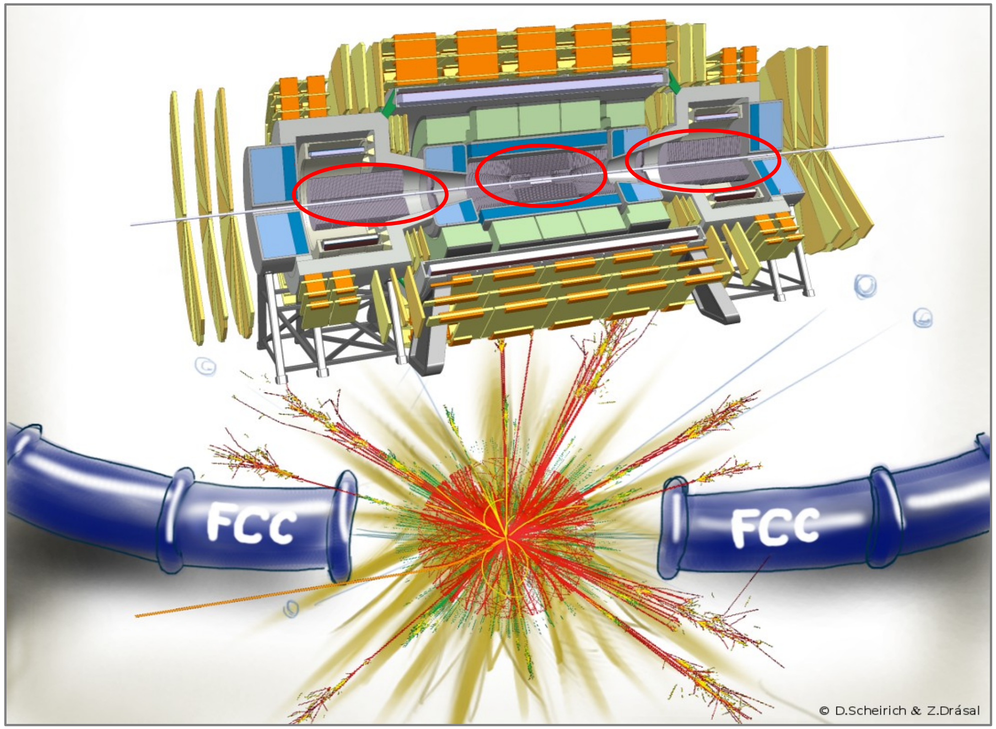
Overview of FCC-hh Tracker Design



Zbyněk Drásal
CERN

On behalf of the FCC-hh detector working group

Overview

- Introduction
  - Physics motivation & challenges
- Tracker design & expected tracker performance
  - Baseline tracker layout v3.03 → for details of all layouts see: http://fcc-tklayout.web.cern.ch
  - Magnetic field scenarios & tracking resolution
  - Expected tracking performance (see also E. Perez's talk) & material budget
  - b,c,τ-tagging → for details see E. Perez's talk
- Implications of high pile-up & high-rate environment
  - Pattern recognition capabilities & granularity in Z → new tilted layout v4.01
  - Vertexing (see also E. Perez's talk) & timing information
  - Data rates & tracker occupancy
- Software toolkits:
  - tkLayout, FCCSW & ACTS → follow FCC SW session: J.Lingemann, J.Hrdinka & V.Volkl's talks
- Summary & Outlook

Physics Motivation & Challenges

- **A few benchmarks to give us an intuitive hints on key tracker parameters:**
  - **e.g. SM & Higgs or VBF**

    → Need **extended** tracking **up-to |η|~4**, efficient VBF jet measurement **up-to |η|~6**

    → Need **tracker hermeticity** for all tracks coming from the luminous region (σ_z~±75mm)
  - **Direct searches (higher mass reach),** e.g. **Z' → μμ** or **Z' → $t\bar{t}$** (high boosted objects)

    → Need for **high dp_T/p_T res. ~10-20% @10TeV/c** (cf. LHC: 10%@1TeV)

    → But still keeping **sensitivity for low p_T tracks**
  - **Precise understanding of SM/New physics** → higher mass reach **(100TeV)**/higher luminosity **$30\mathrm{x}10^{34}$ $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (@25ns)** → **O(1000) pile-up events per bunch crossing expected**

    → **Precision tracking & track association with primary vertex** required

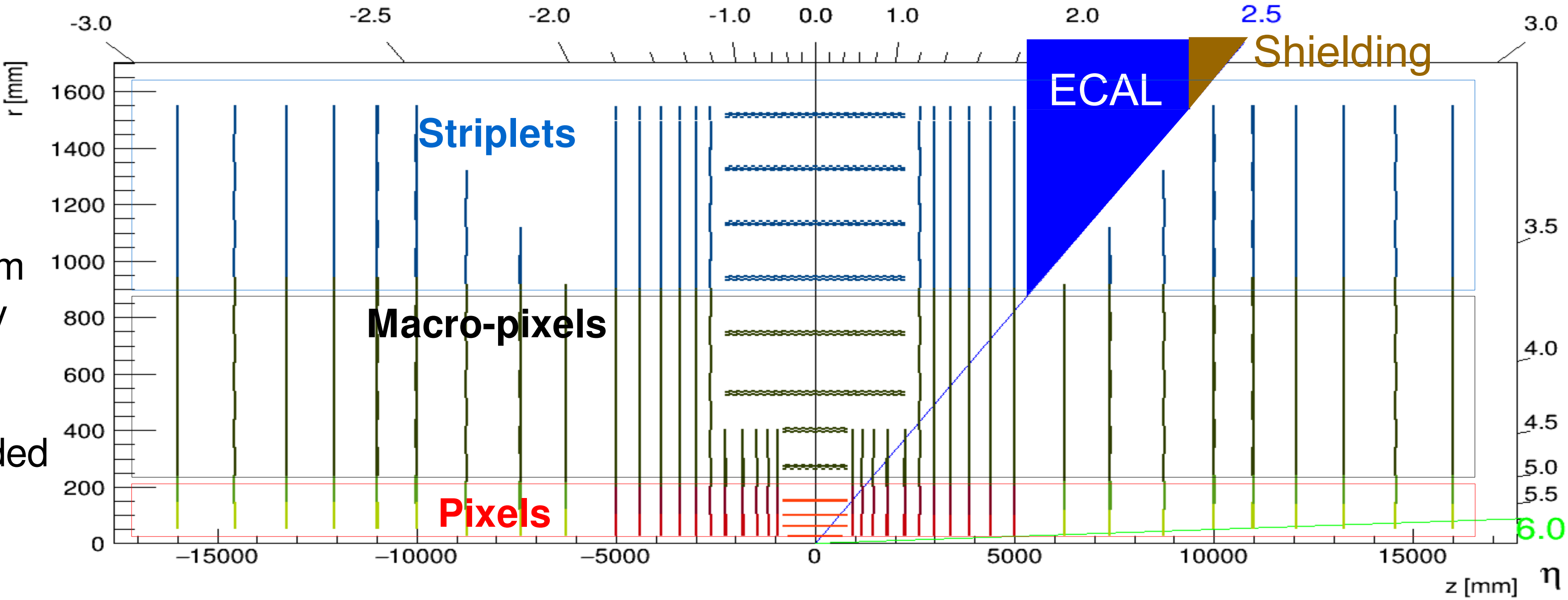
    → **Efficient b, c, τ tagging** despite intense radiation levels at low radii

Baseline Tracker Layout (v3.03)

4 x **4** x **4**
(seeding) BRL
layer structure

Pixel R↗0.9 (0.6) m
due to occupancy
(6T → 4T)

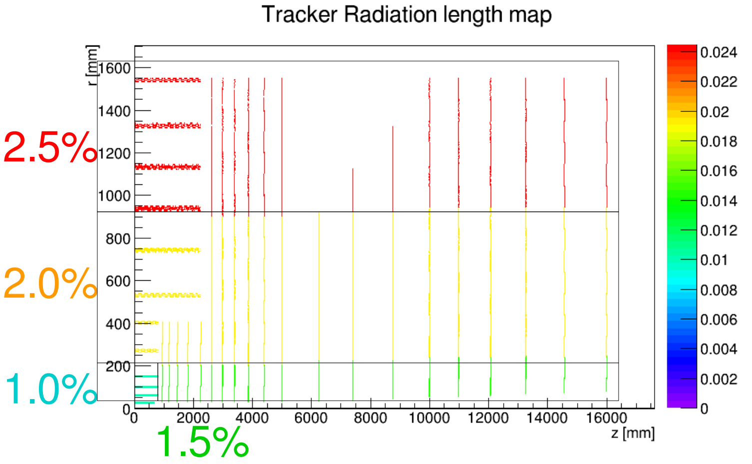
3 IFWD discs needed
by pattern-reco



- **Pixels** (pitch)**:** 25x50um^2 (1-4th BRL layers, EC R1), 100/3x100um^2 (R2), 100/3x400um^2 (R3,R4)
- **Macro-pixels** (pitch)**:** 100/3x400um^2
- **Strips** (pitch)**:** 100/3umx50mm (BRL), 100/3umx10mm (EC)

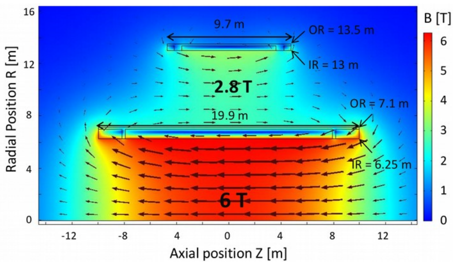
→ **Surface:** 9.6m^2 (pixels), 133m^2 (macro-pixels), 287.8m^2 (strips)

→ **#channels:** 5460.9M (pixels), 9964.4M (macro-pixels), 489.4M (strips)

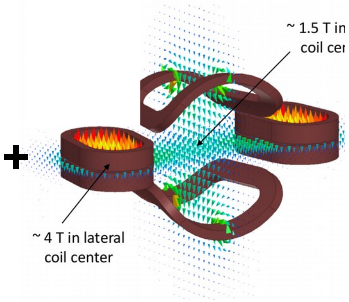


Mag. Field & Tracking Performance

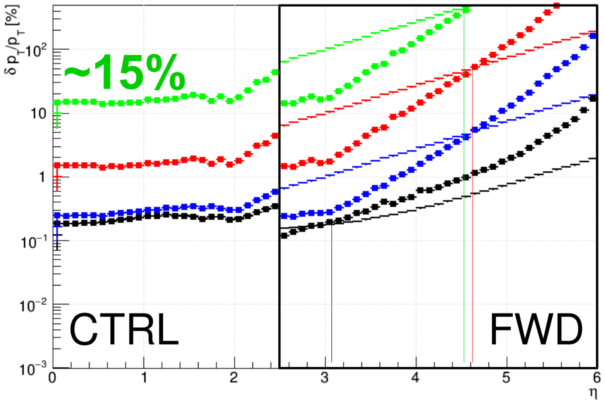
- **A snapshot of mag. field scenario a year ago: 6T twin solenoid + balanced conical shape/10Tm dipole in FWD:**



+



δp_t/p_t [%] versus η



Simulated p_T:

- **10 GeV/c → @η=5 p~700GeV/c**
- **100 GeV/c → @η=5 p~7TeV/c**
- **1 TeV**
- **10 TeV**

▪ **solenoid**

– **dipole**

→ **Solenoid comparable to dipole in tracking resolution!**

→ **6T scenario: technology challenging & costly** option → focus on scenario with **4T** & **more aggressive detector design** (tilted layout + finer granularity)

$$\boxed{\frac{\Delta p_{\mathrm{T}}}{p_{\mathrm{T}}} \simeq \frac{\sigma[\mathrm{m}]\; p_{\mathrm{T}}[\mathrm{GeV/c}]}{0.3B[\mathrm{T}]\; L^2[\mathrm{m}^2]}}$$

6T → 4T scenario ⟶

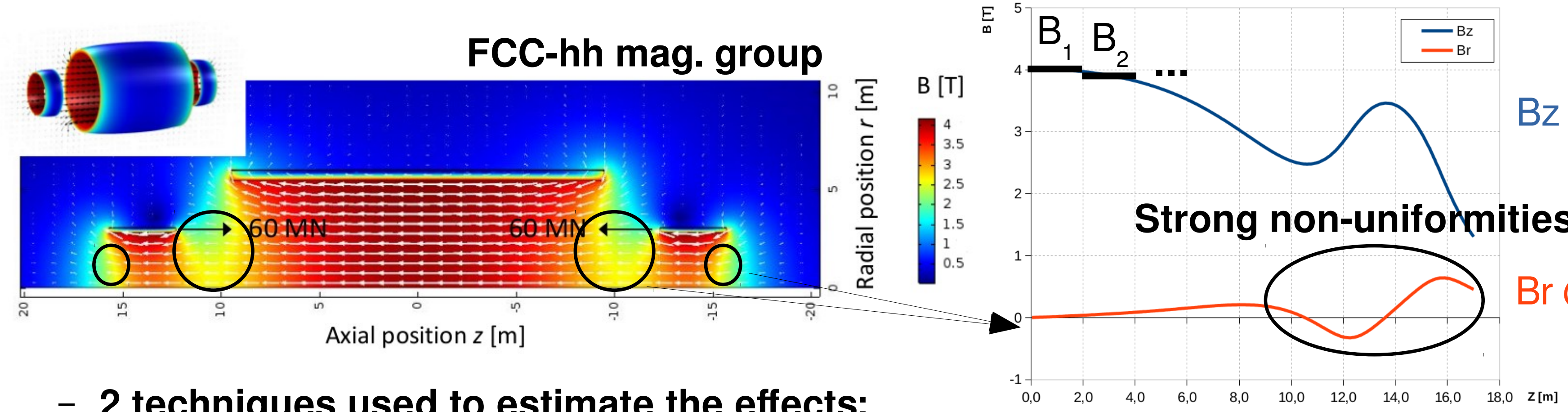
L: 2.4 → 1.55m
B: 6T → 4T
σ: 25um → 10(7.5)um

$$\left.\begin{array}{l}\text{res. degrades} \sim 2.4\text{x} \\ \text{res. degrades} \sim 1.5\text{x}\end{array}\right\} \ 3.6\text{x}$$

res. Improves ~ 2.5 (3.3)x

Mag. Field & Tracking Performance

- **4T solenoid option → how do the mag. field non-uniformities affect FWD tracking?**



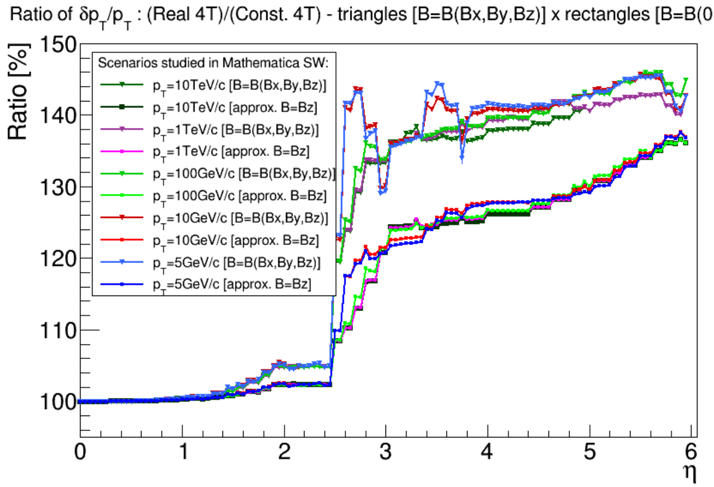
FCC-hh mag. group

Bz @R=1.55m

Strong non-uniformities

Br @R=1.55m

  - **2 techniques used to estimate the effects:**
    - N-parabola approx. (tkLayout) & numerical solution by W.Riegler (Mathematica SW)



Ratio of $\delta p_T/p_T$: (Real 4T)/(Const. 4T) - triangles [B=B(Bx,By,Bz)] x rectangles [B=B(0,0,Bz)]

→ Deterioration due to Bz(r,z) ~**25-35%**

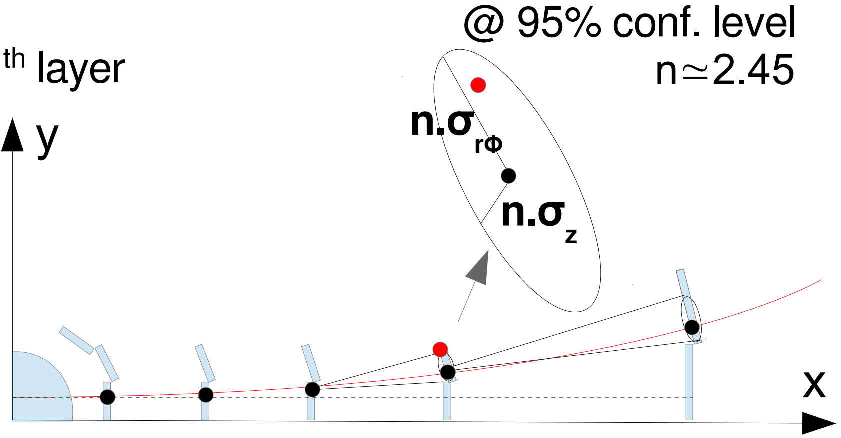
→ **Total deterioration in $\delta p_T/p_T$ due to non-uniformity** of B field (Bz & Br) ~**35-45% @ η=2.5 or higher**

→ **Overall negligible effect!**

Pattern recognition (PR) Capabilities

- Granularity in Z strongly affects **pattern recognition capabilities**, so how to study PR analytically? Strategy: study “**weak**” **spots** in layout!
  - → Assume **perfect seeding** (triplet) → propagate **$\sigma_{r\Phi}$, σ_z** to ith layer
  - → Calculate probability **p** to mis-match a **real hit anywhere on the track** with a **bkg hit** @95% CL **in PU=1000**

$$p = 1 - \prod_{i=4}^{N} (1 - p^{i}_{\mathrm{bkg95\%}})$$



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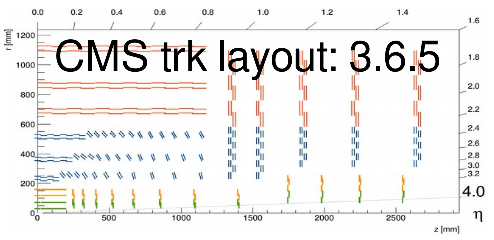
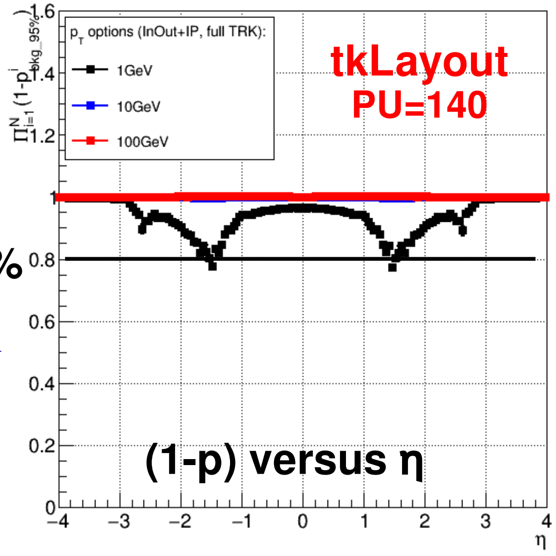
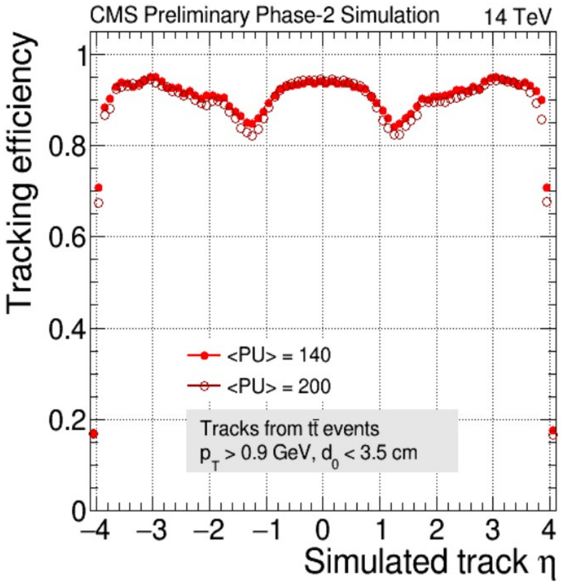
- **How to “qualitatively” interpret *p* ?**
  c.f. CMS Ph2 layout @PU~140…



(1-p) ~ 80%





E.Brondolin: CMS DP-2017/010

→ To keep **similar PR for FCChh @PU~1000**, **set bkg. prob. contamination *p* @20%**

Understanding Pattern Recognition Results

- 4 key parameters affecting propagation of error ellipse:
  - → Multiple scattering & **material effect @ ϑ** (**tilt angle α**)
  - → **Propagation distance**
  - → **Projection factor** on det. plane
  - → **Detector resolution**

$$\sigma^2_{\mathrm{MS}} \approx \langle\vartheta^2_{p_T}\rangle \boxed{\frac{d/X_0}{\sin(\vartheta+\boxed{\alpha})}} \boxed{\Delta r^2} \boxed{f_{\mathrm{proj}}}$$

$$\langle\vartheta^2_{p_T}\rangle = \left(\frac{13.6\,\mathrm{MeV}}{\beta p_T c}\right)^2 \left(1+0.038\ln\frac{d/X_0}{\sin(\vartheta+\alpha)}\right)^2$$

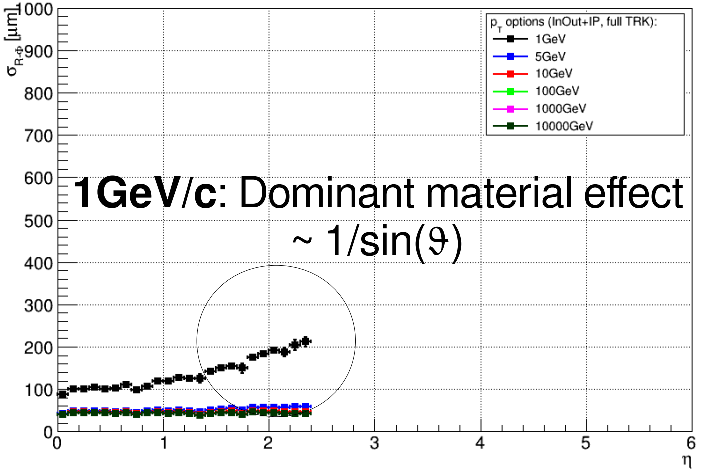
$$\boxed{f_{\mathrm{proj}} = \left(\frac{1}{\sin\vartheta}\right)^2 \quad \text{proj. in Z}}$$

$$\boxed{f_{\mathrm{proj}} = 1 \quad \text{proj. in R–}\Phi}$$

$$\sigma_{R\Phi} = \sqrt{\boxed{\sigma^2_{R\Phi_{\mathrm{loc}}}} + (A/\sqrt{1-A^2}\,\sin\alpha)^2 \boxed{\sigma^2_{Z_{\mathrm{loc}}}}}$$

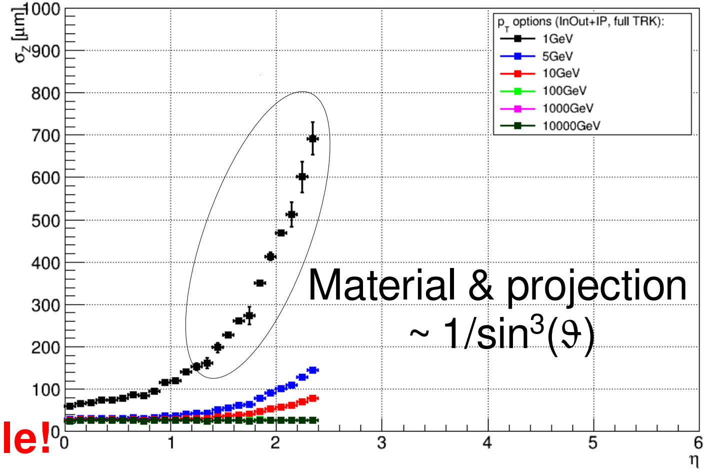
$$A = \Delta r/2R$$

Propagated $\sigma_{R\text{-}\Phi}$ on 4th BRL layer



1GeV/c: Dominant material effect ~ 1/sin(ϑ)

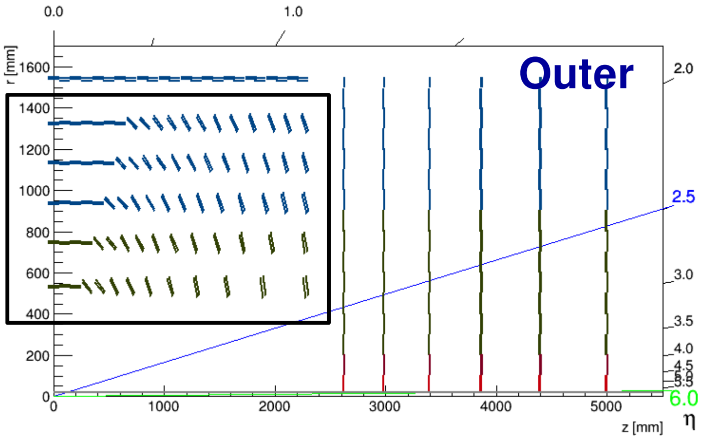
Propagated σ_Z on 4th BRL layer

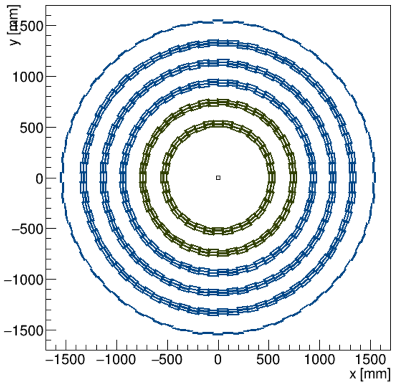


Material & projection ~ 1/sin^3(ϑ)

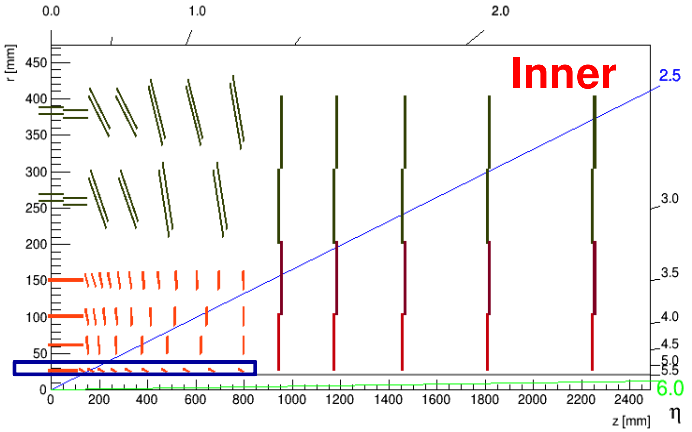
→ **To minimize mat. effects, tracker in tilted layout inevitable!**

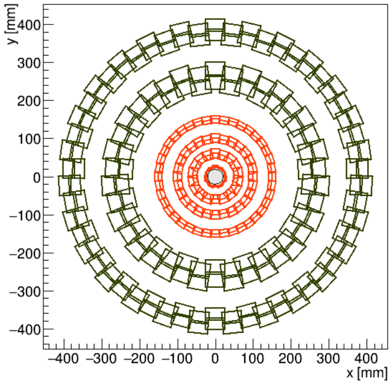
Tilted Geometry: Design Proposal v4.01





- Tilted layout of **outer tracker** driven by requirement to achieve **~0.2 bkg. contam. level** (BCL) in PR:
  - → uppermost layer designed non-tilted to keep the highest possible lever-arm
  - → modules positioned to hermetically cover full luminous region ±75mm
  - → ECs strips res. in Z needed to be set to ~500um (~1mm OK)

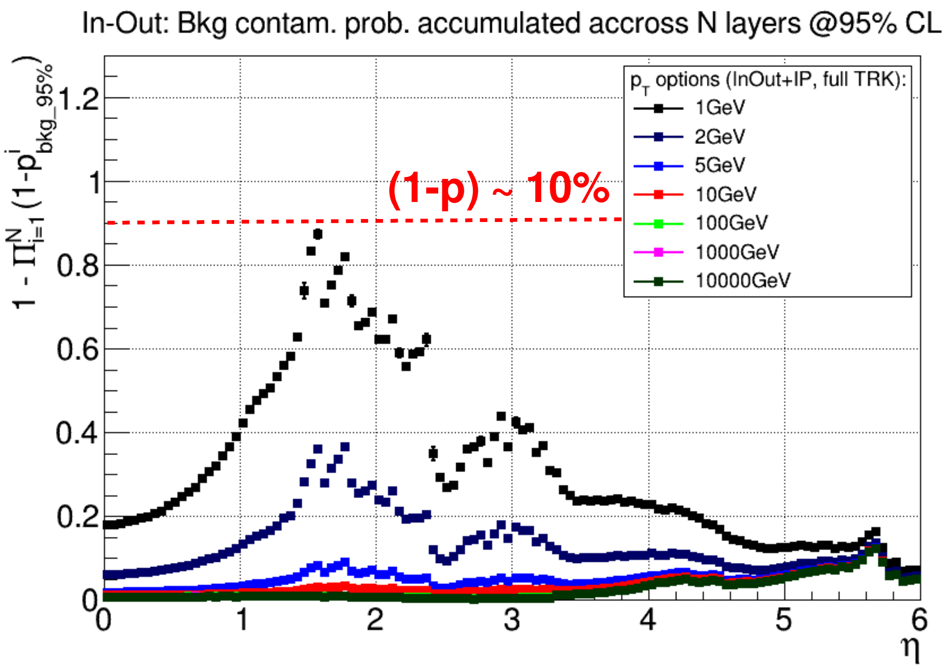




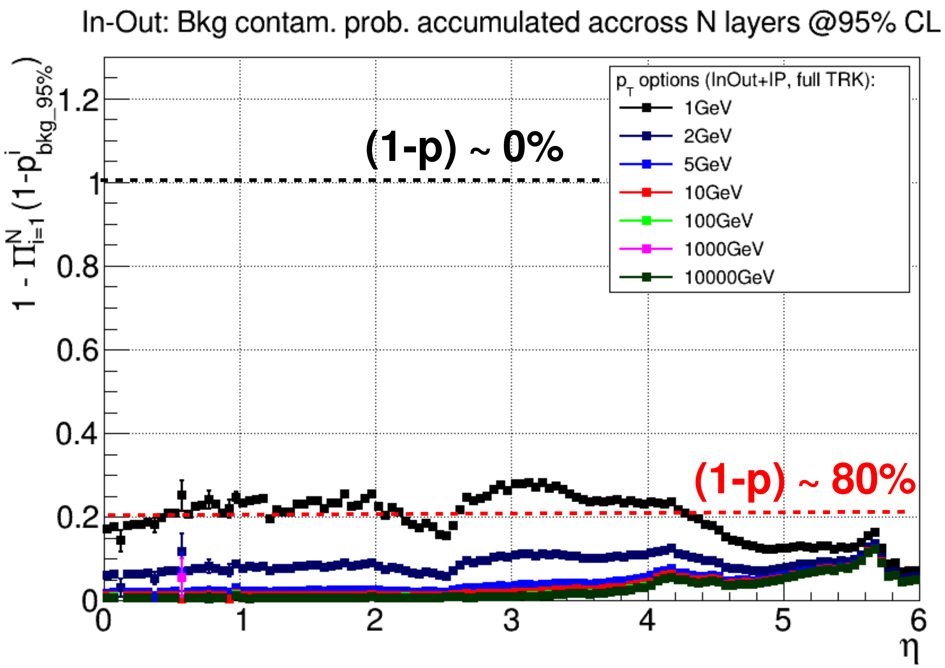
- Tilted layout of **inner tracker** driven by ~0.2 BCL in PR & **highest achievable z0 res.** (to deal with primary vertexing @PU~1000):
  - → tilt angle of 1st layer: $\vartheta_{tilt} \simeq 10^{\circ}$ optimized to achieve a compromise between low MB & higher radial position

Tilted Layout & Pattern Recognition

Non-tilted layout v3.03: in→out approach



Tilted layout v4.01: in→out approach

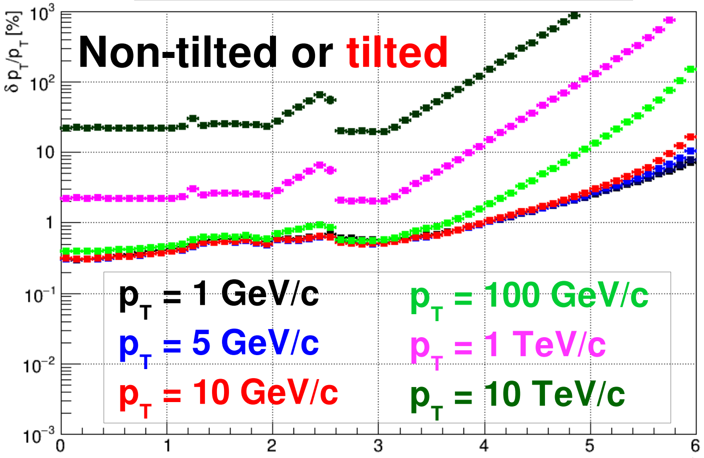


→ **With tilted layout the bkg. contam. level @~20% achievable in PU~1000 for p_T=1GeV/c** (limit value driven by HL-LHC scenario with PU~140 & CMS Phase 2 upgrade tracker layout)

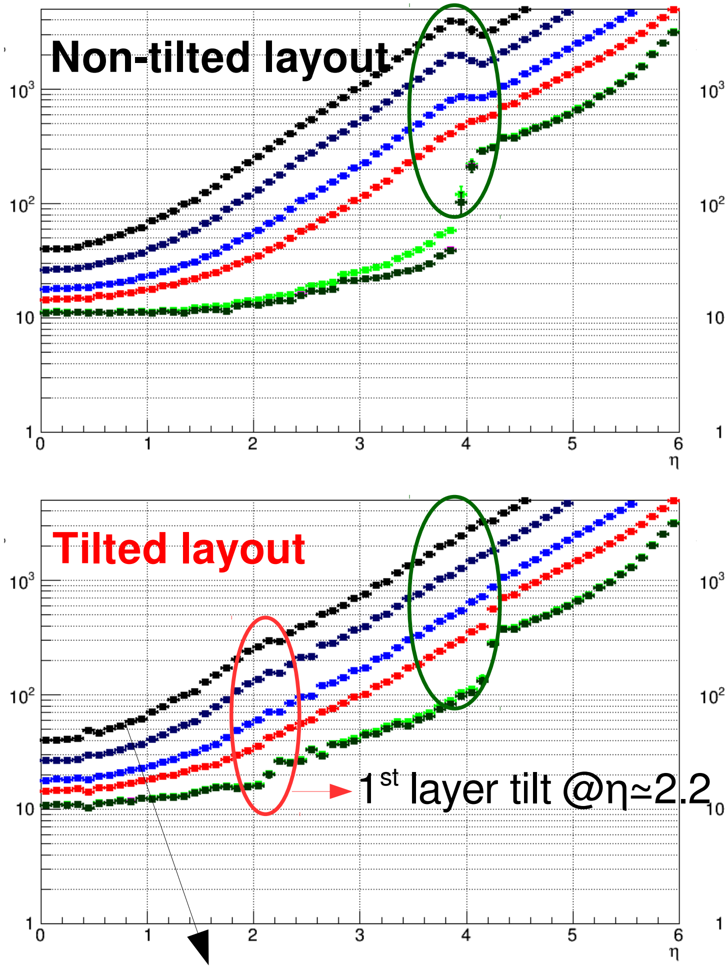
→ **Limits: Mat. budget assumed per module** → NOT fully realistic tilted design → need to consider services & support structure (engineering input necessary)!

Expected Tracking Performance

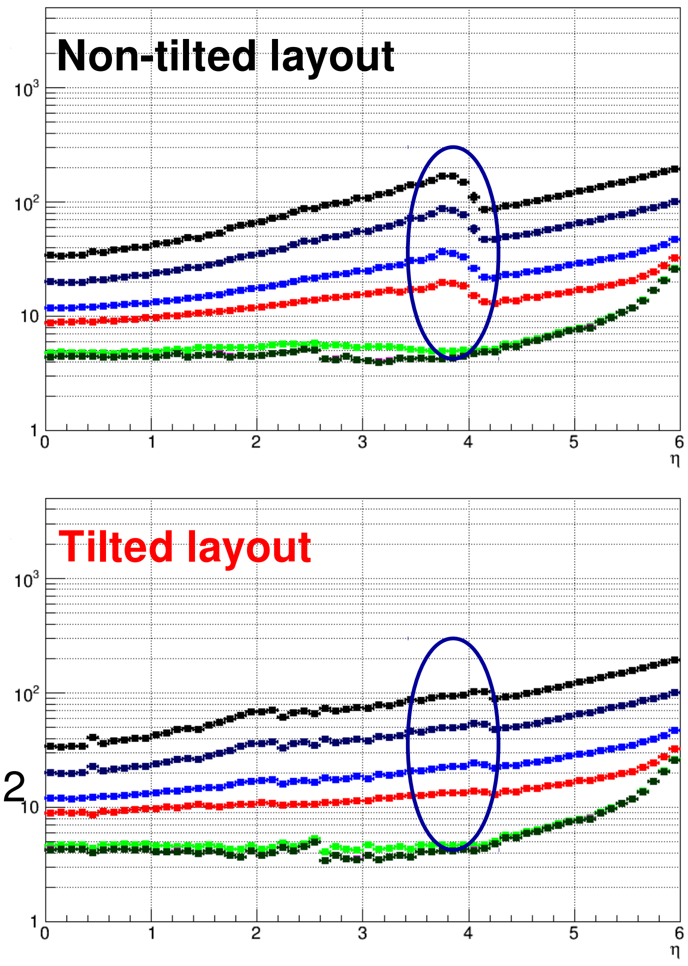
$\delta p_t/p_t$ [%] versus η



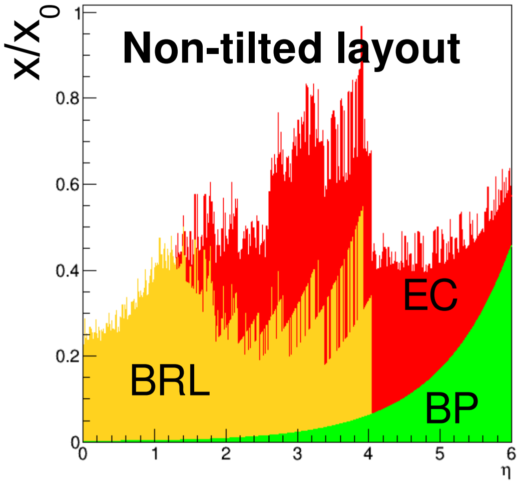
δz0 [um] versus η



δd0 [um] versus η



Material budget



For tilted layout, the shape of 1GeV/c curve dominated by beam-pipe material!

Vertexing @ PU=1000 & Timing Information

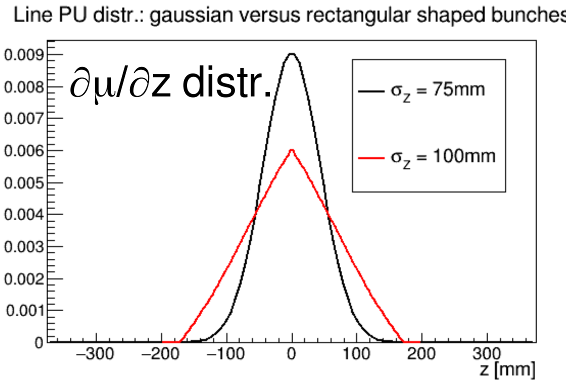
- How the pile-up (PU)~1000 degrades primary vertexing? Does the timing info help?

→ Dependent on scenario for luminous region (Gauss, "rectangular",...) → simulate **1000 PU** vertices according to Gaussian (HL-LHC) Line & Time PU densities (c.f.: PhysRevSTAB.17.111001)

- **Gauss.** bunch: $\frac{1}{\sqrt{2\pi}\sigma_z} e^{-\frac{1}{2}(\frac{z}{\sigma_z})^2}$

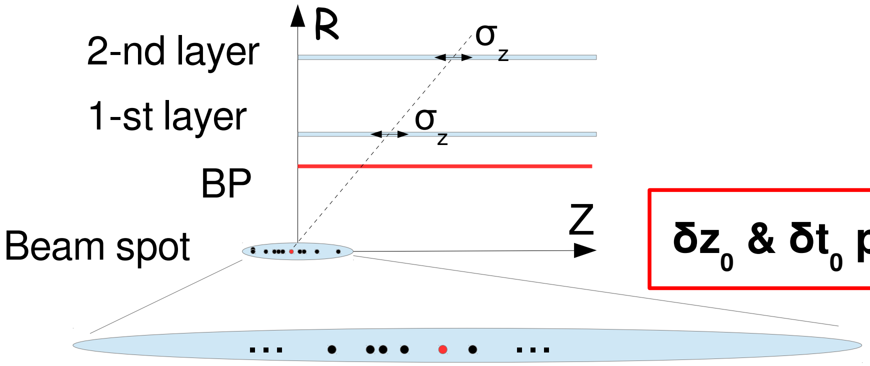
→ **Line PU:** $\frac{\sqrt{1+\phi^2}}{\sqrt{\pi}\sigma_z} e^{-(1+\phi^2)(\frac{z}{\sigma_z})^2}$

→ **Time PU:** $\frac{\sqrt{1+\psi^2}}{\sqrt{\pi}\sigma_z} e^{-(1+\psi^2)(\frac{ct}{\sigma_z})^2}$


Line PU distr.: gaussian versus rectangular shaped bunches

Piwinsky angle Φ ~ 0.67
Time Piw. angle Ψ ~ 0.40

→ Study **what fraction of tracks may be unambiguously assigned to the primary vertex @ 95% CL? Use 2D info** (PV assumed to be "precisely" found from e.g. high p_T tracks)

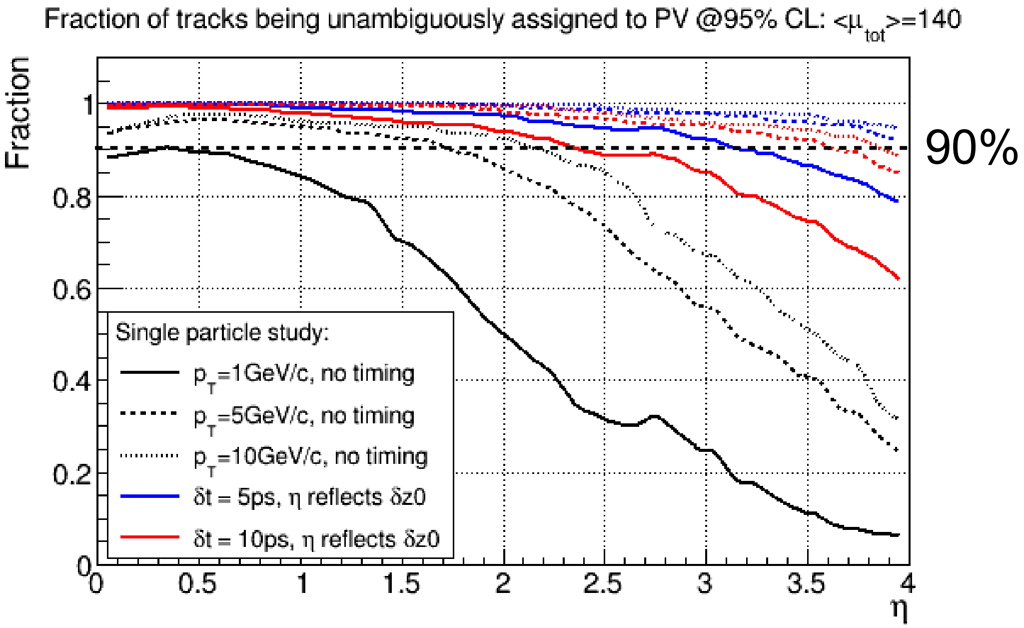


δz_0 & δt_0 play the crucial role!

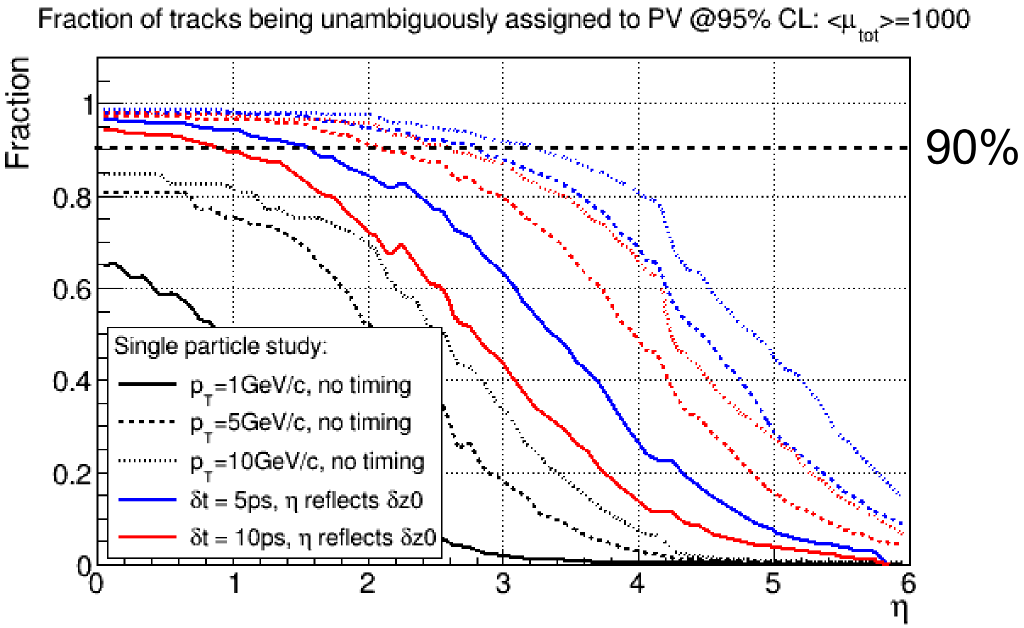
Vertexing @ PU=1000 & Timing Information

→ Compare FCC-hh scenario to HL-LHC conditions (PU~140), using e.g. CMS Ph2 upgrade layout

HL-LHC scenario @ PU=140
CMS Ph2 Upgr. tracker



FCC-hh scenario @ PU=1000
Tilted layout



→ With current FCC-hh scheme **the primary vertexing @ PU~1000 seems very difficult for η>4.0**, even **with timing res. ~5ps** (several time measurements being assumed per track)

Occupancy & Expected Data Rates @ PU=1000

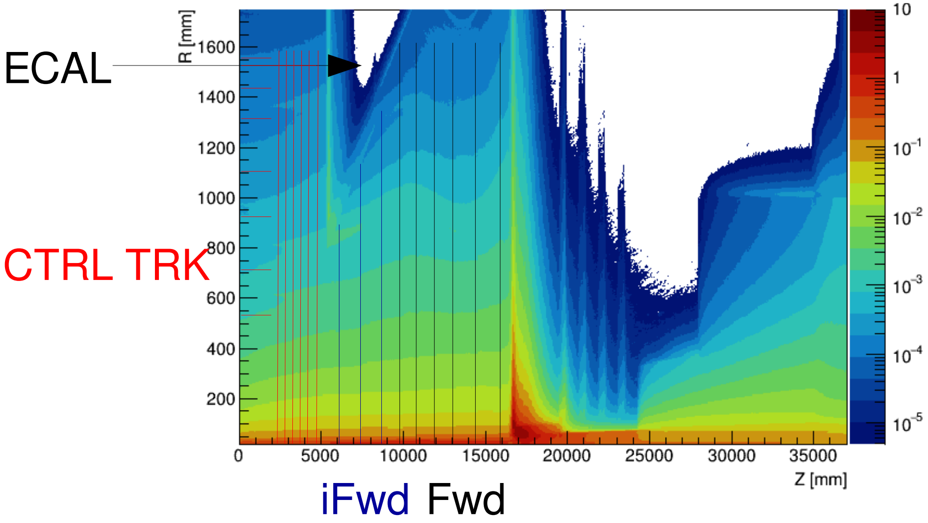
- Have a look at the tracker granularity in a view of hit occupancy (~ <1%), what data rates may we expect at **PU~1000**?

→ **Use Fluka simulated charged particles fluence per pp collision [cm^{-2}] scaled by 1000 PUs**

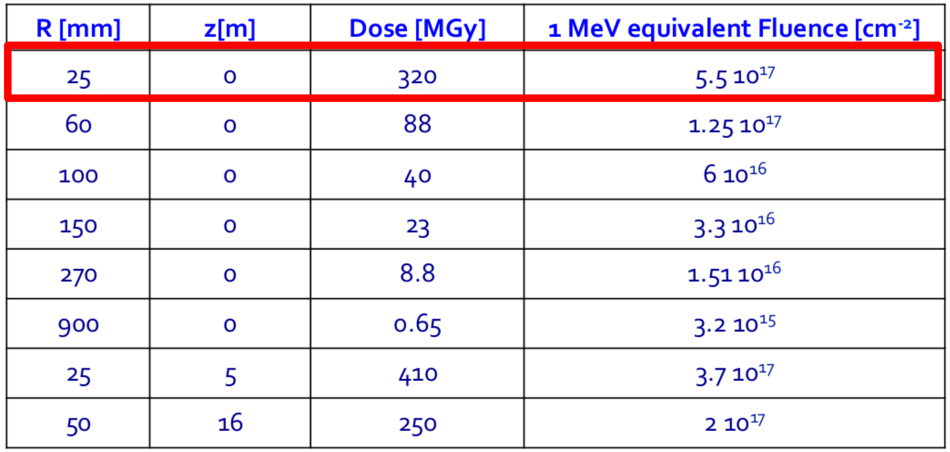
→ Calculate occupancy & hit rates for 2 scenarios:

  - Non-triggered data @ f = 40MHz
  - Triggered data @ f ~ 1MHz (given ~ by hardware limits, e.g. FPGA)

Charged particles fluence per pp collision



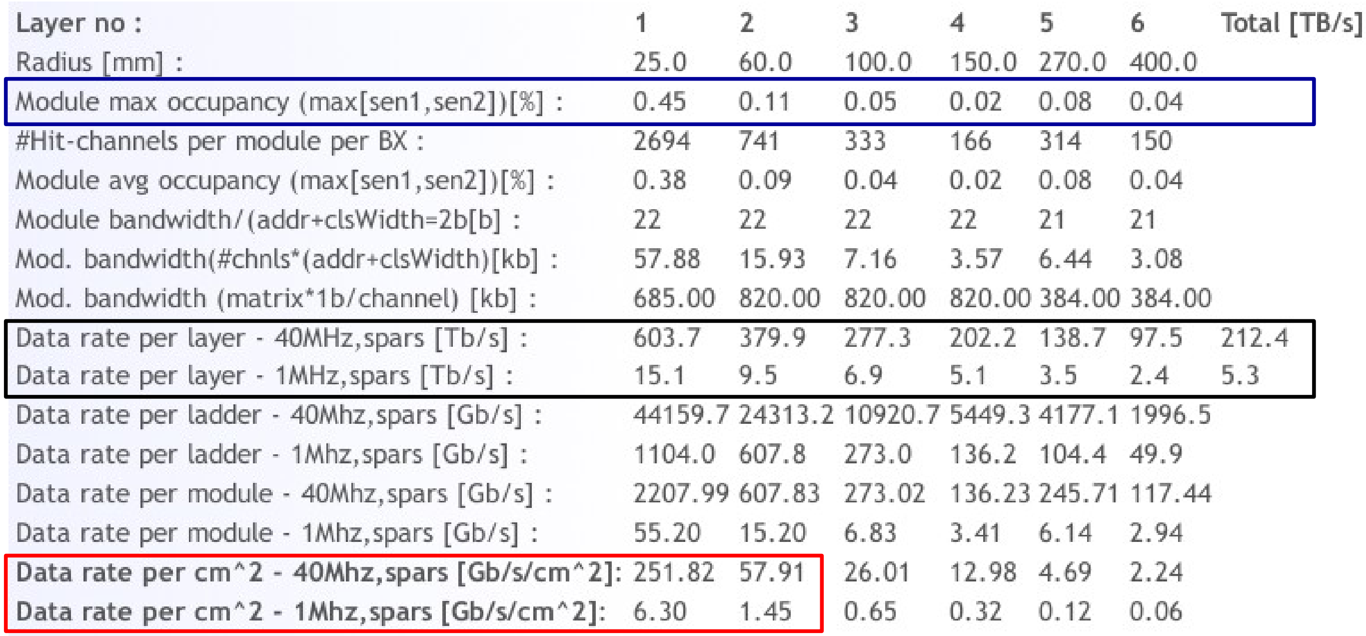
Long-term damage for Tracker after 30ab^{-1}



R [mm]	z[m]	Dose [MGy]	1 MeV equivalent Fluence [cm^{-2}]
25	0	320	5.5 10^{17}
60	0	88	1.25 10^{17}
100	0	40	6 10^{16}
150	0	23	3.3 10^{16}
270	0	8.8	1.51 10^{16}
900	0	0.65	3.2 10^{15}
25	5	410	3.7 10^{17}
50	16	250	2 10^{17}

By M.I.Besana

Inner: Occupancy & Expected Data Rates



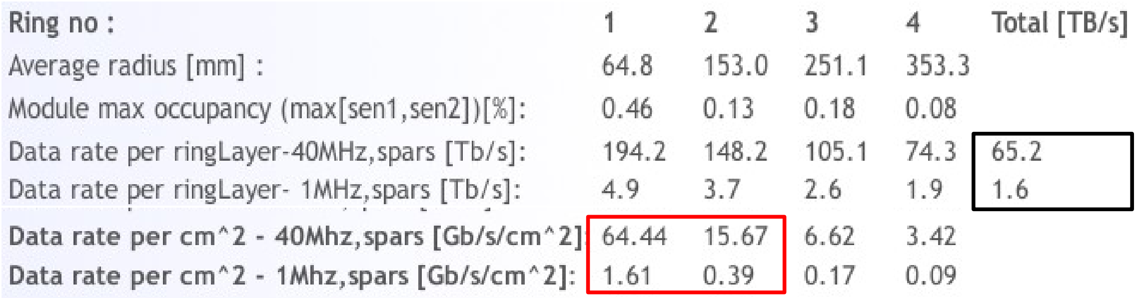
Layer no :	1	2	3	4	5	6	Total [TB/s]
Radius [mm] :	25.0	60.0	100.0	150.0	270.0	400.0	
Module max occupancy (max[sen1,sen2])[%] :	0.45	0.11	0.05	0.02	0.08	0.04	
#Hit-channels per module per BX :	2694	741	333	166	314	150	
Module avg occupancy (max[sen1,sen2])[%] :	0.38	0.09	0.04	0.02	0.08	0.04	
Module bandwidth/(addr+clsWidth=2b[b] :	22	22	22	22	21	21	
Mod. bandwidth(#chnls*(addr+clsWidth)[kb] :	57.88	15.93	7.16	3.57	6.44	3.08	
Mod. bandwidth (matrix*1b/channel) [kb] :	685.00	820.00	820.00	820.00	384.00	384.00	
Data rate per layer - 40MHz,spars [Tb/s] :	603.7	379.9	277.3	202.2	138.7	97.5	212.4
Data rate per layer - 1MHz,spars [Tb/s] :	15.1	9.5	6.9	5.1	3.5	2.4	5.3
Data rate per ladder - 40Mhz,spars [Gb/s] :	44159.7	24313.2	10920.7	5449.3	4177.1	1996.5	
Data rate per ladder - 1Mhz,spars [Gb/s] :	1104.0	607.8	273.0	136.2	104.4	49.9	
Data rate per module - 40Mhz,spars [Gb/s] :	2207.99	607.83	273.02	136.23	245.71	117.44	
Data rate per module - 1Mhz,spars [Gb/s] :	55.20	15.20	6.83	3.41	6.14	2.94	
Data rate per cm^2 - 40Mhz,spars [Gb/s/cm^2]:	251.82	57.91	26.01	12.98	4.69	2.24	
Data rate per cm^2 - 1Mhz,spars [Gb/s/cm^2]:	6.30	1.45	0.65	0.32	0.12	0.06	

→ Hit occupancy [%] (~ <1%)

→ Layer data rate (40MHz)
→ Layer data rate (1MHz, trigger)

→ Data rate per cm^2 (40MHz)
→ Data rate per cm^2 (1MHz, trigger)

Challenge: 6.3 Gb/s/cm^2



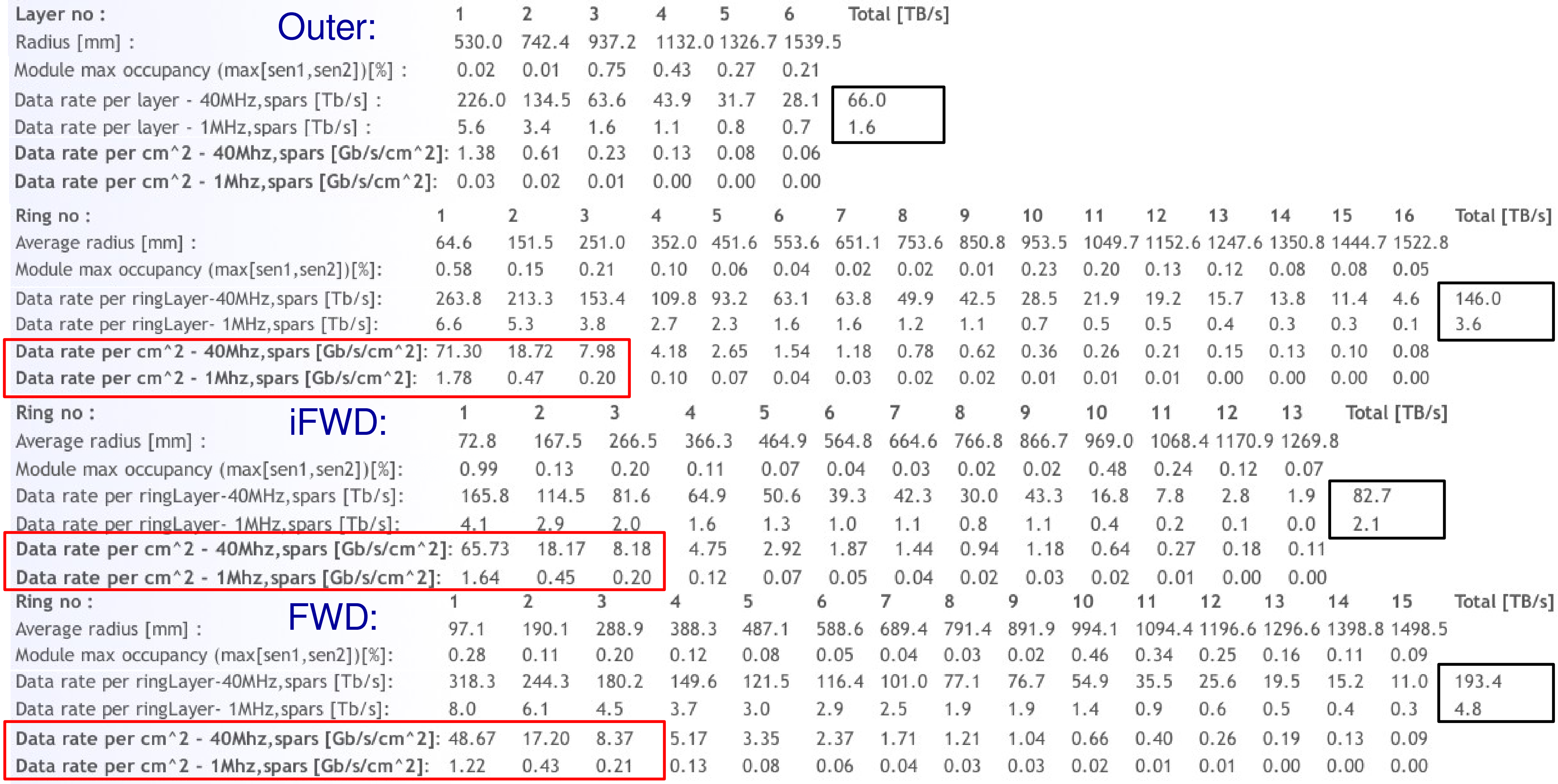
Ring no :	1	2	3	4	Total [TB/s]
Average radius [mm] :	64.8	153.0	251.1	353.3	
Module max occupancy (max[sen1,sen2])[%]:	0.46	0.13	0.18	0.08	
Data rate per ringLayer-40MHz,spars [Tb/s]:	194.2	148.2	105.1	74.3	65.2
Data rate per ringLayer- 1MHz,spars [Tb/s]:	4.9	3.7	2.6	1.9	1.6
Data rate per cm^2 - 40Mhz,spars [Gb/s/cm^2]	64.44	15.67	6.62	3.42	
Data rate per cm^2 - 1Mhz,spars [Gb/s/cm^2]:	1.61	0.39	0.17	0.09	

Extreme data flows >>10Gb/s/module
(even triggered @ 1MHz)

Challenge: 1.6 Gb/s/cm^2

Outer & Fwd: Occupancy & Data Rates

→ Expected **huge tracker data rates: 766 TB/s** (untriggered), **19 TB/s** (triggered @ 1MHz)



```
Layer no :                                     Outer:   1      2      3      4      5      6      Total [TB/s]
Radius [mm] :                                           530.0  742.4  937.2  1132.0 1326.7 1539.5
Module max occupancy (max[sen1,sen2])[%] :              0.02   0.01   0.75   0.43   0.27   0.21
Data rate per layer - 40MHz,spars [Tb/s] :              226.0  134.5  63.6   43.9   31.7   28.1   66.0
Data rate per layer - 1MHz,spars [Tb/s] :               5.6    3.4    1.6    1.1    0.8    0.7    1.6
Data rate per cm^2 - 40Mhz,spars [Gb/s/cm^2]:           1.38   0.61   0.23   0.13   0.08   0.06
Data rate per cm^2 - 1Mhz,spars [Gb/s/cm^2]:            0.03   0.02   0.01   0.00   0.00   0.00

Ring no :                                     1     2     3     4     5     6     7     8     9     10    11     12     13     14     15     16     Total [TB/s]
Average radius [mm] :                         64.6  151.5 251.0 352.0 451.6 553.6 651.1 753.6 850.8 953.5 1049.7 1152.6 1247.6 1350.8 1444.7 1522.8
Module max occupancy (max[sen1,sen2])[%]:     0.58  0.15  0.21  0.10  0.06  0.04  0.02  0.02  0.01  0.23  0.20   0.13   0.12   0.08   0.08   0.05
Data rate per ringLayer-40MHz,spars [Tb/s]:   263.8 213.3 153.4 109.8 93.2  63.1  63.8  49.9  42.5  28.5  21.9   19.2   15.7   13.8   11.4   4.6    146.0
Data rate per ringLayer- 1MHz,spars [Tb/s]:   6.6   5.3   3.8   2.7   2.3   1.6   1.6   1.2   1.1   0.7   0.5    0.5    0.4    0.3    0.3    0.1    3.6
Data rate per cm^2 - 40Mhz,spars [Gb/s/cm^2]: 71.30 18.72 7.98  4.18  2.65  1.54  1.18  0.78  0.62  0.36  0.26   0.21   0.15   0.13   0.10   0.08
Data rate per cm^2 - 1Mhz,spars [Gb/s/cm^2]:  1.78  0.47  0.20  0.10  0.07  0.04  0.03  0.02  0.02  0.01  0.01   0.01   0.00   0.00   0.00   0.00

Ring no :                                    iFWD:  1     2     3     4     5     6     7     8     9     10    11     12     13     Total [TB/s]
Average radius [mm] :                               72.8  167.5 266.5 366.3 464.9 564.8 664.6 766.8 866.7 969.0 1068.4 1170.9 1269.8
Module max occupancy (max[sen1,sen2])[%]:           0.99  0.13  0.20  0.11  0.07  0.04  0.03  0.02  0.02  0.48  0.24   0.12   0.07
Data rate per ringLayer-40MHz,spars [Tb/s]:         165.8 114.5 81.6  64.9  50.6  39.3  42.3  30.0  43.3  16.8  7.8    2.8    1.9    82.7
Data rate per ringLayer- 1MHz,spars [Tb/s]:         4.1   2.9   2.0   1.6   1.3   1.0   1.1   0.8   1.1   0.4   0.2    0.1    0.0    2.1
Data rate per cm^2 - 40Mhz,spars [Gb/s/cm^2]:       65.73 18.17 8.18  4.75  2.92  1.87  1.44  0.94  1.18  0.64  0.27   0.18   0.11
Data rate per cm^2 - 1Mhz,spars [Gb/s/cm^2]:        1.64  0.45  0.20  0.12  0.07  0.05  0.04  0.02  0.03  0.02  0.01   0.00   0.00

Ring no :                                     FWD:  1     2     3     4     5     6     7     8     9     10    11     12     13     14     15     Total [TB/s]
Average radius [mm] :                               97.1  190.1 288.9 388.3 487.1 588.6 689.4 791.4 891.9 994.1 1094.4 1196.6 1296.6 1398.8 1498.5
Module max occupancy (max[sen1,sen2])[%]:           0.28  0.11  0.20  0.12  0.08  0.05  0.04  0.03  0.02  0.46  0.34   0.25   0.16   0.11   0.09
Data rate per ringLayer-40MHz,spars [Tb/s]:         318.3 244.3 180.2 149.6 121.5 116.4 101.0 77.1  76.7  54.9  35.5   25.6   19.5   15.2   11.0   193.4
Data rate per ringLayer- 1MHz,spars [Tb/s]:         8.0   6.1   4.5   3.7   3.0   2.9   2.5   1.9   1.9   1.4   0.9    0.6    0.5    0.4    0.3    4.8
Data rate per cm^2 - 40Mhz,spars [Gb/s/cm^2]:       48.67 17.20 8.37  5.17  3.35  2.37  1.71  1.21  1.04  0.66  0.40   0.26   0.19   0.13   0.09
Data rate per cm^2 - 1Mhz,spars [Gb/s/cm^2]:        1.22  0.43  0.21  0.13  0.08  0.06  0.04  0.03  0.03  0.02  0.01   0.01   0.00   0.00   0.00
```

Summary & Conclusions

- **The key tracker parameters have been studied & optimized:**
  - → **Current layout:** ~430m^2 (391m^2 in tilted layout) of Si with #channels: 5461M (pixels), 9964M (macro-pixels), 489M (strips)
  - → The **granularity in R-Φ** driven mostly by **dp_T/p_T @ p_T=10TeV/c → achieved dp_T/p_T ~20%**
  - → **Non-uniformities of mag. field have a negligible effect on dp_T/p_T res.** → dp_T/p_T degrades in max. by 45% at η>2.5 **(solenoid)**, dipole in FWD region still remains an option → c.f. PV @ PU=1000
  - → The **granularity in Z driven by vertexing** & **pattern recognition** capabilities @ PU=1000:
    - **Tracker in tilted layout essential** (even for vertex detector) to achieve similar pattern recognition performance as with PU~140 & HL-LHC conditions
    - **Primary vertexing & correct PV assignment @ PU=1000 seems feasible up-to η~4**, but only with extra timing information (2D vertex fitting)
    - **Current view on PV from η~4 to 6 seems very difficult** (even with timing information) → need for an intensive discussion on interplay between detector performance & FCC-hh colliding schemes
  - → Expected data rates (**766 TB/s untriggered**, **19 TB/s triggered @1MHz**) implicate need for new read-out technologies (follow J.Brooke's talk on trigger design)
  - → Expected **1MeV neq fluence ~5x10^{17}cm^{-2}** @ **R=25mm** (see M.I.Besana's talk) truly represents **a new challenge** for the tracker technologies and dedicated R&D