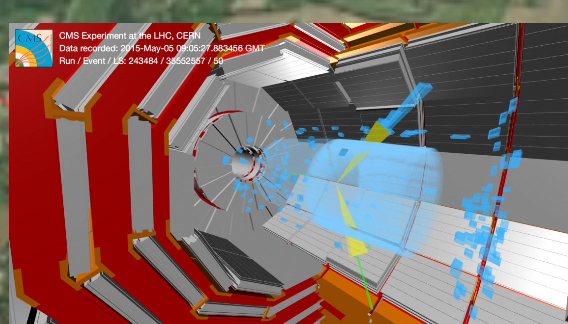
The CMS experiment

Compact
Muon
Solenoid

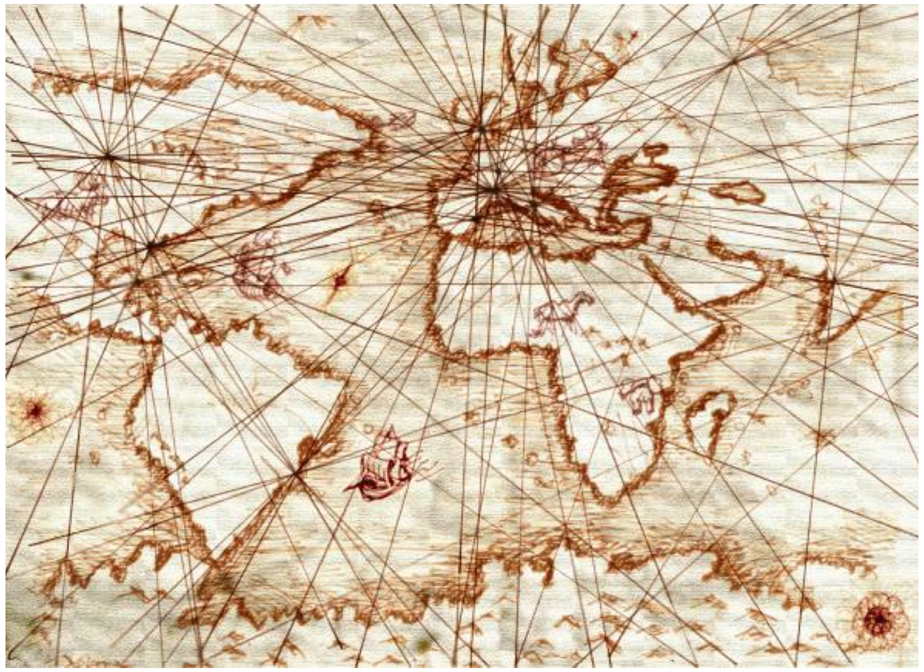


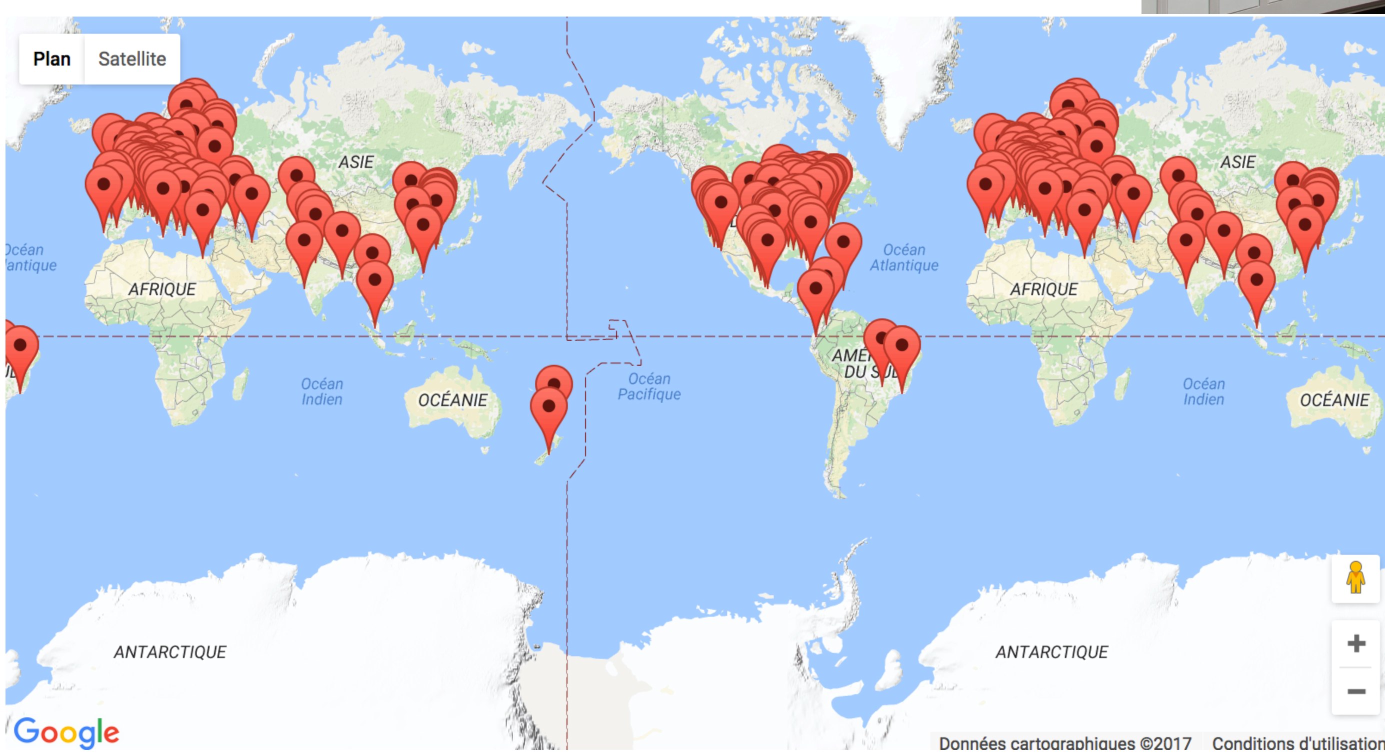
Institut Pluridisciplinaire Hubert CURIEN STRASBOURG

Université de Strasbourg

IN2P3 Les deux infinis

The CMS collaboration





~3500 scientists
from 200 institutes
in 46 countries

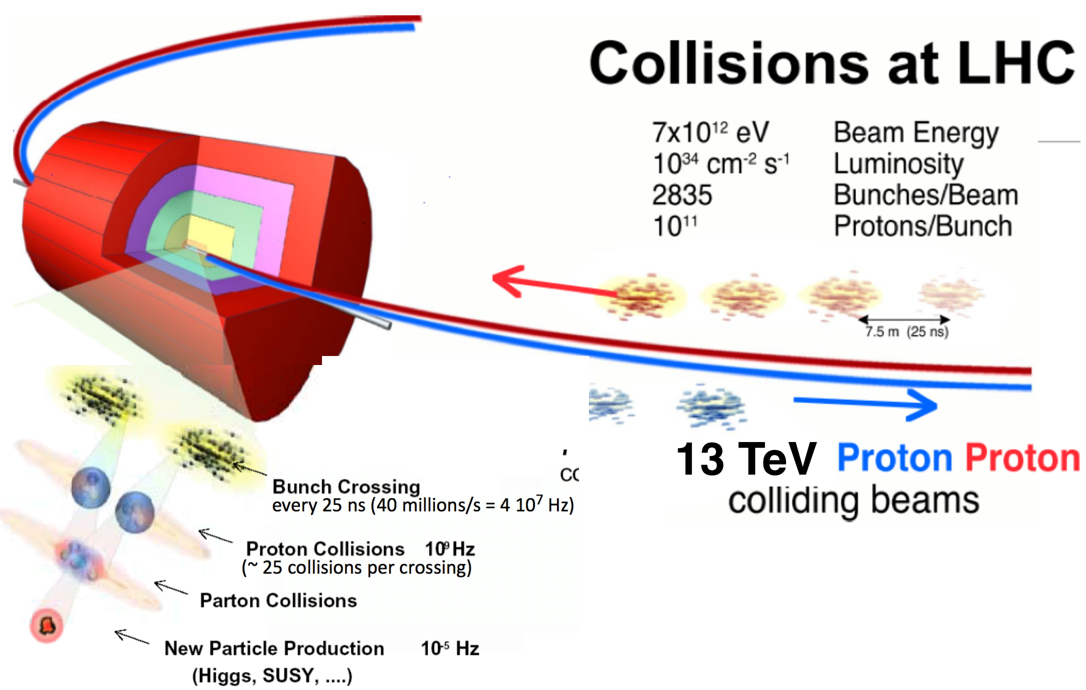
The Large Hadron Collider (LHC)

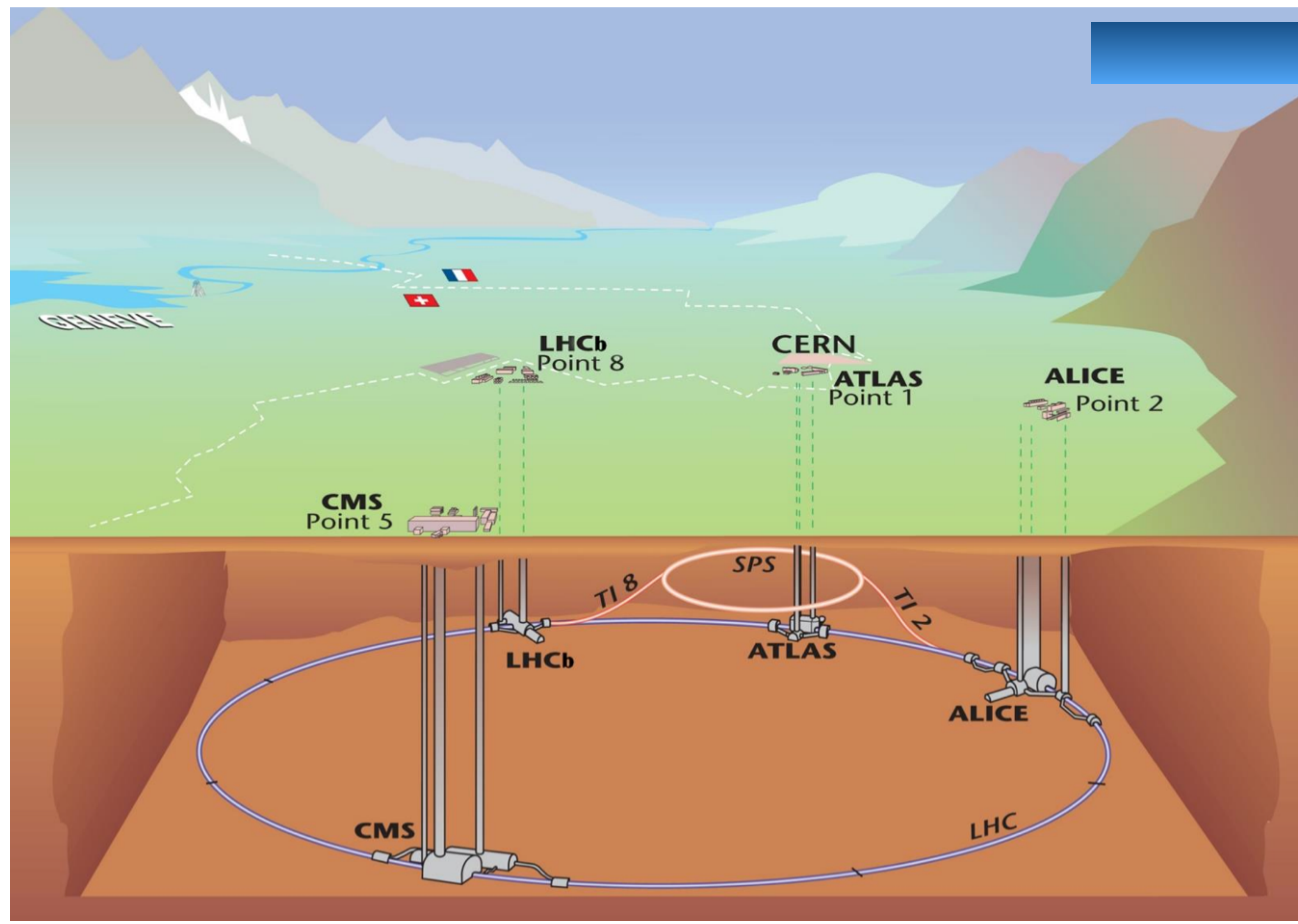
The largest accelerator machine in the world: 27 km, 1232 supraconductor dipoles.

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.

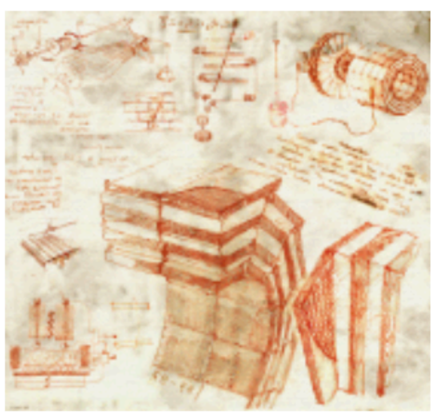




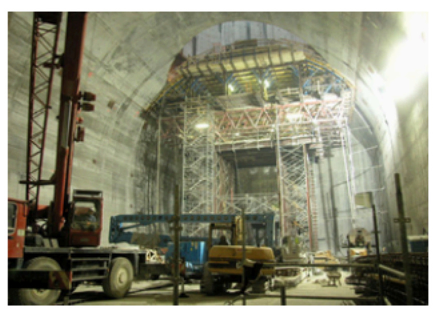
Timeline…

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

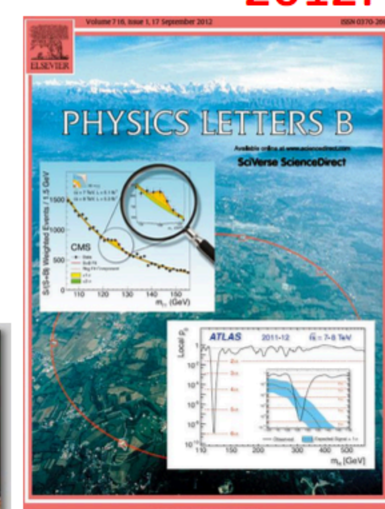
Run1
7 TeV (2010-2011)
8 TeV (2012)

Run2
13 TeV

Long arrêt

Run3
14 TeV

2012: Découverte du Boson de Higgs



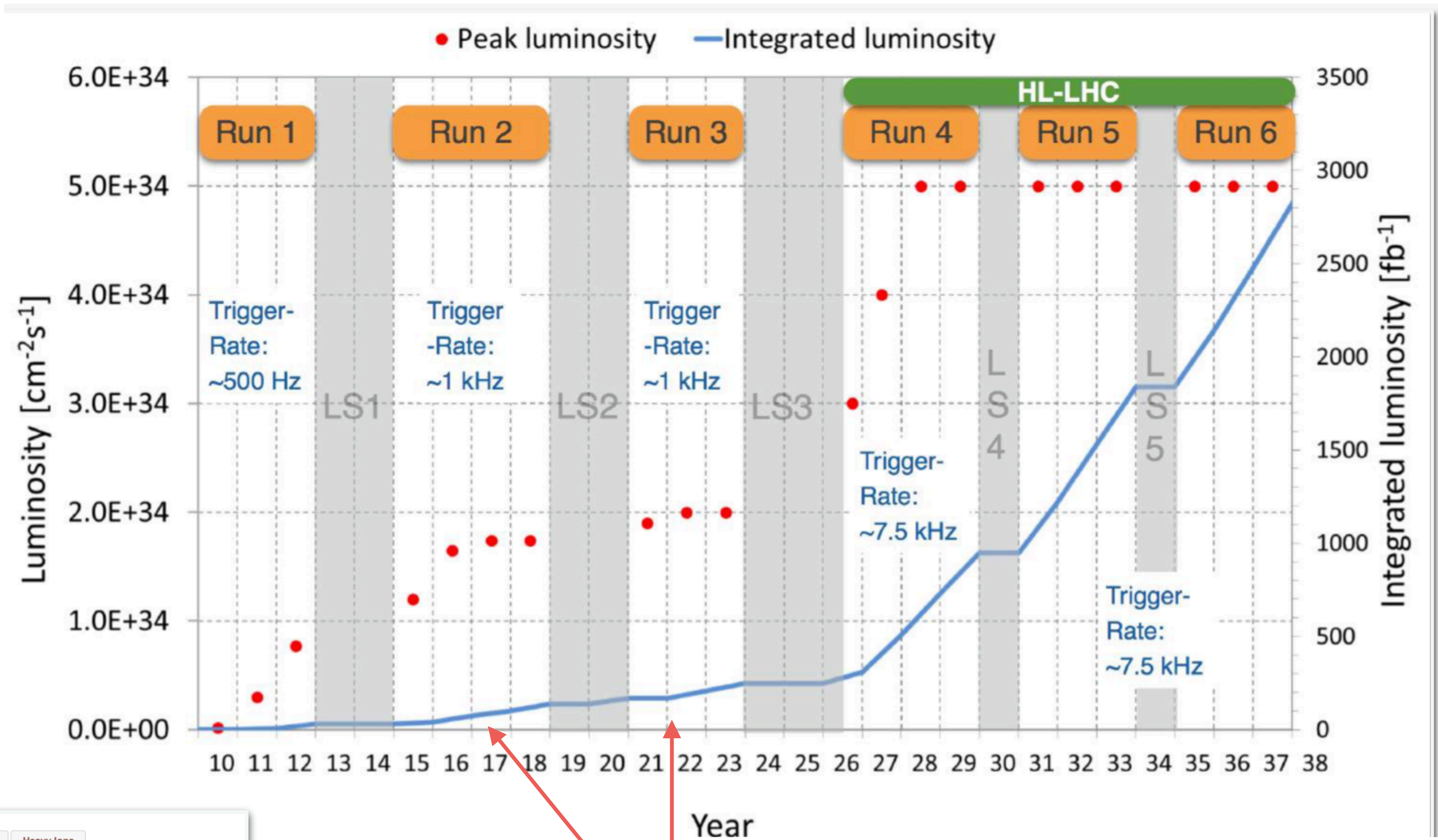
Physics 2013

Photo: Pnicolet via Wikimedia Commons
François Englert

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

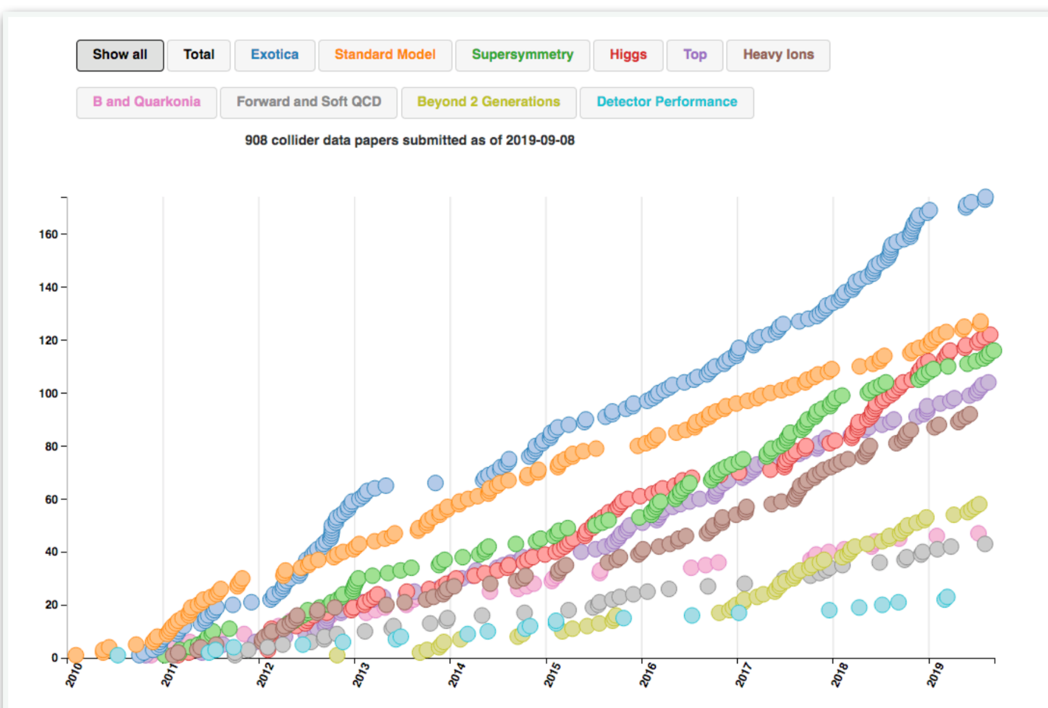
4

Timeline…



Your thesis 2020-2023 (?)

Run 2 (137 fb^{-1} !) and Run 3 data… 😊

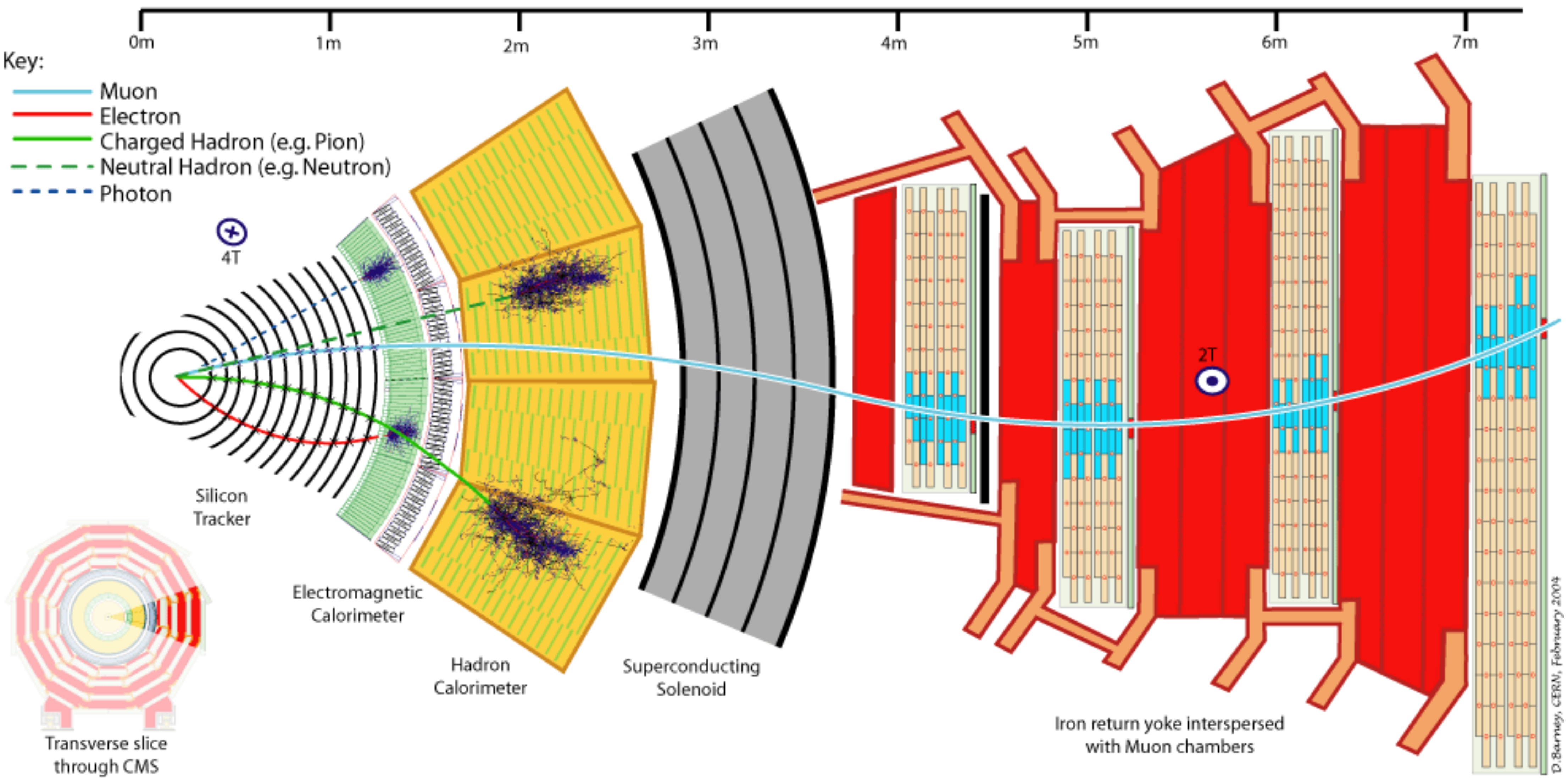


- 64 papers published in 2019

- 910 since the beginning of Run 1

https://tinyurl.com/y9odauv6

How do we identify particles in CMS ?

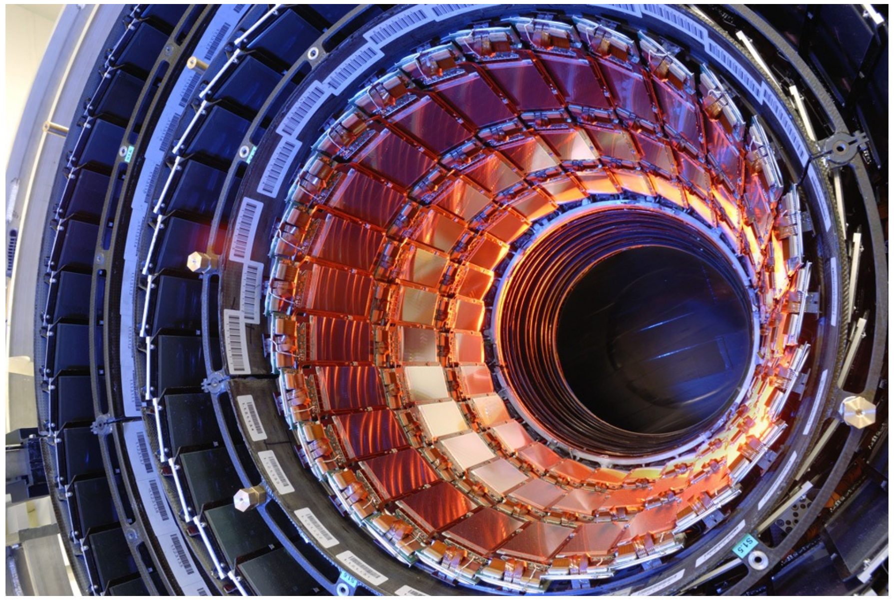


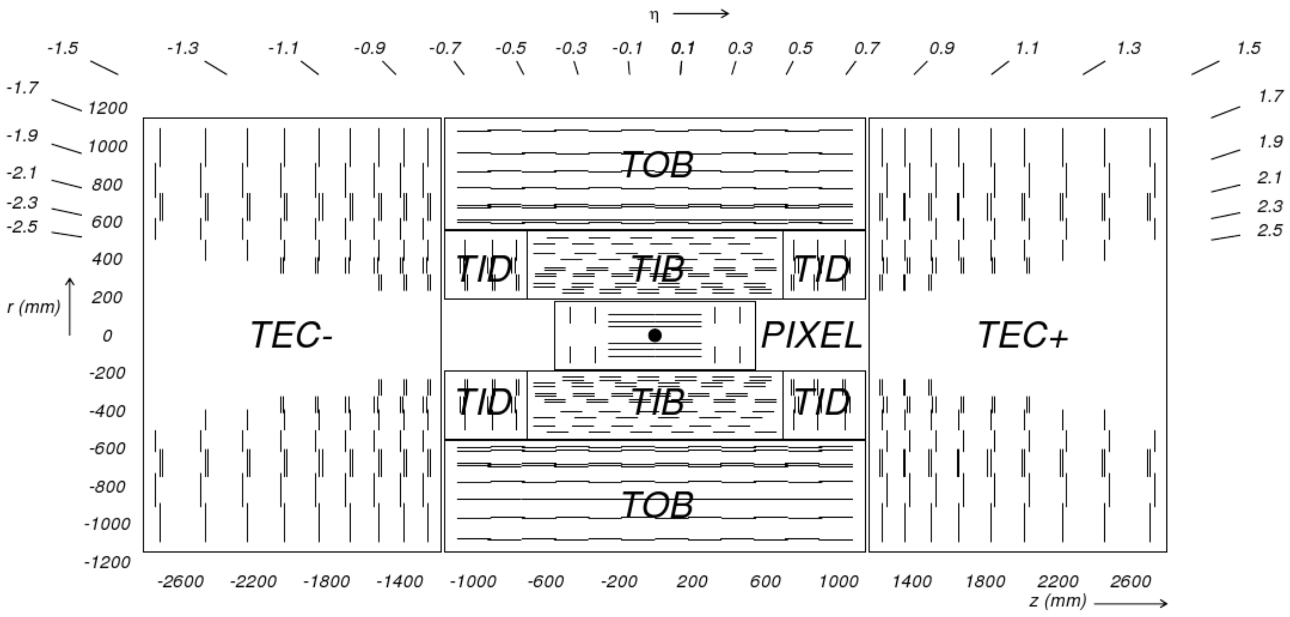
Like an onion.
Each layer/detector measures E or p.

The CMS tracker

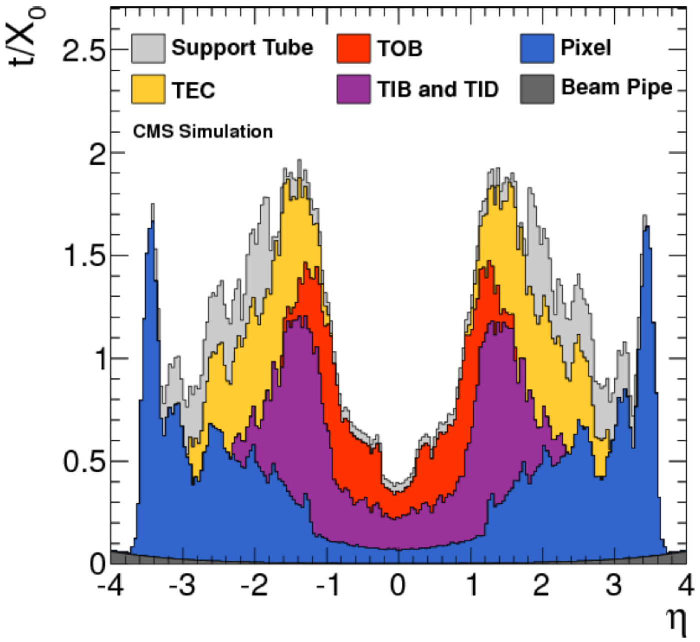
Reconstruct trajectories of all the charged particles from collisions.

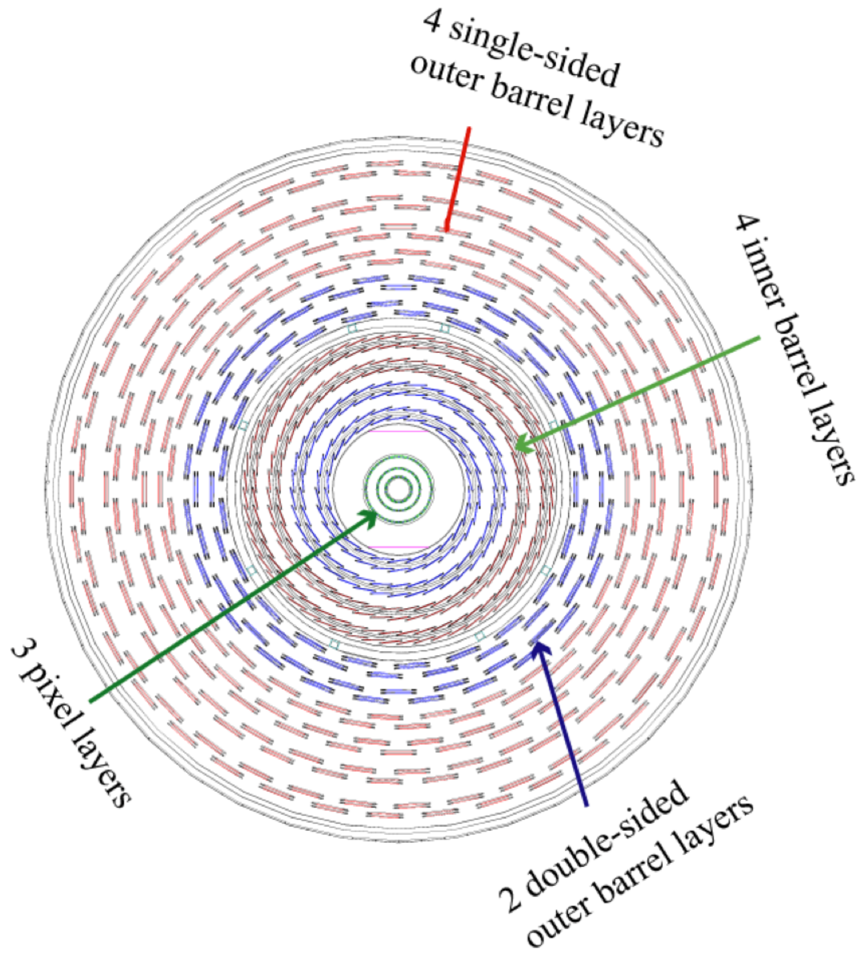
214 m² silicon, 65.9 M silicon pixels, 11.4 M silicon strips.





Heavy material budget !



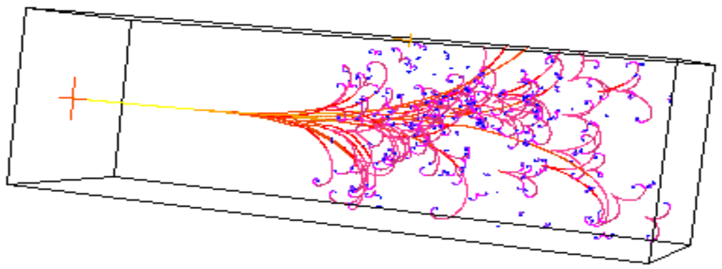


The CMS calorimeters

Detection principle :

stop a particle
measure its signal

ECAL

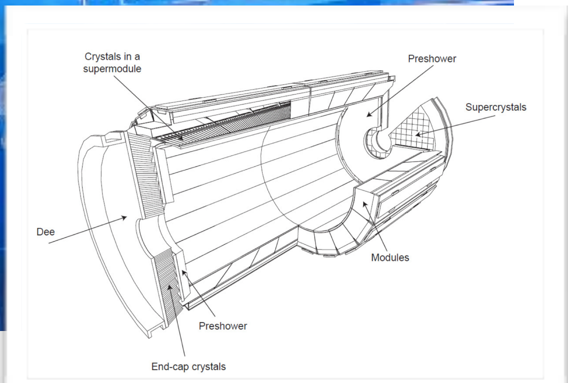


76k scintillating PbWO4 crystals:

→ Heavy (so particles interact with it a lot)

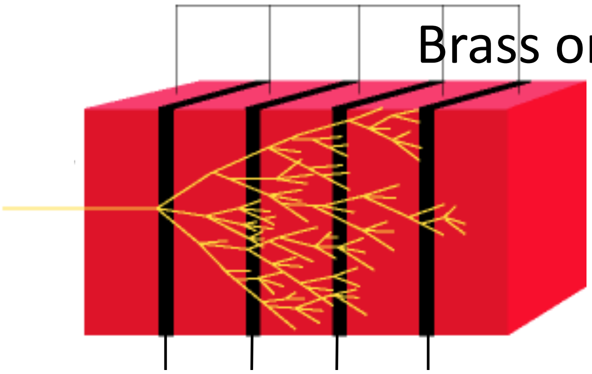
→ Transparent (so you can collect the light at the end)

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

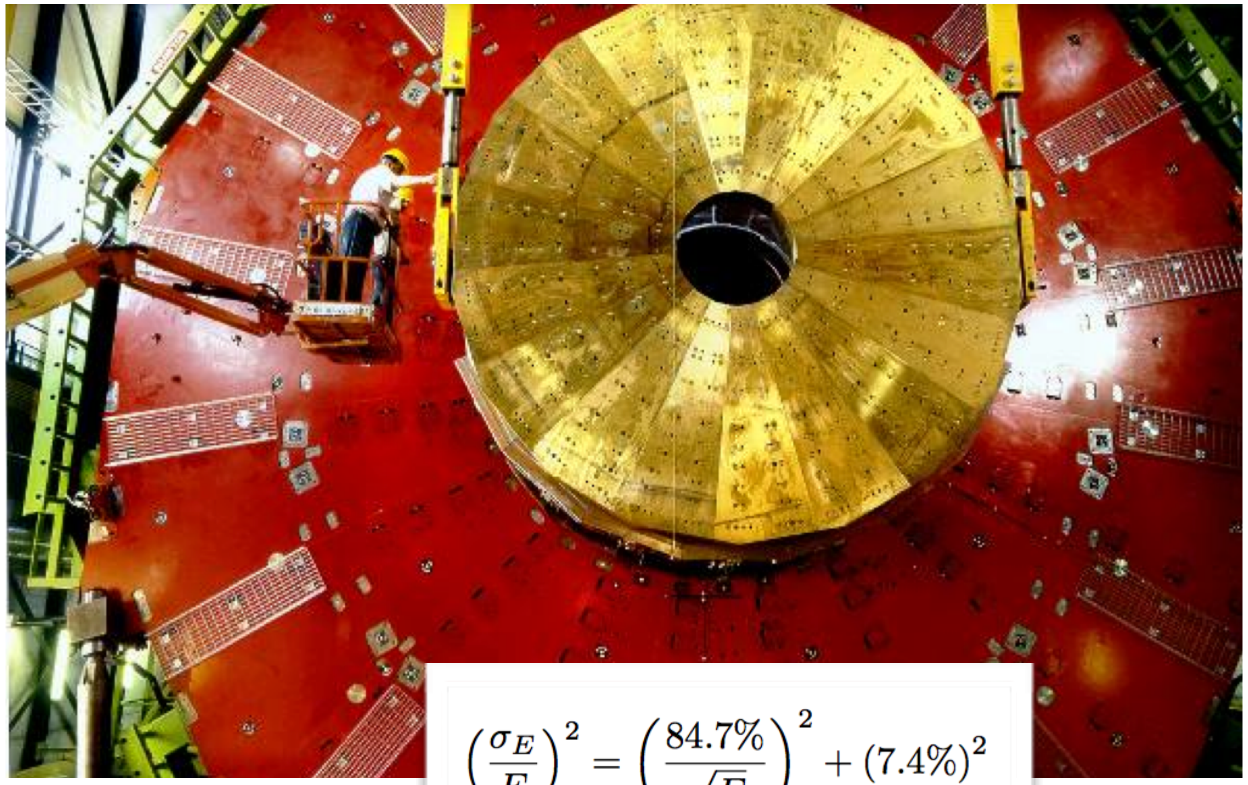


HCAL

Brass or copper walls



Transparent scintillating plastic

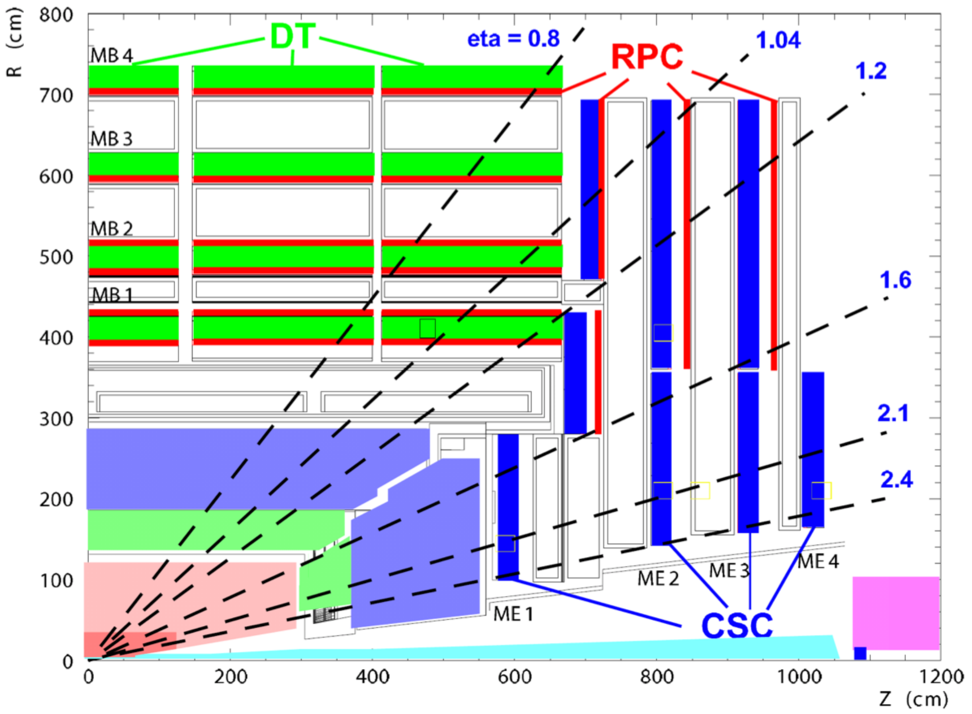


$$\left(\frac{\sigma_E}{E}\right)^2 = \left(\frac{84.7\%}{\sqrt{E}}\right)^2 + (7.4\%)^2$$

Muon chambers

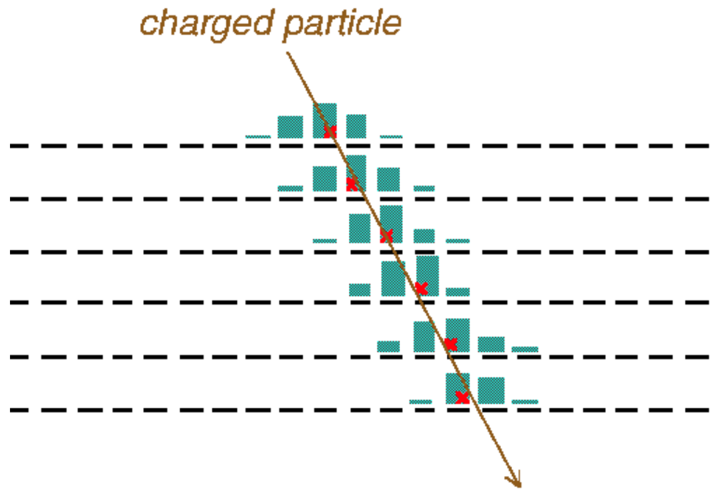
Muons are typically very penetrating.

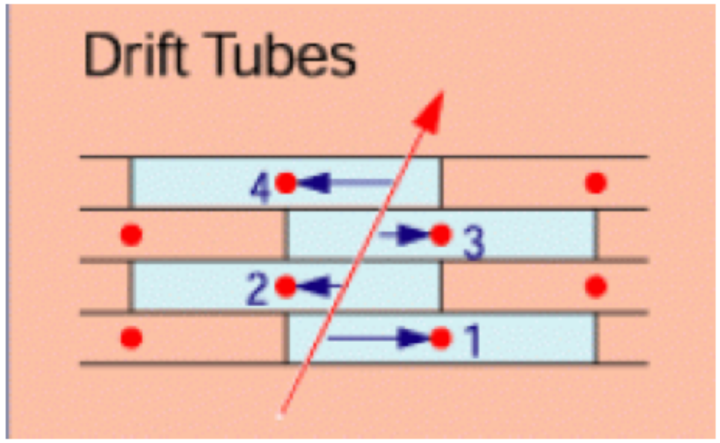
Stick the detectors in giant hunks of iron so nothing else gets through.

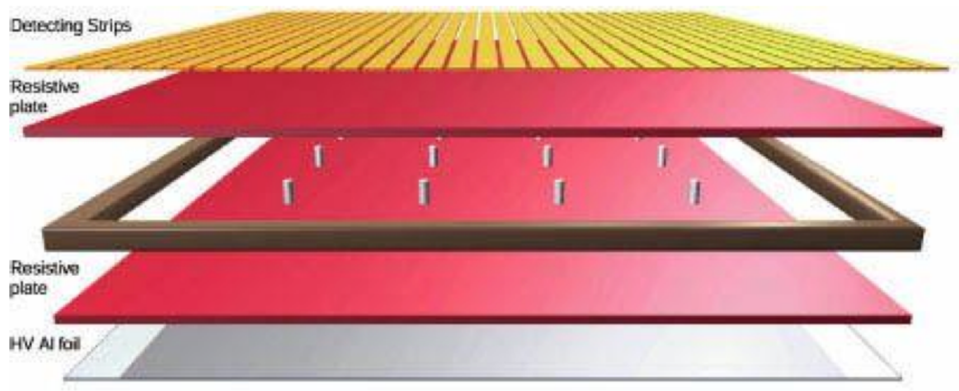


Three types of detectors → redundancy

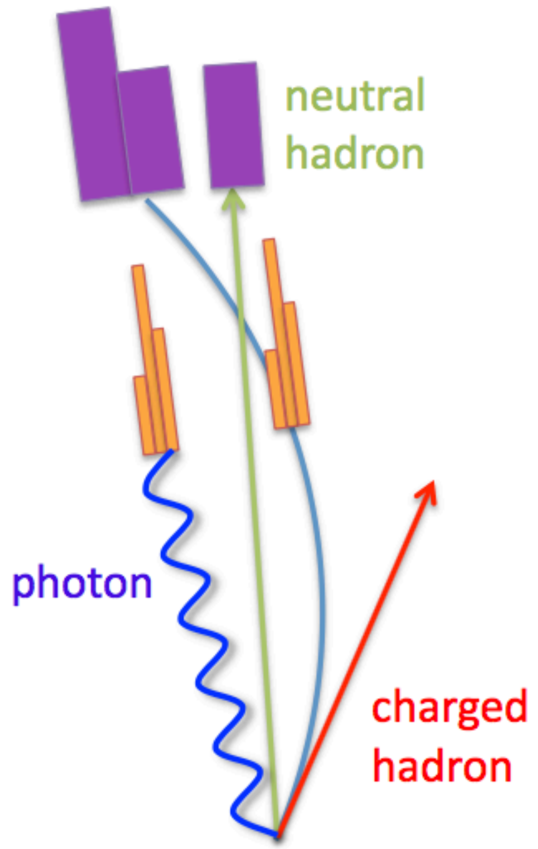
- drift tubes (DT) → fast !
- resistive plate chambers (RPC) → fast, radiation tolerant
- cathode strip chambers (CSC) → radiation tolerant







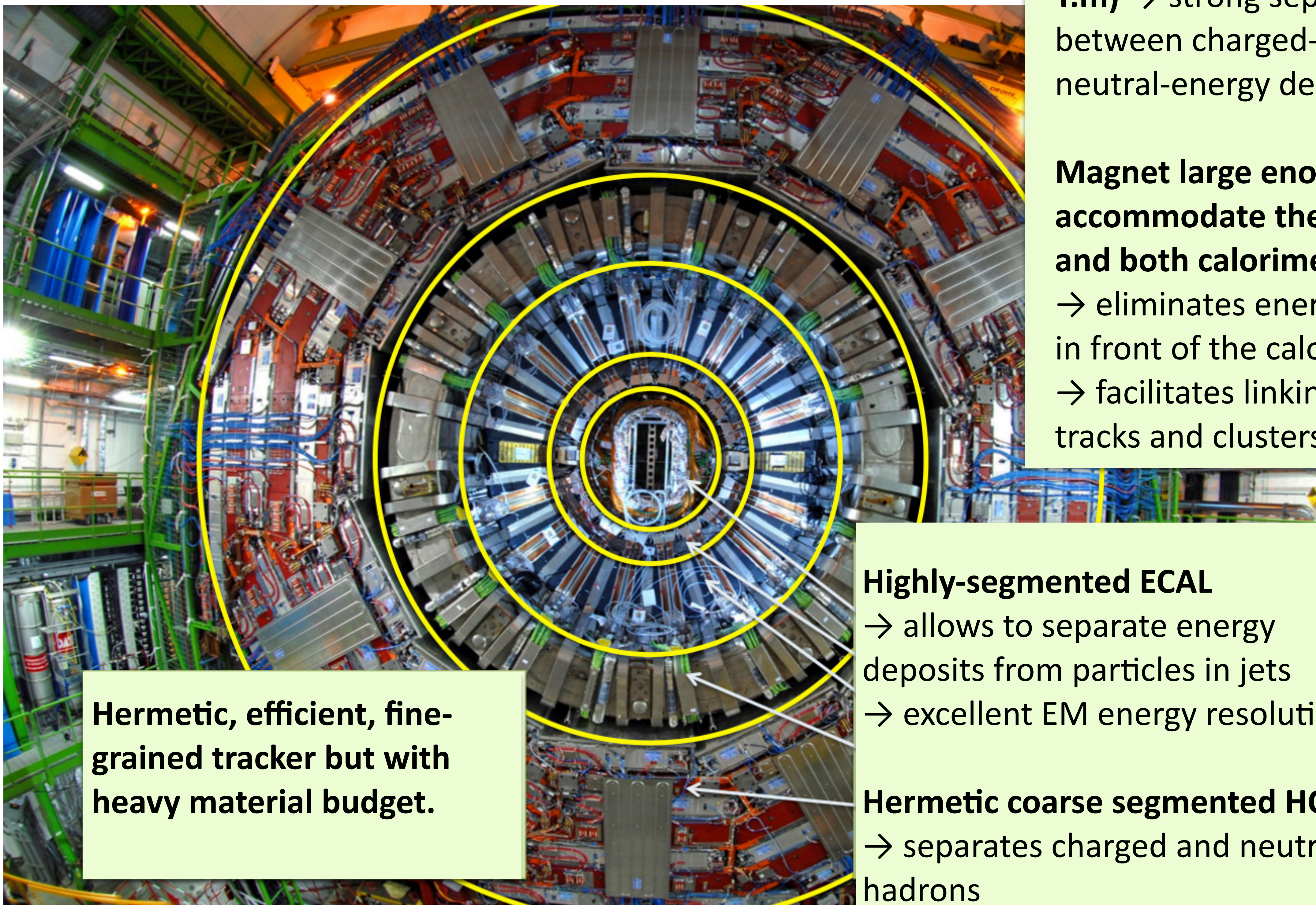
Particle flow ?



- 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

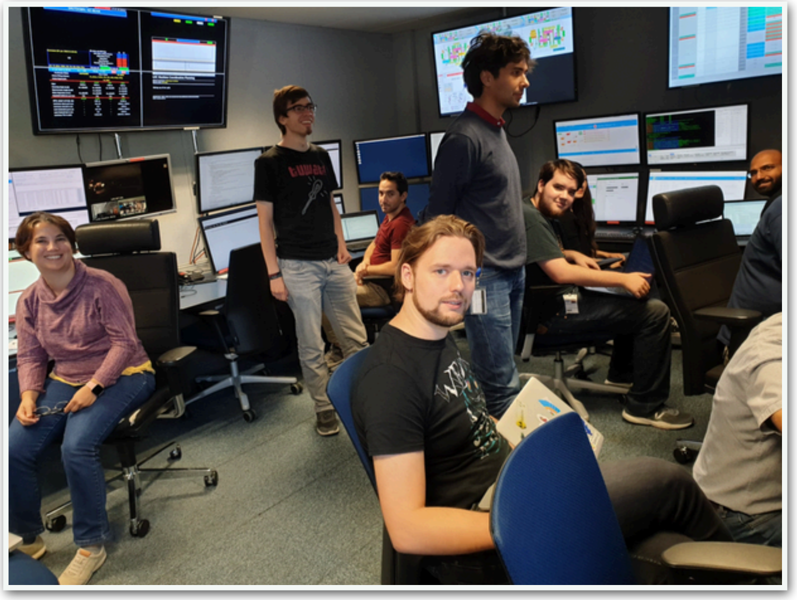
Hermetic, efficient, fine-grained tracker but with heavy material budget.

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

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

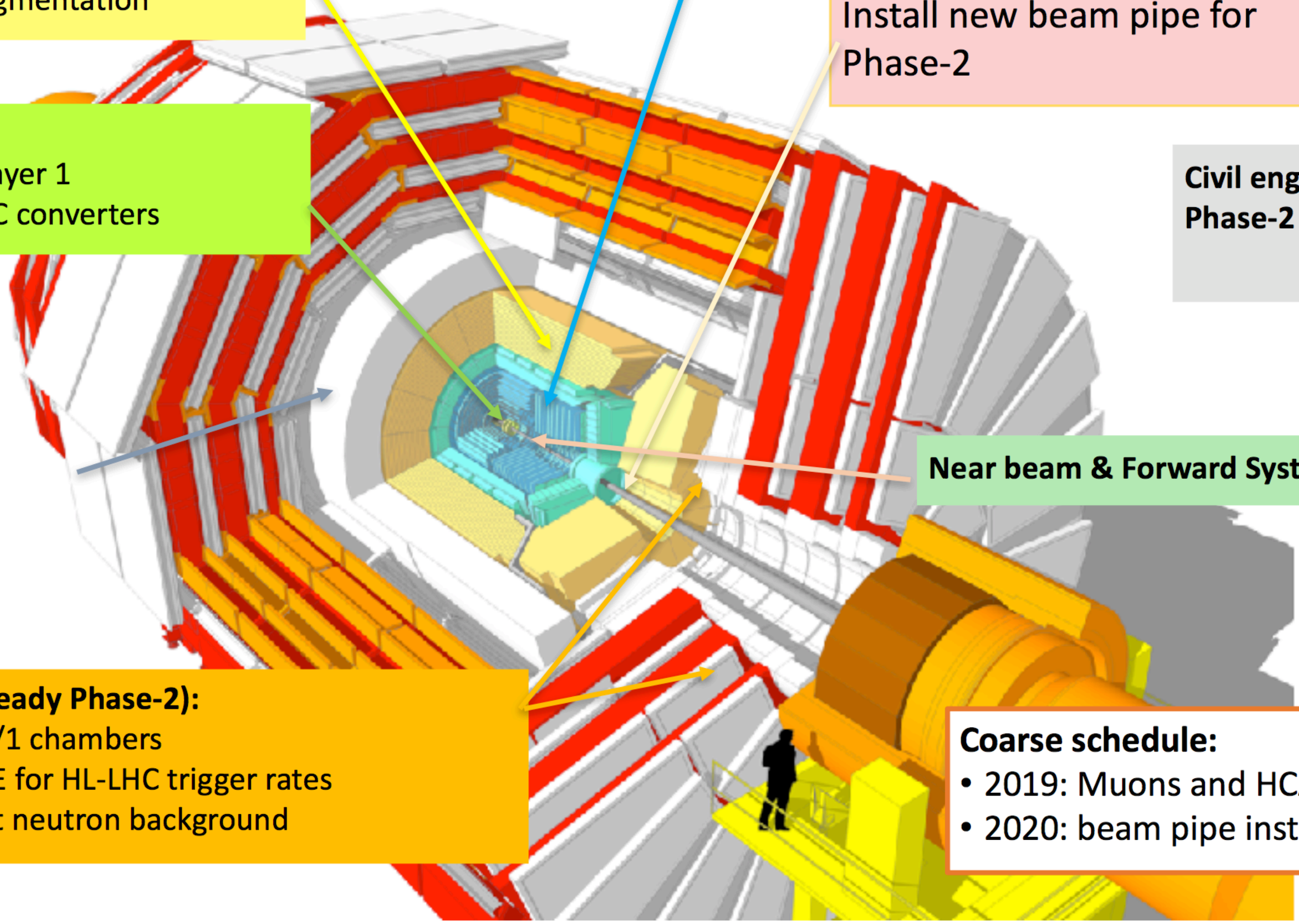
Keep strip tracker cold to avoid reverse annealing

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

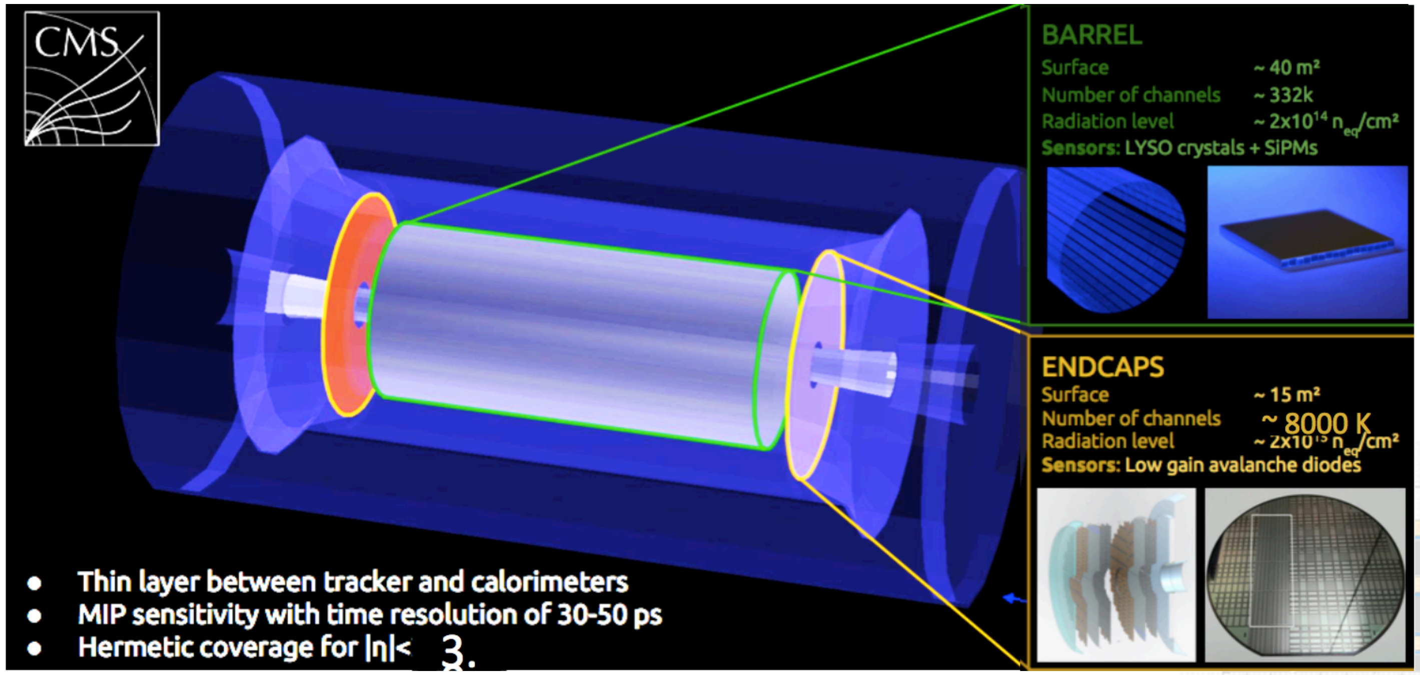
Muon system (already Phase-2):

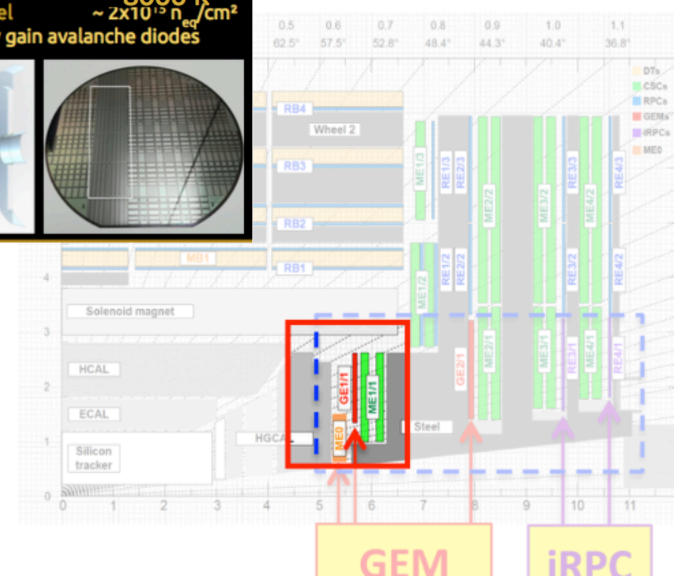
- install GEM GE1/1 chambers
- Upgrade CSC FEE for HL-LHC trigger rates
- Shielding against neutron background

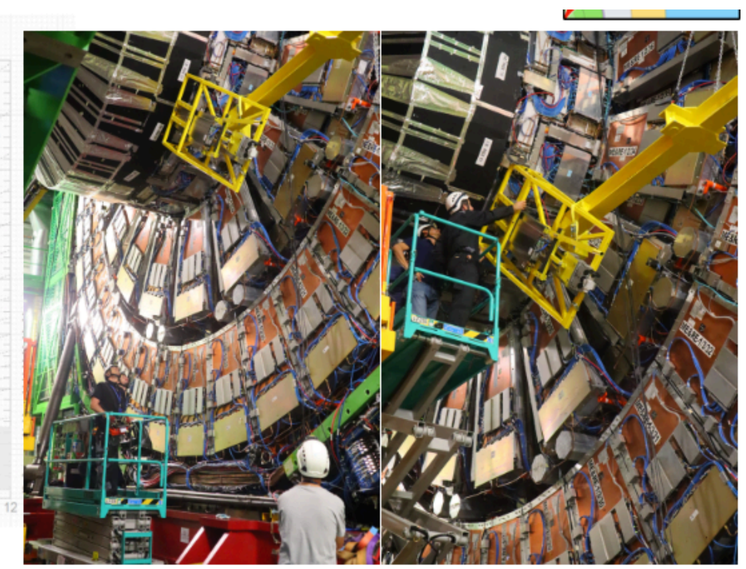
Coarse schedule:

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

Towards HL-LHC…







Timing detector (MTD):

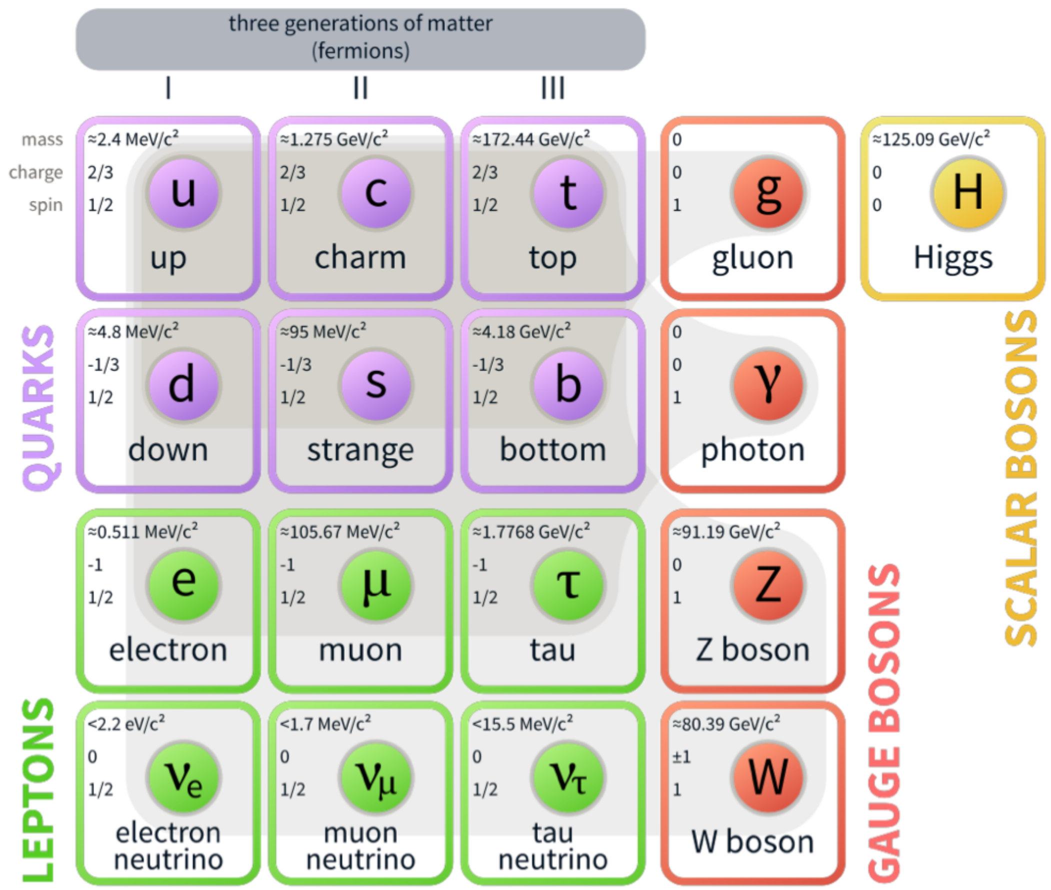
- measure time of tracks
- fight pile-up
- central and forward region in CMS

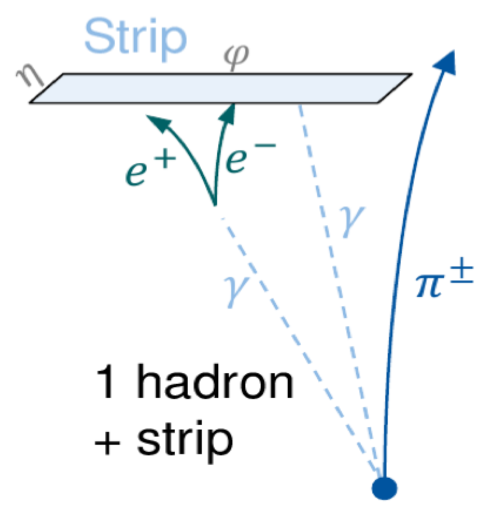
First phase 2 detectors, GEM muon chambers, installed these days

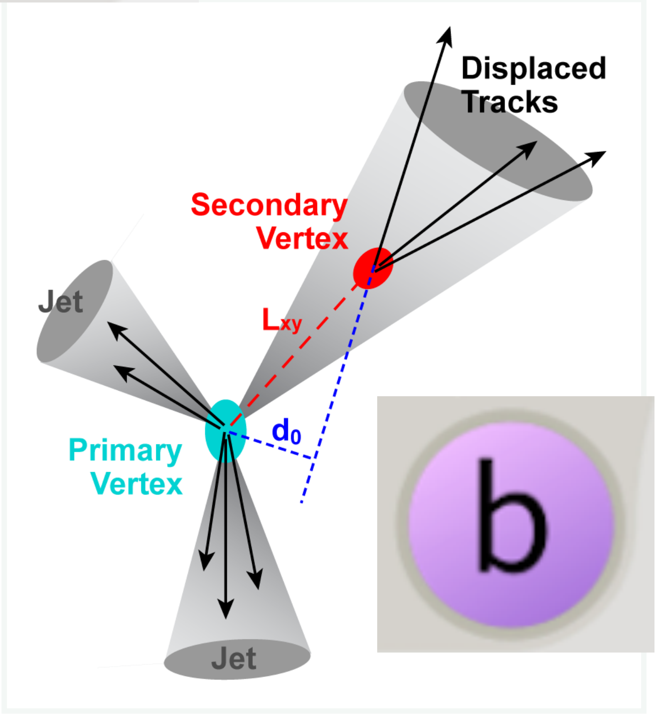
LHCC and the UCG review panels **recommend the CMS MTD project for approval**

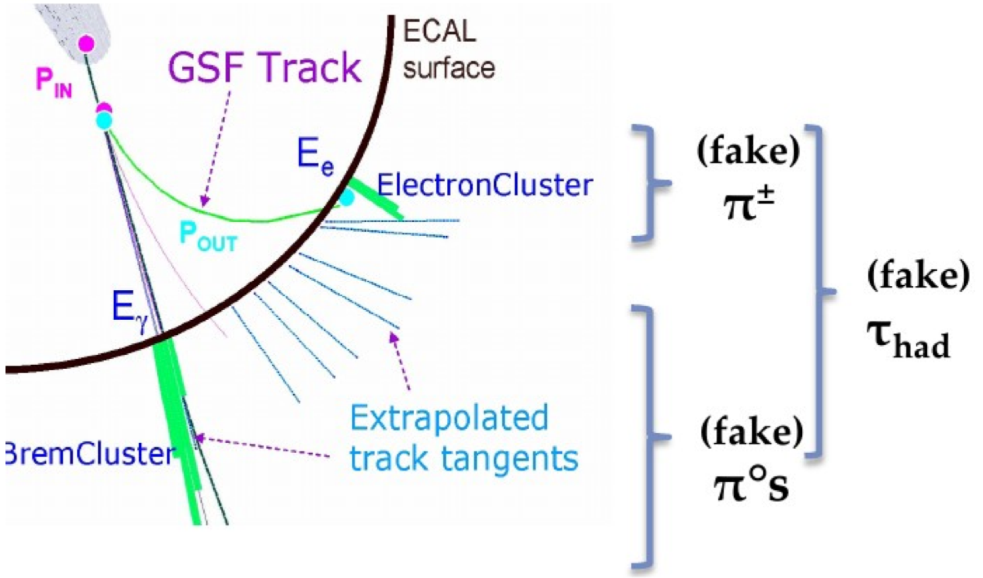
Particle identification

Standard Model of Elementary Particles





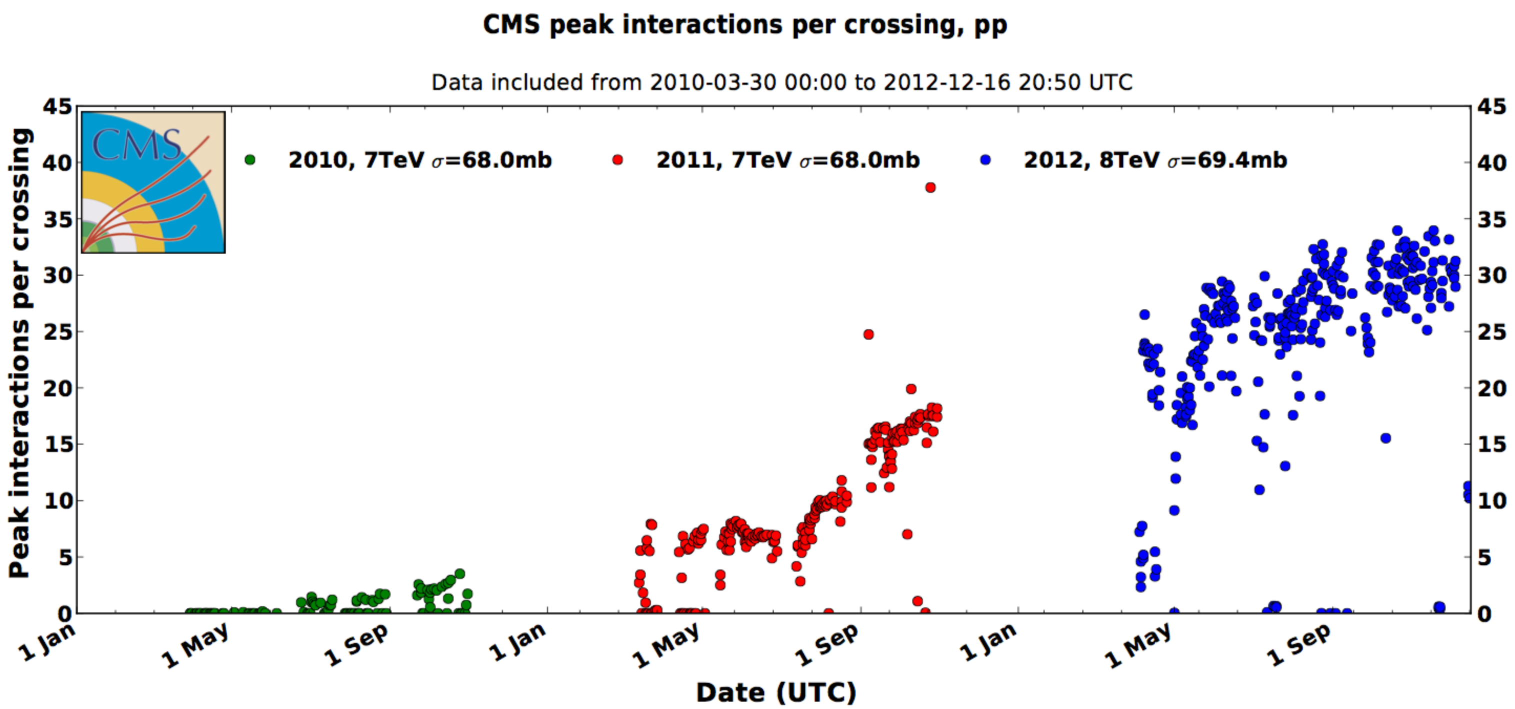




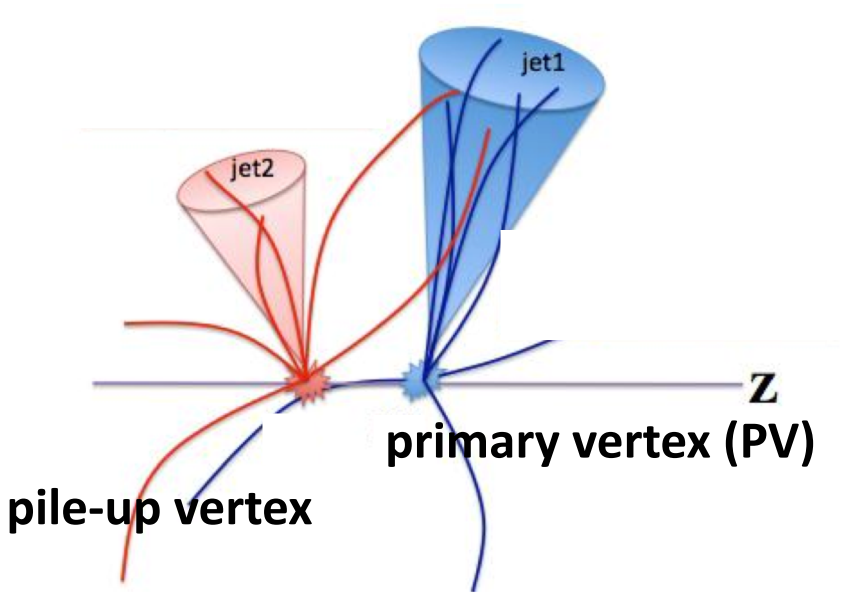
Dedicated algorithms to identify key particles…

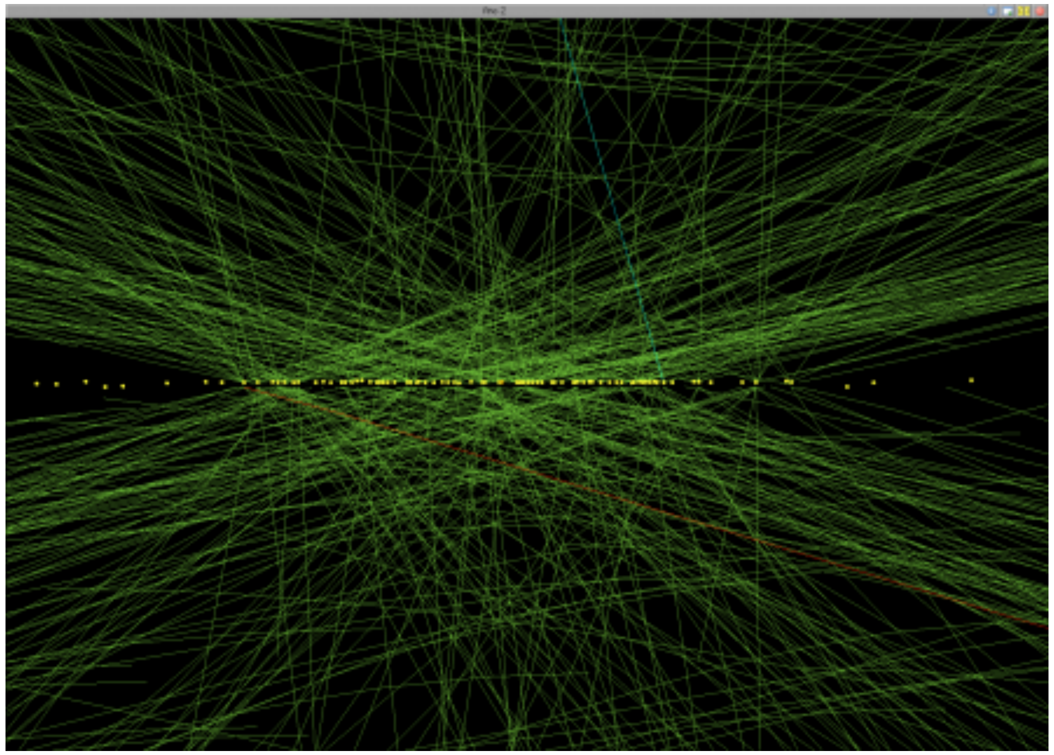
+ μ in muon chambers and γ in ECAL

Pile-up ?



Pile-up :
additional p-p interactions inside a bunch crossing



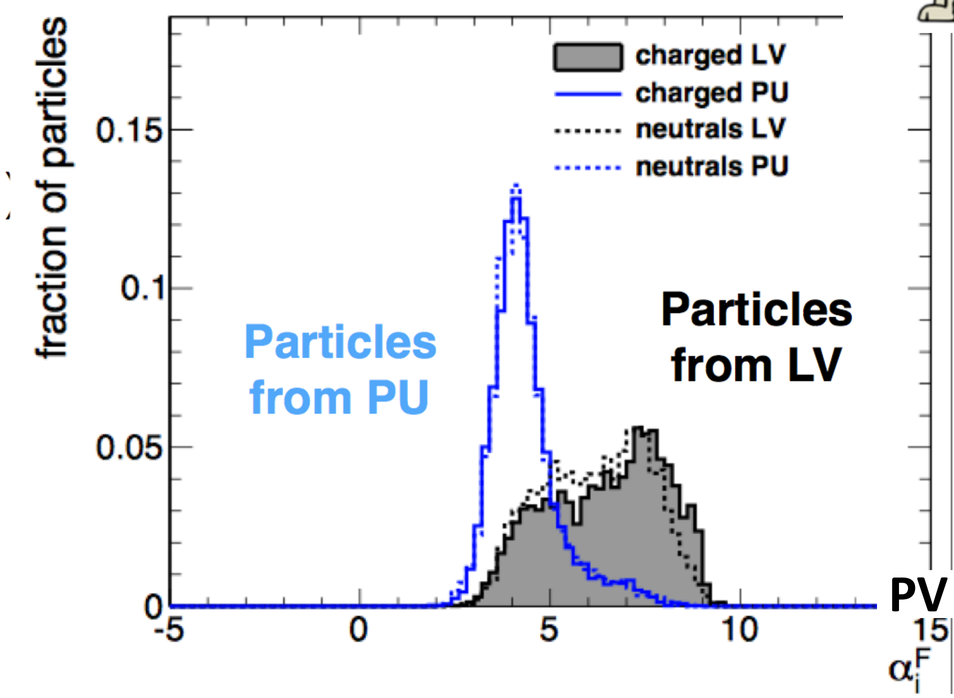


Pile-up removal !

Pile Up Per Particle Identification (PUPPI) method:

Weight each p-flow particle according to the presence of neighbours…

Weight α allows to separate PU particles from others.



$$\alpha_i = \log \sum_{j \in \text{event}} \frac{P_T^j}{\Delta R_{ij}} \Theta(R_{\min} < \Delta R_{ij} < R_0)$$

PT sum weighted with distance

Step function to take into account only particles around it.

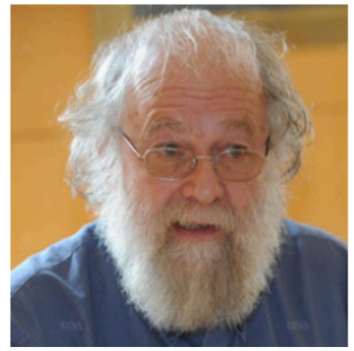
CMS @ IPHC ?

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

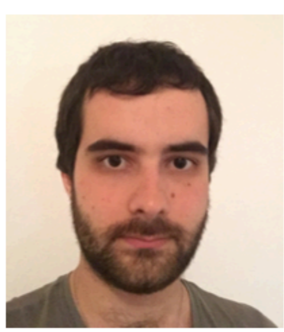

Éric Conte


Éric Chabert


Ulrich Goerlach

11 physicists,
5 phDs,
1 post-doc

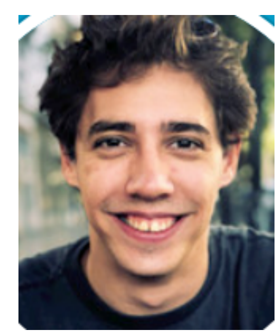

Dr. Nicolas Tonon


Guillaume Bourgatte


Natalia Emriskova


Clément Grimault

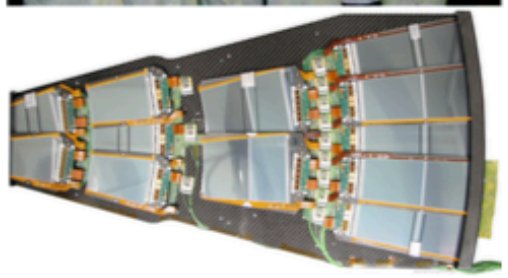

Douja Darej


Dylan Apparu

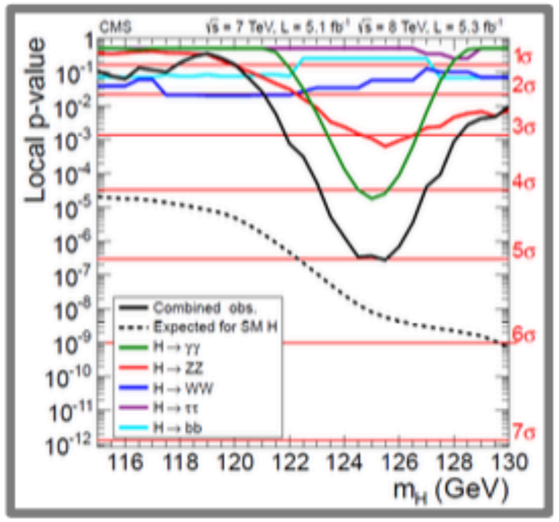

Emery Nibigira (post-doc)

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

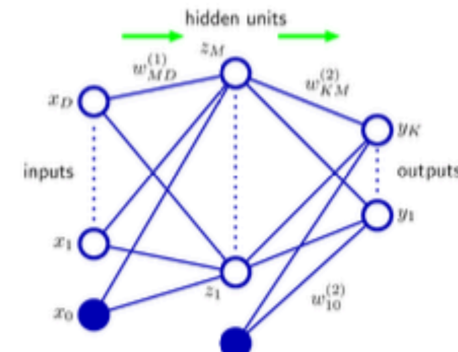
instrumentation



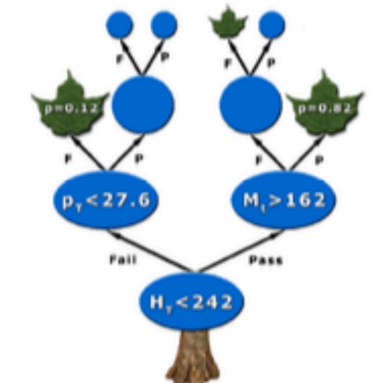
Statistical treatment



algorithms

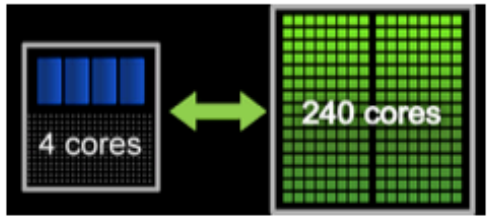


Neural Network



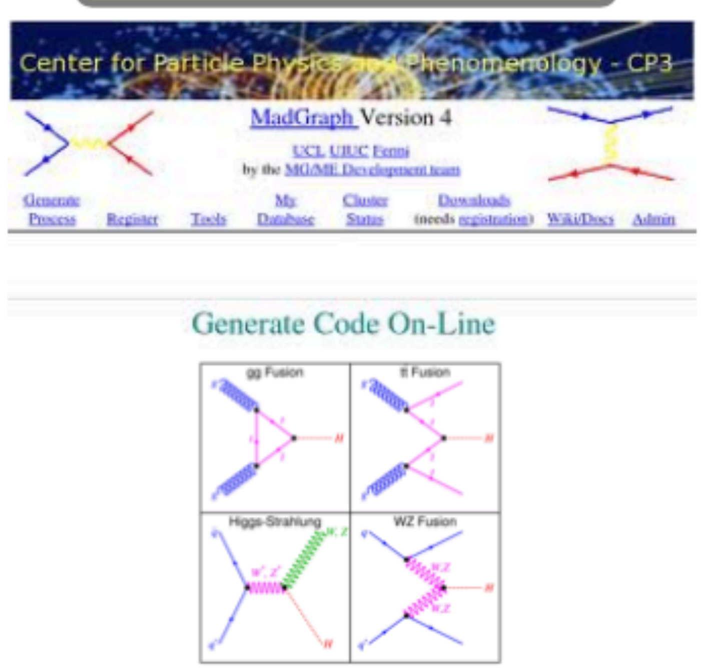
Boosted Decision Tree

Computing

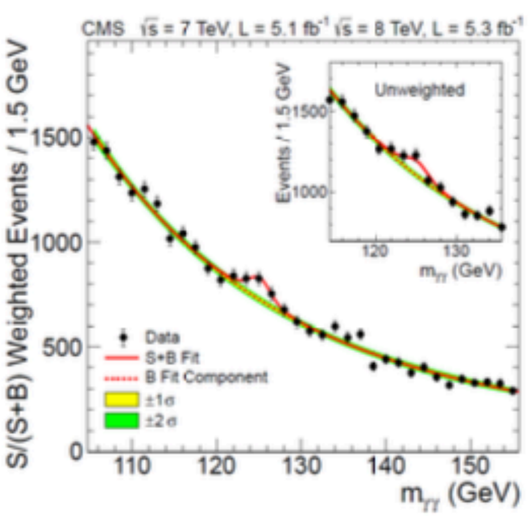


Grid

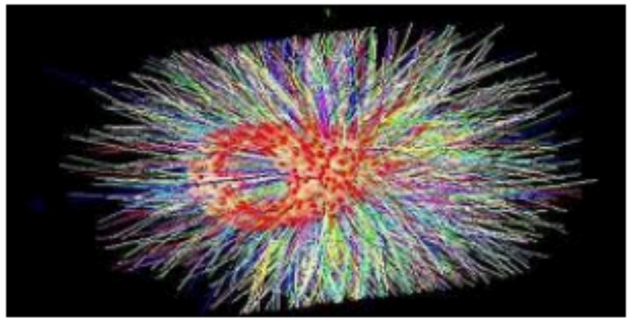
Phenomenology



Physics analysis



Simulation



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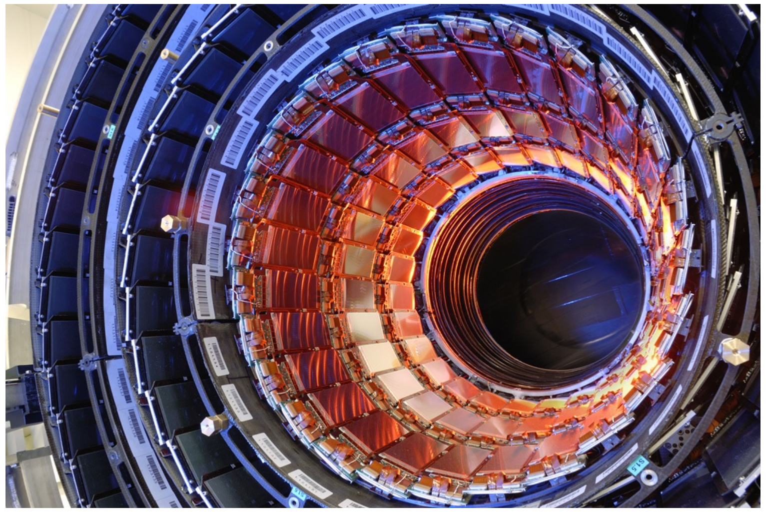
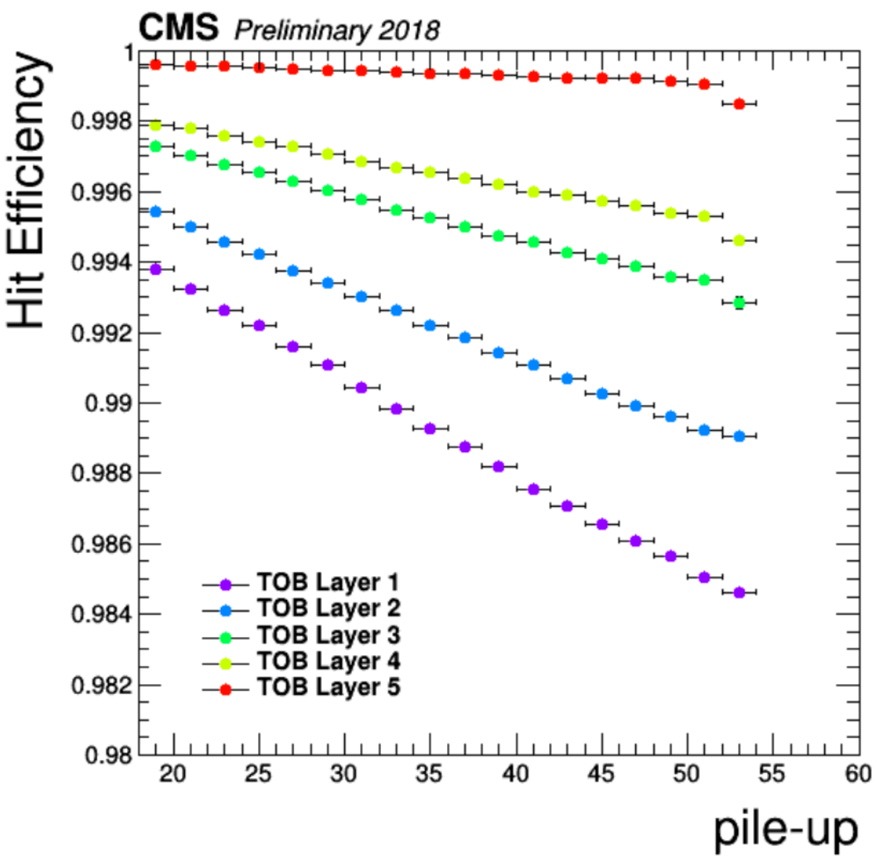
Tracker performance

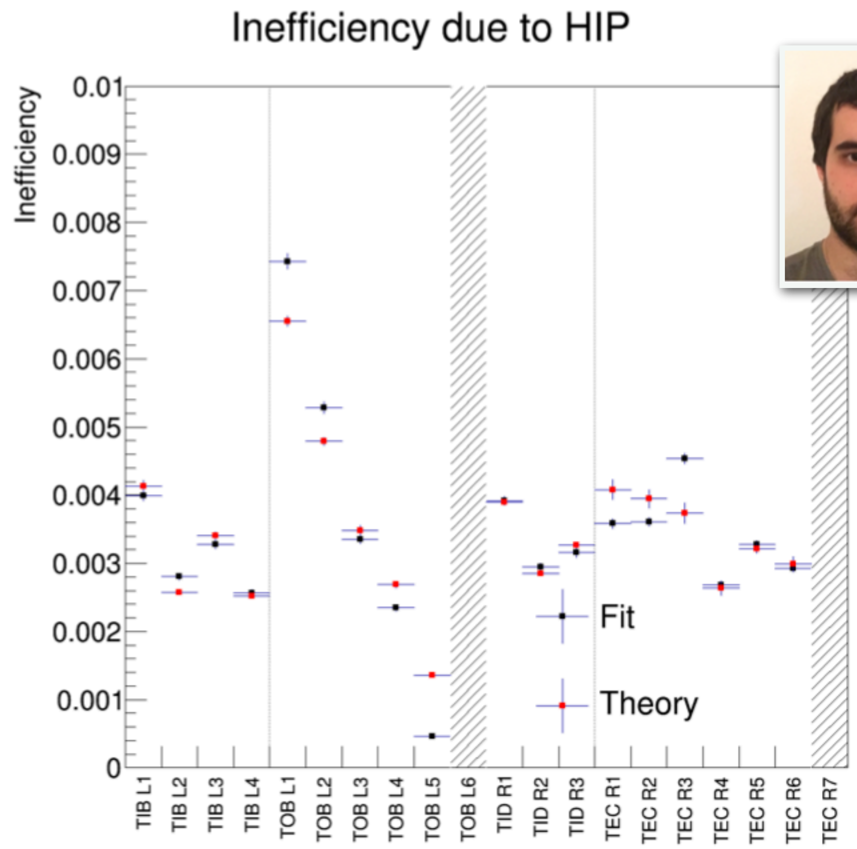


Historical involvement of IPHC

Participation to the construction

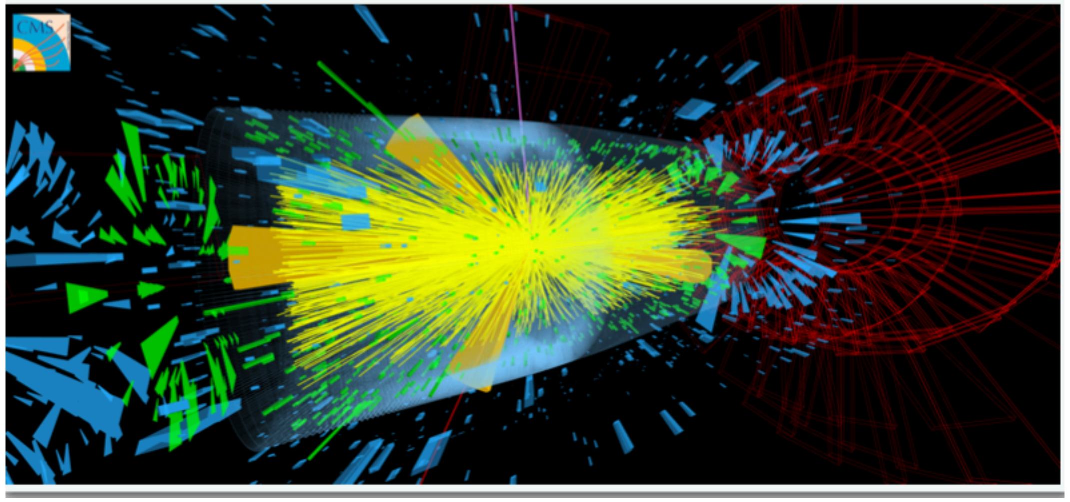
- Data-taking (shifts)
- Study of performances and monitoring: efficiency, ageing studies…



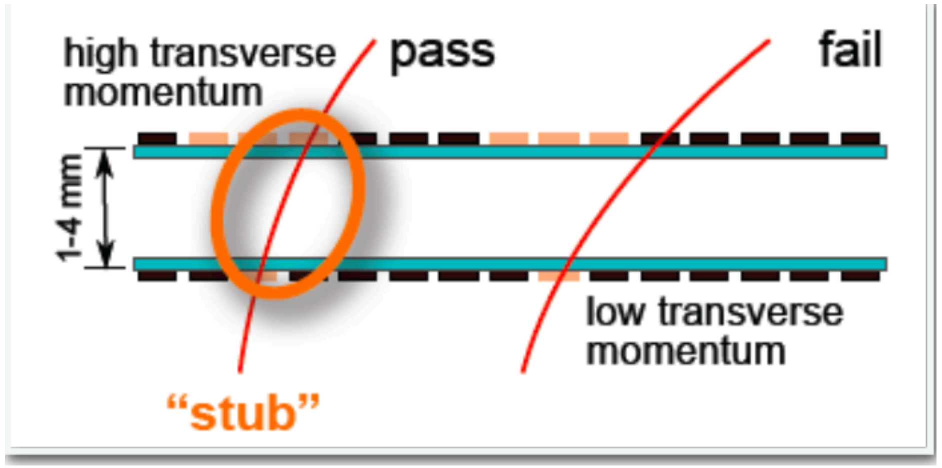


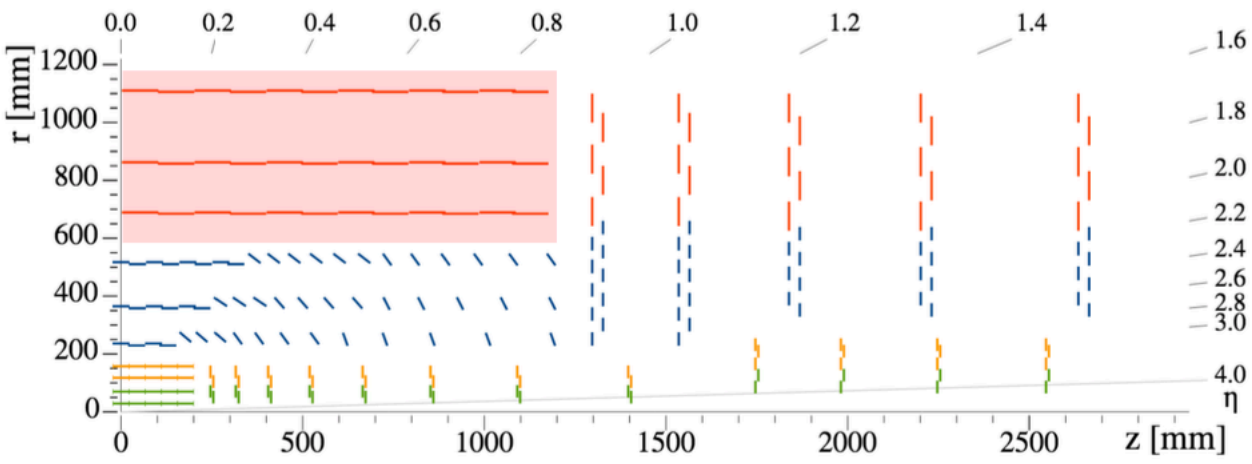
Responsibility of local reco & calibration of the strip tracker.

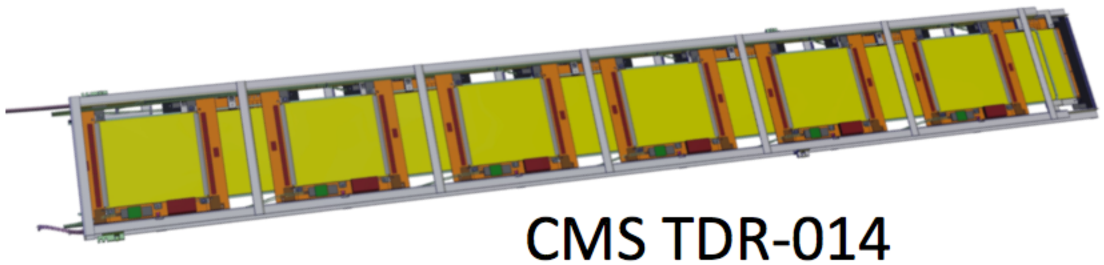
A new tracker for HL-LHC



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





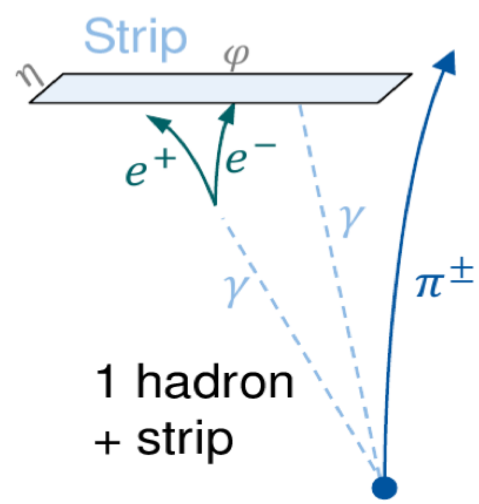


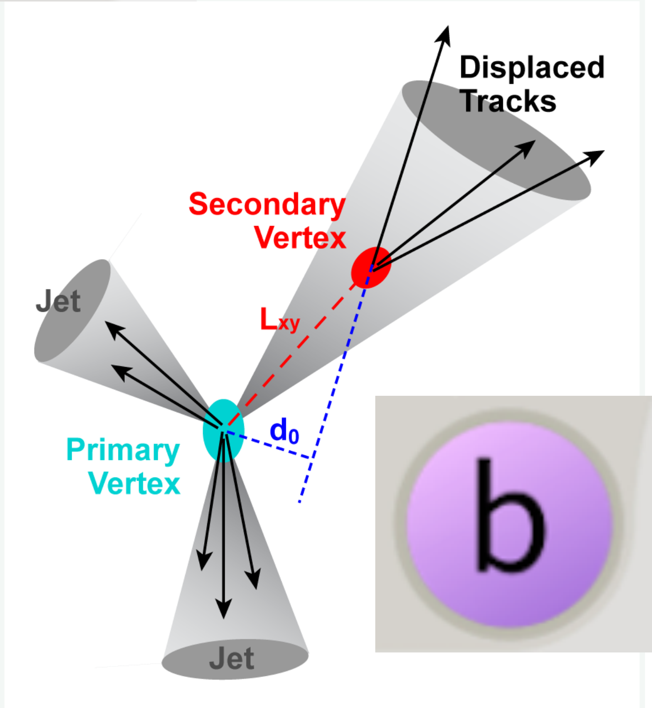
CMS TDR-014

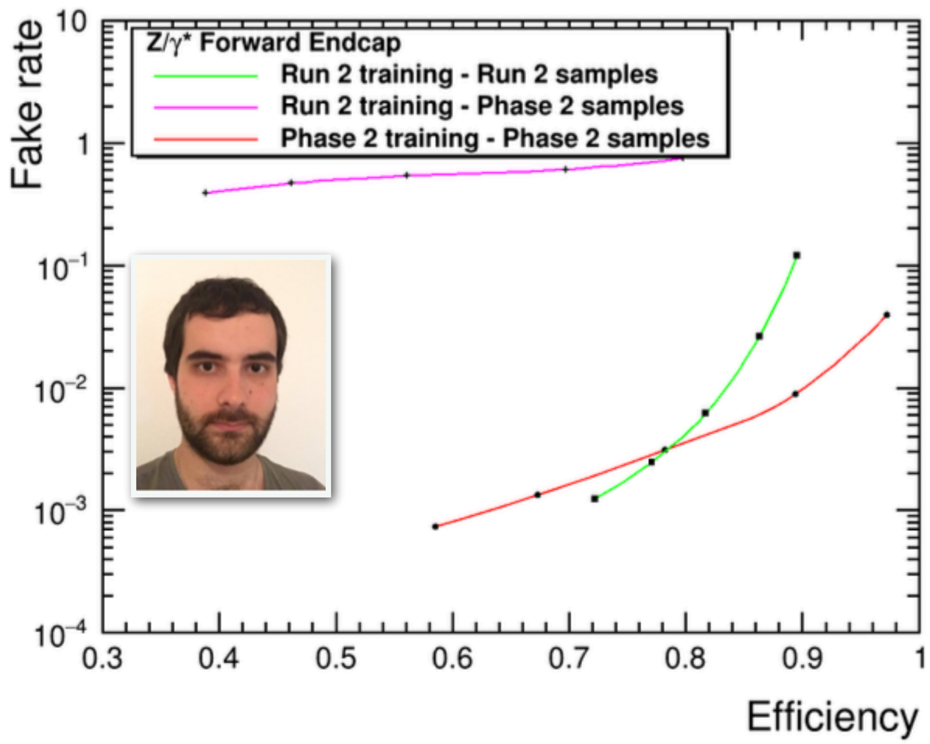
@ IPHC:
Data acquisition system
TB2S mechanics design (in red on the picture)
Module integration in ladders, assembling
Dedicated Cyrcé beam line, beam tests
TB2S commissioning

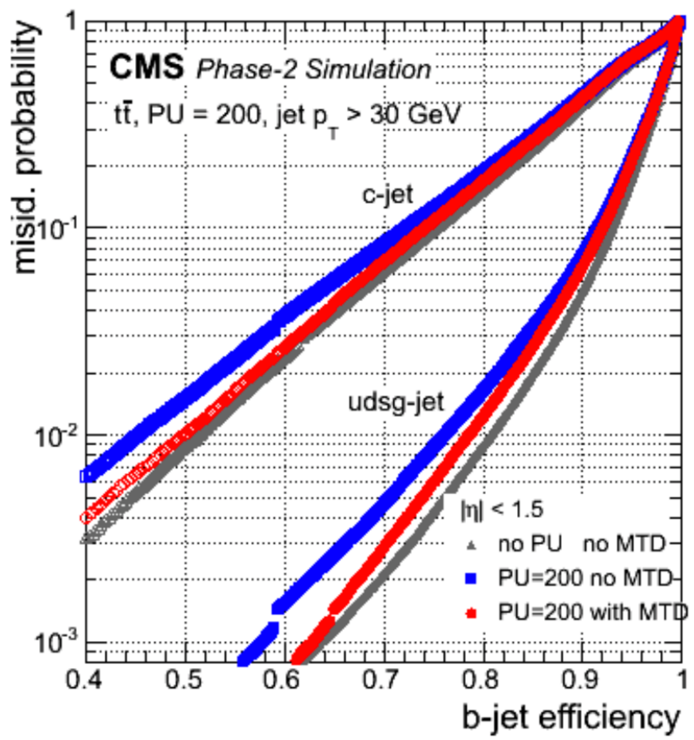
Particle reconstruction

Algorithm optimisation…
Commissioning in data…
Performance measurements…
Upgrade preparation…









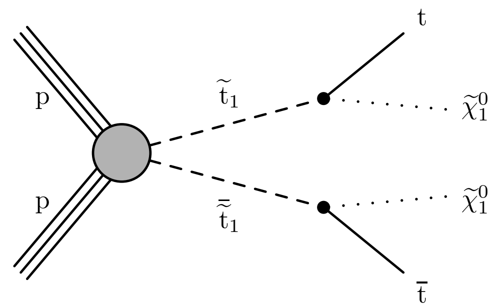
12 boosted decision trees to separate taus and electrons

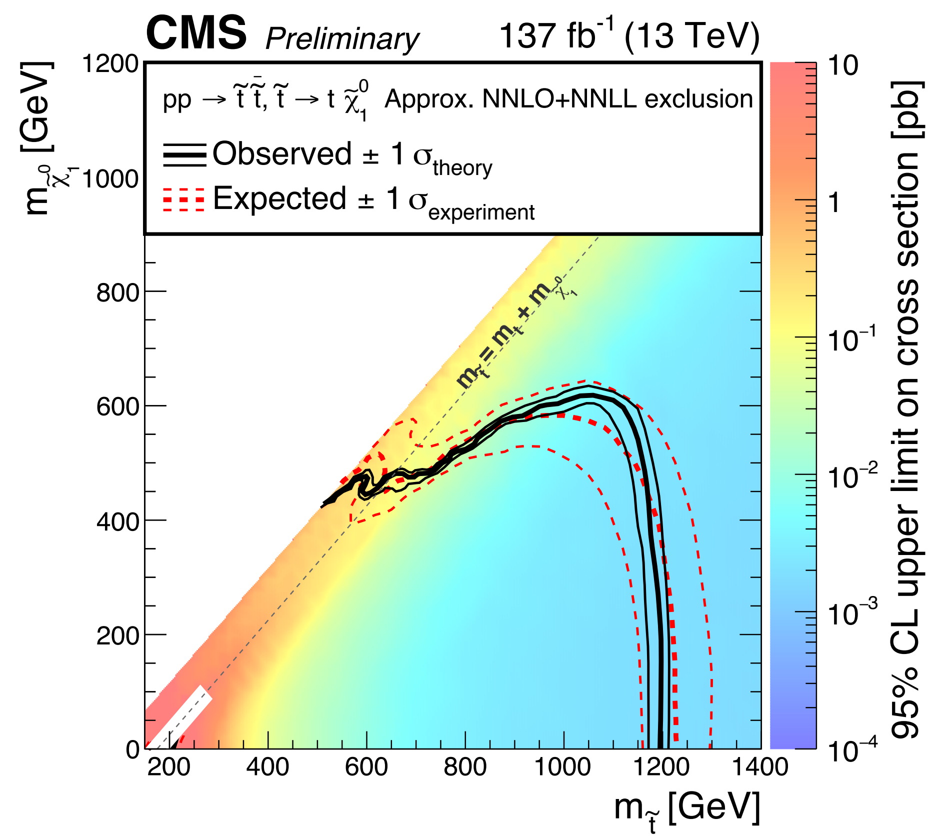
Performance with timing detector (HL-LHC) included…

Direct search for new physics

SUS-19-009

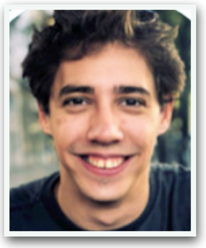
In the past, search for supersymmetric particles, **stringent limits** obtained on the **existence of supersymmetric stops** but with **simplified models**…



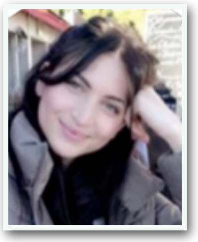


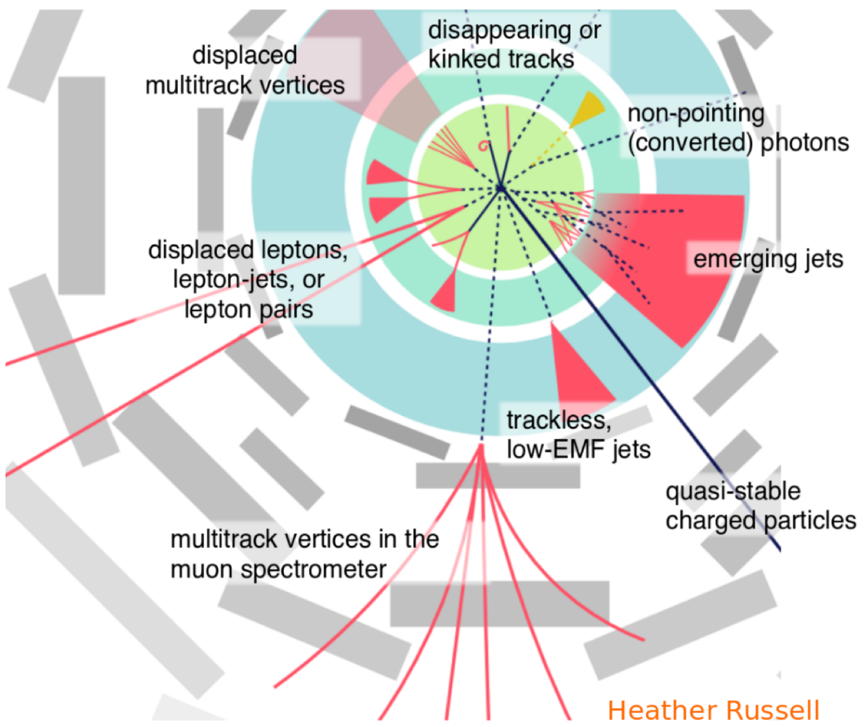
Search now for "exotic" scenarios - R-parity violation, gravitino LSP, compressed spectra…

→ Heavy charged stable particles (dE/dx)

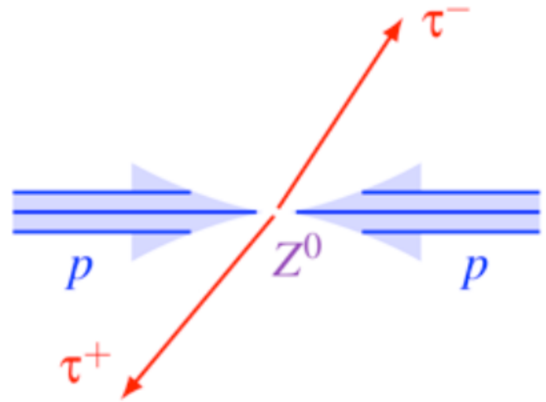


→ Displaced vertices





“Standard model” physics



Neutral bosons mix ⟹ Physical bosons

$$\begin{pmatrix} Z^0 \\ \gamma \end{pmatrix} = \begin{pmatrix} \cos\theta_W & -\sin\theta_W \\ \sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} W^0 \\ B^0 \end{pmatrix}$$

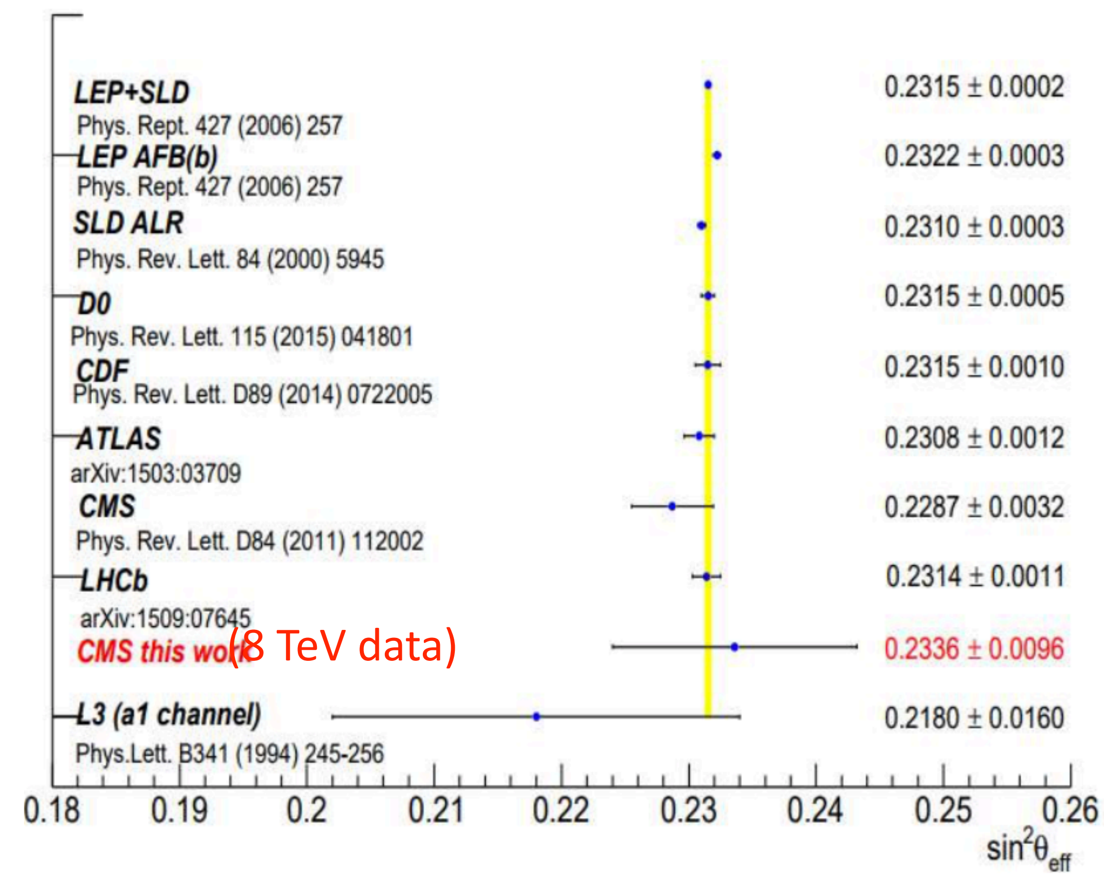
Measurement of the electroweak mixing angle in Z to ττ decays depends on the tau polarisation:

$$P_\tau = \frac{N^+ - N^-}{N^+ + N^-} = \frac{N^+ - N^-}{N^{total}}$$

Polarisation: difference between helicity +1 and -1 particles

Helicity: spin projection along momentum

$$h = \frac{\vec{\sigma}\cdot\vec{p}}{|\vec{p}|} = \pm 1$$



Nail down long existing discrepancies…

Phenomenology

Expertise logiciel

FeynRules,
MadGraph_MC@NLO,
Pythia,
Delphes

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

MAD Analysis 5

Développement

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

Etudes phénoménologiques

Model building

$$\mathcal{L}_{int} = -W_a F^a - W^{*a} F_a^\dagger - \frac{1}{2} W_{ab} \psi^a \cdot \psi^b - \frac{1}{2} W^{*ab} \bar{\psi}_a \cdot \bar{\psi}_b$$

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

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

1ère école internationale
MadAnalysis 5
en Corée (2017)

Publi Monotop hadronique
PhysRevD 84 074025
51 citations

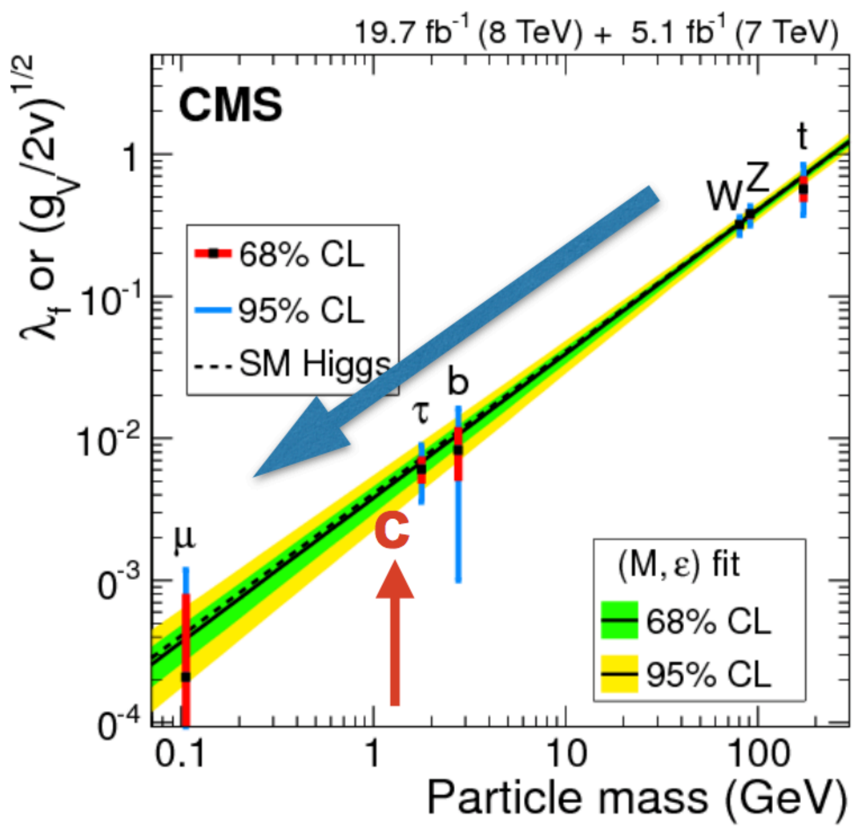
15 publications
depuis 2012

Towards a global picture of the Higgs boson properties

M_H = 125.35 ± 0.12 (stat.) ± 0.09 (syst.) GeV
→ **1.2 per mille accuracy**, 35.9 fb^{-1}, from $H \to \gamma\gamma$ and $H \to 4\ell$ channels

Width: 0.08 < Γ(H) < 9.16 MeV
→ new lower bound

Spin-parity: 0^+



Run 1: discovery using decays to bosons

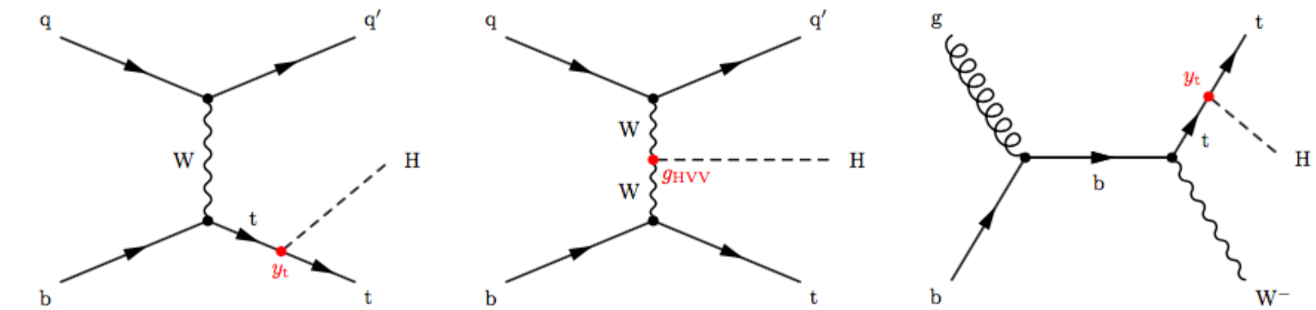
Run 2: couplings to 3rd generation fermions

Run 3: extend sensitivity to physics beyond the SM

HL-LHC: probe the Higgs self-coupling

Search for tH(q)

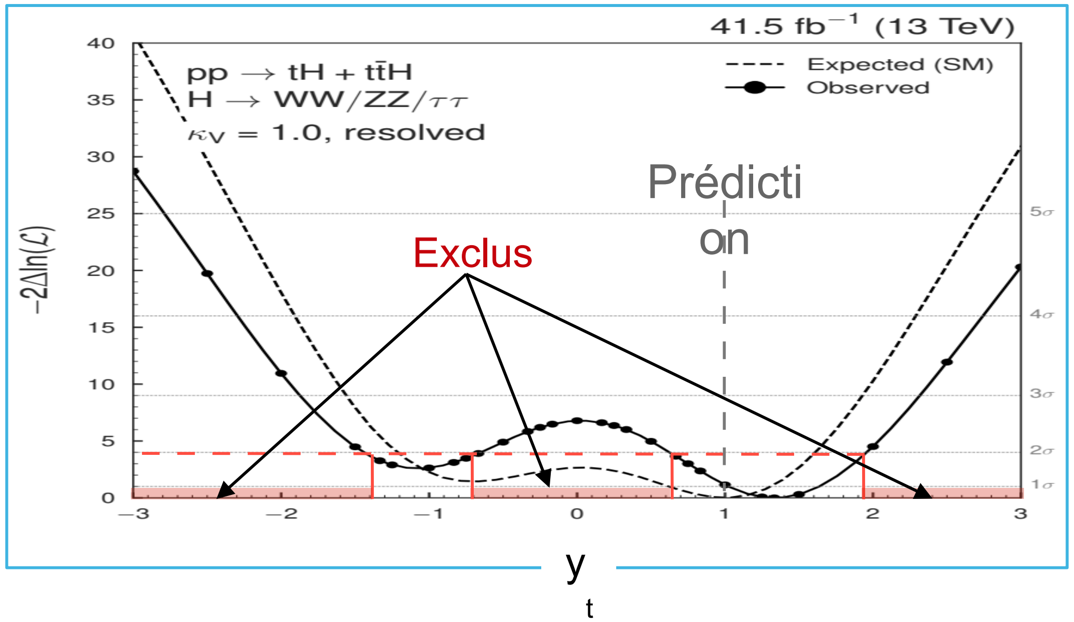
Measure the relative sign of the top Yukawa coupling (w.r.t. κ_V...)



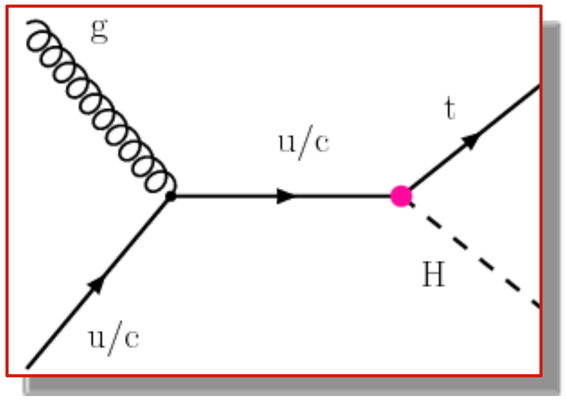
σ(qb →tHq)=0.074 pb
t-channel

σ(qb →tHq)=0.003 pb

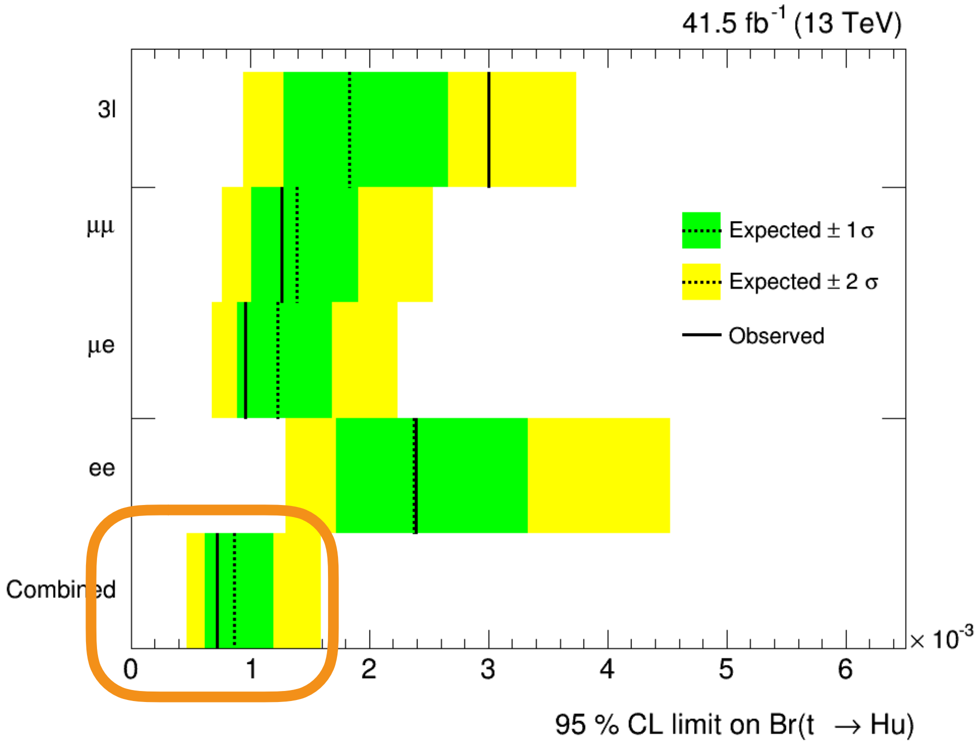
σ(gb →tHW)=0.015 pb
-associated



Search for FCNC processes (forbidden in SM...)



Best limits (95% CL):
Br(t→Hu) < 0.072
Br(t→Hc) < 0.085



Internship and thesis subject

(Mailto: anne-catherine.lebihan@iphc.cnrs.fr)

Spin-parity = 0^- excluded from measurements made in decays into electroweak bosons (Phys.Rev.Lett. 110 (2013) no.8)

But the Higgs boson could have a CP violating term showing up in its Yukawa couplings and have a pseudo-scalar component $J^{CP}=0^{-+}$:

τ Yukawa coupling →

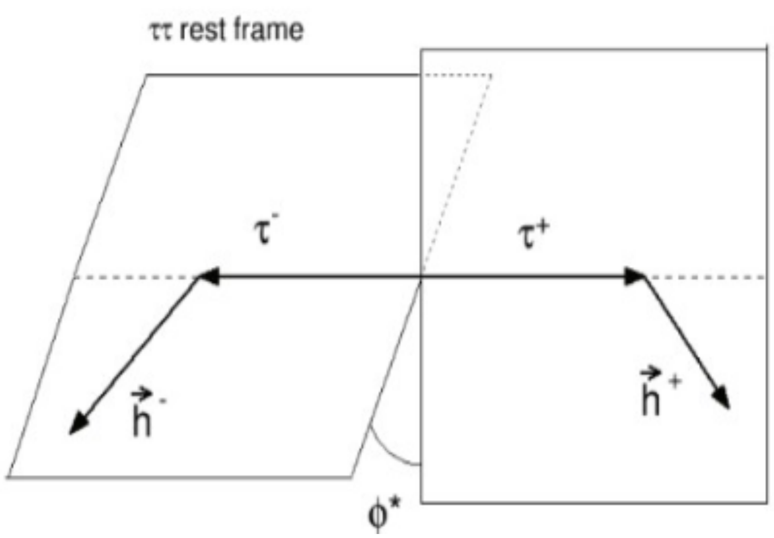
$$L_Y = g_\tau(\cos\alpha_\tau \bar{\tau}\tau + \sin\alpha_\tau \bar{\tau}\gamma_5\tau)$$

α_τ=0 in the SM

pseudo-scalar CP violating term ?

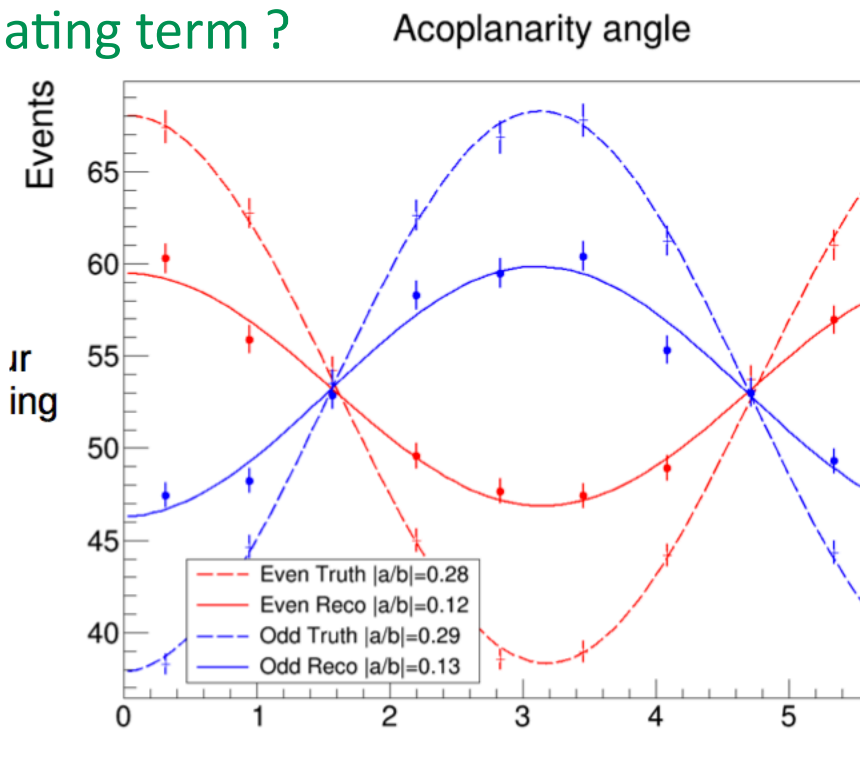
Higgs SM
Higgs pseudo-scalar
a1-a1 $\tau\tau$ final state

Transverse tau spin correlations sensitive to CP violation
Use polarimetric (h) vector to characterise the spin (s)



Tau decay partial width defines polarimetric vector:

$$d\Gamma \propto (1+\vec{h}.\vec{S})$$



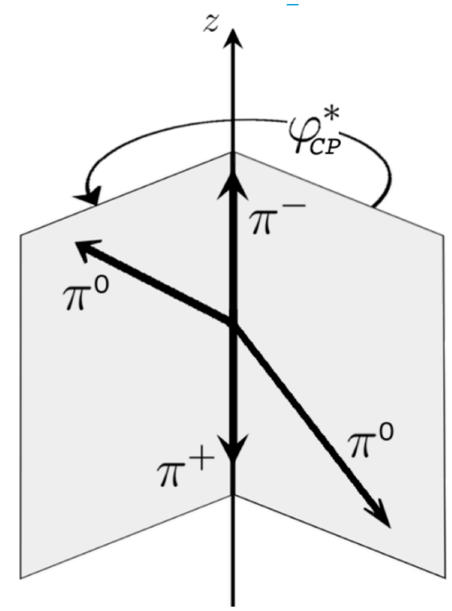
Use acoplanarity angle φ to characterise the tau Yukawa coupling
Model independent method!

Internship and thesis subject

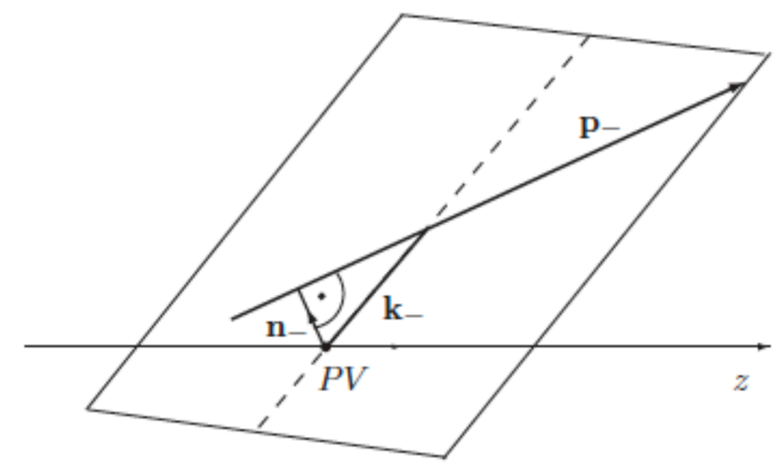
(Mailto: anne-catherine.lebihan@iphc.cnrs.fr)

Compare polarimetric method w/ different methods depending on the tau decay modes….

Decay mode	Meson resonance	$\mathcal{B}$ [%]
$\tau^- \to e^- \overline{\nu}_e \nu_\tau$		17.8
$\tau^- \to \mu^- \overline{\nu}_\mu \nu_\tau$		17.4
$\tau^- \to h^- \nu_\tau$		11.5
$\tau^- \to h^- \pi^0 \nu_\tau$	$\rho(770)$	26.0
$\tau^- \to h^- \pi^0 \pi^0 \nu_\tau$	$a_1(1260)$	9.5
$\tau^- \to h^- h^+ h^- \nu_\tau$	$a_1(1260)$	9.8
$\tau^- \to h^- h^+ h^- \pi^0 \nu_\tau$		4.8
Other modes with hadrons		3.2
All modes containing hadrons		64.8



decay plane method



impact parameter method

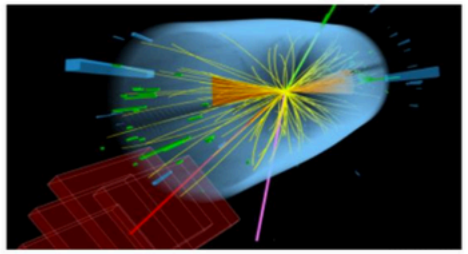
Exploit BDTs and NN in data to select the Higgs boson…

Optimise primary vertex reconstruction, impact parameter, tau momentum estimates…

Collaboration with DESY (Hamburg), Imperial College (London)…

More information about CMS ?

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

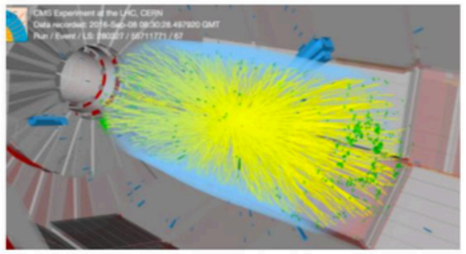


WATCHING THE TOP QUARK MASS RUN

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

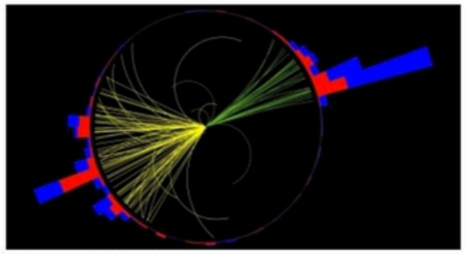


HOW CMS WEEDS OUT PARTICLES THAT PILE UP

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

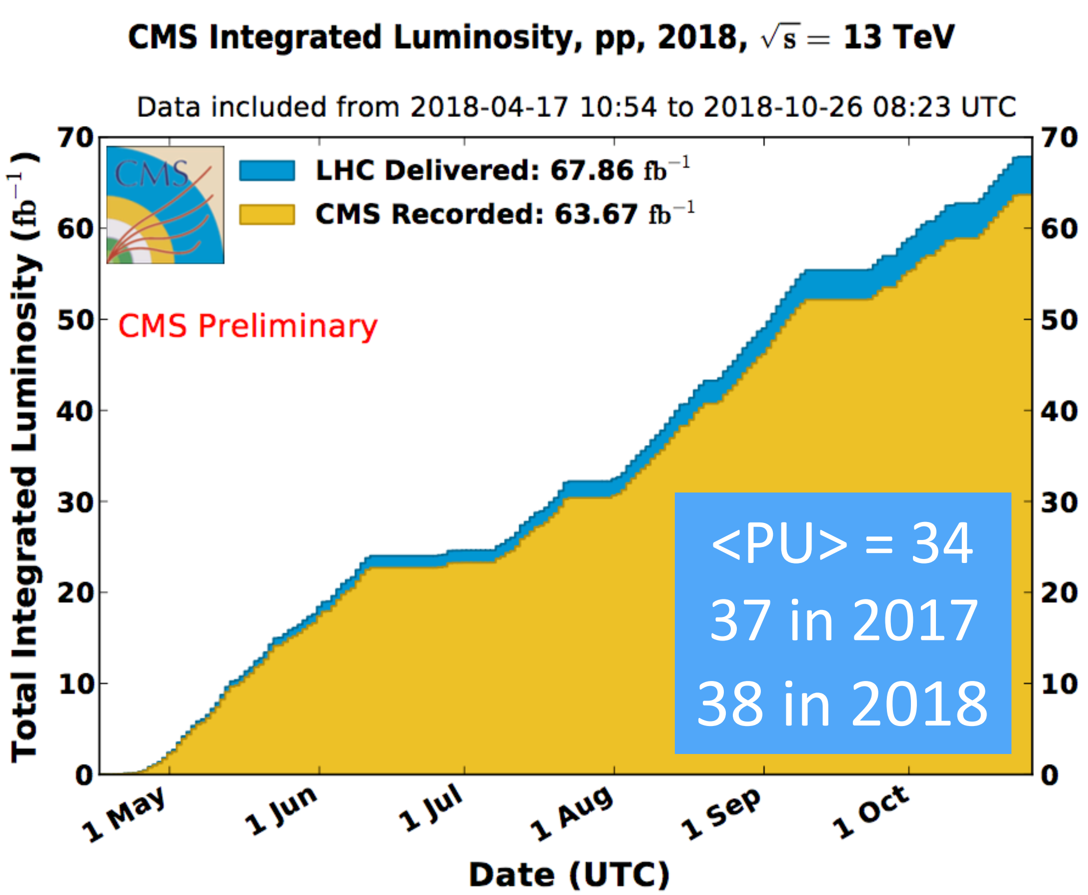
Backup

Run 2 finished in 2018...

Excellent data quality with evolved detector!

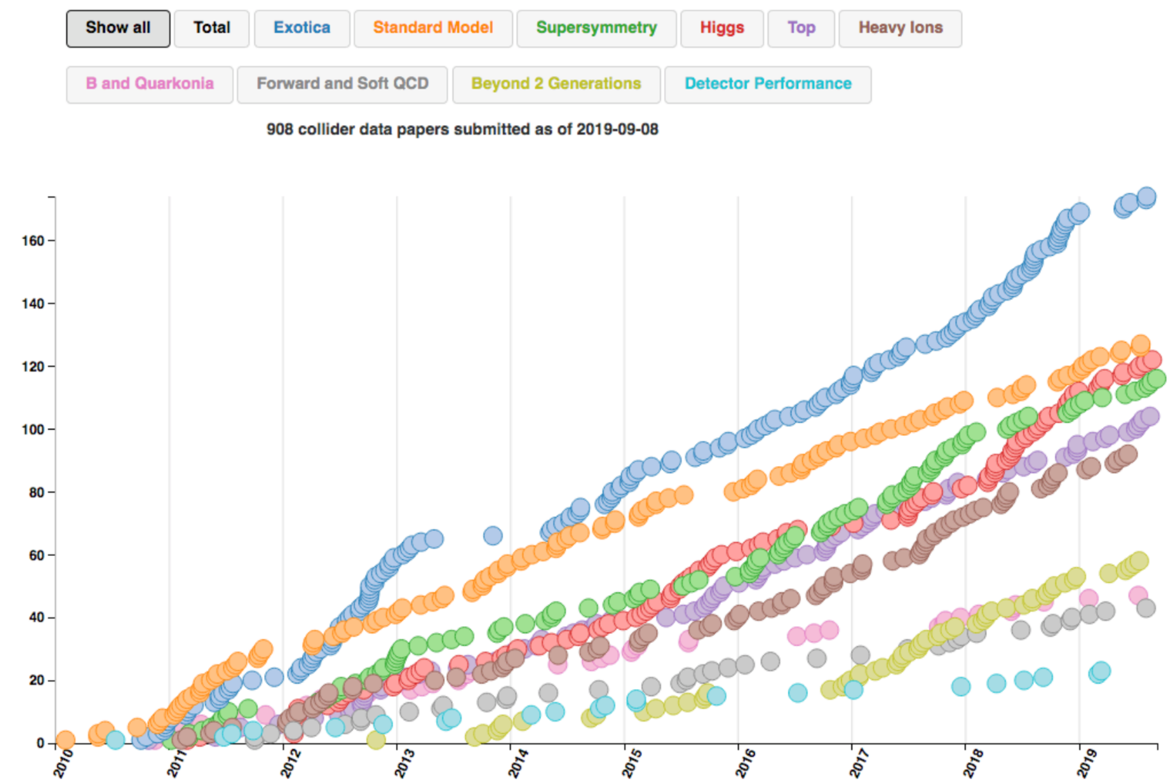
- upgrade of the pixel detector with 4 layers

- upgrade of the HCAL readout (long. segm.)



- 64 papers published in 2019

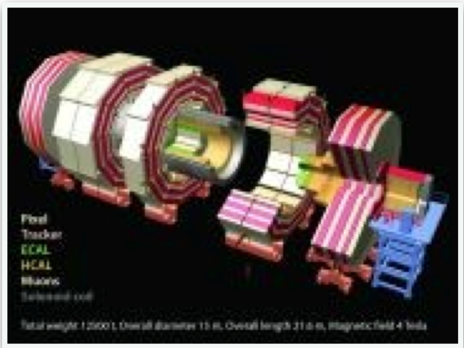
- 910 since the beginning of Run 1

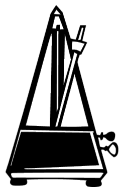


https://tinyurl.com/y9odauv6

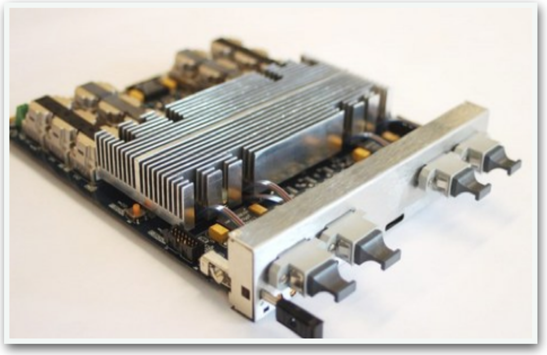
Trigger system

Trigger strategy



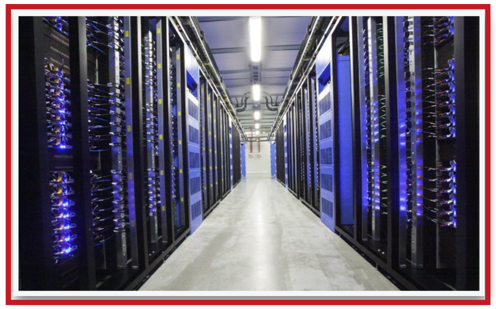


L1 ↓ 40 MHz



hardware

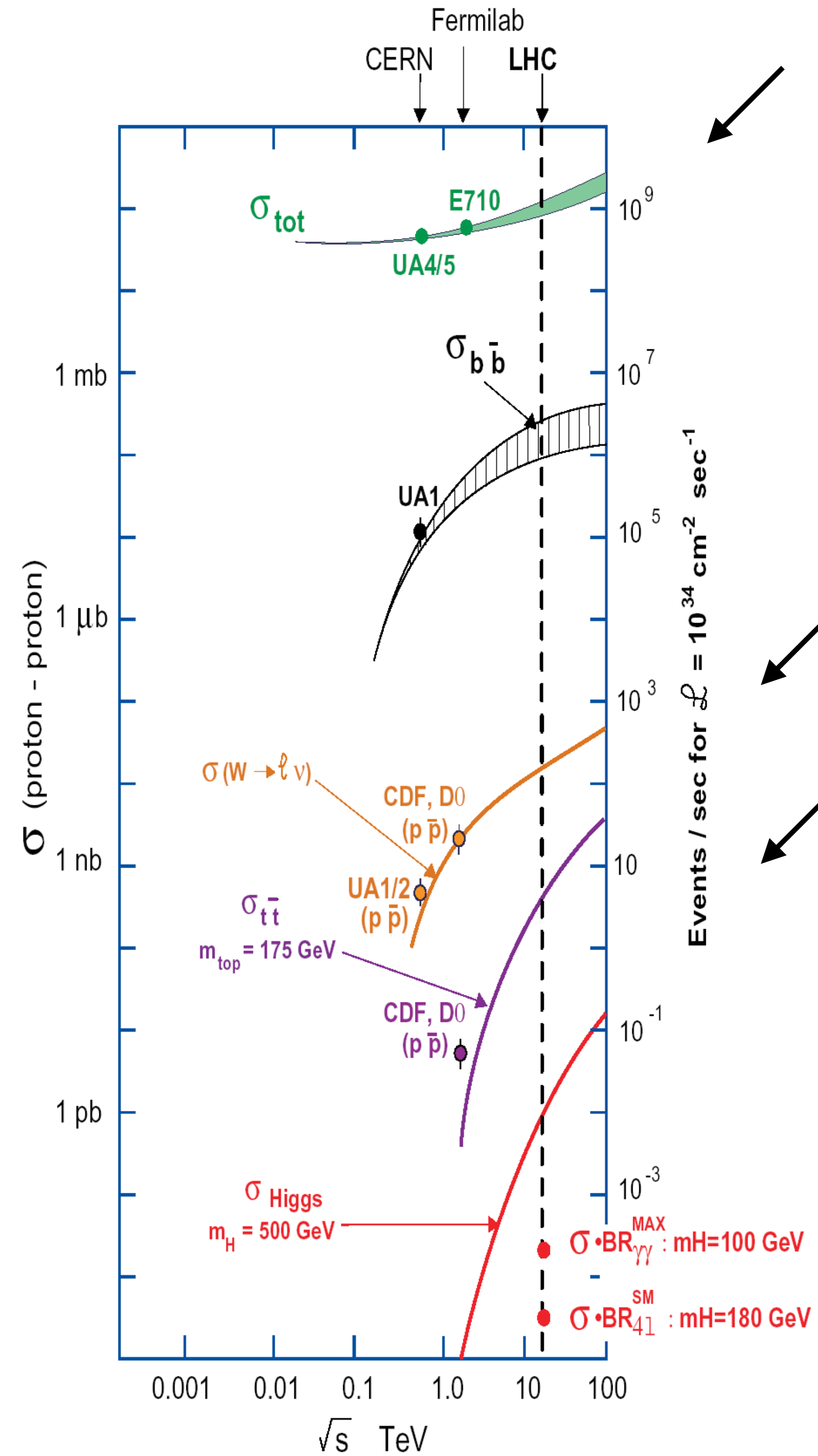
HLT ↓ 100 kHz



software

↓ 1 kHz

STORAGE

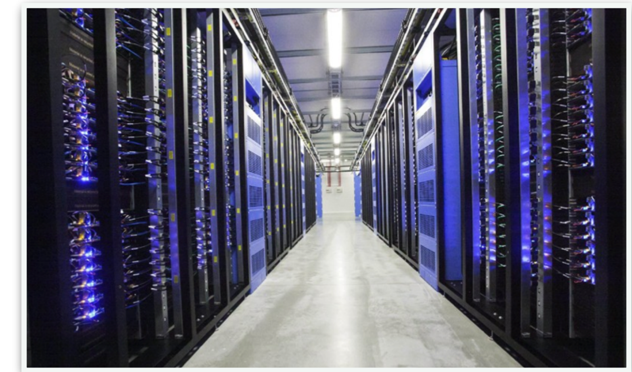


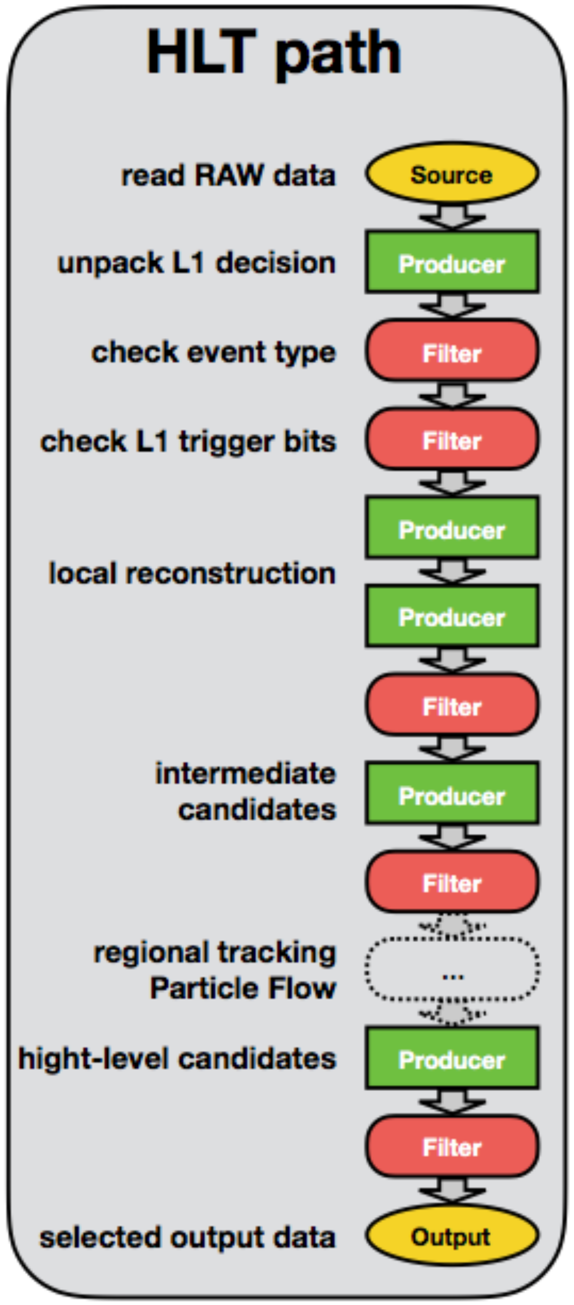
LHC rate = 40 MHz

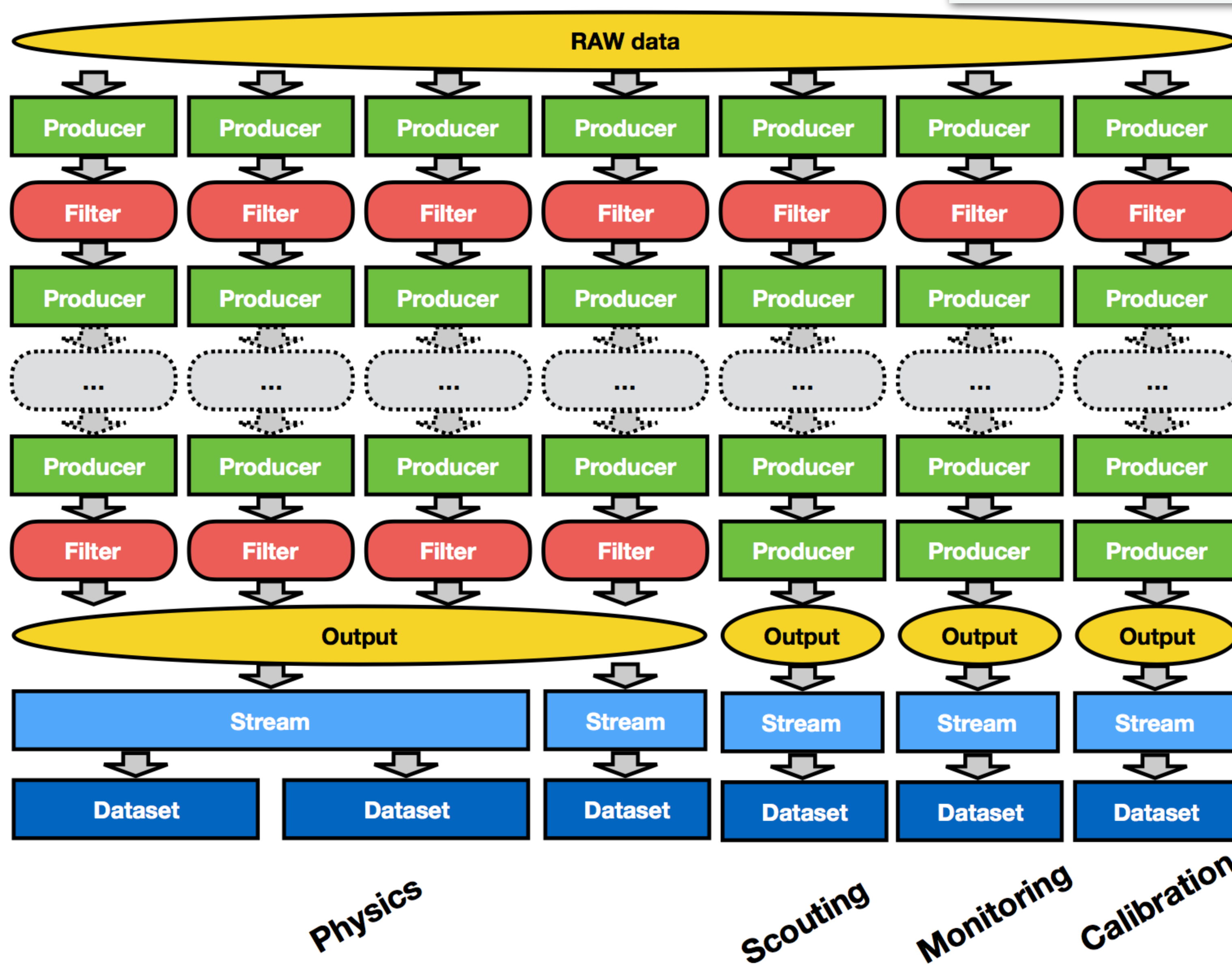
Rate to be written on disk
1 kHz

Physics rate
10 Hz

How does the trigger work ?





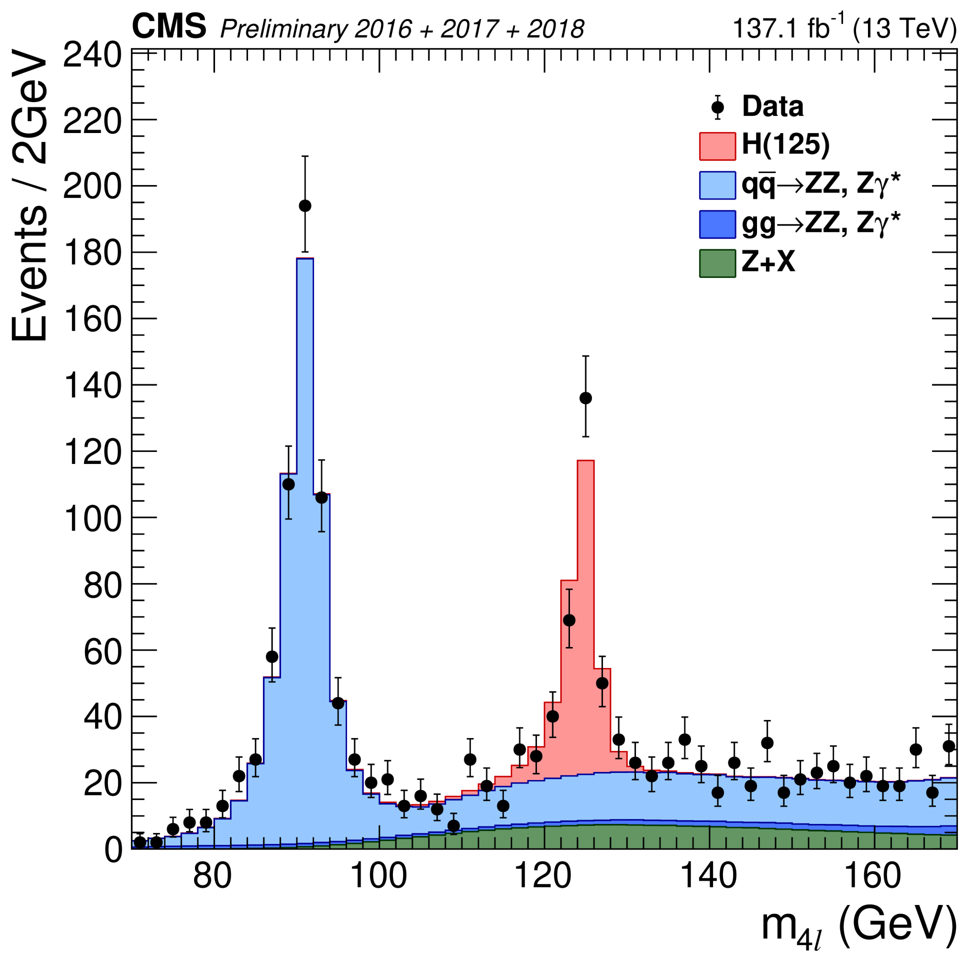


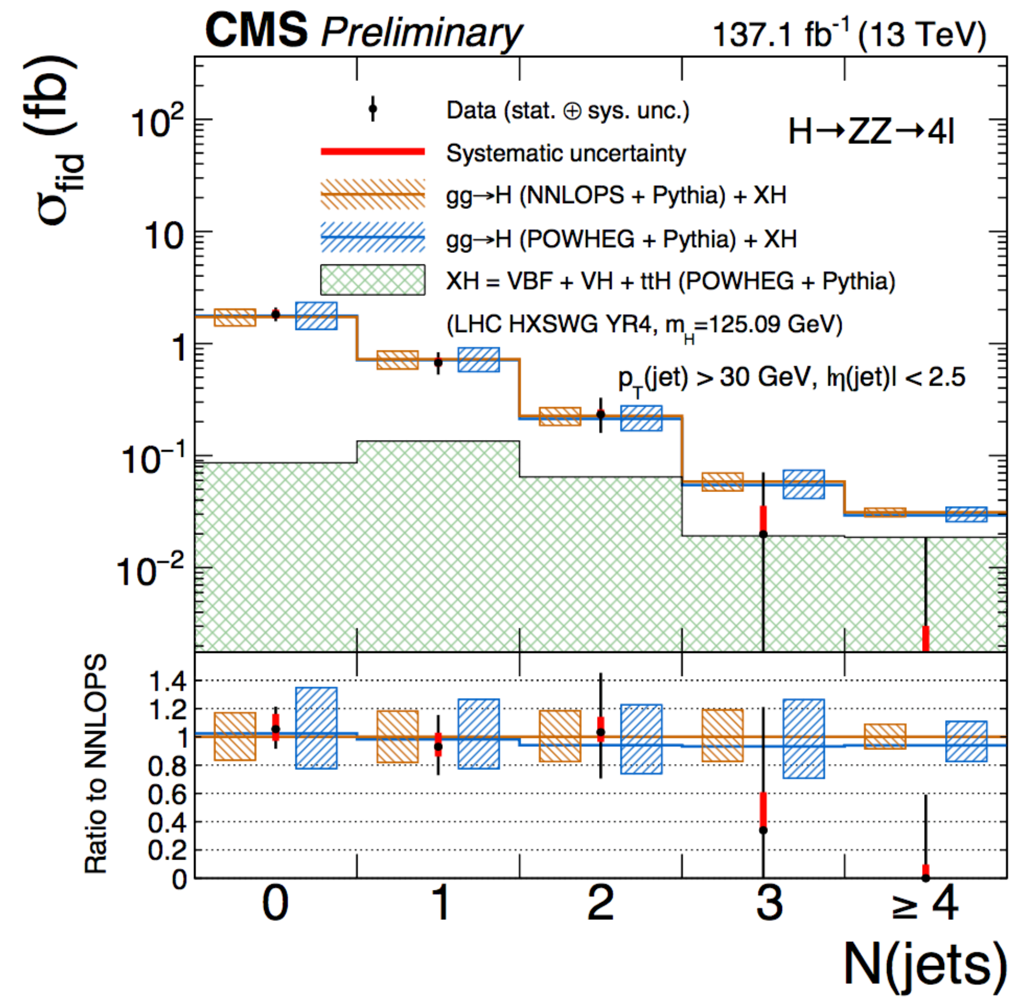
- ✦ Independent trigger paths ;
- ✦ **Common sequences** ;
- ✦ Different **streams and datasets** ;
- ✦ **Specific trigger memus for** commissioning, cosmics, low PU and heavy ions.

ZZ channel

CMS-PAS-HIG-19-001

Excellent channel for H boson characterisation (m_H, Γ_H, S^{CP}, diff. xsec)



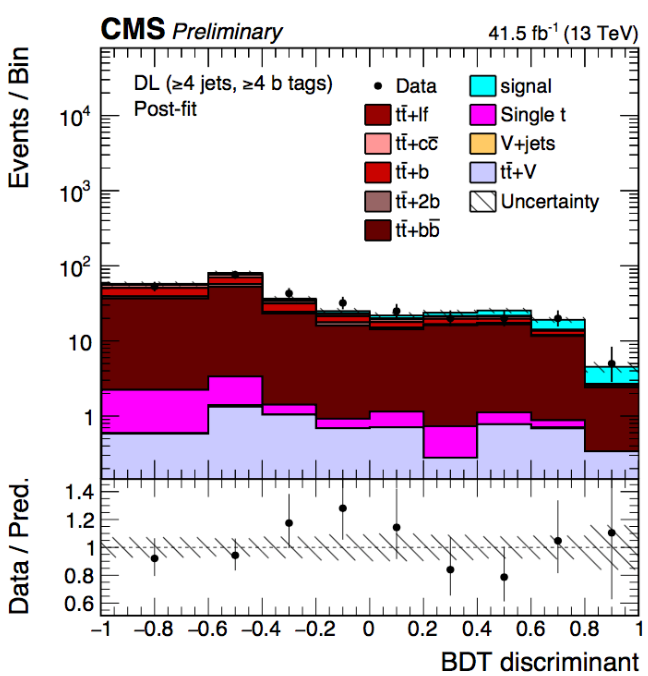


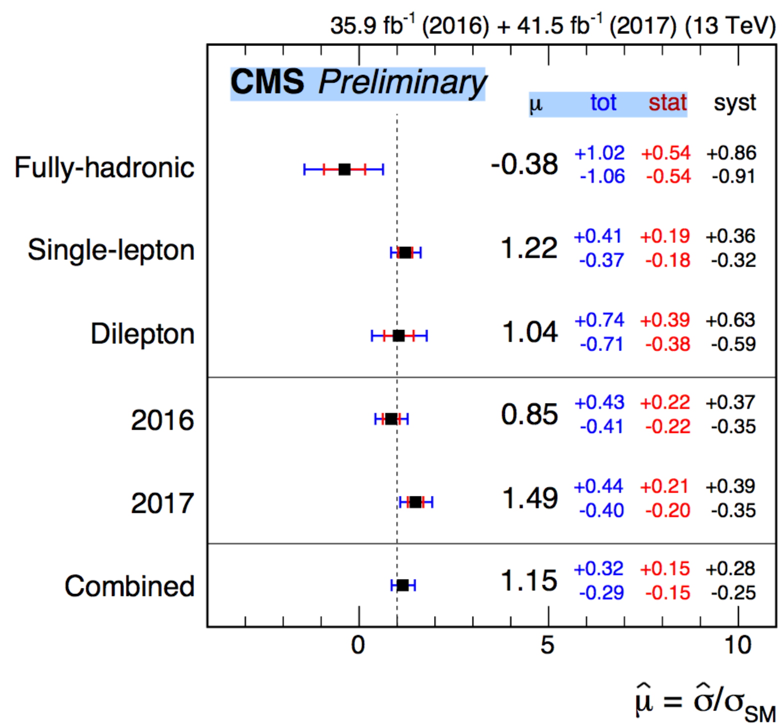
Towards 10% uncertainty on the coupling! Stage 1.1 STXS…

Differential cross sections: vs number of associated jets, pT and rapidity of H, …

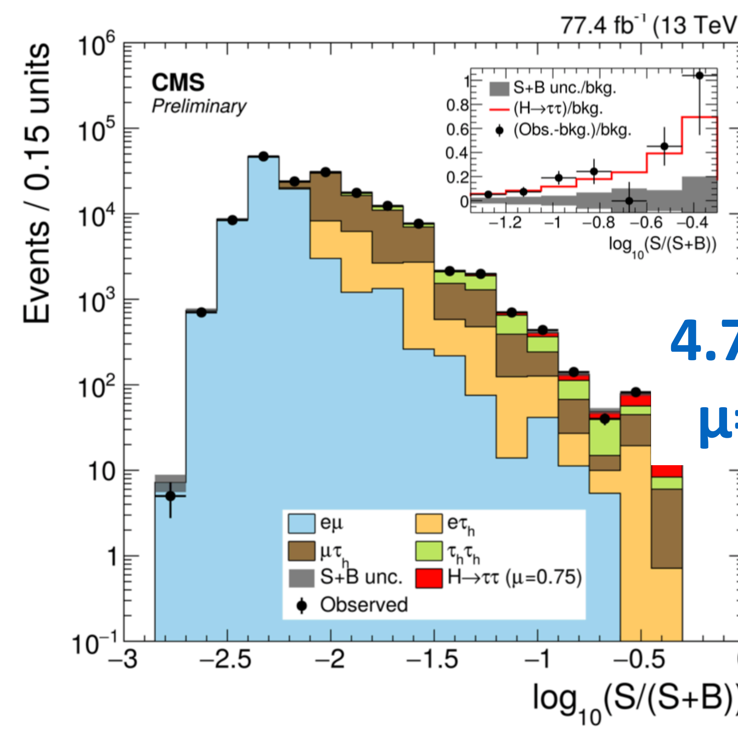
Decays to 3rd generation

ttH, H →bbar, HIG-18-030





H→ττ, HIG-18-032



4.7σ (6.6 exp.)
μ=0.75±0.18

Observation of H→bb by both ATLAS and CMS in 2018

Now: evidence to bb decays using ttH only!

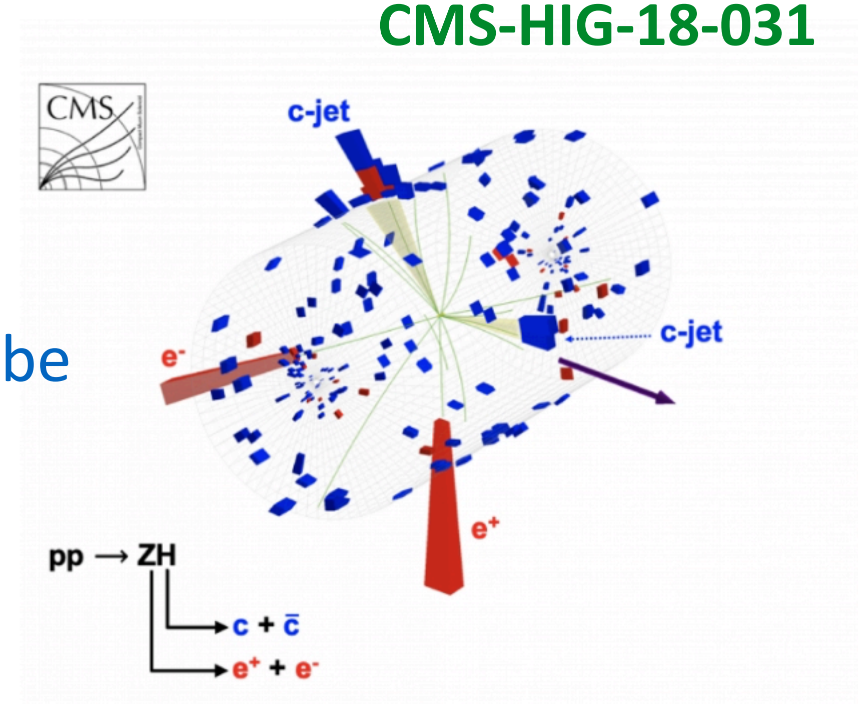
Improved MVA techniques and b-jet identification

NN classification to distinguish productions modes

90% of backgrounds from data

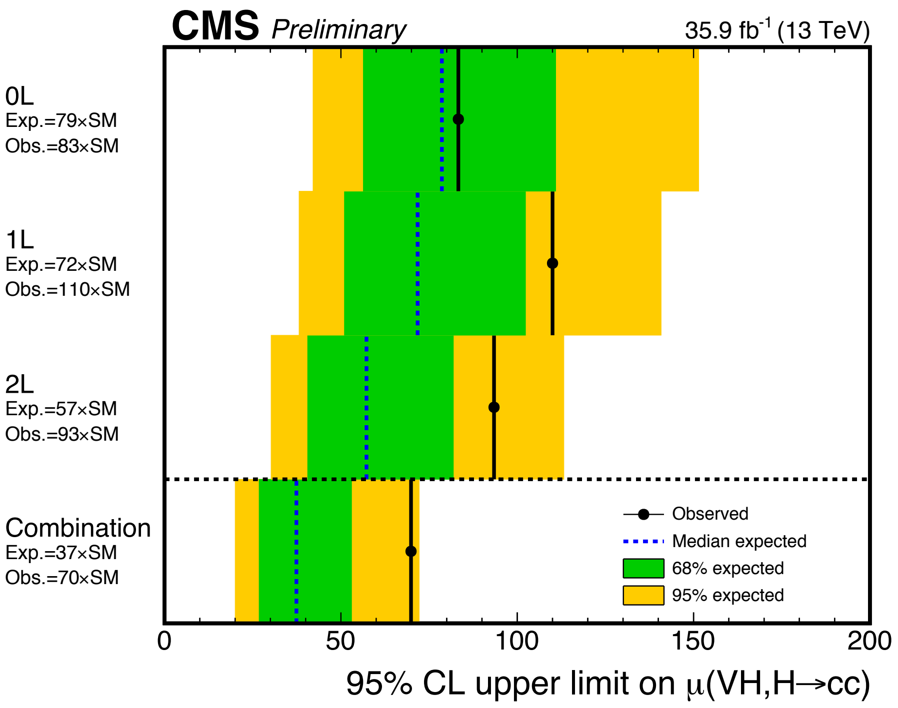
Stage-1 STXS, …

Towards the 2nd generation

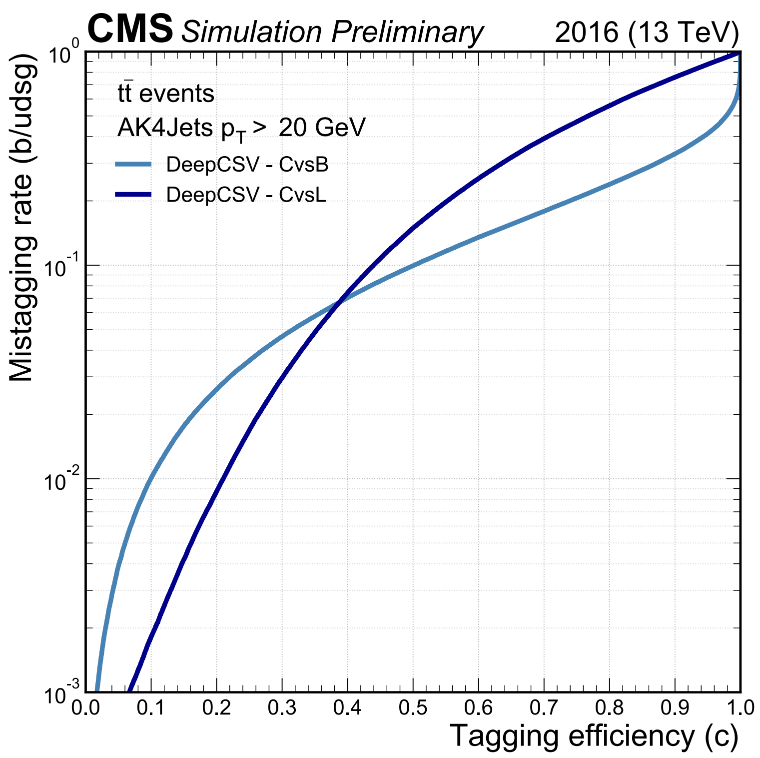


Charm coupling, same order as tau coupling, but harder to probe

- BR(H→cc)~0.05×BR(H→bb)
- large (hadronic) background
- charm jet ID is highly challenging



- Categorisation of lepton multiplicities of V decays
- Advanced charm tagging techniques
- Resolved jets or merged jets



First result, still far away from SM: μ< 70 (obs.), 37 (exp.) at 95% CL…

H→μμ, currently about 2σ expected significance…

Towards HL-LHC…

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

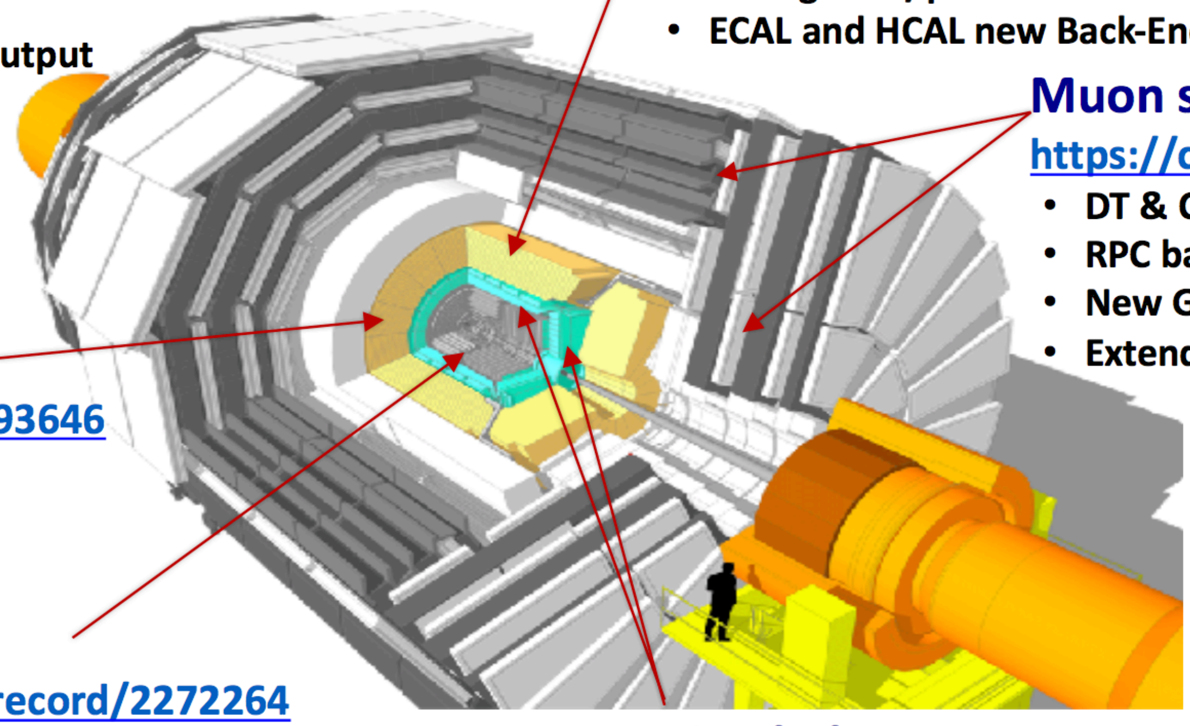
https://cds.cern.ch/record/2283187

- 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 $1.6 < \eta < 2.4$
- Extended coverage to $\eta \simeq 3$



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 $\eta \simeq 3.8$

MIP Timing Detector

https://cds.cern.ch/record/2296612

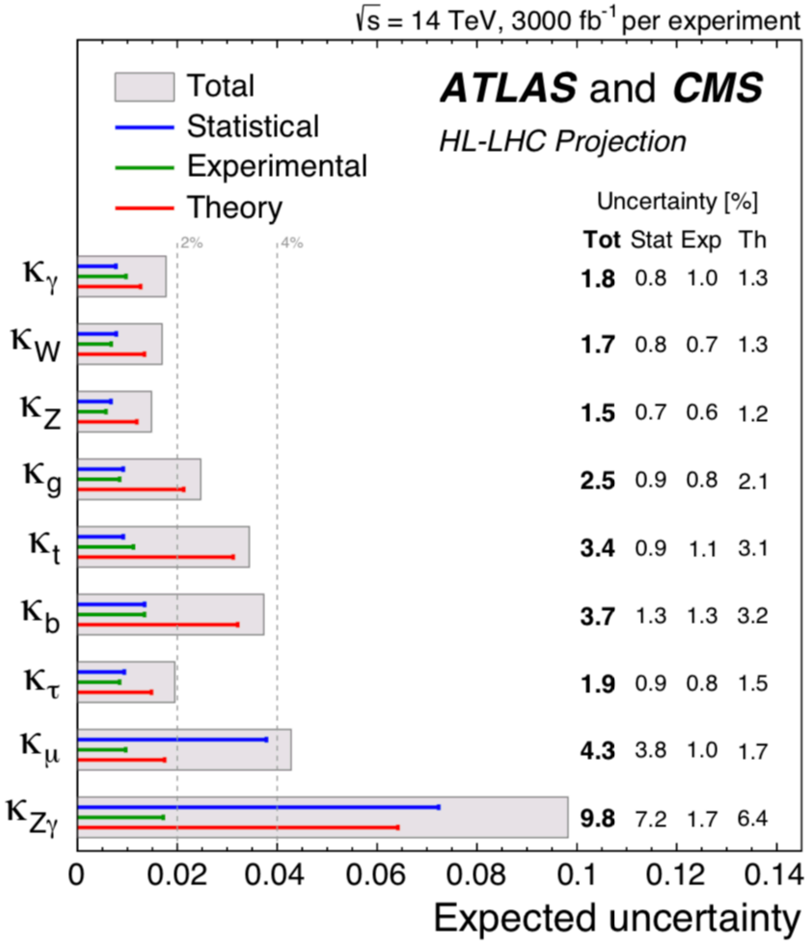
Precision timing with:

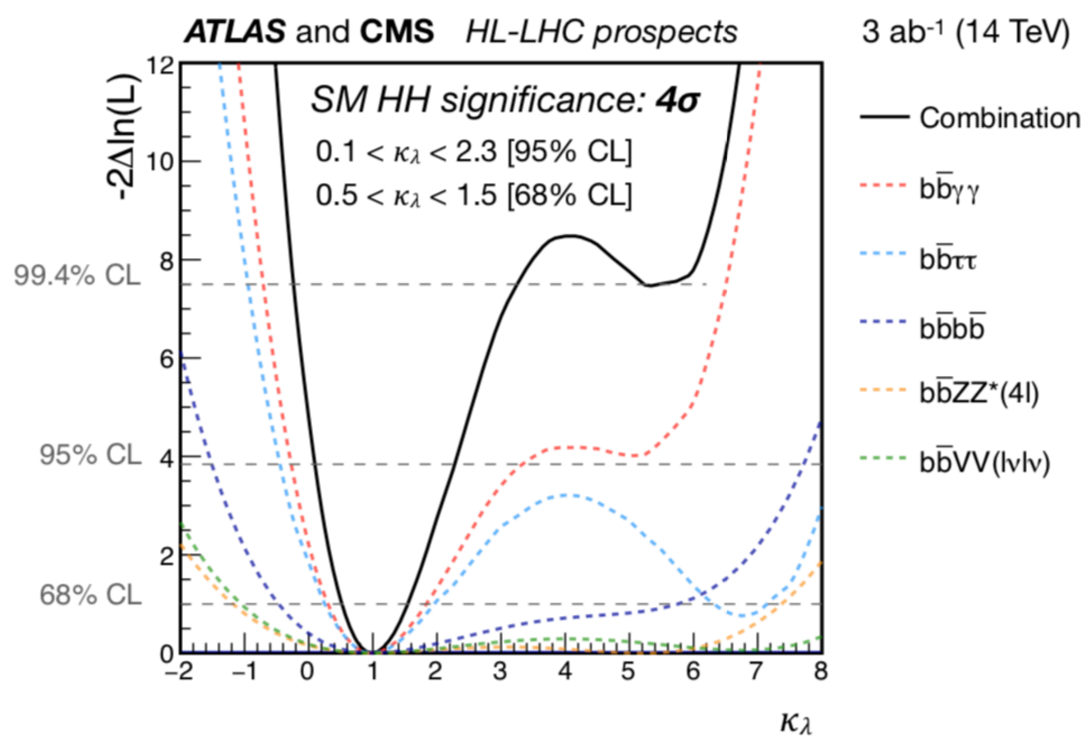
- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes

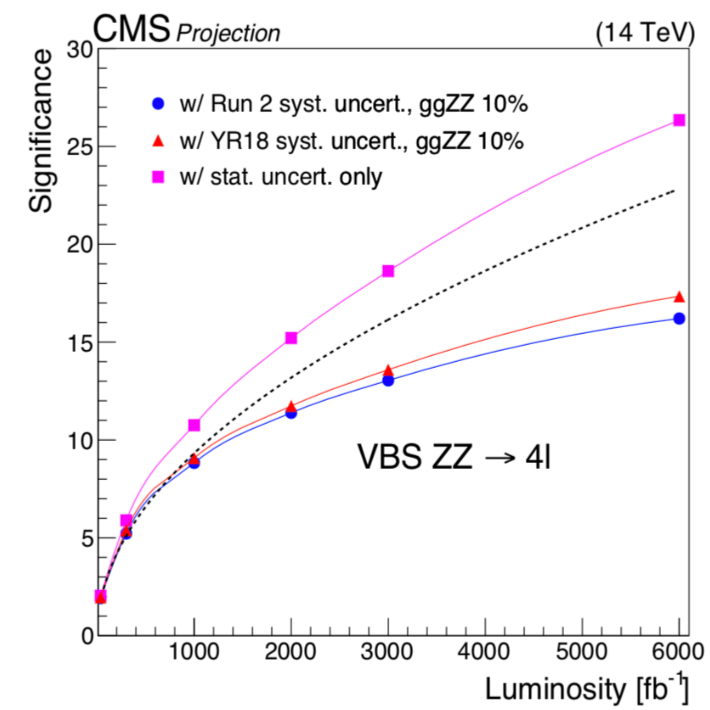
New paradigms (design/technology) for an HEP experiment to fully exploit HL-LHC luminosity

Towards HL-LHC...

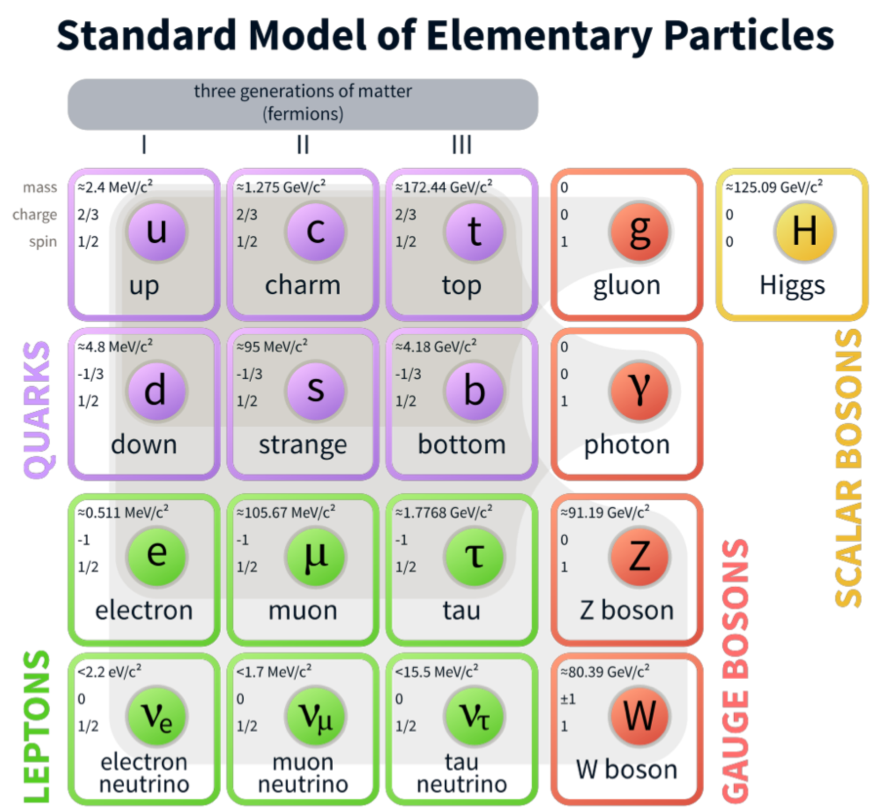
Physics



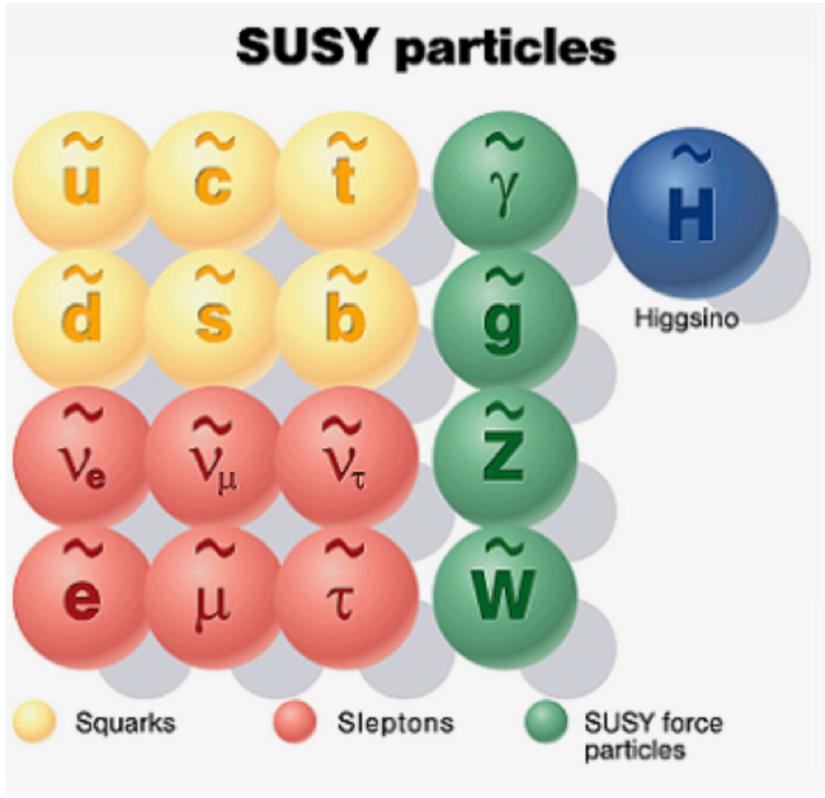




Supersymmetry



+



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