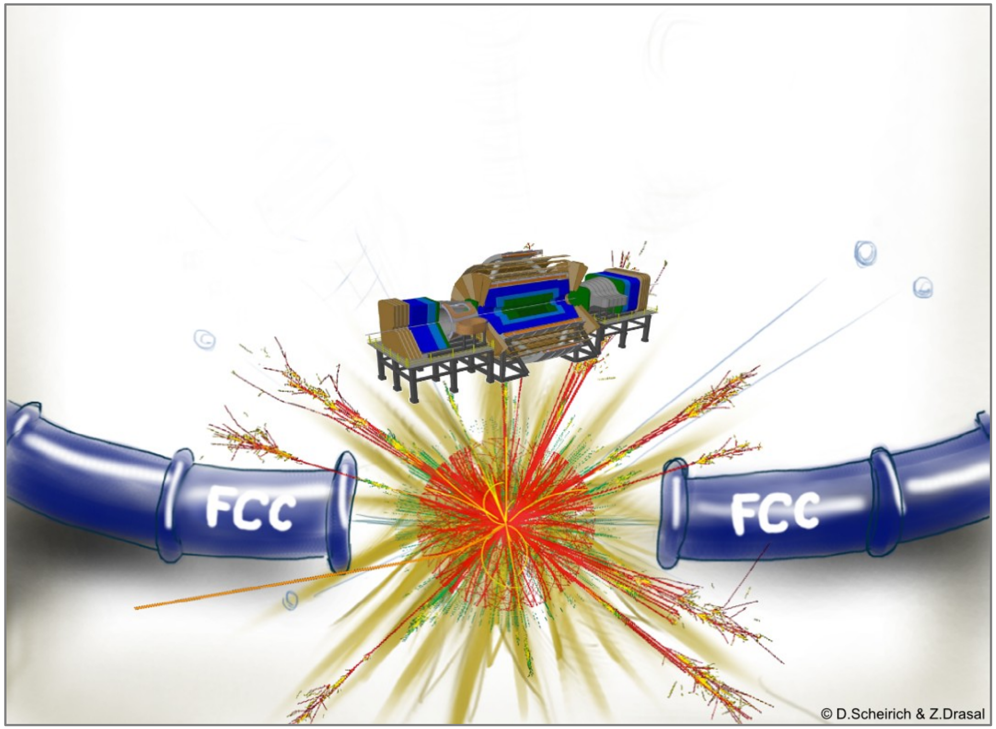
# Conceptual Study of FCC-hh Tracker Design





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CERN

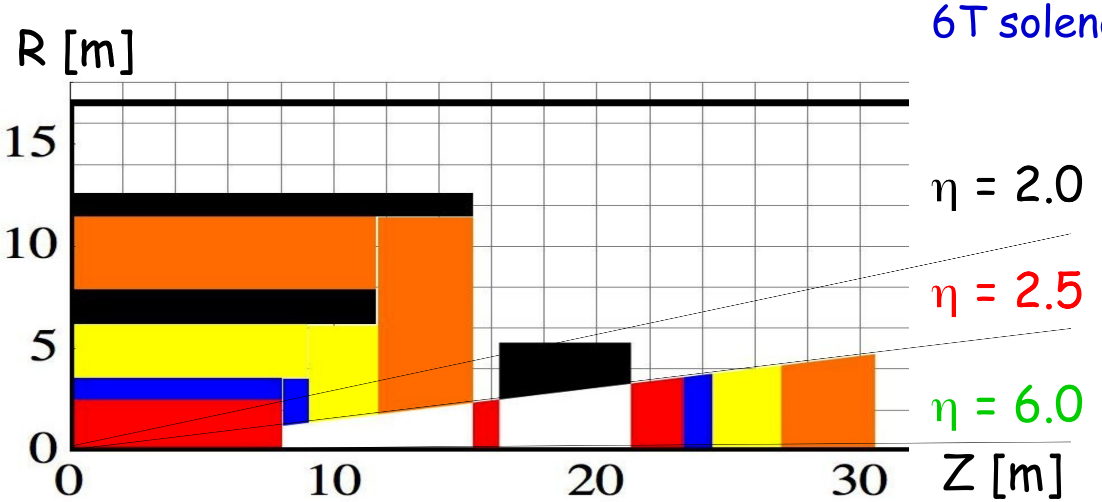

On behalf of FCC-hh detector group

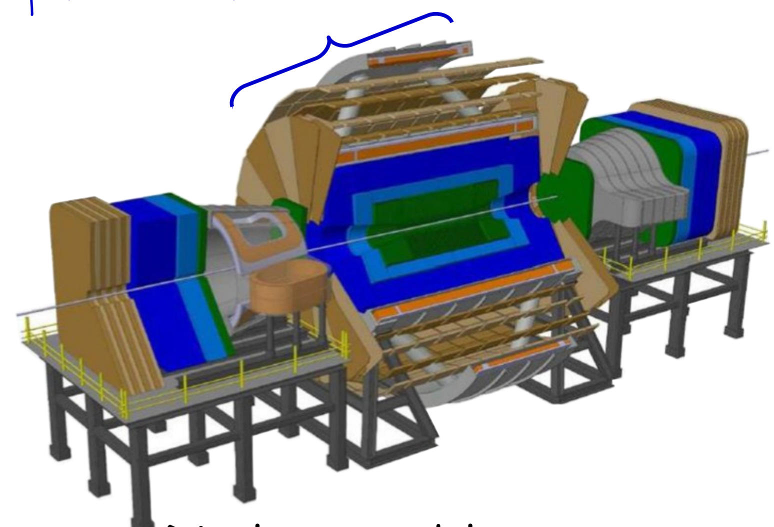
# Overview

- **FCC-hh tracker – Conceptual Design Study:**
  - Introduction:
    - Tracker geometry layout
    - Driving principles of momentum resolution measurement
    - Software toolkit – **tkLayout** (CMS phase 2 upgrade simulation toolkit)
  - Expected tracker performance
    - Tracker geometry layout & material budget
    - Tracker resolution → two scenarios in forward region: forward dipole versus solenoid?
  - Implications of high pile-up & high-rate environment
    - Tracker occupancy
    - Expected data rates
  - Summary & Outlook

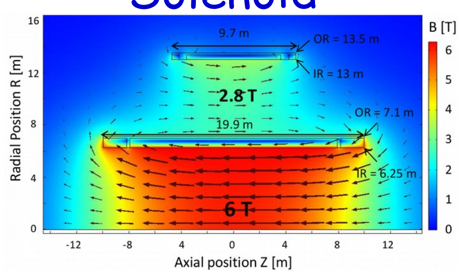
# FCC-hh Detector & Tracker Geometry

6T solenoid: $P_T$ measurement in the central tracker

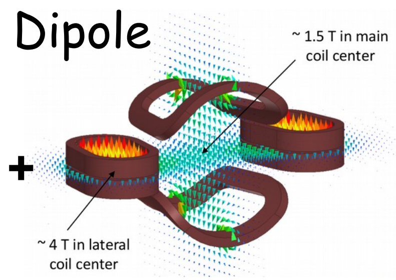


Solenoid

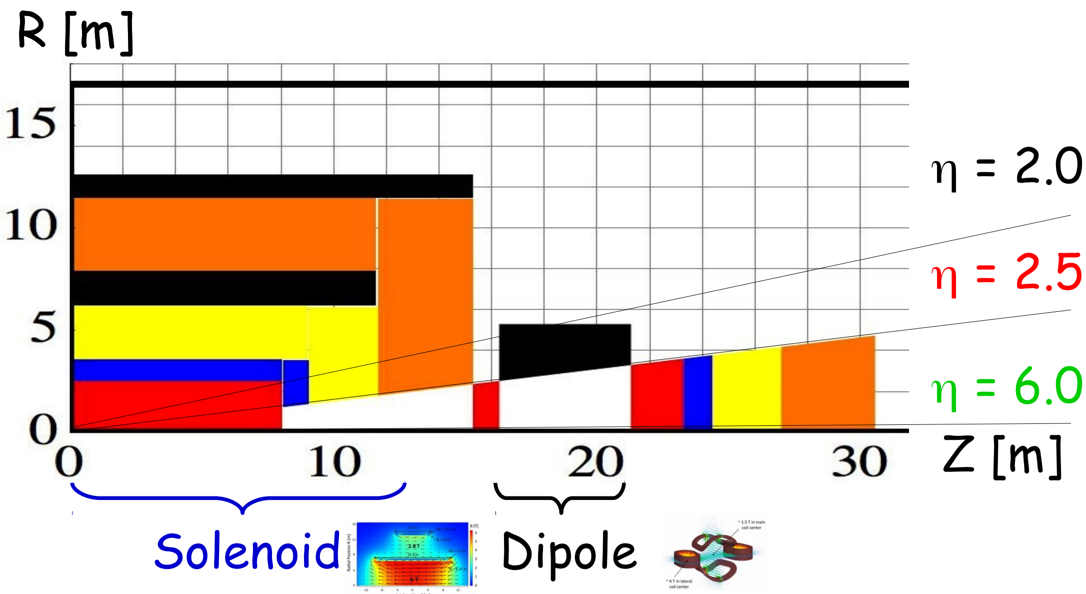


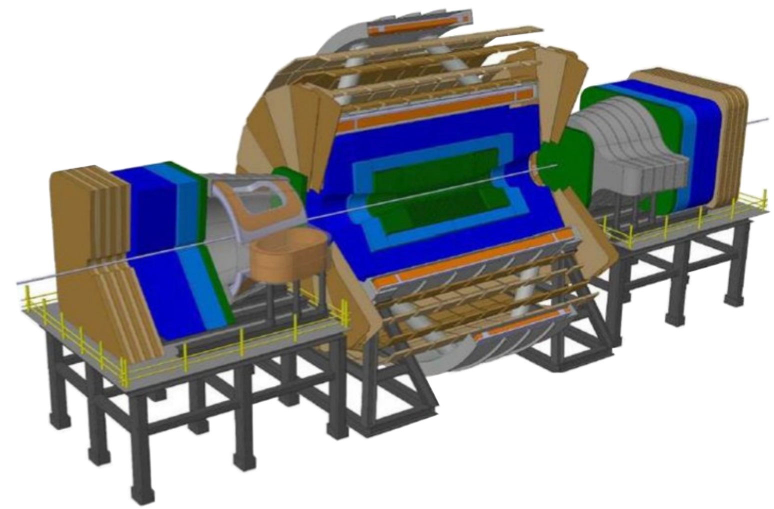

Dipole




Dipoles: standalone p measurement

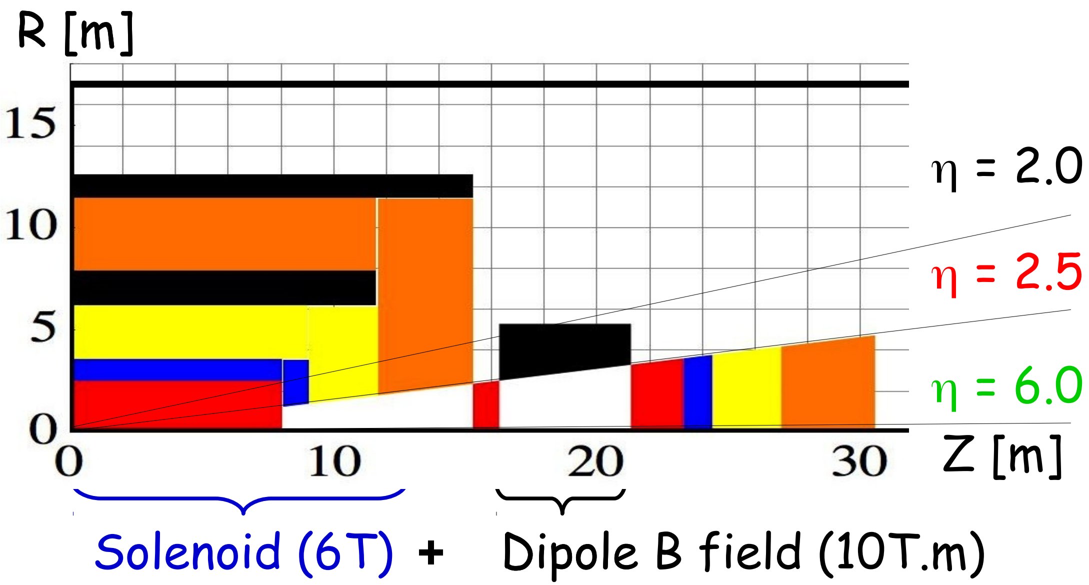
# FCC-hh Detector & Tracker Geometry

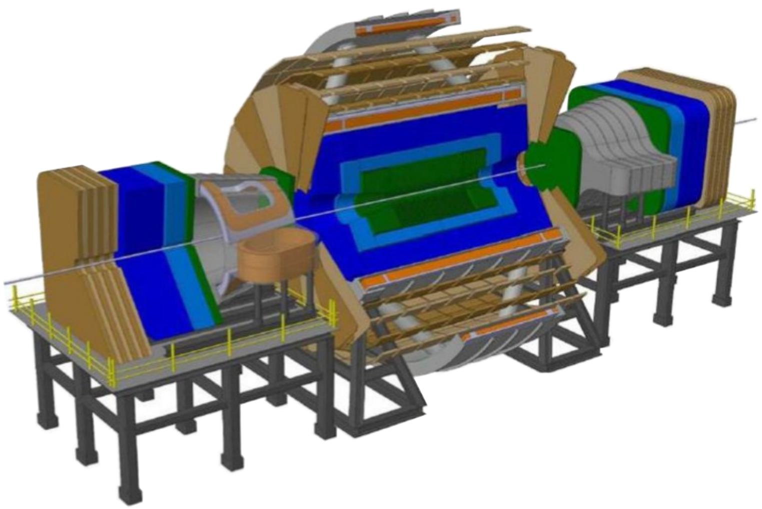


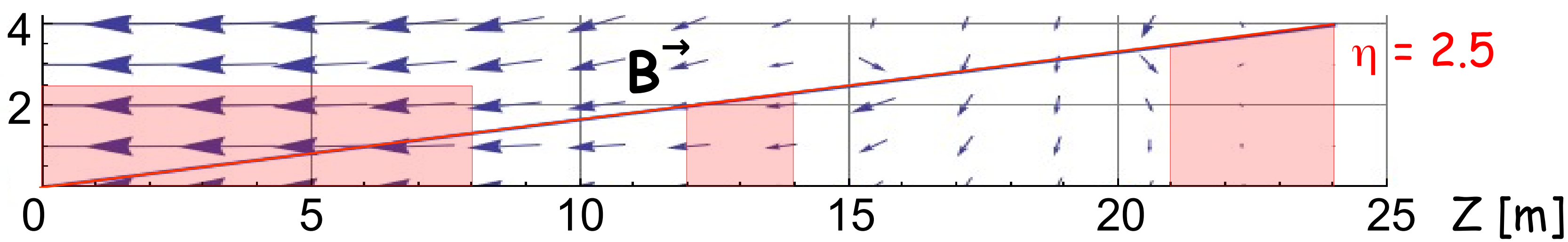



- Beam-pipe (BP):
  - Beryllium R = 20-21mm, **$x/x_0$ = 0.286% → 1/sin(θ) material factor in track fitting!**
  - Z ≥ 8.0m → conical shape with opening angle $\alpha$ = 2.5mrad

# FCC-hh Detector & Tracker Geometry



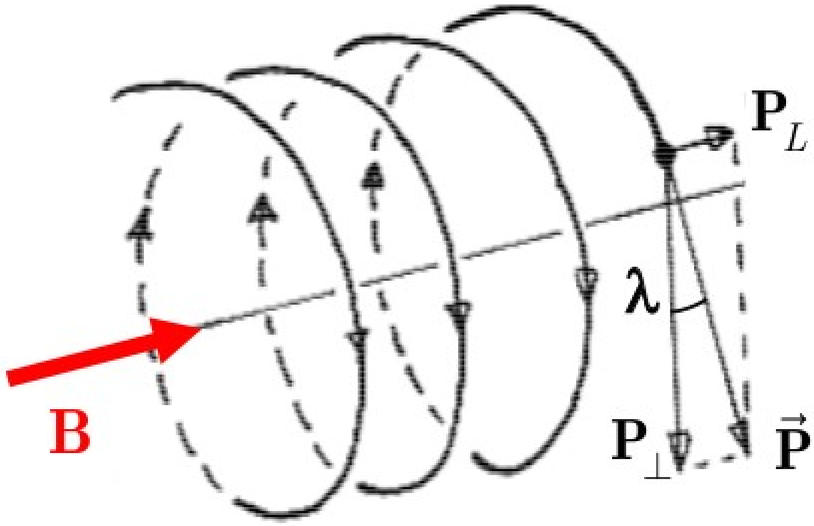



- **Tracker:** assuming **x/x0 = 3% per layer**
  - **Central:** Z = 0 – 8.0m, $R_{max}$ = 2.5m → detector layers (discs) @ **R = 25 – 2400mm**
  - **Fwd: $R_{max}$ limited by η = 2.5** ($R_{min}$ by conical shape of BP)

# Measuring Particle Momentum - Principals

- Tracking in magnetic field:

$$R[\text{m}] = \frac{p_{\text{T}}[\text{GeV}]}{0.3B[T]}$$

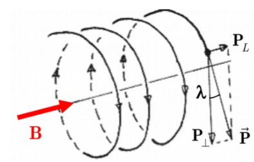



→ **approximative approach:** separate movement in R-Φ plane & s-z projection

– **R-Φ plane → circle fitting → $p_T$ measurement**

# Measuring Particle Momentum - Principals

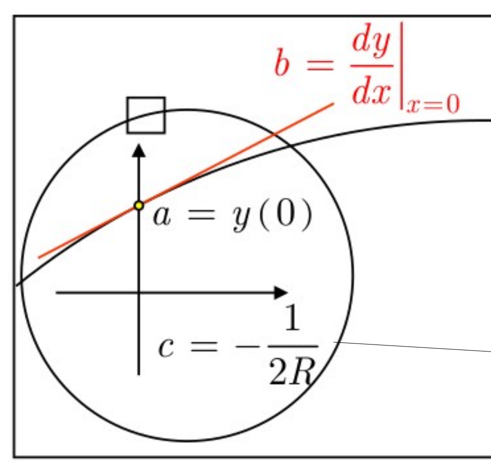
- Tracking in magnetic field: $R[\mathrm{m}] = \frac{p_T[\mathrm{GeV}]}{0.3B[T]}$




  - R-Φ plane → circle fitting → **$p_T$ measurement**

$$
\begin{aligned}
(y - y_0) &= \sqrt{R^2 - (x - x_0)^2} \\
y &\approx y_0 + R\left(1 - \frac{(x - x_0)^2}{2R^2}\right) \\
y &\approx \left(y_0 + R - \frac{x_0^2}{2R}\right) + \frac{x_0}{R}x - \frac{1}{2R}x^2 \\
y &\approx a + bx + cx^2
\end{aligned}
$$

→ **for FCC dimensions: can use parabolic appr. for pT≥10GeV**

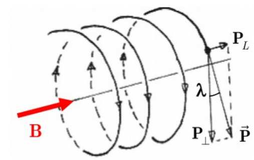



use

$$\frac{\Delta p_T}{p_T} = \frac{\Delta R}{R}$$

# Measuring Particle Momentum - Principals

- Tracking in magnetic field: $R[\mathrm{m}] = \frac{p_T[\mathrm{GeV}]}{0.3B[T]}$




  - R-Φ plane → circle fitting **→ $p_T$ measurement**

    **→ can use parabolic approximation**

$$
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(y - y_0) &= \sqrt{R^2 - (x - x_0)^2} \\
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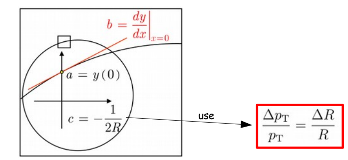
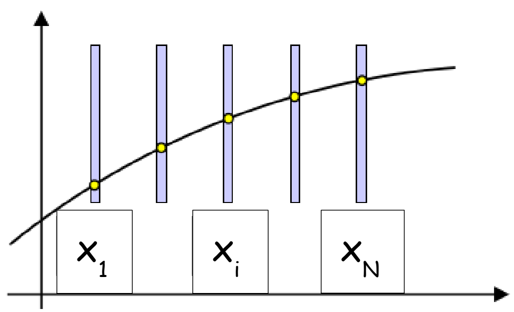



  - Assume N equidistant layers measuring the y-coordinate & applying global $\chi^2$ fit [Gluckstern]




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

→ linearly increases with $p_T$

→ scales linearly: B field (6T), sensor resolution in R-Φ

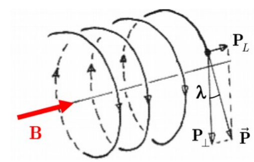
quadratically: level-arm (~ 2.4m)

sqrt: #layers

**→ affects the $p_T$ resolution for high $p_T$**

# Measuring Particle Momentum - Principals

- Tracking in magnetic field: $R[\mathrm{m}] = \frac{p_T[\mathrm{GeV}]}{0.3B[T]}$




  - R-Φ plane → circle fitting → **$p_T$ measurement**

    **→ can use parabolic approximation**

$$
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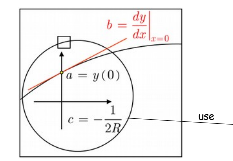
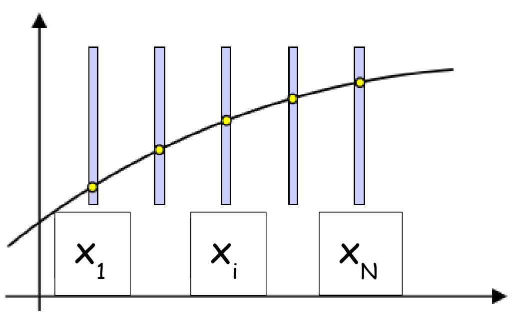



$\frac{\Delta p_T}{p_T} = \frac{\Delta R}{R}$

  - Assume N equidistant layers measuring the y-coordinate & applying global $\chi^2$ fit [Gluckstern]




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

  - CMS → FCC?
    - B = 4T → 6T
    - L = 1.1 (1.2) → 2.4 (2.5)

    } **Factor of 7 improvement**

    → further improvement by optimizing #layers & detector resolution

# Measuring Particle Momentum - Principals

- Multiple Coulomb scattering:
  - $p_T$ resolution **for low $p_T$ tracks** dominated by multiple Coulomb scattering:

$$\frac{\Delta p_{\mathrm{T}}}{p_{\mathrm{T}}} = \frac{0.0136}{0.3\beta\ B[\mathrm{T}]\ L[\mathrm{m}]}\sqrt{\frac{X_{\mathrm{tot}}}{X_0}}\sqrt{\frac{10}{7}}$$

→ $p_T$ constant term

→ scales linearly: B field, level-arm

sqrt: material budget (~ 3% $x/x_0$/layer)

→ **affects the $p_T$ resolution for low $p_T$**

# TkLayout software toolkit

- TkLayout approach to momentum resolution:
  - Use [Karimäki] approach for circle (in polar coordinates)

$$\left(\frac{1}{2R}d^2 + d\right) - \left((1+\frac{d}{R})\sin(\phi_0 - \phi_i)\right) r_i + \frac{1}{2R}r_i^2 \quad = \quad \varepsilon_i$$

$$\sin(\phi_0 - \phi_i) \quad \approx \quad (\phi_0 - \phi_i)$$

$$\left(\frac{1}{2R}d^2 + d\right) - \left((1+\frac{d}{R})(\phi_0 - \phi_i)\right) r_i + \frac{1}{2R}r_i^2 \quad \approx \quad \varepsilon_i$$

→ „Parabolic" approx. in $r_i$

→ $R =$ radius, $d =$ impact parameter in $R - \Phi$, $\phi_0 =$ initial angle, $\varepsilon_i =$ residual for i-th measur.

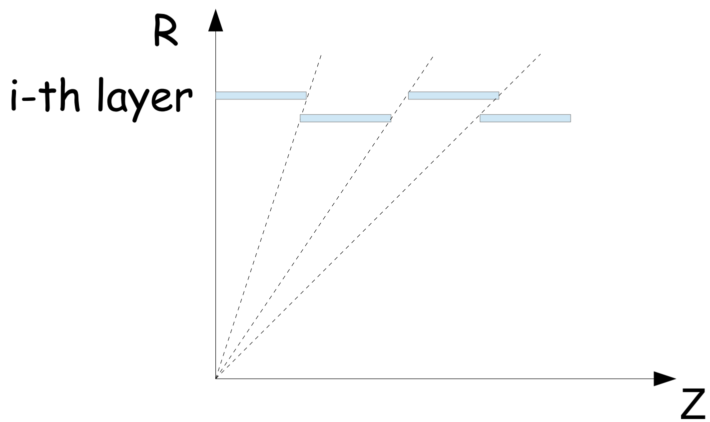
# TkLayout software toolkit

- TkLayout approach:
  - Use [Karimäki] approach for circle (in polar coordinates) → apply "parabolic" approximation:

$$\left(\frac{1}{2R}d^2 + d\right) - \left((1+\frac{d}{R})\sin(\phi_0-\phi_i)\right) r_i + \frac{1}{2R}r_i^2 = \varepsilon_i$$
$$\sin(\phi_0-\phi_i) \approx (\phi_0-\phi_i)$$
$$\left(\frac{1}{2R}d^2 + d\right) - \left((1+\frac{d}{R})(\phi_0-\phi_i)\right) r_i + \frac{1}{2R}r_i^2 \approx \varepsilon_i \longrightarrow \sum_{i=1}^{N} \varepsilon^{\mathrm{T}}\mathbf{V}^{-1}\varepsilon$$

$R$ = radius, $d$ = impact parameter in $R-\Phi$, $\phi_0$ = initial angle, $\varepsilon_i$ = residual for i-th measur.

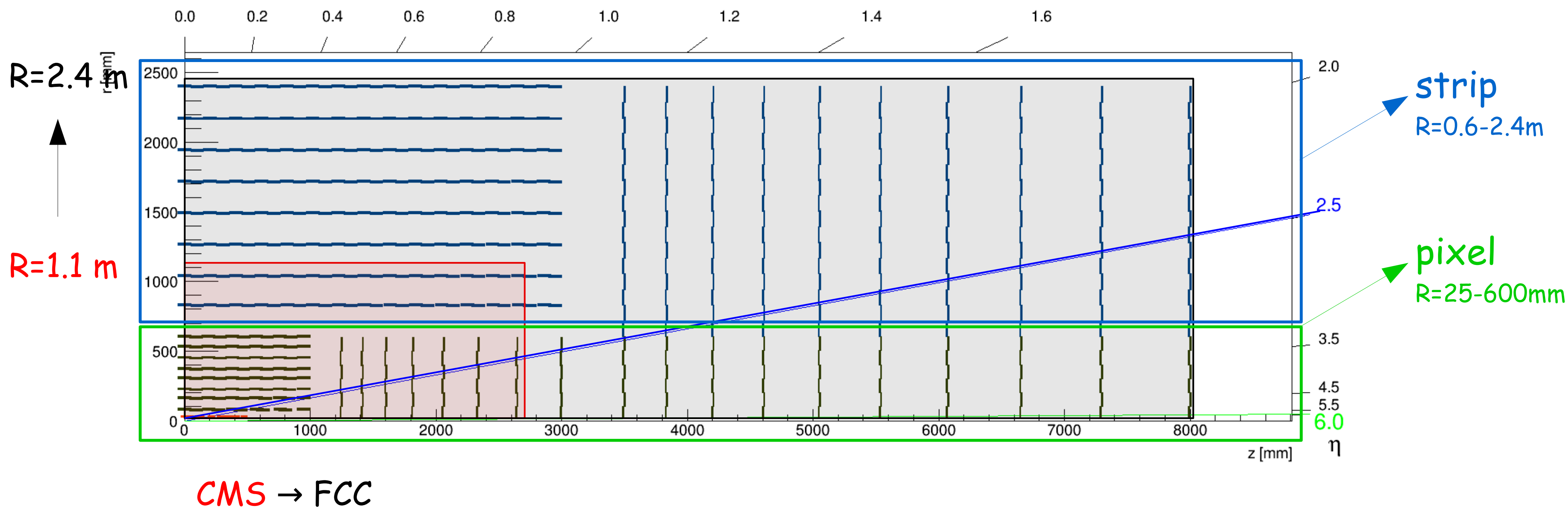
  - Build an optimized geometry layout in ROOT TGeo & do global $\chi^2$ fit $\sum_{i=1}^{N} \varepsilon^{\mathrm{T}}\mathbf{V}^{-1}\varepsilon$




→ tkLayout: SW for tracker studies of CMS Phase 2 upgrade → adapted for FCC-hh

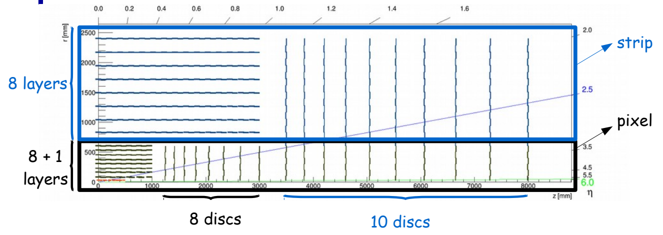
# FCChh Tracker - Material Budget

- Implicitly assumed **$x/x_0$ = 3% per layer** → Expected material distribution?
  - Starting from the following geometry layout ("default") …
    MB of each detector ($t_{mod}$=0.43cm) represented as: 20% Si, 42% C, 2% Cu, 6% Al, 30% Plastic

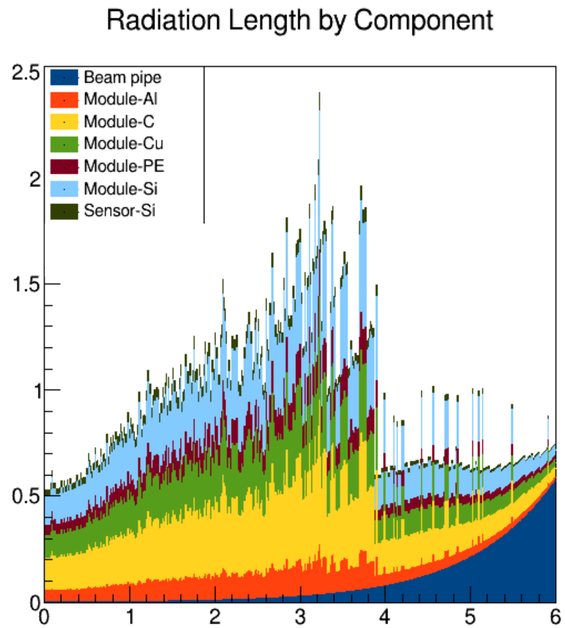


# FCChh Tracker - Material Budget (MB)

- Implicitly assumed **$x/x_0$ = 3% per layer** → Expected material distribution?
  - Starting from the following geometry layout …

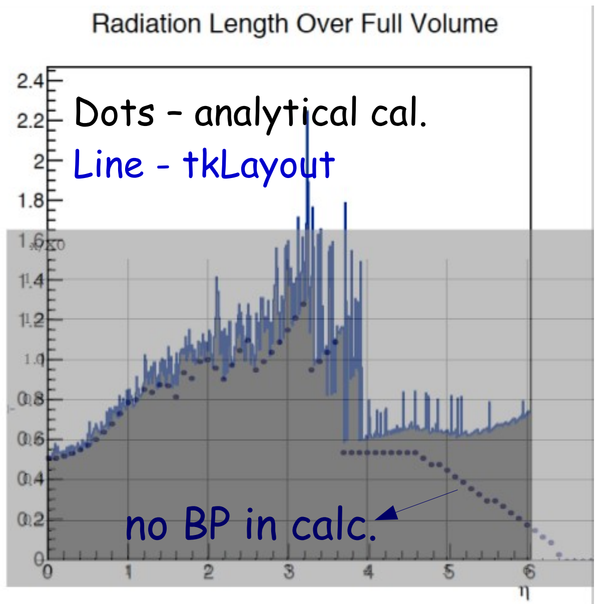



  - **Material budget:**



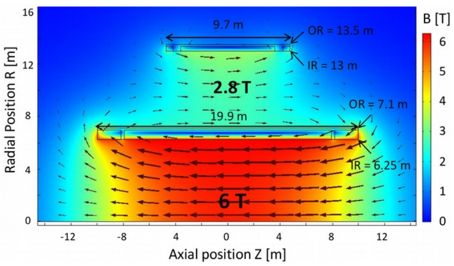

Compared to

analytical calc. by W. Riegler

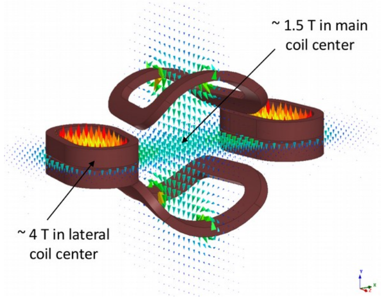


# FCChh Tracker - Resolution Studies

- What is the tracker $p_T$ resolution? Two approaches in fwd region: dipole versus solenoid?
  - Dipole scenario:




+



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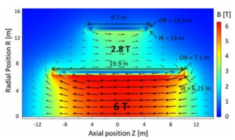
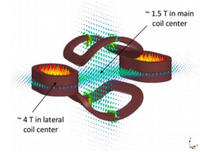
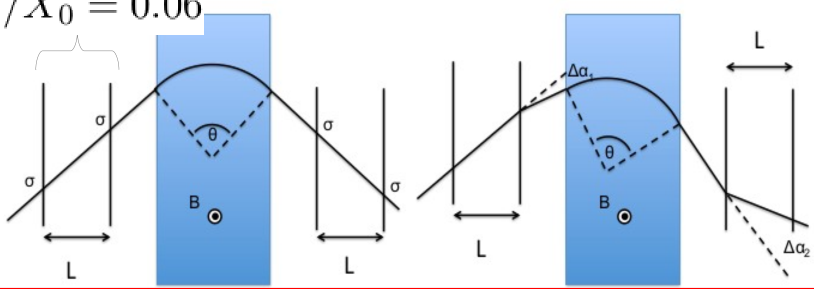
  - Dipole scenario: 



    - Measure $p_L(p)$ using forward tracker & dipole (calculations by W.Riegler):

$x_f/X_0 = 0.06$



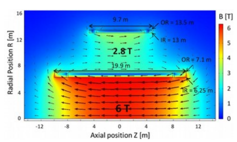

Using $L = 2\,\mathrm{m}$, $\sigma = 30\,\mu\mathrm{m}$, $x_f/X_0 = 0.06$

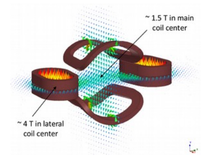
$$\left(\frac{\Delta p_L}{p_L}\right)^2 = \left(\frac{2\sigma\, p_L}{0.3L\int B_T dl}\right)^2 + \left(\frac{0.0136}{0.3\int B_T dl}\sqrt{2\frac{x_f}{X_0}}\right)^2$$

Tracking resolution — MS resolution

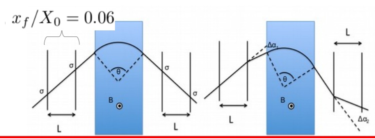
# FCChh Tracker - Resolution Studies

- What is the tracker $p_T$ resolution? Two approaches in fwd region: dipole versus solenoid?
  - **Dipole** scenario:




- Measure $p_L$(p) using forward tracker & dipole (calculations by W.Riegler):




Using $L = 2\,\mathrm{m}$, $\sigma = 30\,\mu\mathrm{m}$, $x_f/X_0 = 0.06$

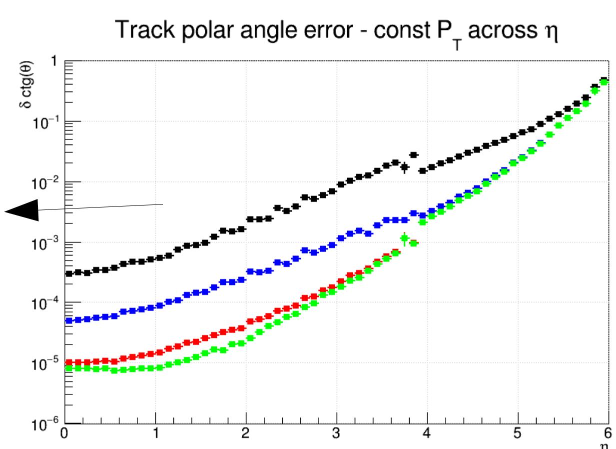
$$\left(\frac{\Delta p_L}{p_L}\right)^2 = \left(\frac{2\sigma\, p_L}{0.3L\int B_T dl}\right)^2 + \left(\frac{0.0136}{0.3\int B_T dl}\sqrt{2\frac{x_f}{X_0}}\right)^2$$

Tracking resolution — MS resolution

- Using the cotg( $\vartheta_{\mathrm{emission}}$ ) measurement (by tkLayout) determine the $p_T$ from $p_L$ (p)

$$p_T = p_L \tan\vartheta_e$$

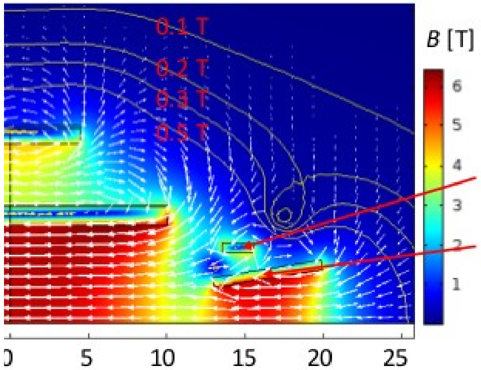
$$\left(\frac{\Delta p_T}{p_T}\right)^2 = \left(\frac{\Delta p_L}{p_L}\right)^2 + \left(\frac{1}{\sin\vartheta_e\cos\vartheta_e}\right)^2 \Delta\vartheta_e^2$$




**Simulated $p_T$:**
- 10 GeV
- 100 GeV
- 1 TeV
- 10 TeV

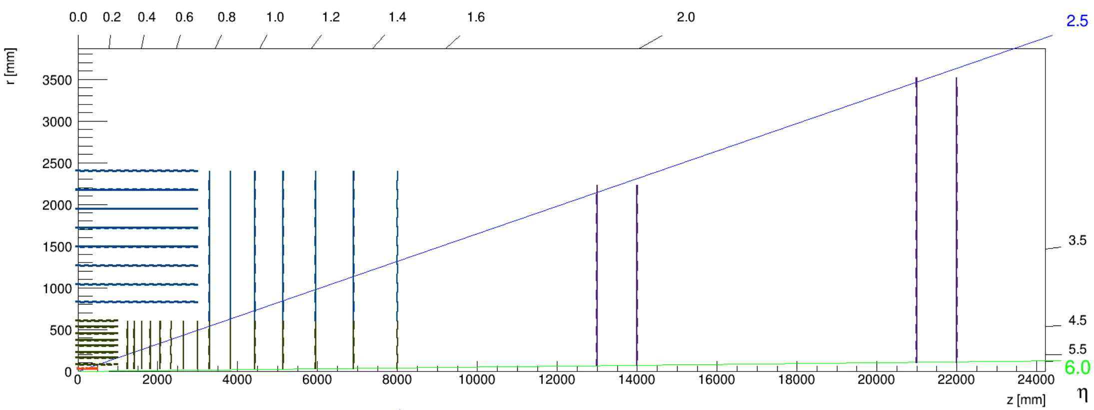
# FCChh Tracker - Resolution Studies

- Compared to the second scenario ...
  - **Solenoid** scenario (see talk by M.Mentink)
    - In tkLayout the 2 solenoids modelled as one 6T solenoid covering central+fwd tracker



# FCChh Tracker - Resolution Studies

- Tracker geometry:




The level-arm playing a role in the solenoid+solenoid scenario

The level-arm playing a role in the solenoid+dipole scenario

Central tracker

- R-Φ res. = 25um

Fwd inner discs:

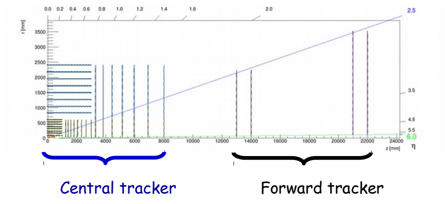
- R-Φ res. = 25um

Fwd outer discs:

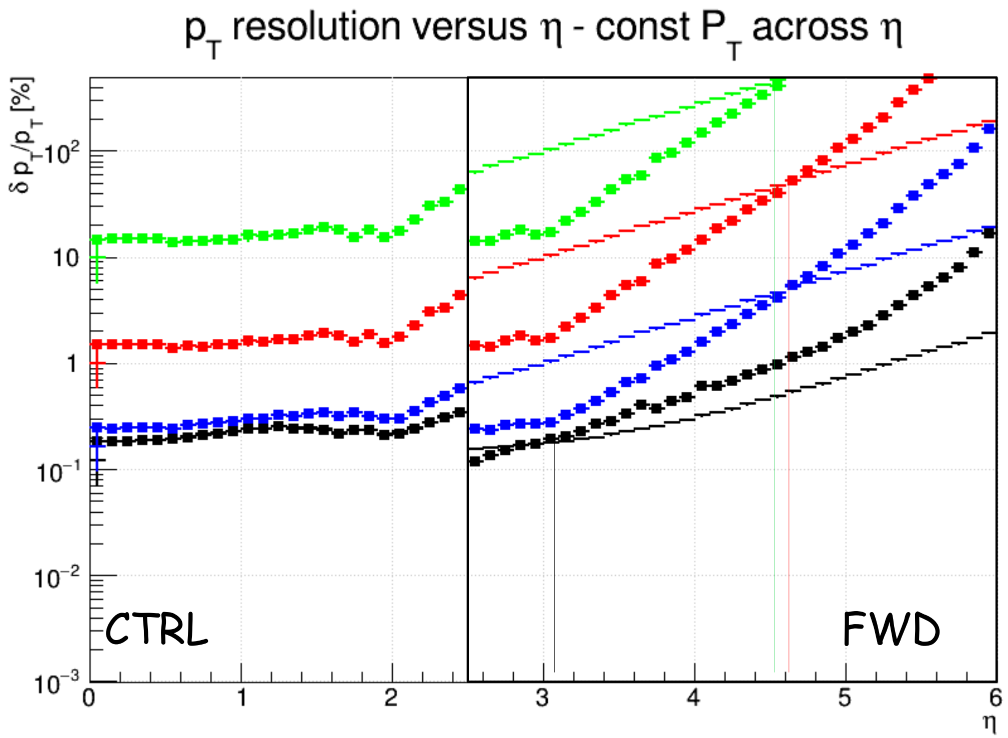
- Variable resol. in R-Φ: 25 – 130um to get const pt resol. to η=3.0 (const. 25um resol. would improve the result even more!)

# FCChh Tracker - Resolution Studies

- Tracker geometry:




- Estimated $p_T$ resolution:




**Simulated $p_T$:**

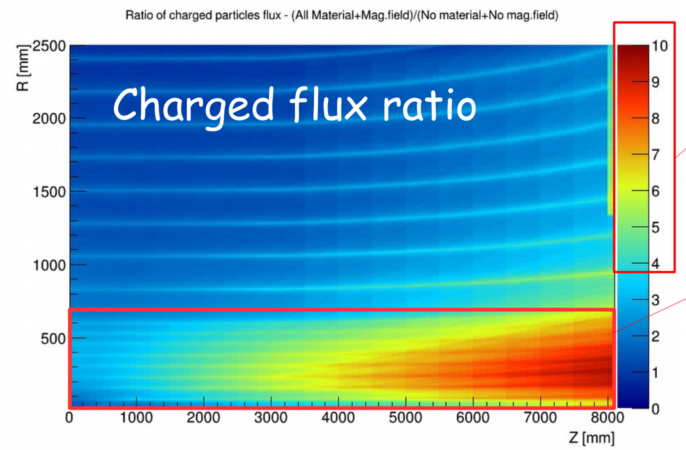
- **10 GeV**
- **100 GeV**
- **1 TeV**
- **10 TeV**

■ **solenoid**

– **dipole**

# Tracker in High Pile-up & High Rate Environment

- Implications of high pile-up and high-rate environment on the tracker design
  - Use Fluka irradiation map (by F.Cerutti & M.I.Besana) → calculate flux ratio: $Flux_{MB\_on + BField\_on}/Flux_{MB\_off + BField\_off}$ → **study effect of MB & B field:**




Multiplication factor → effect of material & B field

Particles compressed to the R = 600mm in strong mag. field of 6T → **region unsuitable for strip detectors**

# Tracker Occupancy Studies

- Study of tracker occupancy:
  - Use the flux [particles/cm$^2$] normalized to 1000 pile-up events
  - **Estimate occupancy & minimum pitch** to get ~ 1% occupancy for pixel detectors

Pixel - BRL

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 |

→ 40x40um$^2$ @ 1$^{st}$ layer

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| 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 |

→ 40x40um$^2$ @ 1$^{st}$ layer

## Pixel - ENDCAP

| 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 |

→ 30x30um$^2$ @ 1$^{st}$ endcap ring

→ **no stringent limit on min pitch** (the dominant limit might be driven by physics of **high collimated objects**)

# Tracker Data Rates

- Expected data rates (required bandwidth):
  - Use Fluka simulated flux scaled to 1000 pile-ups & calculate hit rates:
    - Non-triggered data → f = 40 MHz
    - Triggered data → f ~ 1 MHz (value given by hardware limits, e.g. FPGA etc.)

# Tracker Data Rates

- Expected data rates (required bandwidth):
  - Use Fluka simulated flux scaled to 1000 pile-ups & calculate hit rates:
  - Estimate the bandwidth for **sparsified data**:

→ address read-out channel : nBits = $\log_2$(nRows) + $\log_2$(nColumns)

→ add data block for cluster width: 2bits (cluster width ~ 3)

→ add data block for pulse-height: 0bits (binary read-out), 4-8bits (analog read-out)

# Tracker Data Rates – PXL BRL

– Expected data rates for CMS-like geometry (required bandwidth):
  - Use Fluka simulated flux scaled to 1000 pile-ups & calculate hit rates:
  - Estimate the bandwidth for **sparsified data**:

**Pixel - BRL**

**Total data flow from inner barrel**

Number of pile-up events: 1000

| Layer no : | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | Total [TB/s] |
|---|---|---|---|---|---|---|---|---|---|---|
| Radius [mm] : | 25.0 | 93.3 | 169.2 | 232.9 | 317.9 | 381.6 | 466.5 | 530.1 | 600.0 | |
| Module bandwidth/(addr+clsWidth=2b[b] : | 19 | 19 | 19 | 19 | 19 | 19 | 19 | 19 | 19 | |
| Mod. bandwidth(#chnls*(addr+clsWidth)[kb] : | 96.93 | 11.52 | 8.62 | 5.15 | 2.70 | 1.93 | 1.18 | 0.92 | 0.66 | |
| Mod. bandwidth (matrix*1b/channel) [kb] : | 128.00 | 128.00 | 128.00 | 128.00 | 128.00 | 128.00 | 128.00 | 128.00 | 128.00 | |
| Data rate per layer - 40MHz,spars [Tb/s] : | 823 | 540 | 359 | 295 | 211 | 181 | 134 | 120 | 99 | 345 |
| Data rate per layer - 1MHz,spars [Tb/s] : | 20 | 13 | 8 | 7 | 5 | 4 | 3 | 3 | 2 | 8 |
| Data rate per ladder - 40Mhz,spars [Gb/s] : | 70257 | 15377 | 11513 | 6872 | 3610 | 2579 | 1569 | 1231 | 878 | |
| Data rate per ladder - 1Mhz,spars [Gb/s] : | 1756 | 384 | 287 | 171 | 90 | 64 | 39 | 30 | 21 | |
| **Data rate per module - 40Mhz,spars [Gb/s]:** | 3697.74 | 439.35 | 328.95 | 196.37 | 103.17 | 73.70 | 44.83 | 35.18 | 25.09 | |
| **Data rate per module - 1Mhz,spars [Gb/s]:** | 92.44 | 10.98 | 8.22 | 4.91 | 2.58 | 1.84 | 1.12 | 0.88 | 0.63 | |

9.5 Gb/s/cm$^2$ @ 1MHz trigger & with binary read-out

→ **The triggered (1MHz) data in the first 2 layers with data flows >> 10Gb/s per module**

→ **Out of current scale → need for trigger & advanced technologies!**

# Tracker Data Rates - PXL Endcap

- Expected data rates for CMS-like geometry (required bandwidth):
  - Use Fluka simulated flux scaled to 1000 pile-ups & calculate hit rates:
  - Estimate the bandwidth for **sparsified data**:

**Pixel - BRL** — Total data flow from inner barrel

Number of pile-up events: 1000

| Layer no : | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | Total [TB/s] |
|---|---|---|---|---|---|---|---|---|---|---|
| Radius [mm] : | 25.0 | 93.3 | 169.2 | 232.9 | 317.9 | 381.6 | 466.5 | 530.1 | 600.0 | |
| Module bandwidth/(addr+clsWidth=2b[b] : | 19 | 19 | 19 | 19 | 19 | 19 | 19 | 19 | 19 | |
| Mod. bandwidth(#chnls*(addr+clsWidth)[kb] : | 96.93 | 11.52 | 8.62 | 5.15 | 2.70 | 1.93 | 1.18 | 0.92 | 0.66 | |
| Mod. bandwidth (matrix*1b/channel) [kb] : | 128.00 | 128.00 | 128.00 | 128.00 | 128.00 | 128.00 | 128.00 | 128.00 | 128.00 | |
| Data rate per layer - 40MHz,spars [Tb/s] : | 823 | 540 | 359 | 295 | 211 | 181 | 134 | 120 | 99 | 345 |
| Data rate per layer - 1MHz,spars [Tb/s] : | 20 | 13 | 8 | 7 | 5 | 4 | 3 | 3 | 2 | 8 |
| Data rate per ladder - 40Mhz,spars [Gb/s] : | 70257 | 15377 | 11513 | 6872 | 3610 | 2579 | 1569 | 1231 | 878 | |
| Data rate per ladder - 1Mhz,spars [Gb/s] : | 1756 | 384 | 287 | 171 | 90 | 64 | 39 | 30 | 21 | |
| **Data rate per module - 40Mhz,spars [Gb/s]:** | 3697.74 | 439.[illegible] | 328.95 | 196.37 | 103.17 | 73.70 | 44.83 | 35.18 | 25.09 | |
| **Data rate per module - 1Mhz,spars [Gb/s]:** | 92.44 | 10.9[illegible] | 8.22 | 4.91 | 2.58 | 1.84 | 1.12 | 0.88 | 0.63 | |

9.5 $Gb/s/cm^2$ @ 1 MHz trigger & with binary read-out

## Pixel - ENDCAP

Number of pile-up events: 1000

| Ring no : | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | Total [TB/s] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 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 | |
| Module bandwidth/(addr+clsWidth=2b[b] : | 19 | 19 | 19 | 19 | 19 | 19 | 19 | 19 | 19 | 19 | 19 | |
| Mod. bandwidth(#chnls*(addr+clsWidth)[kb] : | 36.89 | 25.35 | 11.37 | 12.89 | 8.38 | 5.43 | 3.72 | 2.72 | 2.07 | 1.51 | 1.14 | |
| Mod. bandwidth (matrix*1b/channel) [kb] : | 128.00 | 128.00 | 128.00 | 128.00 | 128.00 | 128.00 | 128.00 | 128.00 | 128.00 | 128.00 | 128.00 | |
| Data rate per ringLayer-40MHz,spars [Tb/s]: | 989 | 1223 | 915 | 691 | 584 | 465 | 358 | 305 | 266 | 210 | 177 | 773 |
| Data rate per ringLayer- 1MHz,spars [Tb/s]: | 24 | 30 | 22 | 17 | 14 | 11 | 8 | 7 | 6 | 5 | 4 | 19 |
| Data rate per ring - 40Mhz,spars [Gb/s] : | 28144 | 34814 | 26031 | 19668 | 16621 | 13246 | 10203 | 8703 | 7582 | 5999 | 5040 | |
| Data rate per ring - 1Mhz,spars [Gb/s] : | 703 | 870 | 650 | 491 | 415 | 331 | 255 | 217 | 189 | 149 | 126 | |
| **Data rate per module - 40Mhz,spars [Gb/s]:** | 1407.21 | 967.08 | 433.86 | 491.71 | 319.65 | 206.97 | 141.72 | 103.61 | 78.98 | 57.69 | 43.45 | |
| **Data rate per module - 1Mhz,spars [Gb/s]:** | 35.18 | 24.18 | 10.85 | 12.29 | 7.99 | 5.17 | 3.54 | 2.59 | 1.97 | 1.44 | 1.09 | |

3.6 $Gb/s/cm^2$ @ 1MHz trigger & with binary read-out

**→ Out of current scale → need for trigger & advanced technologies!**

# Summary & Outlook

- tkLayout, a software toolkit for CMS tracker phase 2 upgrade design studies, has been adapted & setup for FCC(-hh) needs:
  - An important toolkit providing "engineering" approach to geometry layout with the capability to study performance of a designed tracker
  - Details of already studied layouts can be found at http://fcc-tklayout.cern.ch
- Design study concentrated on resolution, material budget, occupancy & data rates of FCC-hh tracker in a magnet scenario of 6T has been done:
  - Particularly, with a focus on the interplay between the central tracker & forward region in 2 magnet scenarios: dipole versus solenoid in the forward region
  - Another scenarios (e.g. pushing the detector resolution to their technology limits) can be easily studied with tkLayout
- Future studies need to be focused on the pattern recognition and its impact on the tracker design
  - Either using the tkLayout sofware with a combinatorial approach as a starting study or more advanced techniques using tkLayout and/or FCC full simulation software