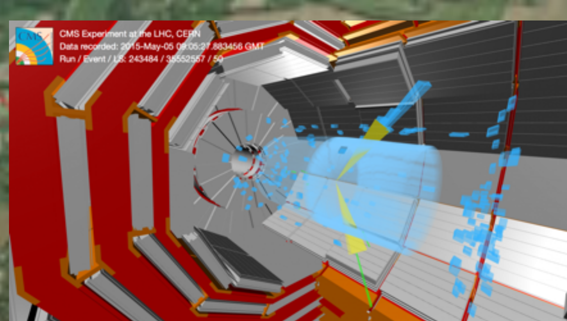
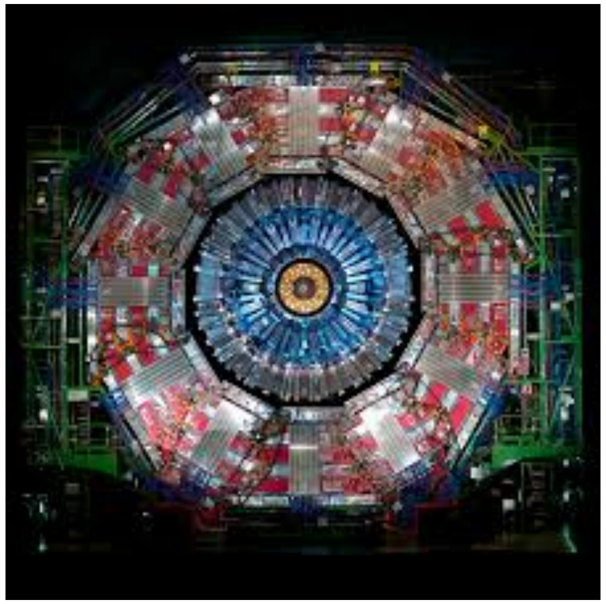
The CMS experiment

Compact
Muon
Solenoid



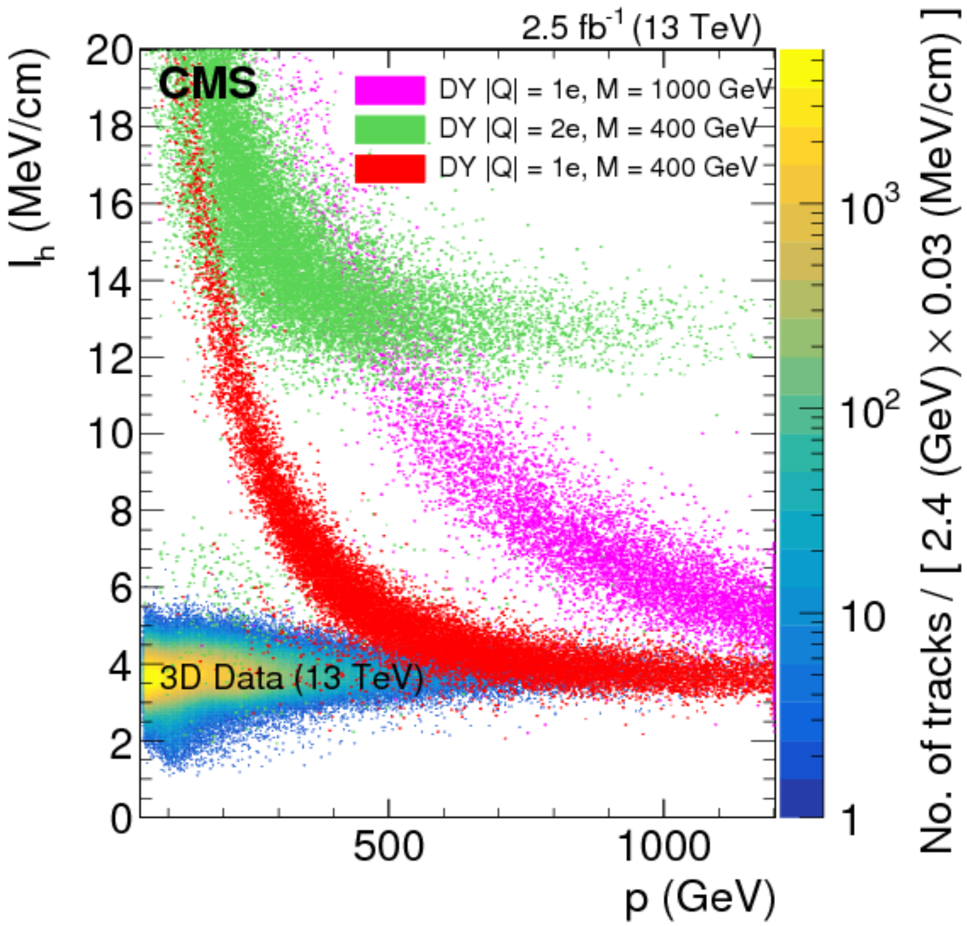
Outline



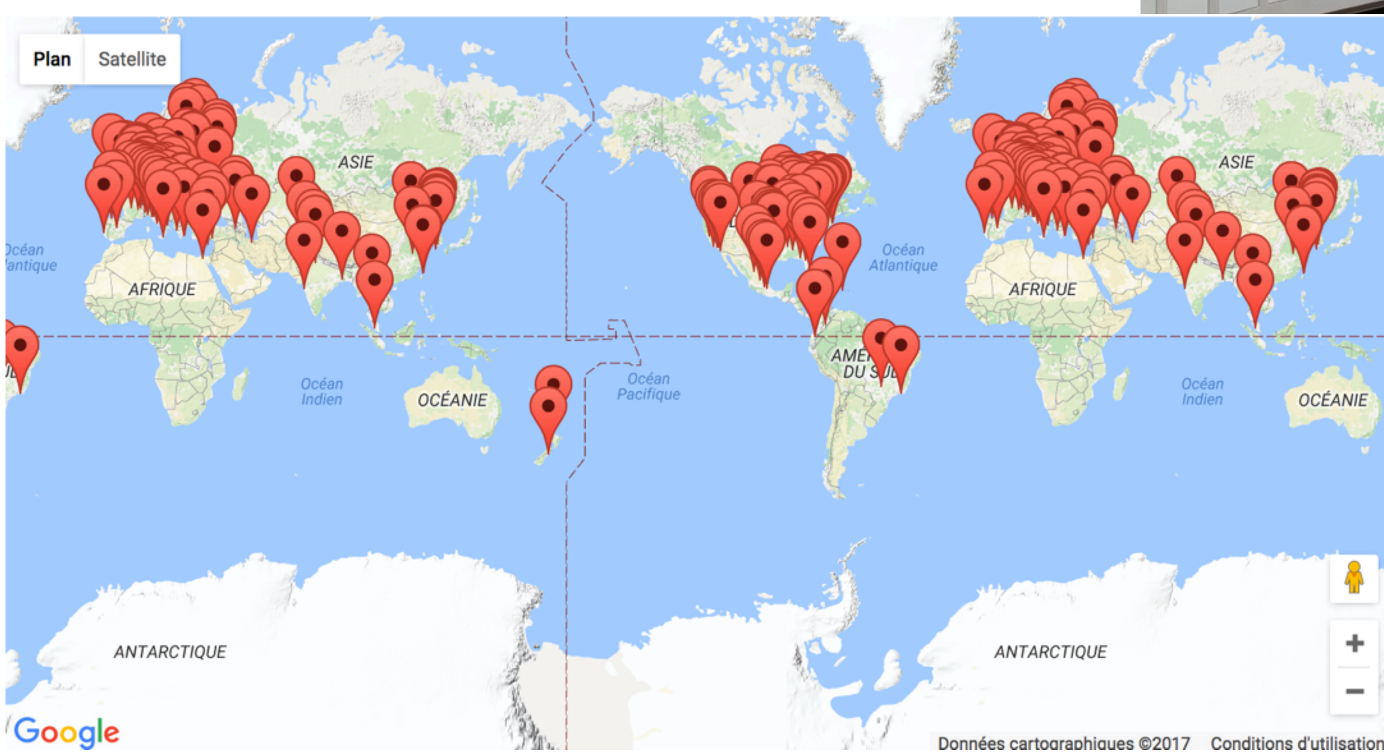
Introduction to CMS collaboration/physics

Activities at IPHC

Intership/PhD subject



The CMS collaboration



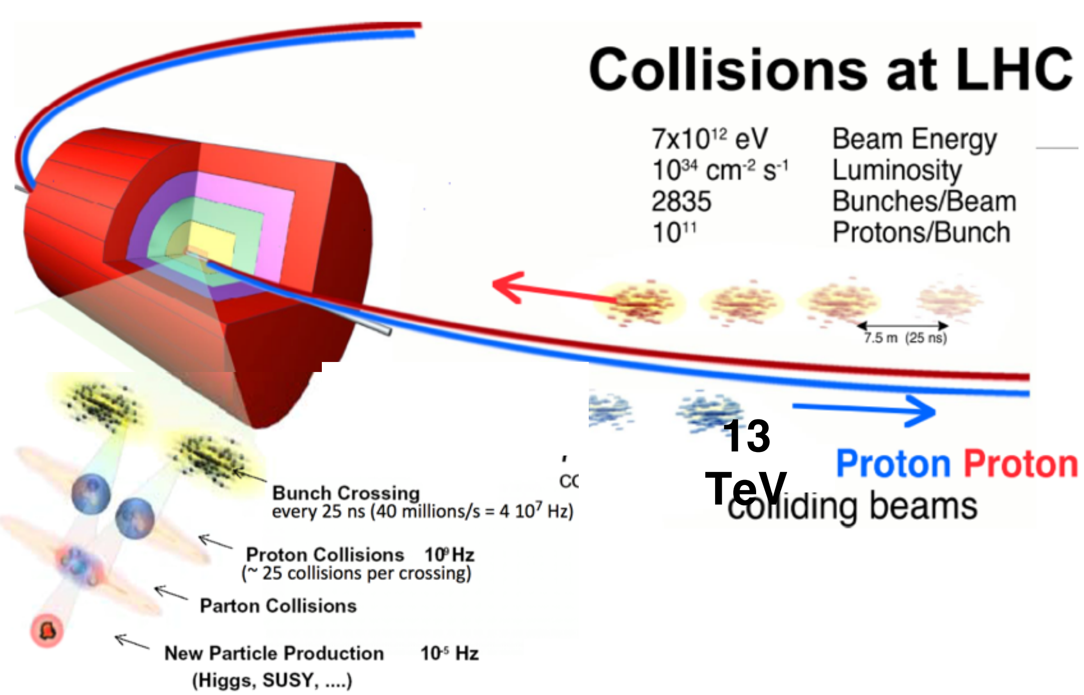
~3500 scientists
from 200 institutes
in 46 countries

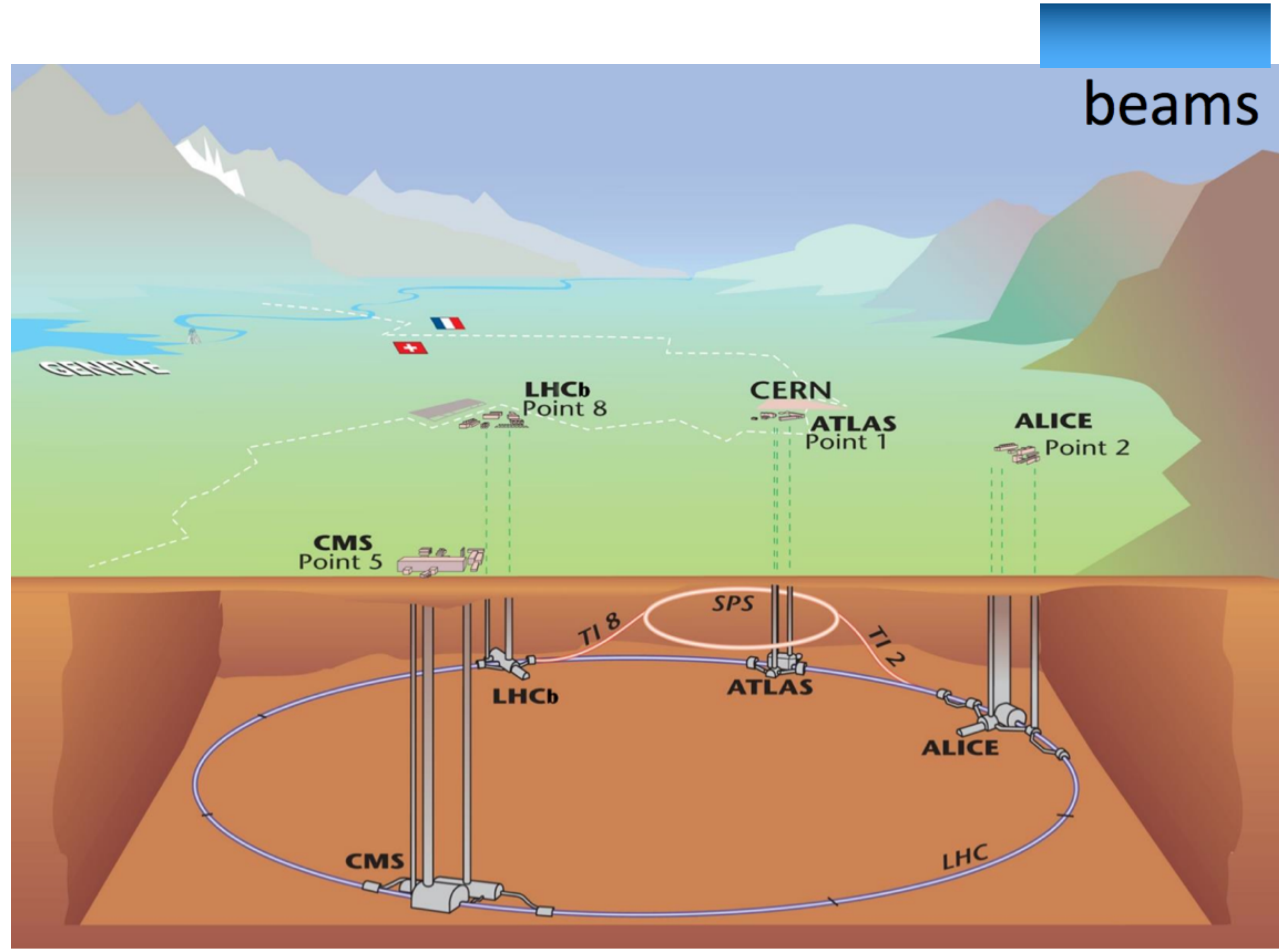
The Large Hadron Collider (LHC)

The largest accelerator machine in the world: 27 km, 1232 supraconductor dipoles.

Most empty place in the solar system (10^{-13} atm), colder than interstellar medium (magnets -271°C).
Collides two counter-circulating beams of protons.

40 millions of collisions per second.

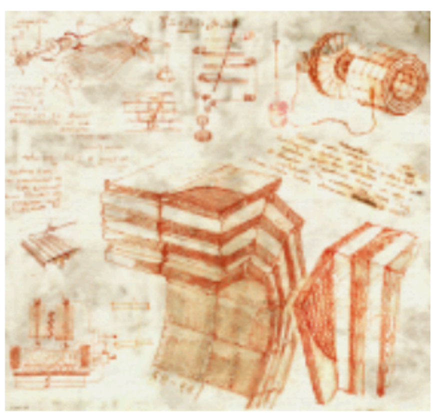




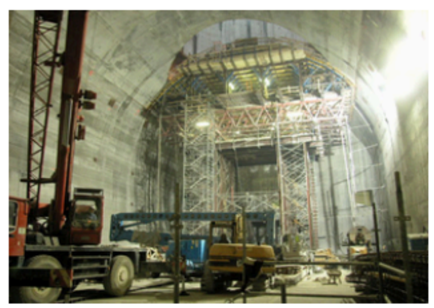
Timeline…

1992 | 1995 | 1998 | 2000 | 2002 | 2005 | 2007 | 2010 | 2012 | 2013 | 2014 | 2015 | 2018 | 2019 | 2020 | 2021 | 2023 | 2024 | 2025

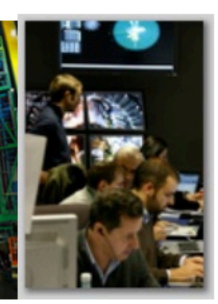
Recherches sur les détecteurs et conception



Construction de la caverne et du détecteur



Mise en route, compréhension du détecteur en fonctionnement



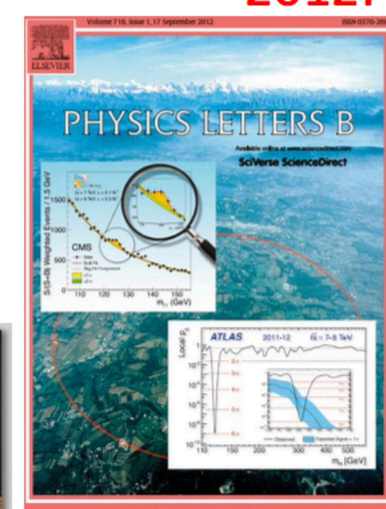
Run1
7 TeV (2010-2011)
8 TeV (2012)

Run2
13 TeV

Long arrêt

Run3
14 TeV

2012: Découverte du Boson de Higgs



Physics 2013

Photo: Pnicolet via Wikimedia Commons
François Englert

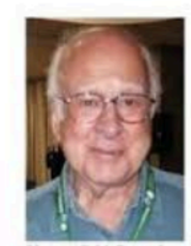


Photo: G-M Greuel via Wikimedia Commons
Peter W. Higgs

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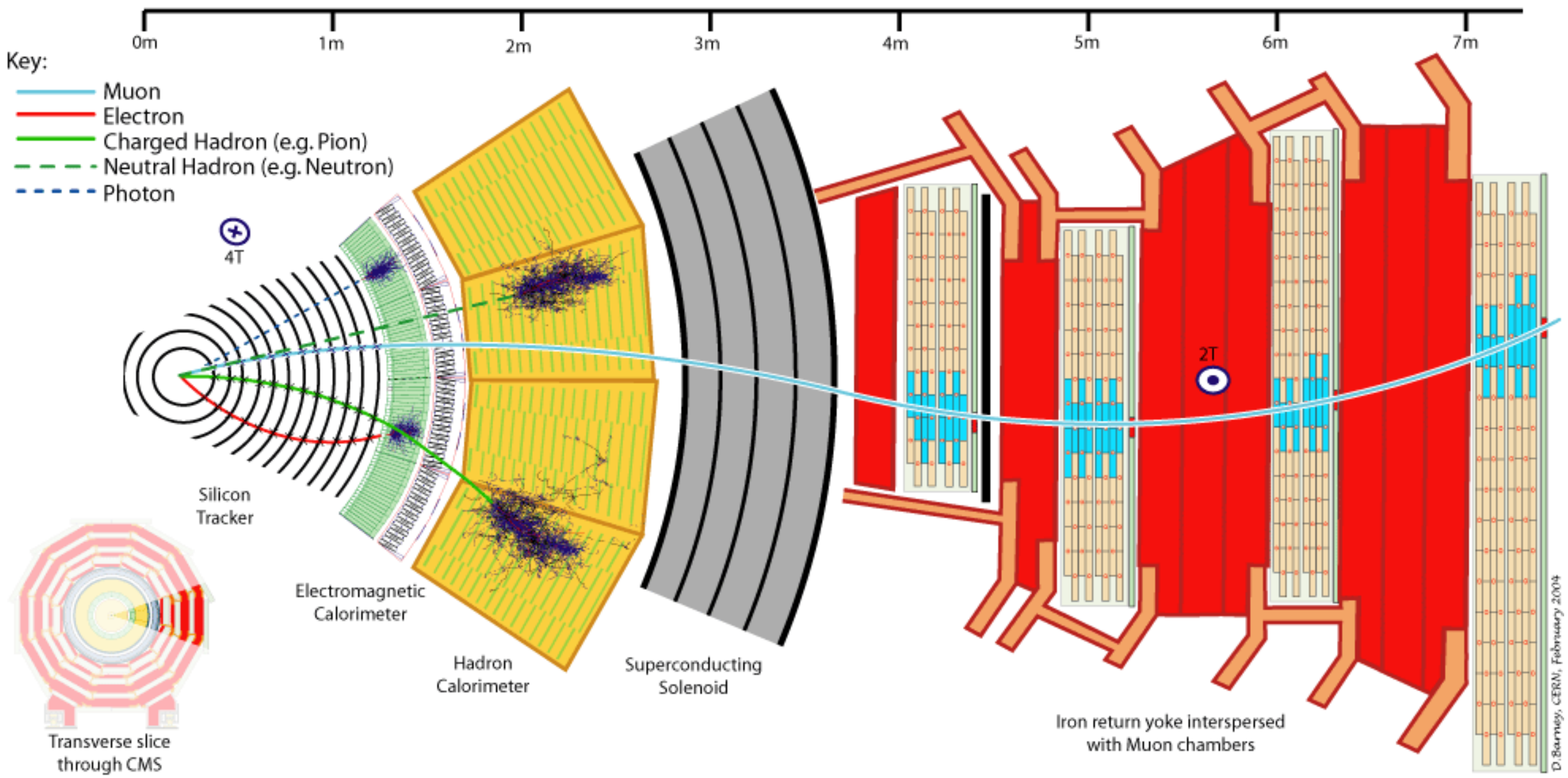
How do we identify particles in CMS ?

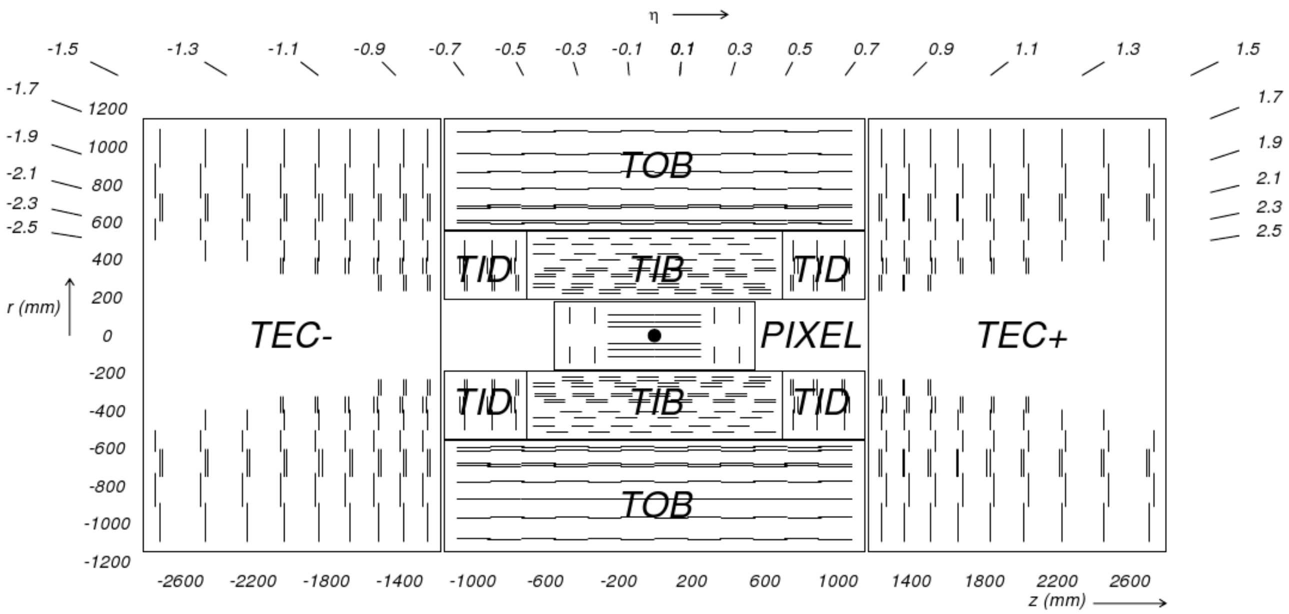


Onion-like detector
Each layer/detector measures E or p.

The CMS tracker

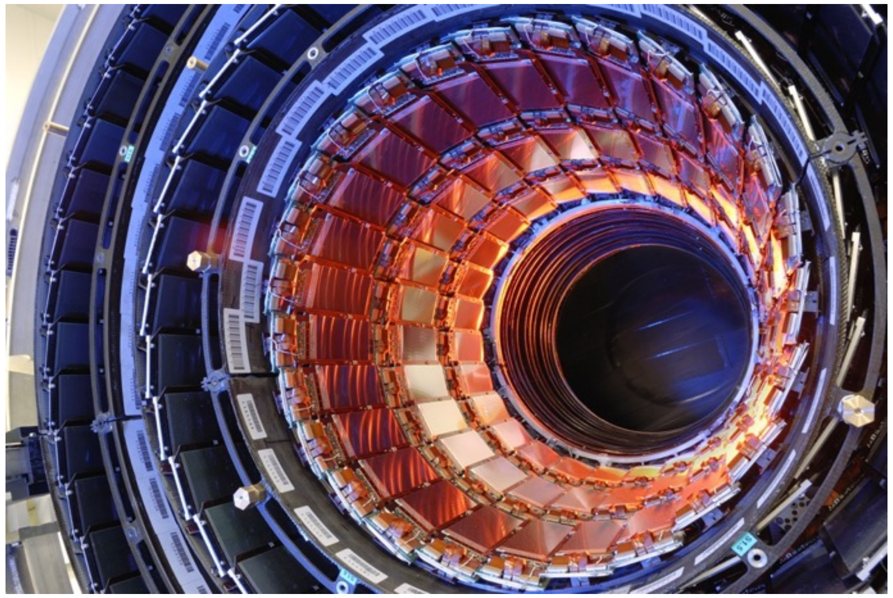
Reconstruct trajectories of all the charged particles from collisions.

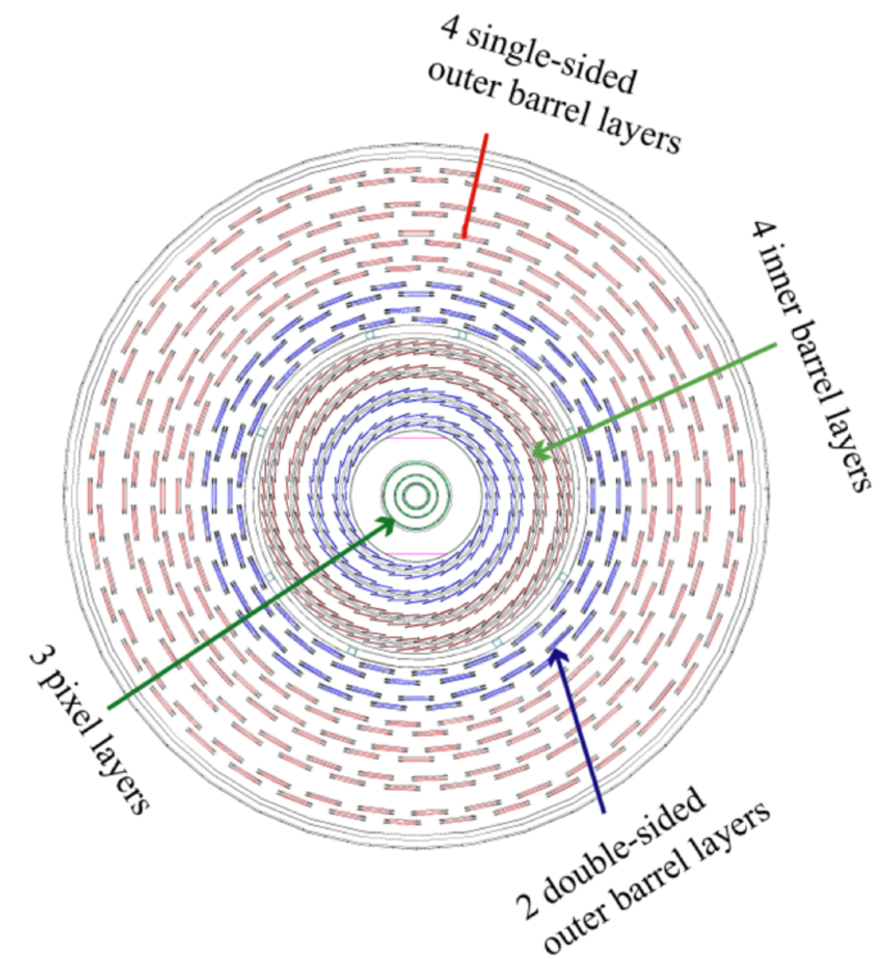
214 m^2 silicon, 65.9 M silicon pixels, 11.4 M silicon strips.



With more than 10 measurements per particles, it is possible to reconstruct tracker with very good performances:

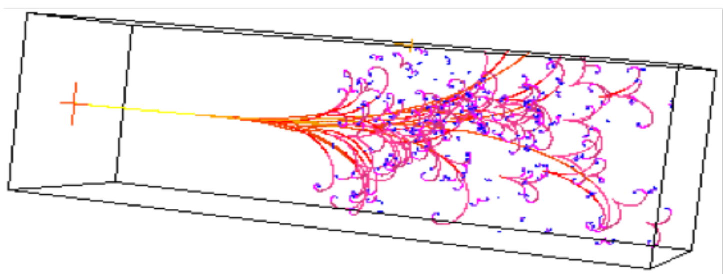
- high efficiency (>90%)
- relative p_T resolution < 2% for [1-100 GeV]
- impact parameters resolution: 100-200 microns





The CMS calorimeters

ECAL

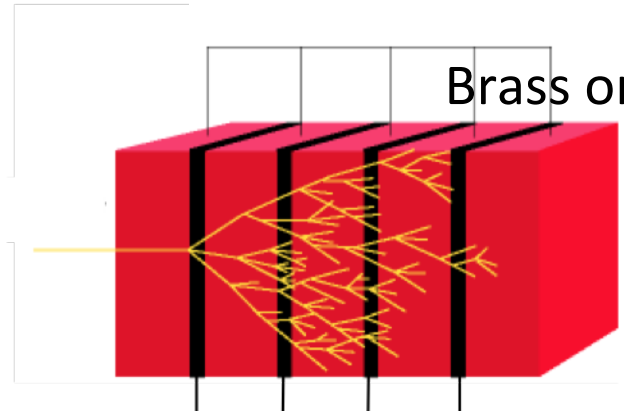


Detection principle :

stop a particle
measure its signal

HCAL

Brass or copper walls



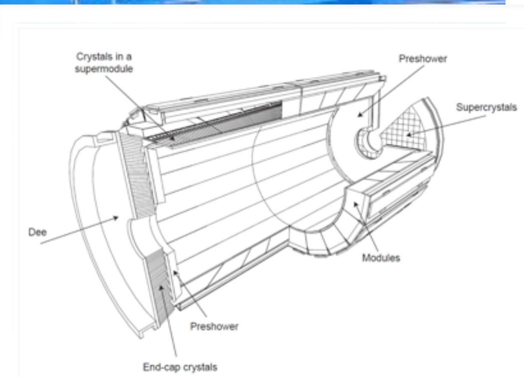
Transparent scintillating plastic

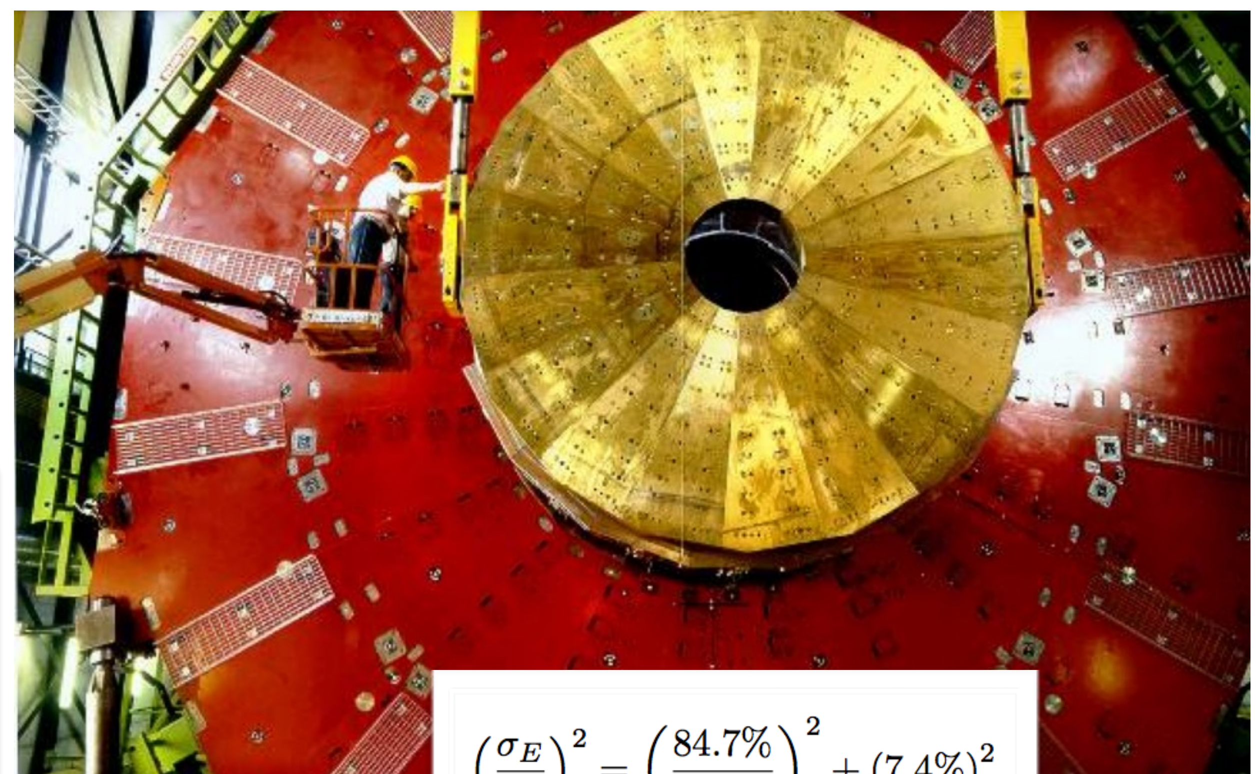
76k scintillating $PbWO_4$ crystals:

→ Heavy (so particles interact with it a lot)

→ Transparent (so you can collect the light at the end)

$$\left(\frac{\sigma(E)}{E}\right)^2 = \left(\frac{0.027}{\sqrt{E}}\right)^2 + \left(\frac{0.12}{E}\right)^2 + 0.005^2$$



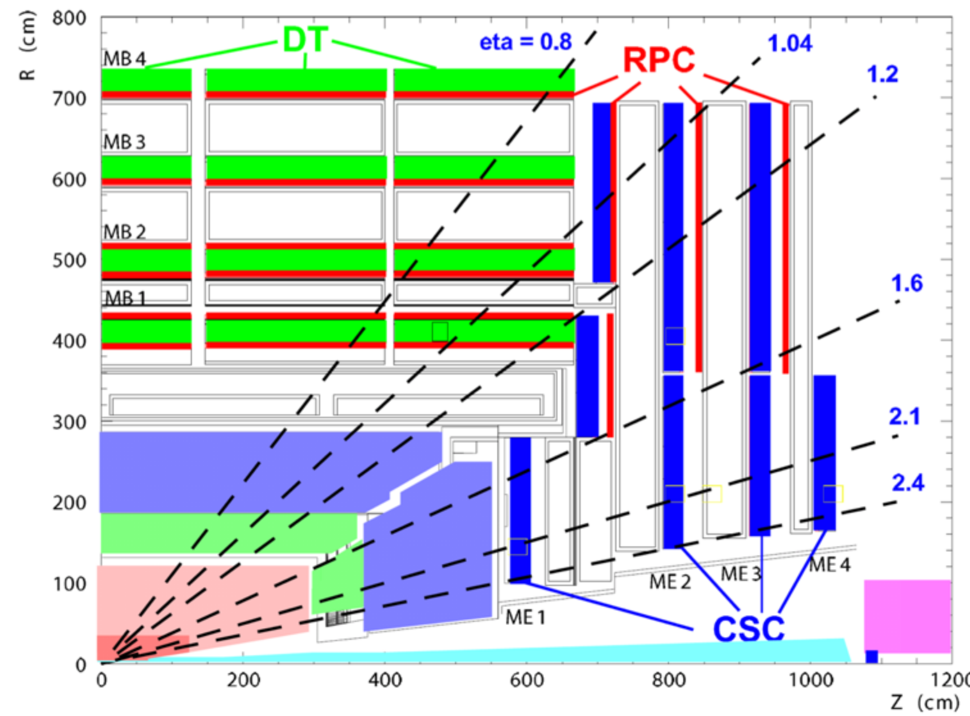


$$\left(\frac{\sigma_E}{E}\right)^2 = \left(\frac{84.7\%}{\sqrt{E}}\right)^2 + (7.4\%)^2$$

Muon chambers

Muons are typically very penetrating.

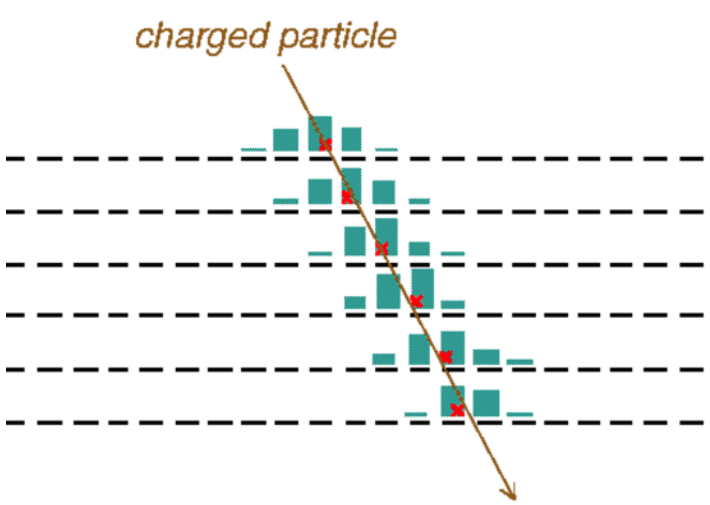
Stick the detectors in giant hunks of iron so nothing else gets through.

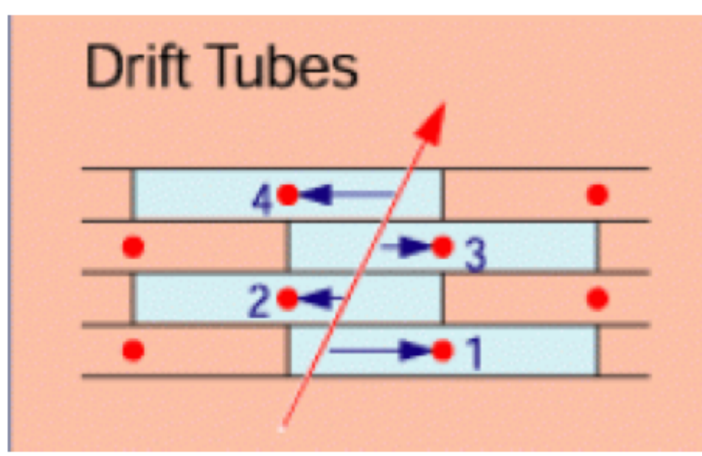


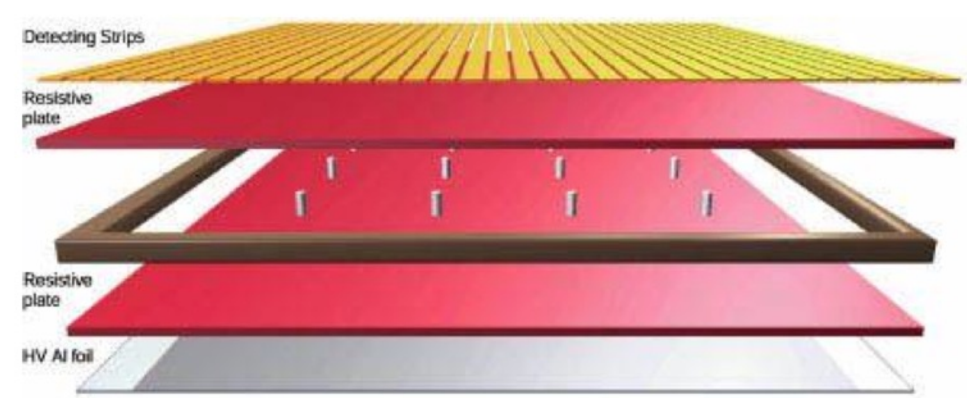
Three types of detectors → redundancy

- drift tubes (DT) → fast !
- resistive plate chambers (RPC) → fast, radiation tolerant
- cathode strip chambers (CSC) → radiation tolerant

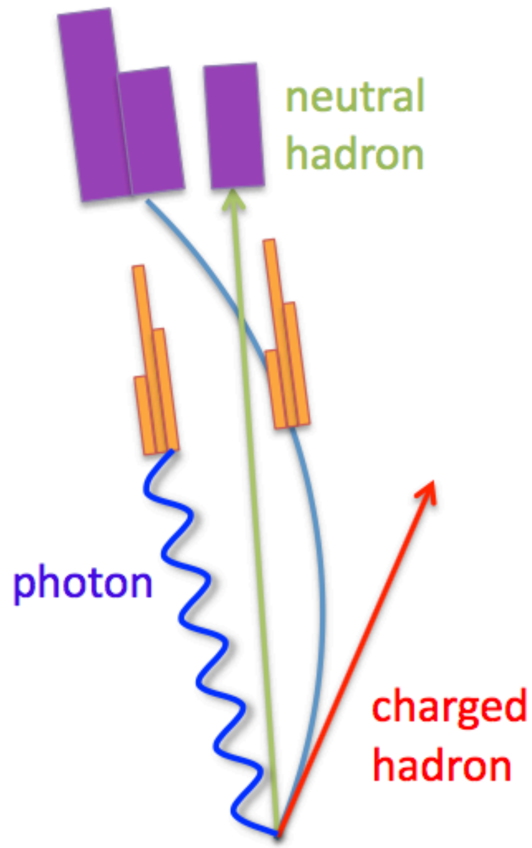
Time-of-flight can be measured with a resolution of o(1) ns







Particle flow ?



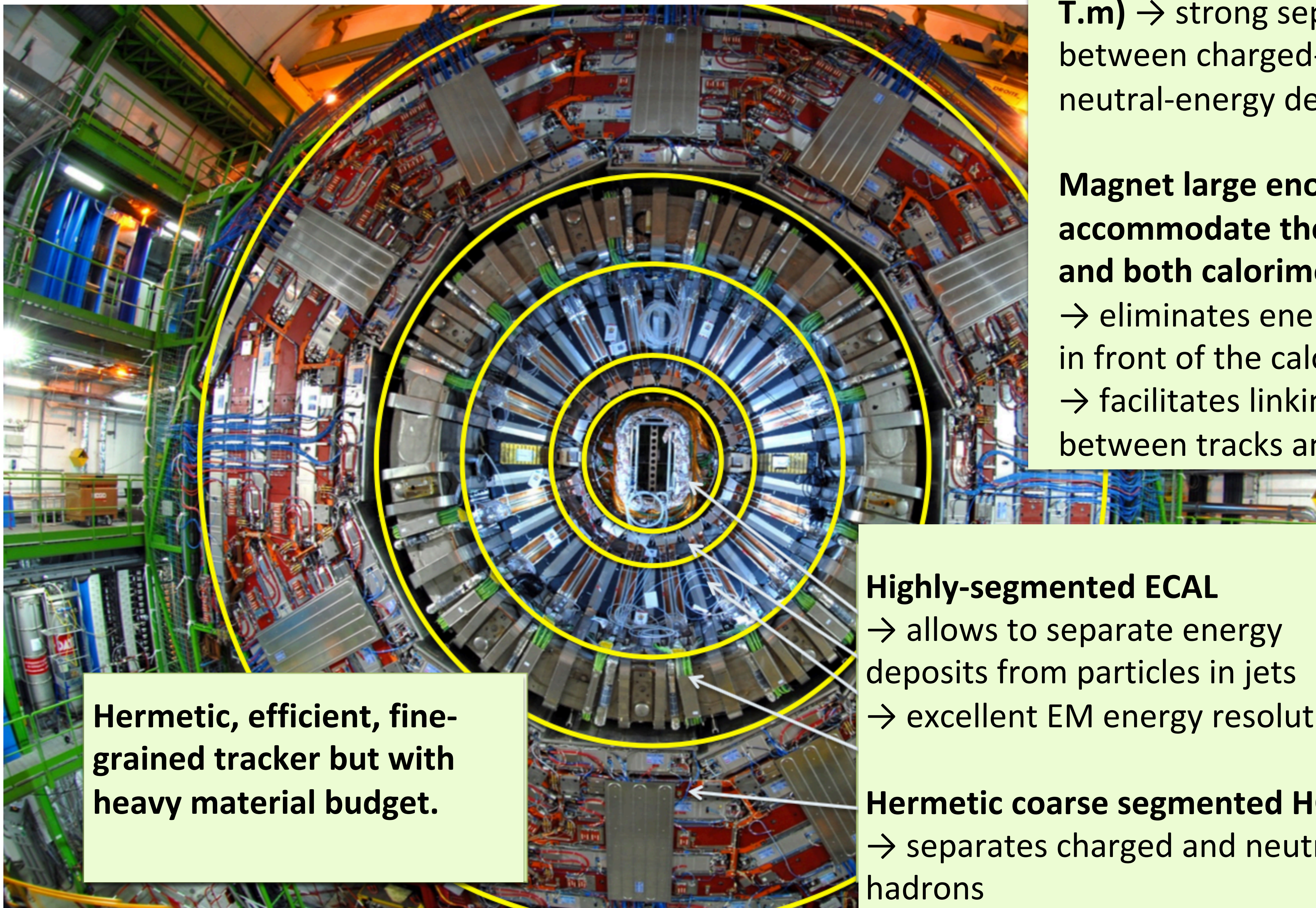
- Calorimeter jet:
  - $E = E_{HCAL} + E_{ECAL}$
  - σ(E) ~ calo resolution to hadron energy: 120 % / √E
  - direction biased (B = 3.8 T)
- Particle flow jet:
  - 65% charged hadrons
    - σ(pT)/pT ~ 1%
    - direction measured at vertex
  - 25% photons
    - σ(E)/E ~ 1% / √E
    - good direction resolution
  - 10% neutral hadrons
    - σ(E)/E ~ 120 % / √E
  - **Need to resolve the energy deposits from the neutral particles…**

Link tracks and calorimeter clusters together, take measurements with the best resolution from each detector, to identify precisely photons, charged hadrons and neutral hadrons, that are key ingredients to reconstruct other particles (taus, electrons…)

A very nice detector for particle flow

Strong magnet (field 3.8 T and bending power of 4.9 T.m) → strong separation between charged- and neutral-energy deposits

Magnet large enough to accommodate the tracker and both calorimeters
→ eliminates energy losses in front of the calorimeters
→ facilitates linking between tracks and clusters



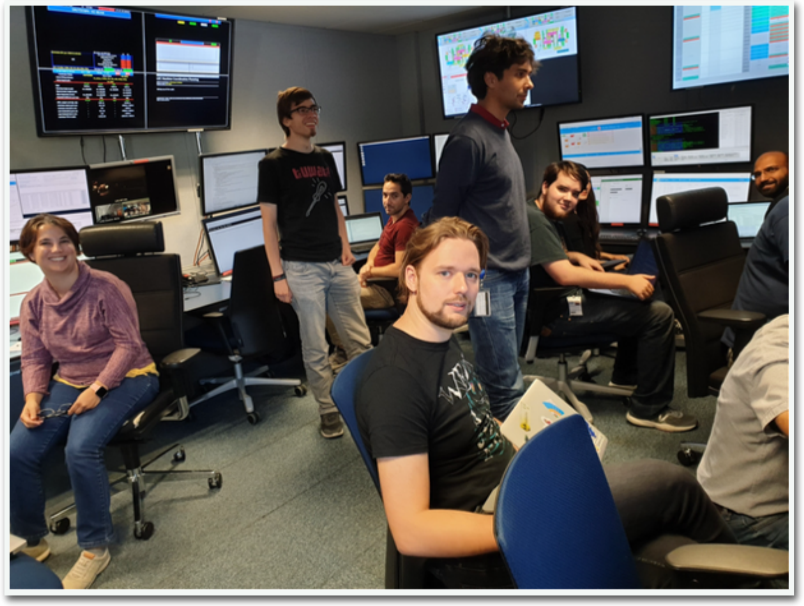
Highly-segmented ECAL
→ allows to separate energy deposits from particles in jets
→ excellent EM energy resolution

Hermetic coarse segmented HCAL
→ separates charged and neutral hadrons

Hermetic, efficient, fine-grained tracker but with heavy material budget.

The detector right now

Three days of global cosmic data taking every 2 months: calibration, commissioning, tests for Run 3…



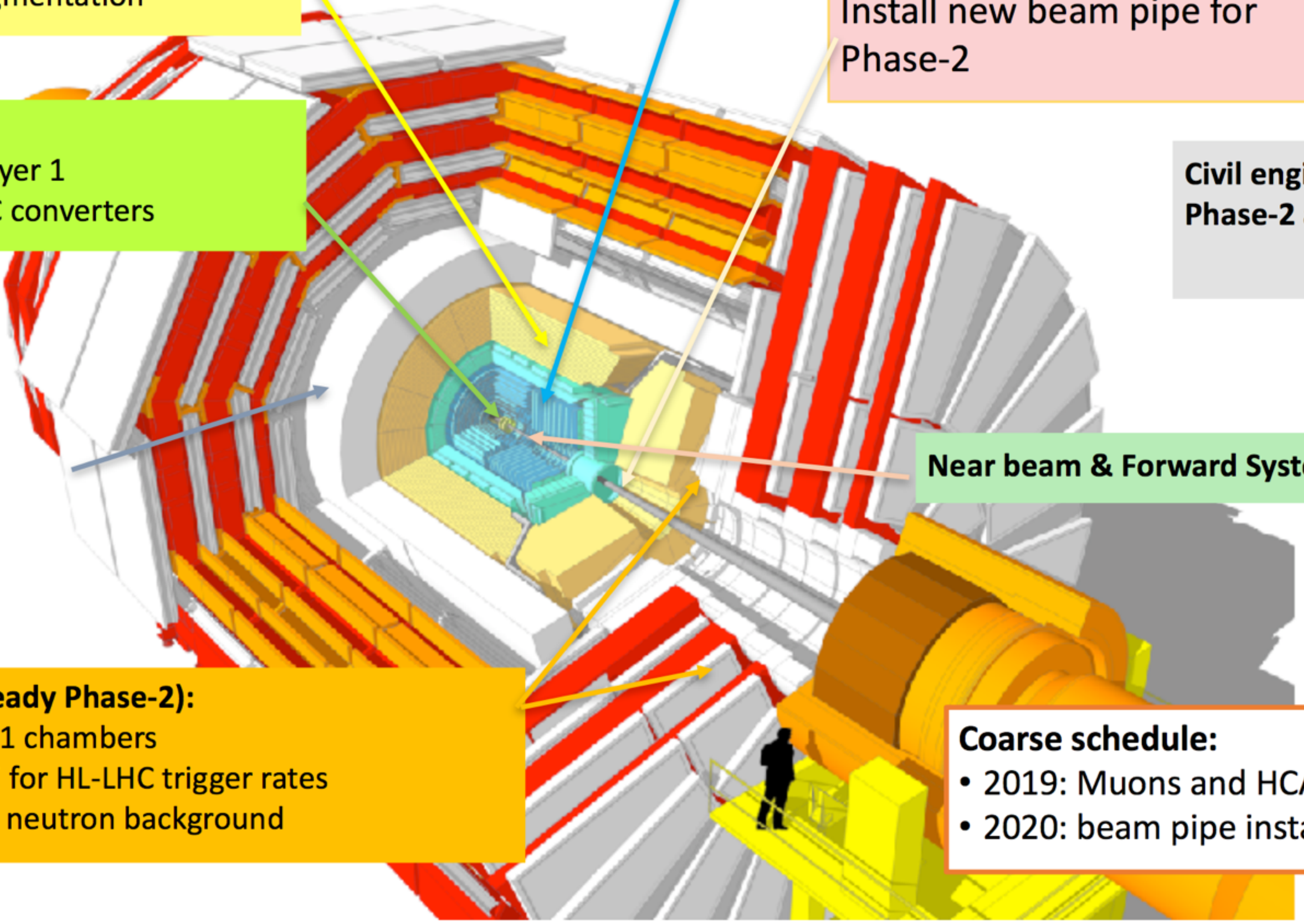
HCAL barrel (last Phase-1):
install SiPM+QIE11-based 5Gbps readout
Increase longitudinal segmentation

Keep strip tracker cold to avoid reverse annealing

Install new beam pipe for Phase-2

Pixel detector:
- replace barrel layer 1
- replace all DCDC converters

Civil engineering on P5 surface to prepare for Phase-2 assembly and logistics



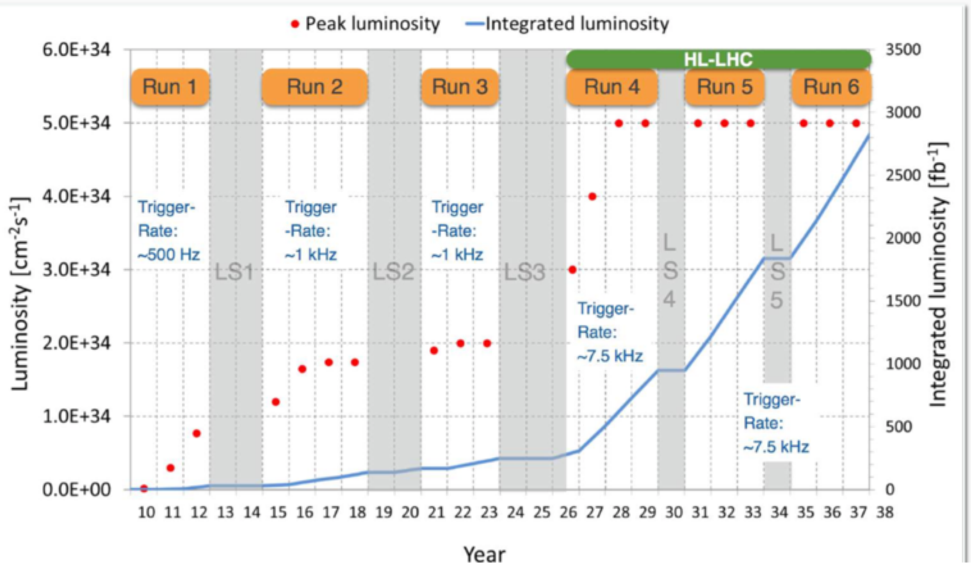
Near beam & Forward Systems

Muon system (already Phase-2):
- install GEM GE1/1 chambers
- Upgrade CSC FEE for HL-LHC trigger rates
- Shielding against neutron background

Coarse schedule:
- 2019: Muons and HCAL interleaved
- 2020: beam pipe installation, then pixel re-installation

Towards HL-LHC…

- Inst. Lumi x2.5
- Integrated lumi x 10
- Upgrade of detector (>200 MCHF)

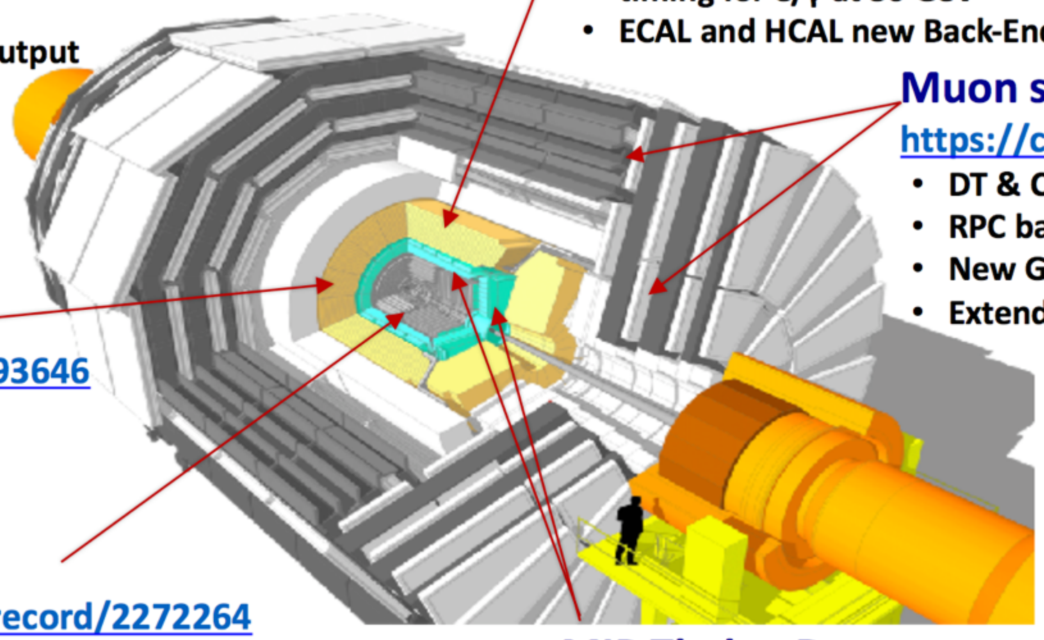


Technical proposal CERN-LHCC-2015-010 https://cds.cern.ch/record/2020886
Scope Document CERN-LHCC-2015-019 https://cds.cern.ch/record/2055167/files/LHCC-G-165.pdf

L1-Trigger/HLT/DAQ
https://cds.cern.ch/record/2283192
https://cds.cern.ch/record/2283193
- Tracks in L1-Trigger at 40 MHz
- PFlow-like selection 750 kHz output
- HLT output 7.5 kHz

Barrel Calorimeters
https://cds.cern.ch/record/2283187
- ECAL crystal granularity readout at 40 MHz with precise timing for e/γ at 30 GeV
- ECAL and HCAL new Back-End boards

Muon systems
https://cds.cern.ch/record/2283189
- DT & CSC new FE/BE readout
- RPC back-end electronics
- New GEM/RPC 1.6 < η < 2.4
- Extended coverage to η ≃ 3



Calorimeter Endcap
https://cds.cern.ch/record/2293646
- 3D showers and precise timing
- Si, Scint+SiPM in Pb/W-SS

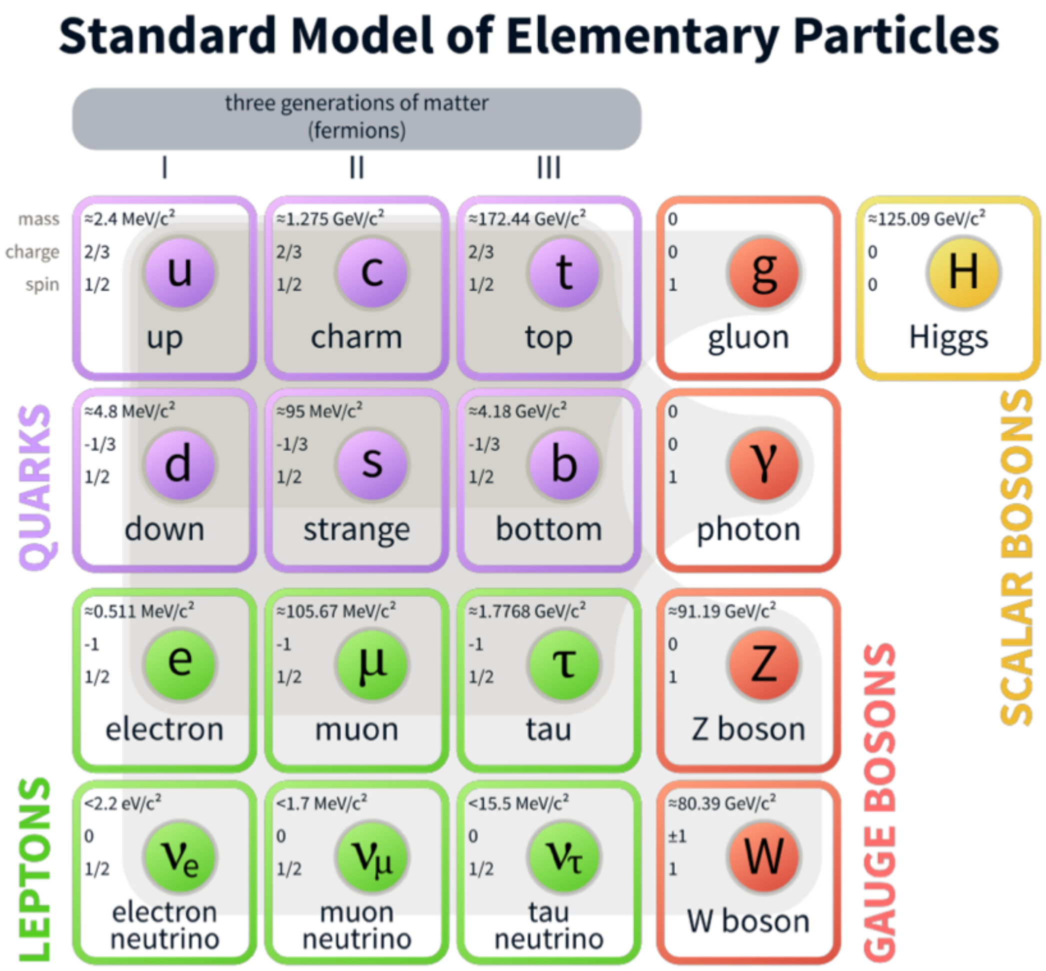
Beam Radiation Instr. and Luminosity, and Common Systems and Infrastructure
https://cds.cern.ch/record/2020886

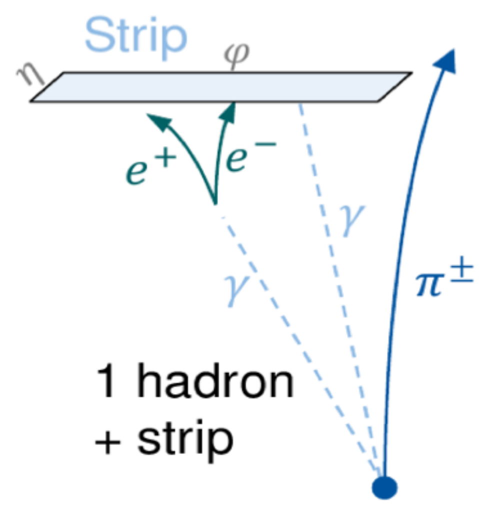
Tracker https://cds.cern.ch/record/2272264
- Si-Strip and Pixels increased granularity
- Design for tracking in L1-Trigger
- Extended coverage to η ≃ 3.8

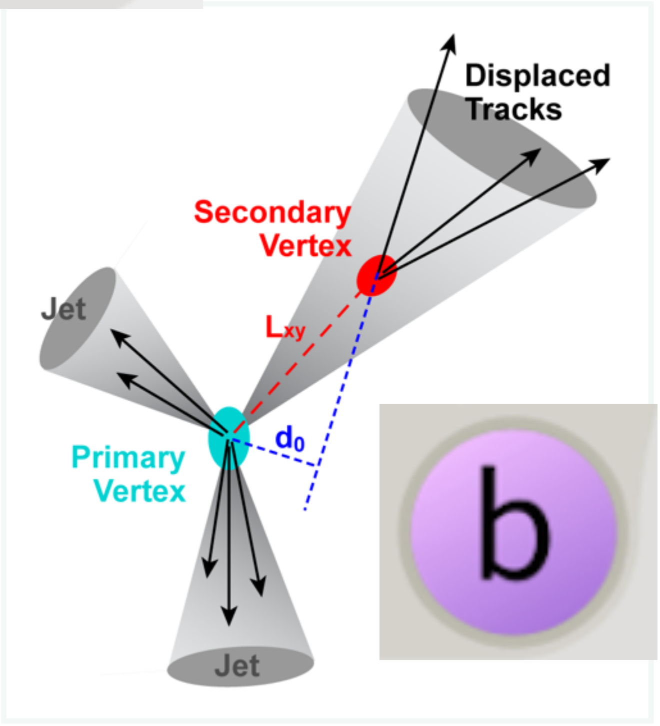
MIP Timing Detector
https://cds.cern.ch/record/2296612
Precision timing with:
- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes

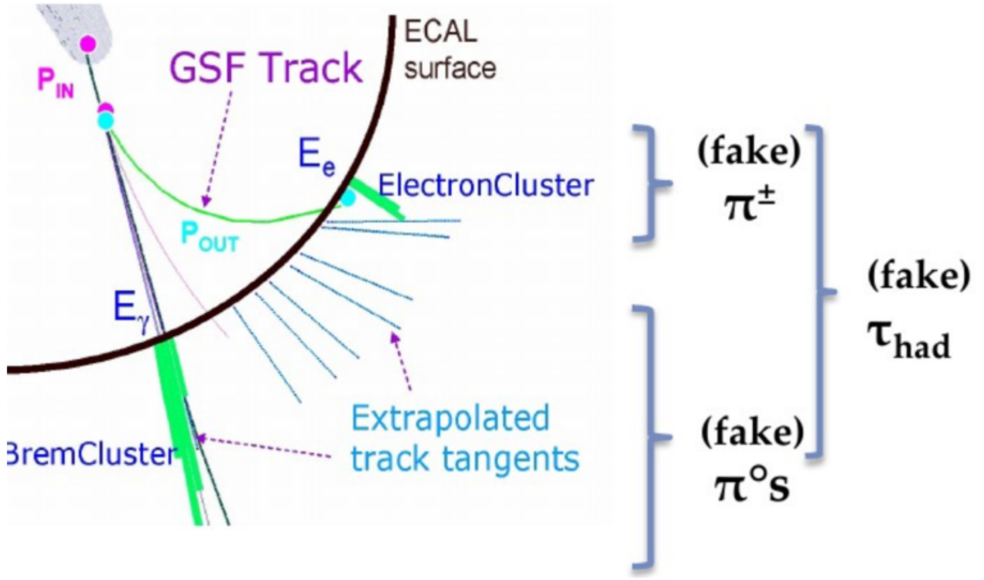
New paradigms (design/technology) for an HEP experiment to fully exploit HL-LHC luminosity

Particle identification







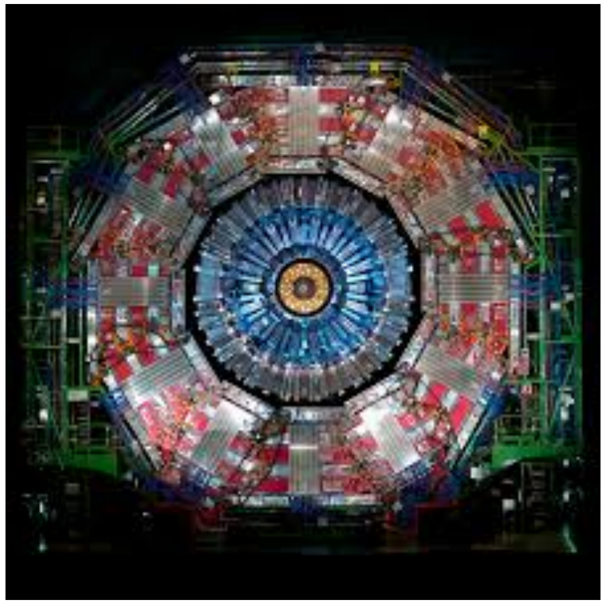


Dedicated algorithms to identify key particles…

+ μ in muon chambers and γ in ECAL

CMS @ IPHC

Outline



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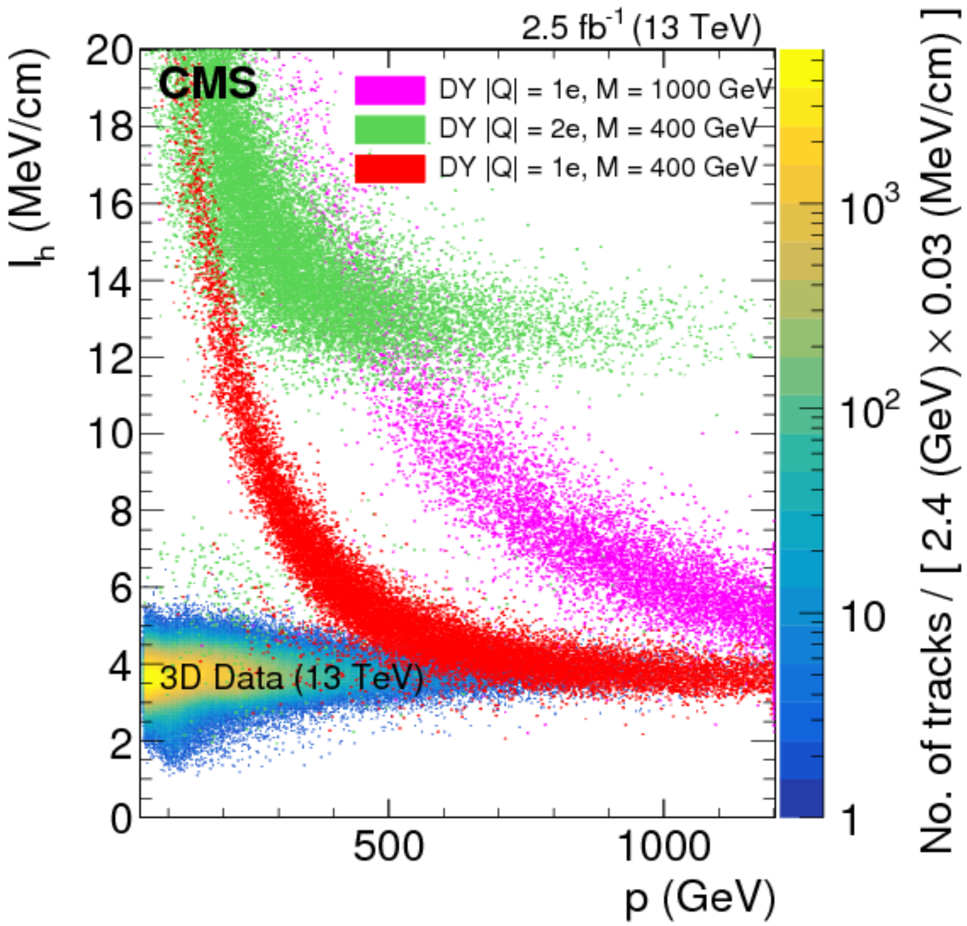


CMS @ IPHC

+ Strong support and expertise form engineers and technicians (DAQ, grid, upgrades)!

Daniel Bloch

Caroline Collard

Jean-Marie Brom

Pierre Van Hove

Jérémy Andrea

Anne-Catherine Le Bihan

Jean-Charles Fontaine

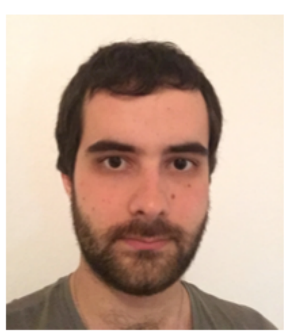
Jean-Laurent Agram

Éric Conte

Éric Chabert

Ulrich Goerlach

11 physicists,
5 phDs,
1 post-doc

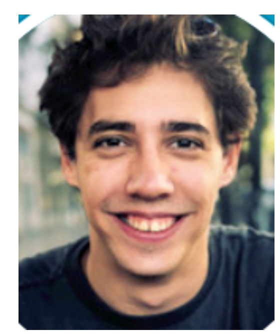


Guillaume Bourgatte

Natalia Emriskova

Clément Grimault

Douja Darej

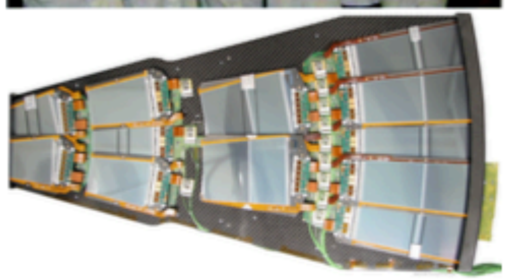


Dylan Apparu

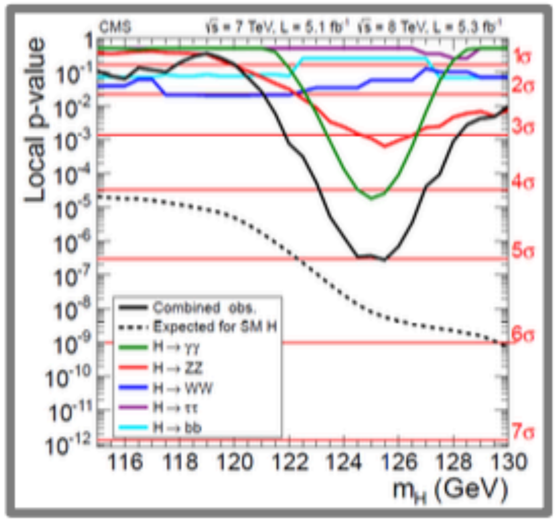
Emery Nibigira (post-doc)

Involved in many of the needed topics to contribute to CMS…

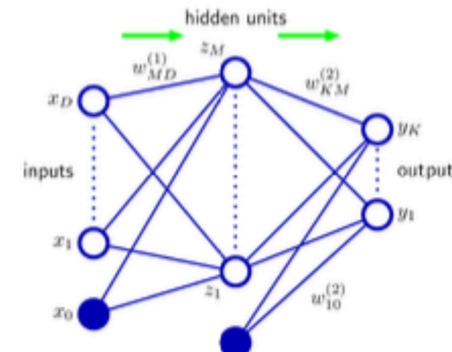
instrumentation



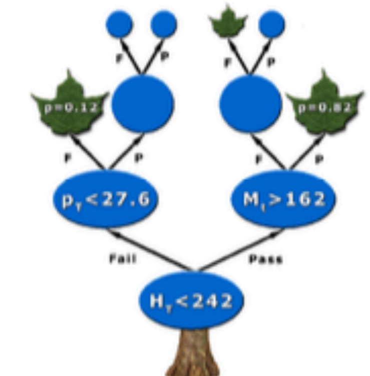
Statistical treatment



algorithms

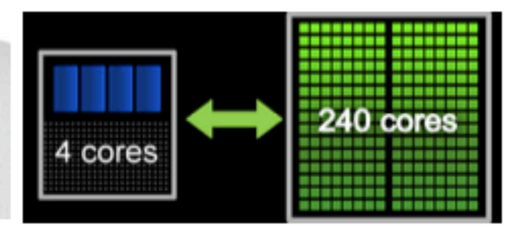


Neural Network



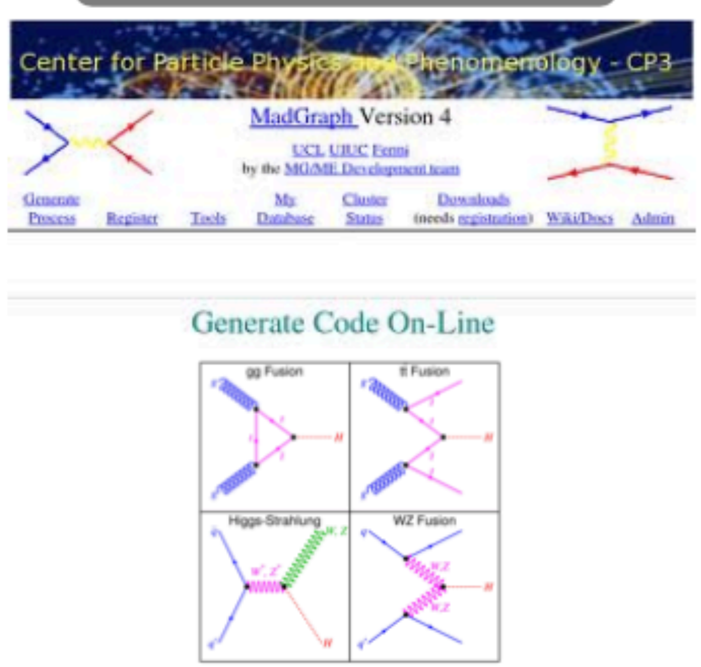
Boosted Decision Tree

Computing

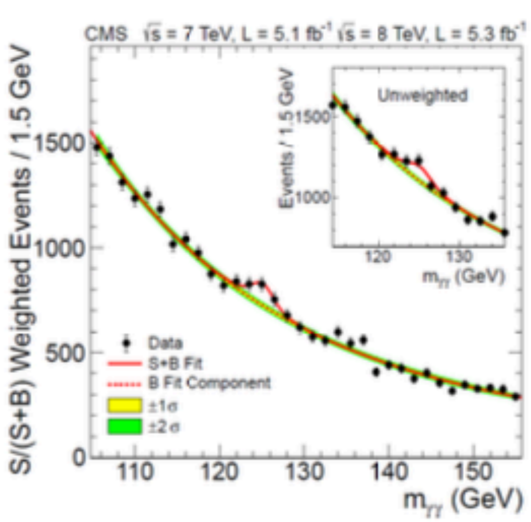


Grid

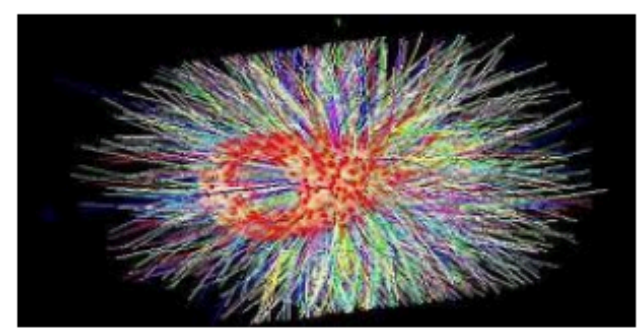
Phenomenology



Physics analysis



Simulation



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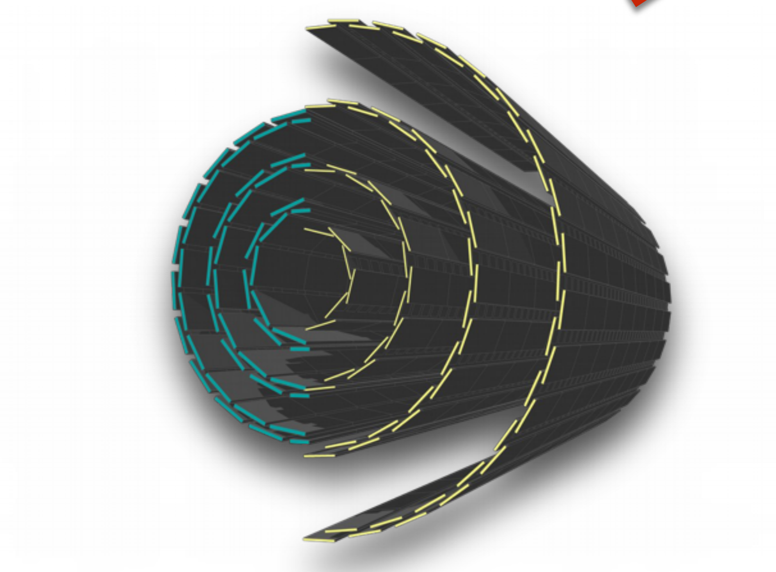
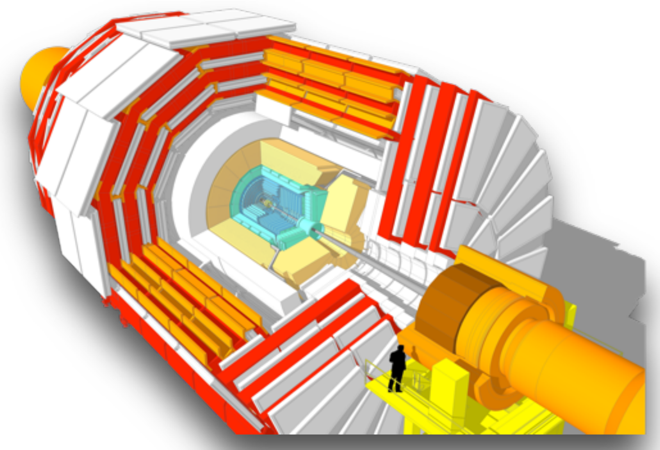
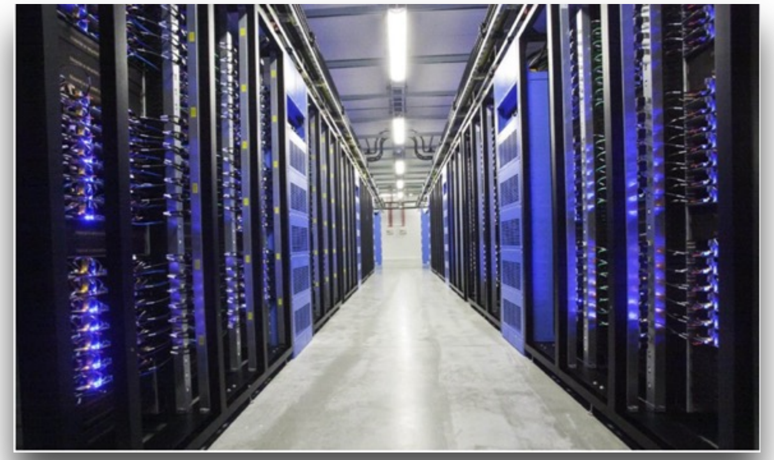
Upgrades



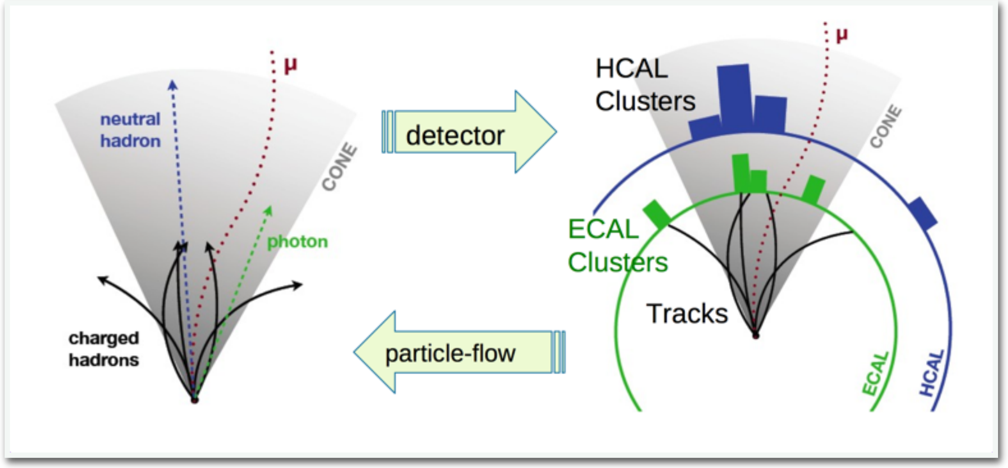
Detector



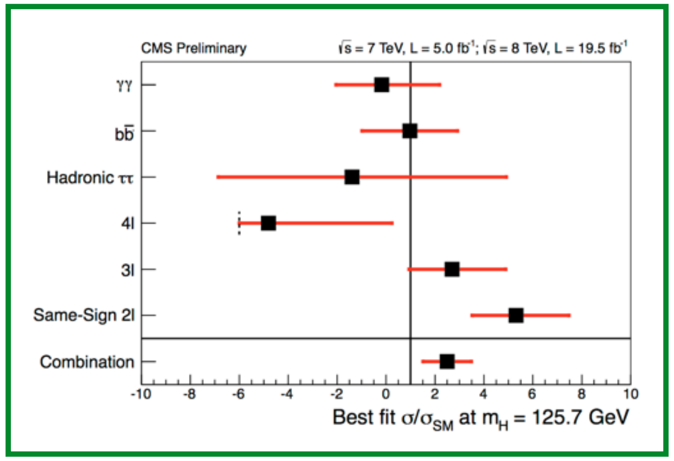
Data taking



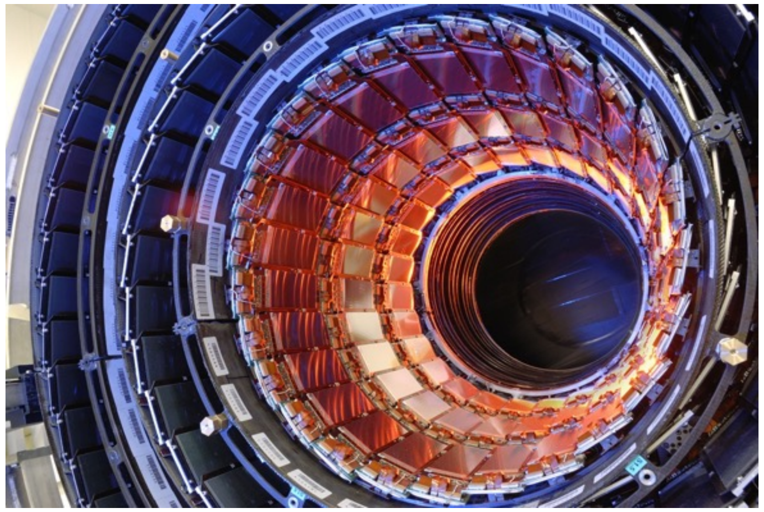
Particle/Event reconstruction



Analysis/Pheno



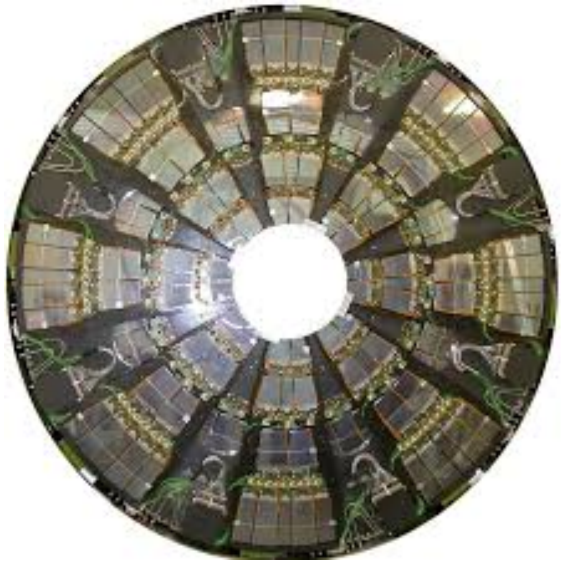
Detector: activities in silicon strip tracker

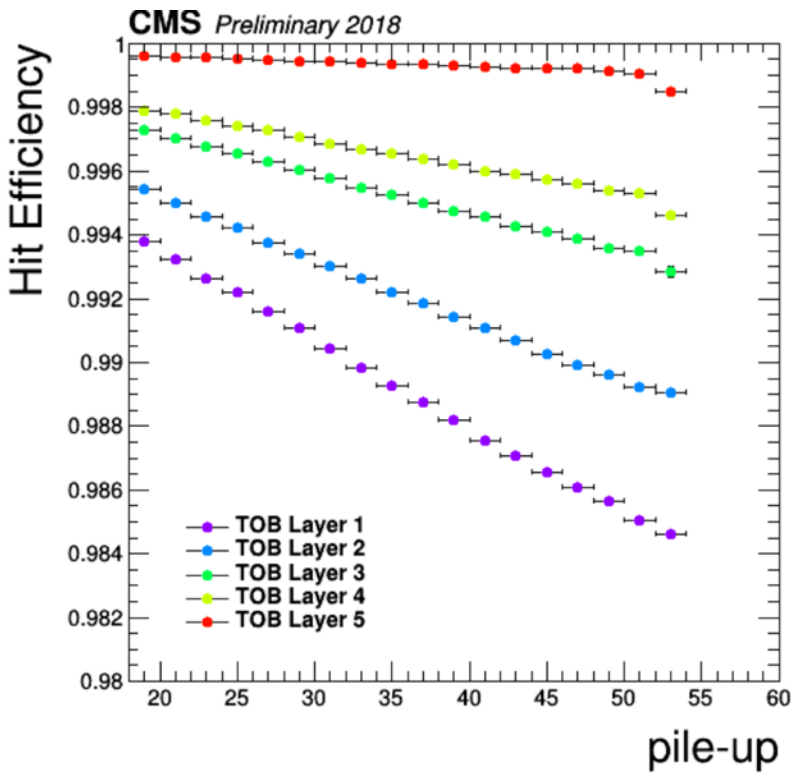


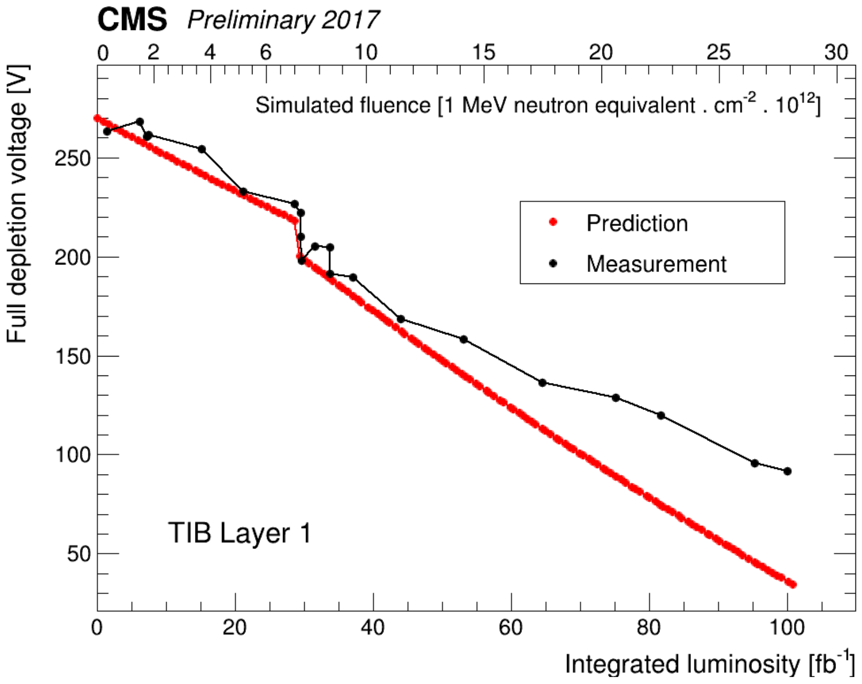
Historical involvement of IPHC

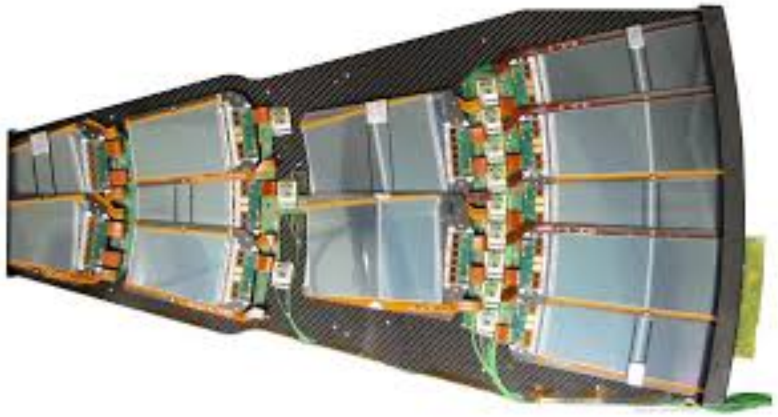
- R&D and construction of the current tracker
- Participation to the operations (data-taking, shifts, DQM, …)
- Monitoring and measurement of tracker performances

  efficiency, resolution, ageing studies, simulation, …

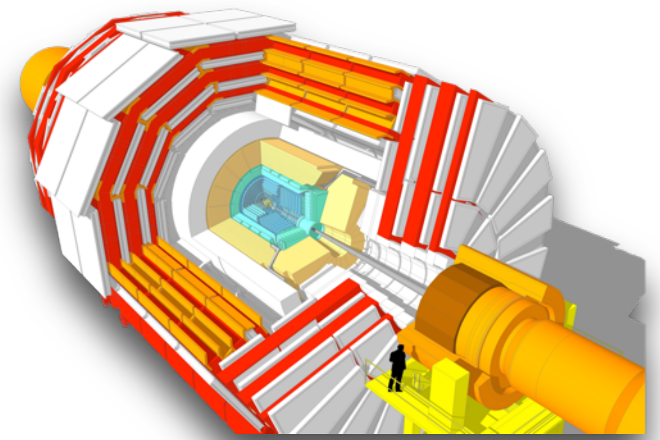




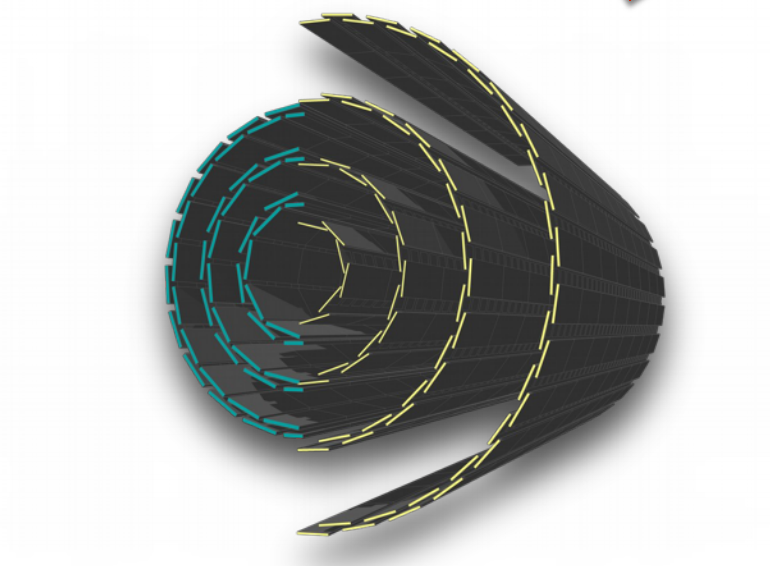




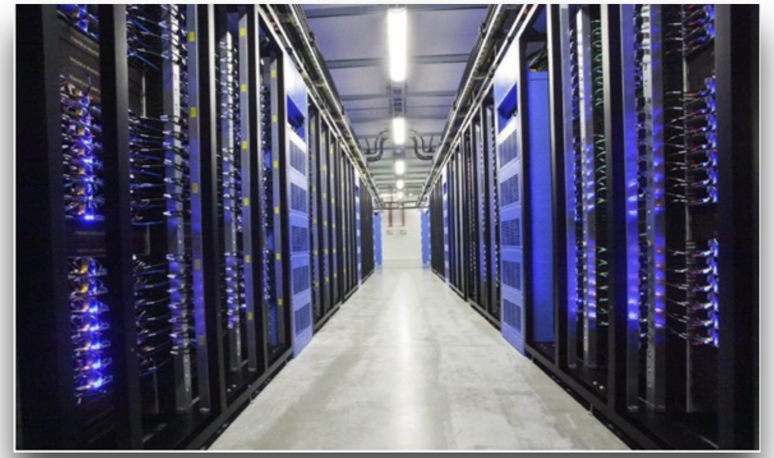
Detector



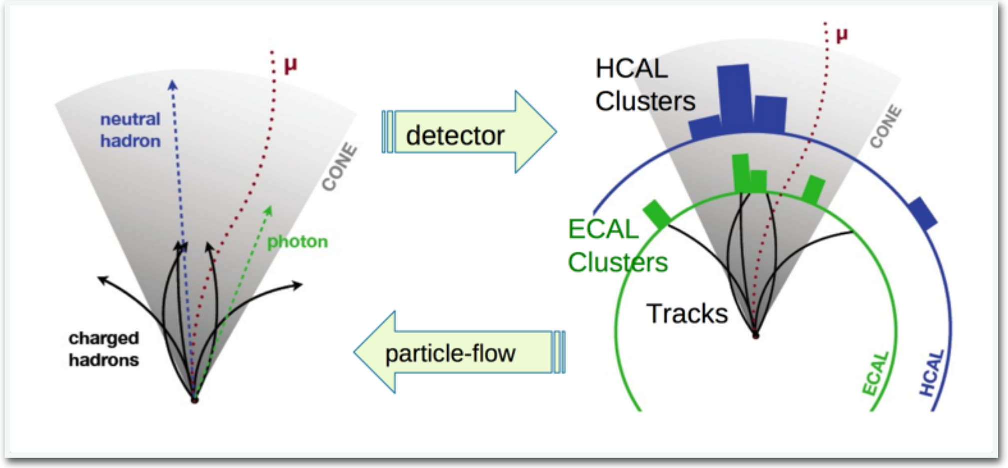
Upgrades



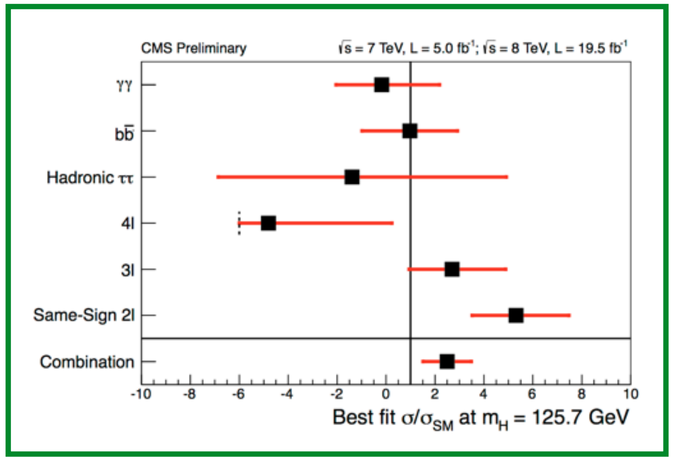
Data taking



Particle/Event reconstruction

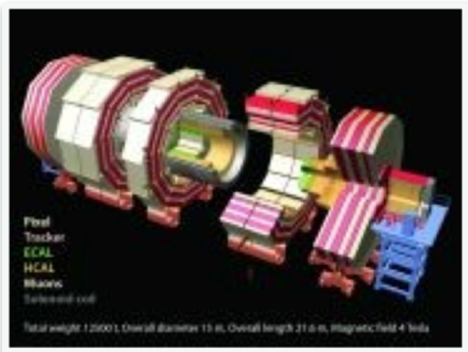


Analysis/Pheno

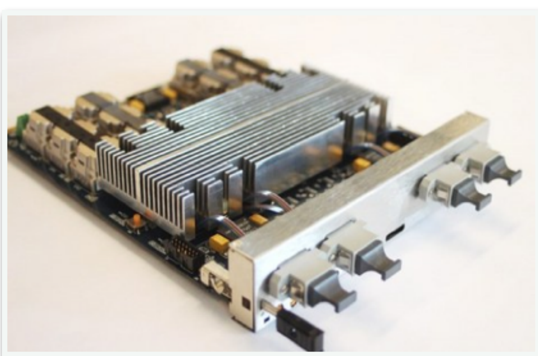


Trigger

CMS Strategy



L1 ↓ 40 MHz



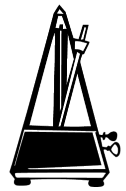
HLT ↓ 100 kHz

↓ 1 kHz

Storage

hardware

software



Purpose:

Selecting the most 1000 interesting physics events over 40 millions of bunch crossing occurring every second

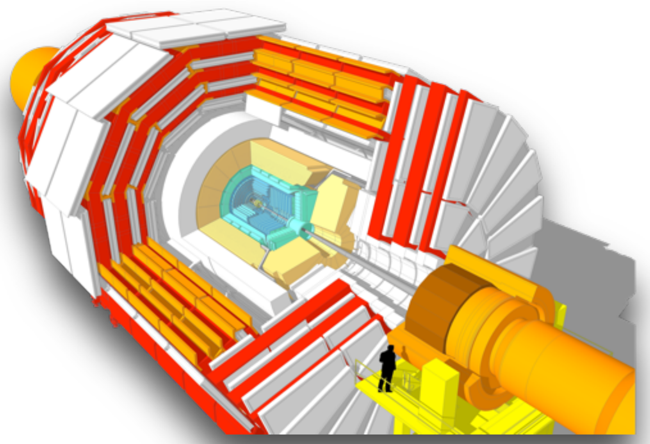
Parallel algorithm running in a CPU(/GPU) farm

Succession of
- Algo producing outputs
- Filters

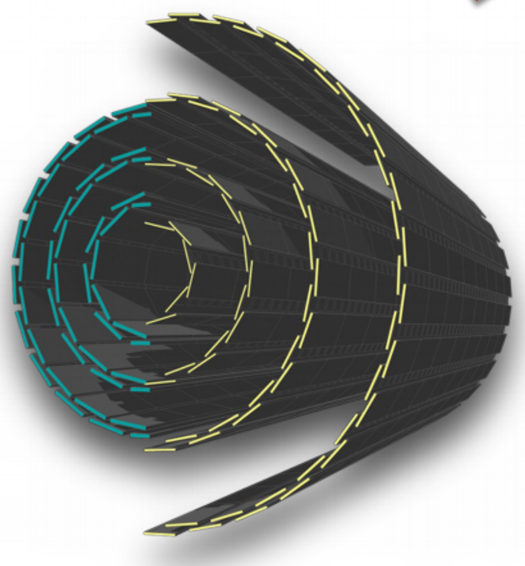
IPHC has been involved in running/optimizing **Machine Learning** algorithms to identify the presence **of b-quarks** (b-jets) in the events

Could be useful for channels such as H→ bb, t→Wb, …
or for BSM searches

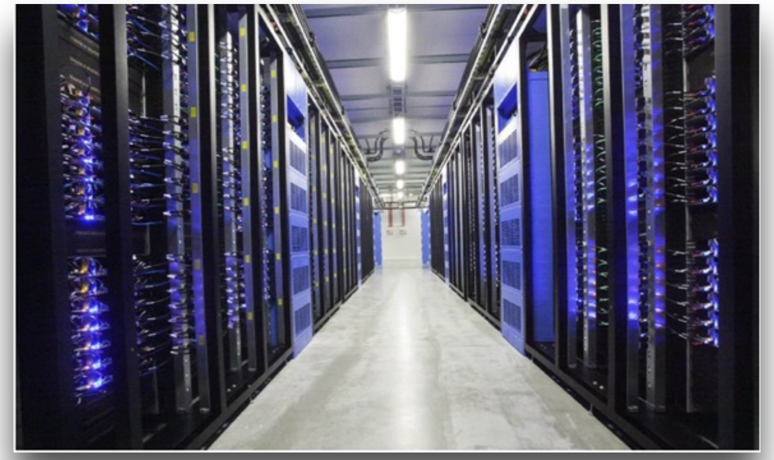
Detector



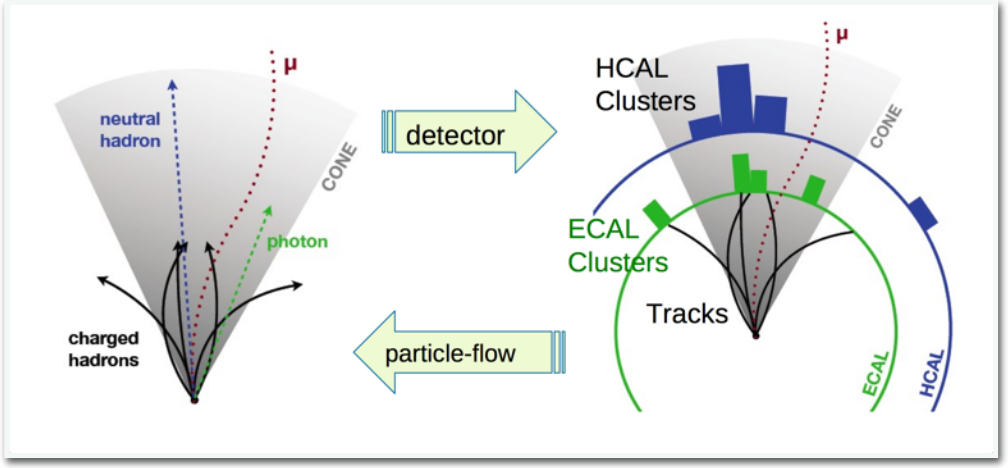
Upgrades



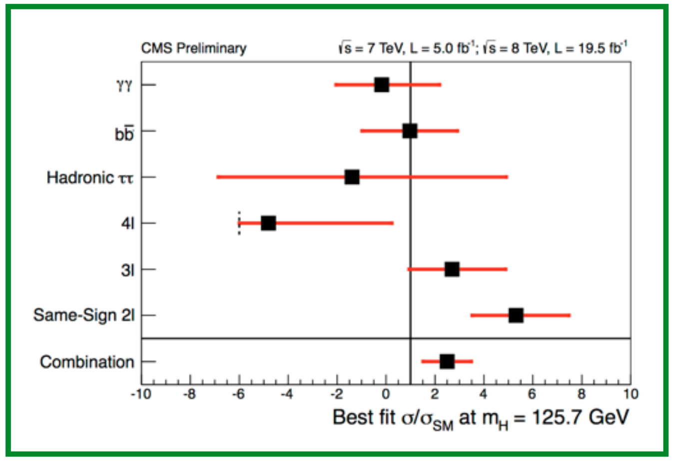
Data taking



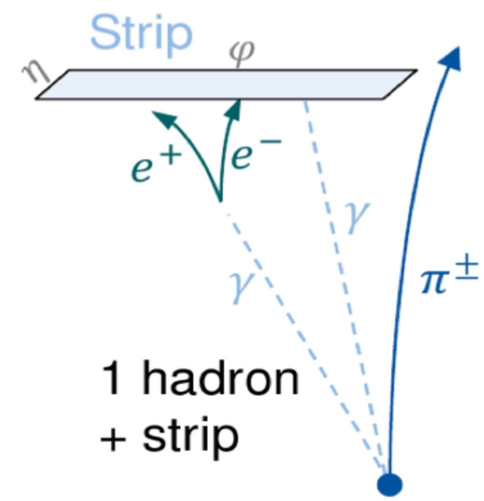
Particle/Event reconstruction



Analysis/Pheno



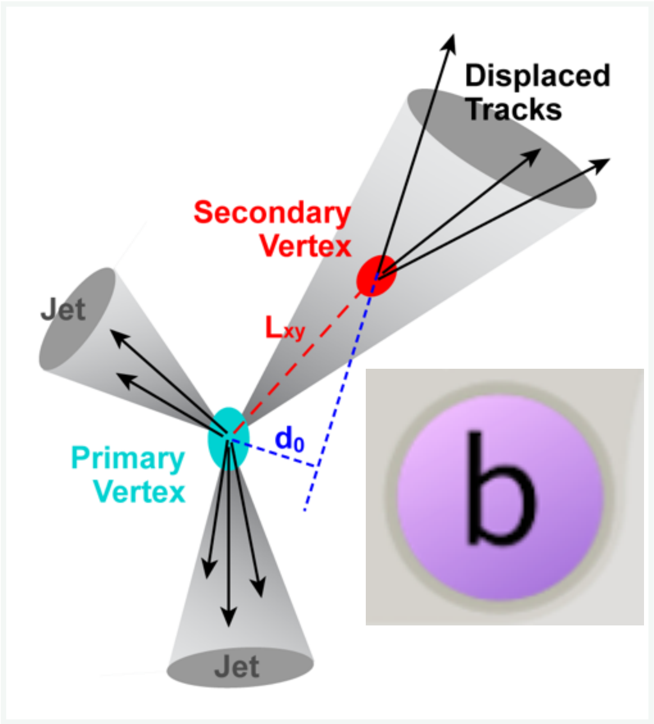
Particle reconstruction

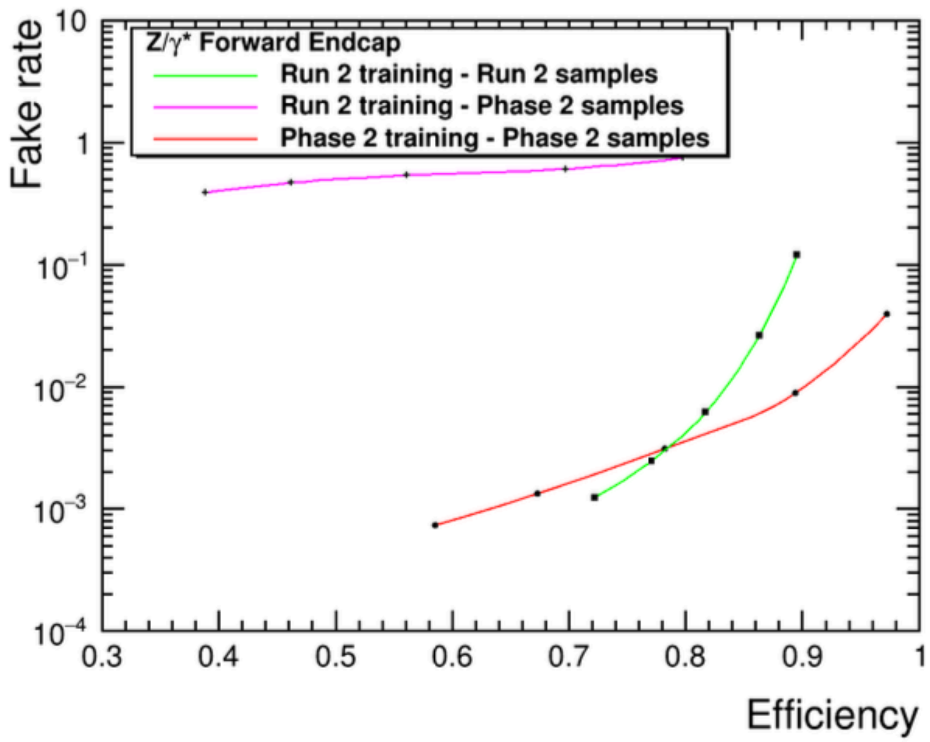


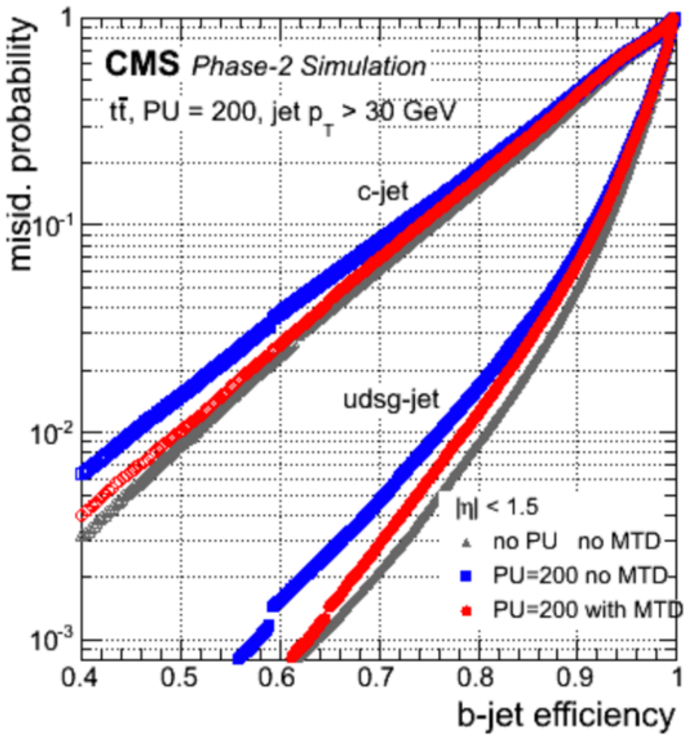
Historical involvement of IPHC in "jet" flavor identification:

b-tagging & hadronic tau-tagging

- Algorithm optimization
- Commissioning in data
- Performance measurements
- Upgrade preparation



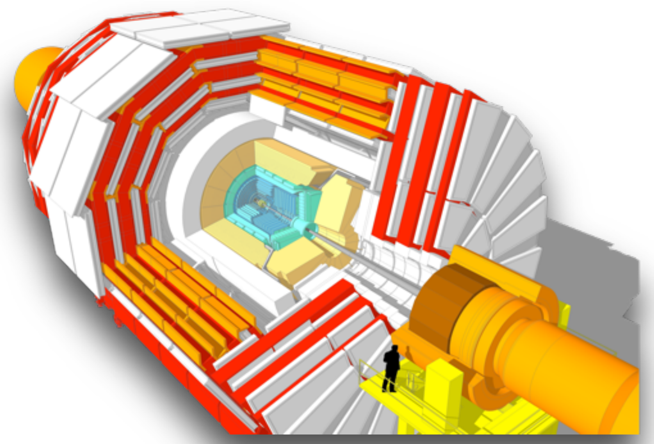




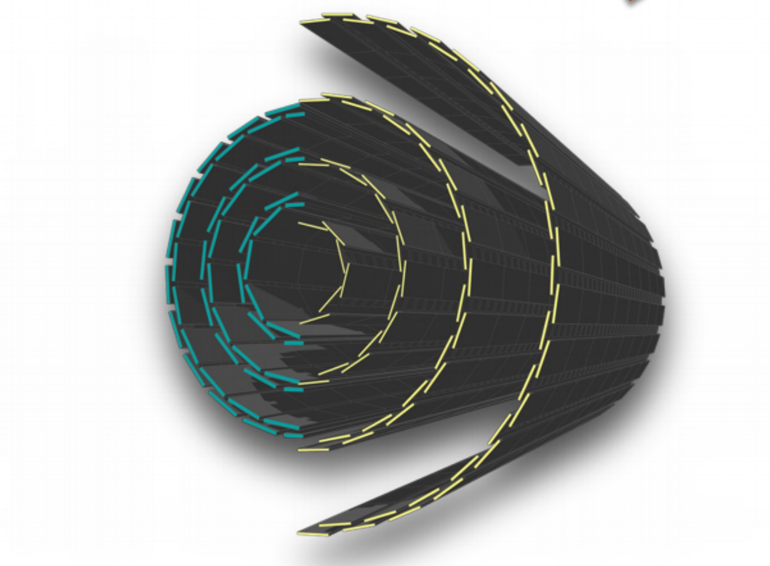
12 boosted decision trees to separate taus and electrons

Performance with timing detector (HL-LHC) included…

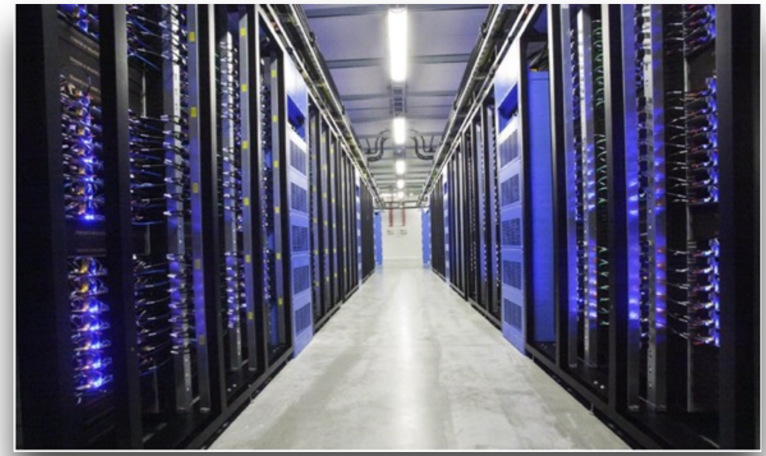
Detector



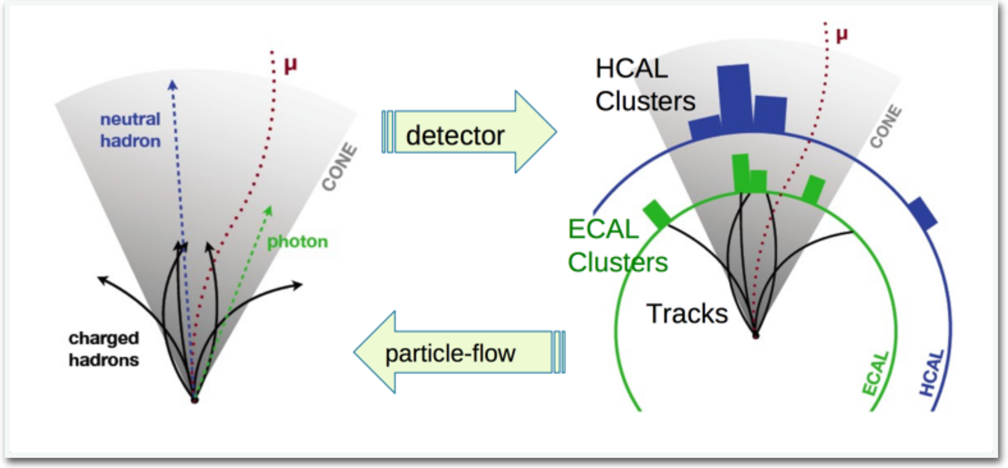
Upgrades



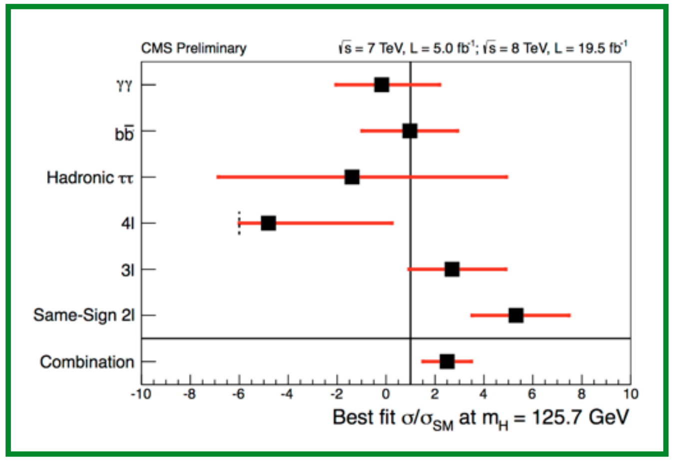
Data taking



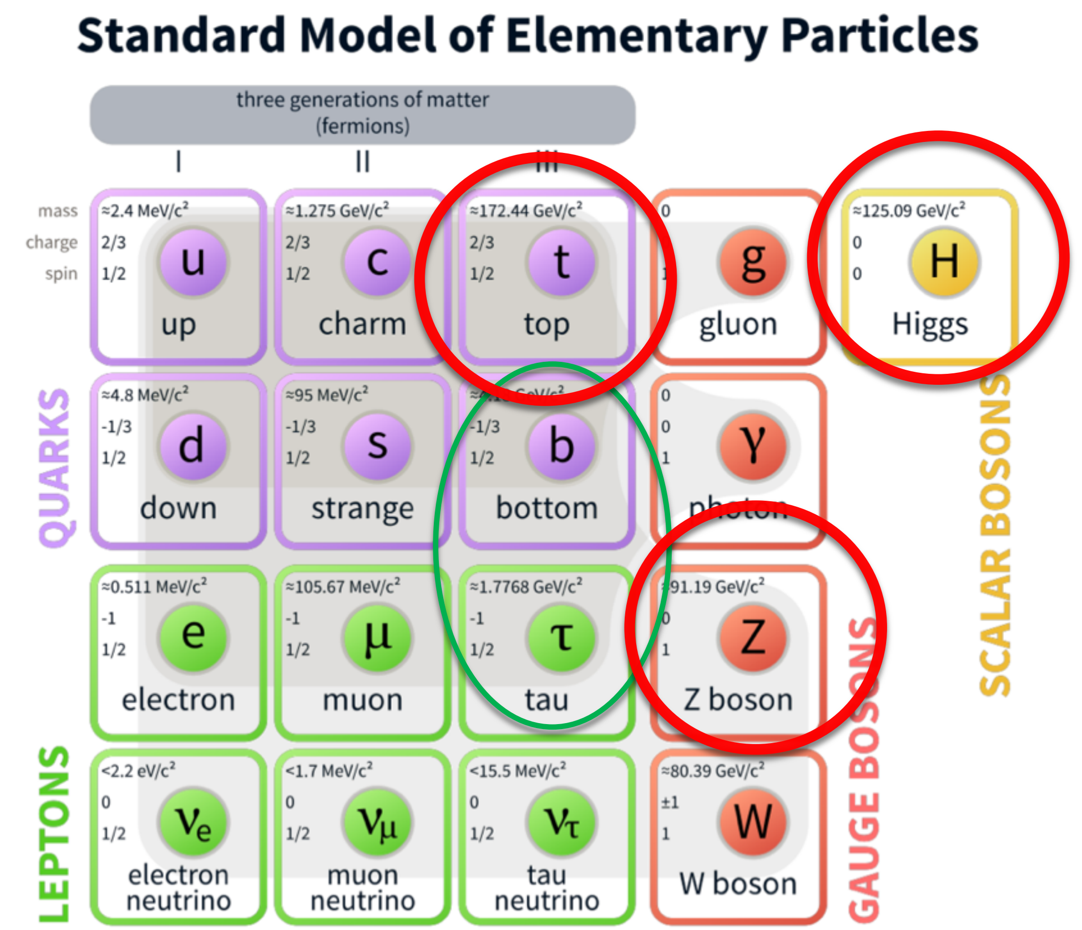
Particle/Event reconstruction



Analysis/Pheno



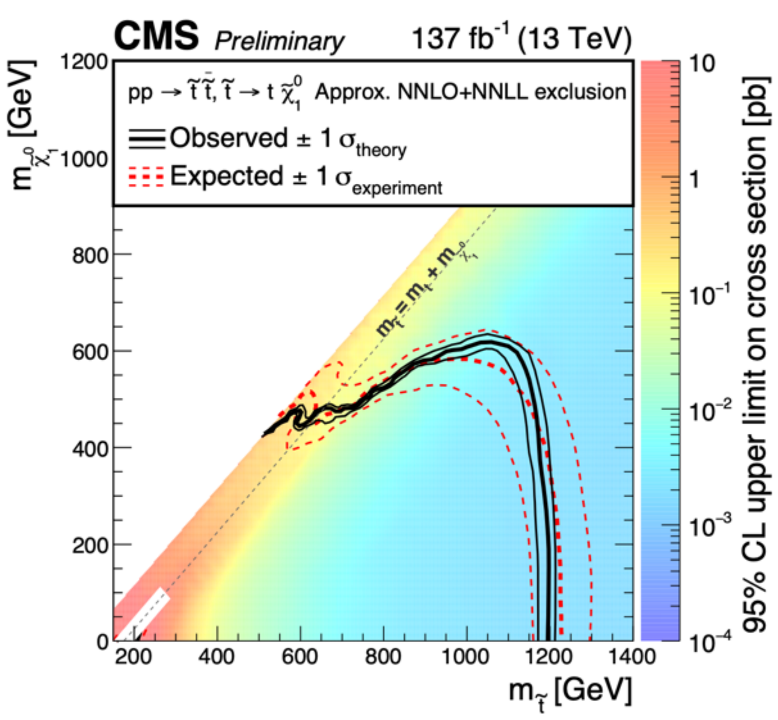
Analysis

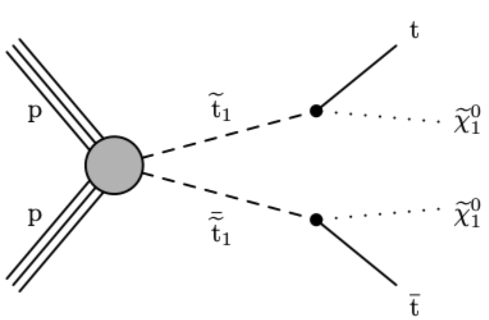


Precise SM measurements

- Top physics (measurements and searches)
- Higgs physics (H→ $\tau\tau$ – CP properties)
- Z boson et sin(ϑ_{EW}) (Z→ $\tau\tau$)

SUS-19-009





Search for new physics

- Mono-top
- SUSY searches: stop pair produced
- Long-lived top
- Long-lived massive charge particles

Phenomenology

Expertise logiciel

FeynRules,
MadGraph_MC@NLO,
Pythia,
Delphes

Framework d'analyse
MA5 (*MadAnalysis 5*)
depuis 2012

MAD Analysis 5

Développement

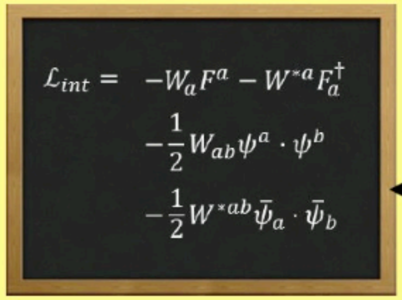
1ère publi MA5,
CPC 184 (2013) 222-256
192 citations

1ère école internationale
MadAnalysis 5
en Corée (2017)

Collaboration internationale
~ 100 analyses publiées
~ 20 analyses ATLAS/CMS réimplémentées

Etudes phénoménologiques

Model building



Phéno ménologie

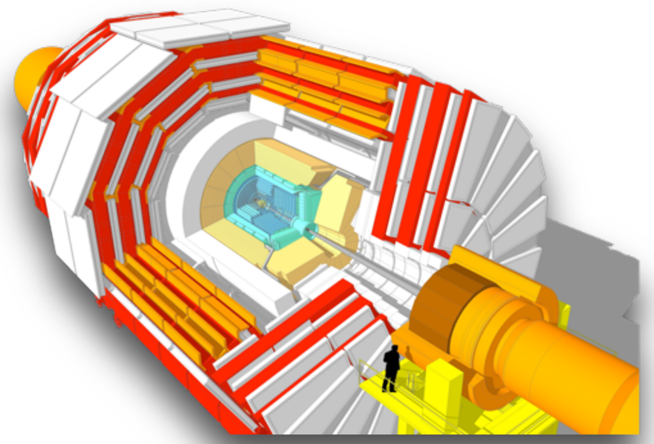
Physique expérimentale

- **Etude de sensibilité**
  Recherche de FCNC dans le secteur du top (Z, g, γ,H)
  Recherche de la signature monotop)
  Recherche de vector-like quarks
- **Réinterprétation de résultats**
  Contraintes sur un modèle top - matière noire

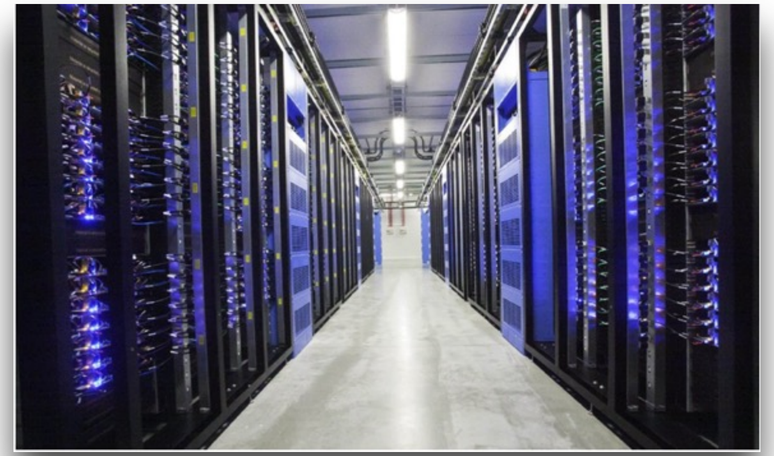
Publi Monotop hadronique
PhysRevD 84 074025
51 citations

15 publications
depuis 2012

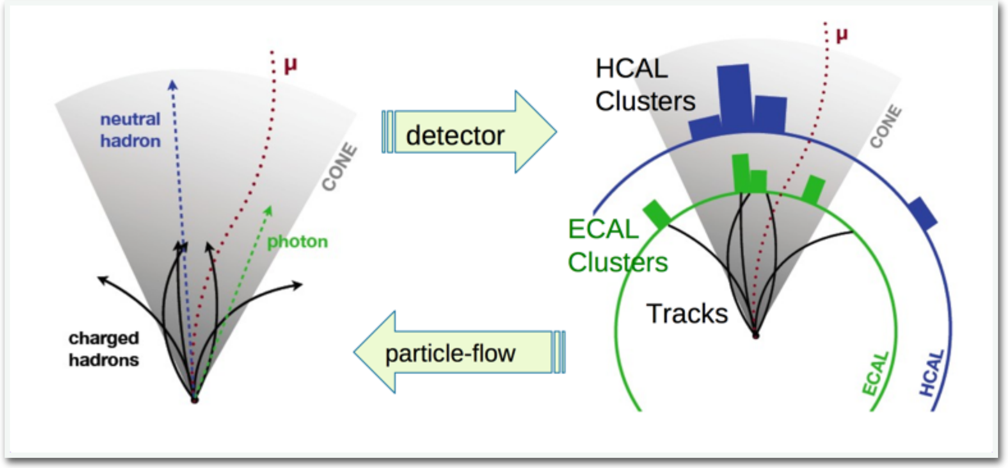
Detector



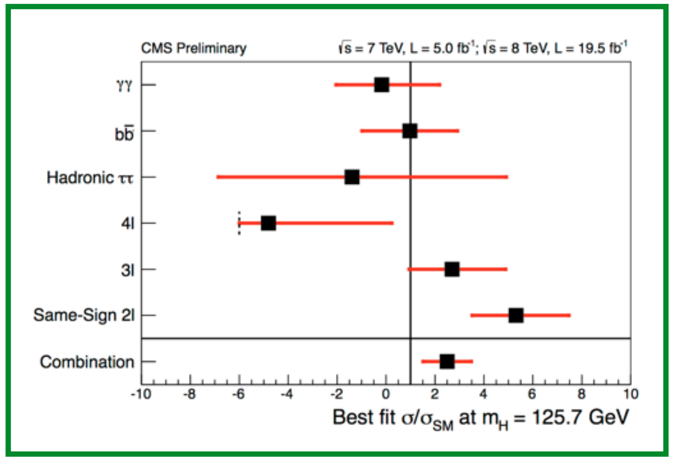
Data taking



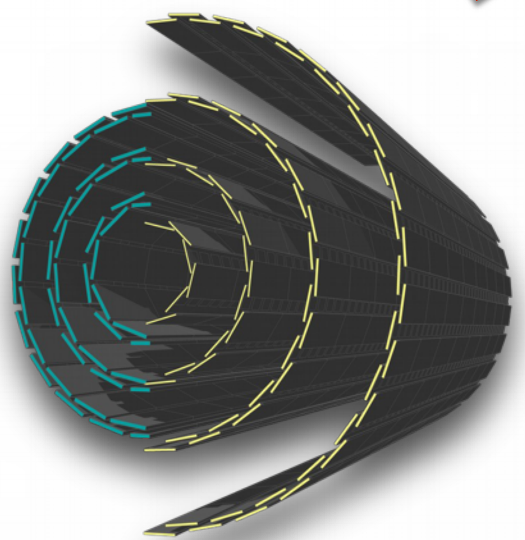
Particle/Event reconstruction



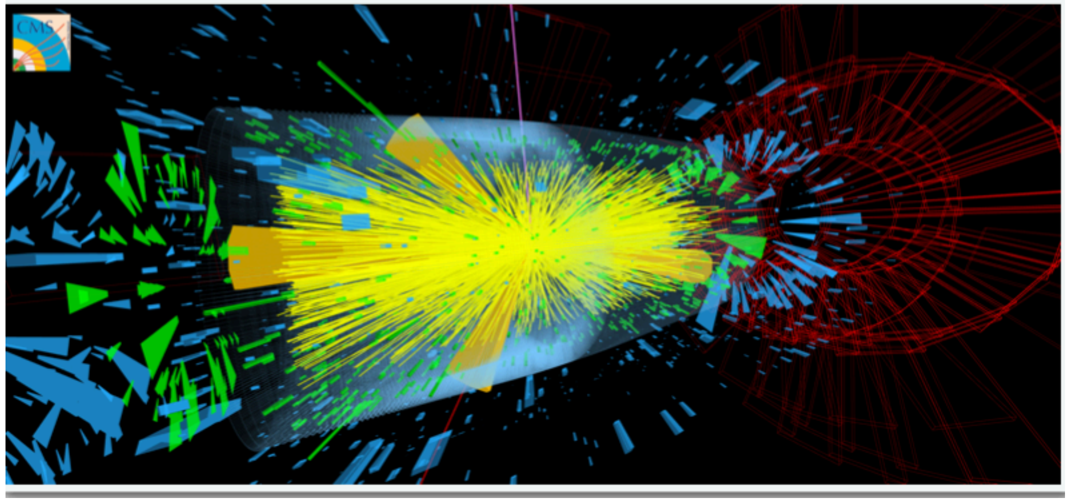
Analysis/Pheno



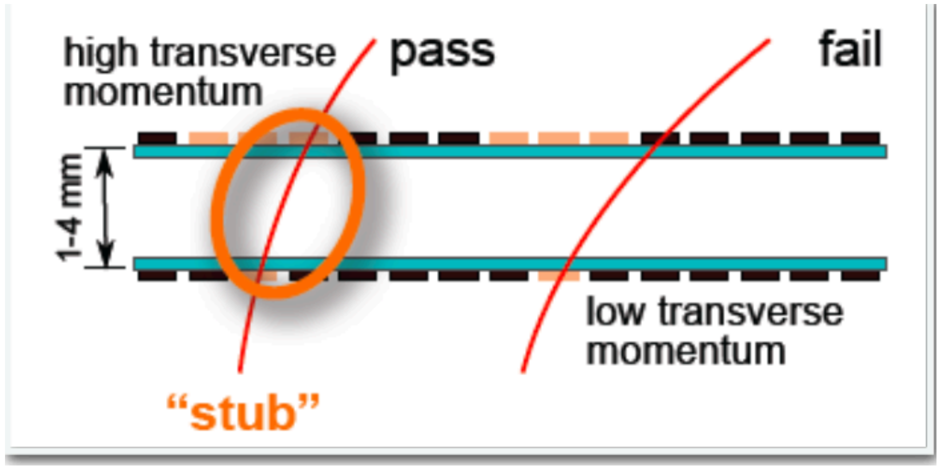
Upgrades

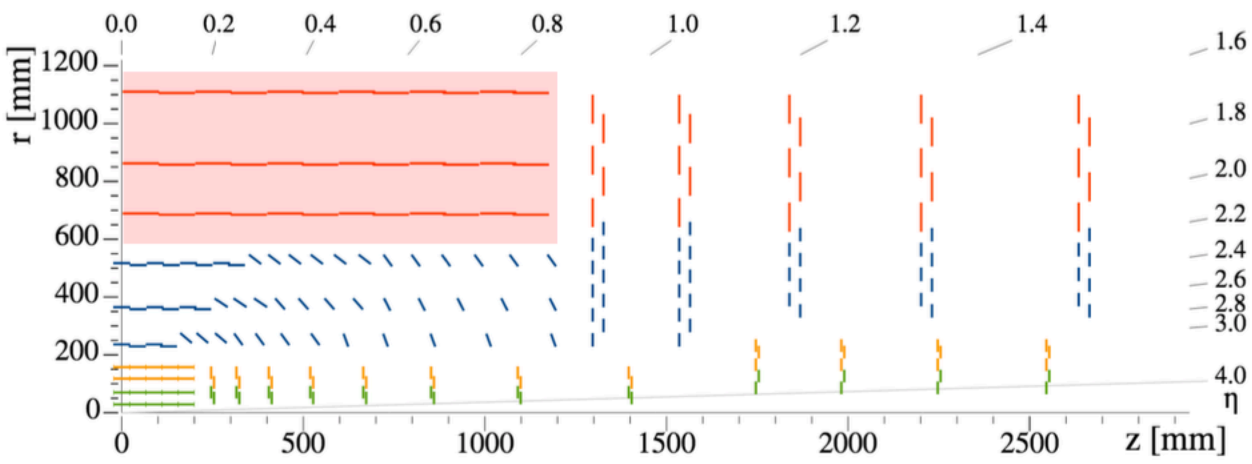


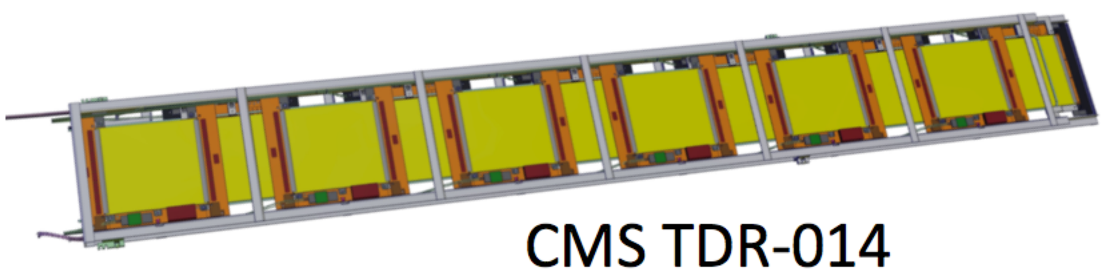
A new tracker for HL-LHC



→ Radiation tolerant
→ High granularity
→ With less material, extended acceptance
→ To be used at trigger level and at high pile-up (200)





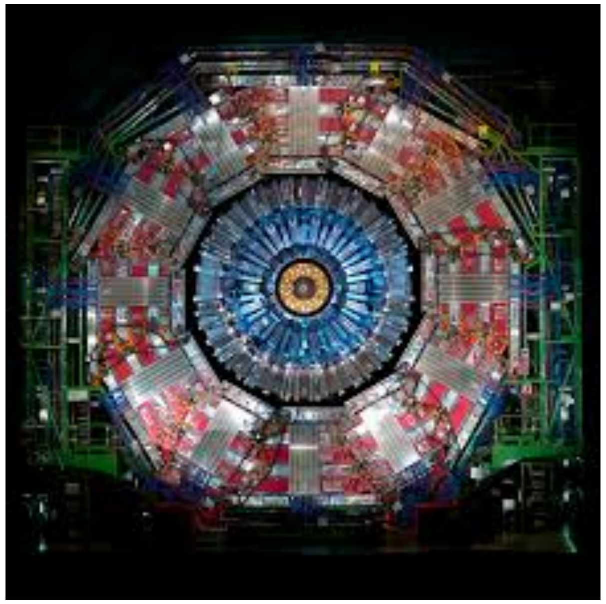


CMS TDR-014

@ IPHC:

- Data acquisition system
- TB2S mechanics design (in red on the picture)
- Module integration in ladders, assembling
- Dedicated Cyrcé beam line, beam tests
- TB2S integration @ CERN - commissioning

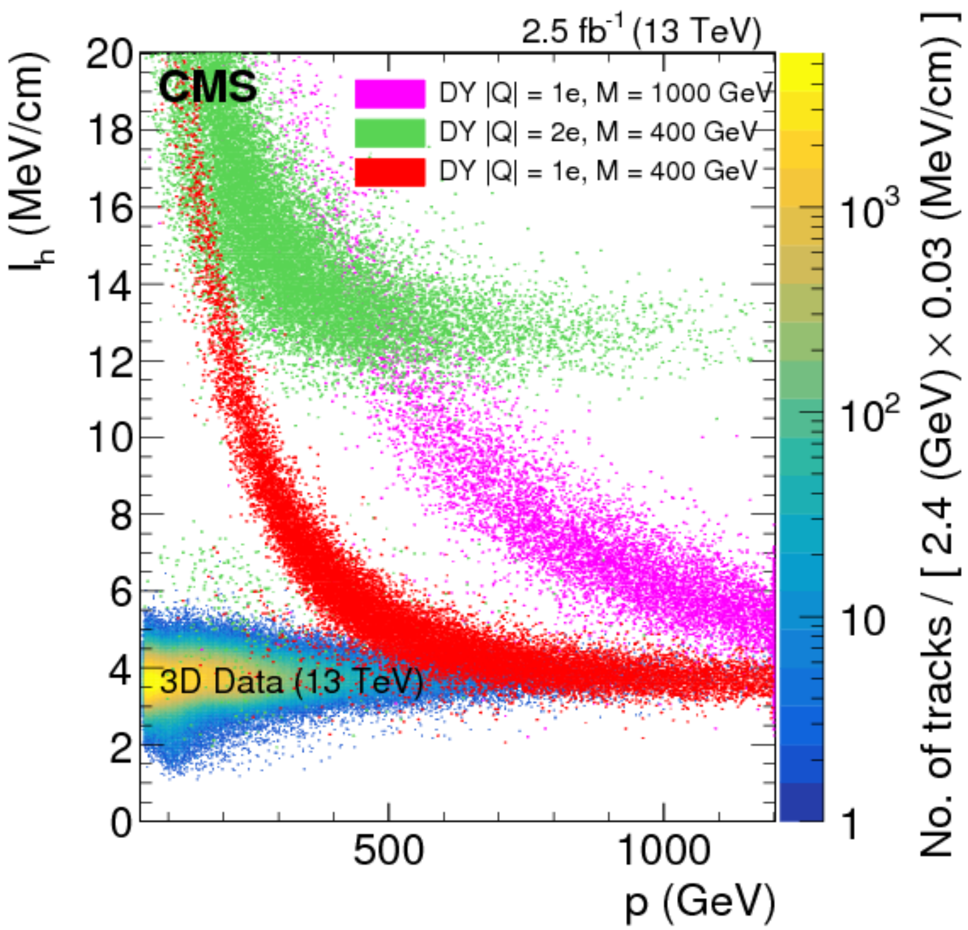
Outline



Introduction to CMS collaboration/physics

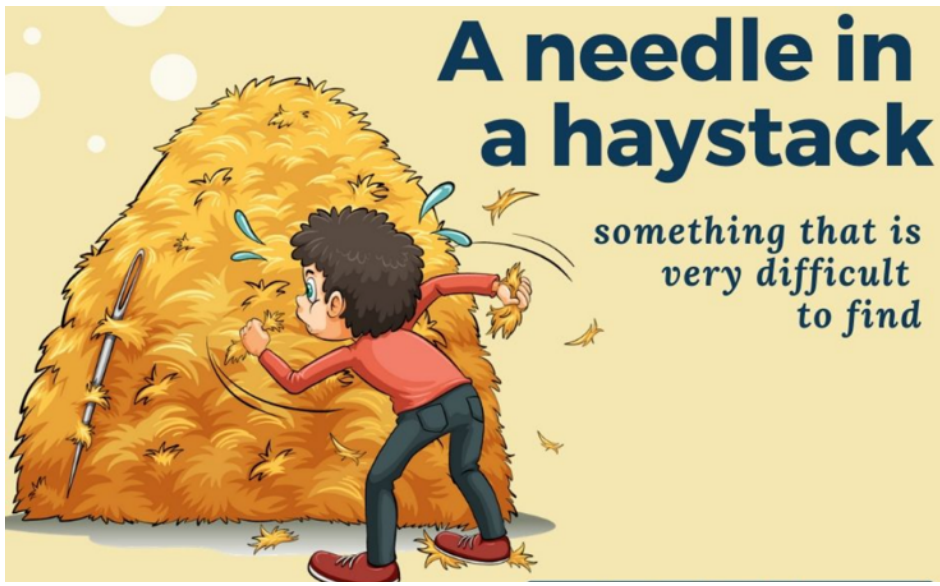
Activities at IPHC

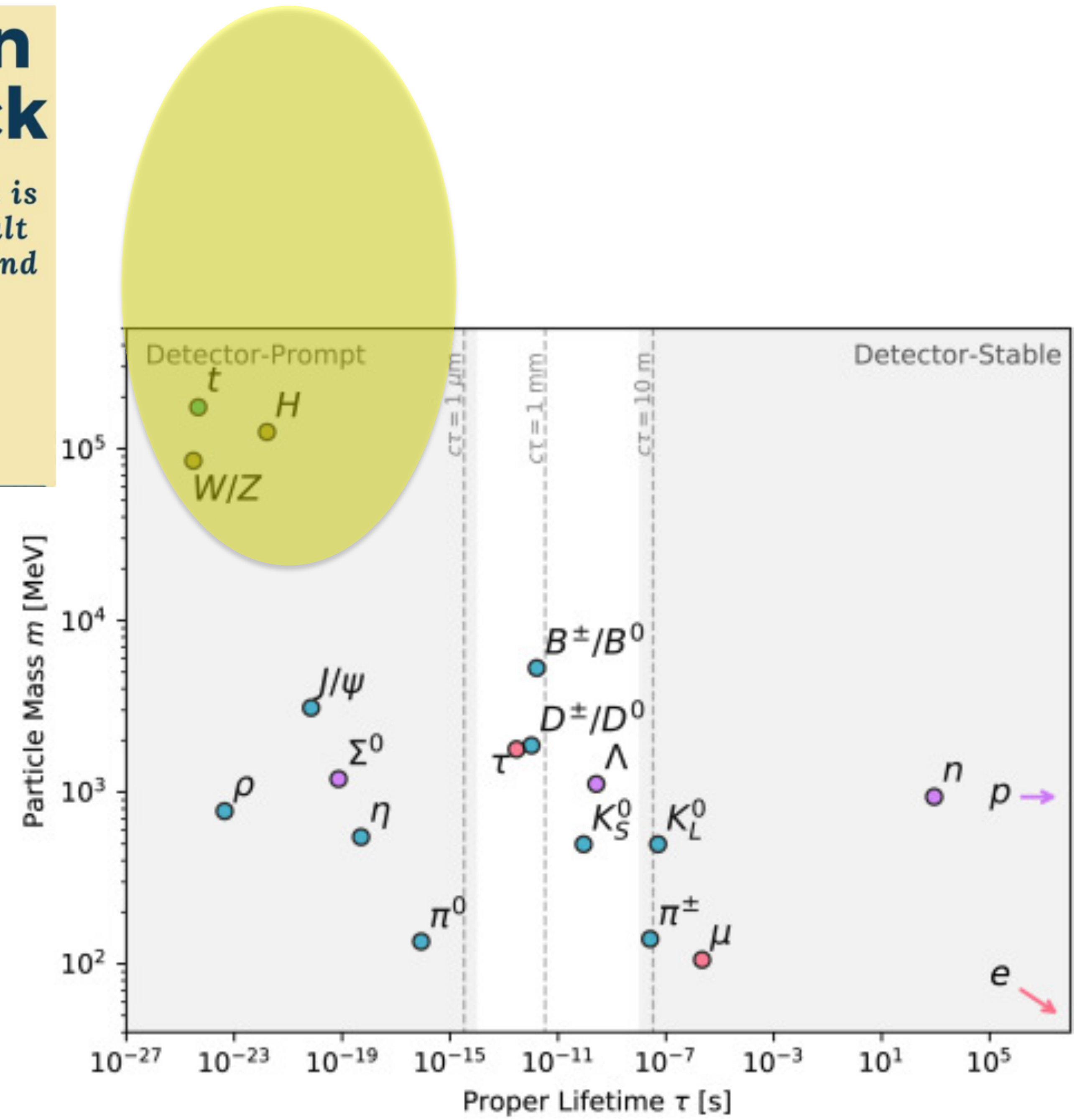
Intership/PhD subject



Search & Lifetime

Most conventional searches focussed on high mass *promptly decaying particle*

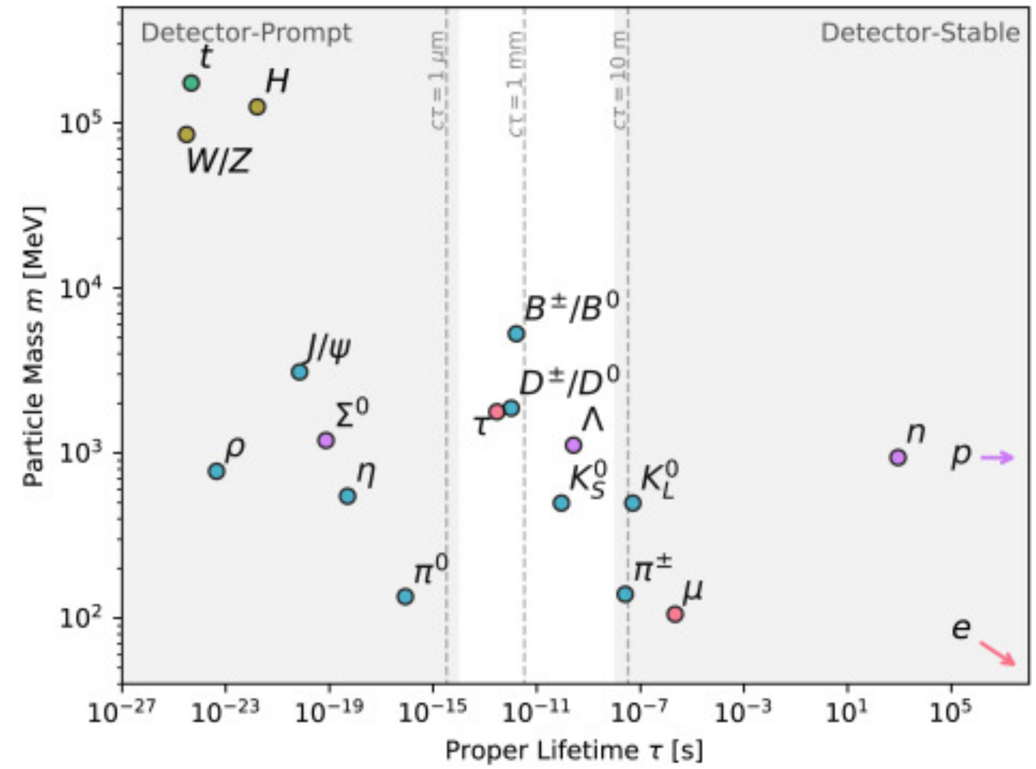




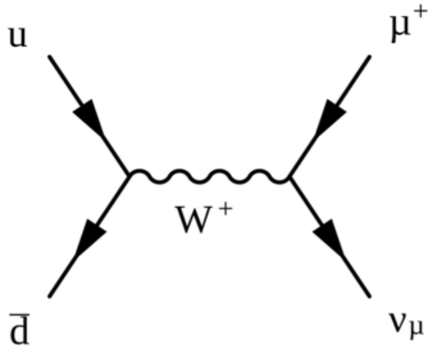
Search & Lifetime

Many particles in SM are long-lived.

Let's take the example of the charged pion



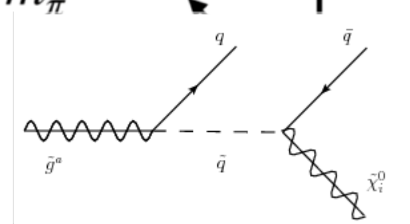
e.g. $\pi^\pm \rightarrow \mu^\pm \nu_\mu$ ($c\tau_0 \sim 7.8$m)



small coupling

$$\frac{1}{\tau} = \frac{f_\pi^2 |V_{ud}|^2}{256\pi m_\pi} \left[\frac{g^2}{M_W^2} \frac{m_\mu}{m_\pi} (m_\pi^2 - m_\mu^2) \right]^2$$

heavy mediator



Due to several mechanisms, lifetime can be large.

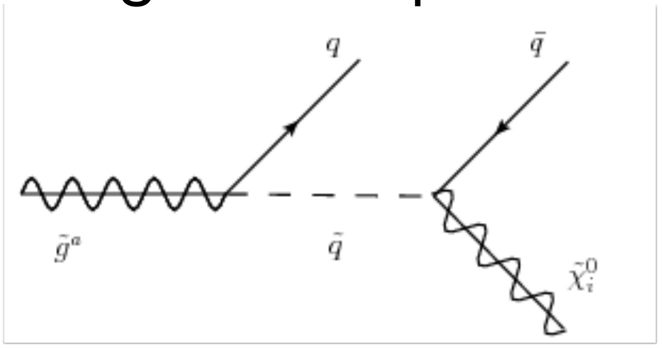
Same mechanisms can also occur in BSM

The absence of discovery could be explained by several hypothesis, including that the new particles have large lifetime

Increasing interesting in looking for long-lived particles in HEP

Search & Lifetime

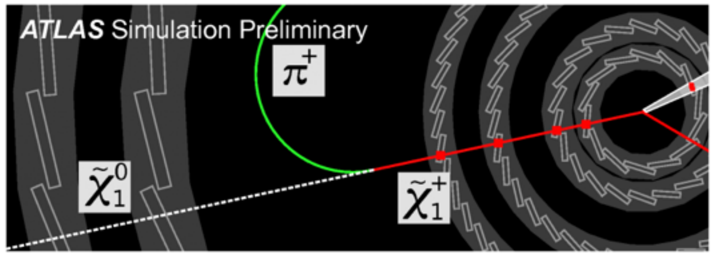
I) Search for gluino in split SUSY



$$c\tau \approx 100\mu m \times \left(\frac{m_{\tilde{q}}}{10^3\,\mathrm{TeV}}\right)^4 \times \left(\frac{\mathrm{TeV}}{m_{\tilde{g}}}\right)^5$$

Long-lived gluino will form bound-states: R-hadrons

II) Search for chargino/neutralino almost degenerated



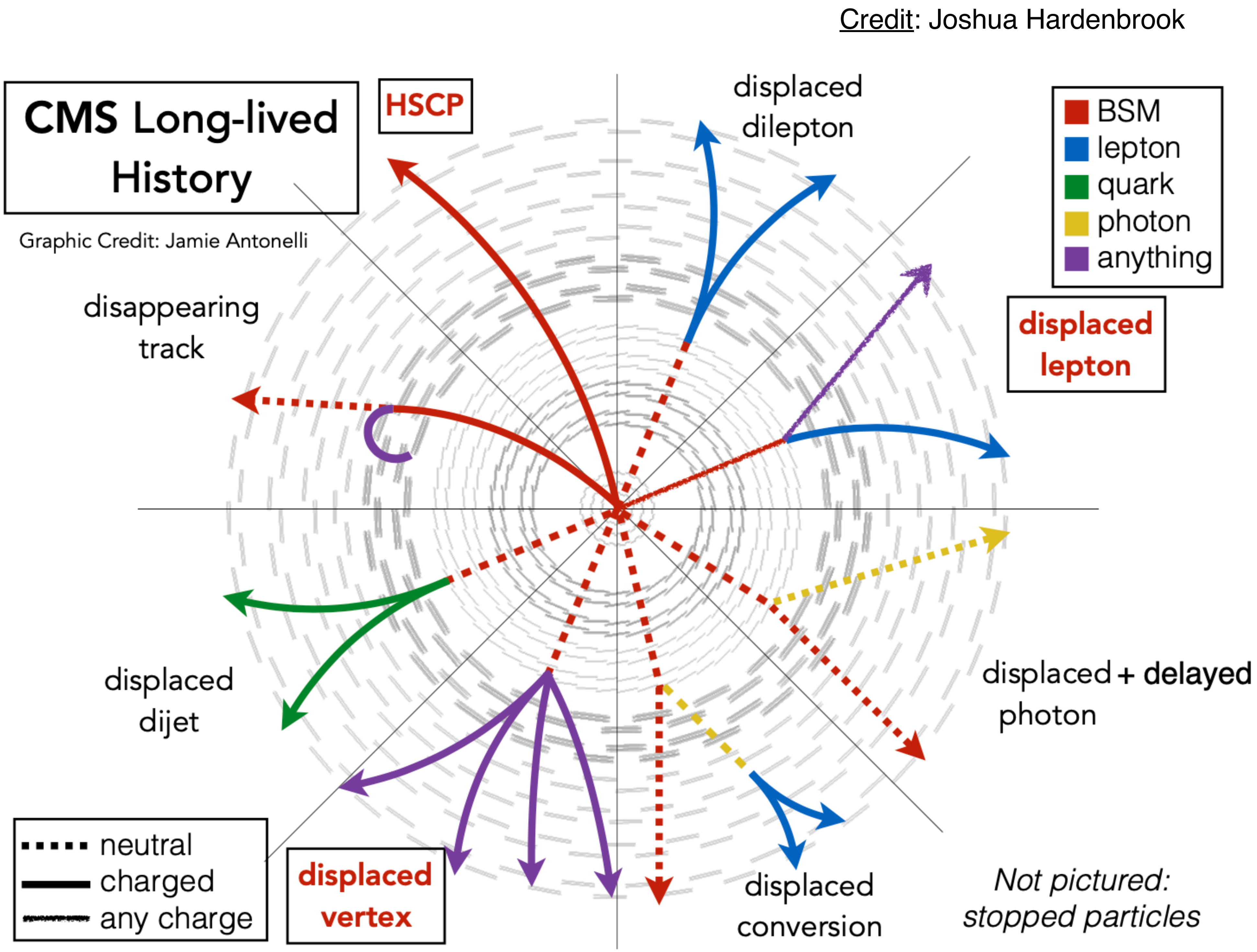
$$c\tau \approx 0.7\,\mathrm{cm} \times \left(\frac{\Delta m}{340\,\mathrm{MeV}}\right)^3$$

Experimentally, the signature will depends notably on the lifetime ….

Overview of experimental signature for Long-Lived Particles

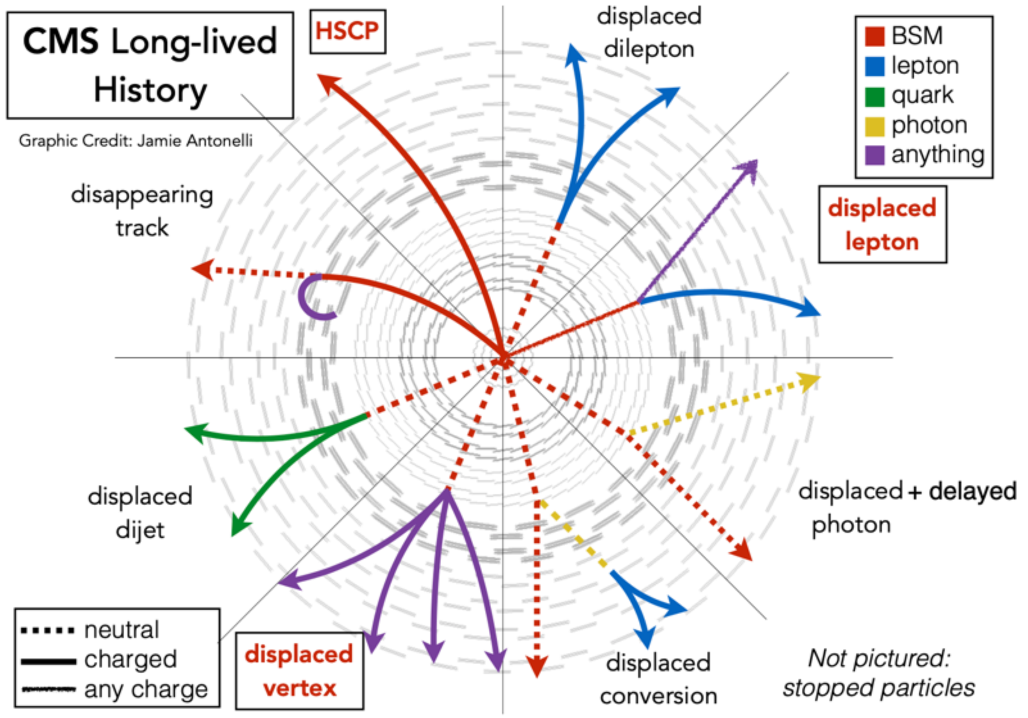
Experimental signature depends on:

- Lifetime
- Electrical charge
- QCD charge
- Decay
- Mass



Aim is to cover as much as possible all hypotheses …

Search for *Very* Long-Lived **Charged** Particles

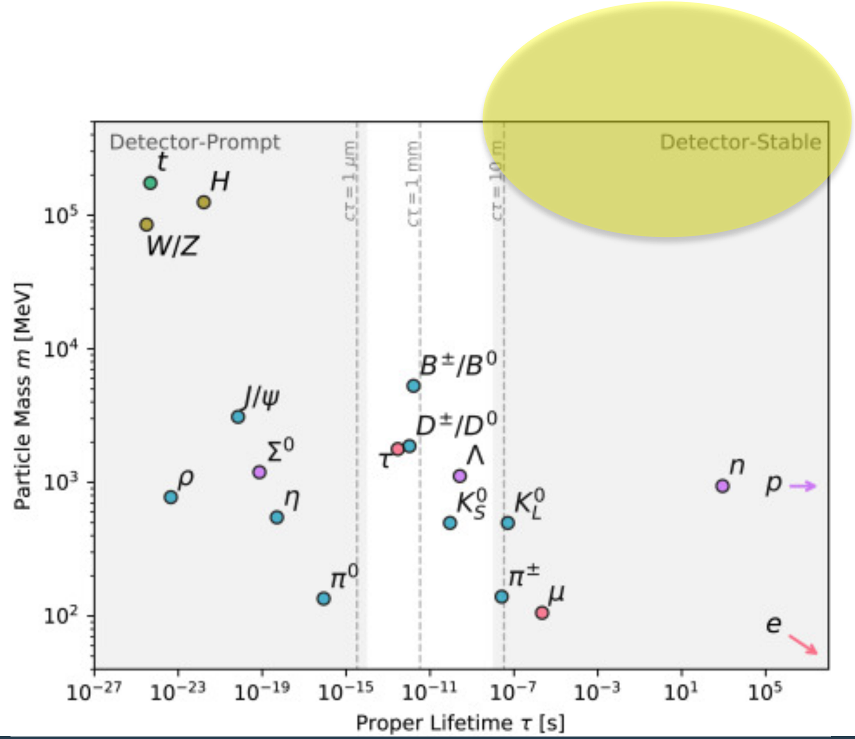


The targeted signature:

Heavy (mass> 100 GeV)
Stable (lifetime > 10 ns) – stable at detector stable
Charged (Q≠ 0 - could be Q ≥1 or even ≥ 1/3e)
Particle (could also be QCD-charged → R-hadron)

This strategy has many advantages and has a unique way to detect some possible new particles:

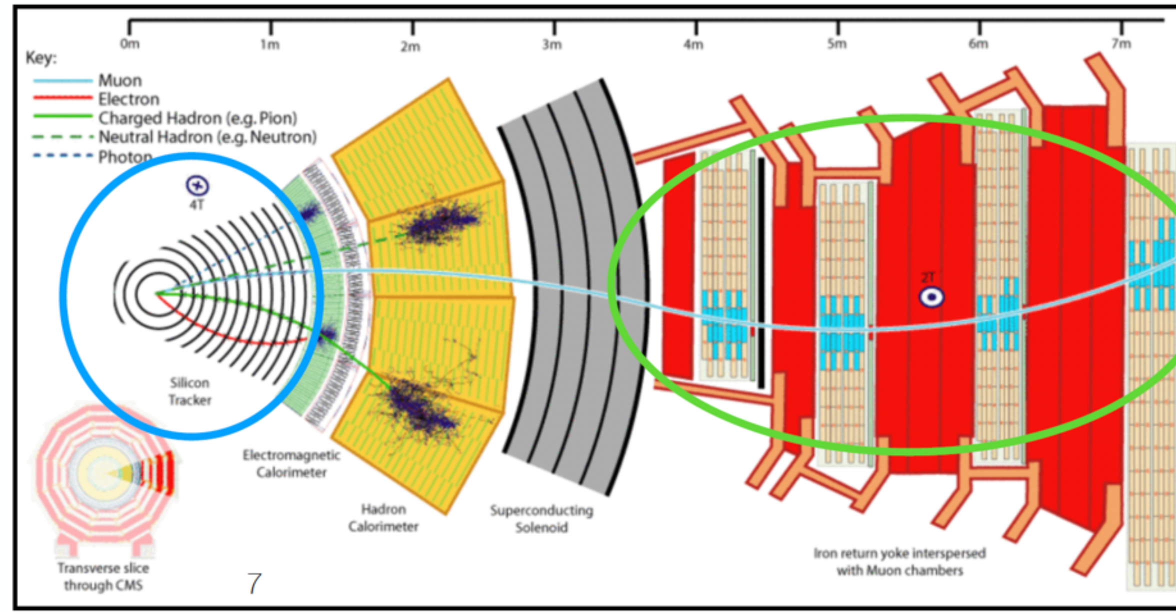
- This search is agnostic regarding the possible **decay**
- Can be sensible for many **charge** hypothesis (but not too low) as Eloss ∝ Q^2
- Sensible to large **range of lifetime**

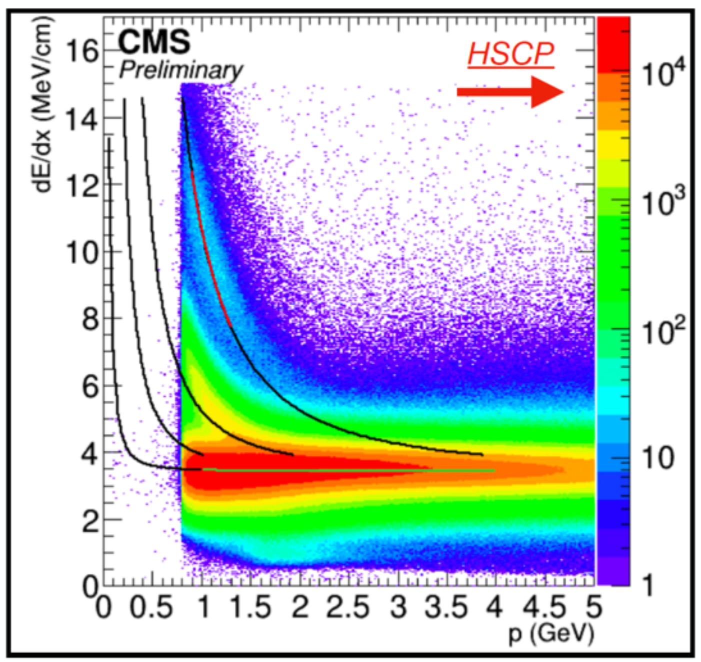


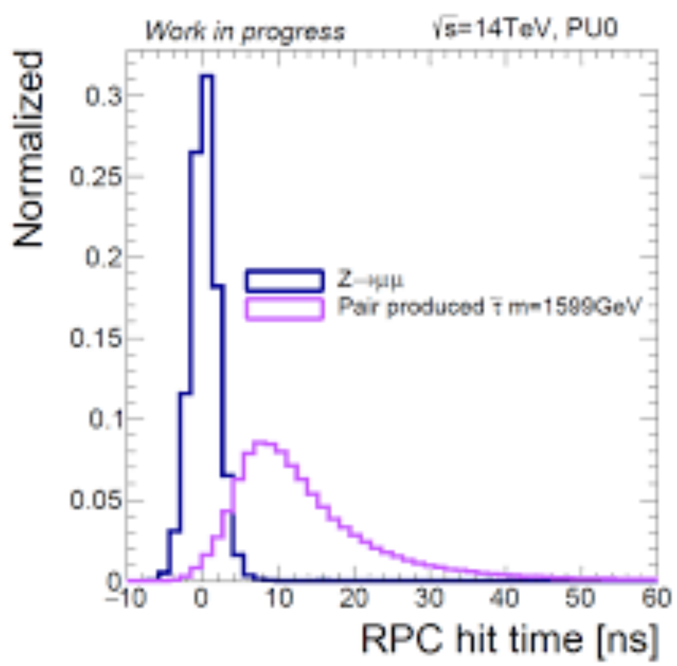
Search for *Very* Long-Lived **Charged** Particles

At the LHC, such a massive particle will be produced with a low velocity (<0.9 c), thus

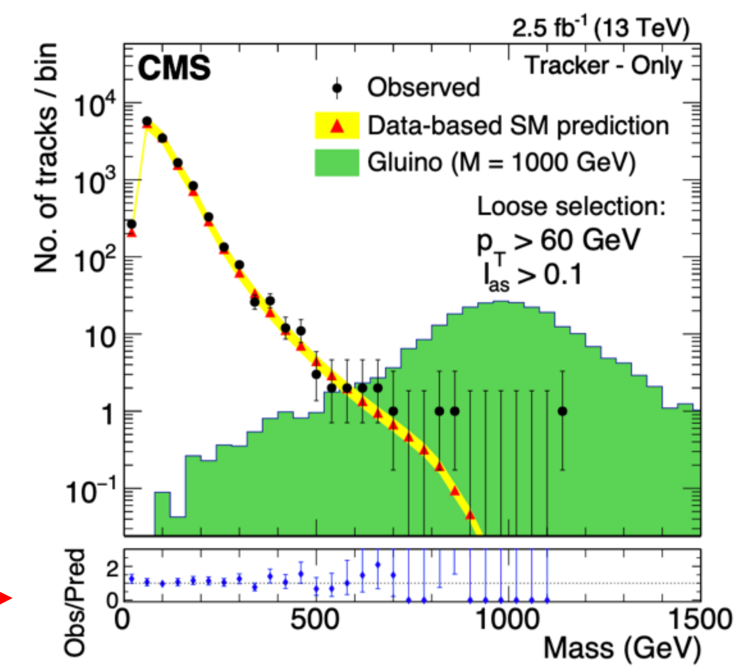
- Tracker: Anomalous ionisation signal (dE/dx)
- Muon: particle should arrive later compared to a photon or ultra-relativist particle (time-of-flight)







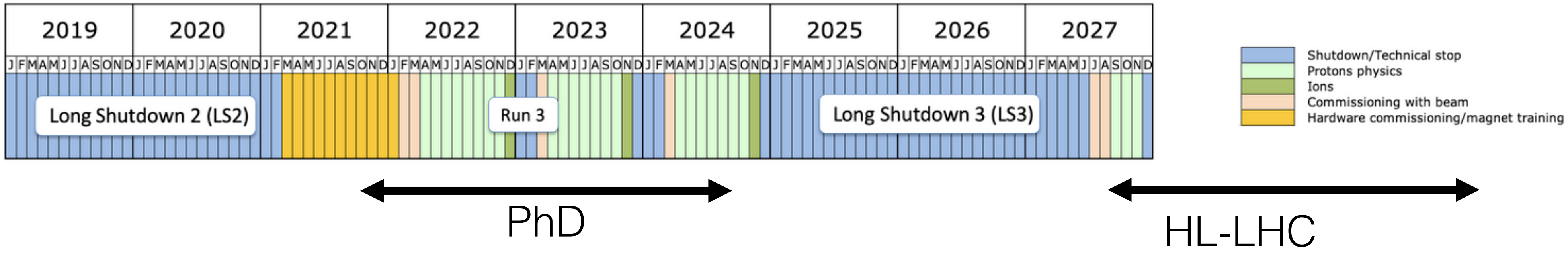
To exploit as much as possible the detector capability, need to understand its behavior



$$\left\langle \frac{dE}{dx} \right\rangle = K \left(\frac{P}{M} \right)^{-2} + C$$

Determination of the mass from the momenta P (track) and either from dE/dx

Internship and thesis subject



Current status

- Last HSCP results does not exploit yet all Run II data (ATLAS/CMS)
- Ongoing effort in the group (PhD ongoing)

Goal of the thesis will be to:

On the analysis side

- Support the ongoing effort for the Run II paper
- Prepare **the search strategy for the Run III search**
- Participate to a paper with 2022/2023 data
- Preparation/simulation for HL-LHC

On the instrumental side

- Ladder integration

Internship and thesis subject

What new can be done on the HSCP search ?

- Improve the trigger efficiency: we don't want to loose event because they are not stored !!!

→ Starting point for the **internship**

- Improvement on the signal selection

➢ Study the possibility to use **Machine Learning** method to improve background rejection

- Improve the **statistical** method for signal extraction (combination of time - dE/dx – p quantities)

- Work on the **interpretation**

➢ as function of lifetime
➢ generic search for reinterpration_

- **Possible extensions** :

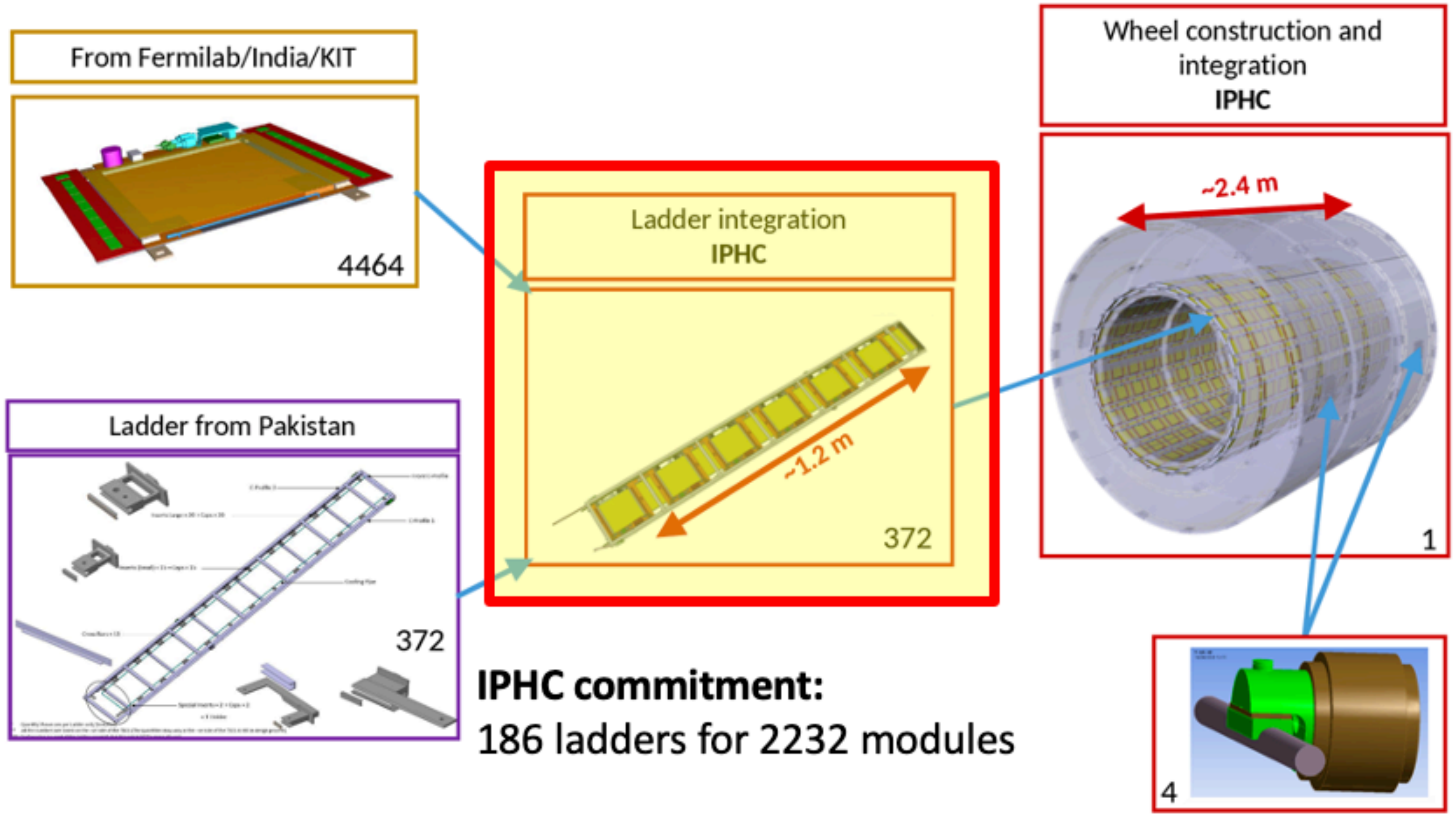
➢ Meta-stable particles (short tracks)
➢ Monopoles (magnetic charge)
➢ Quirks ??

For HL-HLC

- New tracker device (less layers and less bits for dE/dx info)
- New timing layer (30 ps resolution !!!)
- Improvement on muon detector (including at trigger level)

Internship and thesis subject

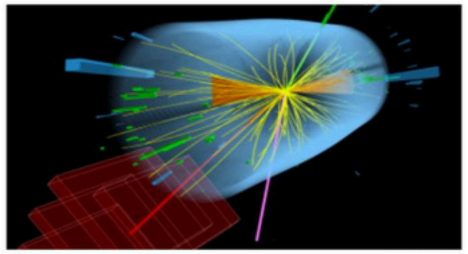
Half of the outer tracker barrel will be integrated at IPHC in the next 3 years …



IPHC commitment:
186 ladders for 2232 modules

More information about CMS ?

https://cms.cern/tags/physics-briefing

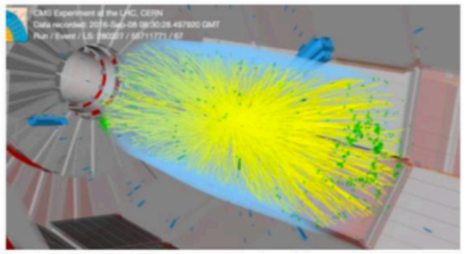


WATCHING THE TOP QUARK MASS RUN

21 SEP | FREYA BLEKMAN | PHYSICS

For the first time, CMS physicists have investigated an effect called the "running" of the top quark mass, a fundamental quantum effect predicted by the Standard Model. Mass is one of the most complex concepts in fundamental physics, which went...

READ MORE

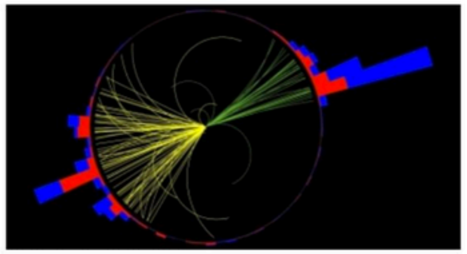


HOW CMS WEEDS OUT PARTICLES THAT PILE UP

11 SEP | FREYA BLEKMAN | PHYSICS

When the CMS experiment records particle collision events, a large number of unwanted extra collisions overlap in the detector and hide the rare particle collision that is worthwhile studying. CMS physicists have developed a new method that gives...

READ MORE



MACHINING JETS

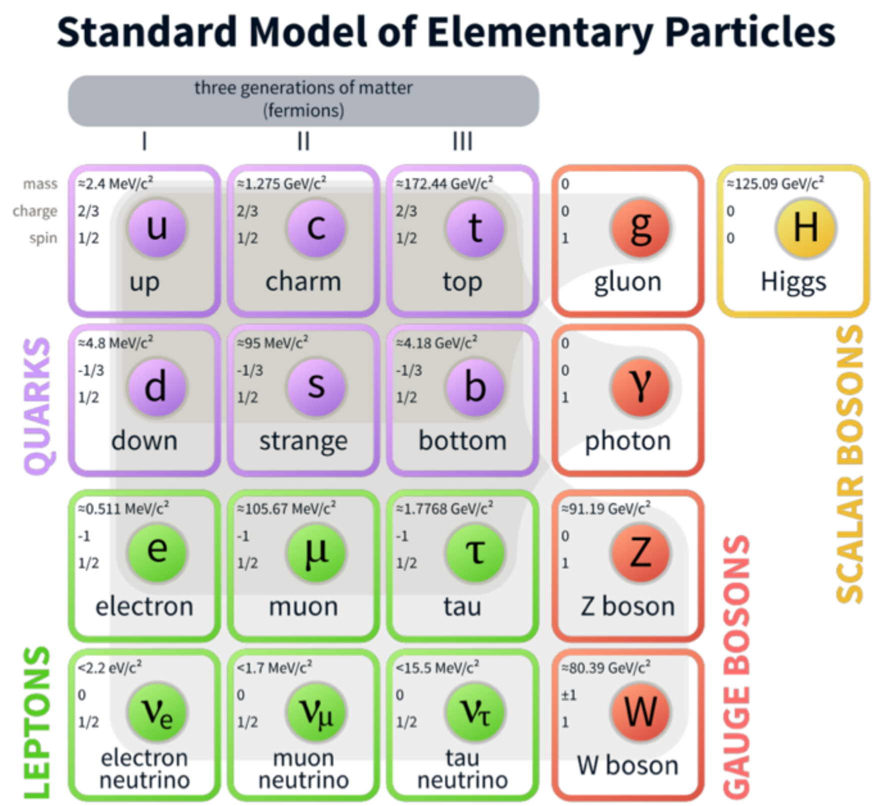
10 SEP | FREYA BLEKMAN | PHYSICS

New algorithms from the Compact Muon Solenoid experiment use the ideas used in mobile phone facial recognition to better understand the collisions at the Large Hadron Collider. One of the most exciting challenges at the Large Hadron Collider is...

READ MORE

Backup

Supersymmetry



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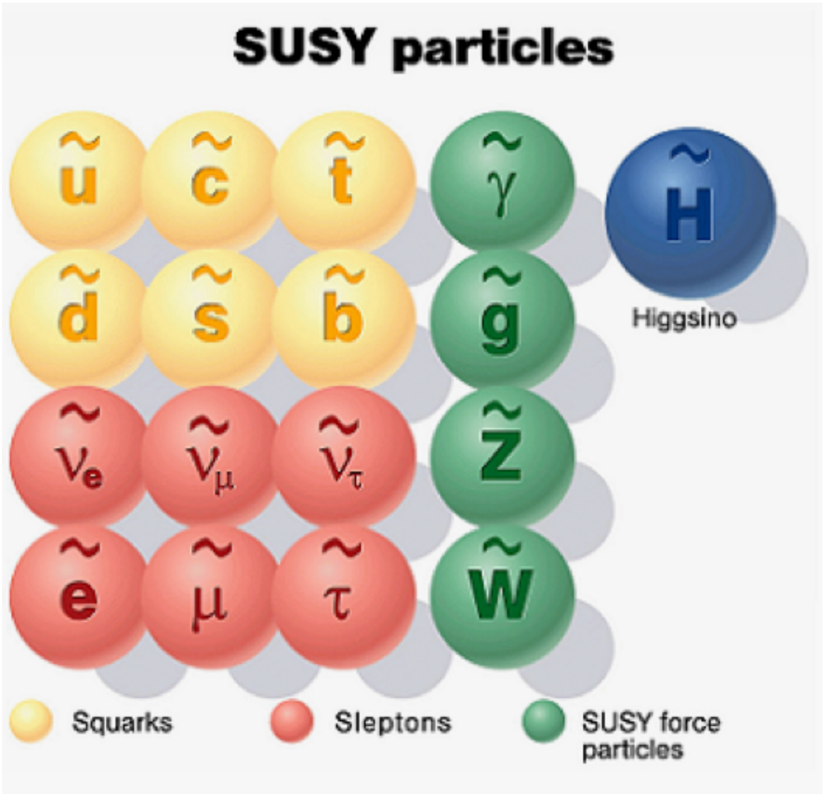

SM bosons:	
gluon ↔ gluino	$\widetilde{g}$
W ↔ wino	$\widetilde{W}$
B ↔ bino	$\widetilde{B}$
Higgs ↔ Higgsino	$\widetilde{h}$

SM fermions:	
quark ↔ squark	$\widetilde{q}/\widetilde{q}^*$
top ↔ stop	$\widetilde{t}$
bottom ↔ sbottom	$\widetilde{b}$
lepton ↔ slepton	$\widetilde{l}$

SUSY particles have not been observed.
→ Supersymmetry must be a broken symmetry
→ SUSY particles must have a higher mass