Tracker Occupancy & Material Studies for FCC-hh

Zbyněk Drásal

CERN

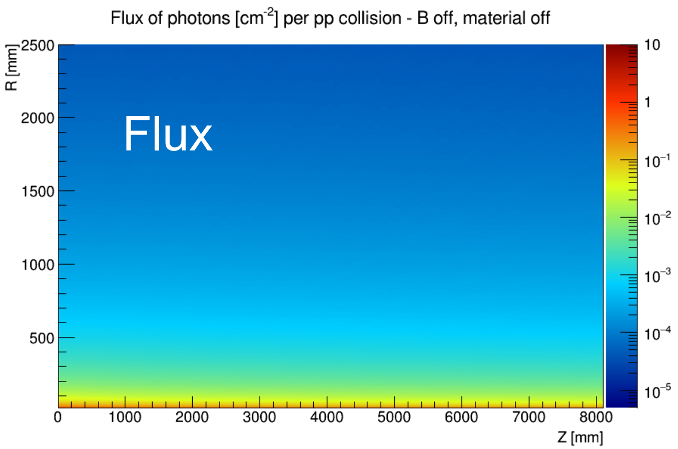
With M. Mannelli

Overview

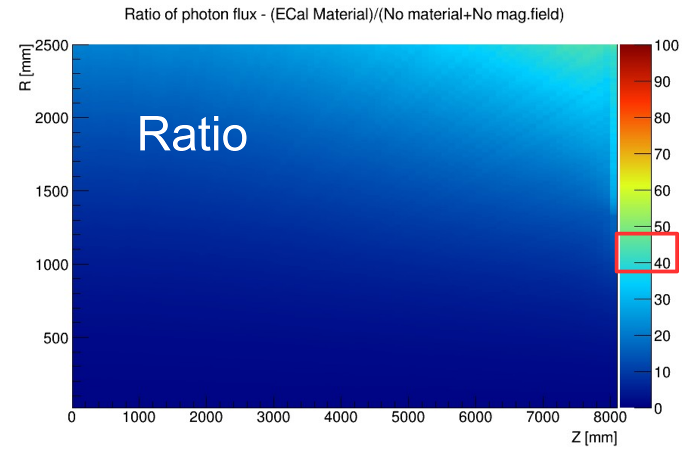
- **Impact of Fluka irradiation studies on FCC-hh tracker** (Fluka fluence maps kindly provided by F. Cerutti & M.I.Besana, B field map by H.T.Kate & M.Mentink)
- **Tracker occupancy studies:**
  - Estimation of minimum pixel sizes
  - Estimation of minimum required strip sizes
- **"Extrapolation" of CMS phase 2 upgrade design to FCC-hh design in tkLayout** (with significant help by S.Mersi!):
  - TkLayout verification study
  - Study of material budget
  - Study of tracker resolution
- **Summary & Plans**

Fluka Simulations: Photons?

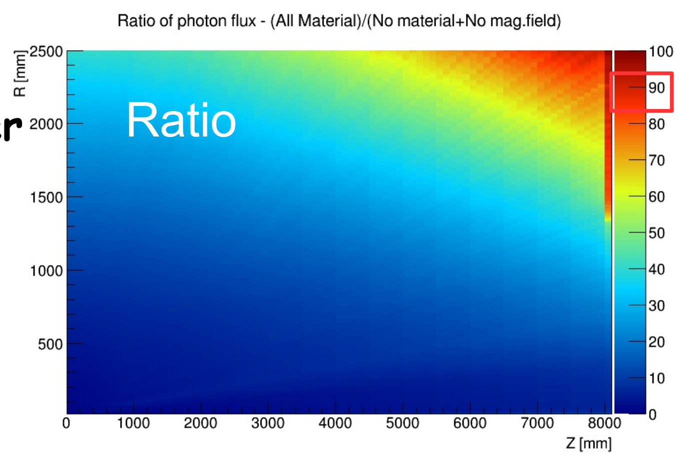
- **Let's have a look at irradiation map per pp collision @ 100TeV and gradually add effects of B field & material (relatively):**



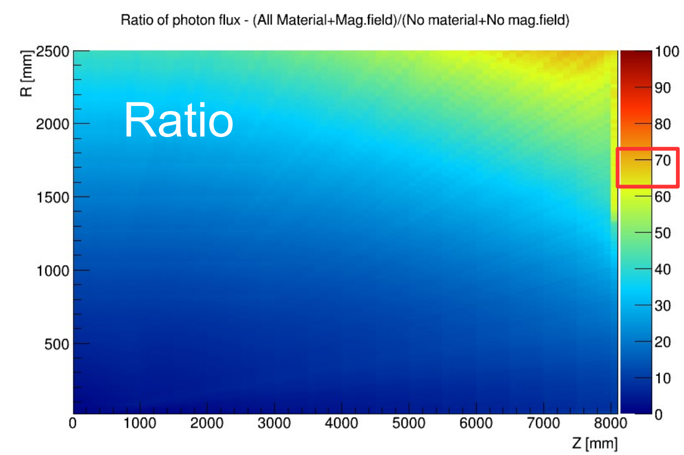
Switch on **ECal**



Switch on **tracker** & ECal

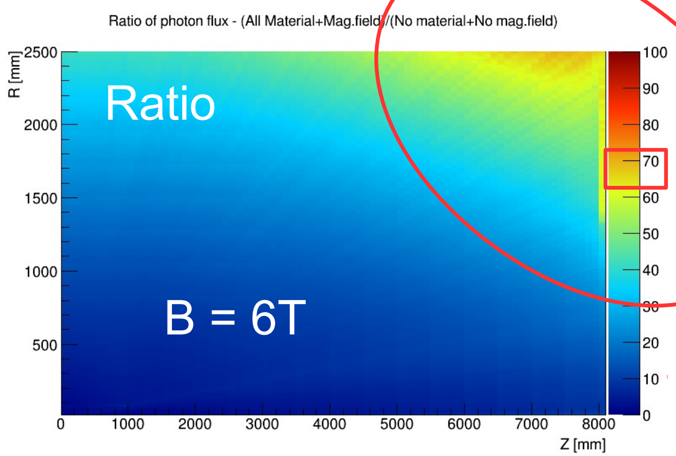


Switch on **B field** & tracker, ECal



Photons Irradiation - Summary

- **Effects of Ecal (backscattered particles?) are clearly visible as increase in flux**

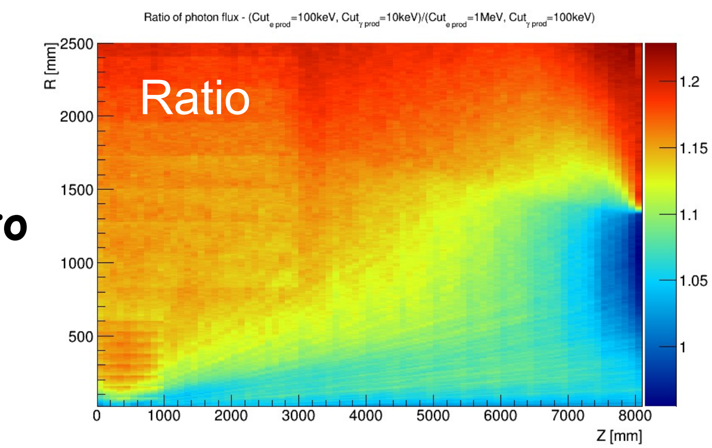


Ecal @1300mm

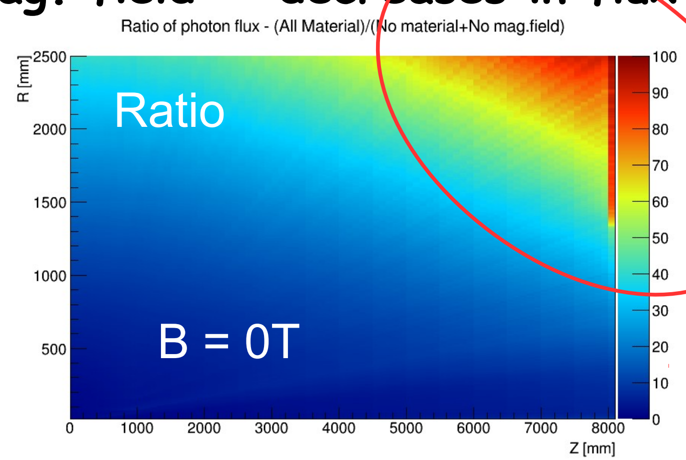
Increase in flux ratio by decreasing prod. cuts:

- e 1MeV → 100keV
- Gamma 100keV → 10keV

  → ~ 20% more

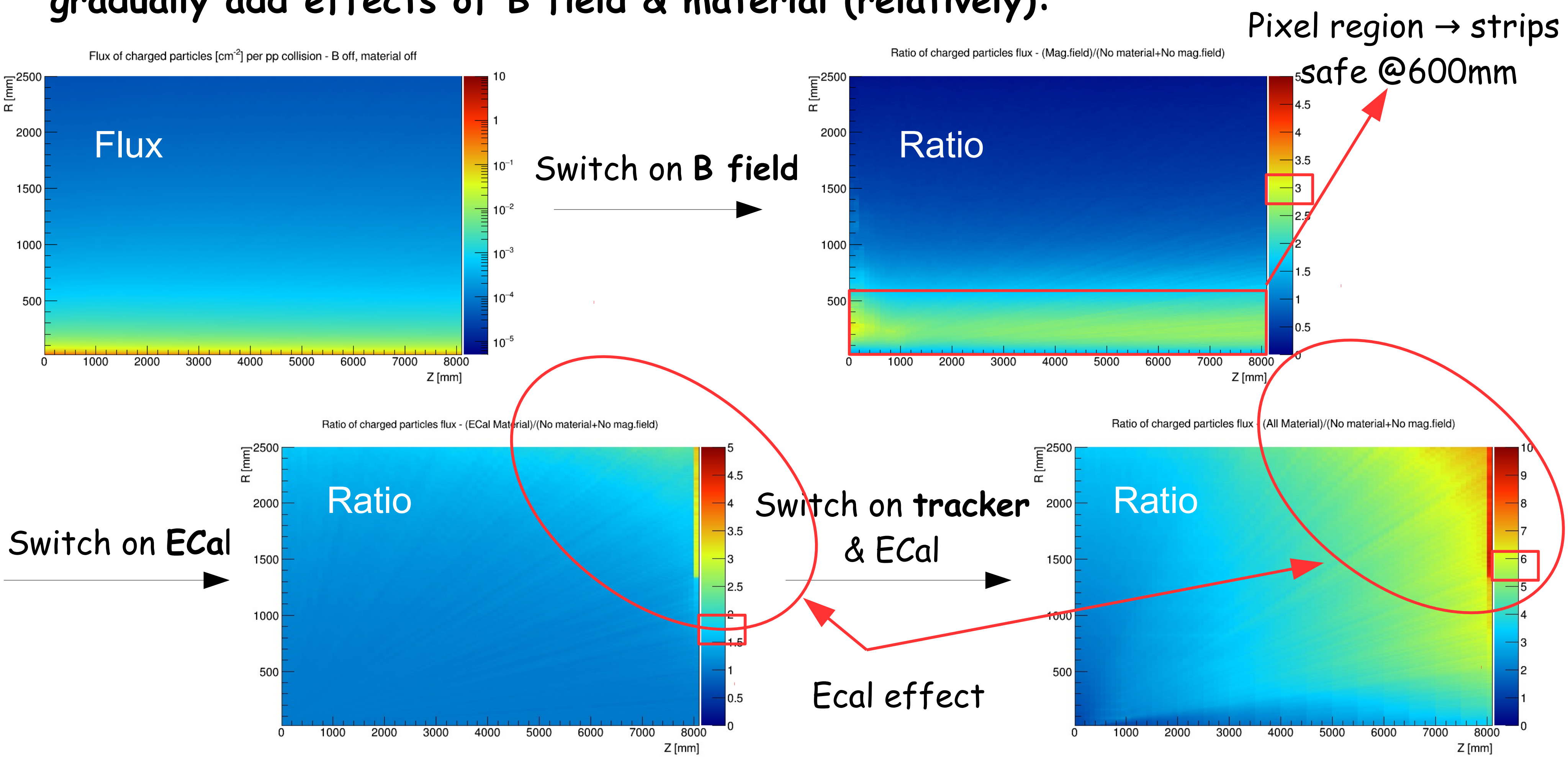


- **Effect of mag. field → decreases in flux due to curl effect**



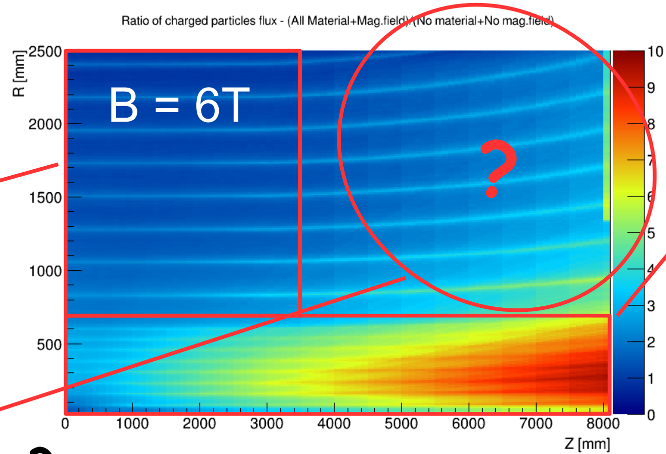
Fluka Simulations: Charged particles?

- The same for charged particles (irradiation map per pp collision @ 100TeV), gradually add effects of B field & material (relatively):



Charged particles irradiation - Summary

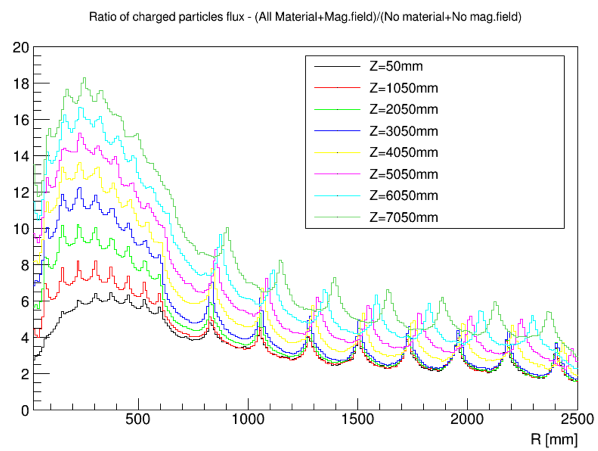
- **All combined effects with B field:**



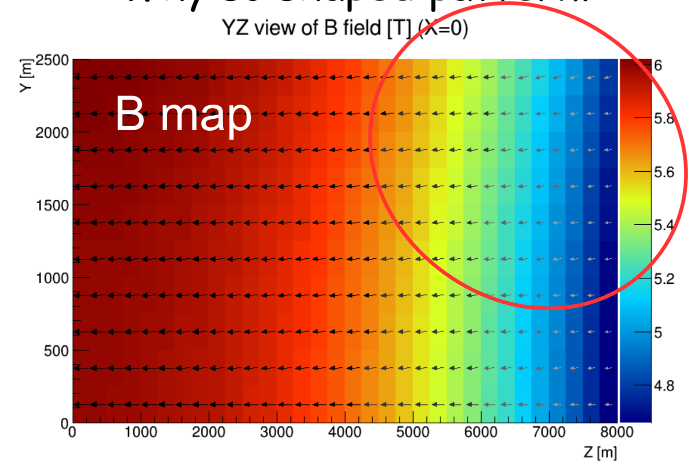
Clear layer structure

- Multiplication effect due to material
- Particles kept by mag. gield
- **Highest fluxes expected for low radii together with high Z**

- ***Arte-facts or true?***
- What are the energies?
  → Radius ~ 25 mm
  → ~ 50 MeV/c part.
  → CSDA e^- Si range~85mm
  (http://physics.nist.gov)

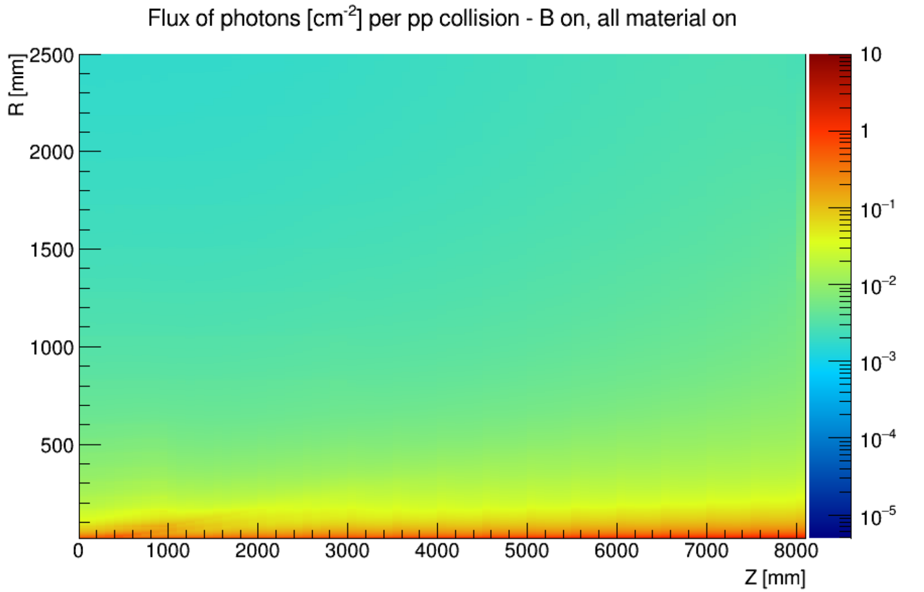


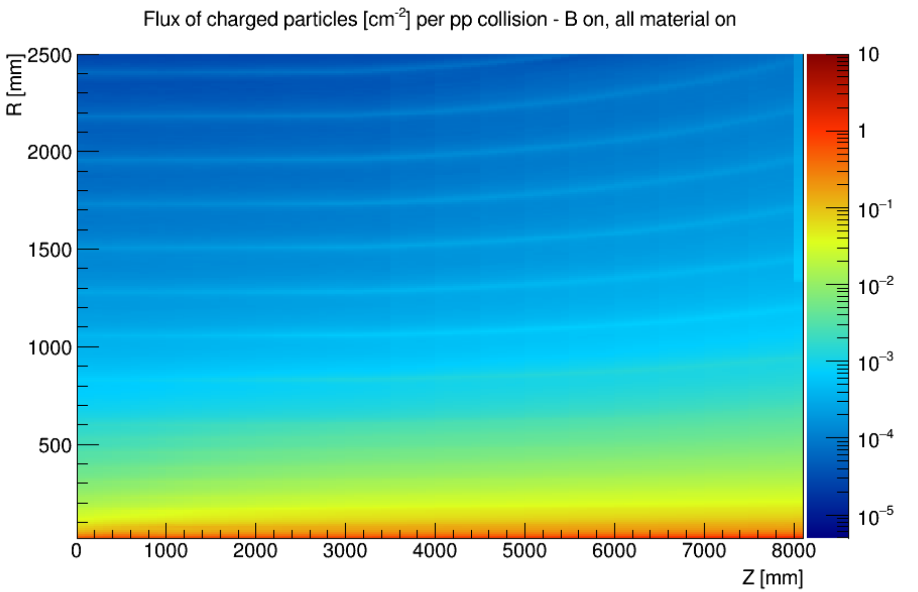
& Why so shaped pattern?



Fluka Simulations: Tracker Results

- **Photons versus charged particles estimated fluxes:**
  - Production cuts for gammas=10keV, for electrons=100 keV (effect of cuts ~ tenths of %)
  - **These maps have been used to estimate the tracker occupancy ...**





TkLayout: Tracker Occupancy Studies

- **With the FCC-hh high pile-up ~ 200-1000 environment some natural questions arise and need to be addressed...**
  - What pixel/strip size to use in order to have reasonable occupancy (i.e. ~ 1% for pixel tracker)? (**will be addressed here**)
  - Where to define a border, from which it is safe to use the strip detector? (**answered on previous slide ~ 600mm**)
  - How many high-granular pixel layers (or hybrid pixel-strip modules) & with what granularity do we need to use in order to handle the pile-up?
  - What are the expected data-rates (bandwidth needed)?
  - ...

→ all these questions can be approximately answered using the Fluka simulations in tkLayout software

Occupancy Studies - Description

- **Let's assume that we want to achieve 1% occupancy in the worst case ...**
  - Use charged particles irradiation map normalized to pp collision
  - Scale the map to 200 pp pile-up or 1000 pp pile-up
  - Scan all sensors in each layer (all rings in each disc) and find the weakest spot with the highest flux → notice that the spot corresponds to the highest Z in most cases
  - Calculate the pixel/strip area to have the required 1% occupancy
  - Geometry used is "coverage optimized" FCC-hh baseline geometry
- **Natural questions:**
  - What is the effect of applied cuts?

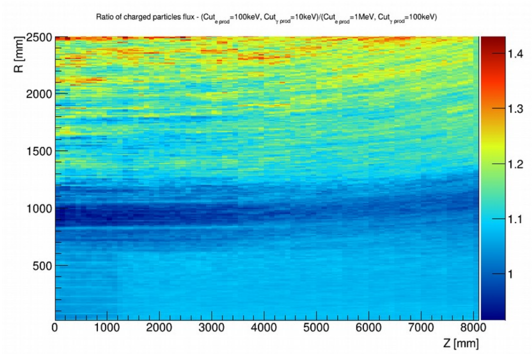
    → ~ 5-10% in the pixel region

    → no dramatic increase
  - Do the gammas also contribute?

    → cut set to 10keV

    → so they contribute mostly due e-,e+, i.e charged particles
  - Is the cluster size taken into account?

    → No! Only full simulation (or data input) would answer such a question...



Occupancy Studies – Pixel Barrel

Number of pile-up events: 200

Layer no :	1	2	3	4	5	6	7	8	9
Radius [mm] :	25.0	93.3	169.2	232.9	317.9	381.6	466.5	530.1	600.0
Min flux in Z [particles/cm^-2] :	93.8	10.4	4.1	2.5	1.3	1.0	0.6	0.5	0.3
Max flux in Z [particles/cm^-2] :	118.5	14.9	5.5	3.3	1.7	1.2	0.7	0.6	0.4
Z position [mm] related to max flux :	500.0	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0
Max cell area in Z (1% occupancy) [mm^2]:	0.0084	0.0673	0.1834	0.3047	0.6013	0.8308	1.4028	1.7710	2.4990

Number of pile-up events: 1000

Layer no :	1	2	3	4	5	6	7	8	9
Radius [mm] :	25.0	93.3	169.2	232.9	317.9	381.6	466.5	530.1	600.0
Min flux in Z [particles/cm^-2] :	468.9	51.8	20.3	12.3	6.7	4.8	3.0	2.4	1.7
Max flux in Z [particles/cm^-2] :	592.5	74.3	27.3	16.4	8.3	6.0	3.6	2.8	2.0
Z position [mm] related to max flux :	500.0	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0
Max cell area in Z (1% occupancy) [mm^2]:	0.0017	0.0135	0.0367	0.0609	0.1203	0.1662	0.2806	0.3542	0.4998

- **Summary: In the worst scenario (#pile-ups=1000) → 40x40um^2 @ 1st layer should be sufficient, but …**

→ current Fluka model is without services! Supports, electronics, … are accounted for in a detector material as a mixture of Si, Cu, … → **more detailed model needed** (composition matters some elements might get activated …)

→ **tkLayout can export the geometry&material in csv format (CMS Fluka approach)**

→ estimation on cluster size should be incorporated→**not possible here (technology dependent)**

Occupancy Studies – Pixel End-cap

Number of pile-up events: 200

Ring no :	1	2	3	4	5	6	7	8	9	10	11
Average radius [mm] :	53.5	78.5	123.5	179.5	235.5	291.5	347.5	403.5	459.5	515.5	571.5
Min flux in R [particles/cm^-2] :	22.1	12.2	7.7	4.0	2.5	1.8	1.3	0.9	0.7	0.5	0.4
Max flux in R [particles/cm^-2] :	229.2	61.7	25.8	12.1	7.3	5.0	3.4	2.5	1.9	1.4	1.1
Z position [mm] related to max flux :	7996.0	8004.0	7996.0	8004.0	7996.0	8004.0	7996.0	8004.0	7996.0	8004.0	7996.0
Max cell area in R (1% occupancy) [mm^2]:	0.0044	0.0162	0.0388	0.0825	0.1366	0.1980	0.2941	0.4061	0.5373	0.7292	0.9509

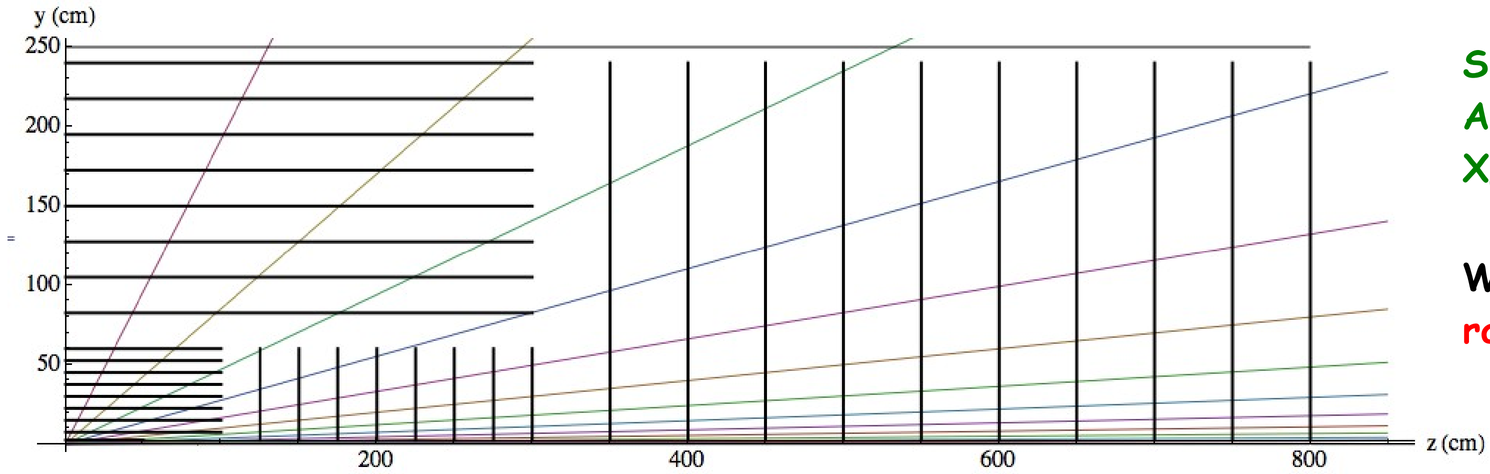
Number of pile-up events: 1000

Ring no :	1	2	3	4	5	6	7	8	9	10	11
Average radius [mm] :	53.5	78.5	123.5	179.5	235.5	291.5	347.5	403.5	459.5	515.5	571.5
Min flux in R [particles/cm^-2] :	110.5	61.1	38.6	20.1	12.6	8.9	6.7	4.5	3.3	2.7	2.1
Max flux in R [particles/cm^-2] :	1145.8	308.6	128.8	60.6	36.6	25.2	17.0	12.3	9.3	6.9	5.3
Z position [mm] related to max flux :	7996.0	8004.0	7996.0	8004.0	7996.0	8004.0	7996.0	8004.0	7996.0	8004.0	7996.0
Max cell area in R (1% occupancy) [mm^2]:	0.0009	0.0032	0.0078	0.0165	0.0273	0.0396	0.0588	0.0812	0.1075	0.1458	0.1902

- **Summary: In the worst scenario (#pile-ups=1000) → 30x30um^2 @ 1st ring should be sufficient, but the same arguments apply…**

Tracker Material & Resolution

- **W.Riegler showed the results for a simplified tracker layout:**



Si 20%, C 42%, Cu 2%, Al 6%, Plastic 30%
X_0 of this mix: 14.37cm

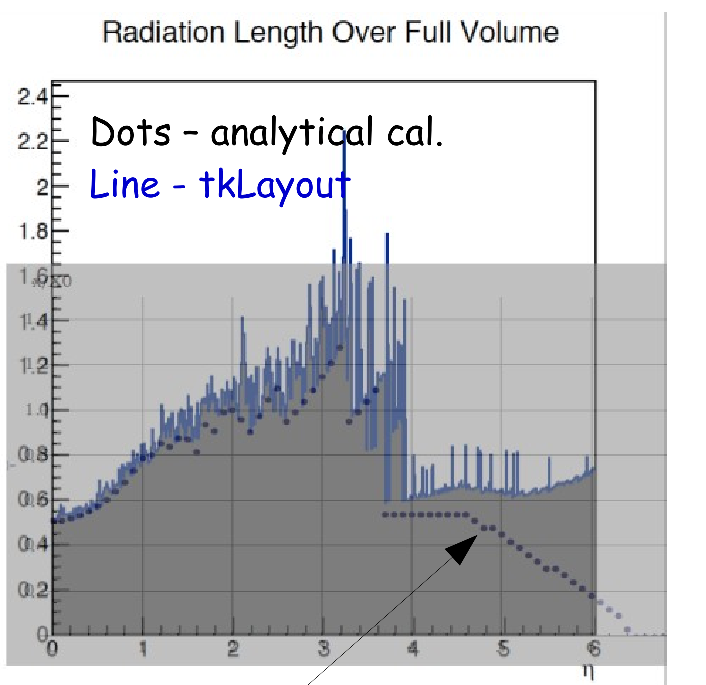
We assumed: 3% of radiation length per layer

→ the question was, how a realistic model (services, supports, etc.) would change these results, if at all?

Simplified Tracker Layout

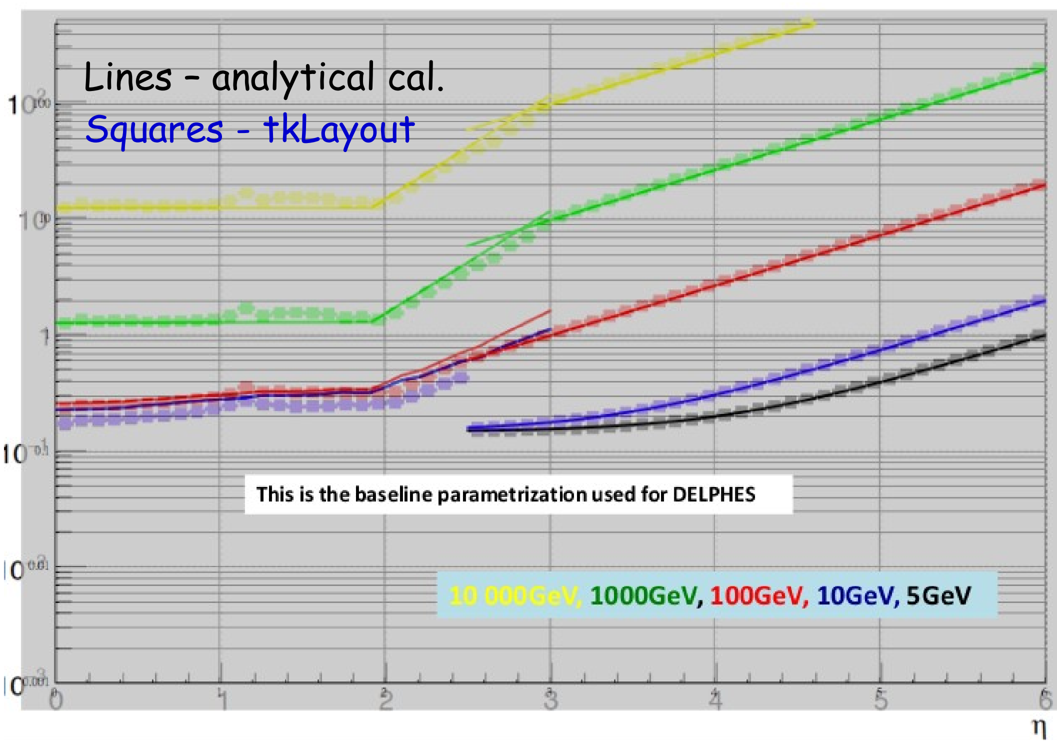
- **Previous results with simplified layout:**

  → Comparison of analytical calculations (W.Riegler) versus TkLayout with track parameter calculations based on parabolic approximation (Z.Drasal) → good agreement



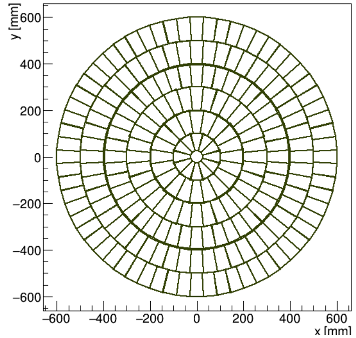
Missing beam-pipe in analytical calc.

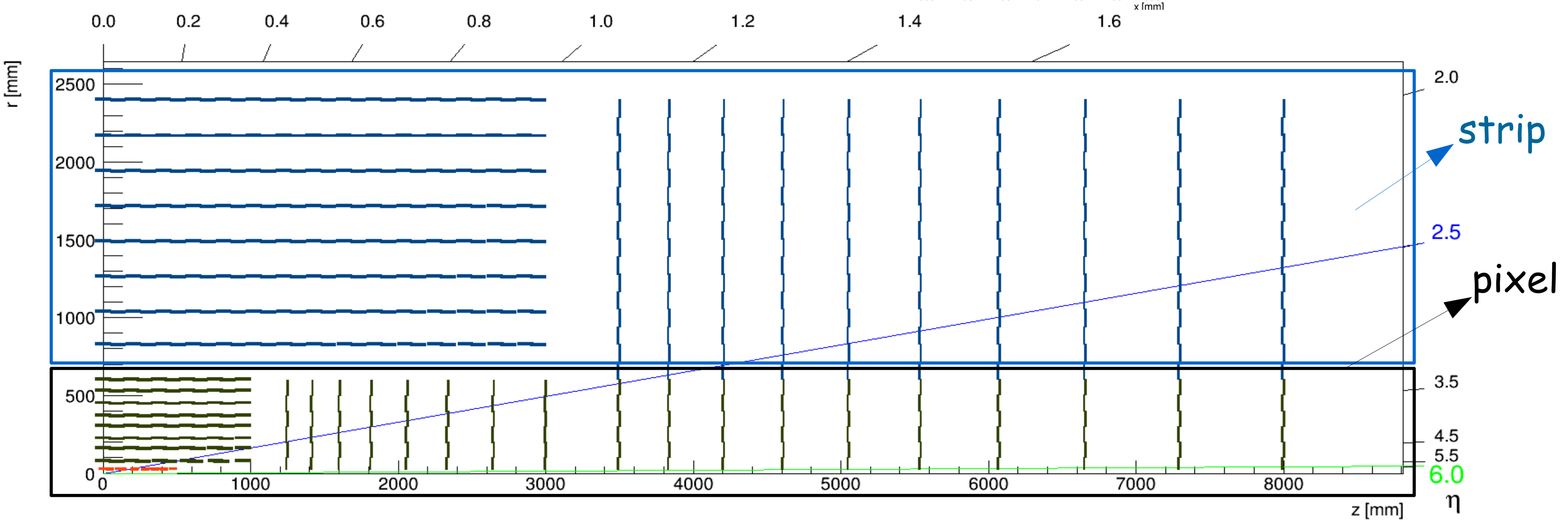
Total (dipole+central) dpt/pt resolution [%]



TkLayout – Verification Study (VS)

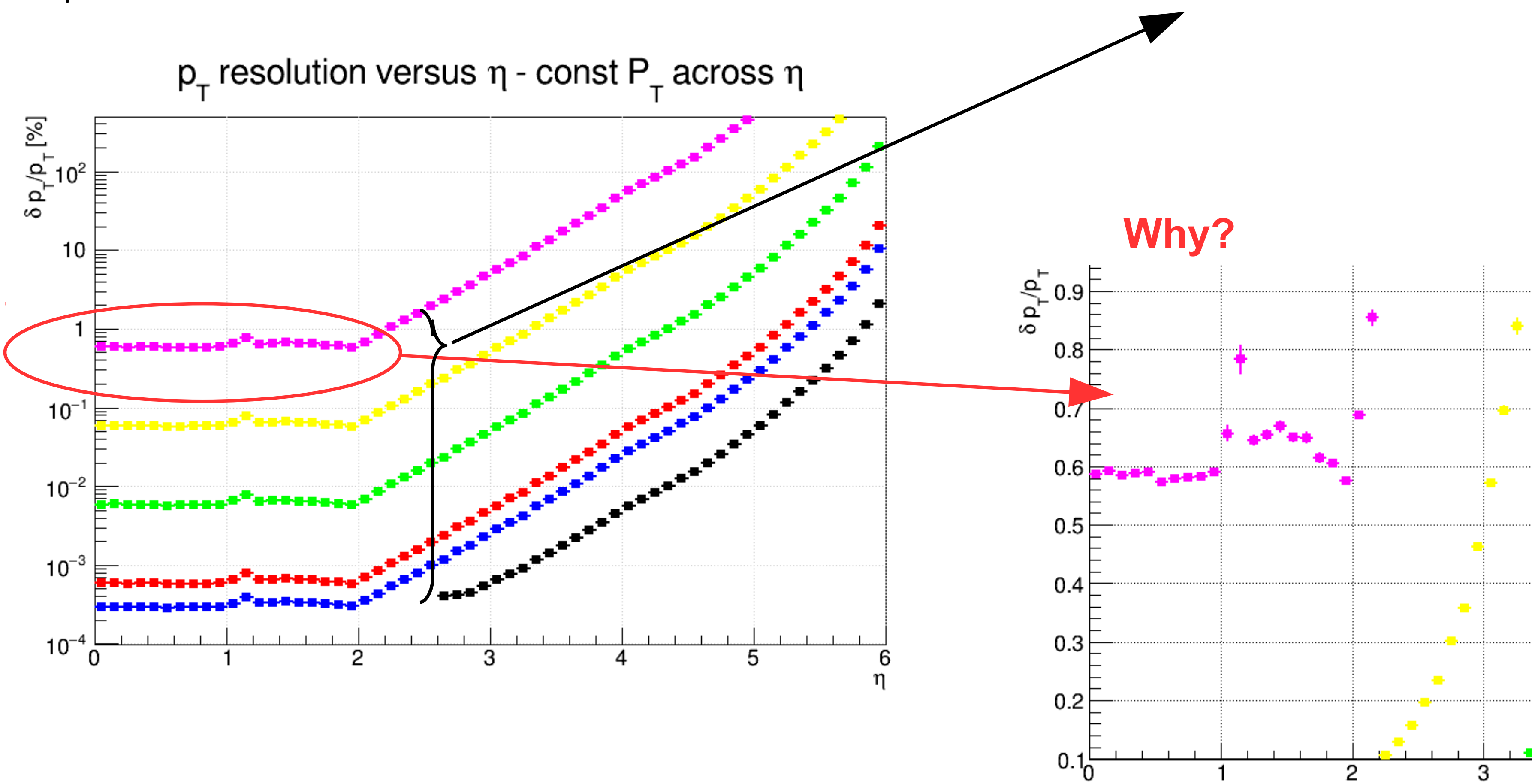
- **Before going to the realistic geometry results by tkLayout, let me build a test geometry to verify the tracking algorithm (parabolic approx.) in tkLayout:**
  - wedge-shaped sensors instead of rectangular at low radii → low overlap → low MB
  - pixel detectors in radii R = 25 – 600mm
  - strip detectors in radii R = 600 - 2400mm





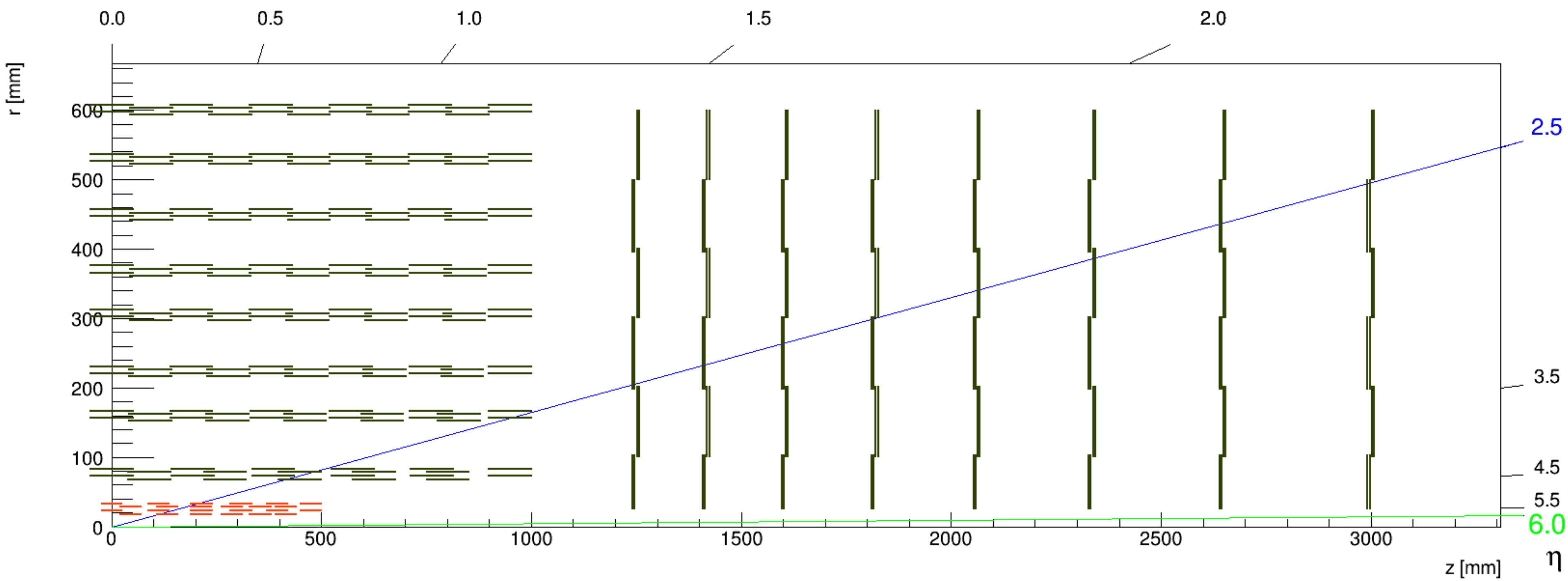
TkLayout (VS) – Ideal resolution

- All detectors defined with 1um x 1um space resolution, no MS:
  - p_T = 1GeV, 5GeV, 10GeV, 100GeV, 1TeV, 10TeV → scales by pT (OK)



TkLayout (VS) - Ideal resolution (pixel only)

- **Let's have a look at pixel detector only (easier)...**



- **and use:**

$$\frac{\Delta p_t}{p_t} = \frac{\sigma[m]\, p[\mathrm{GeV/c}]}{0.3\, B[T]\, L^2[m^2]} \sqrt{\frac{720\,(N-1)^3}{(N-2)\,N\,(N+1)\,(N+2)}}$$

$$\approx \frac{\sigma[m]\, p[\mathrm{GeV/c}]}{0.3\, B[T]\, L^2[m^2]} \sqrt{\frac{720}{N+4}}$$

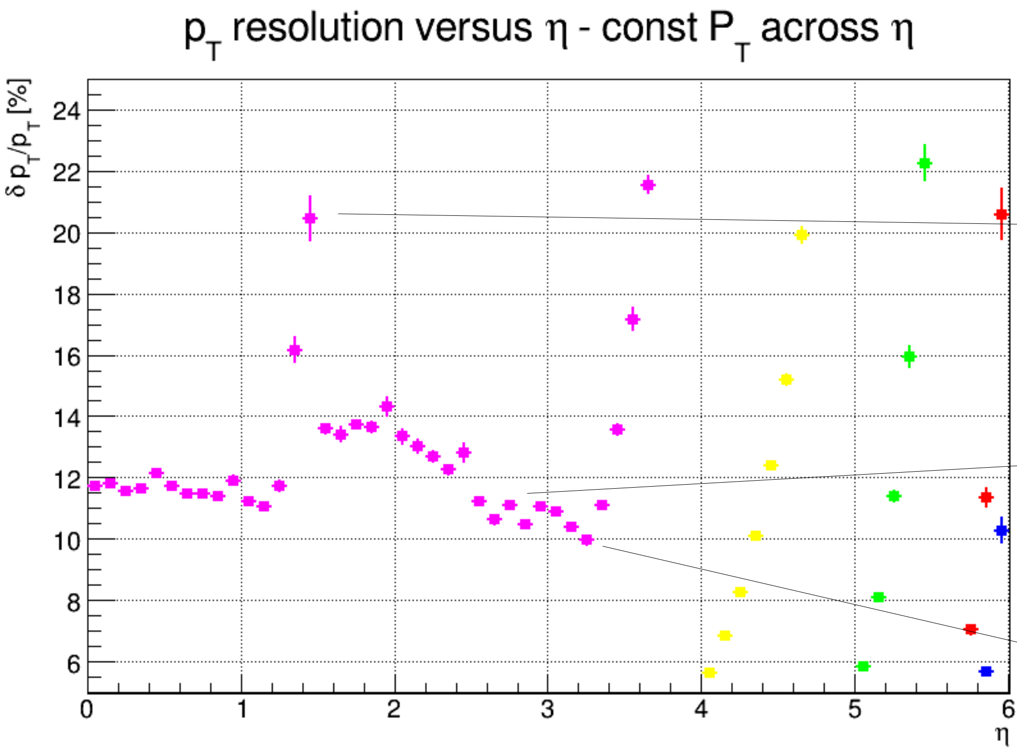
@ 90deg:

N = 9
L = 0.6 m
Pt = 10 000 GeV/c
B = 6T

= 11.3%

TkLayout (VS) - Ideal resolution (pixel only)

- And the result is 11.6% (OK), but ...



Why?

Increase (max @ 20.5%)

Decrease ~ 10%

Break point @ $\eta \simeq 3.25$

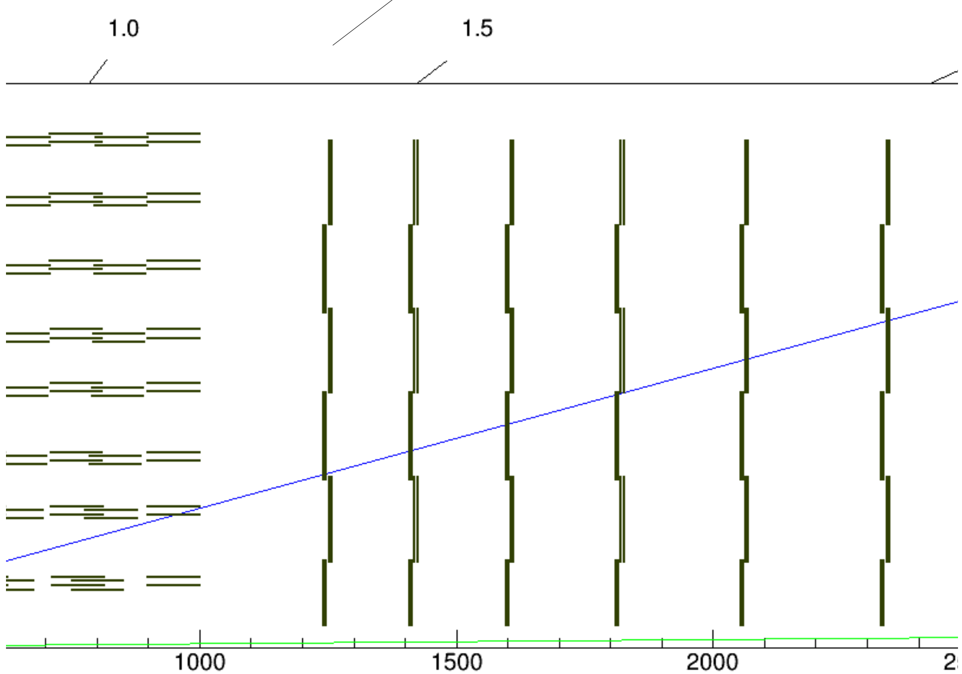
L ~ 0.6m, Z = 8m

→ η = 3.28 (OK)

TkLayout (VS) – Ideal resolution (pixel only)

- **Why increase & decrease in resolution?**

η gap <1.284; 1.480> → N active layers by 2 lower → Effective level arm = 4.49 } **21.5% (OK)**



Longest corner @ η= 3.28
→ N active layers = 20
→ Effective level arm = 0.6m } **9.3% (~OK)**

TkLayout (VS) - Ideal resolution + MS

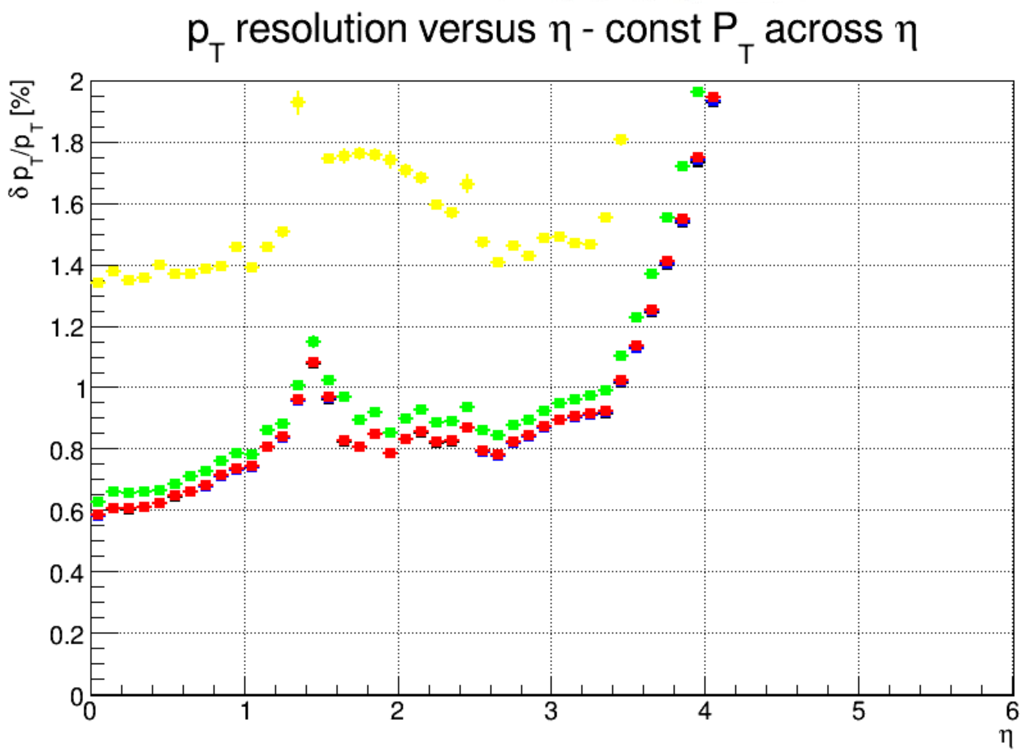
- For low pt, resolution dominated by MS → let's have a look at pixel detector & 1GeV:

$$\frac{\Delta p_t}{p_t} = \frac{0.0136}{0.3\beta\, B[T]\, L[m]} \sqrt{\frac{X_{tot}}{X_0}} \sqrt{\frac{10}{7} \frac{12 + (N-1)N^2(N+1)}{(N-2)N(N+1)(N+2)}}$$

$$\approx \frac{0.0136}{0.3\beta\, B[T]\, L[m]} \sqrt{\frac{X_{tot}}{X_0}} \sqrt{\frac{10}{7}}$$

$X/X_0 = 0.26$

→ **0.74 (~OK)**

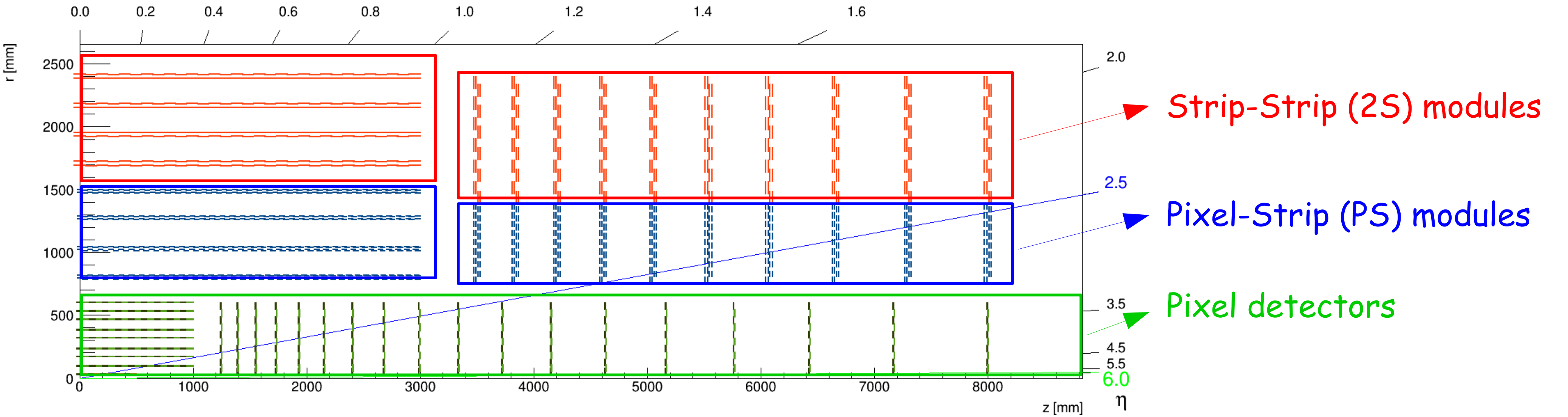


- if we apply log correction, i.e.: $(1 + 0.038 \cdot \ln(X/X_0))$ → **0.70**

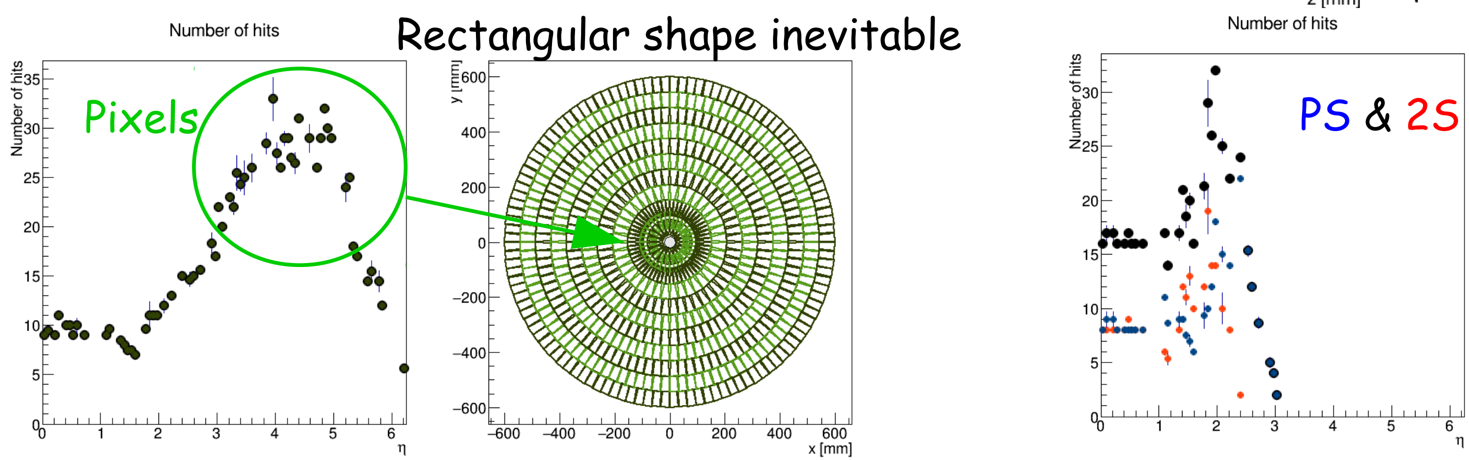
- **Summary: tkLayout works OK**

TkLayout – Realistic Design

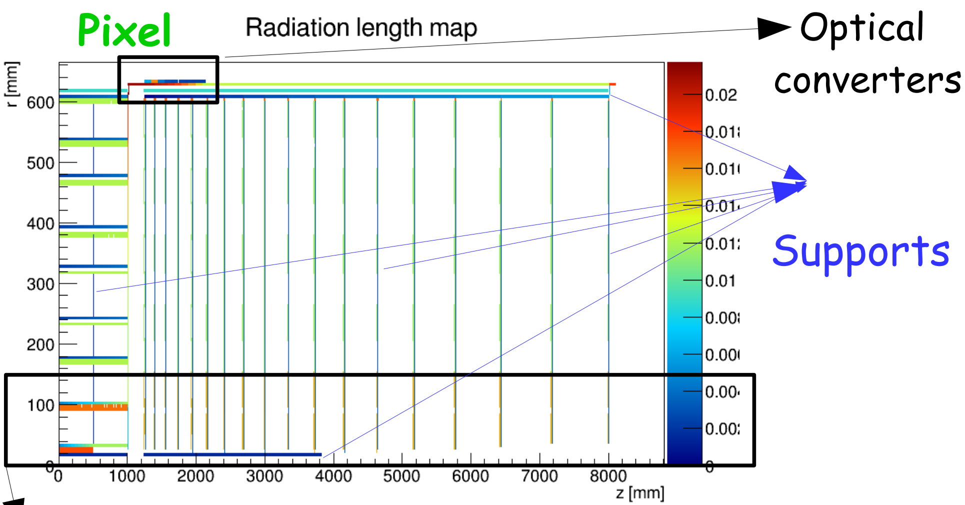
- Let me "extrapolate" the CMS phase 2 layout to FCC dimensions

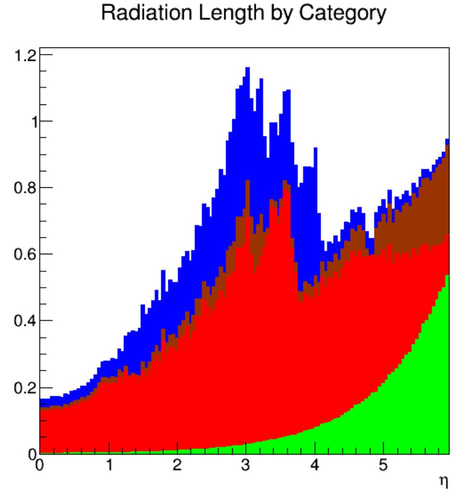


Rectangular shape inevitable



Realistic Design: Material Budget



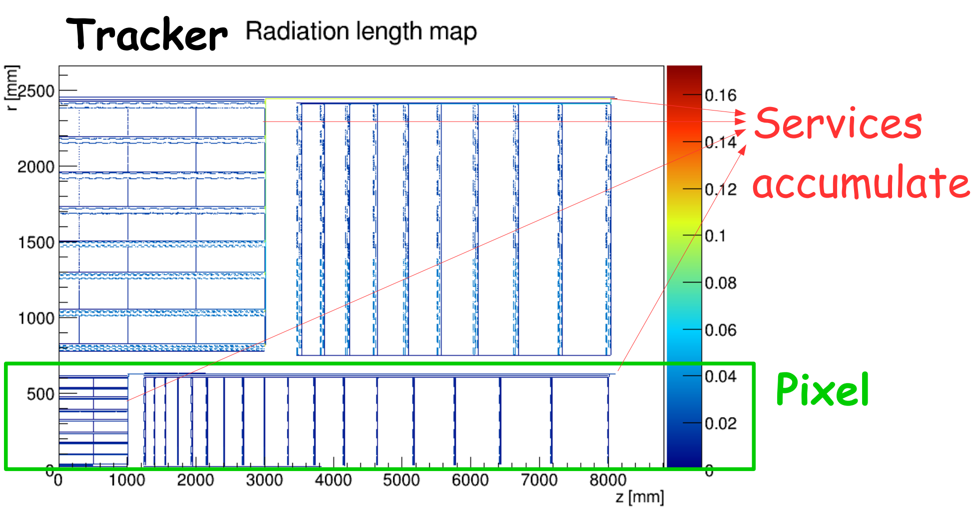


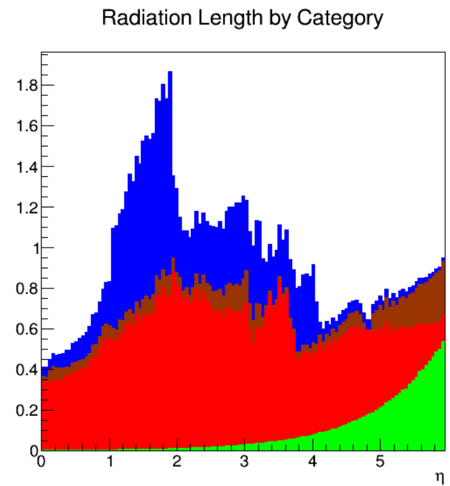
Average (η = [0, 6.0])	Radiation length [%]
Beam pipe (green)	9.61
Modules (red)	34.85
Services (blue)	14.07
Supports (brown)	6.53
Total	65.06

Region:	TRK-BRL	TRK-ENDCAP	TRK-FWD	TRK-IFWD
Min η:	0.0	1.5	2.5	4.0
Max η:	1.5	2.5	4.0	6.0

Material	TRK-BRL	TRK-ENDCAP	TRK-FWD	TRK-IFWD
Rad. length [%]	24.76	56.59	96.36	76.10
Int. length [%]	5.43	13.26	23.44	33.25

Higher occupancy → higher chip activity → more material



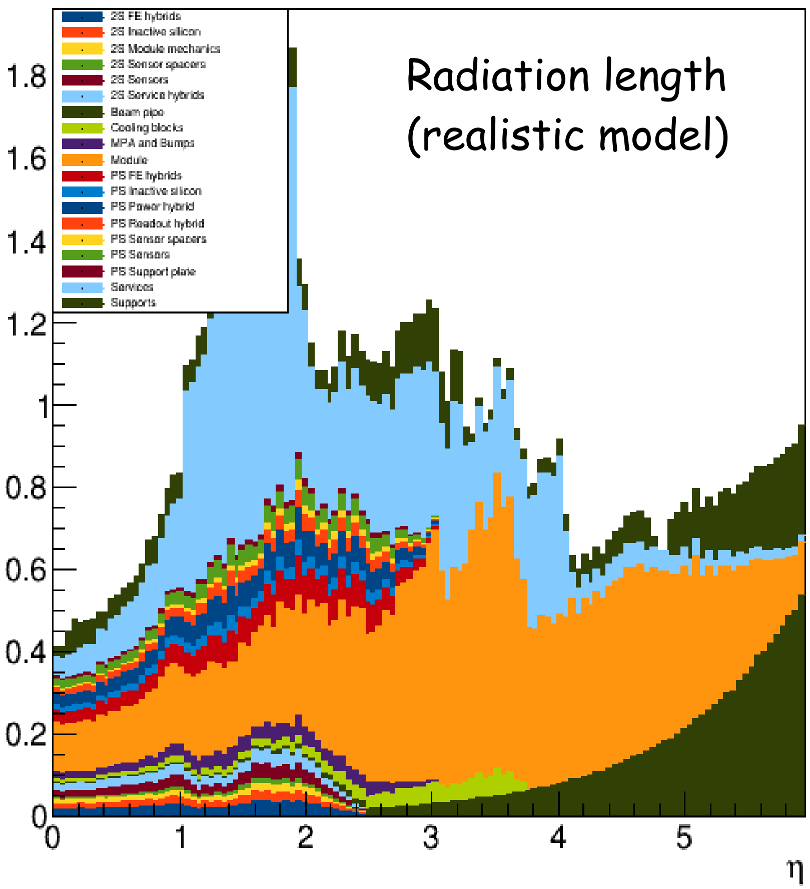


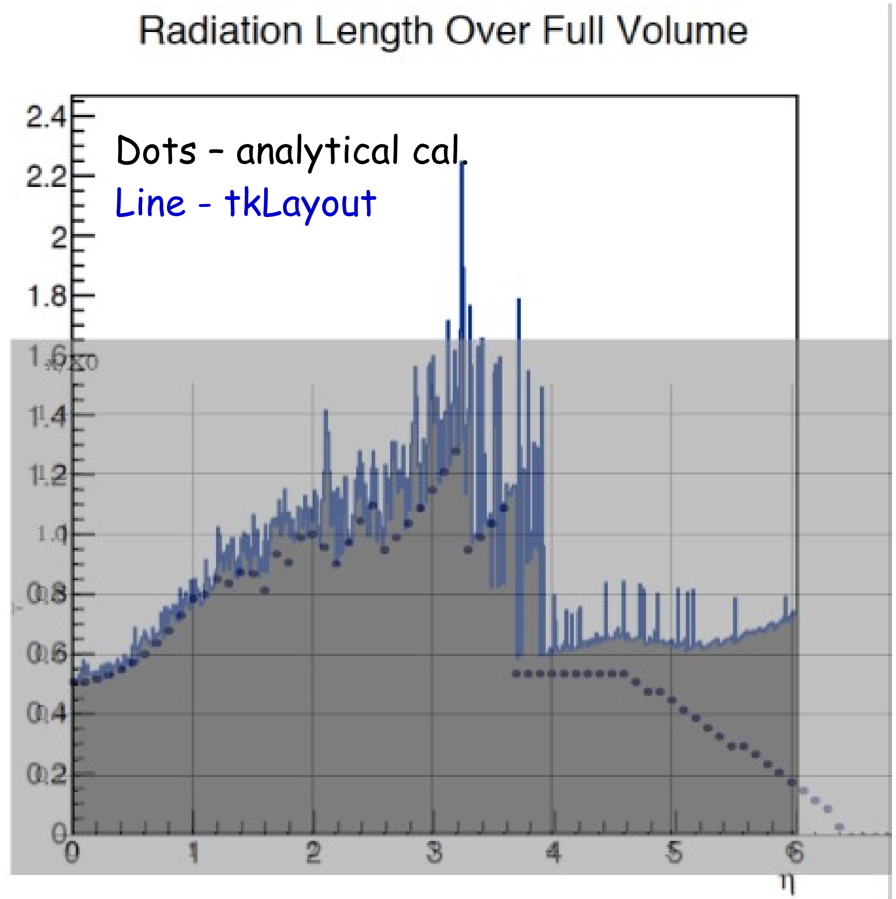
Average (η = [0, 6.0])	Radiation length [%]
Beam pipe (green)	9.61
Modules (red)	50.47
Services (blue)	25.61
Supports (brown)	8.56
Total	94.25

Region:	TRK-BRL	TRK-ENDCAP	TRK-FWD	TRK-IFWD
Min η:	0.0	1.5	2.5	4.0
Max η:	1.5	2.5	4.0	6.0

Material	TRK-BRL	TRK-ENDCAP	TRK-FWD	TRK-IFWD
Rad. length [%]	79.43	137.28	104.58	76.14
Int. length [%]	20.57	35.02	26.06	33.26

Tracker Comparison: Realistic versus Simplified





- **Summary:** The simplistic approach provides reasonable estimate on MB!
- **"Disclaimer":** One has to be careful when using an extrapolated geometry (without true engineering design – correct supports, mechanics, …), but still good hint!

For Reference: Pixel Parameters

Layer no :	1	2	3	4	5	6	7	8	9	Total
Radius [mm] :	25.0	93.3	169.2	232.9	317.9	381.6	466.5	530.1	600.0	
Z-min [mm] :	-500.0	-1000.0	-1000.0	-1000.0	-1000.0	-1000.0	-1000.0	-1000.0	-1000.0	
Z-max [mm] :	500.0	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	
Number of rods :	12	36	32	44	60	72	88	100	116	
Number of modules per rod :	19	35	35	35	35	35	35	35	35	
Number of modules :	228	1260	1120	1540	2100	2520	3080	3500	4060	19408

Disk no :	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	Total
Radius-min [mm] :	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	
Radius-max [mm] :	600.0	600.0	600.0	600.0	600.0	600.0	600.0	600.0	600.0	600.0	600.0	600.0	600.0	600.0	600.0	600.0	600.0	600.0	
Average Z pos. [mm] :	1250.0	1394.2	1555.1	1734.5	1934.6	2157.9	2406.8	2684.5	2994.3	3339.7	3725.1	4154.9	4634.2	5168.9	5765.3	6430.5	7172.5	8000.0	
Number of rings :	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	
Number of modules per disk :	744	744	744	744	744	744	744	744	744	744	744	744	744	744	744	744	744	744	13392

Ring no :	1	2	3	4	5	6	7	8	9	10	11
R-min [mm] :	25.0	50.0	95.0	151.0	207.0	263.0	319.0	375.0	431.0	487.0	543.0
R-max [mm] :	82.0	107.0	152.0	208.0	264.0	320.0	376.0	432.0	488.0	544.0	600.0
Number of modules per ring :	20	36	60	40	52	64	72	84	96	104	116

Tag	PXBL01 PXBL02	PXBL03 PXBL04 PXBL05 PXBL06 PXBL07 PXBL08 PXBL09	PXER01 PXER02 PXER03	PXER04 PXER05 PXER06 PXER07 PXER08 PXER09 PXER10 PXER11	
Type	pixel	pixel	pixel	pixel	
Sensor spacing	0	0	0	0	
Sensor area (mm^2)	969.0	1938.0	969.0	1938.0	
Total area (m^2)	1.4	34.7	4.0	43.8	**84.0**
N. mod	1488	17920	4176	22608	**46192**
N. sens	1488	17920	4176	22608	**46192**
Channels (M)	195.04	2348.81	547.36	2963.28	**6054.48**
Pitch (min/max)	16	33	16	33	
R/Phi resolution (µm)	10	25	18	25	
Y resolution (µm)	10	25	18	25	

Total area

For Reference: PS&2S Parameters

Layer no :	1	2	3	4	5	6	7	8	Total
Radius [mm] :	800.0	1028.0	1272.3	1485.2	1704.5	1936.1	2167.7	2400.0	
Z-min [mm] :	-3000.0	-3000.0	-3000.0	-3000.0	-3000.0	-3000.0	-3000.0	-3000.0	
Z-max [mm] :	3000.0	3000.0	3000.0	3000.0	3000.0	3000.0	3000.0	3000.0	
Number of rods :	54	68	84	98	118	134	150	168	
Number of modules per rod :	147	143	137	135	61	61	61	61	
Number of modules :	7938	9724	11508	13230	7198	8174	9150	10248	77170

Disk no :	1	2	3	4	5	6	7	8	9	10	Total
Radius-min [mm] :	756.6	756.6	756.6	756.6	756.6	756.6	756.6	756.6	756.6	756.6	
Radius-max [mm] :	2400.0	2400.0	2400.0	2400.0	2400.0	2400.0	2400.0	2400.0	2400.0	2400.0	
Average Z pos. [mm] :	3500.0	3836.7	4205.8	4610.4	5054.0	5540.2	6073.2	6657.4	7297.9	8000.0	
Number of rings :	29	29	29	29	29	29	29	29	29	29	
Number of modules per disk :	2900	2900	2900	2900	2900	2900	2900	2900	2900	2900	29000

Ring no :	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
R-min [mm] :	756.6	803.2	833.8	880.5	909.7	956.5	984.5	1031.4	1058.0	1105.1	1130.5	1177.6	1201.8	1249.0	1271.9
R-max [mm] :	802.9	849.5	880.0	926.7	956.0	1002.8	1030.7	1077.7	1104.3	1151.4	1176.7	1223.9	1248.0	1295.3	1318.2
Number of modules per ring	56	56	60	64	64	68	68	72	76	76	80	84	84	88	88

Ring no :	16	17	18	19	20	21	22	23	24	25	26	27	28	29
R-min [mm] :	1319.3	1341.0	1388.5	1462.3	1564.3	1635.1	1737.4	1805.1	1907.7	1972.5	2075.4	2137.3	2240.4	2299.5
R-max [mm] :	1365.6	1387.3	1489.0	1562.8	1664.8	1735.6	1837.9	1905.6	2008.2	2073.0	2175.9	2237.8	2340.9	2400.0
Number of modules per ring	92	92	104	108	116	120	128	132	140	144	152	156	164	168

Tag	TBL05 TBL06 TBL07 TBL08	TBL03 TBL04	TBL01 TBL02	TEDDR18 TEDDR19 TEDDR20 TEDDR21 TEDDR22 TEDDR23 TEDDR24 TEDDR25 TEDDR26 TEDDR27 TEDDR28 TEDDR29	TEDDR01 TEDDR02 TEDDR03 TEDDR04 TEDDR05 TEDDR06 TEDDR07 TEDDR08 TEDDR09 TEDDR10 TEDDR11 TEDDR12 TEDDR13 TEDDR14 TEDDR15 TEDDR16 TEDDR17	
Type	pt2S	ptPS	ptPS	pt2S	ptPS	
Sensor spacing	1.8	1.6	2.6	4	4	
Sensor area (mm^2)	9189.7	4441.0	4441.0	9189.7	4441.0	
Total area (m^2)	639.1	219.7	156.9	599.9	225.2	**1840.8**
N. mod	34770	24738	17662	32640	25360	**135170**
N. sens	69540	49476	35324	65280	50720	**270340**
Channels (M)	141.31	807.45	576.49	132.65	827.75	**2485.64**

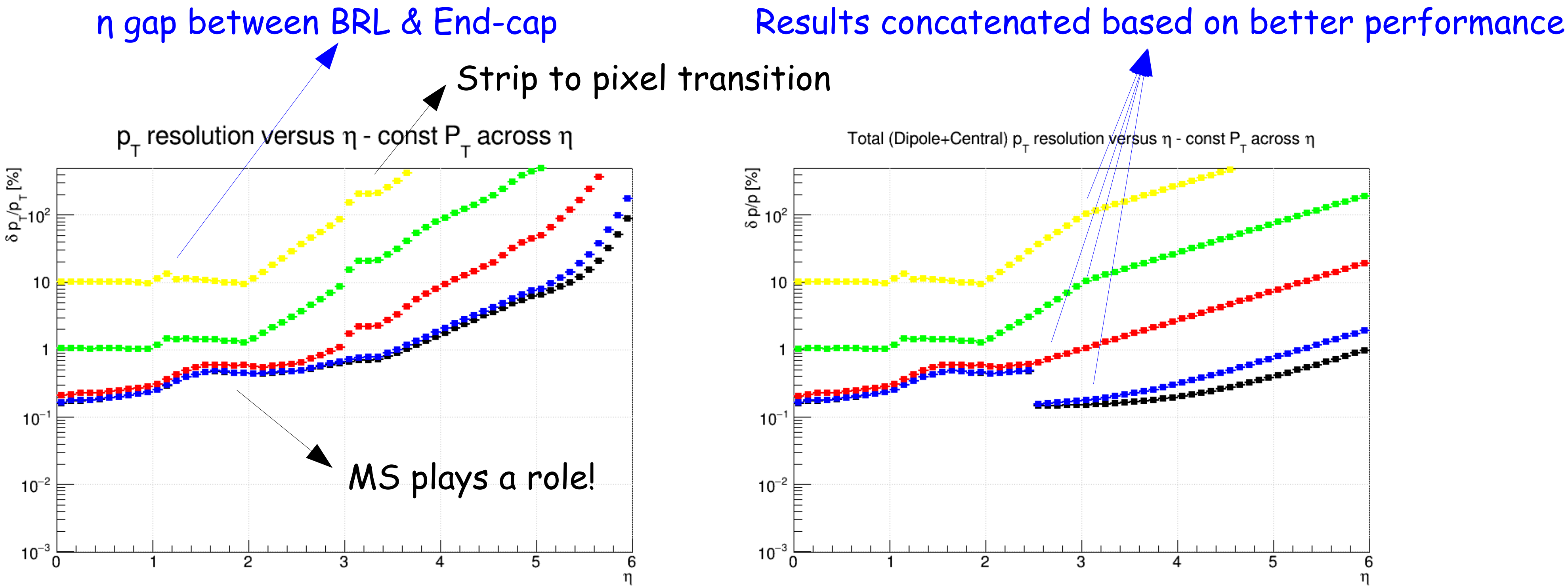
Total area

Tag	TBL05 TBL06 TBL07 TBL08	TBL03 TBL04	TBL01 TBL02	TEDDR18 TEDDR19 TEDDR20 TEDDR21 TEDDR22 TEDDR23 TEDDR24 TEDDR25 TEDDR26 TEDDR27 TEDDR28 TEDDR29	TEDDR01 TEDDR02 TEDDR03 TEDDR04 TEDDR05 TEDDR06 TEDDR07 TEDDR08 TEDDR09 TEDDR10 TEDDR11 TEDDR12 TEDDR13 TEDDR14 TEDDR15 TEDDR16 TEDDR17
Pitch (min/max)	90	100	100	90	100
R/Phi resolution (μm)	18	20	20	18	20
Y resolution (μm)	14506	417	417	14506	417

Tracker Resolution

- **Resolution plots for the realistic geometry layout: central tracker (left) versus full tracker (right)**

  → dipole resolution calculated based on standard formula (see W.Riegler calculation https://indico.cern.ch/event/443015/)



Summary

- **Important message:**
  - **One can use different levels of geometry layout details and tracking algorithm (pattern recognition) complexity to understand the key parameters of the tracker**
  - For that purpose the CMS Phase 2 design has been extrapolated to FCC-hh dimensions (with its limitations) & material budget and resolution have been studied → **the results are compatible with the simplistic design, nevertheless more details are clear/more precise with the detailed geometry**
  - Fluka flux simulations have been used to understand the detector occupancy and how the occupancy is influenced by magnetic field strength & material budget. **These simulations are of crucial importance to study the pattern recognition, layout design ...** → in order to have more realistic estimation, **more layout details should be implemented within Fluka** (e.g. using tkLayout geometry + material output)
- **Plans: Have a look at pattern recognition using tkLayout & Fluka simulations**