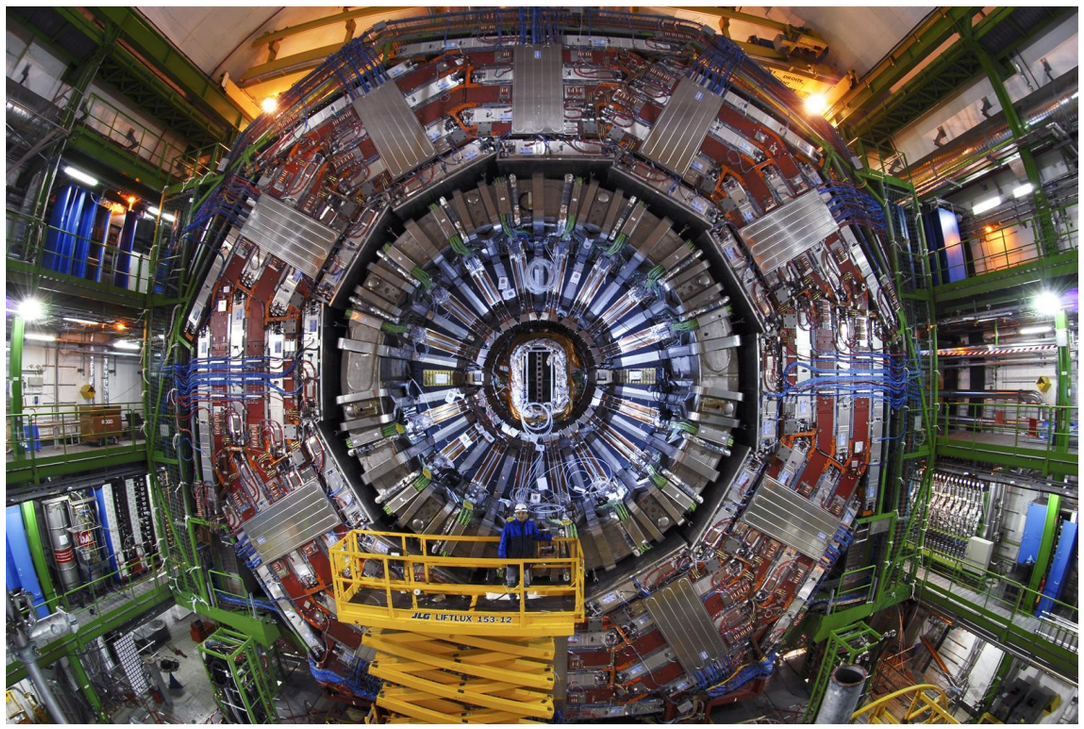
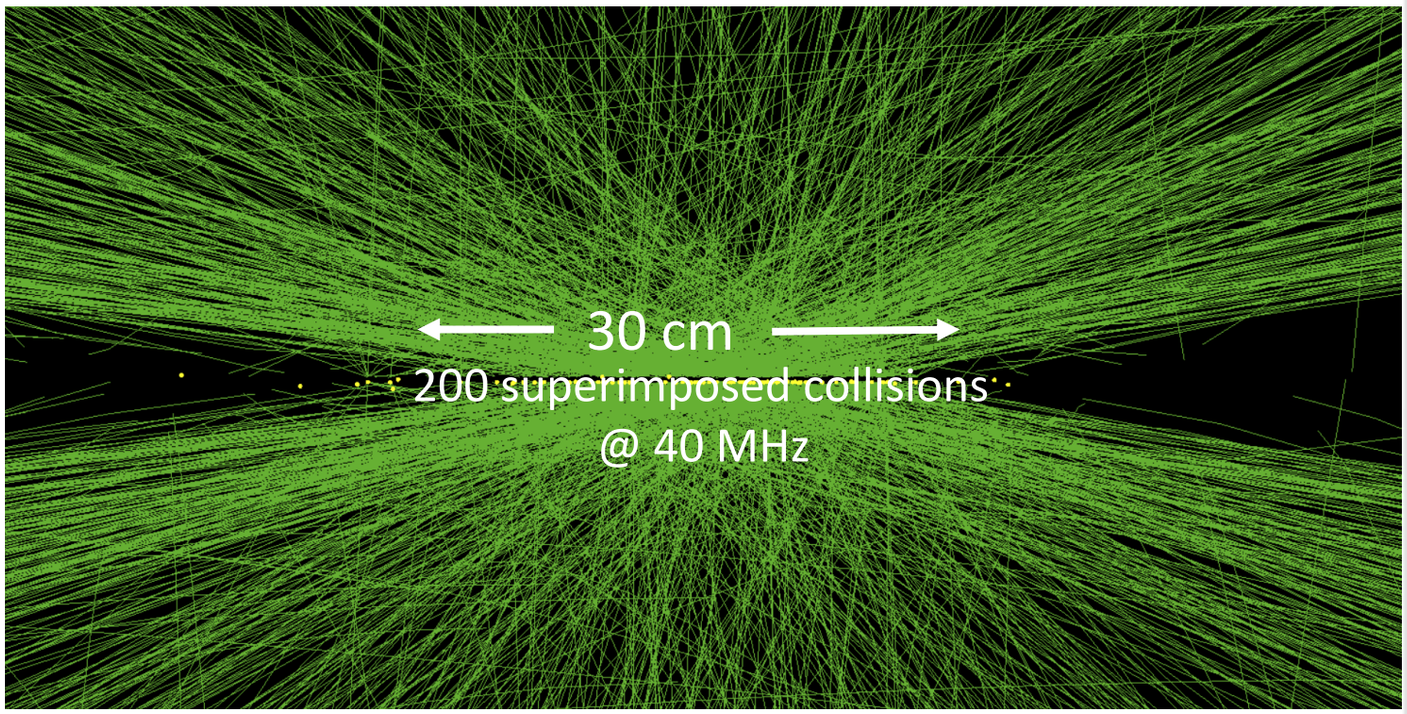
Karlsruhe Institute of Technology

Why we need a CMS Upgrade ?

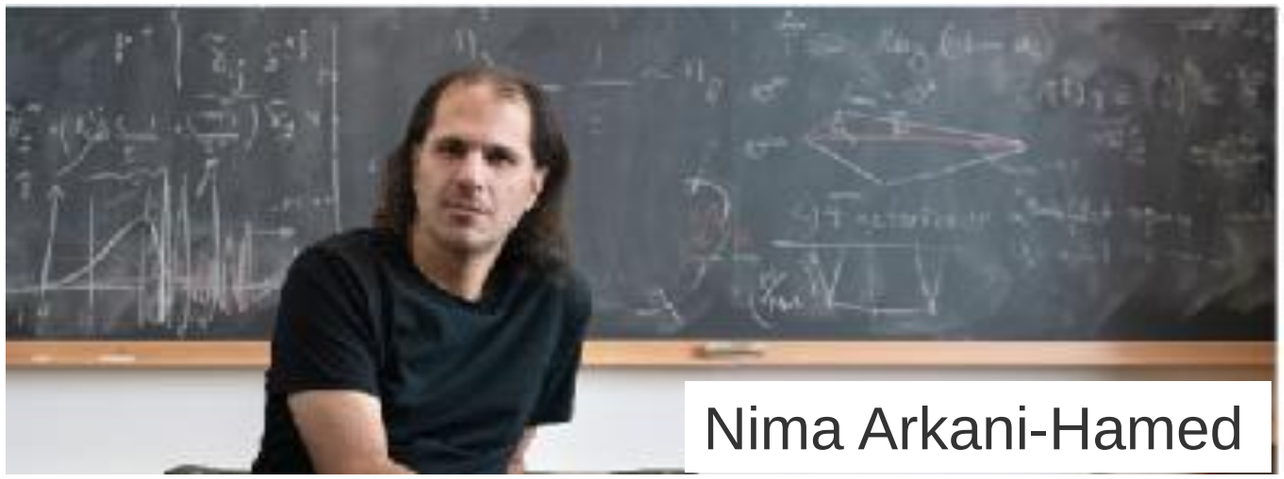
New Technologies to uncover **New** Physics

Frank Hartmann – CMS Upgrade Coordinator





CMS at HL- LHC – In other words ..



CERNCOURIER | International journal of high-energy physics

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FEATURE

Interview: In it for the long haul

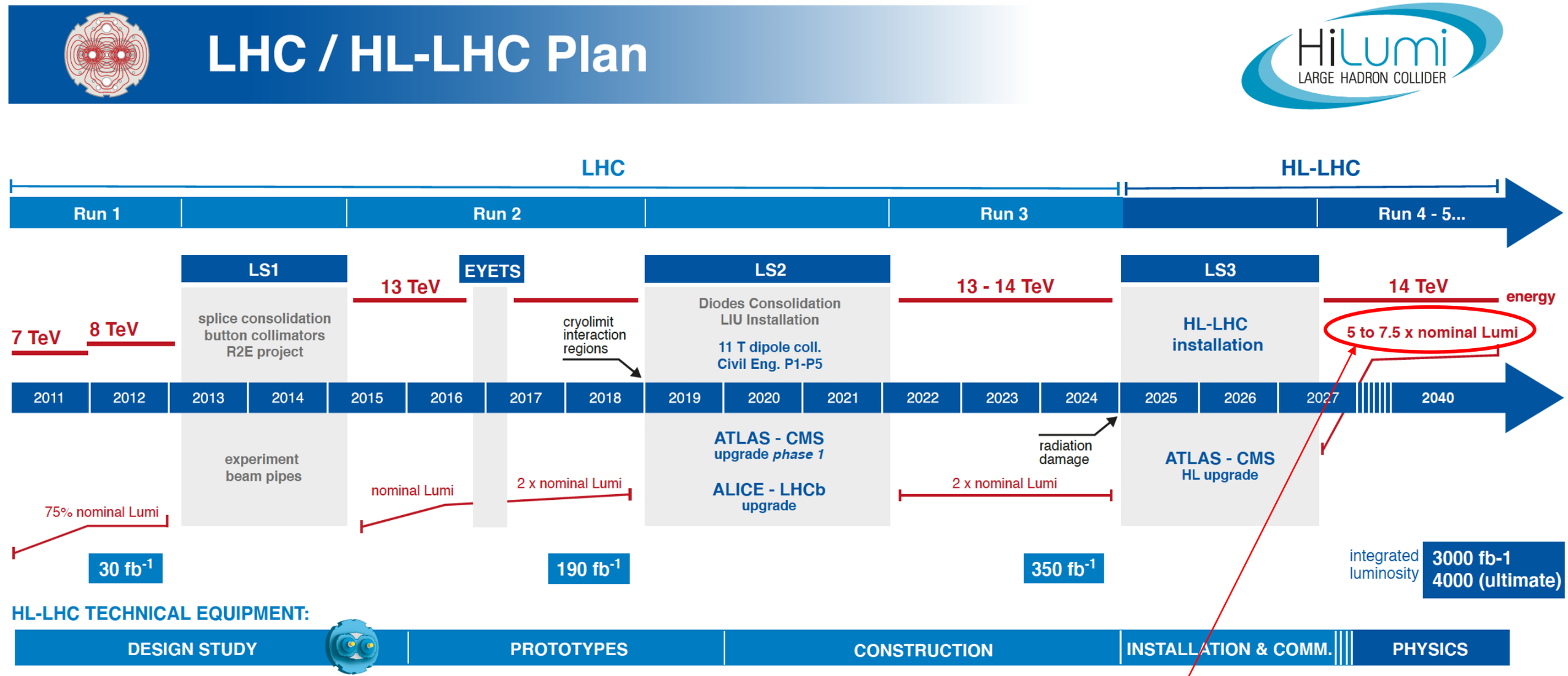
8 March 2019

"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)

“how many collisions per unit time”

“how many collisions in total”

Peak luminosity

Integrated luminosity

Luminosity [cm^{-2}s^{-1}]

Integrated luminosity [fb^{-1}]

6.0E+34
5.0E+34
4.0E+34
3.0E+34
2.0E+34
1.0E+34
0.0E+00

3500
3000
2500
2000
1500
1000
500
0

LS1
LS2
LS3
LS4
LS5

10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39

Year

We are here!

We will eventually be here!

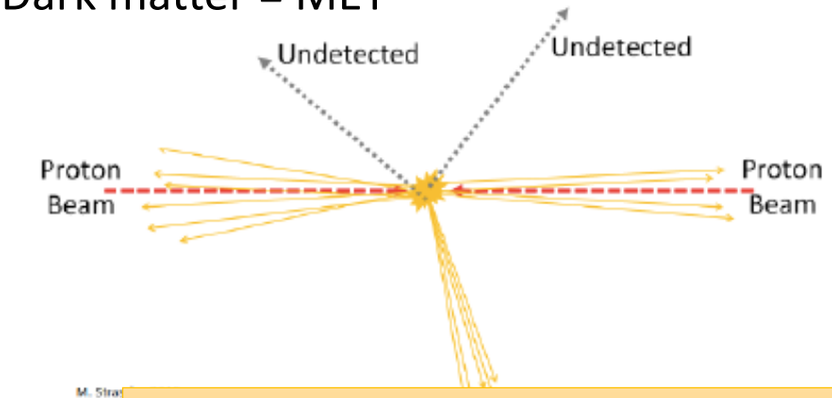
Raison d'être

It's all about high statistics

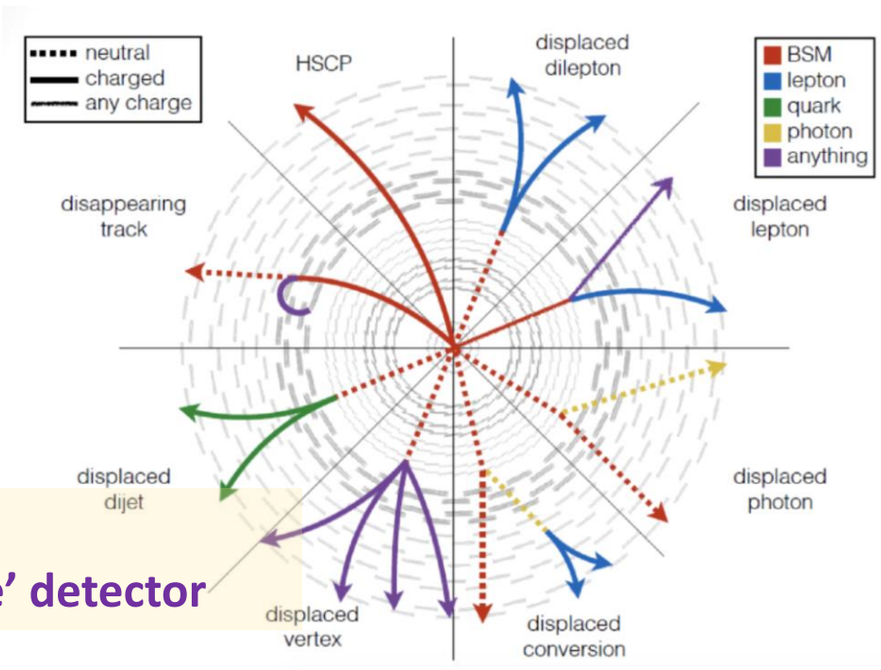
And better detectors

- 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…
- & New Physics – weak scales - low cross-section
  - Long Lived Particles
    - Special triggers will be challenging
  - Dark Matter
  - Supersymmetry
  - Extra Dimensions

Dark matter = MET



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



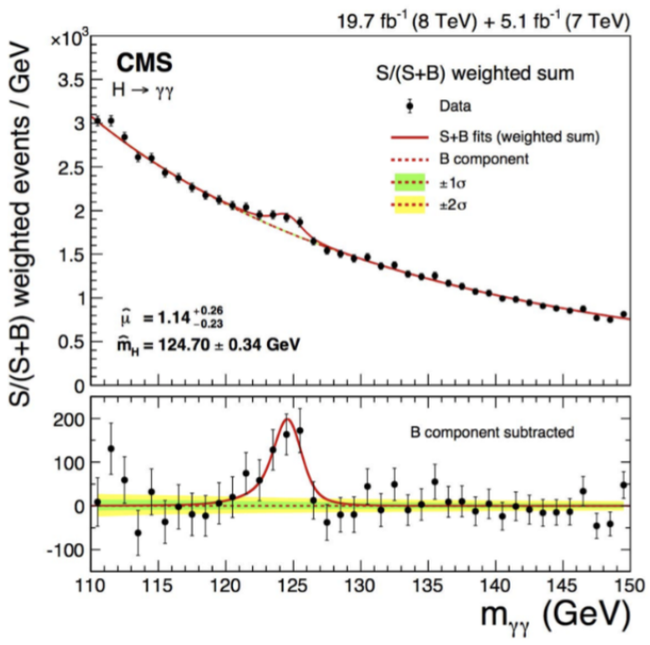
Need
precise & 'flexible' detector

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

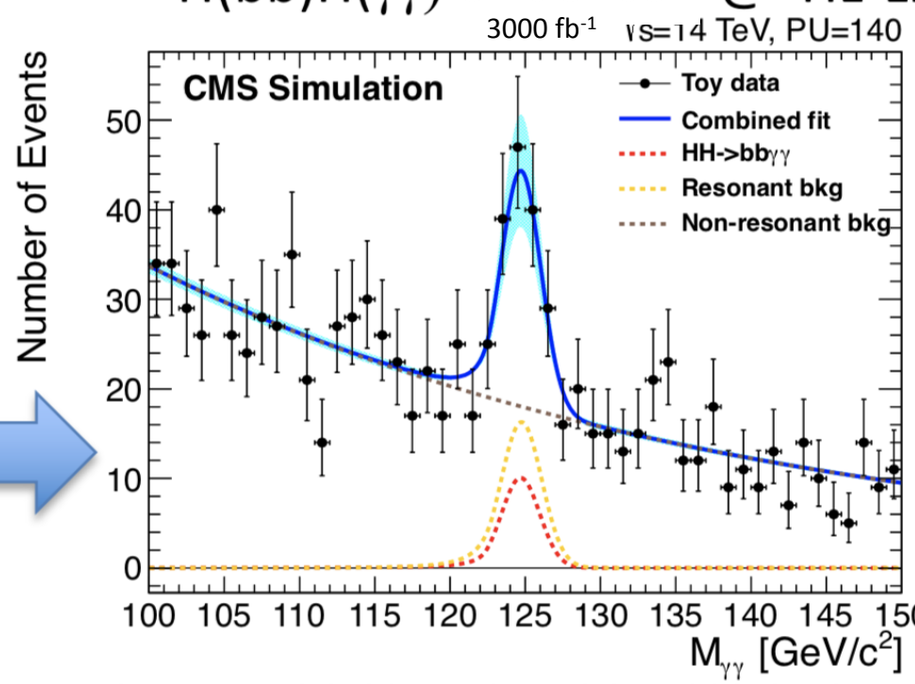
= Endless opportunities (studies, hardware, etc.)

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

H→γγ discovery in Run1



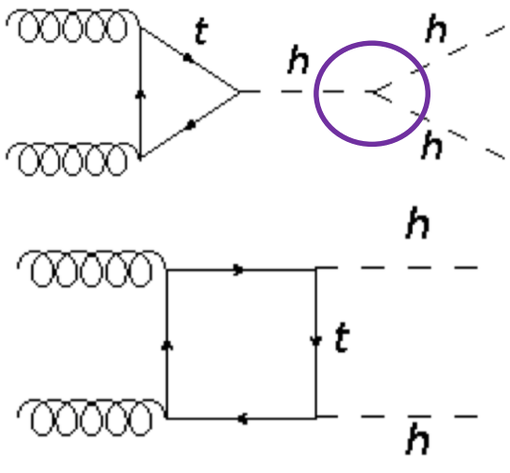
H(bb)H(γγ) evidence @ HL-LHC



CERN-LHCC-2015-10 LHCC-P-008 CMS-TDR 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.)

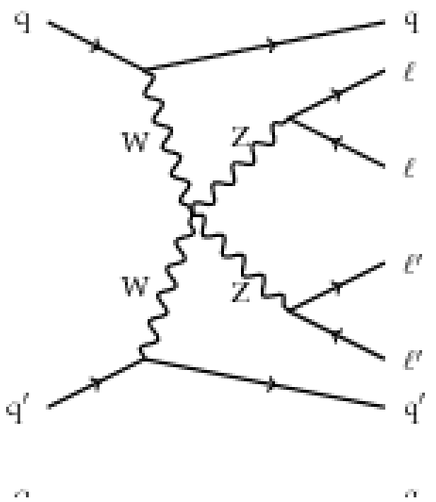
Statistically ***bb*γγ** seems the most promising channel

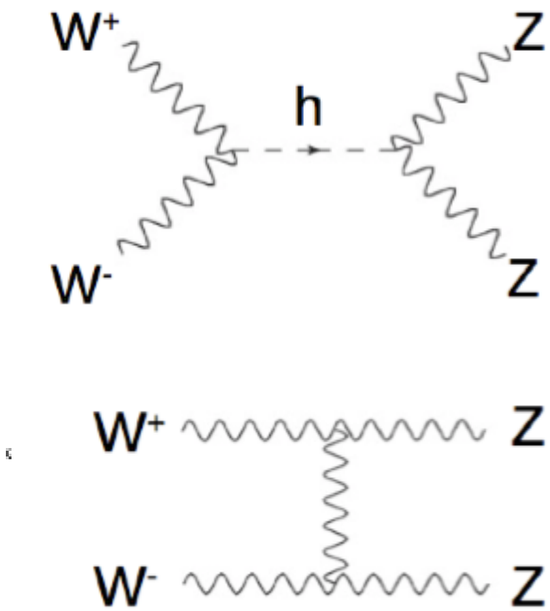
Combined with ATLAS, **4σ** might be possible (3000fb^{-1})

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

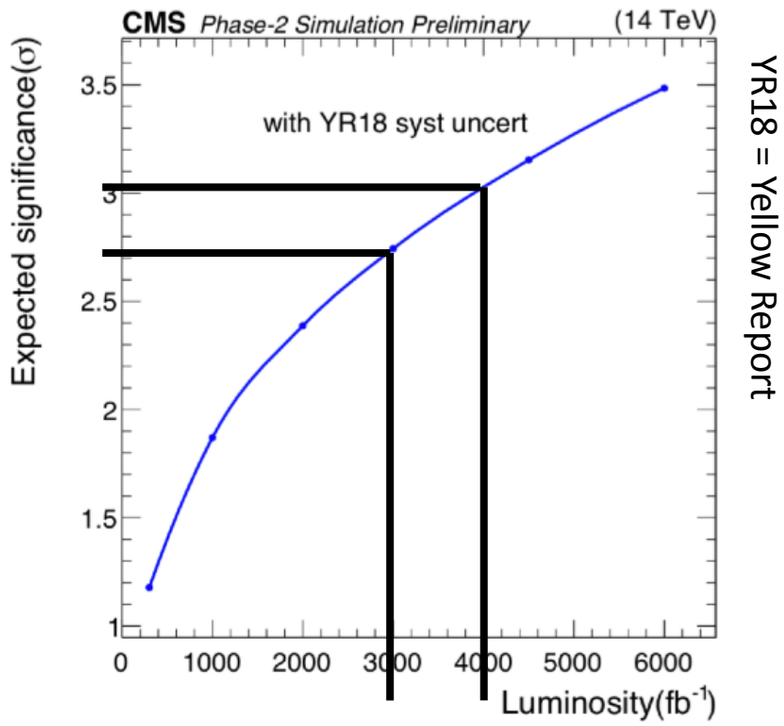
Vector Boson Fusion VBF - Scattering VBS

- The longitudinal W scattering is one of the essential probes of Higgs mechanism
  - The Higgs unitarizes W_L scattering that otherwise would be divergent.
- Deviation = new physics
- VBF - Distinctive signature:
  (forward jets from initial state quarks)
  → **forward region/extension crucial**
  - **CMS is doing this with big verve**
    - **Pixel, Muons, Calorimeter, Timing**



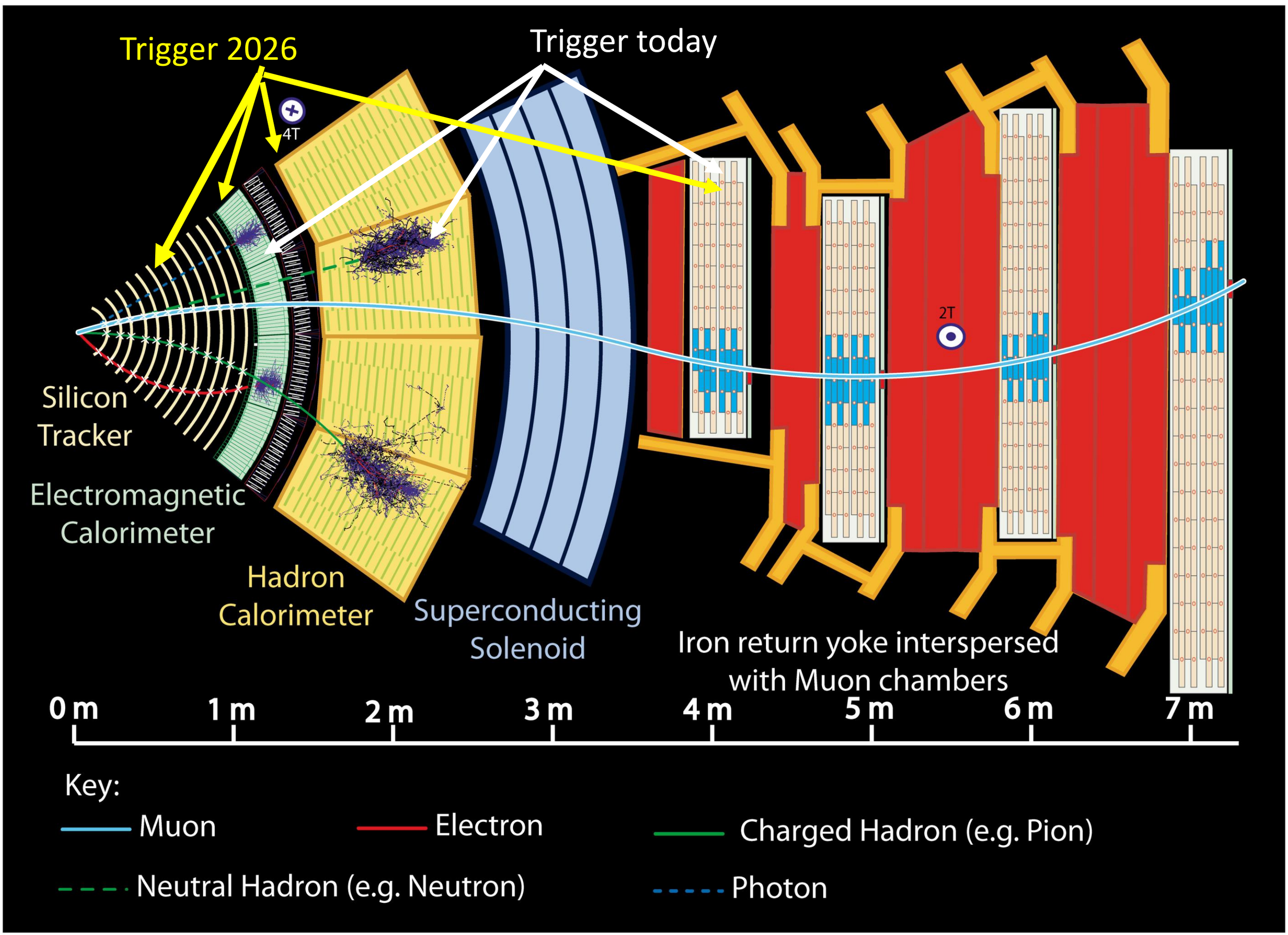


$V_LV_L \rightarrow V_LV_L$ discovery significance
up to 2.75σ (combining WWjj+WZjj)

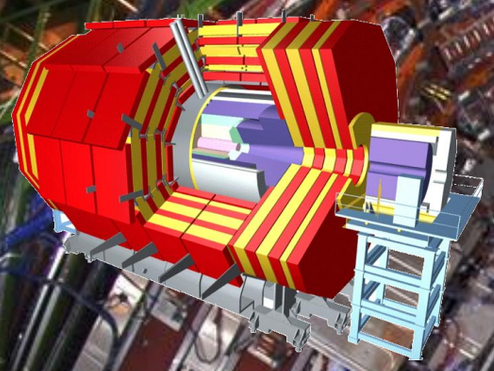


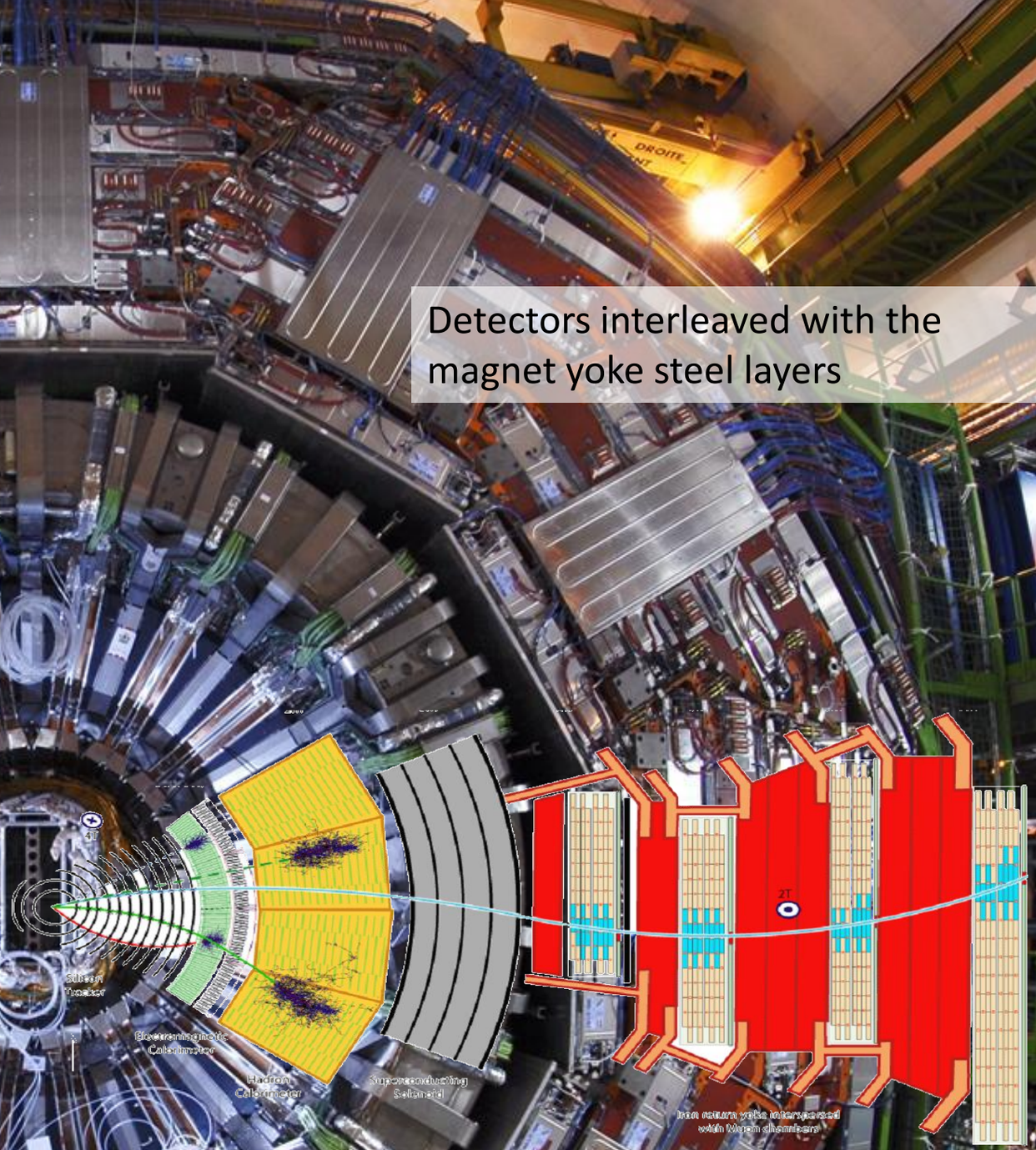
Interested in upgrade physics studies?

Contact:
Sezen Sekmen, Alexander Savin, POGs, systems


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





CMS Experiment at the LHC, CERN
Data recorded: 2016-May-07 02:15:29.192000 GMT
Run / Event / LS: 272775 / 36556333 / 49

2016

~35 vertices = 40 collisions = pile-up
~2’000 tracks
per collision bunch (40MHz)

2026

~200 vertices
~10’000 tracks per collision
40 MHz

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

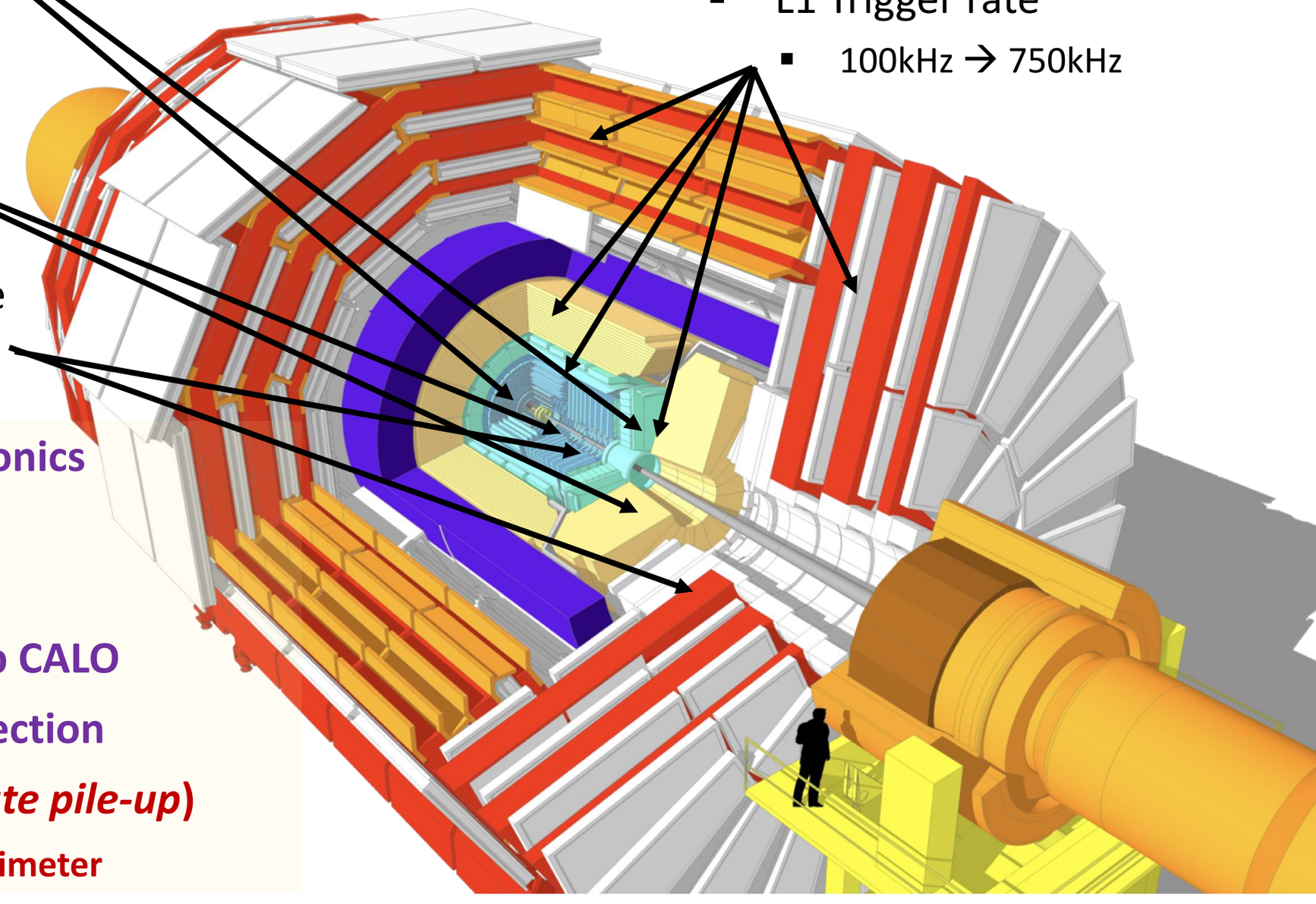
Bottlenecks

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**

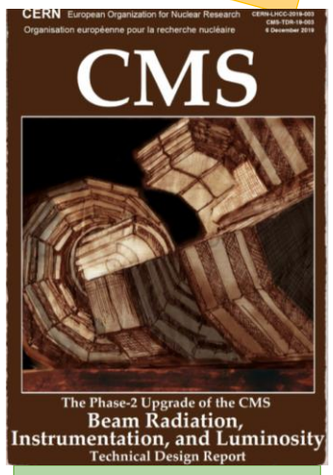
http://cms.cern

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

Who is Who

Mind, you <u>really</u> can!!
This is a unique opportunity!

- Interested in upgrades?
  You want to **<u>build the next detector</u>**? Yes?
- *Whom to contact?*
  - Paolo Rumerio, Tommaso Boccali, myself is a good start
- An even better start are
  the Project Managers (PM) and
  System Upgrade Coordinators (SUC).



BRIL
A. Dabrowski
G. Auzinger

Upgrade Studies
A. Savin, S. Sekmen

Barrel Calo
S. Argiro'
B. Hirosky

HGCAL
K. Gill

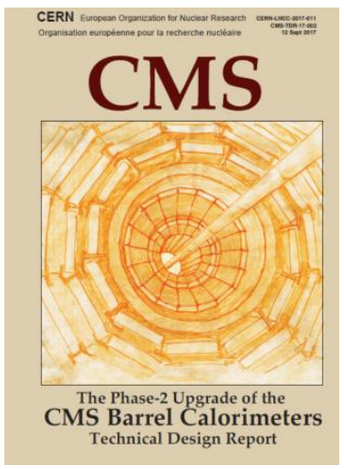
Muon
G. Pugliese
A. Korytov

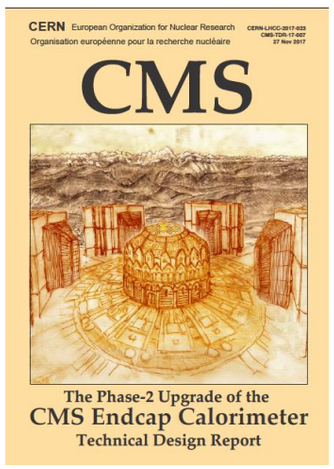
Tracker
E. Butz
A. Venturi

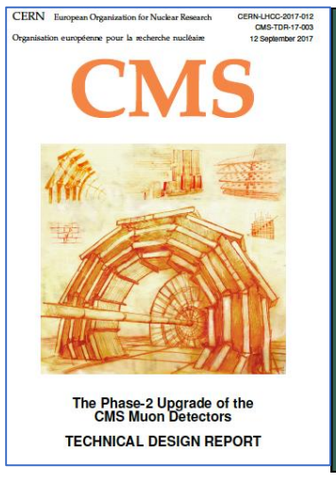
MTD
T. Tabarelli

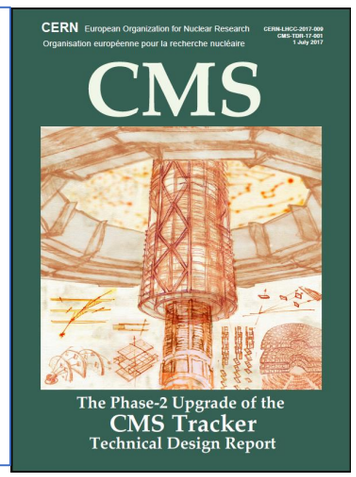
L1 Trigger
A. Zabi
M. Bachtis

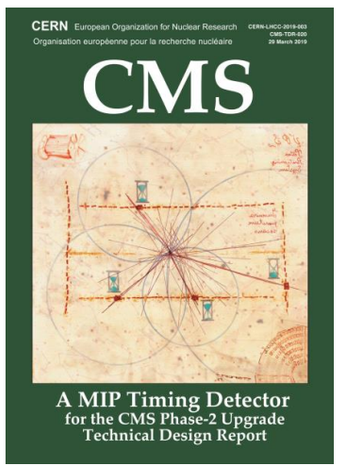
DAQ **E. Meschi**
HLT S. Beauceron
T. Tomei

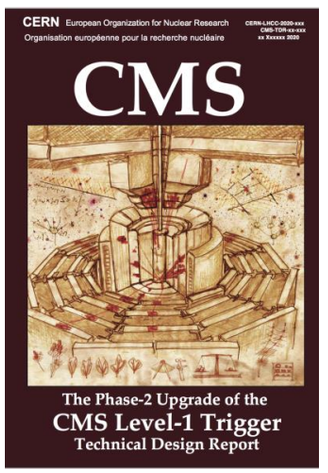


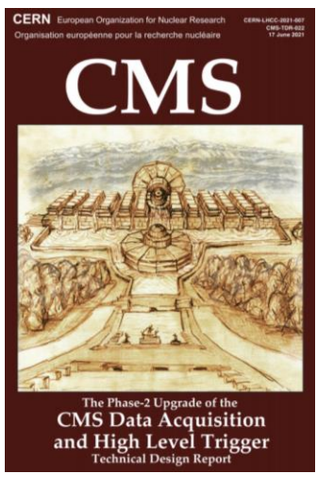








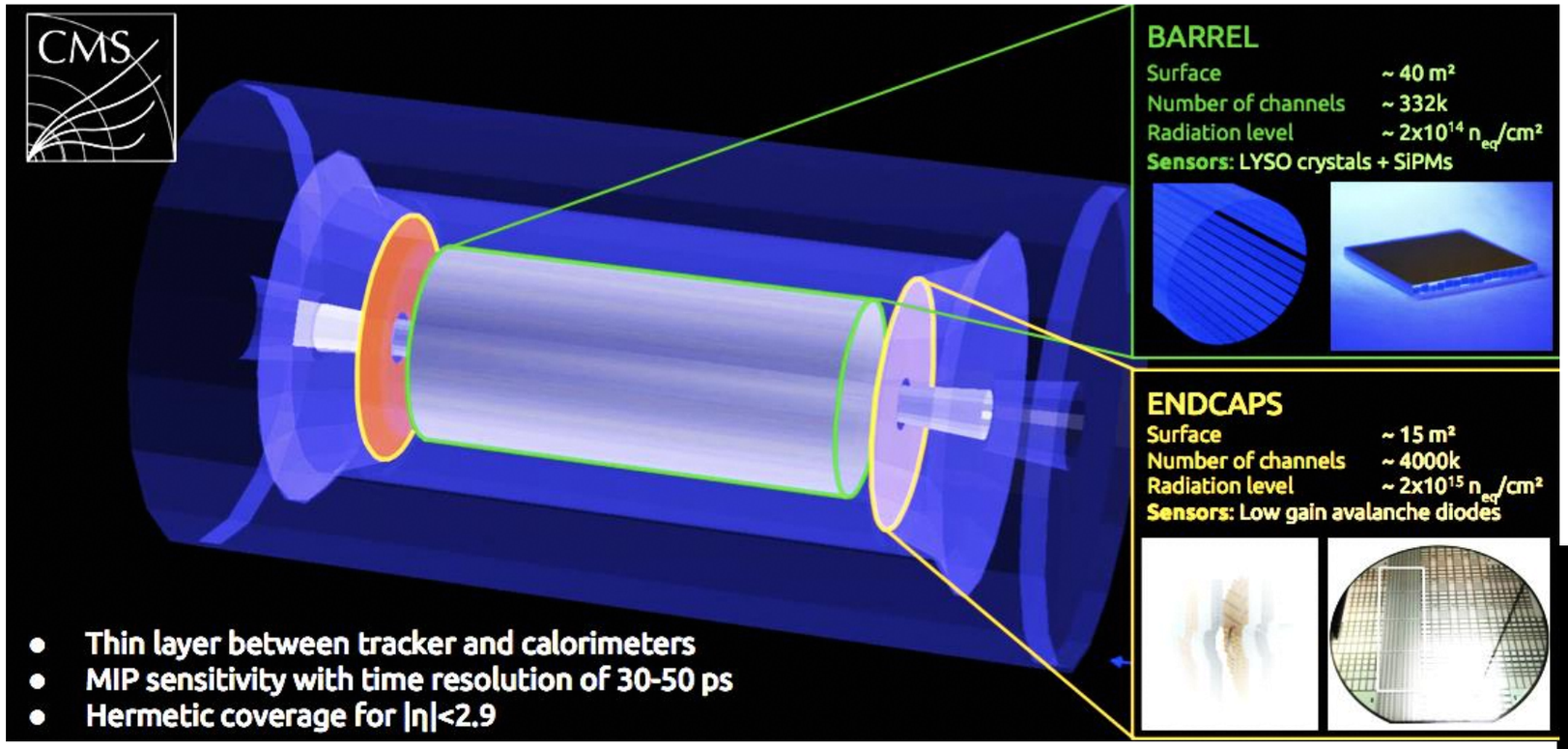




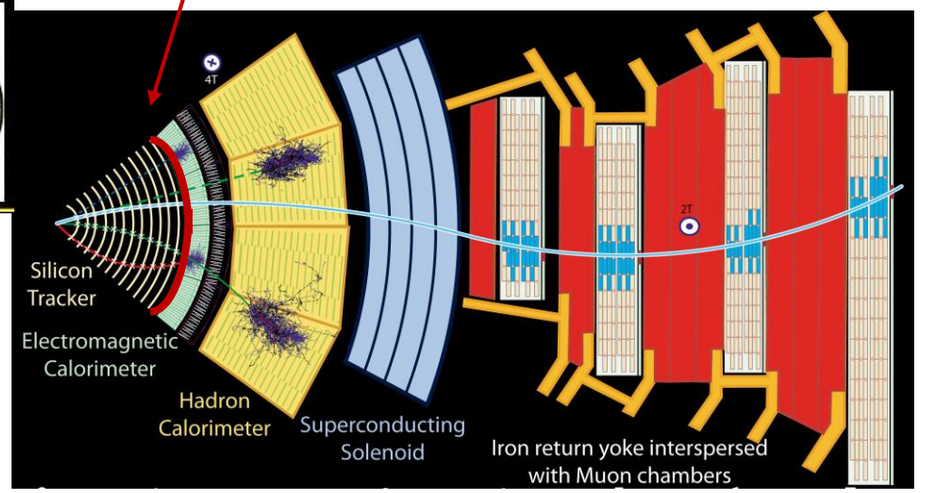
On the technology aspect

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."

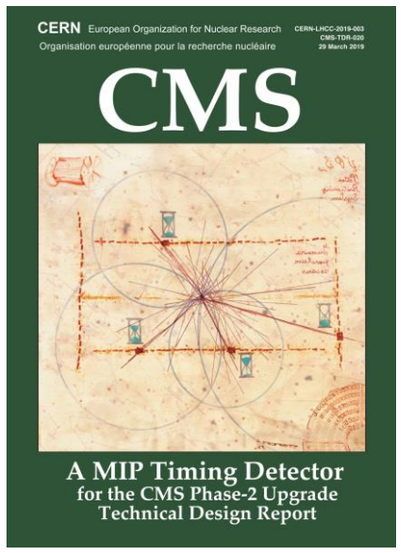


Between Tracker and Calorimeter



30 ps timing – the extra independent parameter makes the difference

MTD MIP Timing Detector

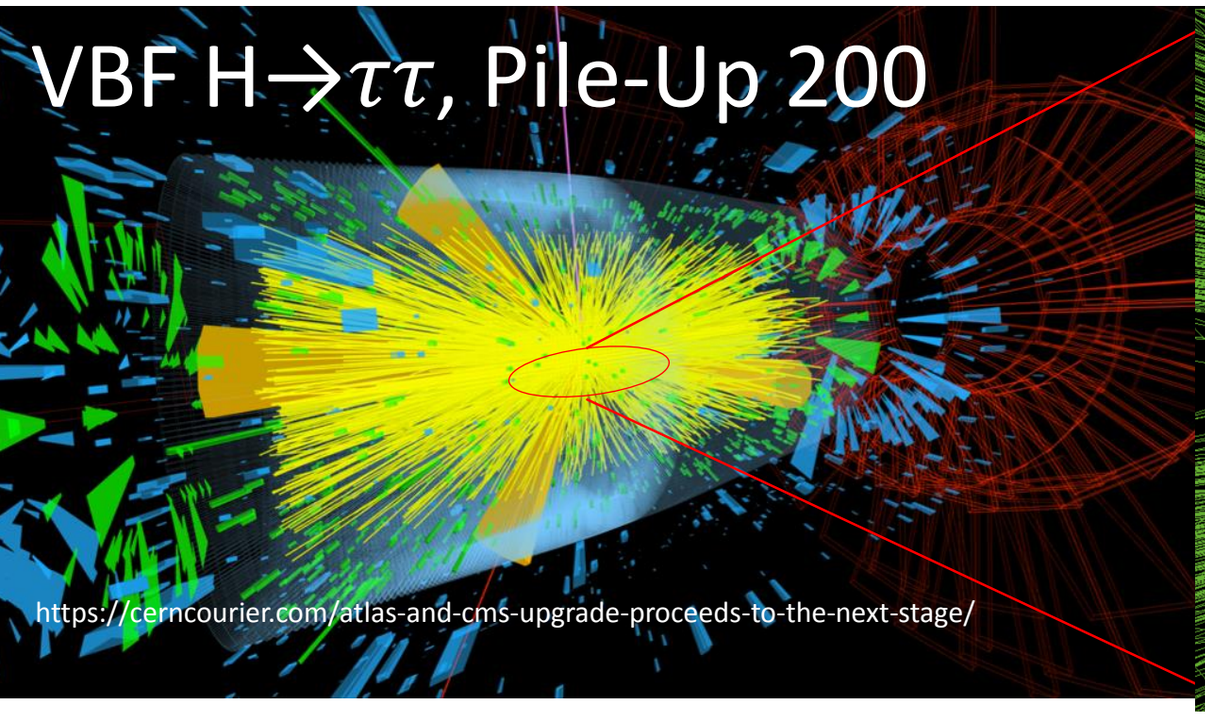


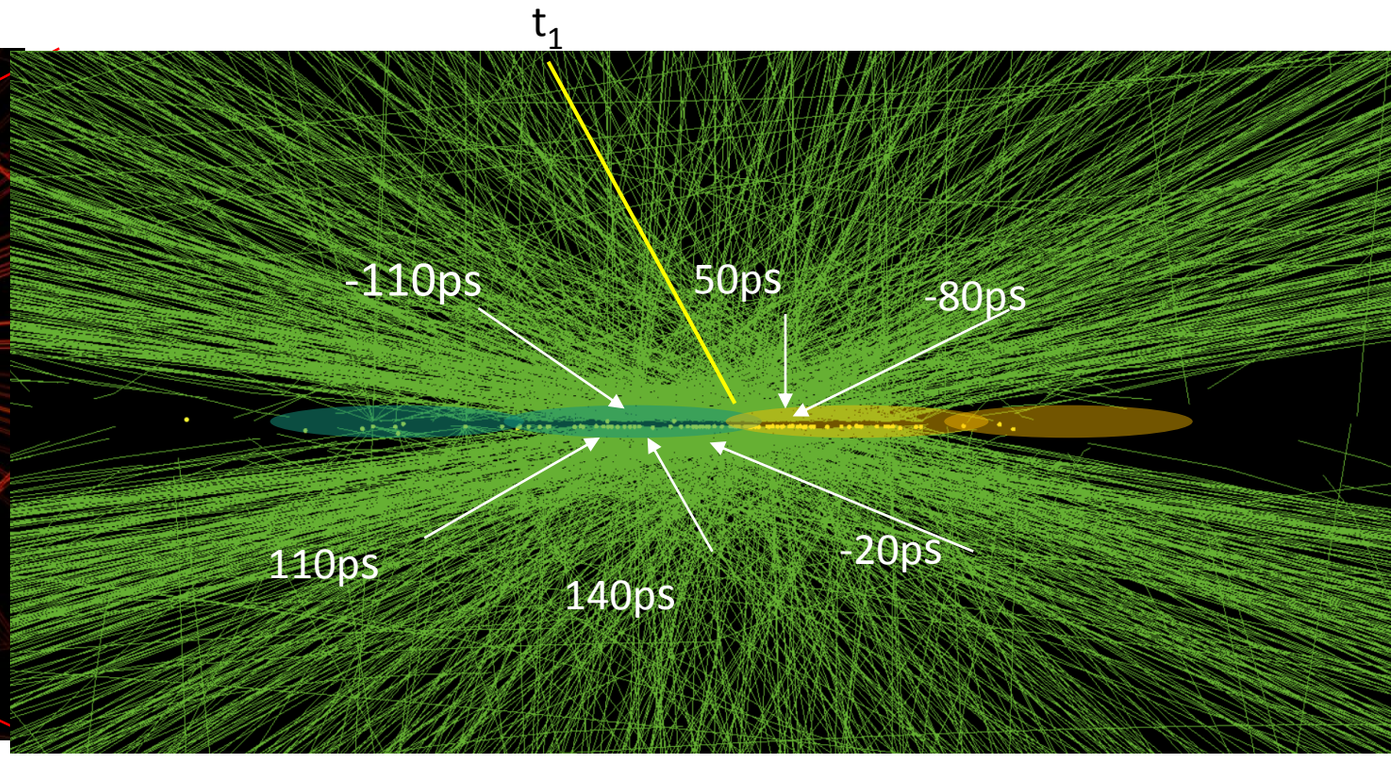
Interested in MTD :

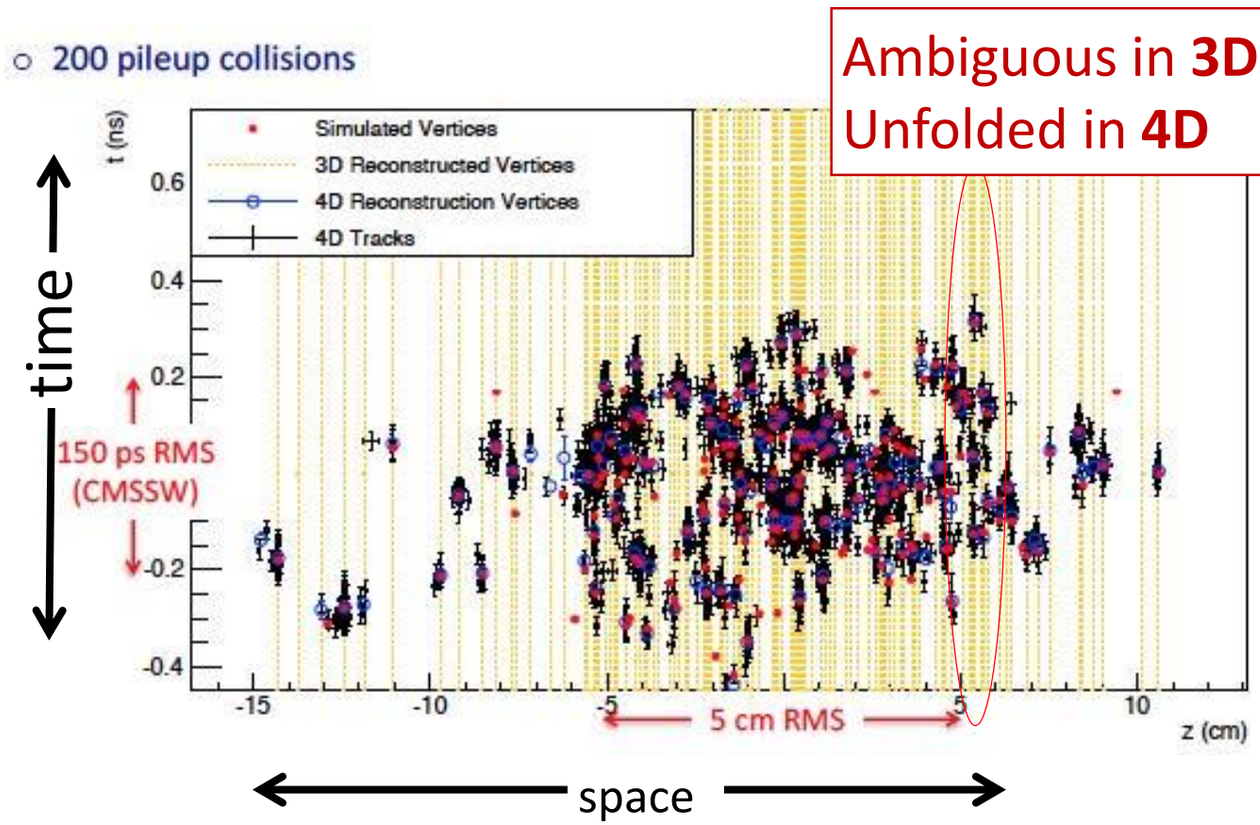
Contact:
Tommaso Tabarelli, David Stuart

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

Sorting the mess even better



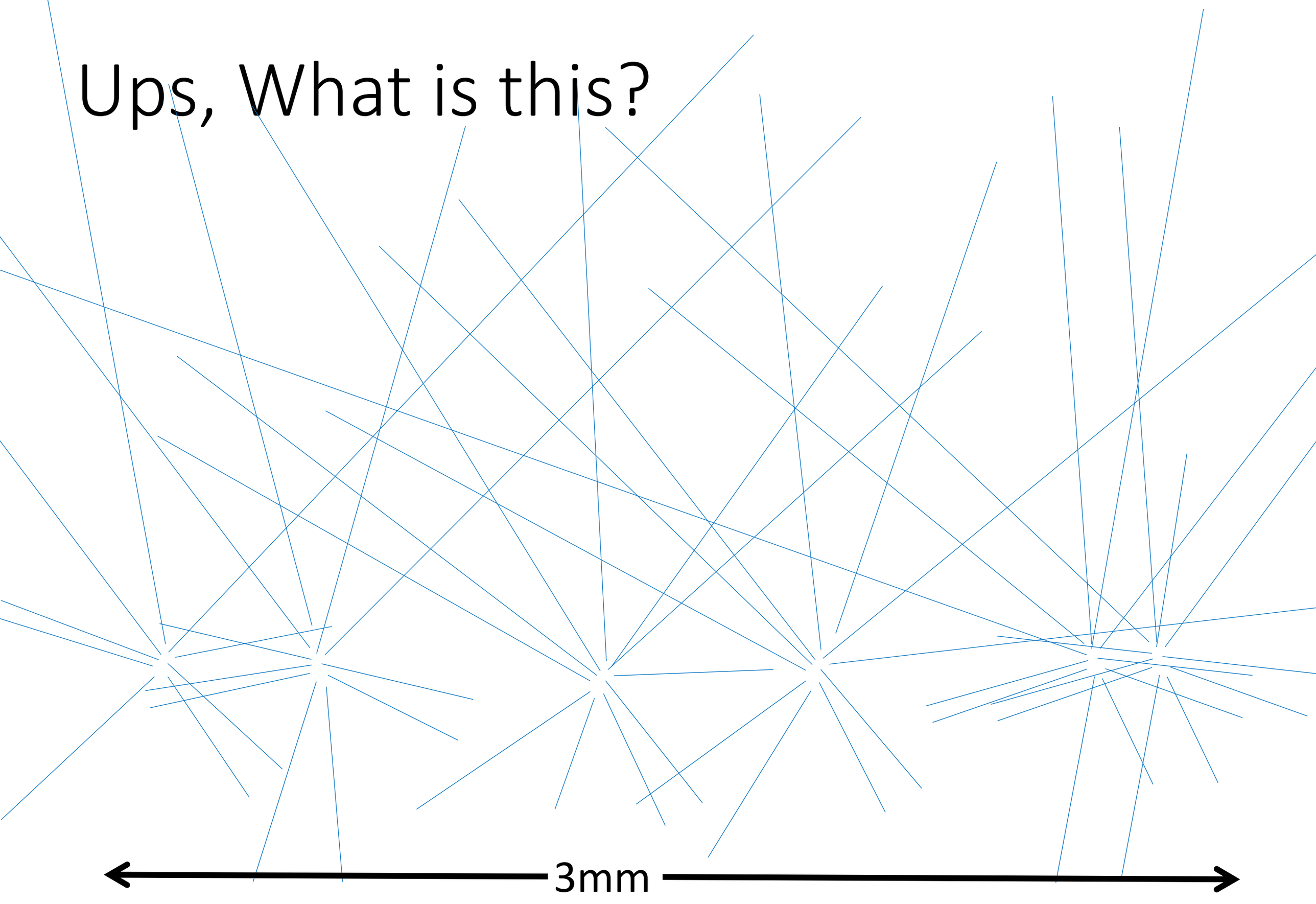




~10'000 tracks
per collision bunch

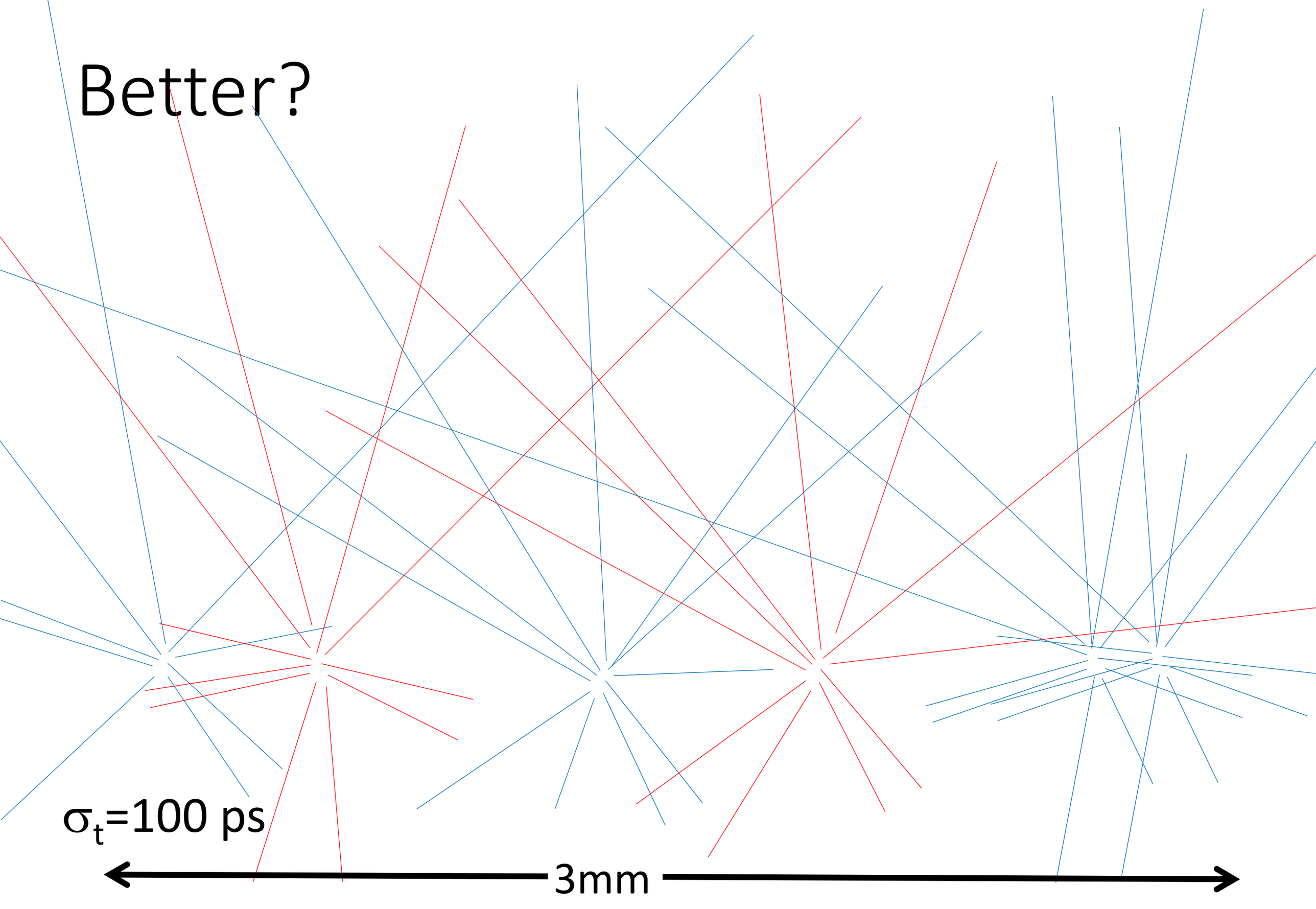
- @ PU=200
  Vertex density ~1 vertex/mm
- A 30 ps resolution (y axis ← plot) allows to resolve vertices at the same z
- "you get close to a Run-2 PU situation"

Ups, What is this?

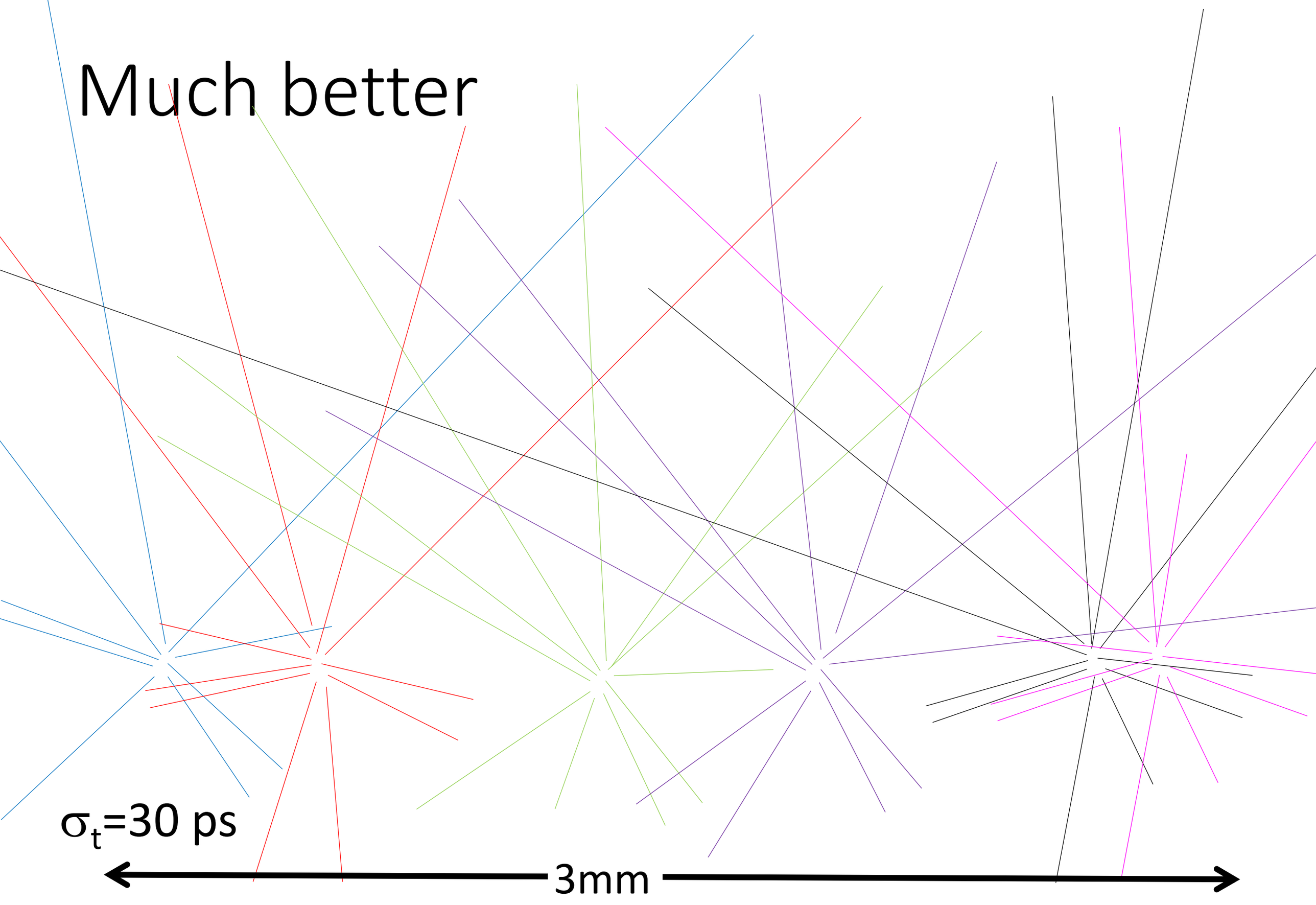


Pile-up of vertices = mess

Better?



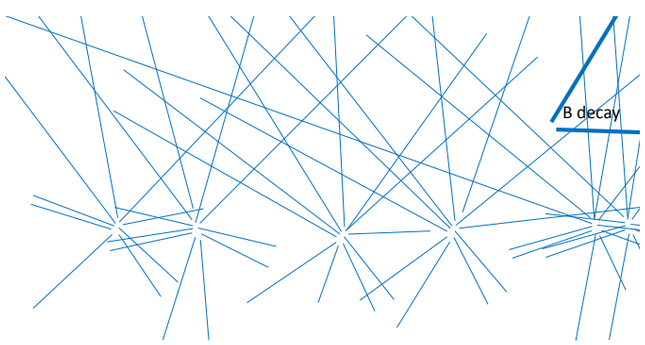
Much better

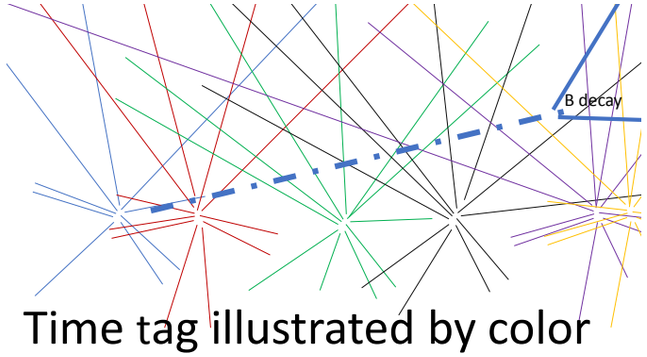


”time” your performance

Mitigates pile-up and vertex cleaning

‘Unfolding’ *b* (e.g. HH → *bbbb*)

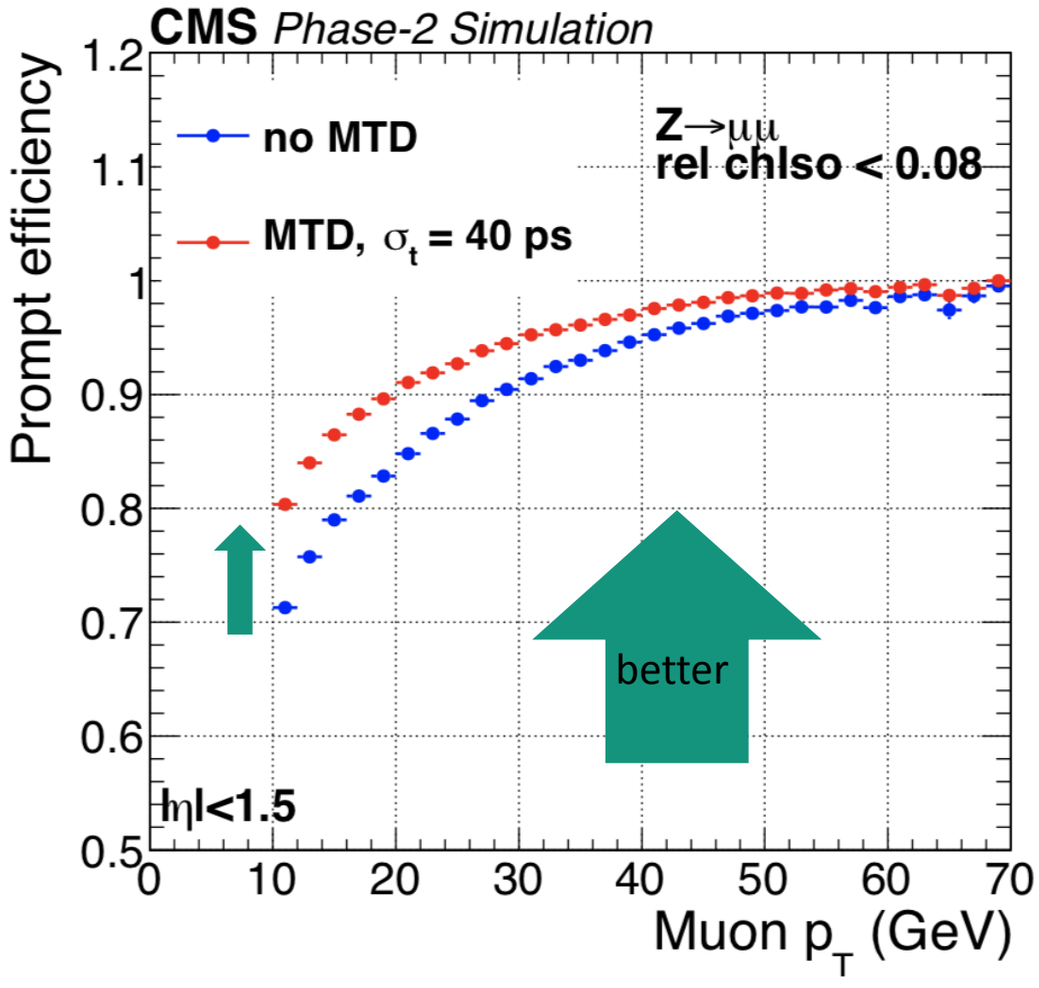




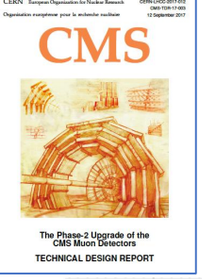
Time tag illustrated by color

better

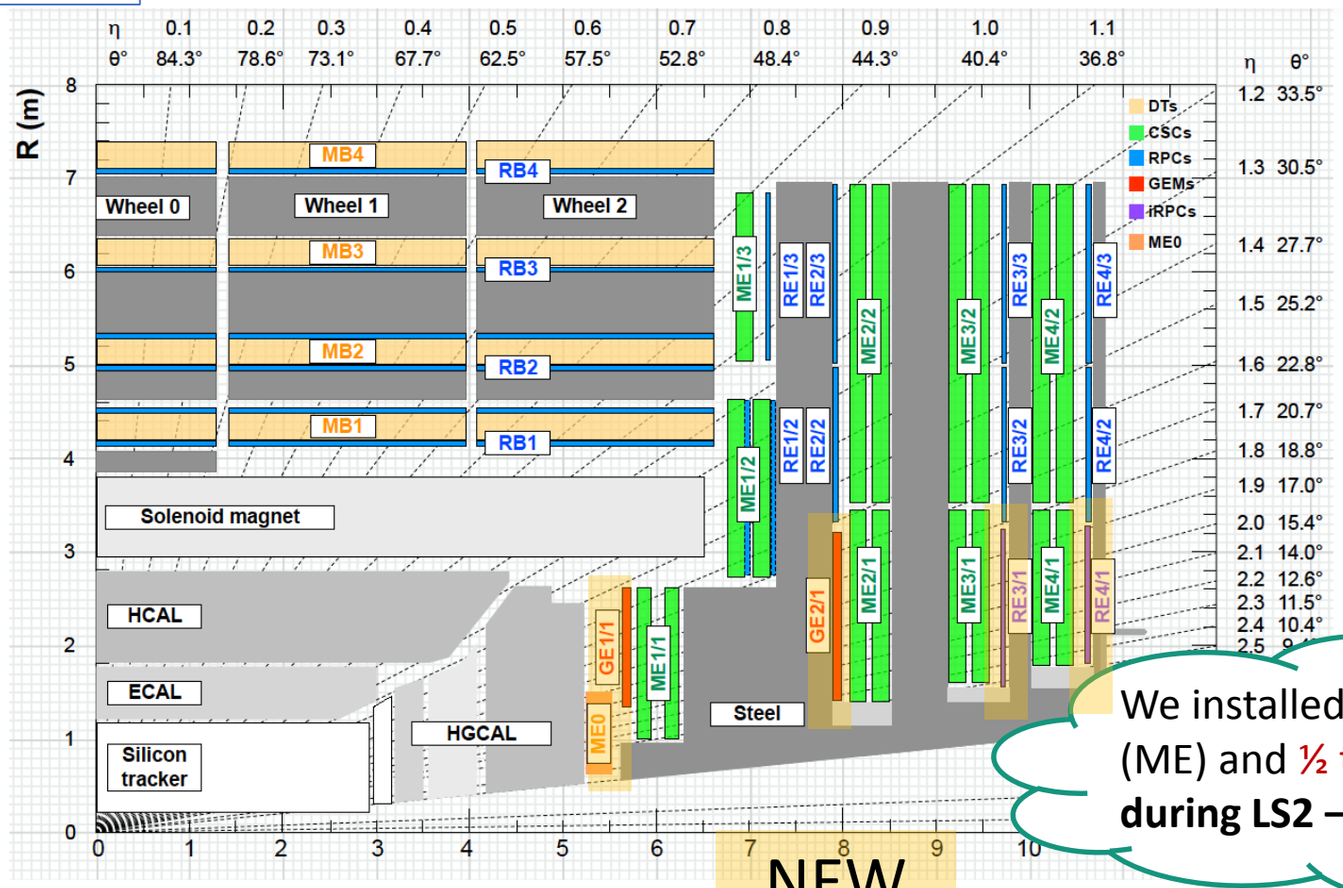
‘Unfolding’ Muons. (e.g. H → 4 μ)

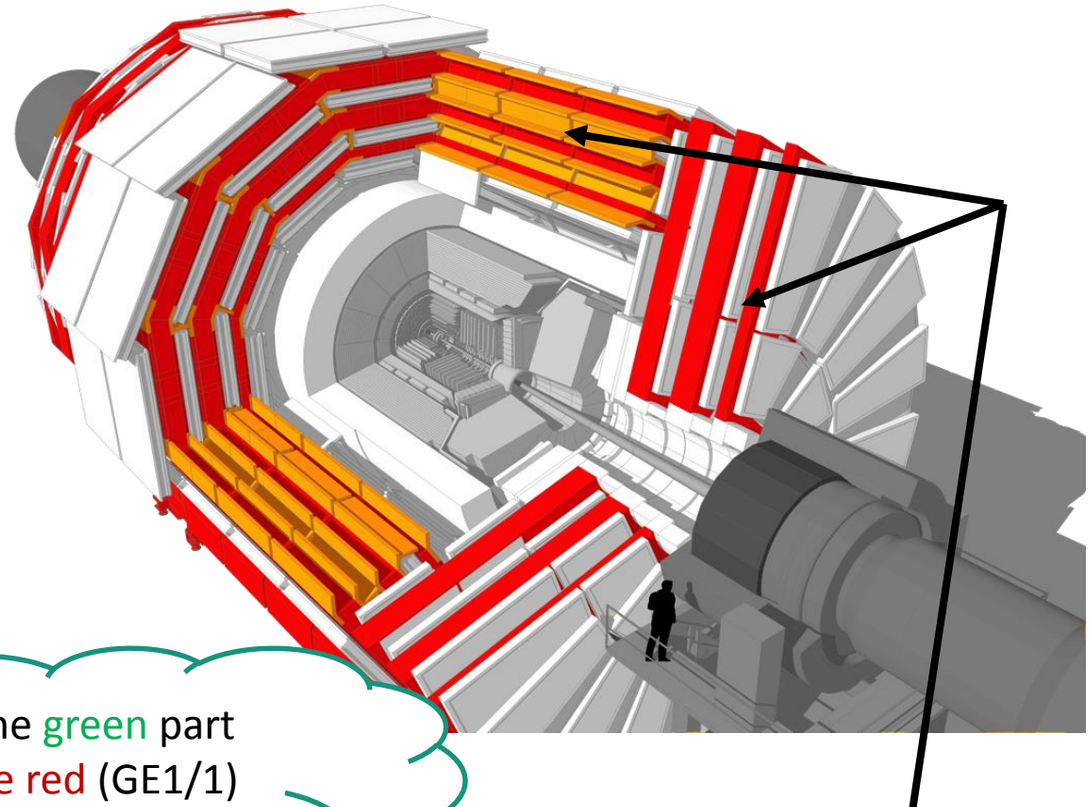


CERN-LHCC-2019-003 CMS-TDR-020



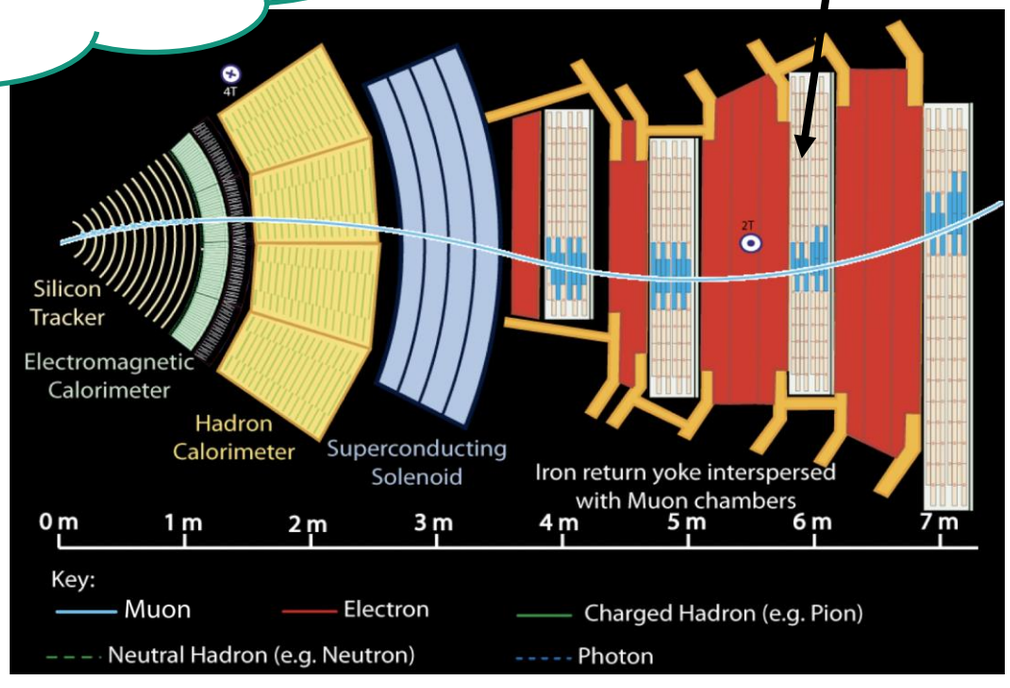
The Muon Detectors





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 !**



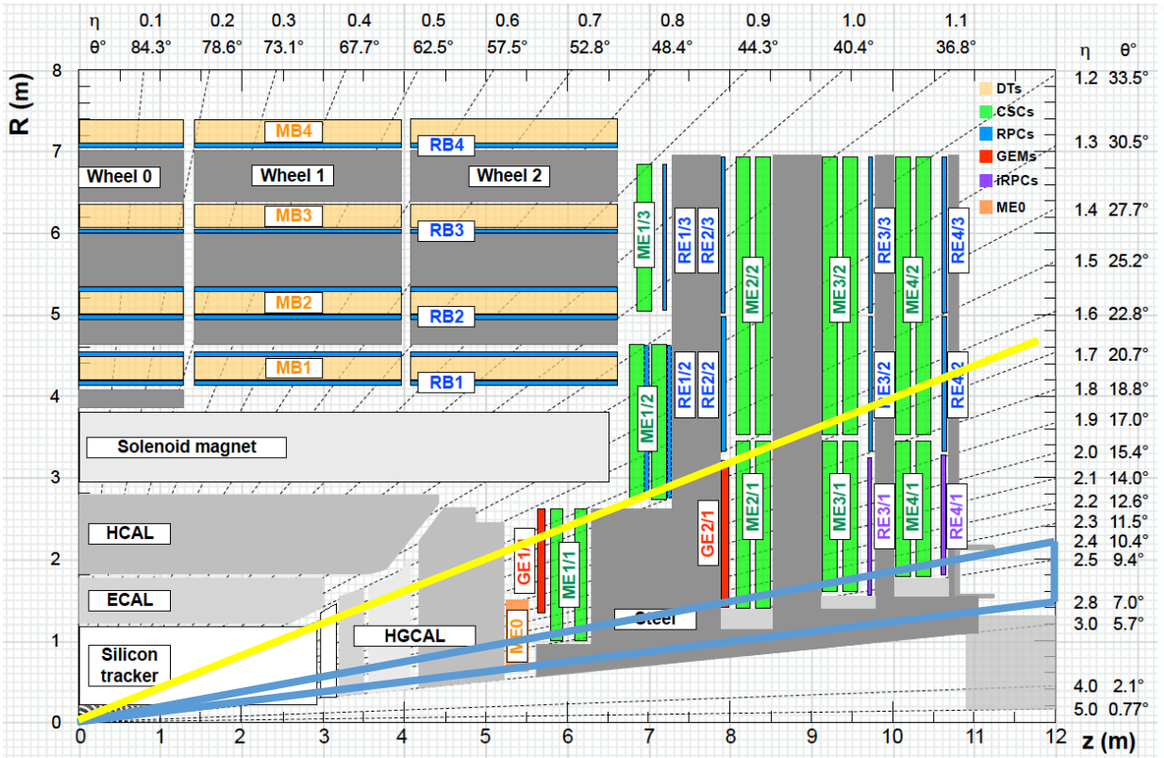
Interested in Muons:

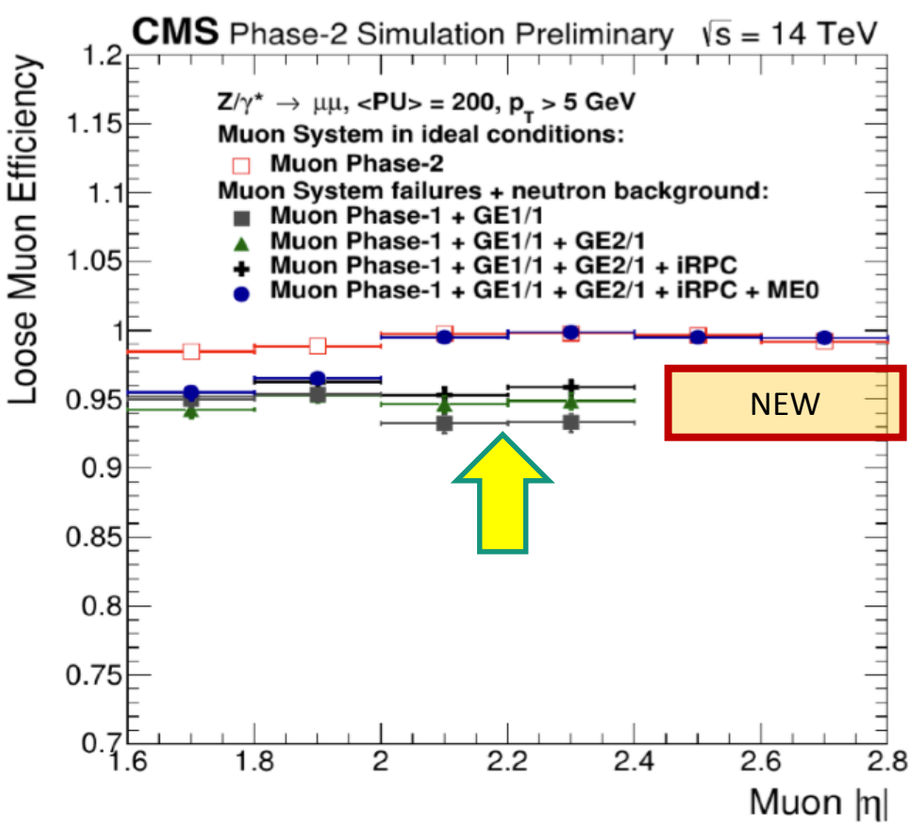
Contact:
Andrey Korytov, Gabriella Pugliese

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

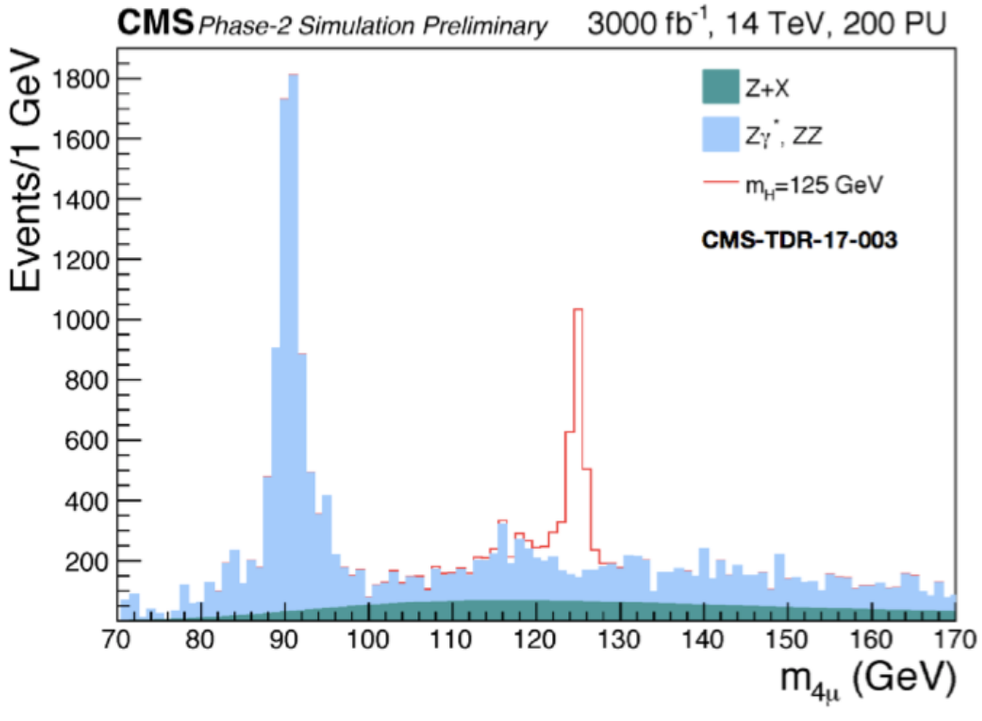
Spike my Muons performance

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



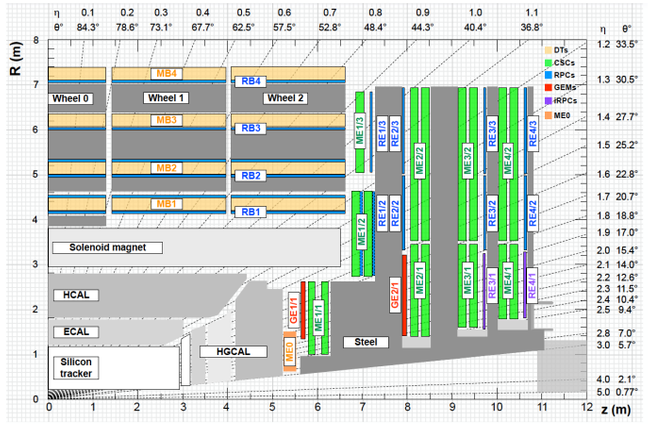


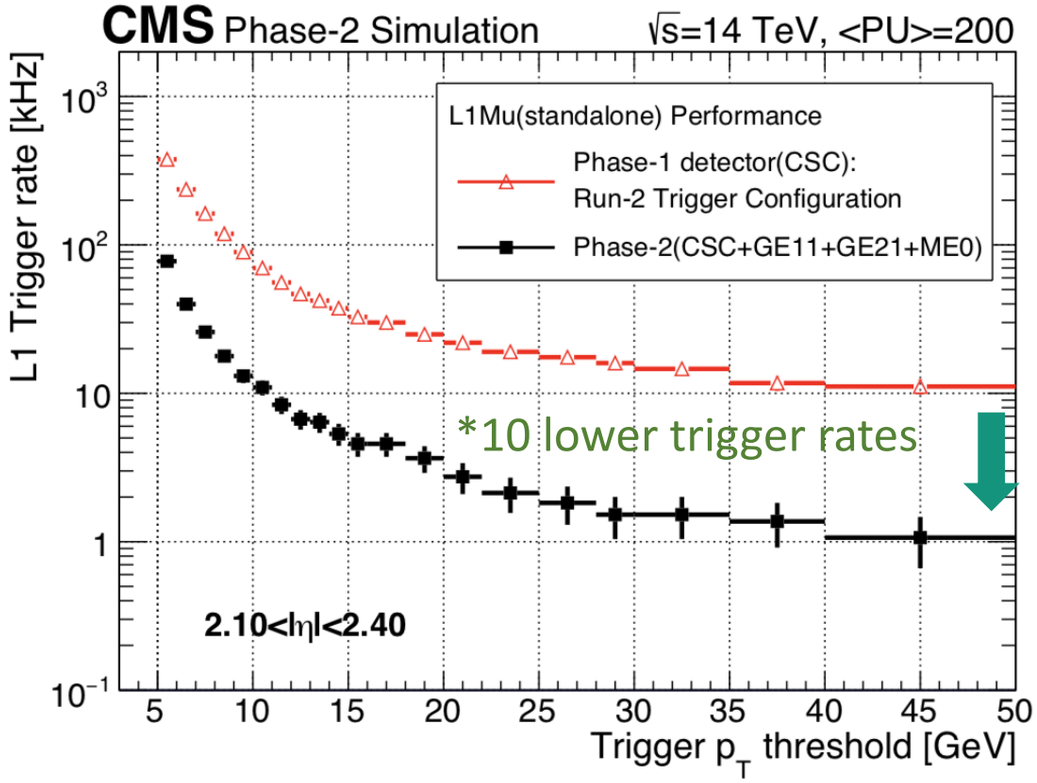
Higgs into 4 leptons:
acceptance increase ~17%



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

Wonderful new opportunities with the new Muon system

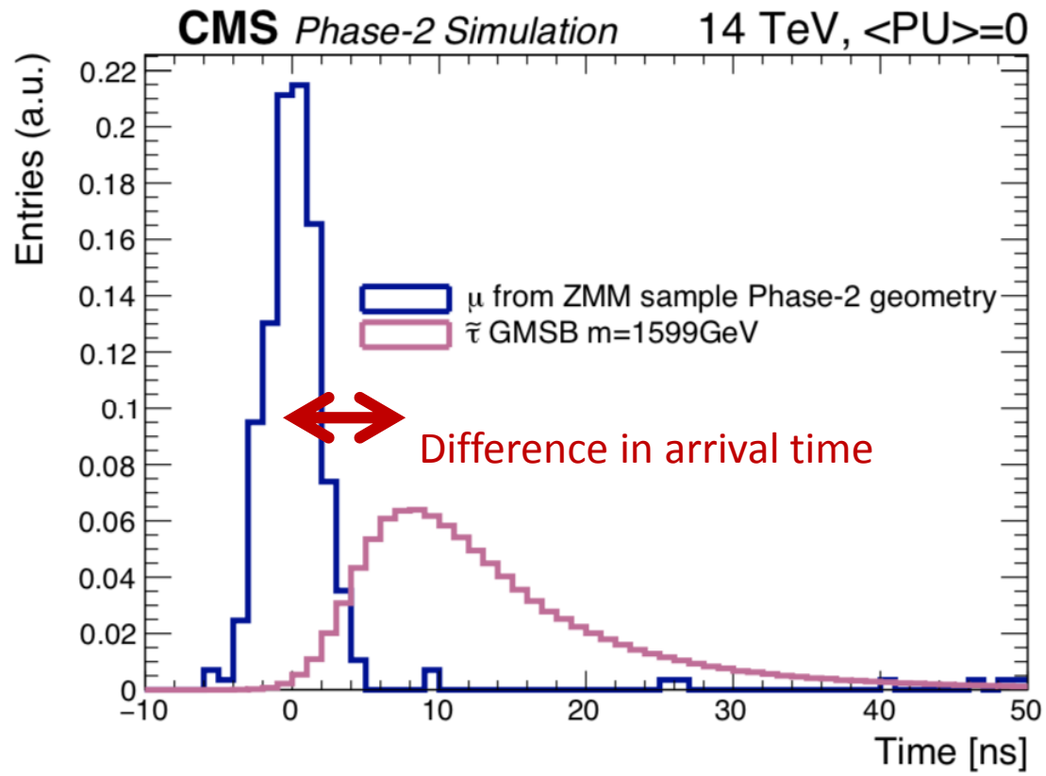




- Rates, efficiencies, precision
  ➔ much better, more flexible trigger
- Allows trigger on displaced tracks
  - No vertex constraint
  - New physics!?!?

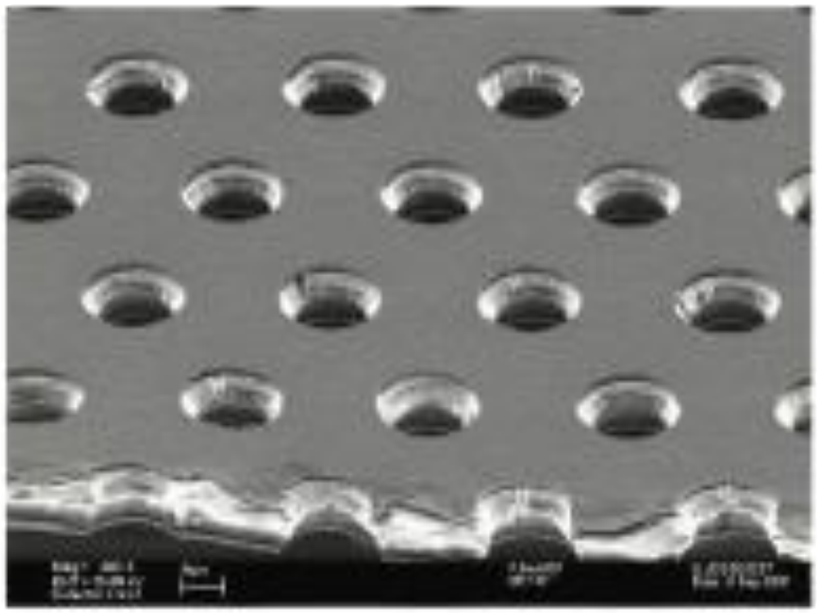
RPC-2 time resolution 1ns (today 25ns)

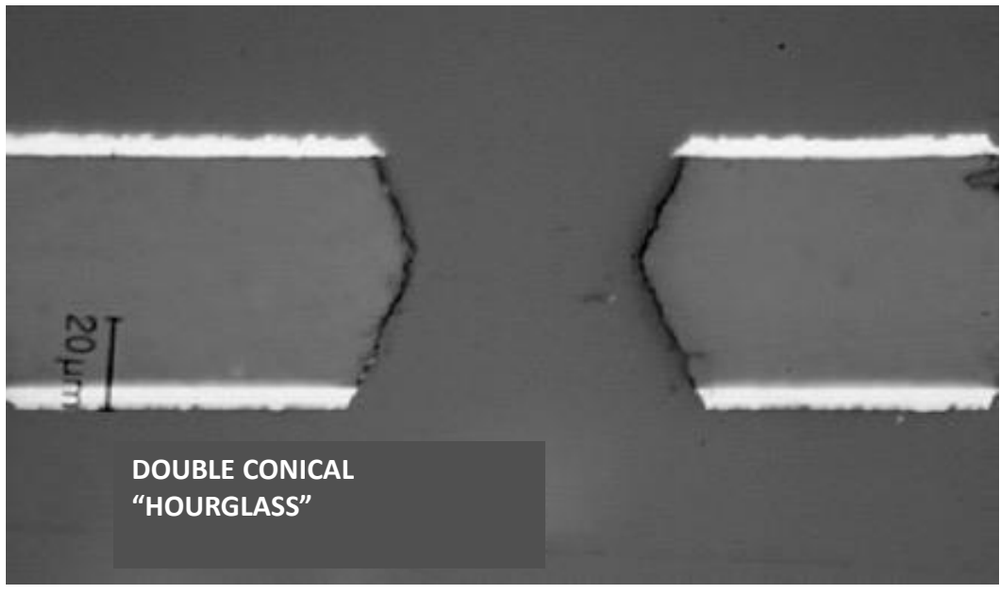
Identify ‘slow” Heavy Stable Charged Particle

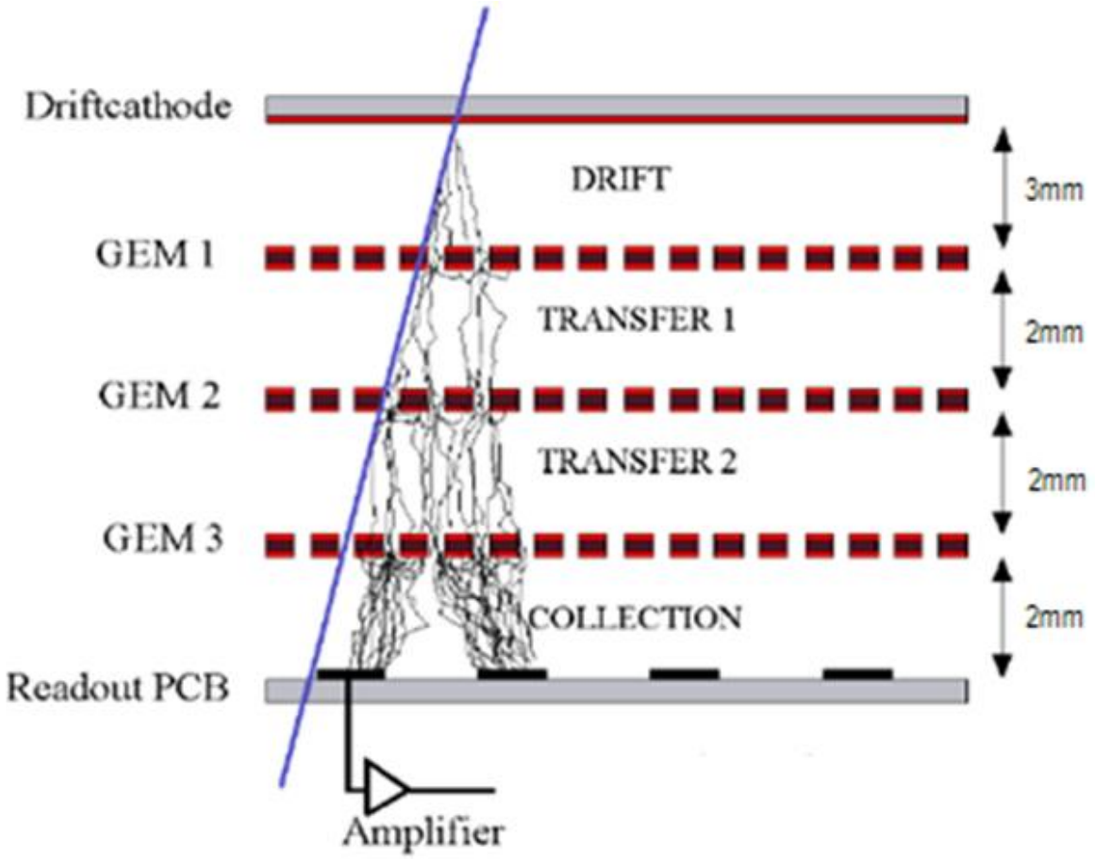


LLP Long Lived particle (NEW)
RPC Resistive Plate Chamber – a Muon detector

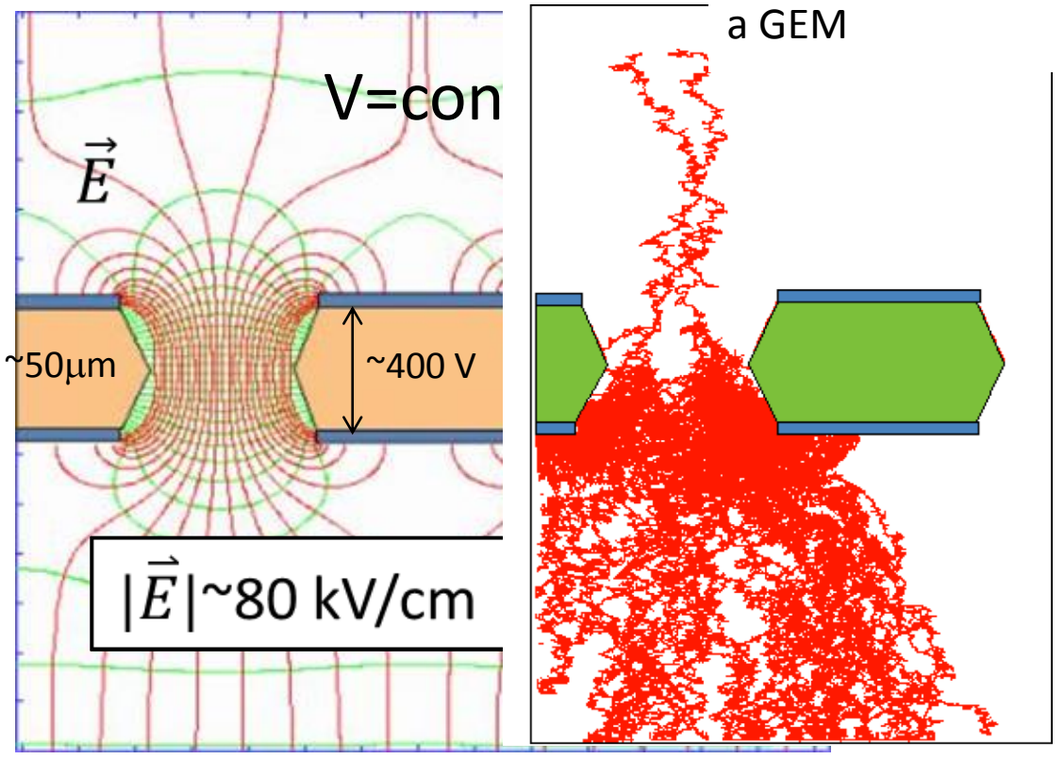
Gas Electron Multiplier (GEM)



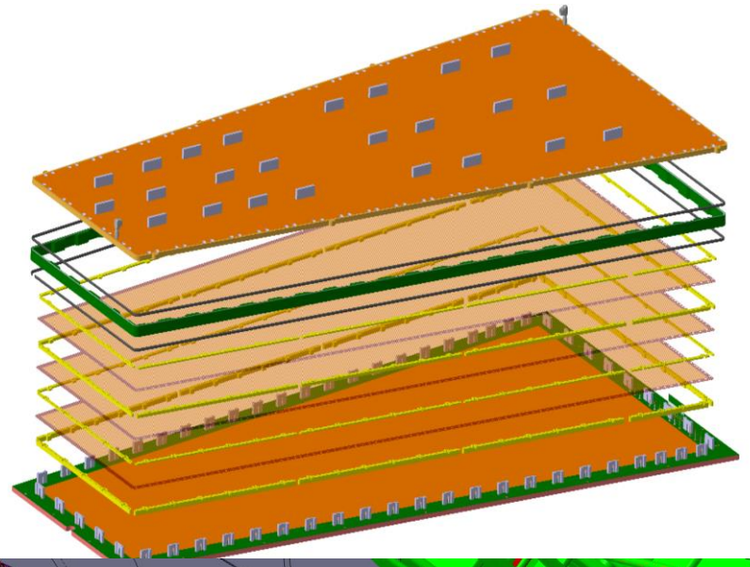


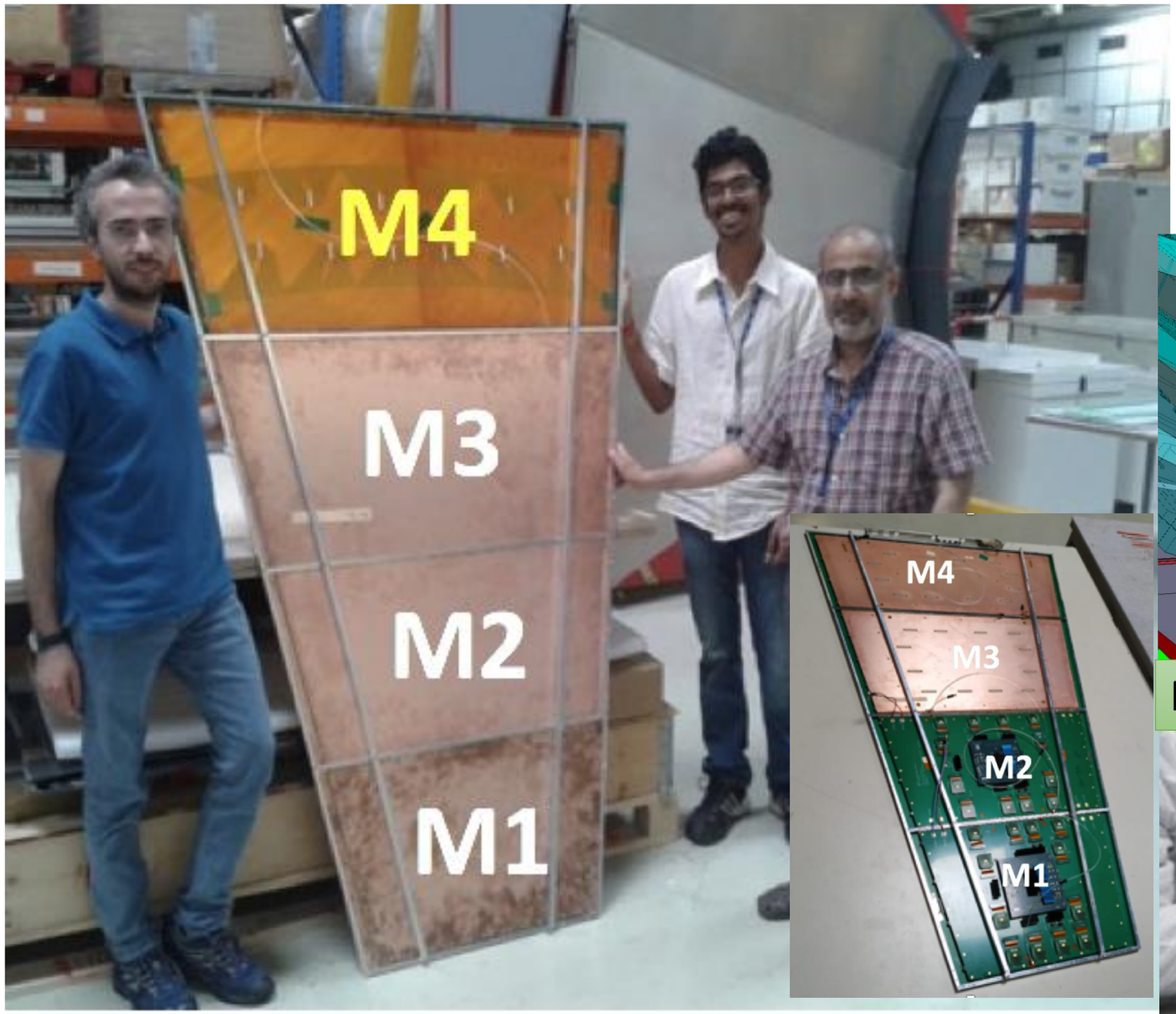


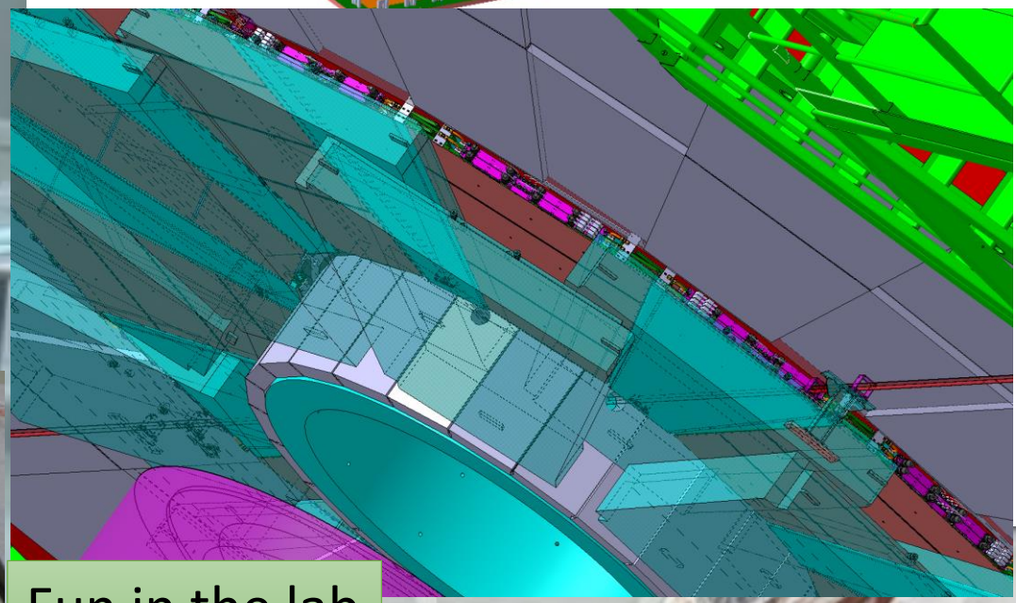
Avalanche across a GEM



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)

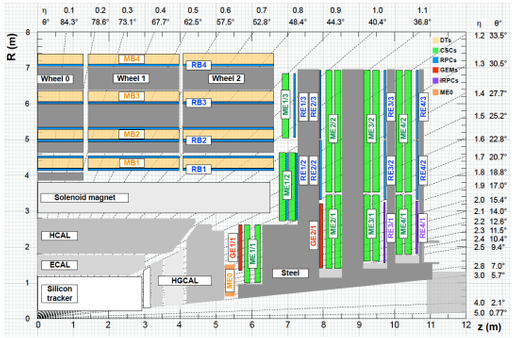
Build and install something TODAY

➔ ongoing step “Fun in Commissioning”

Installing services for RPCs – today

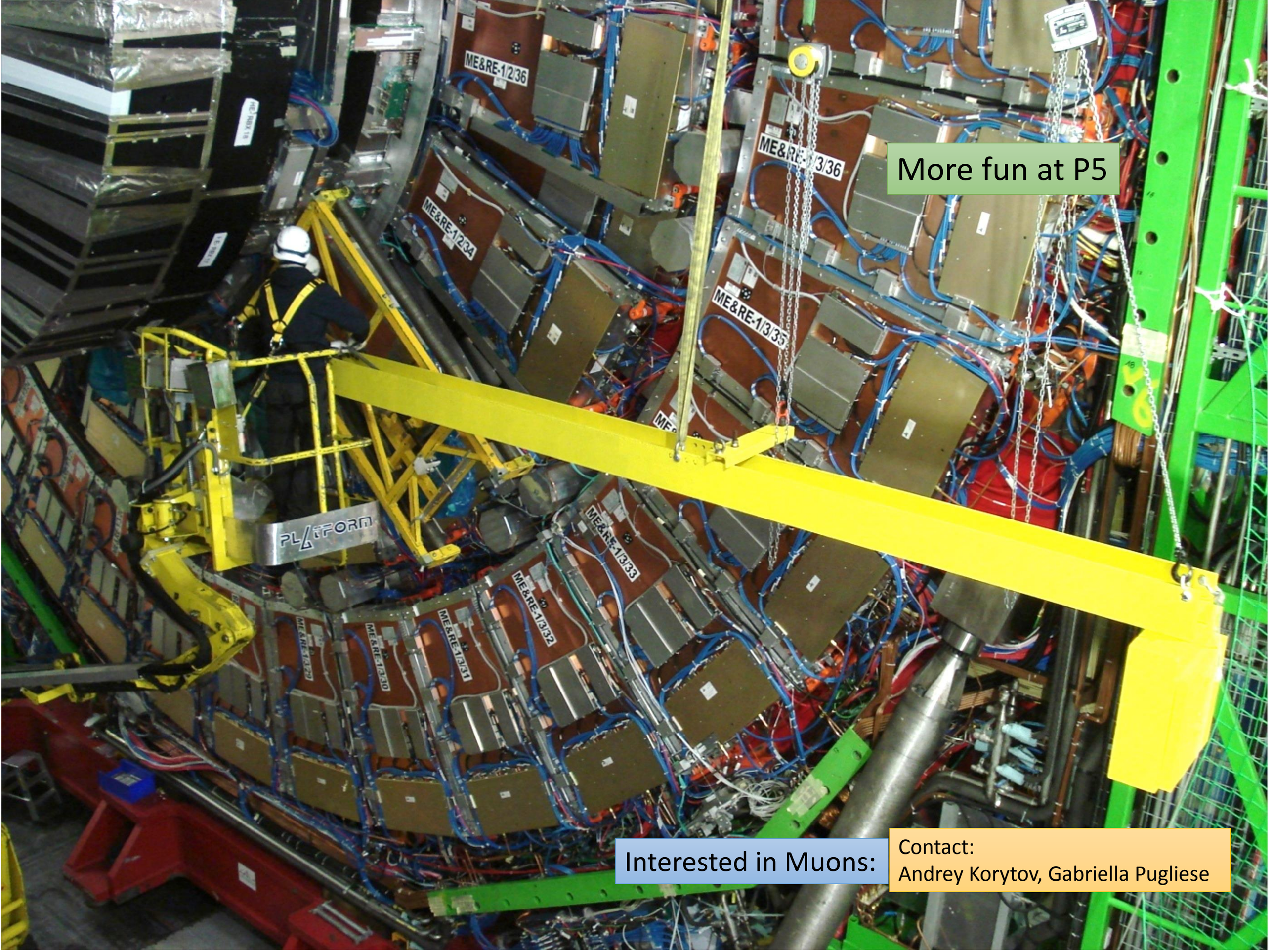
Resistive Plate Chamber

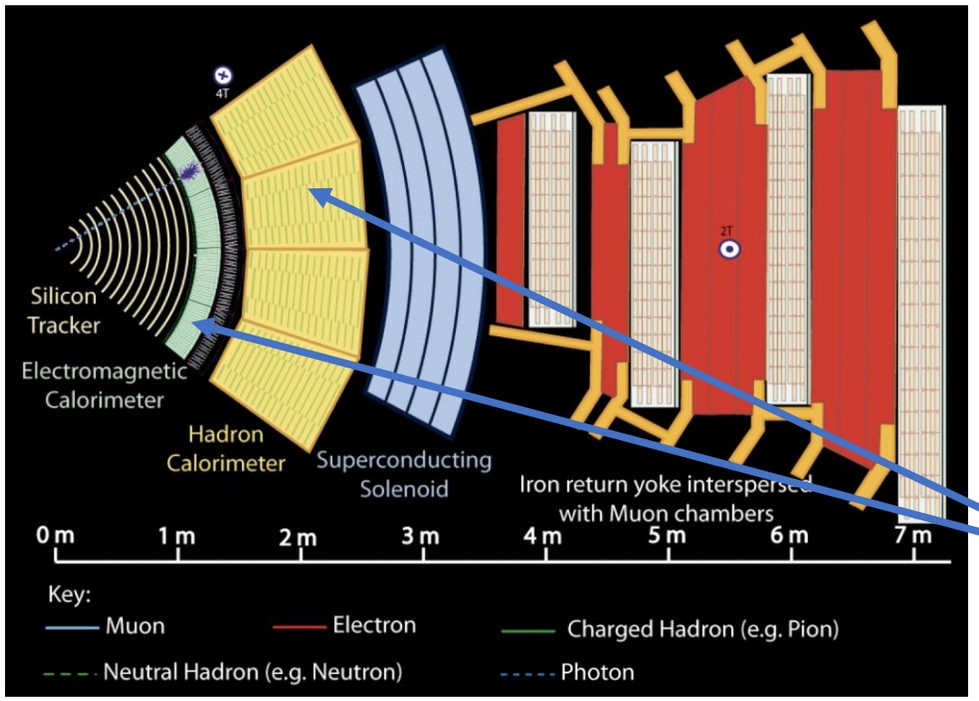
Create the future opportunities today

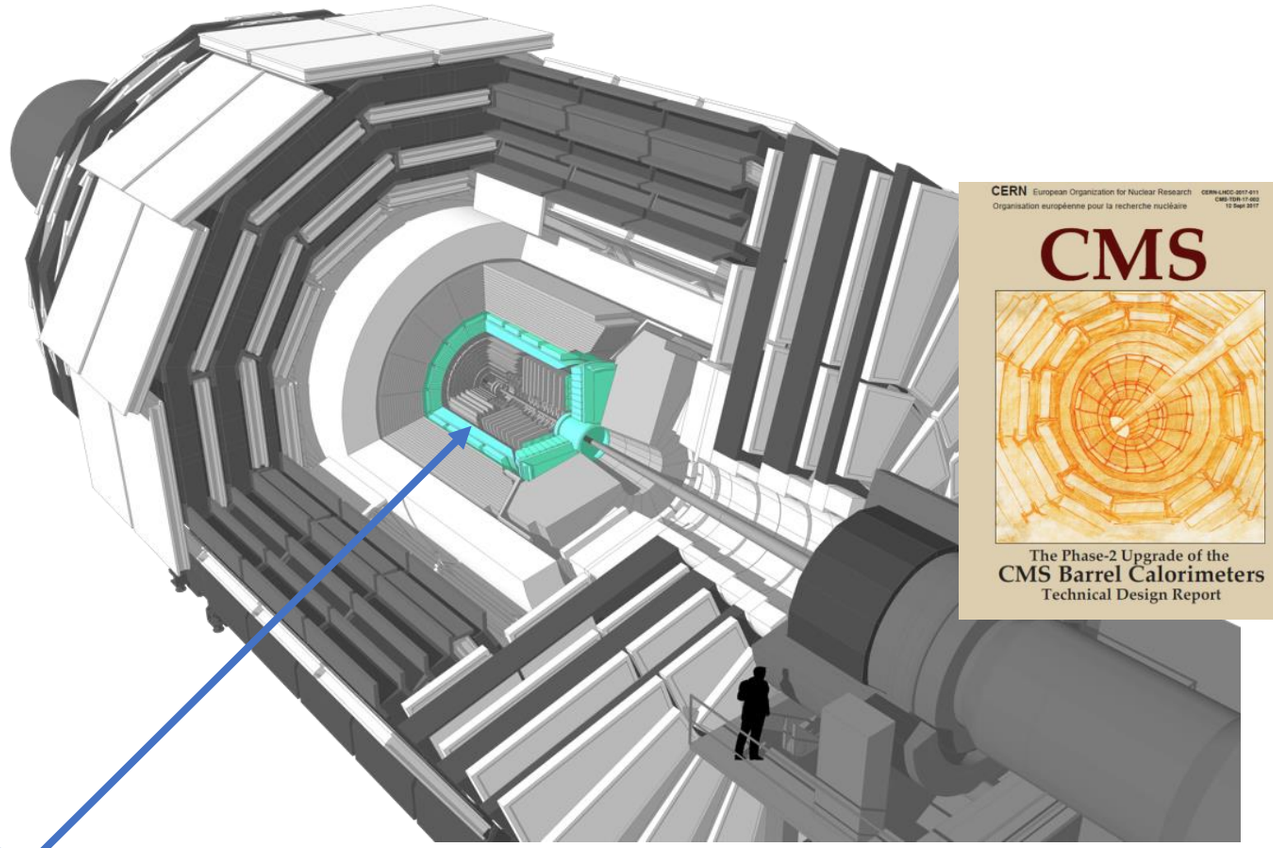


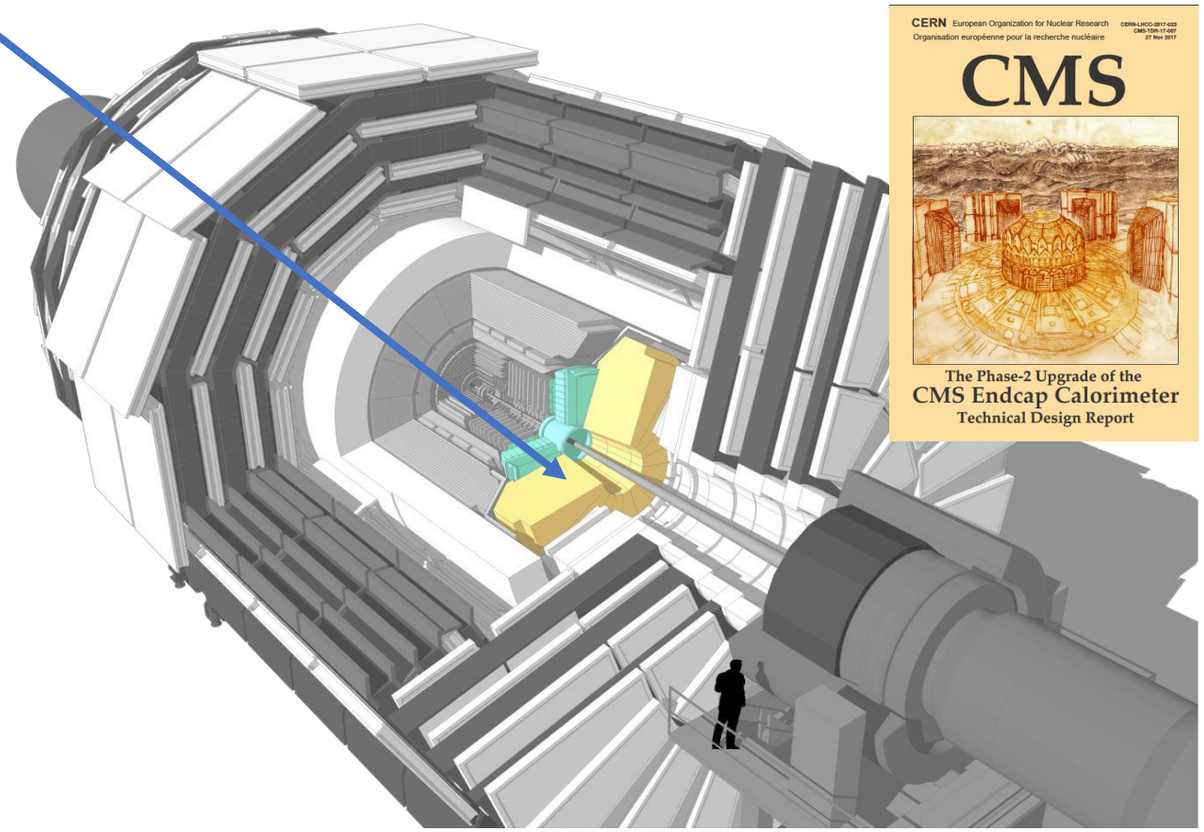
Fun at P5

RPC: Resistive Plate Chamber


More fun at P5
Interested in Muons:
Contact:
Andrey Korytov, Gabriella Pugliese
ME&RE-1/2/36
ME&RE-1/2/34
ME&RE-1/3/36
ME&RE-1/3/35
ME&RE-1/3/33
ME&RE-1/3/32
ME&RE-1/3/31
ME&RE-1/3/30
ME&RE-1/3/29
PLATFORM





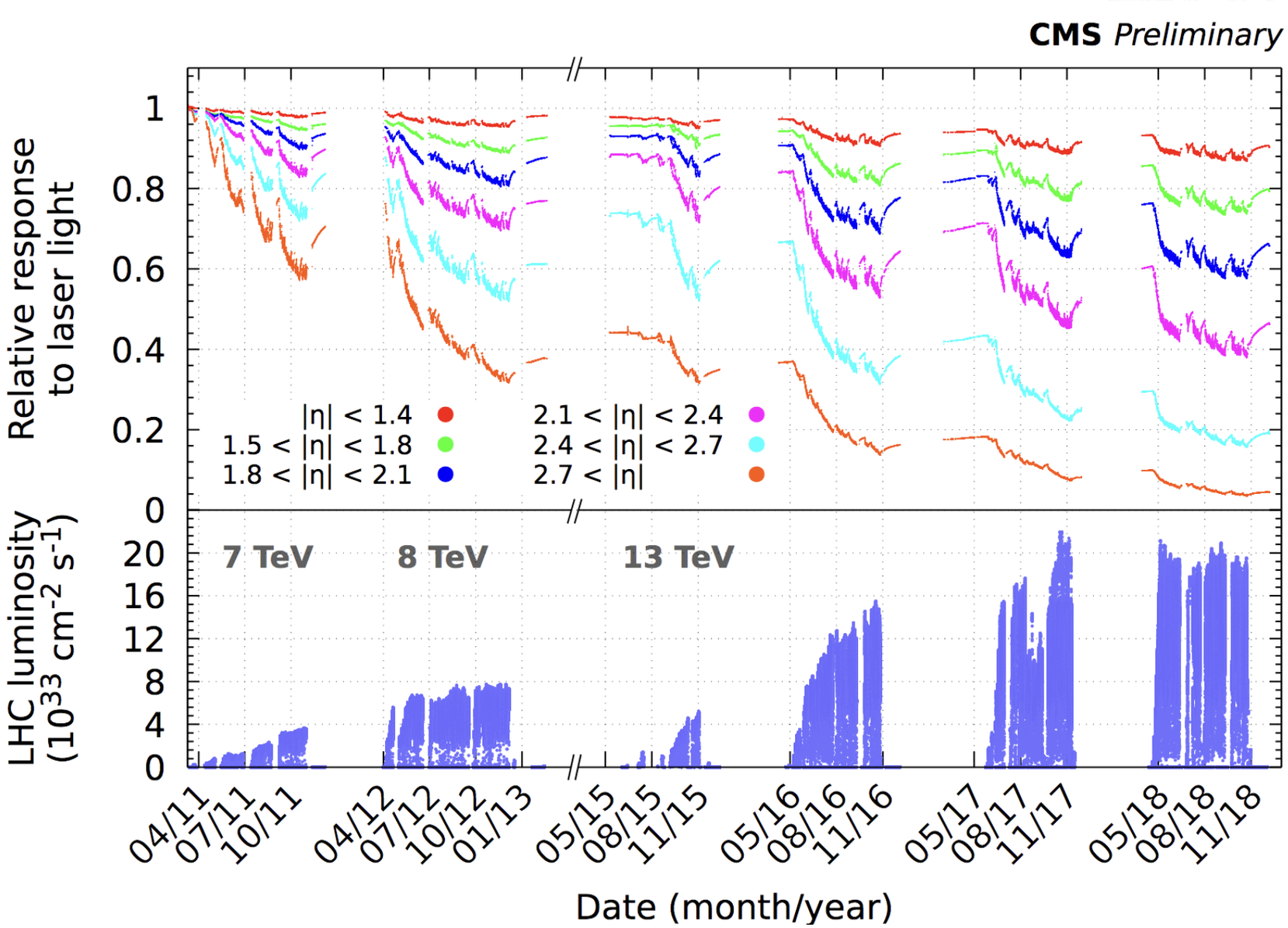


Calorimeter

Barrel and endcap

Which calorimeter to keep/replace?

Electromagnetic Calorimeter Barrel and Endcap



RED (barrel) **OK**

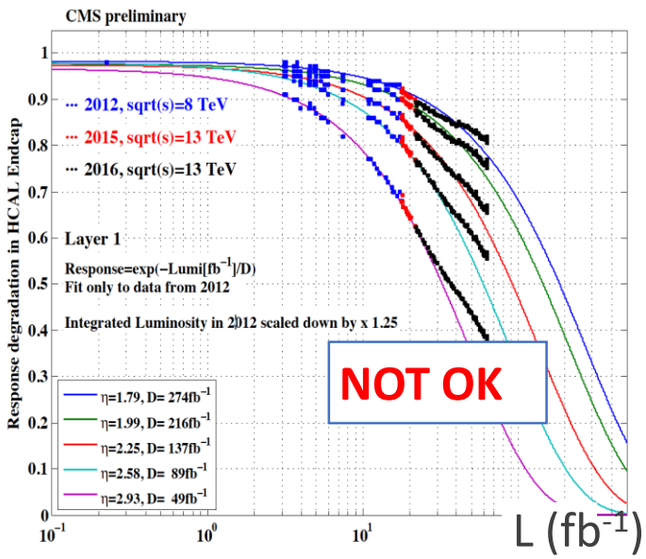
endcap

N

O

T OK

Hadron Calorimeter endcap response vs. Luminosity

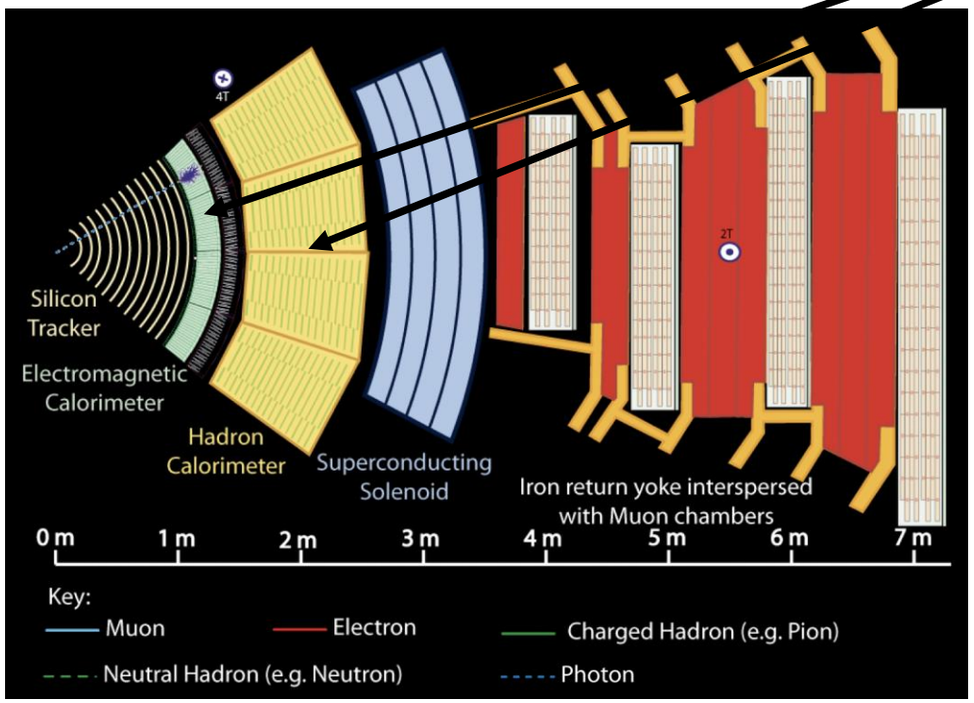


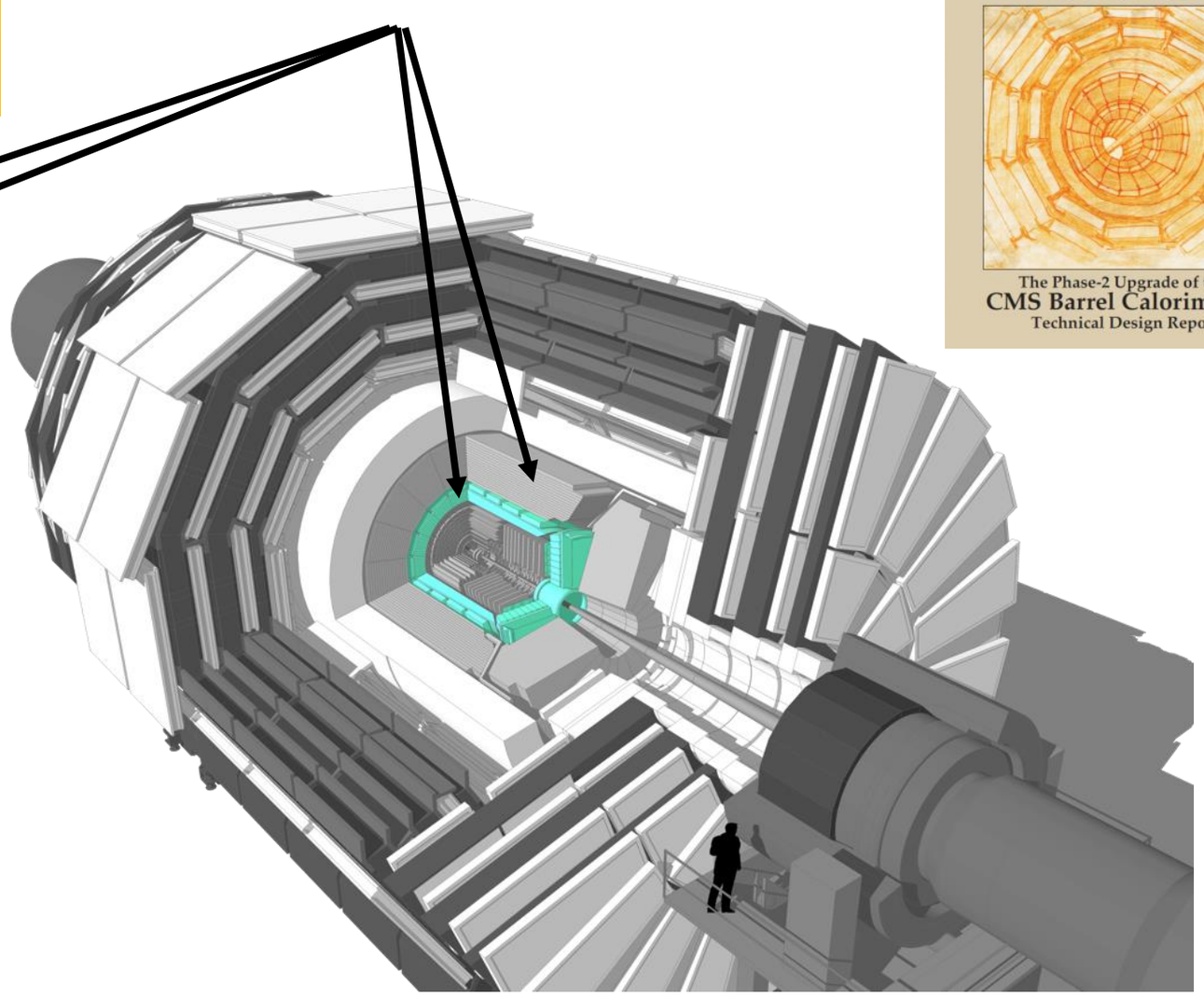
Fun at calibrations and to understand how a detector really works

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

Interested in Barrel Calorimeter:

Contact:
Bob Hirosky, Stefano Argiro’



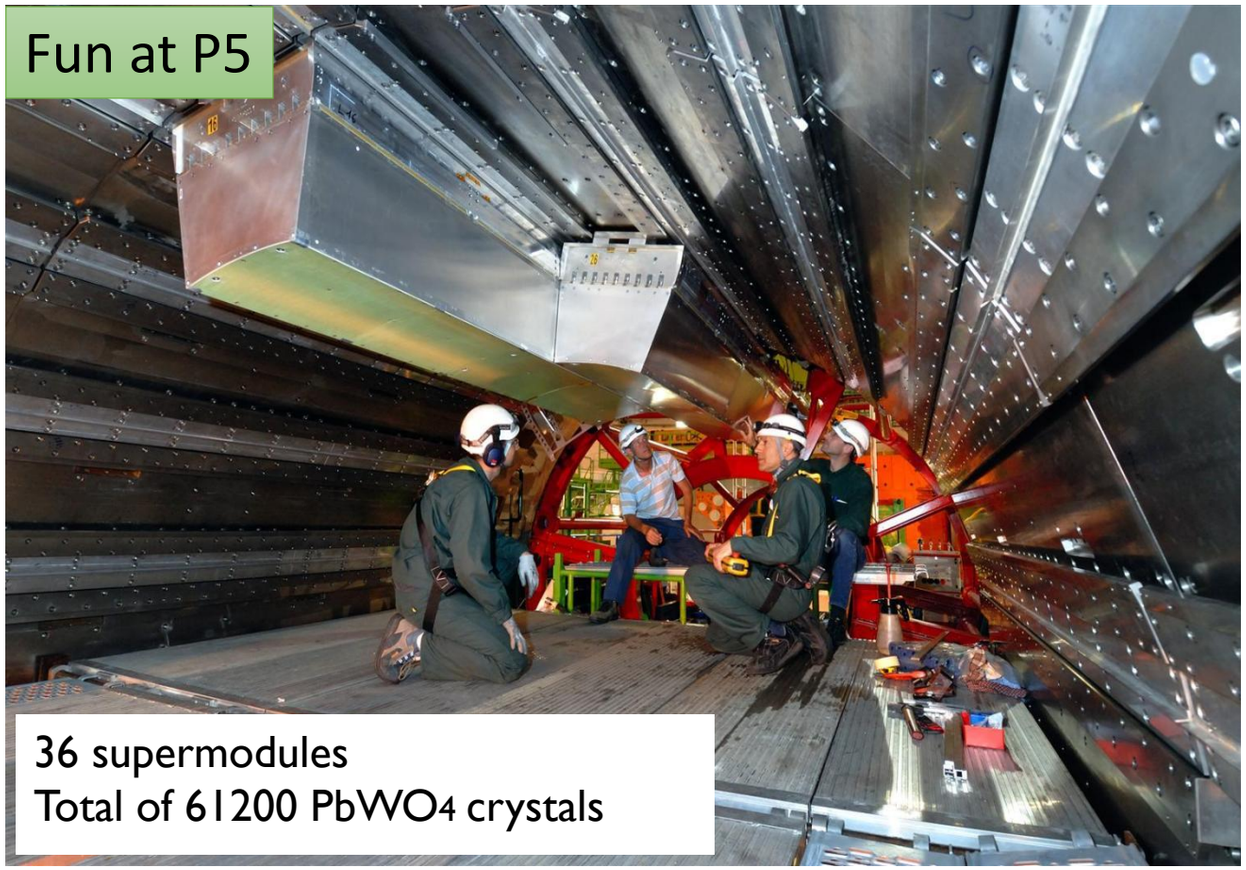


Barrel Calorimeter

Phase 2 upgrade is mainly Electromagnetic

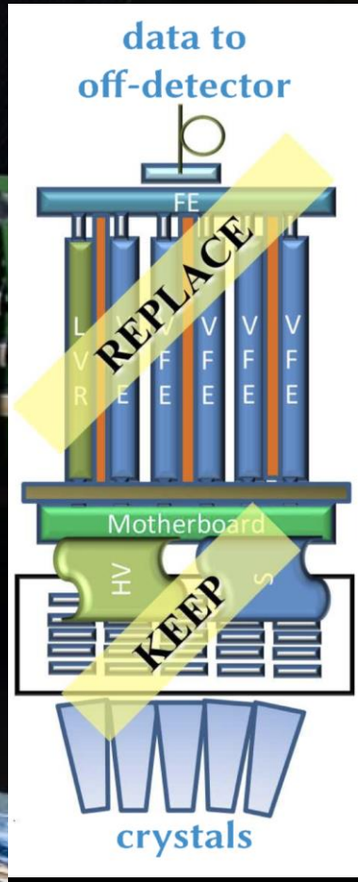
NB.: some years ago, we thought it would be **impossible** to work on it

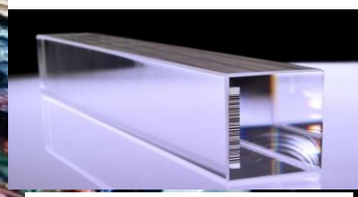
Electromagnetic Barrel Calorimeter – *inaccessible?*



- New electronics (new custom ASICs):
  - Why new? – Simple it would not work otherwise @ HL-LHC – too slow!
    - **full 40MHz readout (no trigger latency)**
    - **add precision timing (30ps)**
  - better resolution at L1 trigger
    - 5 x 5 crystals → single crysta

ETP → ETP Institut für Experimentelle Teilchenphysik





Lead-Tungsten

Choreographed ballet to get it done within LS3 schedule
Extract – crane to surface – refurbish – back down - re-install

For insiders – FE chips will also do spike rejection

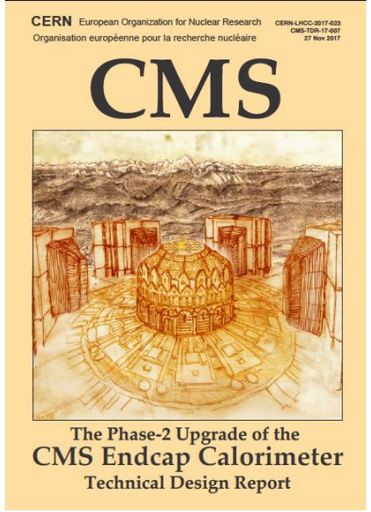
2006 – let’s do it again

Fun at P5

Interested in Barrel Calorimeter:

Contact:
Bob Hirosky, Stefano Argiro’

Multiply by 2 and realize at P5



World's first

High Granularity Calorimeter

- a 5D calorimeter

"5 dimensions" measured → (x,y,z,E,t)

Interested in HGCAL :

Contact:
Karl Gill, M. Mannelli, Jim Strait

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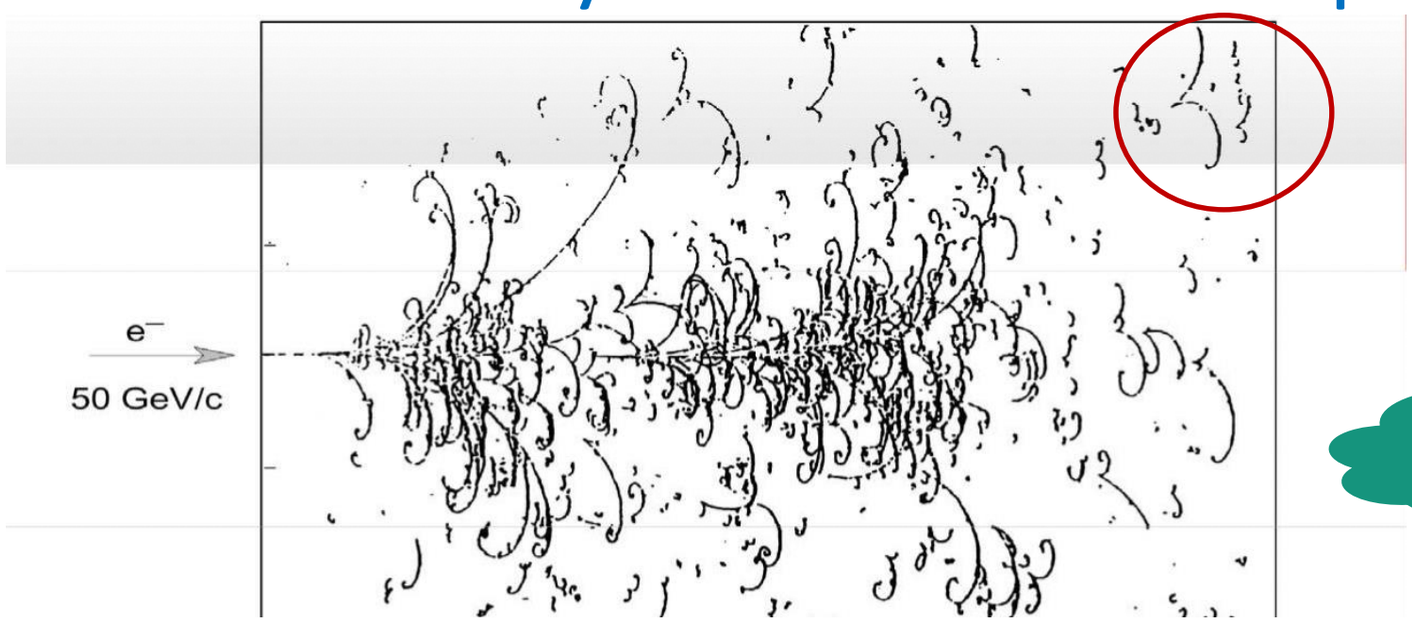
Going Forward by looking backward - Imaging Calorimetry in the endcap

Idea kindly borrowed from D. Barney

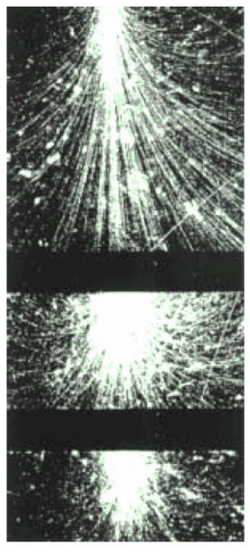
Big European Bubble Chamber
3T; L=3.5m, X_0=34cm

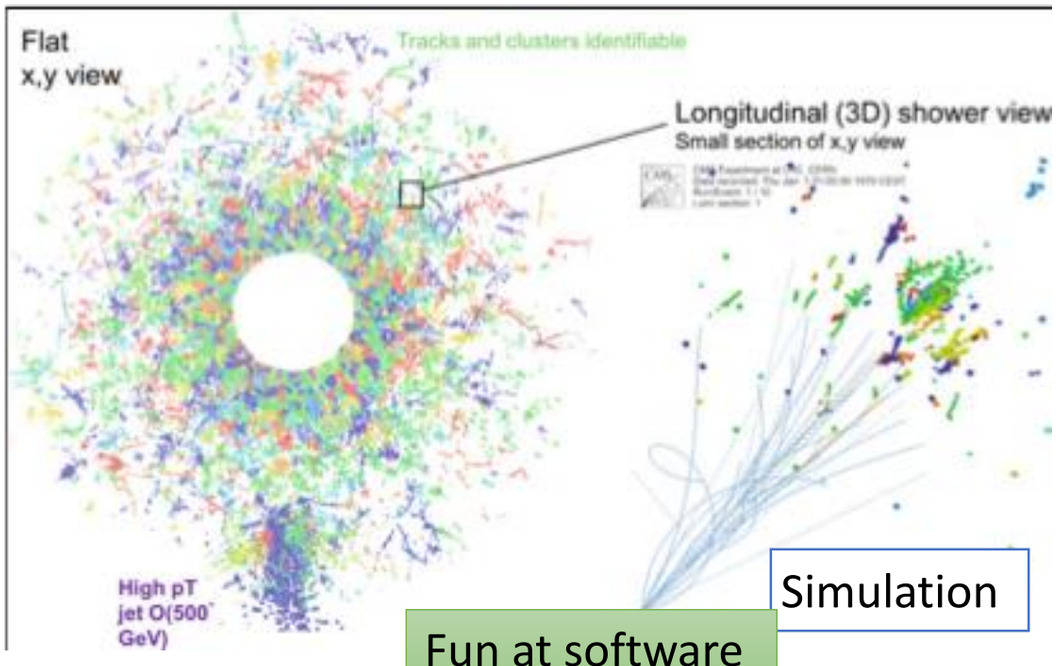


Yes, we can!

The previous generation of calorimeters could "see" showers!

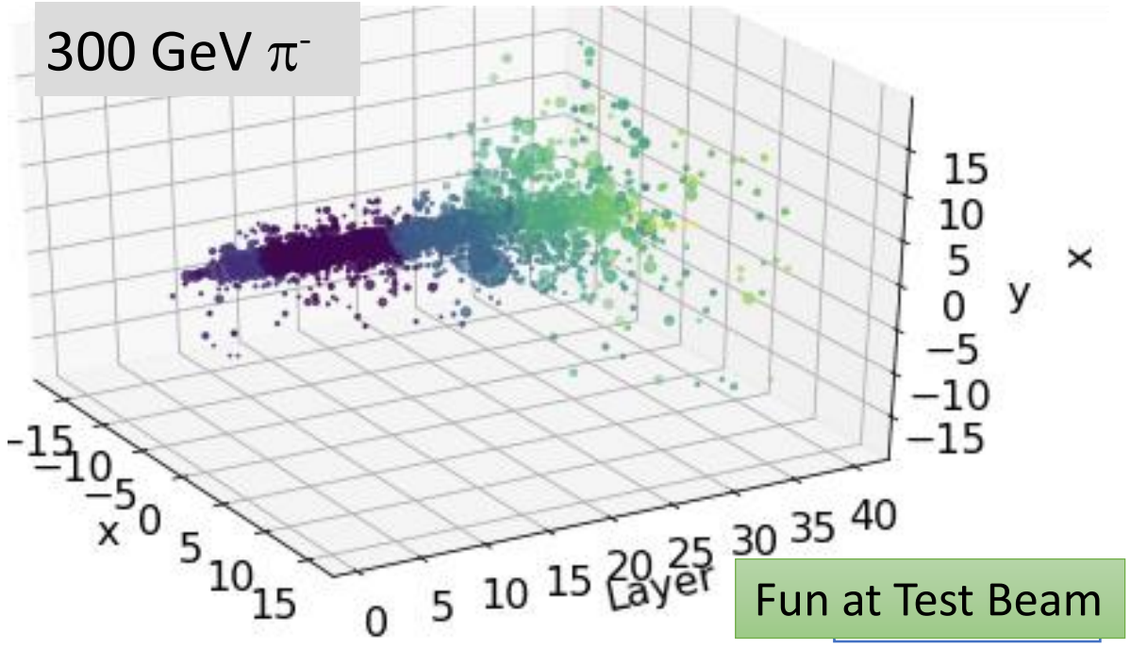
Can we do this again – at 40 MHz and PU=200?





Fun at software

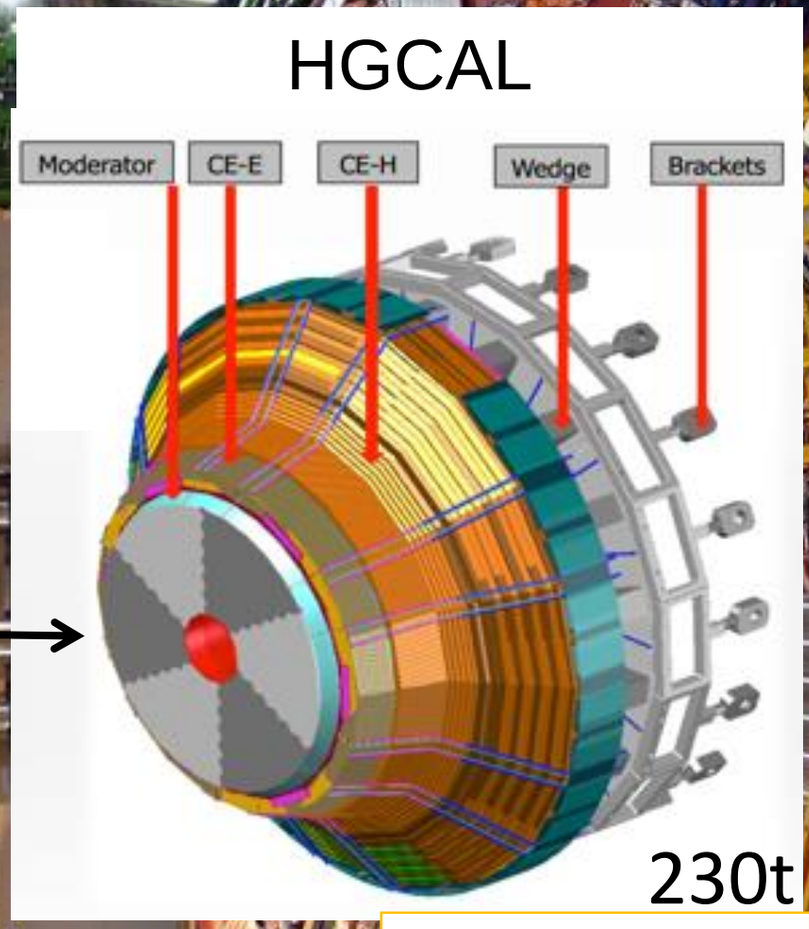
Simulation



Fun at Test Beam

Replace the 230t nose

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



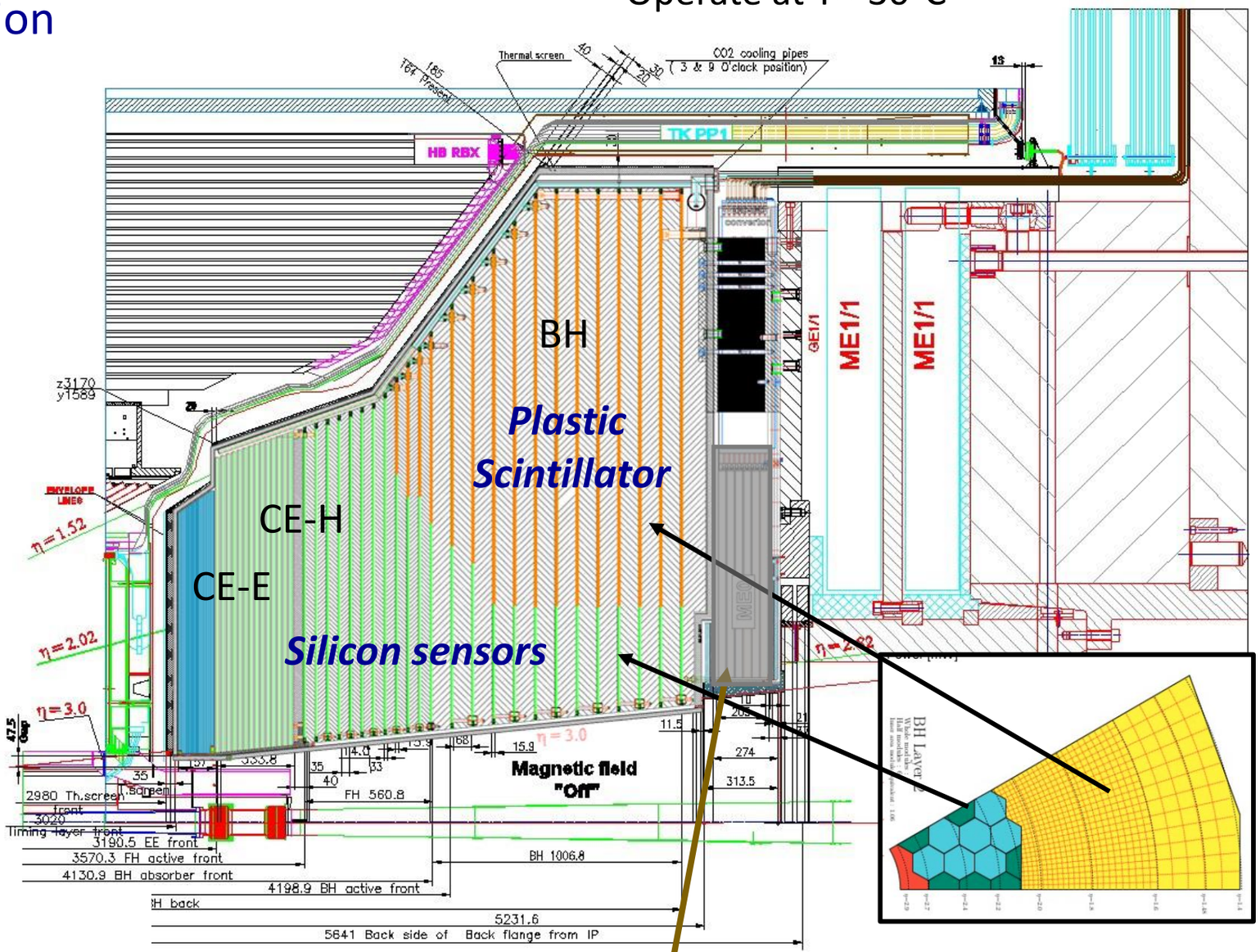
230t

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



Cu/CuW/Pb stainless steel

*CE-E: **28** sampling layers – 26 X_o + ~1.7 λ* ***22** sampling layers – 9 λ*

Btw: Muon GEM

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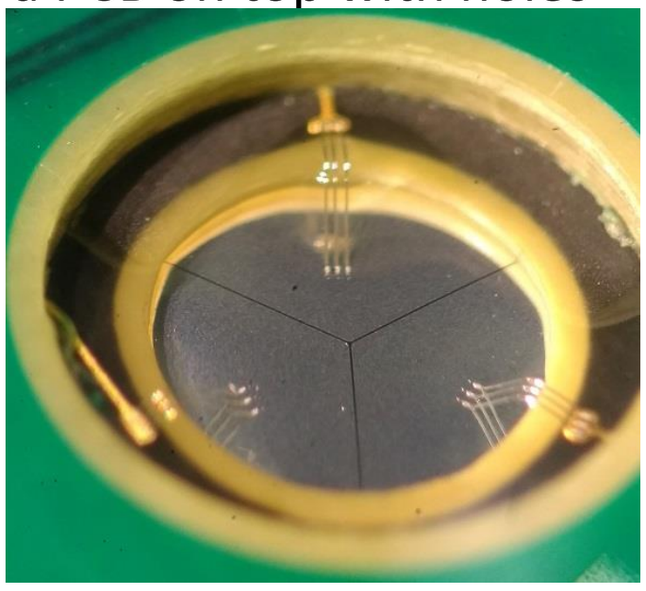
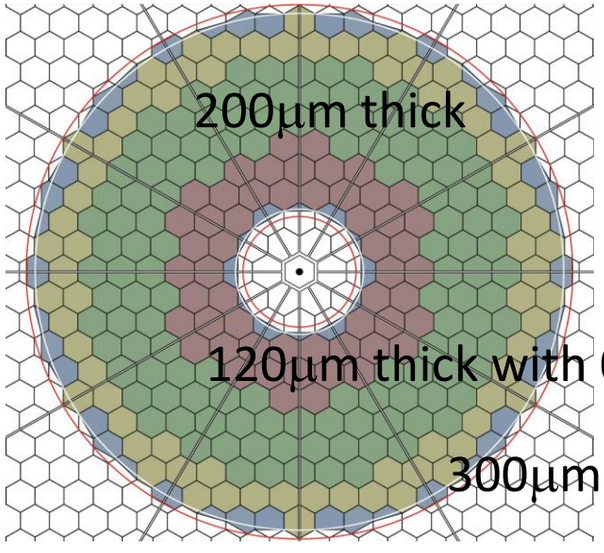
HEP: High Energy Physics

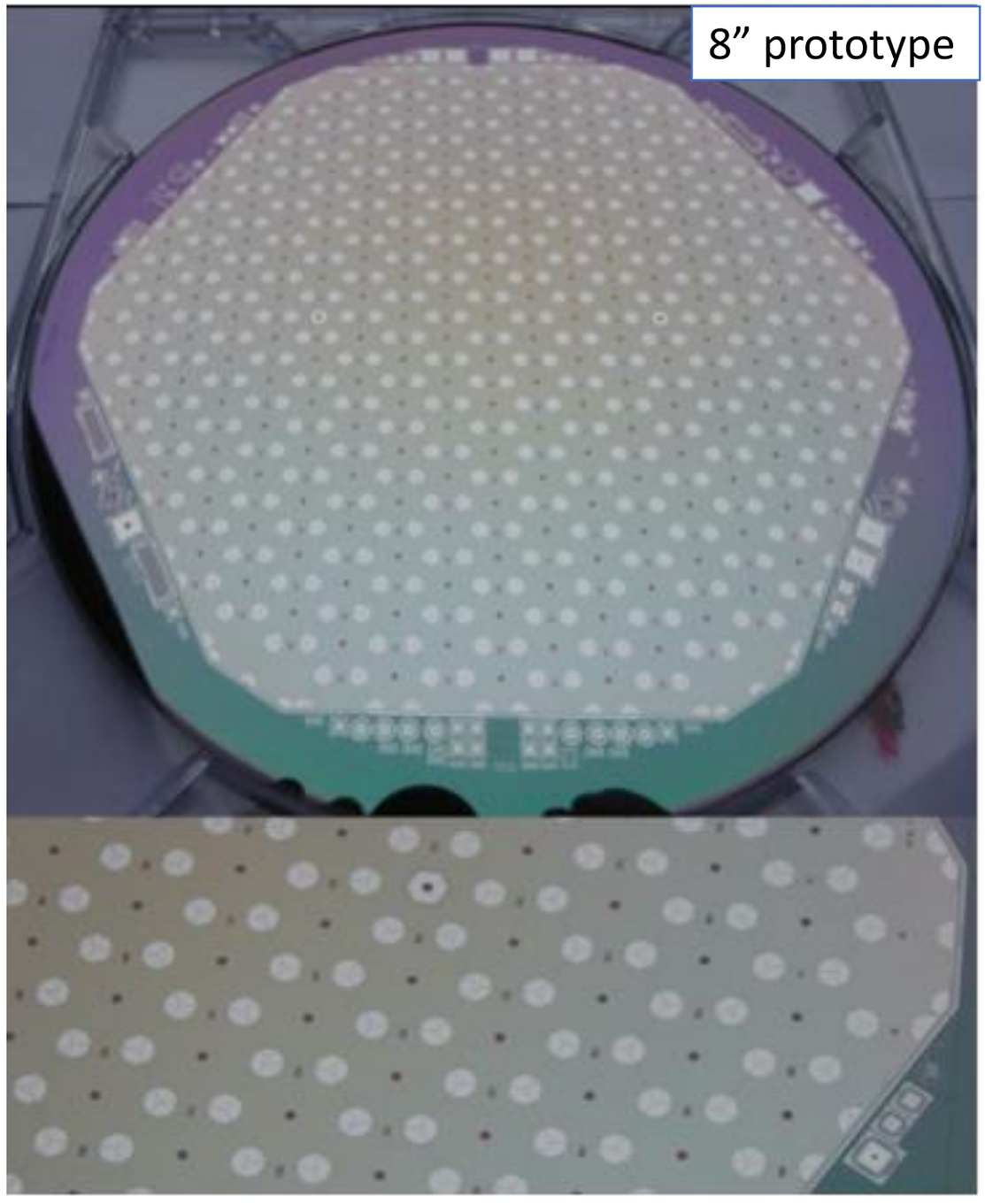
Honeycomb and 8” silicon wafers

– a first in HEP

- **Hexagonal** sensors to maximize use of wafer area (less $$)
- 120, 200, 300 μm thick n-in-p pad sensors
  - Thickness defines radiation tolerance
- Cell size ~0.5 or ~1 cm^2
  - Smaller cell size in central region
    - High occupancy and noise reduction
- Cells are wire-bonded to a PCB on top with holes



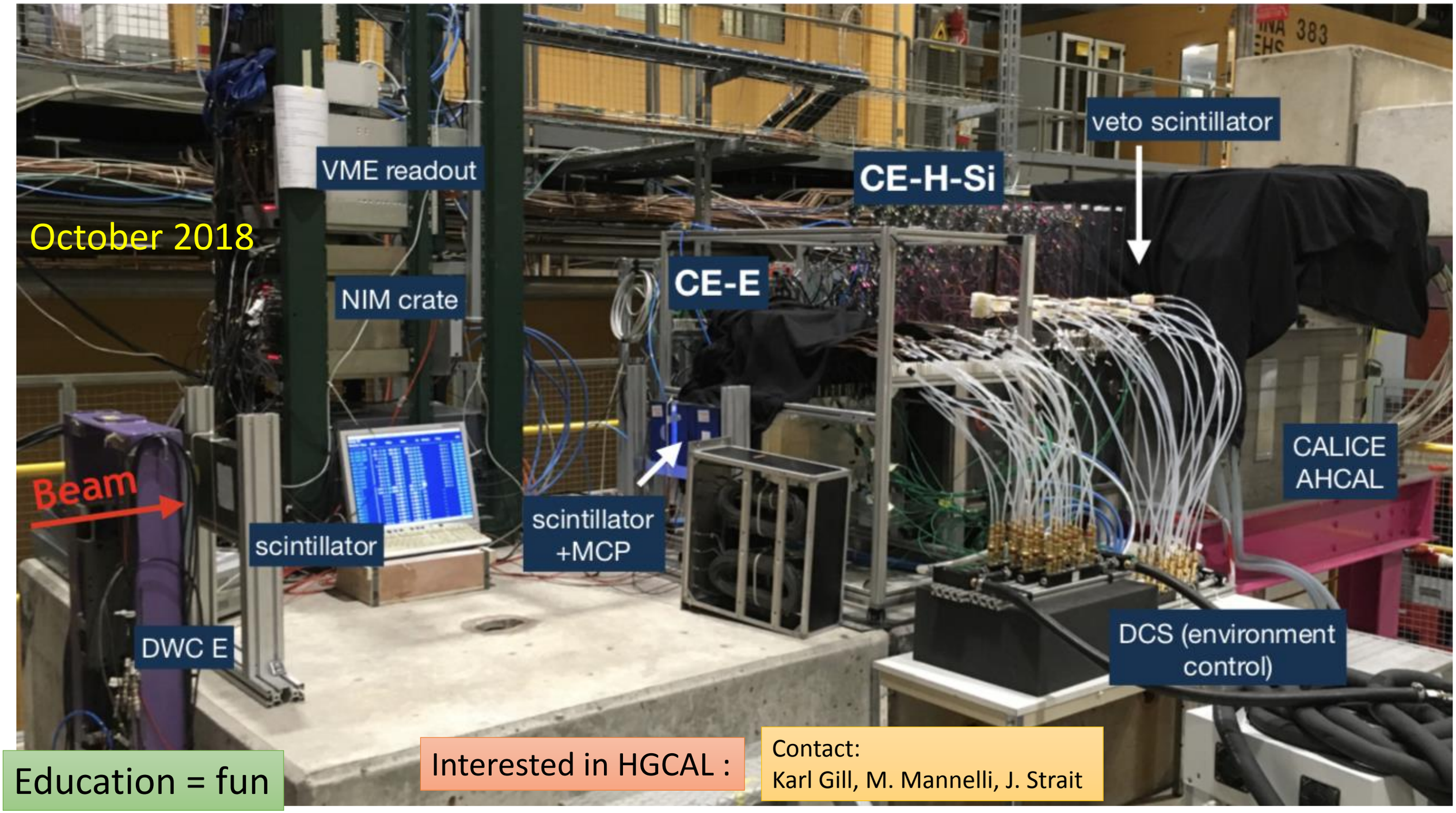




n-in-p more radiation tolerant than p-in-n; thinner = radiation tolerant
Higher radiation at lower radius

May 2017; July 2017, March 2018; October 2018

Fun at Test Beam

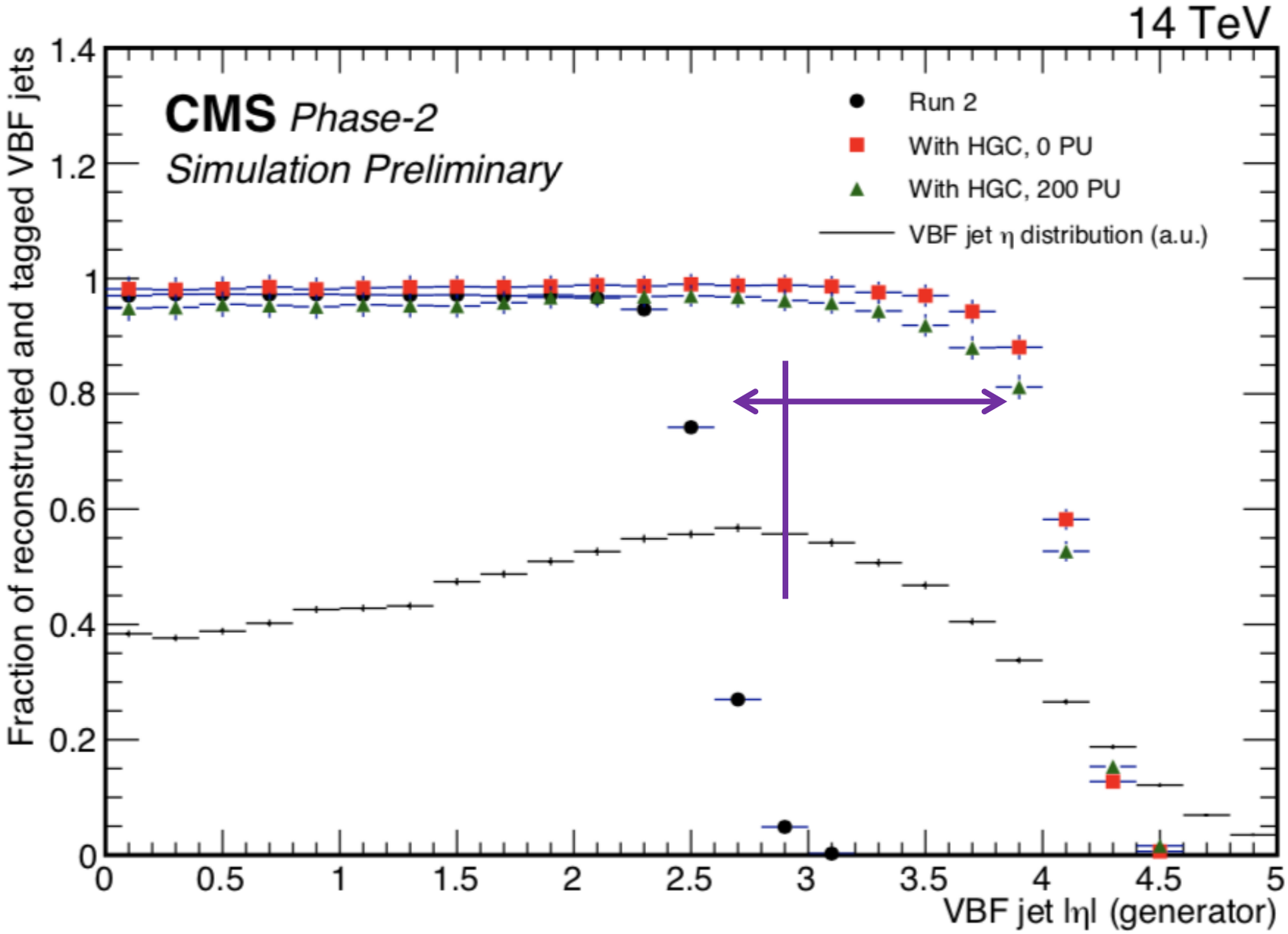


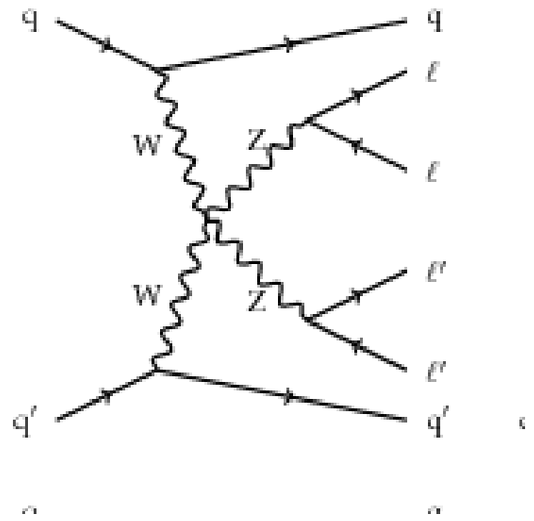
Education = fun

Interested in HGCAL :

Contact:
Karl Gill, M. Mannelli, J. Strait

Vector Boson Fusion VBF jet reconstruction





As said VBF needs forward extension

η Pseudorapidity ~~ angle, forward = large η

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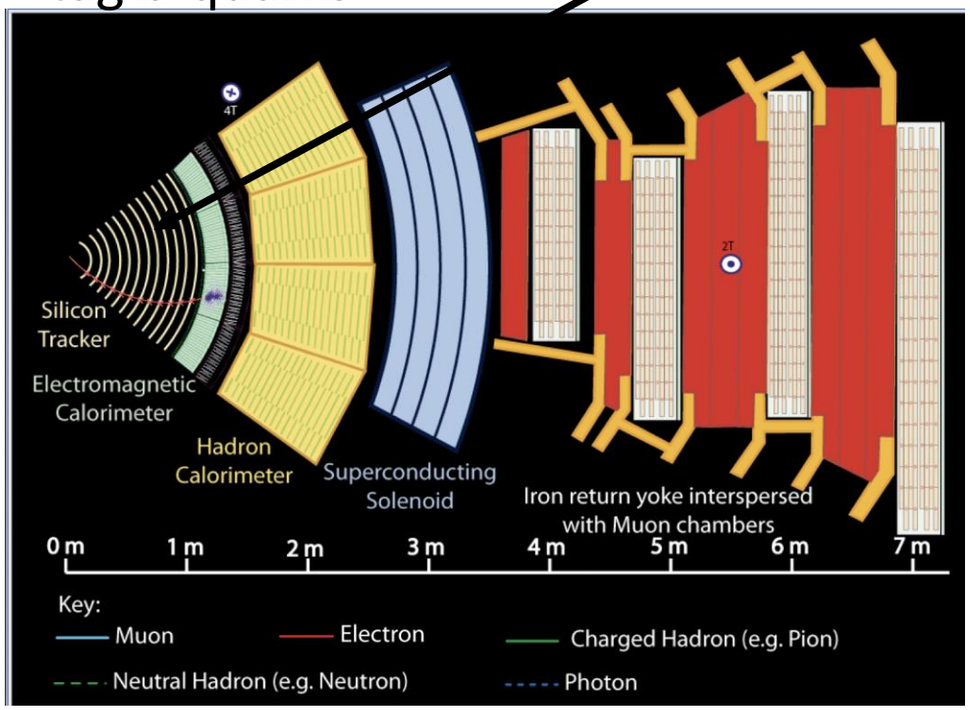
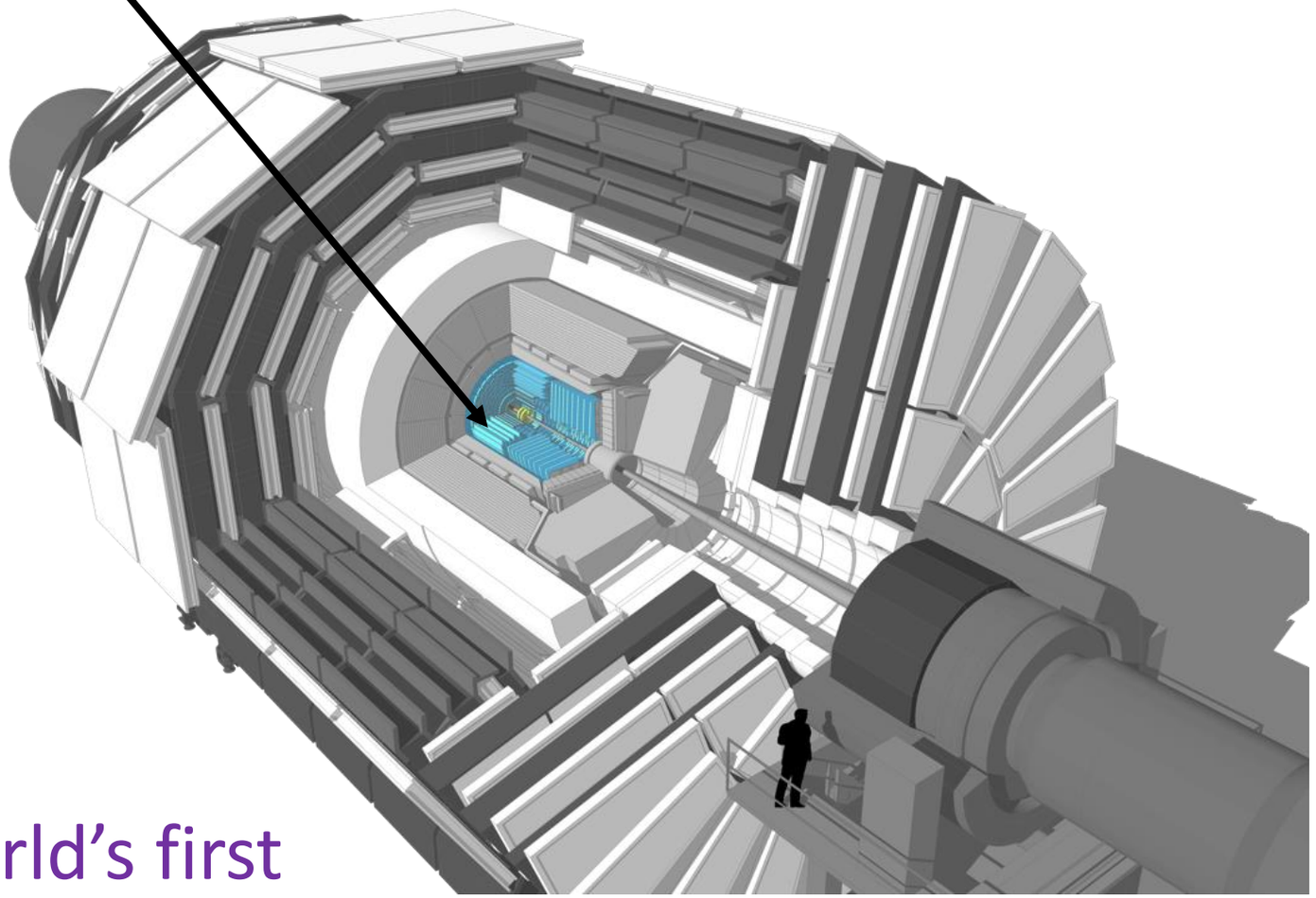
- measure tracks
- tag b-quarks

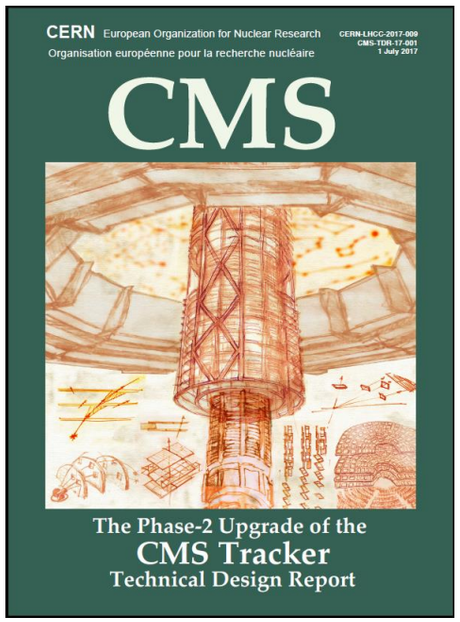




Track Trigger at 40MHz - world's first

Tracker

Build a new, better, more beautiful one



Interested in Tracker :

Contact:
E. Butz, A. Venturi, V. Veszpremi. K. Hahn

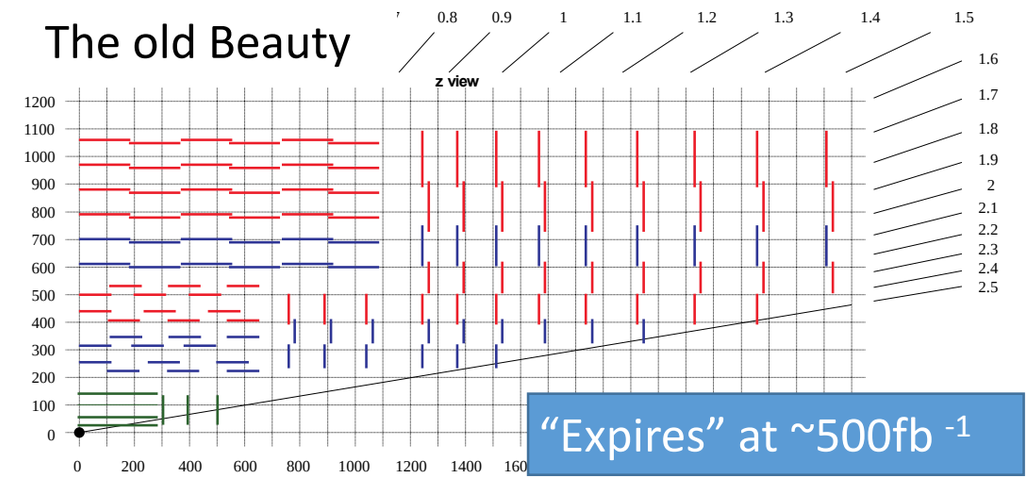
CERN-LHCC-2017-009 CMS-TDR-17-001

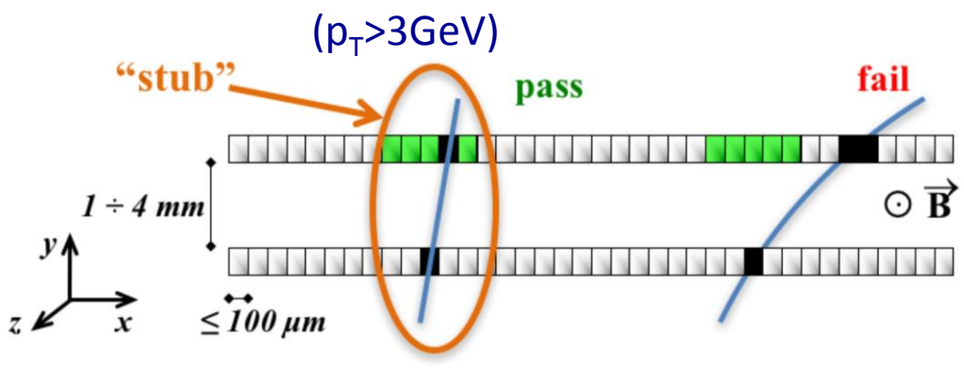
Flying Tracker
2008 in – 2024 out – 2026 new one in

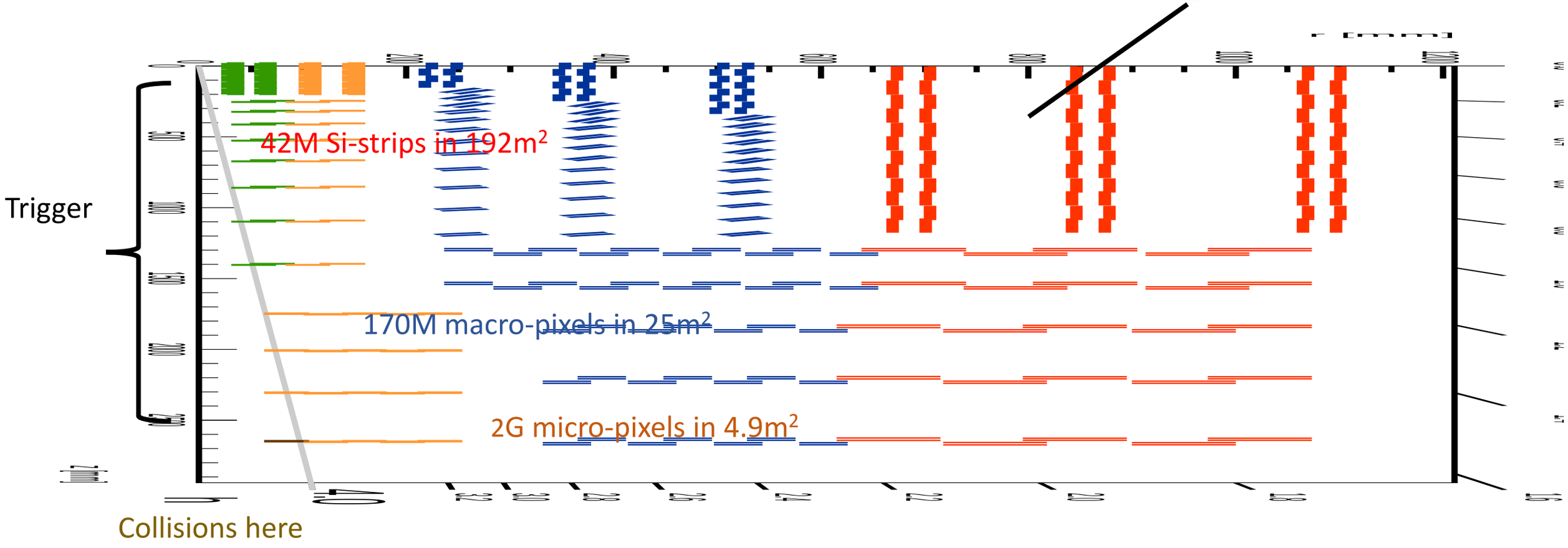
Photo: M.Hoch

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



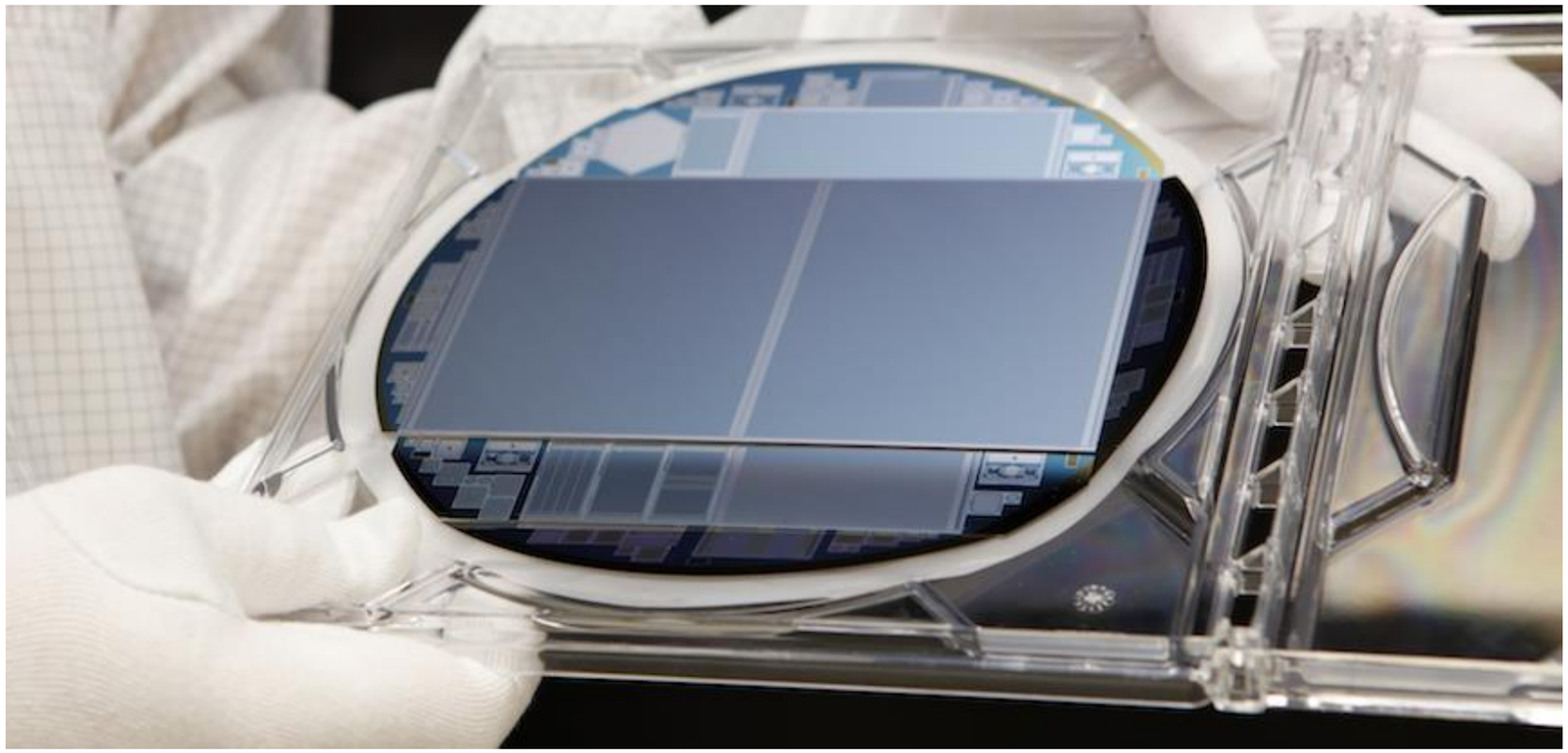




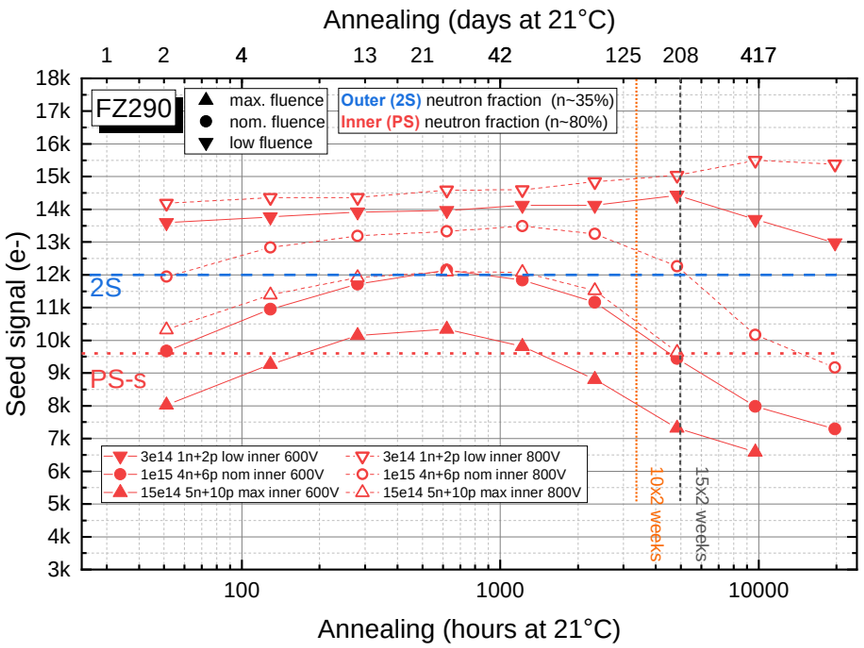
CERN-LHCC-2017-009 CMS-TDR-17-001

p_T transverse momentum

New more radiation tolerant sensors



Fun in the lab



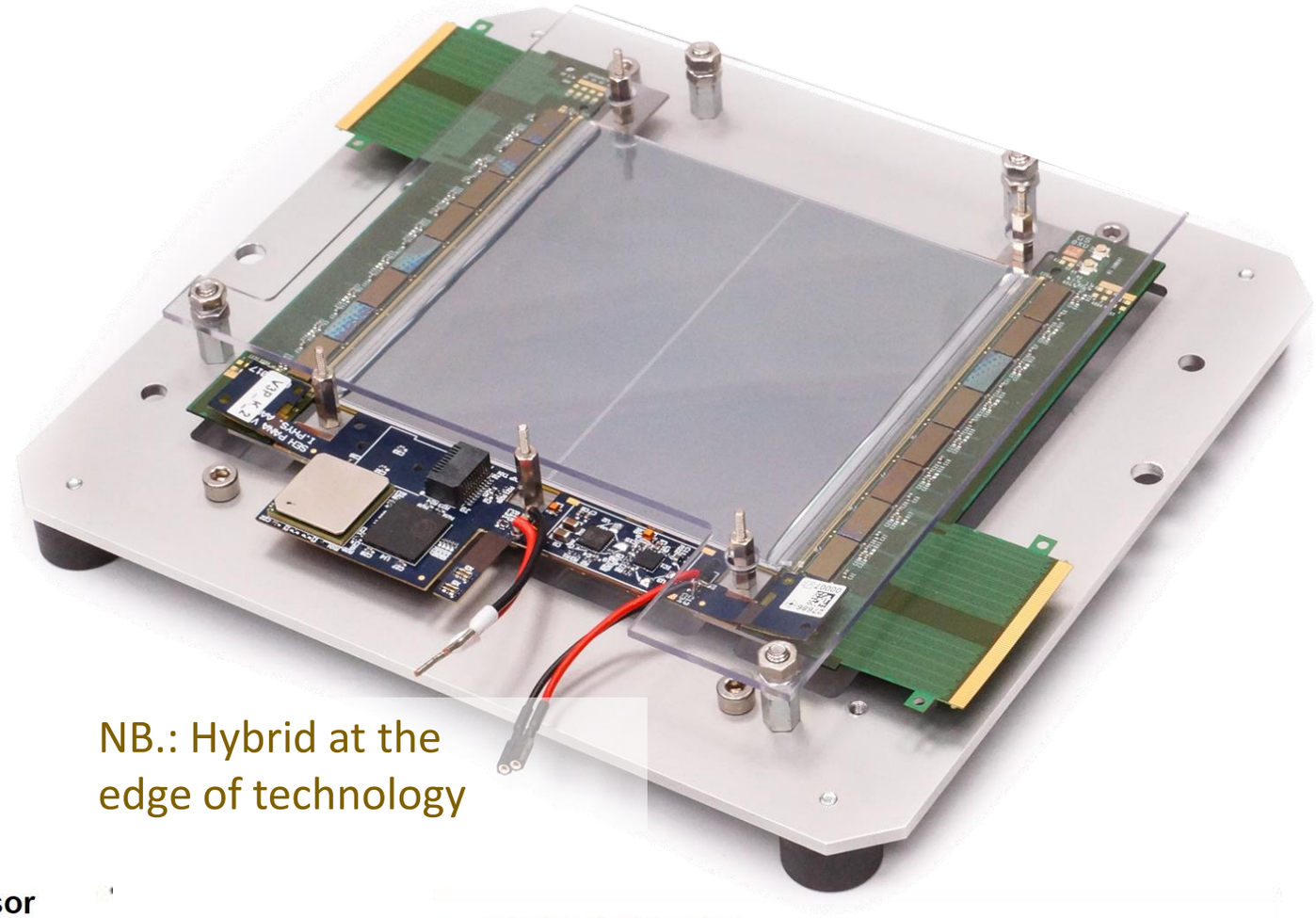
Fun at Test Beam (FNAL)

Today: sensors are 10 times more radiation tolerant!

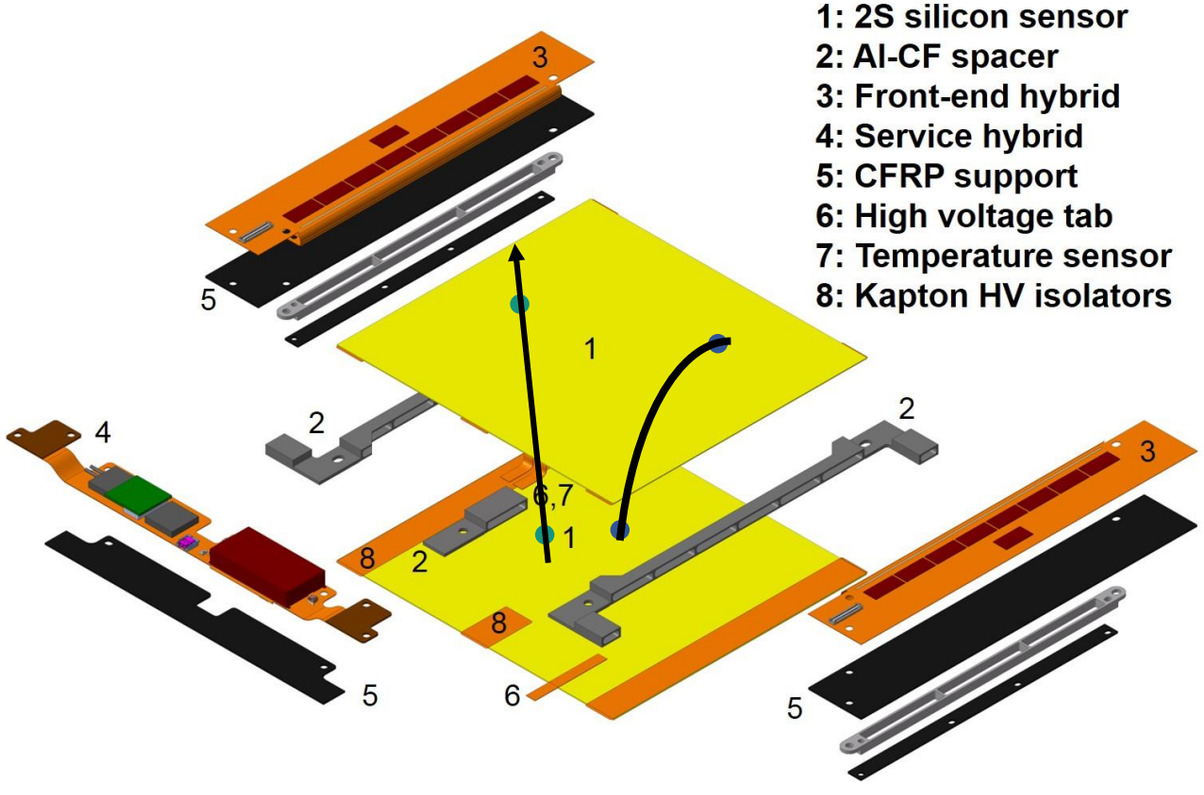
New Technologies – Tracker Module

New concept

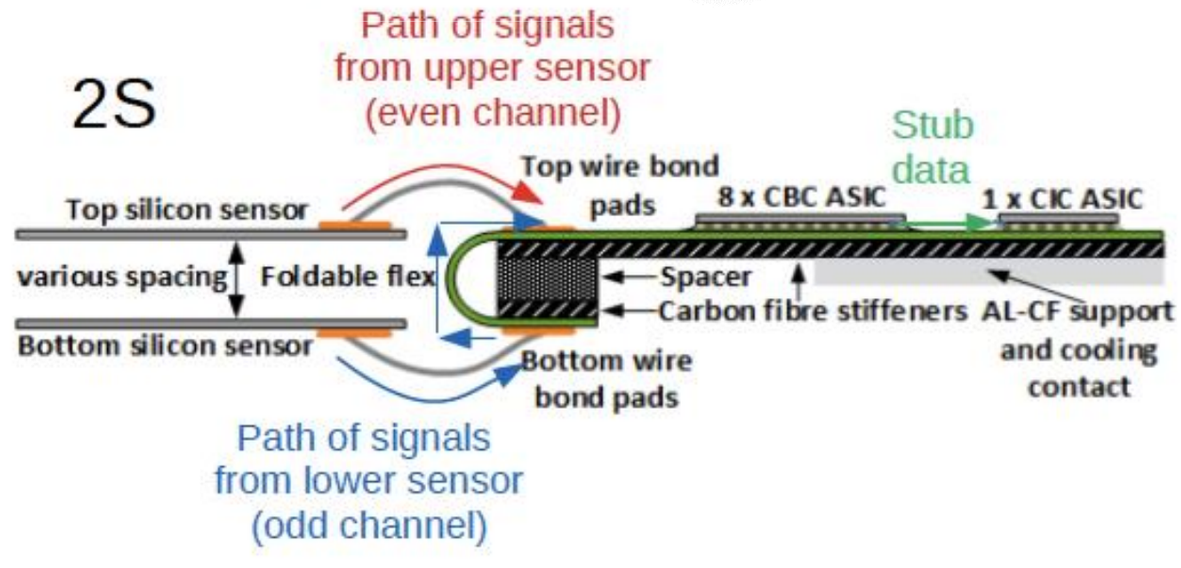
- Contains ALL electronics = full system
- Effective way to have 2 space points in single mechanics – lightweight
- Gives ‘vectors’ instead of points
- Tag high p_T segments



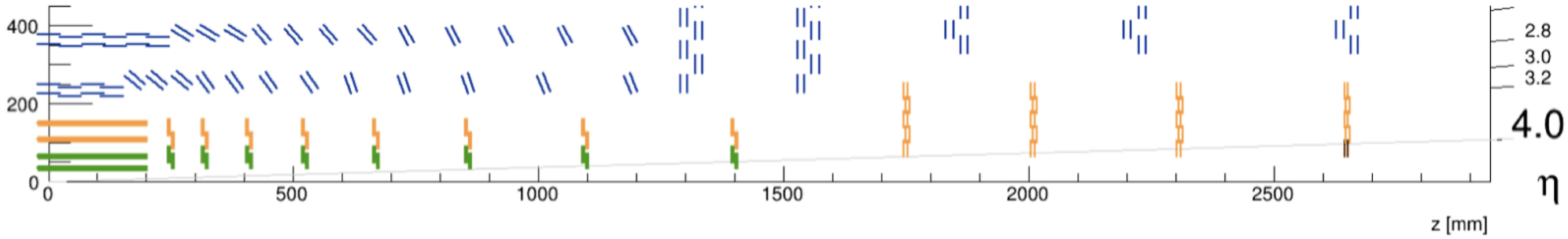
NB.: Hybrid at the edge of technology



NB.: ~5 years of engineering and modelling

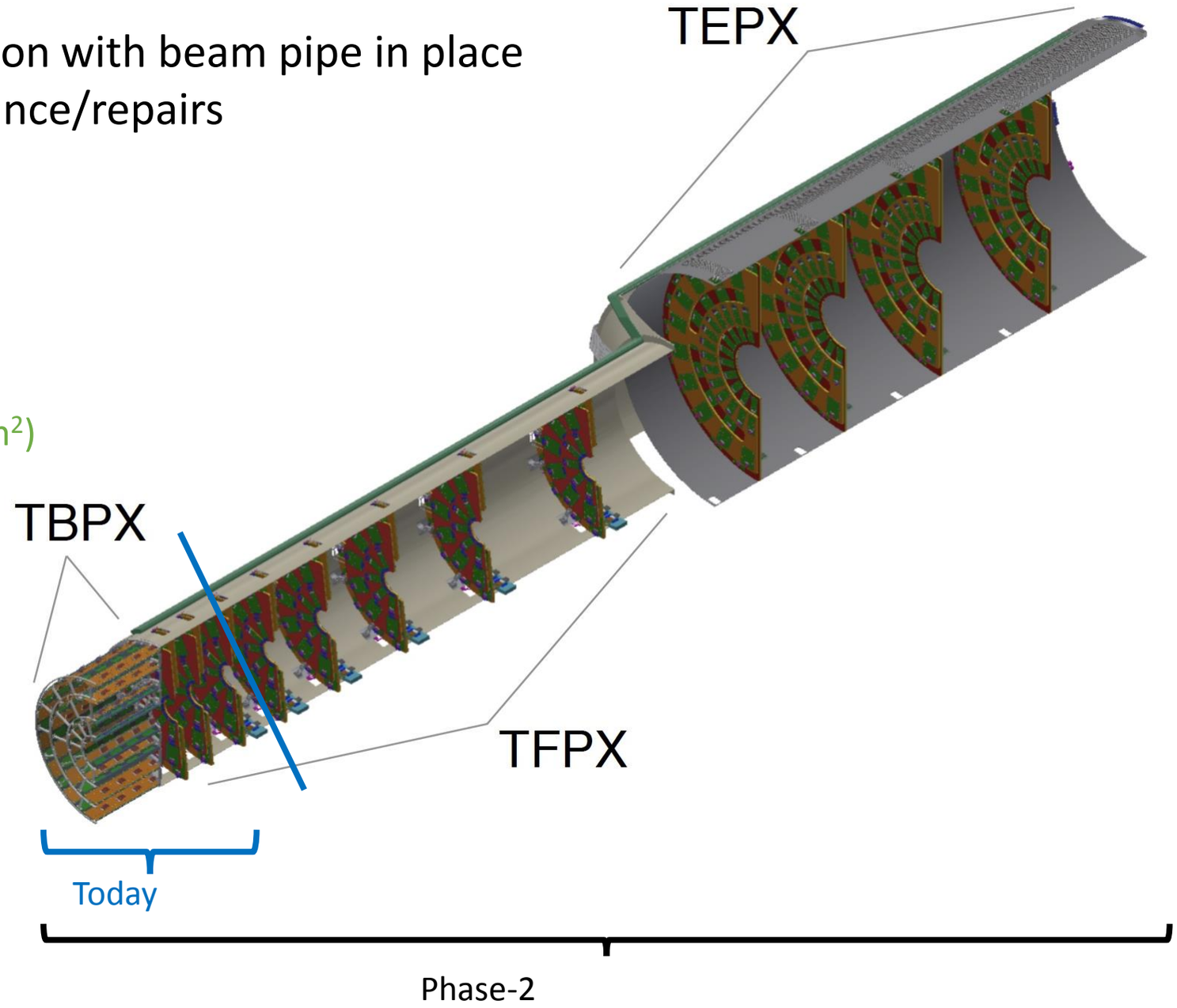


We extend into the forward region



- 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

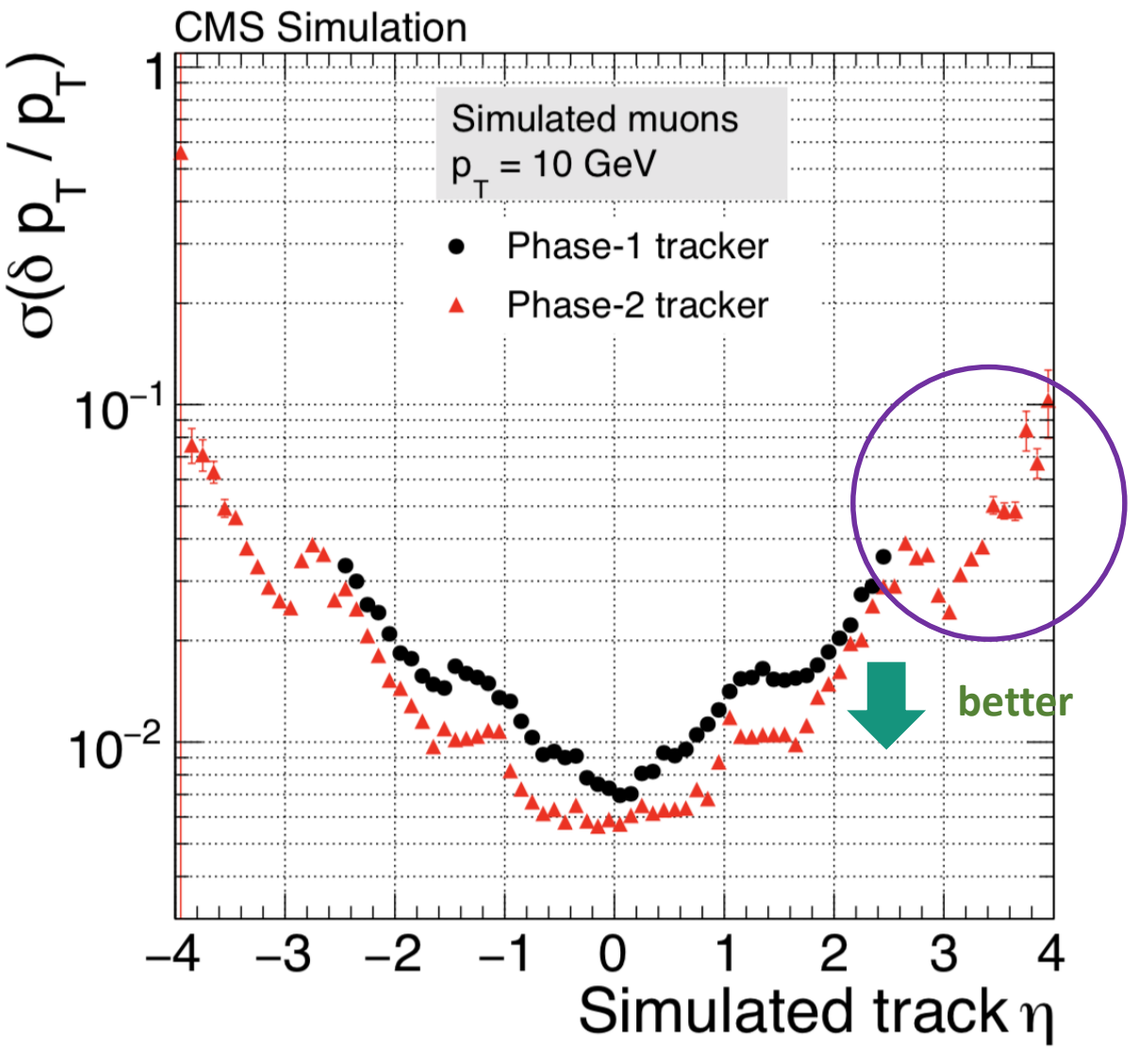
→VBF
→b-tagging
→PU mitigation



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

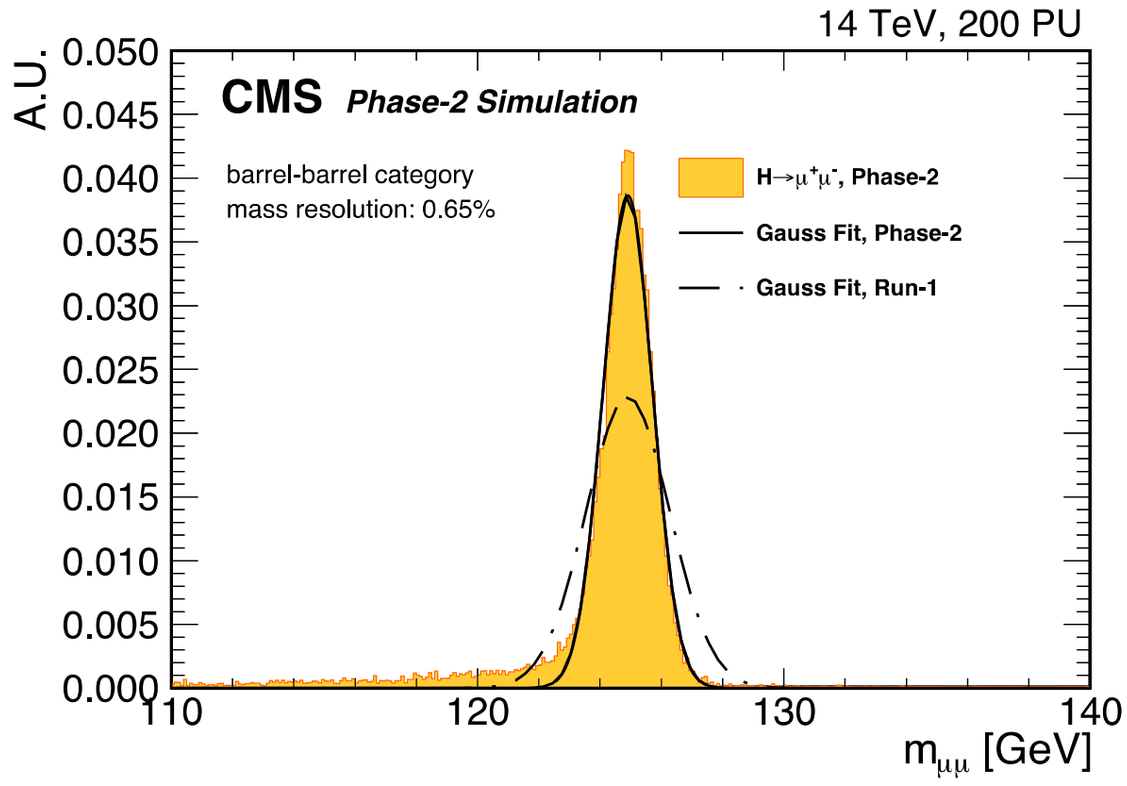
Tracker-2 Performance

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}



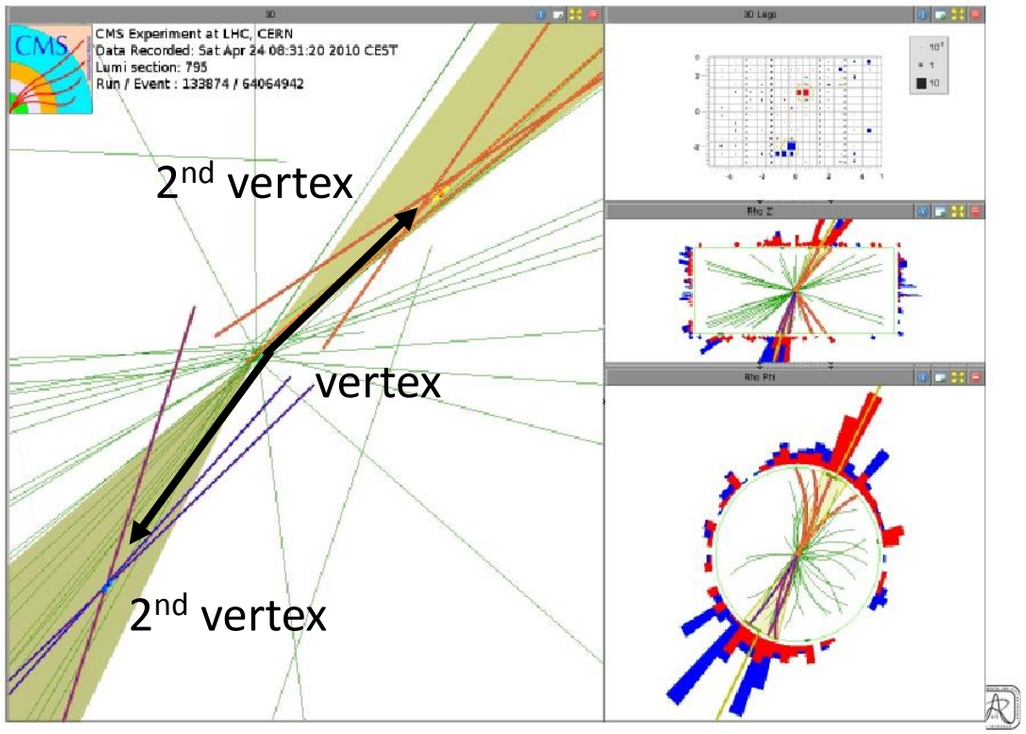
- More precise tracking parameters
  - **Largely due to reduced material budget, thus less multiple scattering**
- Extended coverage, allowing e.g. better forward jet reconstruction
  - **Helps PU-mitigation, VBF, di-Higgs**

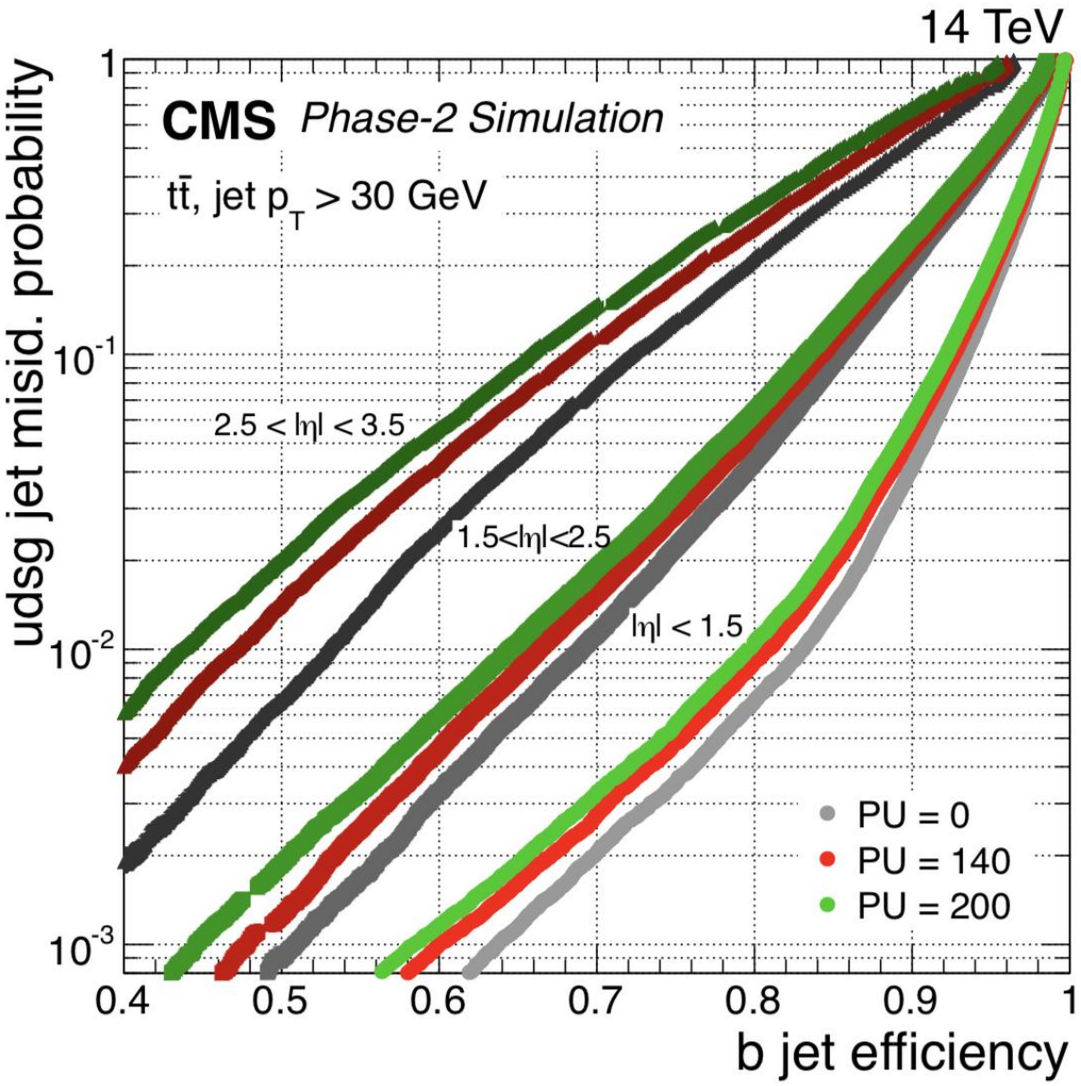
Yes, it is a *b*-quark

Better btagging

Due to excellent pixel detector

- High resolution, very high granularity
- Timing detector improves further





b-lifetime defines pathlength

pathlength identifies ***b***-quark

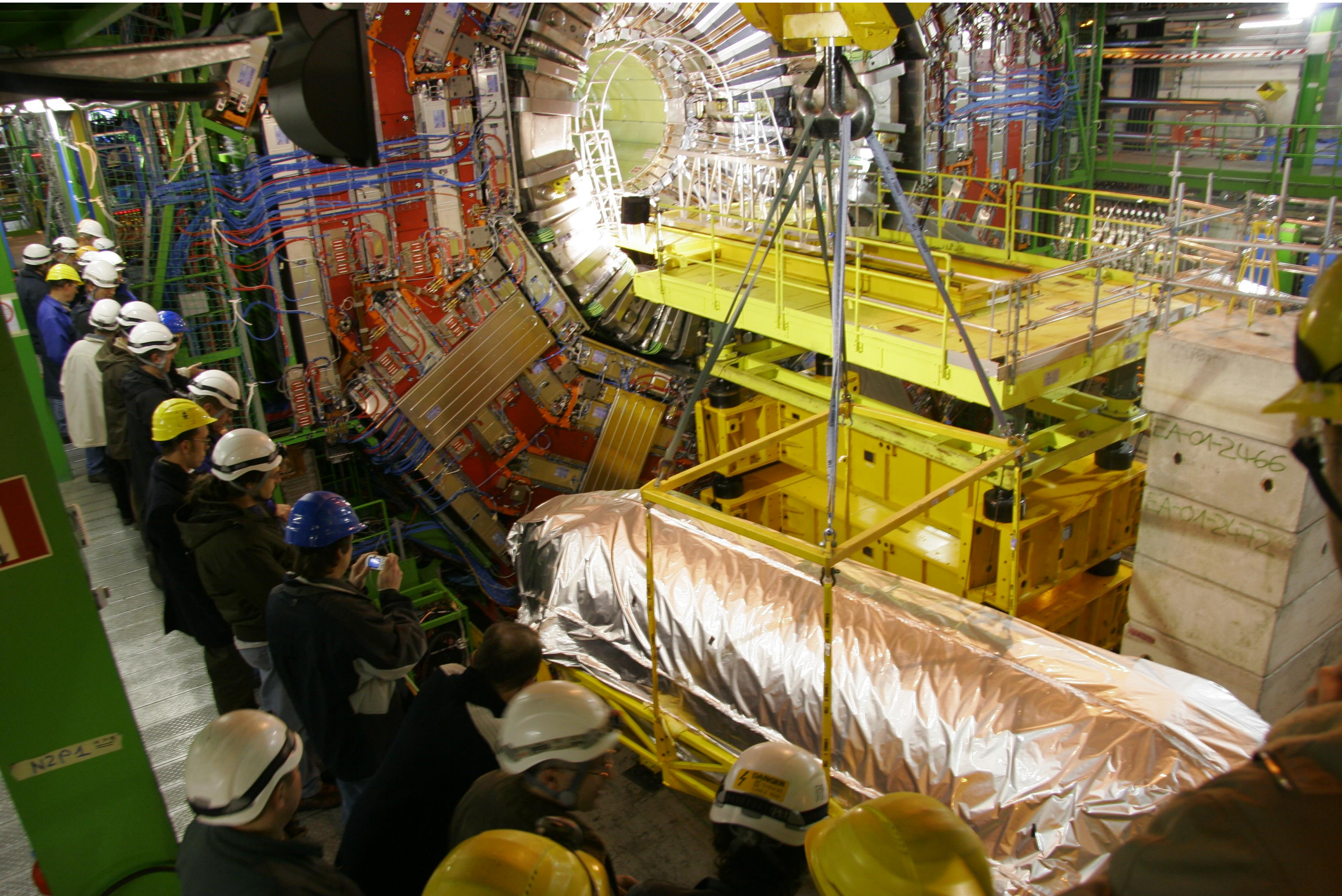
Di-Higgs Production in the $HH \rightarrow bbbb$ decay channel

- +8% acceptance
- +50-70% efficiency of of 4 *b*-Quarks-tagging at 200 pile-up

Pixel at small radius(r~3m) and small Pixels (25x100μm²) – excellent *b*-tagging

CERN-LHCC-2017-009 CMS-TDR-17-001

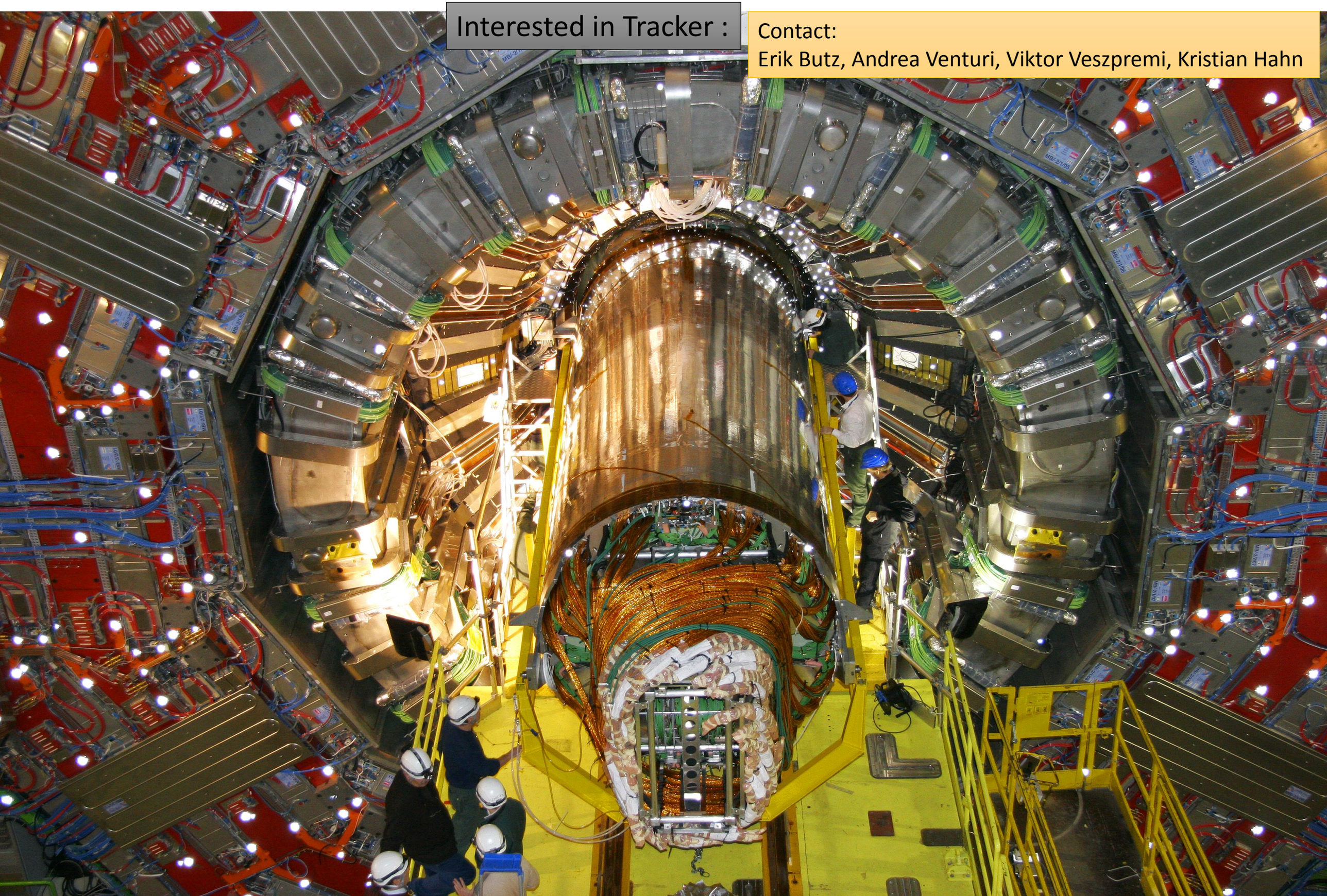
The current Tracker December 2008



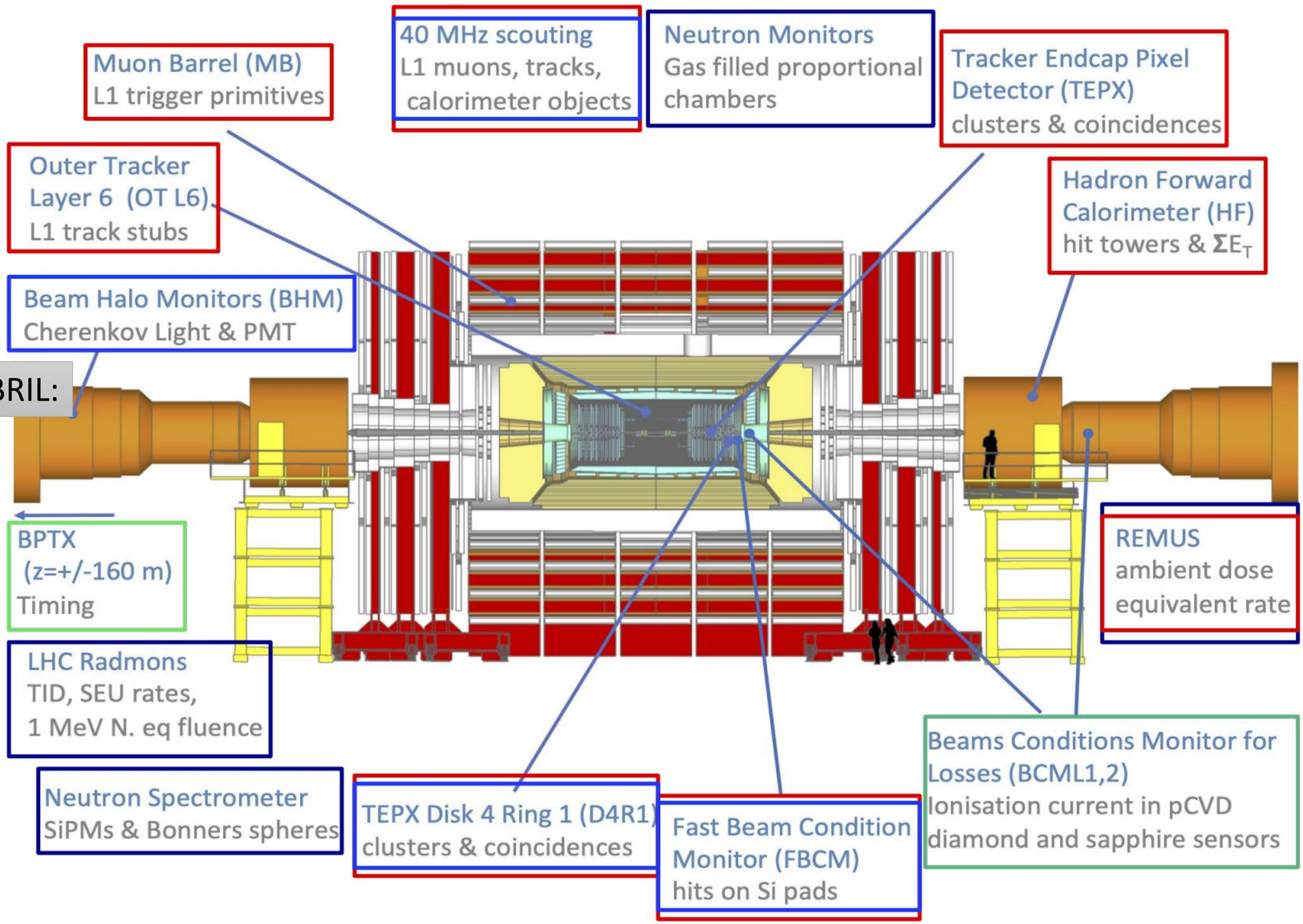
Insertion of the Tracker into the Heart of CMS

Interested in Tracker :

Contact:
Erik Butz, Andrea Venturi, Viktor Veszpremi, Kristian Hahn



Beam Radiation Instrumentation Luminosity - **BRIL**



Interested in BRIL:

Contact:
D. Dabrowski,
A. Auzinger
D. Stickland,
G. Pasztor

Wonderful opportunity to work on special, important but small detectors, where individuals can get significant visibility

Interested in L1 Trigger :

Contact:
Alexander Zabi, Michail Bachtis

Interested in HLT :

Contact:
Stephanie Beauceron, Thiago Tomei

Last but not least

L1 Trigger &
High Level Trigger (HLT)

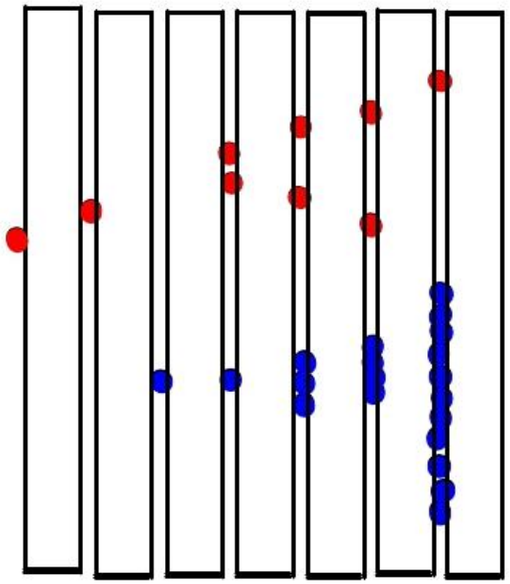
Select the good stuff, as you simply cannot readout and store all events

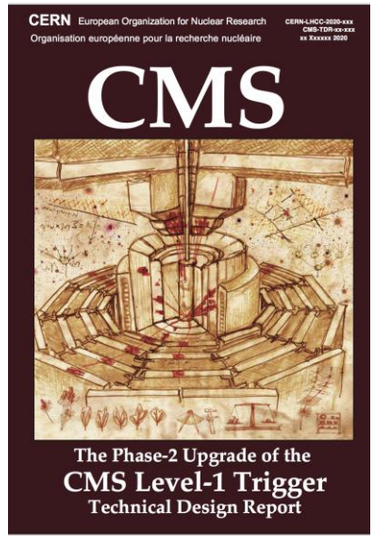
L1 Trigger is becoming even more intelligent

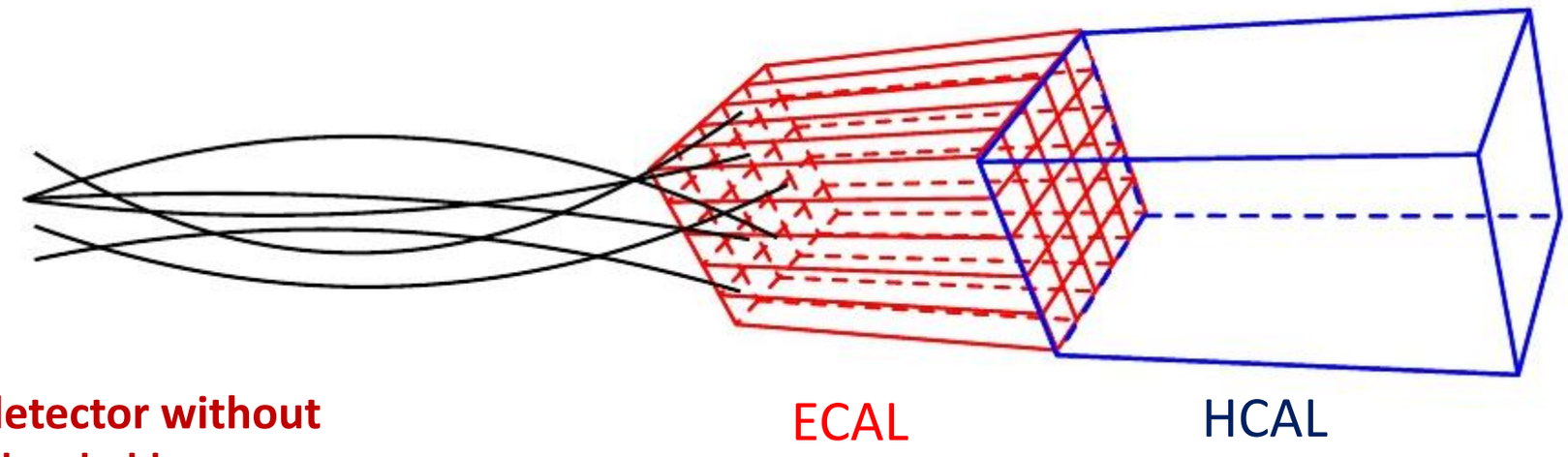
- Increased data & processing
  - ≥ 50 Tbps input; 40MHZ;
    12.5 μs latency, accept rate 750 kHz
  - Barrel Calorimeter: 25x resolution improvement
  - Tracking information: **new** objects available
  - Endcap Calorimeter: 3D High Granularity

➔ **Particle Flow @ L1**

➔ **Machine Learning**

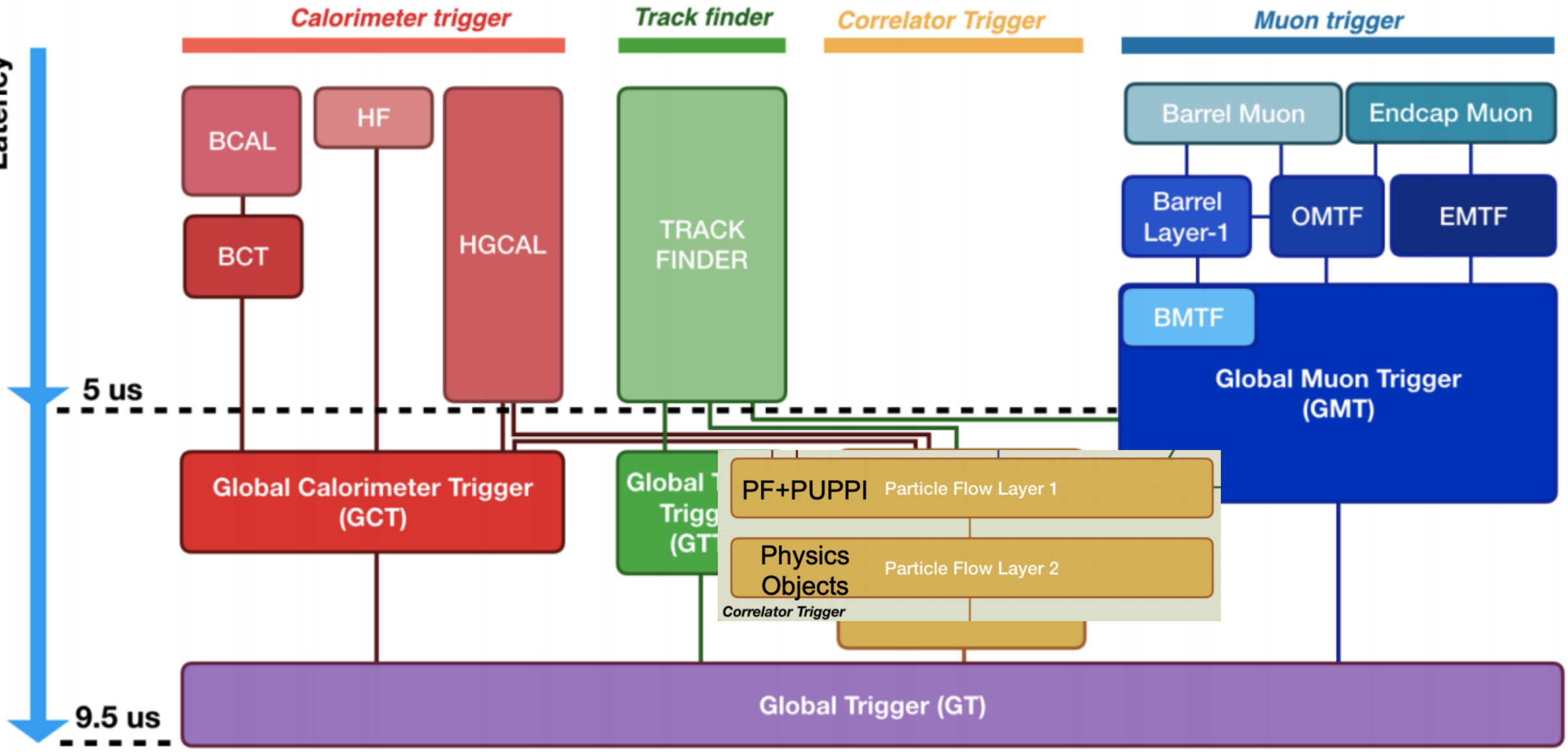






No need to improve resolution of detector without improving resolution at trigger level ~ thresholds

Contact:
Alexander Zabi, Michail Bachtis

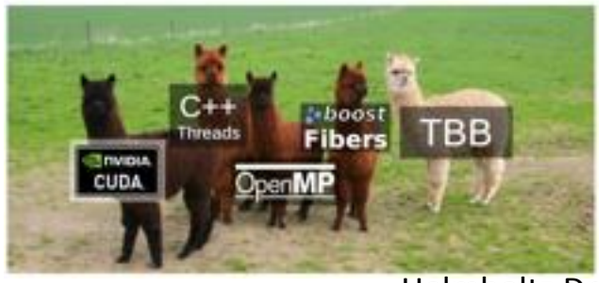


In Phase2 CMS Trigger will be using algorithms much closer to offline:

- PUPPI for PU removal (extremely needed with PU 140-200)
- Capability to run complex algorithms
  - Written in C++ and deployed on FPGA via **High Level Synthesis**
  - Machine learning algorithms trained on standard systems and then again synthesized on FPGA (**hls4ml**, for example)

.. And the High Level Trigger
HLT

- 7.5 kHz out of 750kHz,
  - & event complexity increasing ~6x wrt. Run-3



Alpaka

Helmholtz Dresden,
most mature as of now

- Profit from **heterogeneous** reconstruction computing to use best hardware available in 2027+
  - **Use high level frameworks to write "technology independent" software**
    - **Alpaka** and **Kokkos** seem good candidates
  - On the long run, we should be able to use **CPUs** (various vendors), **GPUs** (various vendors), **FPGAs**, **TPUs**, …

Accelerator Back-ends

Accelerator Back-end	Lib/API	Devices	Execution strategy grid-blocks	Execution strategy block-threads
Serial	n/a	Host CPU (single core)	sequential	sequential (only 1 thread per block)
OpenMP 2.0+ blocks	OpenMP 2.0+	Host CPU (multi core)	parallel (preemptive multitasking)	sequential (only 1 thread per block)
OpenMP 2.0+ threads	OpenMP 2.0+	Host CPU (multi core)	sequential	parallel (preemptive multitasking)
OpenMP 4.0+ (CPU)	OpenMP 4.0+	Host CPU (multi core)	parallel (undefined)	parallel (preemptive multitasking)
std::thread	std::thread	Host CPU (multi core)	sequential	parallel (preemptive multitasking)
Boost.Fiber	boost::fibers::fiber	Host CPU (single core)	sequential	parallel (cooperative multitasking)
TBB	TBB 2.2+	Host CPU (multi core)	parallel (preemptive multitasking)	sequential (only 1 thread per block)
CUDA	CUDA 9.0-10.2	NVIDIA GPUs	parallel (undefined)	parallel (lock-step within warps)
HIP(nvcc)	HIP 3.3+	NVIDIA GPUs SM 3.0+	parallel (undefined)	parallel (lock-step within warps)

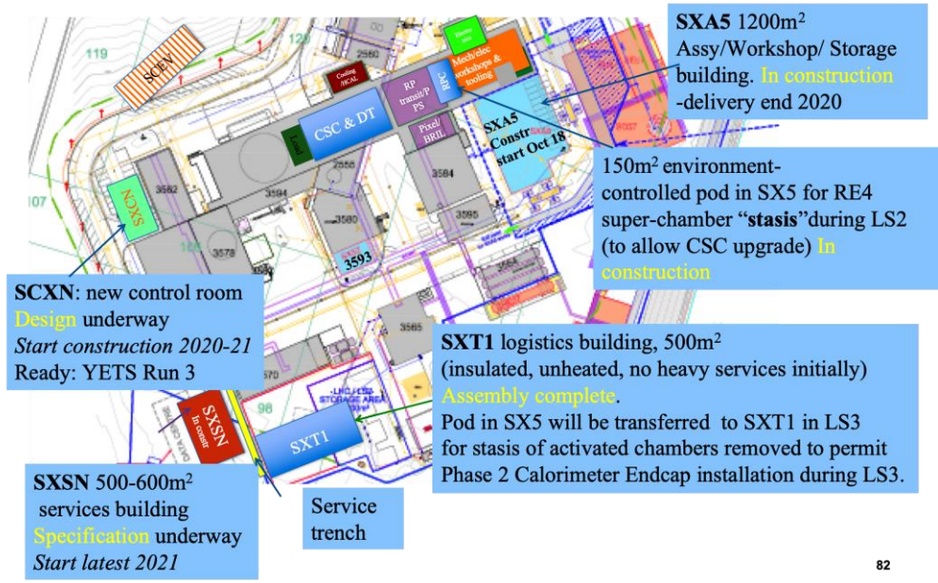
Contact:
Stephanie Beauceron, Thiago Tomei

today's software performance is only a factor 1.6 - 4away

Then are the side-dishes that fewer people talks about

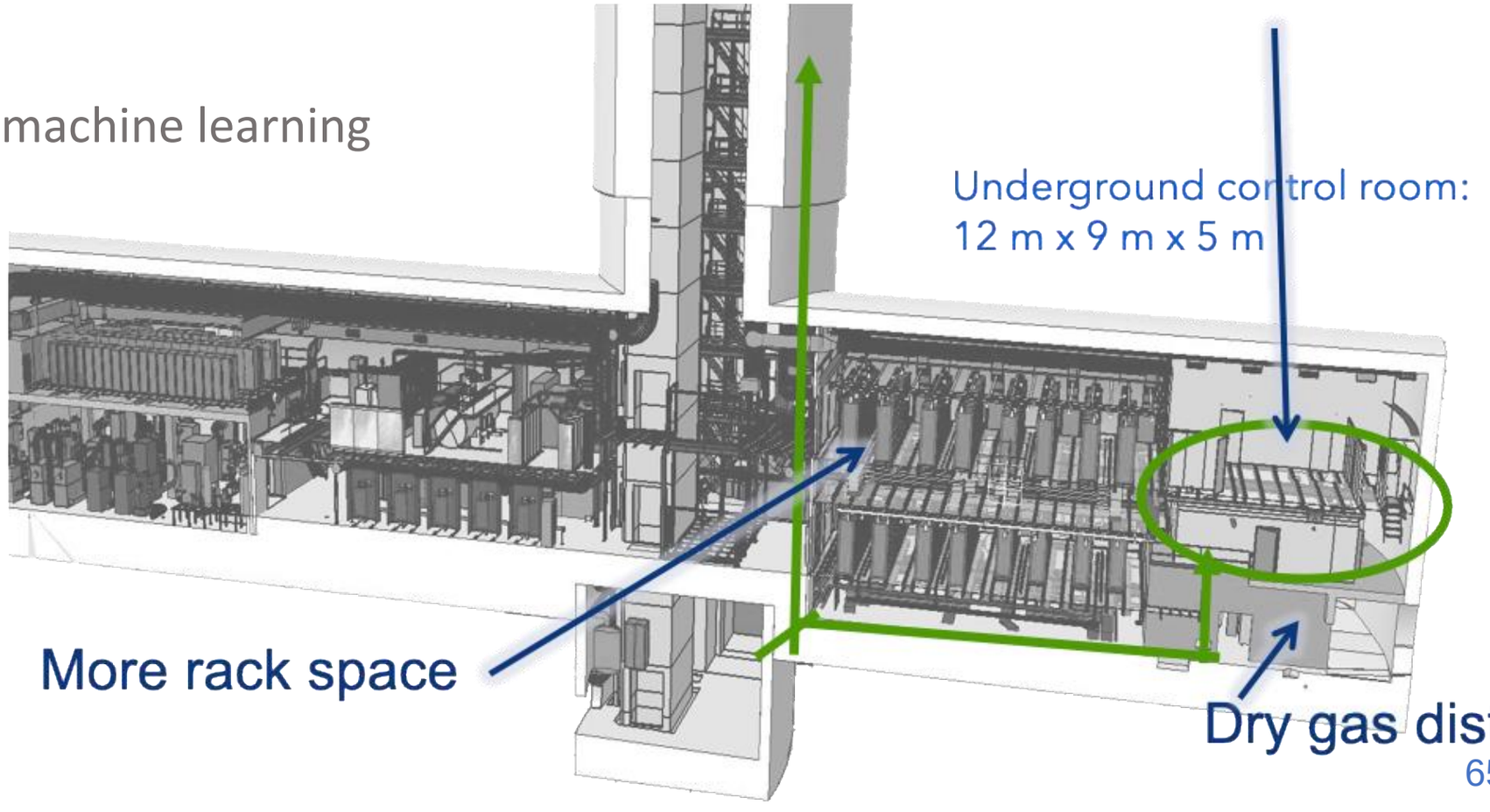
- Buildings, CO_2-cooling, gas distribution, power, safety, databases, service installation (power, fibers, pipes), systems to commissioning (quite cold), Data Acquisition, firmware, control systems, opening and closing 600t-objects, alignment
- Custom chips, custom electronics boards, custom optical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

CMS P5 surface infrastructure plan - all



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