Part I

Intelligent Trackers for Triggers

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III Seminario Nazionale Rivelatori Innovativi
Florence, 4-8 June 2012

Summary

- Why to build "intelligent" trackers
- General principles and architectures
- Local data reduction with embedded intelligence
- Pattern recognition techniques
- Prospects

Disclaimer

- Most of the lecture on ATLAS+CMS approaches
- No time to deal with
  - sensor technology
  - power and cooling
  - fast data-links
  - GPU's

https://indico.cern.ch/conferenceDisplay.py?confId=154525

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WIT2012 Workshop on Intelligent Trackers

3-5 May 2012 *INFN Pisa*
Europe/Paris timezone

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With the increasing capabilities of microelectronic technology, future particle detectors will be able to yield high level features that are not only simple geometrical positions or energy measurements in the sensors used. The ability to compute such high level primitives in near real-time is what we characterize as “intelligence”.

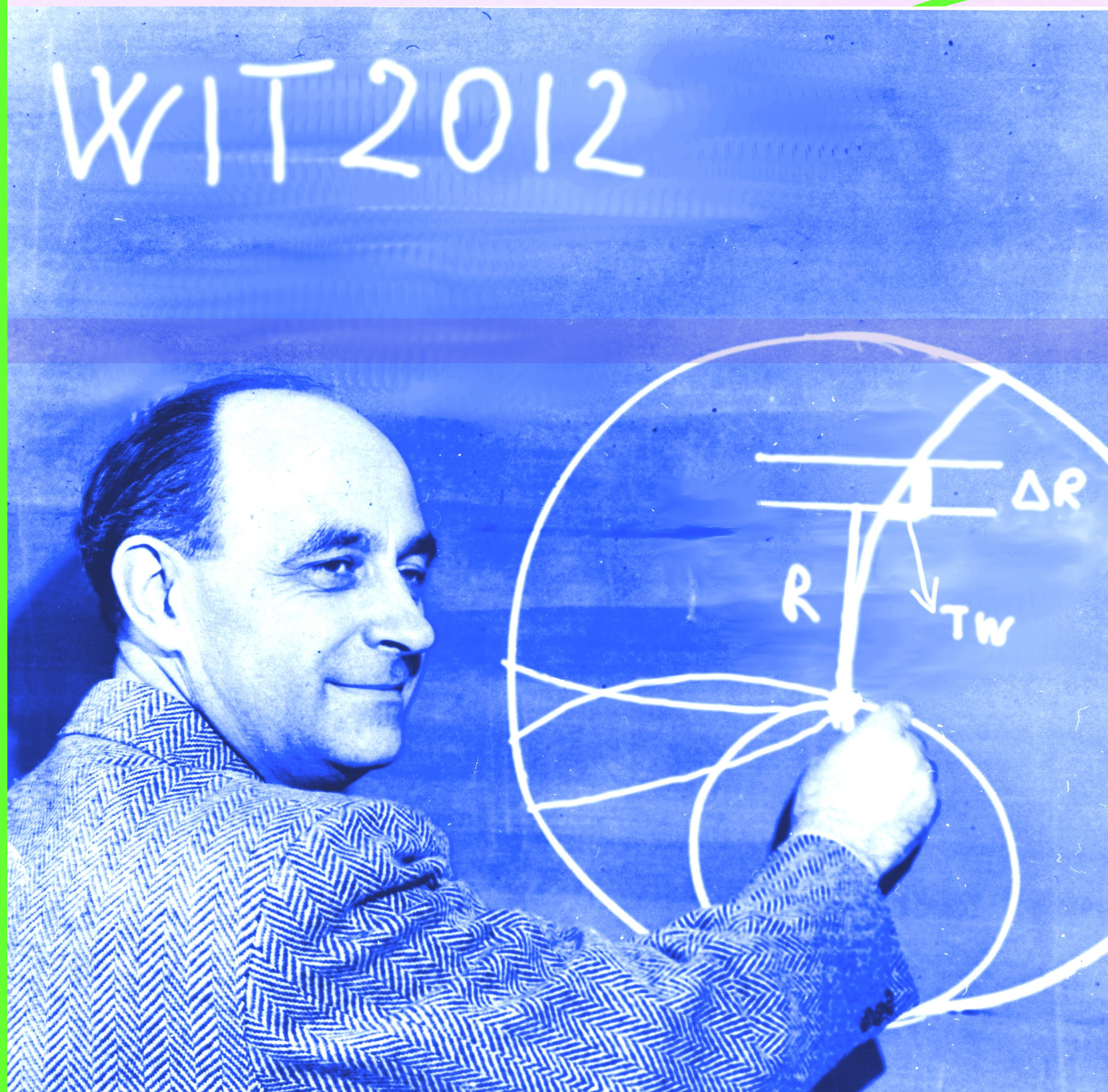
This will enable the construction of detectors with novel functionalities, allowing the trigger logic or even the off-line analysis in experiments to handle immediately more complex features of the measurements. Two examples of new primitives are near real-time charged particle direction or charge clusters without pixel boundary effects. But the addition of such intelligence has practical challenges and in particular system issues must be addressed, such as material budget and power density.

This Workshop would provide a discussion forum for the community of scientists and engineers working on development of intelligent devices.

The objectives of the workshop will be to enhance the cross breeding of ideas, to compare concepts for incorporating intelligence in particle trackers, and to explore possibilities for application to other areas.

The format of the workshop is on plenary sessions, for a duration of 2.5 days.

~50 people - 80% speakers, lively discussions



2nd Workshop on Intelligent Trackers

Pisa, 3 - 5 May 2012

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L. Lilli, A. Messineo, F. Palla

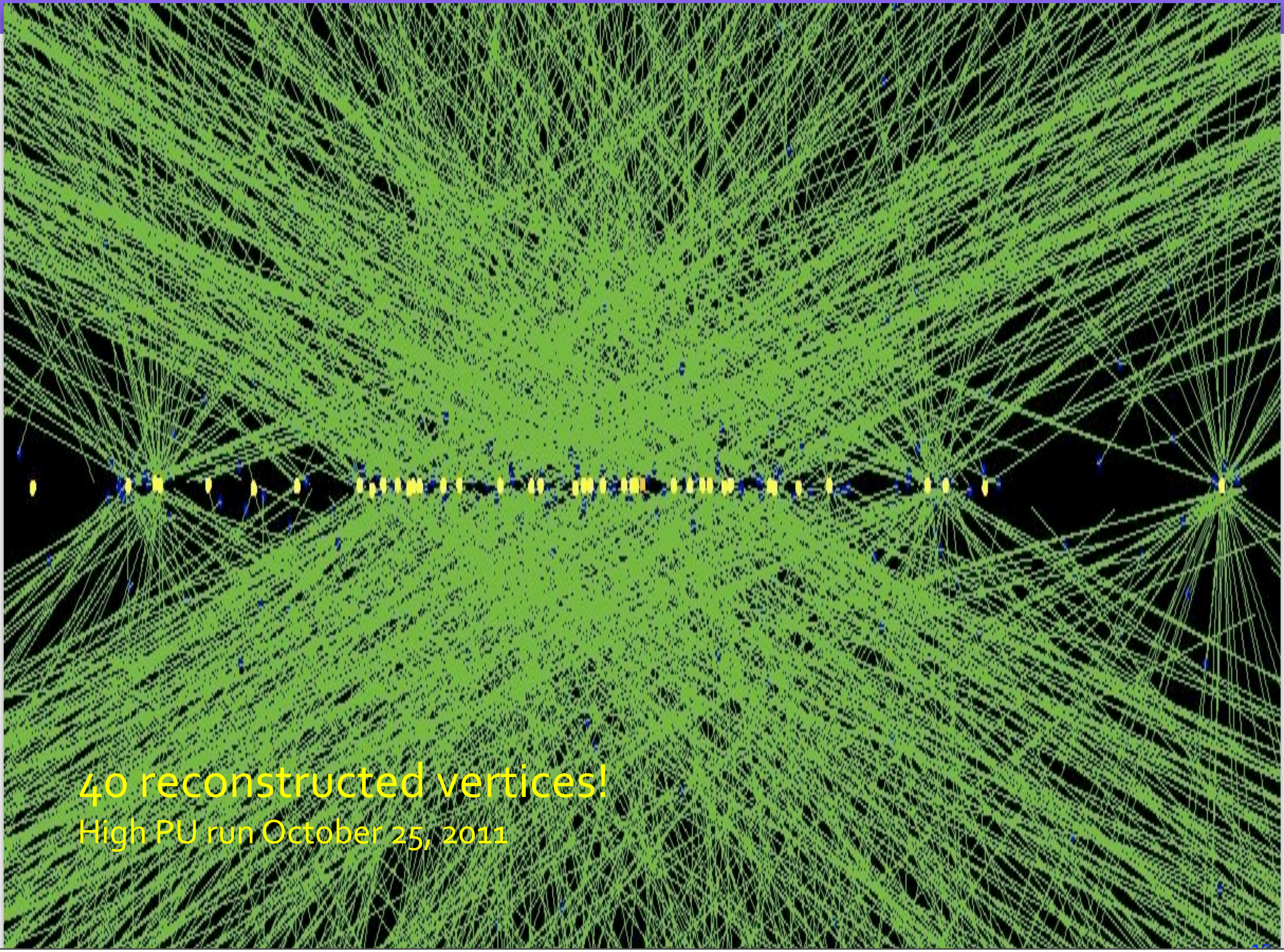
INFN Istituto Nazionale di Fisica Nucleare

F. Ligabue

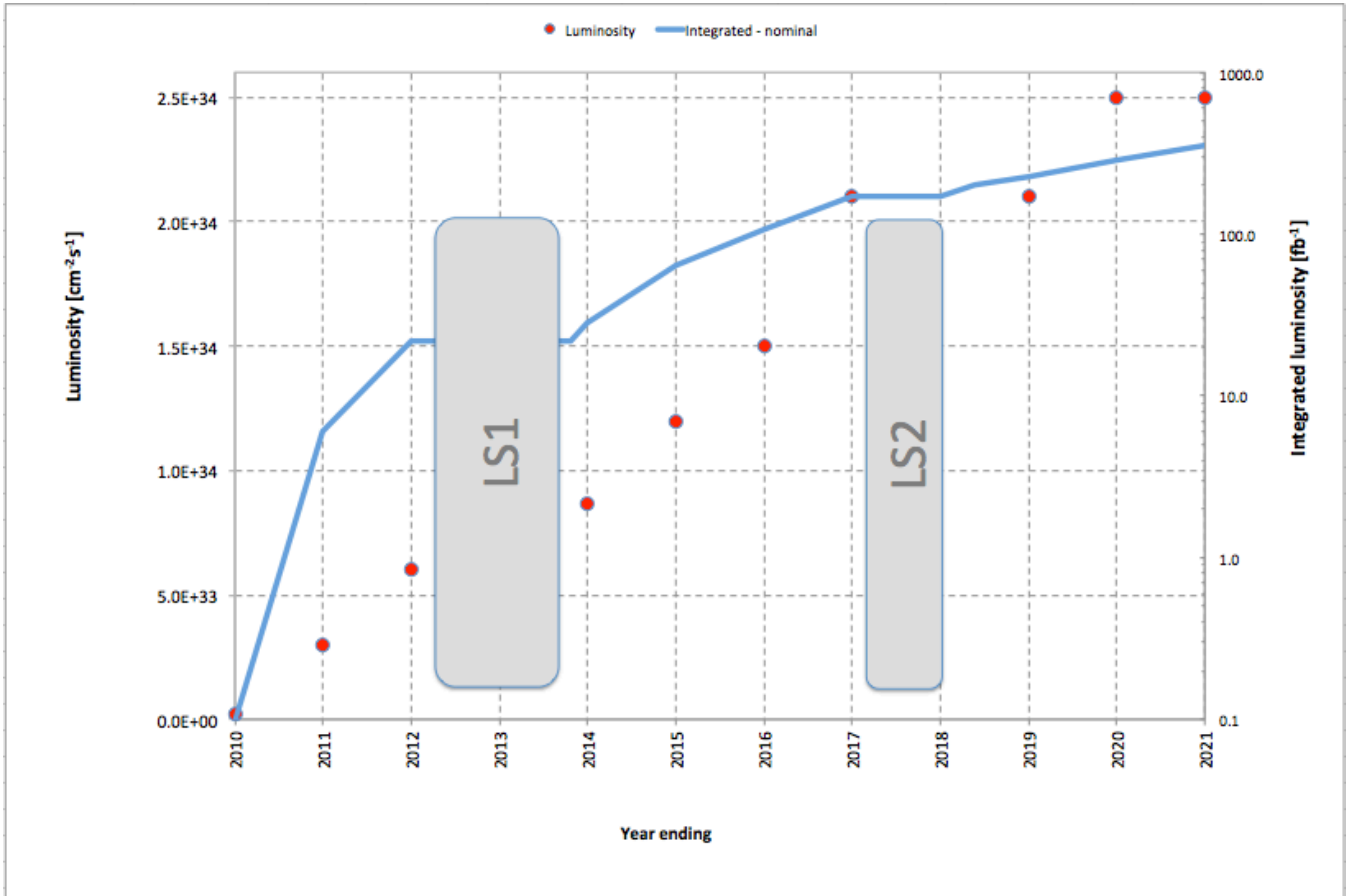
The challenge

- Trigger rates control is extremely challenging in high luminosity hadron collider experiments
    - As the luminosity increases, physics goals change in response to new discoveries and the detector ages.
- It is thus essential that the trigger system be flexible and robust, and have redundancy and significant operating margin
    - **Providing high quality track reconstruction over the full detector can be an important element in achieving these goals.**
    - **This is particularly challenging for hermetic detectors**

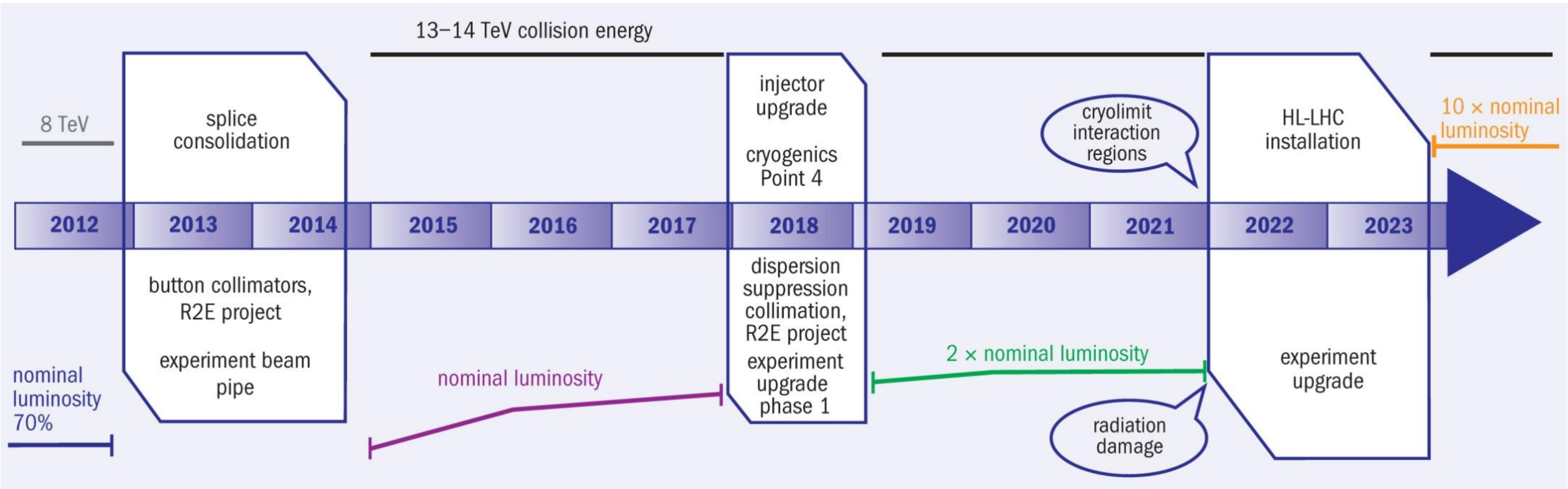
The challenge



LHC 10+ year planning



A TENTATIVE SCHEDULE FOR NEXT 10 (20) YEARS



A plan for the LHC in the next 10 years [L. Rossi, IPAC 2011]

Please note: we are a research lab, we must have a plan but we can change it

Implications for the Tracker

At $5x10^{34}$ cm^{-2} s^{-1}~ up to 200 interactions per bunch crossing

- About 6k primary tracks per bunch crossing (25 ns) in the Tracker volume $|\eta|<2.5$ ...
  - ...plus any other coming from γ conversions and nuclear interactions

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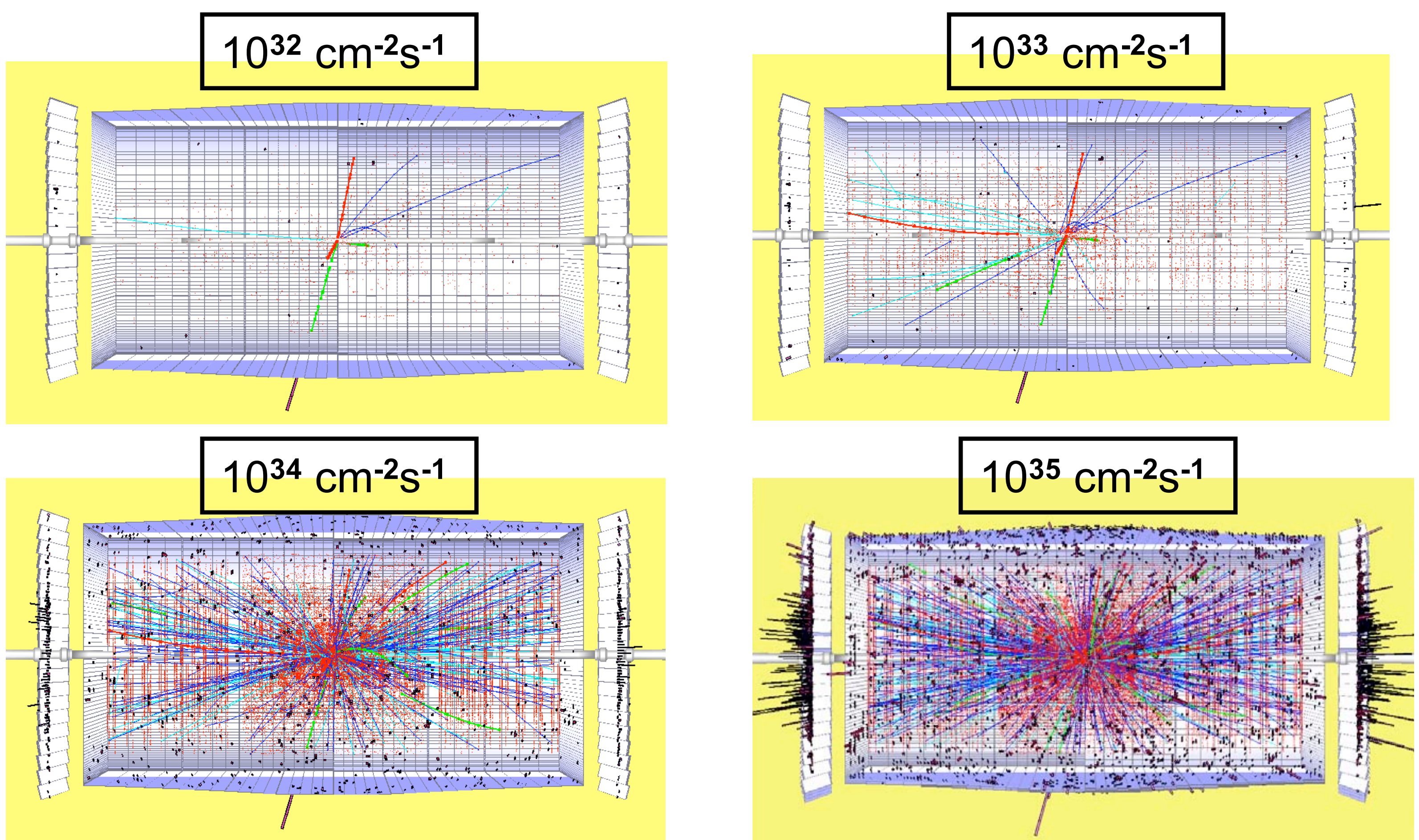
$H \to ZZ \to \mu\mu ee$, M_H= 300 GeV for different luminosities in CMS



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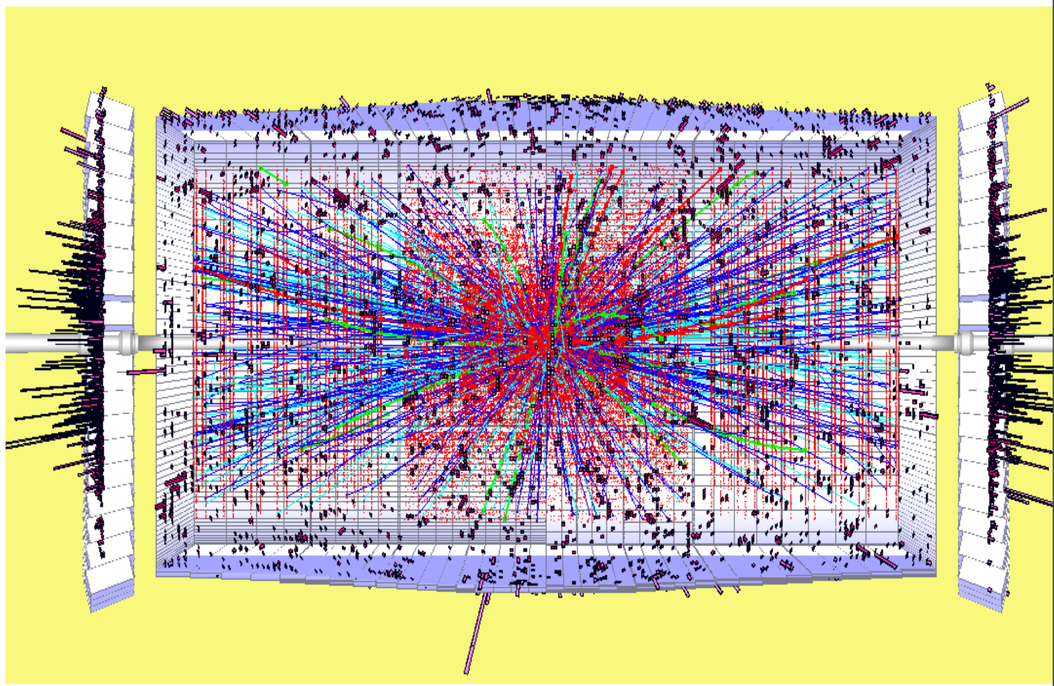
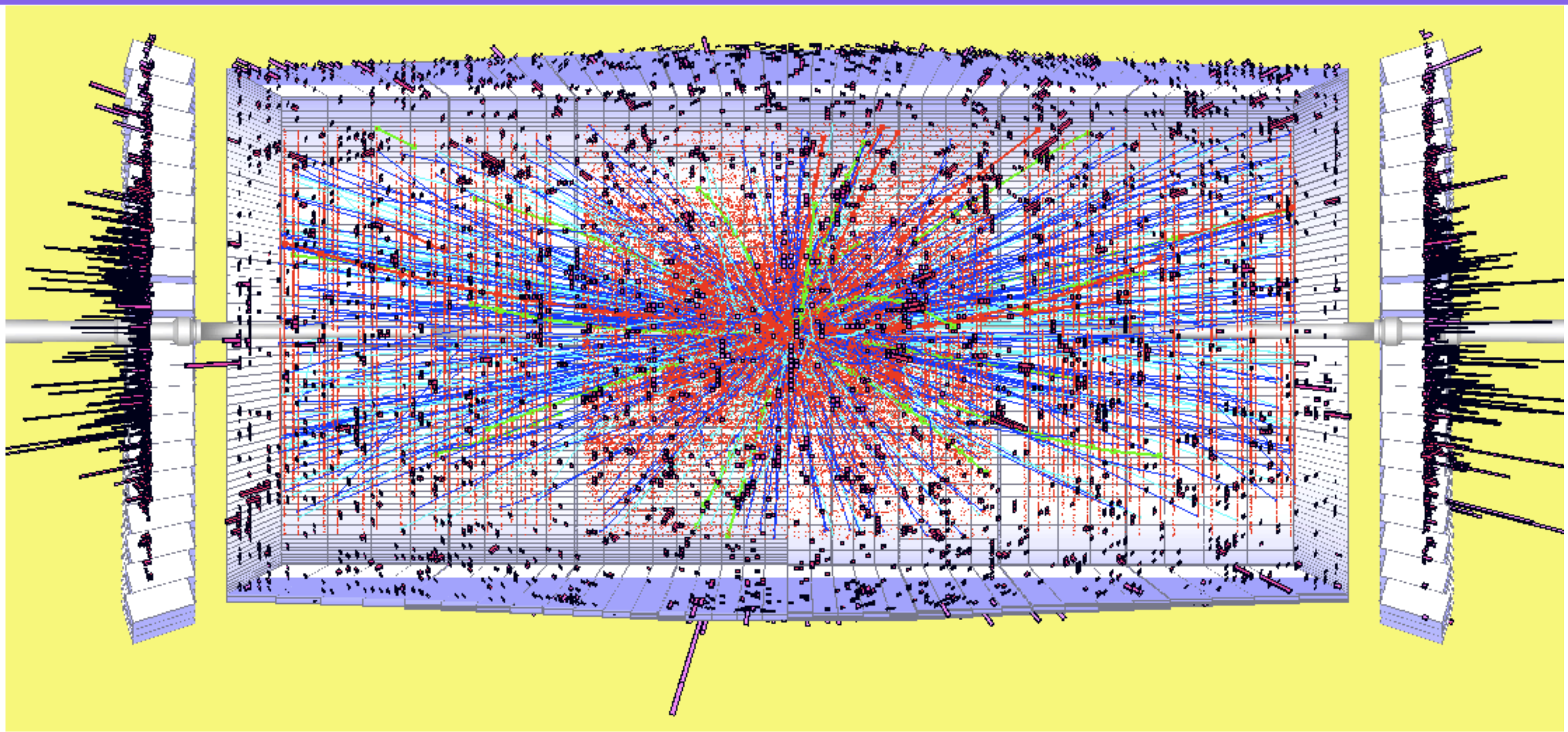


- factor ~10 larger wrt LHC
- higher radiation
- larger occupancy

- Main issues for the Tracker
  - radiation hardness of up to ~10^{16} n_{eq} cm^{-2} in the innermost layers
    - R&D for ultra radiation hard detectors: 3D-silicon, planar (n in p), diamond

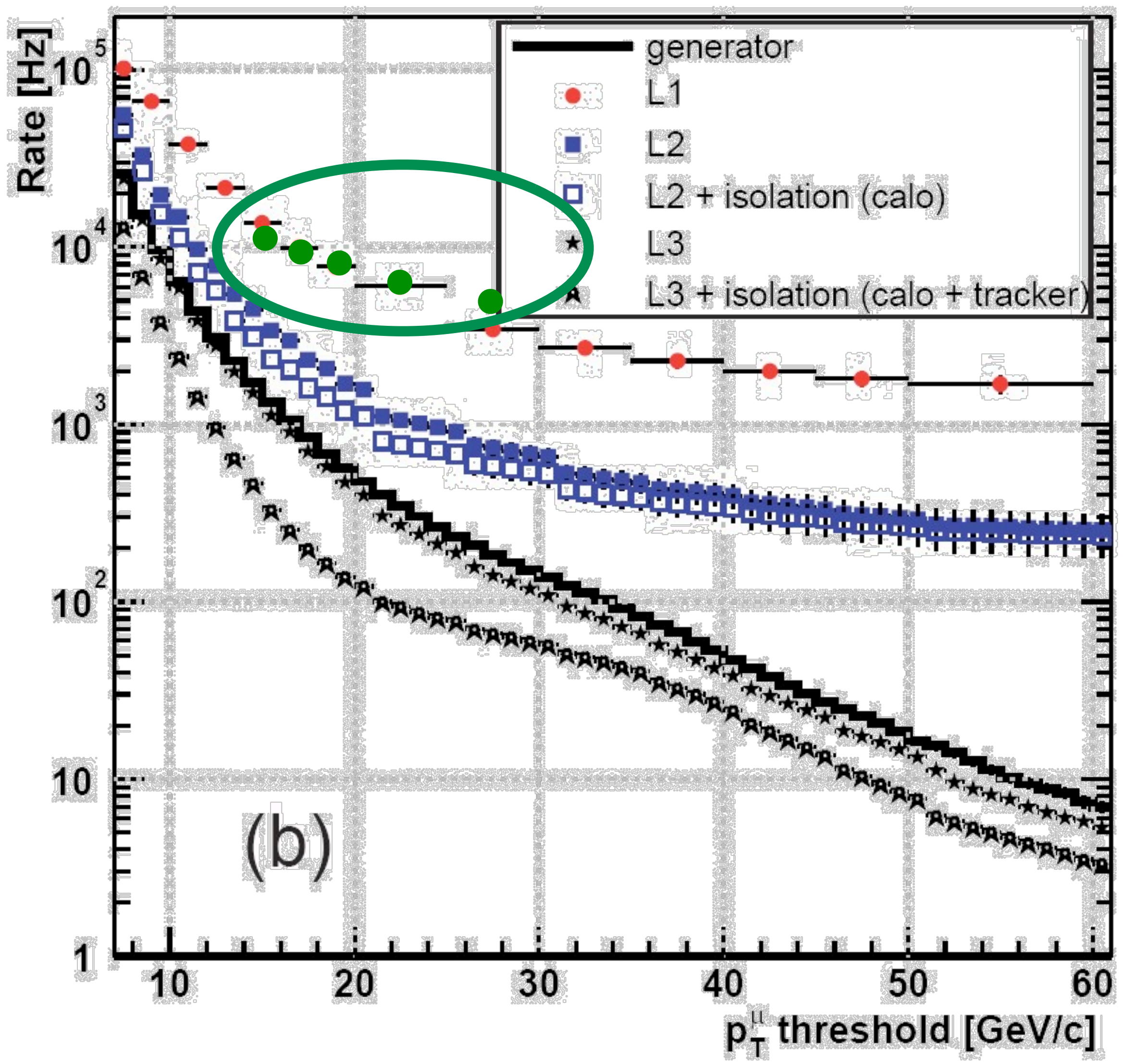
The full Tracker Upgrade: basic requirements



- Granularity
  - Resolve up to 200÷250 collisions per bunch crossing
    - Nominal figure of $5{\times}10^{34}$ cm^{-2} s^{-1} @ 40 MHz corresponds to ≥ 100 collisions
  - Maintain occupancy at the few % level
- Radiation hardness
  - Ultimate integrated luminosity considered ~ 3000 fb^{-1}
    - To be compared with original ~ 500 fb^{-1}

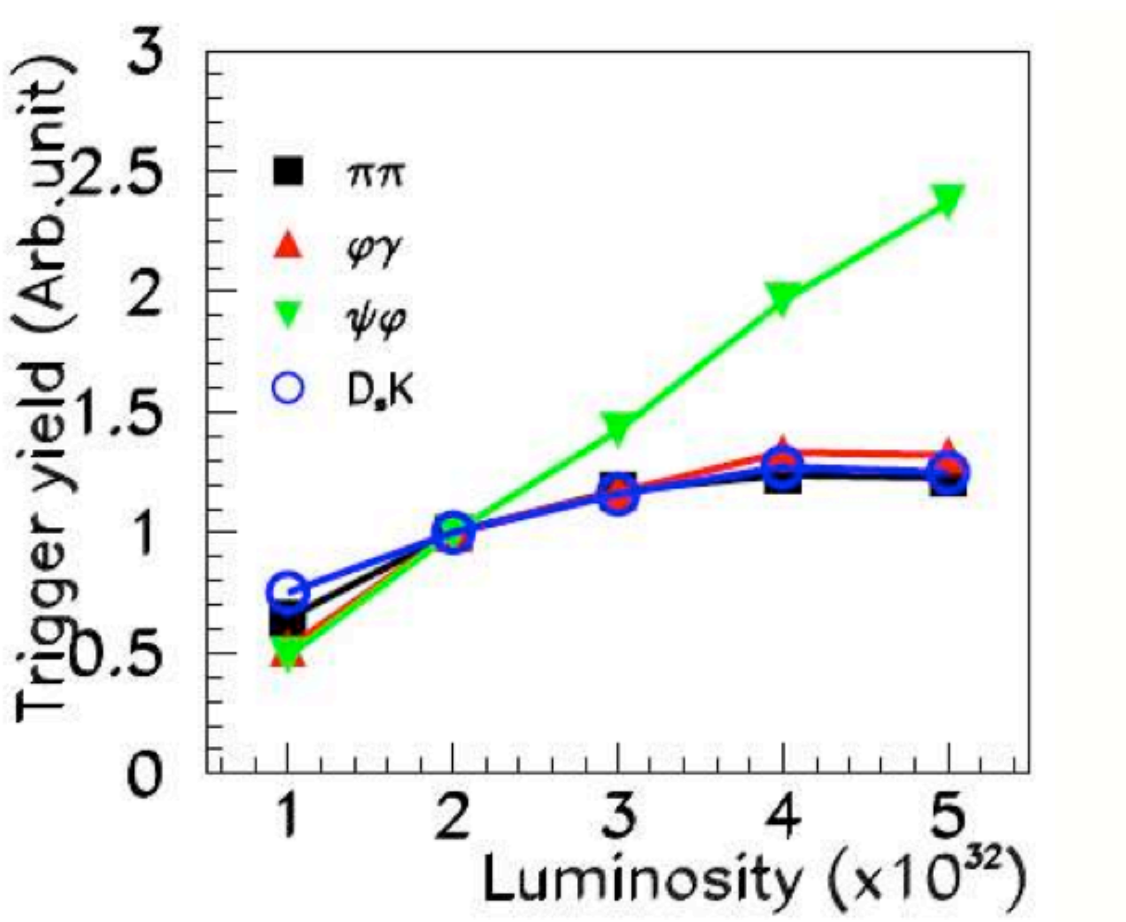
Example: Single Muon Trigger vs. p_T with & without tracker

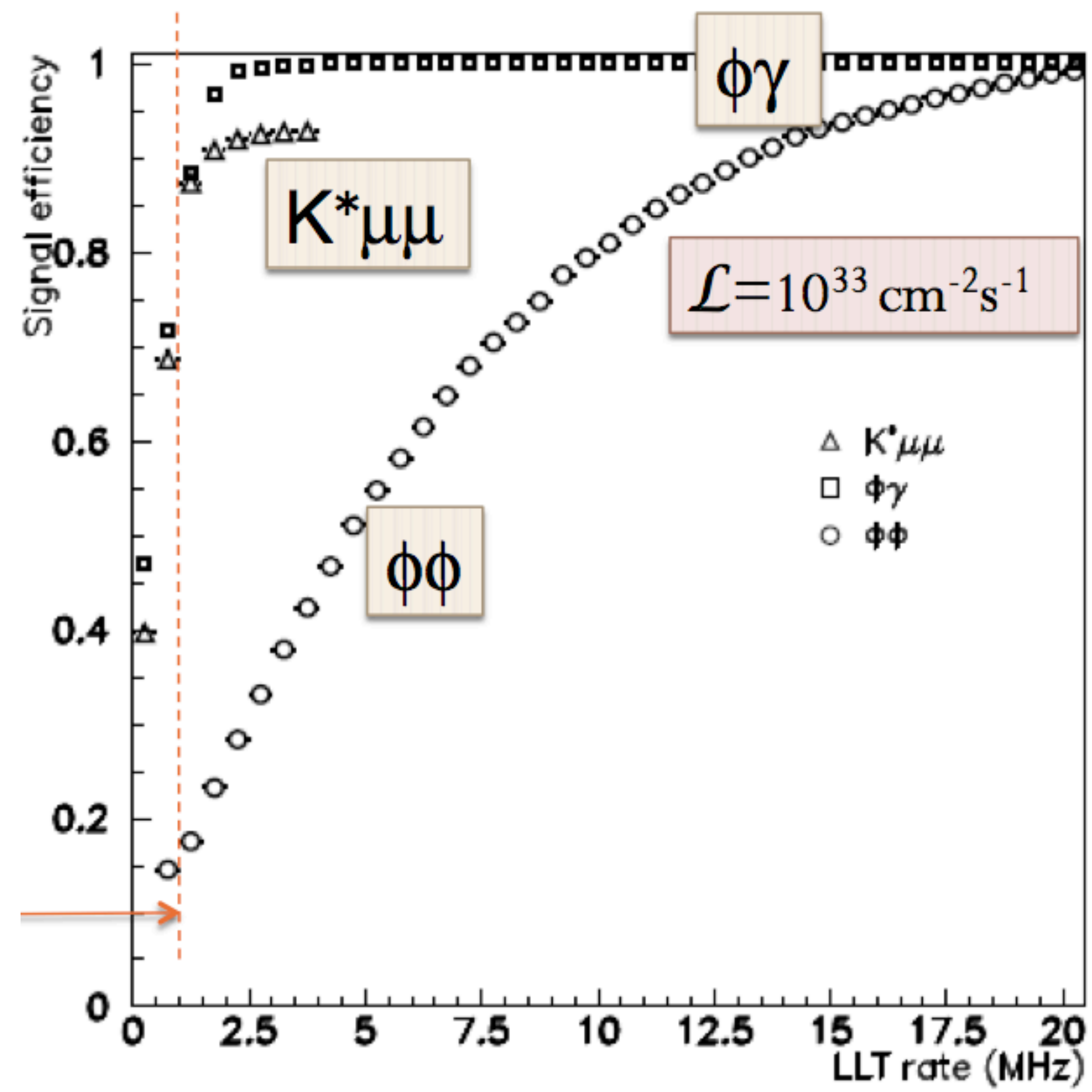
- CMS simulation for L=10^{34} cm^{-2} s^{-1}
- Add **measured** data rates at 8 TeV, extrapolated to 10^{34} cm^{-2} s^{-1}
  - Good agreement in rates, but different √s !



L>3E34 → No p_T threshold may reduce rate enough!

LHCb

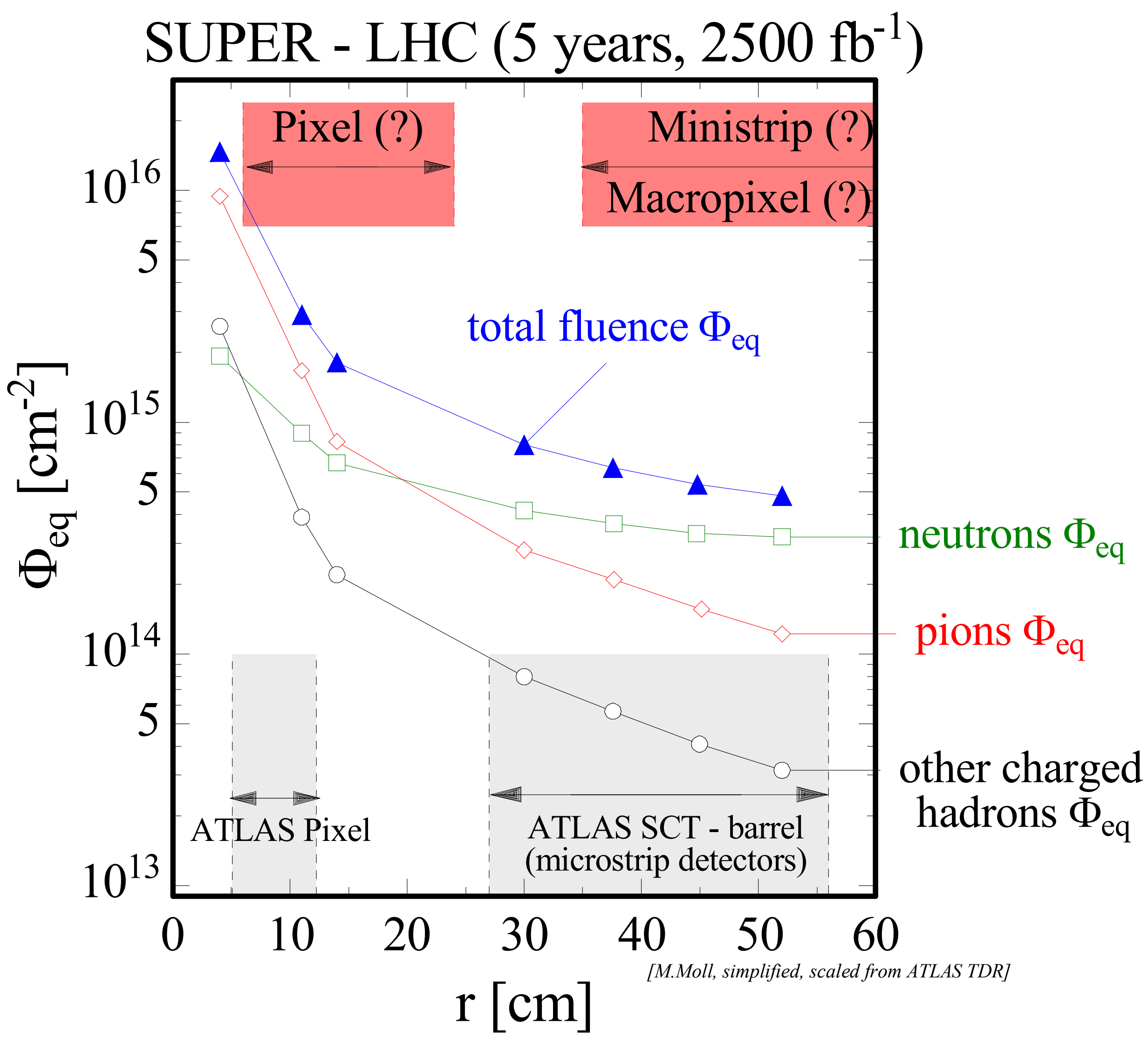


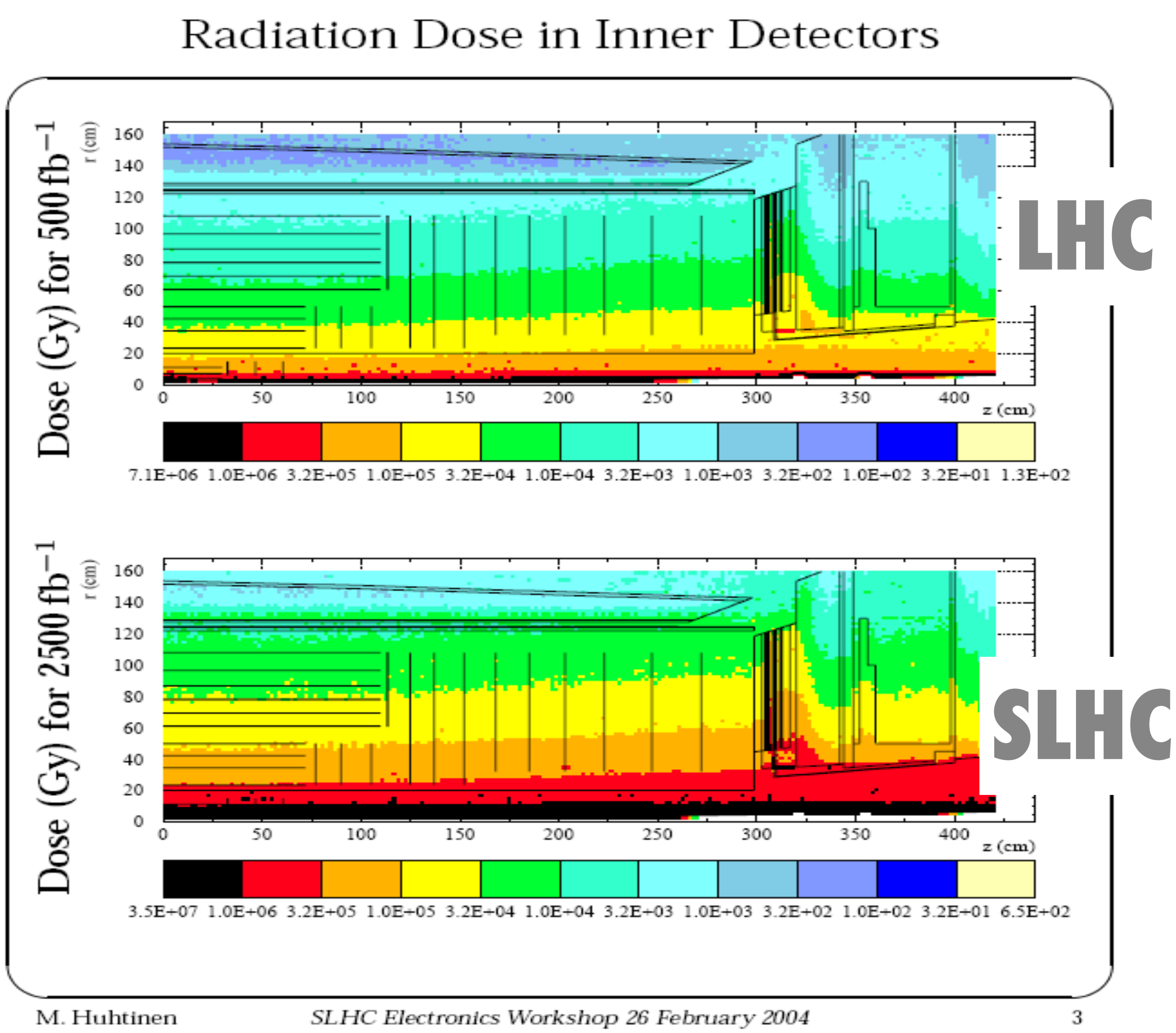


Reduced efficiency for fully hadronic channels

https://cdsweb.cern.ch/record/1443882/files/LHCB-TDR-012.pdf

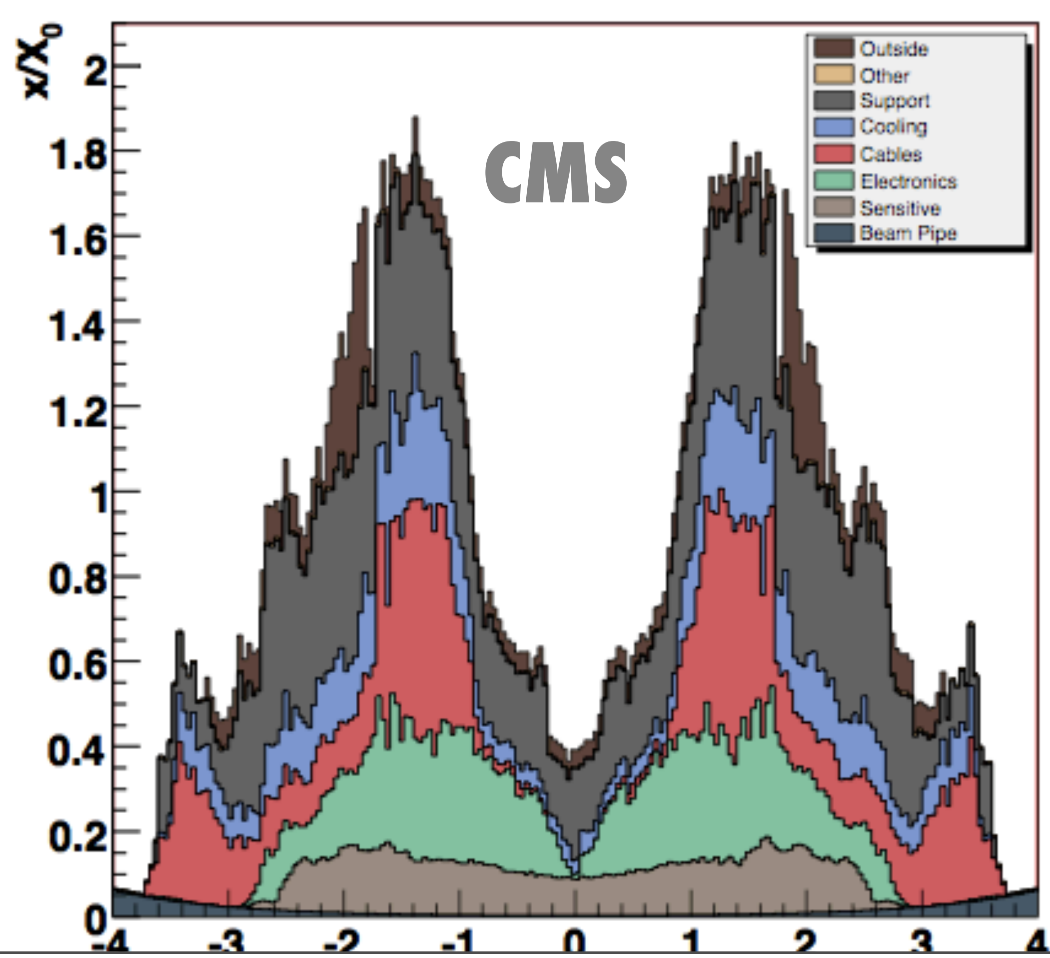
Radiation Issues for SLHC

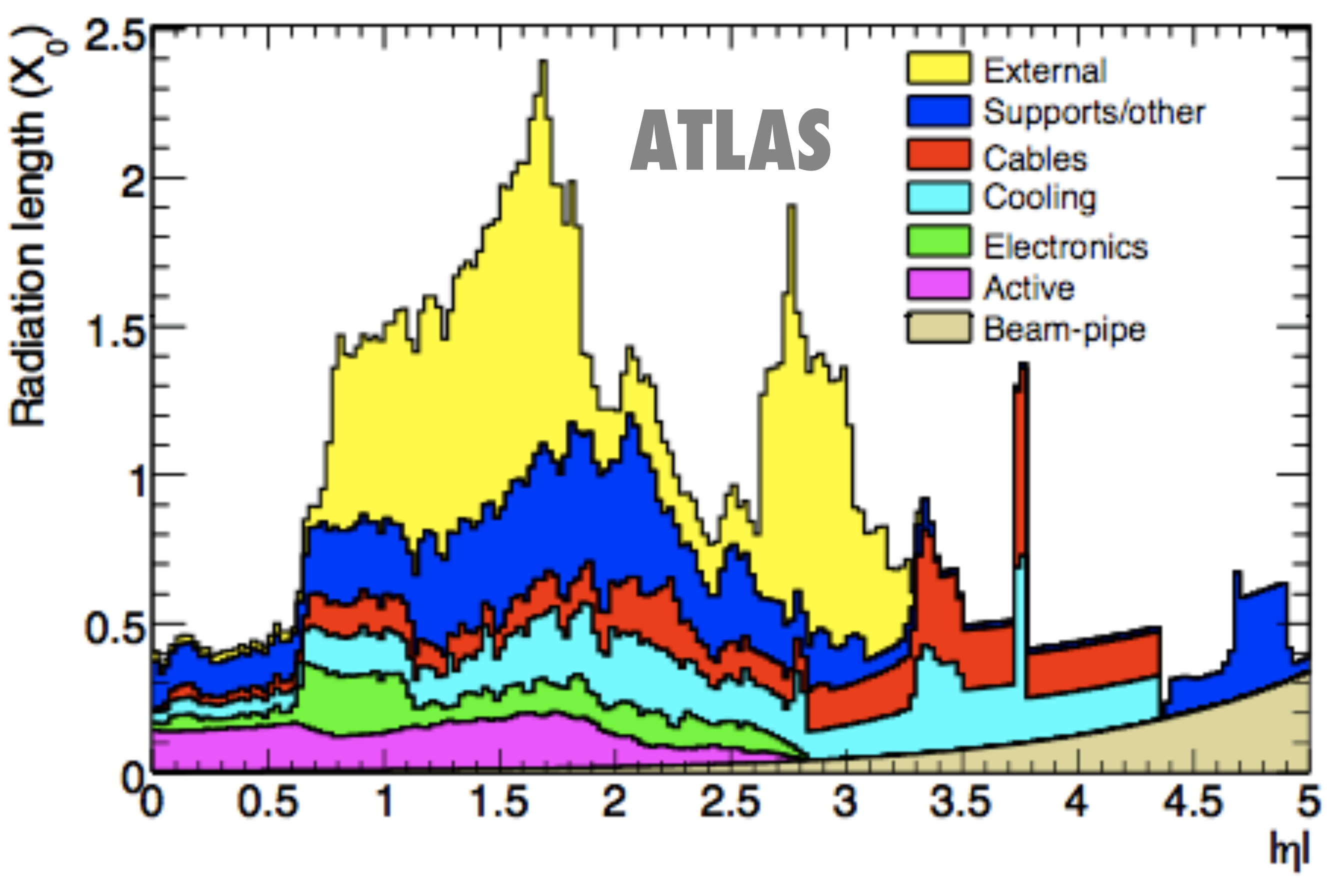




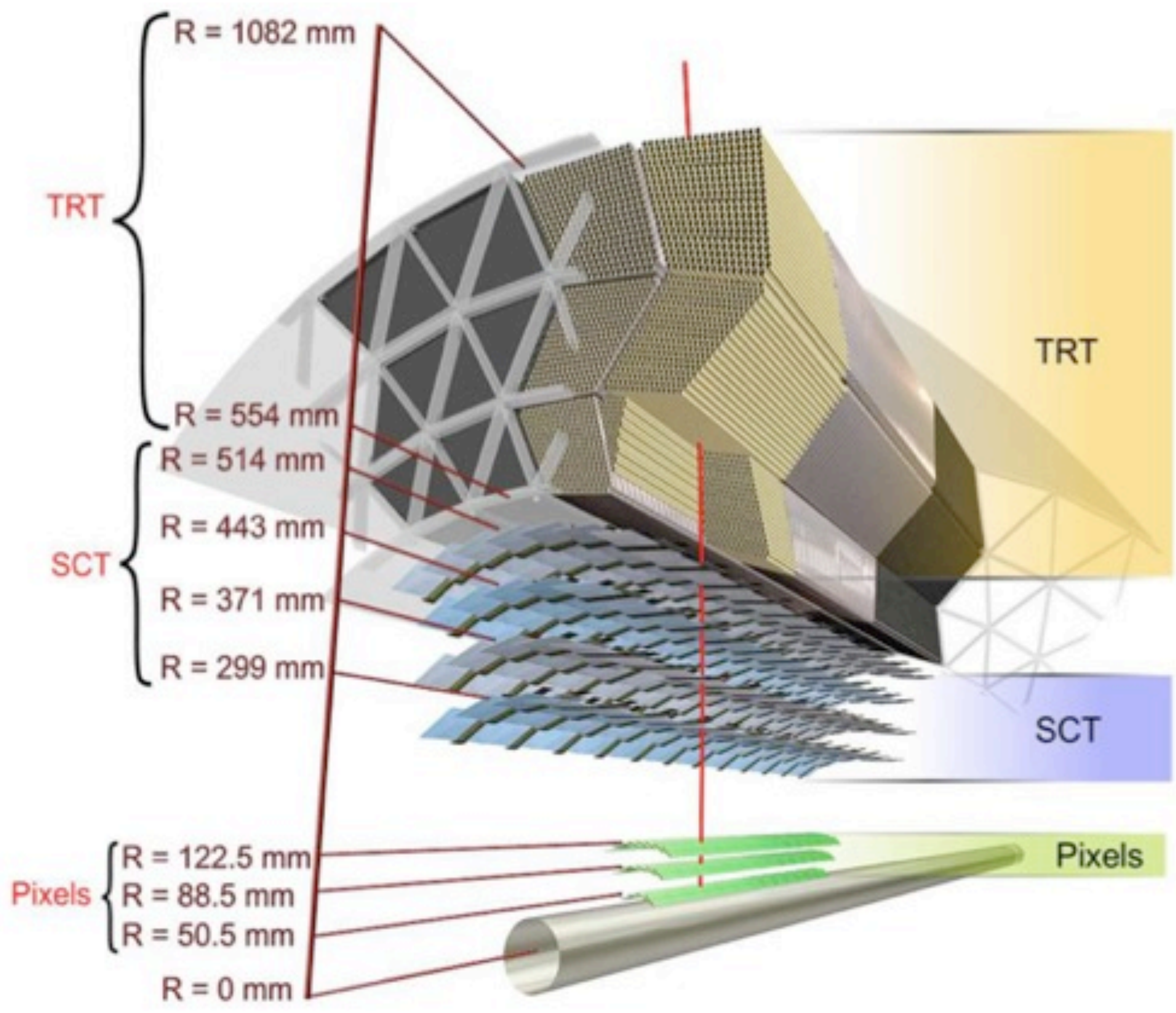
Material budget

- Material budget is weakest point
  - e & γ conversions, hadronic interactions
  - Driven by power & cooling
    - pixels ~3.7 kW.m^{-2}, μstrips ~ 0.1–0.4 kW.m^{-2}



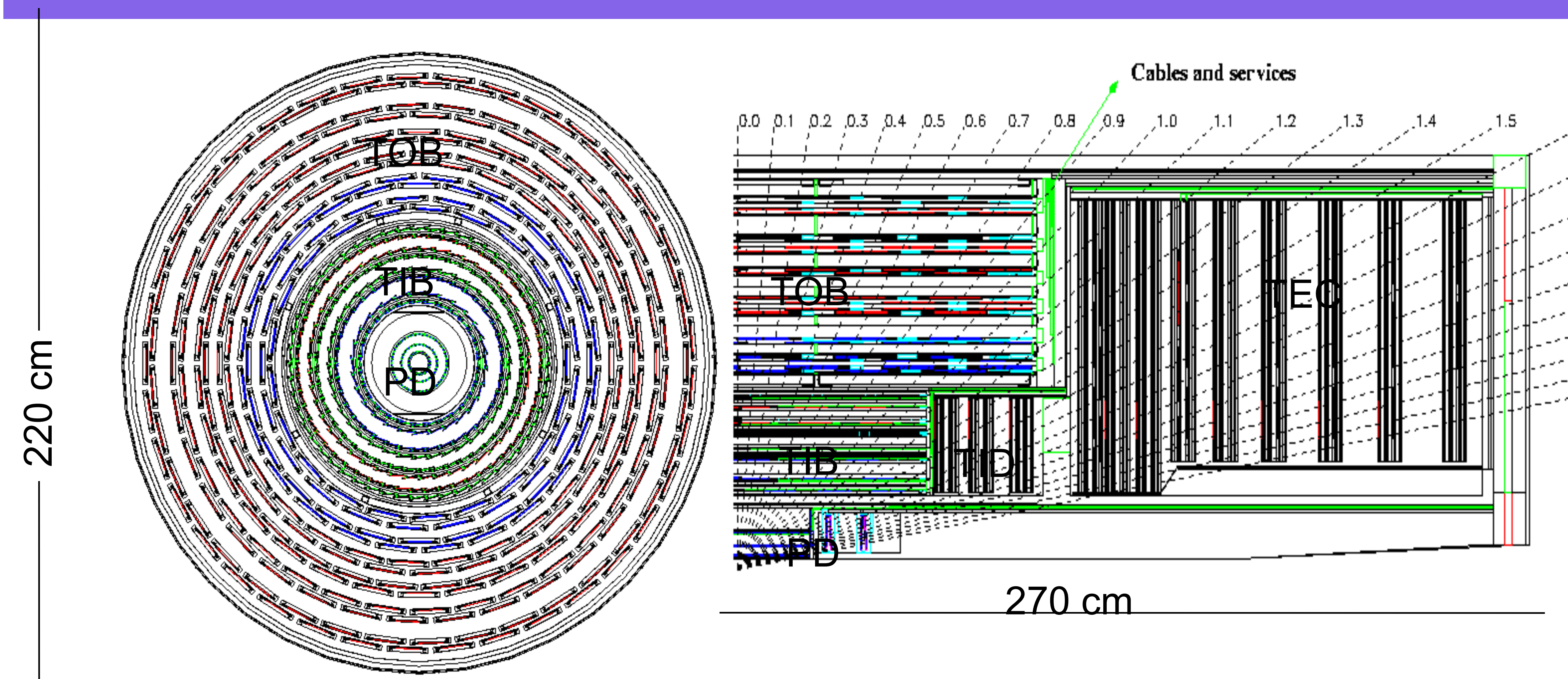


ATLAS Tracker



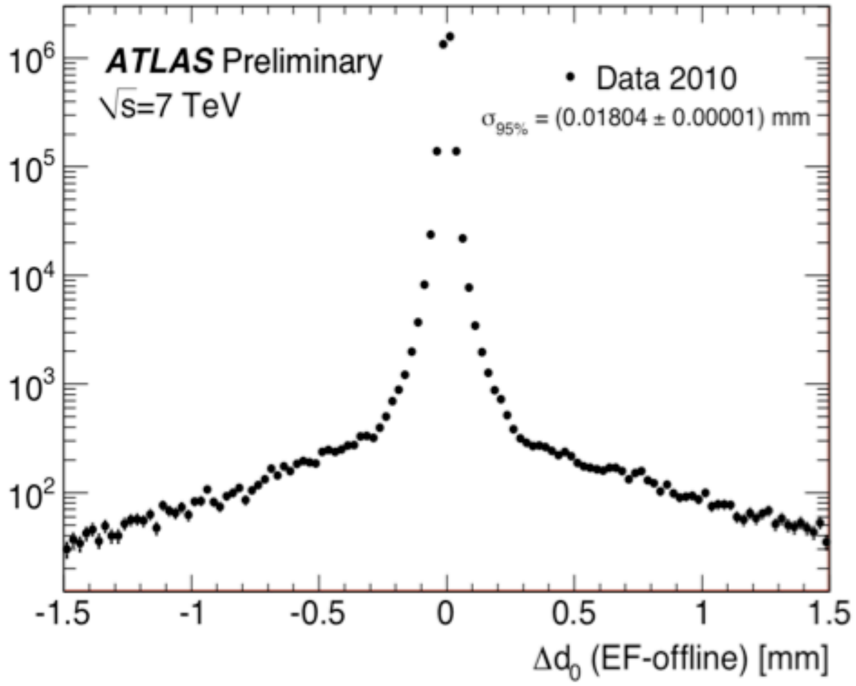
- Inside 2T magnetic field
- 3 layers of 2-D silicon pixel tracking
  – $50x400\mu m^2$ pixels, 80M channels
- 4(x2) (stereo)-layers of 1-D silicon strip tracking
  – 80μm strip pitch, 6M channels
  - Alternating axial and small-angle stereo layers
- Silicon tracking up to $|\eta| < 2.5$
- Total of 11 layers (all SI) used in the FTK system

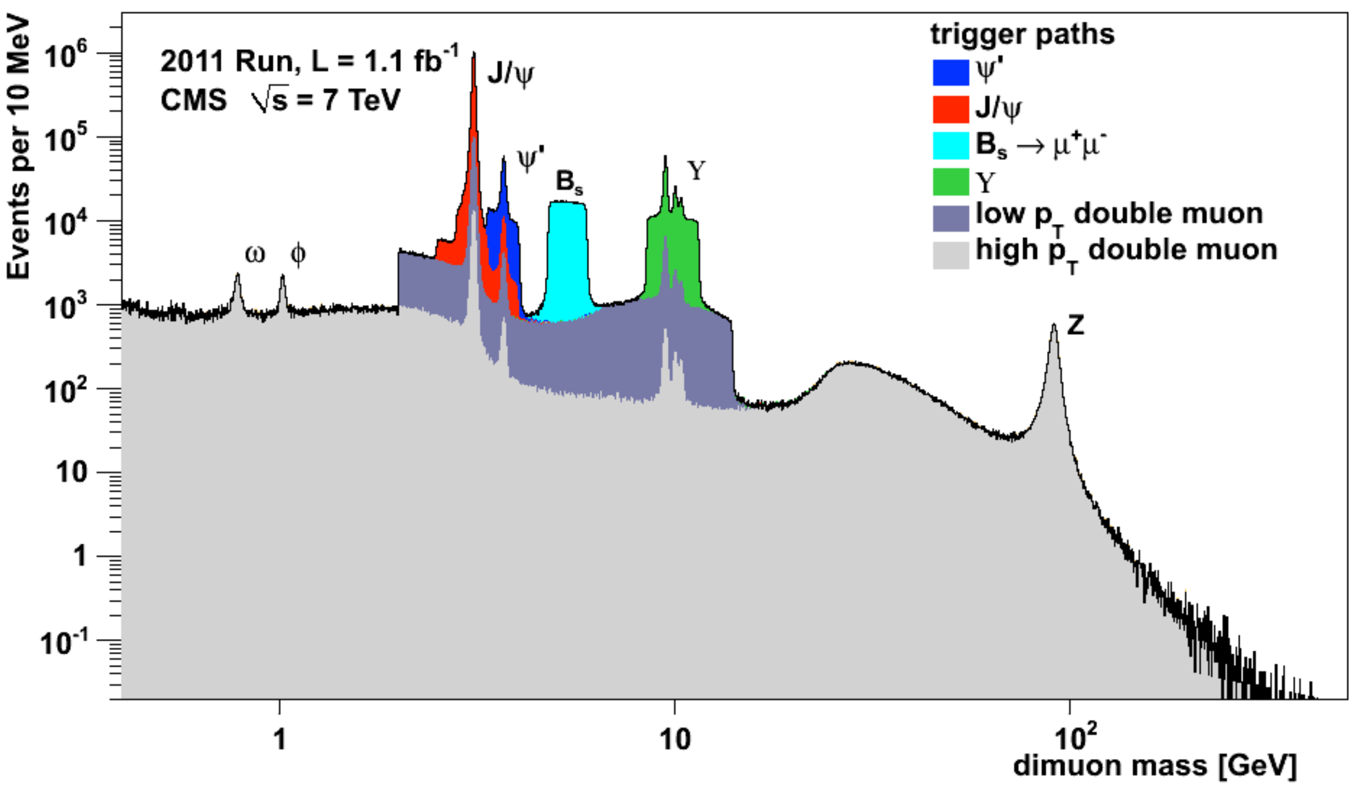
CMS Tracker



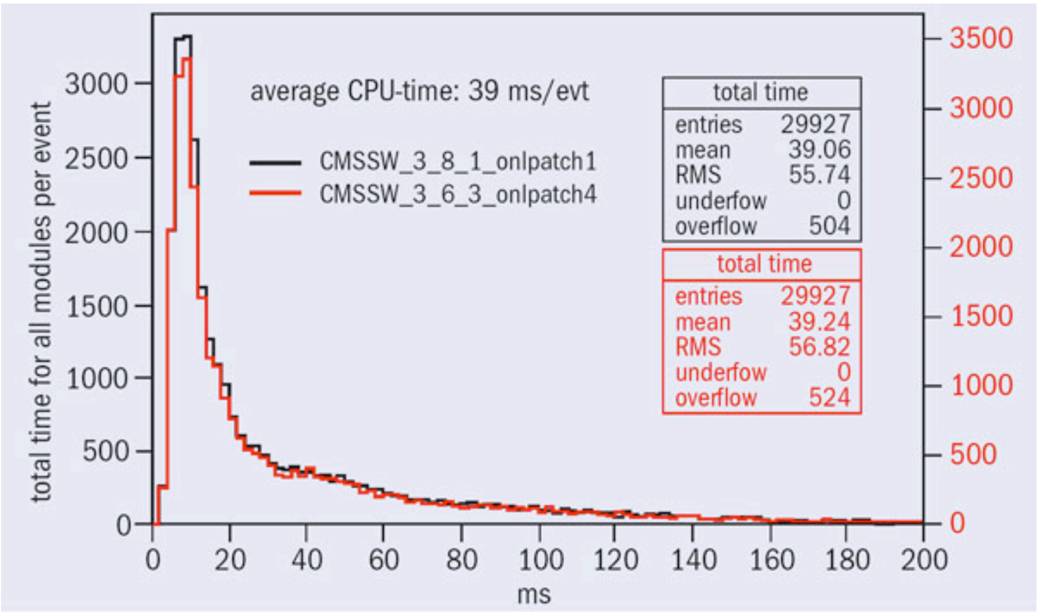
~ 200 m^2 micro-strip silicon detectors 15.232 modules
6136 320µm thick and 18.192 500µm thick sensors (all from 6” wafers).
9.648.128 analog strip channels.
~ 1 m^2 silicon pixel detectors 768 barrel modules and 96 end-caps blades
16000 ROC
66 Million pixels

Current usage of Trackers at HLT





HLT track precision is close to the offline one. Could be used in complex topologies, however is slow for L1 triggers.

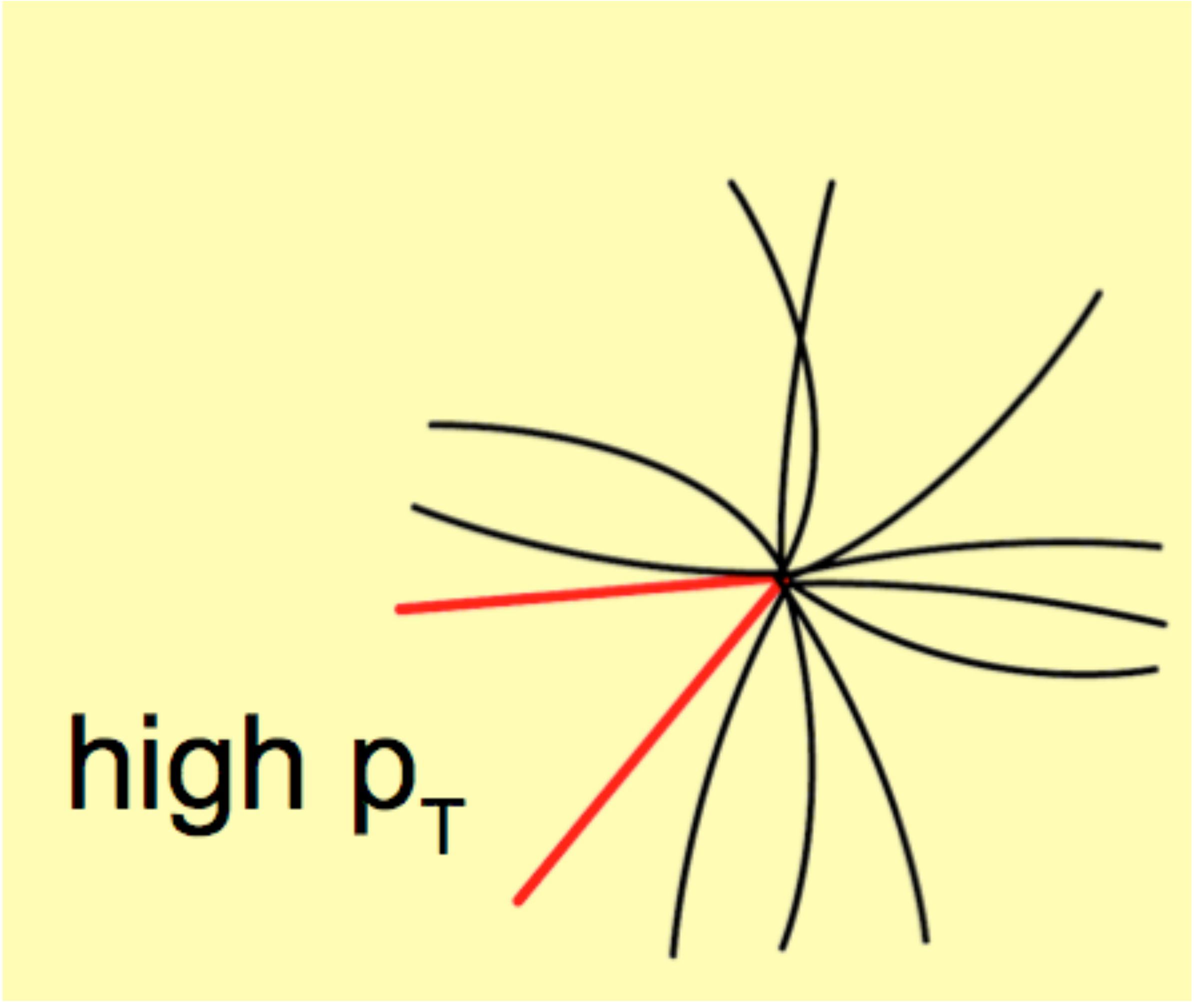


What Trackers should do

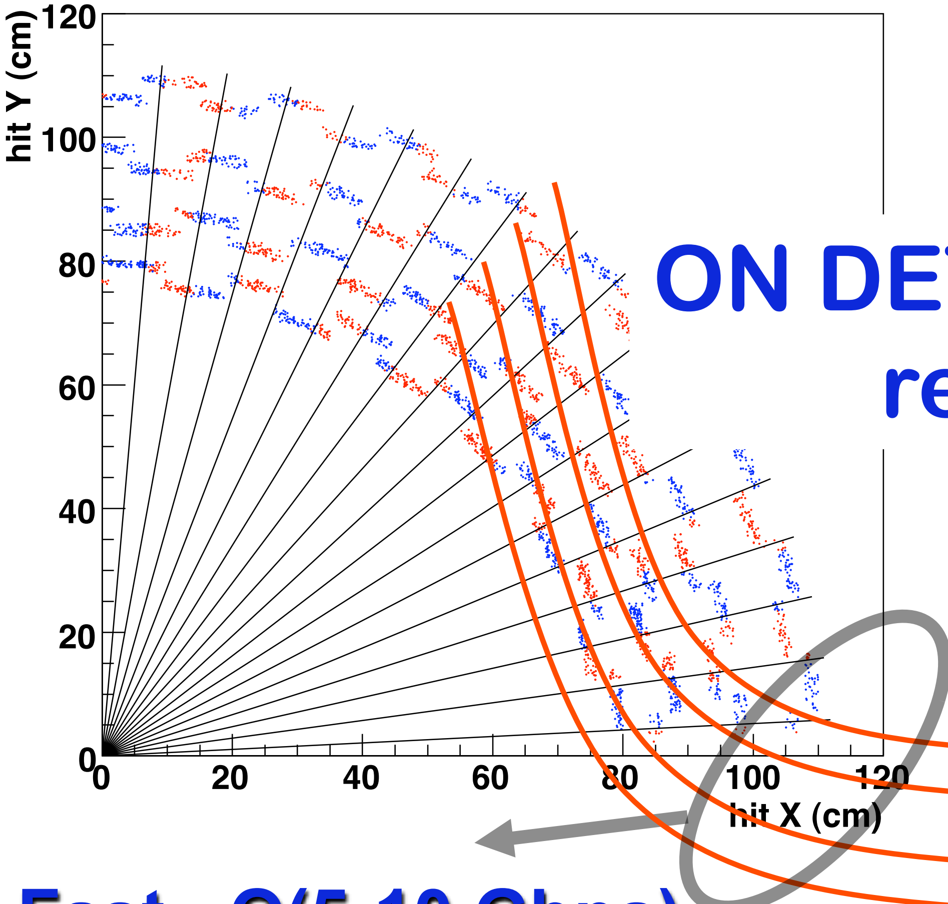
- 1. Data reduction
  - Devices able to discriminate information from “good” tracks
- 2. Track reconstruction on-line
  - Fast pattern recognition in complex environments

Trigger architectures - I

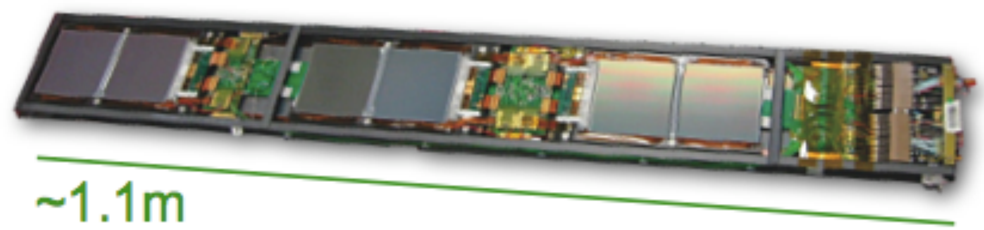
- Track Trigger primitives in a "push" path
  - L1 tracking trigger data combined with calorimeter & muon trigger data
    - With finer granularity than presently employed
  - Physics objects made from tracking, calorimeter & muon trigger data transmitted to Global Trigger



Trigger working principle



ON DETECTOR data reduction

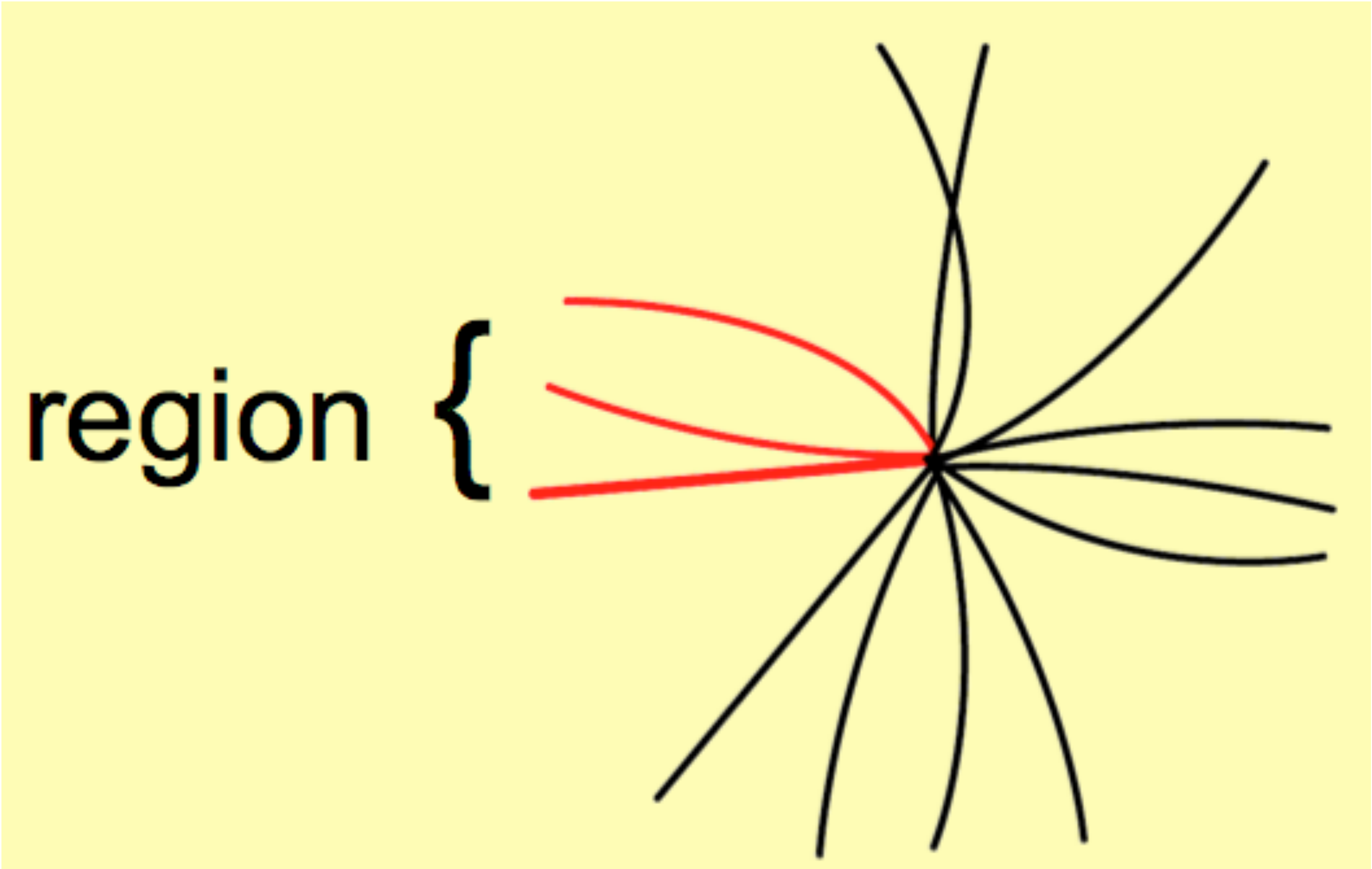


OFF DETECTOR
track pattern recognition

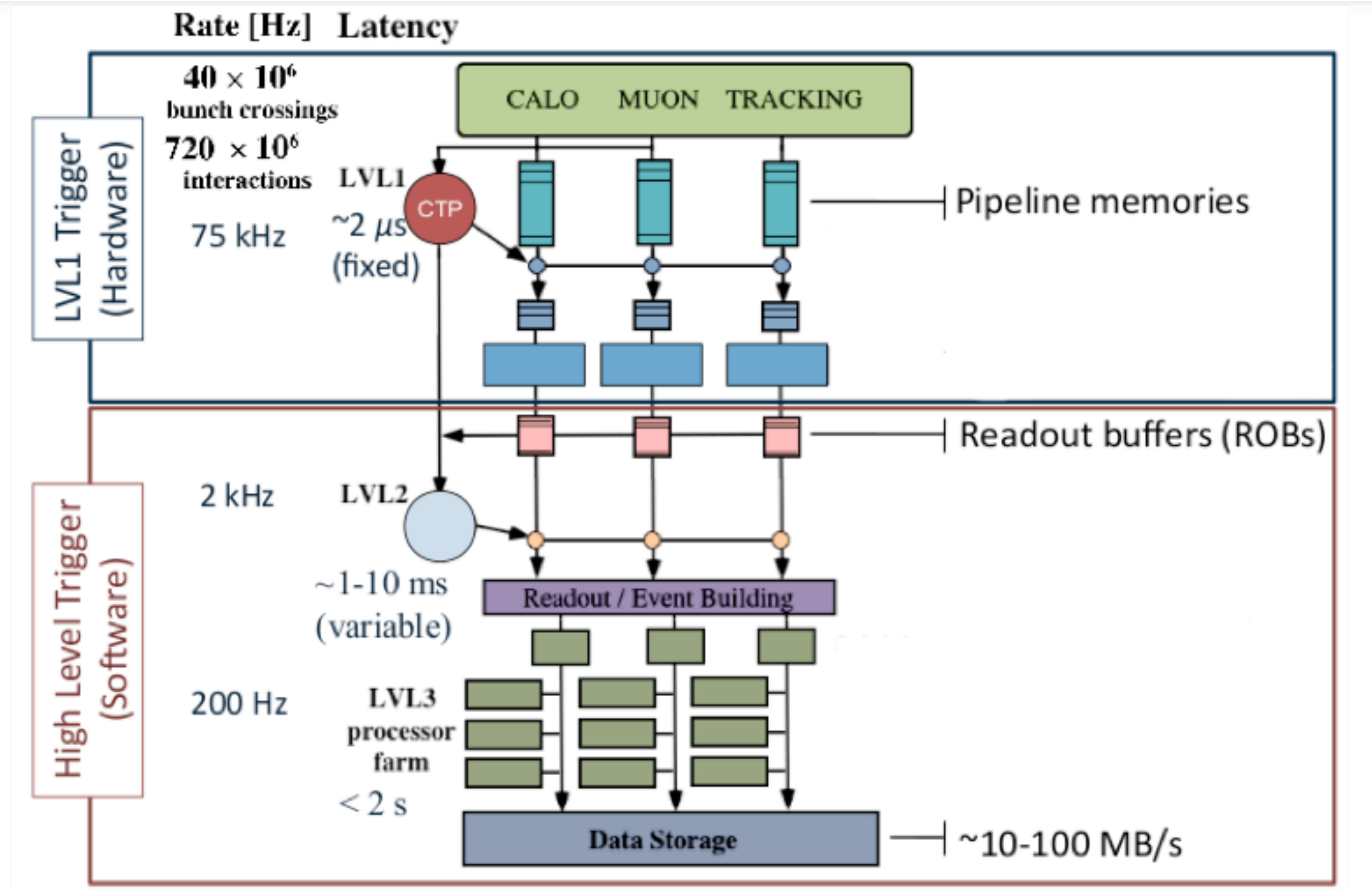
Fast - O(5-10 Gbps) data links

Trigger architectures - II

- Track Trigger primitives in a “pull” path
  - Use present L1 calorimeter & muon triggers to produce a “Level-0” to request tracking information from specific regions
    - Same latency as today’s Level-1
    - Expected rate ~ 1 MHz
  - Tracker sends out information from regions of interest (within a few clock cycles), to form a new combined L1 trigger



Current ATLAS Trigger



Track Trigger using a double buffer scheme (ATLAS)

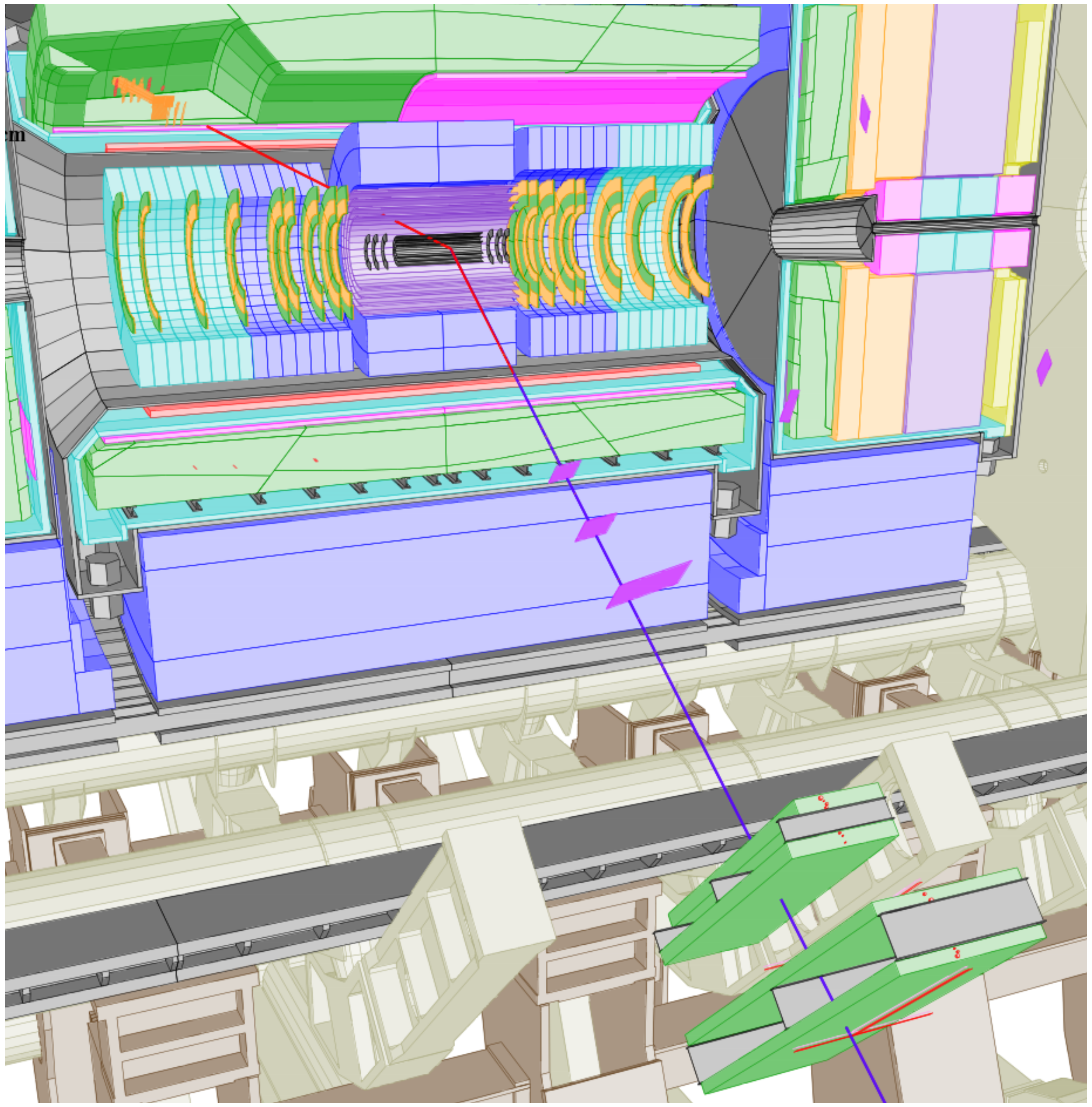
The "L0+L1" scheme

Level-0:

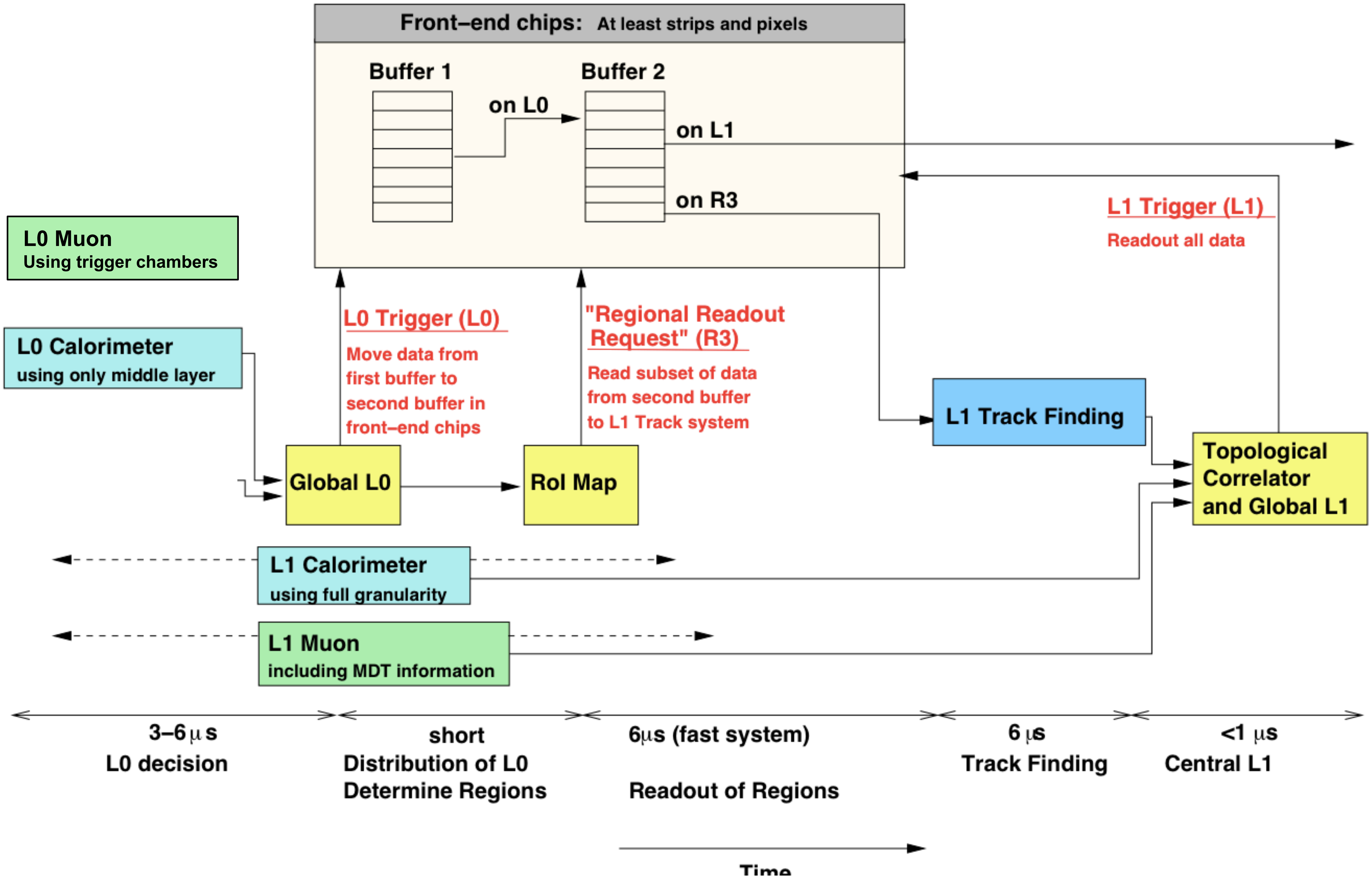
- Coarse calo and muon data
- Rate 40 MHz → 500 kHz
- Latency < 6.4 μs
- Defines Regions of Interest (RoIs) for L1

Level-1:

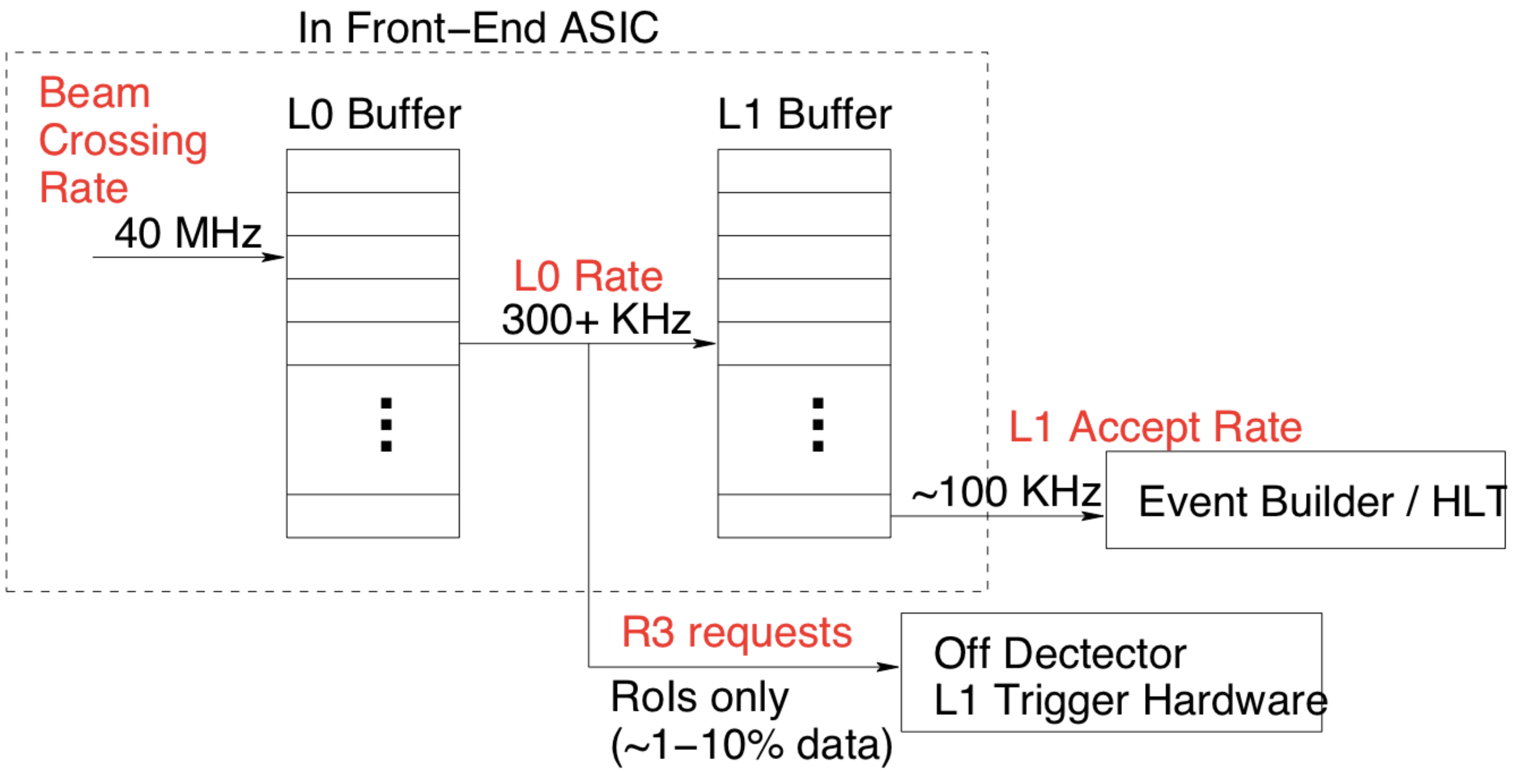
- Tracker data only from RoIs
- Refined information from calorimeters and muons
- Rate 500 kHz → 200 kHz
- Latency < 20 μs



Possible implementation



Front-End – Latencies and Bandwidths



Bandwidth = (L1A rate + RoI data fraction×L0A rate) × event size

e.g. L1A = 100 kHz, L0A = 500 kHz, 10% RoI frac. ⇒ 150 kHz × ev. size

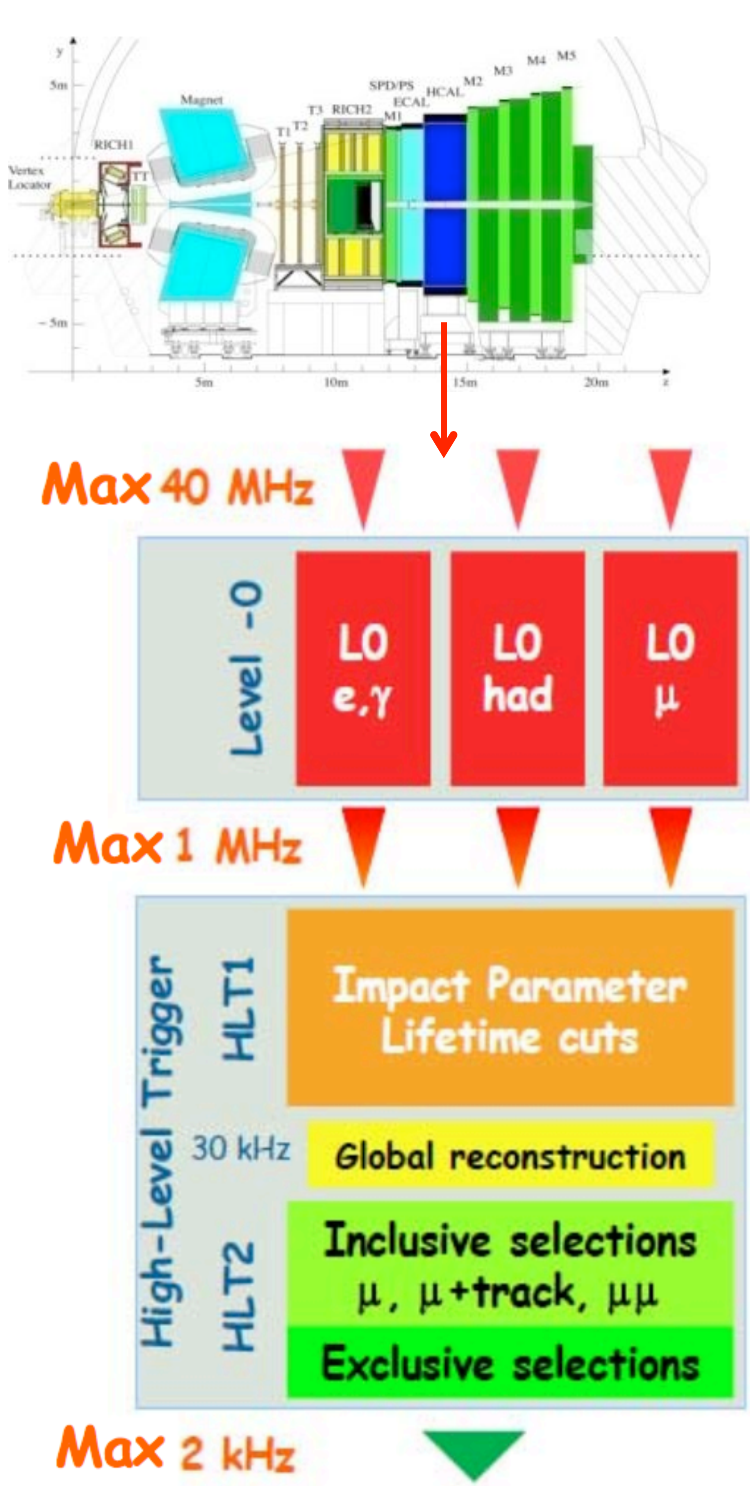
Bandwidth requirement is not great

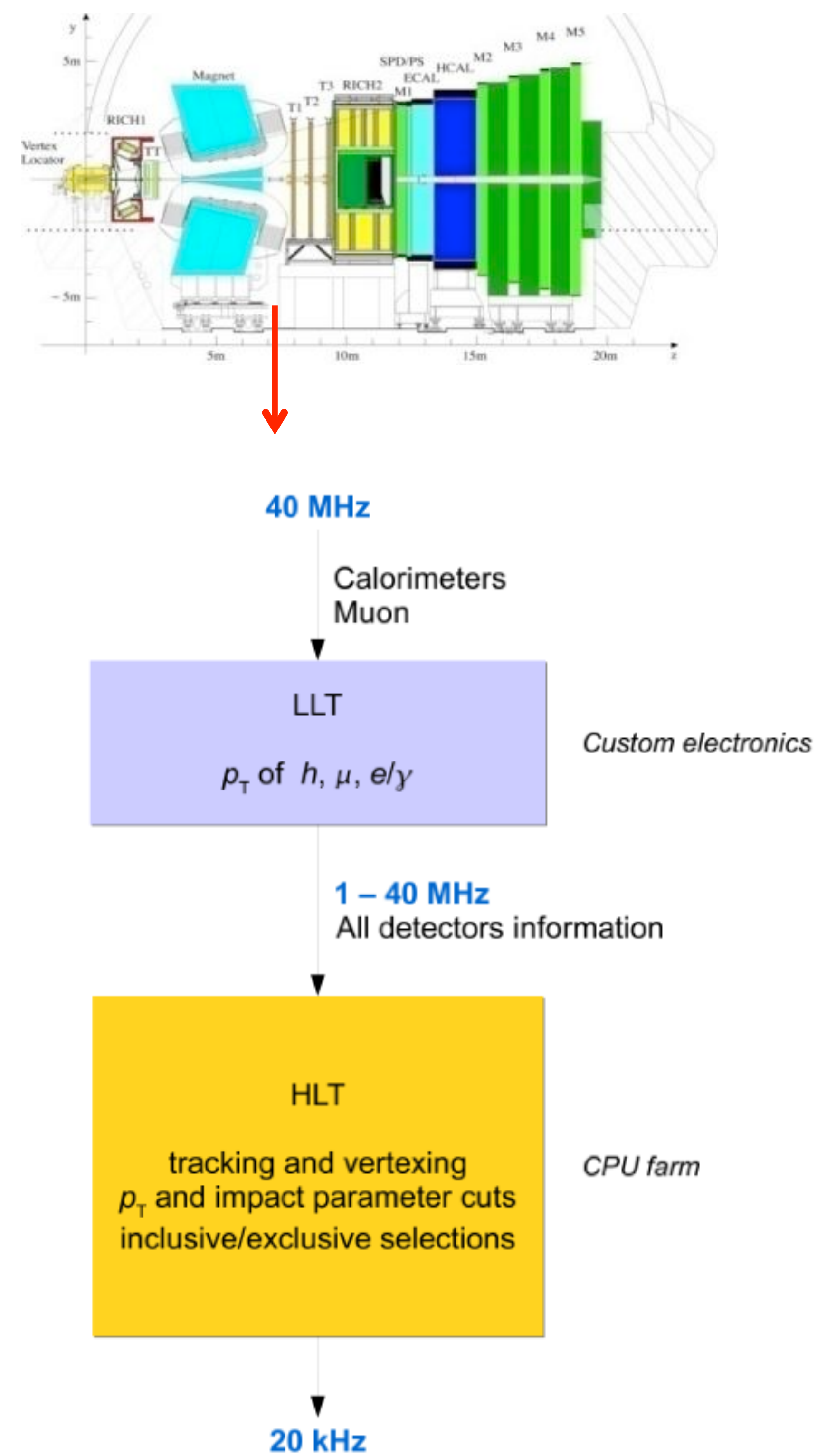
L0 Buffer Length = 6.4 μs × 40 MHz = 256events long

L1 Buffer Length = 20 μs × 500 kHz = 10 events long

Two buffer scheme greatly reduces buffer length needed

Trigger architectures - III





General philosophy

Outer Tracker

- Developing an Integrated Approach with overall ambition of providing
  - A lighter Tracker, with better overall Tracking and Calorimetry performance compared to the present systems
  - A Tracking Trigger including all tracks with p_T above 2 ~ 2.5GeV, well measured and with ~ 1mm primary vertex resolving power
  - Pursuing a “Push” Architecture based on
    - On module filtering of hits from tracks with p_T above ~ 2GeV
    - Low power (low mass) 5GHz optical links

Inner Pixel (not yet mature to be discussed)

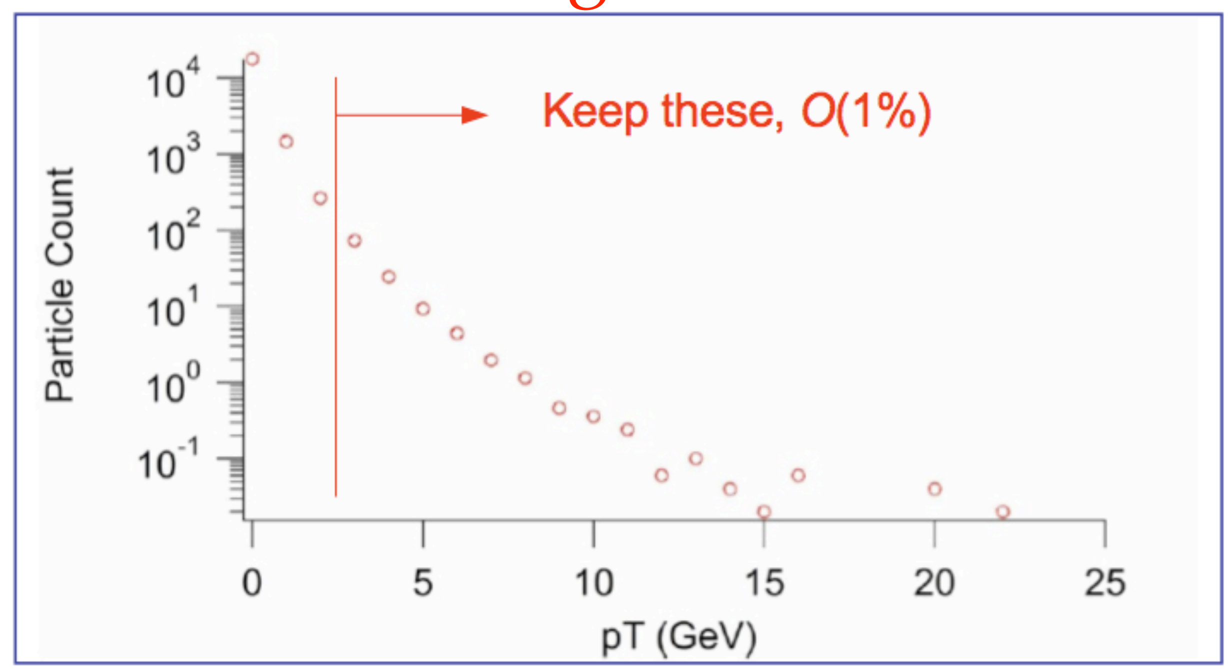
- Exploring a Region of Interest “Pull” architecture
  - As a possible complement to the L1 “Push” Tracking Trigger and/or HLT pre-processor

On-line Data Reduction

Mainly for “outer Trackers” (~30<R<100 cm)
of ATLAS and CMS

Select only hits from "high-p_T" tracks

- Select only tracks above a given p_T since they are few
- Send reduced data volume off detector for further logic



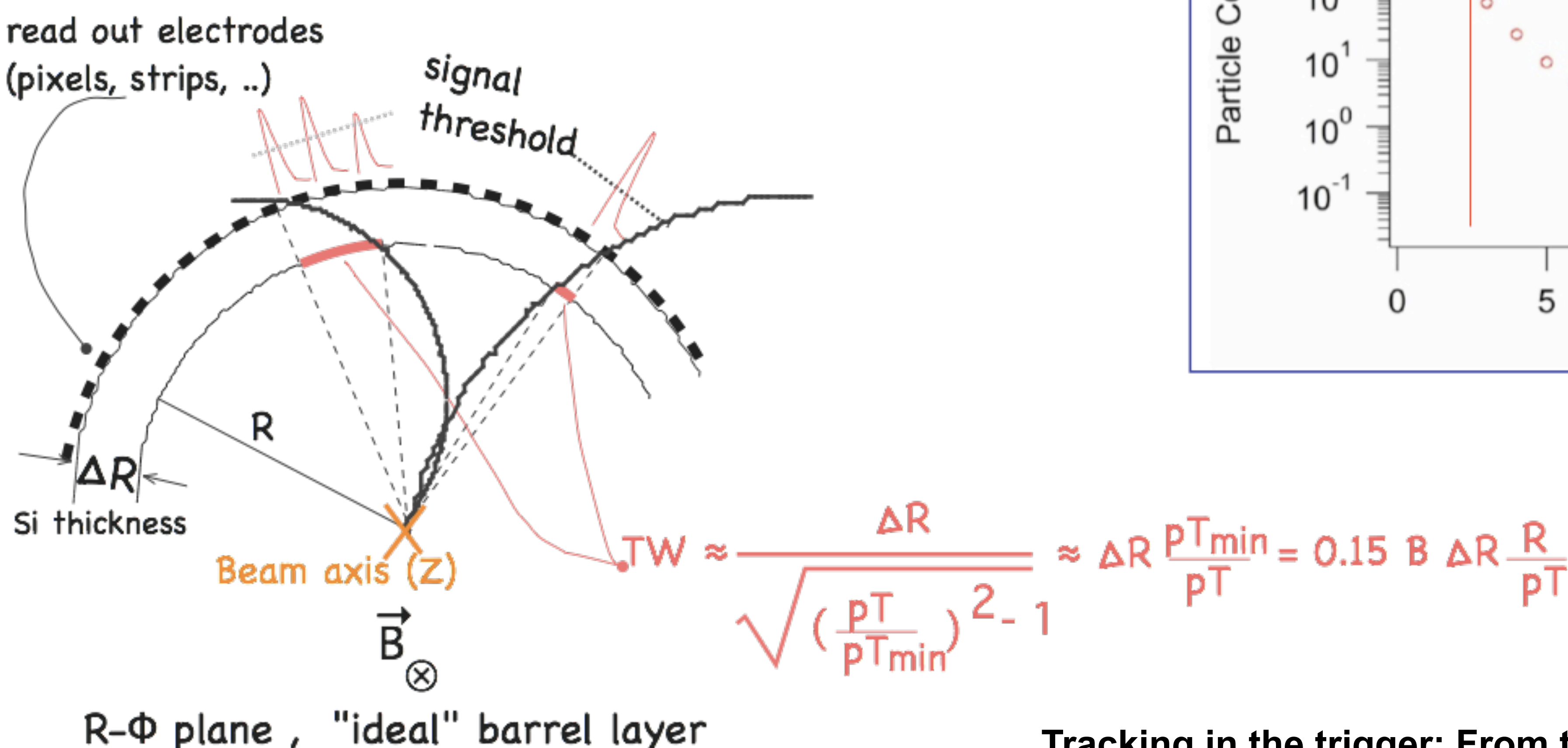


Figure of merit: Thickness/pitch

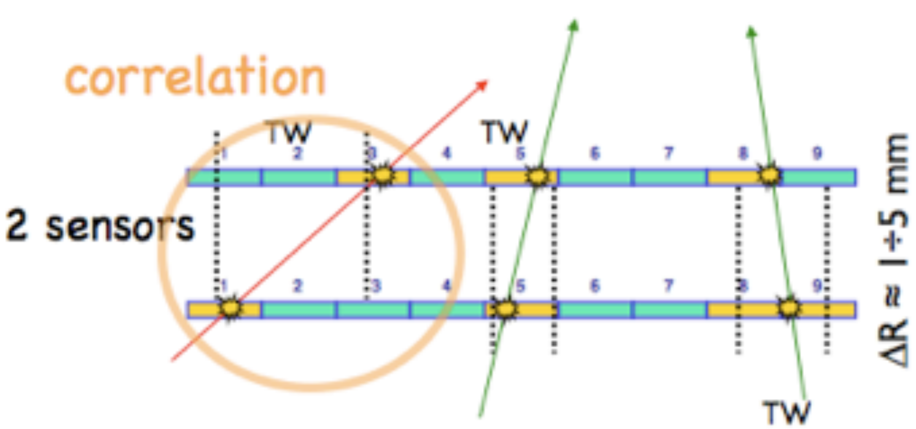
Tracking in the trigger: From the CDF experience to CMS upgrade.
Fabrizio Palla (INFN, Pisa), Giuliano Parrini (Florence U. & INFN, Florence). 2007. 14 pp.
Published in **PoS VERTEX2007 (2007) 034**

Track width measurements

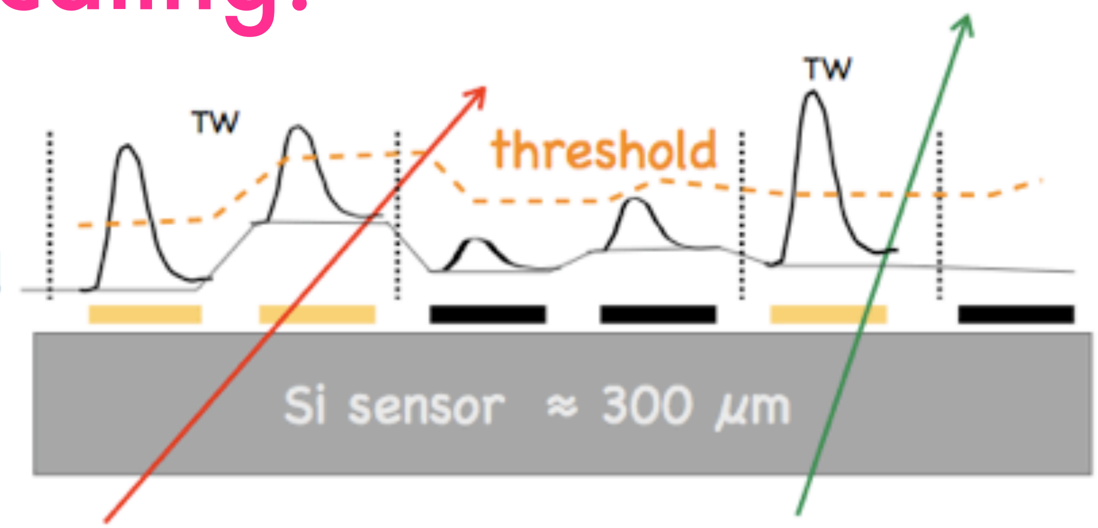
Very similar

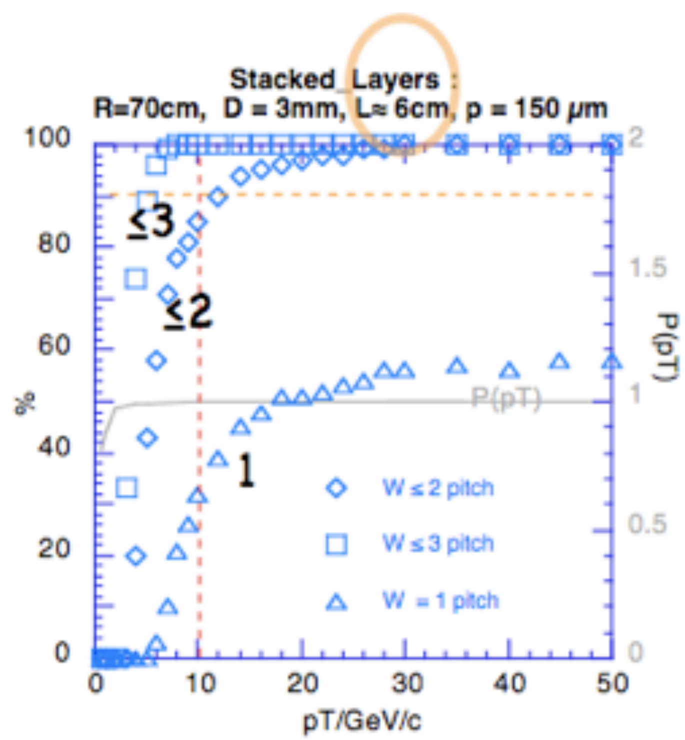
notice scaling!

Stacked Layers

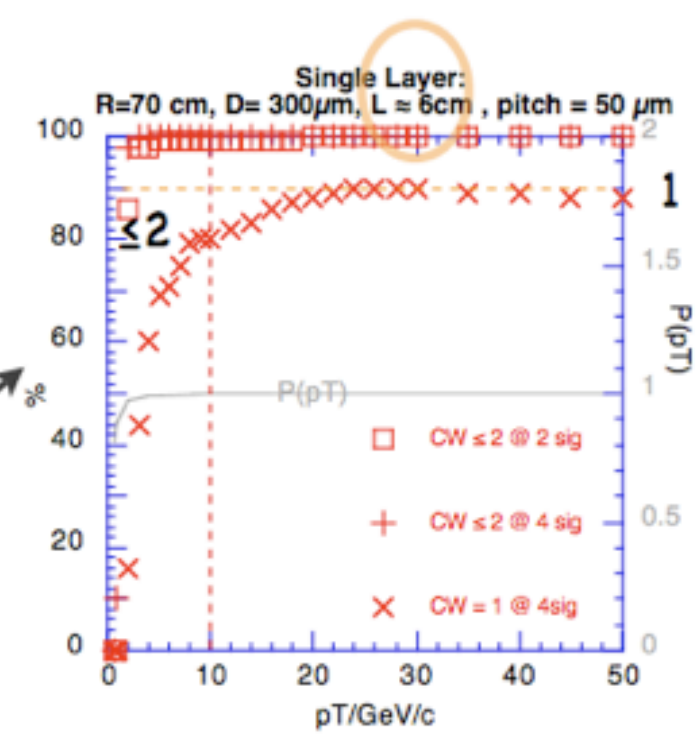


Single Layer





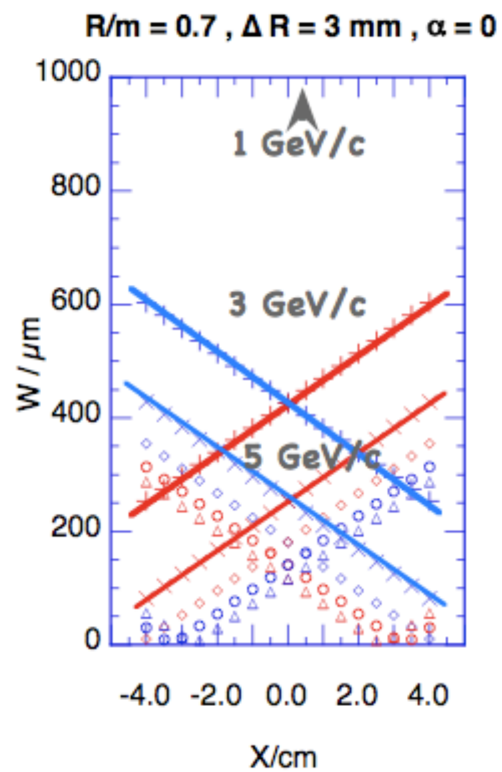
measurements give pT lower limits



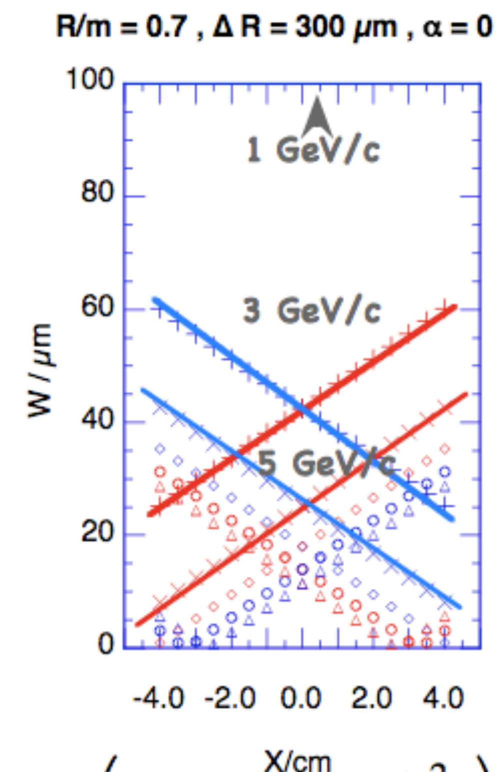
Complications

- Effects due to non-flatness and tilt

Stacked



Cluster width



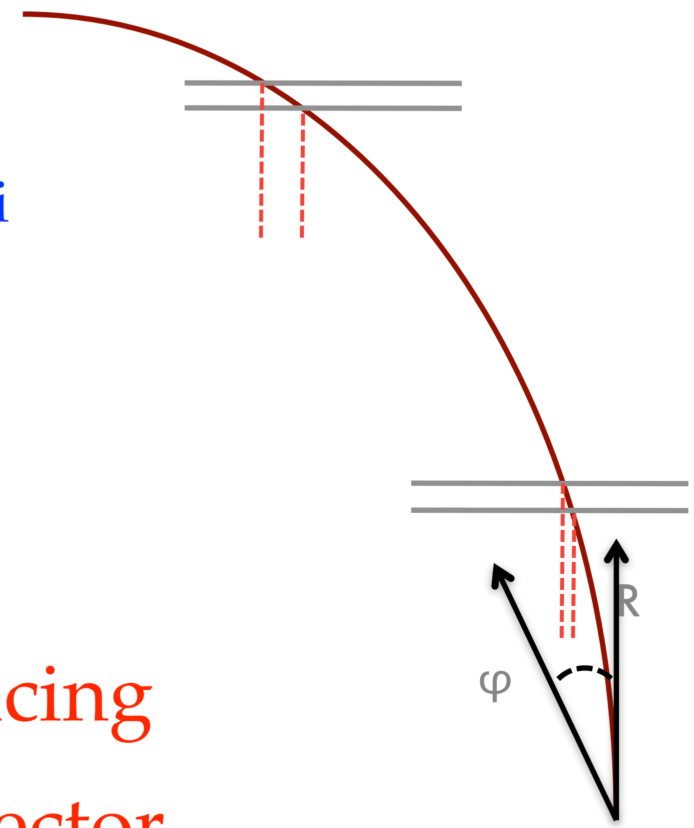
$$TW \approx \Delta R \frac{pT_{\min}}{pT} \pm \Delta R \frac{x}{R}\left(1 + \left(\frac{pT_{\min}}{pT}\right)^2\right)$$

Tilt affects the two in a opposite way:

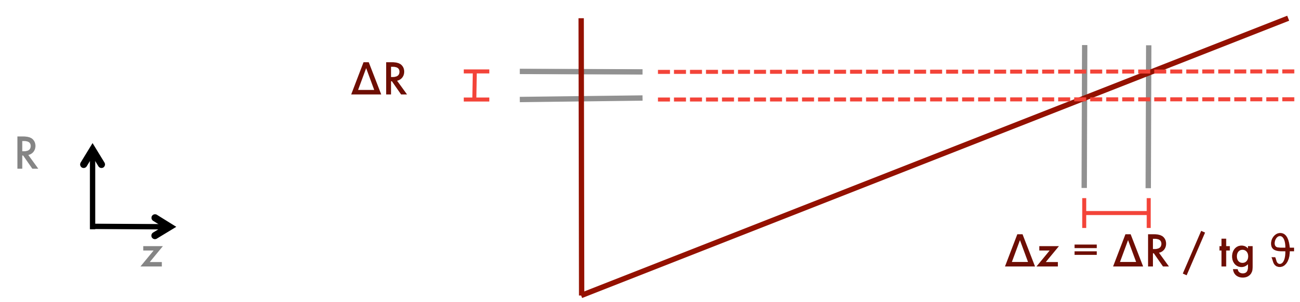
while for the track width goes to correctly compensate
for the stacked introduces an offset that is different for +ve and -ve tracks, though some charge discrimination possible with complex logic

p_T modules in barrel and end-cap

- Sensitivity to p_T from measurement of $\Delta(R\phi)$ over a given ΔR
- For a given p_T, $\Delta(R\phi)$ increases with R
  - A same geometrical cut, corresponds to harder p_T cuts at large radii
  - At low radii, rejection power limited by pitch



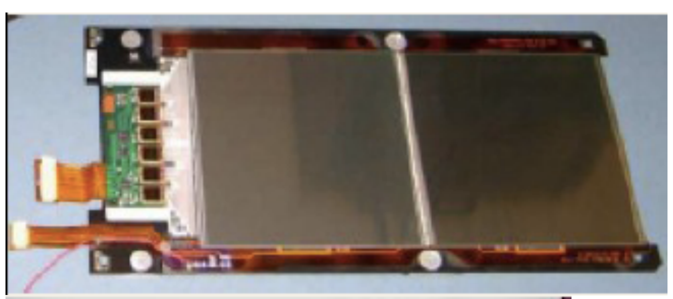
- In the barrel, ΔR is given directly by the sensors spacing
- In the end-cap, it depends on the location of the detector
  - End-cap configuration typically requires wider spacing



Method Validation using LHC collision data in CMS

Double Sided (DS) modules
considered to mimic
the 2-in-1 stacked modules
>> TOB Layer 2
- R = 70 cm
- ToP = 21.9

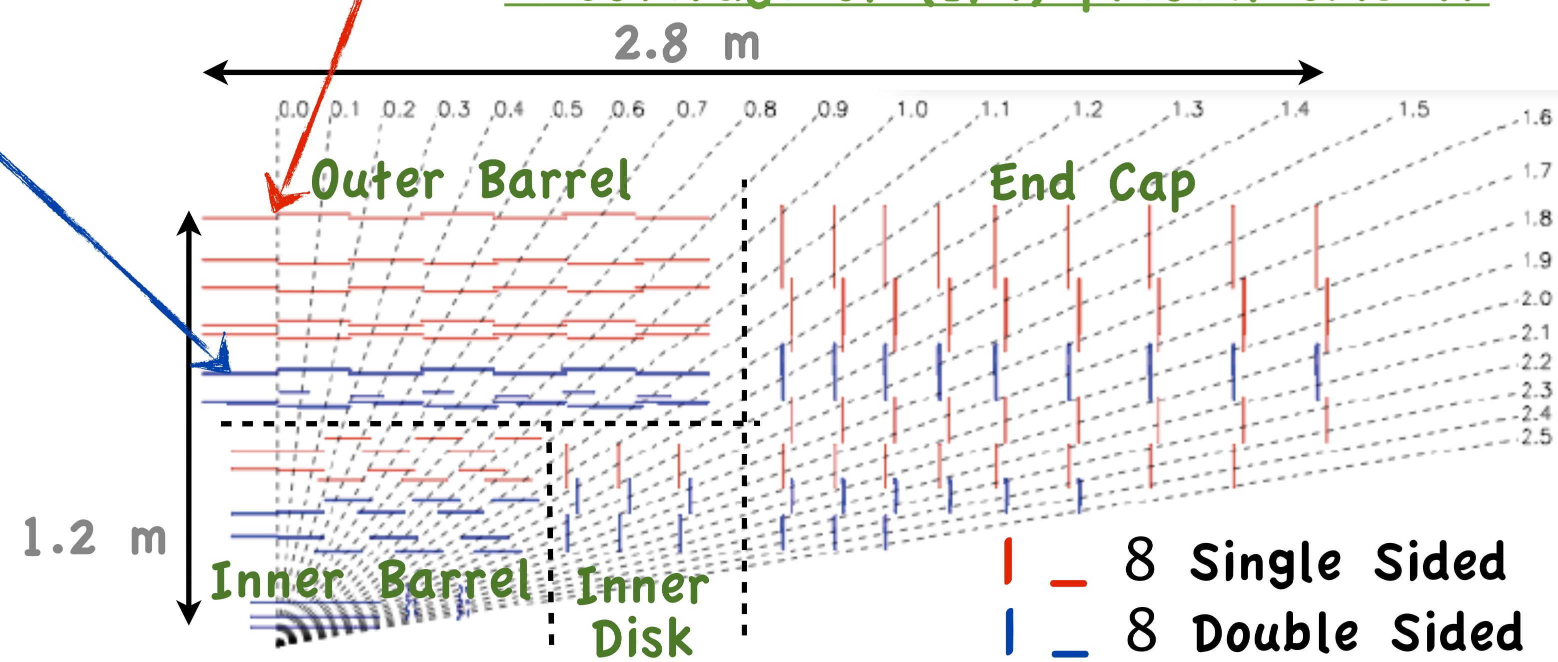
Single Sided (SS) modules
TOB Layer 6
R = 108 cm
ToP = 4.2



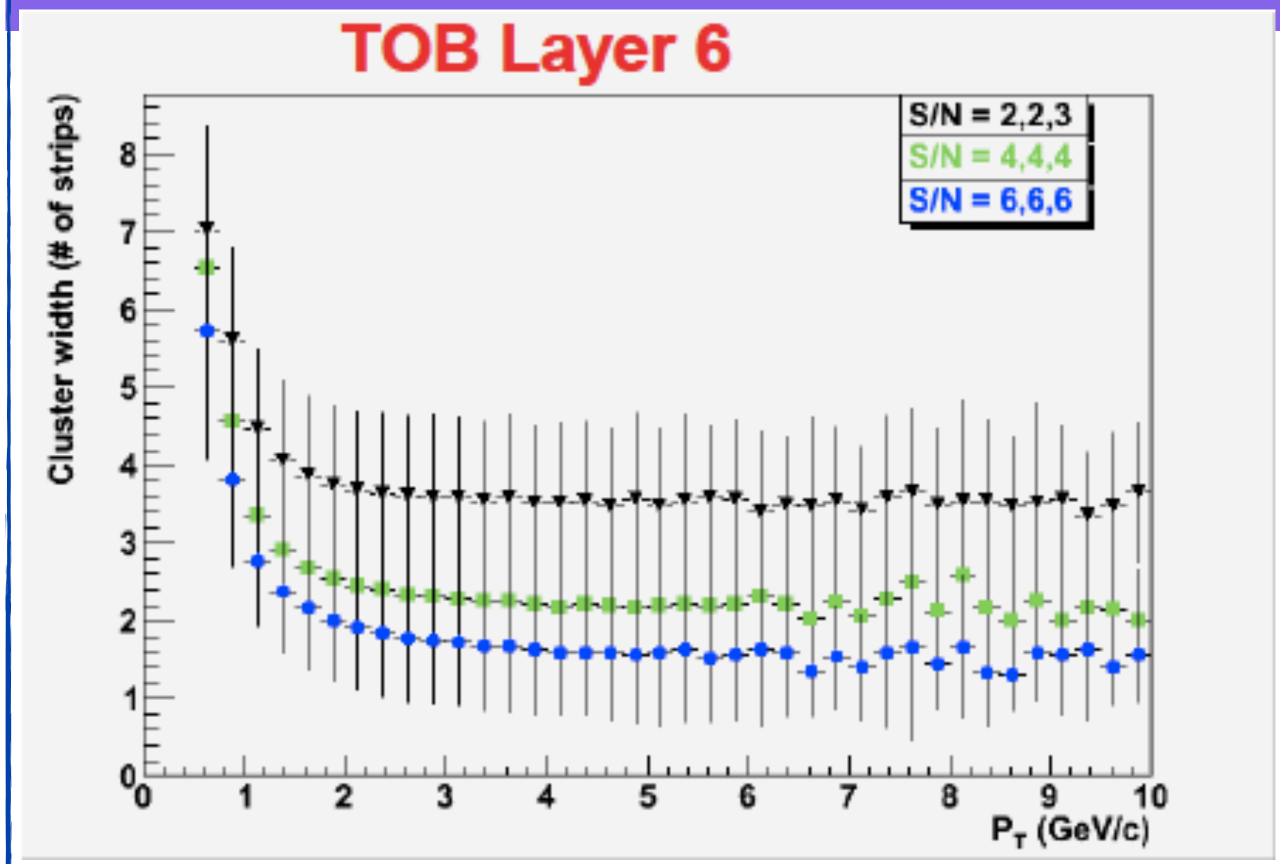
Single Sided Module

Double Sided Module

h Coverage of (1/4) present CMS Tk



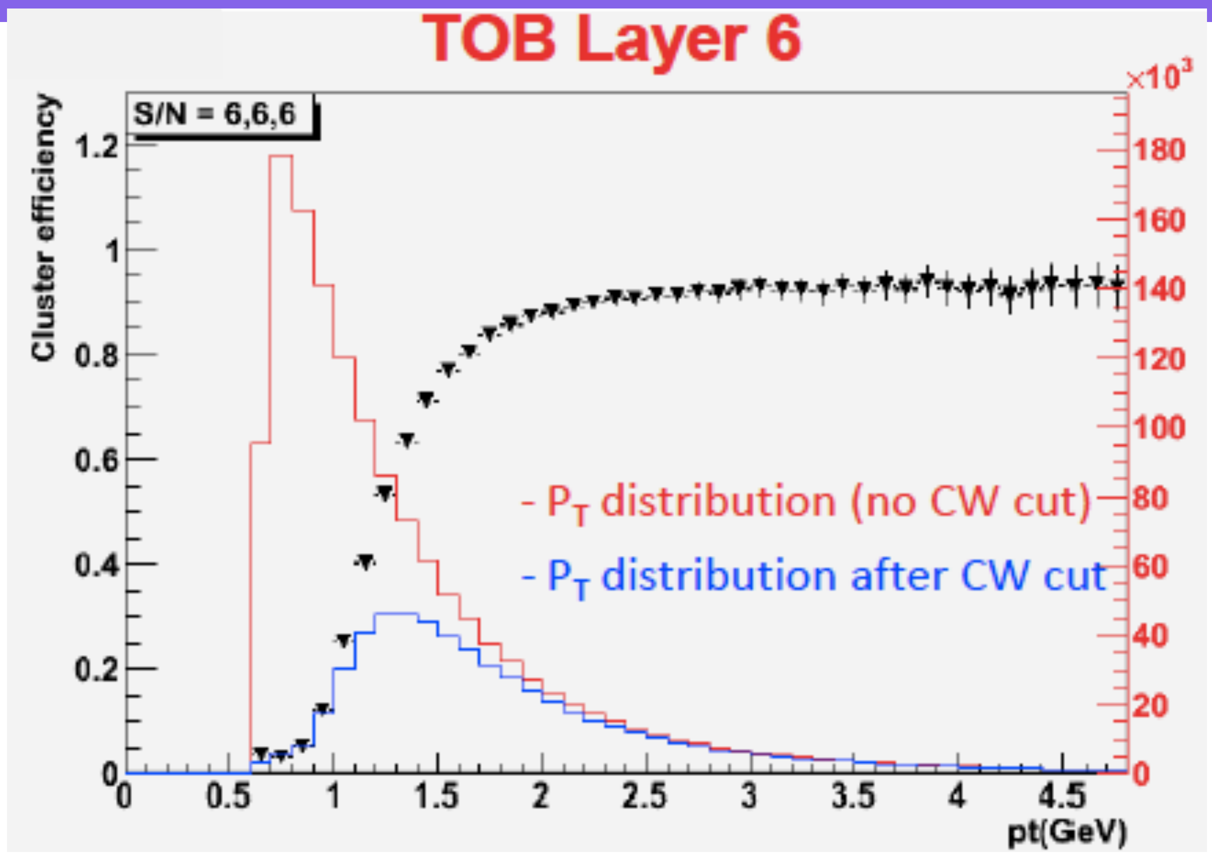
SS: Sensitivity to CW



Tracks CW correlated with reco p_T for various clustering thresholds

>> CW decreases with pT, as foreseen from theoretical model

>> Good pT sensitivity for higher clustering thresholds (S/N > 6) due to suppression of capacitive couplings effects on FE electronics generating false large clusters

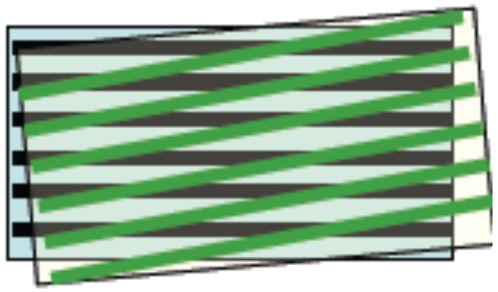


Tracks selected with CW < 3

>> Selection efficiency as a function of p_T superimposed to track p_T distributions

>> Efficiency > 90% yet from 2 GeV/c

Using glued detectors

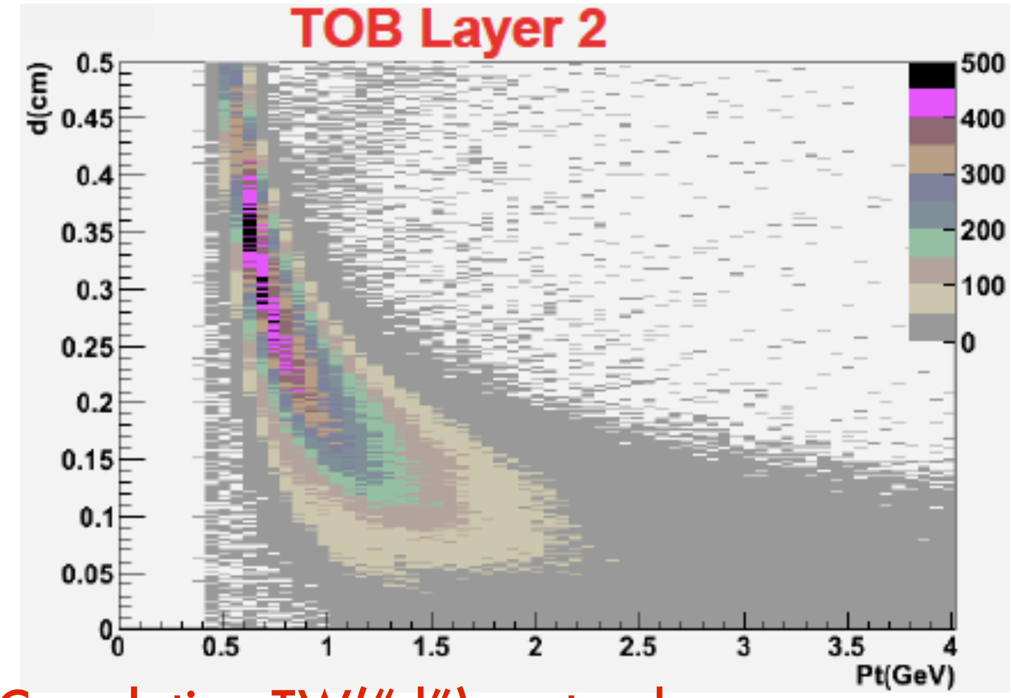


tilt angle: 100 mrad

Glued modules in CMS are used to get z info

>> 2 SS modules are in "stereo" configuration
i.e. rotated by 100 mrad, separated by ~2mm

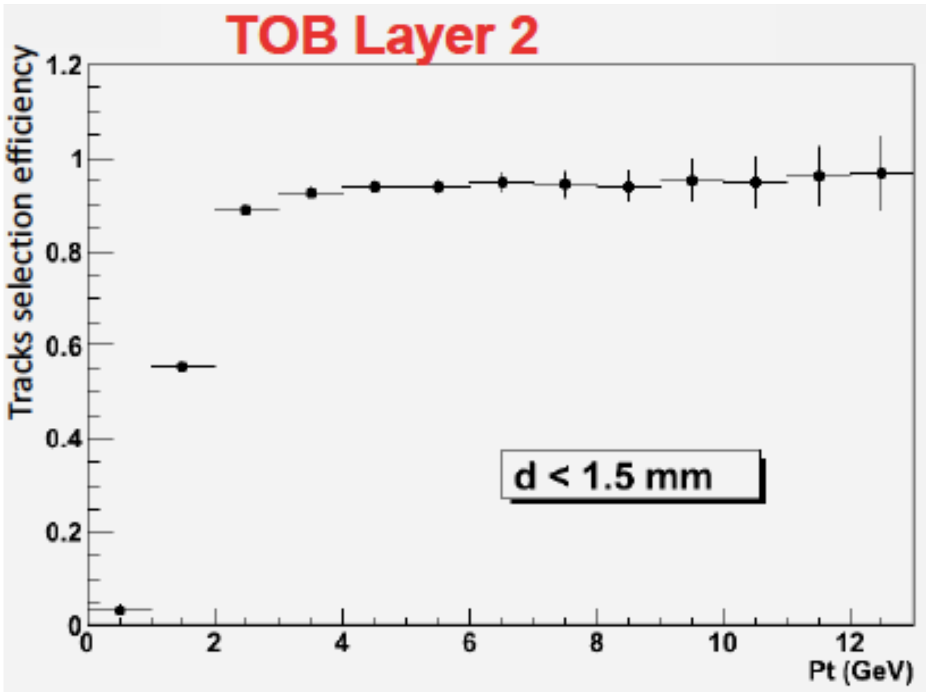
>> Correcting off-line for the stereo angle, we can use these modules as double layer detectors



Correlation TW("d") vs. track p_T

>> High p_T (>2 GeV/c) tracks have clusters almost overlapping

>> Clusters for low p_T ones are far each other



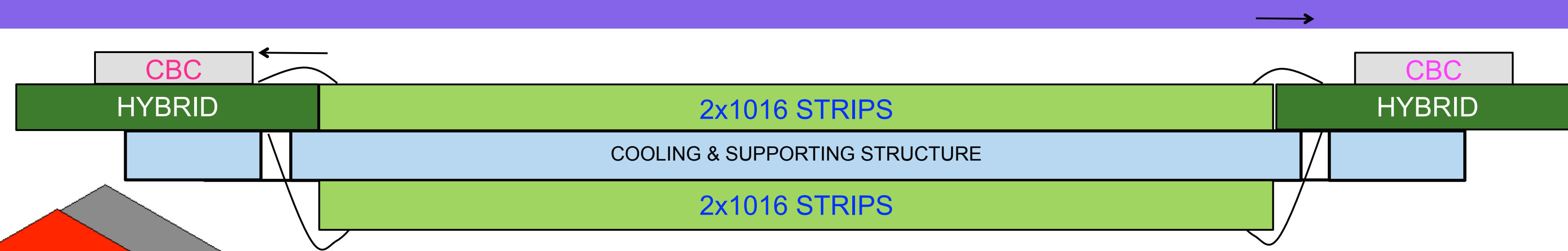
Tracks selected with TW("d") < 1.5 mm

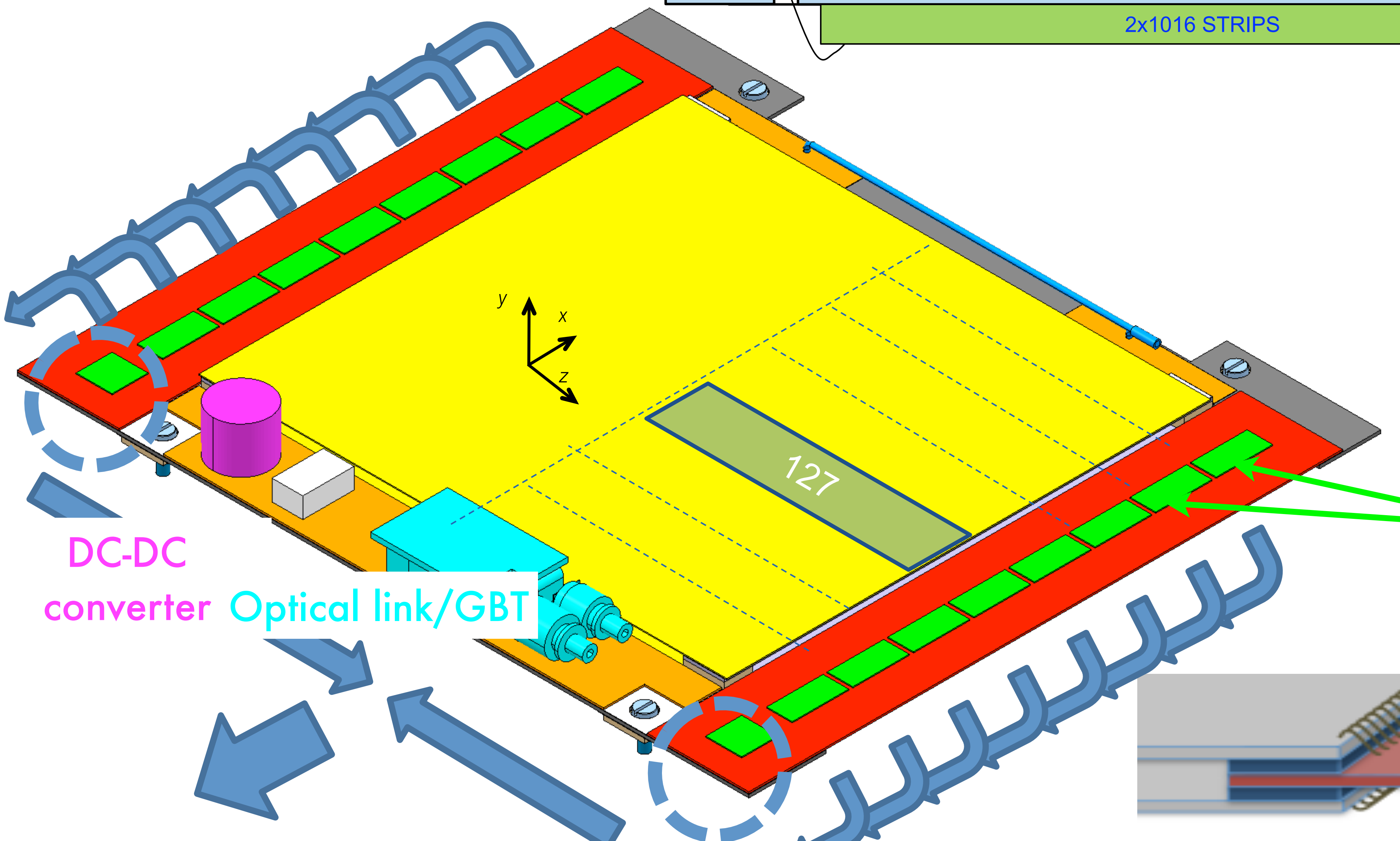
>> Selection efficiency vs. track p_T

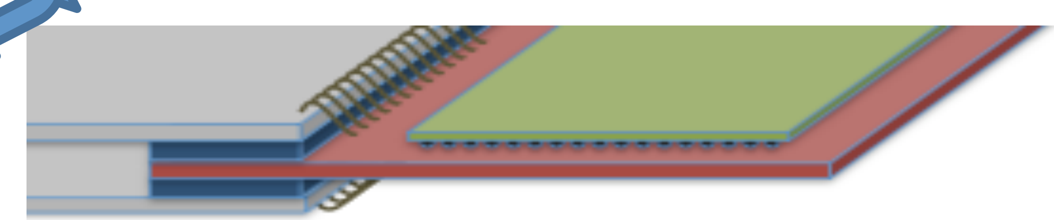
>> Efficient selection (~100%) for high (> 5 GeV/c) p_T tracks

Hardware designs

2S pT-modules



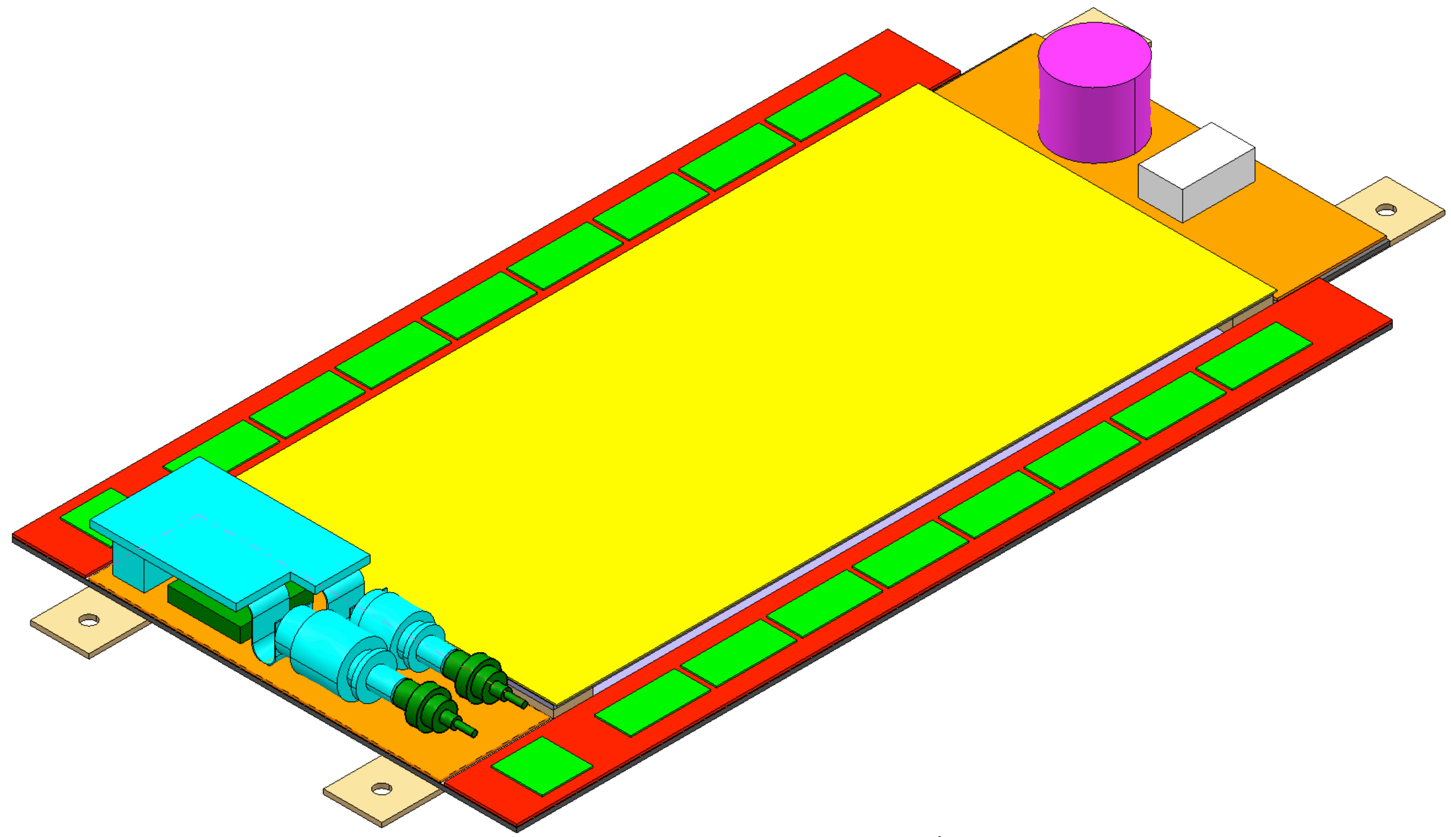


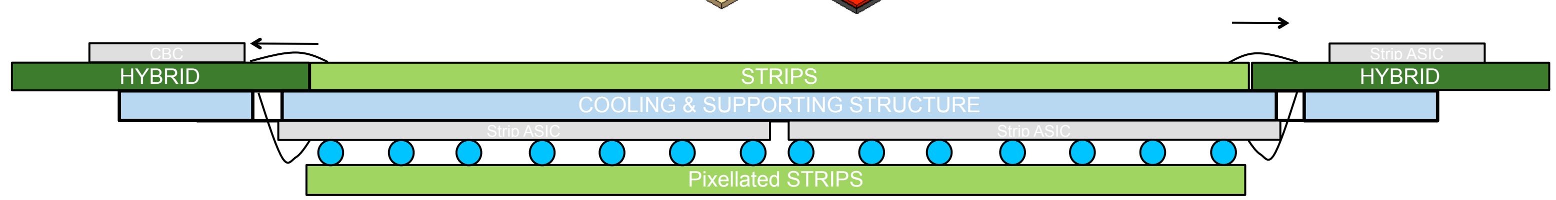


- ≈ 5 cm long strips, ≈ 90 µm pitch, ≈ 10x10 cm^2 overall sensor size
- Wirebonds from the sensors to the hybrid **<u>on the two sides</u>**
  - 2048 channels on each hybrid

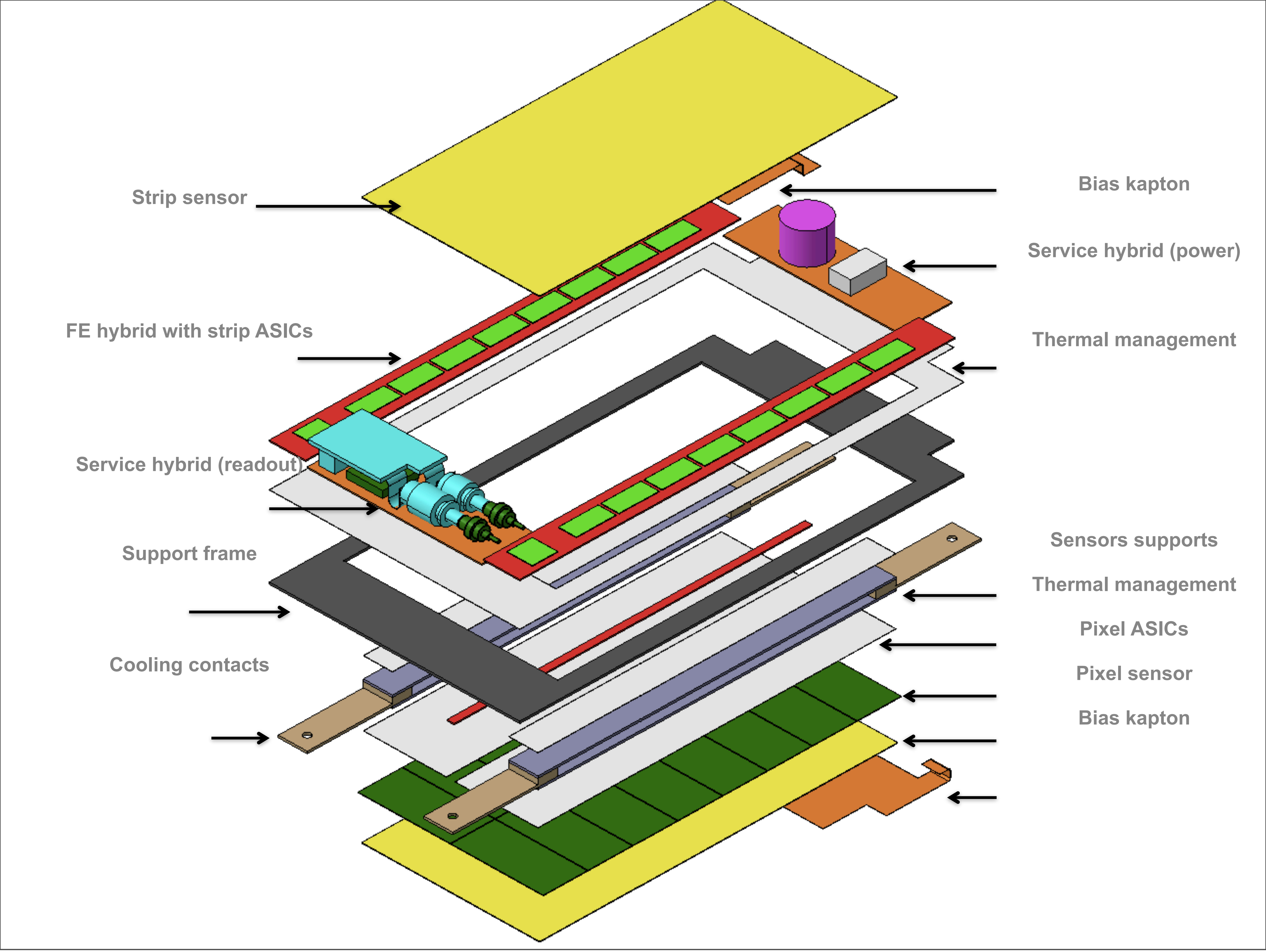
Pixels-Strips (PS) p_T-modules

- Sensors:
  - Top sensor: strips
    - 2×25 mm, 100 μm pitch
  - Bottom sensor: long pixels
    - 100 μm × 1500 μm
  - ≈ 5x10 cm^2 overall sensor size

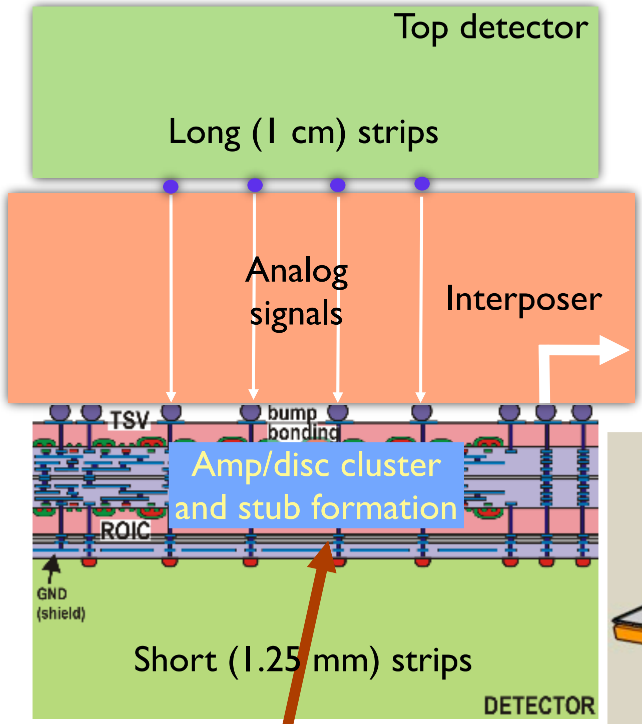




- Readout:
  - Top: wirebonds to “hybrid”
  - Bottom: pixel chips wirebonded to hybrid
  - Correlation logic in the pixel chips


Strip sensor
FE hybrid with strip ASICs
Service hybrid (readout)
Support frame
Cooling contacts
Bias kapton
Service hybrid (power)
Thermal management
Sensors supports
Thermal management
Pixel ASICs
Pixel sensor
Bias kapton

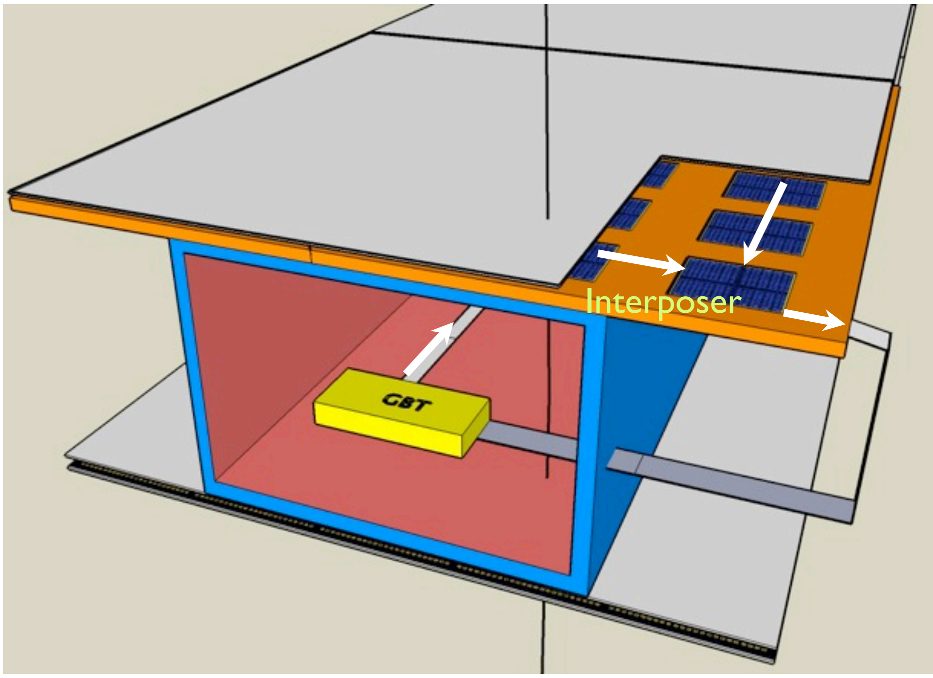
3D p_T-modules

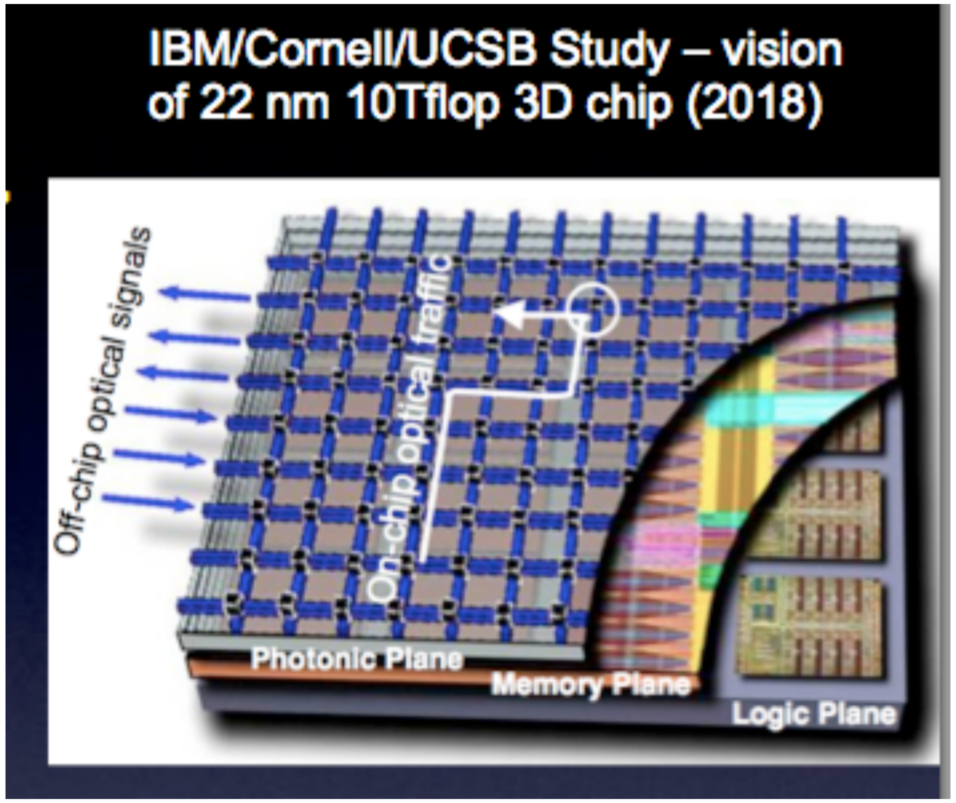


ROIC sees signals from top and bottom sensors all correlations local

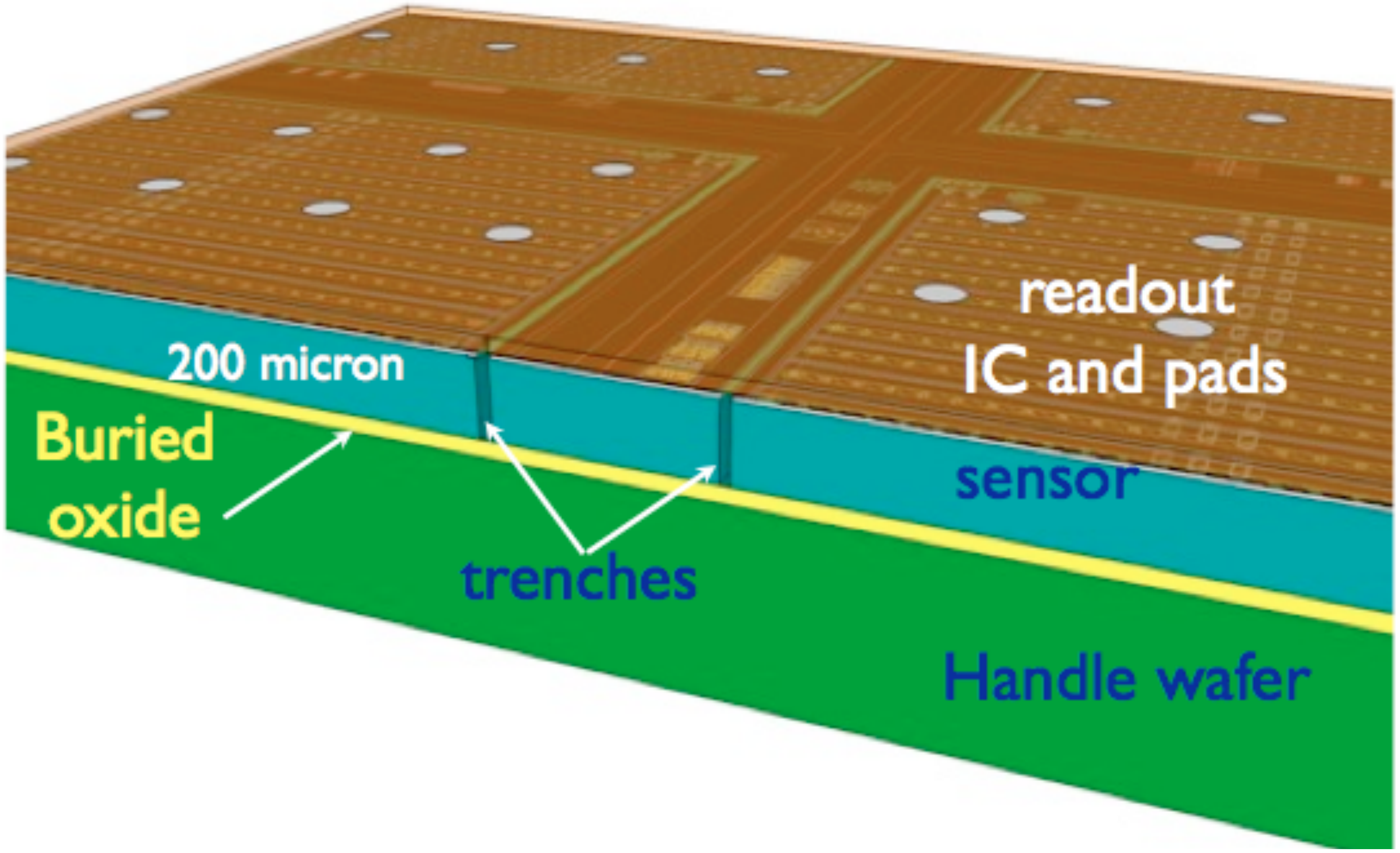
Data Flow

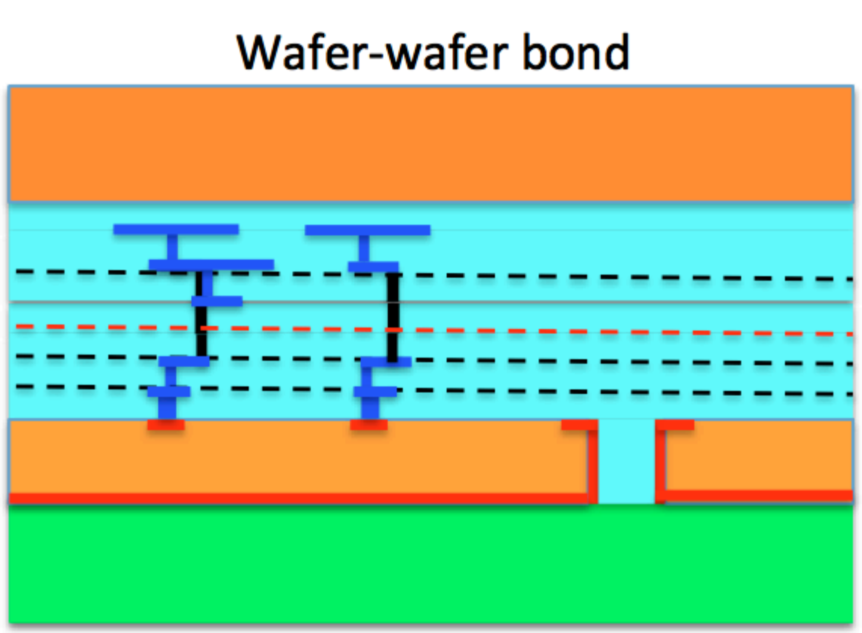
Top sensor analog information flows through interposer to IC mounted on bottom
Long strips on top provide r-phi minimize number of interposer connections
Short strips on the bottom provide Z resolution
ROIC amplifies and discriminates forms stubs and manages pipeline

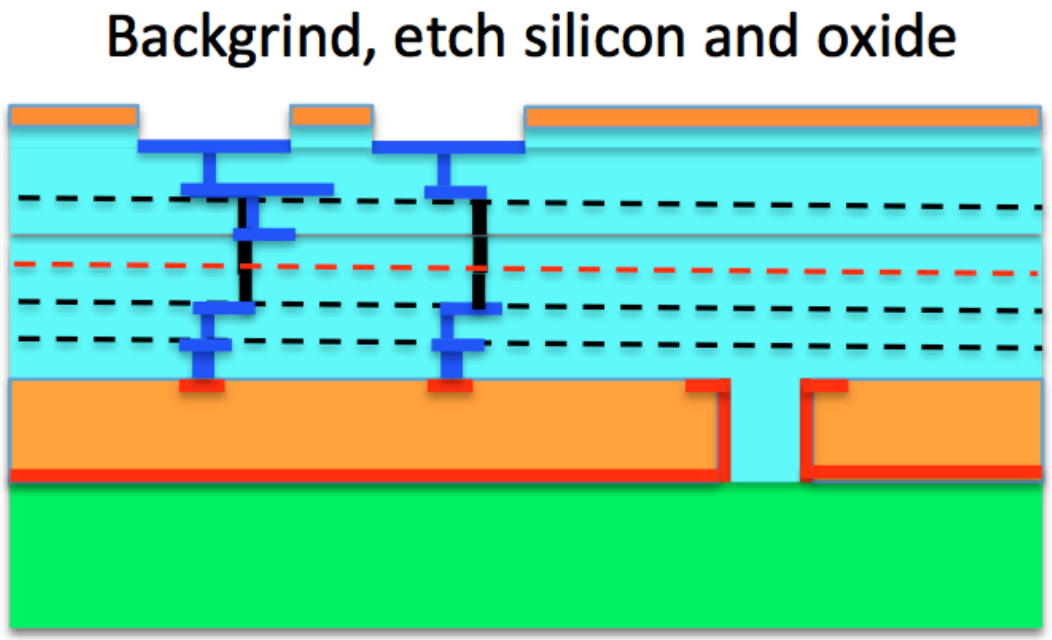




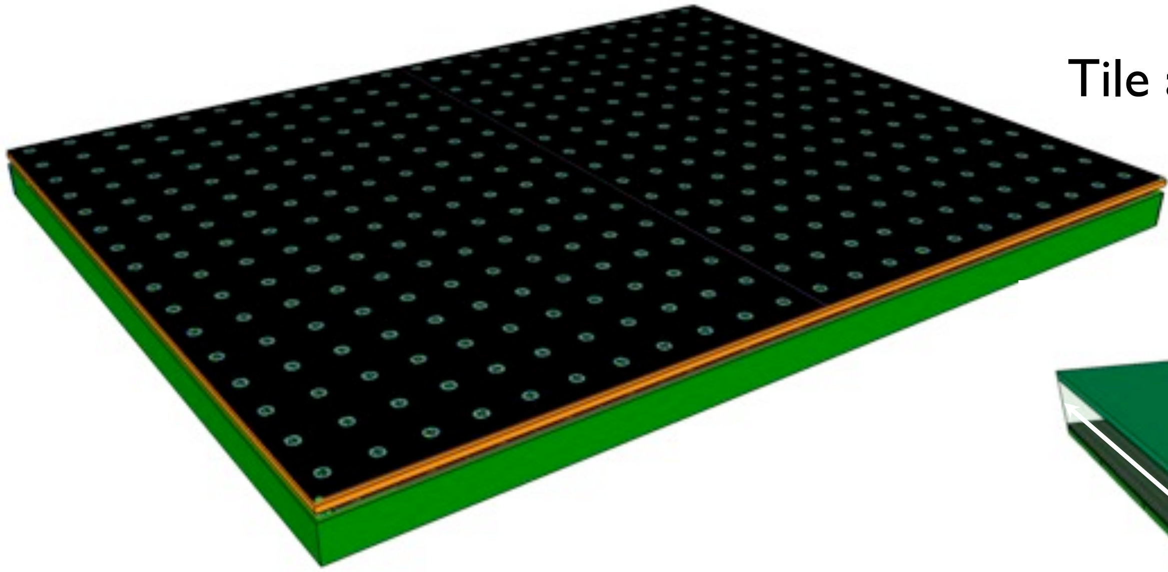
3D modules


200 micron
readout
IC and pads
Buried
oxide
sensor
trenches
Handle wafer


Wafer-wafer bond

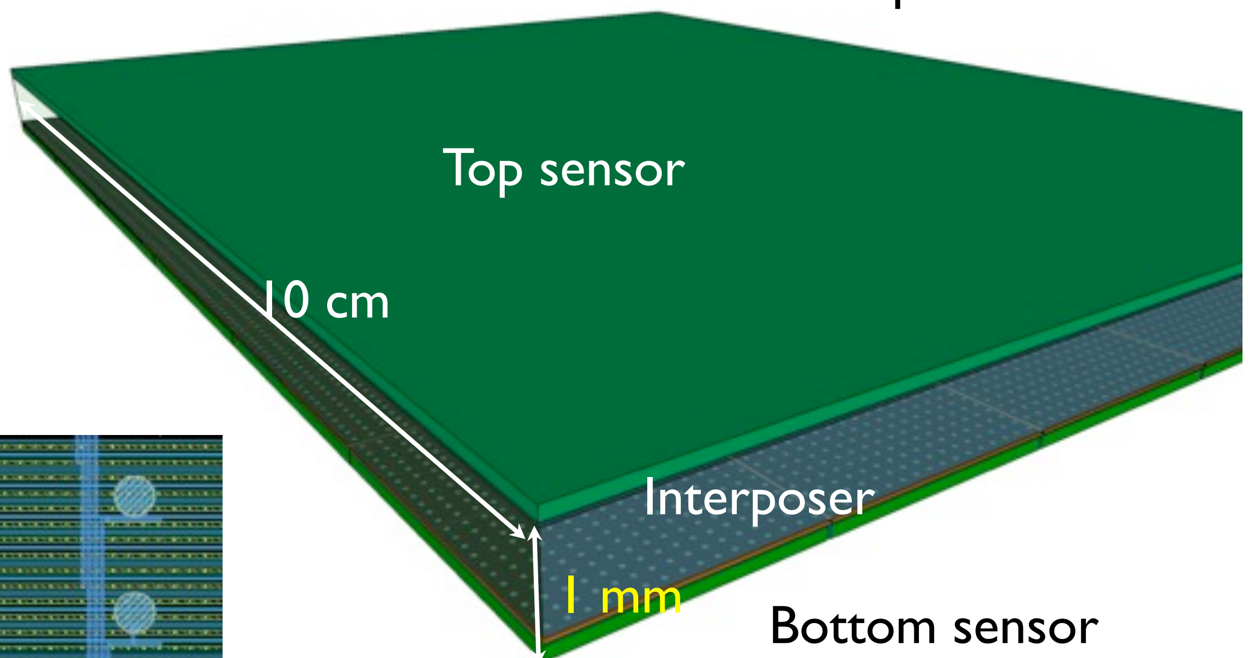

Backgrind, etch silicon and oxide

Tiled Active Edge Modules

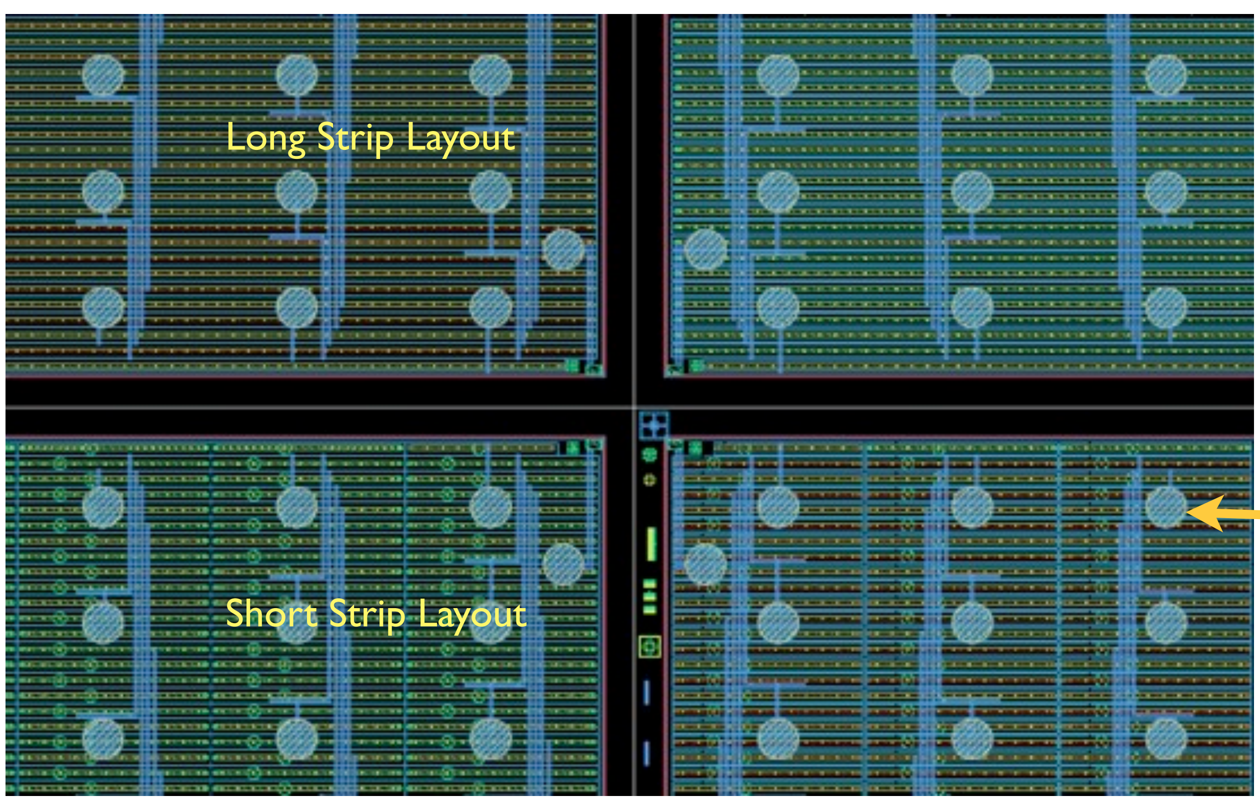


Tile after handle wafer removal and singulation

Full Module with interposer and top sensor



- Design of sensors is complete
- Design of dummy ROIC is complete



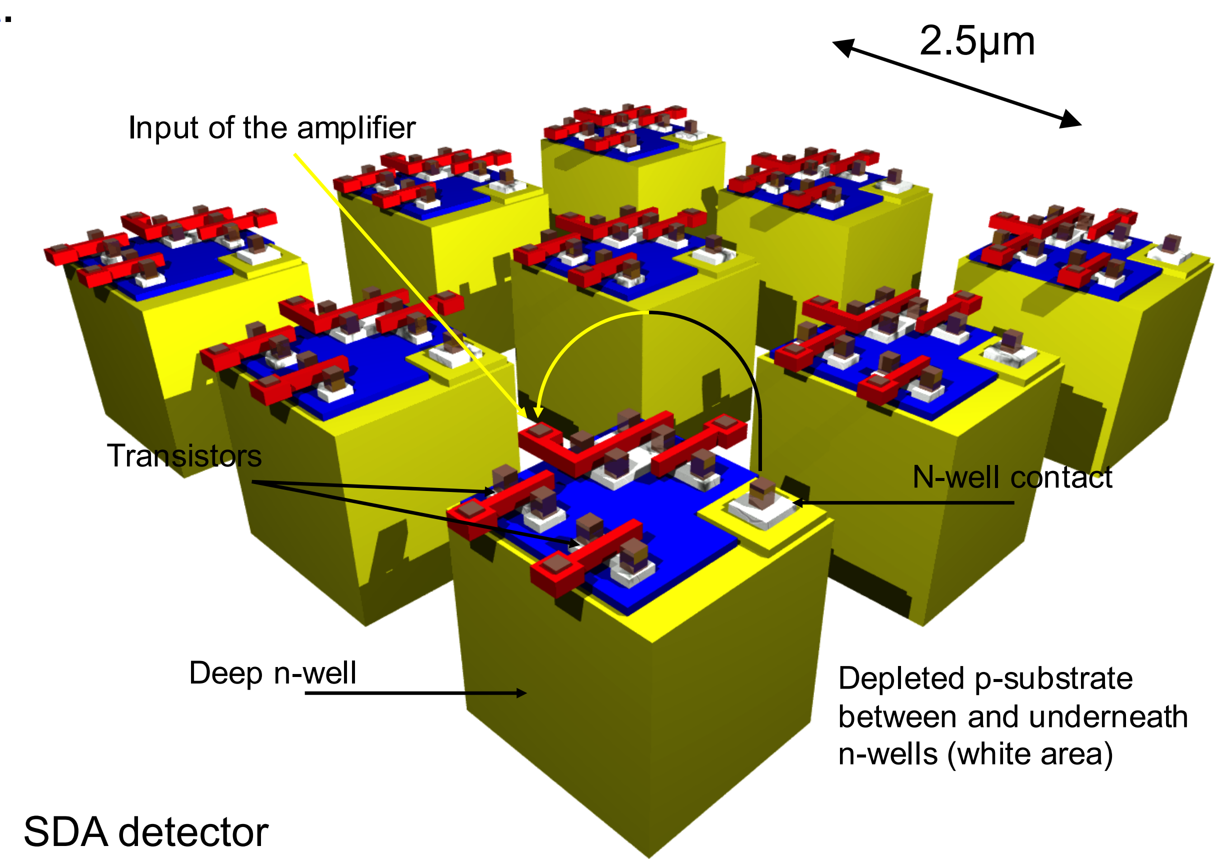
HV CMOS

- High-voltage particle detectors in standard CMOS technologies (or “smart diode arrays” - SDAs) are a new detector family that allows implementation of low-cost radiation-tolerant detectors with good time resolution.

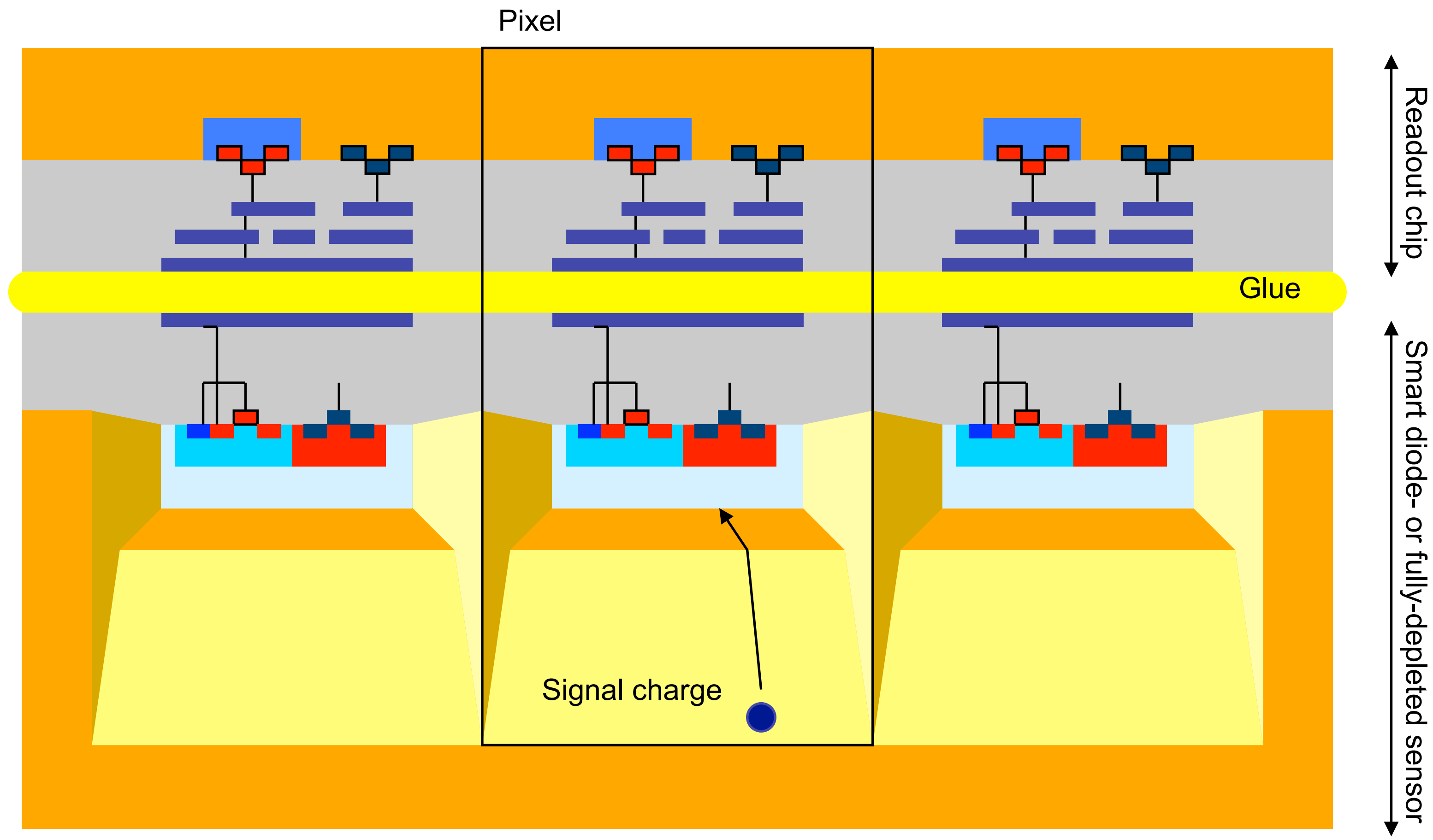
- The deep n-well in a p-substrate is used as the charge-collecting electrode

- The entire CMOS pixel electronics are placed inside the deep n-well. PMOS transistors are placed directly inside the deep n-well, NMOS transistors are situated in their p-wells that are embedded in the deep n-well as well.

- A typical reverse bias voltage is 60 V and the depleted region depth ~15 m. Signal charge collection occurs mainly by drift.



Nine pixels of the SDA-based pixel detector implemented in 65nm CMOS technology.
3D presentation of the real layout.

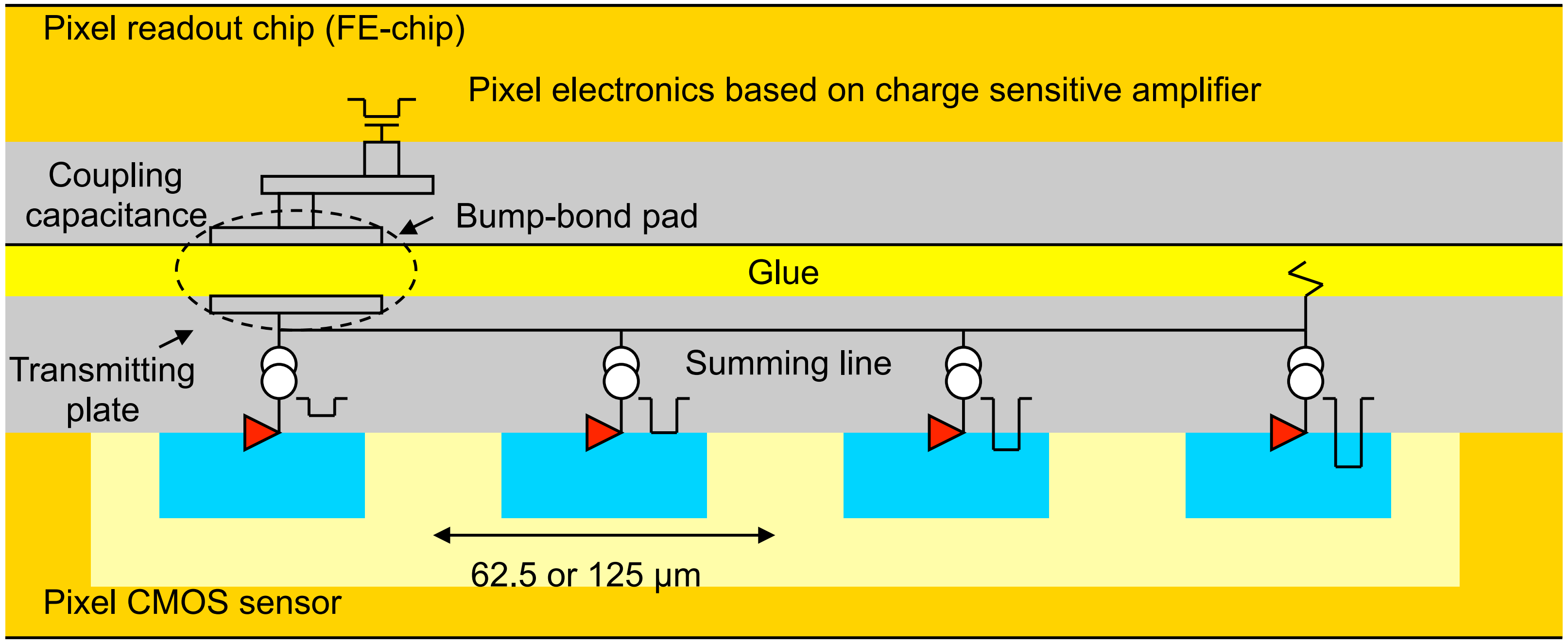


The signal from sensor chip is transmitted capacitively to the readout chip.
The sensor and readout chips are flipped and glued .

- The HVCMOS sensor pixels are smaller than the standard ATLAS pixels, for instance 25μm x 125μm - so that several such pixels cover the area of the original pixel.
- The HV pixels contain low-power (~5 μW) CMOS electronics based on a charge sensitive amplifier and a comparator.

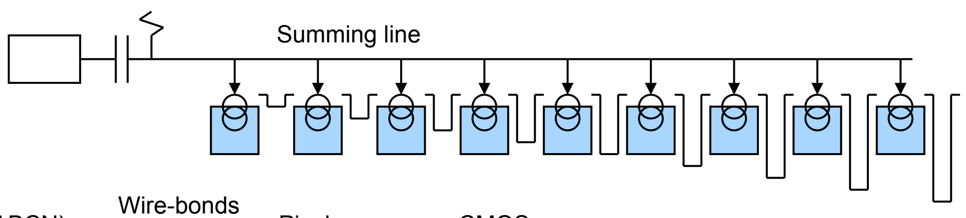
- The signals of a few pixels are summed, converted to voltage and transmitted to the charge sensitive amplifier in the corresponding char of the FE chip using AC coupling.

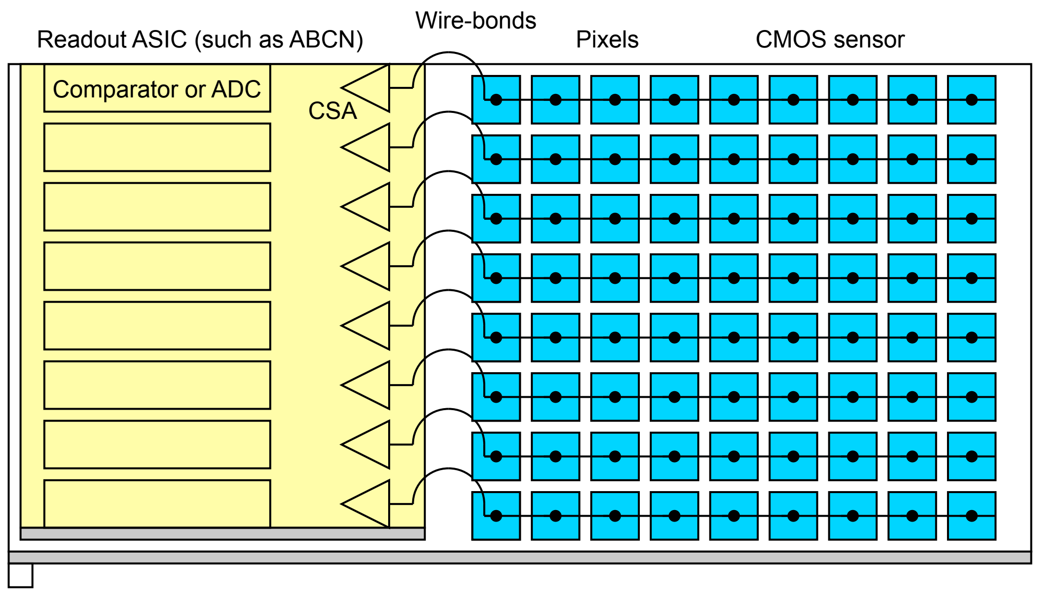
- Each of the pixels that couple to one FE receiver can have its unique signal amplitude, so that the pixel can be identified by examining th amplitude information generated in FE chip.
- In this way, spatial resolution in - and z-direction can be improved



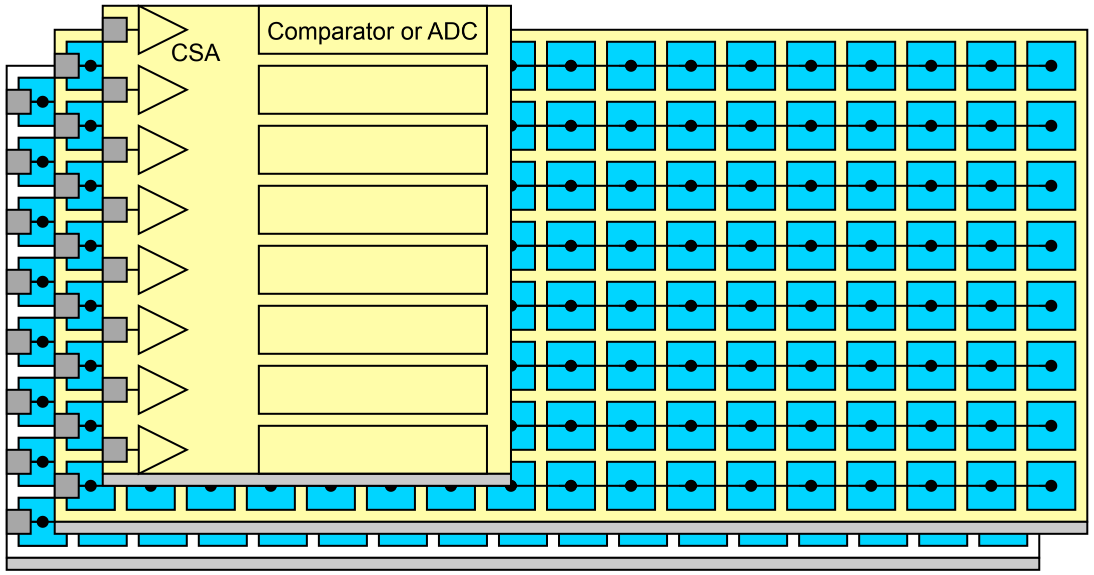
Usage for p_T-modules

- Every pixel generates a digital pulse with unique amplitude of logic one.
- The pixel outputs are summed, converted to voltage signal and transmitted to readout ASIC.

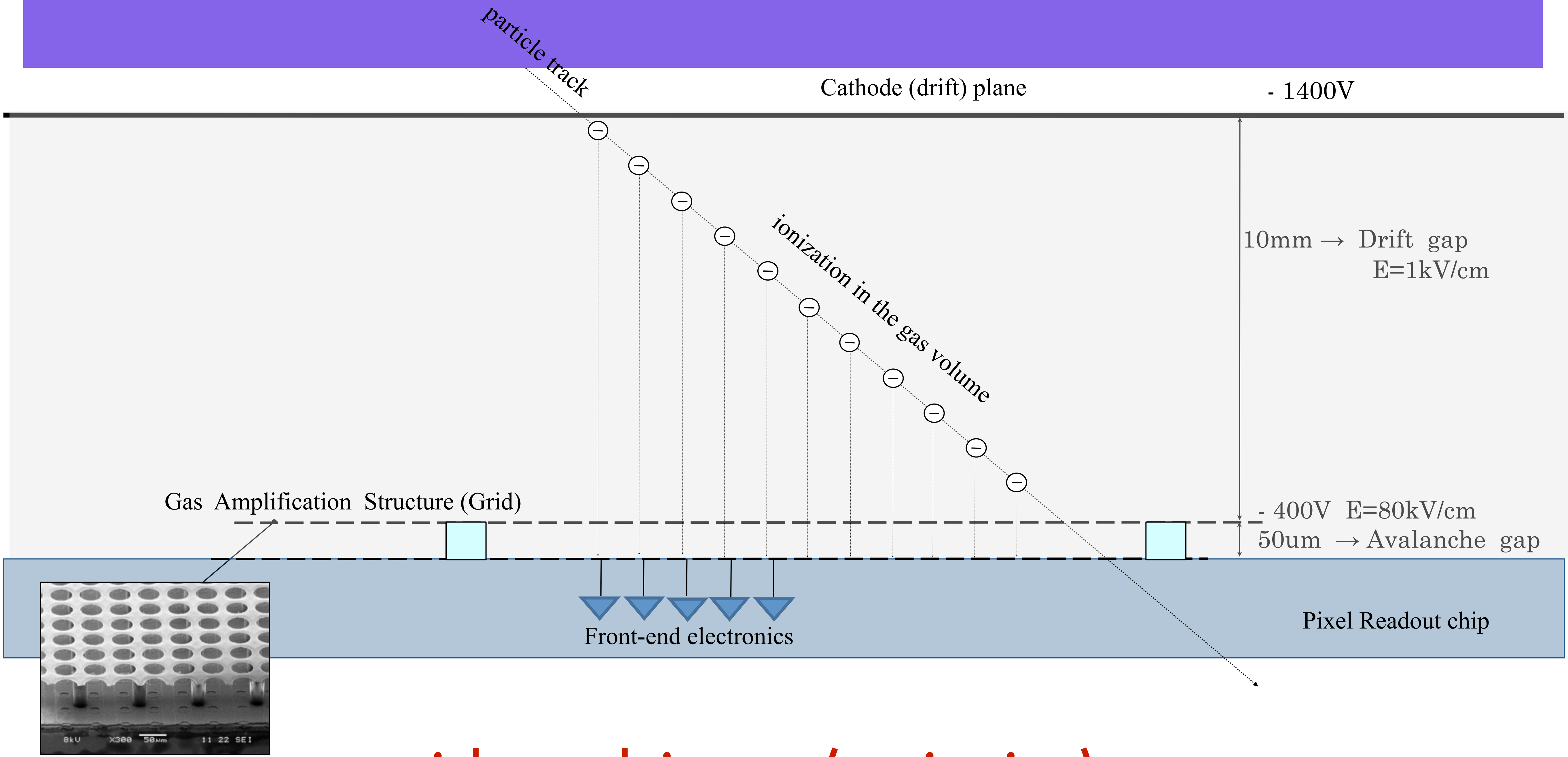




- Simultaneous readout from two 2D sensitive layers. Signals from two sensor layers can be easily combined in a single readout ASIC.

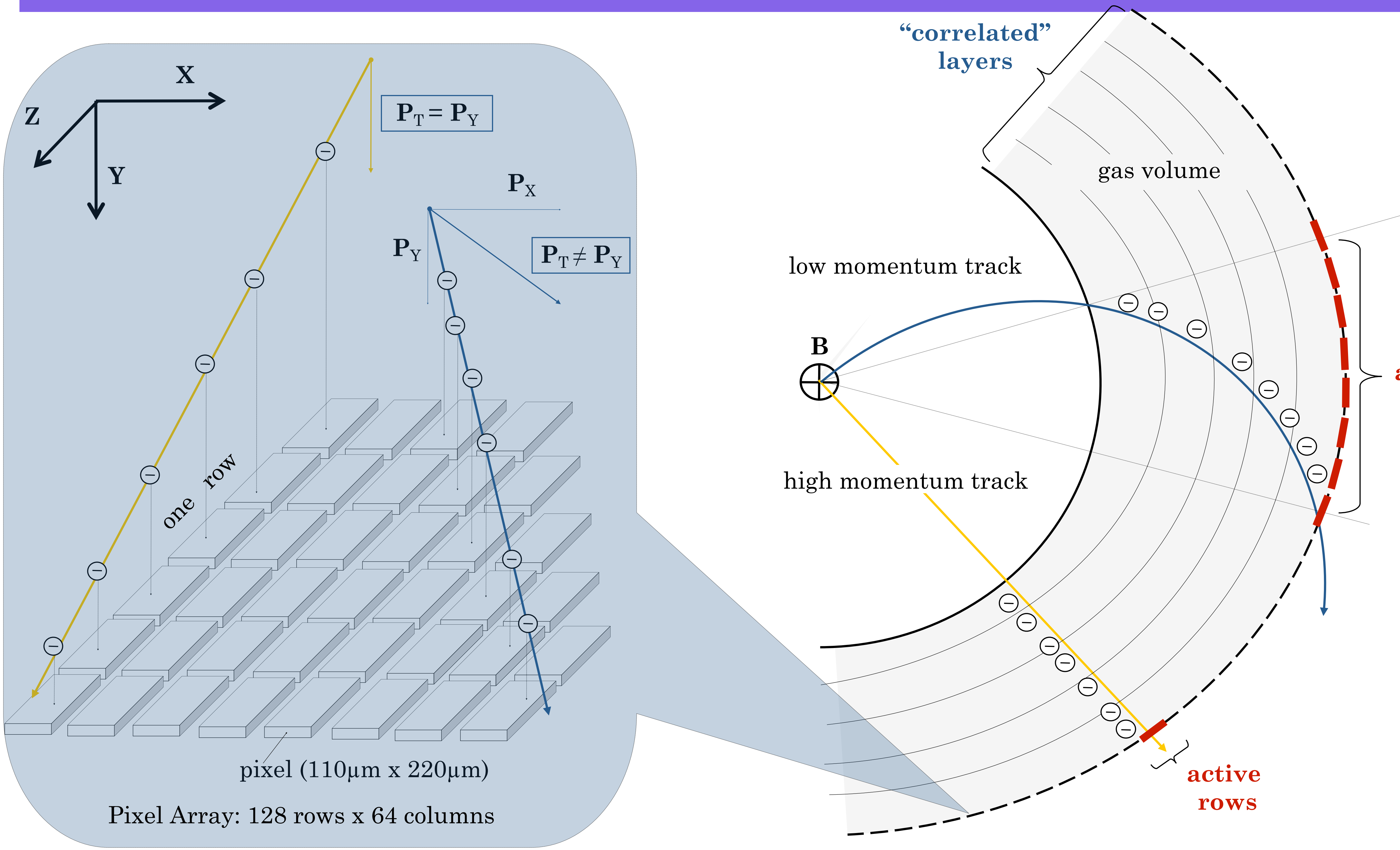


GridPix: Gaseous Pixel Detector



- particle track image (projection)
- 3D track reconstruction

Track p_T discrimination with GridPix



number of active rows can be taken as criteria for high-pT track selection