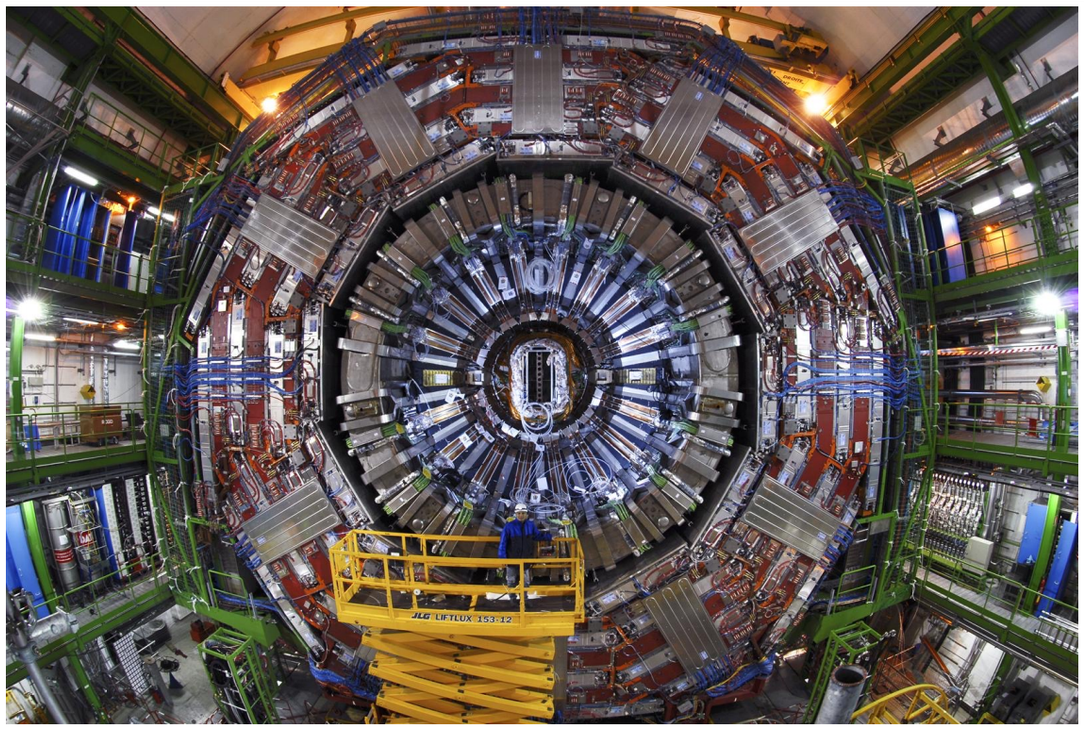
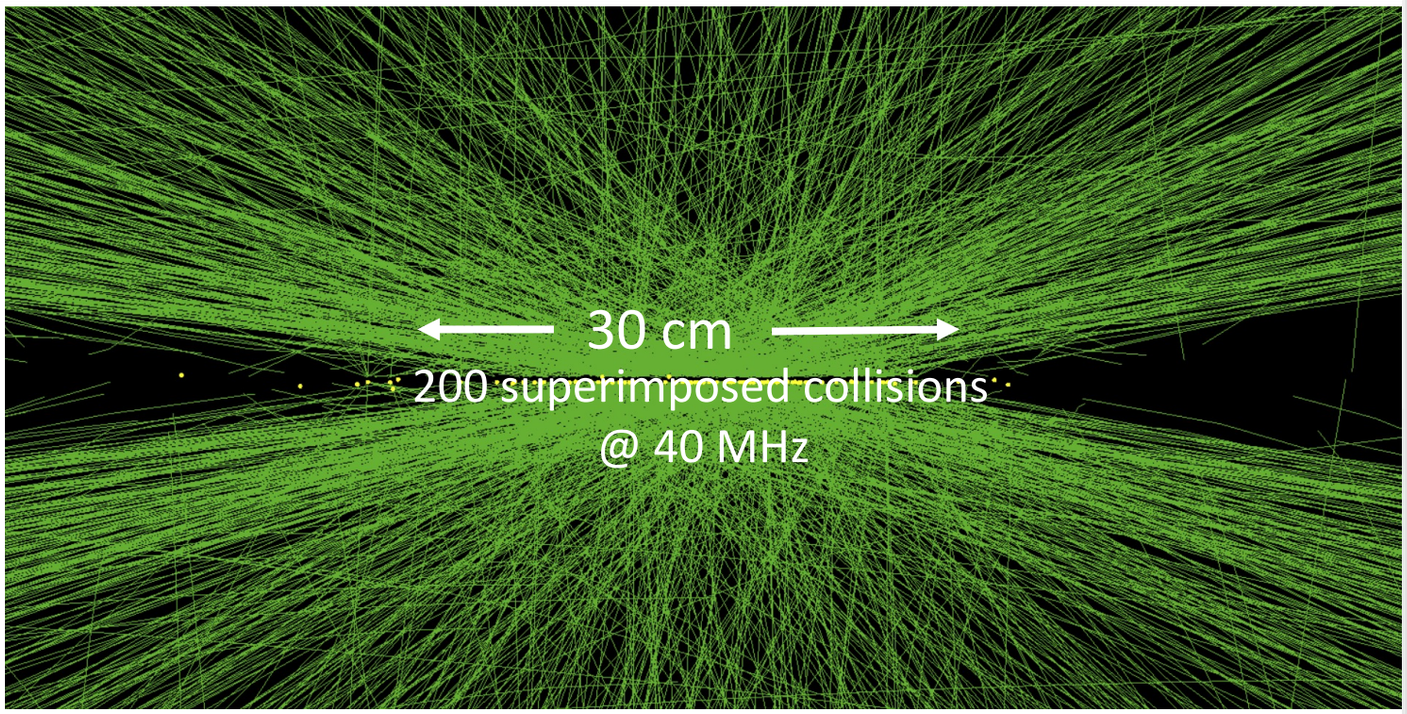
Why we need a CMS Upgrade ?

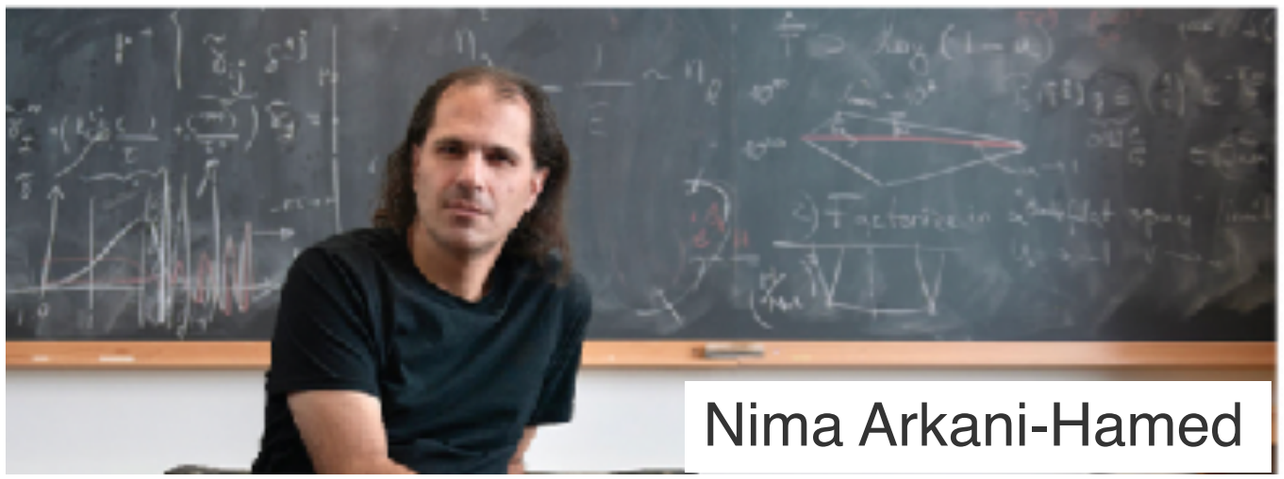
New Technologies to uncover **New** Physics

Frank Hartmann – CMS Upgrade Coordinator





CMS at HL- LHC – In other words ..

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FEATURE

Interview: In it for the long haul

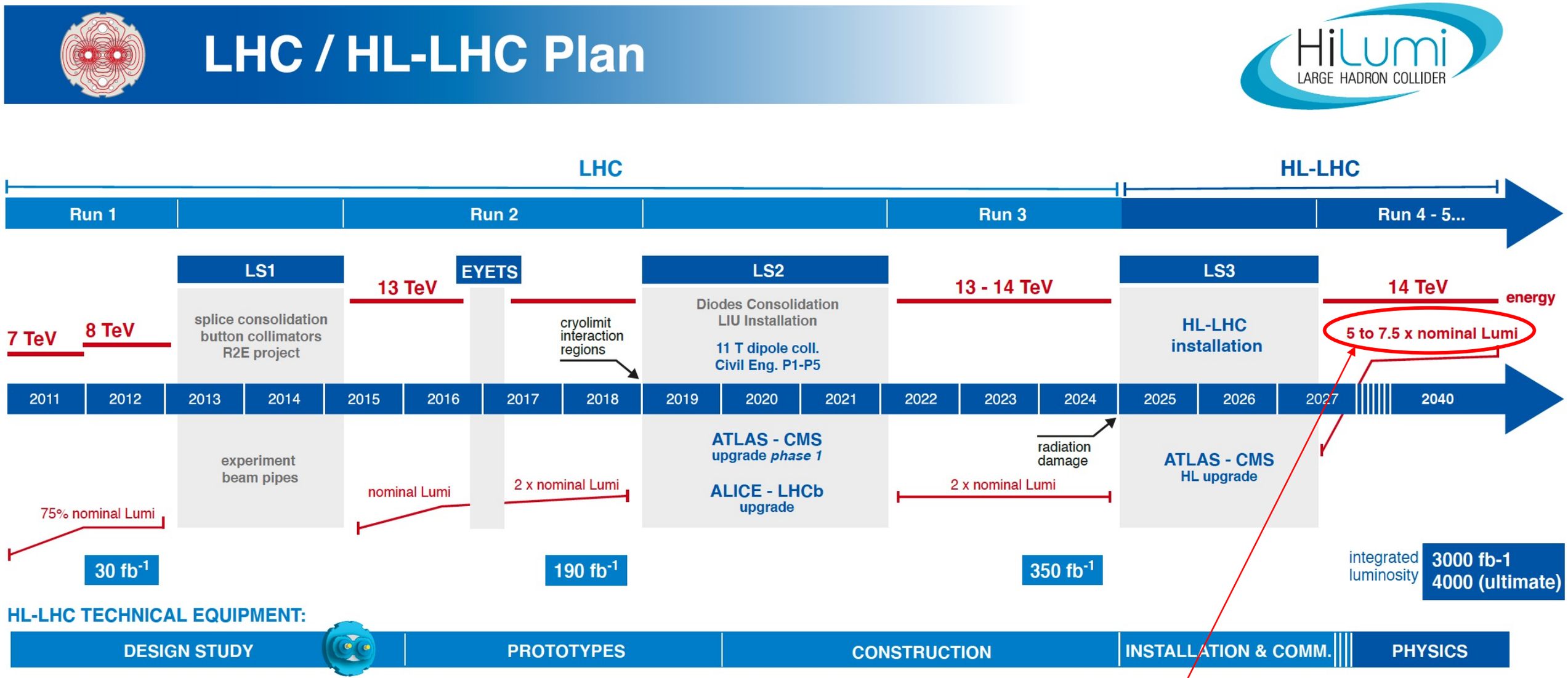
8 March 2019

"The discovery of the **Higgs particle** – especially with nothing else accompanying it so far – is unlike anything we have seen in any state of nature and is profoundly "new physics" in this sense ... theoretical attempts to compute the vacuum energy and the scale of the Higgs mass pose gigantic, and perhaps interrelated, theoretical challenges. While we continue to scratch our heads as theorists, the most important **path forward for experimentalists is completely clear**: **measure the hell out of these crazy phenomena!** "

"**It is the first example we've seen of the simplest possible type of elementary particle. It has no spin, no charge, only mass, and this extreme simplicity makes it theoretically perplexing.** ..."

https://cerncourier.com/in-it-for-the-long-haul/

The LHC Luminosity Plan



x5 Run1

x2 Run2

x10 Run3

So far LHC has delivered 5% or less of the total planned integrated luminosity!

Notice, this is the Nominal Scenario:
L = **5.0**x10^{34} $cm^{-1}s^{-1}$ up to 3000 fb^{-1} (140 PU)
The Ultimate Scenario foresees:
L = **7.5**x10^{34} $cm^{-1}s^{-1}$ up to 4000 fb^{-1} (200 PU)

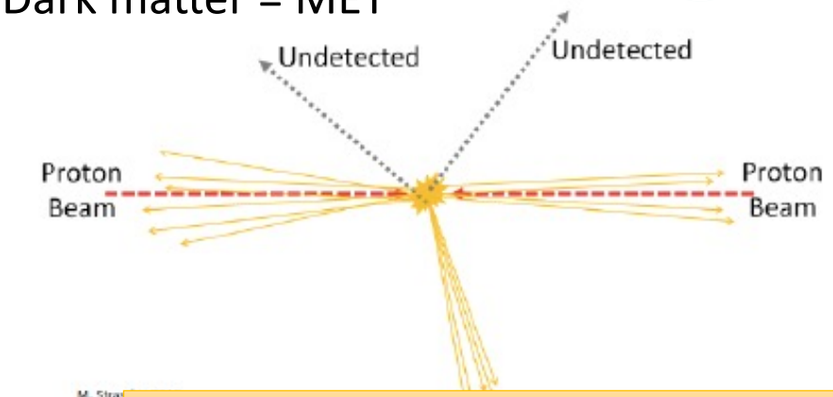
Raison d'être

It's all about high statistics

And better detectors

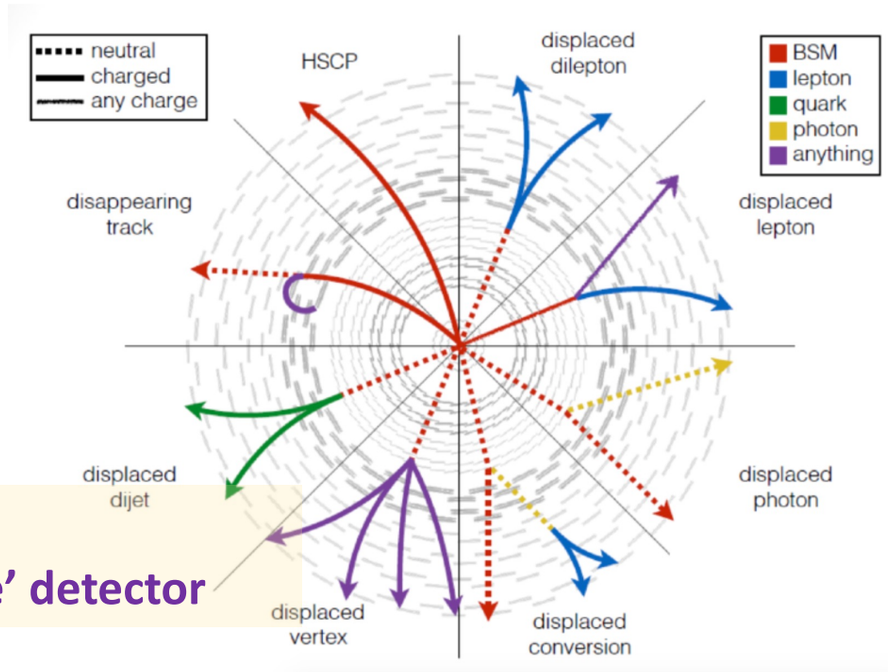
- HL-LHC is a Higgs factory, will produce > 150M Higgs bosons
  - Including ~120k of pair produced events
  - Enables a broad program:
    - Precision O(1-10%) measurements of coupling
      - potential to reveal new, hidden particles in loops
    - Exploration of Higgs potential (**HH** production)
    - Yukawa to 2nd generation, e.g. **H→ μμ**
    - BSM Higgs searches
      - extra scalars, resonances, exotic decays…

Dark matter = MET



Please, can one of you find DM for me!!

- & New Physics – weak scales - low cross-section
  - Long Lived Particles
    - Special triggers will be challenging
  - Dark Matter
  - Supersymmetry
  - Extra Dimensions
- , and vector boson fusion/scattering
  - **Enhance forward region**



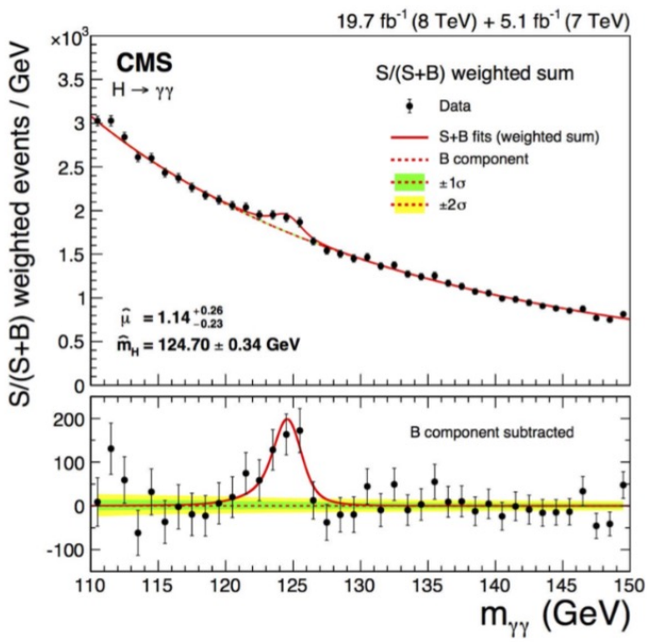
Need
precise & 'flexible' detector

SM: Standard Model BSM: Beyond Standard Model
MET: Missing transverse energy

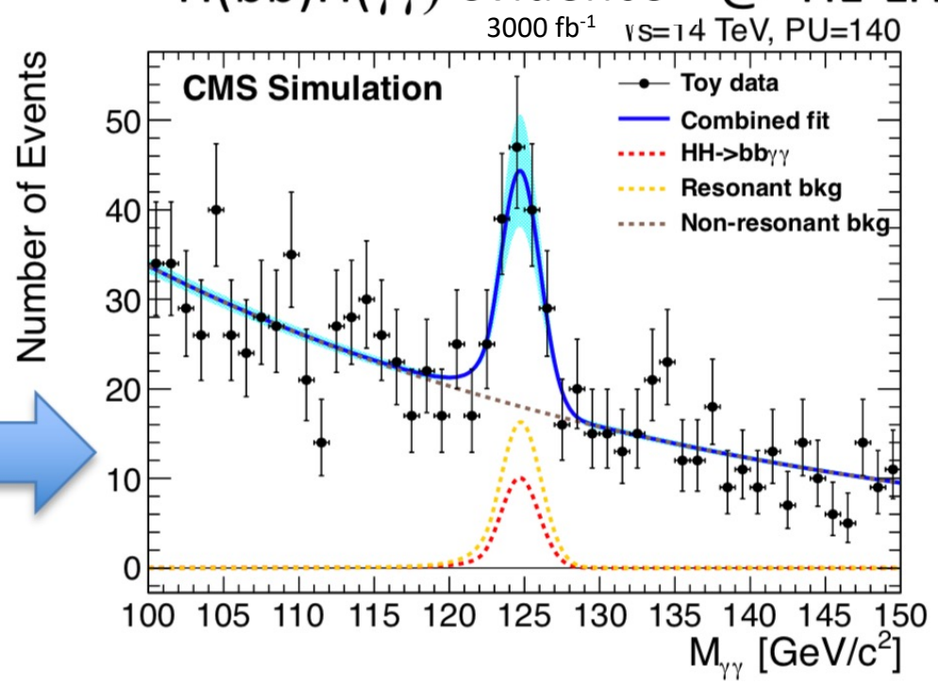
= Endless opportunities (studies, hardware, etc.)

This time, we're after Higgs-Pairs (di-Higgs)

H→γγ discovery in Run1



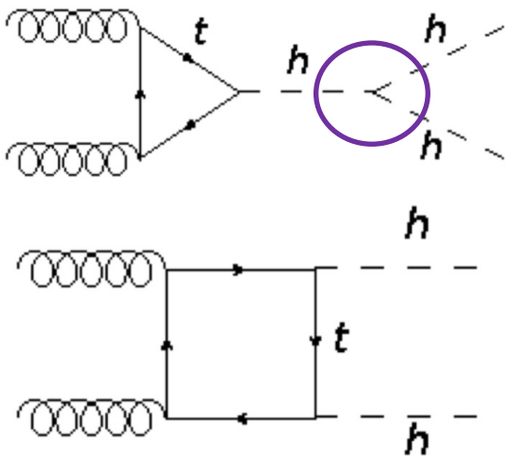
H(bb)H(γγ) evidence @ HL-LHC



CERN-LHCC-2015-10 LHCC-P-008 CMS-TDR-15-02

Channel	Significance	
	Stat. + syst.	Stat. only
bbbb	0.95	1.2
bbττ	1.4	1.6
bbWW($\ell\nu\ell\nu$)	0.56	0.59
bbγγ	1.8	1.8
bbZZ($\ell\ell\ell\ell$)	0.37	0.37
Combination	2.6	2.8

Higgs self-interaction

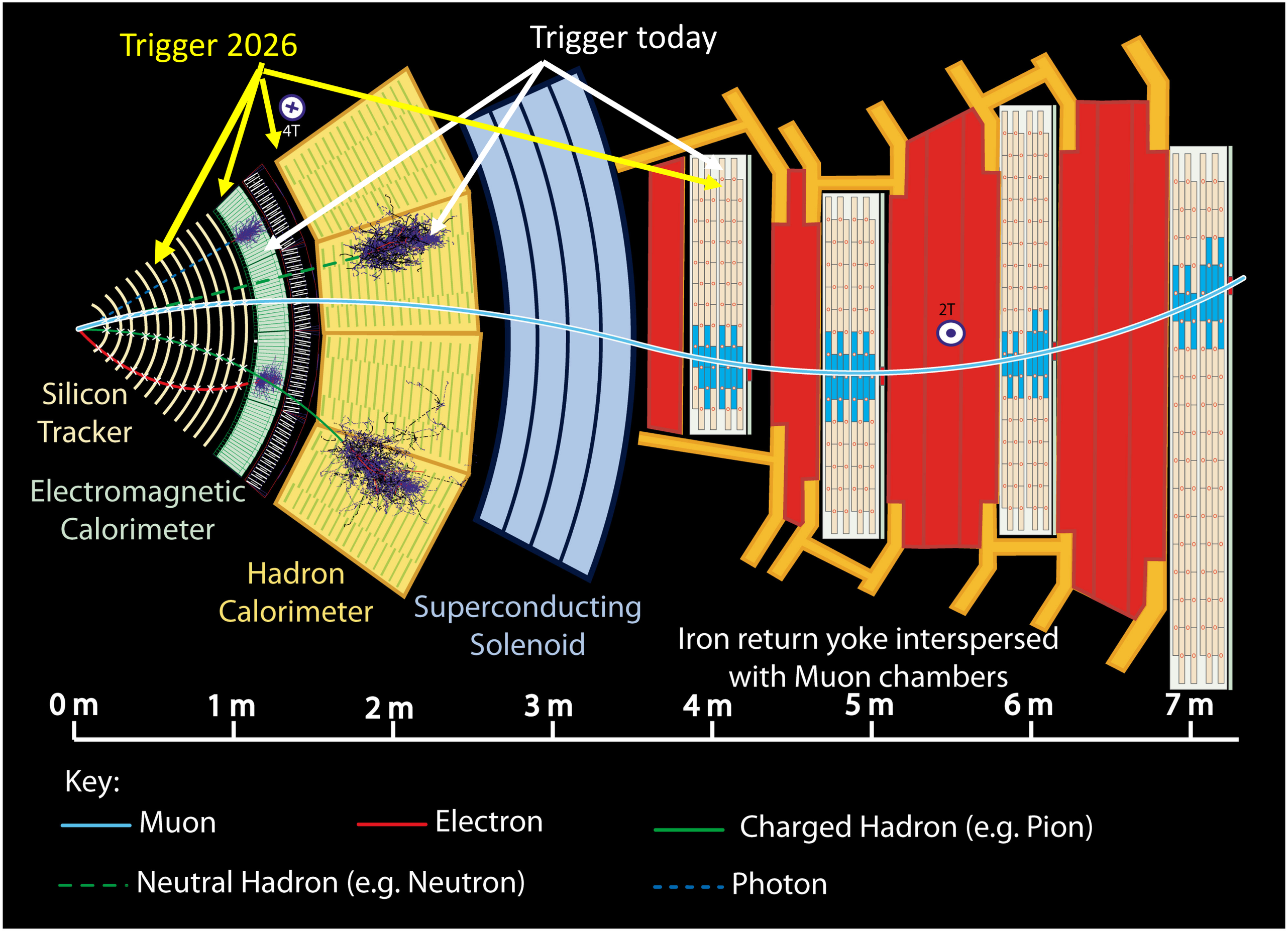


New tracker: +15% efficiency per *b*
HGCAL: +10% efficiency per γ
Muon: + 17% efficiency μ
Timing: another + 6 - 20% (comb.)

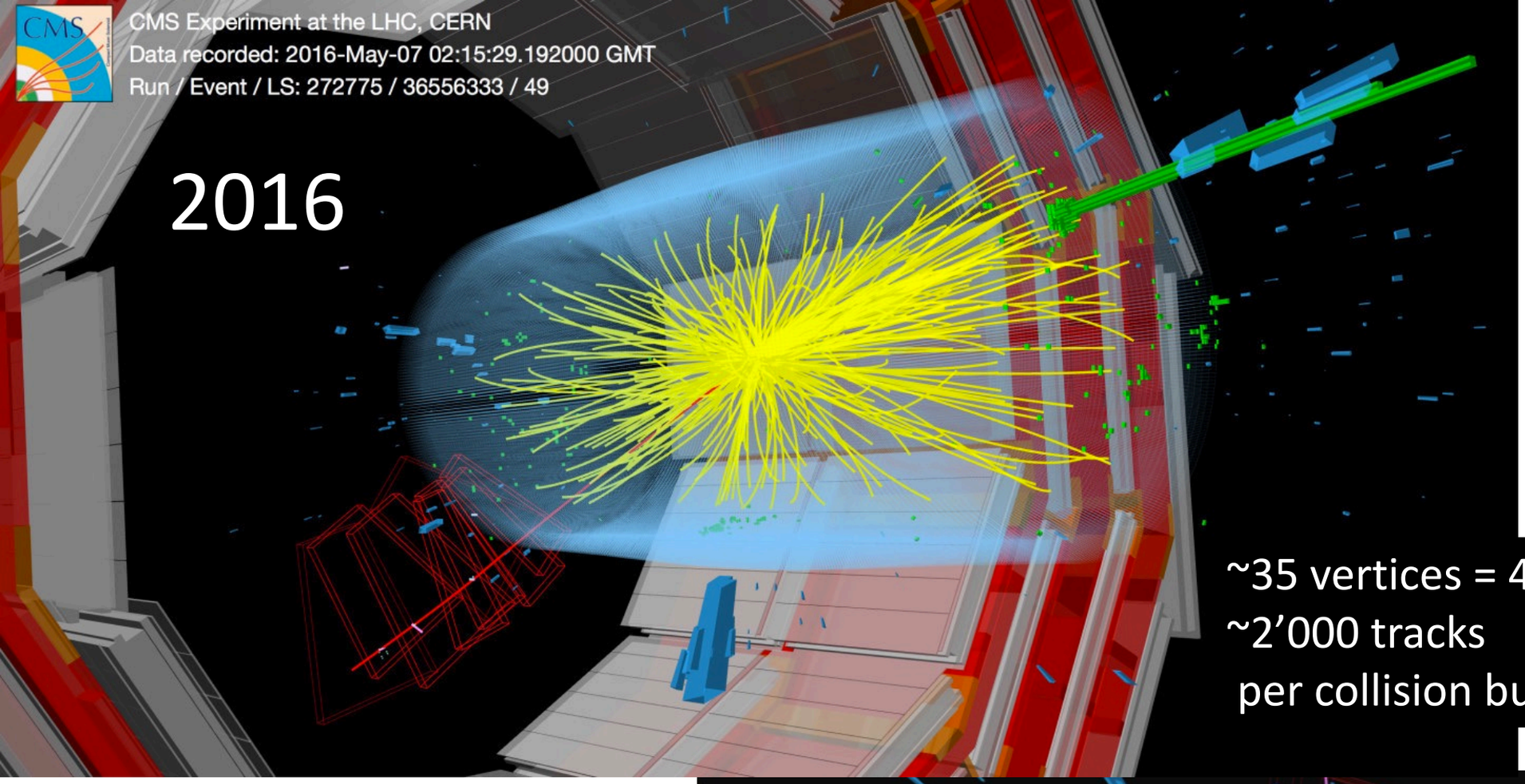
Statistically ***bb*γγ** seems the most promising channel

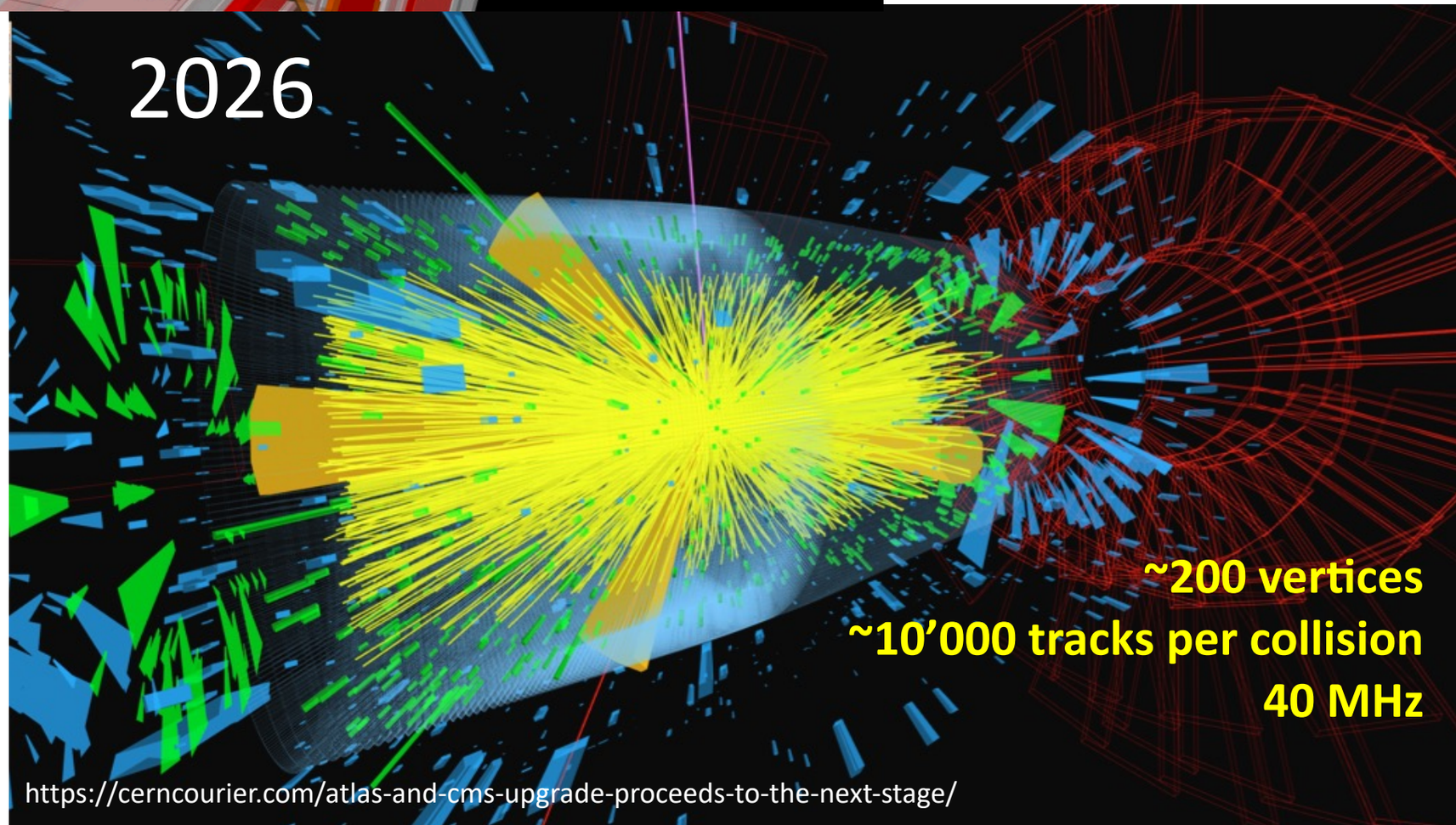
Combined with ATLAS, **4σ** might be possible (3000fb^{-1})

NB.: 20 years to achieve HH with ~3 σ with CMS


Trigger 2026
Trigger today
4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon

Detectors interleaved with the magnet yoke steel layers





https://cerncourier.com/atlas-and-cms-upgrade-proceeds-to-the-next-stage/

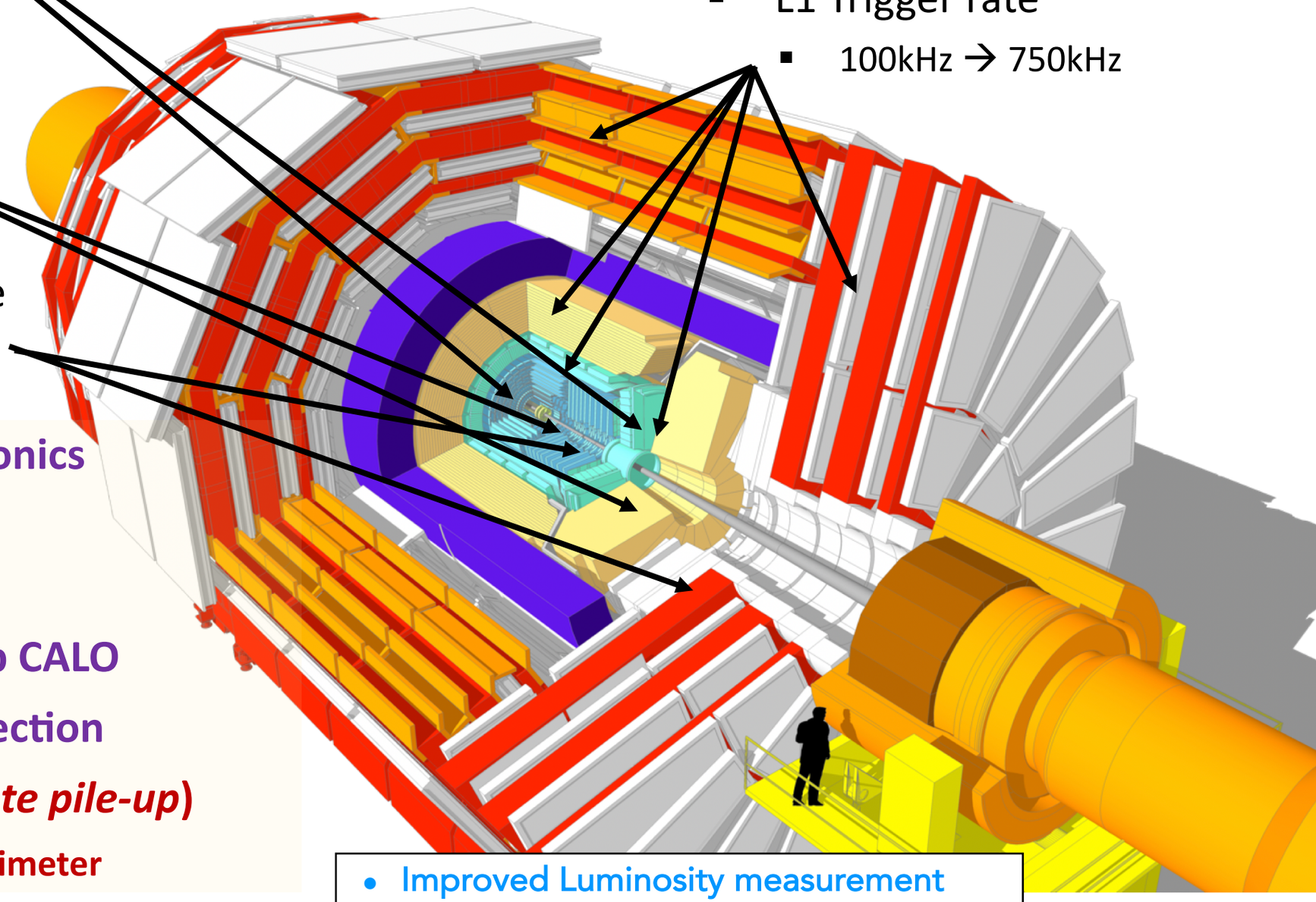
Bottlenecks

Radiation tolerance improvement
(*silicon sensors*)

Channel granularity
Silicon, GEM

Increase coverage
(mostly eta)

- L1 Trigger latency
(storage on FE chip)
  - ECAL 3.8μs → streaming
  - TK 6.4μs → 12.5μs
- L1 Trigger rate
  - 100kHz → 750kHz



- **Replace (most of) the electronics**
  - **Increase bandwidth**
- **New Tracker (incl. trigger)**
- **New high granularity endcap CALO**
- **Extend Muon in forward direction**
- **Add Timing Detector (*mitigate pile-up*)**
  - **Add timing in Muon and calorimeter**

- Improved Luminosity measurement
  - < 1% offline (Lumi POG)
  - < 2% online

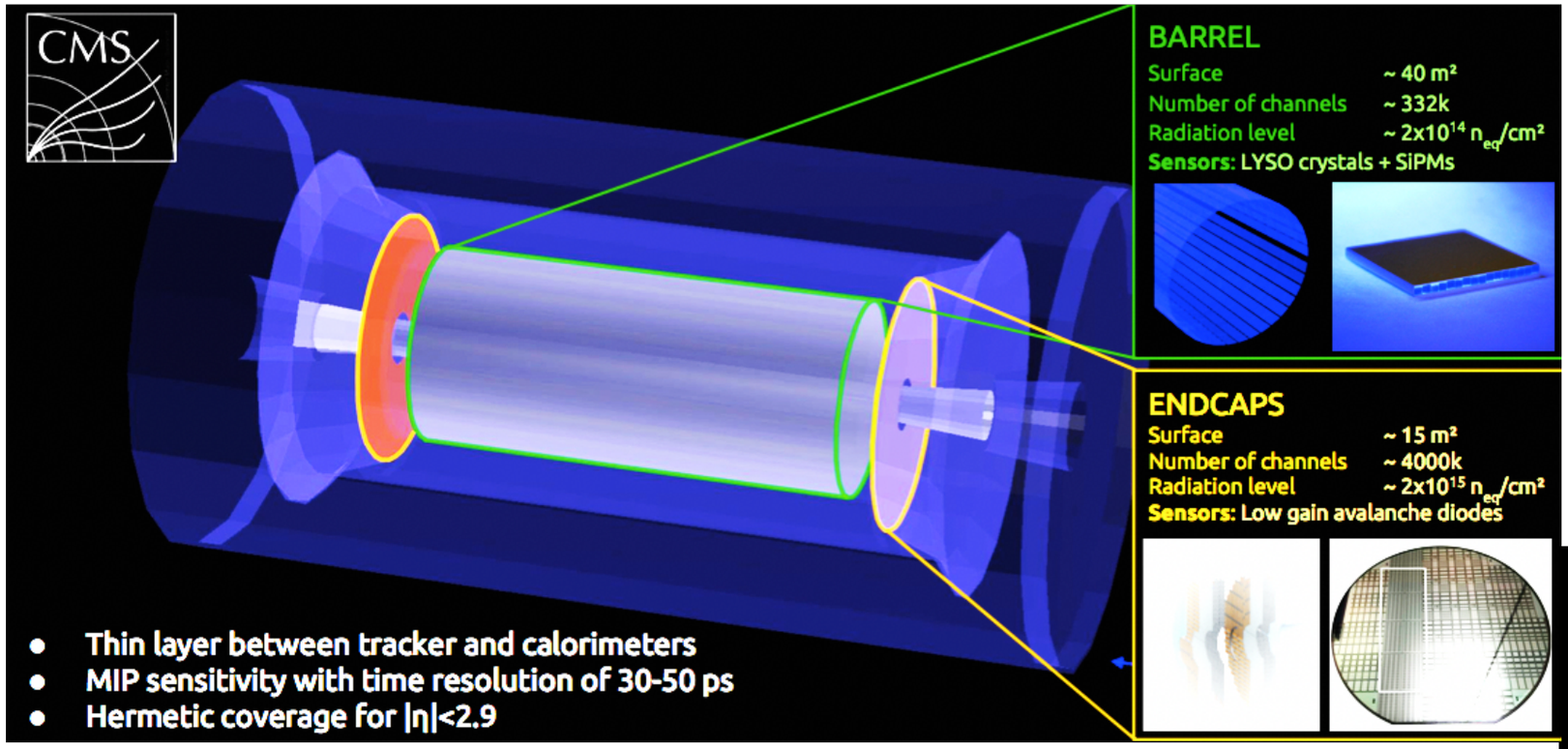
GEM: Gas Electron Multiplier – more later
Timing: precise σ_T=30ps time measurement

http://cms.cern

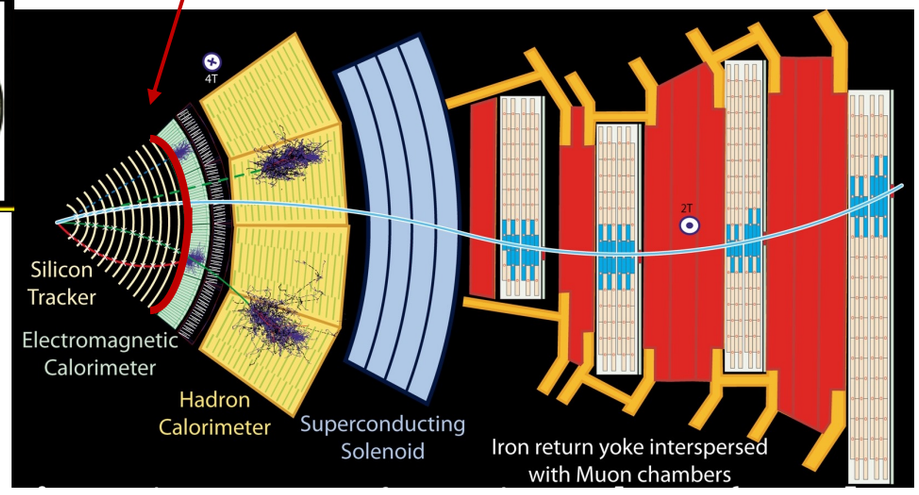
On the technology aspect

From our external reviewers:

"We want to note (again) that these projects are unprecedented in scale in particle physics, shift various paradigms, and employ technologies that have never before been exercised by the field."

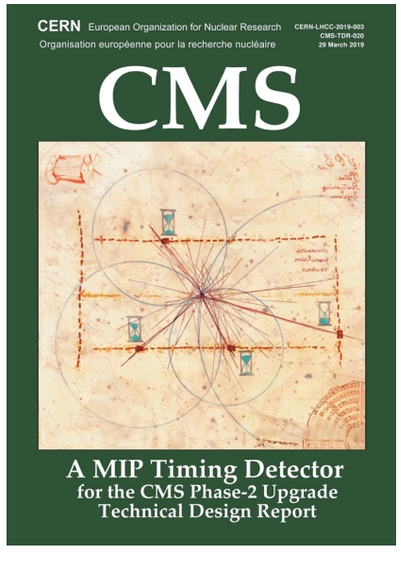


Between Tracker and Calorimeter



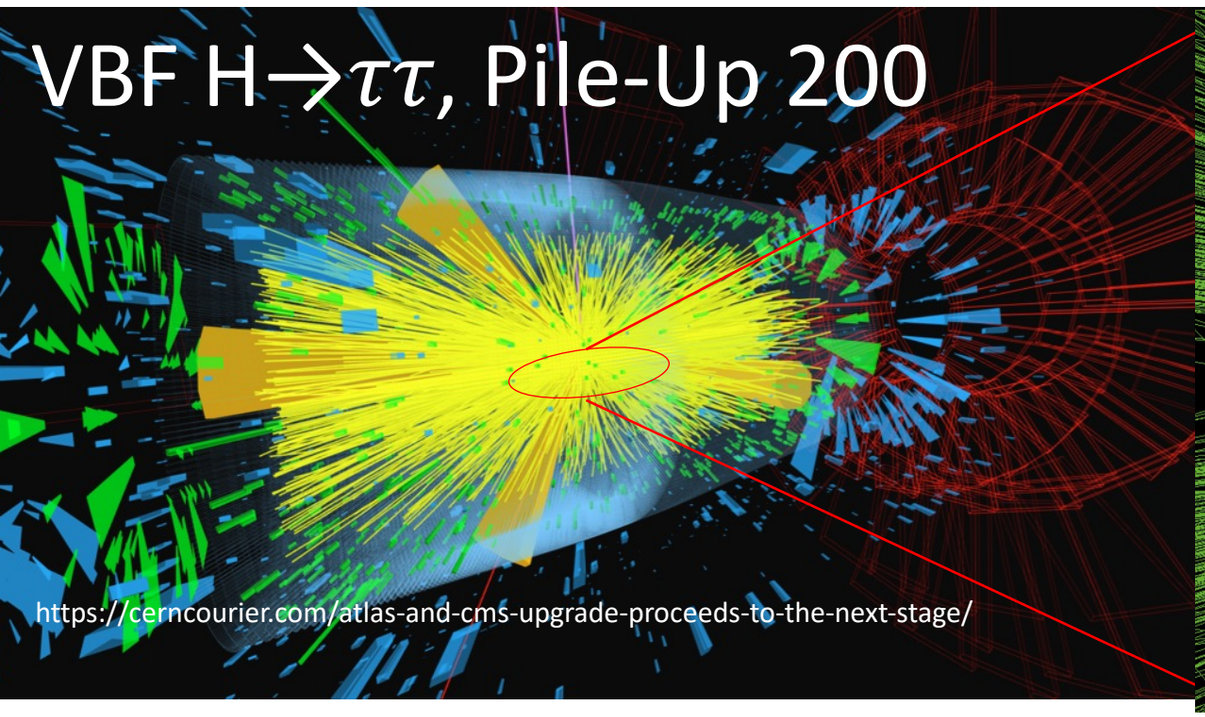
30 ps timing – the extra independent parameter makes the difference

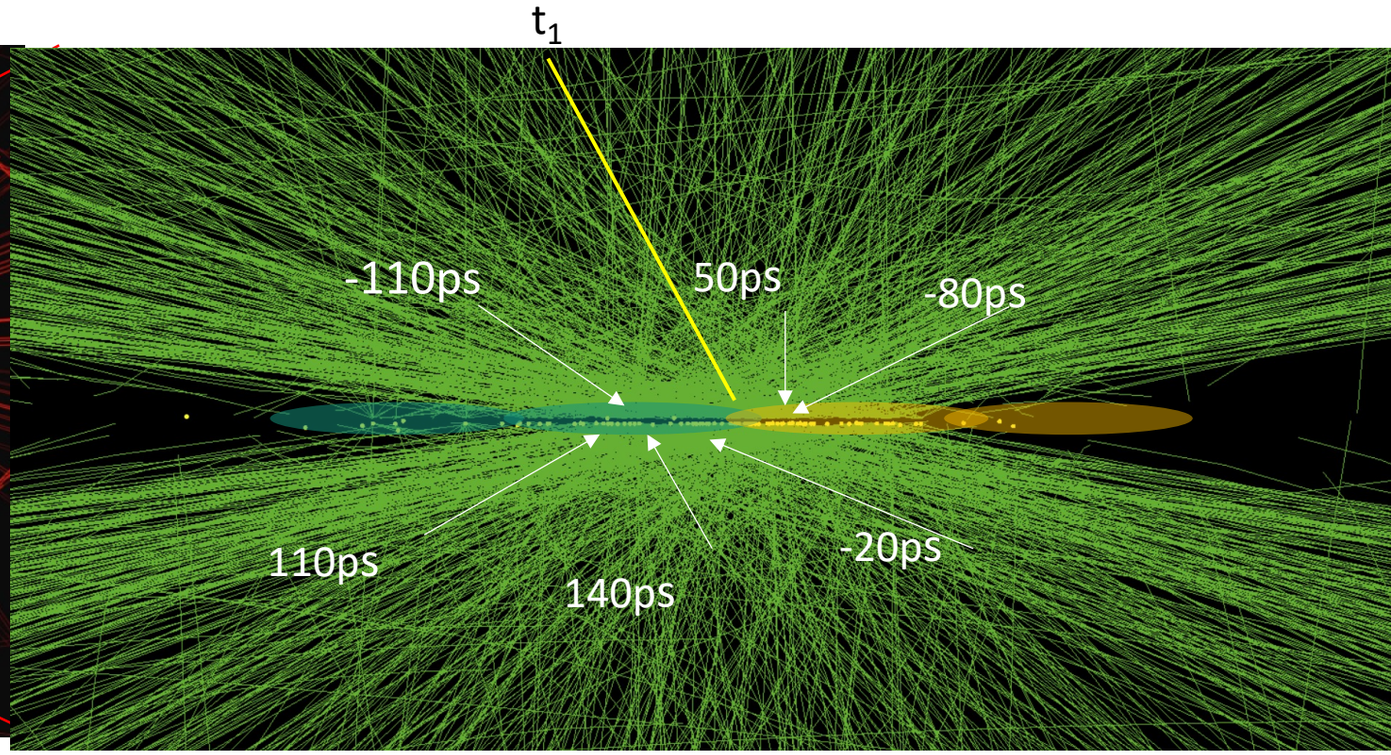
MTD MIP Timing Detector

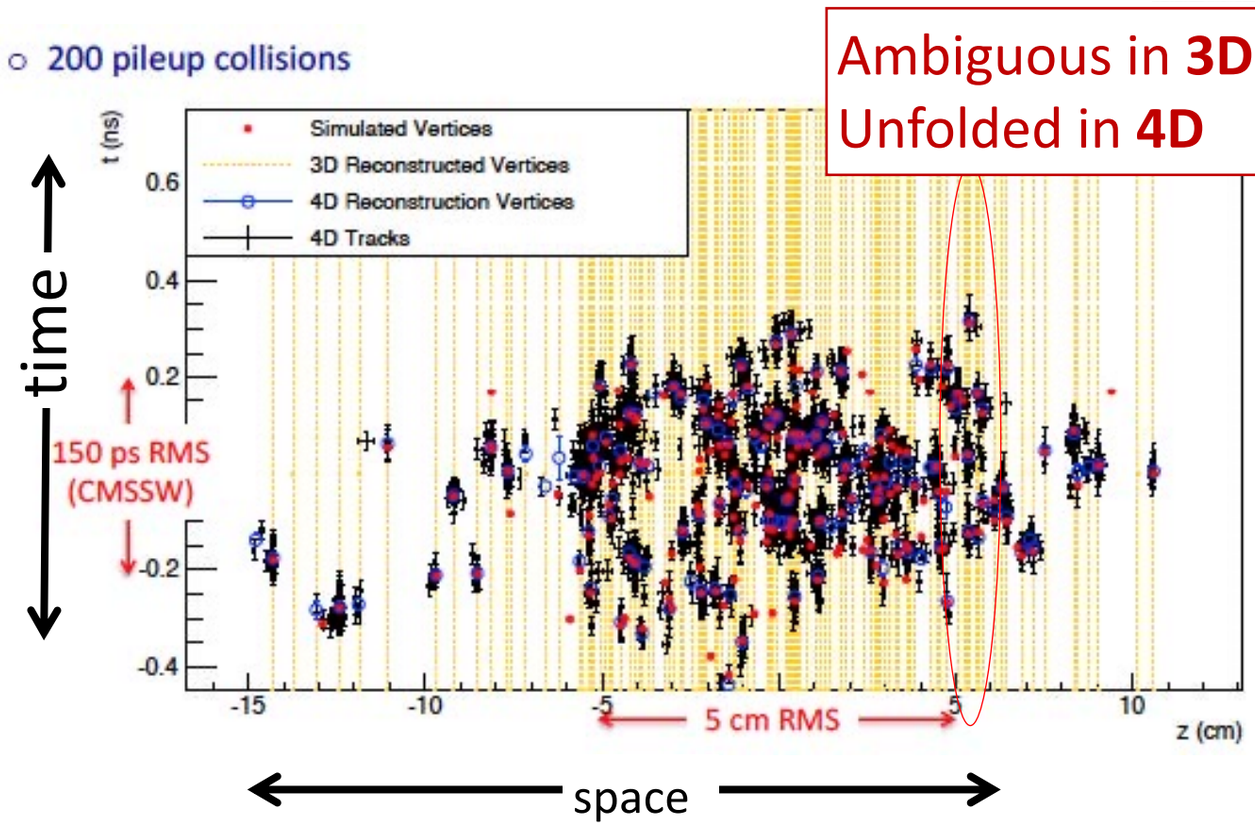


CERN-LHCC-2019-003 CMS-TDR-020

Sorting the mess even better



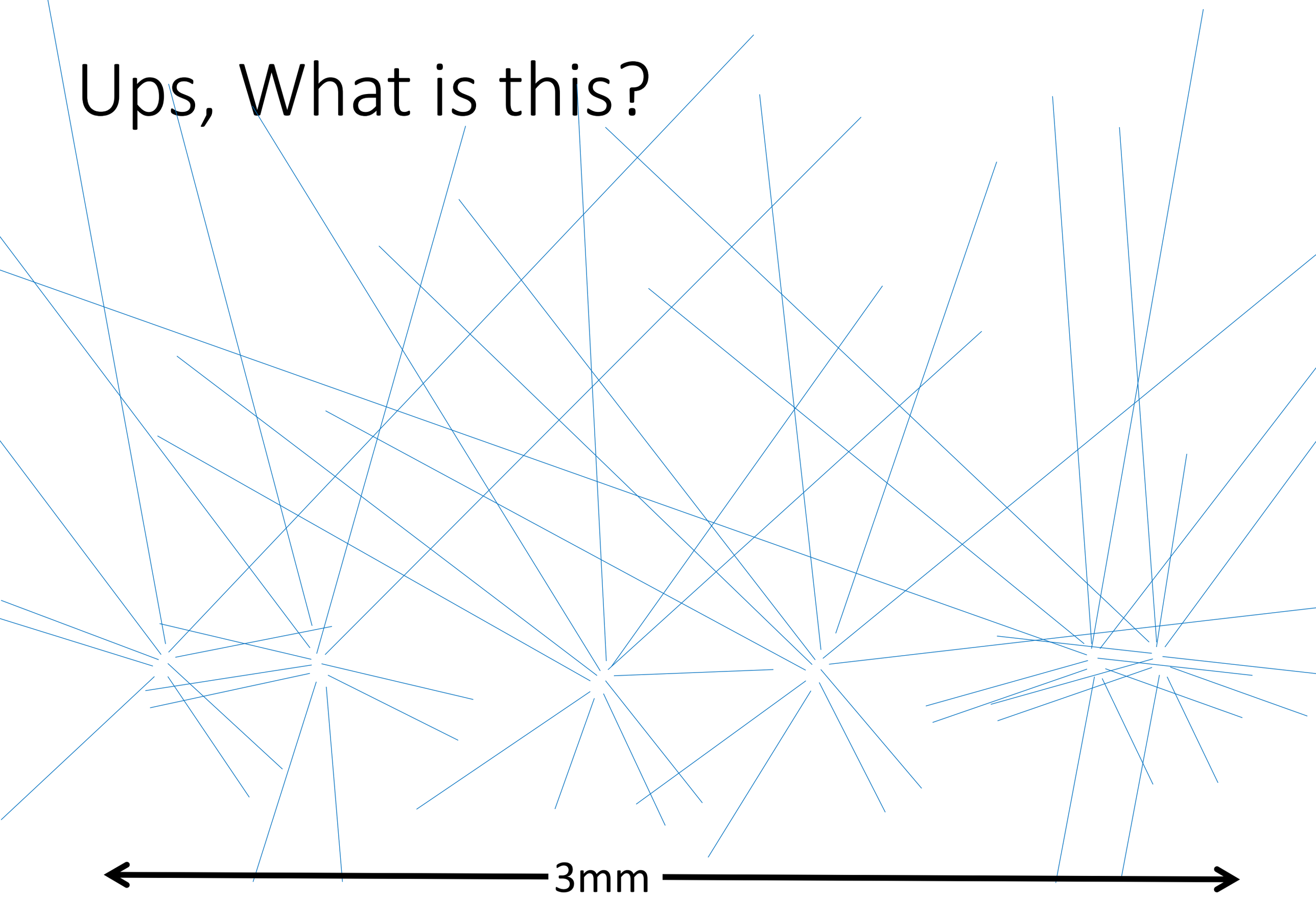




~10'000 tracks
per collision bunch

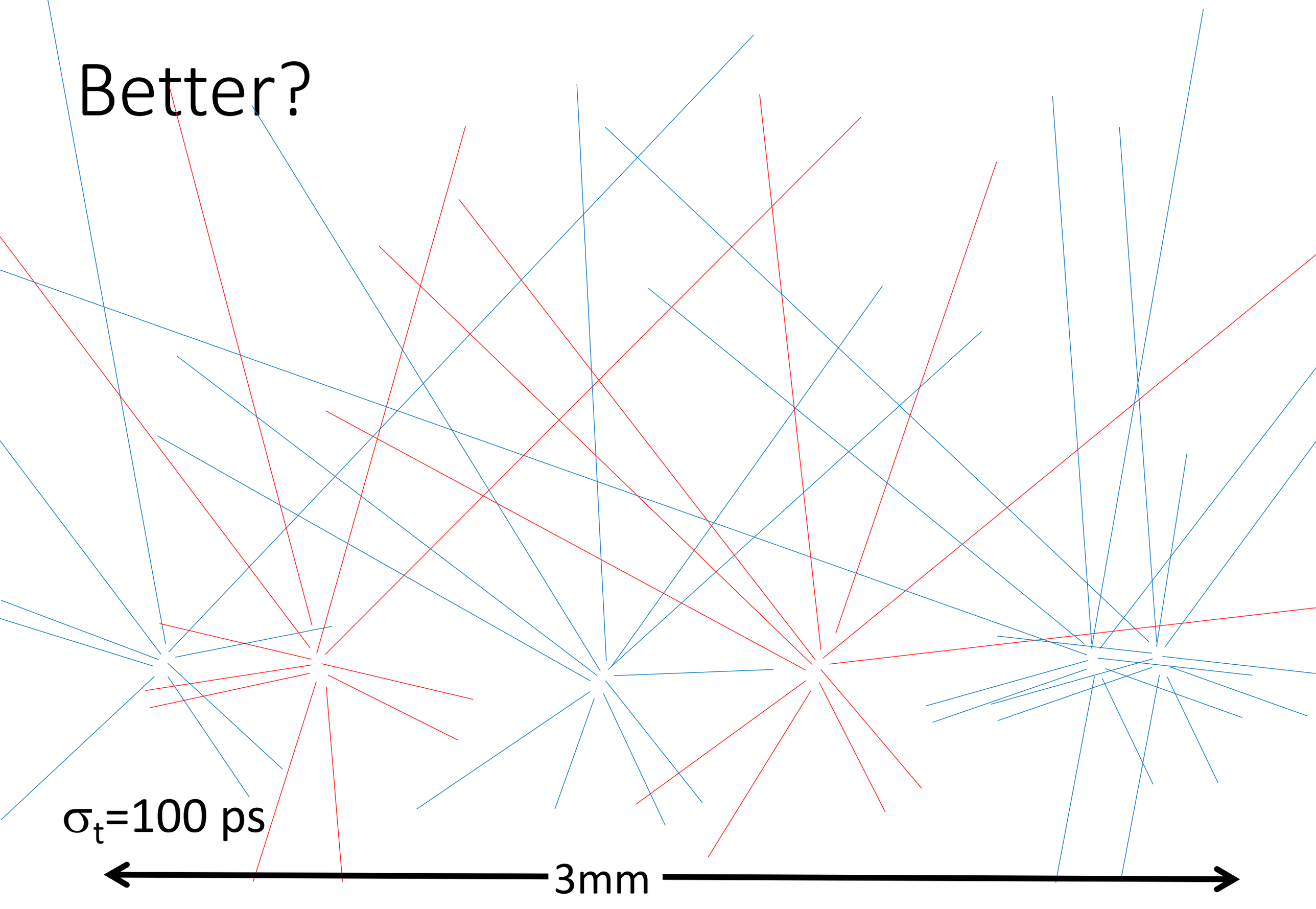
- @ PU=200
  Vertex density ~1 vertex/mm
- A 30 ps resolution (y axis ← plot) allows to resolve vertices at the same z
- "you get close to a Run-2 PU situation"

Ups, What is this?

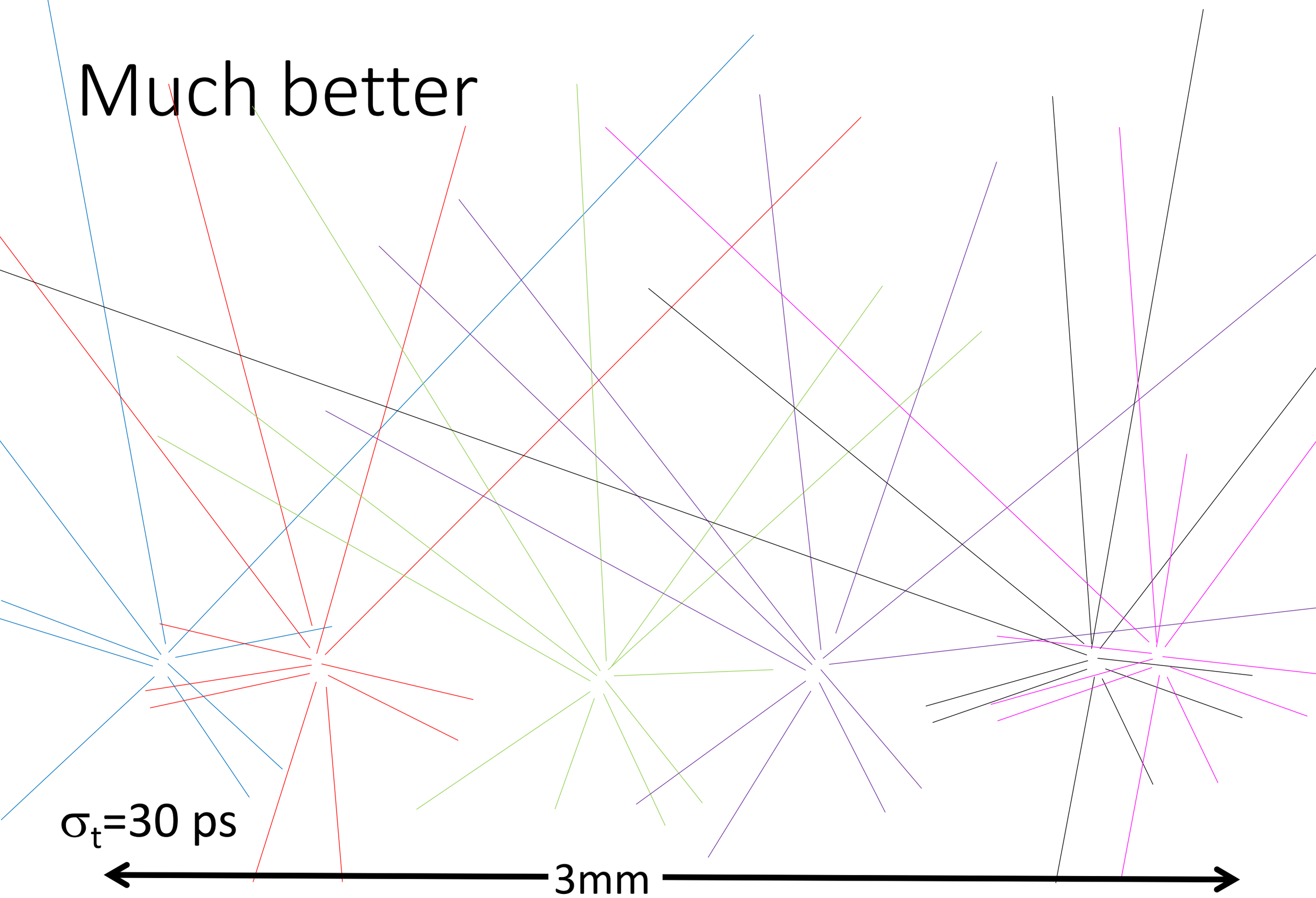


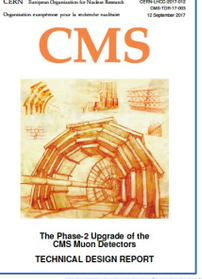
Pile-up of vertices = mess

Better?



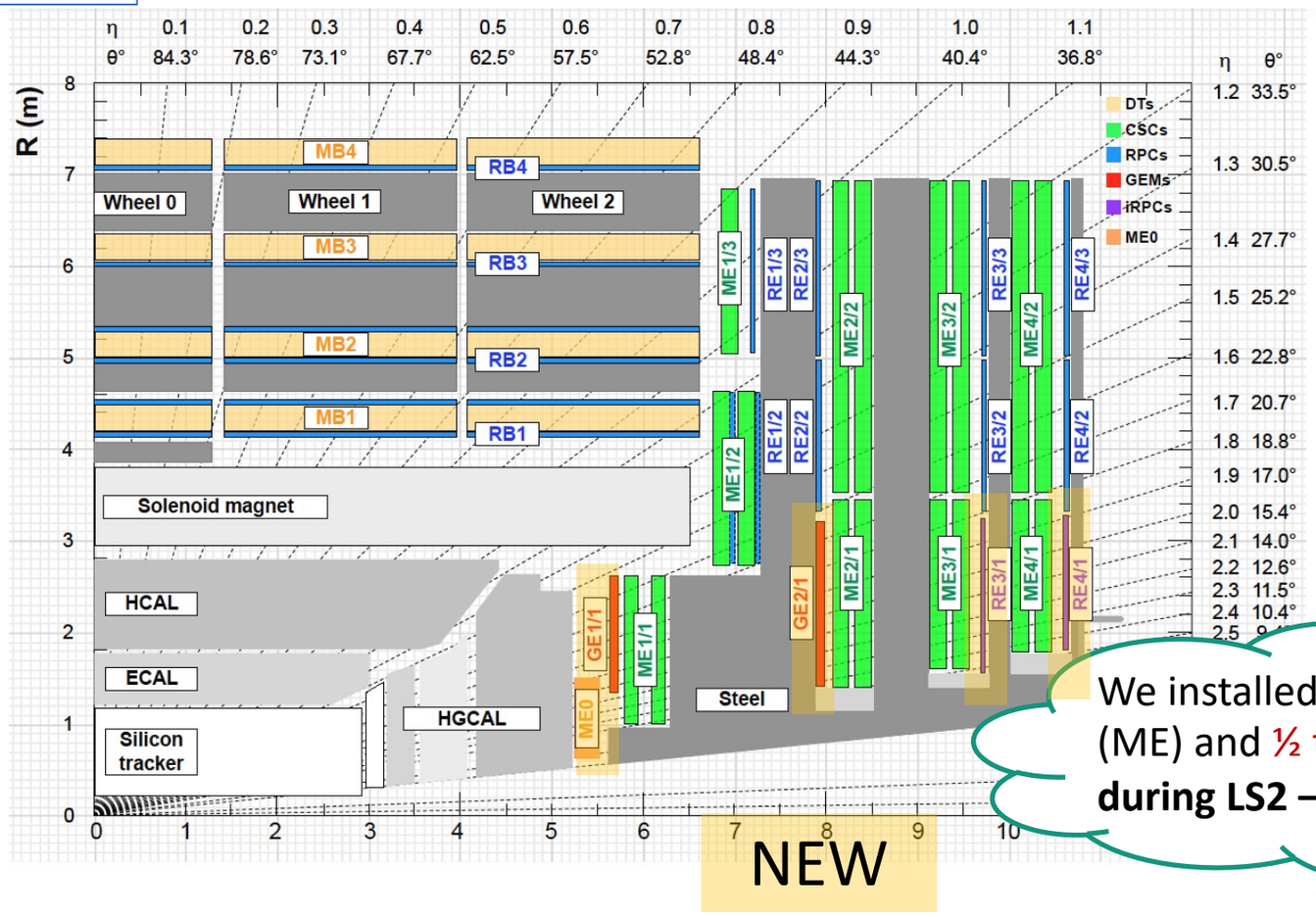
Much better



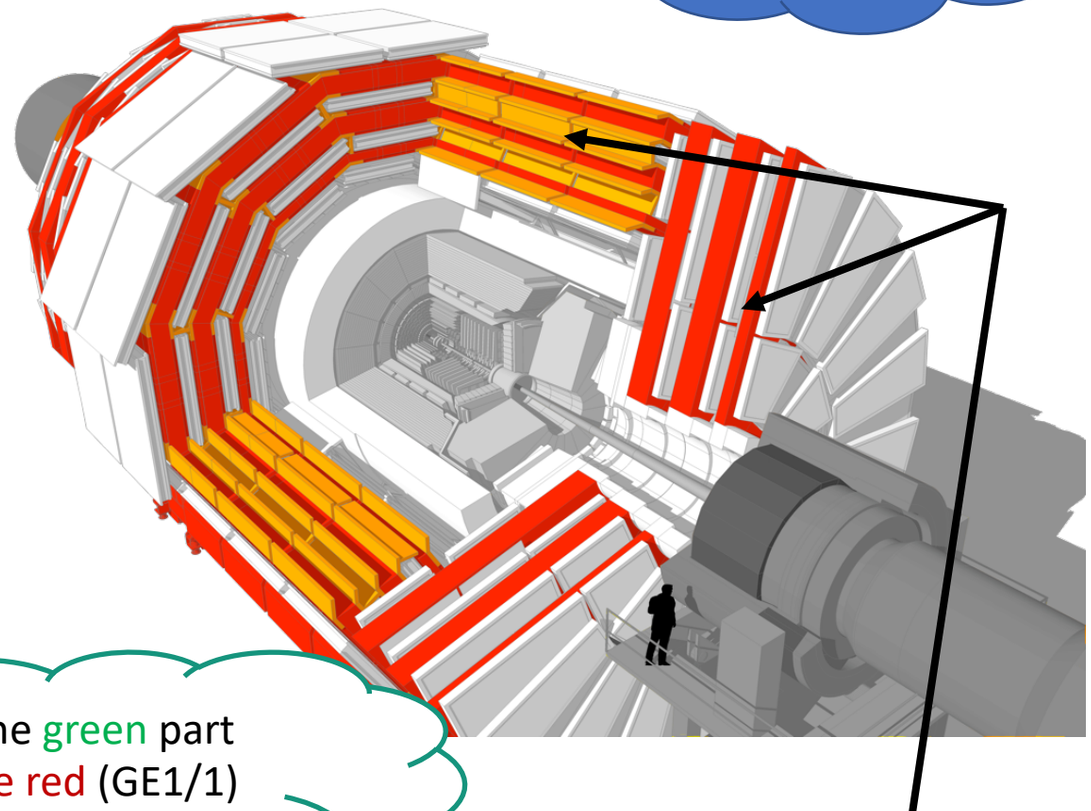


The Muon Detectors

Involvement of IPM

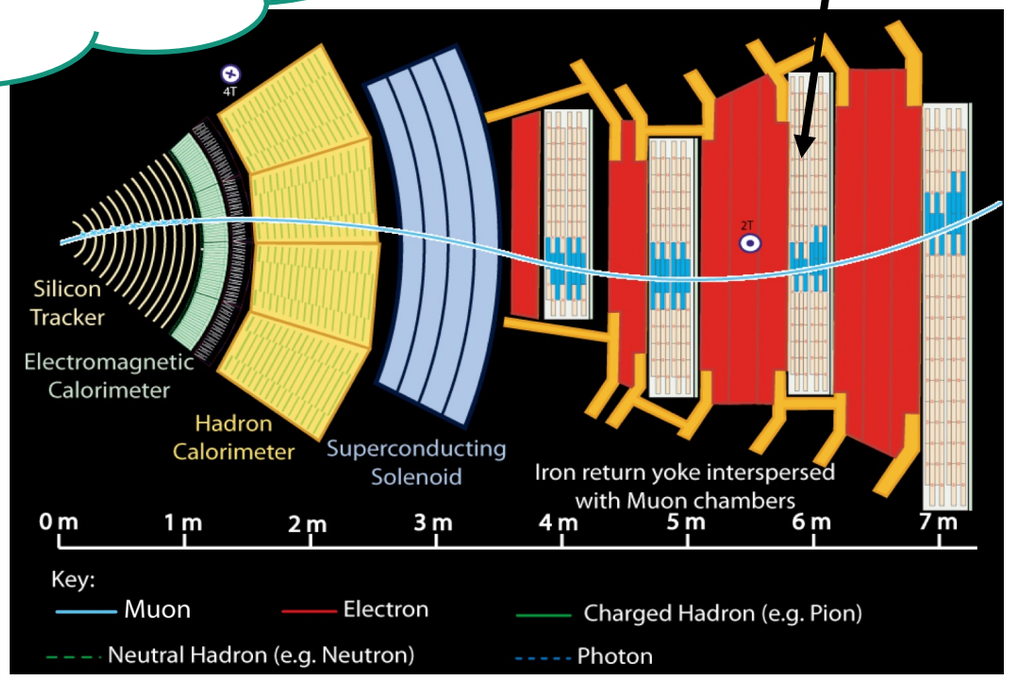


NEW



We installed the green part (ME) and ½ the red (GE1/1) **during LS2 – done!**

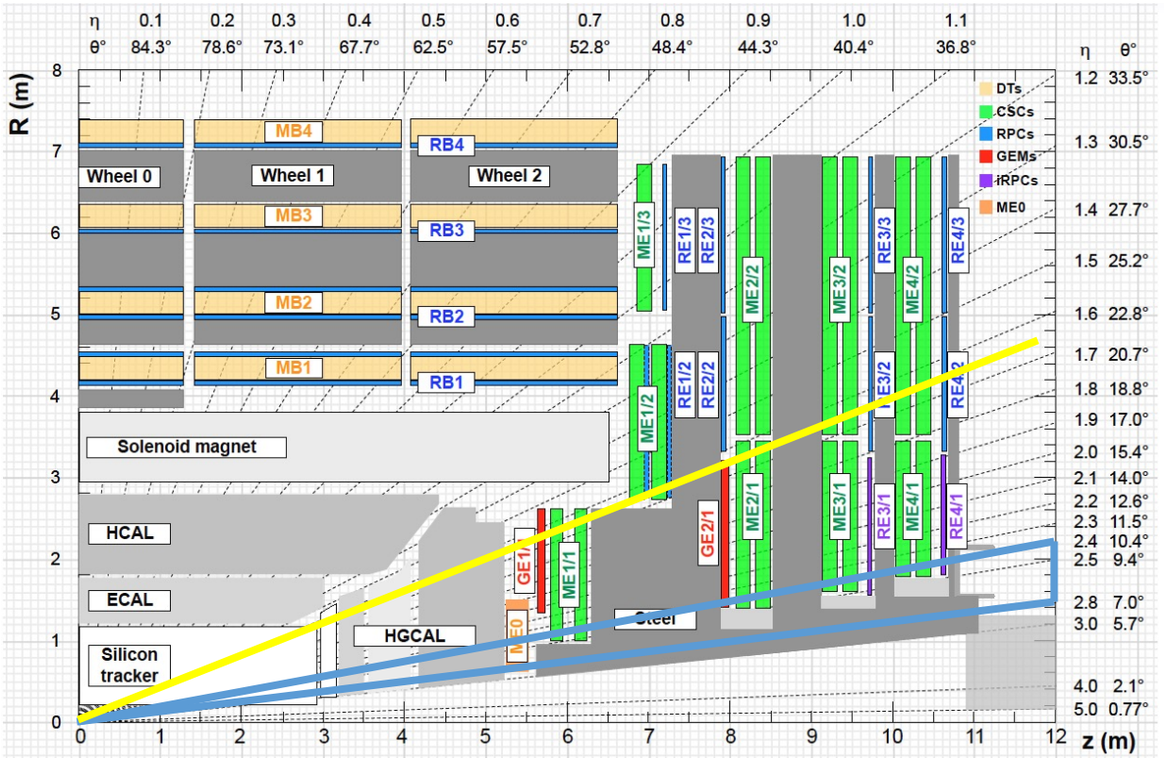
- **New electronics everywhere to cope with 10-fold rates**
  - Extract many, many chambers and re-install
- Add new detectors in very-forward region
  - **New technologies (Gas Electron Multiplier GEM)**
    - Better resolution; much higher rates (MHz/cm^2)
- **Install most, long before LS3 !**

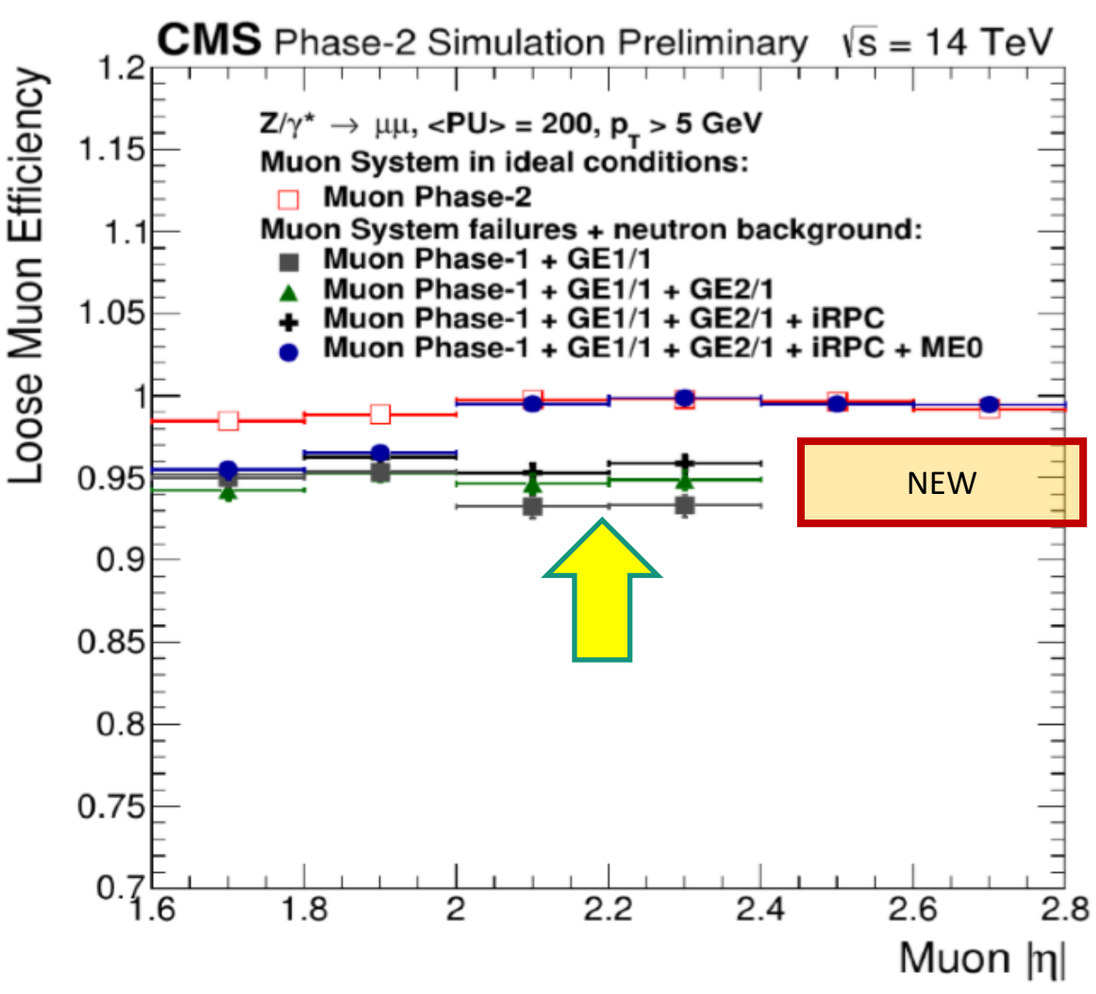


CERN-LHCC-2017-012 CMS-TDR-016

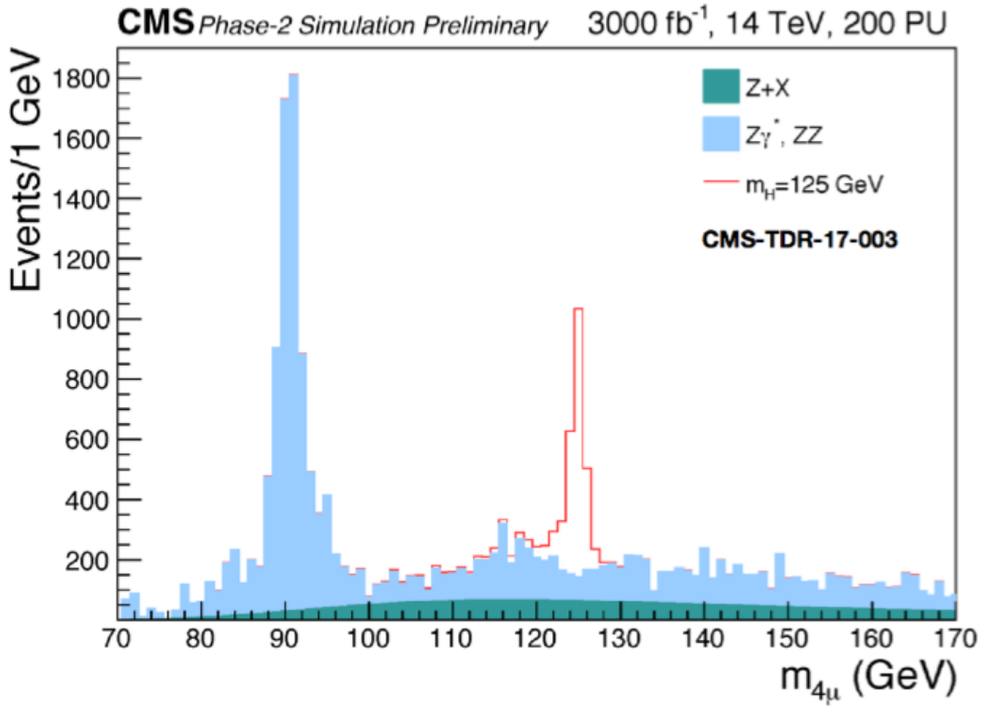
Spike my Muons performance

- New GEM detector
  - Extension in $2.4 < |\eta| < 2.8$
  - Much better resolution
  - Much better rate capability



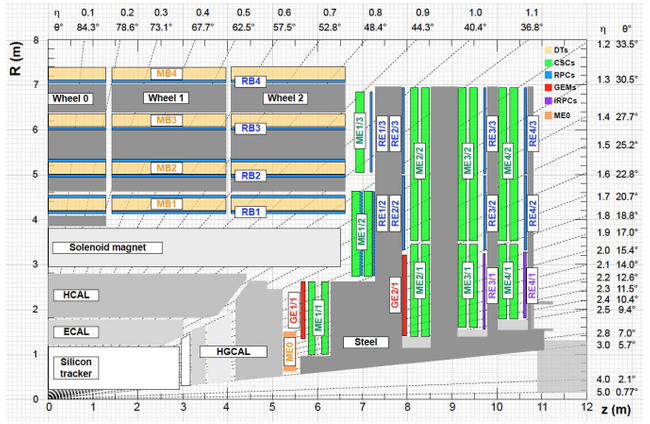


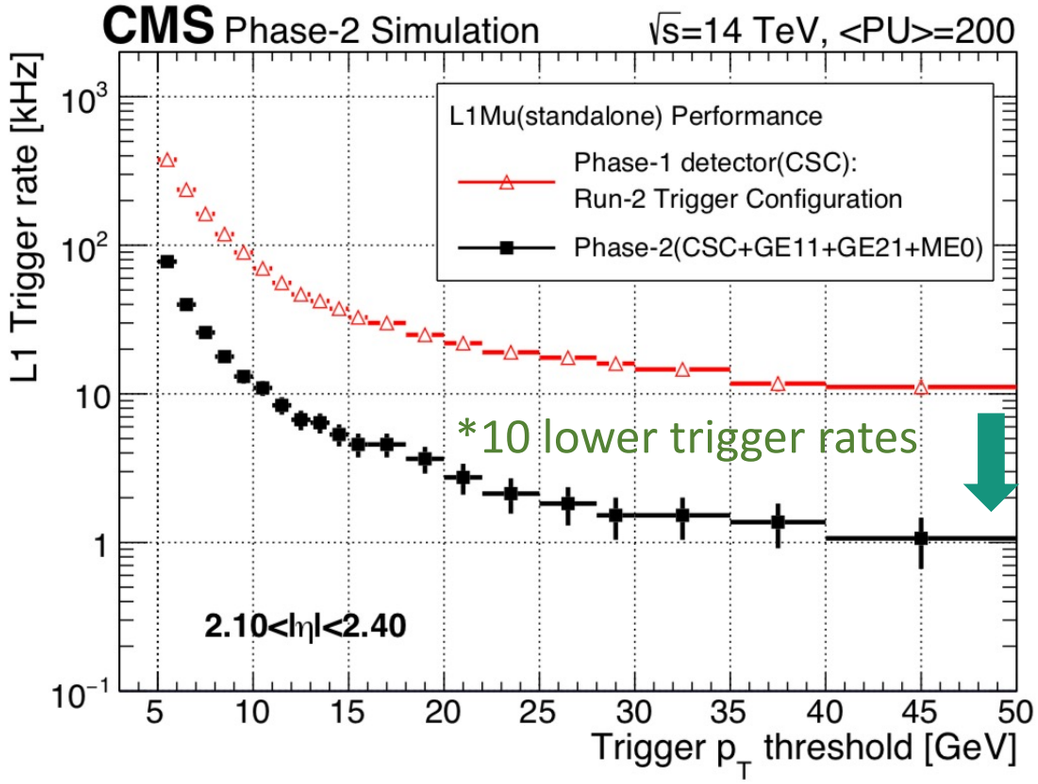
Higgs into 4 leptons:
acceptance increase ~17%



CERN-LHCC-2017-012 CMS-TDR-016

Wonderful new opportunities with the new Muon system

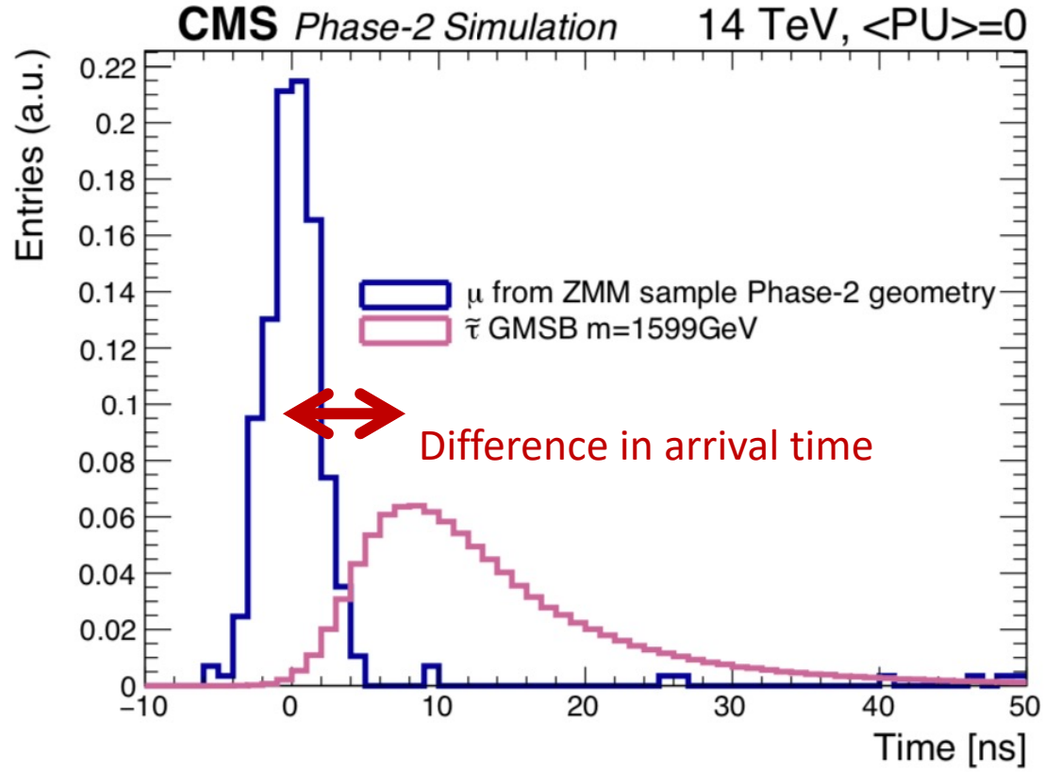




- Rates, efficiencies, precision
  ➔ much better, more flexible trigger
- Allows trigger on displaced tracks
  - No vertex constraint
  - New physics!?!?

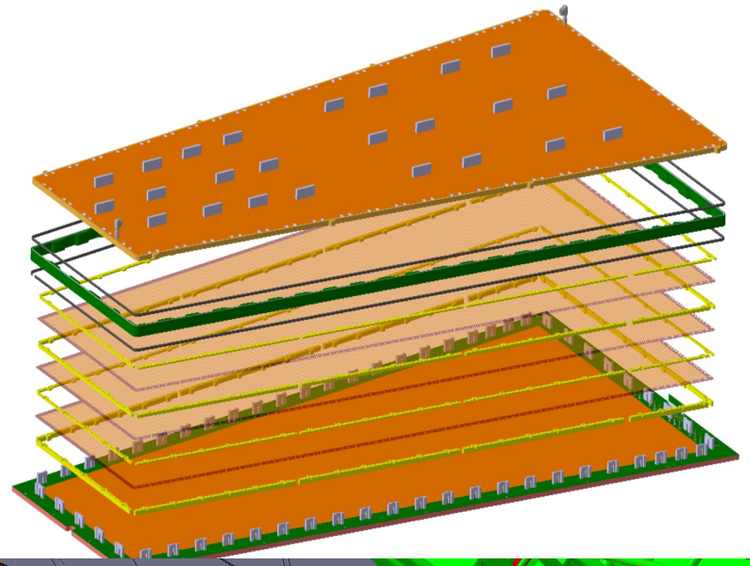
RPC-2 time resolution 1ns (today 25ns)

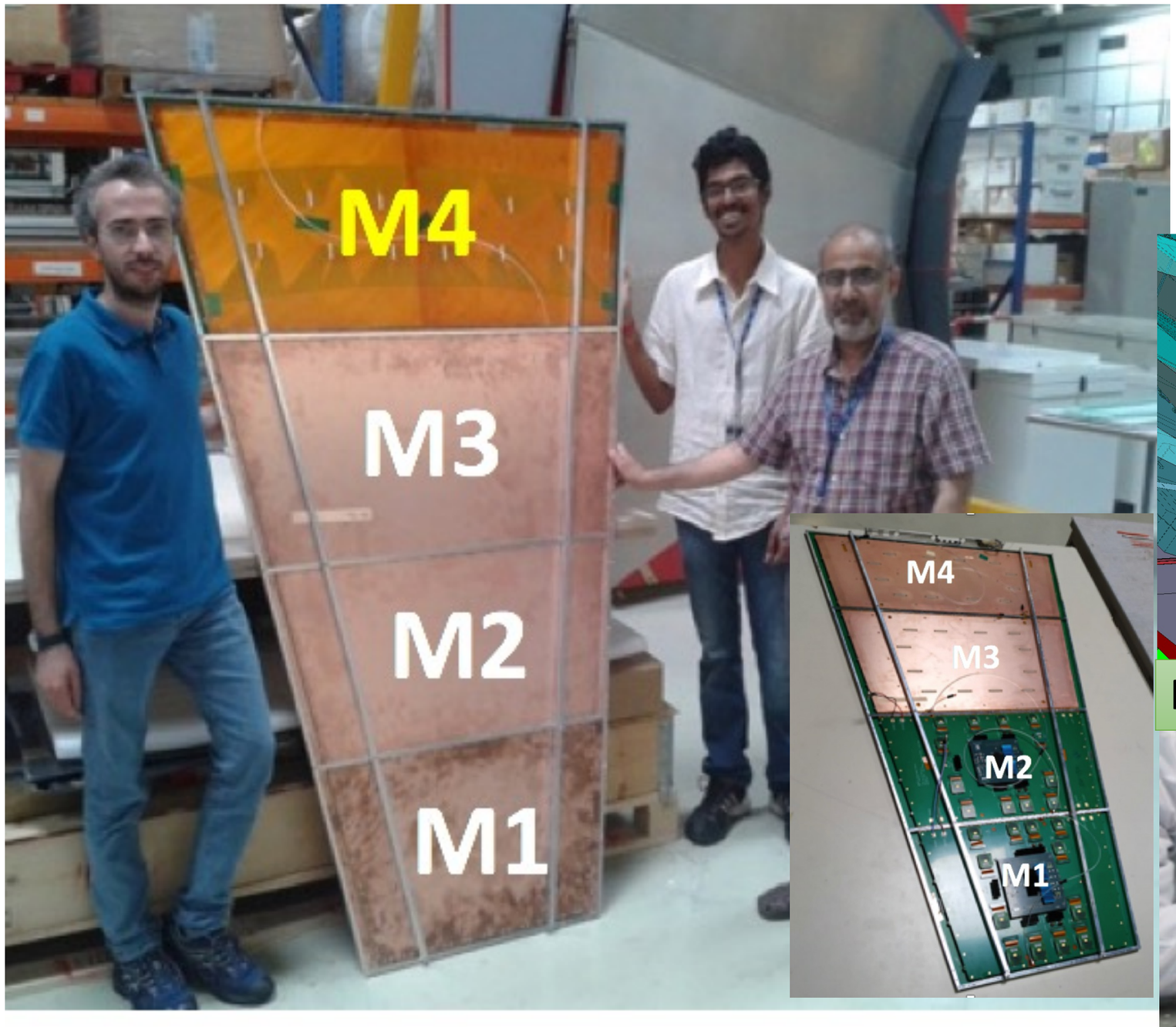
Identify ‘slow” Heavy Stable Charged Particle

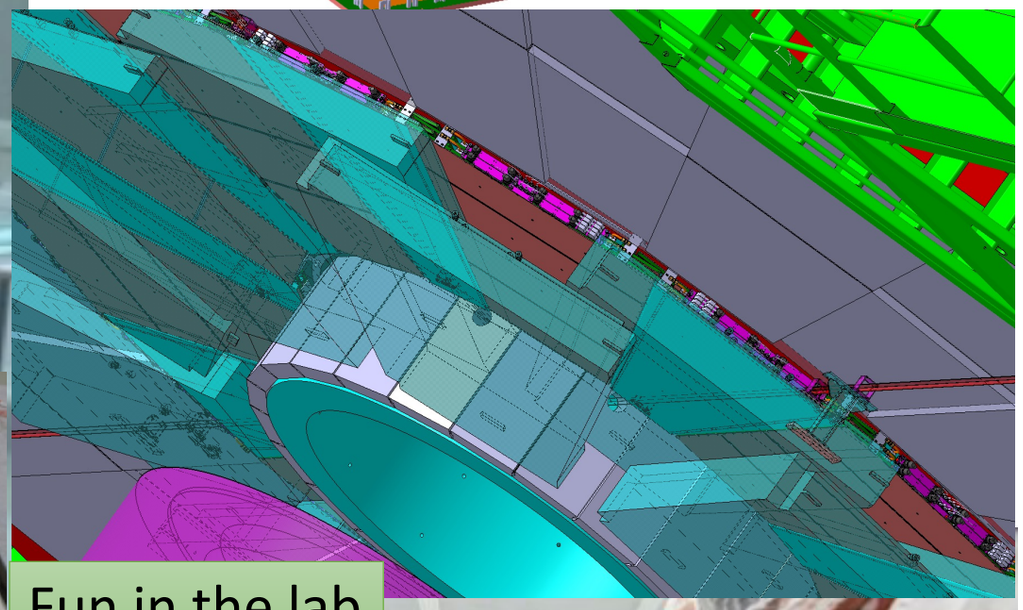


LLP Long Lived particle (NEW)
RPC Resistive Plate Chamber – a Muon detector

Gas Electron Multiplier GEM







Fun in the lab

All 144 needed detectors have been installed

NB: Unprecedented scale of GEM installation!

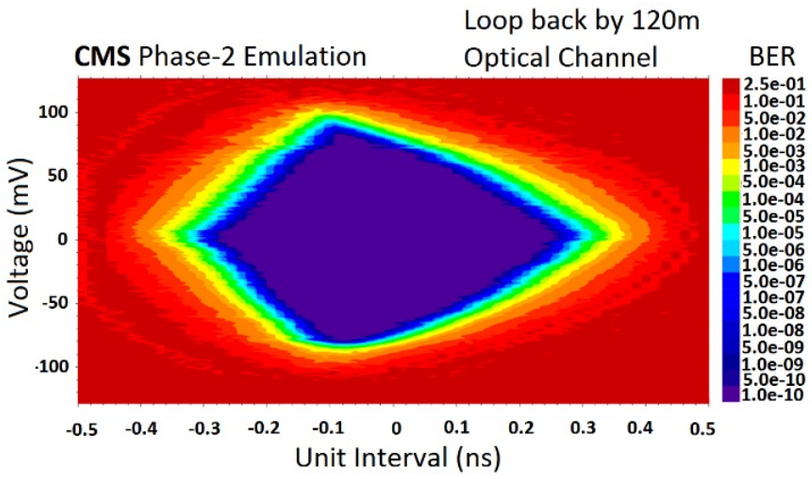
Large installation 2019/20 (done)

RPC: New Link System Status

The RPC Off-detector electronics consist of Link and Control Boards (called "Link System"). The LS is located on the balconies around CMS.

- 3 new Link Boards have been produced at IPM lab. Initial validation successfully performed.
- Firmware deployment is progressing on schedule.

Data transmission GTX @ 10.24 Gbps



- One board arrived CERN in June 2021

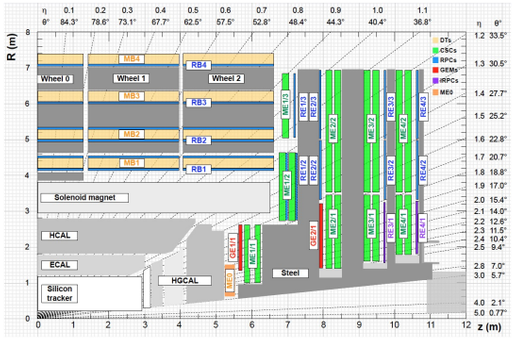
Responsibility of IPM for the whole Muon Resistive Plate Chambers!

21

Installing services for RPCs – today

Resistive Plate Chamber

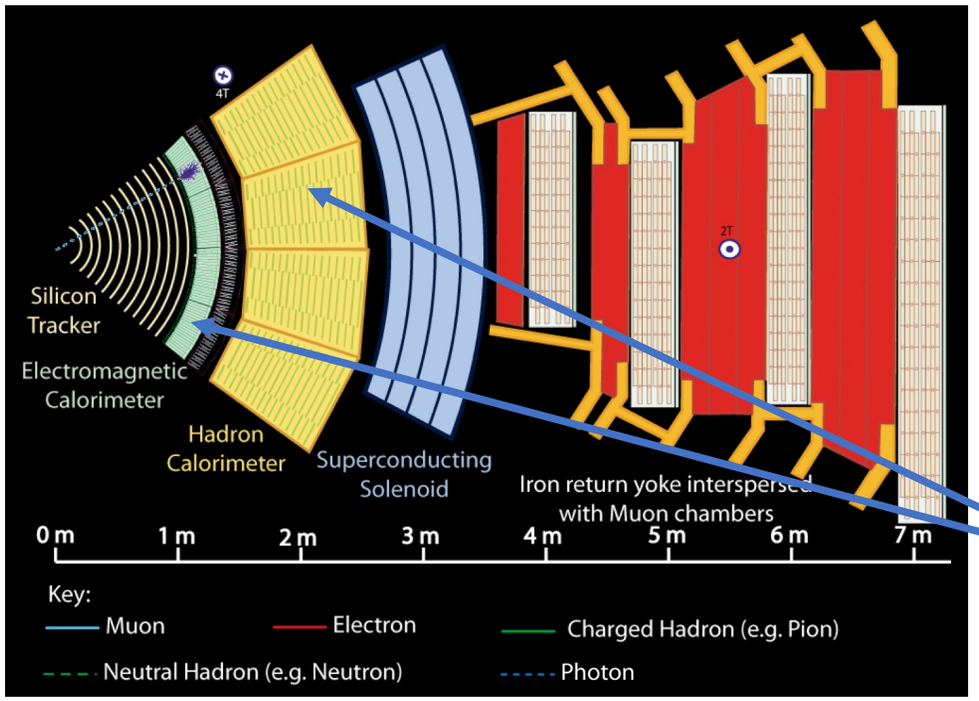
Create the future opportunities today

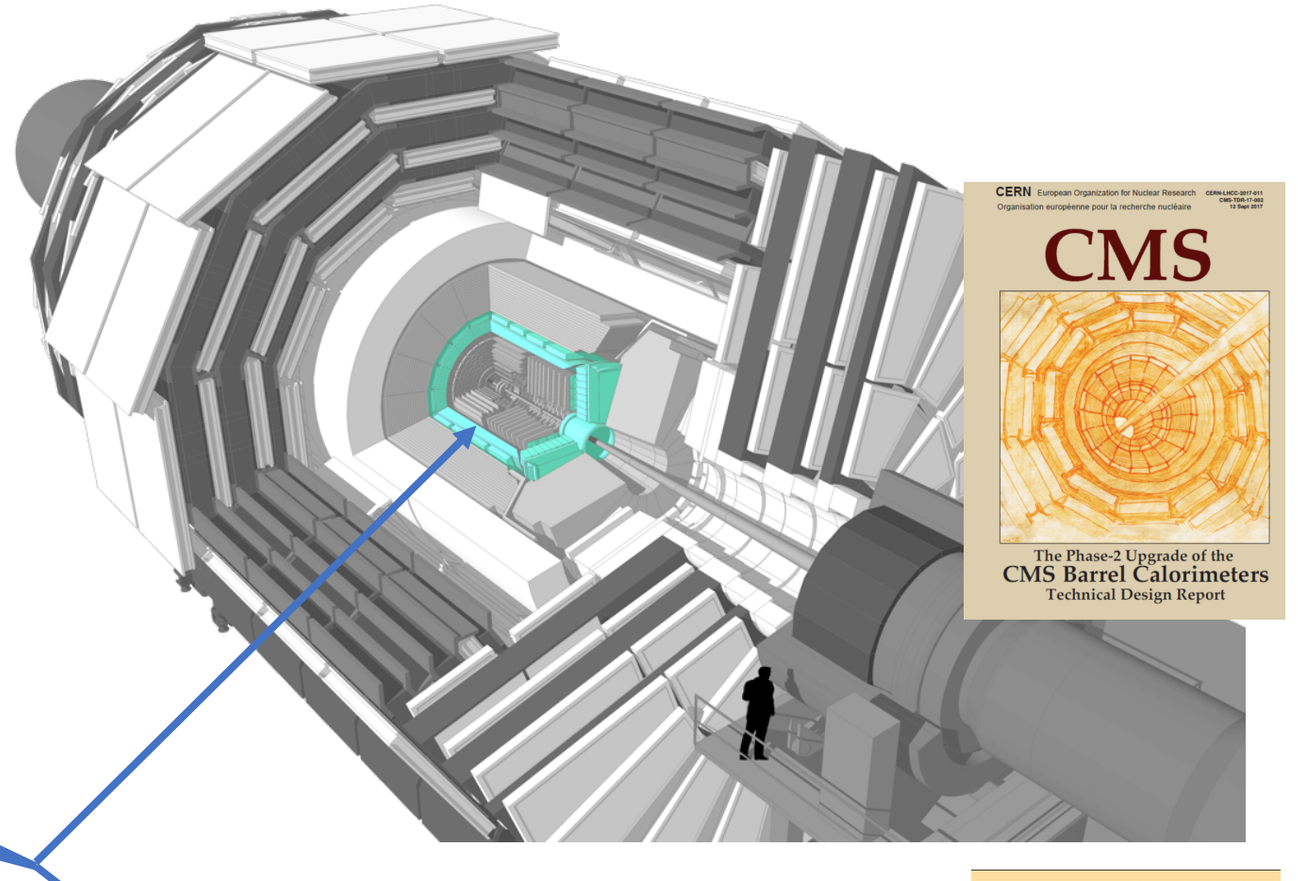


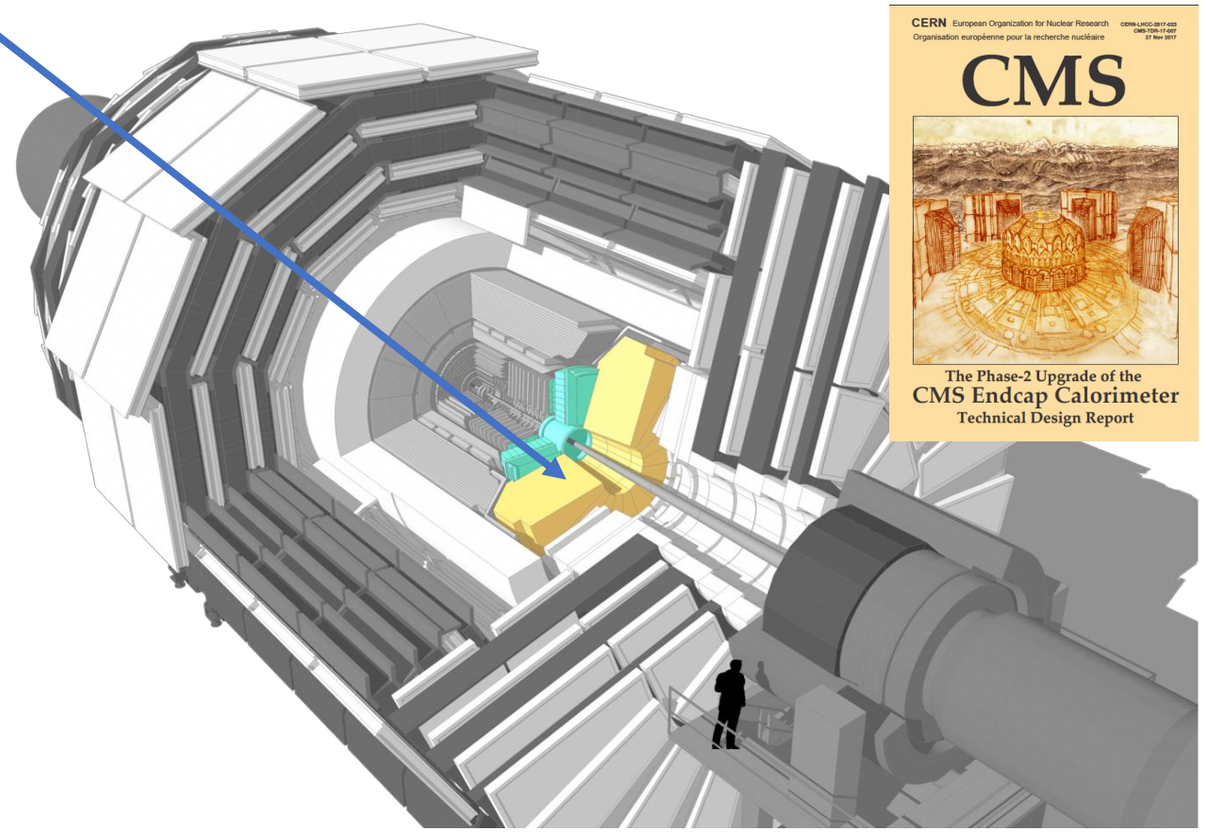
Fun at P5

RPC: Resistive Plate Chamber

More fun at P5





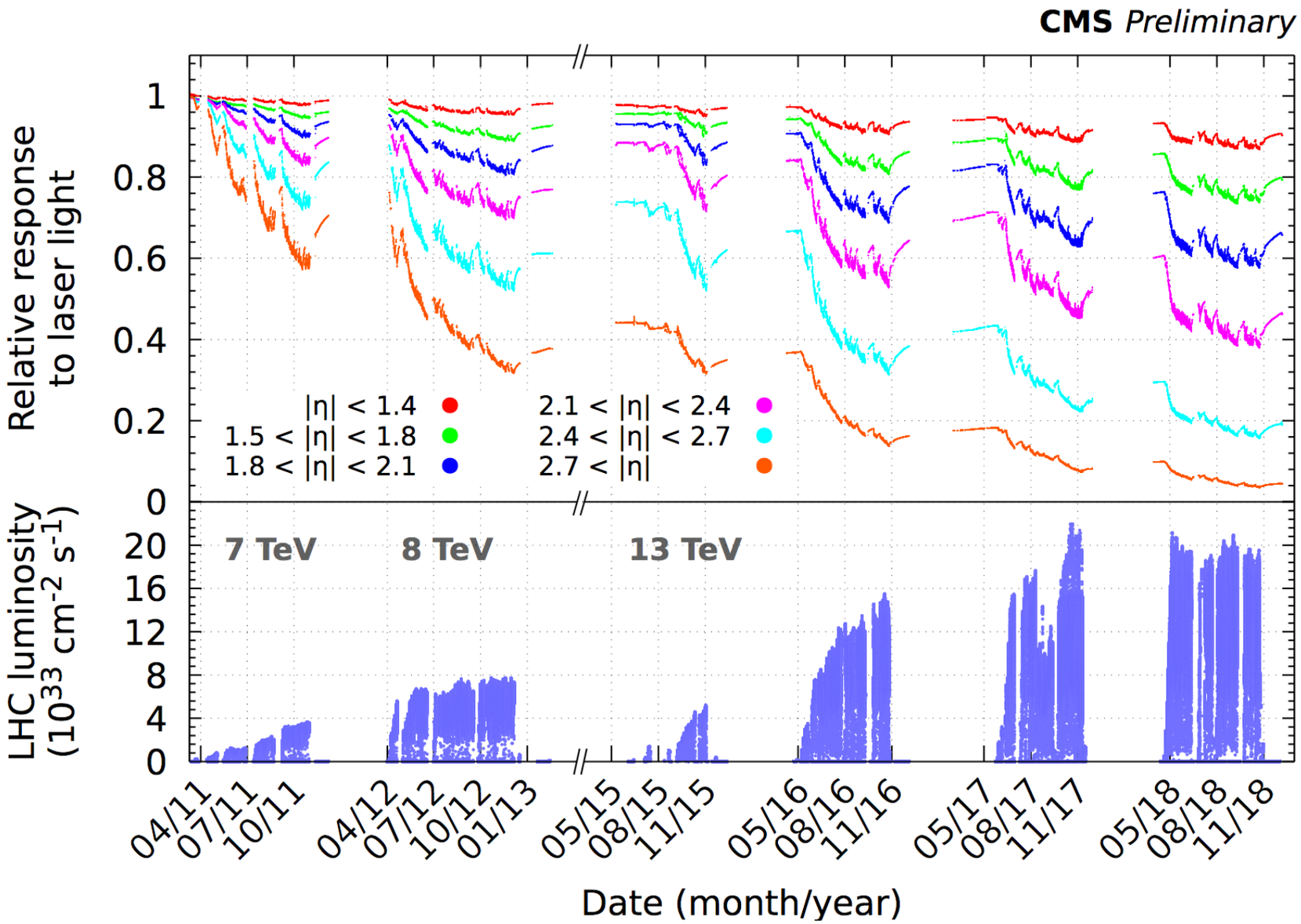


Calorimeter

Barrel and endcap

Which calorimeter to keep/replace?

Electromagnetic Calorimeter Barrel and Endcap



RED (barrel) **OK**

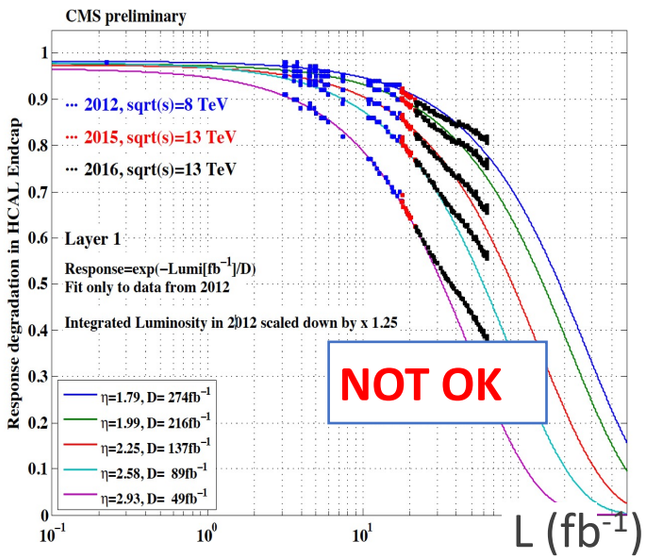
endcap

N

O

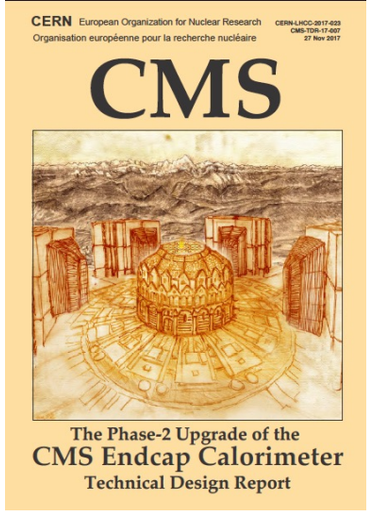
T OK

Hadron Calorimeter endcap response vs. Luminosity



CERN-LHCC-2017-011 CMS-TDR-015

Fun at calibrations and to understand how a detector really works



World's first

High Granularity Calorimeter

- a 5D calorimeter

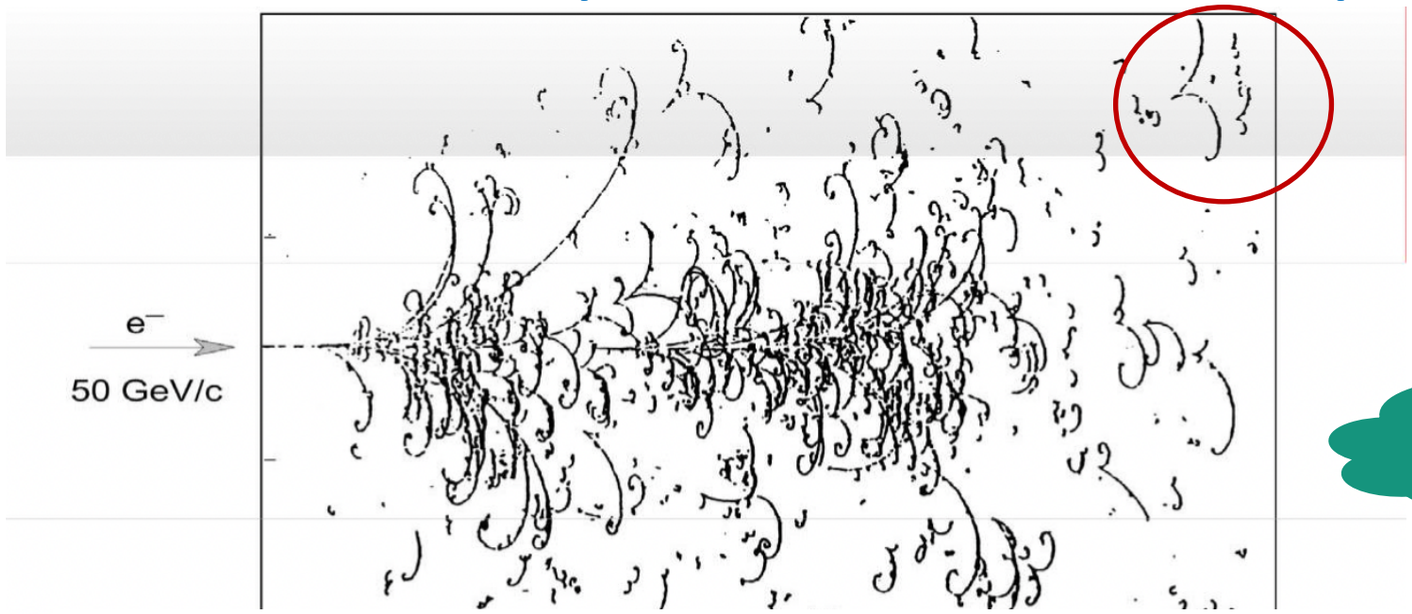
"5 dimensions" measured → (x,y,z,E,t)

CERN-LHCC-2017-023 CMS-TDR-019

Going Forward by looking backward - Imaging Calorimetry in the endcap

Idea kindly borrowed from D. Barney

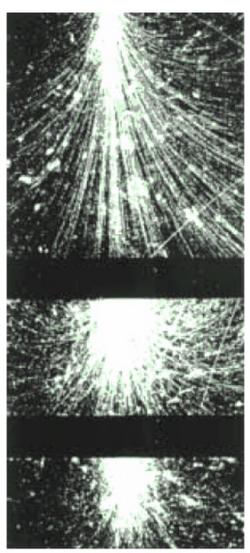
Big European Bubble Chamber
3T; L=3.5m, X_0=34cm

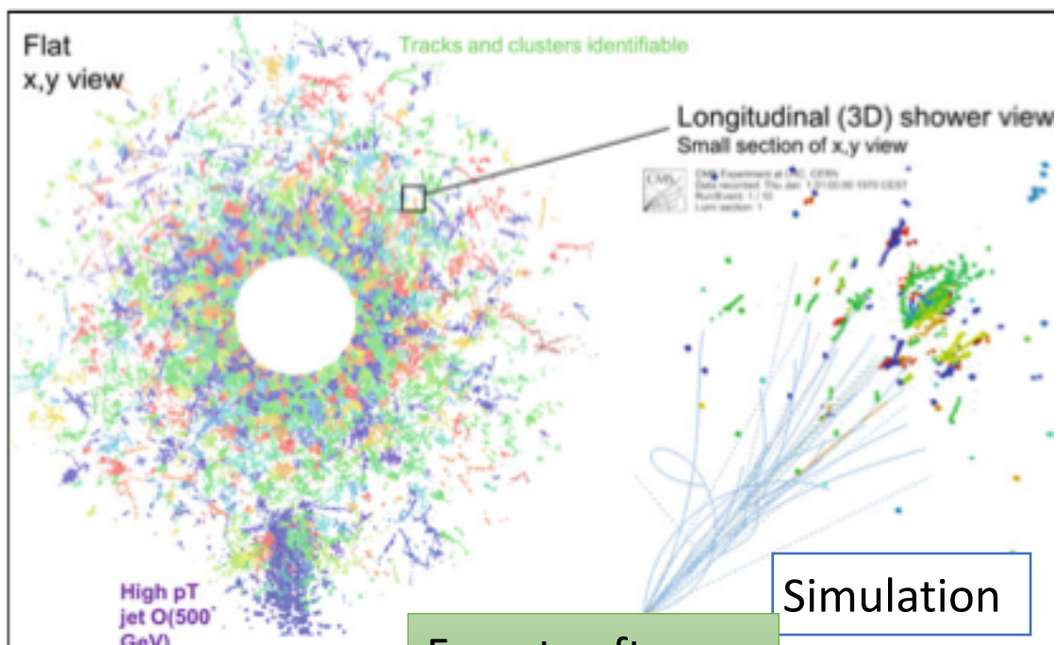


Yes, we can!

The previous generation of calorimeters could "see" showers!

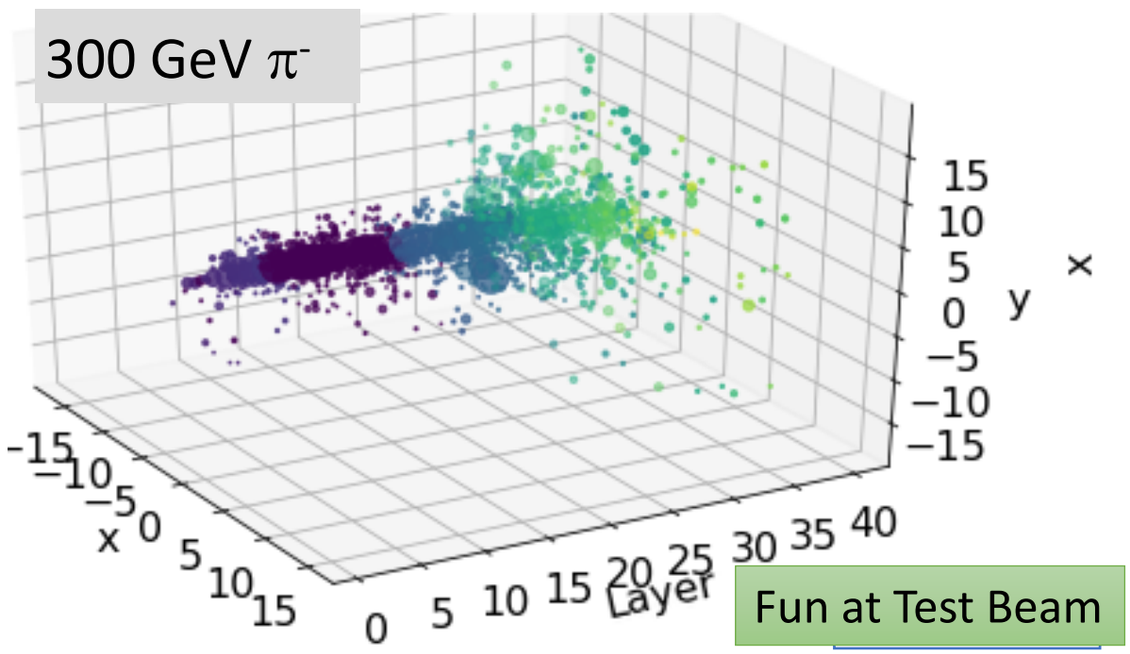
Can we do this again – at 40 MHz and PU=200?





Fun at software

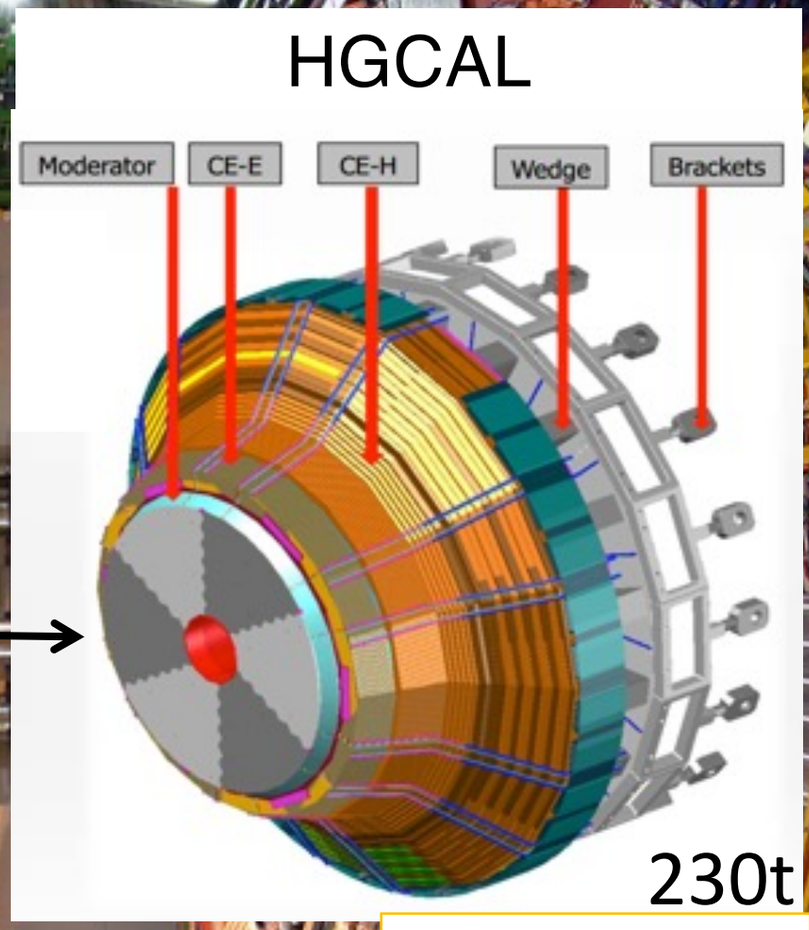
Simulation



Fun at Test Beam

Replace the 230t nose

Channels:	Today	2026
Electromagnetic	15’000 →	6’000’000
Hadron	10’000 →	400’000



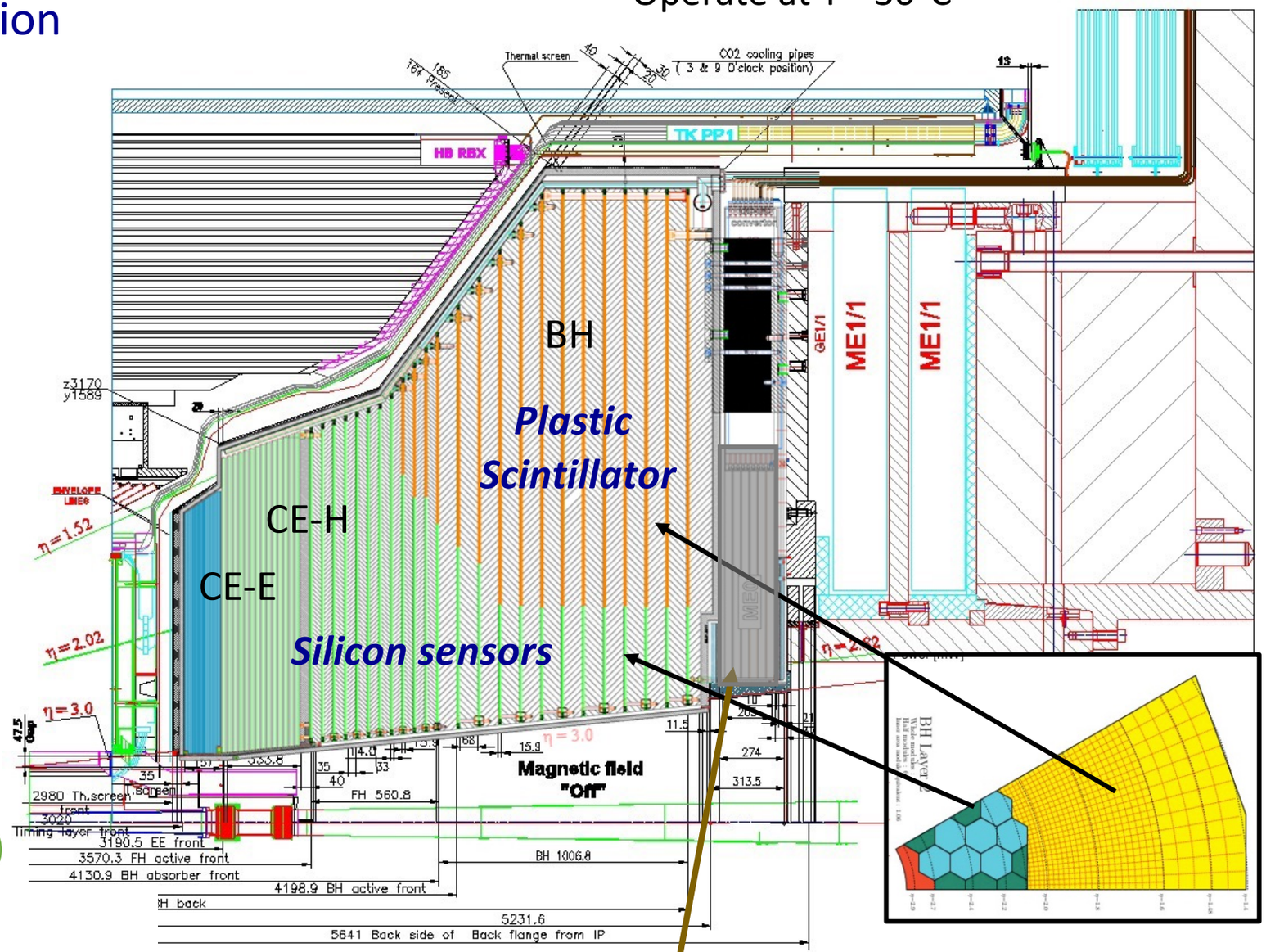
230t

High granularity
Radiation tolerant

Silicon enters calorimetry on large scale – World's first

- 3D shower topology and time resolution of ~ 30 ps (p_T > few GeV) **- 5D**
  - E.g. 2% energy resolution for γ
- **The silicon part** (*more rad tolerant*)
  - 600 m^2 of silicon
  - **8" wafers – a first in HEP**
  - 6M channels, 0.5 or 1 cm^2 cells
  - 25000 modules
- **Plastic scintillator** (*less rad tolerant*)
  - 500 m^2 of scintillators
  - ~400k scintillator & SiPMs on tile
- High granularity
  - A dream for Particle Flow concept (PF)

Operate at T=-30°C



*CE-E: **28** sampling layers – 26 X_0 + ~1.7 λ*

***22** sampling layers – 9 λ*

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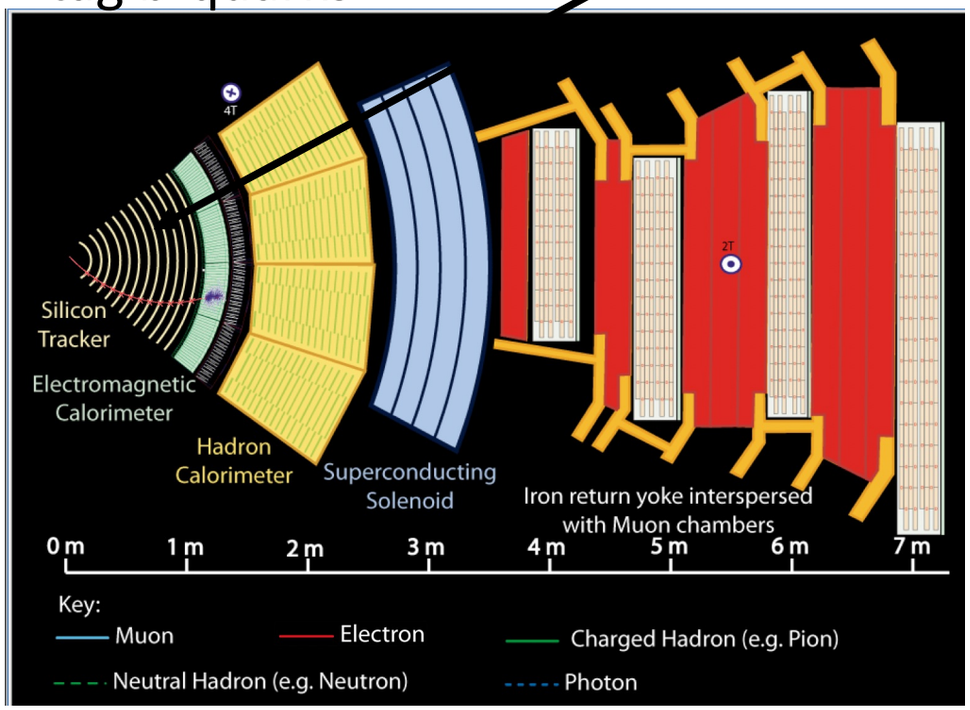
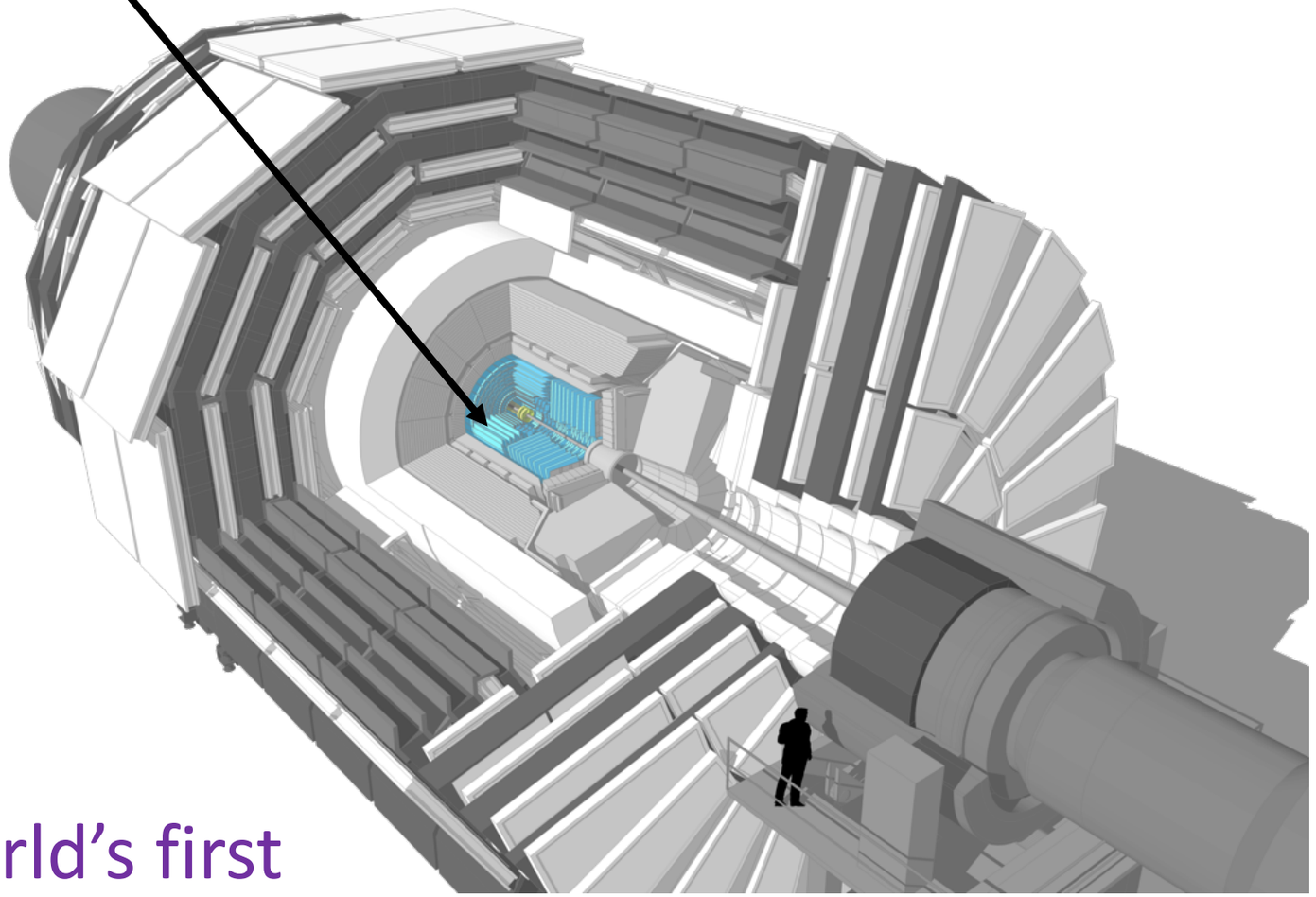
Btw: Muon GEM

HEP: High Energy Physics

- measure tracks
- tag b-quarks

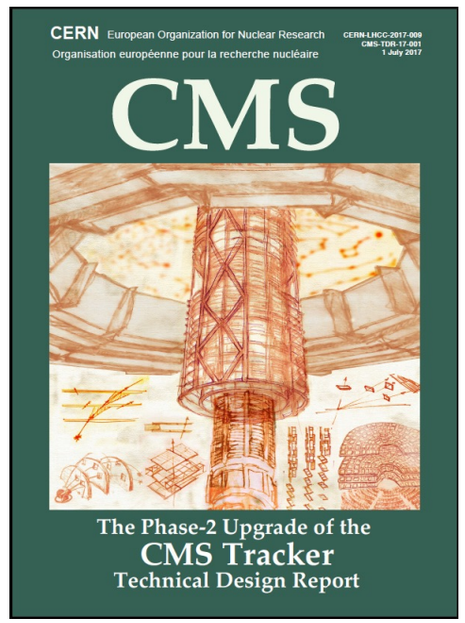




Track Trigger at 40MHz - world's first

Tracker

Build a new, better, more beautiful one



Thank you IPM for supporting Tracker for some years!
Maybe you will join again later!

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Flying Tracker
2008 in – 2024 out – 2026 new one in

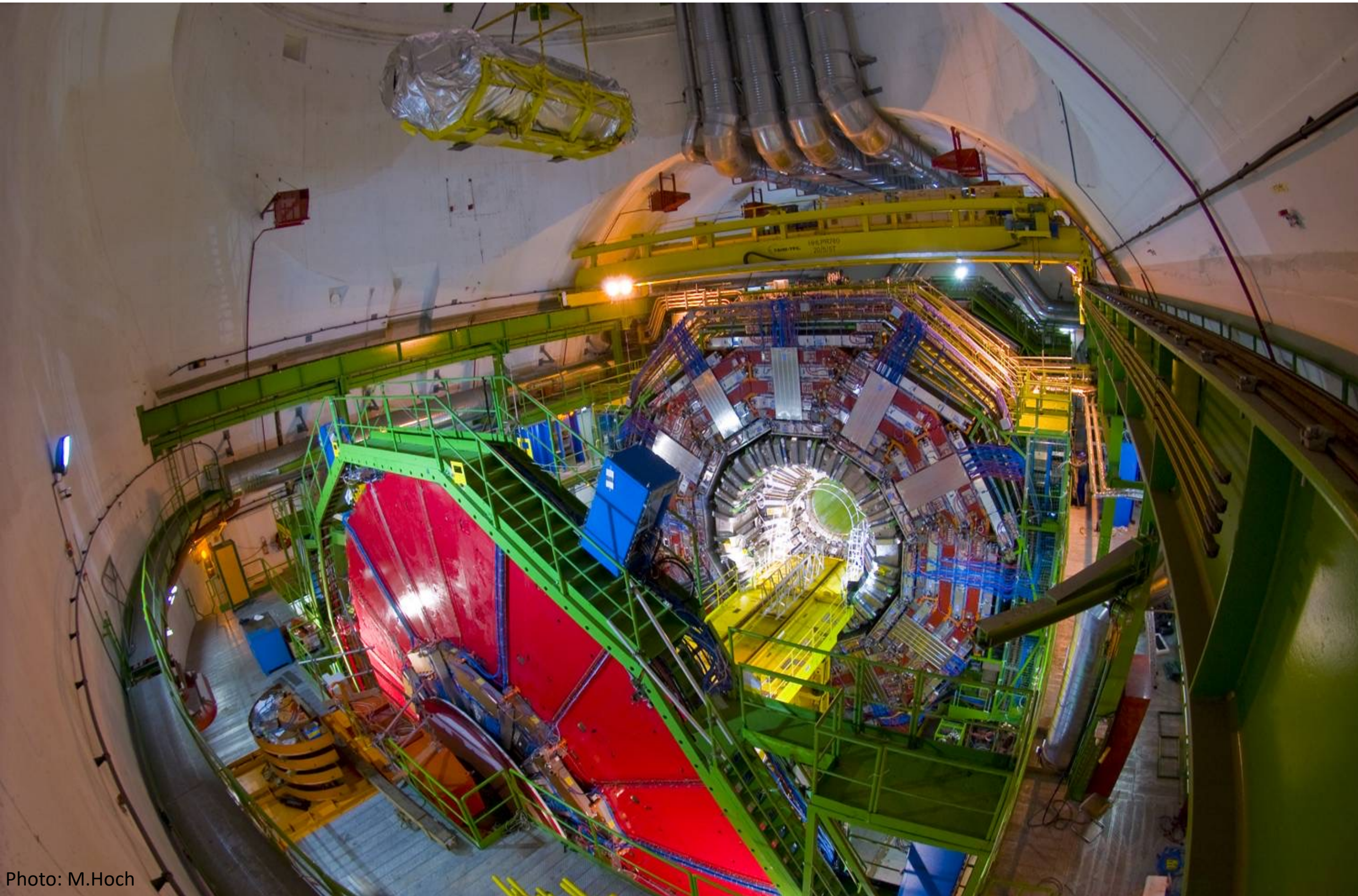
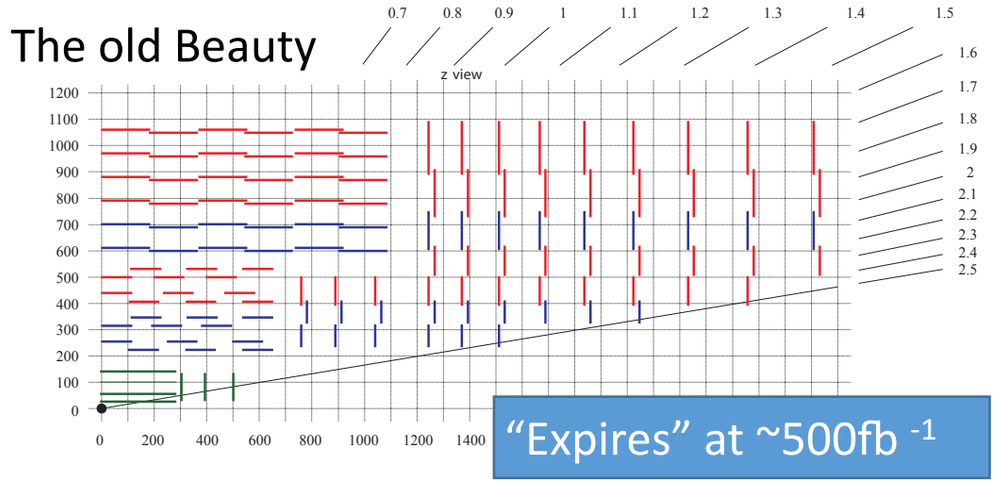
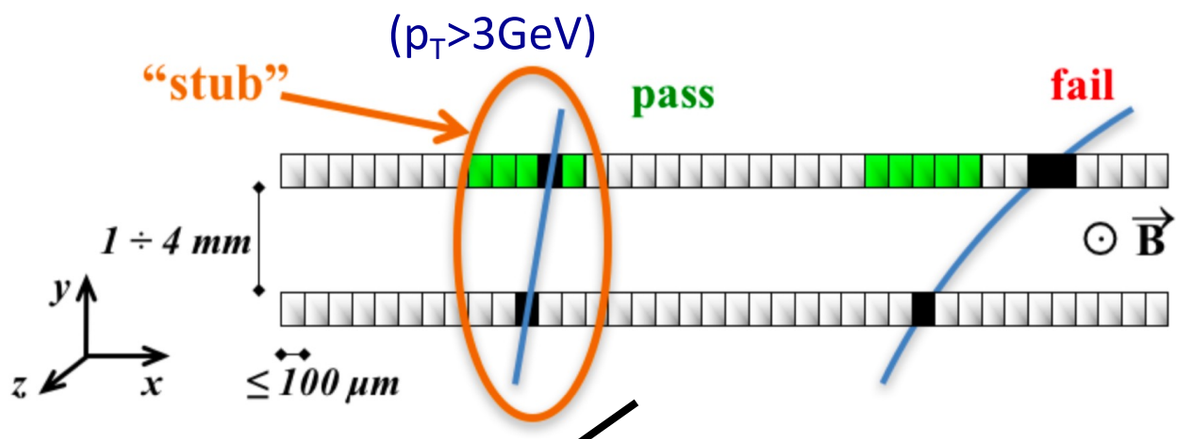


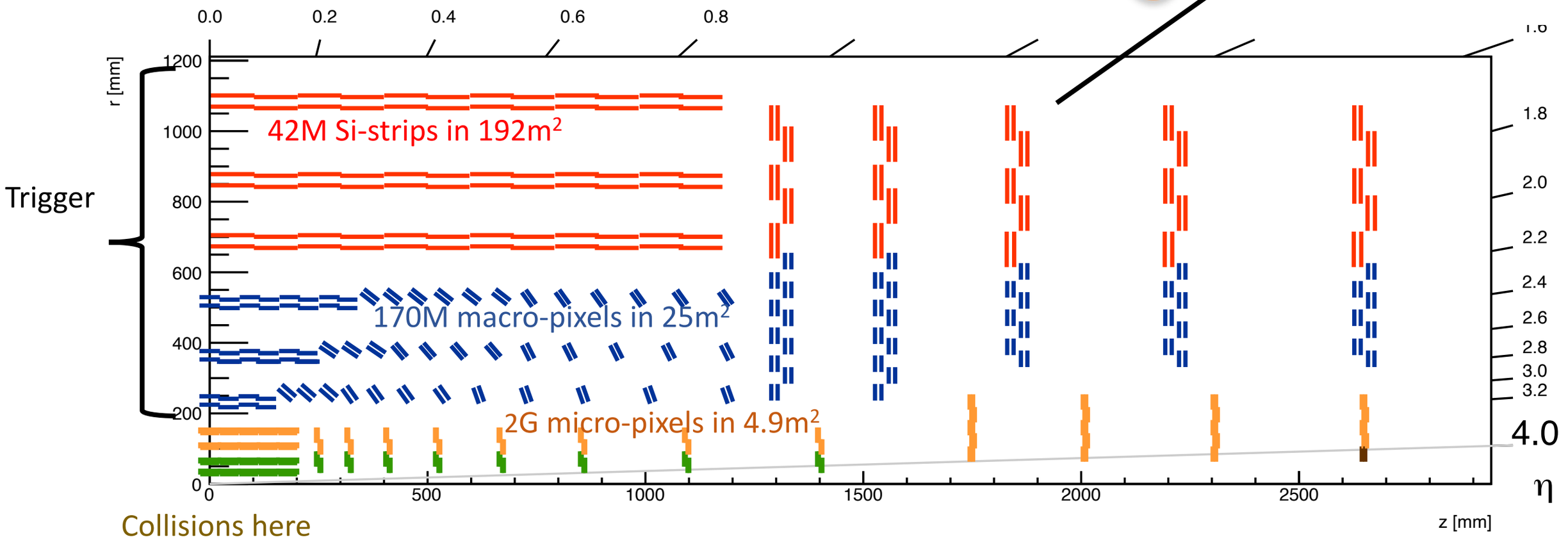
Photo: M.Hoch

The new Beauty

- Outer Tracker design driven by ability to provide **tracks at 40 MHz to L1-trigger** (p_T>3GeV)
  - **World's first**
- Tilted modules in three OT layers
- Inner Tracker (pixel) extend coverage to η ≃ 3.8







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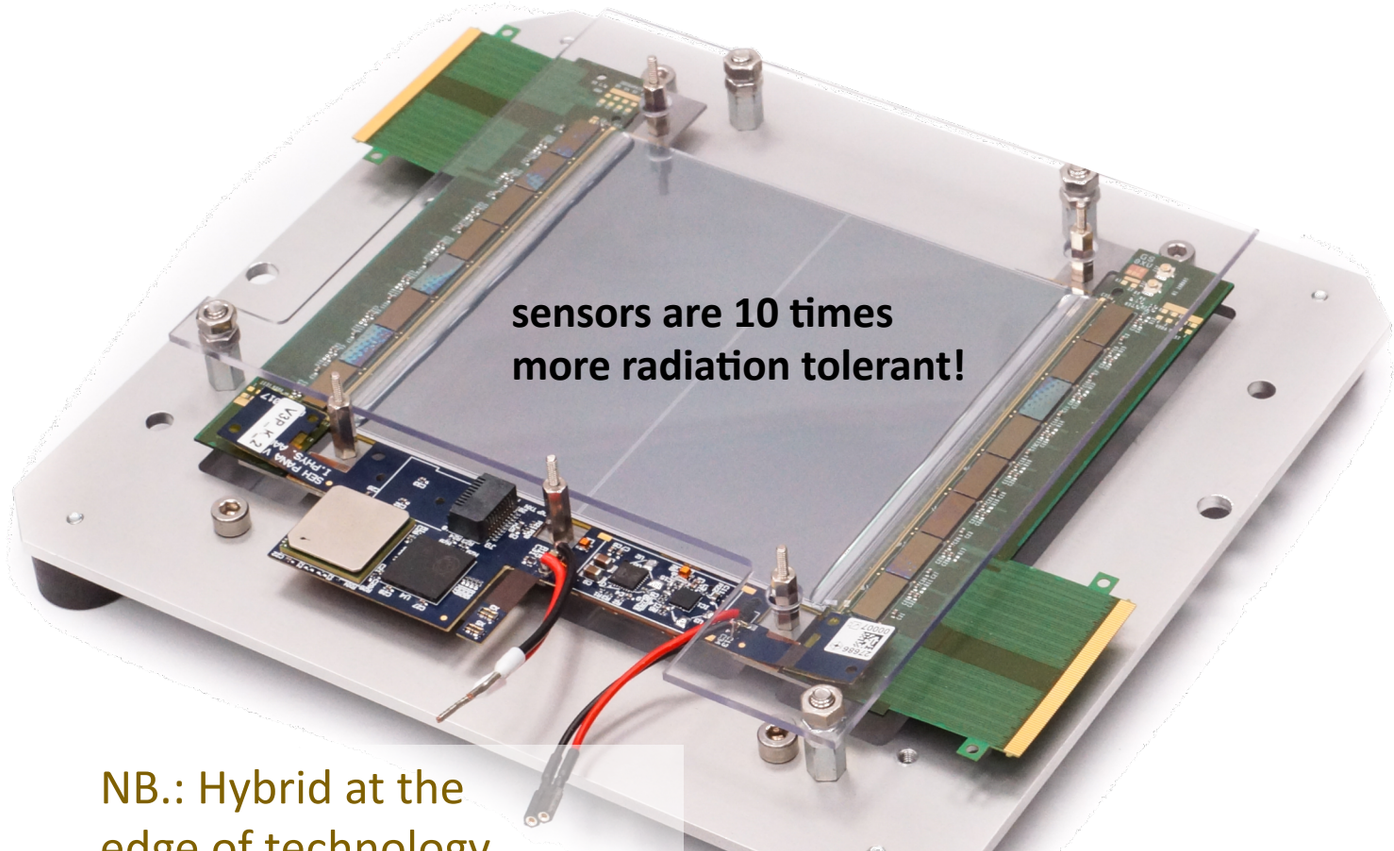
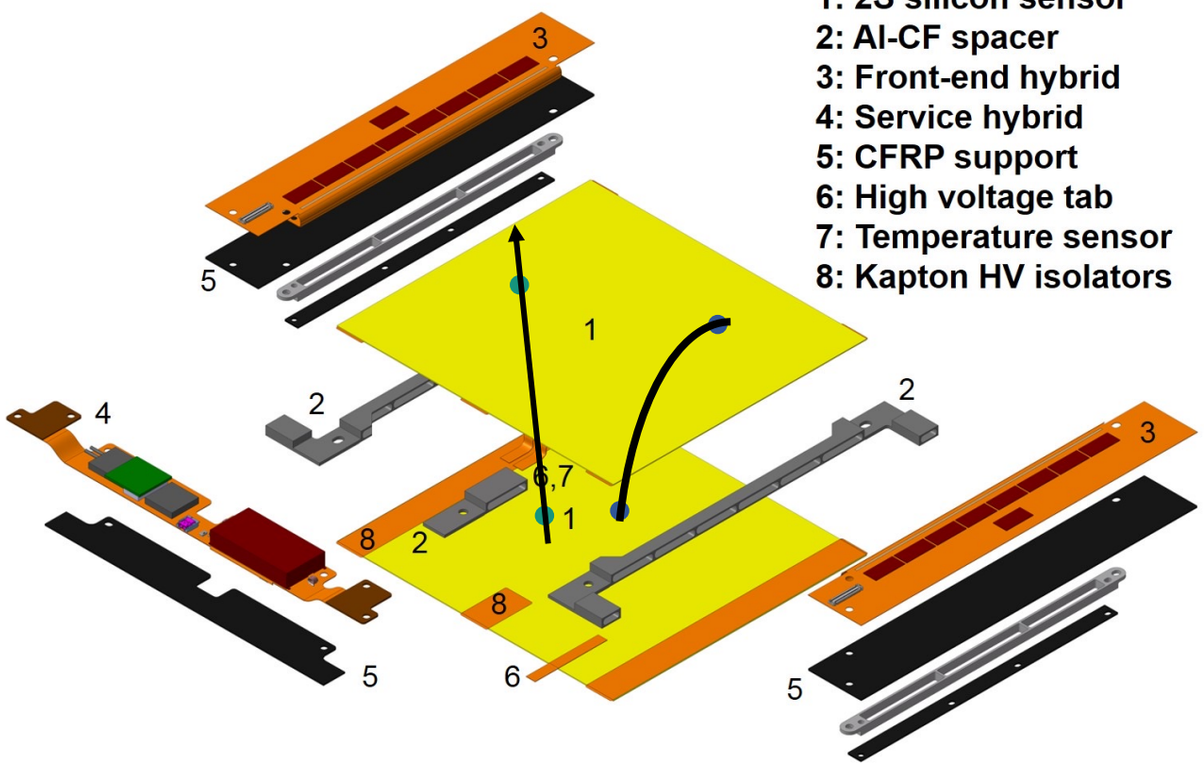
p_T transverse momentum

New Technologies – Tracker Module

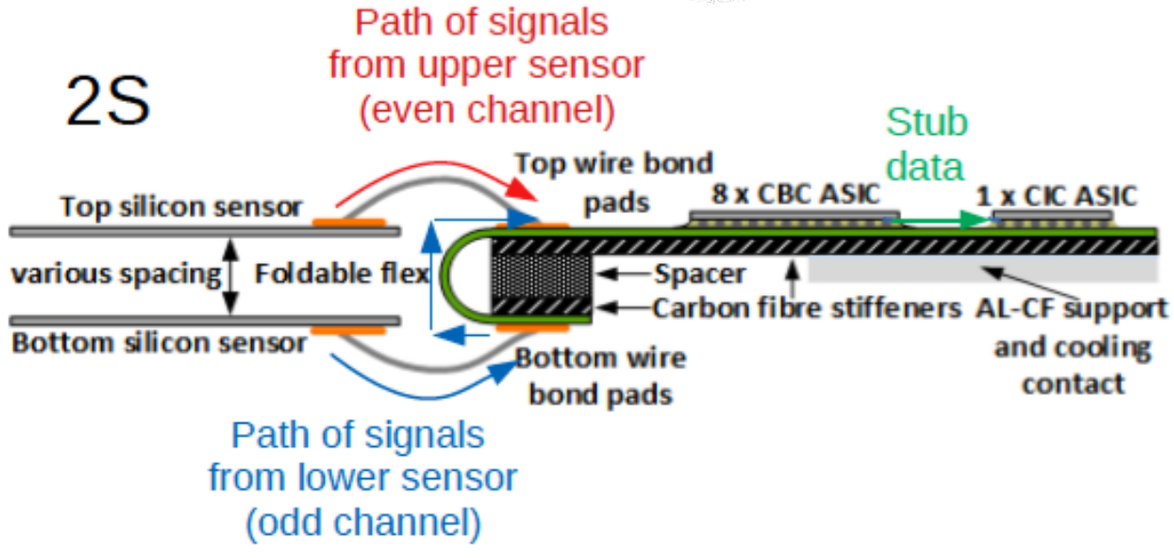
New concept

- Contains ALL electronics = full system
- Effective way to have 2 space points in single mechanics – lightweight
- Gives ‘vectors’ instead of points
- Tag high p_T segments



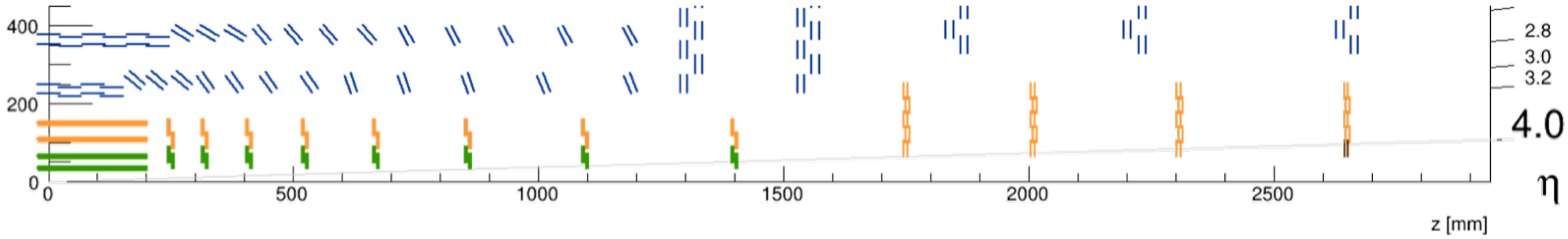


NB.: Hybrid at the edge of technology



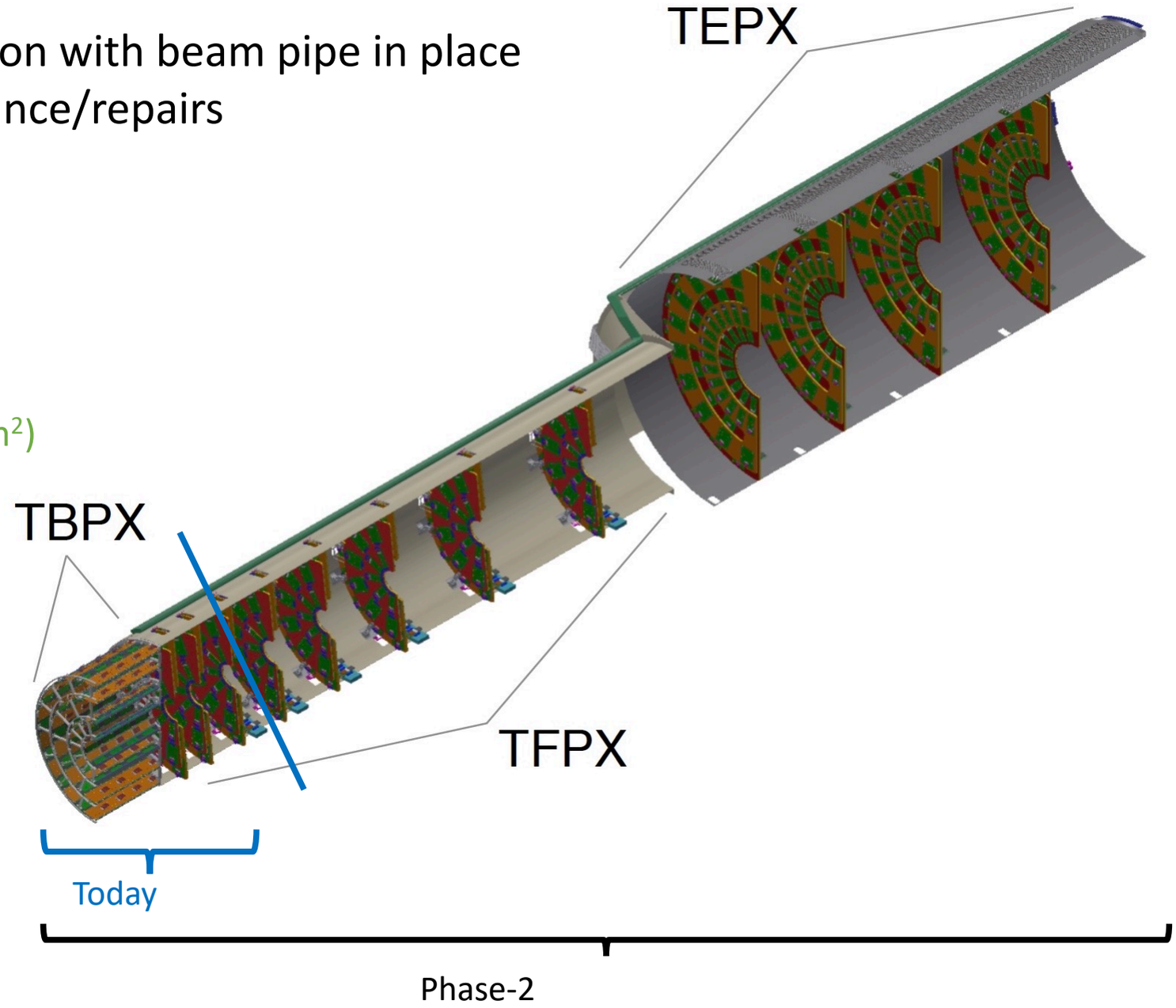
NB.: ~5 years of engineering and modelling

We extend into the forward region



- Half-shells permit installation/extraction with beam pipe in place – **BIG** advantage as it allows maintenance/repairs
  - Low radius helps excellent b-tagging
  - Coverage up to η=4
  - 3.900 modules = 2 billion pixels
  - Surface: 4.9 m^2 (today 1.75)
  - Pixels: 25x100 μm^2 (today 100x150 μm^2)
    - mandatory with high pile-up
  - Hit rate: 3 GHz/cm^2

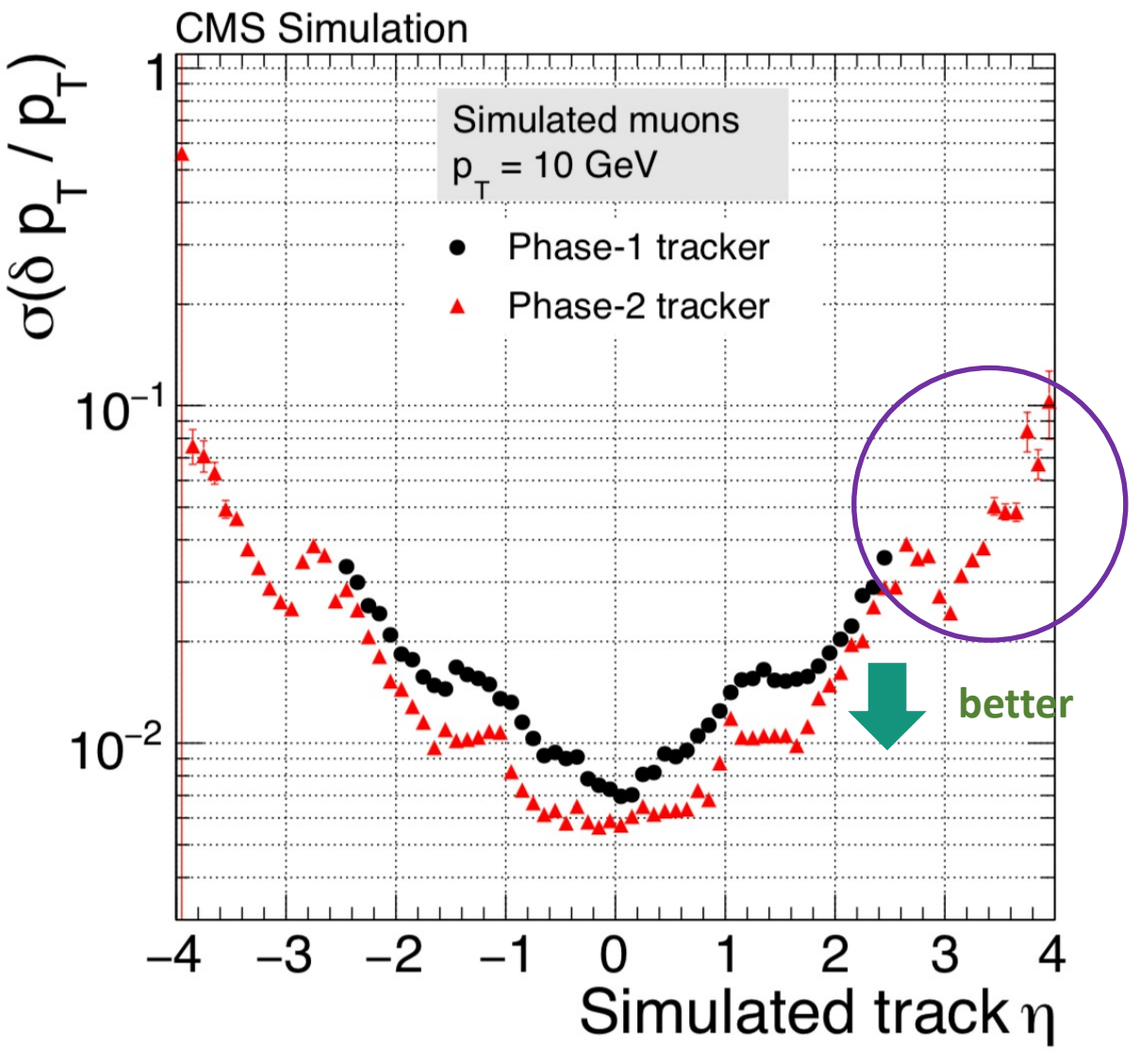
→VBF
→b-tagging
→PU mitigation



NB.: Pixel chip development:
24 institutes - 5 years of work

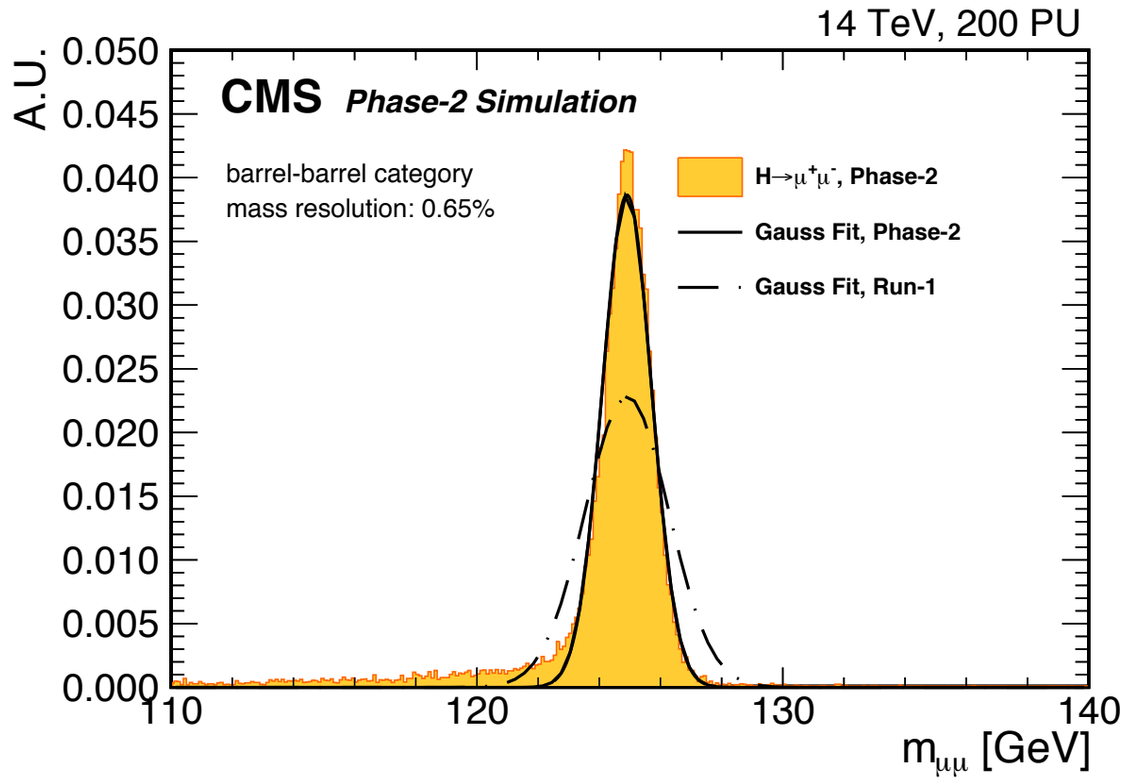
Tracker-2 Performance

p_T resolution



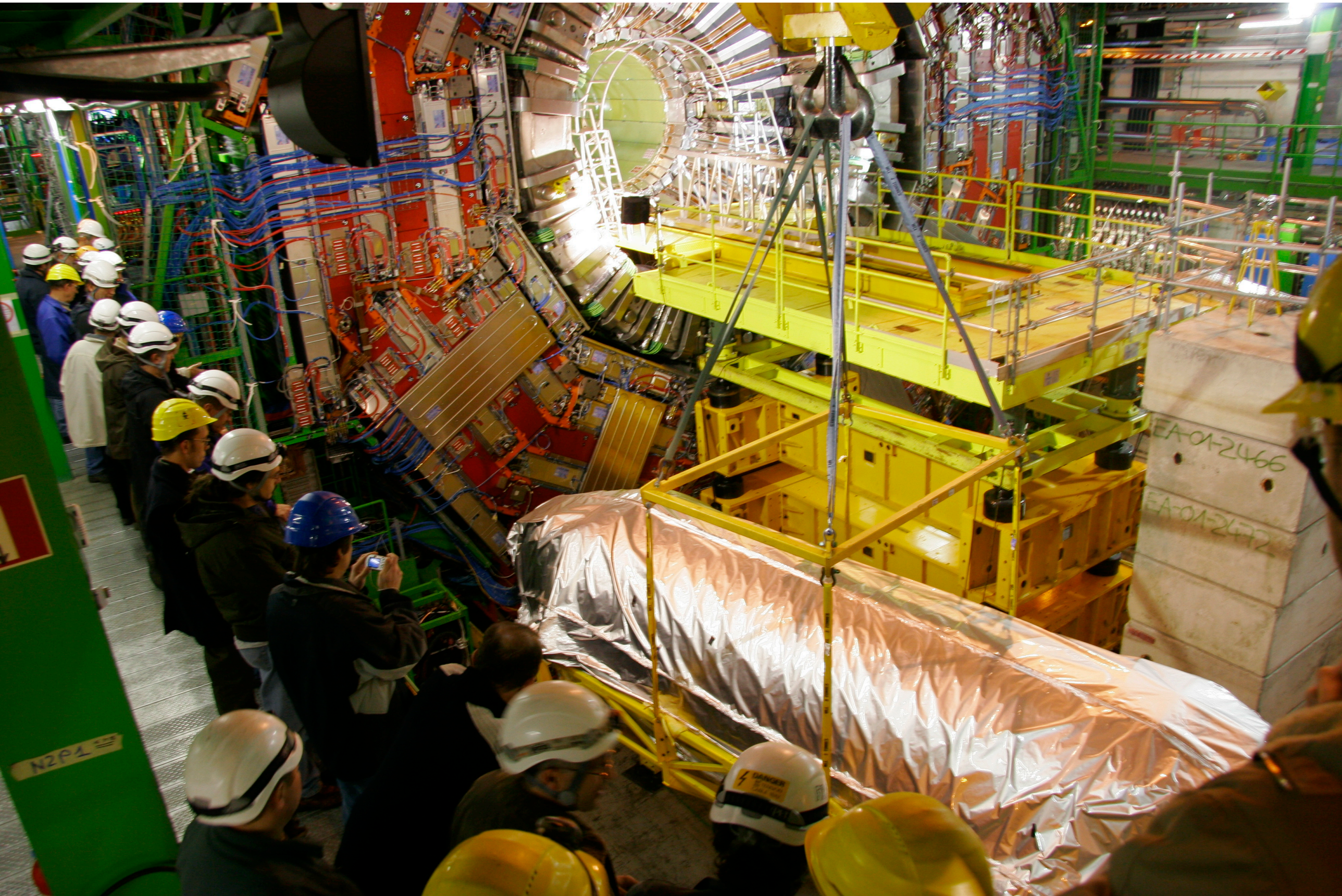
$H \to \mu\mu$: coupling to muons

- 65% improvement on $m_{\mu\mu}$ in barrel-barrel category (0.65% mass resolution)
- 5% coupling precision possible with 3000fb^{-1}

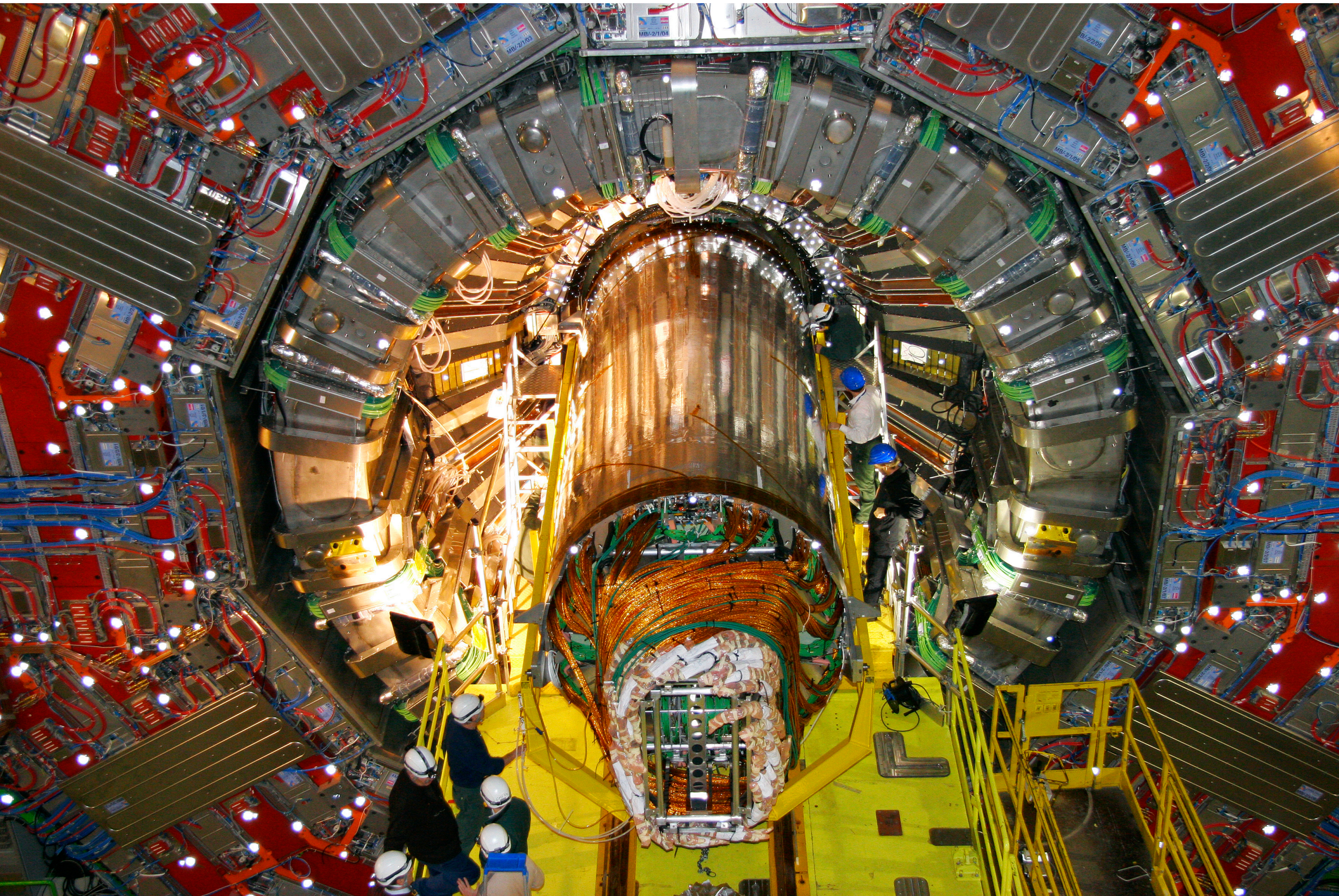


- More precise tracking parameters
  - **Largely due to reduced material budget, thus less multiple scattering**
- Extended coverage, allowing e.g. better forward jet reconstruction
  - **Helps PU-mitigation, VBF, di-Higgs**

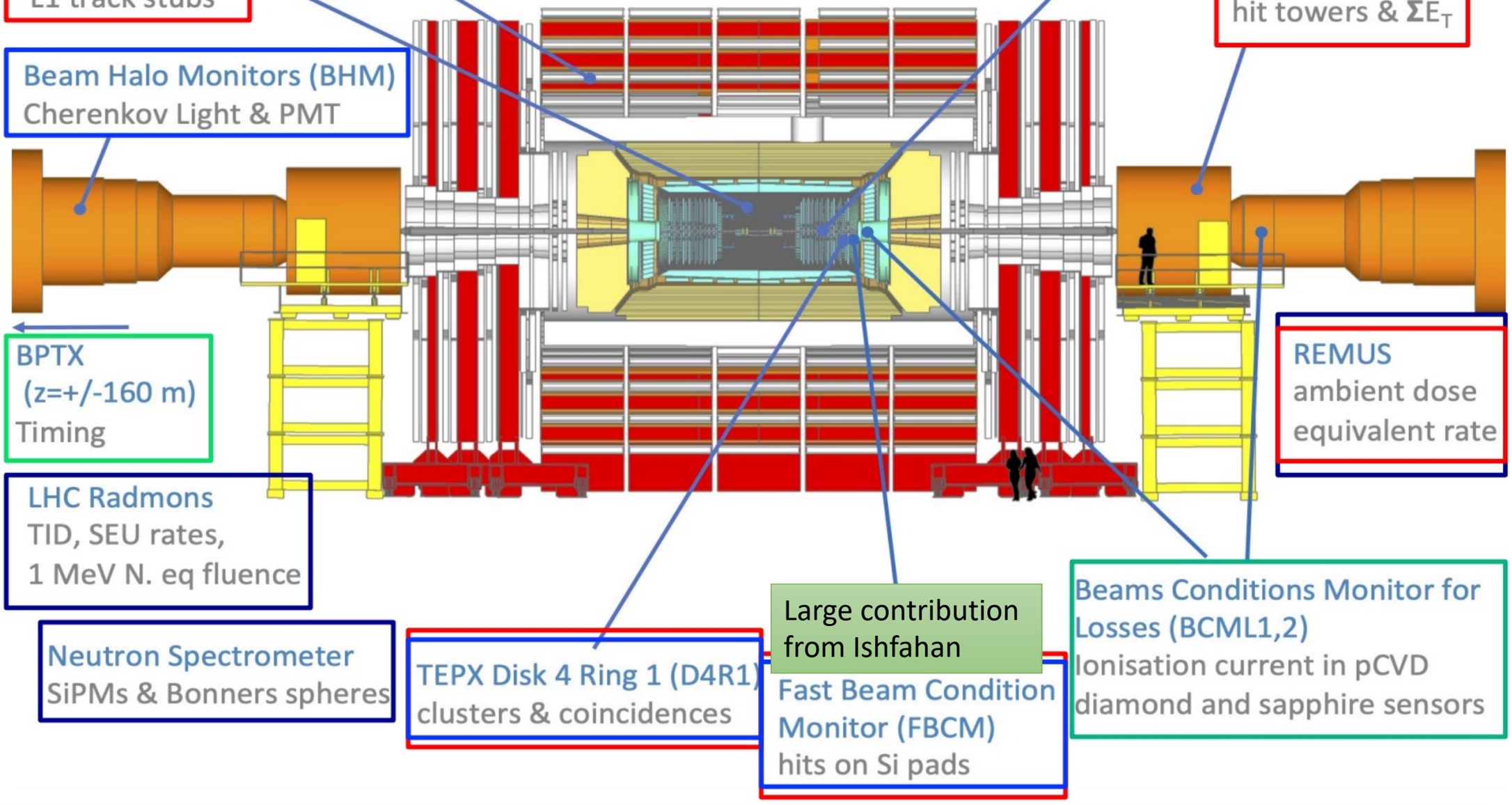
The current Tracker December 2008



Insertion of the Tracker into the Heart of CMS



Beam Radiation Instrumentation Luminosity - BRIL



Wonderful opportunity to work on special, important but small detectors, where individuals can get significant visibility
And without it, CMS cannot run and phyiscs would not be possible

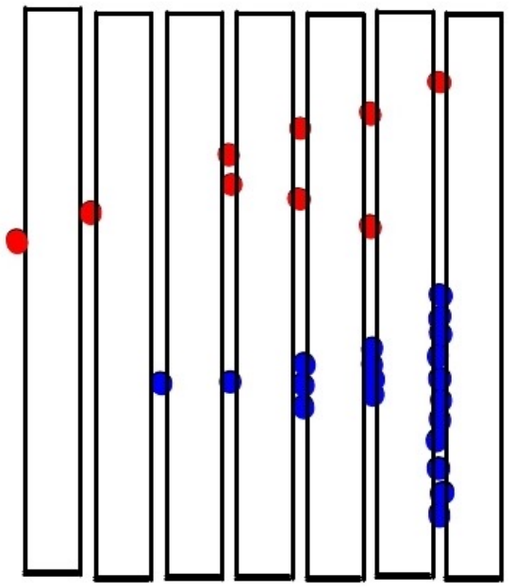
Last but not least
L1 Trigger

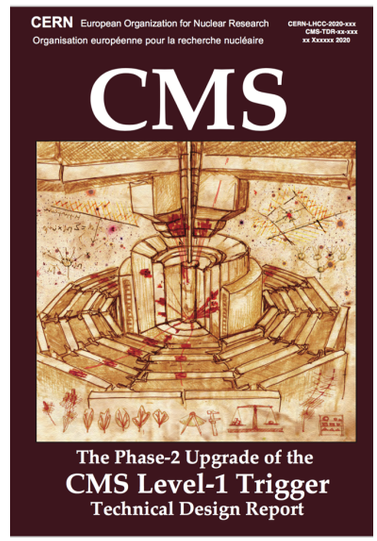
Select the good stuff, as you simply cannot readout and store all events

L1 Trigger is becoming even more intelligent

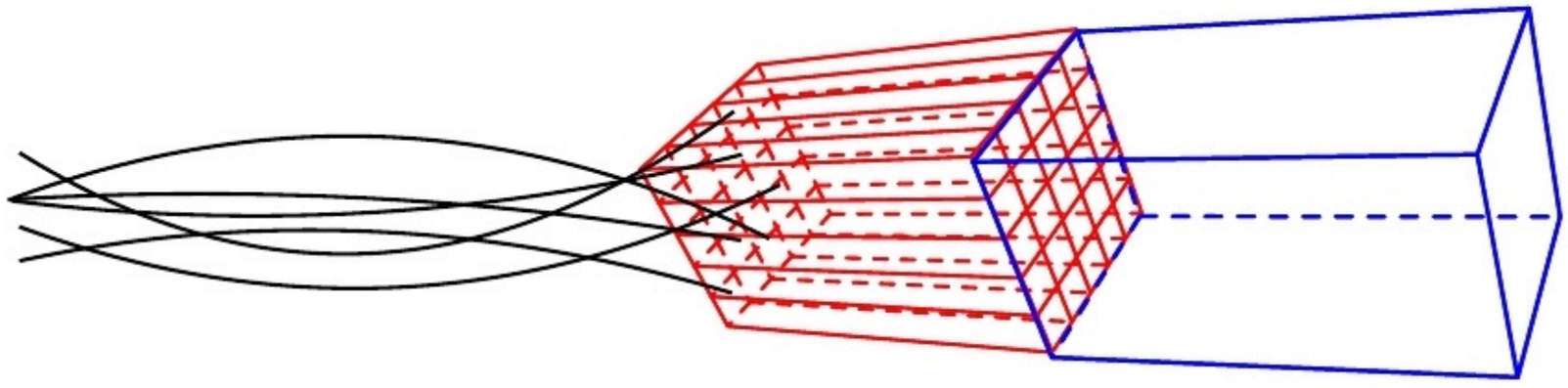
- Increased data & processing
  - ≥ 50 Tbps input; 40MHZ;
    12.5 μs latency, accept rate 750 kHz
  - Barrel Calorimeter: 25x resolution improvement
  - Tracking information: **new** objects available
  - Endcap Calorimeter: 3D High Granularity

➔ **Particle Flow @ L1**





➔ **Machine Learning**

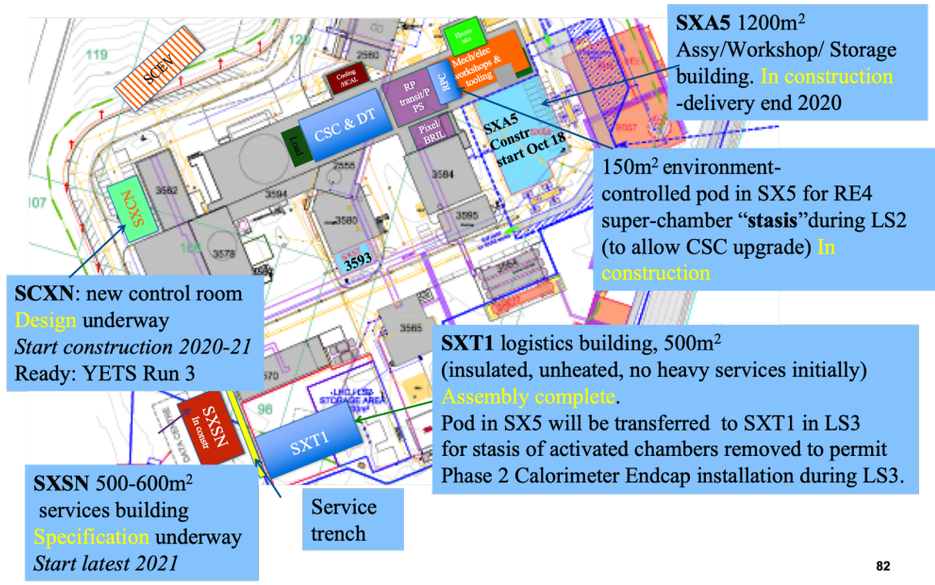


No need to improve resolution of detector without improving resolution at trigger level ~ thresholds

Then are the side-dishes that fewer people talks about

- Buildings, CO_2-cooling, gas distribution, power, safety, databases, service installation (power, fibers, pipes), systems to commissioning (quite cold), Data Acquisition, firmware, control systems, opening and closing 600t-objects, alignment
- Custom chips, custom electronics boards, custom optical transmitters/receivers
- Computing – neural network, machine learning

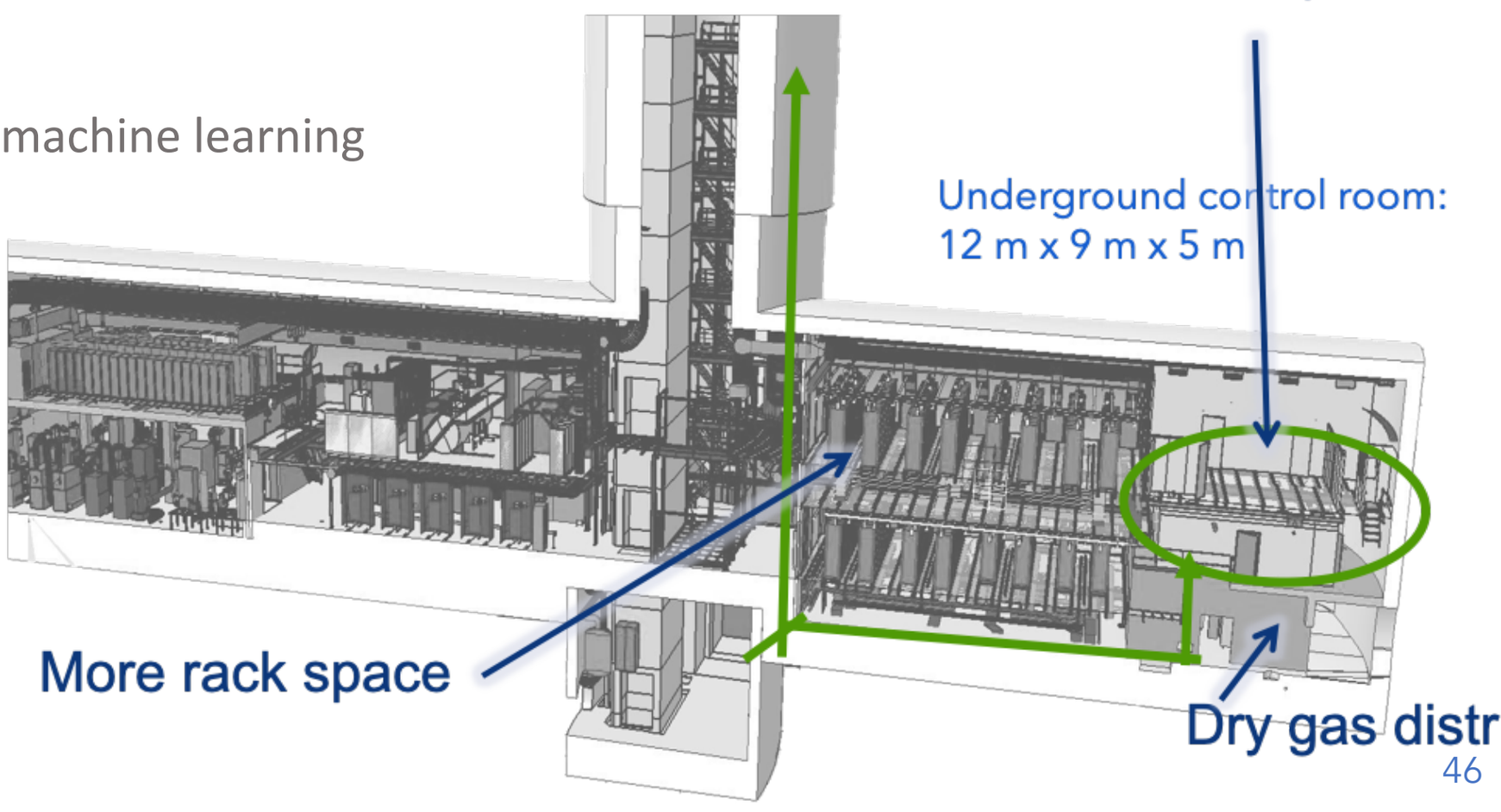
CMS P5 surface infrastructure plan - all



82

To surface storage and main chiller
Via PM 54 shaft (85m)

CO2 plants



Space in the cavern is even more scarce then money

Now the Quiz

- Why are we doing this?
  - **To measure the hell out of these crazy phenomena!**

- What are the real new technologies?
  - Track Trigger
  - High Granularity Calorimeter
  - Particle Flow @ L1
  - ‘Precision Timing’

- Is it fun?
  - **Oh YES! a fantastic tool**

I stop with a realistic illustration of the fun for the next several years