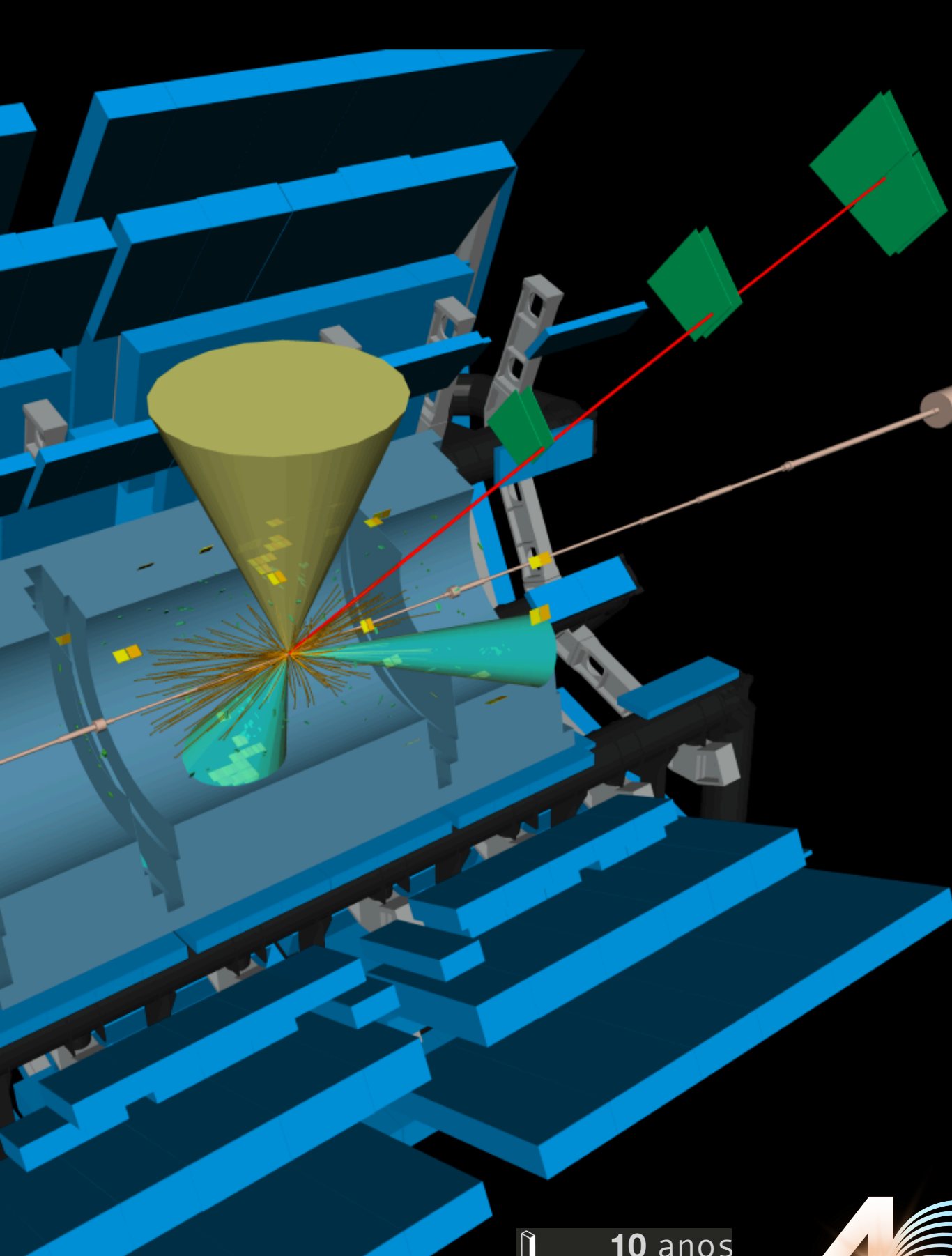
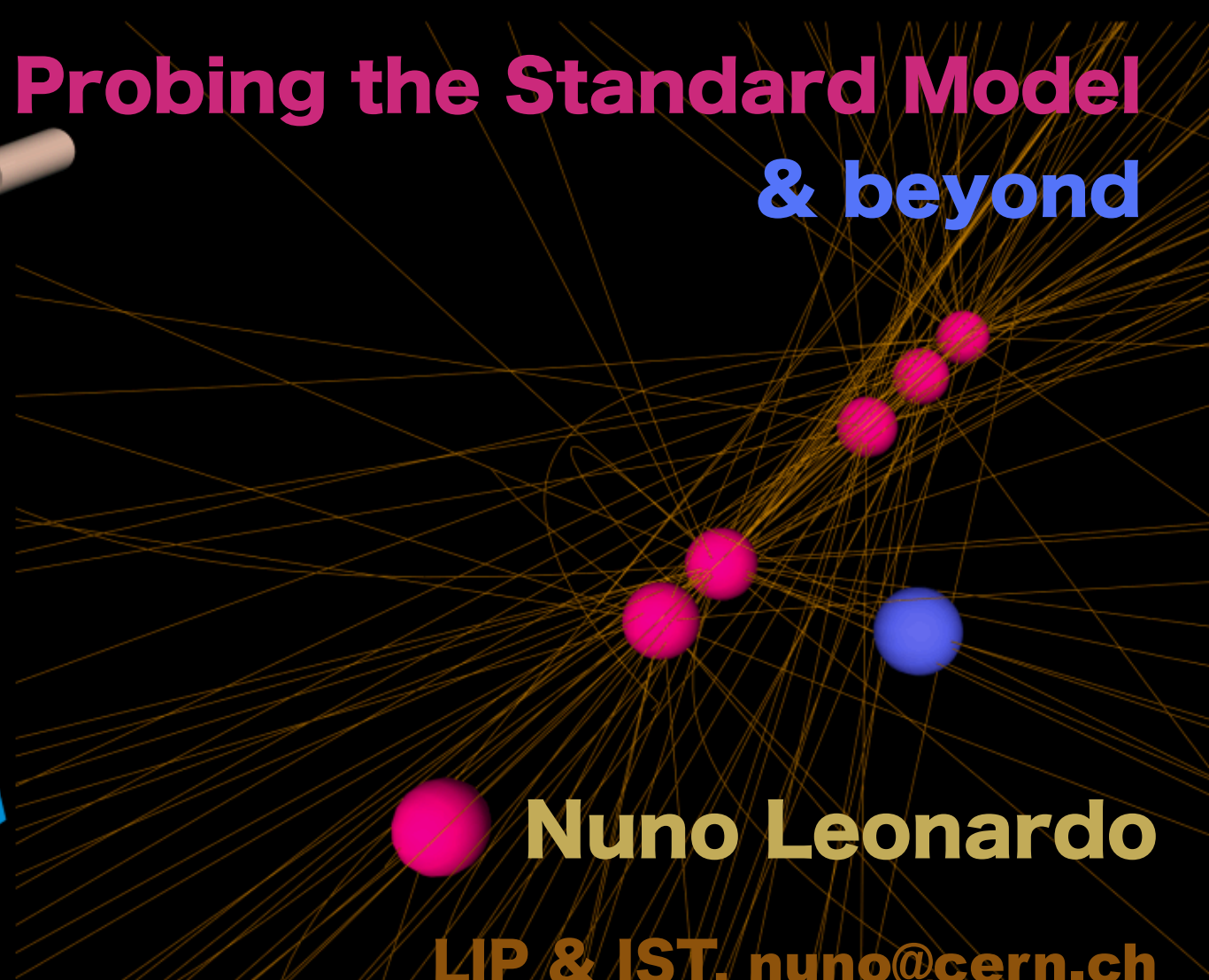




Physics @ LHC

Probing the Standard Model
& beyond



Nuno Leonardo

LIP & IST, nuno@cern.ch

LIP Internship Lectures, July 8th, 2026



FCT



anos 1985 · 2025
Portugal
CERN

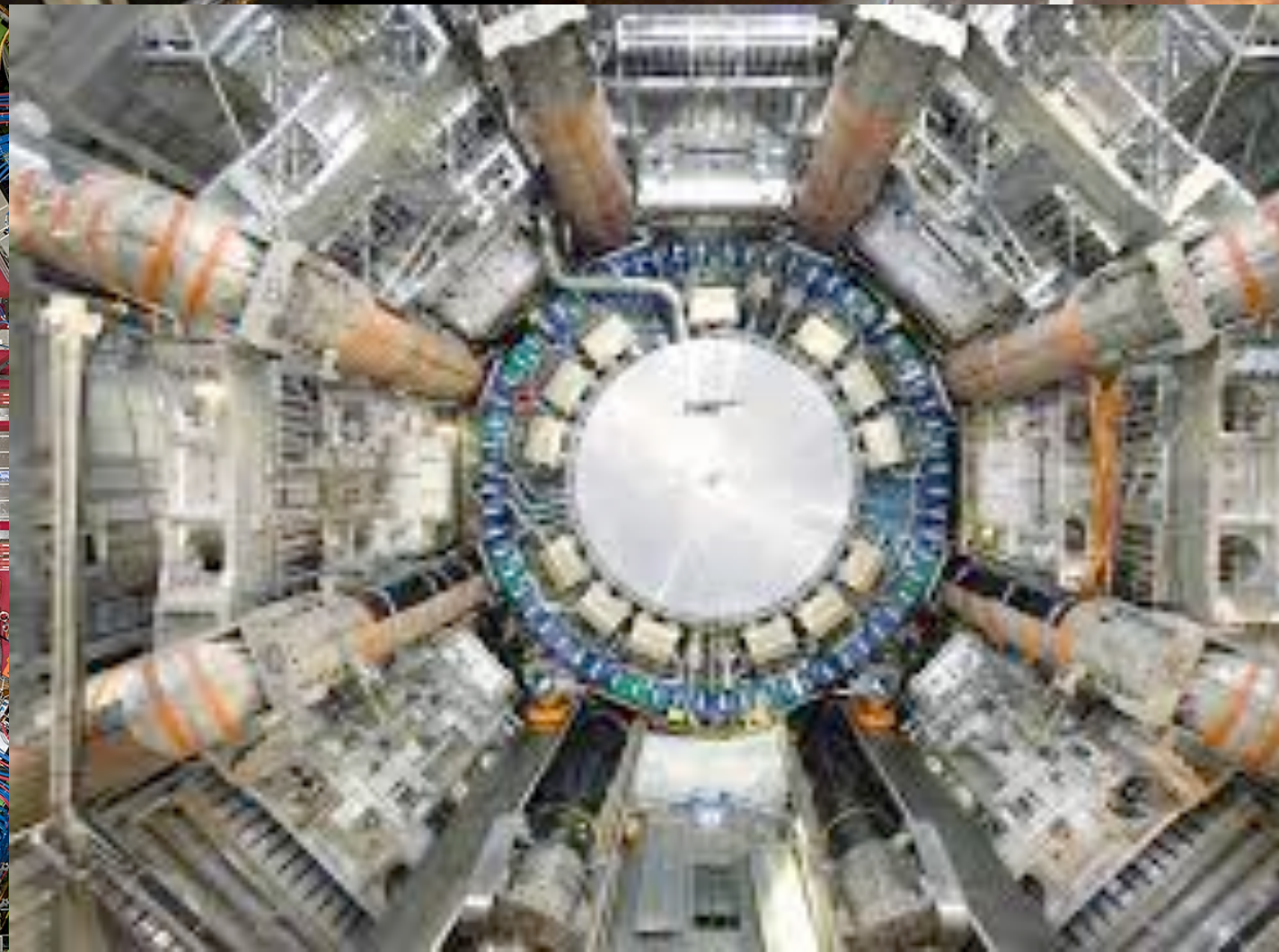
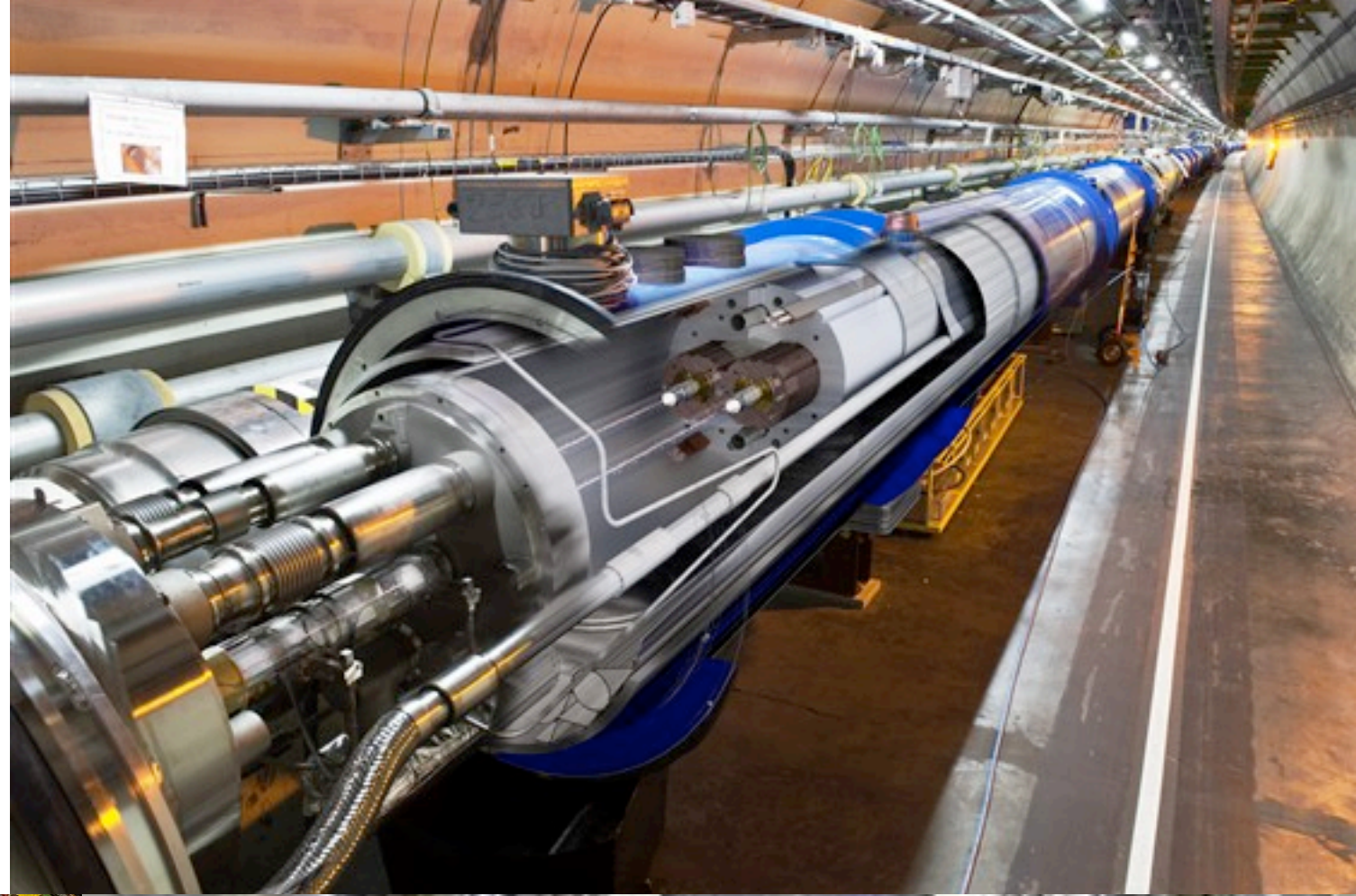


The LHC is the **world-leading** particle accelerator & collider

Delivering **unprecedented** energies and intensities

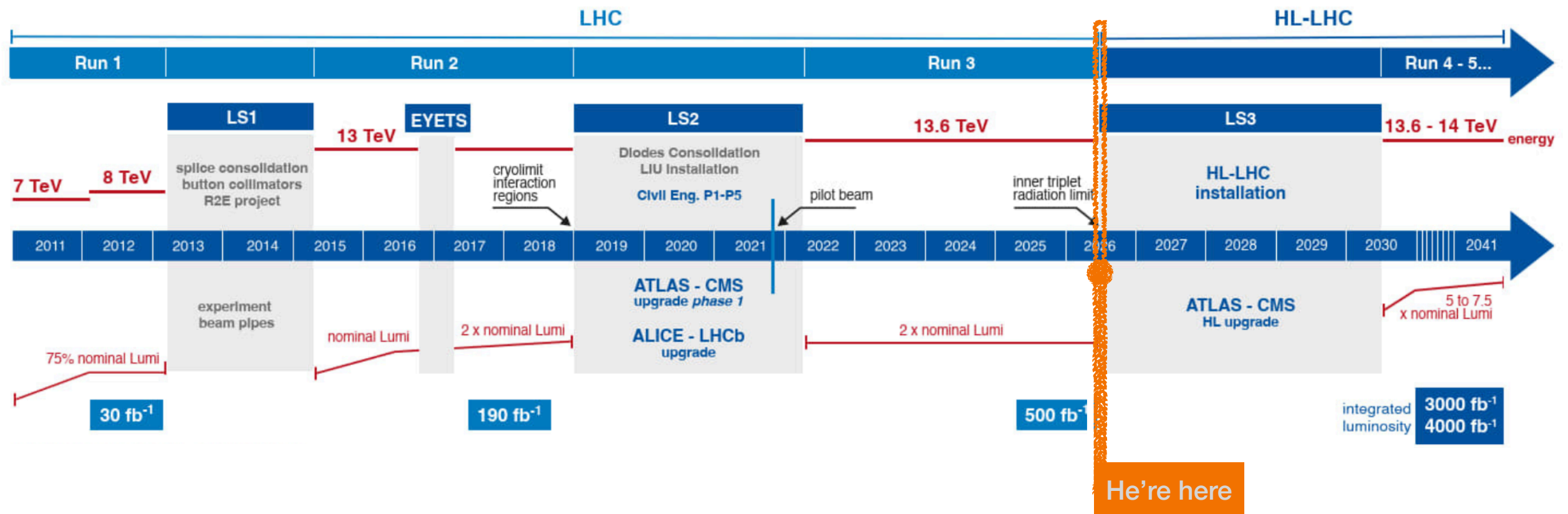
The LHC detectors are the most **sophisticated** scientific tools yet

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



LHC — past & future

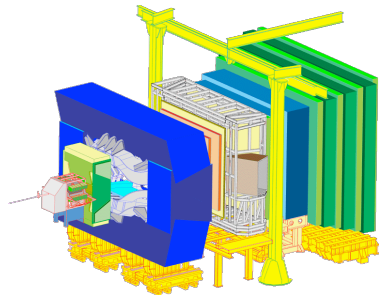
- ↪ We're at the middle of the LHC journey
- ↪ Run 3 just ended last week!



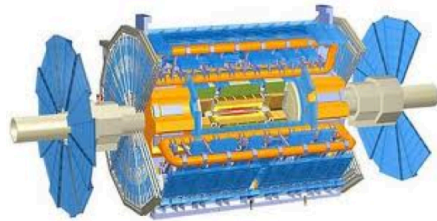
- We have accumulated a very **large, rich dataset** during Run3
 - ↪ available for physics analyses!
- We will be building the **upgraded detectors** for HL-LHC (Run4)
 - ↪ precision measurements + rarer processes
 - **Enhance apparatuses**
 - **Extend physics** scope
 - ↪ increase acceptance for SM & BSM, with improved and new detectors

Physics @ LHC

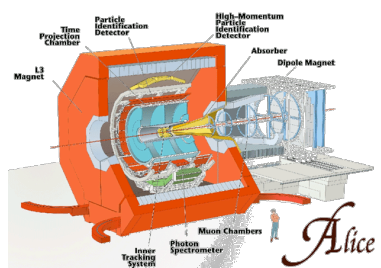
LHCb



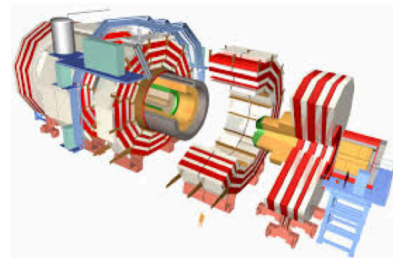
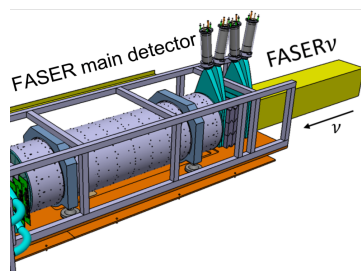
ATLAS



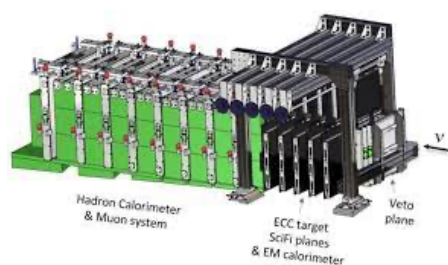
ALICE



CMS

FASER_v

SND@LHC



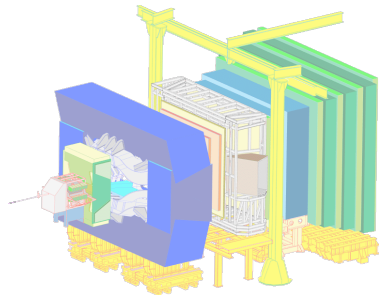
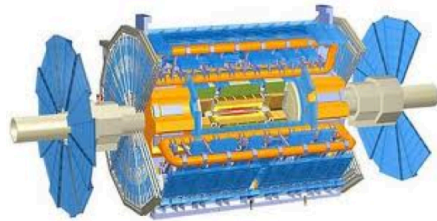
- Study *all* SM particles +interactions
 - ➔ Precision SM measurements
- Look for *new* particles +interactions
 - ➔ Searches for beyond-SM phenomena

	quarks	leptons	gauge bosons	scalar bosons	new particle ?
mass	$\approx 2.2 \text{ MeV}/c^2$	$\approx 0.511 \text{ MeV}/c^2$	$\approx 124.97 \text{ GeV}/c^2$		
charge	$\frac{2}{3}$	-1	0	0	$?$
spin	$\frac{1}{2}$	$\frac{1}{2}$	1	0	
	up	electron	gluon	higgs	
	charm	muon	photon		
	top	tau	Z boson		
			W boson		
	down	electron neutrino			
	strange	muon neutrino			
	bottom	tau neutrino			

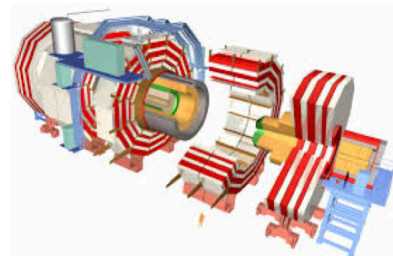
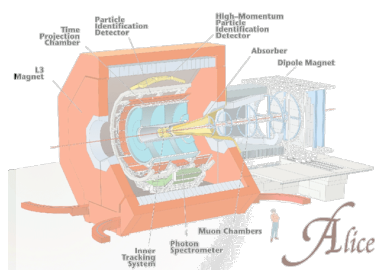
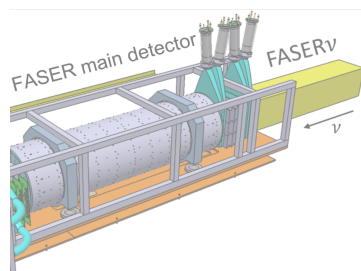
+ antiparticles

Physics @ LHC

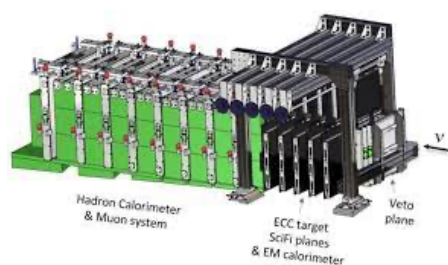
LHCb

**ATLAS**

ALICE

FASER_v

SND@LHC



- Study *all* SM particles +interactions
 - ➔ Precision SM measurements
- Look for *new* particles +interactions
 - ➔ Searches for beyond-SM phenomena

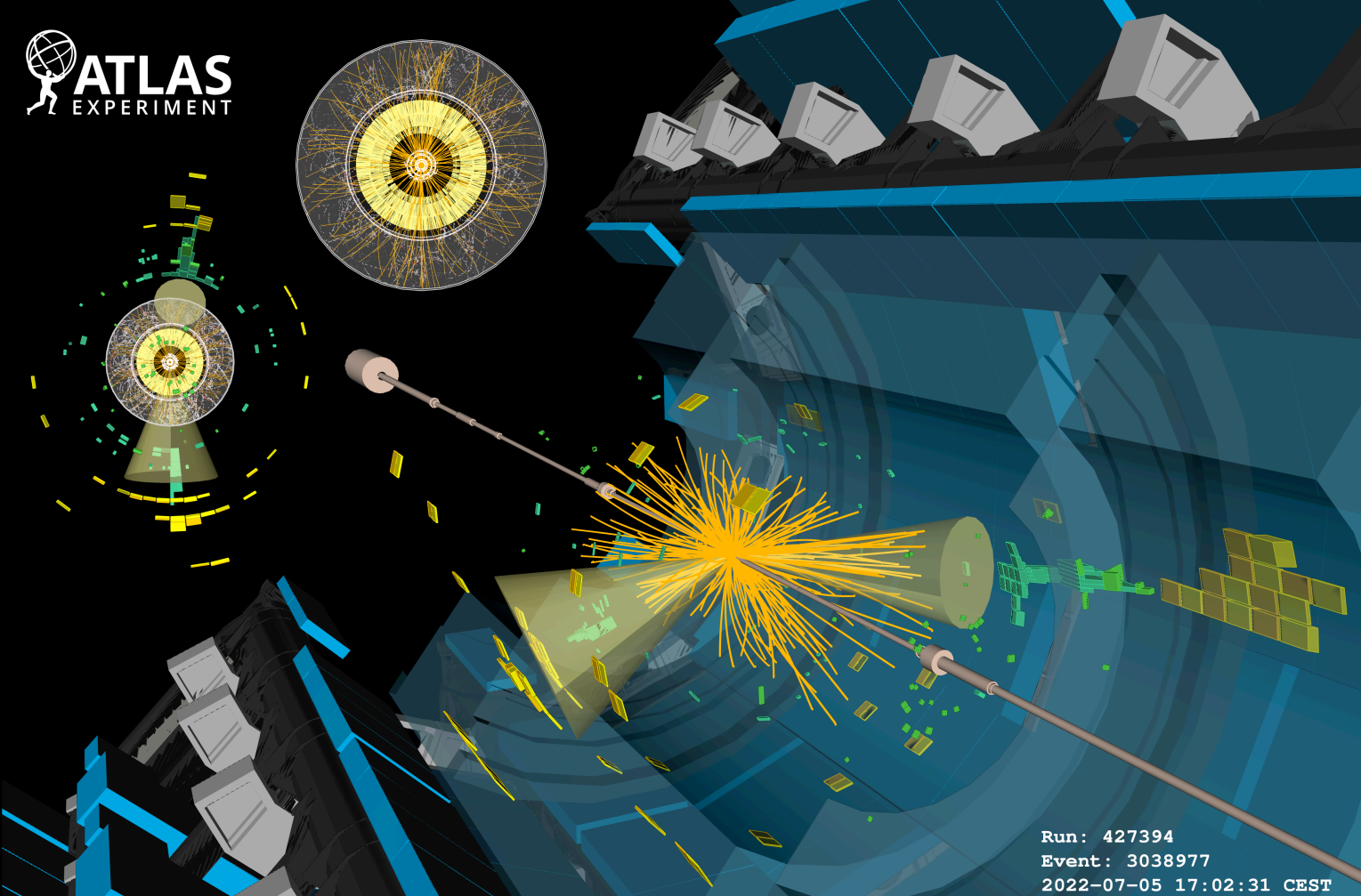
	quarks	leptons	gauge bosons	scalar bosons	new particle ?
mass	$\approx 2.2 \text{ MeV}/c^2$	$\approx 0.511 \text{ MeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$	$\approx 124.97 \text{ GeV}/c^2$	
charge	$\frac{2}{3}$	-1	$\frac{2}{3}$	0	$?$
spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	0	
	up	electron	top	higgs	
	charm	muon	gluon		
	down	electron neutrino	photon		
	strange	muon neutrino	Z boson		
	bottom	tau	W boson		
		tau neutrino			

+ antiparticles

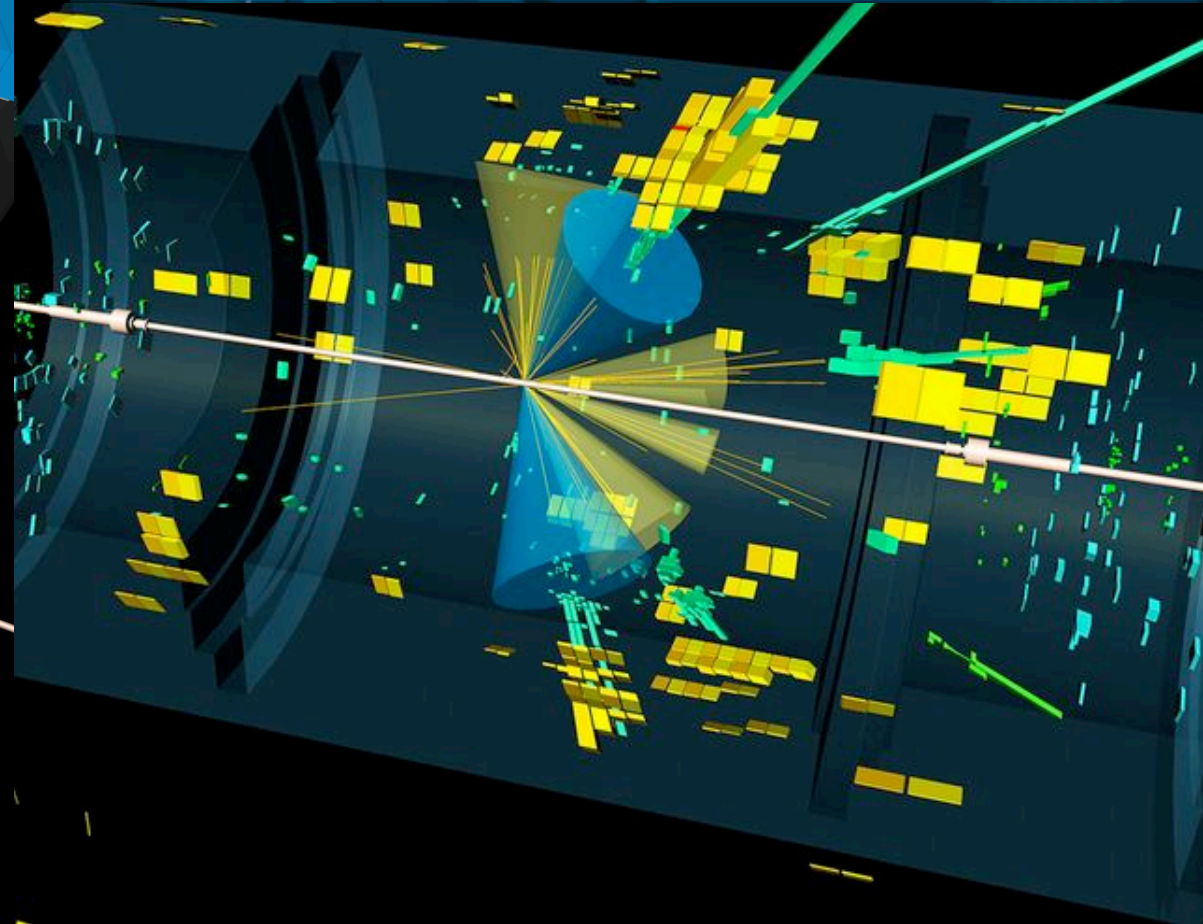
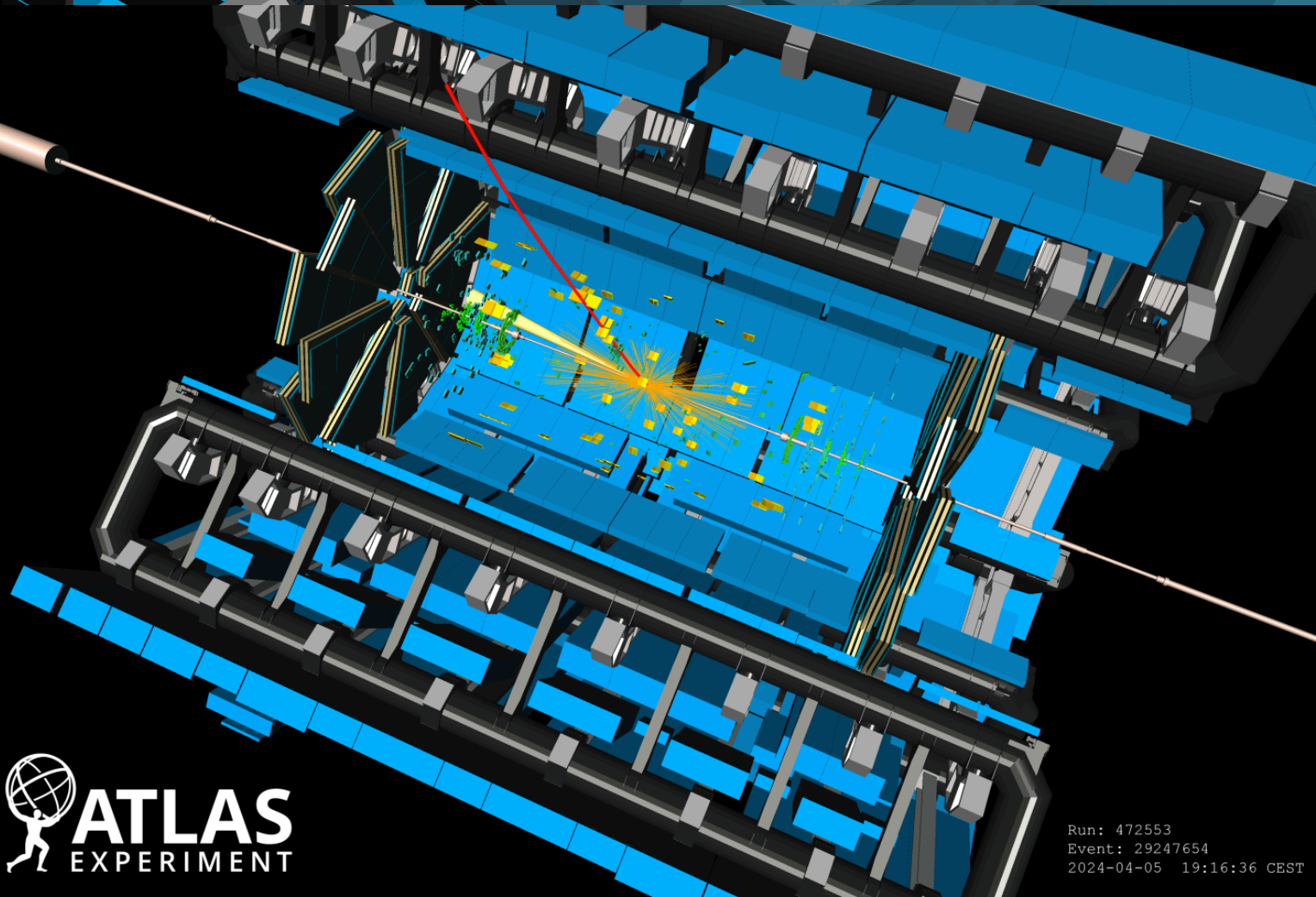
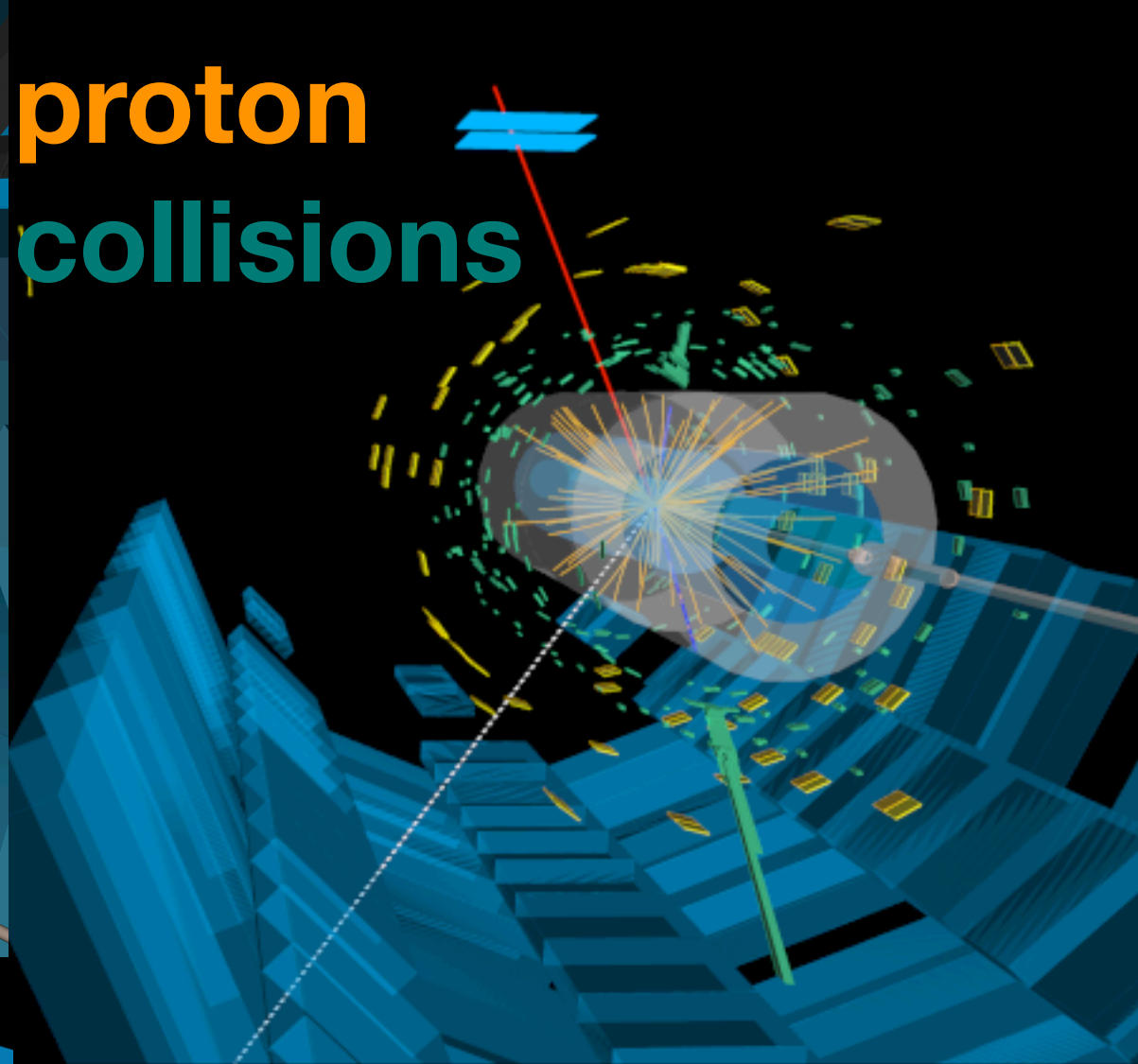
(with



Portuguese participation — LIP)



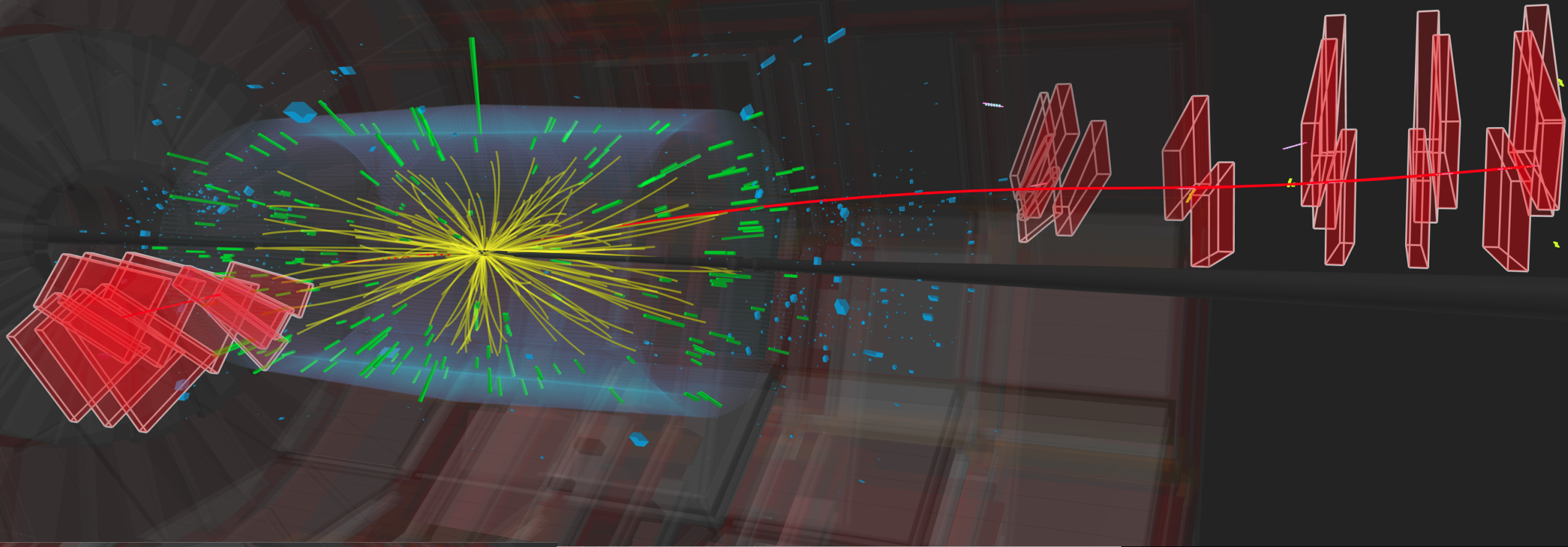
proton collisions



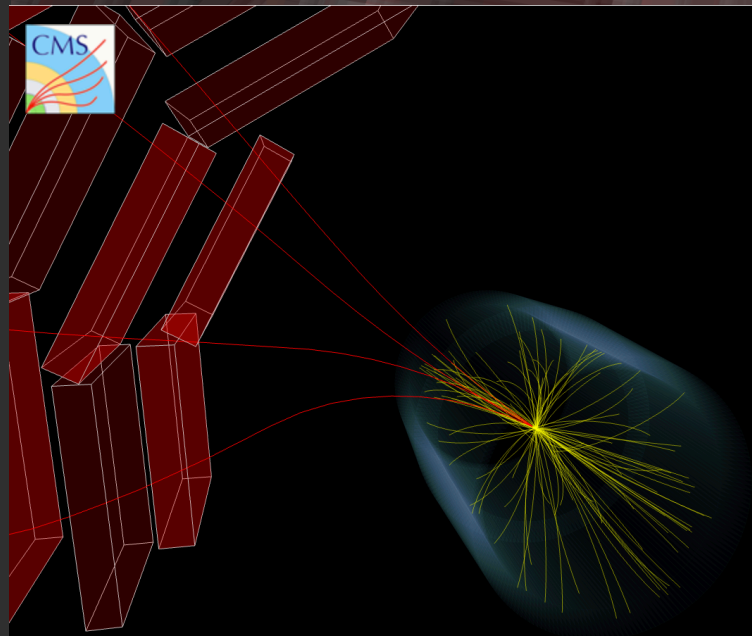
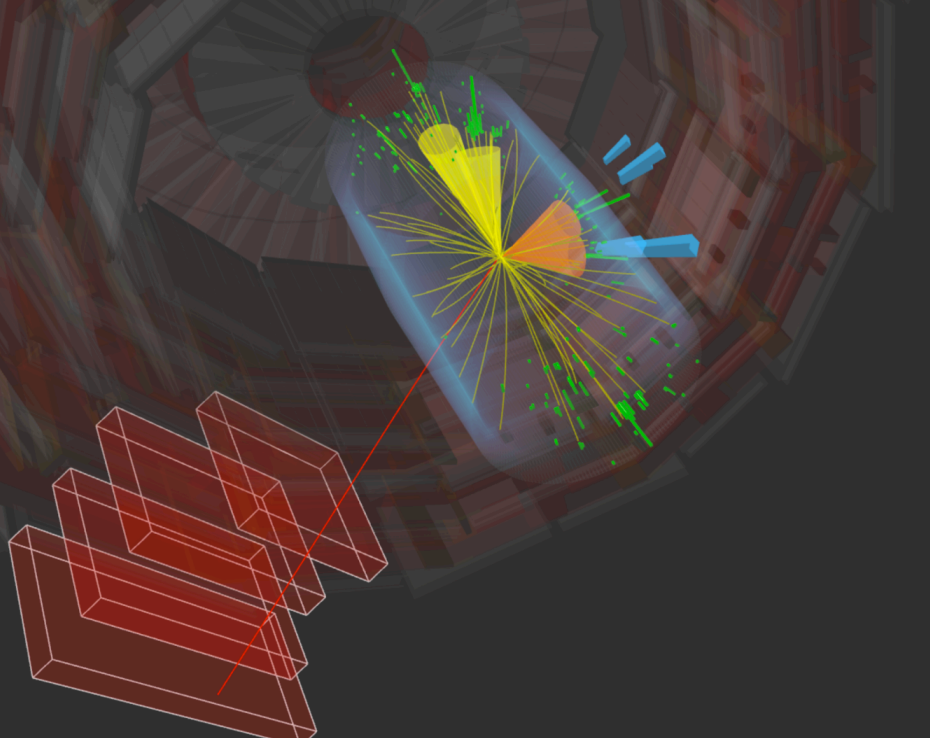


CMS Experiment at the LHC, CERN
Data recorded: 2022-Jul-05 14:48:56.743936 GMT
Run / Event / LS: 355100 / 51596902 / 53

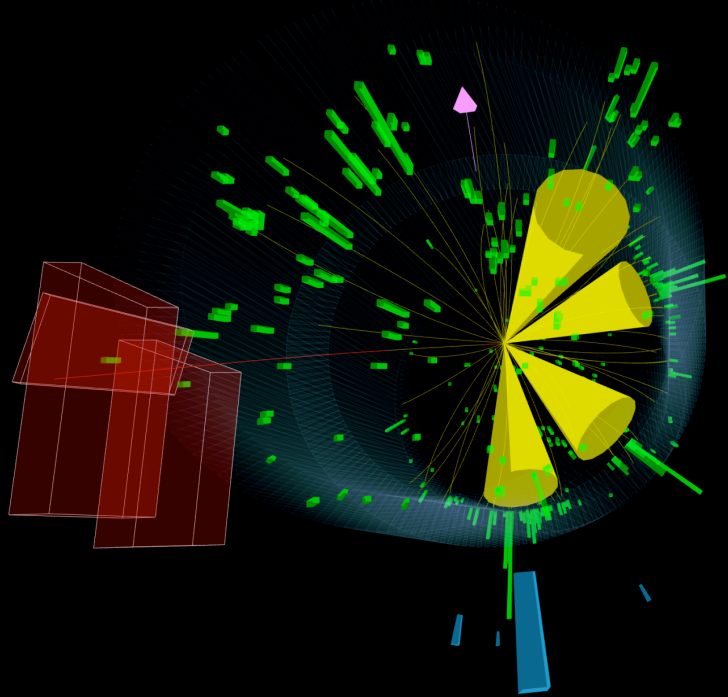
proton collisions



CMS Experiment at the LHC, CERN
Data recorded: 2018-May-08 00:09:43.055040 GMT
Run / Event / LS: 315840 / 580141005 / 471



CMS Experiment at the LHC, CERN
Data recorded: 2016-Aug-17 08:01:23.065024 GMT
Run / Event / LS: 278969 / 229126383 / 184

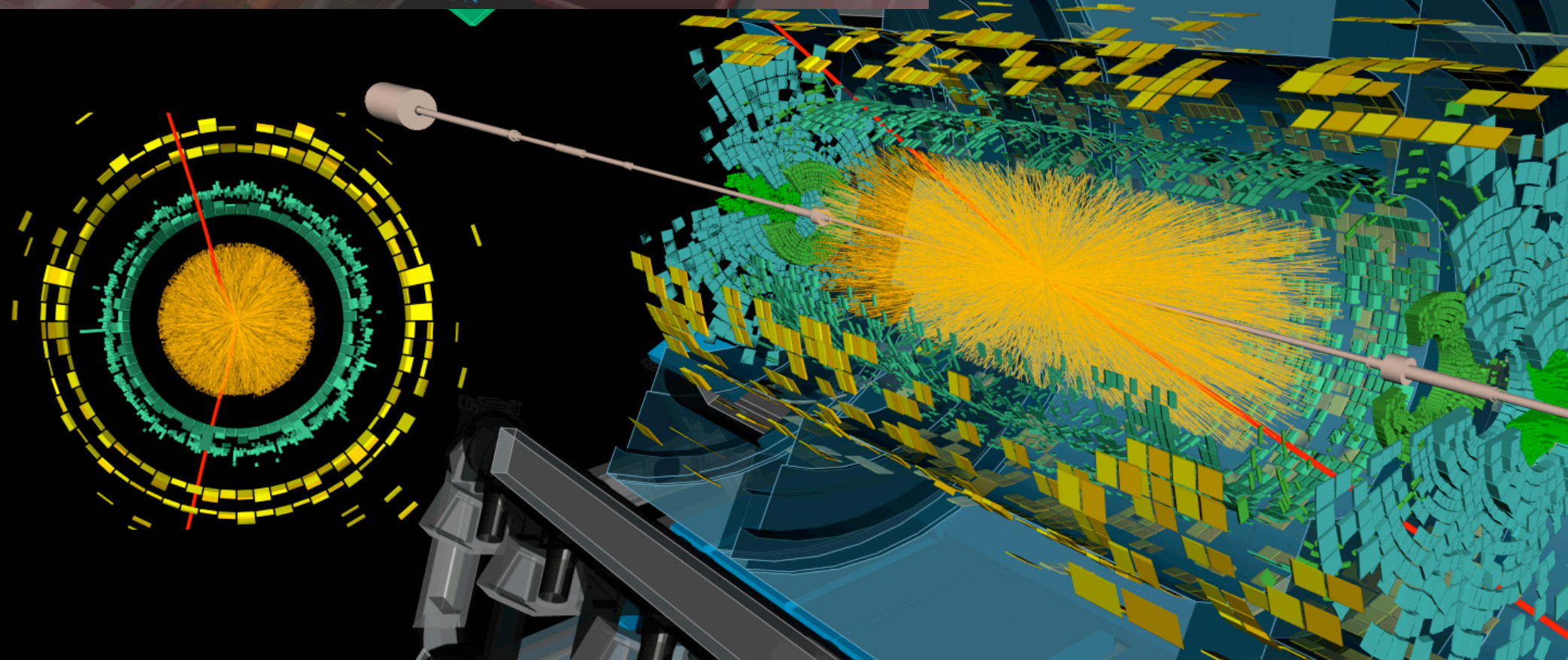




CMS Experiment at the LHC, CERN
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Run / Event / LS: 374288 / 5946329 / 55

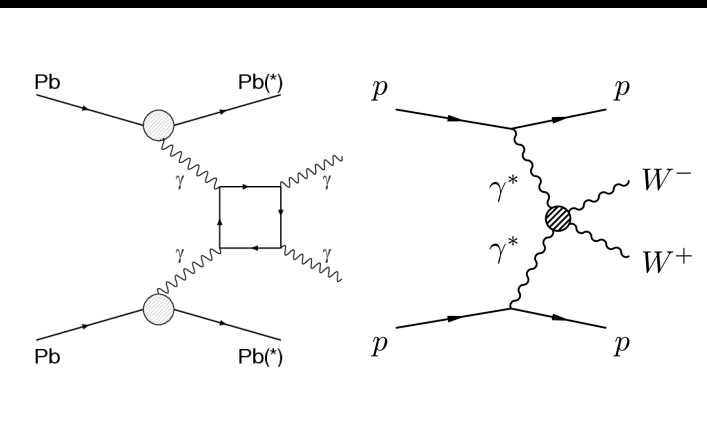
heavy ion collisions

1 month per year the LHC
collides ions (eg PbPb)

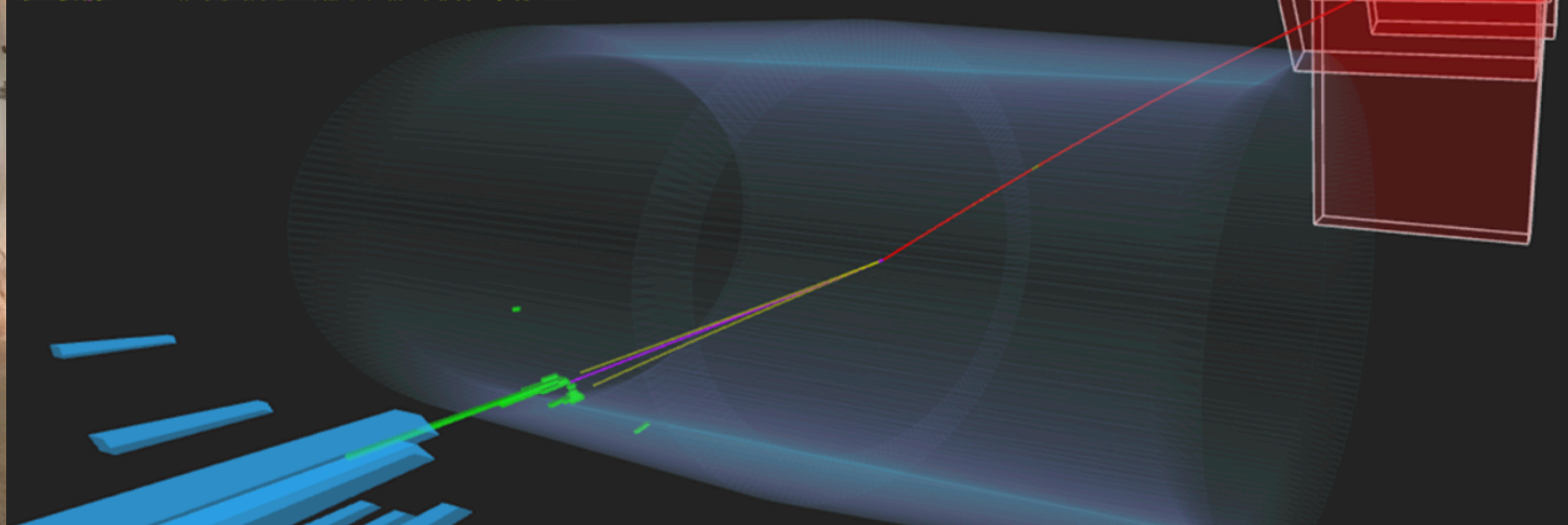
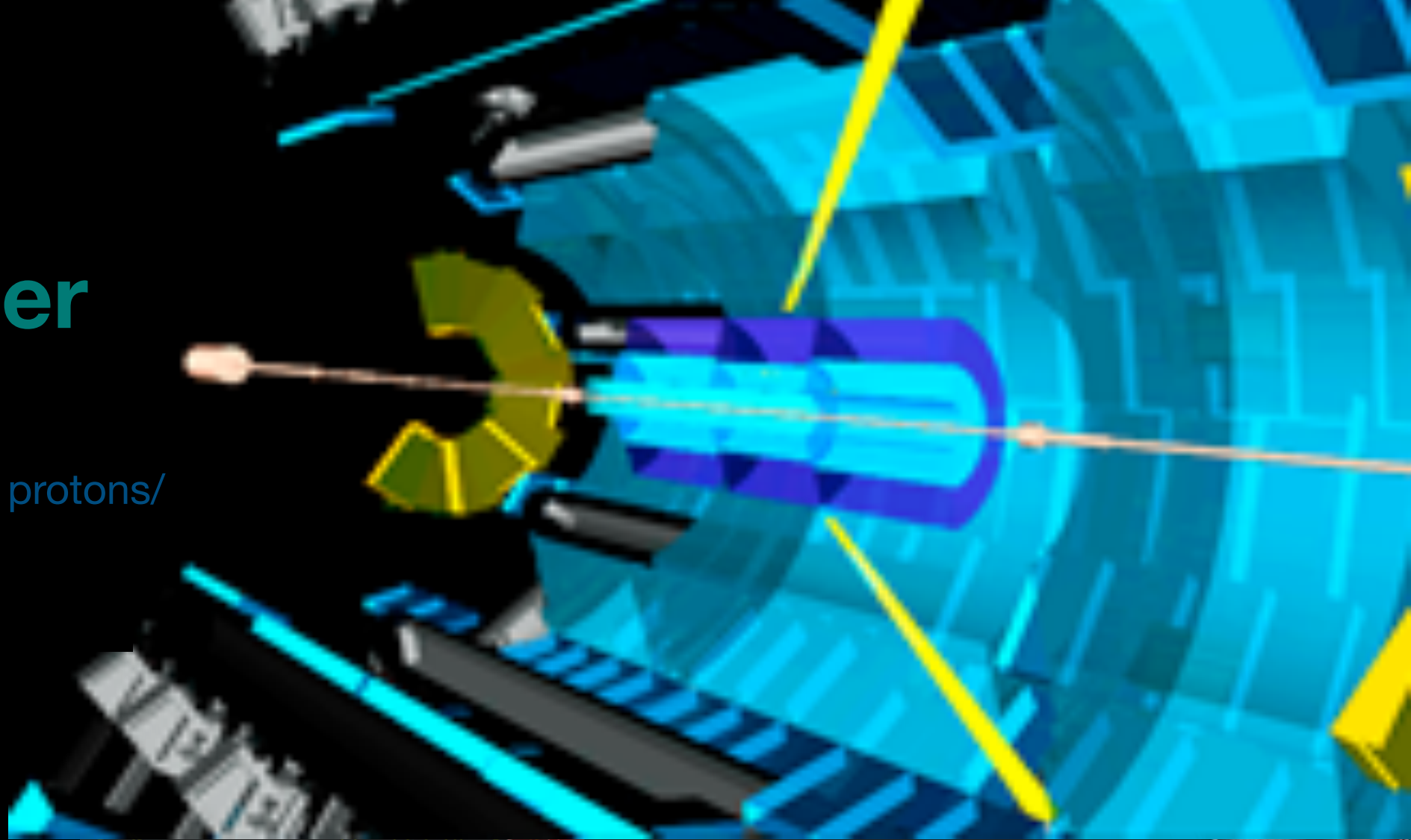
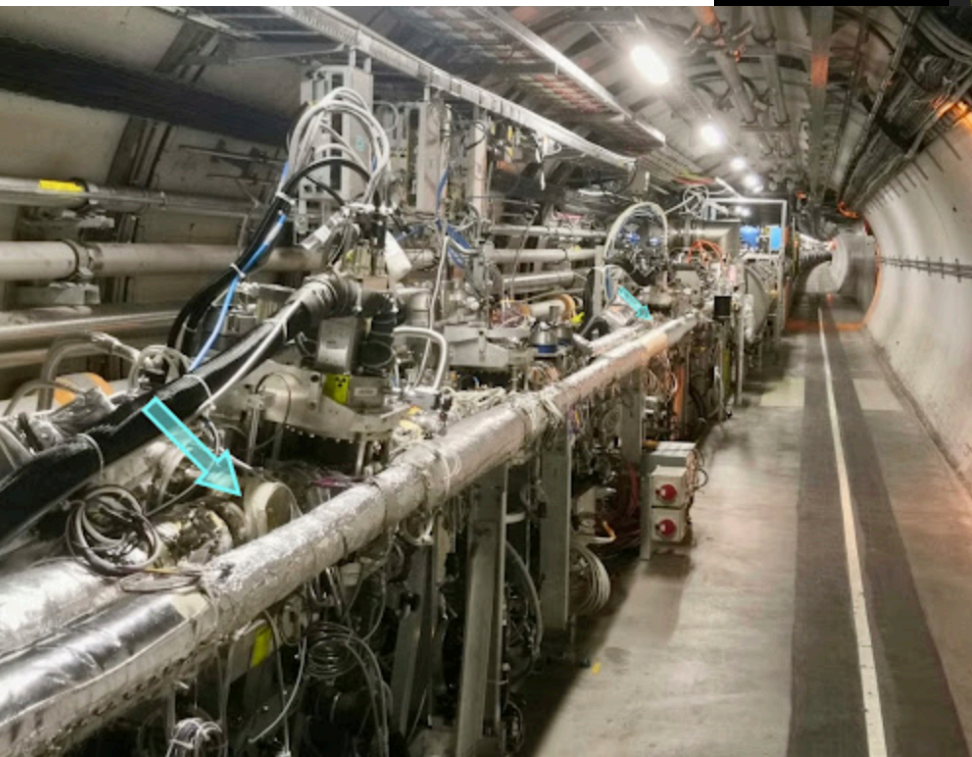


LHC as a photon collider

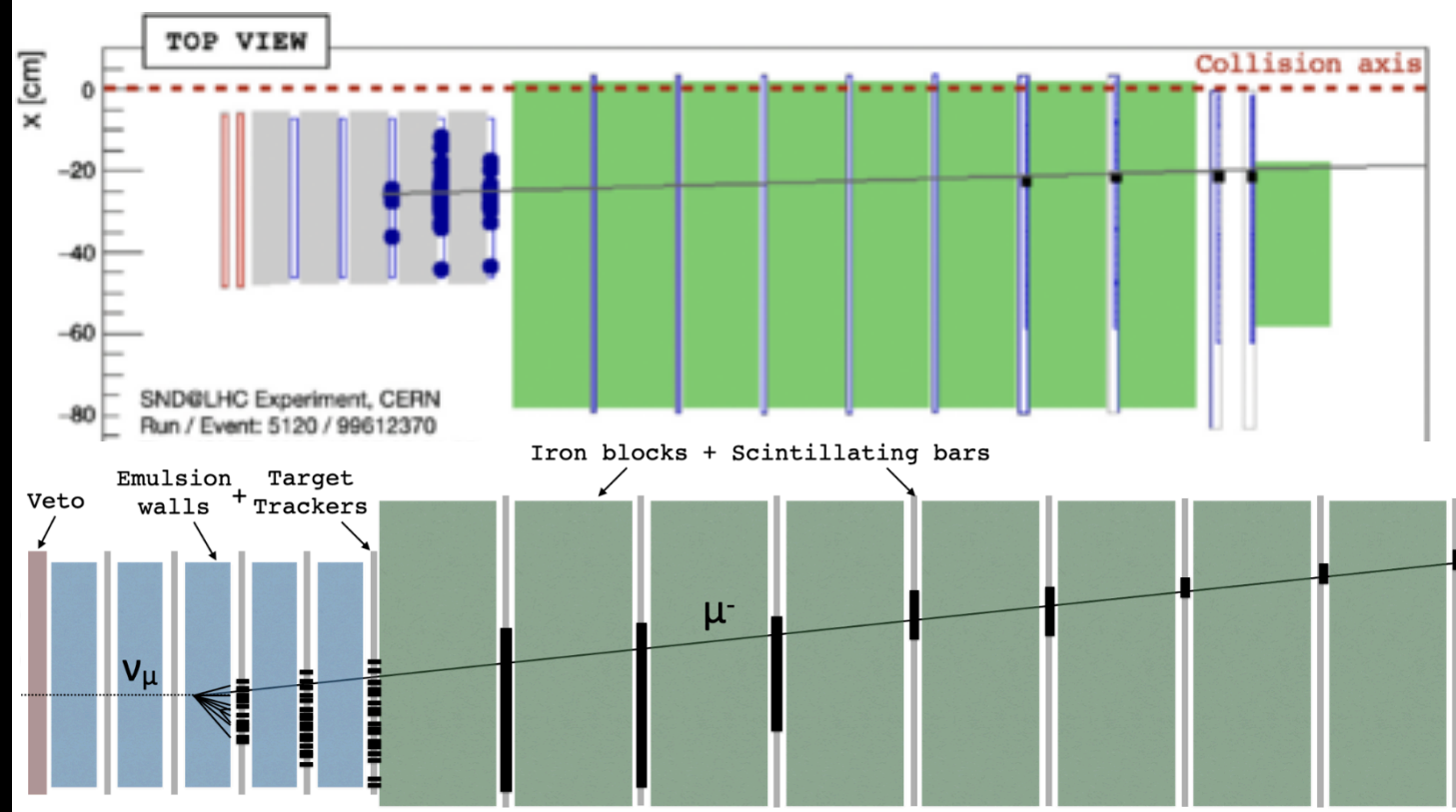
photons radiated from colliding protons/
ions can themselves collide
→ dedicated detectors



AFP, PPS

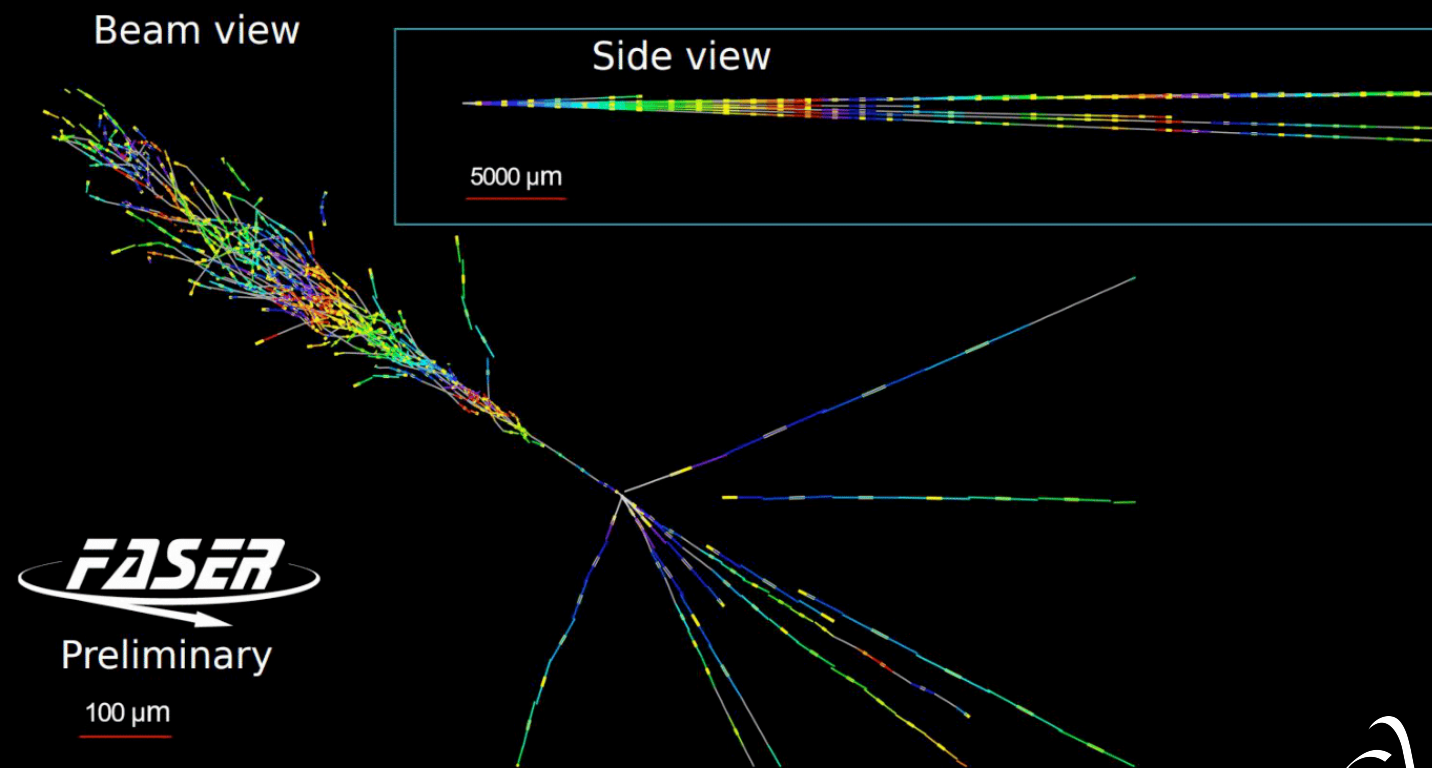


first neutrino interactions @LHC



detection of neutrino interactions @LHC
 ➔ required novel, dedicated detectors (Run3)

SND@LHC



Scattering and Neutrino Detector
at the LHC



LHC — mission & legacy

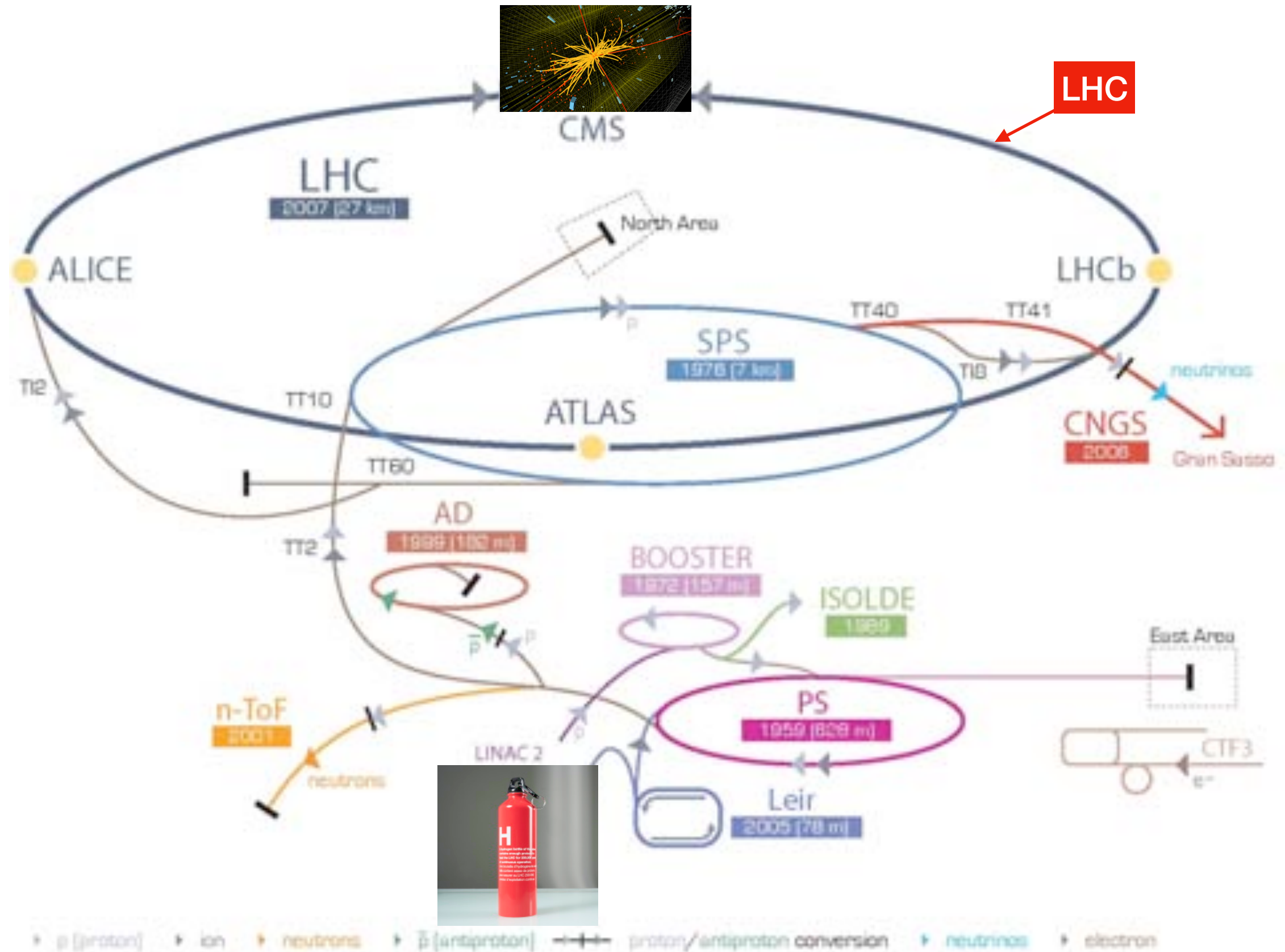
- **energy** frontier — search program at the TeV scale
- **intensity** frontier — precision electroweak measurements
- lifetime/**coupling** frontier — search for long-lived beyond-SM signatures
- heavy **flavour** — explore heavy quarks and leptons: t , b , τ (aka the 3rd family)
- heavy **ions** — ultra-relativistic nuclear collisions, deconfined QCD medium
- **photon** collider — ultra-peripheral collisions and proton tagging
- collider **neutrinos** — direct measurements of all neutrino flavours

↪ replaces+extends previous machines: Tevatron, BaBar/Belle, RHIC, LEP...

The accelerator



the CERN accelerator complex



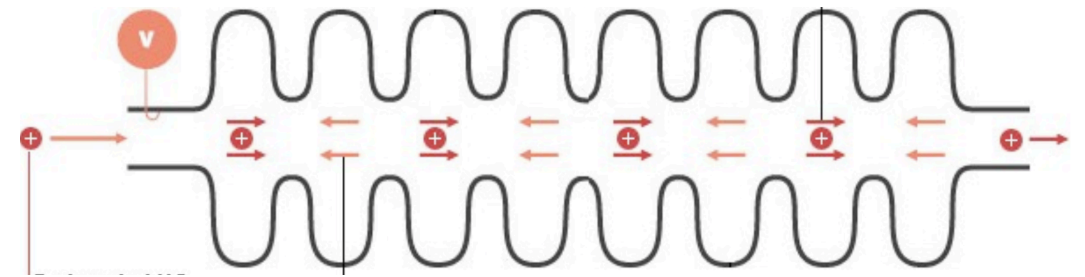
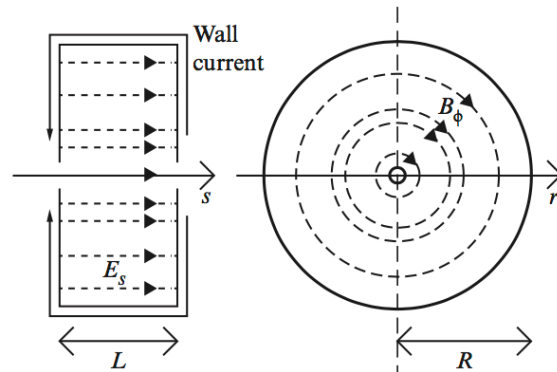
accelerate, bend, focus ...

- only charged particles can be accelerated: p , $\bar{p}$, $e^\pm$, $(\mu^\pm)$, ions
 - e.g. **LHC** (**p+p**, p+Pb, Pb+Pb); Tevatron (pp); LEP, PEP, KEKB (e^+e^-); RHIC (ions); FAIR (p-ions)

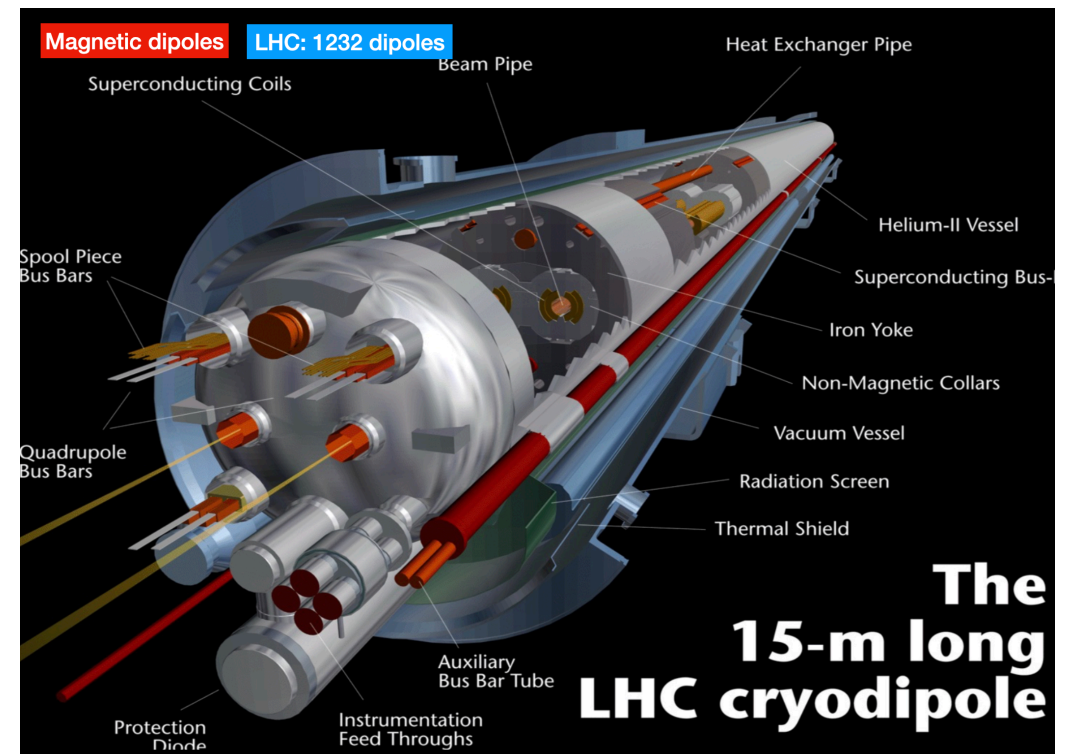
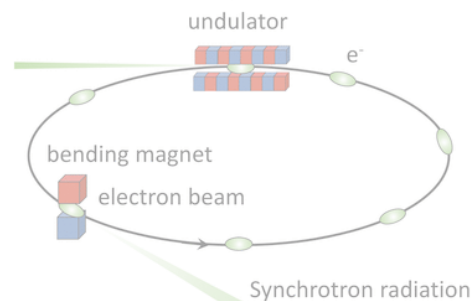
- acceleration by radiofrequency

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

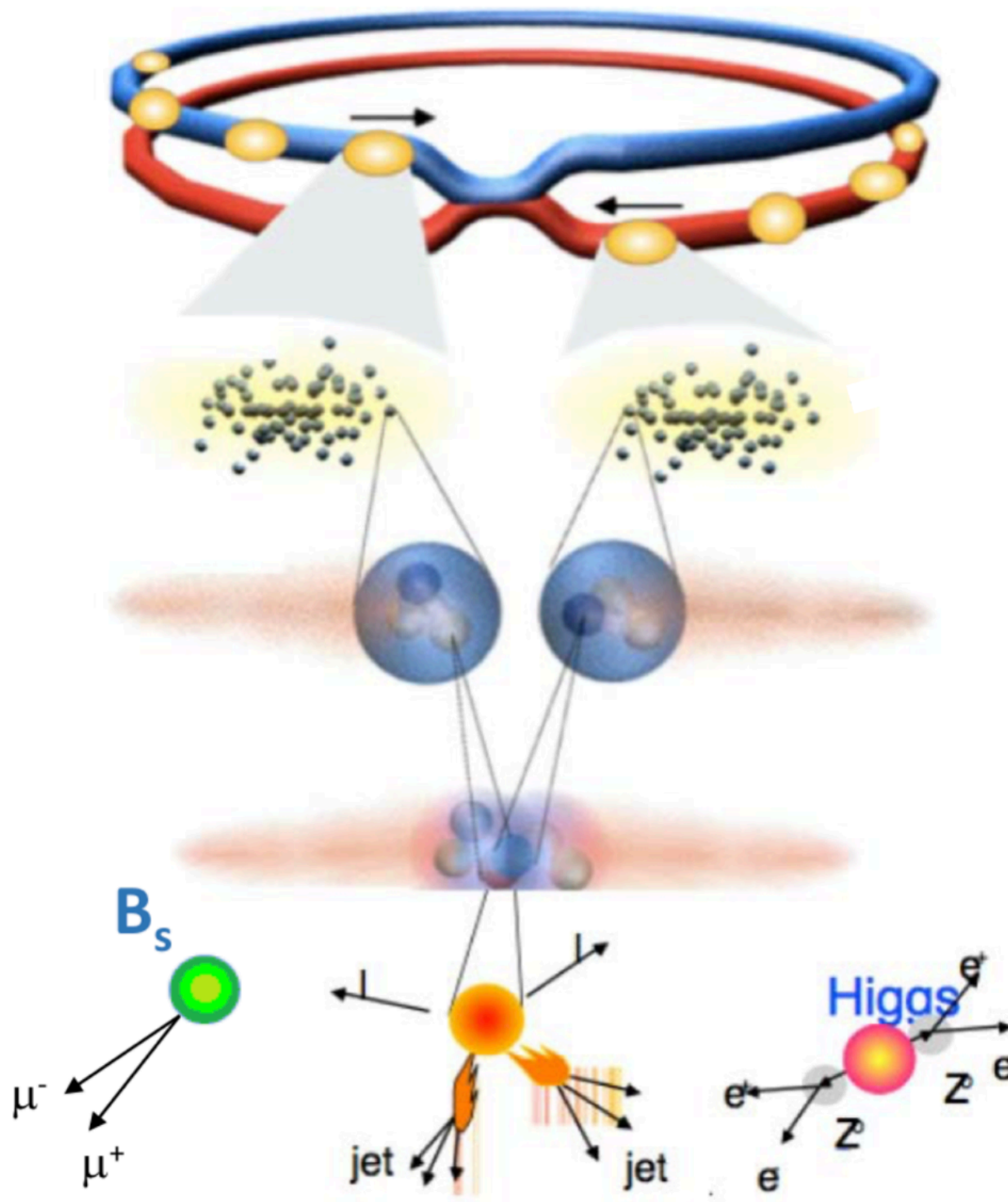
$$\mathbf{E} = -\nabla\varphi - \frac{\partial \mathbf{A}}{\partial t}$$



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



Proton-proton collision



Some specs:

Beam structure

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

Bunch Crossing $4 \cdot 10^7$ Hz

Proton Collisions 10^9 Hz

Parton Collisions

4000 $W^\pm$ s / sec

1200 Z^0 s / sec

17 $t\bar{t}$ s / sec

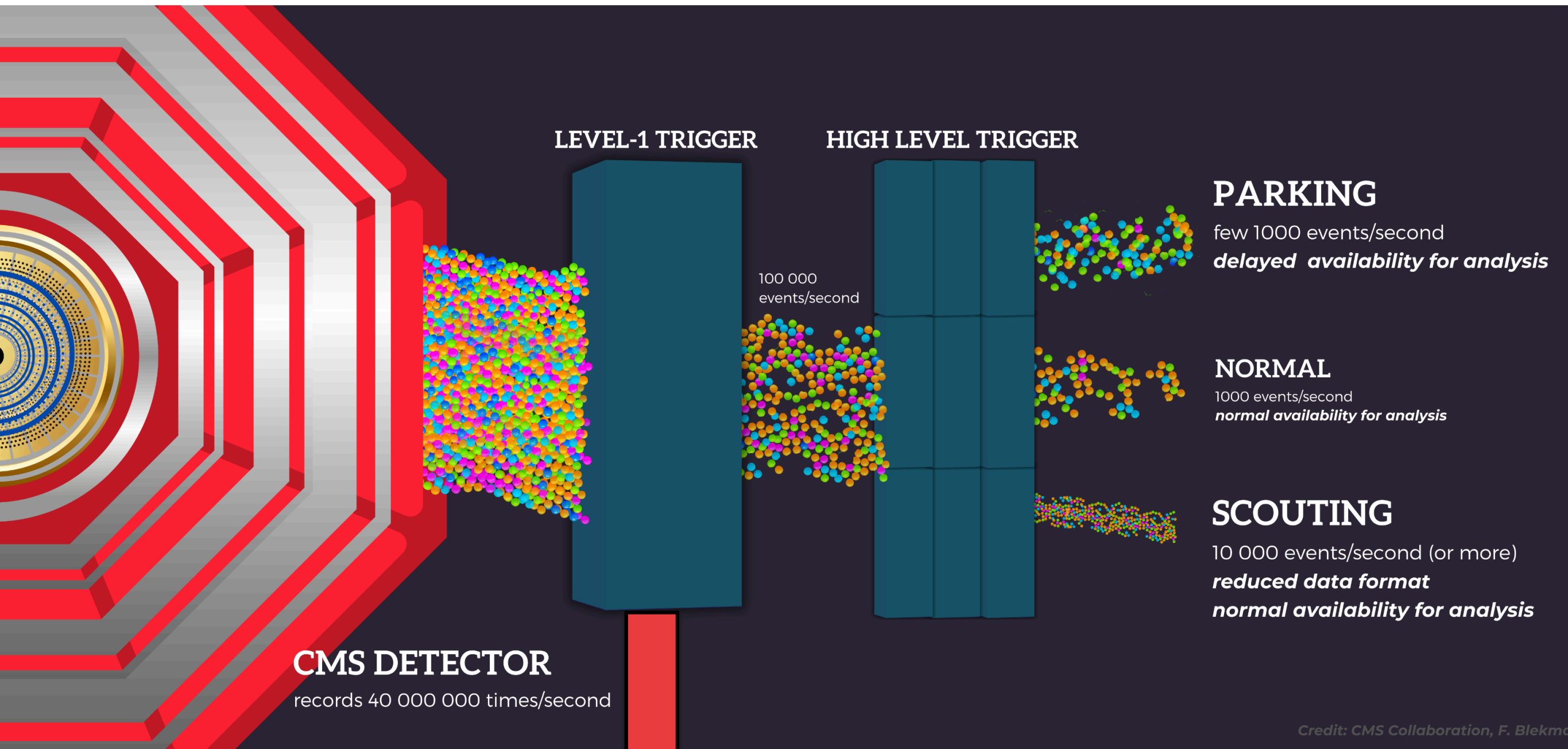
1 h^0 s / sec

New Particle Production 10^{-5} Hz

We're interested in **rare** events

➡ Real-time filtering: **Trigger**

Filtering collision events



novel data-taking paradigms
Run3 & HL-LHC



enhance
physics
sensitivity

Physics sensitivity

Observed
in the data

Driven by
the machine

Driven by
the detector

maximize
sensitivity
stat. $\propto \sqrt{N}$

$$\mathcal{N} = \sigma \times \mathcal{L} \times \mathcal{A} \times \epsilon$$

Cross section

for a given physics process
 $\propto$ collision energy, $\sqrt{s}$

rare processes = small σ
 $\hookrightarrow$ require large Lumi. + Eff

Luminosity

Integrated:
increases $\sim$ linearly with time
challenge: manage large datasets

Instantaneous:
increases with upgraded machine
challenge: manage pileup

Acceptance

Geometric:
Extend detector coverage

Kinematic:
Extend sensitivity to low p_T

Improve with upgraded detector and data acquisition

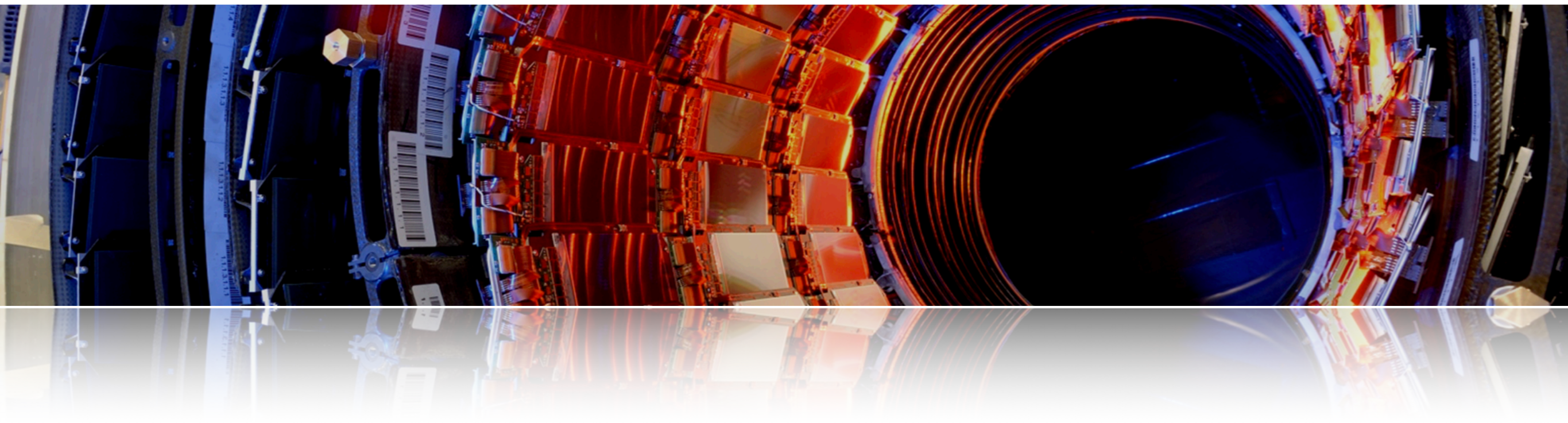
Efficiency

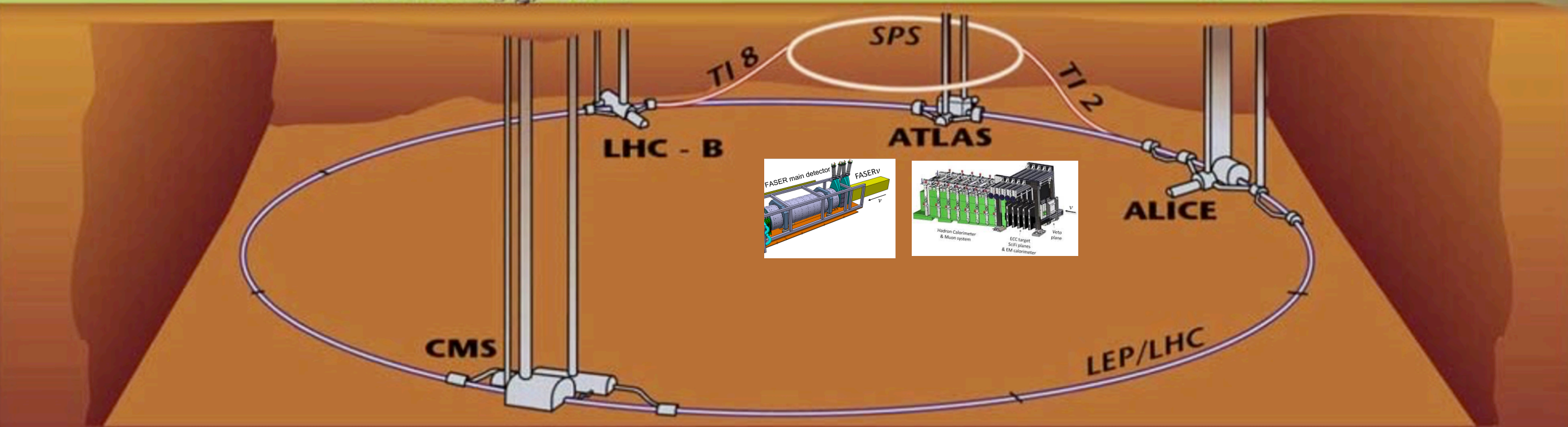
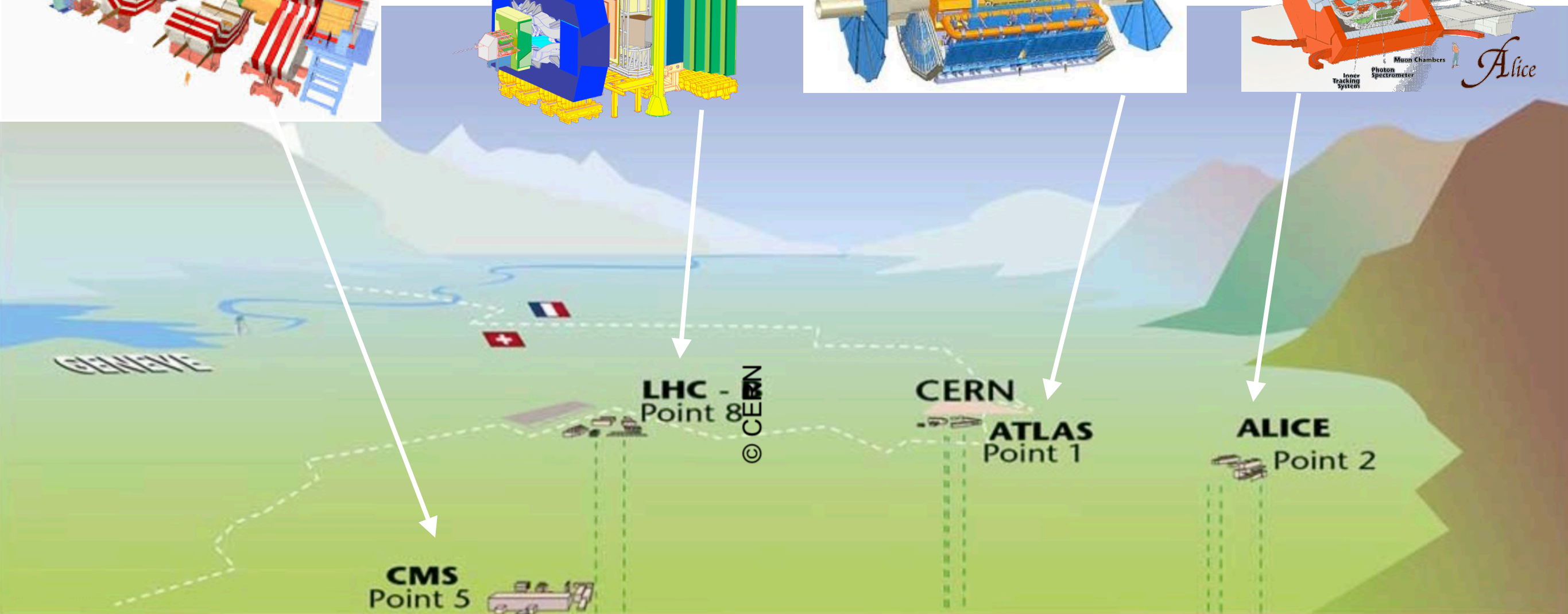
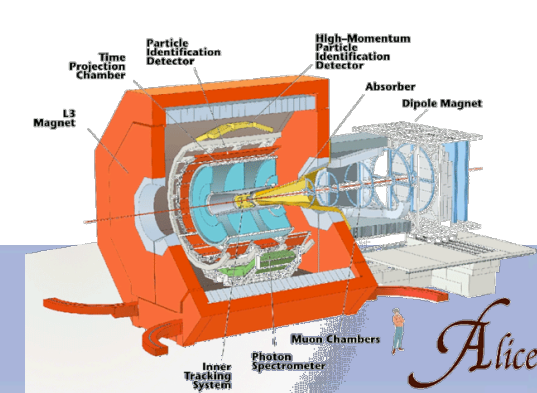
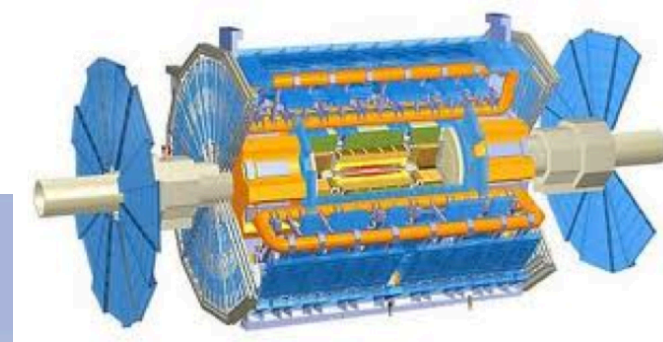
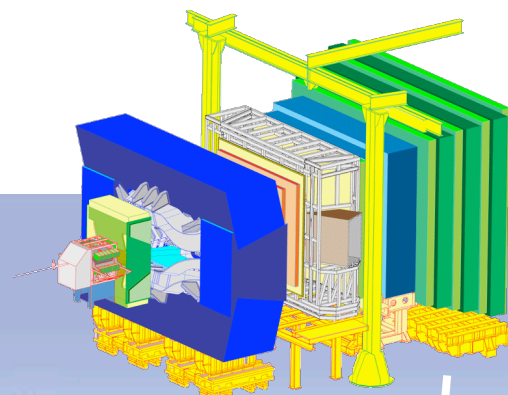
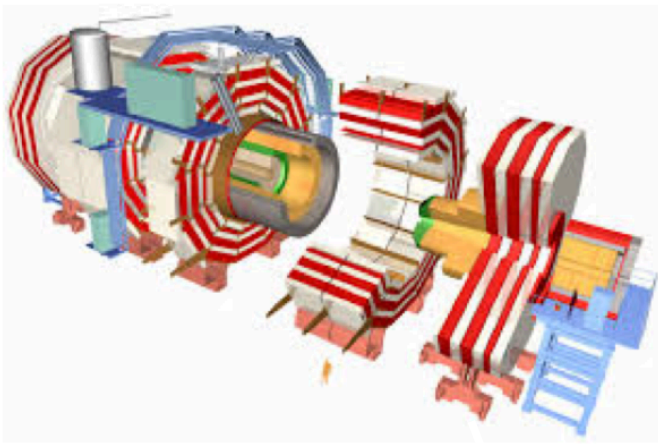
Trigger / DAQ
Physics object Reco. & ID
Background rejection

Improve with upgraded detector and analysis methods (ML)

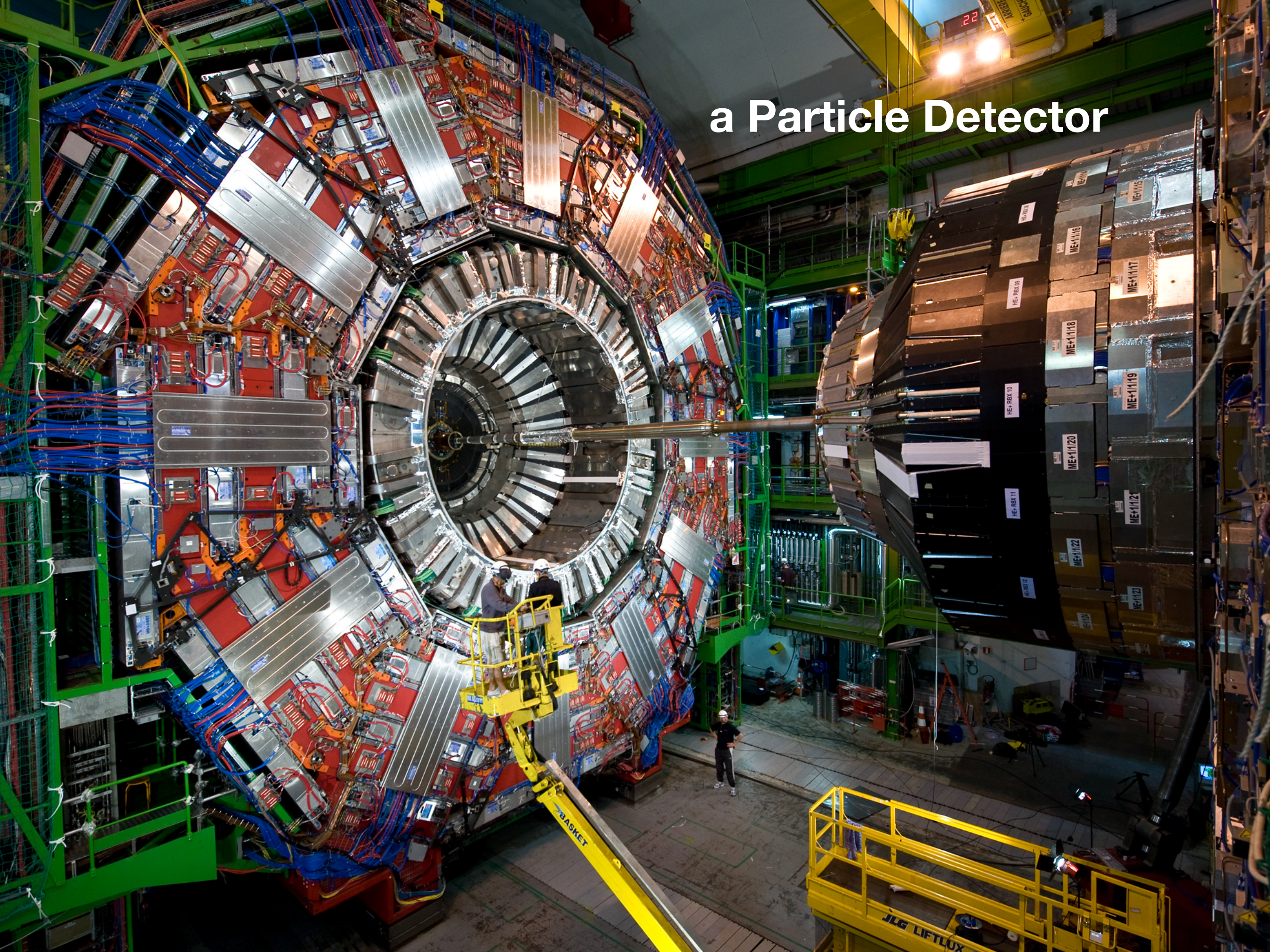
- physics reach determined by:
 - Collision energy** ($\sqrt{s}$) — how deep can we probe matter
 - Luminosity** (L) — quantifies the collision rate (increase!)
 - Detector acceptance** and efficiency (improve/upgrade!)

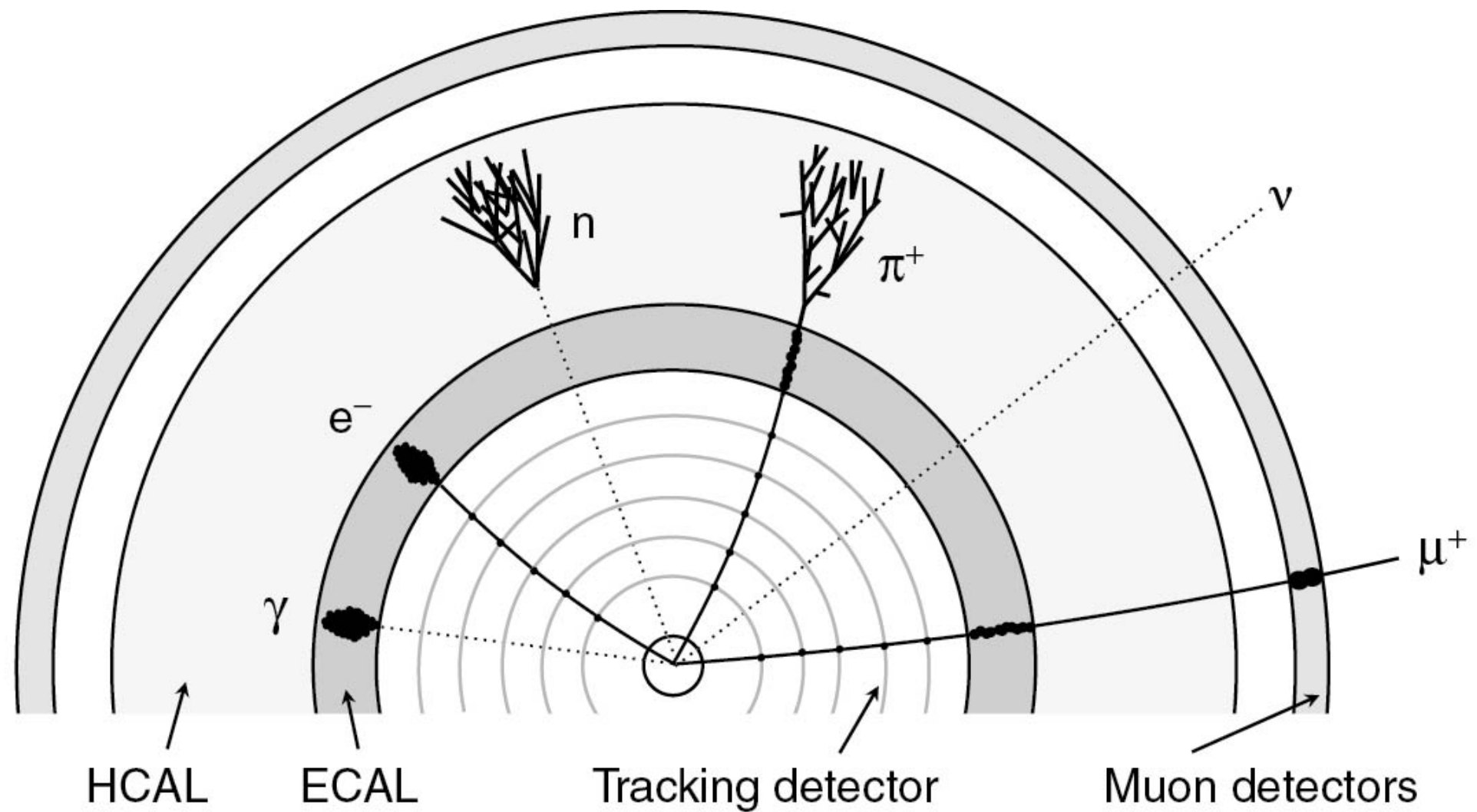
The detectors





a Particle Detector





calorimeters:

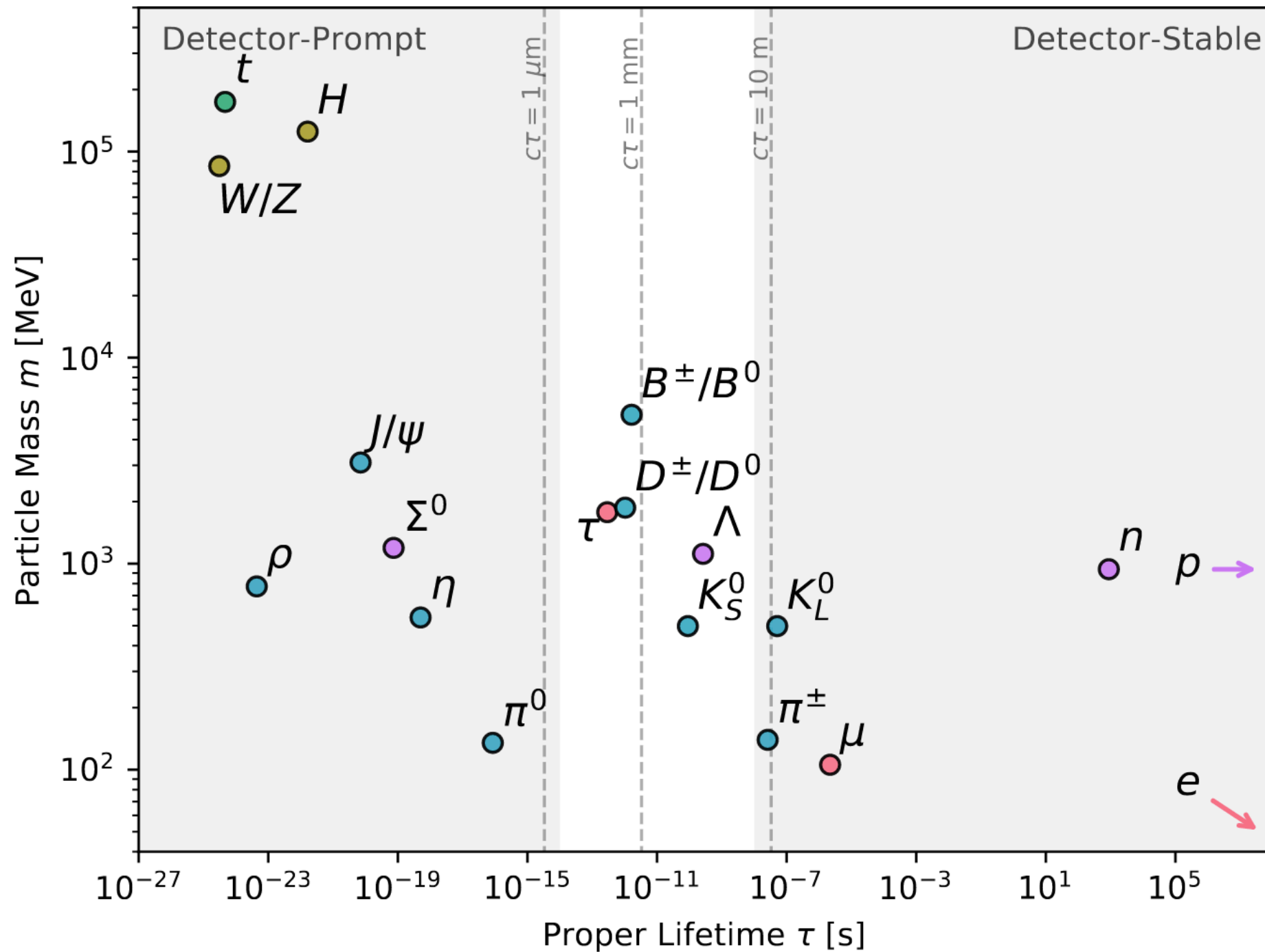
measure particle's
energy by absorbing it

trackers:

detect trajectory
of charged particles

muon chambers:

muons reach outer
detector layers

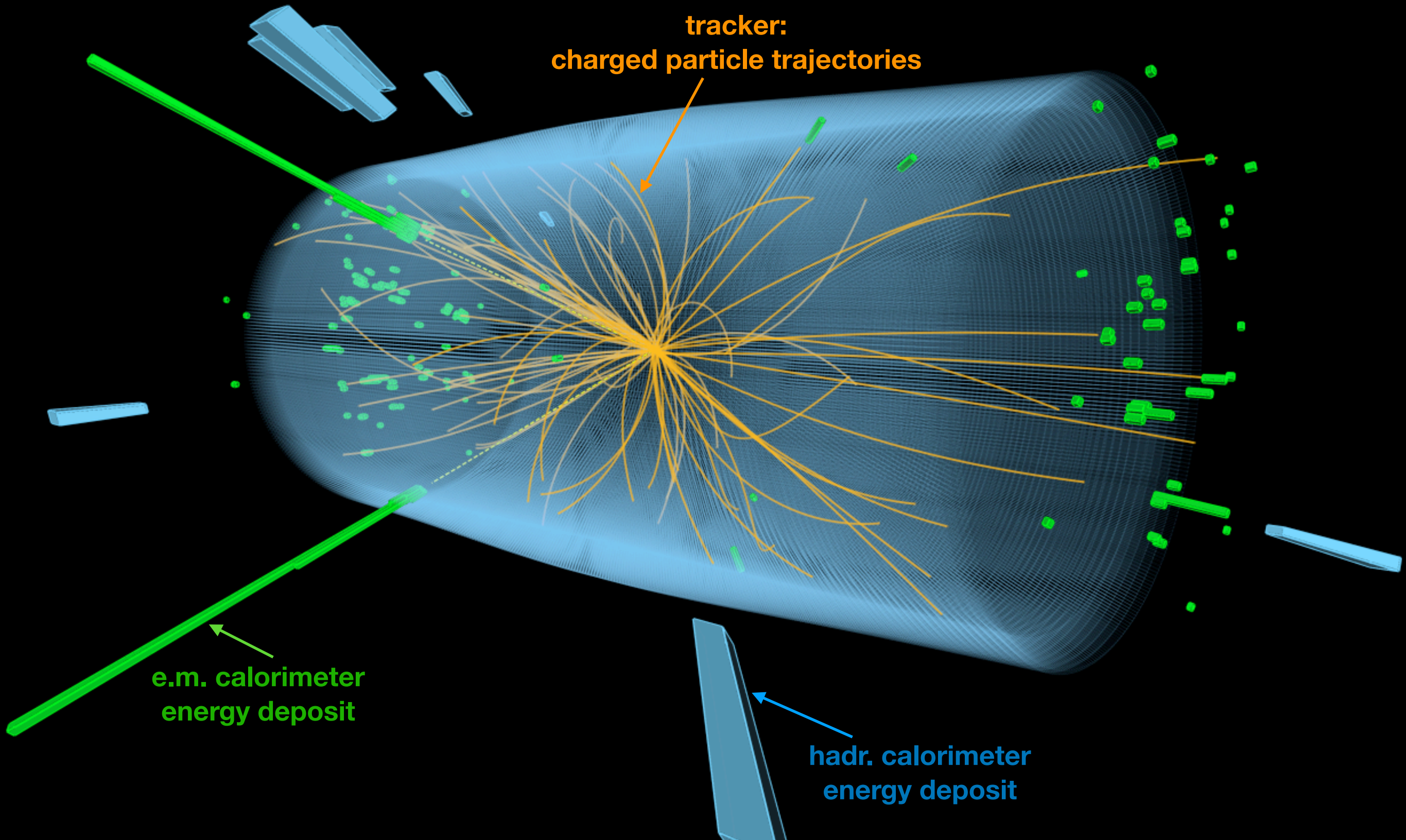


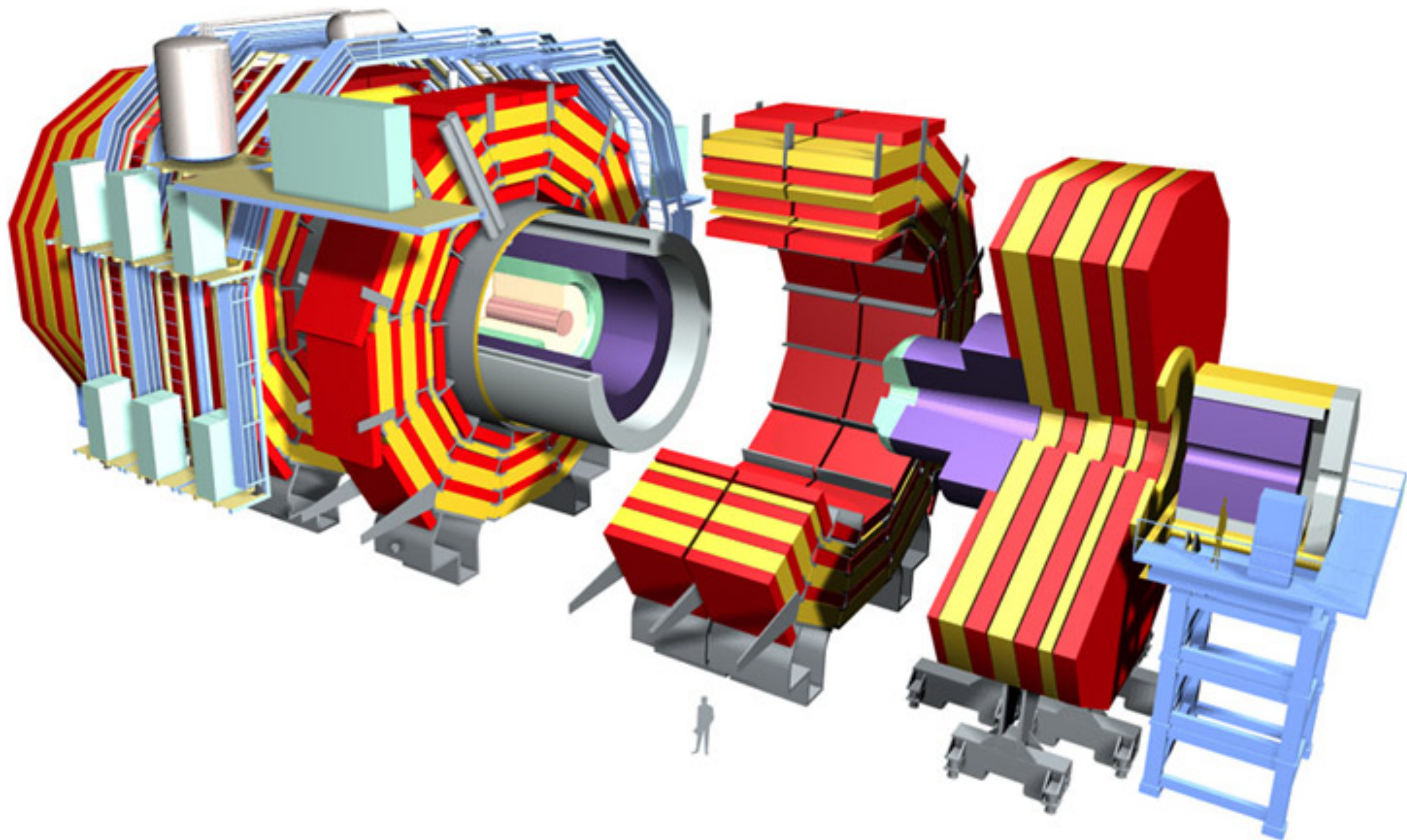
Only *quasi*-stable particles are directly detectable:

$e, \mu, \gamma, \pi, K, p, n$

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

a $H \rightarrow \gamma\gamma$ candidate



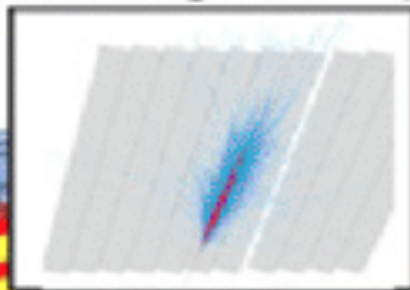


SUPERCONDUCTING COIL

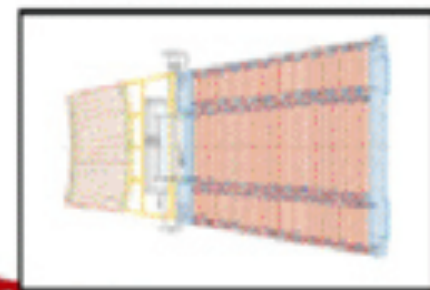
Total weight : 12,500 t
Overall diameter : 15 m
Overall length : 21.6 m
Magnetic field : 4 Tesla

CALORIMETERS

ECAL Scintillating PbWO_4 Crystals

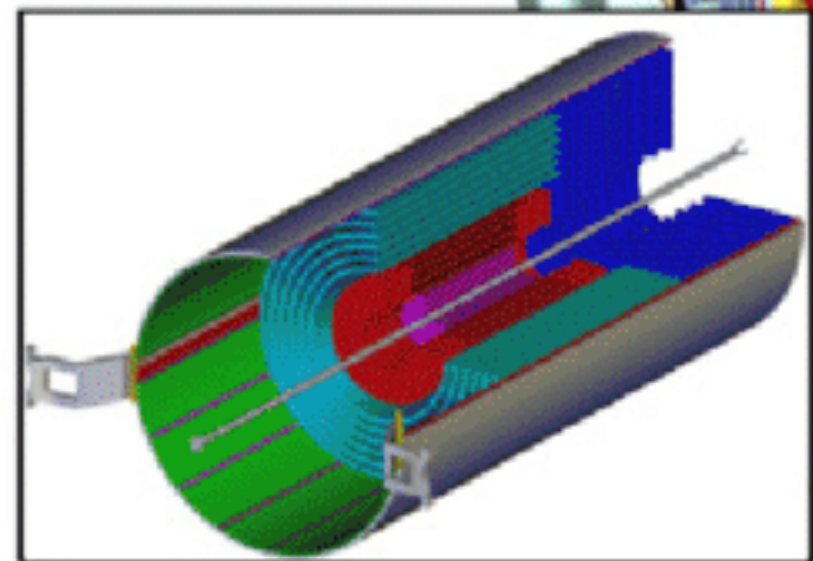


HCAL Plastic scintillator copper sandwich



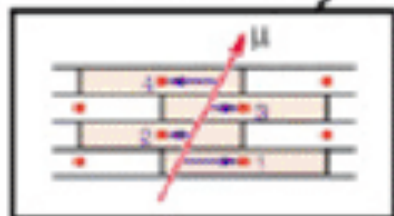
IRON YOKE

TRACKERS

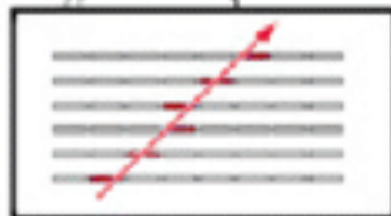


Silicon Microstrips
Pixels

MUON BARREL

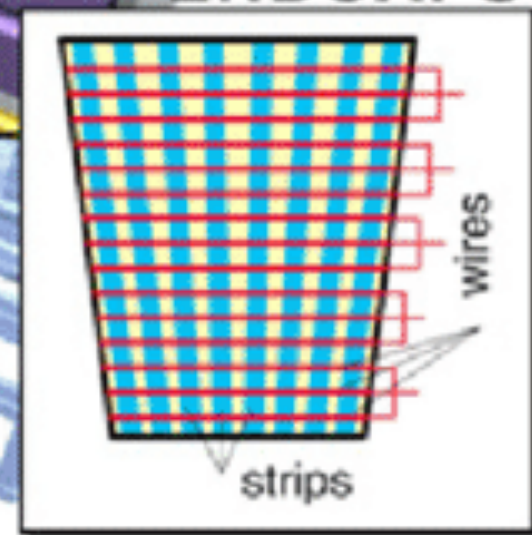


Drift Tube Chambers (DT)

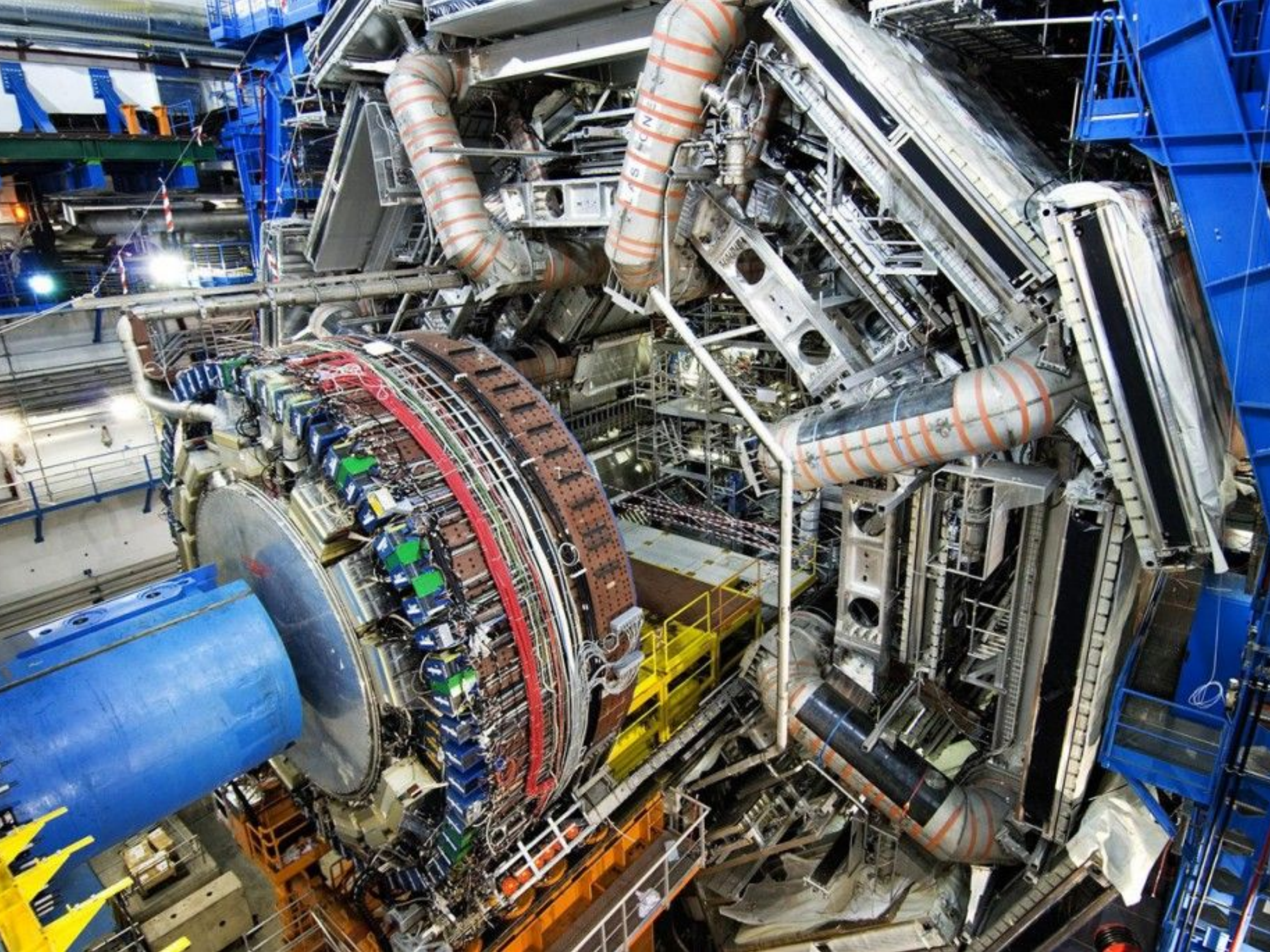


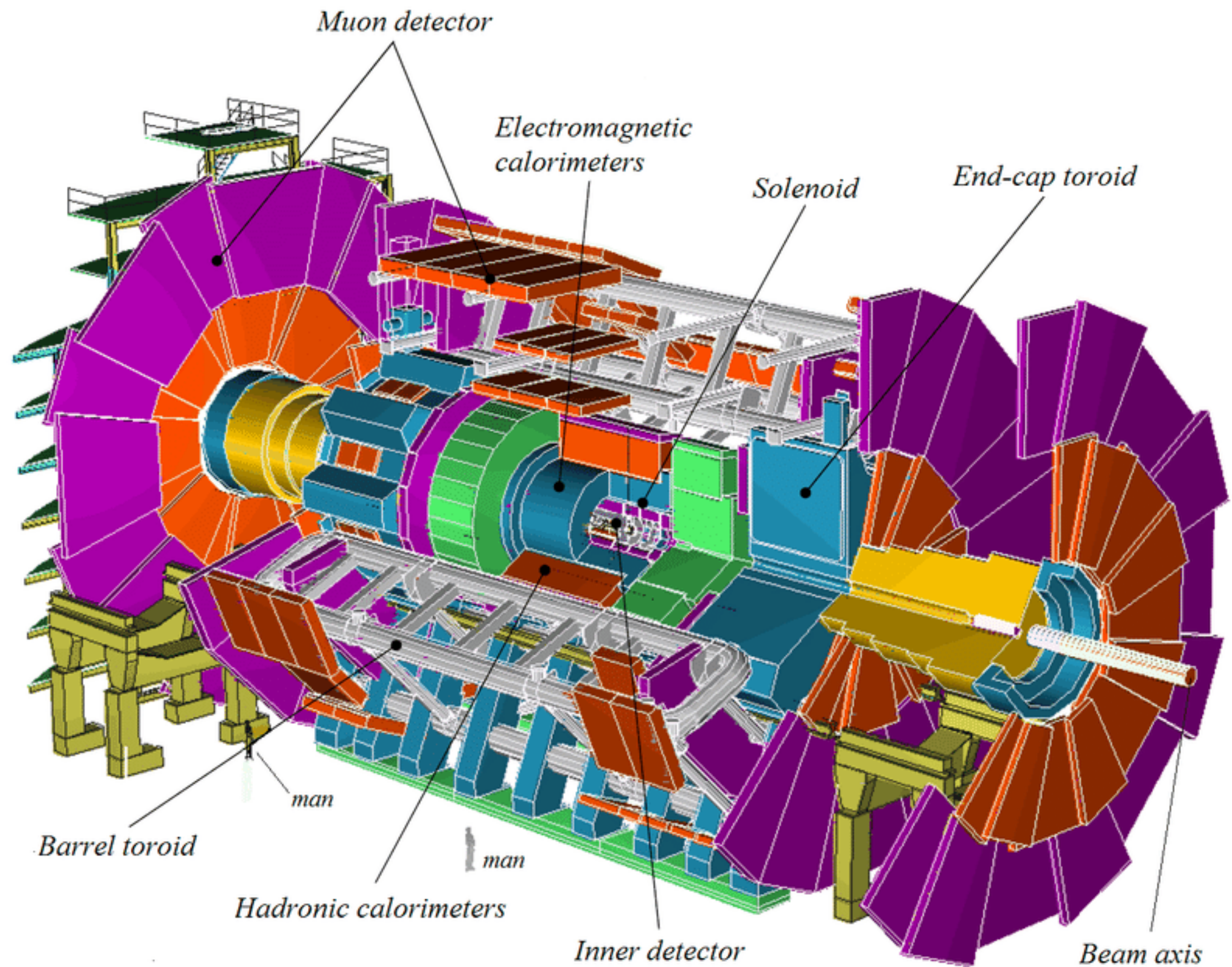
Resistive Plate Chambers (RPC)

MUON ENDCAPS



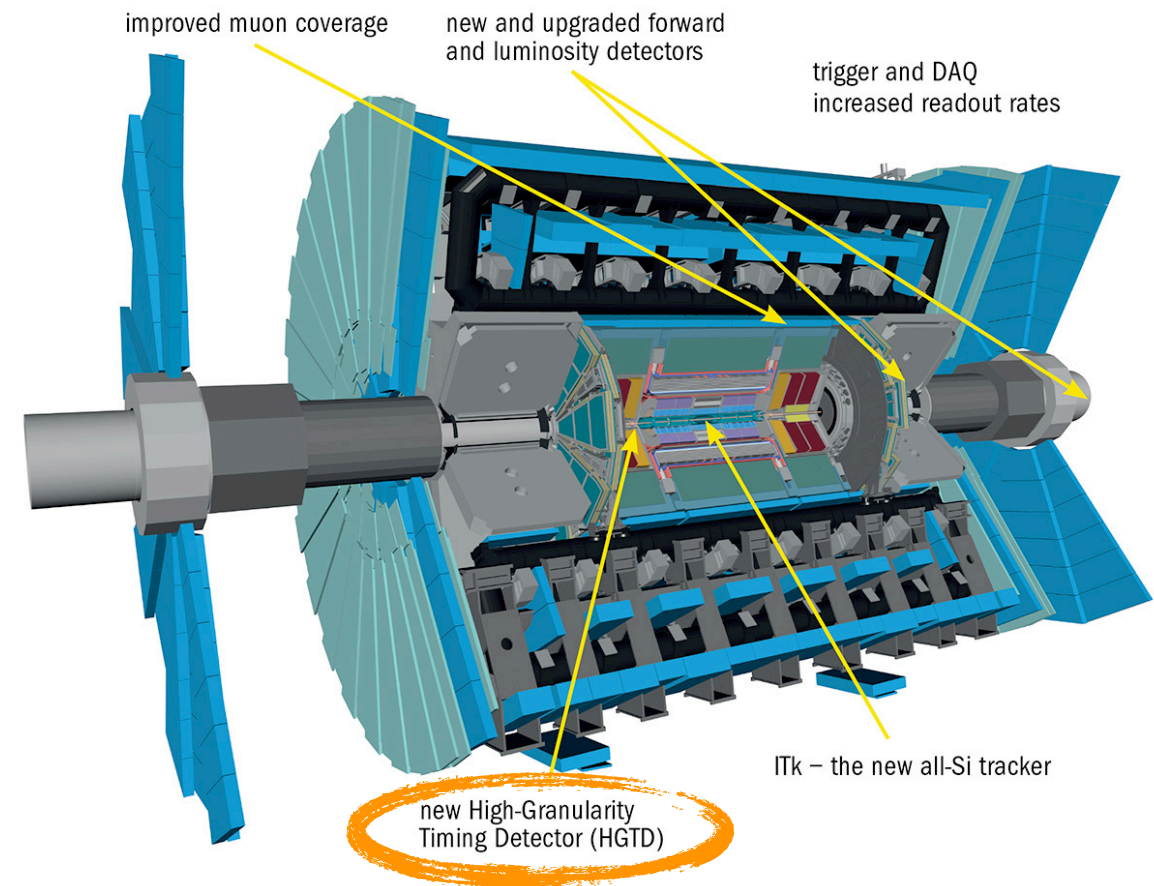
Cathode Strip Chambers (CSC)
Resistive Plate Chambers (RPC)



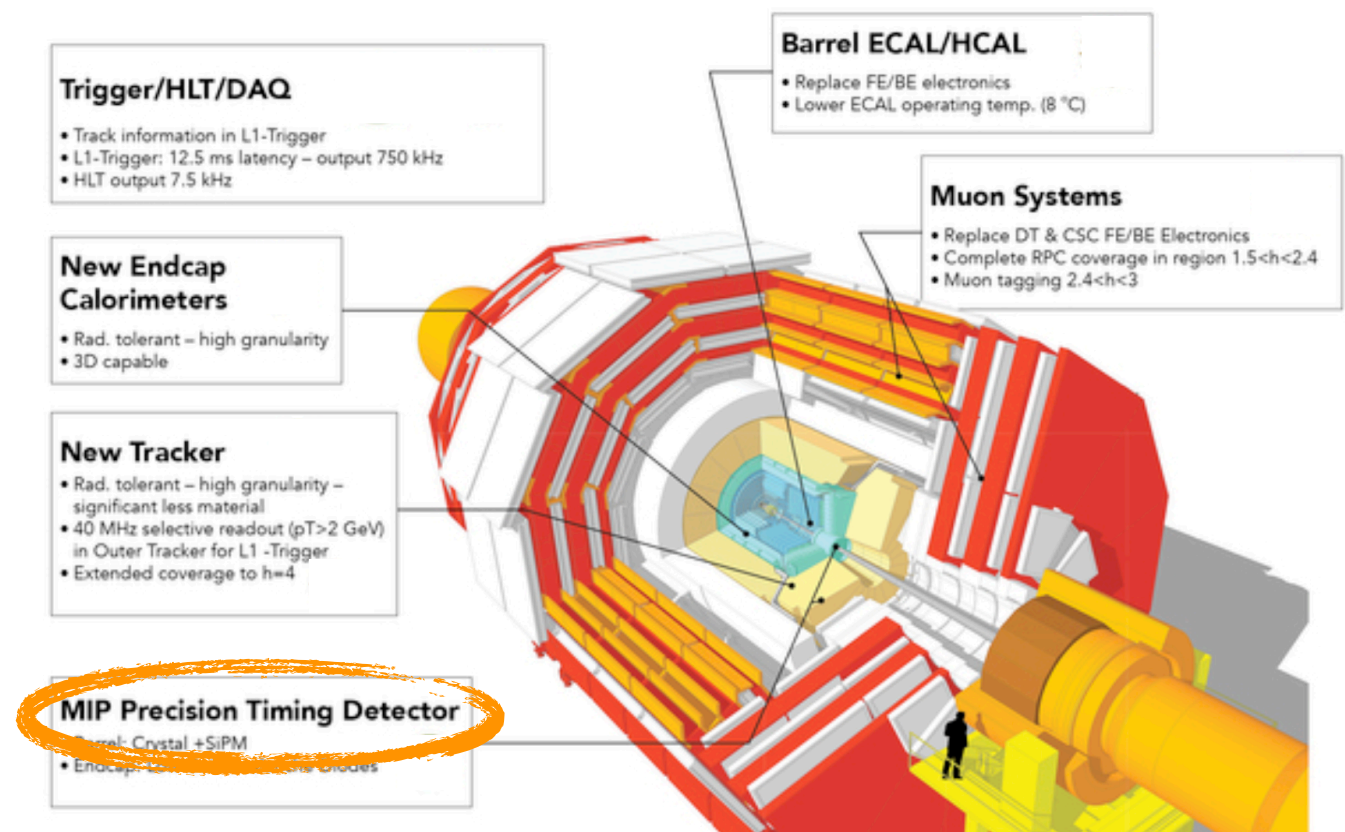
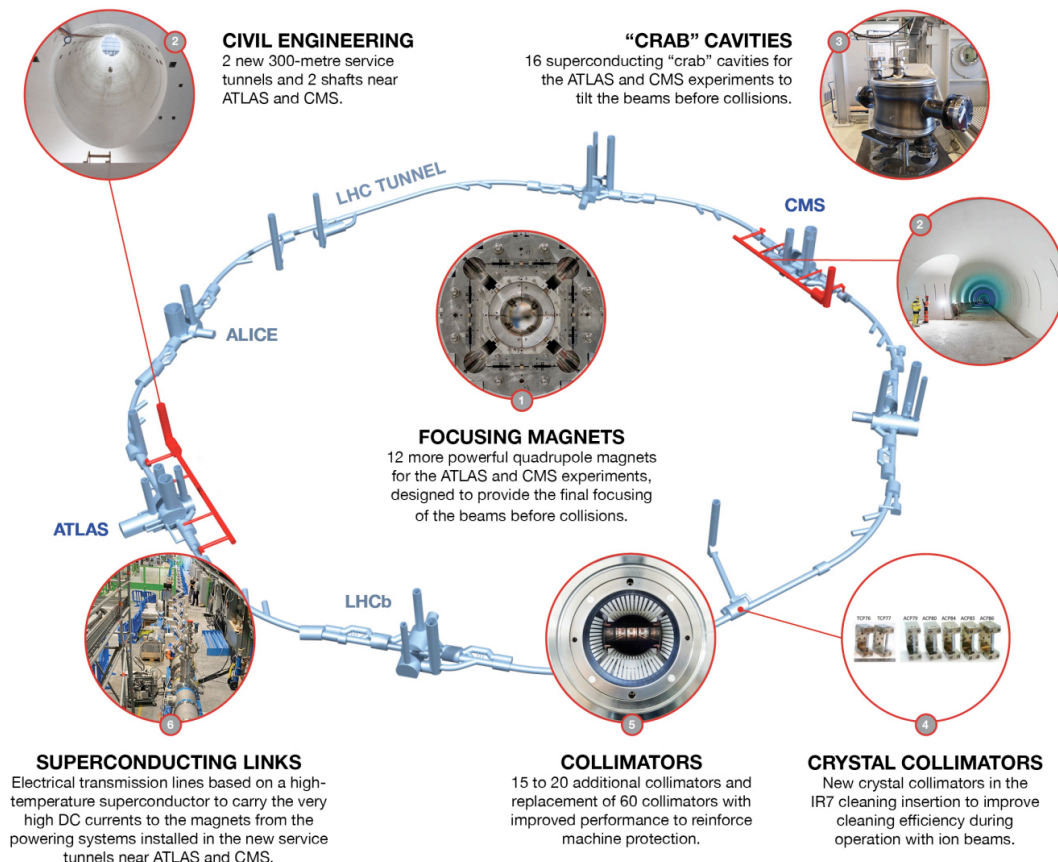


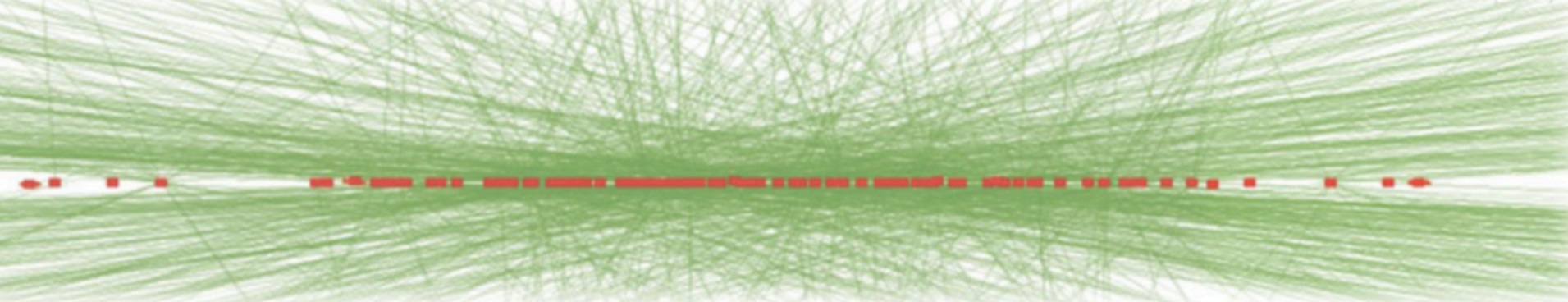
High-Luminosity LHC

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



NEW TECHNOLOGIES FOR THE HIGH-LUMINOSITY LHC





add time !

CMS

Compact Muon Solenoid

Time is measured...
...with extreme precision

ECAL
 $\Delta t \sim 30$ ps

HCAL
 $\Delta t \sim 60$ ps

MUON SYSTEM
 $\Delta t \sim 1$ ns

MTD
 $\Delta t \sim 30$ ps

PRECISION MEASUREMENT
 10^{-12} s

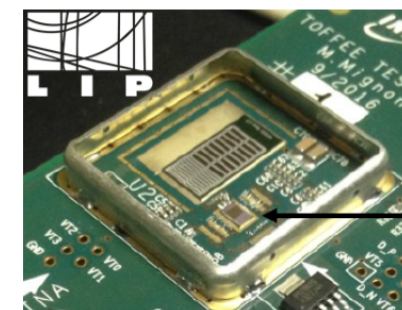
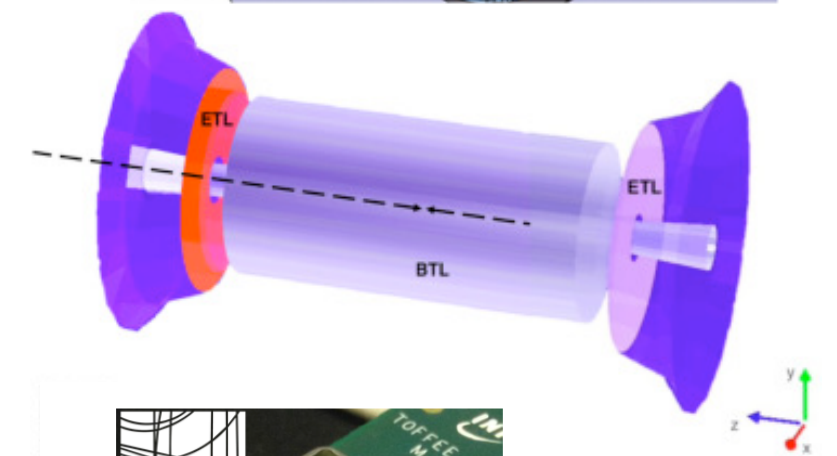
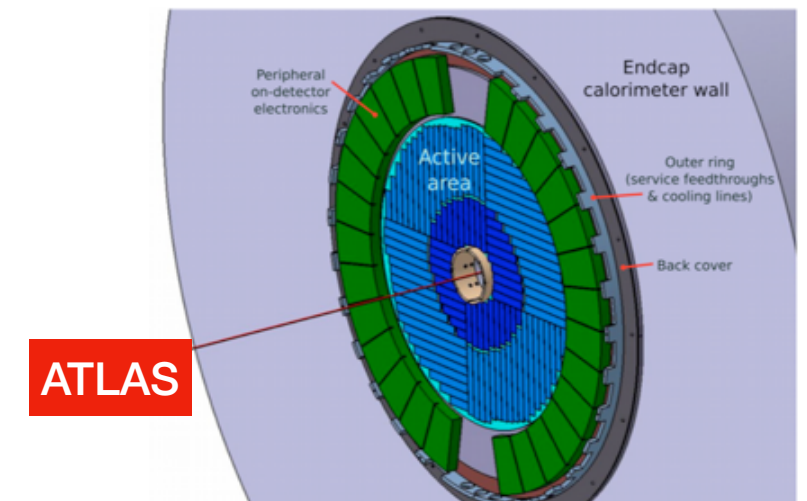
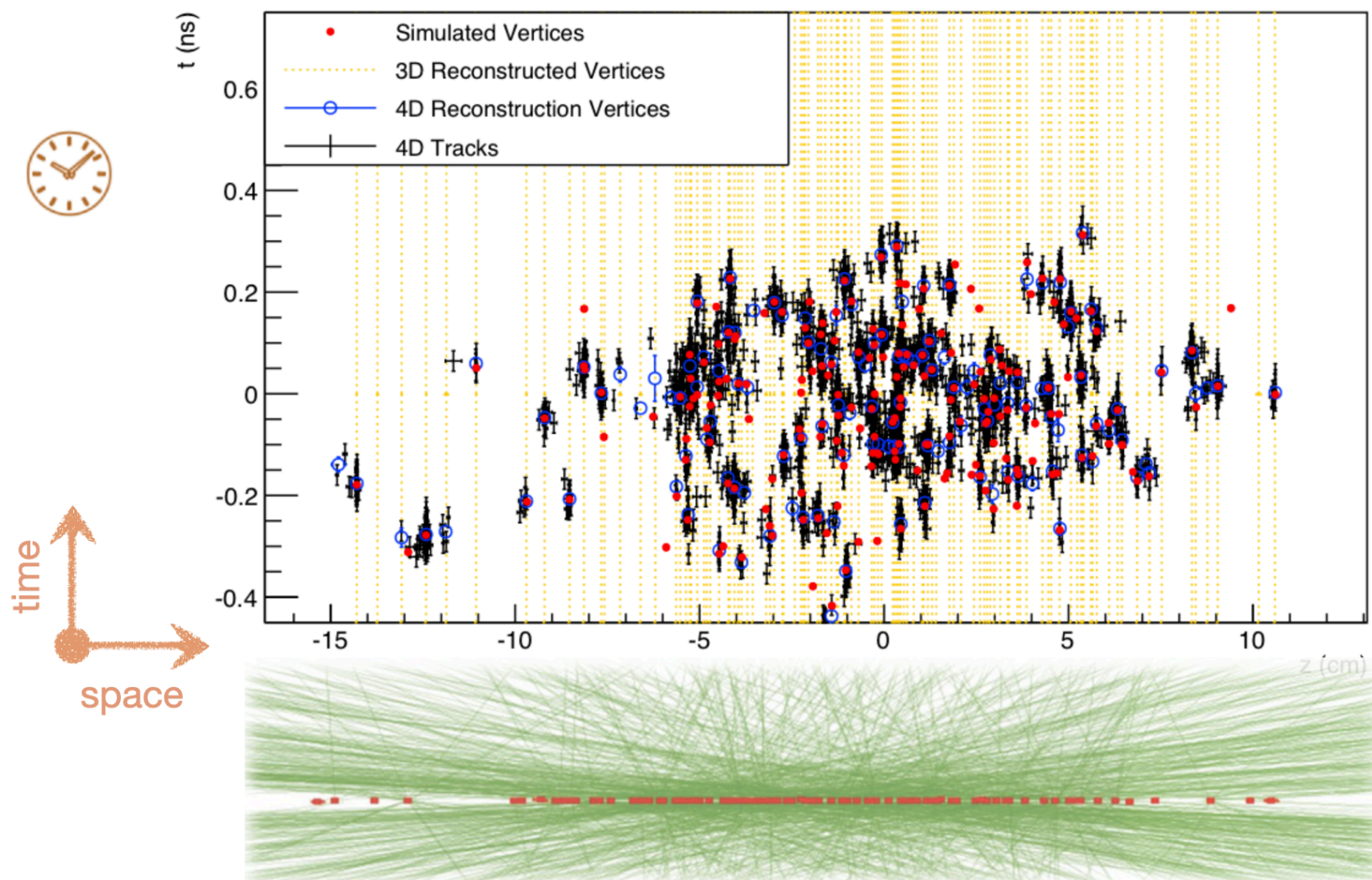
STOPWATCH PRECISION
 10^{-12} s
(picosecond range)

CMS – Precise timing

HL-LHC: adding precision timing detectors

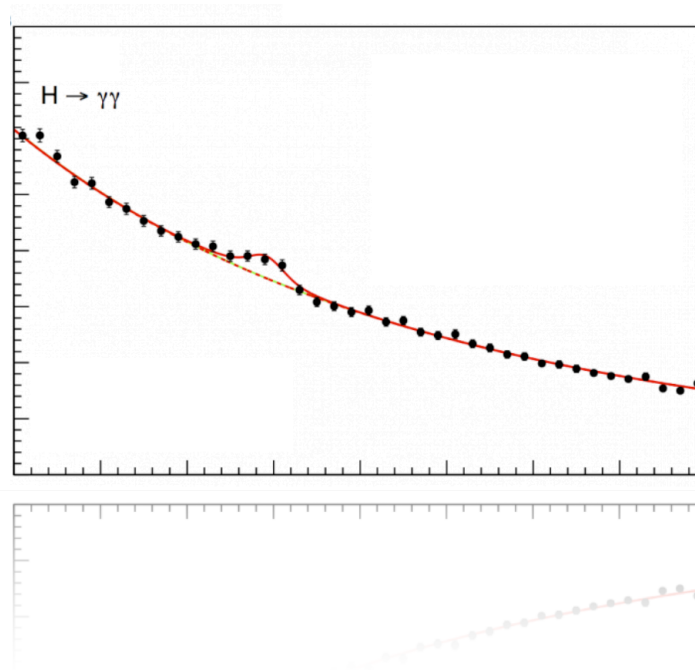
Example challenge for the high-luminosity LHC phase: **pile-up**

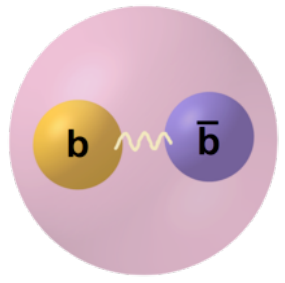
- can expect up to 200 simultaneous collisions per bunch crossing
- detectors do not have the spacial resolution to distinguish resulting vertices
- solution: **add time dimension**, i.e. develop novel precision timing detectors



CMS

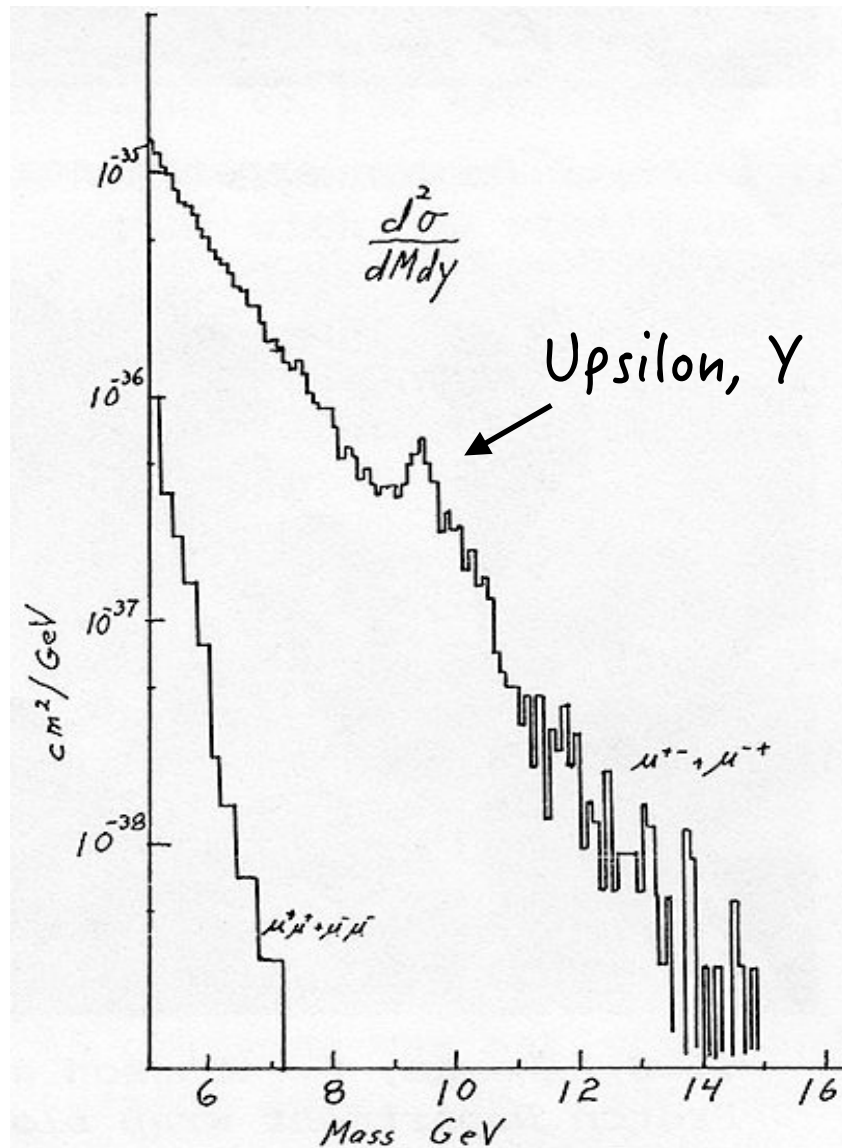
How do we 'see' particles?





the SM discovery

1977

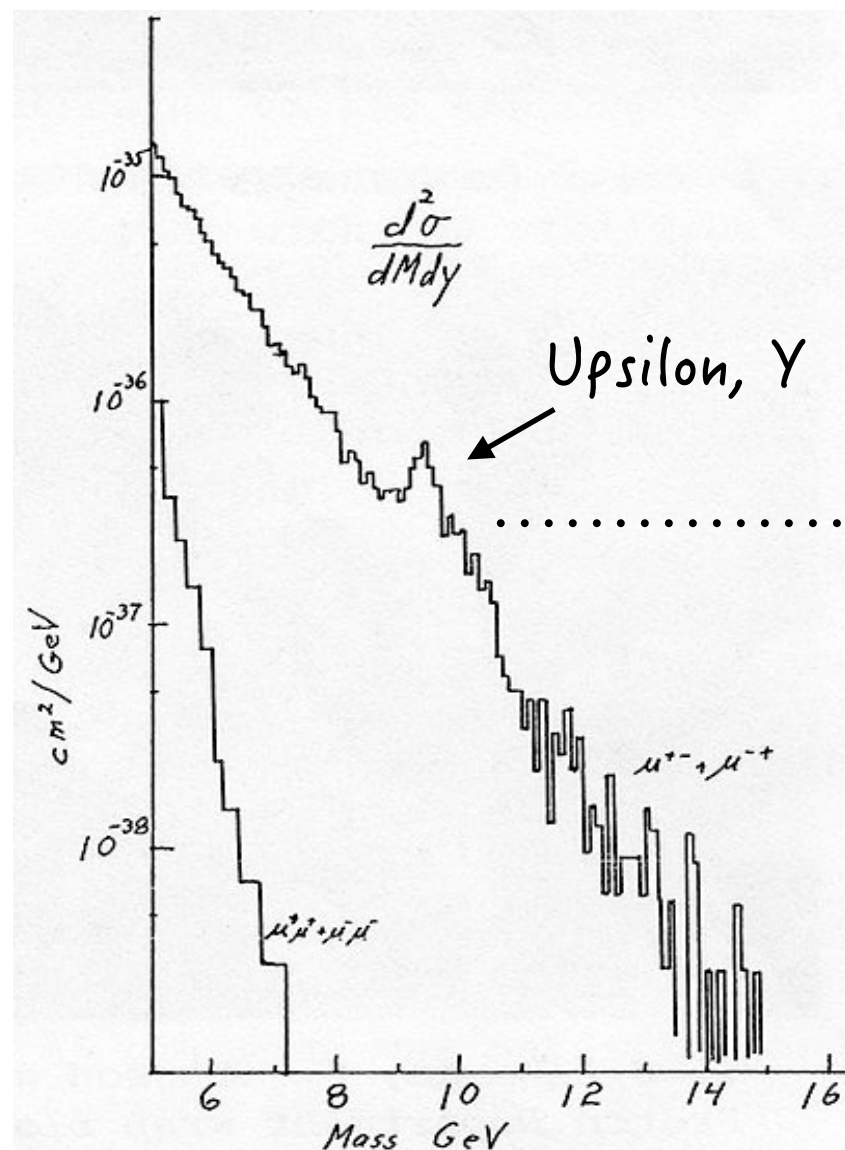


Υ , beauty

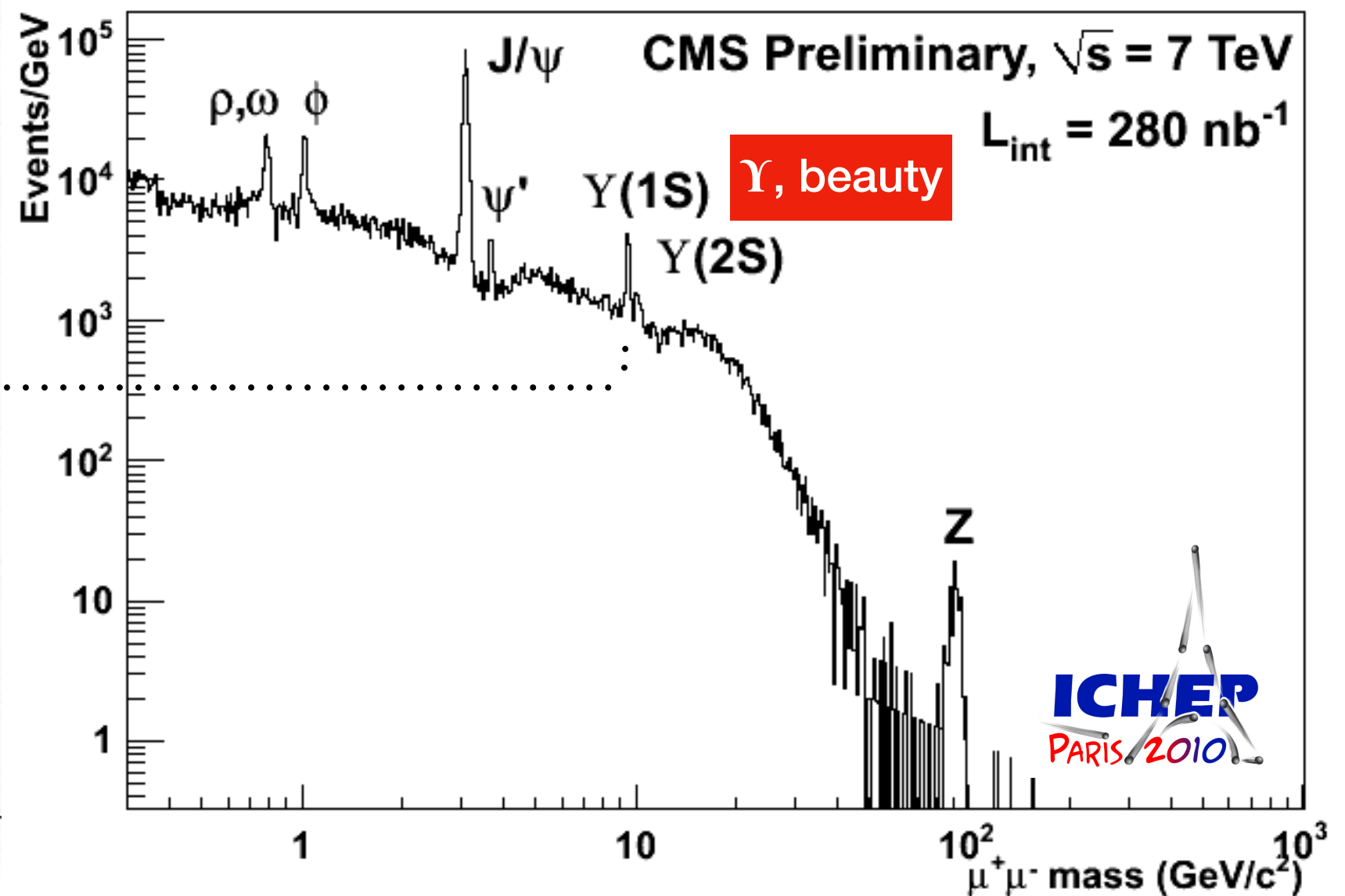
the discovery of the
b quark

the SM *re*-discovery @ LHC

1977

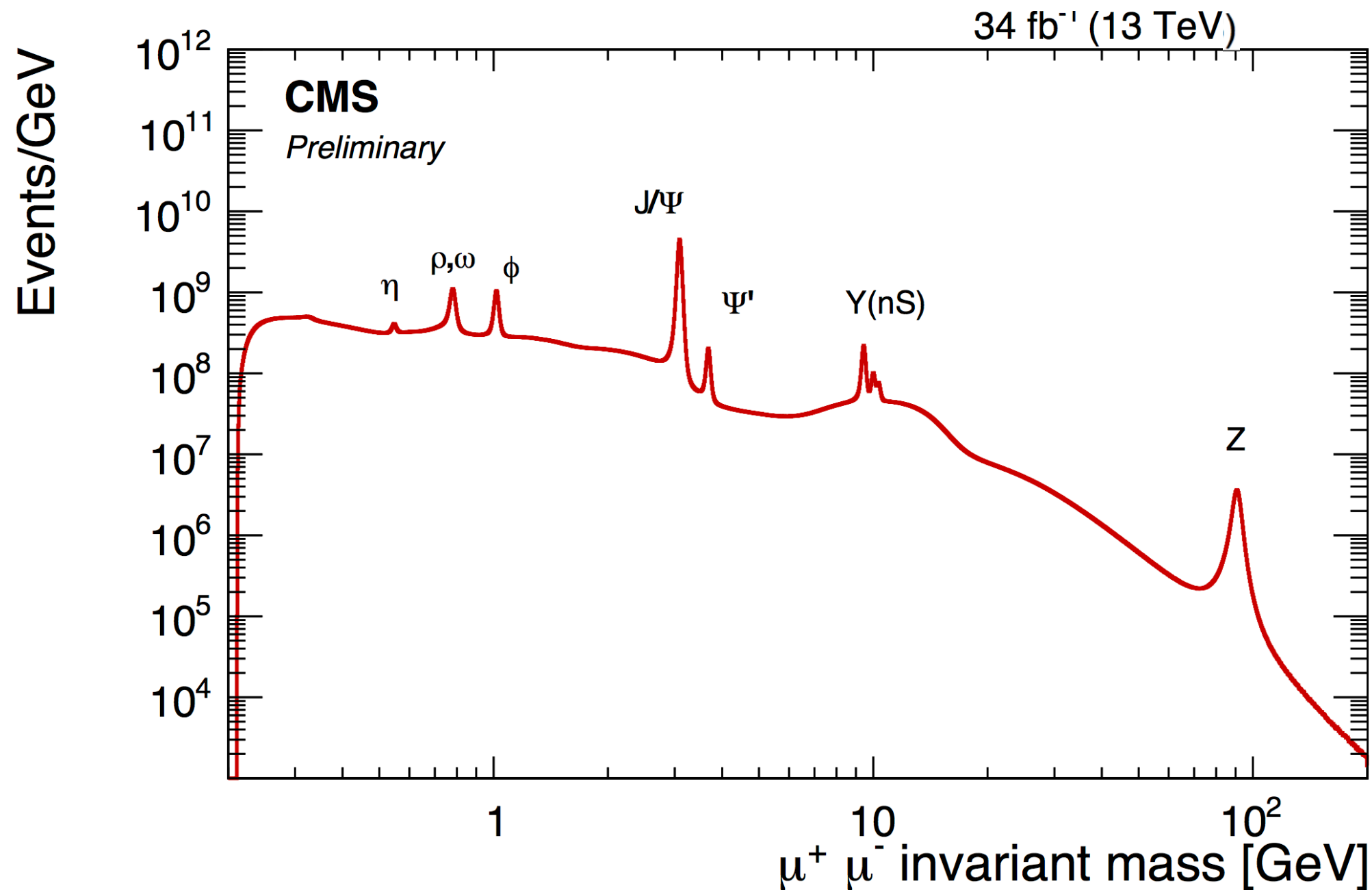


2010



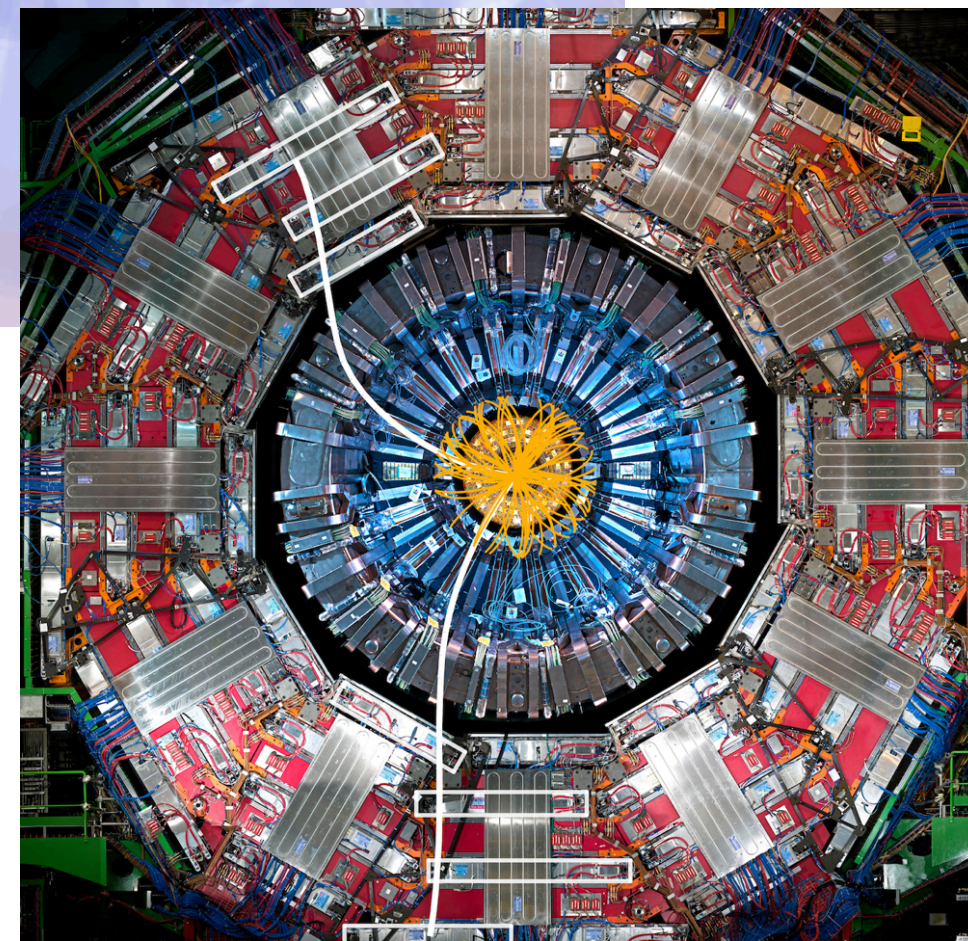
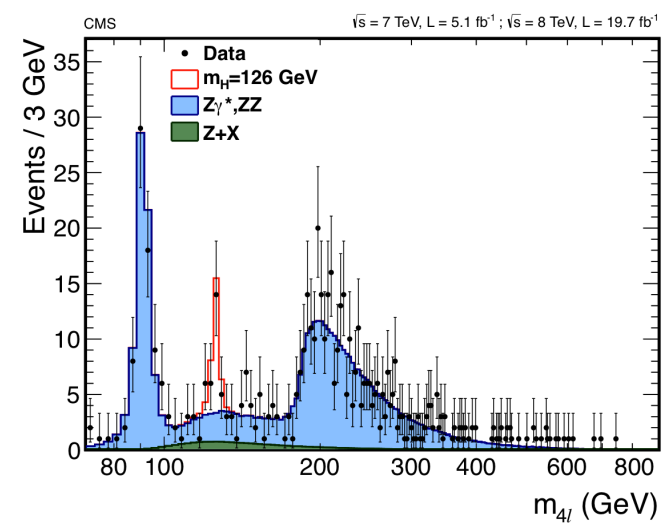
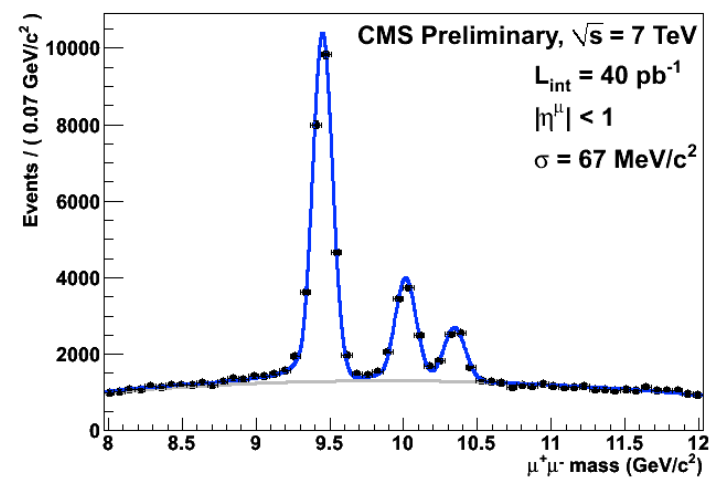
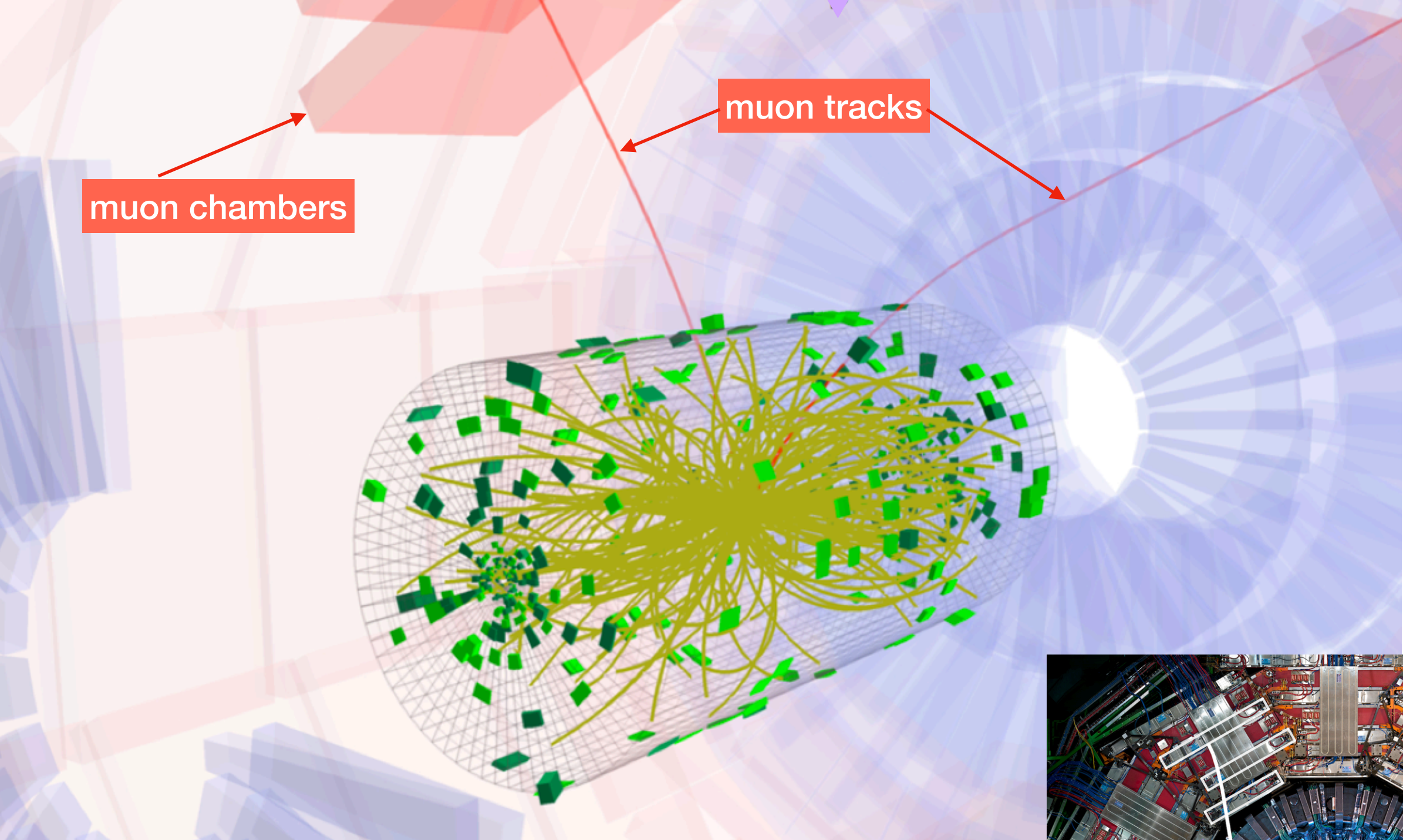
the discovery of the
b quark

the SM *re*-discovery @ LHC



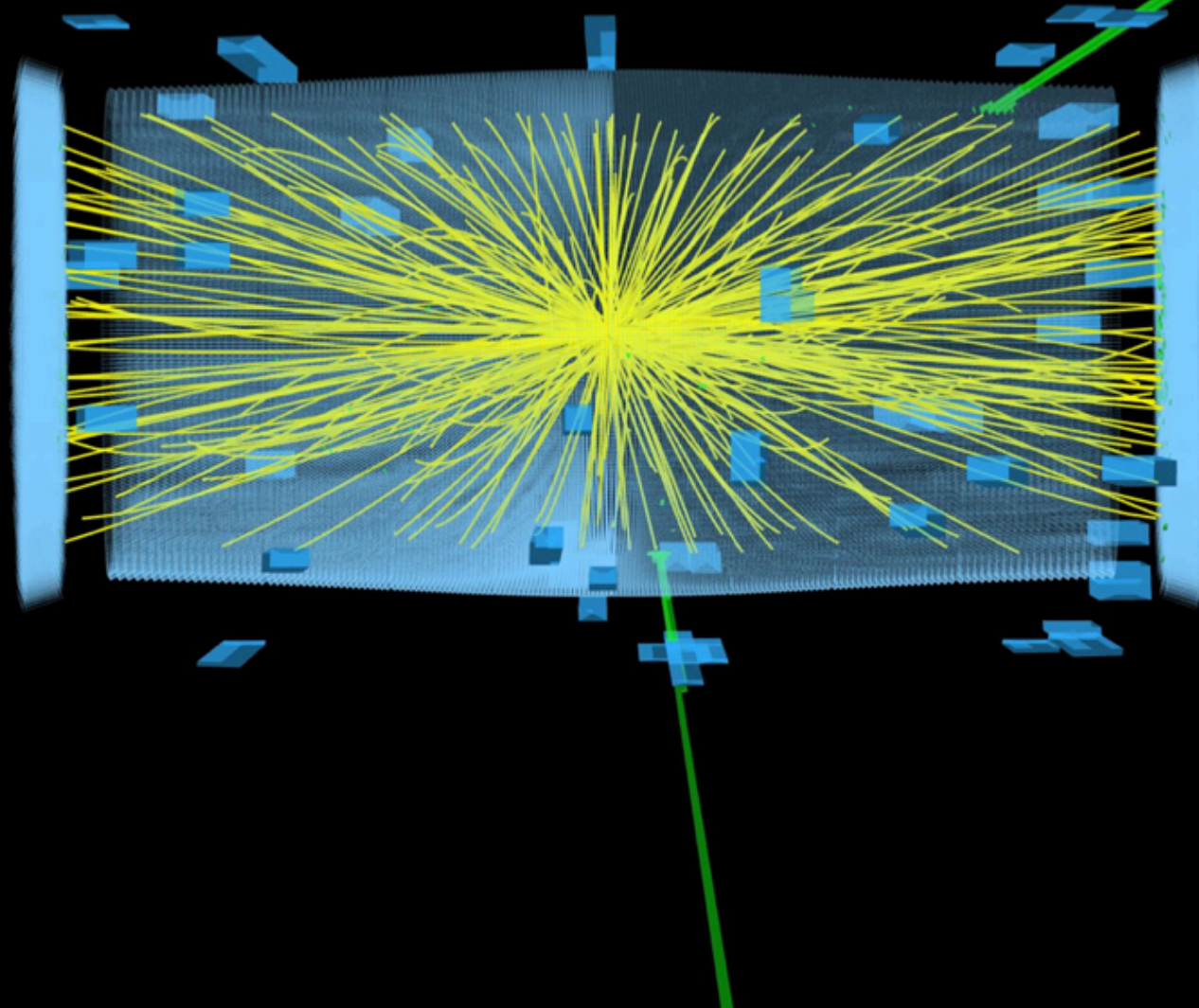
👉 will explore
during Friday's
tutorial!

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

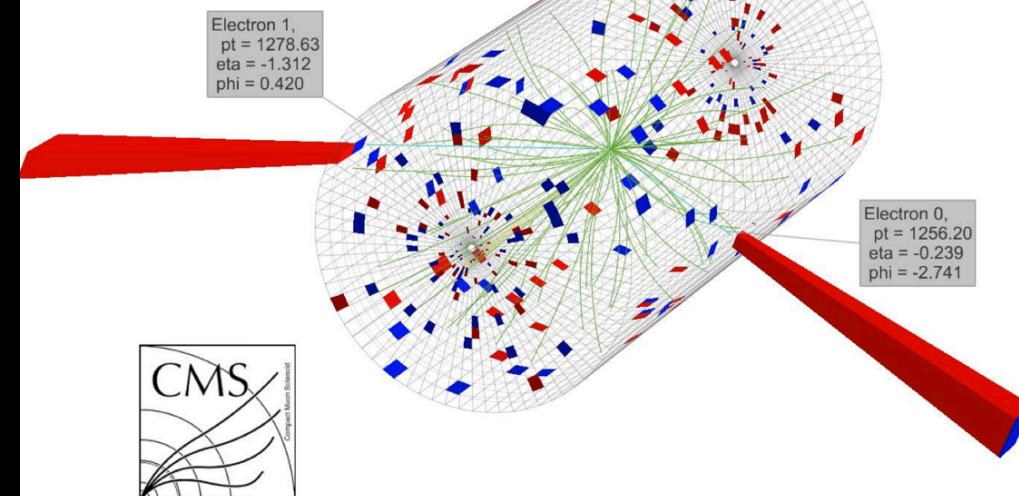




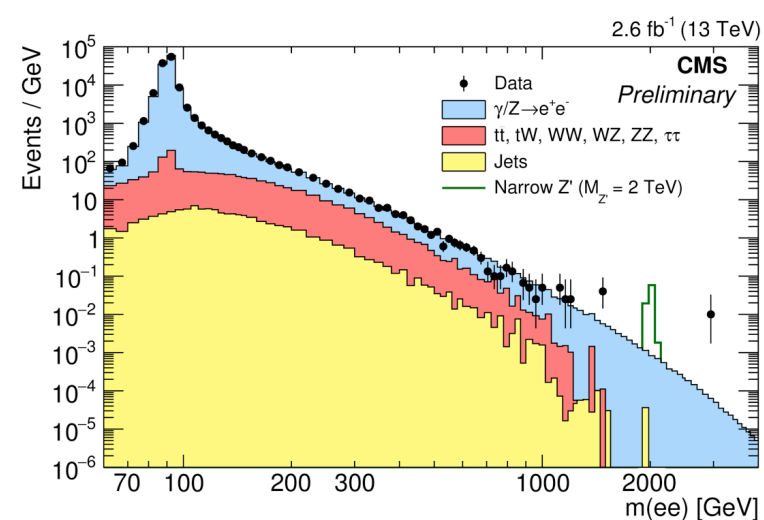
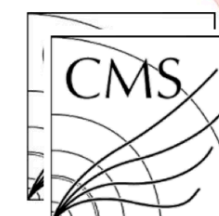
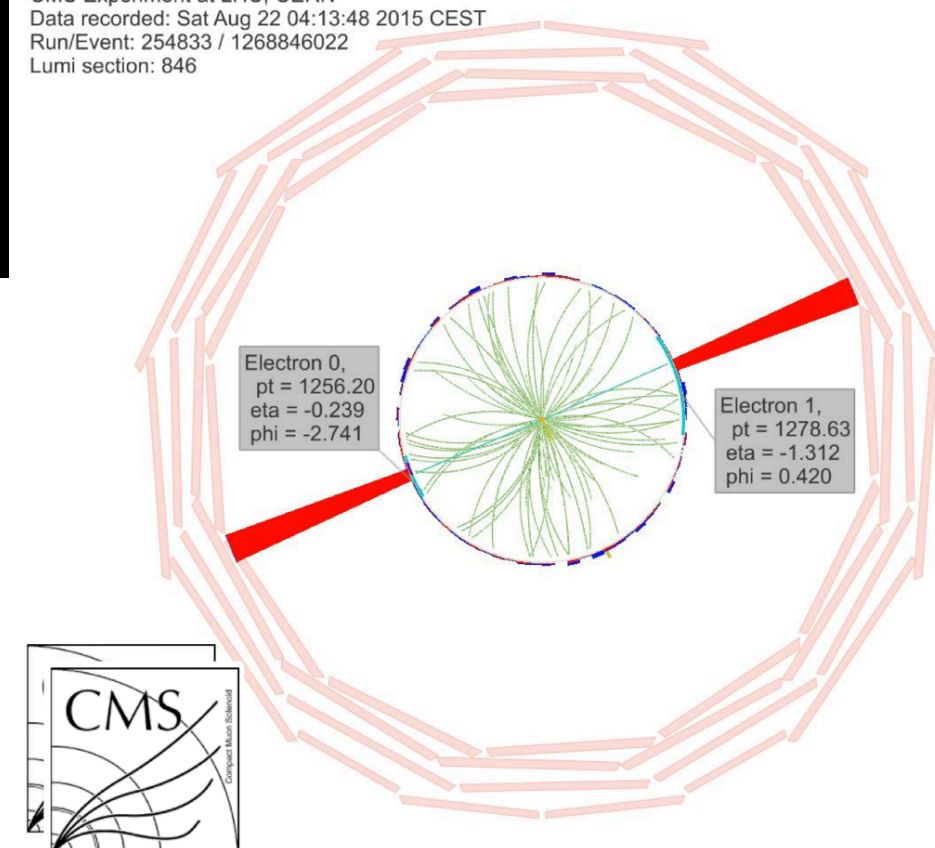
CMS Experiment at the LHC, CERN
Data recorded: 2015-Aug-22 02:13:48.861952 GMT
Run / Event / LS: 254833 / 1268846022 / 846

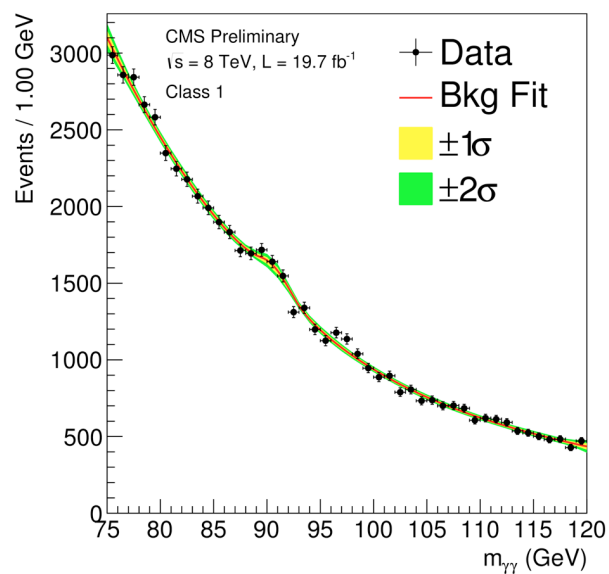
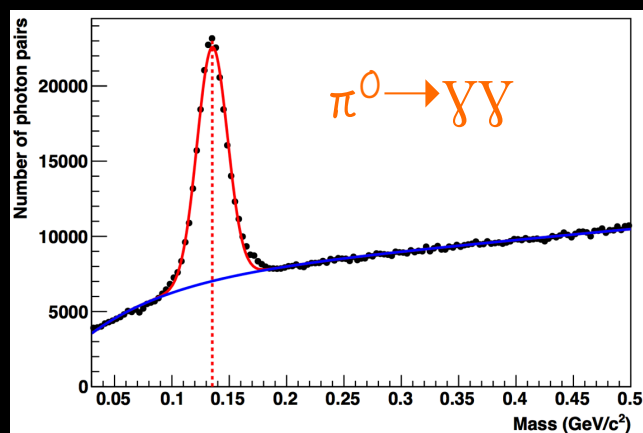
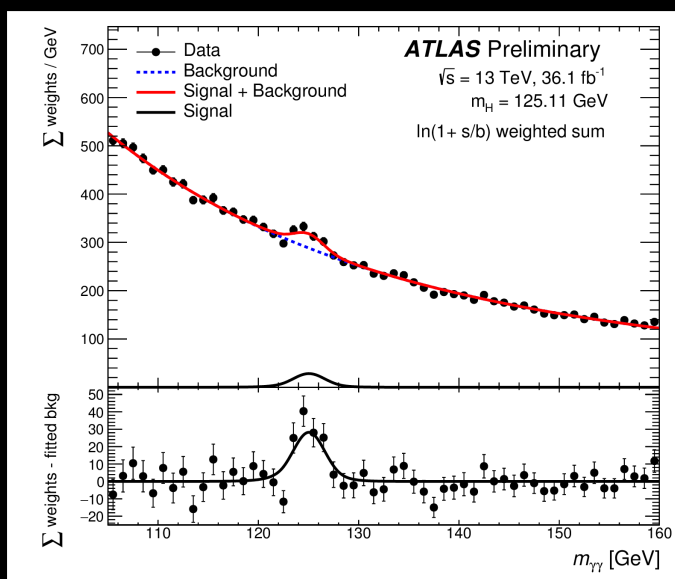


CMS Experiment at LHC, CERN
Data recorded: Sat Aug 22 04:13:48 2015 CEST
Run/Event: 254833 / 1268846022
Lumi section: 846



CMS Experiment at LHC, CERN
Data recorded: Sat Aug 22 04:13:48 2015 CEST
Run/Event: 254833 / 1268846022
Lumi section: 846

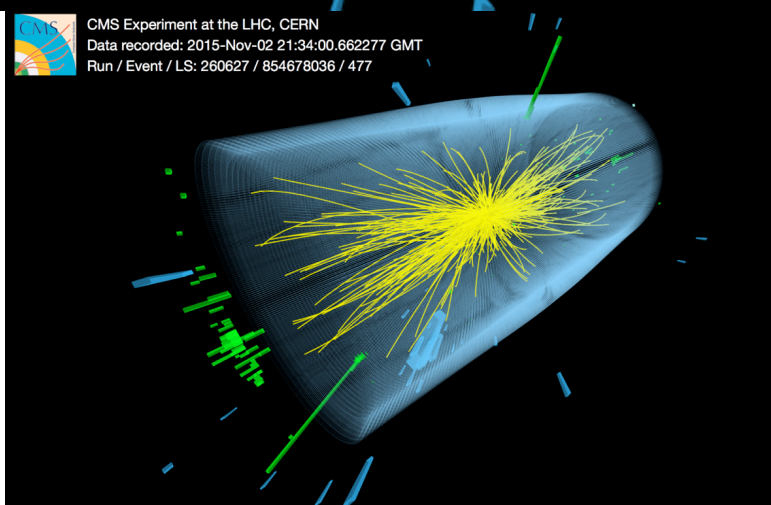




CMS Experiment at the LHC, CERN

Data recorded: 2015-Nov-02 21:34:00.662277 GMT

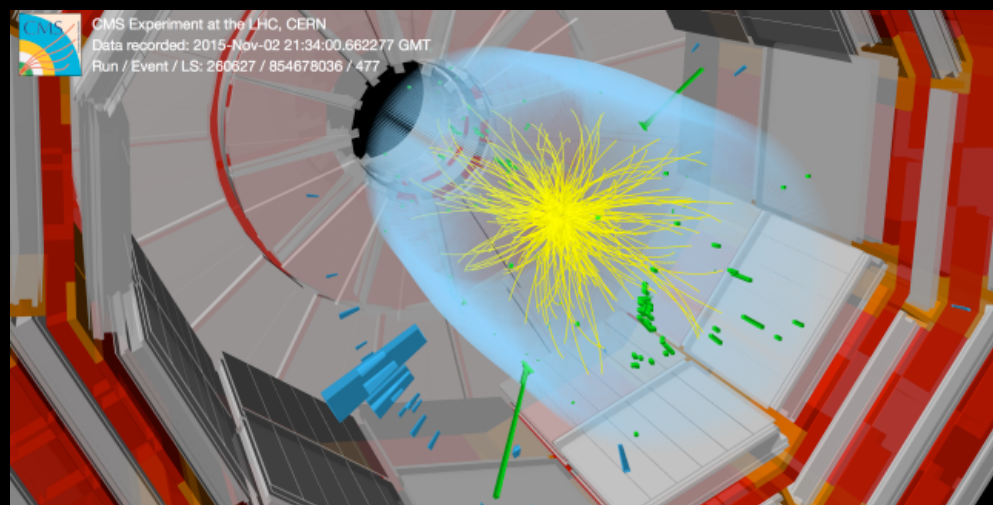
Run / Event / LS: 260627 / 854678036 / 477



CMS Experiment at the LHC, CERN

Data recorded: 2015-Nov-02 21:34:00.662277 GMT

Run / Event / LS: 260627 / 854678036 / 477

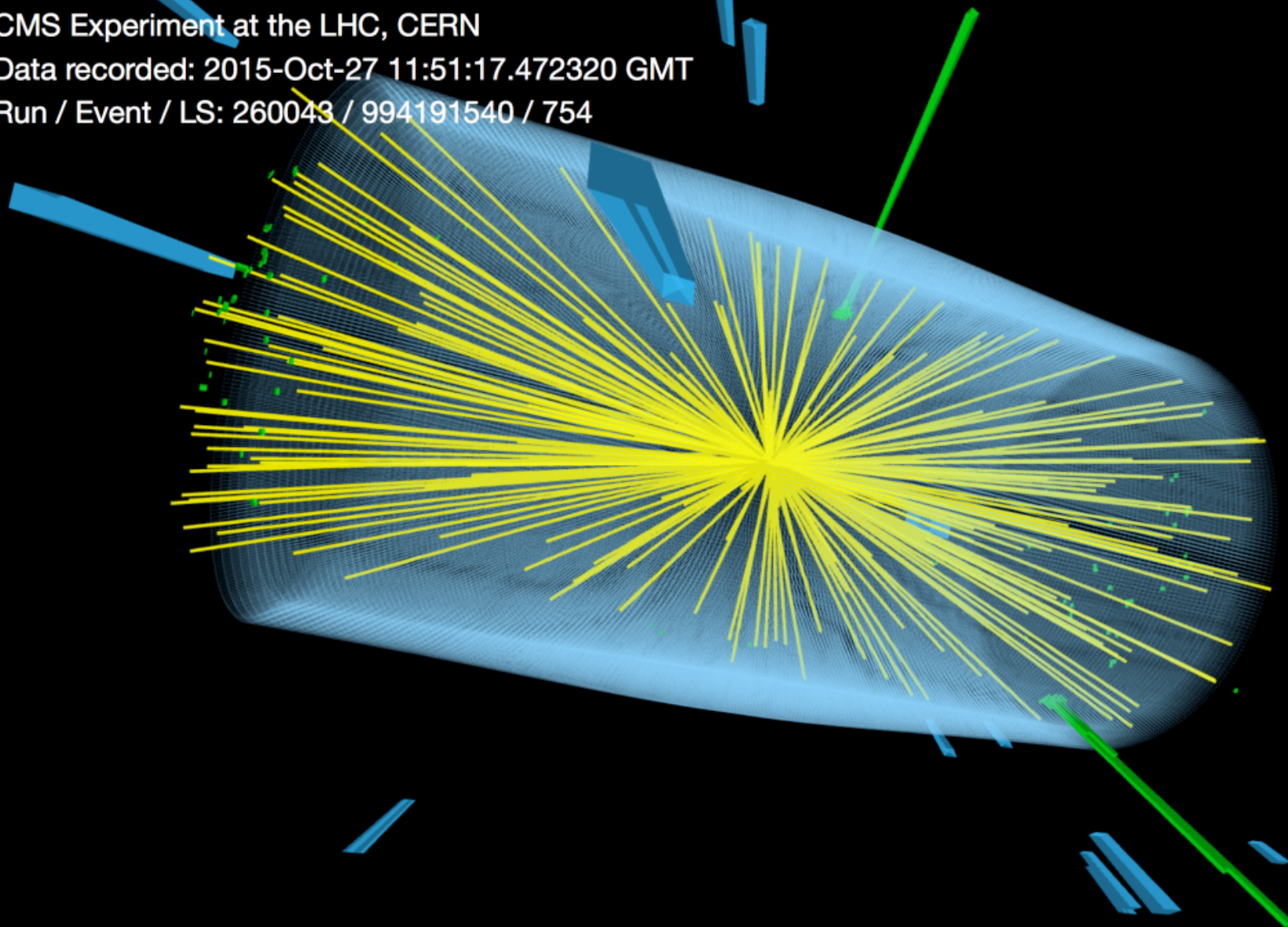




CMS Experiment at the LHC, CERN

Data recorded: 2015-Oct-27 11:51:17.472320 GMT

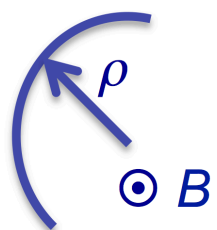
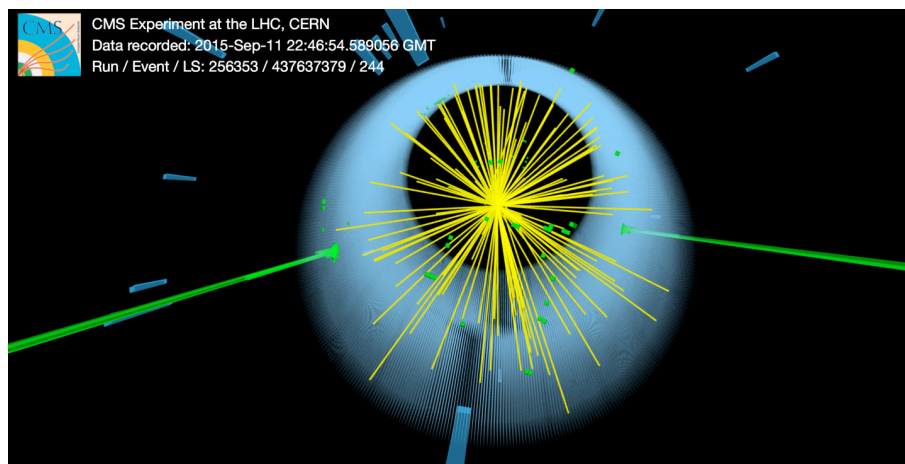
Run / Event / LS: 260043 / 994191540 / 754



CMS Experiment at the LHC, CERN

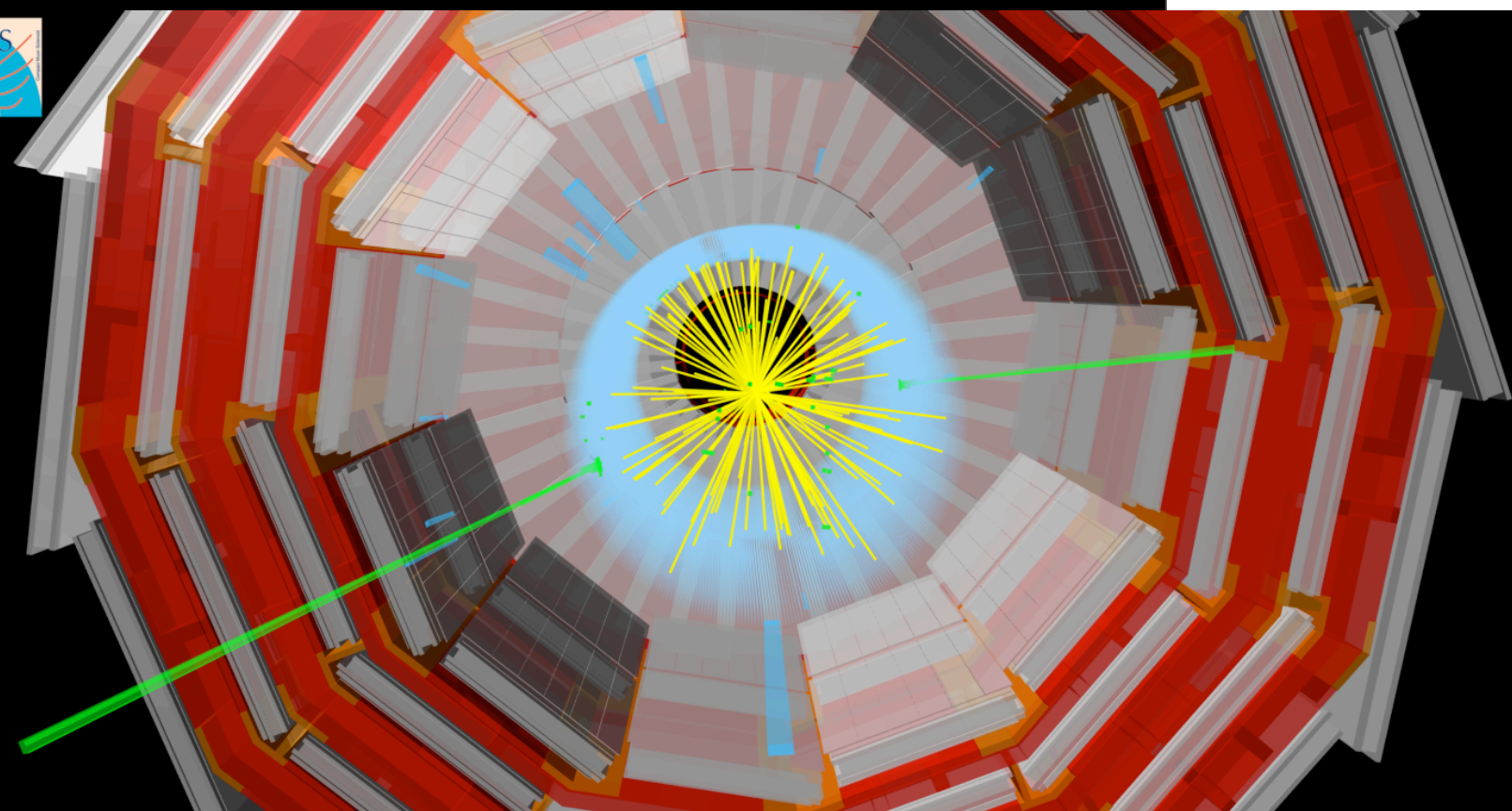
Data recorded: 2015-Sep-11 22:46:54.589056 GMT

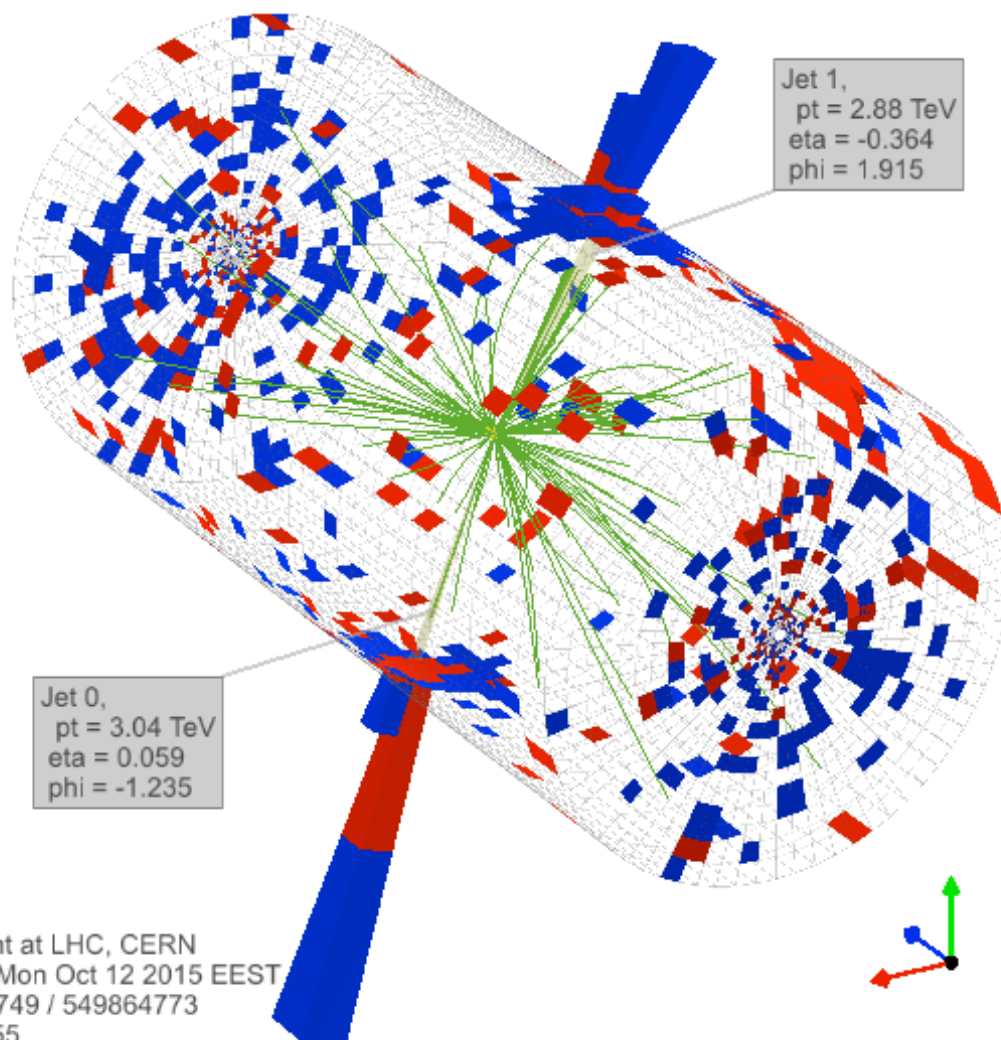
Run / Event / LS: 256353 / 437637379 / 244



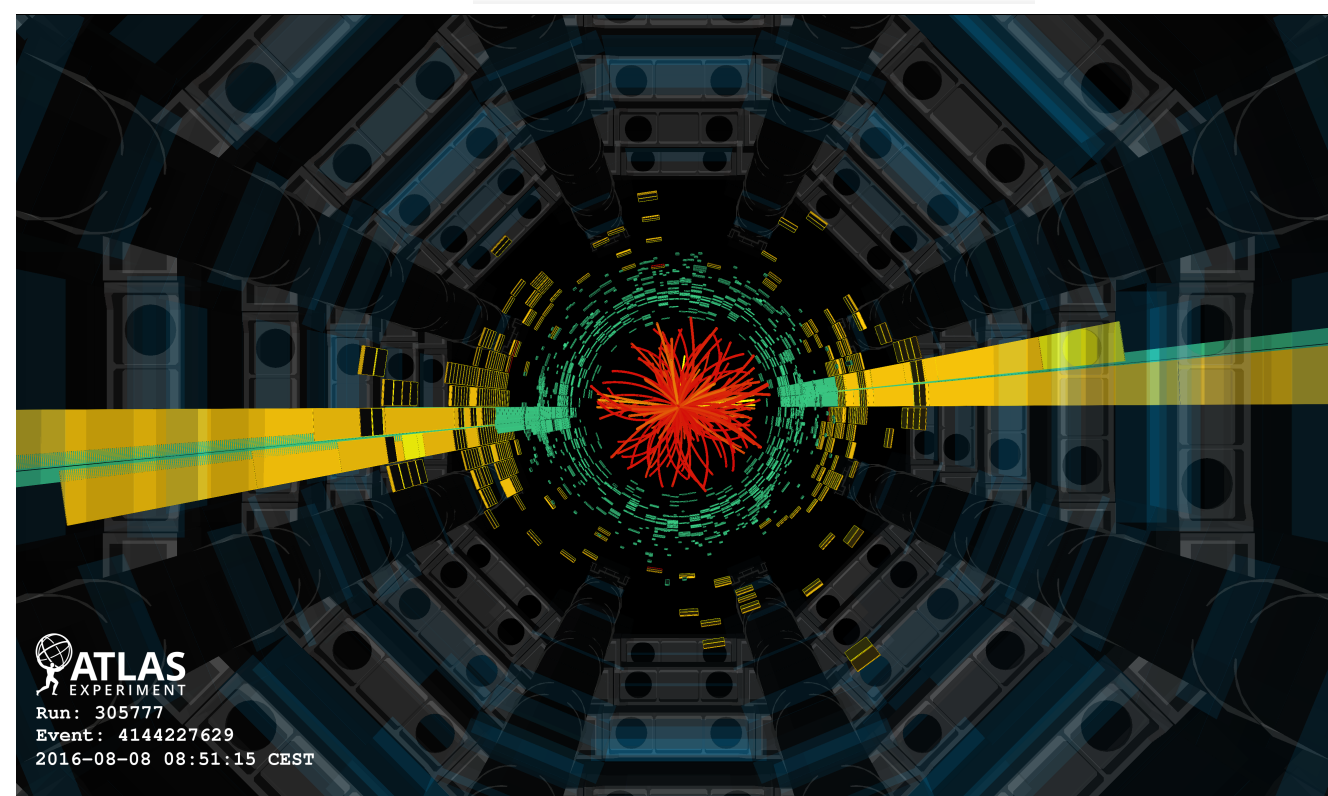
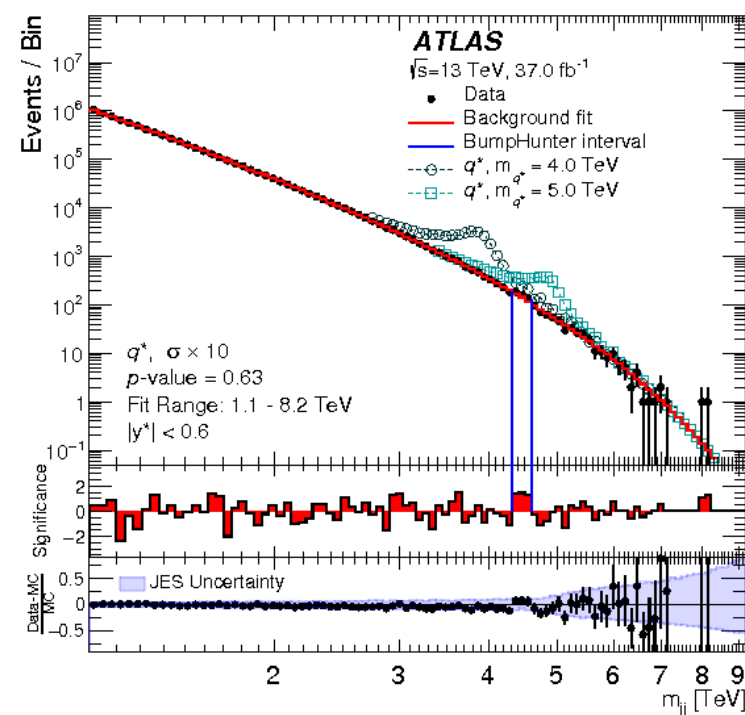
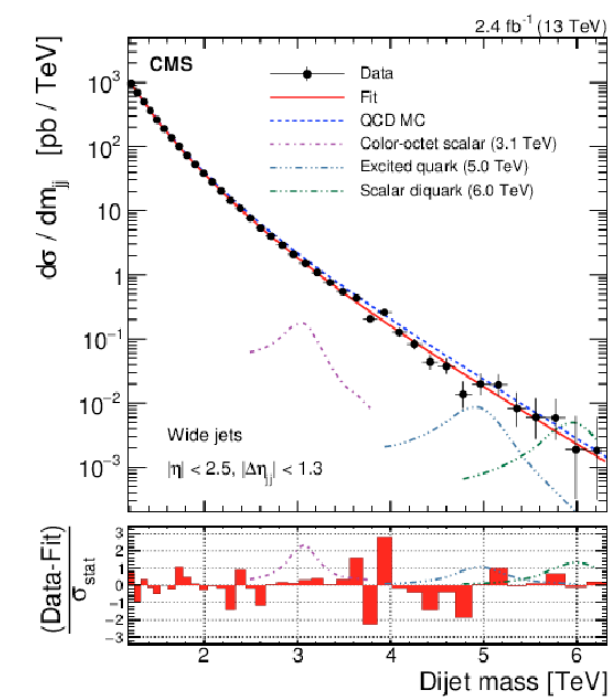
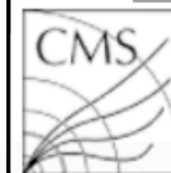
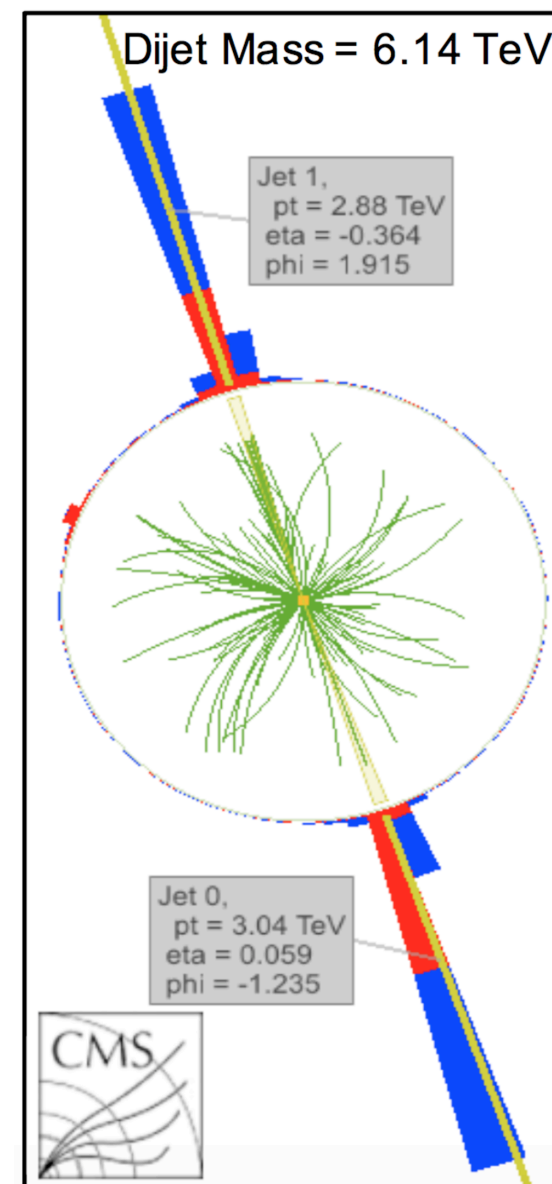
$$\rho = \frac{p}{ZeB}$$

Physics@LHC | Nuno.Leonardo@cern.ch





CMS Experiment at LHC, CERN
Data recorded: Mon Oct 12 2015 EEST
Run/Event: 258749 / 549864773
Lumi section: 355
Dijet Mass: 6.14 TeV





Run 251244 Event 204117665

$\sqrt{s} = 13 \text{ TeV}$

μ_1
 $p_T = 58.7 \text{ GeV}$
 $\eta = 1.8$

$pp \rightarrow ZZ \rightarrow 2e2\mu$

$m_{\mu\mu} = 91.1 \text{ GeV}$

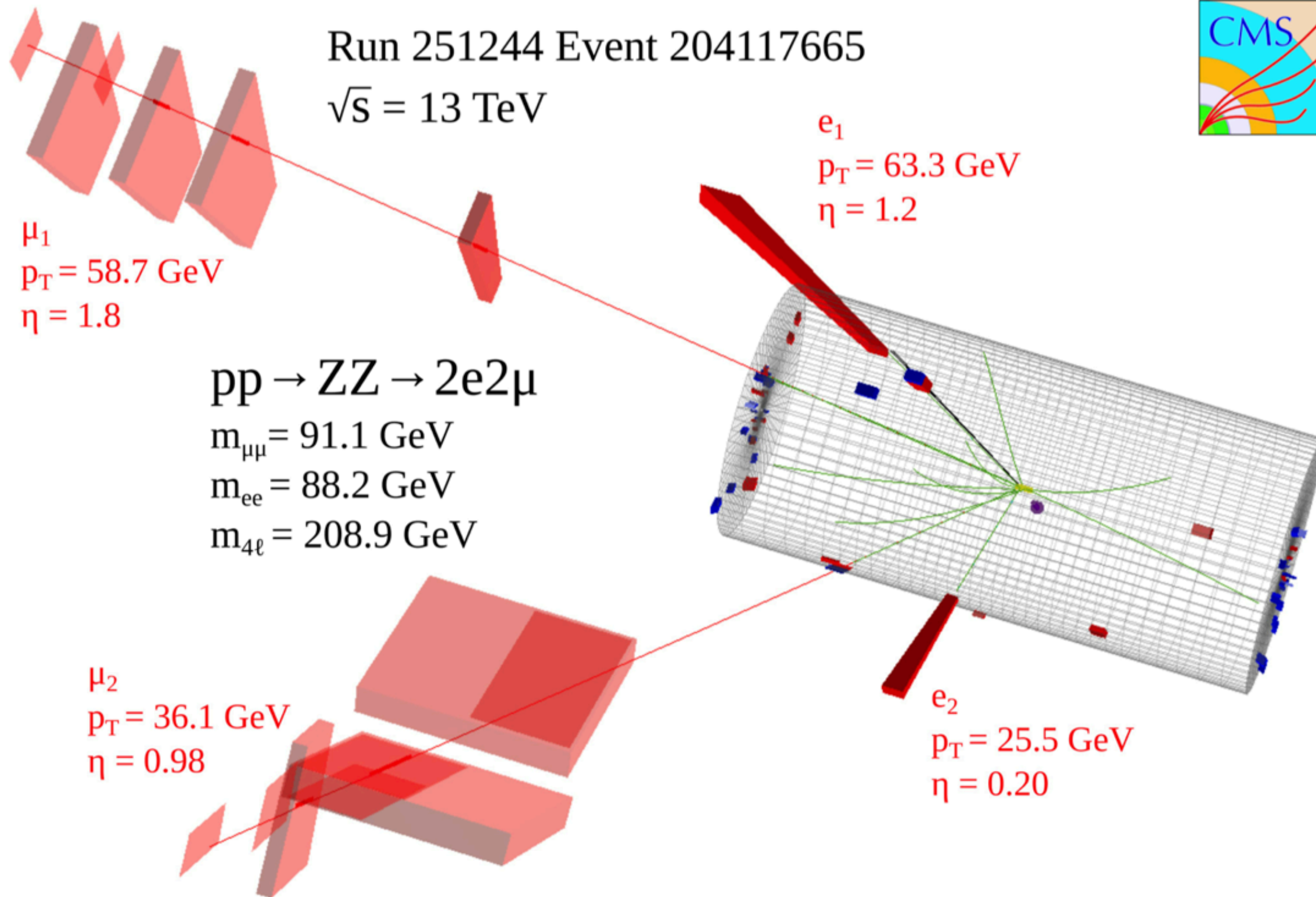
$m_{ee} = 88.2 \text{ GeV}$

$m_{4\ell} = 208.9 \text{ GeV}$

μ_2
 $p_T = 36.1 \text{ GeV}$
 $\eta = 0.98$

e_1
 $p_T = 63.3 \text{ GeV}$
 $\eta = 1.2$

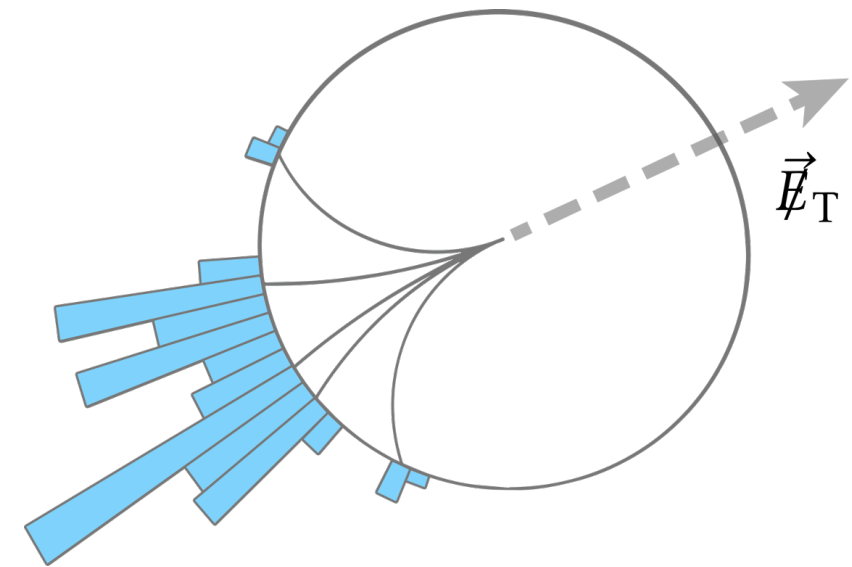
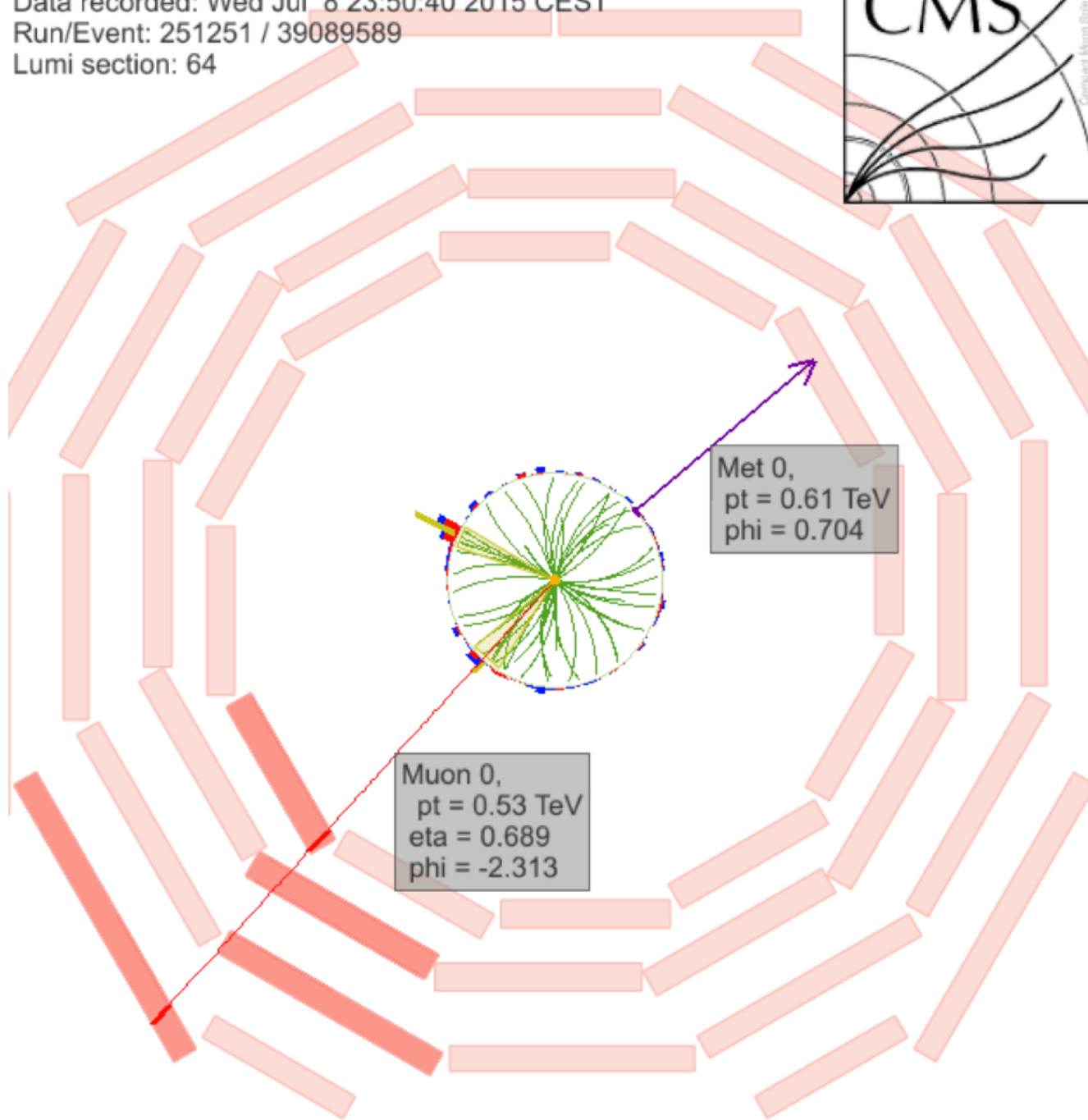
e_2
 $p_T = 25.5 \text{ GeV}$
 $\eta = 0.20$



CMS Experiment at LHC, CERN
Data recorded: Wed Jul 8 23:50:40 2015 CEST
Run/Event: 251251 / 39089589
Lumi section: 64



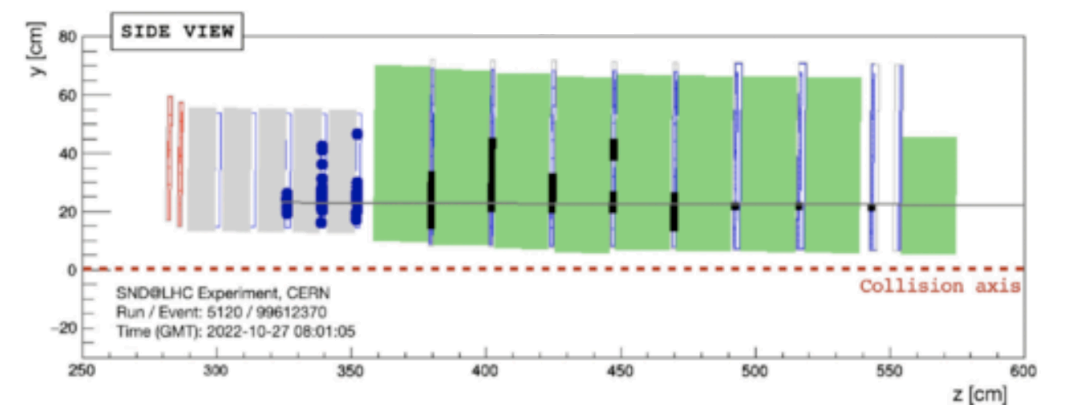
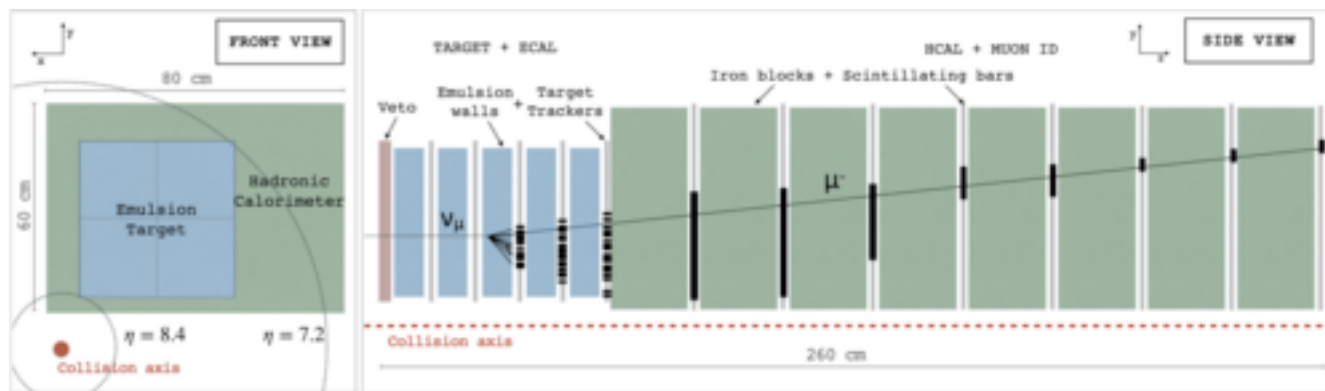
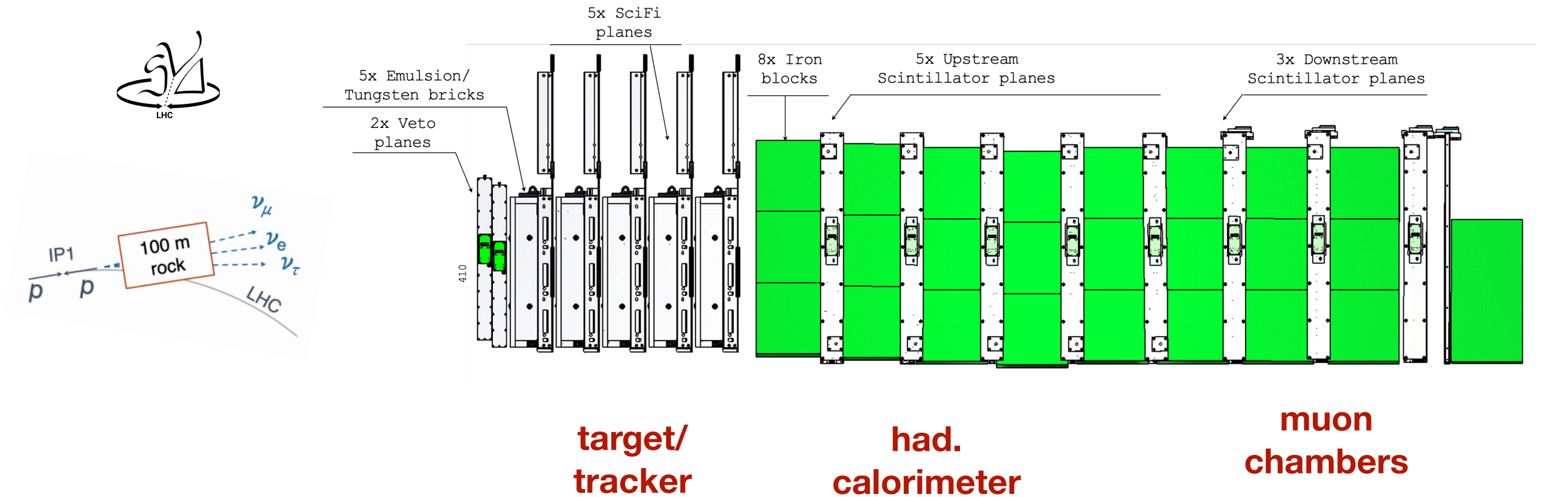
Missing momentum



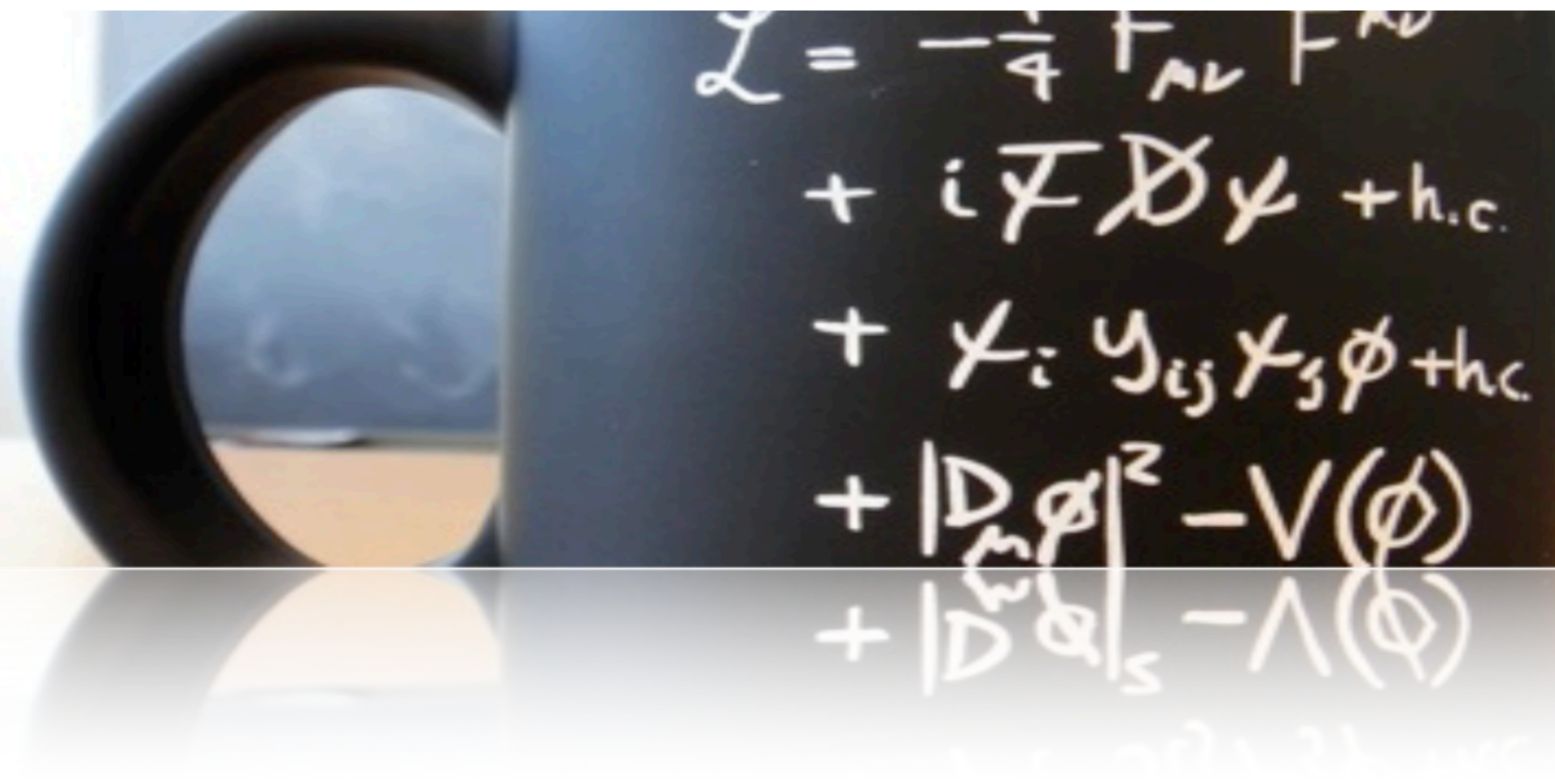
“Did you see it?”
“No nothing.”
“Then it was a neutrino!”

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

The Dawn of Collider Neutrino Physics @LHC



Physics



The image shows a black mug with a white handle, positioned on a white surface. The mug has a chalkboard-like surface with handwritten physics equations in white chalk. The equations are as follows:

$$\begin{aligned}\mathcal{L} = & -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\ & + i \bar{\psi} \not{D} \psi + \text{h.c.} \\ & + \psi_i Y_{ij} \psi_j \phi + \text{h.c.} \\ & + |D_\mu \phi|^2 - V(\phi) \\ & + |D_\mu \chi|^2 - \Lambda(\chi)\end{aligned}$$

The Standard Model of Particle Physics

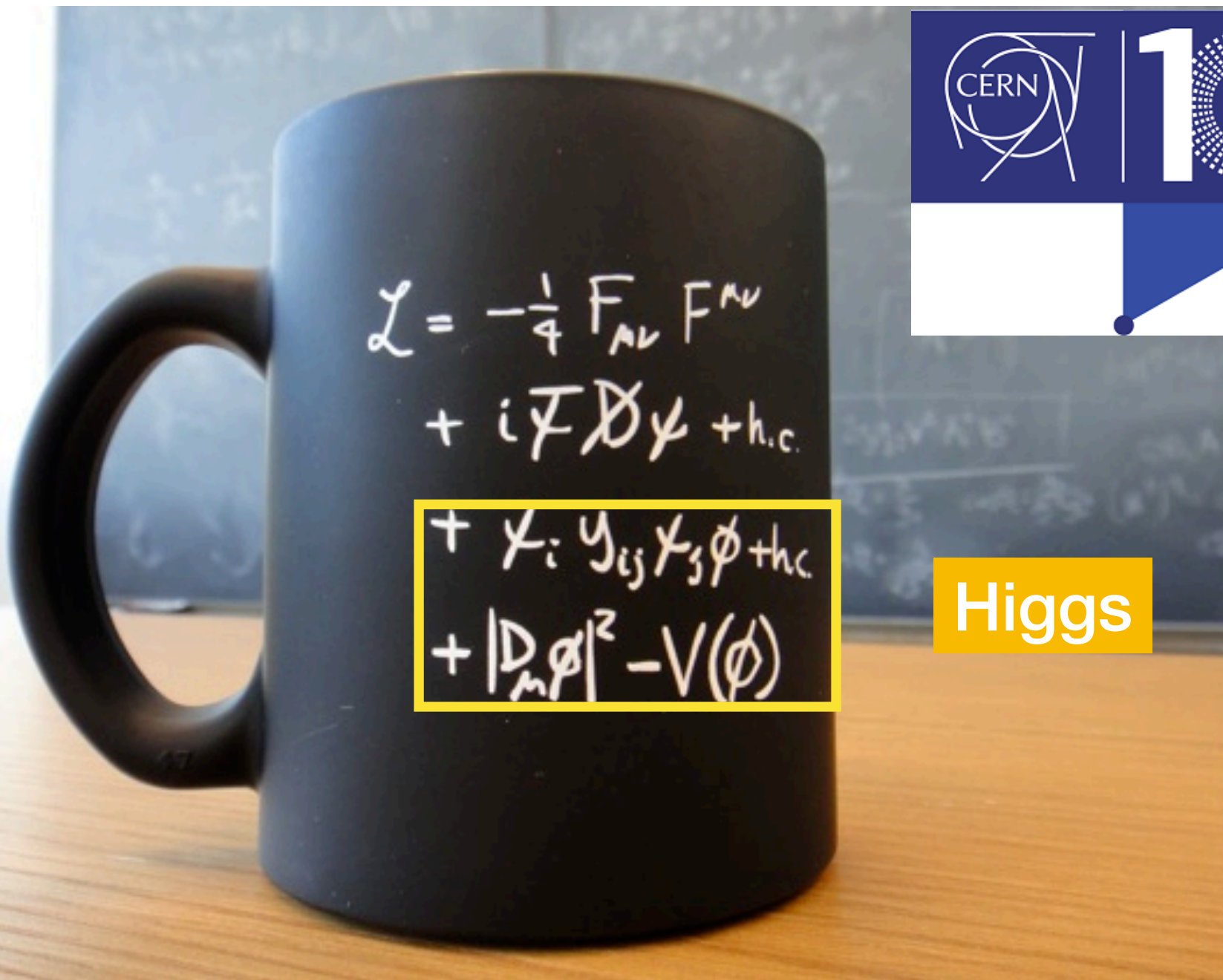
Standard Model Particle Zoo:

	I	II	III		
mass	$\approx 2.2 \text{ MeV}/c^2$	$\approx 1.28 \text{ GeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$	0	$\approx 124.97 \text{ GeV}/c^2$
charge	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0	0
spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	0
QUARKS	u up	c charm	t top	g gluon	H higgs
	$\approx 4.7 \text{ MeV}/c^2$	$\approx 96 \text{ MeV}/c^2$	$\approx 4.18 \text{ GeV}/c^2$	0	
	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	0	
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
	d down	s strange	b bottom	γ photon	
LEPTONS	$\approx 0.511 \text{ MeV}/c^2$	$\approx 105.66 \text{ MeV}/c^2$	$\approx 1.7768 \text{ GeV}/c^2$	$\approx 91.19 \text{ GeV}/c^2$	
	-1	-1	-1	0	
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
	e electron	μ muon	τ tau	Z Z boson	
	$< 2.2 \text{ eV}/c^2$	$< 0.17 \text{ MeV}/c^2$	$< 18.2 \text{ MeV}/c^2$	$\approx 80.39 \text{ GeV}/c^2$	
	0	0	0	± 1	
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	
					GAUGE BOSONS VECTOR BOSONS
					SCALAR BOSONS

SM predictions can be tested against experimental data

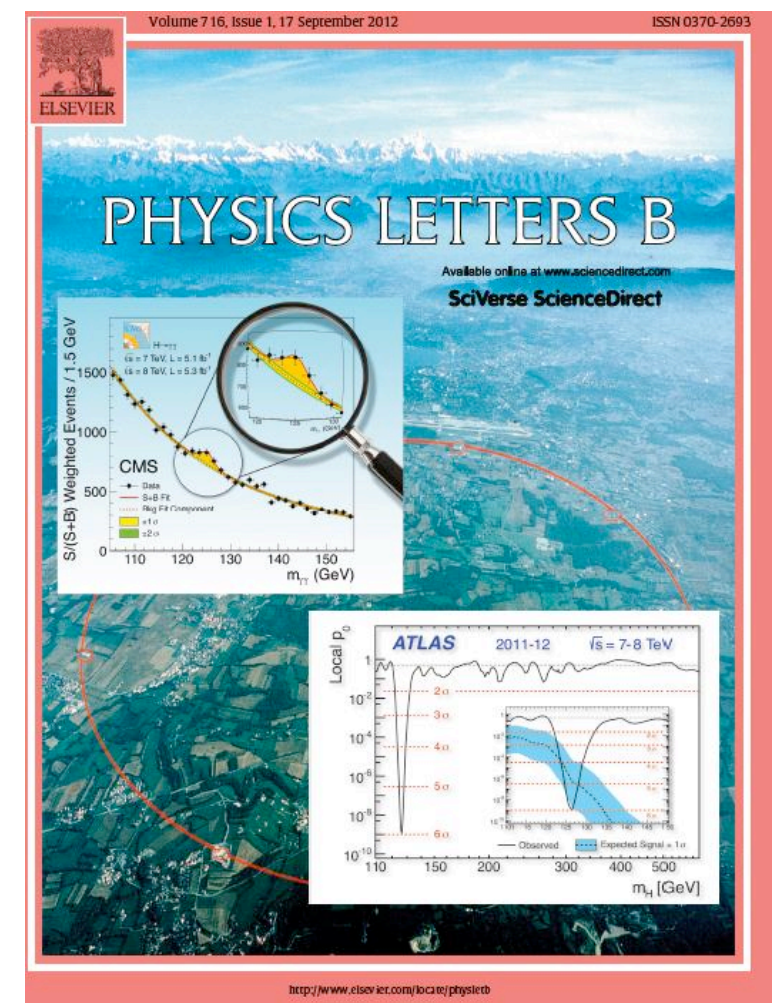
Standard Model = Quantum mechanics + Special relativity (+fields+symmetries)
 Outcome of theory + experiment interplay & discovery
 One of the great achievements of 20th century science.

The Higgs boson



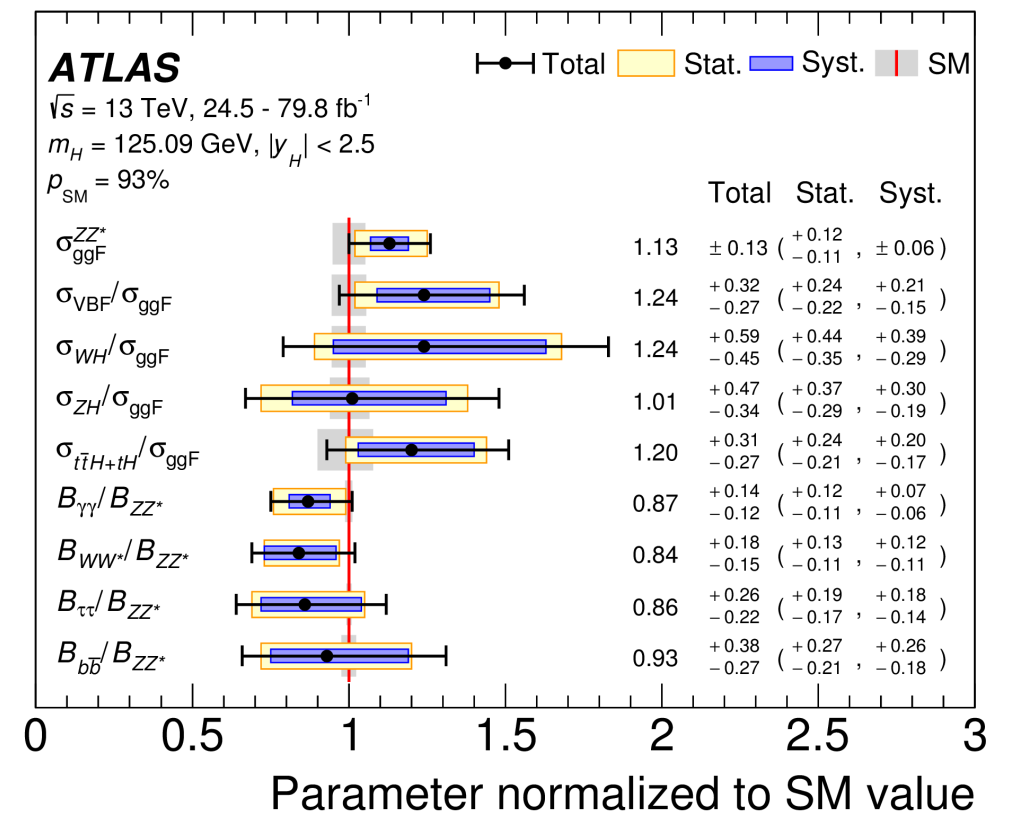
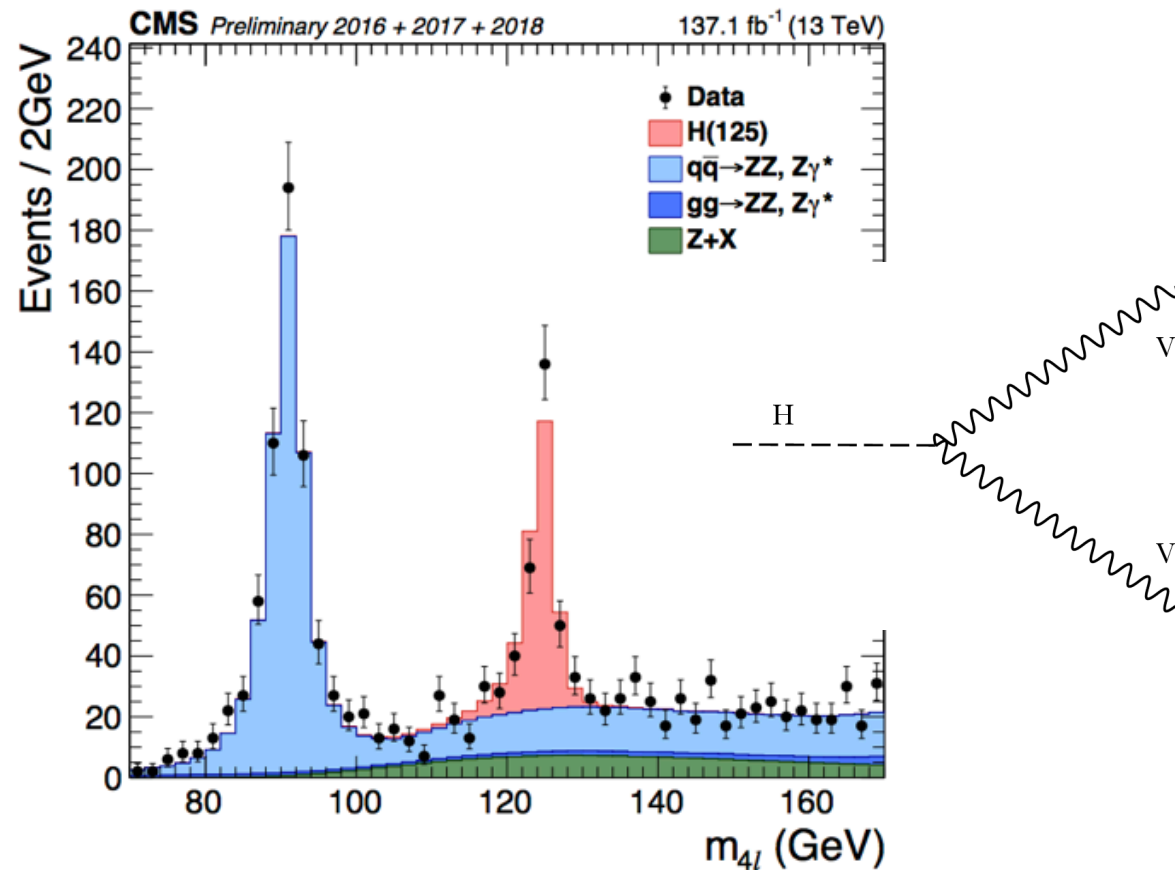
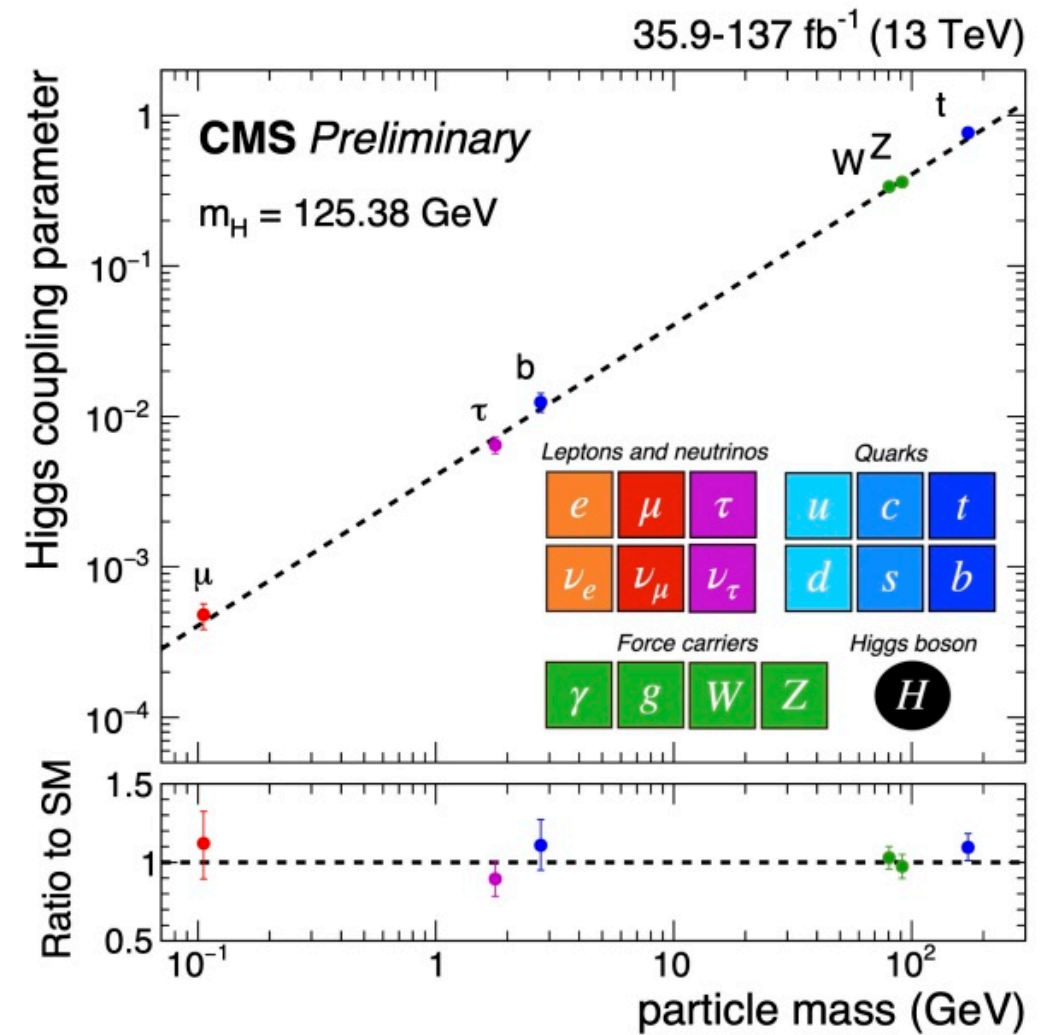
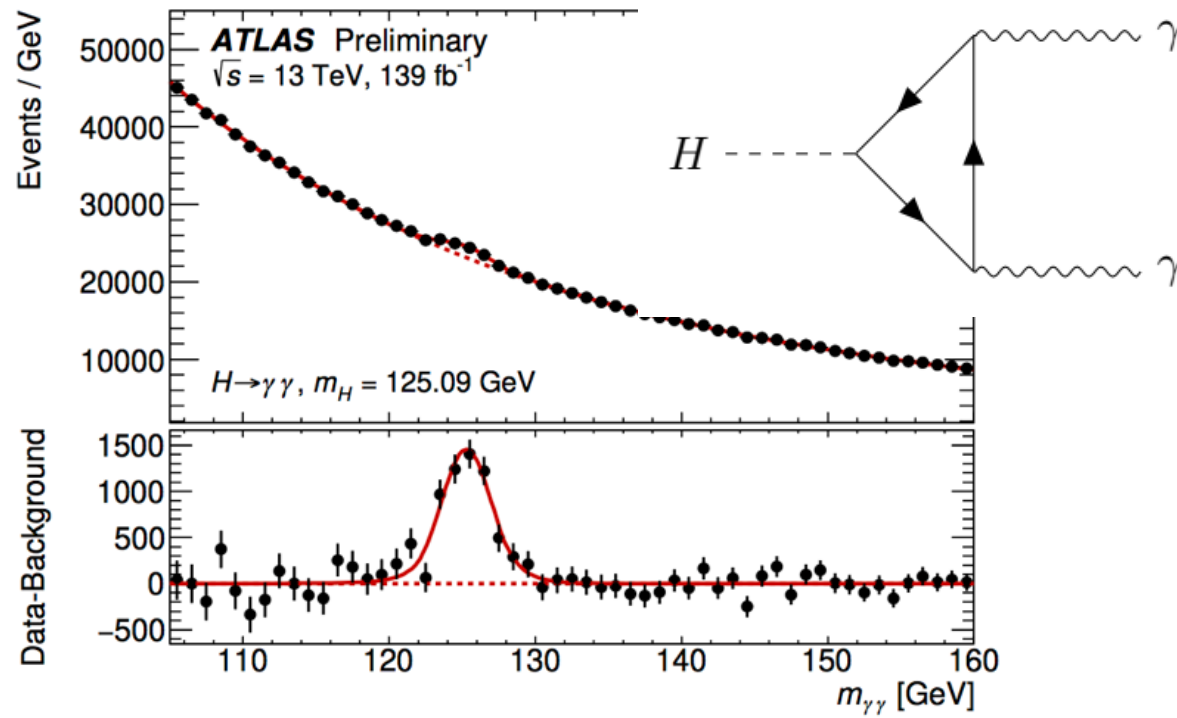
years
HIGGS boson
discovery

Higgs



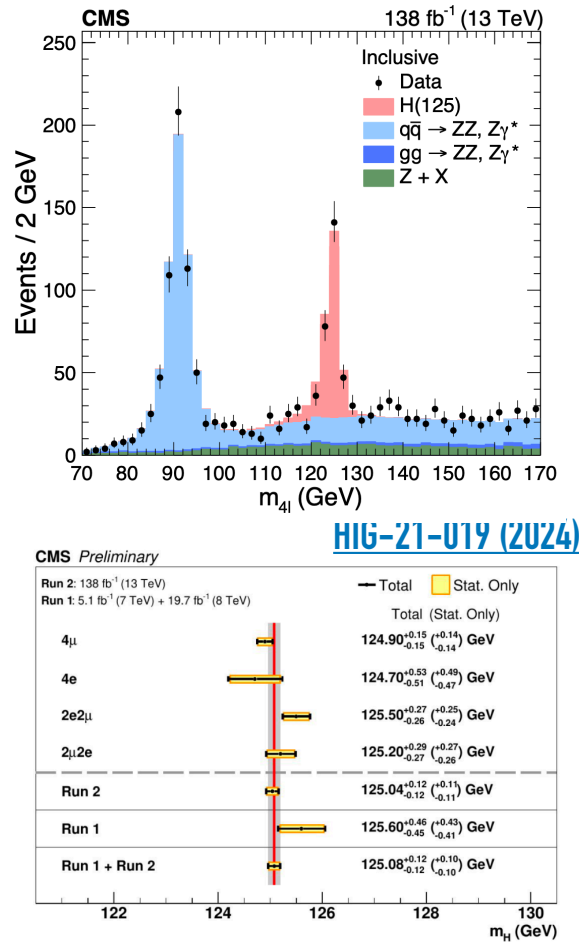
Standard Model = Quantum mechanics + Special relativity (+fields+symmetries)
Outcome of **theory** + **experiment** interplay & discovery
One of the great achievements of 20th century science.

Status of the scalar



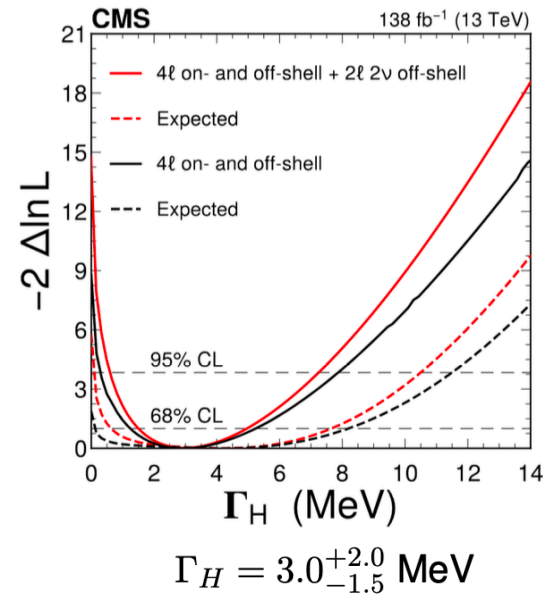
Higgs properties and rare processes

mass



- most precise m_H from single channel to date

width

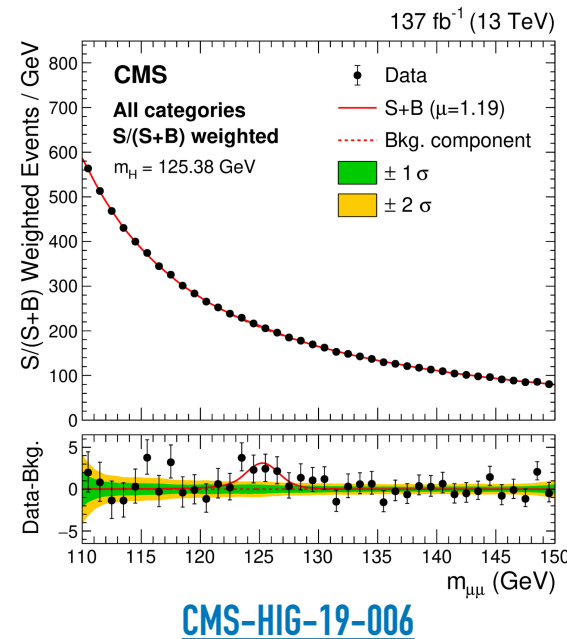


- on- vs off-shell

$$\sigma^{\text{on-shell}} \propto \mu^{\text{on-shell}}$$

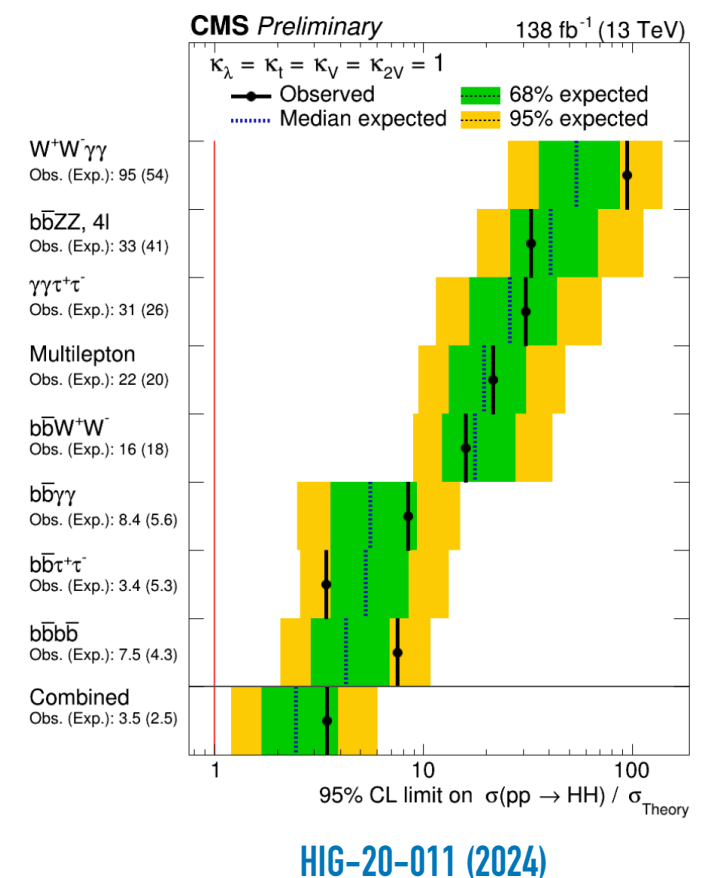
$$\sigma^{\text{off-shell}} \propto \mu^{\text{on-shell}} \Gamma_H$$
- plus interference with ZZ continuum
- best bound on Γ_H to date

rare decay: $H \rightarrow \mu\mu$



- most precise H to μ coupling measurement
- first evidence (3σ) for Yukawa couplings to the second generation

rare production (HH)

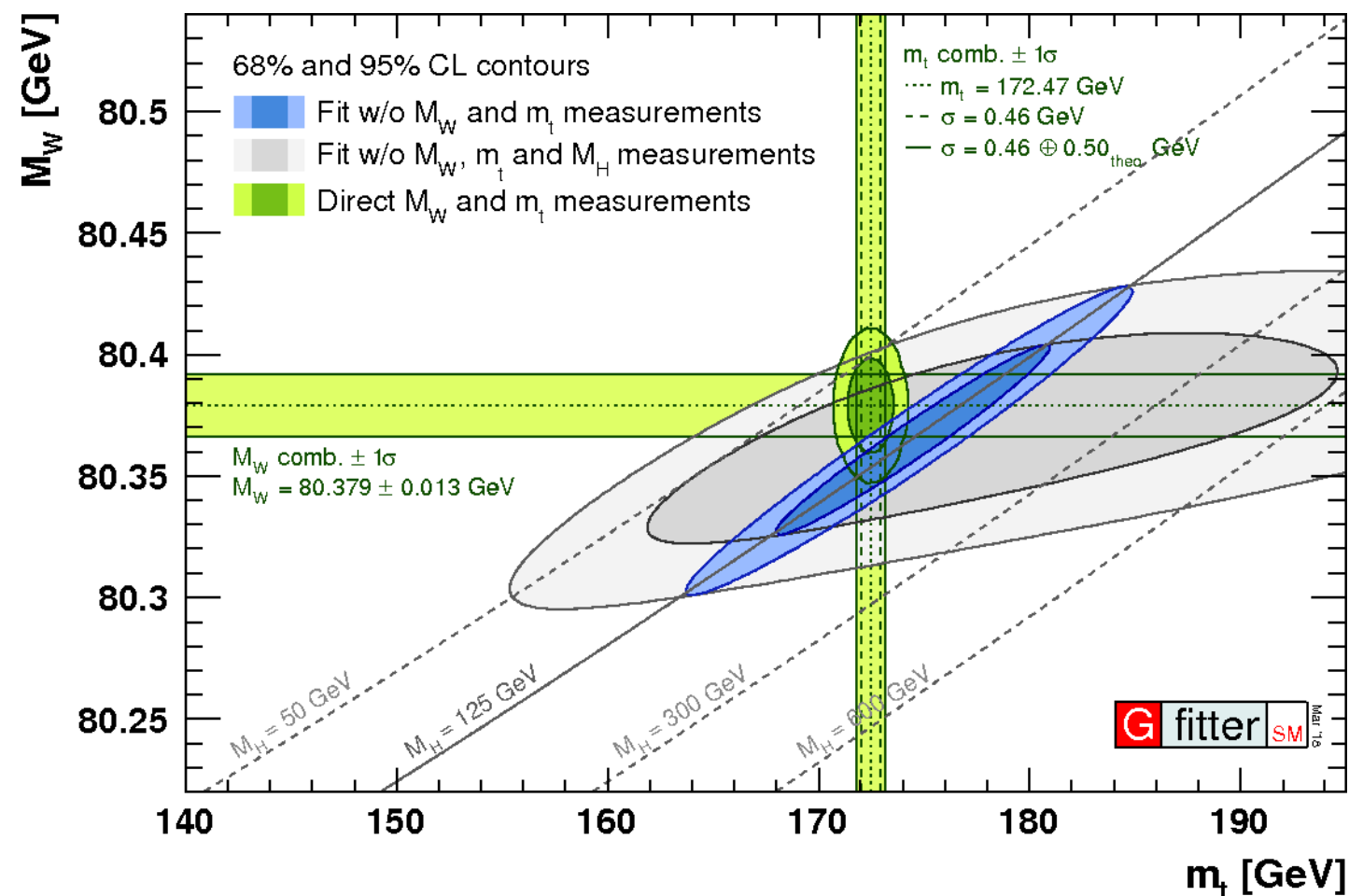
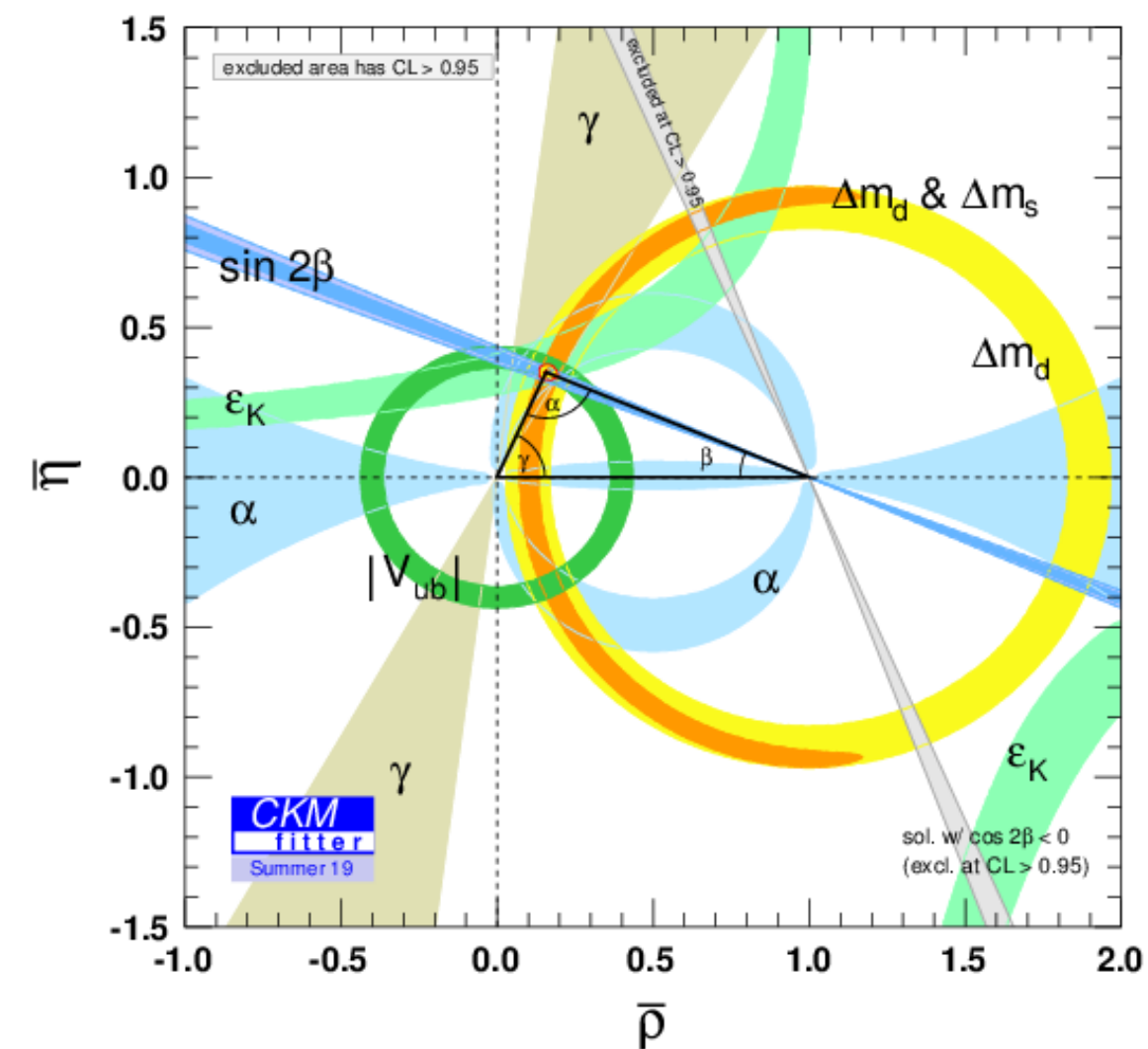


- limit 3.5 (2.5) times SM
- evidence extrapolated to be reached with 2000/fb

The Standard Model: precision measurements

quarks

H vs W vs t



The SM describes all (*) experimental data !

Going beyond the Standard Model

Mug Text:

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi}\not{D}\psi + h.c. + \chi_i Y_{ij} \chi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi) + \text{New Physics}$$

Particle Zoo Table:

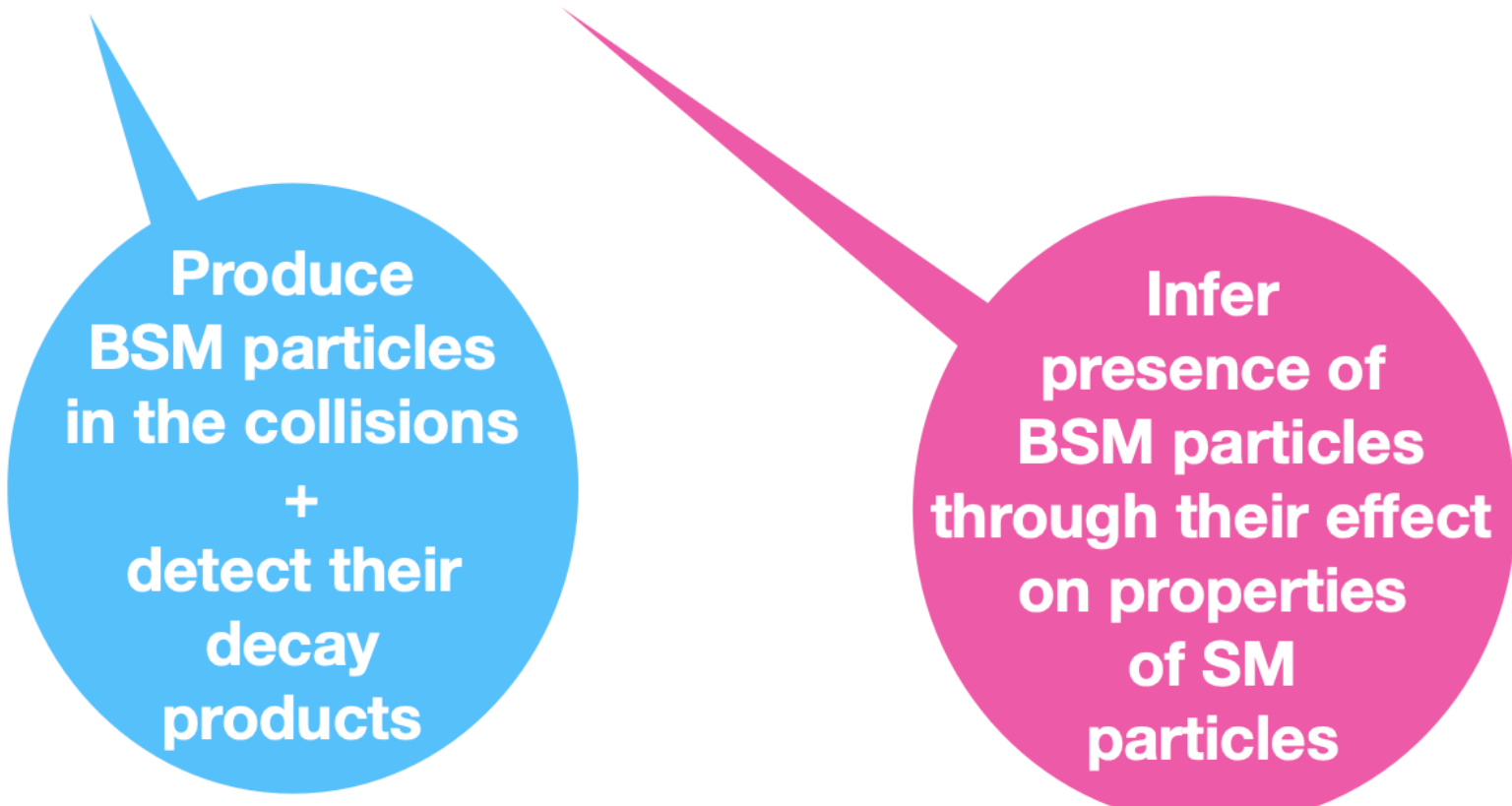
	I	II	III		
QUARKS	mass $\approx 2.2 \text{ MeV}/c^2$ charge $\frac{2}{3}$ spin $\frac{1}{2}$ u up	mass $\approx 1.28 \text{ GeV}/c^2$ charge $\frac{2}{3}$ spin $\frac{1}{2}$ c charm	mass $\approx 173.1 \text{ GeV}/c^2$ charge $\frac{2}{3}$ spin $\frac{1}{2}$ t top	0 0 1 g gluon	$\approx 124.97 \text{ GeV}/c^2$ 0 0 0 H higgs
	mass $\approx 4.7 \text{ MeV}/c^2$ charge $-\frac{1}{3}$ spin $\frac{1}{2}$ d down	mass $\approx 96 \text{ MeV}/c^2$ charge $-\frac{1}{3}$ spin $\frac{1}{2}$ s strange	mass $\approx 4.18 \text{ GeV}/c^2$ charge $-\frac{1}{3}$ spin $\frac{1}{2}$ b bottom	0 0 1 γ photon	
	LEPTONS	mass $\approx 0.511 \text{ MeV}/c^2$ charge -1 spin $\frac{1}{2}$ e electron	mass $\approx 105.66 \text{ MeV}/c^2$ charge -1 spin $\frac{1}{2}$ μ muon	mass $\approx 1.7768 \text{ GeV}/c^2$ charge -1 spin $\frac{1}{2}$ τ tau	$\approx 91.19 \text{ GeV}/c^2$ 0 1 Z Z boson
mass $< 2.2 \text{ eV}/c^2$ charge 0 spin $\frac{1}{2}$ ν_e electron neutrino		mass $< 0.17 \text{ MeV}/c^2$ charge 0 spin $\frac{1}{2}$ ν_μ muon neutrino	mass $< 18.2 \text{ MeV}/c^2$ charge 0 spin $\frac{1}{2}$ ν_τ tau neutrino	$\approx 80.39 \text{ GeV}/c^2$ ± 1 1 W W boson	

SCALAR BOSONS

new thing

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



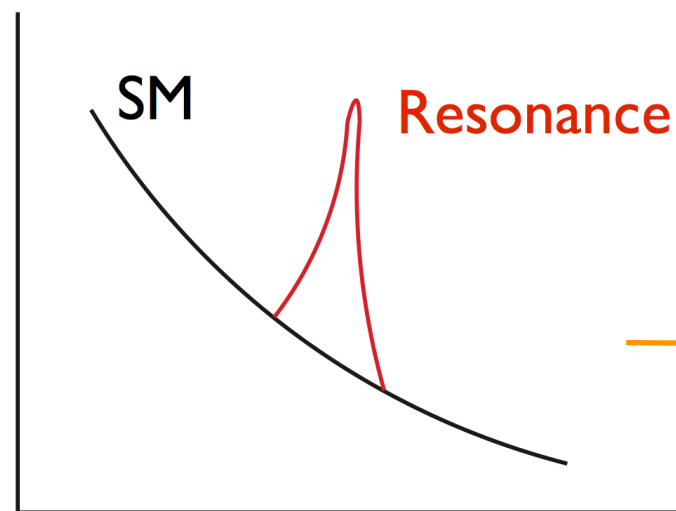
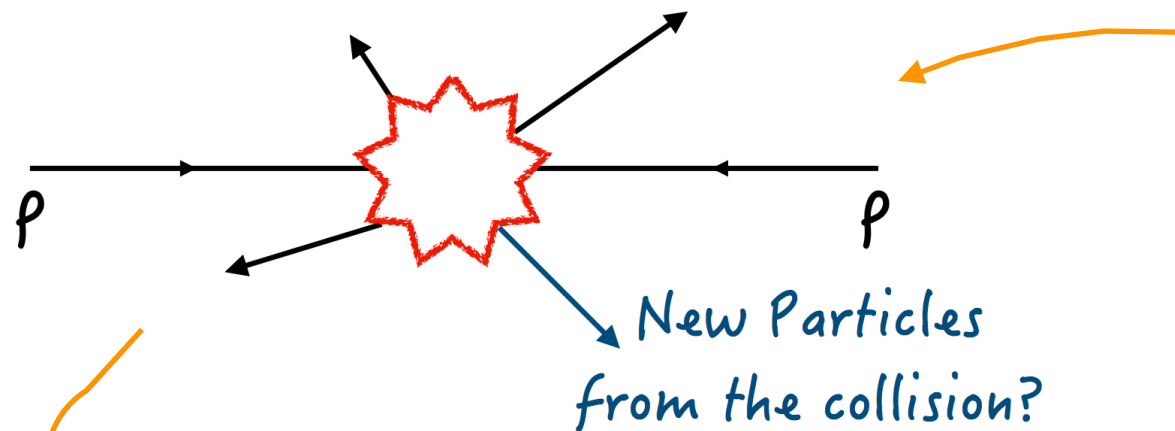
Produce
BSM particles
in the collisions
+
detect their
decay
products

ie "a la Higgs"

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

Going beyond the Standard Model

1) the easy way: direct discovery



	I	II	III	
mass charge spin	$\approx 2.2 \text{ MeV}/c^2$ $\frac{2}{3}$ $\frac{1}{2}$	$\approx 1.28 \text{ GeV}/c^2$ $\frac{2}{3}$ $\frac{1}{2}$	$\approx 173.1 \text{ GeV}/c^2$ $\frac{2}{3}$ $\frac{1}{2}$	$\approx 124.97 \text{ GeV}/c^2$ 0 0
QUARKS	u up	c charm	t top	g gluon
	d down	s strange	b bottom	γ photon
	$\approx 4.7 \text{ MeV}/c^2$ $-\frac{1}{3}$ $\frac{1}{2}$	$\approx 96 \text{ MeV}/c^2$ $-\frac{1}{3}$ $\frac{1}{2}$	$\approx 4.18 \text{ GeV}/c^2$ $-\frac{1}{3}$ $\frac{1}{2}$	0 0 1
LEPTONS	$\approx 0.511 \text{ MeV}/c^2$ -1 $\frac{1}{2}$	$\approx 105.66 \text{ MeV}/c^2$ -1 $\frac{1}{2}$	$\approx 1.7768 \text{ GeV}/c^2$ -1 $\frac{1}{2}$	$\approx 91.19 \text{ GeV}/c^2$ 0 1
	e electron	μ muon	τ tau	Z Z boson
	$< 2.2 \text{ eV}/c^2$ 0 $\frac{1}{2}$	$< 0.17 \text{ MeV}/c^2$ 0 $\frac{1}{2}$	$< 18.2 \text{ MeV}/c^2$ 0 $\frac{1}{2}$	$\approx 80.39 \text{ GeV}/c^2$ ± 1 1
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson
				? new thing

Energy frontier

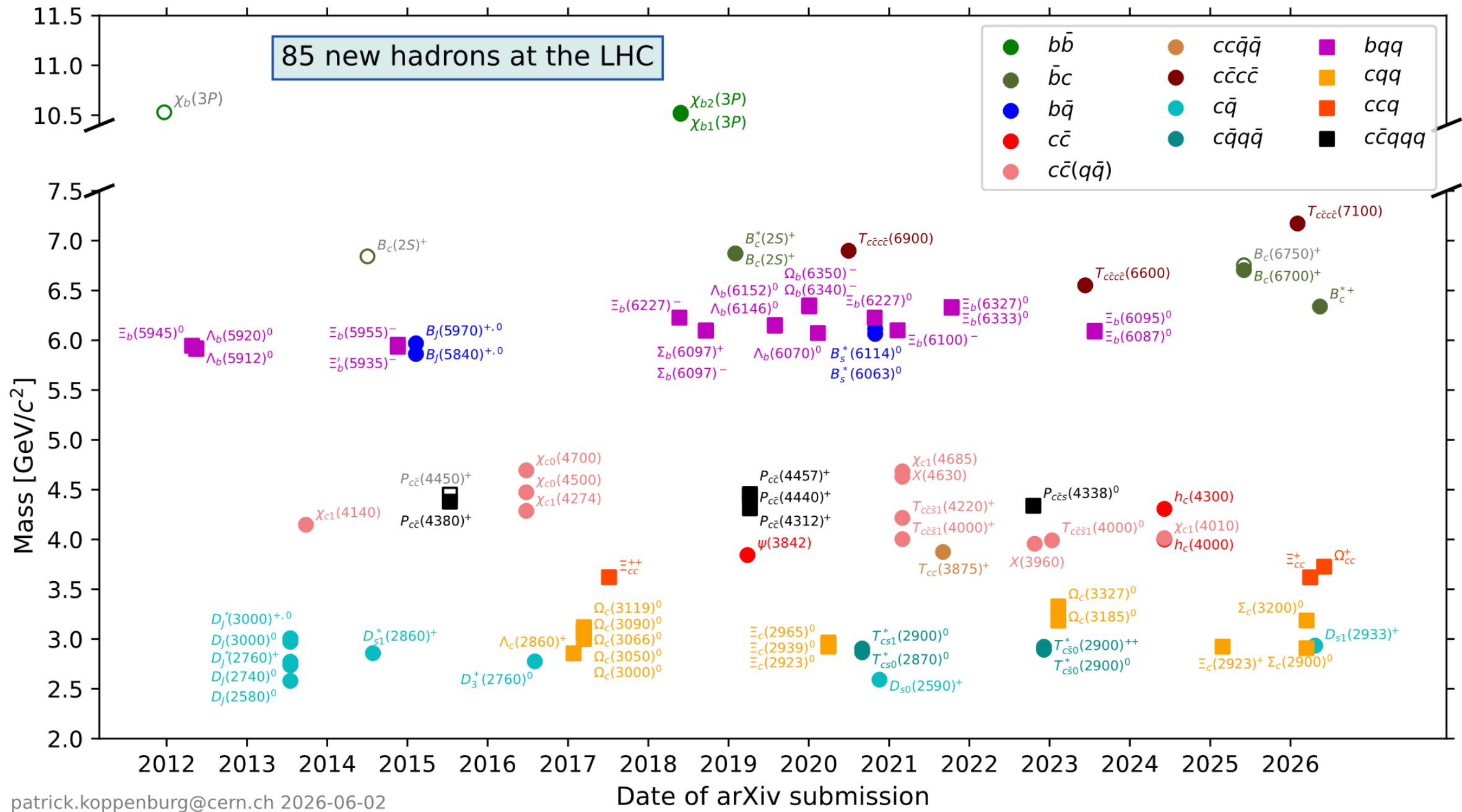
New particles discovered at LHC?

New particles

discovered

at LHC?

New particles discovered at LHC?

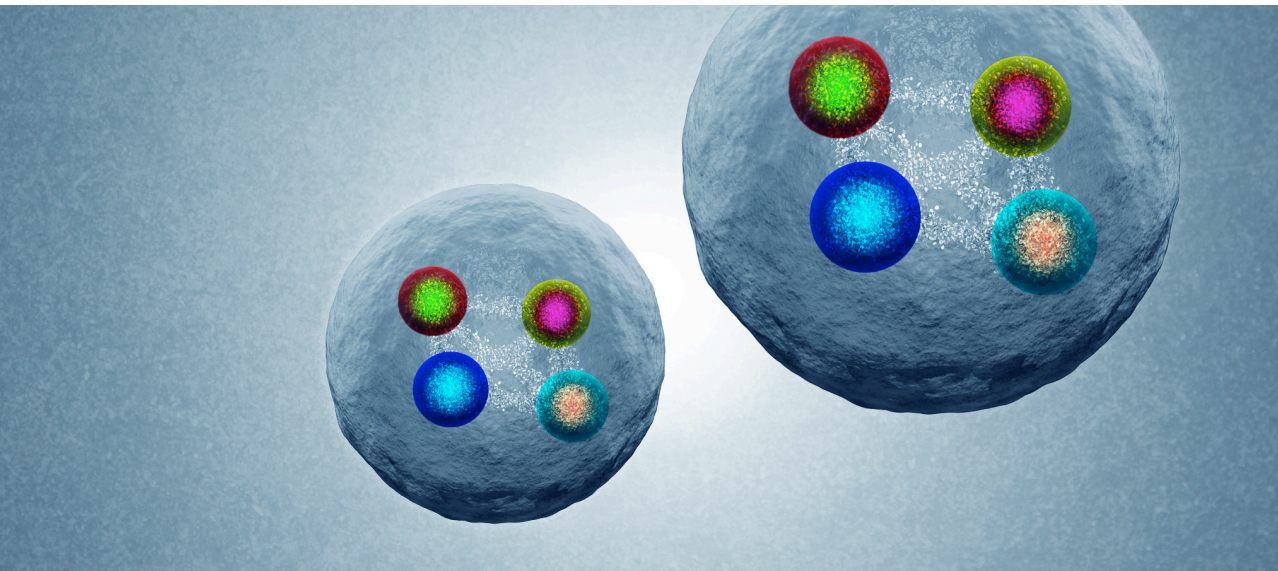


85+1 new particles already discovered — and more awaiting to be discovered !

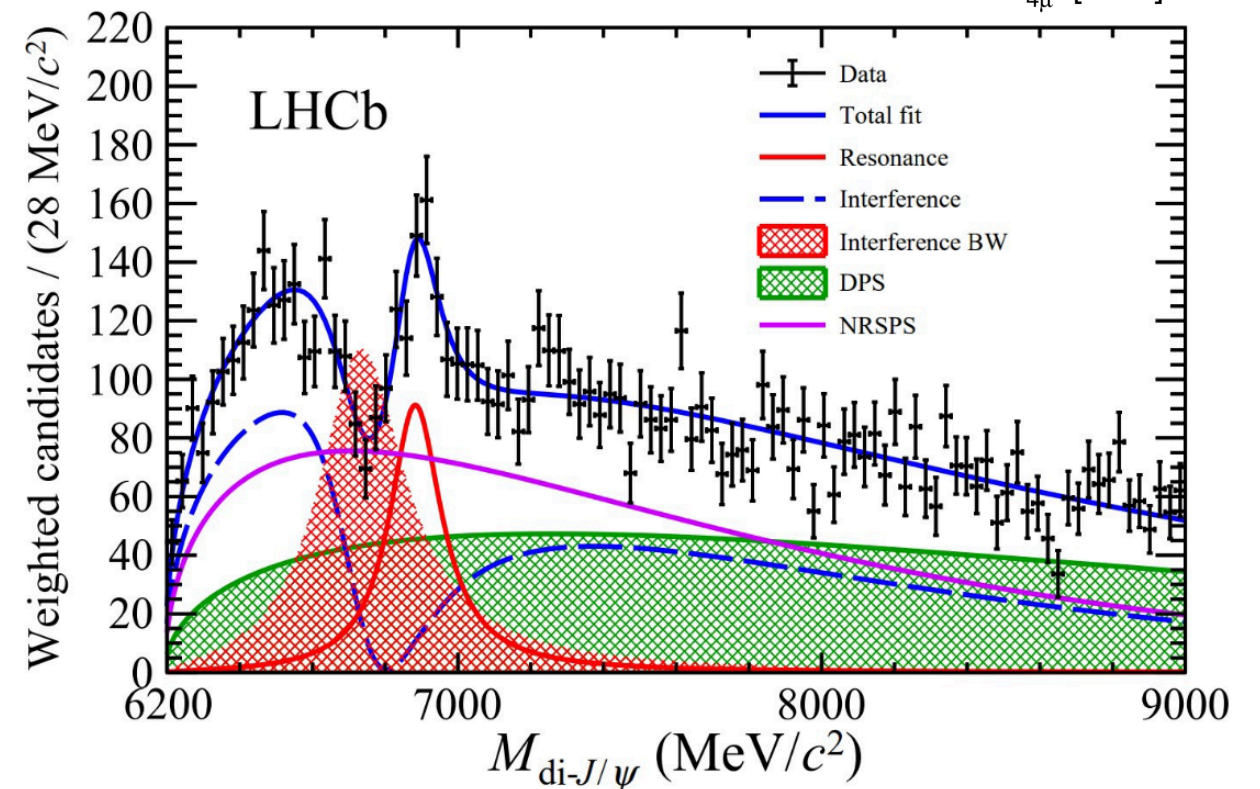
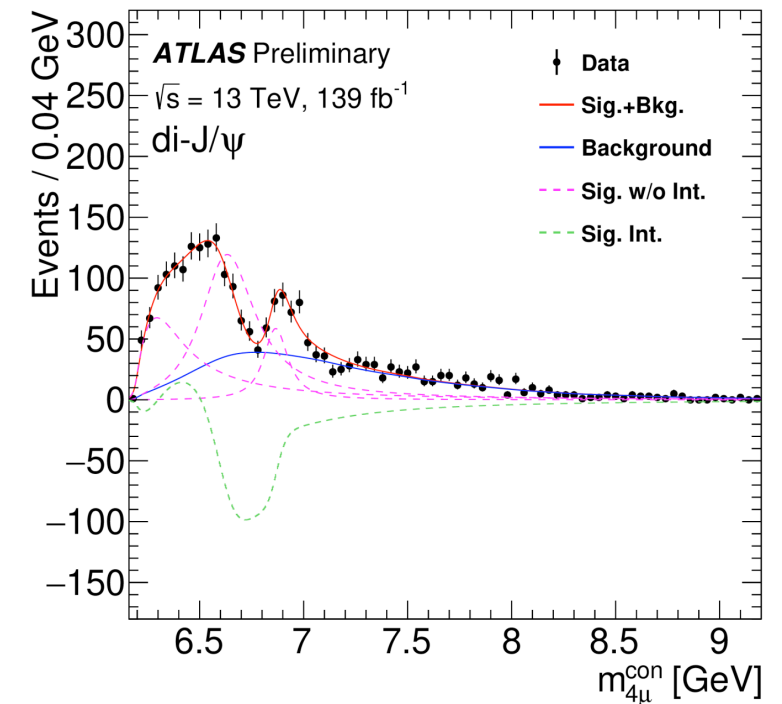
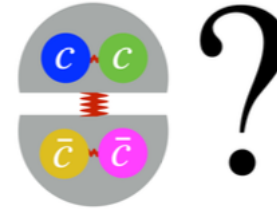
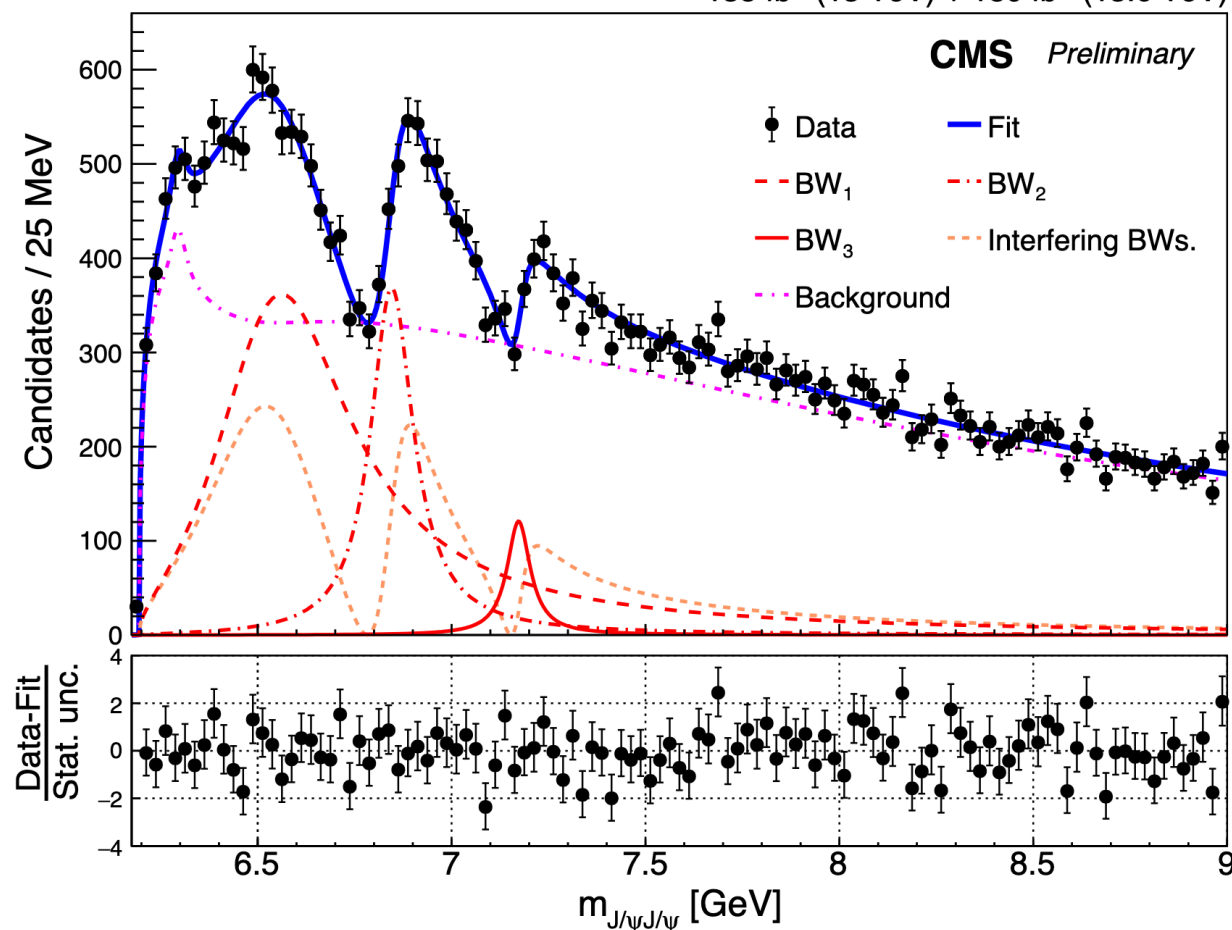
<https://www.nikhef.nl/~pkoppenb/particles.html>

(extra) new particles discovered at LHC?

an all-charm tetraquark (candidates)



135 fb⁻¹ (13 TeV) + 180 fb⁻¹ (13.6 TeV)

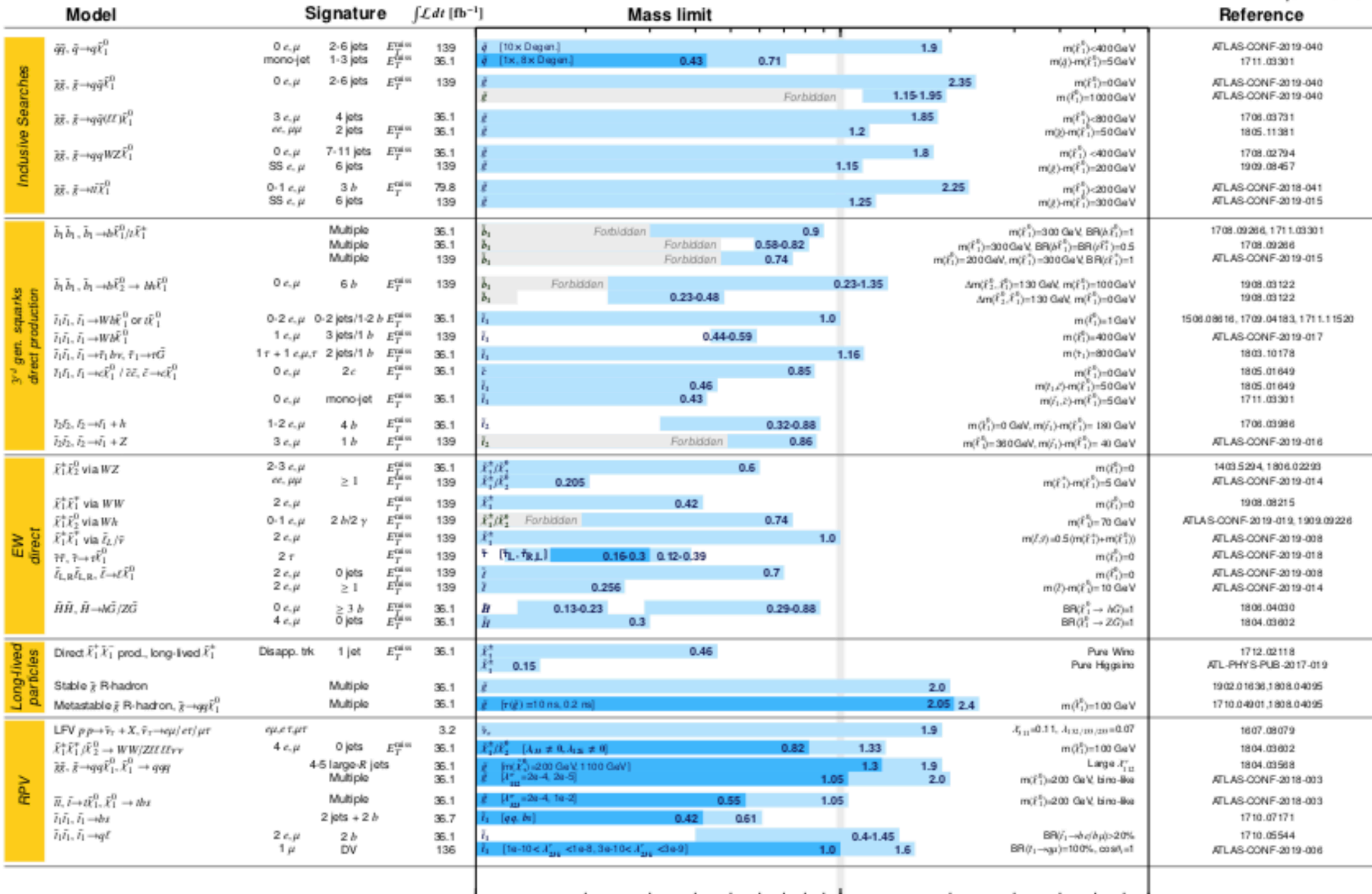


ATLAS SUSY Searches* - 95% CL Lower Limits

October 2019

example: SUSY

ATLAS Preliminary

 $\sqrt{s} = 13 \text{ TeV}$ 

*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.

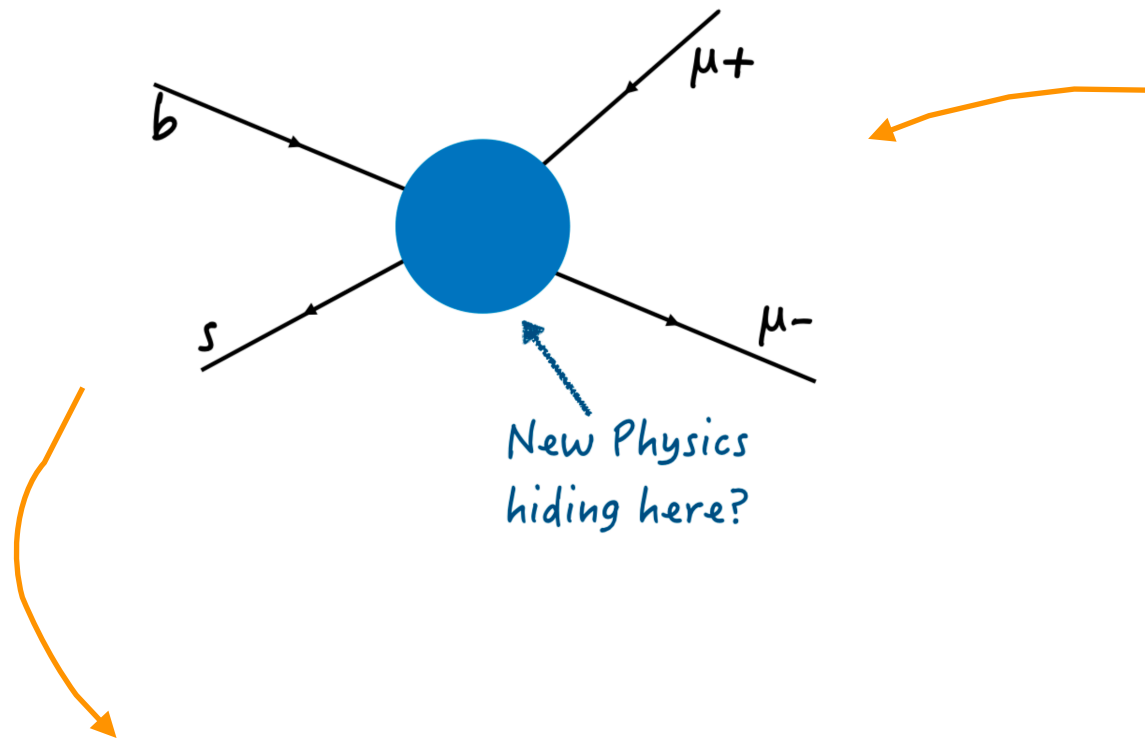
 10^{-1}

1

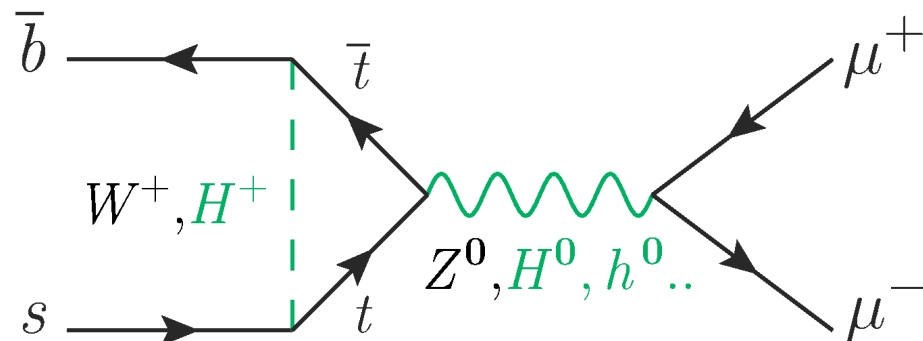
Mass scale [TeV]

Going beyond the Standard Model

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



	I	II	III		
mass	$\approx 2.2 \text{ MeV}/c^2$	$\approx 1.28 \text{ GeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$	0	$\approx 124.97 \text{ GeV}/c^2$
charge	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0	0
spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	0
QUARKS	u up	c charm	t top	g gluon	H higgs
	$\approx 4.7 \text{ MeV}/c^2$	$\approx 96 \text{ MeV}/c^2$	$\approx 4.18 \text{ GeV}/c^2$	0	
	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	0	
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
	d down	s strange	b bottom	γ photon	
LEPTONS	$\approx 0.511 \text{ MeV}/c^2$	$\approx 105.66 \text{ MeV}/c^2$	$\approx 1.7768 \text{ GeV}/c^2$	$\approx 91.19 \text{ GeV}/c^2$	
	-1	-1	-1	0	
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
	e electron	μ muon	τ tau	Z Z boson	
	$< 2.2 \text{ eV}/c^2$	$< 0.17 \text{ MeV}/c^2$	$< 18.2 \text{ MeV}/c^2$	$\approx 80.39 \text{ GeV}/c^2$	
	0	0	0	± 1	
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	



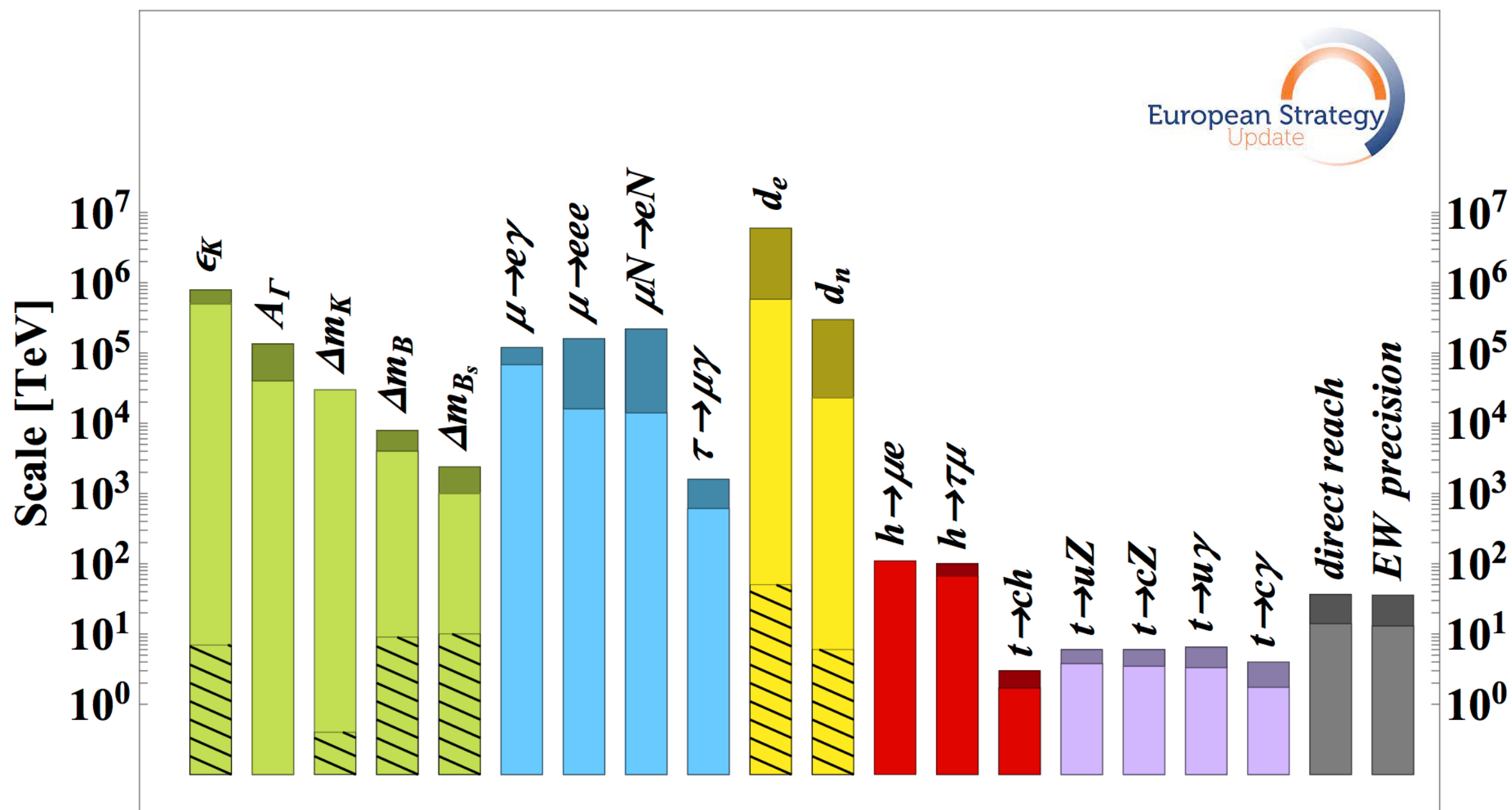
?
new thing

fueled by Quantum Mechanics

Intensity frontier

Going beyond the Standard Model

Indirect searches: fuelled by Quantum Mechanics

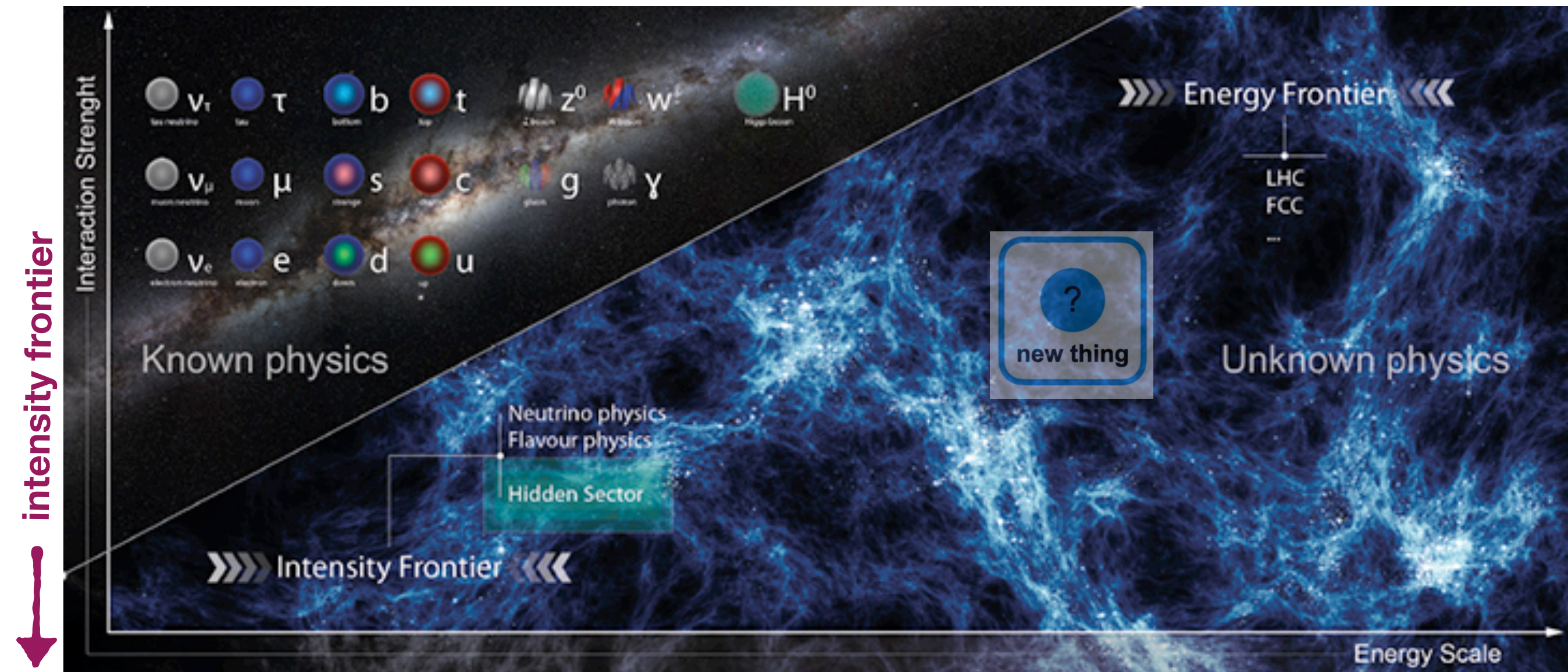


May access to NP scales well beyond collision energy !

Going beyond the Standard Model

LHC — explore both energy and intensity frontiers

energy frontier →



Beam intensity: high luminosity

Beam energy: $\sqrt{s}$

energy scale

$m_{Z,W}$ m_H m_t

Λ_{NP}

1930

...

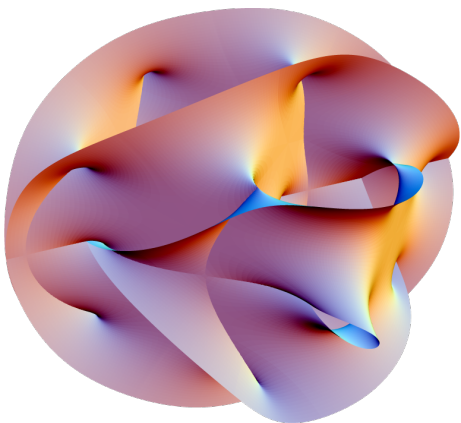
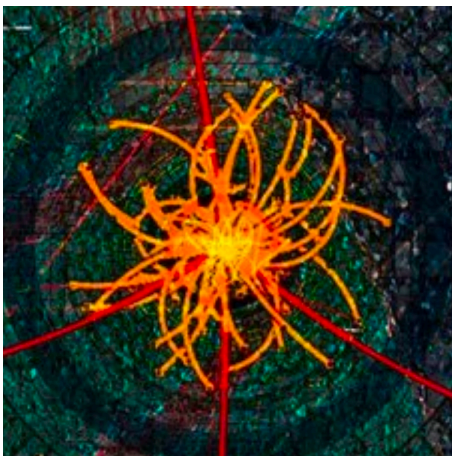
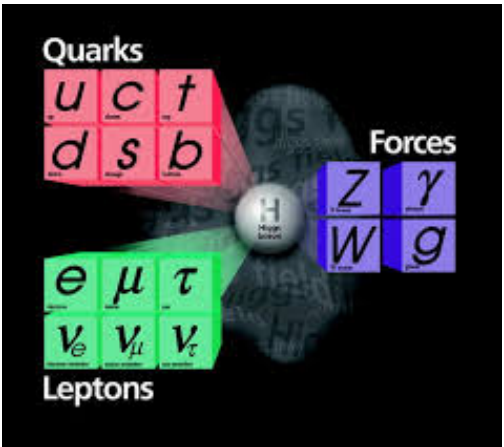
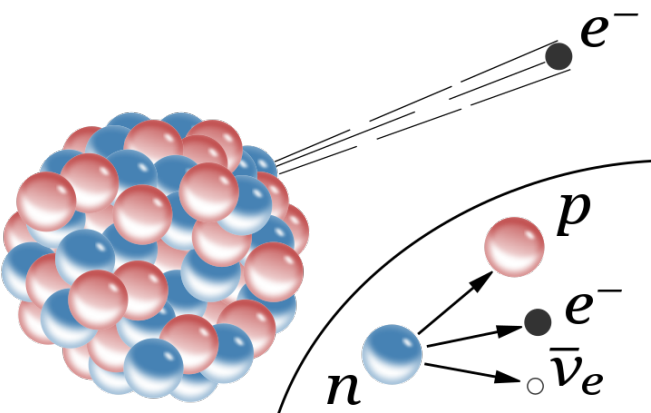
1970

2012

2020

...

future

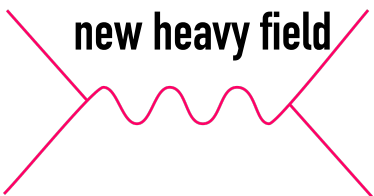
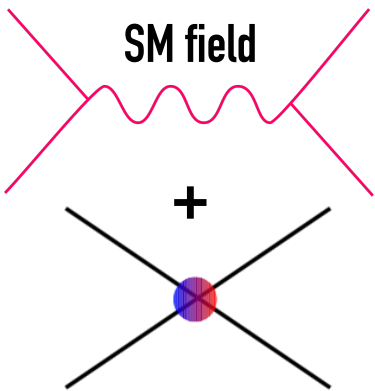
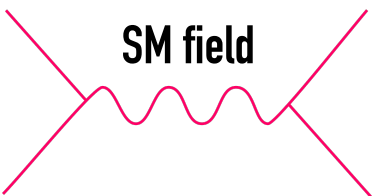
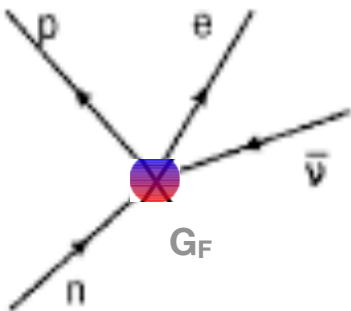


Fermi model

Standard Model

SM-EFT

UV theory



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

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

$$\mathcal{L}_{\text{SM-EFT}} = \mathcal{L}_{\text{SM}}$$

$$+ \sum_i C_i O_i$$

$$\mathcal{L}$$

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