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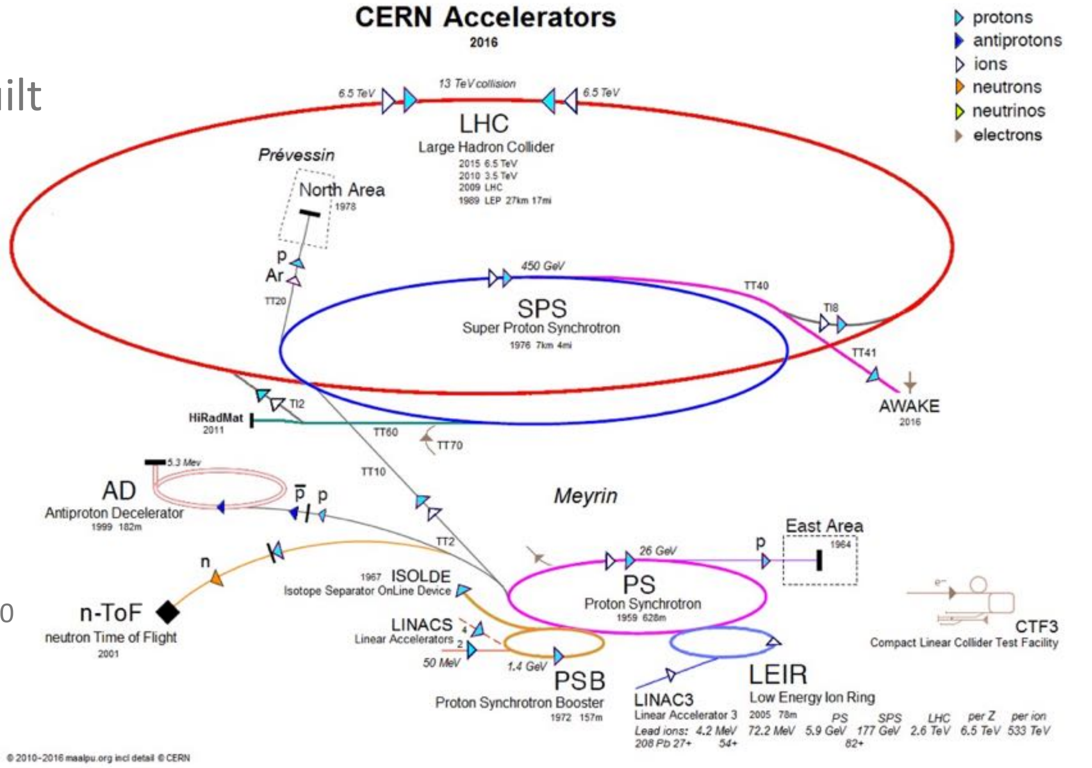
PHP2021: Physics Highlights Perugia 2020/21

Alta luminosità ad LHC: la Fase2 del Tracciatore di CMS

ALESSANDRO ROSSI

Large Hadron Collider

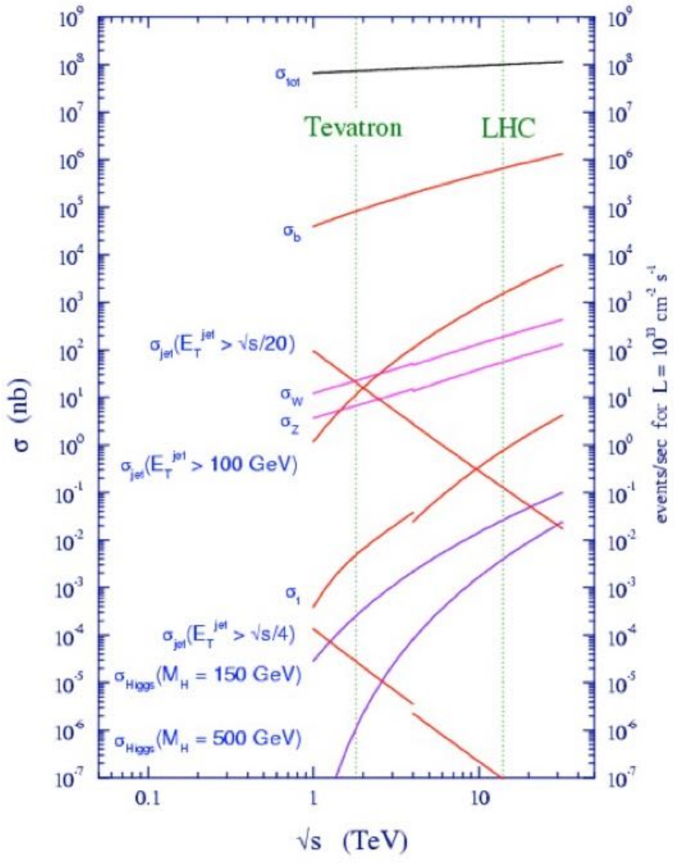
- Last piece of the complex CERN accelerators structure
- Most energetic accelerator ever built → 13TeV …at least!
- Also the largest!
  - With LEP: reuse of LEP tunnel
    - 27Km diameter
- Mainly Proton-Proton collision
  - Project luminosity of $2x10^{34}$ cm^{-2} s^{-1} met and overcome
  - Also the accelerator with the highest luminosity from 2018 up to last June…
    - [SuperKEKB](#) established the new world record on 2020
- Heavy Ion collisions possible
  - Reach program with Lead Ions



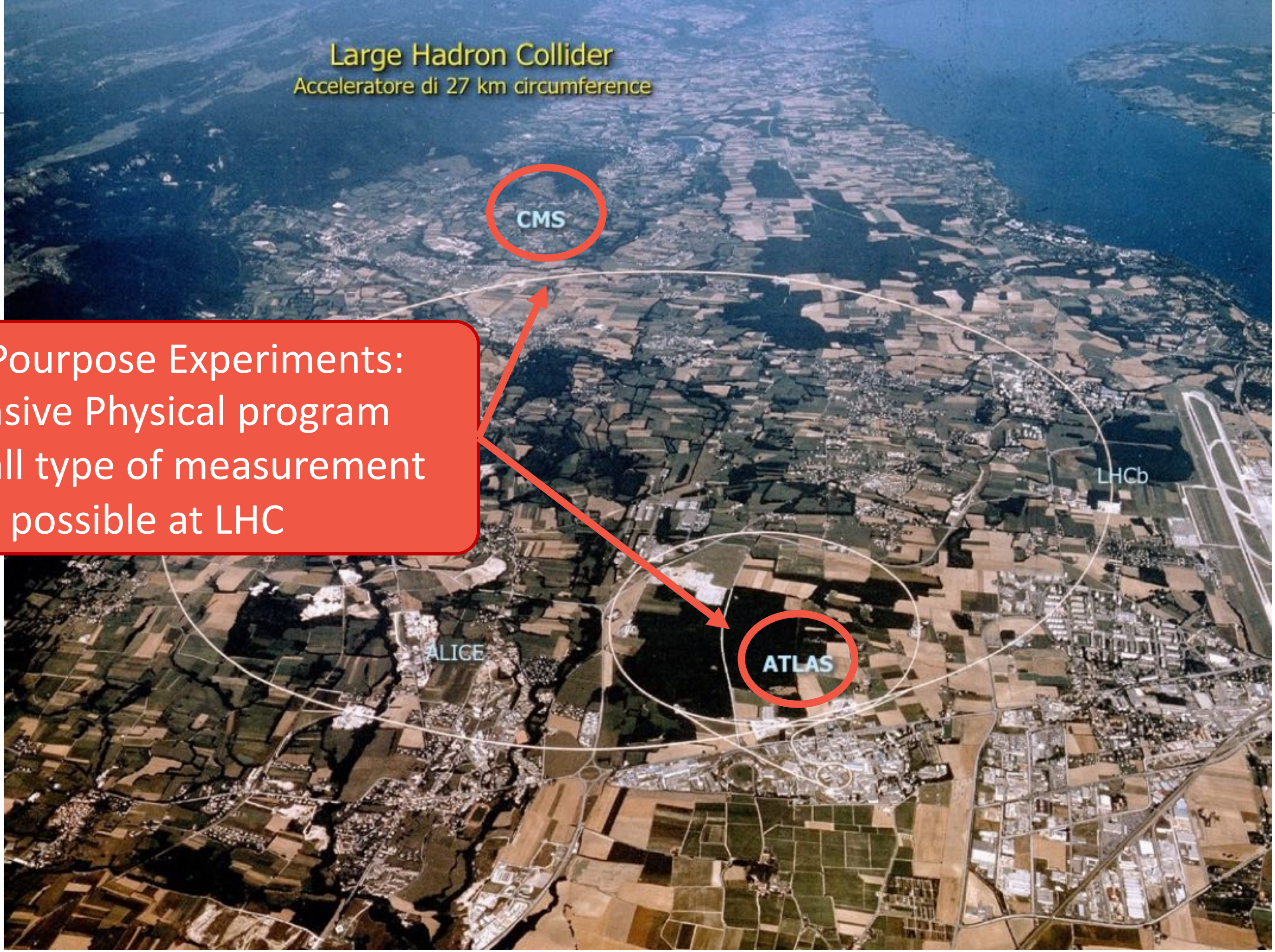
Energy Scale

- High Energy
  - Needed for Higgs production!
  - ...and whatever other particle(s) is there!

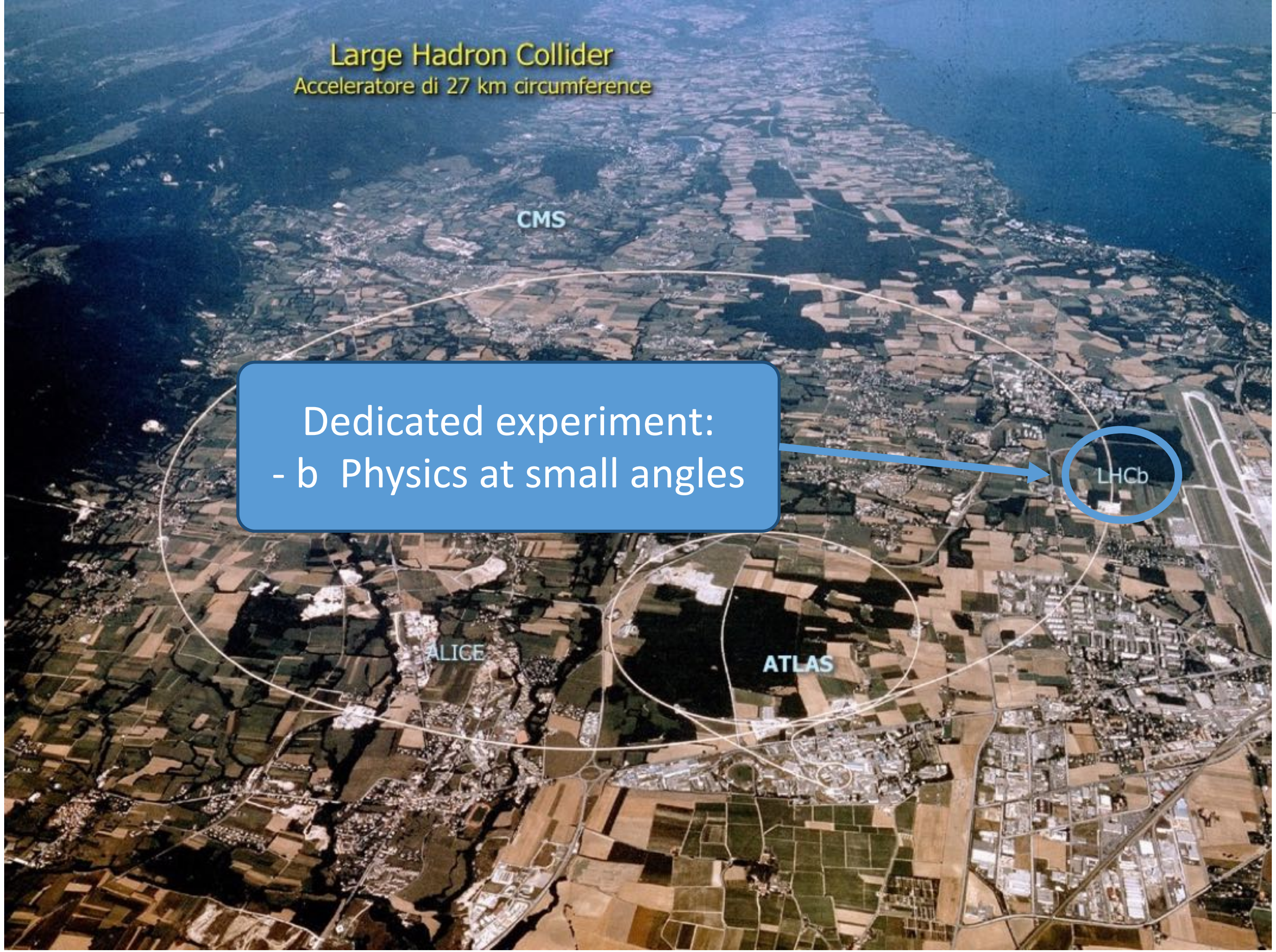
- High Intensity (i.e. Luminosity)
  - Interesting processes quite rare
  - Standard Model testing at high precision needs as many data as possible!

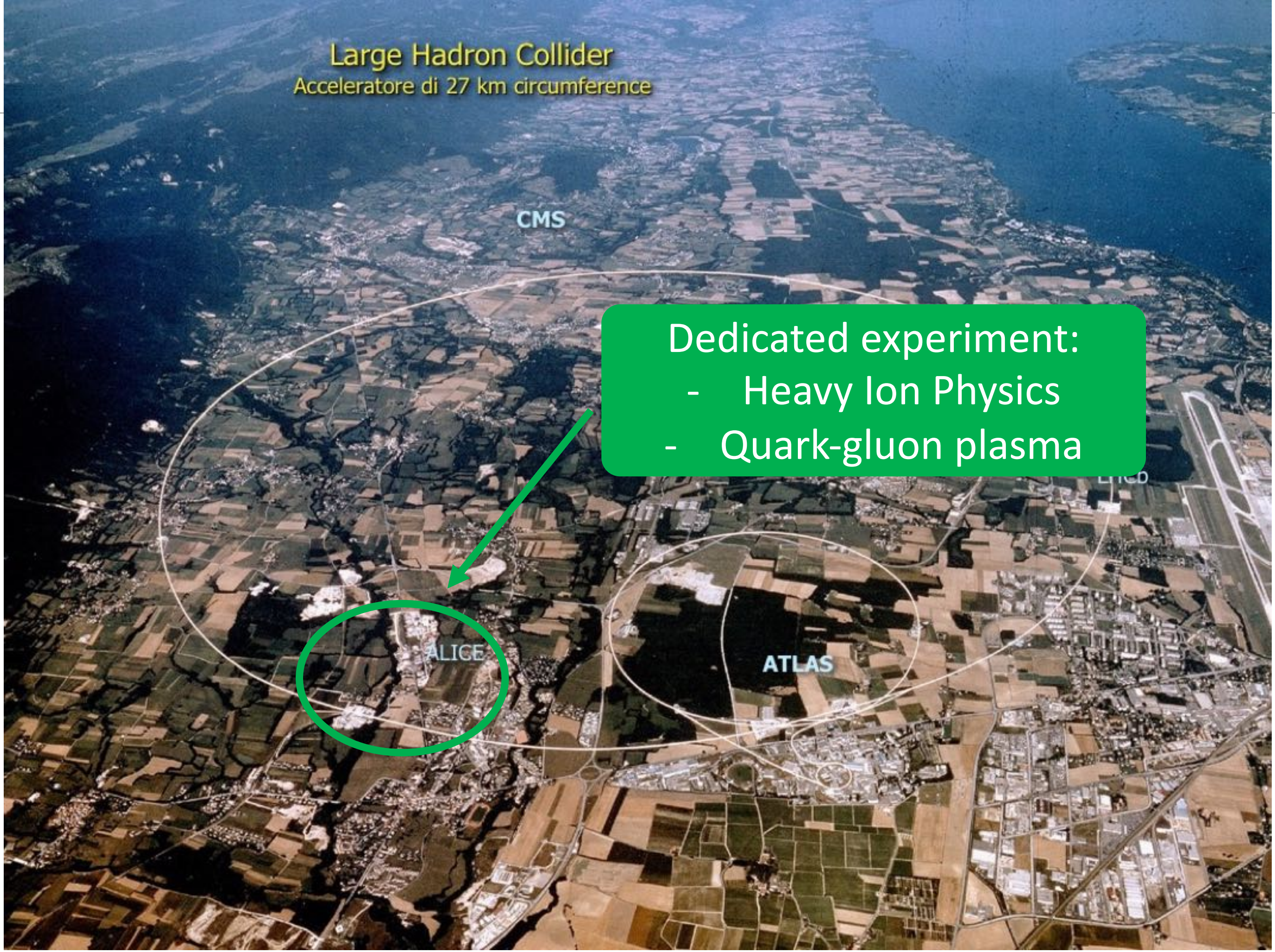



Large Hadron Collider
Acceleratore di 27 km circumference
CMS
LHCb
ALICE
ATLAS

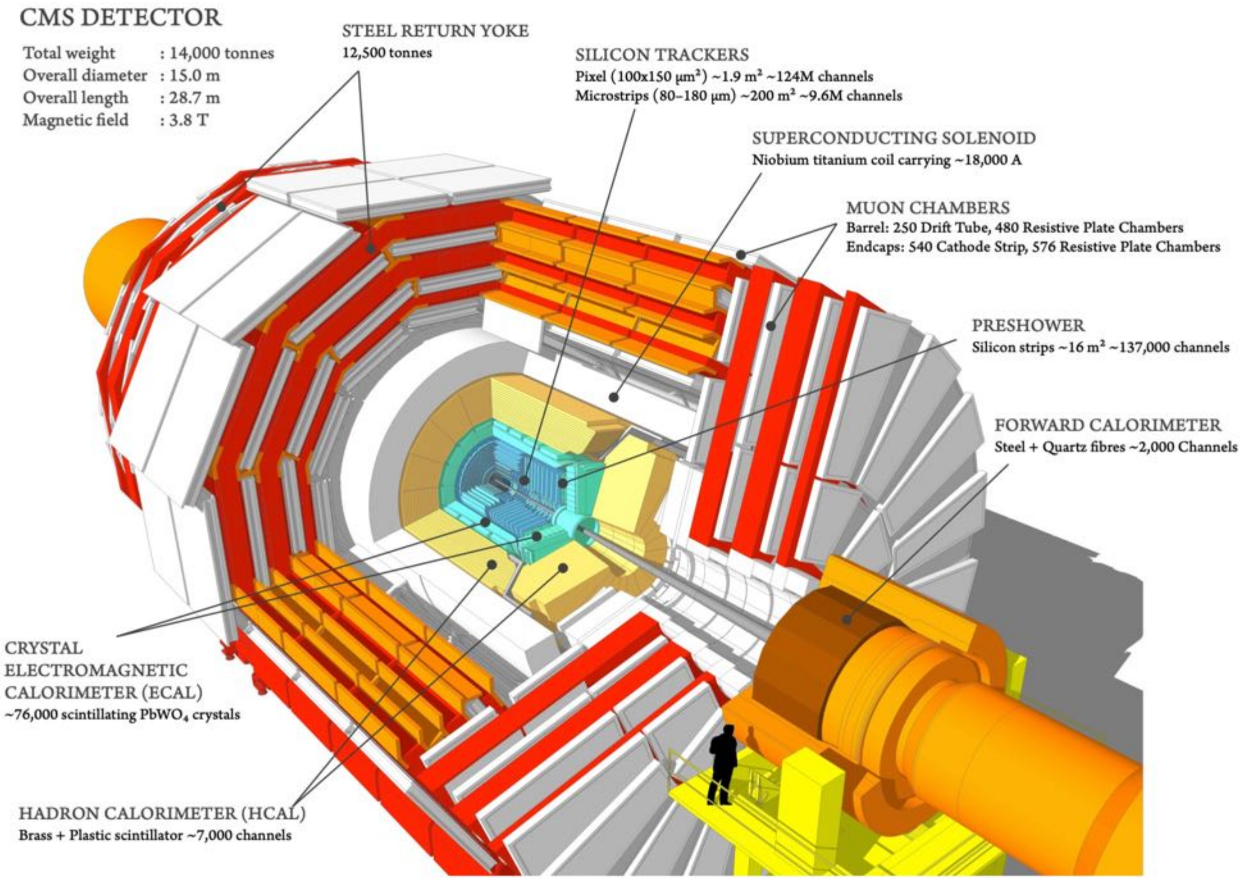


General Pourpose Experiments:
- Extensive Physical program
- Cover all type of measurement possible at LHC

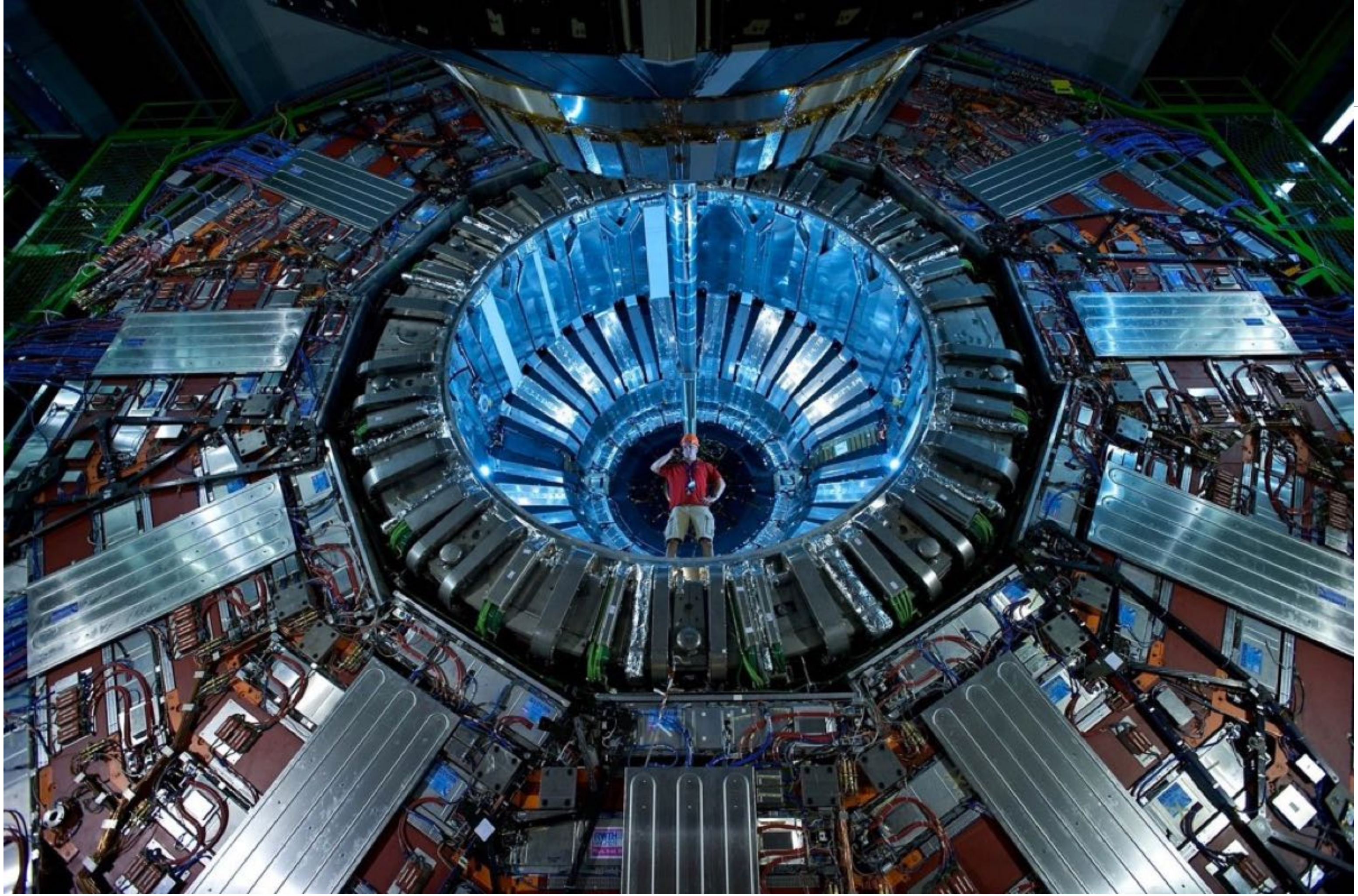

Large Hadron Collider
Acceleratore di 27 km circumference
CMS
Dedicated experiment:
- b Physics at small angles
LHCb
ALICE
ATLAS

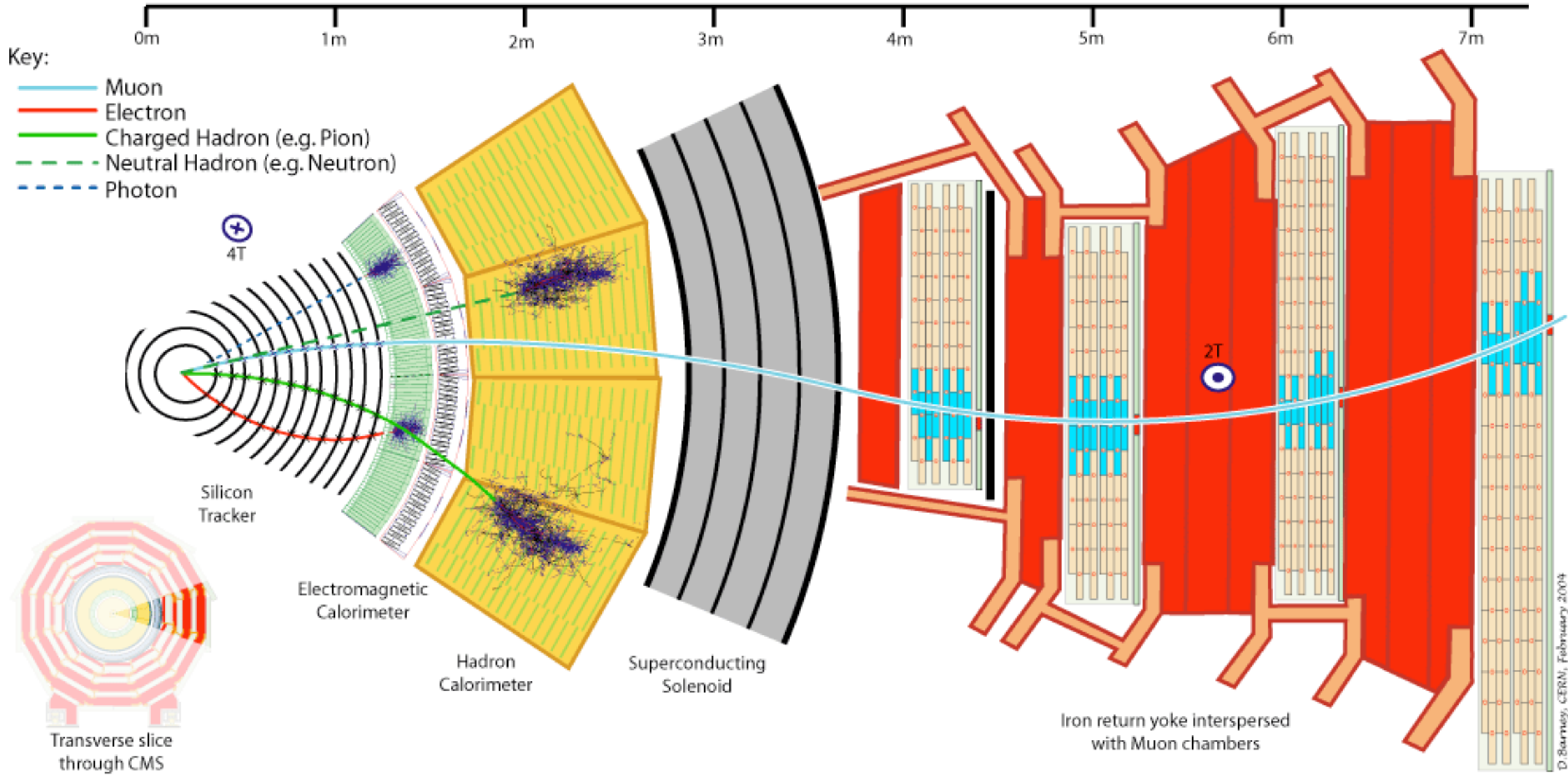

Large Hadron Collider
Acceleratore di 27 km circumference
CMS
ALICE
ATLAS
Dedicated experiment:
- Heavy Ion Physics
- Quark-gluon plasma

CMS



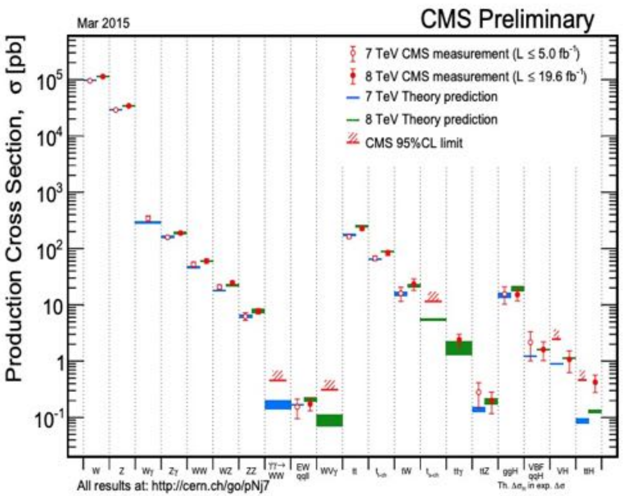
CMS DETECTOR
Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T
STEEL RETURN YOKE
12,500 tonnes
SILICON TRACKERS
Pixel (100x150 μm²) ~1.9 m² ~124M channels
Microstrips (80–180 μm) ~200 m² ~9.6M channels
SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000 A
MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 540 Cathode Strip, 576 Resistive Plate Chambers
PRESHOWER
Silicon strips ~16 m² ~137,000 channels
FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels
CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76,000 scintillating PbWO4 crystals
HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels

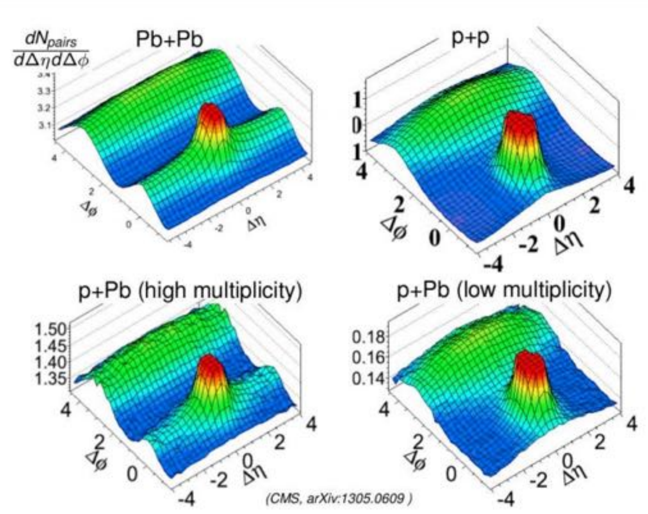


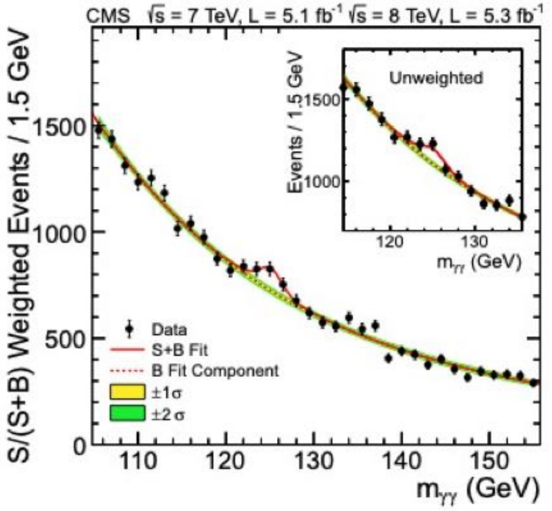

0m
1m
2m
3m
4m
5m
6m
7m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
Transverse slice through CMS
D.Barney, CERN, February 2004

SOME RESULTS

- RUN-1
  - 2009-2013 - Standard Model re-calibration
  - 2010 - Long-range near-side correlation observation (QGP in p-p?)
  - 2012 – Higgs Boson Discovery!

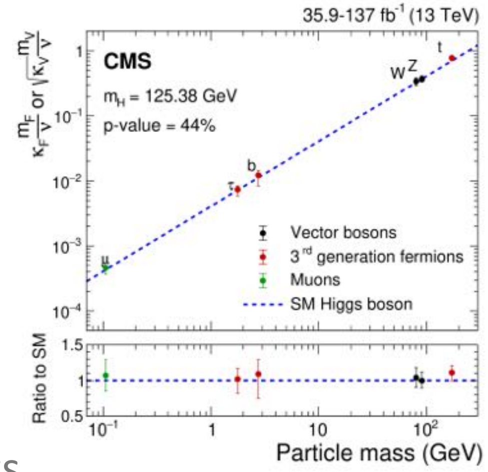


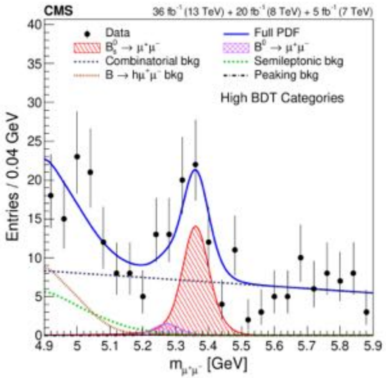


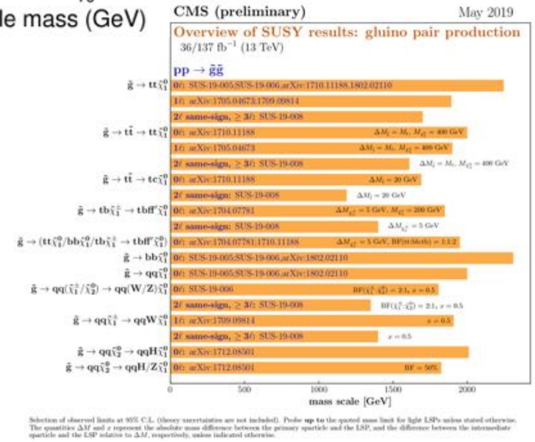


SOME RESULTS

- RUN-1
  - 2009-2013 - Standard Model re-calibration
  - 2010 - Long-range near-side correlation observation (QGP in p-p?)
  - 2012 – Higgs Boson Discovery!
- RUN-2
  - 2015-2018 – Higgs Couplings measurements, SUSY searches, SM precision test







RUN3

- Consolidate Run-2 observation
  - Ie: H→ff, VH, ttH, VV, VBS,…
  - separately in different channels
  - differential measurements
  - systematics becoming relevant
  - …
- Run 3 provides the opportunity to implement novel trigger and new analysis methods and approaches
  - i.e.: Data "Scouting"
    - Also known as trigger-level analysis
    - HLT-reconstructed events with reduced event-content
      - size ~ 1.5 kB/evt
      - rate ~ 5 kHz established
    - No raw data stored
    - No prompt reconstruction

Machine Upgrades:

- 13 → 14 TeV: higher mass reach
- Additional 250 fb-1: factor ~1.7

Detector Upgrades:

- Pixel: Layer1 replacement
- HCAL barrel: install SiPM
- Muon system: install GEM GE1/1 chambers; Upgrade CSC FEE; Shielding against neutron background
- Trigger: heterogeneous Computing at HLT

WHAT NEXT?

- **Substantial upgrade of the accelerator: HL-LHC (high luminosity LHC)**

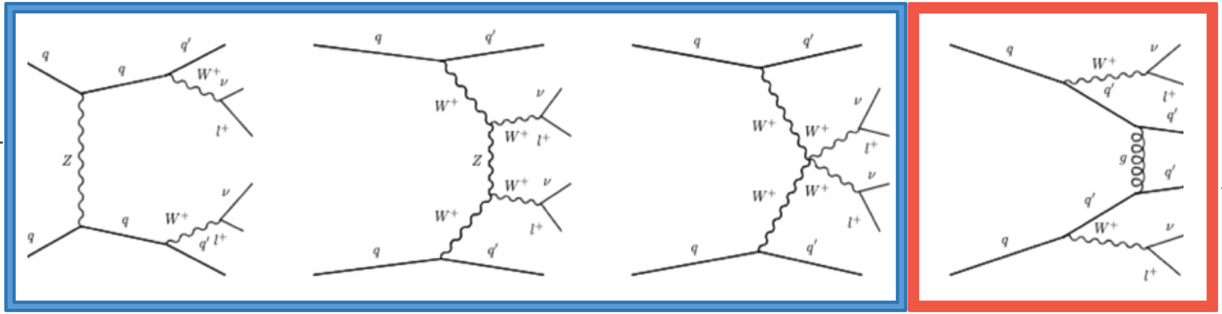
  - Push the reach of precision measurements despite the very complex experimental environment
    - Precision Higgs Measurements
    - Higgs Self Coupling
    - Precision Electroweak Measurements
    - Extend BSM searches to smaller production cross sections
    - Precision measurements of rare B decays
    - Heavy Ion Physics

Vector Boson Scattering

- **Scattering processes with Vector Bosons (V=W,Z):**
  - Reduced QCD activity between the tag jets
  - no color flow between interacting quarks
  - Large pseudorapidity separation and invariant mass between initial quarks (tag jets)
  - Purely electroweak process $O(\alpha^6_{EM})$ at LO
  - Direct access to Spontaneous Symmetry Breaking without Higgs
  - Probe particularly sensitive to contributions from new physics thanks to the quartic vertex

Same Sign WW Vector Boson Scattering

Signal: ssWW EWK processes, xSec= 0.02696 pb



QCD background, xSec=0.02615 pb

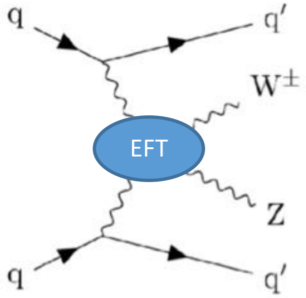
- 4 LO Feynman diagrams for ssWW processess
  - EWK ssWW: pure EWK processes (signal)
  - QCD ssWW: QCD interactions between partons (irreducible background)
- QCD and EWK ssWW production processes have similar xSec
- Boson polarization could be an additional probe

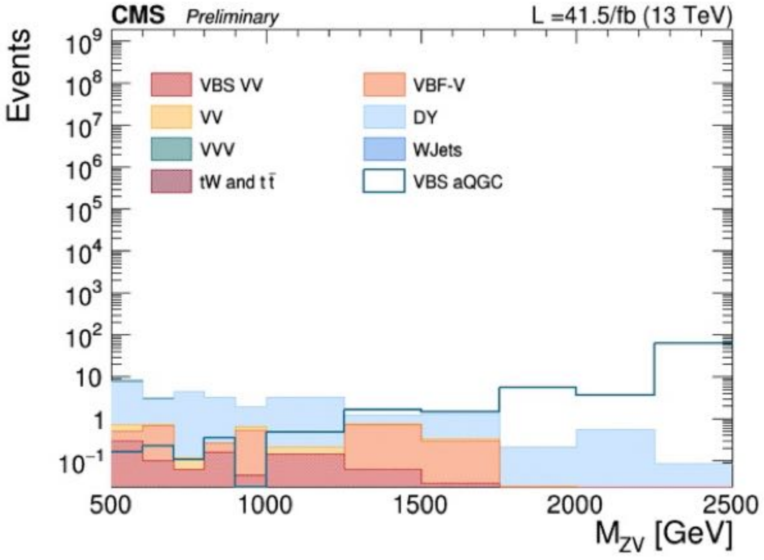
Effective Field Theory

- **Direct detection of New Pbysics could be out of the possible experimental reach**
  - Push the experimental limits in a model independent way
  - Measurement of Effective Field Theory parameters

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_{n=1}^{\infty} \sum_{i} \left(\frac{c_i^{(n)}}{\Lambda^n} \right)_i^{(n+4)}$$

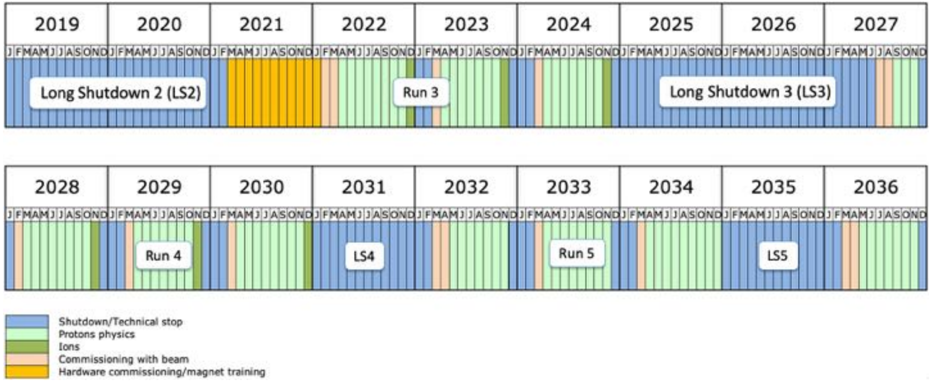
  - Power series of all the possible parameters
  - Enanchement on distribution tails
  - Some processes mediated by effective operator could violate unitarity
    - Add bounds to constraint unitarity

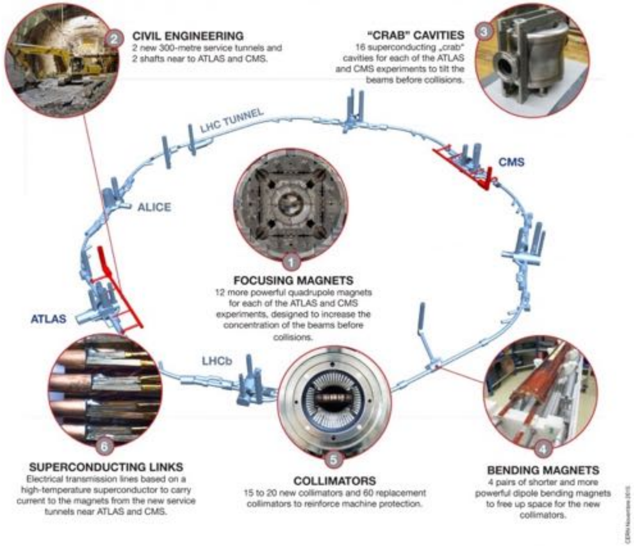




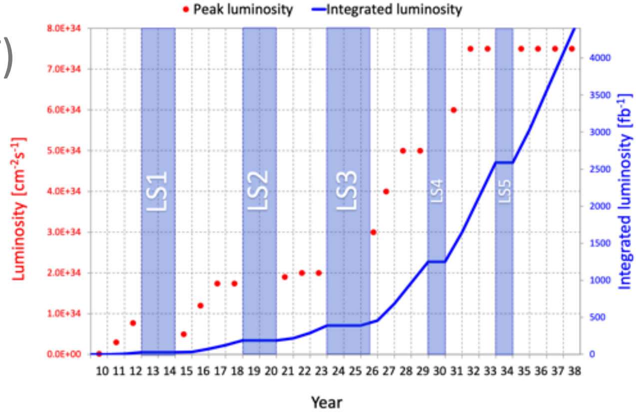
LHC Schedule

- High Luminosity upgrade after LS3
- Peak Luminosity ~$7.5 \times 10^{34} cm^{-2}s^{-1}$
- Expected Pile-up ~200
- Higher rates and radiation dose wrt Run3





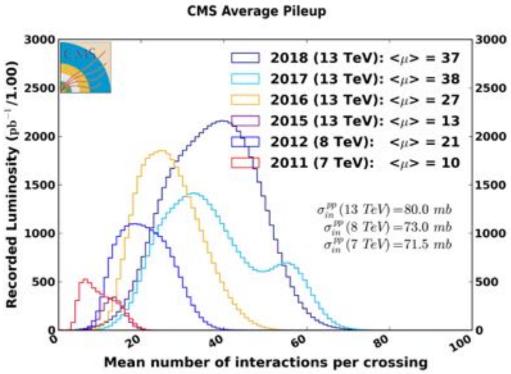
- Crab cavities
- (some) New Magnets (11T)
- Civil engineering:
  - New acces shafts
  - New service tunnels
- …and more!

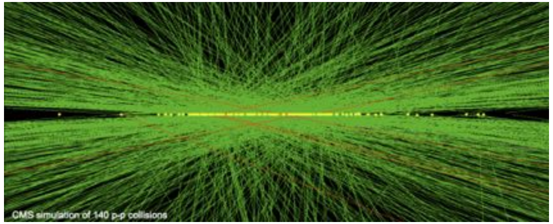


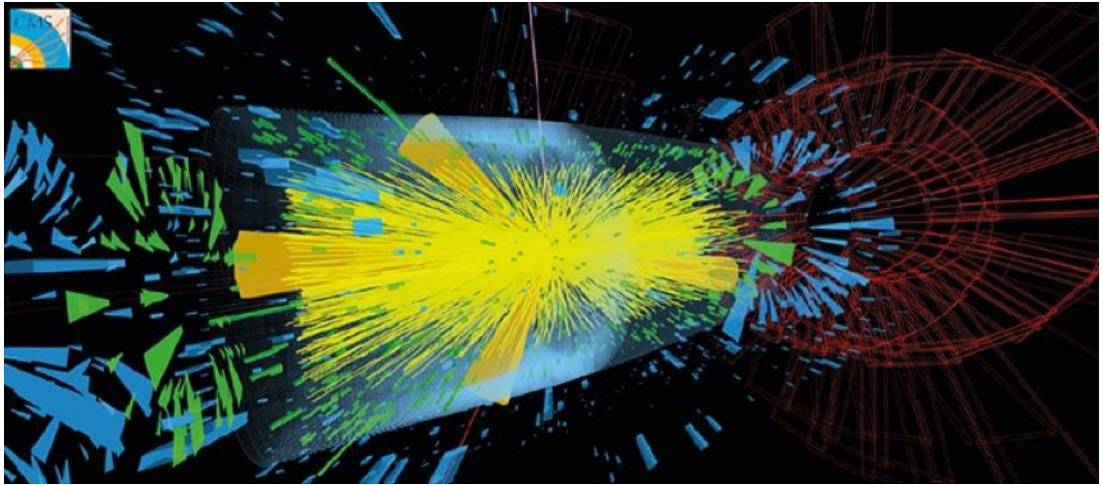
Phase2 Pile Up

- Run2:
  - Mean PileUp 37
- Run3:
  - Mean PileUp ~55
- Phase2
  - Mean PileUp **140-200!**

Pile Up:
Number of interactions in a single bunch crossing







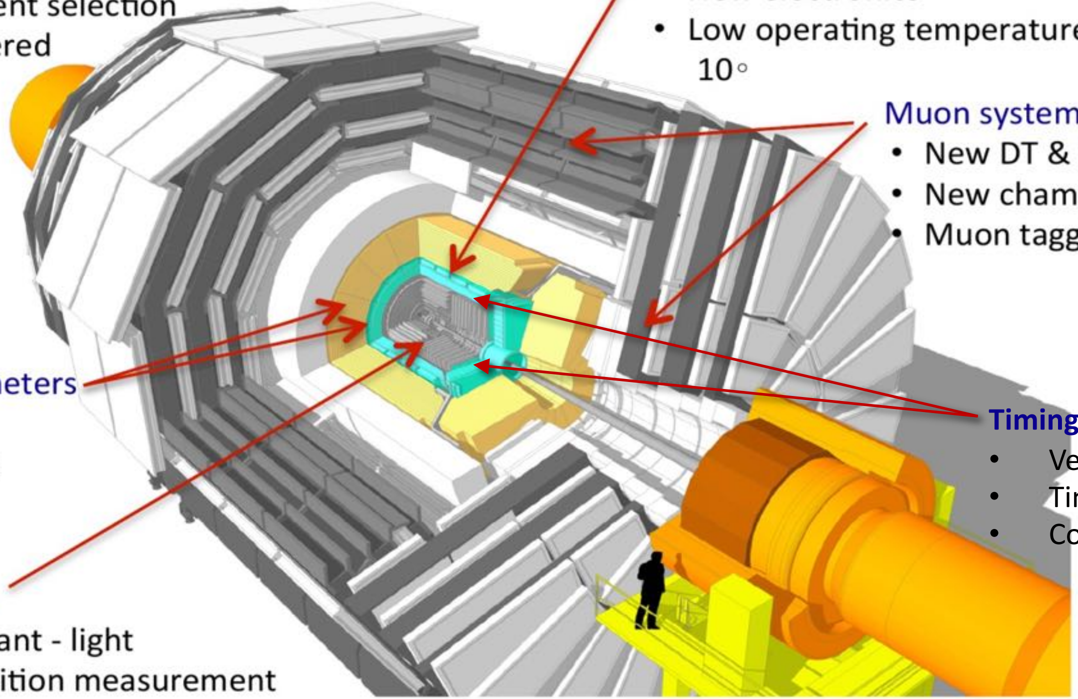
CMS Phase2 Upgrade

Trigger/HLT/DAQ
- Track information in hardware event selection
- 750 kHz hardware event selection
- 7.5 kHz events registered

Run2:
- 80kHz Hardware L1
- 1.5kHz on disk

Barrel EM calorimeter
- New electronics
- Low operating temperature ≈ 10°

Muon systems
- New DT & CSC electronics
- New chambers 1.6 < η < 2.4
- Muon tagging 2.4 < η < 3



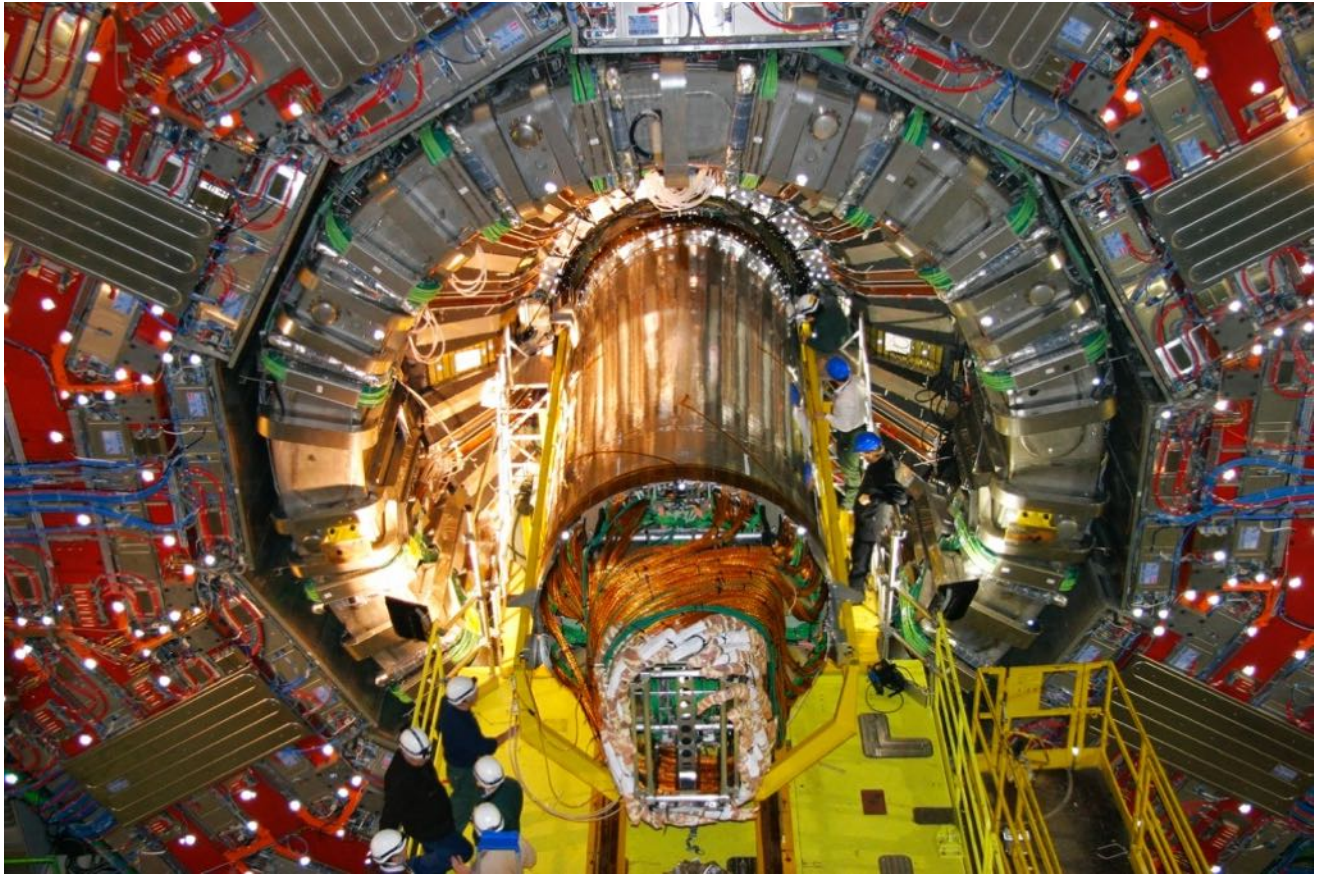
New Endcap Calorimeters
- Rad. Tolerant
- 5D measurement

Timing Layer:
- Vertex-Track association
- Time σ~30ps
- Coverage η<3

New Tracker
- Rad. Tolerant - light
- High Definition measurement
- 40 MHz selective readout for hardware trigger
- Extended Pixel coverage to η ≈ 3.8

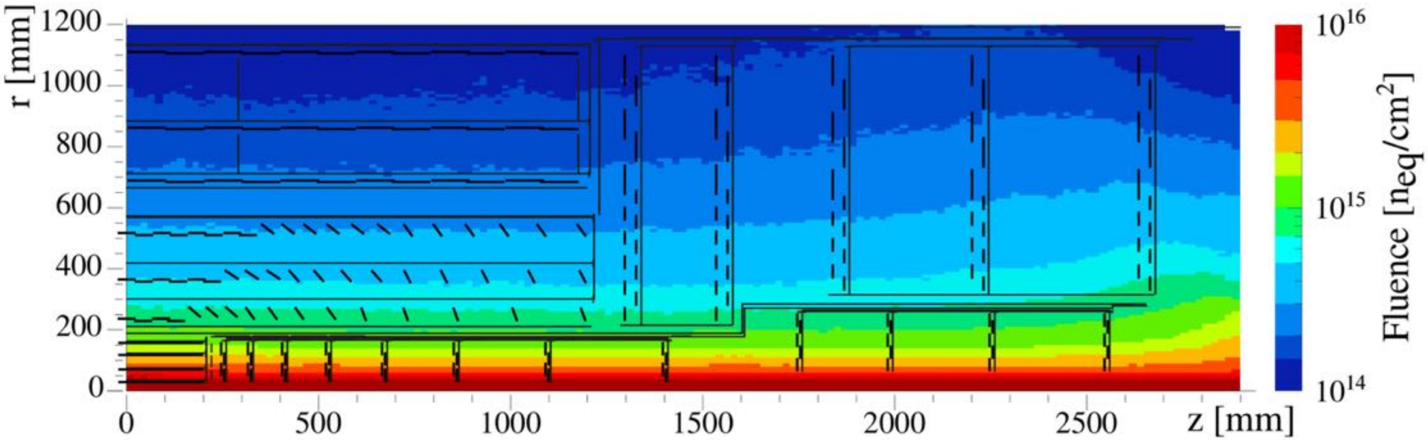
Beam radiation and luminosity
Common systems and infrastructure

Tracker

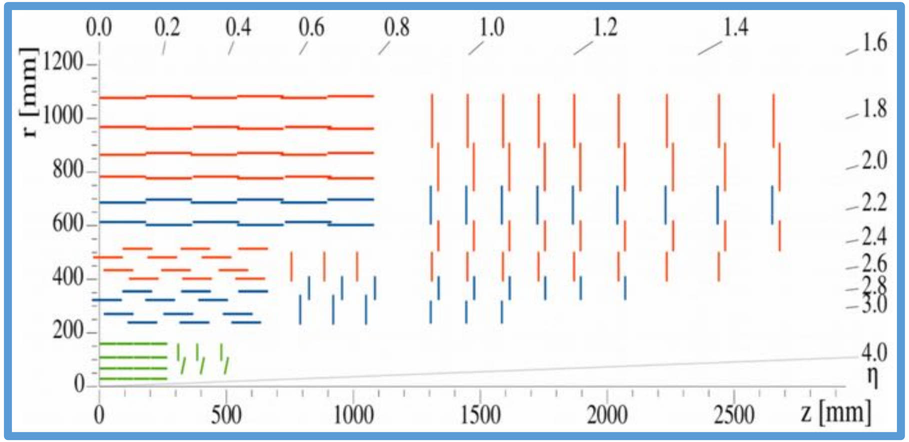


High Luminosity Requirements

- ***Increased granularity***: In order to ensure efficient tracking performance with a high level of pileup
- ***Reduced material in the tracking volume***: The exploitation of the high luminosity will greatly benefit from a lighter tracker
- ***Contribution to the level-1 trigger***: The selection of interesting physics events at the first trigger stage becomes extremely challenging at high luminosity
- ***Extended tracking acceptance***: The overall CMS physics capabilities will greatly benefit from an extended acceptance of the tracker
- ***Radiation tolerance***: The upgraded tracker must be fully efficient up to a target integrated luminosity of $3000 fb^{-1}$
  - Outer layers “far away” from interaction point will see $>10^{14}$MeV neutron equivalent fluence
    - more than innermost strip tracker layers at 20 cm for today's trackers after 10 years of LHC running

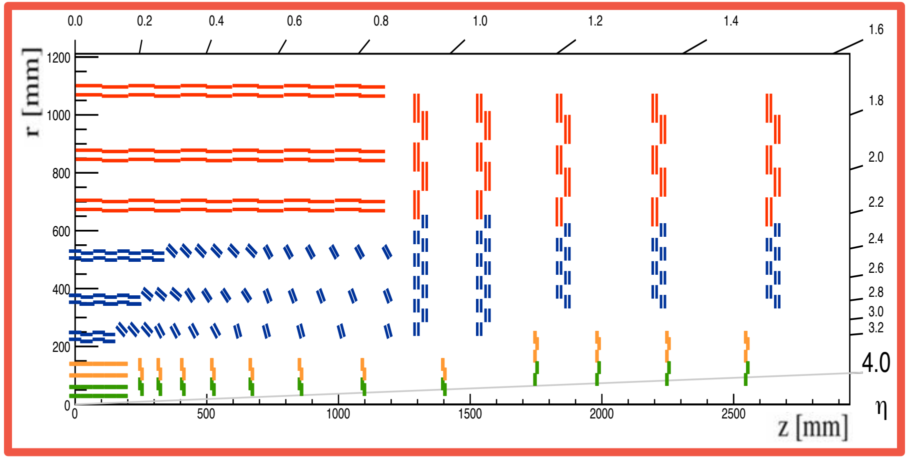


Why change the current Tracker



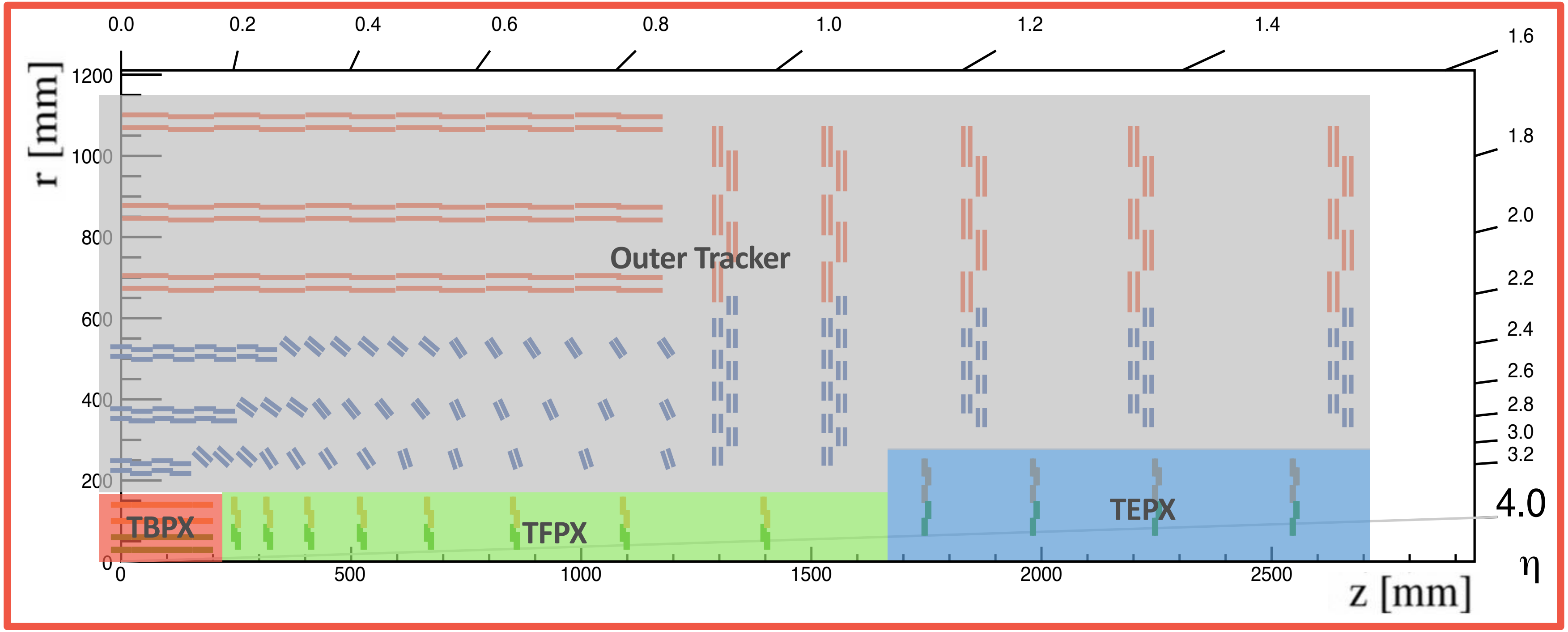
CMS Phase-1 Tracker

- A big part of current strip tracker will become completely in-operational due to either leakage current or full depletion voltage limitations at 1 ab^{-1}
  - full tracker replacement needed for HL-LHC program



CMS Phase-2 Tracker

Phase-2 CMS Inner Tracker



- **TBPX** : Tracker **B**arrel **PiX**el
- **TFPX** : Tracker **F**orward **PiX**el
- **TEPX** : Tracker **E**ndcap **PiX**el

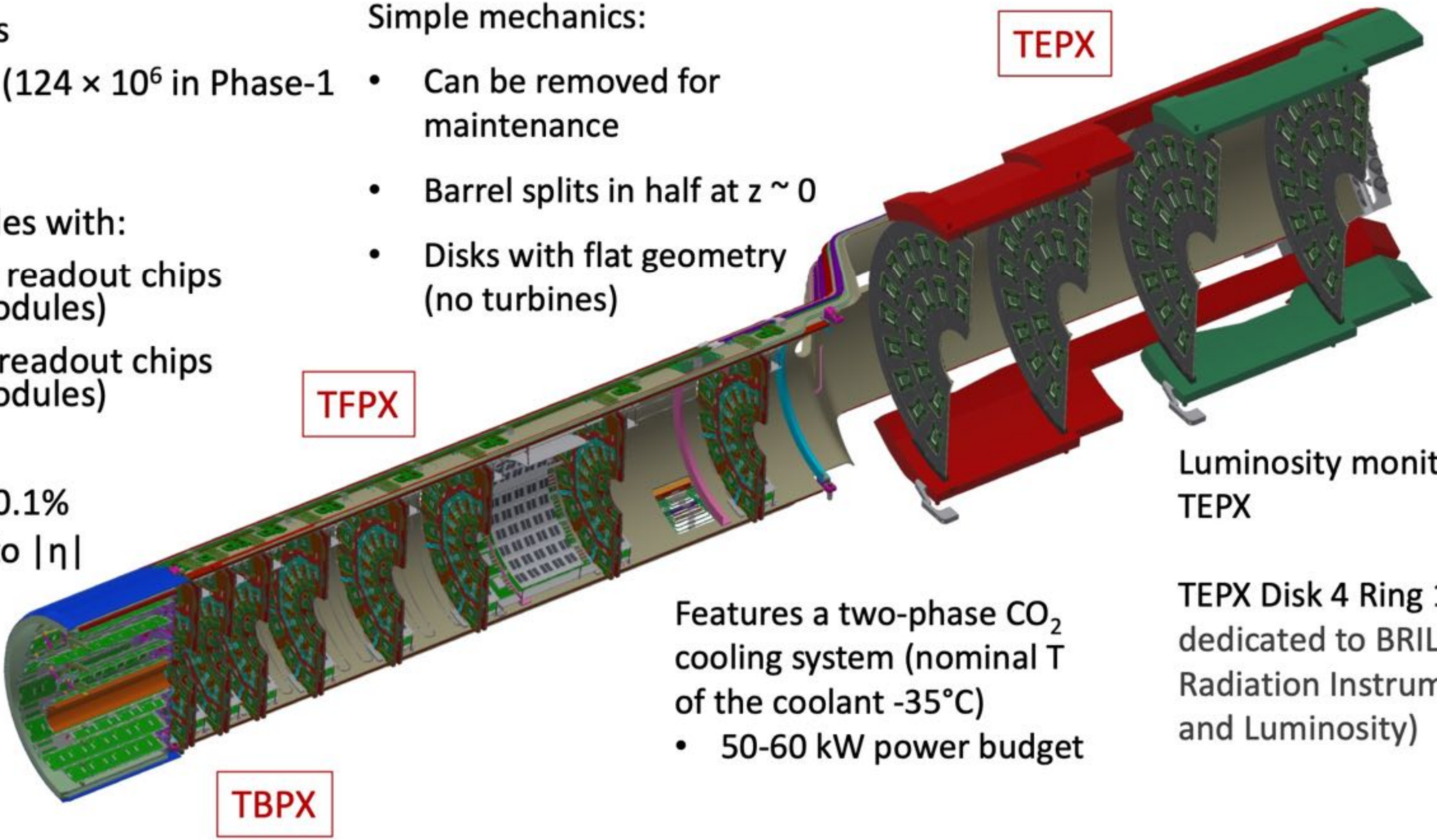
Inner Tracker Overview

- 3892 modules
- 2×10^9 pixels (124×10^6 in Phase-1 upgrade)
- 4.9 m^2
- Hybrid modules with:
  - 2 (1 × 2) readout chips (1156 modules)
  - 4 (2 × 2) readout chips (2736 modules)

- Occupancy < 0.1%
- Coverage up to |η| = 4.0

Simple mechanics:

- Can be removed for maintenance
- Barrel splits in half at z ~ 0
- Disks with flat geometry (no turbines)



Luminosity monitor with TEPX

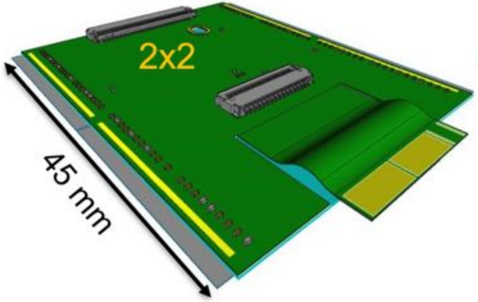
TEPX Disk 4 Ring 1: fully dedicated to BRIL (Beam Radiation Instrumentation and Luminosity)

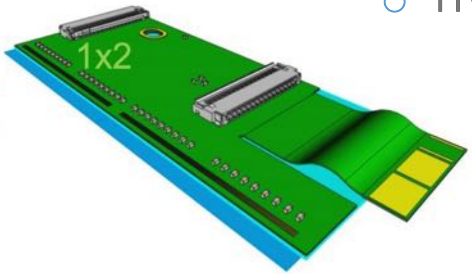
Features a two-phase CO_2 cooling system (nominal T of the coolant -35°C)

- 50-60 kW power budget

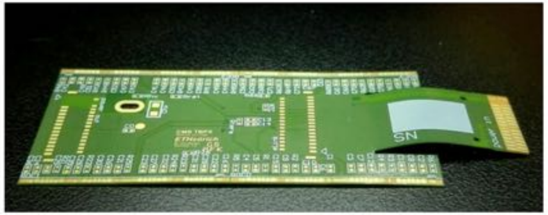
Modules and Read Out

- Read Out Chip (ROC)
  - Being developed by the RD53 Collaboration
  - For both ATLAS and CMS inner detectors
  - low-threshold (≲ 1000 e-)
  - high hit and trigger rate:
    - 160 Mbps control & up to 4 x 1.28 Gbps output links



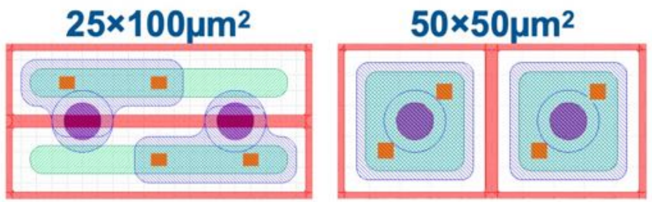


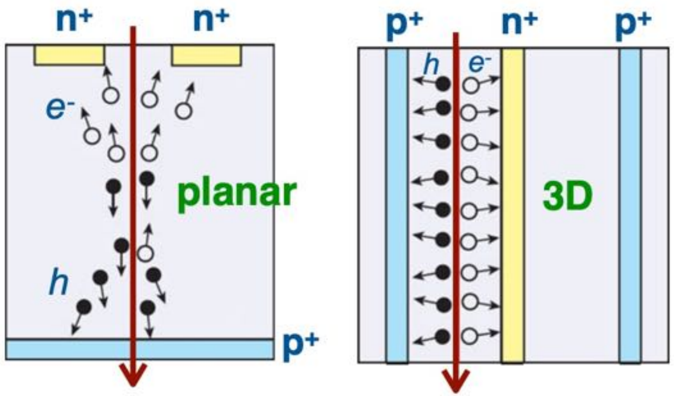
- Simple design
  - ROC is the only active electronics on module
- High Density Interconnection (HDI)
  - Flexible PCB containing only passive components
  - 2 to 4 ROCs per module
  - HV capable up to 1000 V



Sensors: type and geometry

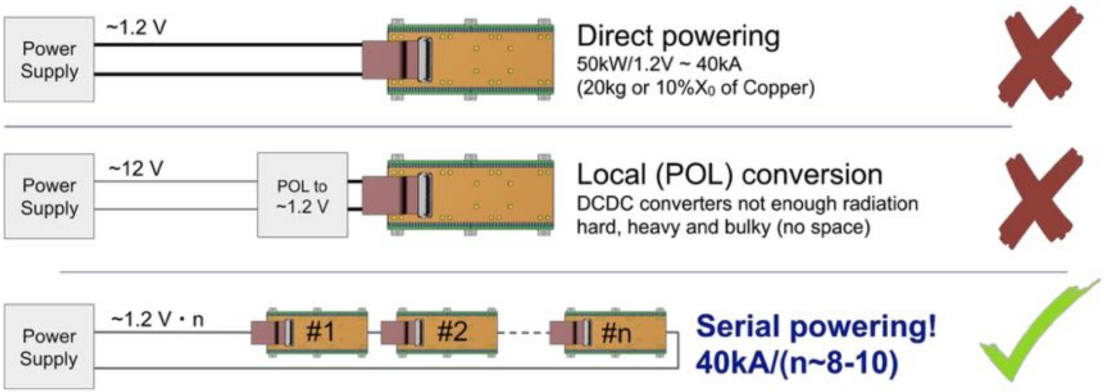
- Radiation tolerance → thin sensors: 150 μm thickness
- expected signal / threshold > 3 at $\Phi_{eq} \approx 8 \times 10^{15}$ cm^{-2}
- Track density → reduce pixel size by factor of six
  - Different geometry under study
    - 25 x 100 μm^2, 50 x 50 μm^2, 25 x 100 μm^2 «bricked»
- High efficiency → pixel cell design
  - Isolation, biasing scheme, layout details
- Study n-in-p planar sensors
- 3D sensors under investigation for layer 1 (6% of the total area) and innermost layer of the TFP





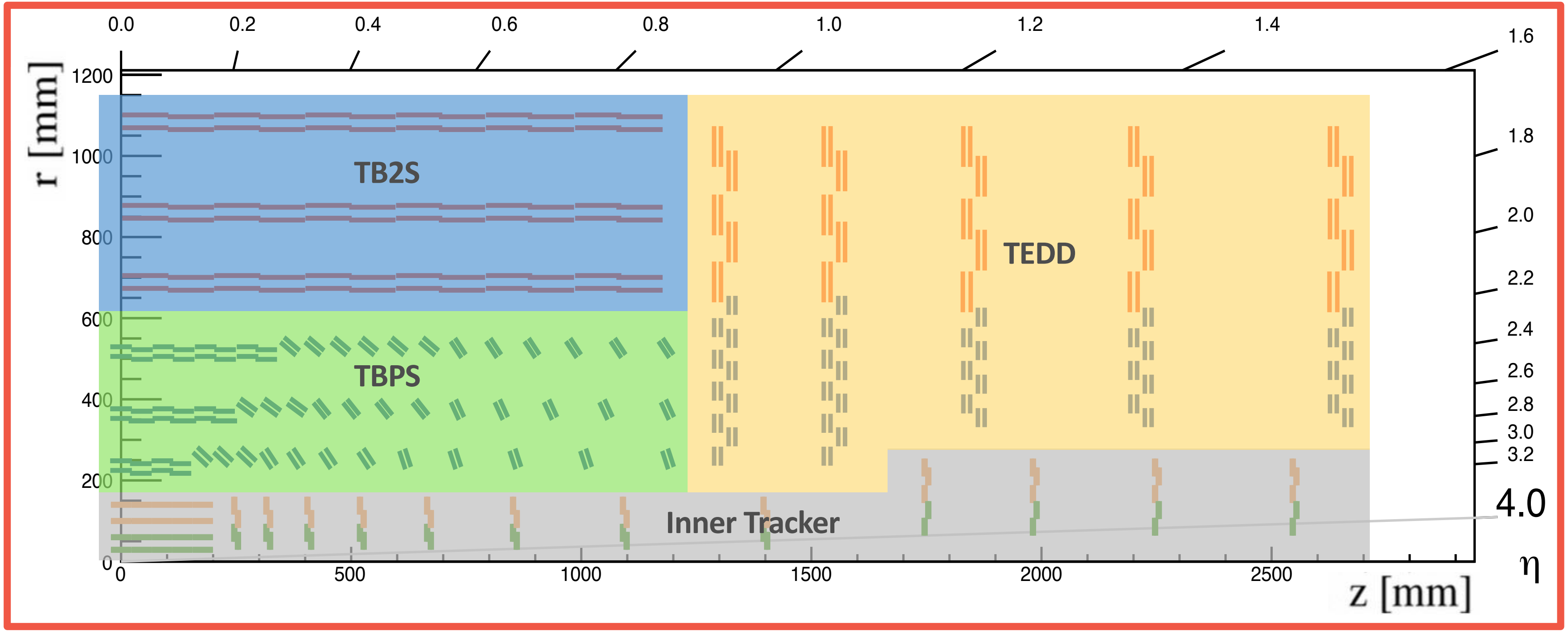
Serial Powering

- Upgraded Inner Tracker power consumption: 50 kW
- ROC in 65 nm technology and with high granularity:
  - high supply current
- Direct parallel powering requires too much material



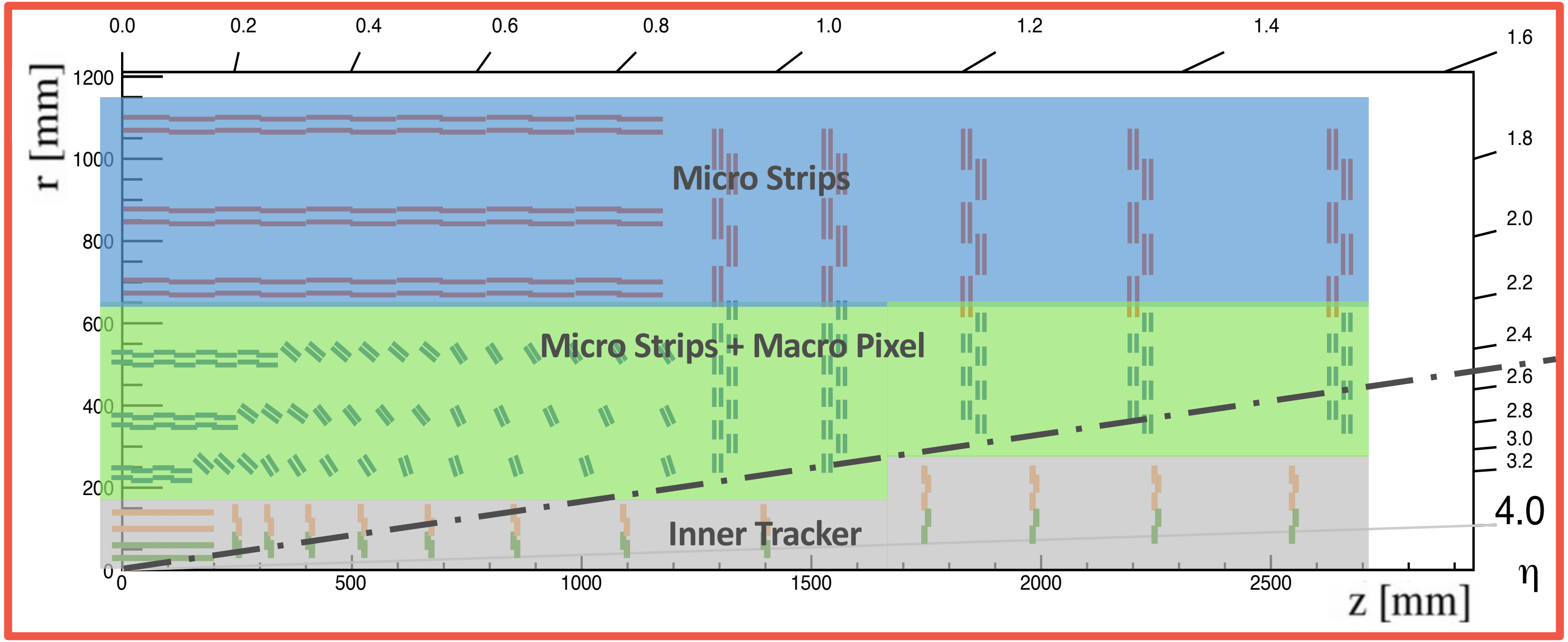
- The serial powering is the unique scheme compatible with HL-LHC physics
- All the elements in a chain see the same current (by construction) while the voltage is equally shared if all elements represent the very same and constant load
- This is the task of the Shunt LDO: no additional ancillary components are needed

Phase-2 CMS Outer Tracker



- **TBPS** : **T**racker **B**arrel with **PS** modules
- **TEDD** : **T**racker **E**ndcap **D**ouble **D**isk
- **TB2S** : **T**racker **B**arrel with **2S** modules

Phase-2 CMS Outer Tracker

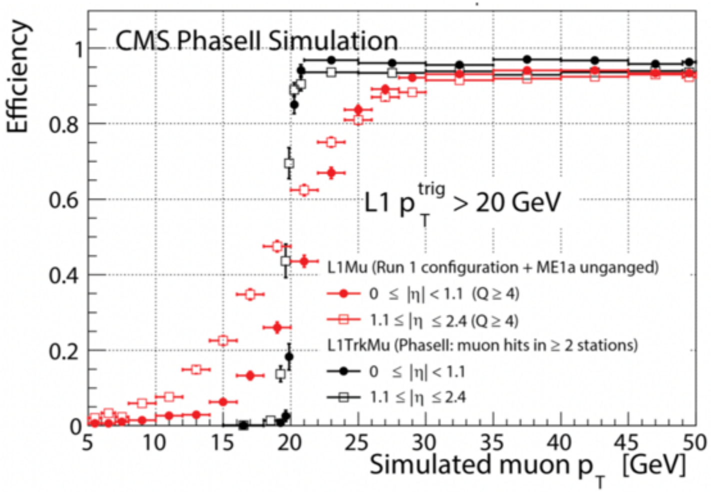


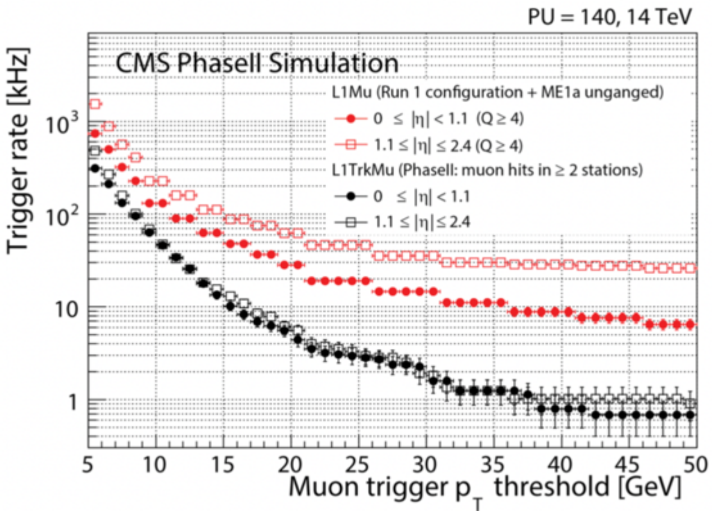
- Outer Tracker coverage up to η~2.5
  - Tracking up to η~4 thanks to InnerTracker
- Two different type of technology: micro-strips and macro-pixels
- Tilted barrel geometry
  - Better trigger performances
  - Reduction on number of modules

Tracks for L1 Trigger

- HL-LHC will deliver an high instantaneus luminosity with a high PileUp
  - It's fundamental to be more selective at L1 trigger in order to keep data rate under control

Include Tracks on L1 decision





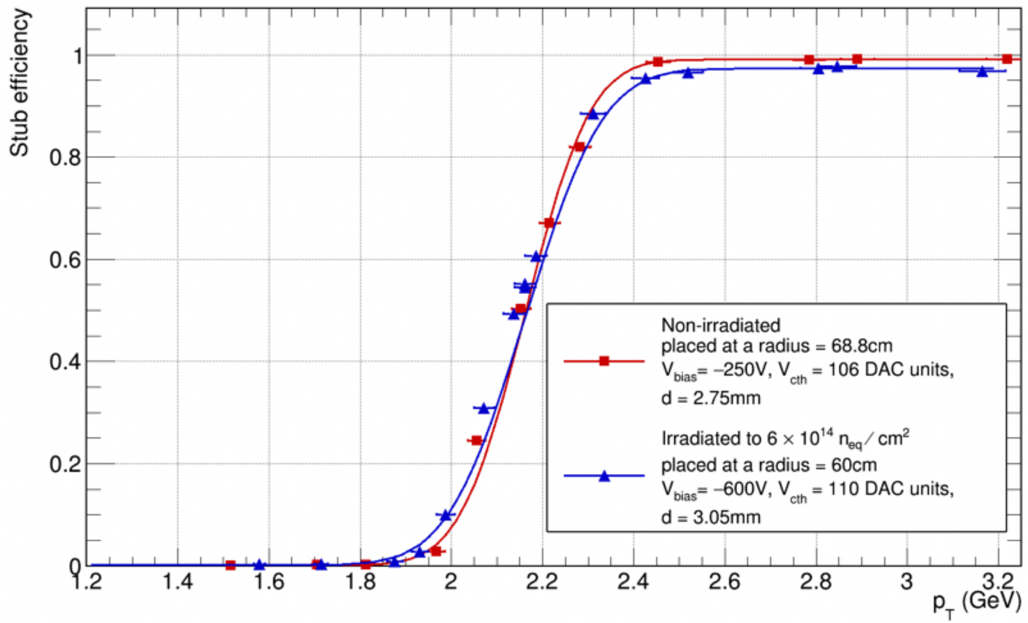
Today's L1 threshold at 200 PU ~ 4 MHz
- **Tracks needed for trigger decision**
- Lepton threshold improvement
- Possibility for new triggers (e.g. displaced or disappearing tracks)

Tracks for L1 Trigger

- HL-LHC will deliver an high instantaneus luminosity with a high PileUp
  - It's fundamental to be more selective at L1 trigger in order to keep data rate under control

Include Tracks on L1 decision

- Most of charged particles have low p_T
- Perform a p_T selection at readout level in order to reduce the L1 tracking input data size



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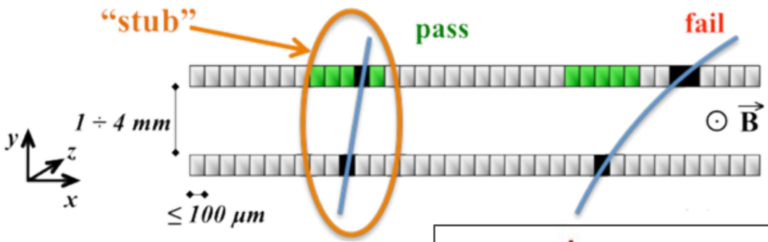
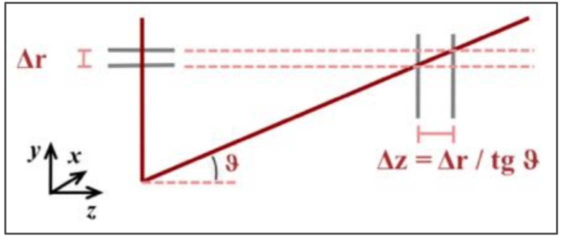
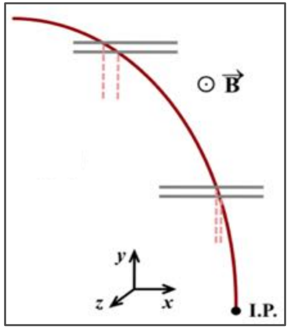
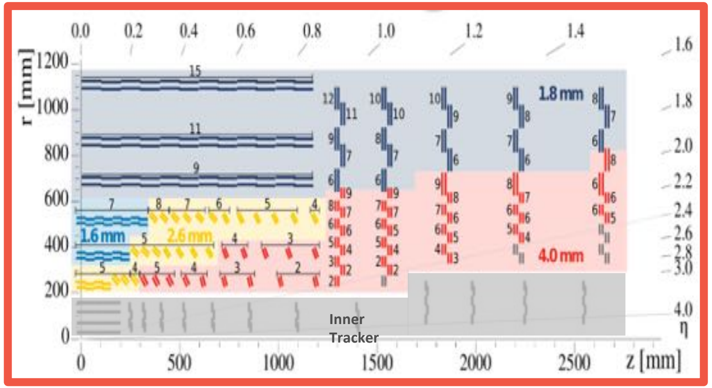
pT Modules

- Two silicon sensors with small spacing in a module
- Flex hybrid in order to get data from both sensors to one ASIC → Select track «stubs»
- Different sensor spacing for different detector region
- Tunable correlation windows

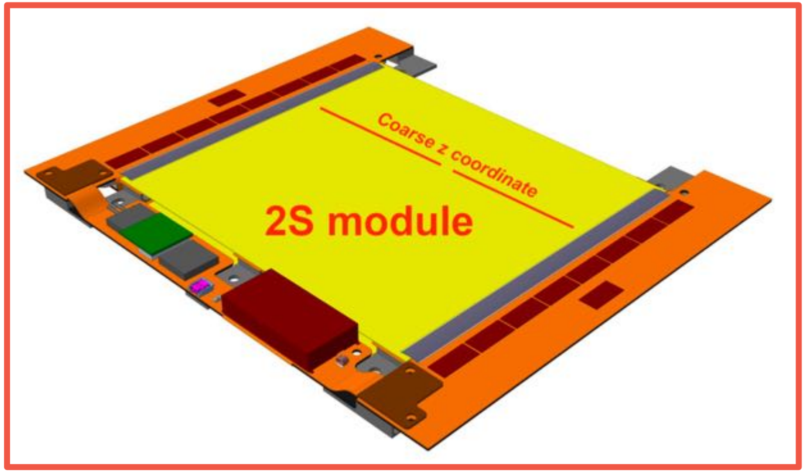


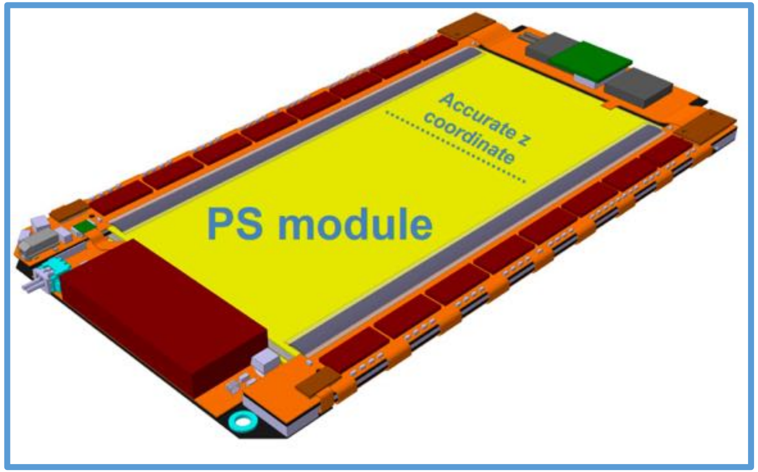






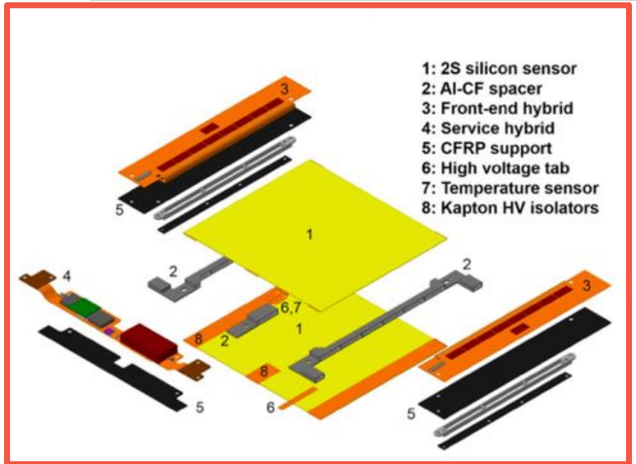
Phase-2 Tracker Modules

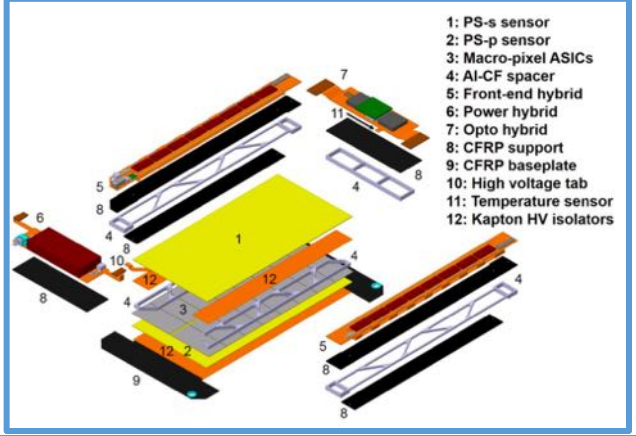




- **Two type of modules:**
  - 2S Modules
    - 2 different spacing : 1.8mm & 4mm
    - 2 micro strip sensors with 5cm x 90µm strips
    - Sensor dimension are 10cm x 10cm
      - two column of 1016 strips
  - PS Modules
    - 3 different spacing : 1.6mm & 2.6mm & 4mm
    - One strip sensor: 2.5cm x 100µm strips
    - One macro Pixel sensor : 1.5mm x 100µm pixels
    - Sensor dimension 5cm x 10 cm
      - two column of 960 strips
      - ~30k pixels

Modules Service Systems

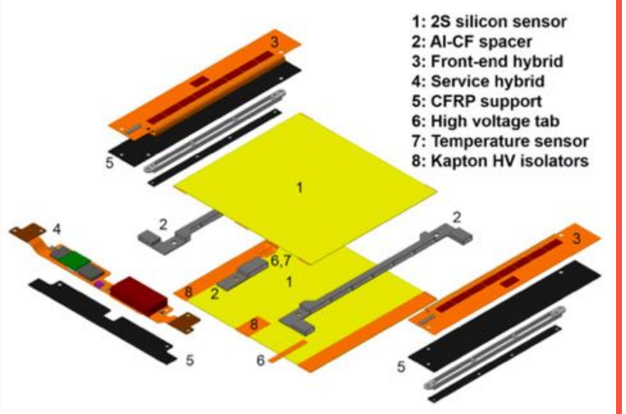


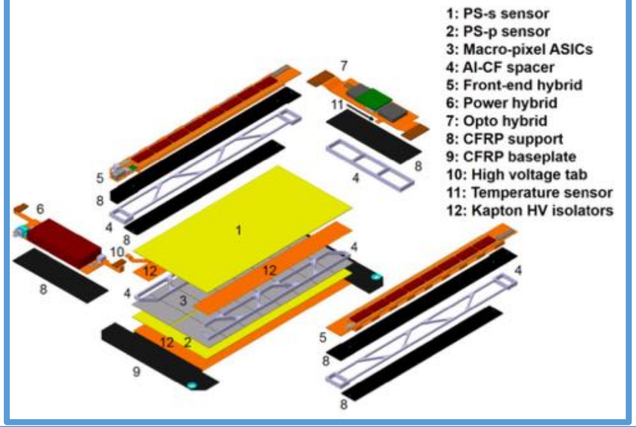


- Module houses both frontend and service hybrids
- Service hybrid(s) has:
  - lpGBT
    - Low Power Gigabit Transceiver
  - VTRx+
    - Versatile Link Plus Transceiver
  - DCDC converters
- Frontend hybrids have readout chip and data concentartor

HL-LHC common development

Modules Service Systems



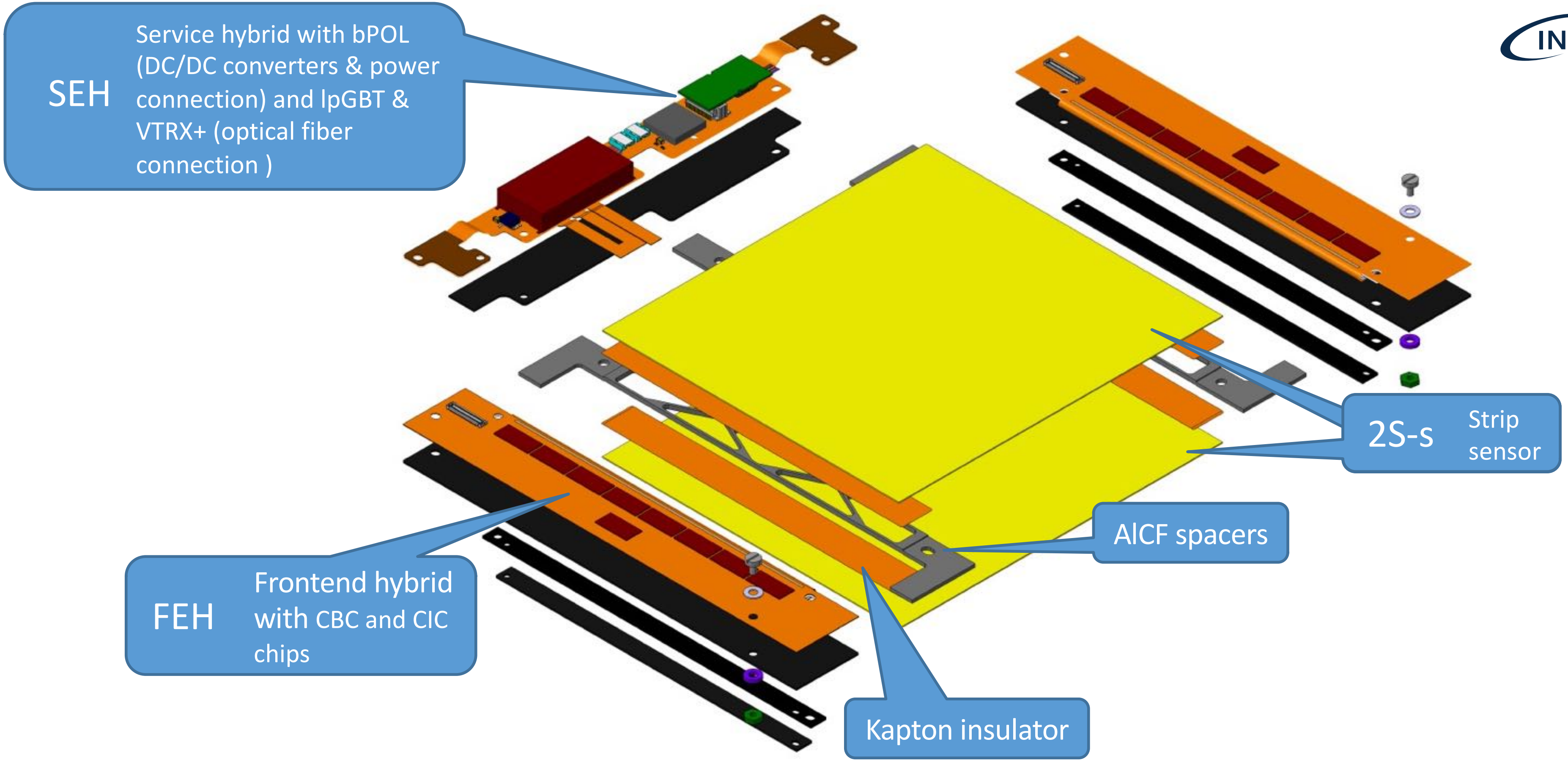


- Module houses both
-
- readout chip and data concentartor

Each module is a functional unit individually connected to:

- ➢ backend power system
- ➢ DTC (Data, Trigger and Control) system via Optical link
- ➢ no token control rings
- ➢ no intermediate power grouping

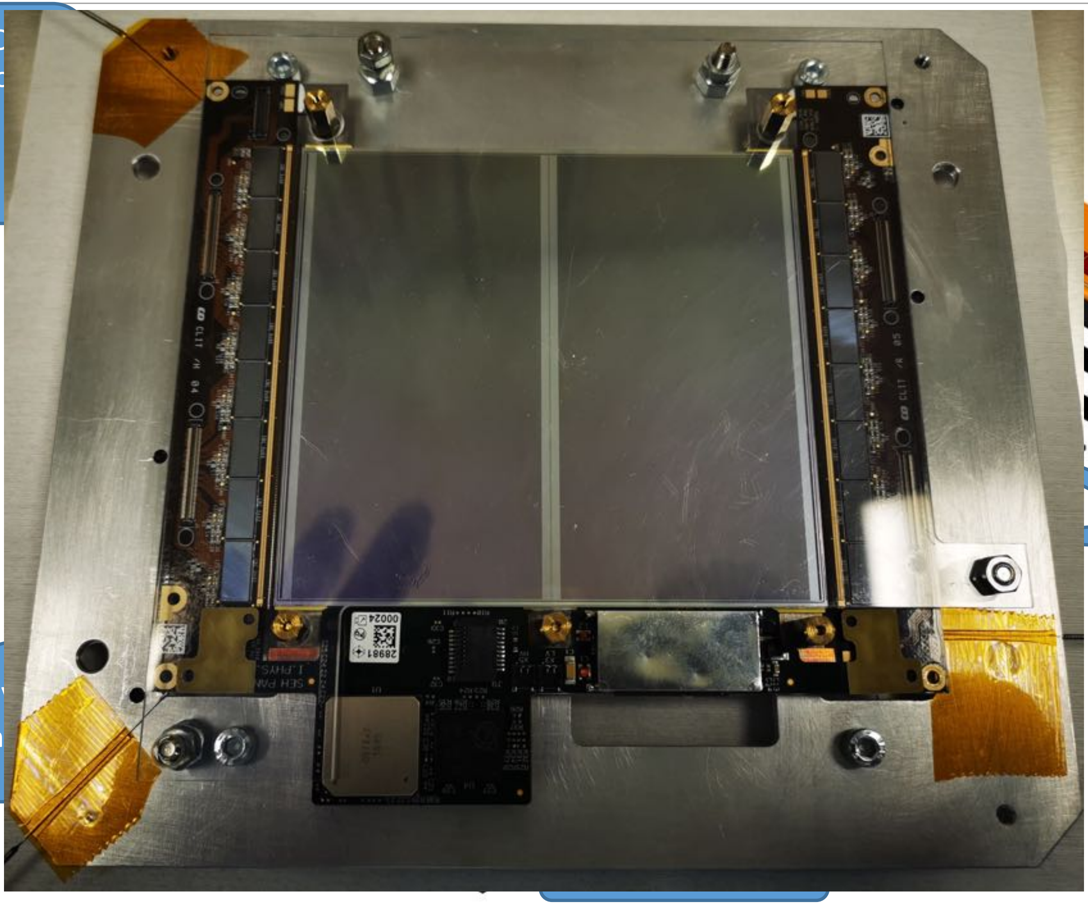
2S module design

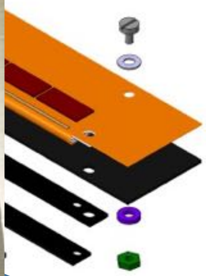


2S module design

SEH

Service hybrid with bPC
(DC/DC converters & po
connection) and lpGBT
VTRX+ (optical fiber
connection)





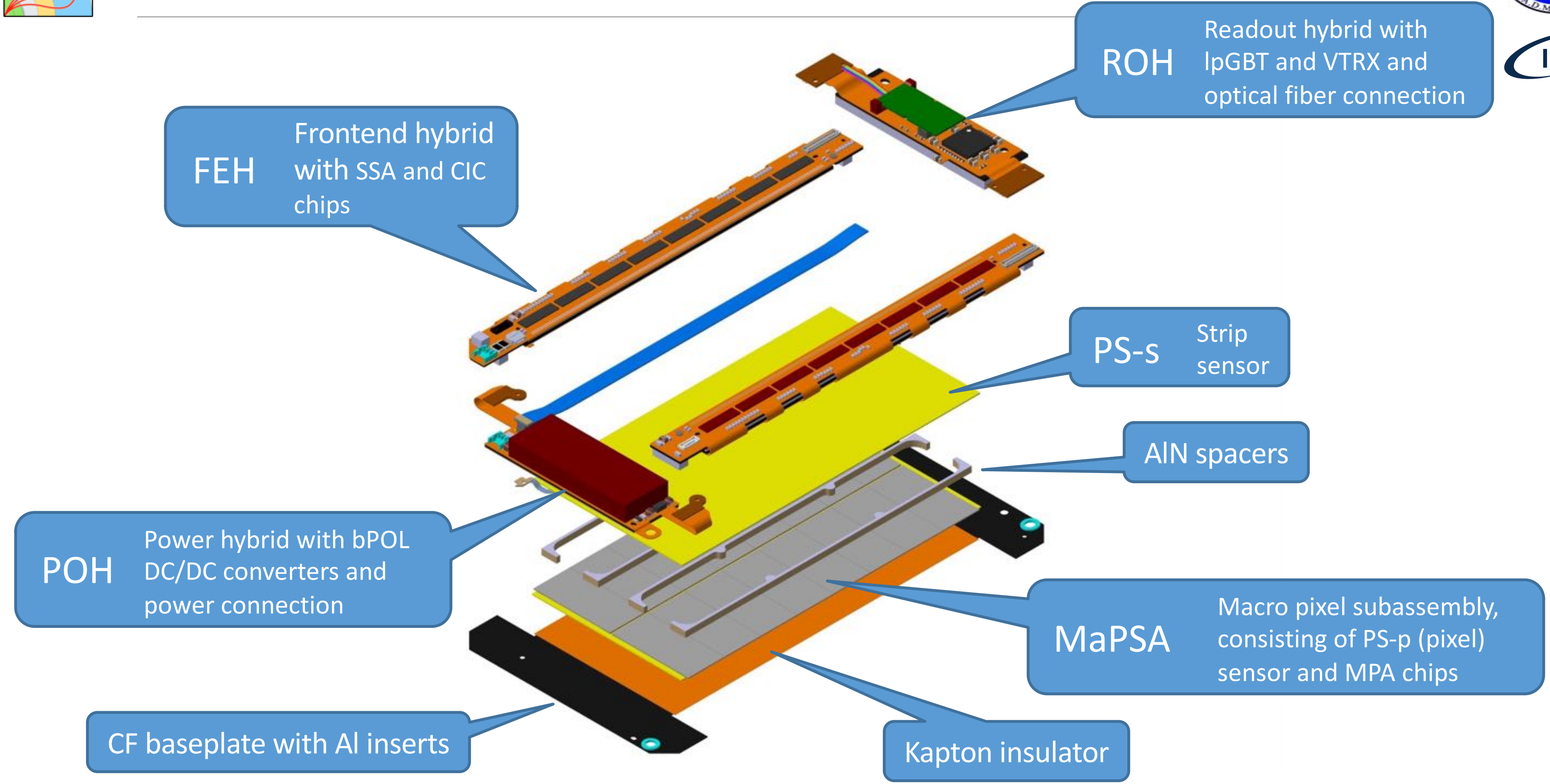
2S-s

Strip sensor

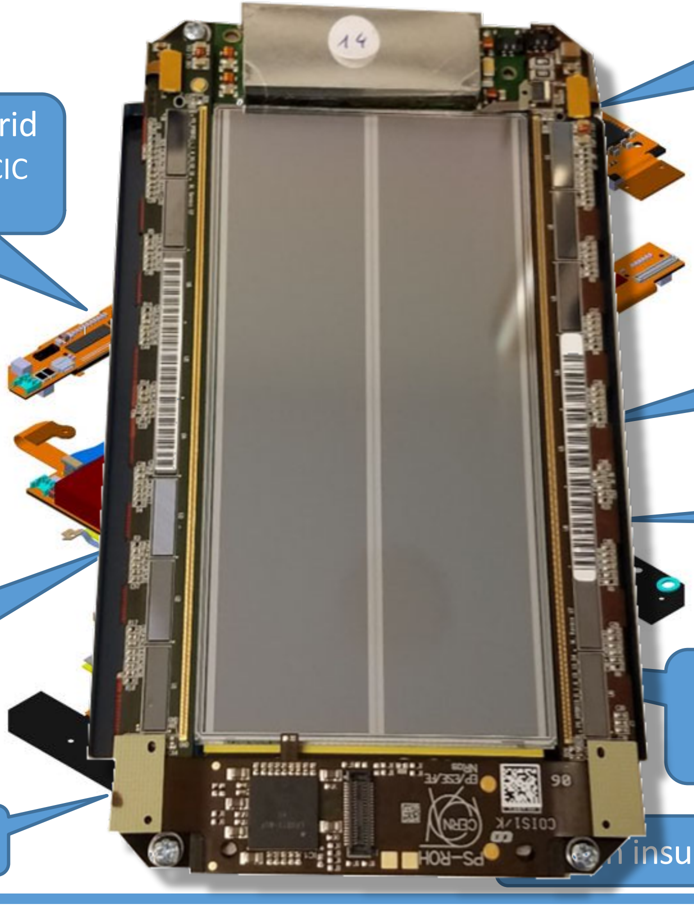
FEH

Frontend h
with CBC an
chips

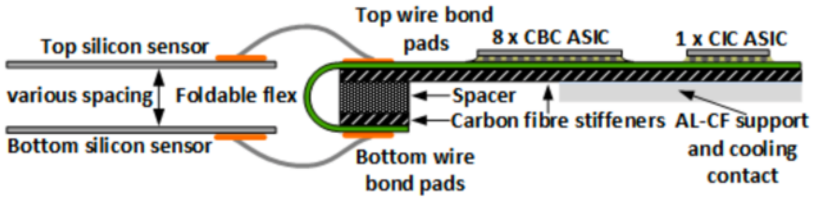
PS module design



PS module design



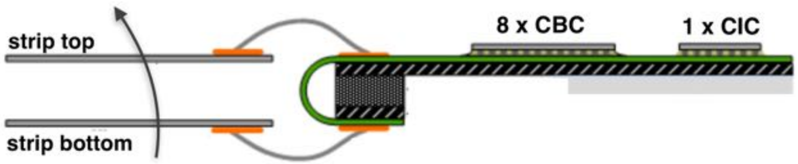
Module Read Out



Top sensor data
Bottom sensor data
Top+Bottom data
Stubs data

- **Strip-strip Module (2S)**
  - CMS Binary Chip (CBC) reads both sensor and identify stubs

Module Read Out



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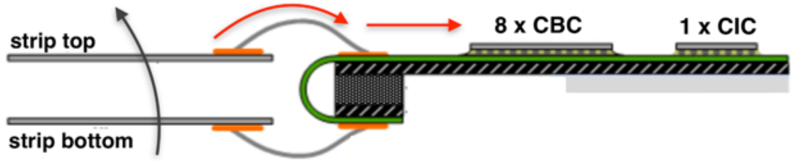

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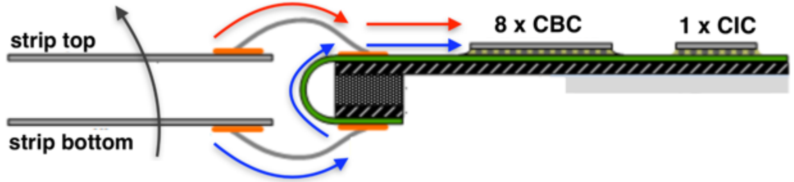

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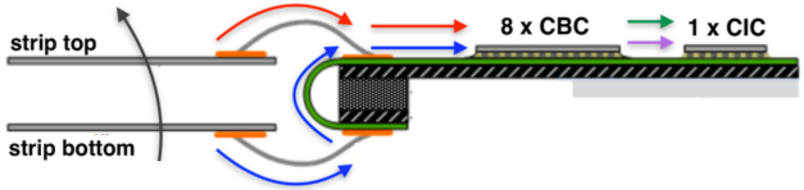

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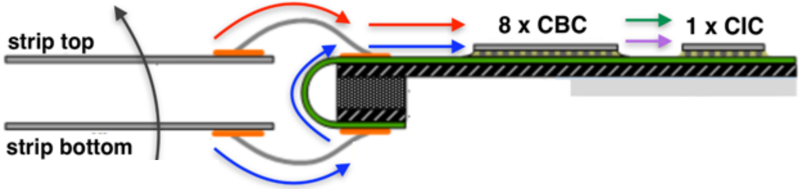

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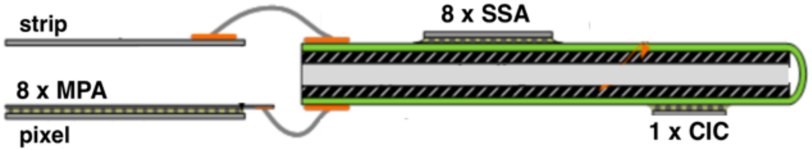

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  - CMS Binary Chip (CBC) reads both sensor and identify stubs
- **Pixel-Strip Module (PS)**
  - Short-strip ASIC (SSA) sends strip cluster and L1 data to the MPA which combines with pixel information and create stubs

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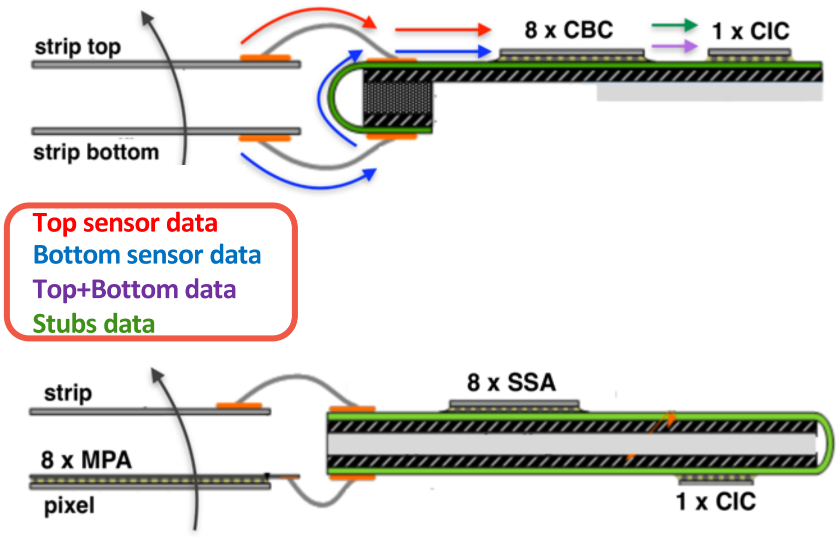

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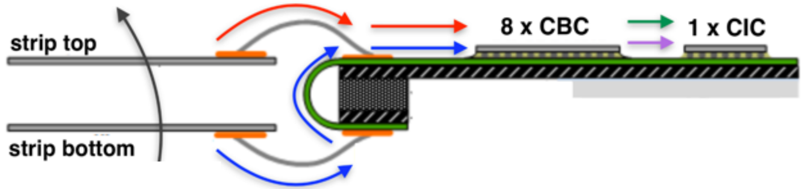

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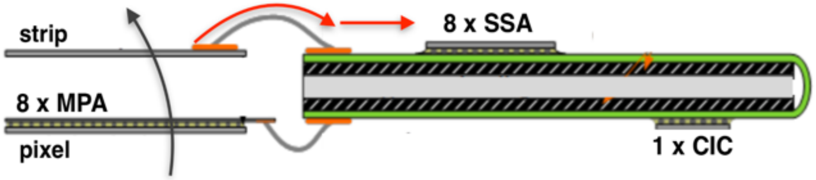

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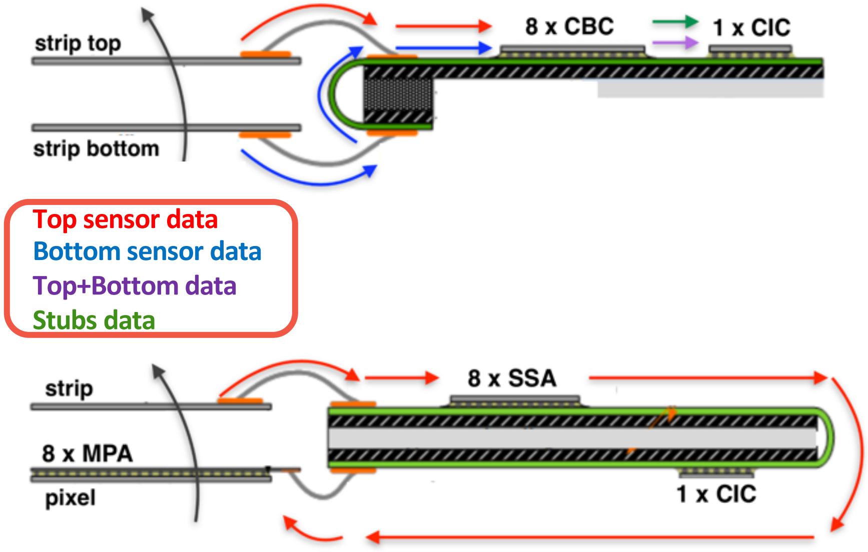

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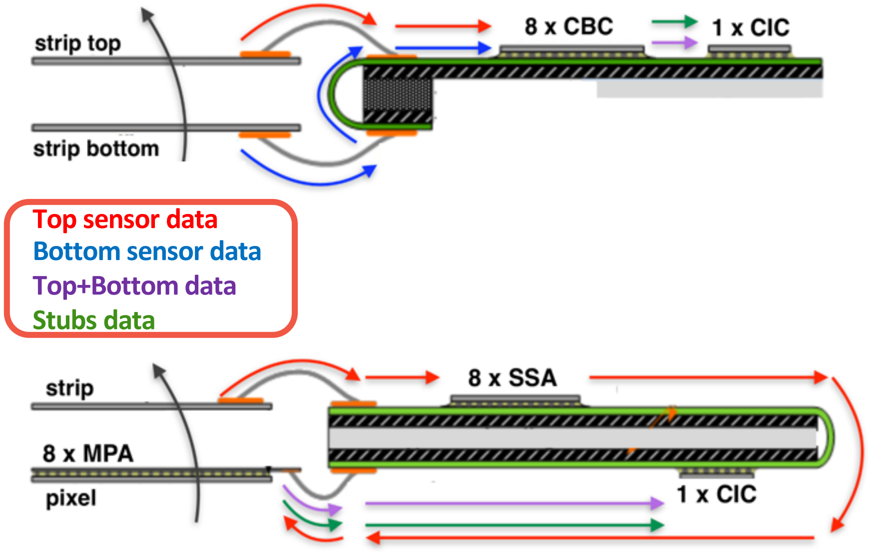

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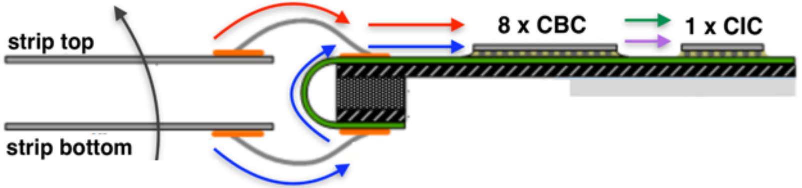

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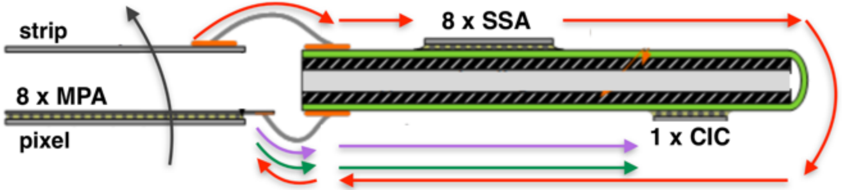

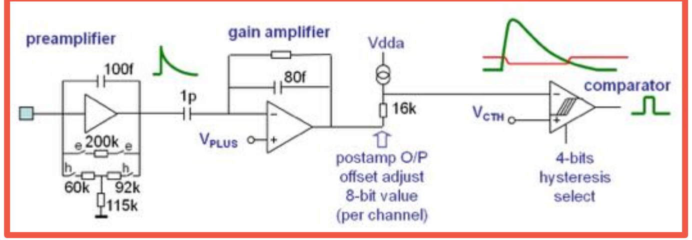

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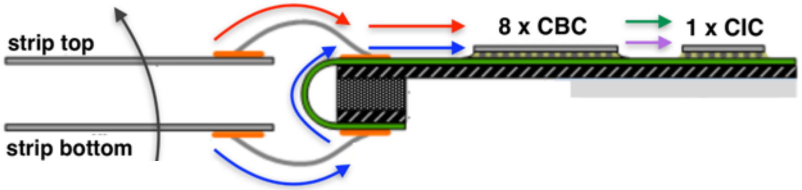
Binary Read Out

- No info about collected charge
- Binary (0/1) info for each strip

Module Read Out



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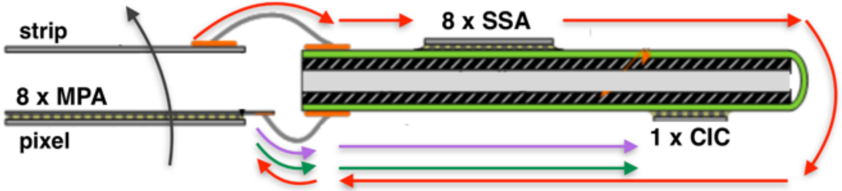

STUB:

→ **Position on Bottom sensors/MAPSA**
  - **Cluster postion, half strip precision**

→ **Bend information**
  - **difference between top/bottom position**

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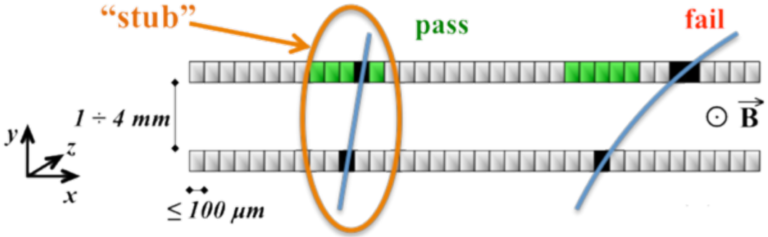
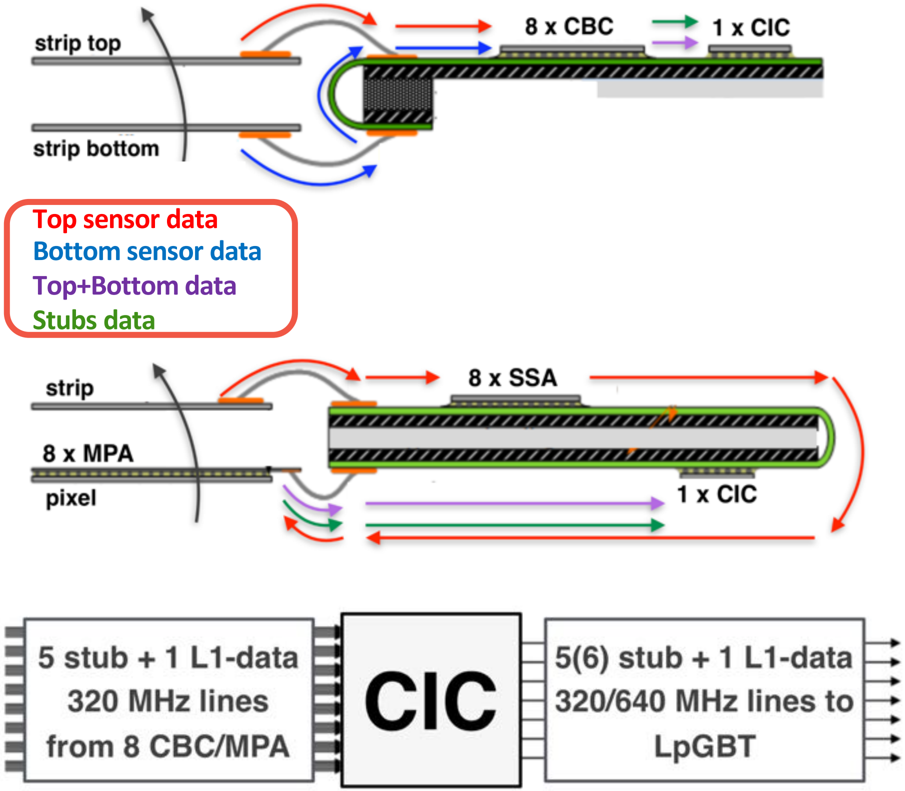


Module Read Out



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  - CMS Binary Chip (CBC) reads both sensor and identify stubs
- **Pixel-Strip Module (PS)**
  - Short-strip ASIC (SSA) sends strip cluster and L1 data to the MPA which combines with pixel information and create stubs
- **CIC concentrator chip**
  - Receives stubs and L1-data and pack them

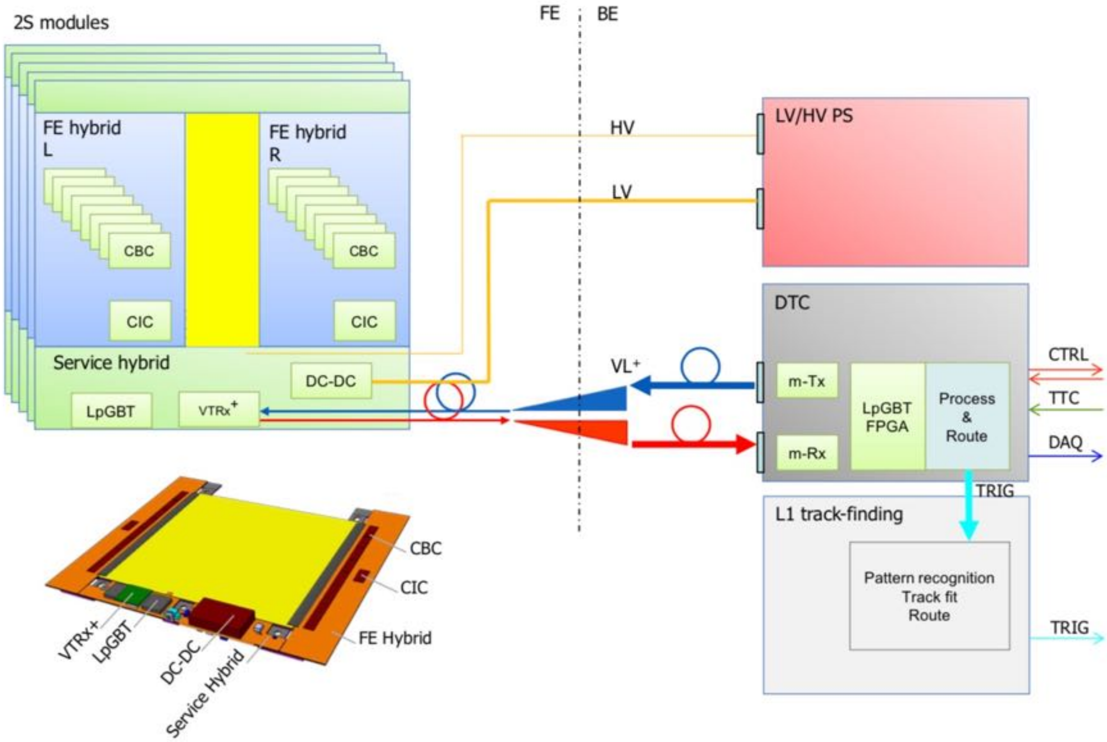
Data AcQuisition

- DTC (**D**ata, **T**rigger and **C**ontrol) boards readout and control module
  - ACTA standard

- Bi-directional optical links
  - **2.56 Gb/s DTC → Module**
    - clock, trigger, fast-commands and programming
  - **5.12 or 10.24 Gb/s Module → DTC**
    - L1 and DAQ data

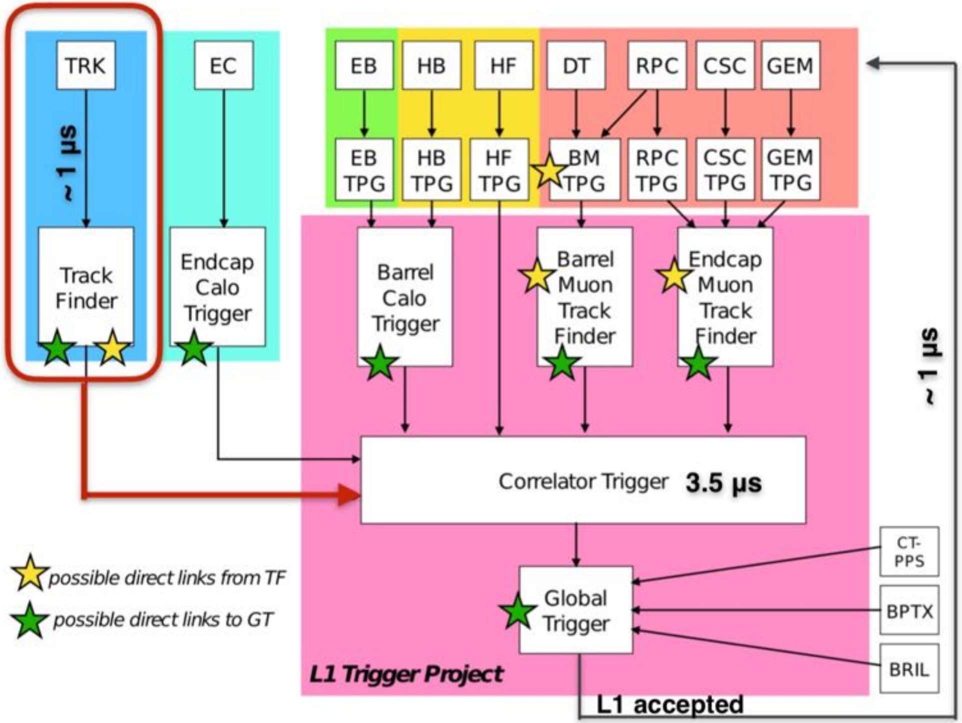
- <u>L1 data at 40 MHz</u>

- DAQ data (after L1) at 750 kHz



L1-tracking constraints and requirements

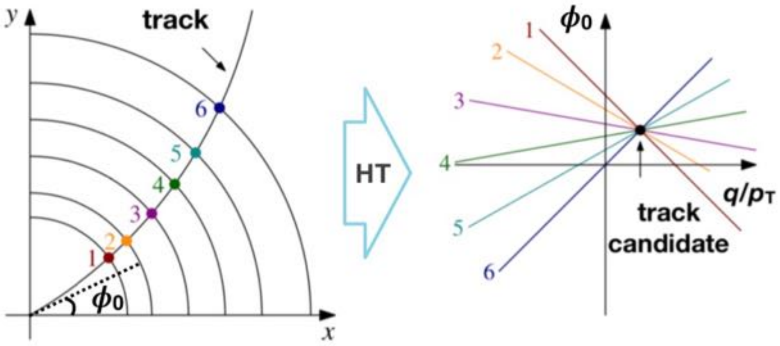
- ~15,000 stubs per bunch crossing @ 200 PU → **Stub bandwidth O(20) Tb/s**
- **~4 µs available for track finding** (12.5 µs total L1 latency)
- Present solution derived from two **all-FPGA developments**:
  - Time-Multiplexed Track Trigger (TMTT)
  - Tracklet algorithm
- Both **tested on HW demonstrator** to measure latency and estimate resource utilization and performance



L1-tracking: aglorithms

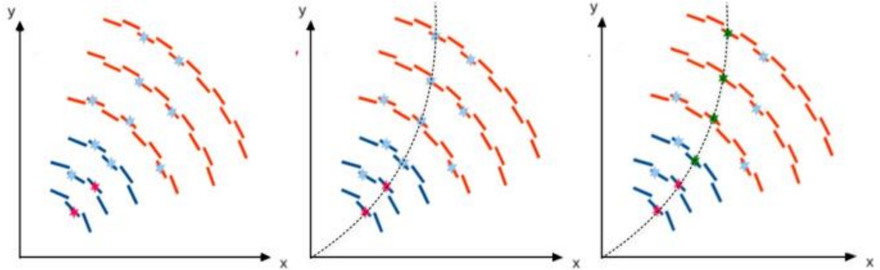
- Time-Multiplexed Track Trigger
  - 8 Geometrical Division in ϕ
  - Some data duplication
  - Hough Transform
    - From r - ϕ to q/p_T - ϕ_0 plane
  - Kalman Filter
    - Repeat until all stubs are added
    - χ2 used to reject false candidates

Latency ~3.5μm



- Tracklet Method
  - 28 Geometrical Division in ϕ
  - No data duplication
  - Road search
    - Pair of adjacent layers used to form seed called a tracklet
  - Linearized χ2 fit
    - Complex calculations pre-computed and stored in look-up tables
    - Remove duplicates by checking for shared stubs and retain track with the lowest χ2/ndf

Latency ~3.3μm



L1-tracking: aglorithms

- Time-Mu
  - 8 Geomet
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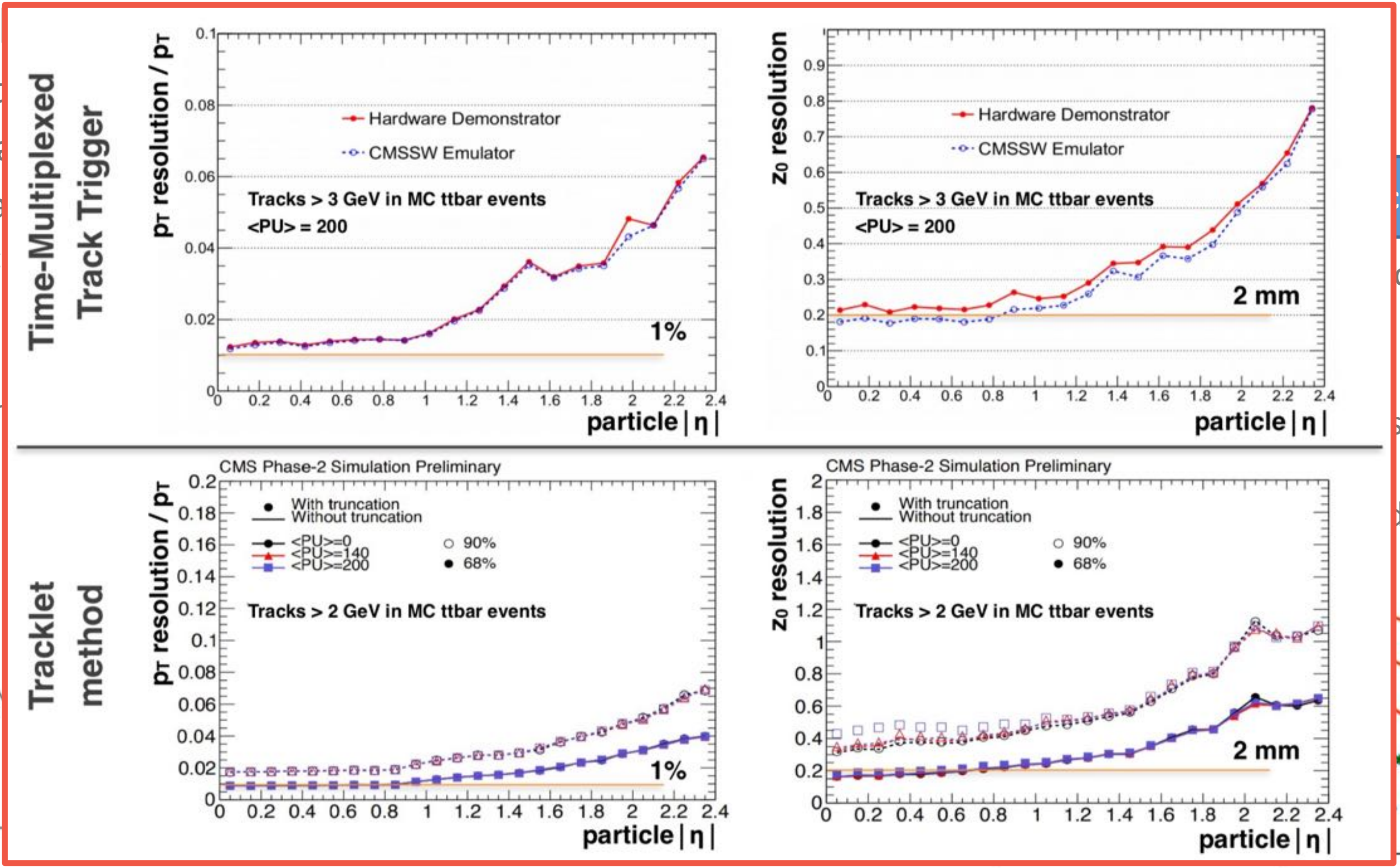
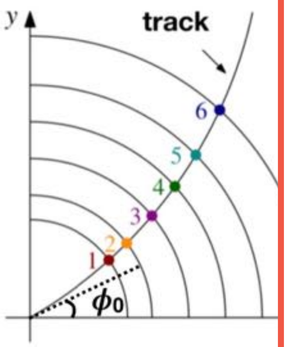
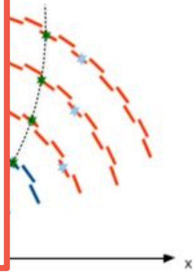
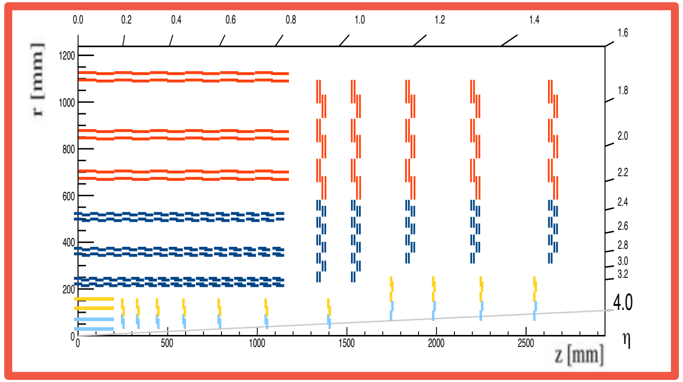
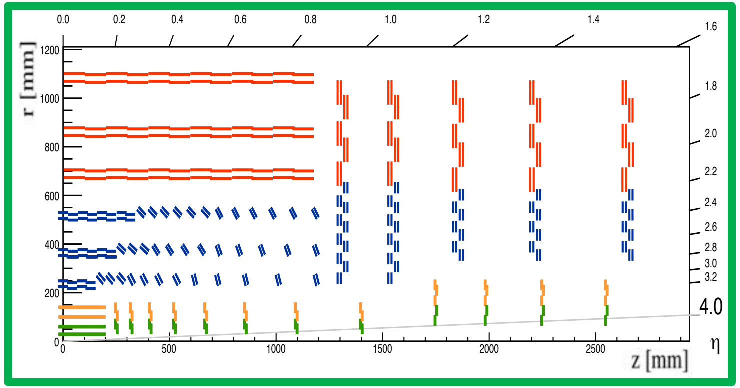




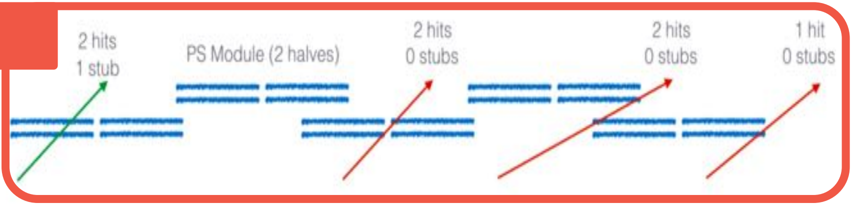


Tilted Barrel Geometry





Flat Geometry



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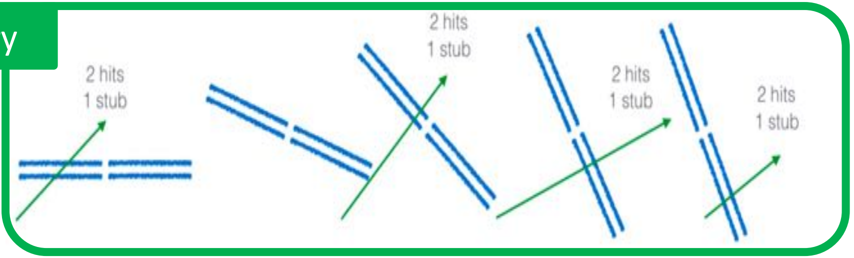
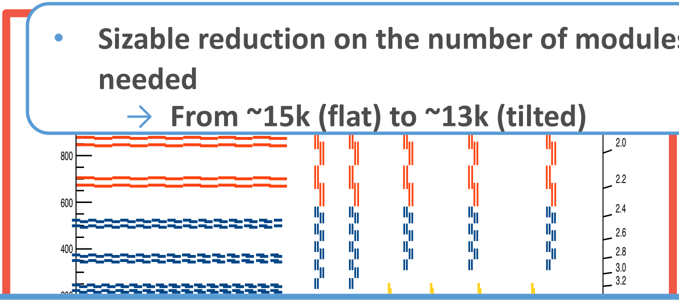


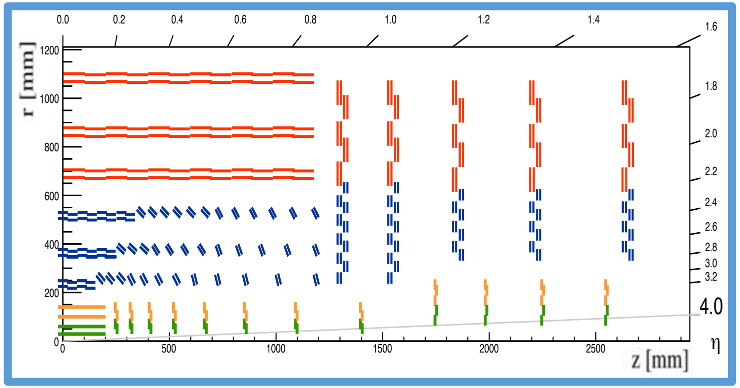
- Stubs generation works only if the charged particle cross the two sensors on the same halve of the same module
- This is not true for (flat) barrel peripherical modules

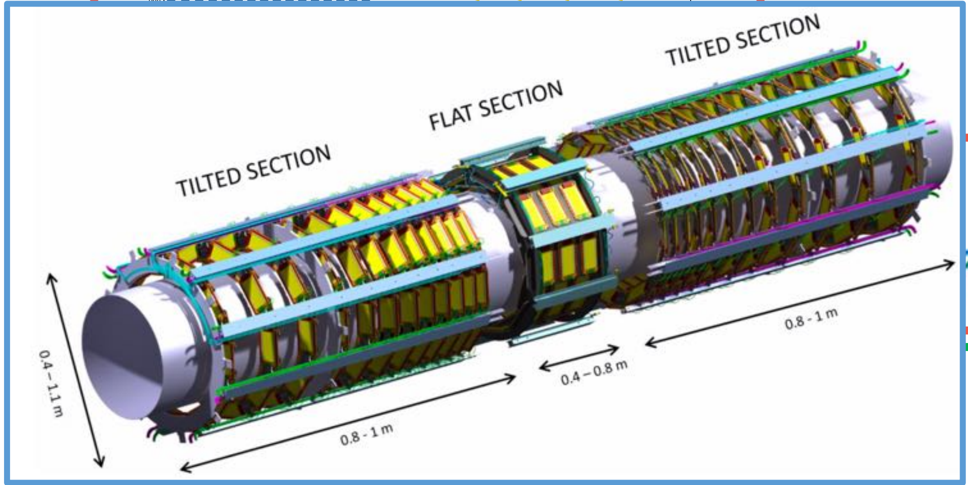
→ **(increasingly) Tilt peripherical barrel modules**

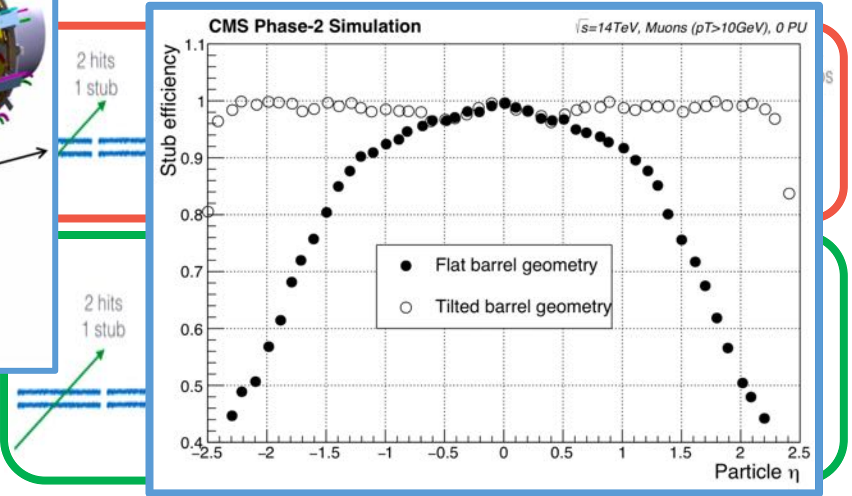
Tilted Barrel Geometry

- **Sizable reduction on the number of modules needed**
  - → **From ~15k (flat) to ~13k (tilted)**



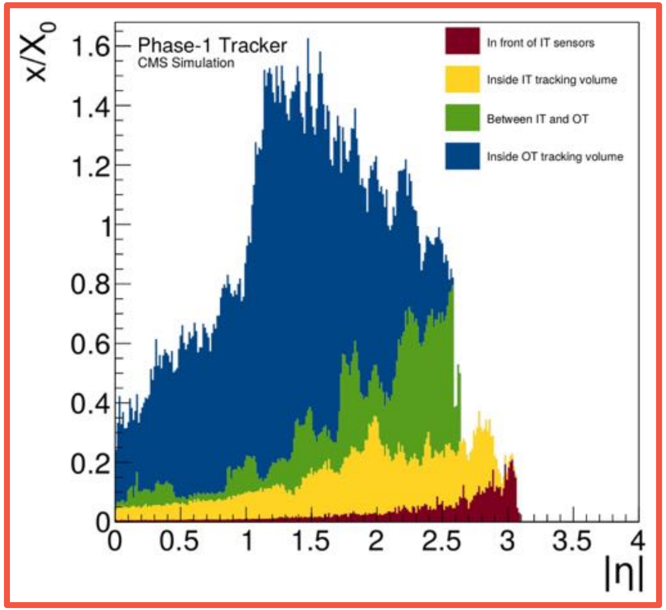


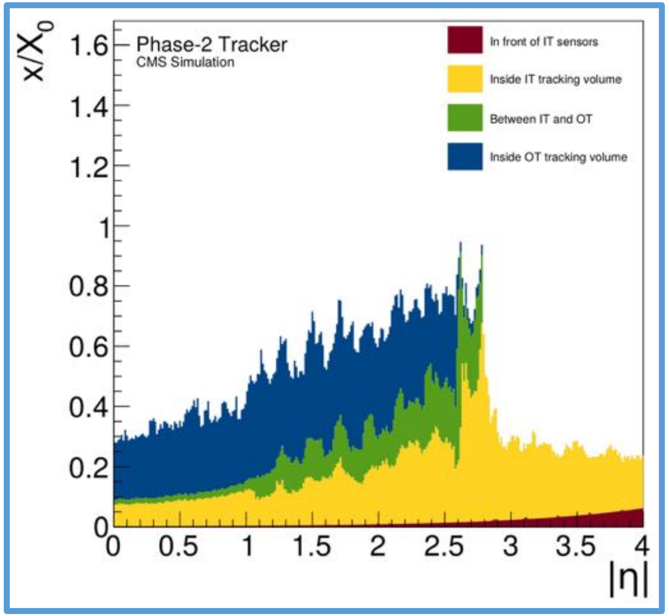




→ **(increasingly) Tilt peripherical barrel modules**

Material Budget





- Material budget much reduced wrt Phase0/1 detector despite an increase in the number of channels

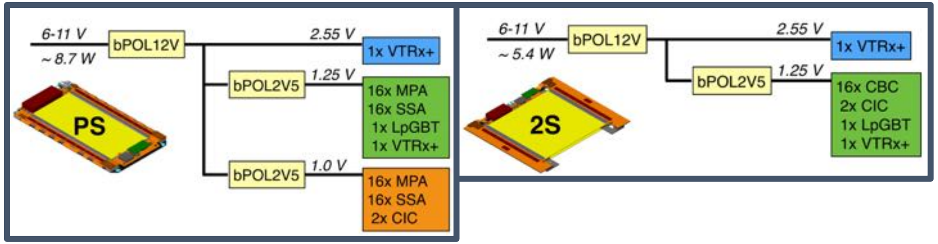
  - *DCDC converters*
  - *Fewer layers*
  - *Lighter materials*
  - *Optimized service routing*
  - *CO_2 cooling*
  - *Inclined geometry*

Powering & Cooling

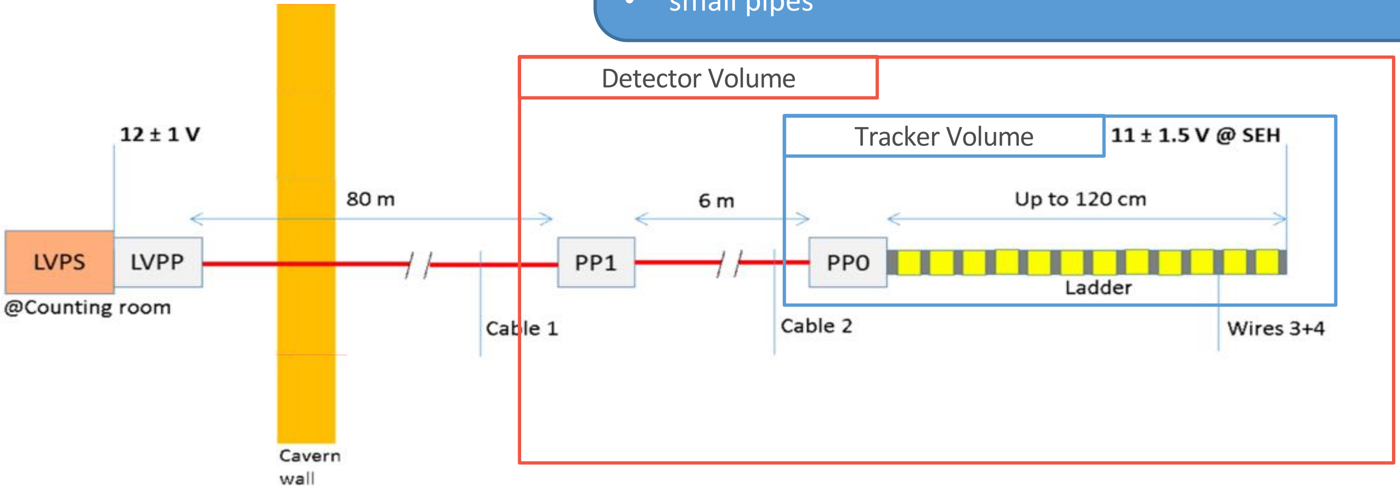
- Large Area + High Granularity

  ↳ High Power Budget : <u>Outer Tracker ~100kW</u>

  ↳ <u>Parallel Powering with on-module conversion</u>

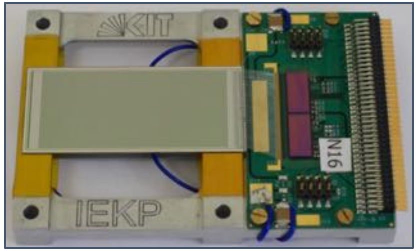


Powerful cooling system:
- (4+1) x 50W cooling plants
- based on two-phase CO_2 cooling system (-35°C set point)
- small pipes

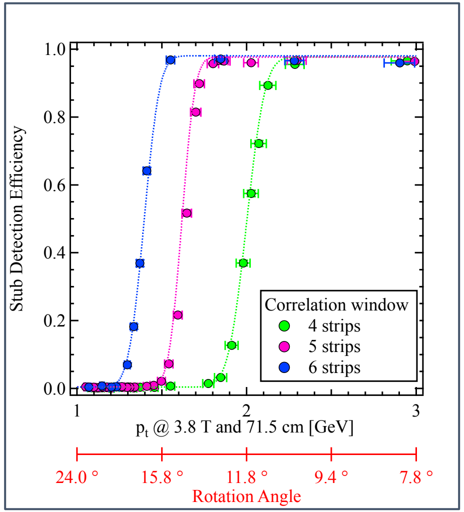


Some highlights from beam tests

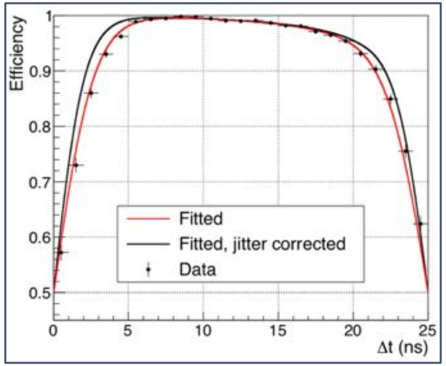
- Different module prototypes tested in particle beam



  - **2S**
    - Full size module and mini-module has been tested
    - No services and no data Concentrator
    - Stubs finding capabilities tested
      - Magnetic bending «simulated» with module rotation

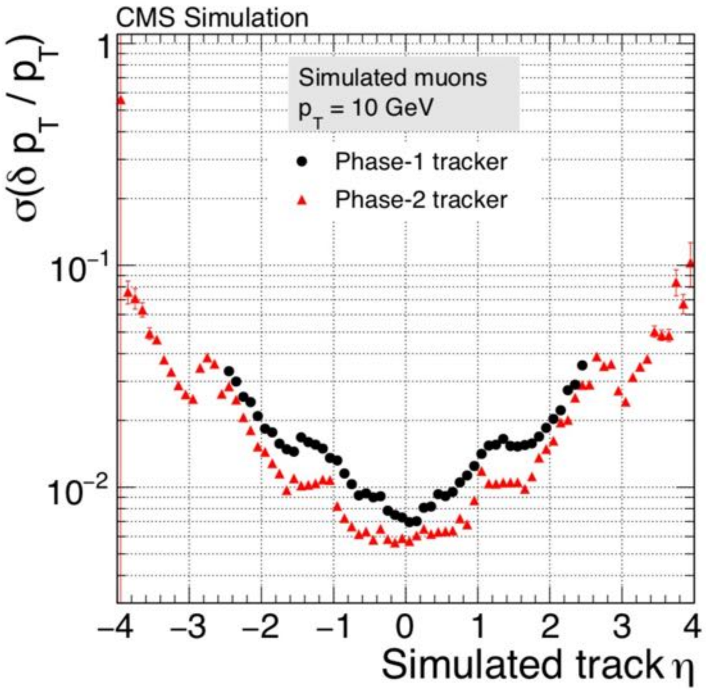


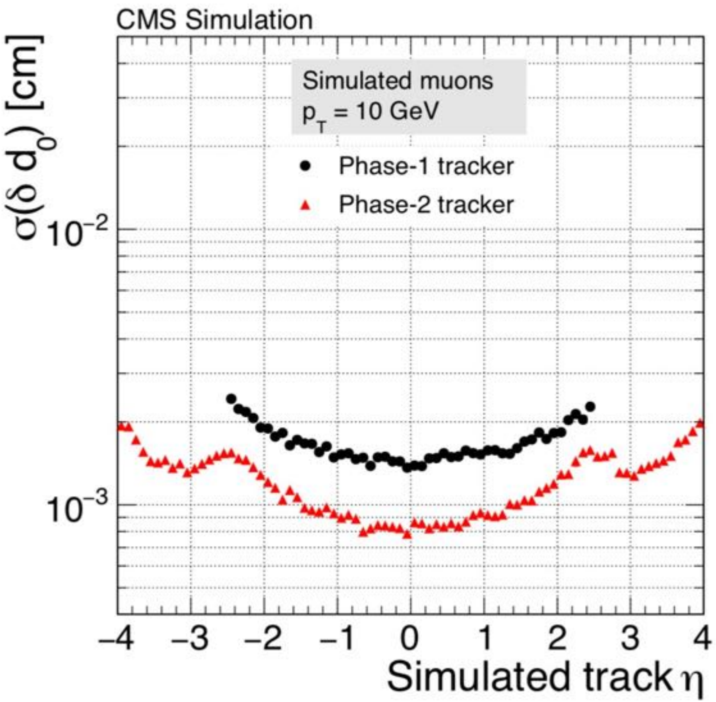
  - **PS**
    - Single sensor (pixel) with MPA readout
      - No stub info
    - MPA+SSA intercommunication was tested on bench
    - First fully working PS module assembled few weeks ago



Performances: Phase-1 vs Phase-2

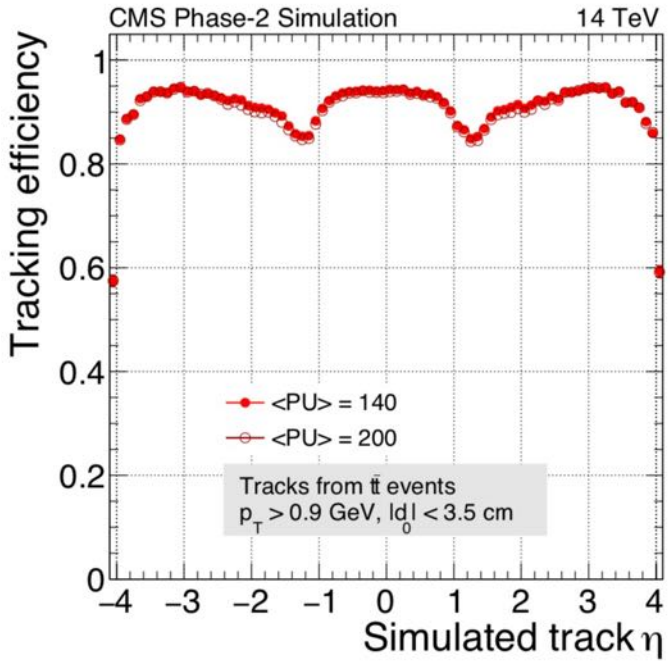
- Track parameters resolution of Phase-2 tracker improve wrt Phase-1
  - Higher granularity and less material
- Significant extention at higher η

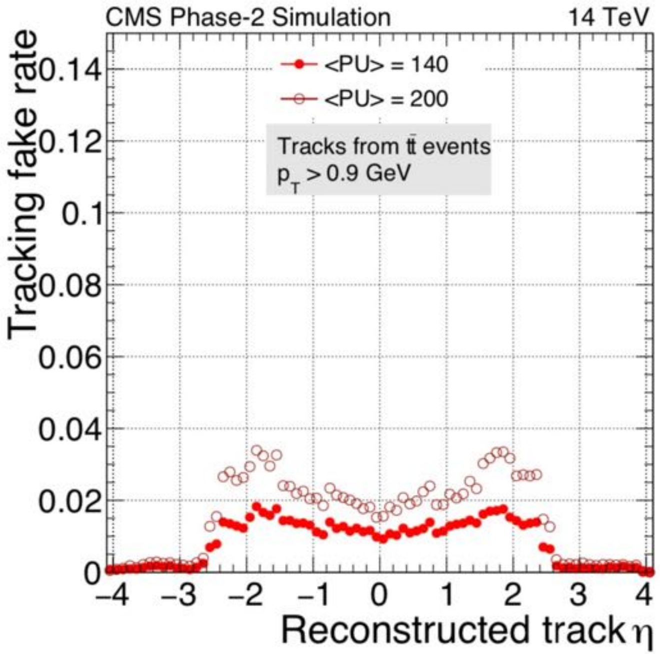




Performances: High PileUp

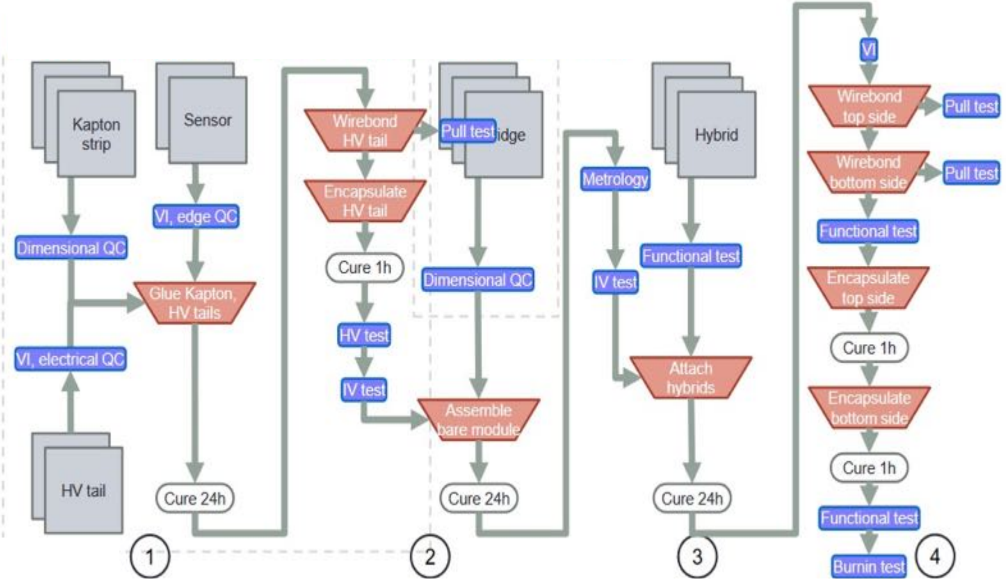
- *Dip around ±1.2η due to Barrel/endcap transition in Inner Tracker*
  - *Due to TDR geometry, reduced by a factor ~2 with optimized geometry*
- High tracking efficiency (~90%) also at 200PU
  - Fake rate below 2(4)% at 140(200)PU



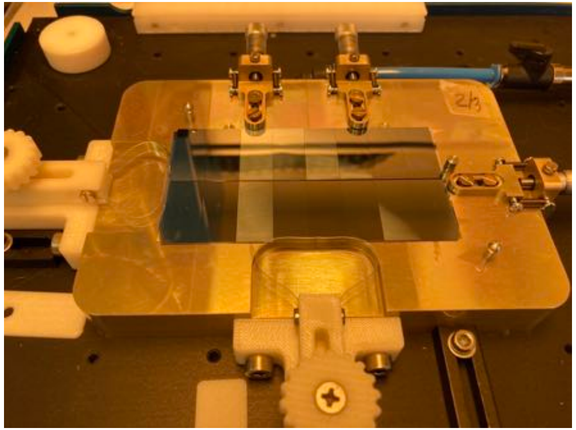
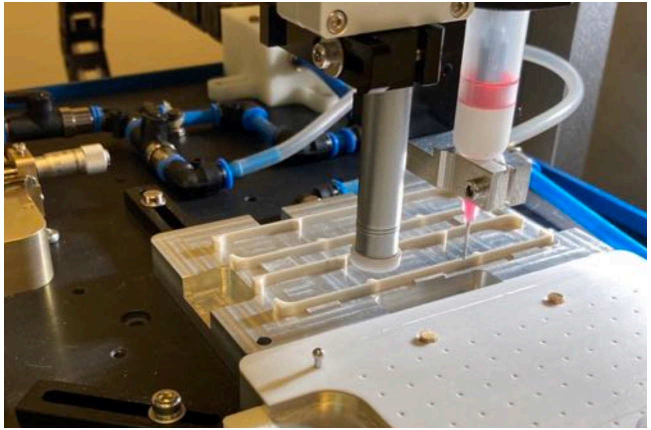
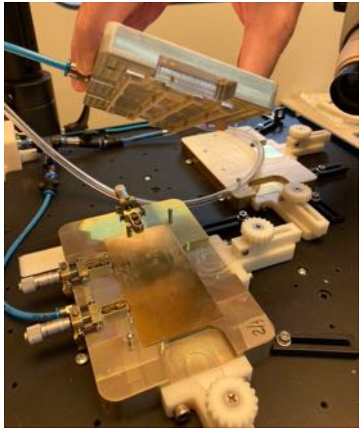
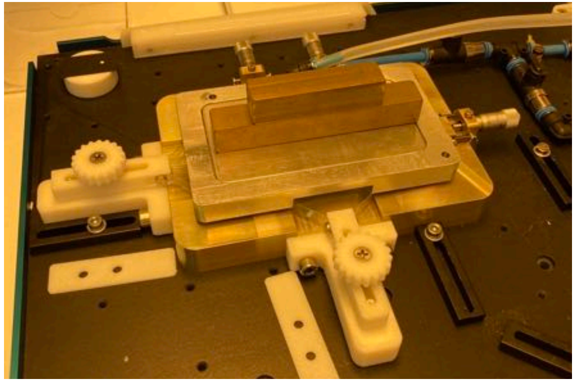


MODULE ASSEMBLY

- Quite complex assembly procedure
- Stringent mechanical requirements
  - Precise sensor-to-sensor alignment crucial for stubs finding algorythm
  - Main constraints:
    - Shift ⊥ to strip: <50µm
    - Shift // to strip: <100µm
    - Relative sensors rotation: <400µm
    - Distance between sensors: ±100µm wrt nominal



MODULE ASSEMBLY

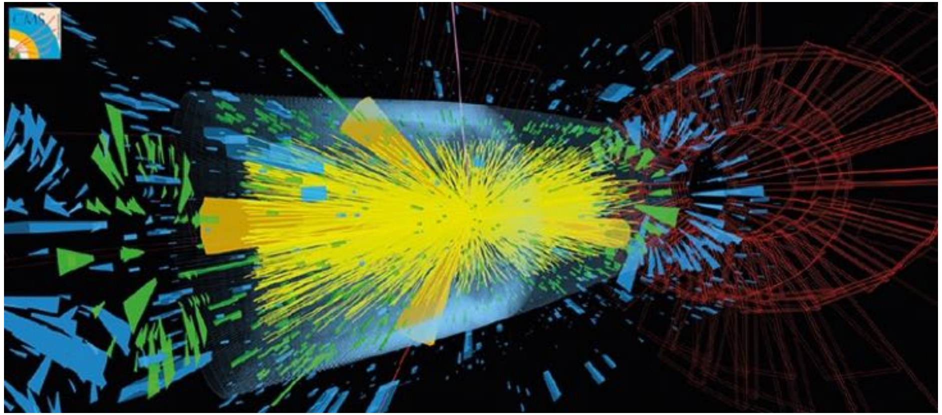
- Assembly based on fixture
  - R&D almost completed
- Pre-production → 2021
- Production → 2022/2024

CONCLUSIONS

- CMS will restart to take data soon!
  - Probably in 2022 Q1
  - Run-3 operation will last at least 3 years
- …meanwhile:
  - Complete the R&D and start the production of all the pieces needed for the HL-LHC phase

A long way towards 2026!

Stay tuned!



ADDENDUM: MUONE

Introduction

- Anomalous magnetic moment of a lepton as precison test for SM
  - Can be (very) precisely calculated in SM framework
  - But… it’s flavor dependent!

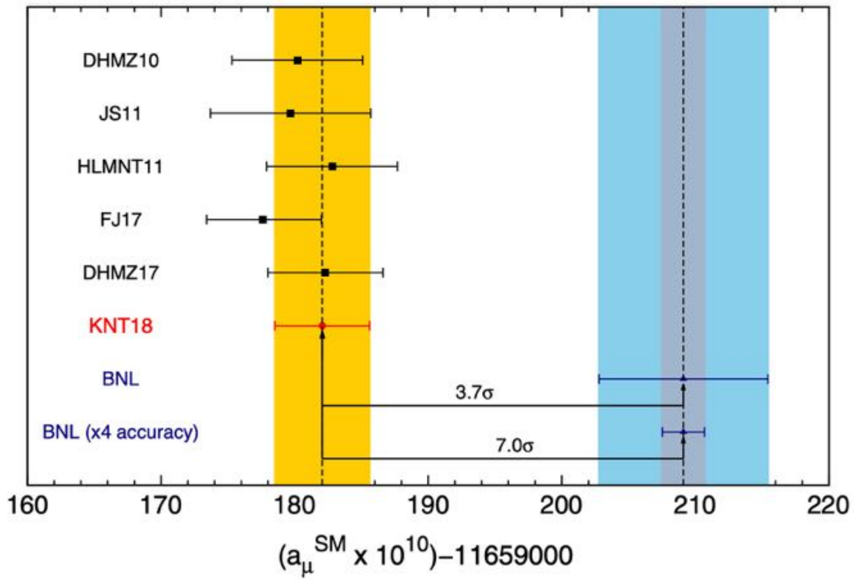
$$\vec{\mu} = g_\mu \frac{e\hbar}{2m_\mu c}\vec{s}$$

- Electron
  - g_e-2 determined with high precision
  - Sensitivity to new particles limited by a ~$(m/M)^2$ factor

$$a_\mu = \frac{g_\mu - 2}{2}$$

- Muon
  - Sensitivity to an higher mass region [GeV, TeV]
  - State of art: 3σ discrepancy from SM prediction

State of the art



$$a_\mu(exp) = 11659209.1(5.4)_{stat}(3.3)_{syst} \cdot 10^{-10}$$

$$a_\mu(exp) - a_\mu(SM) = (27 \pm 7) \cdot 10^{-10}$$

- Most precise measurement from E821 at Brookhaven National Laboratory (BNL)
- Muon g-2 experiment at FNAL want to inprove the accuracy by a factor 4

If

1. Theory remain as it is
2. No relevant change to central value

then

$$\Delta a_\mu = a_\mu(exp) - a_\mu(the) = 6.7\sigma$$

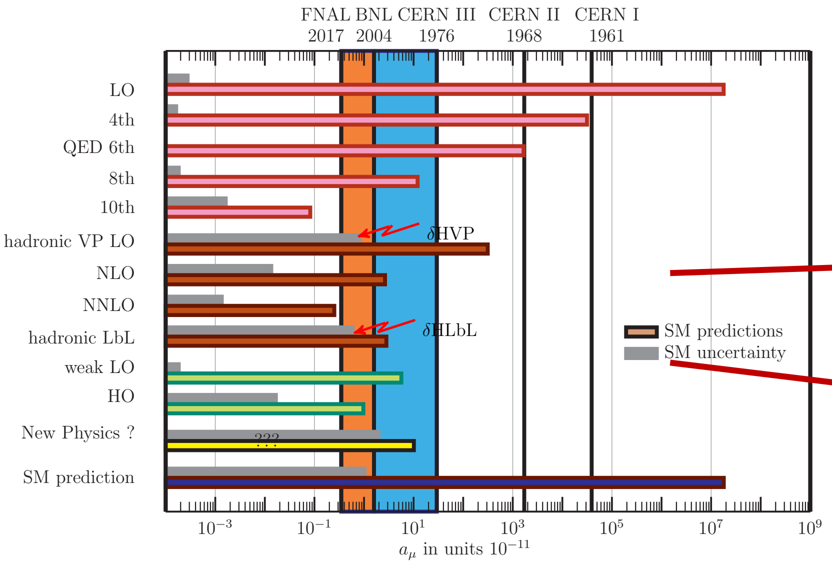
Present theoretical uncertainties

$$a_\mu = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{HAD}$$

Photons and Leptons loop (calculated)

Bosons ($W^{\pm}$,Z,H) loop (calculated)

Hadrons loop (extimated from experimental measurement)



- Main contribution to theo. uncertainty
  - LO hadronic vacuum polarization
  - Light-by-light scattering

a_μ^{HLO}: LO Hadronic contribution

- Traditionally computed via a dispersion integral using hadronic production cross sections in electron-positron annihilation at low energies
- QCD lactice calculation still not competitive
- A novel approach proposed: MUonE
  - **A high precision measurement of a_μ^{HLO} with a 160 GeV μ beam on e^- target at CERN**
  - hadronic contribution to the effective electromagnetic coupling, **Δ𝛼H(q2)** for **space-like** squared four-momentum transfers $q^2 = t < 0$, via scattering data

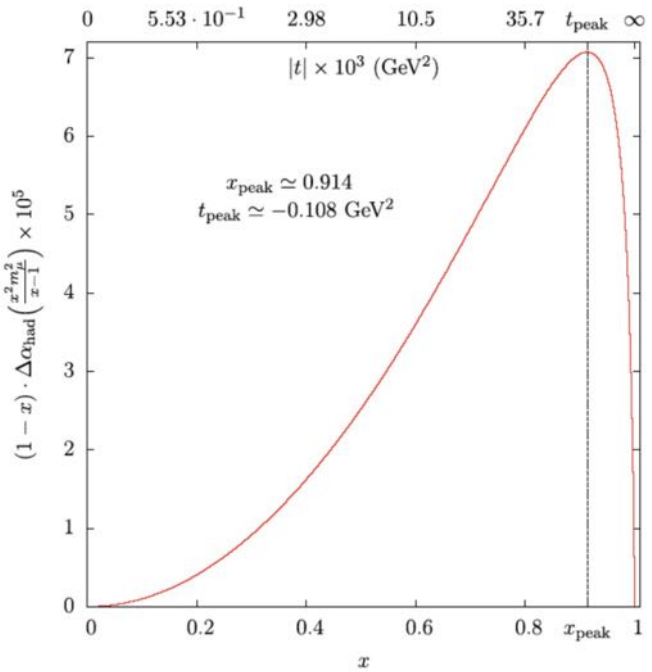
$$a_\mu^{HLO} = \frac{\alpha}{\pi} \int_0^1 (1-x)\Delta\alpha_{had}(t(x))dx$$

$$t(x) = \frac{x^2 m_\mu^2}{x-1} \quad (0 \leq -t \leq +\infty)$$

t : momentum trasfered in the reaction

How to measure?

- $\Delta\alpha_{had}$ (t) can be extracted from **μ-e elastic scattering** using a high energy muon beam (E~160 GeV) on electron low-Z target

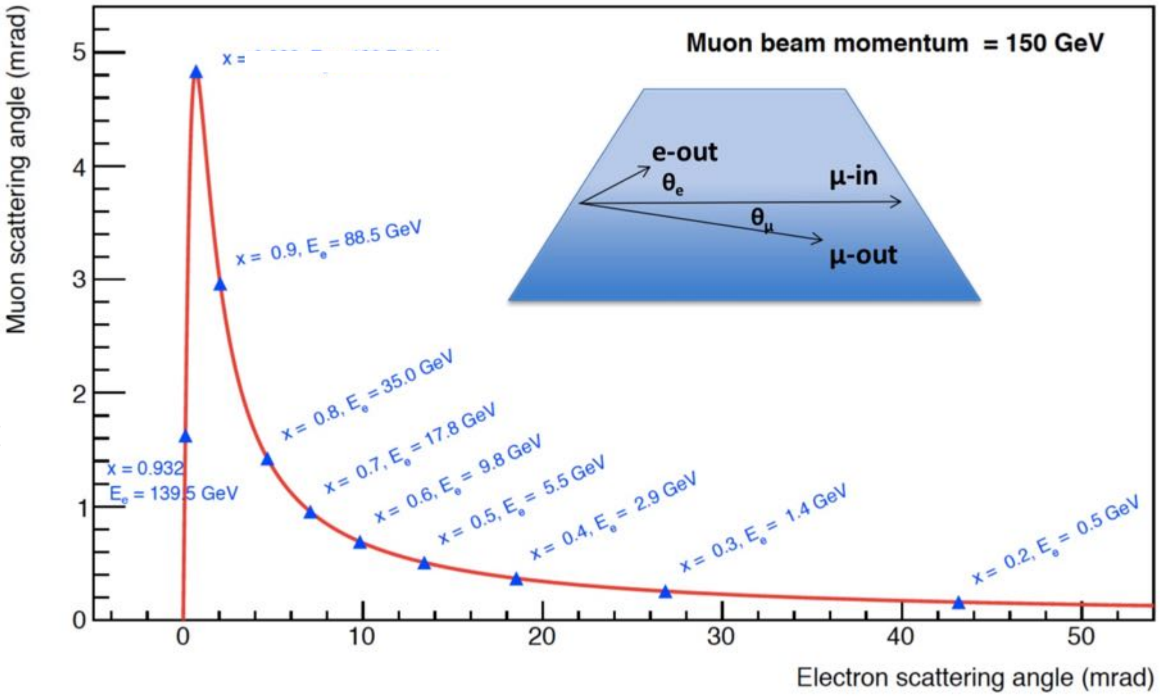


- Experimental kinematic limit
  - $0 < -t < 0.161 GeV^2$

    or
  - $0 < x < 0.93$
- **MUonE will measure ~87% of the area**
  - Can be extrapolated to the 100% with functional model of $\Delta\alpha_{had}$ (t)

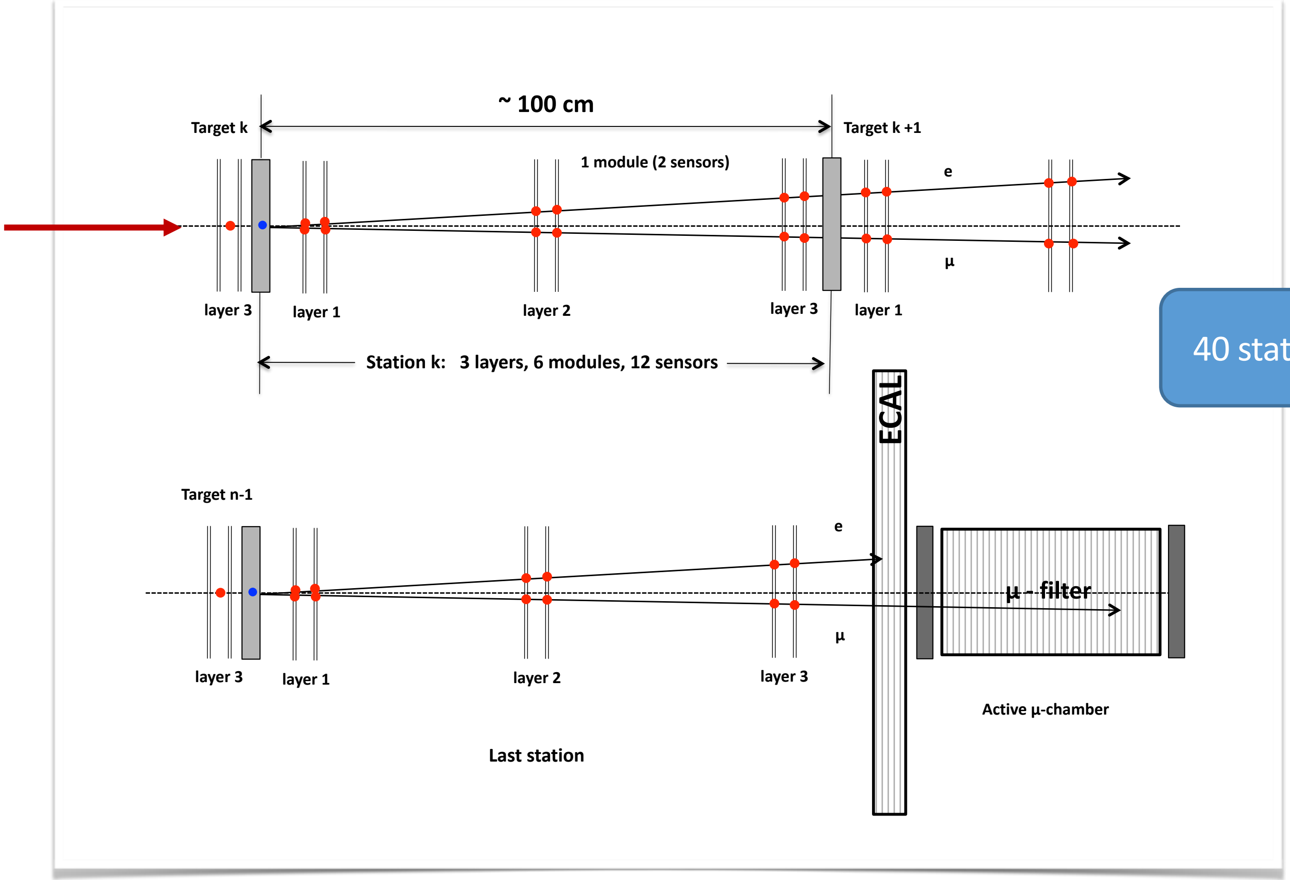
Key element

- The key elemet to achieve the precision required is the measure of the scattering angles
- Experimental needs:
  - PID to separate electron and muon
    - ECAL + μ-filter
  - Precise tracking for angles
    - Tracker
  - Electron energy measurement to add redoundancy and reduce systematics
    - ECAL



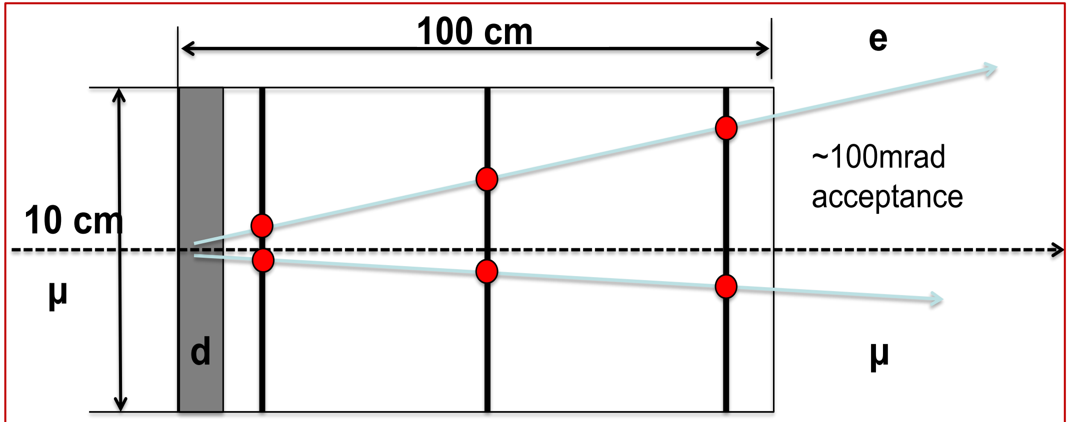
The Detector

μ beam (160GeV)



40 station

A Tracking Station



~1cm
Be Target

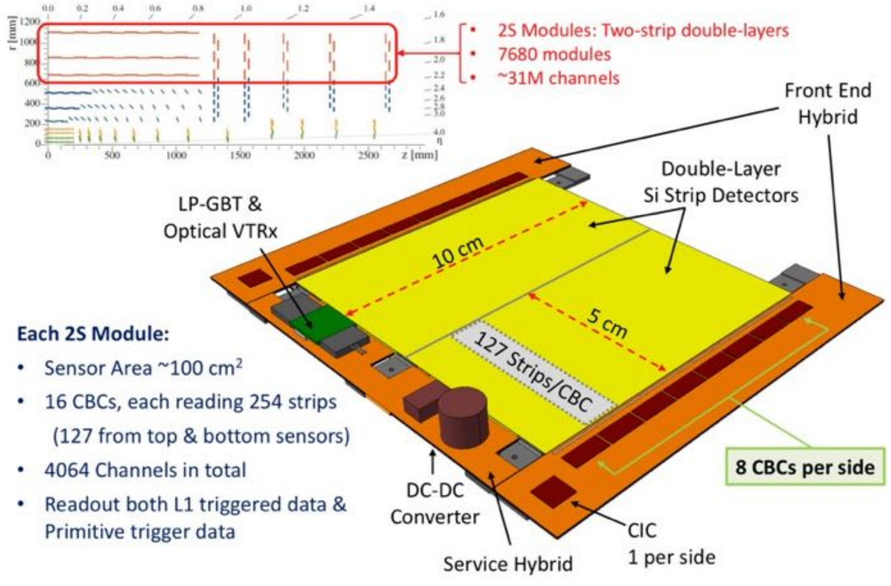
State-of-art Silicon detectors
hit resolution ~20 μm

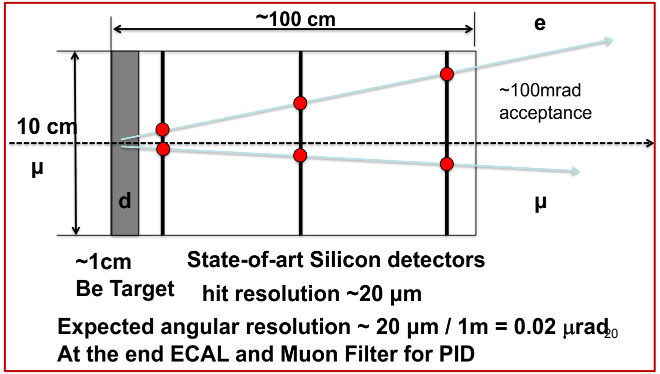
Expected angular resolution ~ 20 μm / 1m = 0.02 μrad
At the end ECAL and Muon Filter for PID

- Requirements:
  - Dimensions: 10 cm x 10 cm
  - Single hit resolution: σ ≤ 20 μm
  - Fast timing (we have to cope with O(50 MHz) μ)
  - Thickness: d ≤ 300 μm

Technology

- Best solution:
  - 2S module from CMS
  - Or better 2 x 2S module for each plane
    - To get x-y info

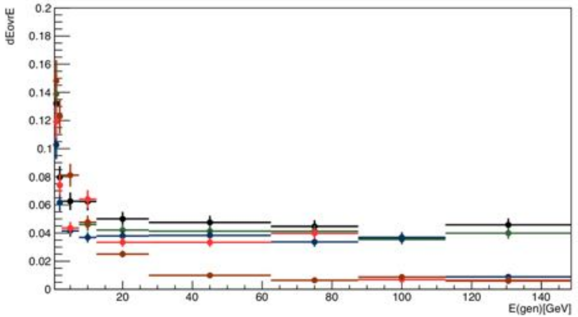


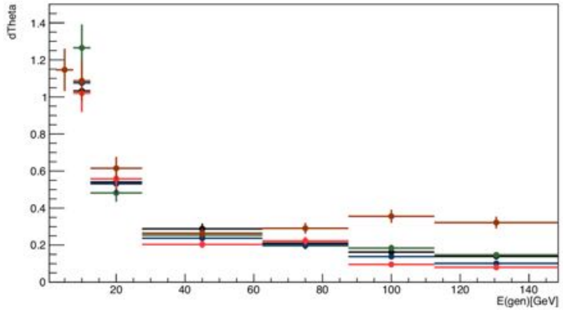


- Enough spatial resolution
- Stub instead of hits
- Fast stub readout O(40MHz)

ECAL

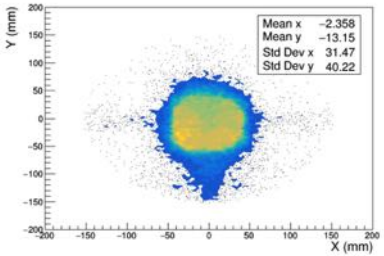
- For particle ID and background rejection
- Radiation hardness is required because of the intense μ beam
- Based on CMS ECAL system
  - PWO crystal
  - APD sensors
  - FEE based on MGPA chip + 12bit ADC
  - DAQ based on Serenity board
  - Laser Calibration System

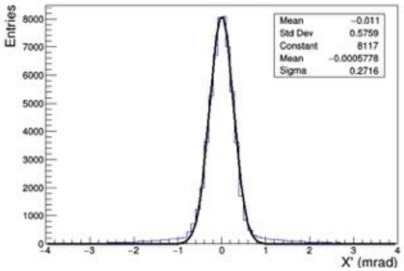


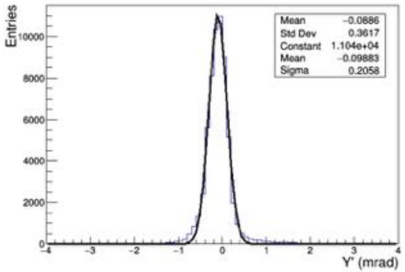


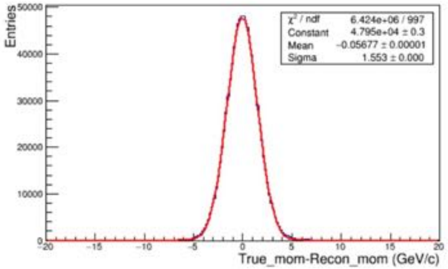
The Beam

- 160GeV/c muon beam @ M2 CERN SPS
- Beam spot size at the entrance of MUonE
  - σ_x = 26mm
  - σ_y = 27mm
- Very small beam diveregence
  - $\sigma_{X'}$ = 0.3mrad
  - $\sigma_{Y'}$ = 0.2mrad
- Momentum Resolution
  - At present BMS provides ~0.8%



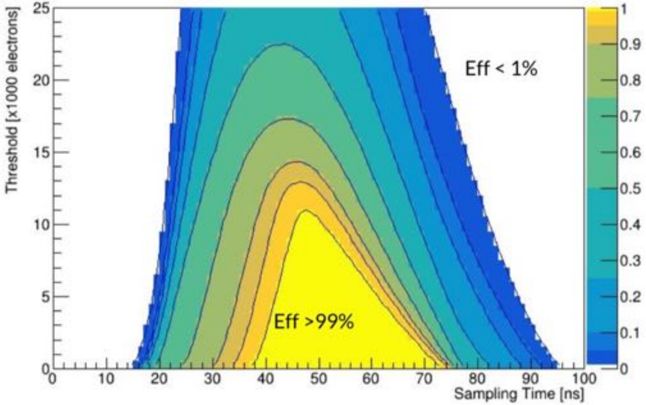


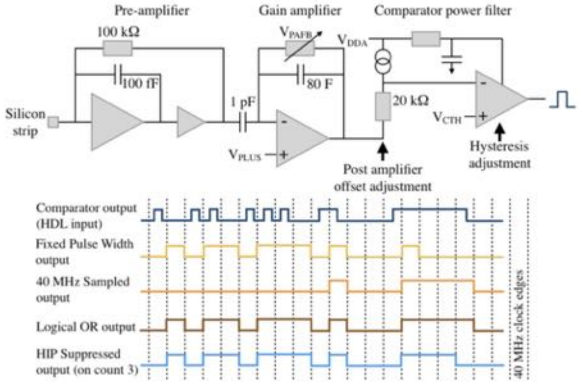




Trigger & DAQ

- The full DAQ system is based on the CMS Serenity Board (Track Trigger)
- No trigger foreseen
  - Stub info have sufficient information and resolution
  - A selection could be added to reduce the data rate on disk
- Expected beam rate 50MHz asyncronous wrt tracker readout (40MHz)
  - Optimization via threshold level and comparator operation mode optimization

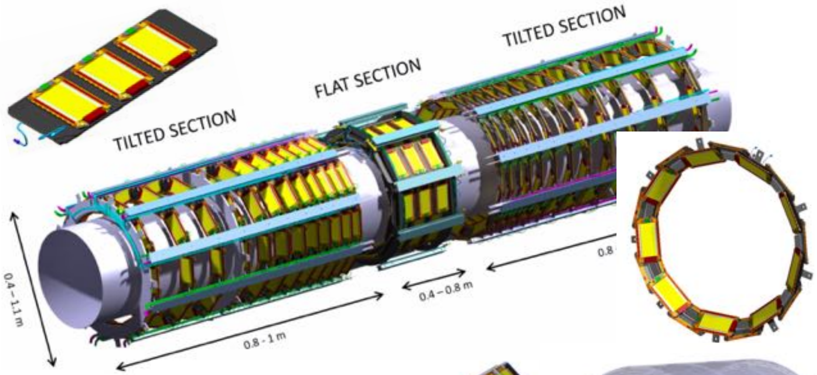


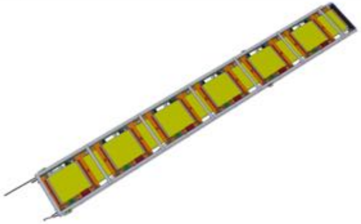


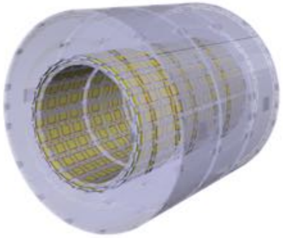
Backup

Mechanics

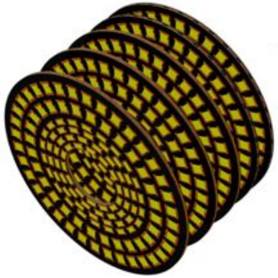
- TBPS
  - Flat Part: planks
  - Tilted Part: rings
- TB2S
  - Ladder support structure
- TEDD
  - Building block: DEE (half disk)
  - Double-Disk to be hermetic also with rectangular modules

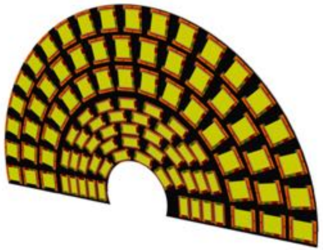






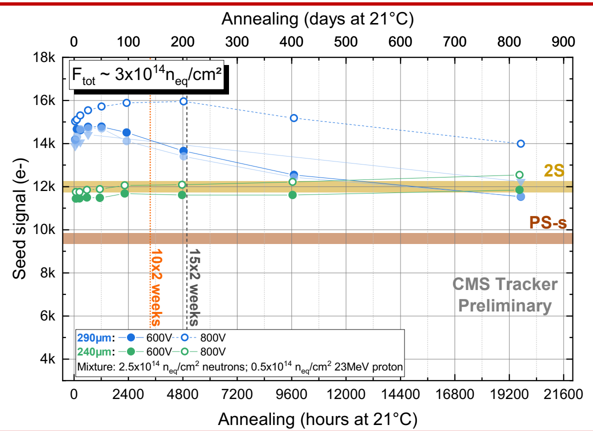
Module type and variant		TBPS	TB2S	TEDD	Total per variant	Total per type
2S	1.8 mm	0	4464	2792	7256	7680
	4.0 mm	0	0	424	424	
PS	1.6 mm	826	0	0	826	5616
	2.6 mm	1462	0	0	1462	
	4.0 mm	584	0	2744	3328	
Total		2872	4464	5960	13296	



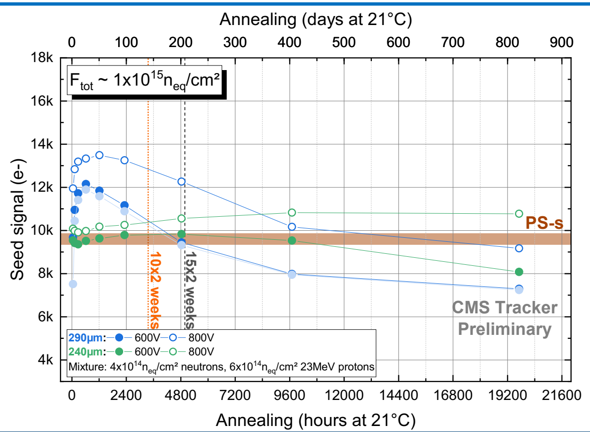


Sensors

- Irradiation campaign to study the sensors behavior and perform a technology choice:
  - Take nominal expected max. fluences for outer (2S) and inner (PS) regions after $3000fb^{-1}$
  - Consider the approximate mixture of neutrons and charged hadrons



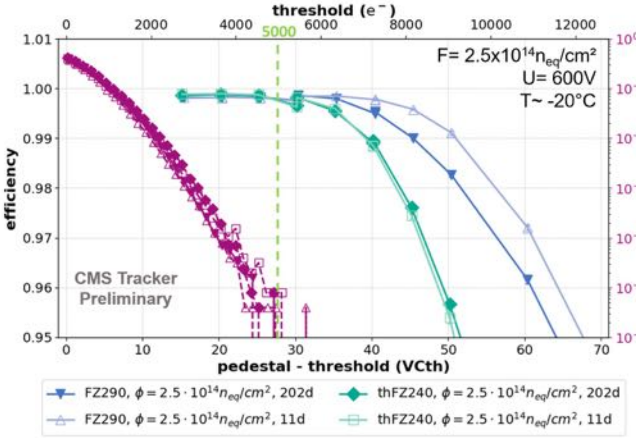
- Expected max. 2S fluence after $3000fb^{-1}$
- Signal measurements:
  - **thFZ240 barely reaches 2S limit**
  - **FZ290 is well above**

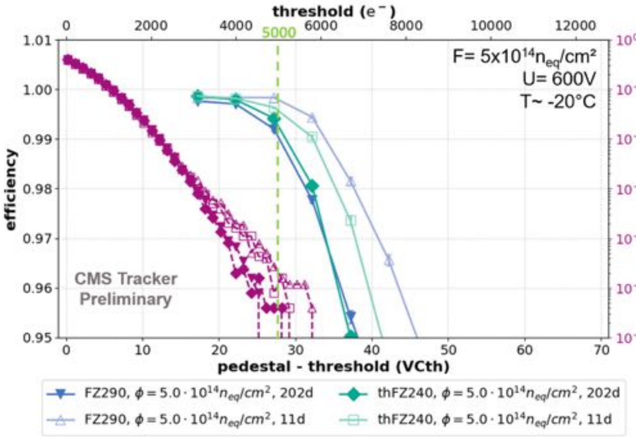


- Expected max. PS fluence after $3000fb^{-1}$
- Signal measurements:
  - **thFZ240 only just above PS-s limit**
  - **FZ290 comfortably above with 800V**

Irradiated Sensors at Beam Test

- Sensor irradiated with neutron only at JSI
- CBC3 readout chip (almost final)
- Charge collection reflected in hit efficiency as a function of threshold
  - FZ290 can tolerate higher thresholds
  - Only after long annealing (200 days) at ultimate $5x10^{14}$neq/cm² both materials are comparable
- dark noise occupancy was measured:
  - lower than 10^{-5} while expected hit occupancy is ~10^{-2}
  - Scale with annealing (current) and not with thickness



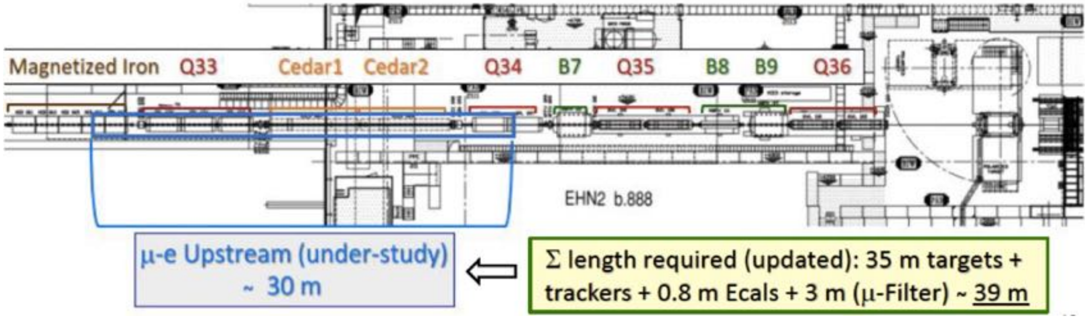


Where

- CERN M2 → between BMS and COMPASS

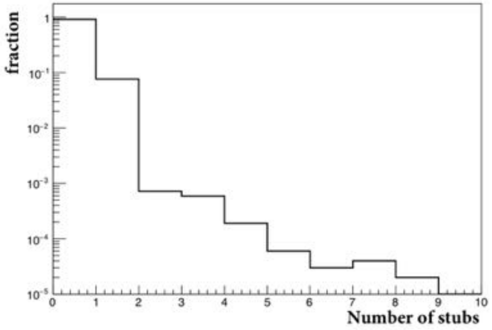
1/ μ-e setup upstream of present COMPASS experiment, i.e. within M2 beam-line

- More upstream of Entrance Area of EHN2 (Proposed by Johannes B. & Dipanwita B.)
  - Will require the removal of some components



Tracker Readout

- The tracker readout is a simplify version of the CMS backend
  - Communication between module and backend system established over a pair of optical fibers with lpGBT protocol
    - 2.56Gb/s downlink for Clock, fast command and slow control
    - 5.12Gb/s uplink for data transmission
  - MUonE will be without a trigger and readout the 40MHz stub data stream
    - Fraction of events with more than 3 stub on a CBC ≤ 0.1%
    - Main constraint due to CIC
      - 16 stub transferred in 8BX per CIC → 32 stub in 16BX per module
      - 1.25 muon per BX expected → enough room to handle fluctuations



DAQ Frontend

- Serenity Board + 2 daughter card with KU15P
- A single Serenity card can handle 12 tracking station
  - 72 modules
- Expected data throughput
  - 16 bit for a stub
  - 64 bit header
  - 3 stub per BX
  - 40Mhz rate

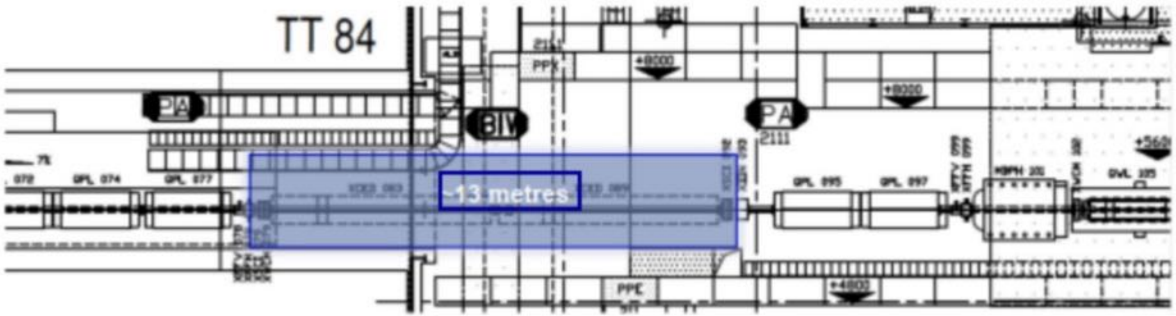
↓

  - ~20Gb/s per station
  - ~240Gb/s ouput per Serenity

- On the serenity
  - Decode 8BX CIC packets into stubs per BX
    - Firmware being developed in CMS
    - Event packing - custom for MUonE
  - Online selection?
    - Assuming no selection at the moment, only potentially event tagging o
    - Realistically some simple event selection could be enabled if required (e.g. stub counting) o
    - In worst case, prescale can be applied, but probably unnecessary
  - Transfer to local storage
    - Output formatting needs to be specified

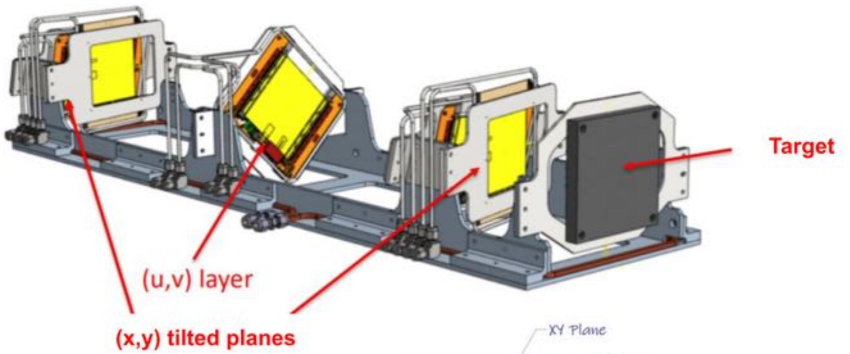
2021 Pilot Run

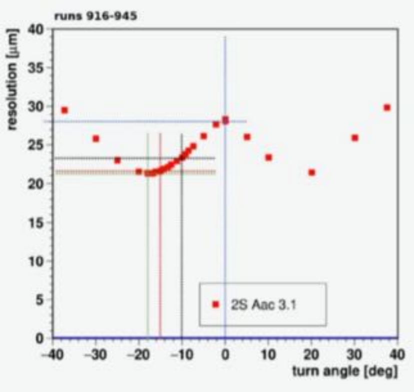
- In Q4 of 2021 a MUonE pilot run is foreseen
  - 2 tracking station + 3 upstream planes (x,y) + ECAL prototype
  - 3 weeks of beam time at M2
  - 1 year to build and integrate the detector

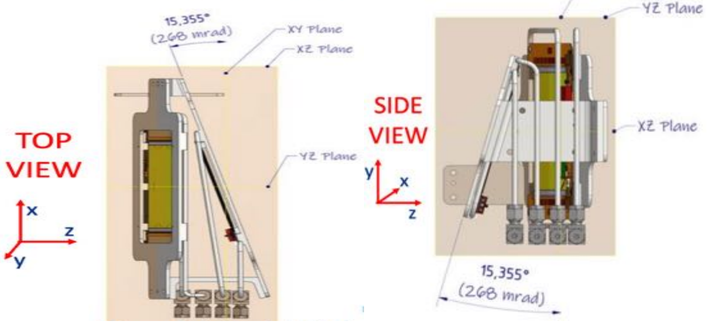


Tracker Mechanics

- Studies to optimize the resolution
  - CMS beam test indicate that the best resolution is obtain with a tilt of ~15° (268mrad)







- Detailed simulation studies ongoing
  - Target: optimize the tilting angle

Tracker Mechanics: enclosure

- The tracker structure is inserted into an enclosure which provides the connections to the services, the light tightness and it thermally isolates the tracker

- Two patch panel for each couple of module
  - One for electrical and optical connections
  - One for hydraulic feedtrhoughs