HighRR

BMBF-Forschungsschwerpunkt
ATLAS-EXPERIMENT
Physik bei höchsten Energien mit dem ATLAS-Experiment am LHC

FSP 103
ATLAS

Triplet Track Trigger for Future Hadron Collider Experiments

André Schöning, Danilo Ferreira,
Jike Wang & Tamasi Kar

Physikalisches Institut,
Universität Heidelberg

HighRR Seminar, Heidelberg
May 15, 2019

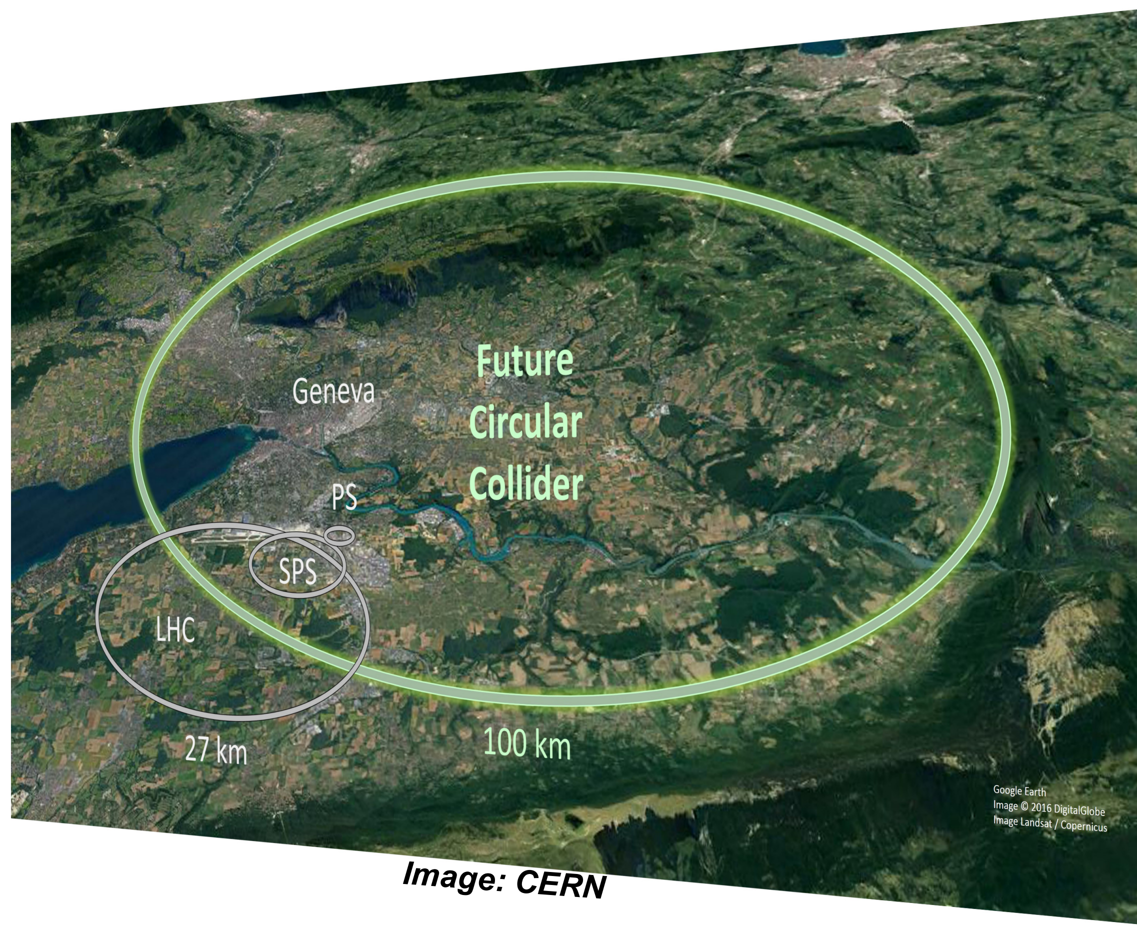


Image: CERN

Outline

- Introduction
  → Need for HL-LHC and Future Hadron Colliders (e.g. HE-LHC, FCC-hh)
  → Challenges

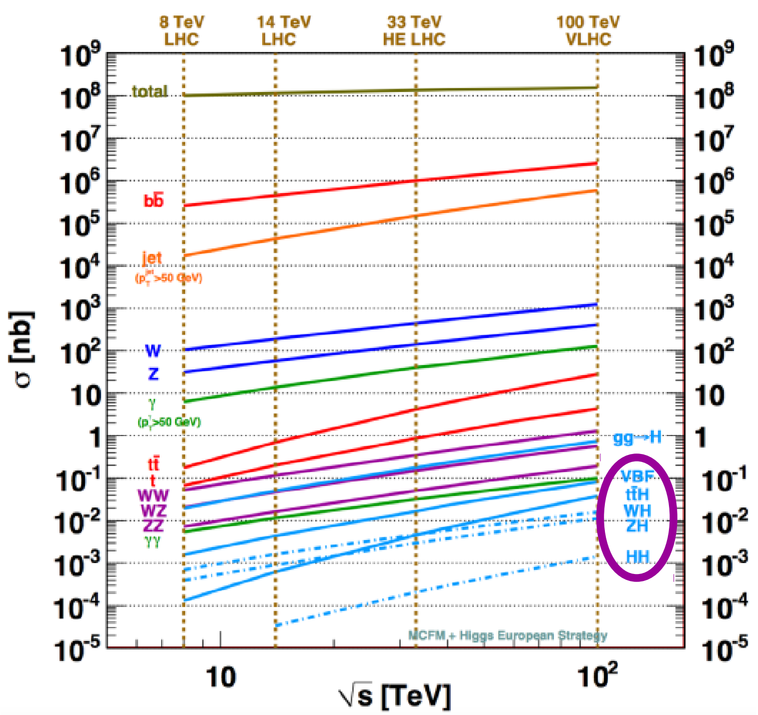
- Track Trigger
  → Physics motivation
  → Triplet Track Trigger (TTT) based on HV-CMOS technology

- Triplet Track Trigger Study
  → ATLAS Full Simulation
  → FCC like detector environment (Geant4 standalone)

- Results and Outlook

Physics Motivation for LHC Upgrade and FCC

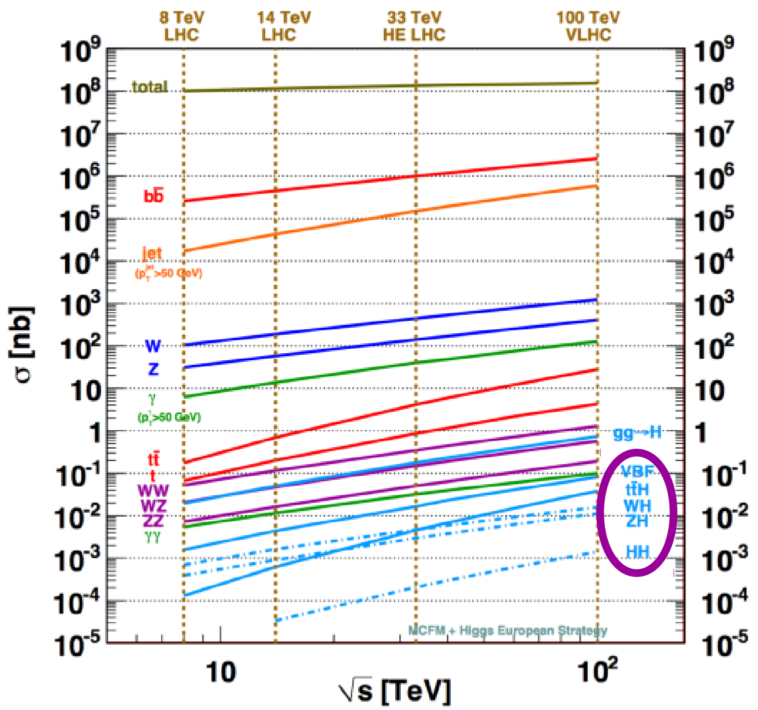
- High precision measurement of Higgs boson properties and Standard Model tests, e.g. Higgs couplings
- Increase discovery potential for new physics at both the high energy and intensity frontier
- Search for rare processes with high sensitivity



Total cross-section as a function of CMS energy

Physics Motivation for LHC Upgrade and FCC

- High precision measurement of Higgs boson properties and Standard Model tests, e.g. Higgs couplings
- Increase discovery potential for new physics at both the high energy and intensity frontier
- Search for rare processes with high sensitivity



Total cross-section as a function of CMS energy

Increase the rate of occurrence of the rare processes

$$\mathcal{R} = \mathcal{L} * \sigma$$

Increase Luminosity

Increase both Luminosity & CMS energy

High Luminosity LHC (HL-LHC)

High Energy LHC (HE-LHC) OR Future Circular Collider (FCC-ee,eh,hh)

Luminosity

- Measure of the number of potential collisions per unit area over a given period of time

Luminosity

- Measure of the number of potential collisions per unit area over a given period of time
- Increasing the luminosity: squeeze in more number of particles per unit area per unit time

Cross-section

- Measure of the probability of a process to happen

Why High Luminosity and High Energy?

The LHC: CMS energy fixed by the 27km tunnel and the 8T dipole field
→ increase the luminosity of the proton beams (HL-LHC)

Beyond HL-LHC: Future Circular Colliders
1. Tunnel length same as the LHC and 16T dipole field: High Energy LHC (HE-LHC)

OR

2. A new 100km tunnel and 16T dipole field: Future Circular Collider FCC(ee, eh, **hh**)

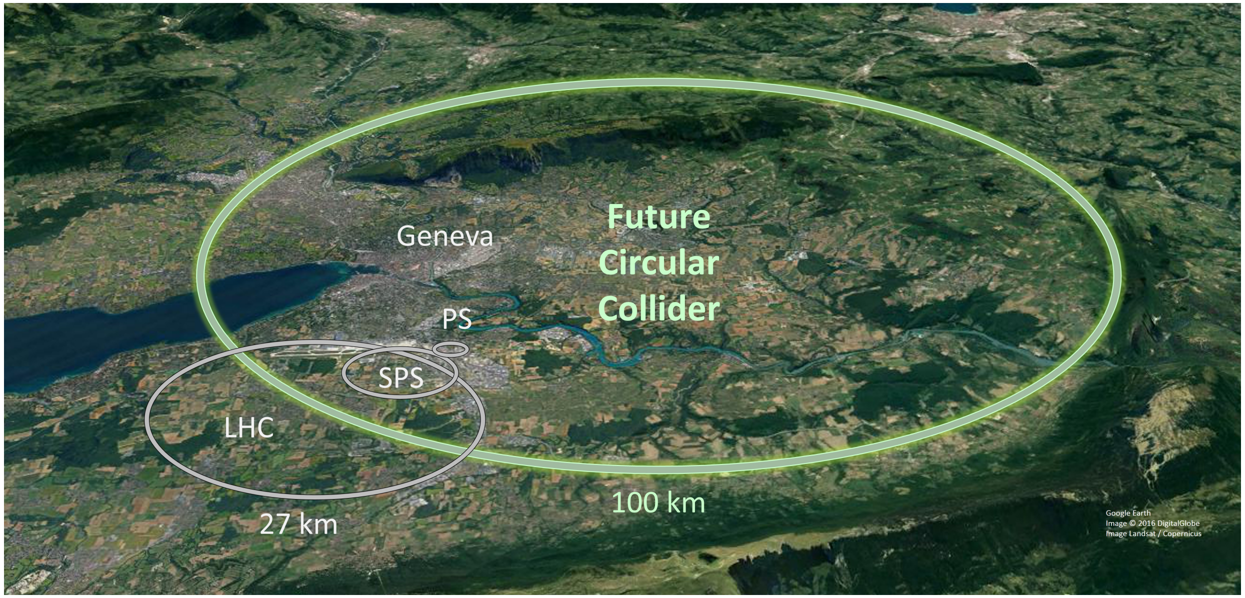


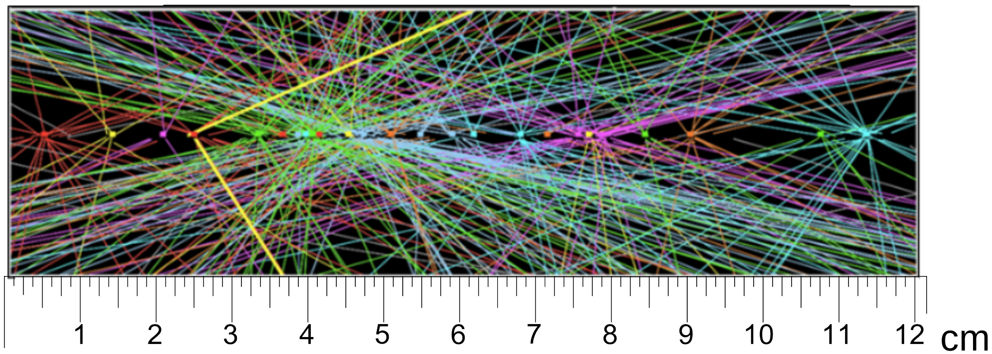
Image: CERN

Future Hadron Colliders → Challenges

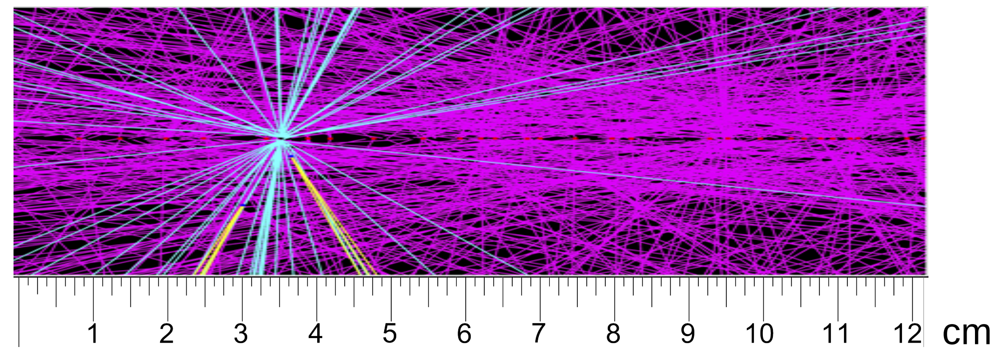
Parameters	LHC (Run2)	HL-LHC	HE-LHC	FCC-hh
CMS energy [TeV]	**13**	**13**	**27**	**100**
Eta coverage	-2.5 to 2.5	-4 to 4	-6 to 6	
Peak Instantaneous luminosity [10^{34} cm^{-2} s^{-1}]	2.1	5 - 7	16	30
Pileup (BX = 25 ns)	34.2	**200**	**500**	**1000**
Radiation fluence [n_{eq}/cm^2]	2×10^{15}	**2×10^{16}**	**$\sim 6 \times 10^{17}$**	
Goal integrated luminosity [ab^{-1}]	0.160	3	10	20

Future Circular Collider Study. Volume 3: The Hadron Collider (FCC-hh) CDR, ATLAS Collaboration Week

Future Hadron Colliders → Challenges



A candidate Z boson event in the dimuon decay with 25 reconstructed vertices.



Simulated ttbar event, $\langle\mu\rangle$=200

Vertex resolution of better than a millimeter required to suppress pileup by a significant amount

Total data rate of 1-2 PB/s @40MHz BX, low storage rate ~1kHz (now) → > 10^2-10^3 kHz (future)?

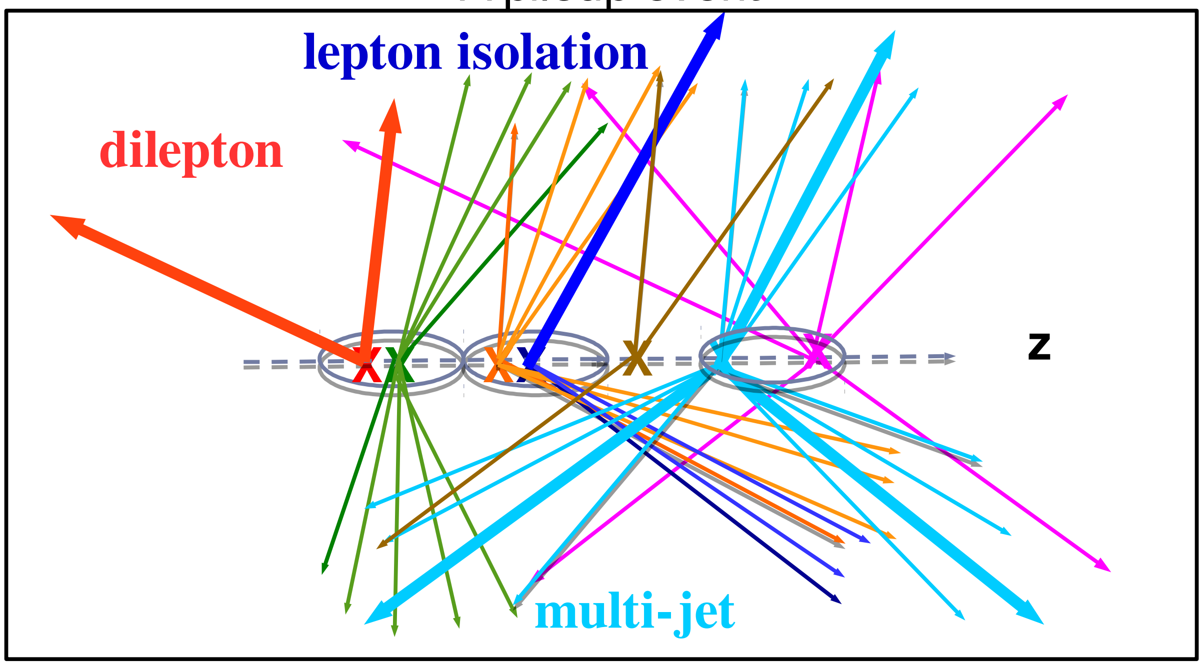
Trigger thresholds are generally increased to limit the rate

Need smart selectivity and radiation hard technology!

Track Trigger: Physics Motivation

- **Goal** : precision measurement of SM processes, new physics beyond SM
  Interesting physics processes : $Z \rightarrow ll$, $B_s \rightarrow \mu\mu$, $hh \rightarrow bb\tau\tau$, $hh \rightarrow 4b$
- **Challenge:** pile up
  (with track information the pile-up problem can be largely reduced → optimally already at trigger level for every bunch crossing e.g. @40 MHz)
- **Track trigger** : event selection based on track (vertex) information

A pileup event



Precise measurement of the Z position of the primary vertices required!

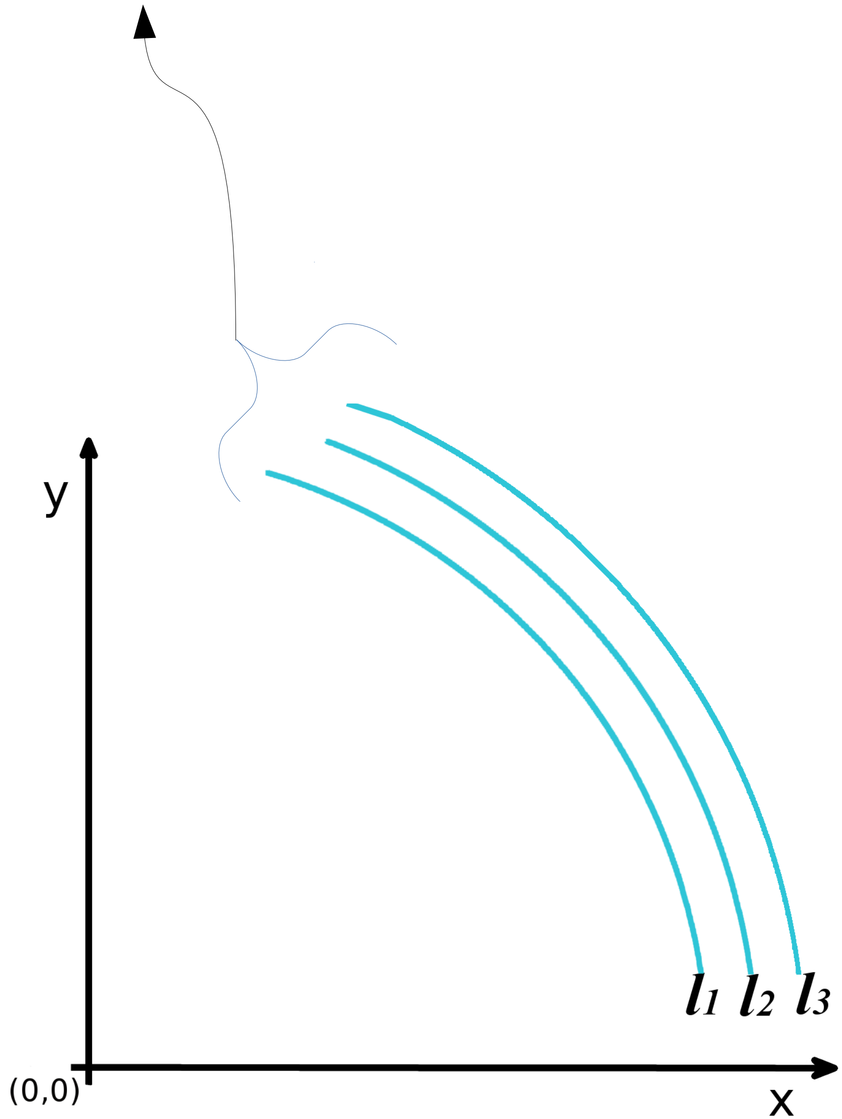
Online, at trigger level!

Crucial for pileup suppression, and to trigger on dilepton and multi-jet channels

Triplet Track Trigger (TTT): Concept

- Triplet: three **closely stacked** detector layers at **large radii**

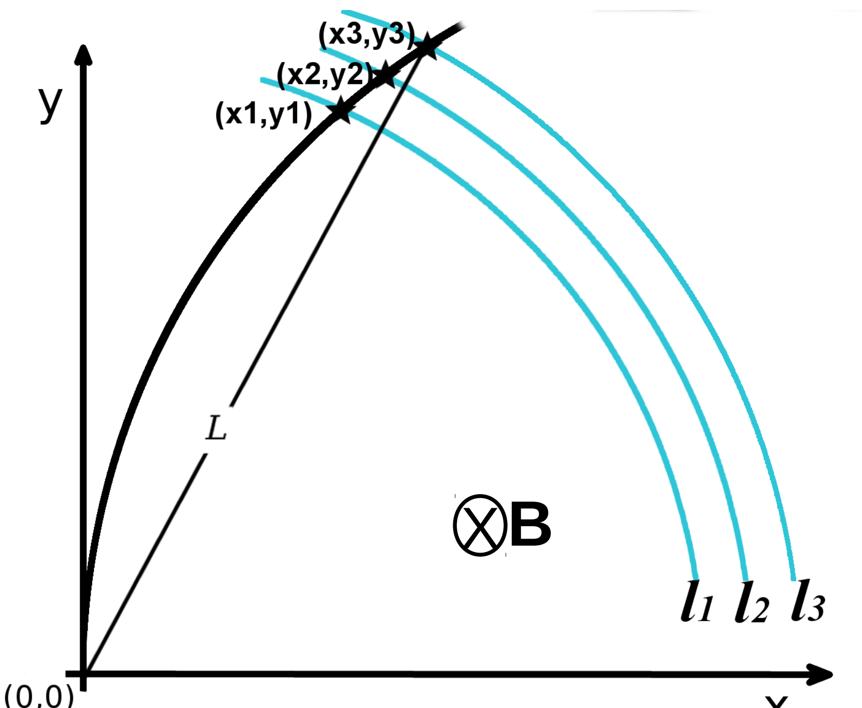
Optimal gap ~ 2 – 4 cm
Hits line up on almost straight lines
→ **easy reconstruction**



Triplet Track Trigger (TTT): Concept

- Triplet: three **closely stacked** detector layers at **large radii**
- Uniform magnetic field B along the axis of the detector layers (z axis)

Why large radii?
→ Large lever arm → $\frac{\sigma_{pt}}{p_t} \propto \frac{1}{L}$
→ Lower occupancy



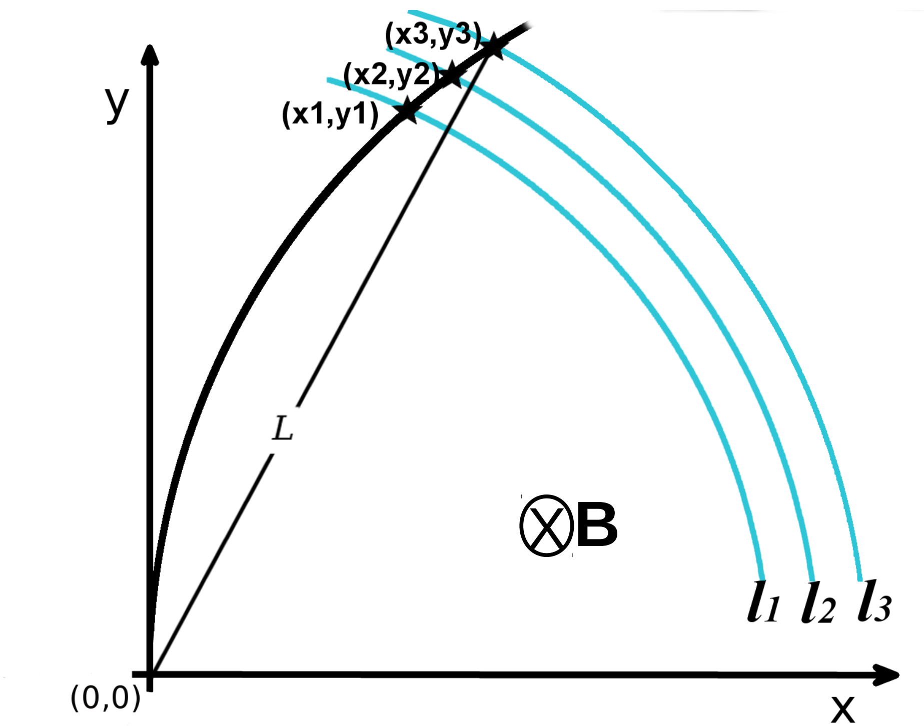
Circular trajectory (x – y plane)

Triplet Track Trigger (TTT): Concept

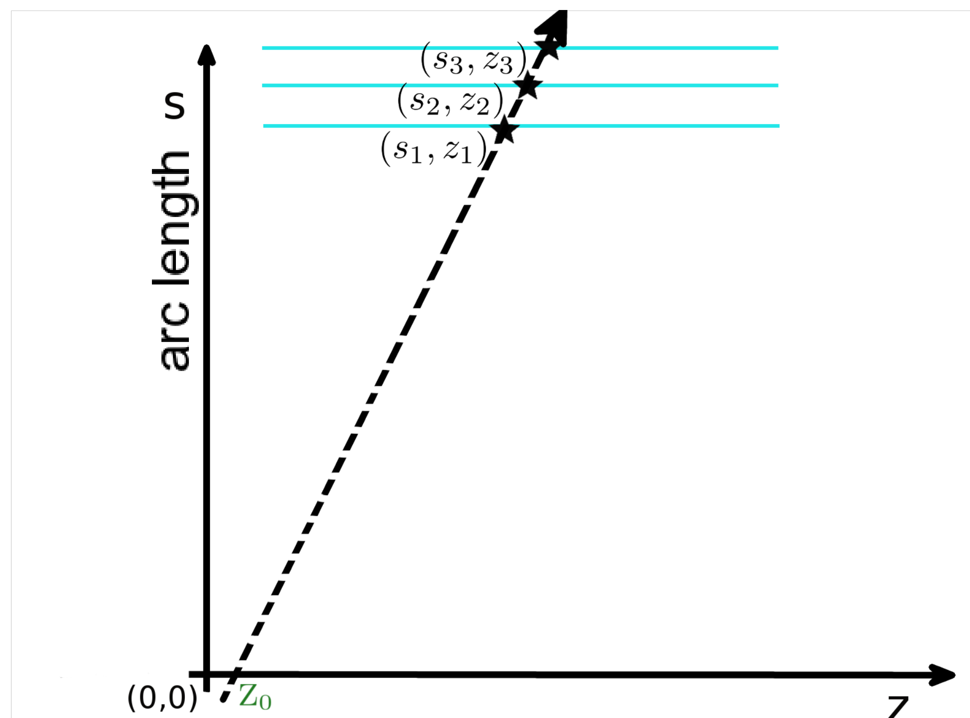
- Triplet: three **closely stacked** detector layers at **large radii**
- Uniform magnetic field B along the axis of the detector layers (z axis)

Why large radii?
→ Large lever arm → $\frac{\sigma_{pt}}{p_t} \propto \frac{1}{L}$
→ Lower occupancy

Pixels (CMOS Monolithic):
→ provides 3d space point
→ precise Z vertex reconstruction
(not possible with strips)



Circular trajectory (x – y plane)

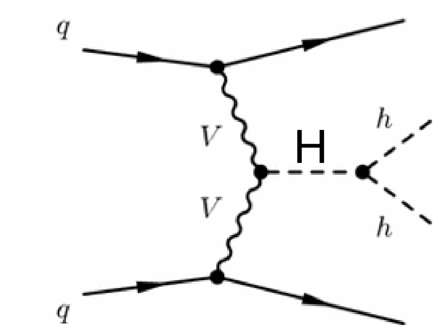


Straight line (s – z plane)

Triplet Track Trigger (TTT) Study

1. Using ATLAS Athena software framework (detailed detector simulation)
   → compare TTT tracks (very first level, three layers) to ITK tracks[1] (nine layers)
2. FCC-hh using a full Geant4 standalone simulation (ref. FCC-hh tracker layout)
   → TTT tracking performance for various gap sizes of the TTT

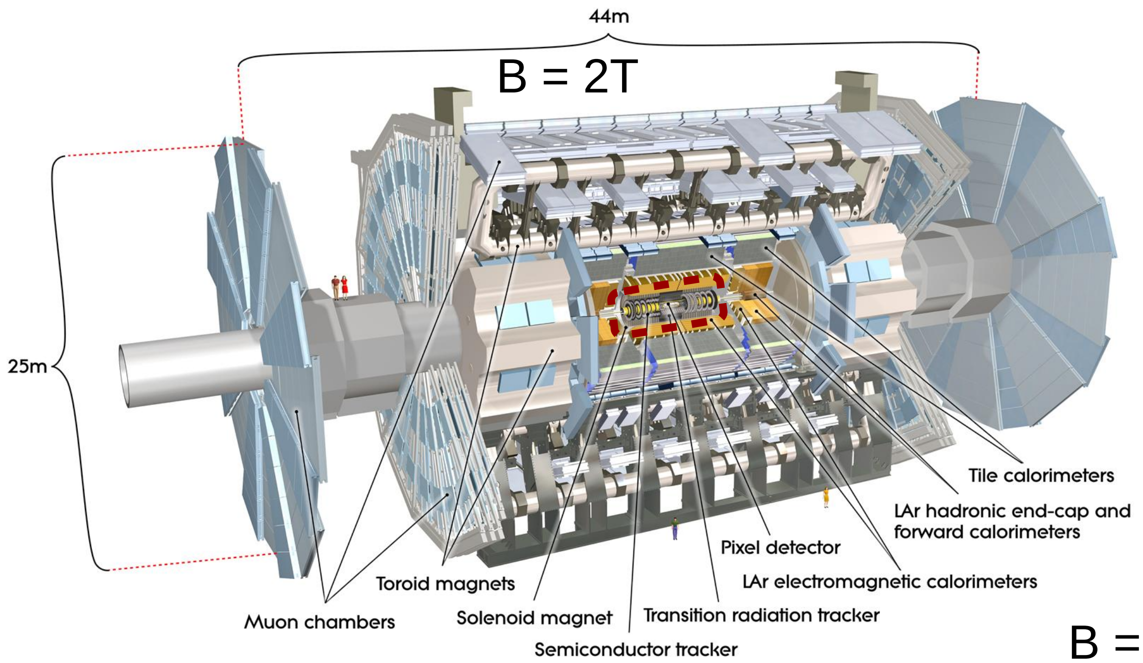
- Physics channel used for the above studies: H → hh → 4b via VBF
  m_H = 1TeV

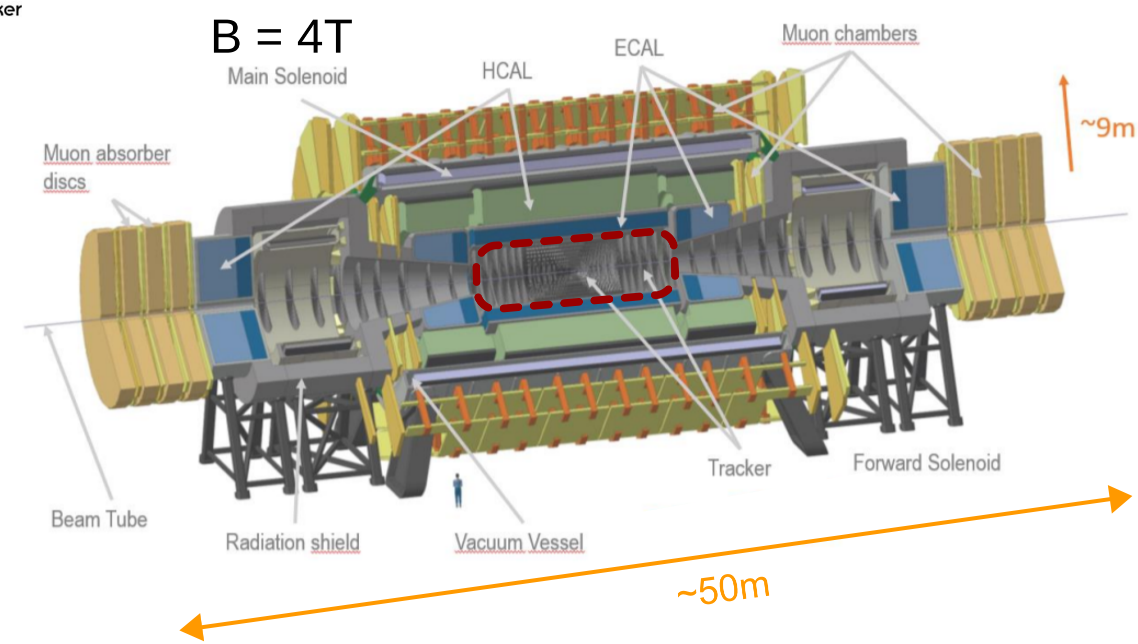


→ in the SM VBF hh production, this will allow the extraction of the trilinear Higgs self-coupling λ

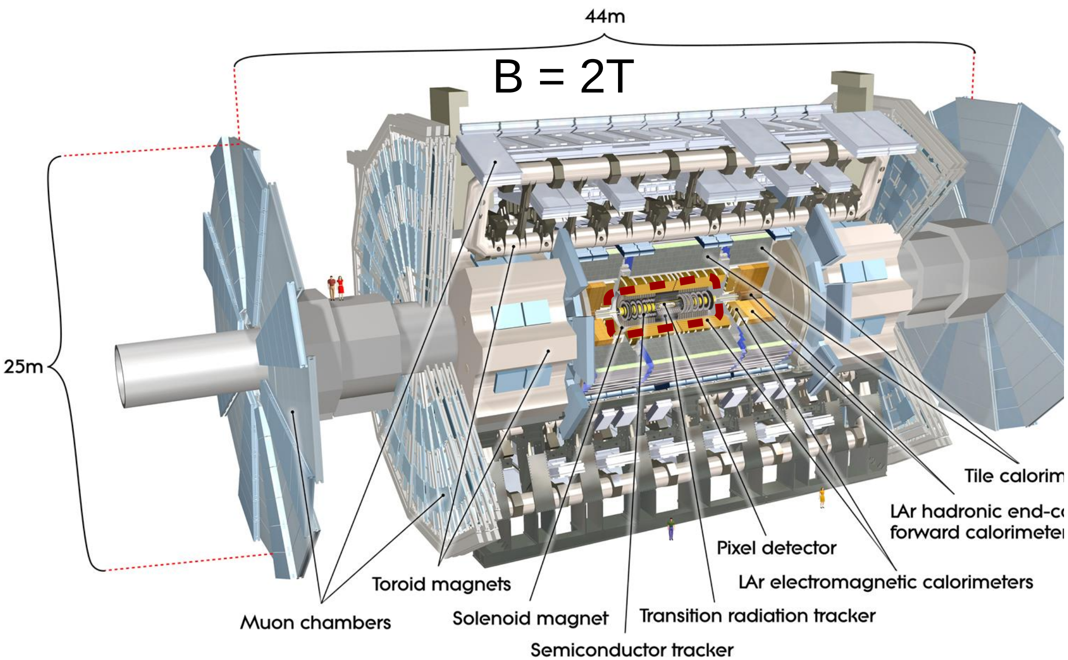
[1]ITK tracks : tracks reconstructed using the inner tracker(offline tracks)

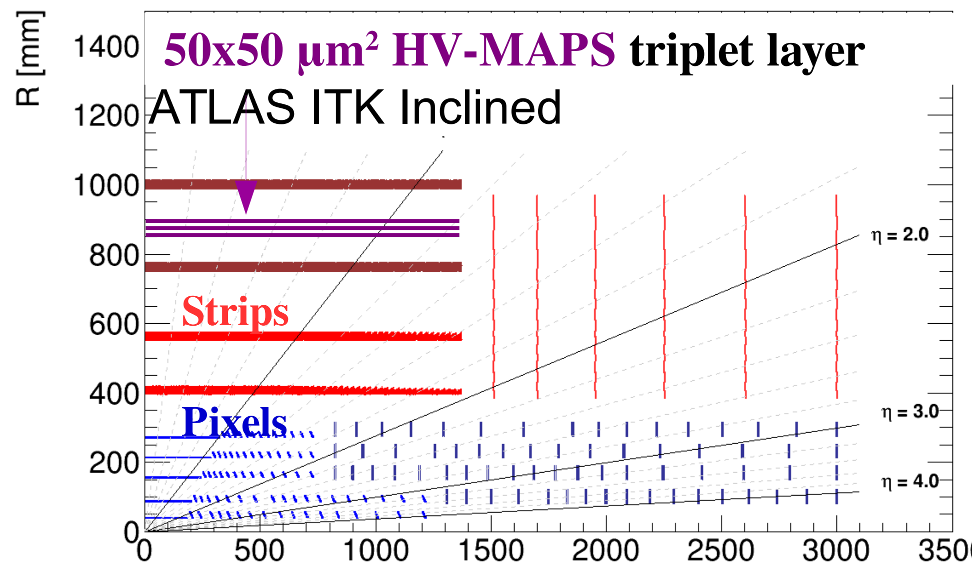
Triplet Track Trigger (TTT) Study





Triplet Track Trigger (TTT) Study

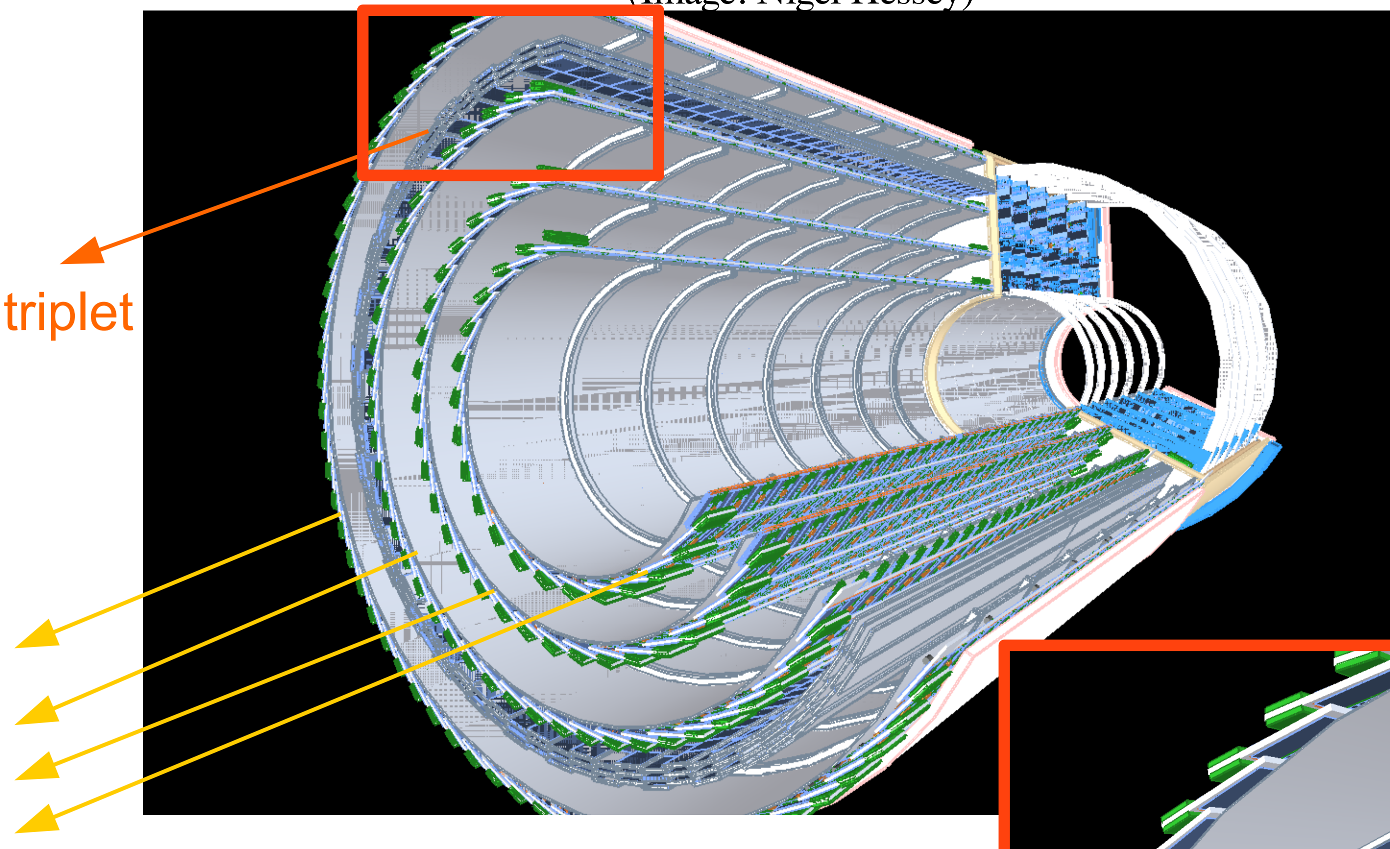




The ATLAS ITK layout for HL-LHC

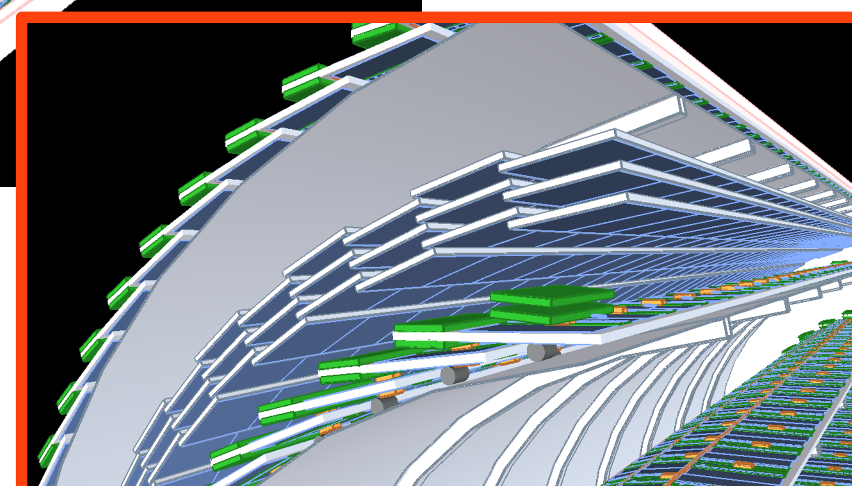
Triplet Track Trigger Study (ATHENA)

ATLAS Strip tracker with the CMOS triplet layers
(Image: Nigel Hessey)



TTT Geometry Specifications:

→ radius: 85cm
→ barrel: 300cm
→ η range: ~|1.5|
→ gap size: 2cm
→ x/X_0: 1.5%
→ sensor: $8x8cm^2$
→ pixel size: $50\mu m^2$
(CMOS Monolithic)



Zoomed view

- Full chain has been implemented in ATHENA:

1. Simulation
2. Digitization
3. Track reconstruction in B = 2T

Triplet Track Reconstruction Algorithm

(1) Triplet Hit Selection (pre-selection of hits)

(2) Triplet Track Parameter determination (pt, z0, eta, phi, d0)

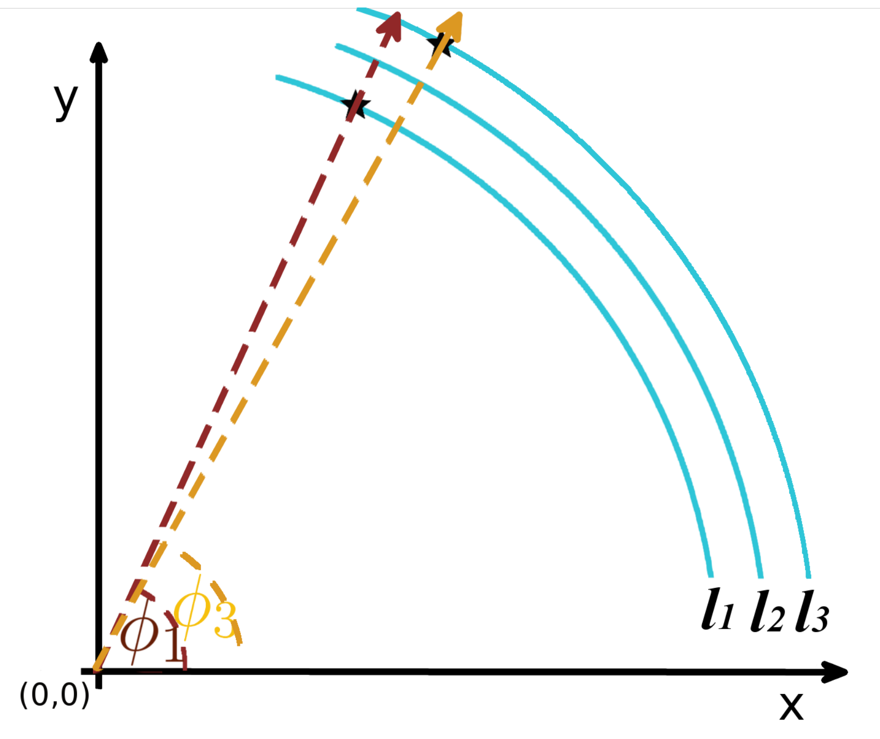
(3) Final track selection

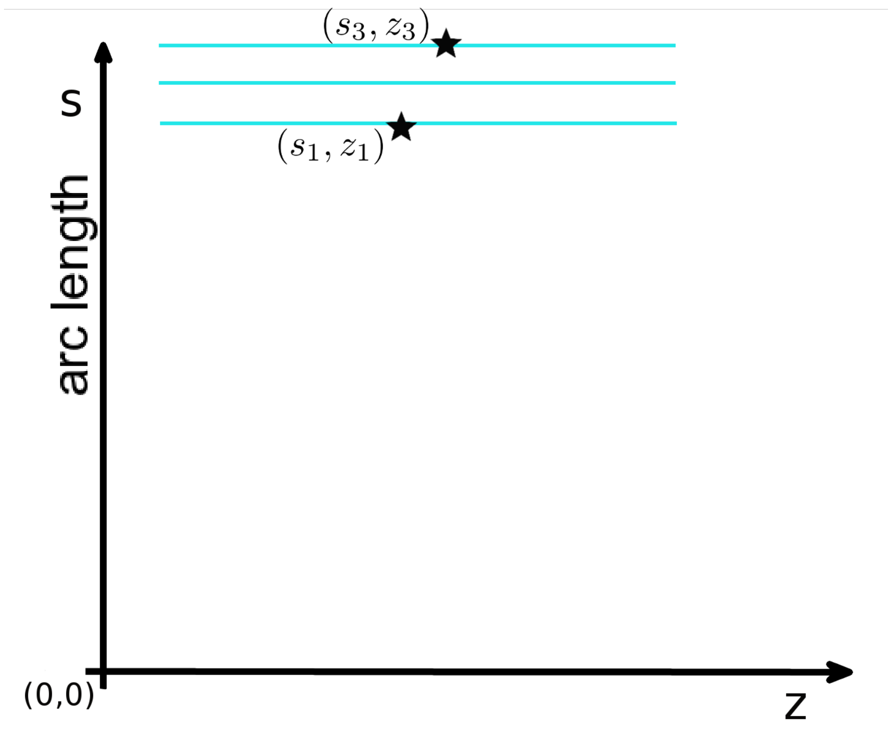
(1) Triplet Hit Selection

1. Transverse barrel cut : $|\phi_3 - \phi_1| < 0.007rad$
2. Longitudinal barrel cut : $|Z_3 - Z_1| < 70mm$

Wide cut

→ track parameters can already be calculated using beamline constraint[2]



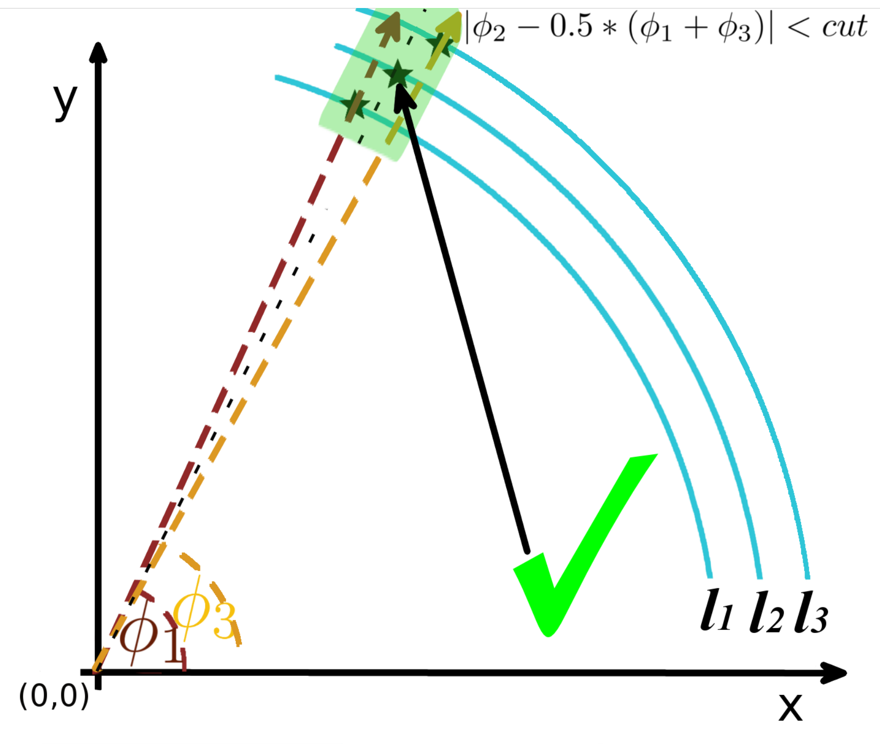


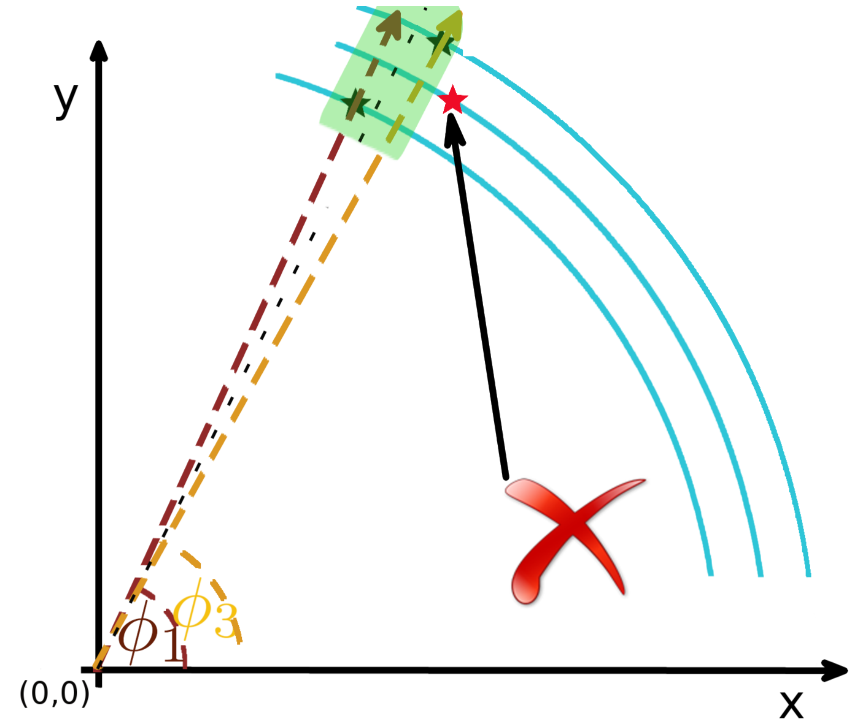
[2]Beamline constraint: (x,y) = (0,0)

(1) Triplet Hit Selection

1. Transverse barrel cut : $|\phi_3 - \phi_1| < 0.007rad$
2. Longitudinal barrel cut : $|Z_3 - Z_1| < 70mm$
3. Transverse residual cut : $|d\phi_2| < 1 * 10^{-4}rad$
4. Longitudinal residual cut : $|dz_2| < 9 * 10^{-2}mm$

Loose cut





(2) Triplet Track Parameter Determination

- <u>Track parameter calculation</u>

  → Using two independent methods:

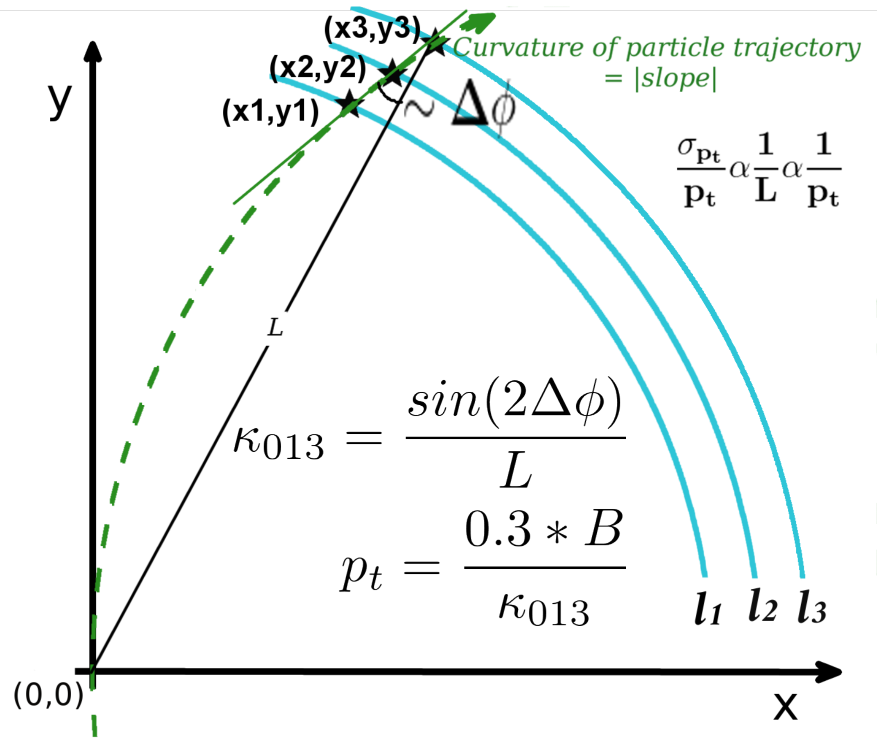
1. without beamline constraint

   small lever arm → κ_{123} not so precise

   when the three hits line up in a straight line(x-y)

2. with beamline constraint[2]

   large lever arm → precise κ_{013}



[2]Beamline constraint: (x,y) = (0,0)

(2) Triplet Track Parameter Determination

- <u>Track parameter calculation</u>

  → Using two independent methods:

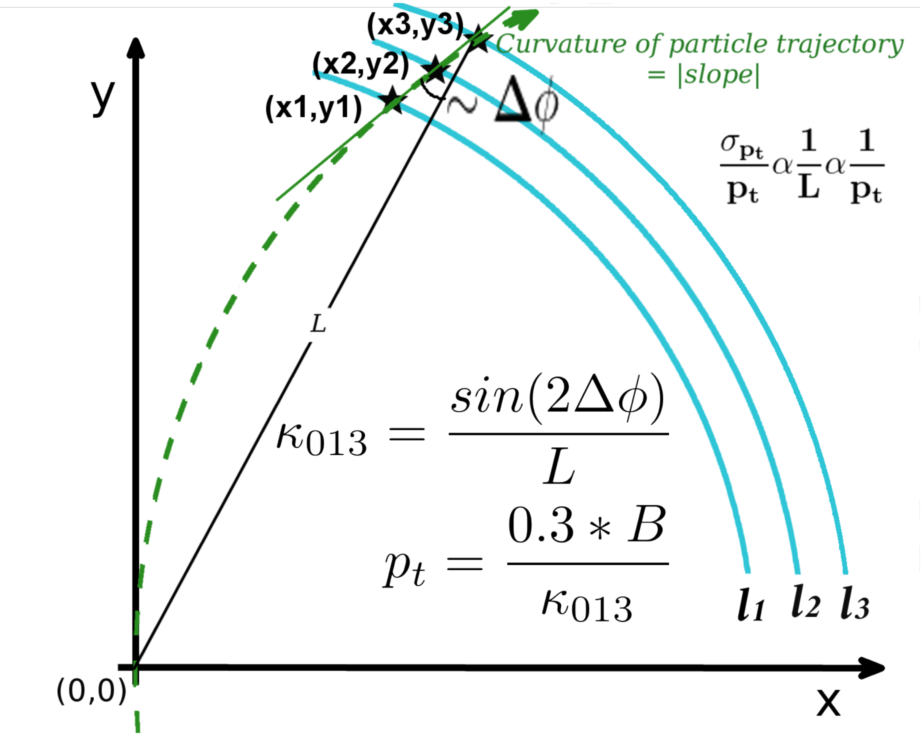
1. without beamline constraint

   small lever arm → κ_{123} not so precise

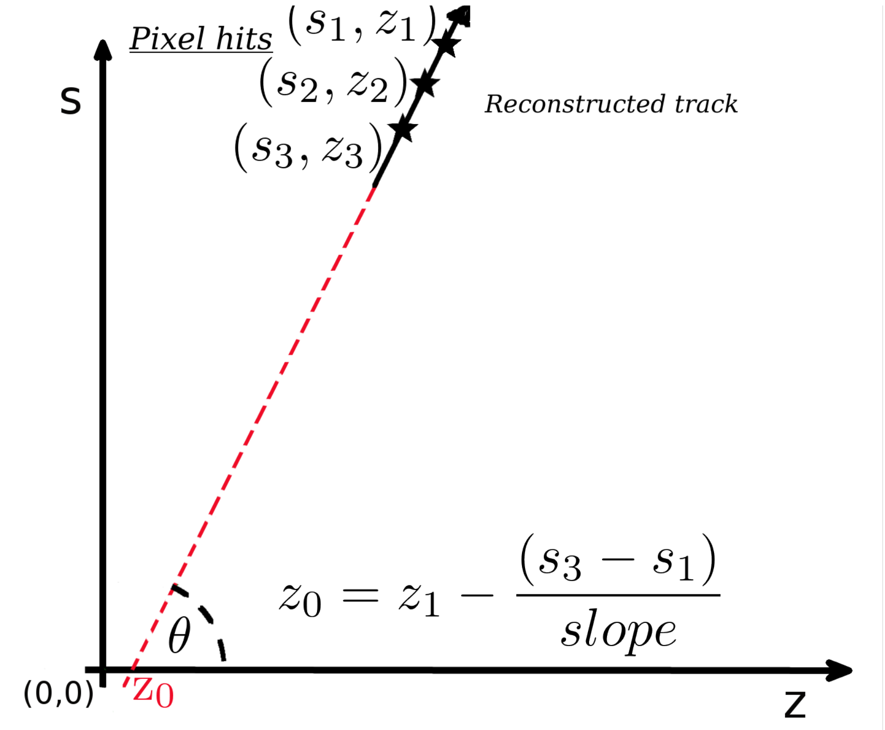
   when the three hits line up in a straight line(x-y)

2. with beamline constraint[2]

   large lever arm → precise κ_{013}



In the longitudinal plane a very precise reconstruction of z vertex is possible



[2] Beamline constraint: (x,y) = (0,0)

(2) Triplet Track Parameter Determination

- <u>Track parameter calculation</u>

  → Using two independent methods:

1. without beamline constraint

   small lever arm → κ_{123} not so precise

   when the three hits line up in a straight line(x-y)

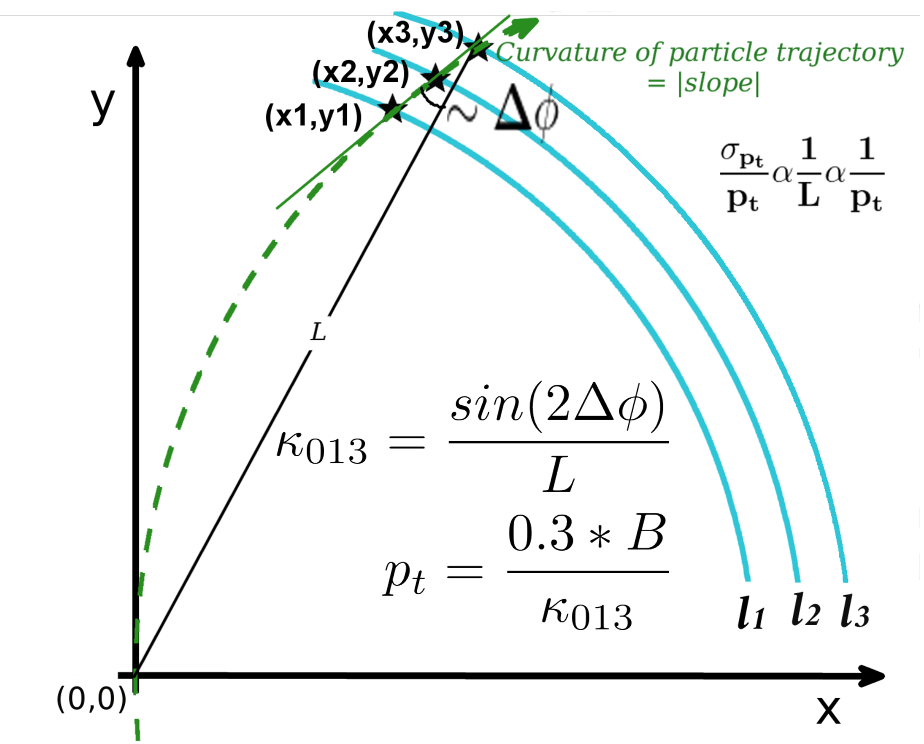
2. with beamline constraint[2]

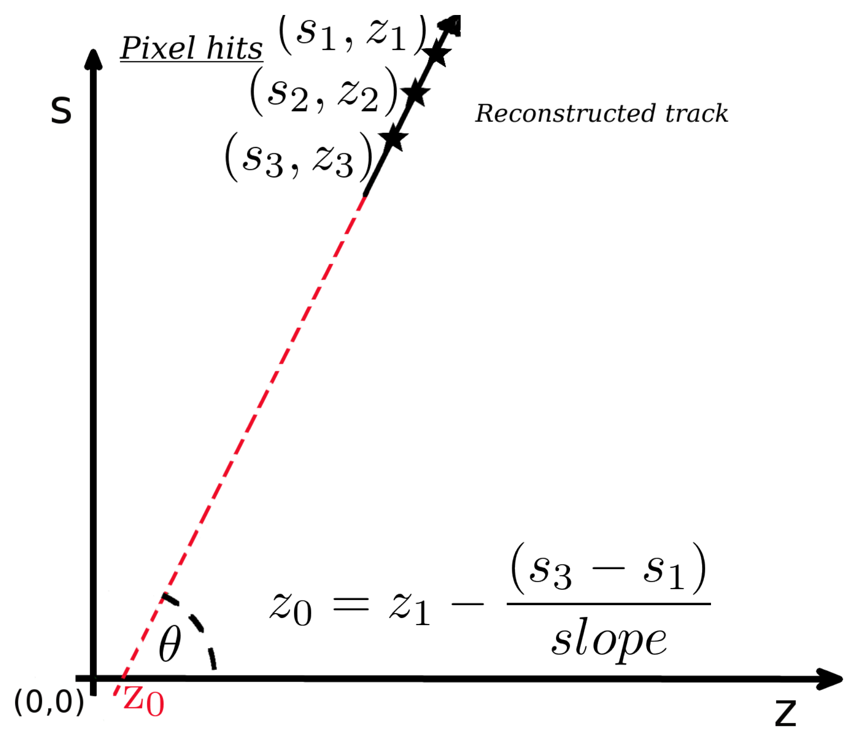
   large lever arm → precise κ_{013}

→ Simple and very fast algorithm!

→ Can be implemented in hardware e.g. FPGA

In the longitudinal plane a very precise reconstruction of z vertex is possible





[2]Beamline constraint: (x,y) = (0,0)

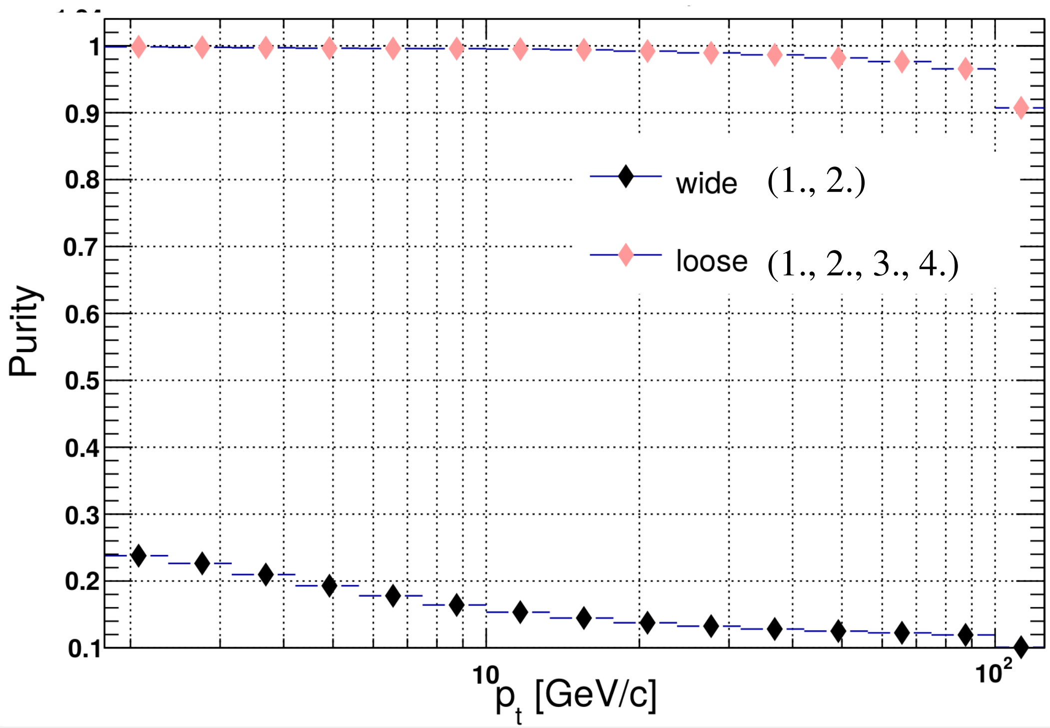
TTT Performance (ATLAS)

- Track purity of TTT tracks

$$p = \frac{\#reconstructed\ tracks(cut + matched)}{\#reconstructed\ tracks(cut)}$$

<u>Matched track:</u>
all the three hits of this track have a unique barcode

1. Transverse barrel cut : $|\phi_3 - \phi_1| < 0.007rad$
2. Longitudinal barrel cut : $|Z_3 - Z_1| < 70mm$
3. Transverse residual cut : $|d\phi_2| < 1 * 10^{-4}rad$
4. Longitudinal residual cut : $|dz_2| < 9 * 10^{-2}mm$



Track purity as a function of pt

- The redundancy cuts implemented on the hits in the middle layer allows rejection of a lot of fake combinations at a very early stage of reconstruction

(3) Final Track Selection

- Final track selection cuts

1. Minimum momentum : $pt_{013} > 2GeV/c$
2. Longitudinal acceptance : $|\eta_{013}| < 1.4$
3. Luminous region : $|Z_{013}| < 100mm$
4. Momentum consistency :

$|\kappa_{123} - \kappa_{013}|/\sigma_\kappa < 5 * \sigma$ ***medium cut***

$|\kappa_{123} - \kappa_{013}|/\sigma_\kappa < 3 * \sigma$ ***tight cut***

$$\sigma_\kappa^2 = 0.5 * (\frac{w}{d^2})^2 + \frac{t}{X_0 * sin(\theta_{013})} * (\frac{13.6MeV * \kappa_{013}}{0.3 * B * d})^2$$

Hit uncertainty ***MS uncertainty***

→ a check on the consistency of momentum (curvature) measurement using two independent methods

→ $\delta\kappa_{013} << \delta\kappa_{123}$ => $|\kappa_{013} - \kappa_{123}|$ depends on $pt(\kappa_{013})$

$w = 50 * 10^{-3}mm$ is the pixel width,
$d = 20mm$ is the spacing between the layers in the triplet,
$\frac{t}{X_0} = 0.015$ relative radiation length in the middle layer &
$B = 2T$ is the magnetic field

(3) Final Track Selection

- Final track selection cuts

1. Minimum momentum : $pt_{013} > 2GeV/c$
2. Longitudinal acceptance : $|\eta_{013}| < 1.4$
3. Luminous region : $|Z_{013}| < 100mm$
4. Momentum consistency :

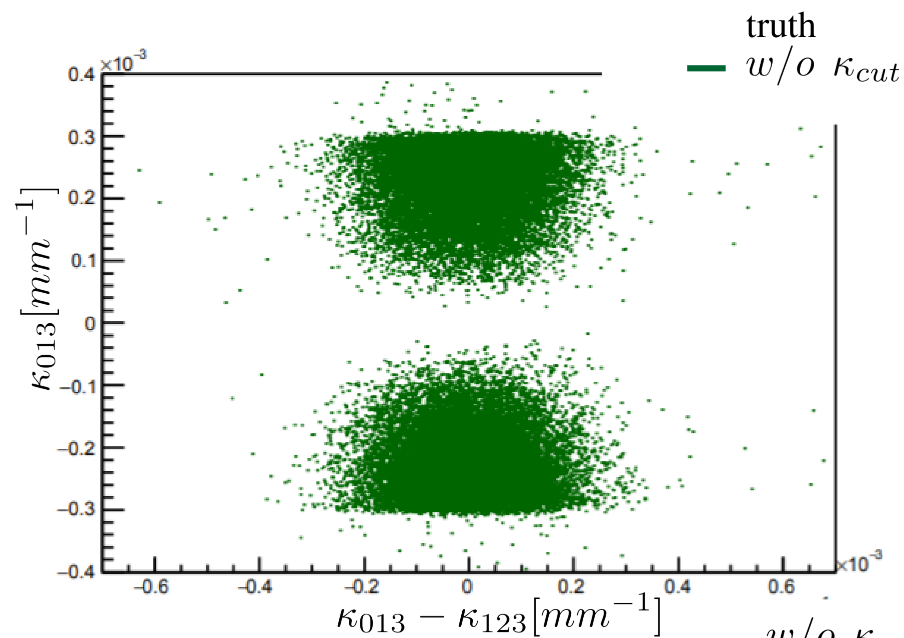
$|\kappa_{123} - \kappa_{013}|/\sigma_\kappa < 5 * \sigma$ ***medium cut***

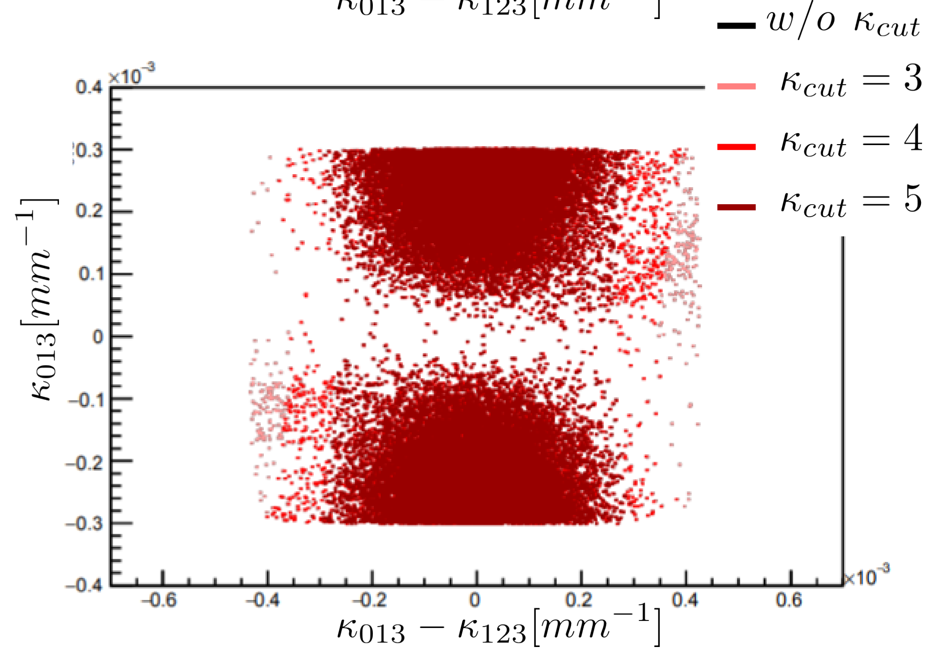
$|\kappa_{123} - \kappa_{013}|/\sigma_\kappa < 3 * \sigma$ ***tight cut***

$$\sigma_\kappa^2 = 0.5 * (\frac{w}{d^2})^2 + \frac{t}{X_0 * sin(\theta_{013})} * (\frac{13.6MeV * \kappa_{013}}{0.3 * B * d})^2$$

Hit uncertainty ***MS uncertainty***

Large smearing effects due to multiple scattering are clearly visible for large values of the curvatures $|\kappa_{013}|$





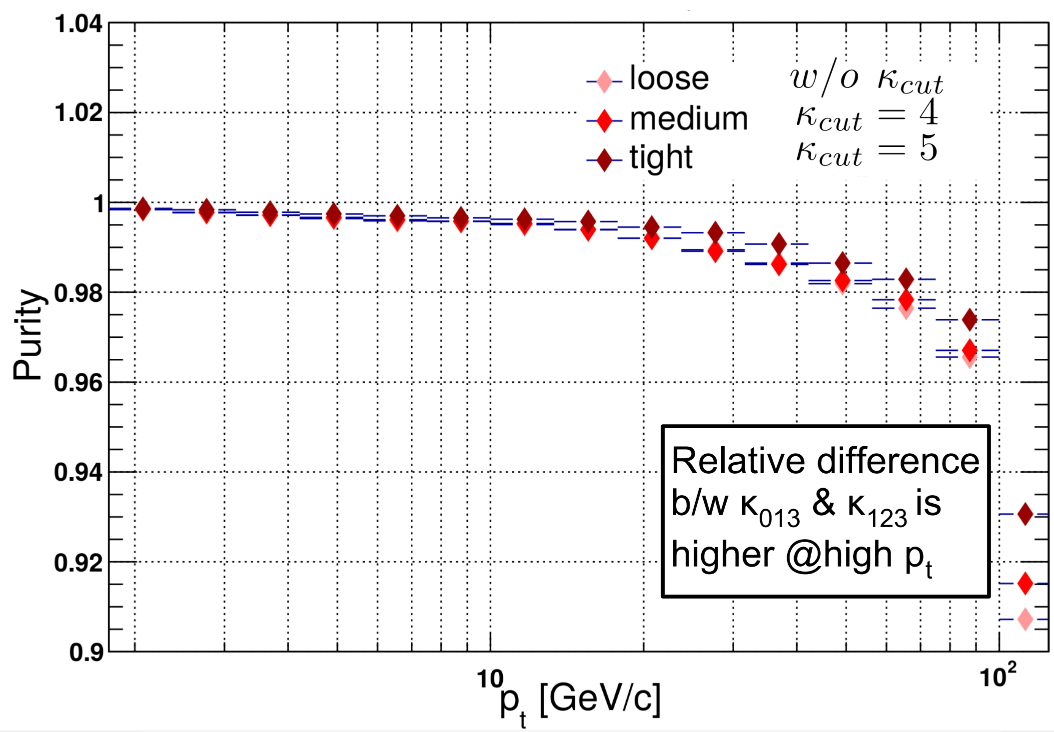
TTT Performance (ATLAS)

- Final track selection cuts

1. Minimum momentum : $pt_{013} > 2GeV/c$
2. Longitudinal acceptance : $|\eta_{013}| < 1.4$
3. Luminous region : $|Z_{013}| < 100mm$
4. Momentum consistency :

$$|\kappa_{123} - \kappa_{013}|/\sigma_\kappa < 5 * \sigma$$ **medium cut**

$$|\kappa_{123} - \kappa_{013}|/\sigma_\kappa < 3 * \sigma$$ **tight cut**



Track purity as a function of pt

$$p = \frac{\#reconstructed\ tracks(cut + matched)}{\#reconstructed\ tracks(cut)}$$

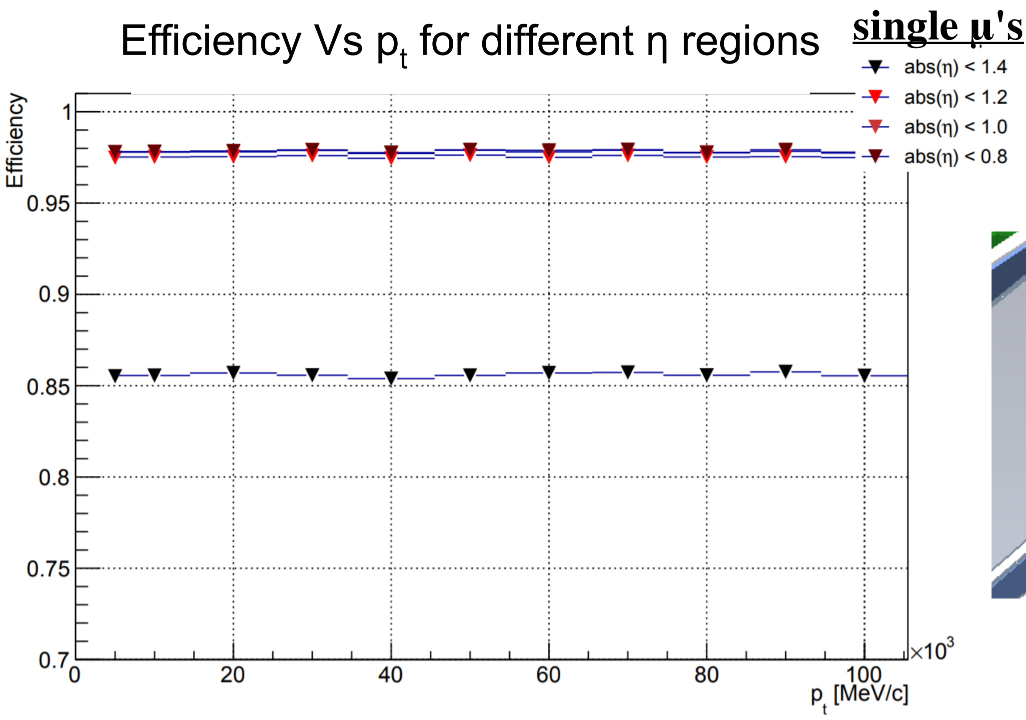
Matched track:
all the three hits of this track have a unique barcode

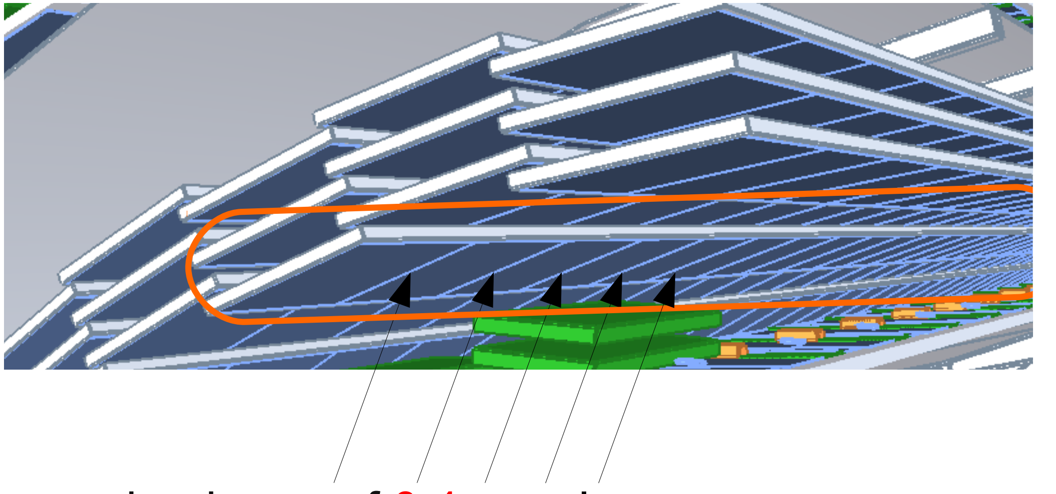
One can gain in track purity at higher track p_t by applying the momentum consistency cut based on tracks reconstructed using two independent methods

Track Reconstruction Performance: Single particles

$$\epsilon = \frac{\#reconstructed\ tracks(cuts + matched)}{\#particles(cuts)}$$

Efficiency Vs p_t for different η regions



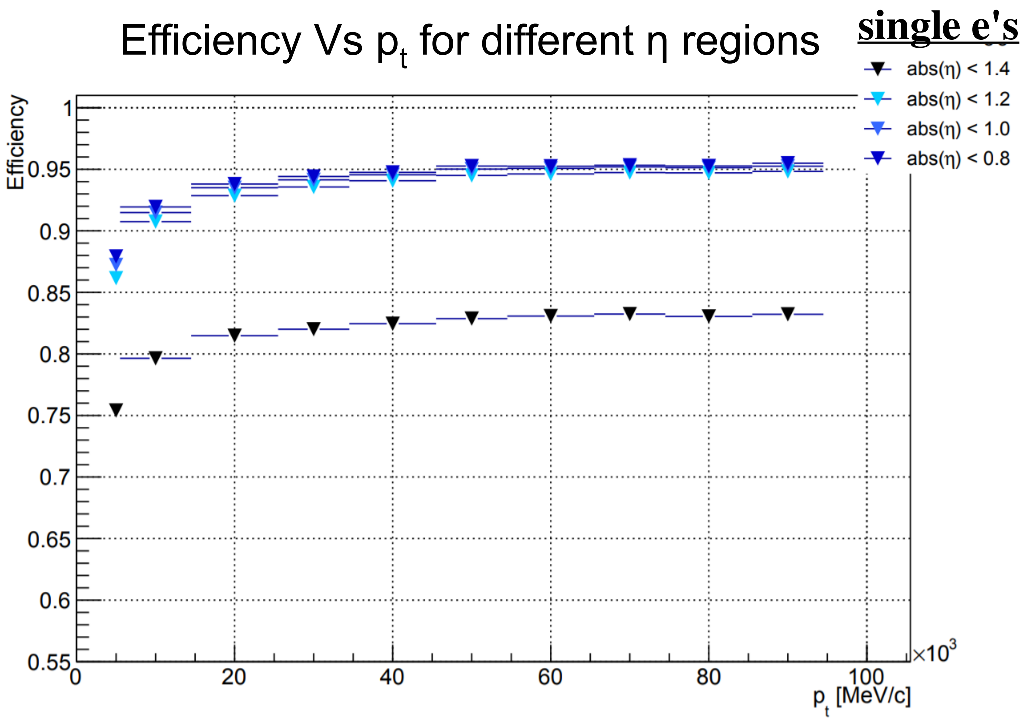


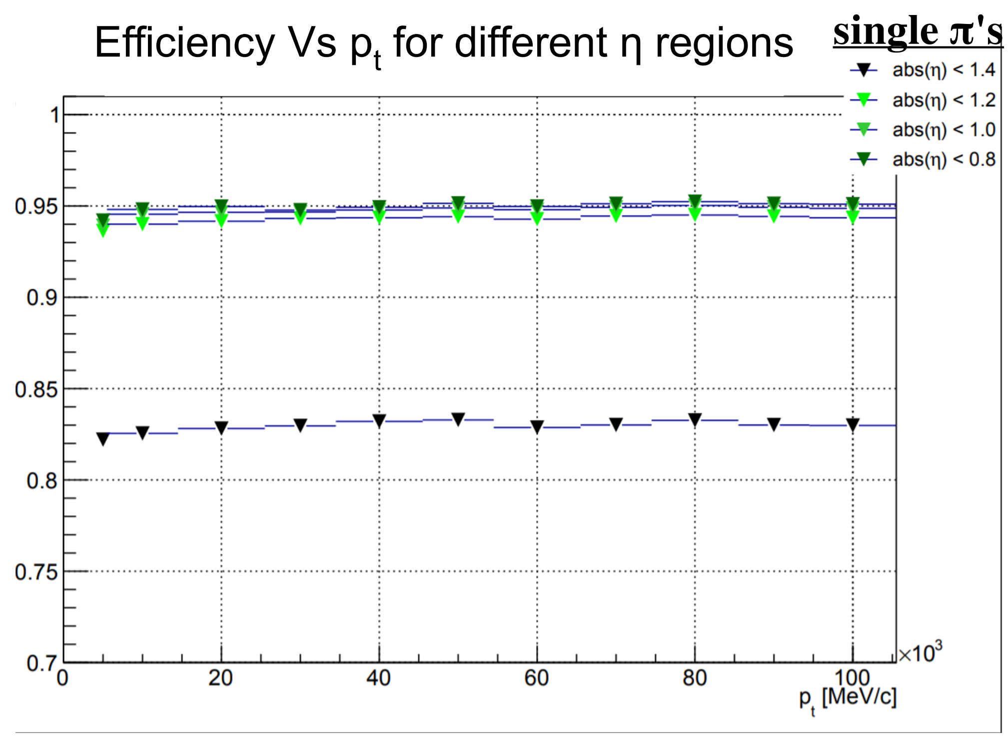
dead area of 0.4mm along a **stave(80 x 80 x 150 mm³)**

- A lot of particles do not make it to the TTT at the edge (η ~ 1.2): interact with inner layers and get detected by the endcaps
- A dead area of 0.4mm between consecutive sensors along a stave → very conservative

Track Reconstruction Performance: Single particles

$$\epsilon = \frac{\#reconstructed\ tracks(cuts + matched)}{\#particles(cuts)}$$



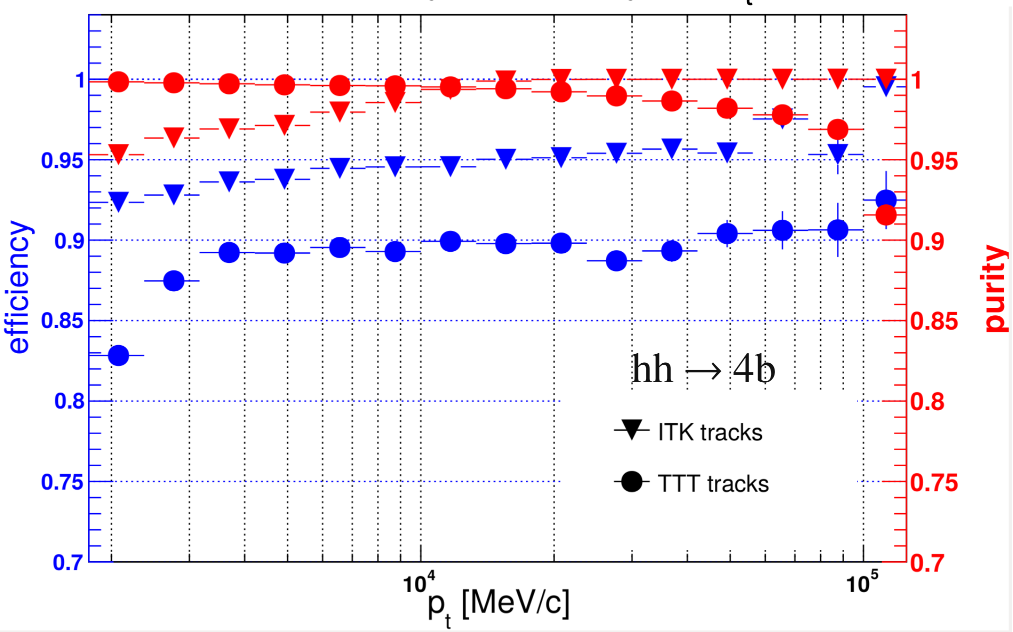


- A lot of particles do not make it to the TTT at the edge (η ~ 1.2): interact with inner layers and get detected by the endcaps
- A dead area of 0.4mm between consecutive sensors along a stave → very conservative
- Inefficiencies: @low p_t - electrons emitting bremsstrahlung, @high p_t – hadron interactions

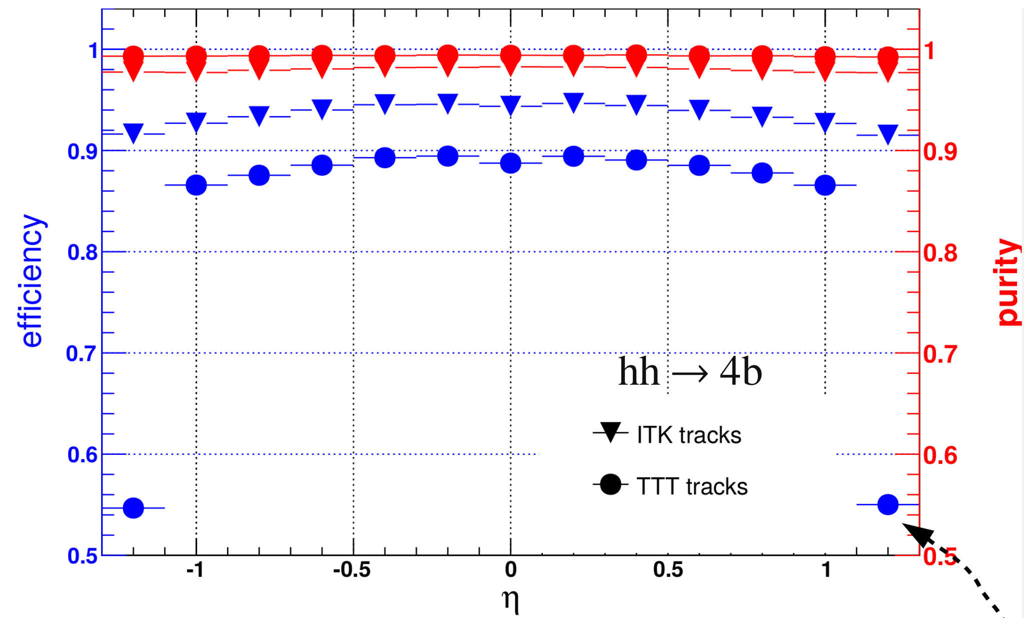
Track Reconstruction Performance Comparisons (TTT Vs ITK)

$$\epsilon = \frac{\#reconstructed\ tracks(cuts + matched)}{\#particles(cuts)}$$

Efficiency and purity Vs p_t

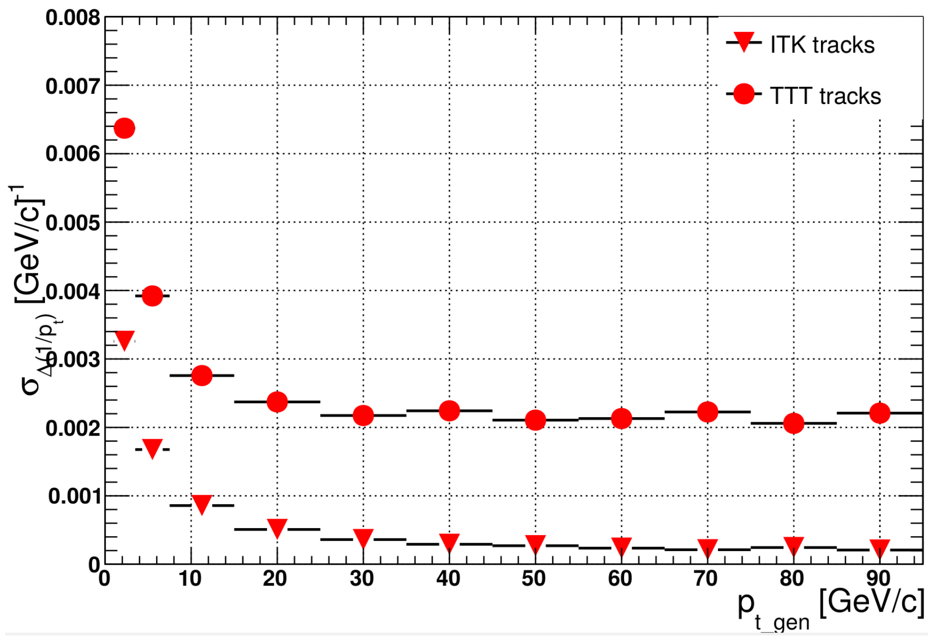


Efficiency & purity Vs η

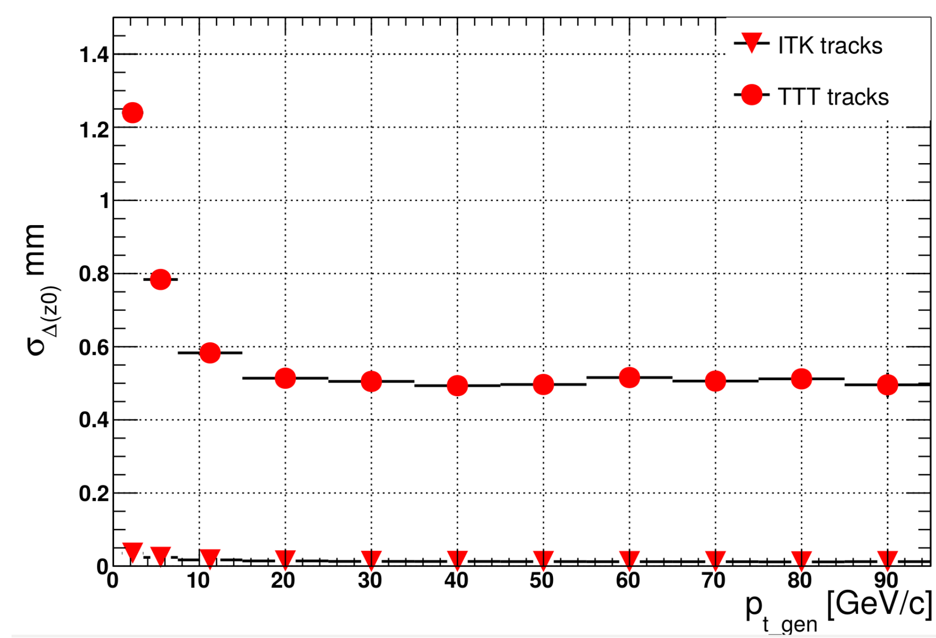


- Inefficiencies (ITK, TTT): @low p_t - electrons emitting bremsstrahlung, @high p_t – hadron interactions (hh → 4b dominated by pions)
- A lot of particles do not make it to the TTT at the edge (η ~ 1.2): interact with inner layers and get detected by the endcaps
- A dead area of 0.4mm between consecutive sensors along a stave in TTT → very conservative

Track Parameter Resolution Comparisons (TTT Vs ITK)



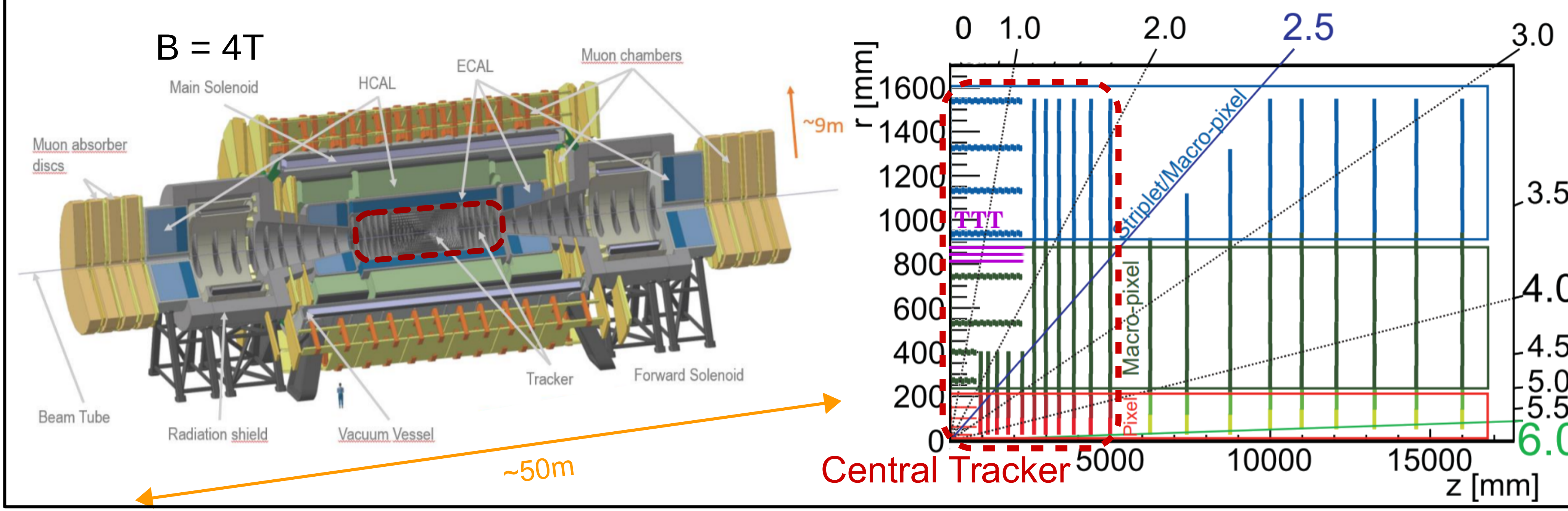
Inverse momentum resolution Vs p_t



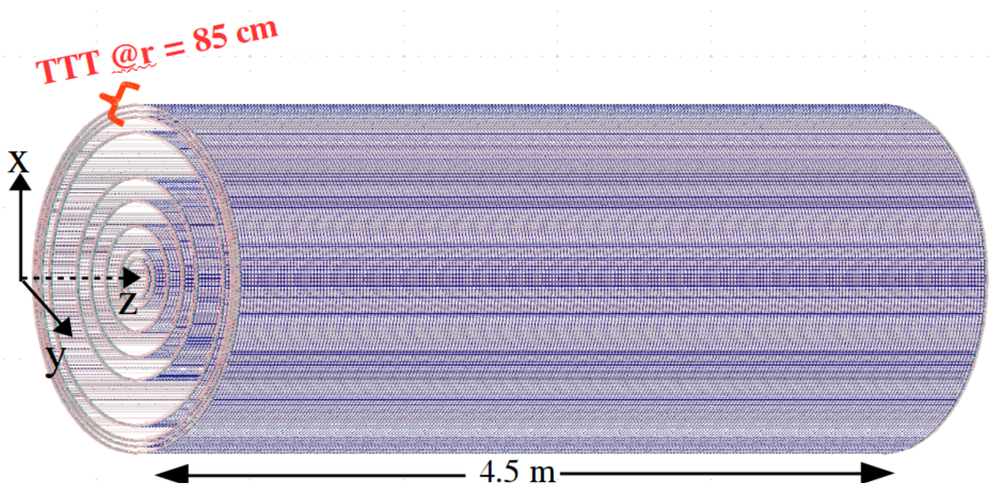
z0 resolution Vs p_t

- ITK tracks have better momentum and z0 resolution than the TTT tracks
- z0 resolution with sub-mm precision for p_t > 4 - 5GeV
  → Can be used to suppress pileup at the very first level
- ITK tracks have much better z0 resolution, as the pixel layers are very much closer to the beamline (@3.9cm → 1st pixel layer)

TTT Study for FCC-hh (standalone G4 simulation)



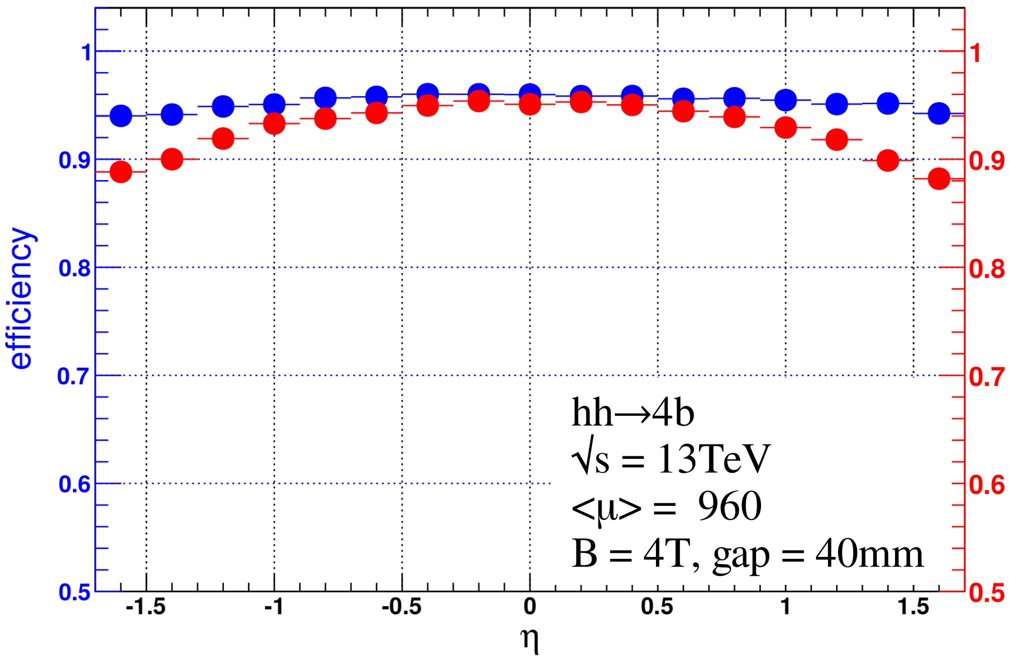
Baseline detector design and tracker layout for FCC-hh (FCC-hh CDR)



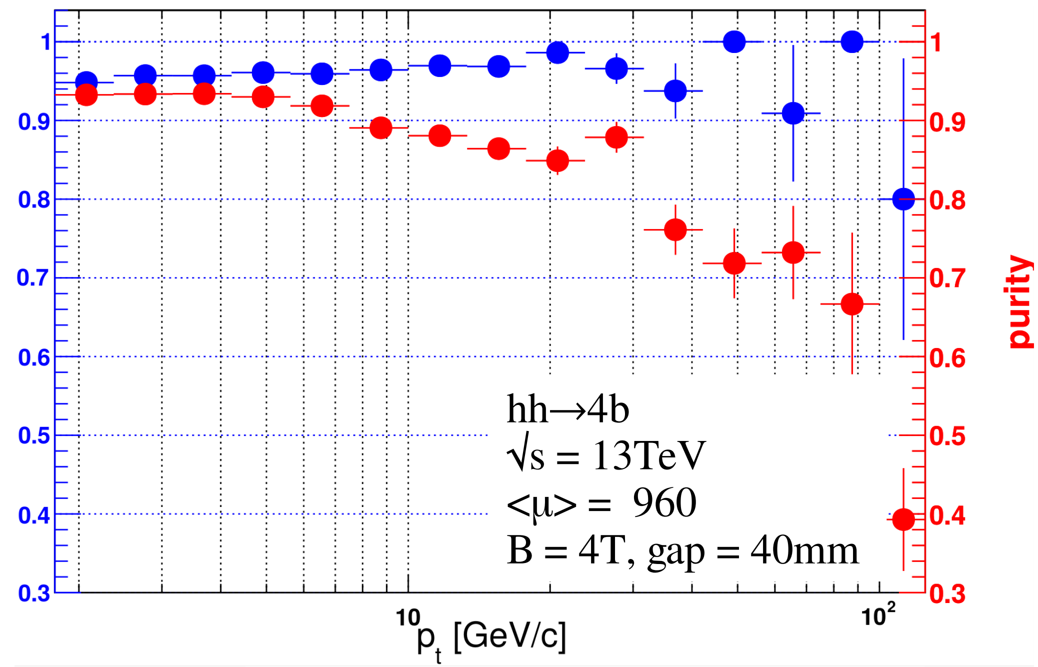
TTT Geometry Specifications in a FCC-hh like detector:

- → radius: 85cm
- → barrel: 450cm
- → η range: |1.7|
- → gap size: 2, 4, 5cm
- → x/X_0 per layer: 2%
- → sensor: 2x2cm^2
- → pixel size: 40μm^2 (CMOS Monolithic)

TTT Performance (FCC-hh)



Efficiency & purity Vs η



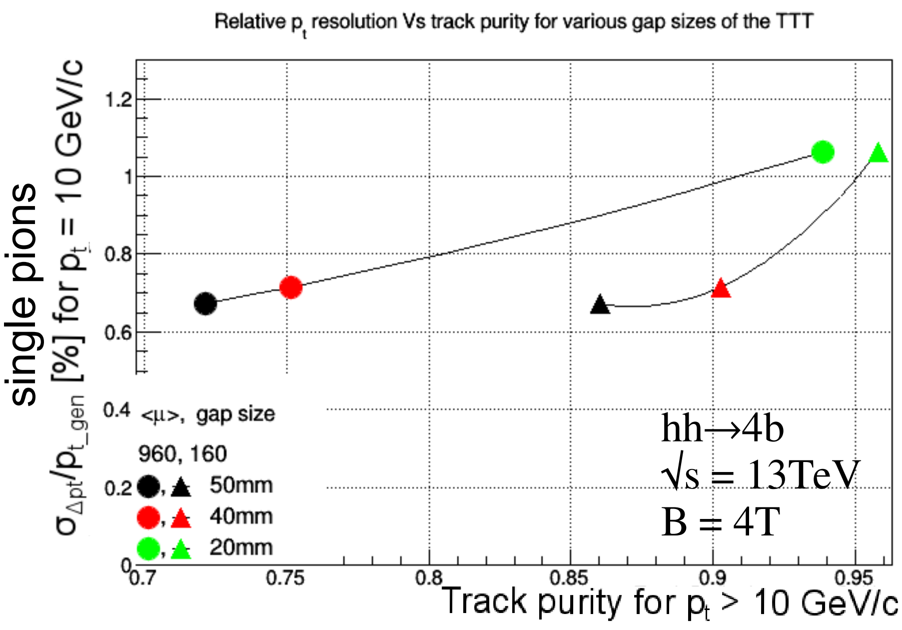
Efficiency & purity Vs p_t

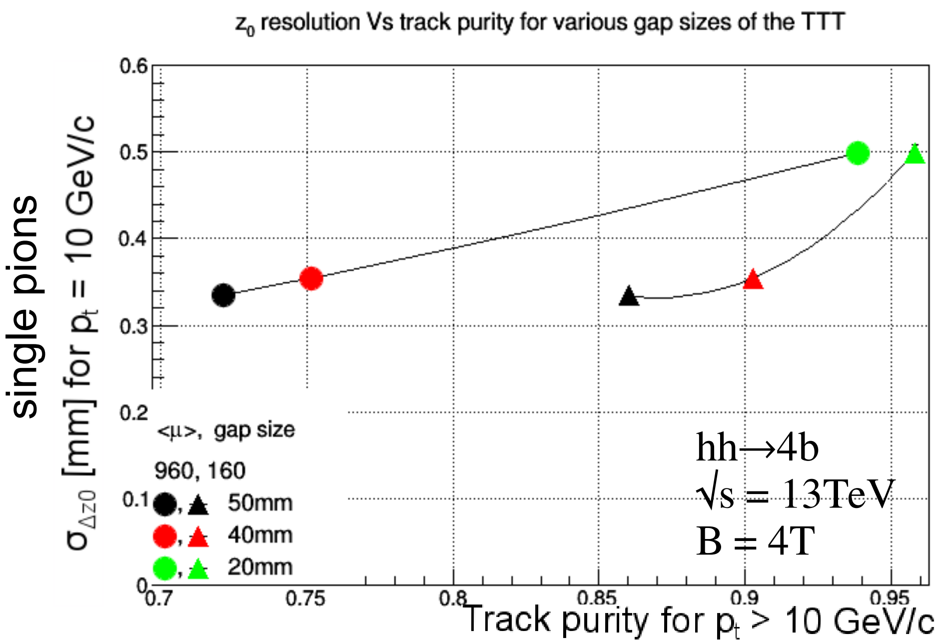
$$\epsilon = \frac{\#reconstructed\ tracks(cuts + matched)}{\#particles(cuts)}$$

$$p = \frac{\#reconstructed\ tracks(cut + matched)}{\#reconstructed\ tracks(cut)}$$

Track reconstruction efficiency >92% and purity ~75% at pileup 1000

TTT Performance (FCC-hh)





- Track purity degrades more rapidly with the gap size of the TTT and with increasing pileup as expected
- Momentum resolution of better than 1% @10GeV/c is achievable using TTT with gap size of >20mm
- Z0 resolution of sub-mm precision possible using TTT @radius = 85cm

Summary

- The concept of TTT based on Monolithic CMOS technology is a very simple and fast track reconstruction algorithm.
- Can be implemented in hardware and will allow online tracking at the very first level!
- Two studies ongoing: ATLAS Athena framework and standalone G4 simulations
- Excellent fake rejection in track reconstruction using TTT possible.
- TTT has momentum and z0 resolution good enough to suppress pileup to a significant amount.
- Early availability of z0 of the tracks will allow pileup suppression, increase the signal acceptance for certain interesting physics processes.

Outlook

- ATLAS: Athena Software Framework

→ Generate pileup samples, quantify pileup rejection using TTT trackjets.

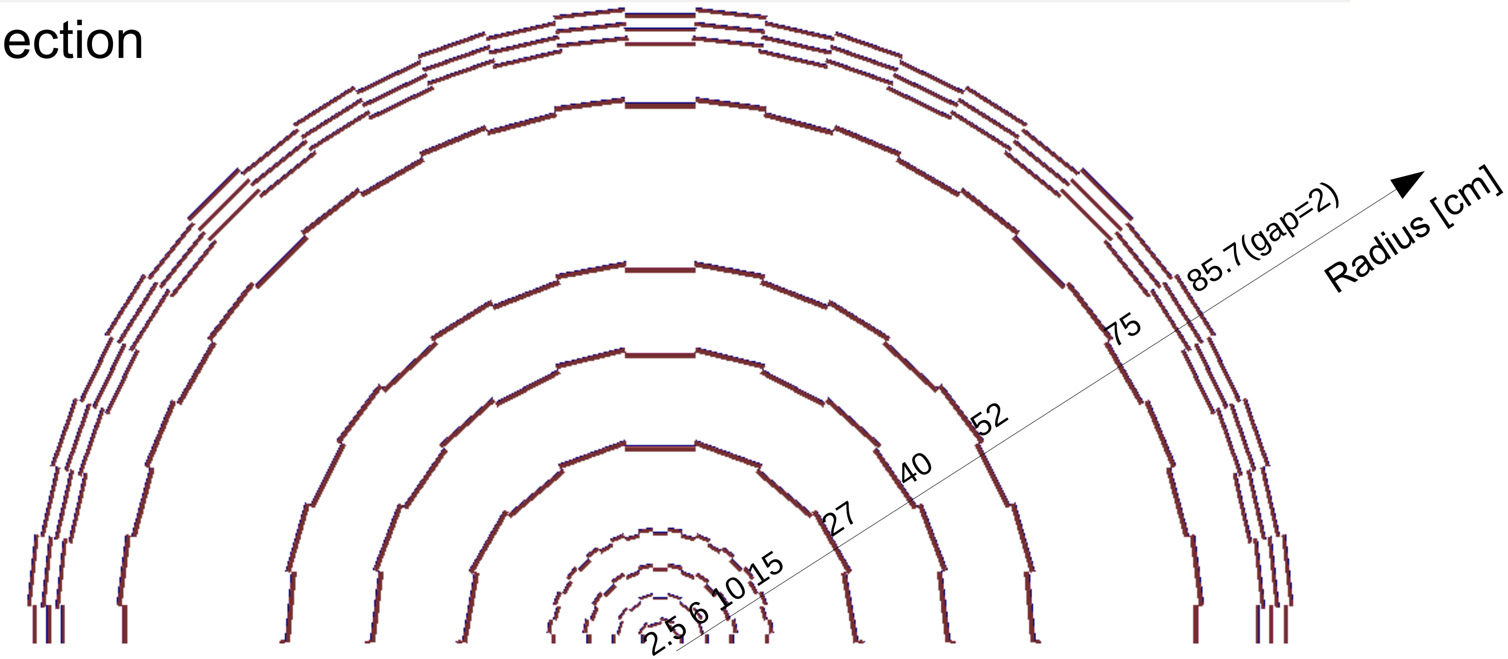
- FCC-hh: G4 Standalone Simulation and Reconstruction

✔ Generate hh → 4b via VBF samples for $\sqrt{s}$ = 100TeV

✔ Castellated tracker design with material budget as defined in FCC-hh CDR

→ Repeat the full chain for different geometry parameters and pileup

→ Pileup rejection



Backup

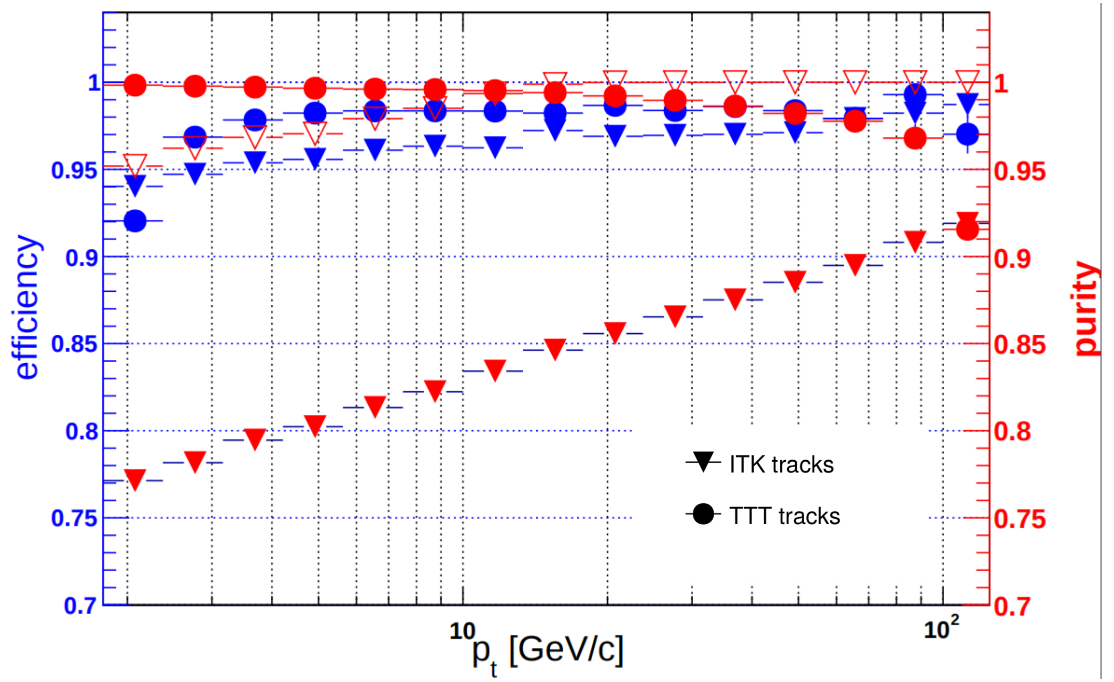
Track Reconstruction Performance Comparisons (TTT Vs ITK)

Track reconstruction efficiency:

$$\epsilon = \frac{\#reconstructed\ tracks(cuts + matched)}{\#particles_{\ making\ a\ hit\ in\ l_3}(cuts)}$$

- Reconstruction efficiency of TTT tracks better than ITK tracks
  $\longrightarrow$ large radius allows reconstruction of many secondaries

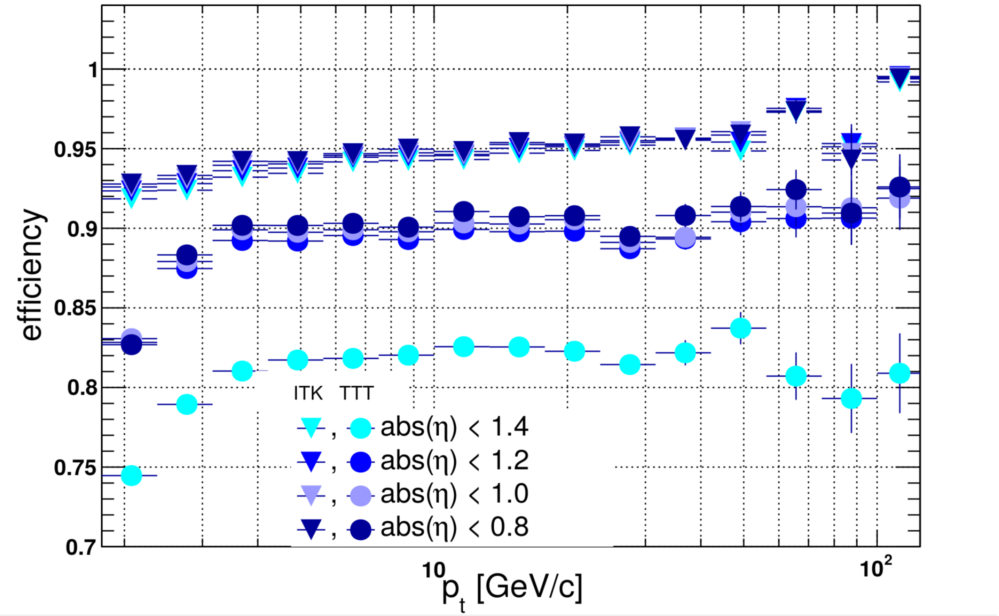
- ▽ Purity of tracks matched to all particles
  $\longrightarrow$ discrepancy(~15%) b/w ▽ & ▼ : these fraction of particles do not exist in the truth particle container that they are matched to



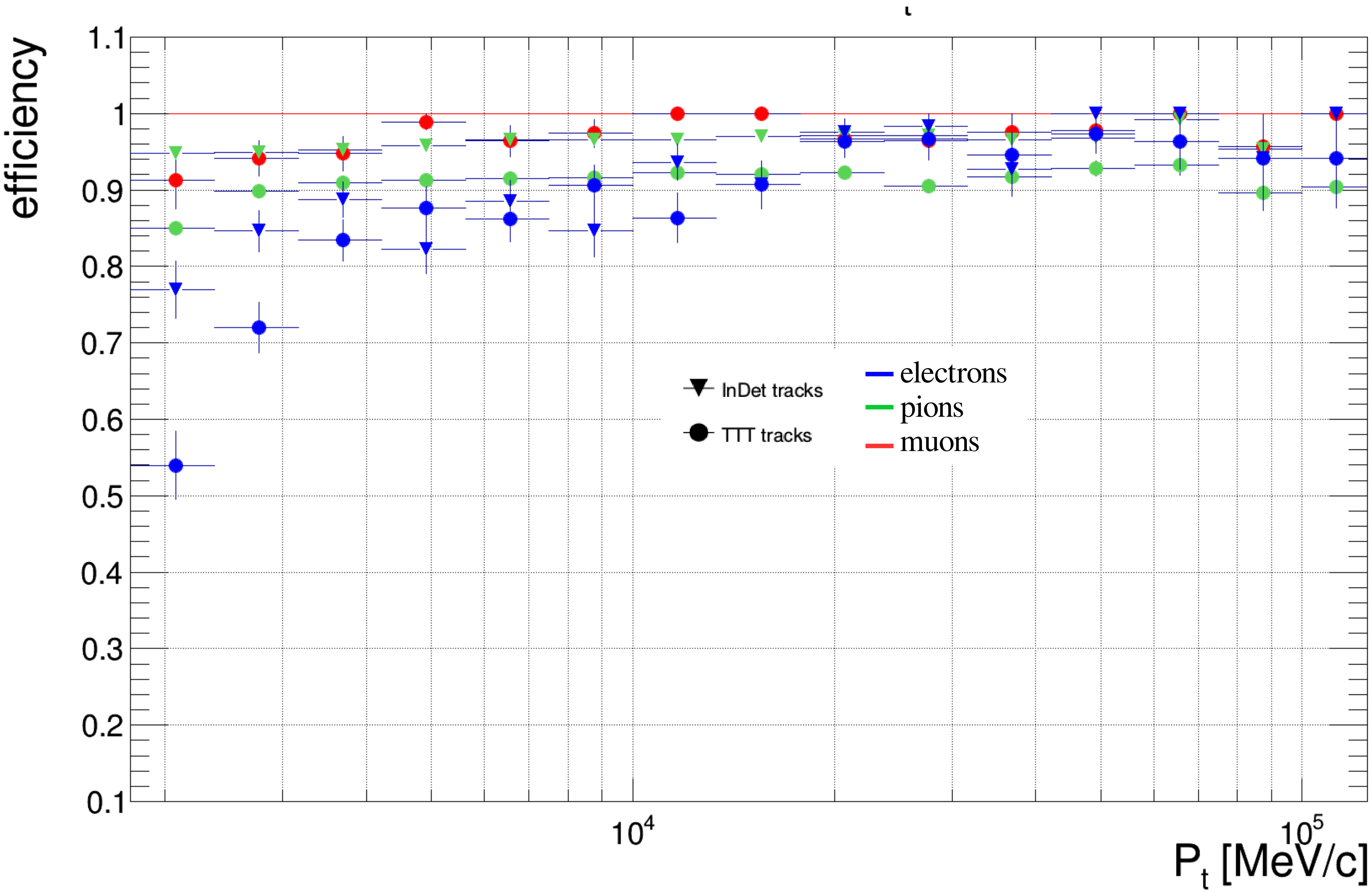
Efficiency & purity Vs p_t

Overall track reconstruction efficiency of ~90% and excellent track purities using only **three detector layers compared to nine detector layers**!

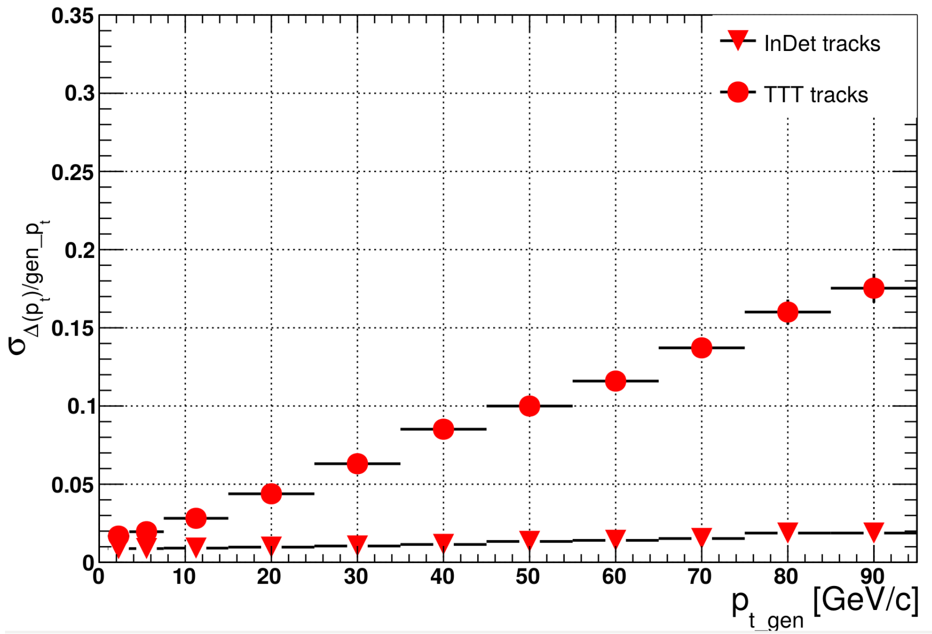
TTT efficiency Vs pt for various eta (ITK Vs TTT)



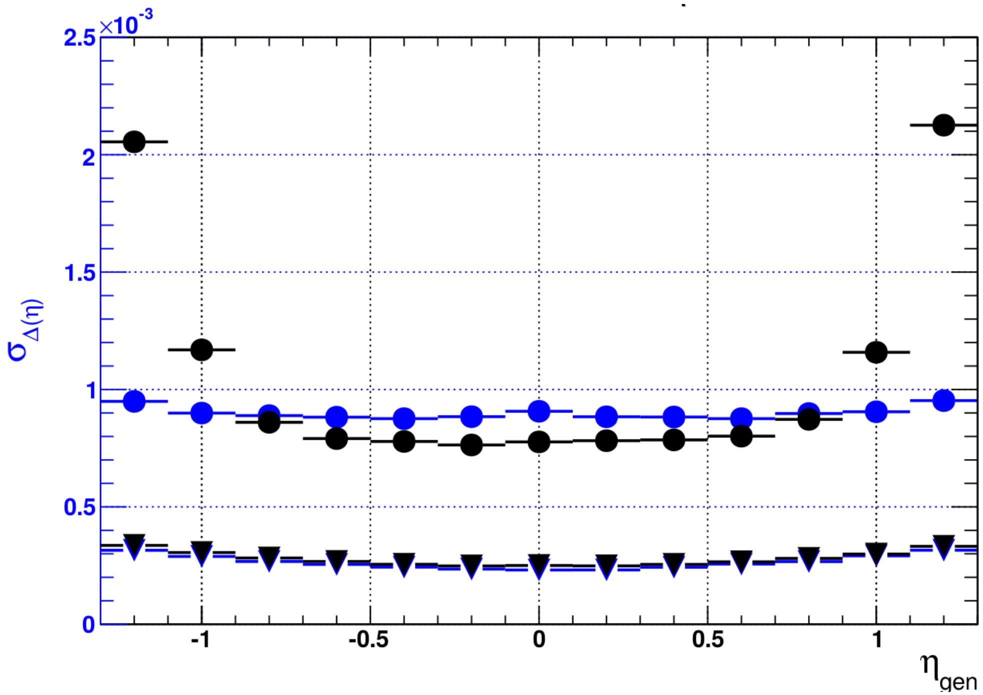
Efficiency comparison of different particles in hh → 4b

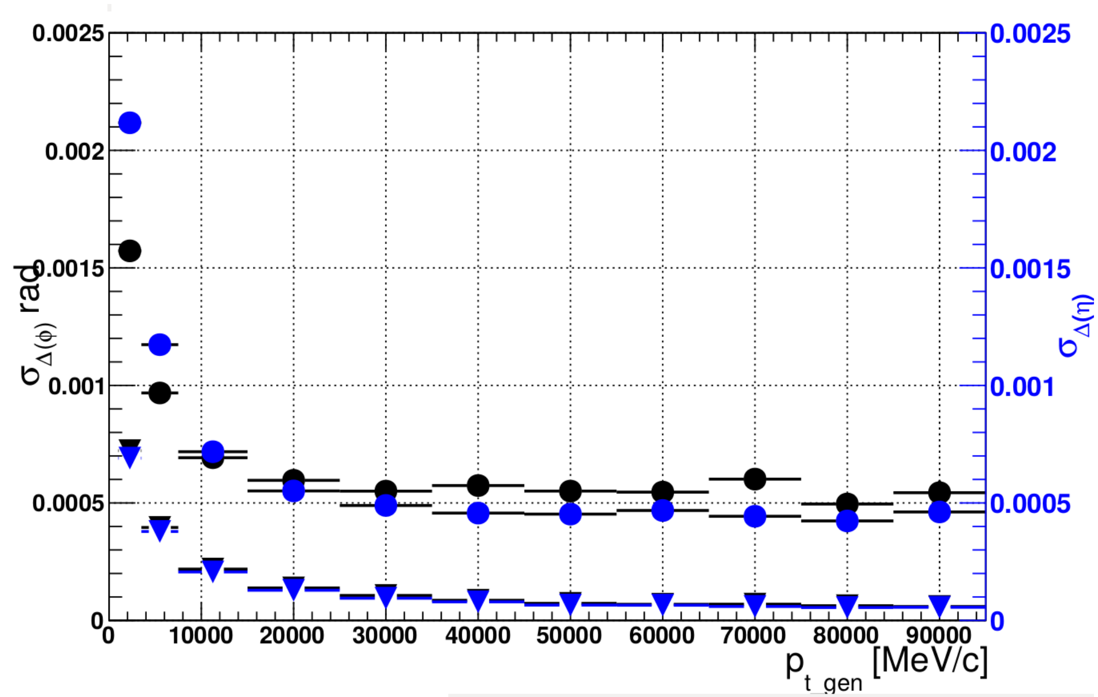


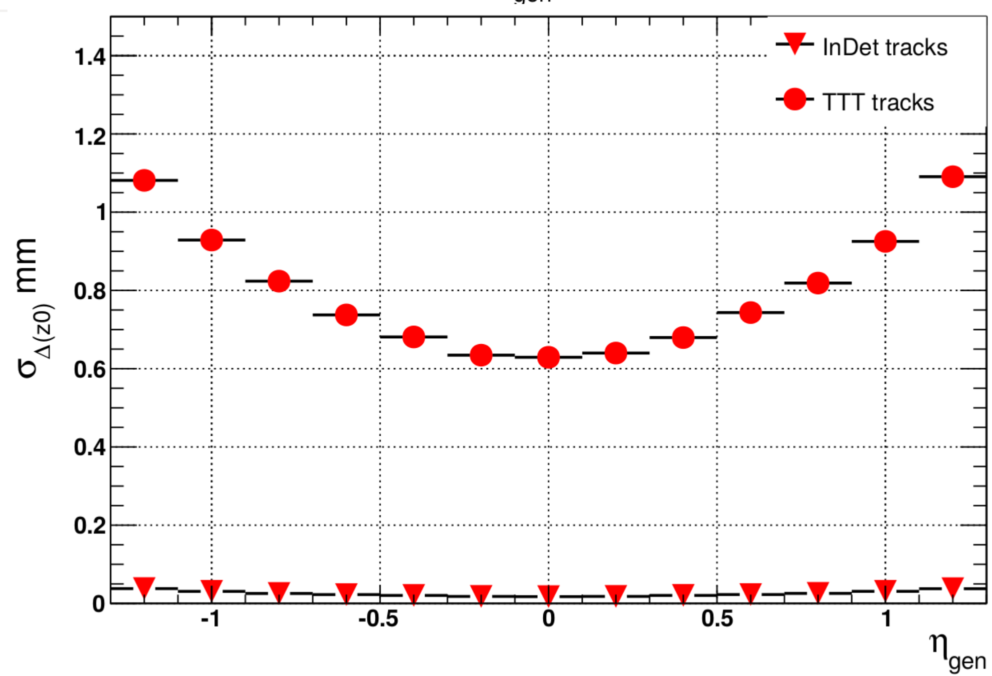
Track Parameter Resolution Comparisons
(ITK Vs TTT)

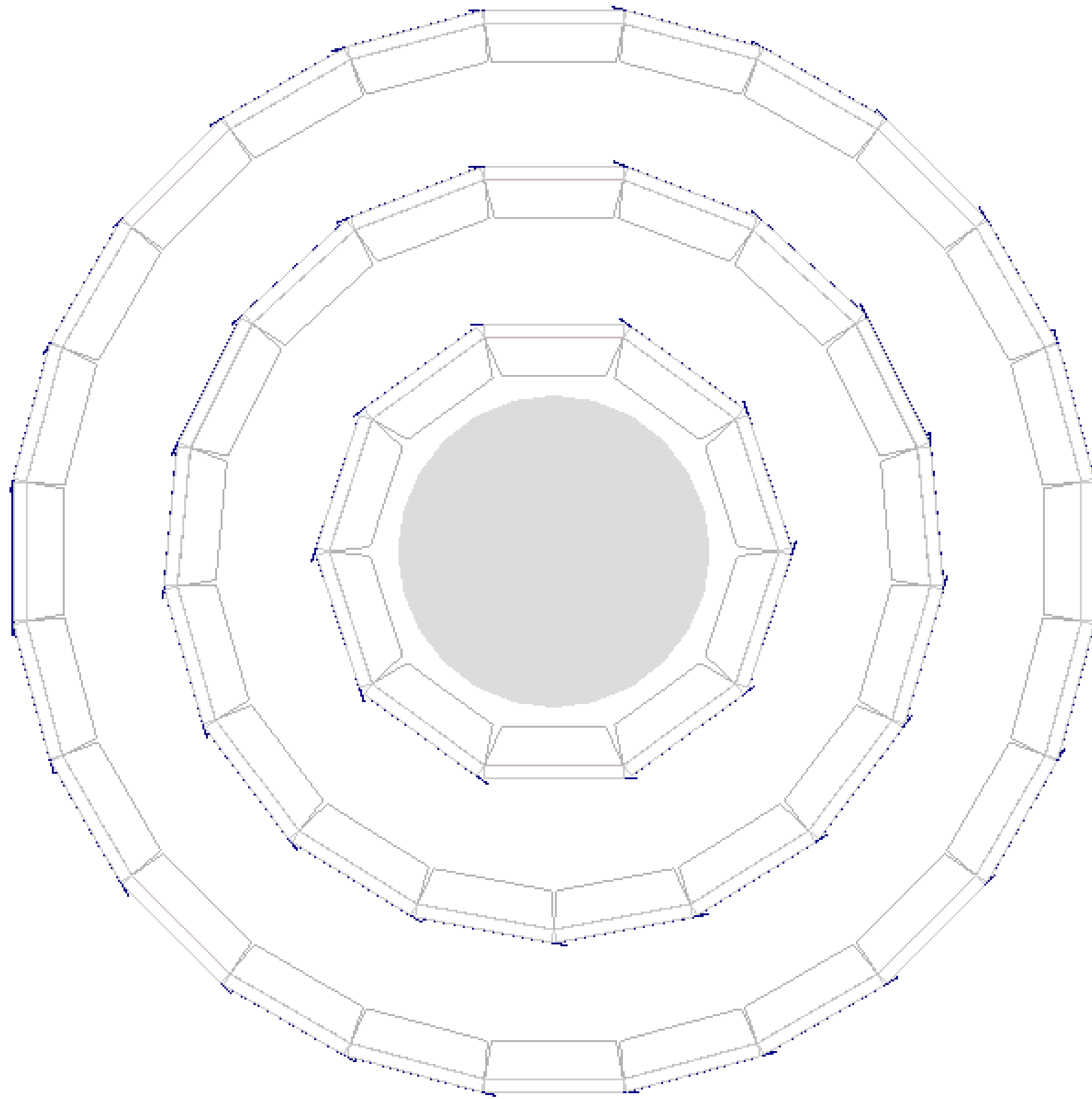


Track Parameter Resolutions

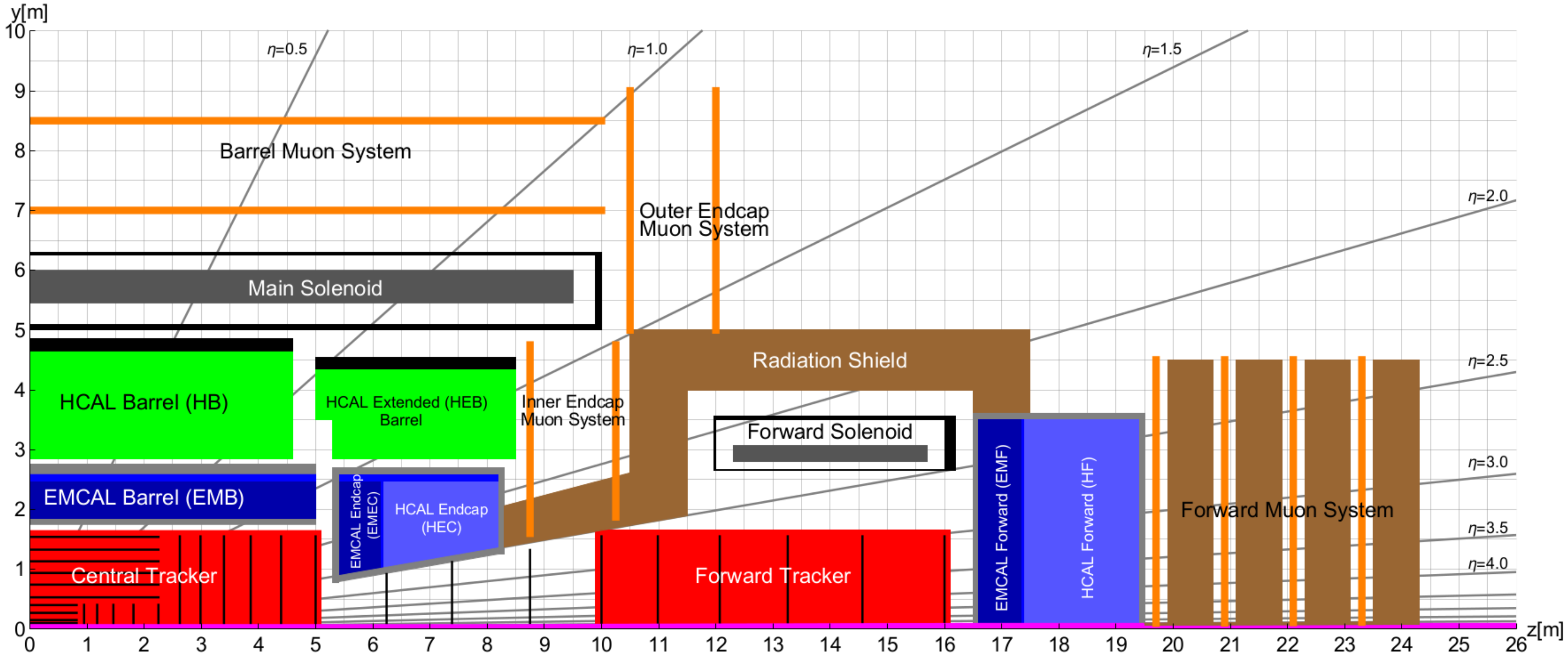








FCC-hh reference detector



FCC-hh: Expected Radiation Fluence

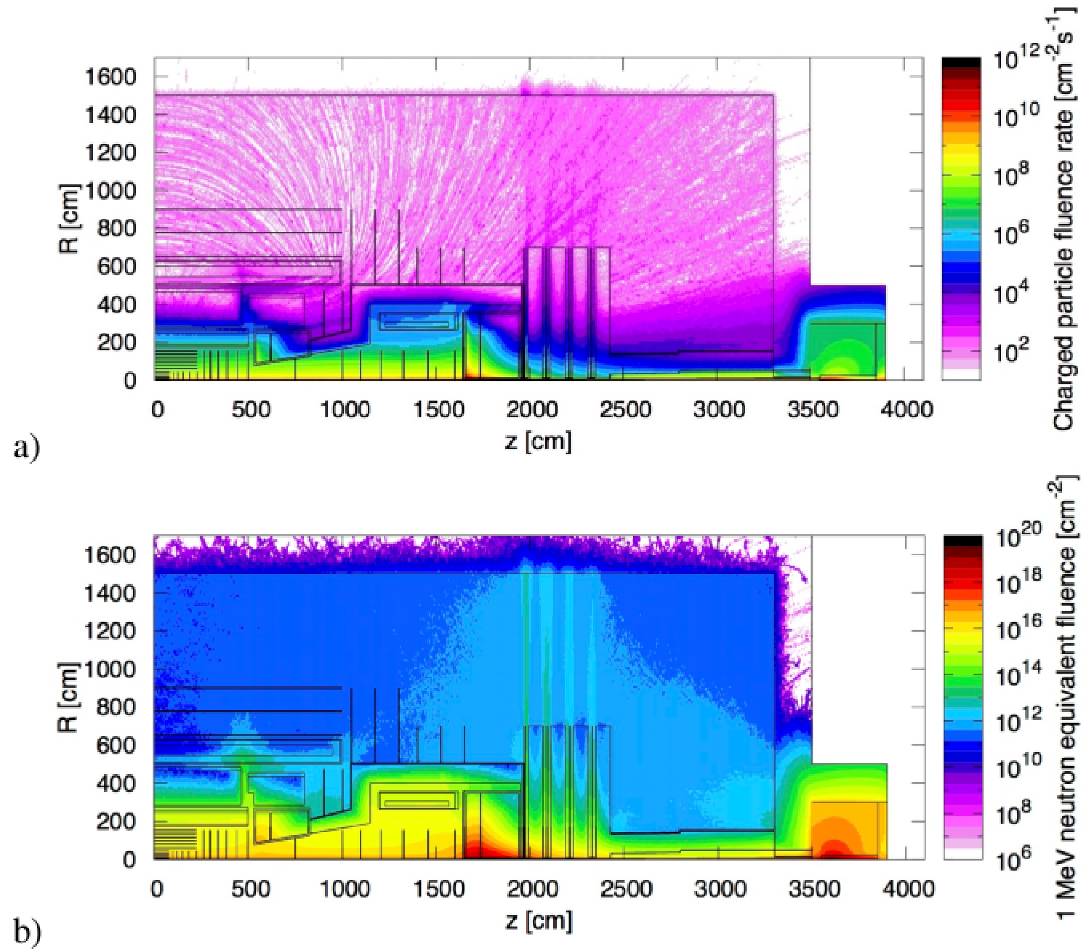
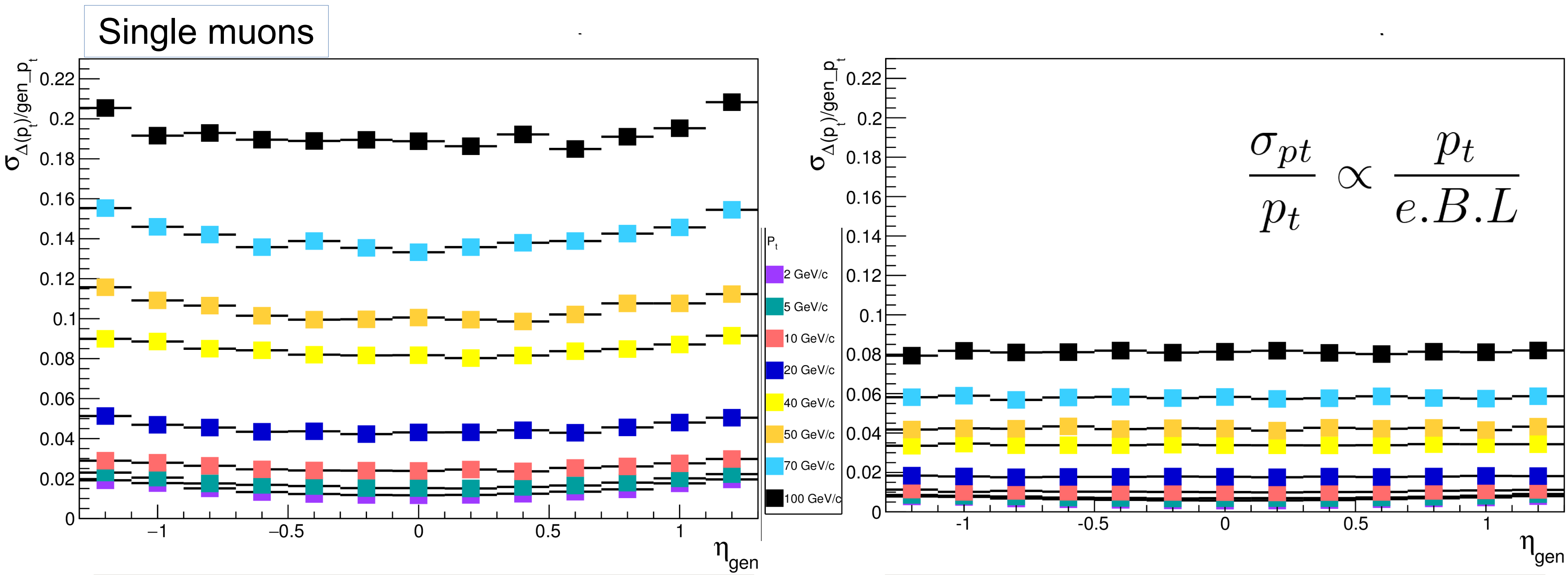


Figure 7.4: a) Charged particle rate for $\mathcal{L}=30\times10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. b) 1 MeV neutron equivalent fluence for $30\,\mathrm{ab}^{-1}$.

Relative momentum resolution

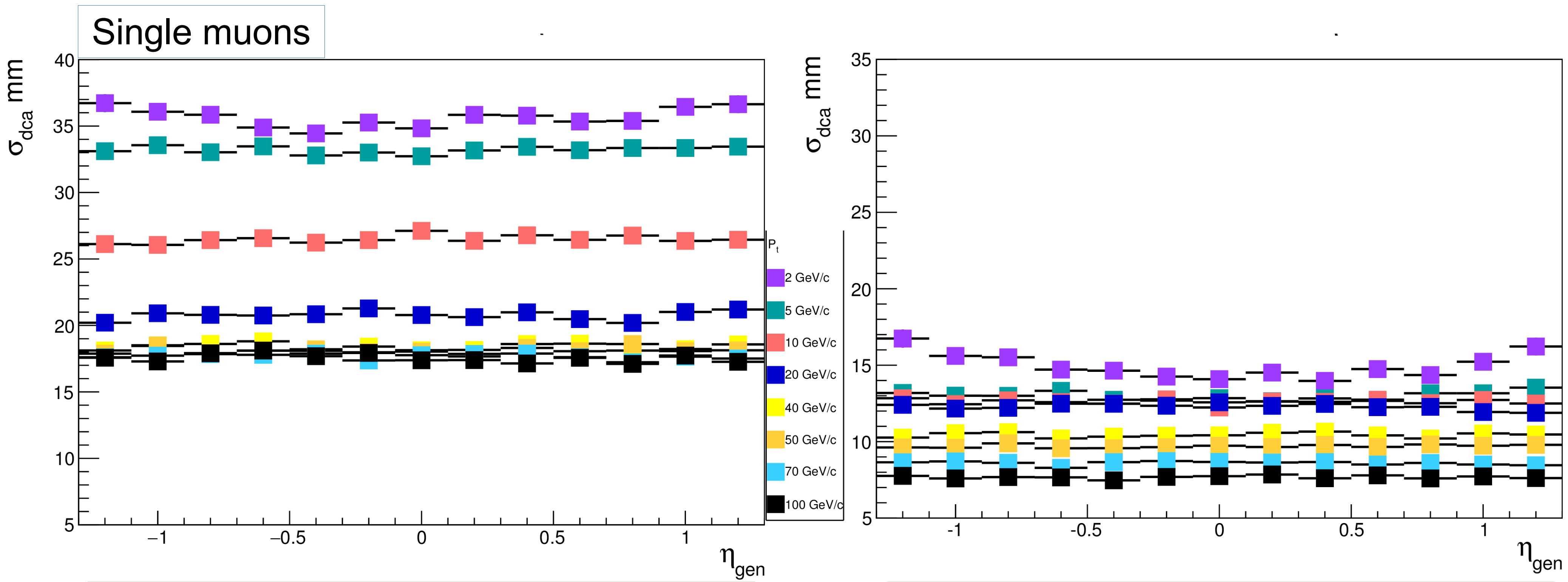


<u>Athena Simulation :</u>
R =857mm, spacing =20mm, B = 2T

<u>Standalone Simulation :</u>
R =857mm, spacing =20mm, B = 4T

- 2 times stronger magnetic field => gain in momentum resolution by a factor of ~2
- resolution < 1% for pt <10GeV/c and < 10% for pt <100GeV/c
- FCC tracker goal : resolution ~ 10 % at pt = 1TeV/c → possible with tracker extending upto 1.6m

d_0 / dca resolution

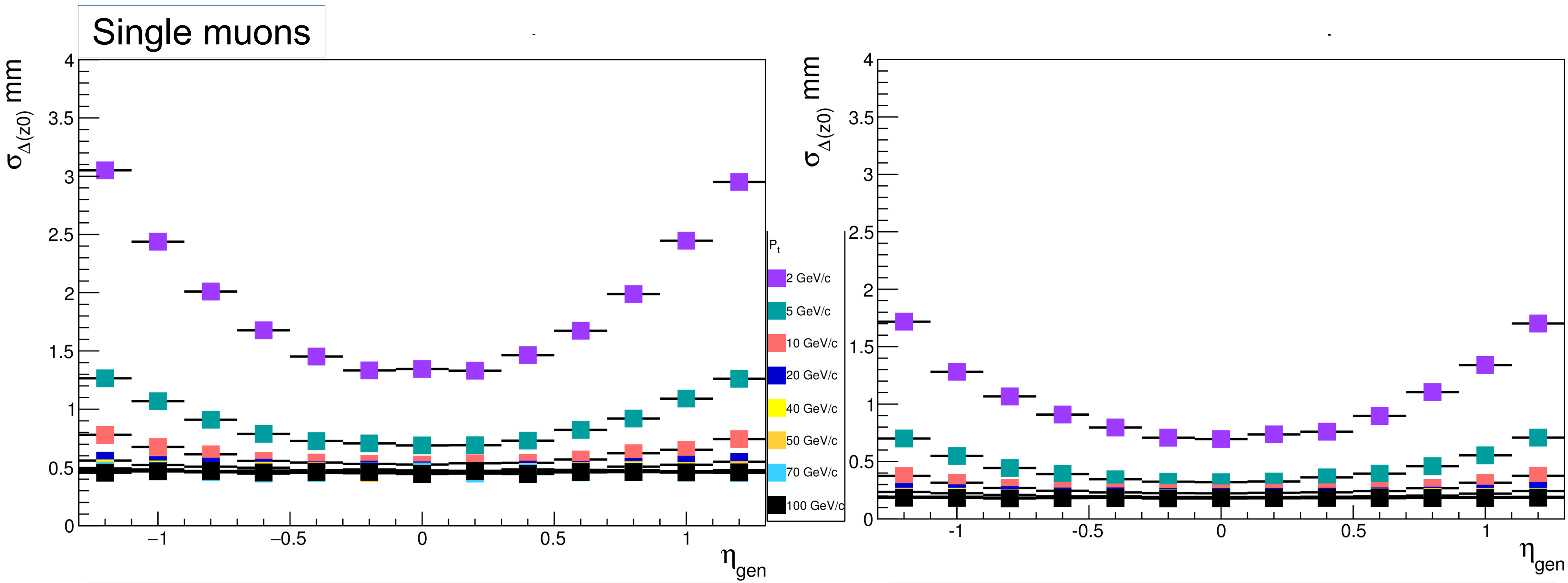


<u>Athena Simulation :</u>
R =857mm, spacing =20mm, B = 2T

<u>Standalone Simulation :</u>
R =857mm, spacing =30mm, B = 4T

- ~2 times gain in dca resolution with increase in layer spacing by 10mm
- Improved fake rejection

Z_0 resolution



<u>Athena Simulation :</u>
R =857mm, spacing =20mm, B = 2T

<u>Standalone Simulation :</u>
R =600mm, spacing =30mm, B = 4T

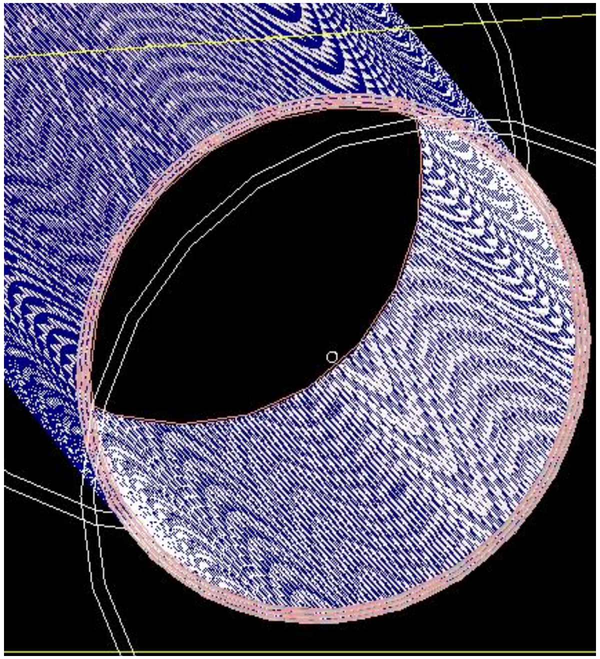
- Triplet tracker can resolve vertices separated ~1mm along the beamline for both HL-LHC and FCC @P_t > 5GeV/c
- Good Z_0 resolution is the key to pileup suppression
- Z_0 resolution increases as one goes closer to the beamline → rate increases at the same time

TTT Study (standalone)

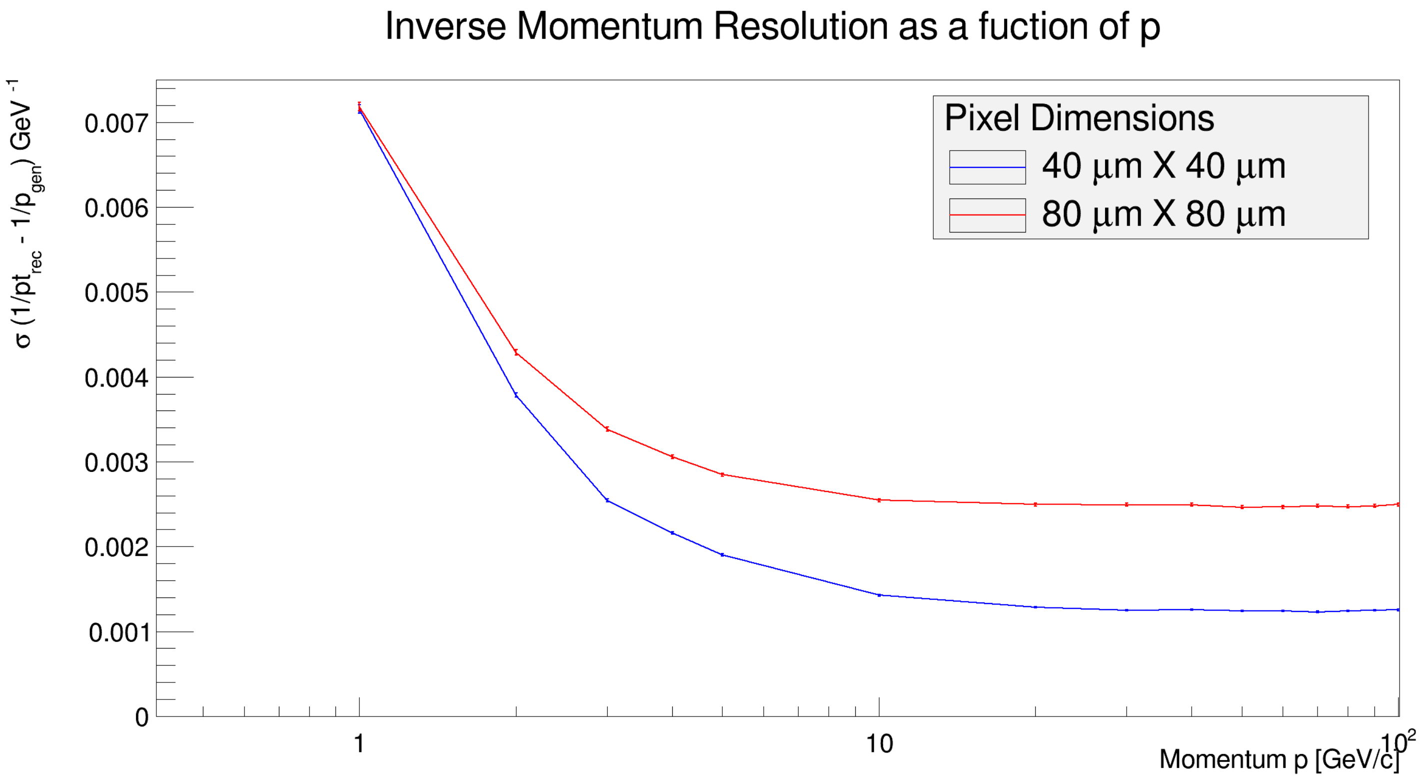
$x/X_0 = 2\%$ per layer

layer spacing between the triplets → 2cm

Muons fired from (0,0,z)



- Effect of pixel size, with no material in front of the detector triplet.



Significant improvement in momentum resolution in the high momenta regime by using pixels of 40 x 40 μm^2

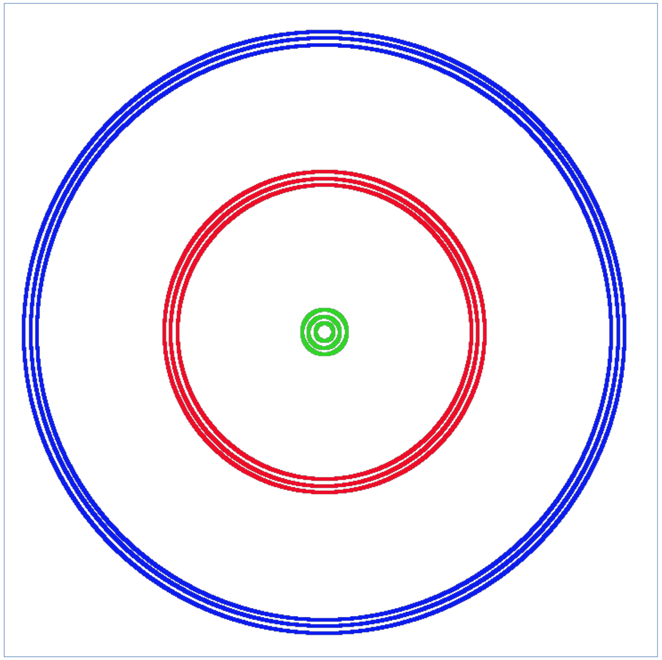
TTT Study (standalone)

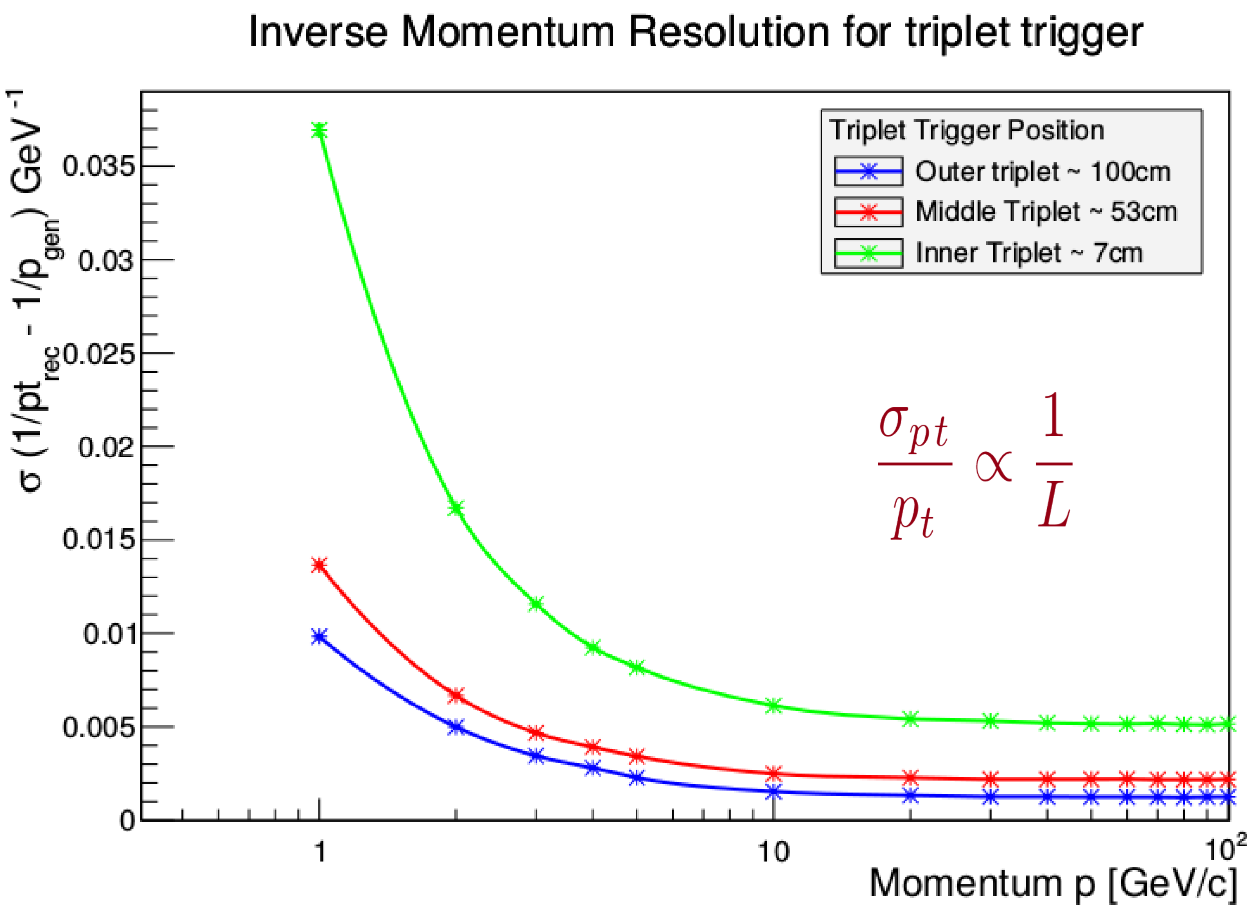
$x/X_0 = 2\%$ per layer

layer spacing between the triplets → 2cm

Muons fired from (0,0,z)

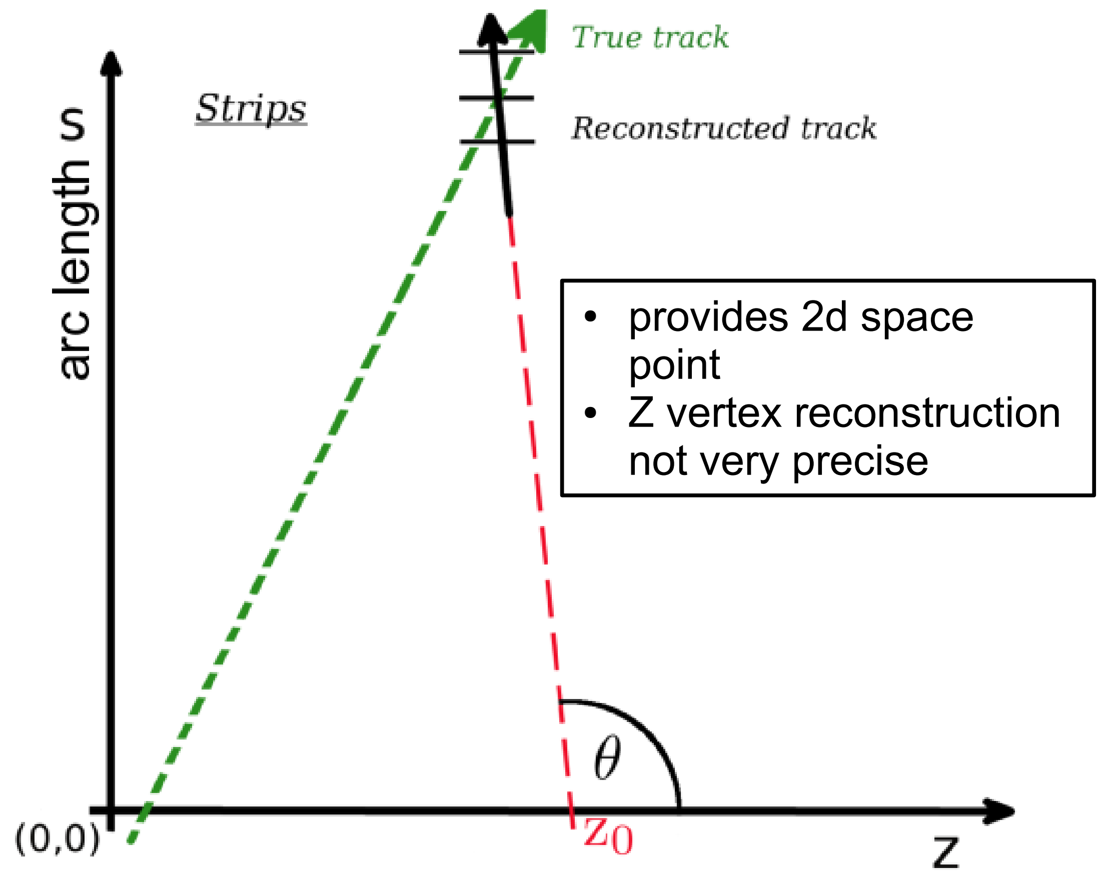
Transverse view of detector





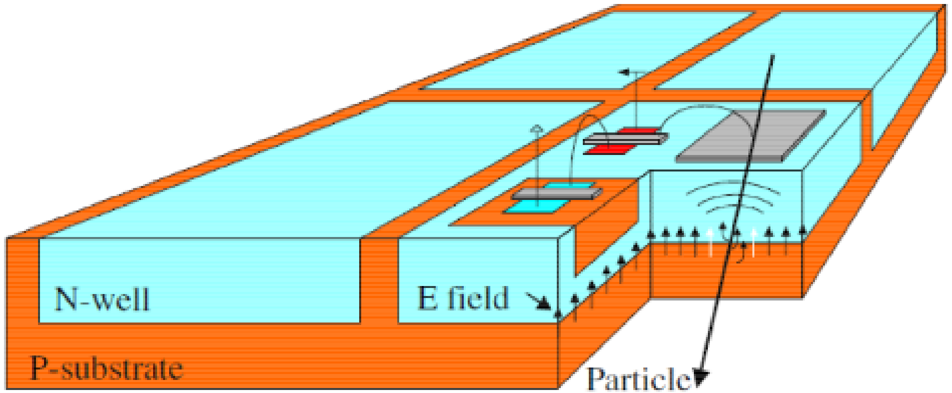
Why pixels and not strips?

- Three closely stacked detector layers at large radii → Triplet
- Uniform magnetic field B along the axis of the detector layers (Z axis)
- Particle propagates in a helical trajectory in B
- Straight line (S – Z plane)



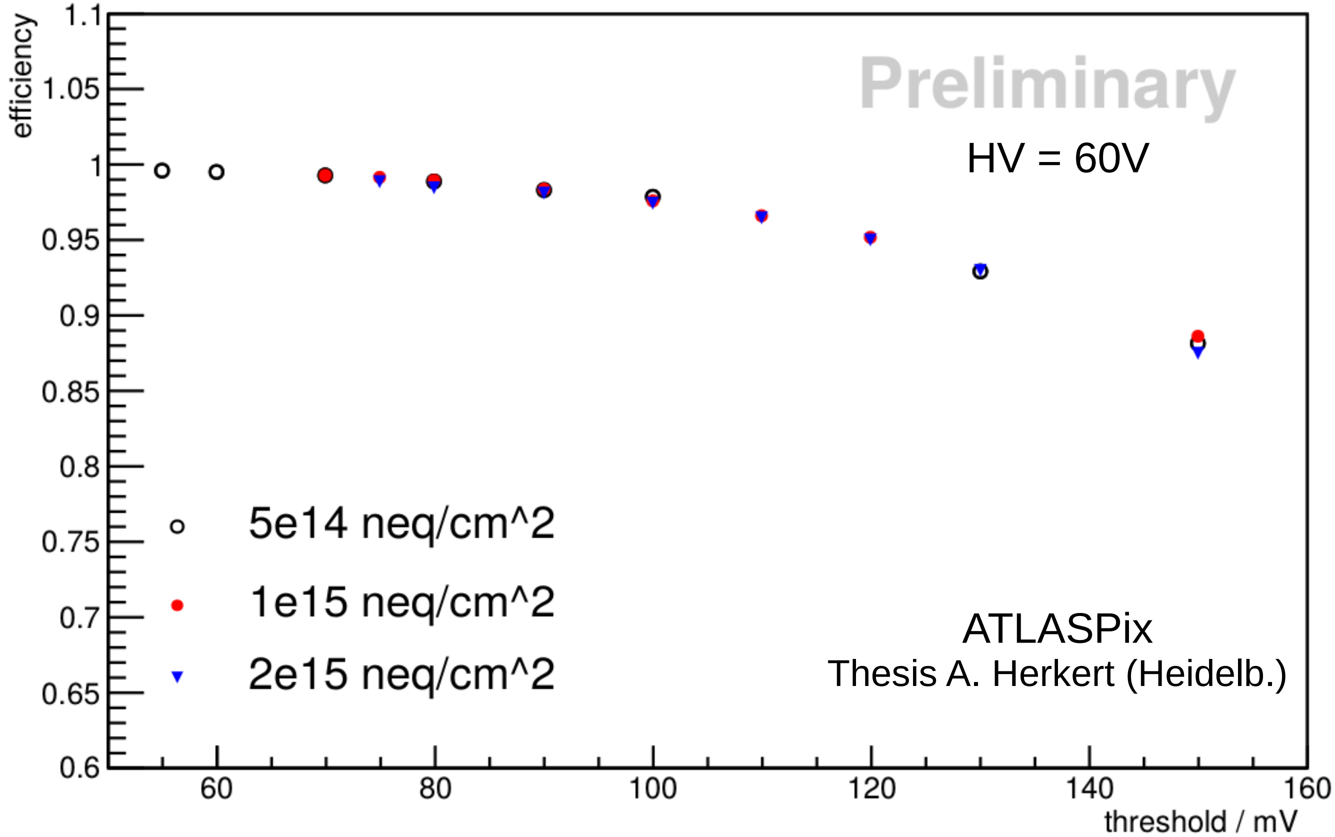
High Voltage Monolithic Active Pixel Sensors

- Moderate cost of production (~€$2/cm^2$)
- Combines sensor and readout electronics into a single unit.
- No bump bonding ➡ Easy fabrication
- Charge collection by drift (Standard HV-CMOS process)



Ivan Perić, NIMA 582 (2007) 876

Radiation Hard ATLASPix



Rate as a function of radius (Fast Simulation)