# CMS Tracker Upgrade for HL-LHC: R&D Plans, Present Status and Perspectives

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on behalf of the CMS Collaboration

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Frontier Detectors for Frontier Physics
13th Pisa Meeting on Advanced Detectors

# Outline

- Motivations for the tracker detector upgrade for the HL-LHC
- Pixel Tracker
- Outer Tracker
- Level 1 Tracking and Performances
- Summary

# Phase-2 Motivations

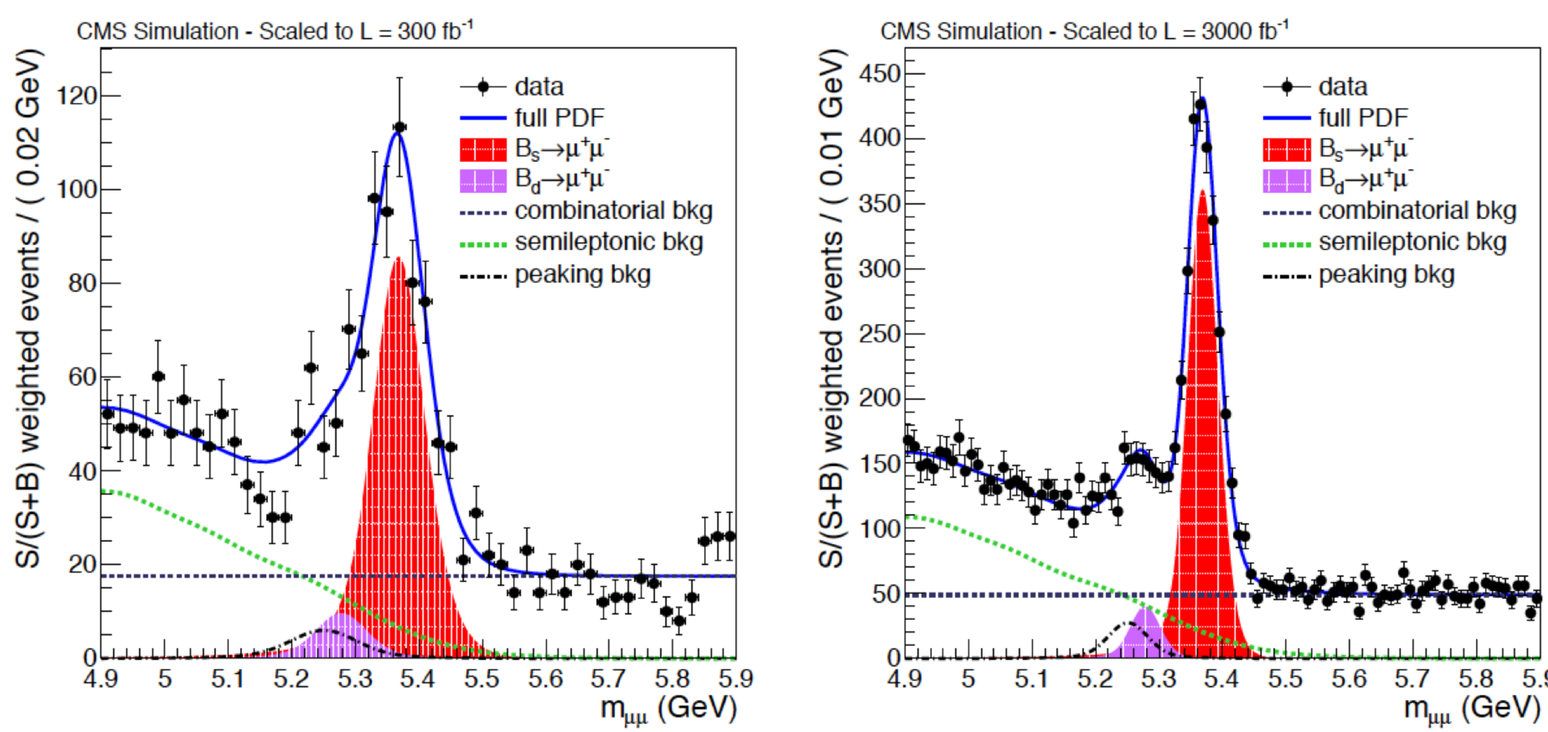
Major achievement of the LHC:
**Higgs boson discovery in 2012**.
But we want to go further…

- **Investigating the Higgs sector**:
  - Higgs couplings and properties
  - Higgs self coupling by searching di-Higgs production
  - Vector Boson Scattering properties

- **Standard Model (SM) measurements**:
  - Precision measurements (e.g. $M_W$, $\sin\theta_W$, $\alpha_s$)
  - Search for rare SM processes, enhanced by BSM (e.g. $B_{s,d} \rightarrow \mu^+\mu^-$)
  - Differential measurements of W, Z, di-bosons, top

Goal: **increase the luminosity by a factor of ~10**

| Luminosity | 300 fb$^{-1}$ | 3000 fb$^{-1}$ |
|---|---|---|
| **Coupling parameter** | 7-parameter fit uncertainties | |
| $k_\gamma$ | 5-7% | 2-5% |
| $k_g$ | 6-8% | 3-5% |
| $k_W$ | 4-6% | 2-5% |
| $k_Z$ | 4-6% | 2-4% |
| $k_u$ | 14-15% | 7-10% |
| $k_d$ | 10-13% | 4-7% |
| $k_l$ | 6-8% | 2-5% |
| $\Gamma_H$ | 12-15% | 5-8% |



# CMS toward HL-LHC Upgrade

| | LHC | | | | | HL-LHC | |
|---|---|---|---|---|---|---|---|
| | Run 1 | LS 1 | Run 2 | LS 2 | Run 3 | LS 3 | Run 4 |
| $E_{CM}$ (TeV) | 7-8 | | 14 | | 14 | | 14 |
| L ($cm^{-2} s^{-1}$) | $7 \times 10^{33}$ | | $2 \times 10^{34}$ | | $2 \times 10^{34}$ | | $5 \times 10^{34}$ |
| PU | ~20-30 | | ~50 | | ~50 | | ~140 |
| $\int Ldt$ ($fb^{-1}$) | 30 | | 300 | | 300 | | 3000 |

| Phase-0 | | | | | | Phase-1 | | | | | | Phase-2 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| past | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | future |

We are here

Installation of the **new CMS Phase-1 pixel detector** during extended winter shut-down

**Tracking degradation of Phase-1 tracker if used in HL-LHC conditions:**

- Impact parameter degradation > 50% after 500 $fb^{-1}$
- Data loss of ~7% at PU = 140

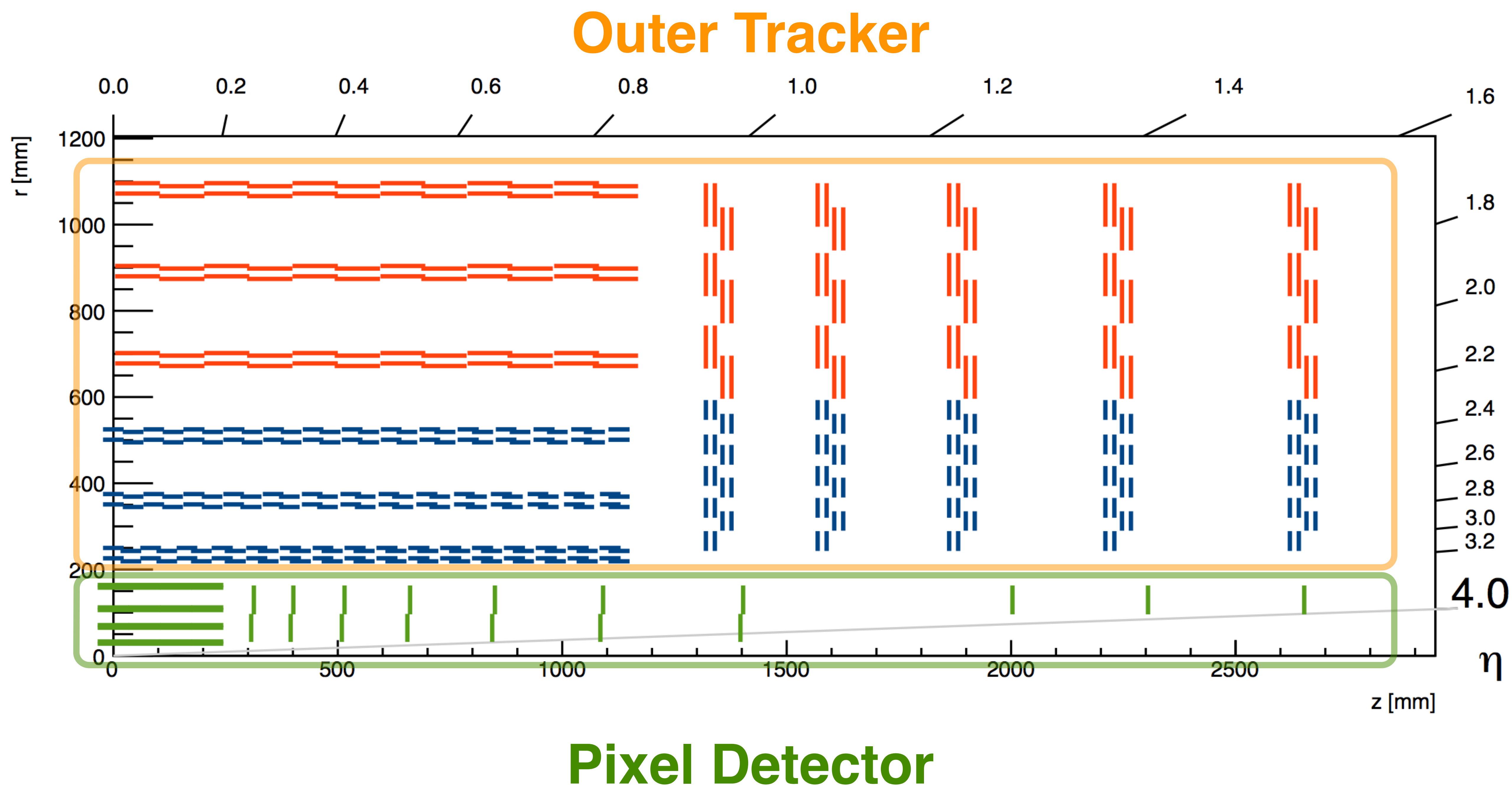
**Phase-2 Pixel Detector Requirements:**

- ~3 times the hit rate of Phase-1
- ~10 times the radiation dose of Phase-1
- ~10 times the particle fluence of Phase-1

**Phase-2 Outer Tracker Requirements:**

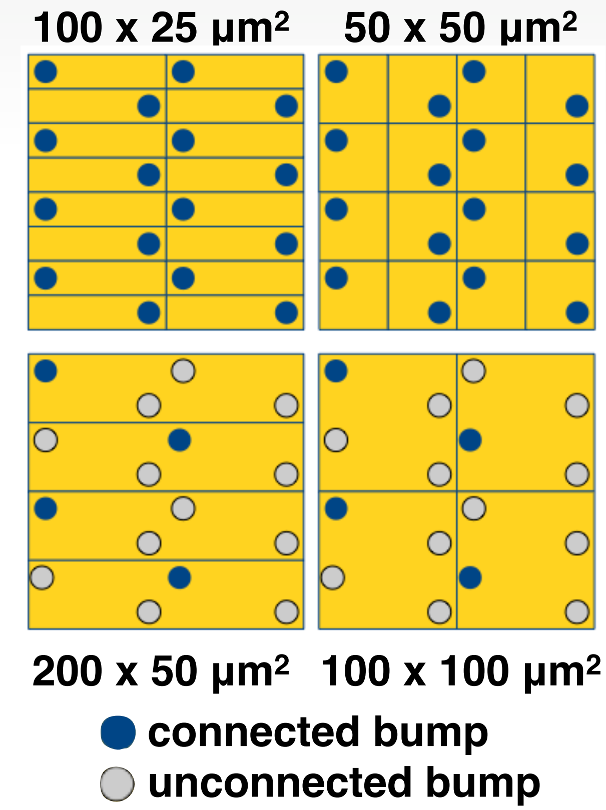
- ~6 times the radiation dose of Phase-1
- Trigger information at level 1 needed

# Phase-2 Tracker Layout



# Pixel Detector

# Pixel Detector Requirements

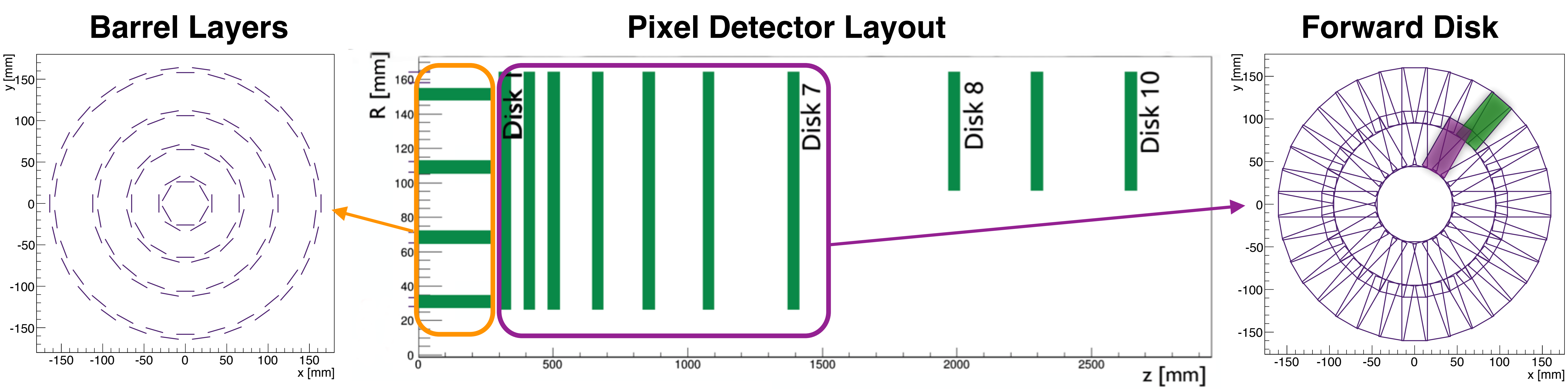



**Increase of granularity**

- Motivation: pixel occupancy reduction, resolution on high-$p_T$ tracks and two-tracks separation improvement
- Solution: small pixel size (100×25 or 50×50 µm$^2$)
- Hit rate up to 2 GHz/cm$^2$ → 100 kHz/pixel
- Outer layers with larger pixels if necessary, with the same chip
- Read-Out Chip (ROC) technology: 65 nm CMOS (RD53 Collaboration)

**Increase of forward acceptance**

- Motivation: to cover jet region of Vector Boson Fusion and Vector Boson Scattering
- Coverage up to pseudo-rapidity η ~4 (now η = 2.4)
- 4 barrel layers + 10 forward disks (now 3 barrel layers + 2 disks)

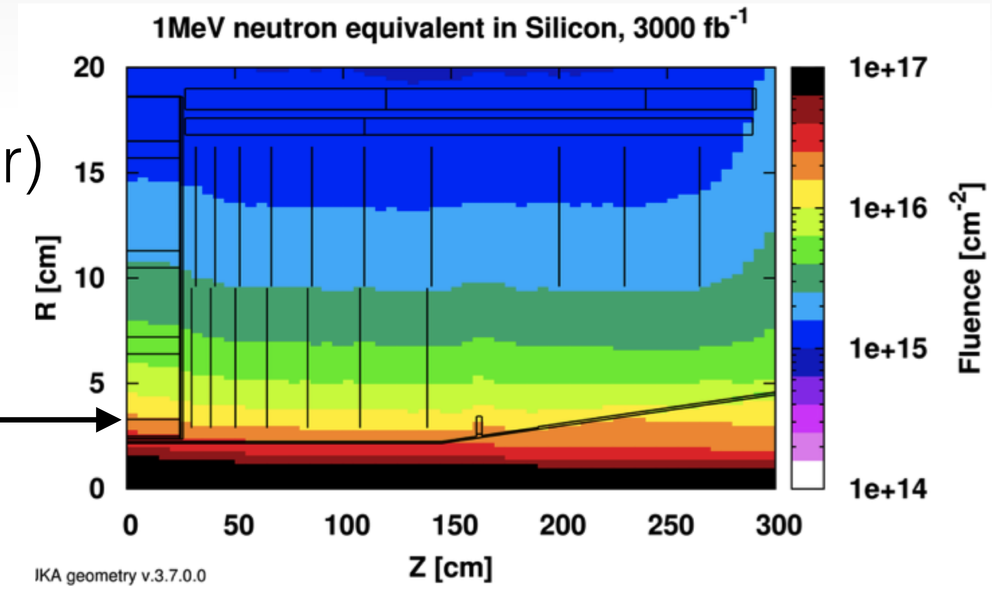


# Radiation Hardness

**ROC radiation hardness**

Expected dose: ~1 Grad @ r = 30 mm (most internal layer)

Solution: 65 nm CMOS technology



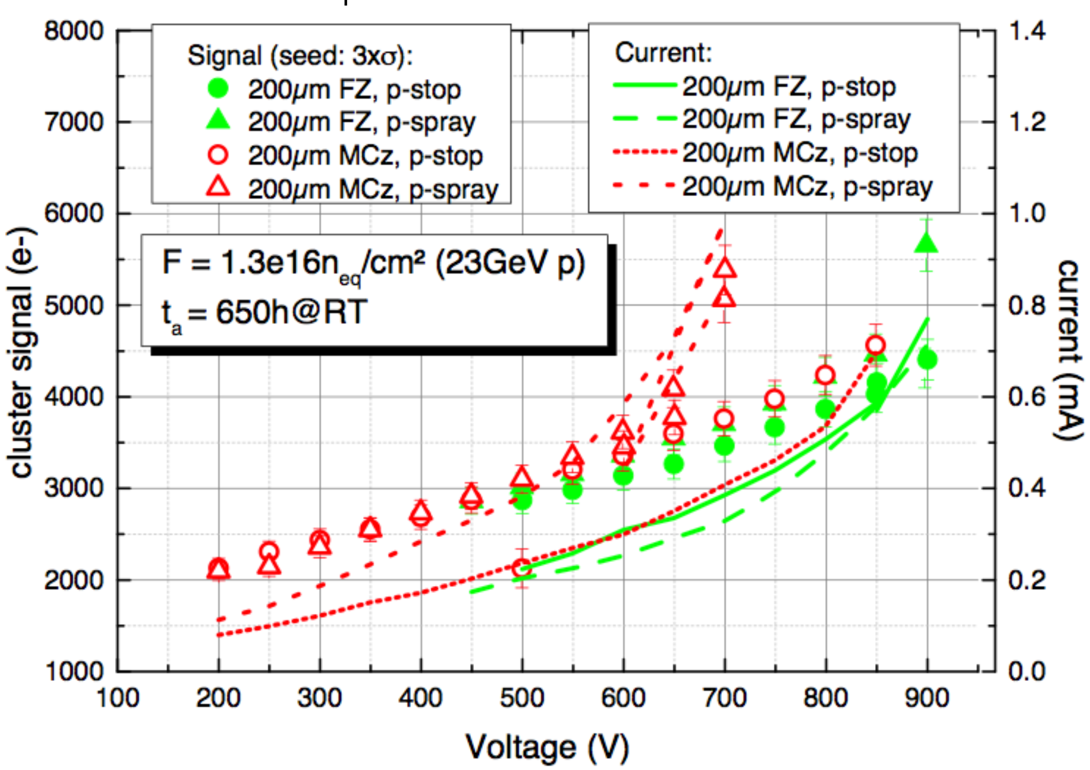

**Sensor radiation hardness**

Expected fluence: ~$2\times10^{16}$ $n_{eq}/cm^2$ @ r = 30 mm

Solution: reduction of the drift distance to reduce the charge lost by trapping:

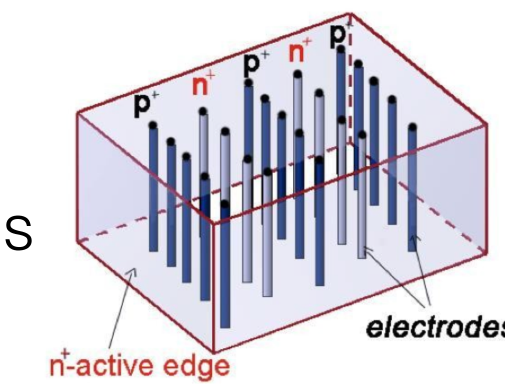
**Thin planar sensors**

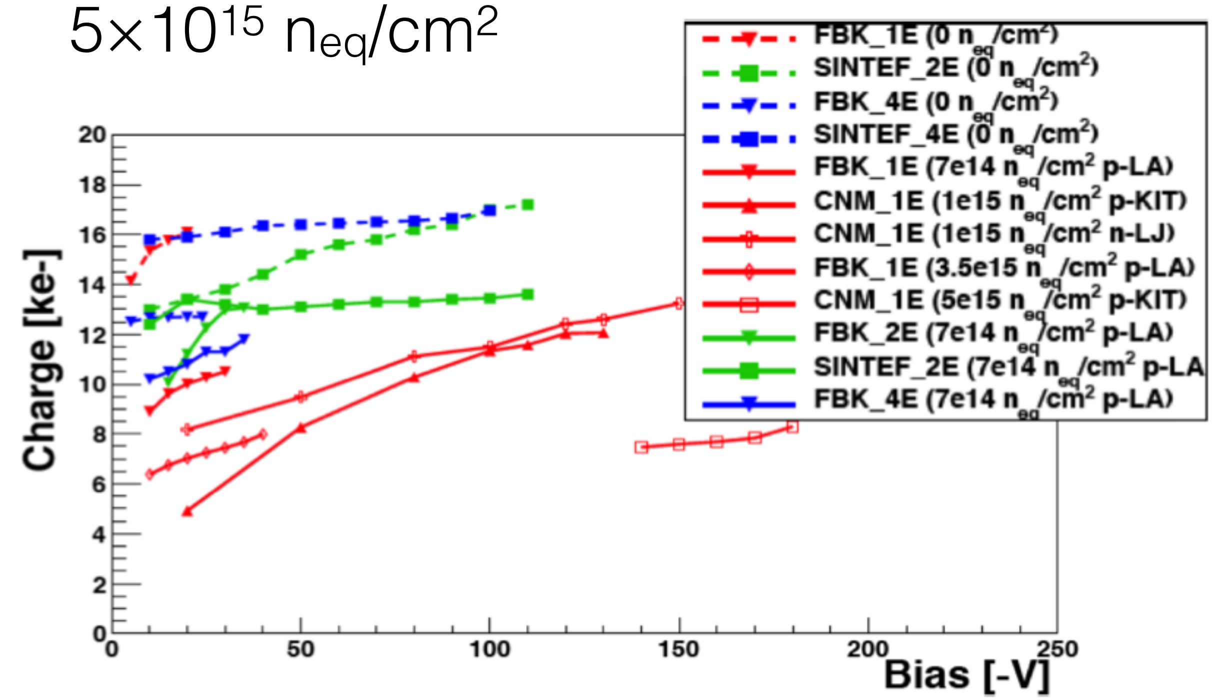
- 100 μm < thickness < 200 μm
- n-in-p implant
- for strip structures ~4000 $e^-$ @ 800V after $1.3\times10^{16}$ $n_{eq}/cm^2$



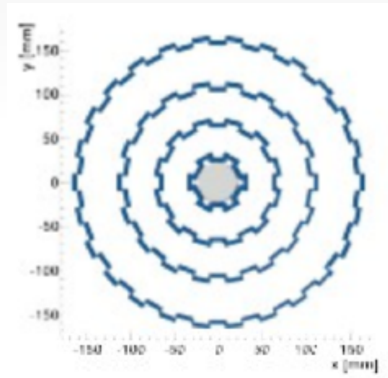
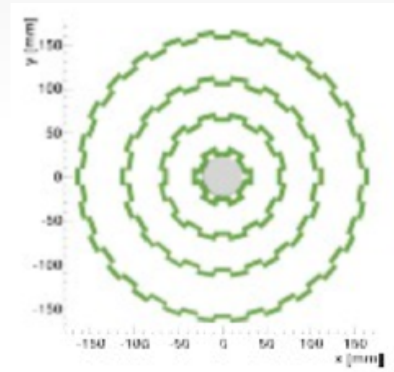
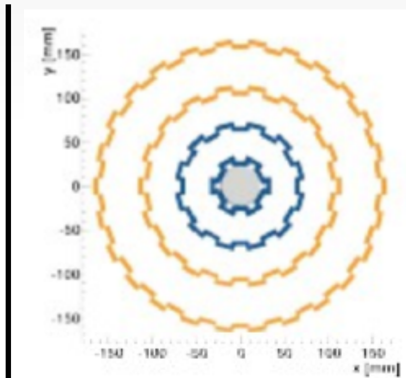
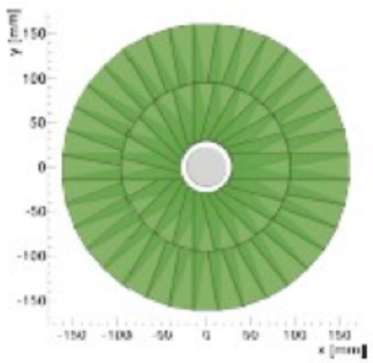
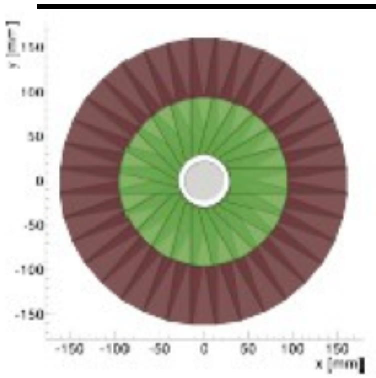

**3D sensors**

- columnar electrodes
- higher radiation hardness
- lower depletion voltage
- ~7000 $e^-$ @ 150V after $5\times10^{15}$ $n_{eq}/cm^2$



# Pixel Detector Layout Studies

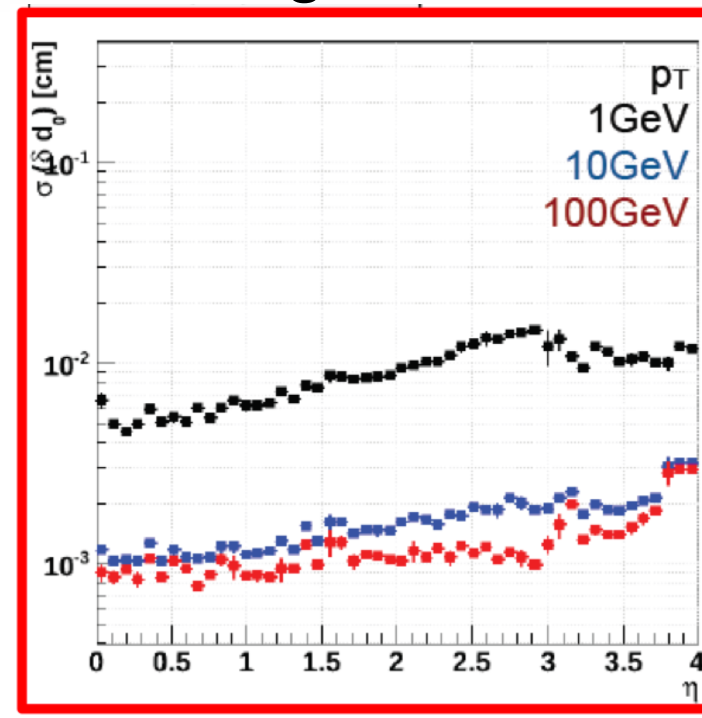
| barrel BPIX / disk FPIX |  |  |  |
|---|---|---|---|
|  | **Configuration #1**<br>**BPIX 25×100**<br>**FPIX 50×50** | **Configuration #2**<br>**BPIX 50×50**<br>**FPIX 50×50** | **Configuration #3**<br>**Inner BPIX 25×100**<br>**Outer BPIX 50×200**<br>**FPIX 50×50** |
|  | **Configuration #4**<br>**BPIX 25×100**<br>**Inner FPIX 50×50**<br>**Outer FPIX 100×100** | Too much $d_0$ degradation | **Configuration #5**<br>**Inner BPIX 25×100**<br>**Outer BPIX 50×200**<br>**Inner FPIX 50×50**<br>**Outer FPIX 100×100** |

**Inner BPIX:** layer 1 and 2
**Outer BPIX:** layer 3 and 4

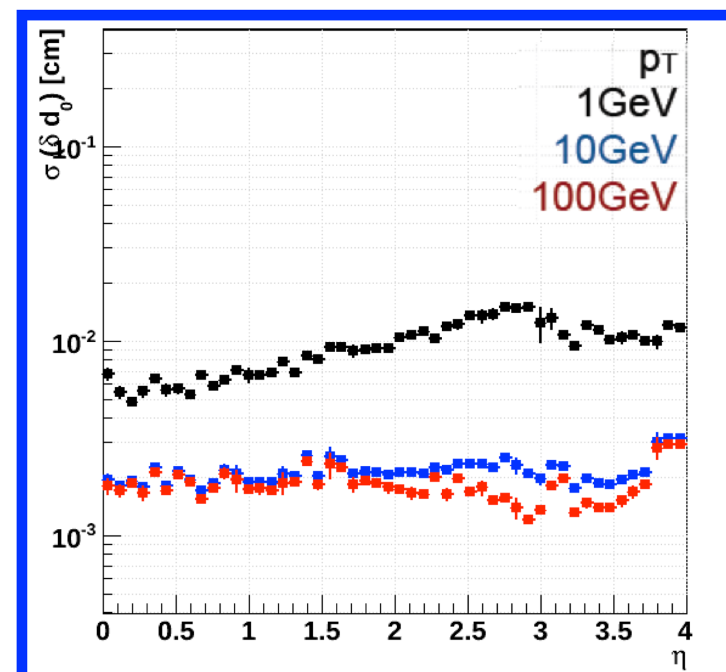
**Inner FPIX:** inner modules
**Outer FPIX:** outer modules

- Too much $d_0$ degradation with pure squared pixels in BPIX → square pixels not suitable for the barrel
- Two extreme configurations, #1 and #5, have comparable tracking performance
- Config. #5 has ~1/2 channels of #1

**Configuration #1**




**Configuration #2**



# Pixel Detector Perspectives

**Sensors:**

- Thin Planar: submission expected in 2015 to study feasibility of small pixel, p-spray and p-stop insulations, radiation tolerance and resolution (in test-beam)
- 3D: 2 submissions expected in 2015:
  - CNM: trial of Phase-2 pixel size with thicker wafer
  - FBK: see talk of Prof. Gian-Franco Dalla Betta

**Front-end ASIC:**

- Good progress in RD53: see poster of Prof. Valerio Re

**Tracker Layout:**

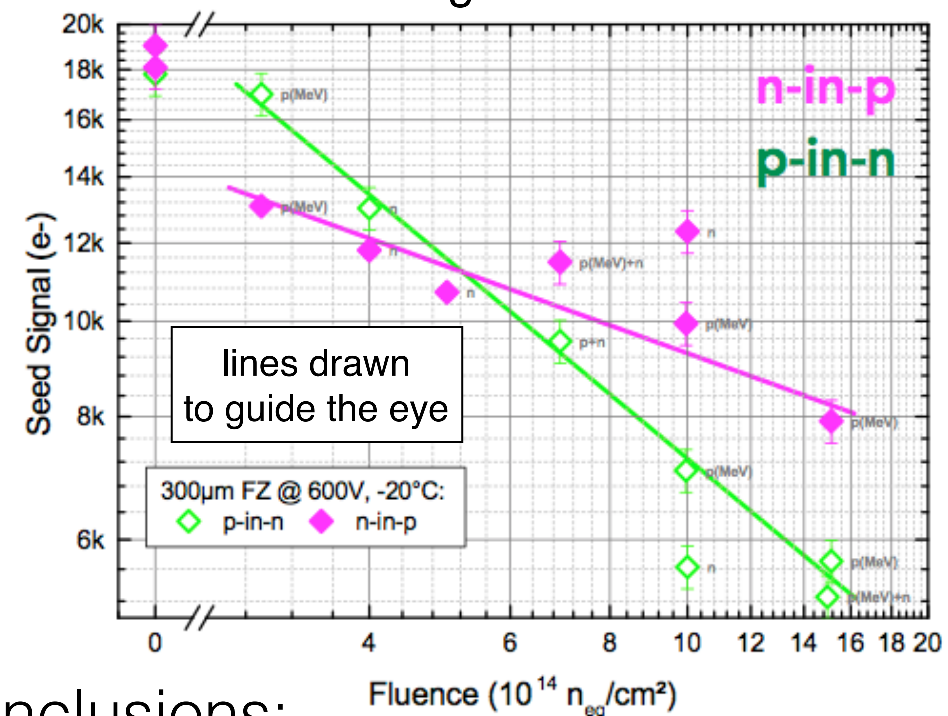
- Ongoing full simulation studies to estimate hit resolution, occupancy and hit rates as a function of pixel pitch, thickness and electronic threshold

# Outer Tracker

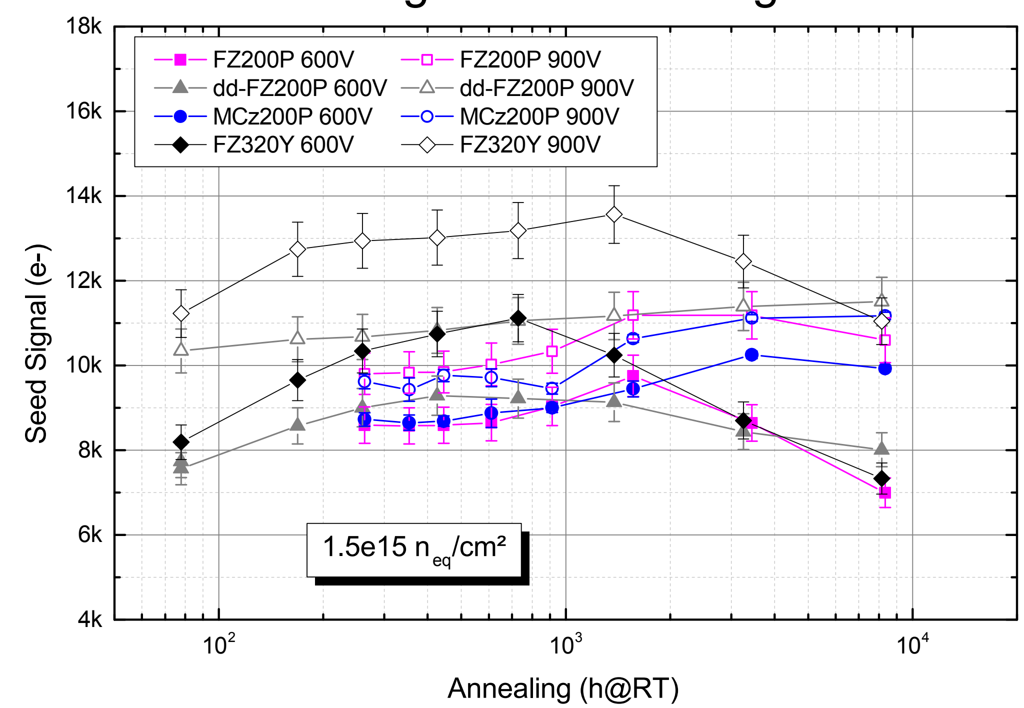
# Radiation Hardness

- Expected fluence up to **$1.5\times10^{15}$ $n_{eq}/cm^2$**
- Investigation based on Hamamatsu test samples:
  - standard, oxygen-rich ([O] > $2\times10^{16}cm^{-3}$) materials
  - p-in-n, n-in-p implant;
  - Float-zone, Magnetic Czochralski, Epi substrate;
  - 300, 200, 100, 50 μm active thickness

Seed Signal vs Fluence



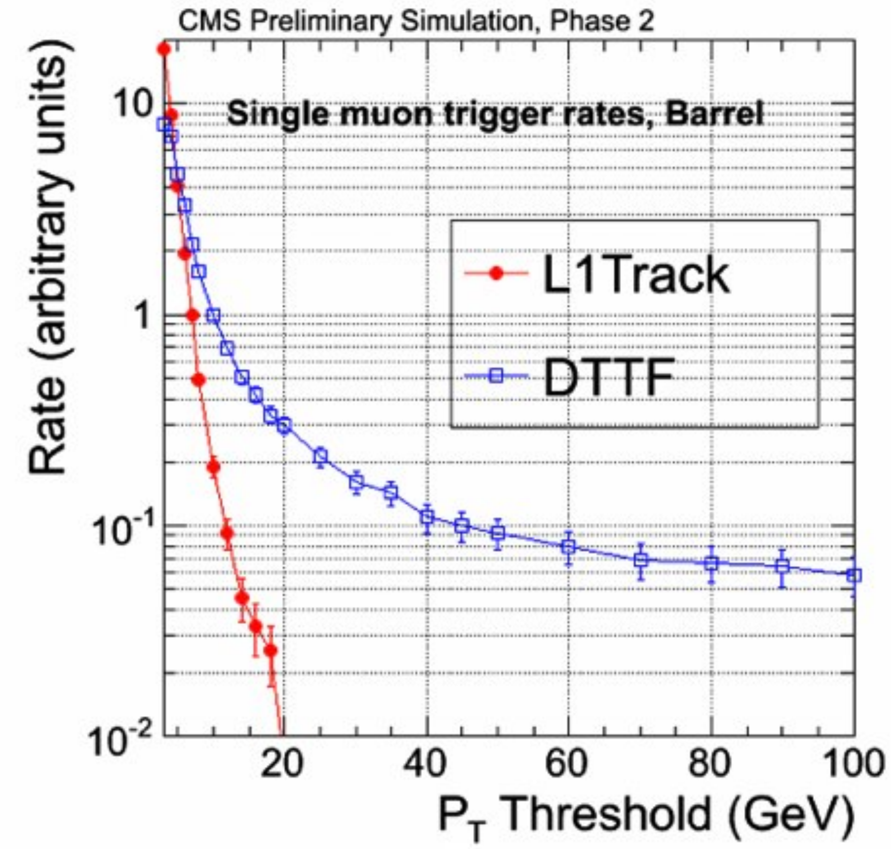

Seed Signal vs Annealing Time



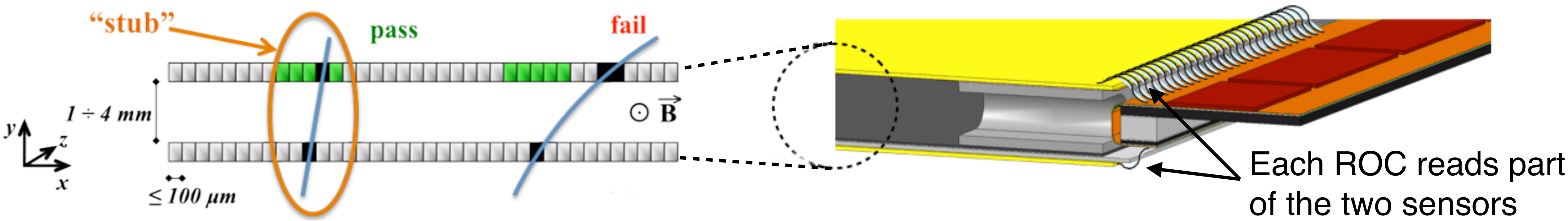

- Conclusions:
  - **n-in-p** better: higher radiation tolerance with respect to p-in-n
  - **MCz sensors**: charge collection not dependent on annealing
  - **200 μm sensors** have lower current and same signal as 300 μm at highest dose
  - **cold operation** (-20°C) is needed at the high doses

# $p_T$-module Concept

**Trigger requirement:**
Despite the foreseen improvements, muon and calorimeter-based L1 will not be able to stand the rates due to the PU and the limited resolution: e.g., in the muon case, no $p_T$ threshold is effective in reducing the rate
→ the Tracker must provide informations to the L1 system

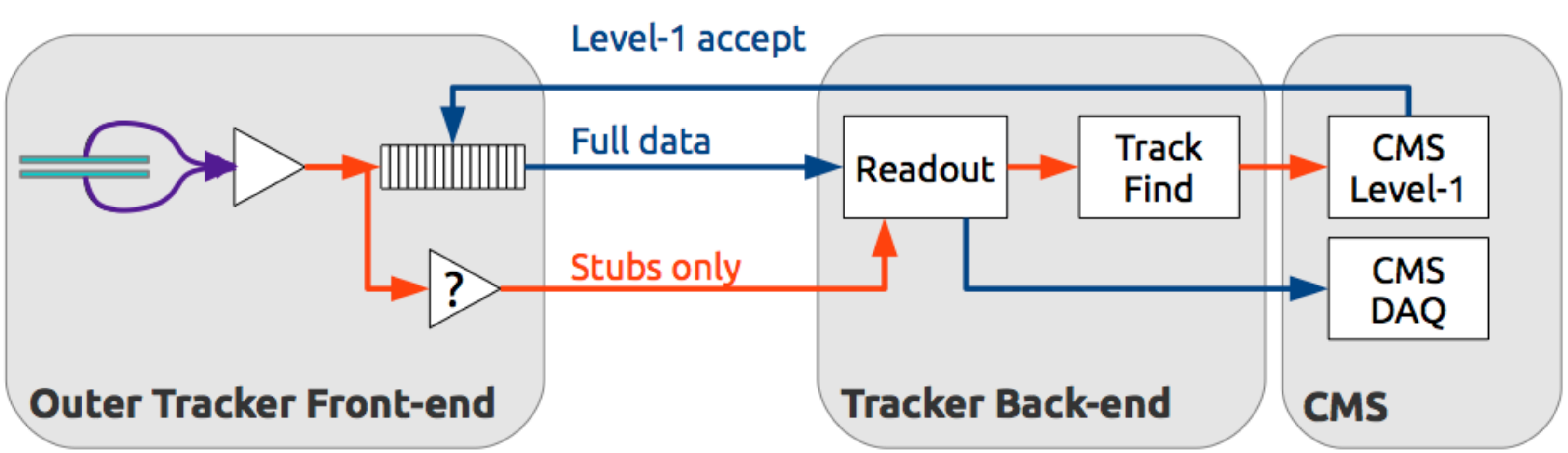



Thanks to the CMS 3.8 T magnetic field, it is possible to discriminate high-$p_T$ tracks




Stubs are processed in the back end to build L1 track primitives

— @ 40 MHz (BX rate)
— @ 750 kHz (L1A rate)



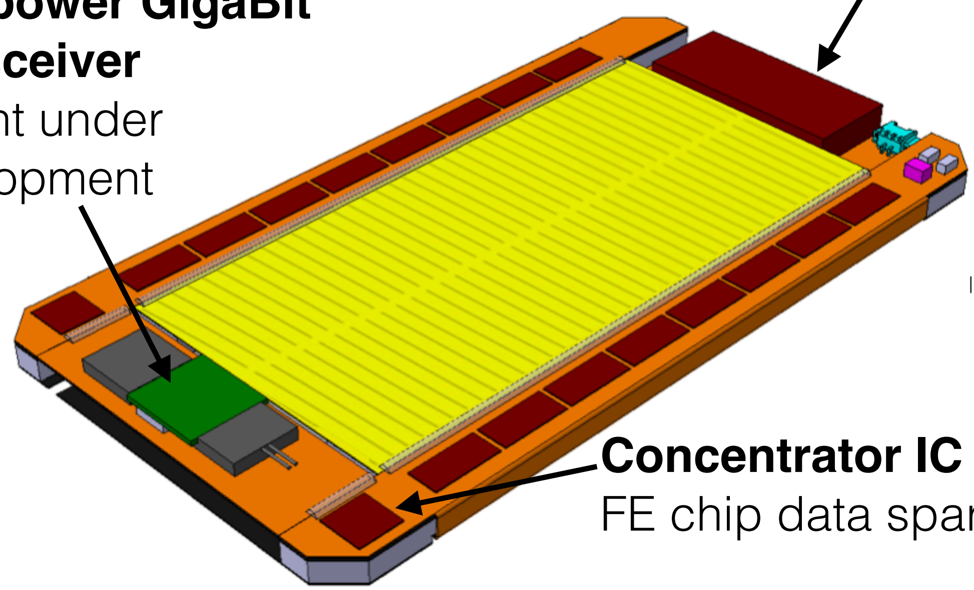
# PS and 2S Modules

## PS modules: Macro Pixel + Strip

Macro Pixel: 1.5 mm × 100 μm DC coupled
Strip: 2.4 cm × 100 μm AC coupled
Module area: ~5 × 10 cm$^2$
Power: ~6-8 W

**DC/DC converter**
10-12V lines: lower current, lower material

**Low-power GigaBit Transceiver**
current under development

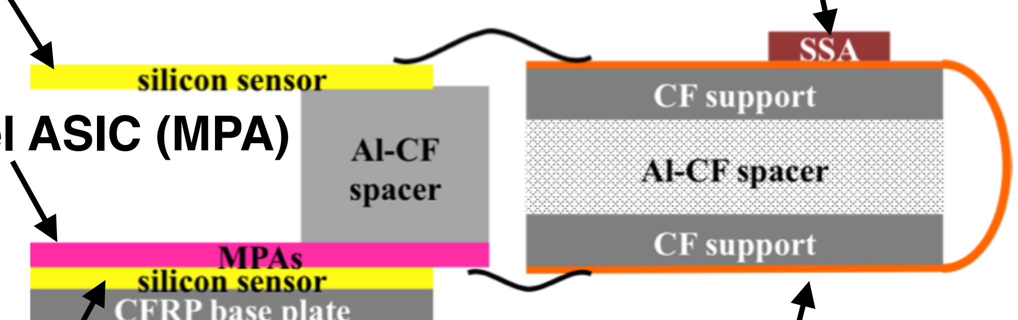


**Concentrator IC (CIC)**
FE chip data sparsification

**Silicon strip sensor**

**Short Strip ASIC (SSA)**

**Macro-Pixel ASIC (MPA)**




**Flexible hybrid**

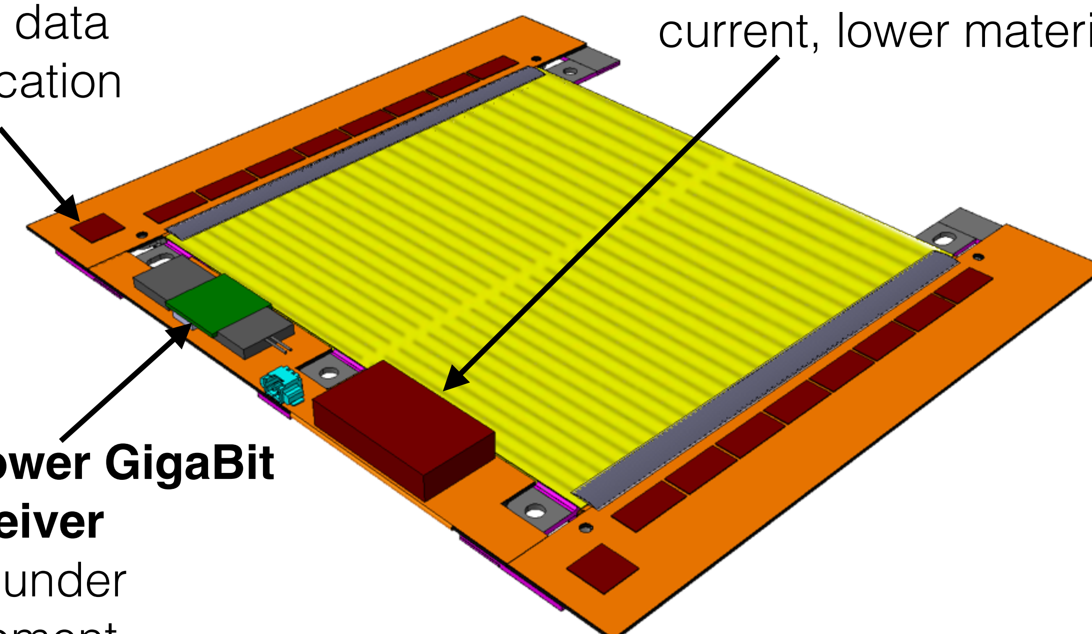
**Silicon pixel sensor**

## 2S modules: Strip + Strip

Strip: 5 cm × 90 μm AC coupled (both sides)
Module area: ~10 × 10 cm$^2$
Power: ~4-5 W

**DC/DC converter**
10-12V lines: lower current, lower material

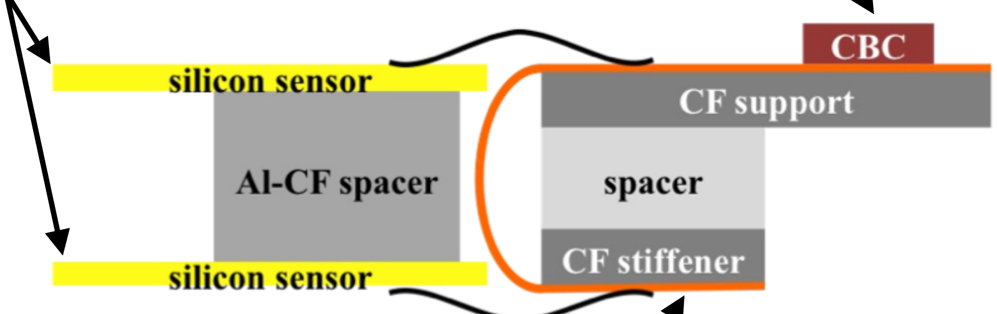
**Concentrator IC (CIC)**
FE chip data sparsification



**Low-power GigaBit Transceiver**
current under development

**CMS Binary Chip (CBC)**

**Silicon strip sensors**



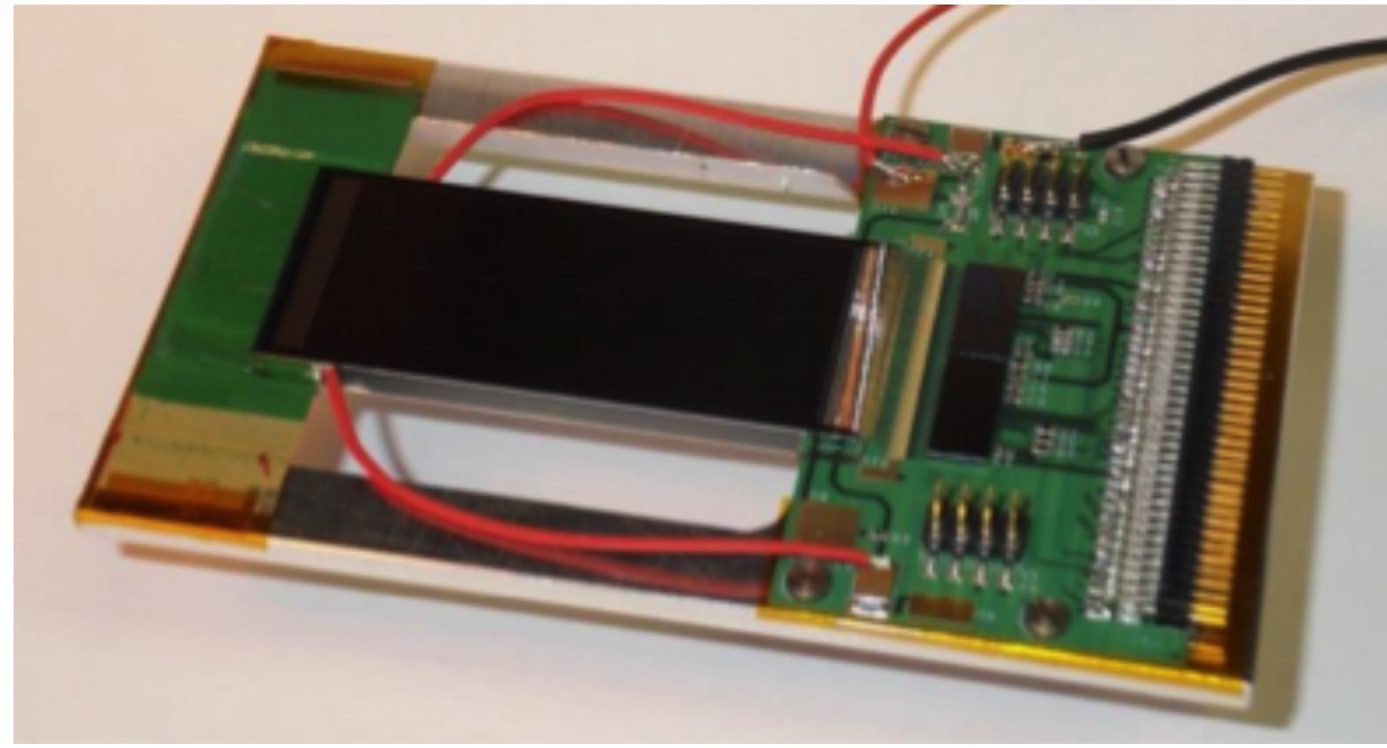

**Flexible hybrid**

# Modules Prototypes

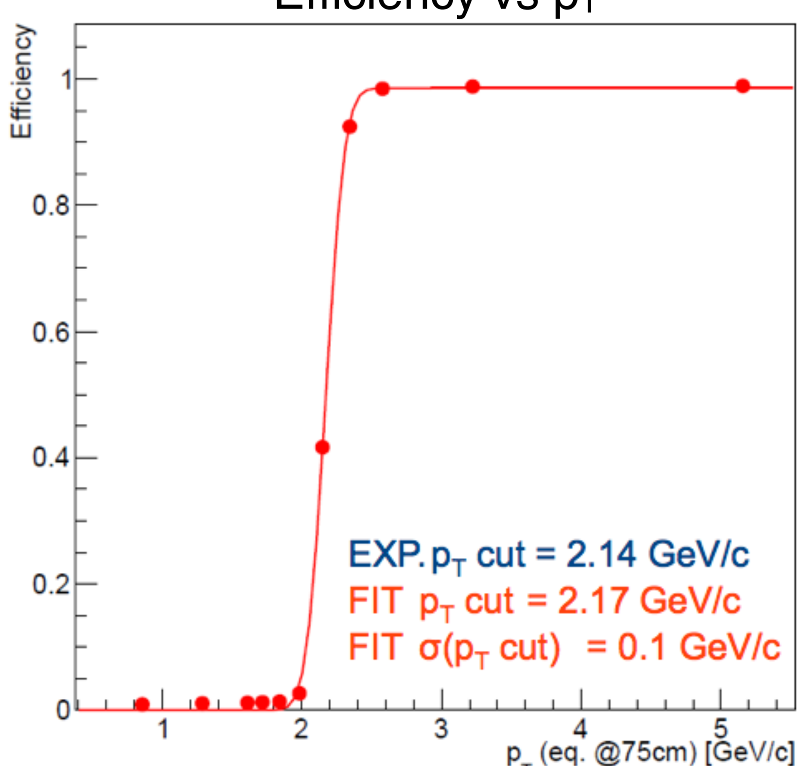
**2×CBC functional module**

Characteristics:

- 2 CBC chips (instead of 8)
- Electrical readout (not optical)
- No data concentrator
- Rigid hybrid
- Stub-finding logic
- Nominal noise and threshold
- Tested on beam (December 2013)

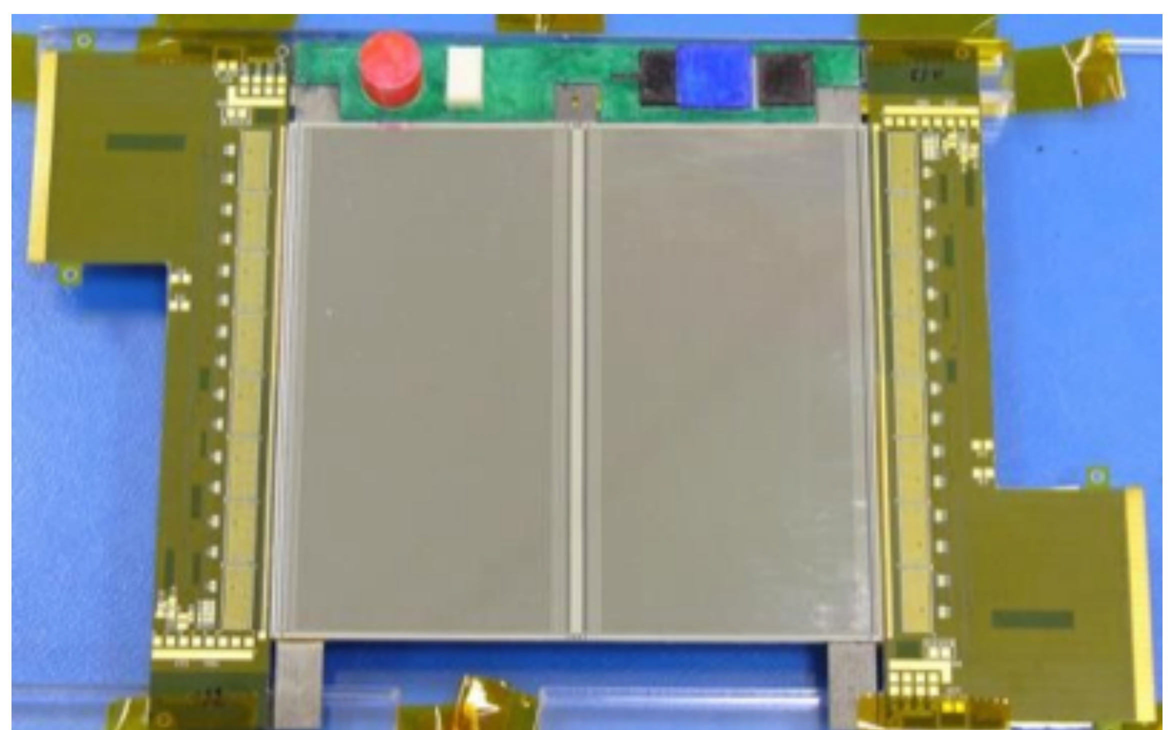


Efficiency vs $p_T$




**module tilted to emulate $p_T$**

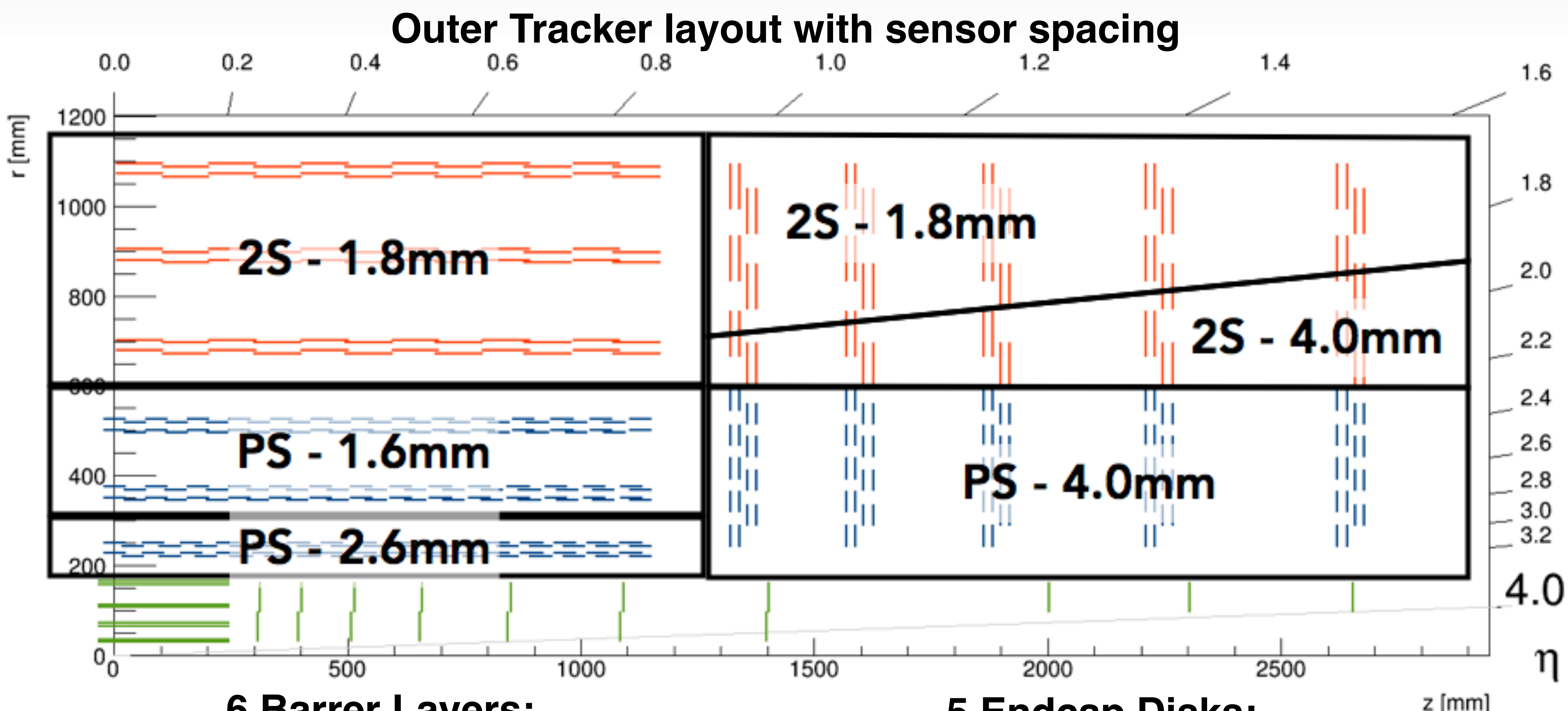
**8×CBC prototype**



Characteristics:

- 2×8 CBC chips
- Flex hybrid
- Just produced
- Used to validate the full-scale assembly

# Outer Tracker Layout




**6 Barrer Layers:**
3 Innermost PS
3 Outermost 2S

**5 Endcap Disks:**
radius < 60 cm PS
radius > 60 cm 2S

Sensor spacing optimised as a function of $p_T$ threshold (2 GeV), module position and sensor pitch. Further tuning performed by adjusting hit-matching windows

**Outer Tracker Shopping List**

~7100 PS modules: higher granularity, z/η info provided
~8400 2S modules: lower costs and lower power density, used at larger radii

# Outer Tracker Perspectives

**Sensors:**

- Several submissions ongoing from different vendors to evaluate different processes, materials (FZ or MCz), design aspects (slim edge, width/pitch variations, inter-strip insulation)
- Market survey
- Radiation qualification

**Front-end ASICs:**

- Good progresses on $p_T$ module ASICs
- Different prototypes for 2S module ASICs already available, new version submissions expected in 2016
- PS ASICs under development, test on prototypes ongoing and new designs in progress

**Modules:**

- Beam test in the summer on irradiated 2S prototype 2xCBC
- Beam test in autumn on unirradiated 2S full-size module

**Tracker Layout:**

- Study of different Outer Tracker geometries using the tkLayout simulation tool, for example tilting PS modules in the barrel as a function of $\eta$

# Level 1 Tracking and Performances

# Level 1 Tracking for Phase-2

**Extreme challenge:** reconstruct O(100) tracks from ~15000 stubs at 40 MHz

### Associative Memories

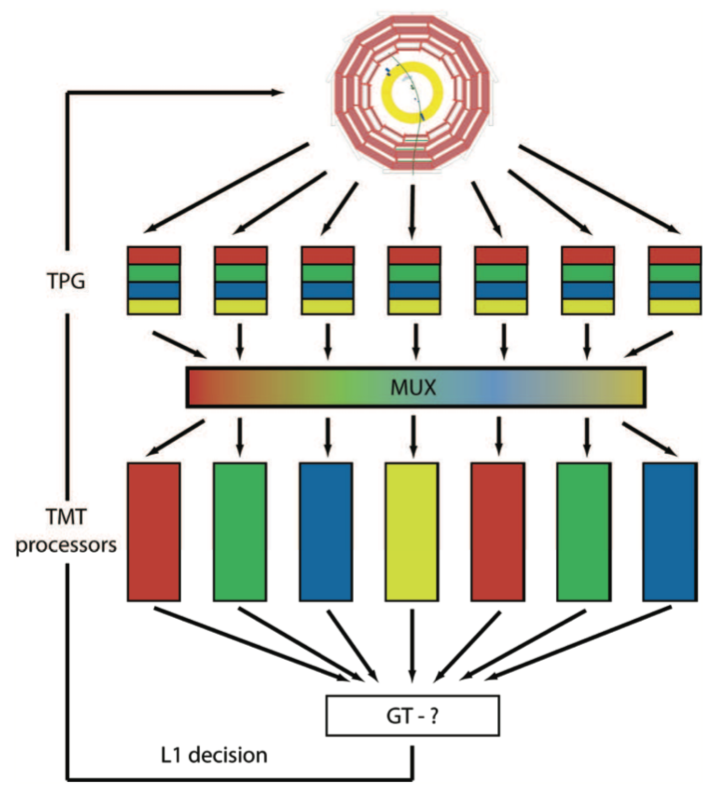
Track matching with a $10^8$ pattern database (custom processor)


Fitting method: PCA, Hough transform or Retina

Slices: 48 = 8×6 (ϕ×η)
MUX Time: Load balancing

### Time Multiplexed Trigger

Multiple detectors send data to a single destination for complete event processing

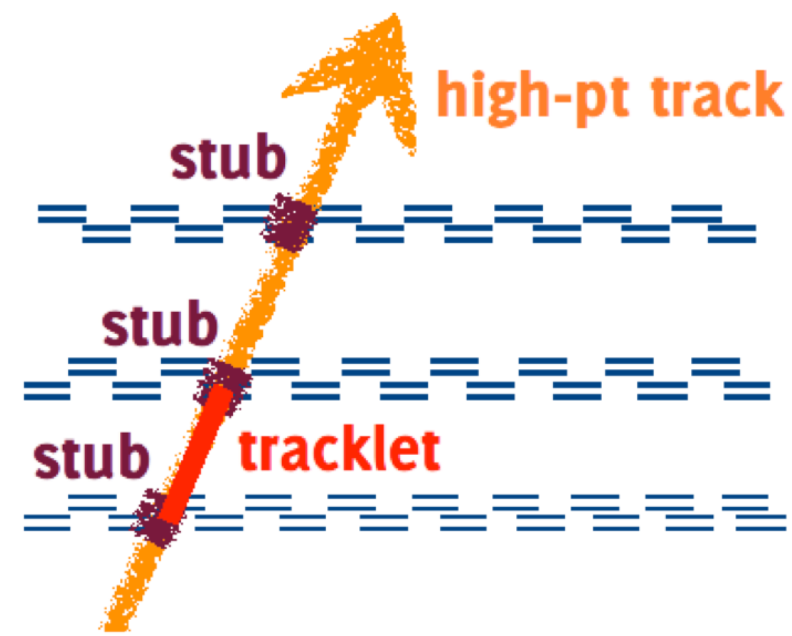



Fitting method: under study

Slices: 5 = 5×1 (ϕ×η)
MUX Time: 24 Bunch Crossing

### Tracklet Algorithm

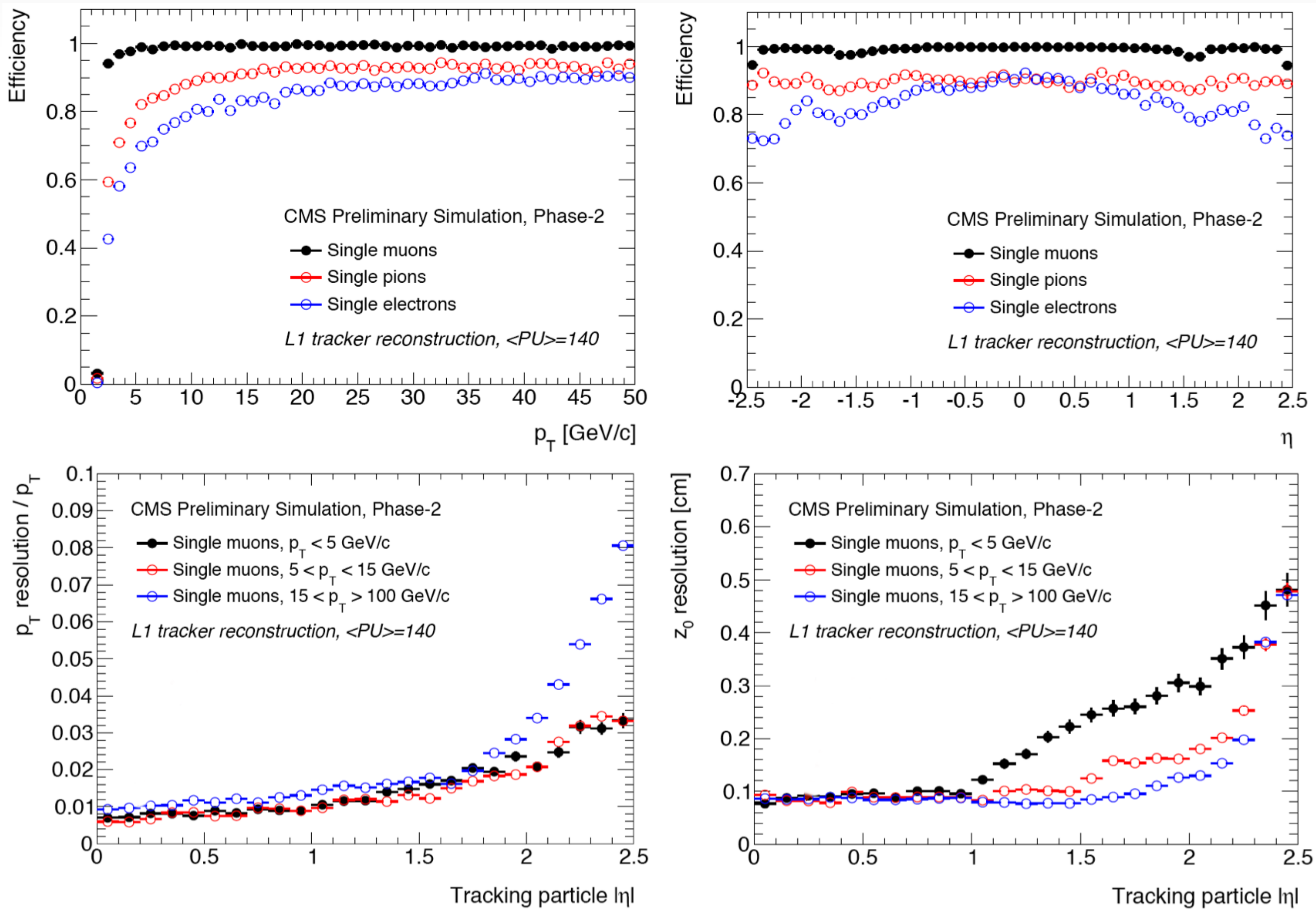
Track seeded by finding pairs of stubs in adjacent layers (tracklet)




Fitting method: linearised $\chi^2$

Slices: 28 = 28×1 (ϕ×η)
MUX Time: 4 Bunch Crossing

# L1-Tracking Performances




Good track-parameter resolutions obtained by L1-tracking simulation, here using tracklet algorithm (similar figures for Associative Memories)

# L1-Tracking Perspectives

**Next steps:**
- Preparing demonstrators in one-two years
- Firmware for data sourcing preparation in progress

**Associative Memories:**
- Production of AM chip and mezzanine prototypes in progress
- Before AM chip arrival, AM functionality will be tested on FPGA (already implemented)
- Optimisation of the AM pattern bank ongoing
- Simulation of different track fitting methods ongoing

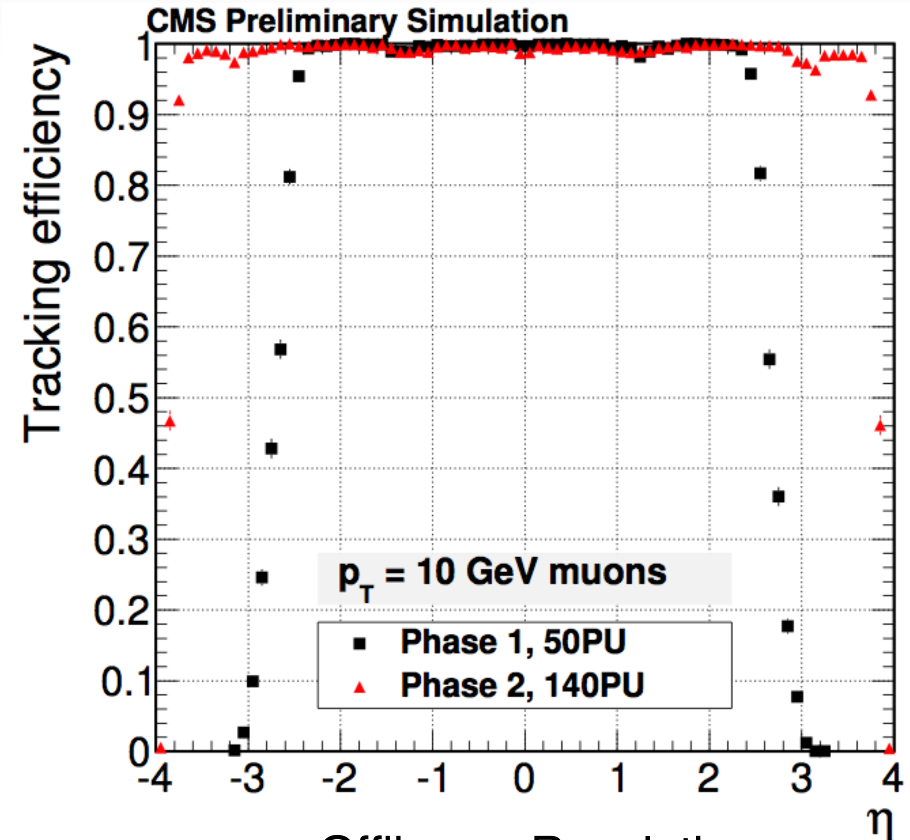
**Time Multiplexed Trigger:**
- Implementation feasibility of track finding algorithm under study
- MP7 demonstrator in preparation for first proof of concept (by August)

**Tracklet Algorithm:**
- Improving electron tracking efficiency
- Study of the barrel-endcap transition region
- Study of fake rate

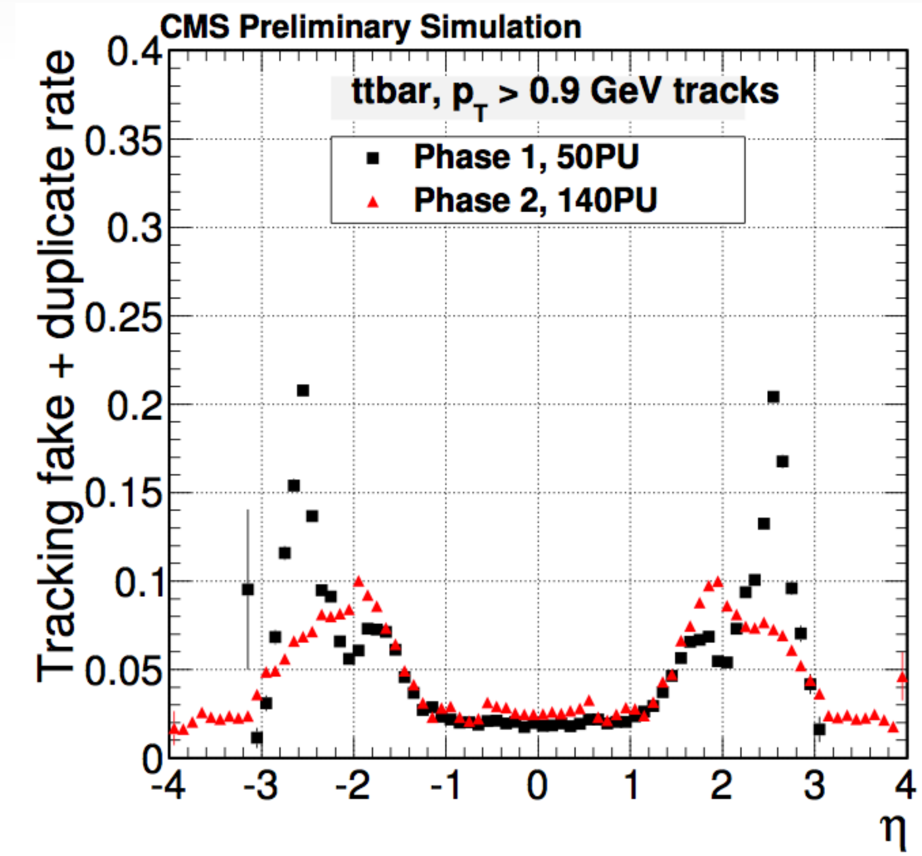
See talk of Prof. Geoff Hall, posters of Dr. Giacomo Fedi and Davide Cieri

# Phase-2 Tracker Performances

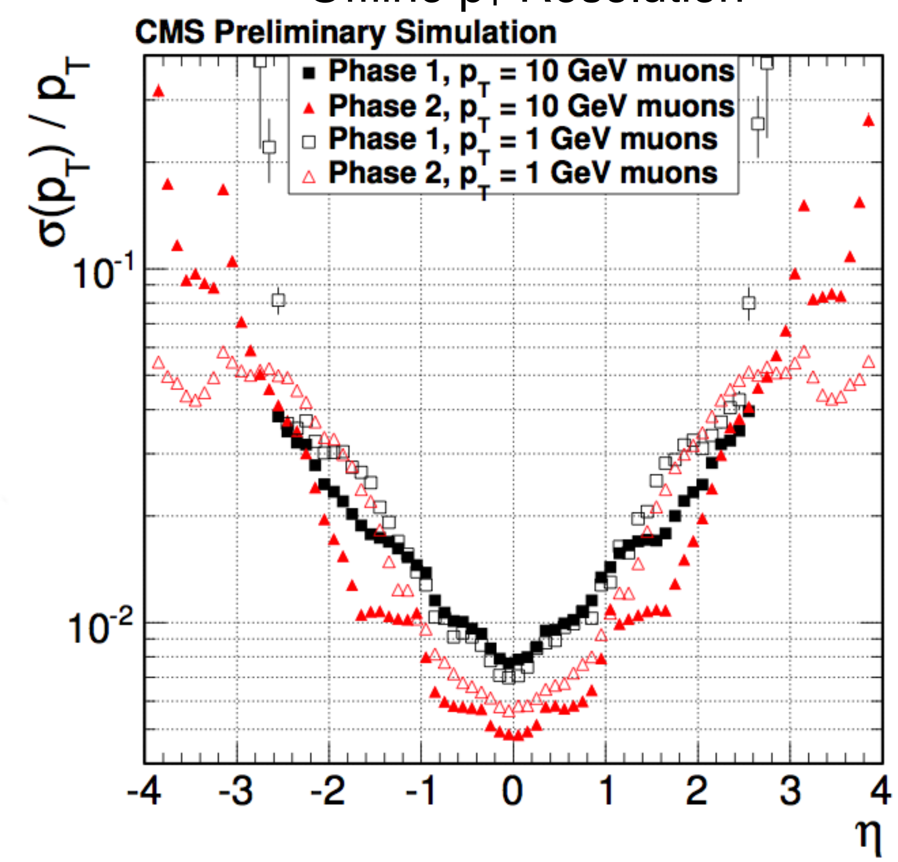
Offline Efficiency




Offline Tracking Fake




Offline $p_T$ Resolution




Track seed from pixel detector, seeds from $p_T$ modules not considered: **Improvements expected!**

# Summary

➡ **Phase-2 Tracker Key Features to Address Physics Challenges**

- $\eta$ coverage extended from 2.4 to ~4
- Transverse momentum resolution increased
- Level 1 tracking

➡ **Pixel Detector**

- Being defined, very challenging
- Pixel size under discussion
- Front-end development by RD53
- Radiation damage studies on sensors and electronics in progress
- Thin planar and 3D sensor submissions foreseen this year

➡ **Outer Tracker**

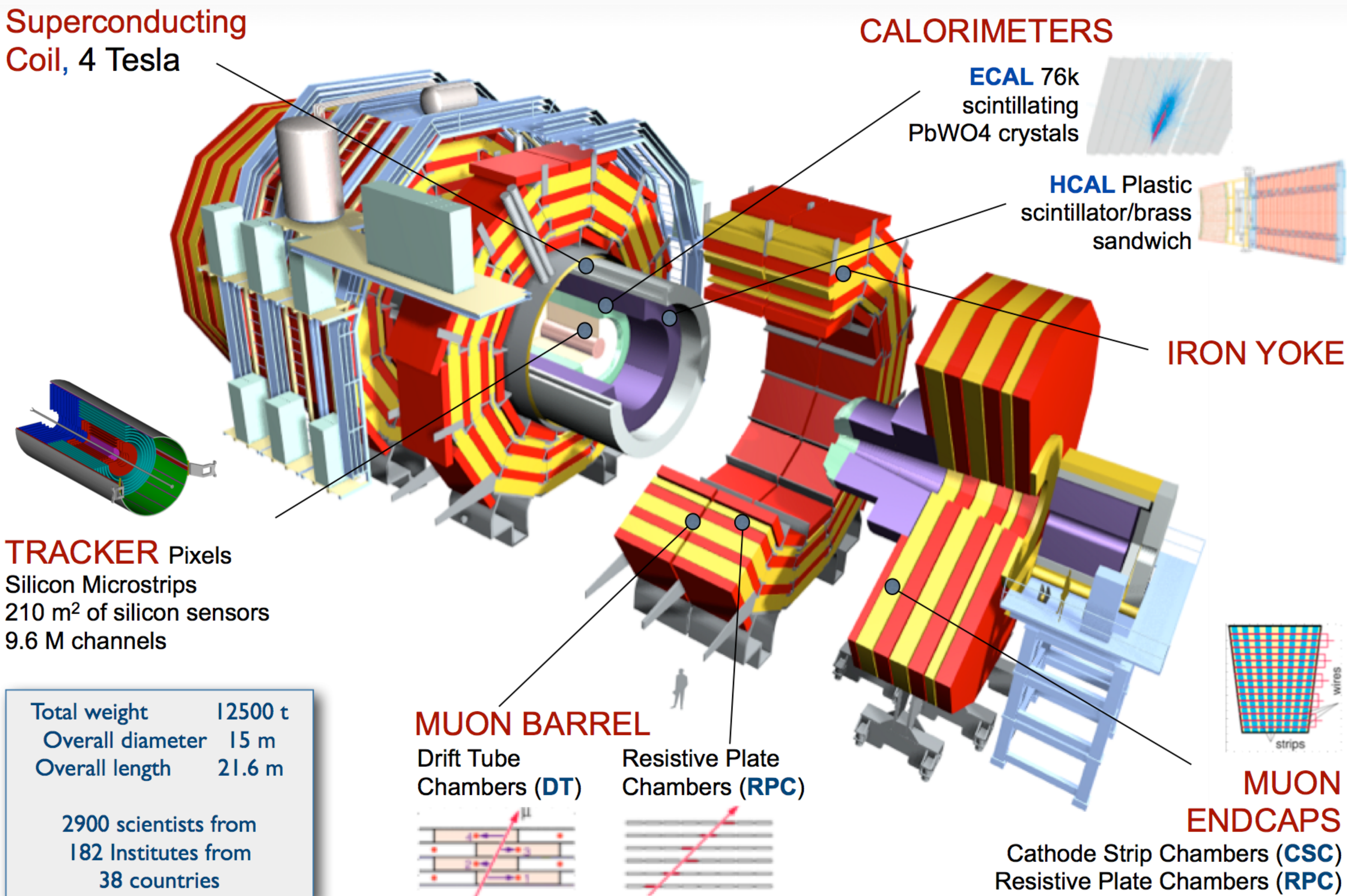
- Irradiated 2S prototypes at beam test in summer
- PS prototypes will be available soon
- Layout configuration almost defined; detailed simulations ongoing

➡ **Level 1 Tracking**

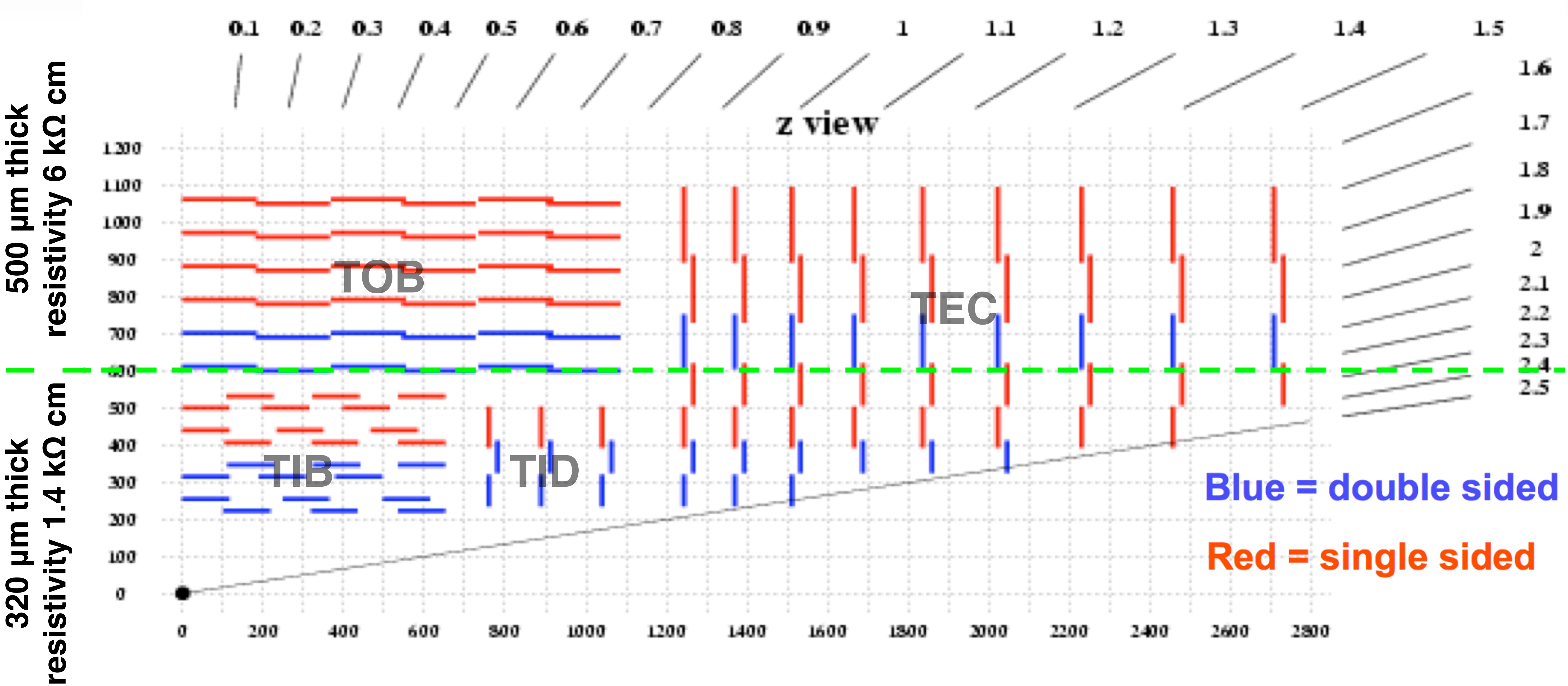
- 3 R&D strands:
  - Associative Memories
  - Time Multiplexed Trigger
  - Tracklet Algorithm
- Good efficiency and transverse momentum resolution obtained with simulations
- Hardware demonstrators under study

# Backup

# Compact Muon Solenoid



# Current Outer Tracker

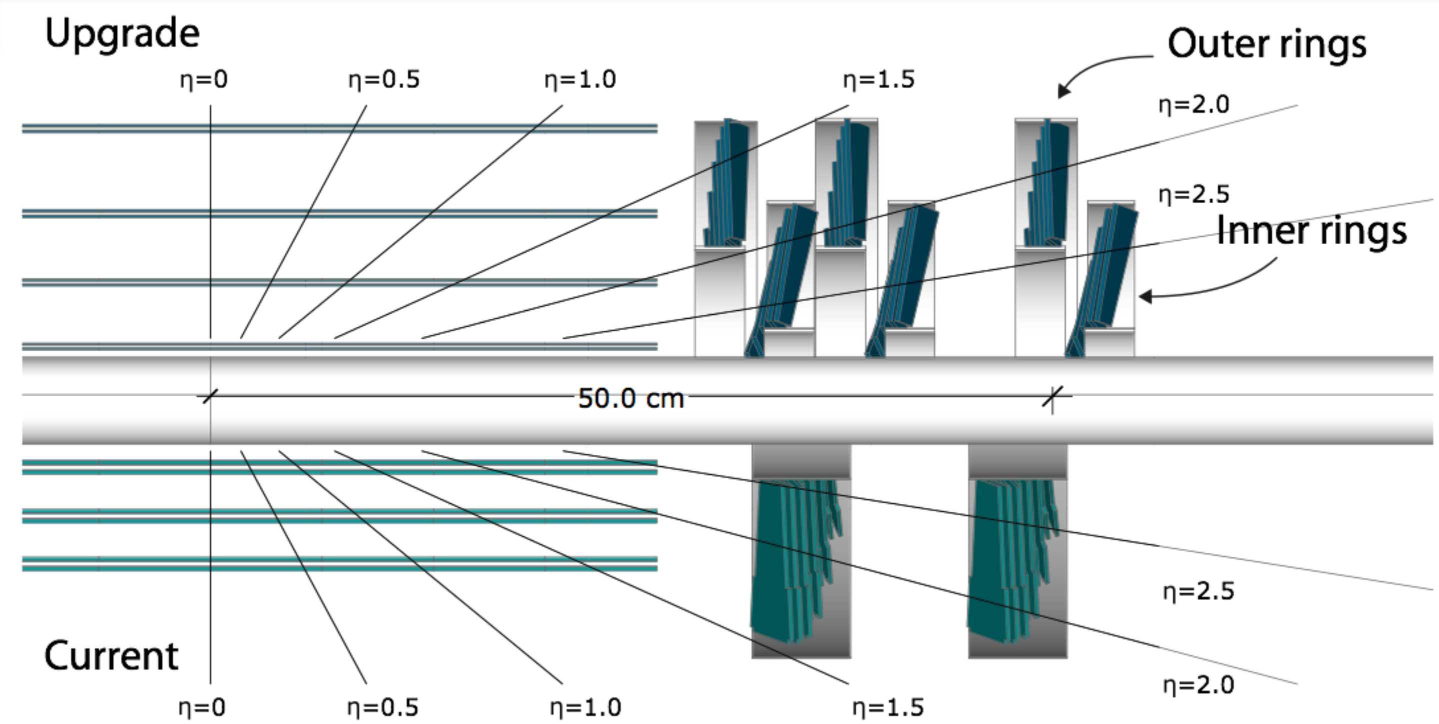


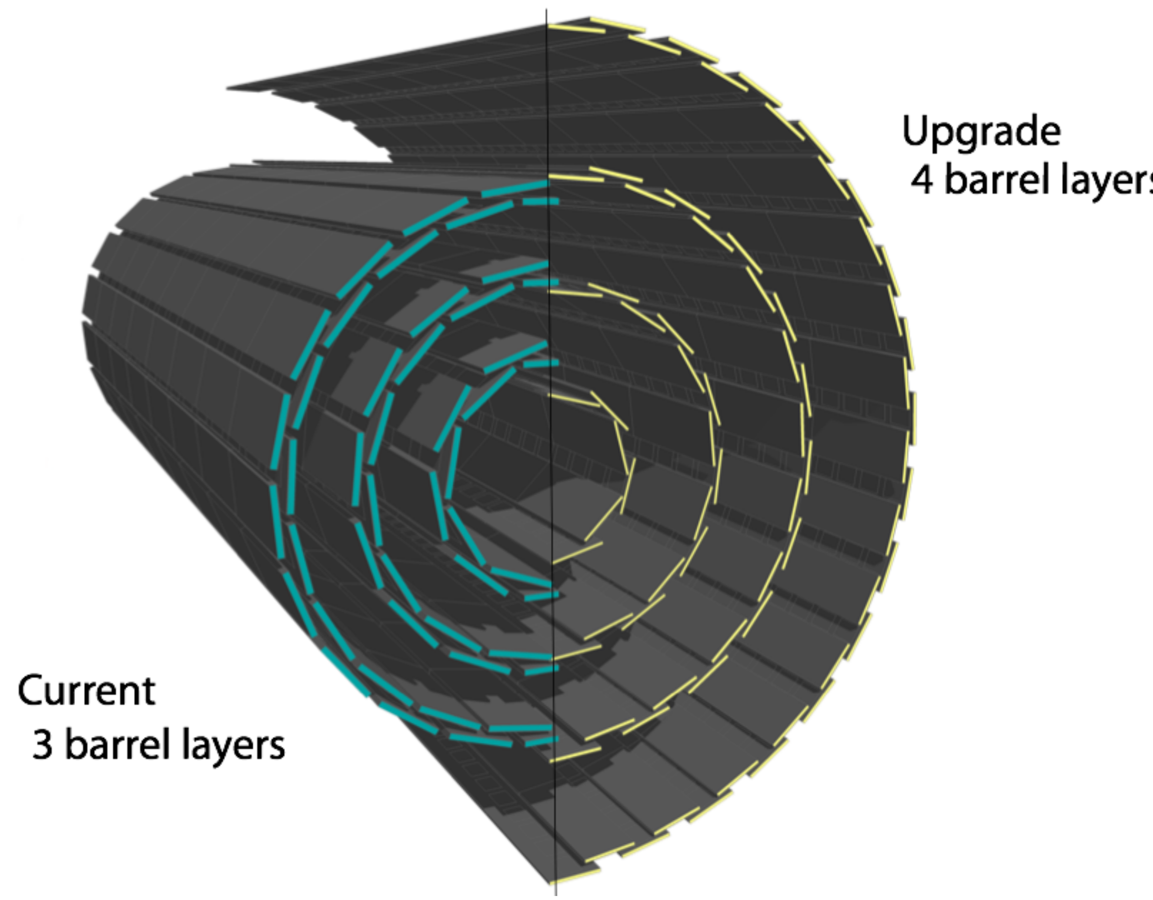

Volume: 24.4 $m^3$
Strip length 10 cm (innermost) to 20 cm (outermost)
Strip pitches 80 µm (innermost) to 205 µm (outermost)
Qualified up to $2.1 \times 10^{14}$ $n_{eq}/cm^2$

Readout chip:
APV25 (0.25 µm IBM CMOS)
128 Channels
Qualified up to 50 Mrad

# Phase-1 Pixel detector

- The Phase-1 pixel detector is an improved version of the current pixel detector
- 4 layer / 3+3 disks (100×150 μm$^2$, n-in-n): improved track resolution and efficiency
- New readout chip: reduced dynamic inefficiency at high rate and PU
- Reduced material: $CO_2$ cooling, new cabling and DC-DC powering scheme
- It will be installed during the 2016 Technical Stop; a pilot disk 3 blade is already installed for testing



# The LHC Timeline

| | LHC | | | | | HL-LHC | |
|---|---|---|---|---|---|---|---|
| | Run 1 | LS 1 | Run 2 | LS 2 | Run 3 | LS 3 | Run 4 |
| E | 7-8 | | 14 | | 14 | | 14 |
| L (cm | 7 x 10 | | 2 x 10 | | 2 x 10 | | 5 x 10 |
| PU | ~20-30 | | ~50 | | ~50 | | ~140 |
| ∫Ldt (fb | 30 | | 300 | | 300 | | 3000 |

| Phase-0 | | | | | | Phase-1 | | | | | | Phase-2 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| pas | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | future |

We are here

Installation of the **new CMS Phase-1 pixel detector**
during extended winter shut-down

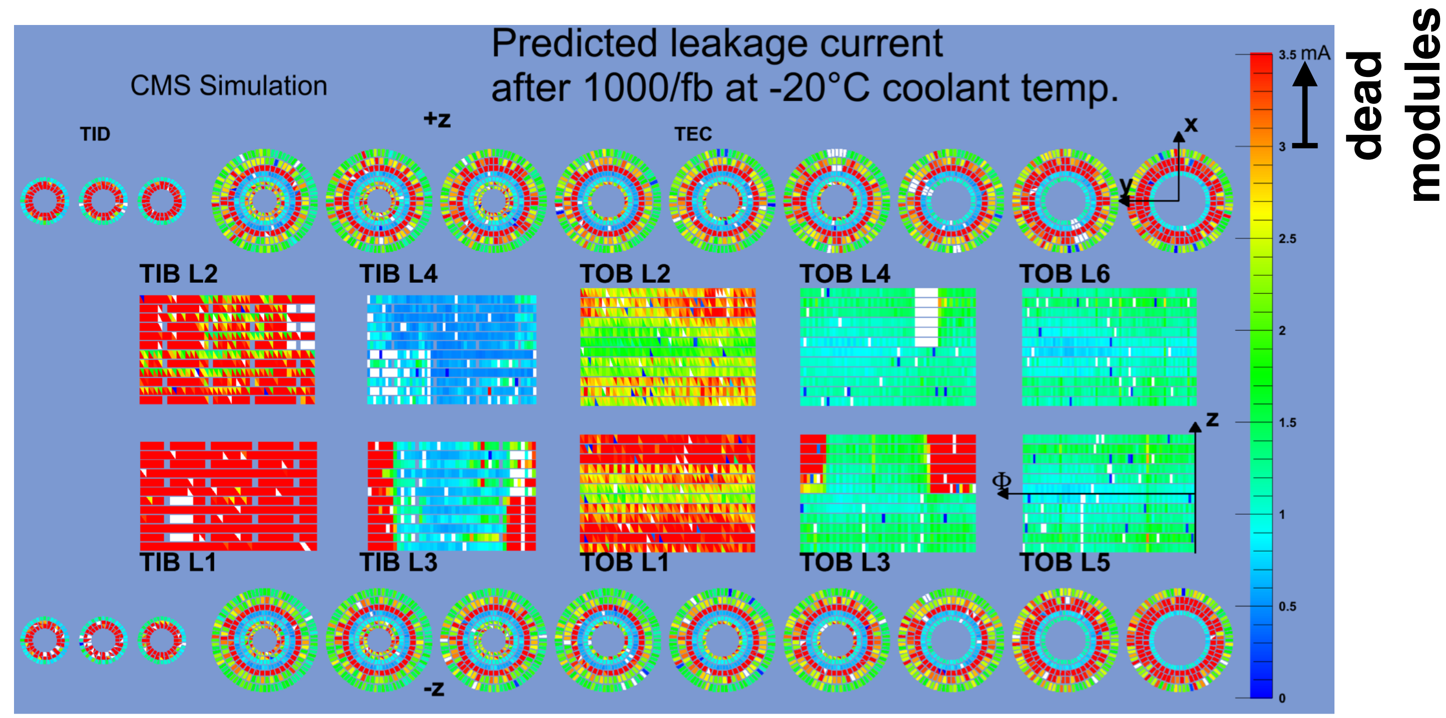
**HL-LHC environment:**

- Upgrade of low-β triplets and installation of crab-cavities to optimise bunch overlaps
- $L_{inst} = 5\text{x}10^{34}$ $cm^{-2}s^{-1}$ (~10 times Run 1) → $L_{tot}$ ~ 3000 $fb^{-1}$ in 10 years
- Bunch crossing (BX) 25 ns (double BX rate of Run 1)
- Pile Up (PU) ~140 (~6 times Run 1)

# Limitation of the Current Tracker

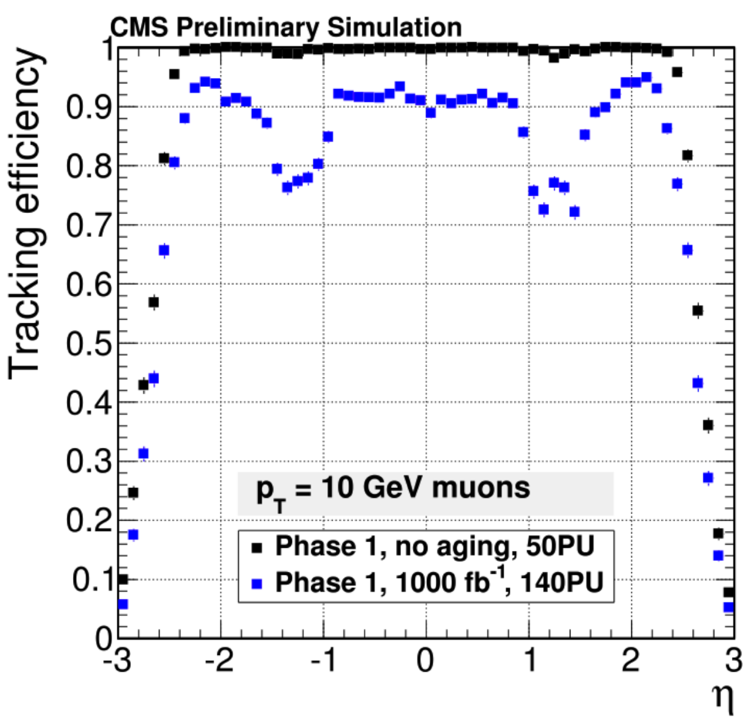
**Phase-2 pixel tracker requirements with respect to the Phase-1**

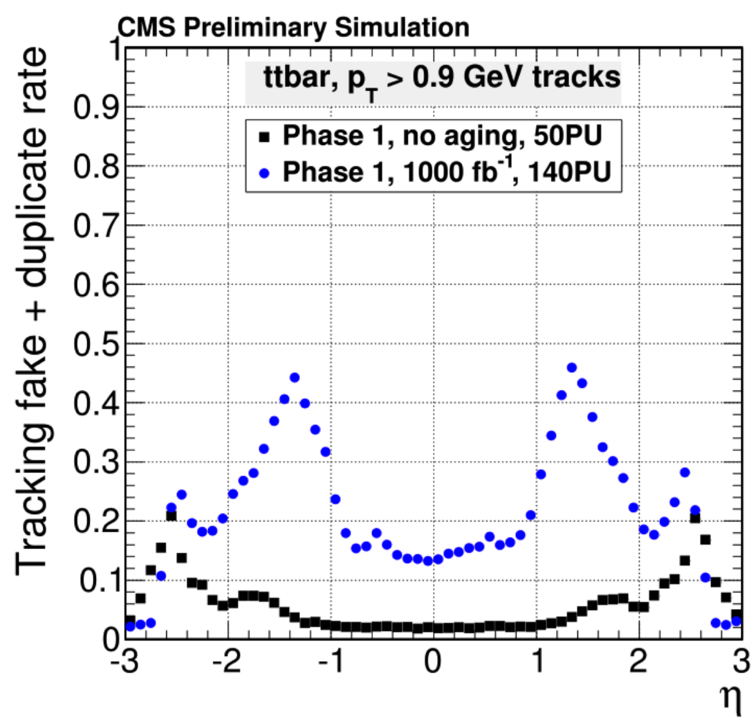
- Hit rate ~5 times larger
- Radiation dose ~3 times larger
- Radiation fluence ~10 times larger




**Phase-2 outer tracker requirements with respect to the Phase-1**

- Radiation dose ~6 times larger
- Trigger information needed

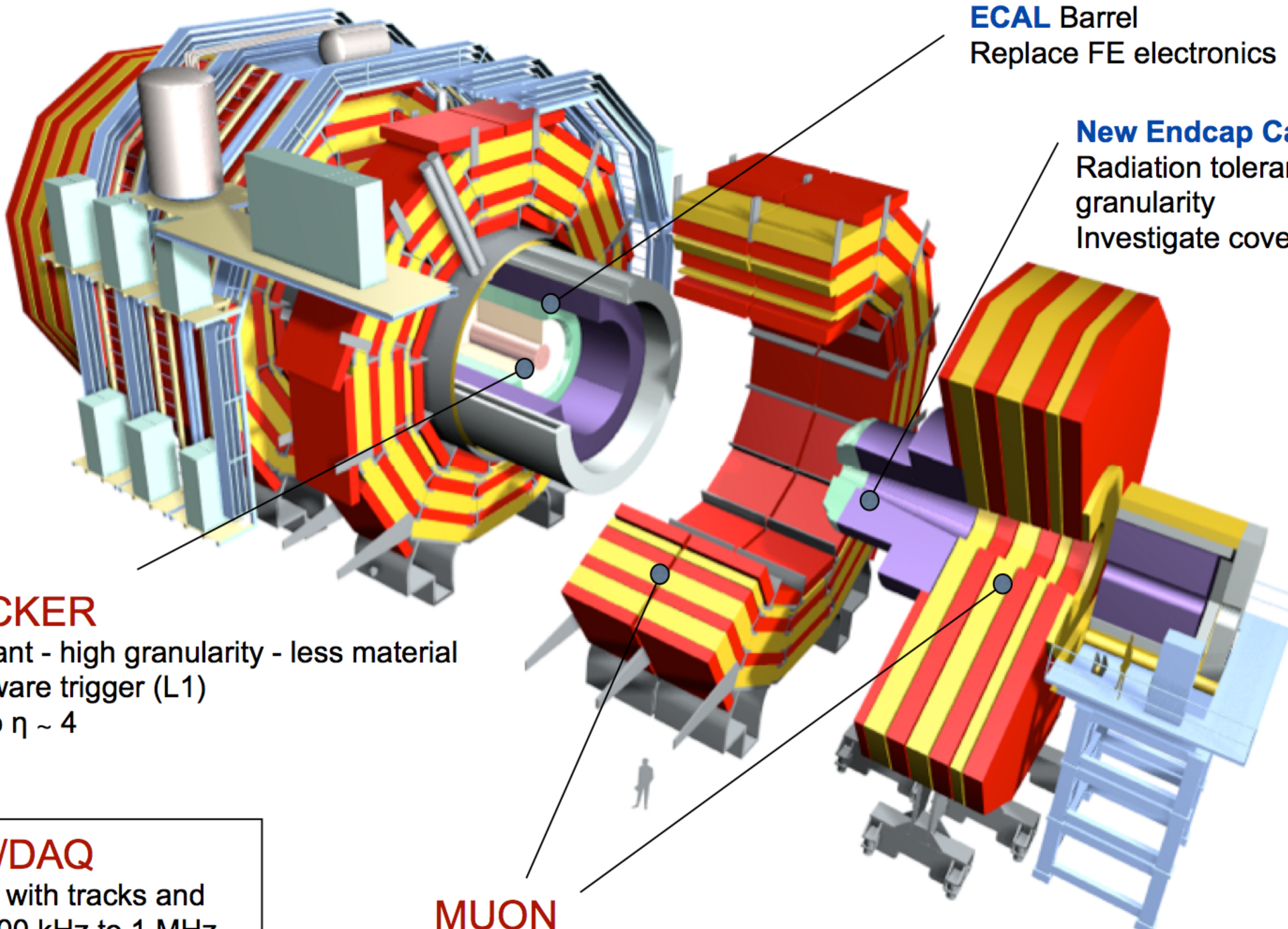



**Tracking degradation:**

- Impact parameter degradation > 50% after 500 fb$^{-1}$
- Data loss of ~7% at PU = 140
- Muon and calorimeter-based Level 1 (L1) trigger will not withstand the rates due to Pile-Up (PU) and limited resolution

# HL-LHC CMS Upgrade



**CALORIMETERS**

**ECAL** Barrel
Replace FE electronics

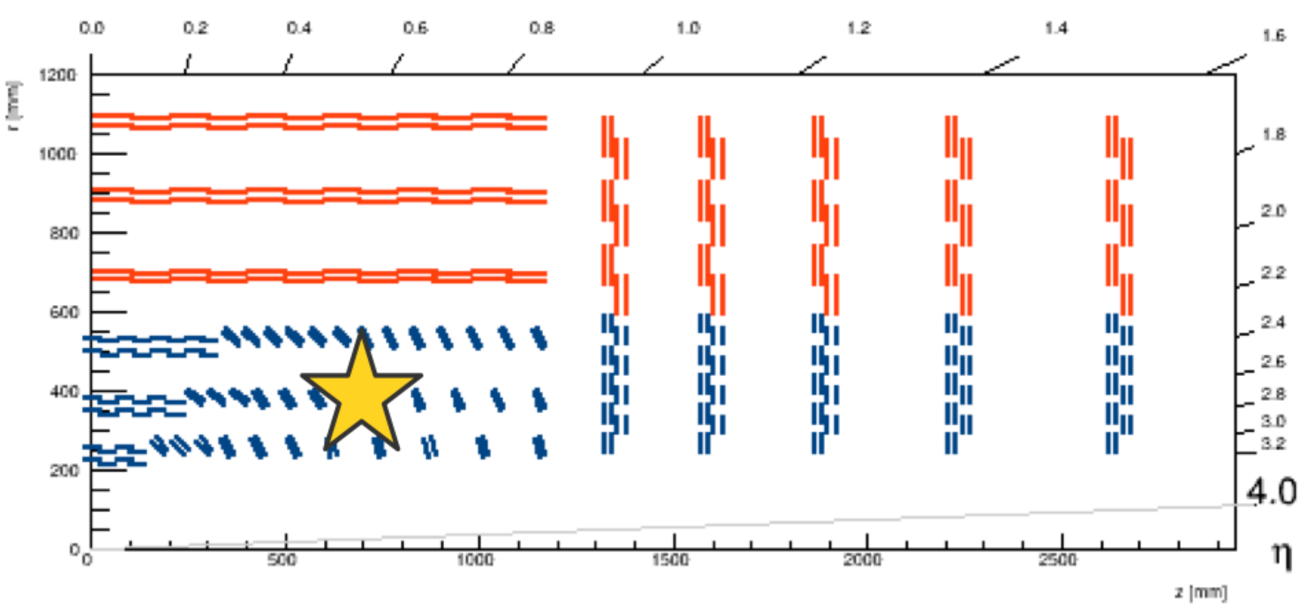
**New Endcap Calorimeters**
Radiation tolerant - high granularity
Investigate coverage up to η ~ 4

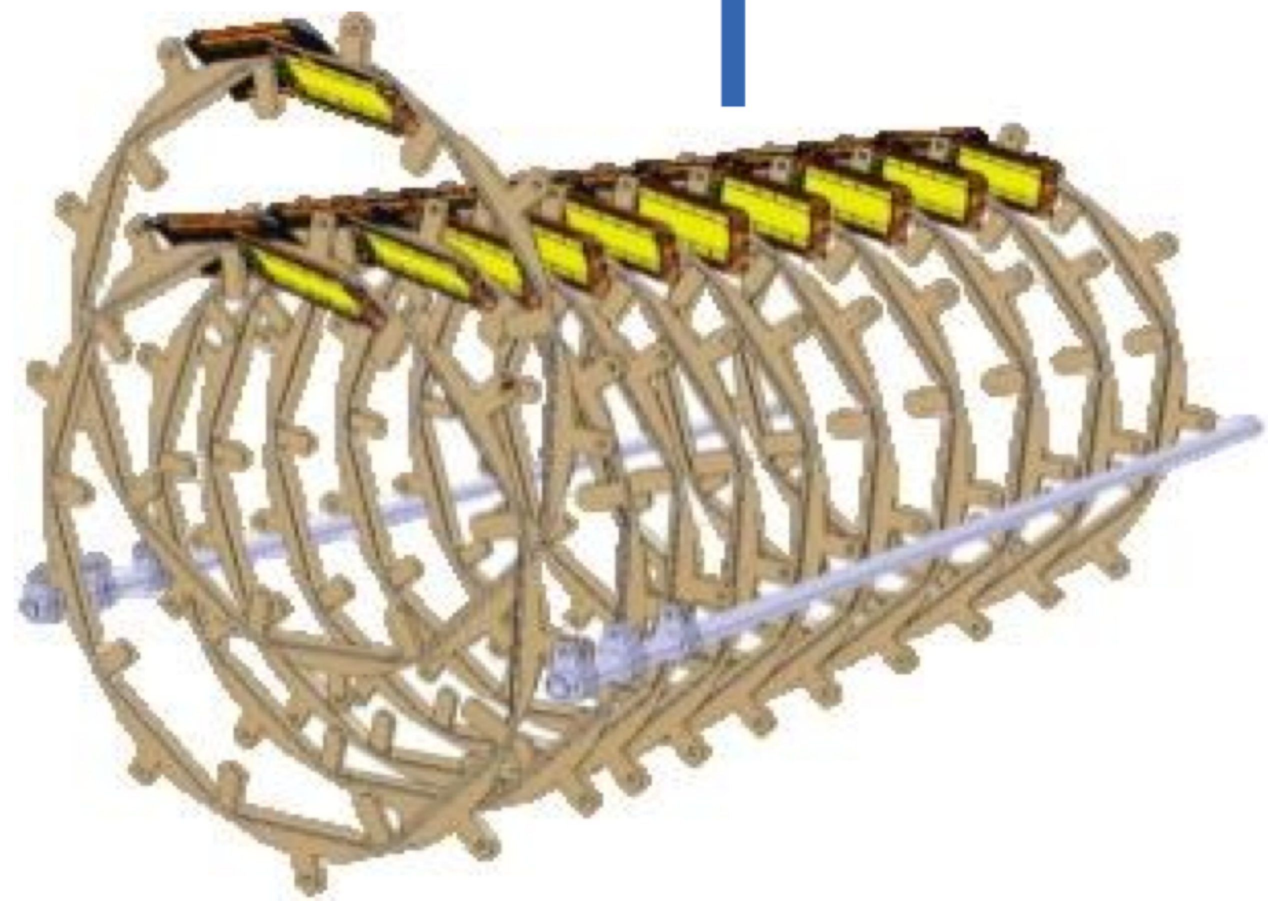
**NEW TRACKER**
Radiation tolerant - high granularity - less material
Tracks in hardware trigger (L1)
Coverage up to η ~ 4

**TRIGGER/DAQ**
L1 (hardware) with tracks and rate up ~ 500 kHz to 1 MHz
Latency ≥ 10 μs
HLT output up to 10 kHz

**MUON**
Replace DT FE electronics
Complete RPC coverage in forward region (new GEM/RPC technology)
Investigate Muon-tagging up to η ~ 4

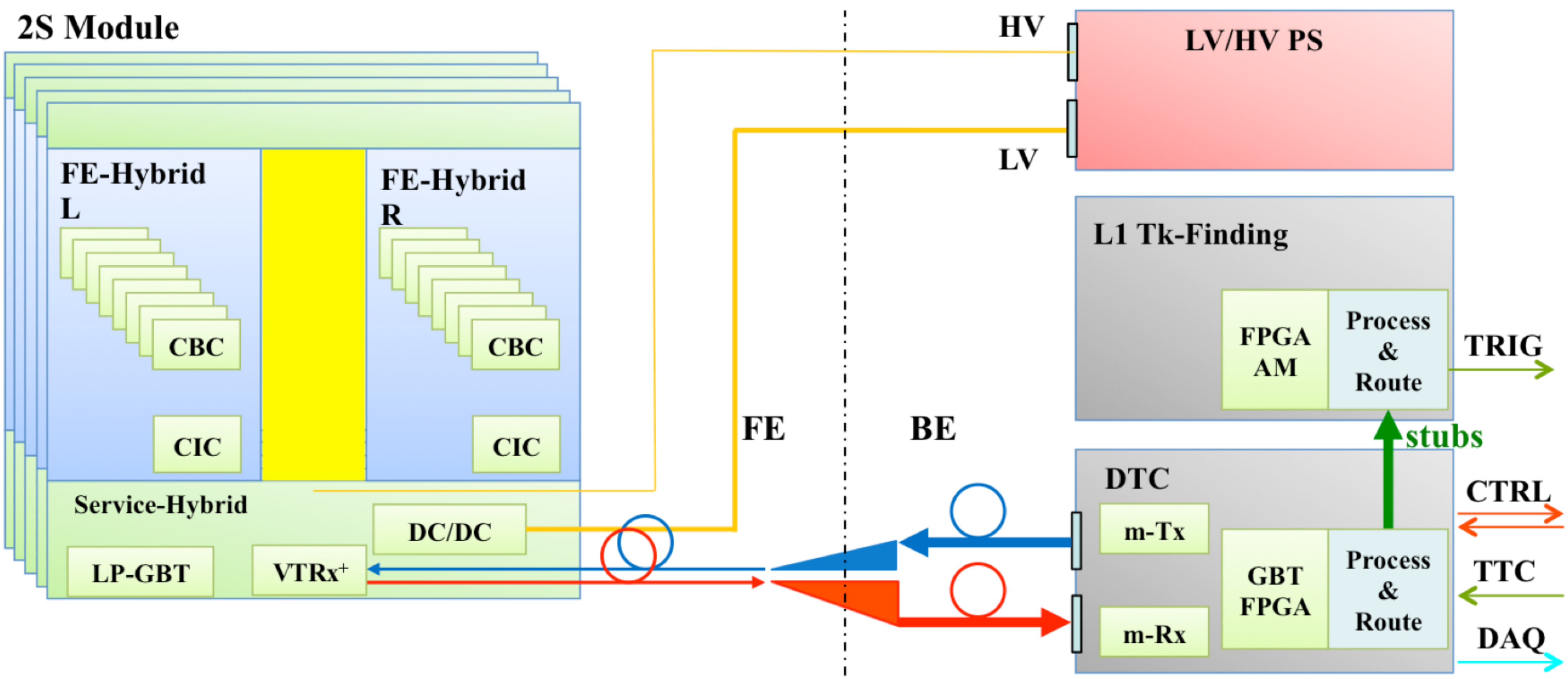
# Alternative Outer Tracker Layout



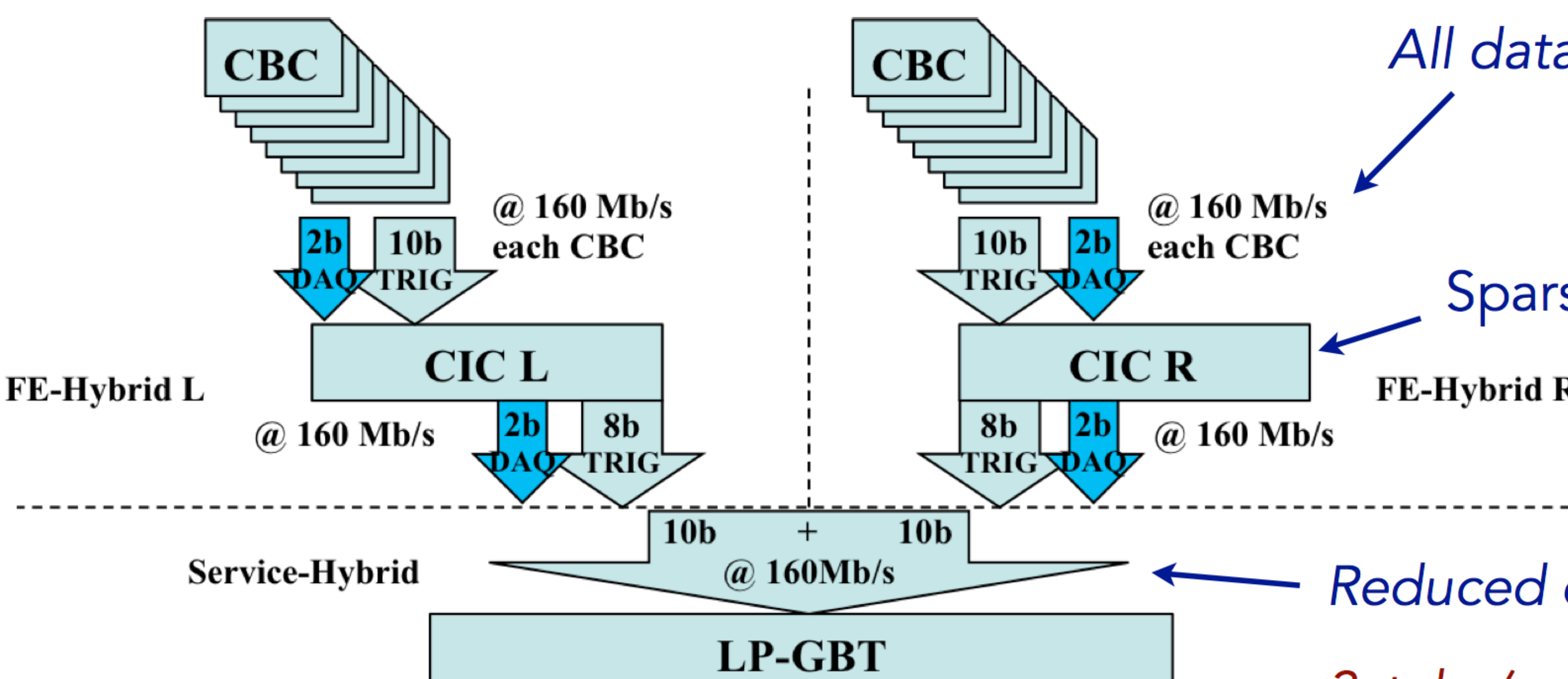



# DAQ Concept

**Low/High Voltage Power Supply**




**Data Trigger & Control**
µTCA board




*All data*

*Sparsification*

*Reduced data*

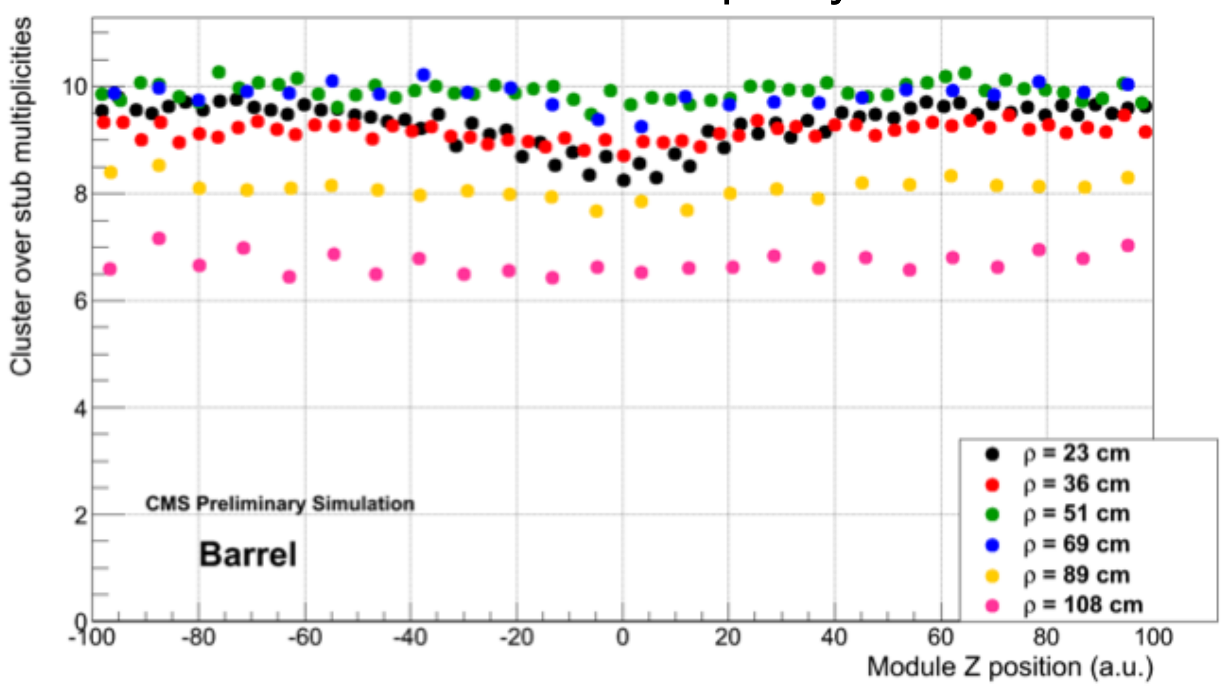
*~<3stubs/mod/BX>*

TRIG: (stubs) [40MHz]

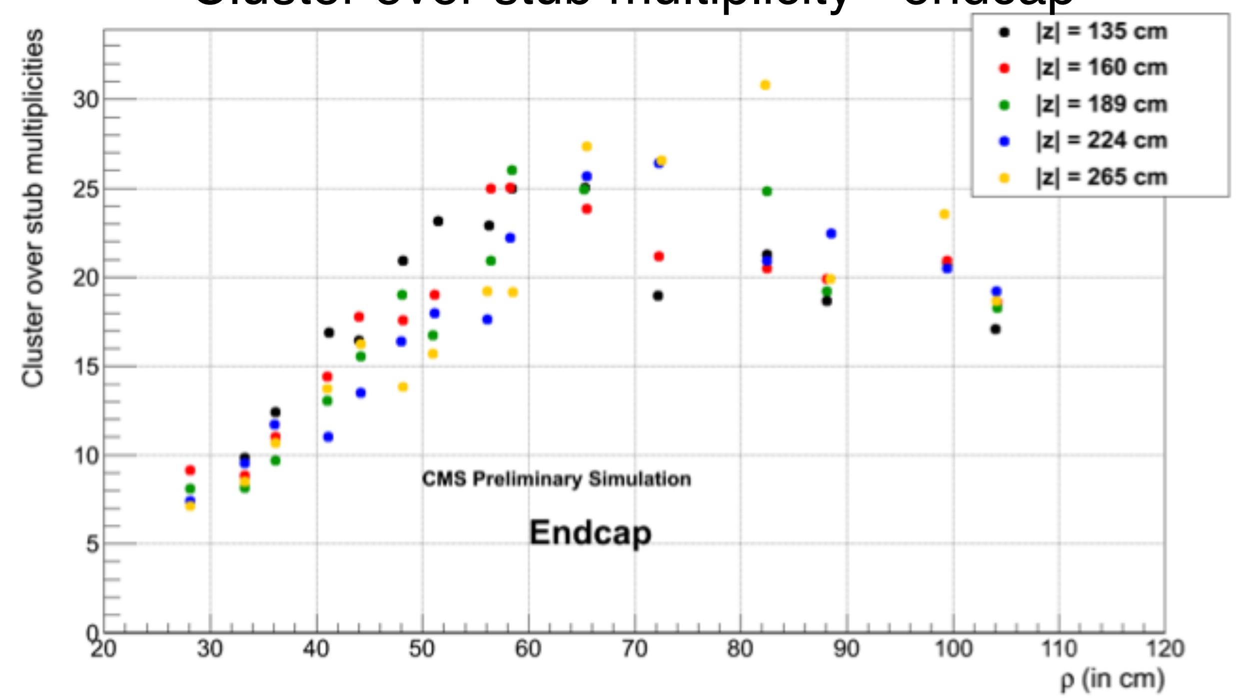
DAQ:full data [500kHz-1MHz]

# Stub Rate

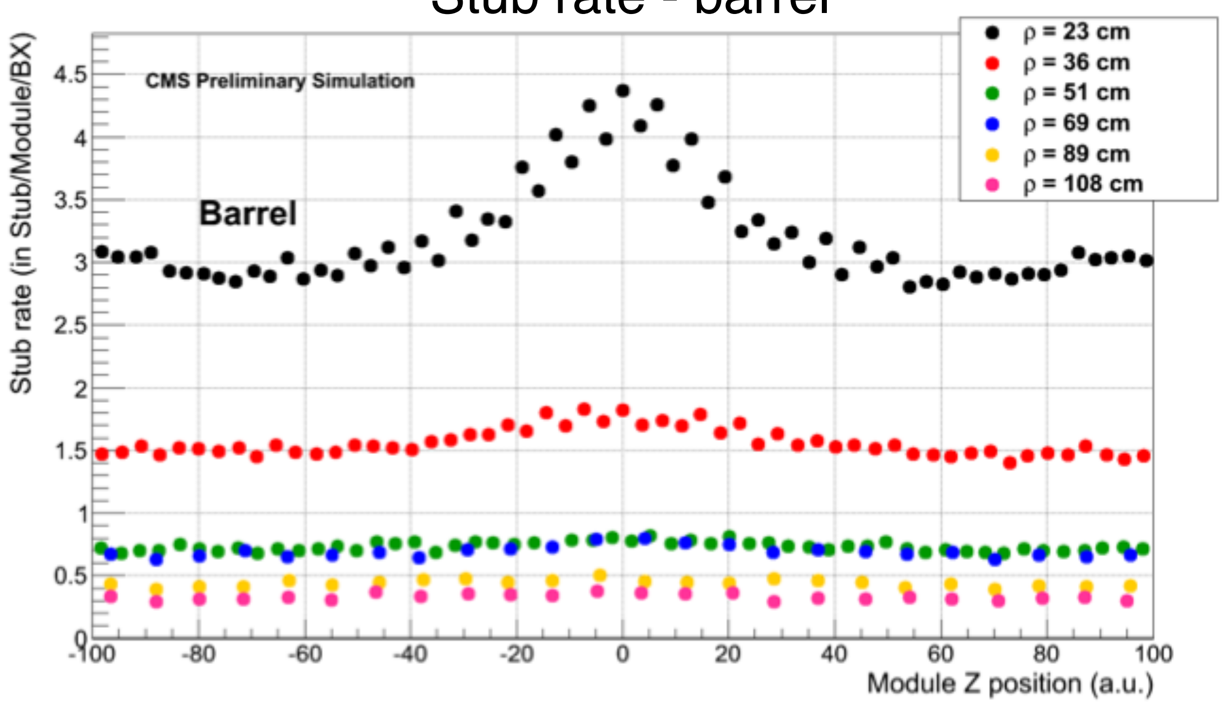
## Cluster over stub multiplicity - barrel



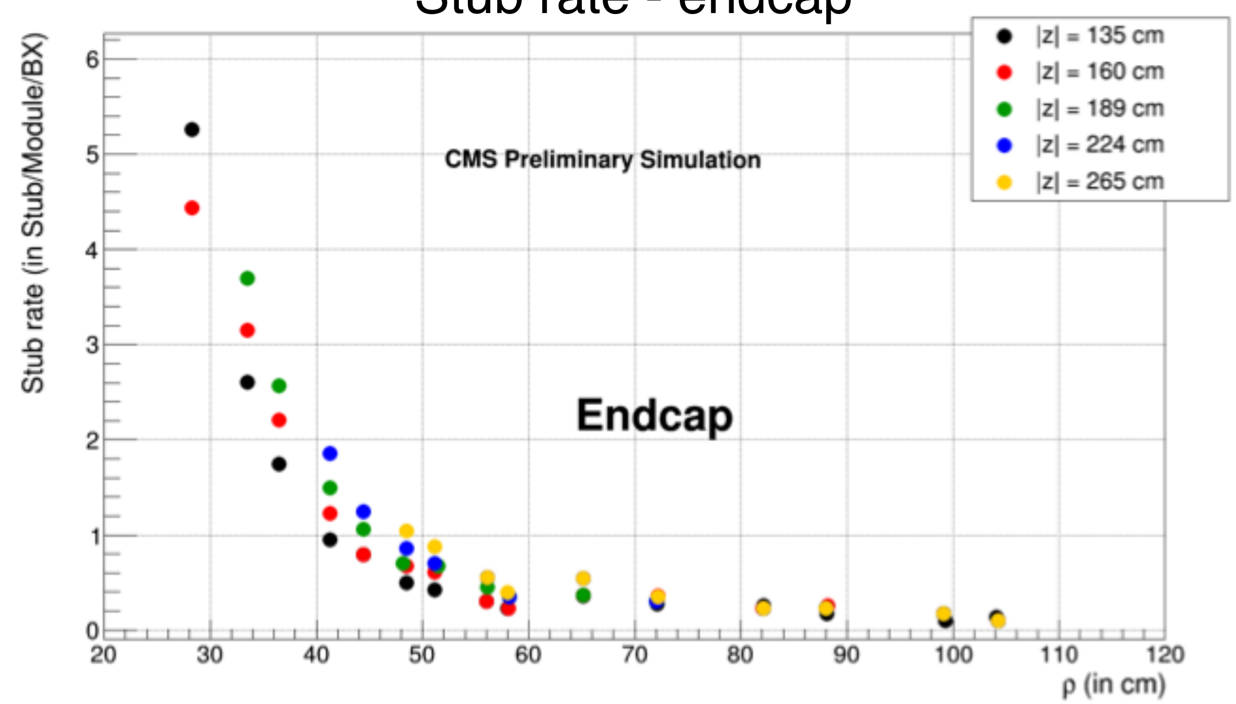

## Cluster over stub multiplicity - endcap




## Stub rate - barrel

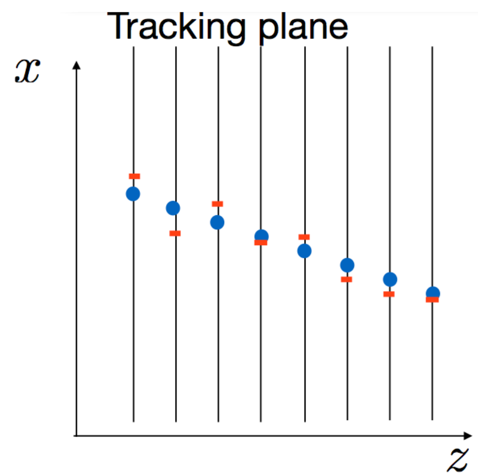



## Stub rate - endcap



# L1 Track Fitting

## RETINA




$s_{ijk}$ distance between cluster in layer $k$ and track receptor $i,j$

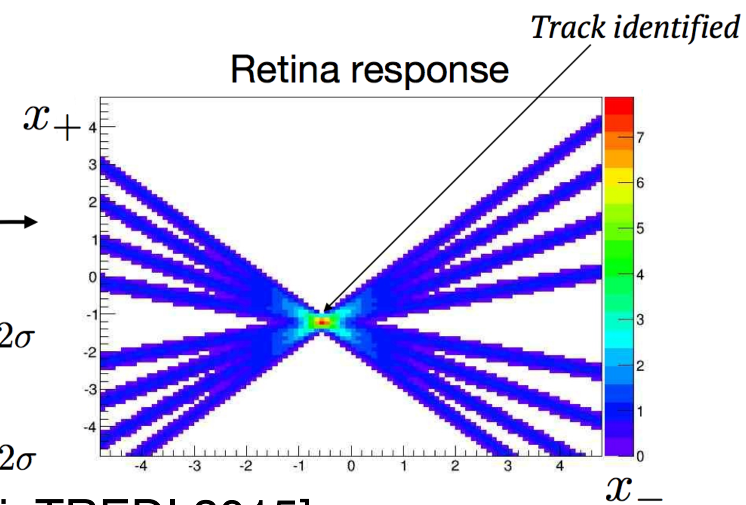
$$s_{ijk} = \left| x_k - x_{j+} - x_{i-}\frac{z_k - z_+}{z_-} \right|$$

- cluster of hits
- track receptors $i,j$

Excitation of the cellular unit i,j

$$W_{ij} = \sum_k \exp\left(-\frac{s_{ijk}^2}{2\sigma^2}\right) \quad \text{if } s_{ijk} < 2\sigma$$

$$W_{ij} = 0 \quad \text{if } s_{ijk} > 2\sigma$$



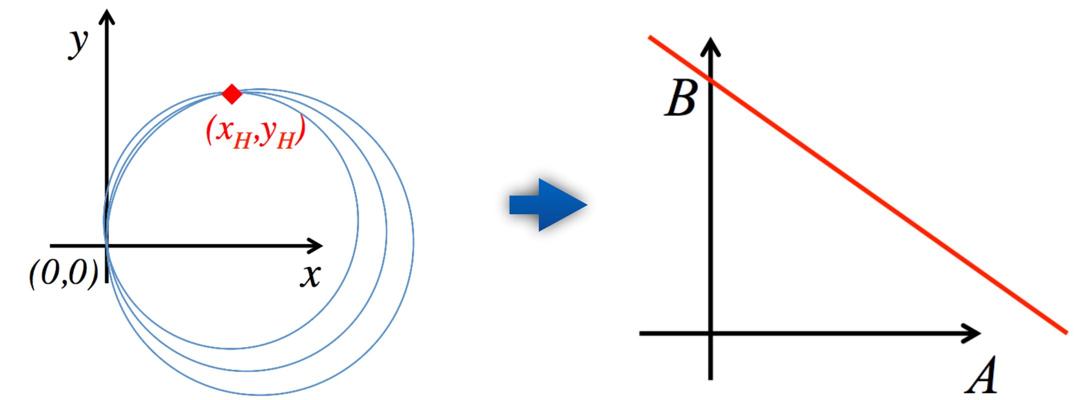

[Nicola Neri, TREDI 2015]

## Principal Component Analysis (PCA)

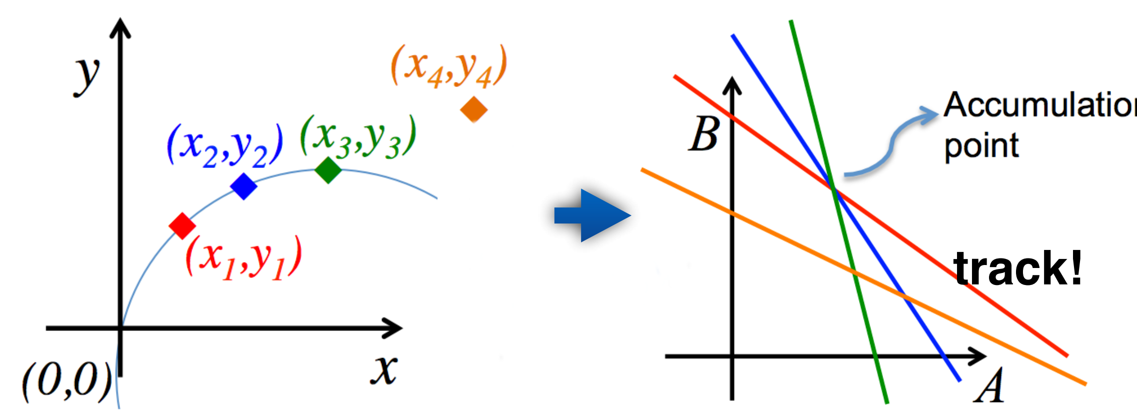
Orthogonal linear transformation of variables in a new cartesian coordinate system in which variable with maximum variance is projected on the first axis, second maximum variance on second axis and so on. Algorithm can be implemented efficiently on FPGA.

## Hough transformation

In a real space there are ∞ circle passing by a points and the axis origin. Circle center lies on a straight line in the Hough Space.




Hits lying on a circle will correspond to lines meeting at the same point in the Hough Space



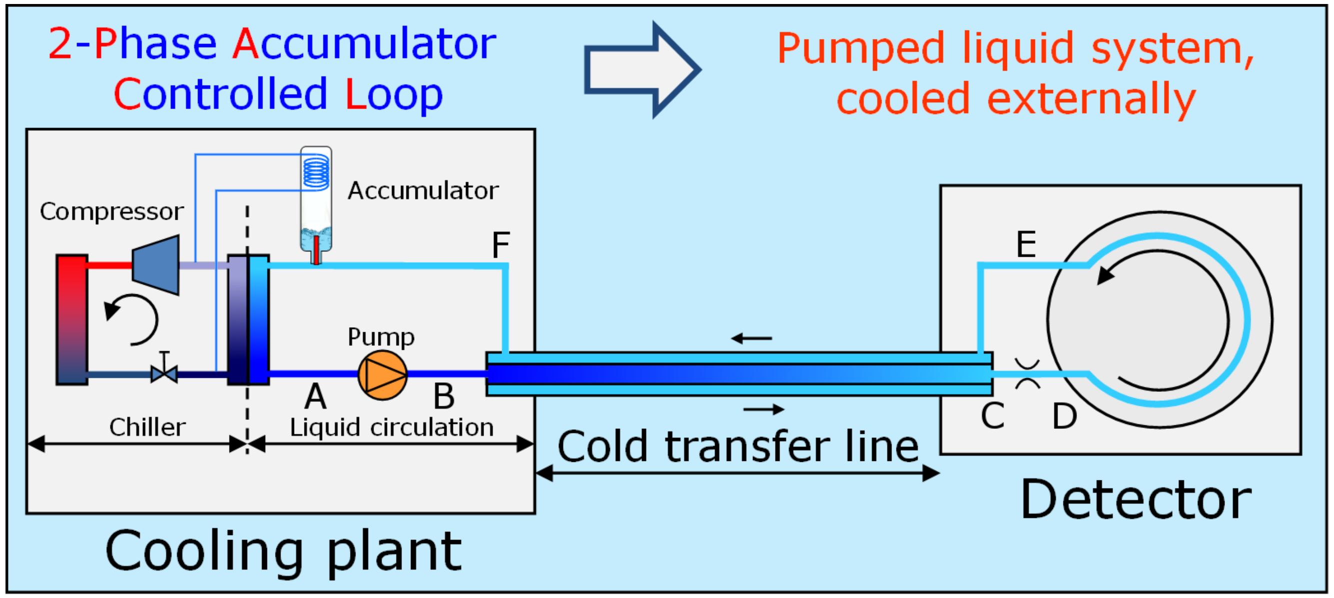
# $CO_2$ Cooling

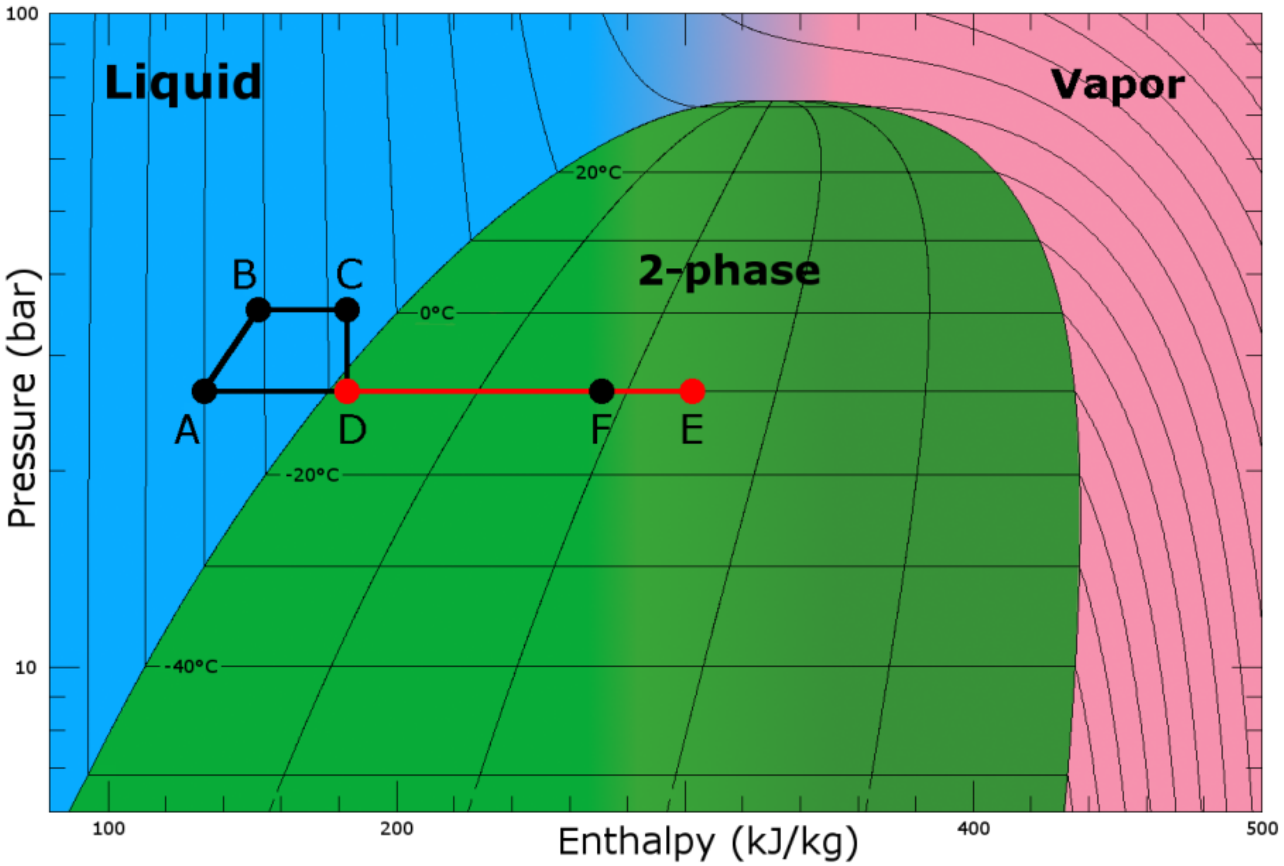
Advantages of $CO_2$:

- Large latent heat
- Low viscosity
- Very small pipes → Low mass
- Cheaper than fluorocarbon refrigerant
- Low impact on environment

$CO_2$ cooling foreseen for Phase-1 upgrade
The technology in principle allows scaling to full tracker (between 5× and 10× w.r.t. pixel)

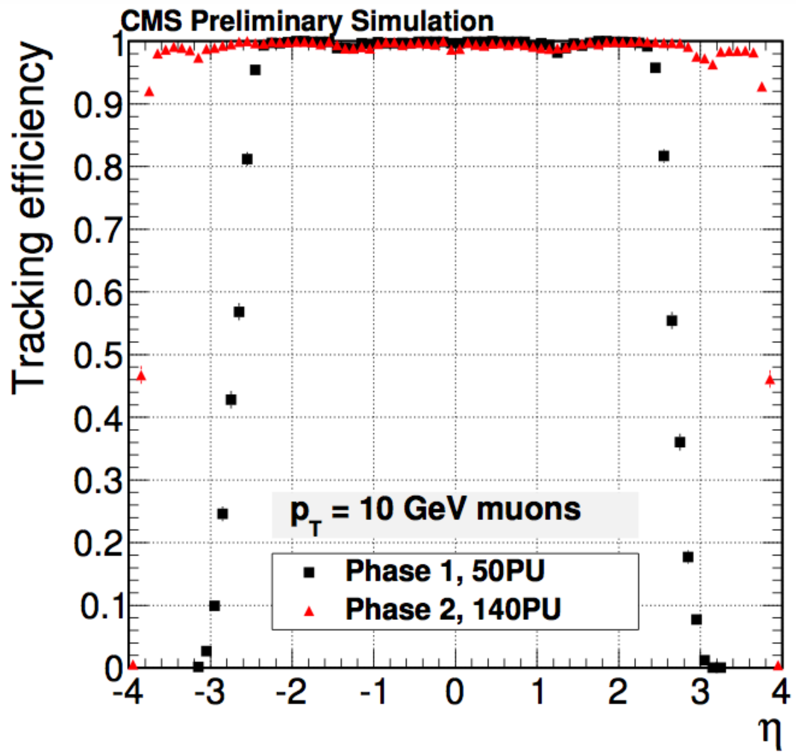
**2-phase evaporating cooling concept**



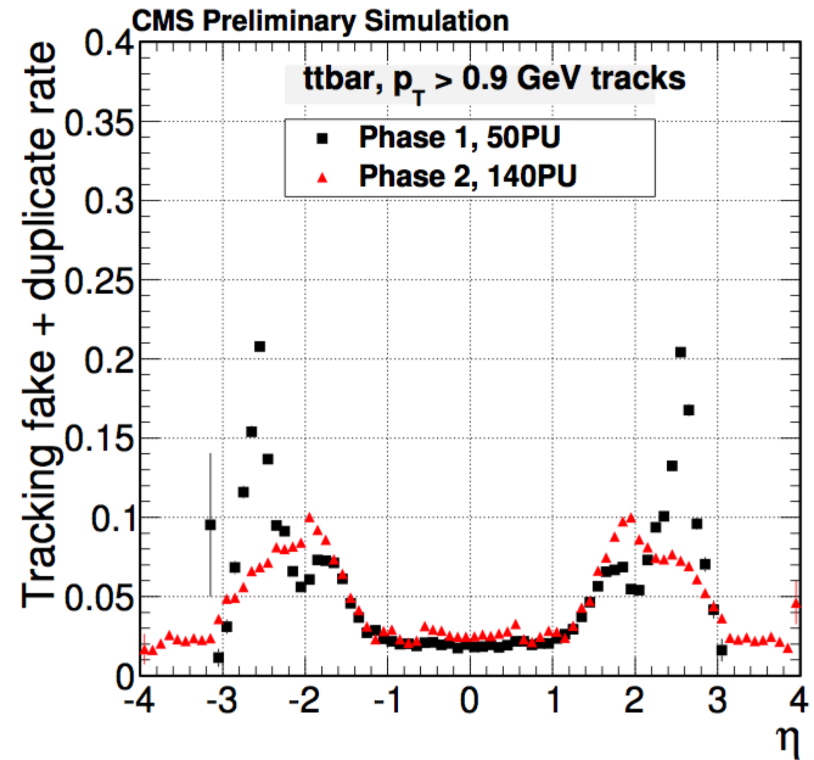



# Phase-2 Tracker Performances

### Offline Efficiency



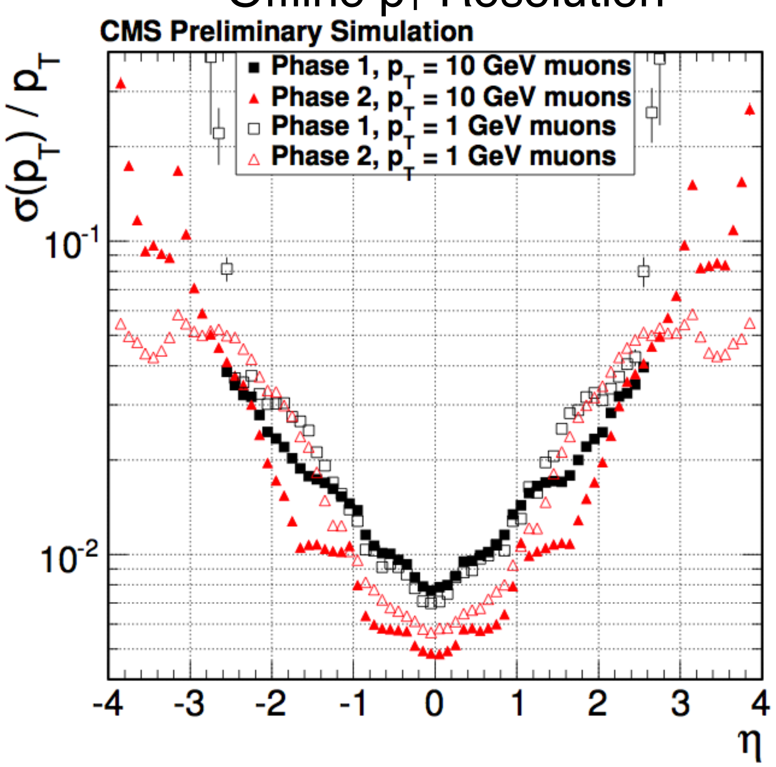

### Offline Tracking Fake



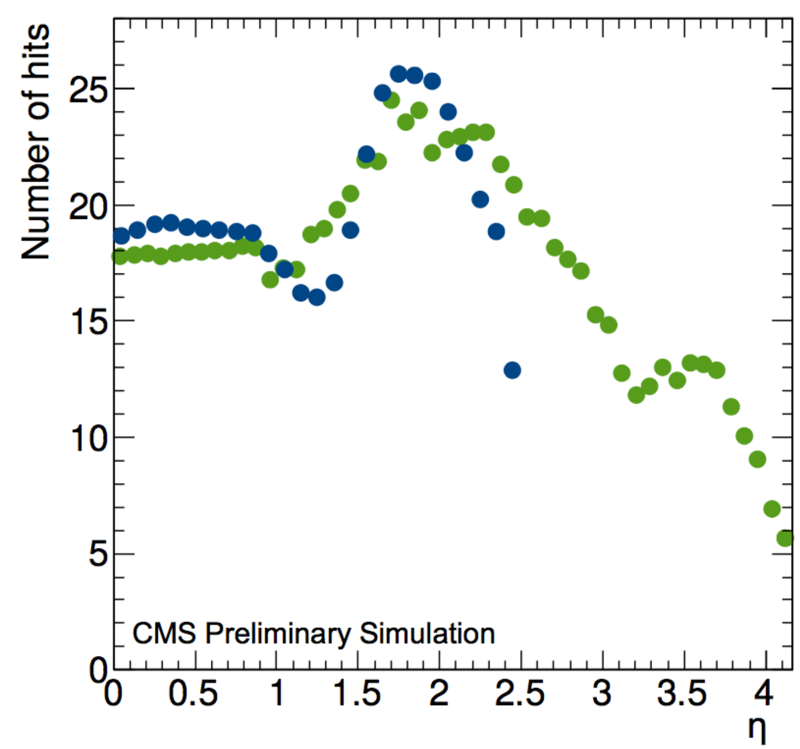

Obtained with the **Phase-1 CMS track reconstruction**: Track seed from pixel detector, seeds from $p_T$ modules not considered: **Improvements expected!**

CMS Phase-1
CMS Phase-2

### Offline $p_T$ Resolution




### Number of hits in full readout




### Material budget