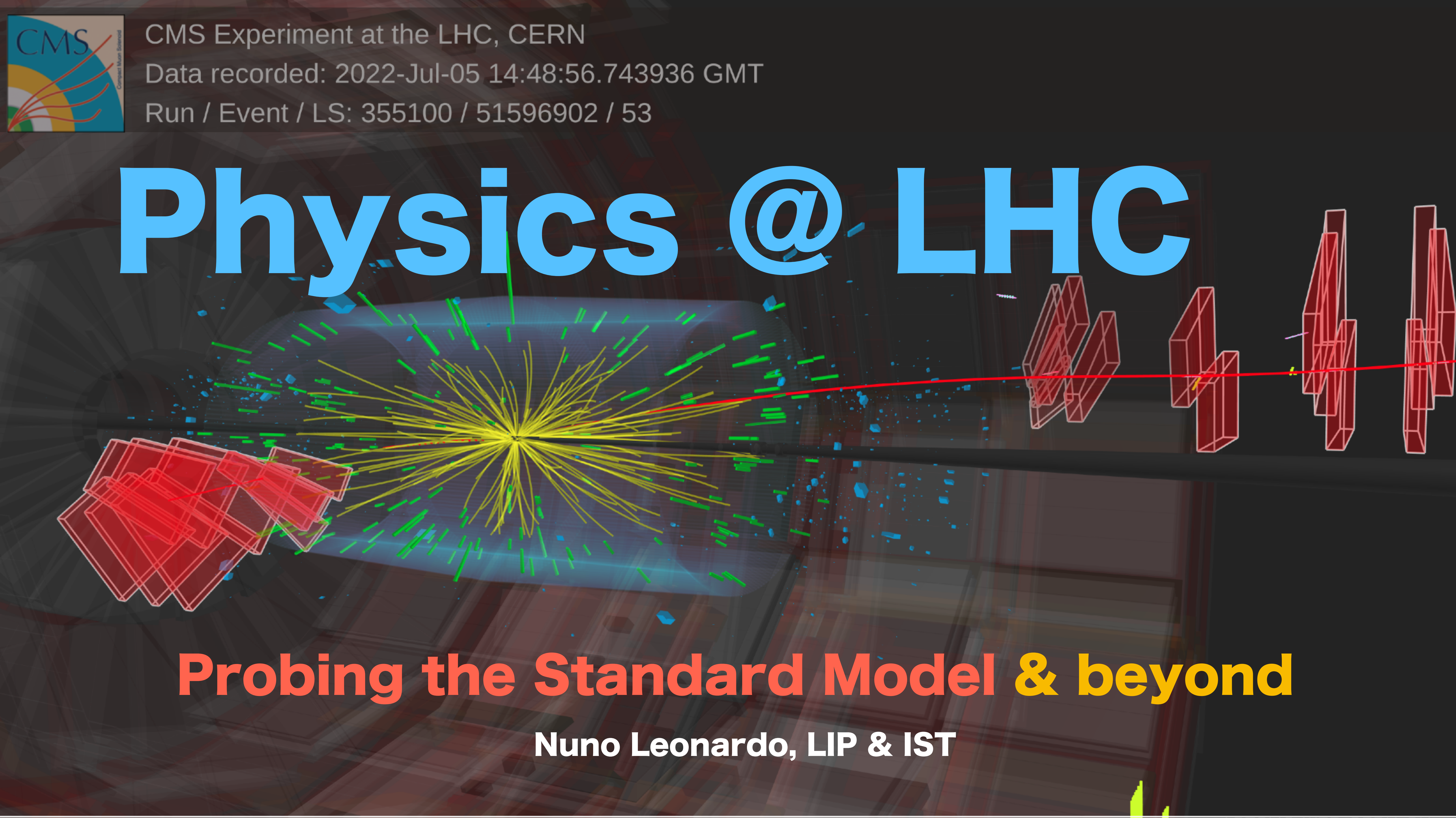


Physics @ LHC

Probing the Standard Model & beyond

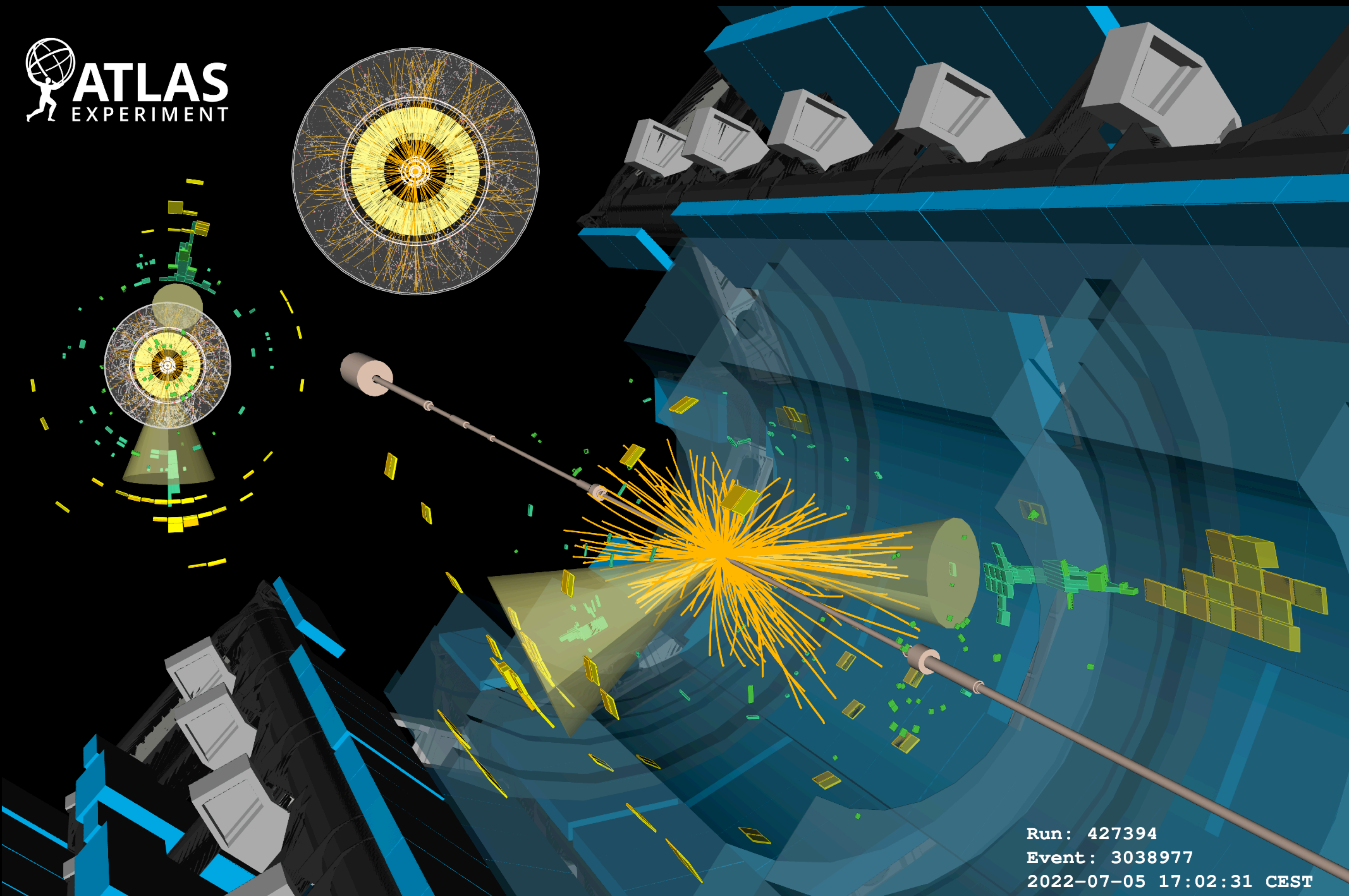
Nuno Leonardo, LIP & IST

9th mini-school
on Particle and Astroparticle Physics

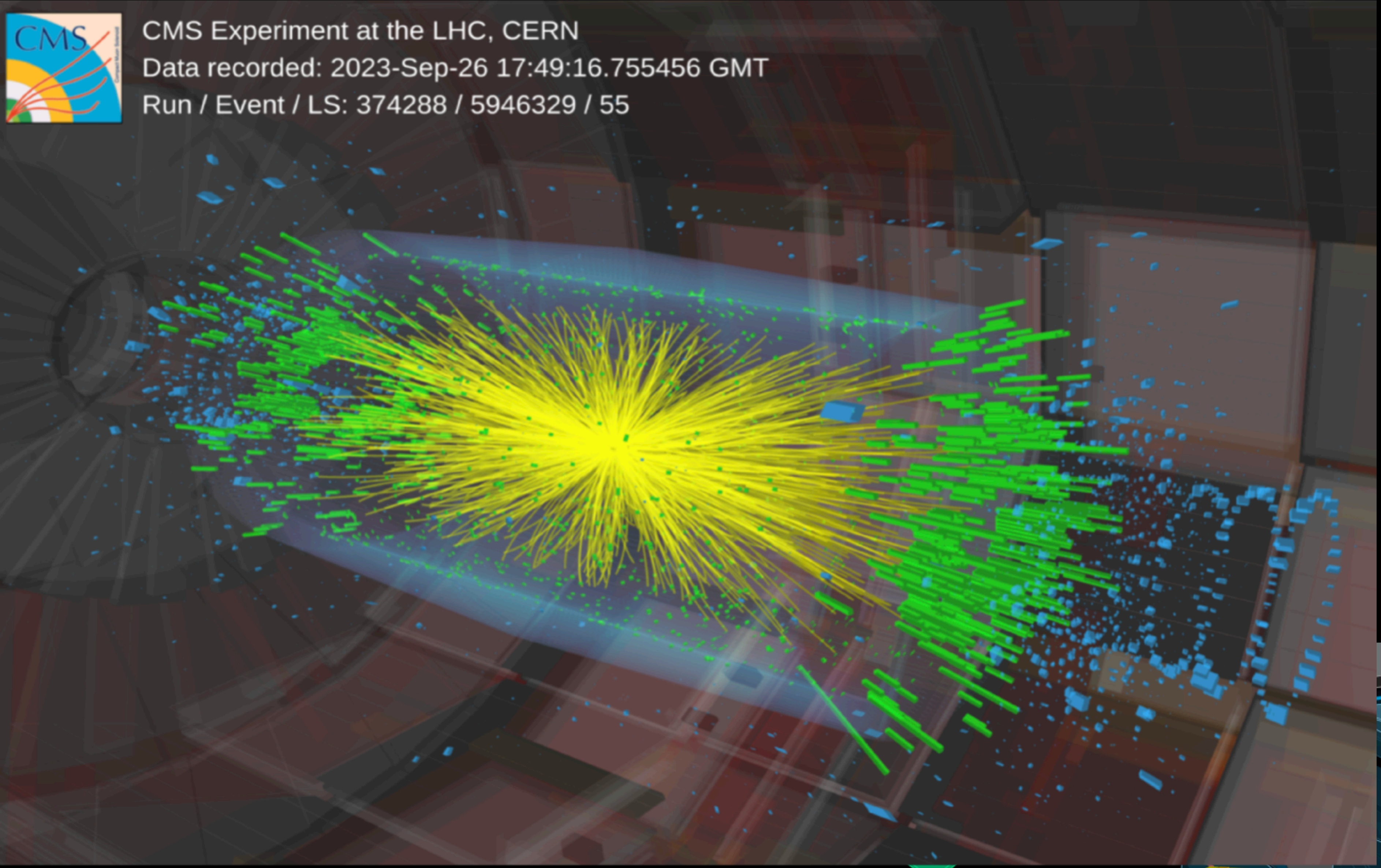
Oeiras 5 - 6 . FEB . 2024

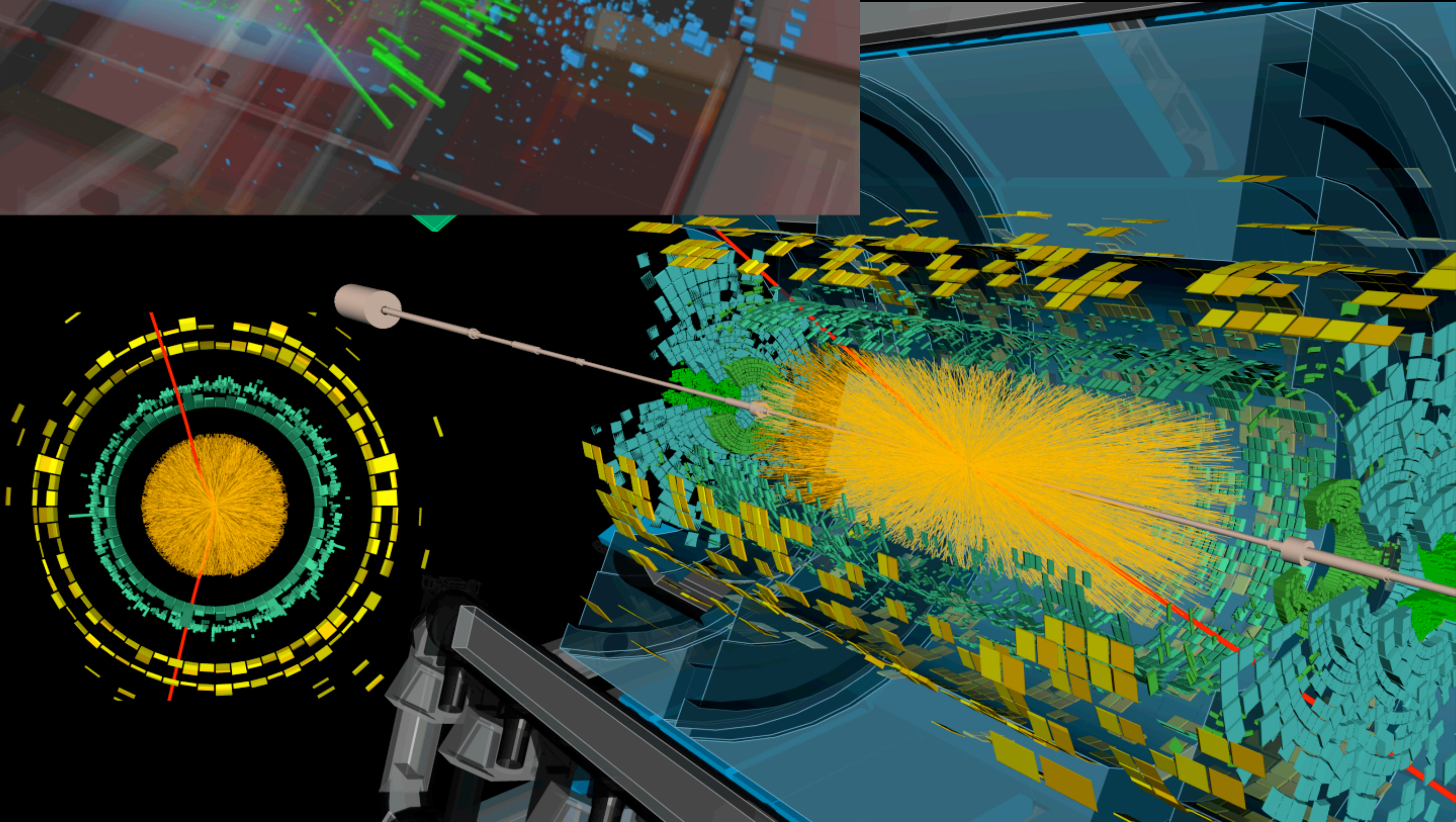
nuno@cern.ch

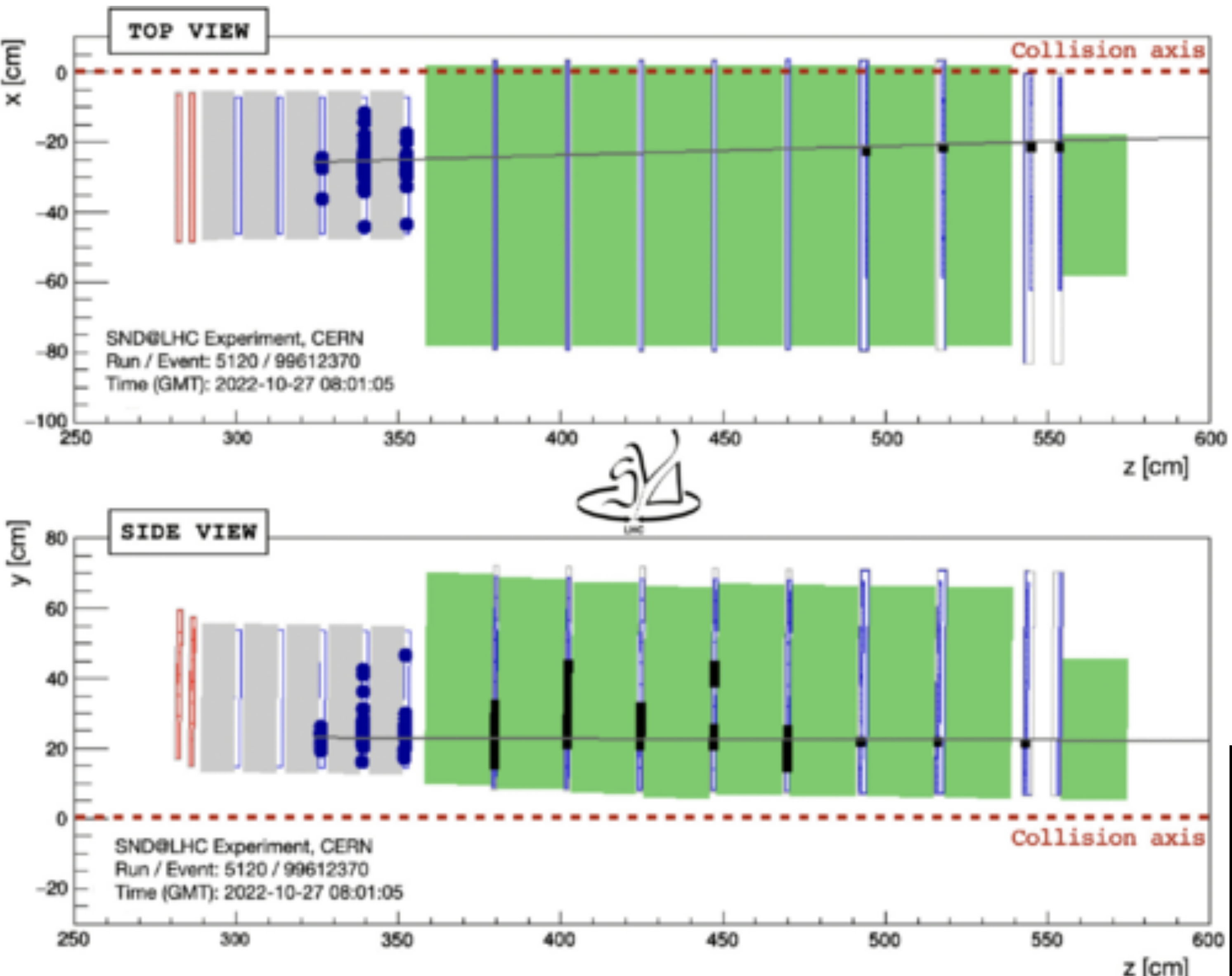
proton collisions @13.6 TeV (Run3)



heavy-ion collisions (2023)

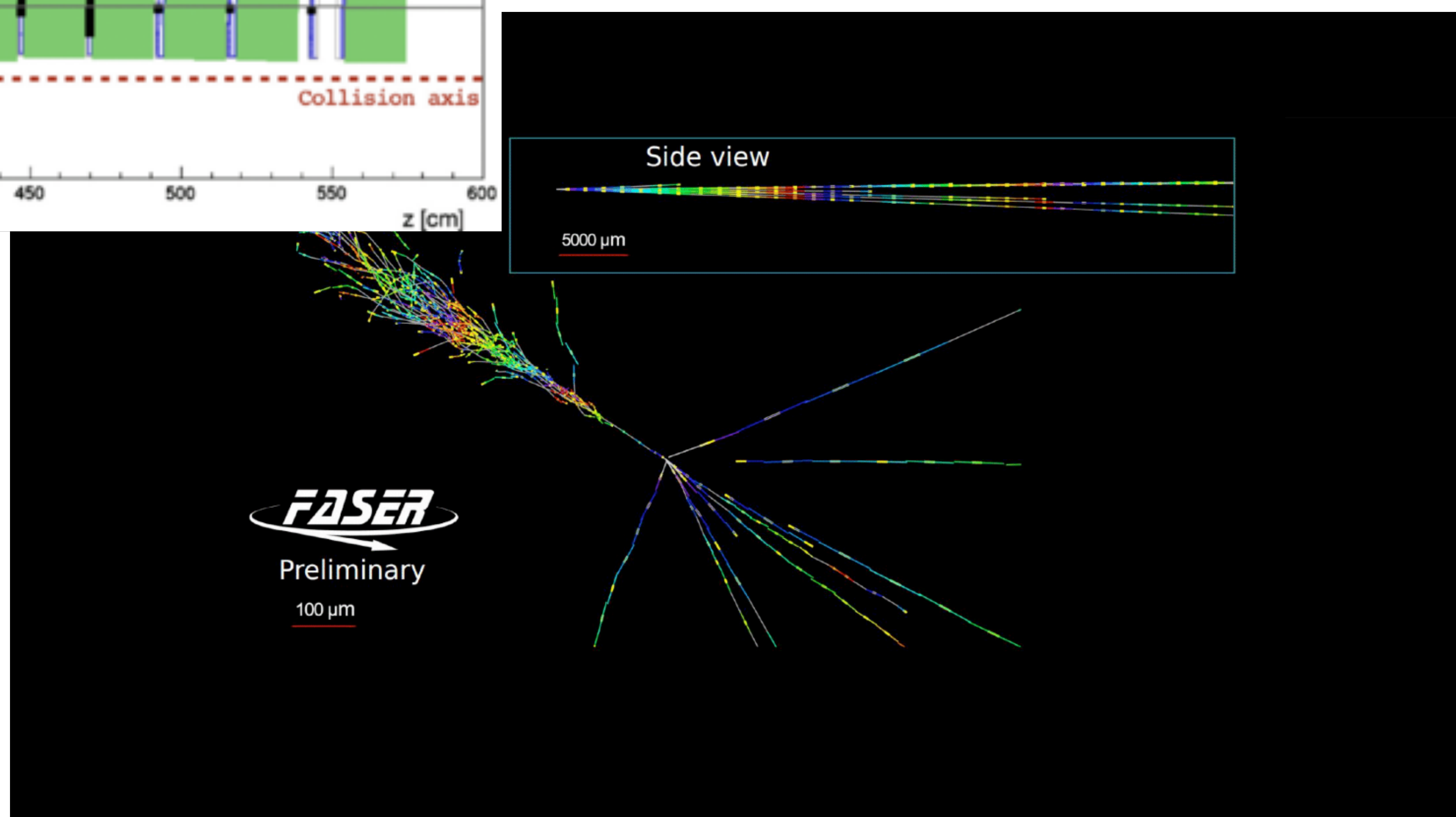






neutrinos

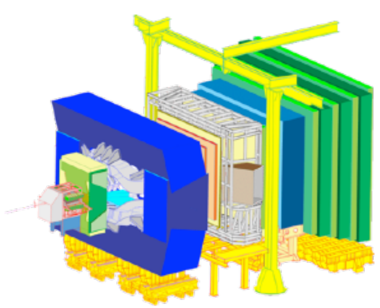
first seen @LHC in 2023



direct detection at the LHC of neutrino interactions required novel dedicated detectors, installed in Run3

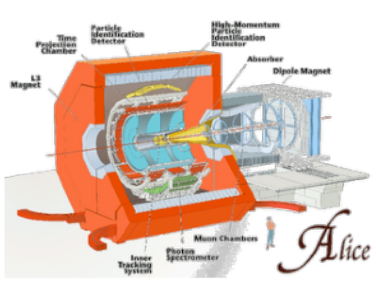
LHC = accelerator + detectors + physics

LHCb

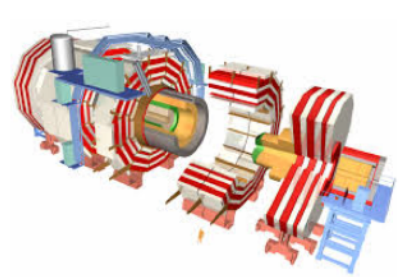


ATLAS

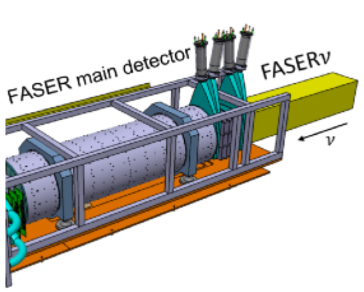
ALICE



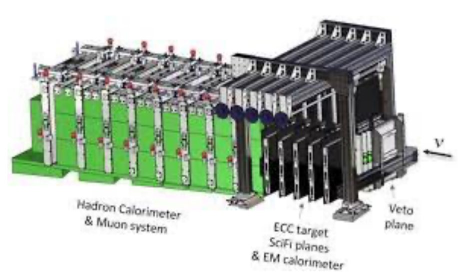
CMS



FASERν



SND@LHC



LHC: the only apparatus capable of creating and detecting *every* standard model particle

mass / charge / spin	≃2.2 MeV/c^2 ⅔ ½ u **up**	≃1.28 GeV/c^2 ⅔ ½ c **charm**	≃173.1 GeV/c^2 ⅔ ½ t **top**	0 0 1 g **gluon**	≃124.97 GeV/c^2 0 0 H **higgs**
QUARKS	≃4.7 MeV/c^2 −⅓ ½ d **down**	≃96 MeV/c^2 −⅓ ½ s **strange**	≃4.18 GeV/c^2 −⅓ ½ b **bottom**	0 0 1 γ **photon**	SCALAR BOSONS
	≃0.511 MeV/c^2 −1 ½ e **electron**	≃105.66 MeV/c^2 −1 ½ μ **muon**	≃1.7768 GeV/c^2 −1 ½ τ **tau**	≃91.19 GeV/c^2 0 1 Z **Z boson**	
LEPTONS	<2.2 eV/c^2 0 ½ ν_e **electron neutrino**	<0.17 MeV/c^2 0 ½ ν_μ **muon neutrino**	<18.2 MeV/c^2 0 ½ ν_τ **tau neutrino**	≃80.39 GeV/c^2 ±1 1 W **W boson**	GAUGE BOSONS VECTOR BOSONS

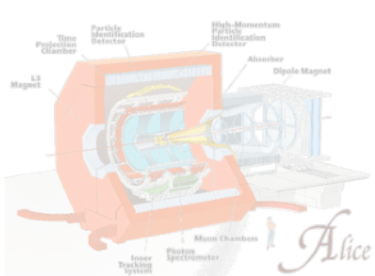
+ *antiparticles*

LHC = accelerator + **detectors** + **physics**

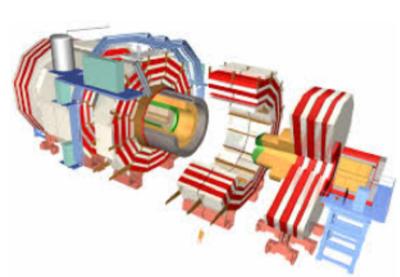
LHCb

ATLAS

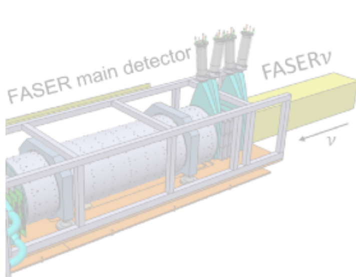
ALICE



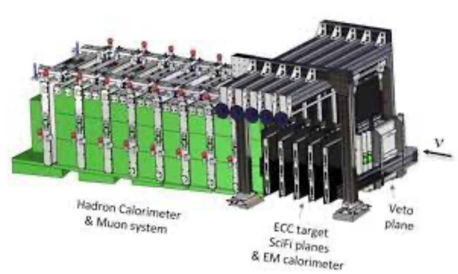
CMS



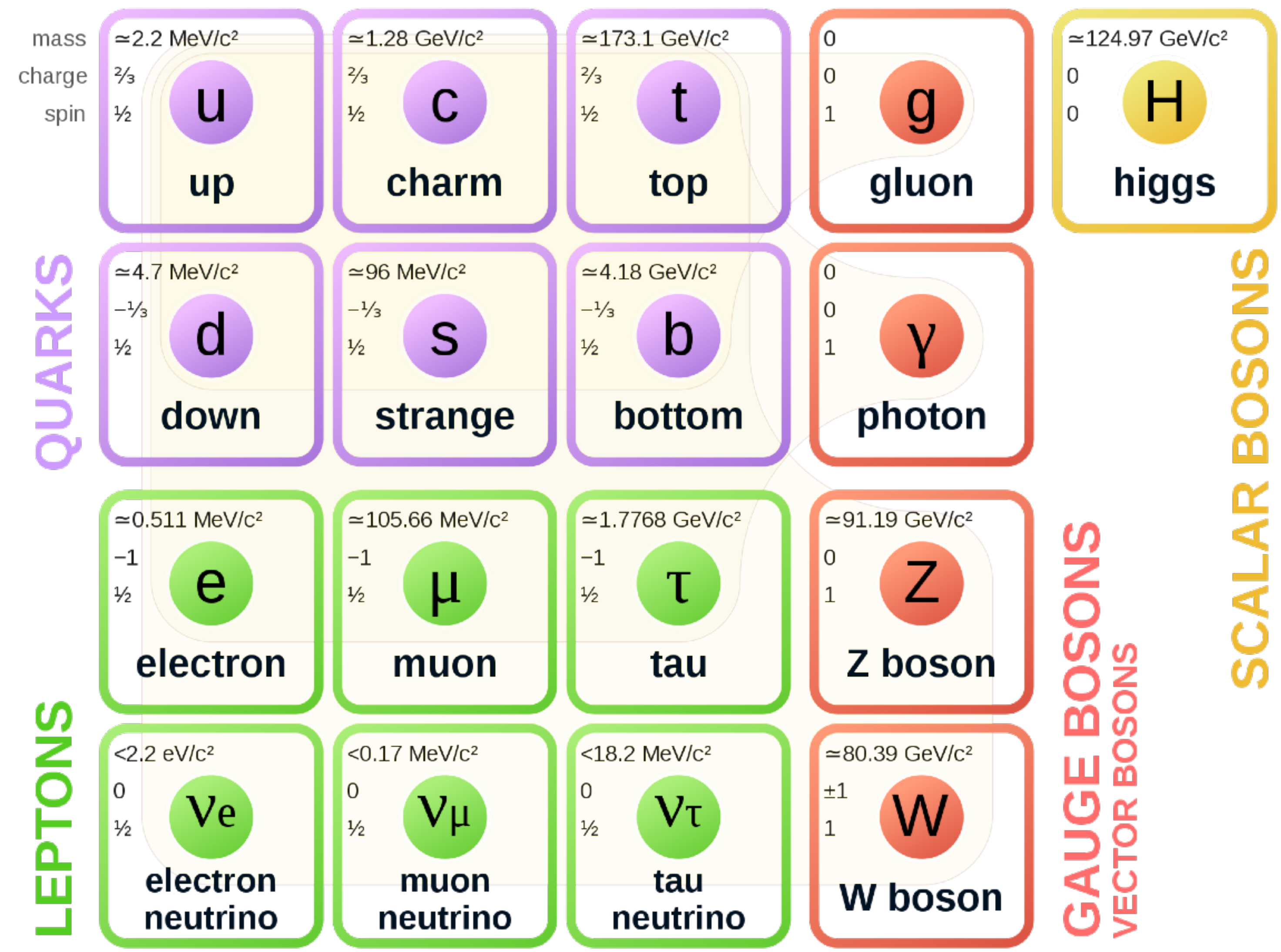
FASERν



SND@LHC



LHC: the only apparatus capable of creating and detecting *every* standard model particle



\+ antiparticles

(with LIP Portuguese participation, LIP & IST)

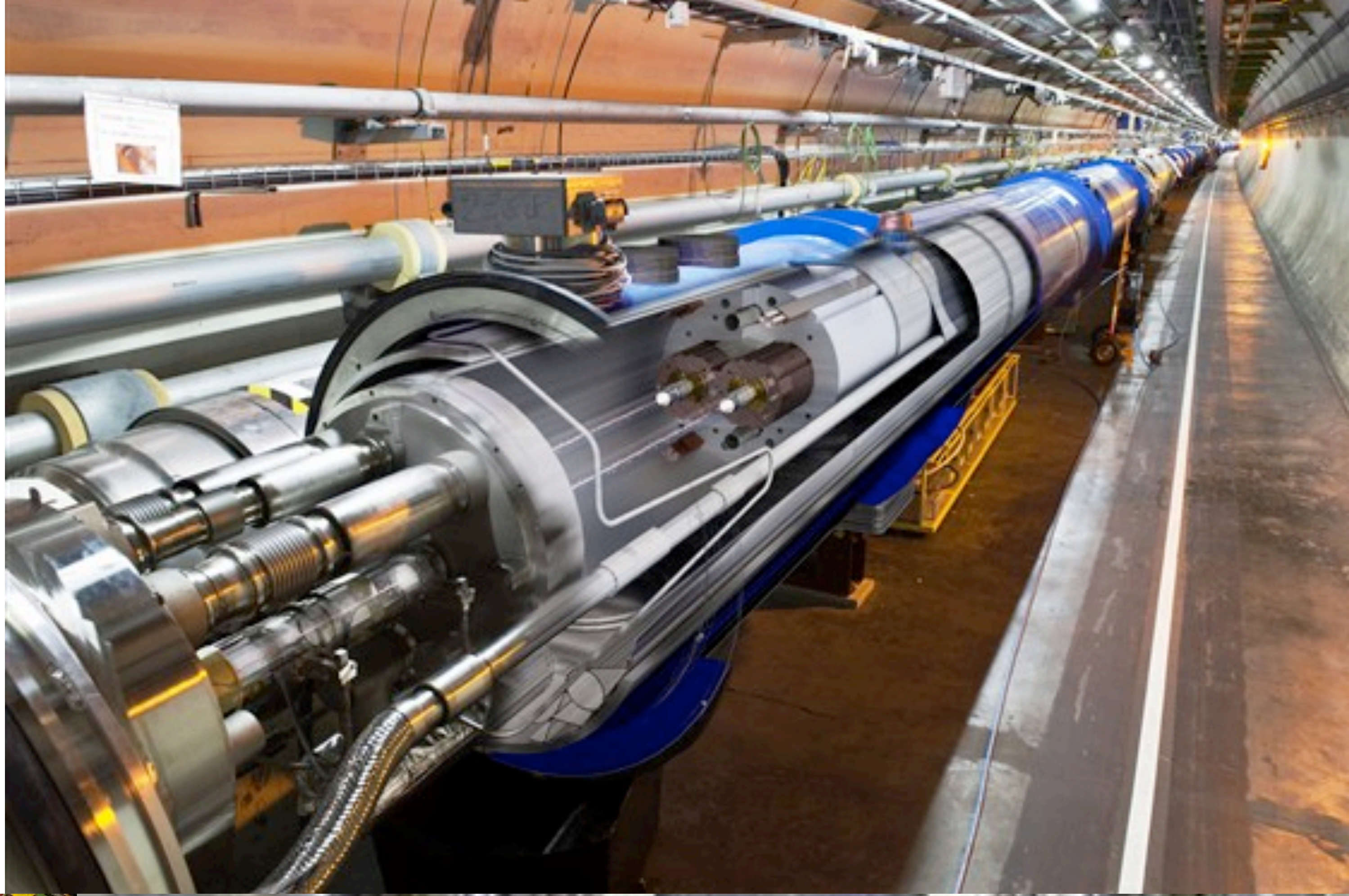
The accelerator

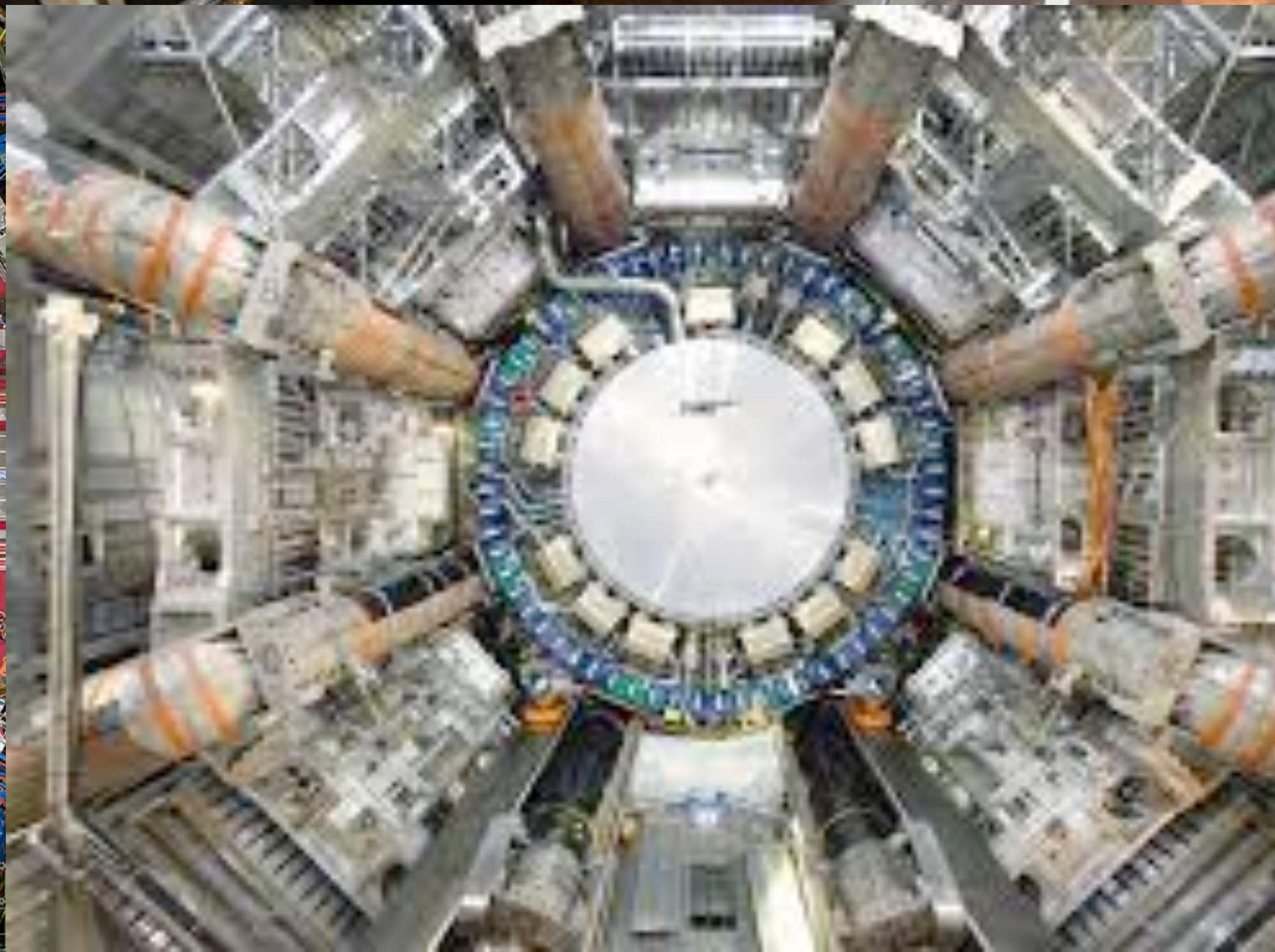
The LHC is the **world-leading** particle accelerator & collider

Delivering **unprecedented** energies and intensities

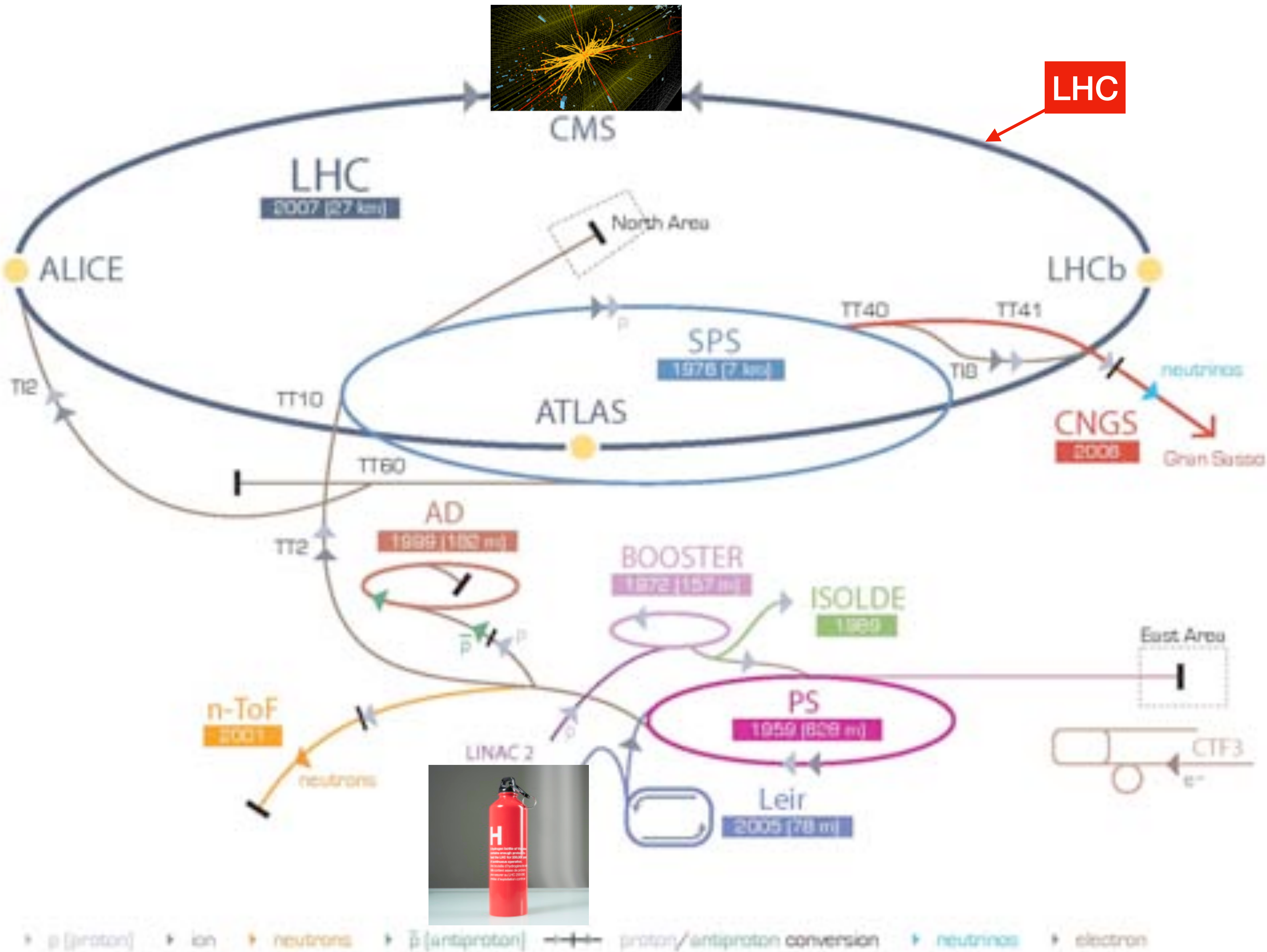
The LHC detectors are the most **sophisticated** scientific tools yet

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





the CERN accelerator complex

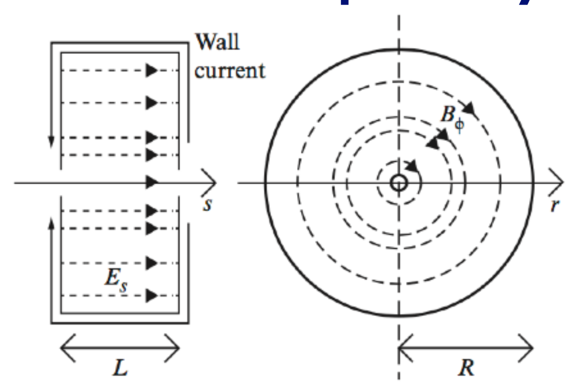


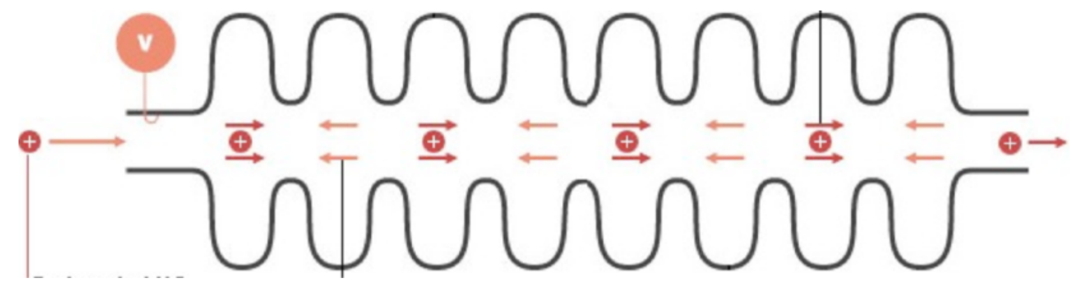
Acceleration & beam optics

- only charged particles can be accelerated: p, $\bar{p}$, $e^\pm$, ($\mu^\pm$), 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

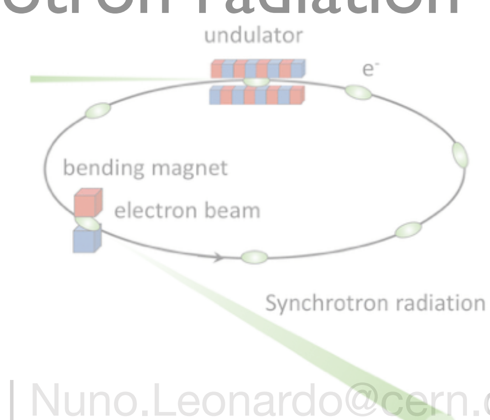
$$\mathbf{F} = q(\mathcal{E} + \mathbf{v} \times \mathbf{B})$$

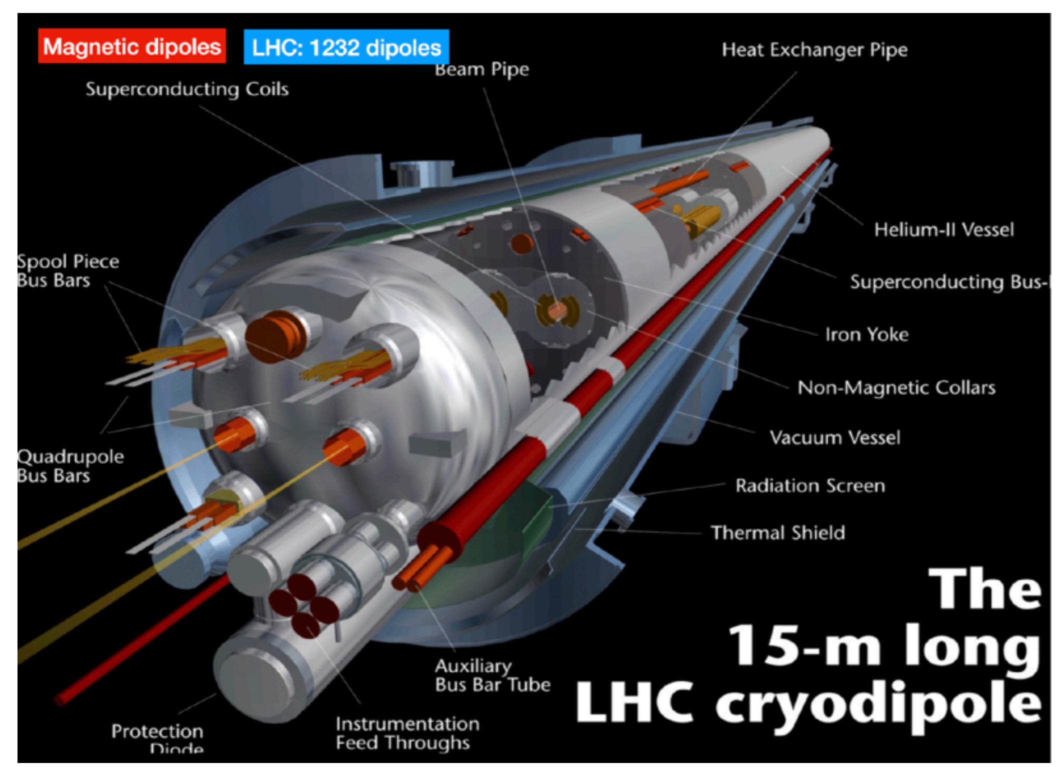
$$\mathbf{E} = -\nabla\varphi - \frac{\partial \mathbf{A}}{\partial t}$$

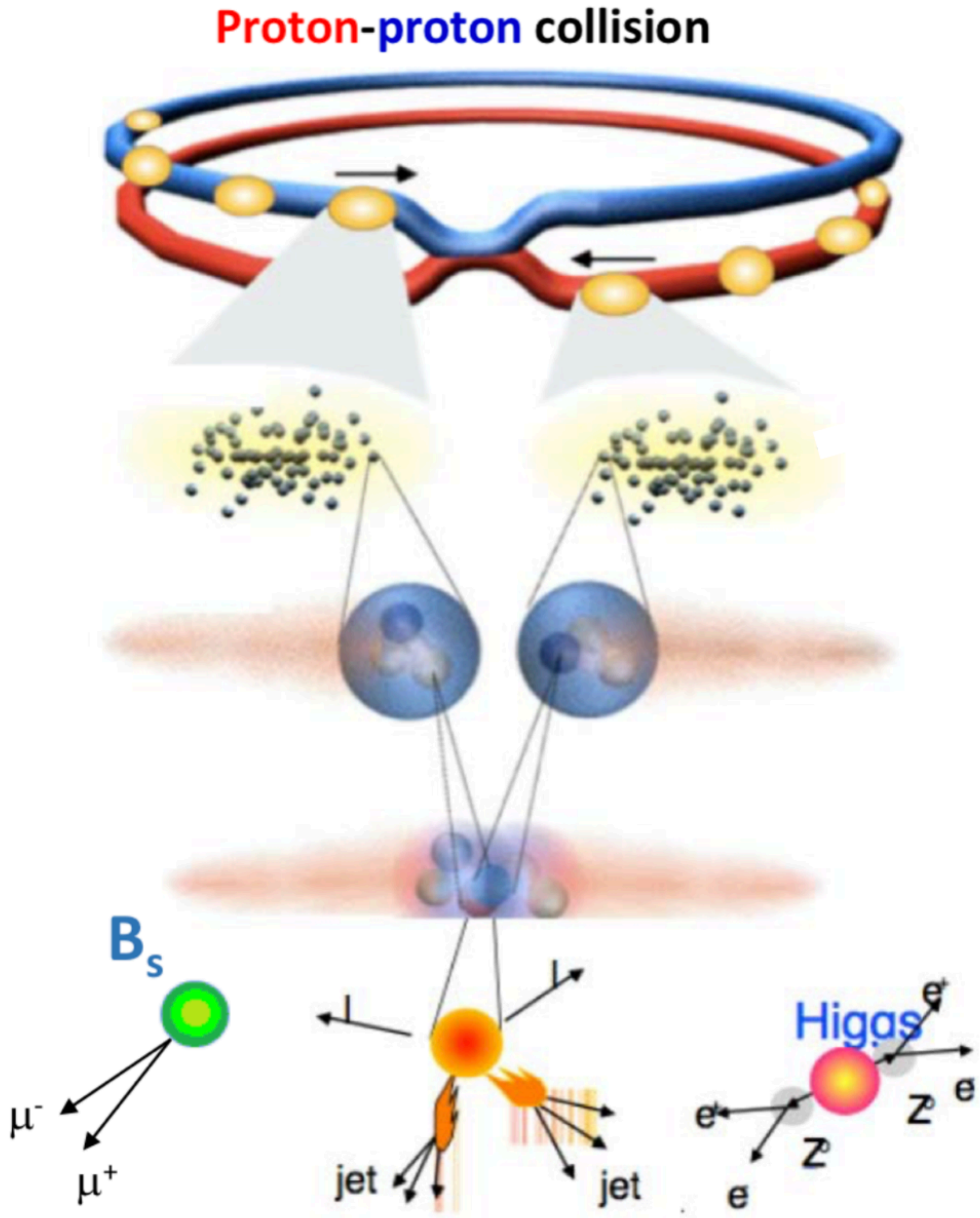




- trajectory bending via dipoles
- beam focusing via quadrupoles
- accelerating particles radiate
  - synchrotron radiation







Some specs:

Beam structure

circumference: 27 km
bunches: 3564 + 3564
protons / bunch: 10^{11}

Bunch Crossing $4\ 10^7$ Hz

Proton Collisions 10^9 Hz

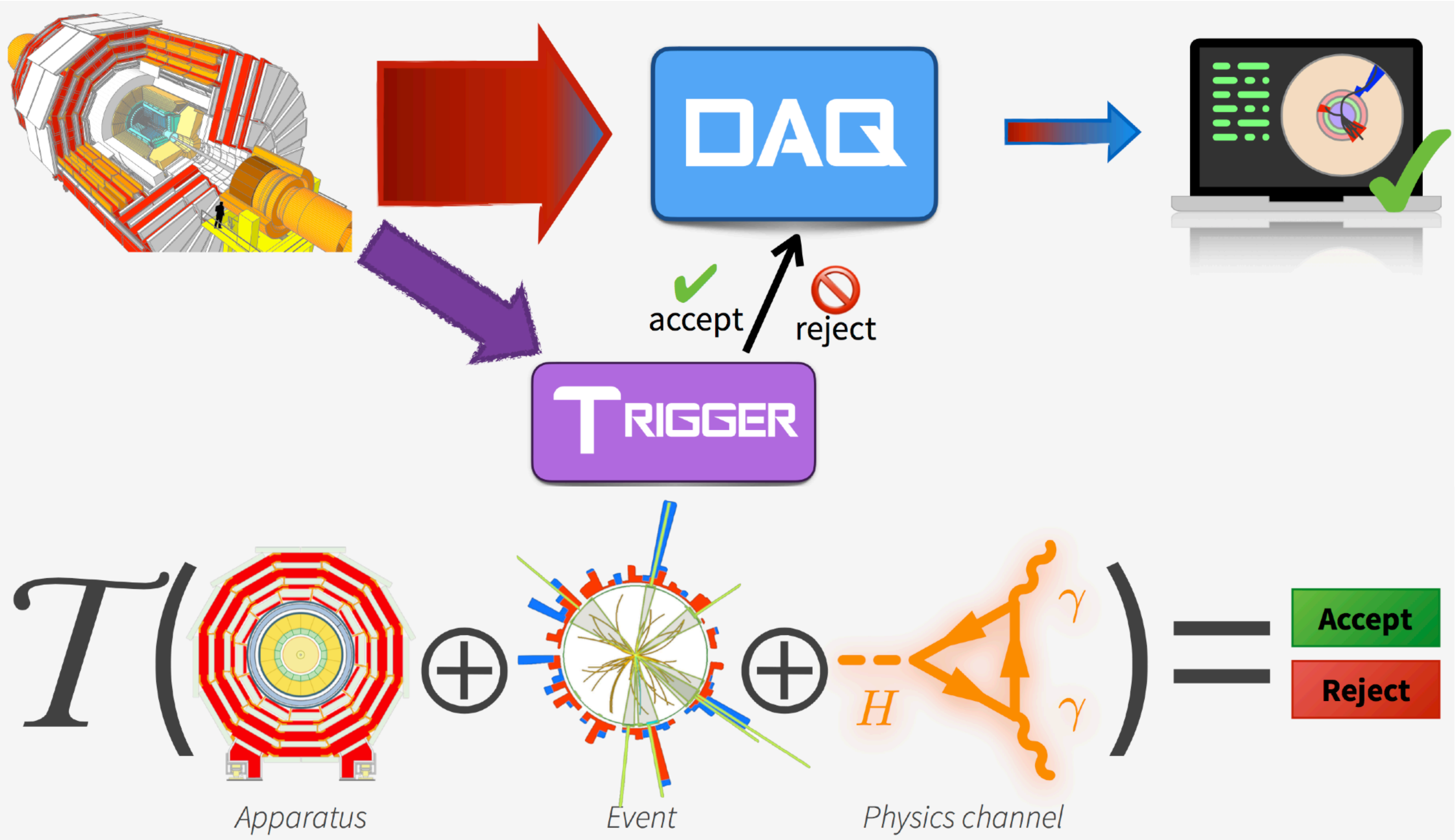
Parton Collisions

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

We're interested in **rare** events

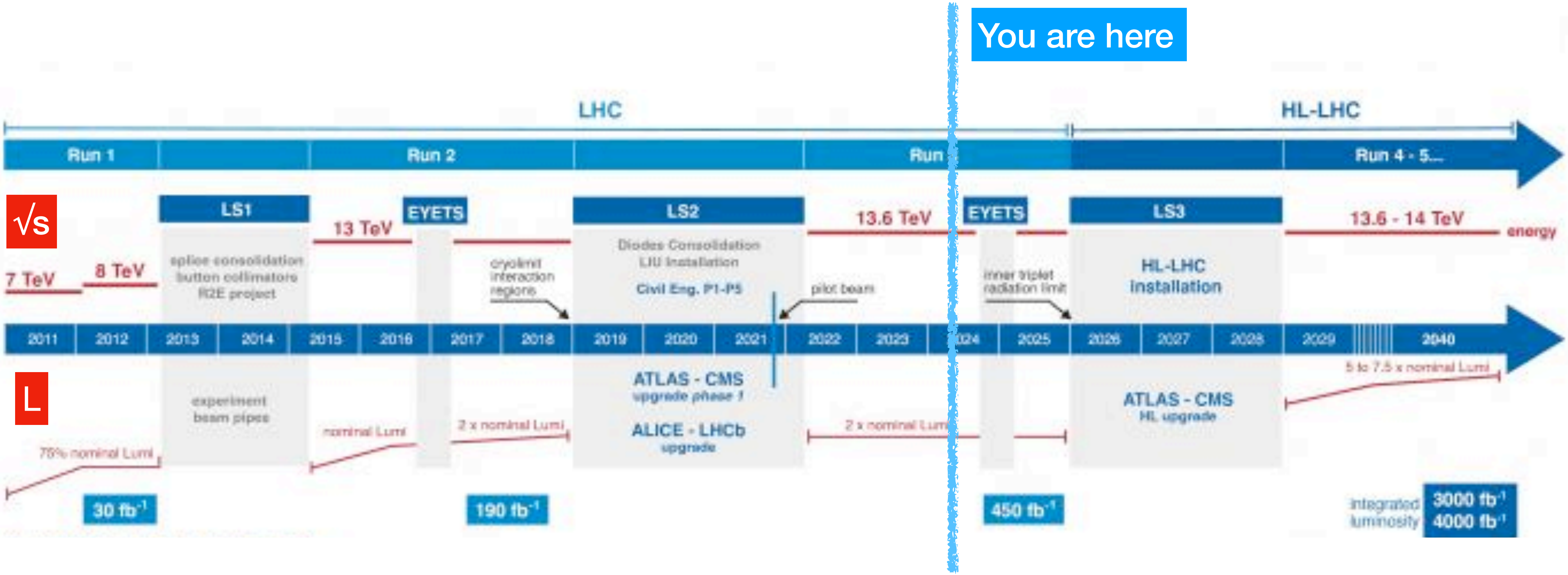
➥ Real-time filtering: **Trigger**



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

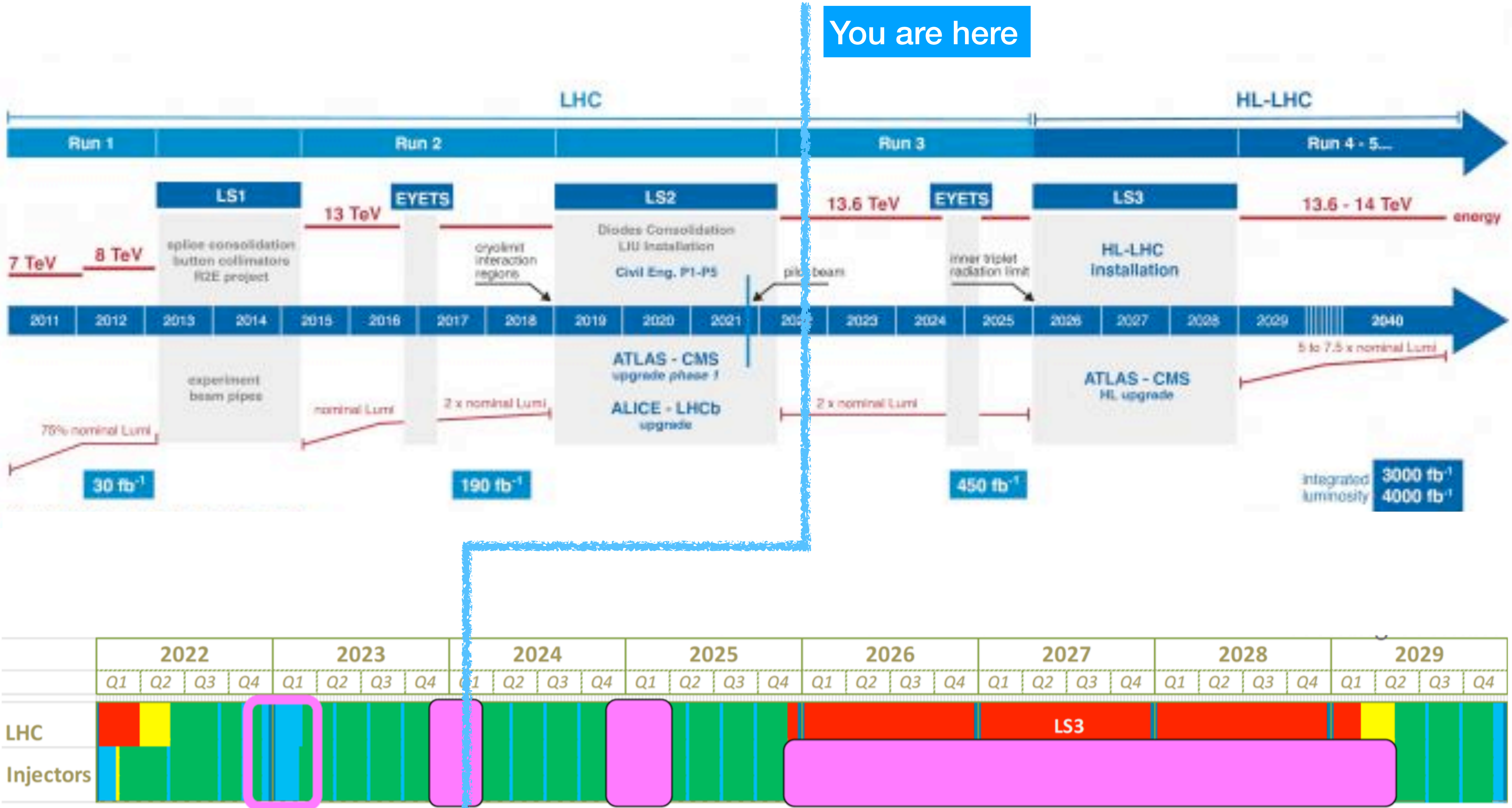
"The trigger does not determine which model is right, only which data is left."

LHC schedule



- The LHC has been operating for almost 15 years, 15more to go
- Two main parameters determine the physics reach
  - Collision **energy** (√s) — in Run3 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

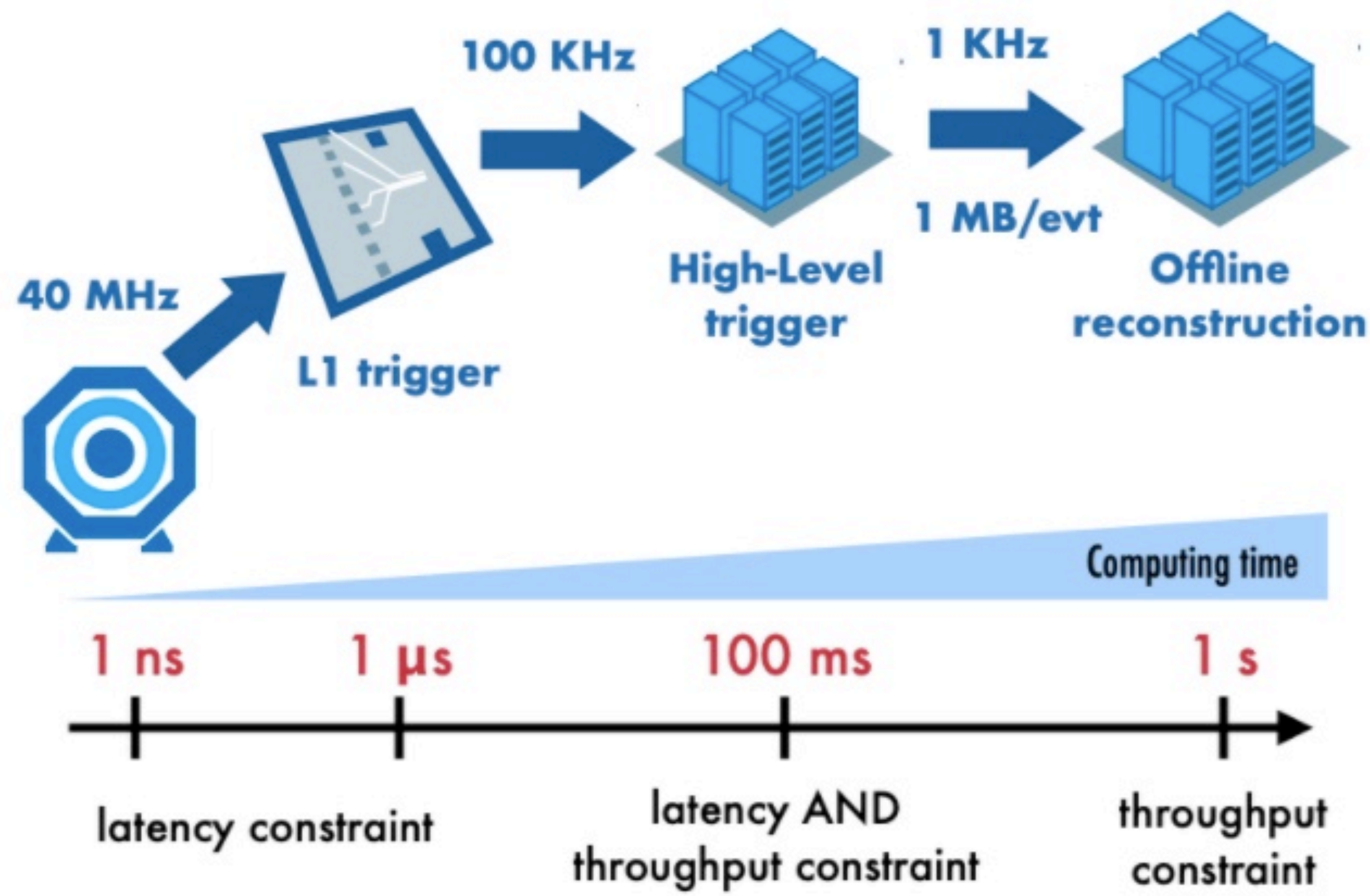


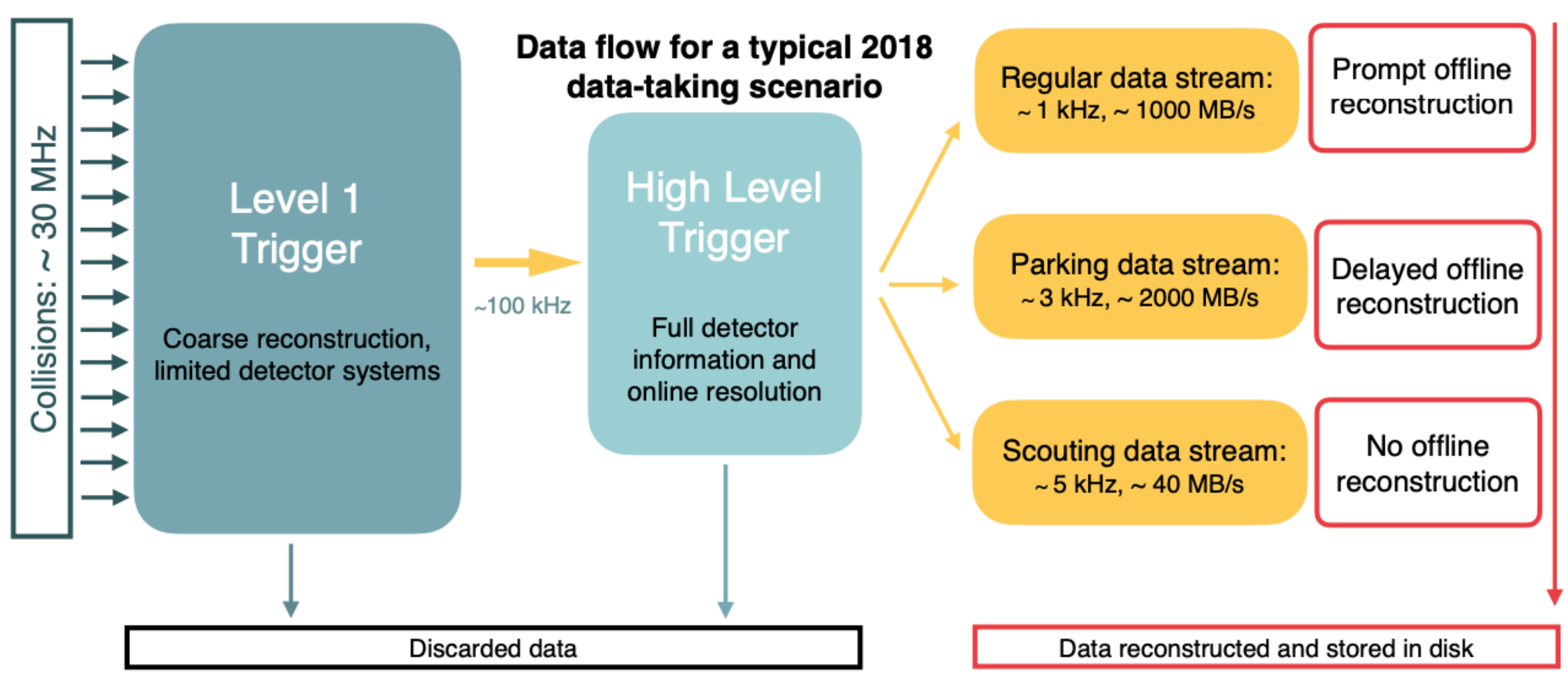
Run 3 : 2022 — 2025

A *new* LHC: HL-LHC, 2026 — 2040

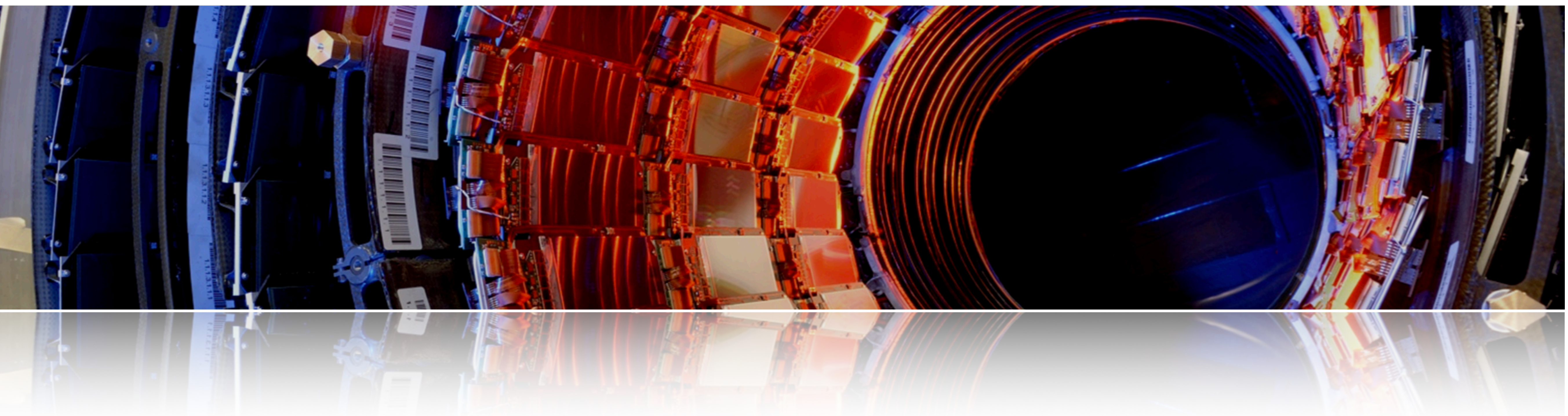
Alternative data-taking paradigms

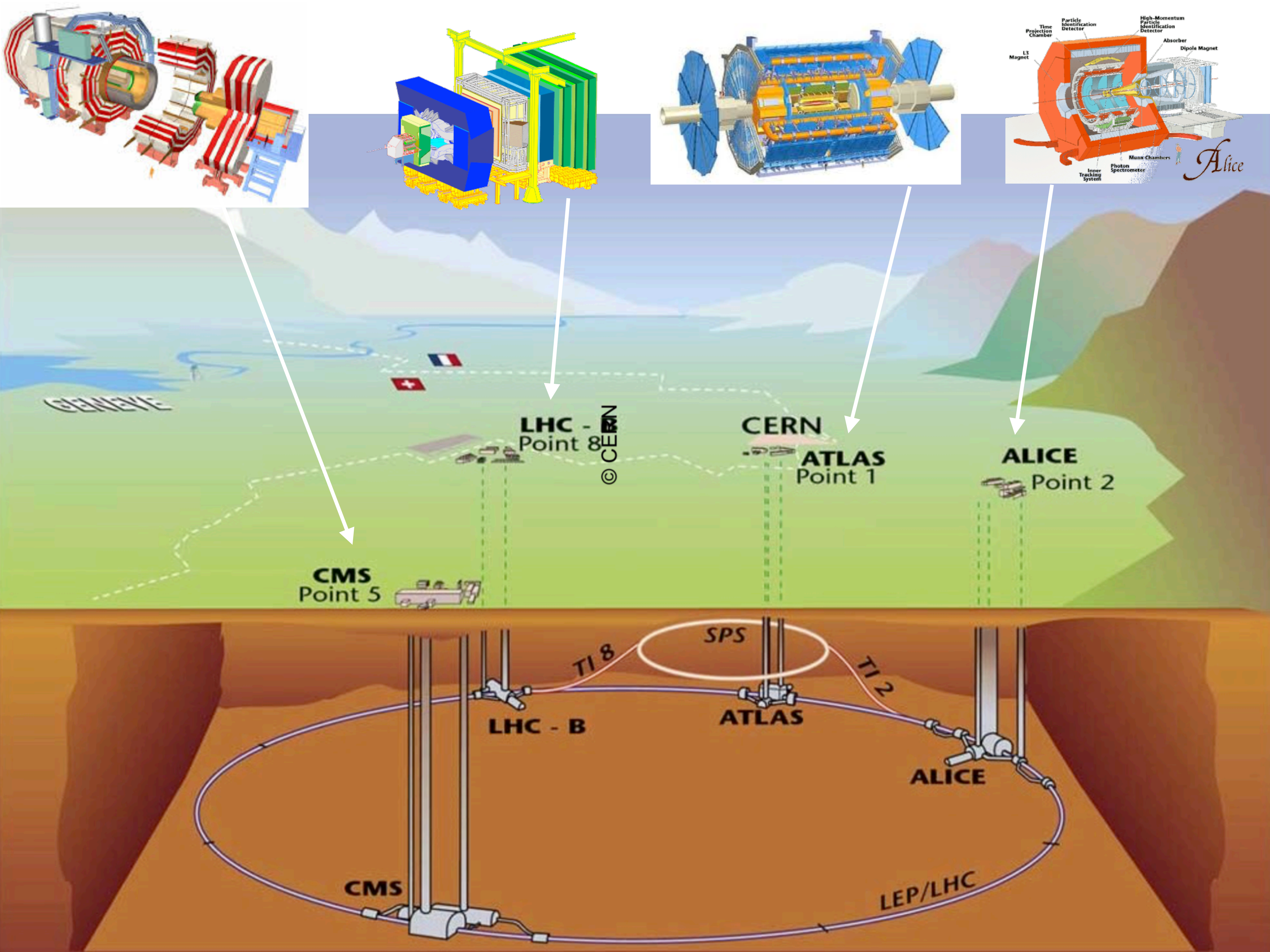
Run3 & HL-LHC





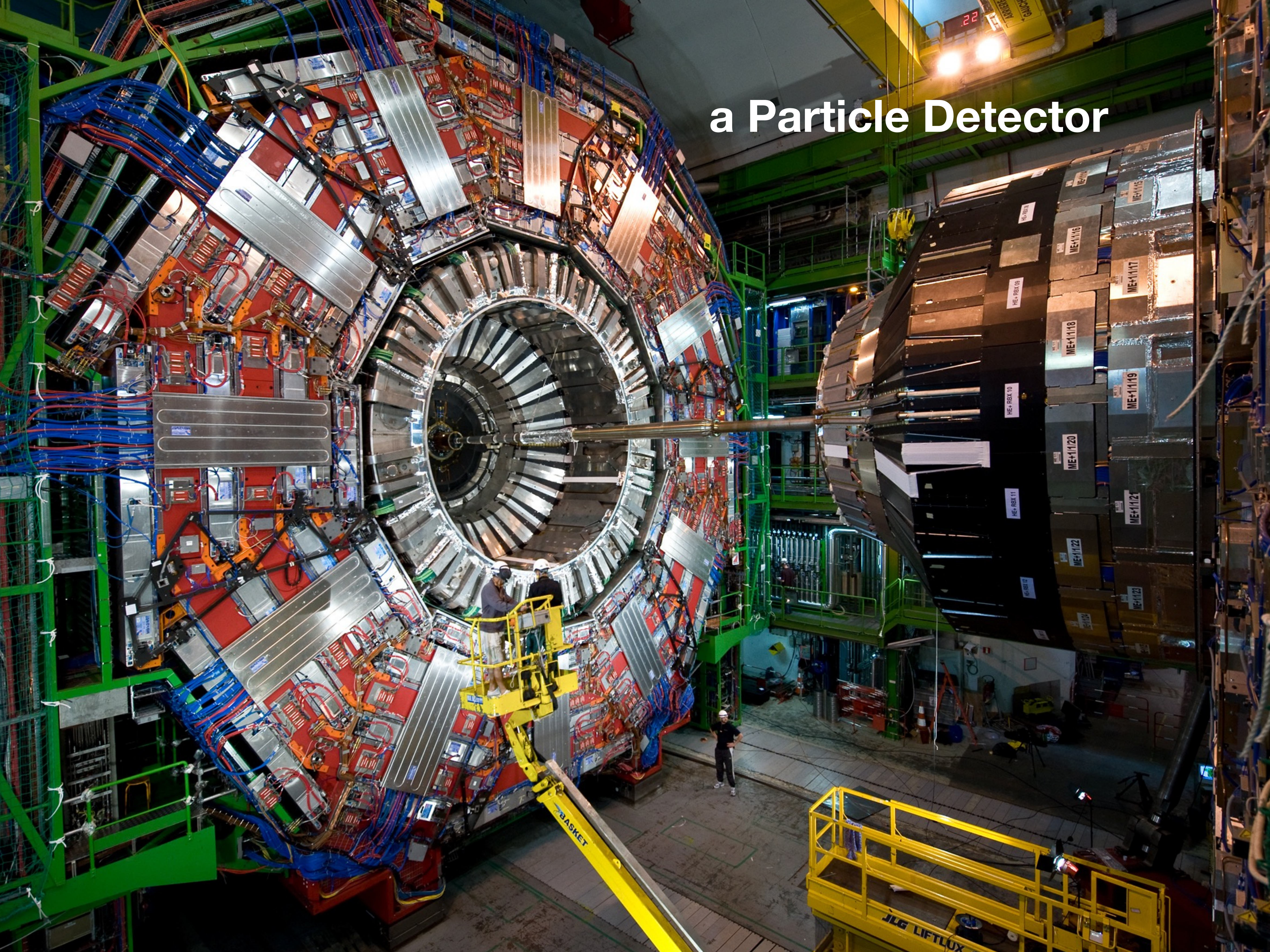
The detectors

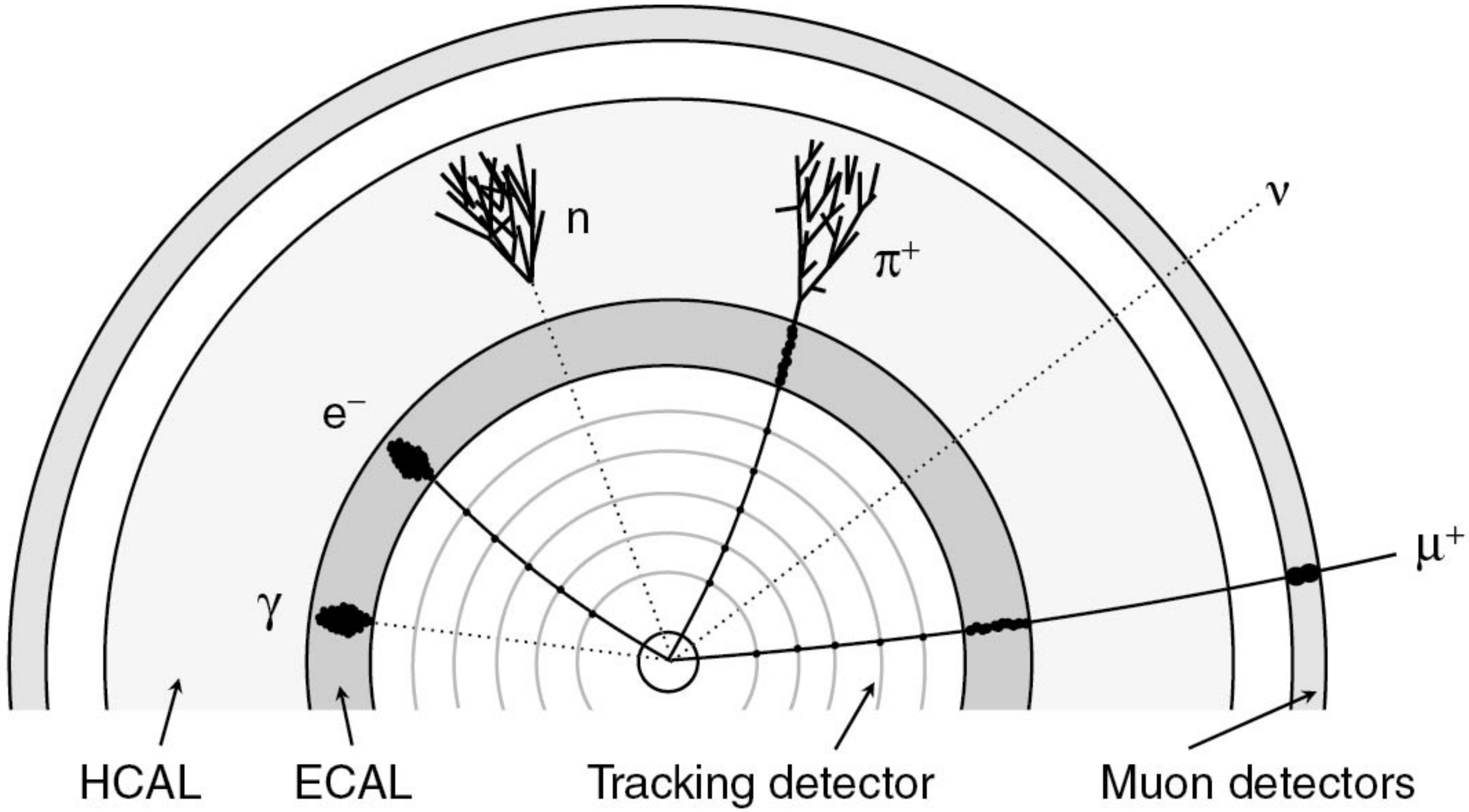




Time Projection Chamber
Particle Identification Detector
High-Momentum Particle Identification Detector
L3 Magnet
Absorber
Dipole Magnet
Muon Chambers
Inner Tracking System
Photon Spectrometer
Alice
GENEVE
LHC - B
Point 8
© CERN
CERN
ATLAS
Point 1
ALICE
Point 2
CMS
Point 5
SPS
TI 8
TI 2
LHC - B
ATLAS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

a Particle Detector

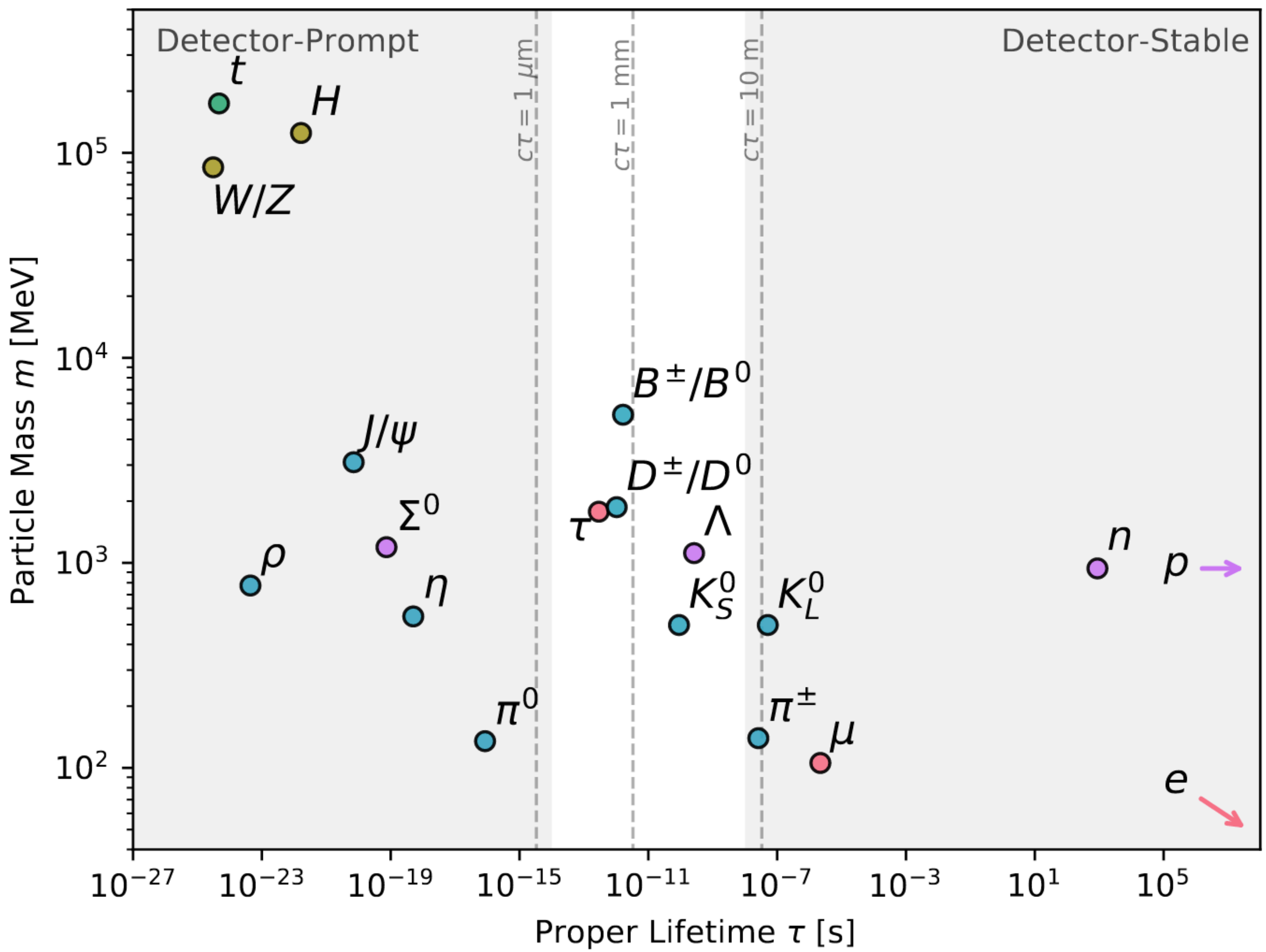




calorimeters:
measure particle's
energy by absorbing it

trackers:
detect trajectory
of charged particles

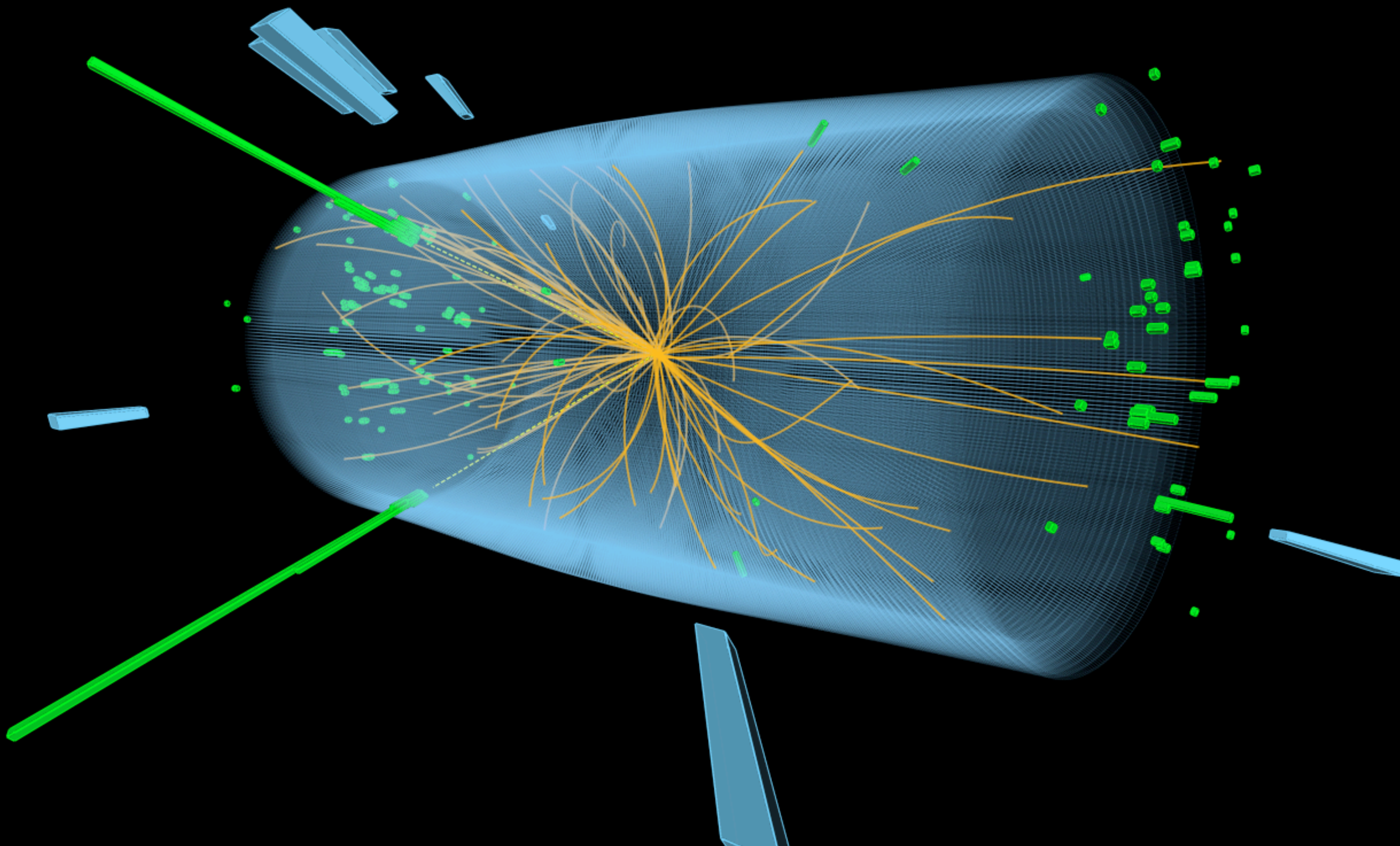
muon chambers:
detected in outer
detector layers

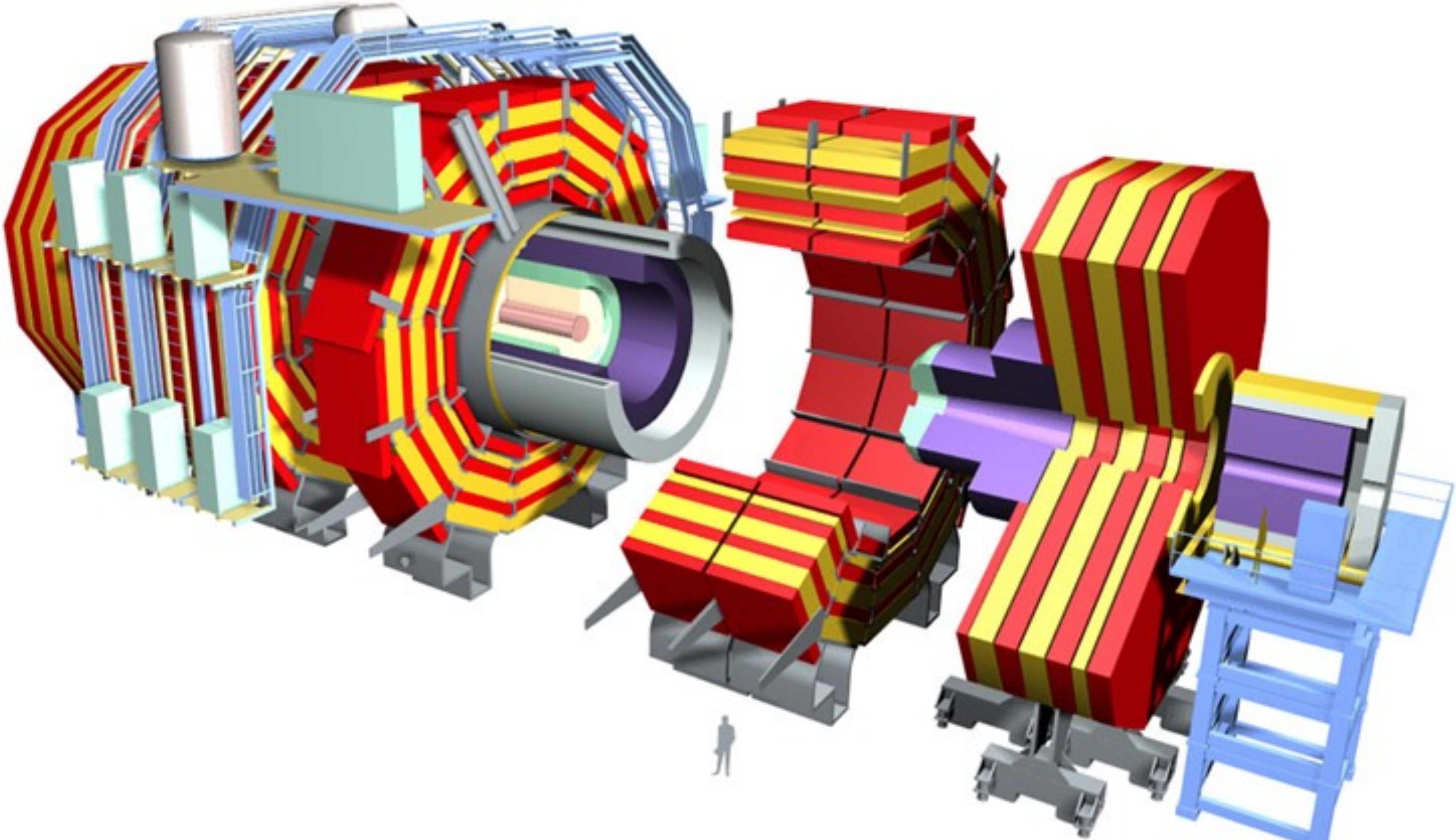


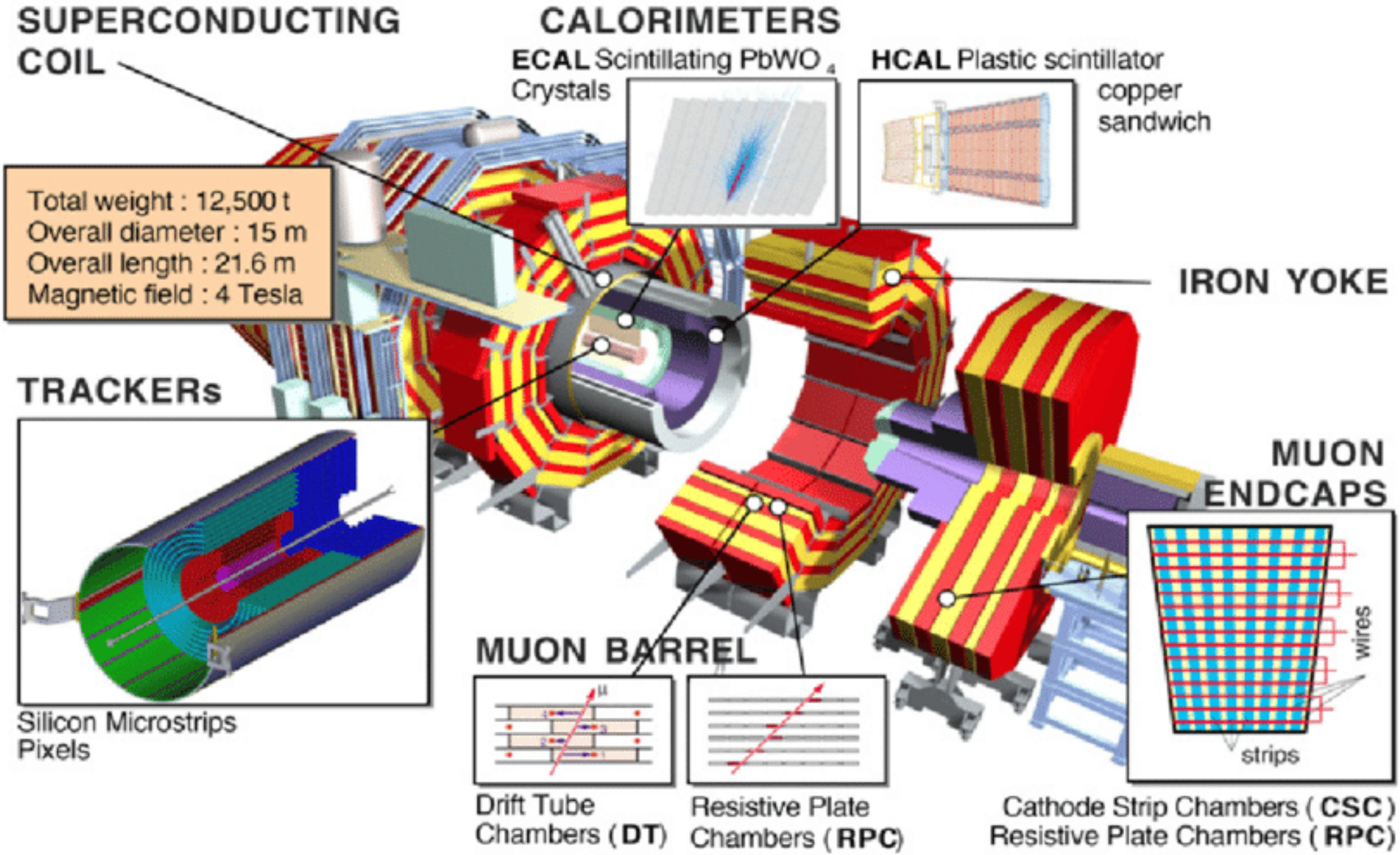
Only *quasi*-sable particles are directly detectable: e, μ, γ, π, K, p, n

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

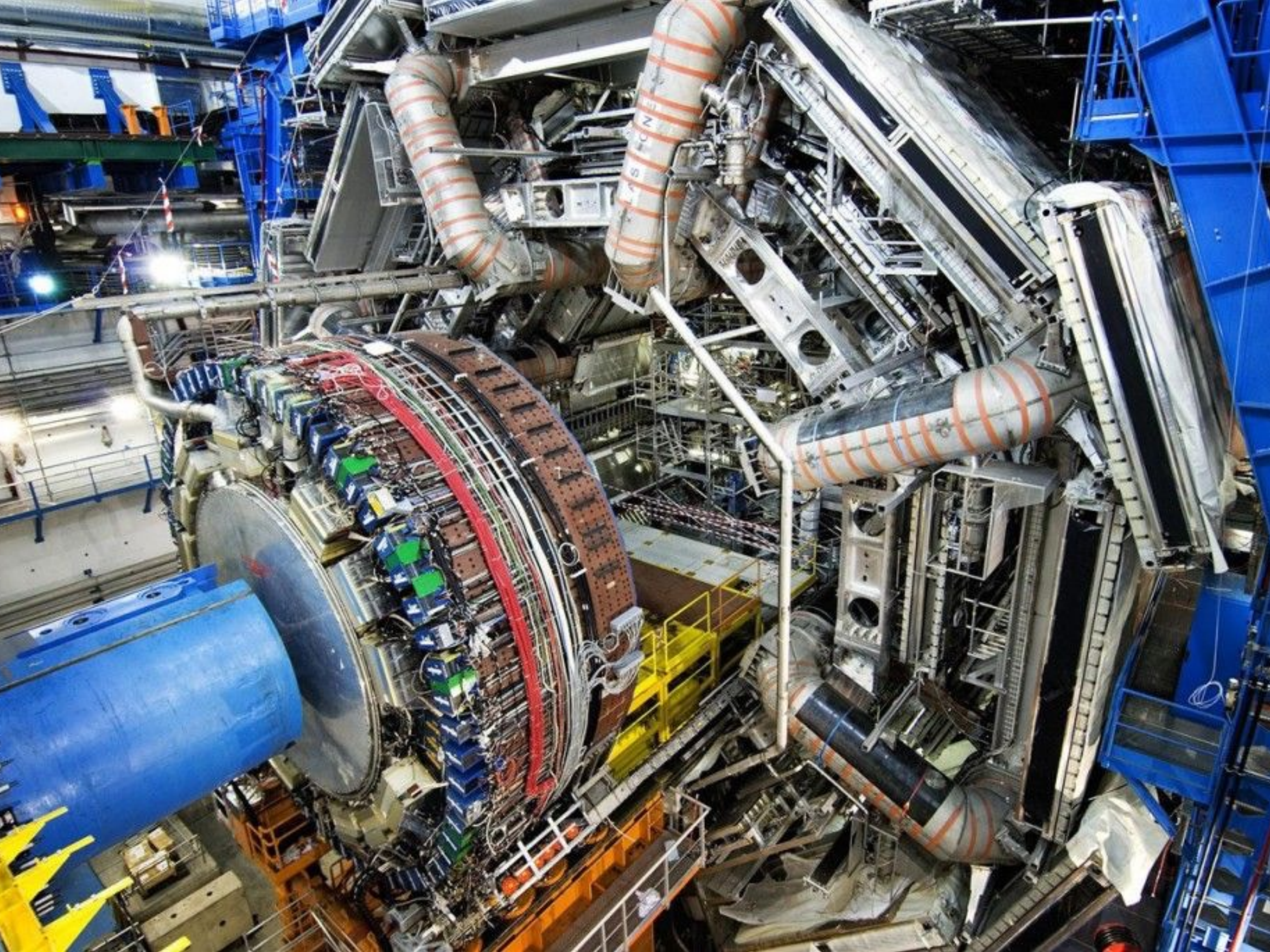
a $H \to \gamma\gamma$ candidate

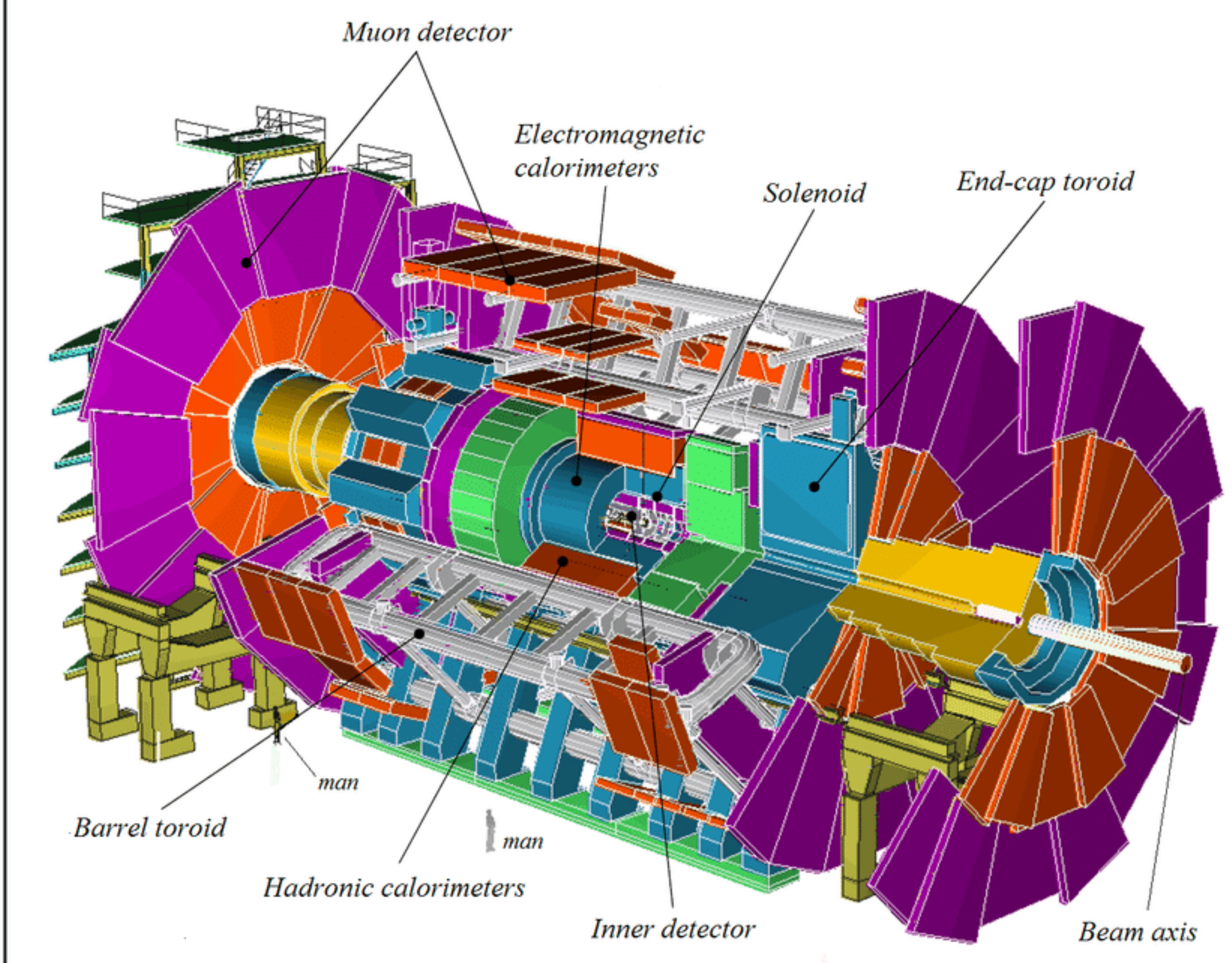






SUPERCONDUCTING COIL
CALORIMETERS
ECAL Scintillating PbWO4 Crystals
HCAL Plastic scintillator copper sandwich
Total weight : 12,500 t
Overall diameter : 15 m
Overall length : 21.6 m
Magnetic field : 4 Tesla
IRON YOKE
TRACKERs
Silicon Microstrips
Pixels
MUON ENDCAPS
MUON BARREL
wires
strips
Drift Tube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

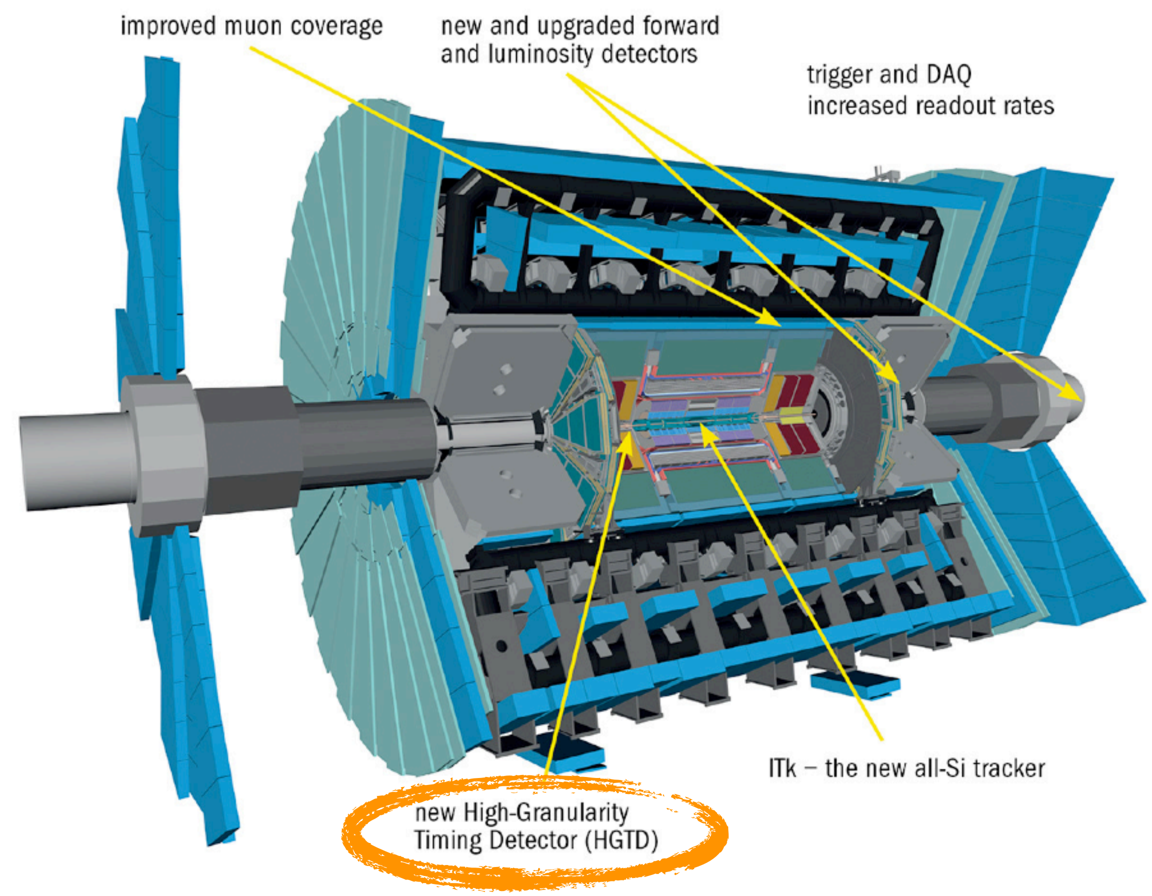


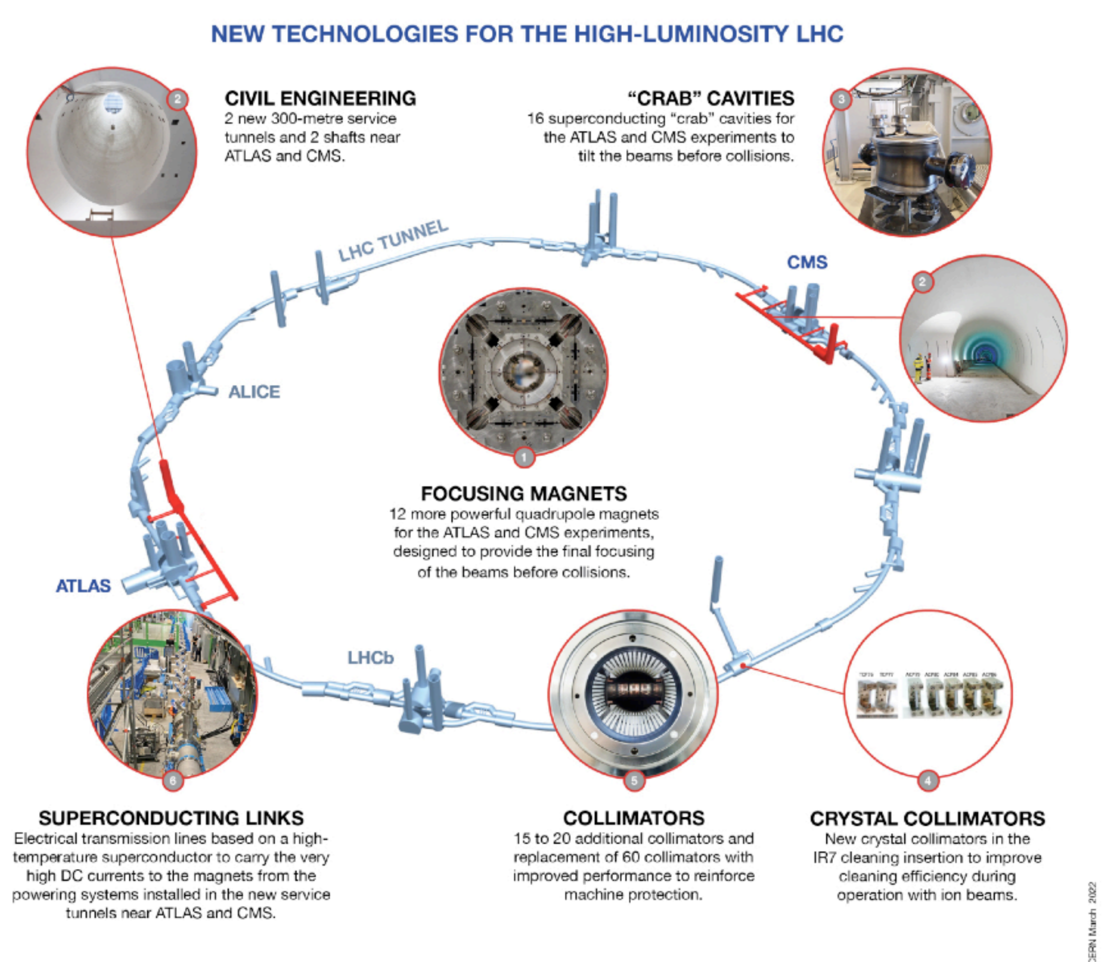


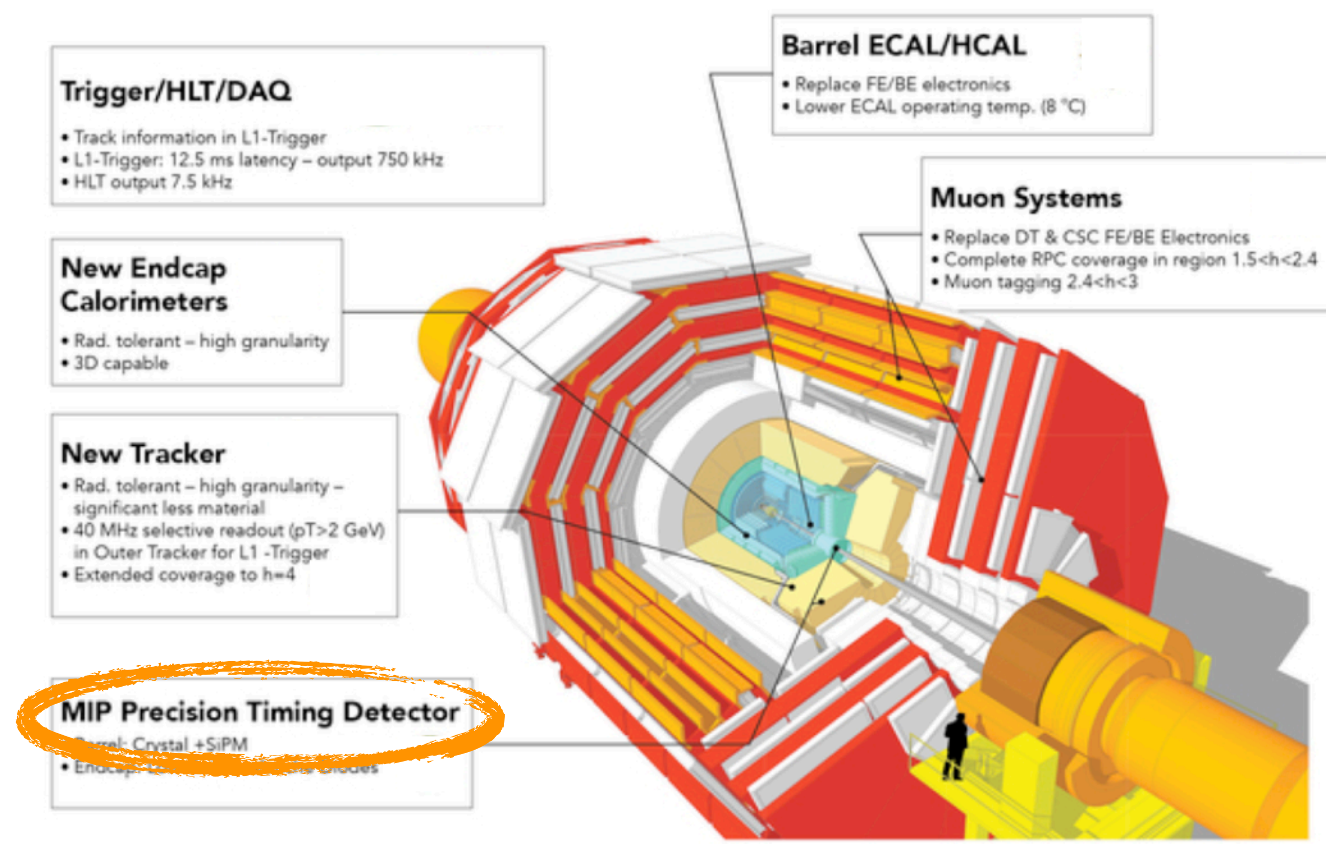
Muon detector
Electromagnetic calorimeters
Solenoid
End-cap toroid
man
Barrel toroid
man
Hadronic calorimeters
Inner detector
Beam axis

High-Luminosity LHC

- an *new*, more intense LHC
- require refurbished detectors!
- upgrade with state-of-the-art technologies
- novel or redesigned detector components
- being advanced now



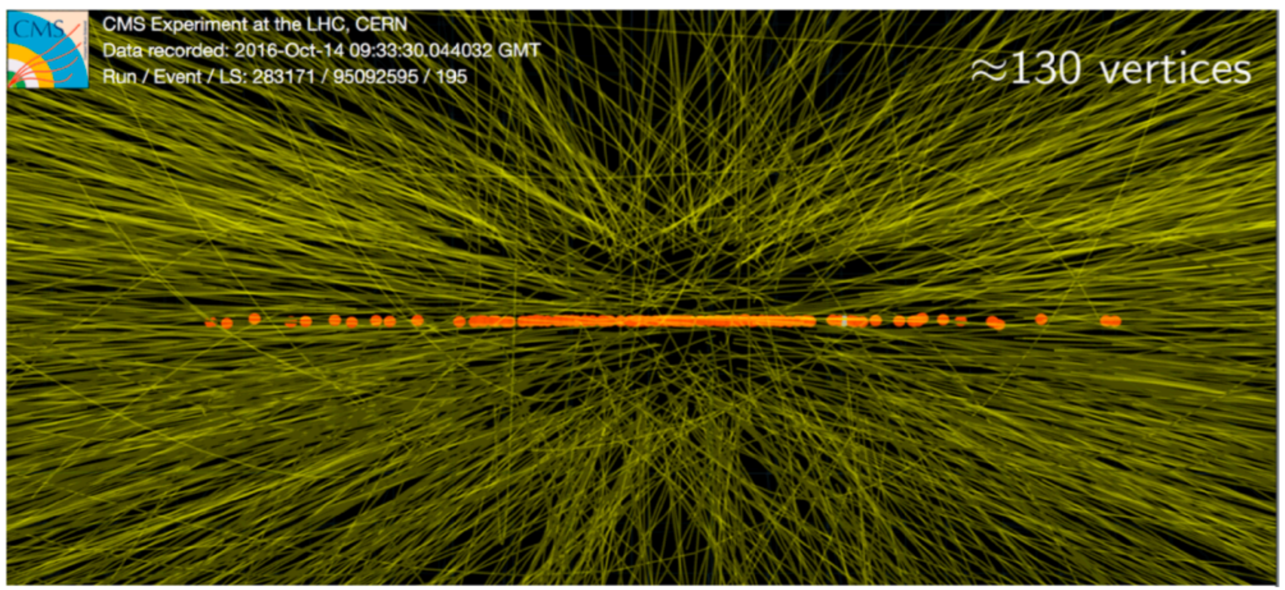




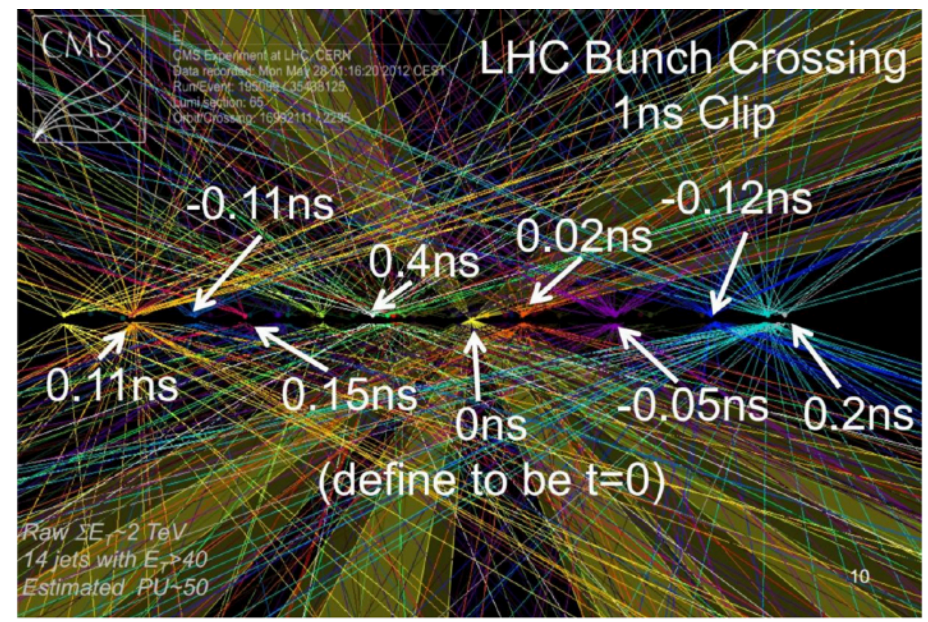
HL-LHC: adding precision timing detectors

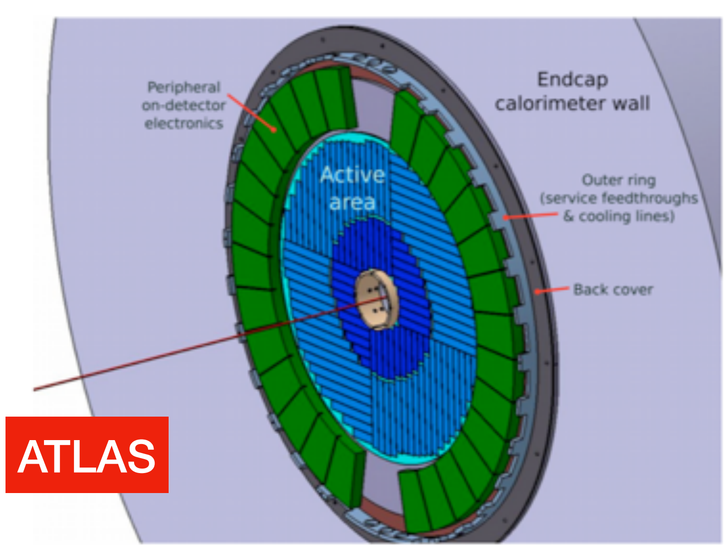
Example challenge for the high-luminosity LHC phase: **pile-up**

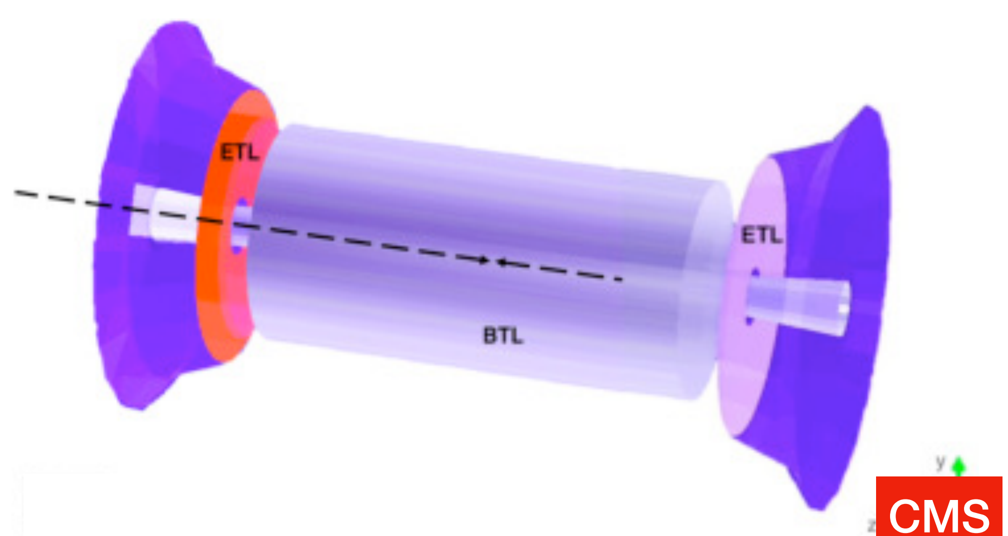
- can expect up to 200 simultaneous collisions per bunch crossing
- detectors do not have the spacial resolution to distinguish resulting vertices
- solution: add time dimension, i.e. develop novel precision timing detectors

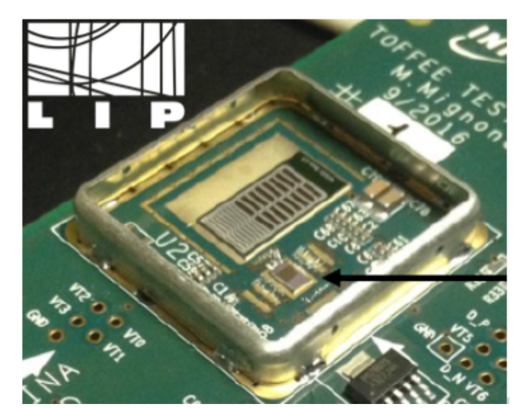


[Real life event from special LHC run in 2016 w/ intensity bunches]



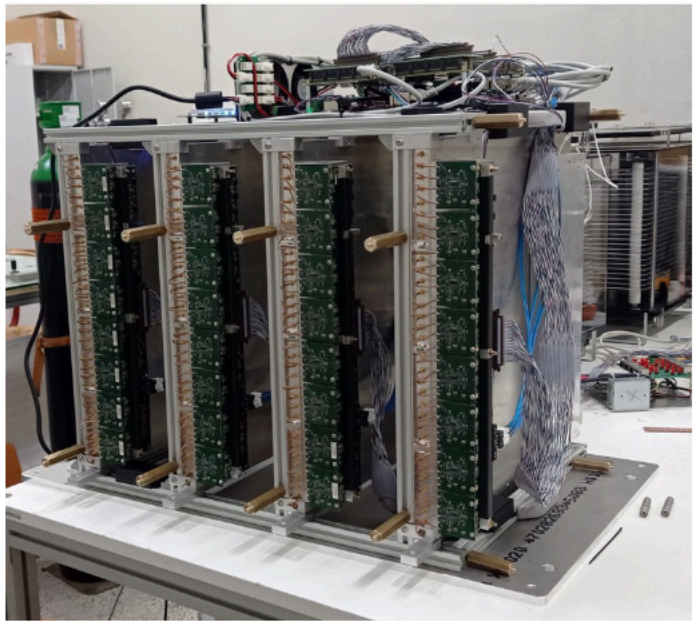


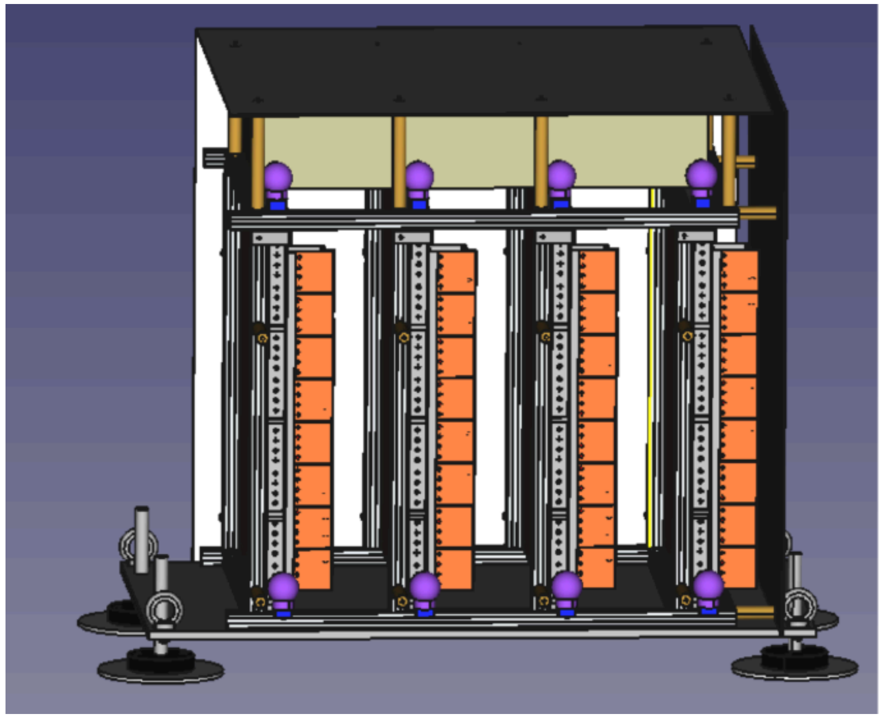


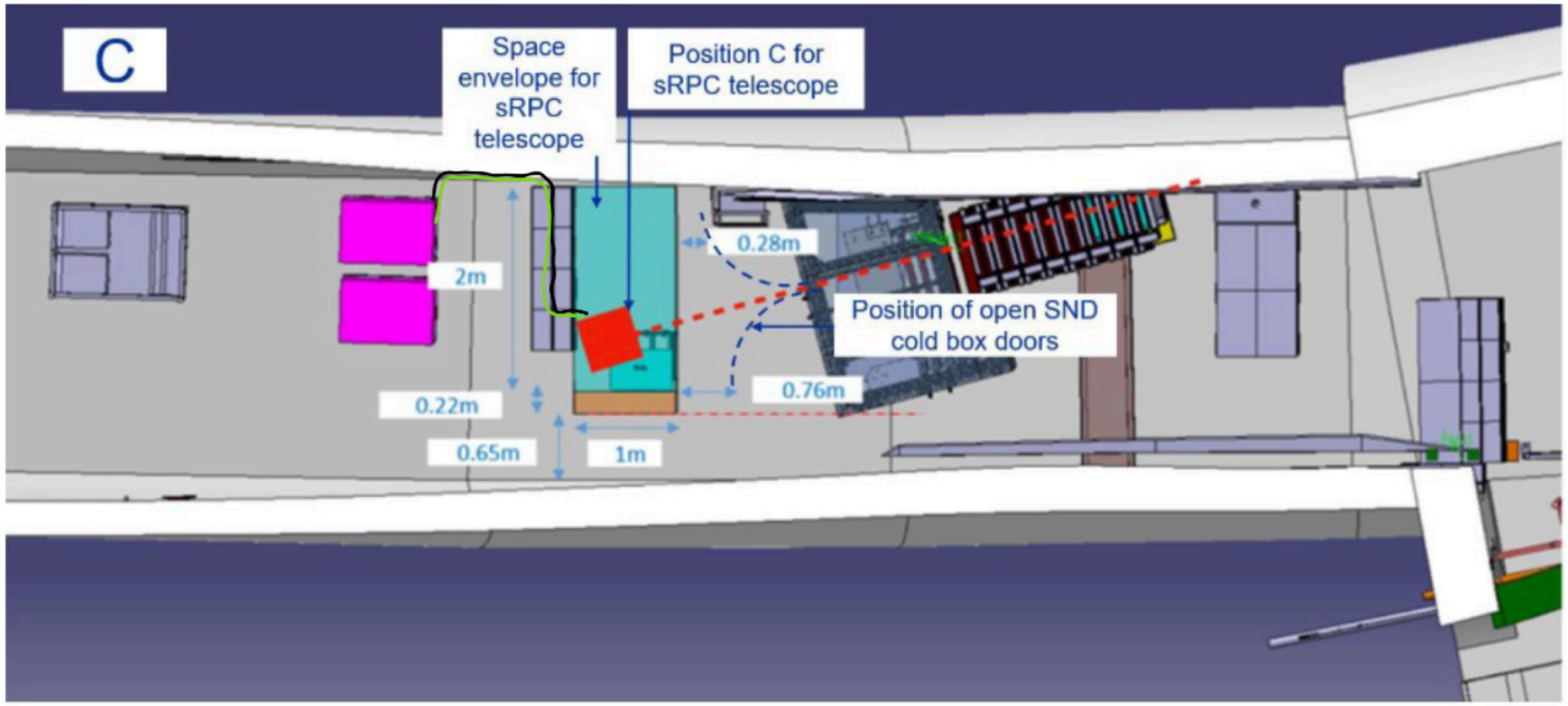


Run3: a muon telescope @LHC

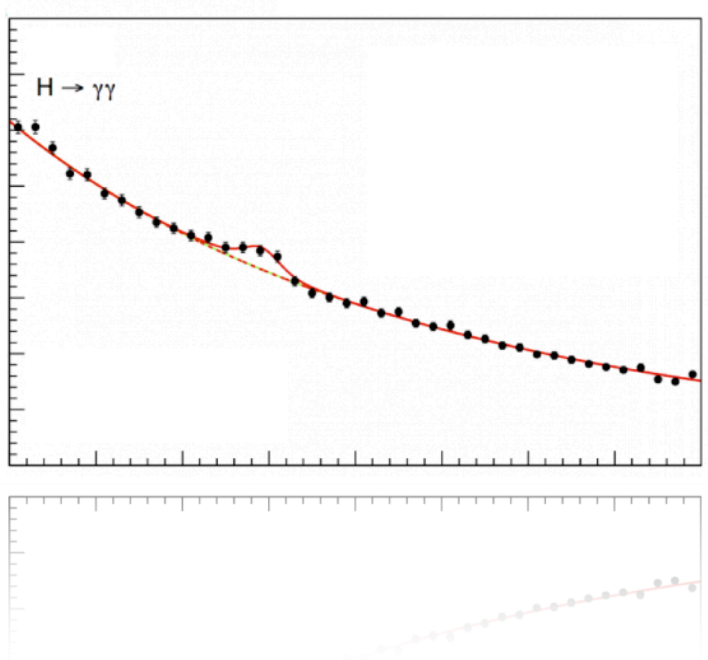
- **Example (ongoing this week!):**
- new detector for measuring **muon flux** at LHC
- establish innovative technology (sRPC), designed and built @LIP, deploying in LHC environment
- being installed in the SND@LHC tunnel this week
- additional uses requested by community, beyond physics measurement (environment, upgrades)



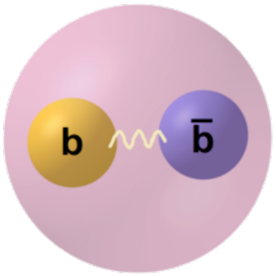




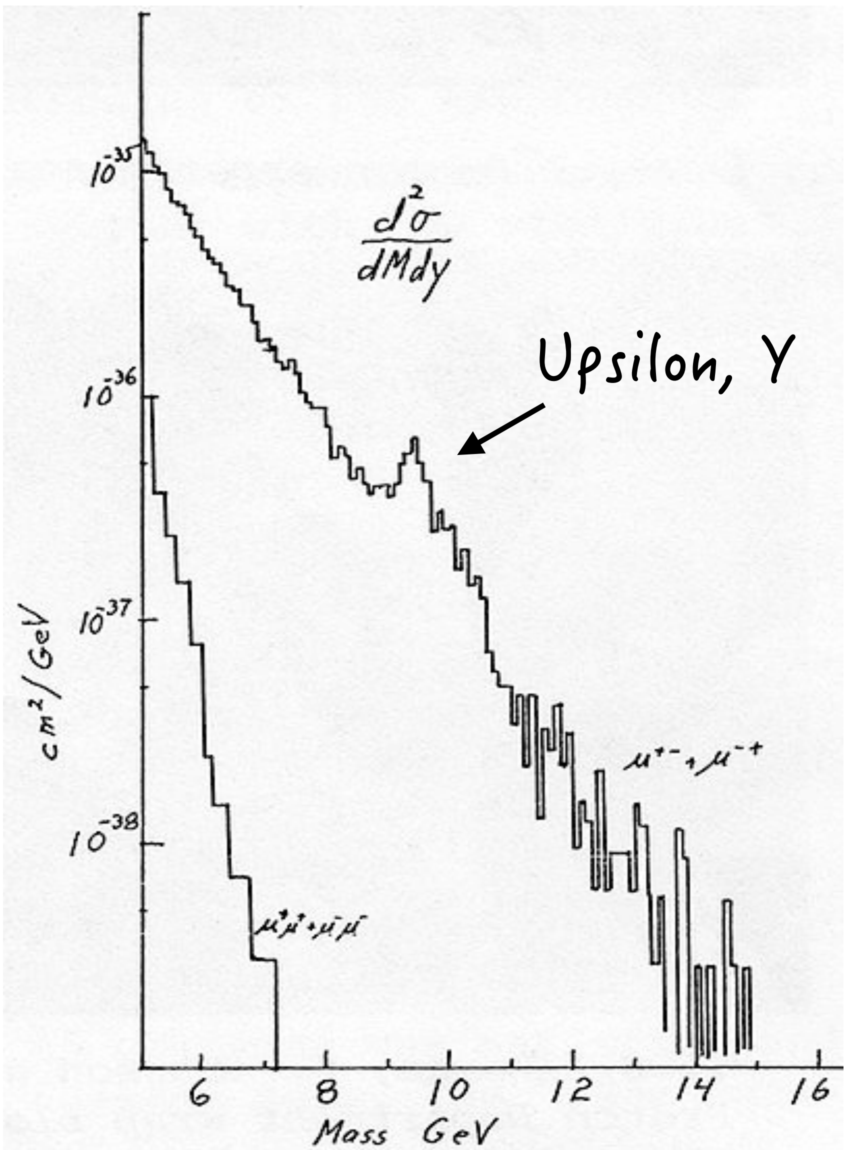
How do we ‘see’ particles?



the SM discovery



1977

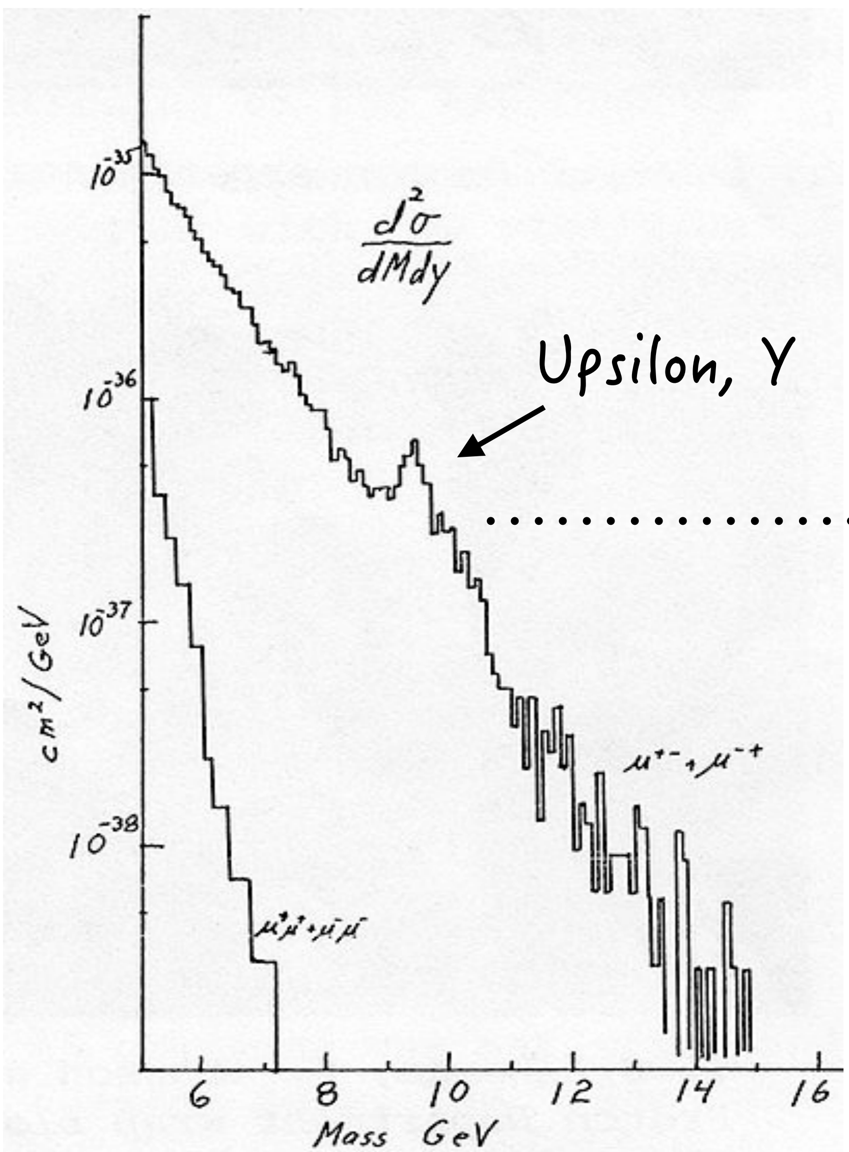


Υ, beauty

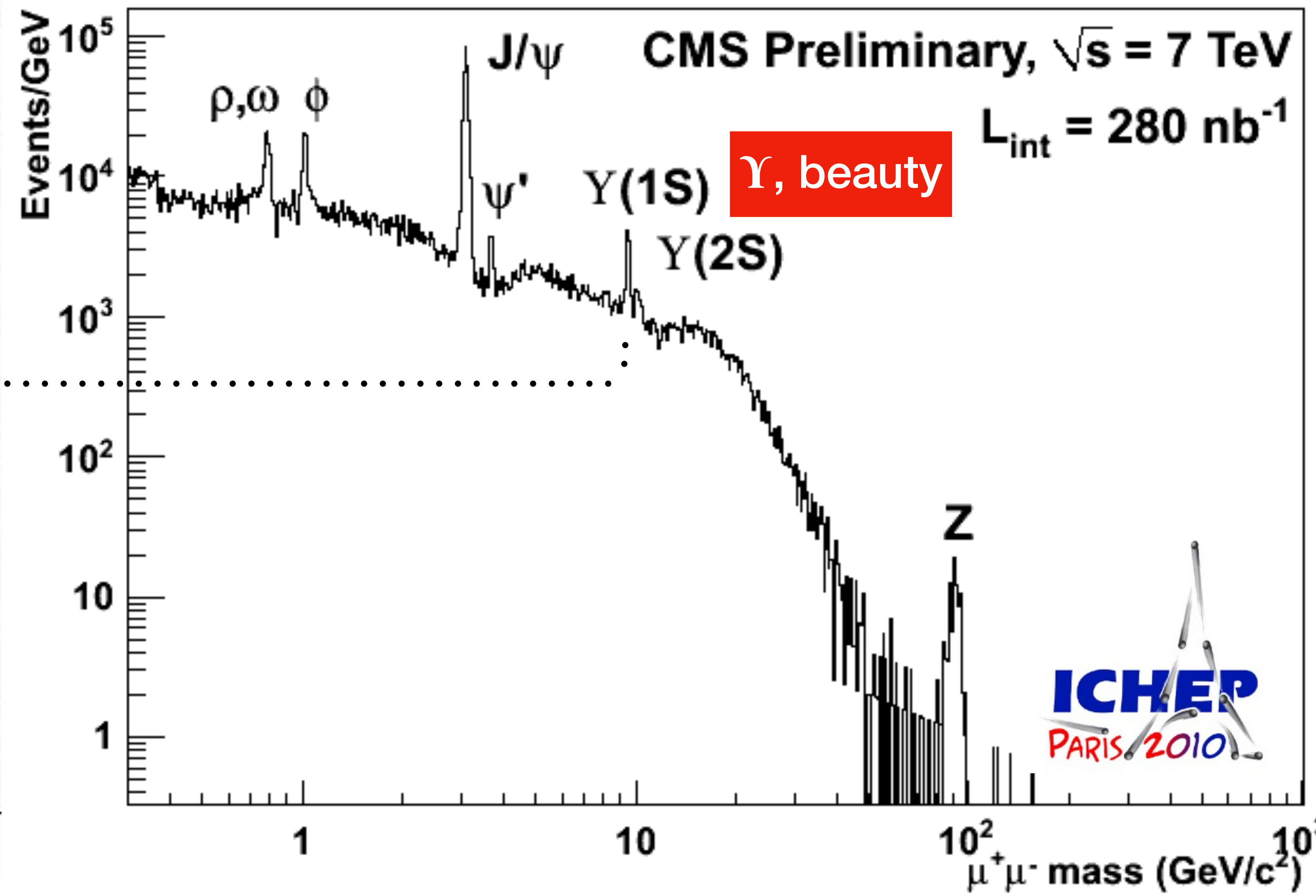
the discovery of the
b quark

the SM *re*-discovery @ *LHC*

1977

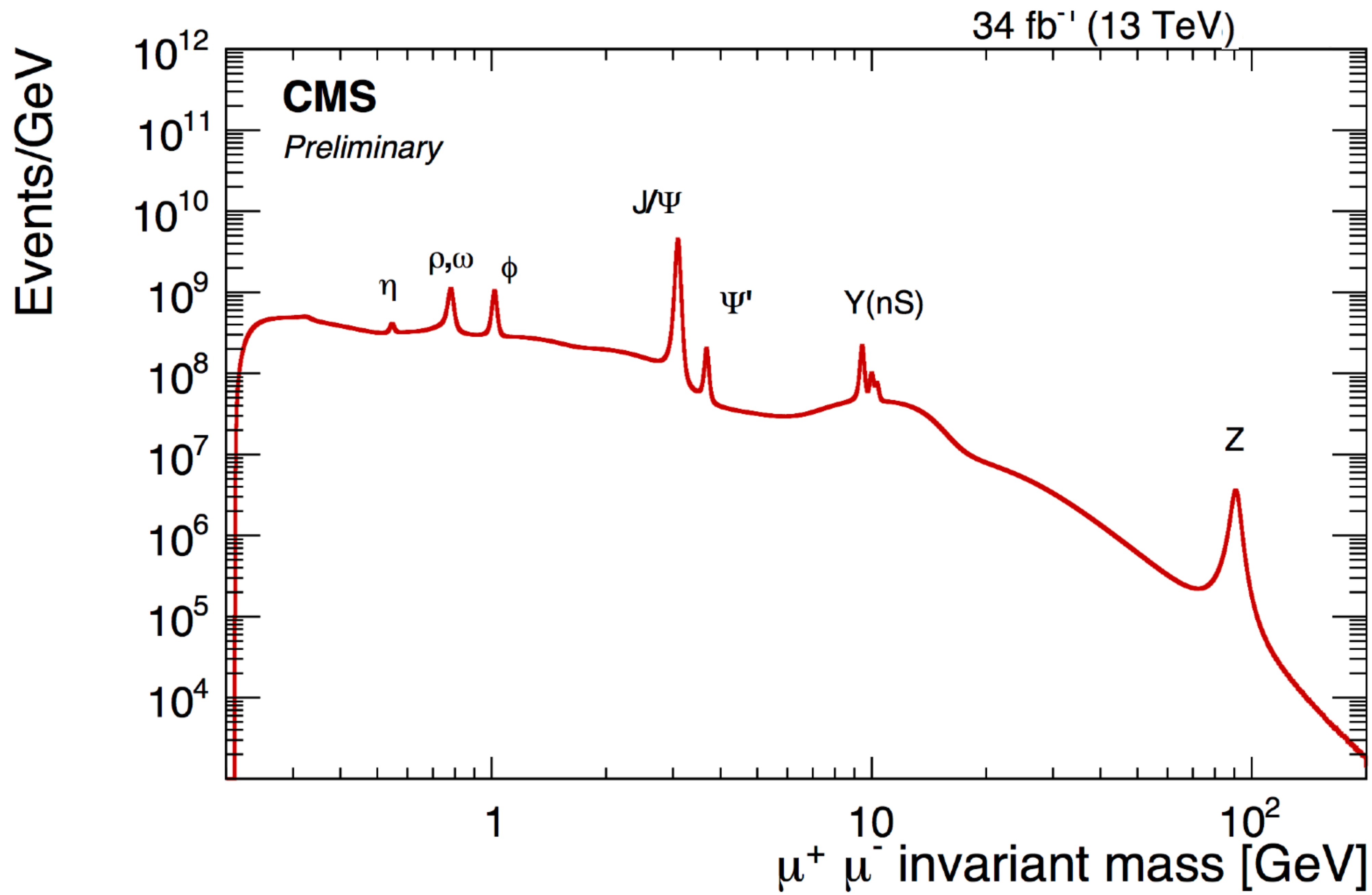


2010

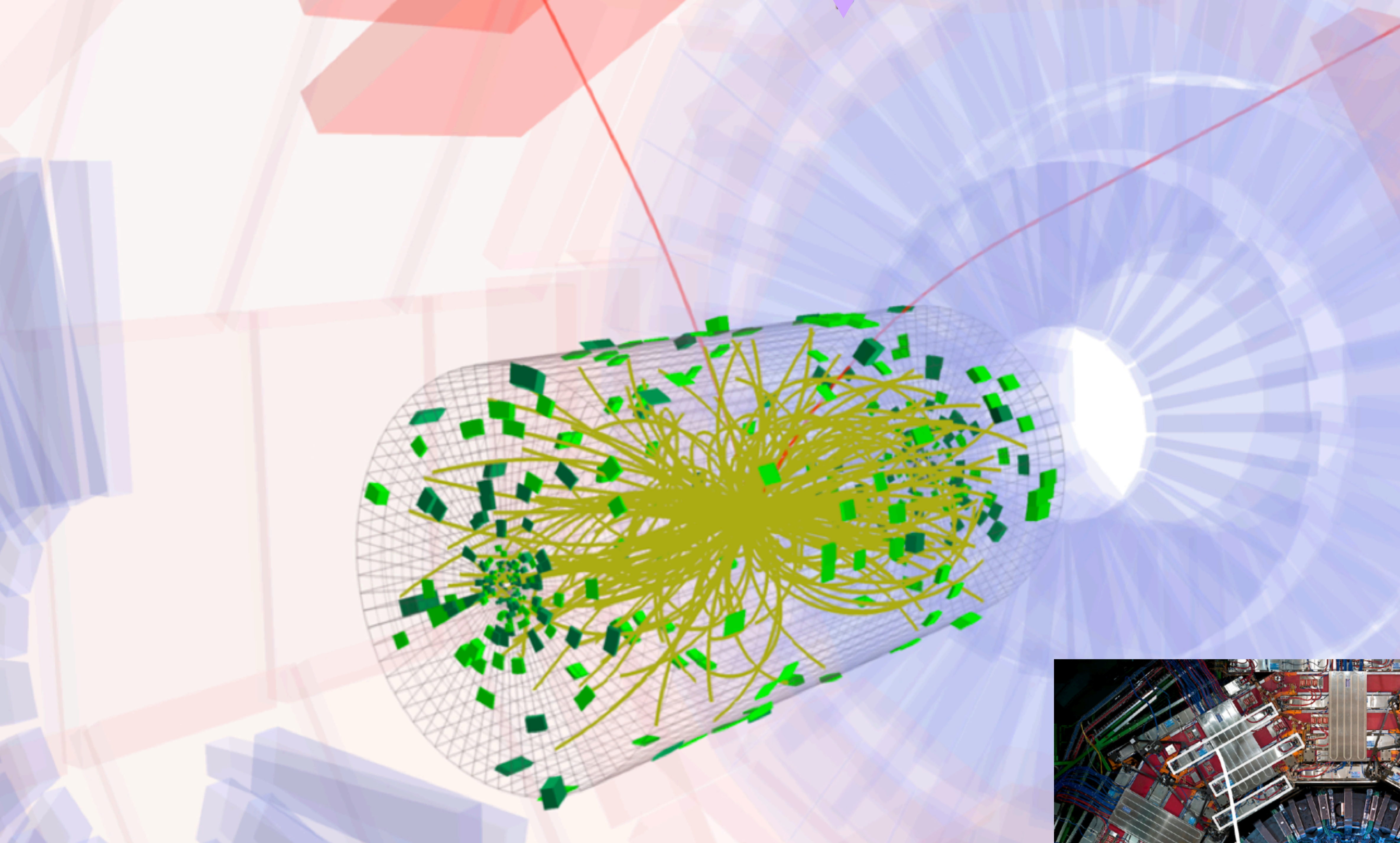


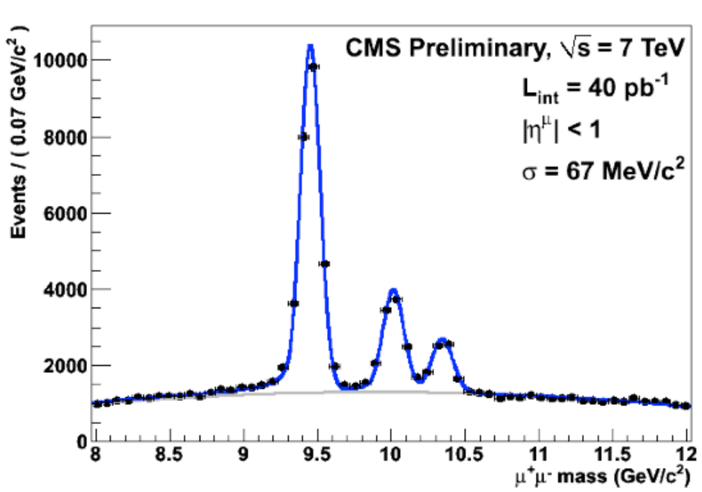
the discovery of the
b quark

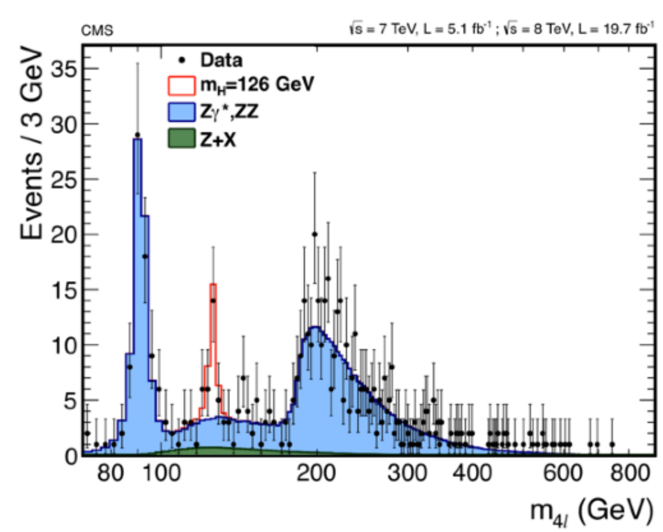
the SM re-discovery @ LHC

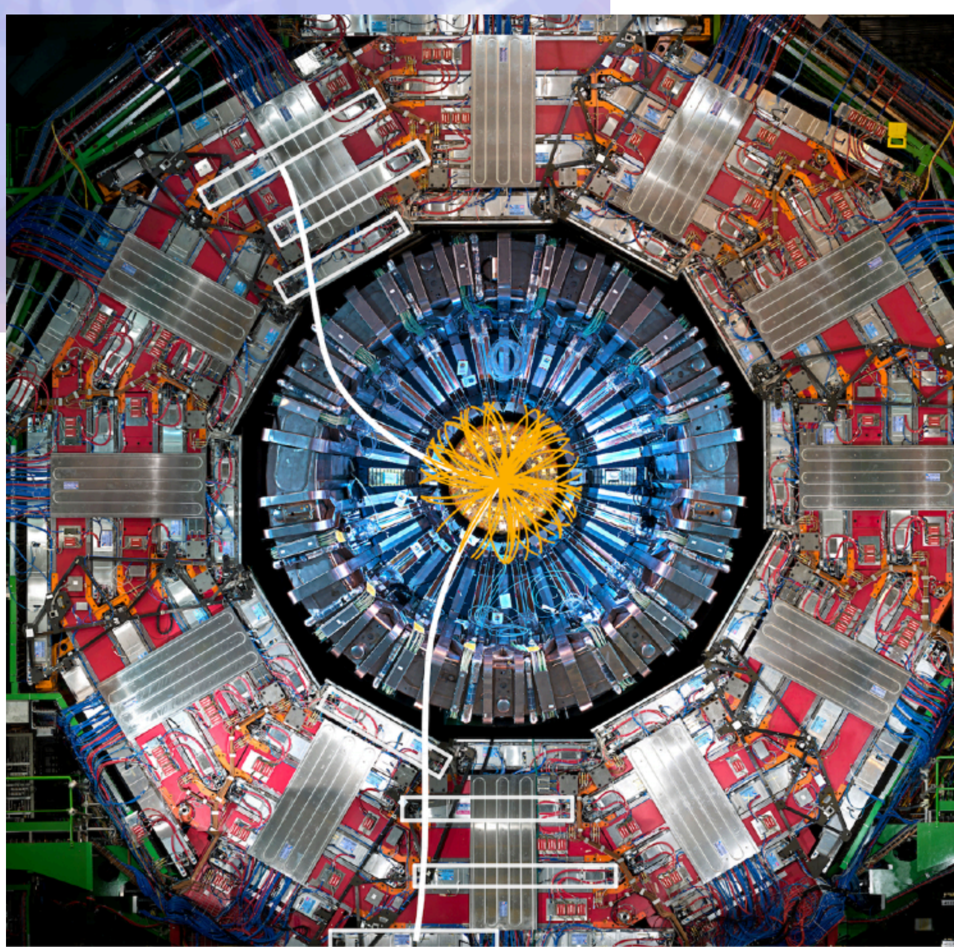


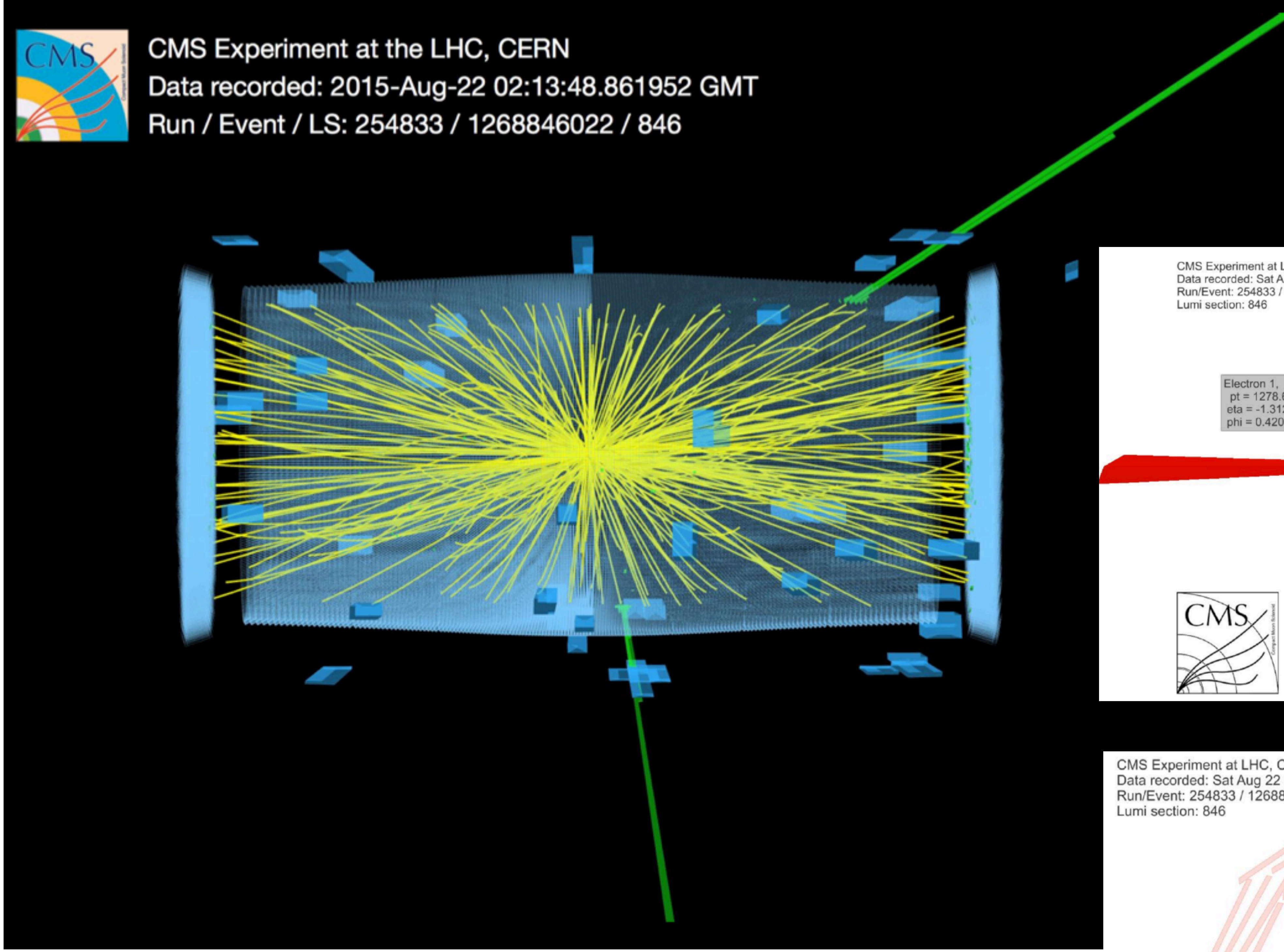
Decades worth of particle physics discovery … in a single plot!

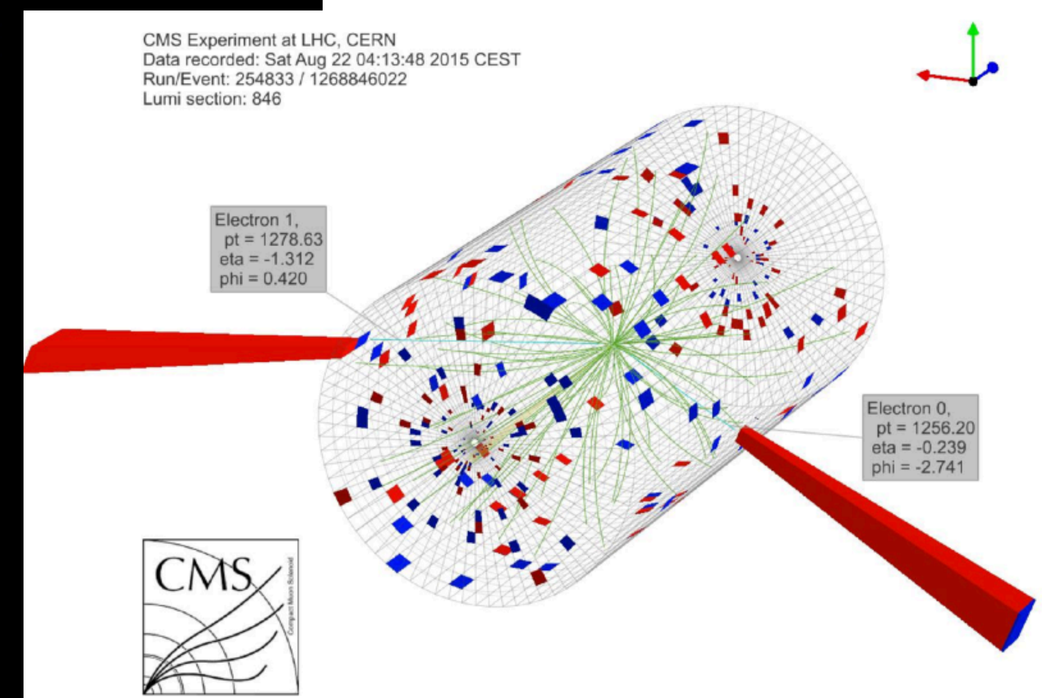


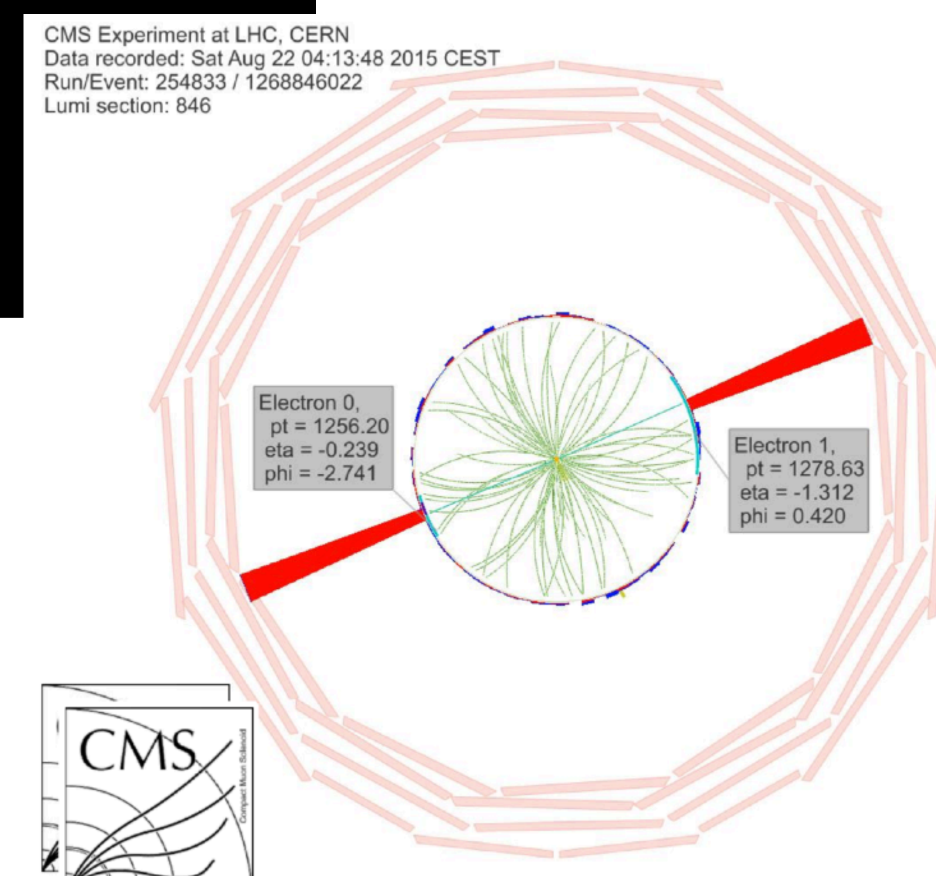

CMS Preliminary, $\sqrt{s}$ = 7 TeV
L_{int} = 40 pb^{-1}
$|\eta^{\mu}| < 1$
σ = 67 MeV/c^2
Events / (0.07 GeV/c^2)
$\mu^+\mu^-$ mass (GeV/c^2)

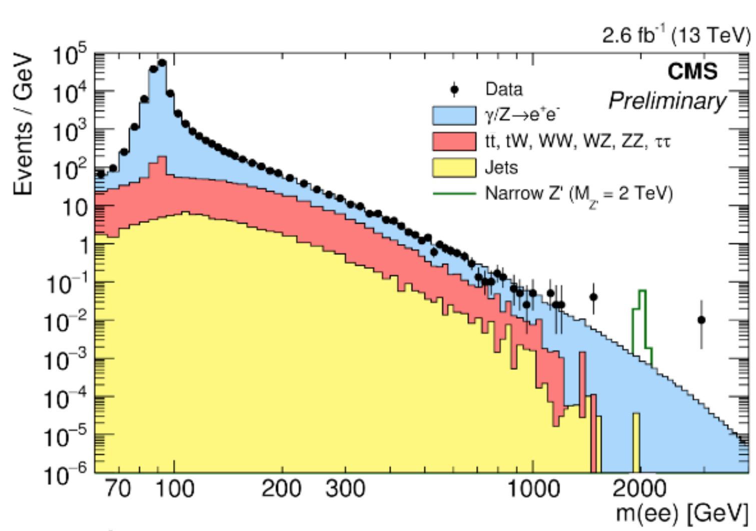

CMS
$\sqrt{s}$ = 7 TeV, L = 5.1 fb^{-1} ; $\sqrt{s}$ = 8 TeV, L = 19.7 fb^{-1}
Data
m_H=126 GeV
$Z\gamma^*$,ZZ
Z+X
Events / 3 GeV
m_{4l} (GeV)

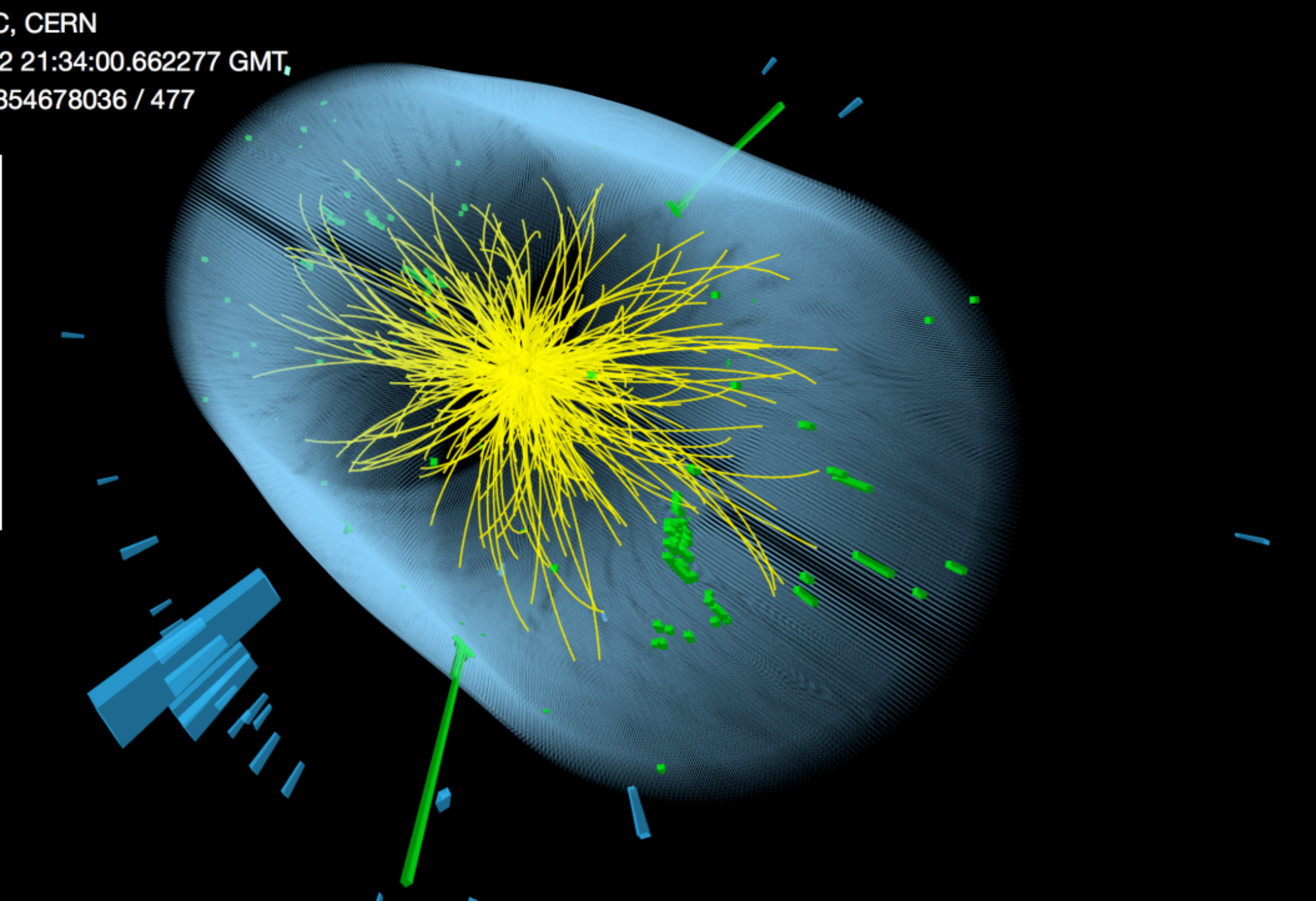


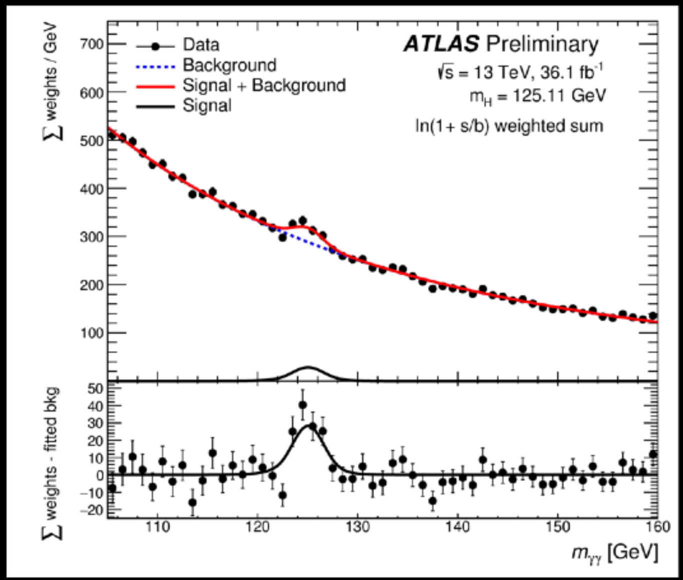

CMS Experiment at the LHC, CERN
Data recorded: 2015-Aug-22 02:13:48.861952 GMT
Run / Event / LS: 254833 / 1268846022 / 846

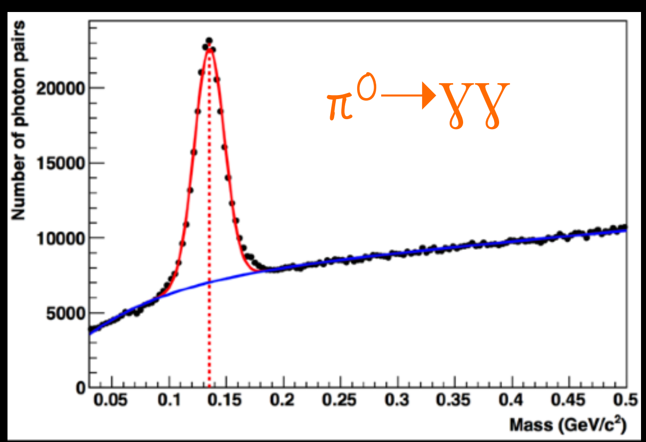

CMS Experiment at LHC, CERN
Data recorded: Sat Aug 22 04:13:48 2015 CEST
Run/Event: 254833 / 1268846022
Lumi section: 846
Electron 1, pt = 1278.63 eta = -1.312 phi = 0.420
Electron 0, pt = 1256.20 eta = -0.239 phi = -2.741
CMS

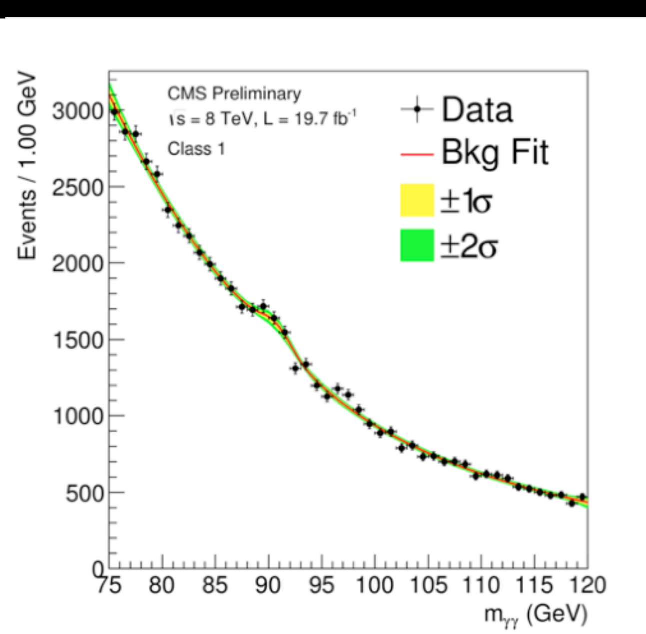

CMS Experiment at LHC, CERN
Data recorded: Sat Aug 22 04:13:48 2015 CEST
Run/Event: 254833 / 1268846022
Lumi section: 846
Electron 0, pt = 1256.20 eta = -0.239 phi = -2.741
Electron 1, pt = 1278.63 eta = -1.312 phi = 0.420
CMS

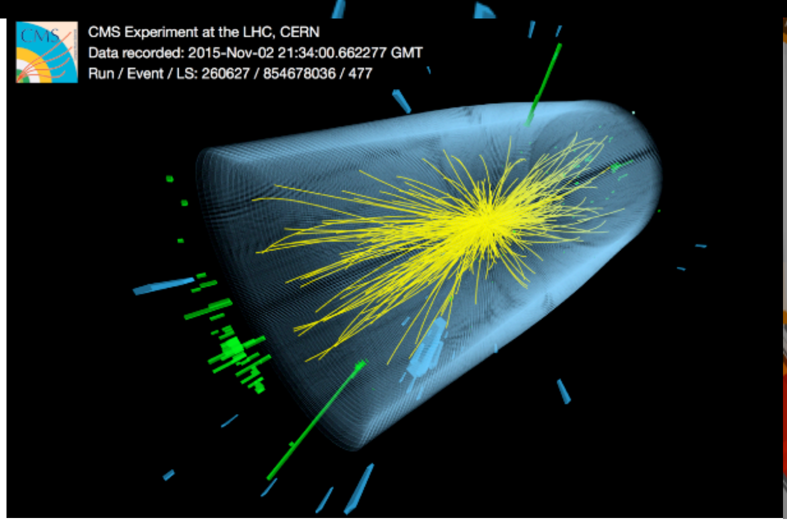

2.6 fb^{-1} (13 TeV)
CMS
Preliminary
Data
$\gamma/Z \rightarrow e^+e^-$
$t\bar{t}$, tW, WW, WZ, ZZ, $\tau\tau$
Jets
Narrow Z' ($M_{Z'}$ = 2 TeV)
Events / GeV
m(ee) [GeV]

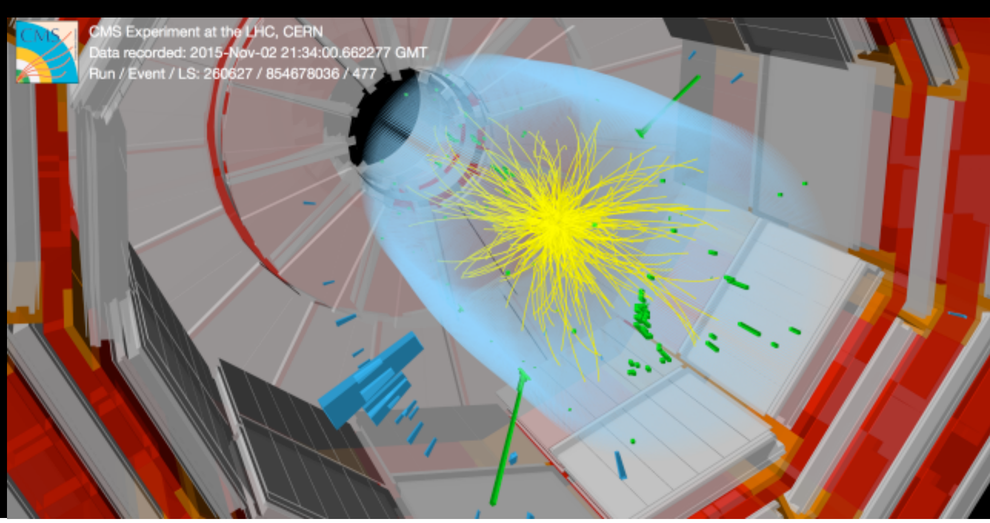

CMS Experiment at the LHC, CERN
Data recorded: 2015-Nov-02 21:34:00.662277 GMT
Run / Event / LS: 260627 / 854678036 / 477

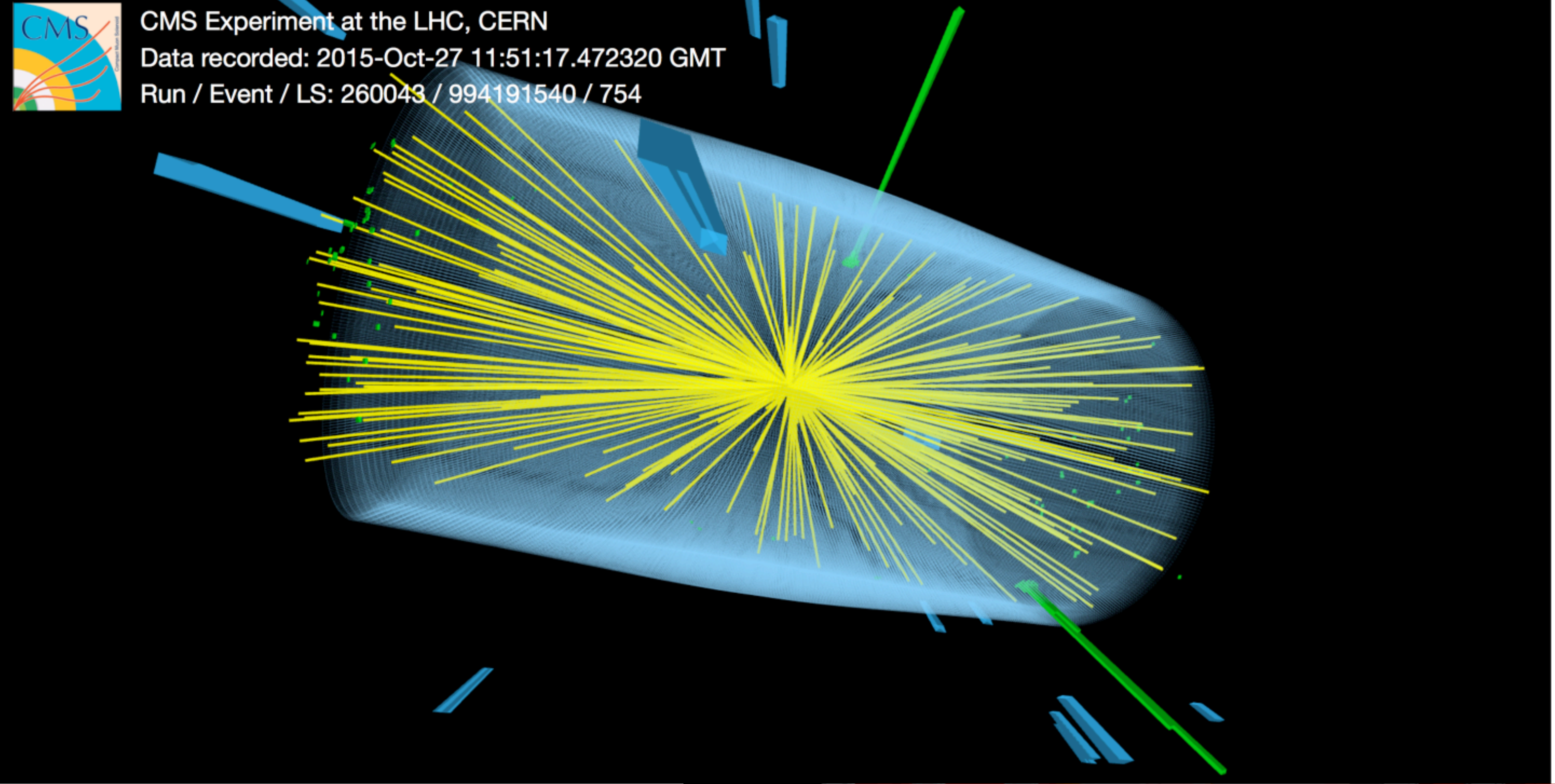

ATLAS Preliminary
√s = 13 TeV, 36.1 fb⁻¹
m_H = 125.11 GeV
ln(1+ s/b) weighted sum
Data
Background
Signal + Background
Signal
∑ weights / GeV
∑ weights - fitted bkg
m_γγ [GeV]

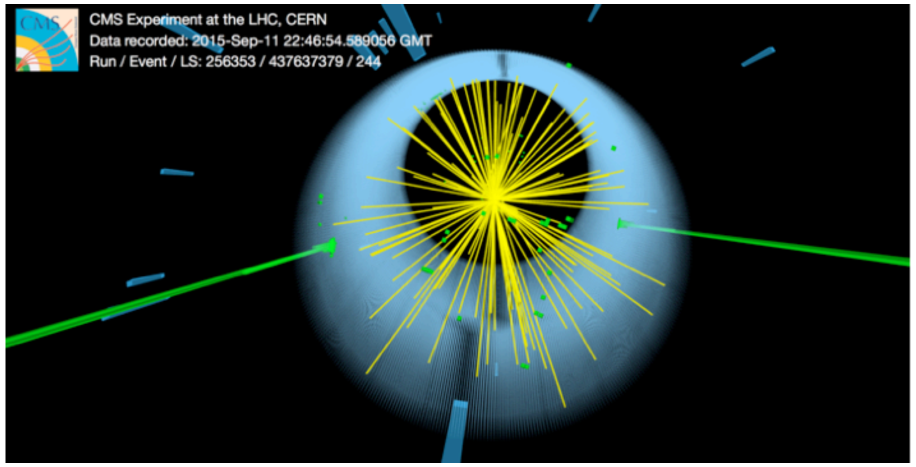

π⁰→γγ
Number of photon pairs
Mass (GeV/c²)

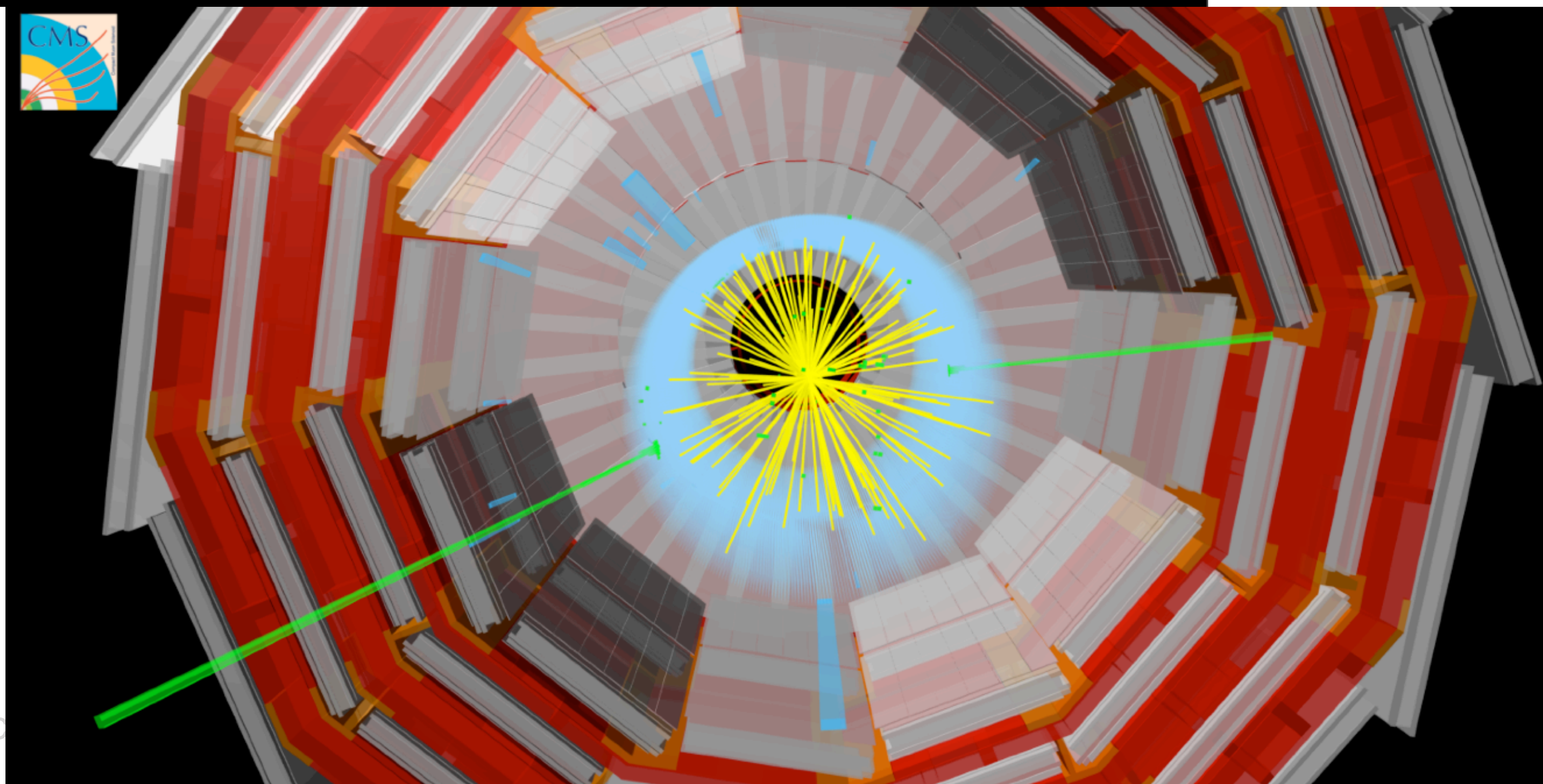

CMS Preliminary
√s = 8 TeV, L = 19.7 fb⁻¹
Class 1
Data
Bkg Fit
±1σ
±2σ
Events / 1.00 GeV
m_γγ (GeV)

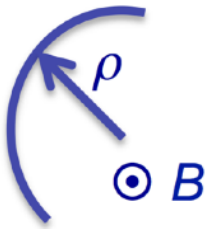

CMS Experiment at the LHC, CERN
Data recorded: 2015-Nov-02 21:34:00.662277 GMT
Run / Event / LS: 260627 / 854678036 / 477


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

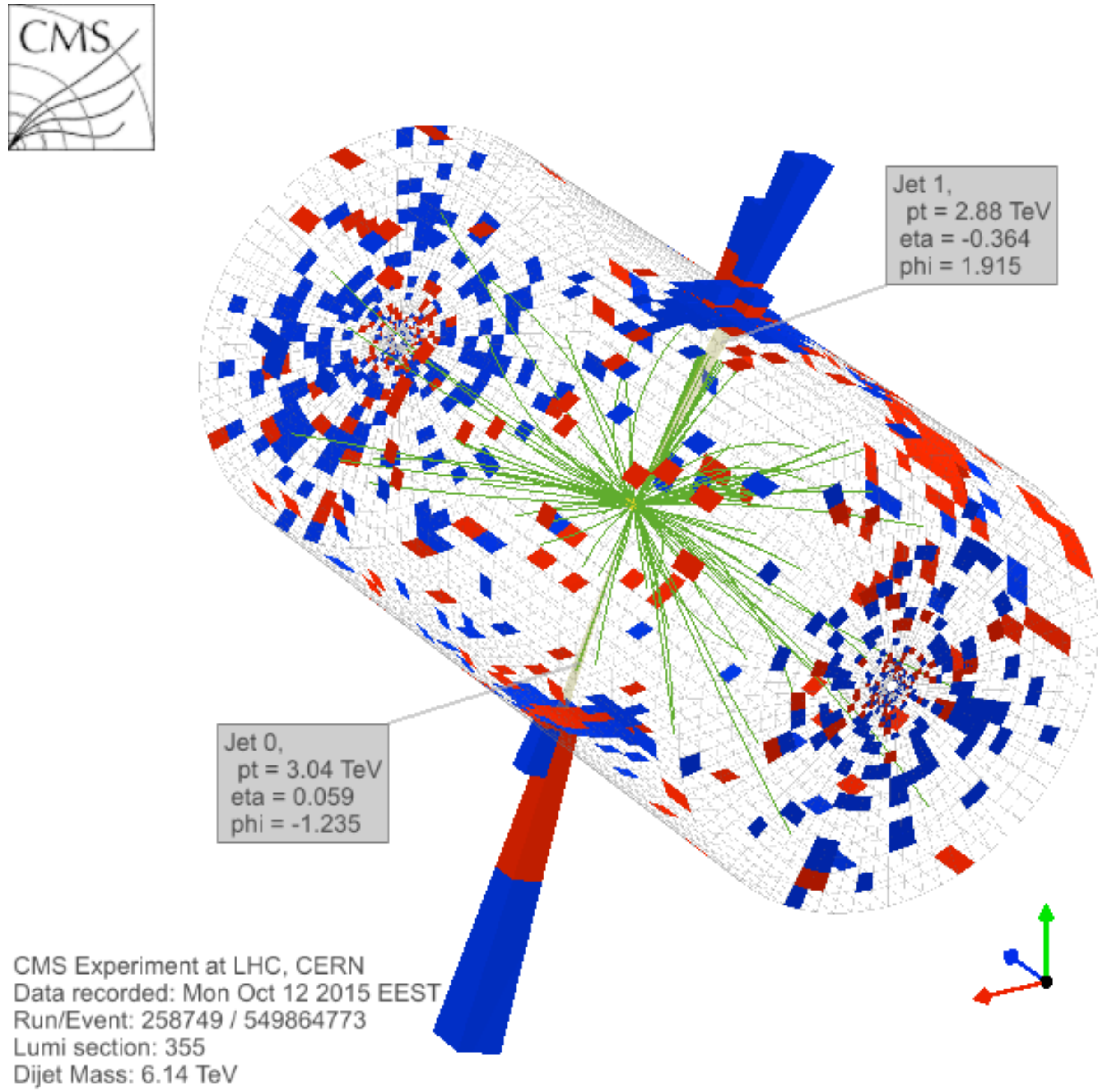


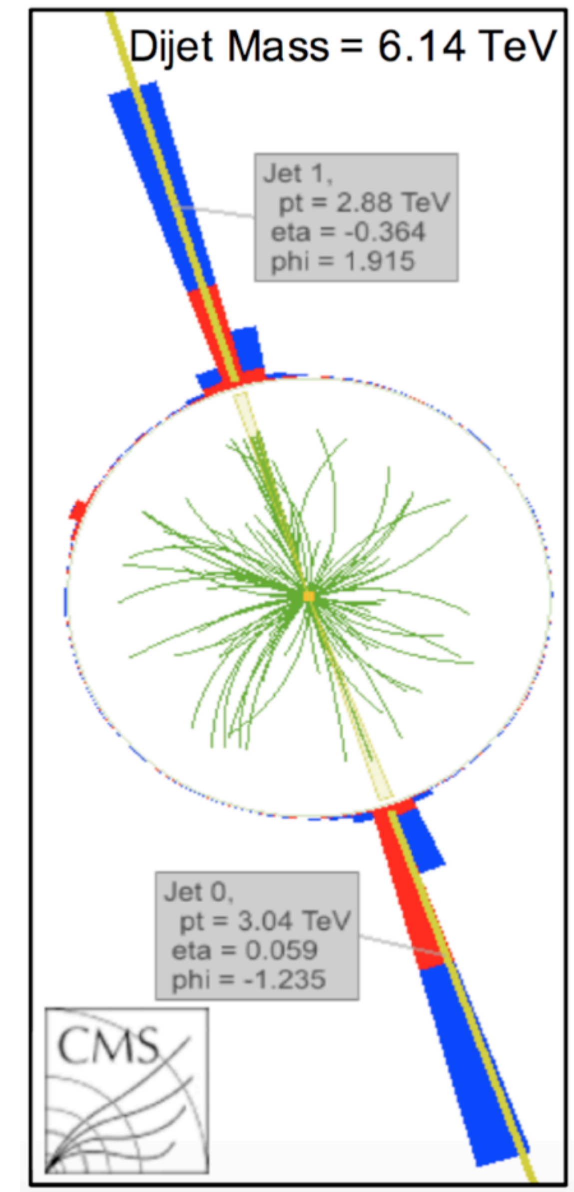


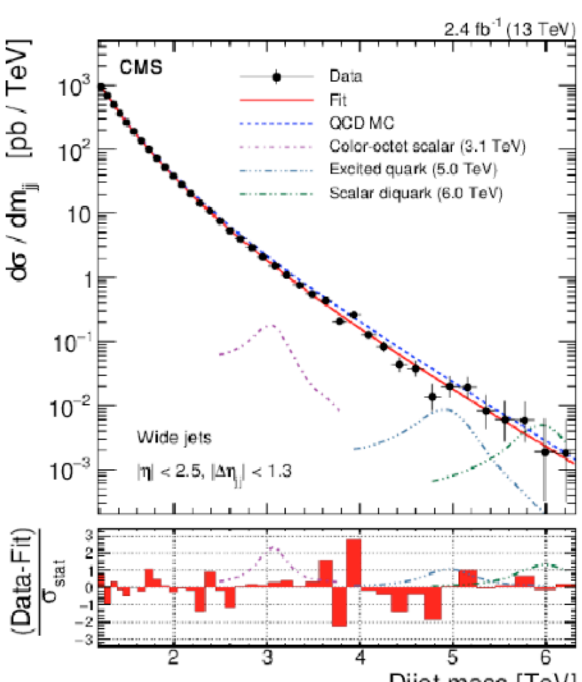


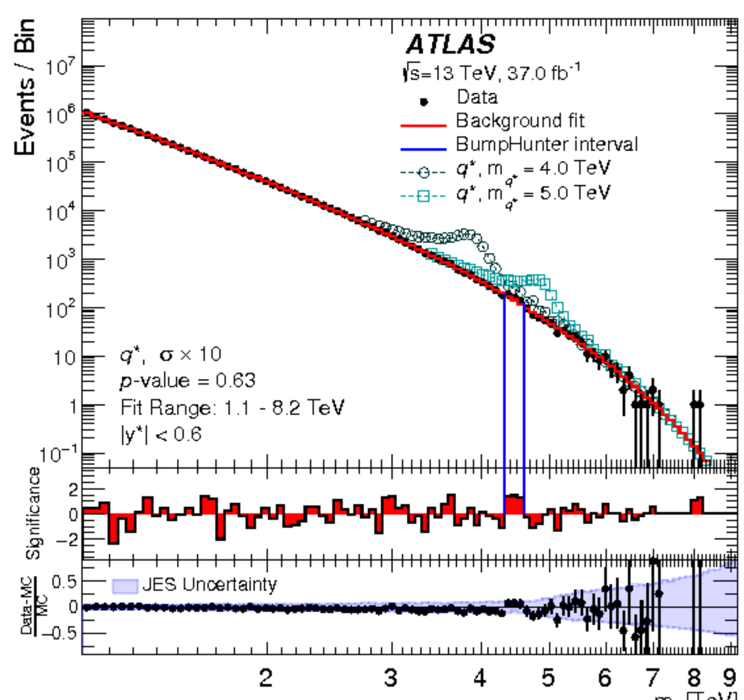


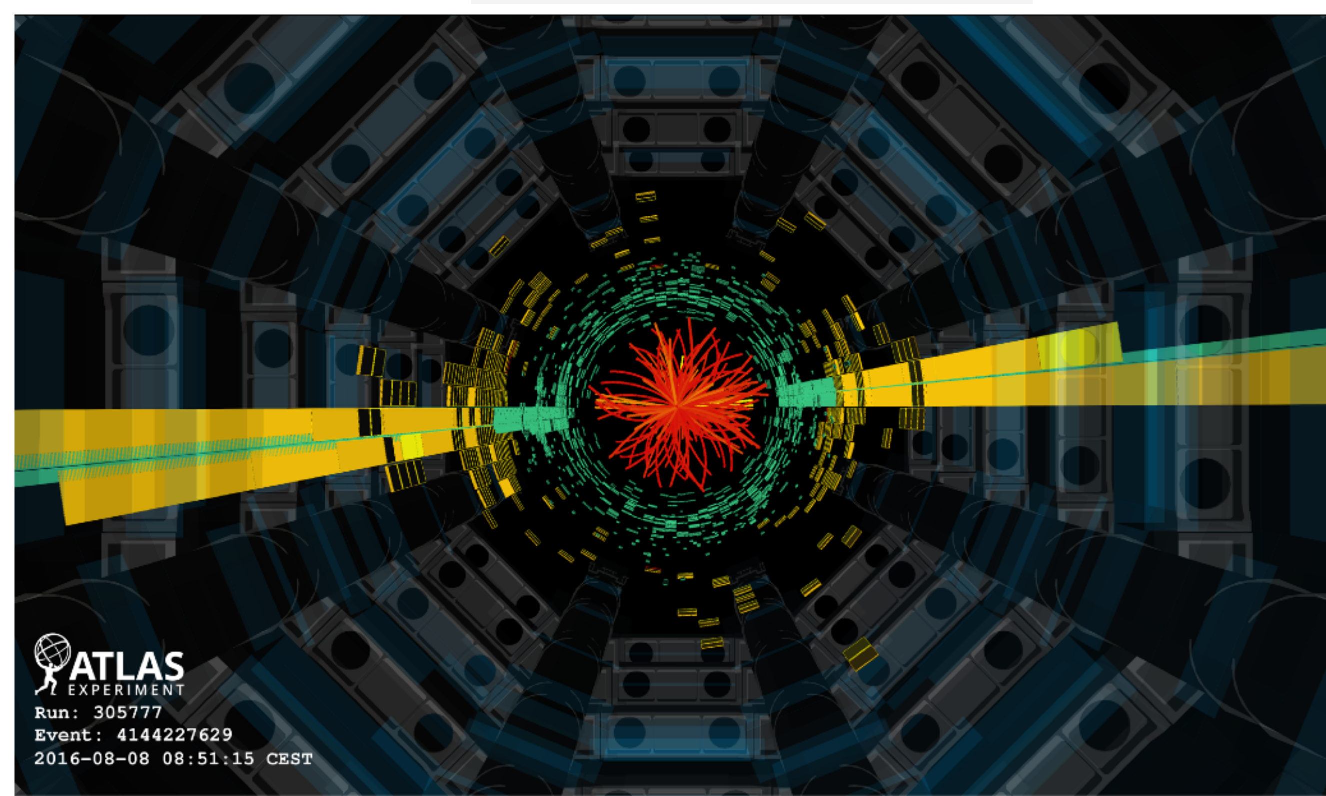
$$\rho = \frac{p}{ZeB}$$

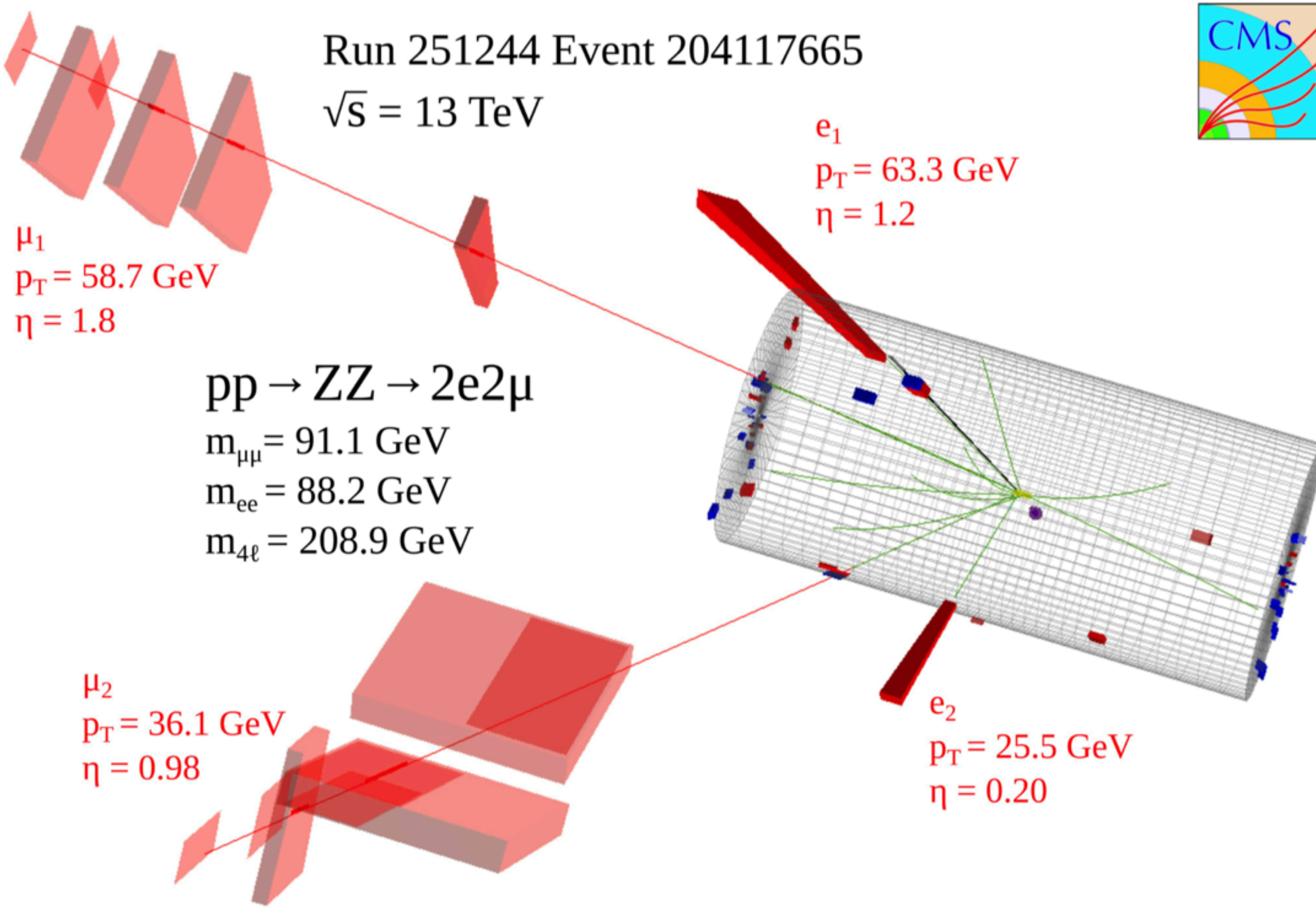

CMS
Jet 1,
pt = 2.88 TeV
eta = -0.364
phi = 1.915
Jet 0,
pt = 3.04 TeV
eta = 0.059
phi = -1.235
CMS Experiment at LHC, CERN
Data recorded: Mon Oct 12 2015 EEST
Run/Event: 258749 / 549864773
Lumi section: 355
Dijet Mass: 6.14 TeV


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

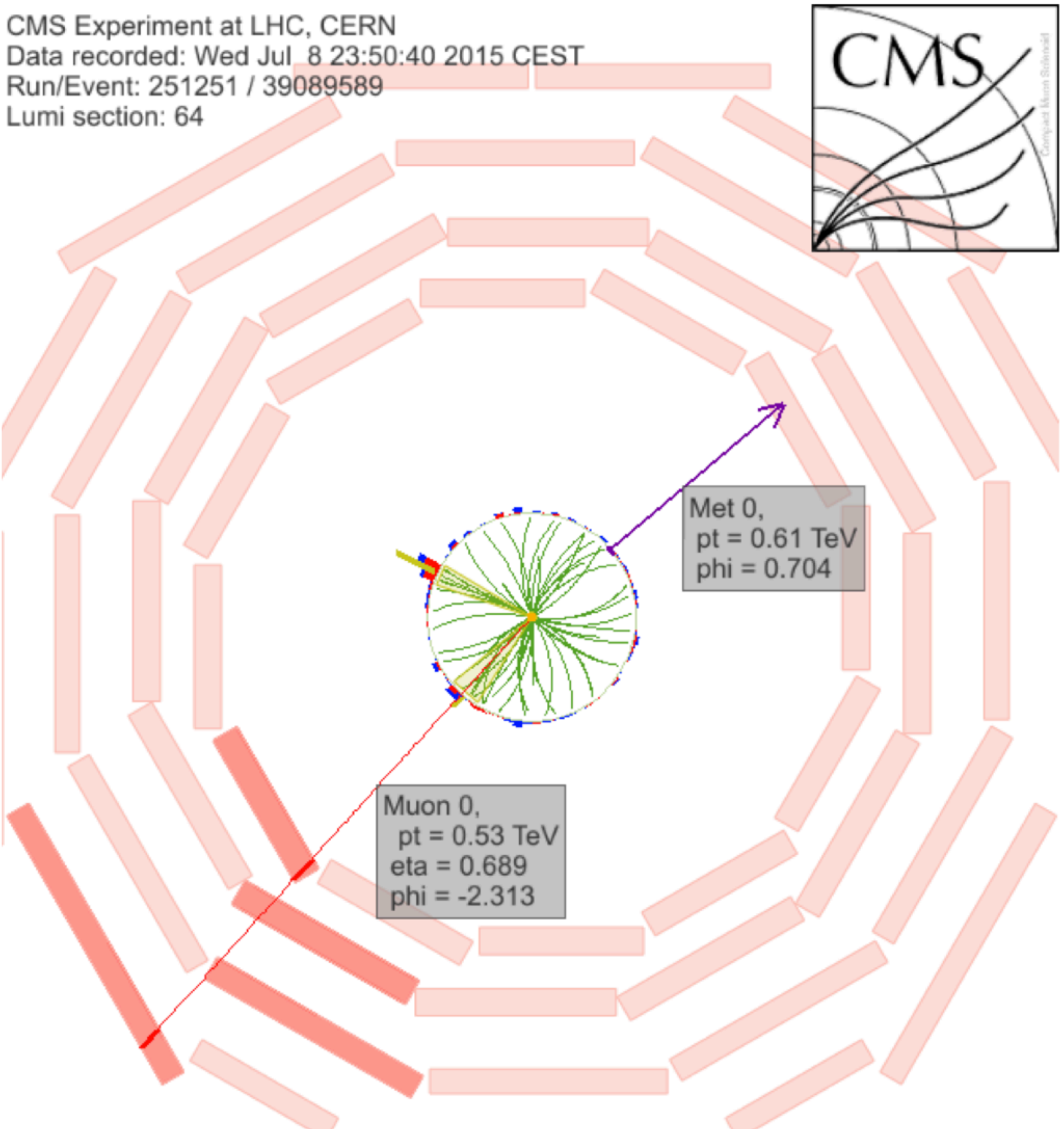

2.4 fb^{-1} (13 TeV)
CMS
Data
Fit
QCD MC
Color-octet scalar (3.1 TeV)
Excited quark (5.0 TeV)
Scalar diquark (6.0 TeV)
Wide jets
$|\eta| < 2.5, |\Delta\eta_{jj}| < 1.3$
$d\sigma / dm_{jj}$ [pb / TeV]
(Data-Fit) / σ_{stat}
Dijet mass [TeV]

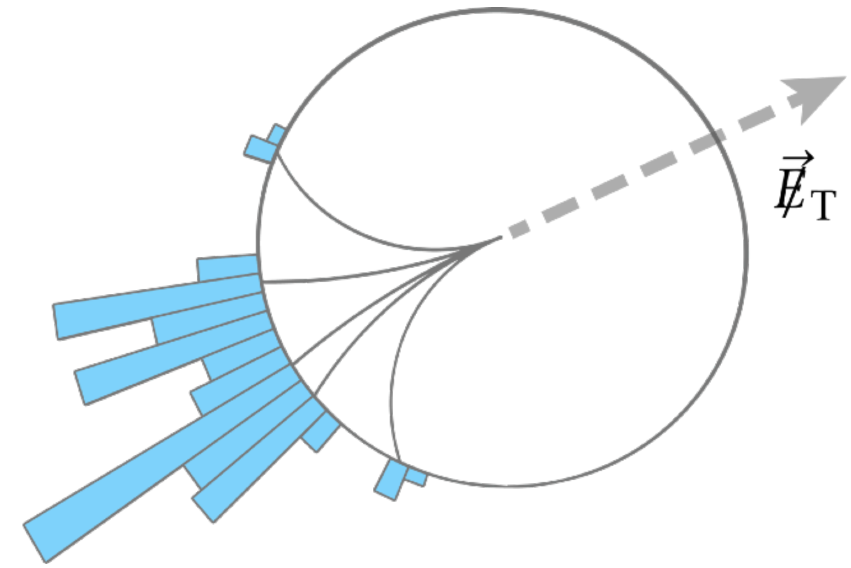

ATLAS
$\sqrt{s}$=13 TeV, 37.0 fb^{-1}
Data
Background fit
BumpHunter interval
q^*, m_{q^*} = 4.0 TeV
q^*, m_{q^*} = 5.0 TeV
q^*, $\sigma \times 10$
p-value = 0.63
Fit Range: 1.1 - 8.2 TeV
$|y^*| < 0.6$
Events / Bin
Significance
JES Uncertainty
Data-MC / MC
m_{jj} [TeV]

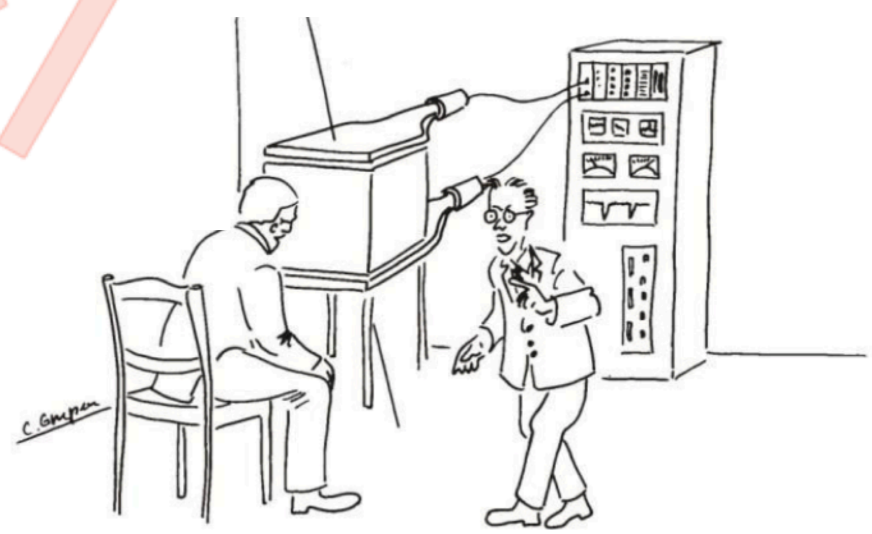

ATLAS
EXPERIMENT
Run: 305777
Event: 4144227629
2016-08-08 08:51:15 CEST


Run 251244 Event 204117665
$\sqrt{s}$ = 13 TeV
μ_1
p_T = 58.7 GeV
η = 1.8
e_1
p_T = 63.3 GeV
η = 1.2
$pp \rightarrow ZZ \rightarrow 2e2\mu$
$m_{\mu\mu}$ = 91.1 GeV
m_{ee} = 88.2 GeV
$m_{4\ell}$ = 208.9 GeV
μ_2
p_T = 36.1 GeV
η = 0.98
e_2
p_T = 25.5 GeV
η = 0.20

Missing momentum



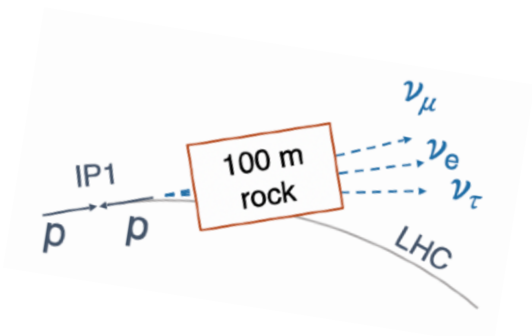


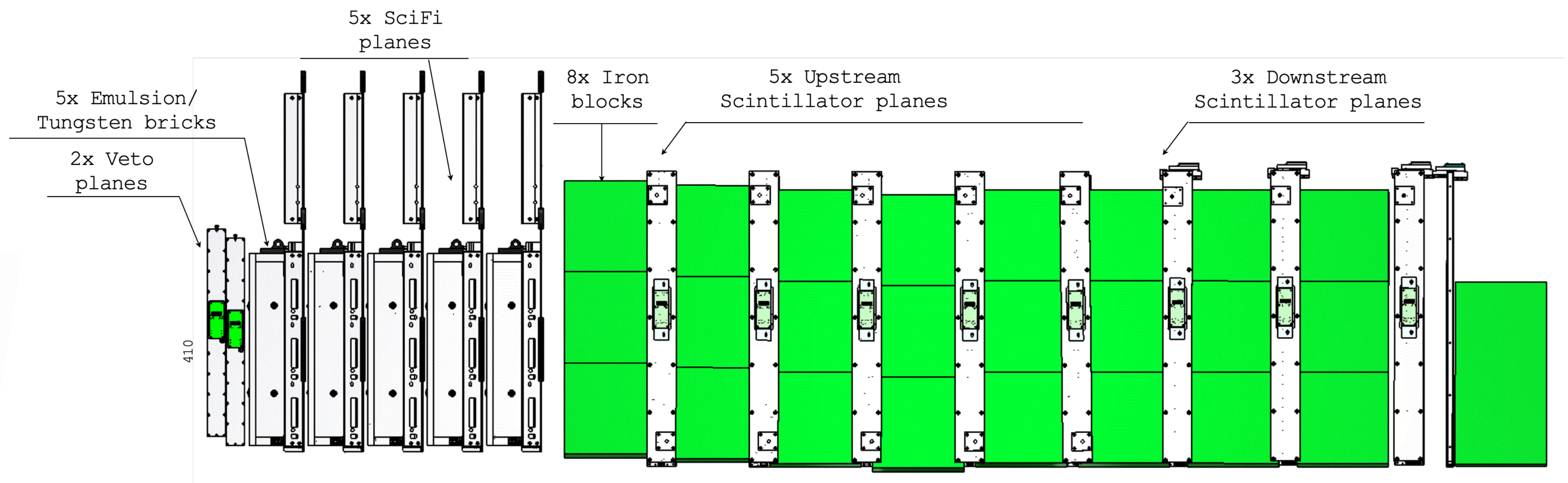


"Did you see it?"
"No nothing."
"Then it was a neutrino!"

Neutrinos cannot be detected at the LHC! … or can they

The Dawn of Collider Neutrino Physics @LHC

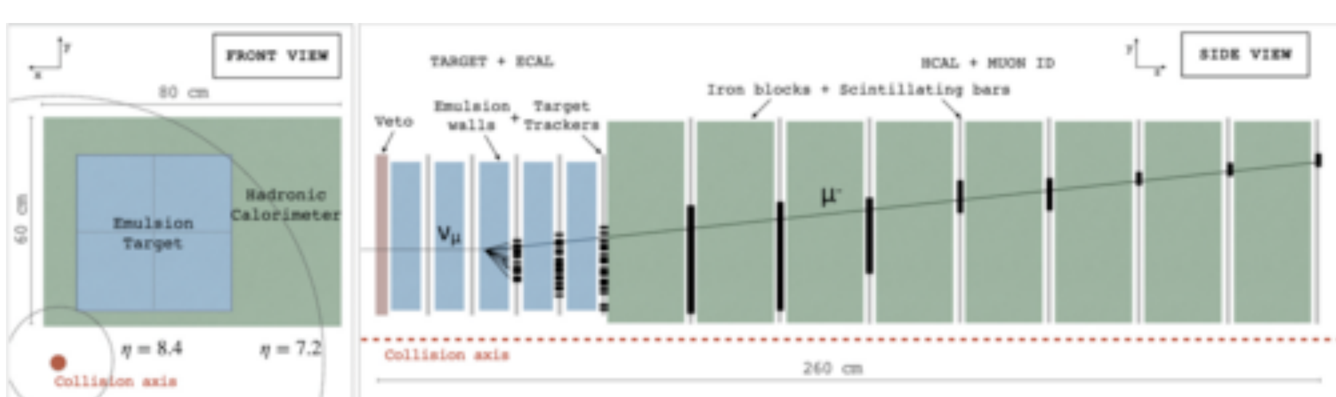


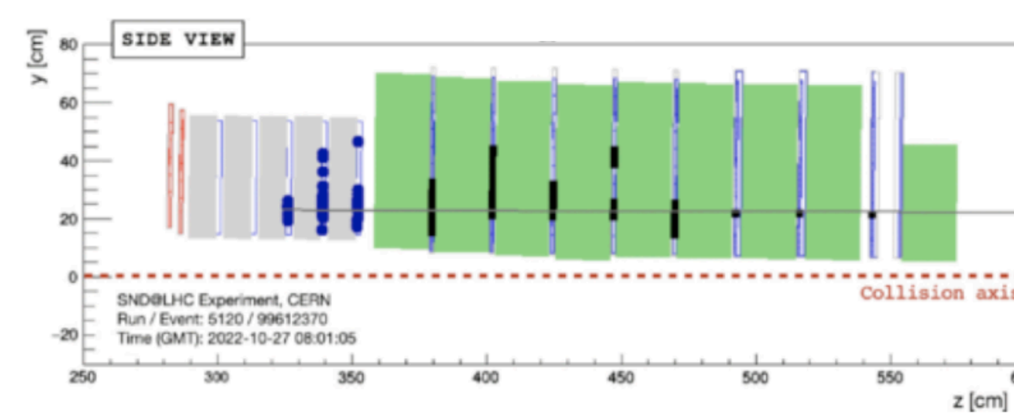


target/ tracker

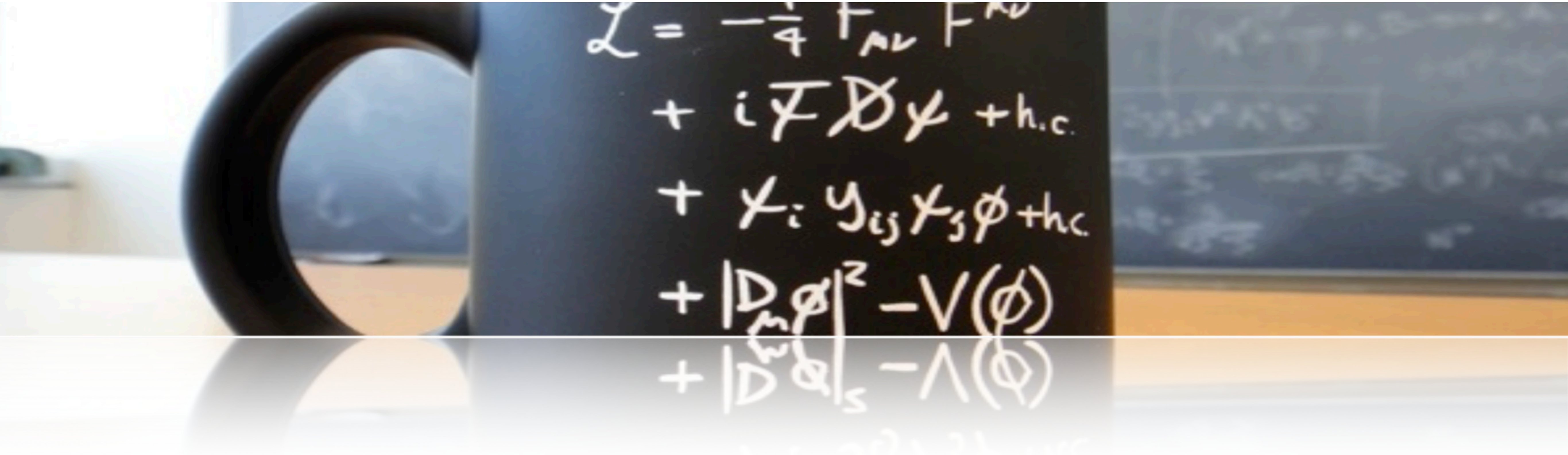
had. calorimeter

muon chambers

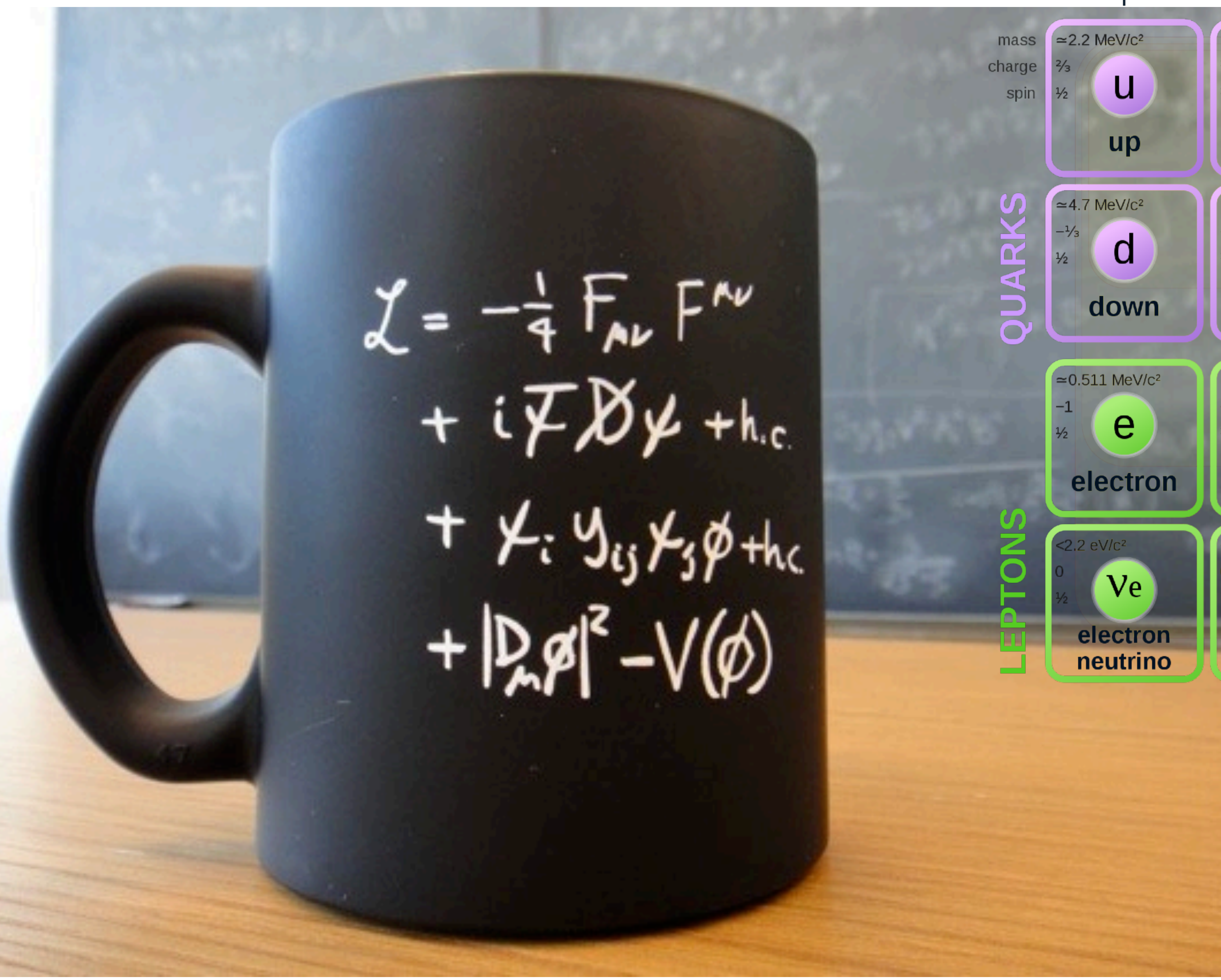


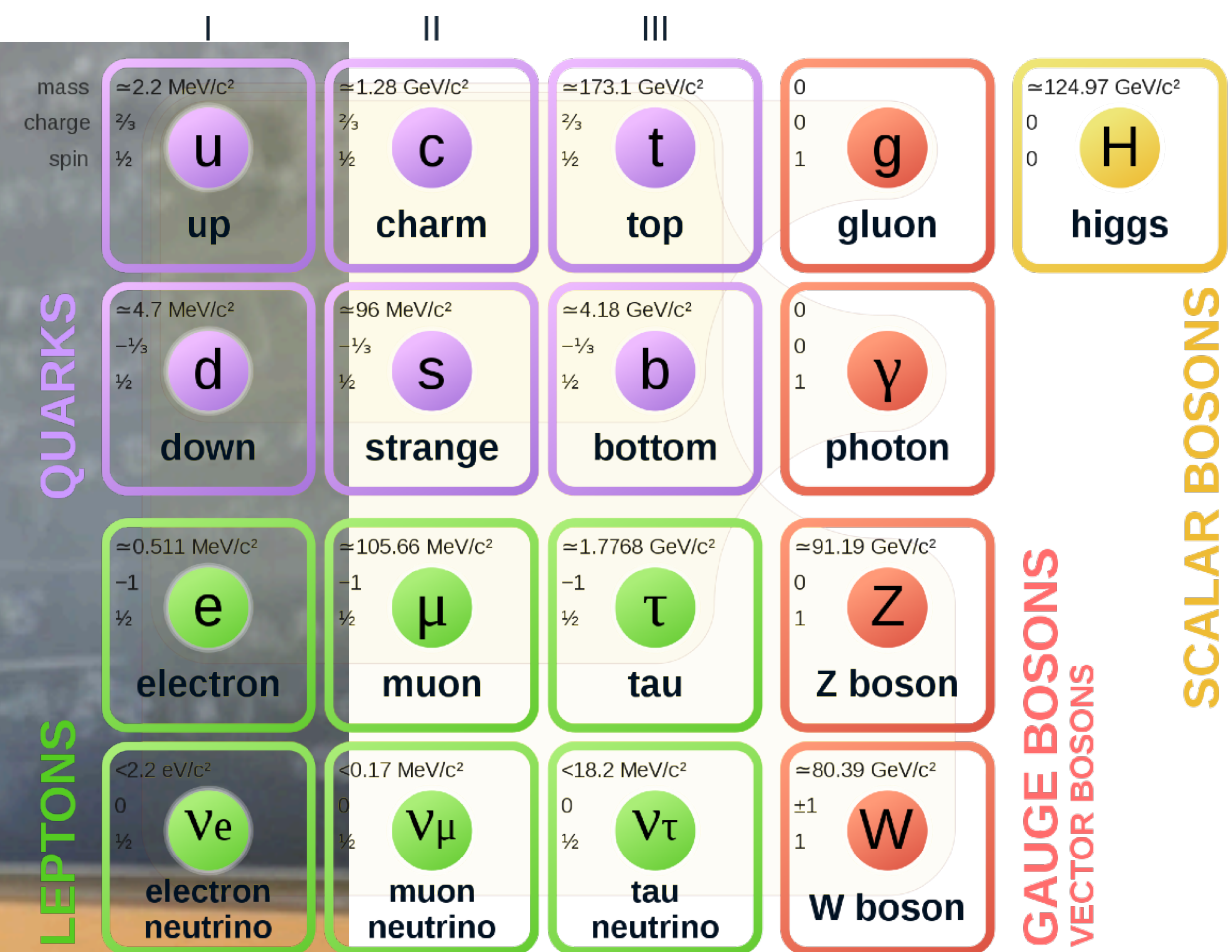


Physics



The Standard Model of Particle Physics



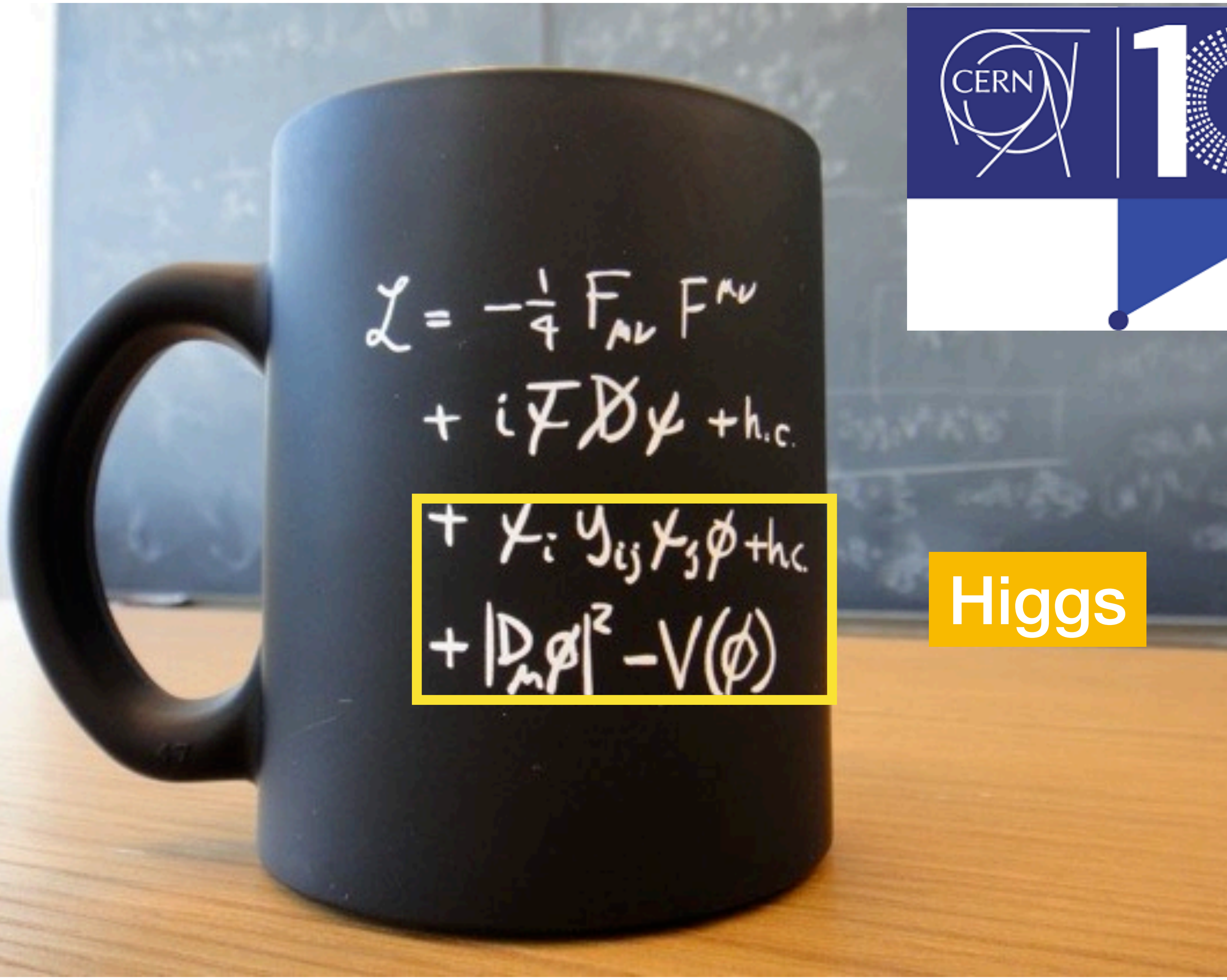


SM predictions can be tested against experimental data

SM = Quantum field theory + Experimental measurement & discovery

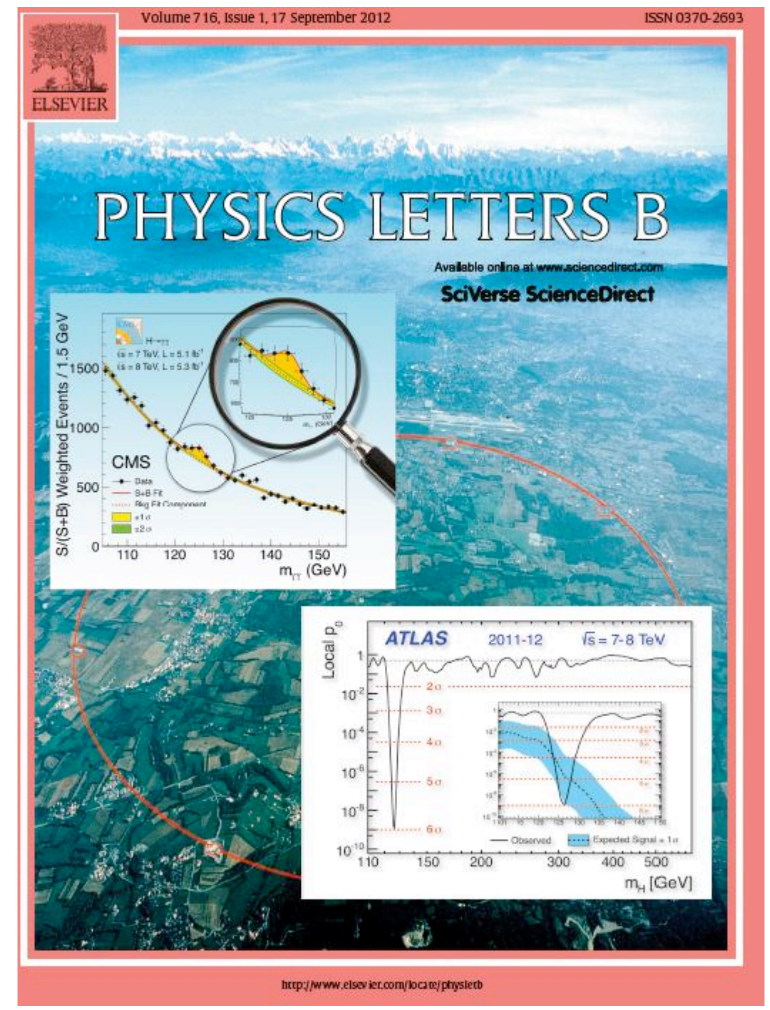
One of the great achievements of 20_{th} century science.

The Higgs boson



Higgs

CERN 10 years HIGGS boson discovery



SM = Quantum field theory + Experimental measurement & discovery

One of the great achievements of 20_{th} century science.

The Higgs boson (discovery) turns 12

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.

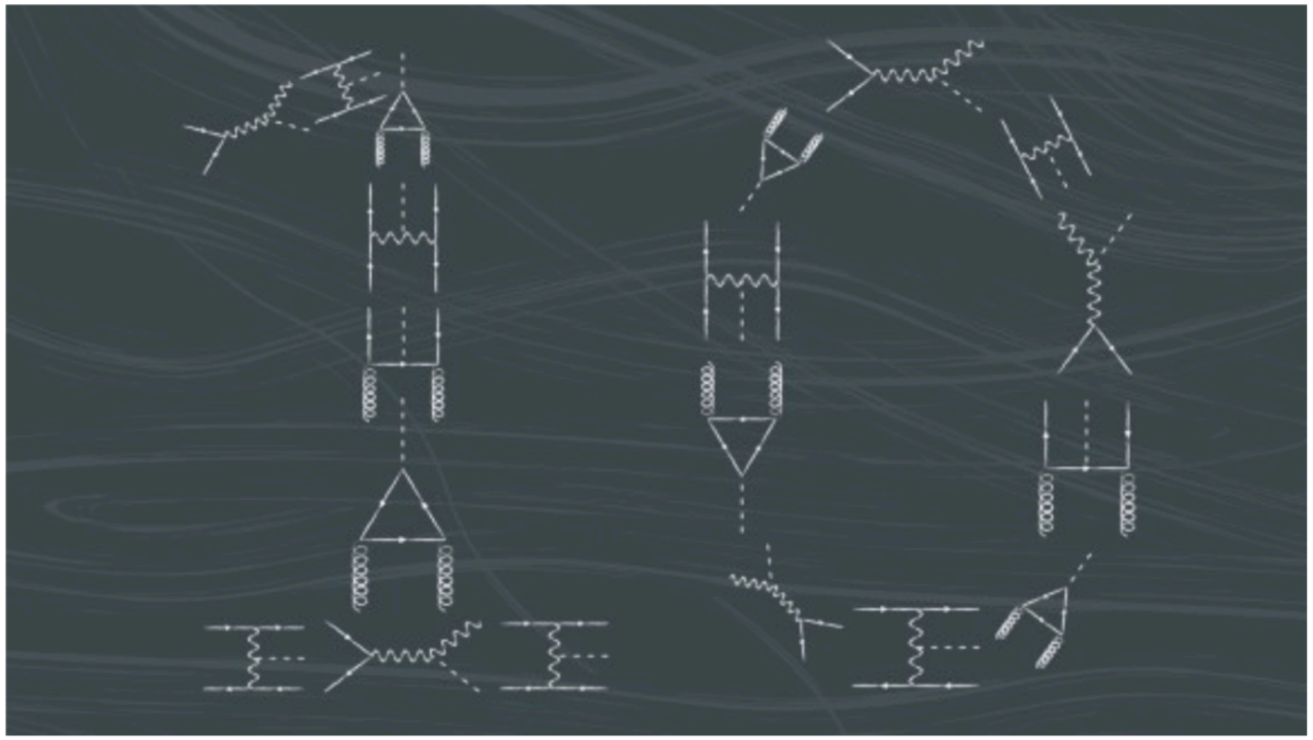
The CMS Collaboration

Article | Open Access | 4 Jul 2022 | Nature

Collection | **04 July 2022**

The Higgs boson discovery turns ten

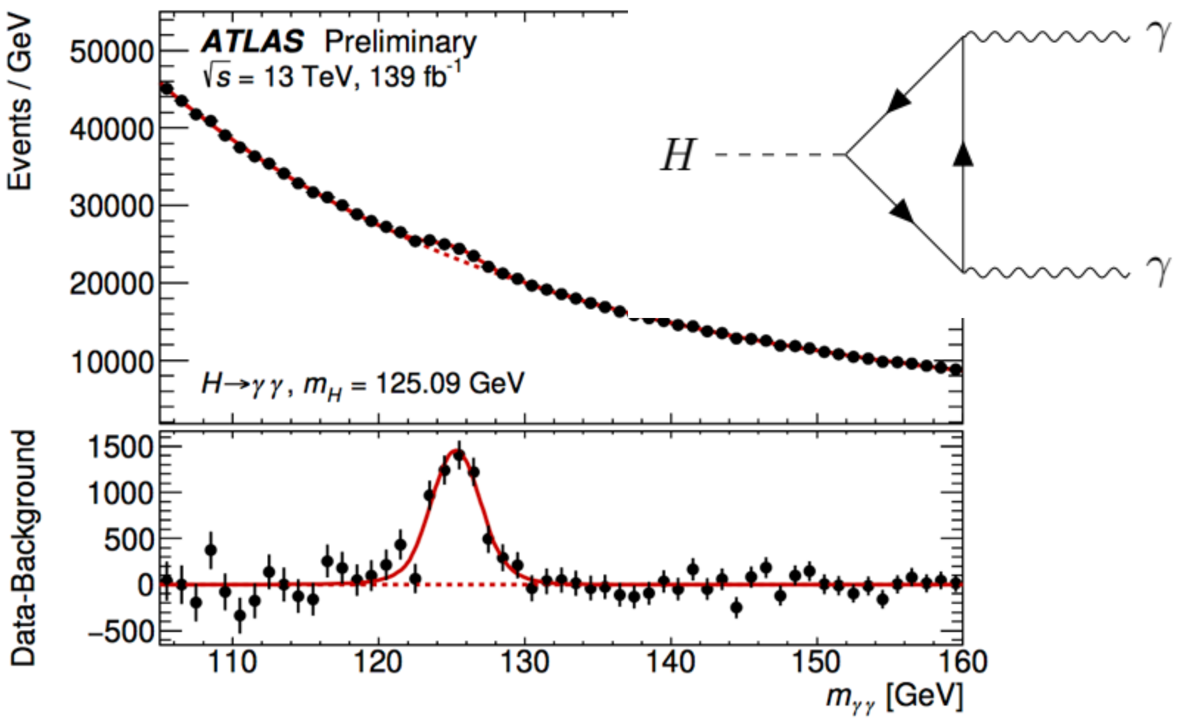
The discovery of the Higgs boson was announced ten years ago on the 4th of July 2012 — an event that substantially advanced our understanding of the origin of elementary particles' masses. In this collection of articles from *Nature, Nature Physics* and *Nature Reviews Physics* we celebrate this groundbreaking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

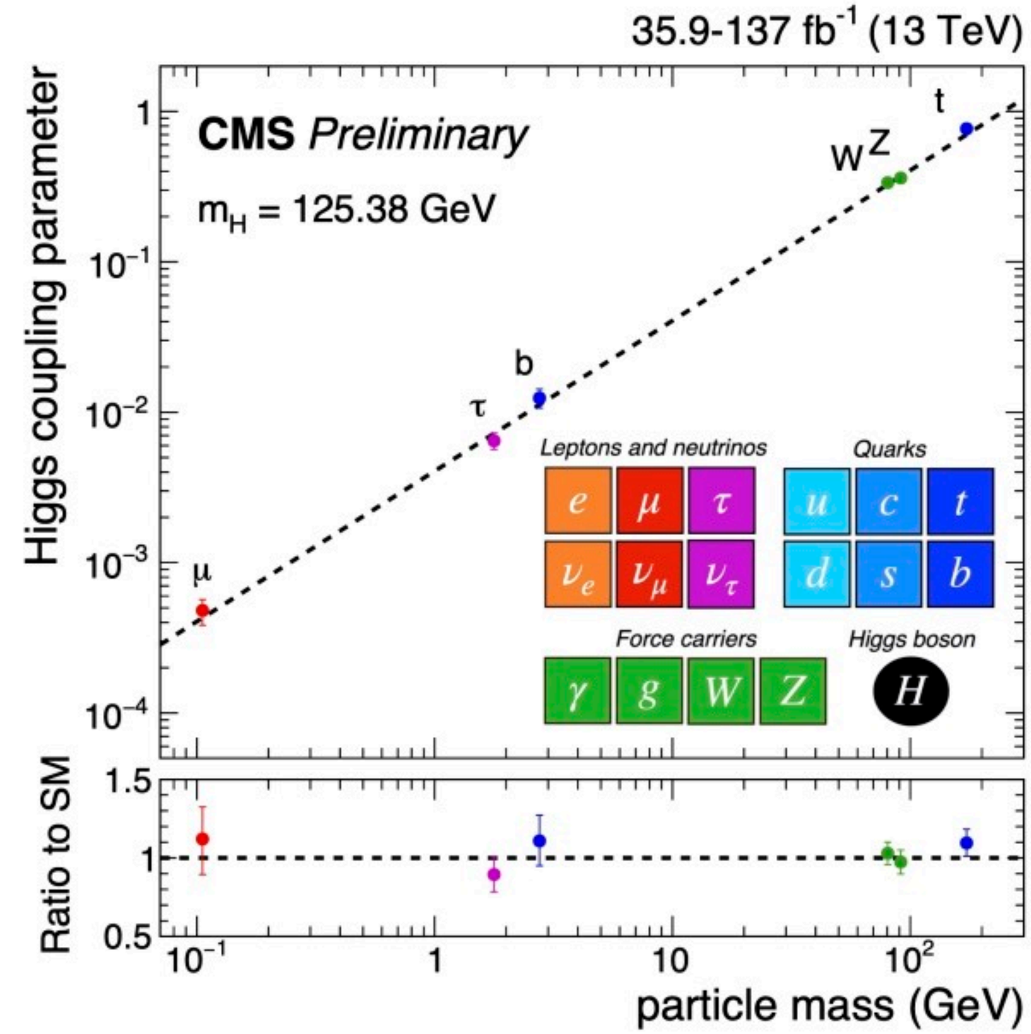


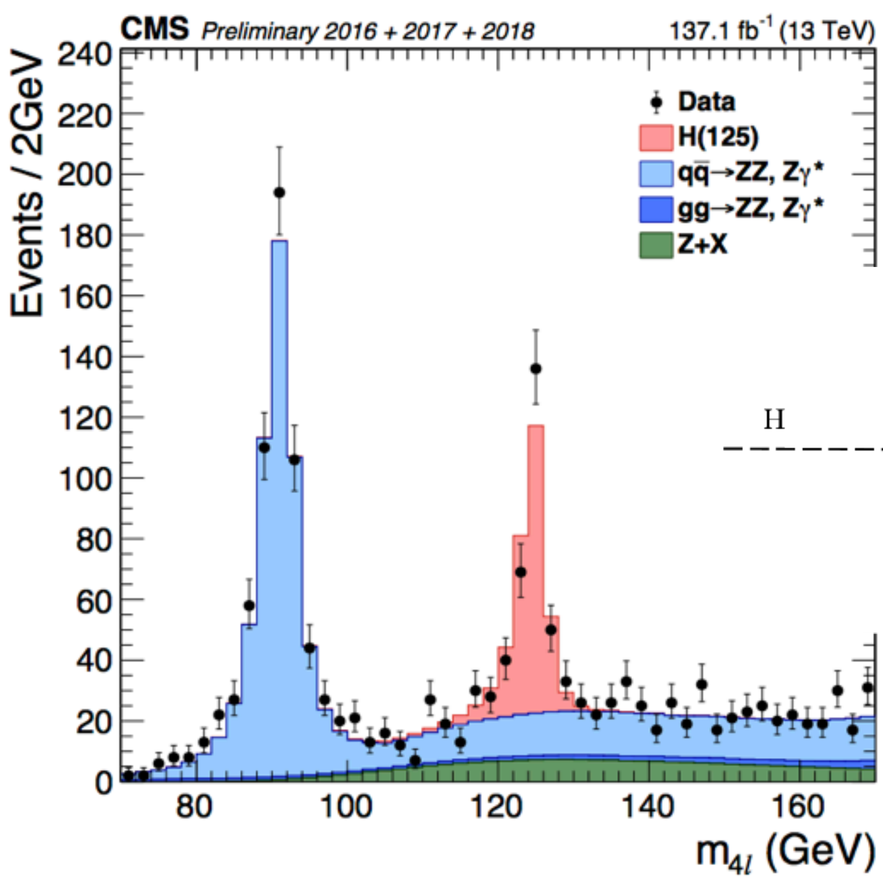
https://home.cern/news/press-release/physics/higgs-boson-ten-years-after-its-discovery

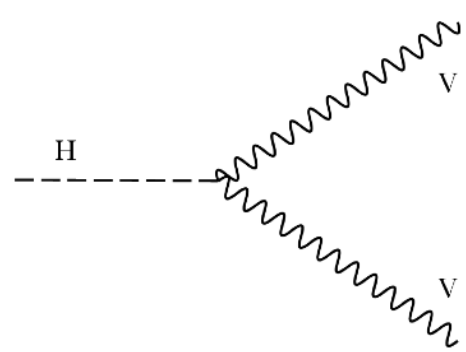
https://www.nature.com/collections/gbfhieacie

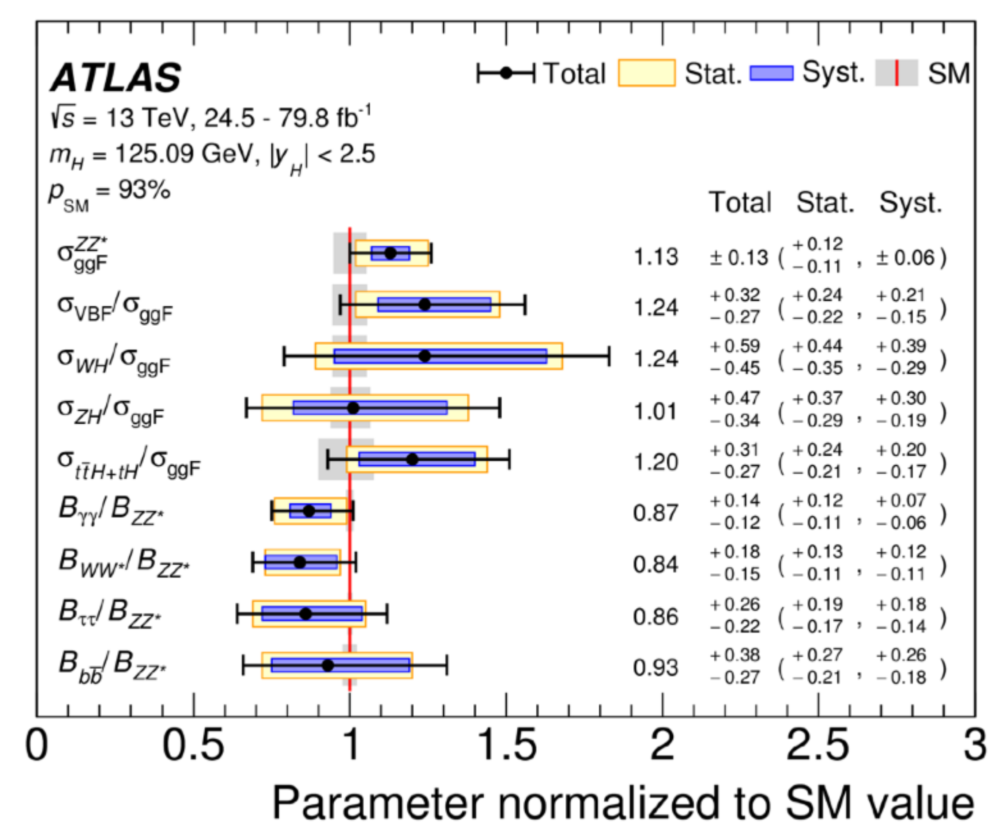
Status of the scalar





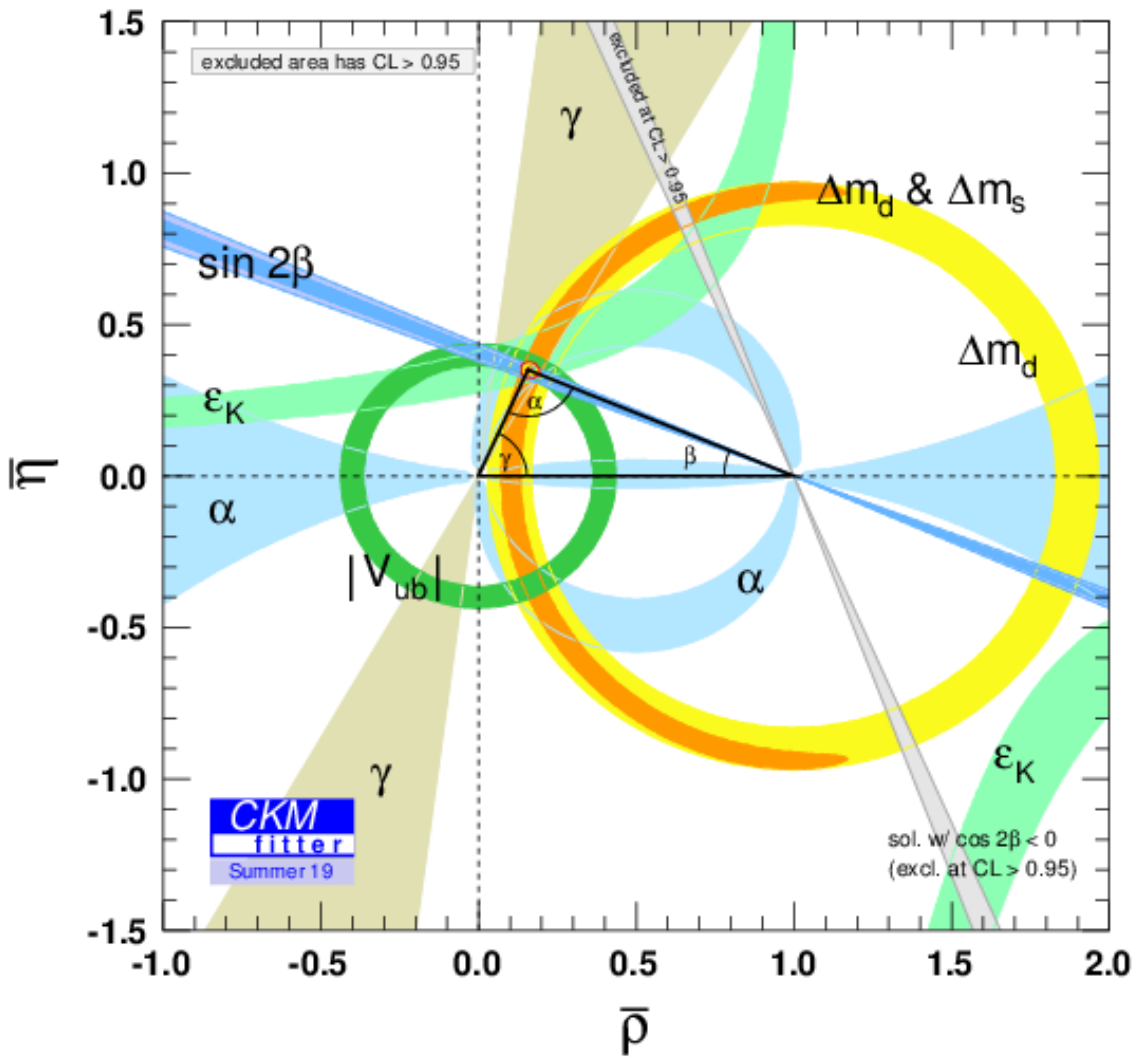




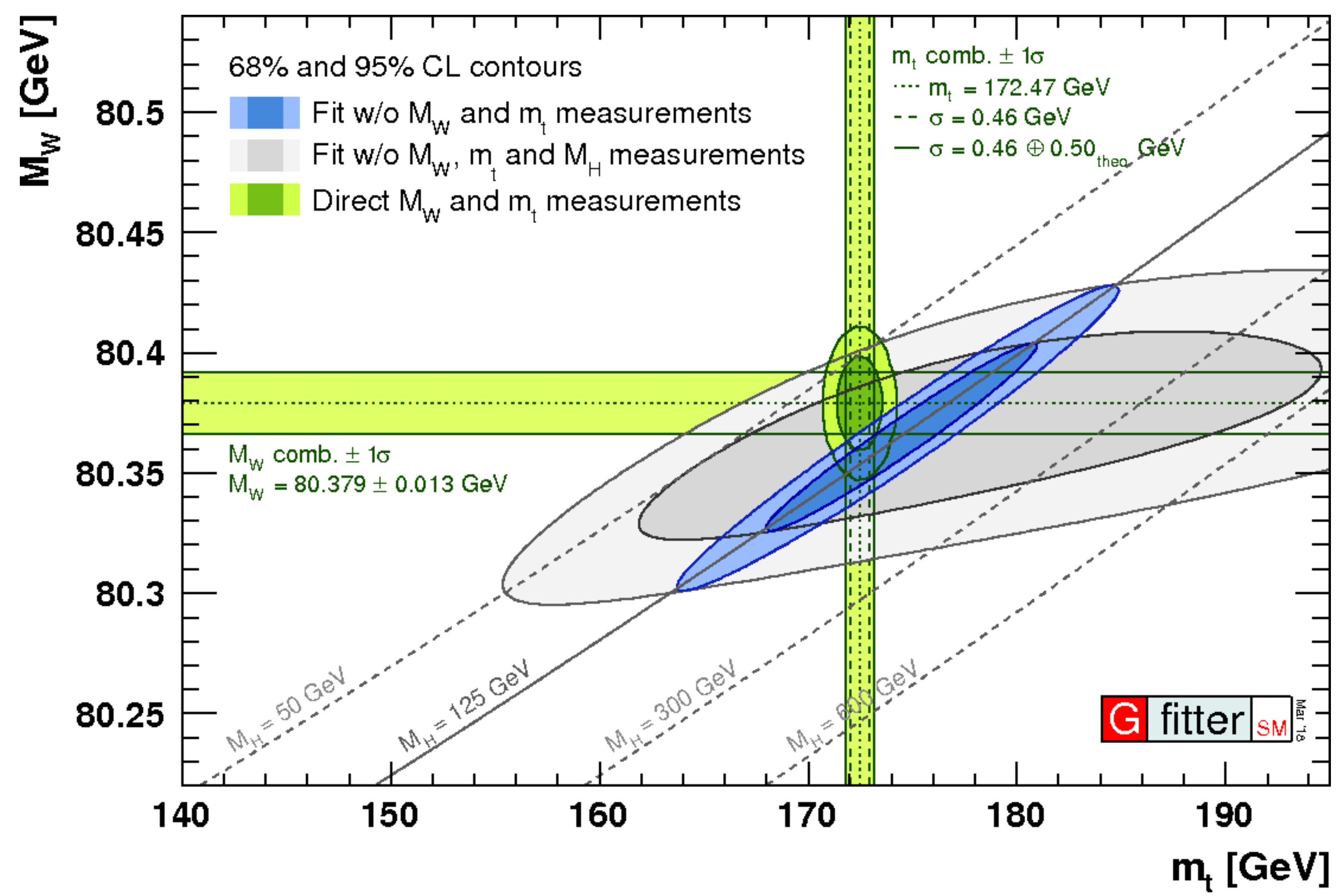


The Standard Model: precision measurements

quarks



H vs W vs t

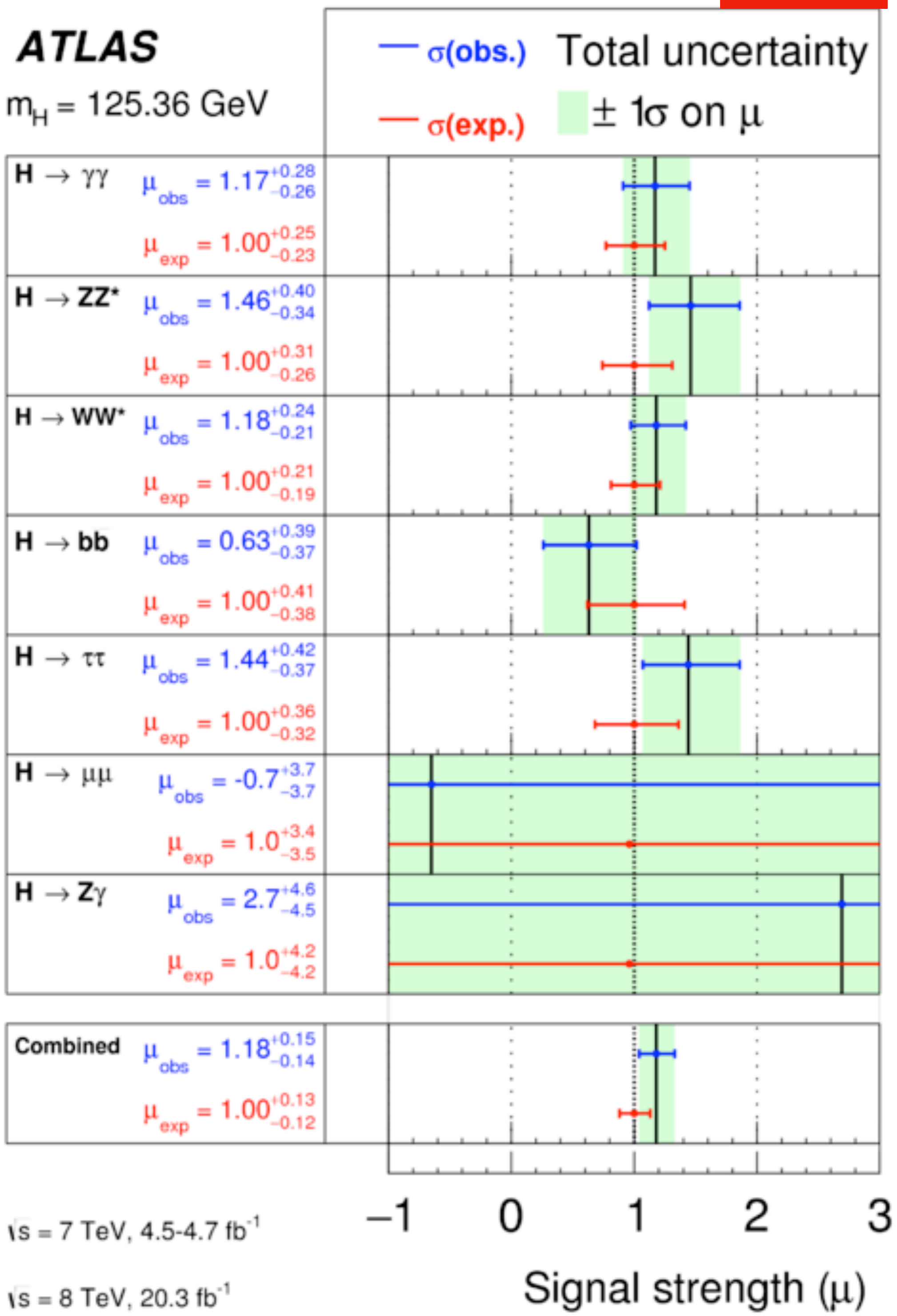


The SM describes all (*) experimental data !

SM = Precision

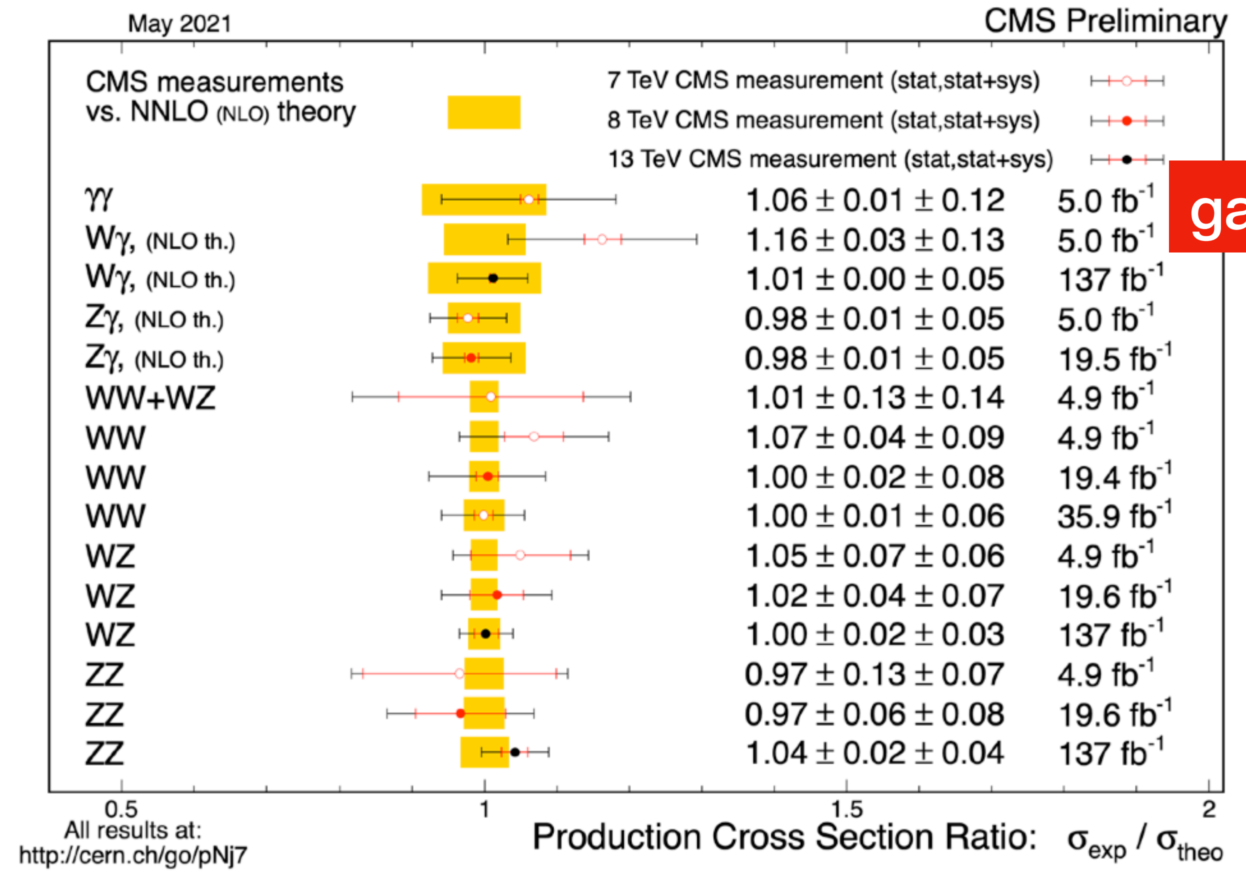
data vs theory

higgs

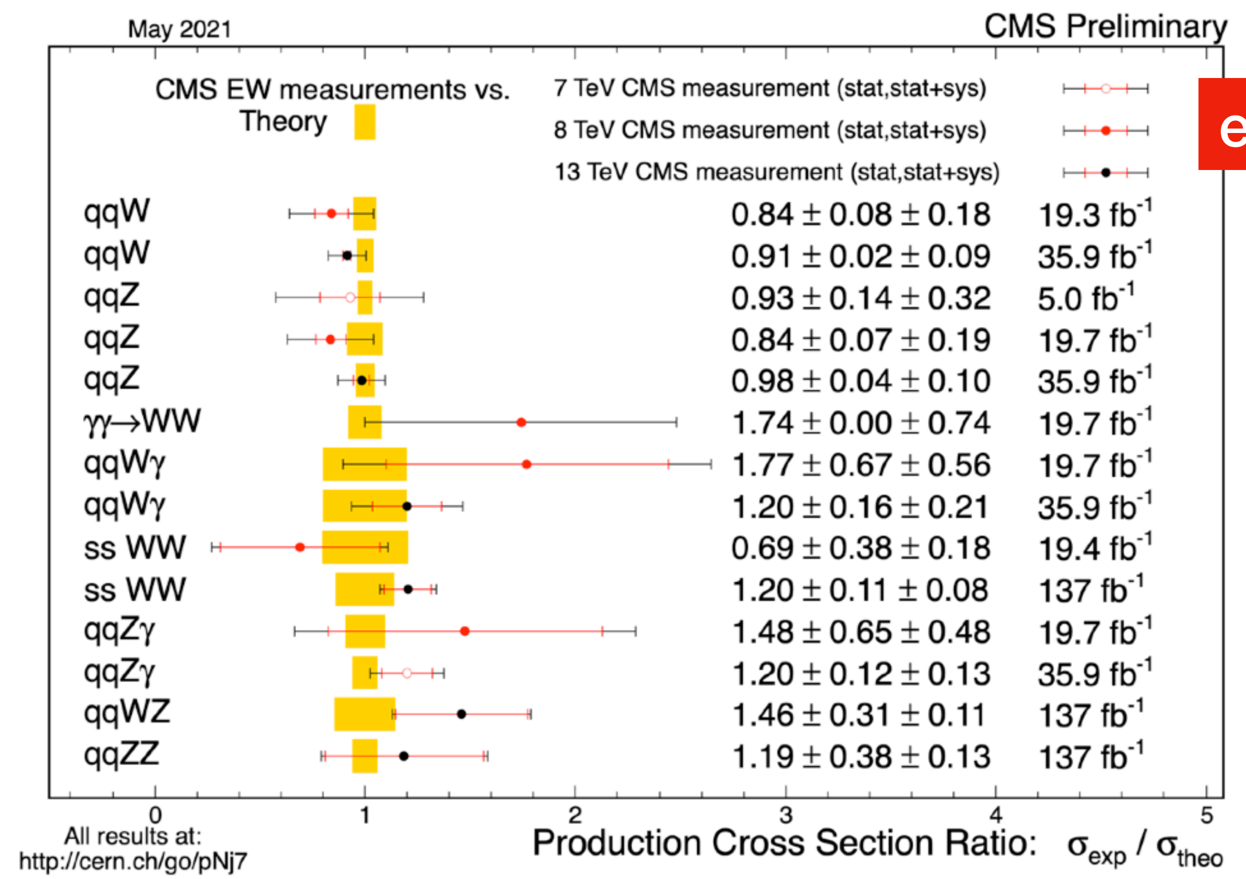


μ = data/SM

gauge

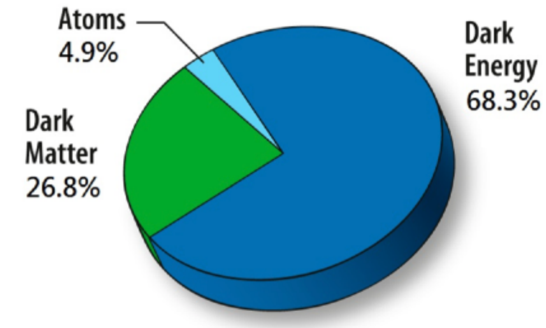


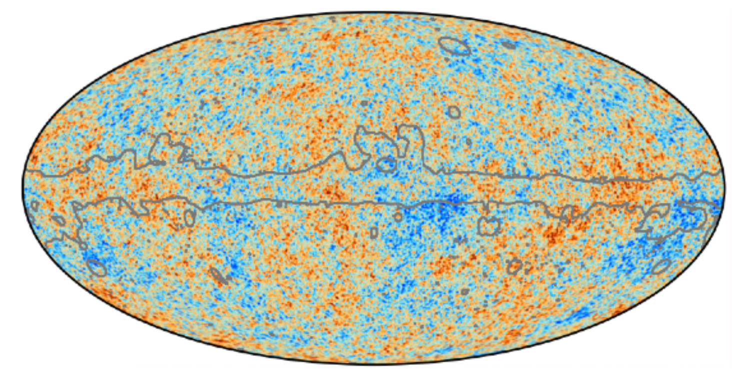
ewk



So, Why the need to go beyond the SM?

SM + gravity ≠ cosmos

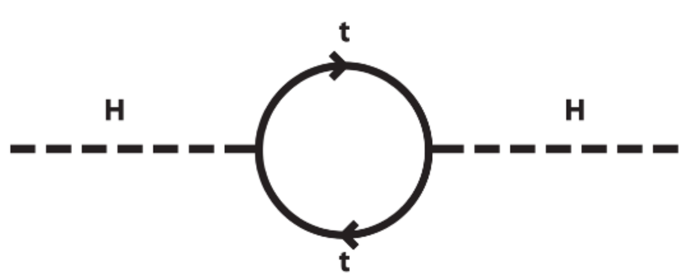




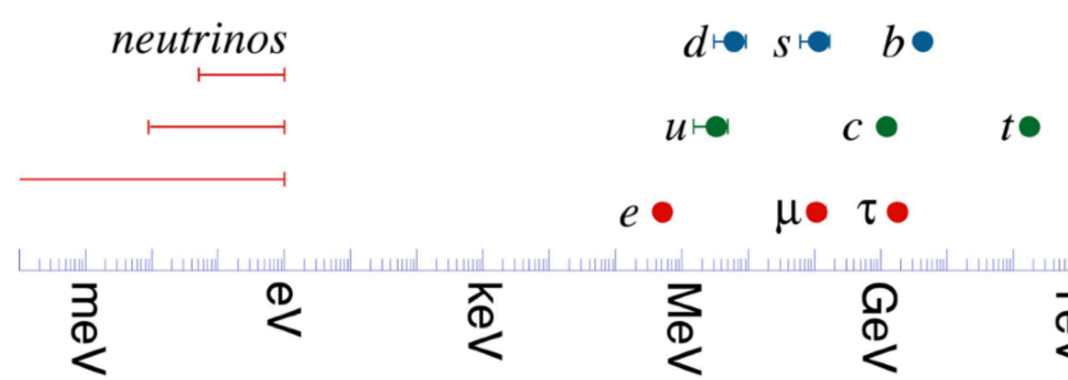
Dados que ***decididamente*** **não conseguimos explicar:**

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

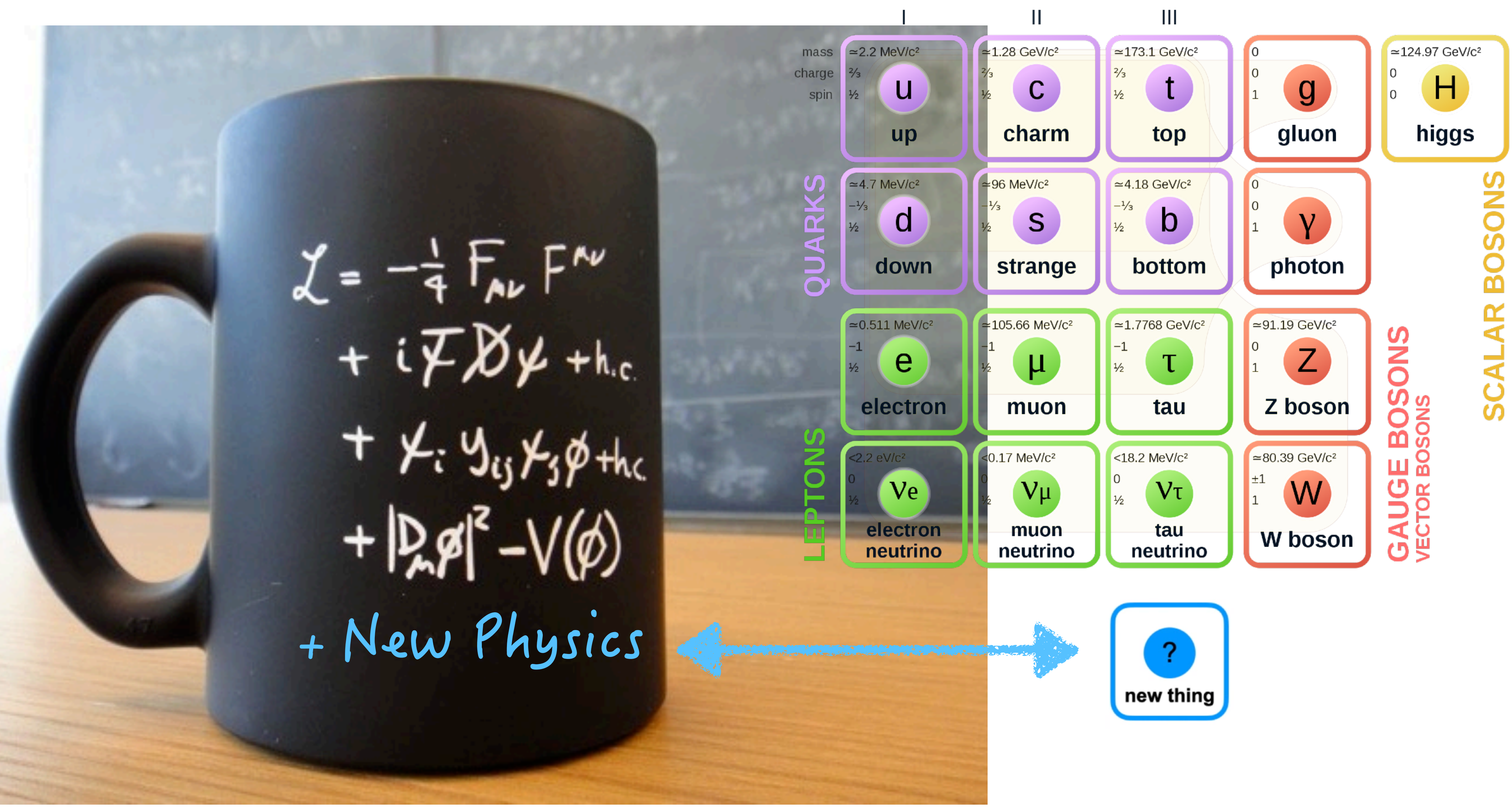
- **Hierarquia electrofraca**
  - Fraca/Gravidade ~10^{24}
  - EWK << Planck (Deserto?)
  - Instabilidade da massa do Higgs
  - Fine tuning
  - Naturalness



- **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?



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

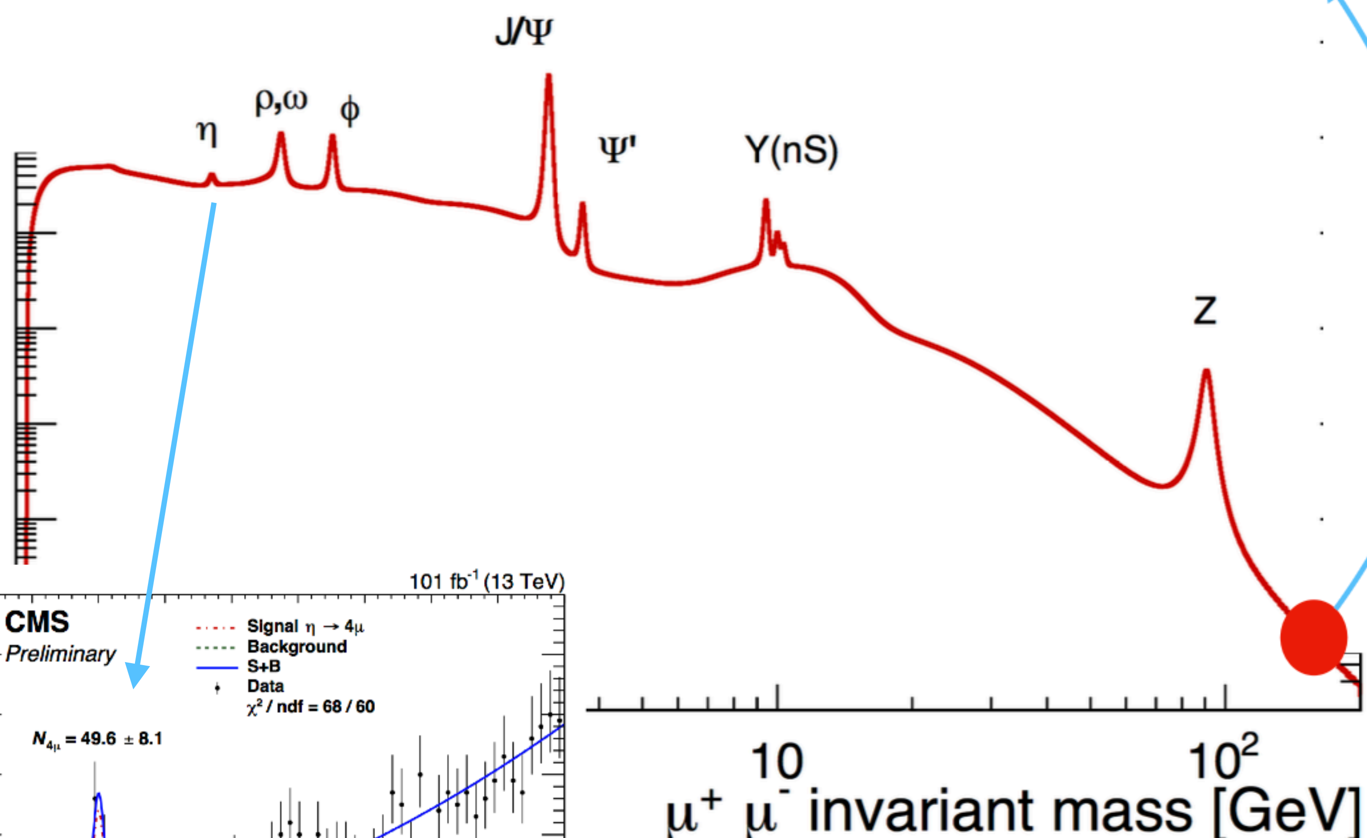
Infer presence of BSM particles through their effect on properties of SM particles

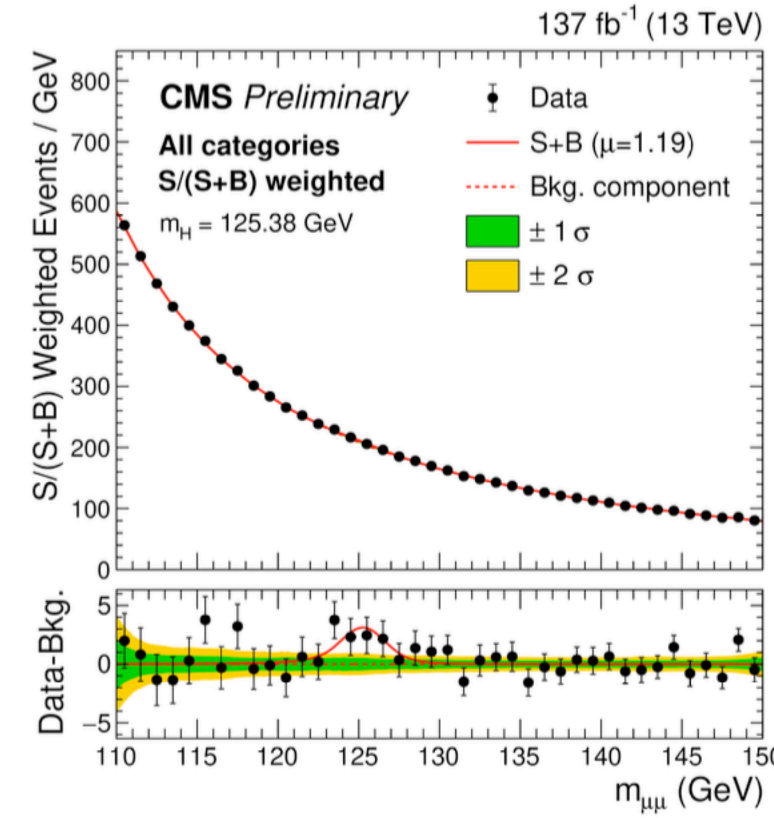
New particles discovered at LHC?

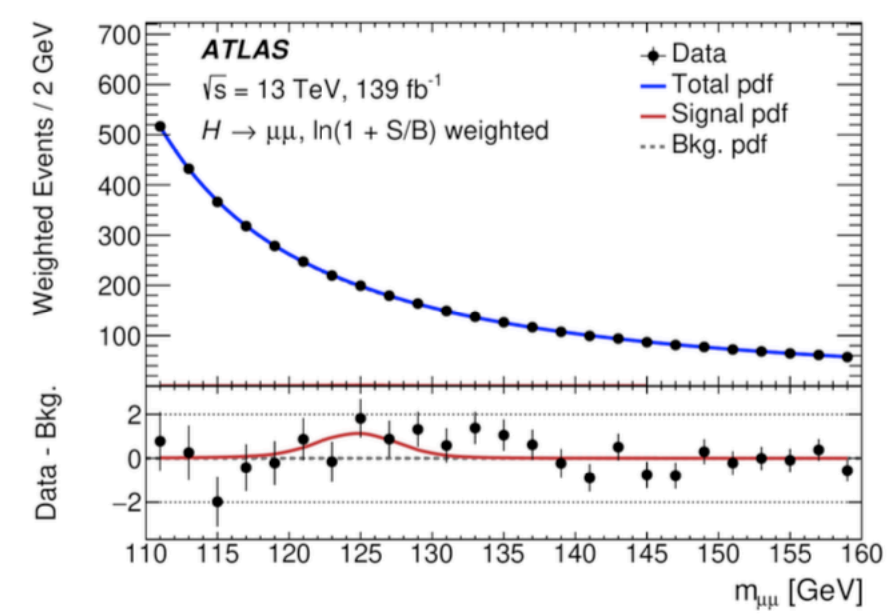
New ~~particles~~ discovered at LHC?
interactions

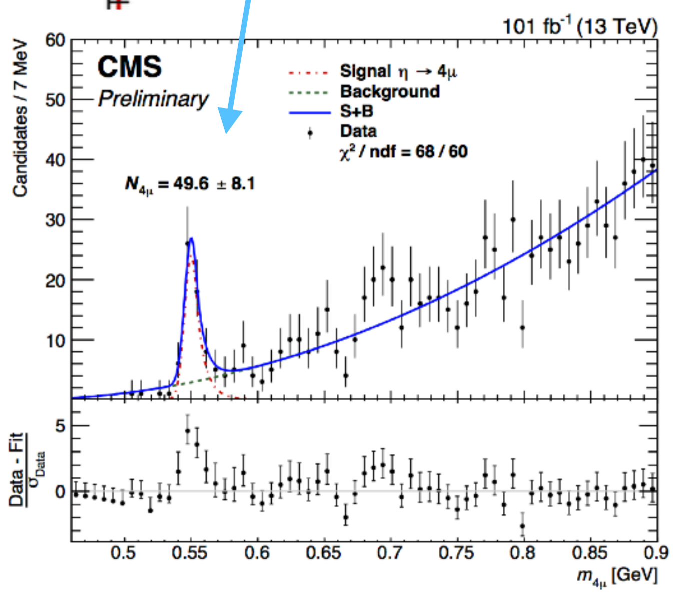
evidence for

H→μμ





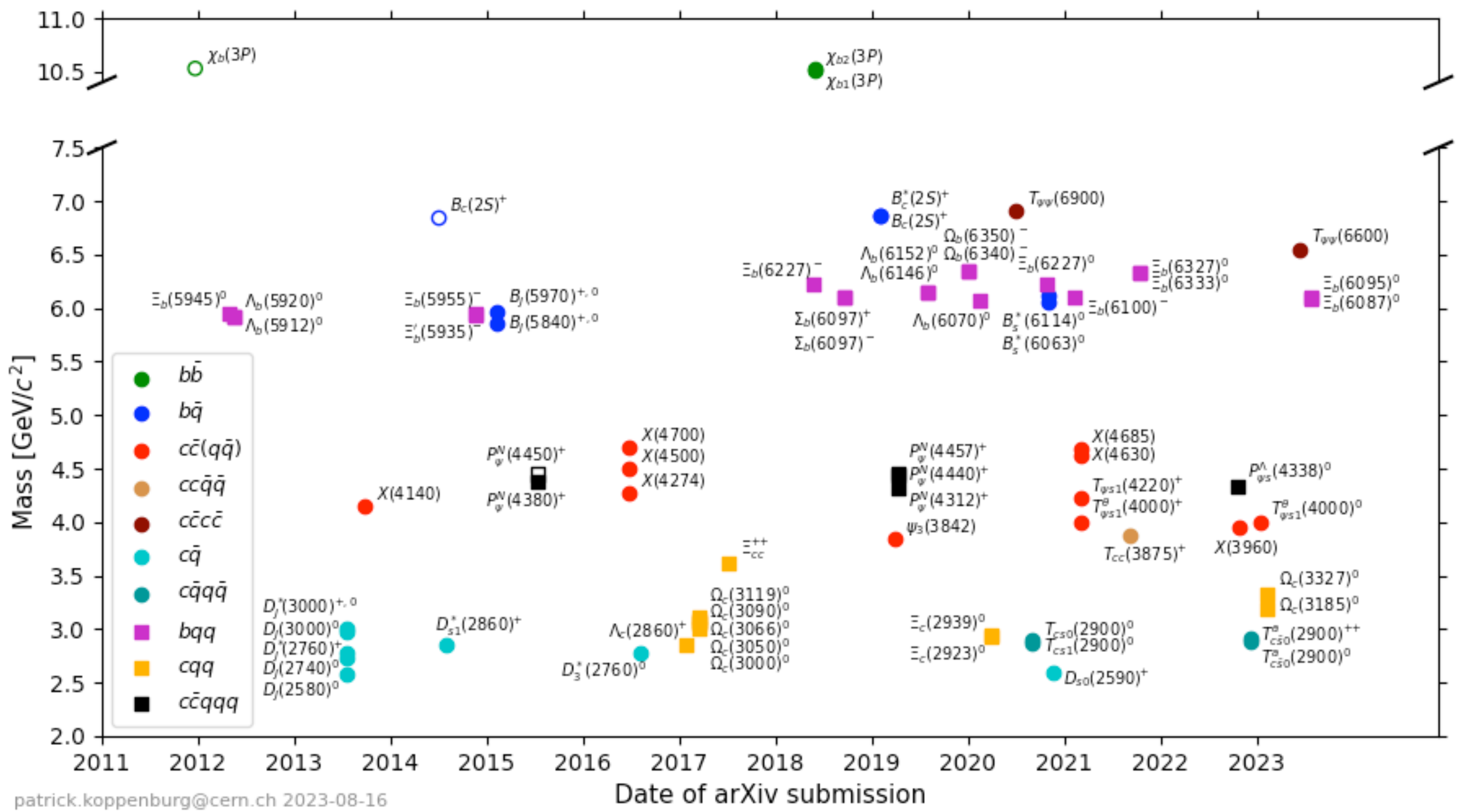




η→μμμμ

observation of new low-mass rare decay (with data scouting)

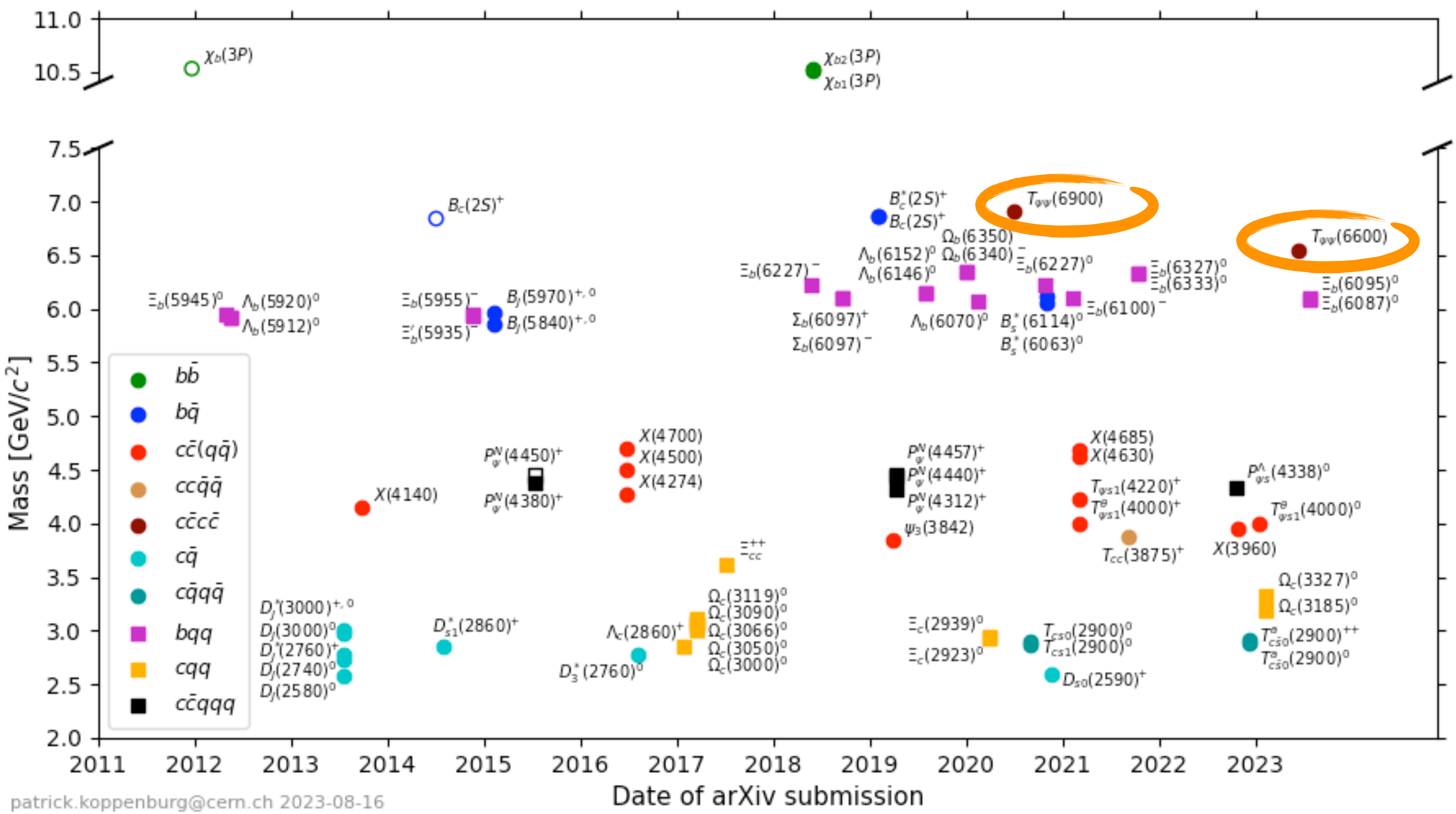
New particles discovered at LHC?



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

https://www.nikhef.nl/~pkoppenb/particles.html

New particles discovered at LHC?

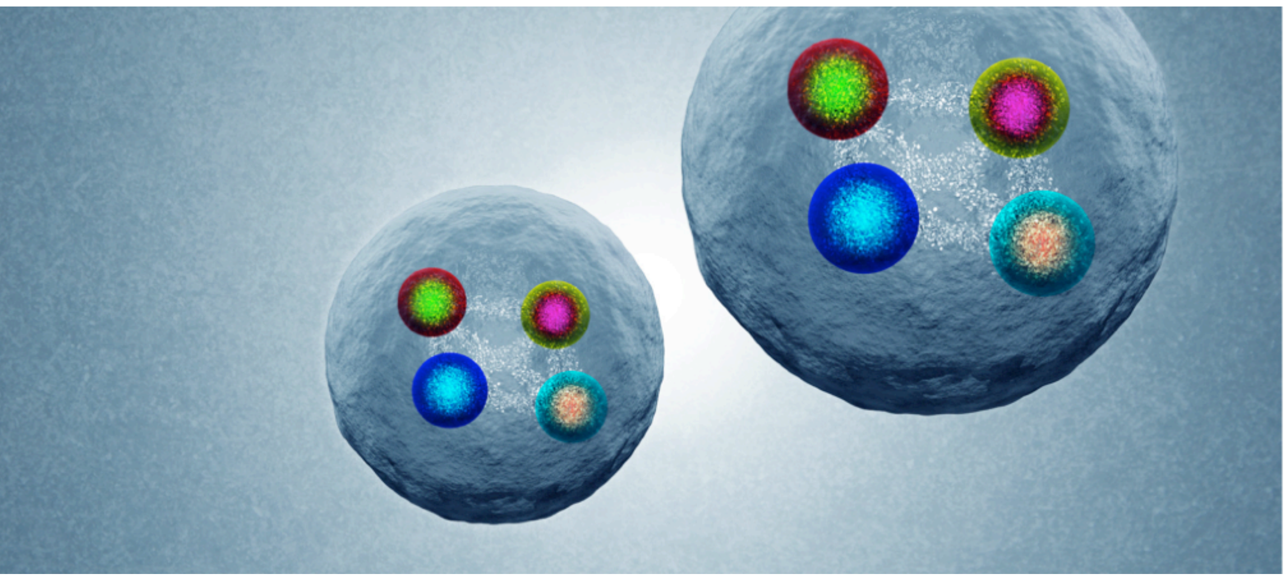


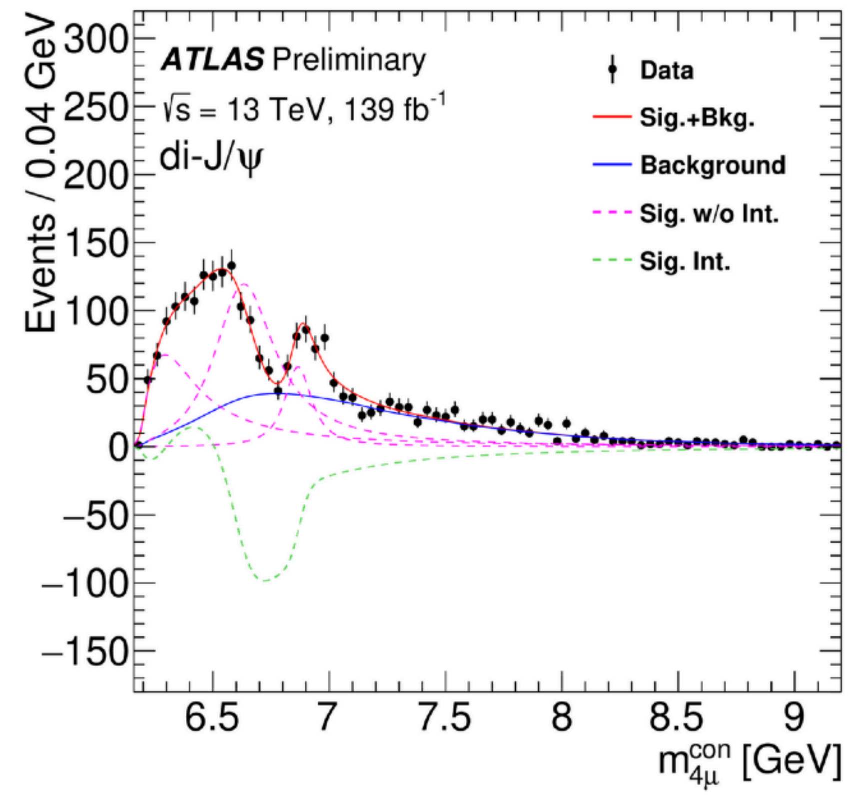
72+1 new particles already discovered — and more awaiting to be discovered !

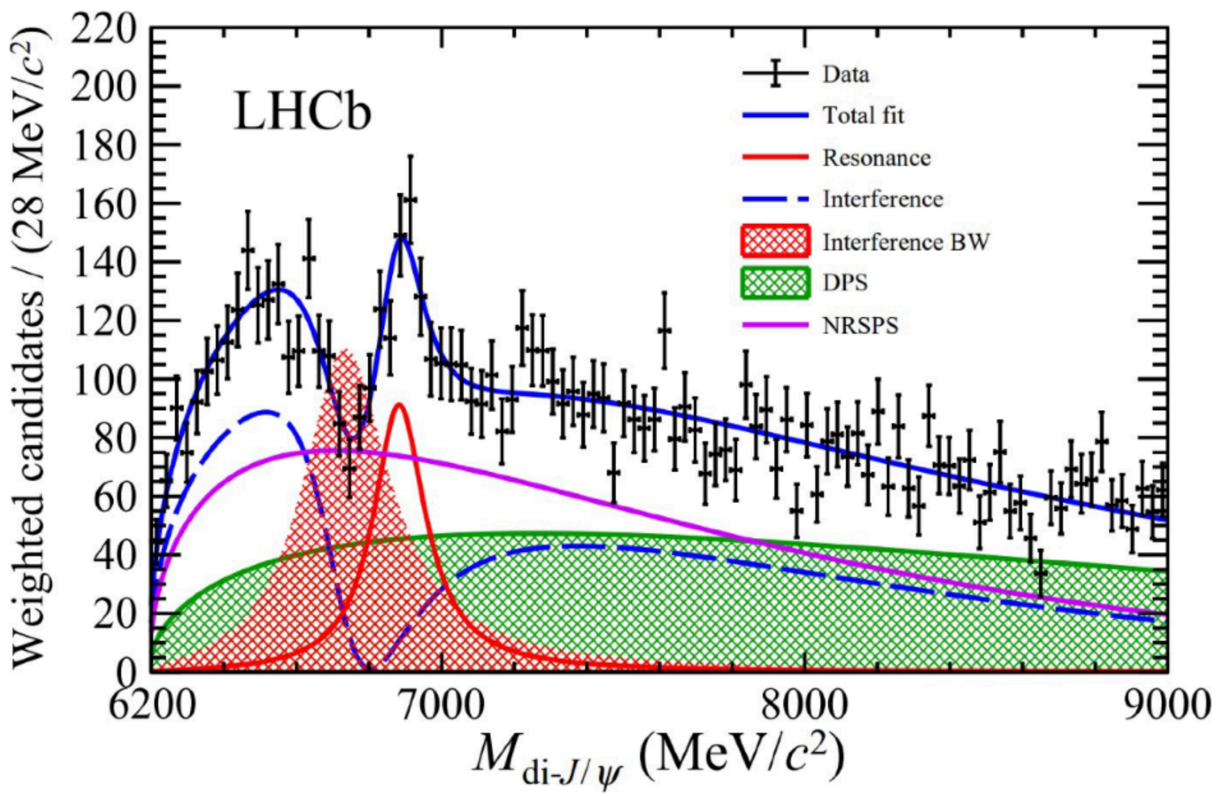
https://www.nikhef.nl/~pkoppenb/particles.html

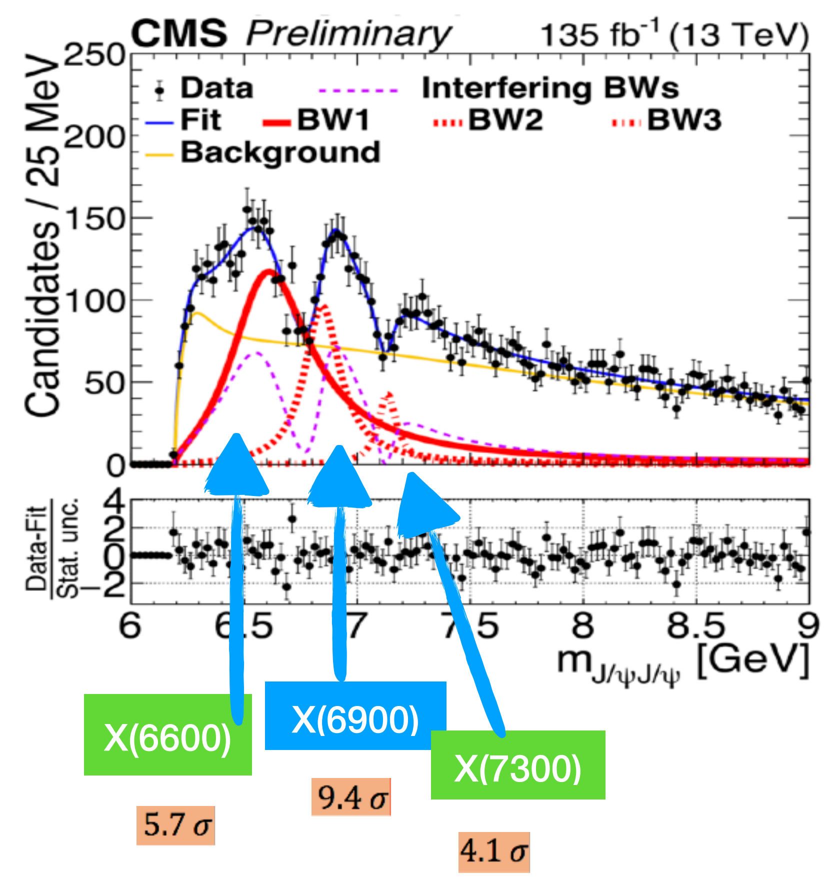
New particles discovered at LHC?

an all-charm tetraquark (candidates)

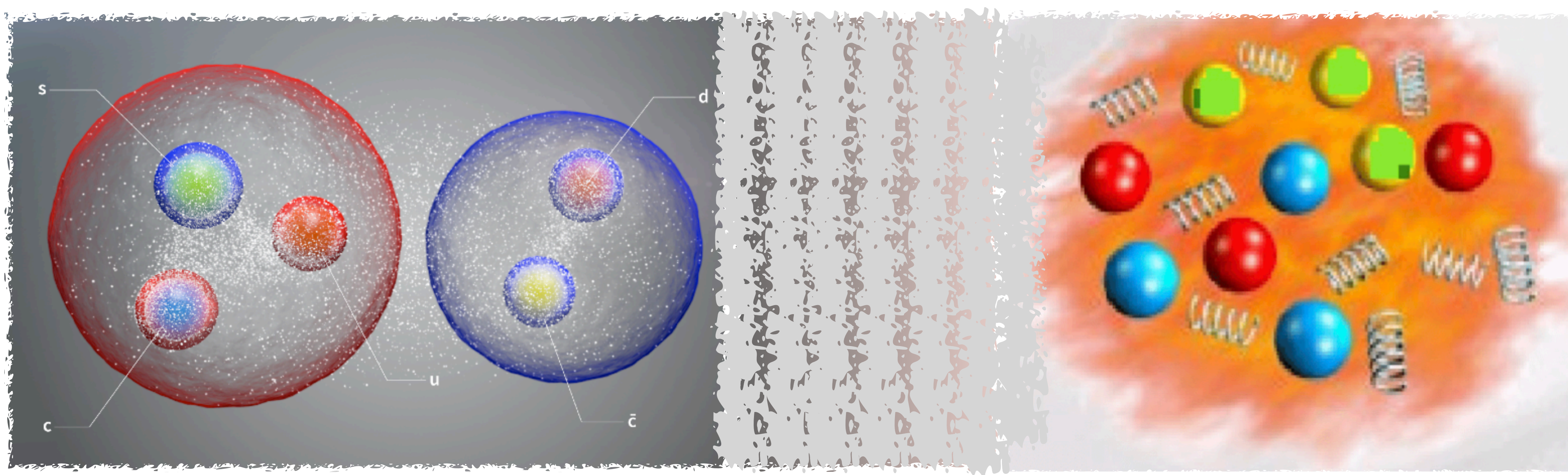


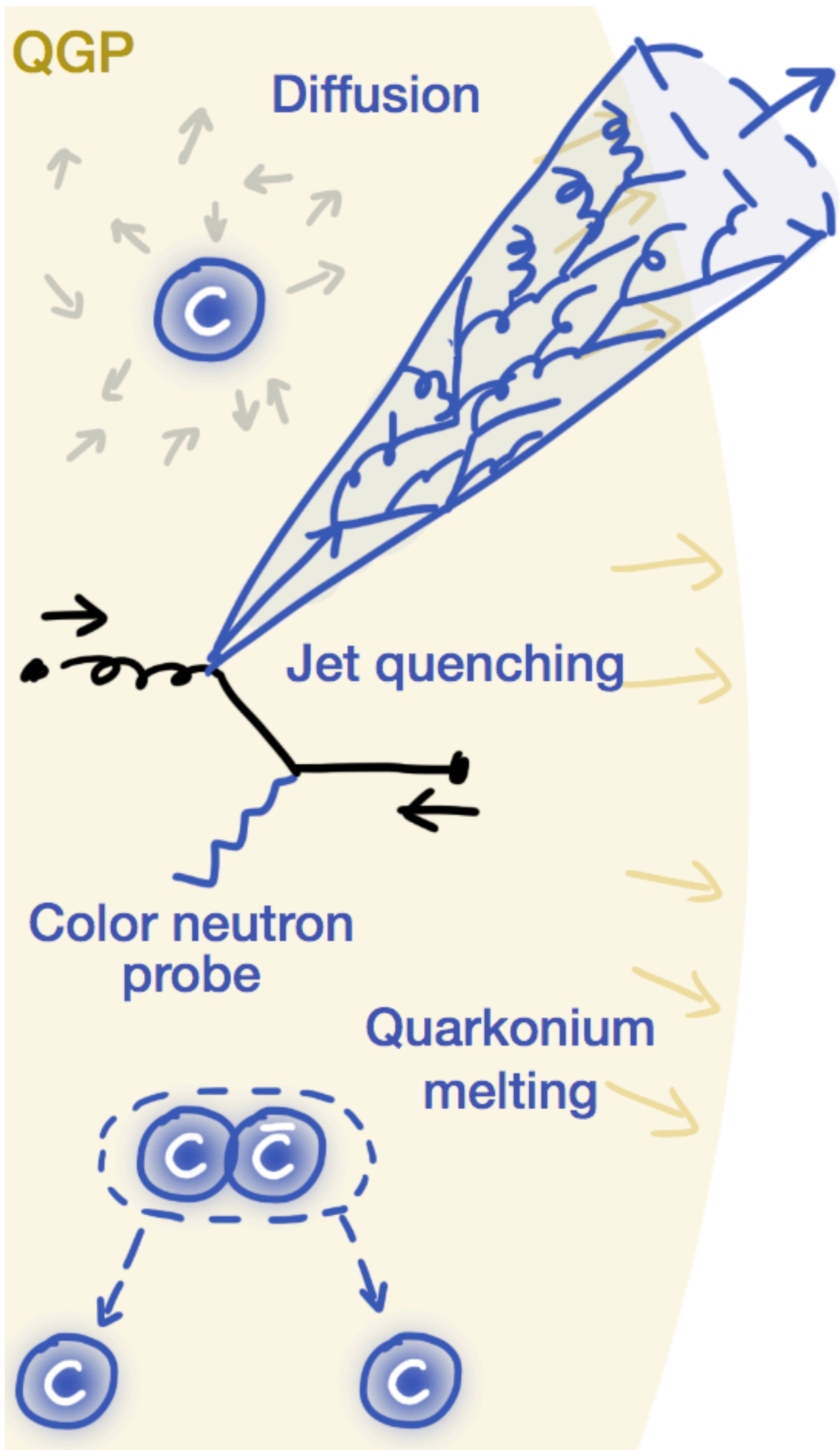


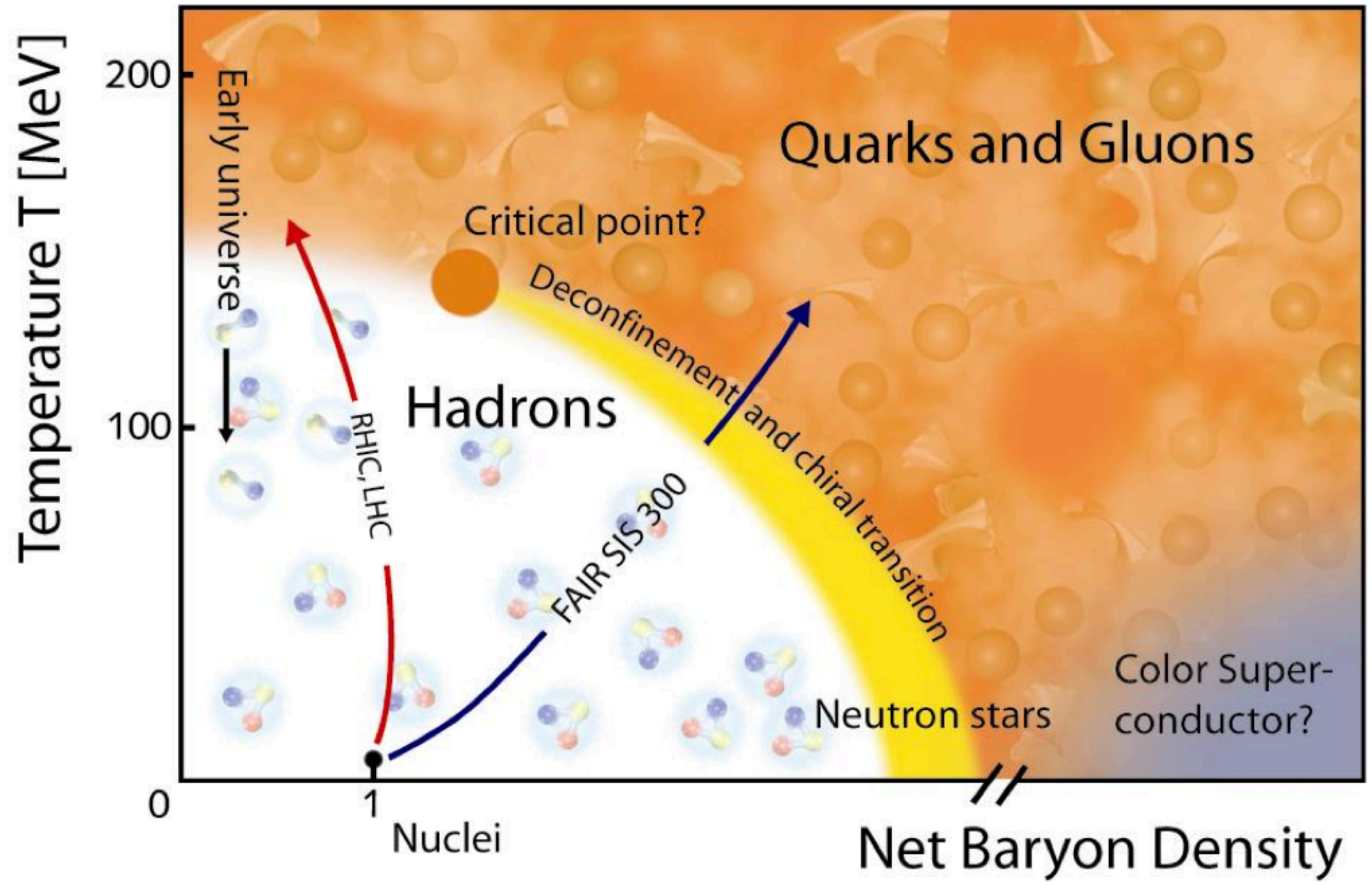




And now, into a hot, deconfined medium



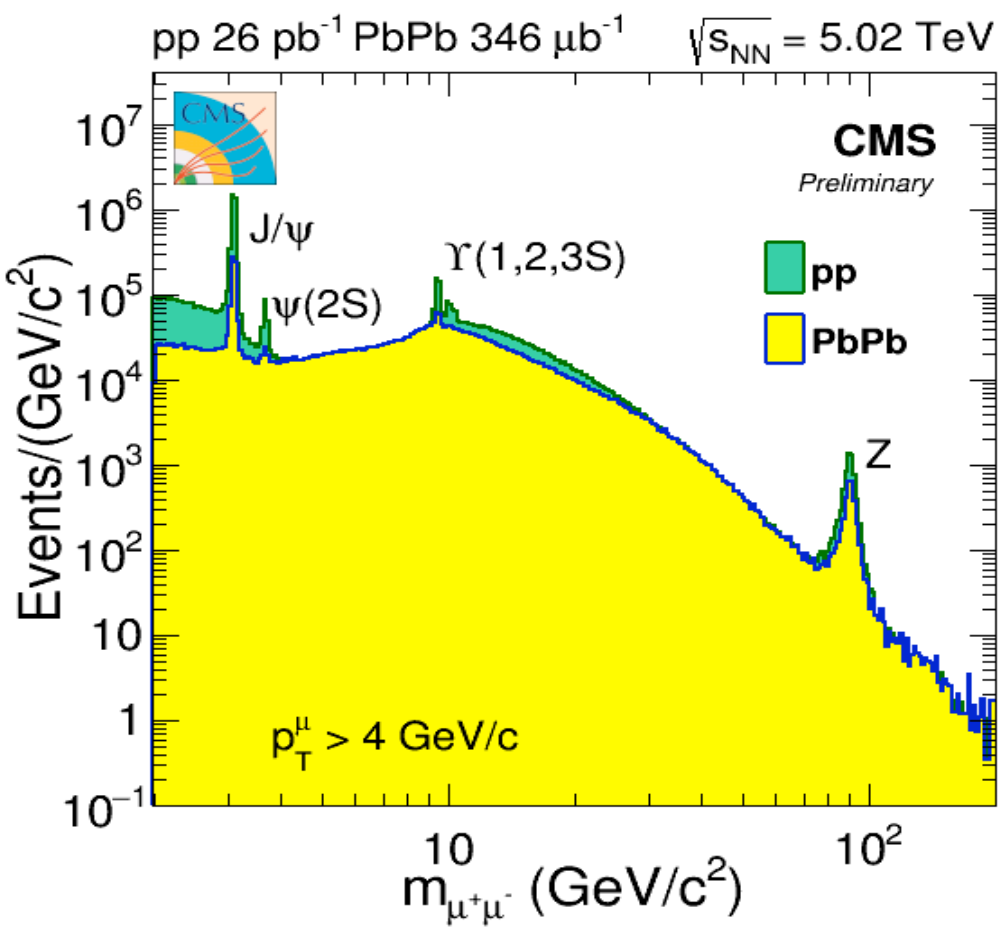


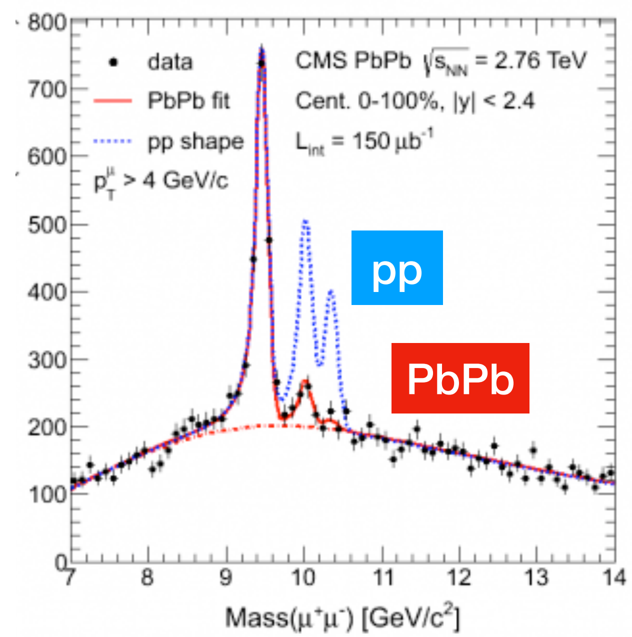


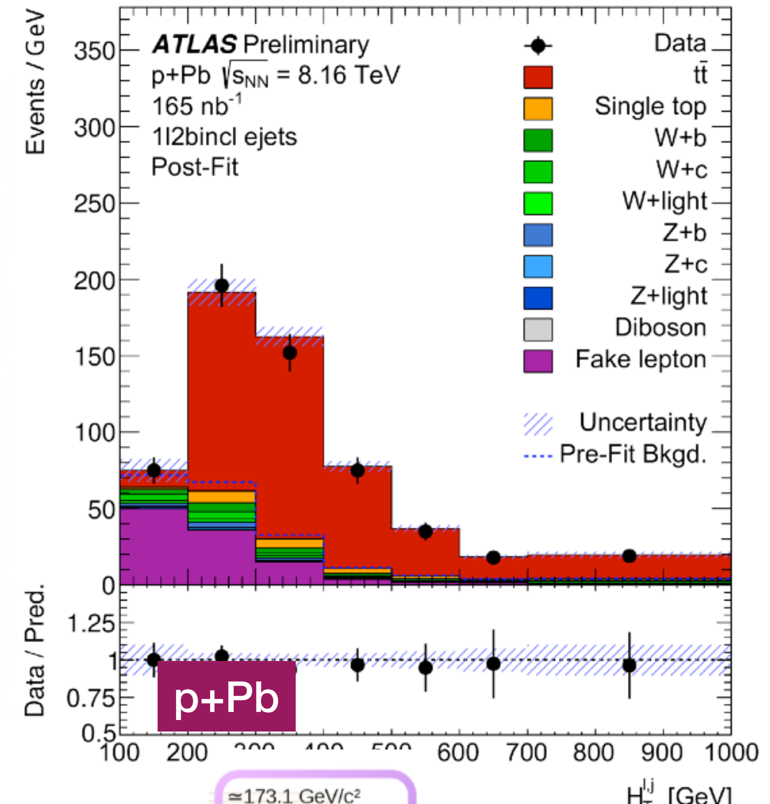
➡ at large energy densities, QCD predicts the existence of a deconfined state of quarks and gluons -- the quark gluon plasma (QGP)

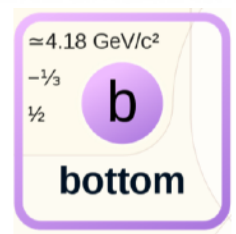
- reproduced in heavy ion collisions

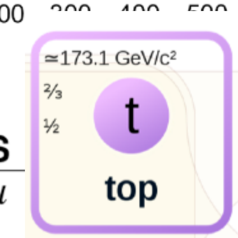
Rediscovering the SM particles… in HI!

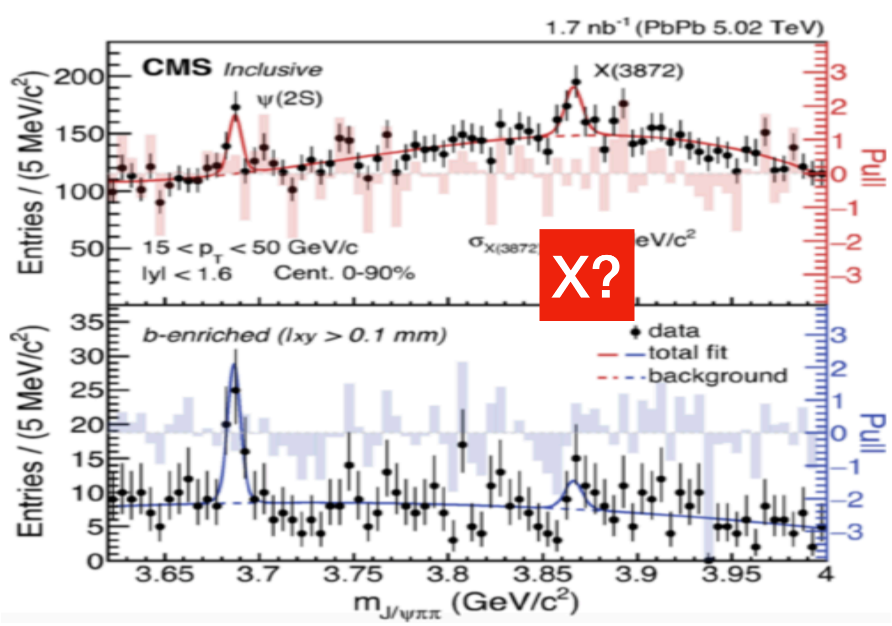


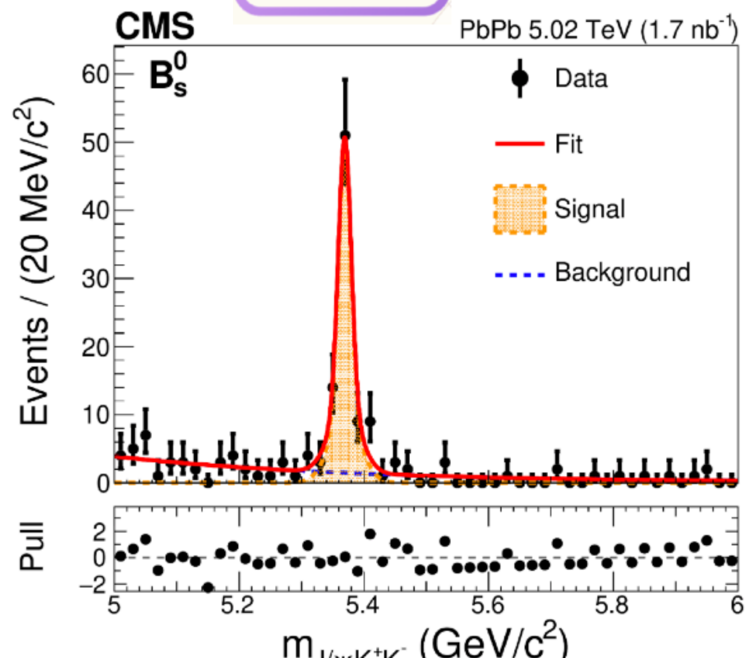


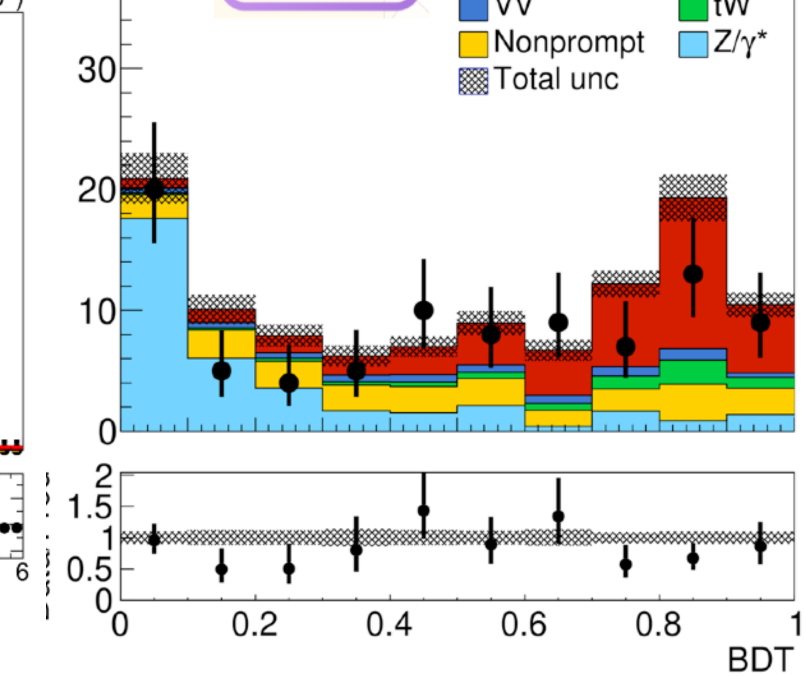




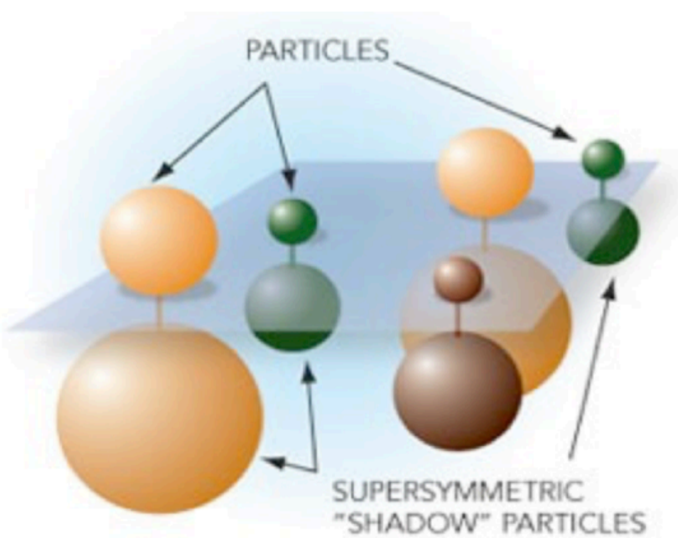


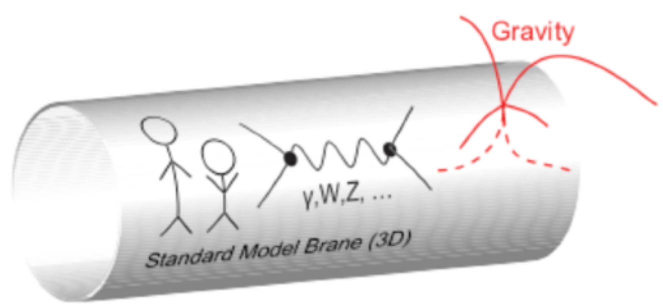


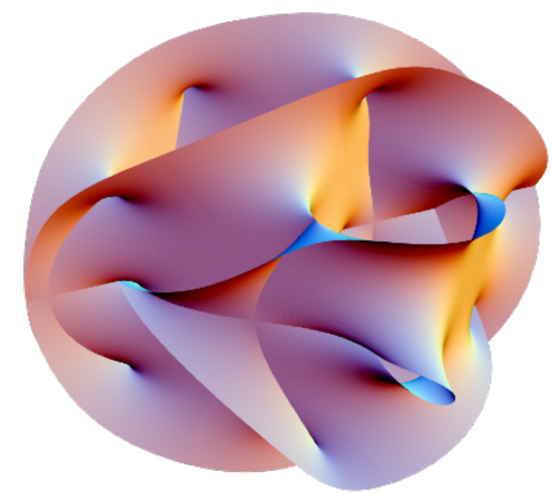




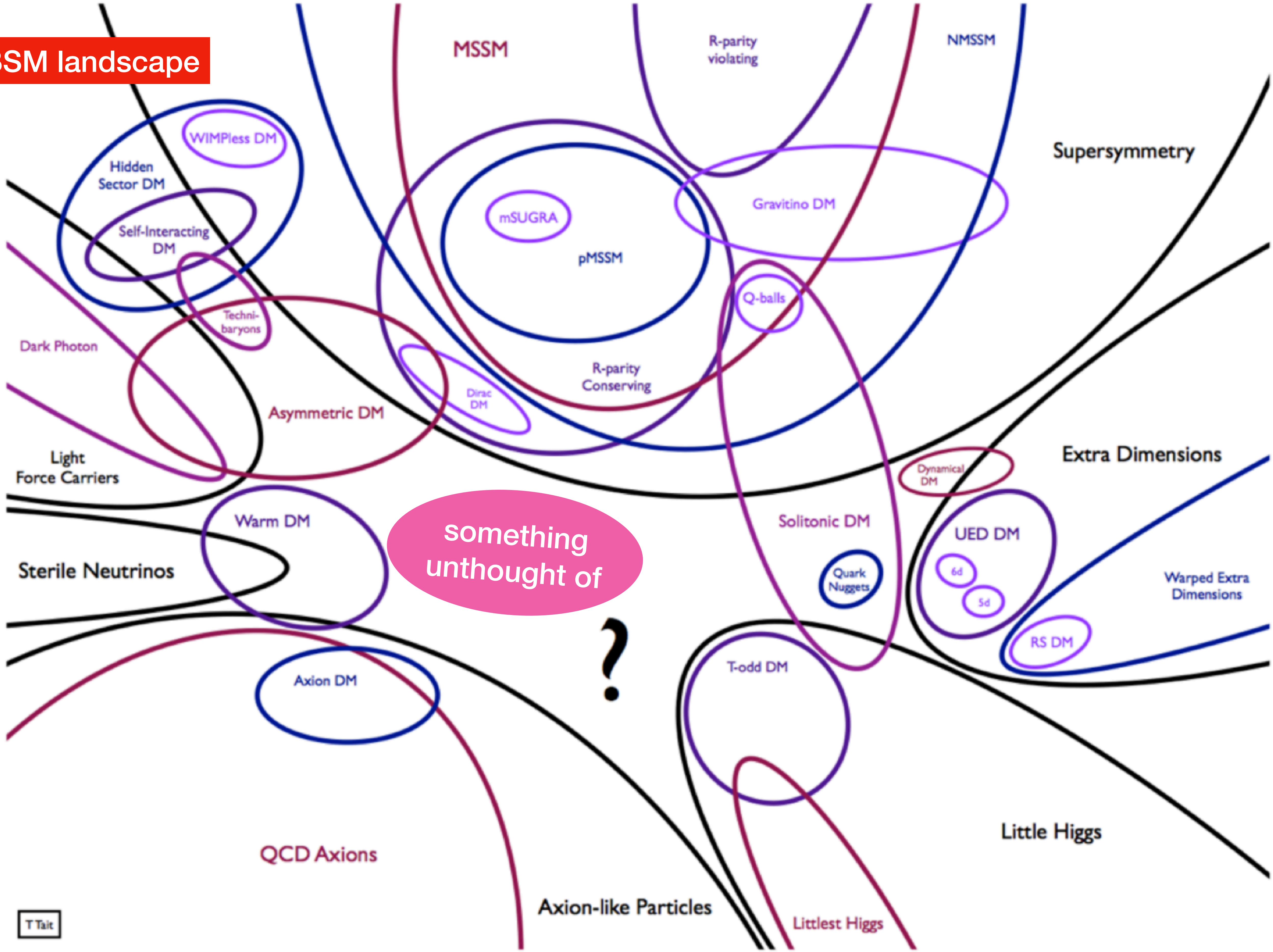
Probing beyond the SM





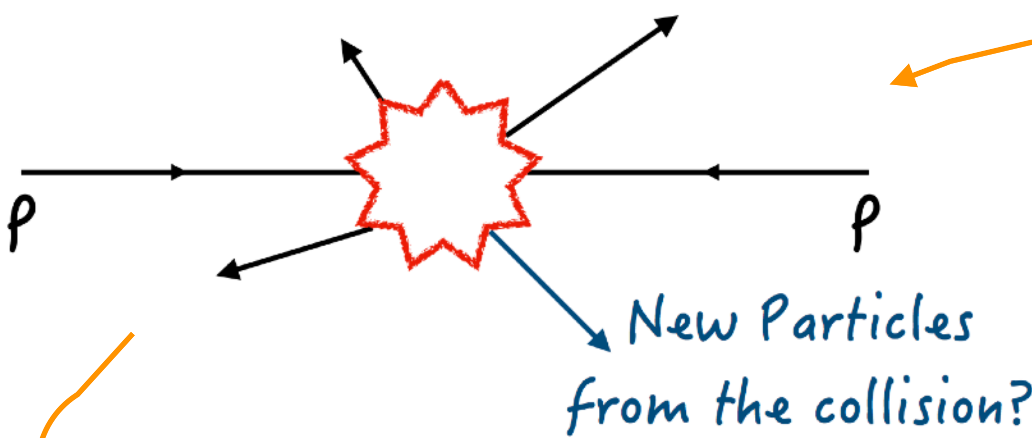


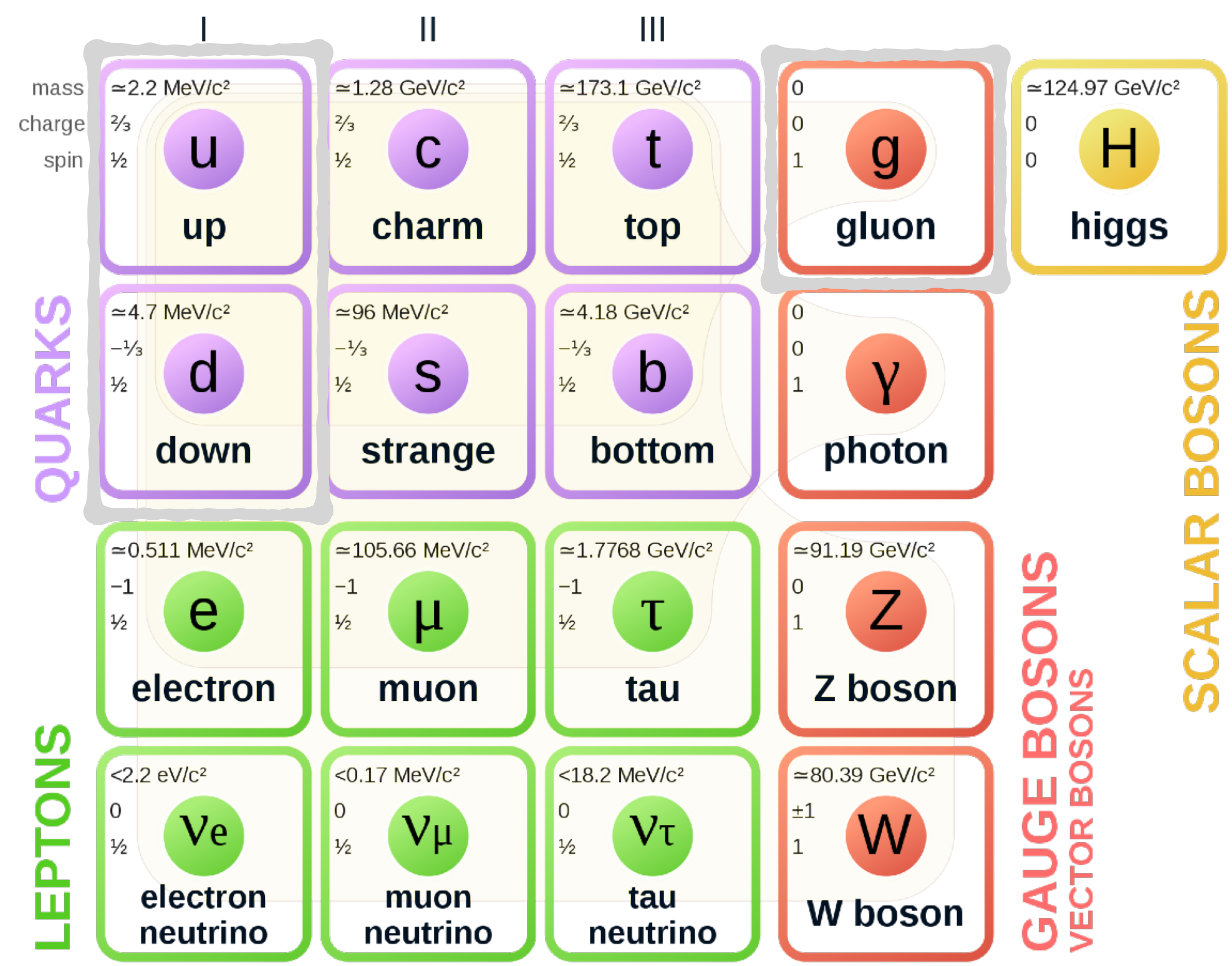
BSM landscape

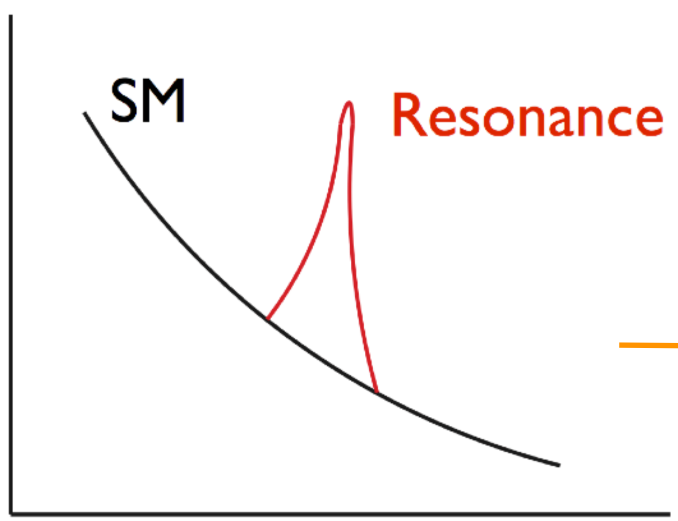


Going beyond the Standard Model

1) the easy way: direct discovery







Energy frontier

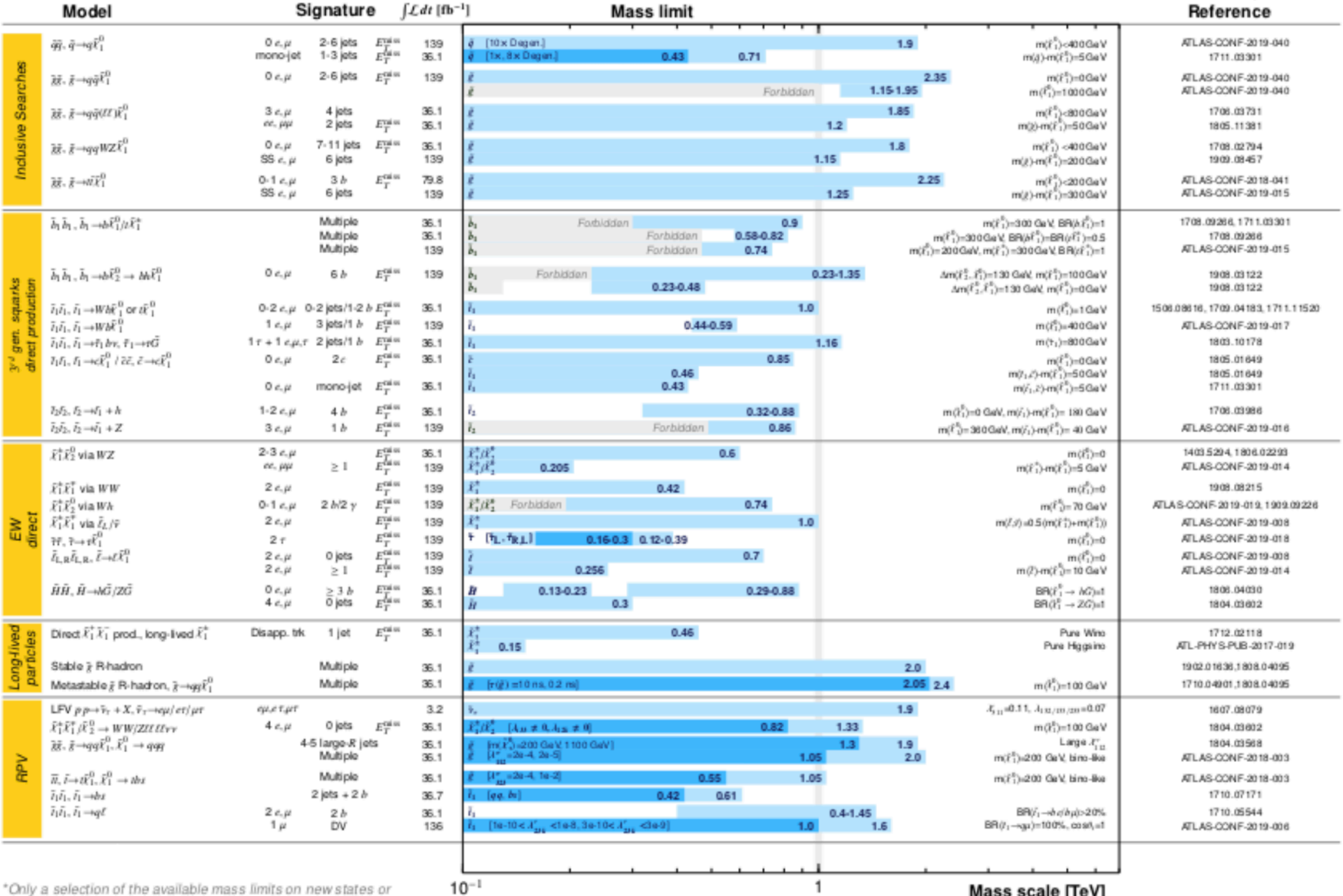
ATLAS SUSY Searches* - 95% CL Lower Limits

October 2019

example: SUSY

ATLAS Preliminary

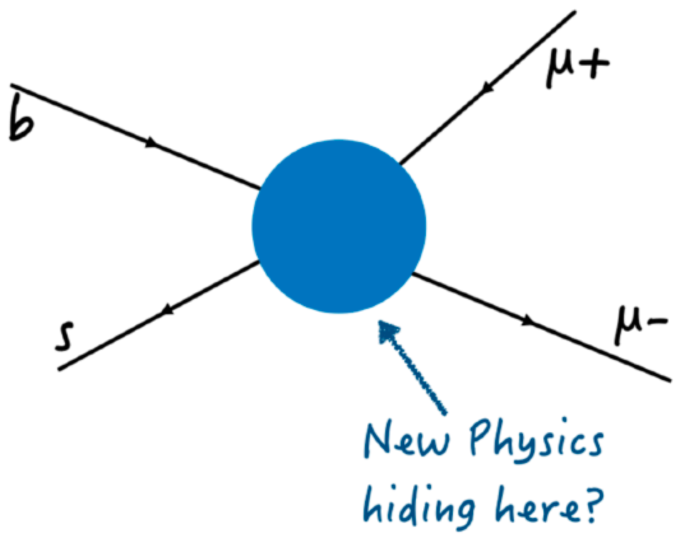
$\sqrt{s}$ = 13 TeV

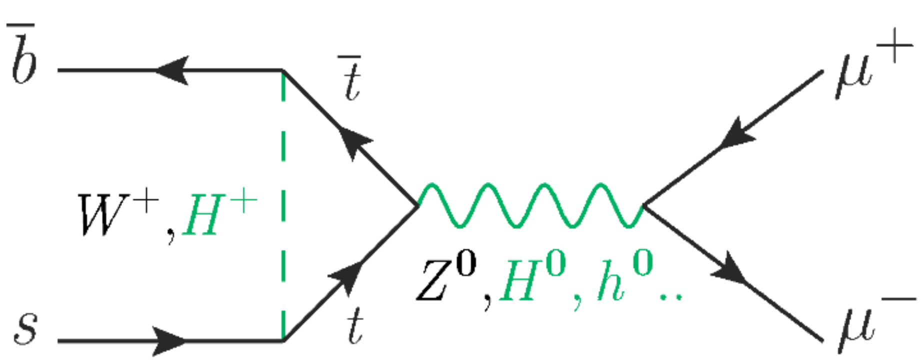


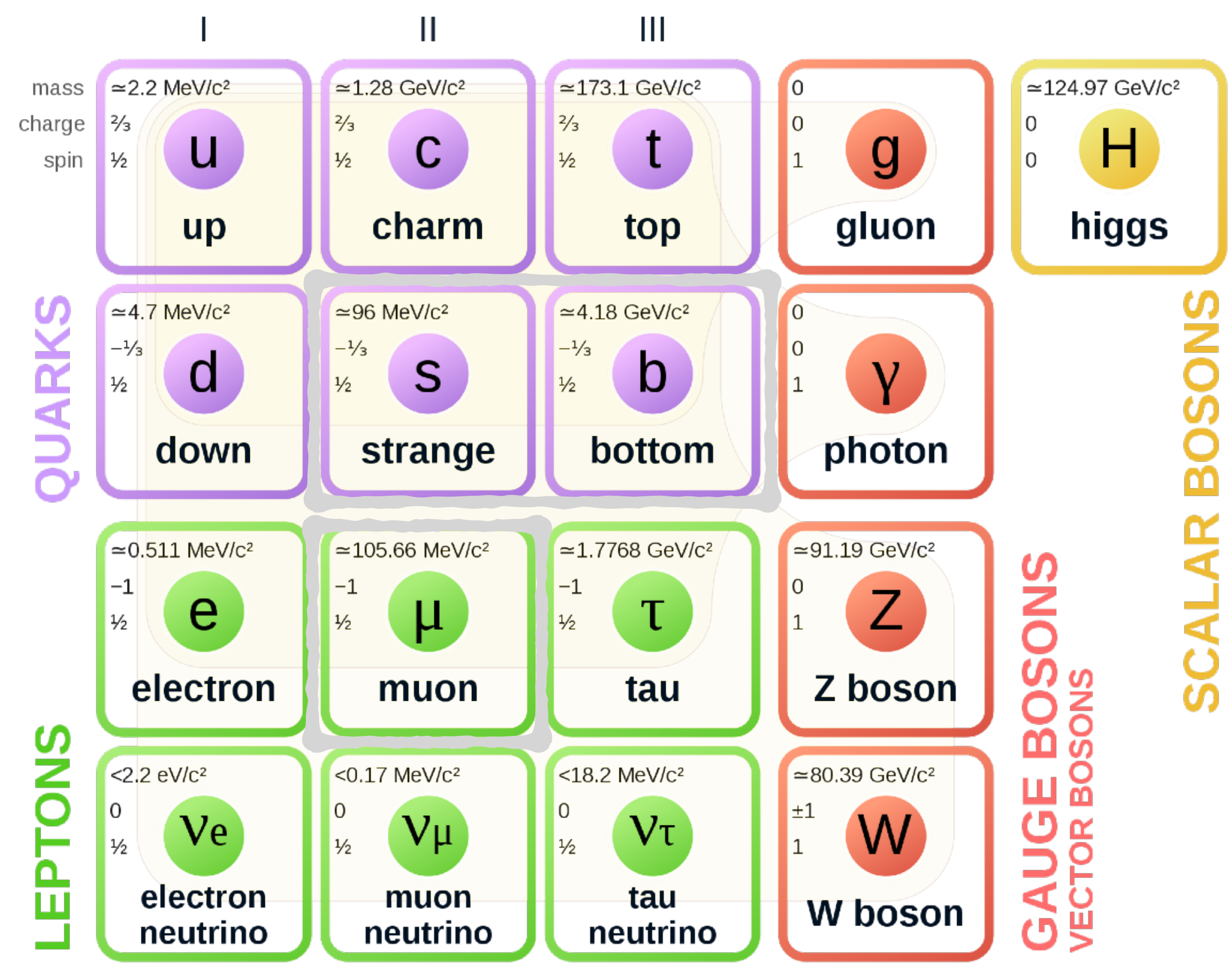
*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

Going beyond the Standard Model

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





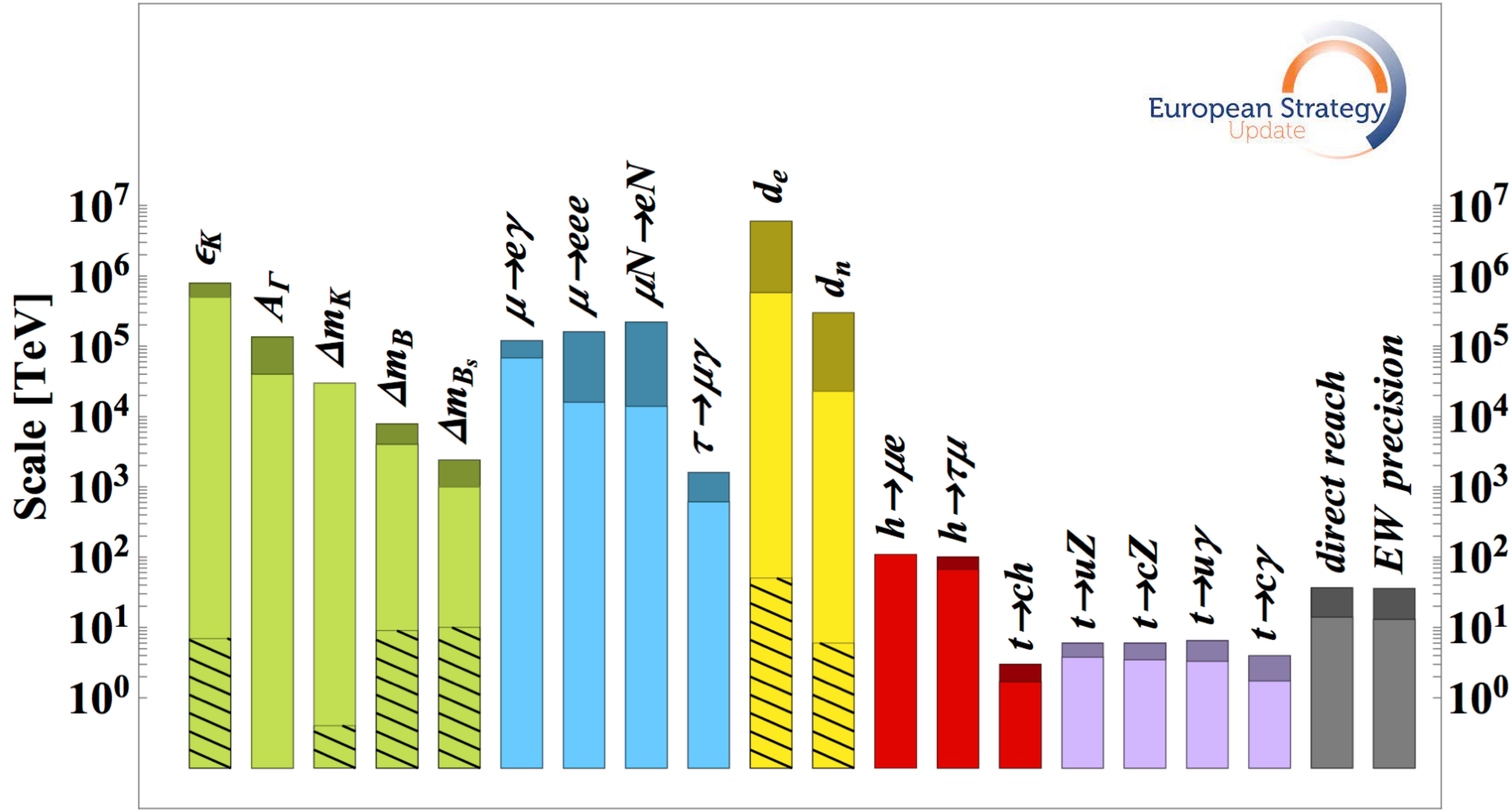


fuelled by Quantum Mechanics

Intensity frontier

Going beyond the Standard Model

Indirect searches: fuelled by Quantum Mechanics



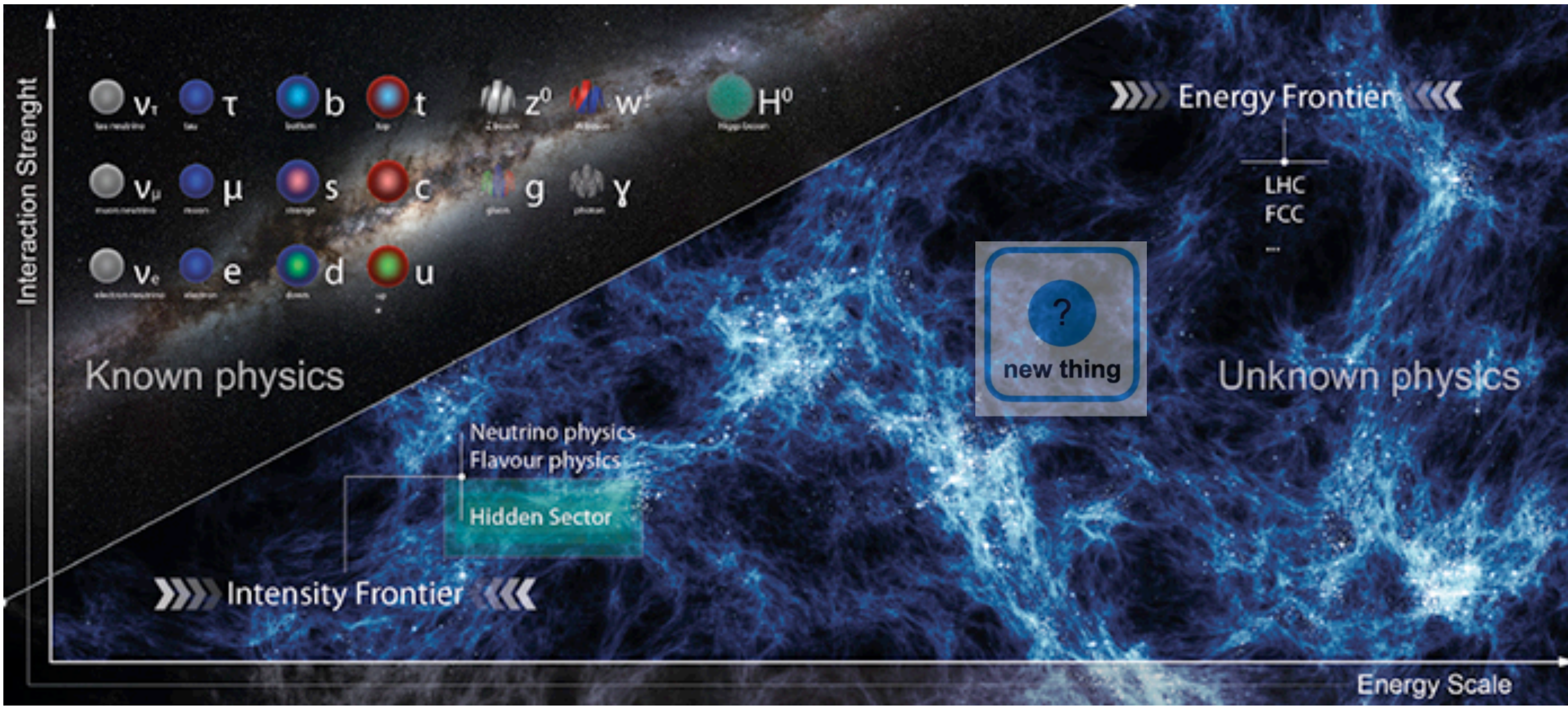
May access to NP scales well beyond collision energy !

Going beyond the Standard Model

LHC — explore both energy and intensity frontiers

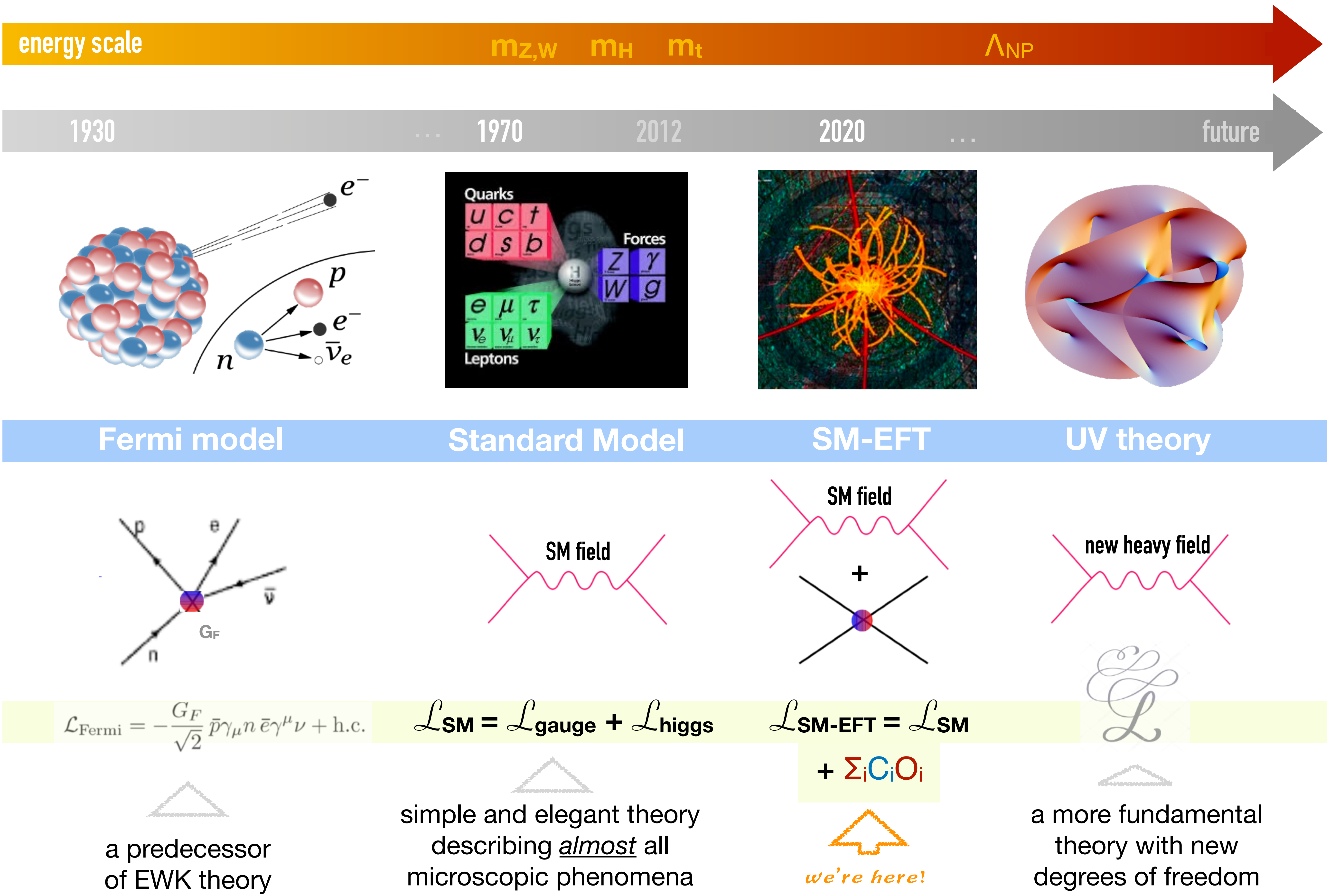
energy frontier

intensity frontier



Beam intensity: high luminosity

Beam energy: $\sqrt{s}$


energy scale
$m_{Z,W}$
m_H
m_t
Λ_{NP}
1930
. . .
1970
2012
2020
. . .
future
e^-
p
e^-
$\bar{\nu}_e$
n
Quarks
u c t
d s b
Forces
Z γ
W g
e μ τ
ν_e ν_μ ν_τ
Leptons
H
Fermi model
Standard Model
SM-EFT
UV theory
p
e
$\bar{\nu}$
n
G_F
SM field
SM field
+
new heavy field
$\mathcal{L}_{\text{Fermi}} = -\frac{G_F}{\sqrt{2}} \bar{p}\gamma_\mu n\, \bar{e}\gamma^\mu \nu + \text{h.c.}$
$\mathcal{L}_{\text{SM}} = \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{higgs}}$
$\mathcal{L}_{\text{SM-EFT}} = \mathcal{L}_{\text{SM}}$
$+ \Sigma_i C_i O_i$
$\mathcal{L}$
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