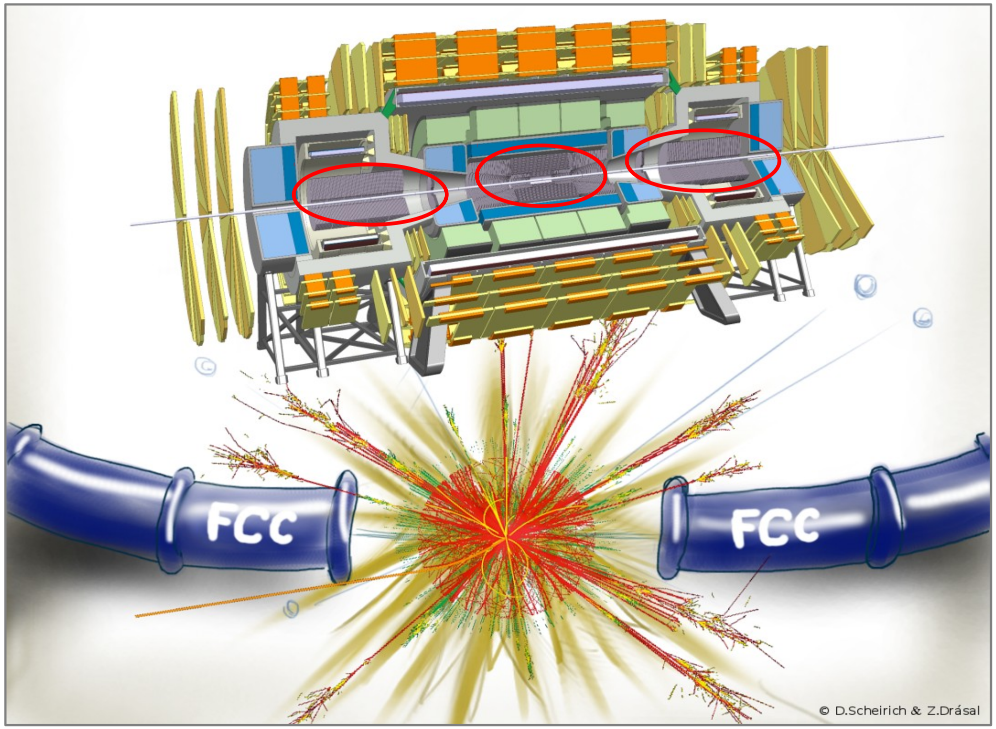
Status and Challenges of Tracker Design for FCC-hh



Zbyněk Drásal

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With special thanks to: M.Mannelli, S.Mersi & W.Riegler

Overview

- Tracker/vertex detector design & expected performance
  - Key FCC-hh challenges & design driving principles
  - Mathematical approach & SW tools
  - Reference layout & tracking performance
  - Effects of non-uniform magnetic field: solenoid vs. dipole
  - Implications of high pile-up & high-rate/occupancy environment
    - → Pattern recognition capabilities & requirements on granularity in Z, tilted vs. flat layout
    - → Primary vertexing in high pile-up & requirements on timing resolution
- Summary & Challenges

FCC-hh & Challenges for Tracker Design

Parameter	FCC-hh		HE-LHC	(HL) LHC
Collision cms energy [TeV]	100		27	14
Dipole field [T]	16		16	8.33
Circumference [km]	97.75		26.7	26.7
# IP	2 main & 2		2 & 2	2 & 2
Beam current [A]	0.5		1.12	(1.12) 0.58
Bunch intensity [10^{11}]	1	1 (0.2)	2.2 (0.44)	(2.2) 1.15
Bunch spacing [ns]	25	25 (5)	25 (5)	25
beta* [m]	1.1	0.3	0.25	(0.20) 0.55
Luminosity/IP [10^{34} $cm^{-2}s^{-1}$]	5	30	25	(5) 1
# Events/bunch crossing	170	<1020 (204)	~800 (160)	(135) 27
Stored energy/beam [GJ]	8.4		1.3	(0.7) 0.36
Synchrotron rad. [W/m/ap.]	28.4		4.6	(0.33) 0.17

14TeV → 100 TeV

$\sigma_{inelastic}$: 80mb → 108mb

average p_T: 0.6 → 0.8 GeV/c

$multiplicity_{charged/unit\ \eta}$: 5.4 → 8

5x increase in pile-up wrt HL-LHC

- The min. bias events @FCC are quite similar to ones @HL-LHC, but …

  → Pile-up per bunch crossing **O(1000)** is a big challenge

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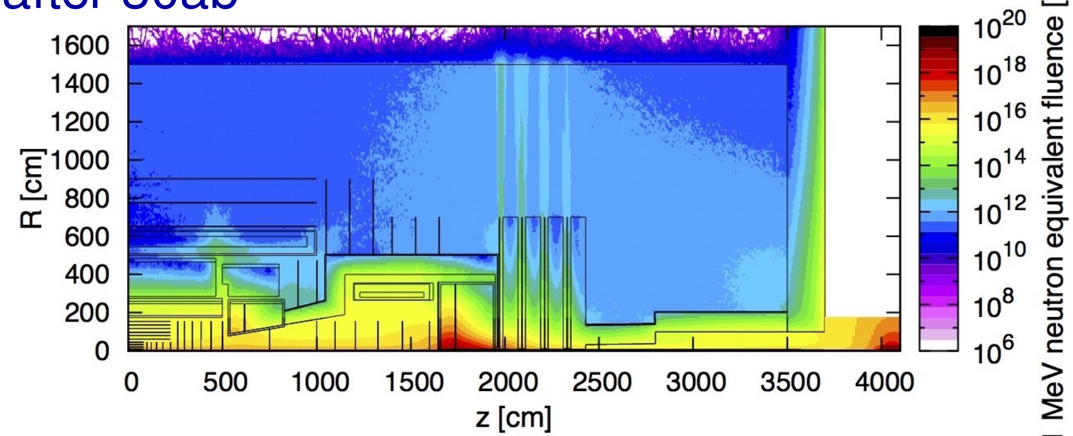
6x increase in luminosity wrt HL-LHC

- The min. bias events @FCC are quite similar to ones @HL-LHC, but …
  - → Pile-up per bunch crossing **O(1000)** is a big challenge
  - → Huge particle/data rates & significantly higher rad. levels in the inner/fwd detector are expected due to luminosity increase

Tracker: Long-term Damage & Data Rates

- Fluka simulation: 1 MeV neq fluence after $30ab^{-1}$

Courtesy of M.I.Besana



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	$2\ 10^{17}$

Radiation @ FCC:

→ @R=25mm: **~$6x10^{17}$ neq cm^{-2} ,TID~0.4GGy**

- **LHC** = **1**
- **HL-LHC → 20x LHC**
- **FCC → 600x LHC**

HL-LHC rad. tolerance limit @R~270mm

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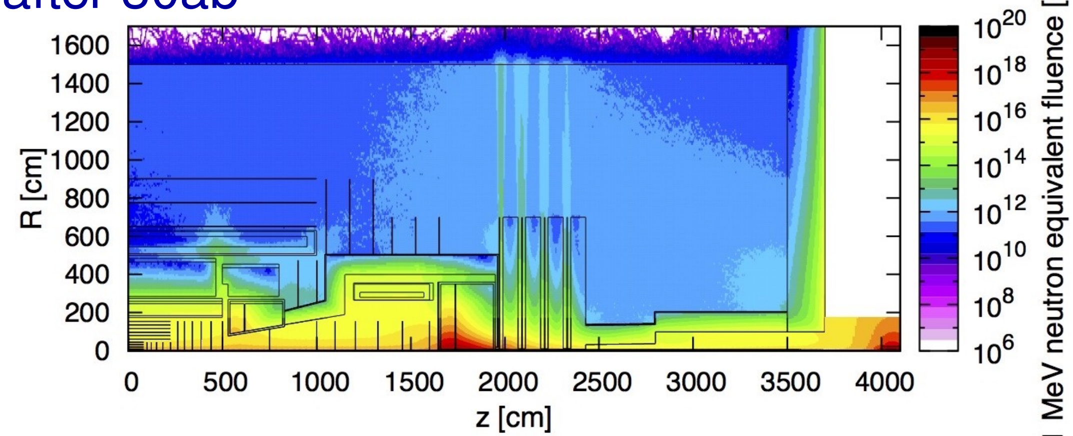

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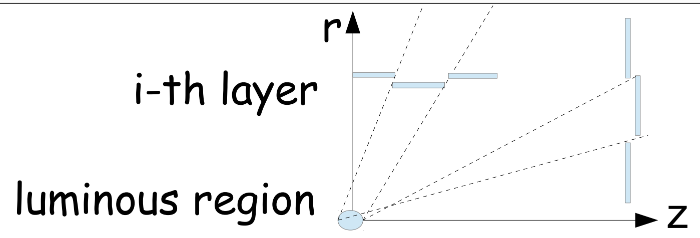
True challenge for sensor/chip R&D & high fluence rates for data output (trigger)

→ data rates: **766 TB/s** (@40MHz), **19 TB/s** (@1MHz)

→ data flows in innermost layers: **≳1Gb/s/cm2 @1MHz**

Tracker: Layout & Design Driving Principles

- **Hermetic tracking up-to |η|~4** (c.f. |η|~2.5 for LHC exp.)
  + efficient **VBF jet** meas. **up-to |η|~6**



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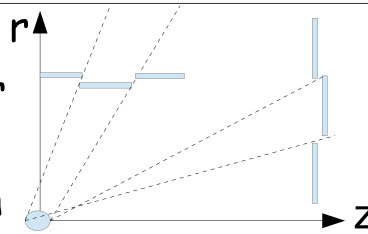

- **Granularity in R-Φ →** driven by dp_T/p_T, efficient b,c,τ-tagging (d0) & low occupancy limit (~1%)

$$\frac{\Delta p_T}{p_T} = \frac{\sigma[\mathrm{m}]\, p_T[\mathrm{GeV/c}]}{0.3\, B[\mathrm{T}]\, L^2[\mathrm{m}^2]} f(N)$$

L: 1.55m
B: uniform 4T
$\sigma_{R\text{-}\Phi}$: 10(7.5)um

} ~ **20% @ 10TeV/c** (cf. LHC: 10% @1TeV)

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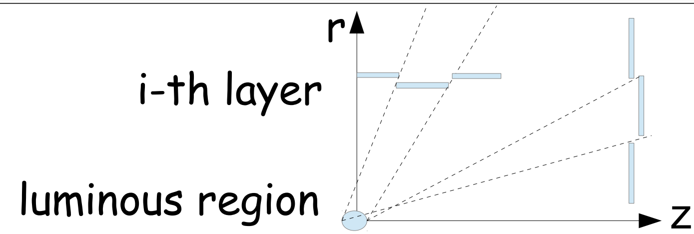

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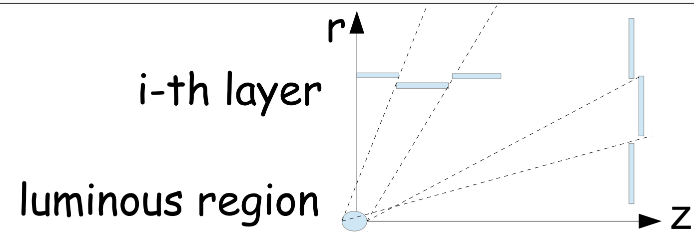

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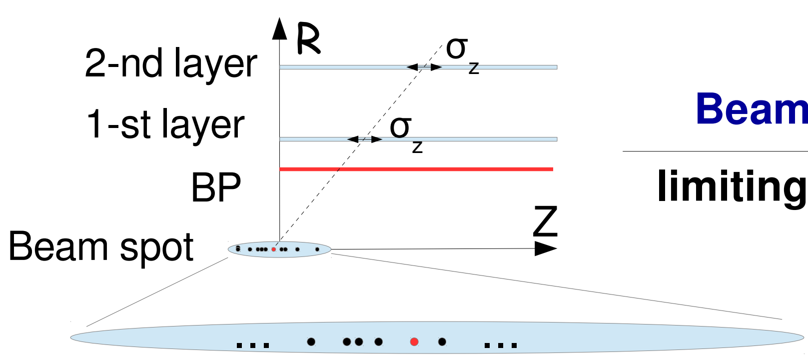
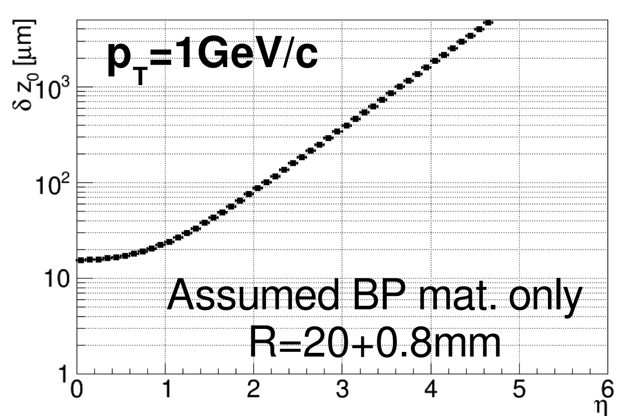
- **Granularity in Z** → driven by pattern recognition, low occupancy limit (~1%) & primary vertexing in expected pile-up **O(1000)**



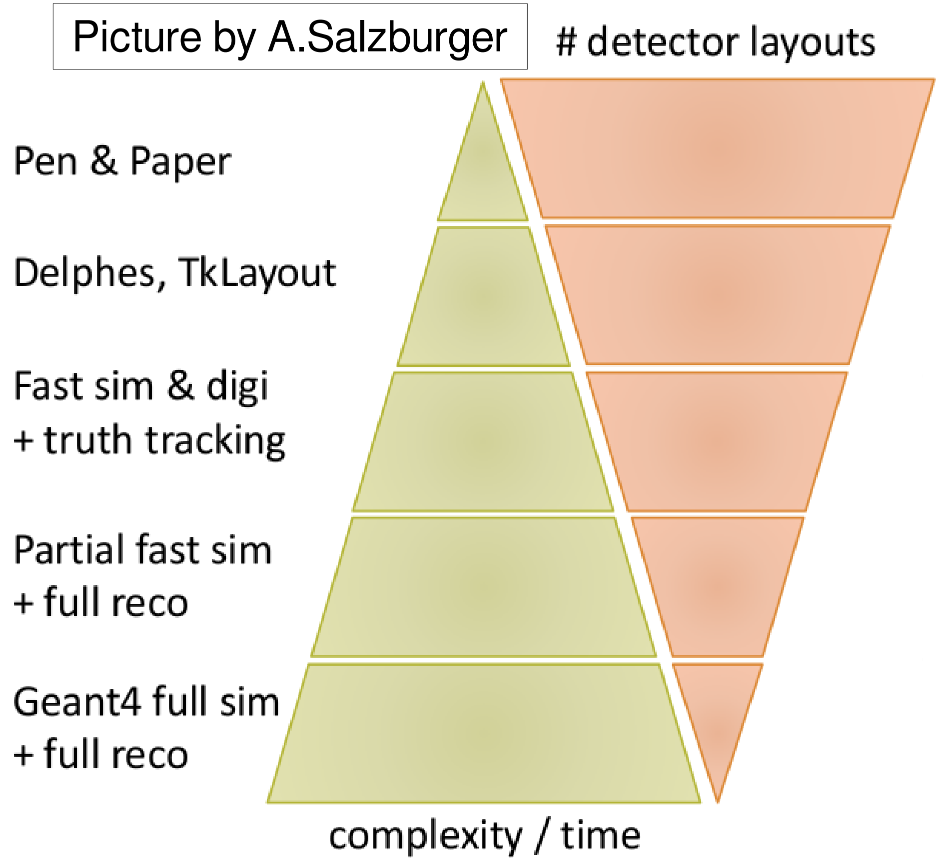
Beam-pipe → **limiting factor!**



Mathematical Techniques & SW Tools

- **Extremely important to choose the right tools given the tight schedule for CDR…**

Picture by A.Salzburger



The tracker layout mainly optimized by applying:

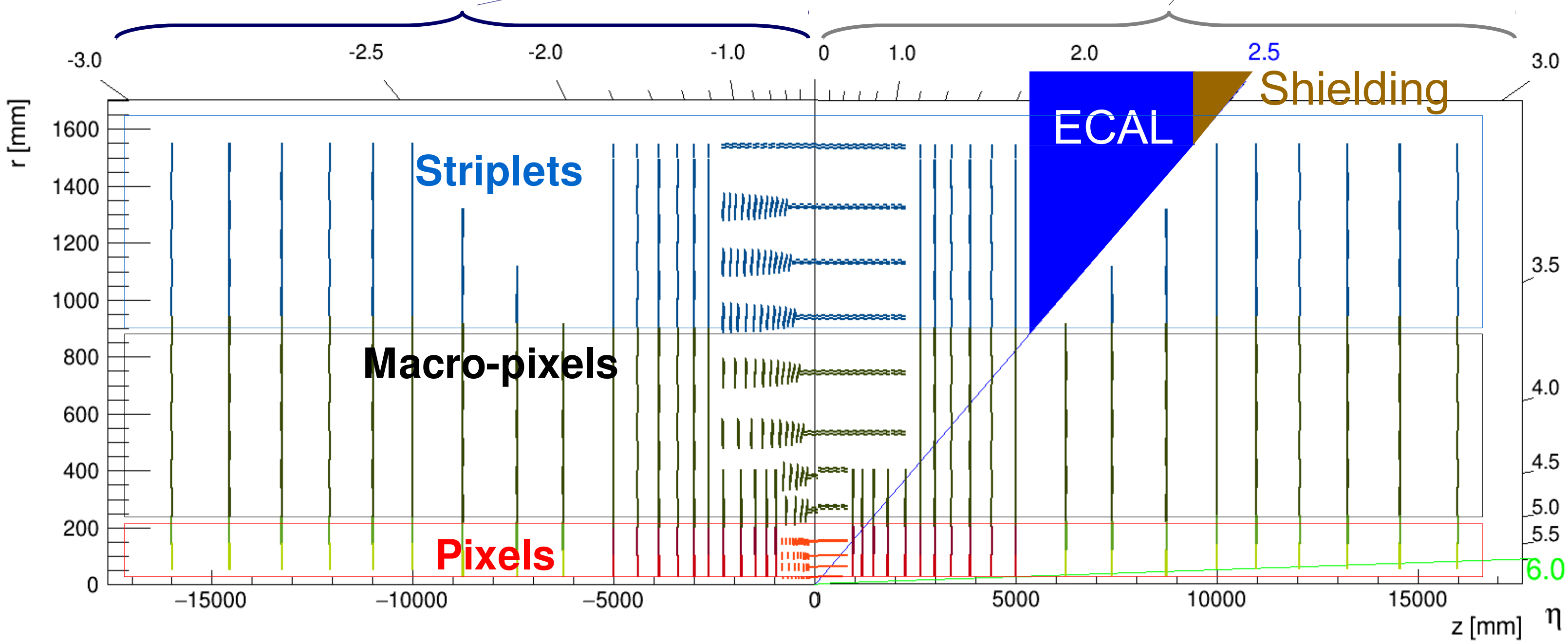
- Approx. analytical approach: **tkLayout** (CMS)
- Numerical approach: **Mathematica**
- + using B field maps & Fluka simulated fluence map

Ref. Tracker Layout: Tilted v4.01 vs. Flat v3.03

Surface: ~430 (391)m^2
#Channels: 489.4M
9964.4M
5460.9M

(Macro)-pixel R↗0.9 m due to occupancy

4 (seed) BRL layers



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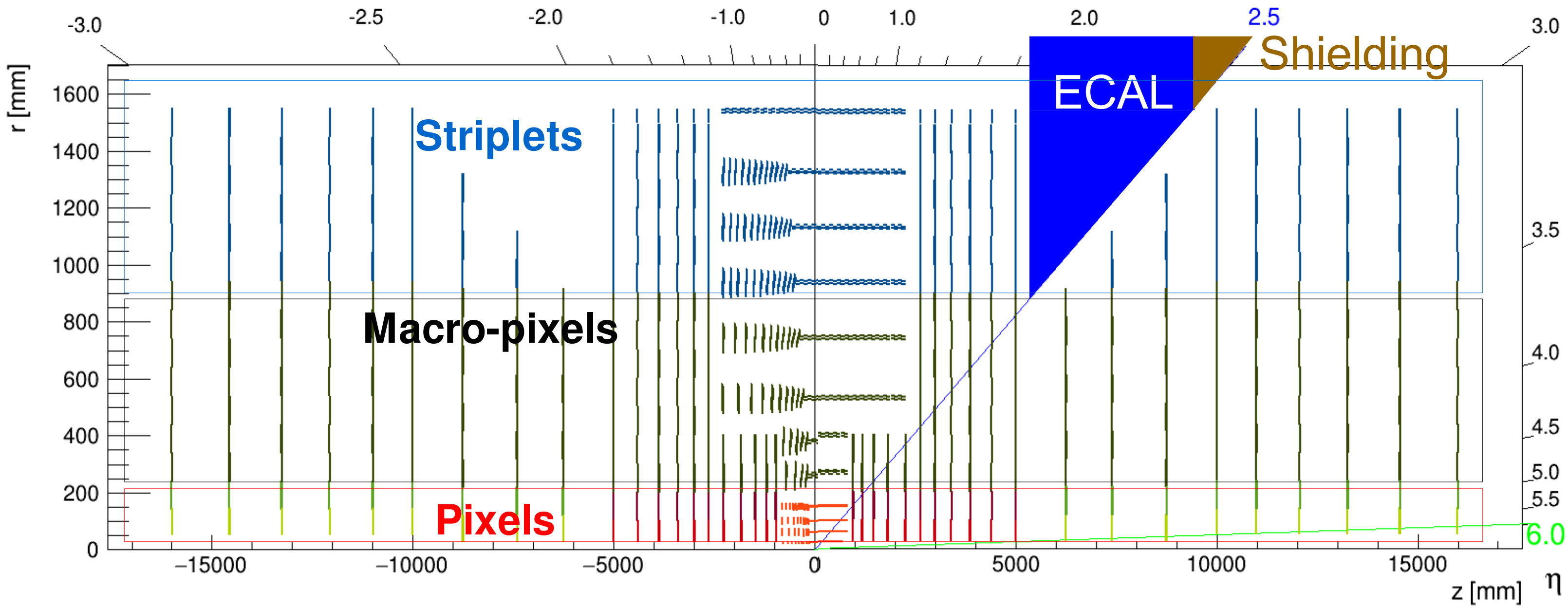


Granularity of flat design:

Pixels : 25x50um^2 (1-4th BRL layers, EC R1), 100/3x100um^2 (R2), 100/3x400um^2 (R3,R4)

Macro-pixels: 100/3x400um^2

Strips : 100/3umx50mm (BRL), 100/3umx10mm (EC)

→ Assumed binary R/O → res. ~ pitch/√12

Huge increase in #pixel channels wrt LHC exp. due to:

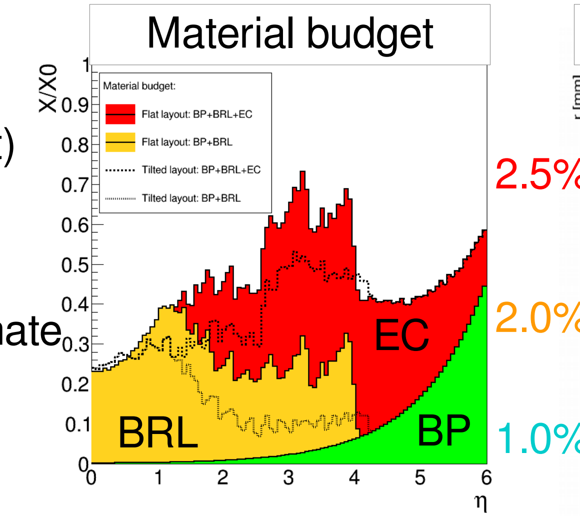
- requirements on tracking up to **η=6**
- resilience to **high rad. levels** generated by FCC-hh

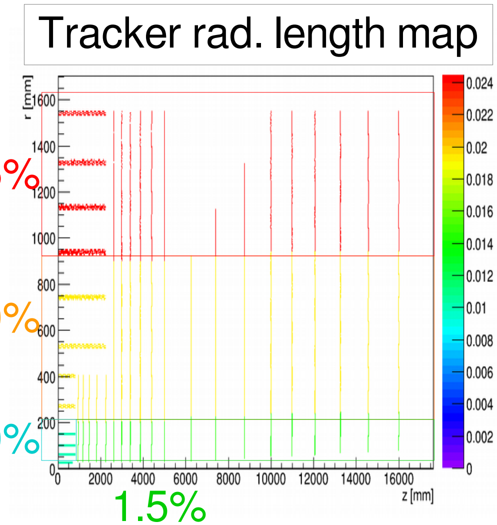
For details see http://fcc-tklayout.web.cern.ch

Material Budget & Tracking Resolution

- A simplified model for MB assumed:
  - x/x0 ~1-2.5% per layer (services accumul. effect) (20% Si, 42% C, 2% Cu, 6% Al, 30% Plastic)

→ **technology input needed** for more real. estimate





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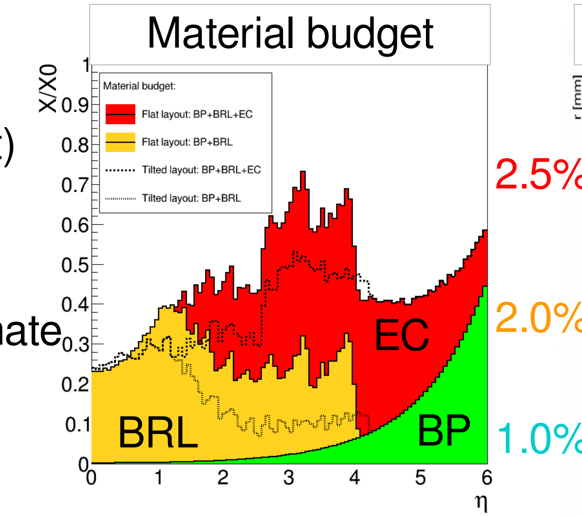
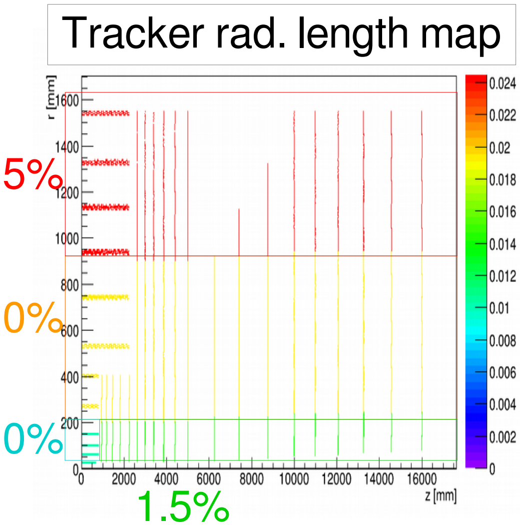
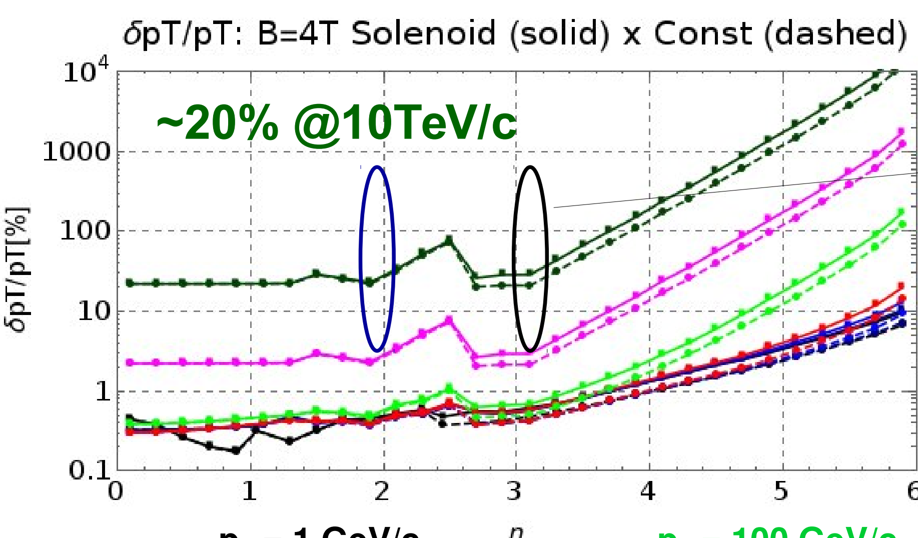


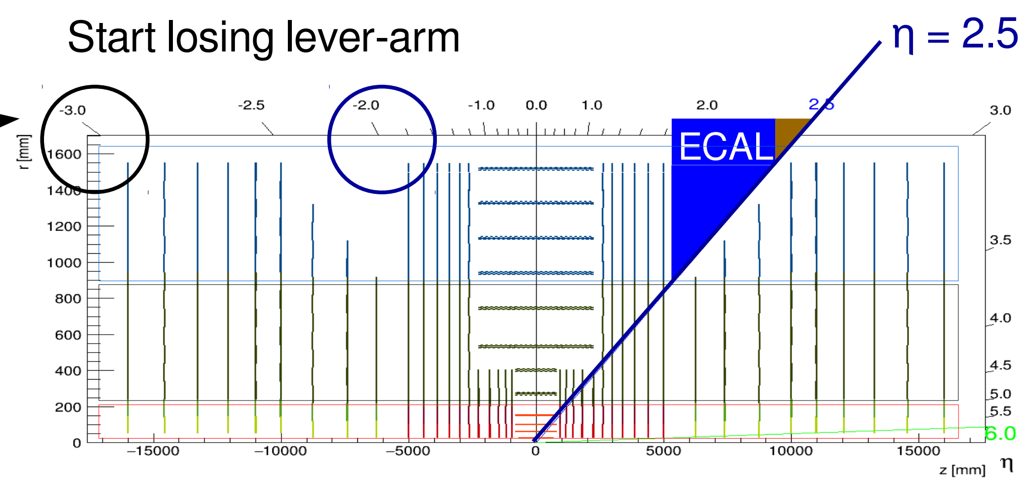


- Tracking resolution:



p_T = 1 GeV/c
p_T = 5 GeV/c
p_T = 10 GeV/c
p_T = 100 GeV/c
p_T = 1 TeV/c
p_T = 10 TeV/c

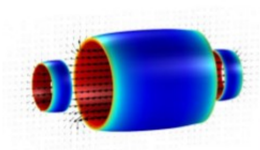
Start losing lever-arm

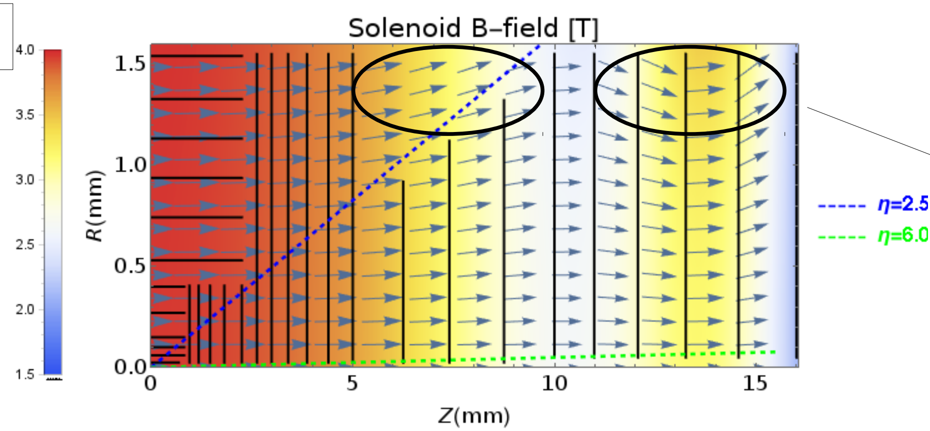


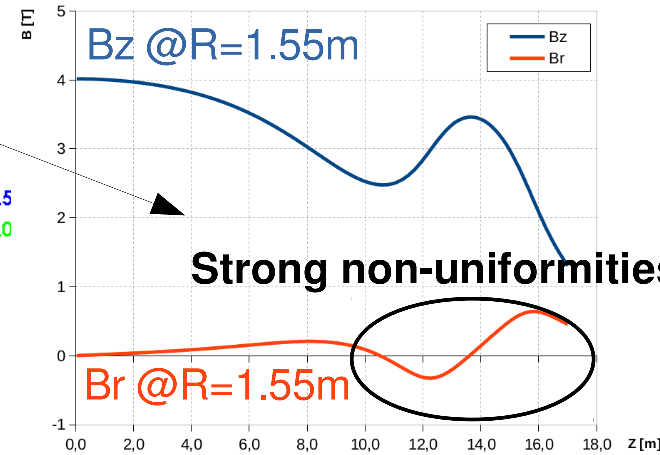
Solenoid Scenario & dp_T/p_T Resolution

- Full solenoid B field map → effect on $dp_{T/}p_T$?

Courtesy of E. Bielert







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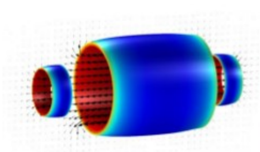
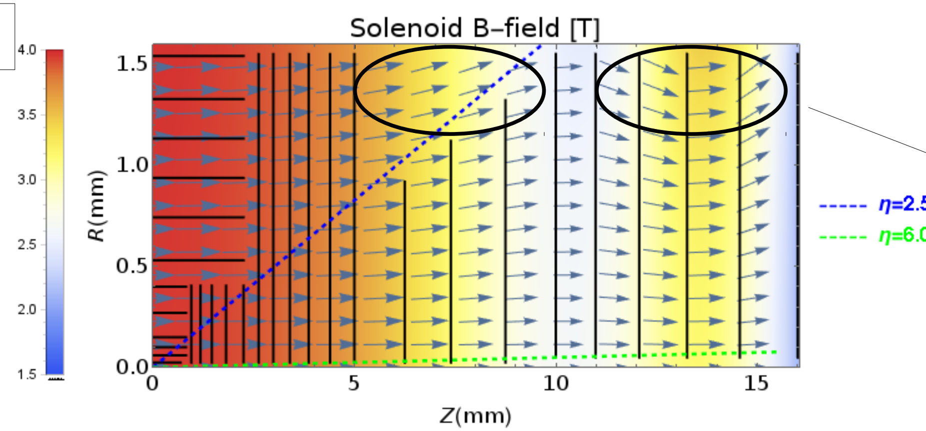
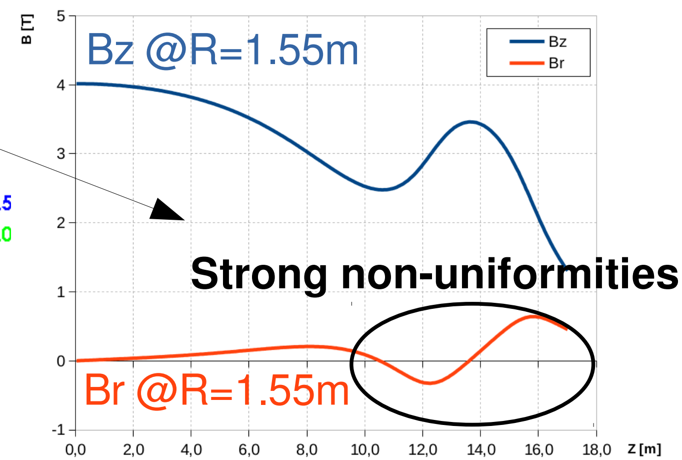
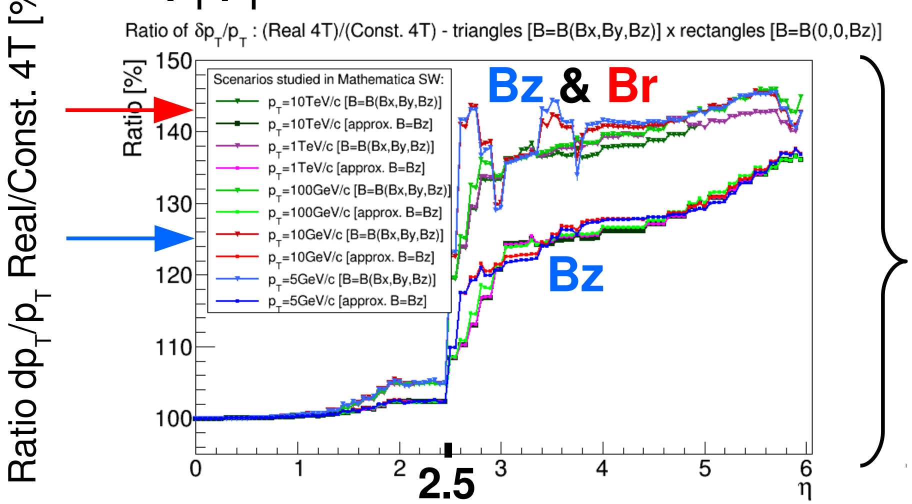




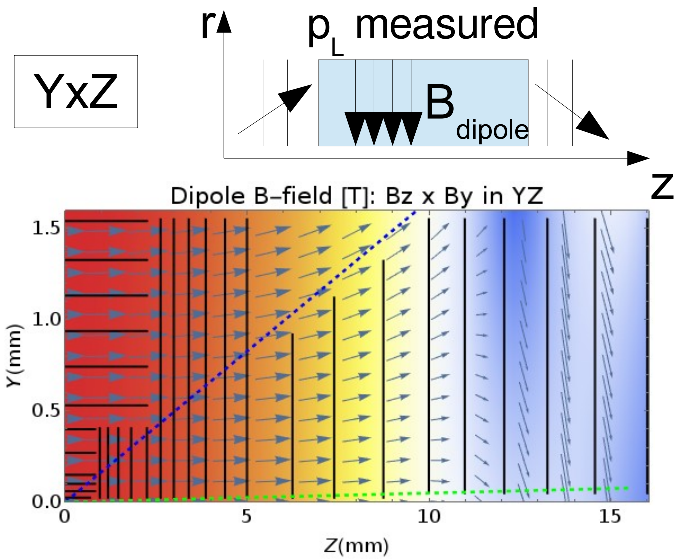


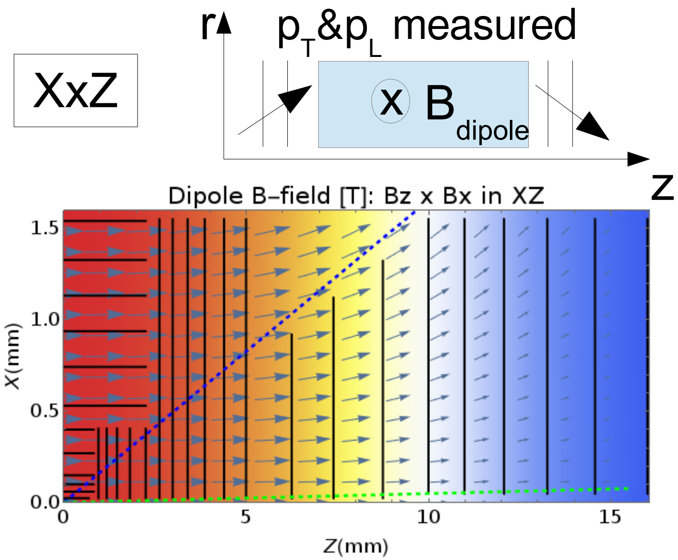
– **dp_T/p_T resolution:**



Total deterioration in $\delta p_T/p_T$ due to non-uniformity of solenoid B field **~35-45% @ η=2.5 or higher**

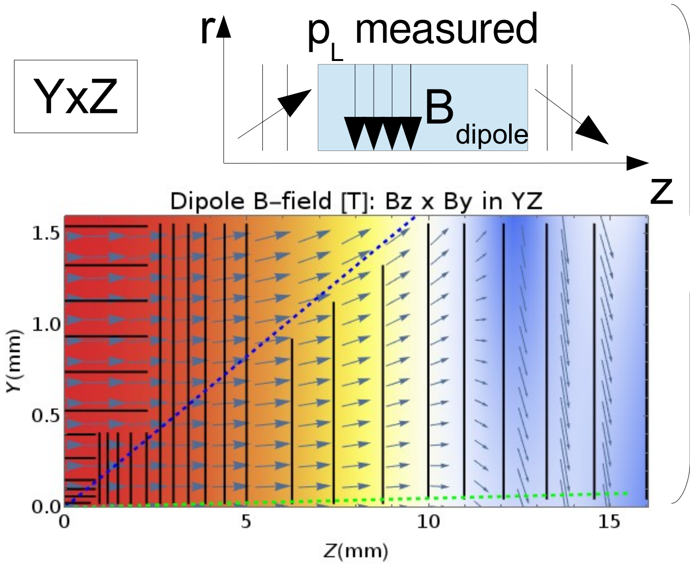
Dipole Alternative & dp_T/p_T Resolution

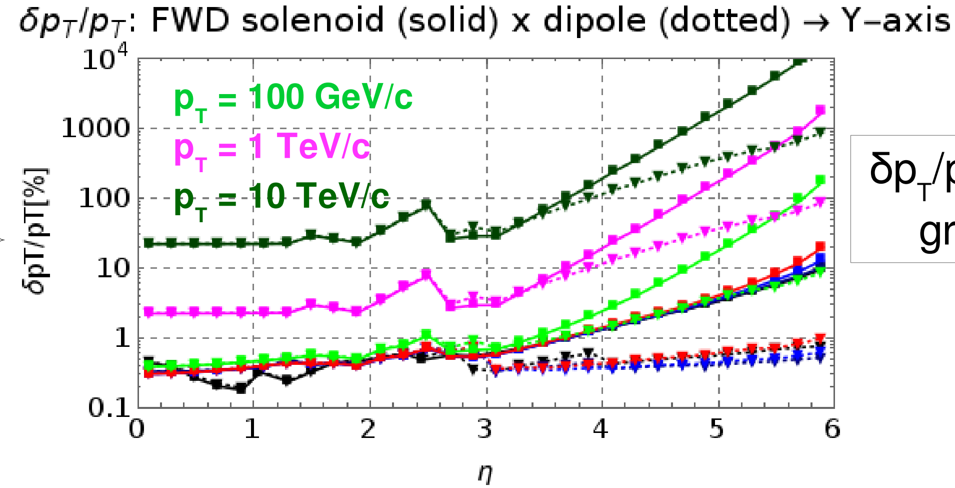




Dipole Alternative & dp_T/p_T Resolution

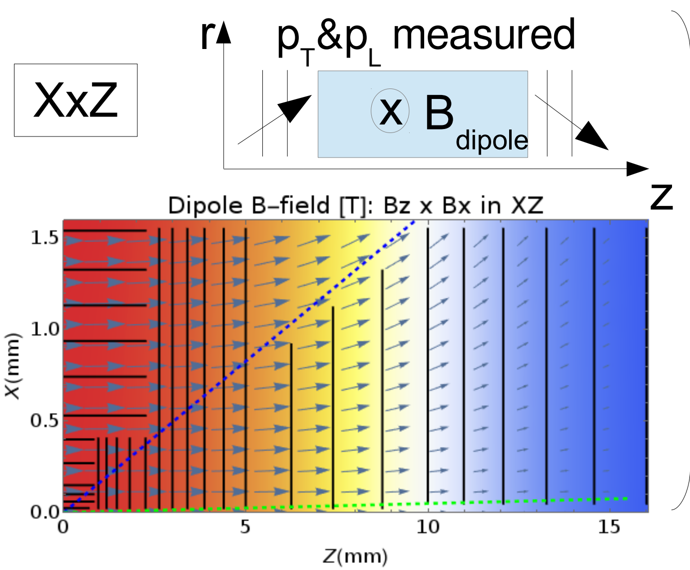
YxZ

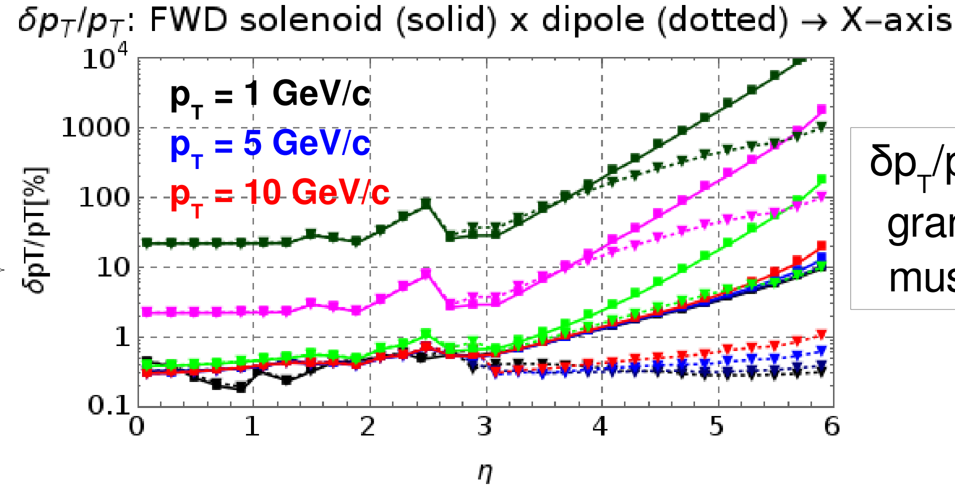




$\delta p_T/p_T$ affected only by granularity in R-Φ

XxZ





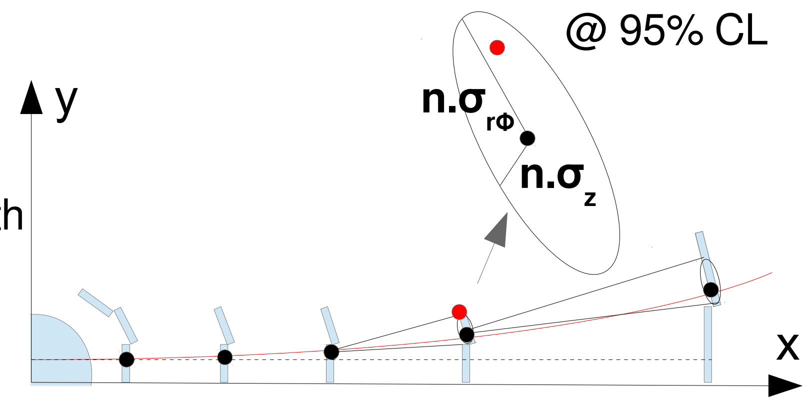
$\delta p_T/p_T$ affected by both granularity in R&R-Φ, must be comparable!

→ **Dipole: $\delta p_T/p_T$ improves by: x2.5, x5.0, x13.0 @ η=4.0, 5.0, 6.0**

Pattern Recognition (PR) Capabilities

- PR limit given by Multiple Scattering (MS) (low p_T tracks affected most) → use **track propagator** & analyze **layout "weak" spots**:
  - → assume **perfect seeding** (nontrivial)
  - → propagate $\boldsymbol{\sigma}_{r\Phi}$, $\boldsymbol{\sigma}_z$ to i^{th} layer (in → out)
  - → calculate probability that a **signal hit** is not mismatched with a **bkg hit** anywhere on the track @95% CL **in PU=1000**

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



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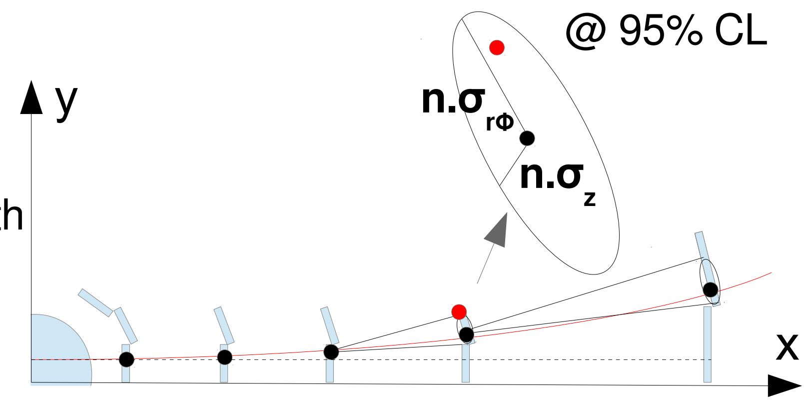

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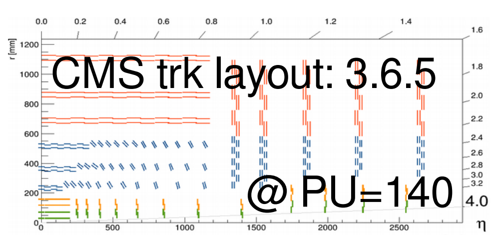
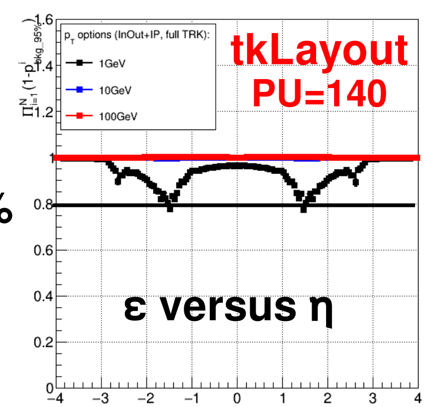
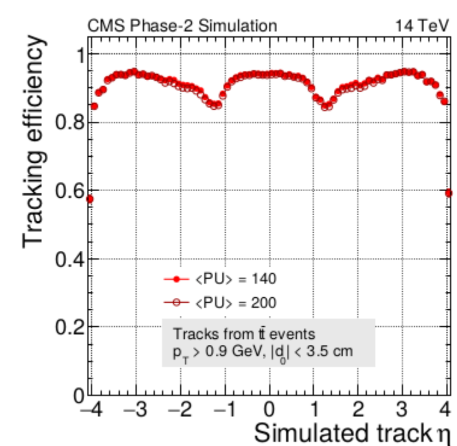
→ How to interpret & "calibrate" a limit value on **ε ~ efficiency?**



ε ~ 80%

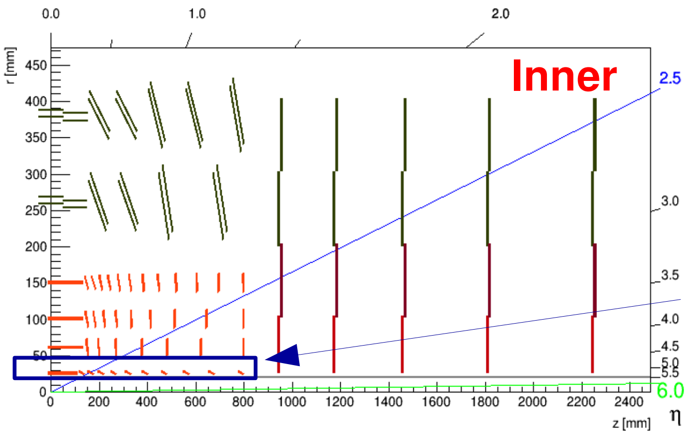




The Ph.2 Upgrade of the CMS Tracker
http://cds.cern.ch/record/2272264

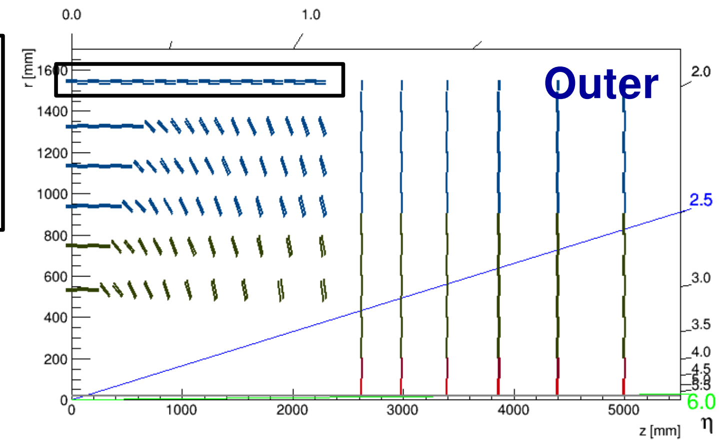
Tilted Layout 4.01 & PR Performance

- **Tilted geometry** minimizes MS → final layout as optimized by PR & δz0 (vertexing in PU):



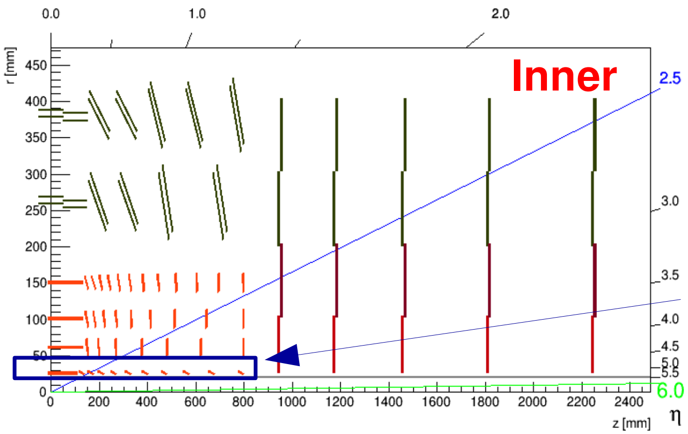
Flat BRL layer → lever arm
Striplet granularity in Z:
50(10)mm → 1.75mm

1^{st} layer: $\vartheta_{tilt} \simeq 10^{\circ}$
low MB x pos. in R (δd0)



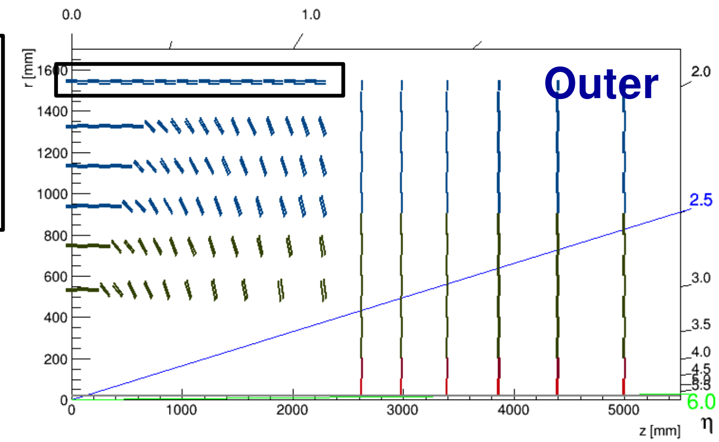
Tilted Layout 4.01 & PR Performance

- **Tilted geometry** minimizes MS → final layout as optimized by PR & δz0 (vertexing in PU):

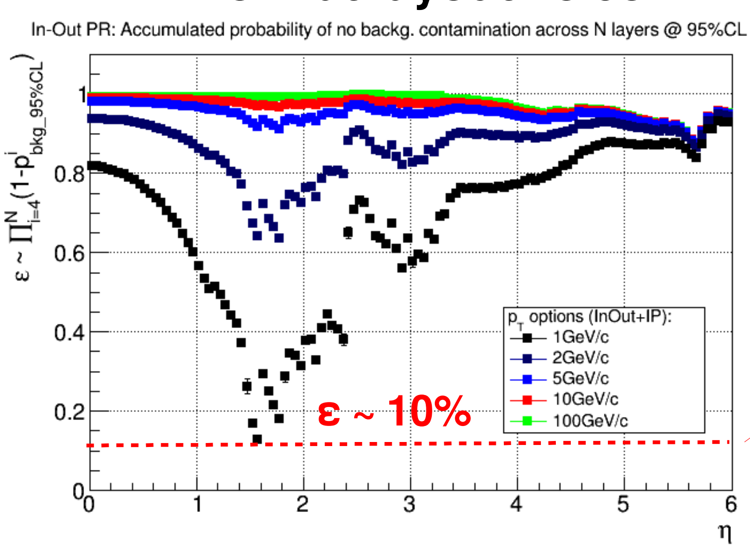


Flat BRL layer → lever arm
Striplet granularity in Z:
50(10)mm → 1.75mm

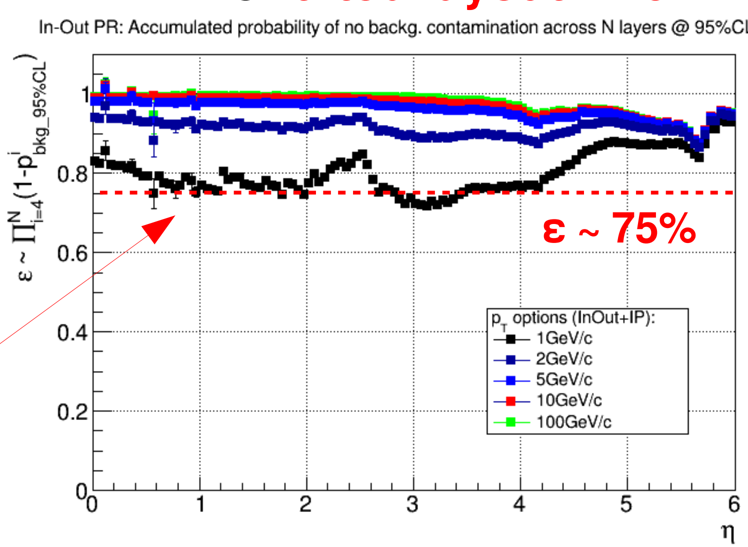
1st layer: $\vartheta_{tilt} \simeq 10^{\circ}$
low MB x pos. in R (δd0)



PR for flat layout v3.03:



PR for tilted layout v4.01:

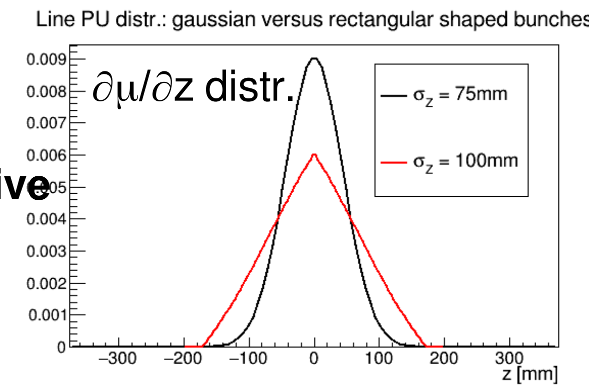


p_T = 1 GeV/c
p_T = 5 GeV/c
p_T = 10 GeV/c
p_T = 100 GeV/c

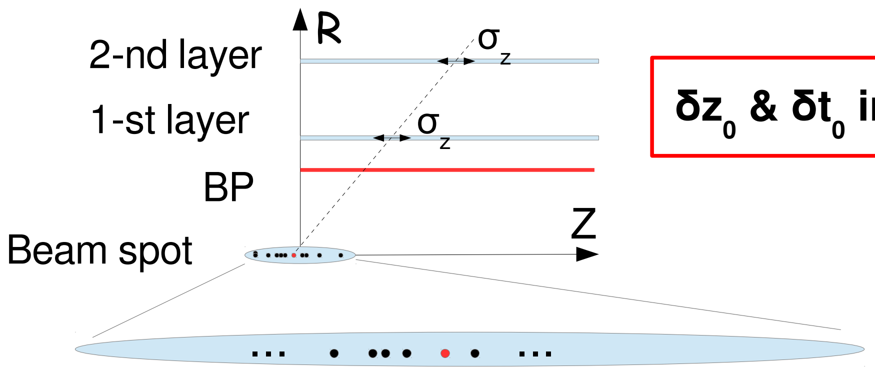
Vertexing @ PU=1000 & Timing Information

- Primary vertexing in huge pile-up (PU)~1000:

  → Study how many PU vertices are effectively contained within 95% CL interval of the primary track wrt primary vertex (LV) → **estimate effective PU** (LV assumed to be "precisely" found from e.g. high p_T tracks)



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

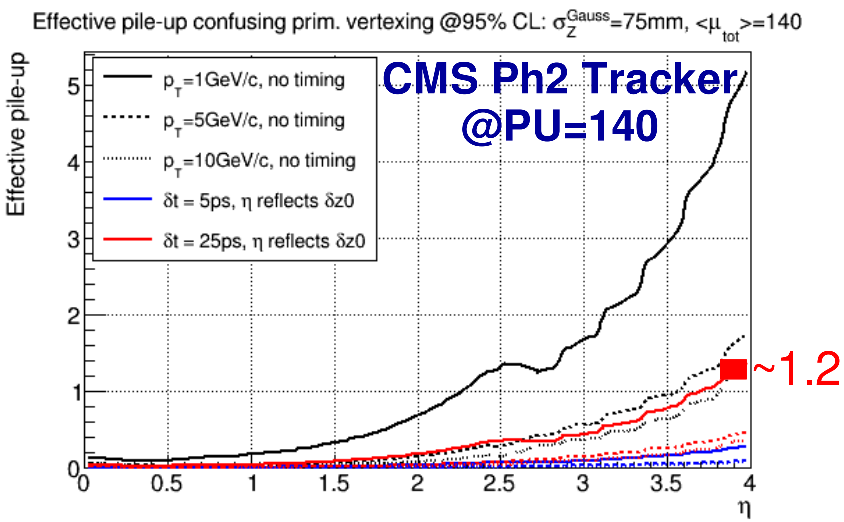


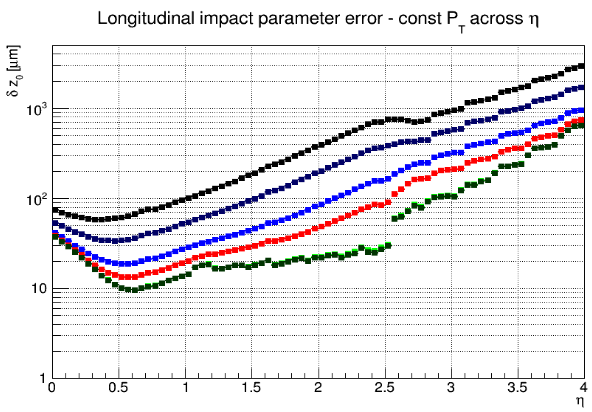
δz_0 & δt_0 interplay crucial!

$\sigma_z^{lum.region}$ ~ 44mm & $\sigma_t^{lum.region}$ ~ 165ps

Effective Pile-up Rate & Timing Information

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





Decrease in δz0 needs to be "compensated" by extra timing info (in FWD)

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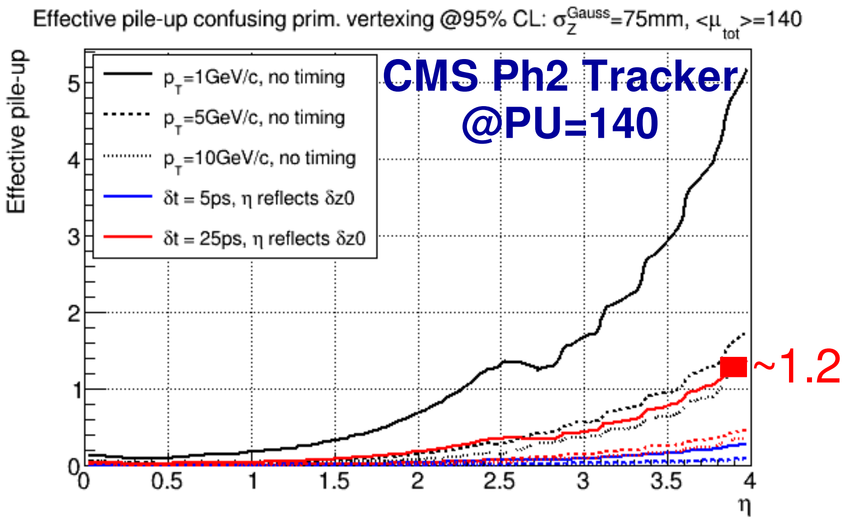
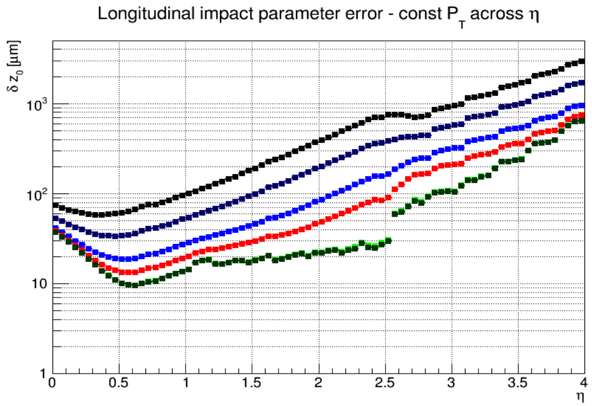
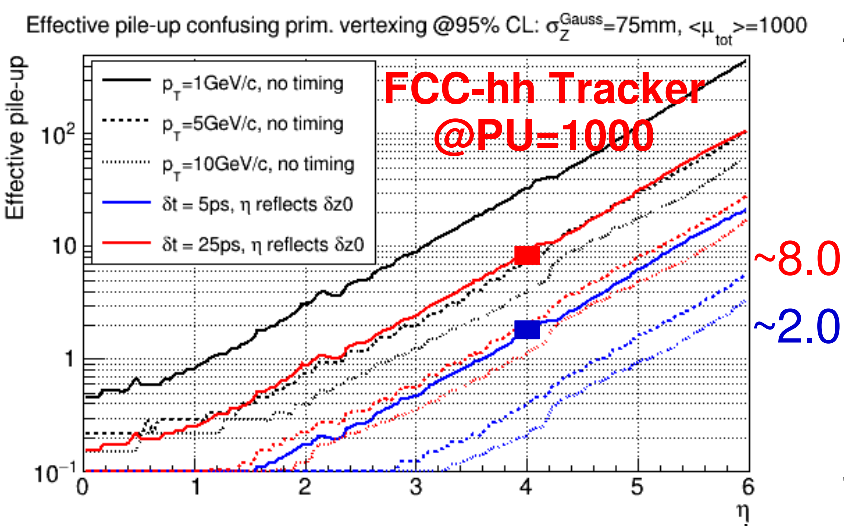




Decrease in δz0 needs to be "compensated" by extra timing info (in FWD)



FCC-hh: 2D vertexing (time & z) essential, namely in the FWD region! But..., may not be sufficient to mitigate the PU effect for tracks @ η>4.0

Summary & Challenges

- **The key tracker/vertex detector parameters understood:**

→ Layout with extended coverage up-to η=6 designed: ~430m^2 (391m^2 in tilted layout) of Si

→ Granularity in R-Φ mostly driven by dp_T/p_T @p_T=10TeV/c → **achieved dp_T/p_T ~20%**

→ Effect of dipole on dp_T/p_T in the FWD region assessed → **x13** improvement **@η=6.0** vs. solenoid

→ Granularity in Z driven by prim. vertexing & pattern recognition **@PU=1000**:

  - To minimize the effect of MS (mat. budget), **tracker design in tilted layout suggested**
  - To mitigate the pile-up effect, **tracking with precise timing information required (δt~5-10ps per track)** → the limiting factor for low p_T tracks **remains still the beam-pipe material**

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    - To mitigate the pile-up effect, **tracking with precise timing information required (δt~5-10ps per track)** → the limiting factor for low p_T tracks **remains still the beam-pipe material**
- **The key technology challenges:**
  → Huge data rates: 766 TB/s (untrig. @40MHz) & extreme data flows (densities) at low radii ≳**1Gb/s/cm2 @1MHz** implicate need for **new read-out technologies** & dedicated trigger design!
  → Fluences ~**$6x10^{17}n_{eq}/cm^2$** @ innermost tracker radii represent **a new challenge for the R&D**
  → Tracker technology providing **simultaneously position & timing information along the track** would open a new & powerful direction in the future track/vertex reconstruction

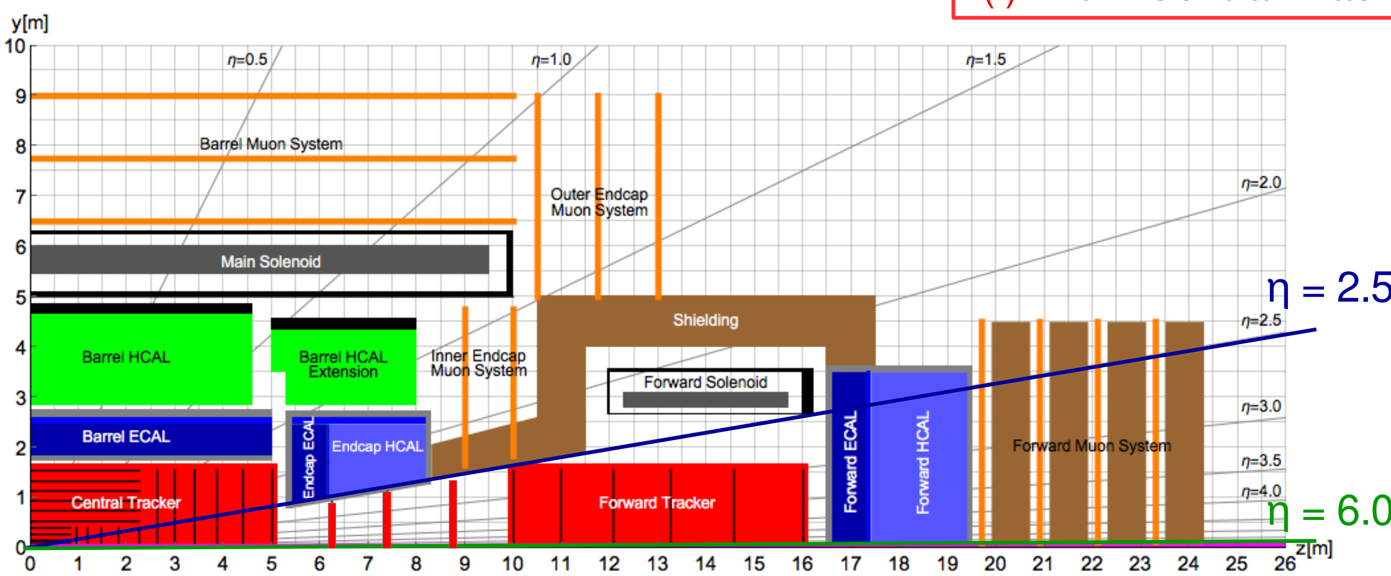
Back-up Slides

Back-up Slides:

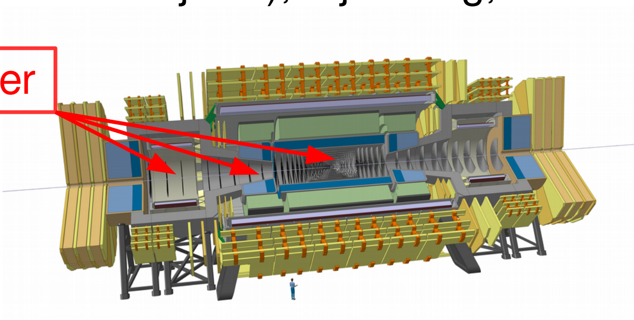
Reference Design & Tracker Requirements

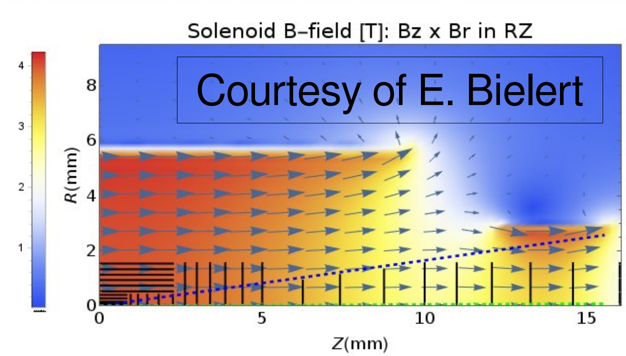
Reference Design & Tracker Requirements

- **FCC opens us a new kinematic & dynamical regime + physics @100TeV highly boosted → challenging requirements on tracker/vertex detector design:**
  - → **Extended tracking up-to |η|~4** (c.f. |η|~2.5 for LHC exp.) + efficient **VBF jet** meas. **up-to |η|~6**
  - → **High p_T res. ~10-20% @ 10TeV** (cf. LHC: 10% @1TeV) & still **keep sensitivity to low p_T tracks**
  - → **Provide efficient b,c,τ-tagging despite huge PU & high energies**
  - → **High tracker granularity essential** to resolve jet-substructure (collimated objects), reject bkg,...



(i)Fwd + Central Tracker





Tracker Granularity: Tilted vs. Flat Layout

Pixels (inner)	Macro-pixels (middle)	Striplets/Macro-pixels (outer)
$25 \times 50\,\mu m^2$ (1–4th BRL, 1st EC ring)	$33.3 \times 400\,\mu m^2$	$33.3\,\mu m \times 50\,mm$ (BRL)
$33.3 \times 100\,\mu m^2$ (2nd EC ring)		$33.3\,\mu m \times 10\,mm$ (EC)
$33.3 \times 400\,\mu m^2$ (3–4th EC ring)		

Table 1: Flat layout: The summary of assumed in-detector resolutions for different categories of sensors.

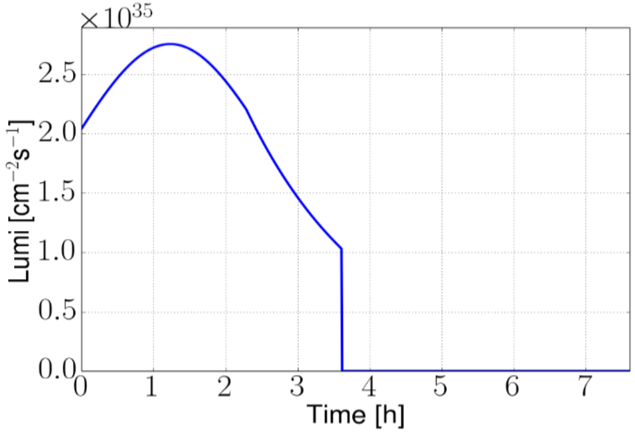
Pixels (inner)	Macro-pixels (middle)	Striplets/Macro-pixels (outer)
$25 \times 50\,\mu m^2$ (1–4th BRL, 1st EC ring)	$33.3 \times 400\,\mu m^2$	$33.3\,\mu m \times 1.75\,mm$ (BRL & EC)
$33.3 \times 100\,\mu m^2$ (2nd EC ring)		$33.3\,\mu m \times 50\,mm$ (12th BRL layer)
$33.3 \times 400\,\mu m^2$ (3–4th EC ring)		

Table 2: Tilted layout: The summary of assumed in-detector resolutions for different categories of sensors.

Pile-up Numbers: Estimation for FCC-hh

- How to estimate pile-up limits for FCC-hh?

→ numbers extrapolated (plot from D.Schulte's talk at FCC Week)



$$\langle\mu\rangle = \frac{\sigma_{inel} . L}{n_B . f_r}$$

- σ_{inel} ~ 108mb @ 100TeV FCC-hh
- **Tunnel length** = 97.500 km
- n_B (HL-LHC) = 2748
  (Bunches fill-up factor f_{up} = 2748/3554 ~ 77.3%)
  → **n_B (FCC-hh)= 10050** (using f_{up} factor)
- **f_r = 3.075kHz** (revolution frequency assuming FCC tunnel)
- **Ultimate Luminosity** ~ **30 x 10^{34}** $cm^{-2}s^{-1}$
- **Levelled luminosity (assuming loss in int. L ~20%) = 15 x 10^{34}** $cm^{-2}s^{-1}$

– **Luminosity variations** between bunches ± 8% (see e.g. ATL-PHYS-PUB-2013-014)

– **Pile-up: μ is Poisson distributed** → quantify **limits** by 95% confidence interval (σ~1.96√N)

→ **FCC-hh Ultimate: <μ> = [(1048 ± 84) ± 66] → Max O(1200), Avg ~ O(1000)**

→ **FCC-hh Levelled: <μ> = [(524 ± 42) ± 47] → Max O(600)**

Back-up Slides:

Hit Occupancy & Expected Data Rates

Occupancy & Expected Data Rates @ PU=1000

- Tracker granularity in a view of hit occupancy (~ <1%) → data rates @ **1000 PU**?

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

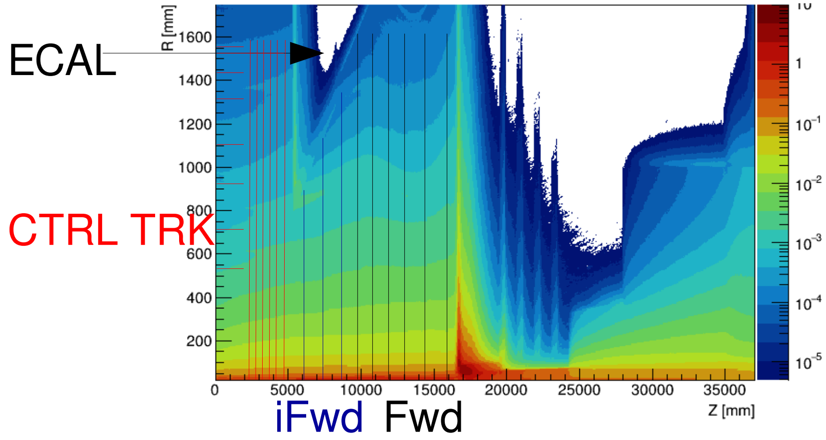
→ Calculate occupancy & hit rates for 2 scenarios:

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

→ Assume sparsified data read-out scheme:

- address each channel: **nBits** = $\log_2$(nRows) + $\log_2$(nColumns)
- add data block for cluster-width: assuming avg cluster-size ~3 → **2bits**
- add data block for pulse-height: **0bits** (binary read-out)

Charged particles fluence [cm^{-2}] per 1 pp collision



Inner Flat: 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	

Challenge: 1.6 $Gb/s/cm^2$

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

Outer & Fwd Flat: Occupancy & Data Rates

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

Outer:

Layer no :	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	

iFWD:

Ring no :	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	

FWD:

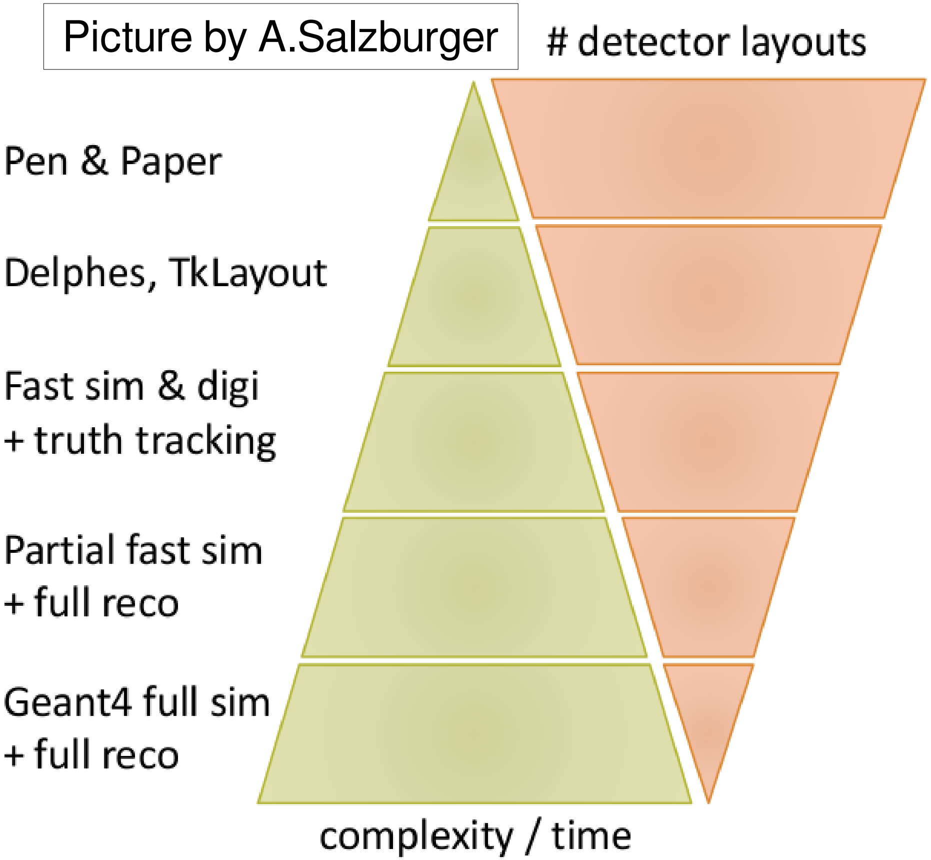
Ring no :	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Total [TB/s]
Average radius [mm] :	97.1	190.1	288.9	388.3	487.1	588.6	689.4	791.4	891.9	994.1	1094.4	1196.6	1296.6	1398.8	1498.5	
Module max occupancy (max[sen1,sen2])[%]:	0.28	0.11	0.20	0.12	0.08	0.05	0.04	0.03	0.02	0.46	0.34	0.25	0.16	0.11	0.09	
Data rate 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	

Back-up Slides:

SW Tools & Mathematical Approach to Track Resolution

Mathematical Techniques & SW Tools

- **Extremely important to choose the right tools given the tight schedule for CDR…**



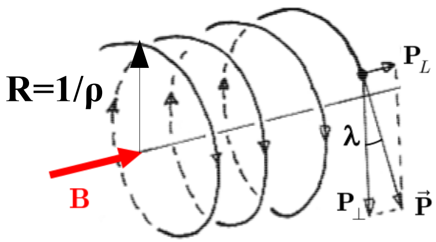
The tracker layout mainly optimized by applying:

- Approx. analytical approach: **tkLayout** (CMS)
- Numerical approach: **Mathematica**
- + using B field maps & Fluka simulated fluence map

Mathematical Approach: Analytical & Numerical

- **Estimate 5x5 cov. matrix of track parameters** (global $\chi 2$ with MS)

$$\rho,\ \phi_0,\ d_0,\ \mathrm{cotg}(\vartheta),\ z_0$$



$$\mathrm{cov}(\vartheta_i,\vartheta_j) = \left(A^T V^{-1} A\right)^{-1},\ A_{ij} = \left.\frac{\partial y_i(\vartheta_j)}{\partial \vartheta_j}\right|_{\vartheta=\hat{\vartheta}}$$

$$V = V_{\mathrm{det}} + V_{\mathrm{MS}}$$

Tracker precision & material

- **"Parabolic" approximation** (tkLayout SW) vs. **full numerical approach** (Mathematica):

Approx. analytical approach to $\frac{d^2\vec{x}(s)}{ds^2} = \frac{0.3}{p}\frac{d\vec{x}(s)}{ds} \times \vec{B}(\vec{x}(s))$ → assume const. B field & separate r-Φ & s-z:

- r-Φ → circle in polar coordinates: $0 = \frac{\rho}{2} r_i^2 - \sin(\varphi_i - \varphi_0)(1 + d_0\rho) r_i + d_0 (1 + d_0 \frac{\rho}{2})$

$d_0\rho \ll 1$

cyl. symmetry → $\phi_0 \equiv 0$

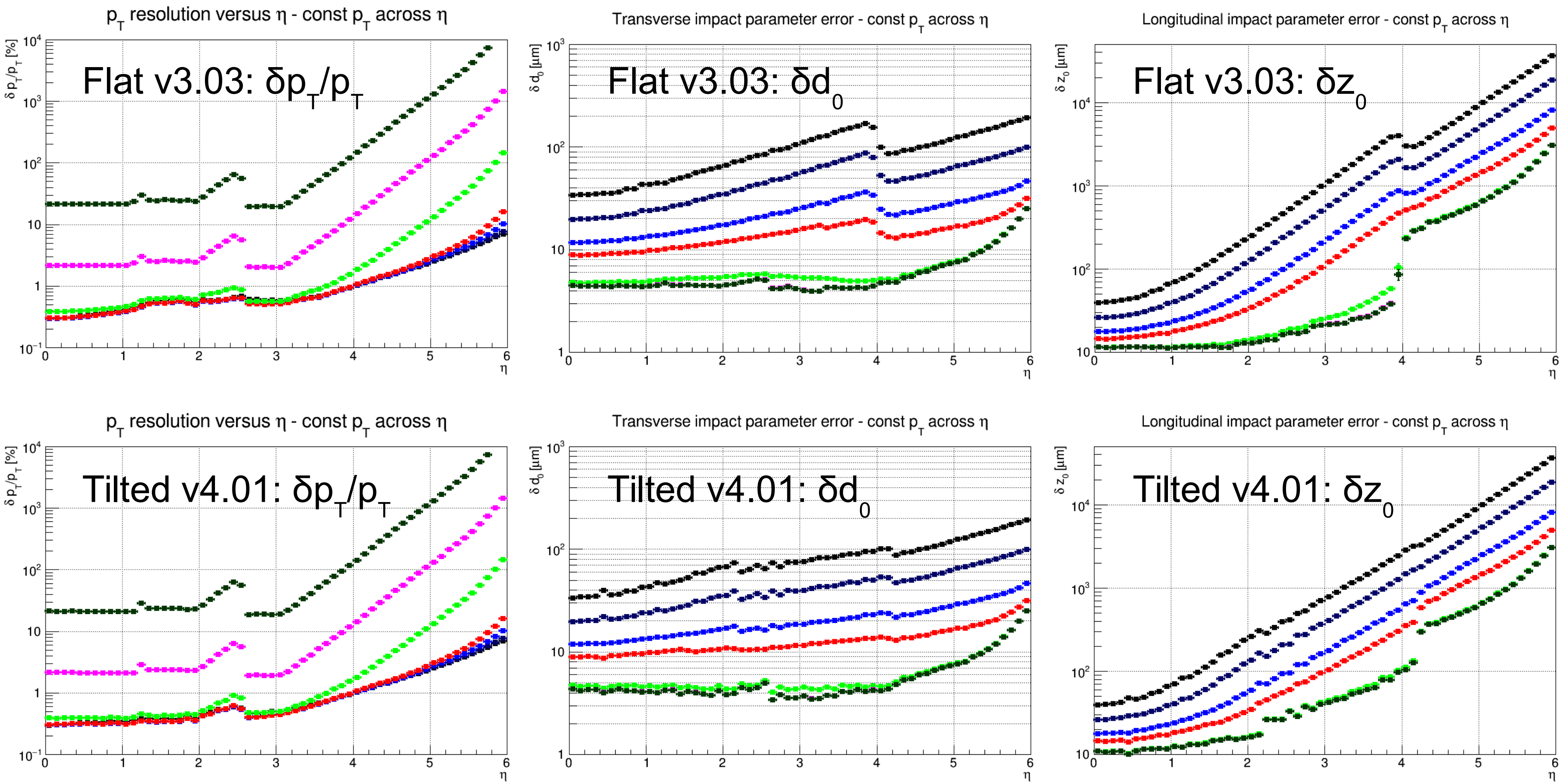
- s-z: → approx. path length s~r $z_i = z_0 + s_i \sin\lambda$
- Note:

$$V_{ij}^{\mathrm{MS}} = \sum_{k=1}^{\max[i-1,j-1]} (s_i - s_k)(s_j - s_k) f_i^{\mathrm{proj}} f_j^{\mathrm{proj}} \langle \vartheta_k^2 \rangle$$

$$\langle \vartheta_k^2 \rangle = \left(\frac{13.6\,\mathrm{MeV}}{\beta p c}\right)^2 \frac{d_k/X_0}{\sin(\vartheta_k + \alpha_k)} \left(1 + 0.038 \ln \frac{d_k/X_0}{\sin(\vartheta_k + \alpha_k)}\right)^2$$

- f_i^{proj}: projection of track ⊥ error ellipse to meas. plane (module)
- α_k: tilt angle of meas. plane
- d_k/X_0: module thickness in X0

Layout v3.03 x v4.01: Track Parameters Res.



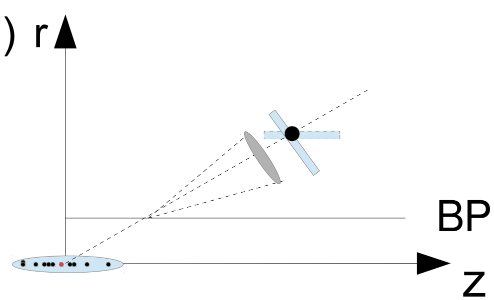
For details see http://fcc-tklayout.web.cern.ch

Back-up Slides:

Track Propagator & MS Effects

Track Propagator in PR & MS

- 4 key parameters affecting propagation of error ellipse:
  - **material effect @ ϑ** (**tilt angle α**)
  - **radial propagation distance** (notice dependence on p_T not p)
  - **projection factor** on det. plane



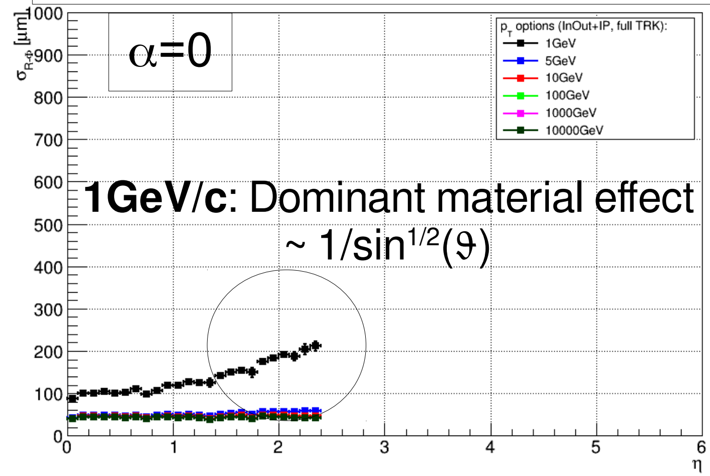
$$\sigma^2_{\mathrm{MS}} \approx \langle\vartheta^2_{p_T}\rangle \frac{d/X_0}{\sin(\vartheta+\alpha)} \Delta r^2 f_{\mathrm{proj}}$$

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

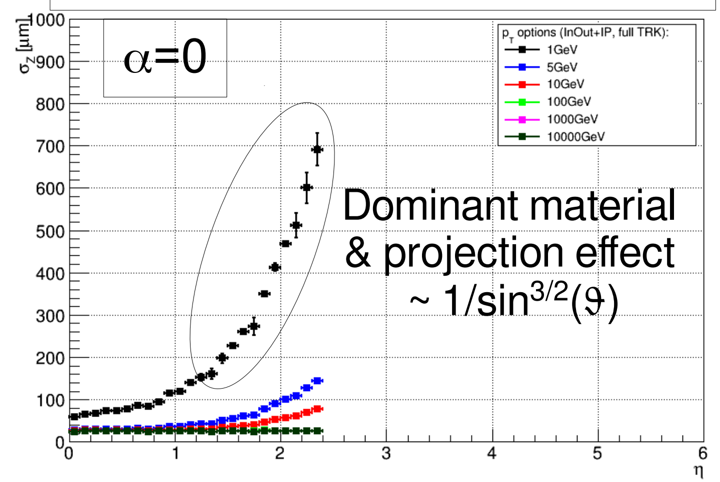
$$f_{\mathrm{proj}} = \left(\frac{1}{\sin(\vartheta+\alpha)}\right)^2 \quad \text{proj. in Z}$$

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

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

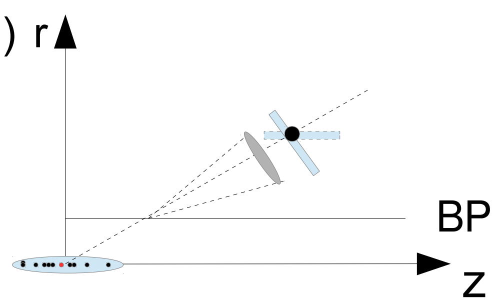


Propagated σ_Z on 4th BRL layer



Track Propagator in PR & MS – Ideal Tilting

- 4 key parameters affecting propagation of error ellipse:
  - **material effect @ ϑ** (**tilt angle α**)
  - **radial propagation distance** (notice dependence on p_T not p)
  - **projection factor** on det. plane



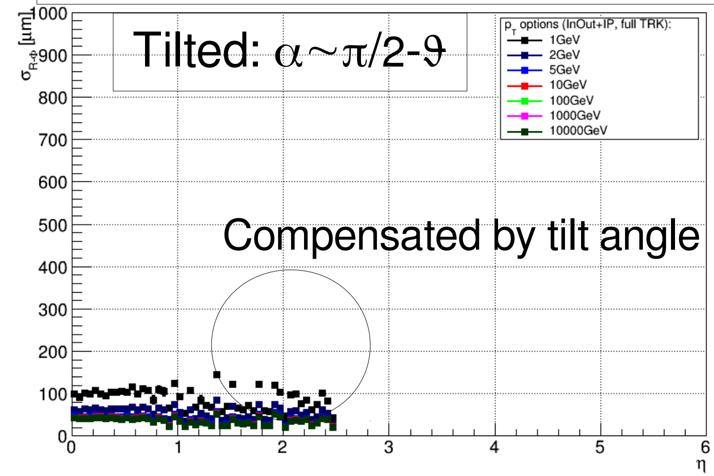
$$\sigma^2_{\mathrm{MS}} \approx \langle \vartheta^2_{p_T} \rangle \frac{d/X_0}{\sin(\vartheta+\alpha)} \Delta r^2 f_{\mathrm{proj}}$$

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

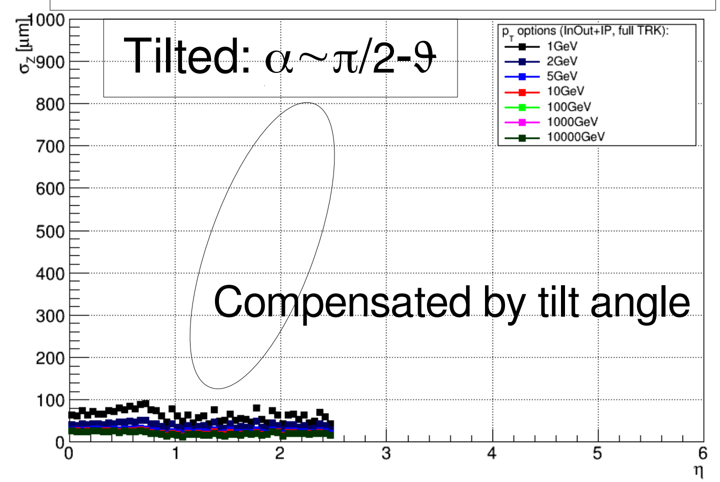
$$f_{\mathrm{proj}} = \left(\frac{1}{\sin(\vartheta+\alpha)} \right)^2 \quad \text{proj. in Z}$$

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

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



Propagated σ_Z on 4th BRL layer



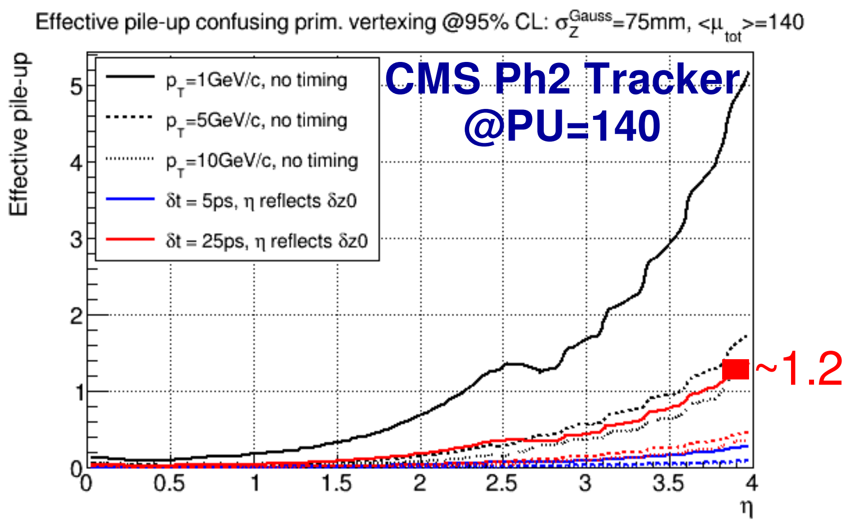
- **To min. mat. effects, tracker in tilted layout advantageous!**

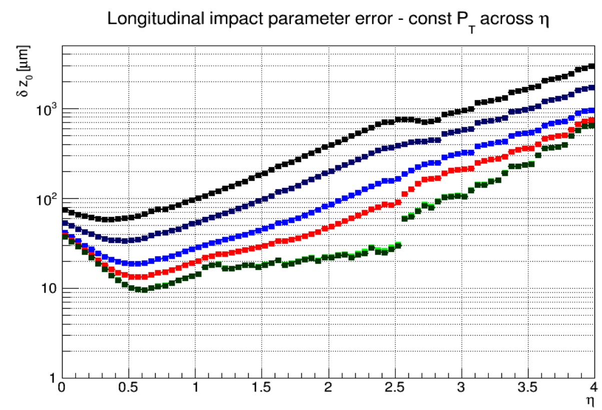
Back-up Slides:

Implications of High Pile-Up on Primary Vertexing

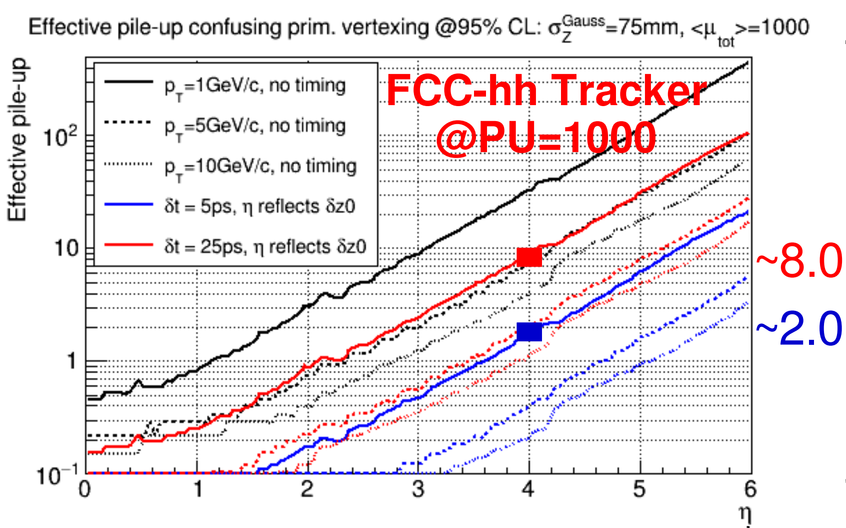
Effective Pile-up Rate

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





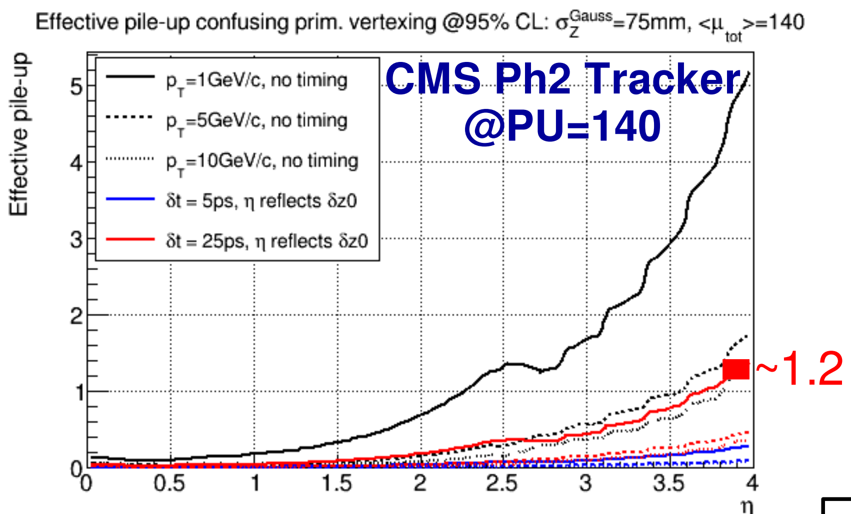
Decrease in δz0 needs to be "compensated" by extra timing info (in FWD)

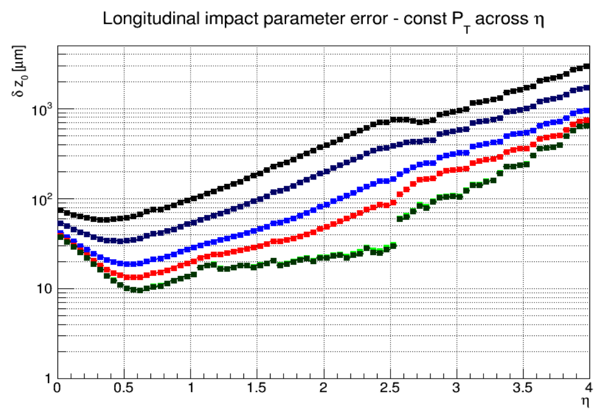


FCC-hh: 2D vertexing (time & z) essential, namely in the FWD region! But..., may not be sufficient to mitigate the PU effect for tracks @ η>4.0

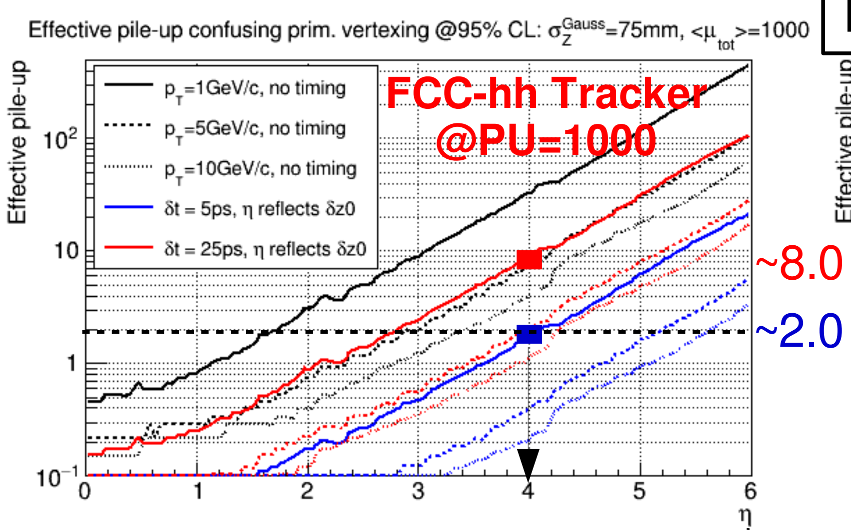
Effective Pile-up Rate & Effect of Bunch Size

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

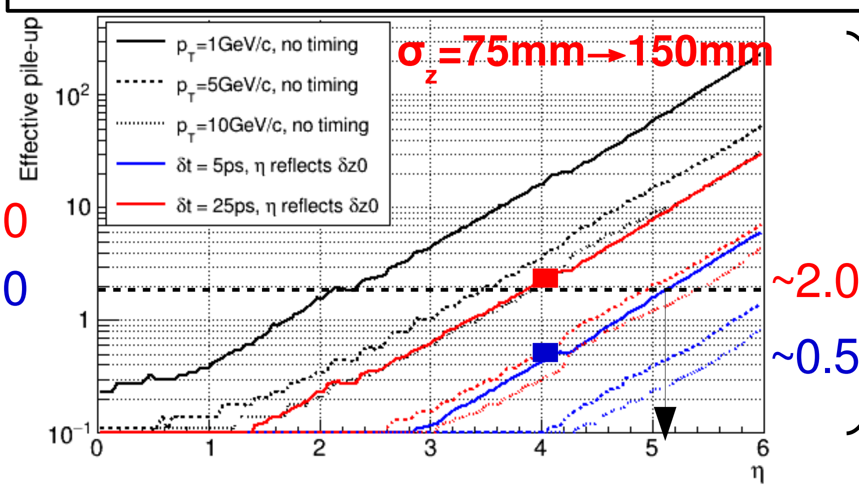




Decrease in δz0 needs to be "compensated" by extra timing info (in FWD)



How about increasing bunch size in Z?



Improves quadratically due to 2D VTX