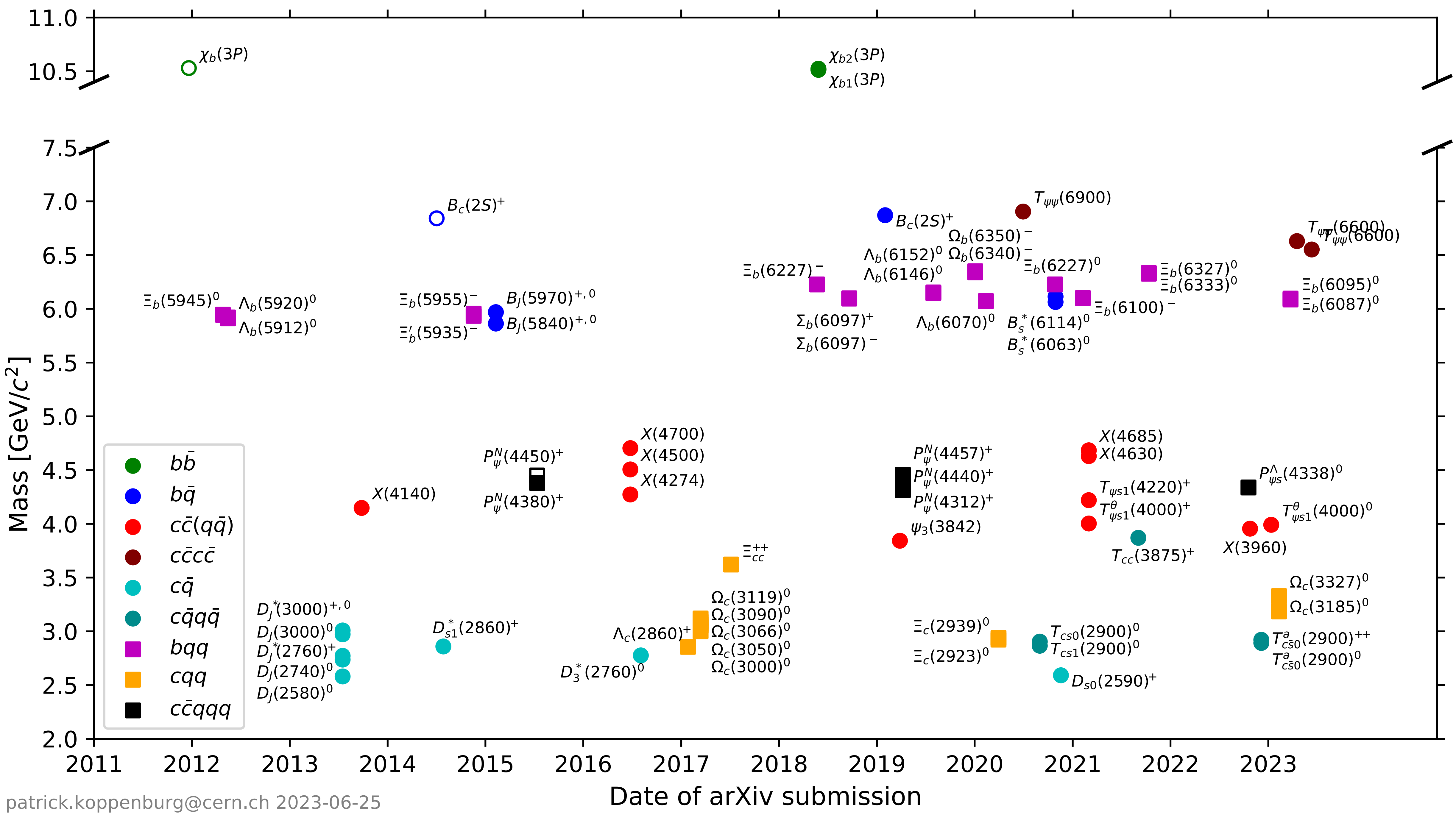
H→μμ





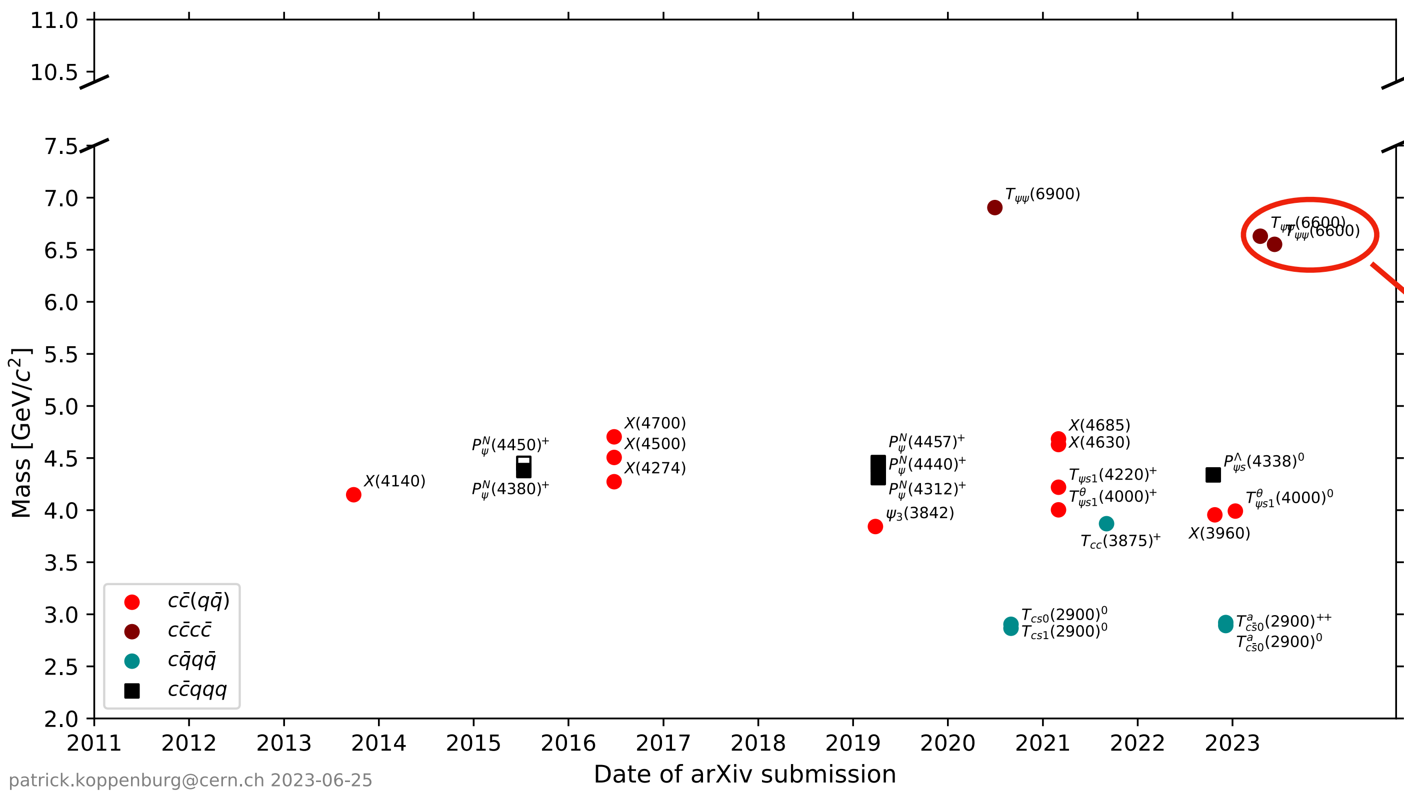
New particles discovered at LHC?

New particles discovered at LHC?



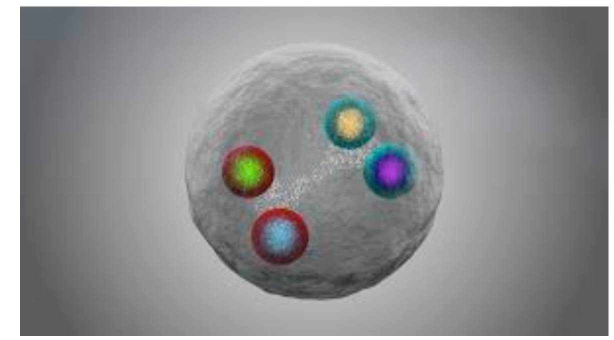
72+1 new particles already discovered — and more awaiting to be discovered @LHC !

New particles discovered at LHC?



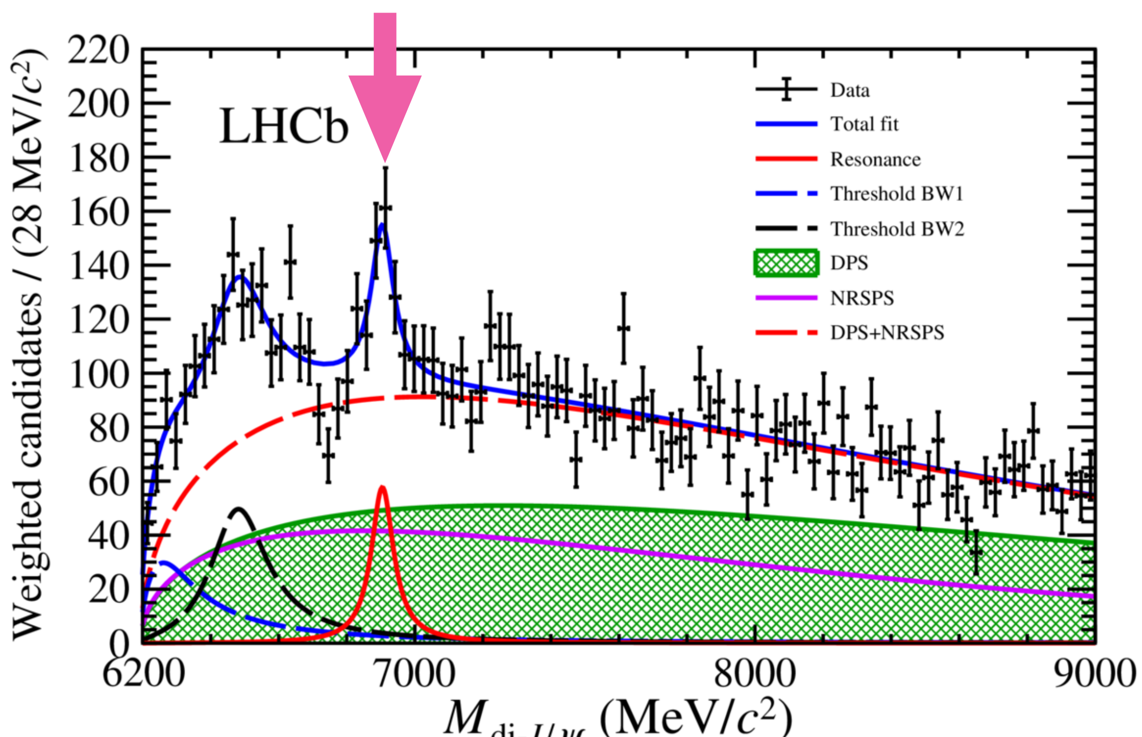
23 new exotic hadrons!

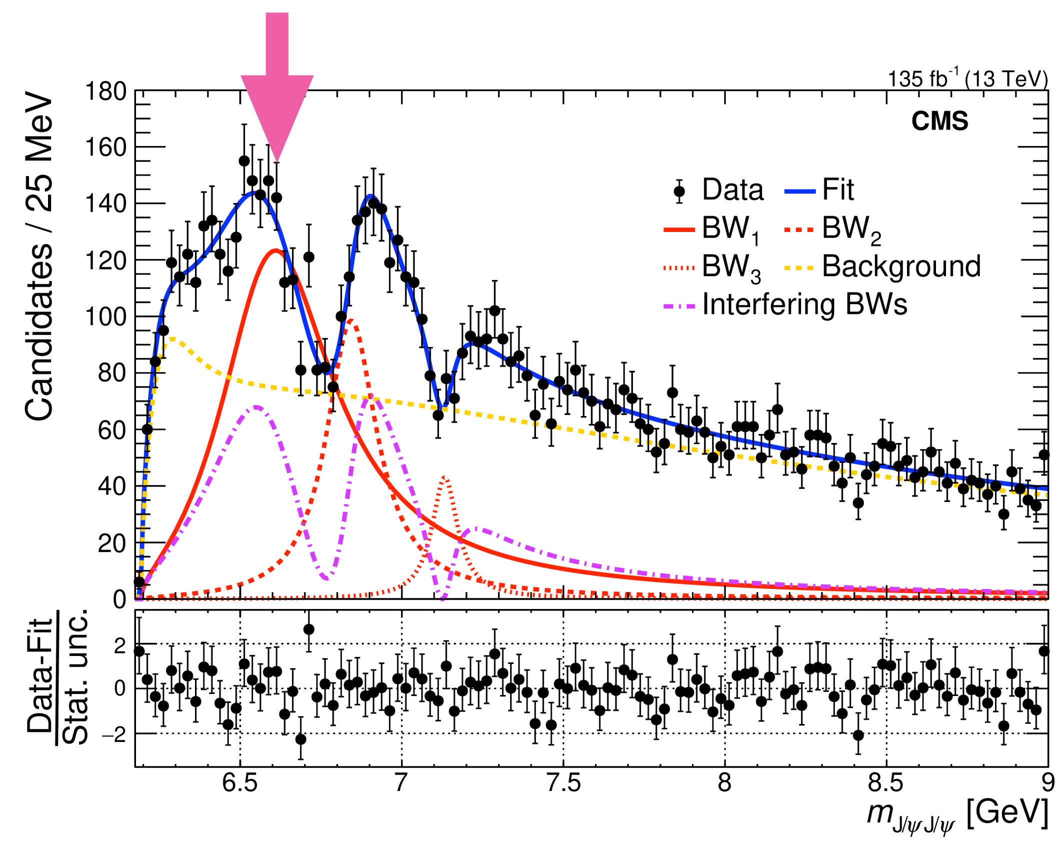
(**exotic** = nature not yet understood)



the latest discovered: **X(6600)**

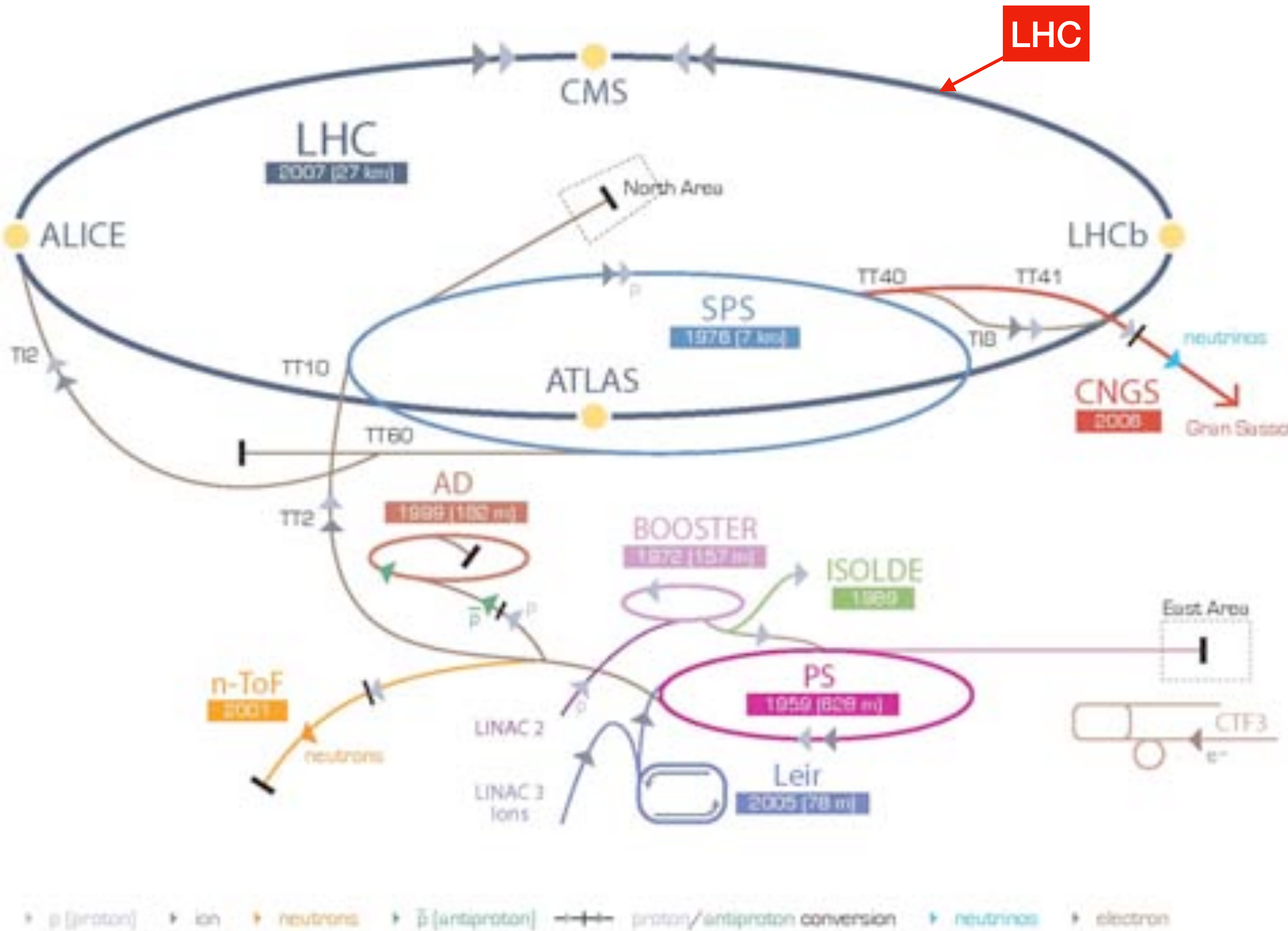
(an all-heavy-flavour tetraquark)



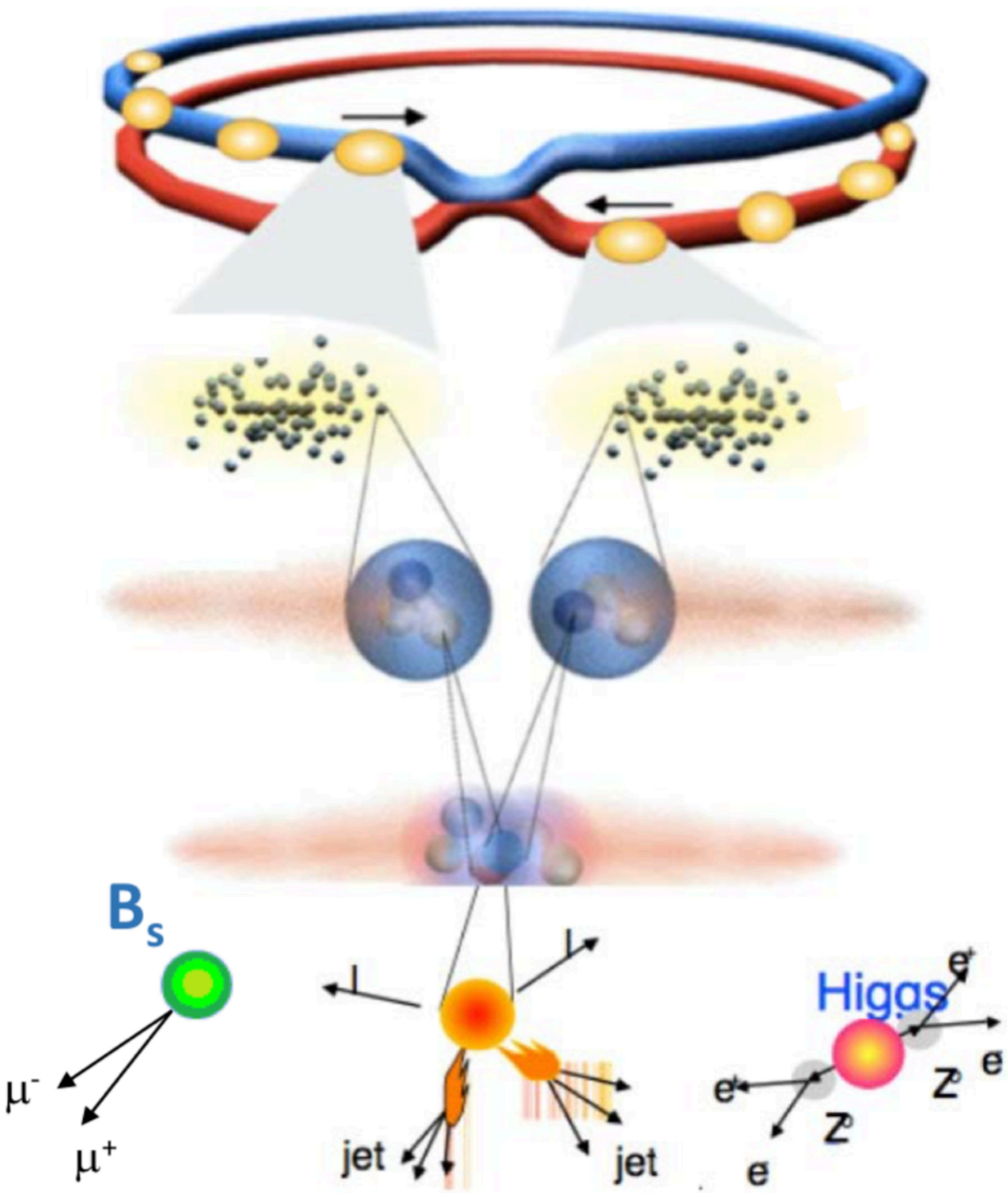


The accelerator

the CERN accelerator complex



Proton-proton collision



proton-proton
circumference: 27 km
bunches: 3564 + 3564
protons / bunch: 10^{11}
beam energy: ~~2 x 3.5 (7)~~ TeV **13.6 TeV**
luminosity: 10^{33}-10^{34} $cm^{-2}s^{-1}$
bunch spacing: 25 ns

Bunch Crossing $4\ 10^7$ Hz

Proton Collisions 10^9 Hz

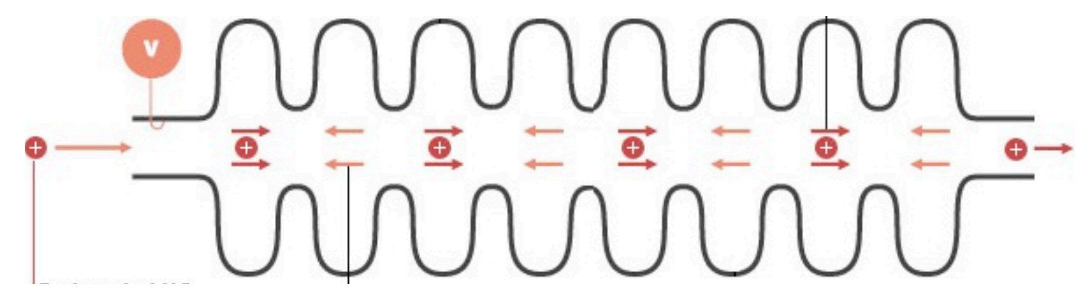
Parton Collisions

4000 $W^{\pm}$ s / sec
1200 Z^0 s / sec
17 $t\bar{t}$ s / sec
1 h^0 s / sec

New Particle Production 10^{-5} Hz

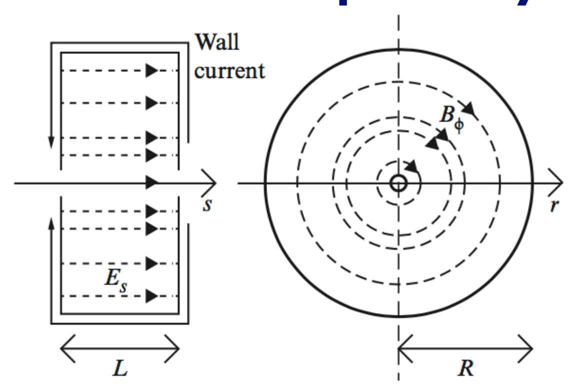
Acceleration & beam optics

- charged particles may be accelerated: **p**, $\bar{p}$, e±, (μ±), ions
  - e.g. **LHC** (**pp**,p-Pb, PbPb); Tevatron (p$\bar{p}$); LEP, PEP, KEKB (e^+e^-); RHIC (ions); FAIR (p-ions)
- acceleration by radiofrequency

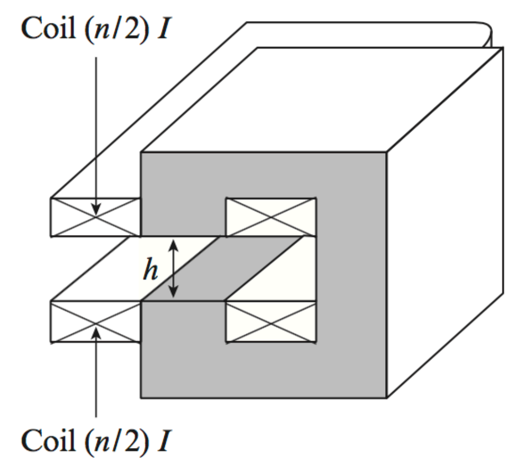


$$\mathbf{F} = q(\mathcal{E} + \mathbf{v} \times \mathbf{B})$$

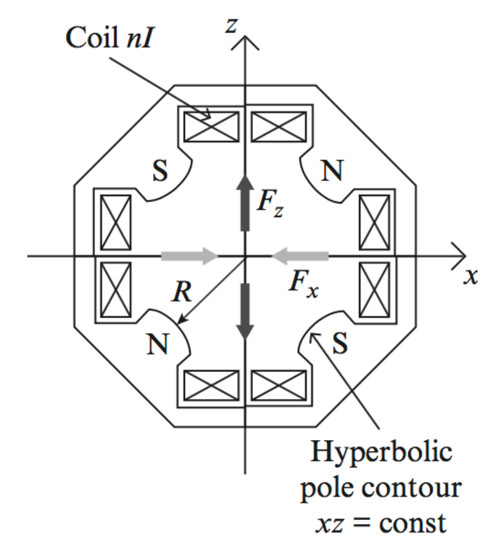
$$\mathbf{E} = -\nabla\varphi - \frac{\partial \mathbf{A}}{\partial t}$$



- trajectory bending via dipoles

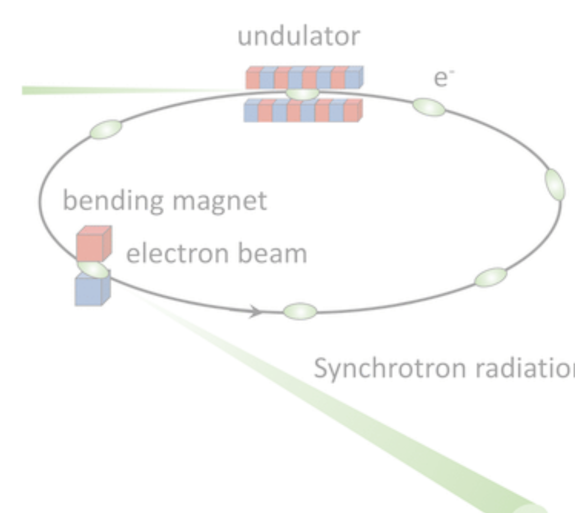


- beam focusing via quadrupoles



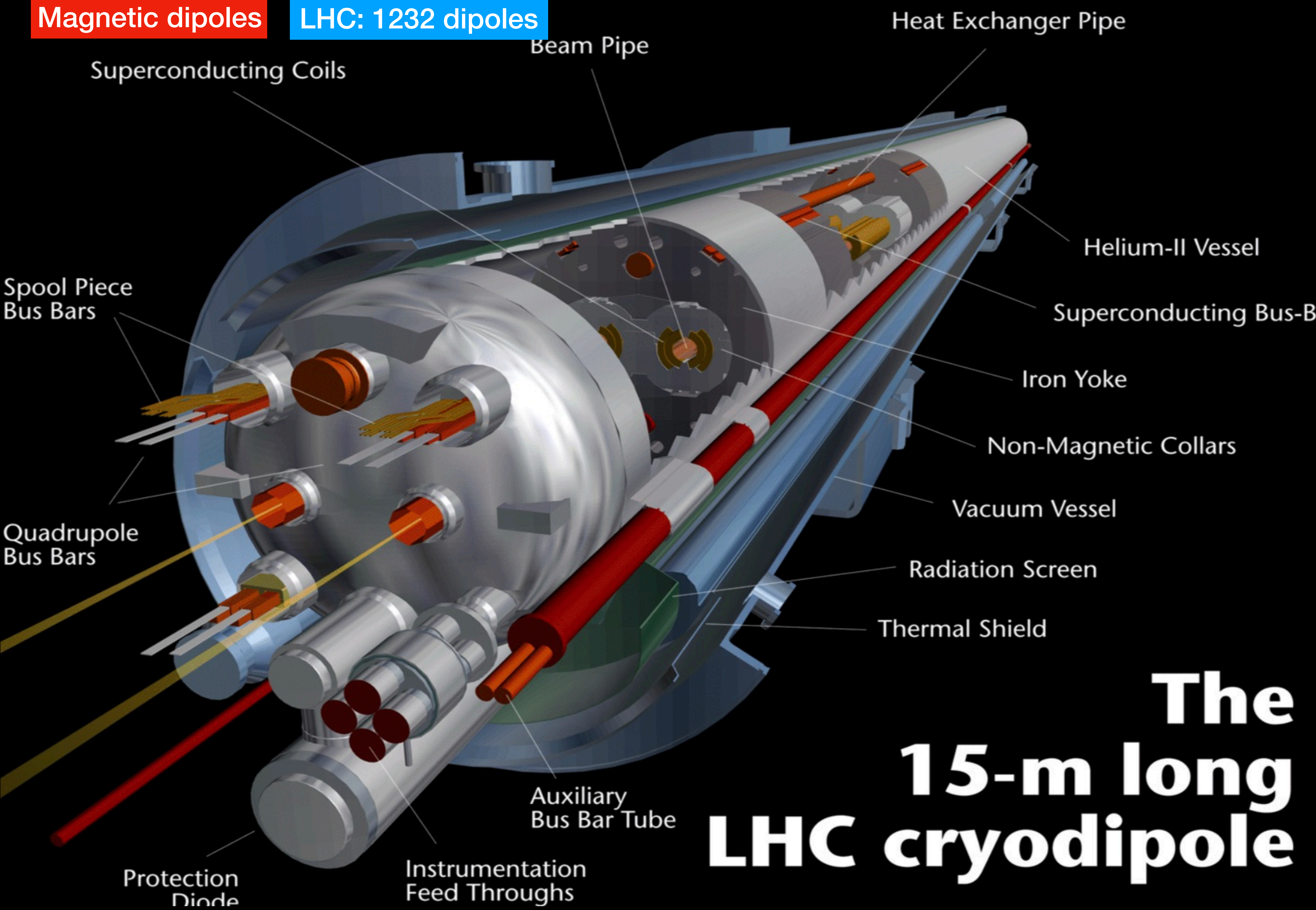
- accelerating particles radiate
  - synchrotron radiation

$$P \propto \gamma^4 = \left(\frac{E}{m}\right)^4$$

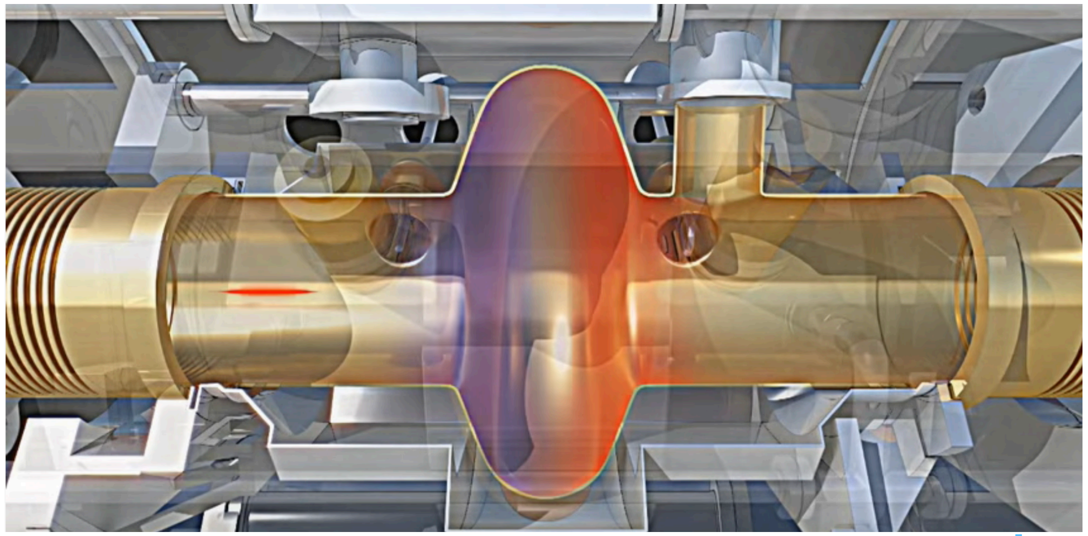


Magnetic dipoles

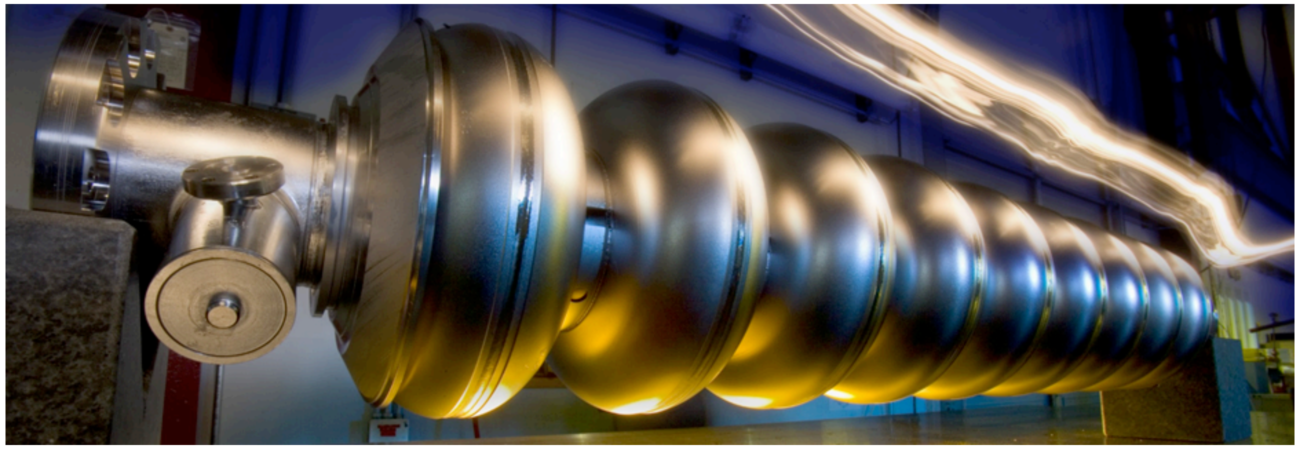
LHC: 1232 dipoles



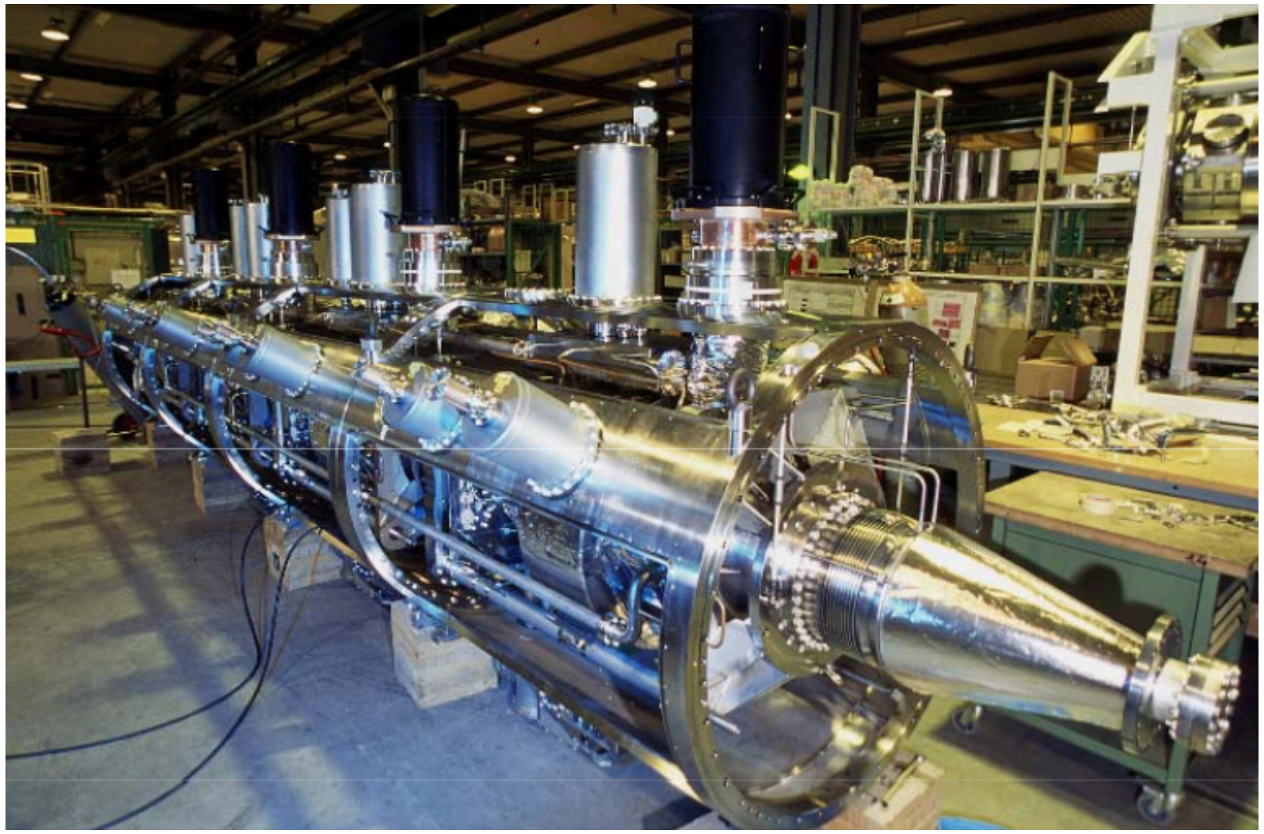
RF cavities



youtube

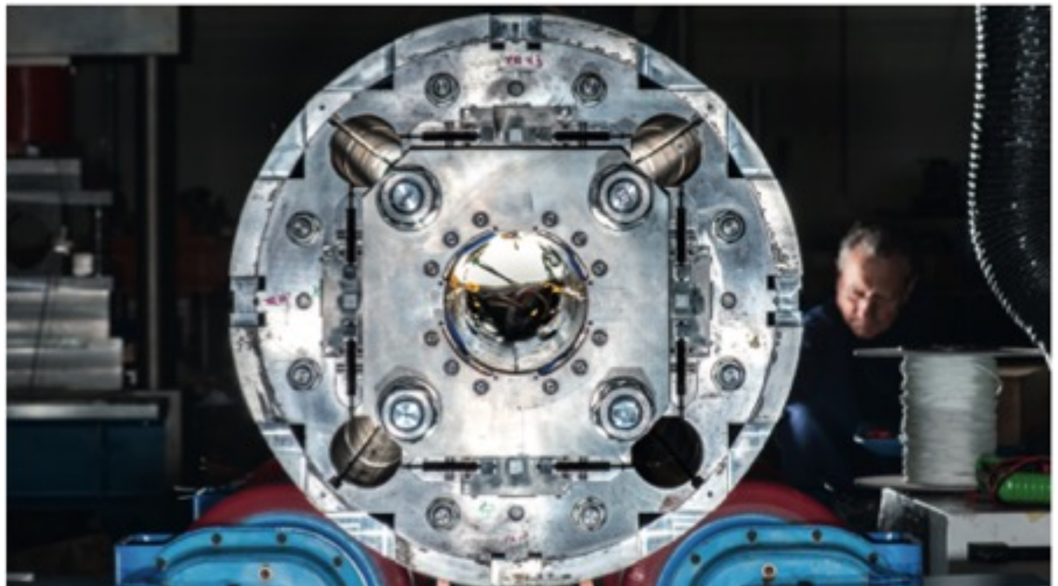


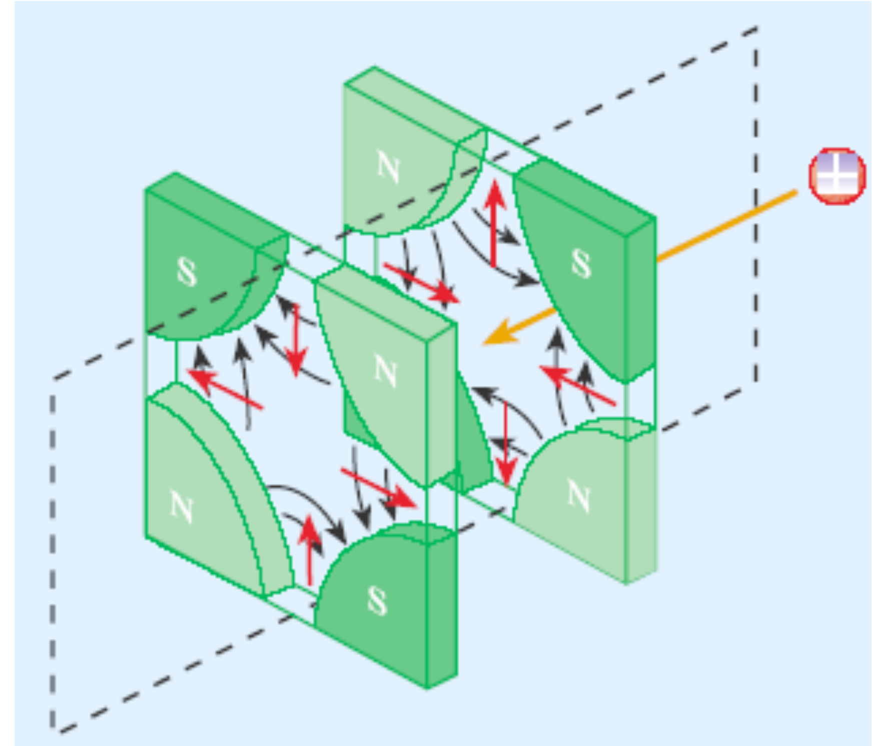
LHC: 16 RF cavities

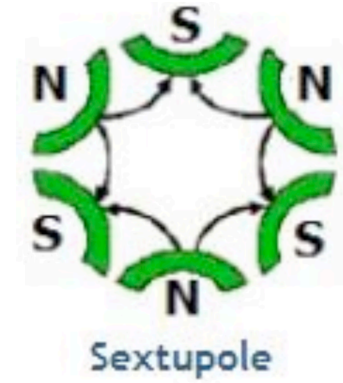


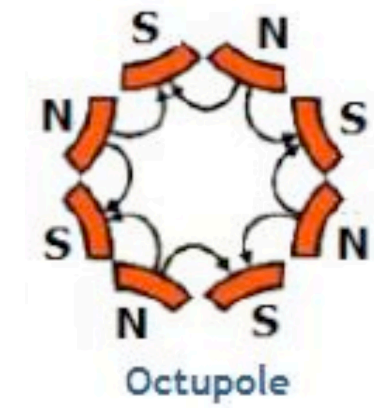
Magnetic multipoles

focus the beam
squeeze the bunches





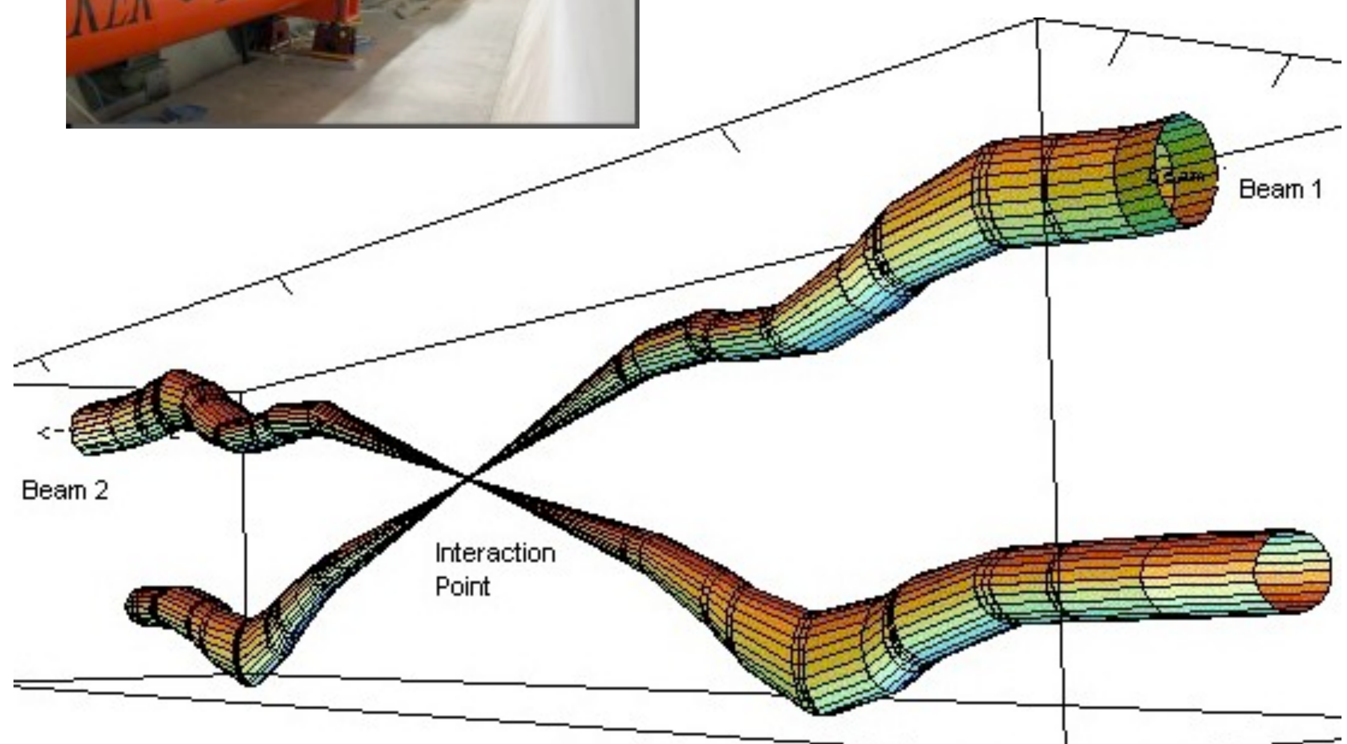




LHC: 474 quadropoles

size of bunches

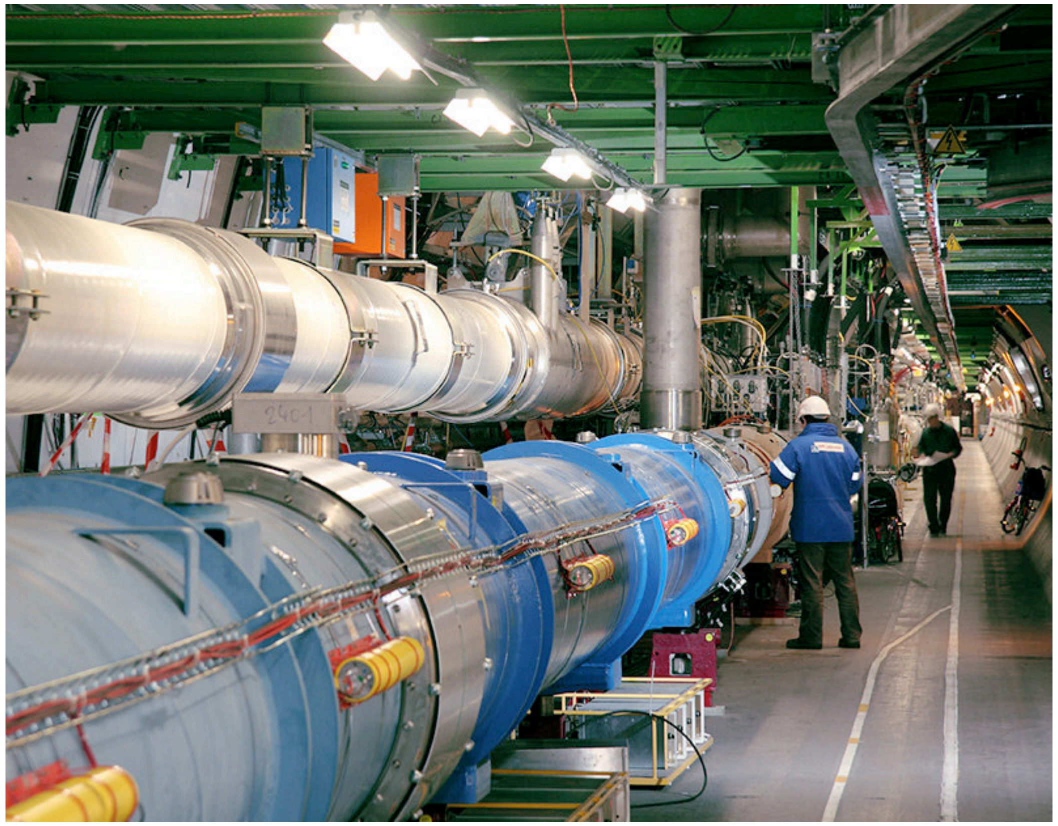
- at IP (ATLAS, CMS) 16 μm
- in the triplets ~1.6 mm
- in the arcs ~0.2 mm



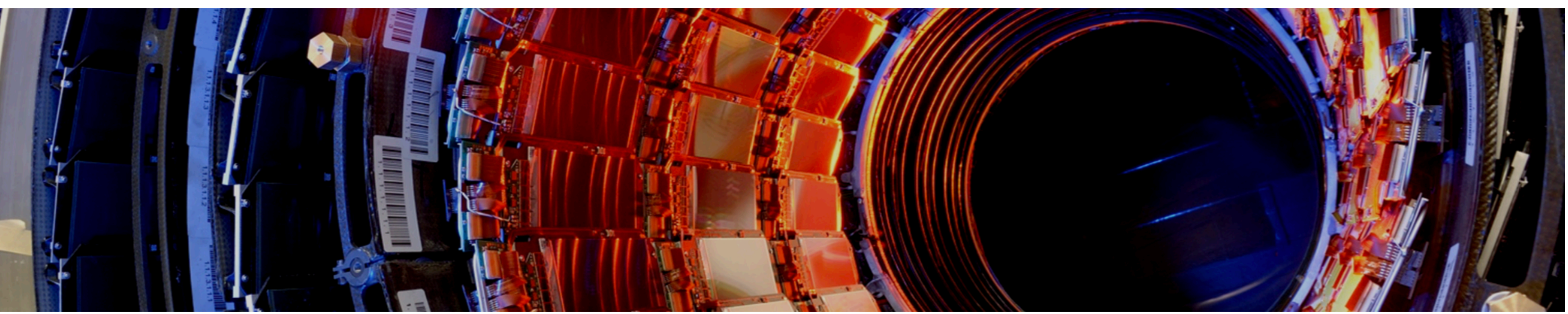
Superconductors, cooling, vacuum

- strong magnetic field achieved with superconducting electromagnets (e.g. made of niobium-titanium)
- operating at temperatures ~1.8K (colder than outer space)
- requires distributions systems of liquid Helium (5000 tons)
- e.g. LHC tunnel has 2 rings
  - magnets and proton accelerating RF cavities, i.e. the LHC
  - cryogenic ring, aka QRL, for transmitting cold power

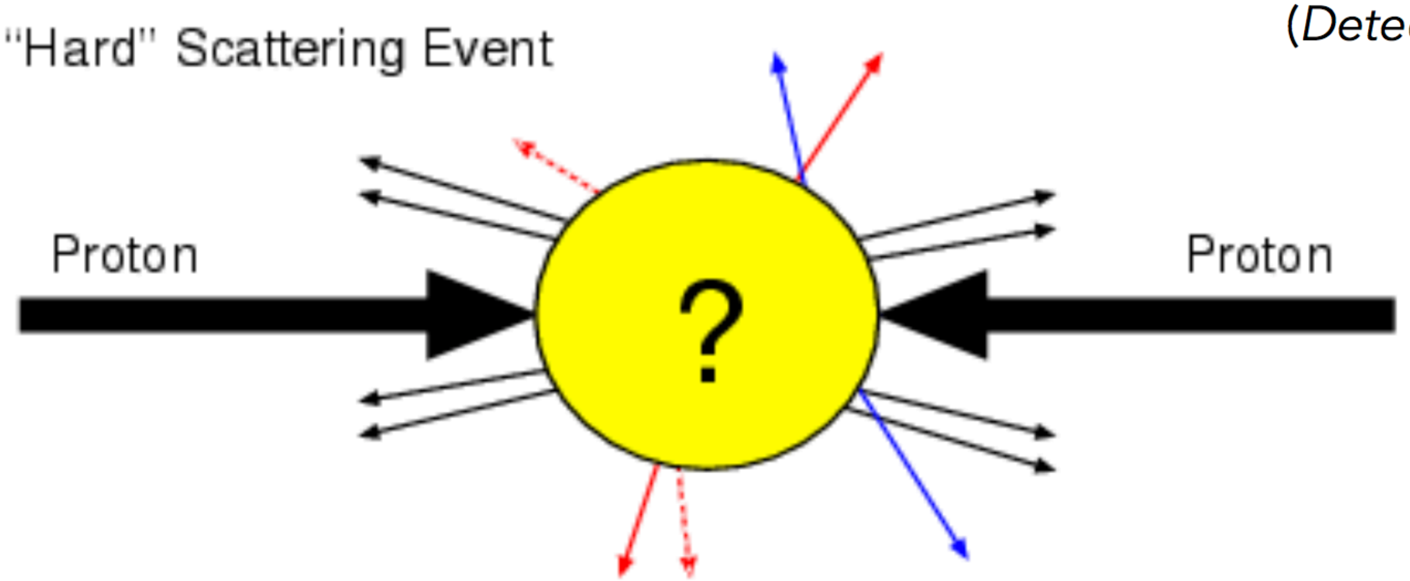
the LHC beam pipe



The detectors

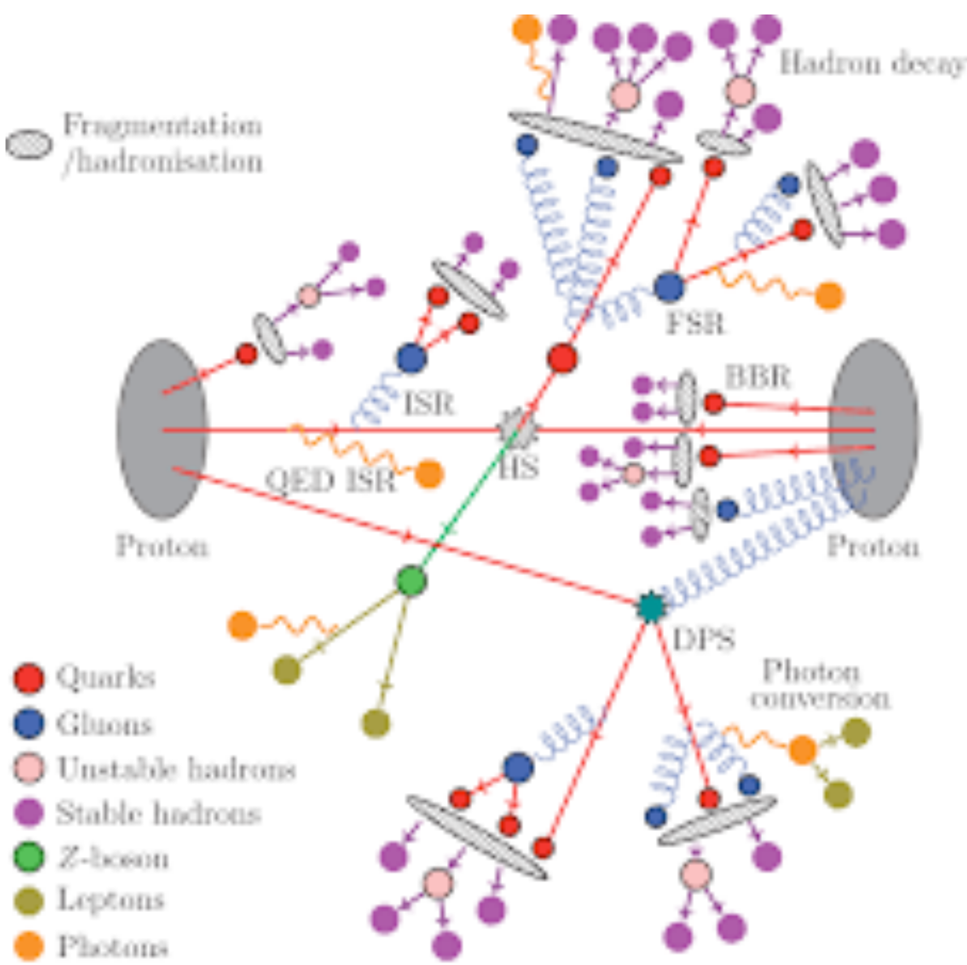


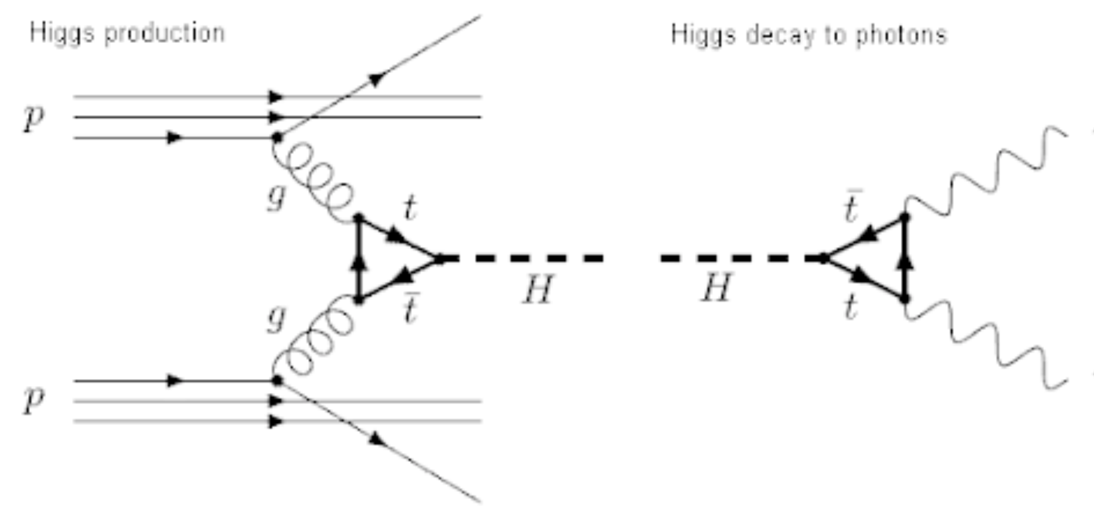
Detection of the reaction products
(*Detectors*)

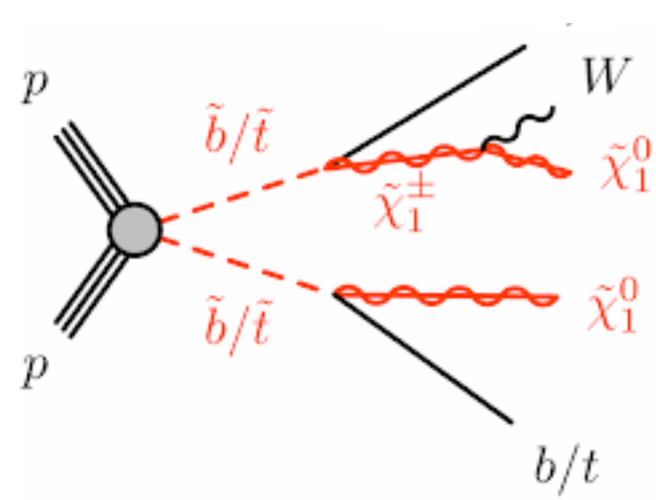


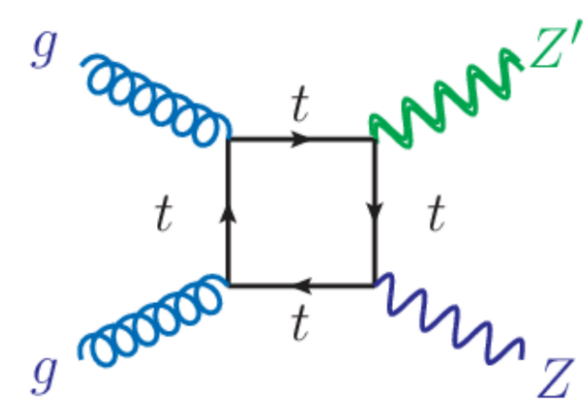
Acceleration and **collision** of particles
(*Accelerators*)

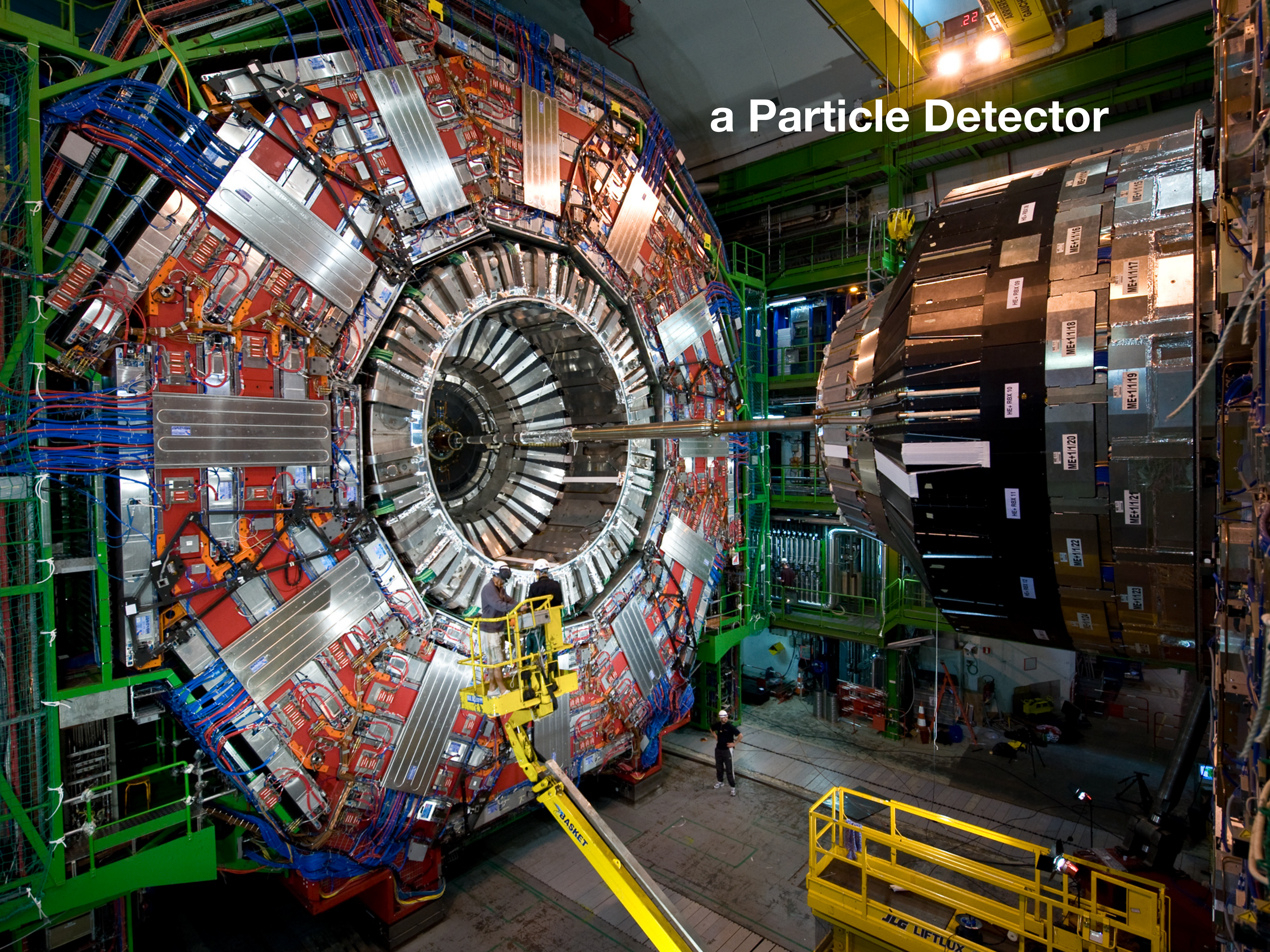
Test the comprehension on **observables**
(*Theory/Models*)



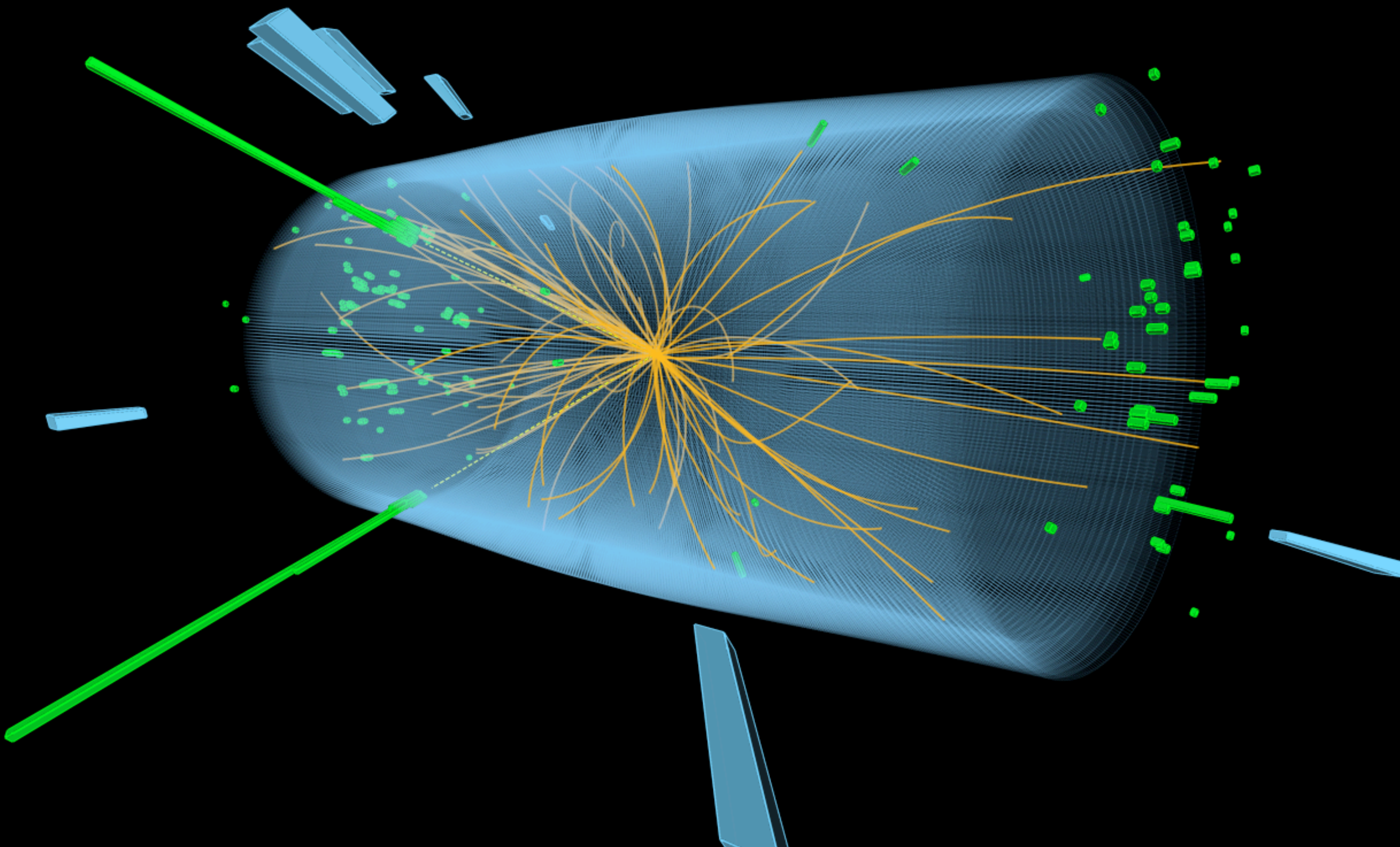


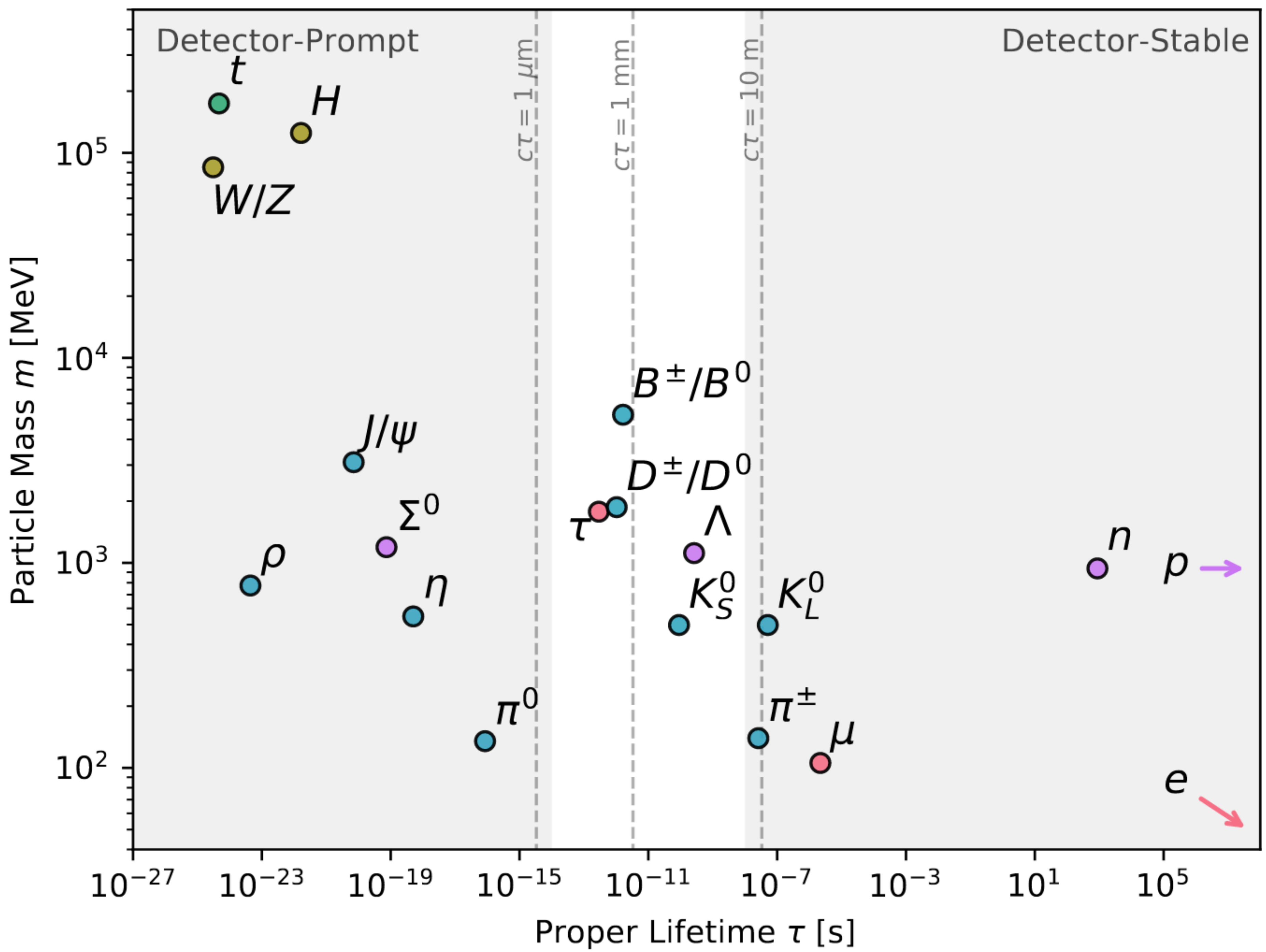





a Particle Detector
BASKET
JLG LIFTLUX

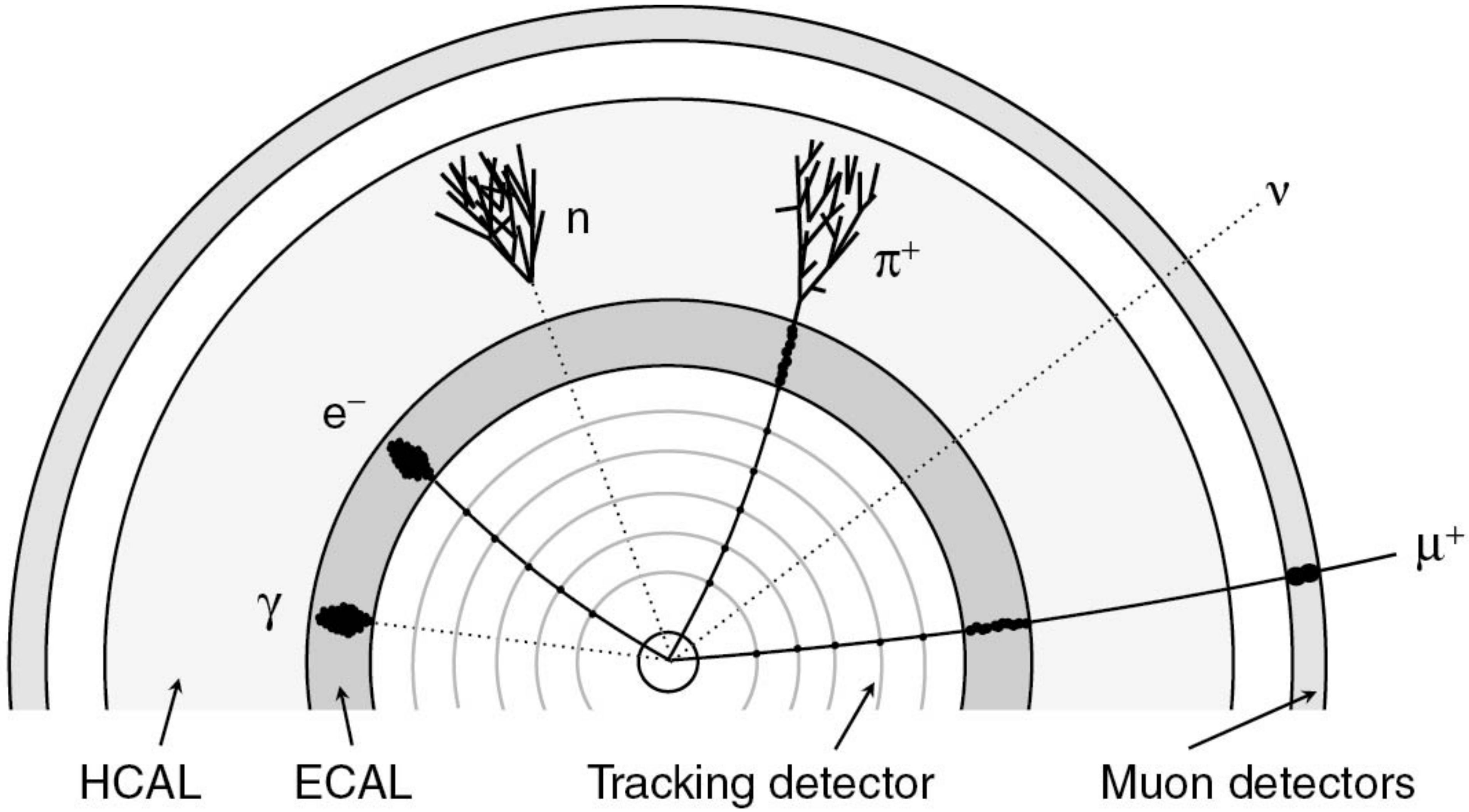
a H→γγ candidate





Only *quasi*-sable particles are directly detectable: e, μ, γ, π, K, p, n

All other, unstable particles decay, and their (stable) final states are detected.

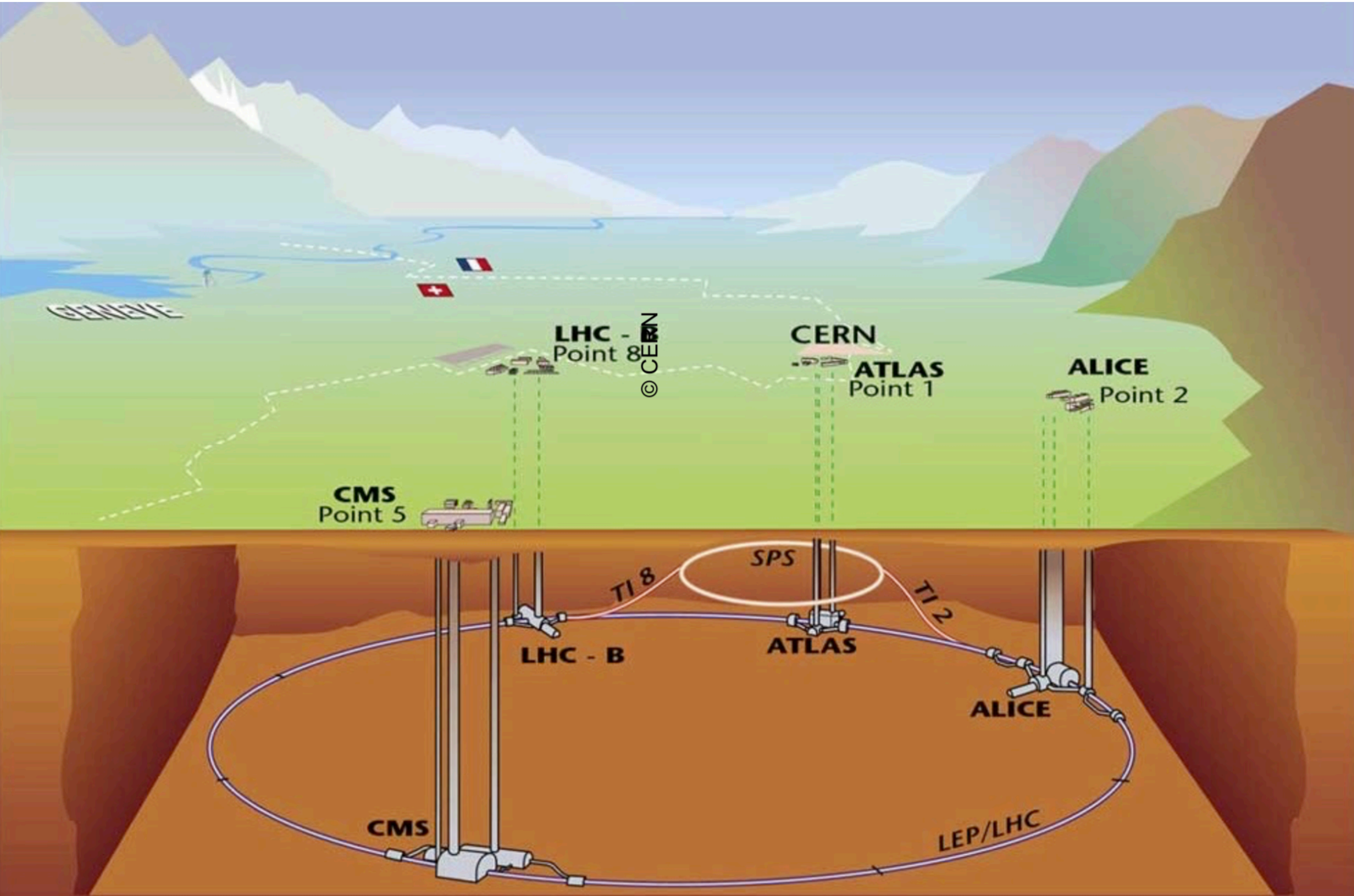


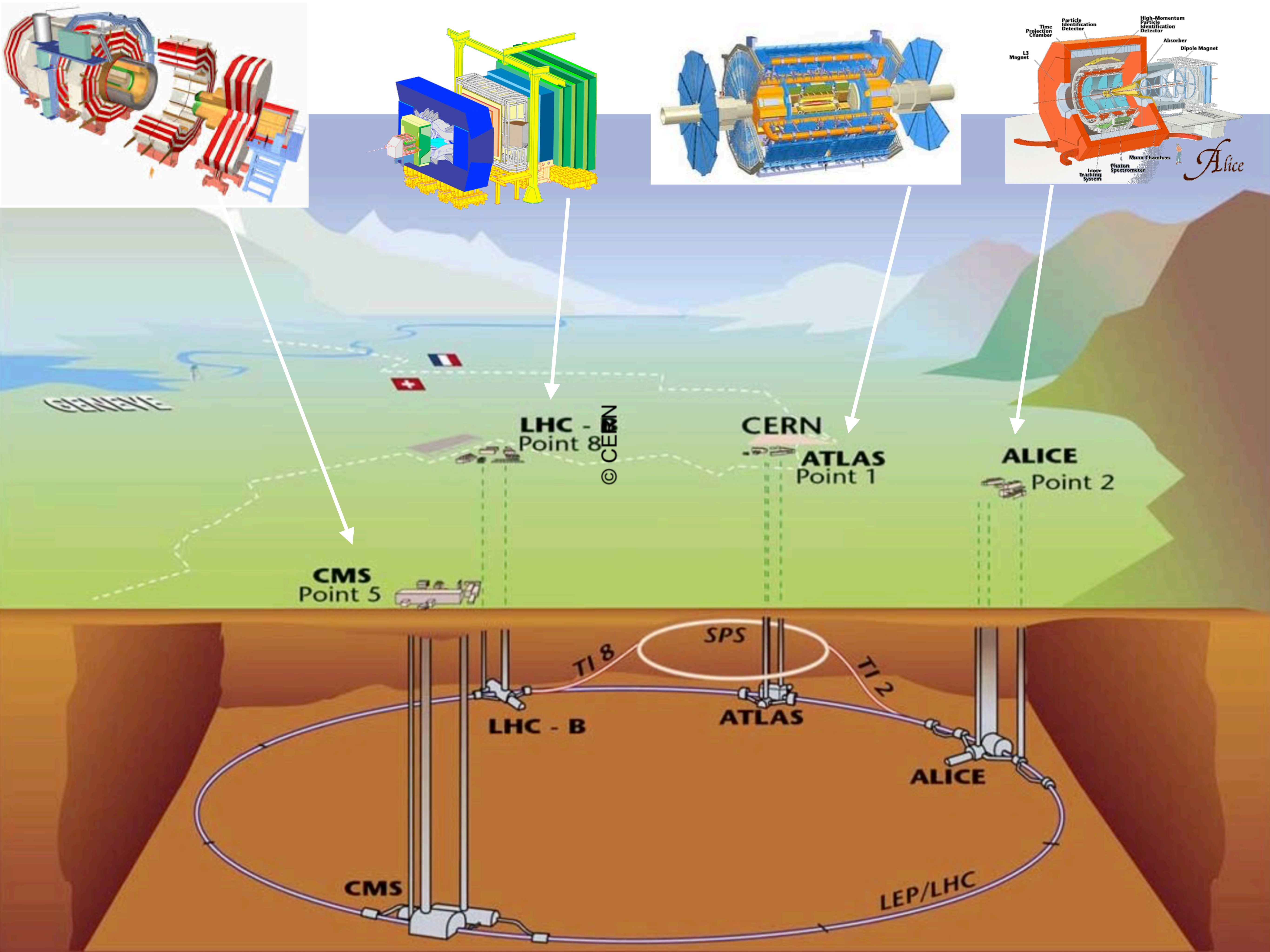
calorimeters:
measure particle's
energy by absorbing it

trackers:
detect trajectory
of charged particles

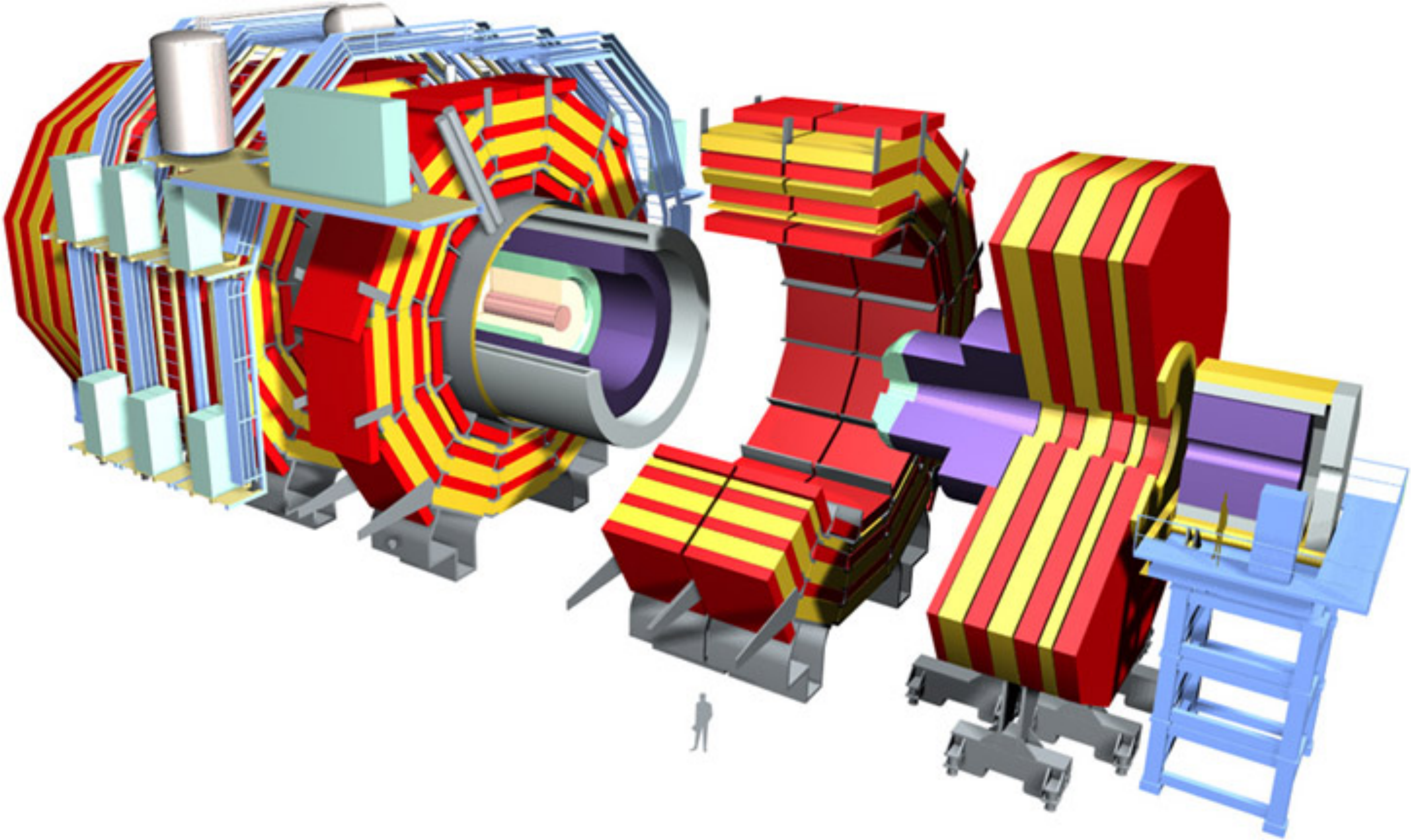
muons:
detected in outer
detector layers

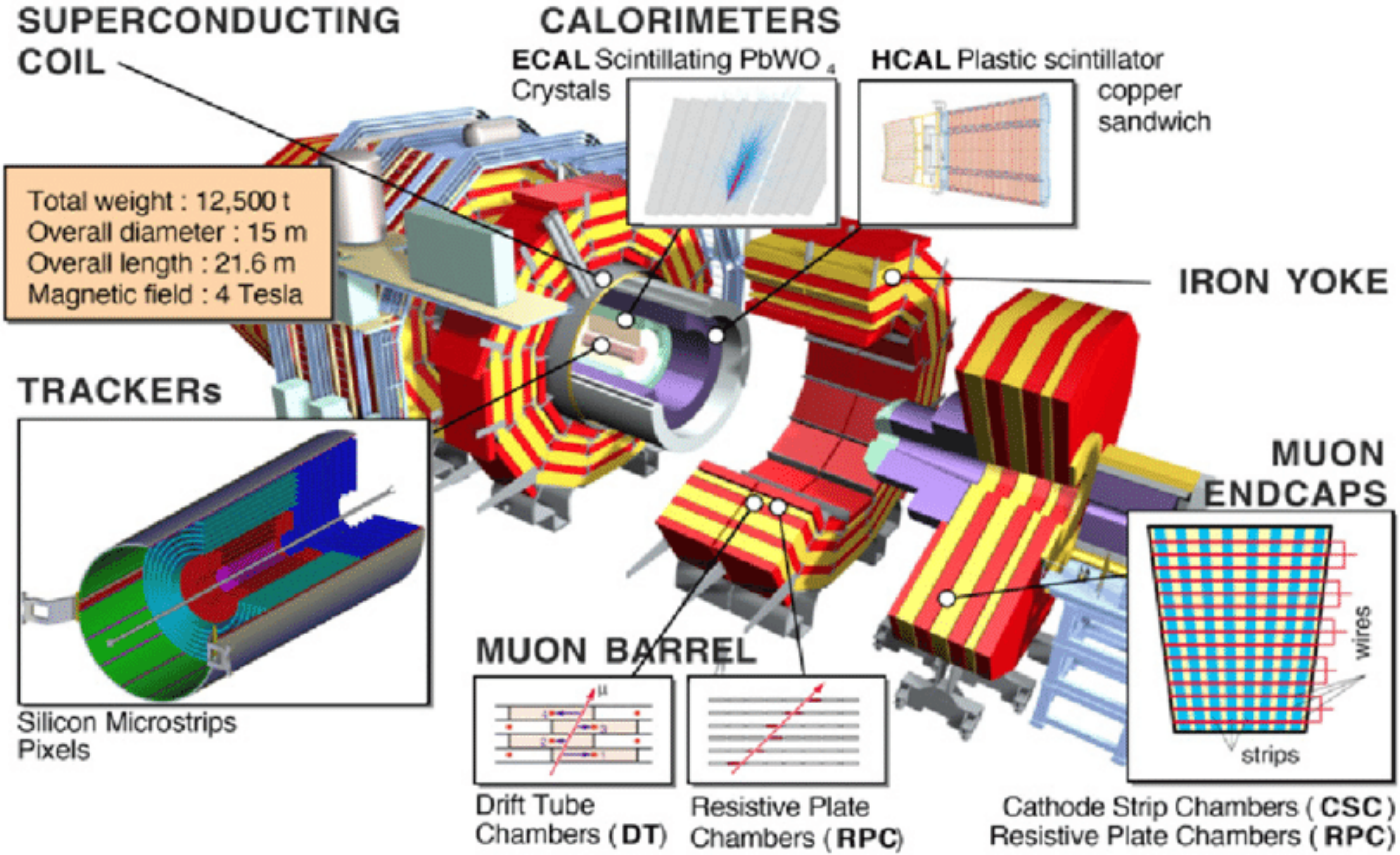
The LHC beams collide at **4 interaction points** across the ring — surrounded by detectors

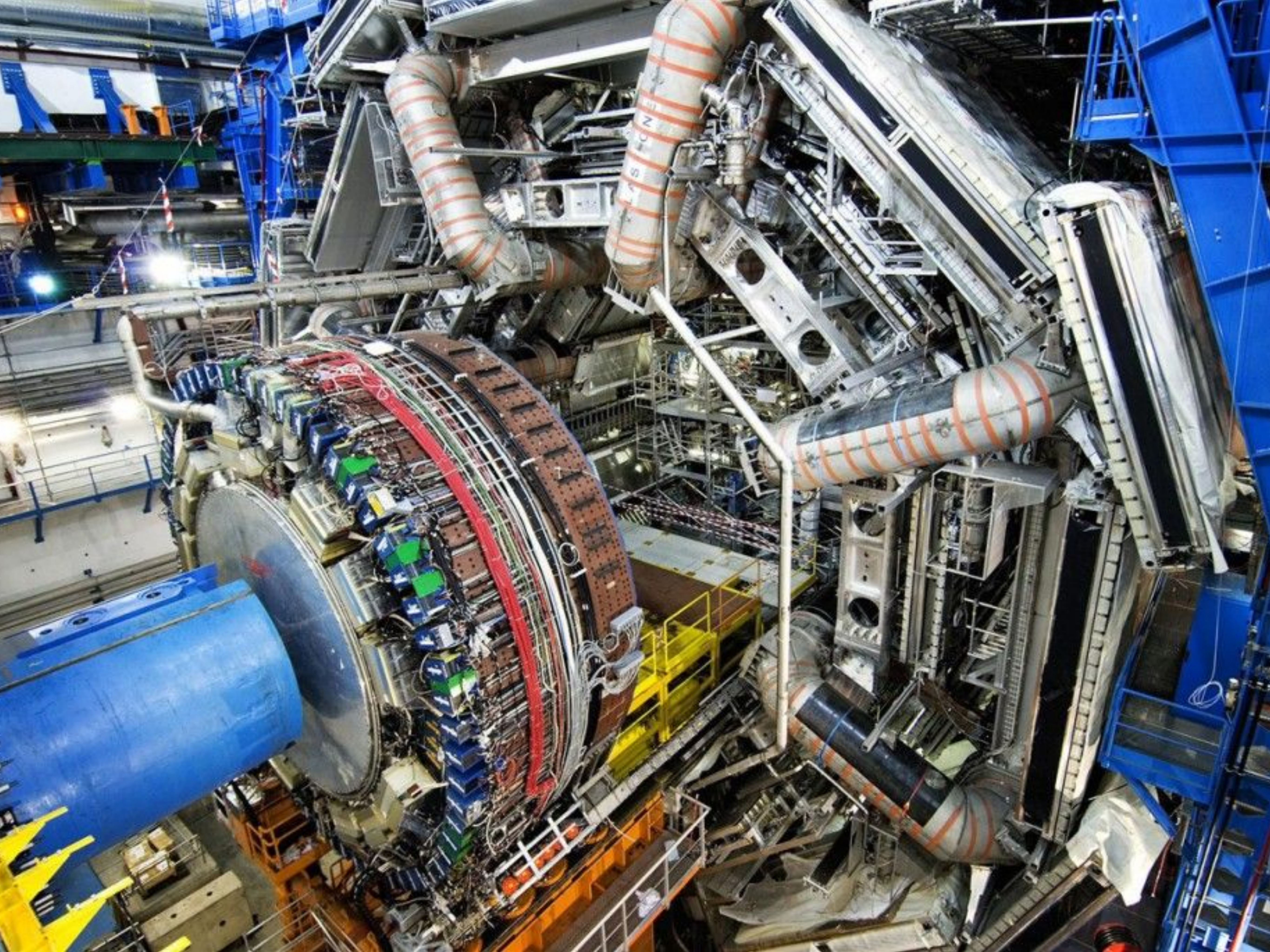


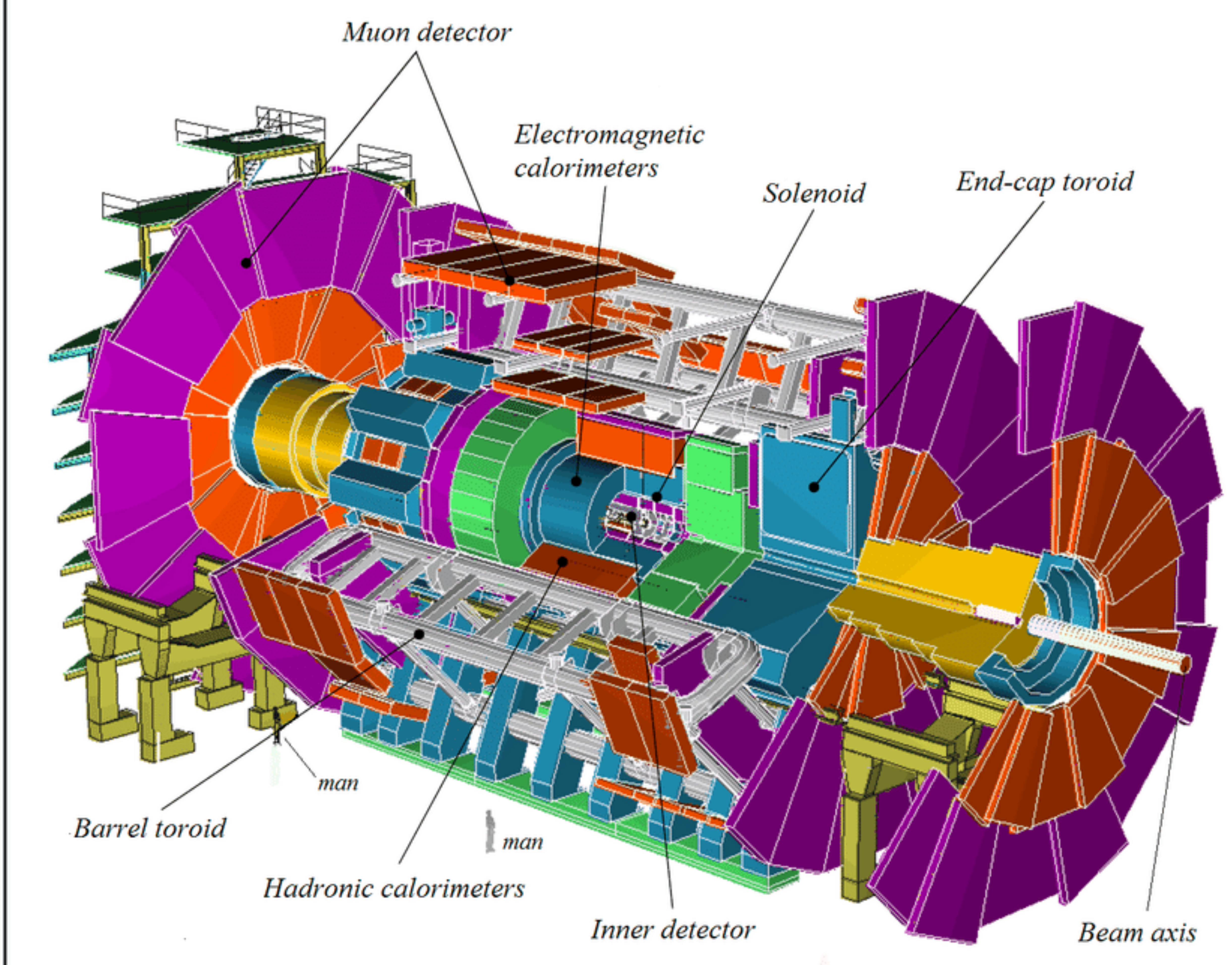


L3 Magnet
Time Projection Chamber
Particle Identification Detector
High-Momentum Particle Identification Detector
Absorber
Dipole Magnet
Muon Chambers
Photon Spectrometer
Inner Tracking System
Alice
GENEVE
LHC - B
Point 8
© CERN
CERN
ATLAS
Point 1
ALICE
Point 2
CMS
Point 5
SPS
TI 8
TI 2
LHC - B
ATLAS
ALICE
CMS
LEP/LHC




SUPERCONDUCTING COIL
CALORIMETERS
ECAL Scintillating PbWO4 Crystals
HCAL Plastic scintillator copper sandwich
Total weight : 12,500 t
Overall diameter : 15 m
Overall length : 21.6 m
Magnetic field : 4 Tesla
IRON YOKE
TRACKERs
Silicon Microstrips
Pixels
MUON ENDCAPS
MUON BARREL
wires
strips
Drift Tube Chambers (DT)
Resistive Plate Chambers (RPC)
Cathode Strip Chambers (CSC)
Resistive Plate Chambers (RPC)

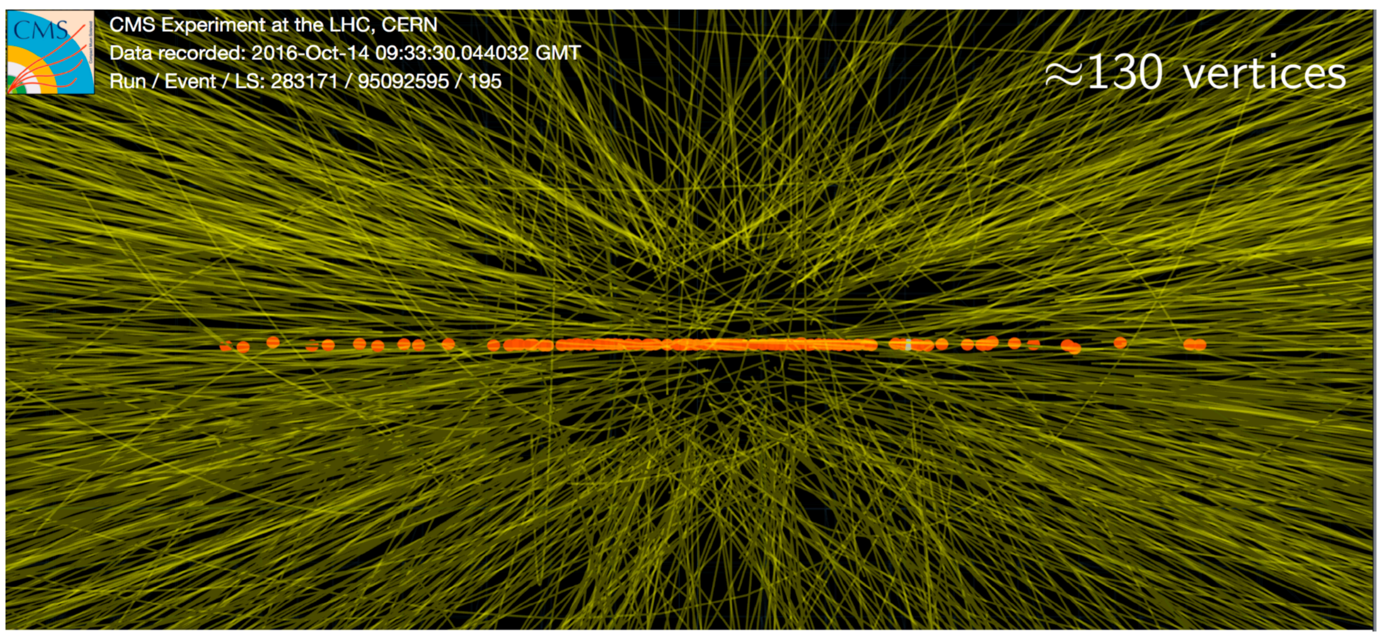



Muon detector
Electromagnetic
calorimeters
Solenoid
End-cap toroid
man
Barrel toroid
man
Hadronic calorimeters
Inner detector
Beam axis

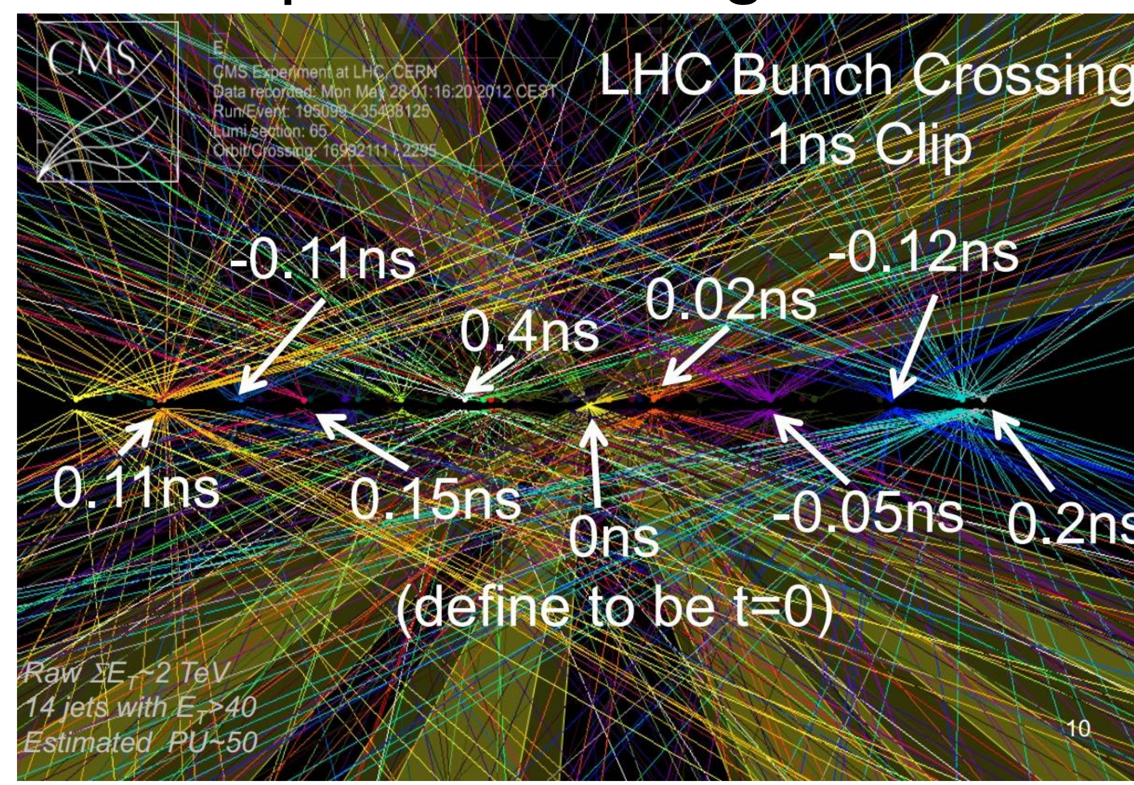
HL-LHC: “new” detectors needed!

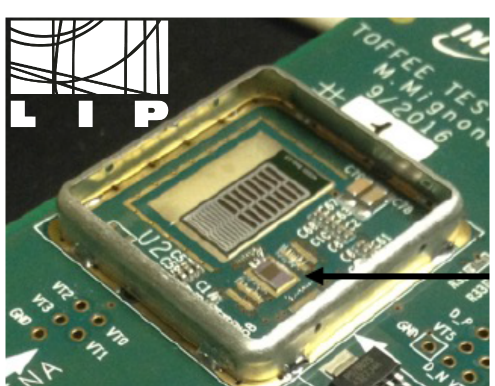
Example challenge for the high-luminosity LHC phase: pile-up

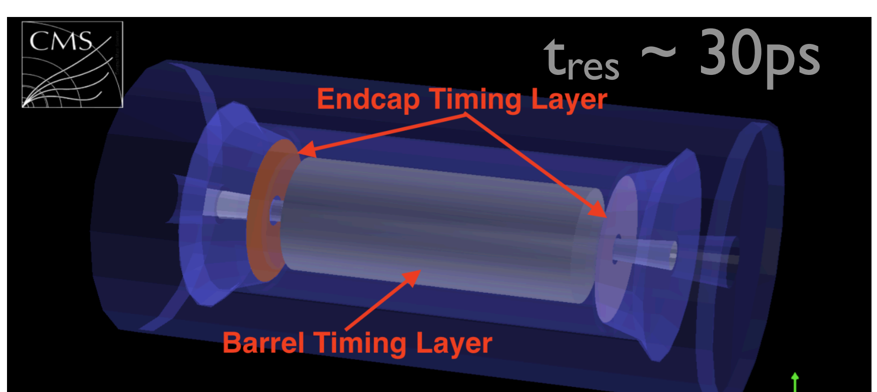
- can expect up to 200 simultaneous collisions per bunch crossing
- detectors do not have the spacial resolution to distinguish resulting vertices
- solution: add time dimension, i.e. develop a novel precision timing detector



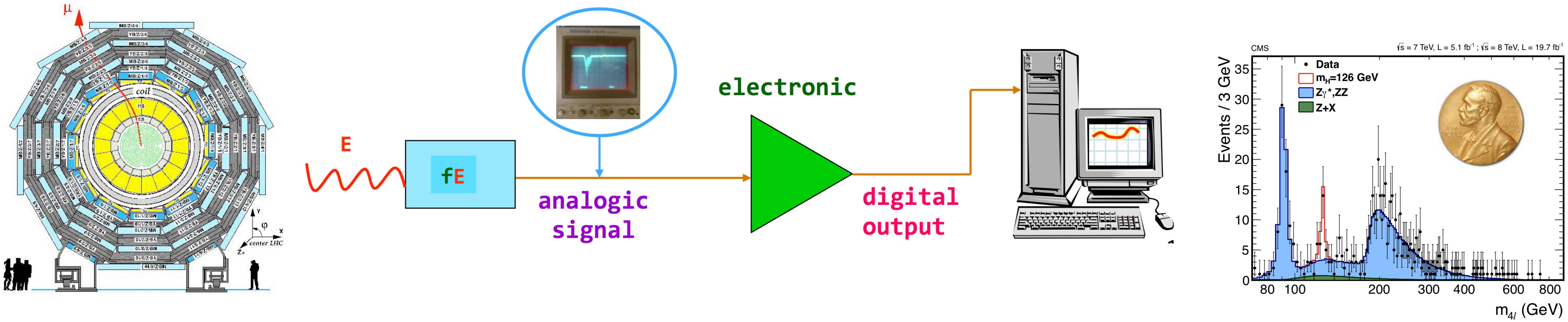
[Real life event from special LHC run in 2016 w/ intensity bunches]

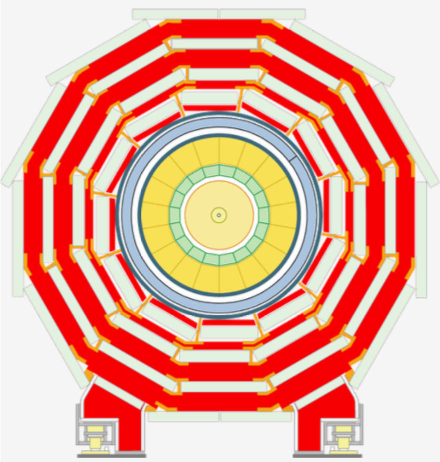






- addition of such a new timing layer should allow to recover current high levels of physics performance in the harsher hi-lumi environment

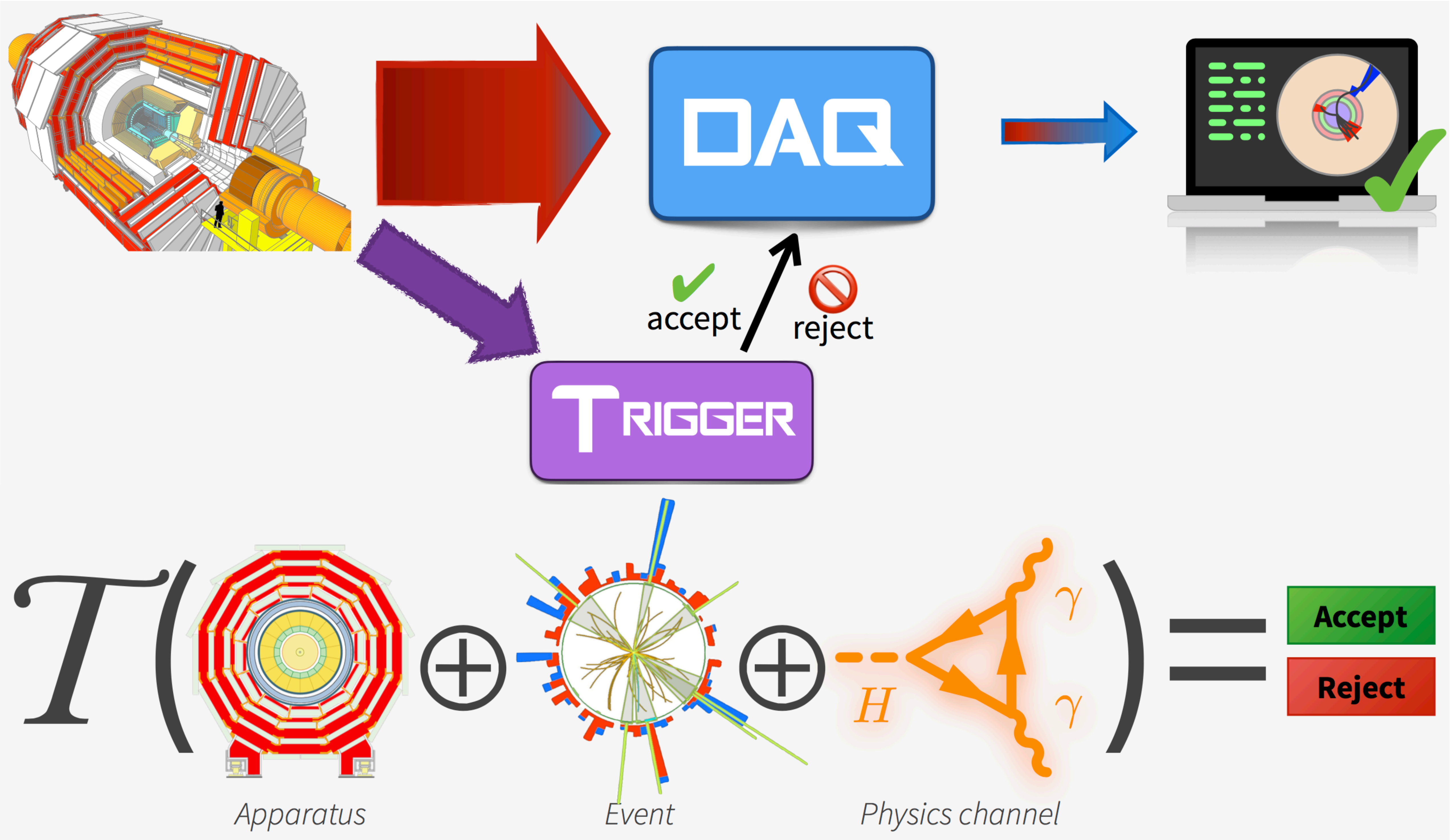




i.e. LHC experiments (ATLAS/CMS)

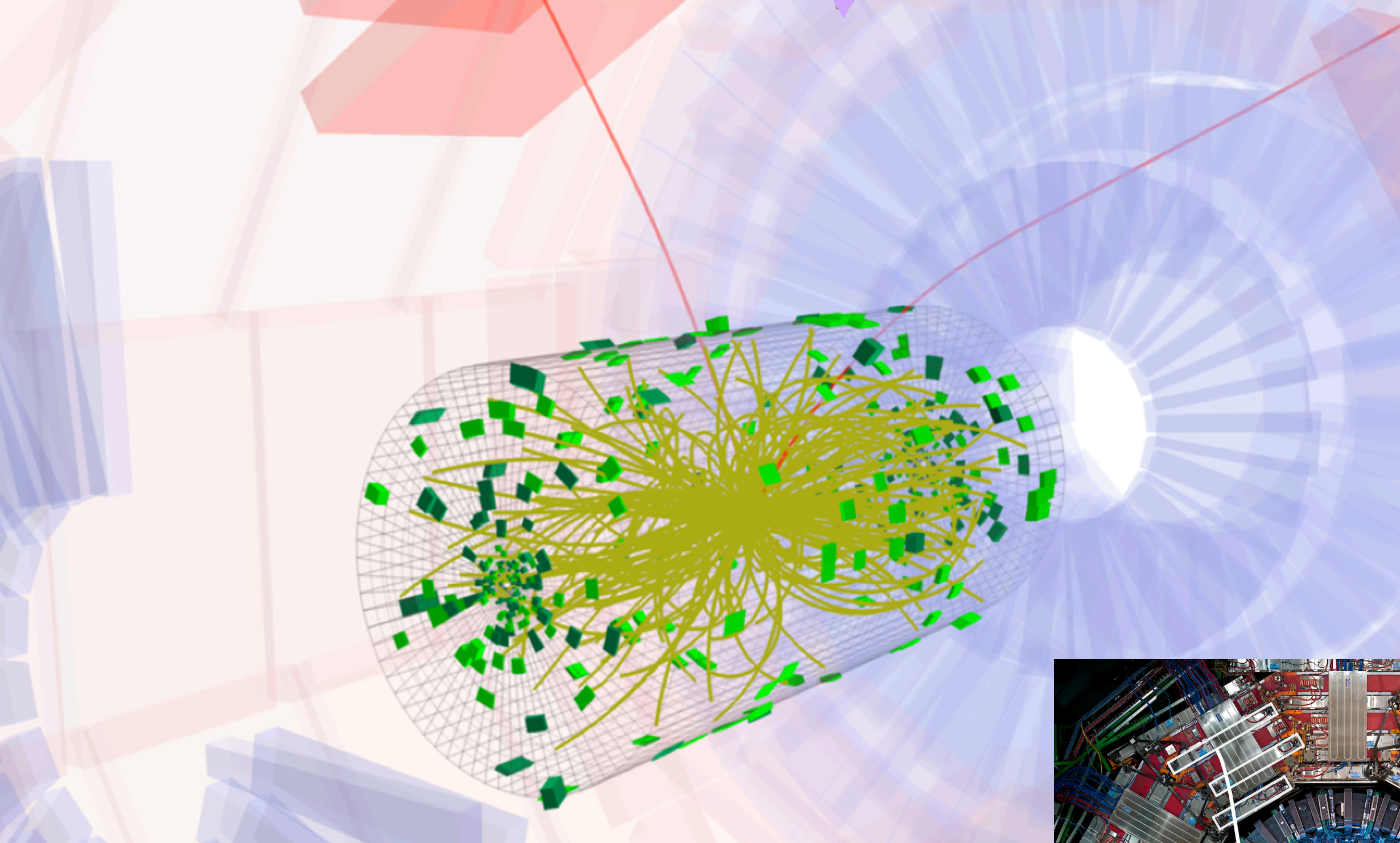
- **~100M channels**
- **~1-2 MB** of RAW data per measurement

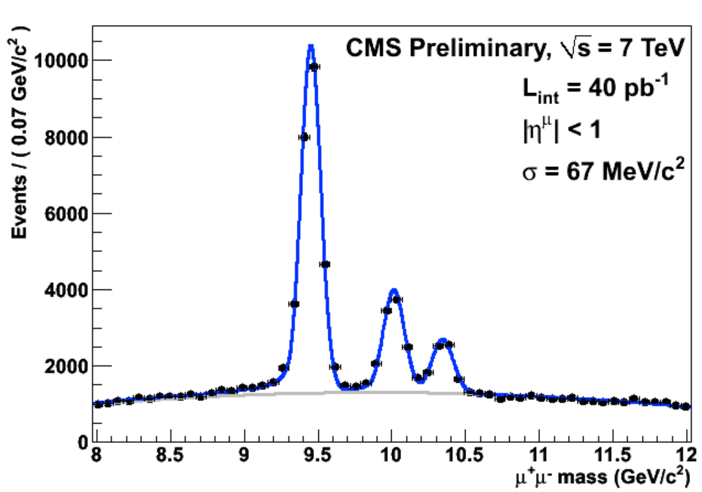
- **~40 MHz** measurement rate (every 25 ns - @ the LHC)

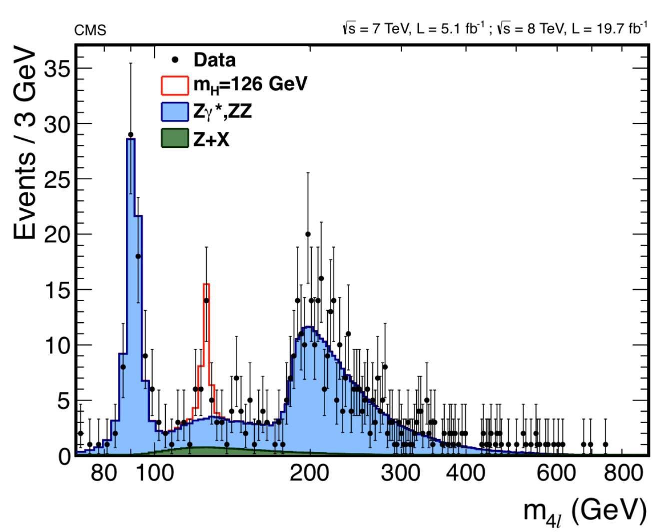


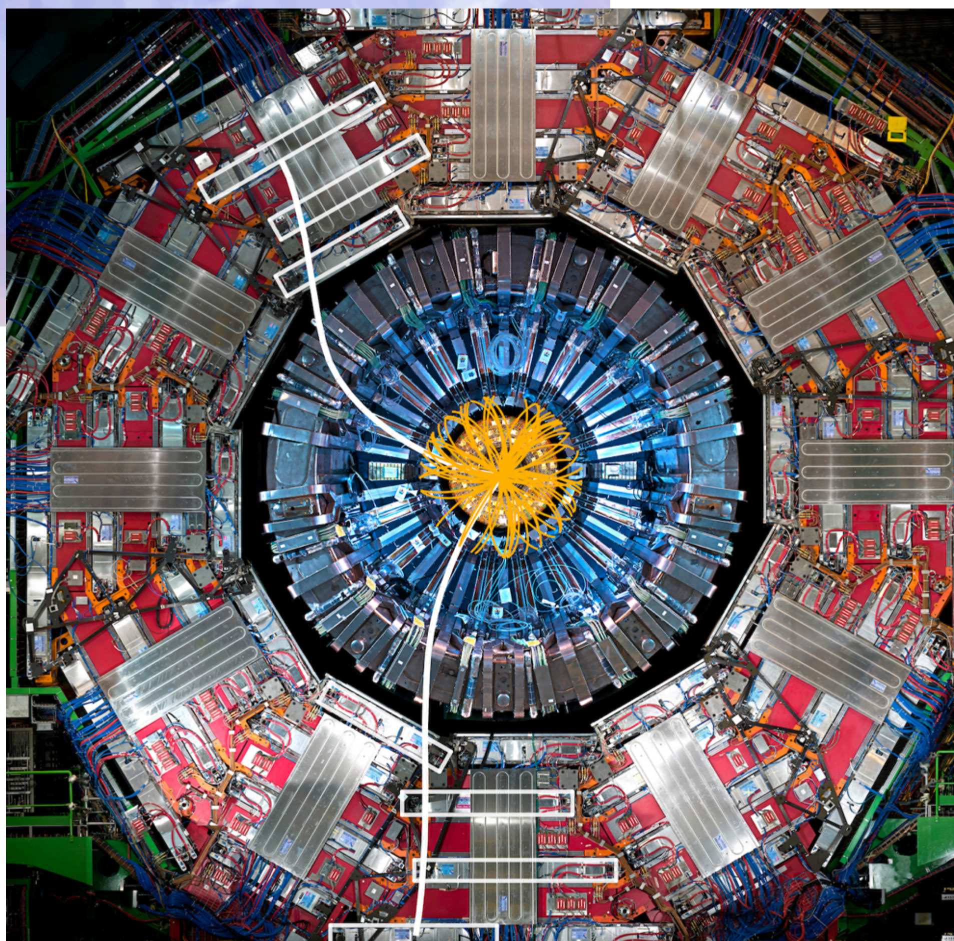
Trigger is a crucial & risky business: discarded events can never be recovered.

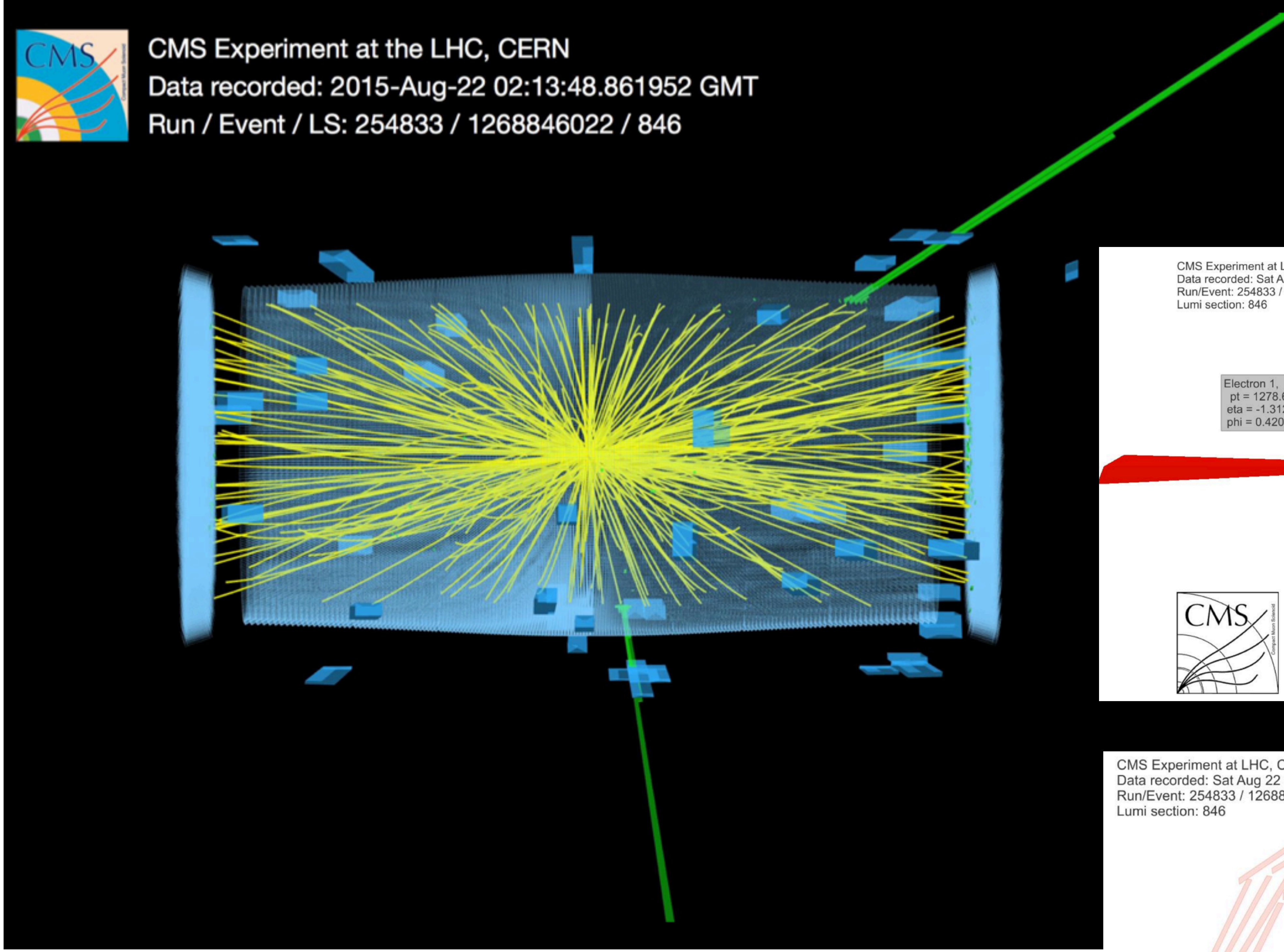
"The trigger does not determine which model is right, only which data is left."

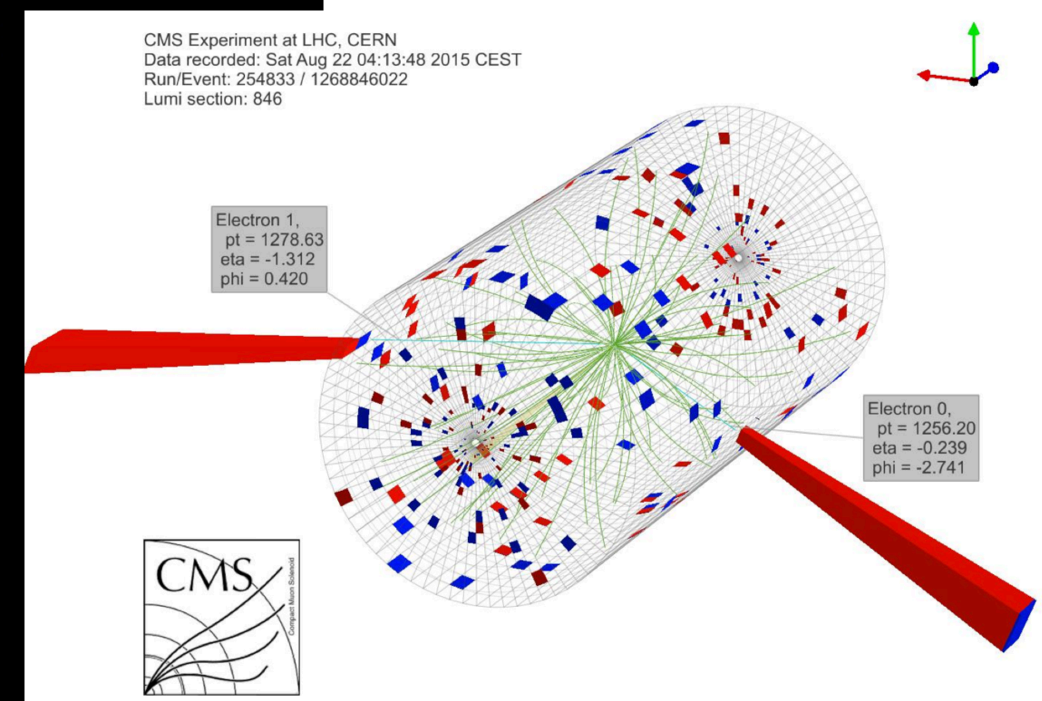


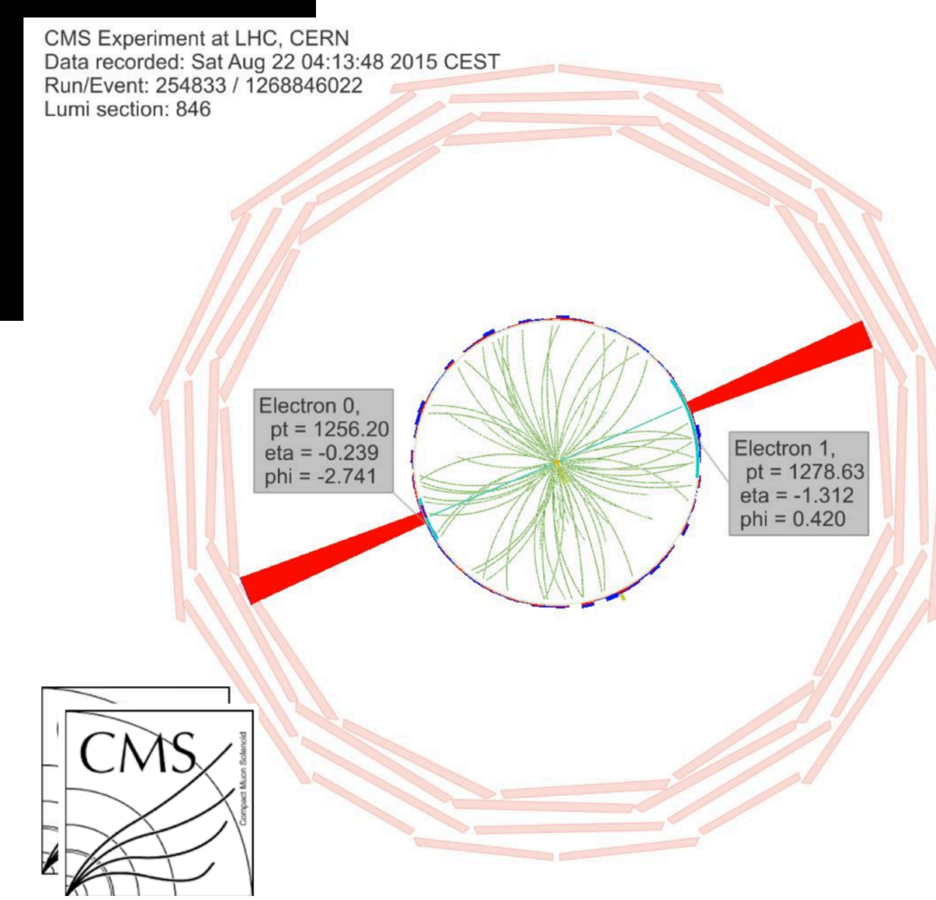

CMS Preliminary, $\sqrt{s}$ = 7 TeV
L_{int} = 40 pb^{-1}
$|\eta^{\mu}|$ < 1
σ = 67 MeV/c^2
Events / (0.07 GeV/c^2)
10000
8000
6000
4000
2000
0
8
8.5
9
9.5
10
10.5
11
11.5
12
$\mu^+\mu^-$ mass (GeV/c^2)

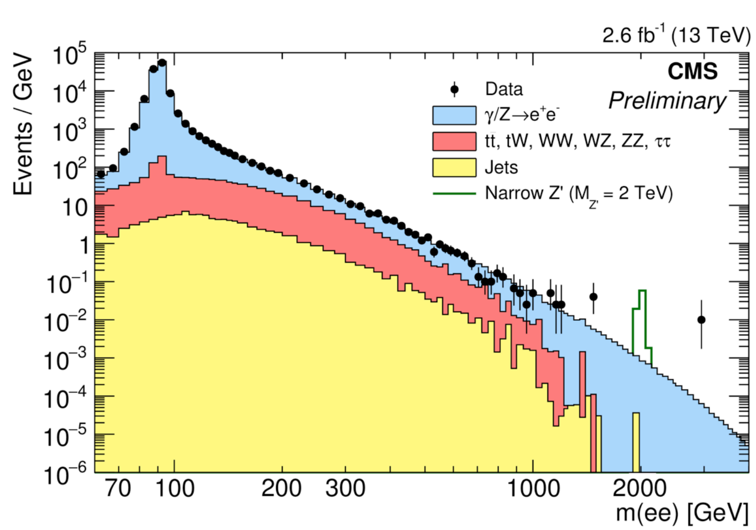

CMS
$\sqrt{s}$ = 7 TeV, L = 5.1 fb^{-1} ; $\sqrt{s}$ = 8 TeV, L = 19.7 fb^{-1}
Data
m_H=126 GeV
Zγ*,ZZ
Z+X
Events / 3 GeV
35
30
25
20
15
10
5
0
80
100
200
300
400
600
800
m_{4l} (GeV)



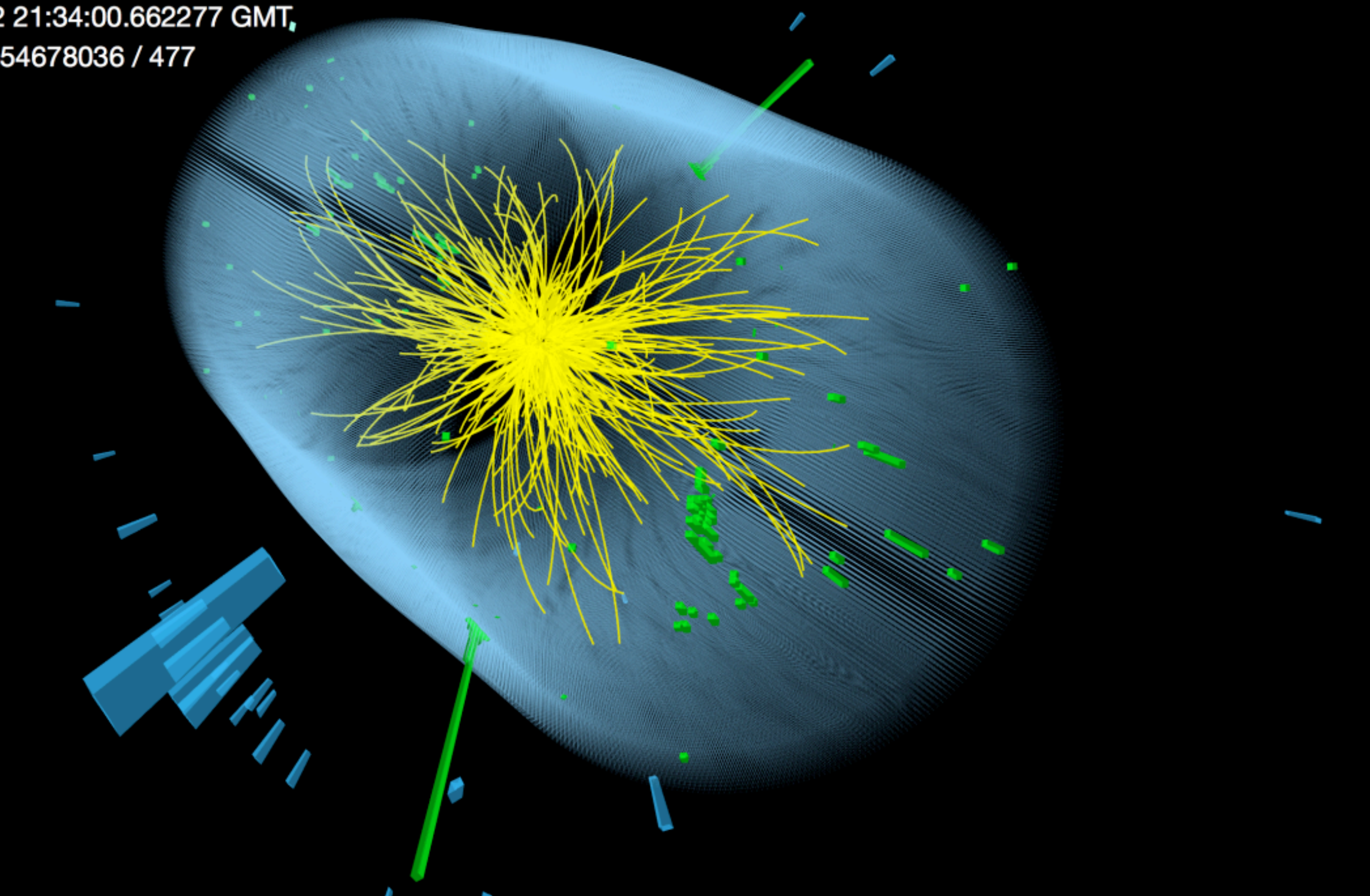

CMS Experiment at the LHC, CERN
Data recorded: 2015-Aug-22 02:13:48.861952 GMT
Run / Event / LS: 254833 / 1268846022 / 846

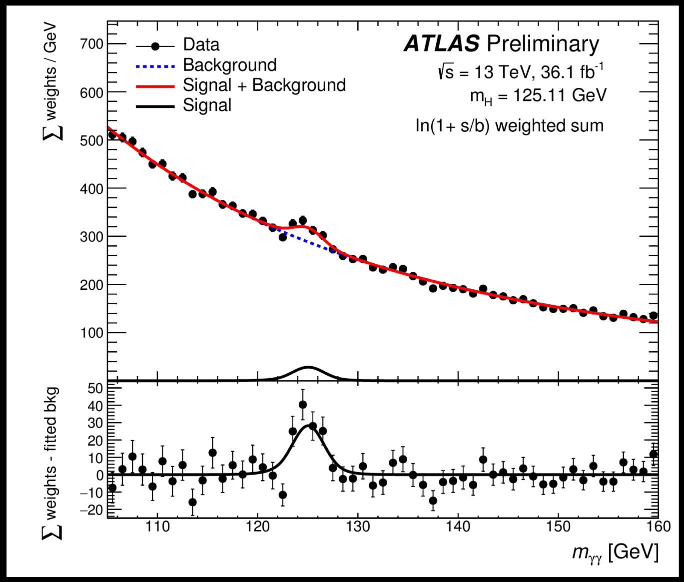

CMS Experiment at LHC, CERN
Data recorded: Sat Aug 22 04:13:48 2015 CEST
Run/Event: 254833 / 1268846022
Lumi section: 846
Electron 1,
pt = 1278.63
eta = -1.312
phi = 0.420
Electron 0,
pt = 1256.20
eta = -0.239
phi = -2.741
CMS

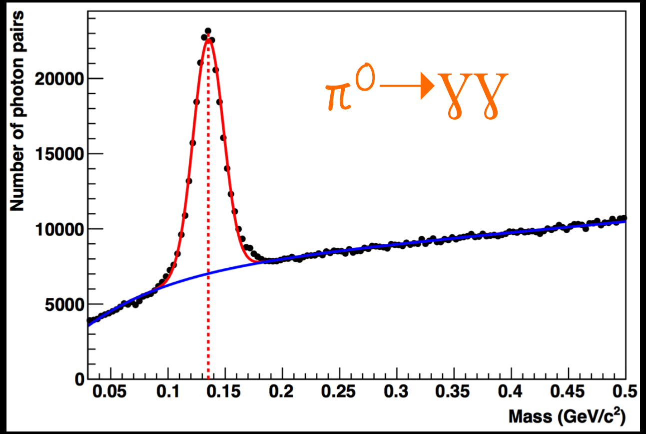

CMS Experiment at LHC, CERN
Data recorded: Sat Aug 22 04:13:48 2015 CEST
Run/Event: 254833 / 1268846022
Lumi section: 846
Electron 0,
pt = 1256.20
eta = -0.239
phi = -2.741
Electron 1,
pt = 1278.63
eta = -1.312
phi = 0.420
CMS

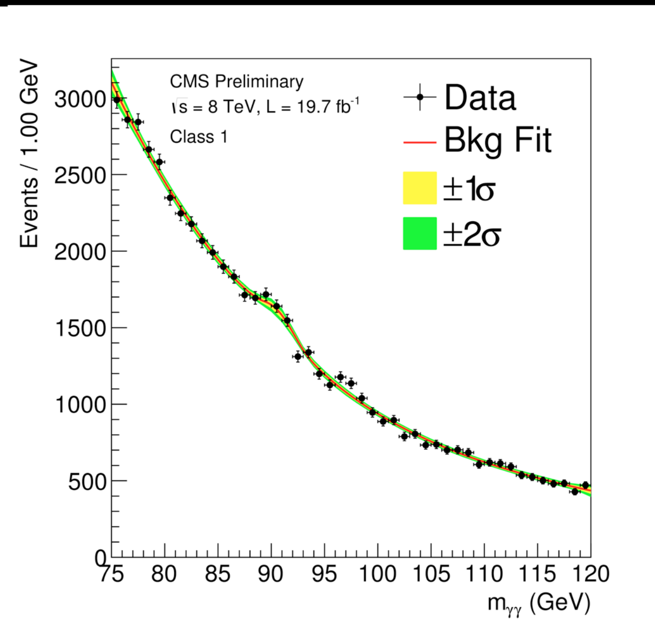

2.6 fb^{-1} (13 TeV)
CMS
Preliminary
Data
$\gamma/Z \rightarrow e^+e^-$
tt, tW, WW, WZ, ZZ, ττ
Jets
Narrow Z' ($M_{Z'}$ = 2 TeV)
Events / GeV
m(ee) [GeV]

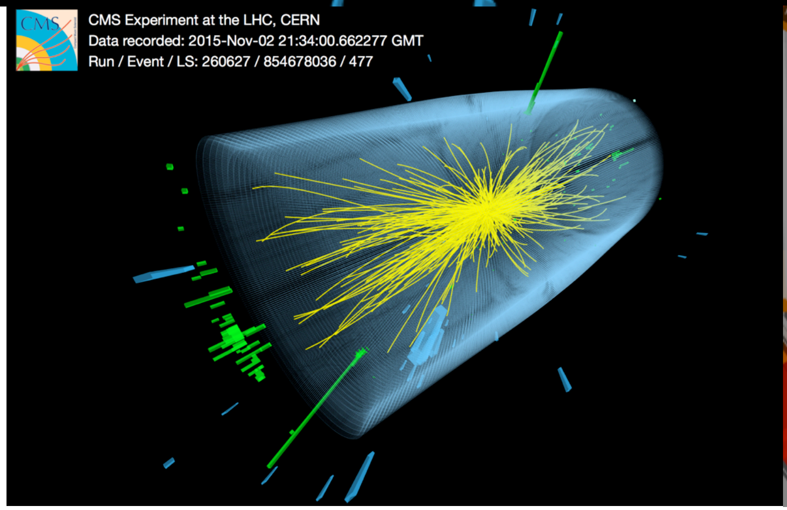
Physics@

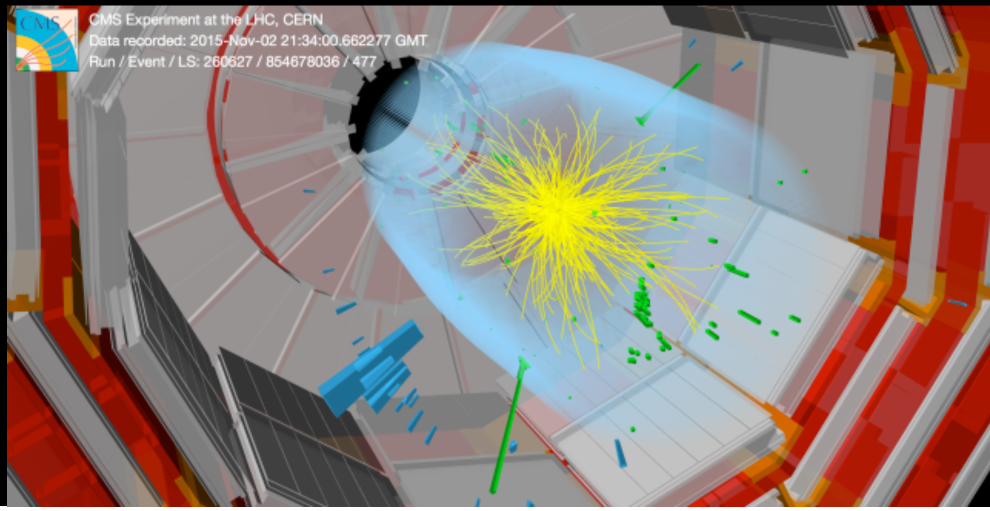

CMS Experiment at the LHC, CERN
Data recorded: 2015-Nov-02 21:34:00.662277 GMT
Run / Event / LS: 260627 / 854678036 / 477

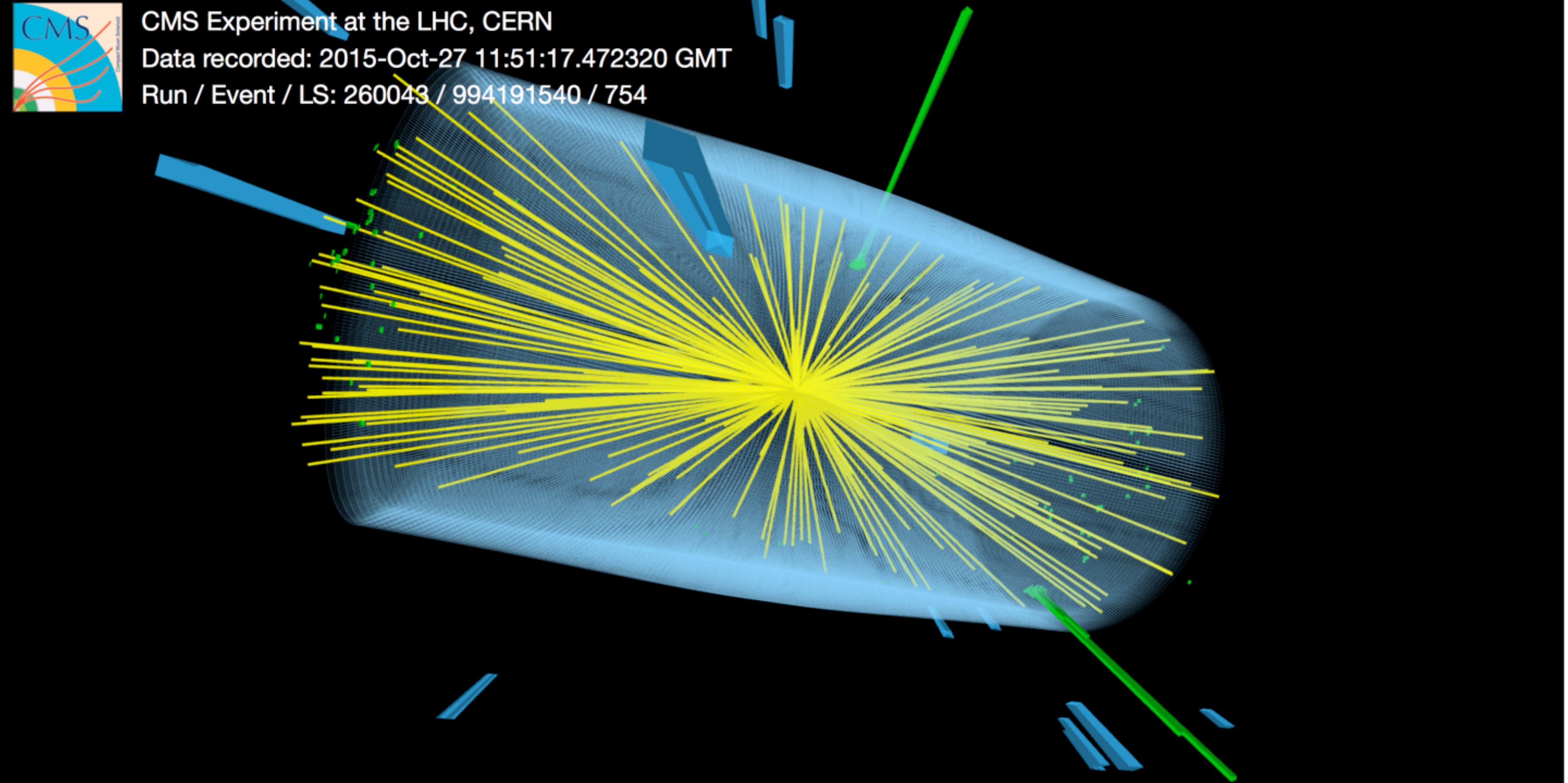

ATLAS Preliminary
√s = 13 TeV, 36.1 fb⁻¹
m_H = 125.11 GeV
ln(1+ s/b) weighted sum
Data
Background
Signal + Background
Signal
∑ weights / GeV
∑ weights - fitted bkg
m_γγ [GeV]

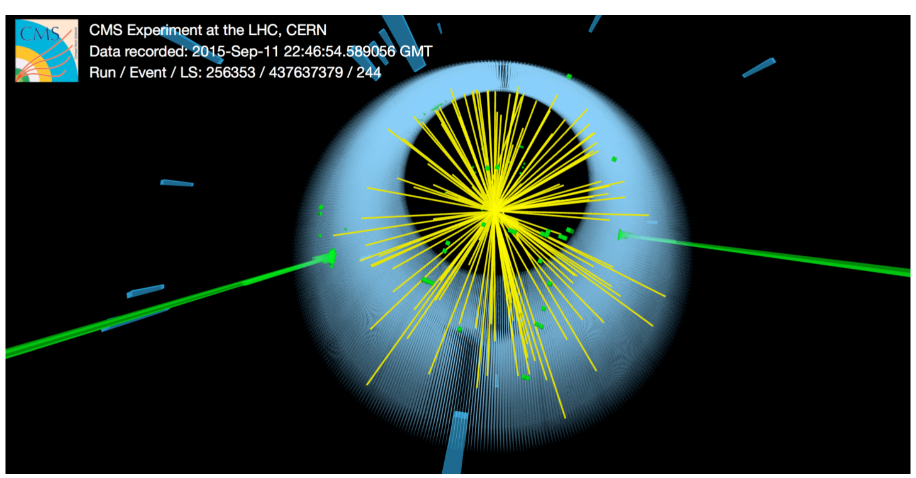

π⁰→γγ
Number of photon pairs
Mass (GeV/c²)

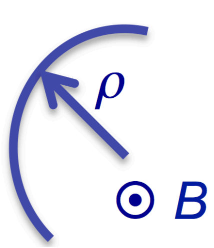

CMS Preliminary
√s = 8 TeV, L = 19.7 fb⁻¹
Class 1
Data
Bkg Fit
±1σ
±2σ
Events / 1.00 GeV
m_γγ (GeV)


CMS Experiment at the LHC, CERN
Data recorded: 2015-Nov-02 21:34:00.662277 GMT
Run / Event / LS: 260627 / 854678036 / 477

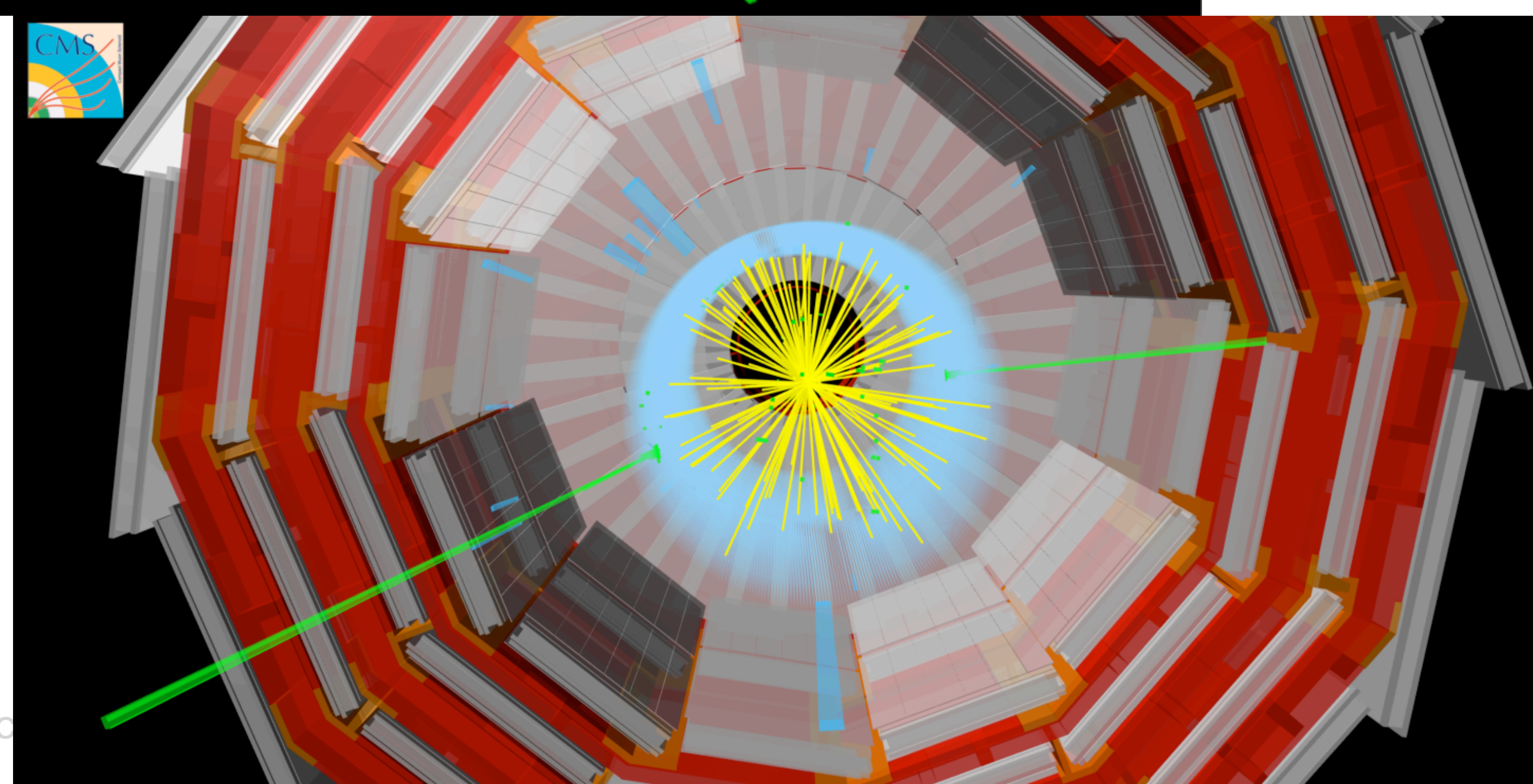

CMS Experiment at the LHC, CERN
Data recorded: 2015-Nov-02 21:34:00.662277 GMT
Run / Event / LS: 260627 / 854678036 / 477

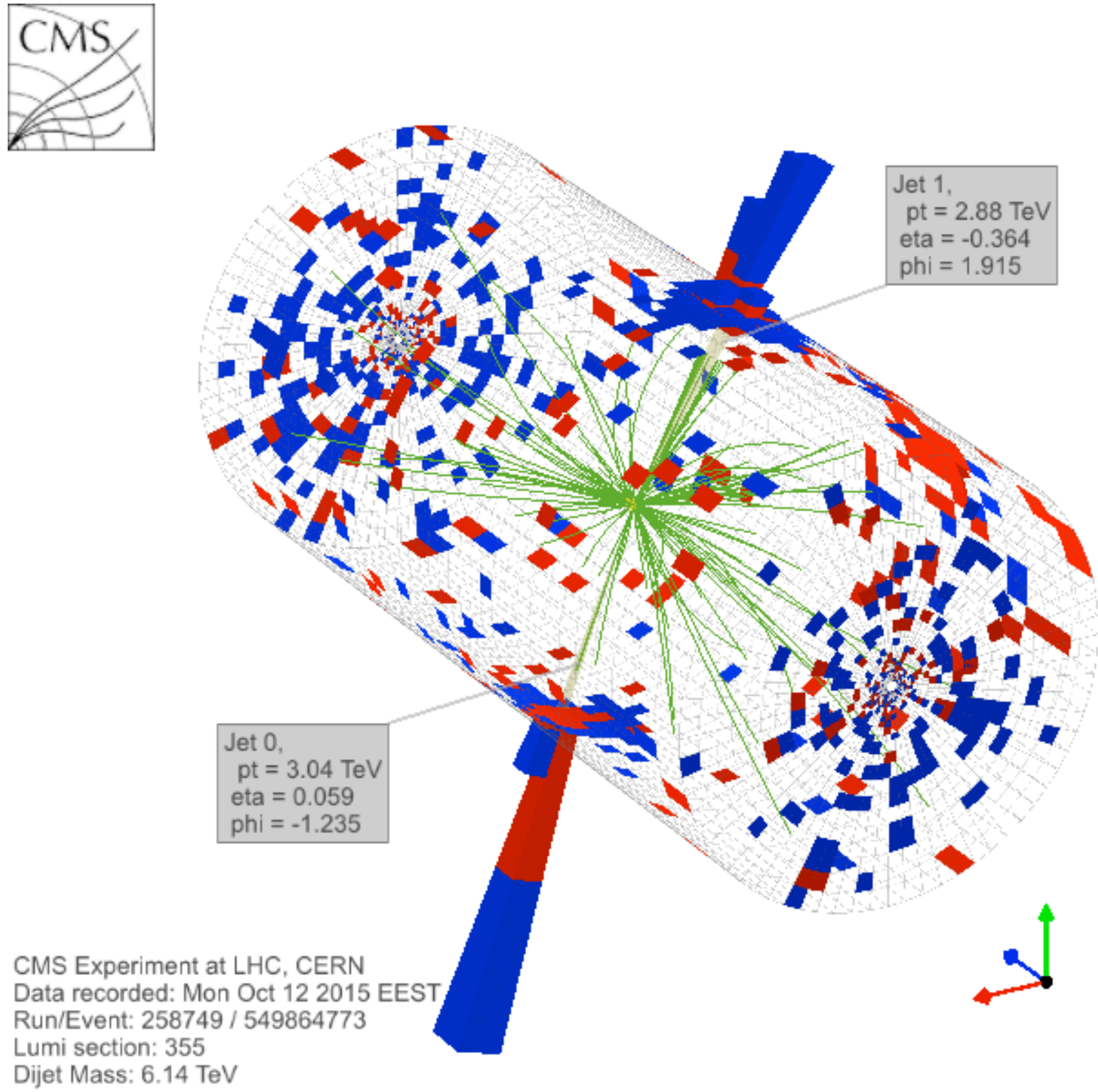


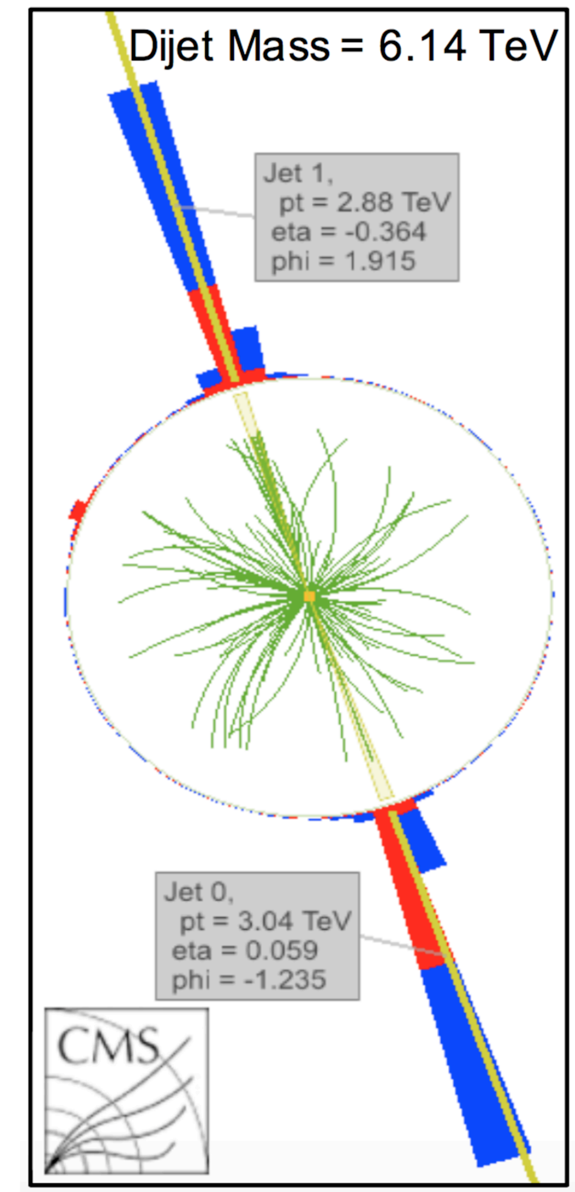


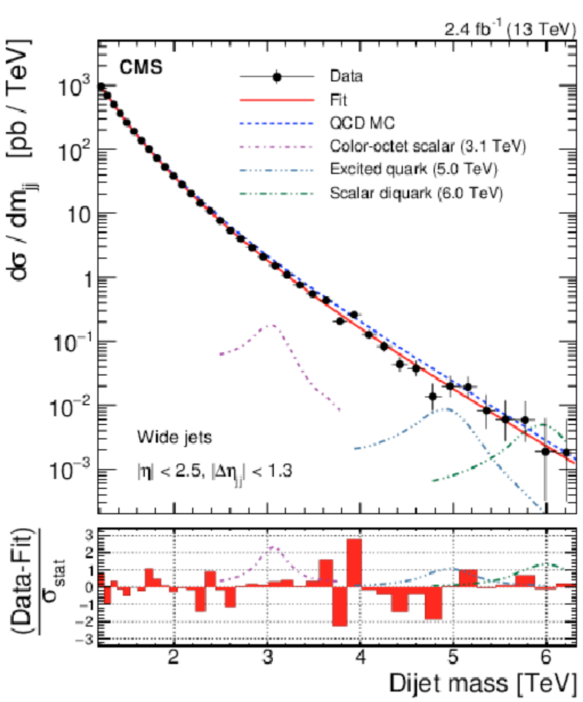


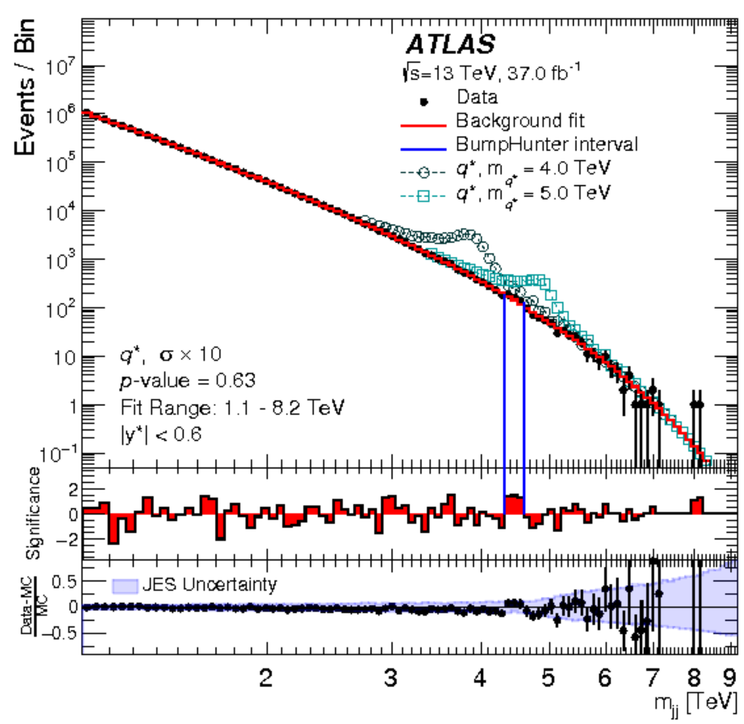
$$\rho = \frac{p}{ZeB}$$

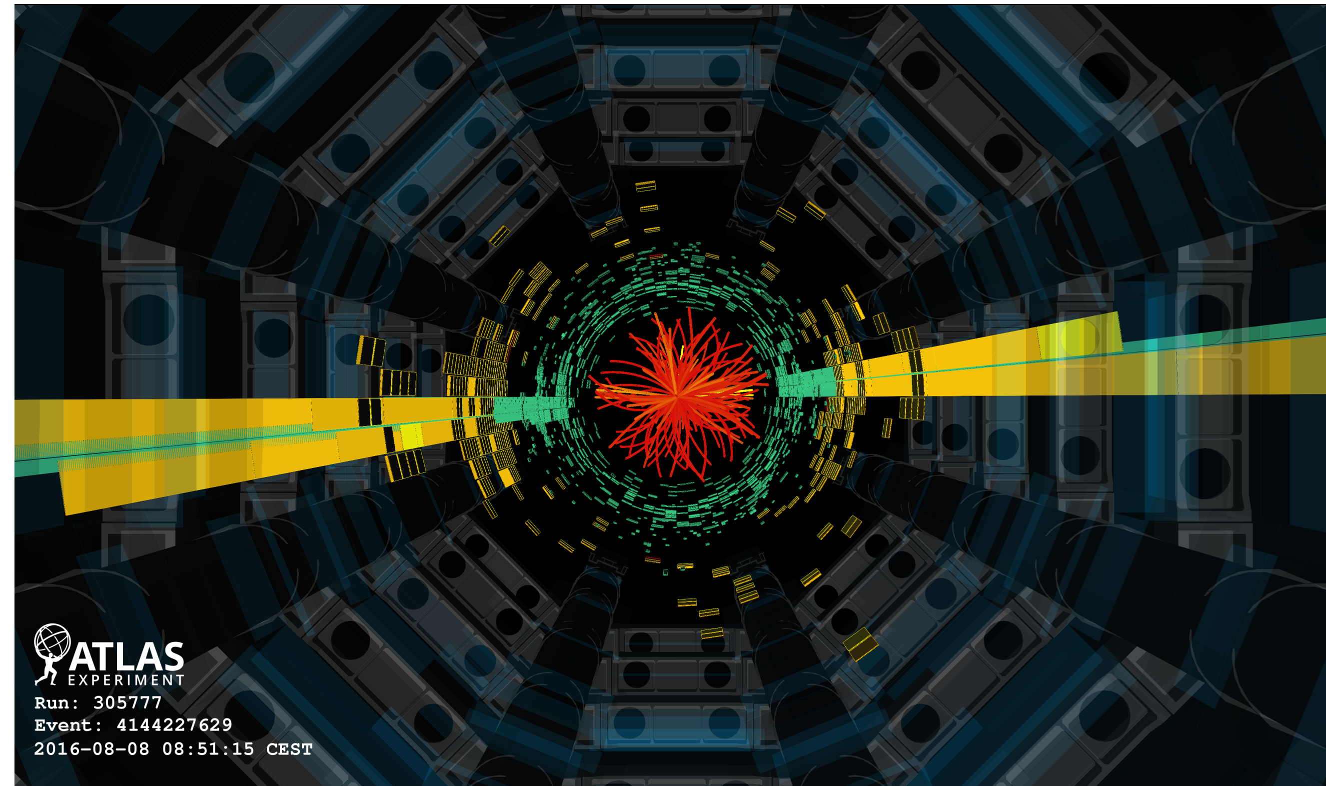


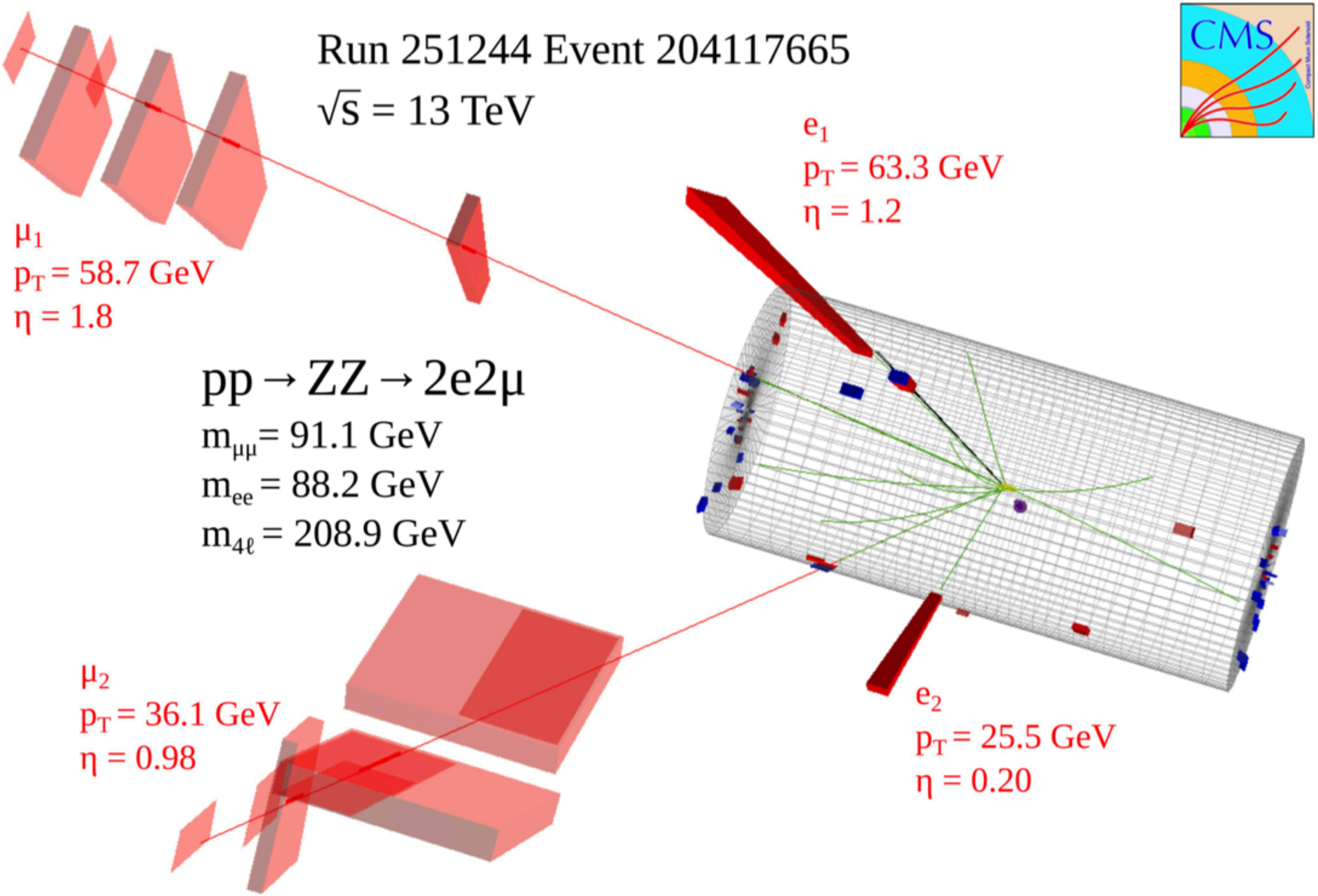

CMS
Jet 1,
pt = 2.88 TeV
eta = -0.364
phi = 1.915
Jet 0,
pt = 3.04 TeV
eta = 0.059
phi = -1.235
CMS Experiment at LHC, CERN
Data recorded: Mon Oct 12 2015 EEST
Run/Event: 258749 / 549864773
Lumi section: 355
Dijet Mass: 6.14 TeV

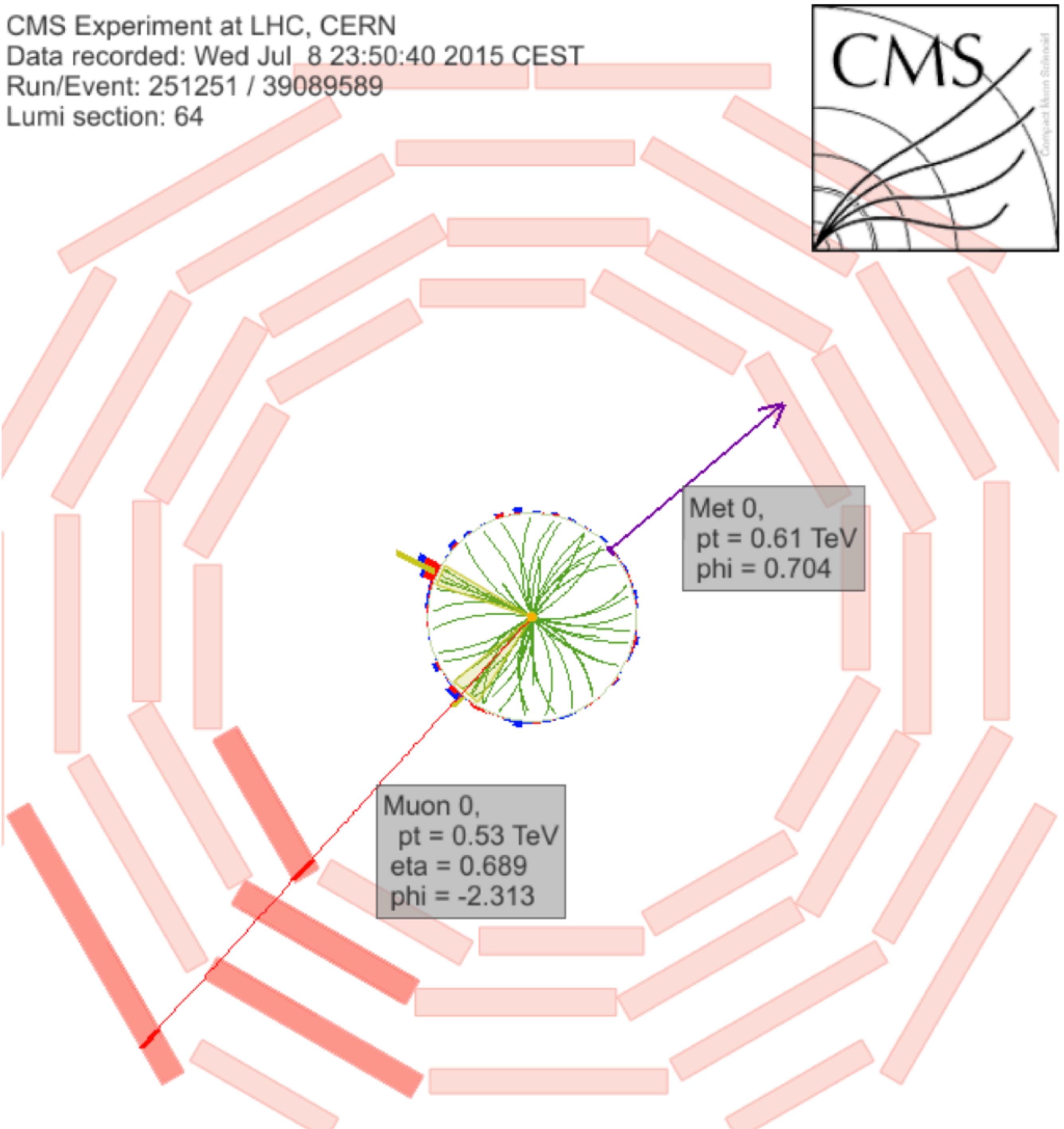

Dijet Mass = 6.14 TeV
Jet 1,
pt = 2.88 TeV
eta = -0.364
phi = 1.915
Jet 0,
pt = 3.04 TeV
eta = 0.059
phi = -1.235
CMS


2.4 fb^{-1} (13 TeV)
CMS
Data
Fit
QCD MC
Color-octet scalar (3.1 TeV)
Excited quark (5.0 TeV)
Scalar diquark (6.0 TeV)
Wide jets
$|\eta| < 2.5, |\Delta\eta_{jj}| < 1.3$
$d\sigma / dm_{jj}$ [pb / TeV]
$\frac{(Data-Fit)}{\sigma_{stat}}$
Dijet mass [TeV]

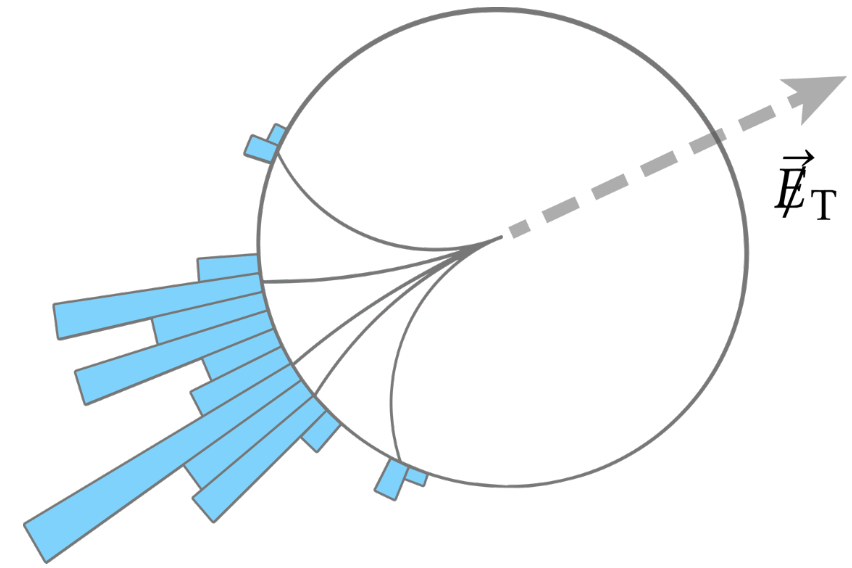

ATLAS
$\sqrt{s}$=13 TeV, 37.0 fb^{-1}
Data
Background fit
BumpHunter interval
q^*, m_{q^*} = 4.0 TeV
q^*, m_{q^*} = 5.0 TeV
q^*, $\sigma \times 10$
p-value = 0.63
Fit Range: 1.1 - 8.2 TeV
$|y^*| < 0.6$
Events / Bin
Significance
JES Uncertainty
$\frac{Data-MC}{MC}$
m_{jj} [TeV]

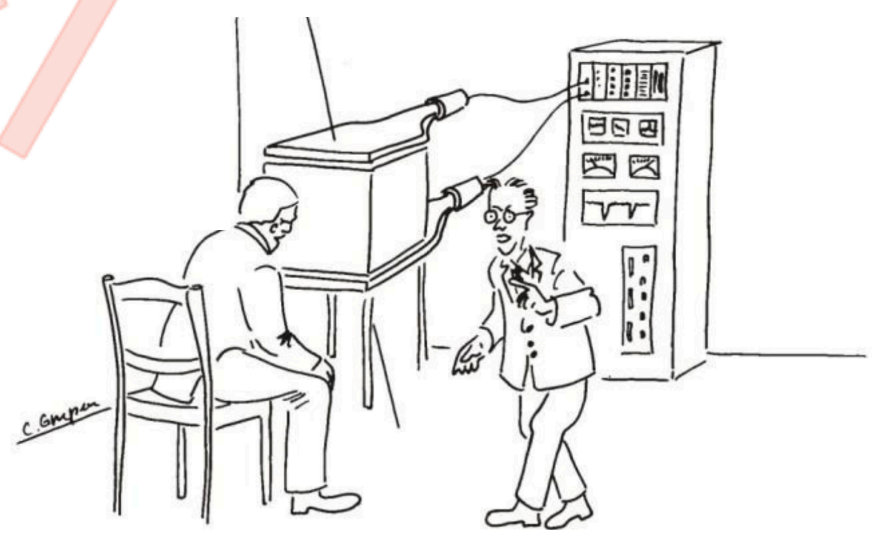

ATLAS
EXPERIMENT
Run: 305777
Event: 4144227629
2016-08-08 08:51:15 CEST


Run 251244 Event 204117665
√s = 13 TeV
CMS
e1
pT = 63.3 GeV
η = 1.2
μ1
pT = 58.7 GeV
η = 1.8
pp → ZZ → 2e2μ
mμμ = 91.1 GeV
mee = 88.2 GeV
m4ℓ = 208.9 GeV
μ2
pT = 36.1 GeV
η = 0.98
e2
pT = 25.5 GeV
η = 0.20



Missing momentum

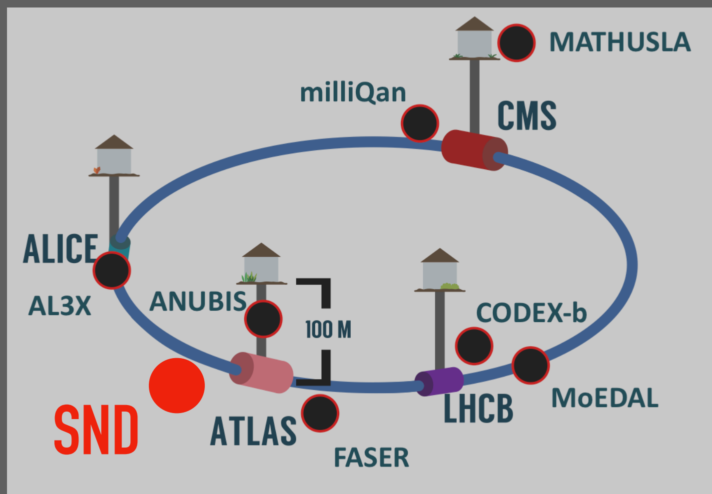


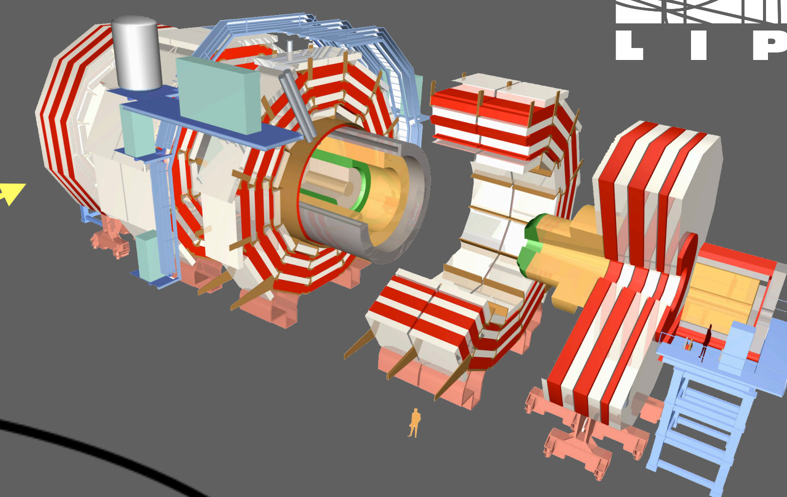


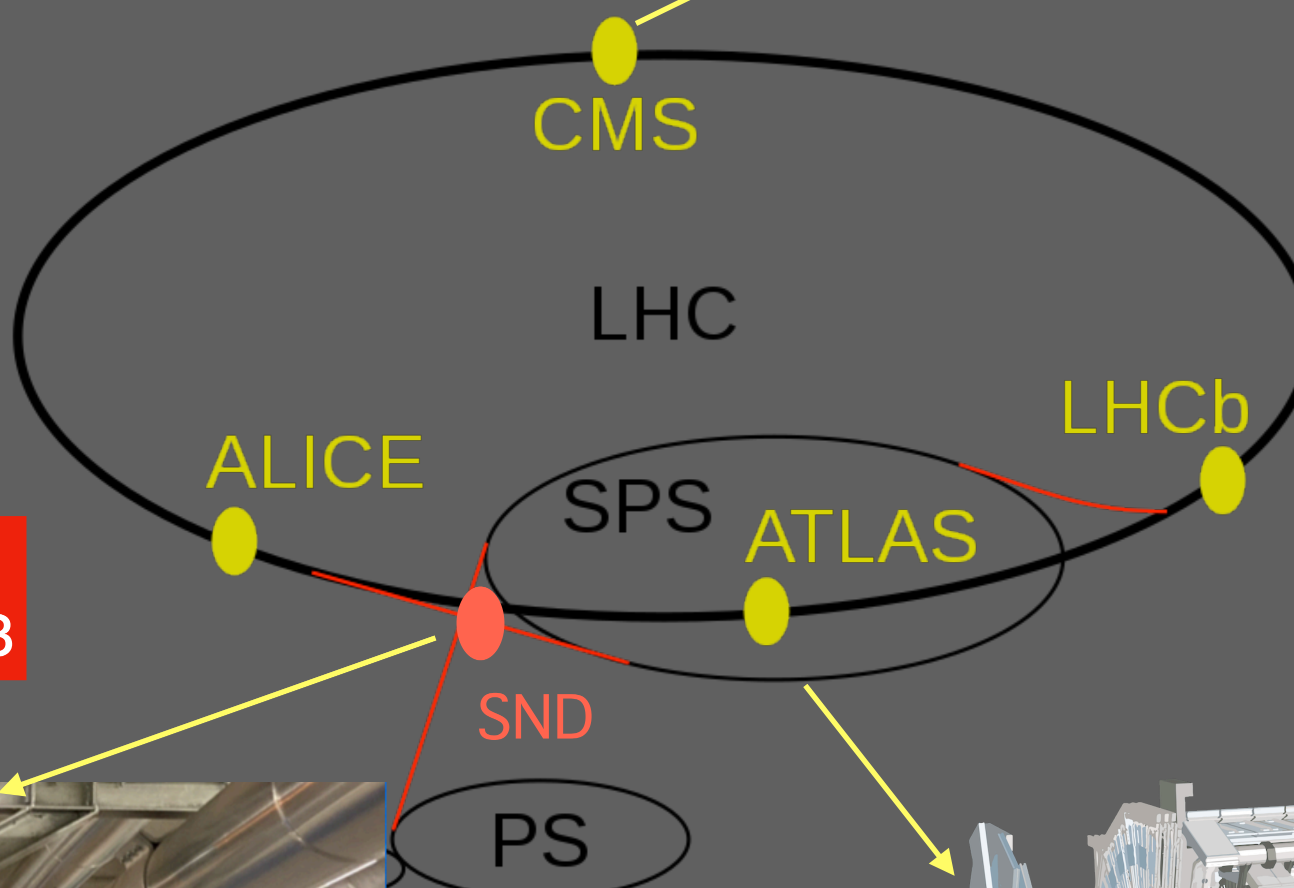
"Did you see it?"
"No nothing."
"Then it was a neutrino!"

Neutrinos cannot be detected at the LHC … or can they

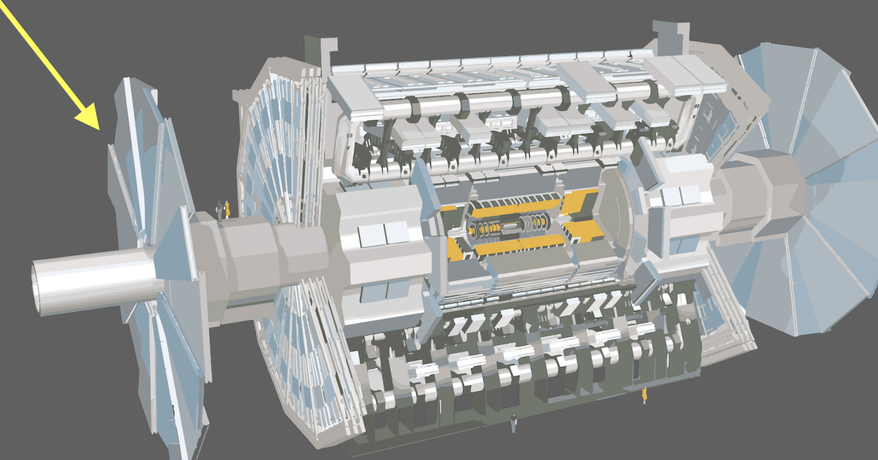
Neutrino detector at the LHC







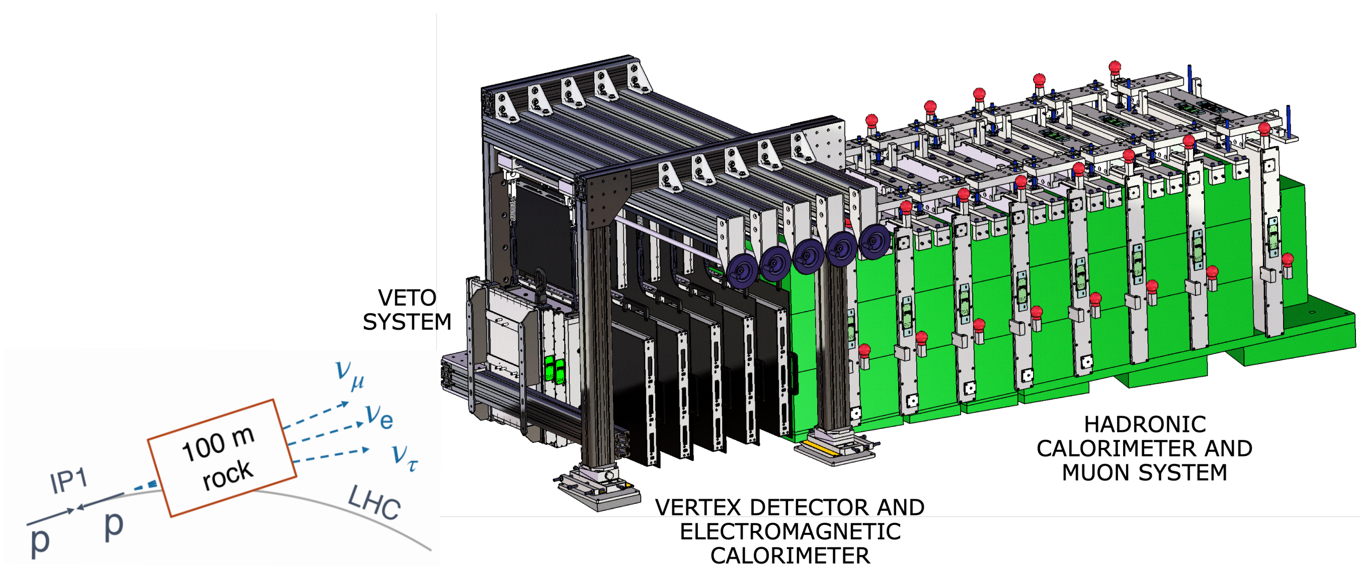
SND@LHC — the most recent LHC experiment!, started Run3

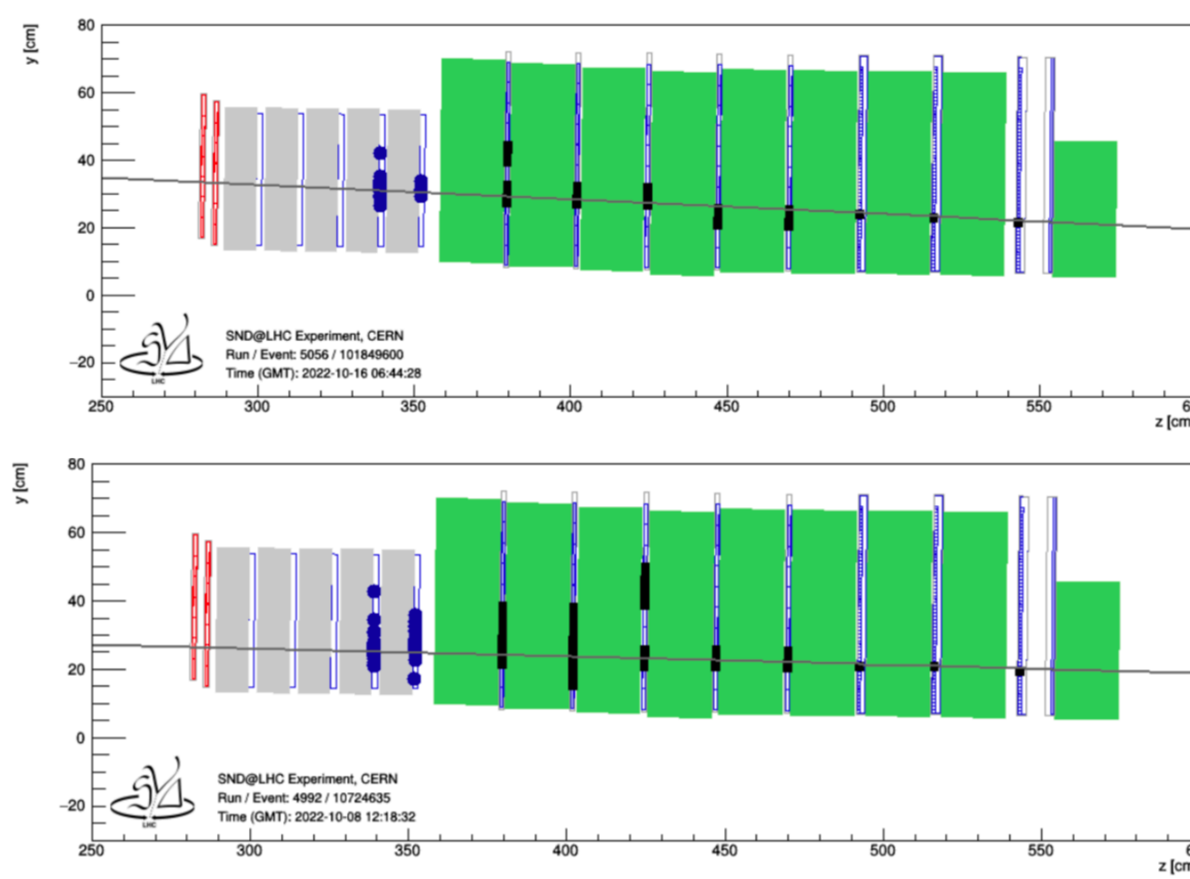


Observation of collider neutrinos (2023)

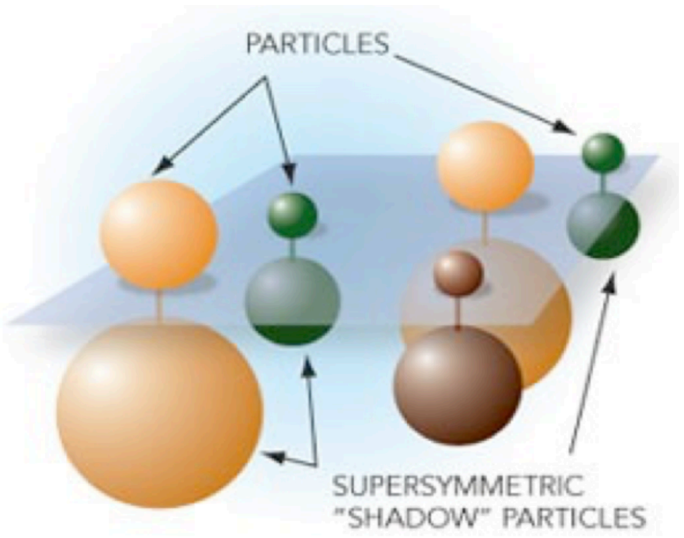
- the dedicated LHC experiments SND@LHC and FASER have just reported the first direct observation of neutrinos at the LHC
- what makes it possible?
  - high collision rate → large ν flux (esp. along beam direction)
  - high collision energy → large ν interaction cross section
- opens new window of LHC research into neutrino physics

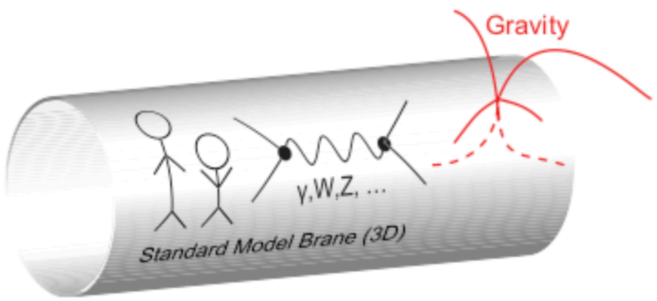
$\nu_\mu \rightarrow \mu + X$

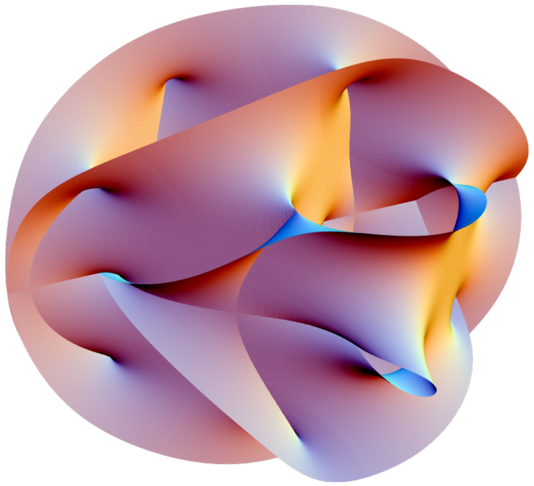




Probing beyond the SM

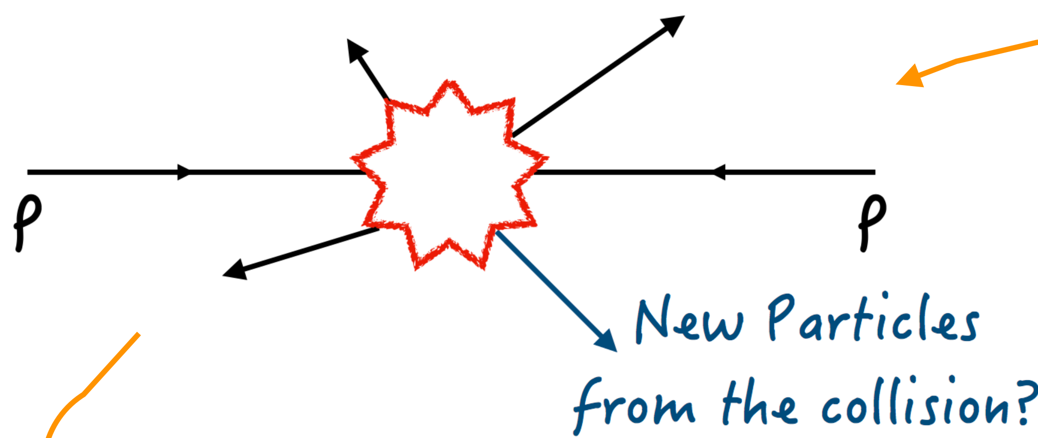


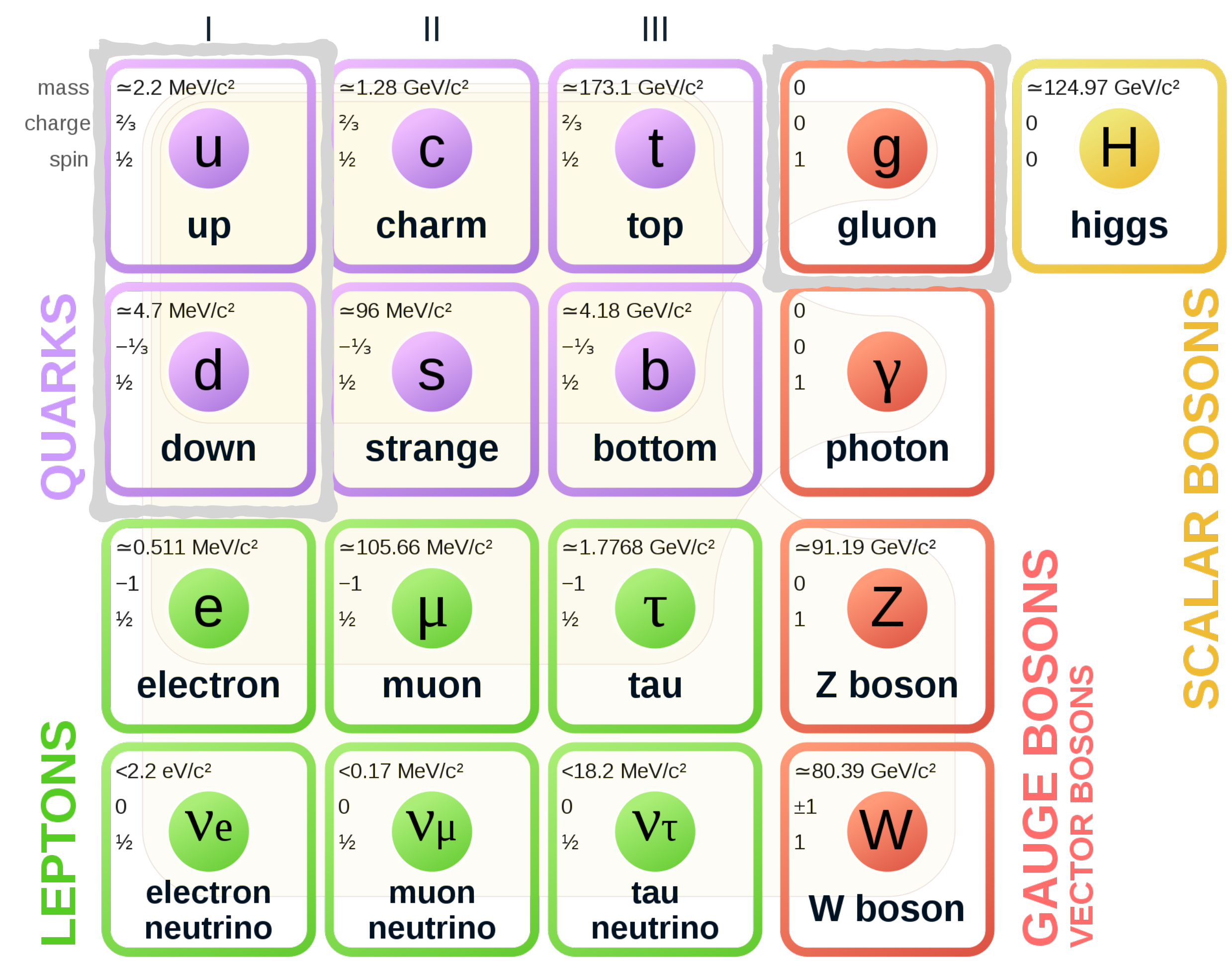


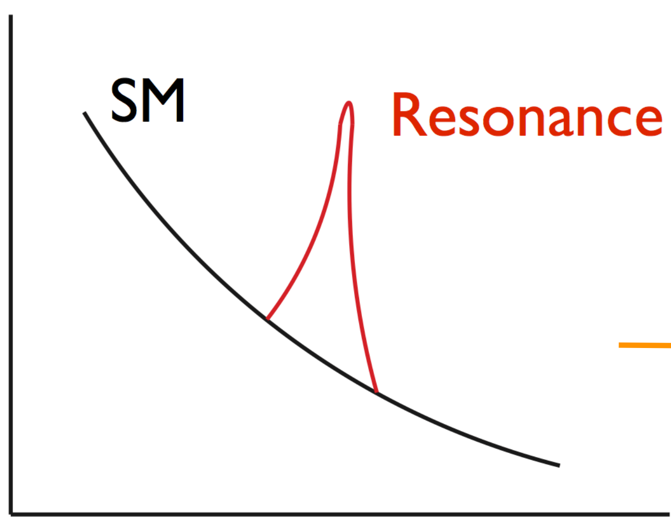


Going beyond the Standard Model

1) the easy way: direct discovery







Energy frontier

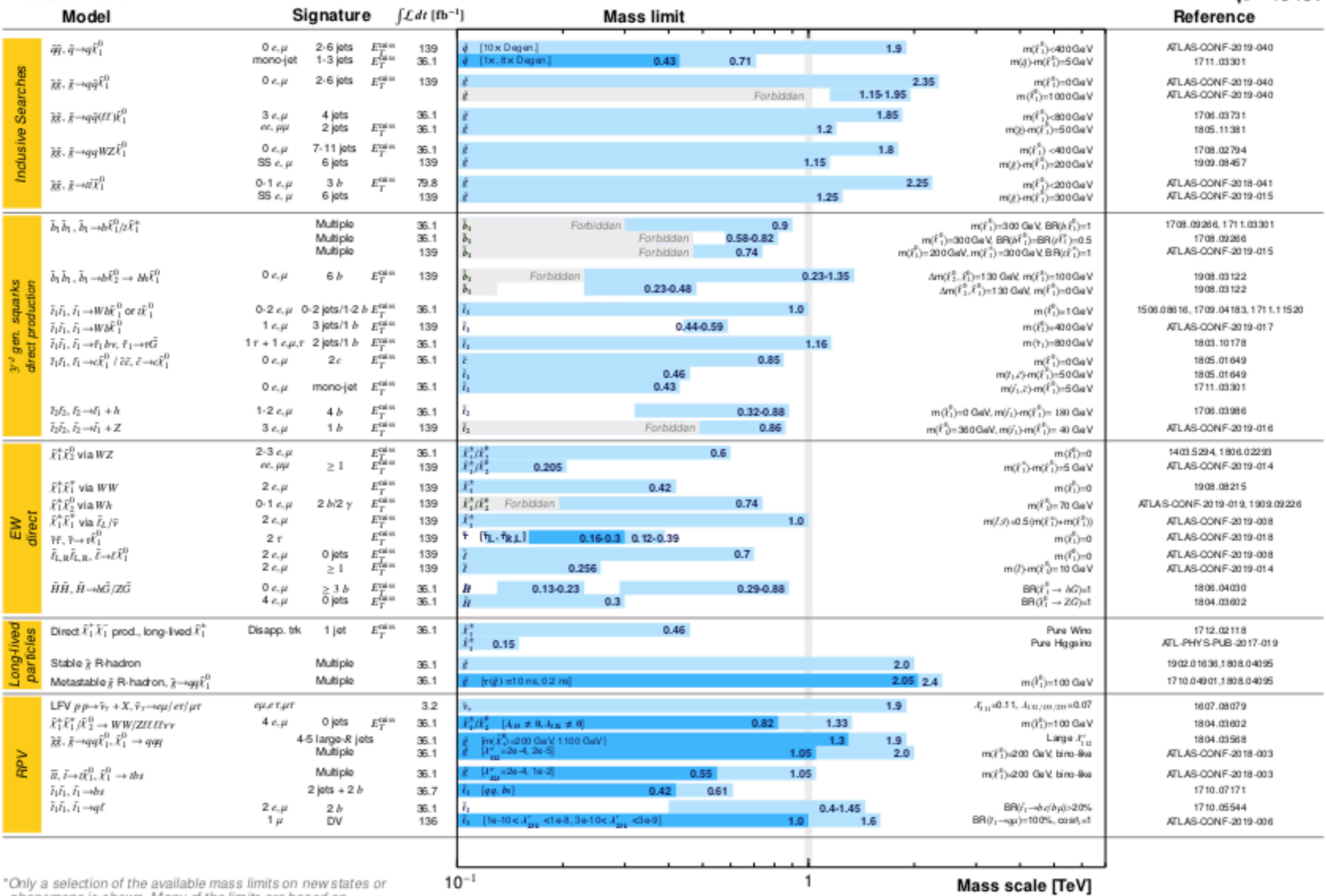
ATLAS SUSY Searches* - 95% CL Lower Limits

October 2019

example: SUSY

ATLAS Preliminary

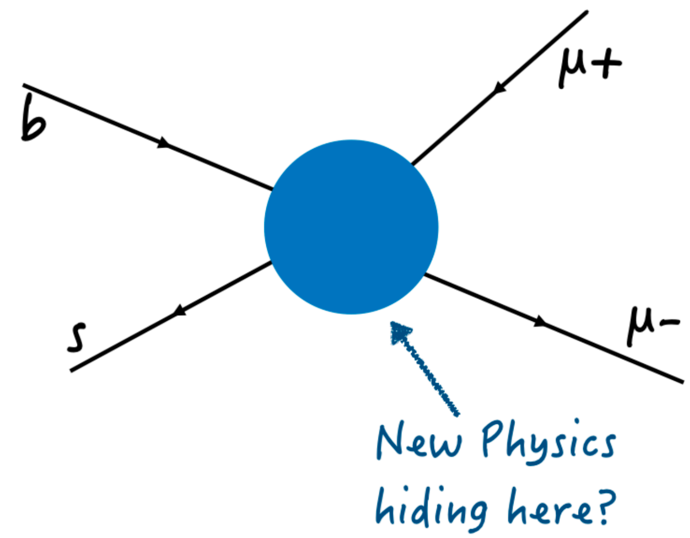
$\sqrt{s}$ = 13 TeV

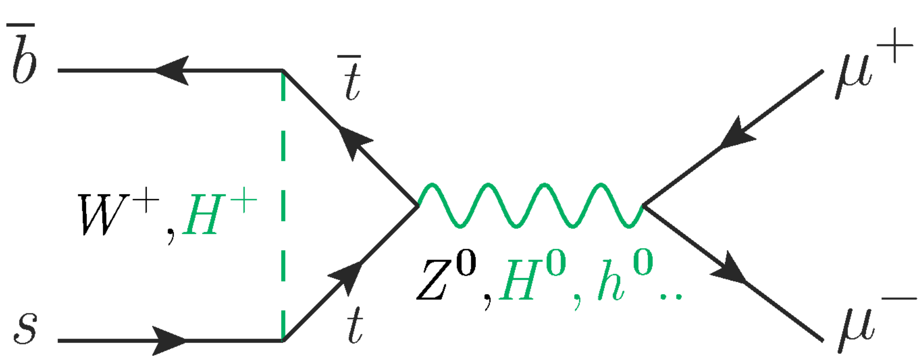


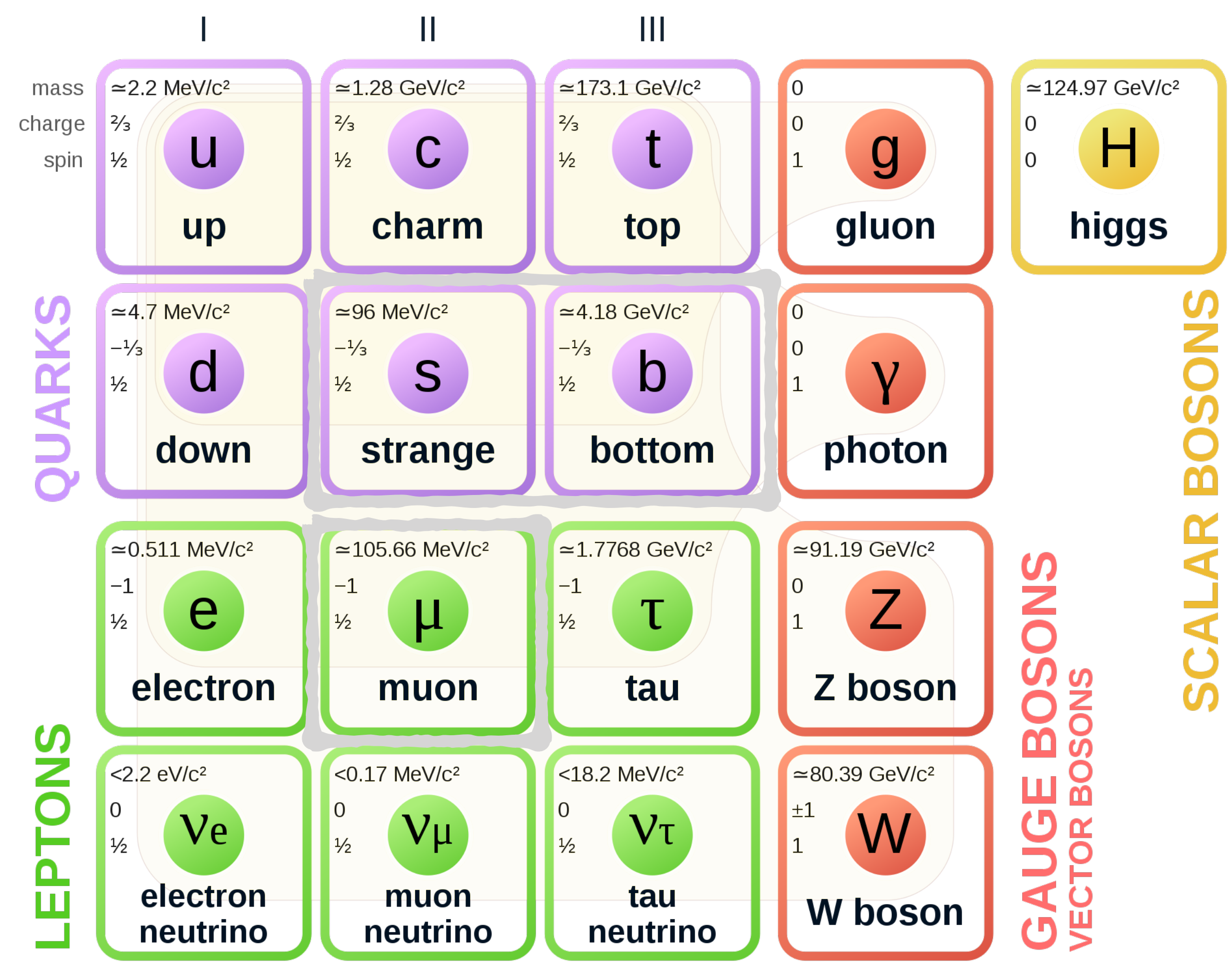
*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

Going beyond the Standard Model

2) the not-so-easy way: *indirect* discovery





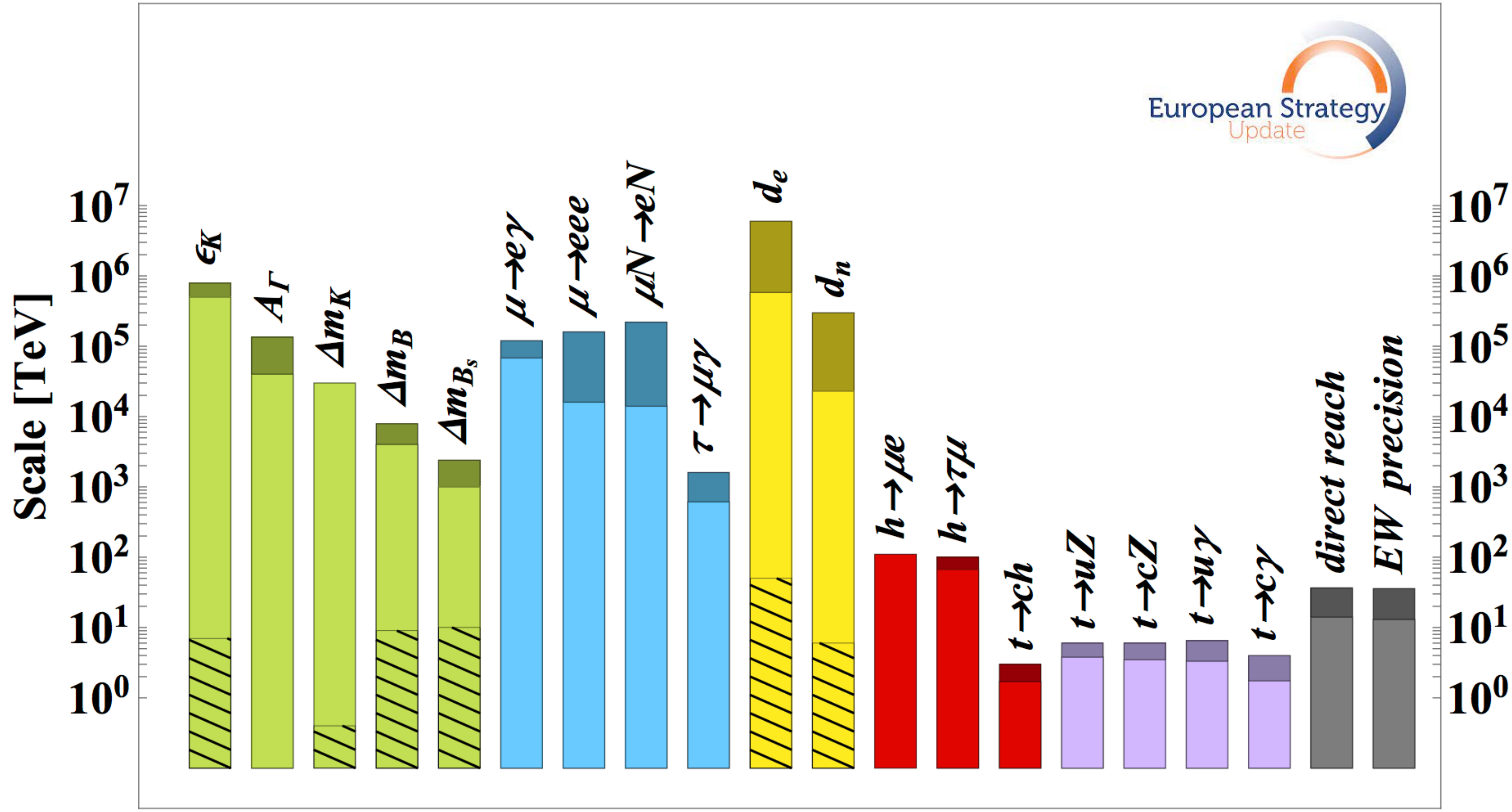


fuelled by Quantum Mechanics

Intensity frontier

Going beyond the Standard Model

Indirect searches: fuelled by Quantum Mechanics



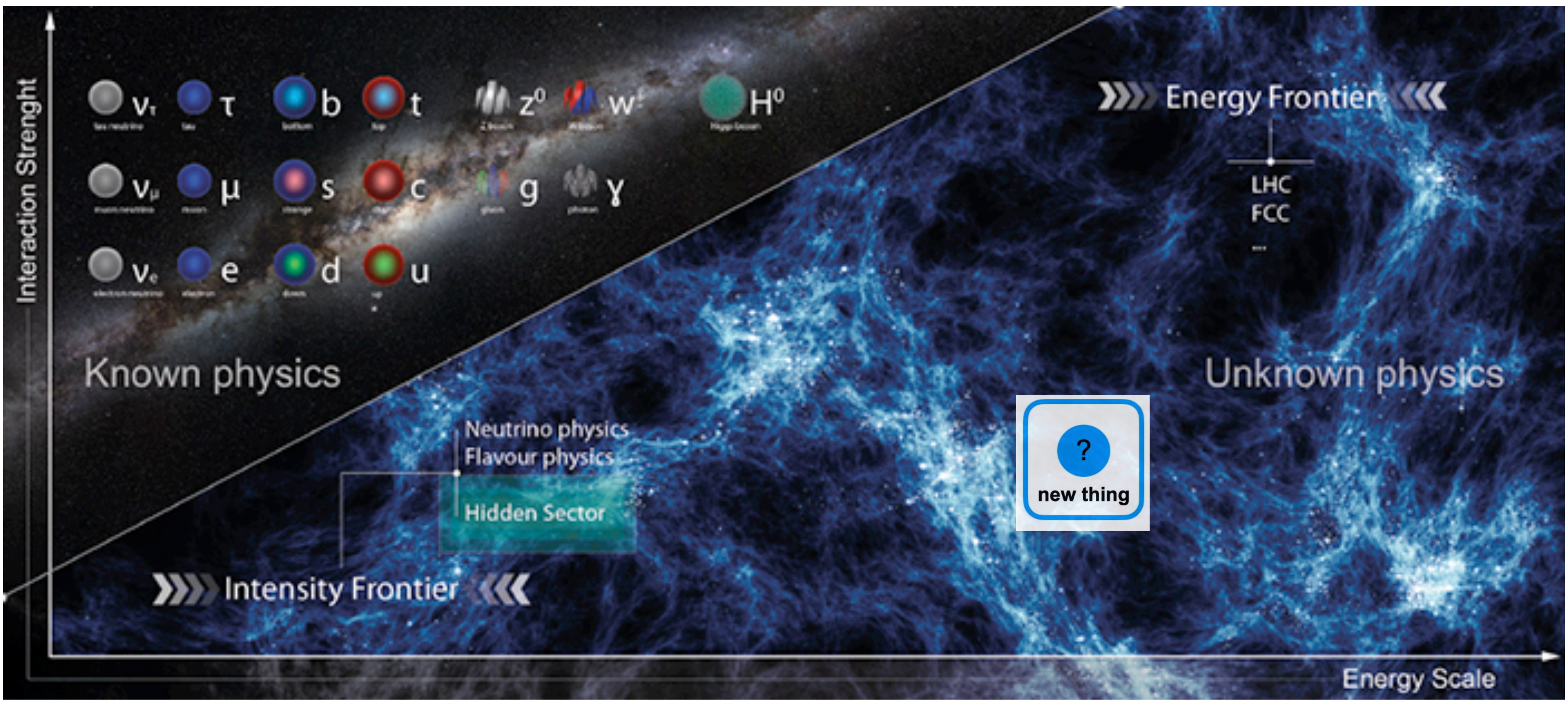
May access to NP scales well beyond collision energy !

Going beyond the Standard Model

LHC — explore both energy and intensity frontiers

energy frontier

intensity frontier



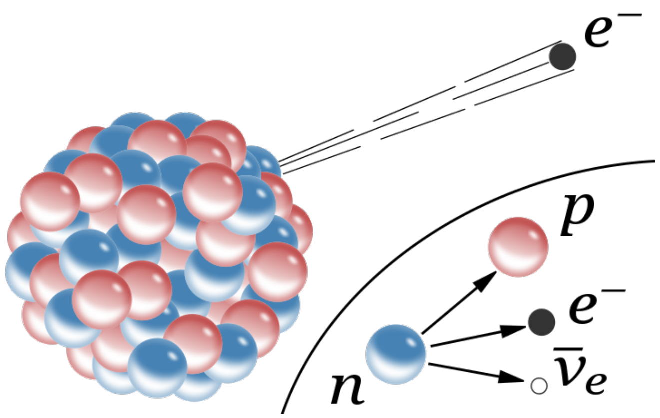
Beam intensity: high luminosity

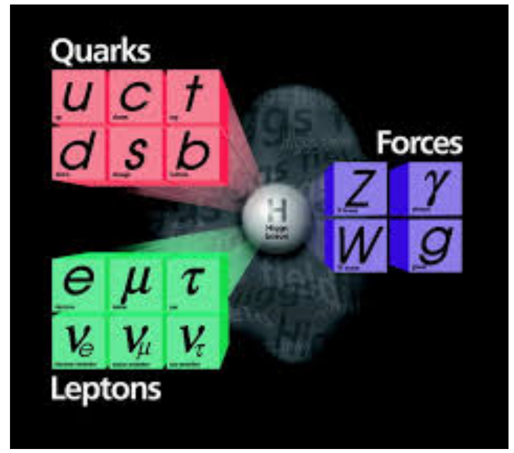
Beam energy: √s

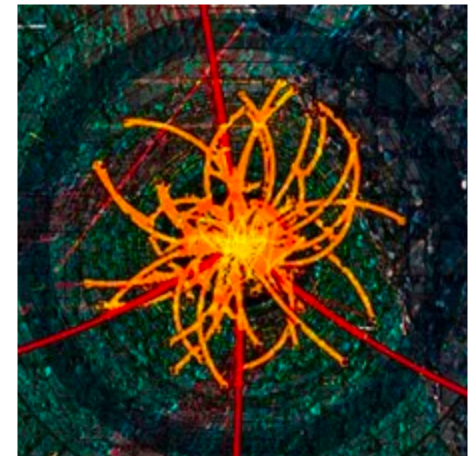
(Nuno's field view)

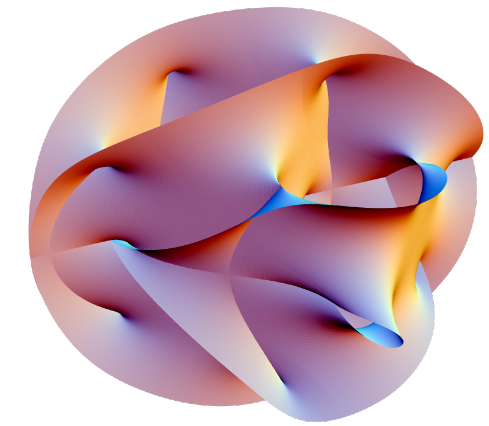
energy scale — $m_{Z,W}$ — m_H — m_t — Λ_{NP}

1930 … 1970 — 2012 — 2020 … future

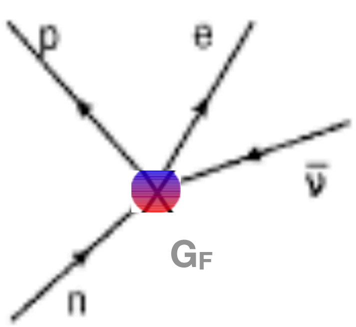


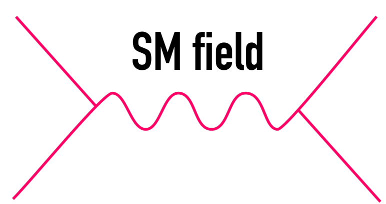


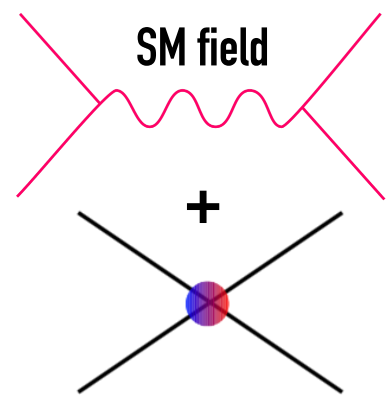


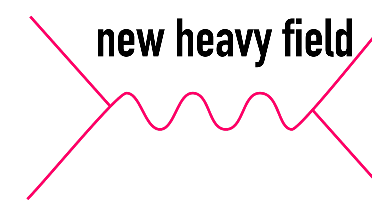


Fermi model	Standard Model	SM-EFT	UV theory









$\mathcal{L}_{\text{Fermi}} = -\frac{G_F}{\sqrt{2}} \bar{p}\gamma_\mu n\, \bar{e}\gamma^\mu \nu + \text{h.c.}$

$\mathcal{L}_{SM} = \mathcal{L}_{gauge} + \mathcal{L}_{higgs}$

$\mathcal{L}_{SM\text{-}EFT} = \mathcal{L}_{SM} + \Sigma_i C_i O_i$

$\mathcal{L}$

a predecessor of EWK theory

simple and elegant theory describing *almost* all microscopic phenomena

we're here!

a more fundamental theory with new degrees of freedom