Tracking

Kristian Hahn

Our Project Managers

Gabriella Pugliese

Deputy Hafeez Hoorani

&

Erik Butz

Deputies: Kristian Hahn, Viktor Veszpremi

https://twiki.cern.ch/twiki/bin/view/CMS/MuonWikiHome

https://twiki.cern.ch/twiki/bin/view/CMS/DrupalTracker

Tracking/Muon in CMS

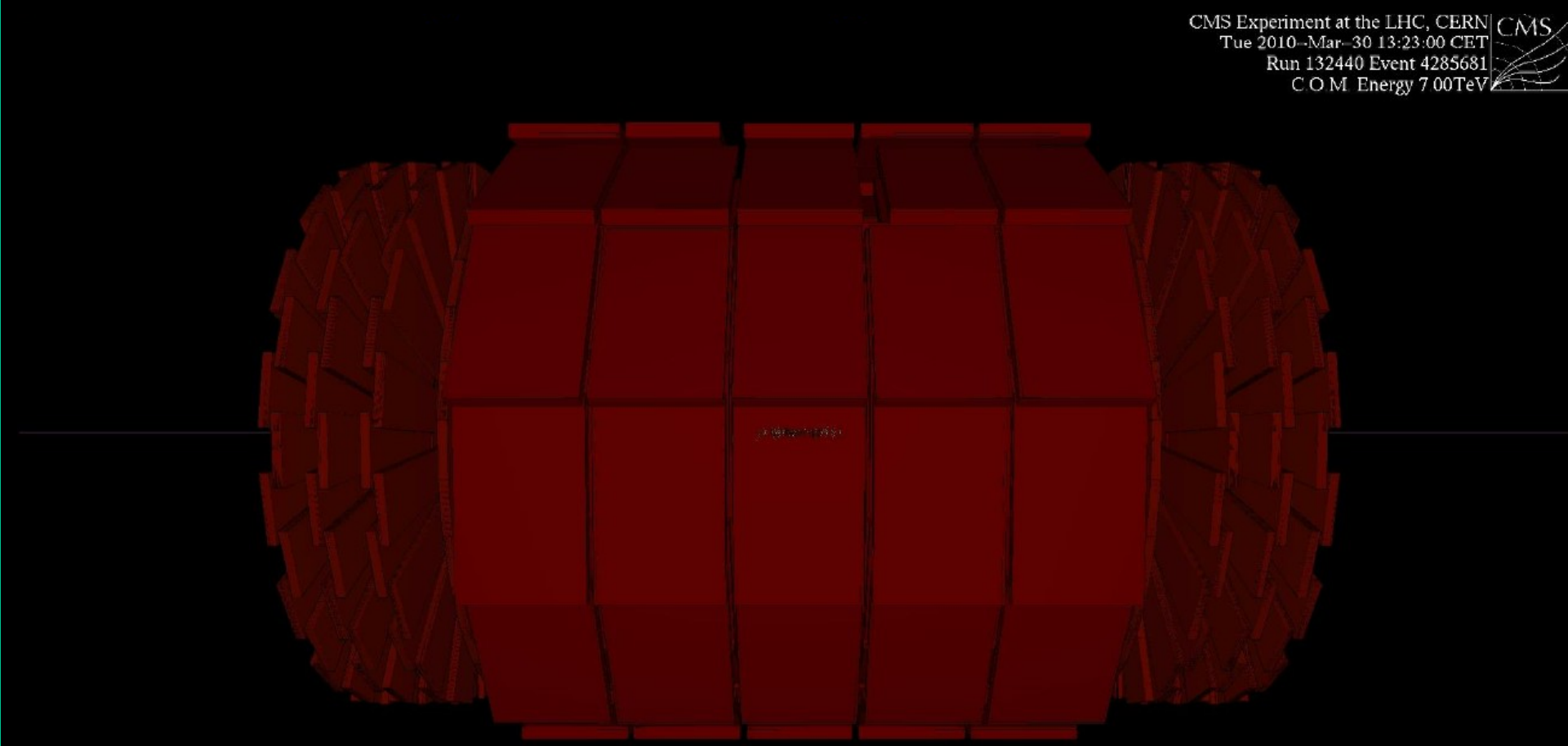
- Grand purpose
- Fundamental operation of our detectors
- Tracking and muon detectors: what, where
- Readout, reconstruction, and other challenges
- People and Opportunities
- Segue to upgrades of tracker and muon

What do we want/need from tracking to do the physics we want to do?

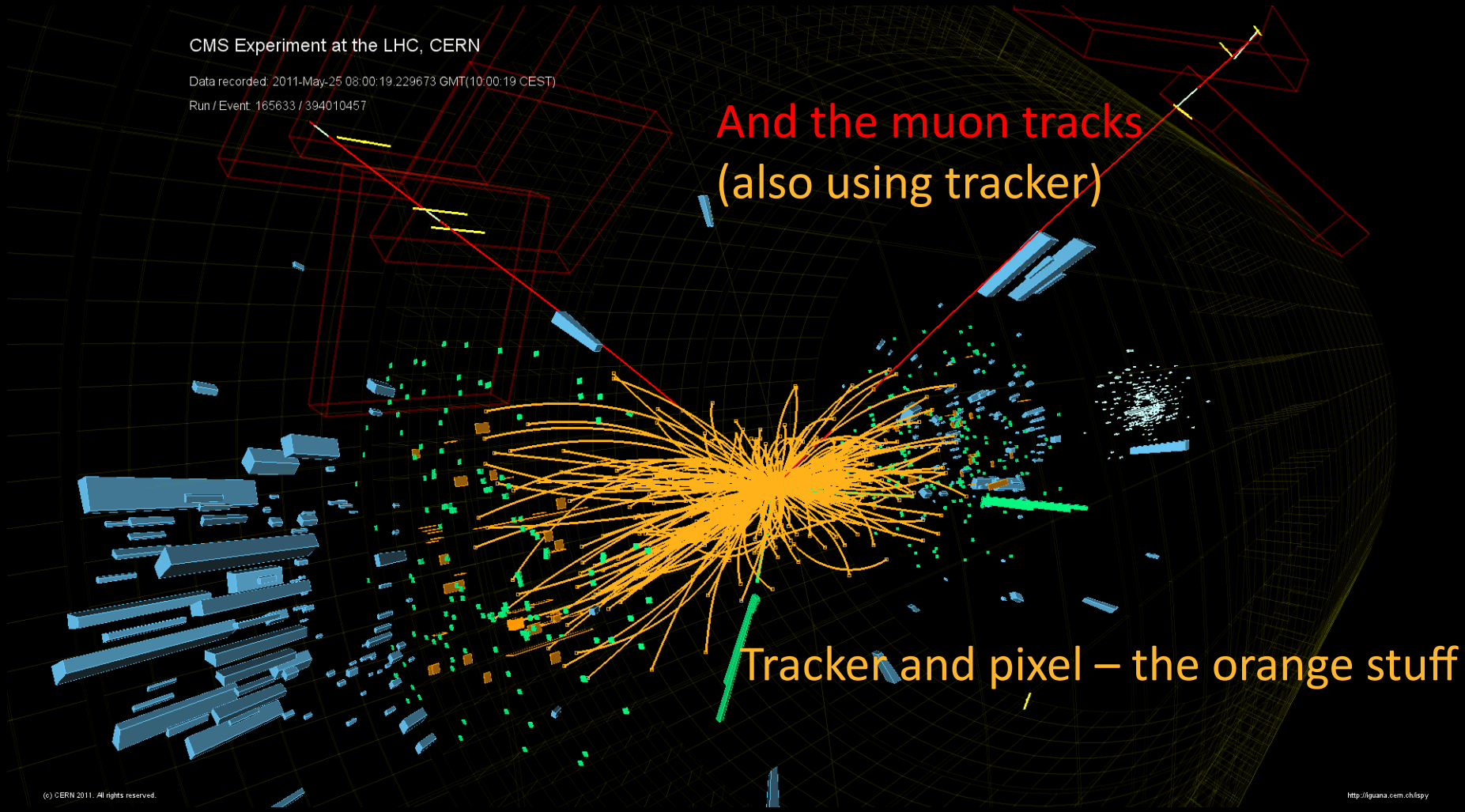
GRAND PURPOSE

A pp interaction at CMS

This is where your data is coming from!

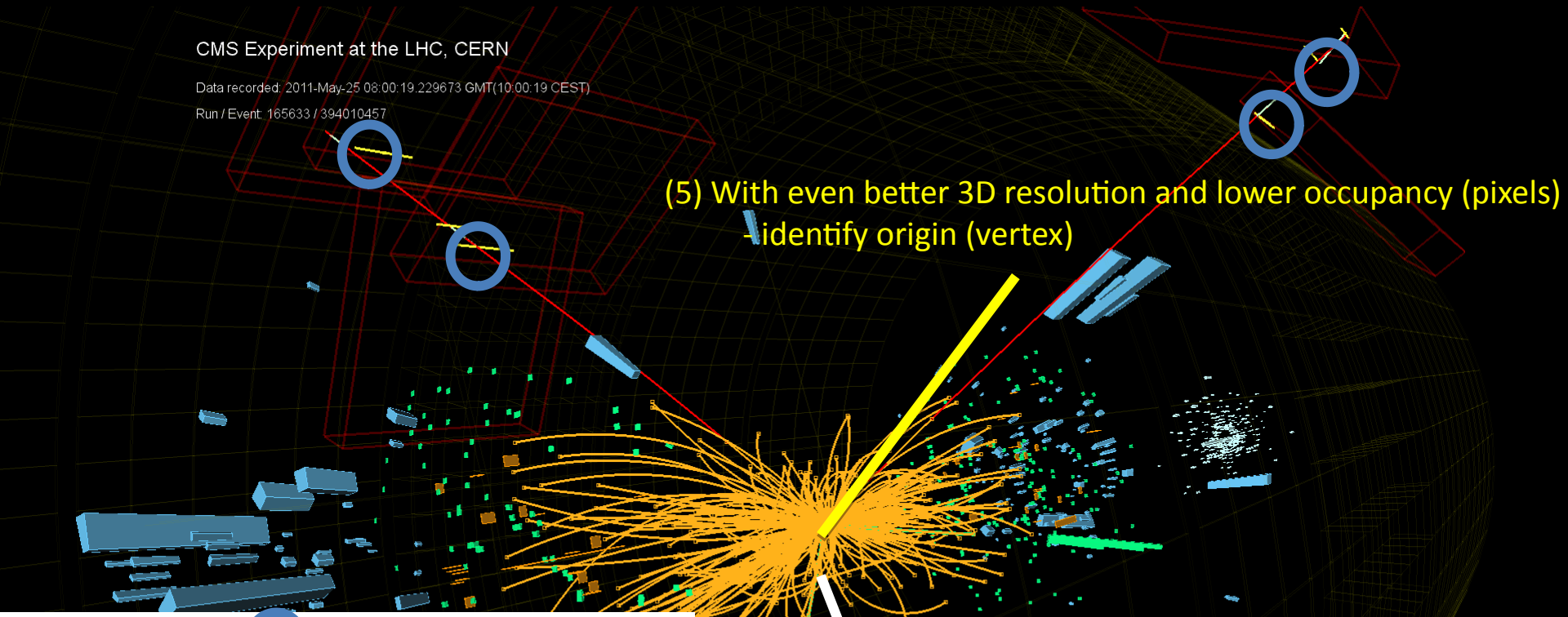


Tracking component of the events



What are the ingredients to get THAT???

What is the task of these detectors?

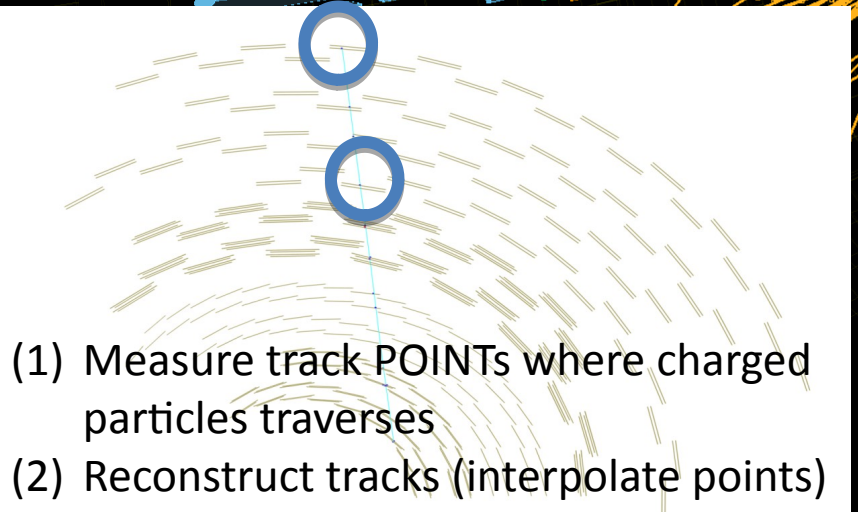


(5) With even better 3D resolution and lower occupancy (pixels)
- identify origin (vertex)

(2) Magnetic field bends the tracks
→ Momentum

(3) With good resolution and low occupancy
– isolate tracks in this mess

http://iguana.cern.ch/ispy

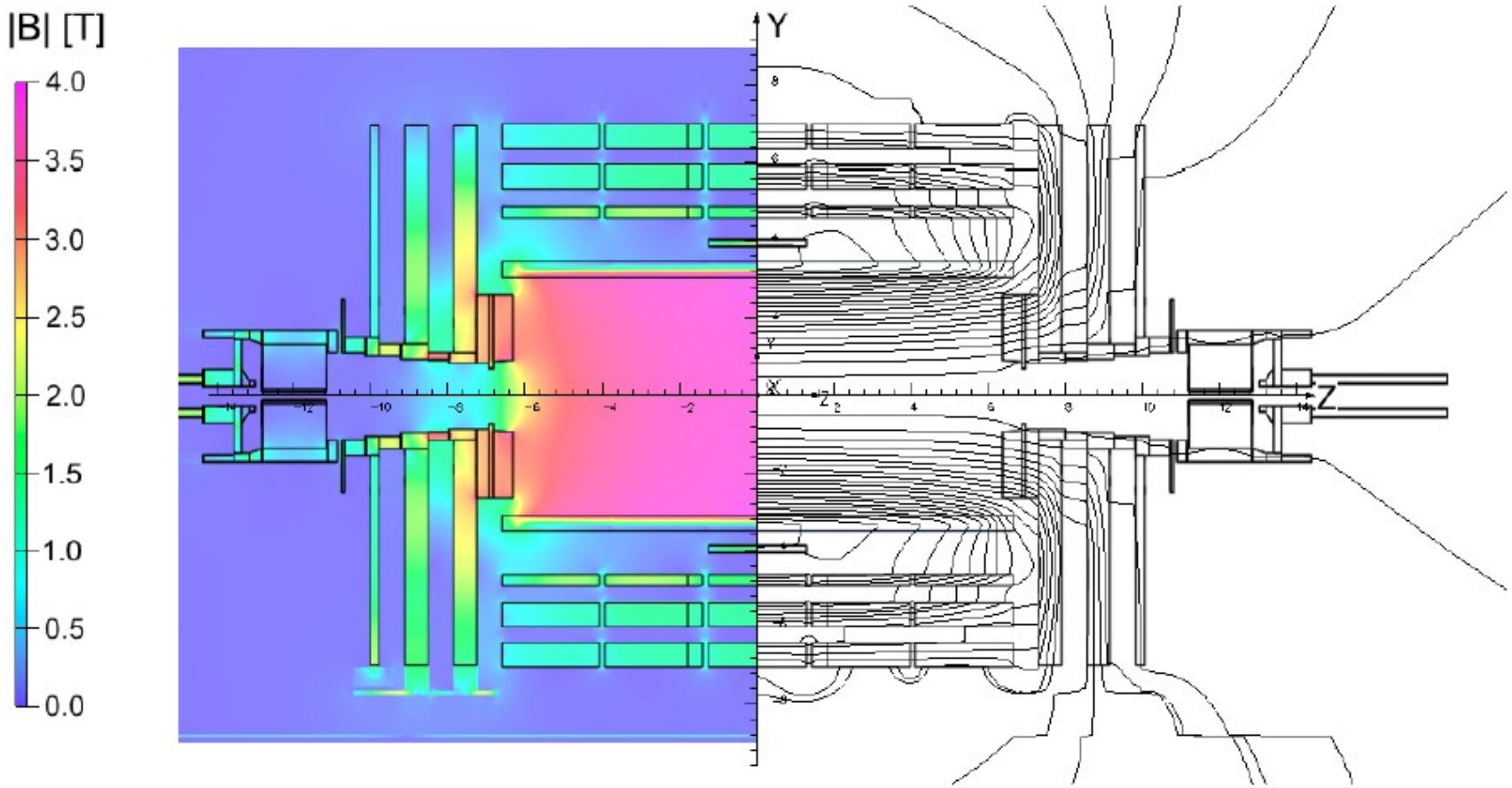


(1) Measure track POINTs where charged particles traverses
(2) Reconstruct tracks (interpolate points)

(4) In conjunction with calorimeter identify particle (more later)

CMS magnetic field

- 3.8T coil is outside of the hadronic calorimeter
  - Silicon Tracking detectors are inside the coil
  - Muon detectors are outside the coil



CMS outer detectors "thickness" in λ

- Pions, kaons, other hadronic particles stop in calorimeter and magnet except fraction **exp(-λ/λ$_o$)**, so **>10λ$_o$** is a very good hadron stopper

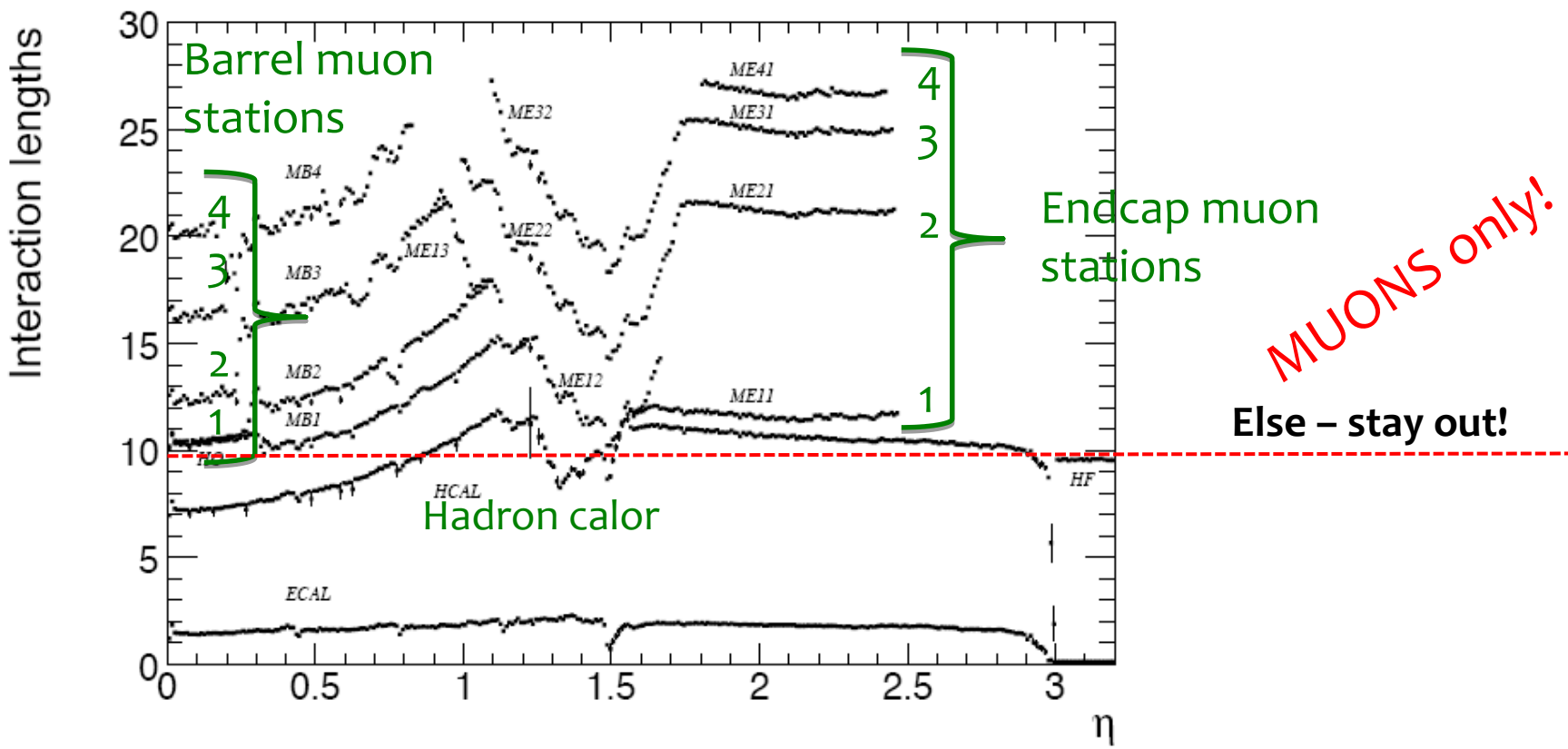


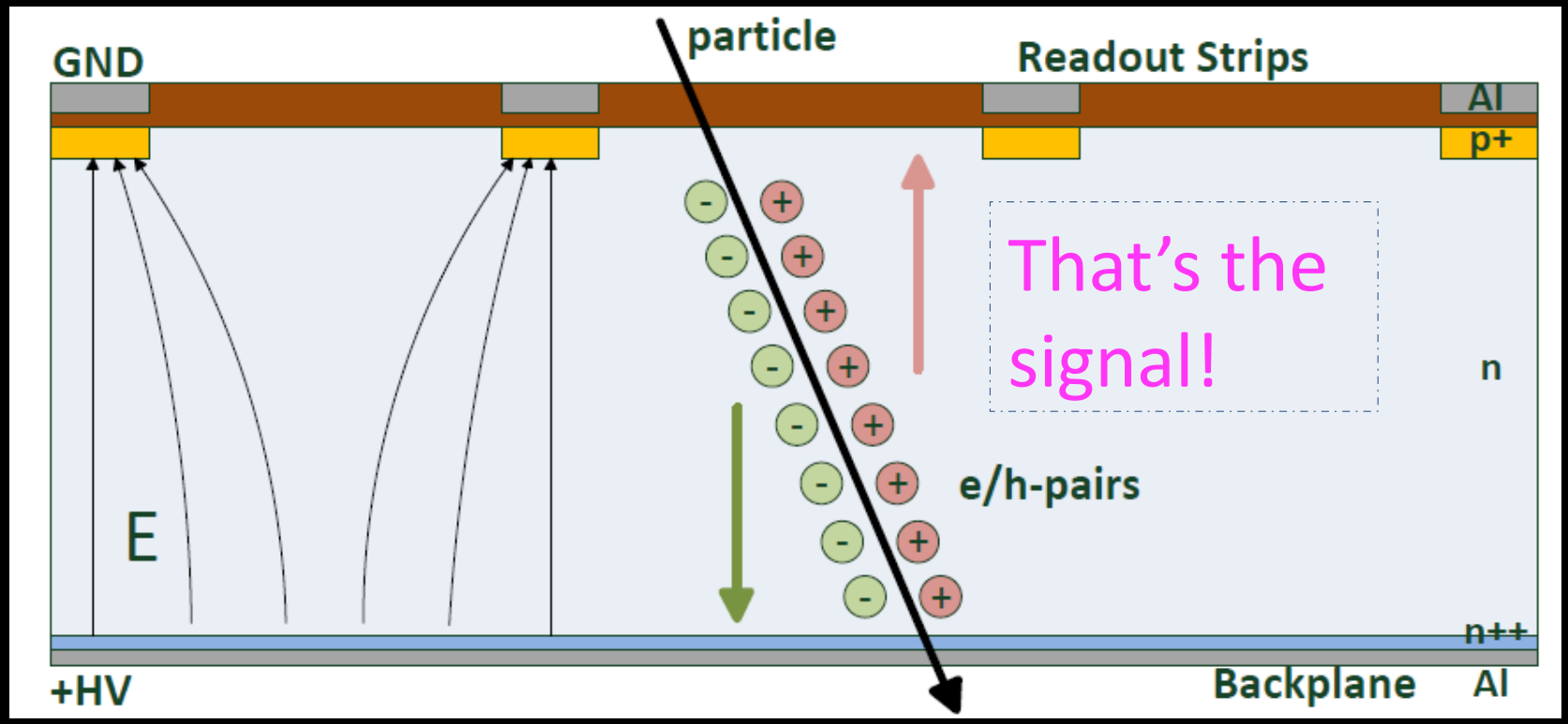
Figure 1.4: Material thickness in interaction lengths after the ECAL, HCAL, and at the depth of each muon station as a function of pseudorapidity. The thickness of the forward calorimeter (HF) remains approximately constant over the range $3 < |\eta| < 5$ (not shown).

The microscopic mechanisms working in CMS tracking detectors

CHARGED PARTICLE DETECTION

Working principle of silicon sensors

- Electron-hole-pairs generated by ionizing particles traversing the silicon are separated by E-field and 'drift' to the electrodes
- Reverse bias to remove intrinsic carriers, leaving only ionization signal



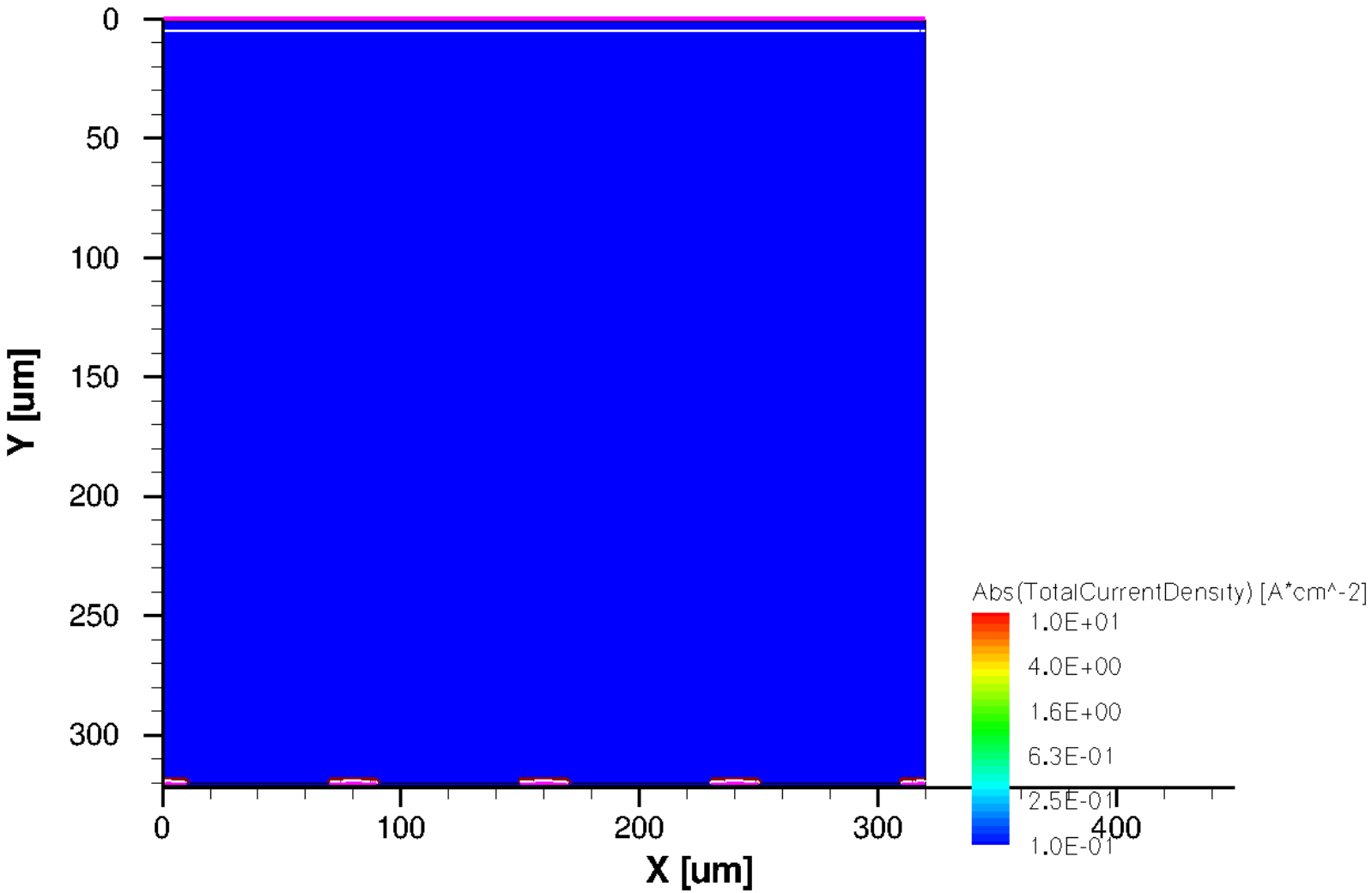
R. Eber, E L ECTRIC F I E LDS AND CHARGE CARRI ER DRI F T IN HIGHLY IRRADIAT ED S I L ICON PART ICL E DE T ECTORS, PhD, IEKP, KIT, 2013

Basically the same for pixels and strips

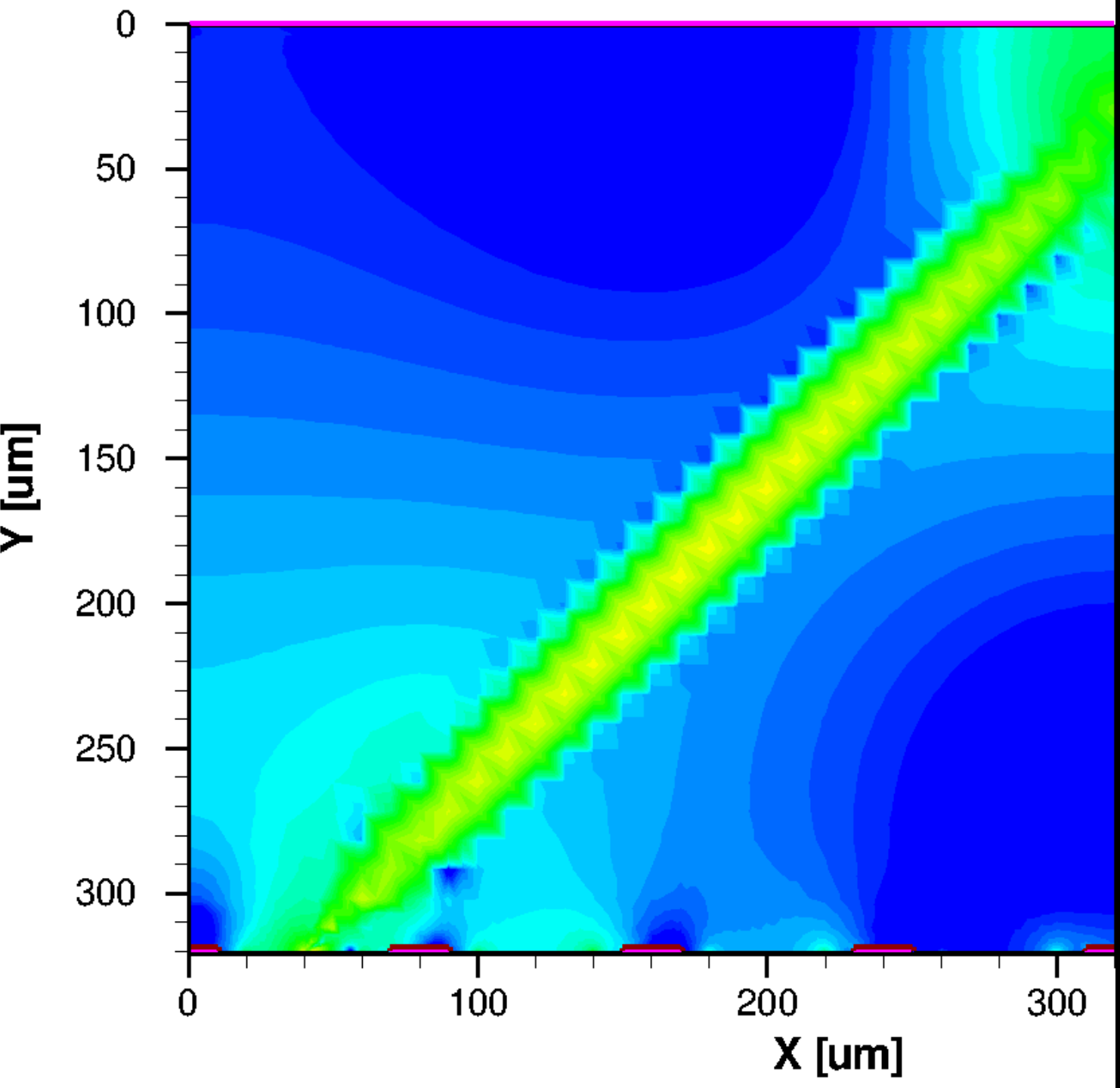
- CMS Strips 'collect' holes
- CMS Pixel 'collect' electrons

Simulated Current Density

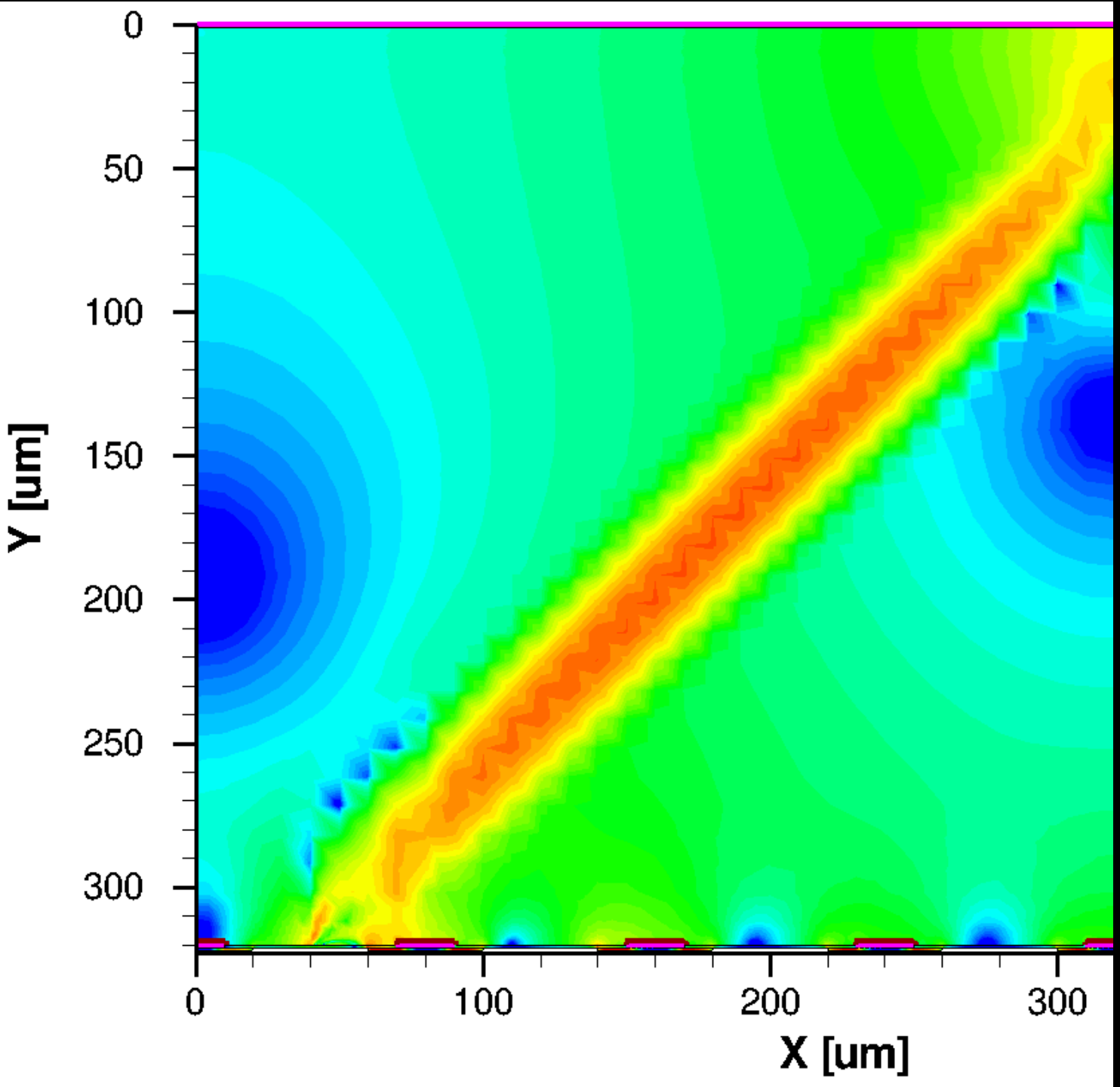
Ionizing particle with 45° angle t=0 s



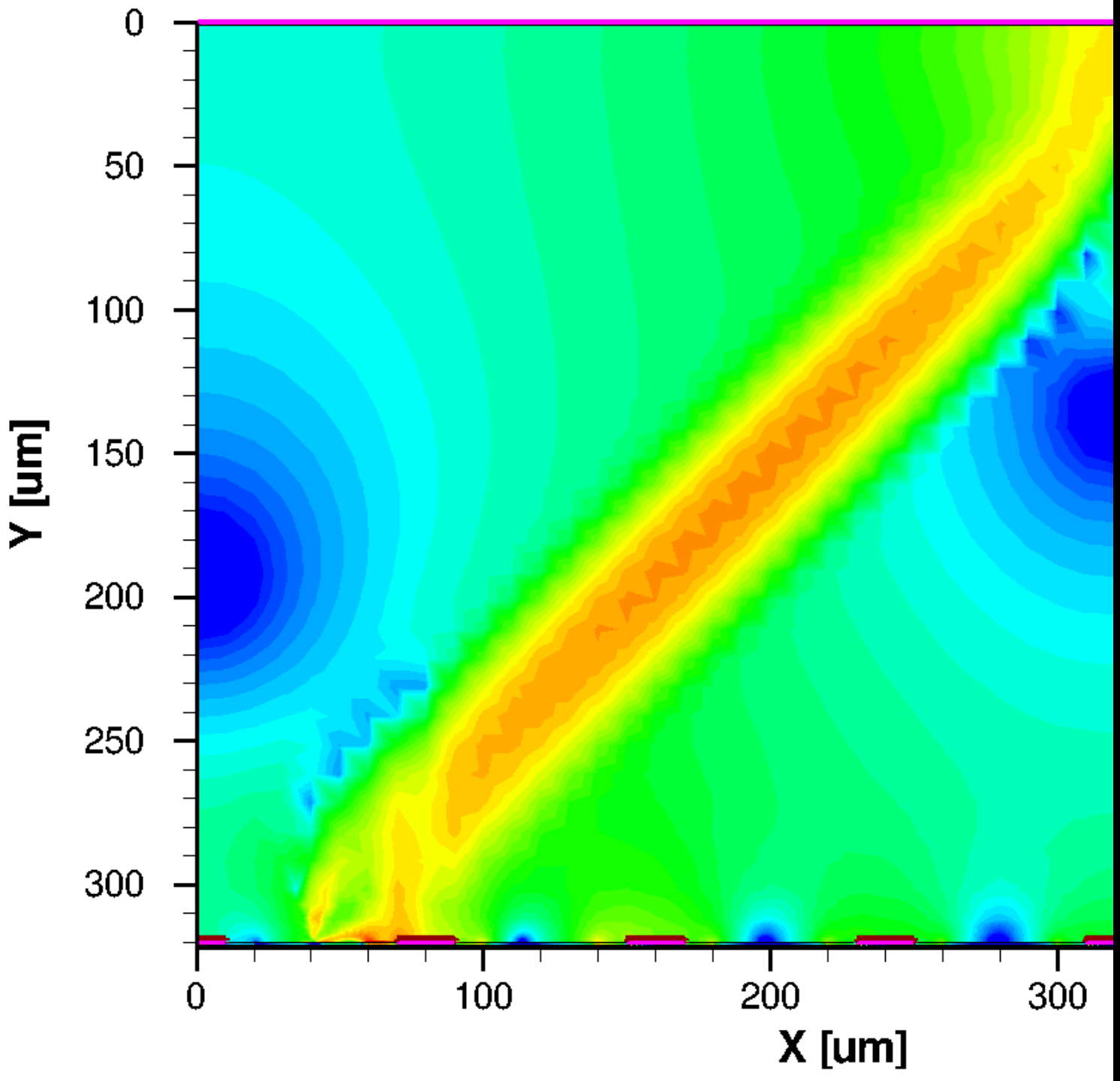
Simulation Thomas.Eichhorn@kit.edu



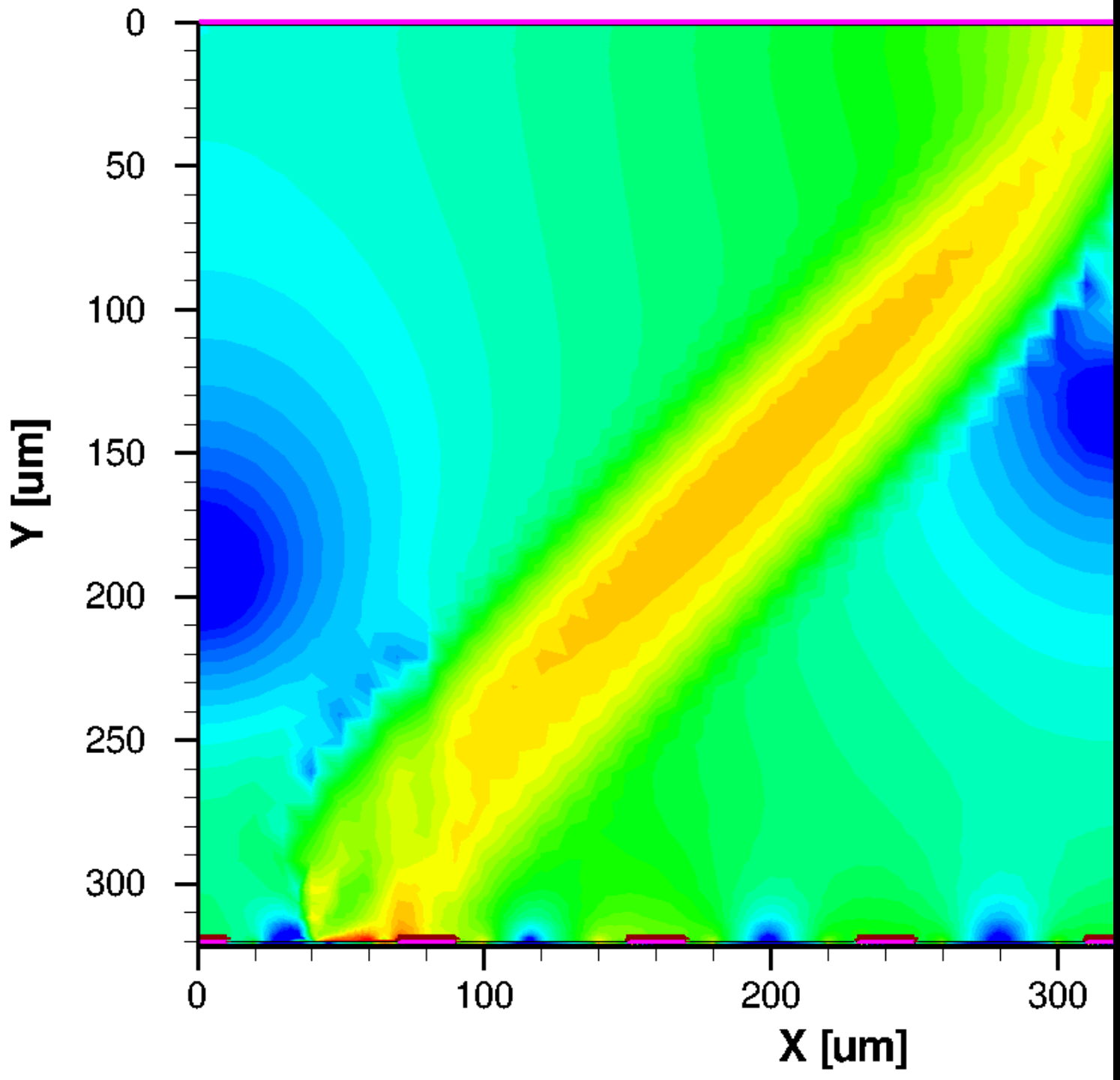
t=1 ns



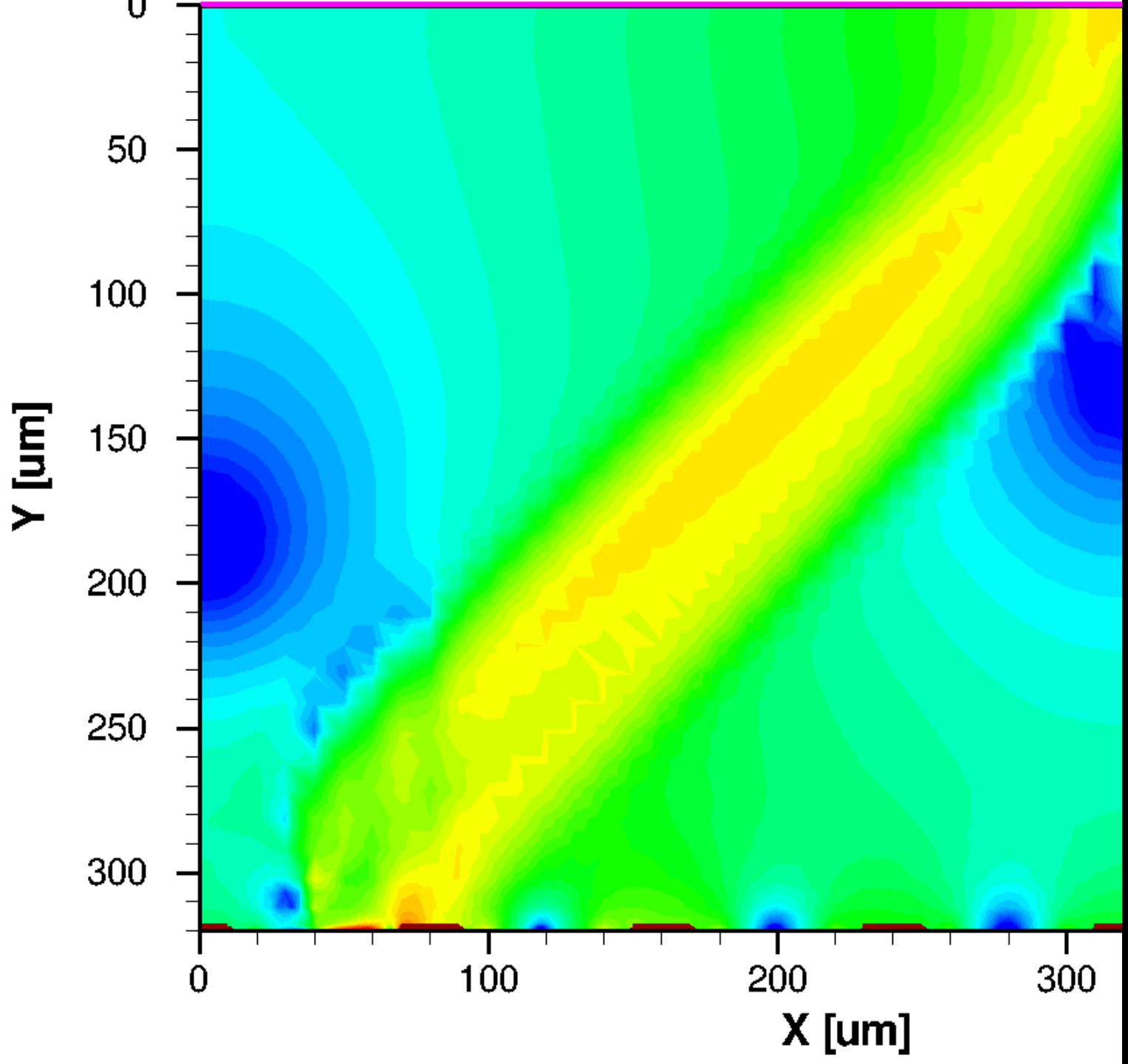
t=1,1 ns



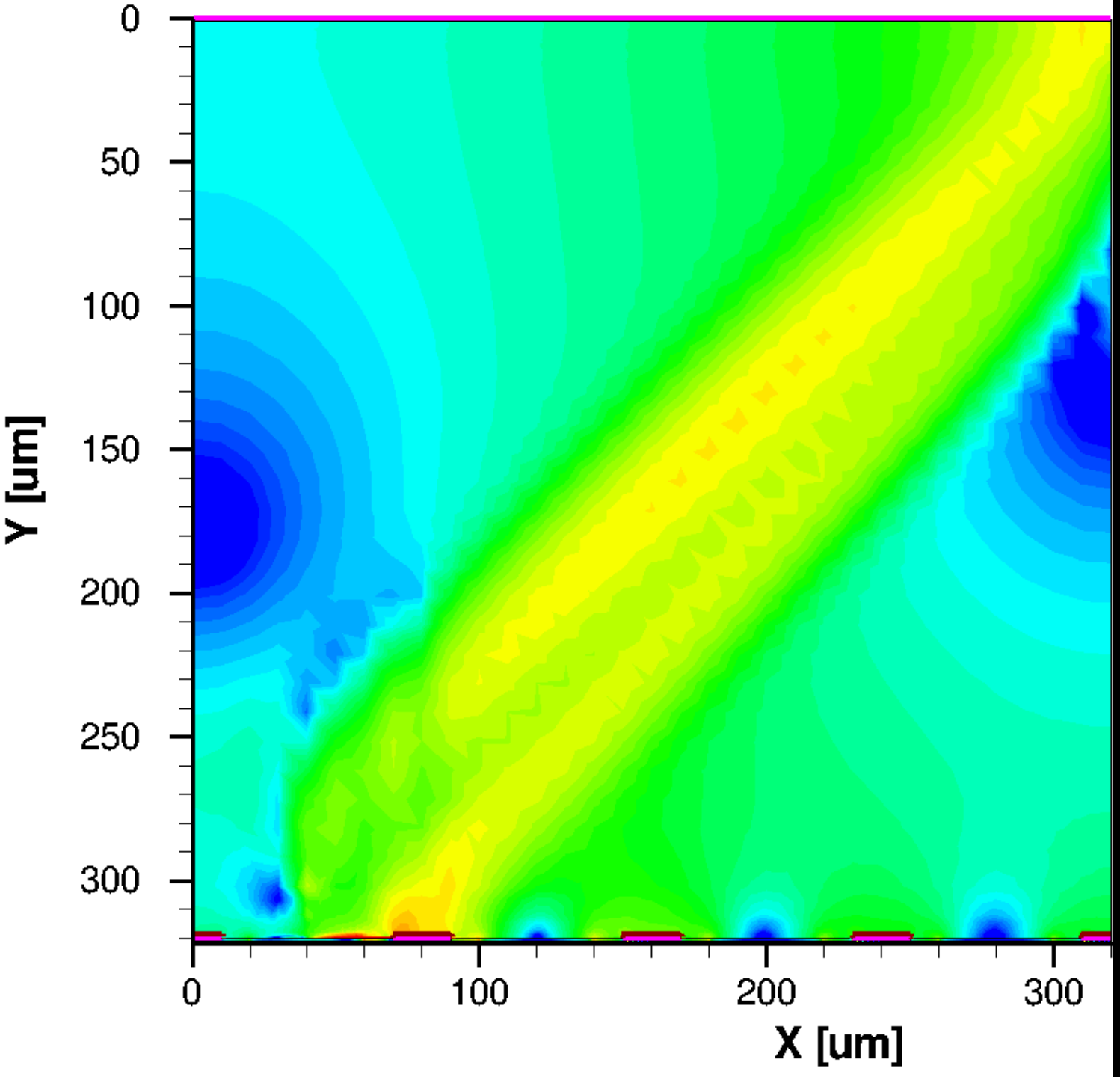
t=1,2 ns



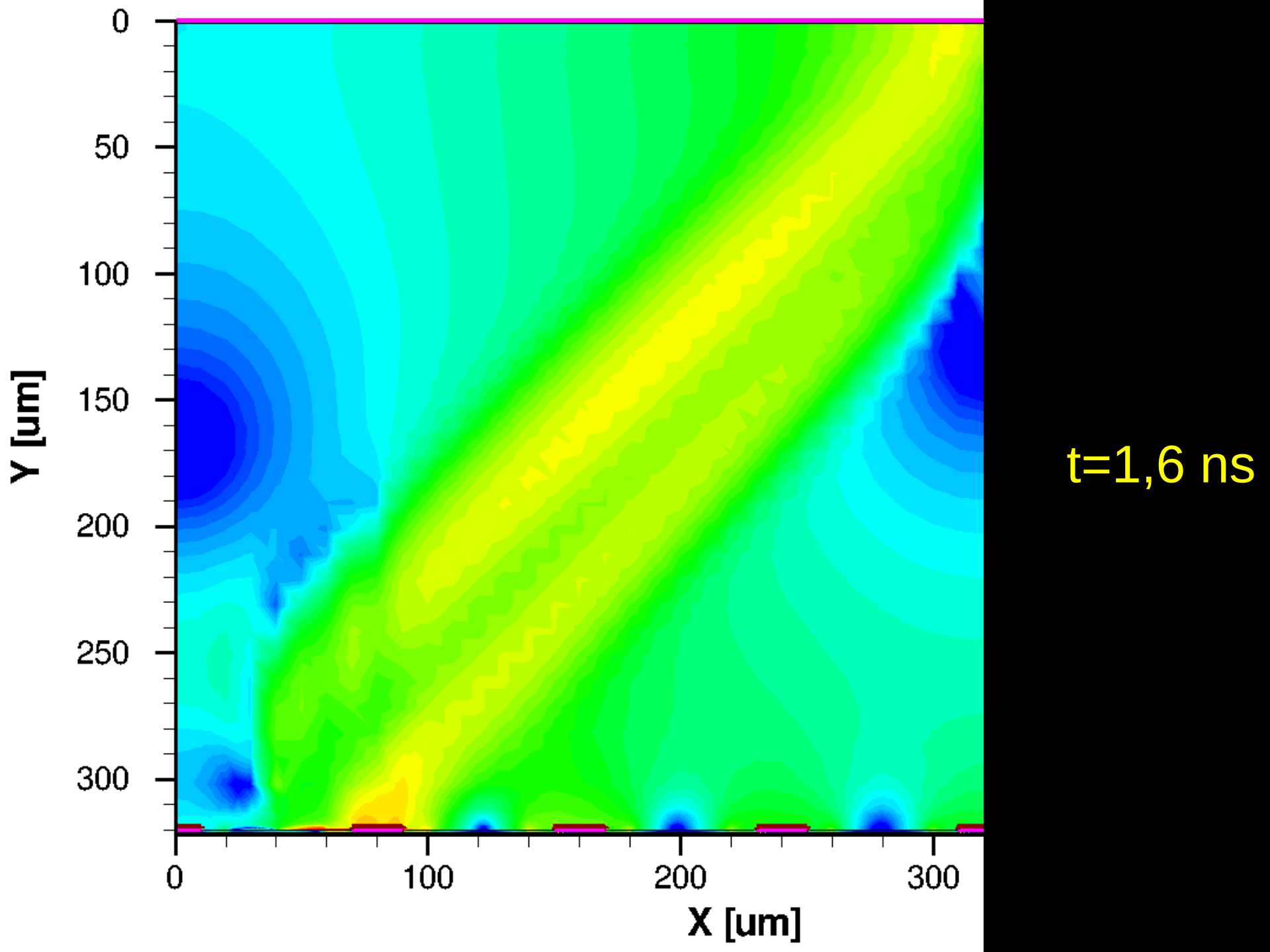
t=1,3 ns

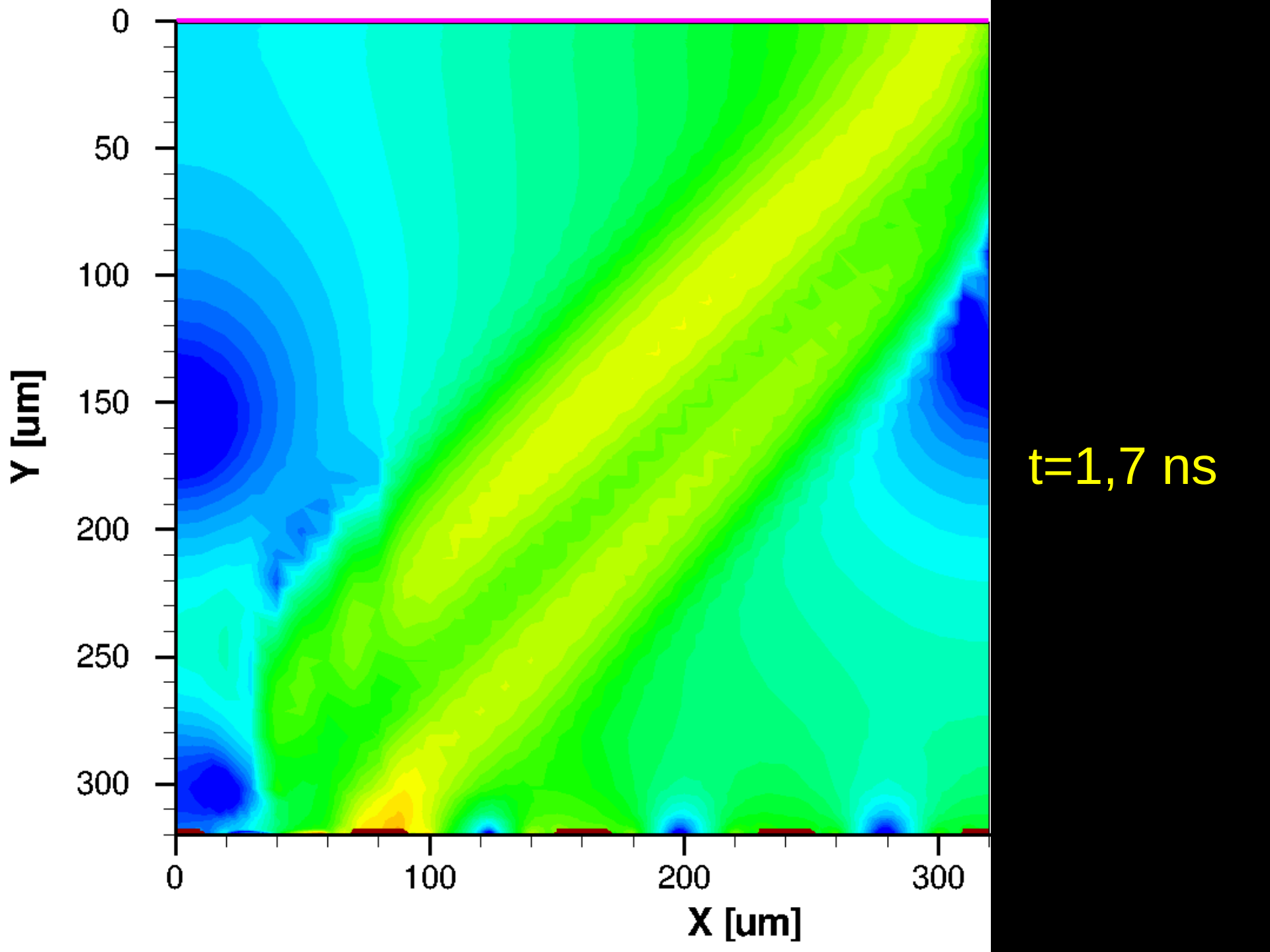


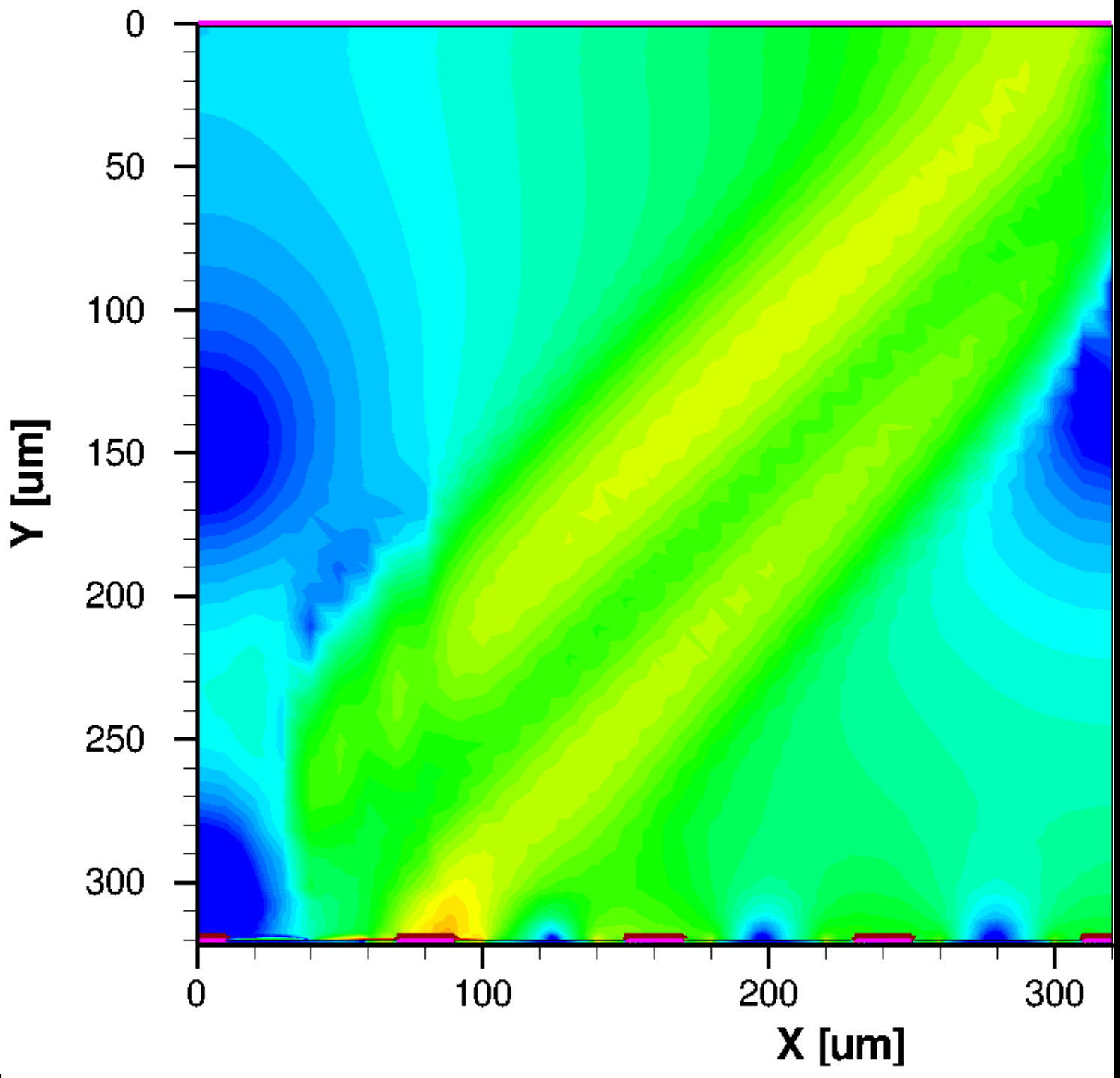
t=1,4 ns



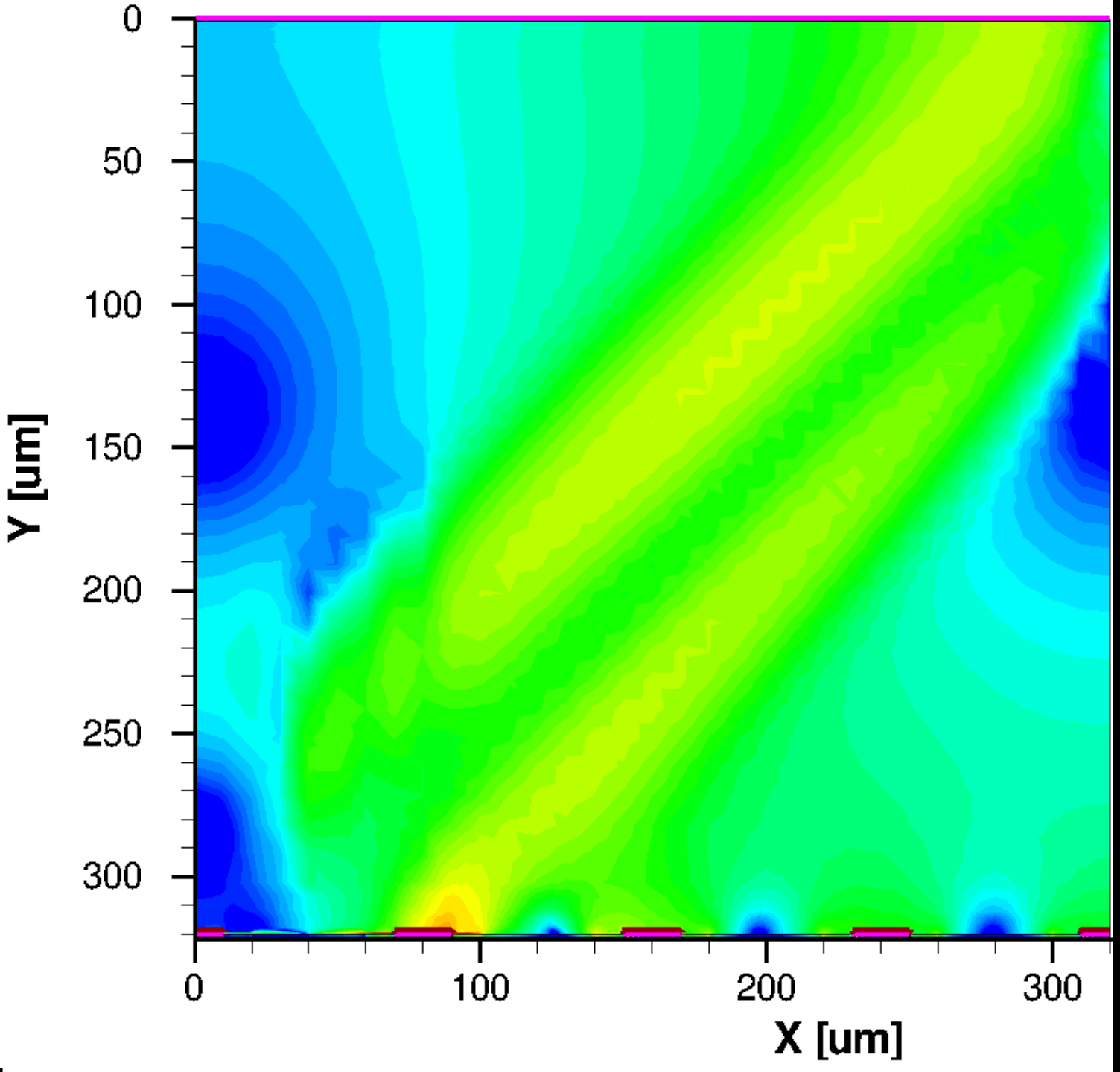
t=1,5 ns


0
50
100
150
200
250
300
Y [um]
0
100
200
300
X [um]
t=1,6 ns

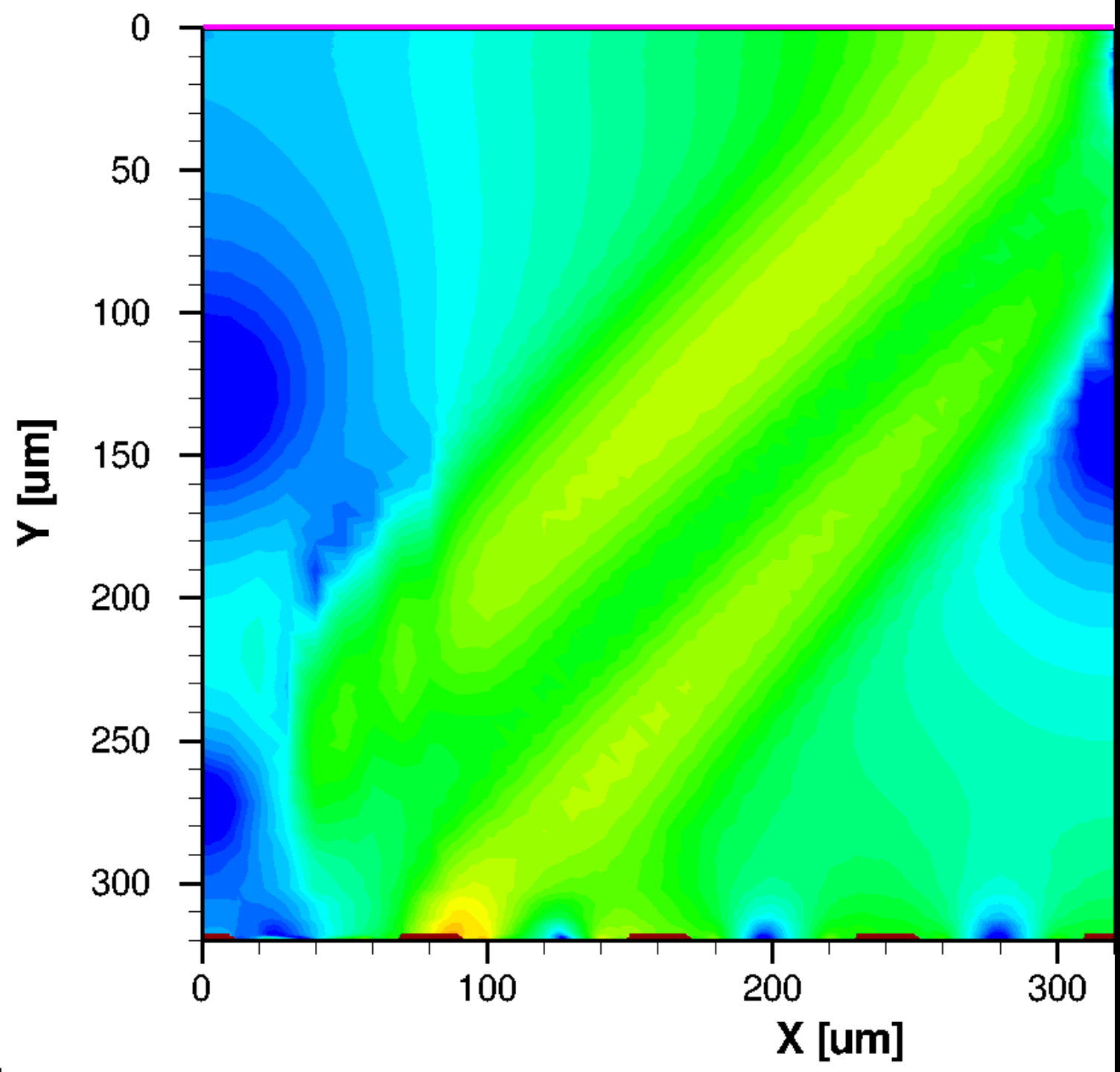

0
50
100
150
200
250
300
Y [um]
0
100
200
300
X [um]
t=1,7 ns



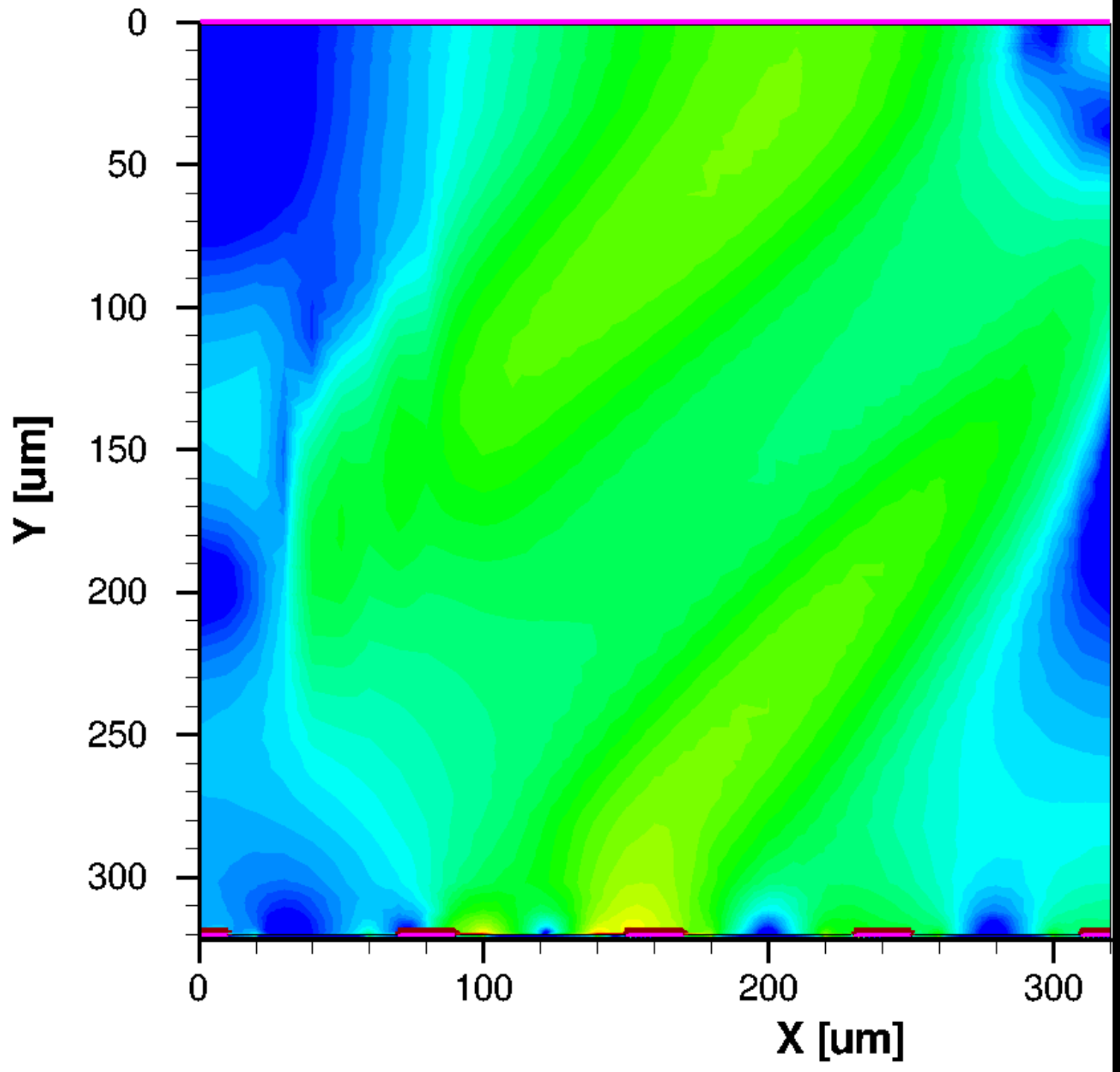
t=1,8 ns



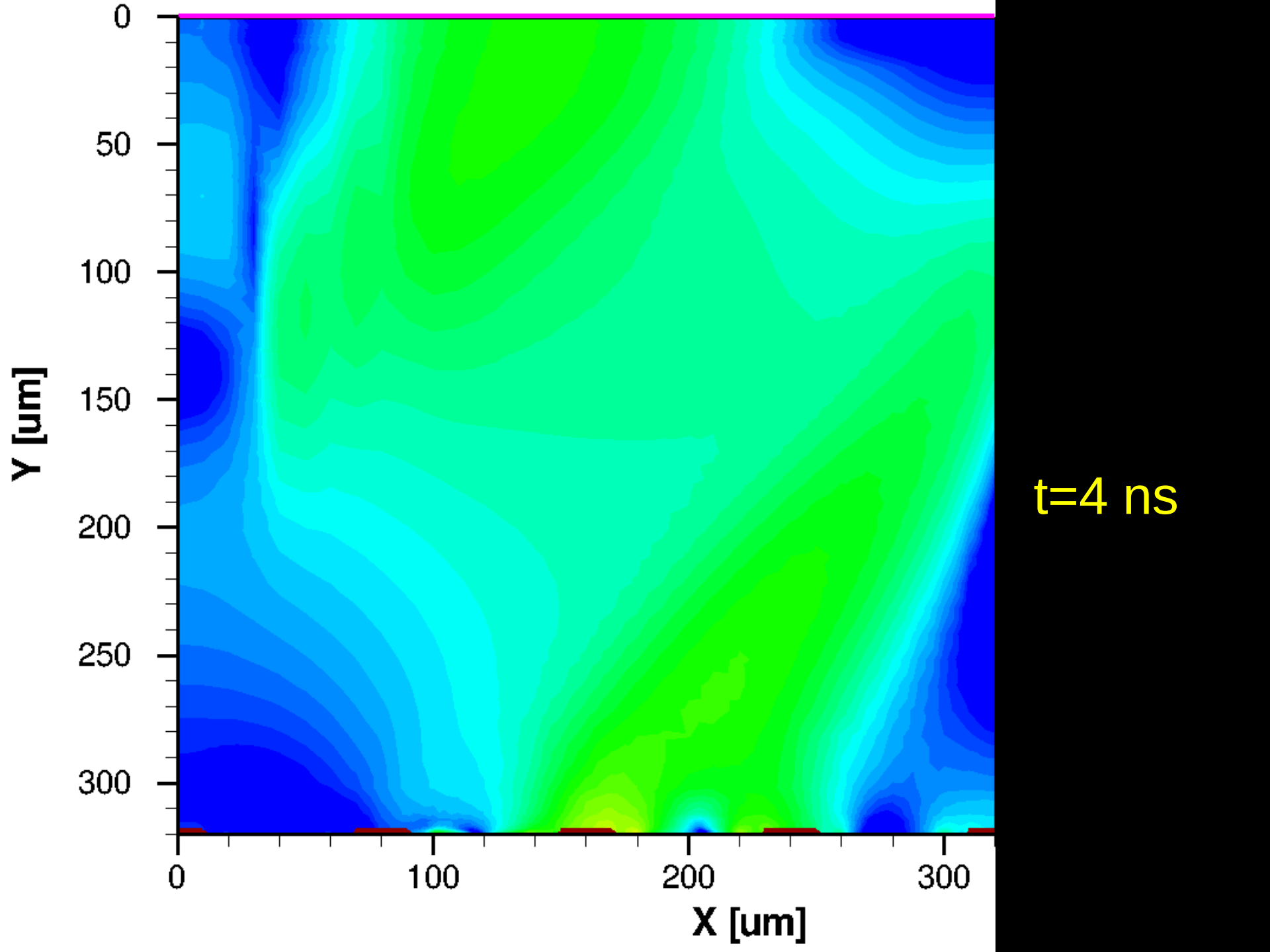
t=1,9 ns

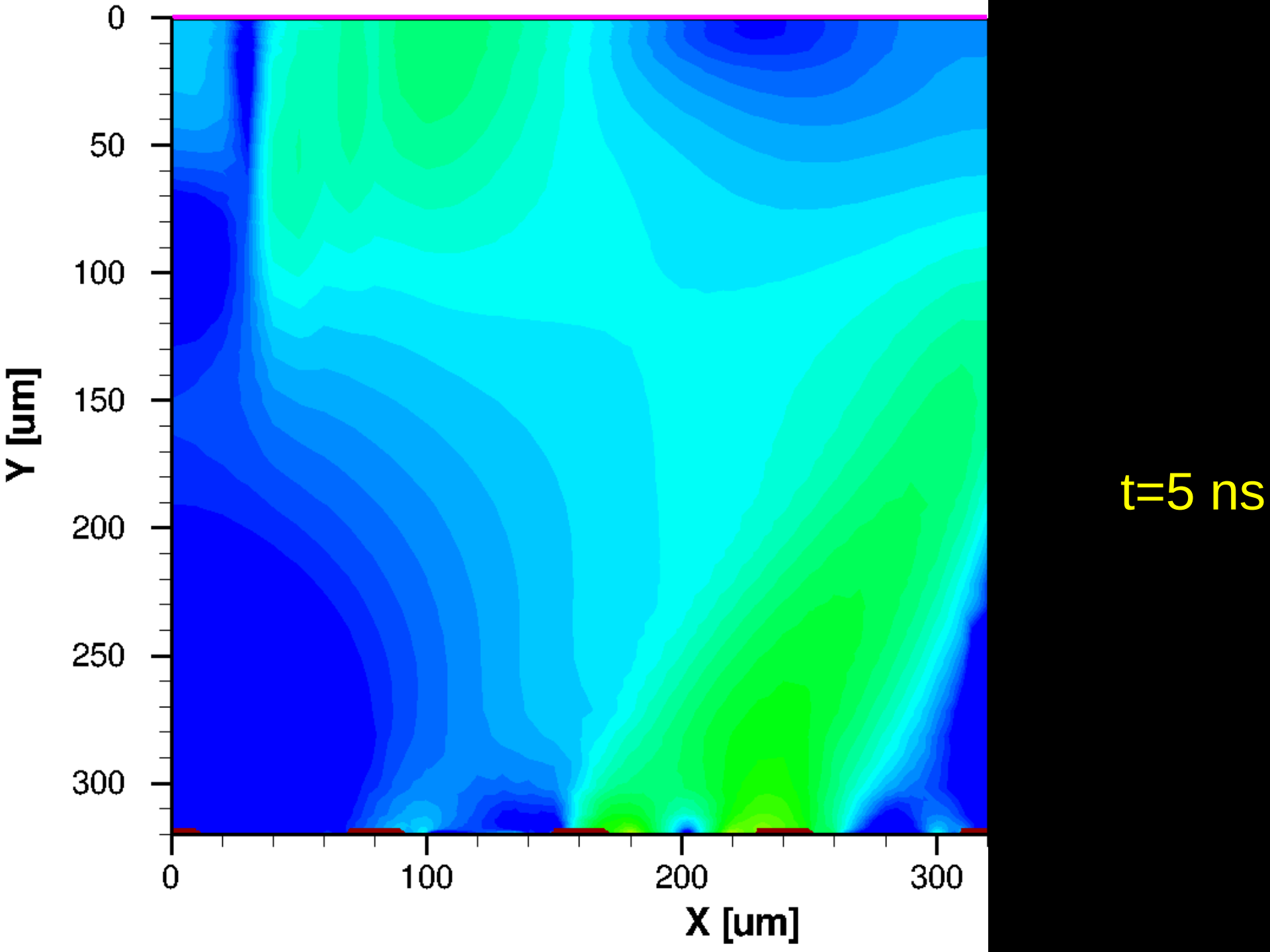


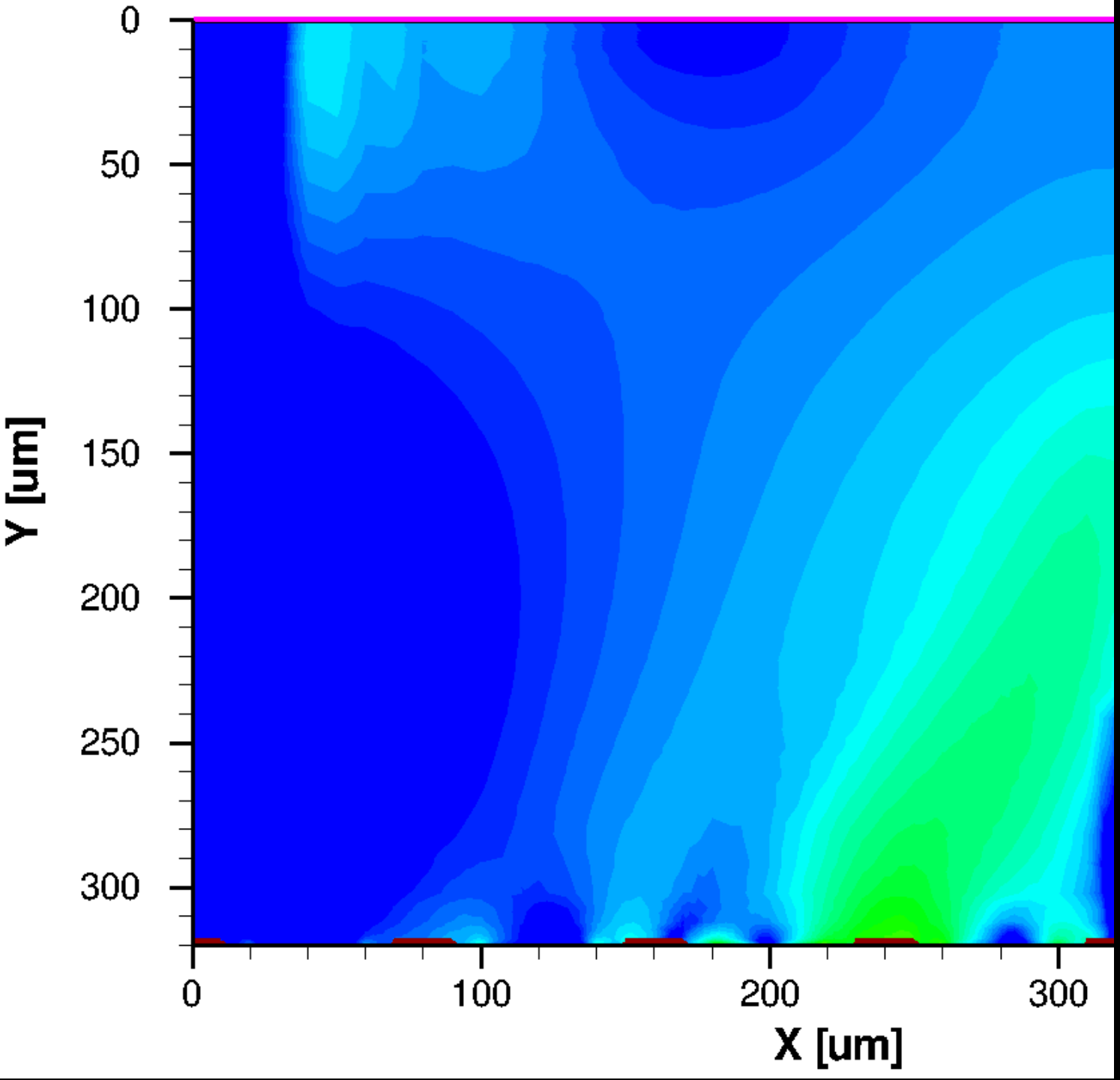
t=2 ns



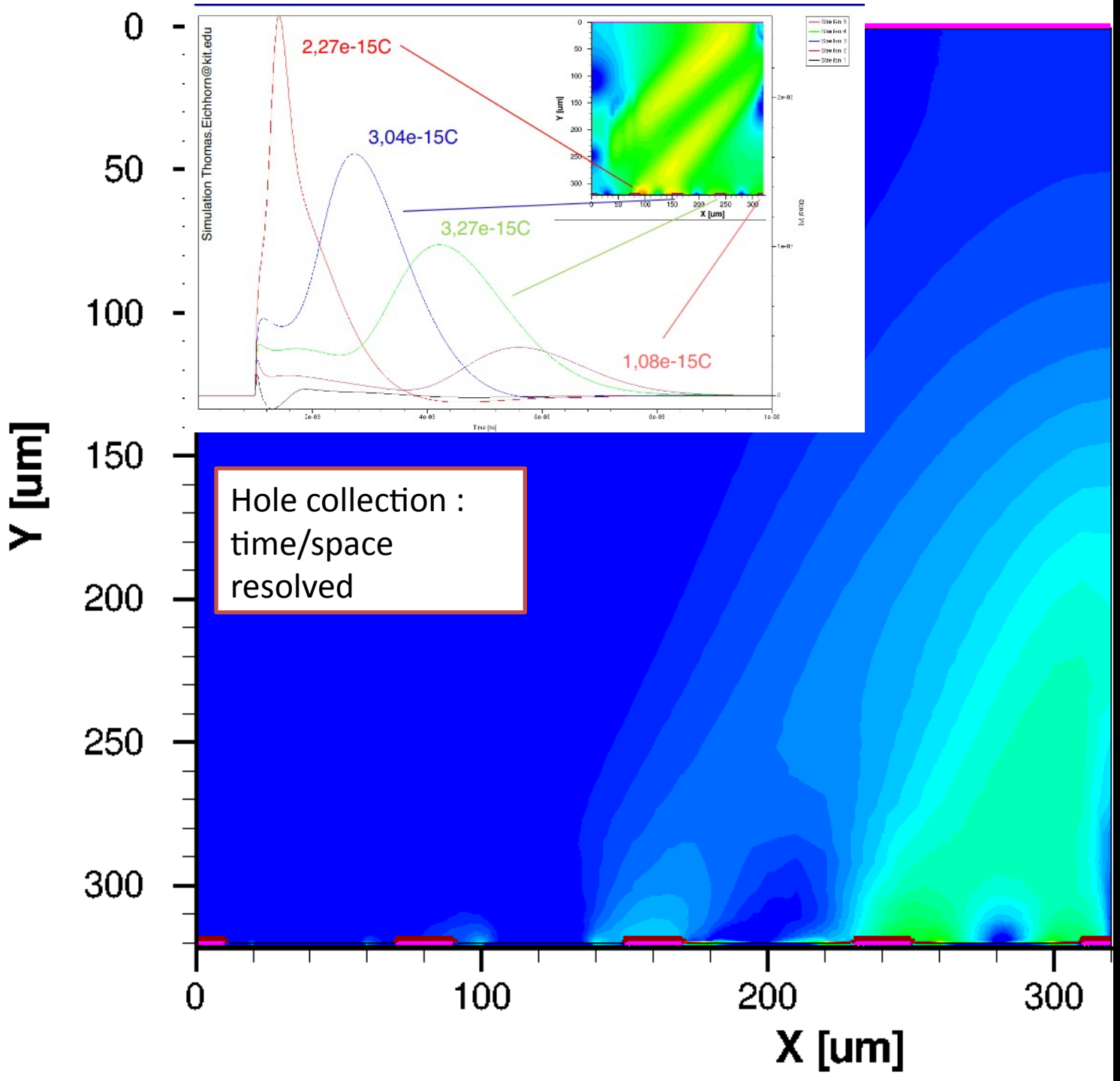
t=3 ns


0
50
100
150
200
250
300
Y [um]
0
100
200
300
X [um]
t=4 ns


0
50
100
150
200
250
300
Y [um]
0
100
200
300
X [um]
t=5 ns



t=6 ns



t=7 ns

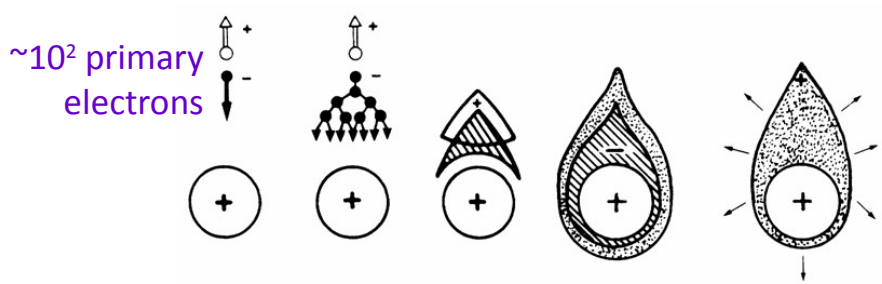
Mind all electrons/ holes collected

For the final position calculate centre-of-charge

Muon detector basics: DT, CSC, RPC

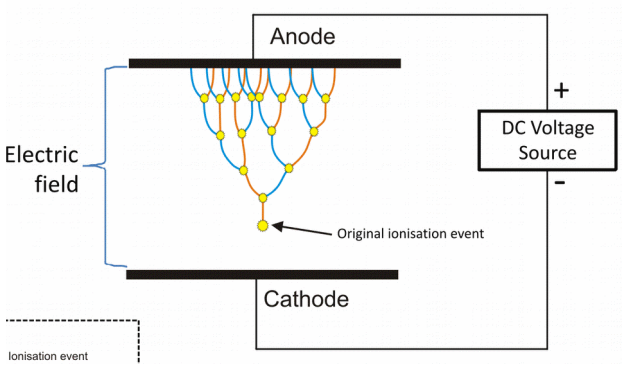
- Muon detectors are on the outside, so must be large
- Economics: use gas detectors for a large surface area
  - Need amplification of the electron ionization signal w/in gas volume
  - Factors of 10^5-10^7 are typical, using wires or parallel plates

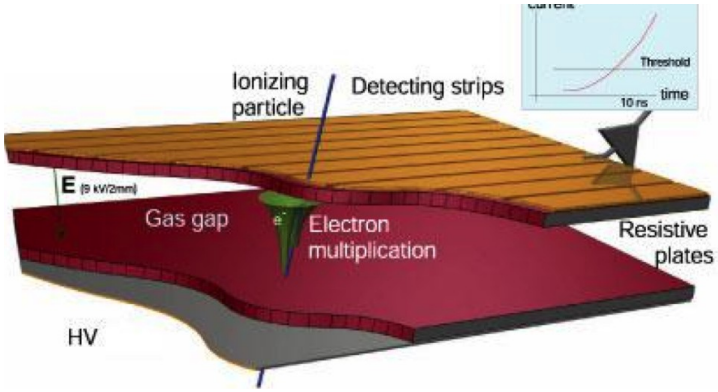
Wire chambers:



~ 10^5 – 10^7 gas amplification
~10^7 – 10^9 electrons
~1-100 pC

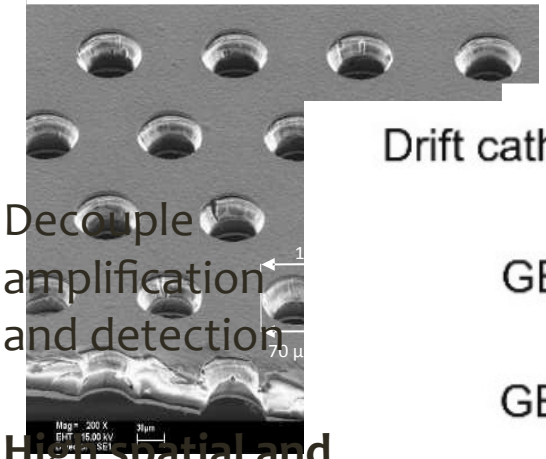
Parallel plate (RPC) chambers:

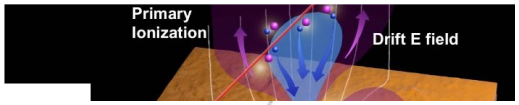




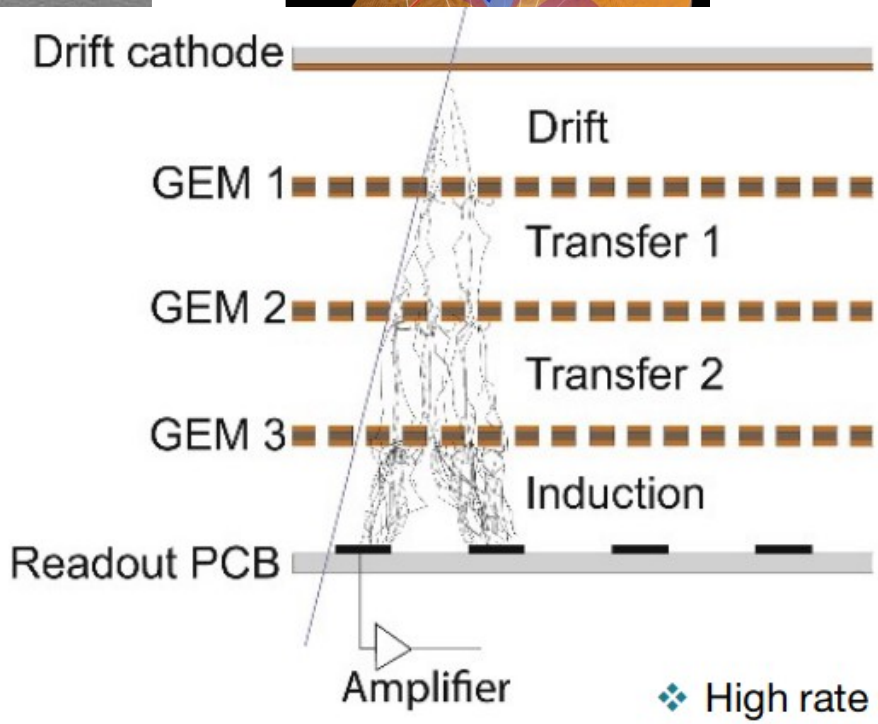
Muon detector basics: Micro-Pattern Gas Detectors (MPGD):GEM

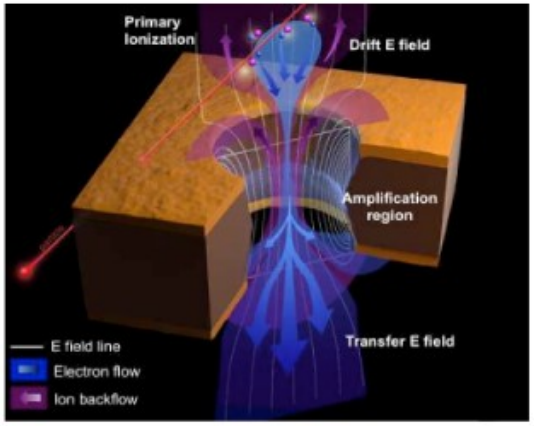
GEM: Gas Electron Multiplier

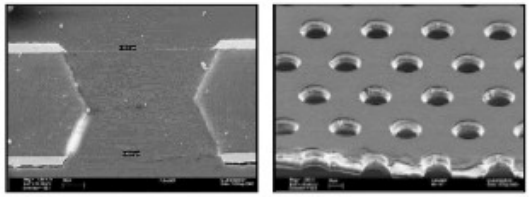




- Decouple amplification and detection
- **High spatial and good time resolution**







- High rate capability, up to O(MHz/cm^2)
- Efficiency > 98%
- Space (time) resolution ≈ 300 μm (8 ns) [1]
- Gas mixture: Ar/CO_2 70/30

[1] CMS Technical Design Report for the Muon Endcap GEM Upgrade, CERN-LHCC-2015-012

Where are the detectors? What do they really look like?

CMS TRACKING AND MUON DETECTORS

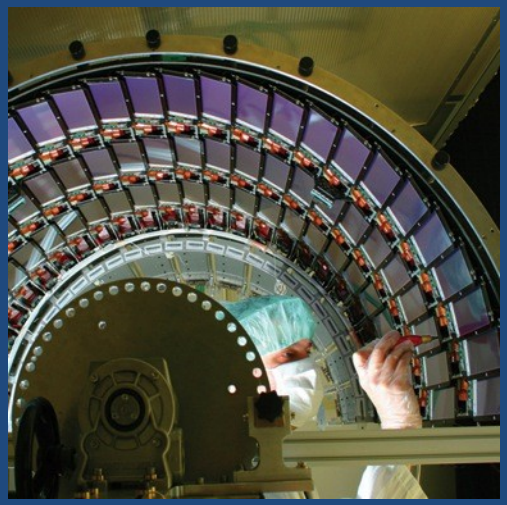
The Layers of CMS: Tracker

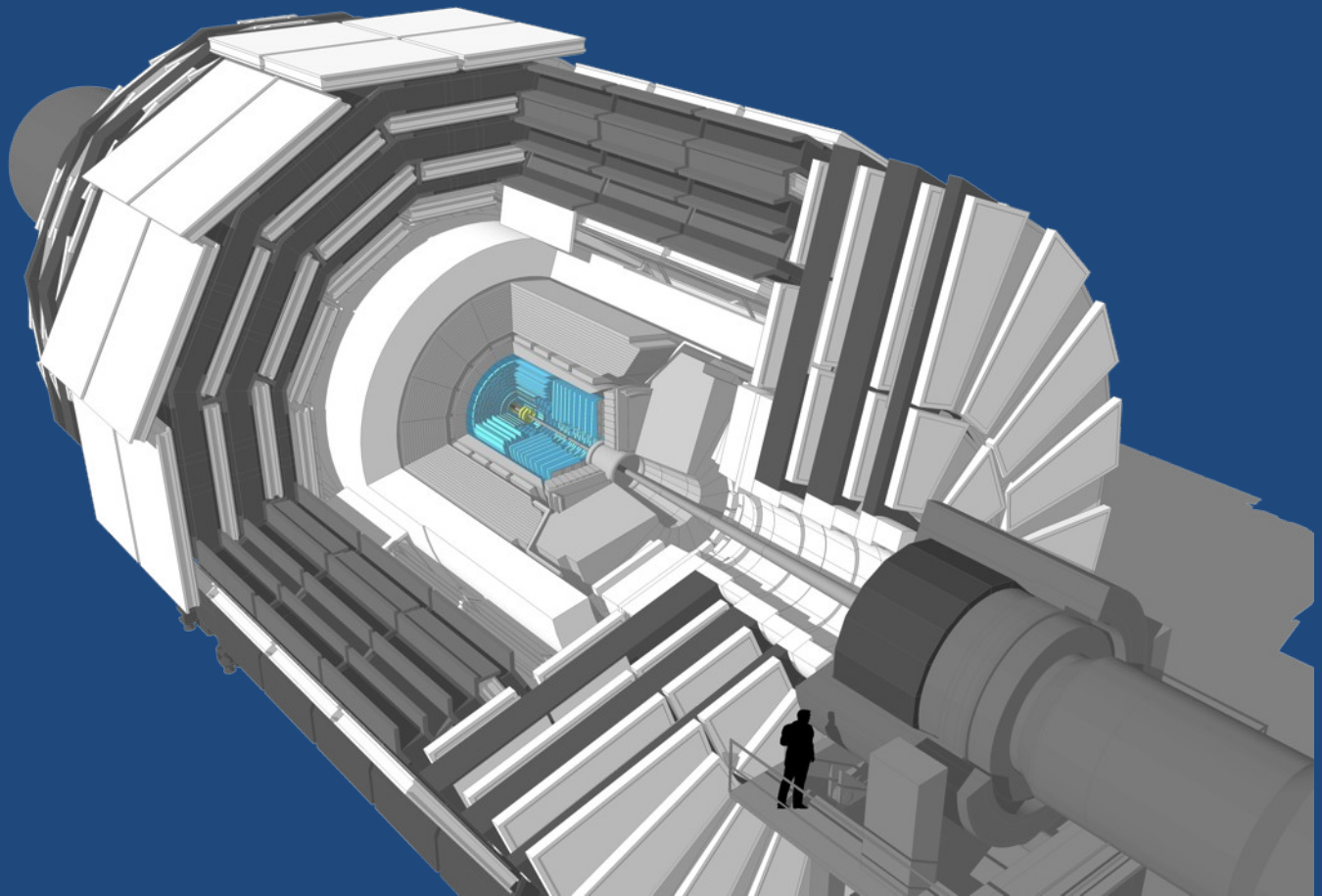
Finely segmented silicon sensors (strips and pixels) enable charged particles to be tracked and their momenta to be measured.

And their vertex identified ☺

127 Million Pixel – 2 m^2

10 Million Strips – 200 m^2





Silicon PIXEL

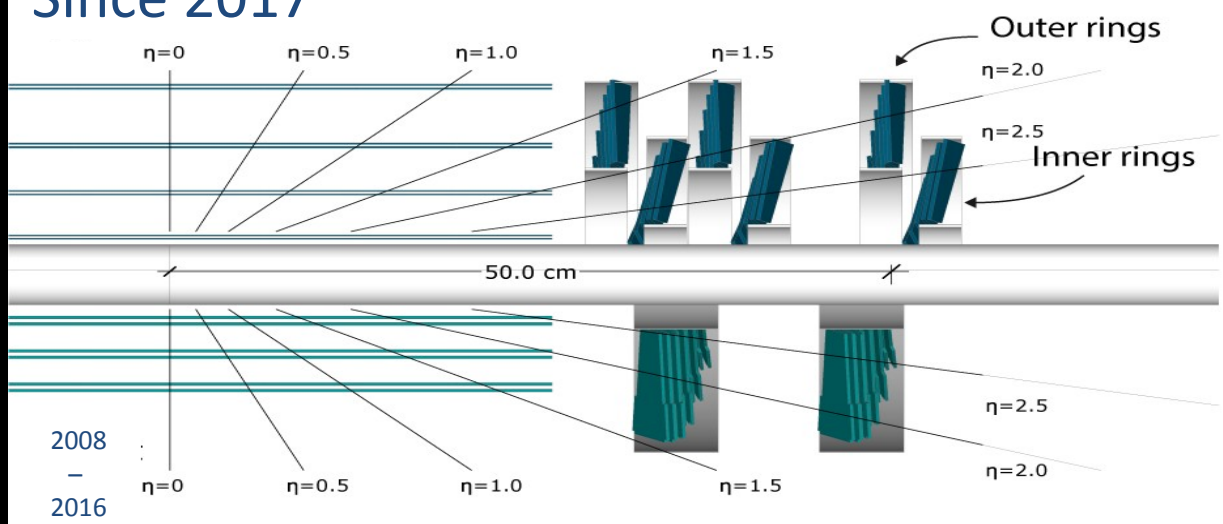
Sensor technology: n+ implant in n bulk (n-in-n)
100X150 μm^2 pixel

Operation: −22°C

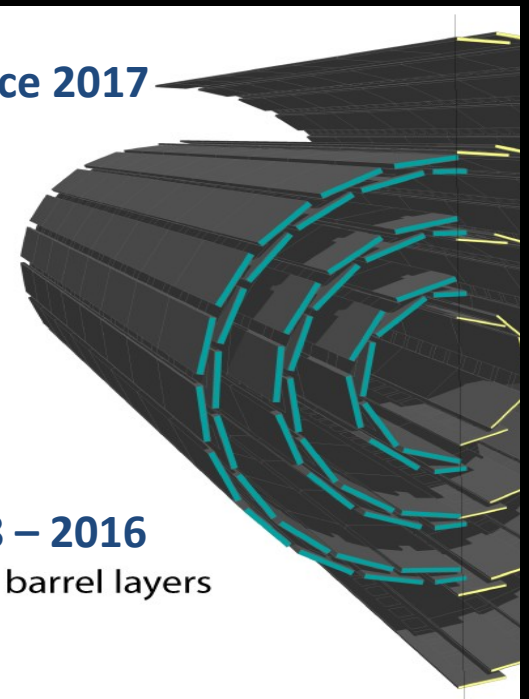
At r = 3cm
600 MHz/cm^2 above peak LHC design luminosity
$(L=2x10^{34}\ cm)^{-2}s^{-1}$
Radiation tolerance: $3x10^{14}\ n_{eq}/cm^2/yr$
Occupancy: 10^{-3}

45M forward and
79M barrel pixels

Since 2017



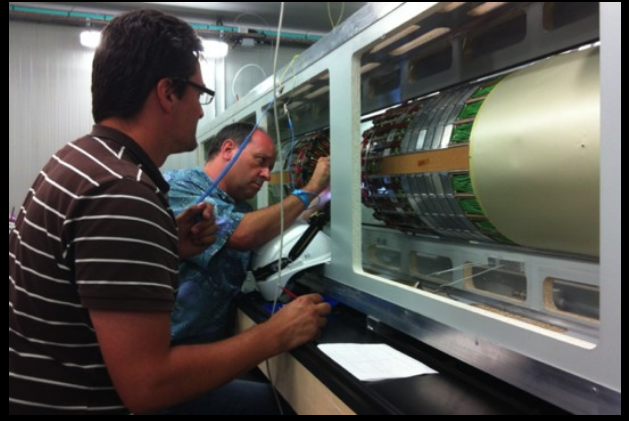
Since 2017



2008 – 2016
3 barrel layers

Tracking
- 4 space points to **$|\eta|$=2.5, ~10 μm spatial resolution**
- Seeds most tracking > 95% efficiency
- Vertexing

Pixel system is flexible

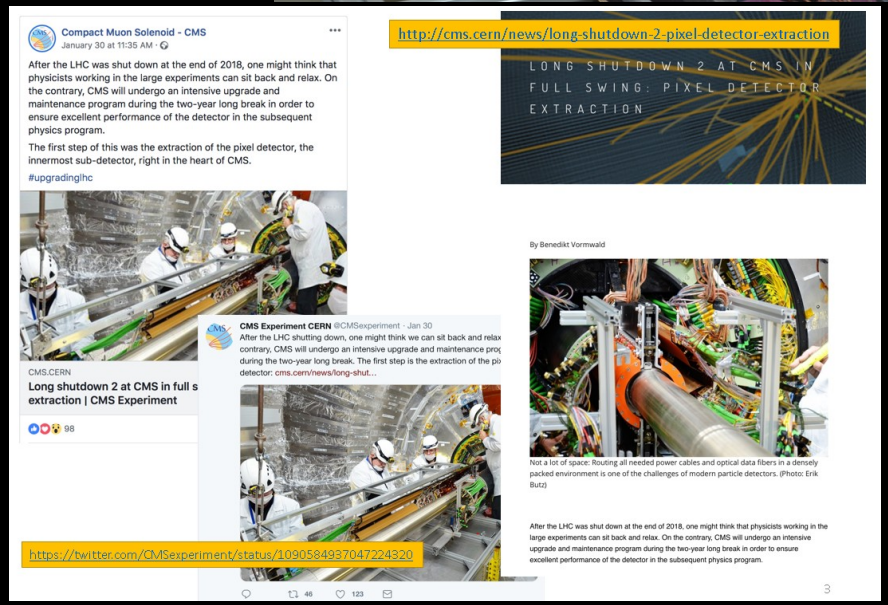


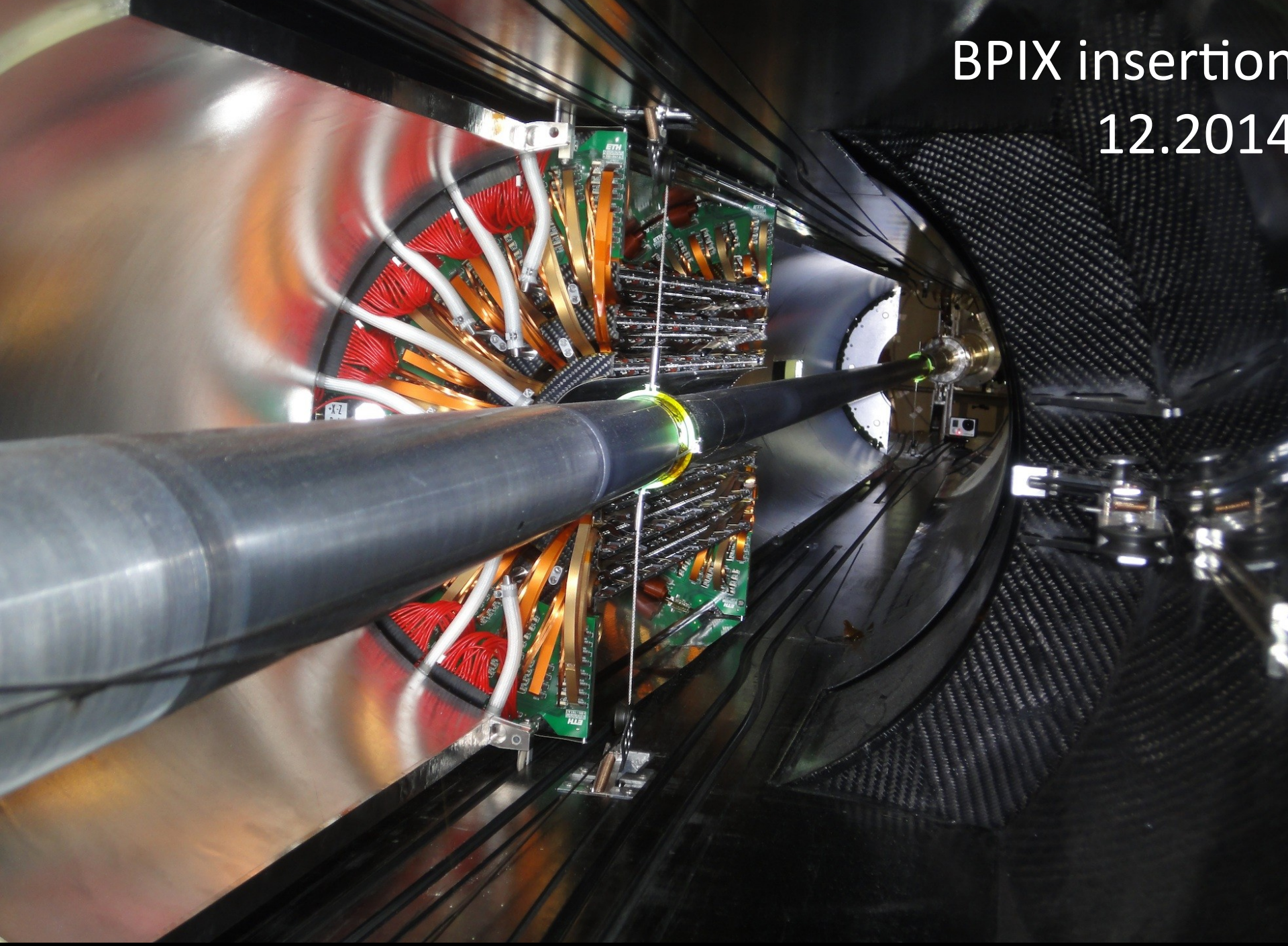
Long shutdown 1

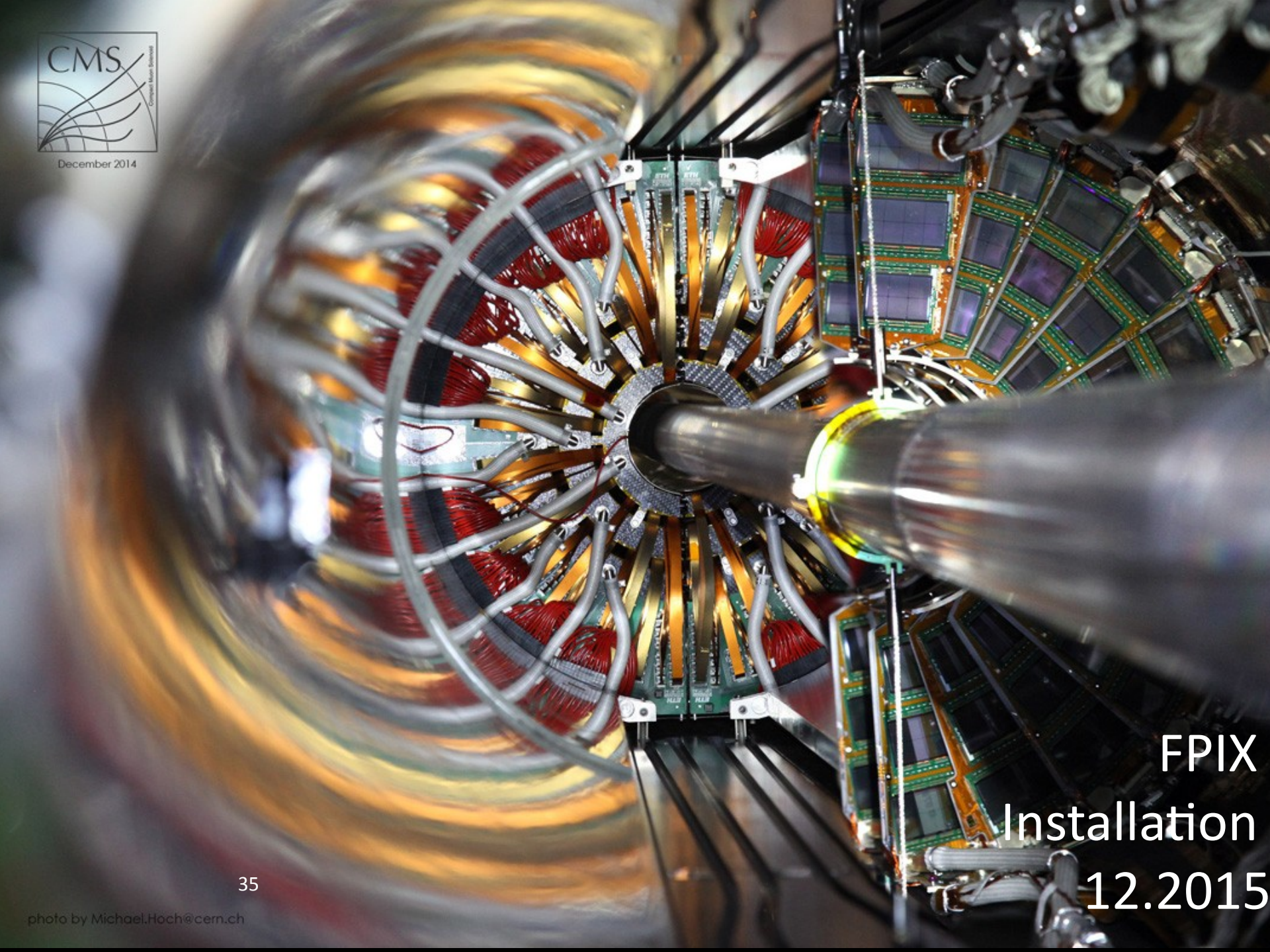
Long shutdown 2

- Removed, repaired and re-inserted
  - in 2009
- Removed, repaired and re-inserted
  - during 2013/2014

- New system installed 2017
  - 66M → 124M channels
  - Reduced material
- Re-installed 2018 after repair
- Extracted at start of LS2
  - Replacement of innermost barrel layer
  - Various maintenance
  - Reinstalled this summer (2021)



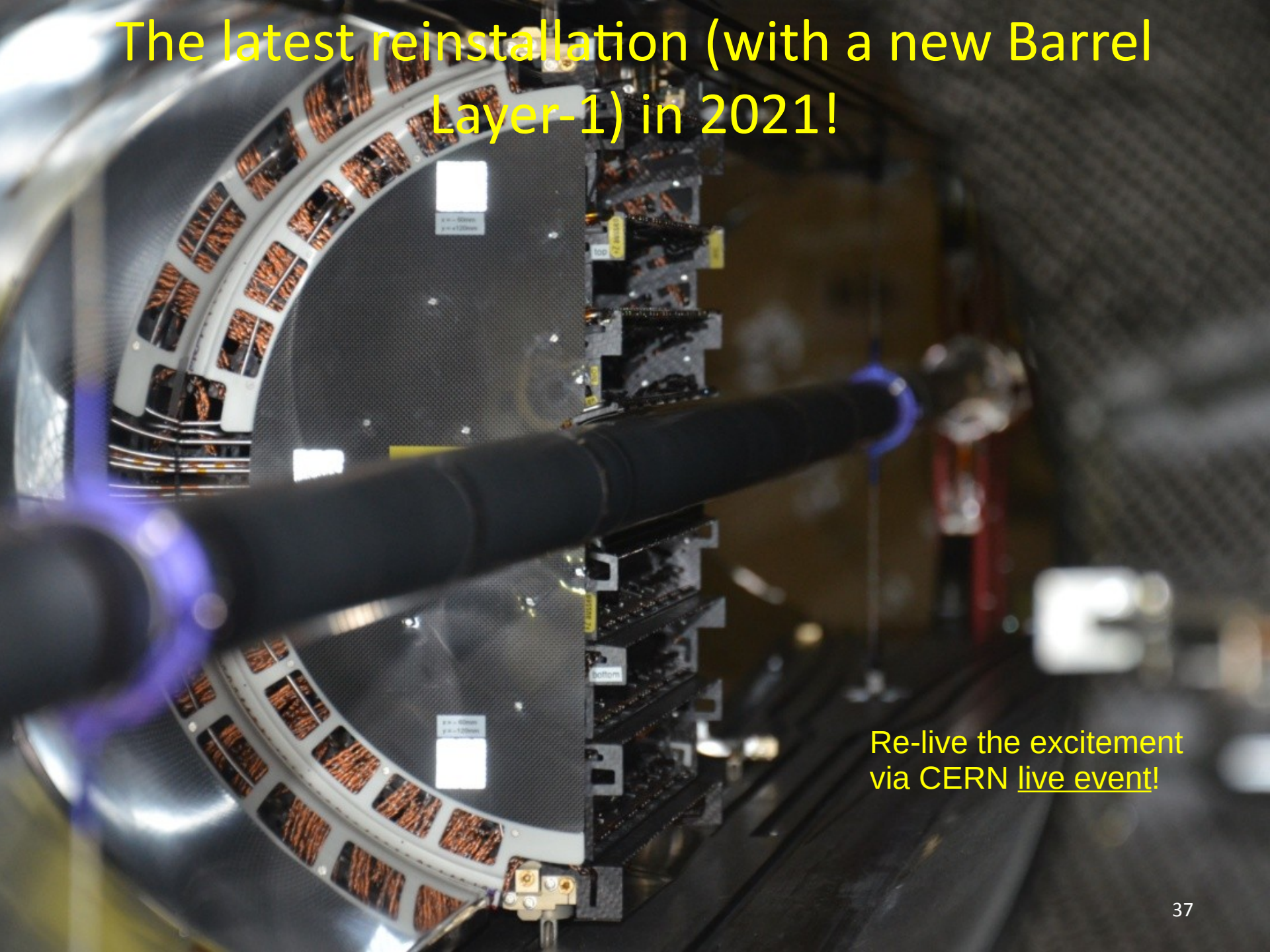

BPIX insertion
12.2014



FPIX Installation 12.2015

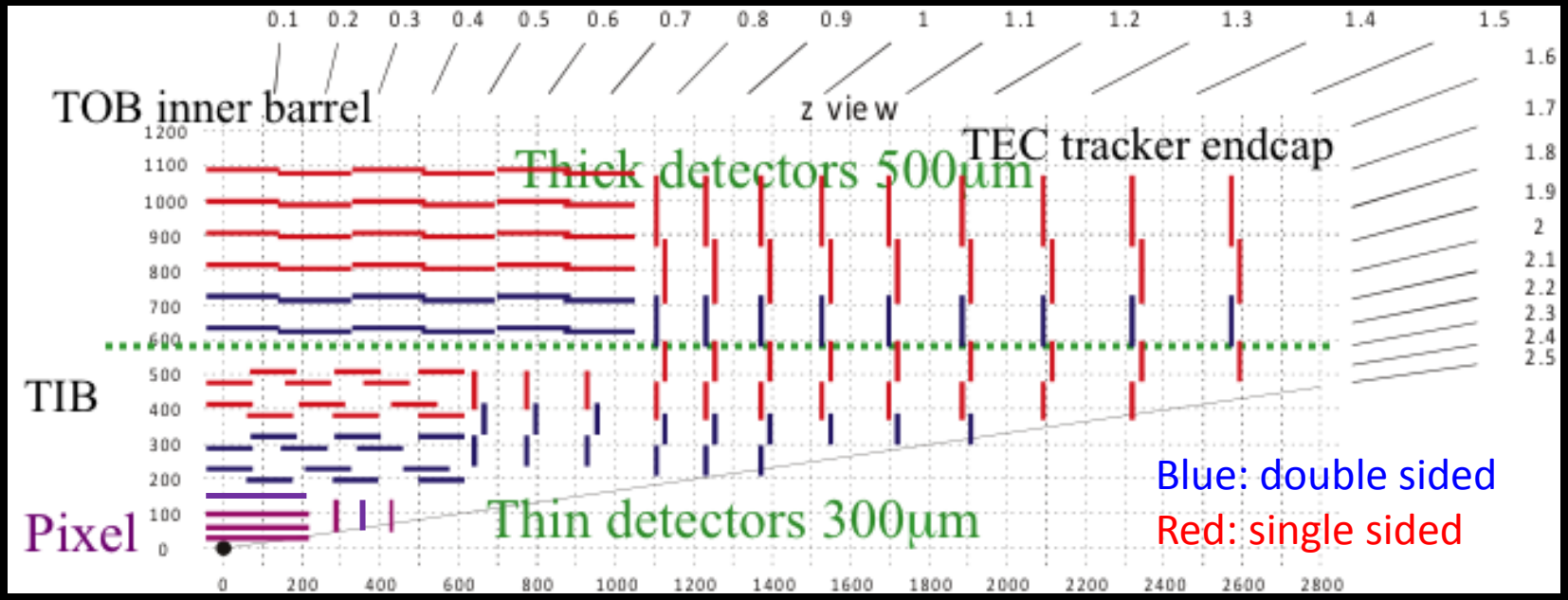
A new one installed in 2017 - Lots of fun

The latest reinstallation (with a new Barrel Layer-1) in 2021!



Re-live the excitement via CERN live event!

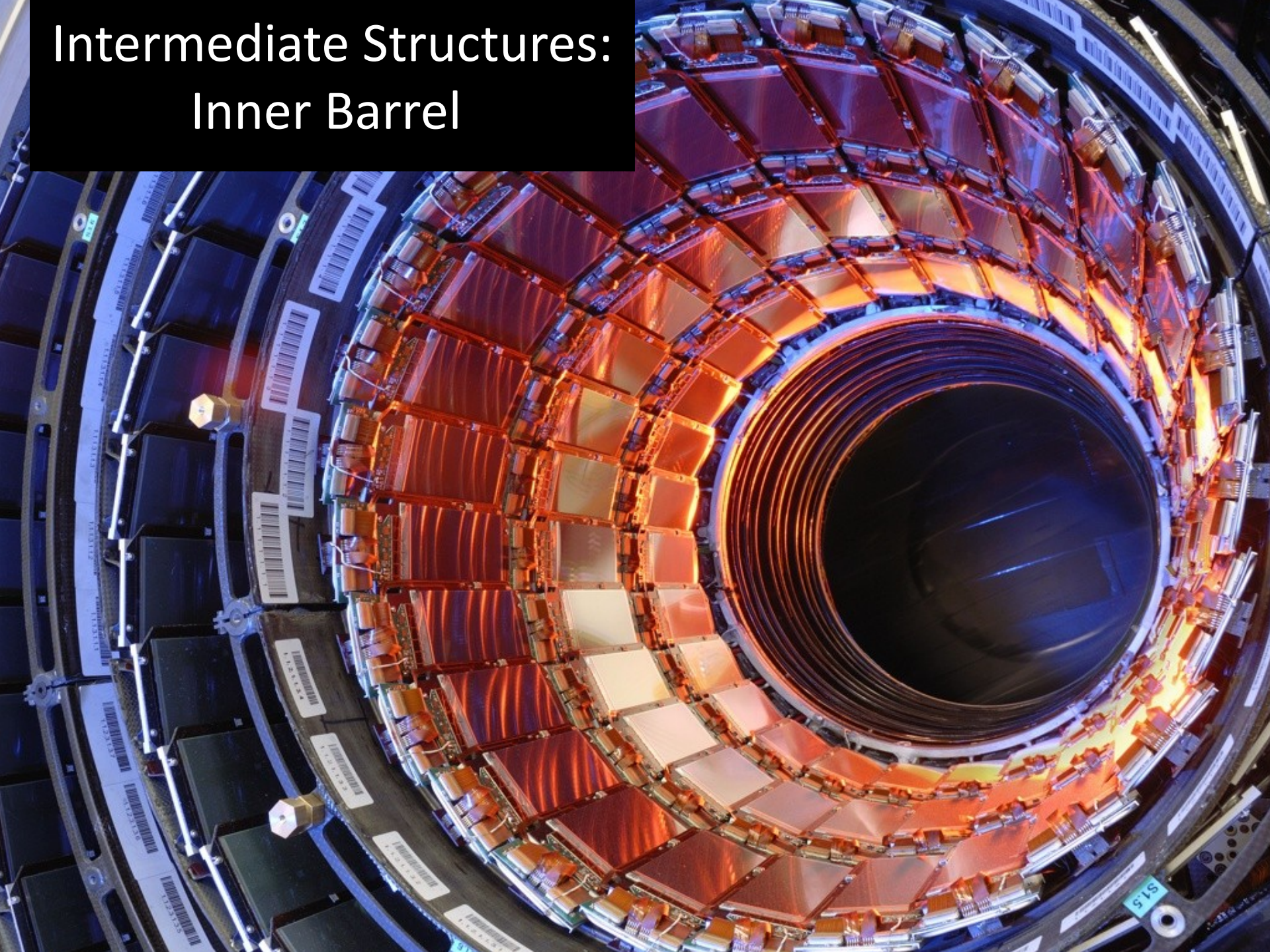
Silicon Strip Tracker



- Sensor Technology p-in-n
- Design occupancy 1-3% - resolve & isolate tracks
  - Outer cell size ~20cm x 100-200μm
  - Inner cell side ~10cm x 80μm
- Operation -20C
- Signal / noise ~20 (above 10 after radiation)
- Radiation tolerance ~1.5×10^{14} n_{eq}/cm^2

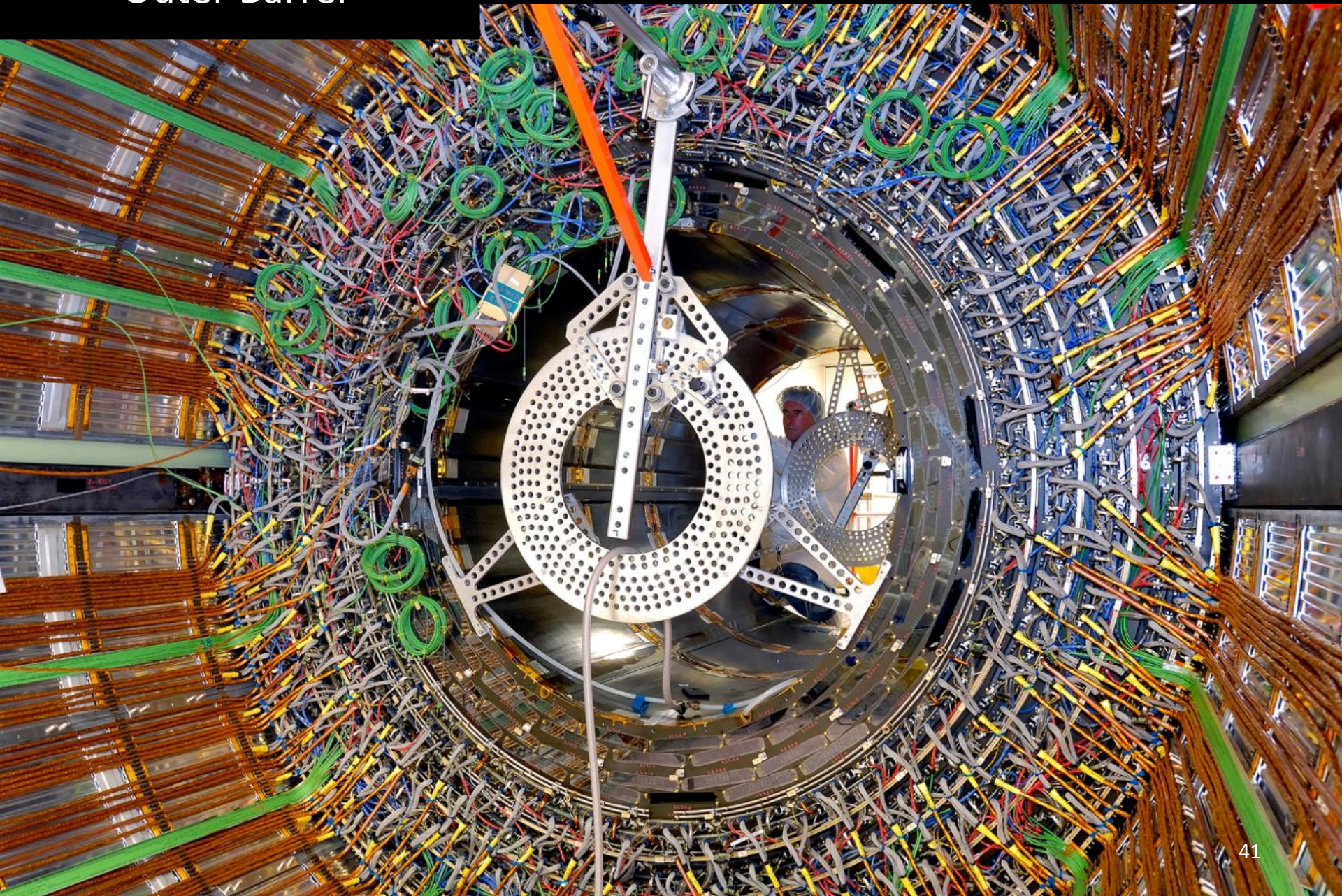
- Large radius = lever arm
- Many layers = redundancy

Intermediate Structures: Inner Barrel



??????
MEGADETH
SUPER COLLIDER
S15

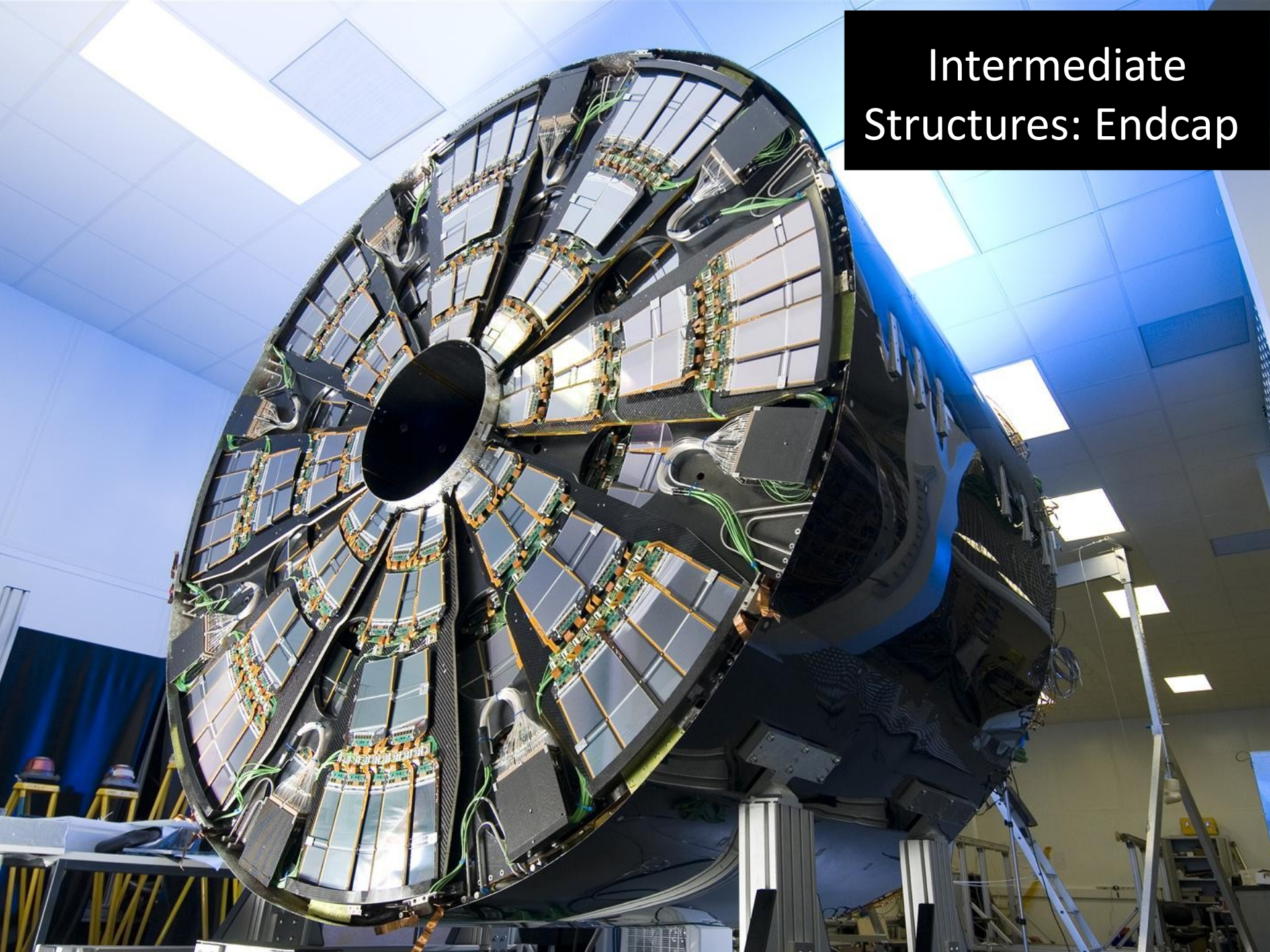
Intermediate Structures: Outer Barrel



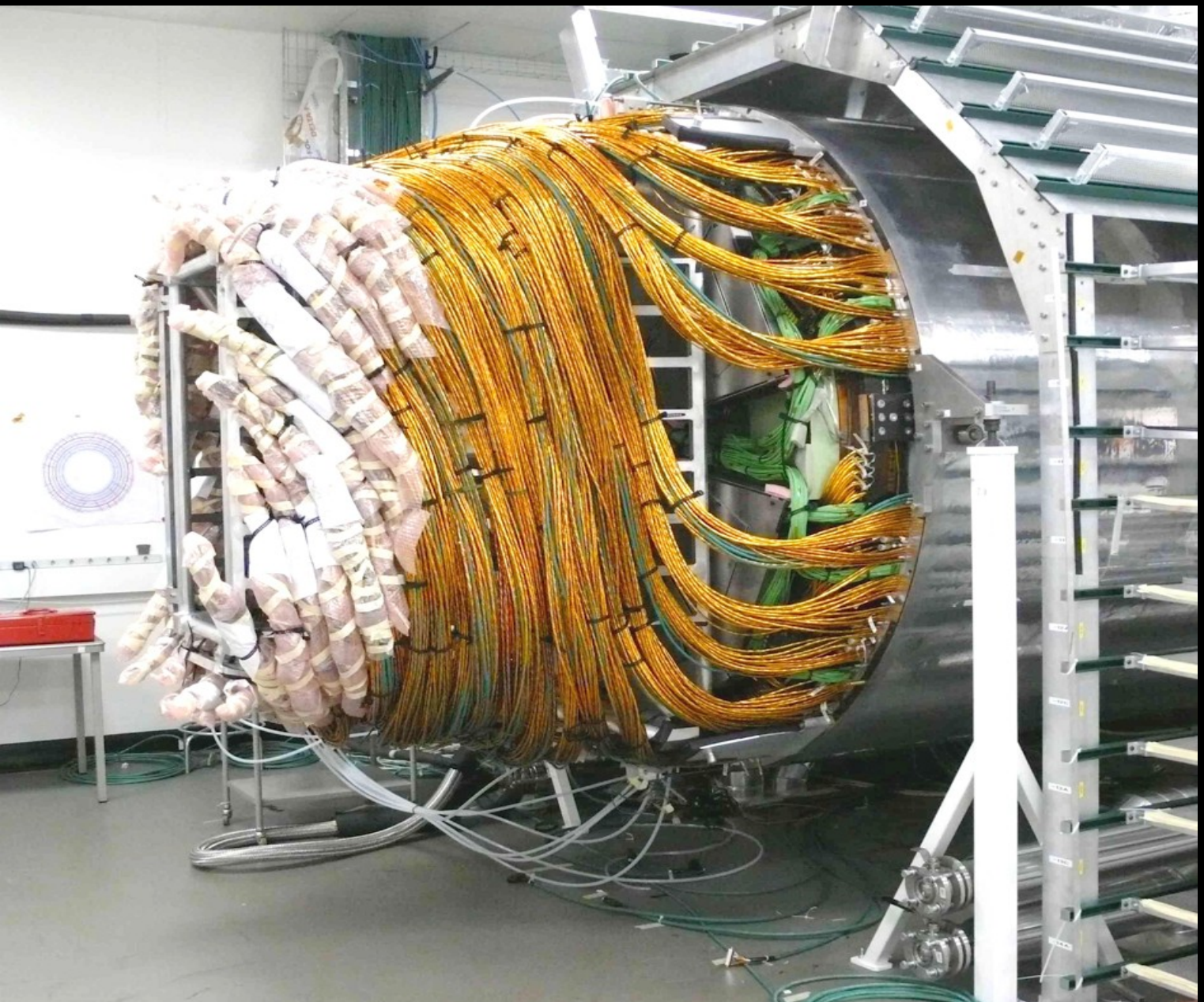
Intermediate Structures: Petals

400 Different Pieces Makes one Petal, a Fairly Complicated Object: We needed 288 in total!

Intermediate Structures: Endcap



Multiservice Cables Dressed



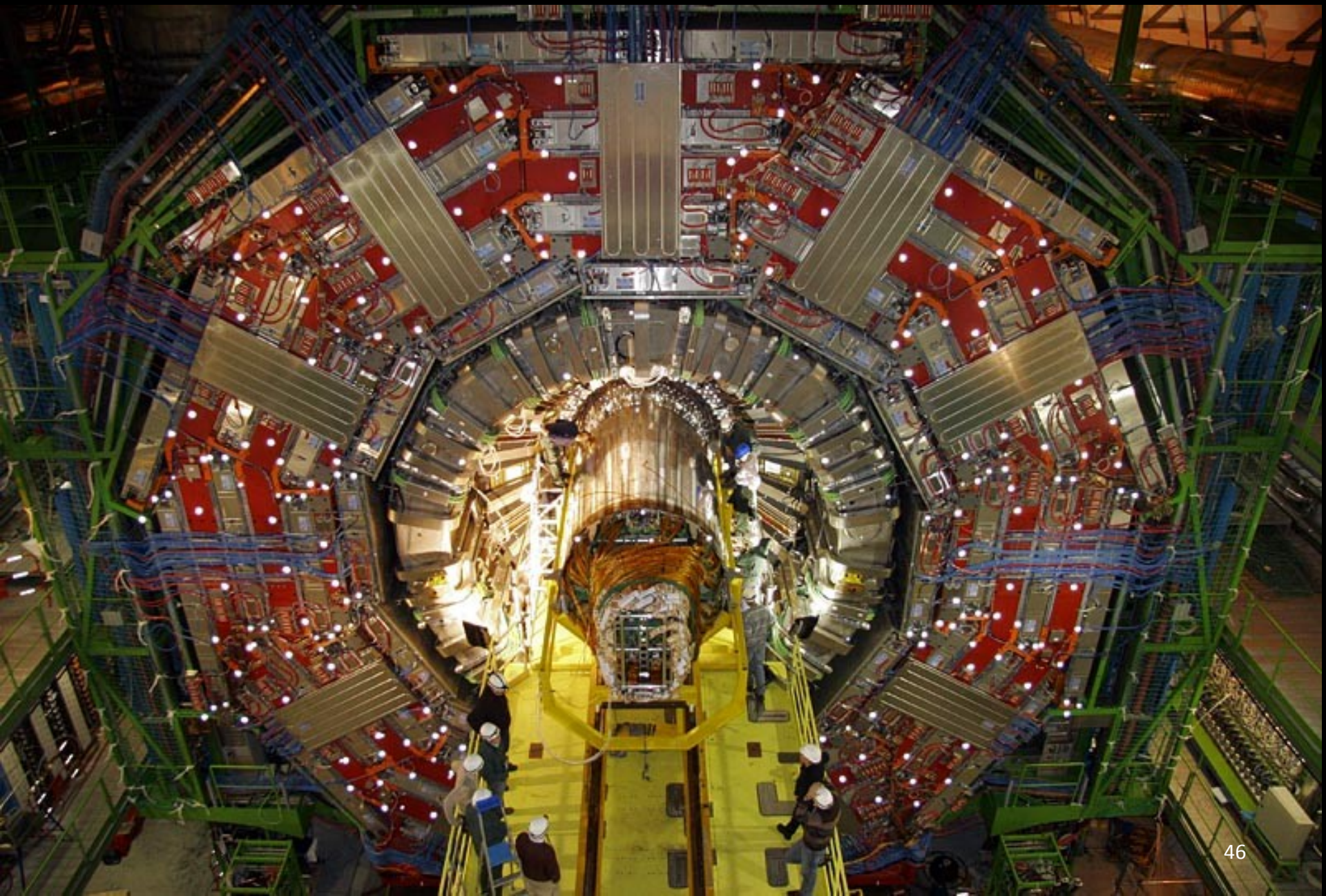
Tracker on the Way Down

- 6.5 tons
- 100 MCHF
- 2000 man years
- 100 m deep shaft below
- Not insured ;-)

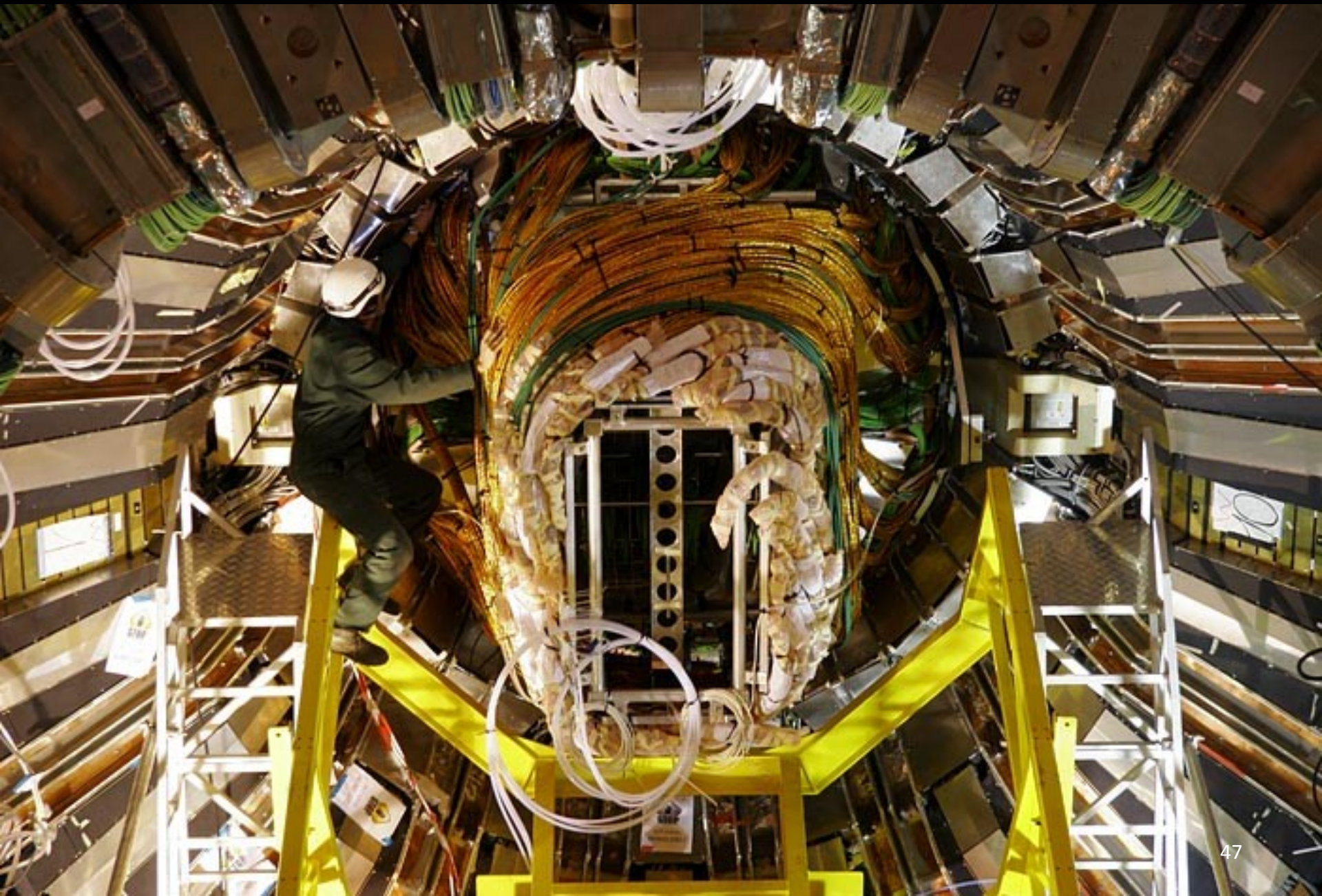
On one hook!

- Several frightened physicists

Insertion of the CMS Tracker into the Heart of CMS



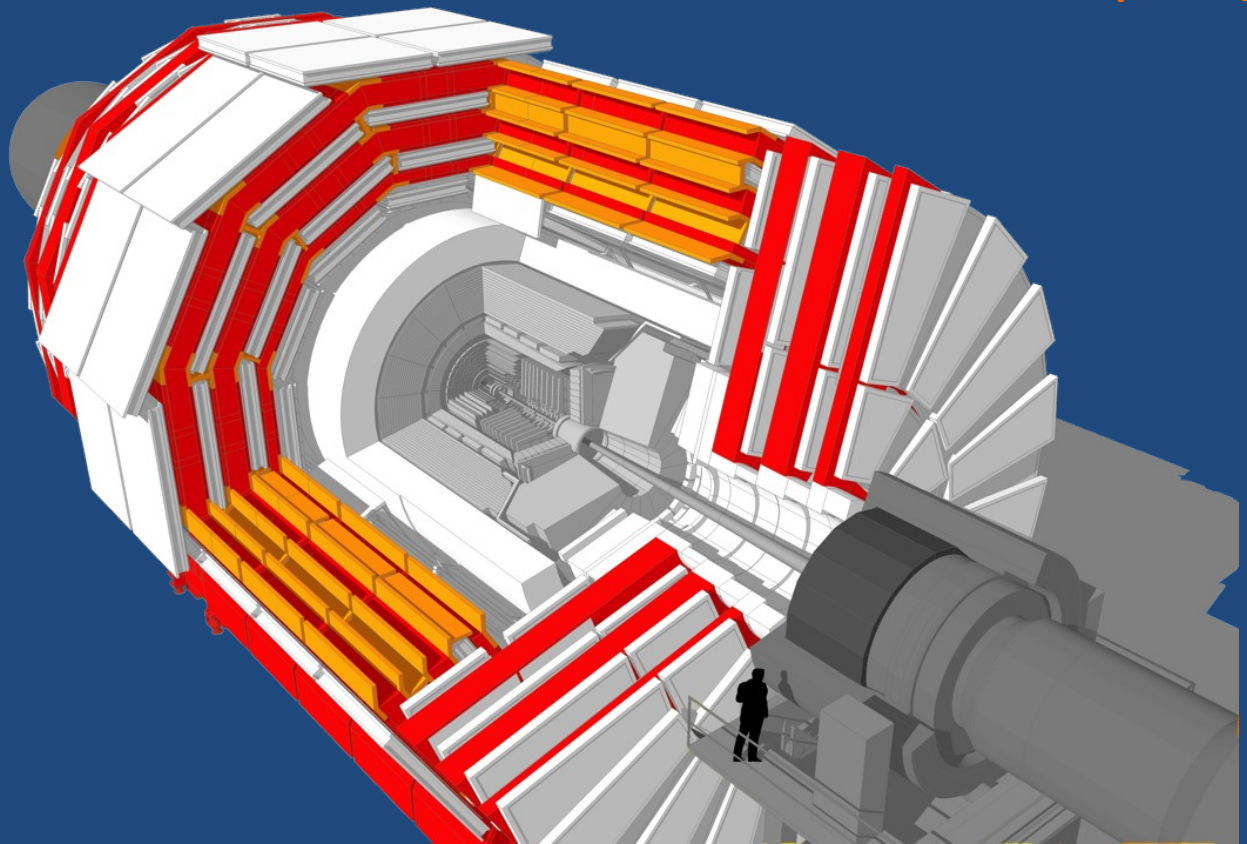
DONE, TRACKER IS IN (Sunday 15.12.07 01.30)



The Layers of CMS: MUON

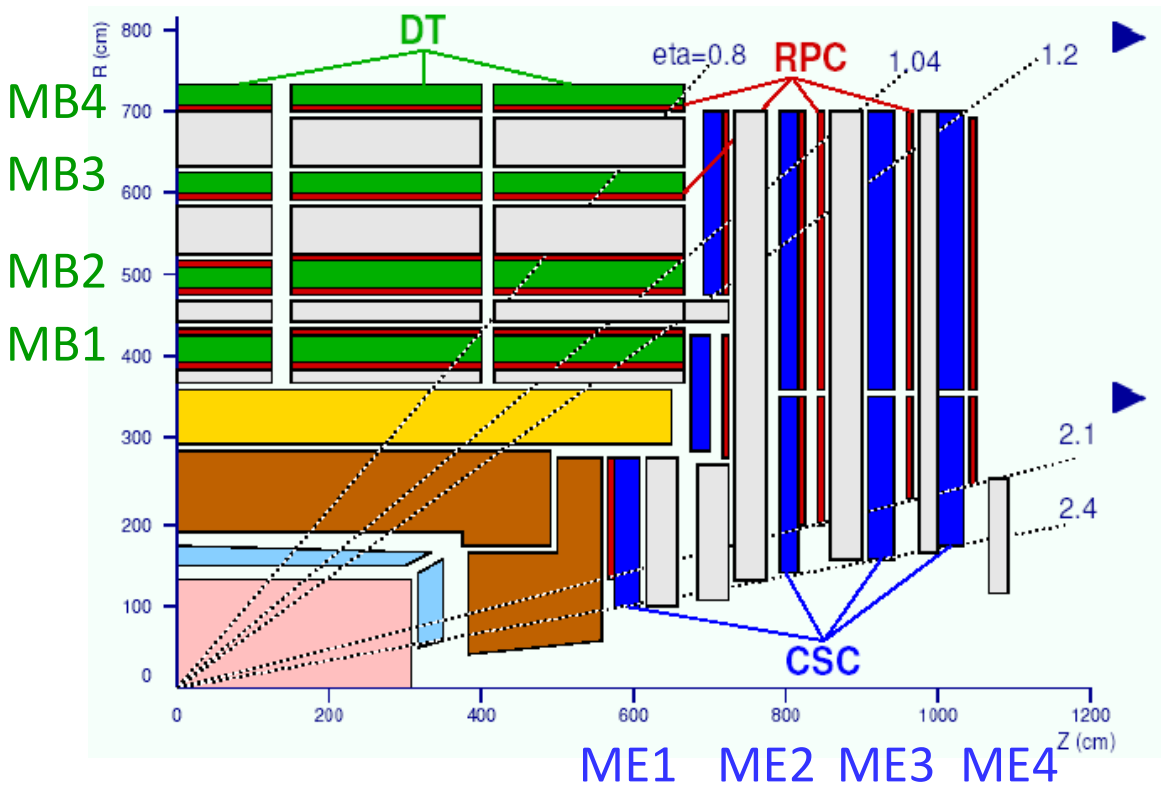
To identify muons (essentially heavy electrons) and measure their momenta, CMS uses three types of detector:

- drift tubes - **DT**,
- cathode strip chambers - **CSC**
- resistive plate chambers – **RPC**
- **new: Gas Electron Multipliers (GEM)**



Cross section of CMS (r-z)

- Three types of detector:
  - Precise position measurement and triggering by Drift Tubes (DT) in the barrel, and Cathode Strip Chambers (CSC) in the endcap
  - Redundant triggering by Resistive Plate Chambers (RPC)



Barrel: $0 < |\eta| < 1.2$

5 wheels / 4 stations instrumented with DTs and RPCs

Endcap: $0.9 < |\eta| < 2.4$

3 discs / 4 stations instrumented with CSCs and RPCs

Spatial precision 75-150 μm /station

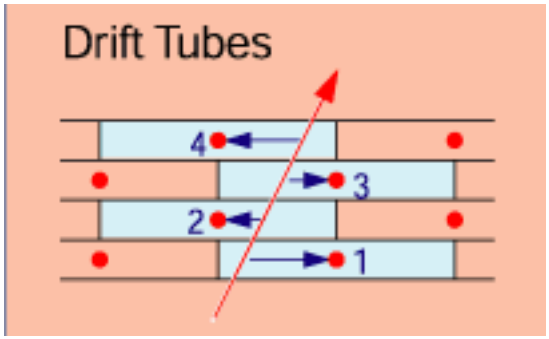
Drift Tubes (DT)

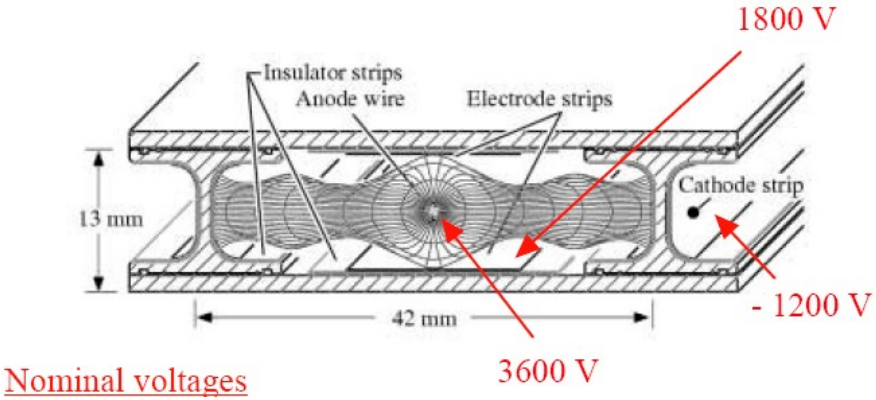
- **240 chambers in CMS <u>barrel</u>** – 5 wheels

- Drift time measurement, gives **distance (d)** to wire to **~250 µm accuracy**

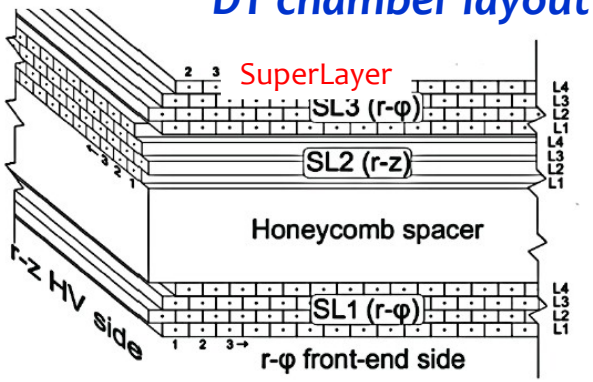
$$d = (T - T_0) \times V_{drift}$$

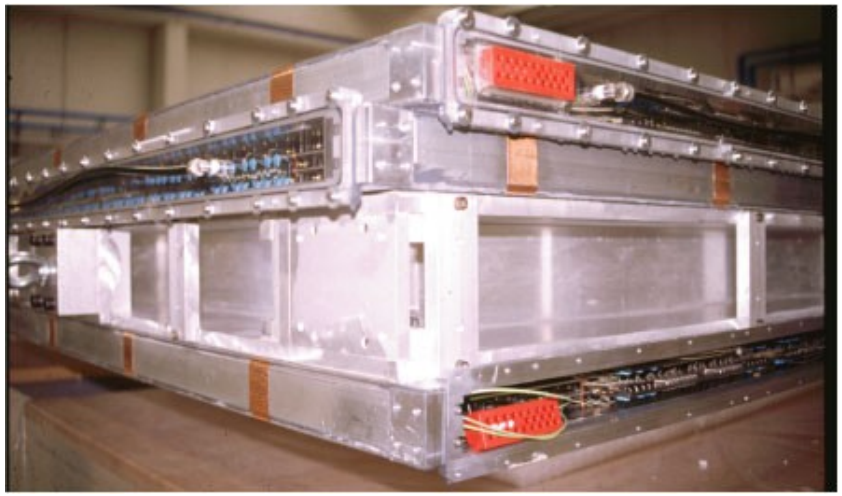
- **4** stations
  - **12** layers per station in groups of 4
    - 8 axial (r-ϕ), 4 longitudinal (r-z)





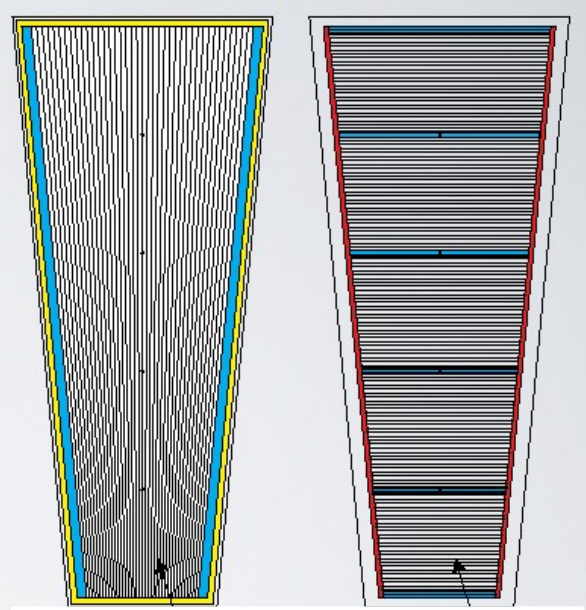
DT chamber layout



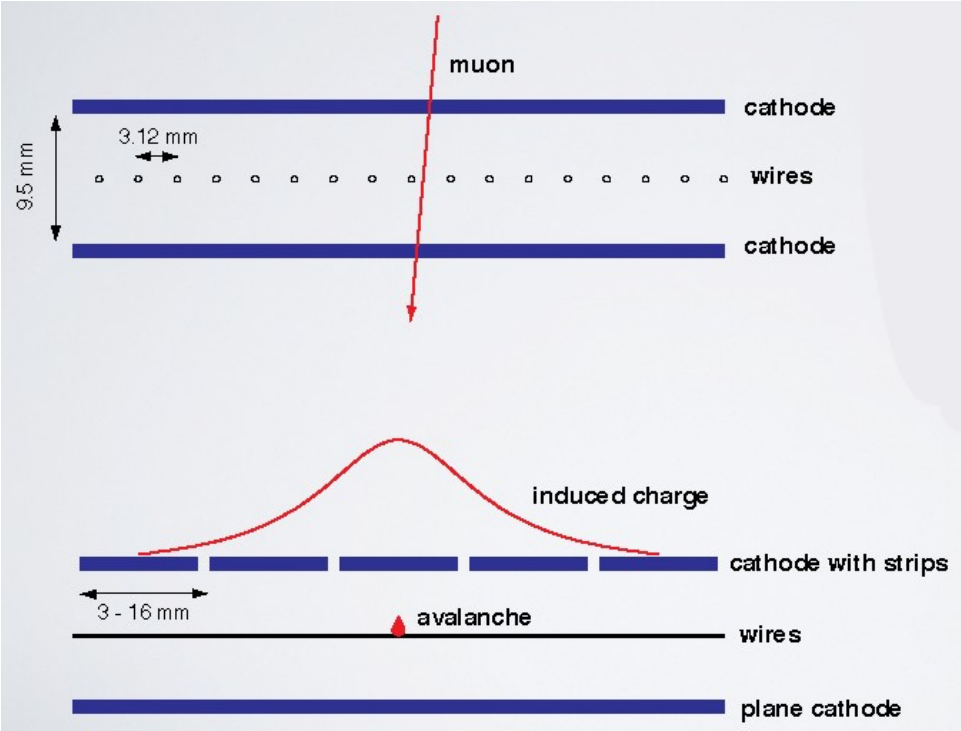


Cathode Strip Chambers (CSC)

- **540 trapezoidal chambers in CMS <u>endcaps</u>**
- Electrons drift to wires, **induce** opposite charge on perpendicular cathode strips
- Precise ~2% interpolation of cathode charge on ~cm strips gives ~200 μm accuracy
- 6 layers: precision ϕ from cathode strips, coarse ***r*** and timing from anode wires

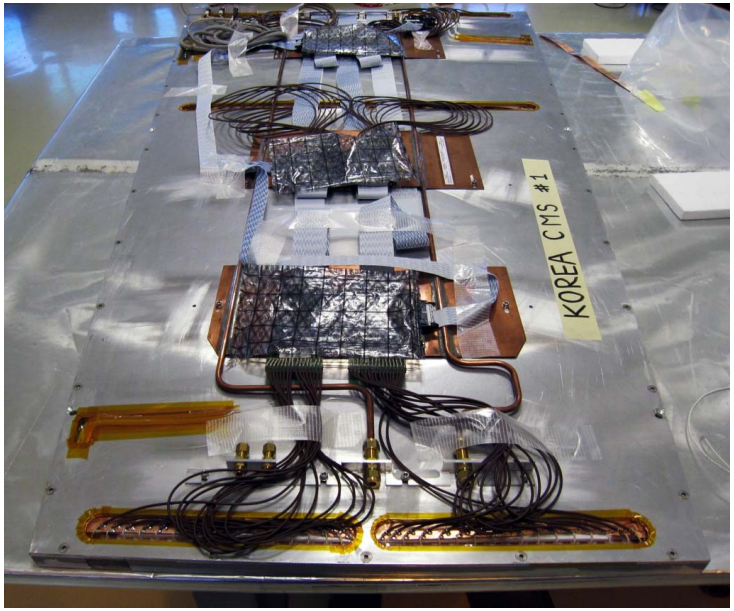


Strips wires

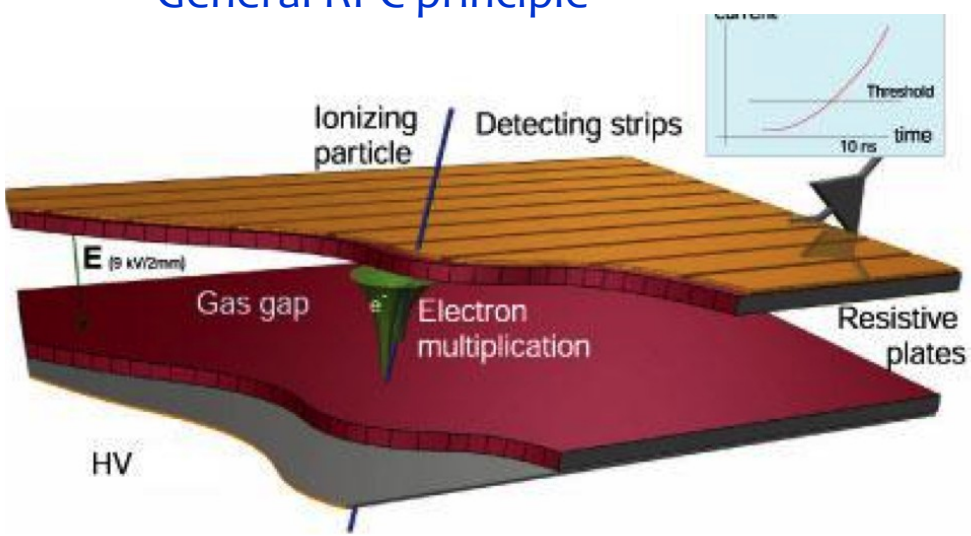


Resistive Plate Chambers (RPC)

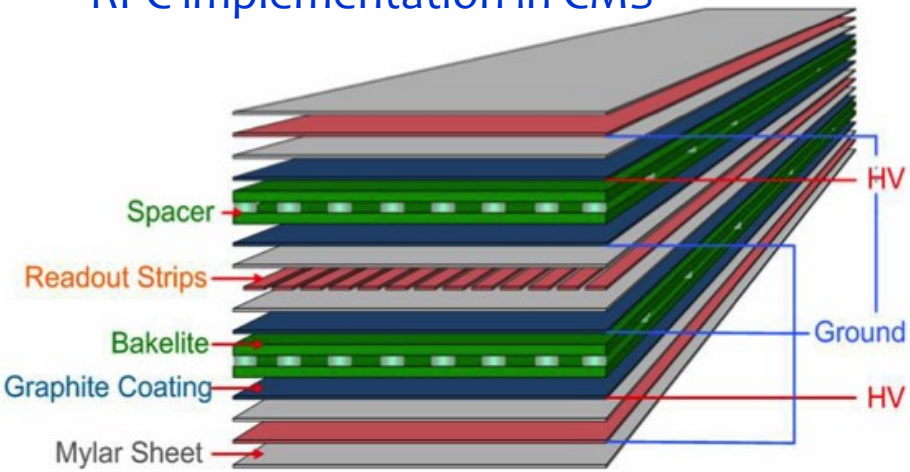
- **480 <u>barrel</u>** and **576 <u>endcap</u>** chambers
- Charge induced onto external strips
  - Resistive layer (Bakelite plastic) with $\rho \sim 10^{10}\ \Omega$cm is transparent to signal
- Spatial resolution 0.8-1.2 centimeters
- Double gap, each 2 mm, for high ε
- Fast - triggering



General RPC principle



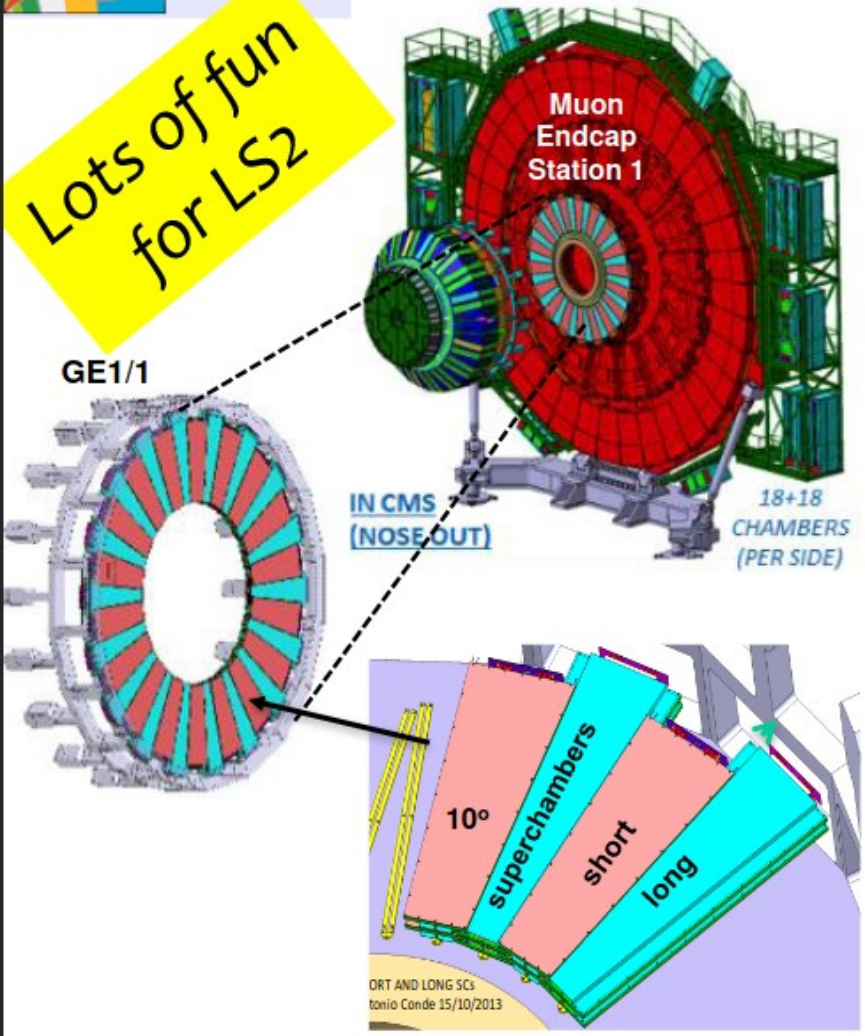
RPC implementation in CMS



52

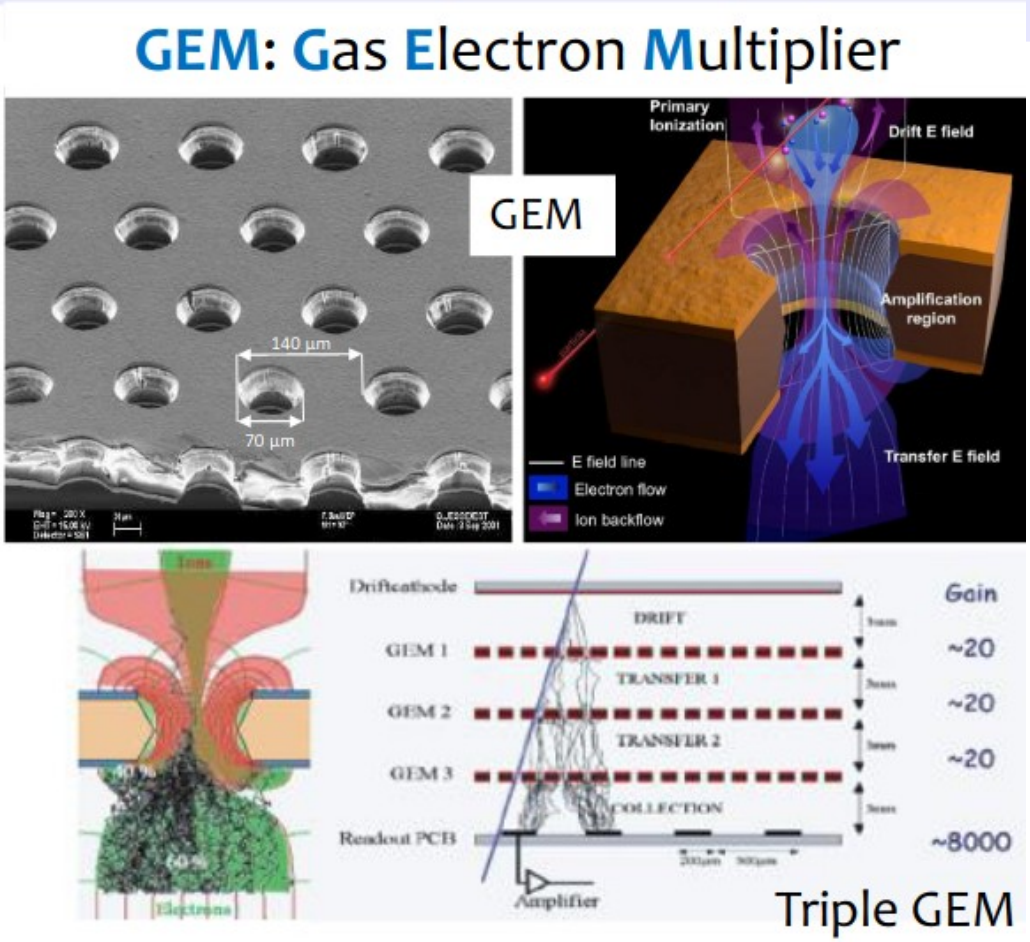
New - Micro-Pattern Gas Detectors :GEM

Lots of fun for LS2



Long (1.5<|η|<2.2) and short (1.6<|η|<2.2) version

36 superchambers in each endcap

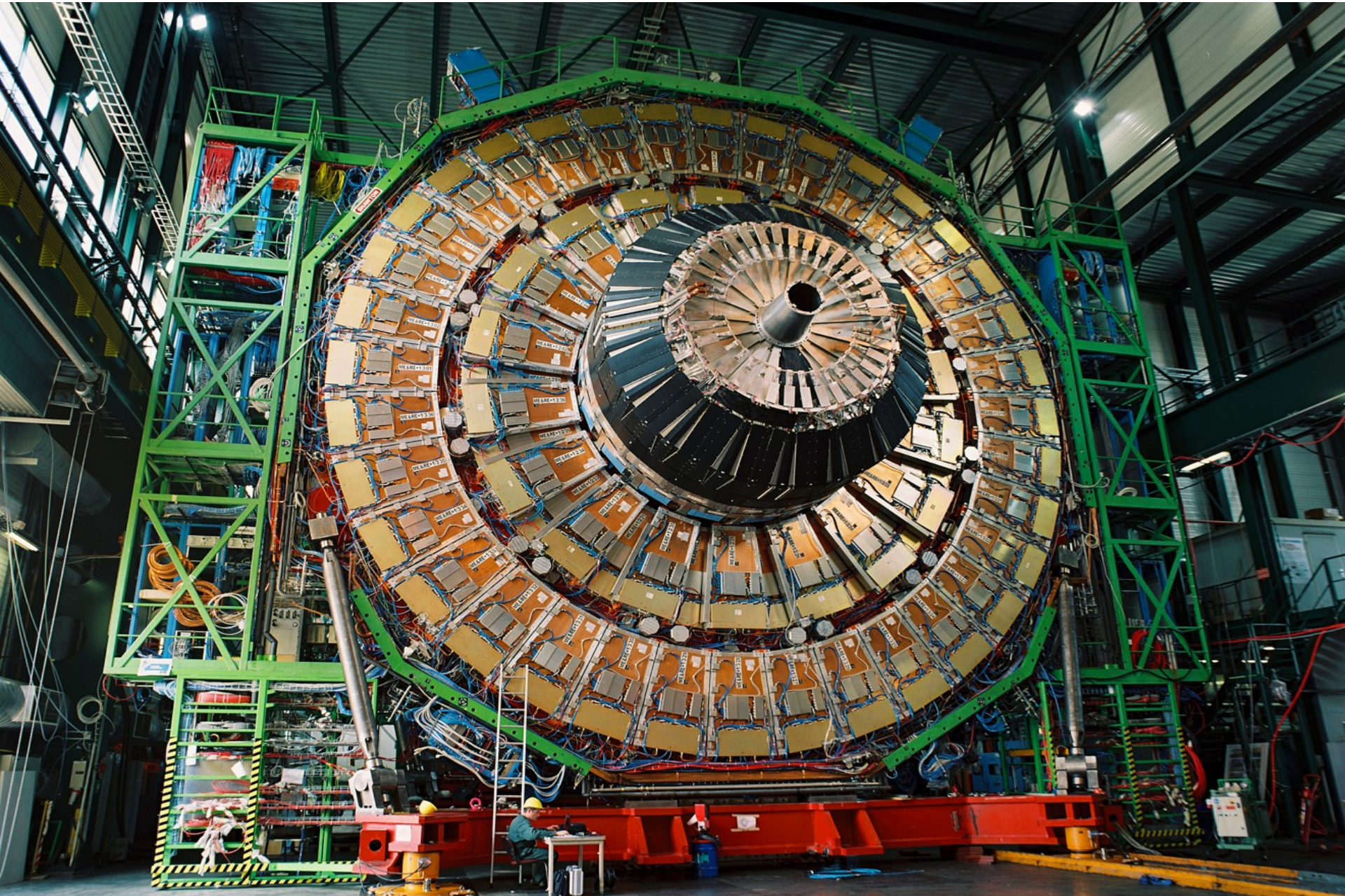


1st half of GE1/1 installed in 2019

2nd half in 2020 – despite COVID!

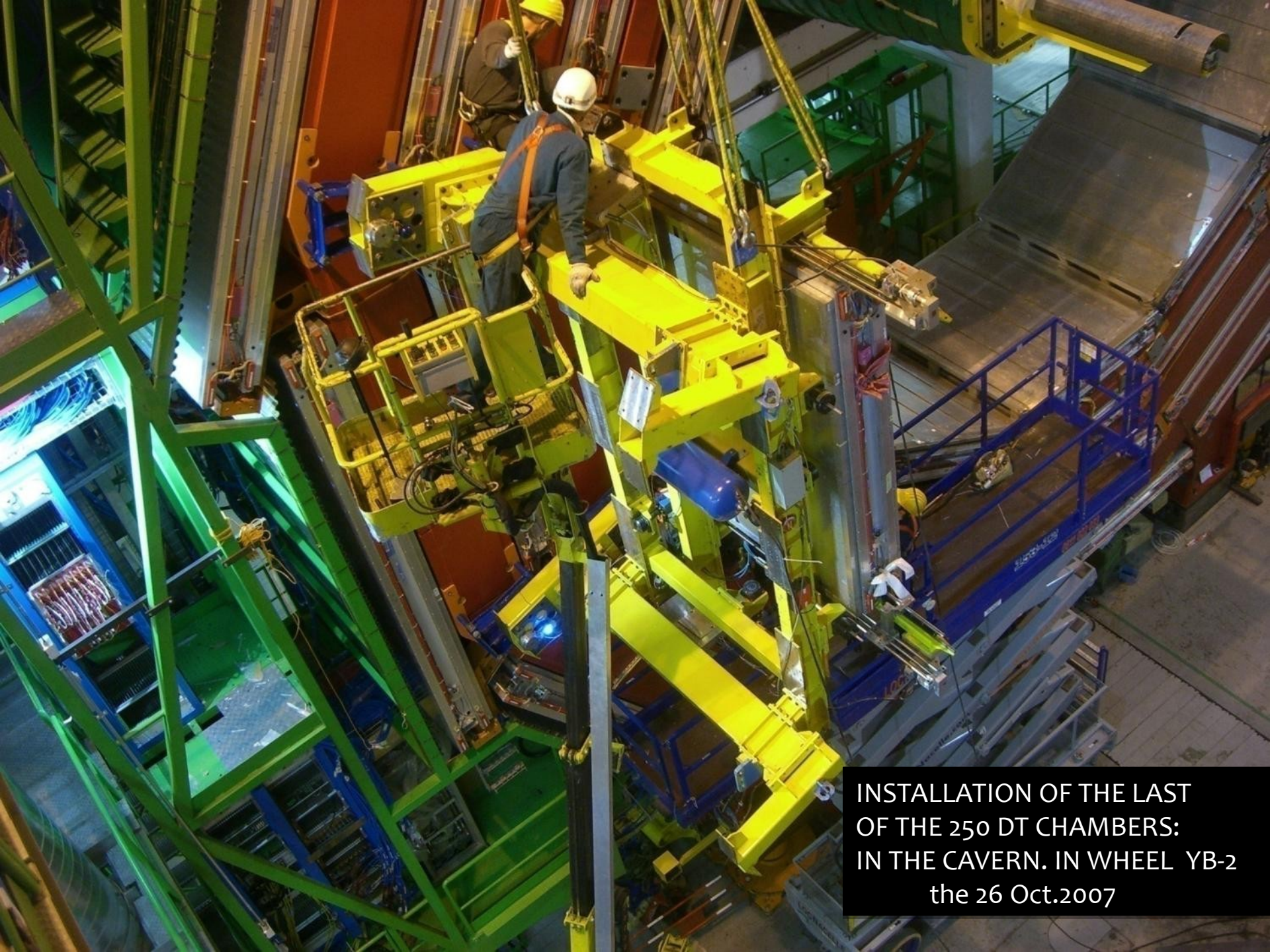
First installation of new detector hardware for Phase-2!

Historically – All but GEM Installed in Surface Hall



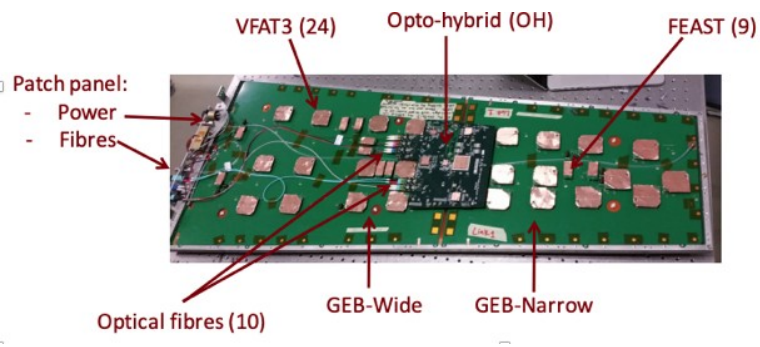
10° and 20° CSC
chambers (2nd station)

20° DT chambers
with thin barrel
RPCs attached
MB1
MB2
MB3
MB4



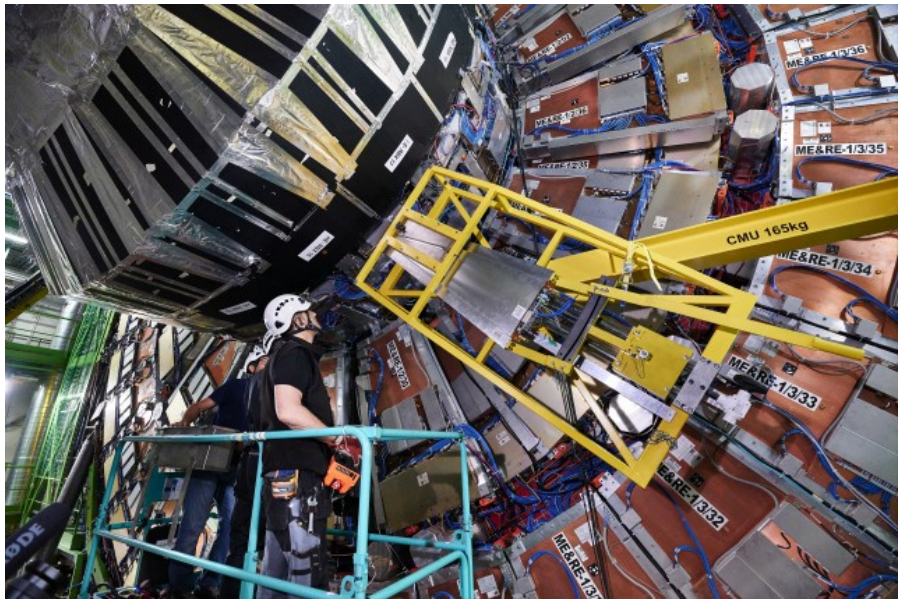
INSTALLATION OF THE LAST
OF THE 250 DT CHAMBERS:
IN THE CAVERN. IN WHEEL YB-2
the 26 Oct.2007

GEM – GE1/1



Mounting of the OH and fibers

Final verification OH voltages & FEAST levels



Installation of a GEM Chamber. 360° live broadcast from the CMS cavern at CERN

https://youtu.be/fUoujGWbeQo

Installation of the last GE-/1 Chamber
October 2019

Installation of the last
GE+/1 Chamber
September 2020

From detector hits to physics objects

READOUT, RECONSTRUCTION AND OTHER CHALLENGES

- 25 ns readout!
- 100kHz trigger rate – readout rate!

- Signal dynamics must be understood and programmed into computer code
  - Not to forget the calibration
  - Noise, bad channels; channels with intermittent problems
- Need to know precise location of modules/channels in 3D space (alignment)

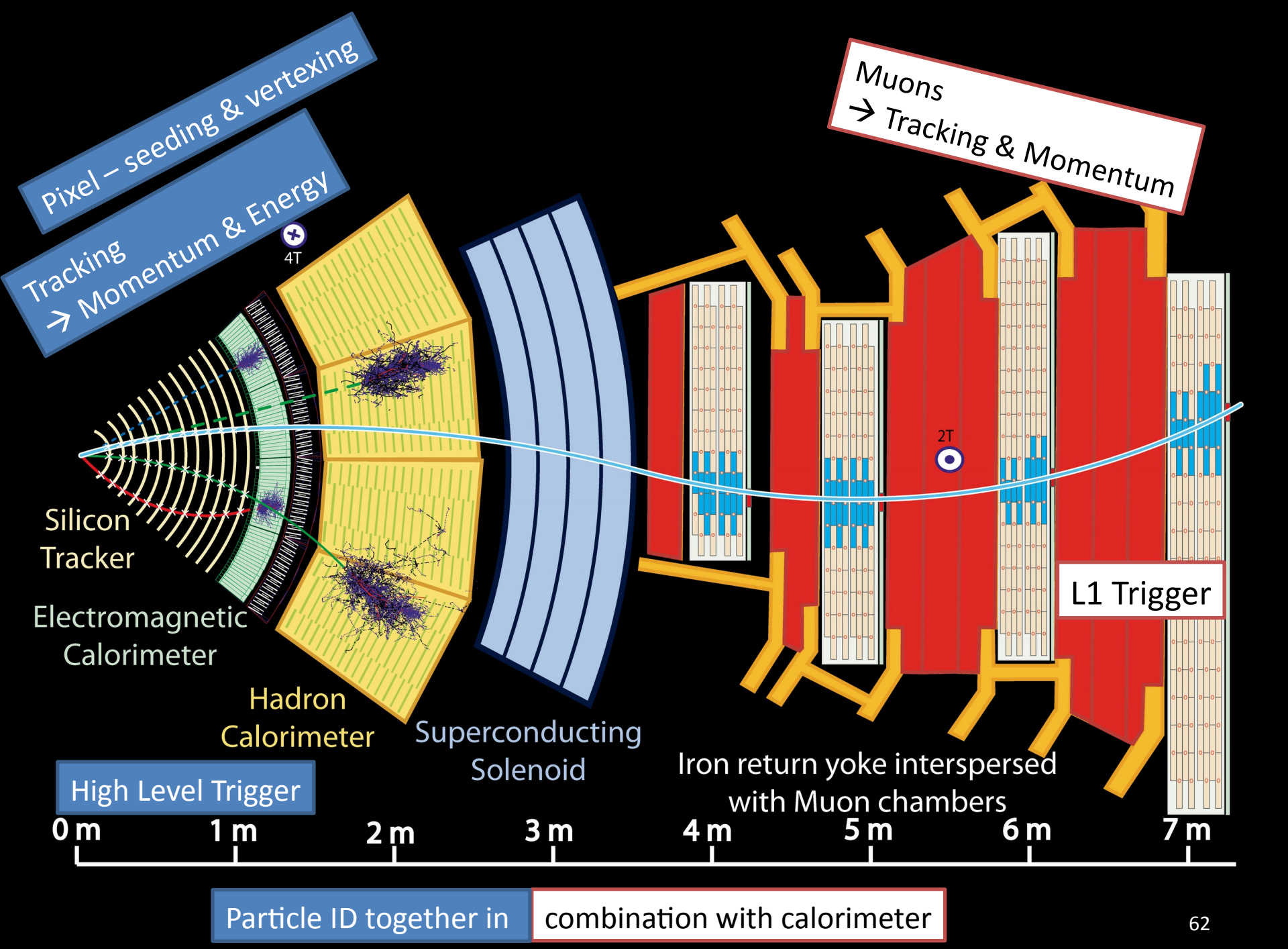
- **Level 1 Trigger (Muons)**
- Data sparsification (Tracker)

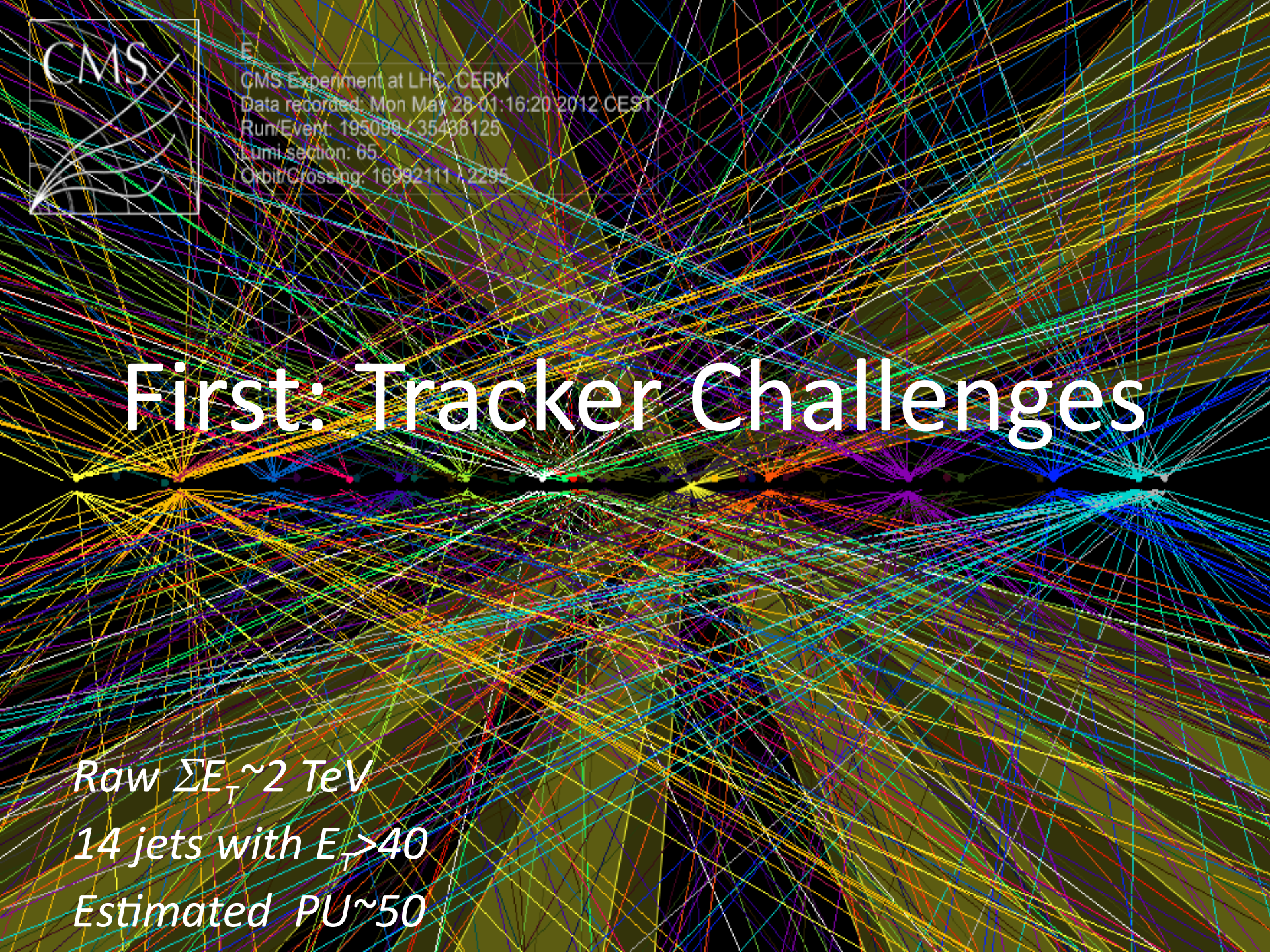
HOW DOES IT WORK? IS IT SIMPLE?

→ Let's see how the signal is created; transmitted and treated before one can use it for physics

- And the group taking care of the different aspects

It is a team effort


Pixel – seeding & vertexing
Tracking
→ Momentum & Energy
Muons
→ Tracking & Momentum
4T
2T
Silicon
Tracker
Electromagnetic
Calorimeter
Hadron
Calorimeter
Superconducting
Solenoid
Iron return yoke interspersed
with Muon chambers
L1 Trigger
High Level Trigger
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Particle ID together in
combination with calorimeter



First: Tracker Challenges

Raw ΣE_T~2 TeV

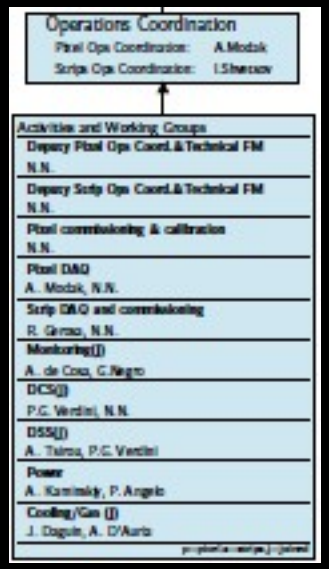
14 jets with E_T>40

Estimated PU~50

Tracker

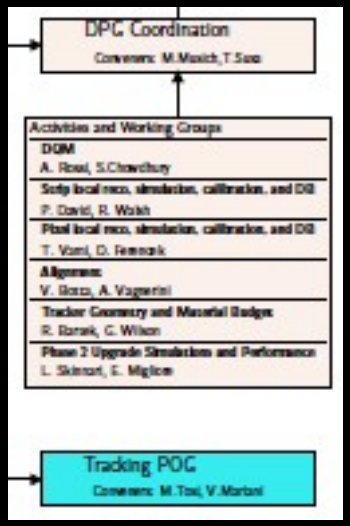
Ops TEAM

- Hardware @ P5
  - Power; cooling; gas
  - Front End Driver FED
  - Front End Control FEC
  - Lots of computers
  - Programmable Logic Controlers PLC
- Online Software
  - Get the data out
    - Detector Control
    - Noise; pedestals; sparsification
- Detector Safety

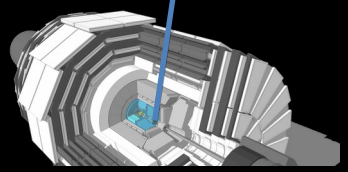


DPG(Offline) TEAM

- Tracker Offline/DPG
  - Calibration & Local Reconstruction
    - How does the signal look like?
    - Simulation
    - Clusters
    - Lorentz Angle
    - Etc.
  - Alignment
    - Where are the sensors; where are the sensor cells?
  - Track reconstruction

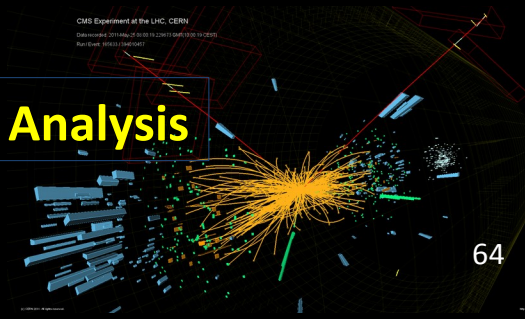


Physics Analysis

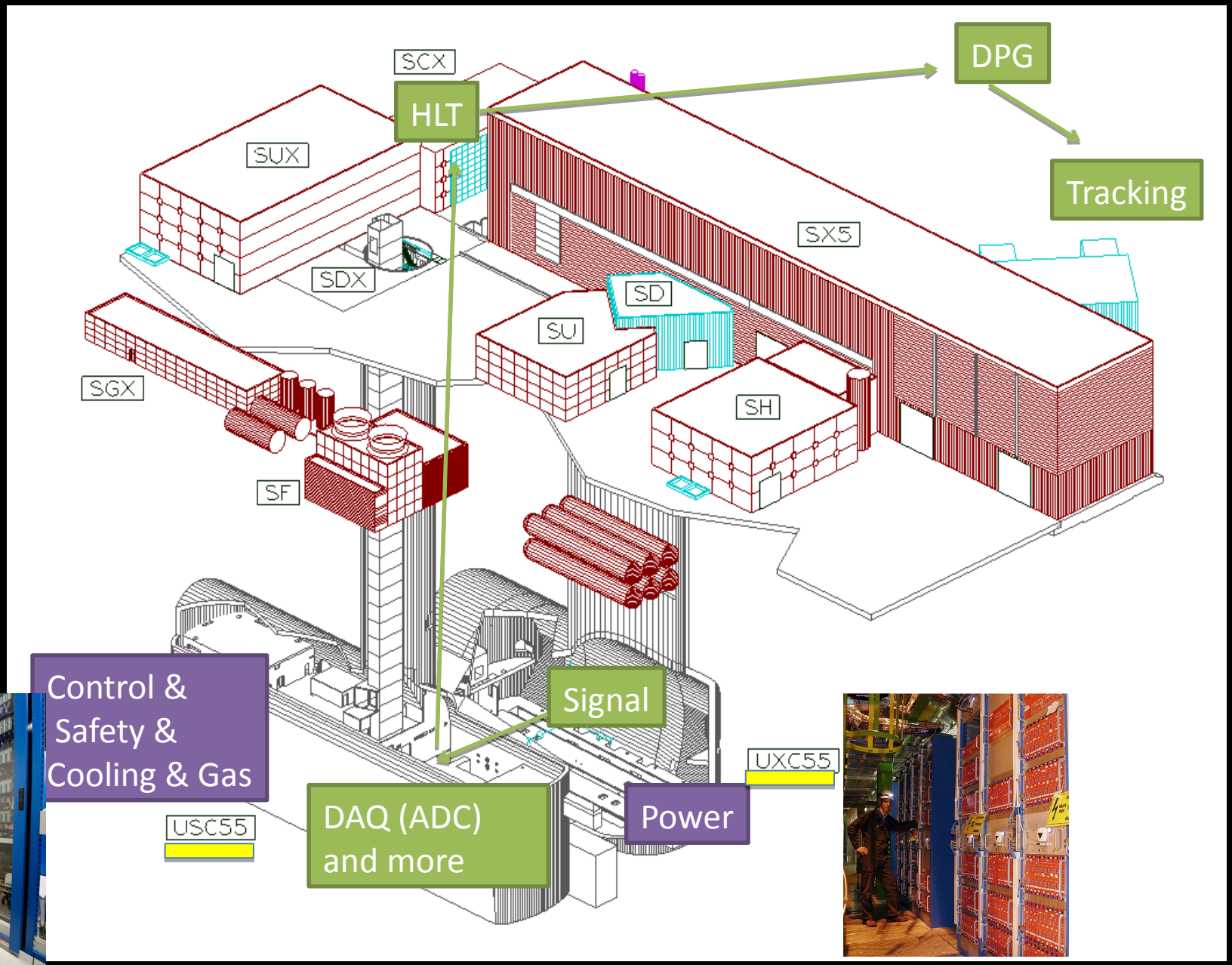


YOUR Physics Signal

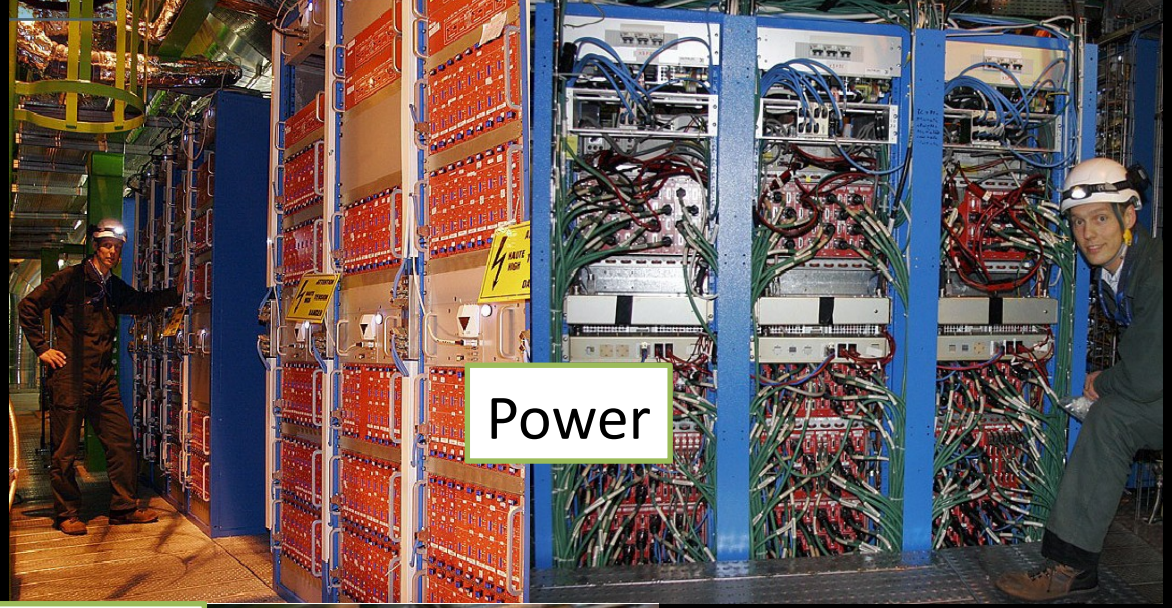
Muon - similar



The signal path and processing



Safety



Power

Dry gas

Tracker Services

Cooling

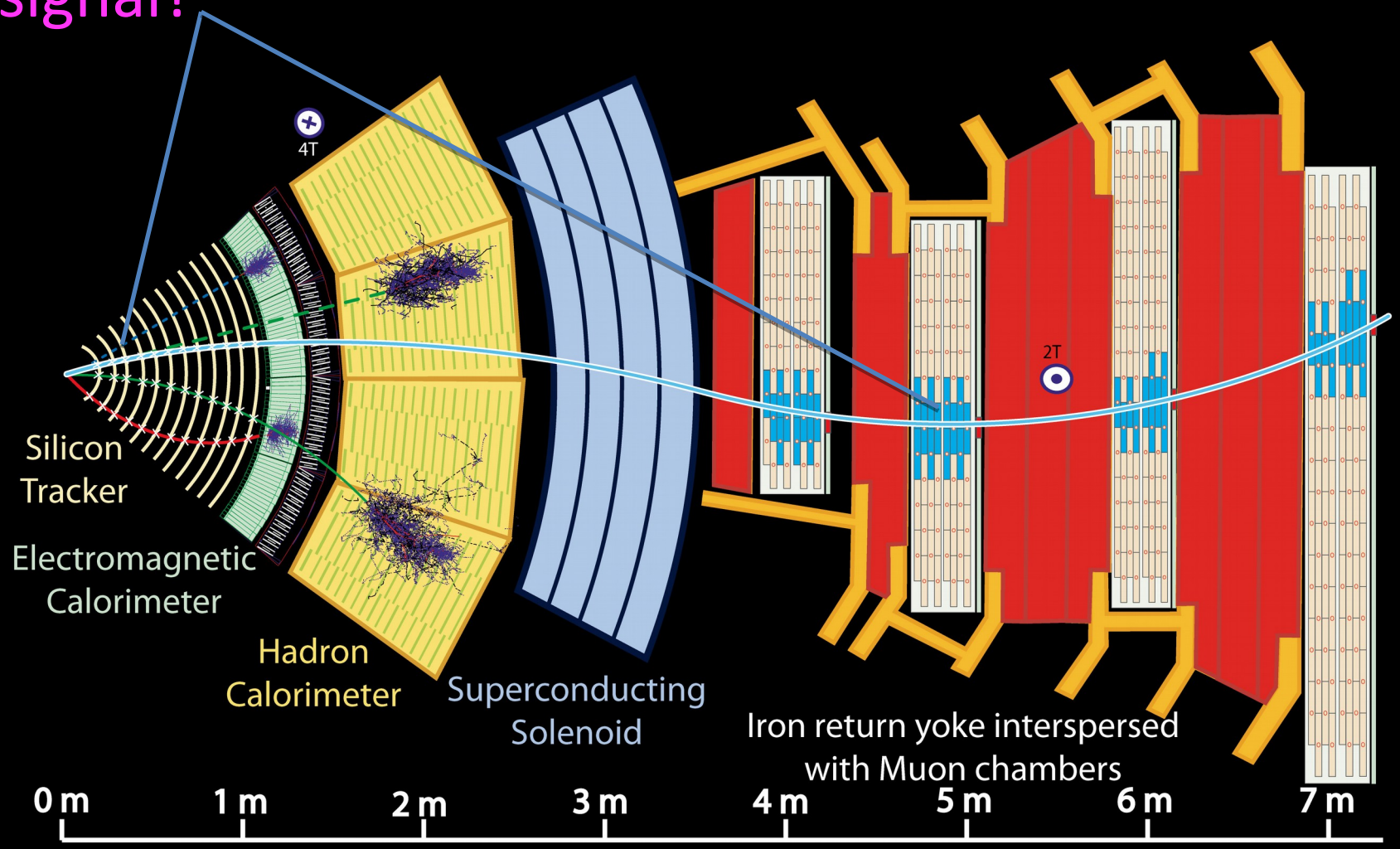
New SS1 cabinet

How is it transferred from the detector and processed to be used in the physics analysis?

What is a signal?

Tracker as example

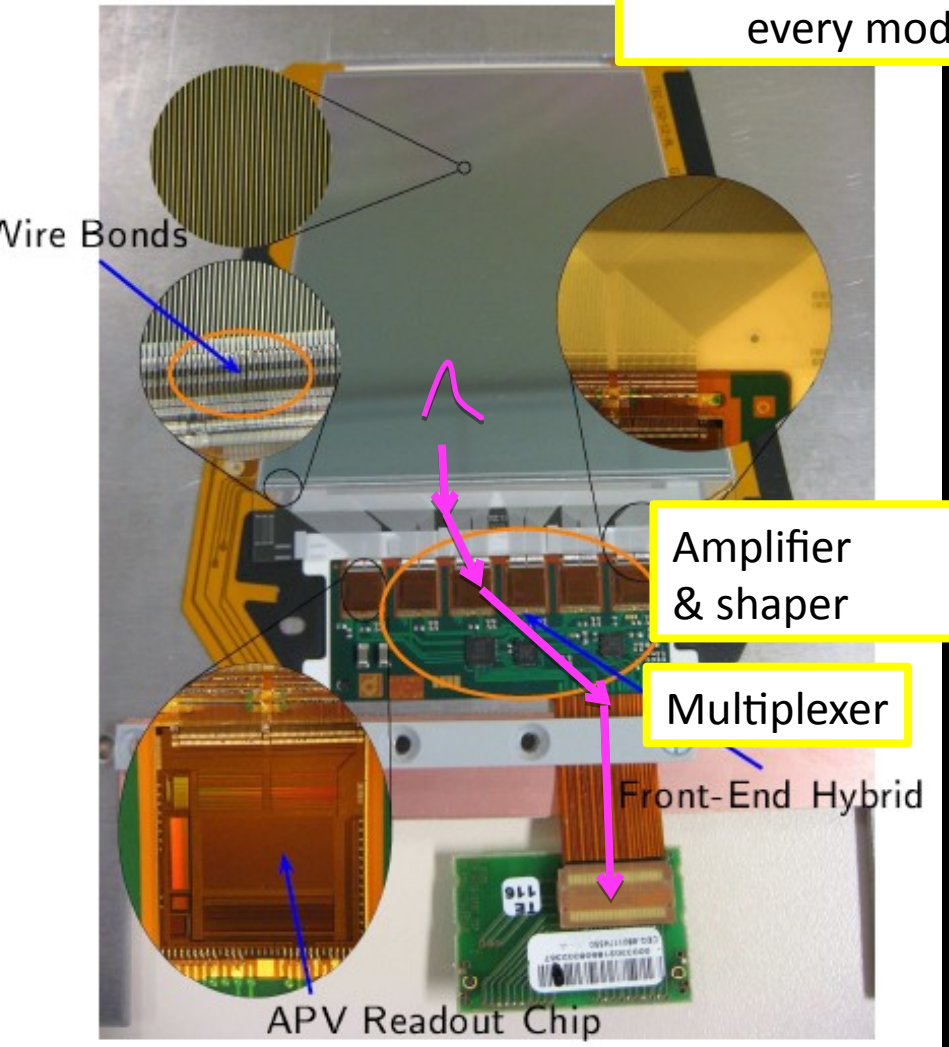
Muons already explained

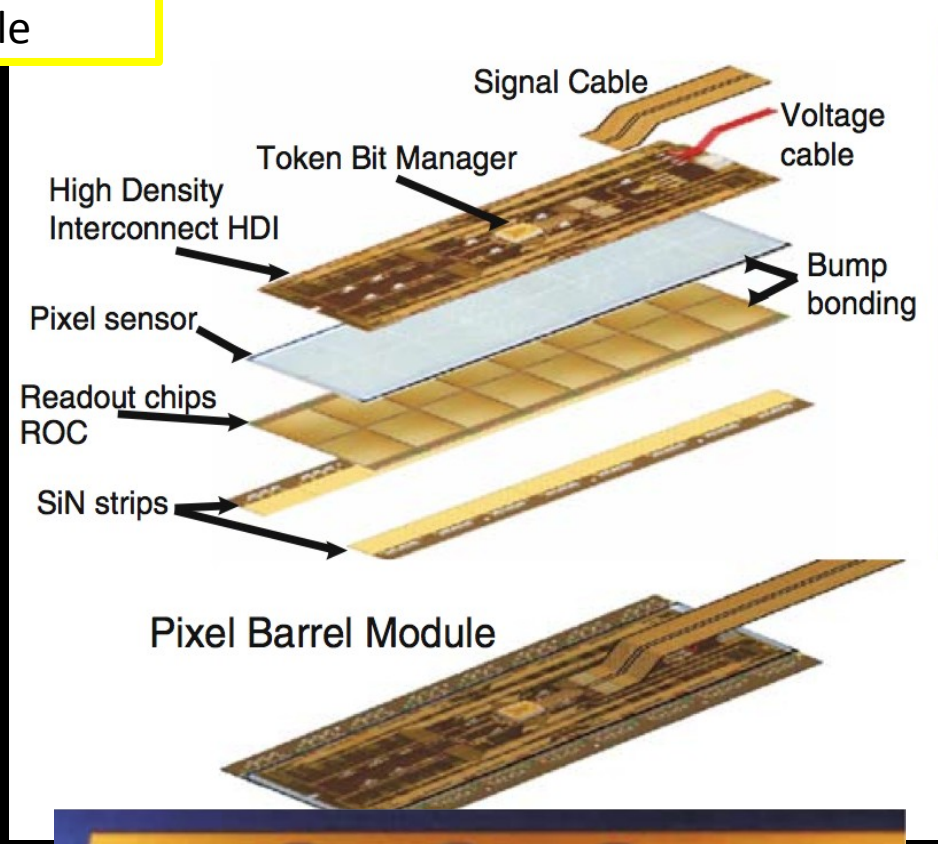


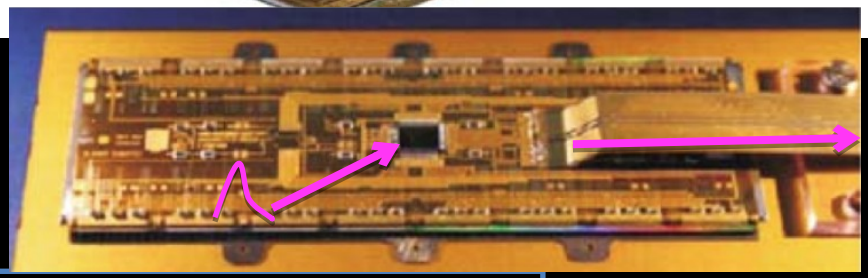
Strips

Ops Team:
Configure & sync (~1ns) every module

Pixels



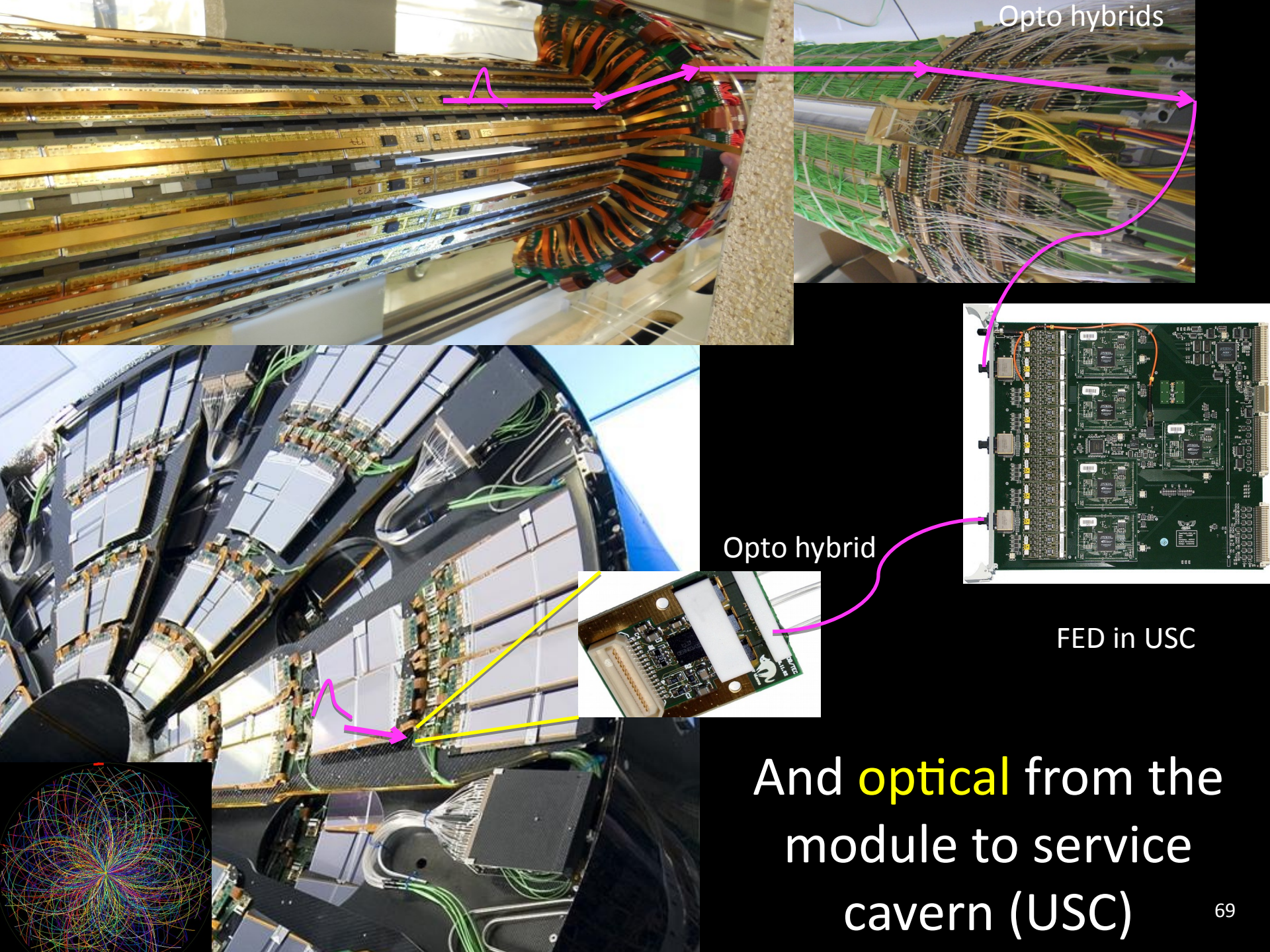




Full analogue pulse height information

Strips - synchronous ergo **full info**

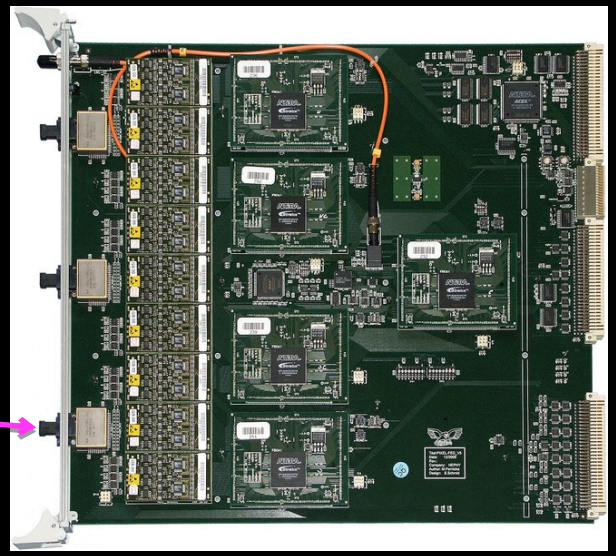
Pixel – asynchronous – **zero suppression**



And optical from the module to service cavern (USC)

Backend processing

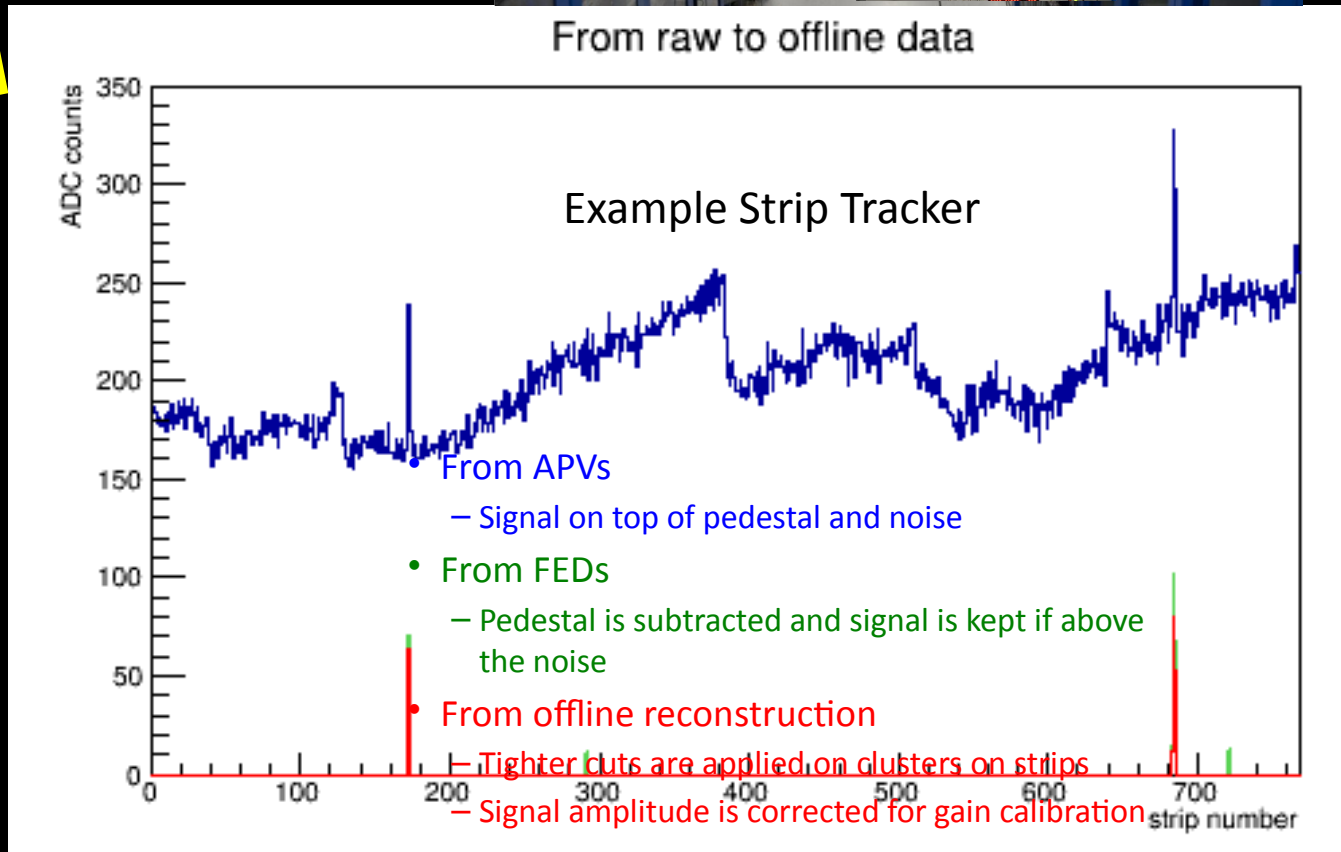
Signal



Ivan.Schvetsov@cern.ch
Anantu.Modak@cern.ch

Frontend Driver FED

- ADC (Analogue → Digital)
- Common Mode and pedestal subtraction
- Zero suppression
  - For strips
- Data Packaging
  - Then to Offline

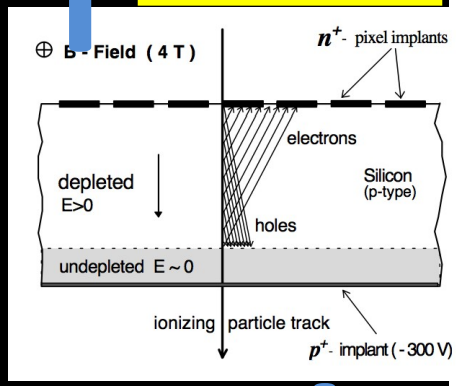


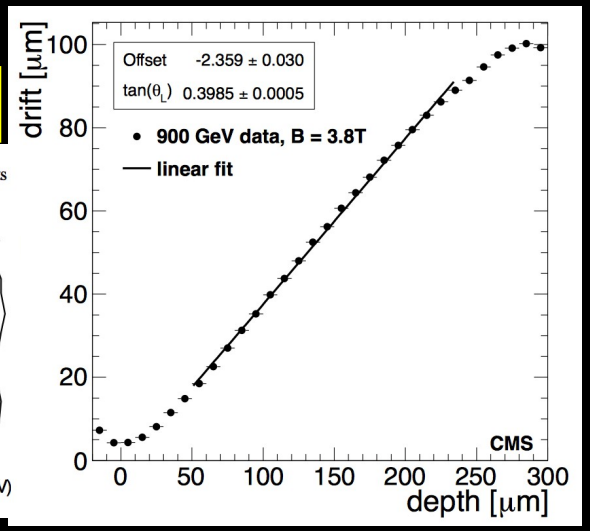
OFFLINE DPG – https://cms.web.cern.ch/org/tracker-dpg

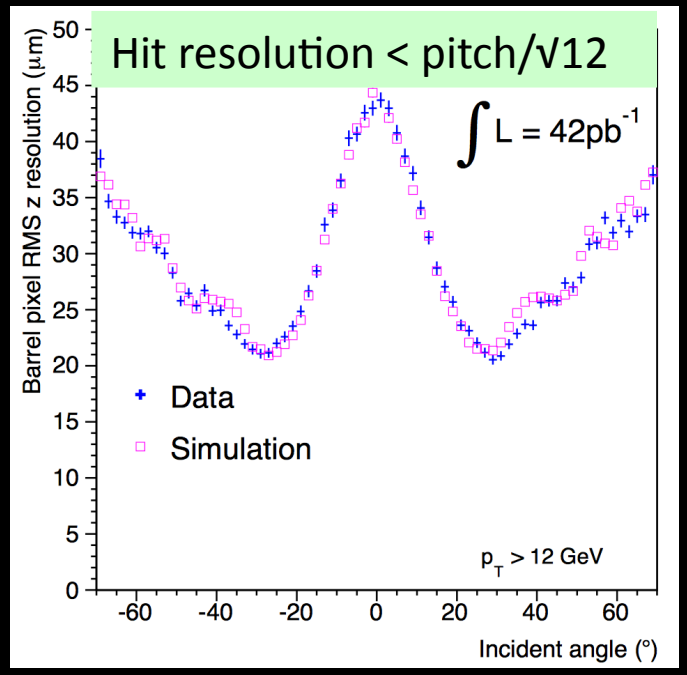
- DPG Task#1:
  Ultimate hit position

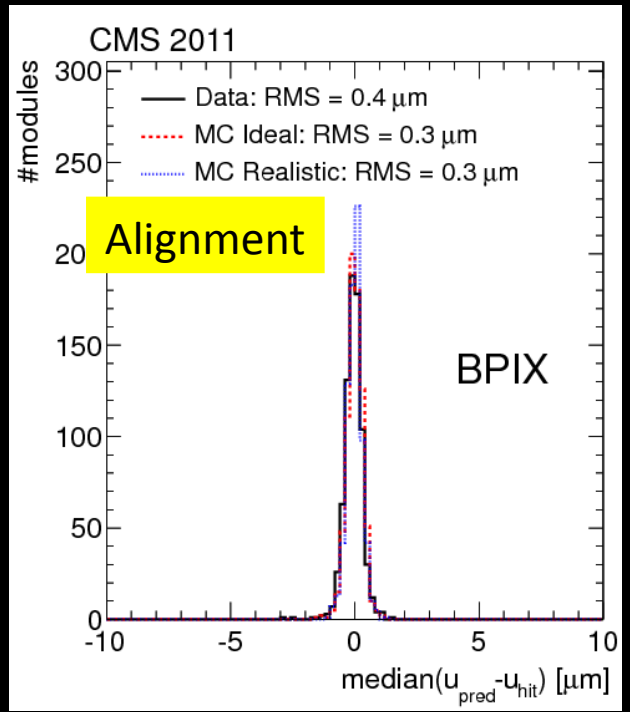
Clustering

Lorentz Angle









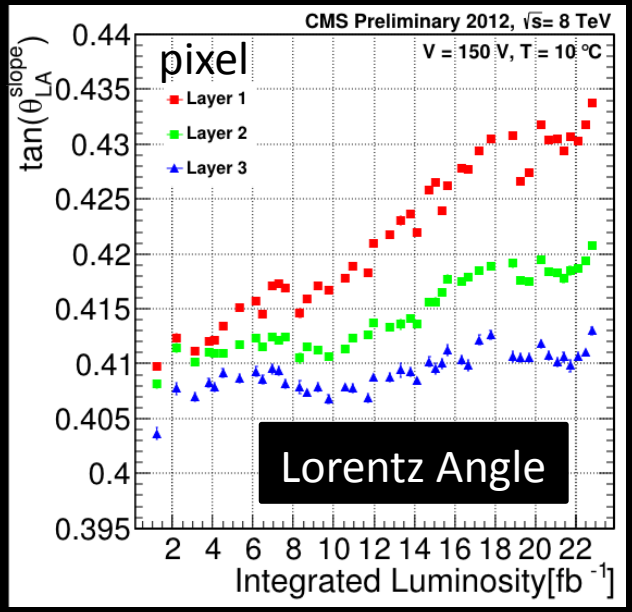
Tanja Susa <tatjana.susa@cern.ch>
Patrick Connor <patrick.connor@cern.ch>

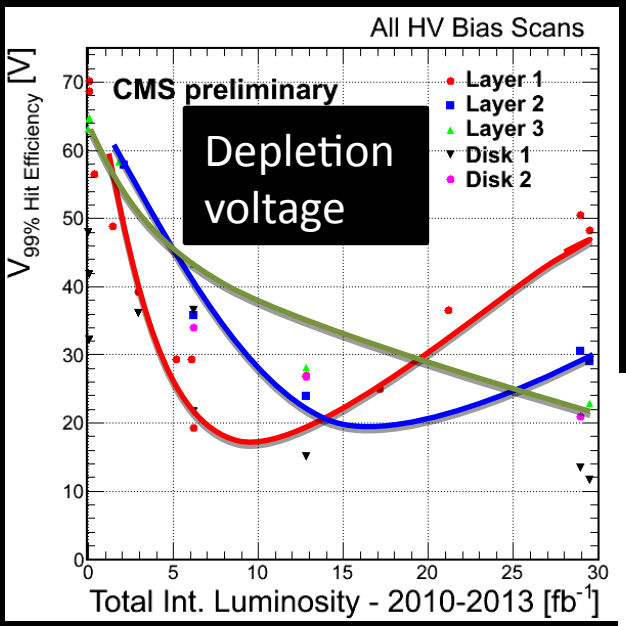
Alignment with Cosmics 2009 http://arxiv.org/abs/0910.2505
Tracker Performance 2010 http://arxiv.org/abs/1007.1988
Alignment with Tracks 2014 http://arxiv.org/abs/1403.2286
Tracking performance 2014 https://arxiv.org/abs/1405.6569

DPG & Ops: Evolution of sensor parameters

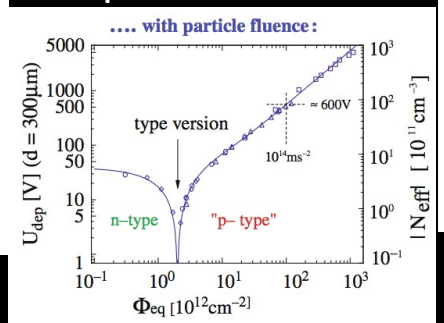
- Radiation changes:
  - Electric field
  - Defects
  - Doping

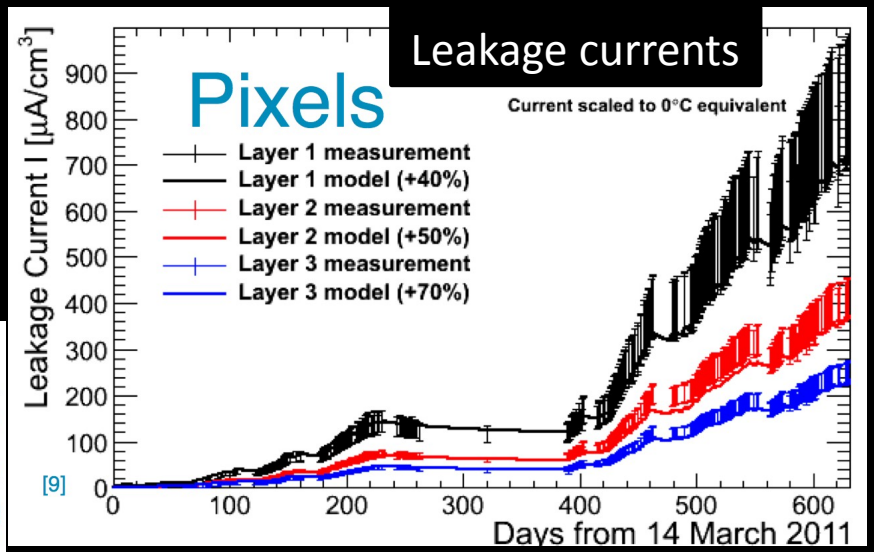
To be compensated and corrected for (DPG)



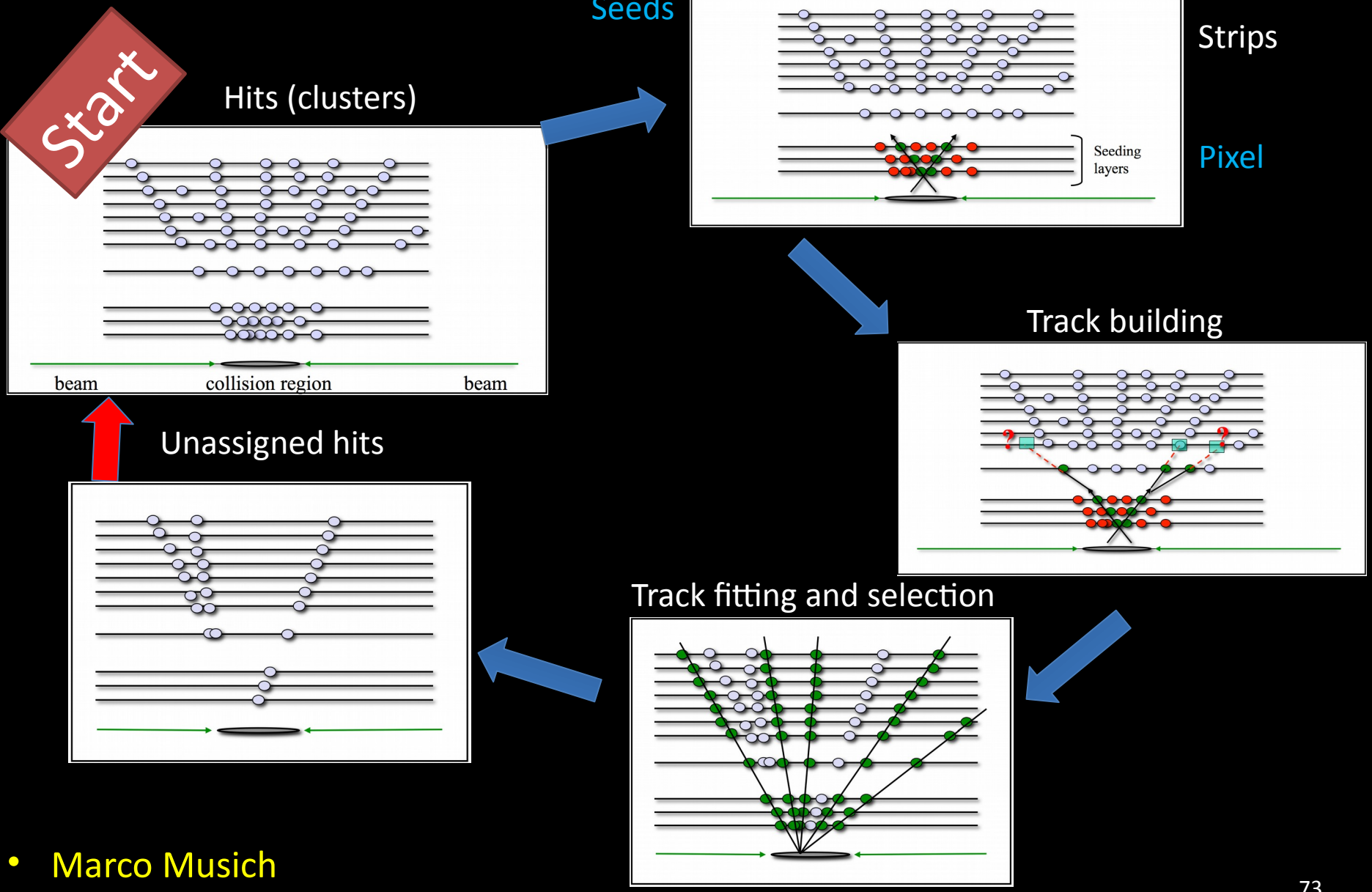


expectation



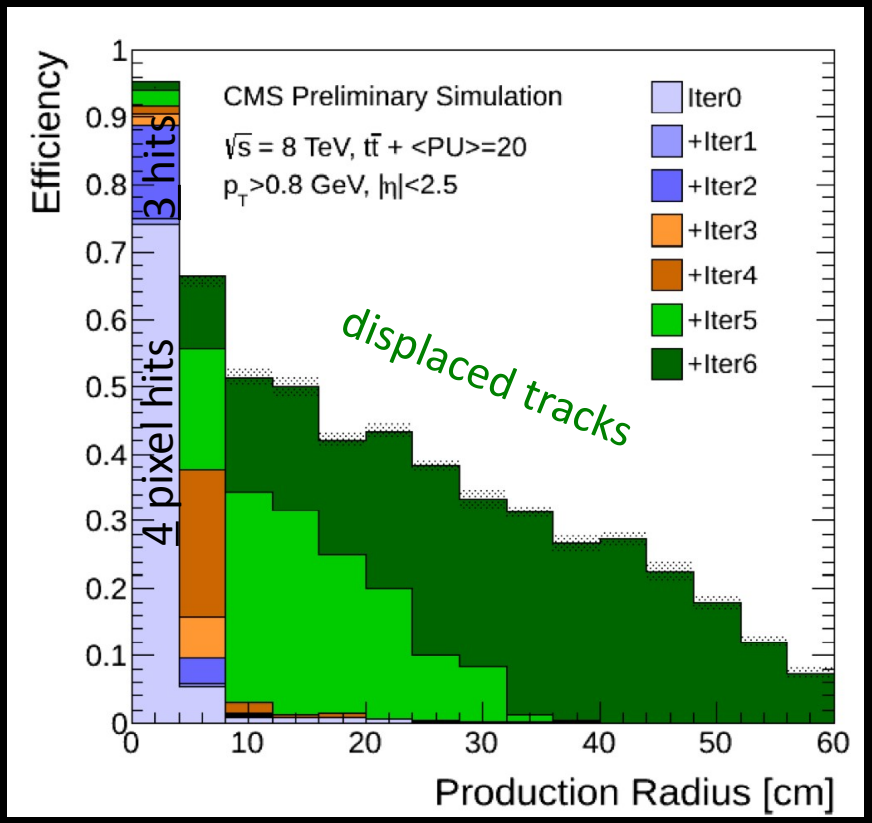


Tracking – https://cms.web.cern.ch/org/**tracking-pog**



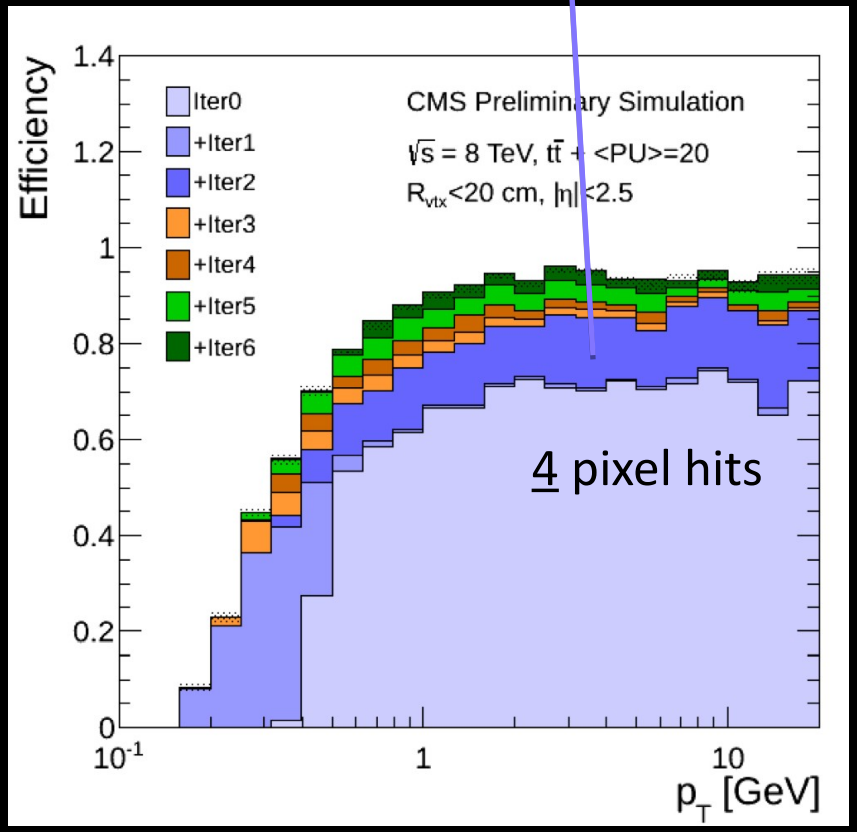
- Marco Musich
- Valentina Mariani

Iterative tracking



Iterations beyond the first one **improve the acceptance** either in *p_T or in displacement*

Only 3 pixel hits ...



0: pixel quadruplets
1: low pt pixel quadruplets
2: pixel triplets. Recover gaps in pixel
3: displaced tracks with pixel quadruplets
4: mixed pixel/strip quadruplets
5: TIB/TEC
6: TOB/TEC

The Goal – Tracking and Vertexing

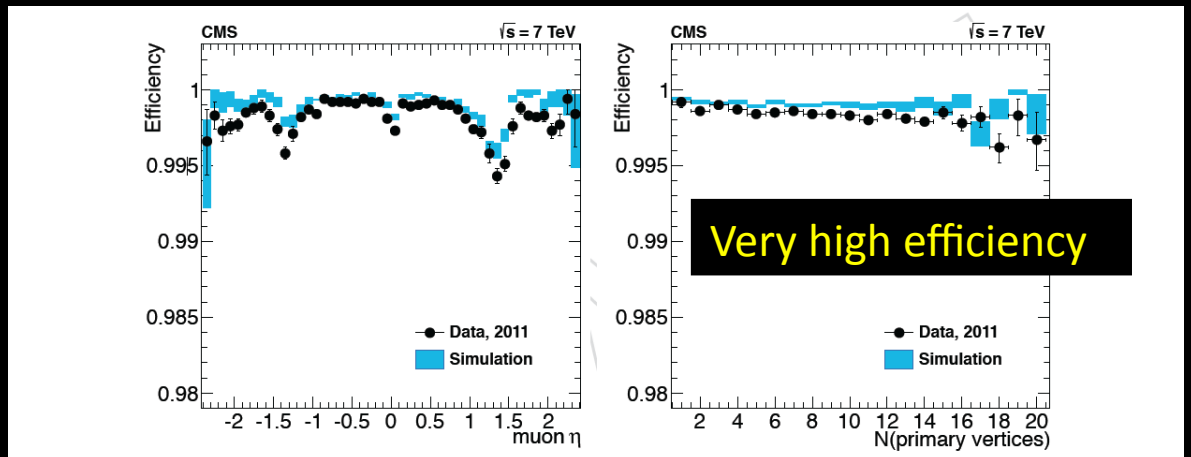
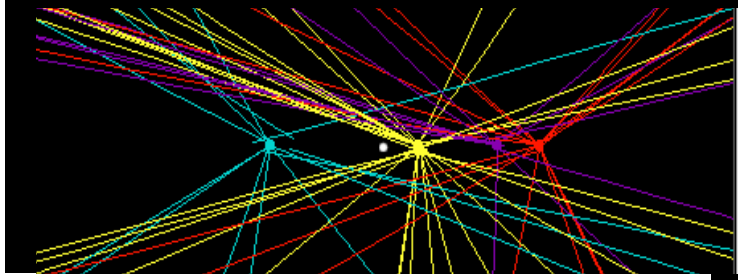
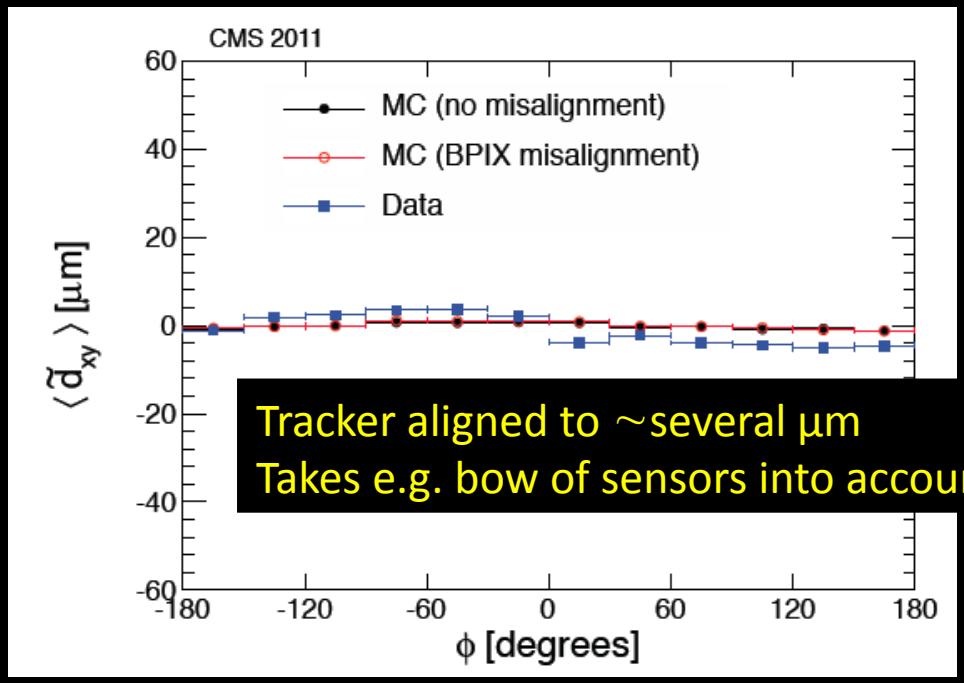
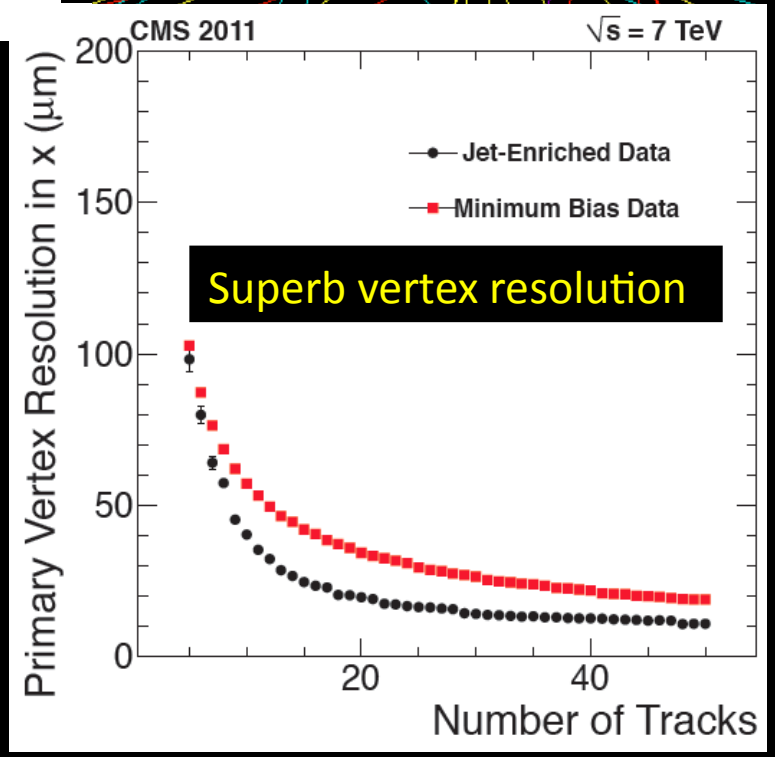


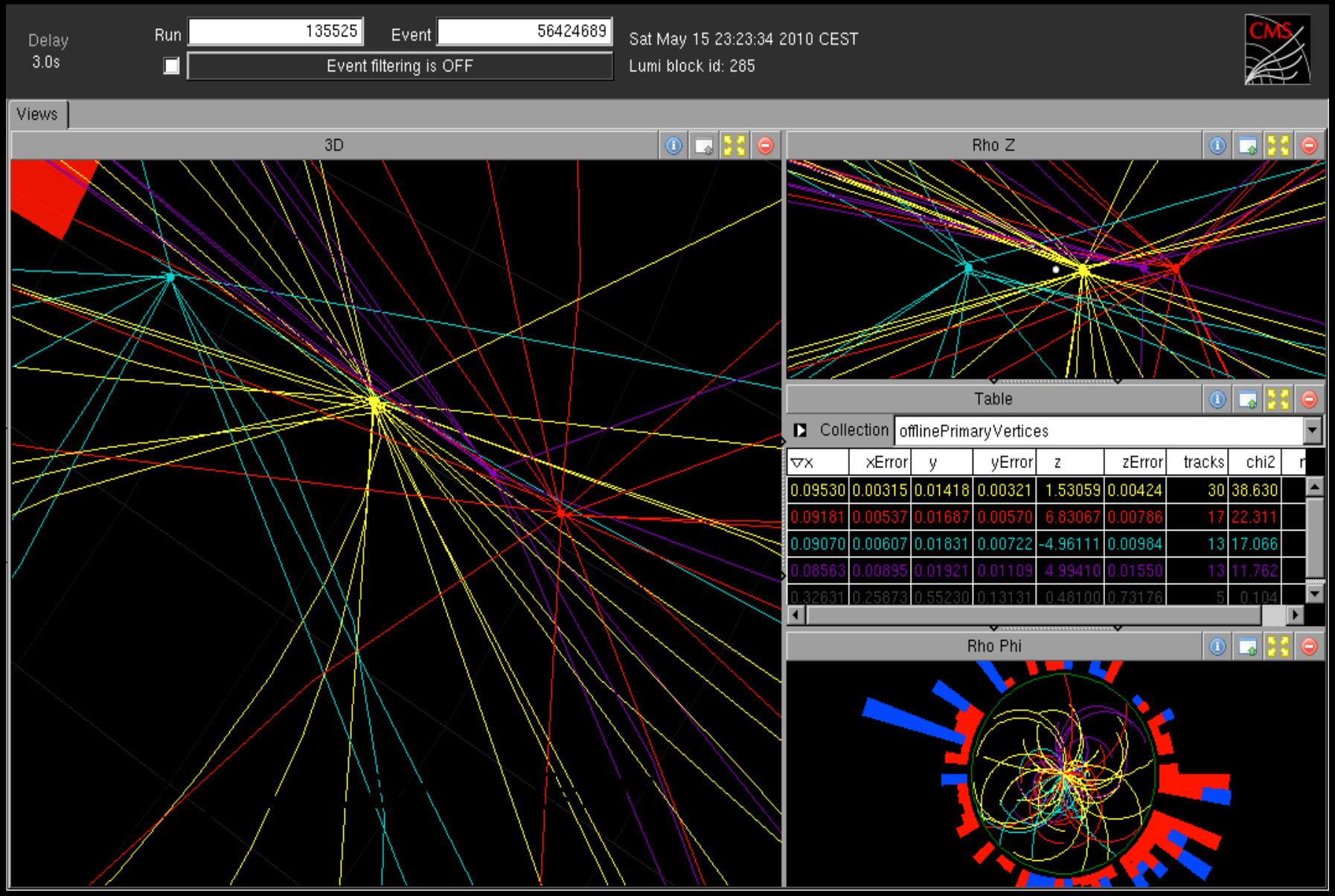
Figure 13: Tracking efficiency measured with a tag-and-probe technique, for muons from Z^0 decay, as a function of the muon η (left) and the number of reconstructed primary vertices in the event (right) for data (black) and simulation (blue).



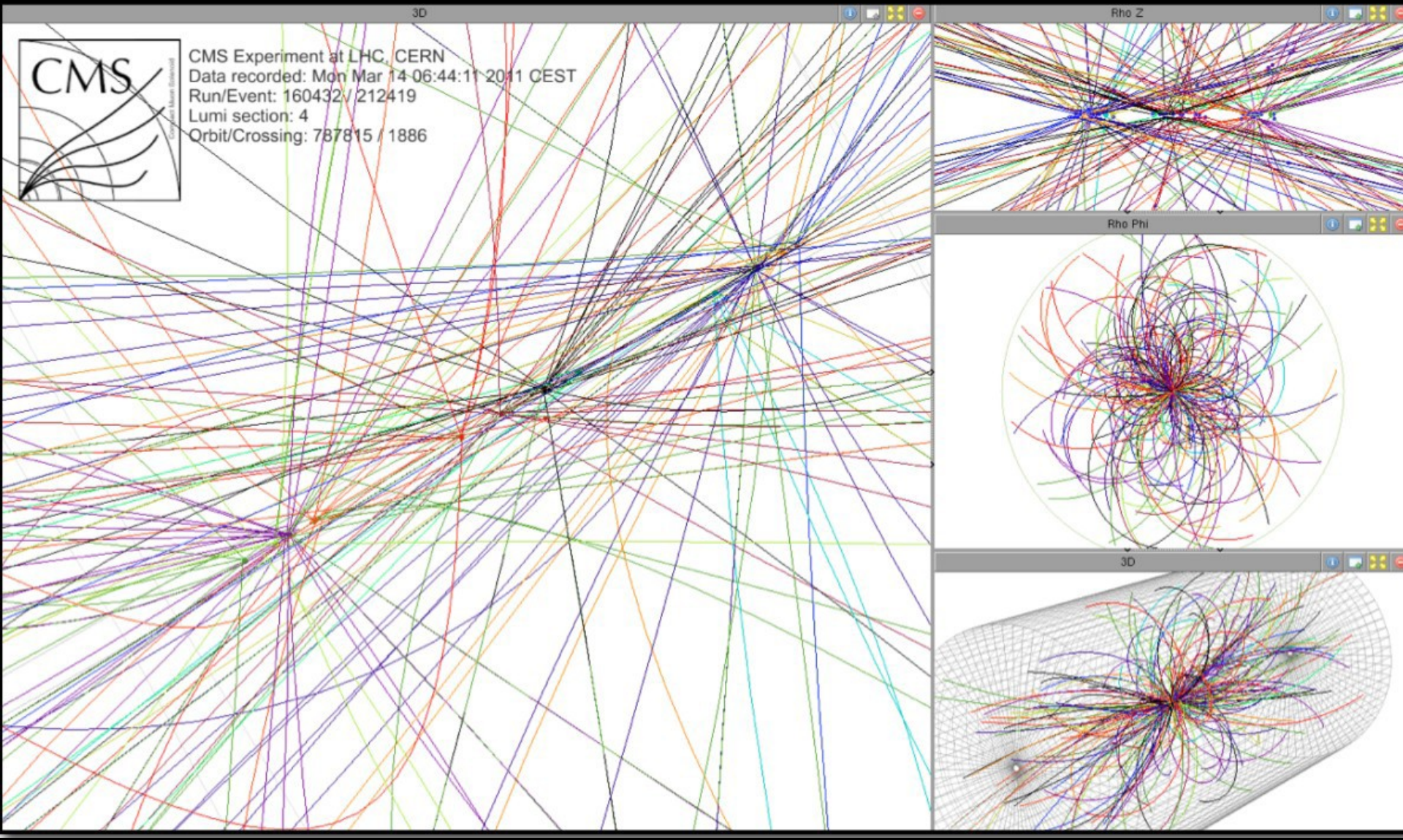




Challenge: overlapping events – pile-up

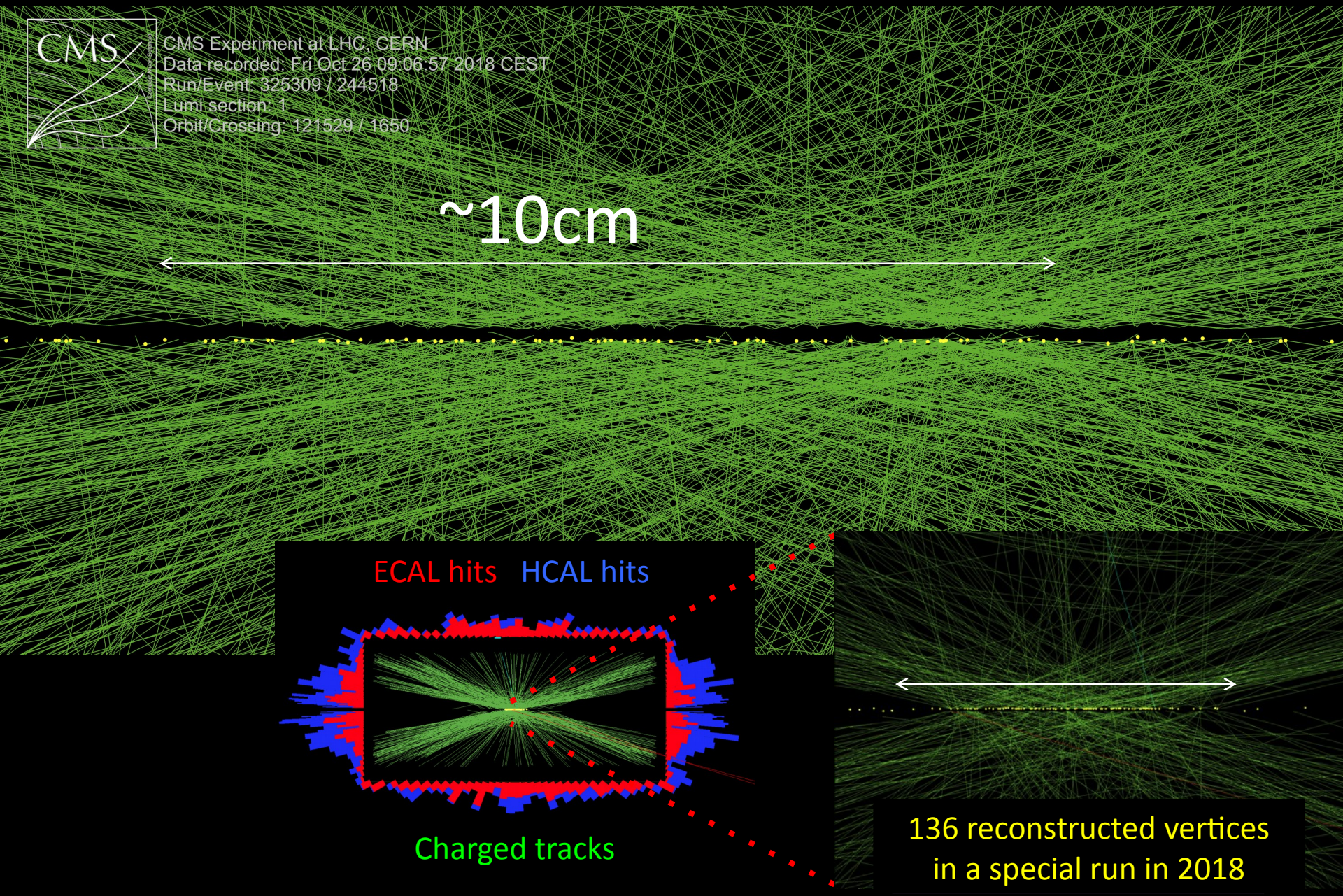


And more pile-up

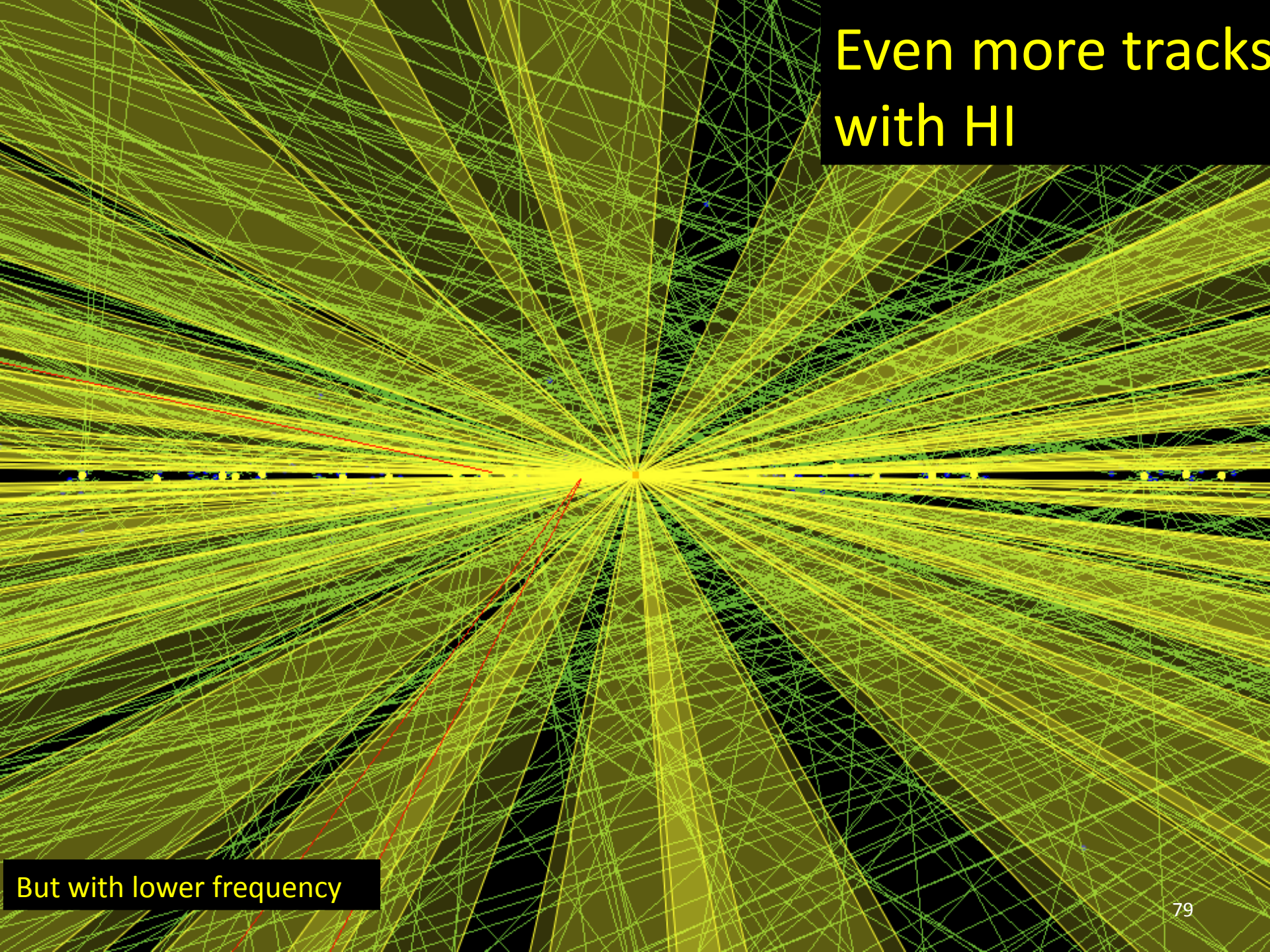


Not the end of the story; mind also the computing power you need to analyze this

The ultimate Pile-Up, so far



Even more tracks with HI



But with lower frequency

Now: The Use of Muon Data

Muon Detector Reconstruction

Local reconstruction

DT

Hit position = $(T - T_0) \times V_{drift}$

8 Layers r-ϕ + 4 Layers r-Z (8 + 4 hits) → **Local 3D DT Segment** (Spatial position + direction)

CSC

Hit position

ϕ: Interpolated **charge** from *cathode strips*
→ gravity center

r: *anode wire "group"* **position**
(wires ganged into wire groups 1-2cm)

6 Layers ϕ + 6 Layers Z (6 + 6 hits) → **Local 3D CSC Segment** (Spatial position + direction)

RPC

Hit position

ϕ: Interpolated **charge** from *cathode strips*
→ gravity center

1 Layer (1 hit) → **RPC Spatial position**

Stand Alone muon tracks

Reconstructed combining information from the 3 subsystems

Use of muon detector data

- **Triggering*** CMS is crucial:
  - Impossible to read out all data from 40 MHz LHC crossings
  - Muon Level 1 trigger rate is ~10 kHz, a factor O(100K) reduction, before tracker and other detectors read out to computer farm

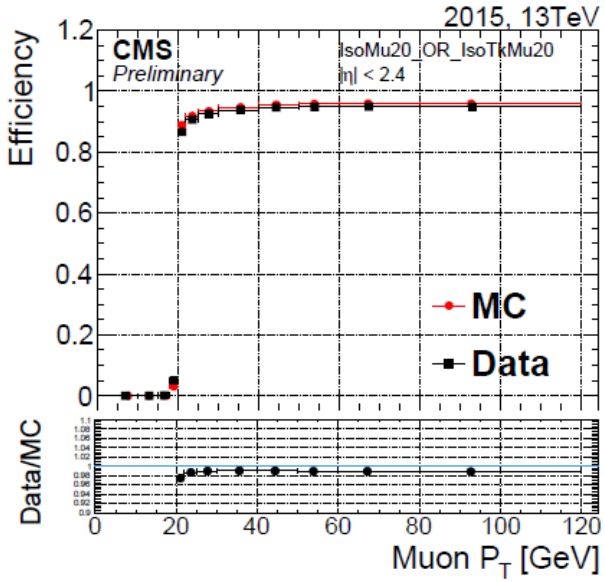
- **Muon ID:** tracks well associated with muon hits are called muons for offline physics analysis

- **TeV muon momentum measurement:** much improved
  – makes use of 3 times longer path length to the solenoid
  (**3 m versus 1.1 m** radius of silicon tracker)

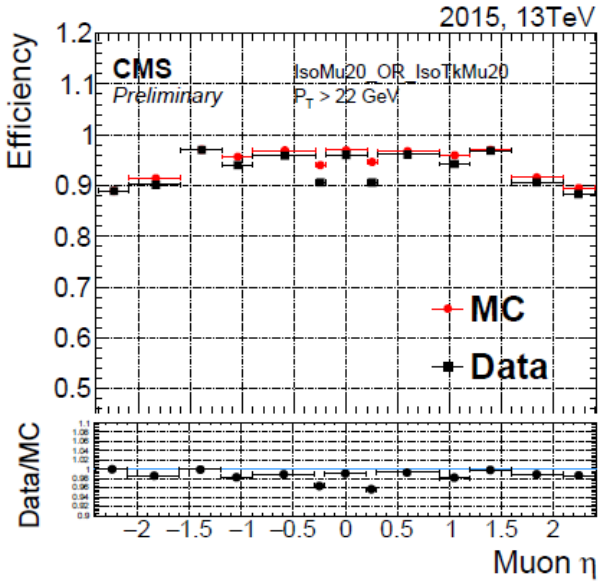
Muon trigger and offline efficiencies

High-Level trigger

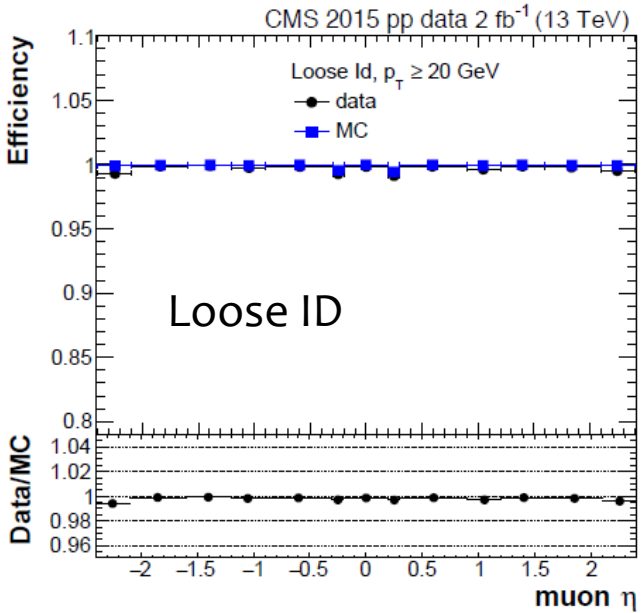
versus momentum



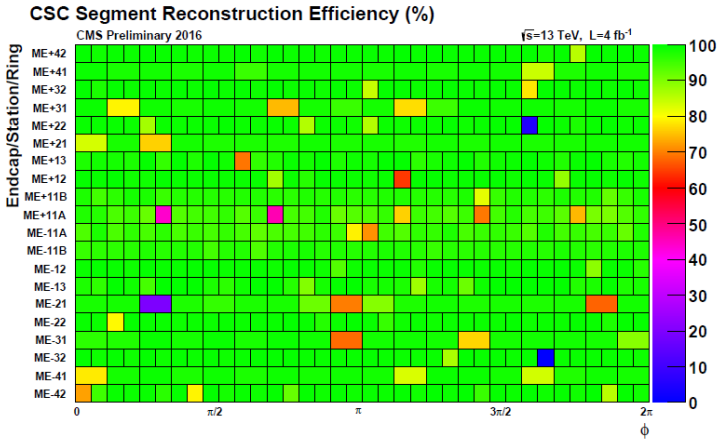
versus pseudorapidity



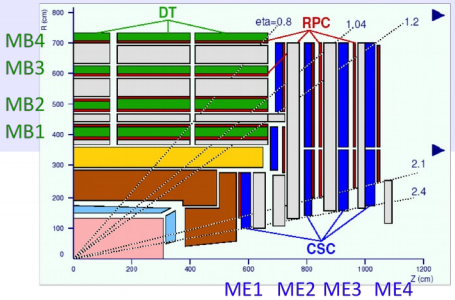
Reconstruction + ID efficiency vs η -- simulation



Example: CSC segment efficiency, per chamber

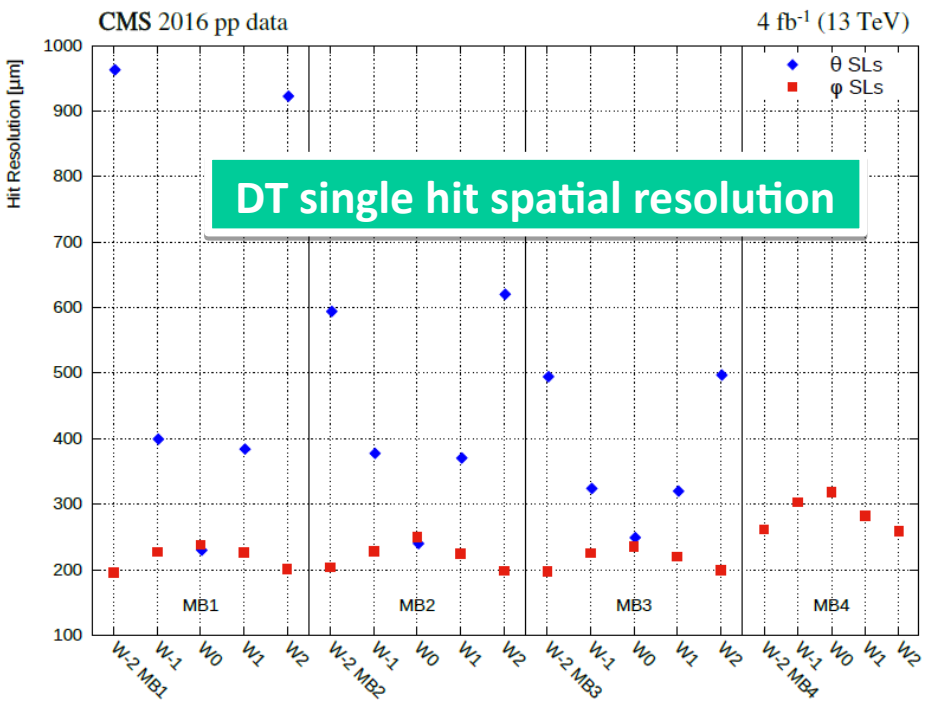


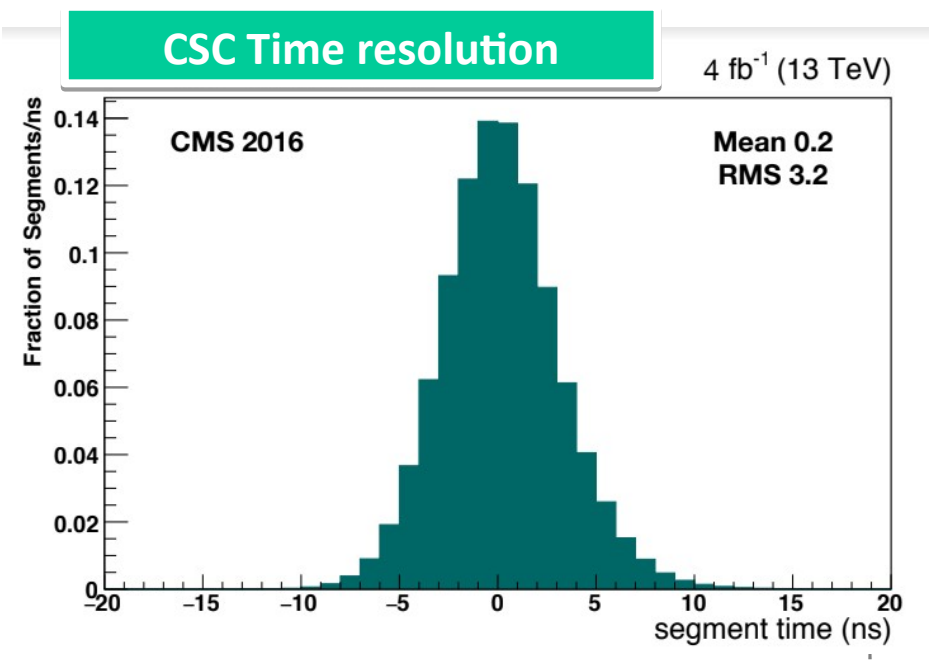
Local muon performance



Source http://dx.doi.org/10.1088/1748-0221/8/11/P11002:

- The spatial resolution per chamber was
  - 80-120 μm in the DTs,
  - 40-150 μm in the CSCs,
  - and 0.8-1.2 centimeters in the RPCs
- The time resolution achieved was 3 ns or better per chamber for all 3 systems





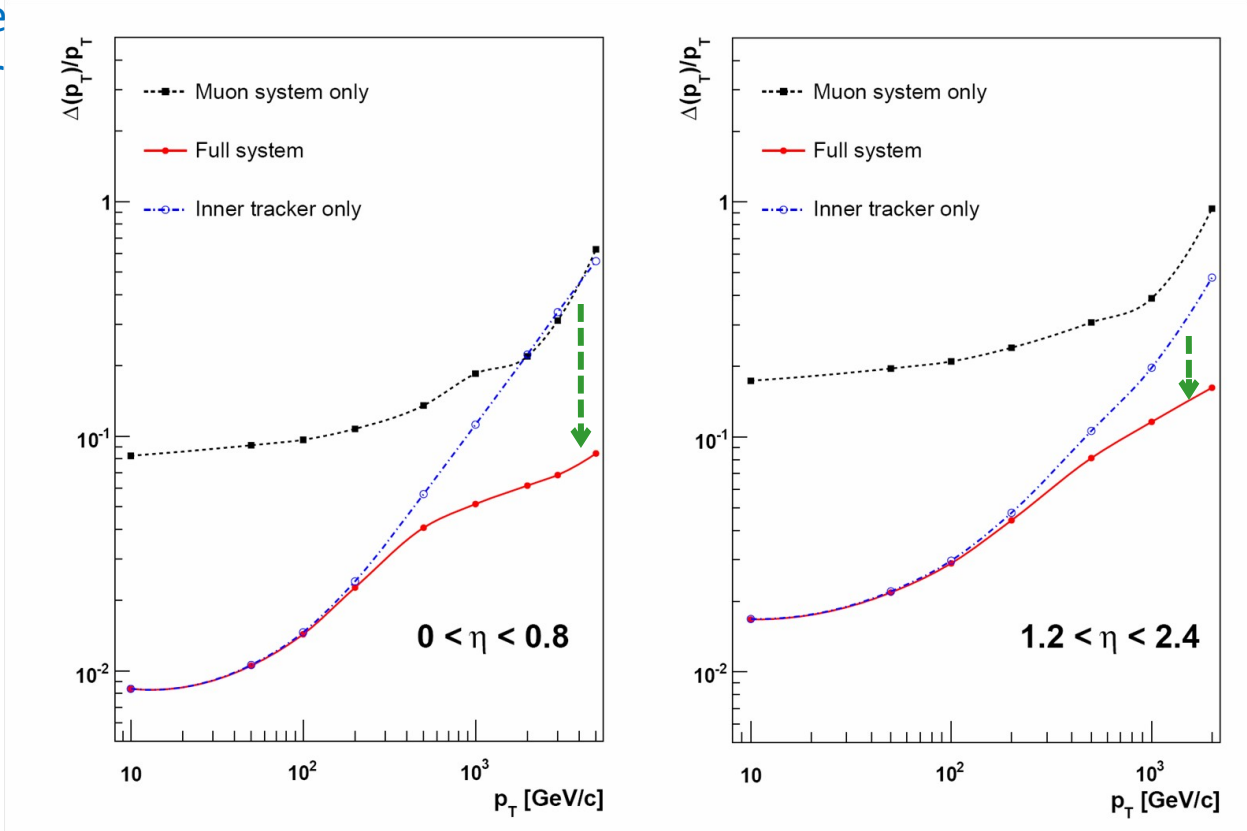
Muon resolution and alignment

The μ measurements improve the momentum resolution for p_T > 200 GeV/c if the DT/CSC chambers are properly aligned

Especially for p_T>1 TeV

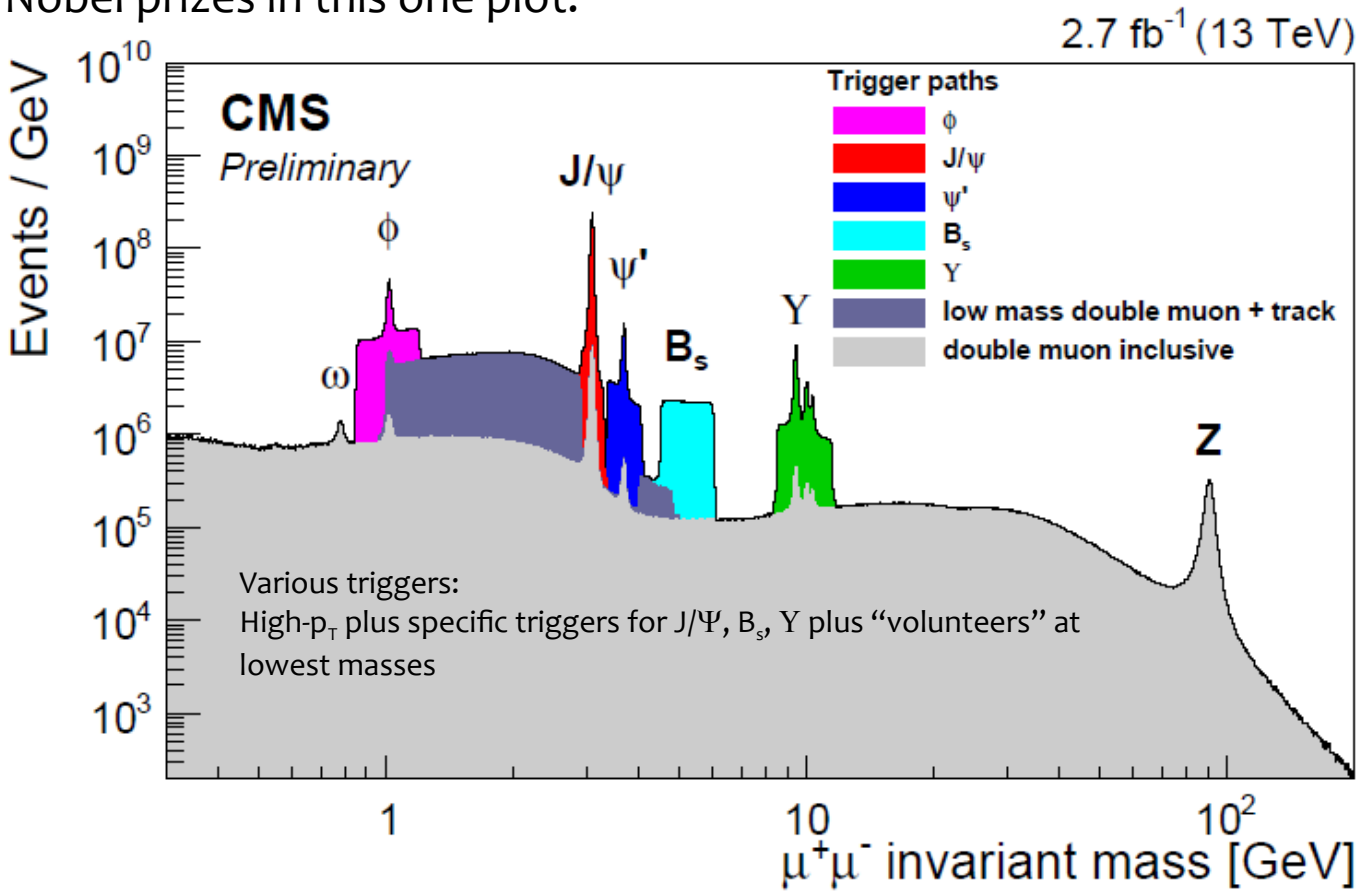
Alignment is done with hardware sensors to **<1 mm** level, then track-based correction to chamber positions to **~10 μm** level

Design muon transverse momentum resolution



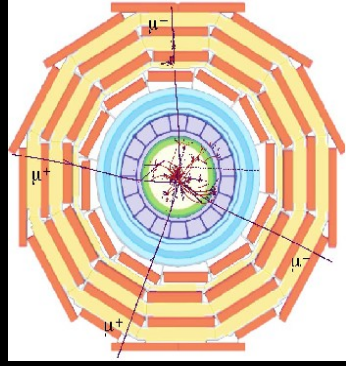
Physics example: dimuon mass spectrum

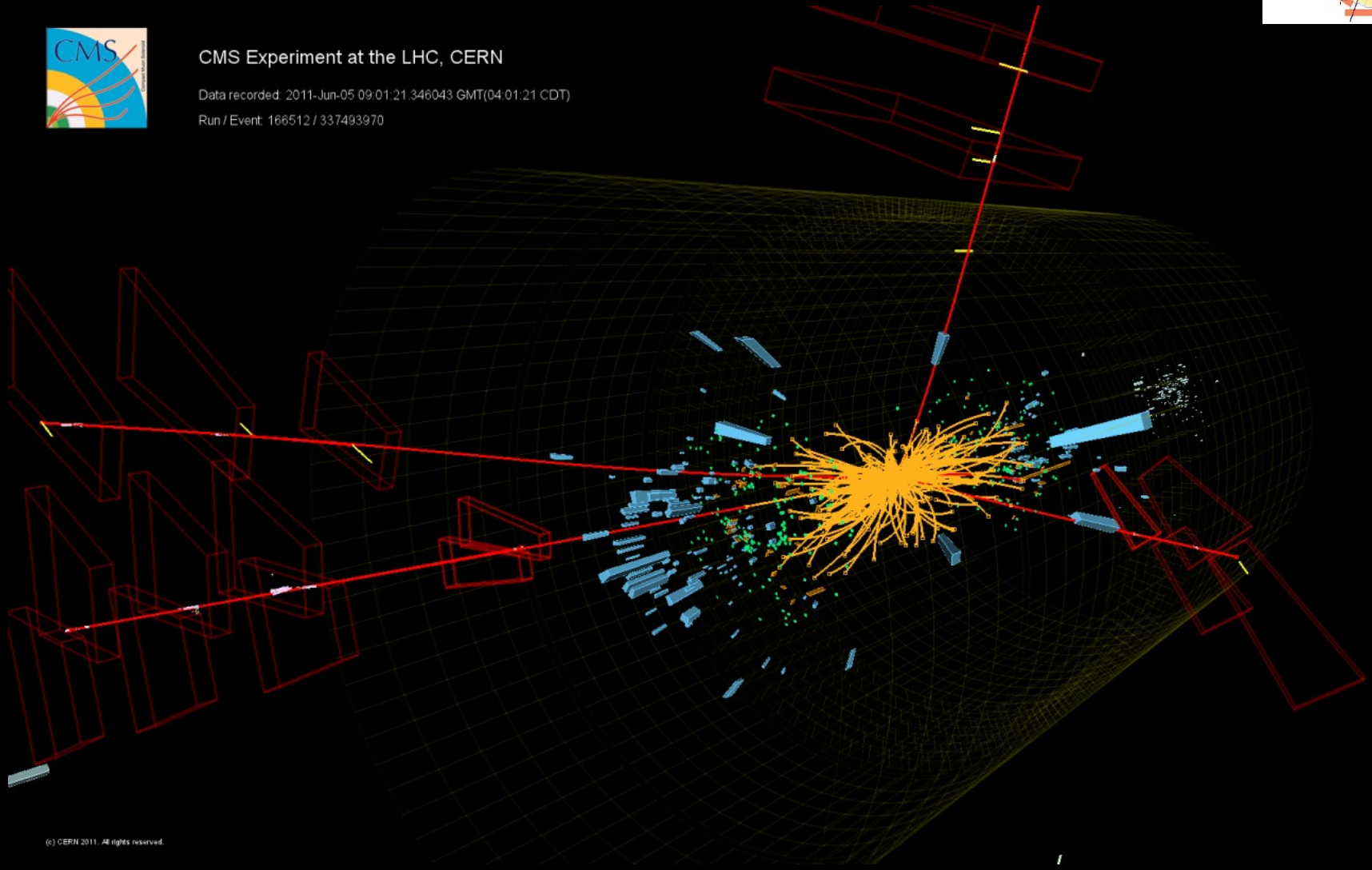
- Trigger CMS readout on muon pairs of various types
- Verify high muon quality by matching muon hits with silicon tracker tracks; use momentum vectors from the silicon tracker fitting
- From invariant mass of muon pair
- Several Nobel prizes in this one plot:



All together Resulting in

Eg : A possible Higgs boson decaying to four muons in CMS

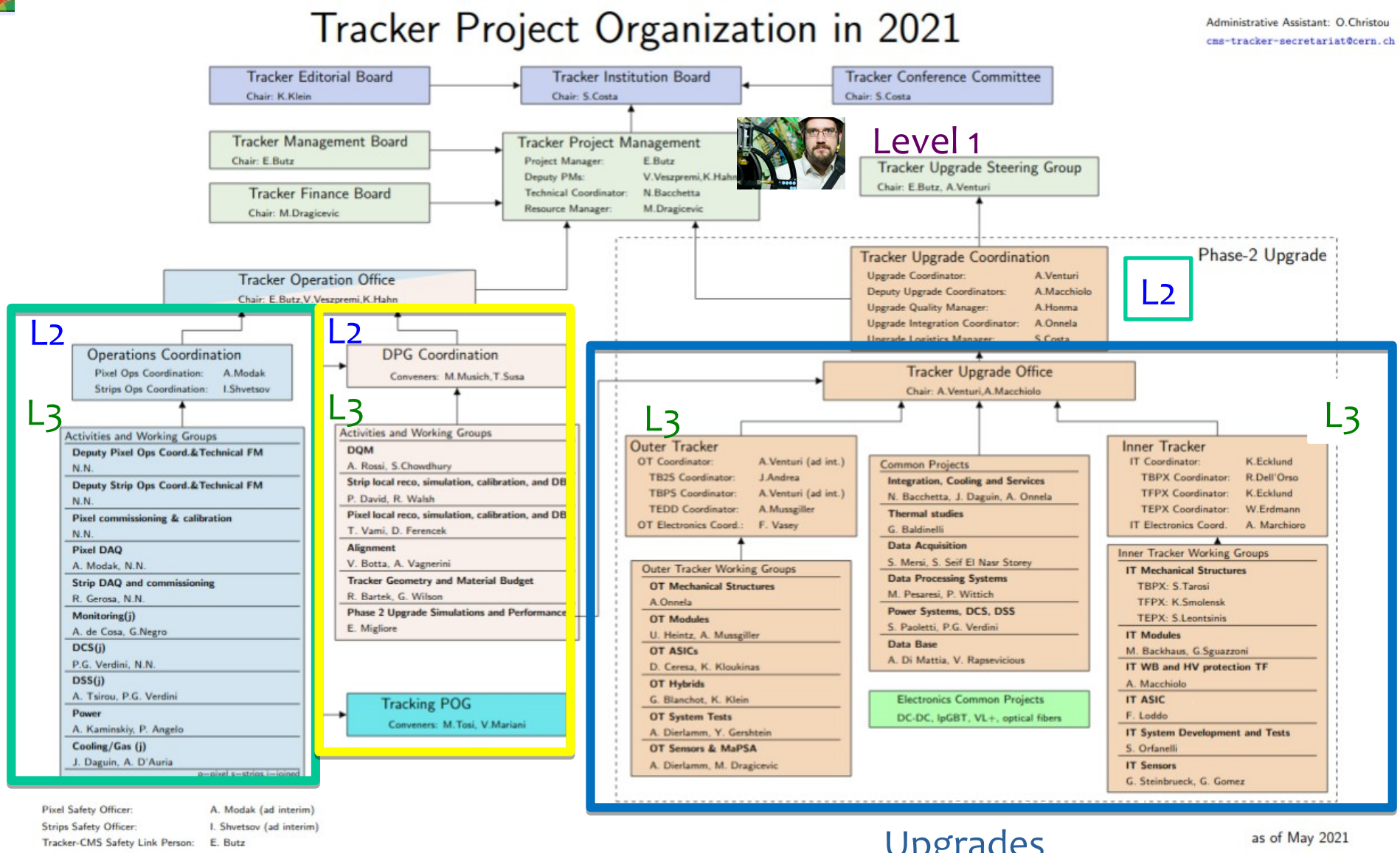




Who is coordinating these detectors? How do you find out what is going on and where you can contribute?

PEOPLE AND OPPORTUNITIES

The Tracker Team embedded in CMS



Upgrades

Ops team @P5

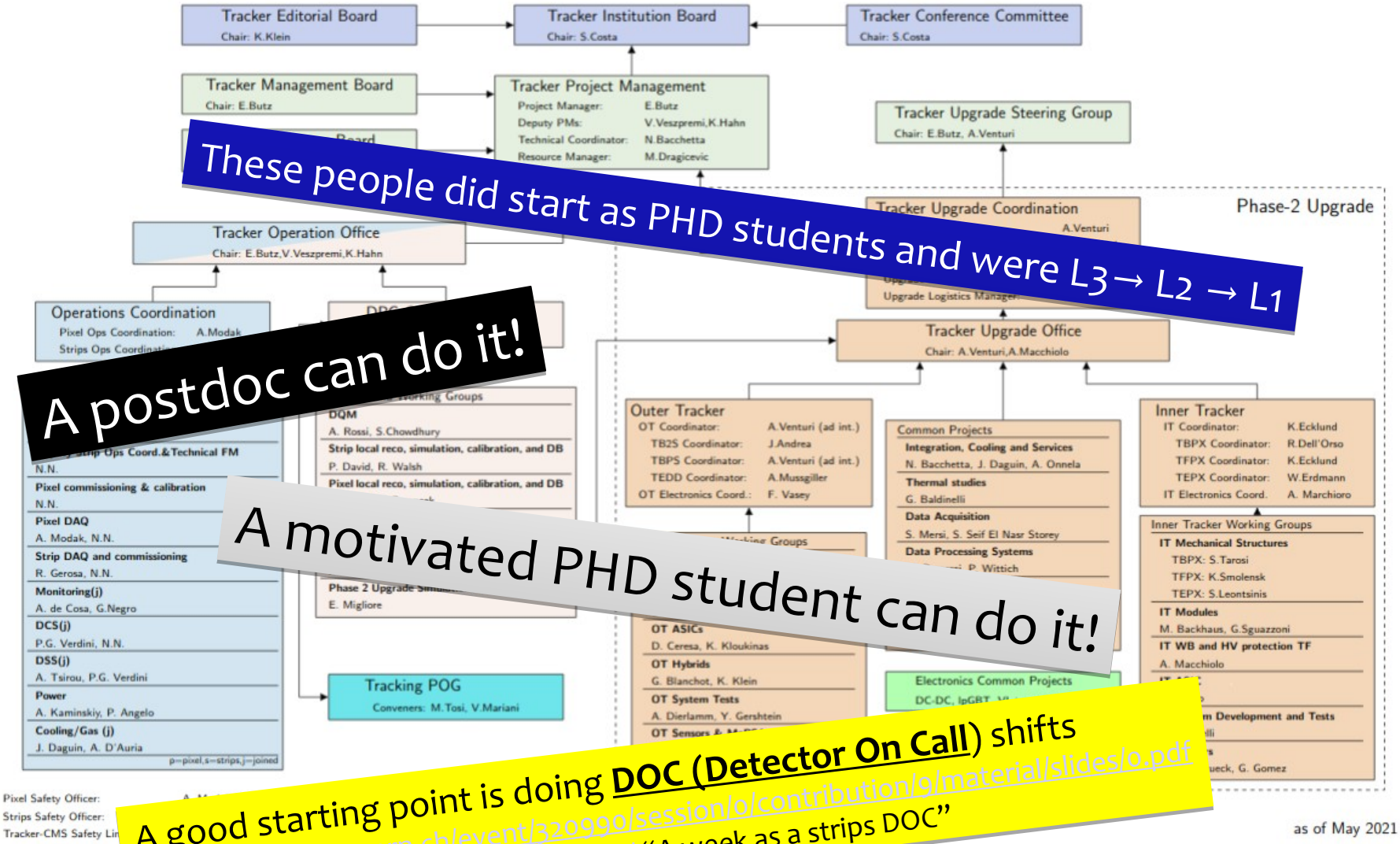
The offline team - DPG

All the above can be approached 24/7 – they LIKE to help!

The Tracker Team

And we are actively helping conveners to find a job

Tracker Project Organization in 2021



These people did start as PHD students and were L3→ L2 → L1

A postdoc can do it!

A motivated PHD student can do it!

A good starting point is doing **DOC (Detector On Call)** shifts
See https://indico.cern.ch/event/320990/session/0/contribution/9/material/slides/0.pdf
And https://indico.cern.ch/event/324519/ "A week as a strips DOC"

Muon Institution Board

Muon IB Chair
A. Colaleo
Deps: P. Iaydjiev, R. Erbacher

CSC IB Chair
S. Durkin

DT IB Chair
K. Hoepfner

GEM IB Chair
P. Giacomelli

RPC IB Chair
T.J. Kim

Conf. & Pub. Board B. Pavlov (Chair), J. Puerta Pelayo (Deputy)
(DT) B.A. Gonzalez, J. Piedra; (CSC) M. Herndon, J. Richman, R. Breedon, D. Loveless; (RPC) M.F. Shopova S. Qian, E.F.Vazquez, K.S. Lee, ; (GEM) P. Karchin, O. Bouhali, P.S.Iaydjiev, F.Fallavollita, I.Vai; (DPG) R. Hadjiiska

Internal Scrutiny Group
M. Dalla Valle (Chair), B. Choudhary, F. Geurts, U. Yang, M. Dragicevic (ext)

Outreach
J.P. Pelayo

Muon SM
G. Pugliese
Dep.: H. Hoorani

Muon Management Board

CSC PM
J. Wang
Dep: D. Morse

DT PM
D. Fasanella
Dep: C. Battilana

RPC PM
S. Buontempo
Deps: N. Zaganidis
S. Fonseca

GEM PM
A. Sharma
Deps: A. Safonov,
G. Lentdecker

Reps.

TCO
TBD

RMO
TBD

DPGO
TBD

UCO
TBD

ECO
TBD

CSC RM
M. Herndon

CSC TC
M. Ignatenko
Dep: D. Morse

CSC DPG
T. Cox
Dep: V. Valuev

CSC UC
J. Kim
Dep: E.Kuznetsova

CSC RunC
I. De Bruyn
Dep.:J.S.Bonilla Castro

CSC Elec
S. Durkin
Dep.: J. Gilmore

DT RM
S. Maselli

DT TC
L. Borgonovi
Dep: D. Dattola

DT DPG
F.R. Cavallo
Dep: C. Battilana

DT UC
C.F. Bedoya
Dep.:I.G. Caballero

DT RunC
A. Sharma
Dep: B. Kiani

DT Elec
S. Ventura
Dep: D. Elissev

RPC RM
P. Salvini

RPC TC
A. Dimitrov
Dep: K. Mota

RPC DPG
A.Cabrera
Dep: J.J. Goh

RPC UC
M.A. Shah
Dep: M. Gouzevitch

RPC RunC
A.Aleksandrov
Dep: F. Silva

RPC Elec
B. Boghrati
Dep: S. Meola

RPC Trigger
R. Hadjiiska
Dep: Z. Liu

GEM RM
C. Riccardi

GEM TC
M. Bianco
Dep: Z. Szillasi,A. Kumar

GEM DPG
T. Kamon
Dep: J. Lee

GEM UC
A. Safonov
Dep: M. Hohlmann

GEM RunC
C. Galloni
Deps: I. Vai, D.Teyssier

GEM Elec
G. K. Black
Deps: E. Juska, F. Licciulli

GEM HW
J. Merlin
L. Benussi F. Fallavolita

GEM Pr. Eng.
A. Conde Garcia

RM Office

TC Office

DPG Office

UC Office

Alignment
T. Kamon (DPGO)
Z.Szillasi (TCO,UCO)

Elec Office

CMS MUON ORG
(Sept. 15, 2021)

Some of the muon people

- Muon Institution Board chair: Anna Colaleo
- Muon System Manager/Deputy: Gabriella Pugliese/Hafeez Hoorani
- Subdetector Project Managers: Daniele Fasanella (DT), Salvatore Buontempo (RPC), Jian Wang (CSC), Archana Sharma (GEM)

Anna

Gabriella

Hafeez

Daniele

Salvatore

Jian

Archana

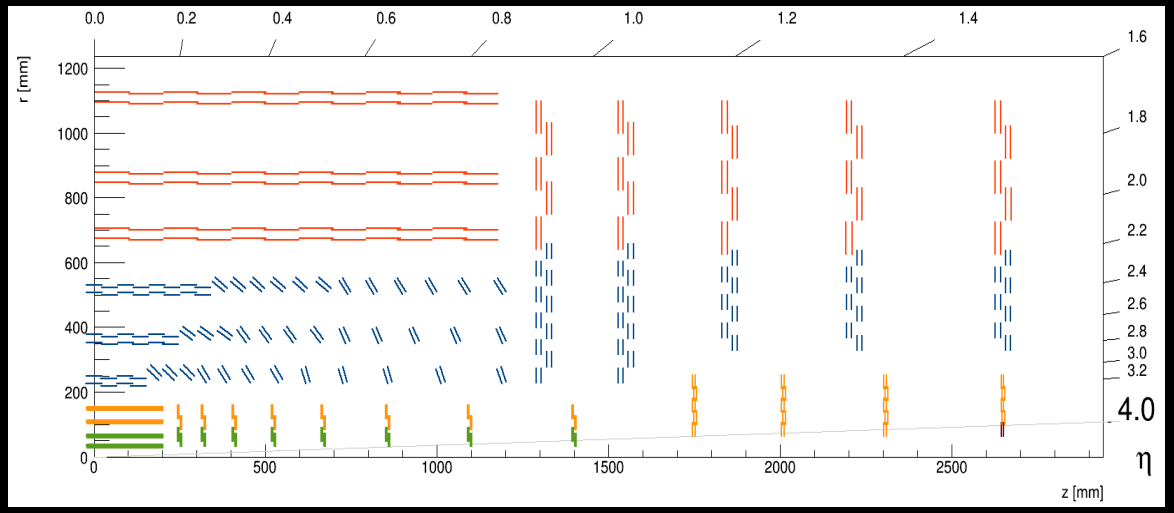
The future in a single slide*)

UPGRADES

*) Much more tomorrow: Why we do need a CMS Upgrade ?, F. Hartmann

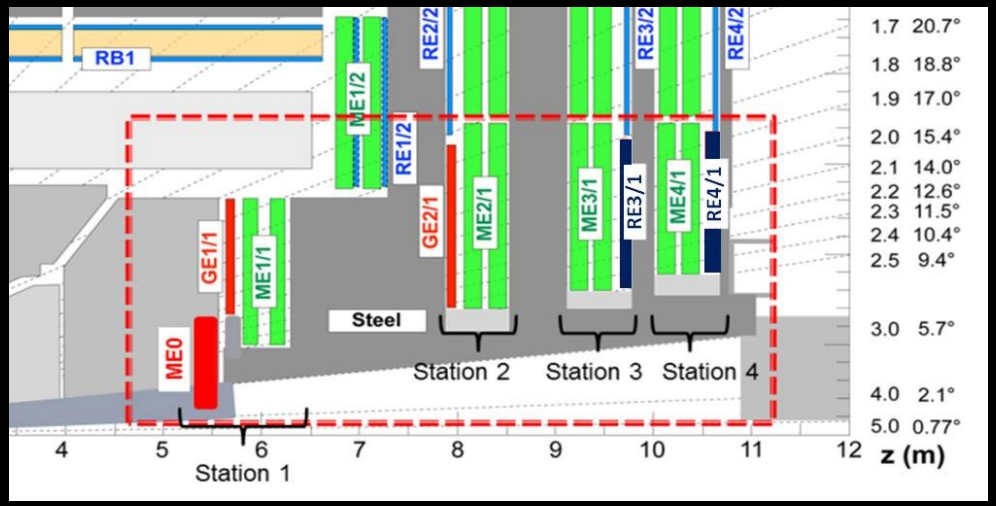
The future

~2025 - LS3



- New pixels and strips
  - L1 trigger capability
  - Forward extension η≈4
  - More radiation tolerant
  - Finer granularity to cope with higher PU ~140-200
  - Lower Mass

2019 and 2024



Future, forward muon upgrades

- Schedule very advanced – some installations in LS2 and Run 3
- 2019-20 Added GEM to 1st station
  - Big L1 trigger improvement
  - 2017 Added GEM demonstrator
- 2024 to stations 2-4
  - Add lever arm & redundancy for high η

Want Non-stop fun & excitement???
– work on Tracking Detector
Operations and Upgrades !!!

Gabriella & Erik

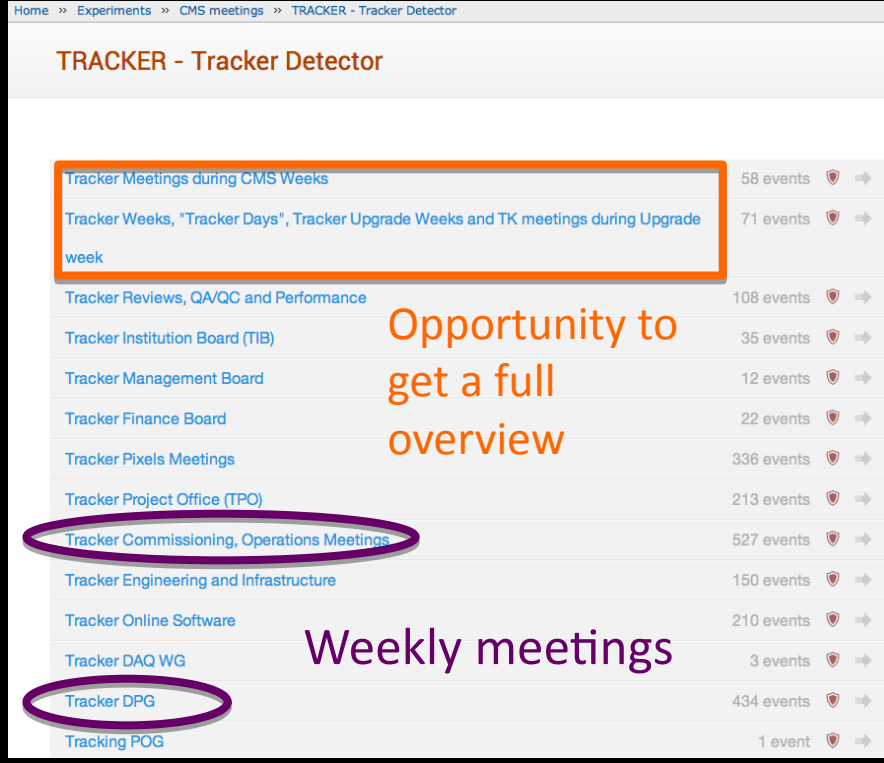
More references are in the Backup
also hypernews and meeting schedules

BACKUP SLIDES

Tracker Meetings and Hypernews

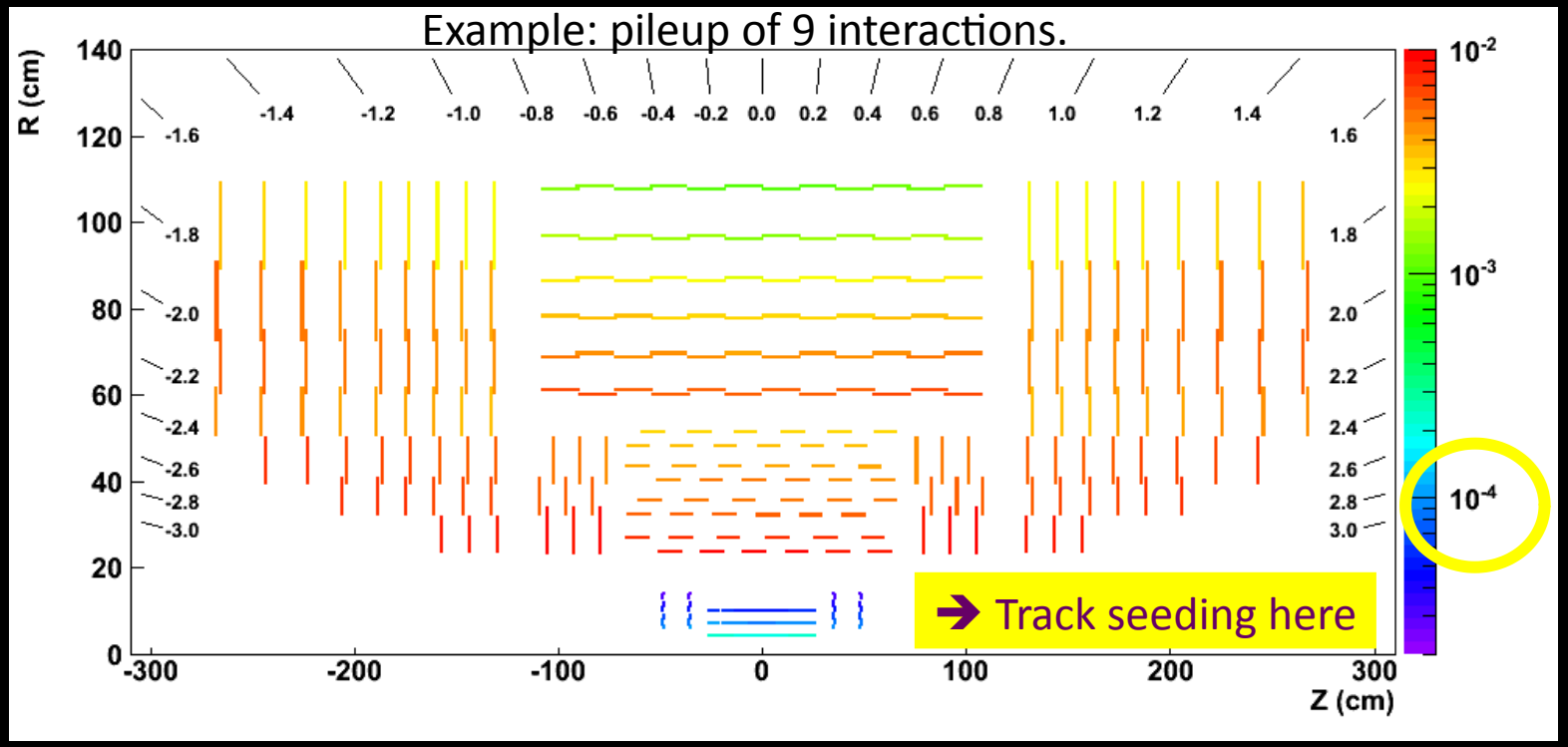
- **THE** way to follow Tracker activities is to regularly participate to the weekly meetings
  - Announced in the diverse hypernews also INDICO https://indico.cern.ch/category/62/
  - All meetings are chaired by the L2 & L3 coordinators
    - Operations Meetings – Monday at P5
    - Detector Performance Group (DPG) – Tuesday, Wednesday and Friday in the CMS Center and 28-S-029
    - Monitoring meetings - Thursday

- Tracker Weeks are perfect opportunities to get a full status and to meet people
  - **Don't be shy – talk to us**



- Hypernews
  - Register and learn
  - Also ask questions
  - hn-cms-tk-commissioning@cern.ch
  - hn-cms-trackerperformance@cern.ch
  - hn-cms-pixel-commissioning@cern.ch
  - hn-cms-alignment@cern.ch
  - hn-cms-pixelofflinesw@cern.ch
  - And more
  - Plus many PhaseII e-groups

Reality - Detector occupancy



- Pixel detector occupancy is at least one order of magnitude smaller than strips.
  - Occupancy depends on
    - distance from collision point and
    - channel size (pitch and length)

Tracker Useful Bibliography

- Technical Design Reports:
  - **Tracker TDR http://cds.cern.ch/record/368412/files/Tracker_TDR.pdf**
  - **Addendum TDR http://cds.cern.ch/record/490194/files/cer-2244540.pdf**
  - **TDR pixel phase I https://cdsweb.cern.ch/record/1481838/files/CMS-TDR-011.pdf**
  - TDR Tracker Phase II https://cds.cern.ch/record/2272264
- Papers
  - SiStrip Tracker Commissioning and Tests at TIF http://arxiv.org/abs/0901.4316
  - SiStrip Tracker Alignment at TIF http://arxiv.org/abs/0904.1220
  - Track Reconstruction at TIF http://arxiv.org/abs/0902.1860
  - Pixel Detector Commissioning with Cosmic Rays http://arxiv.org/abs/0911.5434
  - SiStrip Detector Commissioning with Cosmic Rays http://arxiv.org/abs/0911.4996
  - Alignment with Cosmics 2009 http://arxiv.org/abs/0910.2505
  - Tracker Performance 2010 http://arxiv.org/abs/1007.1988
  - Alignment with Tracks 2014 http://arxiv.org/abs/1403.2286
  - Track Reconstruction 2014 http://arxiv.org/abs/1405.6569
- Physics Analysis Summaries
  - Momentum Scale http://cds.cern.ch/record/1279137/files/TRK-10-004-pas.pdf
  - Material Budget Studies http://cds.cern.ch/record/1279138/files/TRK-10-003-pas.pdf
  - Tracking Efficiency http://cds.cern.ch/record/1279139/files/TRK-10-002-pas.pdf
  - Tracking and Vertexing http://cds.cern.ch/record/1258204/files/TRK-10-001-pas.pdf, https://cds.cern.ch/record/1279383/files/TRK-10-005-pas.pdf
- CMS Notes
  - SiStrip Tracker Commissioning CMS NOTE – 2009/021
- CMS Detector at JINST
  - http://iopscience.iop.org/1748-0221/3/08/S08004
- Semiconductor Detectors - Basics
  - G.Lutz, *Semiconductor Radiation Detectors*, Springer, Berlin (1999)
  - H. Spieler, Semiconductor Detector Systems, 2005, ISBN-10: **0198527845** | ISBN-13: **978-0198527848**
  - F. Hartmann; Evolution of Silicon Sensor Technology in Particle Physics **2nd Edition**; Springer Series: Springer Tracts in Modern Physics , Vol. 275 (2017)
  - Advances in Tracking Detectors; *Annu. Rev. Nucl. Part. Sci. 2011. 61:197–221; 10.1146/annurev-nucl-102010-130052*

Quite some material about CMS Tracker

Muon Twiki tree

https://cms.web.cern.ch/org/cms-collaboration

https://twiki.cern.ch/twiki/bin/view/CMS/MuonWikiHome

Subdetectors:

https://twiki.cern.ch/twiki/bin/view/CMS/RPComm

https://twiki.cern.ch/twiki/bin/view/CMS/MuonCSC

https://twiki.cern.ch/twiki/bin/view/CMS/MuonDT

https://twiki.cern.ch/twiki/bin/view/CMS/MuonGEM

DPG groups:

https://twiki.cern.ch/twiki/bin/view/CMS/DpgRpc

https://twiki.cern.ch/twiki/bin/view/CMS/MuonDPGCSC

https://twiki.cern.ch/twiki/bin/view/CMS/MuonDPGDT

https://twiki.cern.ch/twiki/bin/view/CMS/GEMsforCMSSimulation

POG group: https://twiki.cern.ch/twiki/bin/view/CMS/MuonPOG

Upgrades: https://twiki.cern.ch/twiki/bin/view/CMS/CMSMuonUpgrades

Help wanted: https://twiki.cern.ch/twiki/bin/view/CMS/MuonWikiHome#Muon_Help_wanted_lists_for_2016

Sources of muon information

- Overall CMS muon detector design:
  - The muon Technical Design Report (TDR) from 1997, CERN/LHCC 97-32, http://cdsweb.cern.ch/record/343814/
- Basic principles, mostly from the Particle Data Group (PDG):
  - PDG on passage of particles through matter http://pdg.lbl.gov/2013/reviews/rpp2013-rev-passage-particles-matter.pdf
    - Includes particularly energy loss (31.2), multiple scattering (31.3), high-energy muon energy loss (31.6)
  - PDG on detectors http://pdg.lbl.gov/2013/reviews/rpp2013-rev-particle-detectors-accel.pdf
    - Includes particularly gaseous detectors (32.6), low-noise electronics (32.8), superconducting magnets (32.10)
  - Punchthrough measurement RD5 http://dx.doi.org/10.1007/BF01650426
  - Backgrounds
  - Triggering
- CMS detector implementation
  - Gas amplification detection (Sauli 1977) http://cdsweb.cern.ch/record/117989/files/CERN-77-09.pdf
  - DT, RPC, CSC
  - GEMs (maybe)
- Overall CMS muon detector performance (based on 2010 data): http://dx.doi.org/10.1088/1748-0221/8/11/P11002
- Local and global reconstruction methods: the Muon Workshop of 04-Oct-2012 https://indico.cern.ch/event/210563/
- Performance (resolution, efficiency) from the muon POG: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsMUO
- ICHEP 2012 DT and RPC talk by Gabriella Pugliese https://indico.cern.ch/event/181298/session/74/contribution/705

Phase I and Phase II

MUON & TRACKER UPGRADES

Future for the muon detector

- NB improvements have been made during Long Shutdown 1
  - Handle triggering at $L=2x10^{34}$ with new and refurbished chambers in endcap stations 1 and 4, new shielding walls (YE4)
  - Improved Track Finders on the way as Phase 1 upgrades

- Further Phase 2 improvements planned to handle $L=5x10^{34}$
  - New DT and CSC electronics, additional endcap stations, extend "tagging" coverage beyond current limit $|\eta| < 2.4$ in a new endcap

Best before day

Phase 2 Upgrade
Coordinator: D. Abbaneo
Deputy: G. Sguazzoni
Integration: A. Onnela
Quality Manager: A. Honma

IT coordinator: K. Ecklund
IT electronic coordinator: J. Christiansen

IT Sensors: G. Gomez, G. Steinbrueck
IT ASIC: F. Loddo (RD53)
IT service electronics: NN
IT Modules: M. Backhaus
IT System Develop. & Tests: S. Orfanelli
IT Mechanics: J. Alexander, A. Jung

OT Coordinator: NN
OT electronic coordinator: F. Vasey

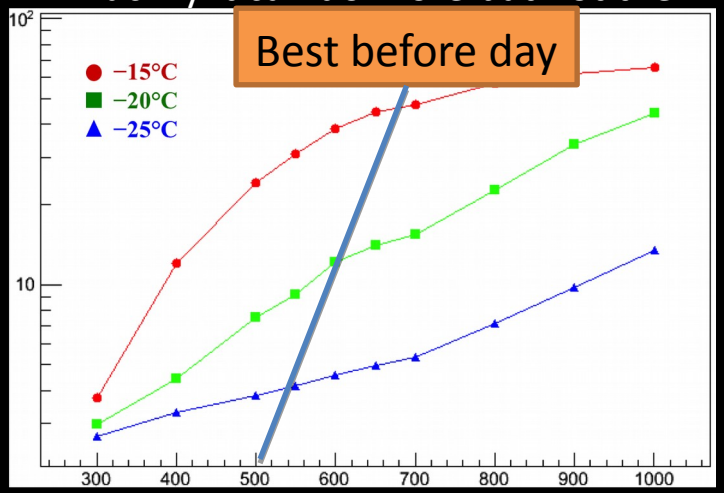
OT Sensors & MaPSA: A. Dierlamm, M. Dragicevic
OT ASICs: K. Kloukinas, D. Ceresa
OT hybrids: G. Blanchot, K. Klein
OT Modules: U. Heinz, A. Mussgiller
OT System Tests: Y. Gershtein, A, Dierlamm
OT mechanics: A. Onnela

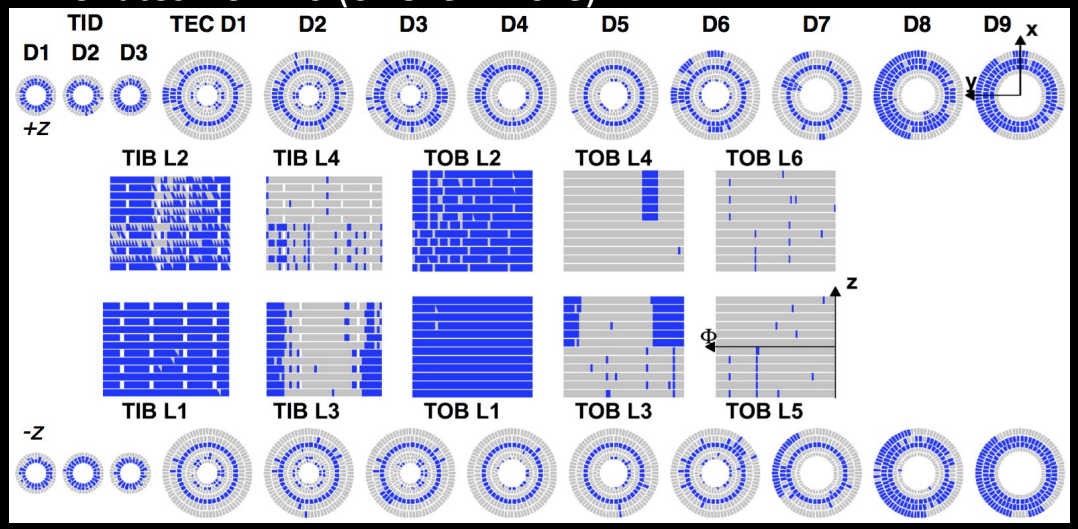
Integration, cooling, services: N. Bacchetta, J. Daguin, A. Onnela
Power, Control and Safety Systems: S. Paoletti, P.G. Verdini
DAQ: S. Mersi, S. Seif El Nasr Storey
Data Processing: K. Hahn, M. Pesaresi
Detector Modelling: S. Mersi
Database: A. Di Mattia, V. Rapsevicius

DPG Team

Tracker Geom and Material: R. Bartek
Phase 2 Upgrade Simulations and Performance
P. Wittich
E. Migliore

- The current outer tracker was designed to endure about 500fb^{-1} integrated luminosity
  - While HL-LHC will g up to 3000fb^{-1}
- It was designed for 20 pile-up
  - Luckily it can do more but not the HL- LHC rates PU-140 (or even more)

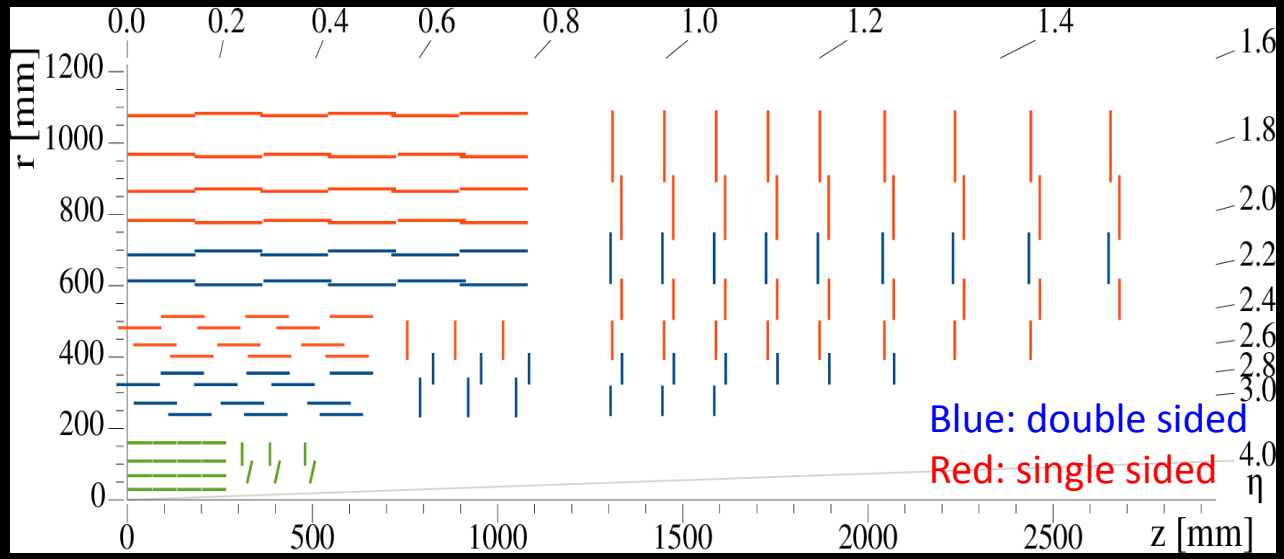


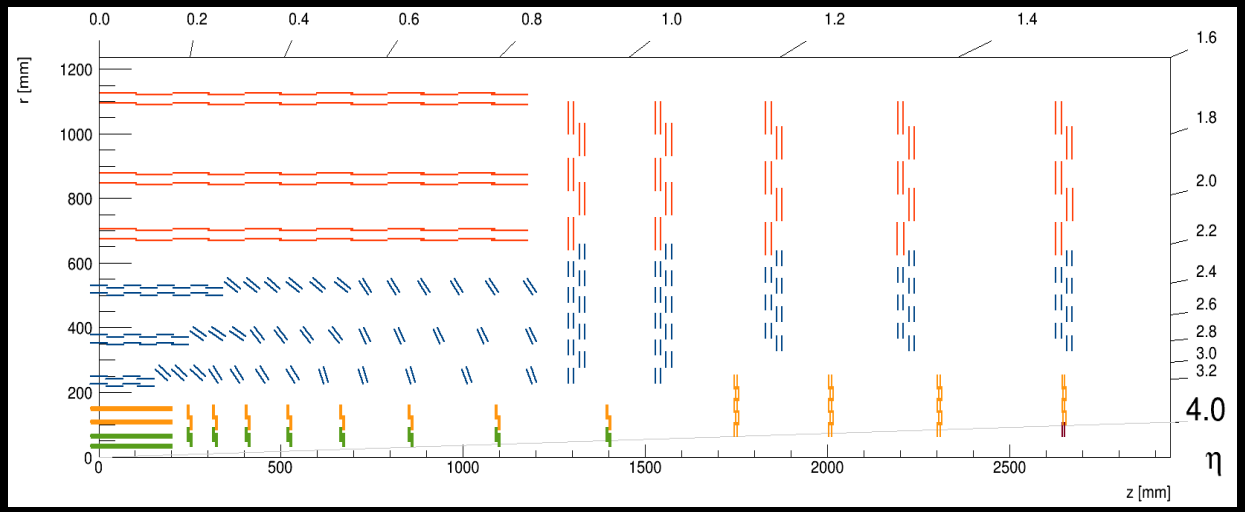


Non-functional modules after 1000fb^{-1}

➔ We need a new tracker after LS3 (2025)
Clearly we will do a better one ☺

Today vs Phase II



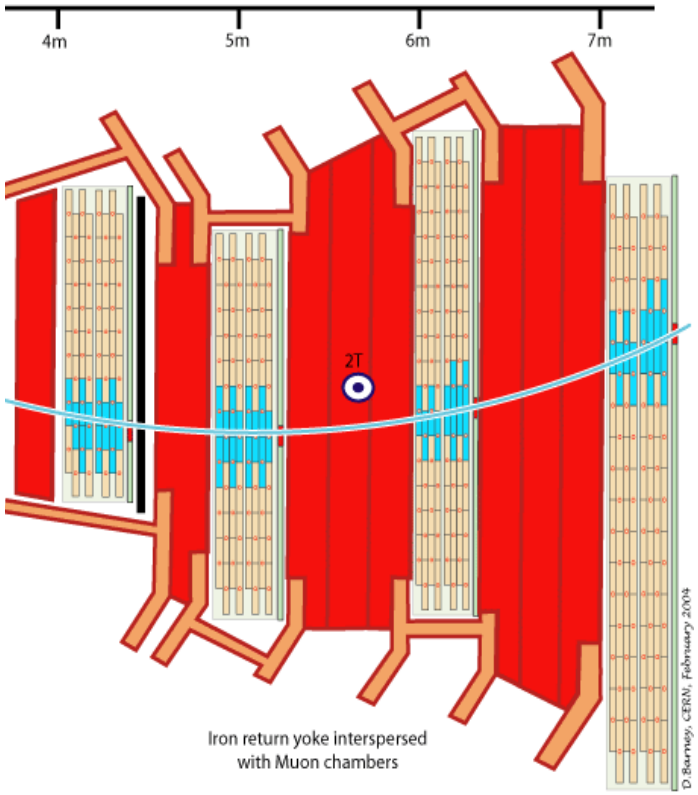


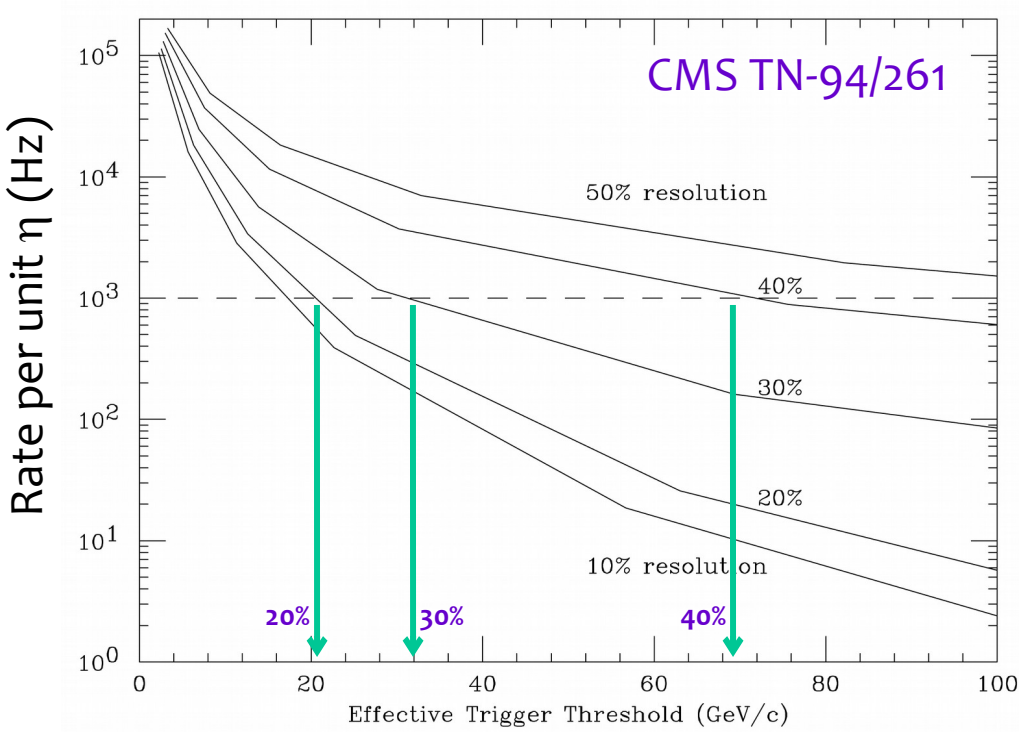
Red: Strip-Strip modules Blue: Pixel-Strip modules Green/Orange: pixel

- Phase 2
  - More radiation tolerant
  - Finer granularity to cope with higher PU
  - Lower Mass
  - L1 trigger capability
  - Forward extension η~4

Muon P_T resolution for L1 trigger

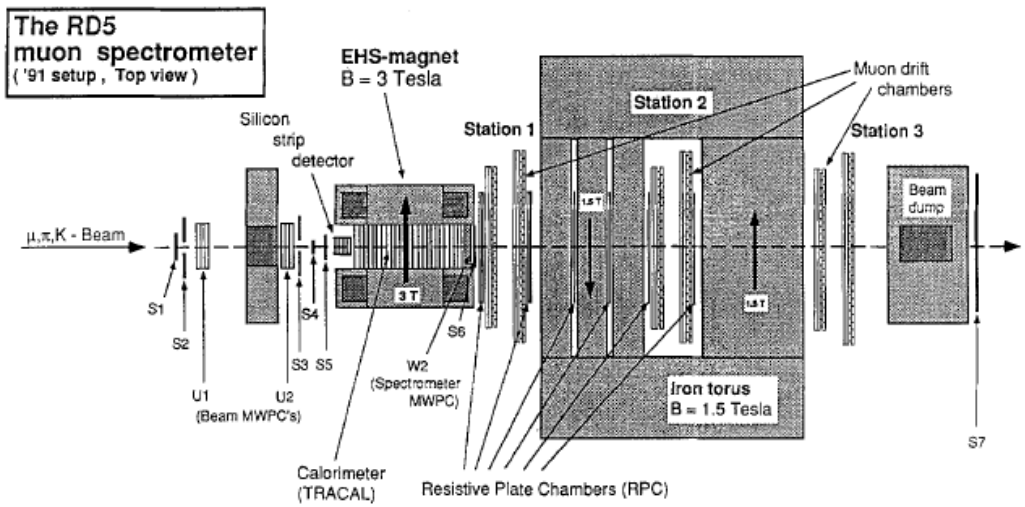
- Assume no backgrounds other than mis-measurement of low-p_T muons
- Muon trigger rate (Hz) per unit rapidity at 90% eff. point
- For $L=10^{34}/cm^2s$, resolution of 20% desirable, 30% acceptable
  - Lots of iron - multiple scattering is large – better than 15% resolution very difficult

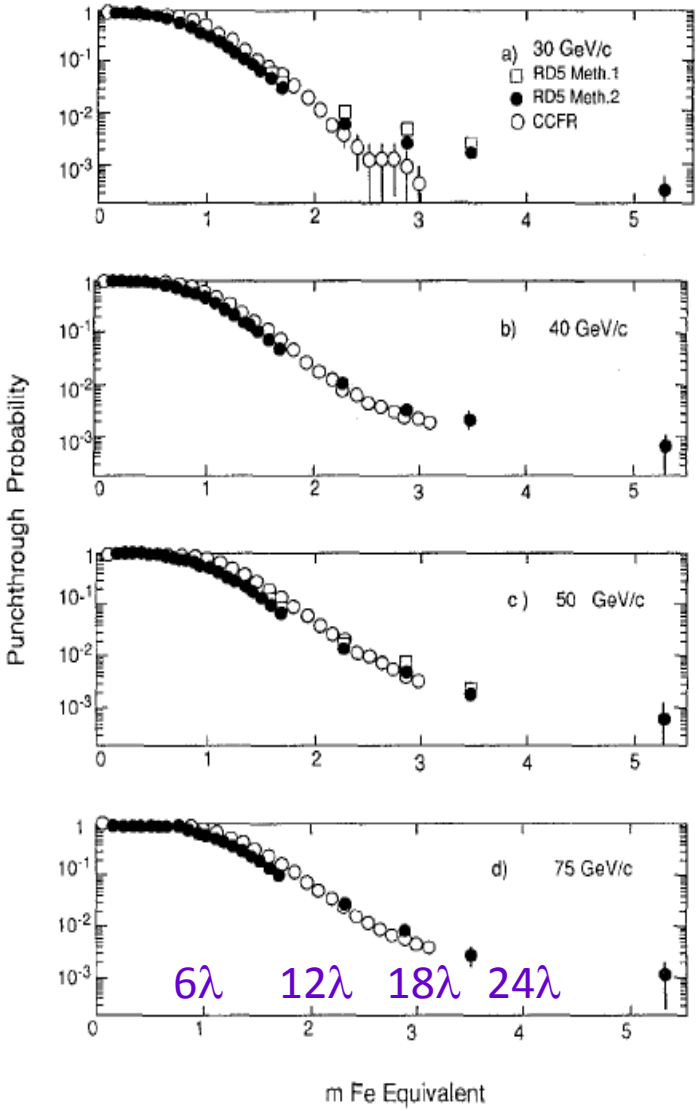




Punchthrough measurements

RD5, predecessor of CMS:





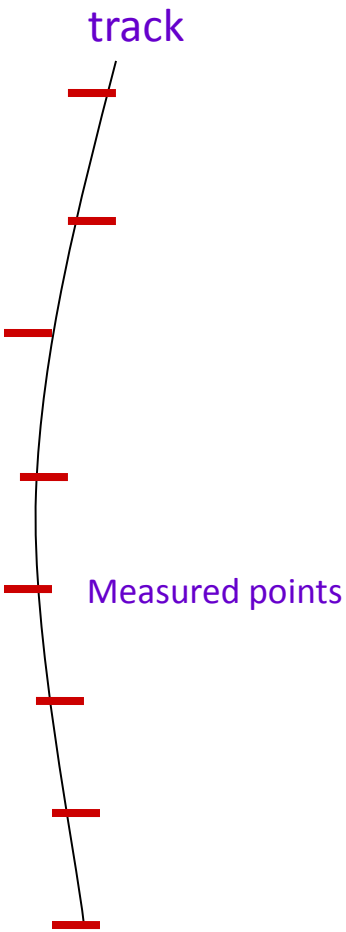
Tracking: momentum accuracy

If many (≥ 10) uniformly spaced position measurements are made along a trajectory in a uniform medium,

δ(curvature) = $$\delta k_{\text{res}} = \frac{\epsilon}{L'^2}\sqrt{\frac{720}{N+4}}\,, \qquad (28.46)$$

where N = number of points measured along track
L' = the projected length of the track onto the bending plane
ϵ = measurement error for each point, perpendicular to the trajectory.

If a vertex constraint is applied at the origin of the track, the coefficient under the radical becomes 320.



- Curvature and momentum inversely related
- For good resolution:
  - High B-field
  - Maximize L2 from 1st to last measurement
  - Minimize sensor position error

Gluckstern, NIM 24, pp. 381-389 from 1963

Quoted numbers

- Multiple scattering gives about 0.01 minimum to momentum measurement
- Curvature measurement in CMS:

$$\sigma(p_T)/p_T = 0.15 \times p_T\,(\mathrm{TeV}/c) = 0.00015 \times p_T\,(\mathrm{GeV}/c)$$

- Increases linearly with transverse momentum, "typical" at 100 GeV this gives 0.015 i.e. 1.5% resolution
- Directional accuracy – superb, e.g. 10^{-5} for 10 μm over 1 m

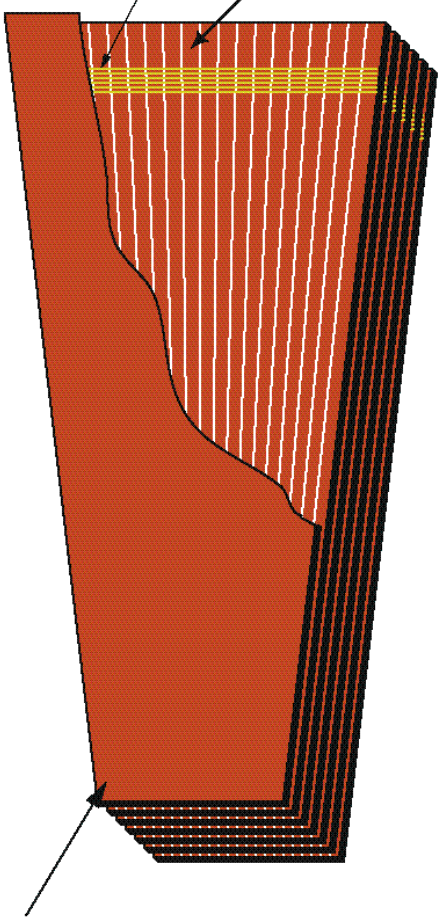
Penetration & Punchthrough – w/details

- Penetration of muons in iron (ρ=7.87 g/cm^3):
  - dE/dx ~ 2 MeV/gcm^2 = 1.57 GeV/m = 0.26 GeV/λ
  - Need p>2.6, 3.2, 4.2, 5.2 GeV to penetrate 10, 12, 16, 20λ (MB1, 2, 3, 4)
  - Lower momentum muons come to rest.
  - Note lower p_T threshold in the endcap region due to $p_T/p=\sin\theta$, e.g. p>7.0 GeV for η=2, 27λ in ME4/1, but p_T>1.9 GeV)

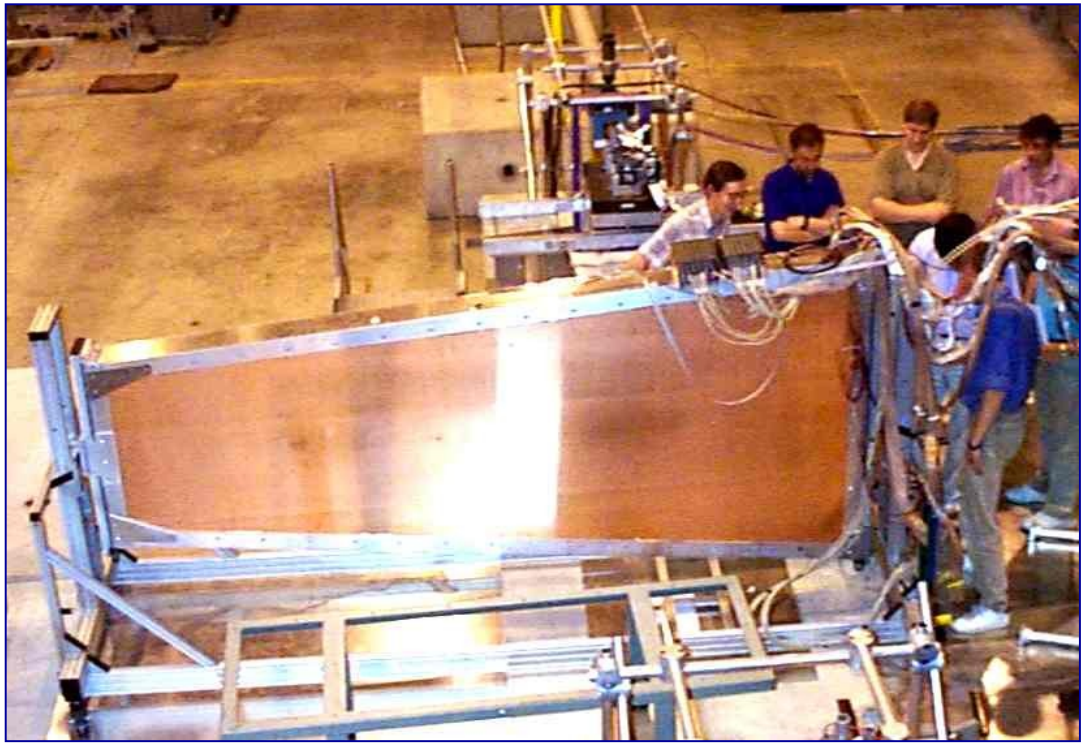
- Punchthrough: jets include a spectrum of $\pi^\pm$, $K^\pm$, p
- These give rise to hadronic showers – or not!
  - Prob. of no interaction = exp(-x/λ), e.g. 3x10^{-4} at 8λ, 4.5x10^{-5} at 10λ
  - The numerous particles produced in the showers can also penetrate w/o interaction
- Decays in flight to muons from $\pi^\pm \rightarrow \mu^\pm \nu$, likewise for kaons

CSC Chambers - 1997 test beam

EMU Cathode Strip Chamber



- 468 CSCs of 7 different types/sizes
- > 2,000,000 wires (50 μm)
- 6,000 m^2 sensitive area
- 1 kHz/cm^2 rates



RPC large installations: brief history

1992 1996 2003 2013 2019

LEP/L3	BaBar	CMS/ATLAS	RE4	Phase II
10 years	5 years*	10 years		
10^{11-12} Ωcm	10^{11-12} Ωcm	2-5 10^{10} Ωcm	1-2 10^{10} Ωcm	7-8 10^{09} Ωcm
300 m²	2000 m²	7000 m²	300 m²	200 m²
streamer	streamer	avalanche	avalanche	avalanche
Heavy mechanic	Gap Industrial prod. (Italy)	2nd gap company (Korea)	improved HPL prod. (Italy)	
Few leaks	eco gas mix	Oiling procedure improved a lot		new eco gas mix
FE chip Napoli	FE chip Napoli	FE chip Bari	FE chip Bari	FE chip Bari+
0.3 Hz/cm²	< 3 Hz/cm²	< 15 Hz/cm²	150 Hz/cm²	1000 Hz/cm²**

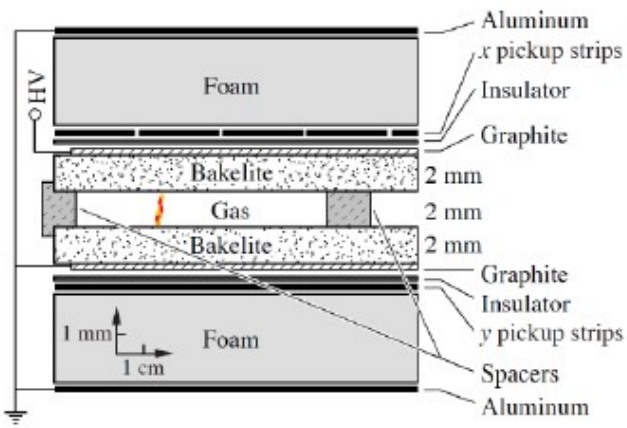
* First batch failed for high temperature (27-30 °C). Then oiling procedure was improved a lot

** very maximum rate (safety and energy factor included)

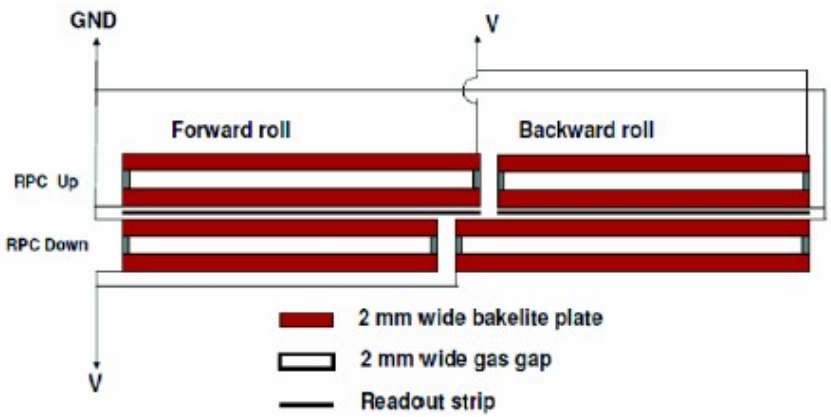
+ possible upgrade in collaboration with ATLAS

RPC technology

A first important step: from streamer to avalanche (CMS-ATLAS) 2000



(a) Babar single gap RPC



(b) CMS double gap RPC

RPC in Streamer mode

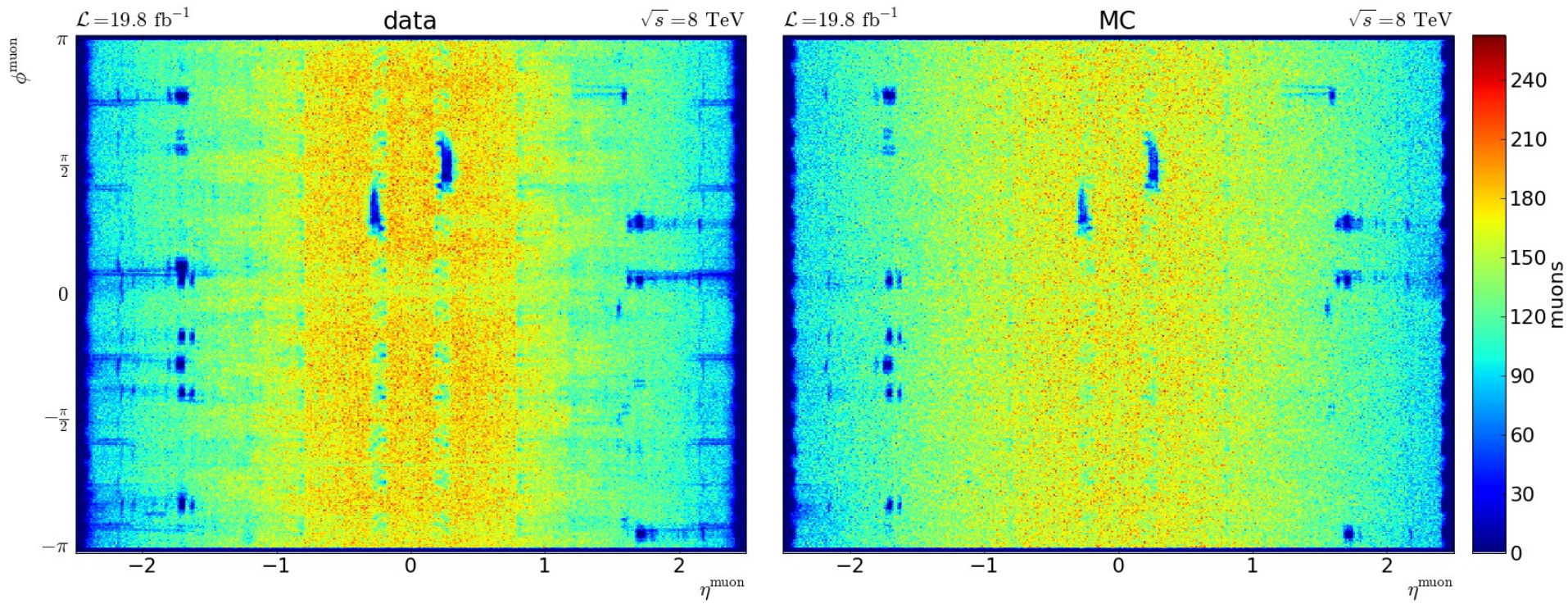
- Ar + i-C_4H_{10} & $C_2H_2F_4$
- Large signal ($\sim$ 300 mV, 100 pC)
- No need for Electronic Amplification
- Resistivity $\rho = 10^{11}$–10^{12} Ωcm
- Rate Capability of 40–100 Hz/cm^2 (for Bakelite, depends on ρ material)
- Ex: **L3** (DG) & **Babar** (SG)

RPC in Avalanche mode

- $C_2H_2F_4$ (85–97%) + i-C_4H_{10} (2–5%) + SF_6 (0.1–10%)
- Small signal ($\sim$ 1 mV, 20–30 pC)
- Need Electronics for Amplification
- Resistivity $\rho = 1$–$5 \cdot 10^{10}$ Ωcm
- Rate Capability up to 1 kHz/cm^2
- Ex: **CMS** (DG) & **ATLAS** (SG)

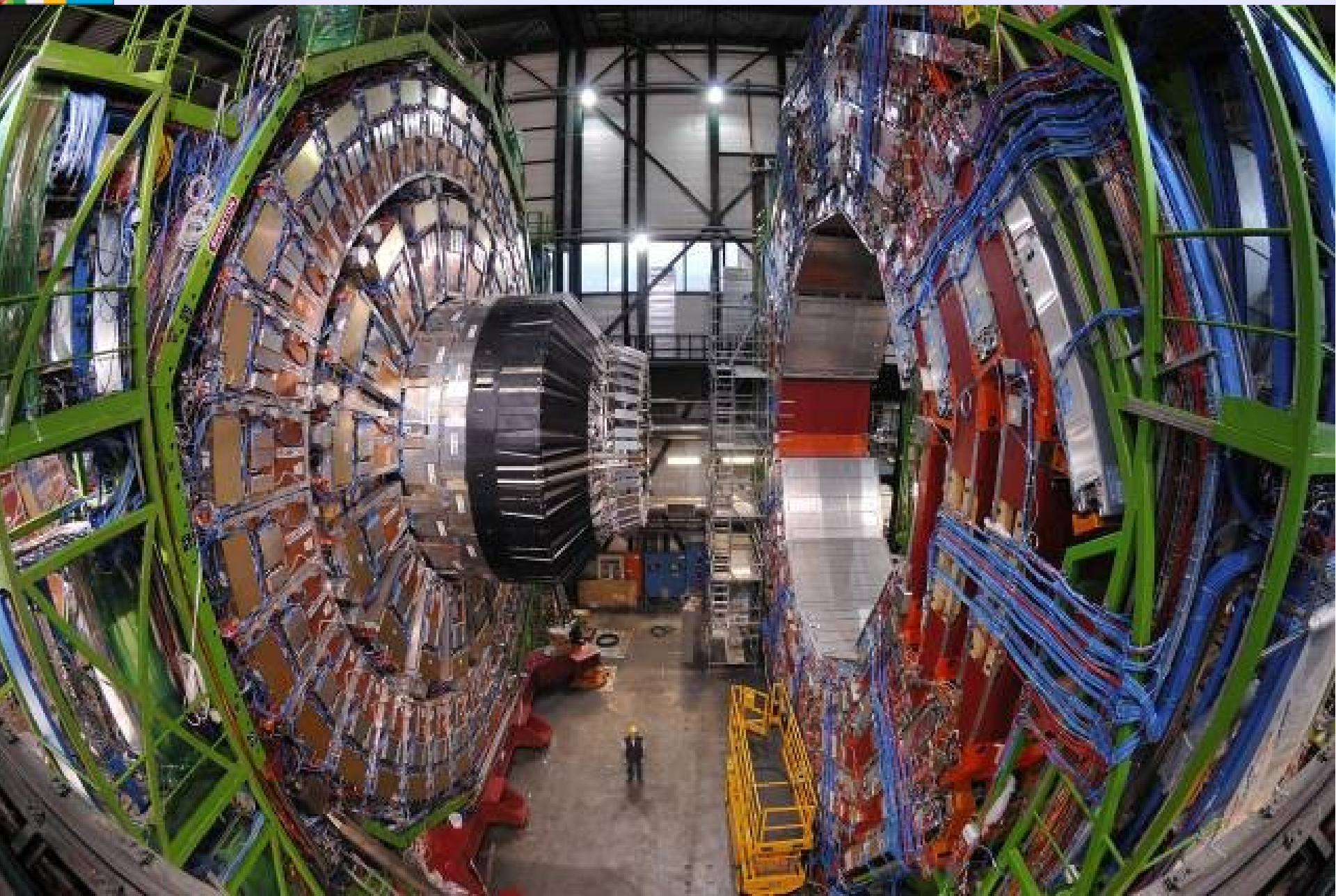
Muon reconstruction uniformity

- Entire dimuon trigger sample (p_T>17 and 8 GeV) from 2012

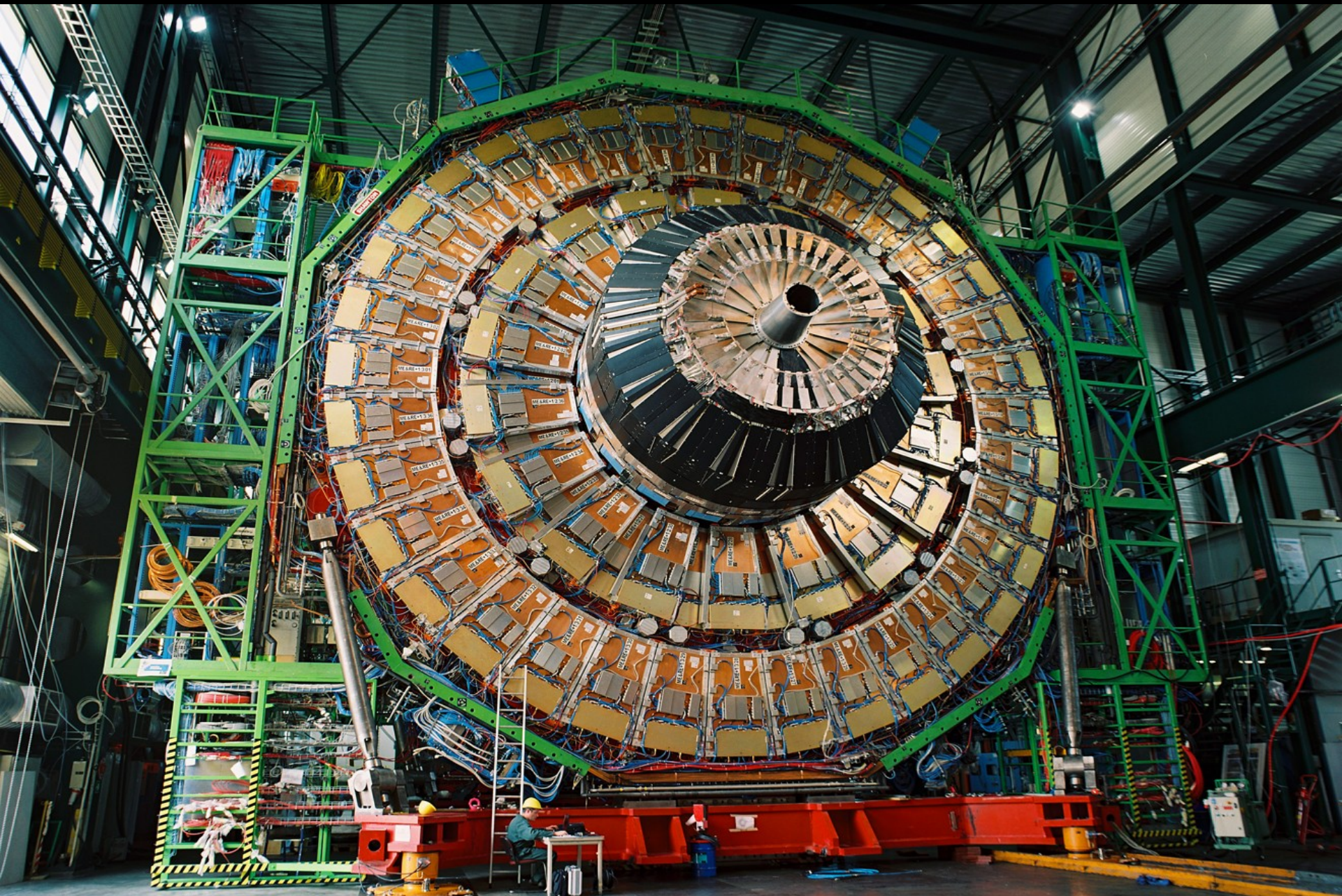


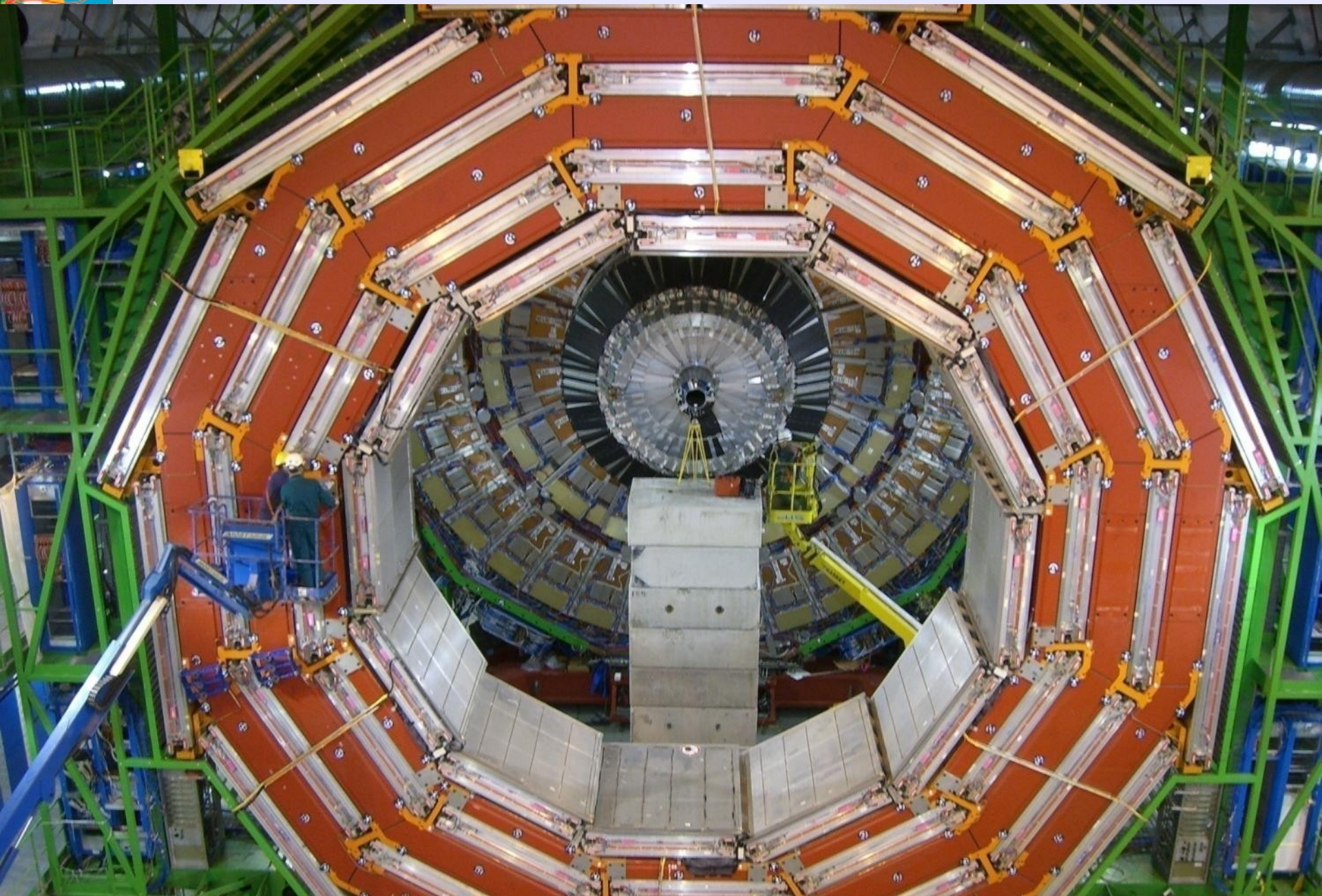
Dominik Haitz

Another pretty muon picture



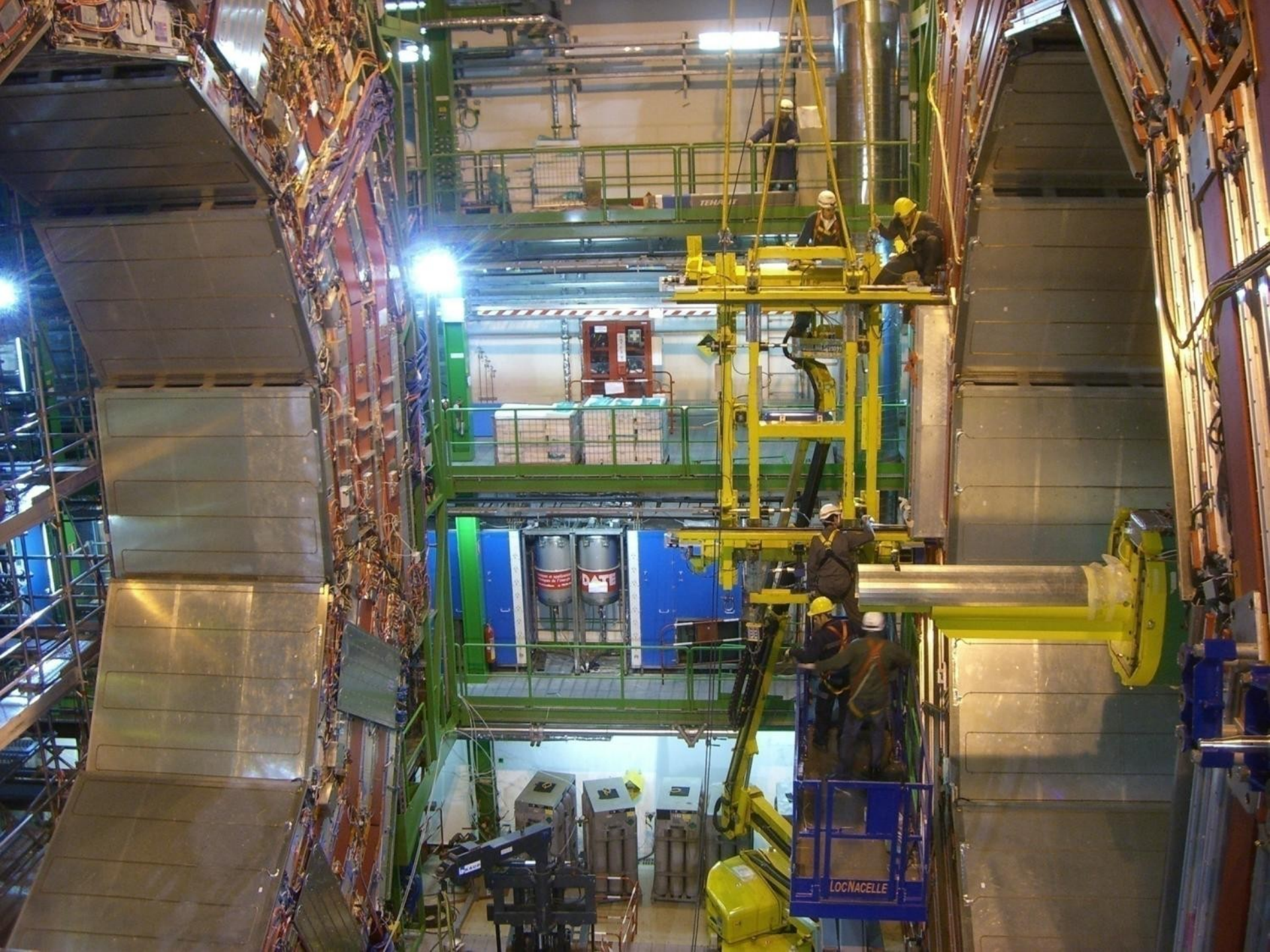
Surface Hall: Endcaps

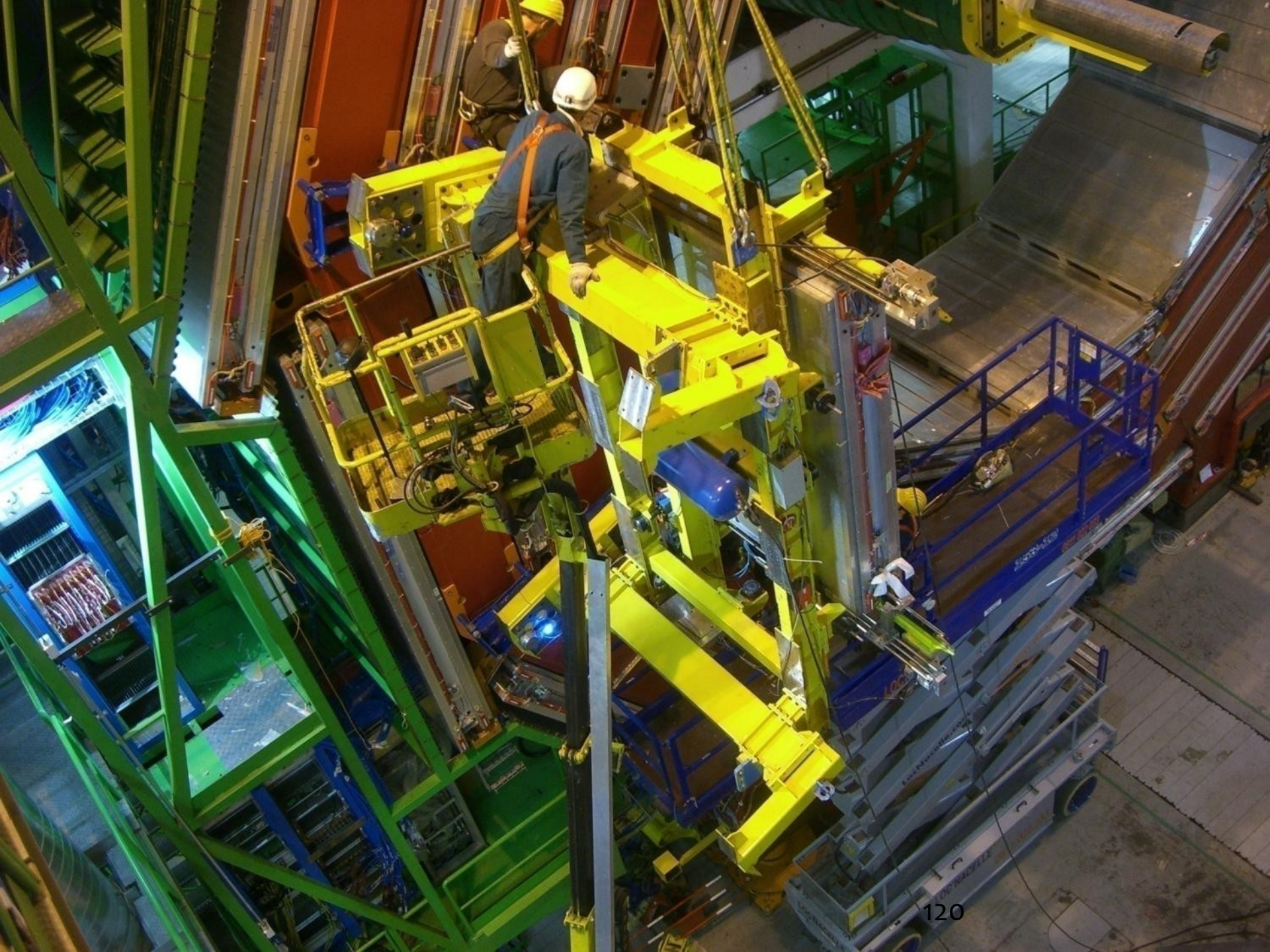




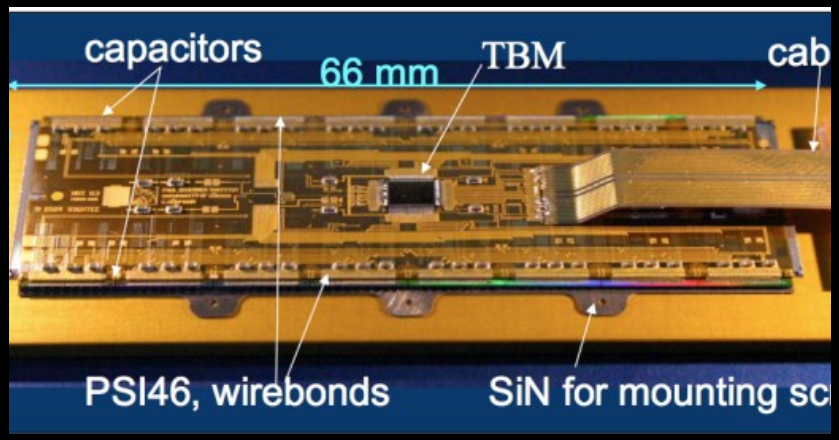
ARRIERE
DROITE
GAUCHE
AVANT

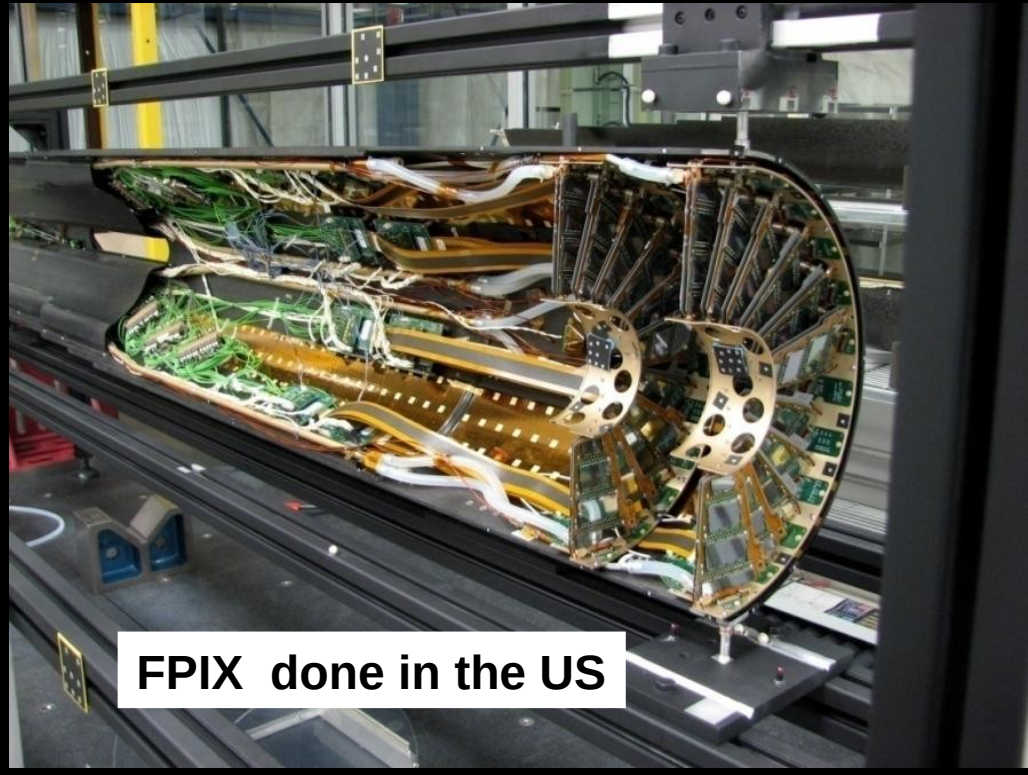
153-12
0811 022 033
LOCNACELLE

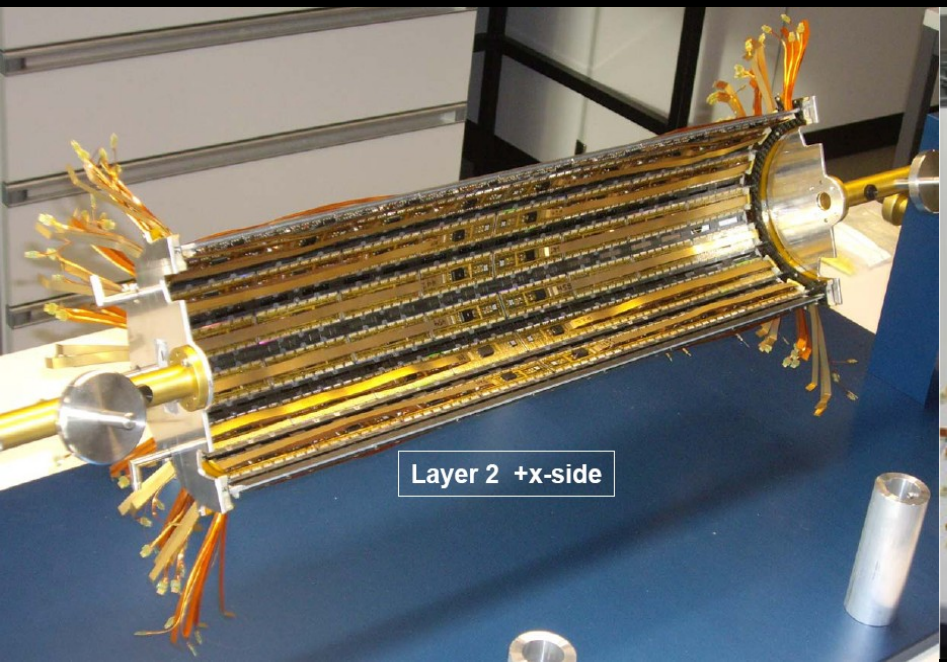

LOCNACELLE

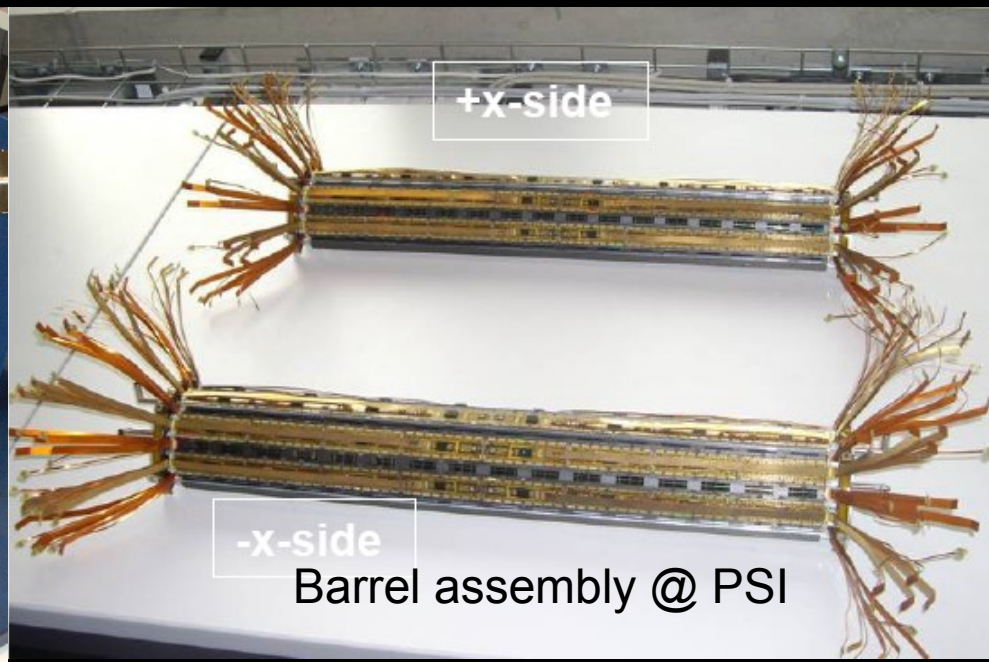


Pixels



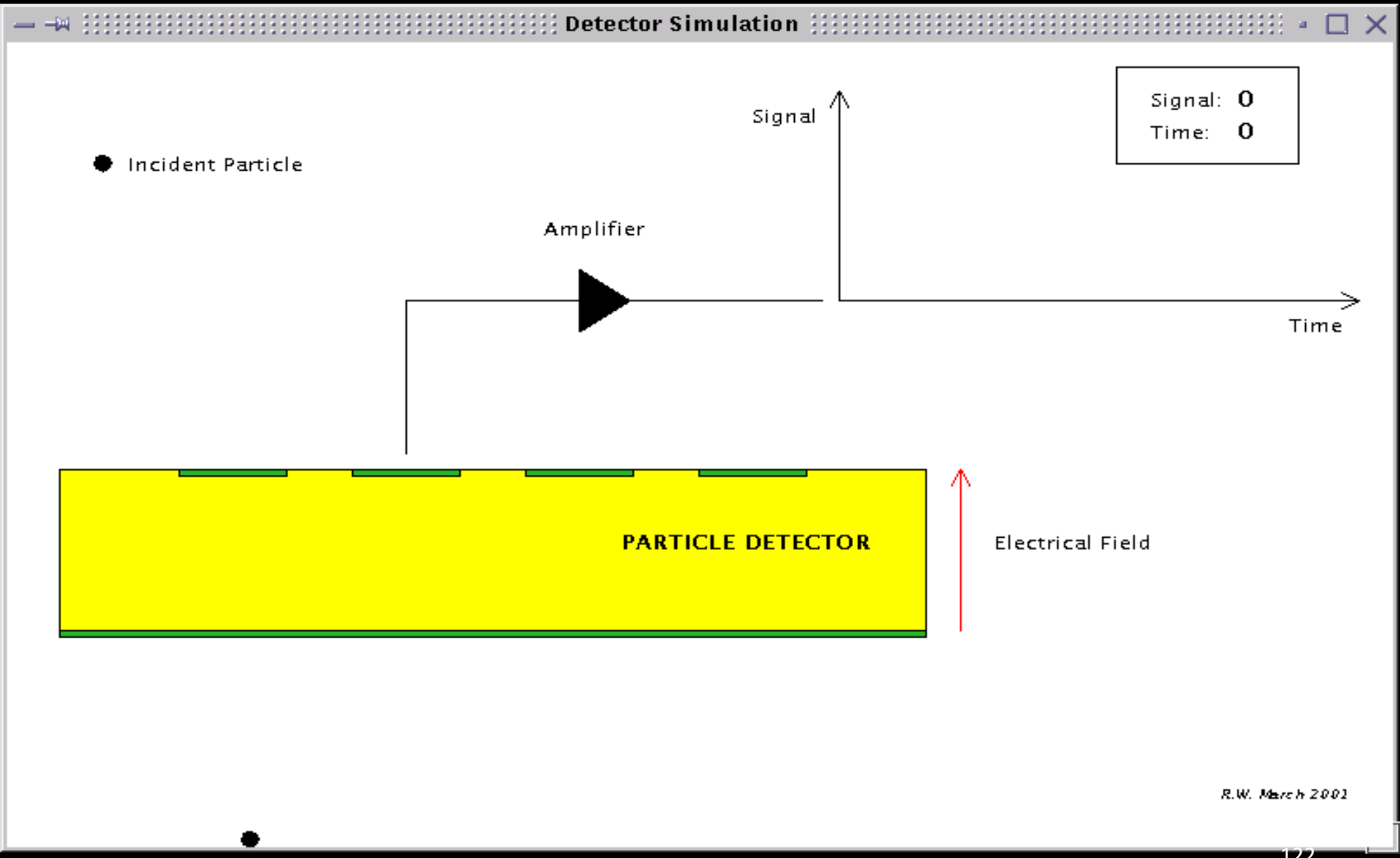




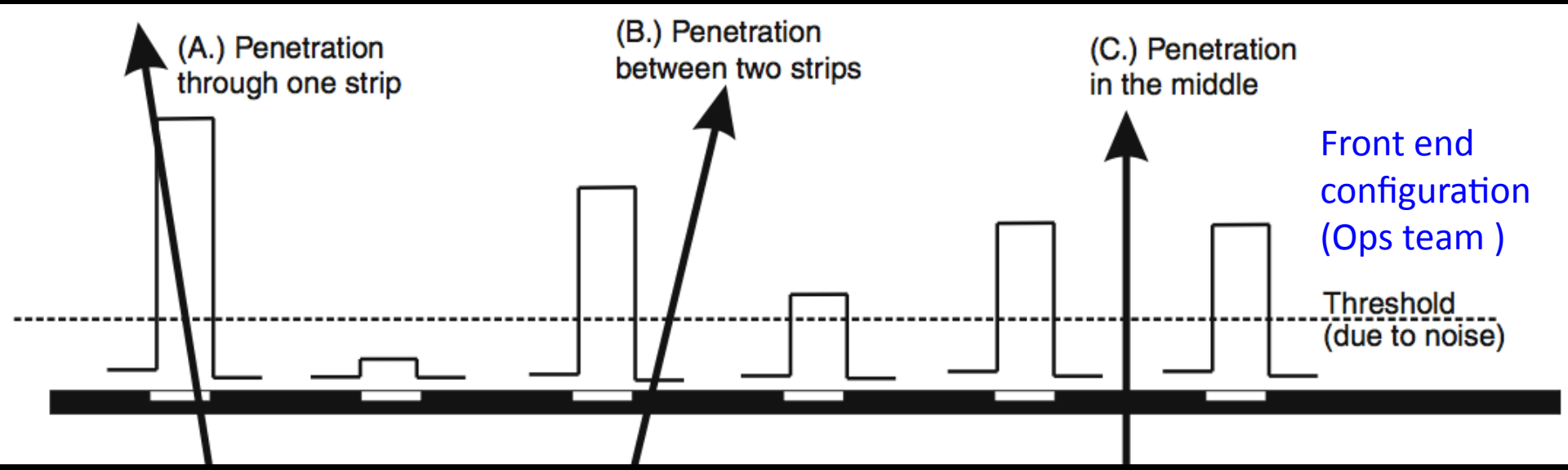


Barrel assembly @ PSI

Tracker Detectors Work Like This



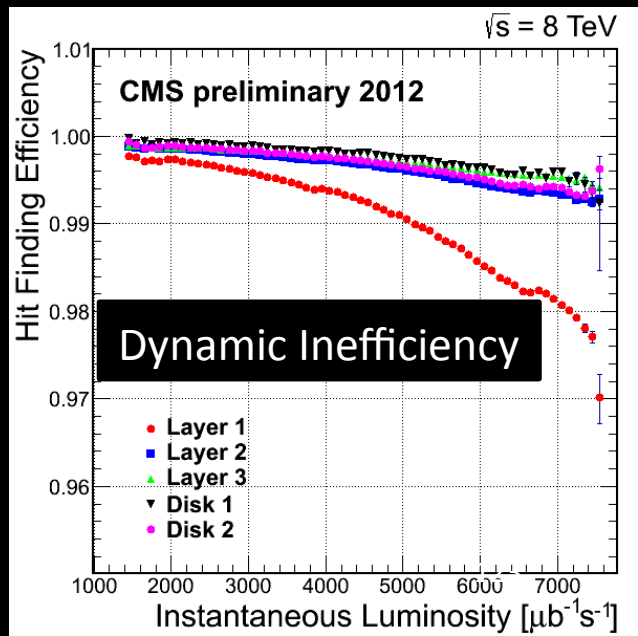
Position ~ Cluster



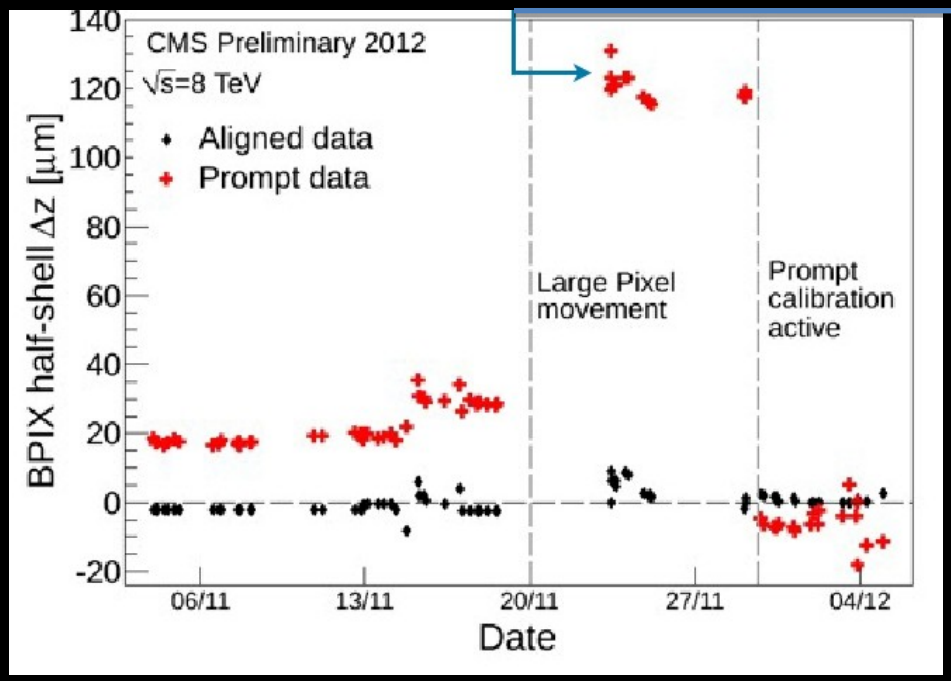
Tracker data send out optically and fully analogue

- Pixel with 66M channels sparsifies data on chip - asynchronous data transfer
  - rate driven by data rate and dynamic losses in case of high rate
    - To be taken into account for analysis and simulation
- Strips with 10M channels sends the full data synchronously

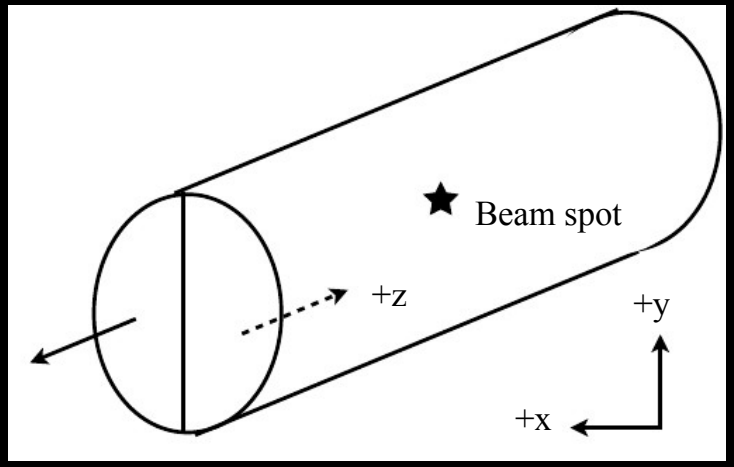
Ops Team ⟷ DPG Team



DPG - Prompt monitoring and realignment

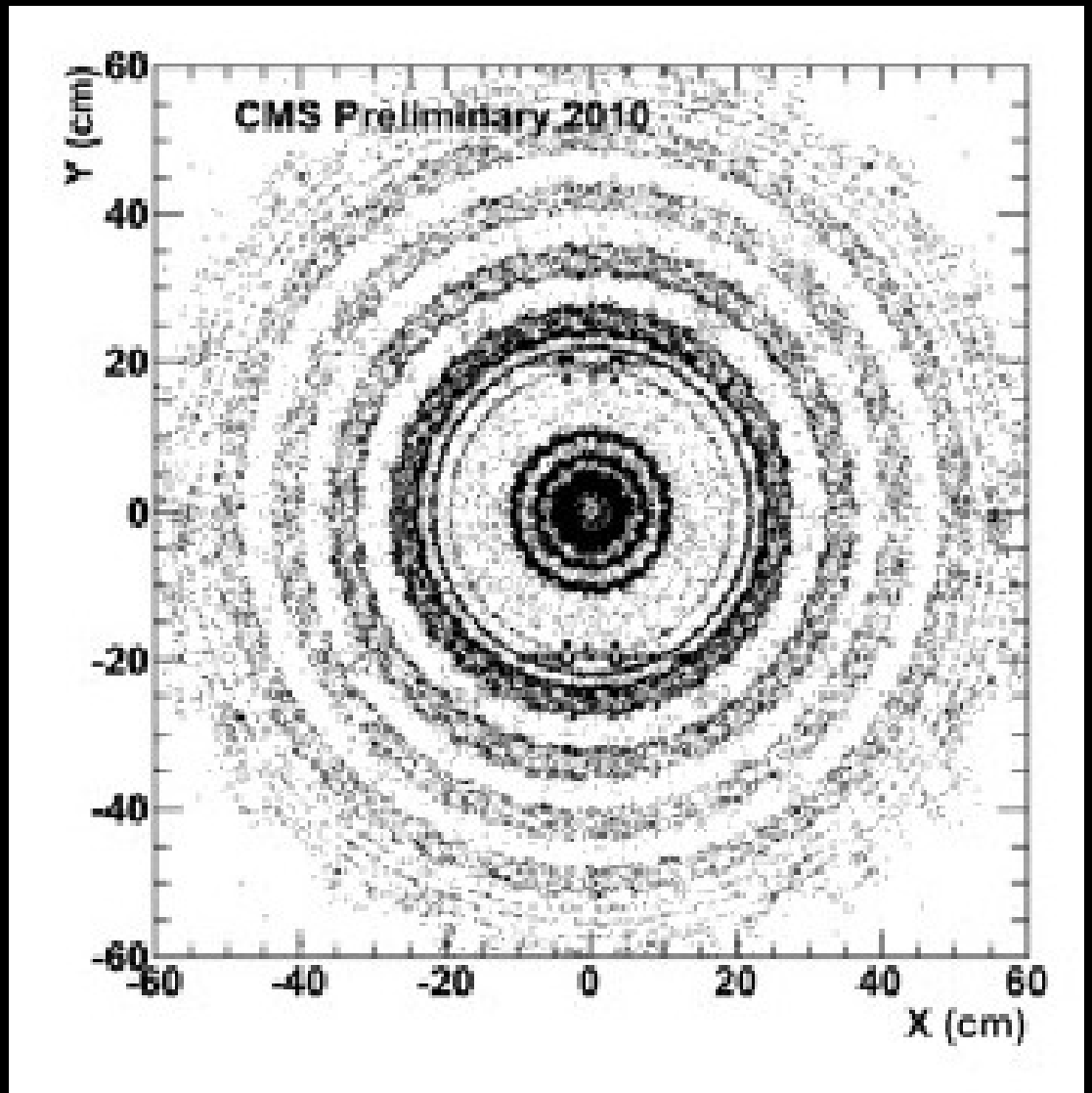


Thermal cycling on November 22



- Barrel pixel (BPIX) half shells can move over time, especially in z
- Prompt calibration loop implemented in the second half of 2012
  - Pixel movements checked on every run with >20k events
  - If a significant movement is found, the alignment is re-computed on a run of 100k events
  - If the misalignment is confirmed, the new alignment constants are automatically picked up for the next data taking run

Tracker image via Photon conversions



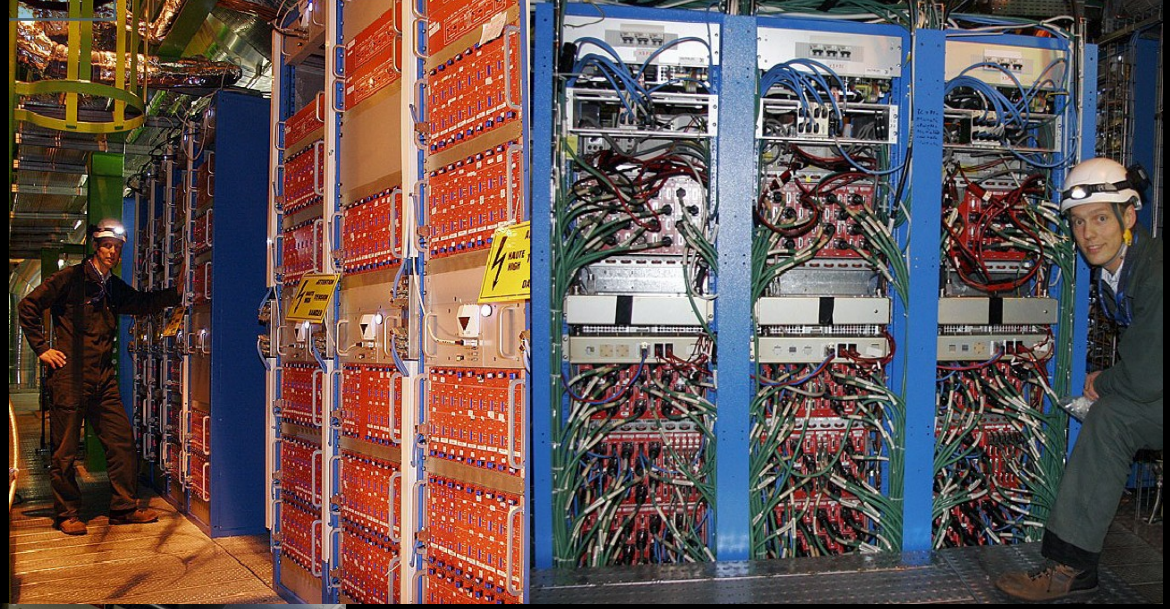
Iteration definitions

#step	seed type	seed subdetectors	P_T^{min} [GeV/c]	d_0 cut	z_0 cut
0	triplet	pixel	0.6	**0.02** cm	4.0σ
1	triplet	pixel	0.2	**0.02** cm	4.0σ
2	pair	pixel	0.6	**0.015** cm	0.09 cm
3	triplet	pixel	**0.3**	**1.5** cm	**2.5**σ
4	triplet	pixel/TIB/TID/TEC	**0.5-0.6**	**1.5** cm	10.0 cm
5	pair	TIB/TID/TEC	0.6	2.0 cm	10.0 cm
6	pair	TOB/TEC	0.6	2.0 cm	30.0 cm

0: pixel triplets
1: low pt pixel triplets
2: pixel pairs. Recover gaps in pixel detector layers
3: displaced tracks with pixel triplets
4: mixed pixel/strip triplets
5: TIB/TEC
6: TOB/TEC

- Later iterations cover wider phase space
  - Ideally profiting of the reduced hit multiplicity
  - …but it is not so easy
  - ➔ tighter requirements to build those tracks

TK Services



7 main plus 5 auxiliary racks of PLC (Programmable Logic Controllers) in the service cavern (USC) guaranteeing a safe operation

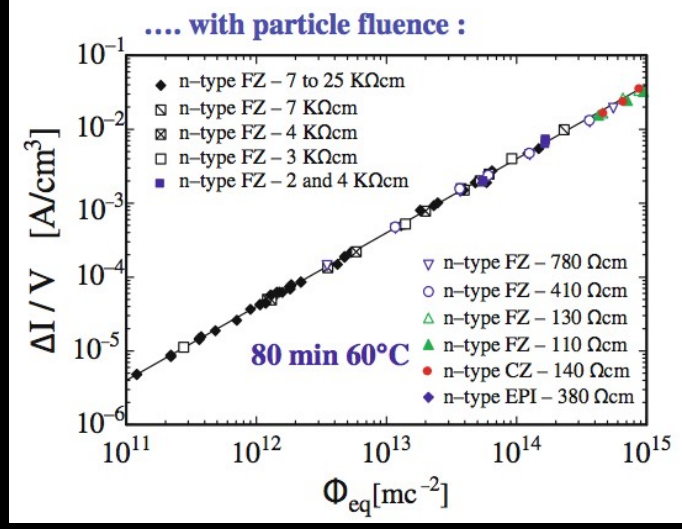
Power:
31 full racks in experimental cavern (UXC)
Strips operation voltage: 300V
Pixel operation voltage: 150V

Cooling, Gas and Tracker Cold Operation

- Sensor Leakage Current exponentially dependent on temperature
- Leakage current increases with radiation
  - ➔Operate cold T=-15C
  - ➔Large need of services

Temperature correction based on:

$$j(T) = j(T_0) * (\frac{T}{T_0})^2 * e^{-\tau(\frac{1}{T}-\frac{1}{T_0})}$$

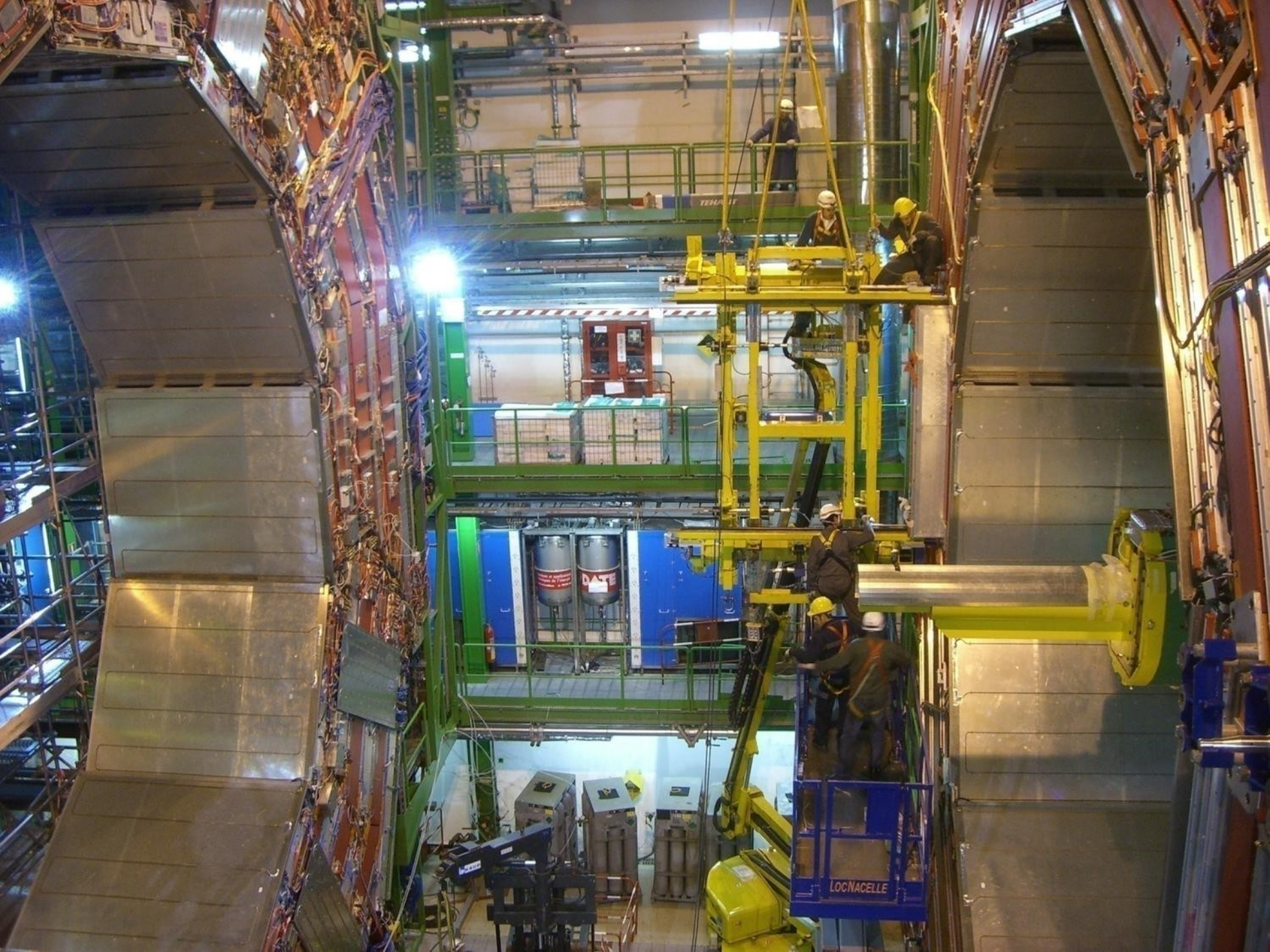


5 cooling stations in UXC (plus primary in USC)

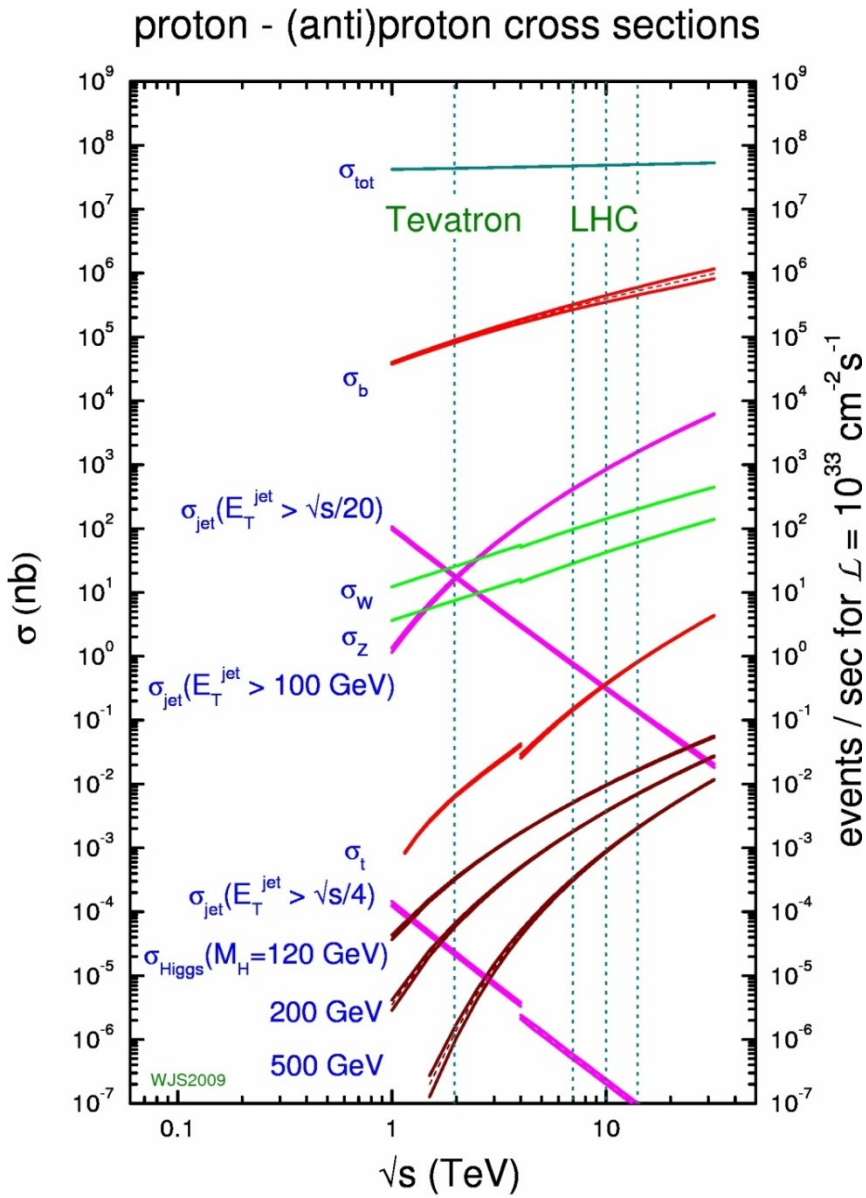
Dry gas (nitrogen or air during shutdown) – plant on surface

ARRIERE
DROITE
GAUCHE
AVANT

153-12
0811 022 033
LOCNACELLE


LOCNACELLE

CMS muon detector basics III

- Trigger on muons to select interesting physics
  - W, Z, t, H, and BSM
  - LHC makes **many MHz** of penetrating muons, want to trigger at **~0.01 MHz**

- Need high-p_T for the L1 trigger:
  - Cannot use present Tracker
  - Use multiple (4) stations of muon detectors
  - Use the reverse bending of muons in the return B-field of the solenoid
  - **Select only the straightest patterns of muon hits in electronics within 3.2 μs!**