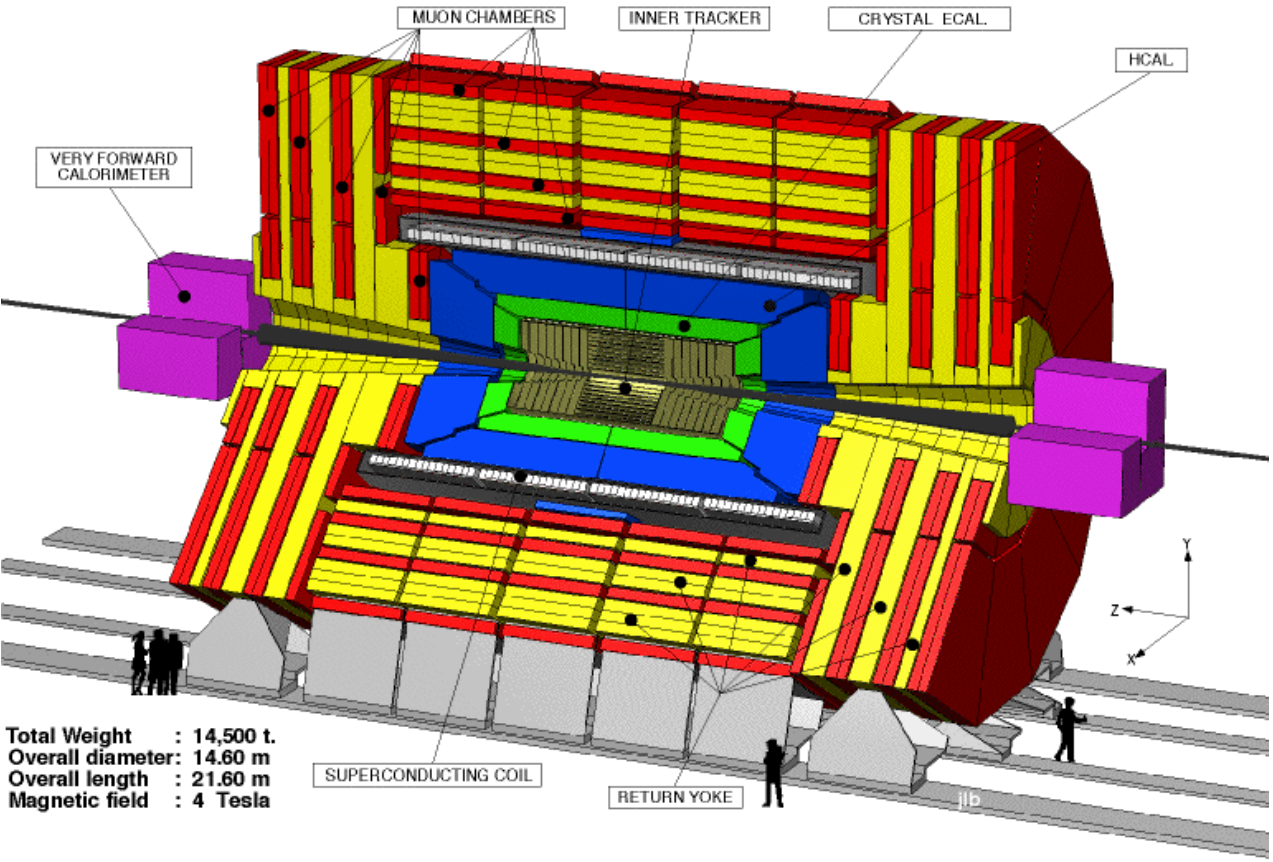
CMS Track Trigger: Tower definition and optimization

Olmo Cerri – September 22th 2016

Supervisor: Luciano Ristori

The Compact Muon Solenoid



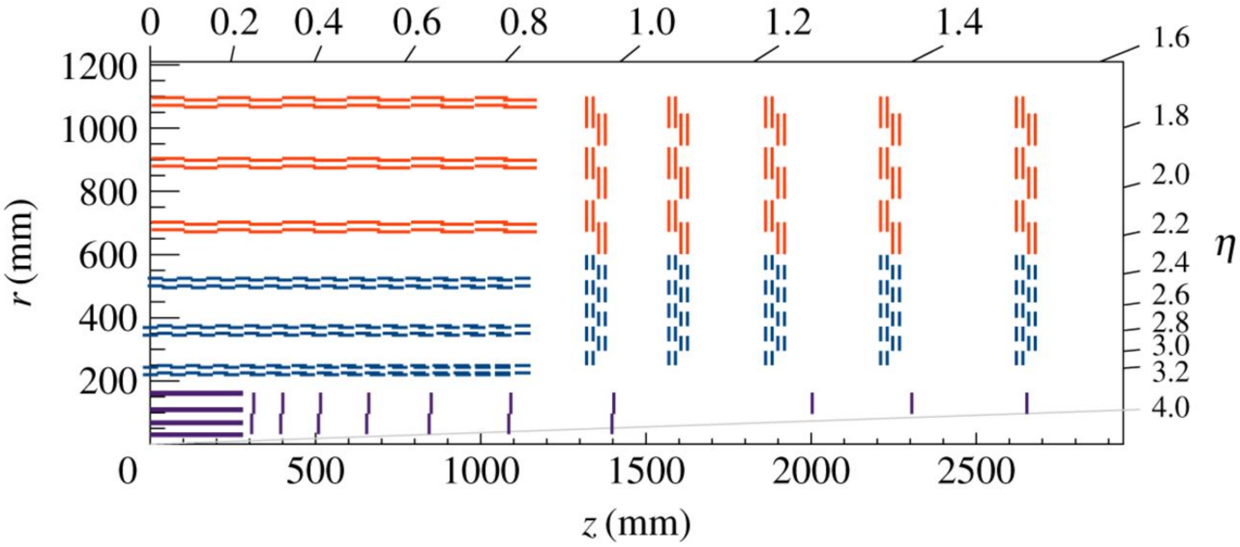
Collaboration:
- 3500 scientist
- 43 countries

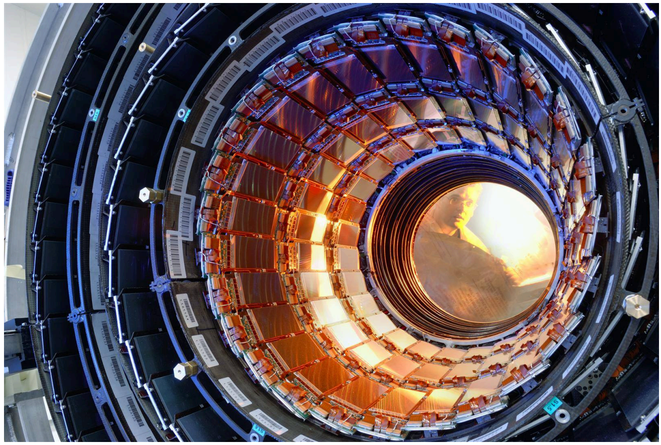
Location:
- Worldwide construction
- Now at LHC – IP8

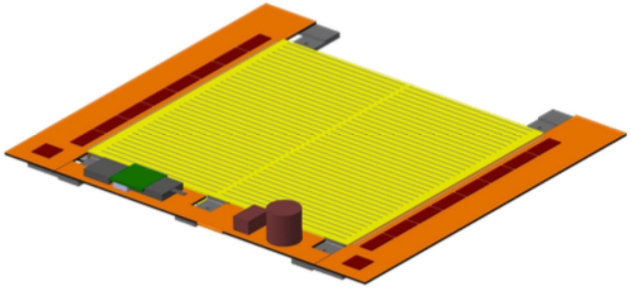
Strength:
- Hermeticity
- Precise measurement of charged tracks momenta
- Particle ID

General purpose experiment:
- Standard Model (Higgs, top…)
- New physics searches: (BSM, dark matter…)

CMS Tracker

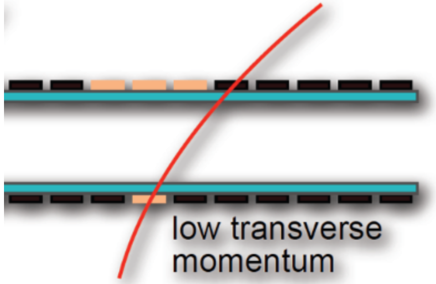




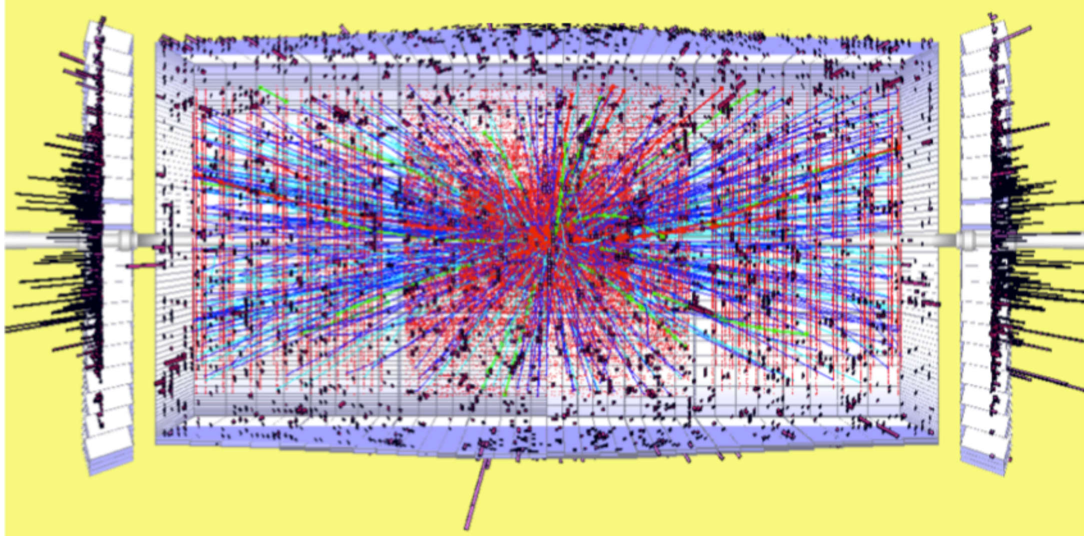


Silicon strip:

- 200 m^2 active area, 9.6 M channel
- 10x10 cm^2 modules
- Strip dimensions: 90µm x 5cm
- 2 strip sensors on top of each other : crude P$_T$ threshold

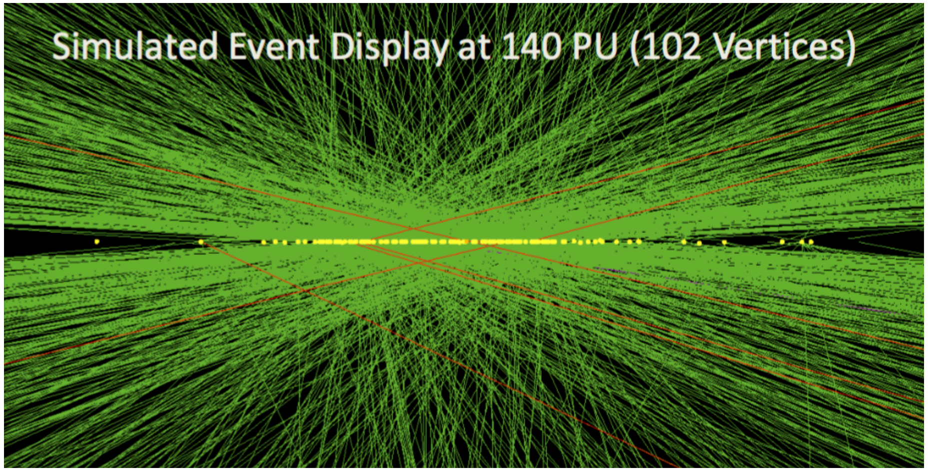


The challnge: HL-LHC



Machine:

- Same tunnel as LHC
- Installation in 2023
- Physics run in 2026
- from 300 to 3000 fb^{-1}
- 25 nm bunch crossing
- $L_{peak} \geq 5 \times 10^{34}\ \text{cm}^{-2}\text{s}^{-1}$



Each event:

- 14 TeV energy
- Up to 200 average simultaneous interactions
- 1000 Tb/s from silicon tracker

Trigger

All data can not be stored at that rate

➡ Trigger: real-time event selection

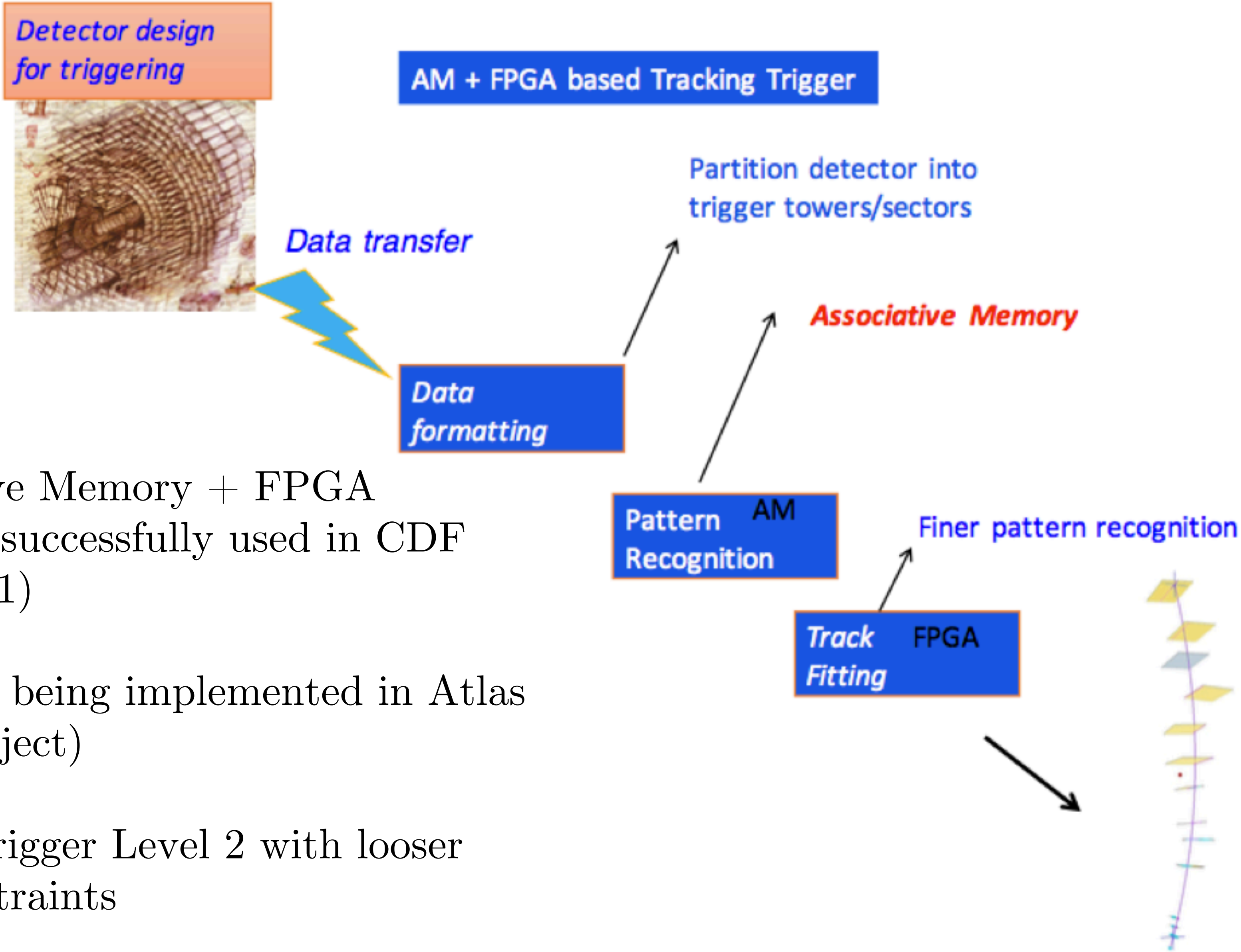
Phase II upgrade goal:

Implement tracks reconstruction in few µs for L1 trigger use

Extremely challenging goal:

- 40 MHz crossing frequency (one each 25 ns)
- ~ 20,000 hits/crossing
- ~ 100 tracks to be identified above 2GeV/c P_T
- Track parameters to be extracted with quasi-offline precision

AM + FPGA approach


Detector design for triggering

AM + FPGA based Tracking Trigger

Data transfer

Partition detector into trigger towers/sectors

Associative Memory

Data formatting

Pattern Recognition AM

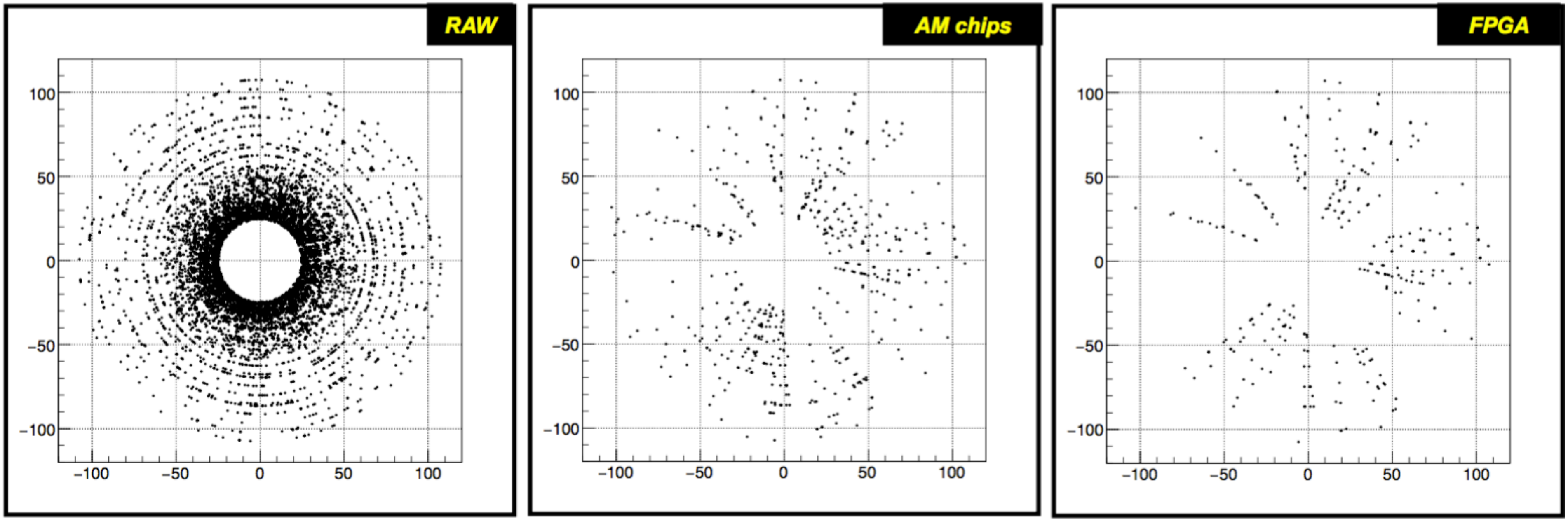
Finer pattern recognition

Track Fitting FPGA

- Associative Memory + FPGA approach successfully used in CDF (2002-2011)
- Currently being implemented in Atlas (FTK project)
- Both at trigger Level 2 with looser time constraints

Simulated example

Stubs → **Matched roads** → **Tracks**

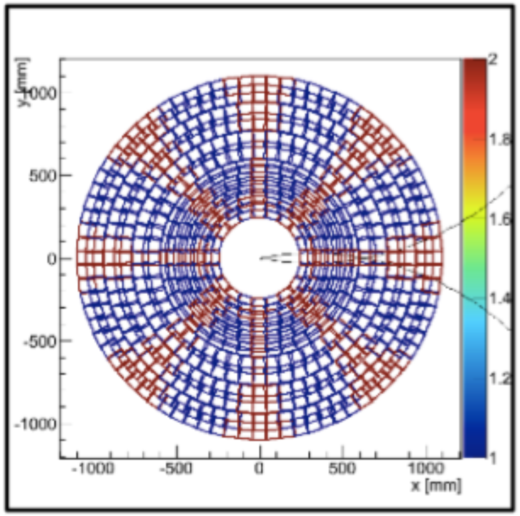


8240 stubs → **532 stubs and proto track candidates** → **281 stubs and fitted tracks**

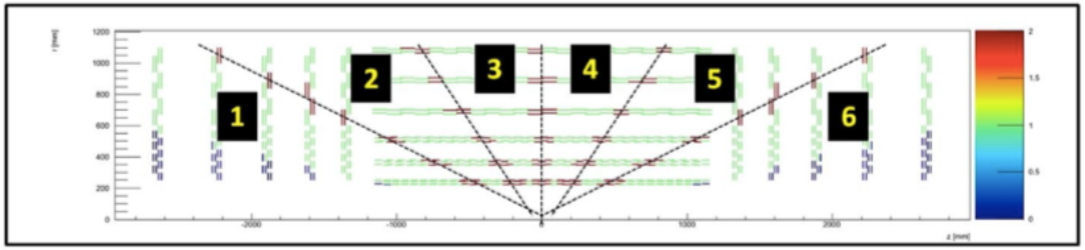
Balancing the workload:

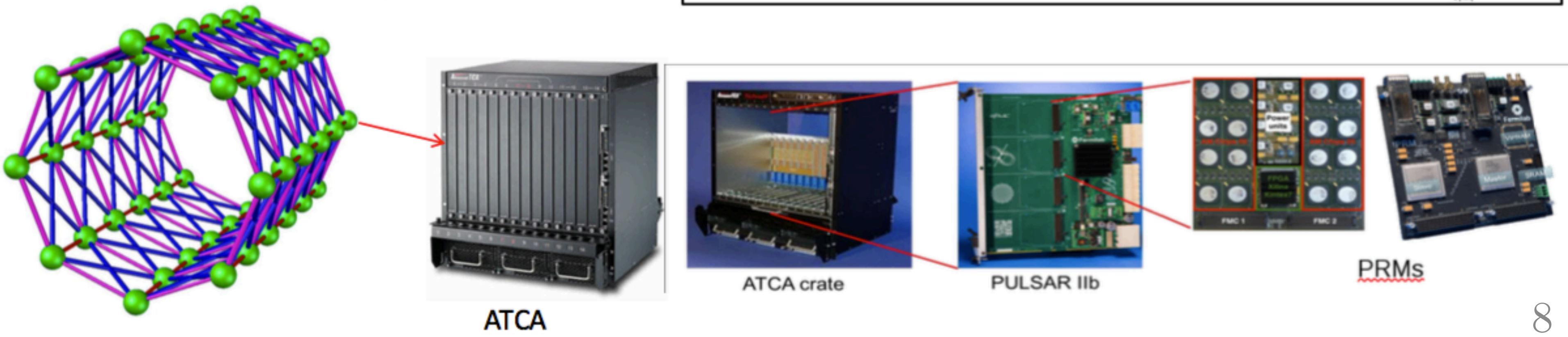
AM Pattern Bank size VS FPGA resources/latency

Divide and conquer



- Detector can be sliced into independent regions (Trigger Towers)
- Each one need its own electronics (ATCA crate)
  - Data collection from front-end modules
  - AM pattern recognition
  - FPGA for track fitting
- 8 region in ϕ and 6 in η
- $=$ 48 towers



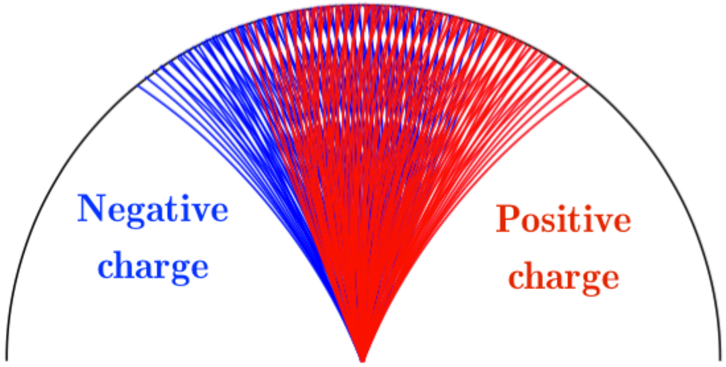


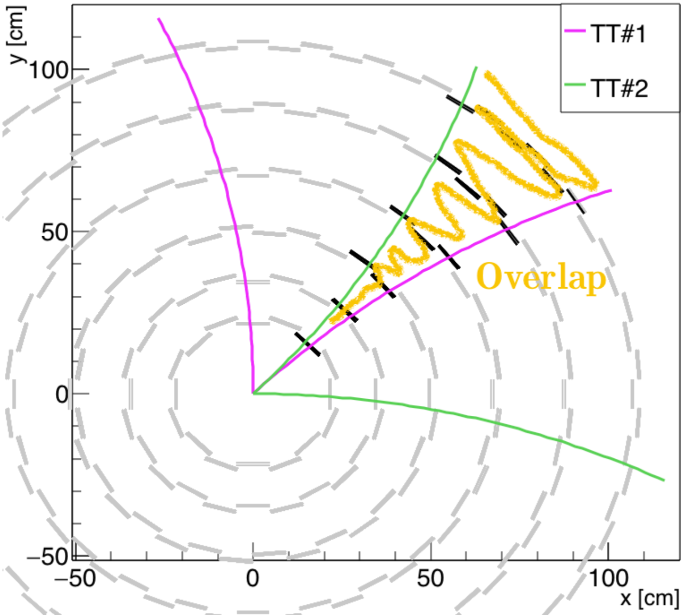
TT definition procedure

- Divide parameter space into 48 non-overlapping regions
- Assign one tower to each region
- Define 48 “training samples”, one per tower
  - Use single muon sample
    - 2π in φ and $\eta = [-2.4, +2.4]$
    - $P_T \geq 2$ GeV and $\sigma_z = 5$ cm
    - Select tracks from one of the 48 regions
- Assign modules to a tower
  - Go through the tracks in the corresponding training sample
  - Add all modules hit by at least one track

TT definition problem

- Track parameter space is 4-dim (q/P_T, ϕ, η, v_z)
- 4-dim region can be conveniently defined by the intersection of two weakly correlated projections: (q/P_T, ϕ) and (η, v_z)
- Disjoint phase-space regions correspond to overlapping physical regions
- Overlap due to track curvature (ϕ) and to finite v_z dimension (η)

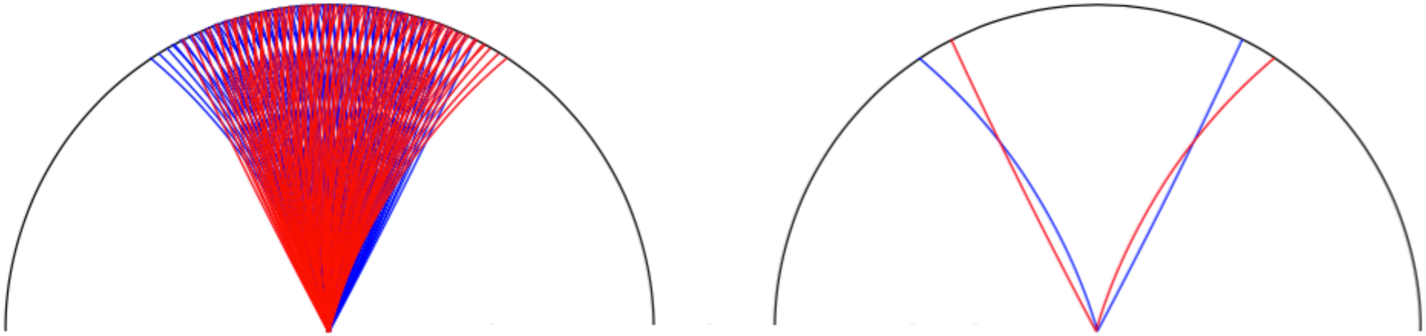




One of the goals is to minimize overlap regions without compromizing acceptance

Minimizing the Overlap

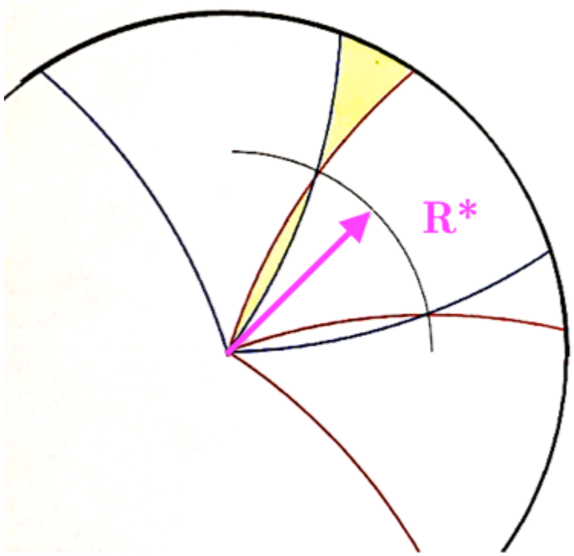
Shift positive wrt negative tracks:



Less overlap needed!

Regions are better defined in terms of $\phi(R^*)$ instead of $\phi(0)$

- Minimize the number of detector modules to be shared among trigger towers

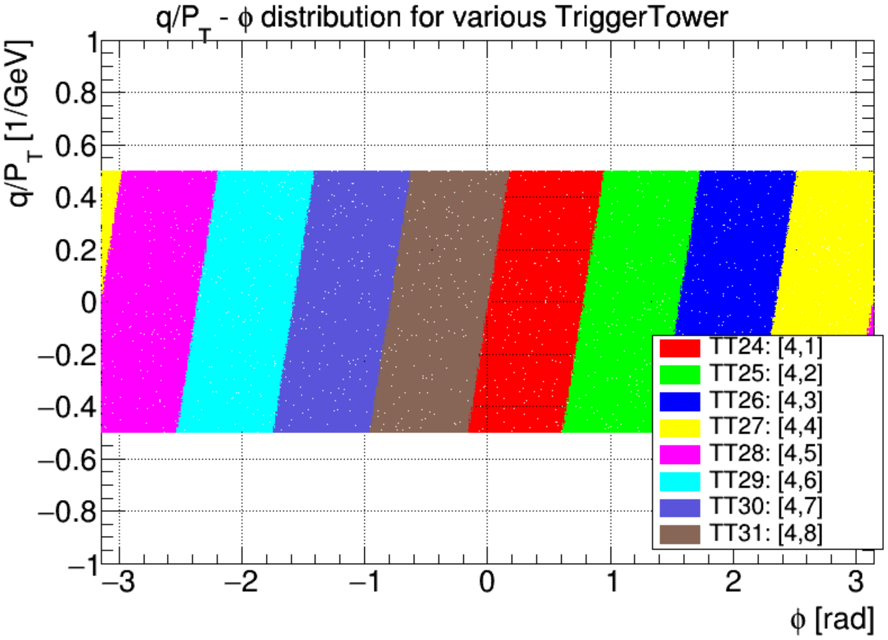


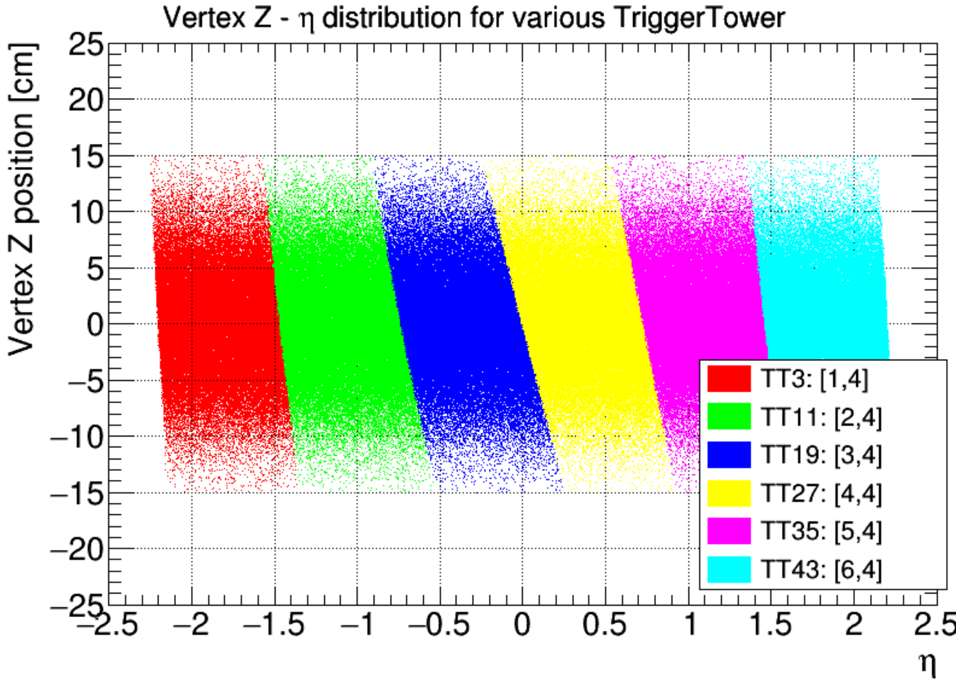
Parameter space regions

- Defined in terms of R*:
  - $\eta^* = \eta(R^*)$
  - $\Phi^* = \Phi(R^*)$
- 8 equal division in Φ^*
- 6 equal division in η^*

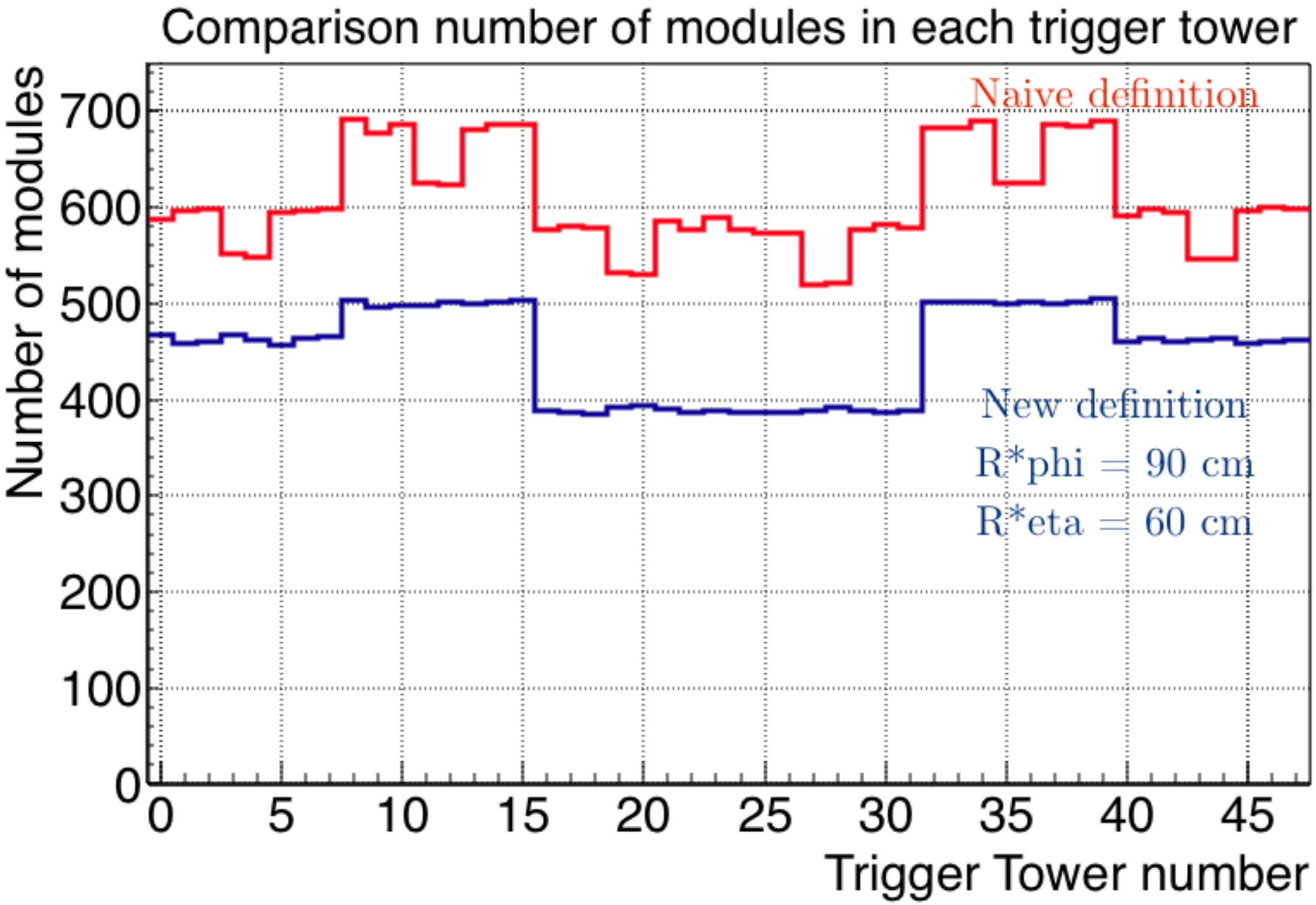
$$\boxed{R^*_\phi = R^*_\eta = 58.89 \text{ cm}}$$

Might be further optimized



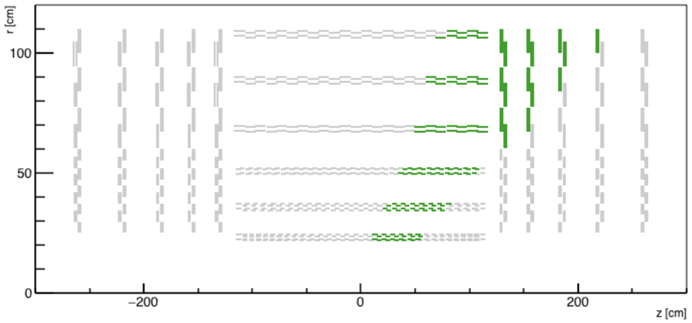


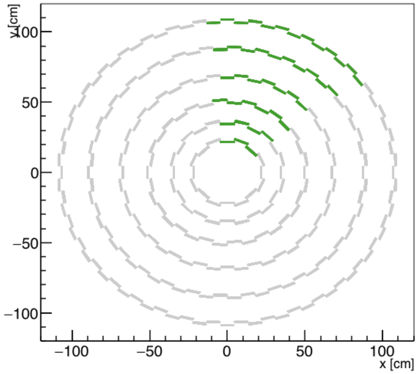
Naïve vs New definition

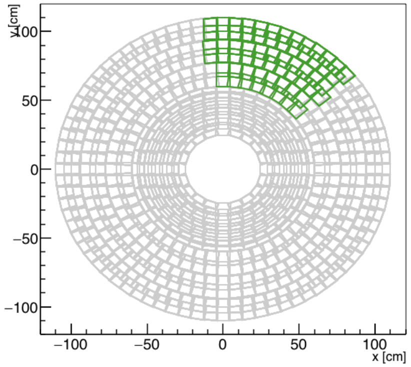


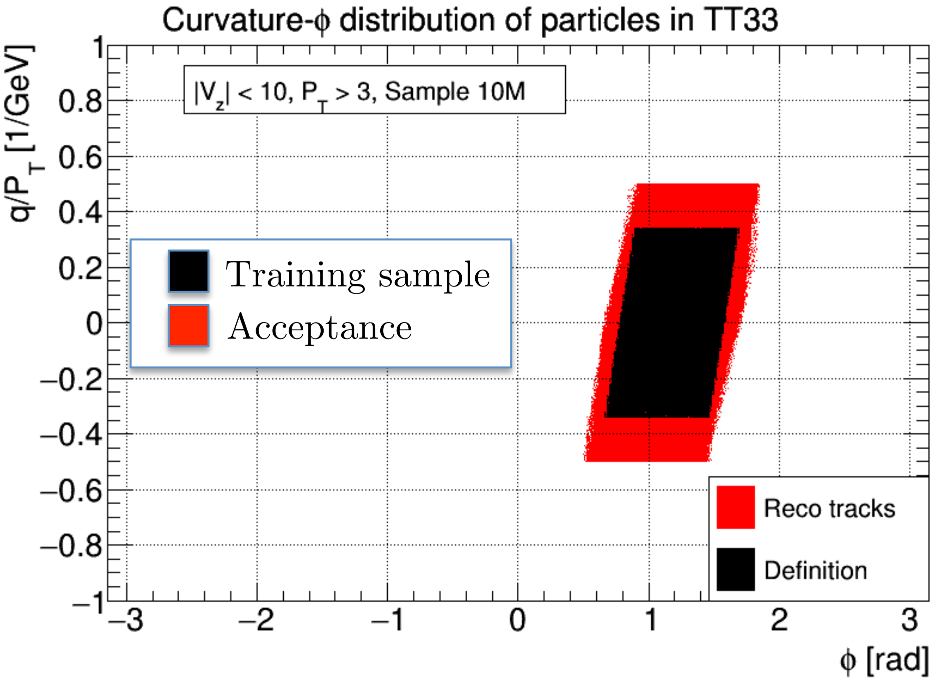
Each tower needs to see 400-500 front-end modules

Intermediate example – TT[5,2]

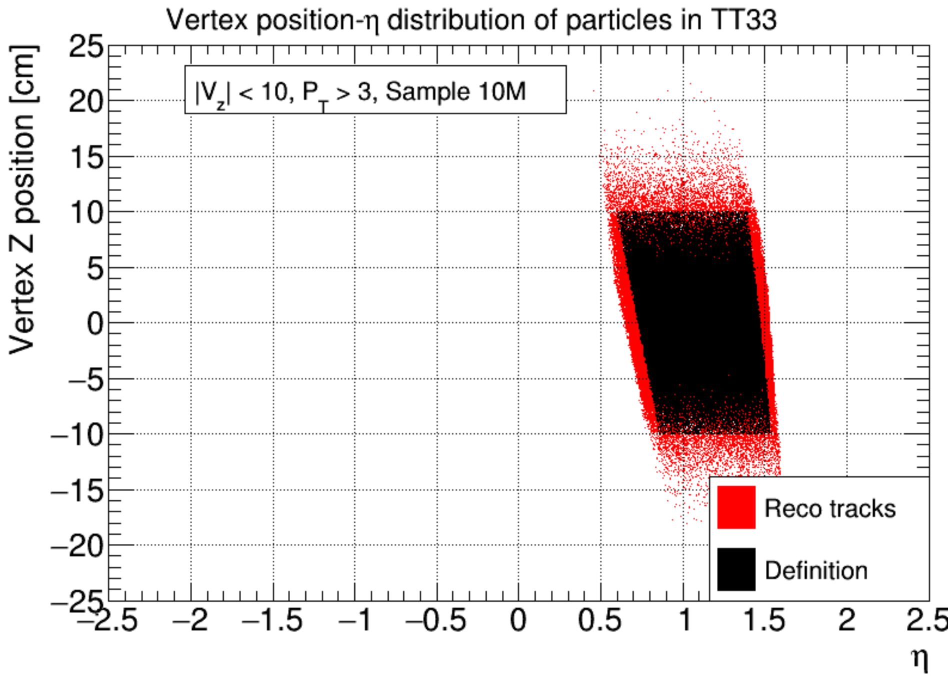






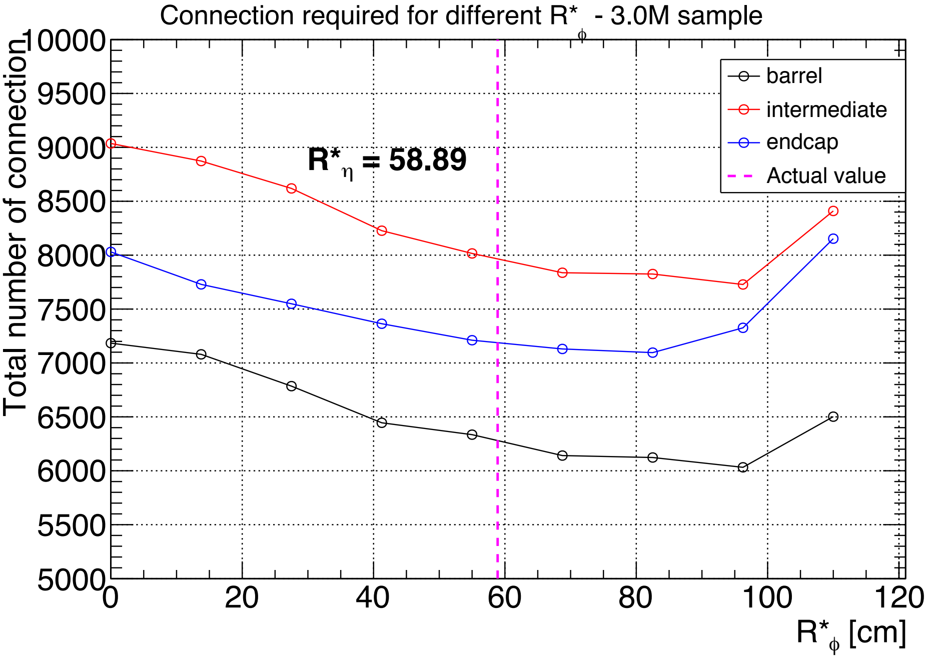


■ Training sample
🟥 Acceptance

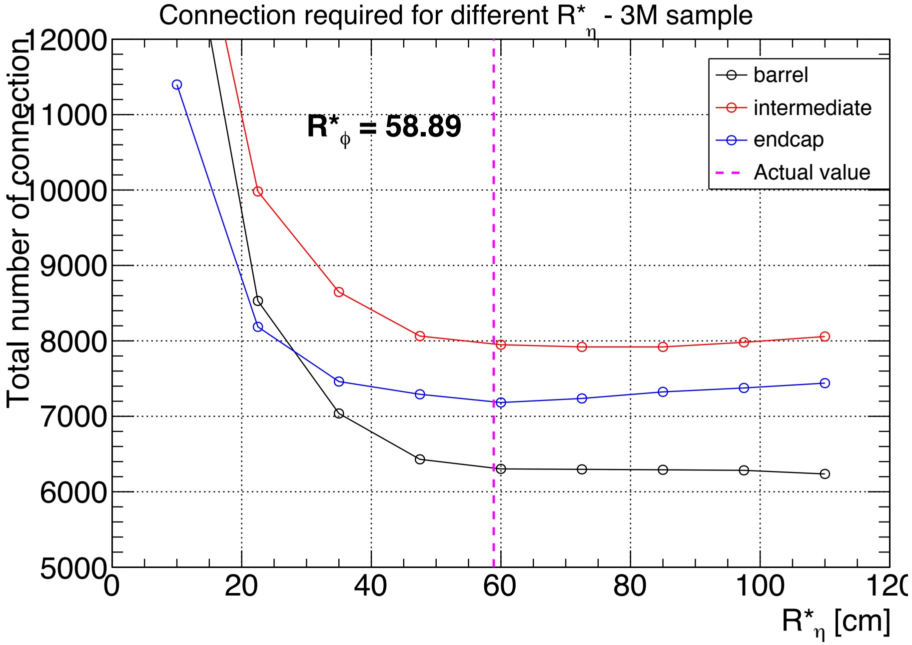


R* optimization

- Optimization parameter: total number of connection between TT and modules
- Barrel, intermediate and forward regions treated separately
- Scan R* in one view for a given R* on the other



$R*_\phi$ can be optimized up to 5%



$R*_\eta$ is already in a minimum plateau

A different R* optimization

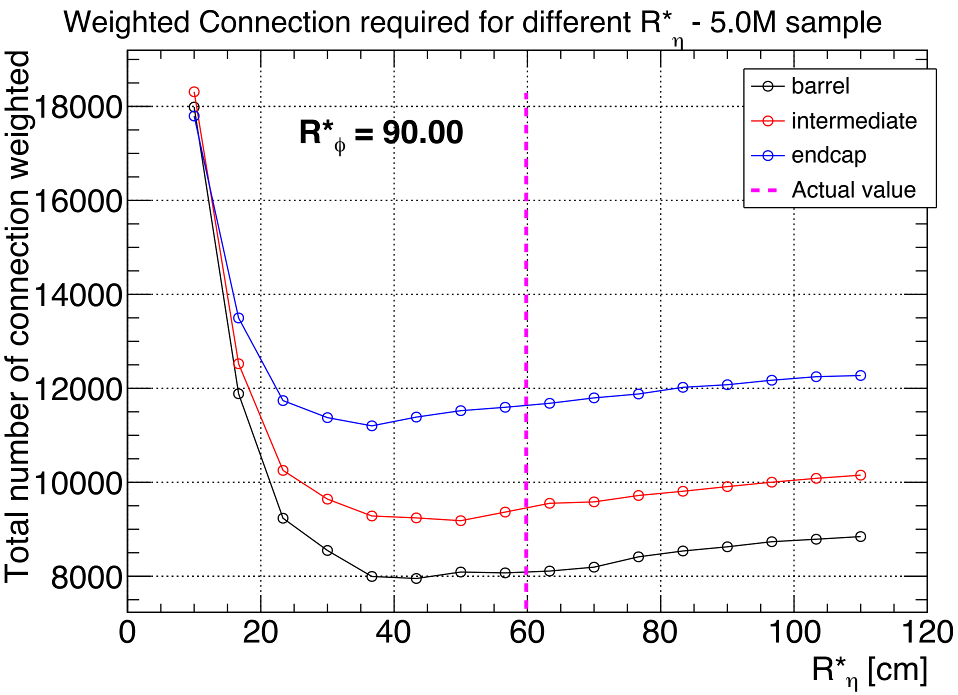
- Number of modules R* optimization:
  - Goal: Minimize the number modules connected
  - High R^*_{phi} are favored because of module dimensions

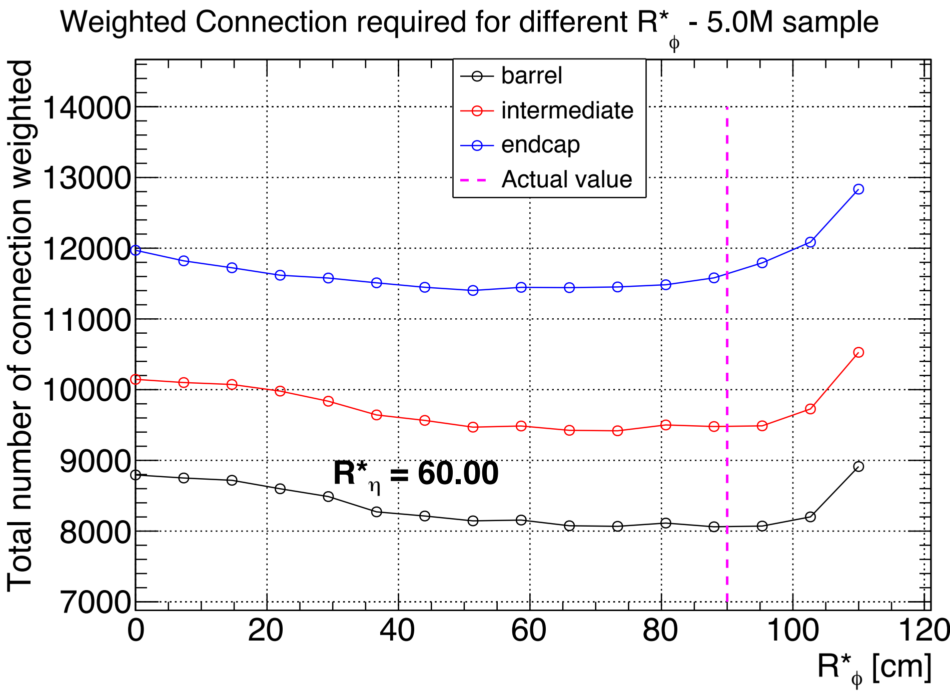
- First study does not take in account that same modules produce a significant larger number of stubs wtr to other ones
  - E.g. inner or forward modules are more likely to be overcrowded by pileup events

- New different study has been done to take in account this effect
  - Each module has to be weighted using the amount of stubs that produce on average
    - ✦ PU only events can be used to establish weights
  - Minimize the sum of the weights
  - Inner and forward modules are disfavored

R* weighted results

Actual values corresponds also
to previous study minimum





- To be compared with slide 15
- Different approach different results
- Minima seems slightly deeper and displaced to lower R*
- To be understand what will be the real bottleneck and which optimization is more useful

Modules per tower - acceptance trade-off

Target:

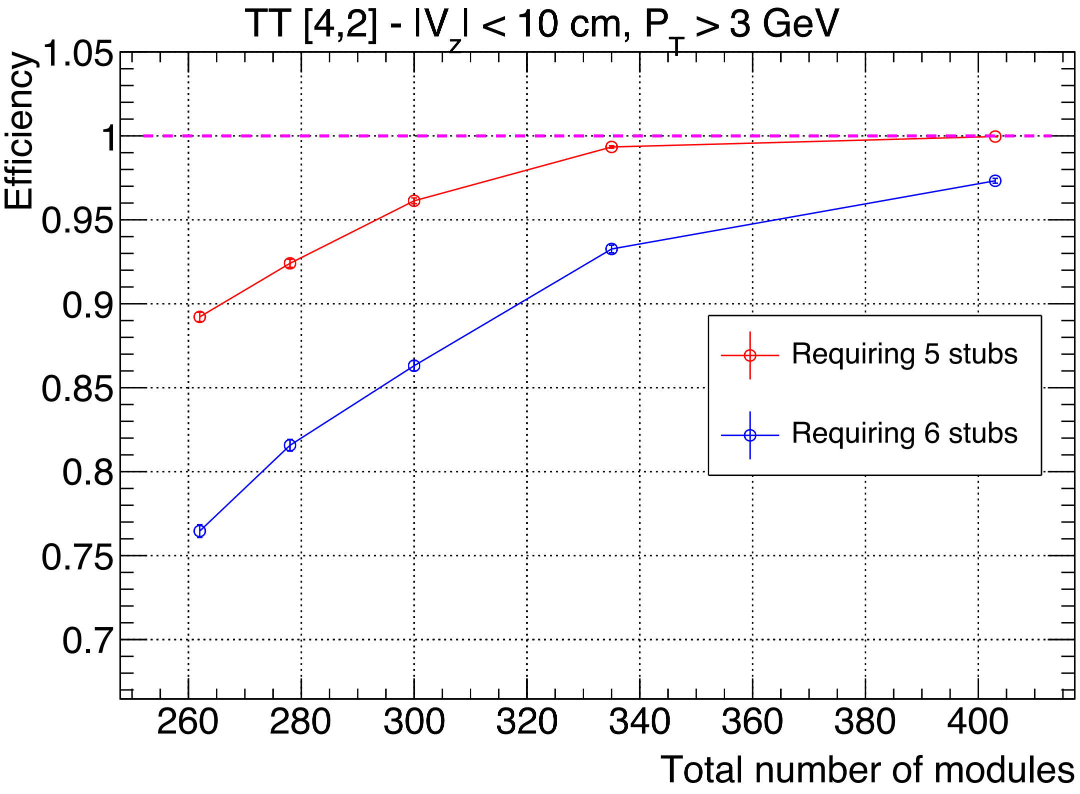
- Minimize the number of modules included in each tower:
  - Remove modules less involved
  - Compromise between acceptance and simplicity

Strategy:

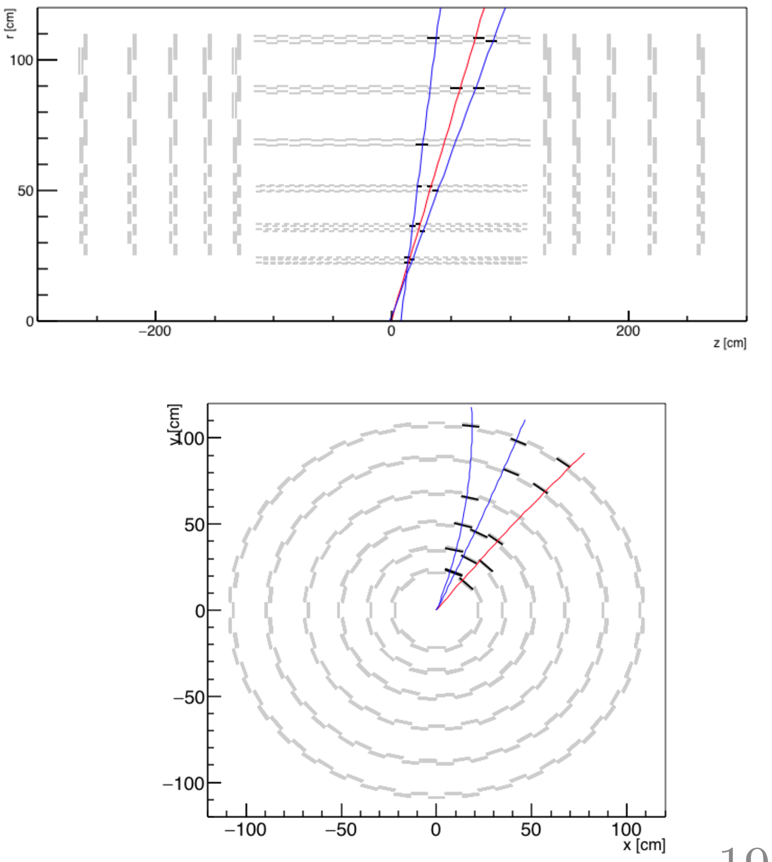
- Inclusive simulation: 4π muons shooting
- For each TT: counters of stubs detected in each module
  - Inside layer: modules sorting by the number of stubs detected
    - For each layer: include modules in TT list following the order and stop when the sum reaches a given threshold
- Compute efficiency:
  - Denominator: all tracks whose parameters fall inside the appropriate phase-space region
  - Numerator: tracks that have at least 5(6) stubs in modules belonging to the TT in 5(6) different layers

Efficiency: Barrel

Thr values = $\{1., 0.99, 0.97, 0.95, 0.93\}$



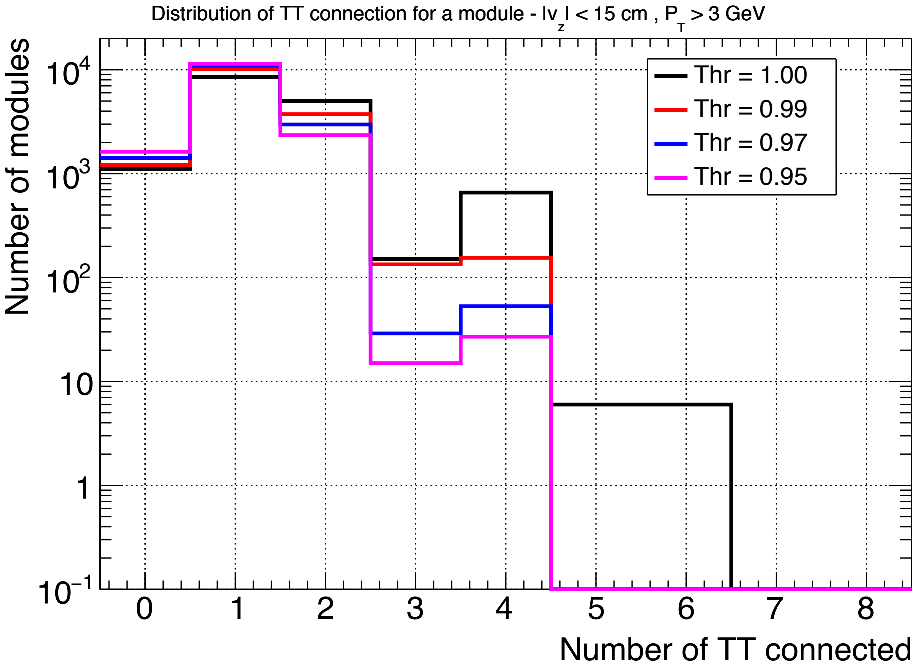
Example of inefficiencies:



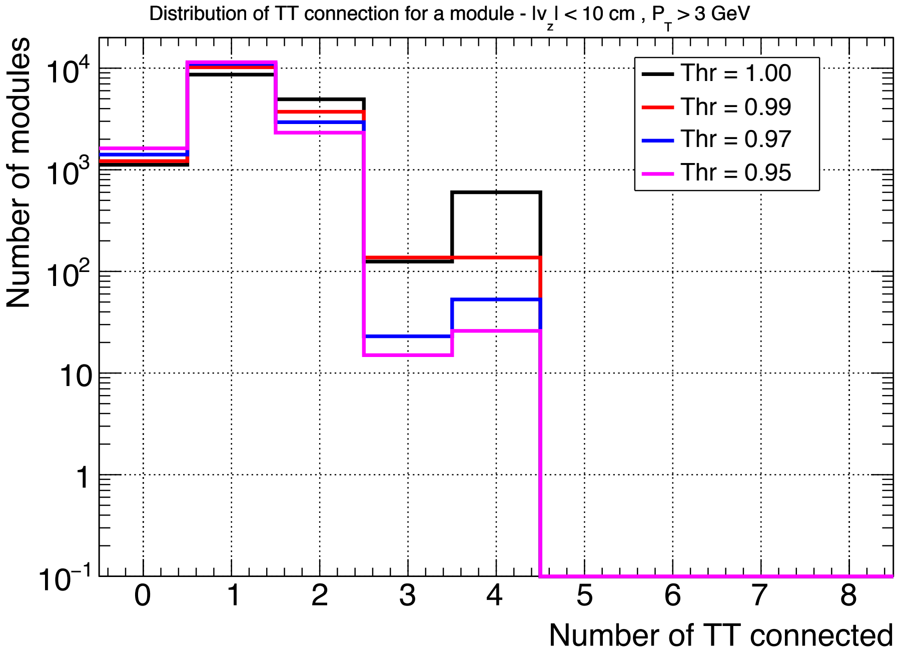
- With 17% less modules, efficiency drop by few percent

Connection per module – Threshold tradeoff

v_z = [-15 cm, +15 cm]



v_z = [-10 cm, +10 cm]



- The distribution remains essentially the same
- Multiple connection can be avoided paying some acceptance

From Parameters to CSV file

INPUT

- P_T threshold
- v_z acceptance
- R^*_{phi}
- R^*_{eta}
- Single Muon sample

FULL SIMULATION

OUTPUT

- TT modules list
- TT physical boundaries on each layer
- Whole detector
- Format: ".csv" file

Current setup:

- $P_T > 3$ GeV
- $v_z = [-15$ cm, $+15$ cm$]$
- $R^*_{phi} = 90$ cm
- $R^*_{eta} = 60$ cm
- 20M Single Muon event (4π generation)

Tracking trigger simulation

- Only for TT25: [4,2] (Old TT27)
- Using current L1TT simulation code + modification (https://github.com/ocerri/SLHCL1TrackTriggerSimulations)
- Pattern bank generation
  - Raw sample of 1G single muon
  - Stub cleaning and sample shrinking
  - Pattern bank generation
- Performance check
  - New vs Old bank size comparison
  - Average number of roads in TTbar + PU140 events
  - Efficiency and resolution

Training sample generation

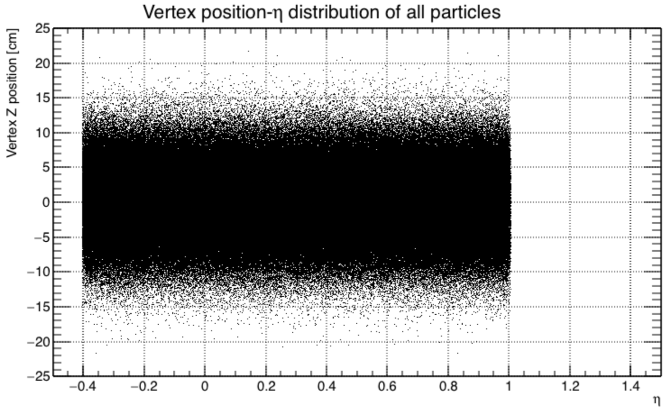
Raw sample:

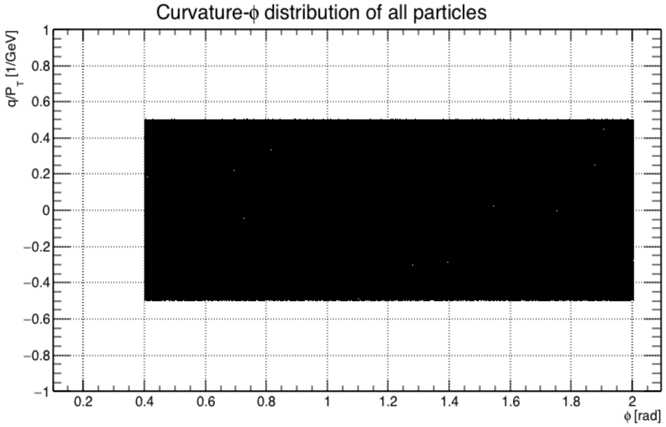
- 800M single muon events
- Wider for future studies

Stub Cleaner
&
Shrinking

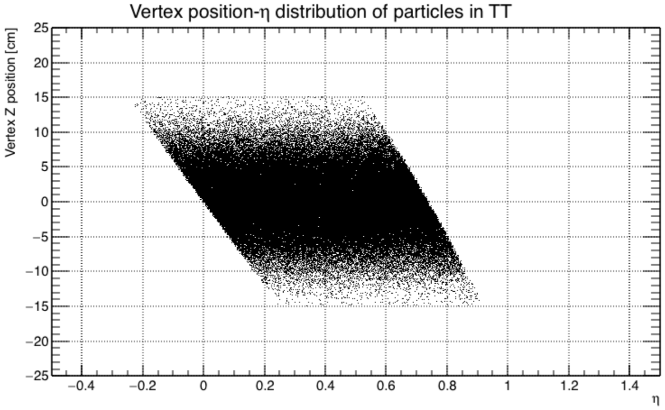
PB training sample:

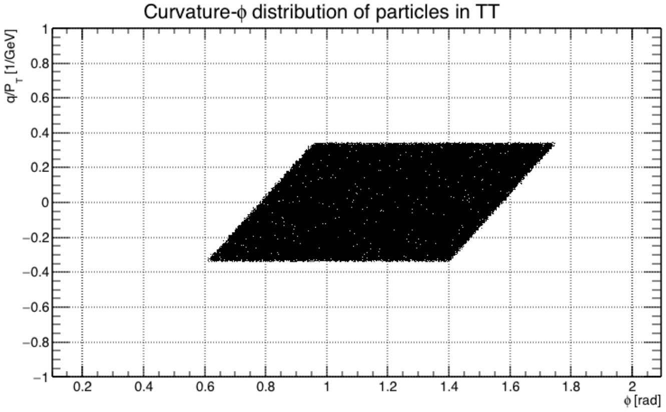
- About 134M muons
- Strict TT25 definition


Vertex position-η distribution of all particles


Curvature-ϕ distribution of all particles

StubCleaner.cc


Vertex position-η distribution of particles in TT


Curvature-ϕ distribution of particles in TT

Pattern bank generation

- Pattern bank training sample effective size: 134M+66M = 200M events
- Super-strips defined using full simulation boundaries
- Generated for 6 different configurations:
  - L5x2 or L5x2_L10x2
  - nz: 4, 6, 8

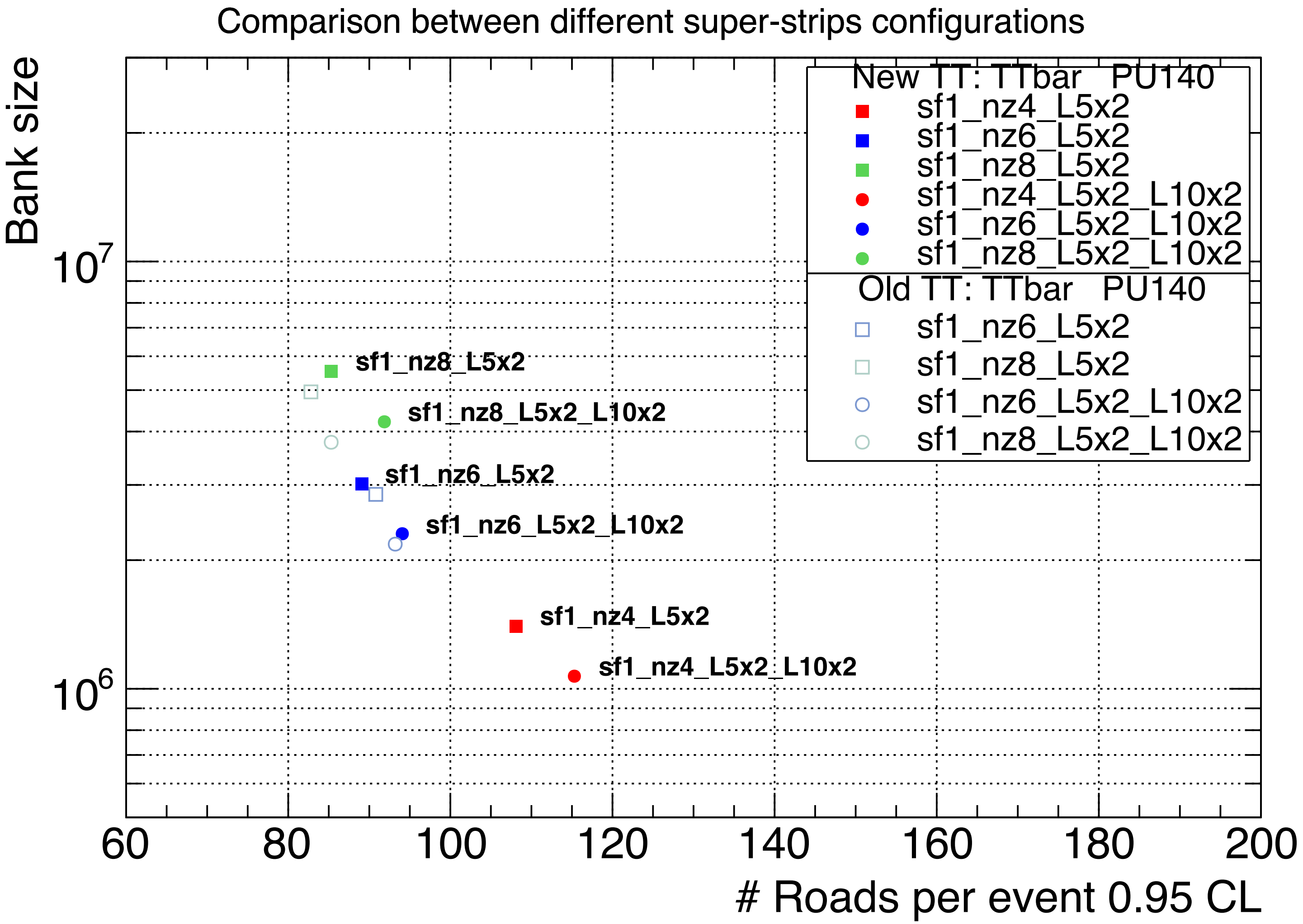
		NEW			OLD		
SSConfig		Bank size 95%	Popularity		Bank size 95%		Diff
sf1_nz4_L5x2		1.40E+06	13		1.31E+06		6.8%
sf1_nz6_L5x2		3.02E+06	6		2.85E+06		5.9%
sf1_nz8_L5x2		5.53E+06	3		4.95E+06		11.6%
sf1_nz4_L5x2_L10x2		1.07E+06	18		1.00E+06		6.9%
sf1_nz6_L5x2_L10x2		2.31E+06	9		2.18E+06		5.8%
sf1_nz8_L5x2_L10x2		4.22E+06	5		3.77E+06		11.7%

Popularity

- nz4: Very Good (about 15)
- nz6: Good(more than 5)
- nz8: Fine (more than 3)

Increase in PB size given by inconsistency fixing (backup for more infos)

Average roads



Old results from *Status of Pattern Bank Optimization* (2016-05-20 Update), Ristori et al.

Efficiency performance

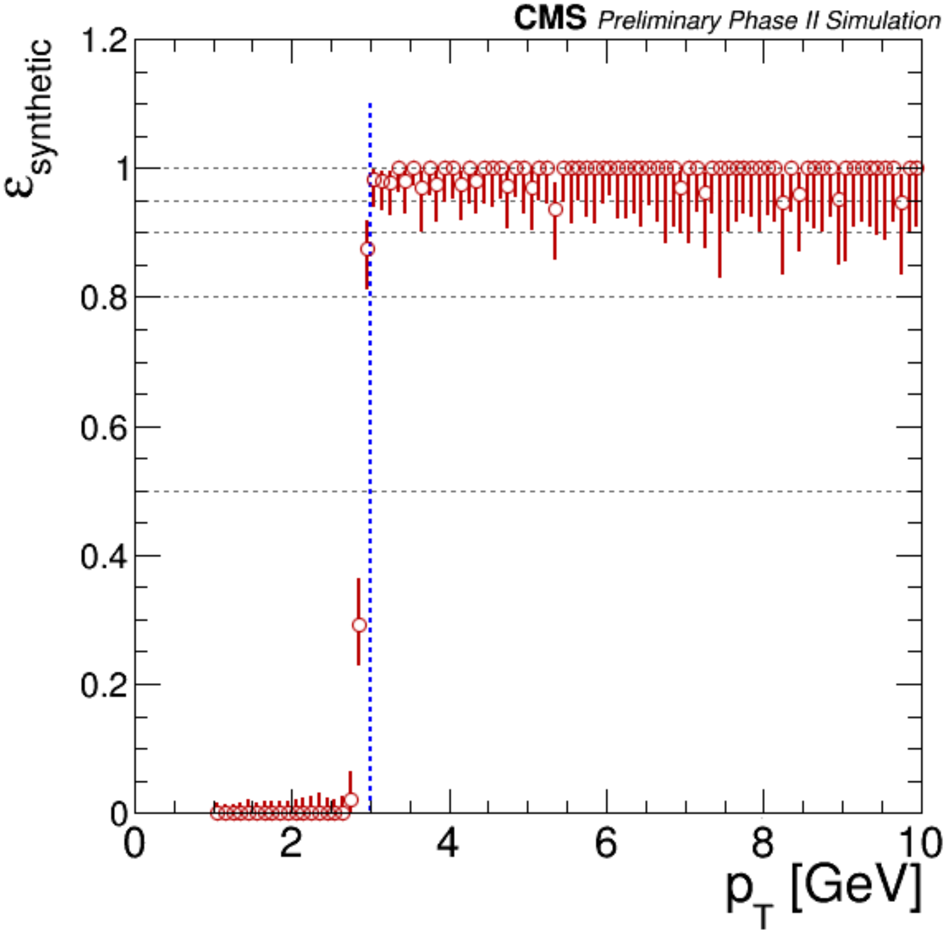
- Goals
  - Test efficiency
  - Effective TT dimensions and turn-on near edges

- Single Muons Test sample
  - Single muons but with delta rays
  - raw 100k events (effective 20k)

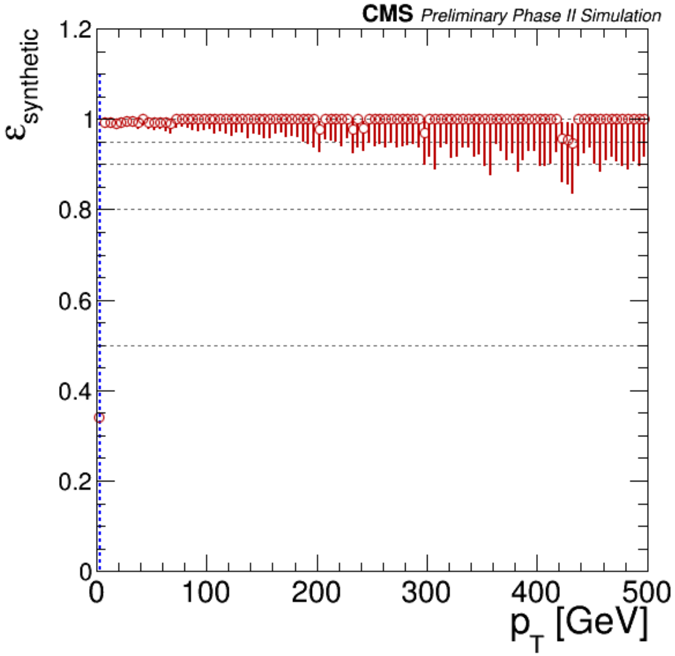
- Denominator definition
  - Global: Tracks inside TT phase-space
  - Binned: TT bound removed in the scanned dimension
    - e.g.: scanning $\varepsilon(p_T)$ denominator tracks must be inside TT phase-space in ϕ^*, η^* and v_z, no cut p_T is applied
  - 1 miss allowed: 5 out of 6 efficiency

Efficiency vs P_T

nz4_L5x2



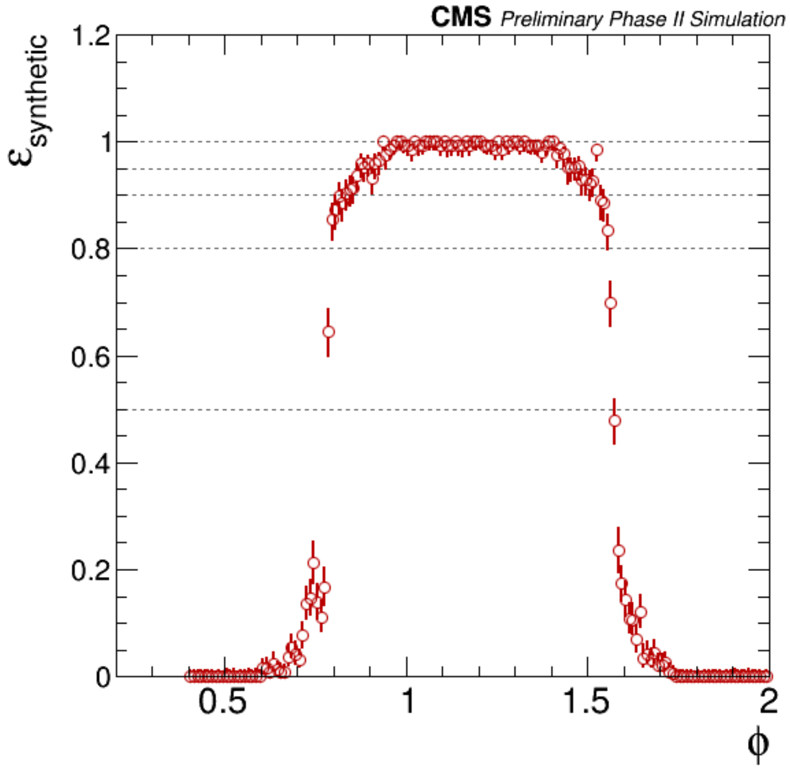
nz4_L5x2

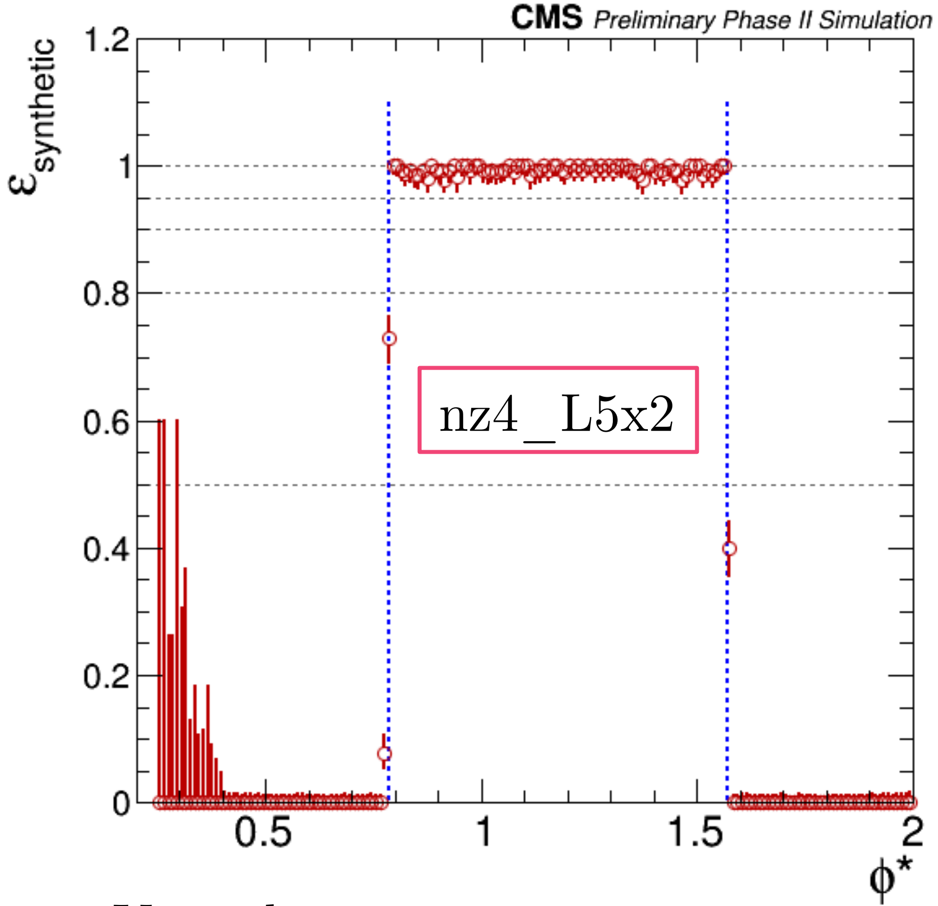


- Sharp turn on
- Average efficiency for P_T>3 GeV 99.2±0.1 %
- No significant differences for nz6 and nz8

Efficiency vs ϕ^*

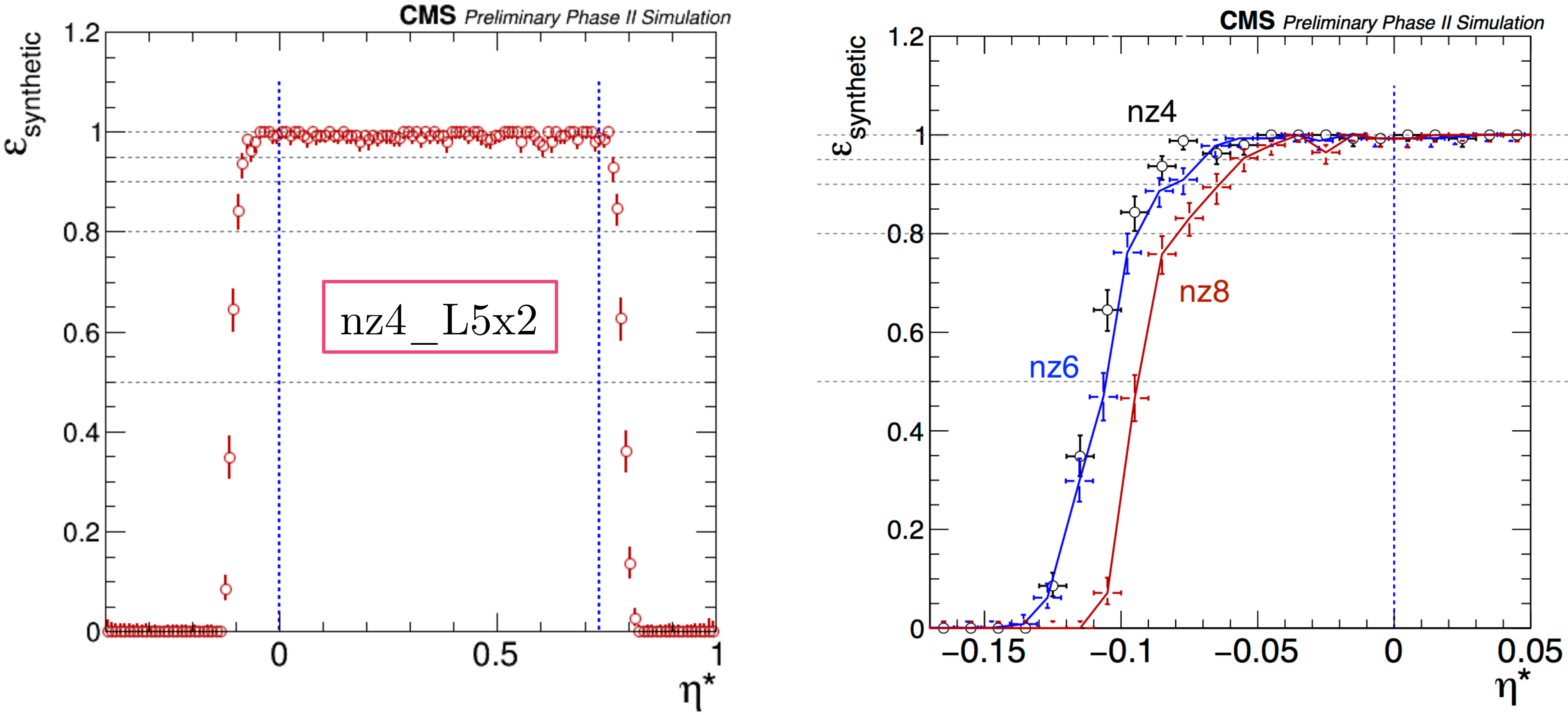
- Blind variable ϕ^* (used to define TT)
- nz4 shown (no significant differences for nz6 and nz8)
- ϕ profile in agreement with expectations (see slide 12)





- Very sharp turn on
- Average efficiency inside TT: 99.2±0.1 %
- Null efficiency outside TT borders (no duplicates)

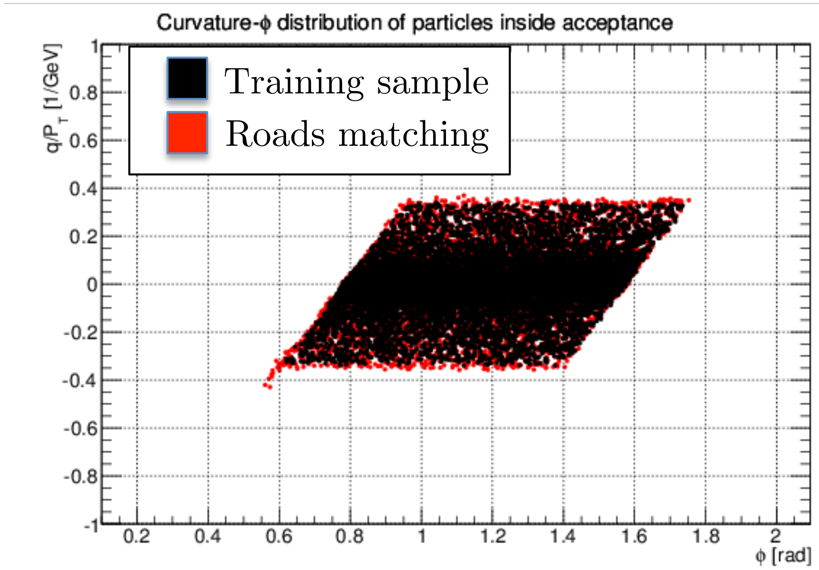
Efficiency vs η^*

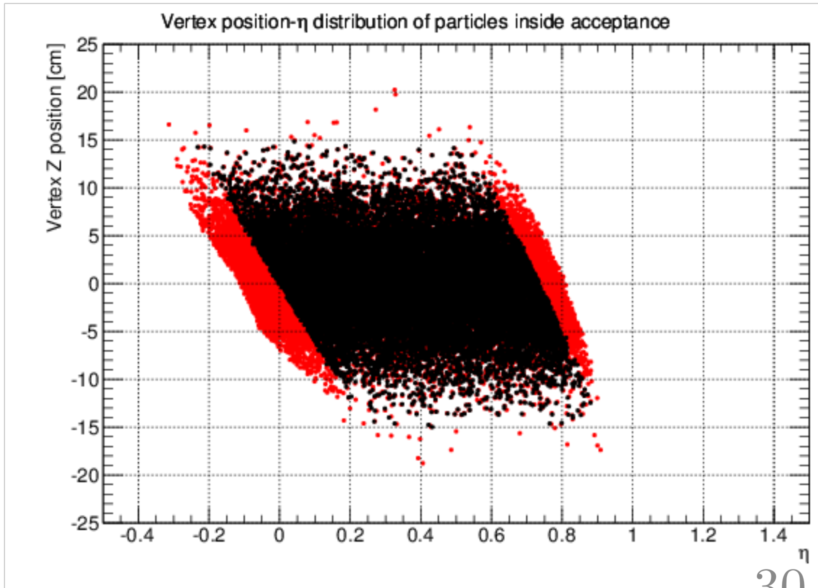


- Early turn on, effective efficiency wider than definition
- Average efficiency inside TT: 99.2±0.1 %
- Turn on dependence from SS configuration

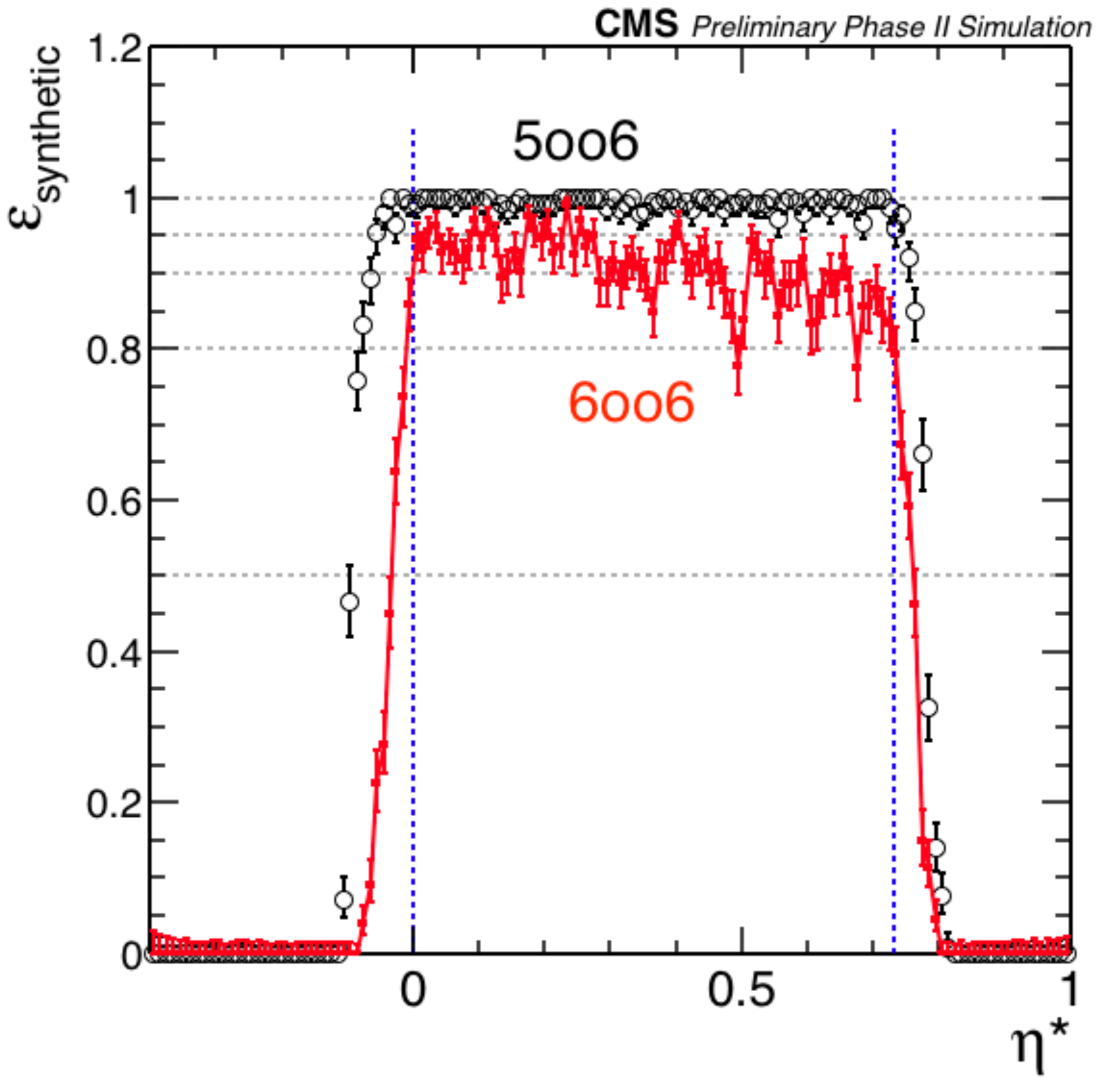
Outside track roads matching

- Particle outside TT definition match roads:
  - Super strips are defined taking the maximum range of interesting particles on TT
  - A single training particle does not lay on the border of every layer
    - Outside particles can do that!!
- Pattern bank acceptance is broader than training sample
- Dependence from SS dimensions
  - Happens in ϕ too but it is far smaller



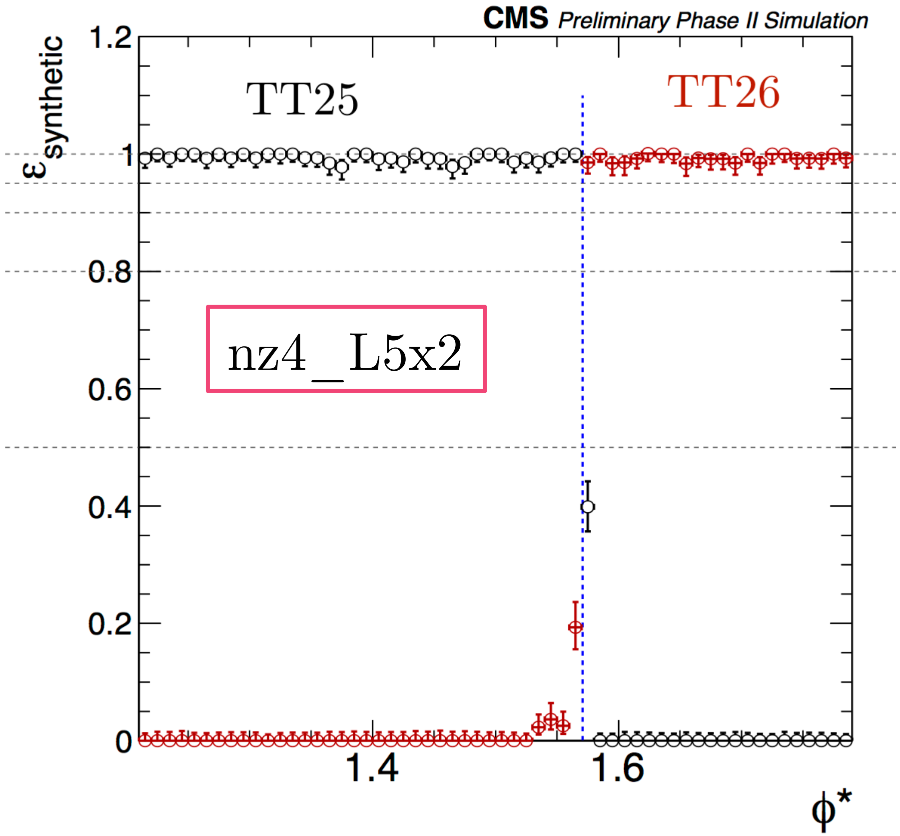


Efficiency vs η^* 6oo6



- Sharper turn on w.t.r. to 5oo6
- Average efficiency inside TT: 90.8±0.3 %
  - PB 95% cut
  - Si efficiency = 1
- Module geometry effect
  - Efficiency drops
  - Slope towards high η

Efficiency near borders

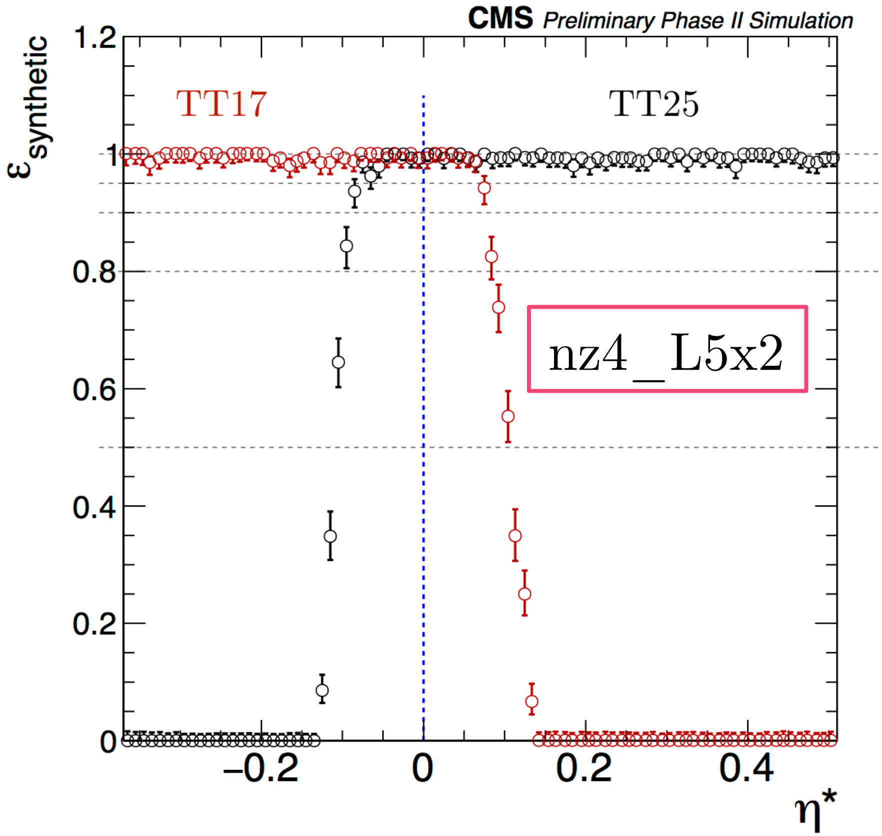


ϕ border :

TT25 = [4,2]

TT26 = [4,3]

TT24 same



η border :

TT25 = [4,2]

TT17 = [3,2]

TT33 in progress

No edge issues!

Conclusions

What has been done:

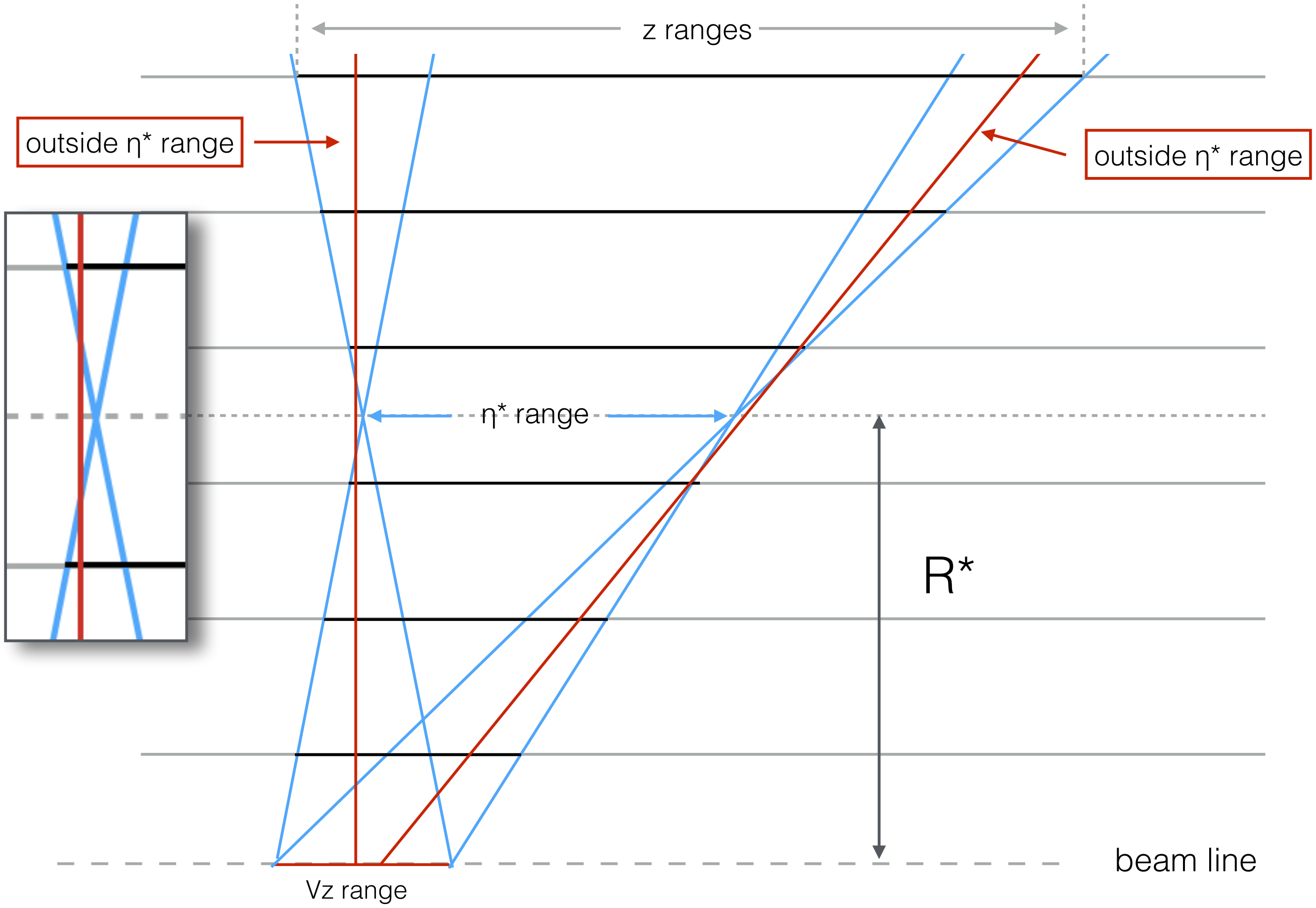
- Study of a new definition of trigger towers
- Optimization of the R* value
- Efficiency – number of modules trade-off
- Production of new module lists
- Generate AM pattern banks for the new towers
- Make the new towers and the new AM pattern banks available to the full trigger simulation
- Run the full simulation to evaluate new performance parameters
    - Efficiency, Resolutions...

Thank you all!

BACKUP

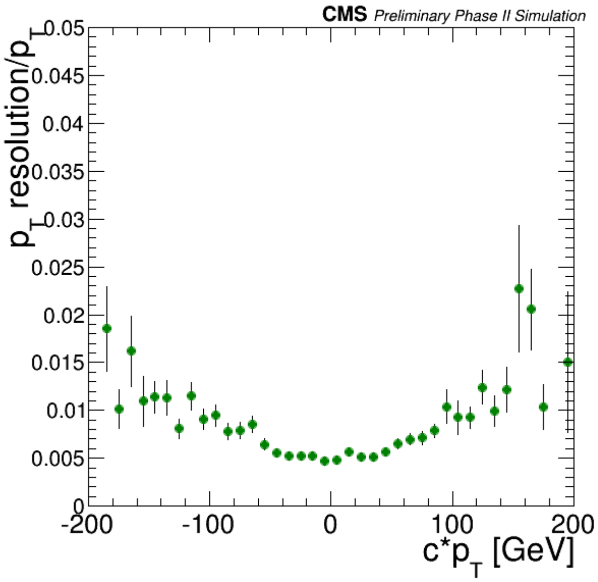
Out TT track example

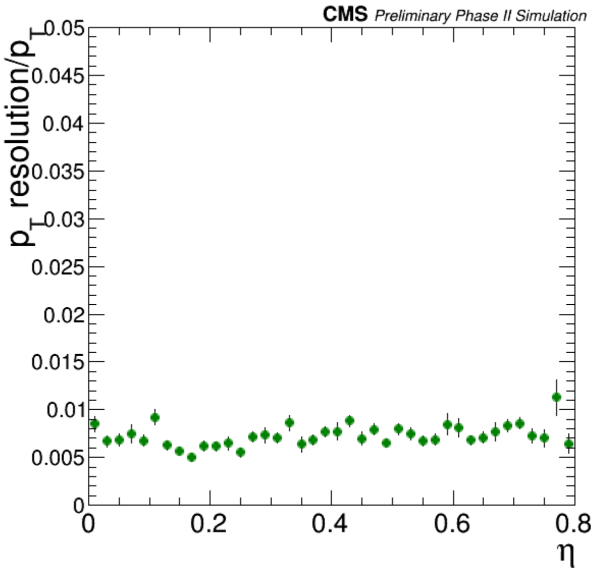
- Tracks outside TT definitions may match roads if are near border because of SS finite dimensions
- Intrinsic duplicate generation
- Less impact on 6 out of 6

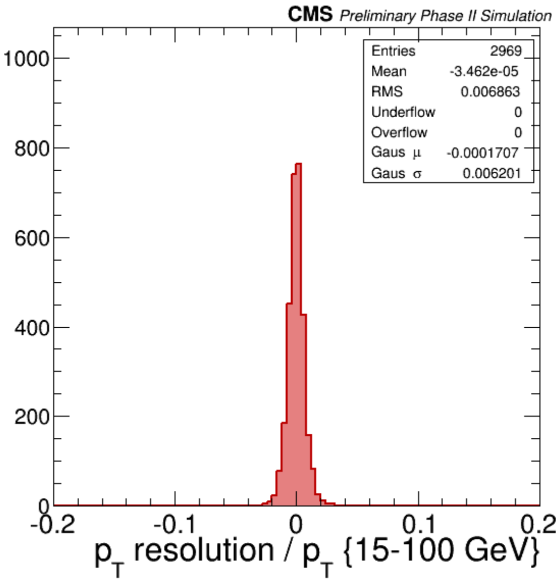


Resolution

nz8_L5x2

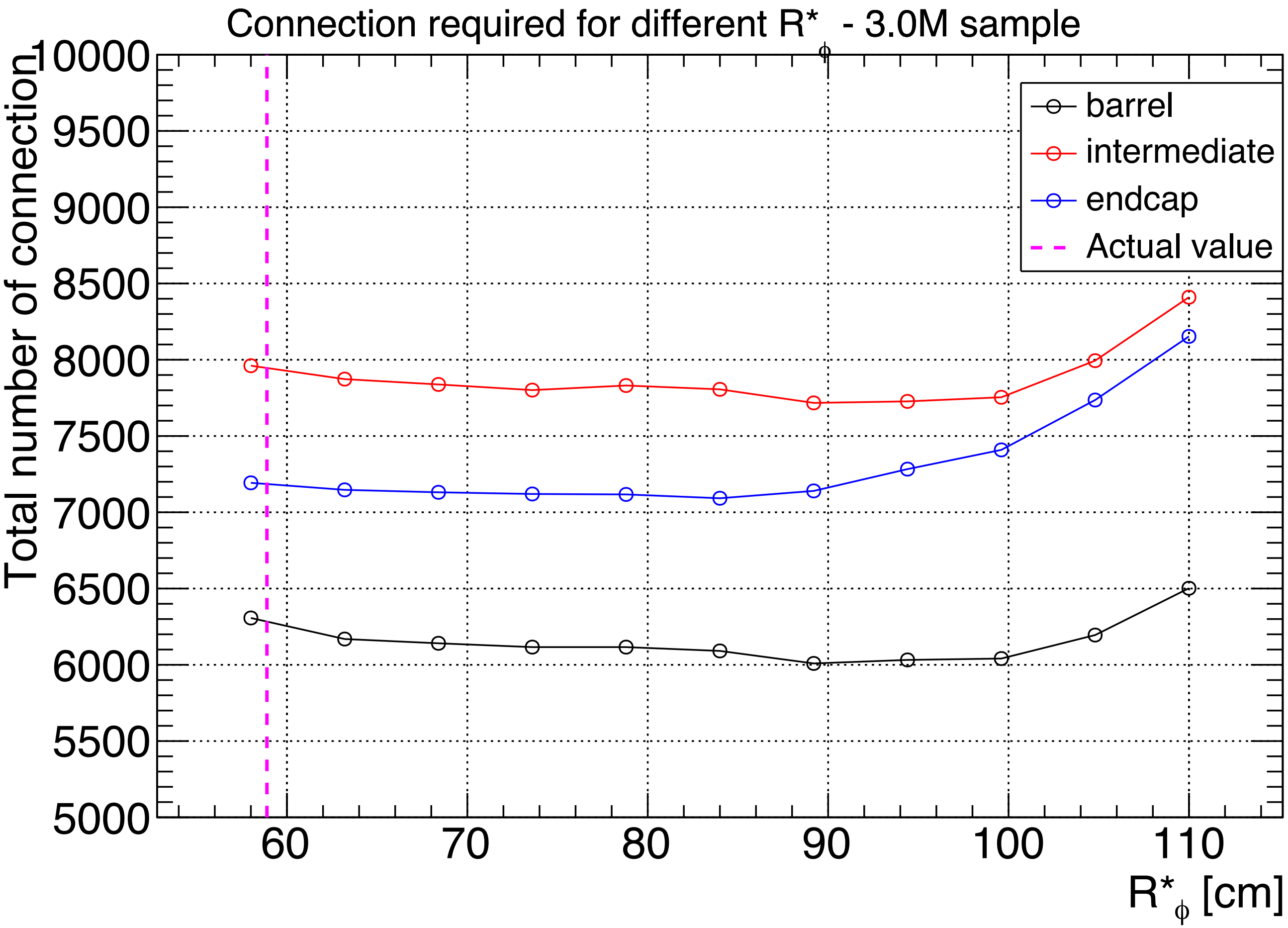






Essentially unchanged!

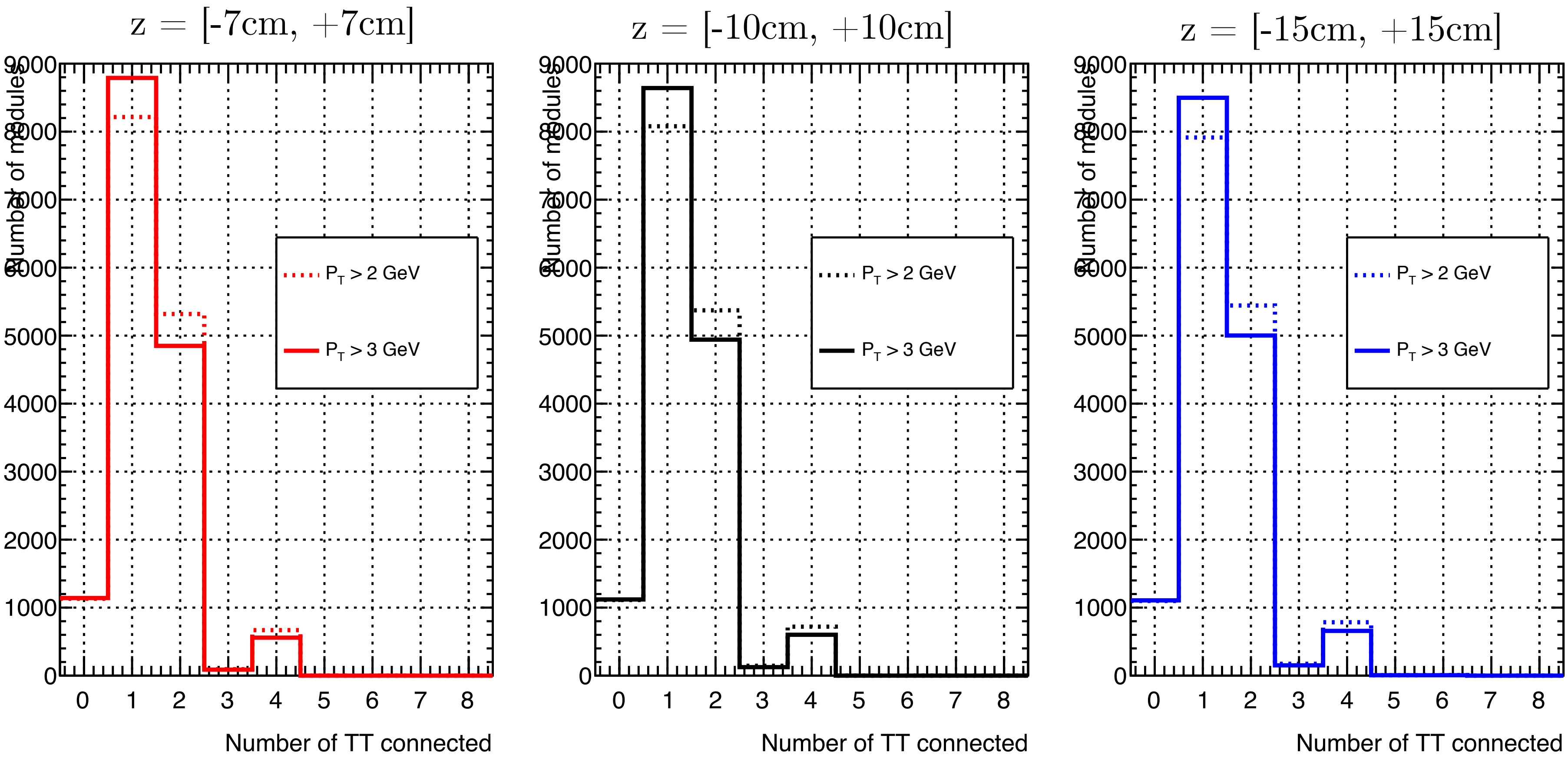
Focusing on R$^*_\phi$



- Max optimization:
  - 4% (intermediate)
  - 1% (forward)
  - 5% (barrel)

Module fan-out

Number of towers to which stubs from a single module must be delivered

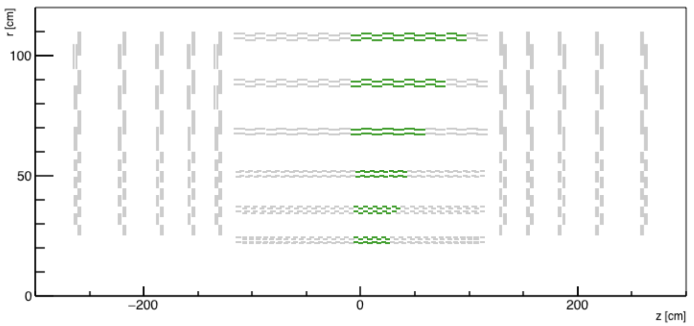


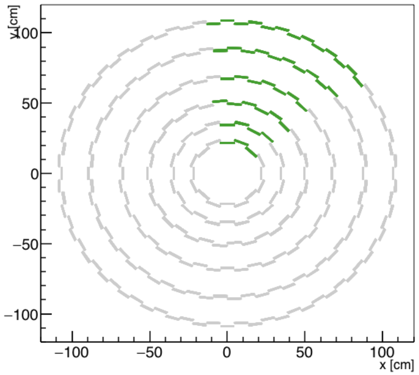
z = [-7cm, +7cm]

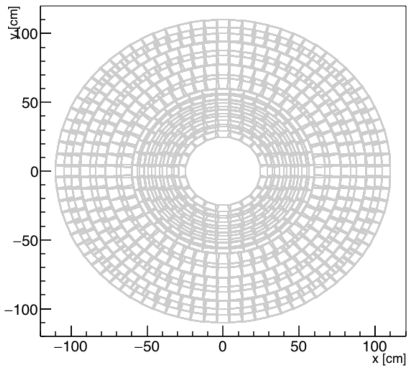
z = [-10cm, +10cm]

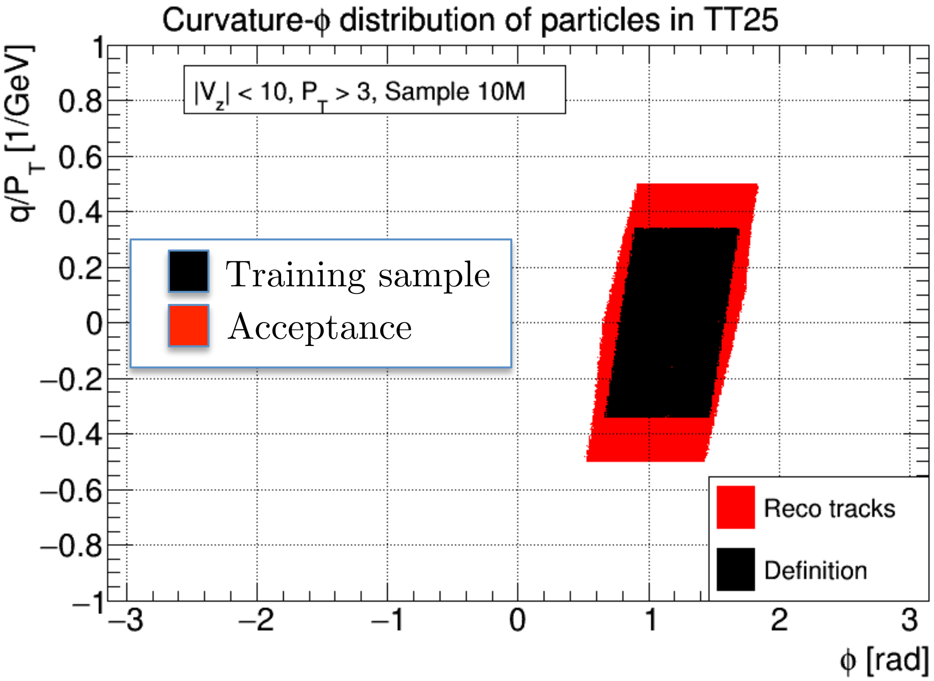
z = [-15cm, +15cm]

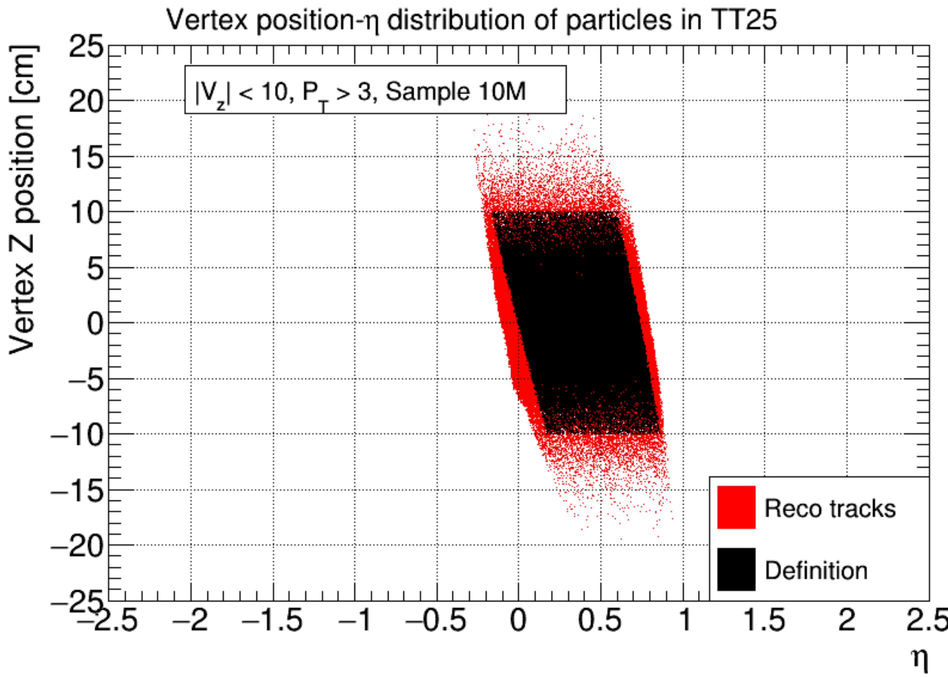
Barrel example – TT[4,2]



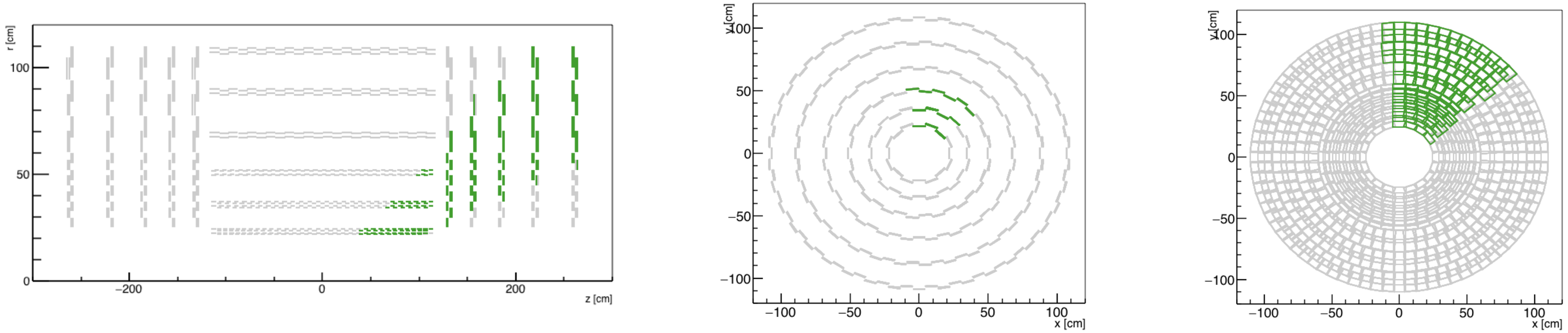


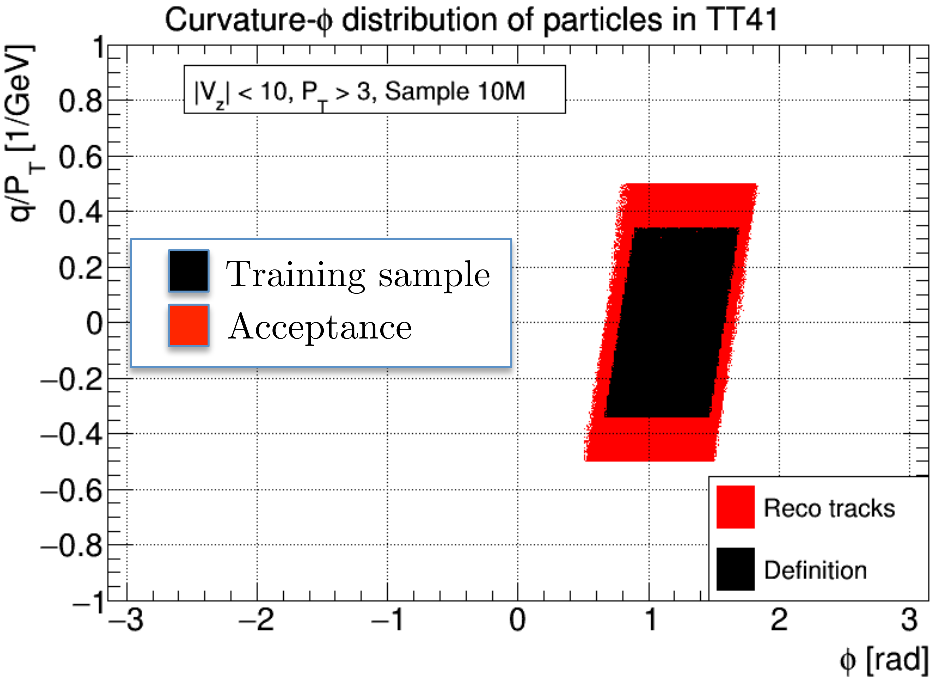


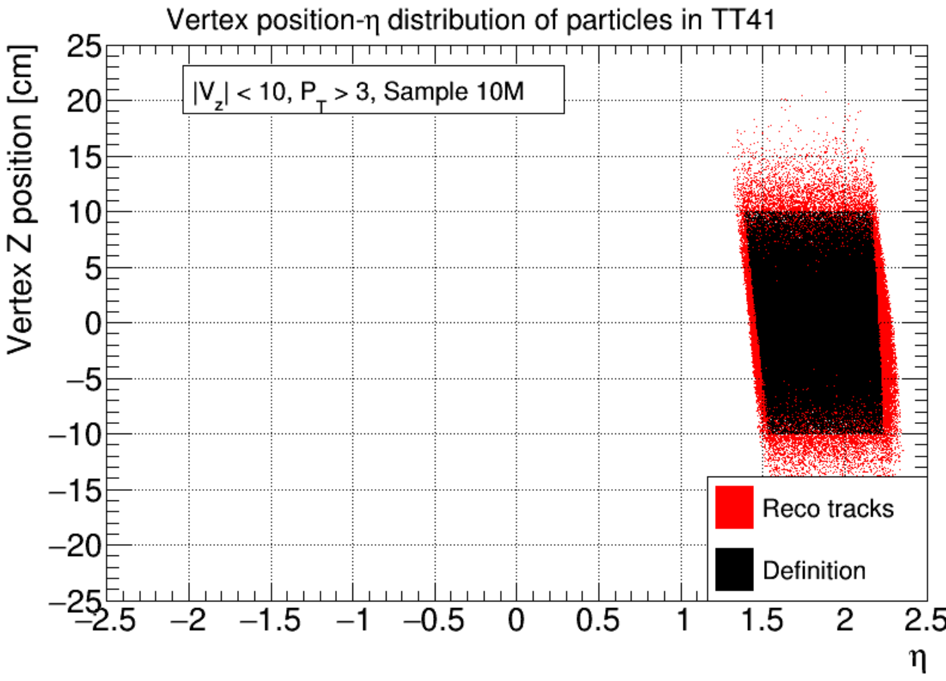




Forward example – TT[6,2]

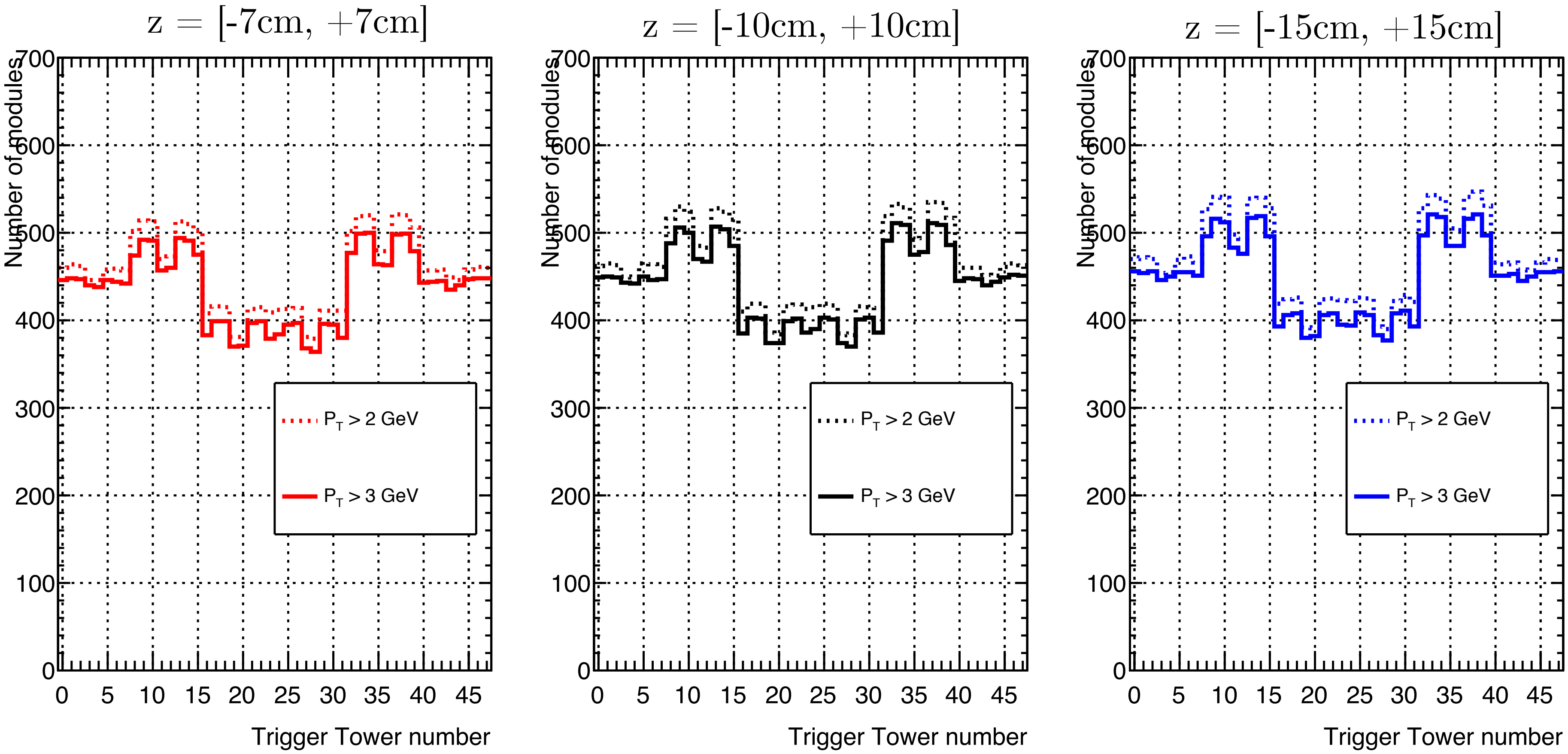






How many modules?

Total number of modules from which each tower must receive information (2GeV vs. 3 GeV)

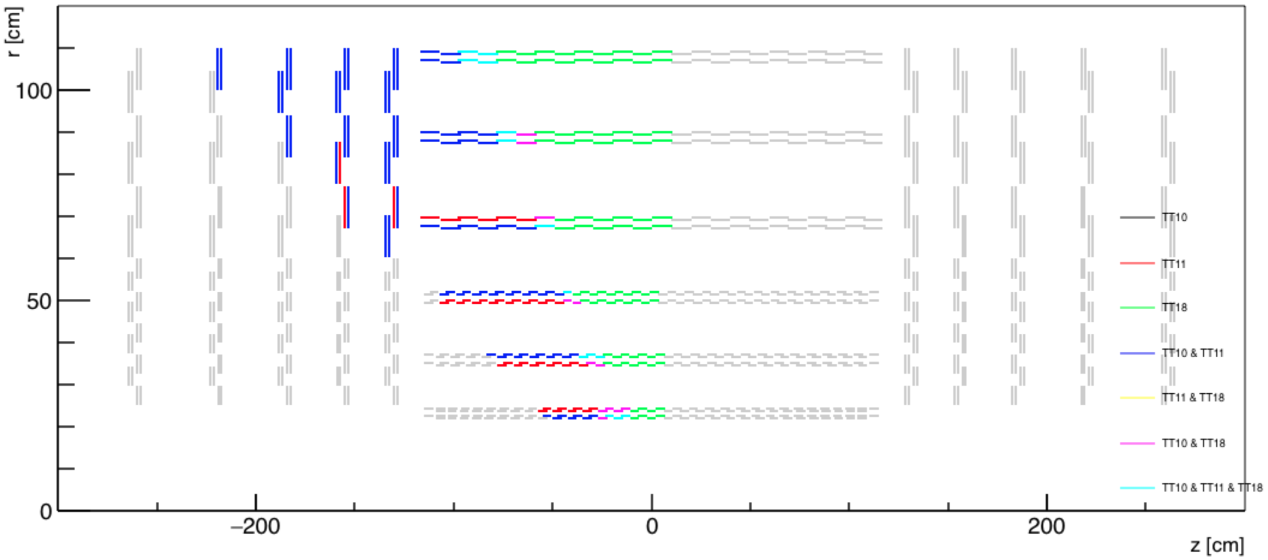


z = [-7cm, +7cm]

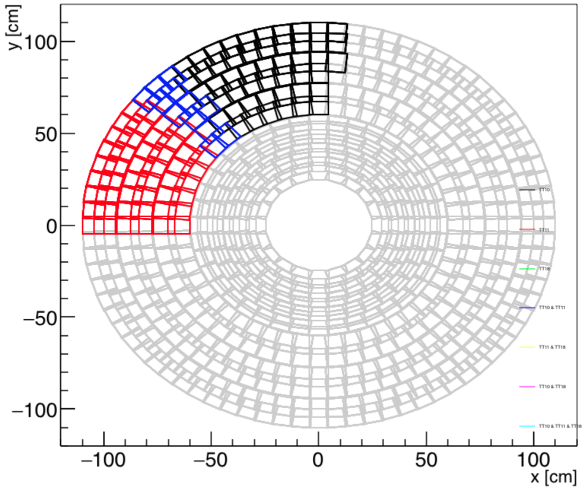
z = [-10cm, +10cm]

z = [-15cm, +15cm]

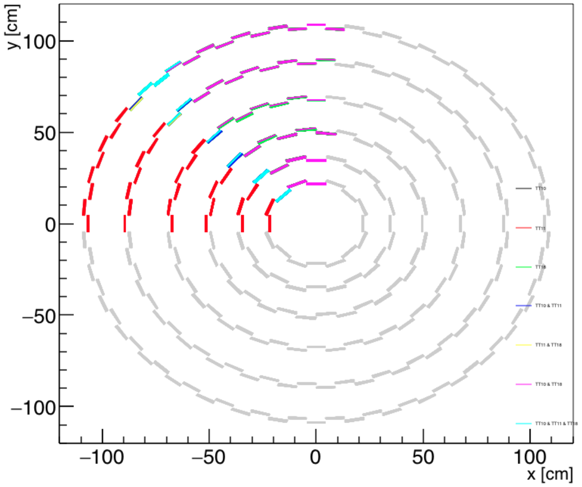
Triple shared modules



Full r-z projection



Endcap x-y projection



Barrel x-y projection

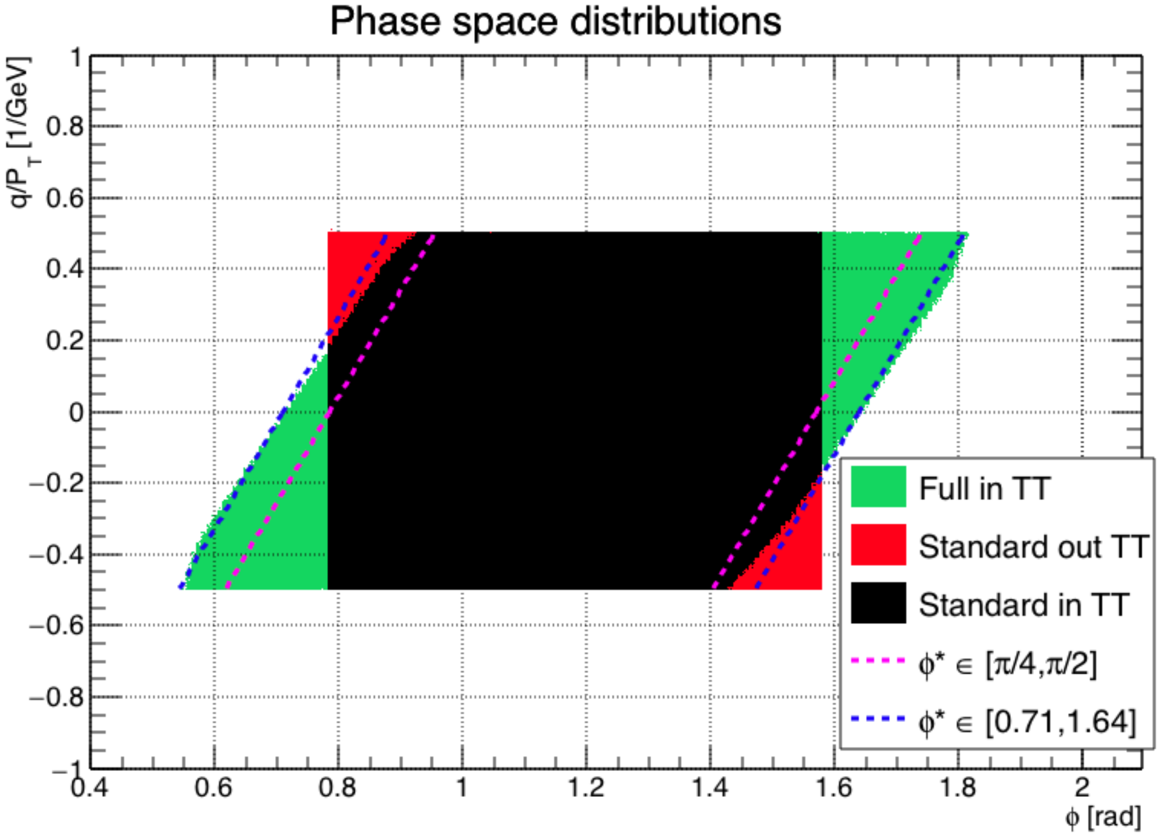
- Less than 1% triple sharing
- Order 4% 4-sharing
- 16 6-time shared modules only with $|v_z|$ up to 15 cm

q/P_T vs ϕ summary plot

Equation of boundary:

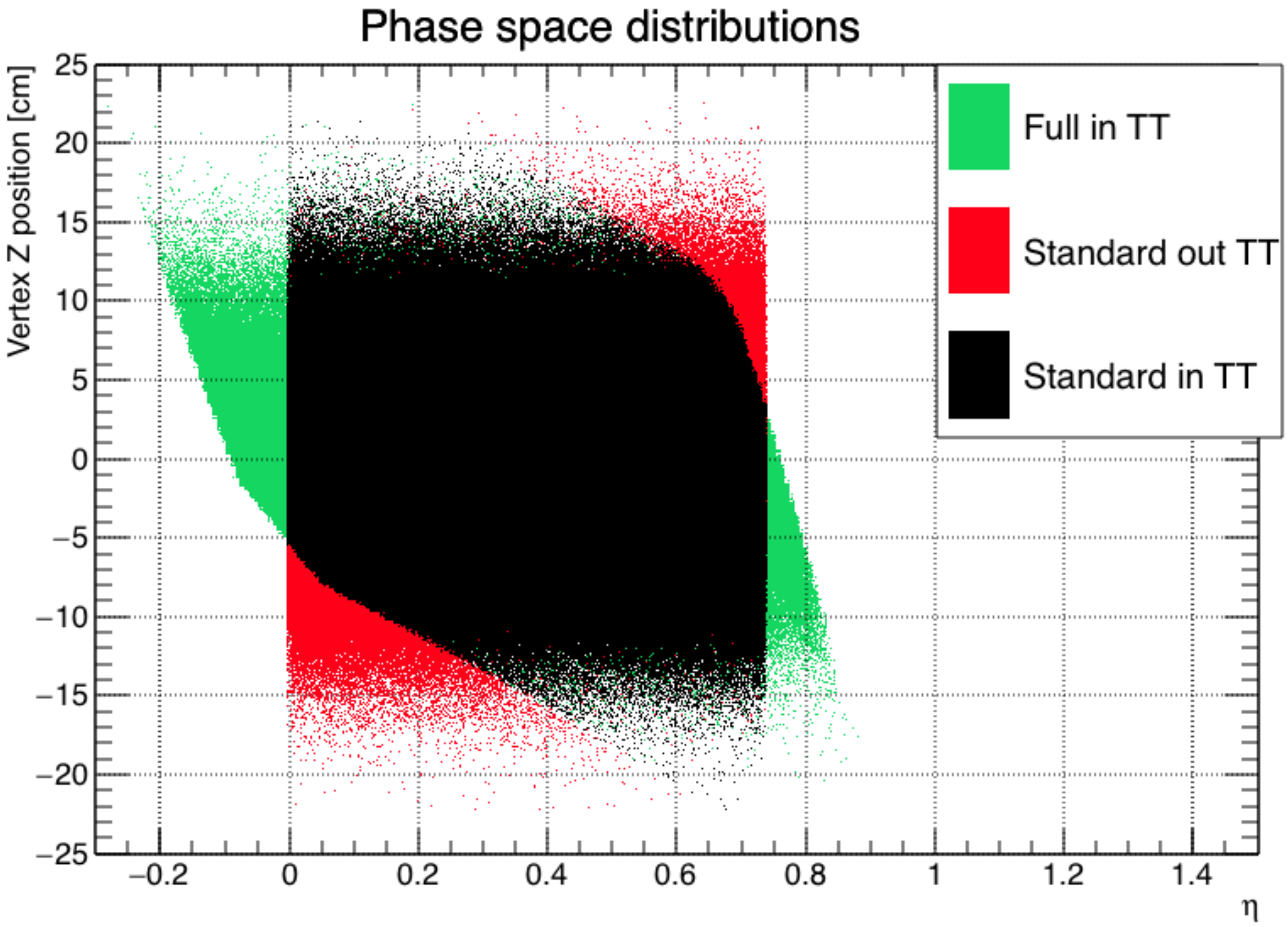
$$\frac{q}{P_T} = \frac{2\alpha}{R^*} \sin\left(\phi_0 - \phi^*_{edge}\right)$$

$$\boxed{\begin{gathered} R^* = 58.89\text{cm} \\ \alpha = \rho/P_T = 87.72\text{cm/GeV} \end{gathered}}$$



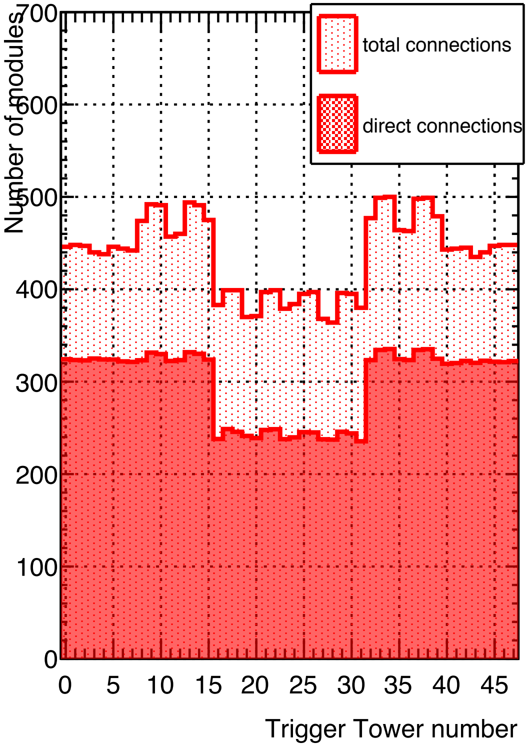
➡ Overcoverage possibly due to finite module dimensions?

$z_0$vs. η summary plot



How many modules?

- Dark area: modules directly connected to the TT
- Light area: modules connected to the TT via TT2TT connections
- Solid line: total number of modules connected
- 3 GeV/c P_T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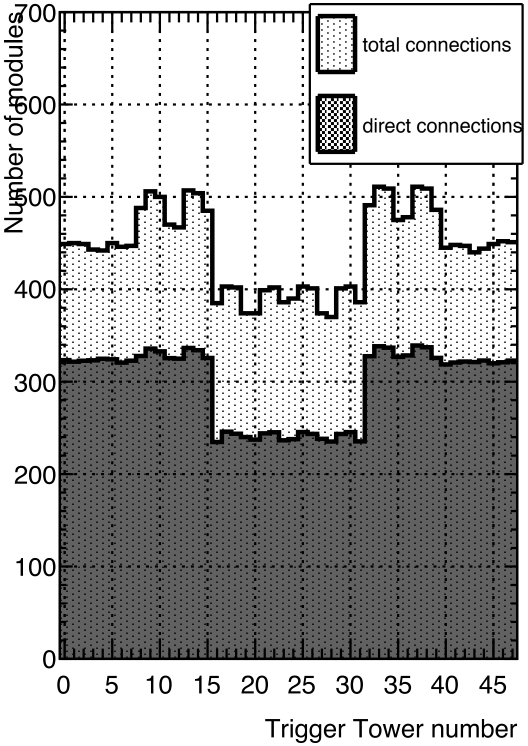
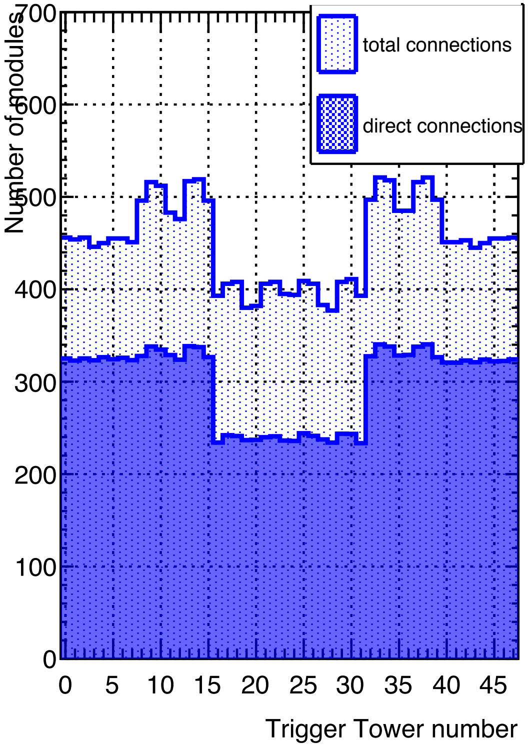

z = [-10cm, +10cm]


z = [-15cm, +15cm]