# UPGRADE OF THE CMS TRACKER WITH TRACKING TRIGGER

R&D and ideas for implementation

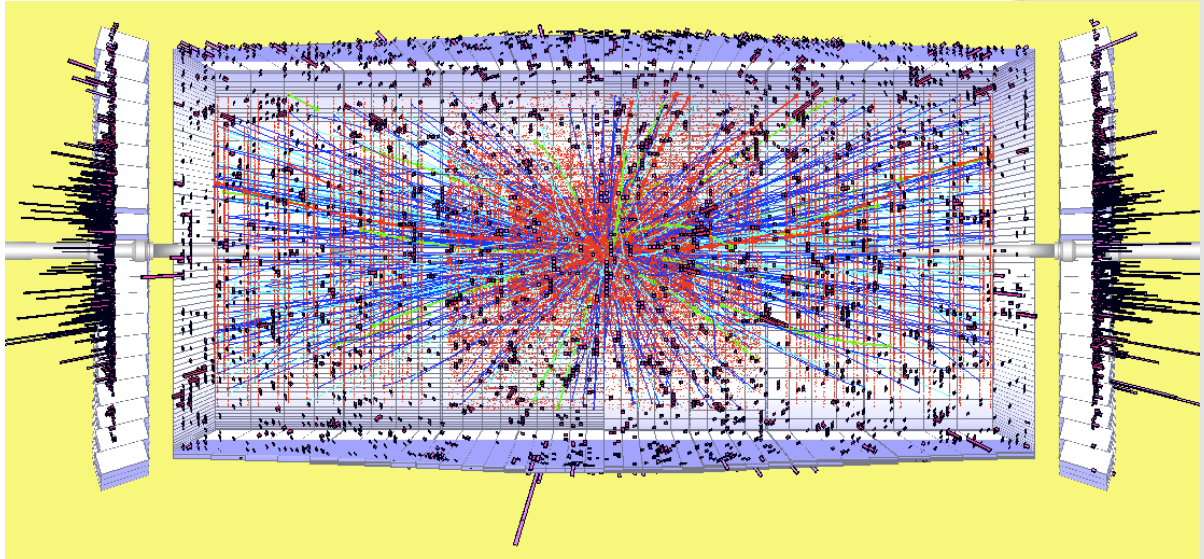
# Outline

- Introduction: the Tracker Upgrades
- Requirements for HL-LHC
- Implementation of trigger functionality
  - Modules with $p_T$ discrimination
  - Study of possible Tracker geometries
  - Possible track trigger system concepts
- Conclusions and outlook

# The Tracker Upgrades

- Pixel upgrade
  - Foreseen for the middle of this decade
    - 4-layers / 3 disks
    - Optimized design, substantially reduced mass
    - $CO_2$ cooling, DC-DC converters for powering
    - Electronics more robust @ high rate
- Full Tracker upgrade
  - Foreseen for the beginning of the next decade
  - Large project, vast R&D program covering all detector aspects
    - Includes requirement of tracking in Level-1 trigger
  - Will also involve one further upgrade of the pixel detector
    - Focus has been mostly on the outer tracker, for the time being

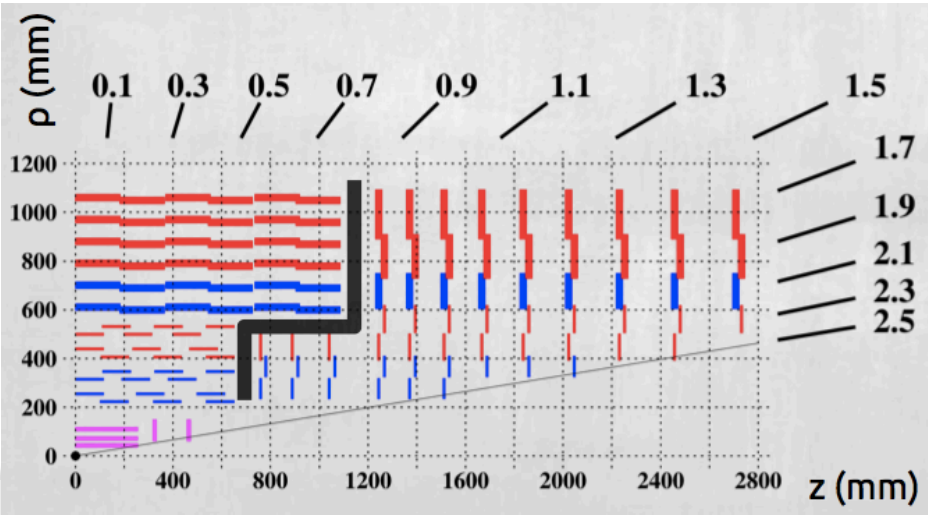
# The full Tracker Upgrade: basic requirements

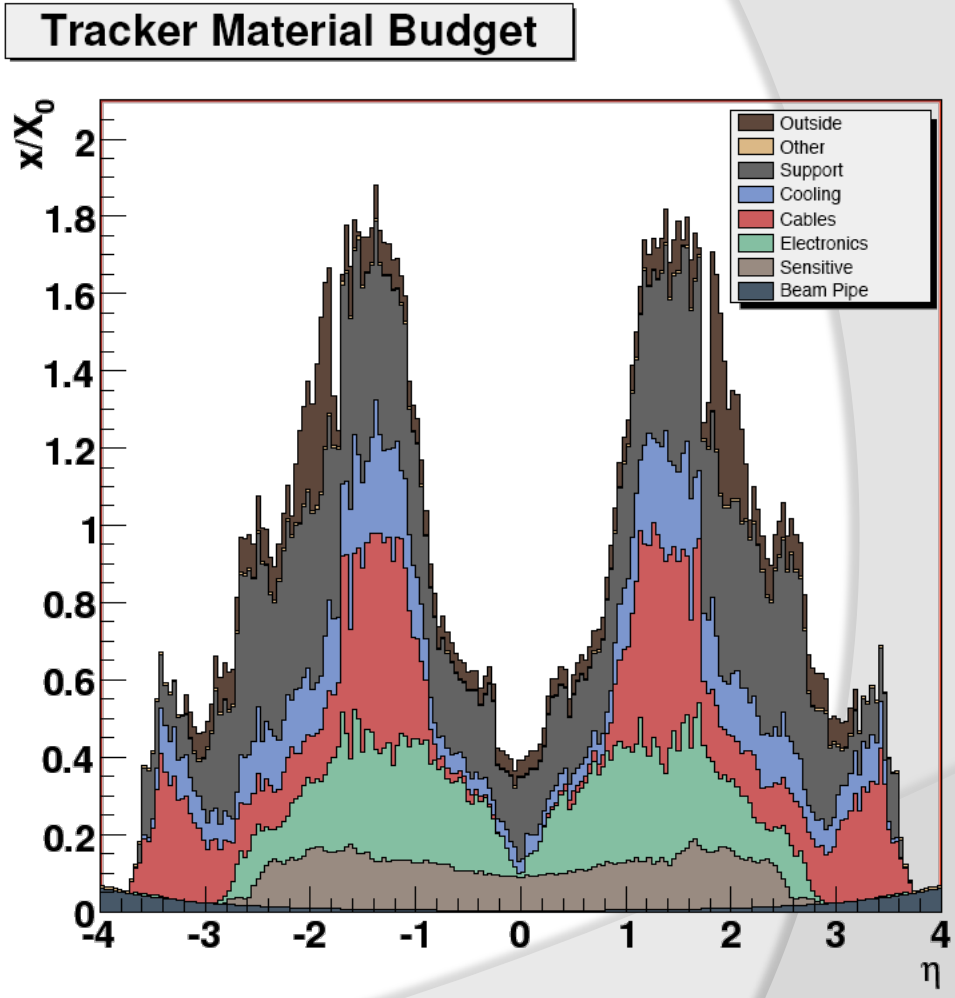


- Granularity
  - Resolve up to 200÷250 collisions per bunch crossing
    - Nominal figure of $5\times10^{34}$ cm$^{-2}$ s$^{-1}$ @ 40 MHz corresponds to ≥ 100 collisions
  - Maintain occupancy at the few % level
- Radiation hardness
  - Ultimate integrated luminosity considered ~ 3000 fb$^{-1}$
    - To be compared with original ~ 500 fb$^{-1}$

# An “old” requirement

- Improve Tracking performance
- Current Tracker has a lot of material
  - Modules, power cables, cooling, support structures
  - Particularly between barrel and end-caps




**Minimize material in the Tracking Volume**

# A “new” requirement

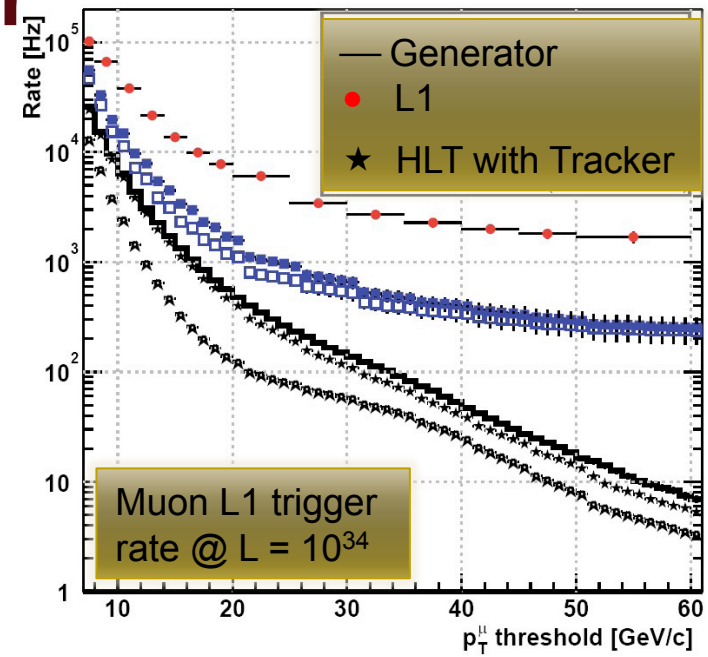
- μ, e and jet rates would exceed 100 kHz at high luminosity
- Increasing thresholds would affect physics performance
  - Performance of algorithms degrades with pile-up
    - Muons: increased background rates from accidental coincidences
    - Electrons/photons: reduced QCD rejection at fixed efficiency from isolation
- Planned “phase-1” trigger upgrades are not sufficient
  - 4th CSC muon station in the forward
  - More granularity/segmentation from calorimeters and muons

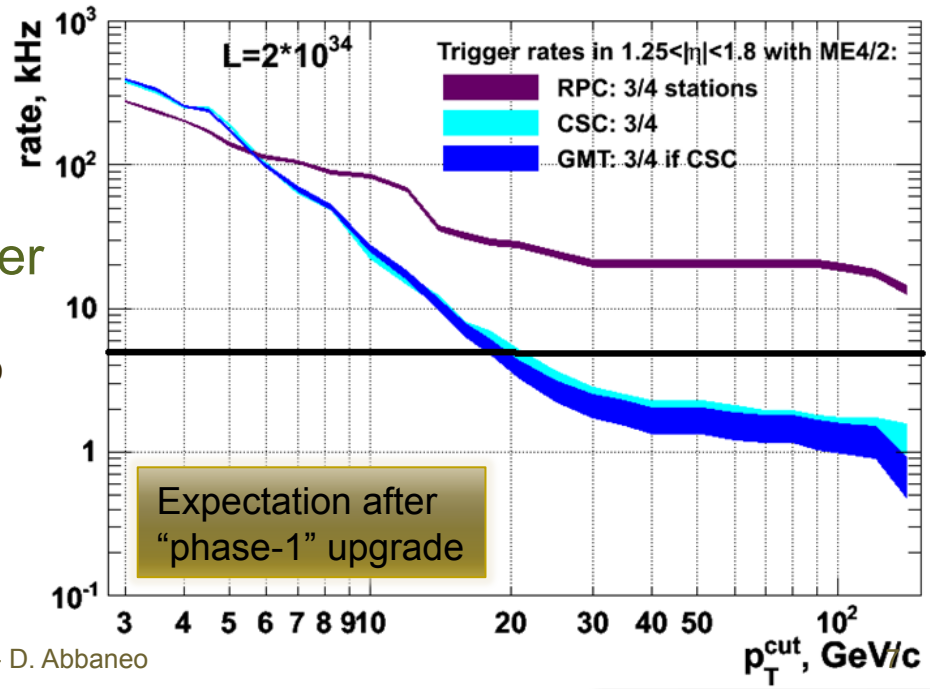
## Tracker input to Level-1 trigger

- Goals:
  - Maintain overall L1 rate within 100 KHz
  - Keep latency within ~ 6 μs (ECAL pipeline 256 samples = 6.4 μs)
    - The current limit is the Tracker

# Example: single muon trigger

- Phase-1 trigger upgrade should provide ≥ ×2 improvement in rejection power
- However, rate remains ~ flat at high $p_T$
  - Mis-measured tracks would ~ saturate the available rate eventually
  - Muon system alone cannot cope with $5\times10^{34}$ and above
- Matching Tracker coordinates can potentially improve the resolution by one order of magnitude
- Similar issue for single electron trigger
  - Isolation cuts using tracks may need some discrimination on primary vertex z position, to avoid rejecting good electrons



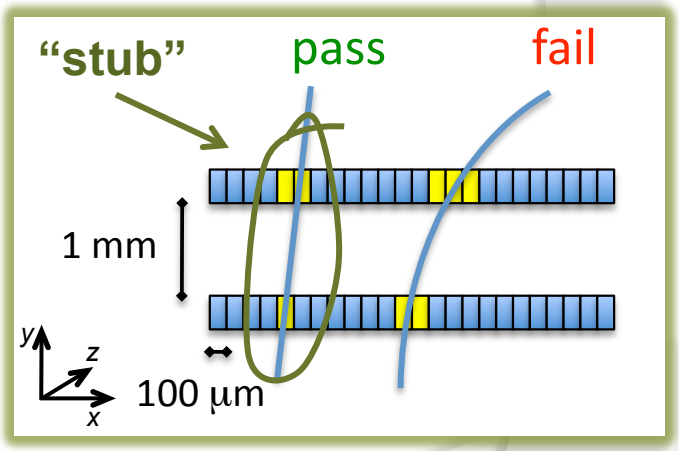



# Trigger architectures

- (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
- (b) “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 (~3 μs)
    - Expected rate ~ 1 MHz
  - Tracker sends out information from regions of interest (within a few clock cycles), to form a new combined L1 trigger
    - Within the remaining ~3 μs
- Mostly focusing on option (a) so far
  - Maintains present architecture
  - Requires local data reduction (i.e. rejection of low-$p_T$ tracks)
    - Possible implementation exploits the strong CMS magnetic field

# Modules with $p_T$ discrimination

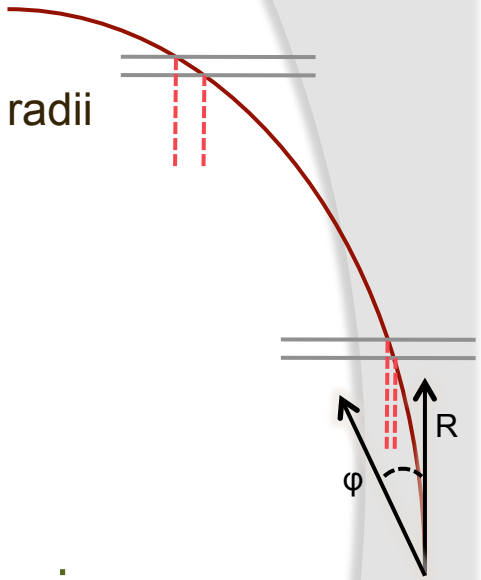
- Select locally hits from particle above a $p_T$ threshold ("$p_T$ module")
  - Threshold 1 to a few GeV → data reduction of one order of magnitude or more
- Correlate signals in two closely-spaced sensors
  - Exploits the strong magnetic field of CMS



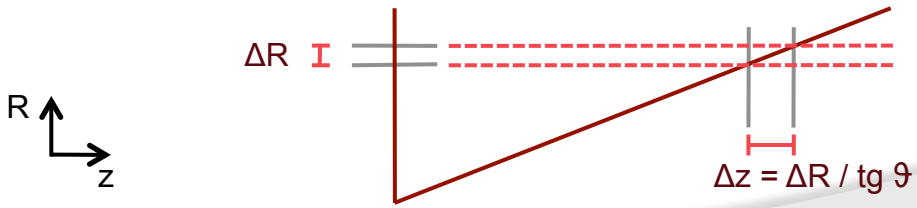

- Several options considered:
  - With strip sensors only
  - With pixellated sensors
  - With vertical interconnection through an interposer
  - With interconnection at the sensors edge

# $p_T$ modules in barrel and end-cap

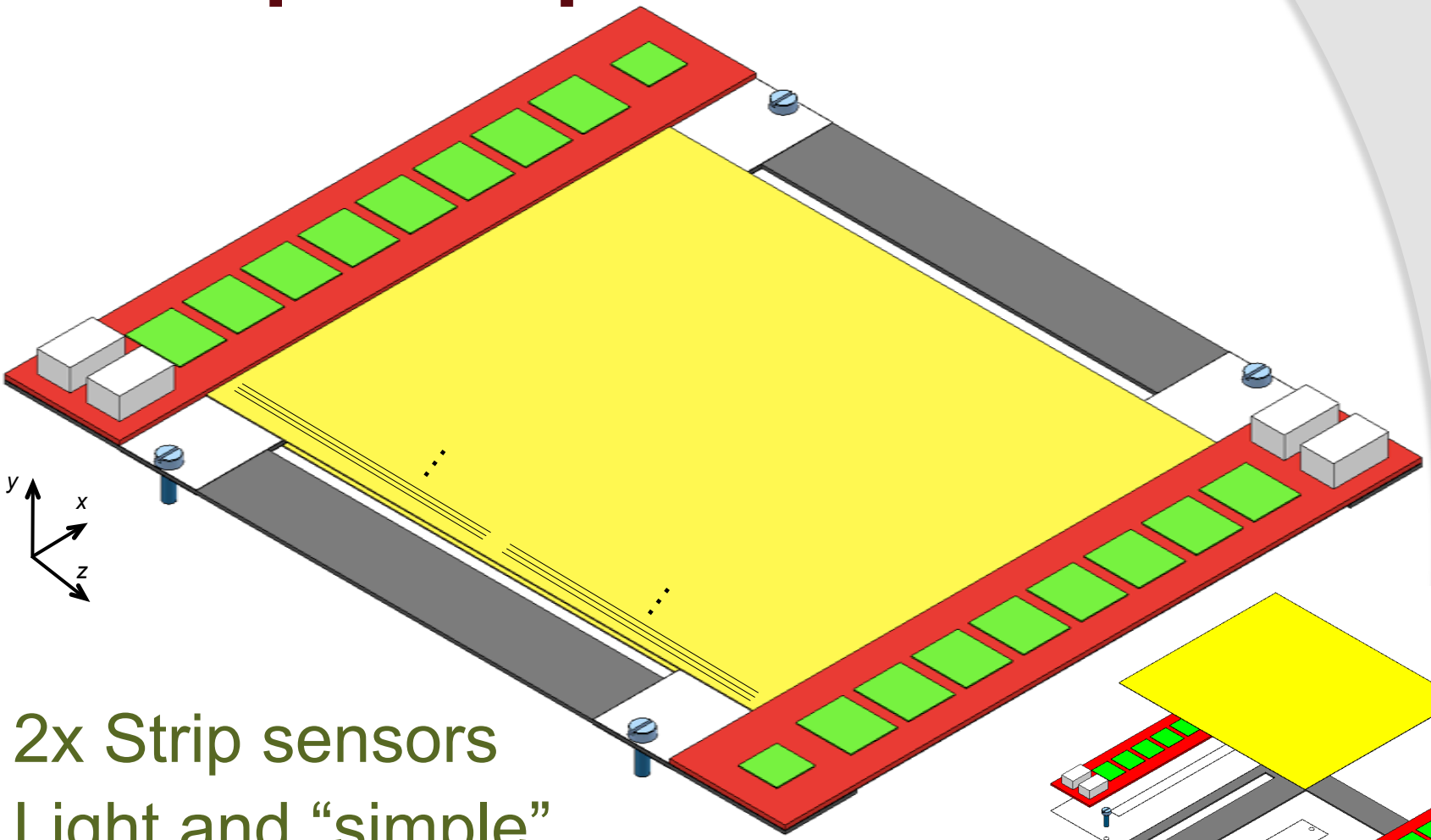
- Sensitivity to $p_T$ from measurement of $\Delta(R\varphi)$ over a given $\Delta R$
- For a given $p_T$, $\Delta(R\varphi)$ increases with R
  - A same geometrical cut, corresponds to harder $p_T$ cuts at large radii
  - At low radii, rejection power limited by pitch



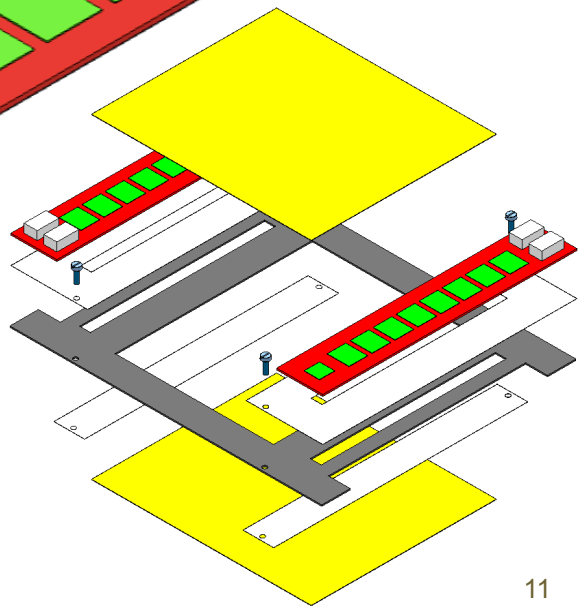

- In the barrel, $\Delta R$ is given directly by the sensors spacing
- In the end-cap, it depends on the location of the detector
  - End-cap configuration typically requires wider spacing



# Simplest option: “2S Module”

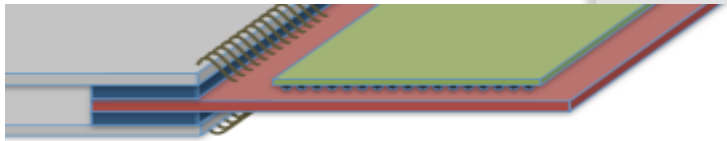



- 2x Strip sensors
- Light and “simple”
- No z information
- Suitable for outer part

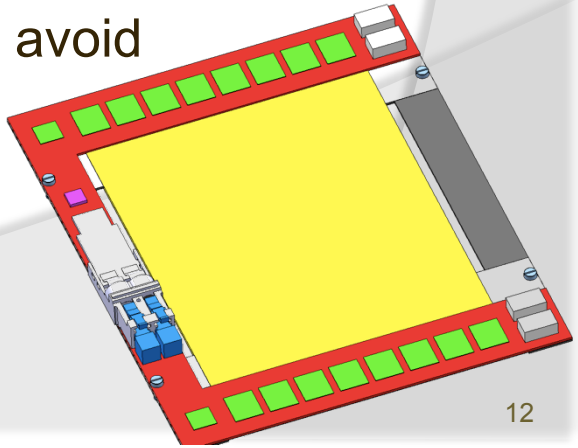


# 2S Modules: possible features

- ≈ 5 cm long strips, ≈ 90 μm pitch
- Wirebonds from the sensors to the hybrid **<u>on the two sides</u>**
  - 2048 channels on each hybrid

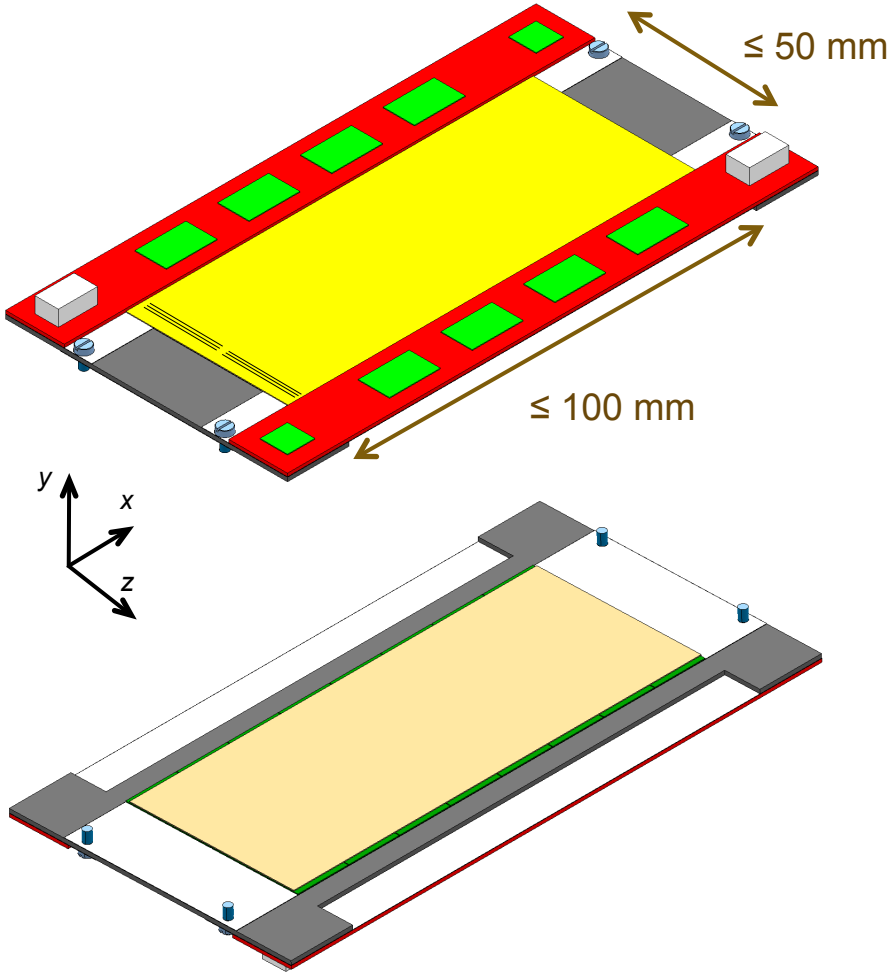


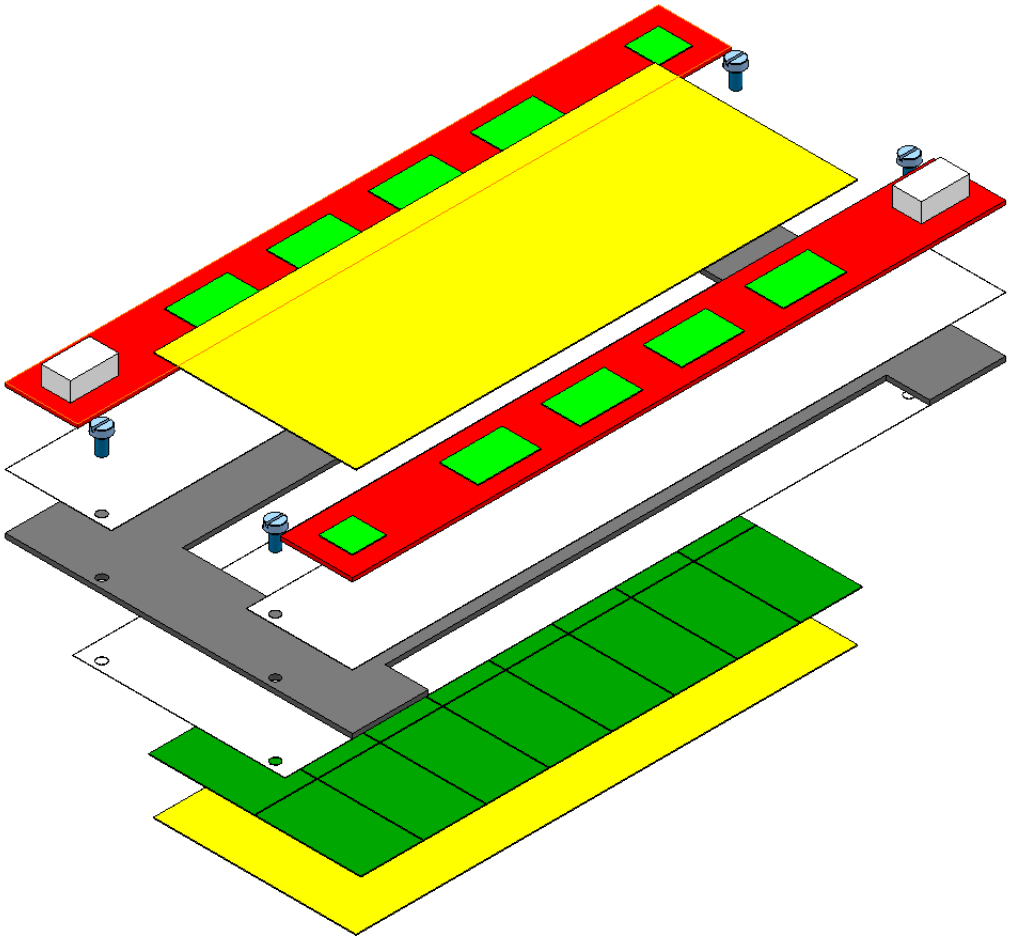
- Chips bump-bonded onto the hybrid
- Neat and lightweight design
- Should use 1 link / module
  - Ideally to be integrated in the module itself, to avoid cumbersome connectivity
    - ★ Option under study



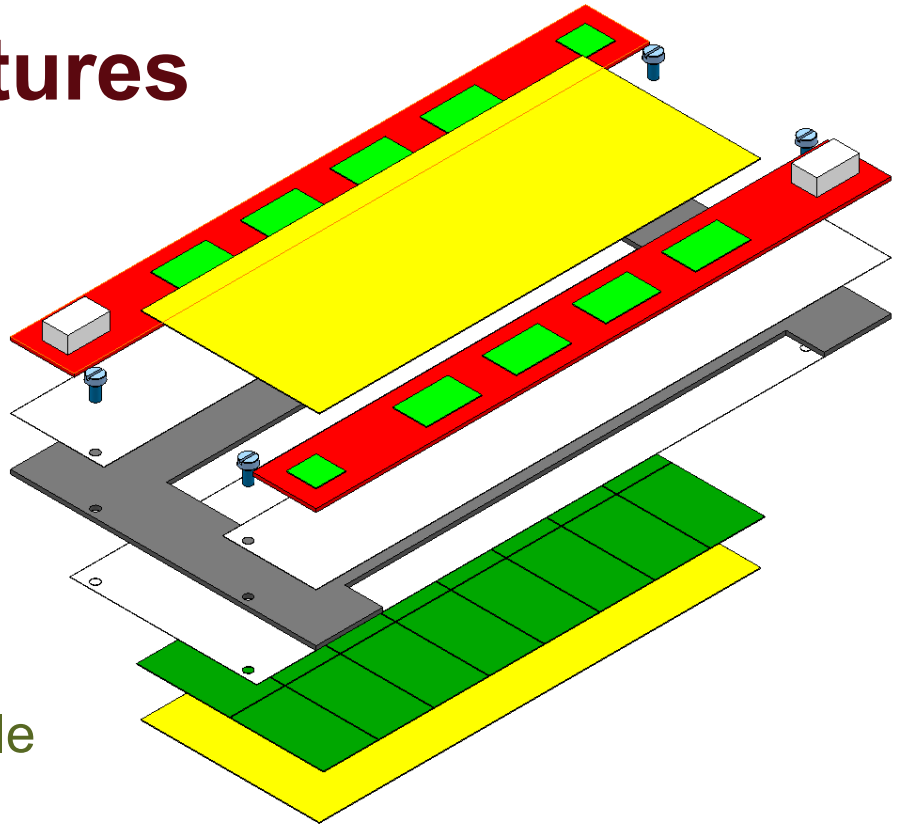
# “PS” module

- Pixel + strip sensor with horizontal connectivity

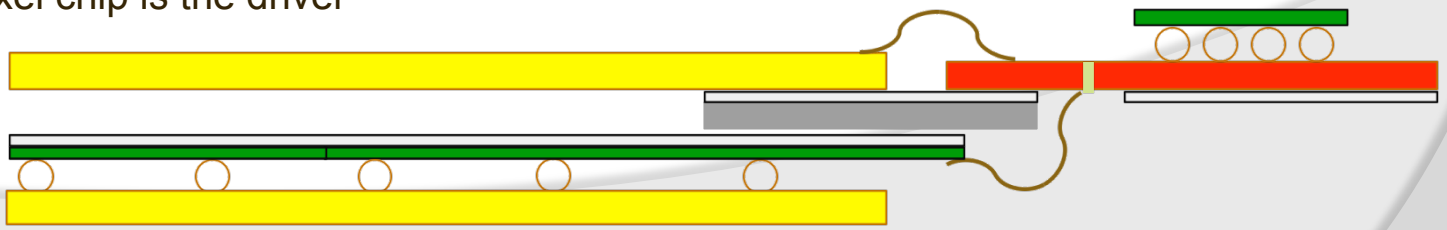


# PS modules: some features

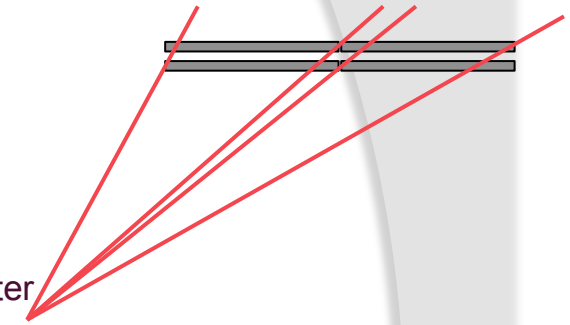


- Sensors:
  - Top sensor: strips
    - 2×25 mm, 100 μm pitch
  - Bottom sensor: long pixels
    - 100 μm × 1500 μm
- Readout:
  - Top: wirebonds to “hybrid”
  - Bottom: pixel chips wirebonded to hybrid
  - Correlation in the pixel chips?
- No interposer, sensors spacing tunable
- Power estimates
    - Pixels ~2.62 W
    - Strips ~0.51 W
    - Logic ~ 0.24 W
    - Low-power GBT ~ 0.5 W
    - Power converter ~0.4 W
  - Total ~ 4.5 W
  - Pixel chip is the driver



# Vertical interconnections: “VPS module”

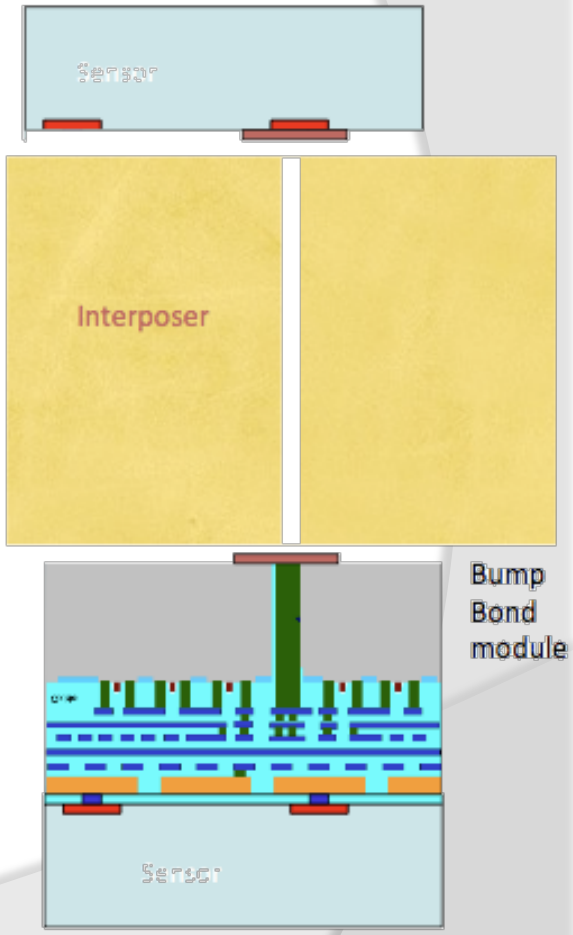
- Meant to improve upon limitations of “horizontal” PS modules
- Possible advantages
  - Module size independent of granularity
    - In principle 10×10 $cm^2$ module feasible
      - Can help for integration in hermetic surfaces, services etc…
    - Strip length tunable, not constrained to ½ module length
    - Mitigate geometrical inefficiency for stub finding at the edges and in the center



- Several difficult issues involved
  - Interconnection technologies
  - Size of the assembly may be eventually limited anyway, by difficulty/yield
  - Need interposer covering the whole surface of the module
    - May significantly affect the module mass
  - Sensor spacing determined by thickness of interposer (not tunable)
    - Not well adapted to end-cap configuration
- Possible advantages in terms of system aspects are to be proven, and depend on module details

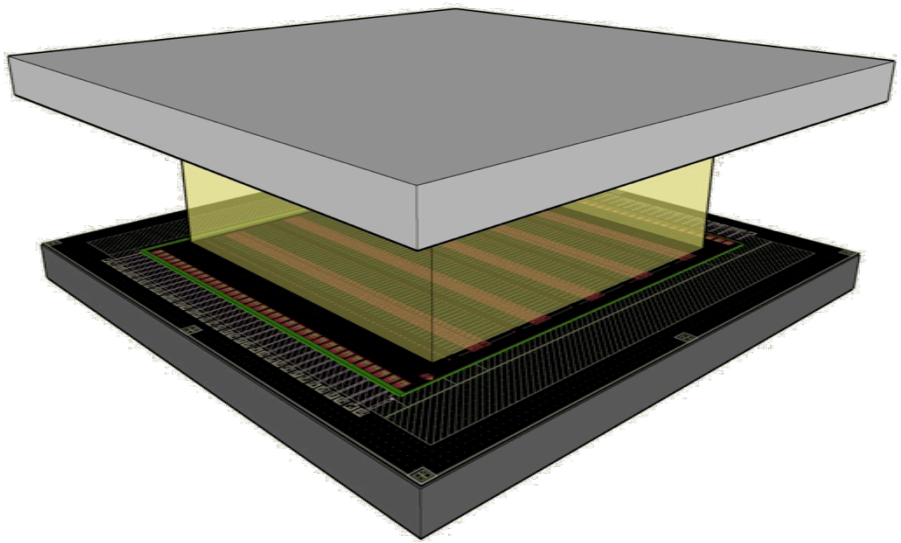
# One development based on 3d electronics

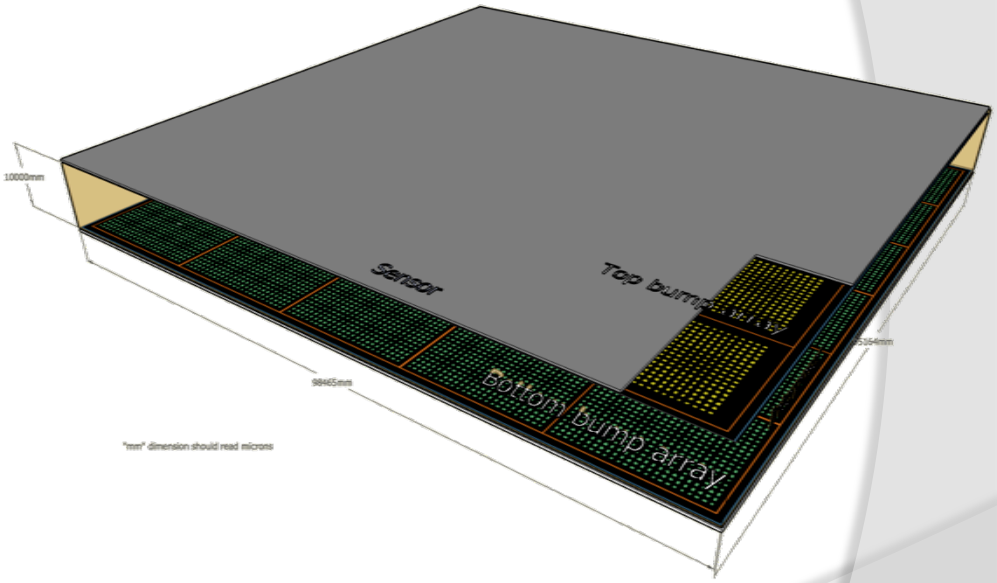
- A single chip connected to top and bottom sensors
- Analogue paths through interposer from top sensor, segmented in ~ cm long strips
- Bottom sensor provides z precision (~ mm long pixels)
- Electronics and connectivity (interposer) are technological challenges (yield, robustness, mass, large–size module)



# Development in steps

- Demonstrator 5×5 → module 100×100?






- A long way to go for large surface, and volume production
- Lightweight interposer is a key for the module quality

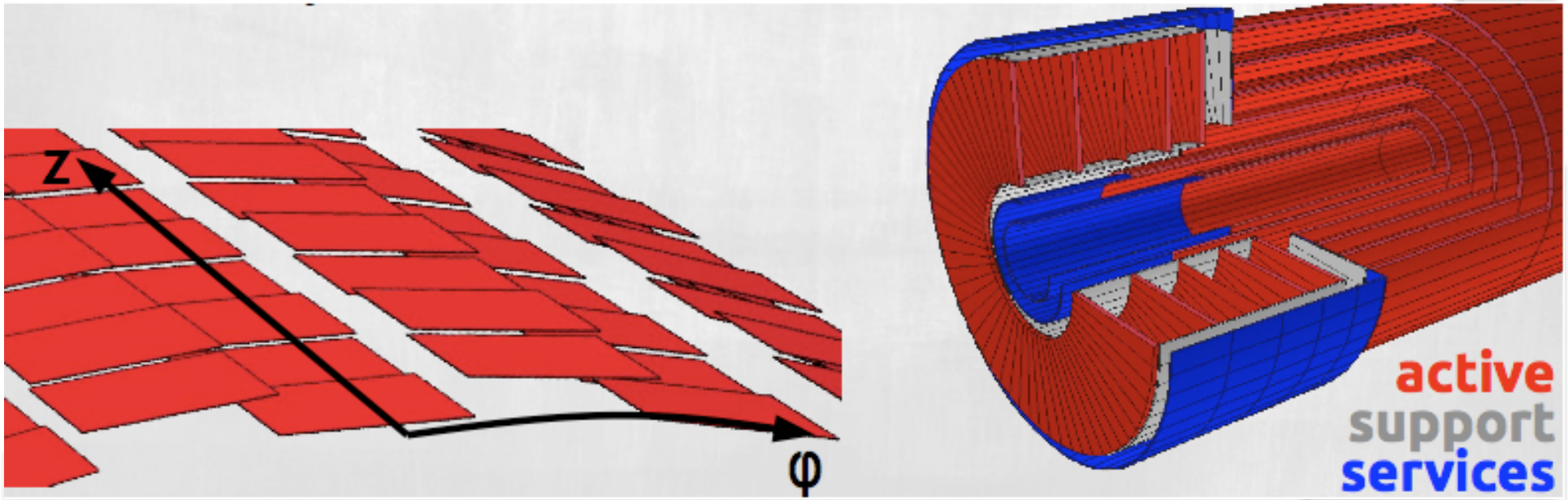
# Evaluation of different options: layout modelling

- Dedicated standalone software package©

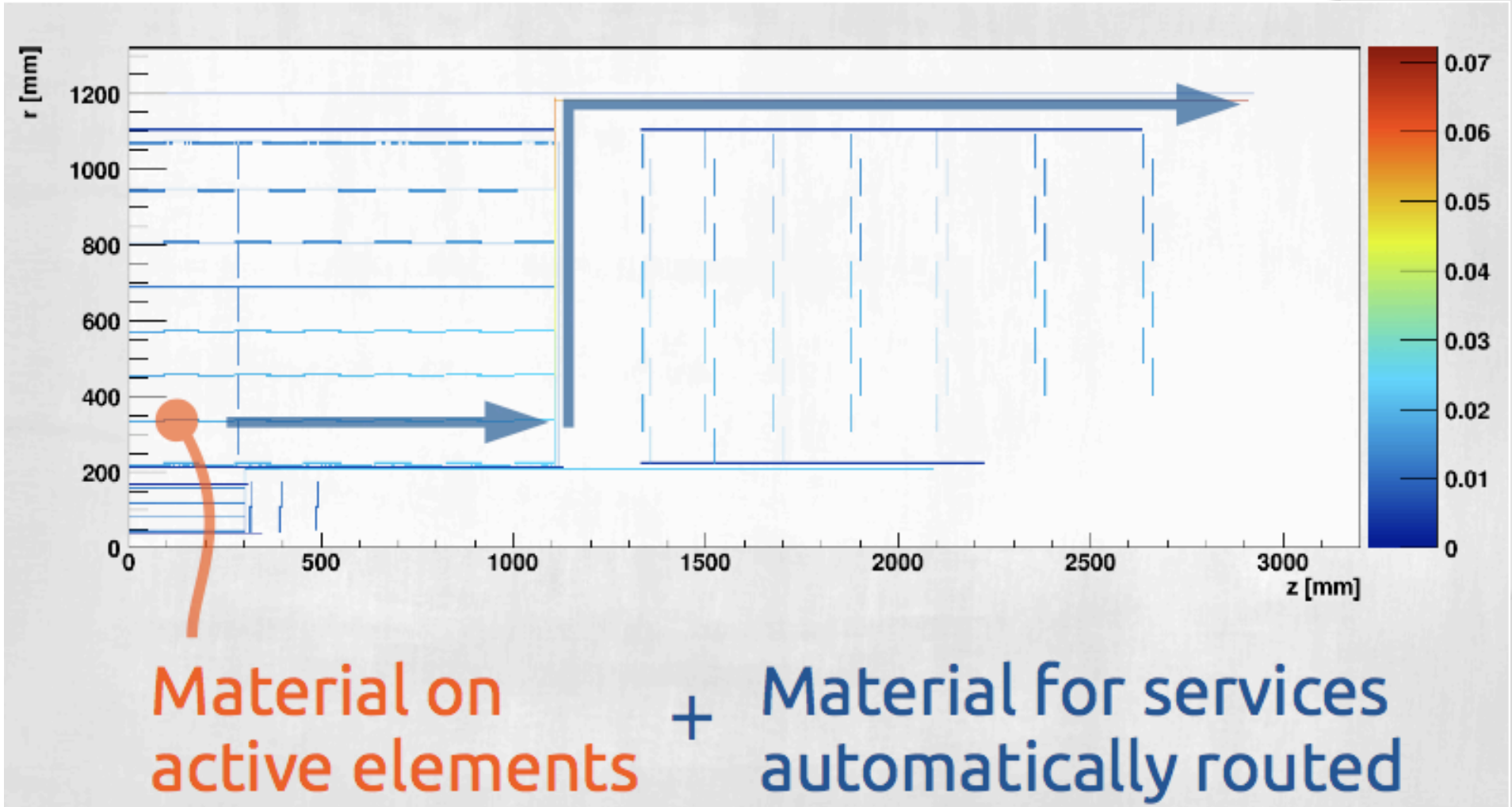
  © N. De Maio, S. Mersi

  Based also on work from V. Karimaki and G. Hall

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

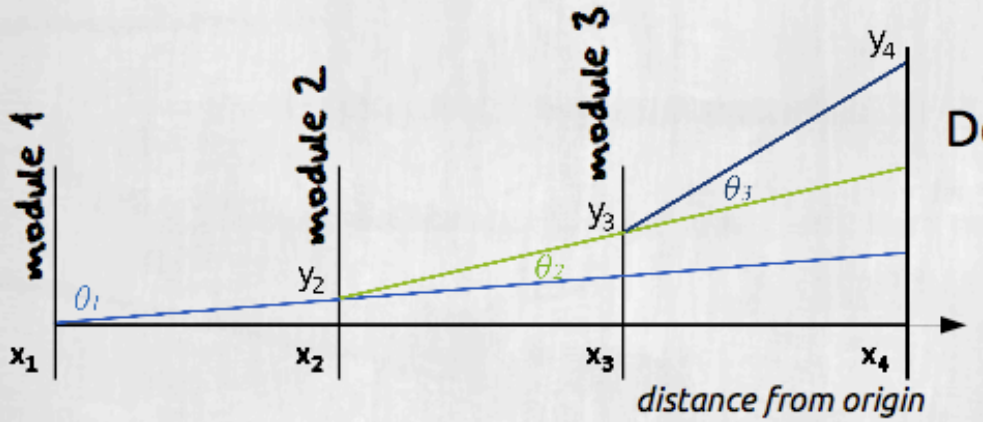


# ➢ Simple (semi-automatic) modelling of services



- Implements estimates of tracking performance

- Use measurement errors to estimate the errors in track fit parameters
- **Multiple scattering** treated as (correlated) a measurement error




Deviation due to scattering:

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

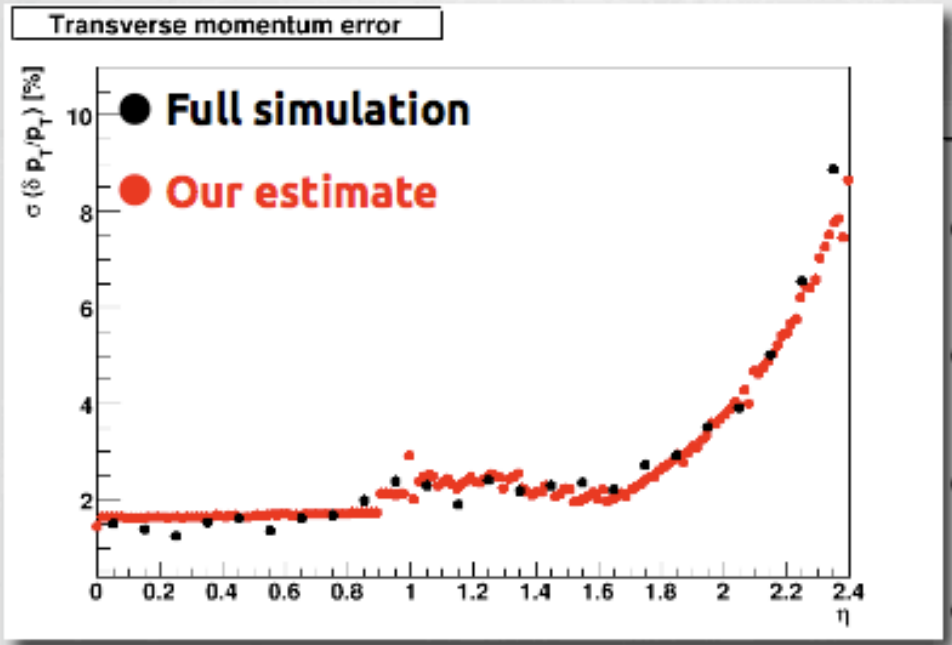
Error correlation matrix:

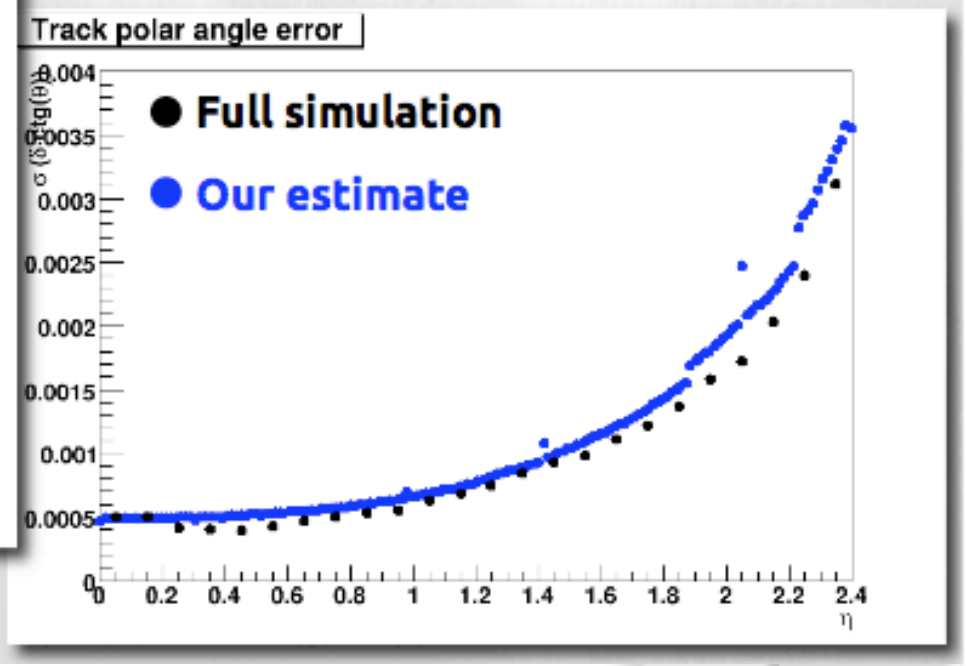
$$\sigma_{n,m} = \langle y_n y_m \rangle = \sum_{i=1}^{n-1} (x_m - x_i)(x_n - x_i)\langle \theta_i^2 \rangle$$

$$\sigma_n^2 = \frac{p^2}{12}$$

- As well as fraction of interacting particles
- Can be used in the same way to evaluate trigger performance potential

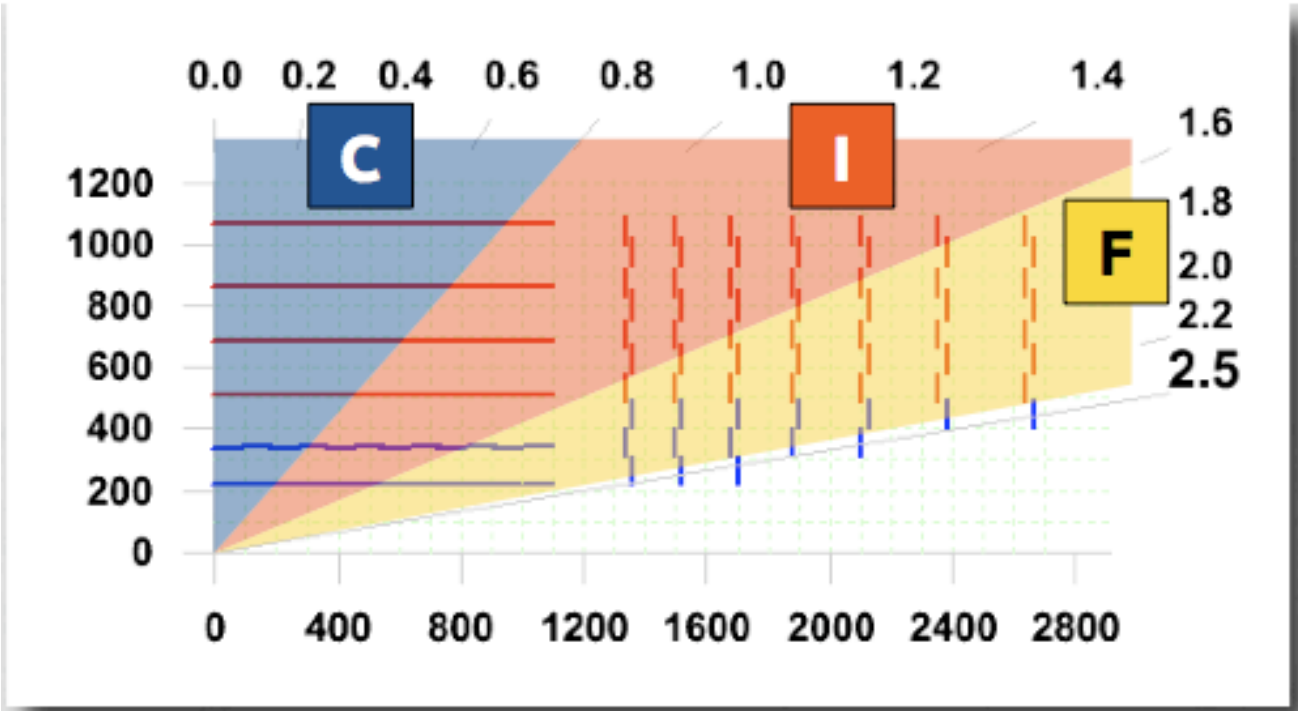
- Validated by modelling the present tracker




- Spectacular accuracy out of the box!

- Summarize results in three rapidity regions



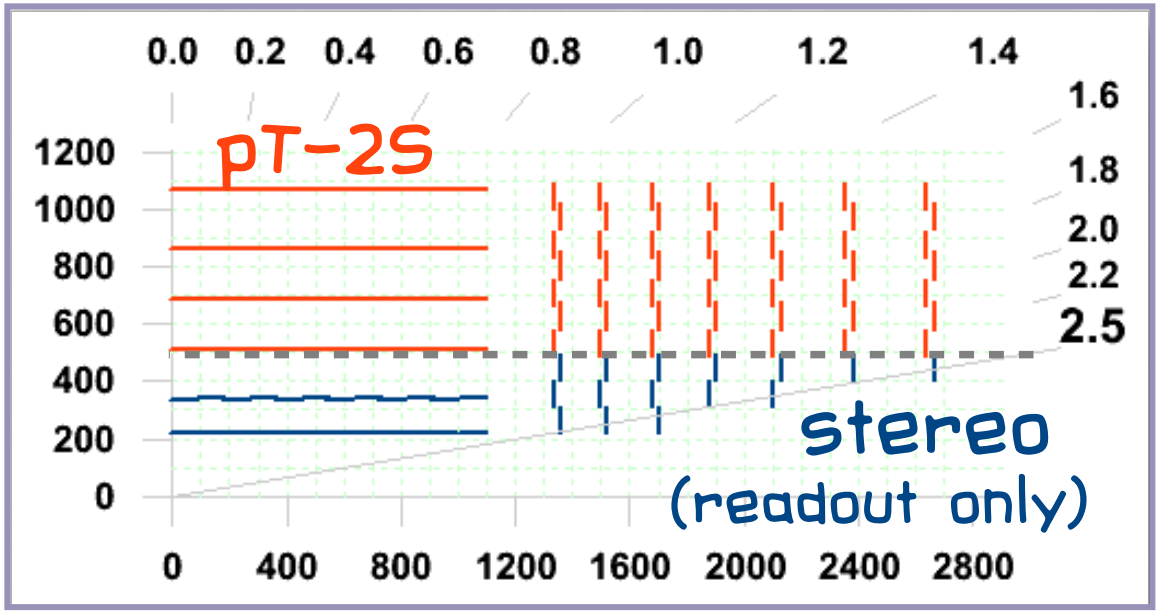

η

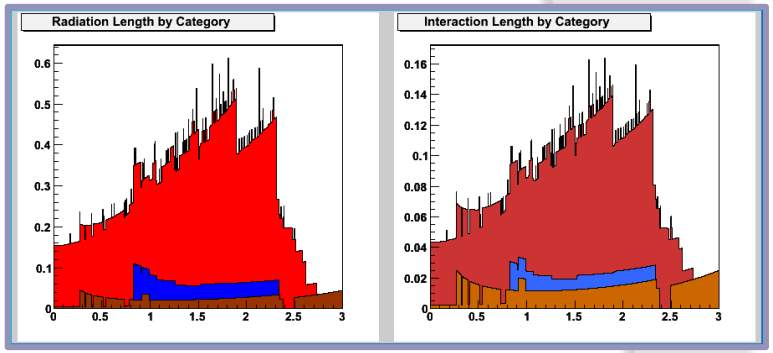
| | |
|---|---|
| C | 0 → 0.8 |
| I | 0.8 → 1.6 |
| F | 1.6 → 2.4 |

$\Delta\eta = 0.8$

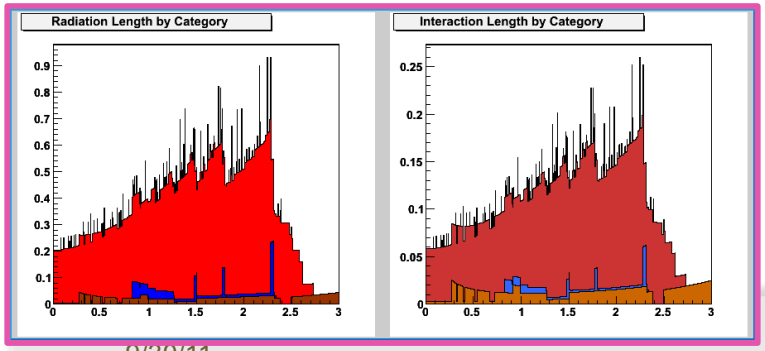
Roughly same number of tracks expected

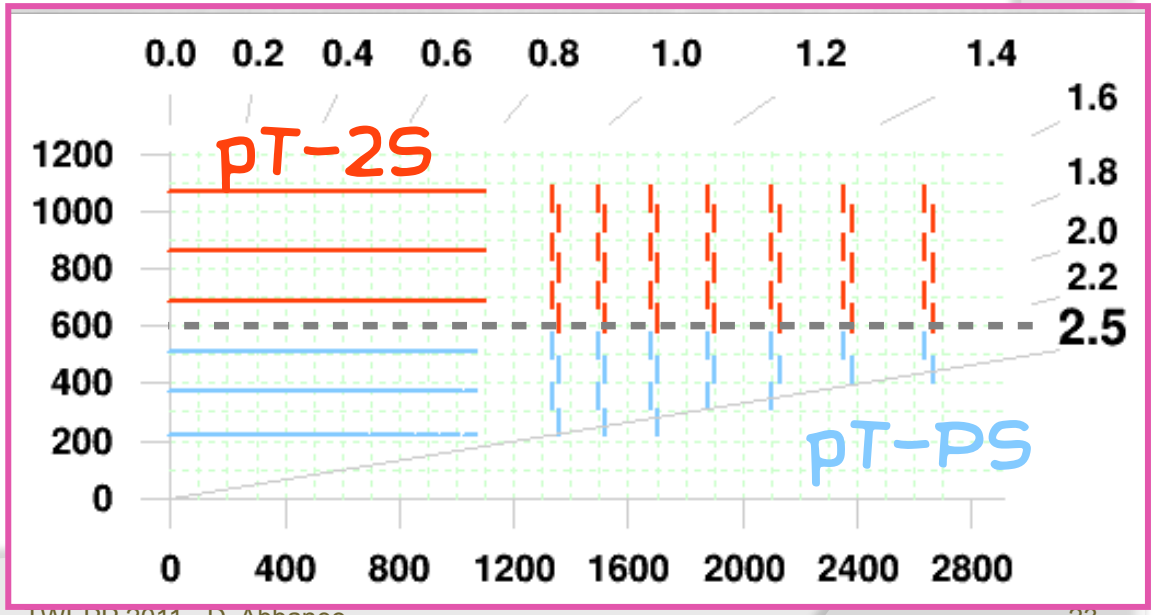
# Layout studies: some results



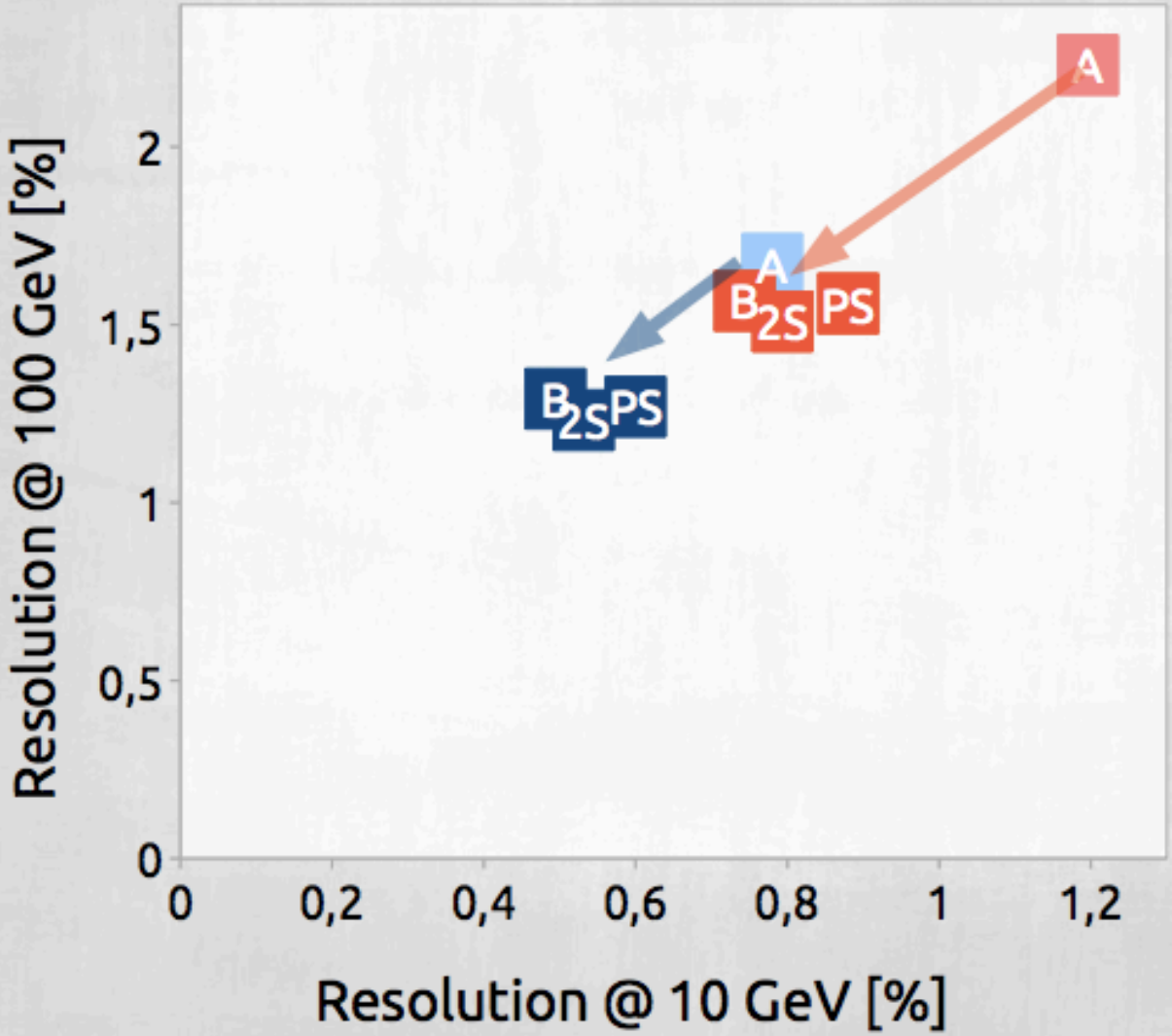




- Compare options with different levels of trigger functionality
  - Evaluate trigger performance potential and impact on tracking performance
  - Compare with present tracker



# Momentum resolution




η

C 0 → 0.8

I 0.8 → 1.6

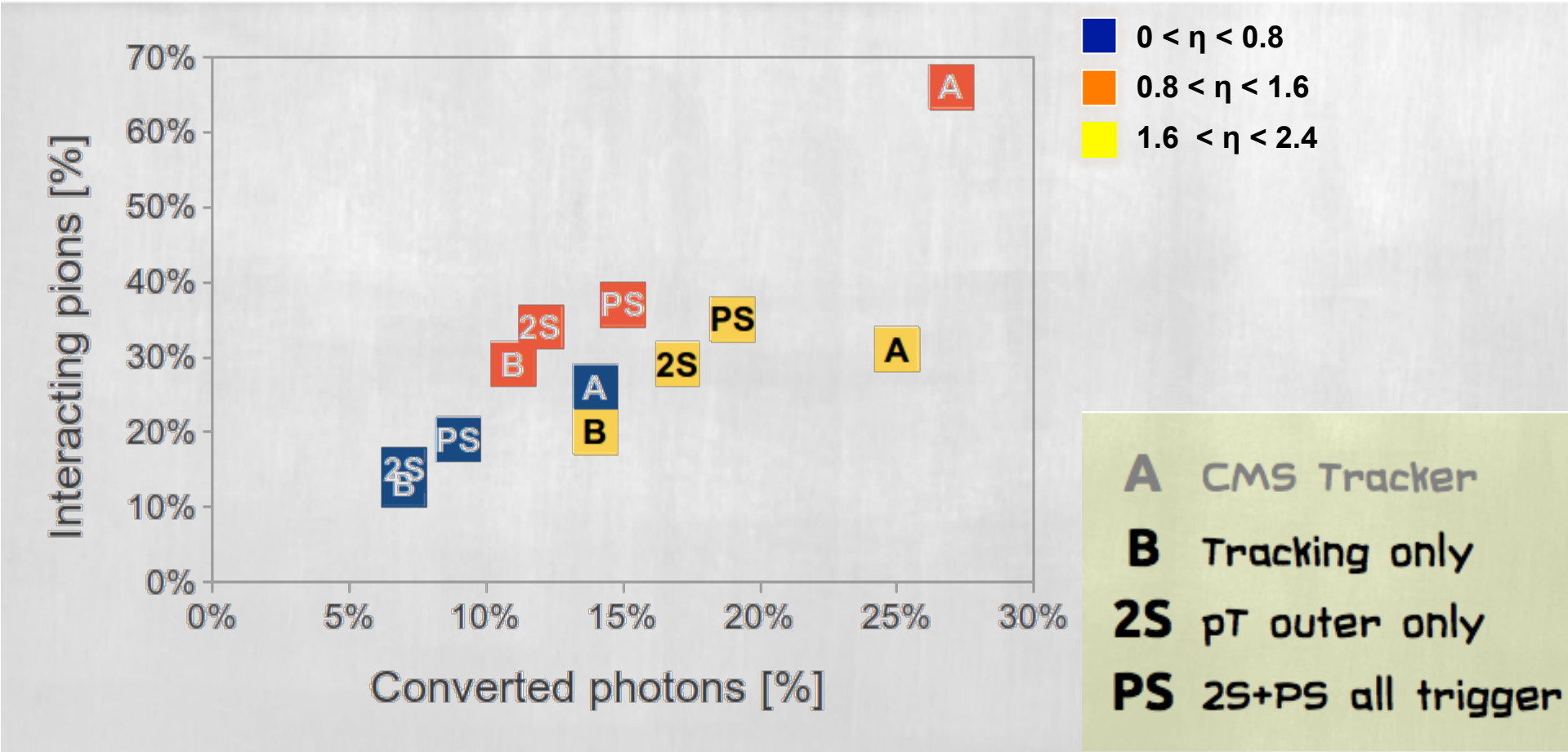
A CMS Tracker

B Tracking only

2S pT outer only

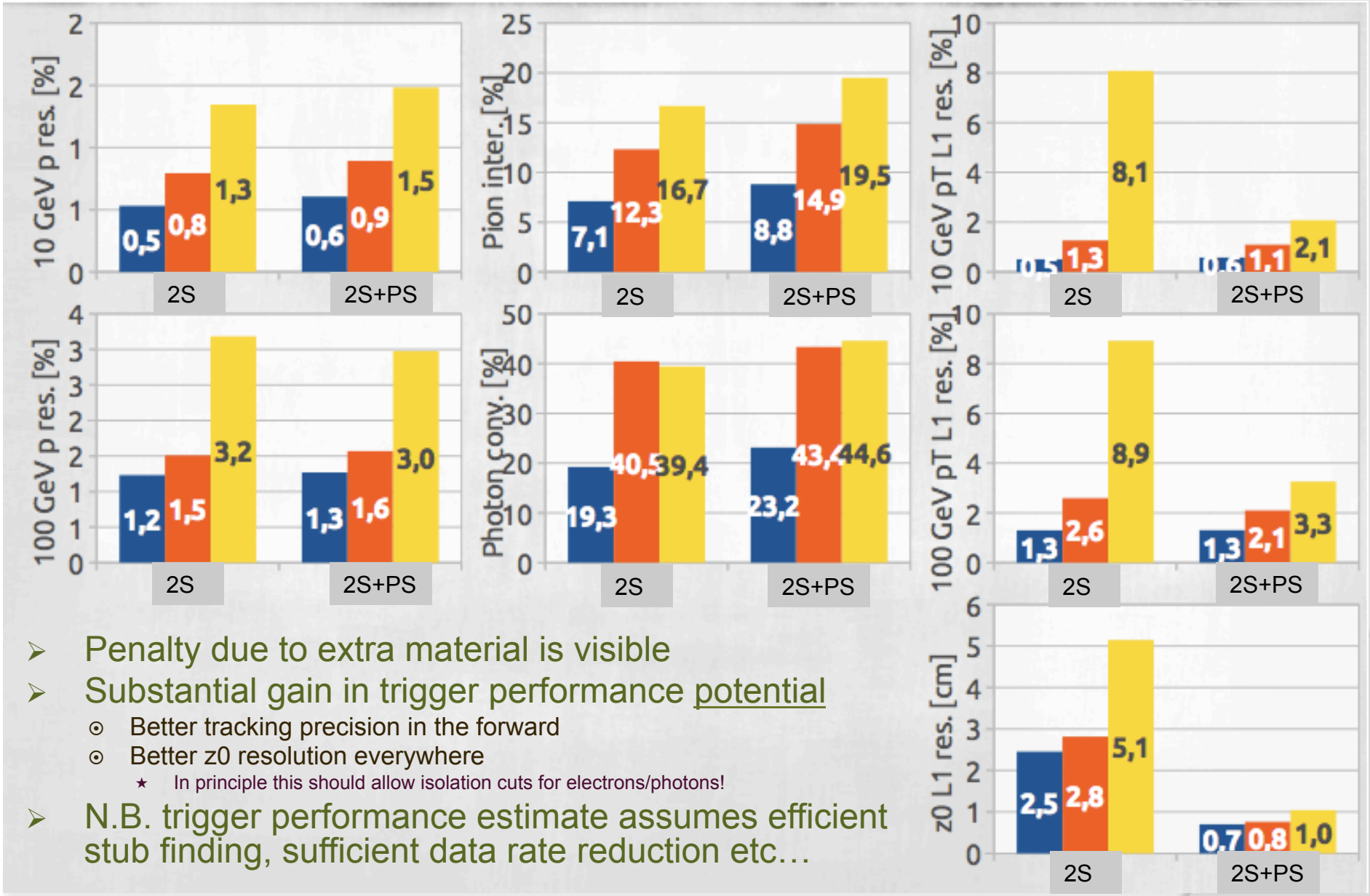
PS 2S+PS all trigger

# Particle interactions




- The impact of trigger modules is well visible, but not too disruptive

# Overall comparison

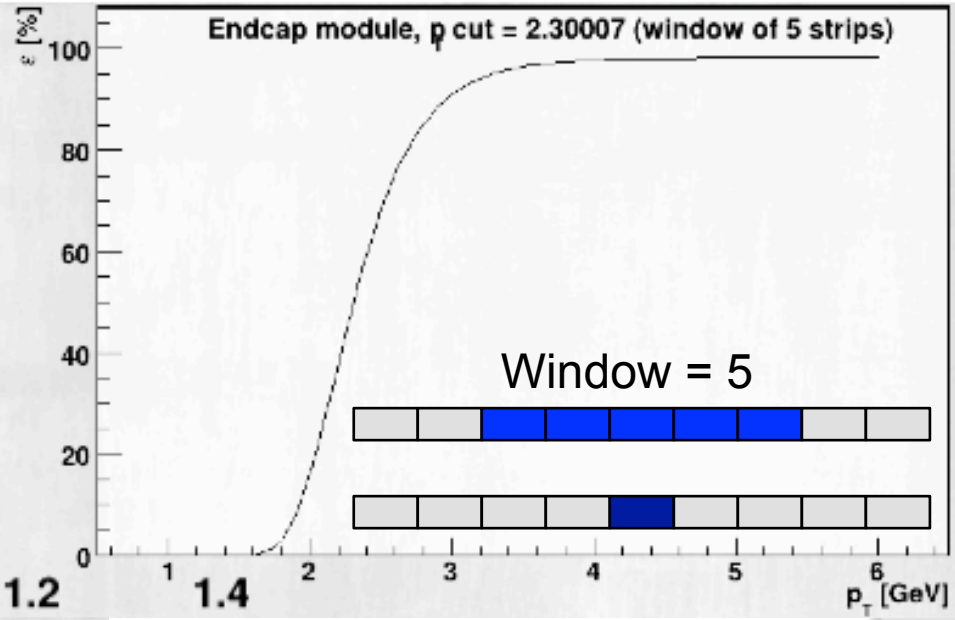


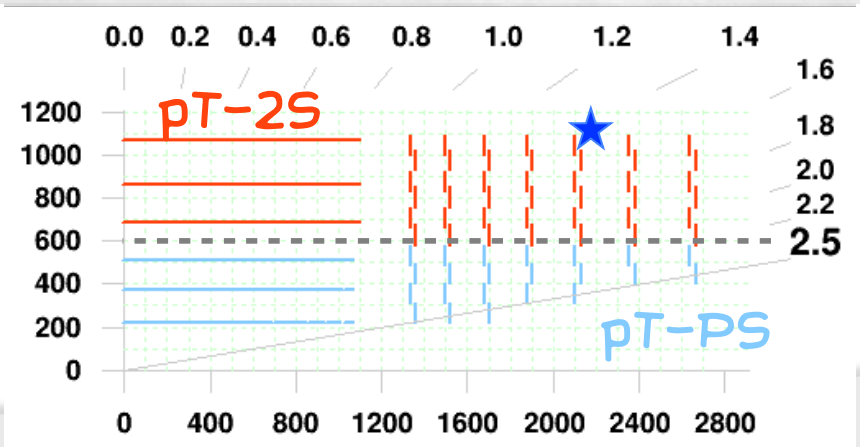

- Penalty due to extra material is visible
- Substantial gain in trigger performance potential
  - Better tracking precision in the forward
  - Better z0 resolution everywhere
    - In principle this should allow isolation cuts for electrons/photons!
- N.B. trigger performance estimate assumes efficient stub finding, sufficient data rate reduction etc…

# Towards implementation

- Layout modelling software also used to estimate efficiency of individual $p_T$ modules
  - E.g. to choose starting value for sensor spacing
  - Can play at the same time with sensors spacing and width of the window

For any module: fraction of hits transmitted vs. pT (geometric efficiency also considered)



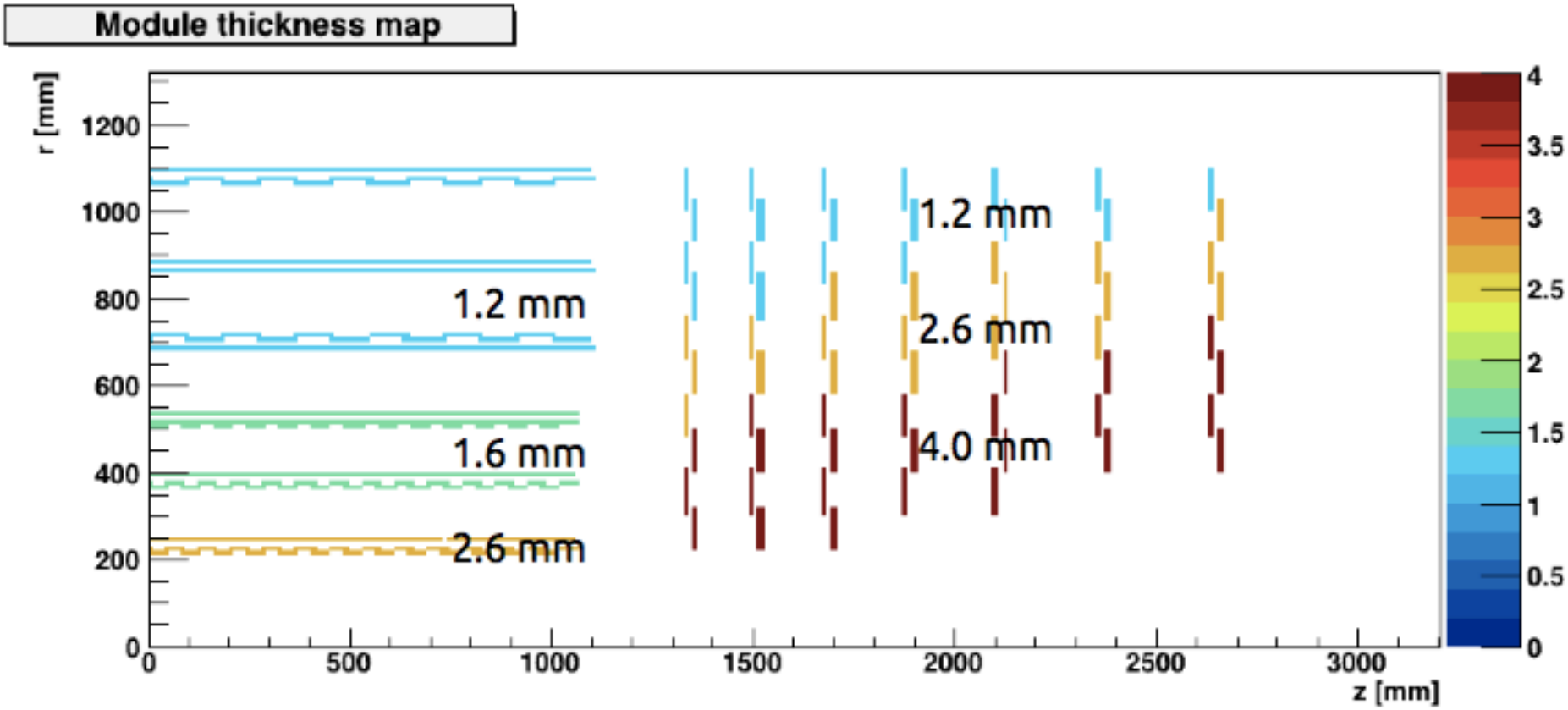




| | | |
|---|---|---|
| pitch | 90 | μm |
| strip_l | 46.3 | mm |
| mod. z | 2000 | mm |
| mod. r | 1080 | mm |
| mod. d | 1.5 | mm |

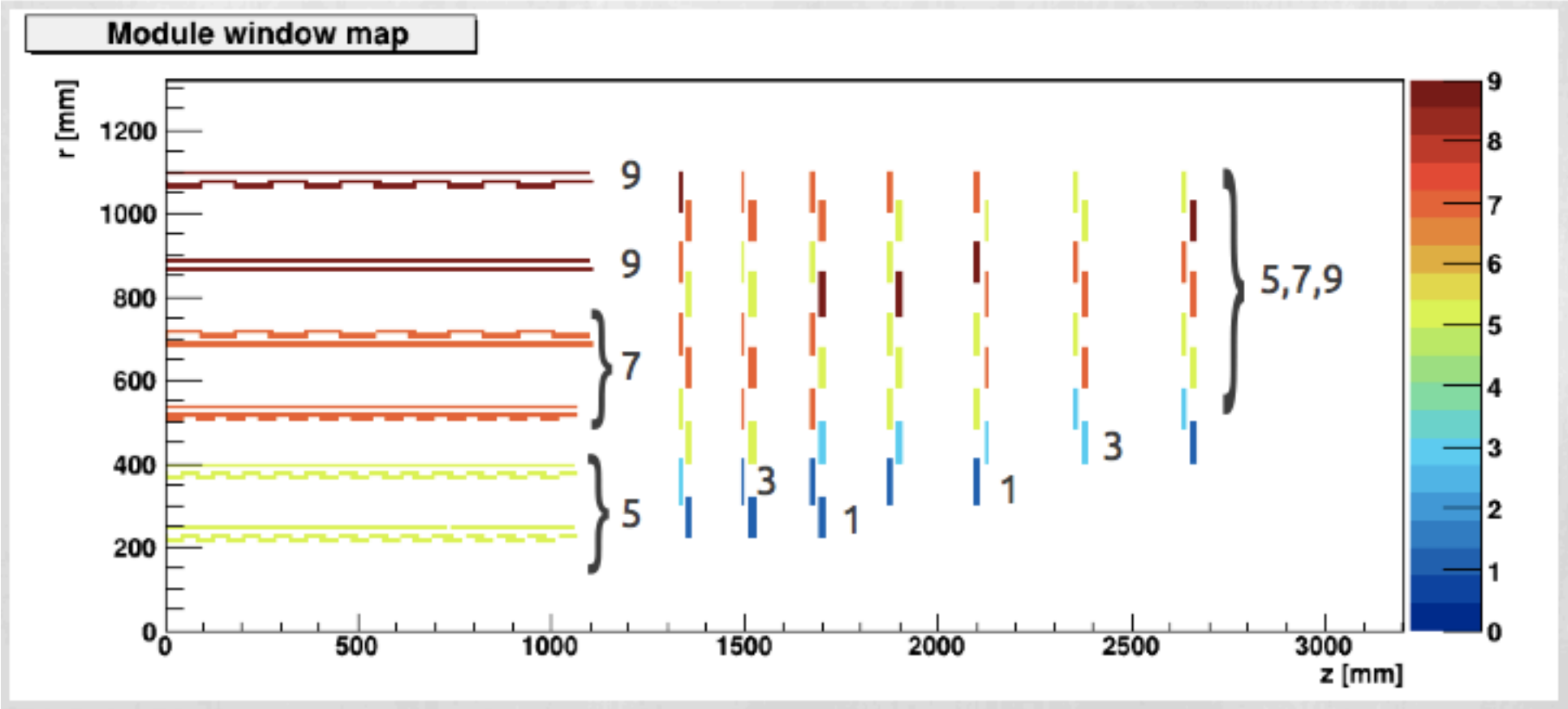
# First optimization exercise

**preliminary**

- Keep as ideal targets:
  - 0% efficiency @ $p_T$ = 1GeV
  - 100% efficiency @ $p_T$ = 2 GeV
- Limit choice of spacing to “a few” different values

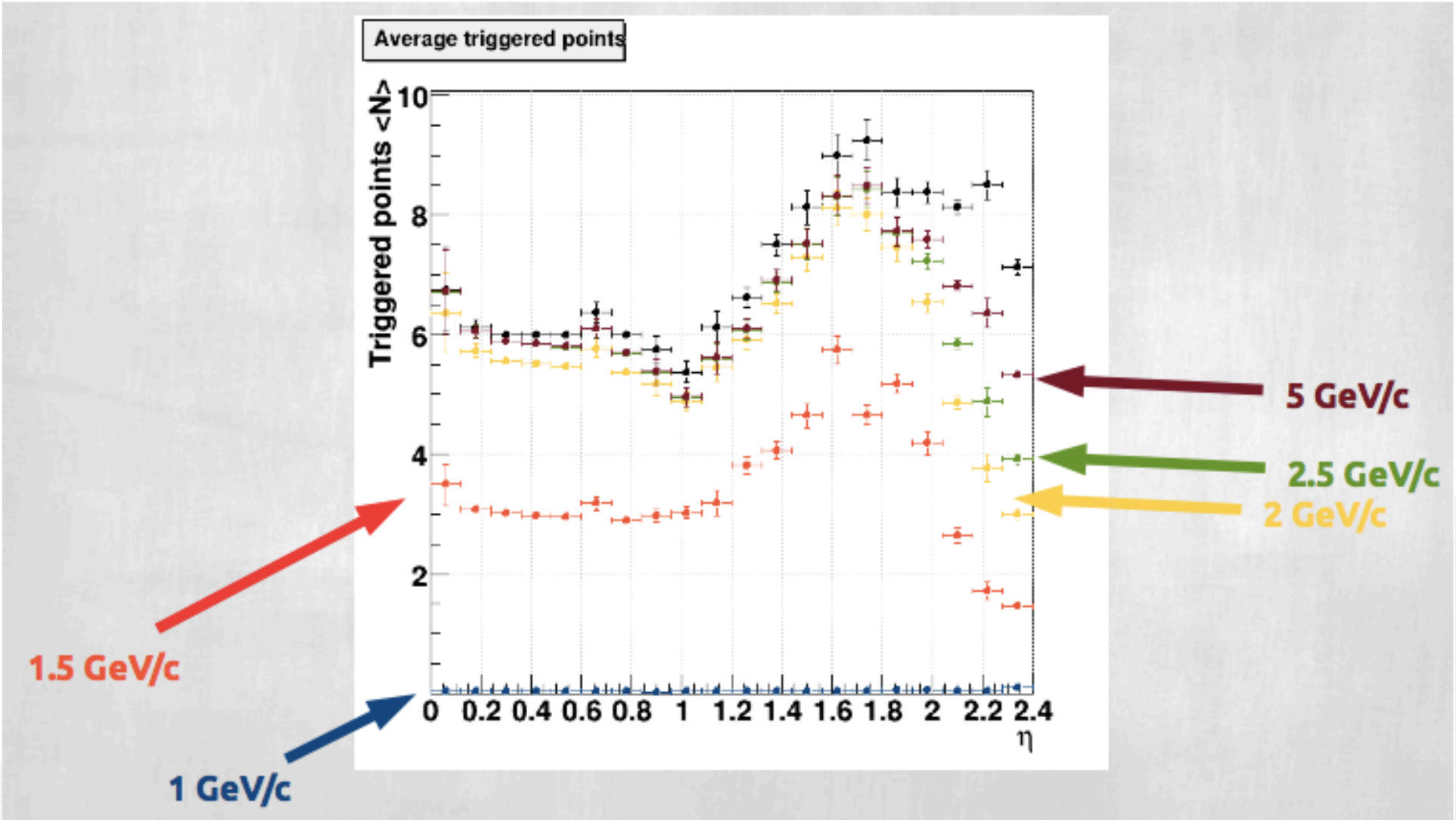


- Optimize width of the window at the same time…

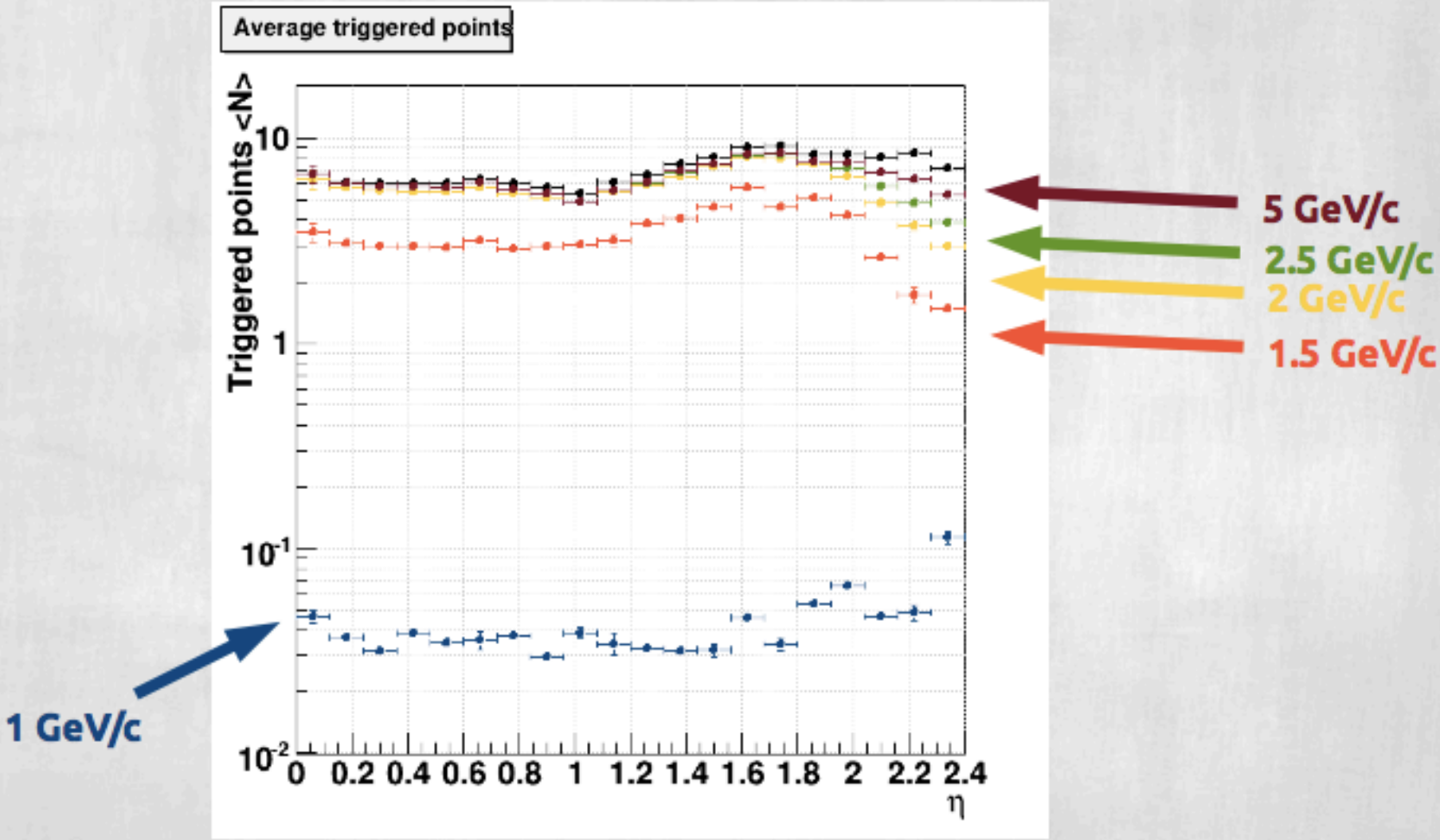


# Expected n of coordinates @ L1

- Almost full efficiency @ $p_T$ = 2 GeV up to η ≈ 2



- Low $p_T$ rejection looks OK!

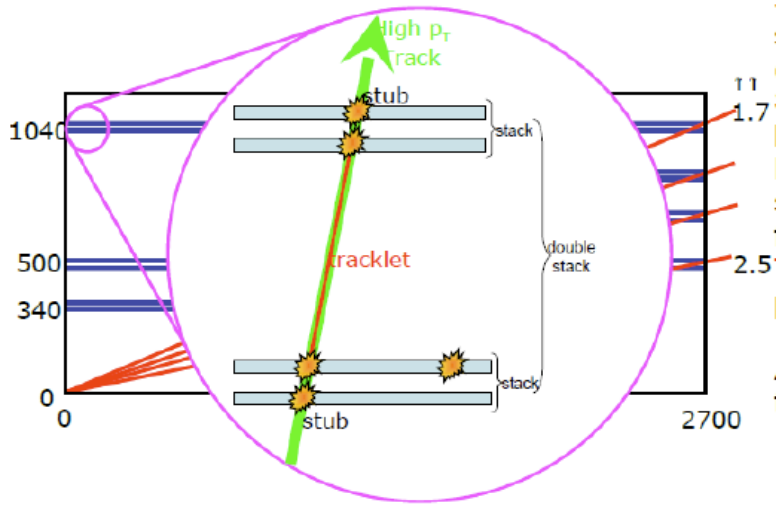


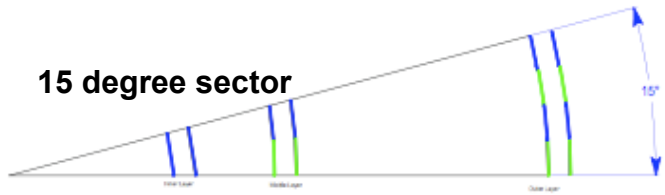
# From stubs to tracks

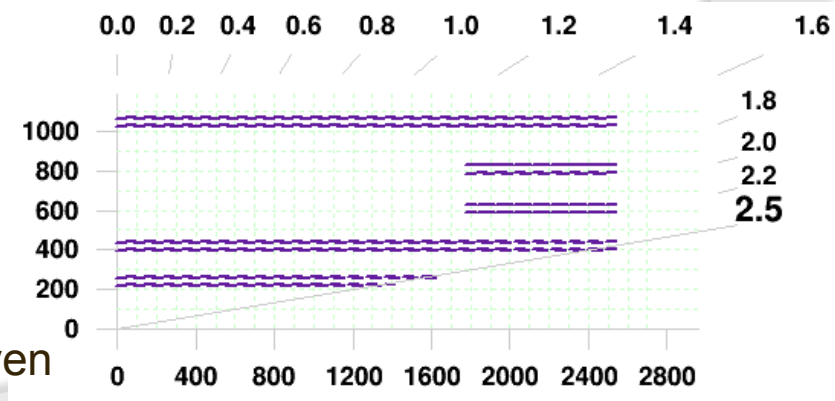
- Full-scope goal: reconstruct all tracks above ~2 GeV
  - Inspired from isolation cuts presently used in High-Level Trigger
    - N.B. Association of stubs directly to muon/calorimeter primitives does not seem viable
- Two approaches considered so far to process “stubs” at the back end
  - Still in the speculative stage…

# Track finding - I

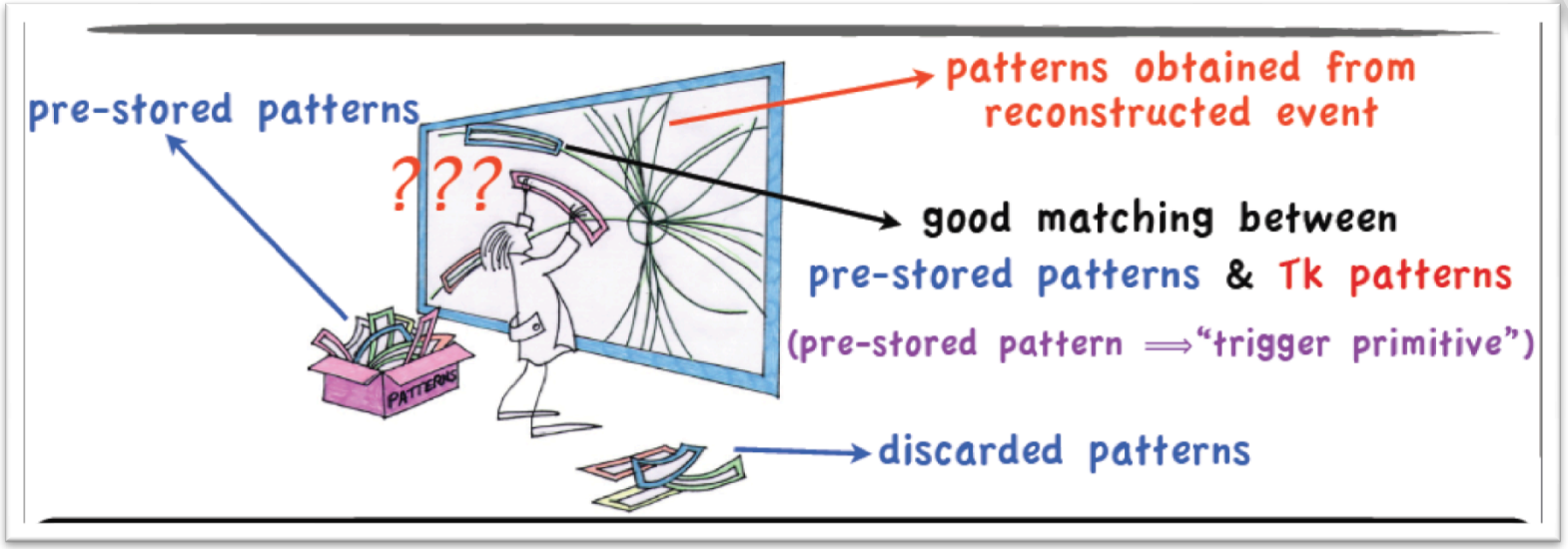
- Hierarchical stub/tracklet/track processing in FPGAs
  - Pairs of layers closely spaced to moderate combinatorial problem
    - "Double-stack" geometry
    - Pairs of stubs are combined into a "tracklet", that has sufficient precision to extrapolate to the next double stack
    - Find track if at least one tracklet is found (plus two stubs)
  - Geometry tuned to have well-defined sectors in the rφ view
  - Concept studied only in the barrel geometry (…so far…)
  - Would lead to a detector layout entirely determined by trigger architecture
    - Penalty in tracking performance non-negligible
- Concept studied in some details
  - Feasibility of FPGA processing still to be proven



# Track finding - II




- 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!

# … and beyond tracks?

- Study of possible use of Level-1 tracks in combined triggers not yet really started
- Trigger group busy with “Phase-1” upgrade
- Current thinking mostly inspired by use of tracking info in HLT

  - For one of the next TWEPPs…

# Conclusions

- Good progress in identifying options for the implementation of the tracking trigger
- Providing information that offers potential for sufficiently precise tracking @ Level-1 appears plausible
  - With acceptable impact on tracking performance
- We are still exploring the phase-space of possible options
  - Non trivial, no obvious privileged corner…
- A lot of demanding developments involved
- How to process the L1 Tracking information is an open problem
- Excellent software tools to qualify options have been developed
  - Will help all along the design of the detector!