CMS Silicon Tracker upgrade for HL-LHC

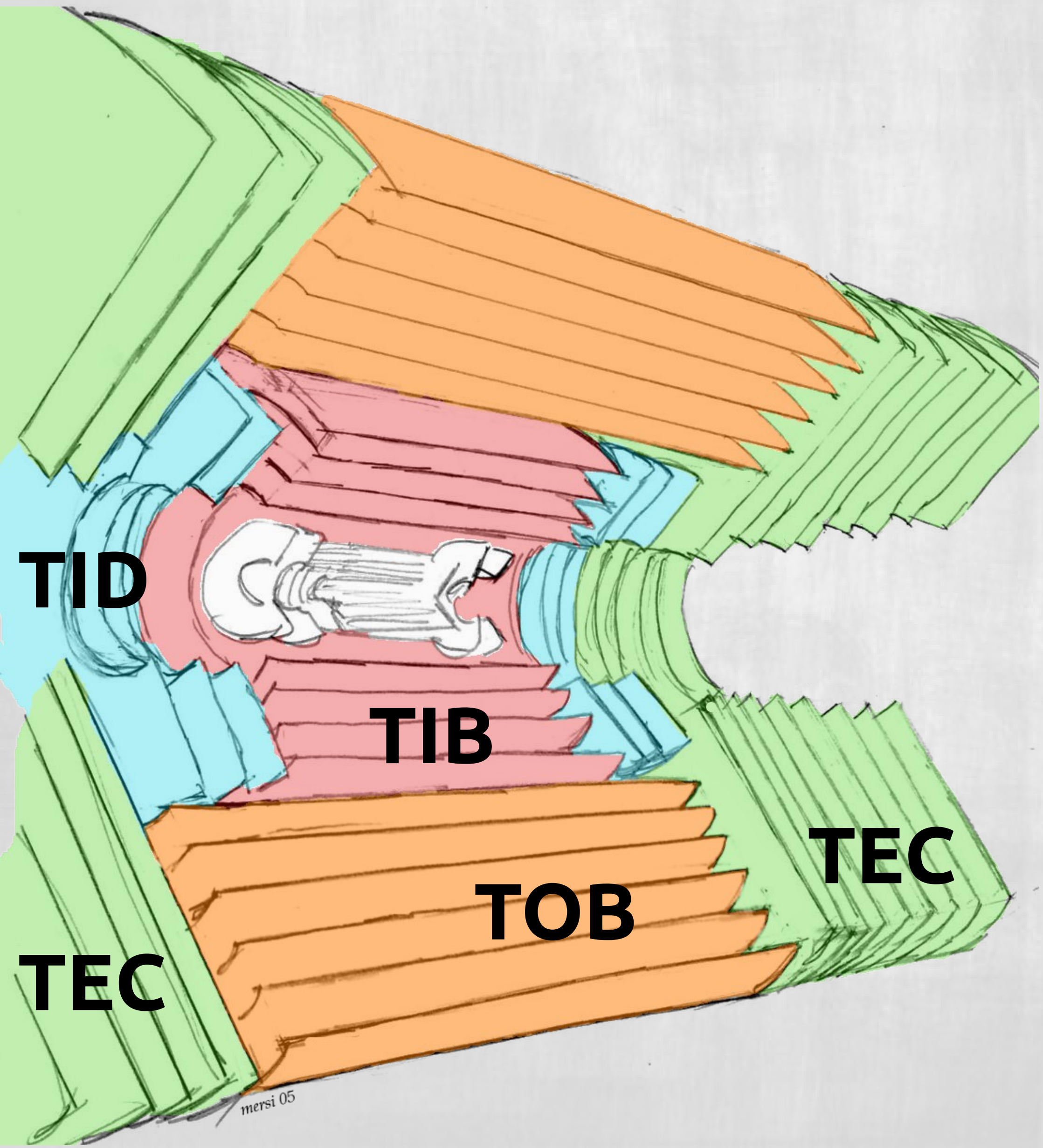
Stefano Mersi – RD11

Florence – July 8th 2011

Current CMS tracker,
LHC & Tracker upgrades

Upgrading the outer tracker
Upgrade technologies
The building blocks: modules
System integration
Level-1 tracking?
And the vertex detector?
Conclusions

The detector



Volume	23 m^3
Active area	200 m^2
Modules	15'148
Front-end chips	72'784
Read-out channels	9'316'352
Bonds	24'000'000
Optical channels	36'392

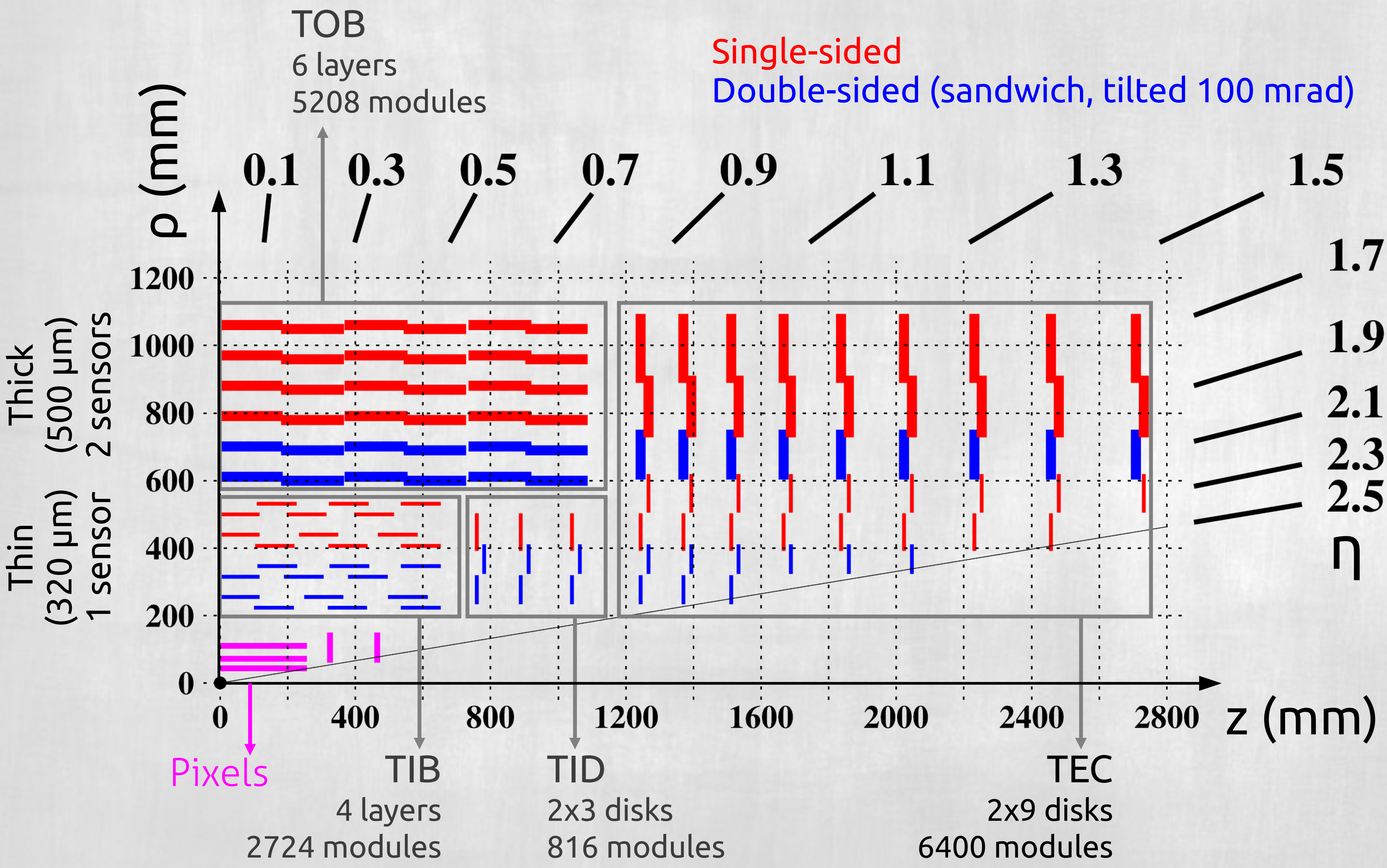
Raw data rate: 1 Tbyte/s

Power dissipation: 30 kW

Nominal operate T: -10°C

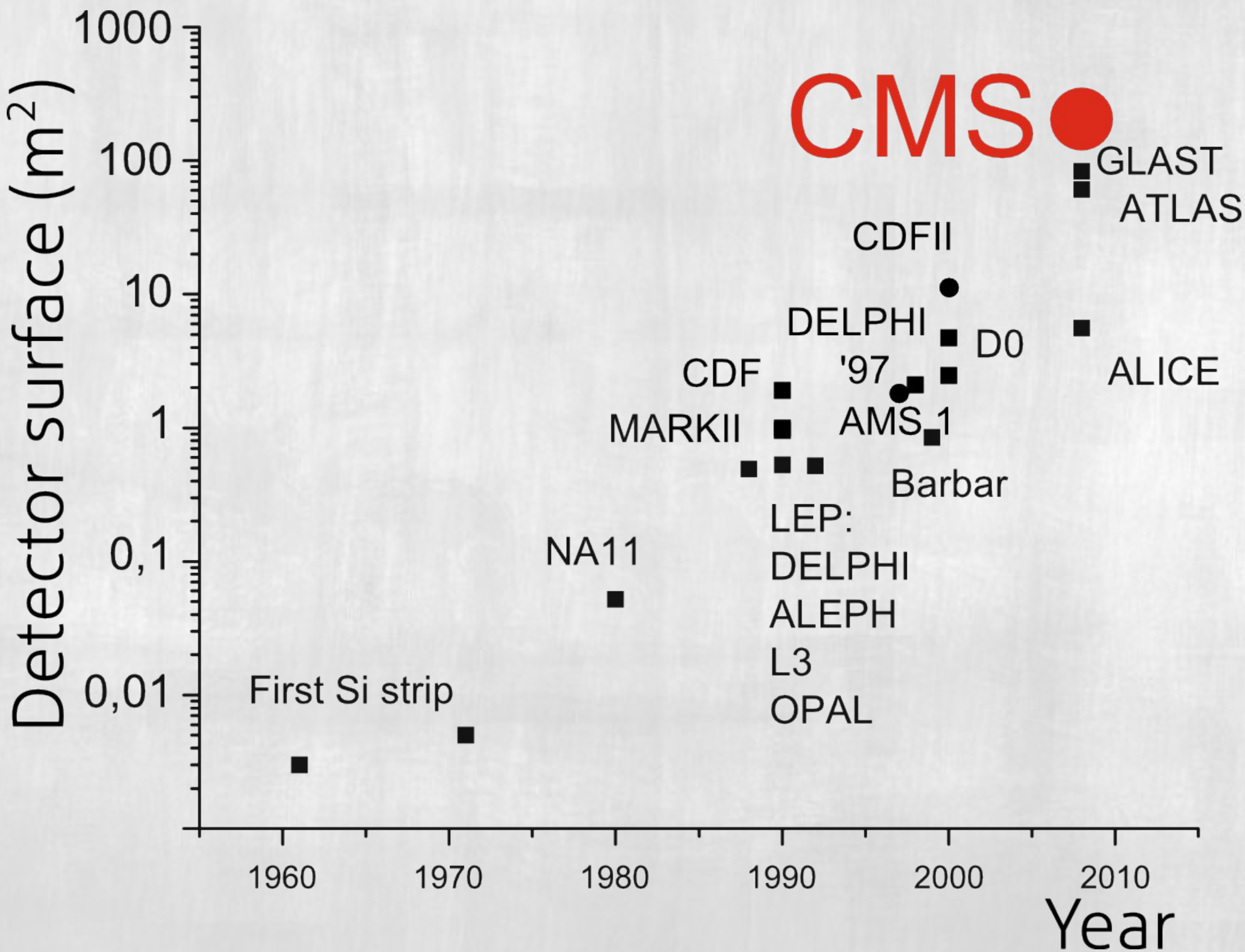
Magnetic field: 3.8 T

The layout



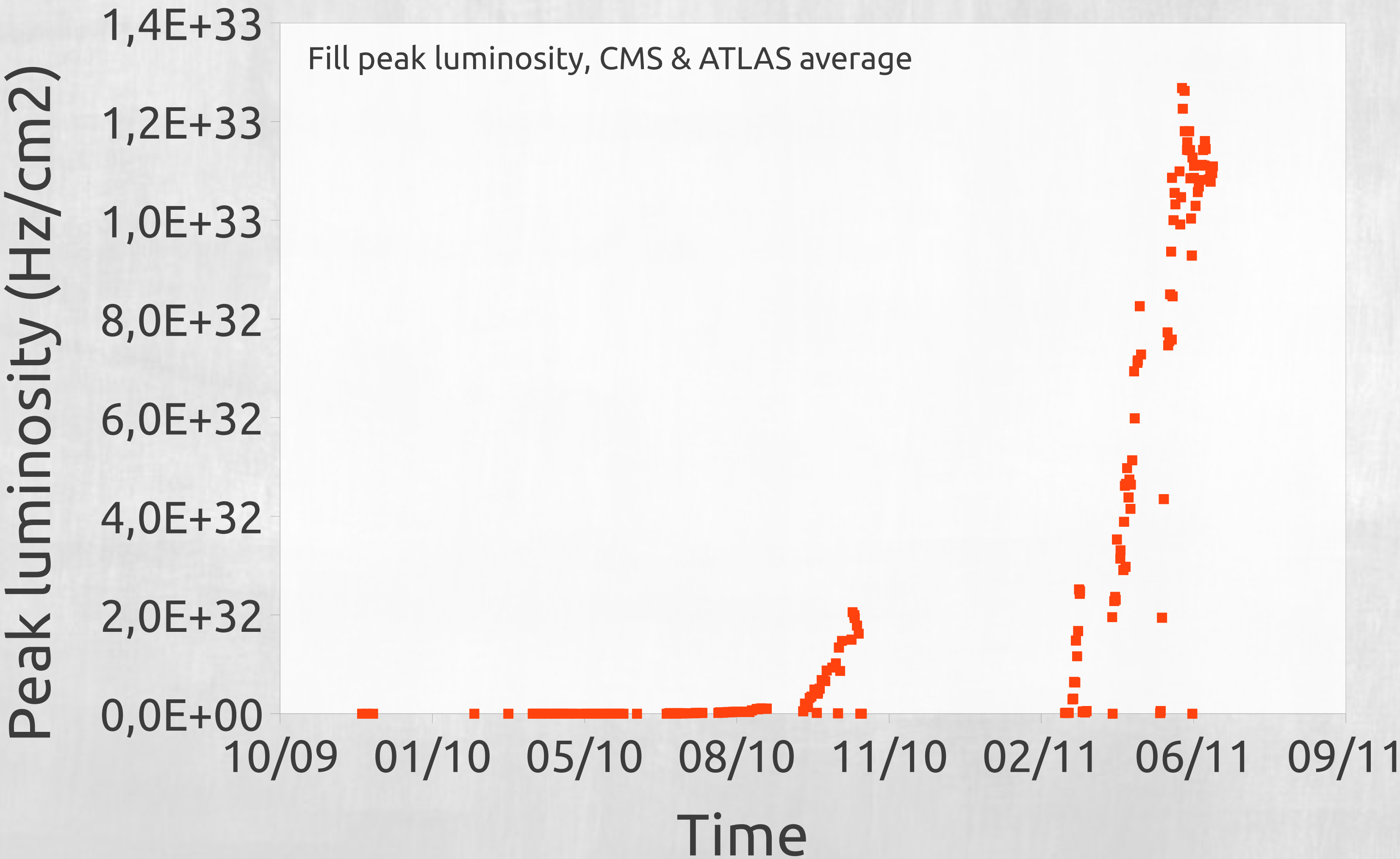
TOB
6 layers
5208 modules
Single-sided
Double-sided (sandwich, tilted 100 mrad)
ρ (mm)
0.1
0.3
0.5
0.7
0.9
1.1
1.3
1.5
1.7
1.9
2.1
2.3
2.5
η
1200
1000
800
600
400
200
0
Thick (500 μm) 2 sensors
Thin (320 μm) 1 sensor
0
400
800
1200
1600
2000
2400
2800
z (mm)
Pixels
TIB
4 layers
2724 modules
TID
2x3 disks
816 modules
TEC
2x9 disks
6400 modules

Some perspective



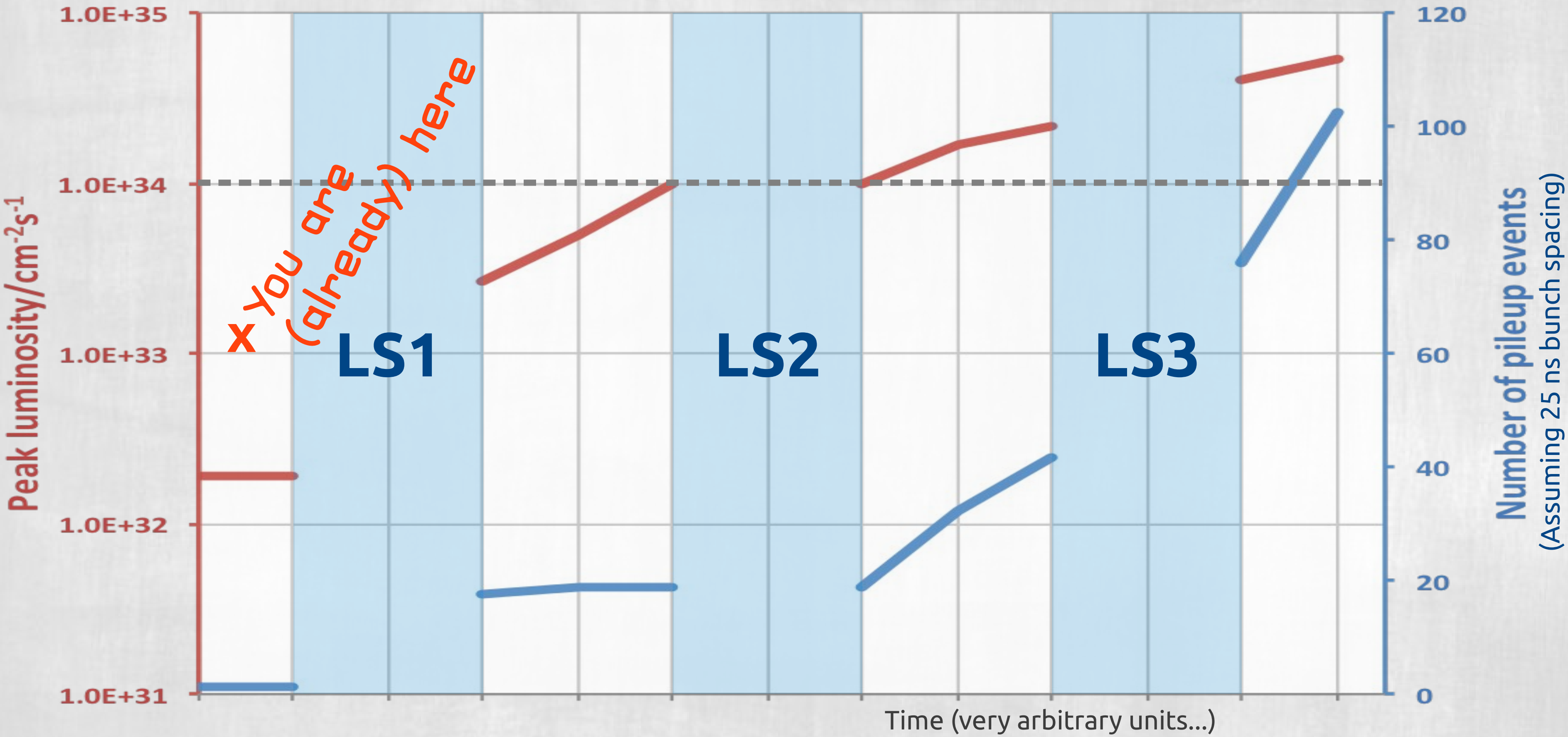
LHC Luminosity

The LHC performance is increasing at an impressive rate:



Luminosity increase

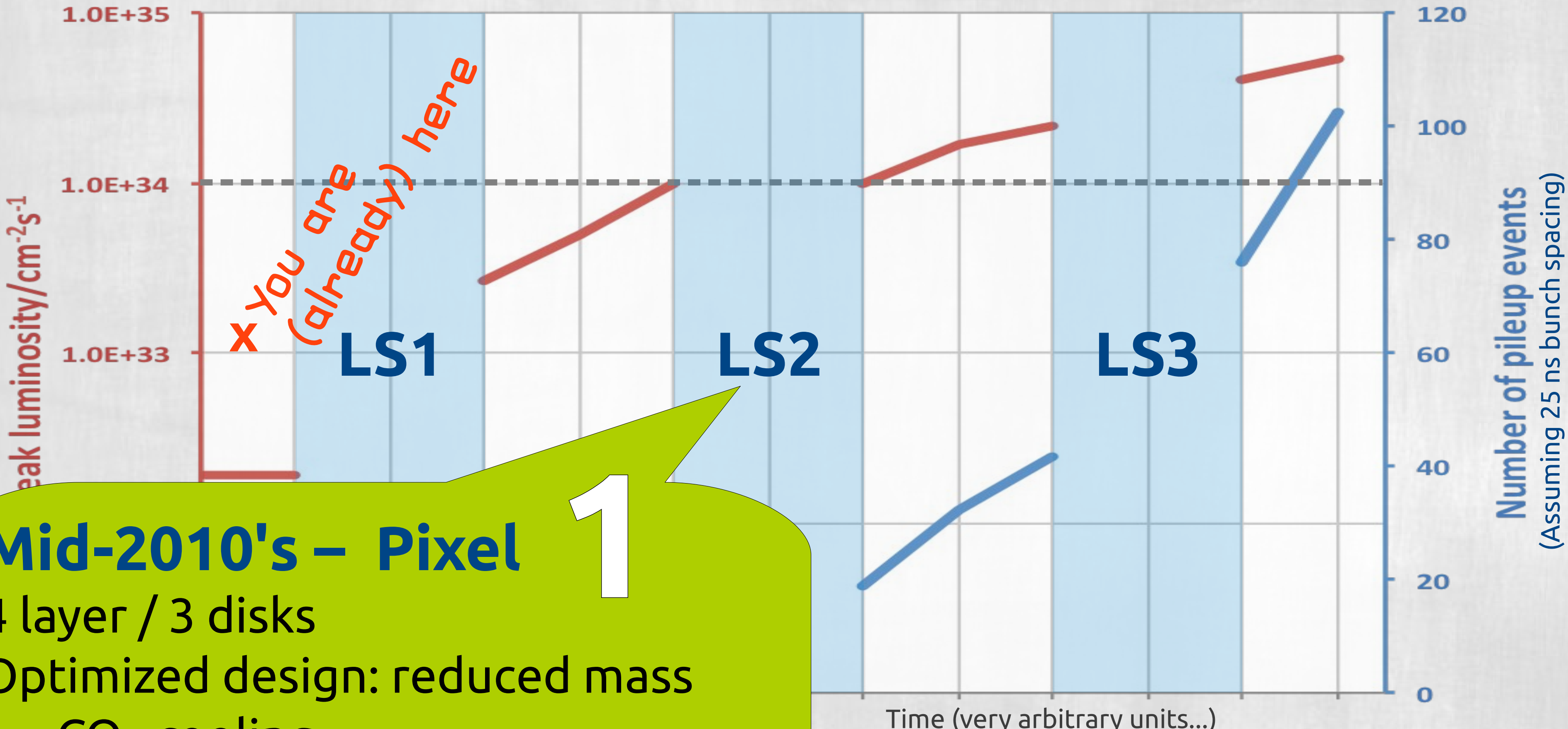
Three "Long Shut-downs" will improve various aspects of LHC
(see Jose Bernabeu's talk yesterday for a thorough description)



CMS was originally designed to run at 1×10^{34} cm^{-2} s^{-1}...

...we will soon exceed that!

Detector upgrades



Mid-2010's – Pixel 1

4 layer / 3 disks

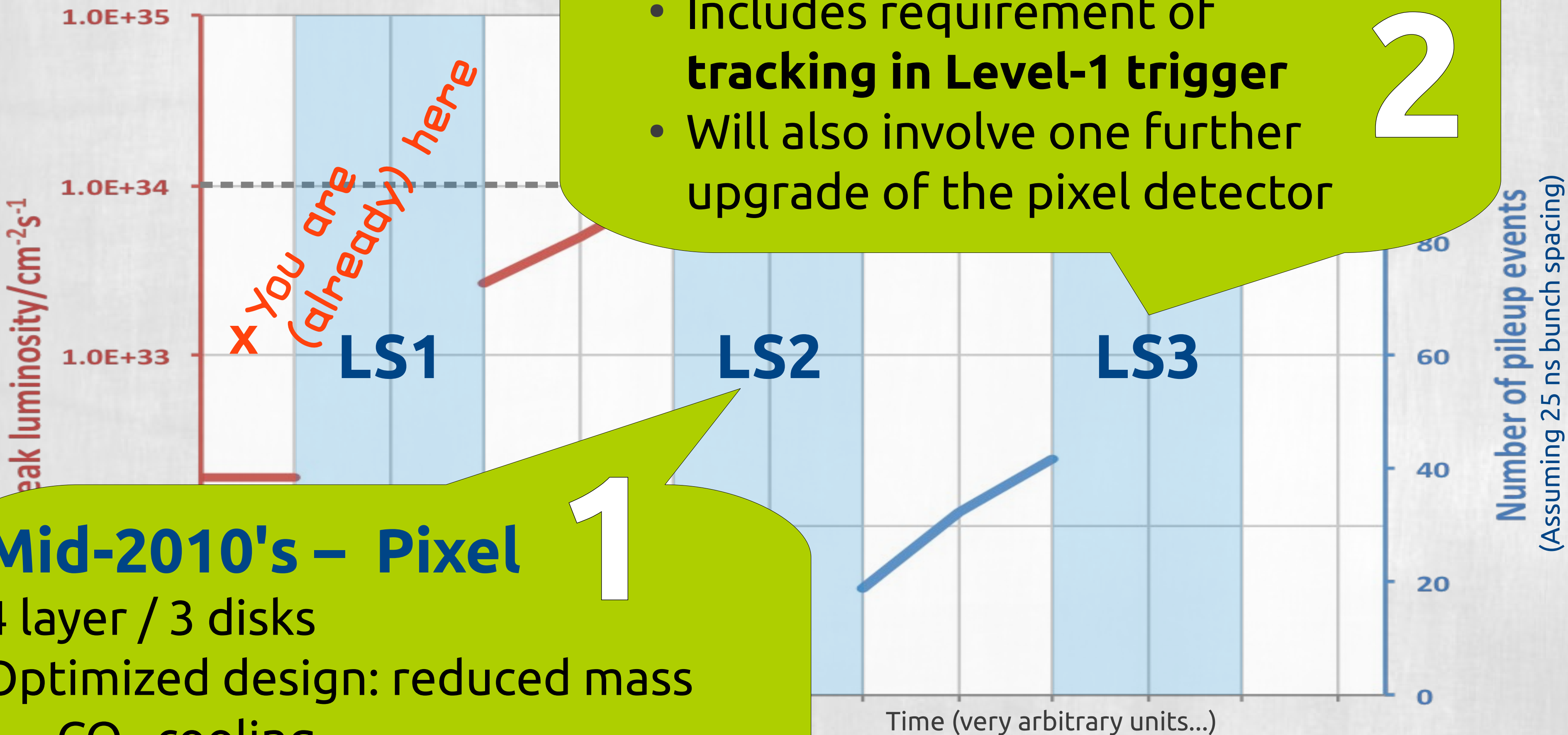
Optimized design: reduced mass

- CO_2 cooling
- DC-DC converters for powering
- Robust electronic for high rate

...t 1×10^{34} cm^{-2} s^{-1}...

...we will soon exceed that!

Detector upgrades



Early-2020's – Full tracker

2

Large project, vast R&D program

- Includes requirement of **tracking in Level-1 trigger**
- Will also involve one further upgrade of the pixel detector

Mid-2010's – Pixel

1

4 layer / 3 disks

Optimized design: reduced mass

- CO_2 cooling
- DC-DC converters for powering
- Robust electronic for high rate

t 1×10^{34} cm^{-2} s^{-1}...

...we will soon exceed that!

~~Current CMS tracker,~~

~~LHC & Tracker upgrades~~

Upgrading the outer tracker

Upgrade technologies

The building blocks: modules

System integration

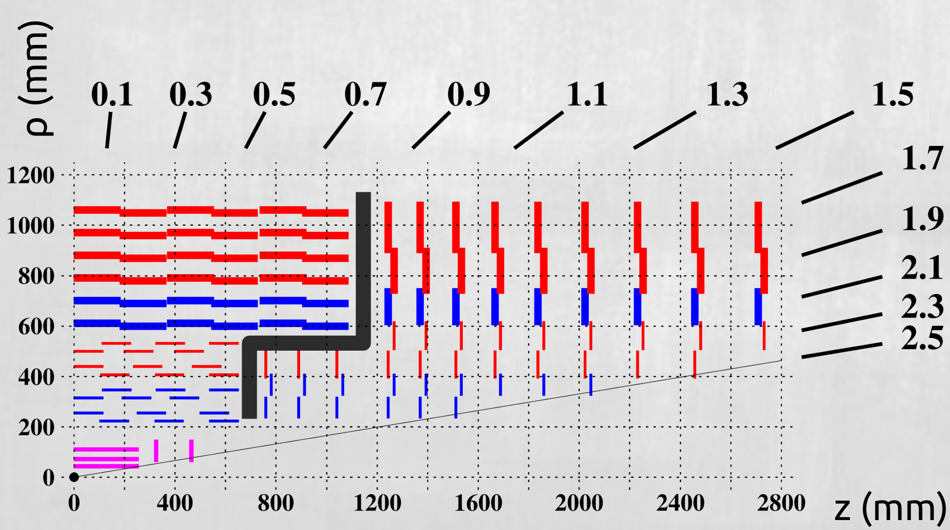
Level-1 tracking?

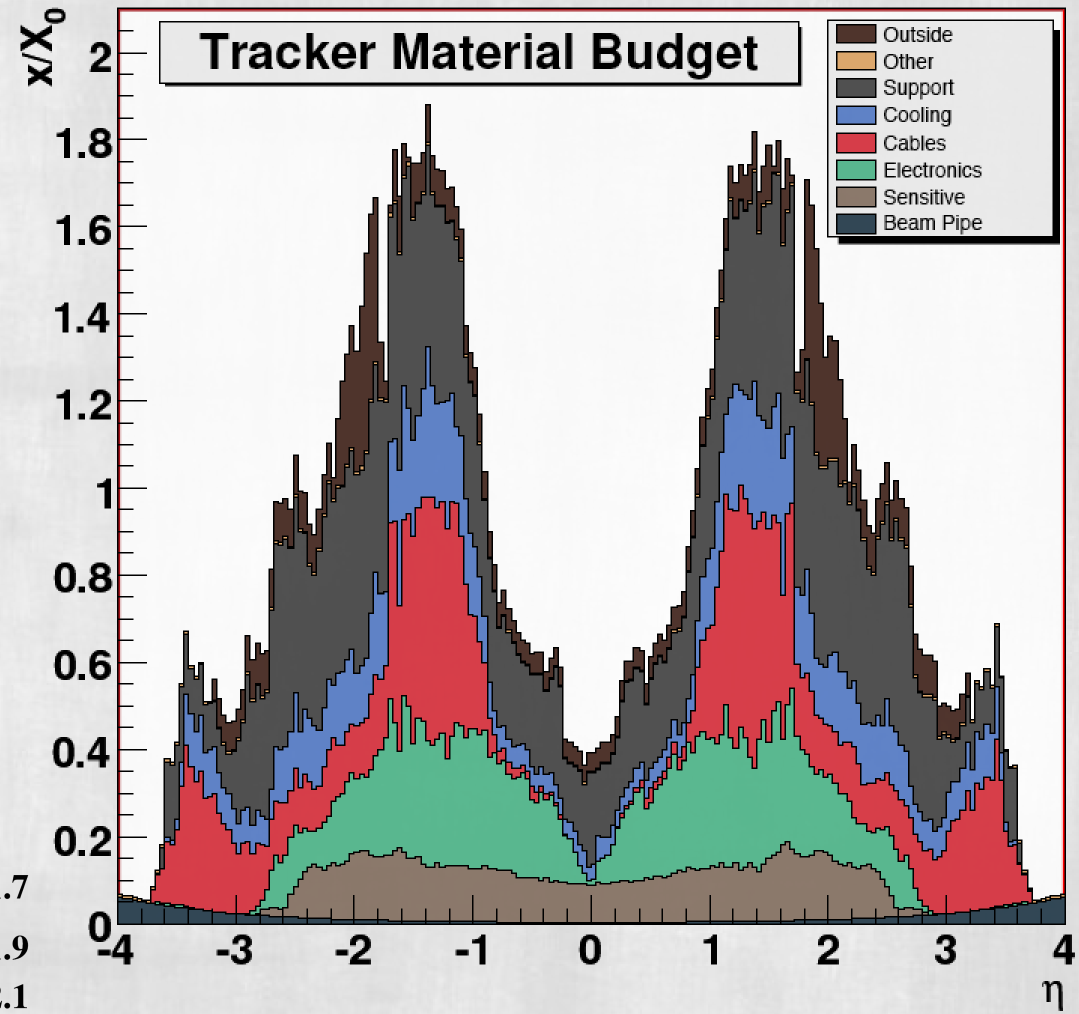
And the vertex detector?

Conclusions

Upgrade requirements

- Improve Tracking **performance**
- Current Tracker has a lot of **material**
  - Modules
  - **Services**, especially between barrel and end-cap
    - Power cables, cooling, support structures

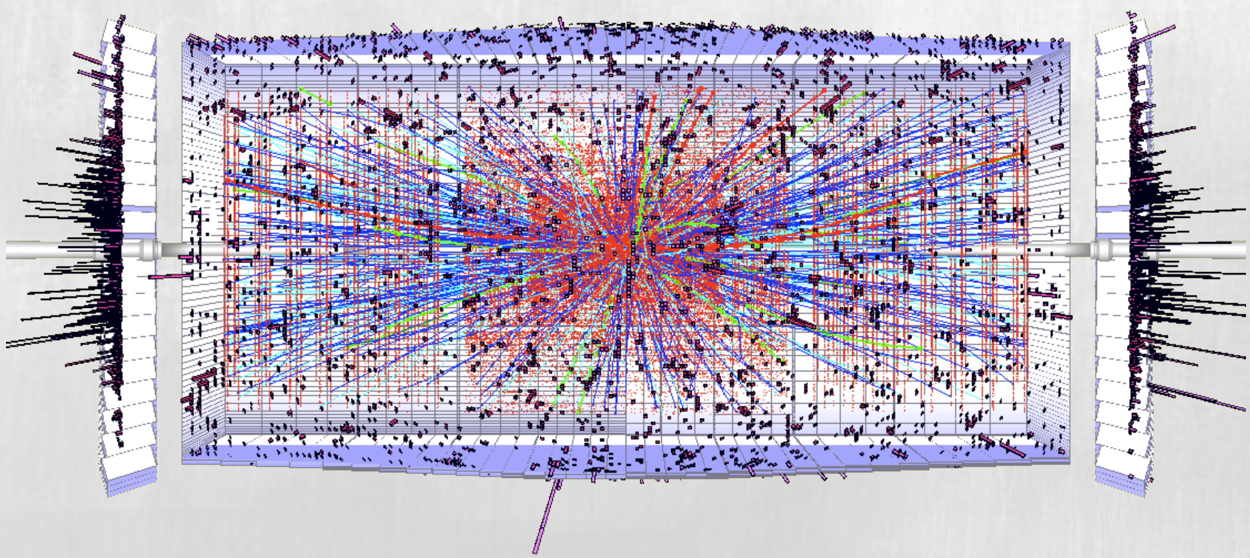




Minimize material in the Tracking Volume

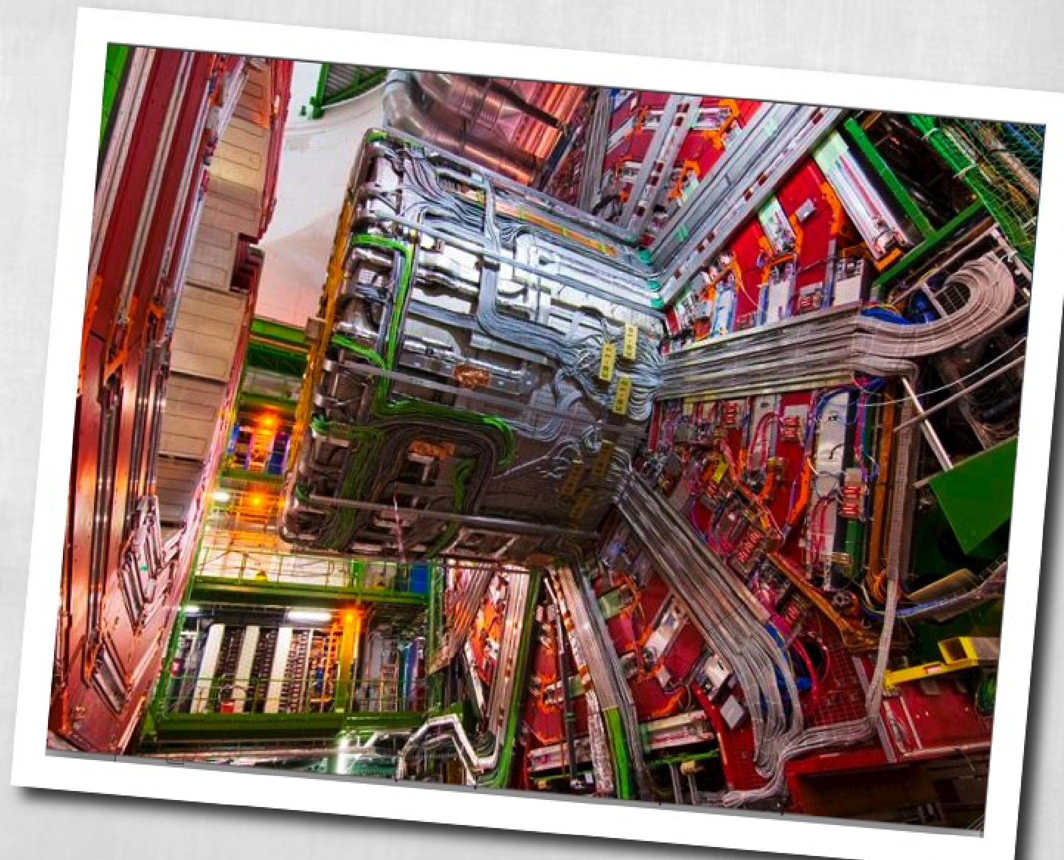
Upgrade requirements

- Granularity (5× at least)
  - Resolve up to 200÷**250 collisions** per bunch crossing
  - Maintain **occupancy** at the few % level
- Radiation hardness
  - **Ultimate** integrated luminosity considered ~ **3000 fb^{-1}**
  - **Design** integrated luminosity: ~ **500 fb^{-1}**



Upgrade requirements

- Use only currently **installed services**:
  - Power/HV cables
  - Cooling lines
  - Readout/control fibres
- **Simplify** the system if possible
  - Like: avoiding 22 module flavours...



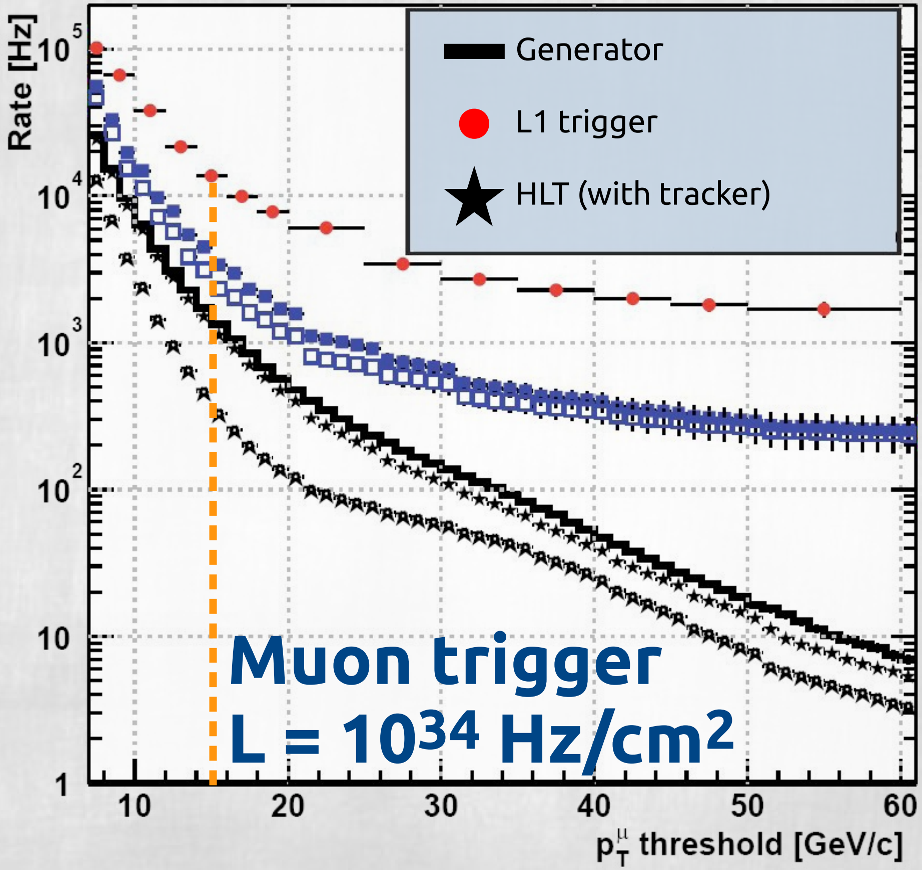
Additional requirement

Providing **tracking information** to the Level-1 Trigger!

Trigger requirements

- Standalone L1 muon rate too high at 10^{35} cm^{-2} s^{-1}
- Need to maintain **L1 < 100 kHz**

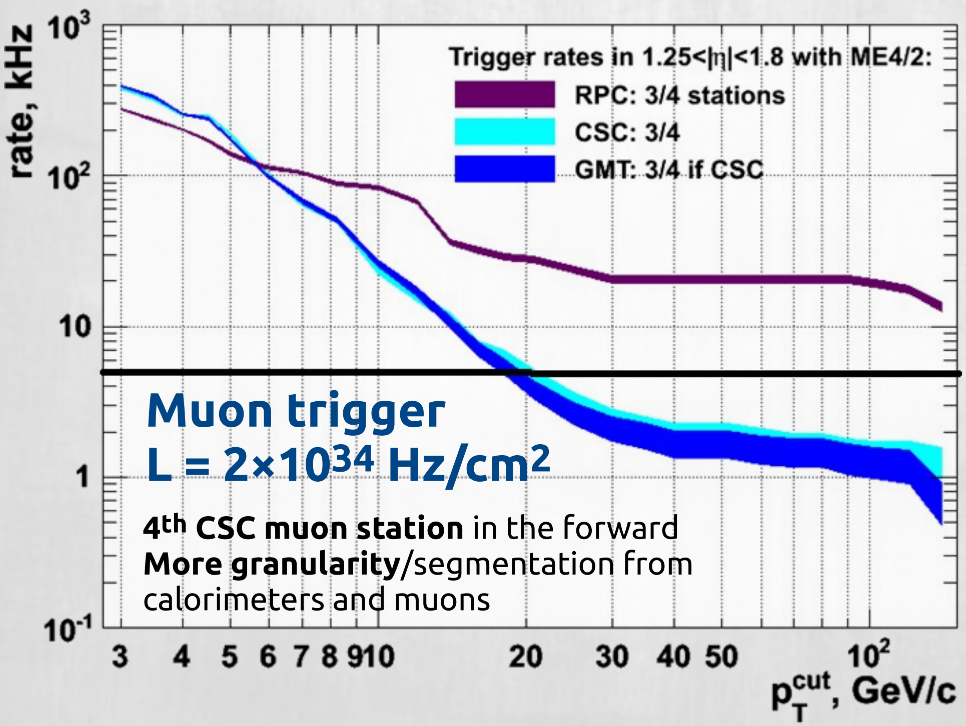
Single *μ*, *e* and *jet* rates Exceed 100 kHz at HL-LHC



Trigger requirements

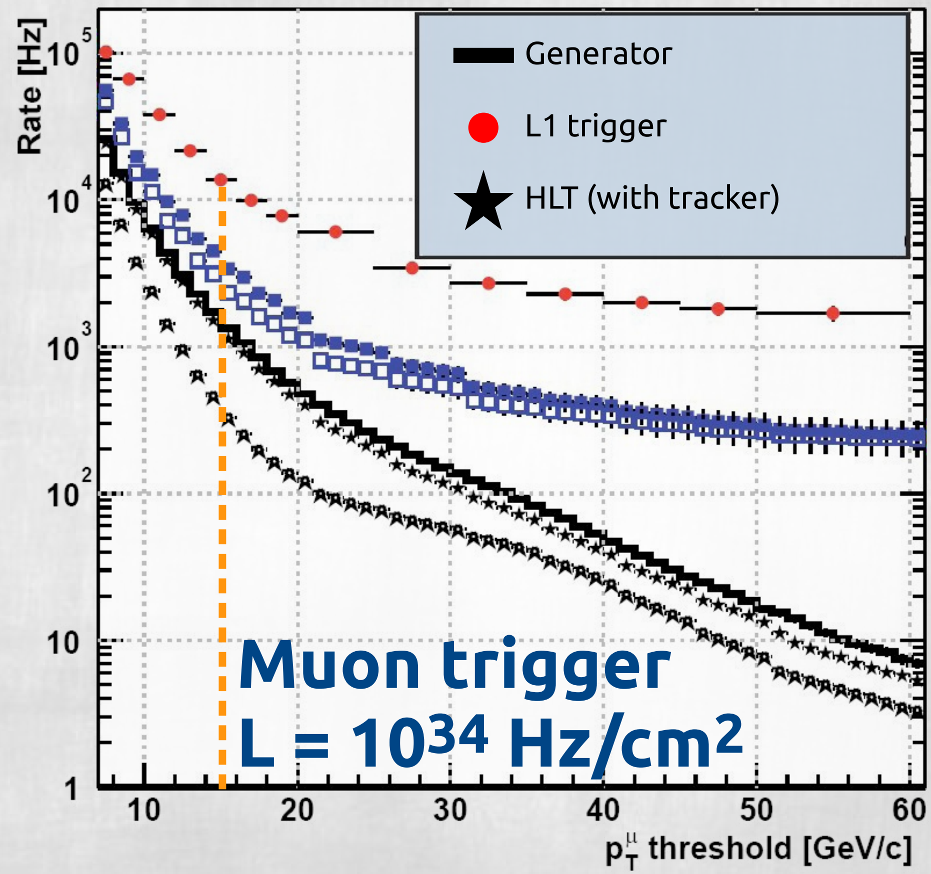
- Standalone L1 muon rate too high at 10^{35} cm^{-2} s^{-1}
- Need to maintain **L1 < 100 kHz**

- Phase-1 trigger upgrade should provide ≥ 2 × improvement



- Not enough for L > 5×10^{34}

Single *μ*, *e* and *jet* rates
Exceed 100 kHz at HL-LHC



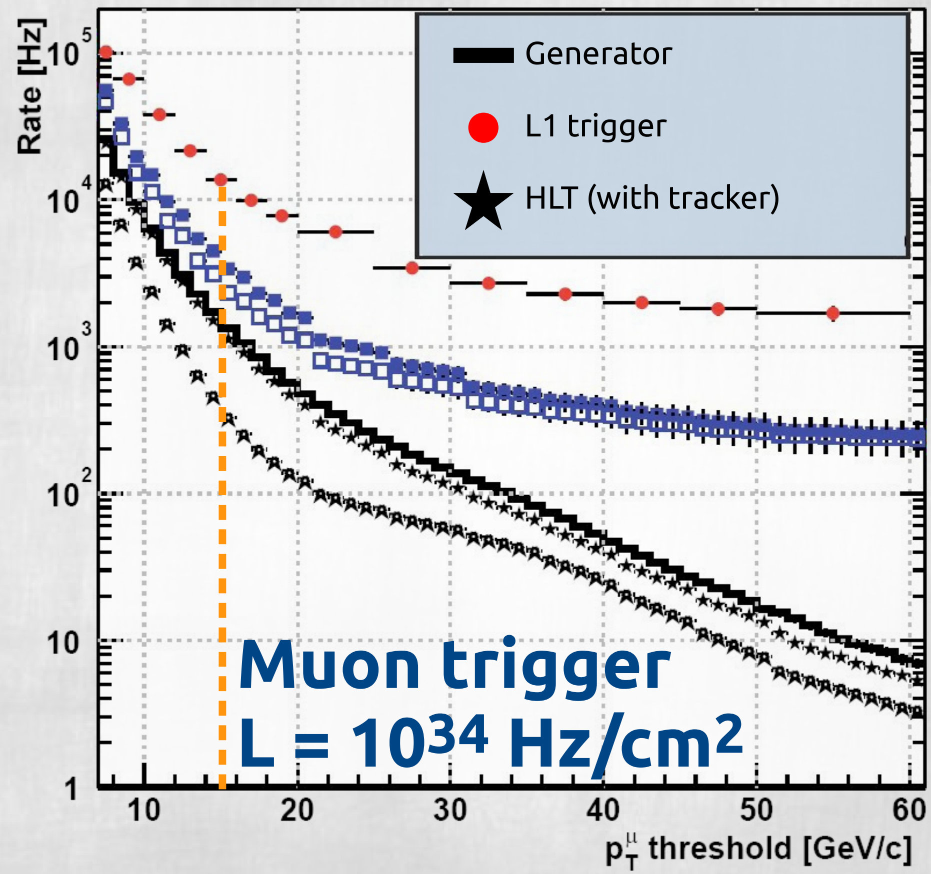
Trigger requirements

- Standalone L1 muon rate too high at 10^{35} cm^{-2} s^{-1}
- Need to maintain **L1 < 100 kHz**

- Matching tracking coordinates can **potentially 10× improve** the rejection power

This is the MAIN CHALLENGE!

Single *μ*, *e* and *jet* rates Exceed 100 kHz at HL-LHC



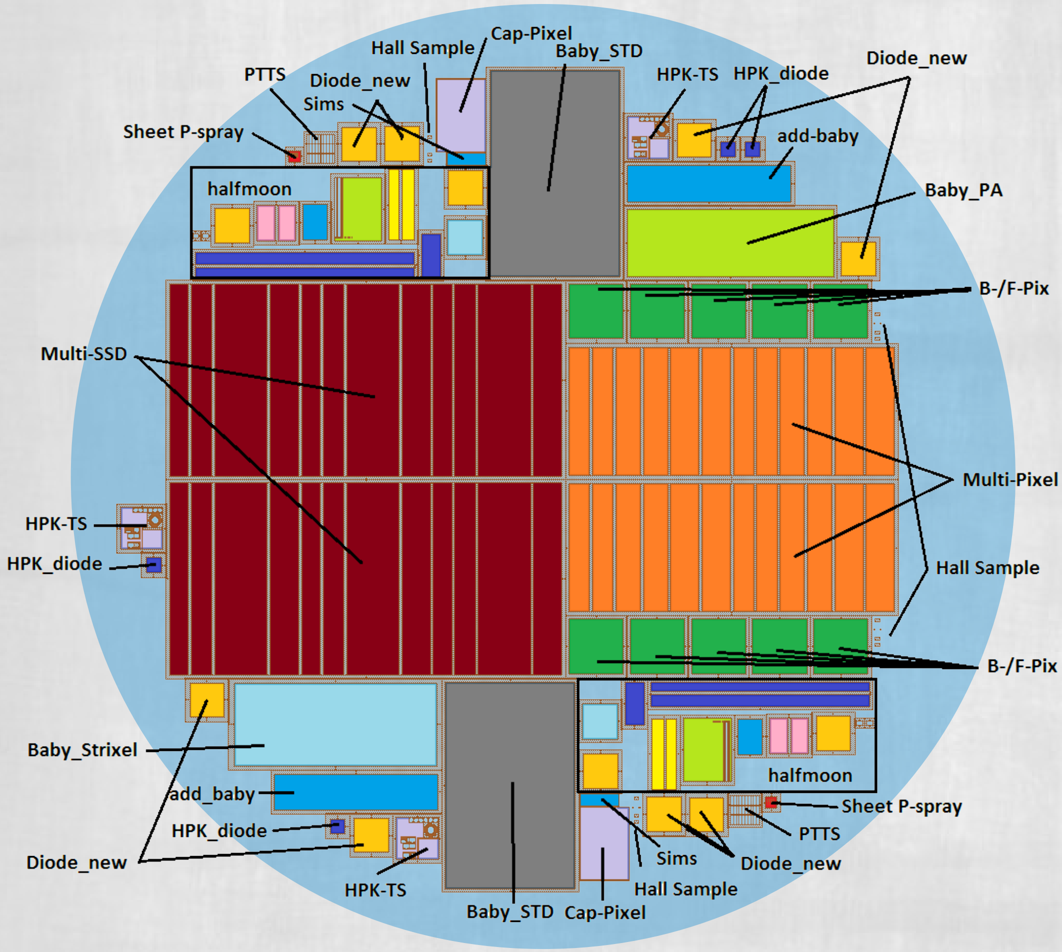
Trigger requirements

- CMS needs to be upgraded as a whole detector

- Tracker input to Level-1 trigger
  - Maintain overall L1 **rate** within 100 kHz
  - Keep **latency** within ~ 6 μs
  - With on-detector **p_T cut** can reduce data rates
    - Cannot deliver data @ 40 MHz
    - p_T> 1÷2GeV/c to obtain 20× reduction in inner strip layers
  - **Primary z vertex** would improve also isolation

~~Current CMS tracker,~~
~~LHC & Tracker upgrades~~
~~Upgrading the outer tracker~~
Upgrade technologies
The building blocks: modules
System integration
Level-1 tracking?
And the vertex detector?
Conclusions

Sensor R&D



158 wafers ~ 30 pieces per wafer ~ 5000 pieces

Many Structures:

- New pixels (more **rad-hard**?)
- Multi-**geometry** strips
- Multi-**geometry** pixel
- Standard: **irradiation**
- Pitch-Adapter: new **routing**?
- Strixel: new **design**
- Diodes: **irradiation**
- Test-structures
- **Lorentz angle** sensor

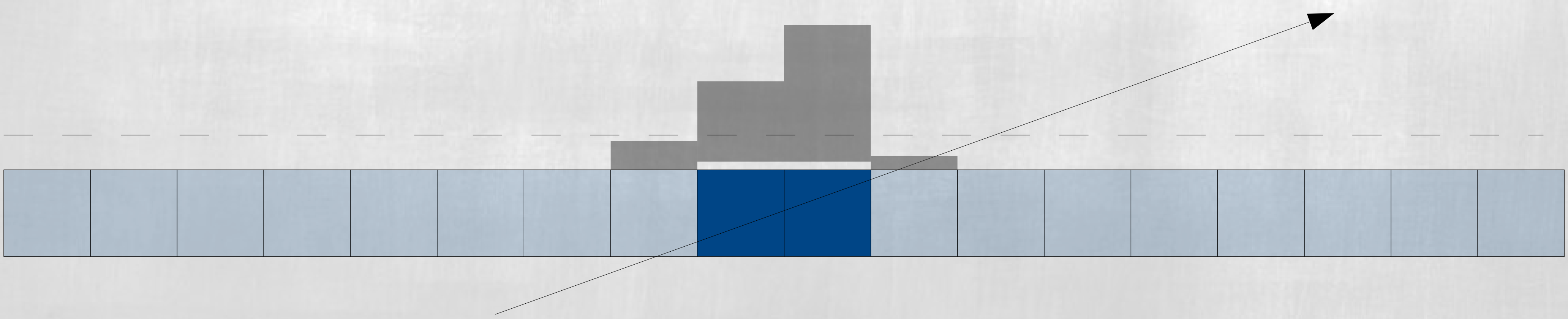
See **Joachim Erfle's talk** yesterday

Binary readout

- At least 5× **increase in granularity**
  - Strip length goes from 10÷20 cm to 2.5÷5 cm
  - Pitch ≤ present Tracker (≈ 90 μm)
  - Channel count ≈ 50 million
- Problem: **limited output bandwidth**
  - Limited power for transmitters
  - Limited number of fibres (to current)

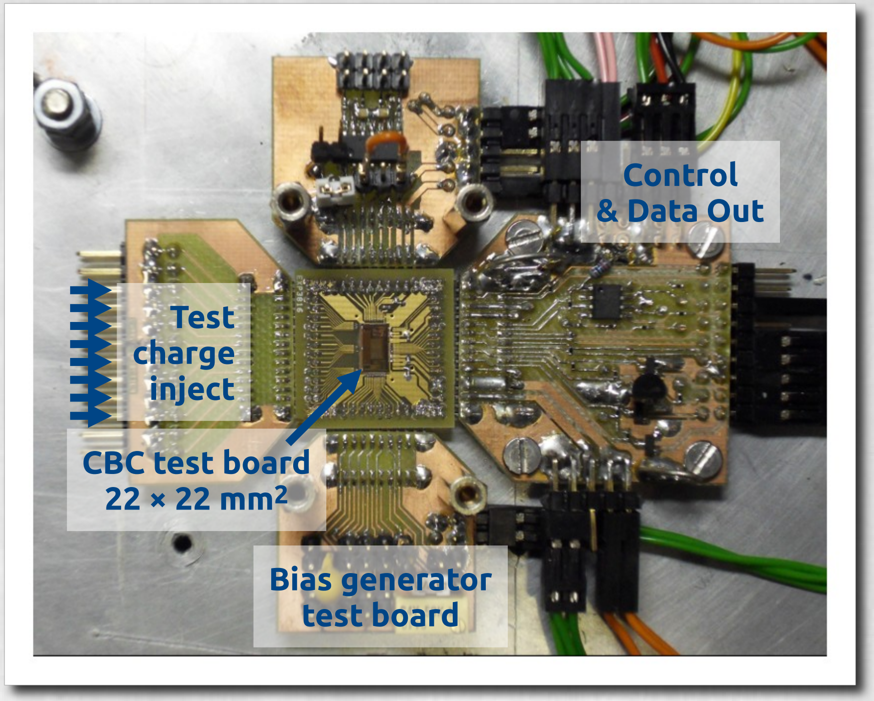
Binary readout

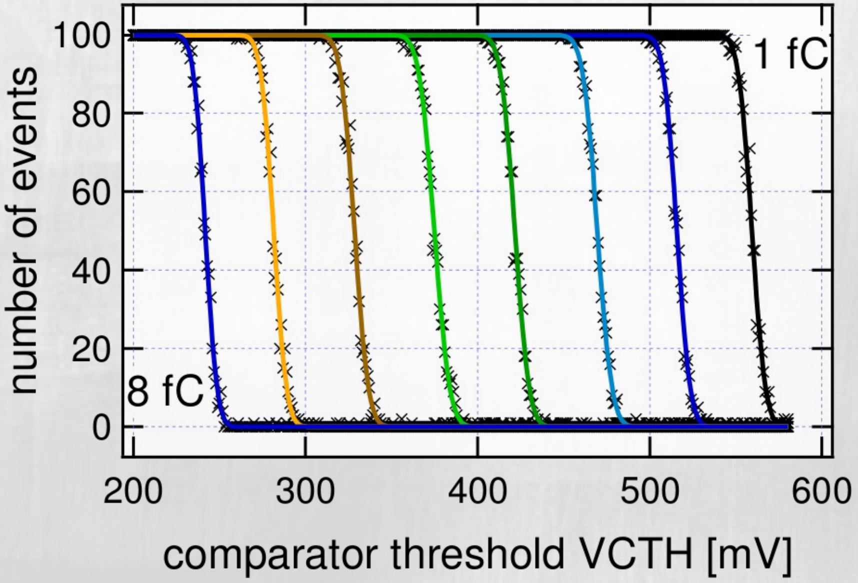
- 2 Chips currently being developed
  - CBC
  - FEAFS
- Both with binary readout
  - No Centre of Gravity algorithm possible
  - Probably the same threshold for all strips
- Resolution? Lorentz angle?



Front-end: CBC

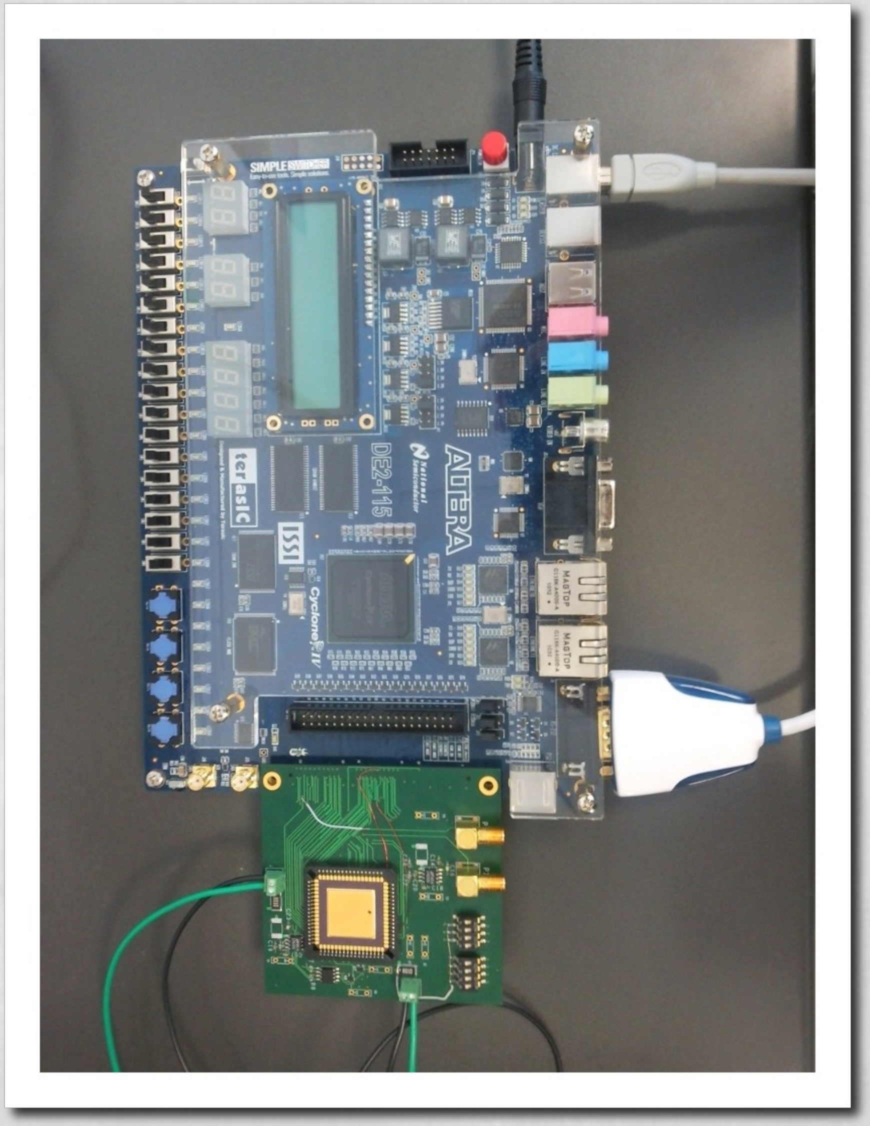
- Chip for **strip readout modules** in 130 nm CMOS
  - Binary un-sparsified (synch)
  - Optimized for < 5 cm strips
  - 256-deep pipeline (6.4 μs)
  - Bi-polar
- Main specifications:
  - **Noise** < 1000 e^- @ 5 pF
  - **Power** < 5 mW / channel
- Full prototype working
  - Detailed tests ongoing





Front-end: FEAFS

- Chip for **strip P_T modules** in 130 nm CMOS
- Pre-amplifier and comparator stage not included in first chip version
- Cluster finding + tunable correlation logic
- Asynchronous readout on one data link for trigger stubs and full read-out data
- First prototype under test

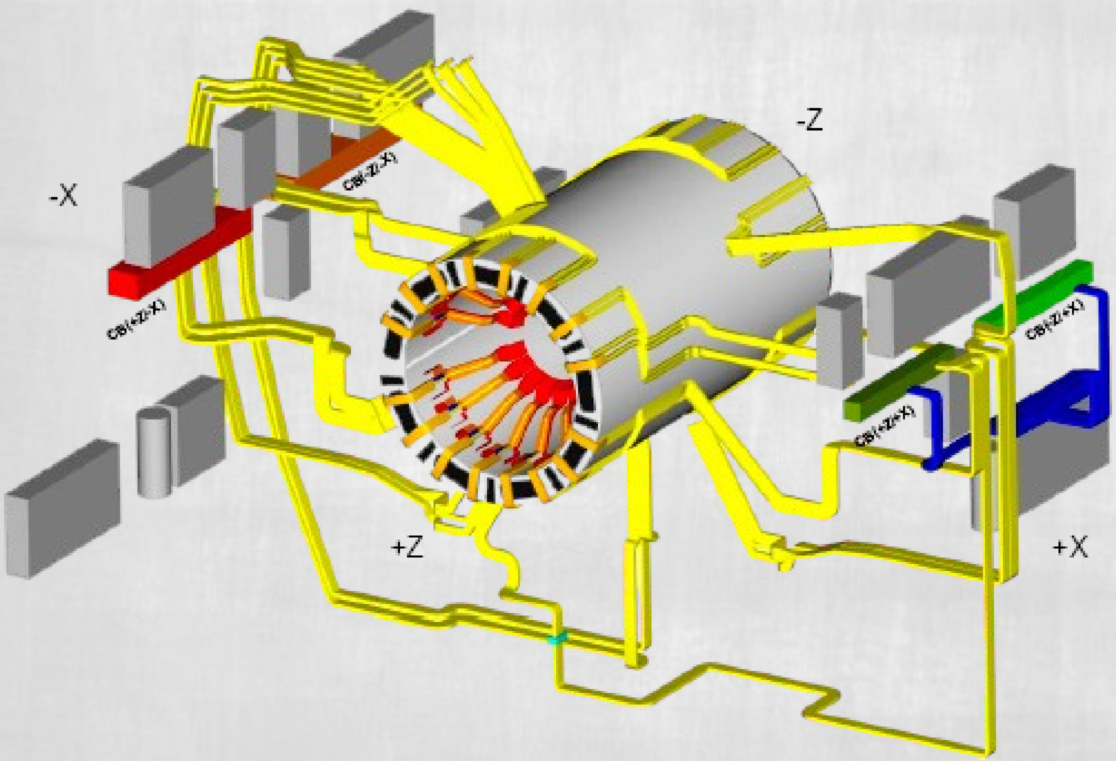


High bandwidth: the GBT

- A **high-speed bi-directional** link is being developed for the LHC detectors upgrade (90 nm CMOS)
- CMS is trying to **customize the GBT**
  - Idea: **1 link/module** (65 nm)
  - Same bandwidth, reduced power, and simplified I/O
  - New opto-link with **small footprint**
  - **Feasibility study** to assess what is likely to be achievable
- Advantages
  - Simplified integration
    - Compared to present system with separate control/readout link
  - Optimal for CMS Tracker (many fibres available)
  - Minimizes (heavy) electrical connectivity
  - Modules become self-contained working elements

DC/DC conversion

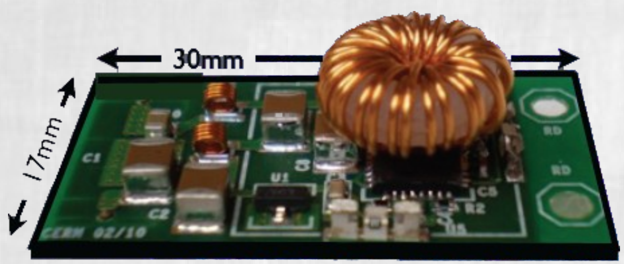
- More power is expected
- Cabling cannot be changed
- 40% power is already dissipated in cables

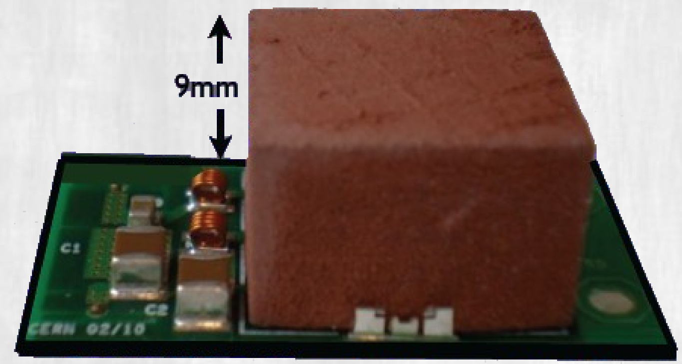


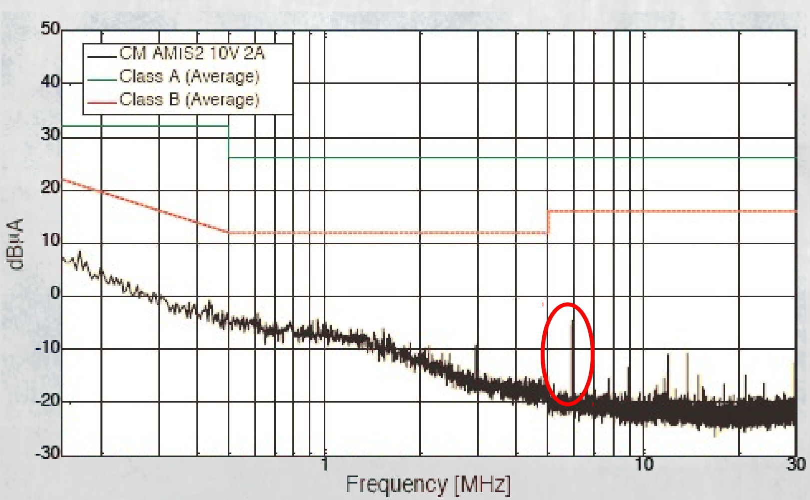
- Reduce current: radical solution
  - Deliver power at higher V
  - Conversion DC/DC on module

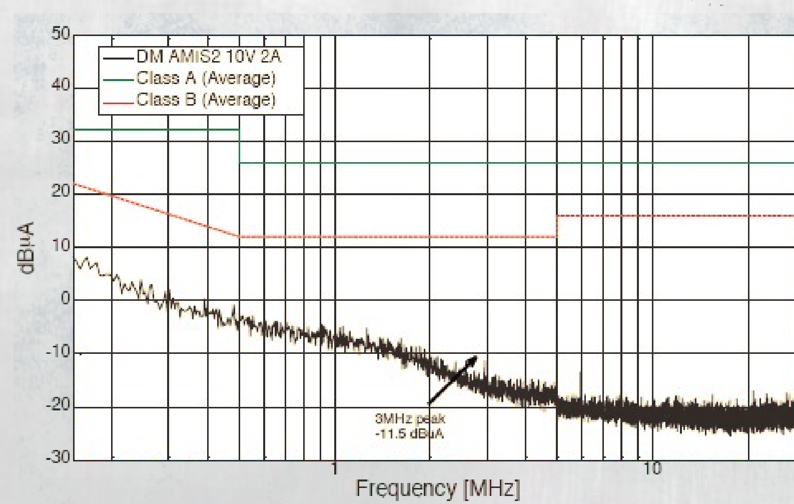
DC/DC converter

- Converter chips are being **finalized**
  - AMIS2 chip, AMIS4 in preparation
- **Very low noise** with air coil shielded
  - (Pixel Phase-I studied)
- **Integration** looks OK



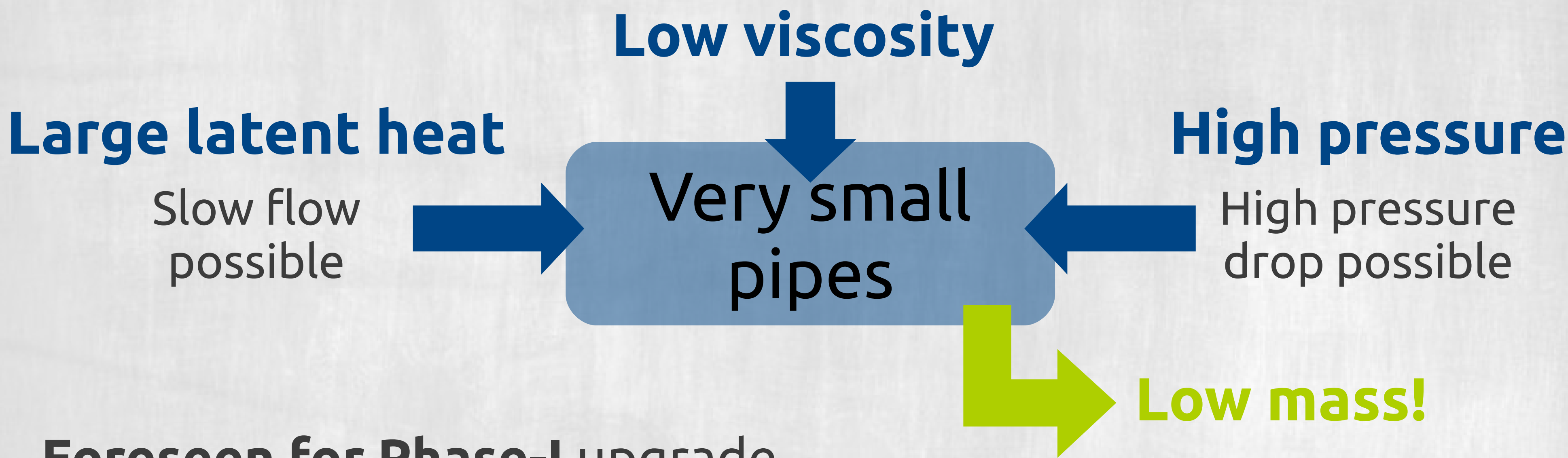






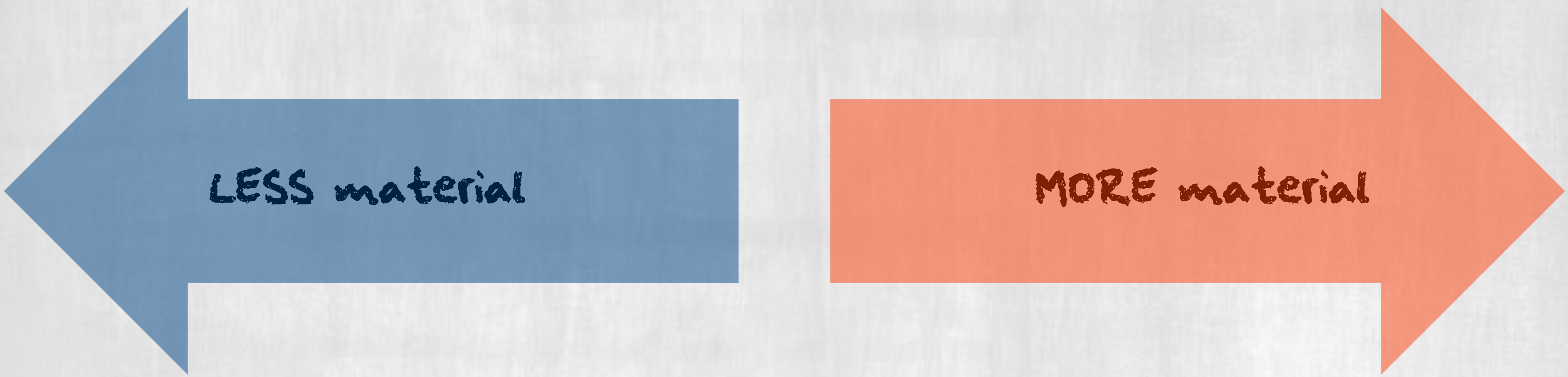
CO_2 cooling

2-Phase evaporative CO_2 cooling



- **Foreseen for Phase-I** upgrade
  - Project in an advanced stage
- The technology in principle allows scaling to full Tracker
  - between 5× and 10× w.r.t. pixel
- Additional research needed for an optimized engineering of such a large system

Upgrading only tracking



New technologies

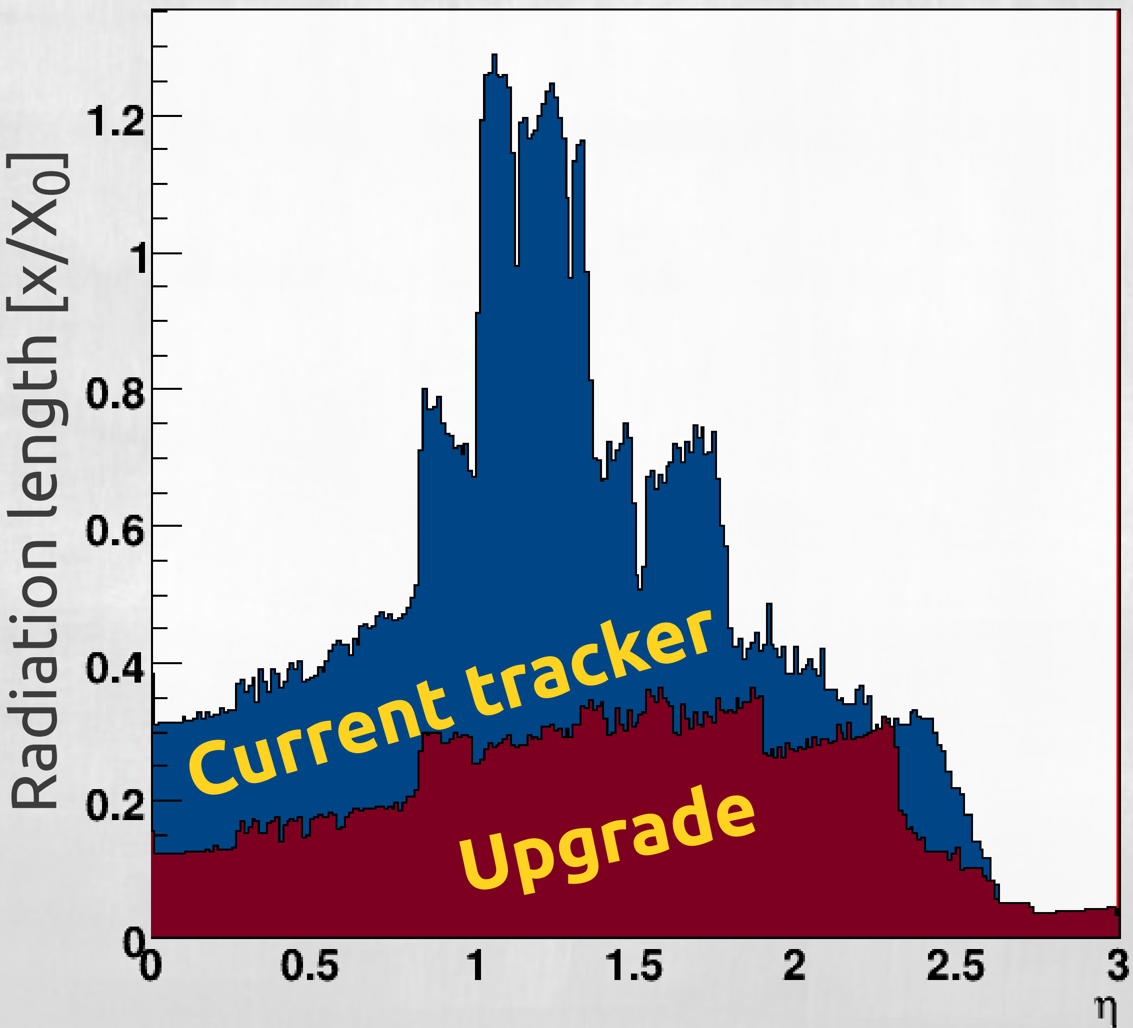
- DC-DC converters
- CO_2 cooling
- GBT
- CBC/FEAFS

Less layers

Higher granularity

Upgrading only tracking

With these technologies & no other constraint, the **material amount** can be significantly **reduced**



Estimate with realistic assumptions on material

New challenge: trigger!

LESS material

MORE material

New technologies

- DC-DC converters
- CO_2 cooling
- GBT
- CBC

Less layers

Higher granularity

Trigger capabilities!

On-module pT selection

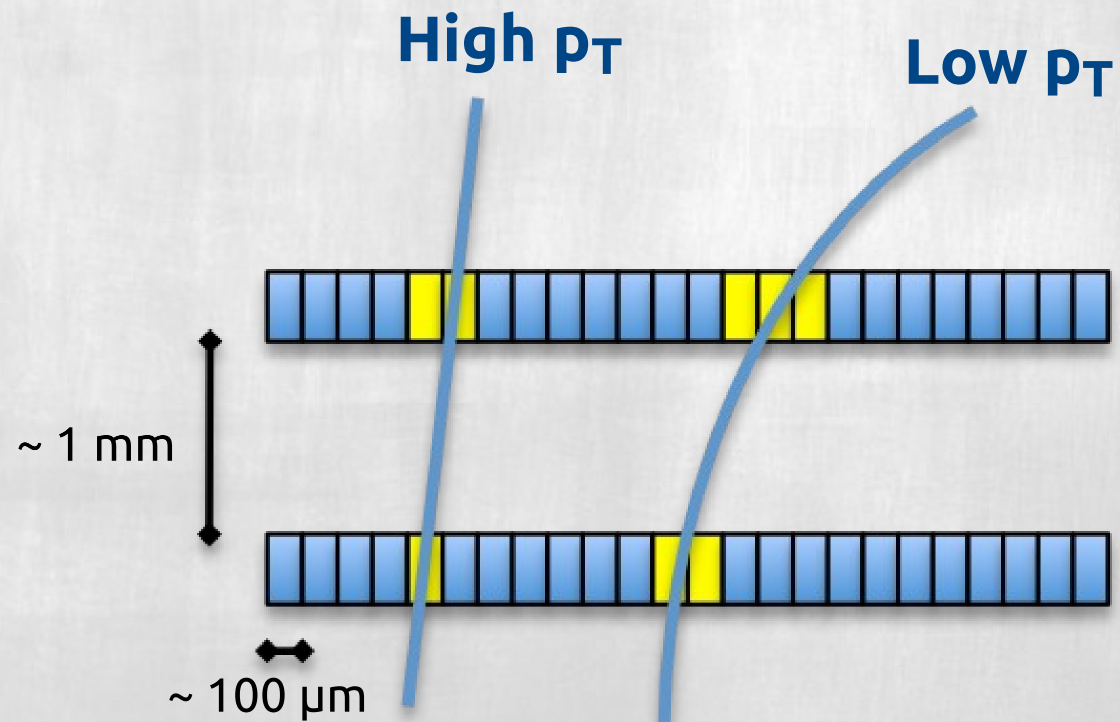
- Exploit CMS's intense B field
- Correlate hits in two closely-spaced sensors
- On-module: select matching hits in a **search window**

p_T threshold:

1 GeV ≈ 1 order of magnitude reduction

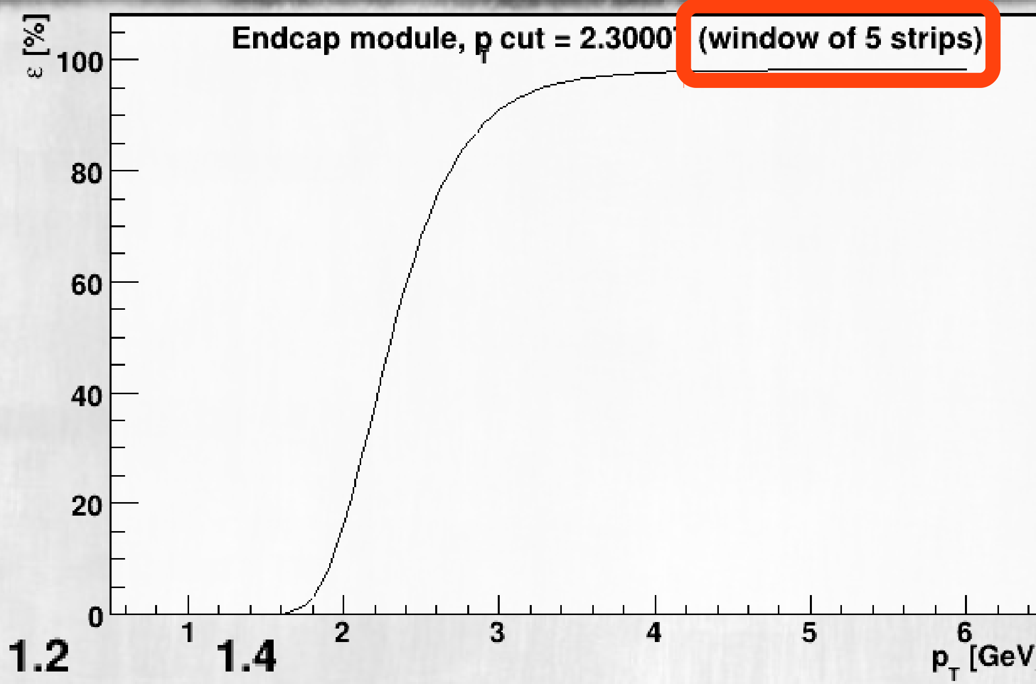
p_T threshold depends on

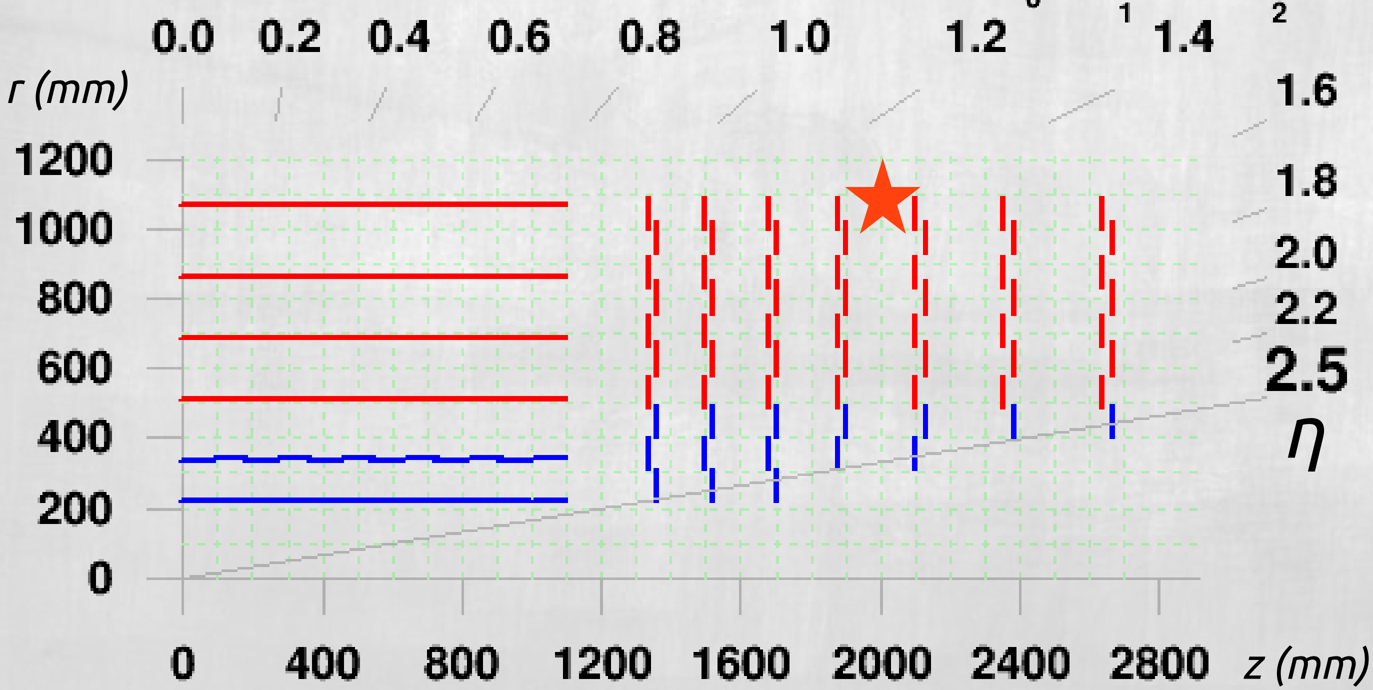
- Sensor distance
- Search window
- Module position



Trigger threshold

Example of expected trigger performance: fraction of hits transmitted vs. pT



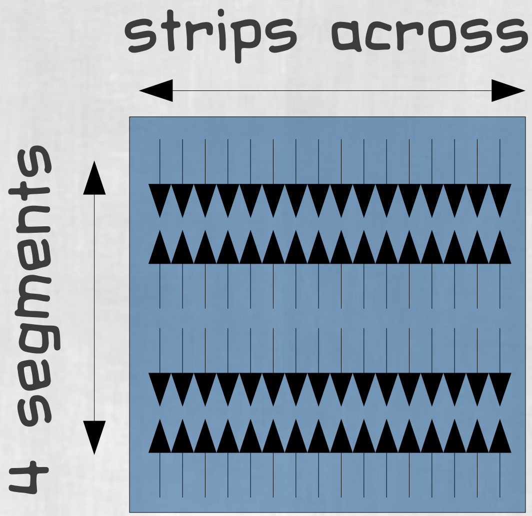


pitch	90	µm
strip_l	46.3	mm
mod. z	2000	mm
mod. r	1080	mm
mod. d	**1.5**	**mm**

~~Current CMS tracker,~~
~~LHC & Tracker upgrades~~
~~Upgrading the outer tracker~~
~~Upgrade technologies~~
The building blocks: modules
System integration
Level-1 tracking?
And the vertex detector?
Conclusions

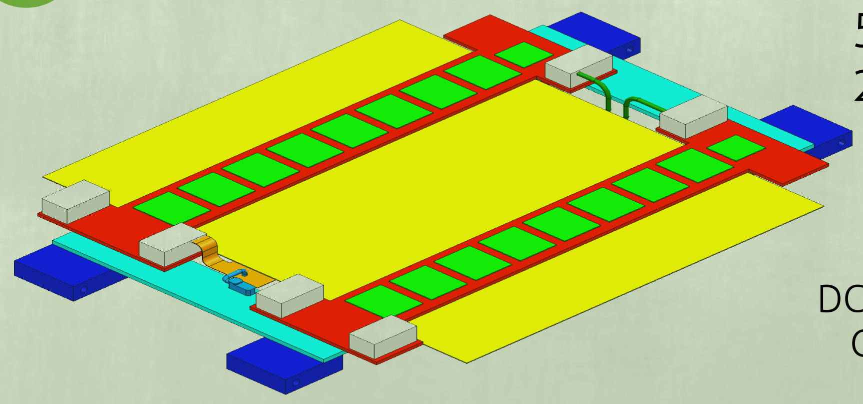
R-phi module

- Evolution of current r-phi module
- Higher granularity



Single-sided module

5 cm long strips
2.5 cm long strips

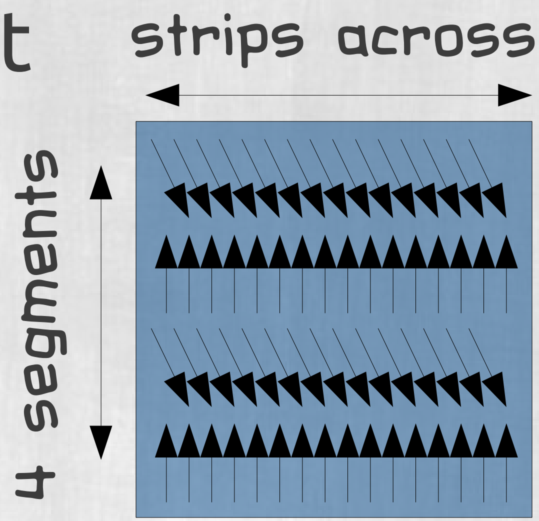


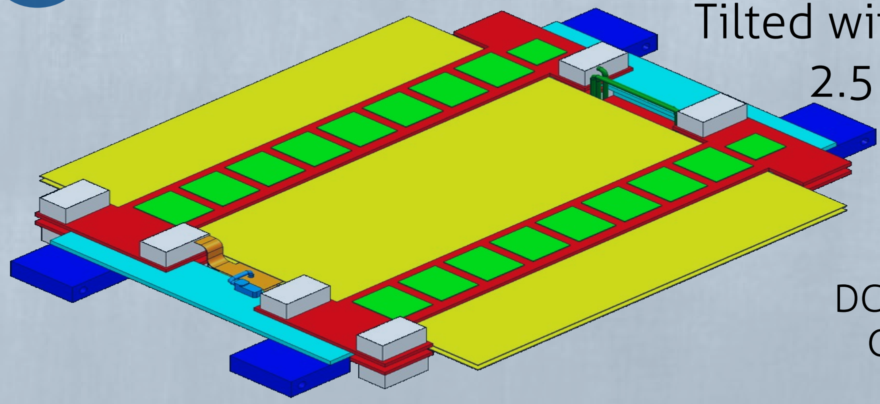
DC/DC for each module
GBT at the end-flange

10 cm × 10 cm

Stereo module

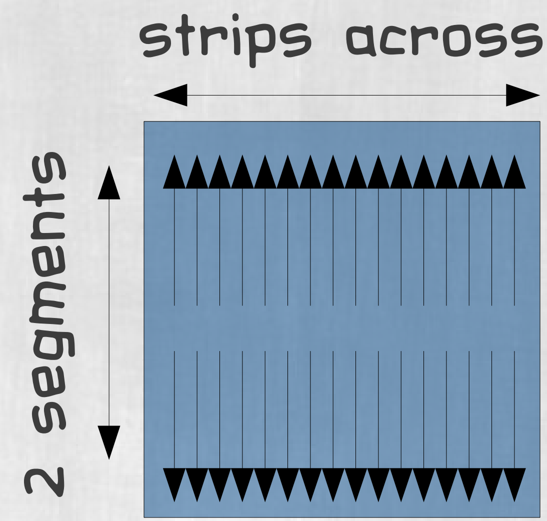
- Evolution of current stereo concept
  - Tilted and straight strips on the wafer mask
- Standard readout

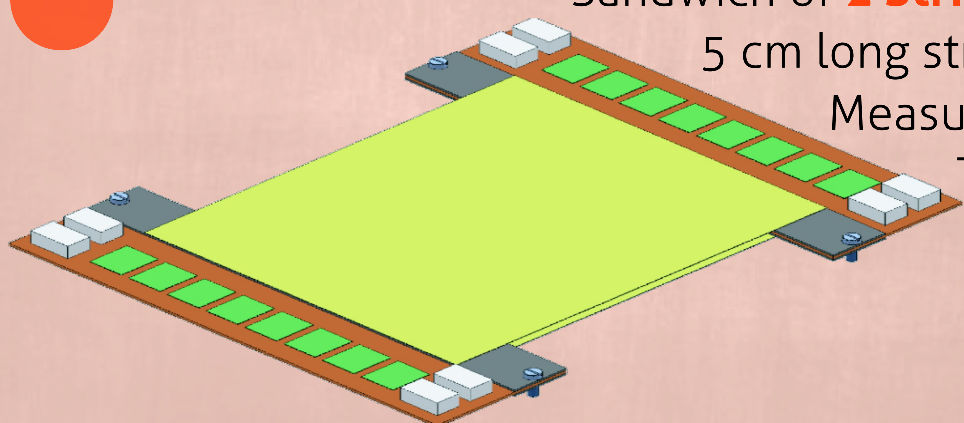




PT module: pT-2S

- 2 Strip sensors
- Light and "simple"
    - Hit matching logic on the chip
- No z information
- Suitable for the outer part



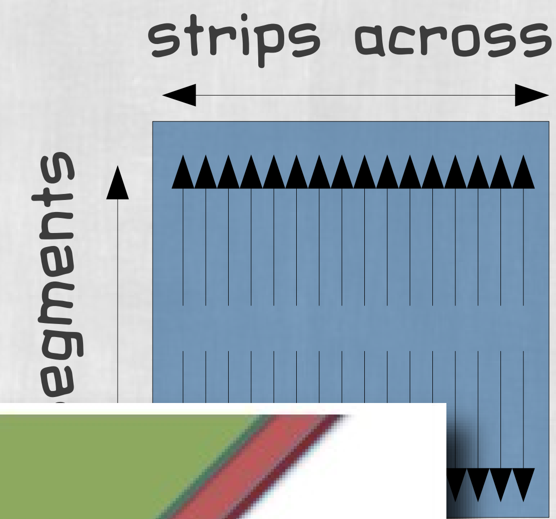


Sandwich of **2 Strip sensors**
5 cm long strips
Measuring pT locally
Trigger output

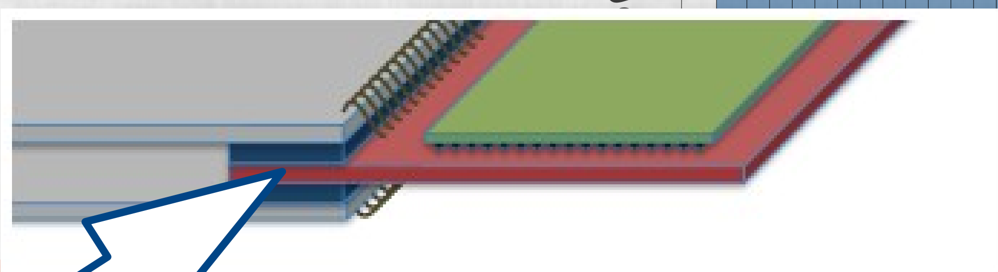
GBT + DC/DC for each module

10 cm × 10 cm

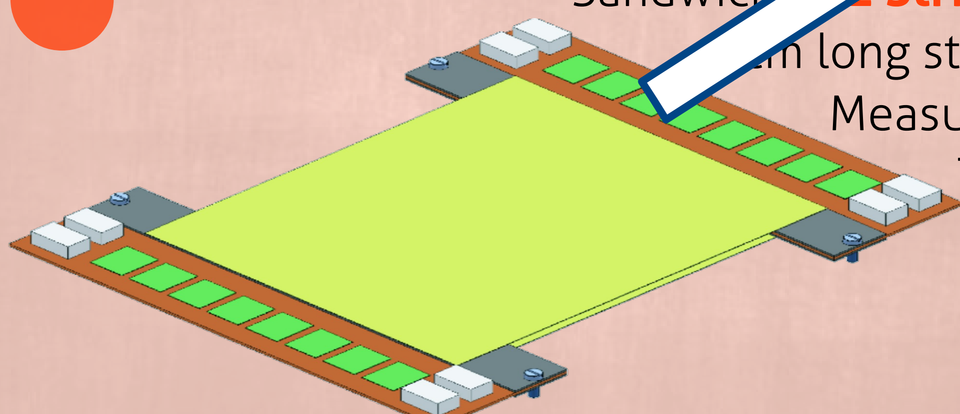
PT module: pT-2S



Simple internal connectivity
(wire bonds)



Sandwich ... Strip sensors
...m long strips
Measuring pT locally
Trigger output

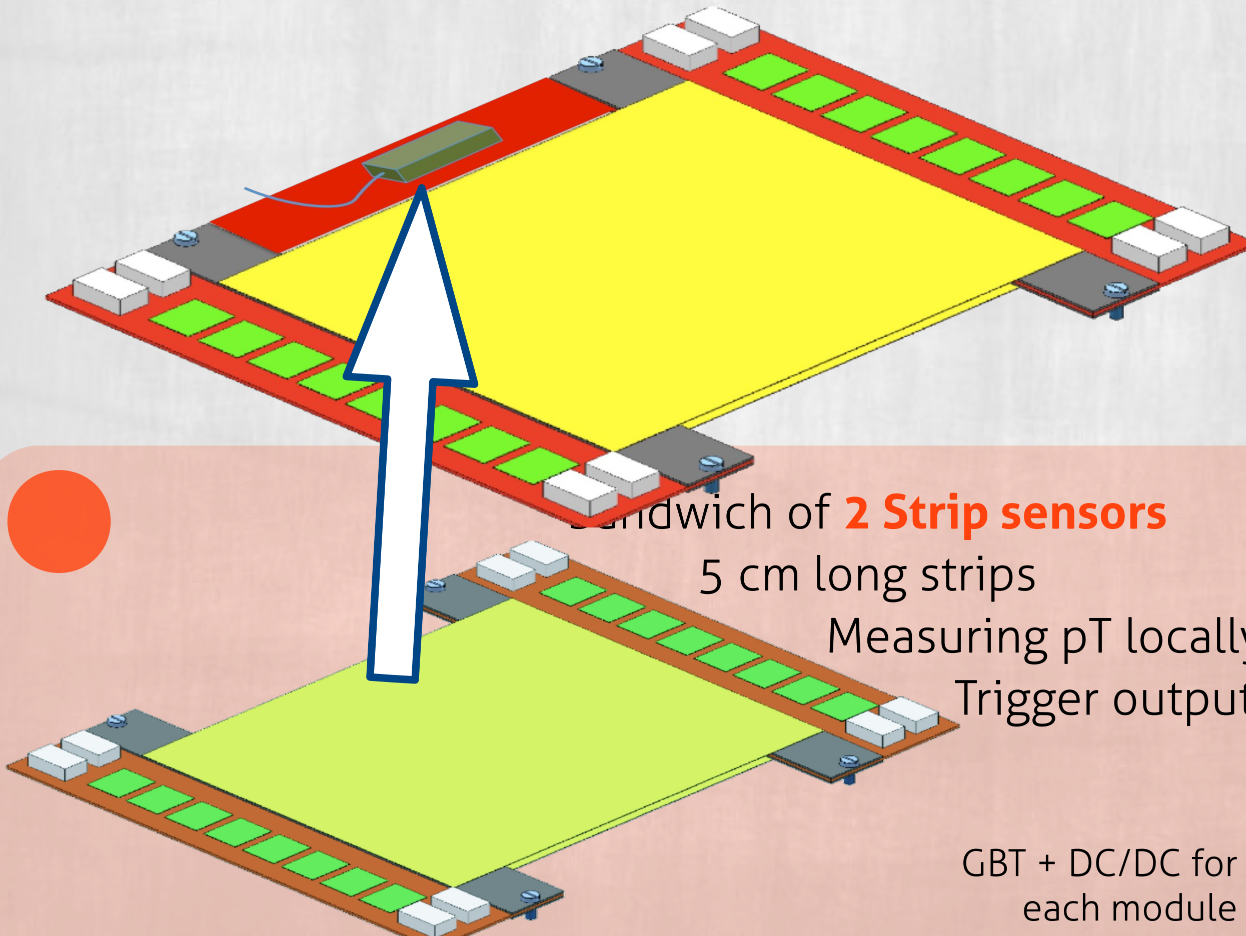


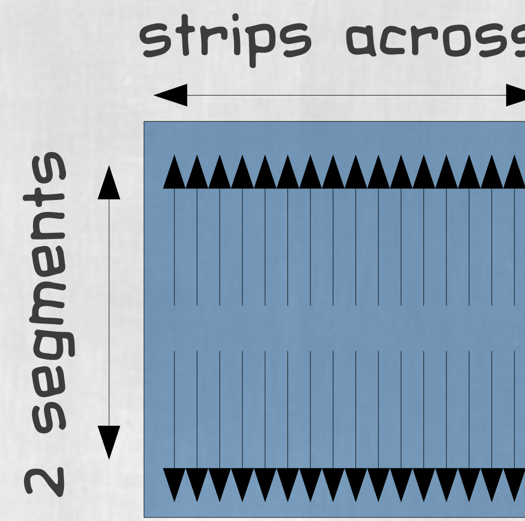
GBT + DC/DC for each module

10 cm × 10 cm

PT module: pT-2S

Host the opto-link (GBT) on board?
Need a special GBT





Sandwich of **2 Strip sensors**

5 cm long strips

Measuring pT locally

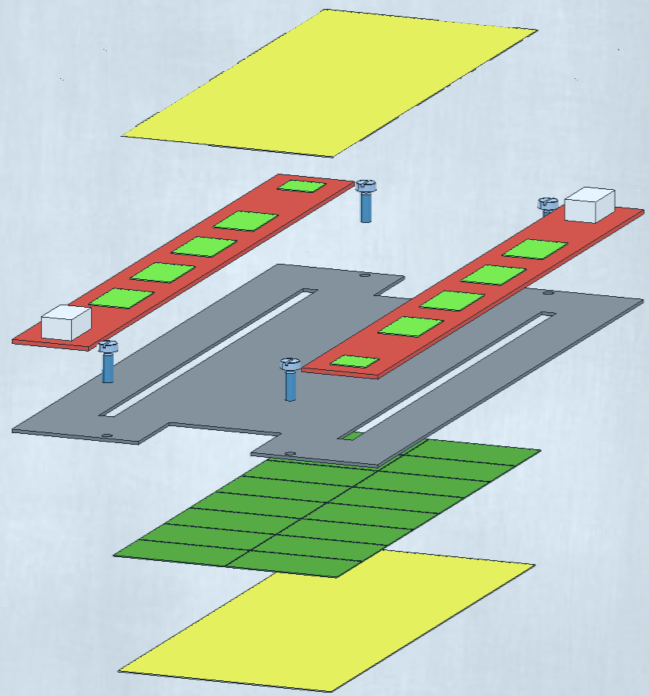
Trigger output

GBT + DC/DC for each module

10 cm × 10 cm

PT module: pT-PS

- One sensor is made by pixels
  - Seems feasible
    - Wire-bond on strips
    - Bump-bond on pixels
  - Provides local z measurement
    - To extrapolate tracks to the end-cap
    - To measure longitudinal IP z_0

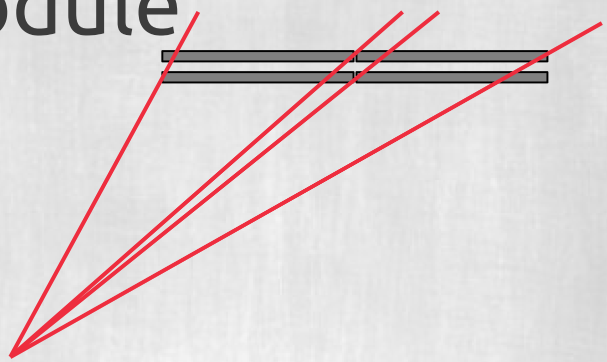


New idea (2011)
Pixel + Strip assembly
Measuring pT locally

+ Simple interconnection tech.
+ Relatively low power & mass
+ Tunable sensors spacing

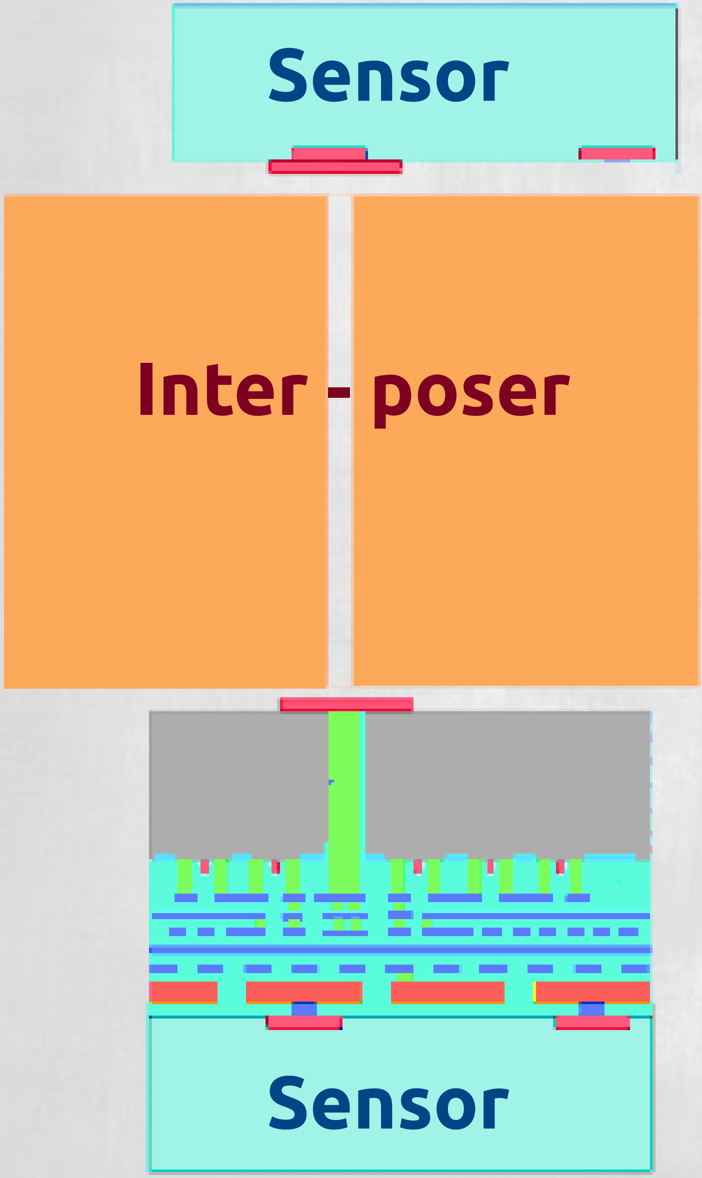
– About **10 cm × 4 cm**

PT module: pT-VPS



- Vertically-integrated Pixel+Strip module
- Meant to improve upon limitations of "horizontal" PS modules
  - Limitation to ½ **wafer size**
  - Impact of **geometrical inefficiency** for p_T matching at the edges and in the centre
- Several issues to tackle
  - Difficult interconnection technologies
    - Yield could **limit the size** of assembly
  - Need interposer covering on the whole surface
    - May significantly affect the module mass
  - The devil hides in the details!

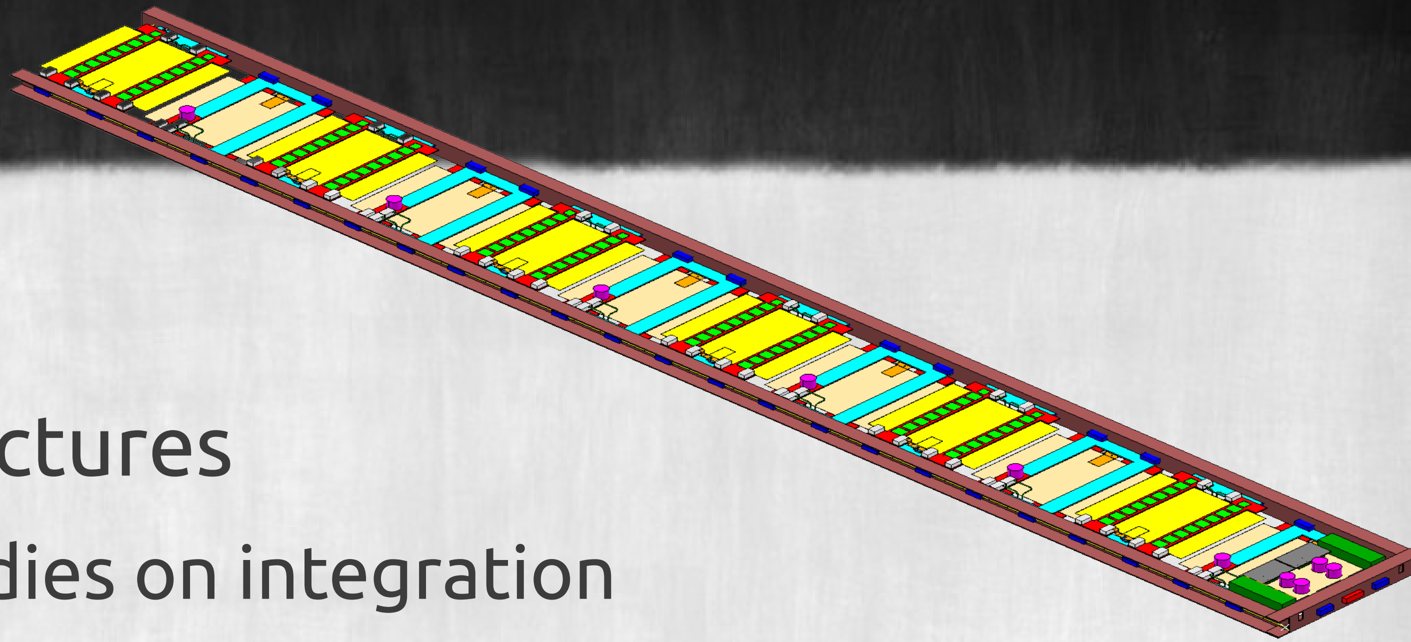
An example of pT-VPS



- Using 3D-silicon technology
  - One chip connected to both sensors
  - Analogue vias through interposer
- Top sensor: ~ cm strips
- Bottom sensor: ~ mm long pixels
  - Provides z measurement
- Technologically very challenging, possibly rewarding

~~Current CMS tracker,~~
~~LHC & Tracker upgrades~~
~~Upgrading the outer tracker~~
~~Upgrade technologies~~
~~The building blocks: modules~~
System integration
Level-1 tracking?
And the vertex detector?
Conclusions

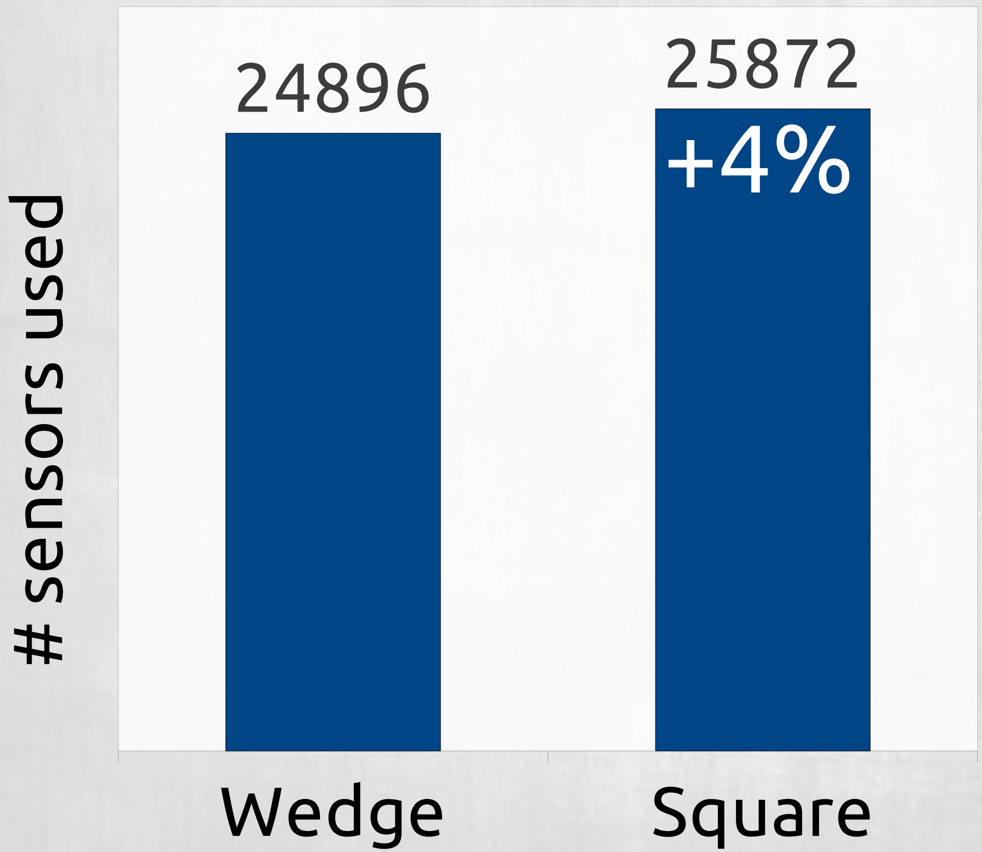
Barrel

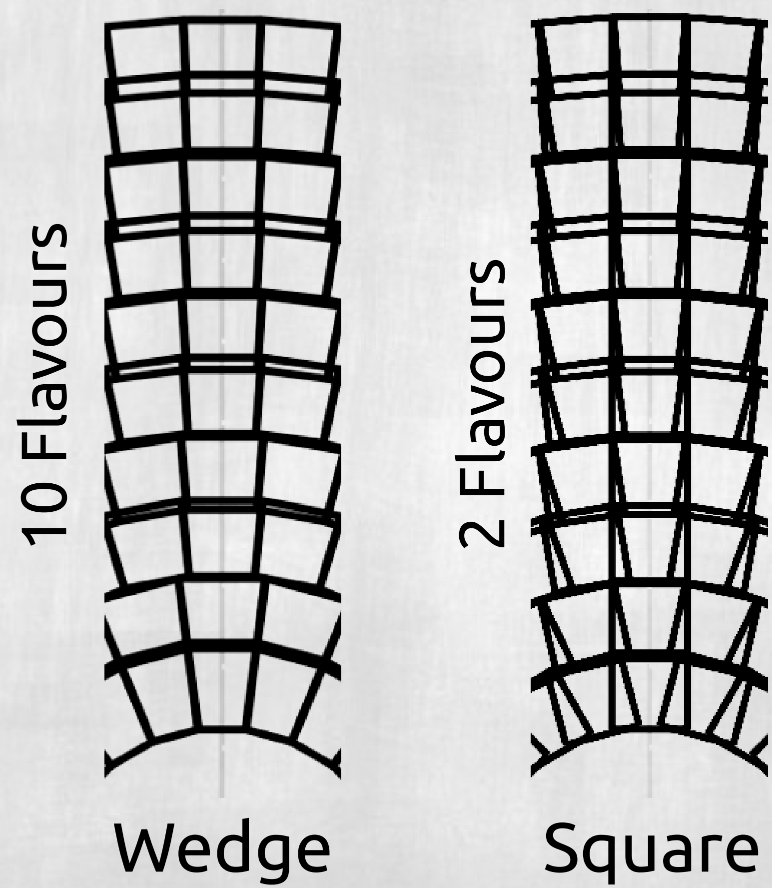


- **ROD**-like structures
  - Ongoing studies on integration
  - Keeping as a reference the present Tracker
  - Serve as basis for thermal / deformation analysis
- Started from simple case, evolving into more complicated one:
  - rphi, stereo, p_T-2S done
  - p_T-PS is ongoing

End-cap

- Increase in material is **very minor** and there is **no visible degradation** in tracking performance
- Use of silicon:

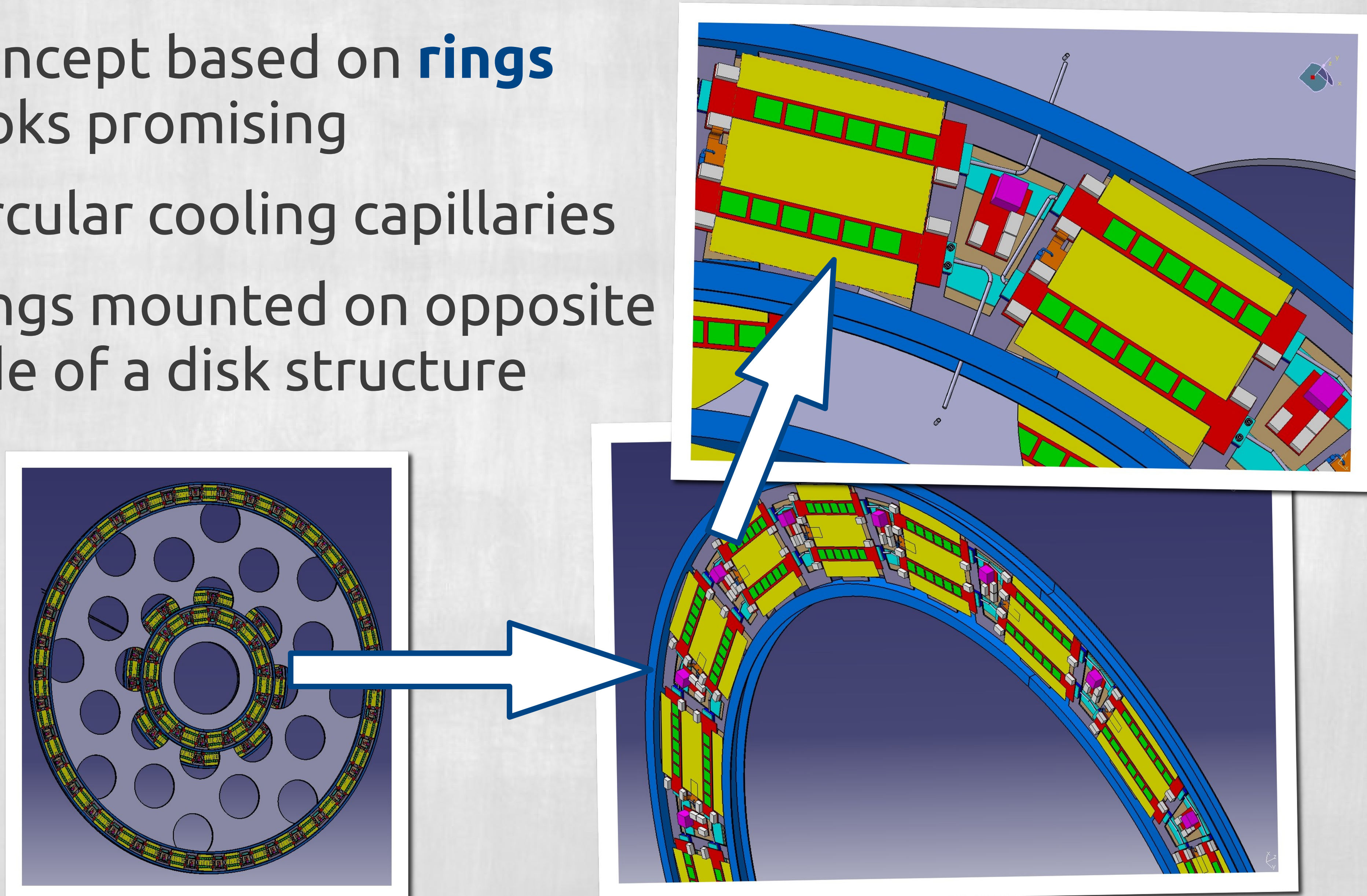




In this region **using square modules is safe**

Curved rods

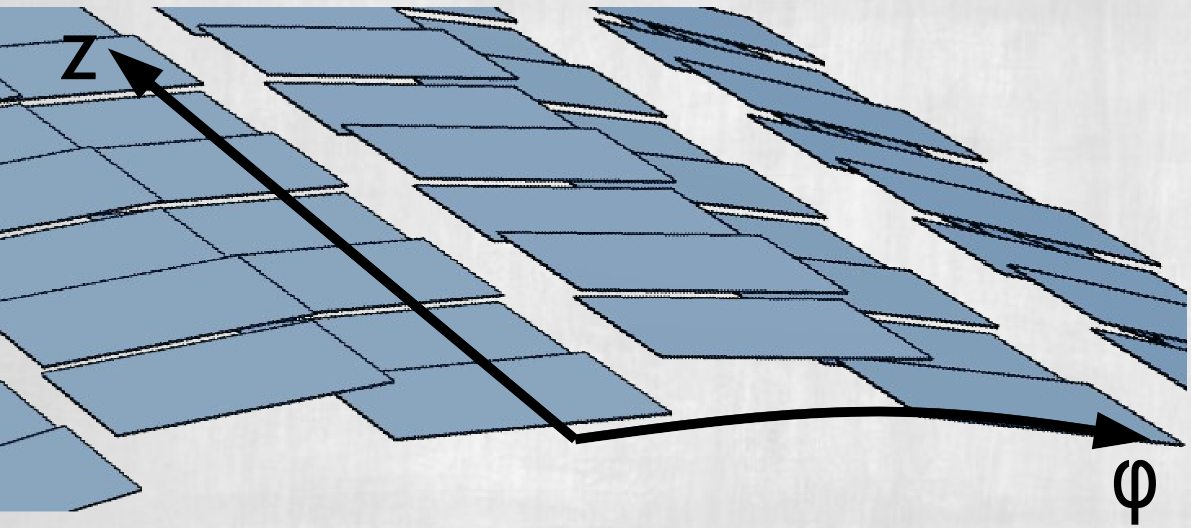
- Concept based on **rings** looks promising
- Circular cooling capillaries
- Rings mounted on opposite side of a disk structure

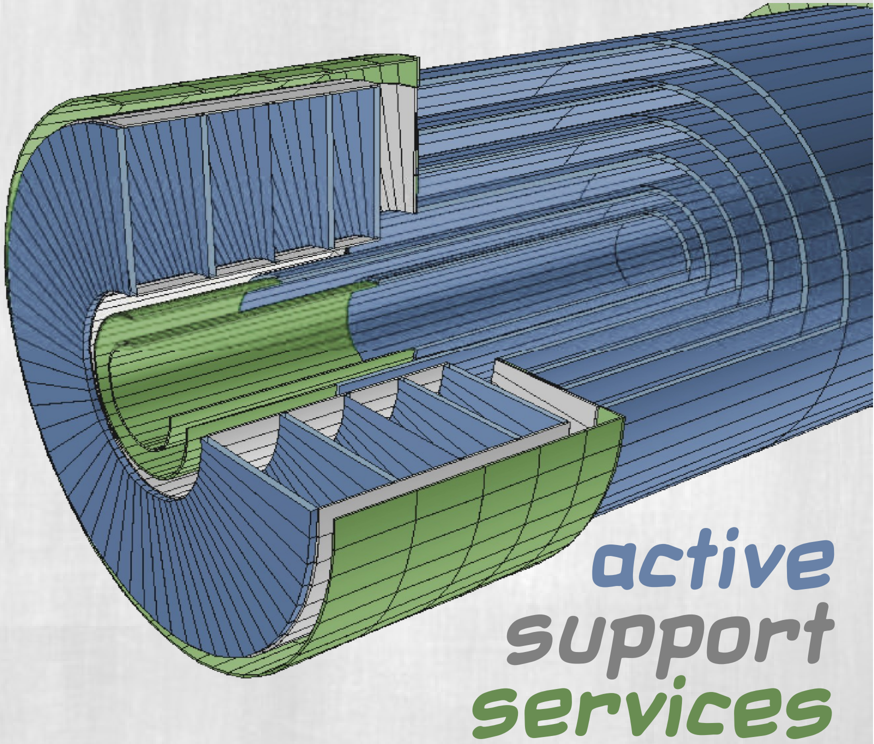


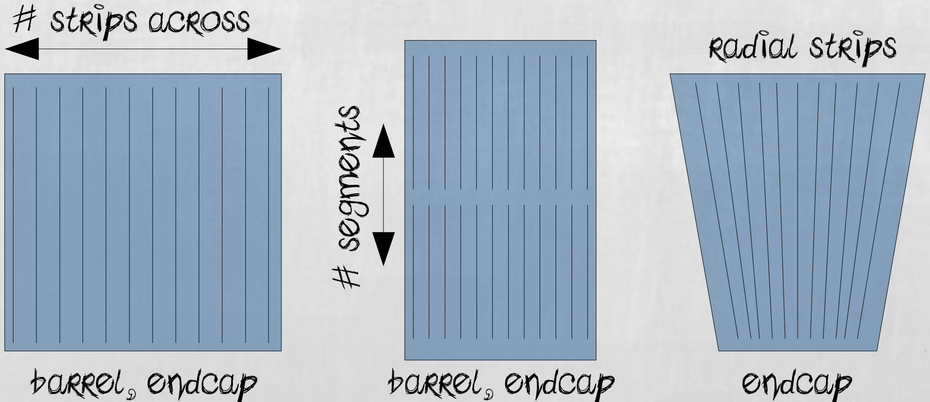
Performance evaluation

Dedicated standalone software package
© N. De Maio, S. Mersi
Based also on work by V. Karimaki and G. Hall

Allows to place in space active and passive volumes
Starting from a small sets of simple parameters

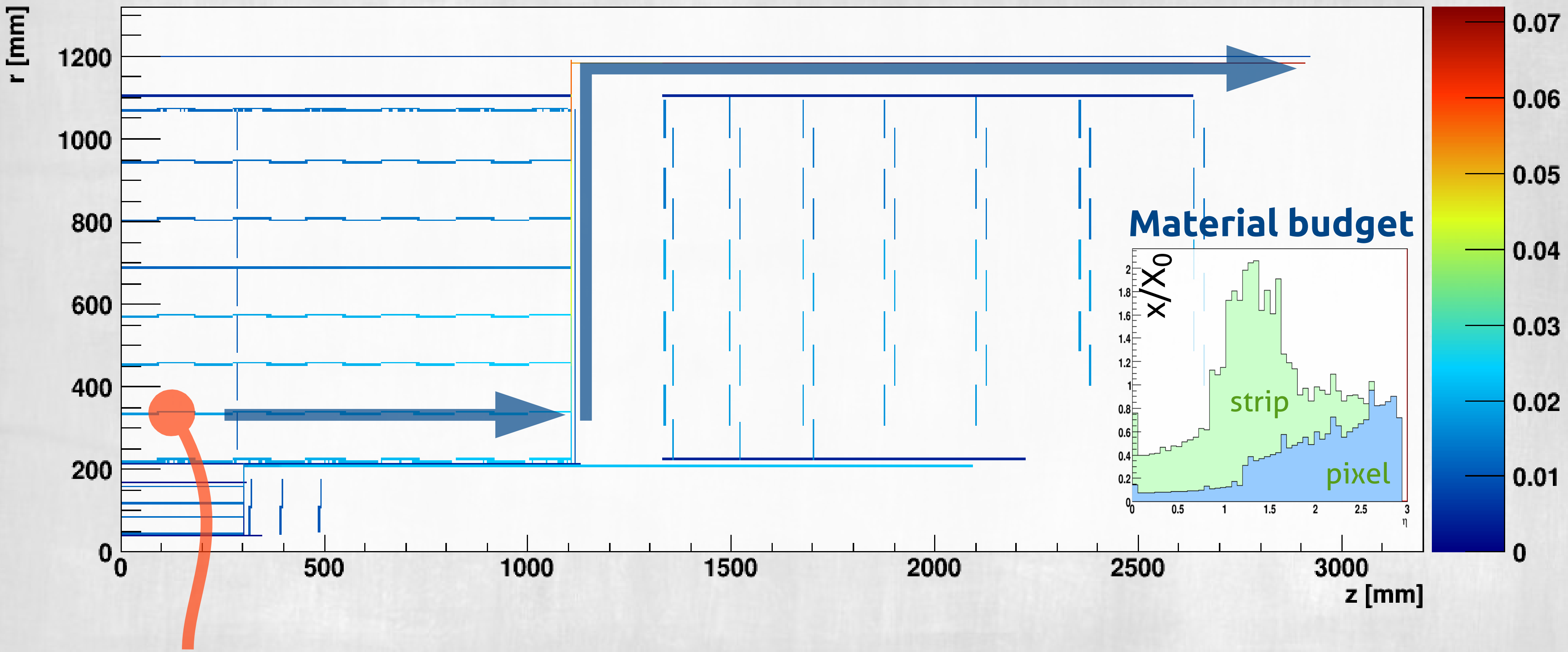






Modules are represented by simple geometric shapes with a small set of parameters describing the sensor design

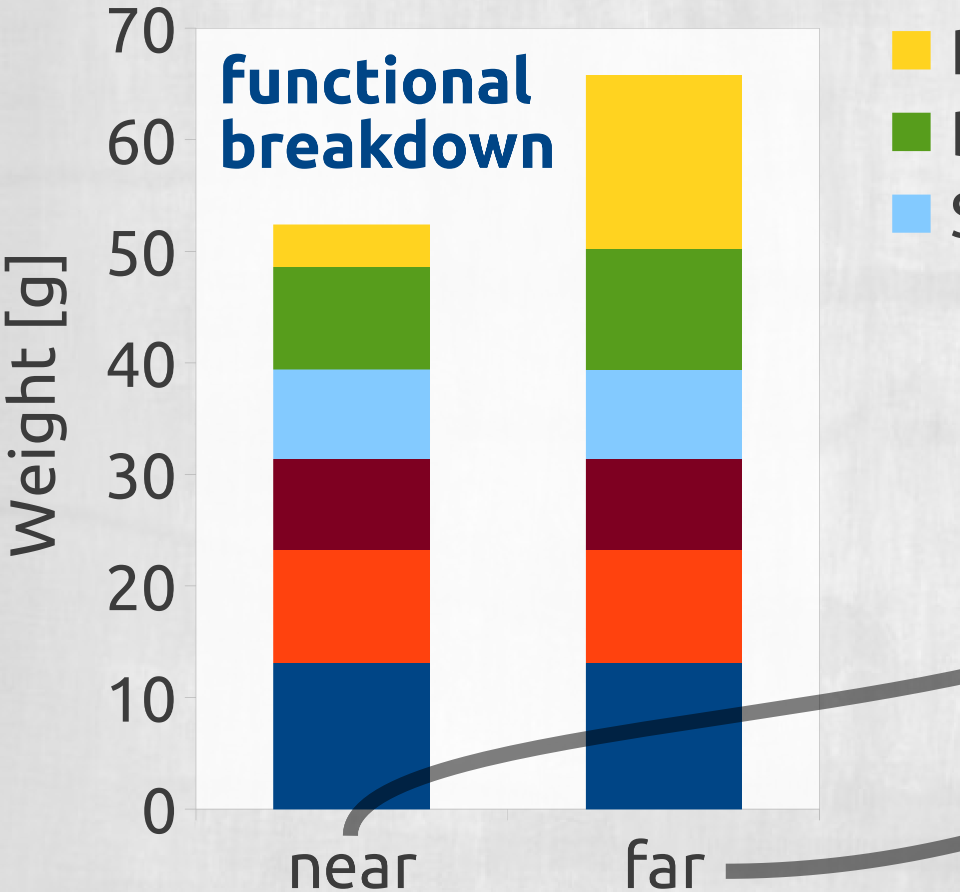
Material budget

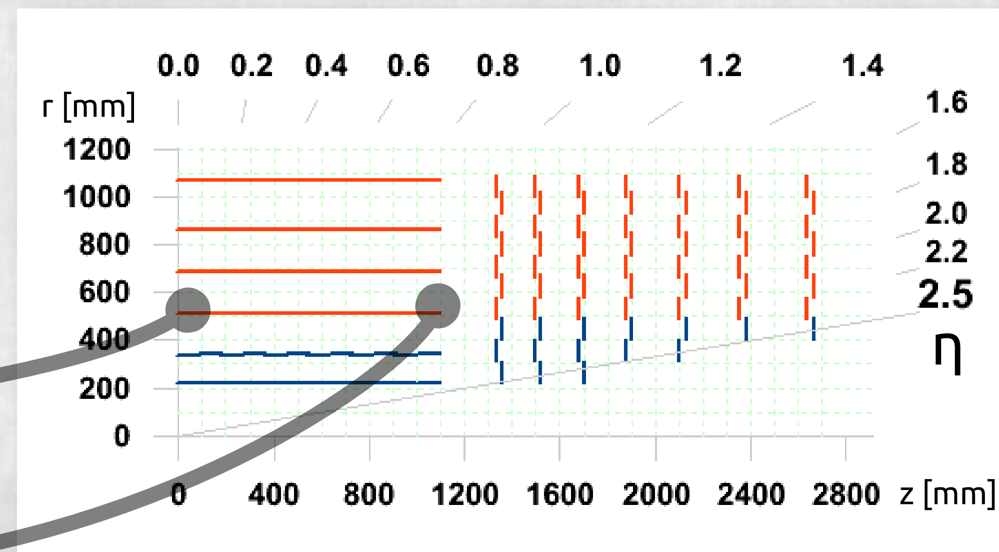


Material on active elements + Material for services automatically routed

Simple (semi)automatic modelling

Material budget





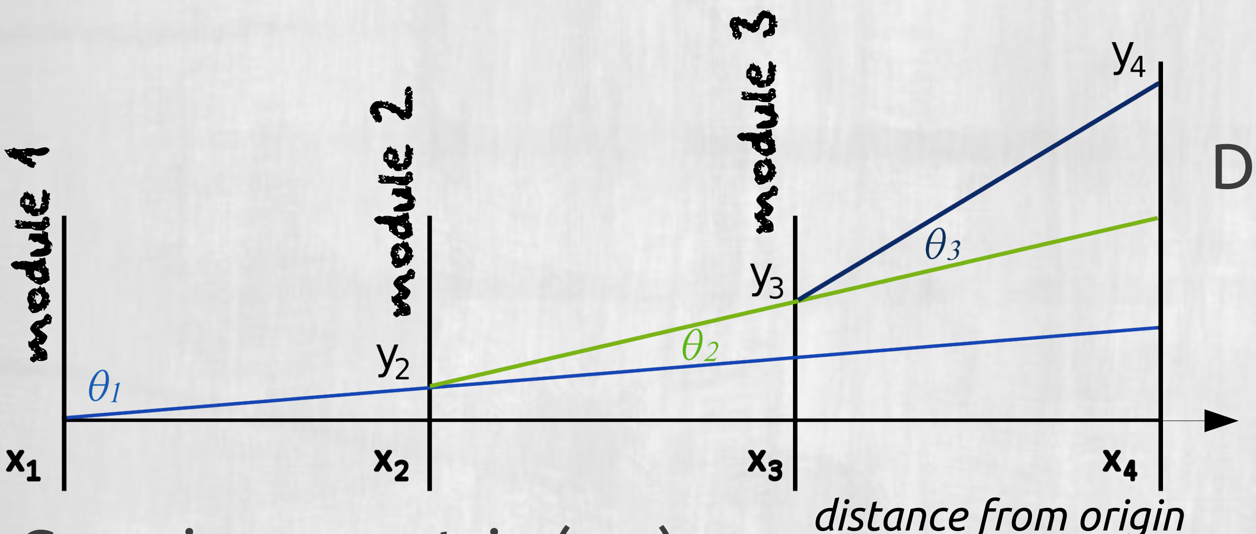
Used to evaluate the probability of **nuclear interaction** and **photon conversion**

Performance estimate

Implements **a priori estimates** of tracking accuracy

Measurement errors used to estimate the errors in track fit parameters

Multiple scattering treated as (correlated) a measurement error



Deviation due to scattering:

$$y_n = \sum_{i=1}^{n-1} (x_n - x_i)\, \theta_i$$

Covariance matrix (r,φ):

$$\sigma_{n,m} = \langle y_n\, y_m \rangle = \sum_{i=1}^{n-1} (x_m - x_i)(x_n - x_i)\, \langle \theta_i^2 \rangle$$

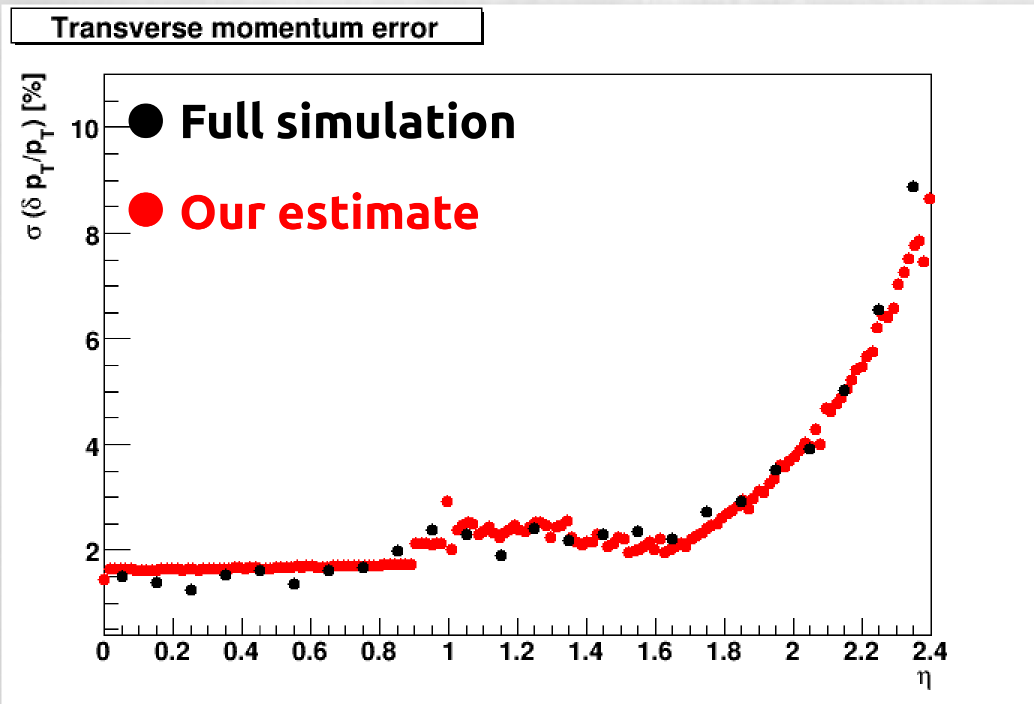
$$\sigma_n^2 = \langle y_n\, y_n \rangle + \frac{pitch_n^2}{12}$$

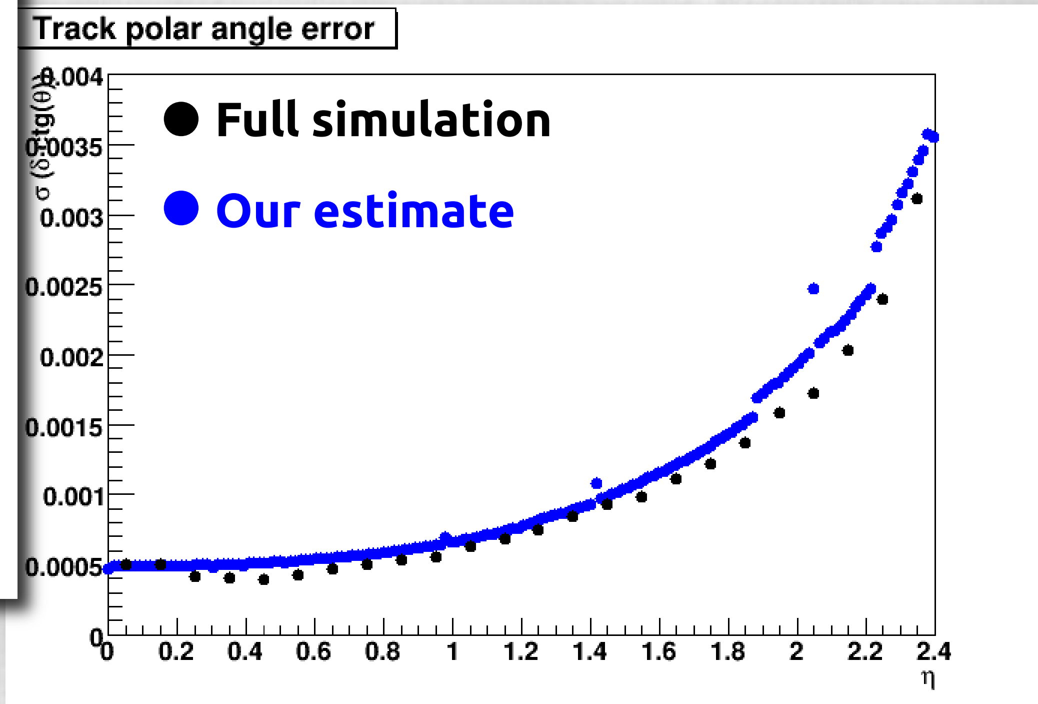
Similar method for (r,z) plane

Can be used in the also to evaluate **trigger performance potential**

Validation

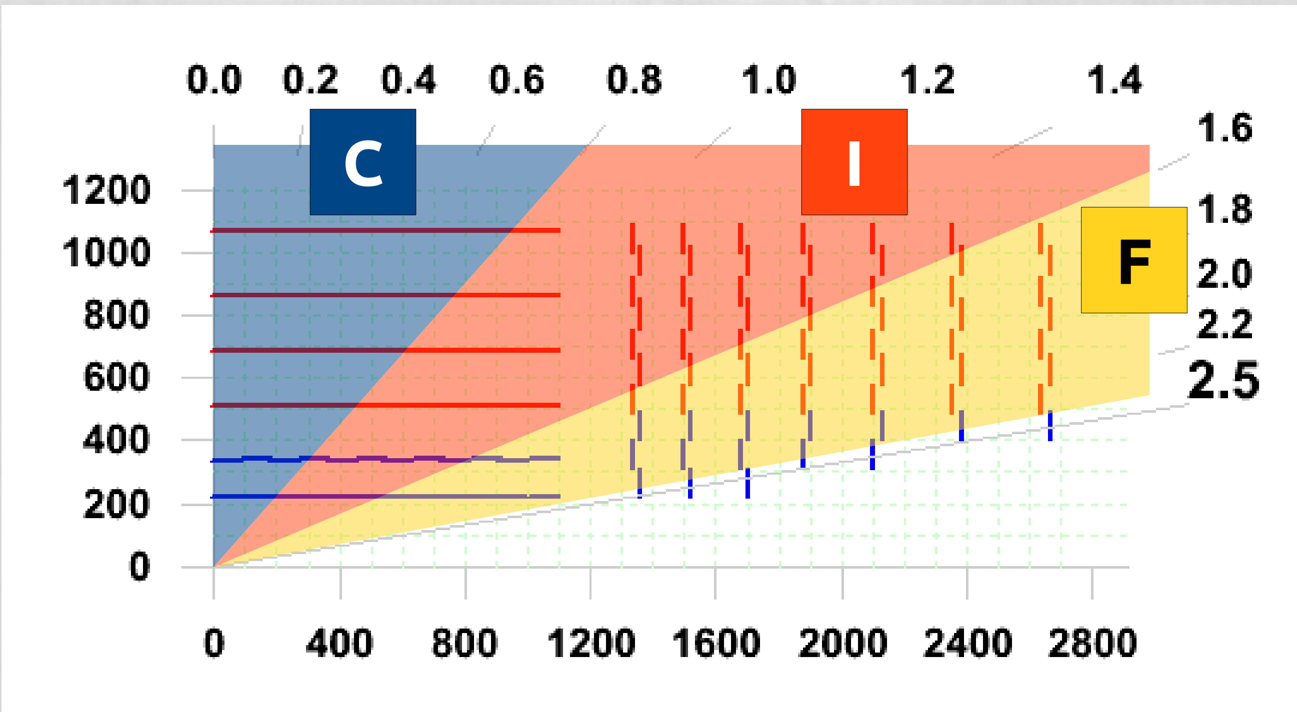
Validated by modelling the present tracker





Spectacular accuracy!

Performance estimate



η

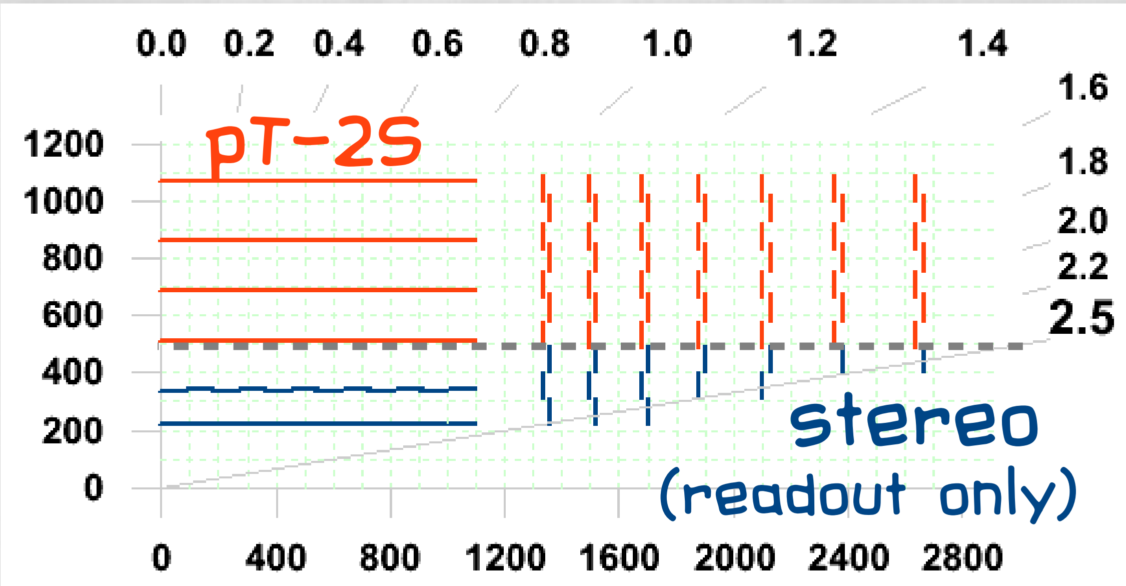
C	0 → 0.8
I	0.8 → 1.6
F	1.6 → 2.4

$\Delta\eta$= 0.8

Roughly same number of tracks expected

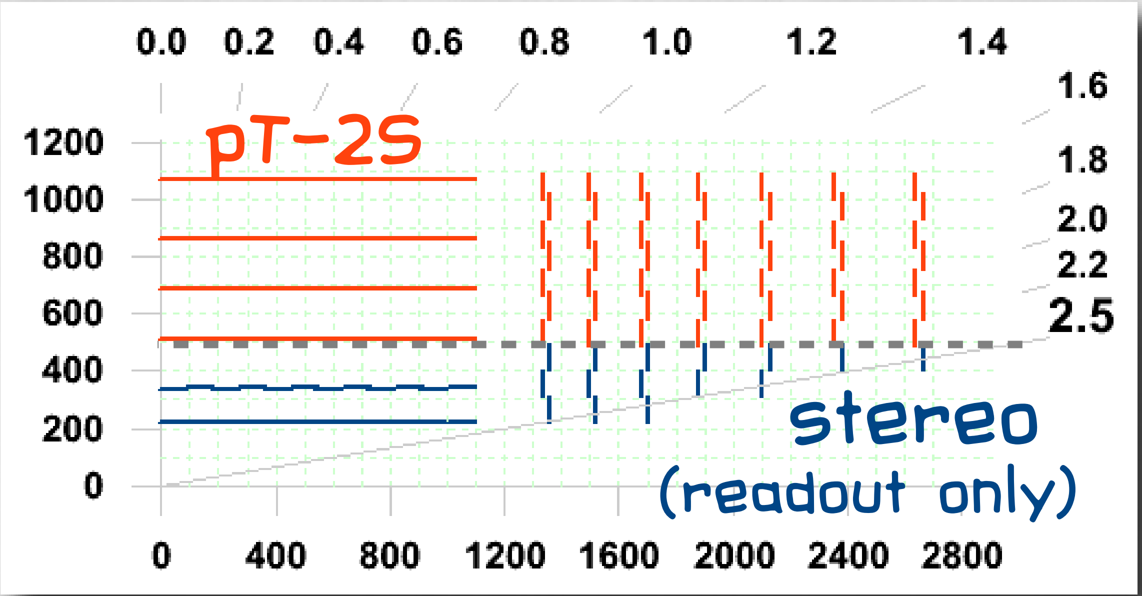
($\Delta\eta$= 0.7 used for trigger studies)

Some layout studies

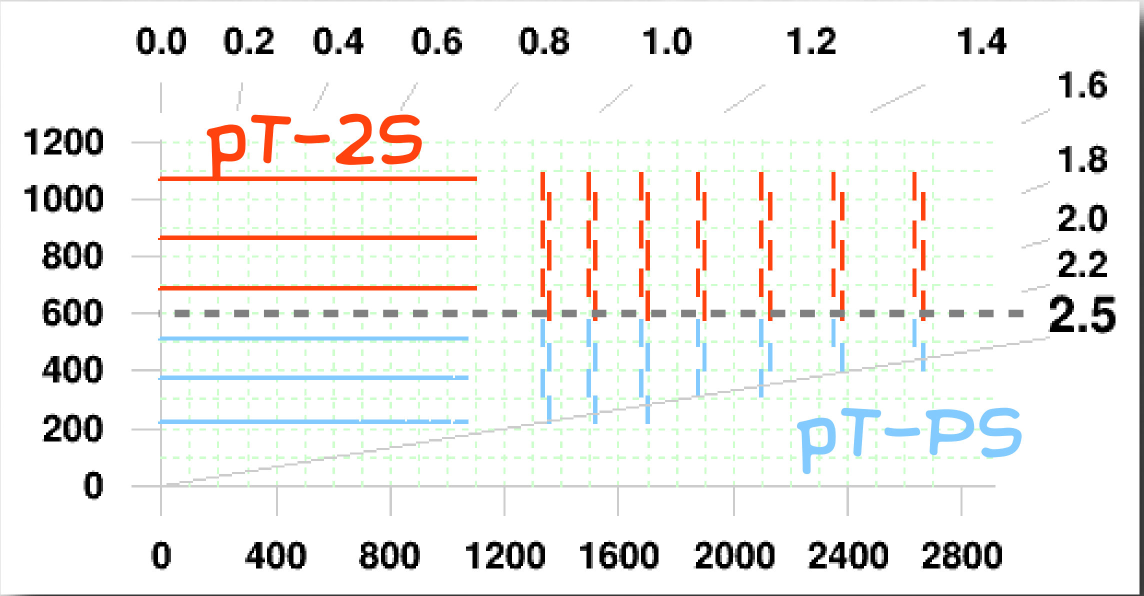


2S only: higher density of tracks inside is tackled with **short strips** and simple modules providing θ measurement, while trigger is obtained from p_T modules only outside

Some layout studies

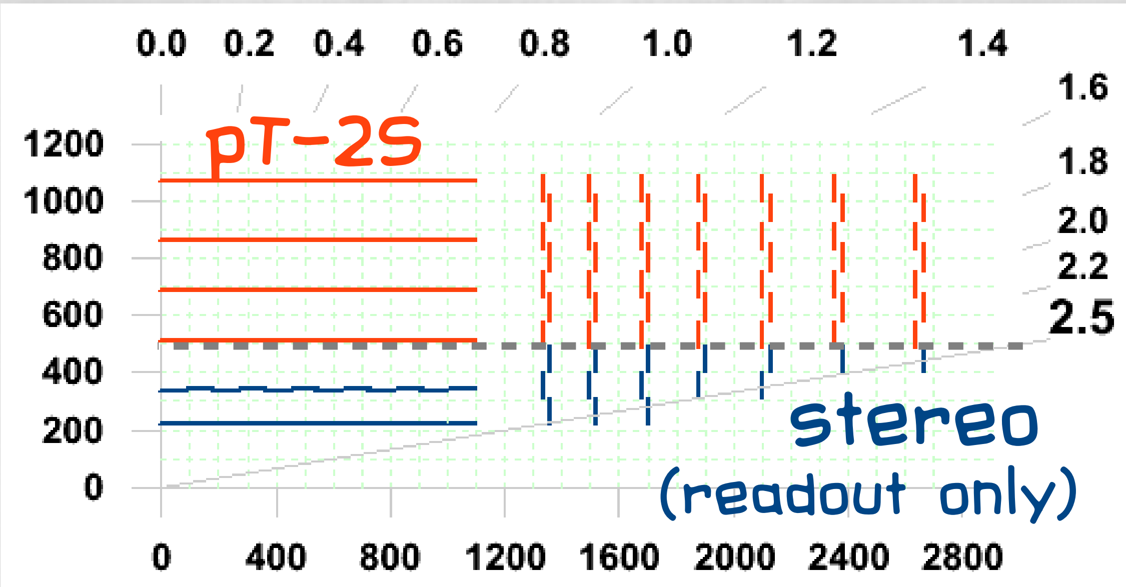


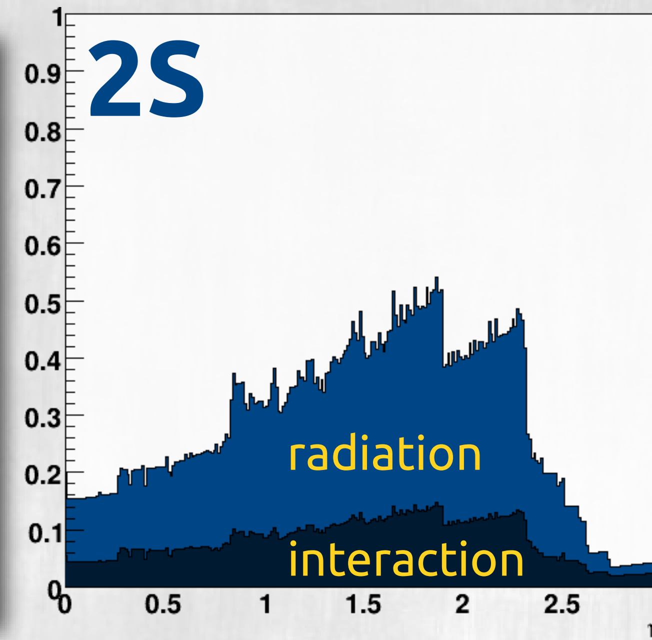
2S only: higher density of tracks inside is tackled with **short strips** and simple modules providing θ measurement, while trigger is obtained from p_T modules only outside

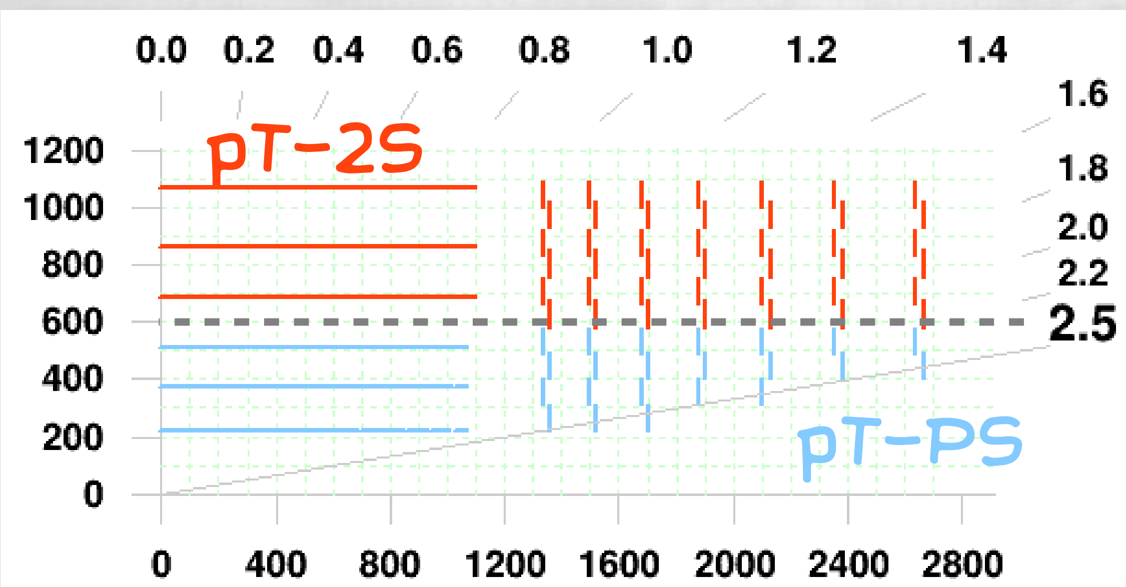


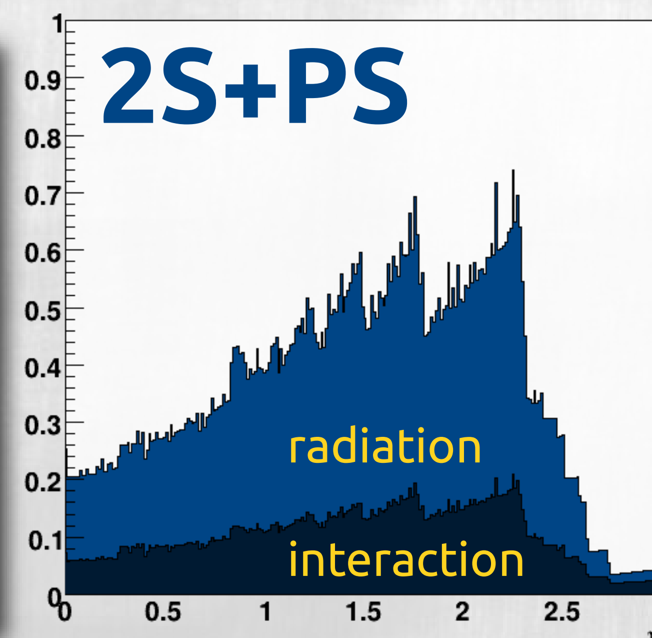
2S+PS: to provide **precise z and θ measurement to L1-trigger**, the inner layers are populated with pixel+strip modules

Some layout studies



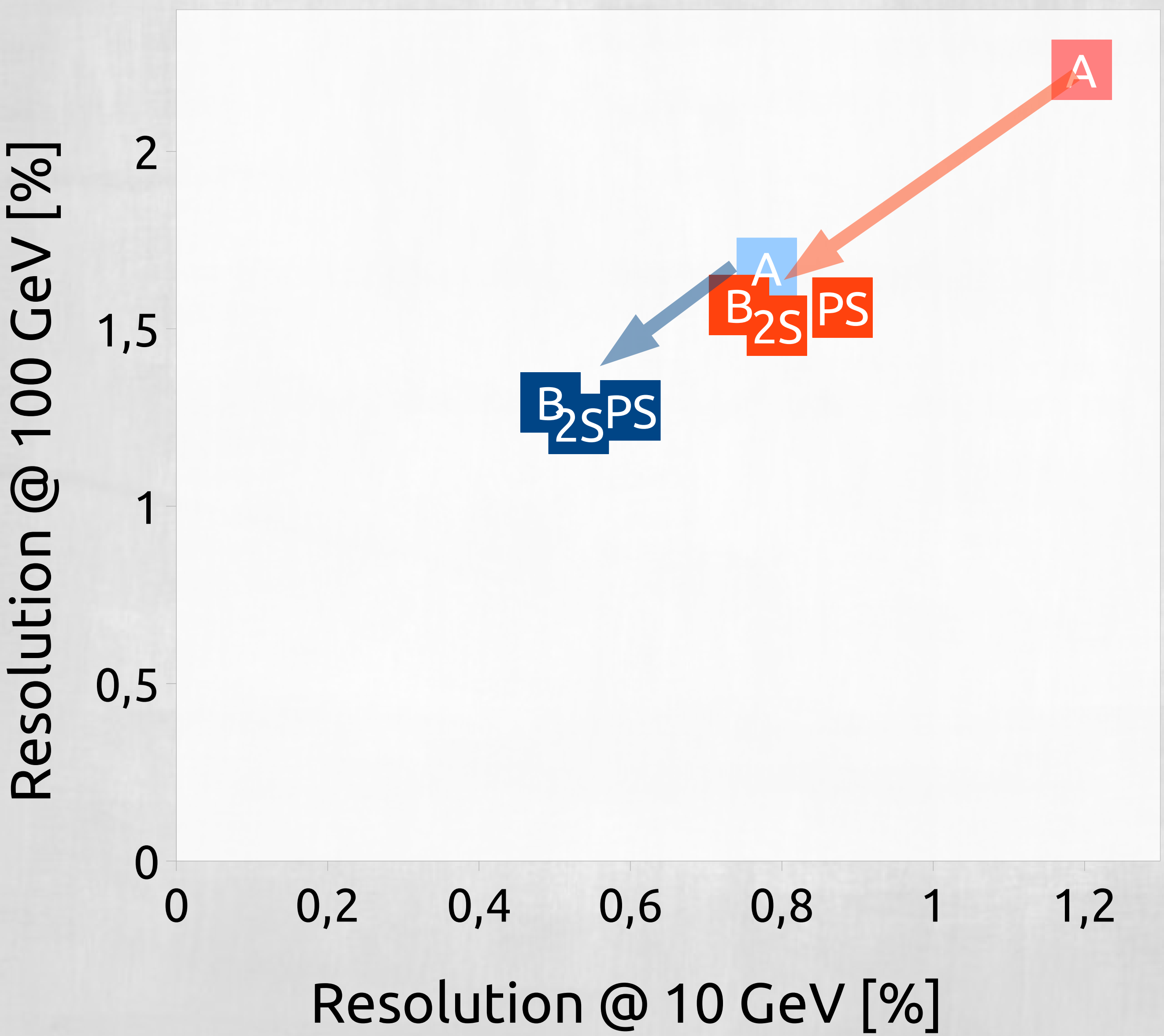






Material amount
in tracking volume

Momentum resolution



η

C	0 → 0.8
I	0.8 → 1.6

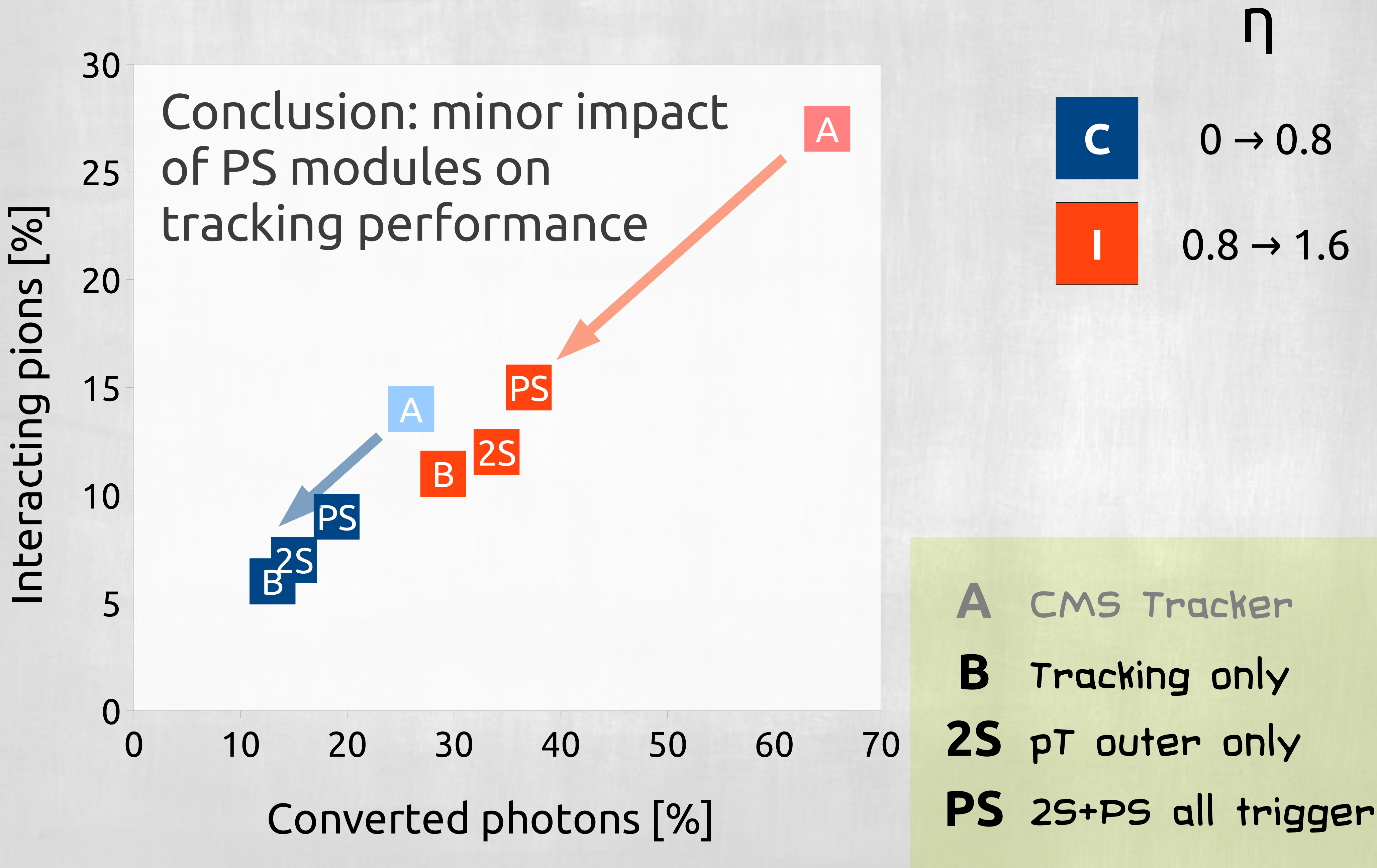
A CMS Tracker

B Tracking only

2S pT outer only

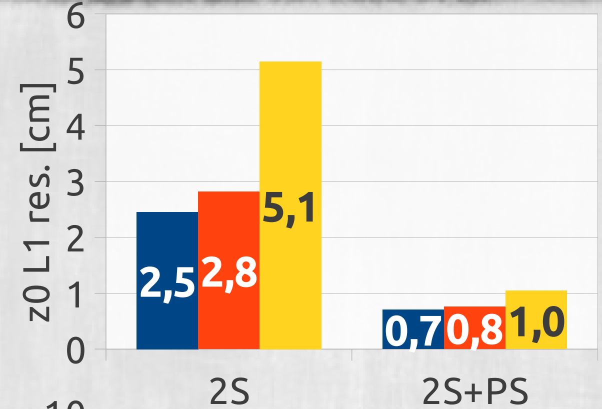
PS 2S+PS all trigger

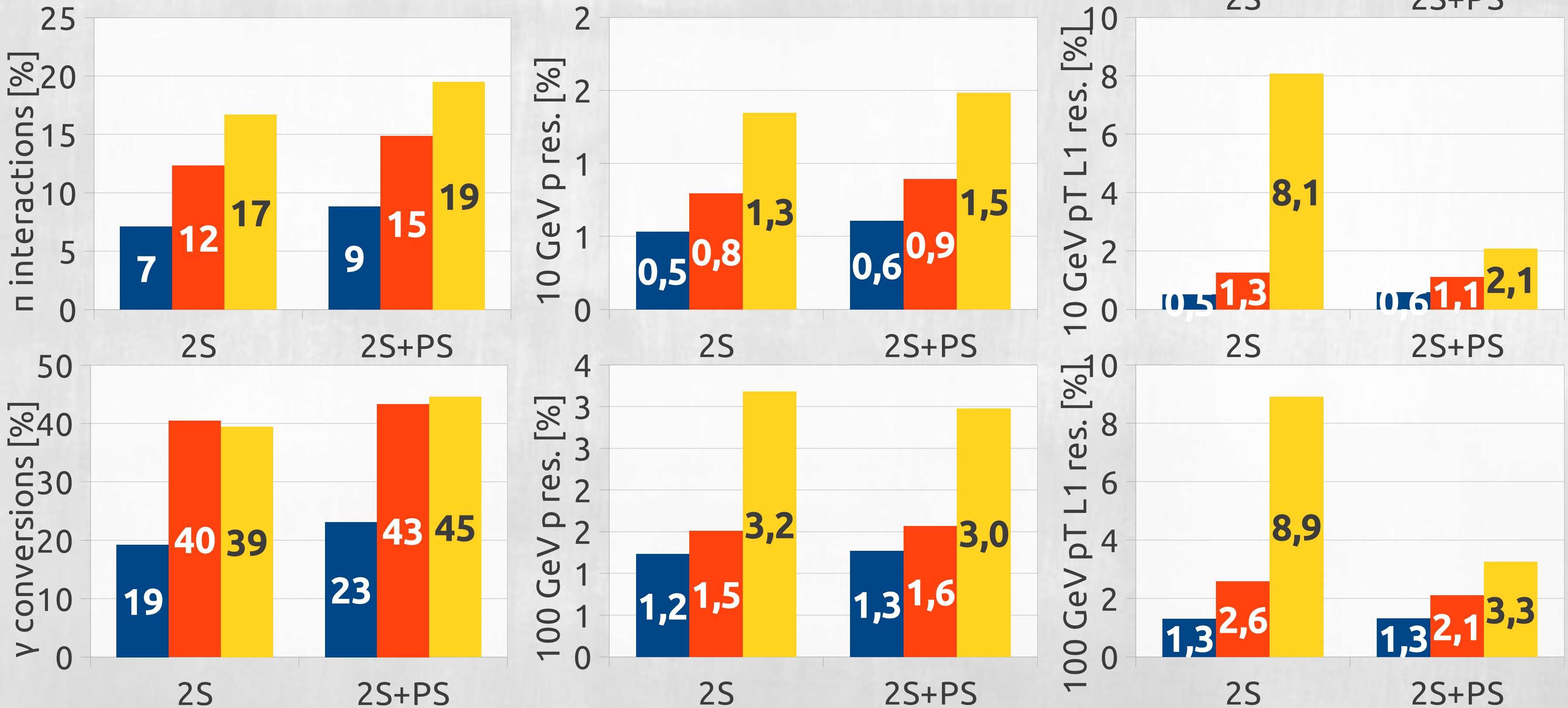
Particle interactions



Comparison 2S vs. PS

- Penalty due to extra material is visible
- Substantial gain in trigger performance potential
    - Better tracking precision in the forward
    - Better z0 resolution everywhere
        - In principle this should allow isolation cuts for electrons/photons!





Particle interactions | **Tracking resolution** | **Trigger resolution**

~~Current CMS tracker,~~

~~LHC & Tracker upgrades~~

~~Upgrading the outer tracker~~

~~Upgrade technologies~~

~~The building blocks: modules~~

~~System integration~~

Level-1 tracking?

And the vertex detector?

Conclusions

Track finding

- High-p_T hits (*stubs*) → tracks
- Ultimate goal: reconstruct all **tracks above ~2 GeV**
    - Inspired from isolation cuts presently used in High-Level Trigger
        - N.B. Association of stubs directly to muon/calorimeter primitives does not seem viable

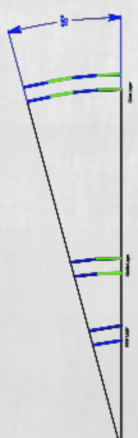
Two approaches considered so far:

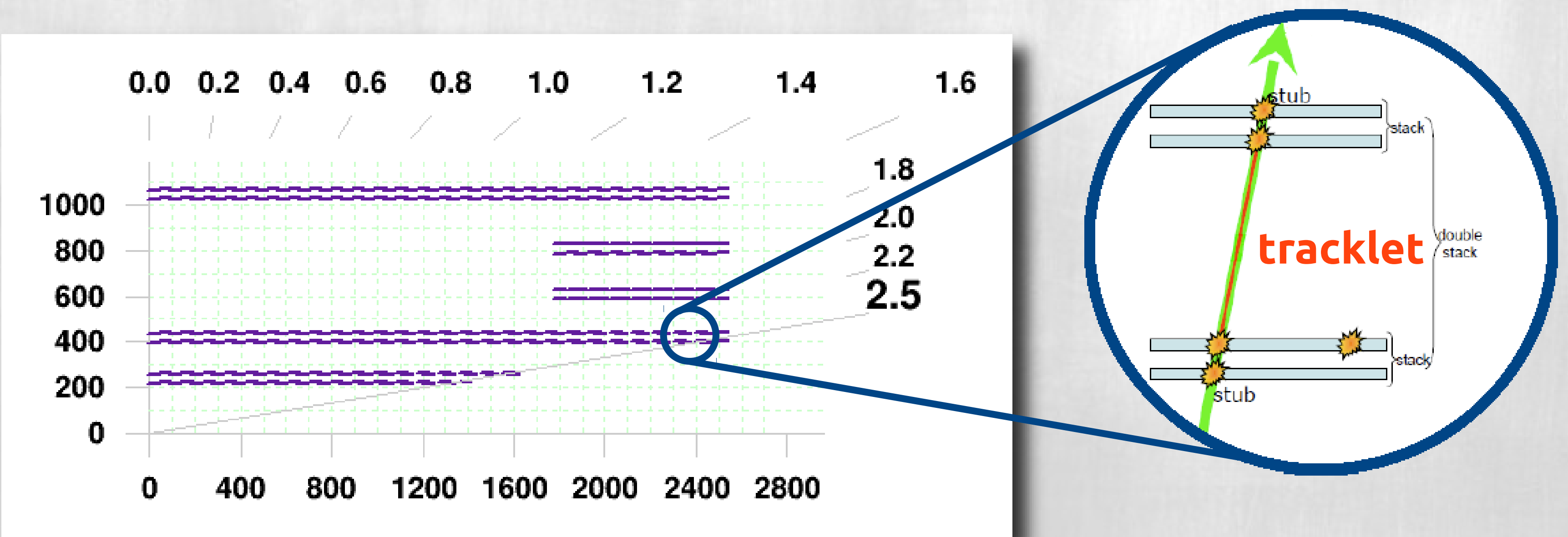
(still in the speculative stage)

- Hierarchical: stub → **tracklet** → track
- **Associative memories**: stubs → track

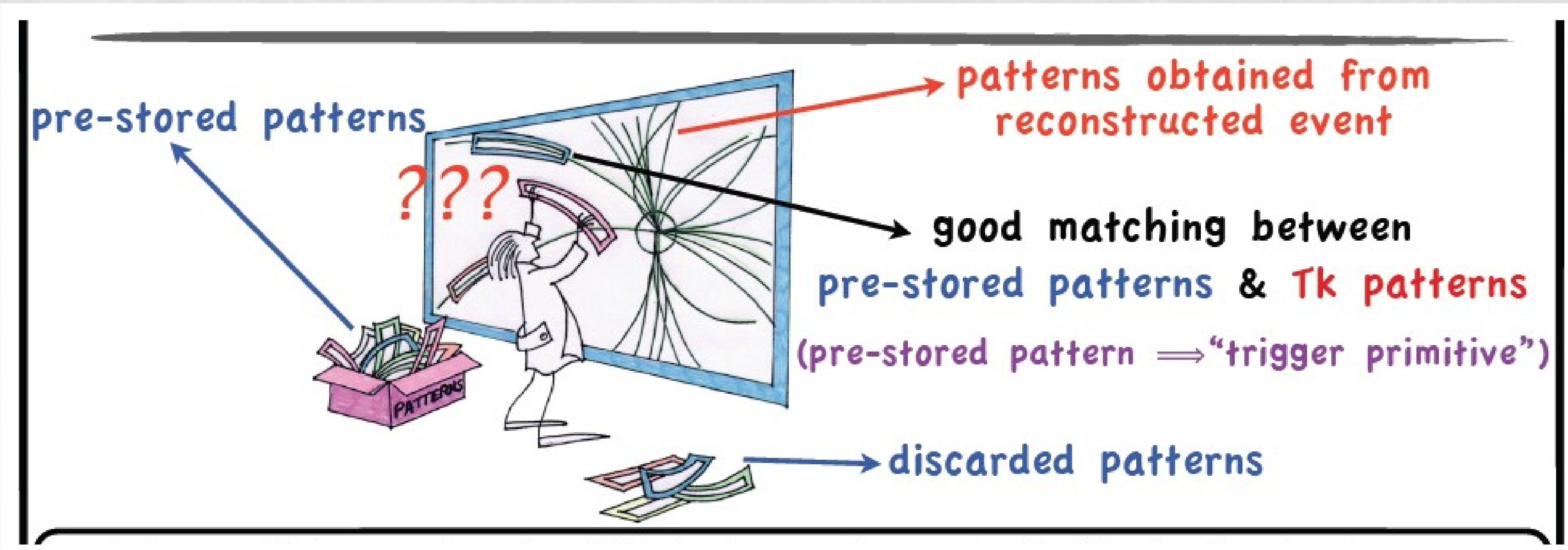
Track finding: tracklets

- Hierarchical stub → **tracklet** → track processing in FPGAs
  - Pairs of layers closely spaced (to mitigate the combinatorial)
  - Studied on a barrel-only layout optimized for trigger
    - Well defined sectors in rφ
    - Penalty in tracking performance in forward region
- Concept **studied in some detail**


15° sector



Track finding: AMs



Parallel processing in **Associative Memories**

- AMs used in **CDF** and now considered in **ATLAS**
- In principle powerful approach for this kind of problems
- Should be applicable to different detector geometries
  - However size of the application unprecedented
  - A first exercise done so far, using only three outermost layers, and 2S modules

… to be followed up!

~~Current CMS tracker,~~

~~LHC & Tracker upgrades~~

~~Upgrading the outer tracker~~

~~Upgrade technologies~~

~~The building blocks: modules~~

~~System integration~~

~~Level-1 tracking?~~

And the vertex detector?

Conclusions

Phase-II pixels?

3D electrodes

- Narrow columns
  Φ = 10 μm d = 50 – 100 μm
- Lateral depletion

Lower depletion voltage

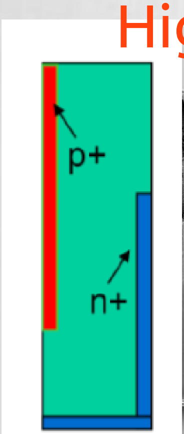
Thicker detectors possible

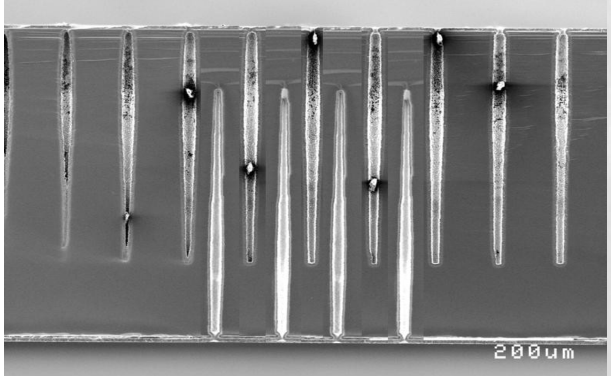
Fast signal

Higher CCE

Radiation hard up to several 1E15-1E16 p/cm^2

Higher capacitance → noise ?





CMS started to process 3D sensor
on the footprint of the CMS pixel
chip – full size module

Diamonds

Radiation hard

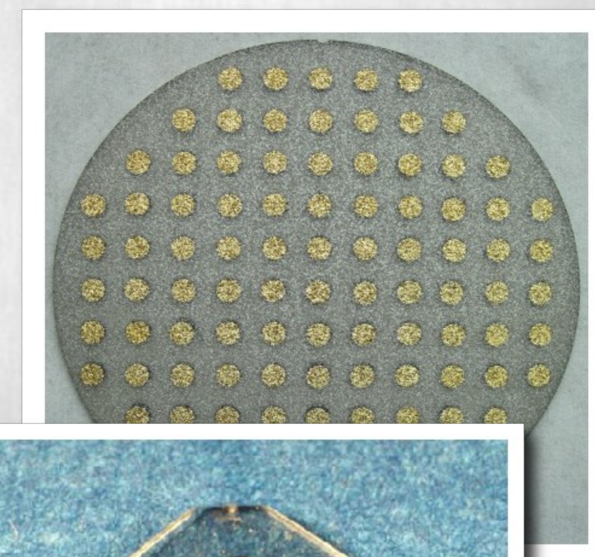
Low capacitance → Low noise

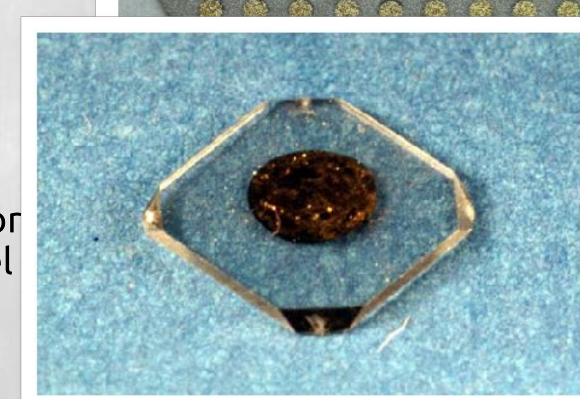
Very good thermal conductivity

Fast signal

$I_{LEAK} = 0$

Small size





~~Current CMS tracker,~~

~~LHC & Tracker upgrades~~

~~Upgrading the outer tracker~~

~~Upgrade technologies~~

~~The building blocks: modules~~

~~System integration~~

~~Level-1 tracking?~~

~~And the vertex detector?~~

Conclusions

Conclusions

- **Good progress on R&D** for the tracker @ High-Luminosity LHC
  - **Sensors**: large measurement/irradiation campaign started
  - **Services**: DC/DC power, CO_2 cooling, GBT data transmission
  - **Front-ends**: CBC, FEAFS
  - **Module concepts**: rphi, stereo, 2S, PS, VPS
  - **Structures** for the integration: rods, disks
  - **Layouts**: many...
- Can profit from Phase-I upgrade, but much more is required
  - Scale (size) and Level-1 Trigger
- Developed **software tools** to assess the performance potential of the available options

  Providing useful information for precise **tracking @ Level-1 appears plausible** (and compatible with a good tracking resolution)

  Open problem: how to **process track information @ Level-1?**

Thank you