2nd International conference on Technology & Instrumentation in Particle Physics

Design & Studies of μ-strip stacked module prototypes for tracking at S-LHC

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CMS

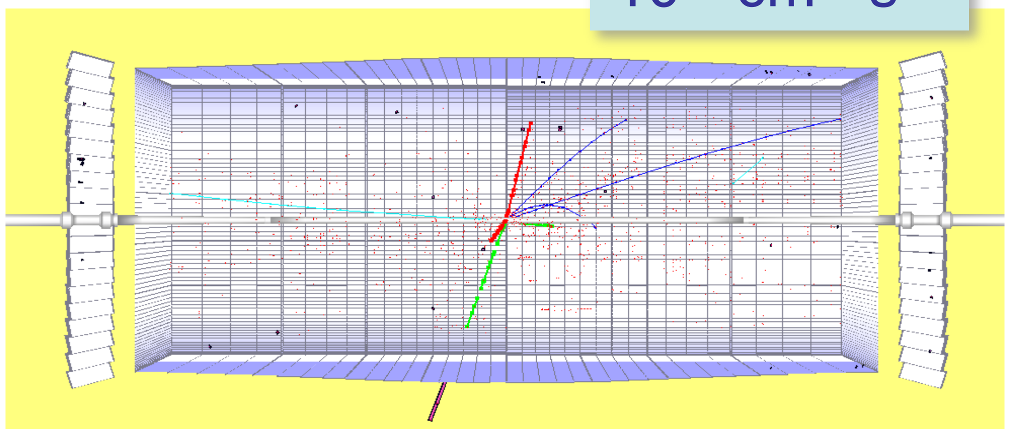
on the behalf of the CMS collaboration at CERN

Talk Outlines

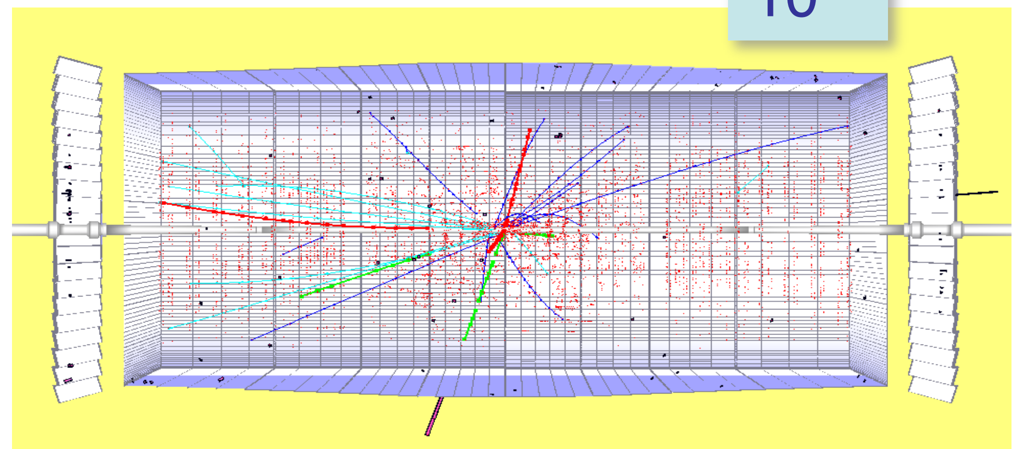
- Tracking on high luminosities hadron colliders
  - >> Constraints at S-LHC
- A first (rough) tracking estimation at module level: stacked modules
  - >> Working principles & theoretical aspects
  - >> Presentation of few prototypes designs
- Tests on real prototypes built with Si sensors & electronics used in the present CMS tracker
  - >> Study in terms of S/N & tracking performances
  - >> Validation of the method with CMS Tk modules at 7 TeV LHC collisions
  - >> Results of first prototypes with Cosmic Rays & a dedicated beam test experiment
- Simulation of stacked modules, study of trigger capabilities
  - >> A cylindrical barrel three-layers layout equipped with stacked modules considered here
  - >> Preliminary results about performances discussed in terms of p_T resolution & trigger capabilities (STUB definition as a trigger primitive, data rates, ...)

The S-LHC Scenario

10^{32} cm^{-2} s^{-1}

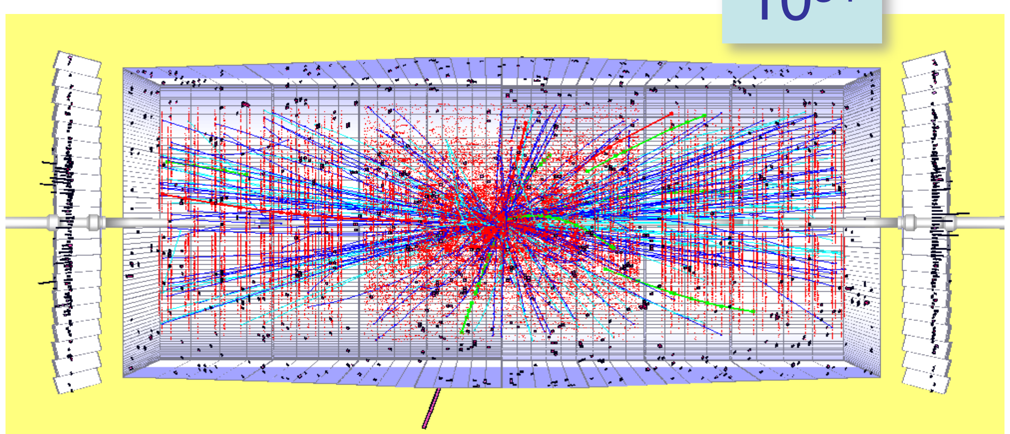


10^{33}

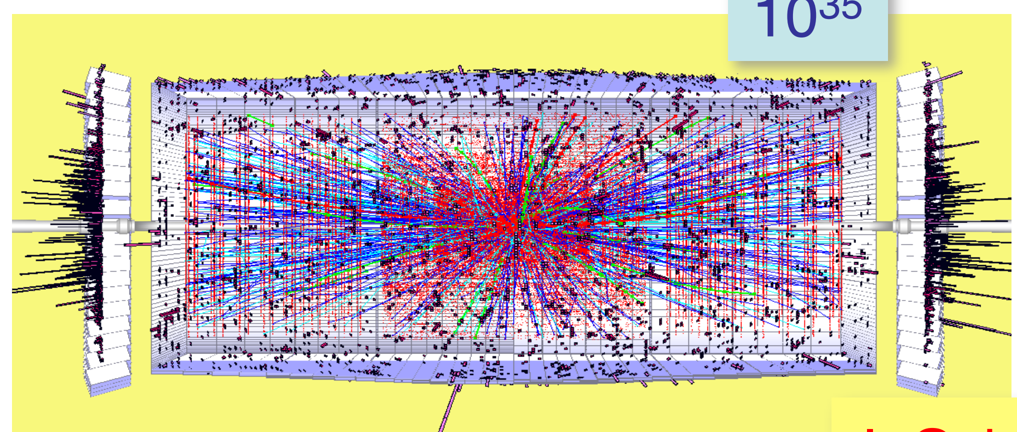


Present track density in CMS Tk

10^{34}



10^{35}



I. Osborne

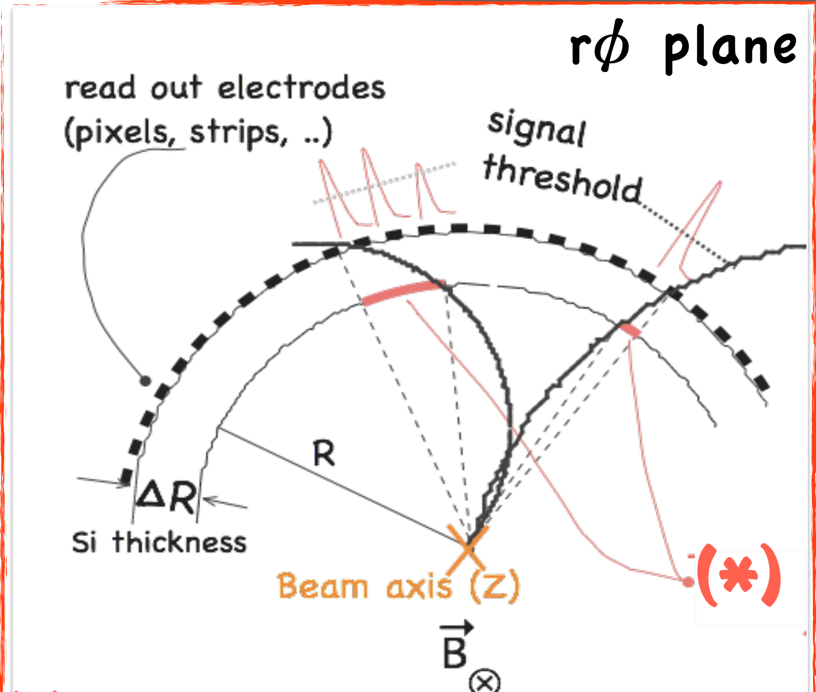
SLHC track density foreseen in CMS Tk

⇝ The Tracker (Tk) is the key detector which will require upgrading in SLHC

>> The Challenge: Build a replacement Tk for $\mathcal{L}>10^{34}$ cm^{-2}s^{-1} with L1 trigger capabilities

>> Develop sensors able to give infos about track p_T & direction, with high radiation hardness to keep detector occupancy as low as possible for a further good fine tracking

Basic Idea: p_T measure



(*) $TW \approx \frac{\Delta R}{\sqrt{\left(\frac{pT}{pT_{min}}\right)^2 - 1}} \approx \Delta R \frac{pT_{min}}{pT} = 0.15\ B\ \Delta R \frac{R}{pT}$

⇝ In a B field, ideal case of cylindrical layers with non-flat modules

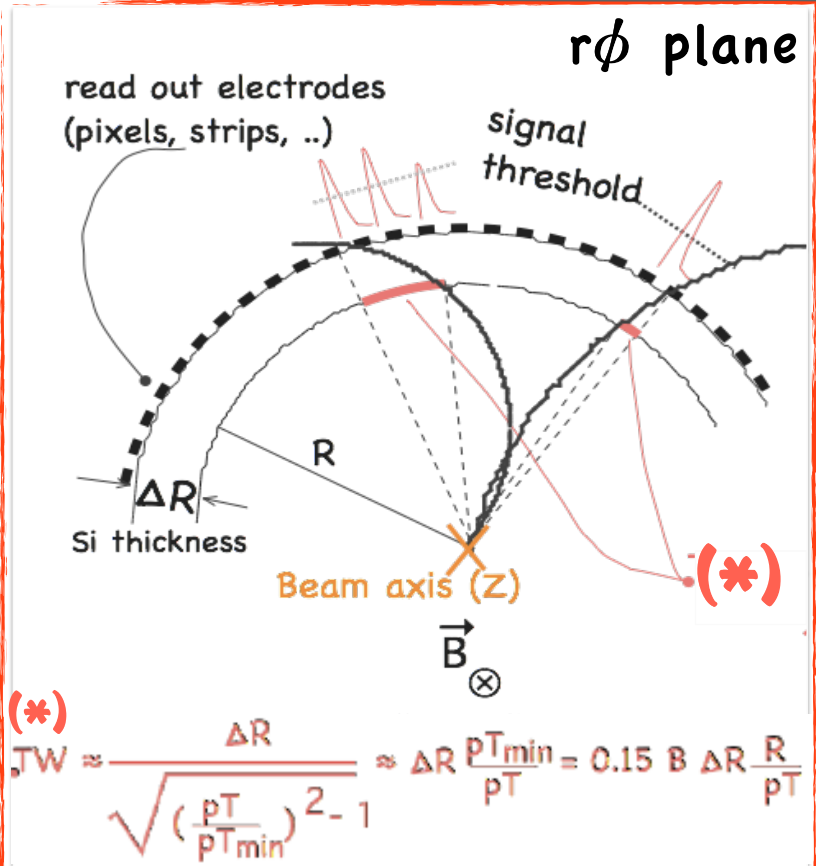
⇝ TW is the cluster size in terms of pitches

$$p_T^{meas}[GeV/c] = 0.15\, B_{[T]}\, R_{[m]} \frac{\Delta R_{[\mu m]}}{TW_{[\mu m]}} \equiv$$

$$\equiv \frac{0.15\, B_{[T]}\, R_{[m]}}{TW_{[\#\,of\,pitches]}} \cdot ToP \qquad \left(ToP \equiv \frac{\Delta R_{[\mu m]}}{pitch_{[\mu m]}} \right)$$

⇝ ToP ratio sets the (p_T) discriminating power of the method

Basic Idea: p_T measure



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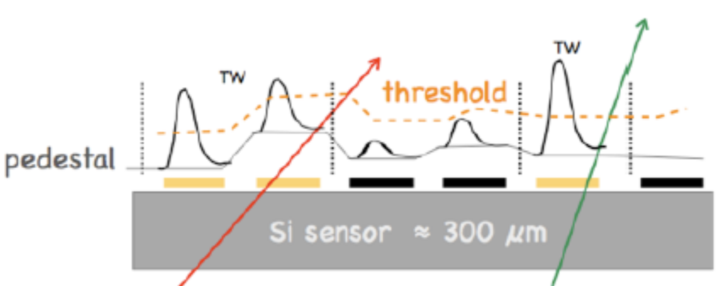
⇝ ToP ratio sets the (p_T) discriminating power of the method

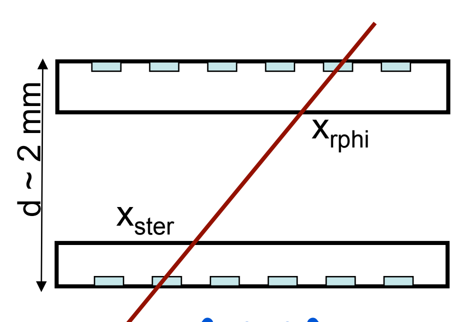
⇝ Two possibility can be used in p_T measurement with a single module:

>> CASE I: Module based on single sensor (ΔR~Si thickness, TW~reconstructed Cluster Width (CW))

>> CASE II: Module based on 2 stacked sensor (ΔR~d, TW~distance reconstructed Cluster Centroids)



(I)



(II)

⇝ Case II represents a 2-in-1 module that can:

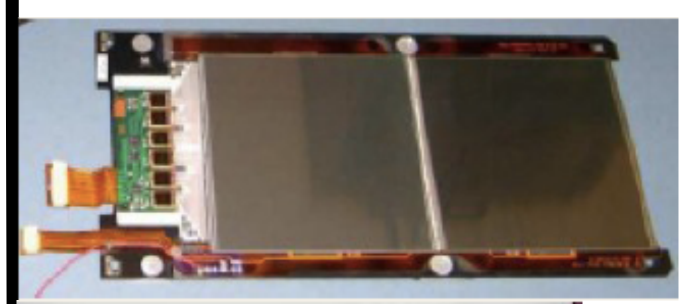
>> bring to improved values of ToP in the p_T measurement at module level

>> achieve good angular resolution (~100 μm strip pitch over 2 mm lever arm)

⟹ p_T & direction infos for trigger purposes!

Method Validation

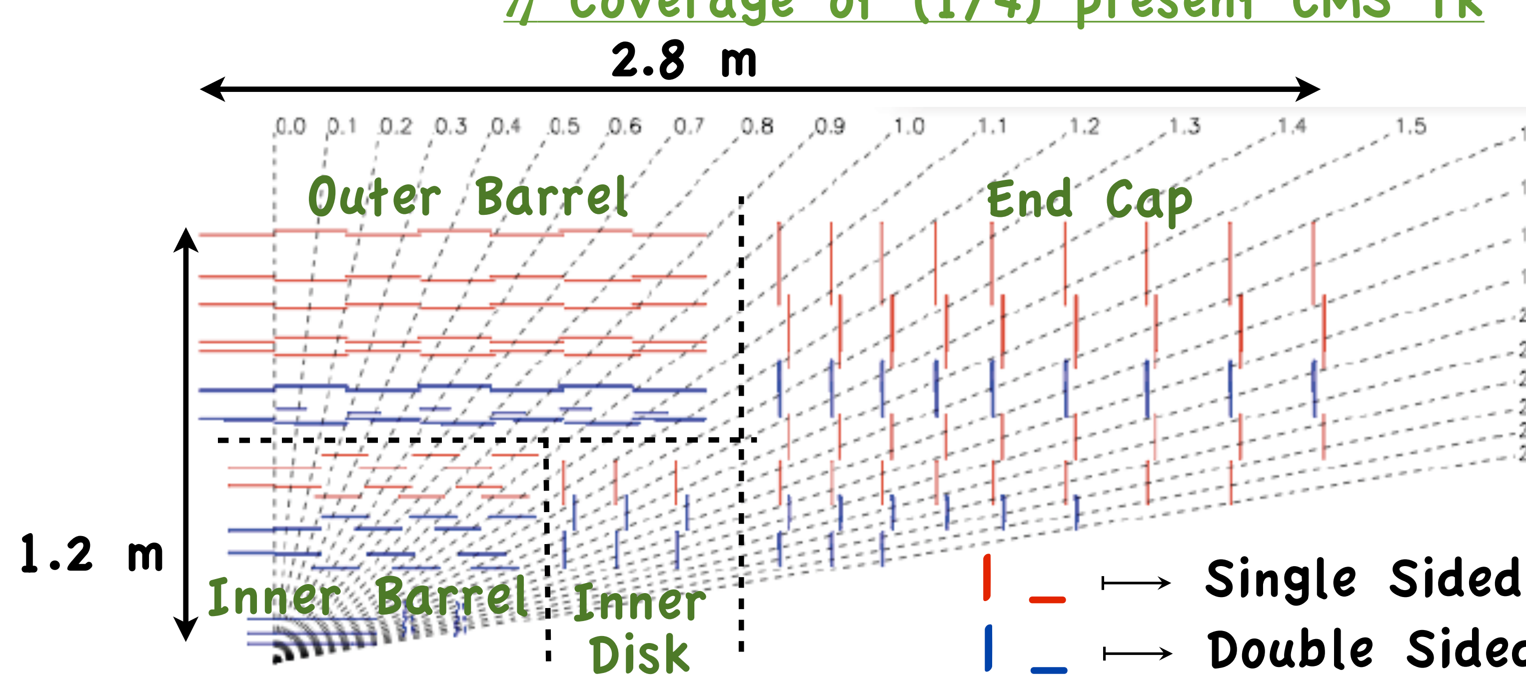
- Performance of 2-in-1 modules measured in CMS data (7 TeV p-p collisions)
  - >> Firstly MinBias/QCD events, π's & μ's (from B\D semileptonic decays) tracks inside hadronic jets
  - >> good quality tracks selected: $\chi^2<2$, $\#_{hits}>11$, $\#_{pixel}>1$, $z_0<10$ cm, $d_0<0.1$ cm (π's) \ 5 cm (μ's)



Single Sided Module

Double Sided Module

η Coverage of (1/4) present CMS Tk



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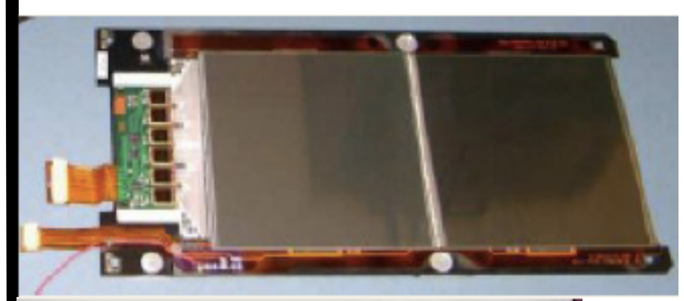
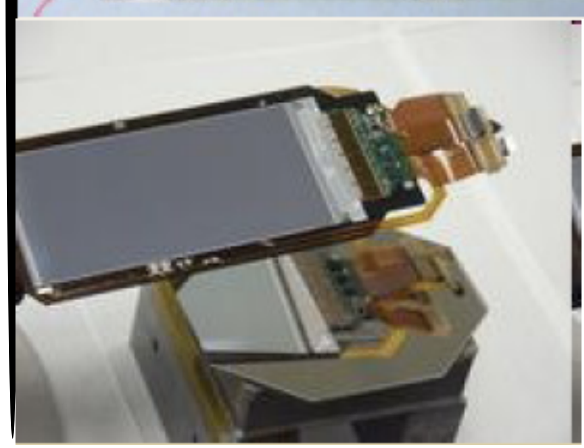
Single Sided (SS) modules considered to study CW (CW=TW in SS) selection

>> TOB Layer 6

- R = 108 cm
- ToP = 4.2



Single Sided Module



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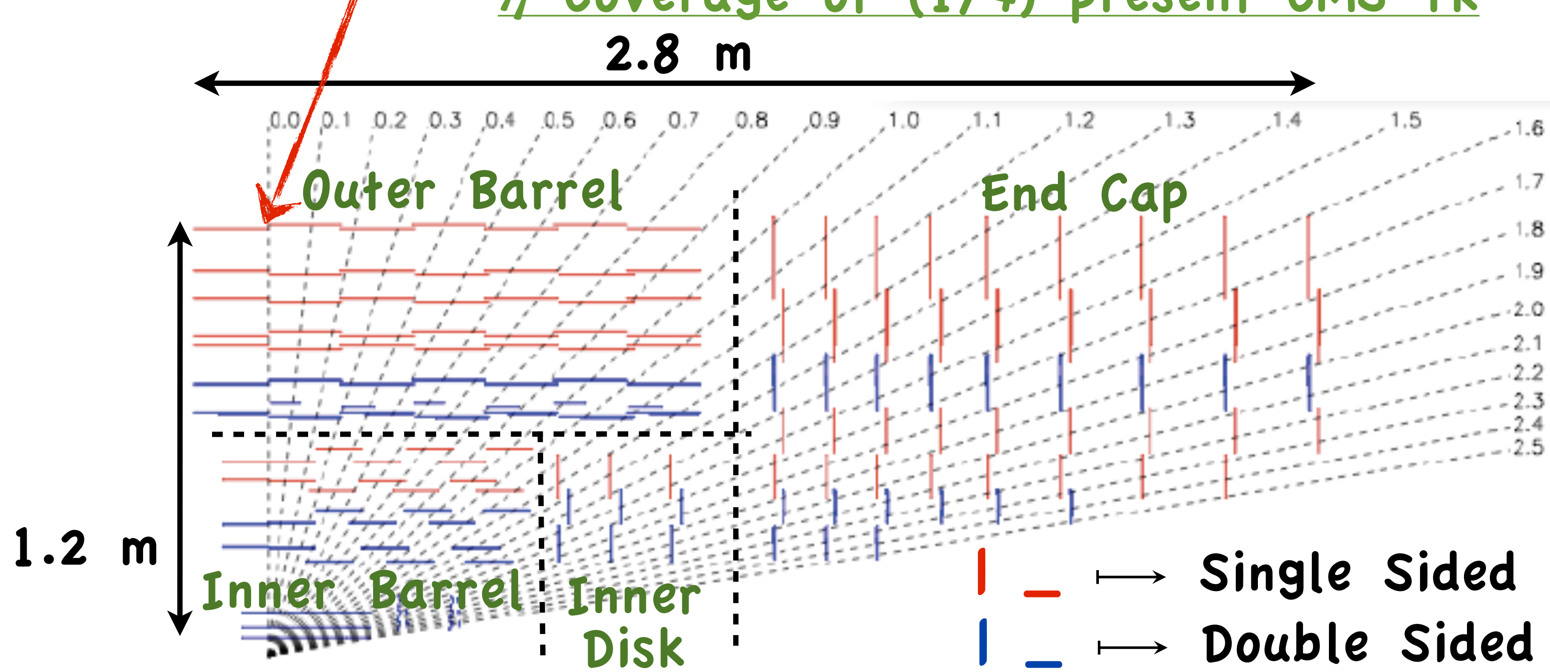

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Double Sided (DS) modules considered to mimic the 2-in-1 stacked modules

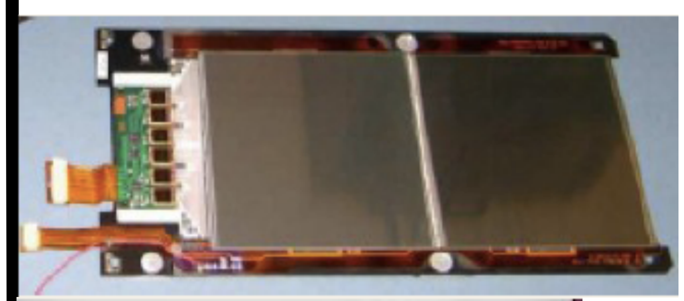
\>> TOB Layer 2

- R = 70 cm
- ToP = 21.9

Single Sided (SS) modules considered to study CW (CW=TW in SS) selection

\>> TOB Layer 6

- R = 108 cm
- ToP = 4.2



Single Sided Module

Double Sided Module

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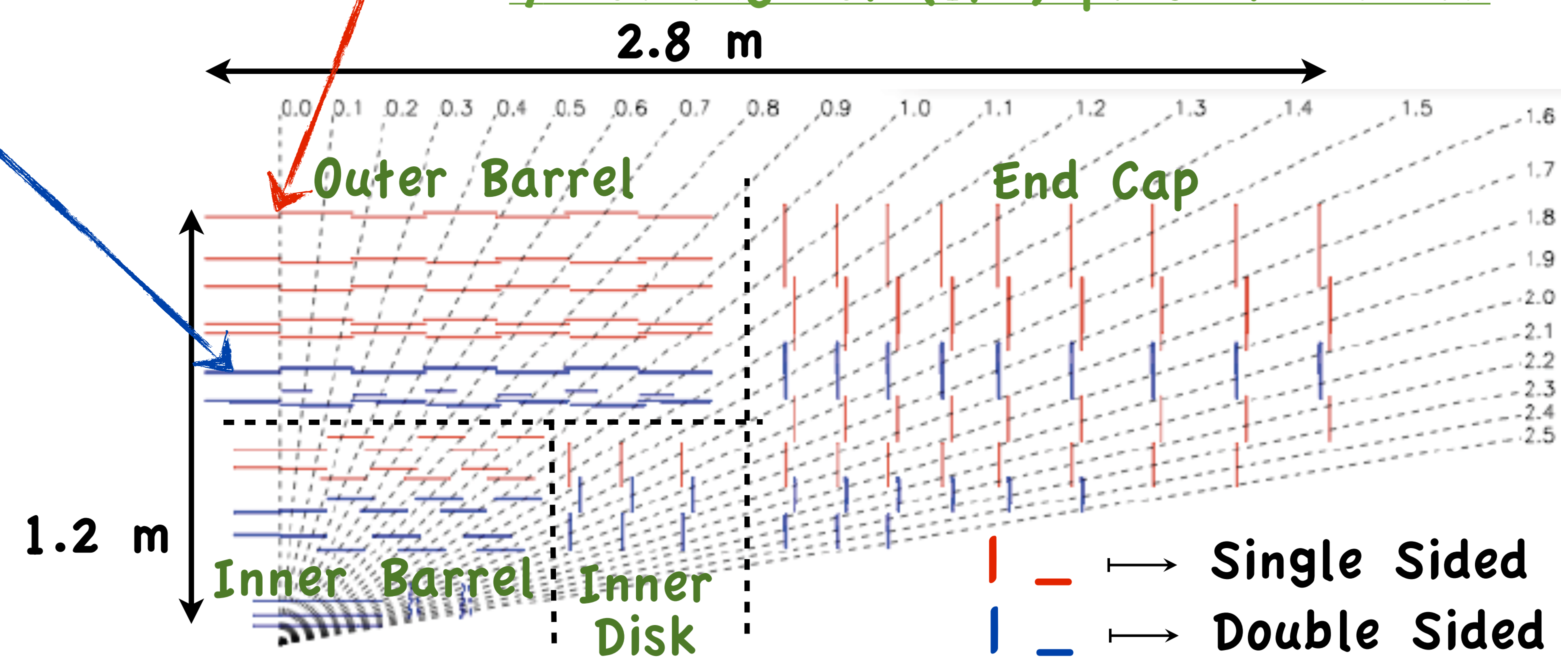
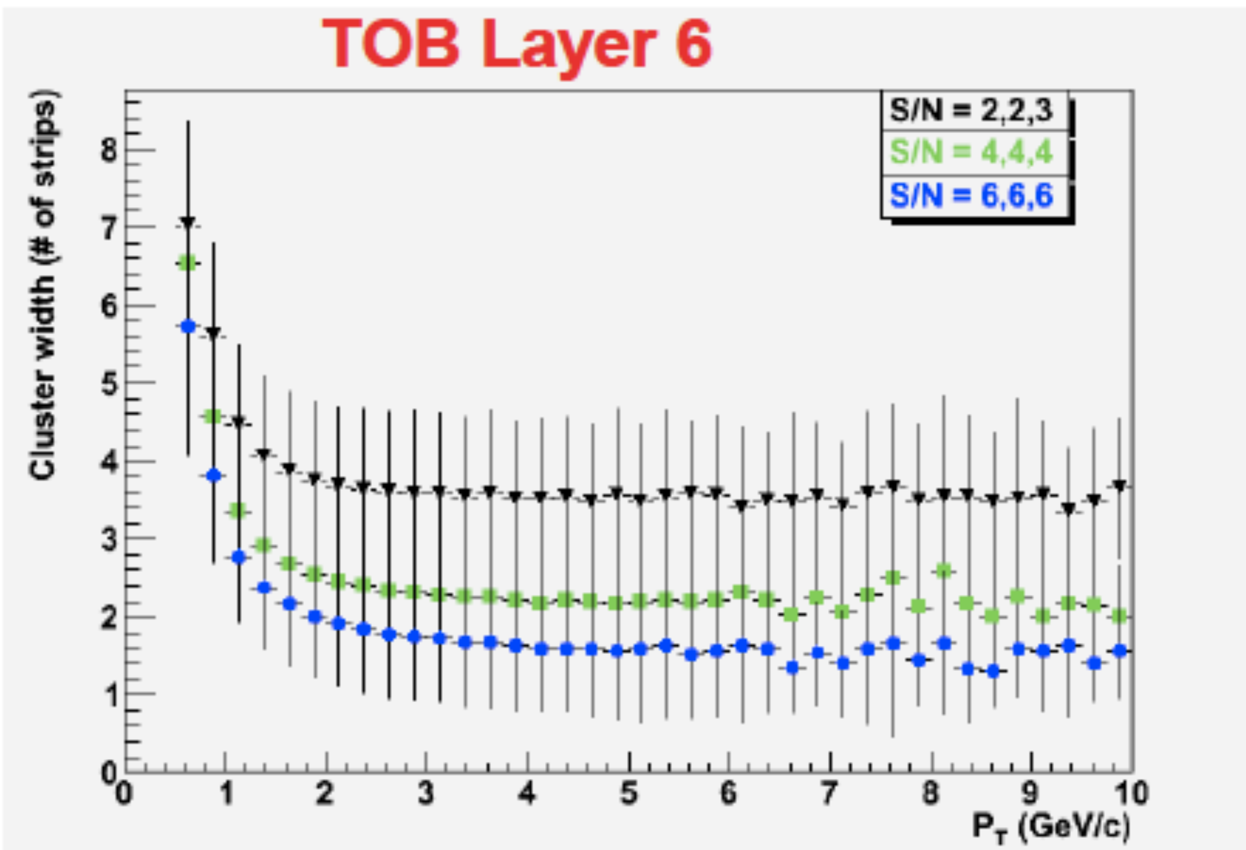
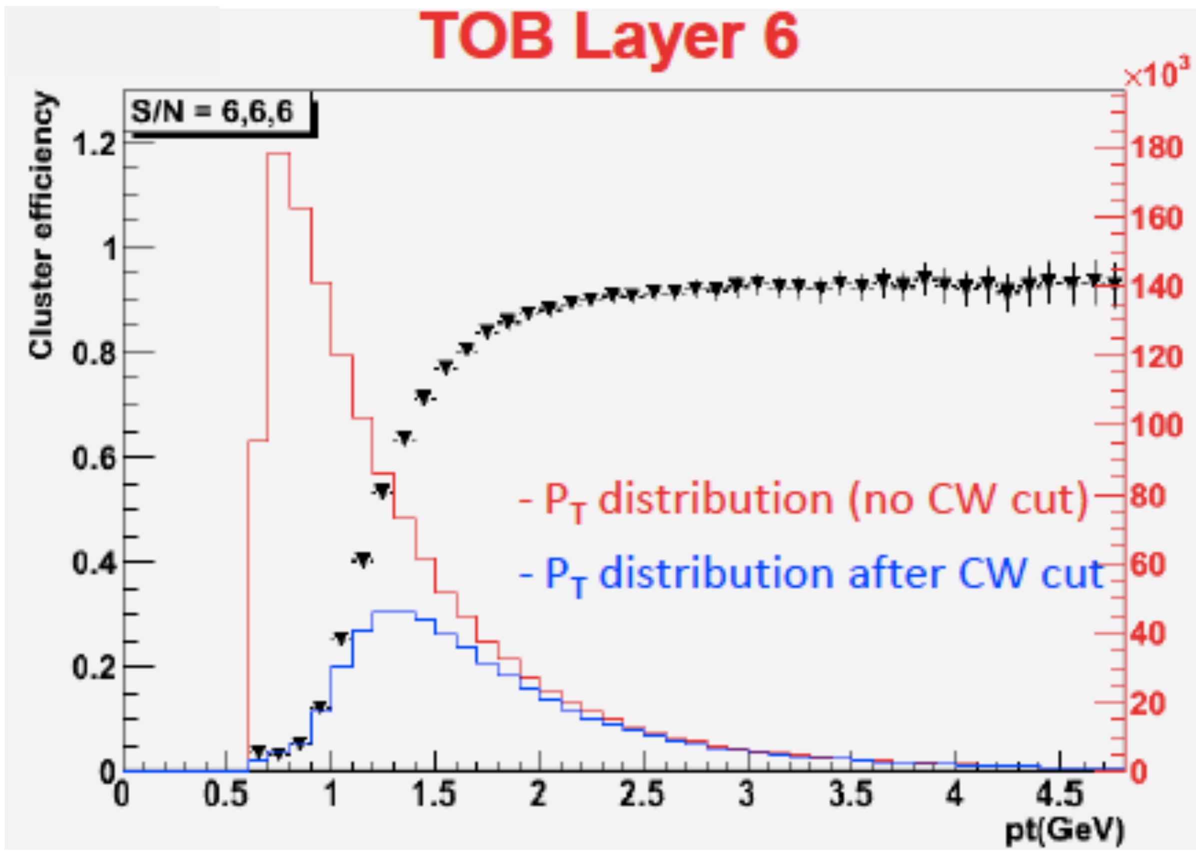


SS: Sensitivity to CW

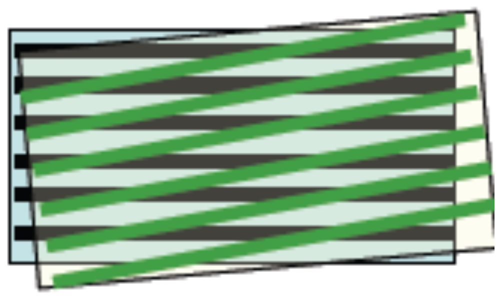


- Tracks CW correlated with reco p_T for various clustering thresholds
  - >> CW decreases with p_T, as foreseen from theoretical model
  - >> Good p_T sensitivity for higher clustering thresholds (S/N > 6) due to suppression of capacitive couplings effects on FE electronics generating false large clusters



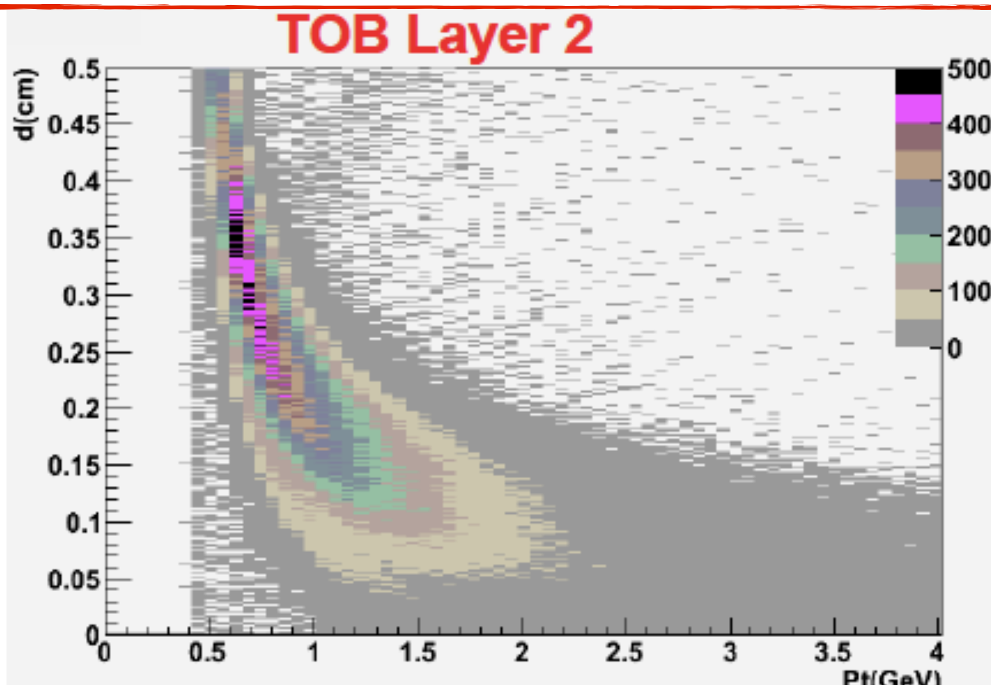
- Tracks selected with CW < 3
  - >> Selection efficiency as a function of p_T superimposed to track p_T distributions
  - >> Efficiency > 90% yet from 2 GeV/c

DS: Sensitivity to p_T

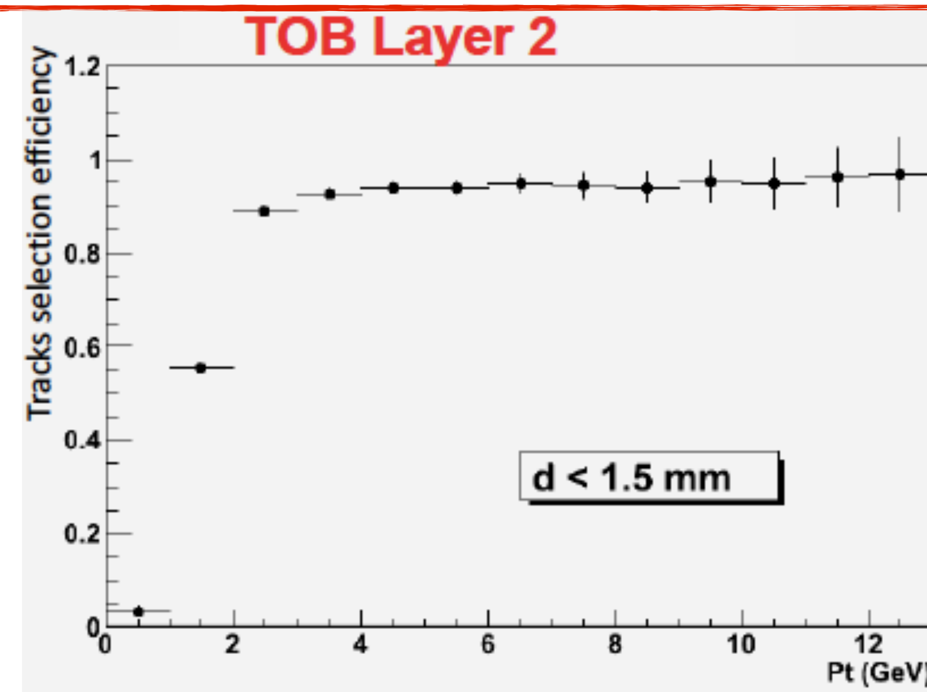


tilt angle: 100 mrad

- DS in CMS are used to get z info
  - >> 2 SS modules are in "stereo" configuration i.e. rotated by 100 mrad
  - >> Correcting off-line for the stereo angle, we can use DS modules as double layer detectors



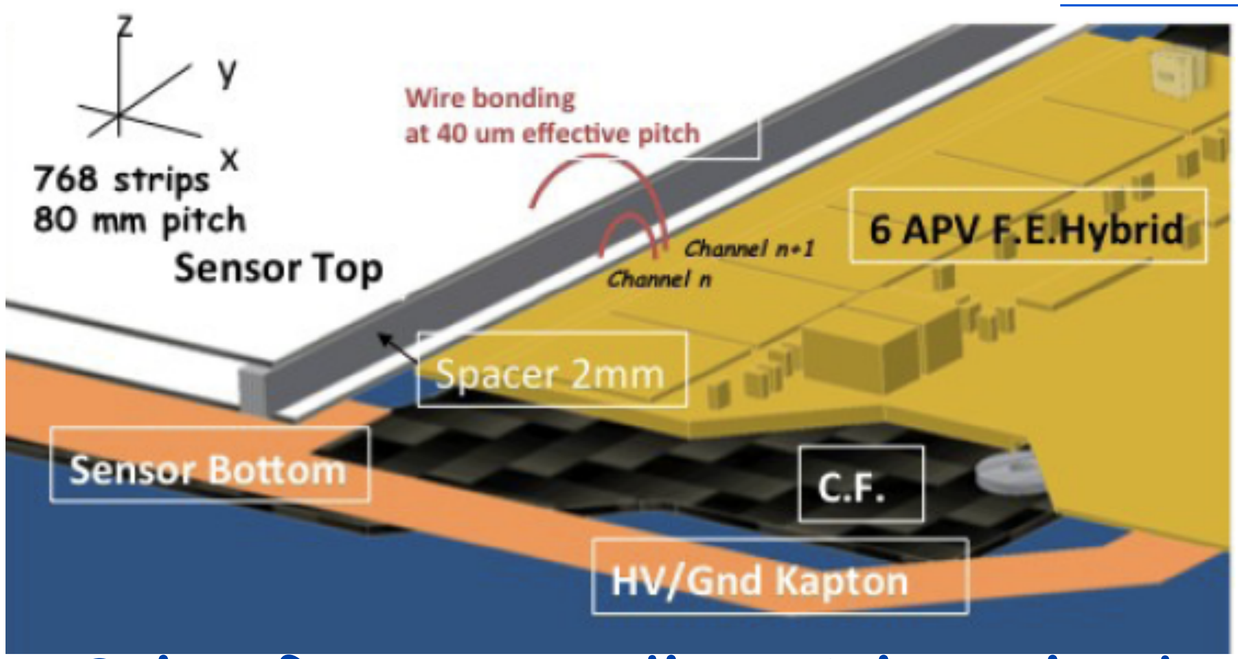
- Correlation TW("d") vs. track p_T
  - >> High p_T (>2 GeV/c) tracks have clusters almost overlapping
  - >> Clusters for low p_T ones are far each other

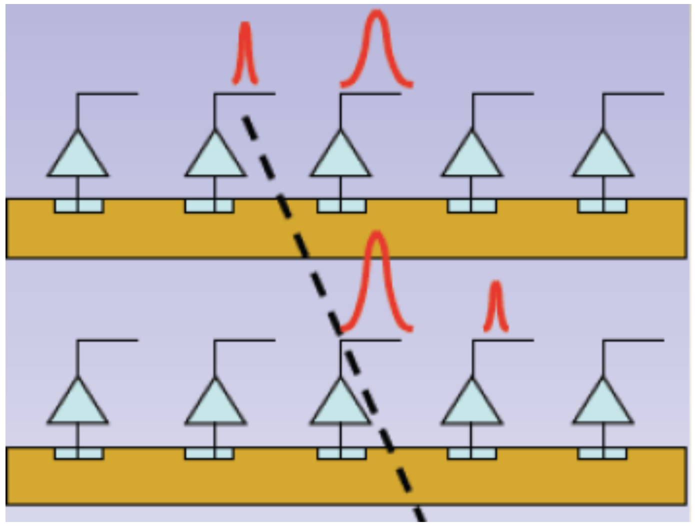


- Tracks selected with TW("d") < 1.5 mm
  - >> Selection efficiency vs. track p_T
  - >> Efficient selection (~100%) for high (> 5 GeV/c) p_T tracks

First Prototypes

Module A



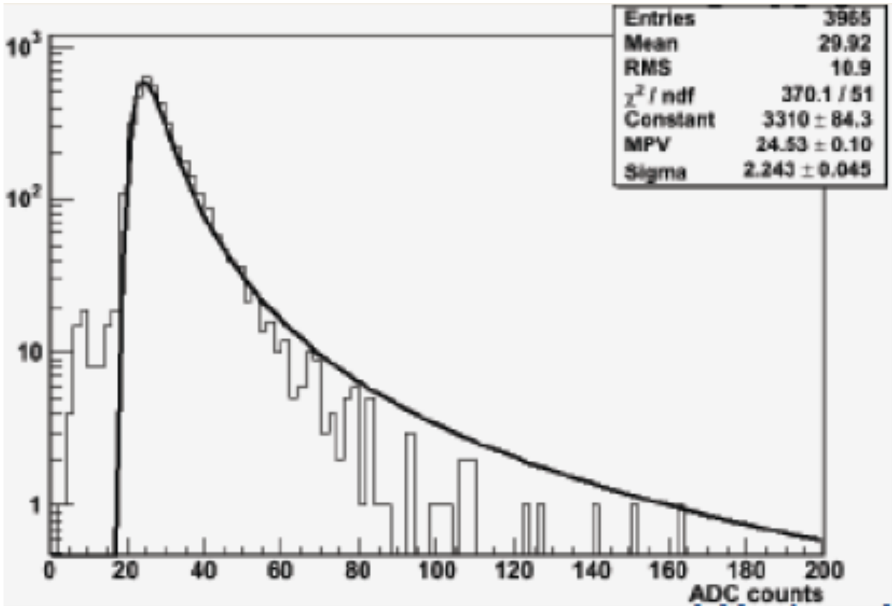


- Tracks generate signals on both sensors
- Signals collected independently
- Top & Bottom Cluster position & CW reco independently
- Top & Bottom sensors correlation needed

- Pair of corresponding strips wire-bonded to a pair of neighboring read-out channels
- Sensor pairs with:
  - >> 80 μm pitch \ 768 μ-strip

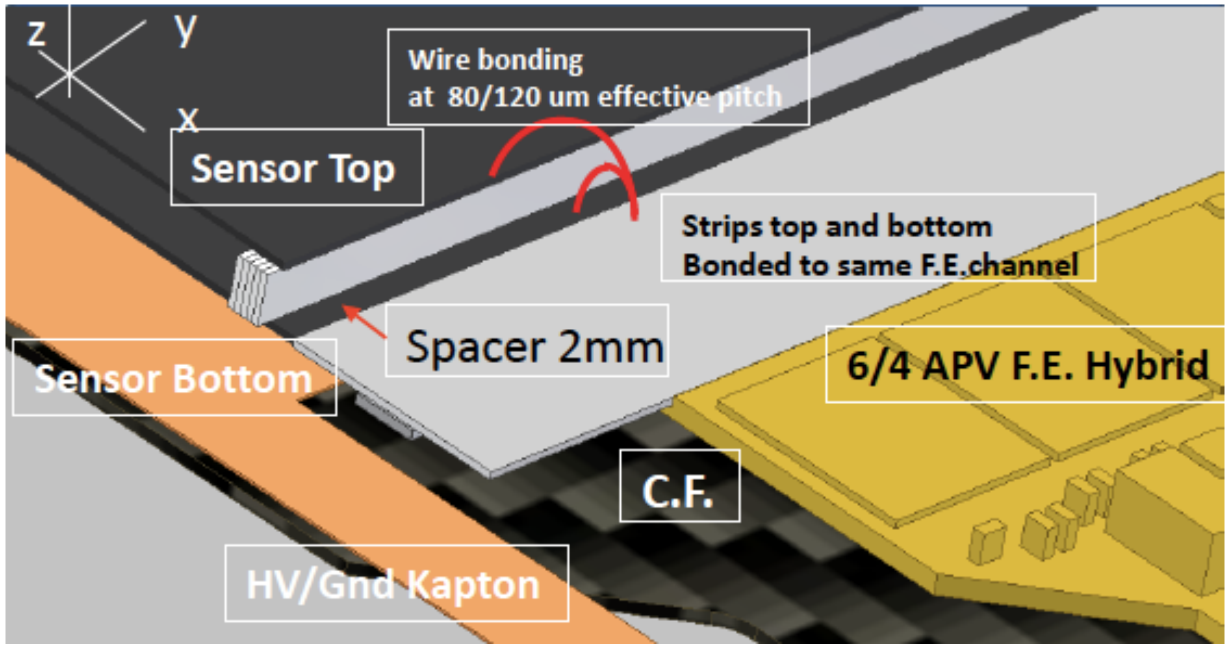
Off-detector Cluster Analysis:

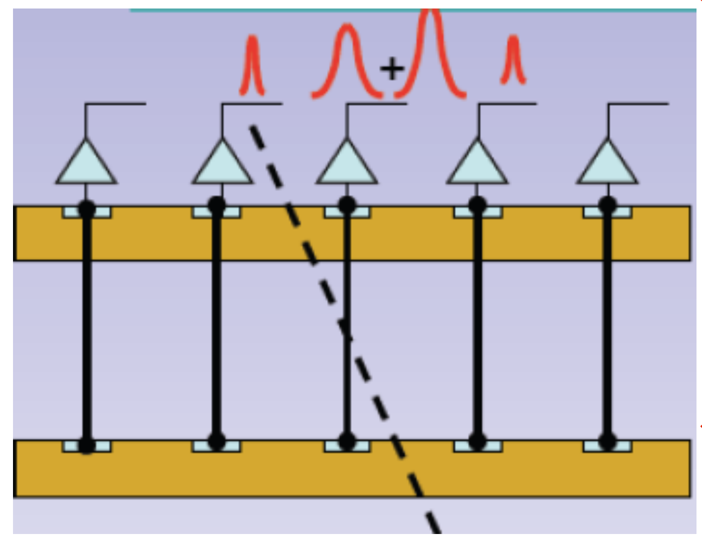
- >> Select event with 2 clusters only
- >> No Cross-Talk between strips affects performance
- >> Fit on S/N distribution: Landau, MPV=24.5±0.1



First Prototypes

Module B



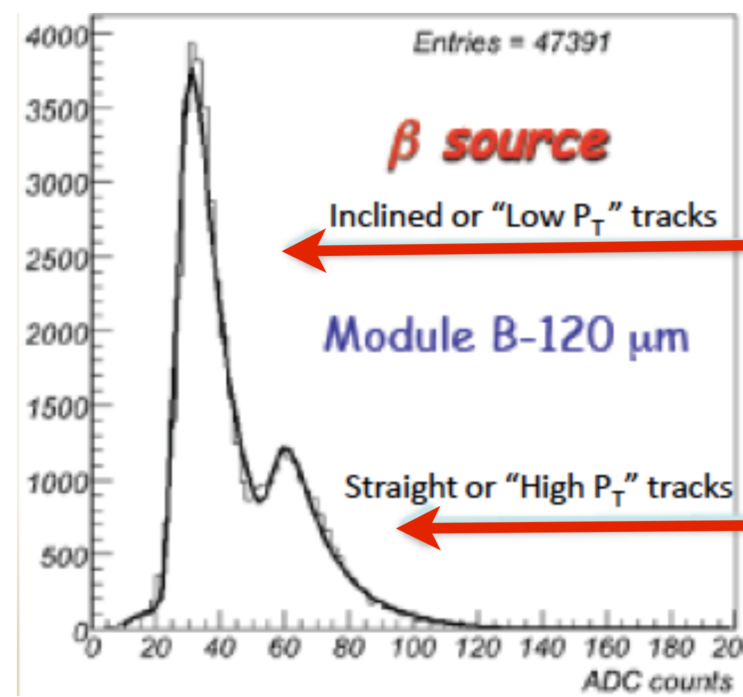


- Tracks generate signals on both sensors
- Signals are summed by wire bonding
- Cluster position & CW reco as for SS
- Limit case: only 1 cluster/track reco for too close clusters

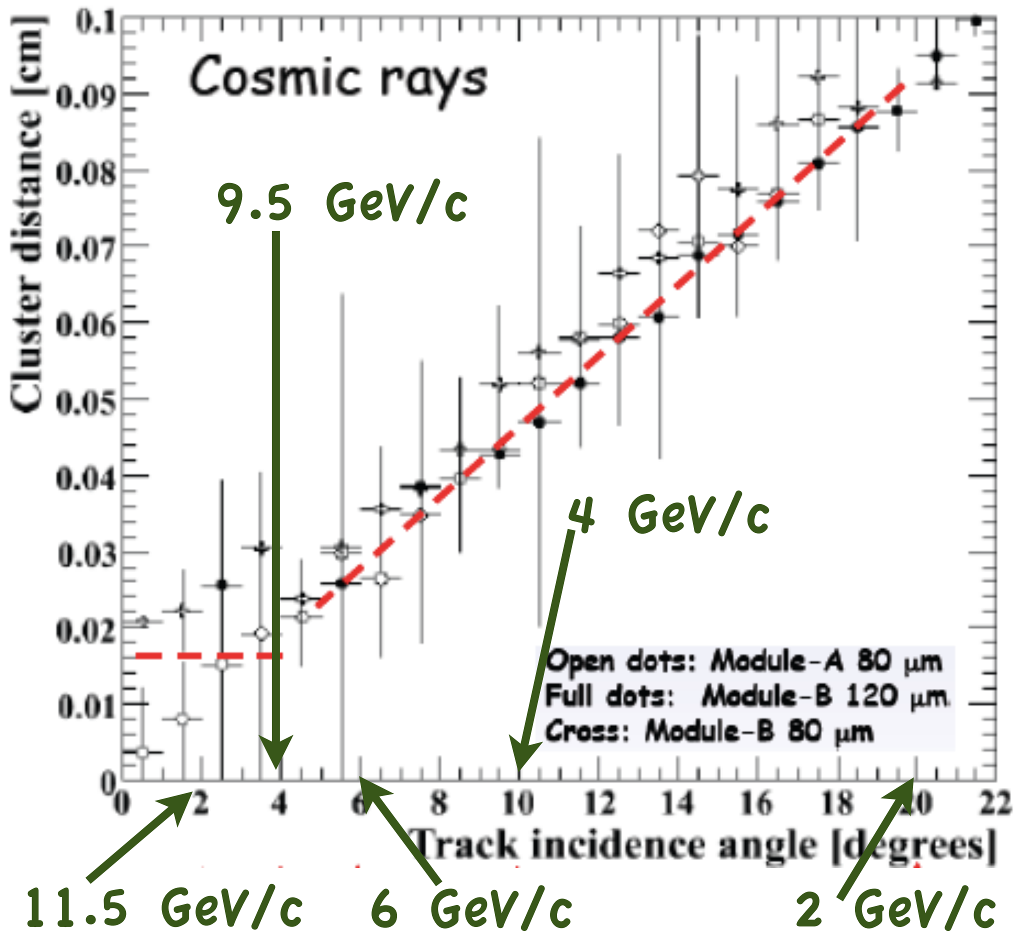
- Pair of corresponding strips wire-bonded to the same read-out channel
- Sensor pairs with:
  - >> 80 μm pitch \ 768 μ-strip
  - >> 120 μm pitch \ 512 μ-strip

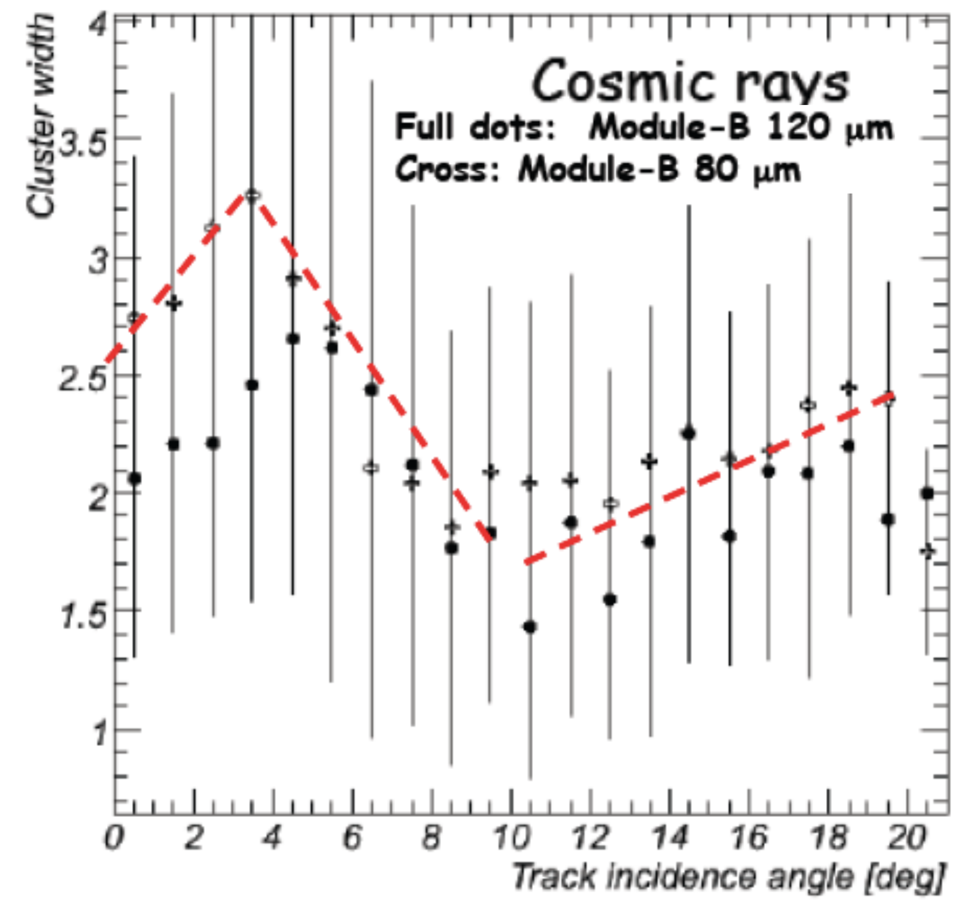
Off-detector Cluster Analysis:

- >> Clustering performed for track with 1(*) or 2(**) clusters
- >> Fit on S/N distribution: (*) Landau, MPV=39.2±0.5
  (**) Landau, MPV=20.8±0.2



Cosmic Rays





⤳ Cluster Distance (TW) vs. inc. angle

>> Module A linear in the full range of incidence angle

>> Module B non linear for small incidence angle values (where clusters overlap)

>> This allows p_T discrimination in a B field
Example of p_T discrimination for B=4 T at R=108 cm

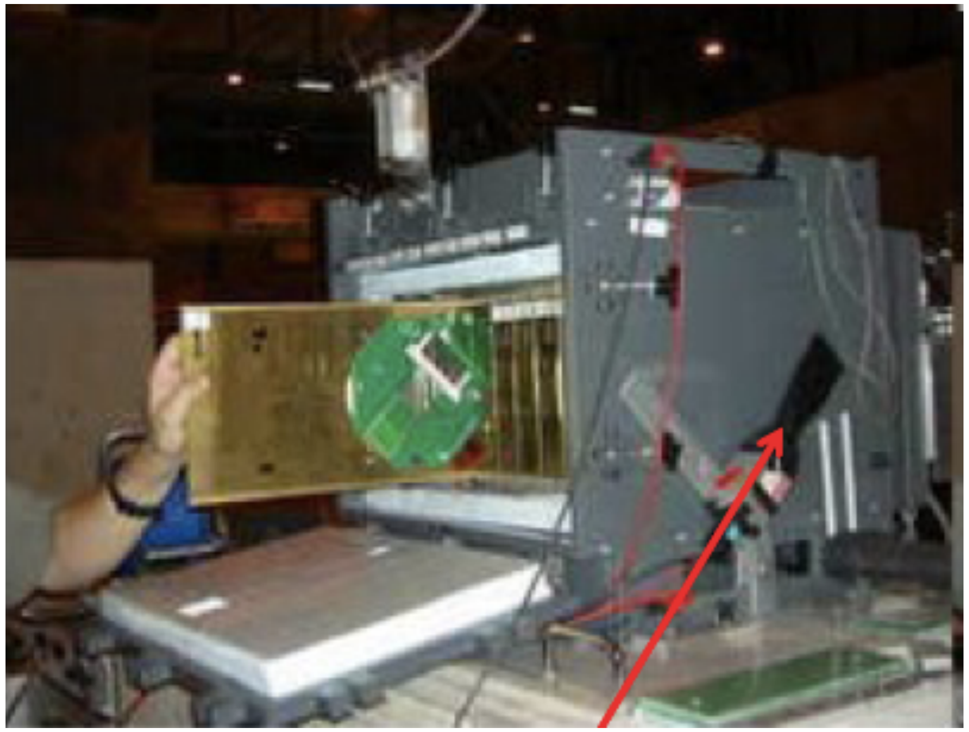
⤳ CW (# of strips) vs. inc. angle

>> Increases until top & bottom sensor produces events with 1 cluster

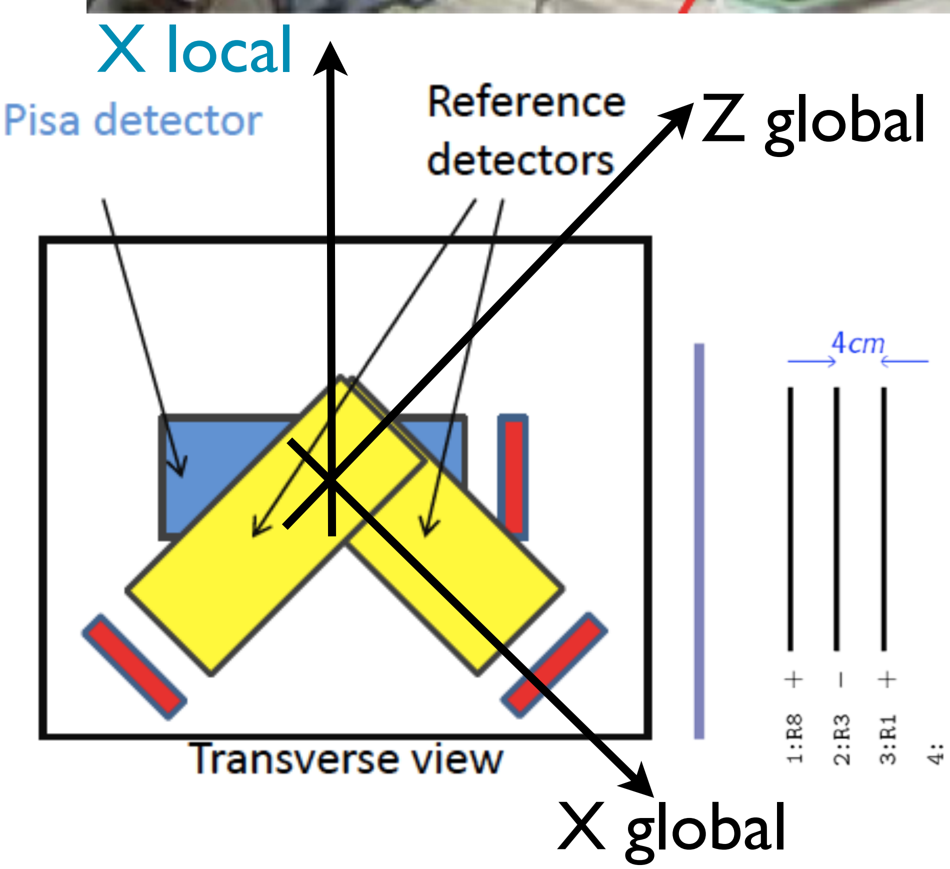
>> Drops for angles with 2 clusters splitting

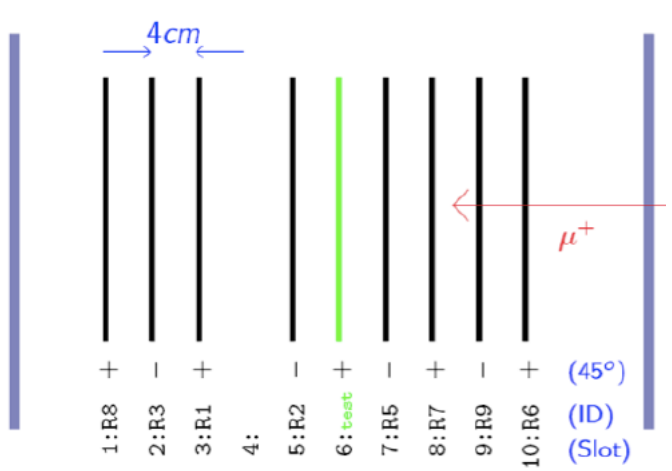
>> Then follows a standard behavior at larger angle (where 2 clusters event are collected)

Beam Test (Setup)

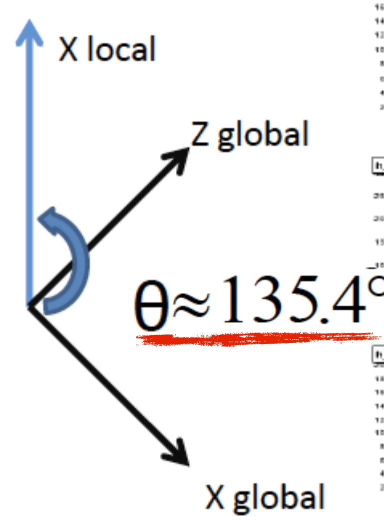


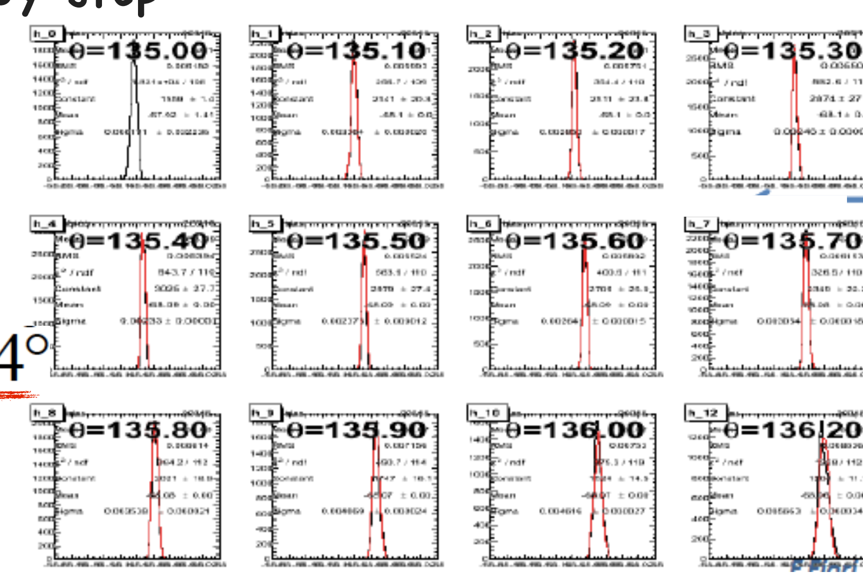
- Telescope Setup:
  - Trigger made by coincidence of two scintillators mounted on both sides of the telescope
  - 8 reference planes (Si μ-strip sensors 50 μm pitch) rotated by ±45°, only $8<\#_{hits}<13$ tracks retained
  - reference detectors alignment & clusters\track reco in global reference provided by Helsinki HIP team (thanks to T. Mäenpää et al.)



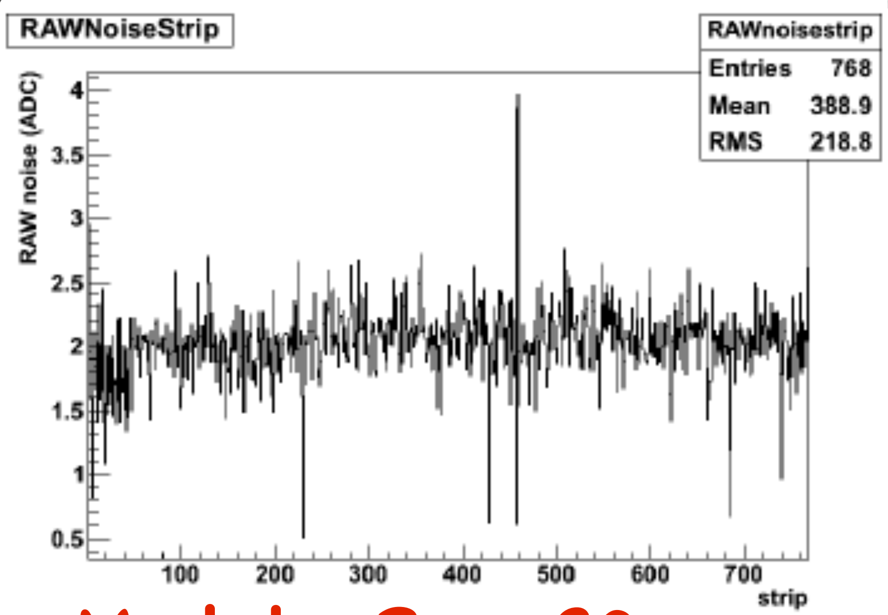


- To identify fakes & calculate the incidence beam angle we have to align Pisa det. to global frame
  - Minimizing the residuals $x_{loc}-x_{glob}$ rotating frames step-by-step

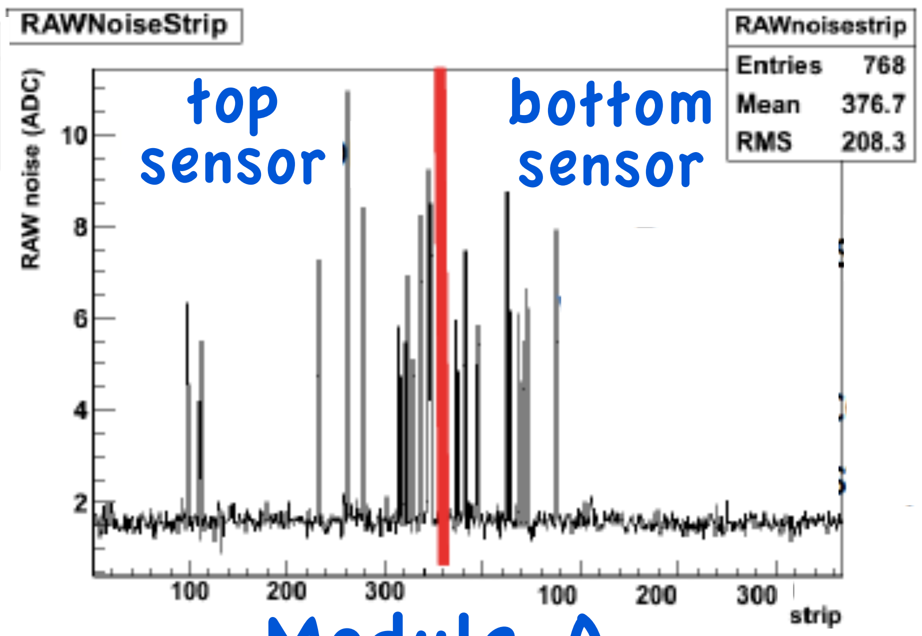




Beam Test (Results)



Module B - 80 μm

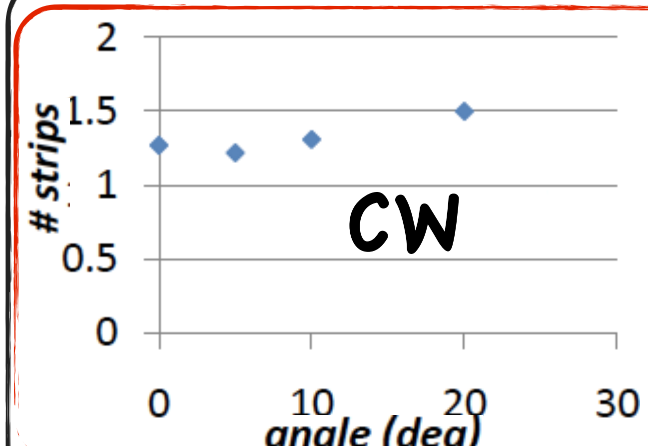


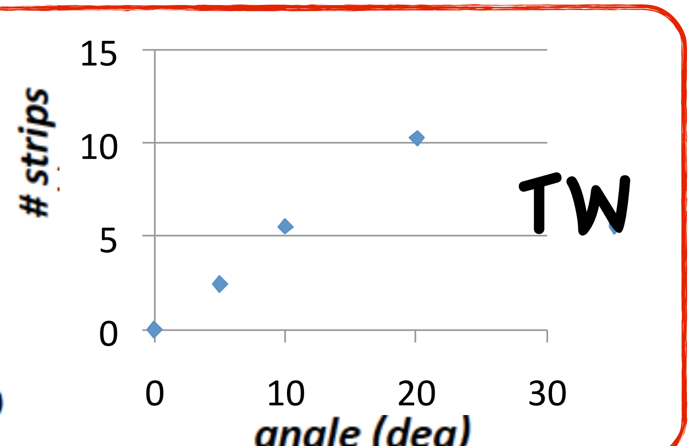
Module A

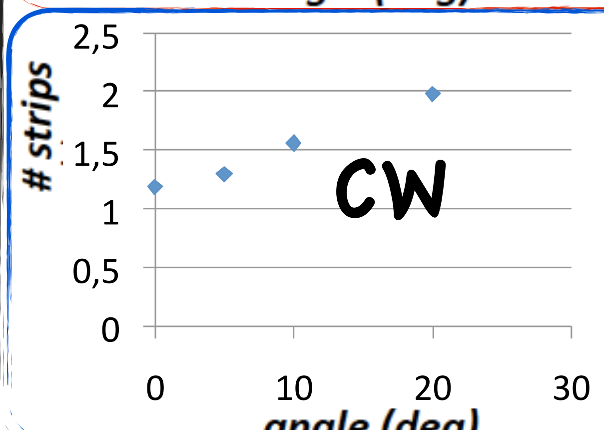
Noise Performance

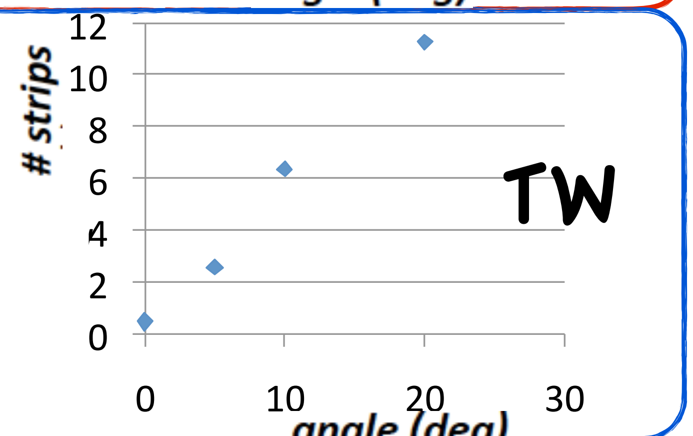
>> spikes due to unconnected strips

>> Module B: RMS~2.03
Module A: RMS~1.58
Higher noise due to higher capacitive load in the wire-bonding to the same read-out channel









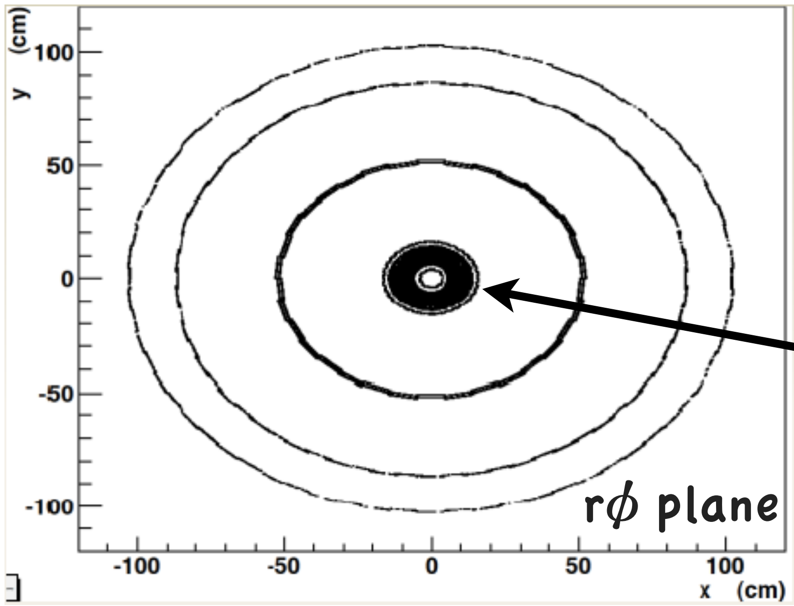
TW(cluster distance) & CW vs. inc. angle

>> Module B
- Considered angles: 0°, 5°, 10°, 20° to mimic different p_T tracks

>> Module A
- Considered angles: 0°, 5°, 10°, 20° to mimic different p_T tracks

>> Similar behaviors of TW, quite higher CW values for module A

Simulation Framework



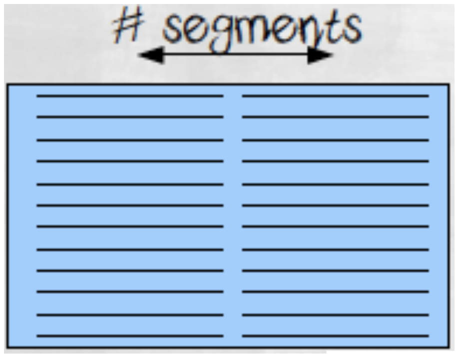
Si Pixel Vtx Detector

layer	L1	L2	L3
Radius (cm)	51	86	102

⤳ Particles 4-momentum propagation inside material based on GEANT4, Tk layout geometry & material budget description based on XML files architecture

>> MinBias: generated with the Pythia MC generator
single $\mu^{\pm}$: generated with "single particle gun" MC generator

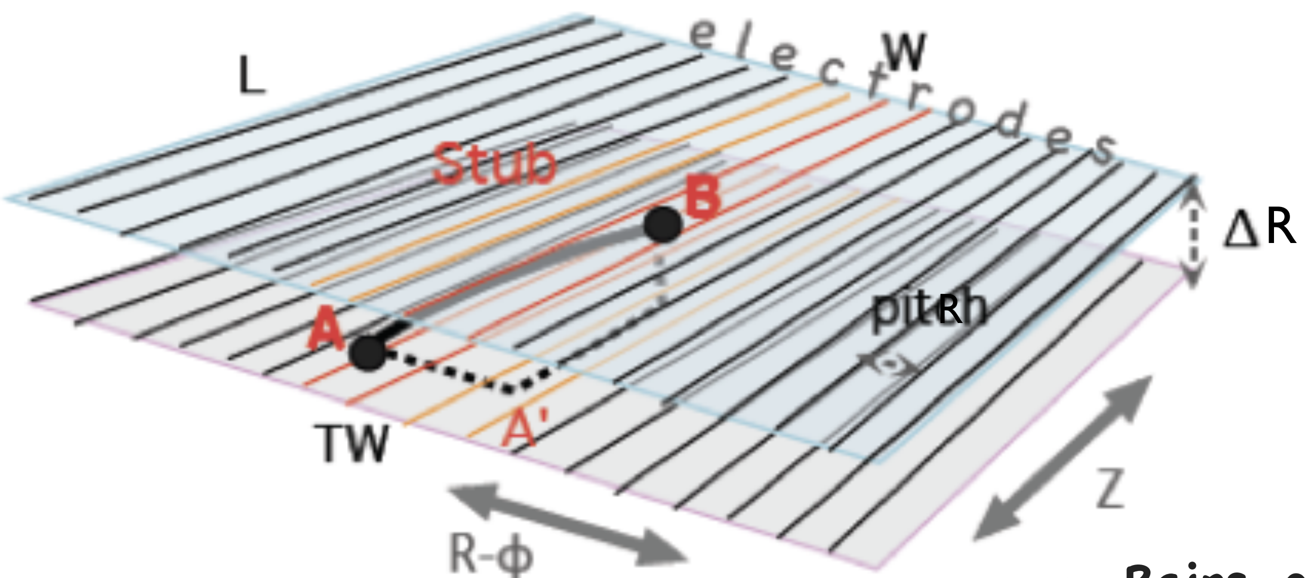
>> Tk Geometry: 3 barrel layer (1.2 m long) outside Si Pxl Vtx,
Si sensors Stacked modules 10 X 10 cm².
Module Topology: μ-strip 98 μm pitch 4.6 cm long, 300 μ m thickness,
ΔR=1 mm, active area 9.2 X 9.2 cm²



>> Digital μ-strip read-out via ADC, channels of both sensors read-out independently (Module A emulation)

Stub as Trigger primitive

Stub Definition



⇝ Pairs of clusters are correlated through algorithms based on geometrical constraints with P.V. & $\vec{B}$ field knowledge inside the module ΔR

>> Intrinsic cut ~2 GeV/c due to geometrical constraints in stub reconstruction algorithms

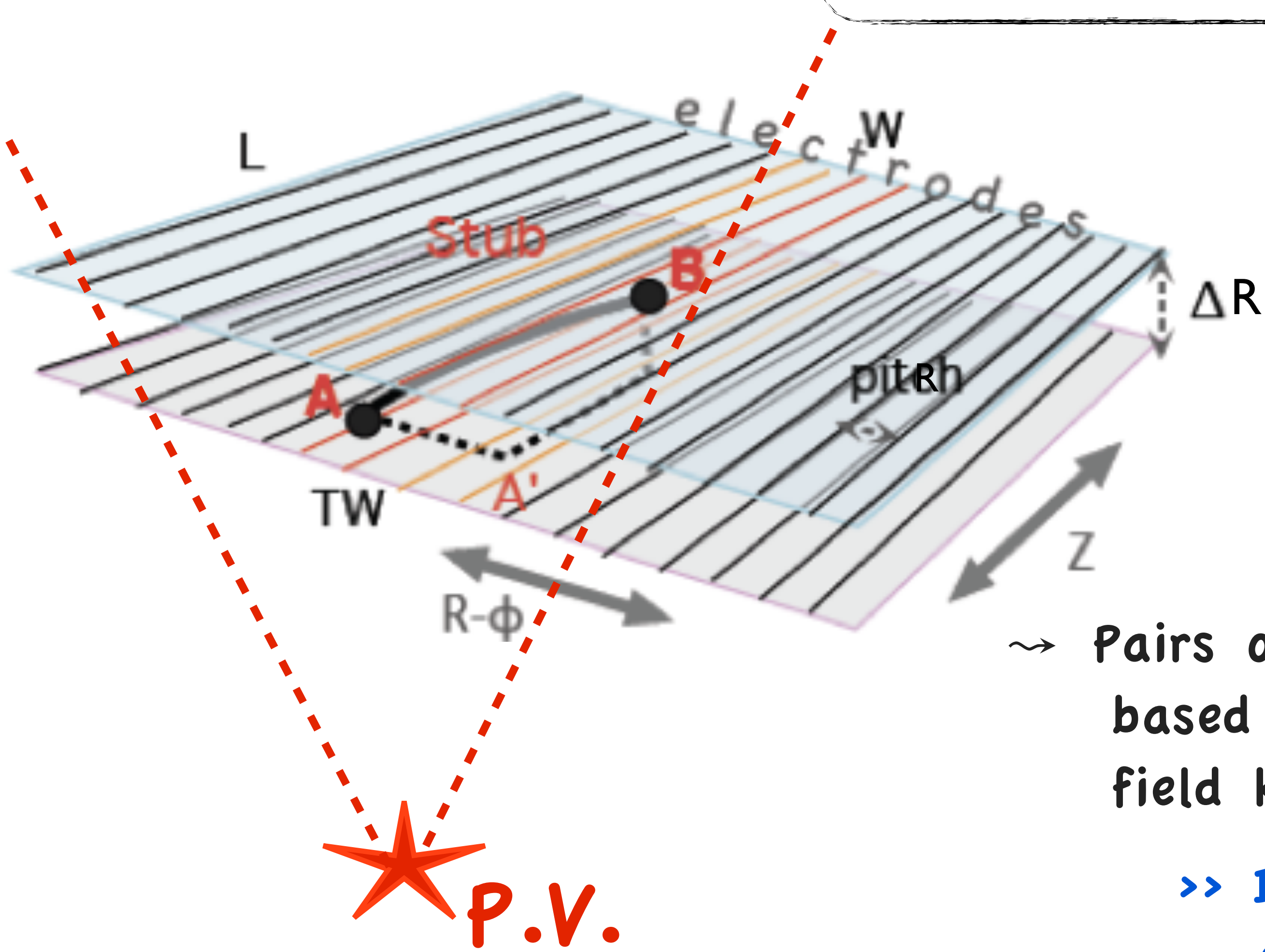
>> Kinematic infos (position, $\vec{p}_T$, CW of both sensors) are encoded into a single object called "stub"

Stub encoding:

Stub = 3-vector$^{(\text{global pos.})}$ + 2-vector$^{(\text{flight dir.})}$ + scalar$^{(p_T)}$ (+ two scalars$^{(\text{CW in both sens.})}$)

Stub as Trigger primitive

Stub Definition



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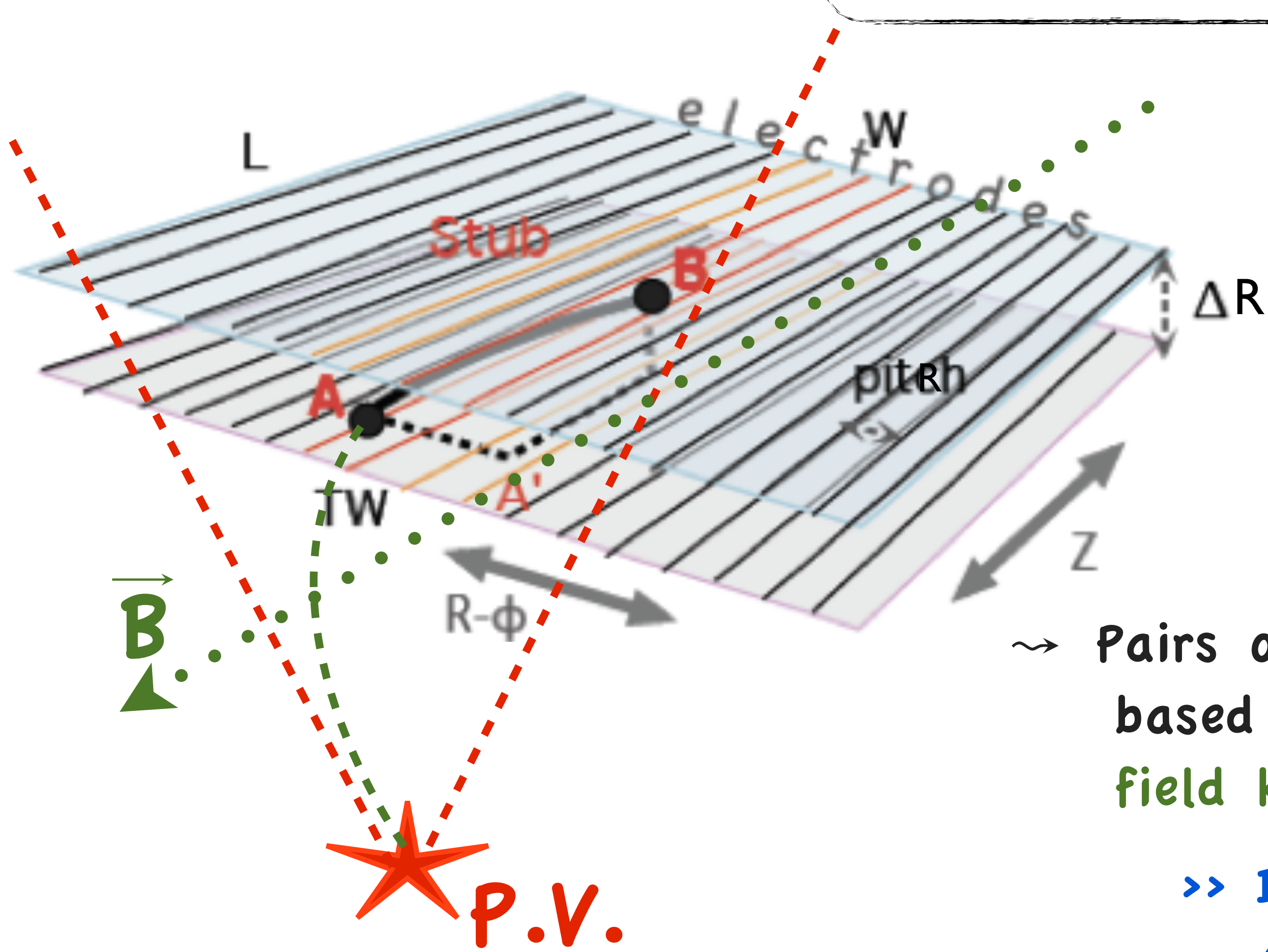

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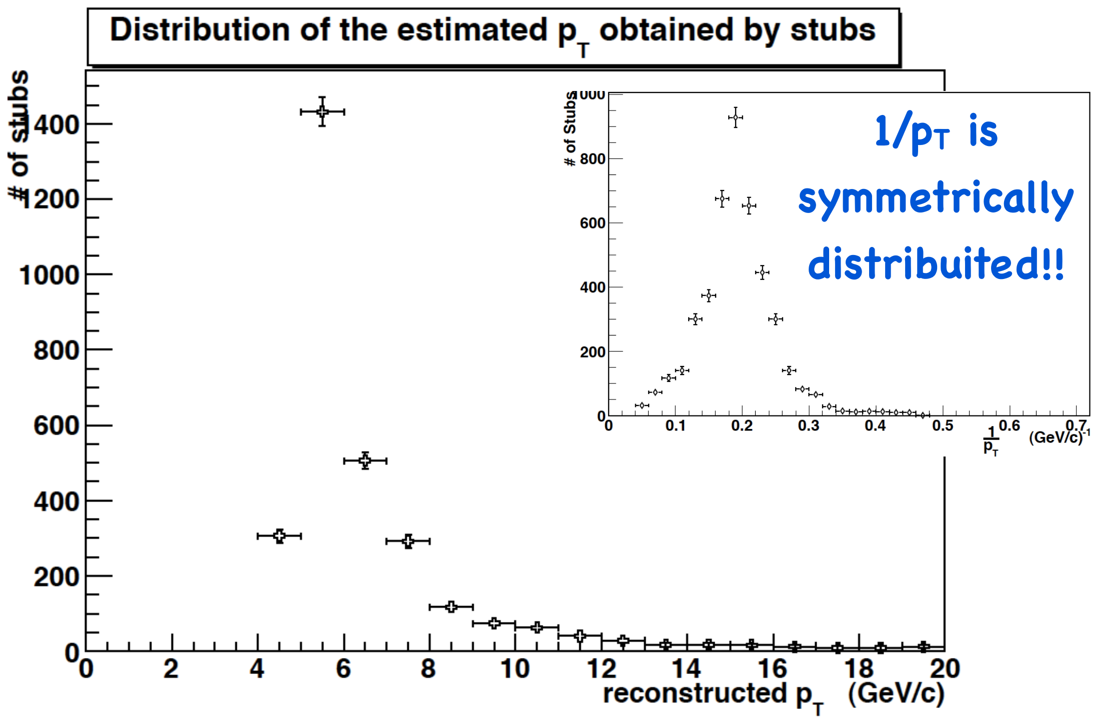
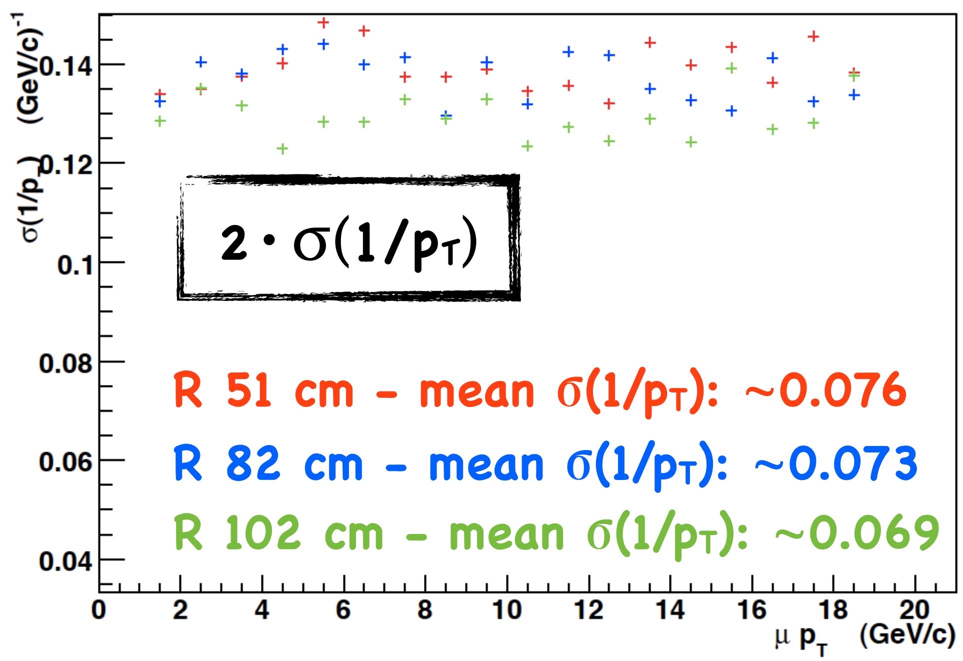
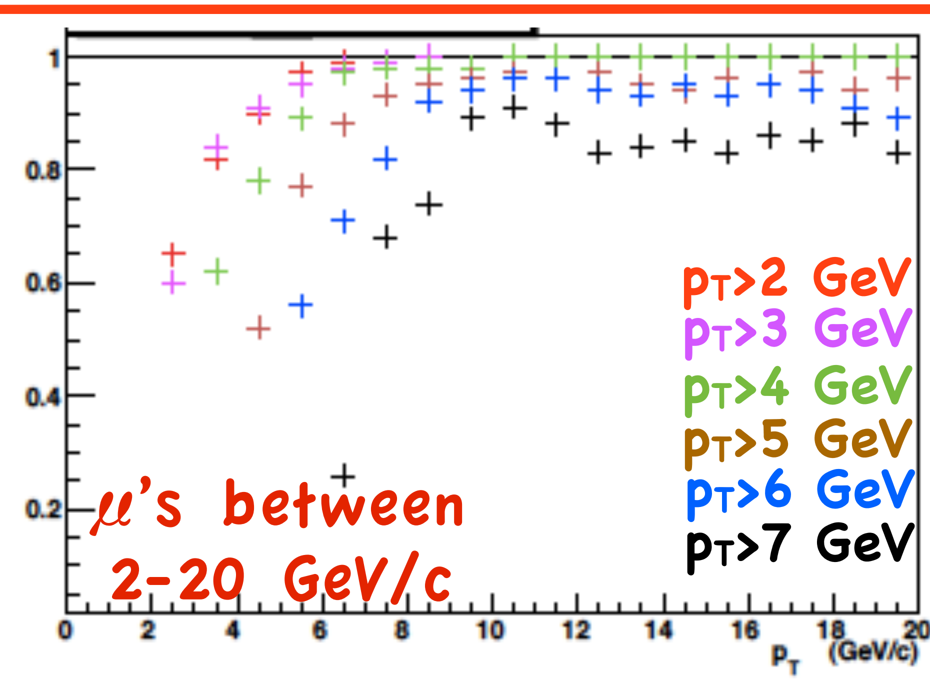
Stub p_T Measurement

⤳ p_T measurement resolution: Single μ's @ 5 GeV/c

>> Evaluation of reconstructed pT from the stub (see slide 1): $\frac{\sigma(p_T^{meas})}{(p_T^{meas})^2} \equiv \sigma(\frac{1}{p_T^{meas}}) \simeq 5\%$







⤳ Layer @ 102 cm equipped with Stacked Modules

>> p_T selection strongly depends from p_T^{meas} resolution $\sigma(p_T)$ that:

(1) increases as $(p_T^{meas})^2$

(2) is not gaussian & skewed toward larger p_T^{meas}

>> Inefficiencies appears for p_T > 5 GeV/c because of (1). Anyway, rejection at high p_T is milder because of (2)

Trigger Rates

SLHC "Phase II" scenario:

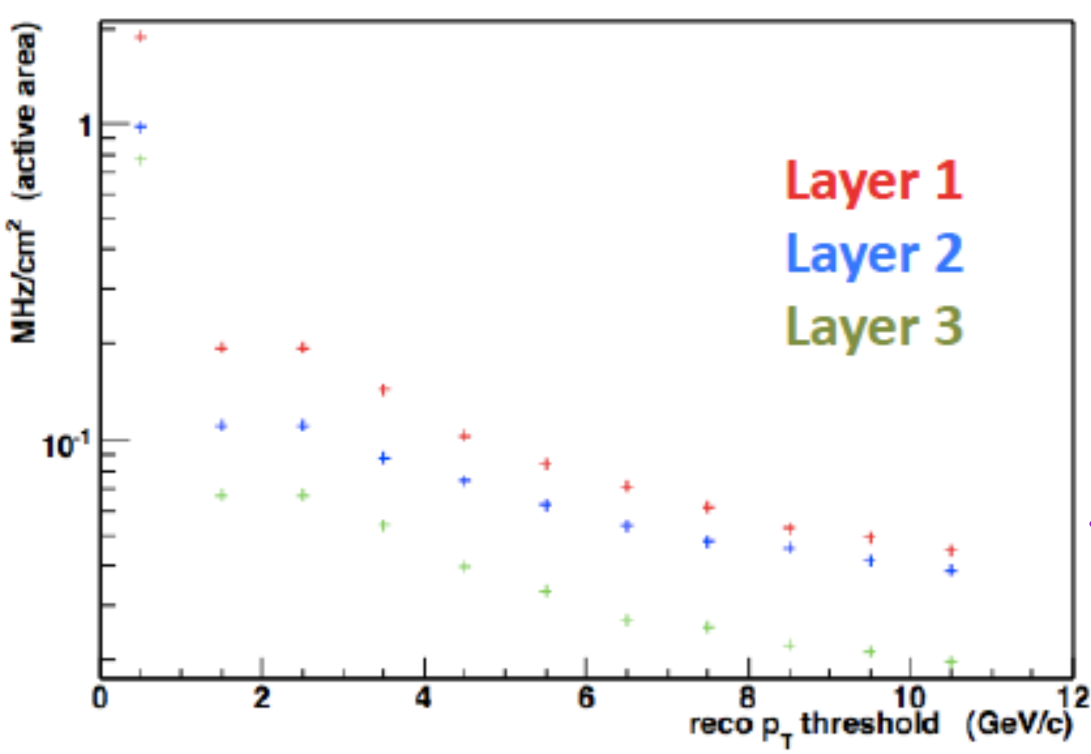
pp @ $\sqrt{s}$=14 TeV, $\mathcal{L}$=10^{35} $cm^{-2}s^{-1}$, 200 MinBias/BunchX

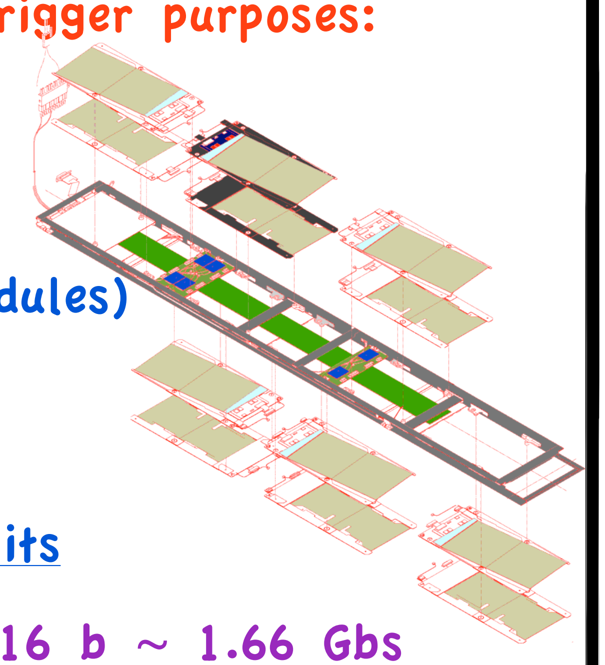
⇝ Simulation of 200 MinBias overlapping events (BunchX rate 40 MHz)

layer	L1	L2	L3
Radius (cm)	51	86	102
Strip Occupancy (%)	1.5	1.1	0.9

>> Cut on p_T^{meas} estimated through stubs also at 1 or 2 GeV/c is enough to reduce the information rate to manageable level for trigger purposes:

Stub production rate per cm²





- CMS Tk is read-out per "rods" (12 modules)
- each module has 9.2X9.2 = 84.64 cm² active area surface
- supposing to encode stub infos in 16 bits

$BW_{Read\text{-}Out} \sim$ 100 kHz/cm² · 86.64 cm² · 12 · 16 b ~ 1.66 Gbs

Within the range of available data link speeds

Conclusions & Outlooks

⇝ Stacked Modules design is a viable solution for Tracker Trigger. Proven to work with:

- >> Real LHC collision data
- >> Prototypes involved both in Cosmic Rays & Beam Tests
- >> Full Tracker simulation of foreseen SLHC scenario

⇝ Main features:

- >> Low material budget and hardware optimized
- >> Capable to decrease p_T trigger data rate down to ~100 kHz/cm^2
- >> Local Trigger & low-level p_T evaluation

⇝ Some R&D remains to be done, this activity will continue since is needed

- >> Implement detector optimized design (module/layout)
- >> Trigger performance simulation study on benchmark channels (e.g. $H \longrightarrow WW$)
- >> Optimization of INTRA sensor module connectivity
- >> Optimization of INTER rod\layer module connectivity (hardware, implementation of Associative Memories based on stubs, ...)

References

- Publications:

  - >> "Concepts for a tracker trigger based on a multi-layer layout and on-detector data reduction using a cluster size approach", JINST 5:C08002, 2010
  - >> "Track momentum discrimination using cluster width in silicon strip sensors for SLHC" Published in *Prague 2007, Electronics for particle physics* 80
  - >> "Tracking in the trigger: from the CDF experience to CMS upgrade" Pos VERTEX2007:034, 2007
  - >> "Design and development of micro-strip stacked module prototypes for tracking at S-LHC", JINST 5:C11018, 2010
  - >> "Design and development of micro-strip stacked module prototypes to measure flying particle directions", JINST 5:C07014, 2010

- Talks:

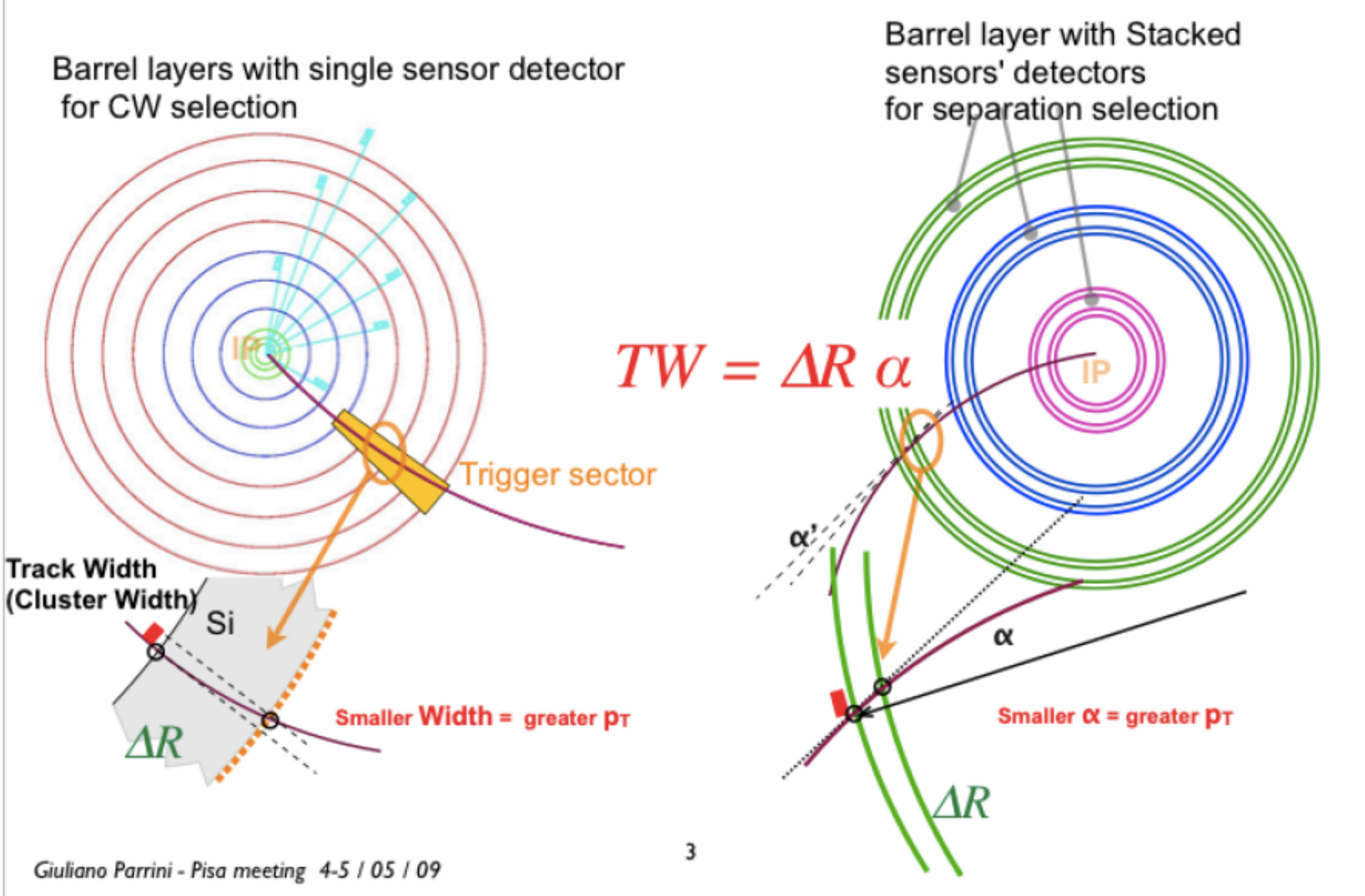
  - >> http://indico.cern.ch/contrbutionDisplay.py?sessionId=0&contribId=16&confId=68677
  - >> G. Parrini, Talk at Joint SLHC Trigger-Tracker meeting 2007, CERN and TWEPP 2007
  - >> http://indico.cern.ch/getFile.py/accesscontribId=80&sessionId=29&resId=0&materialId=paper&confId=11994

Work financed by MIUR PRIN2008 project

Back Up Slides

p_T measurement

▷ The two approaches for a quick "measure" of pT



p_T measurement

Simplified formulas

Using **acceptances W/ R < 0.2** the stub width formula can be simplified

$$TW_r \text{ " } \quad F + \left(1 + F^2\right)\,(x/R)$$

$$F = \pm \frac{1}{\sqrt{\text{"}\frac{pT}{pT_{\min}}\text{\%}^2 (1}} \;)\; \pm \left|\text{"}\frac{pT_{\min}}{pT}\text{\%}\right. \times \left|\text{"}\,1 + \frac{1}{2}\,\text{"}\frac{pT_{\min}}{pT}\text{\%}^2 + ...\text{\%}\right.$$

If pT^* >> 1

$$TW \text{ " } \quad \pm \text{\#}\frac{pT_{\min}}{pT}\text{\&}(+ x/R = \pm 1/pT^{)} + x/R$$

(br)

"Linear"
cylindrical layer (pT^* any)
+
flat layer (pT^* =!)

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p_T measurement

pT selection : from TW to pT

$$\frac{TW}{pitch} = TW_r \frac{''}{pitch} \# \left(\begin{matrix} \% \ \% \\ ',\pm,' \end{matrix} \frac{1}{\&\ \&pT^*} \right) + \frac{X}{R+} + \tan, \; + (2\,D/'')\tan\theta_L \left(\frac{''}{pitch} \right)$$

$TW_{measured}$

cylindrical layer

flat layer

rotation

Lorentz spread

ToP

After the digitization the inverse transformation gives not unique results:

if **$TW_{measured}$ = Nxpitch** we have **N-2 %TW < N**

This observation is the starting point to calculate the threshold of the selection

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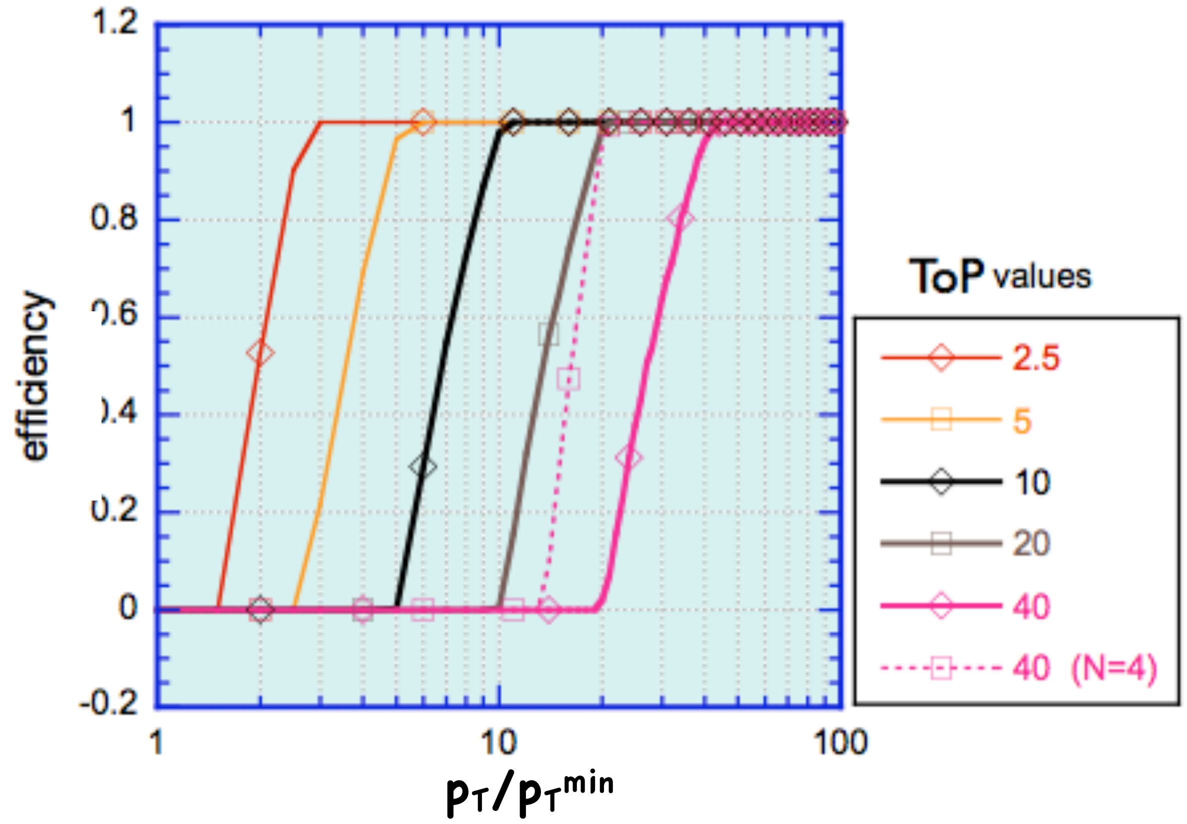
Basic Idea: p_T measure

⤳ Fraction of tracks leaving hits with at least CW~2 pitches

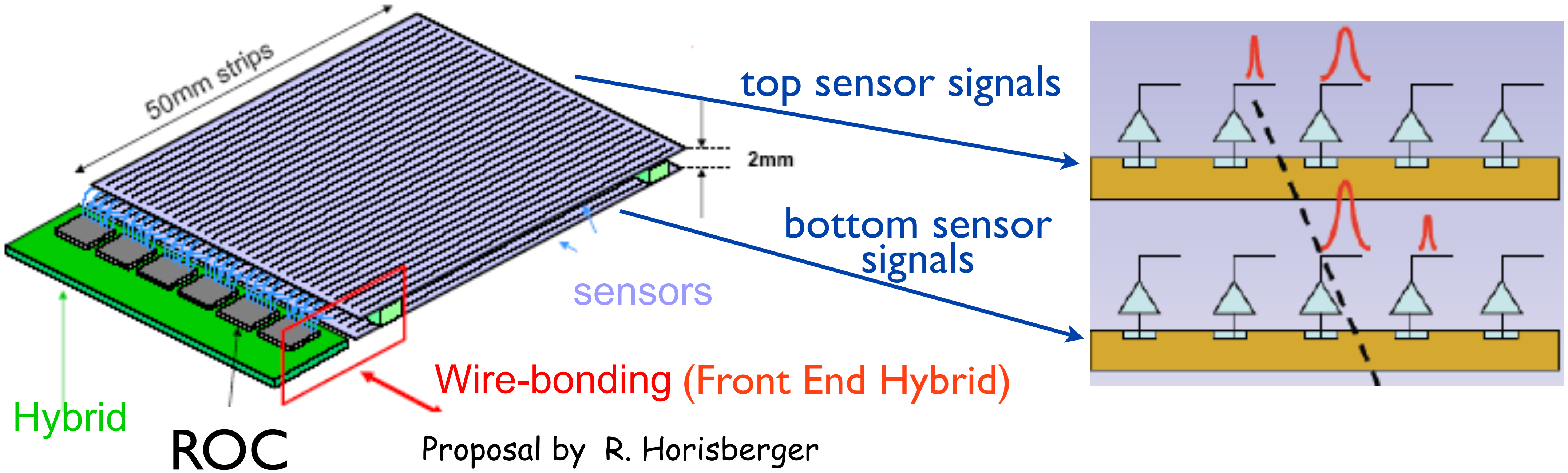


$p_T^{min} = 0.15\ B\ R$

⤳ ToP ratio sets the (p_T) discriminating power of the method
⟹ higher values discriminates larger p_T ranges

(G. Parrini, talk given @ TWEPP2007)

2-in-1 module design

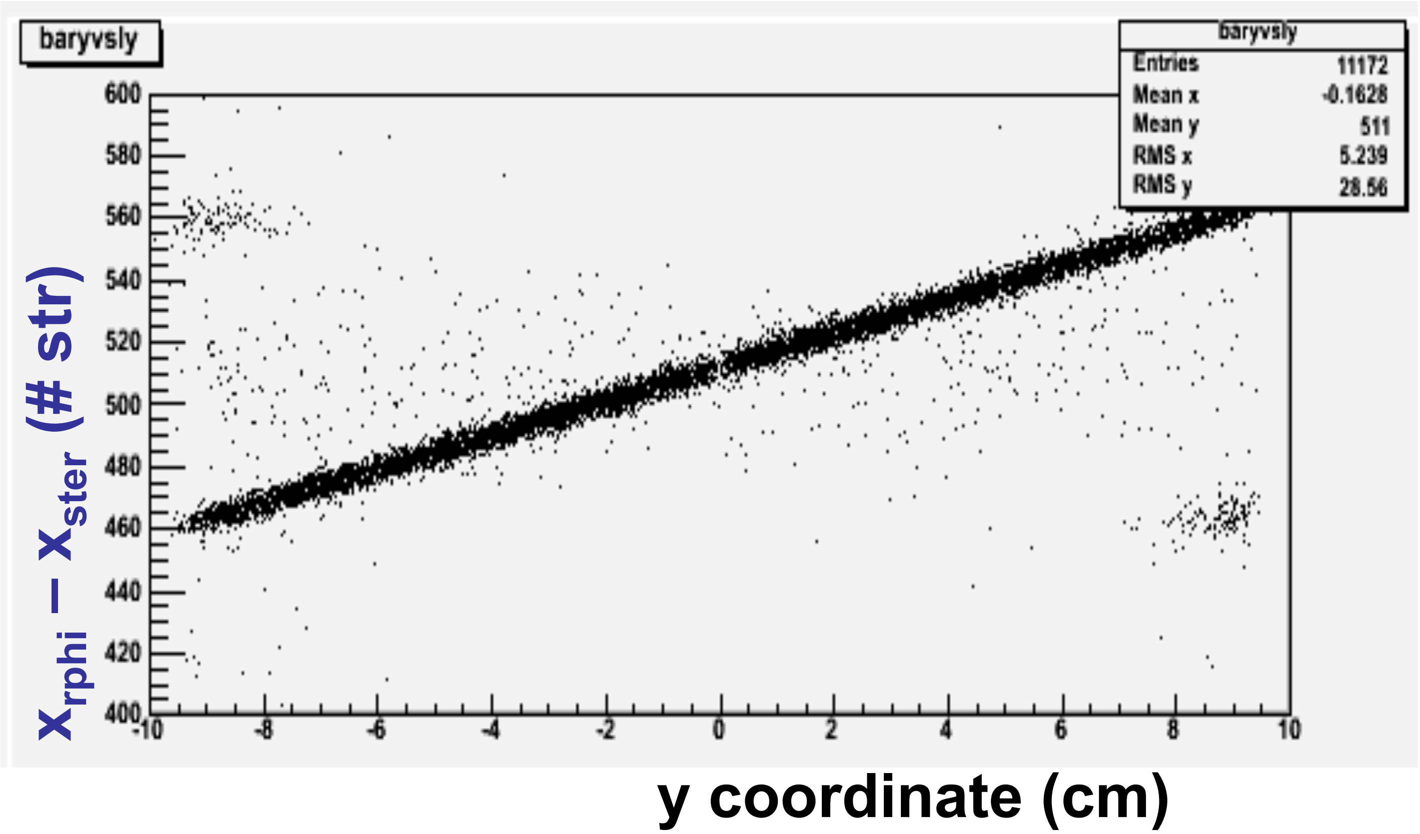


Proposal by R. Horisberger

- wire μ-bonding connects the stacked sensors to a single read-out hybrid
- Two clusters of signals produced per charged tracks
  - >> Correlation between sensitive planes needed (see the various prototypes solutions in next slides)

- The 2-in-1 module design optimizes the common use of:
  - >> ASSEMBLY INFRASTRUCTURES: mechanical, material, ROC, cooling, cabling, ...
  - >> READ-OUT ELECTRONICS: brings to a simple logic to correlate hits, no need of high speed links or external correlation circuits, saving power, ...
- In this way it is possible to maximize the benefit/cost ratio

Tilt Angle Correction

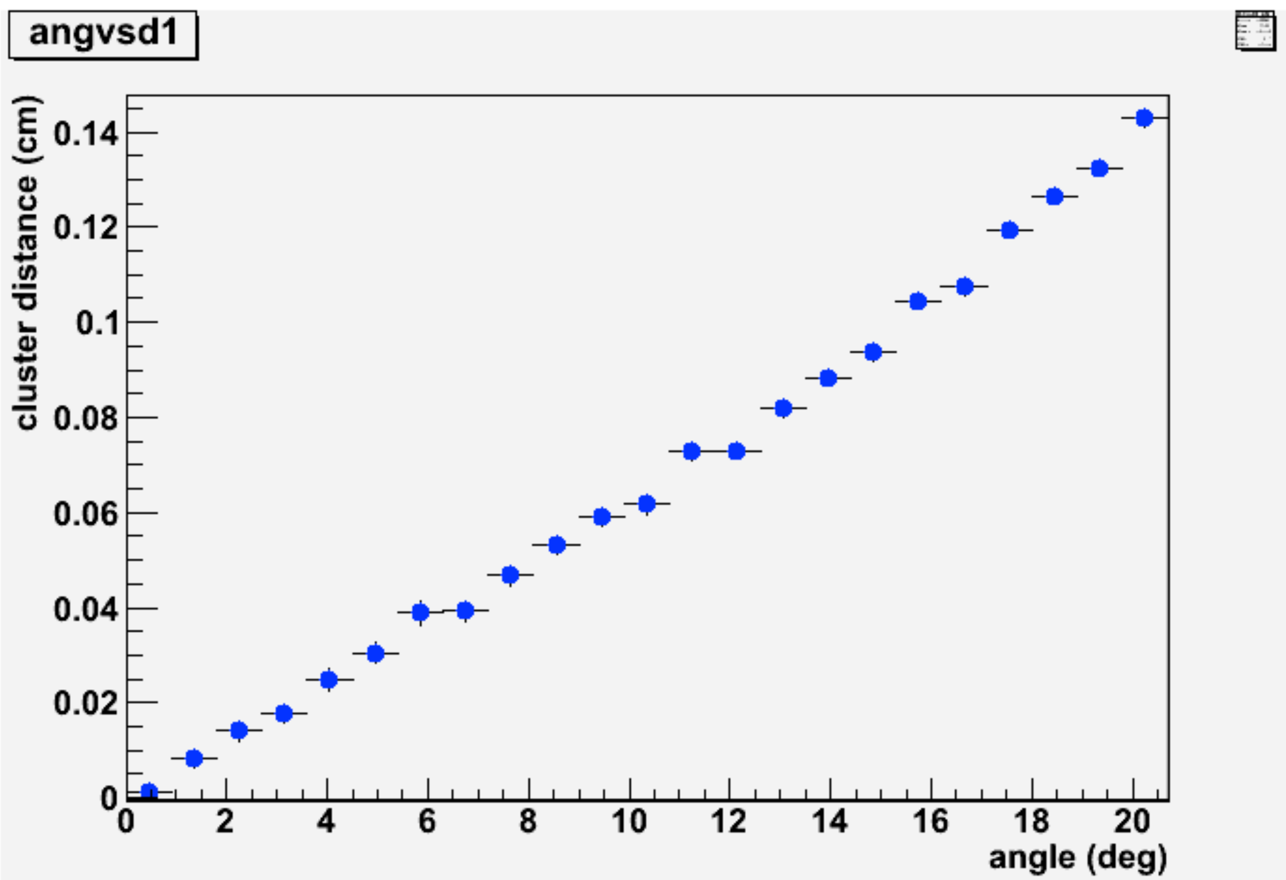


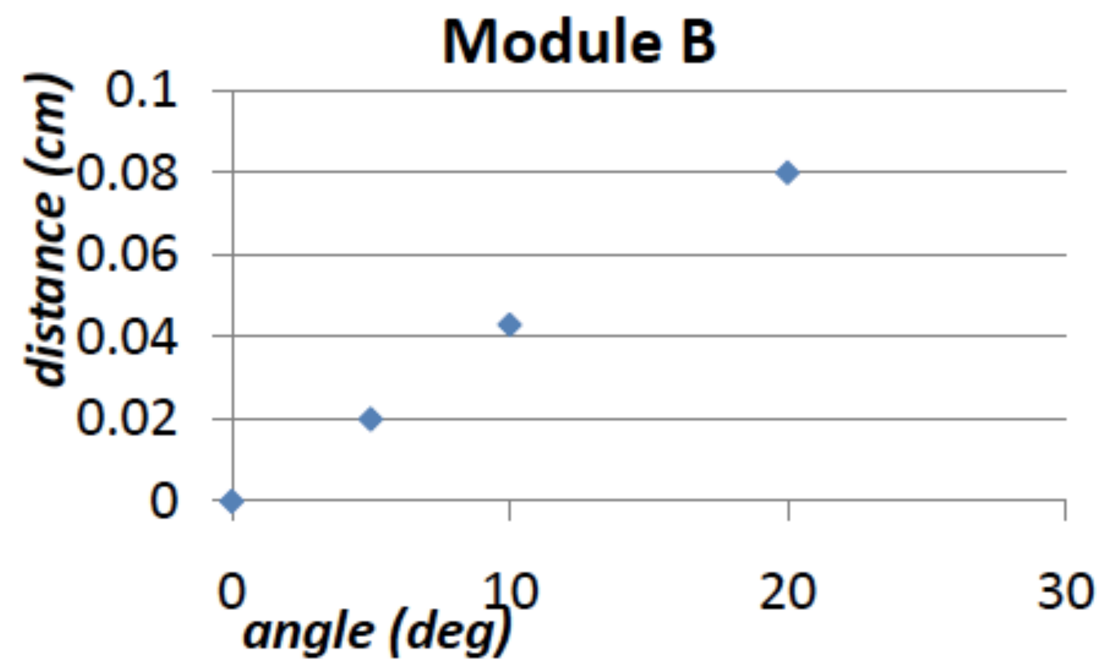
Change of local coordinates: x=A-x'+By

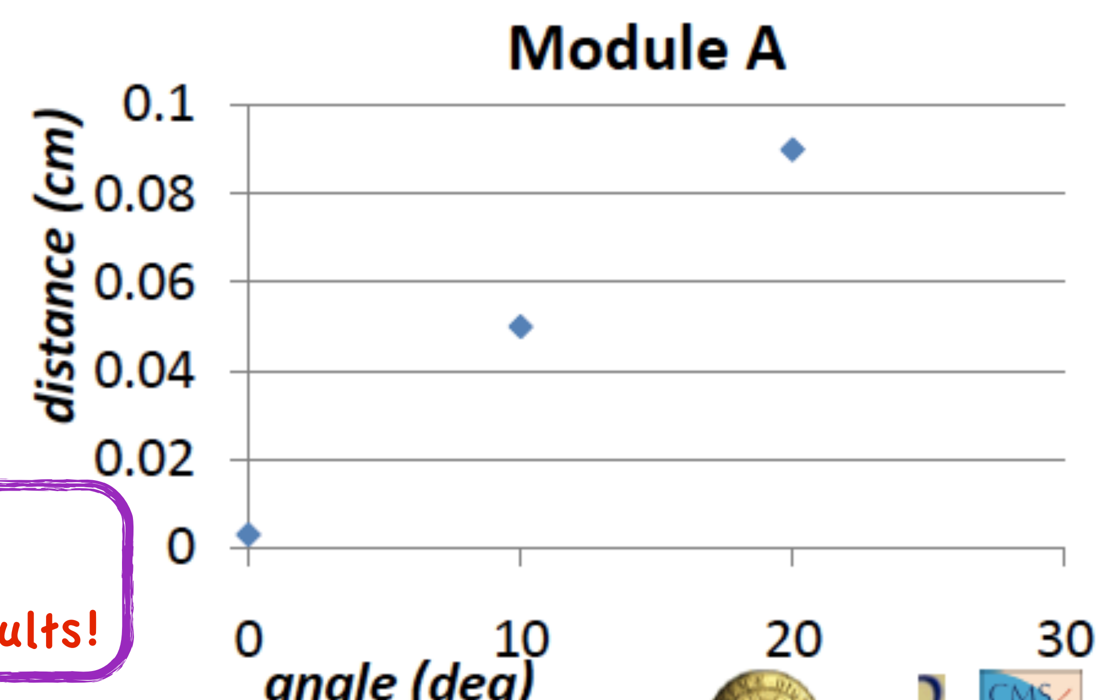
- Plotting the correlation between difference of <u>local</u> X (i.e. pitch position in in the sensor) variables and the global Y variable retrieved by reconstructed tracks it is possible to obtain the transformation matrix to rotate and align strips of the tilted sensor

Comparison CMS\Beam

Comparison with CMS stereo module







- $\Delta R^{test\ beam} \sim 2$ mm
- $\Delta R^{TOB\ CMS} \sim 4$ mm   not directly comparable results!

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