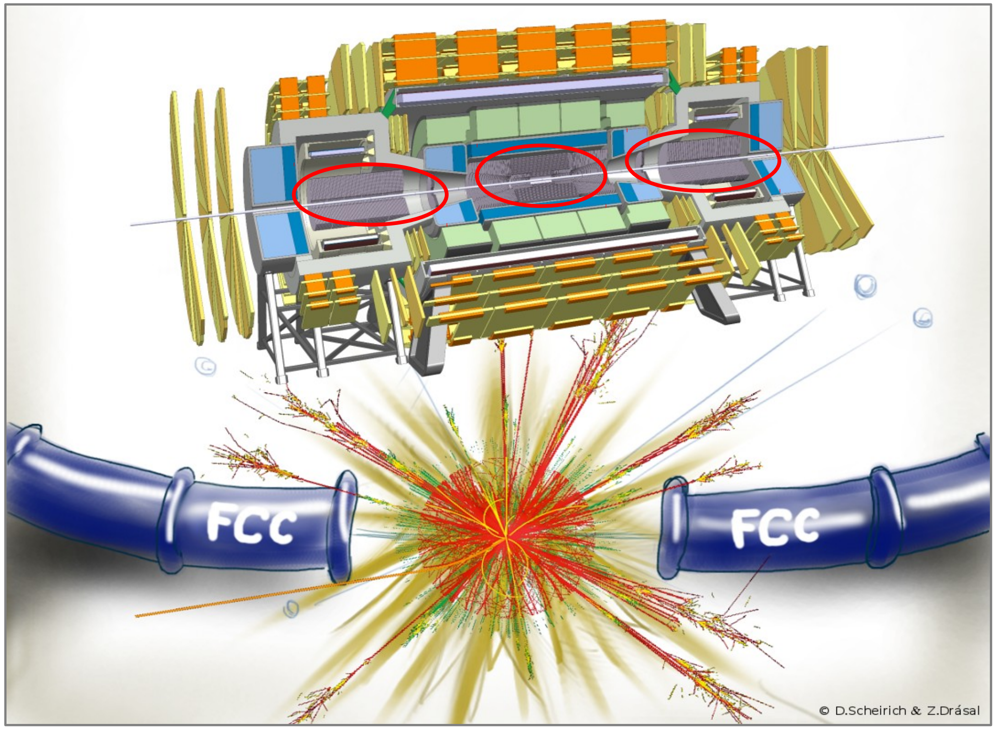
Status & Challenges of Tracker Design for FCC-hh



Zbyněk Drásal
CERN

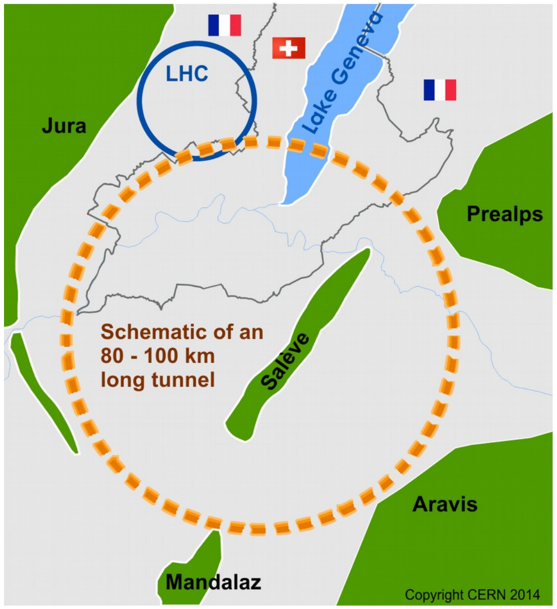
On behalf of the FCC-hh detector working group

Overview

- Introduction
  - Future Circular Collider with focus on FCC-hh (pp) option
  - Physics motivation & Reference Detector Layout
- FCC-hh & Radiation Studies
- Tracker design & expected tracker performance
  - Reference tracker geometry & design driving principles
  - Granularity in R-Φ & tracking resolution
  - Implications of high pile-up & high-rate environment
    - → Pattern recognition capabilities & requirements on granularity in Z
    - → Primary vertexing in high pile-up & requirements on timing information
    - → Expected tracker occupancy & data rates
- Summary & Challenges

Future Circular Collider

- **FCC machine:**
  - FCC-hh (pp collider): final goal defining the whole infrastructure
    → ~ 16T magnets → 100TeV pp collider in 97.75km tunnel
  - FCC-ee: as a potential first step
  - FCC-eh: as an option



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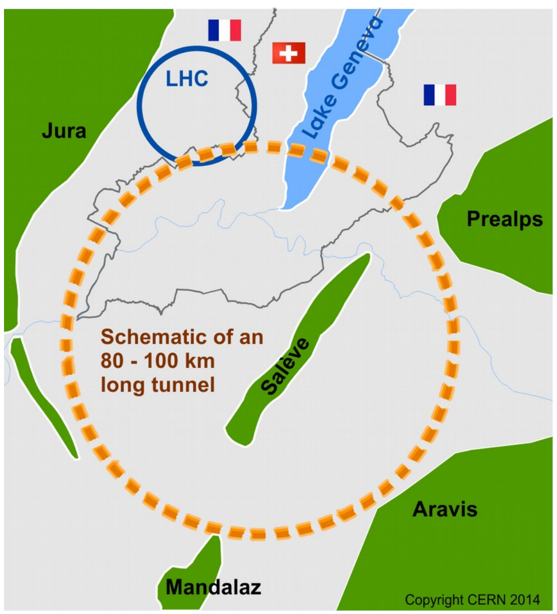

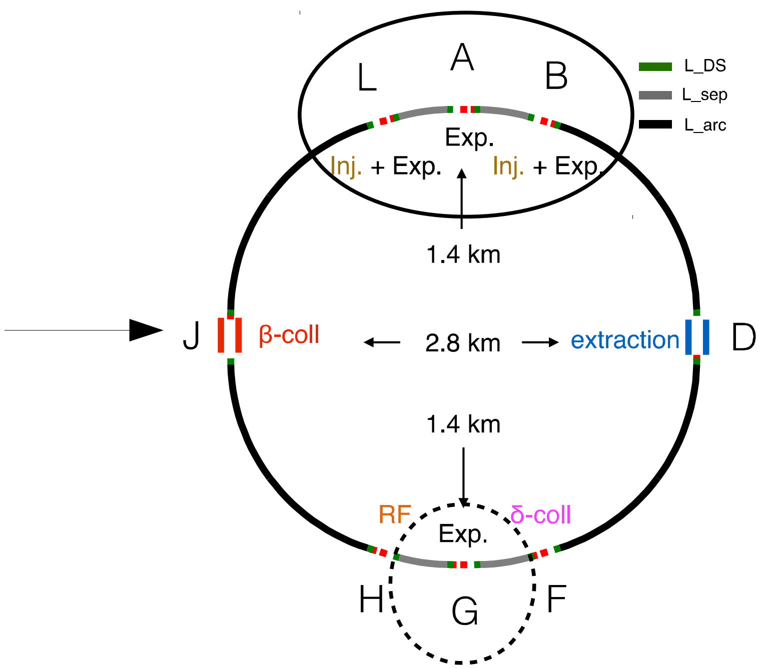

- A&G 2 high-luminosity exp.
- L&B 2 other exp.

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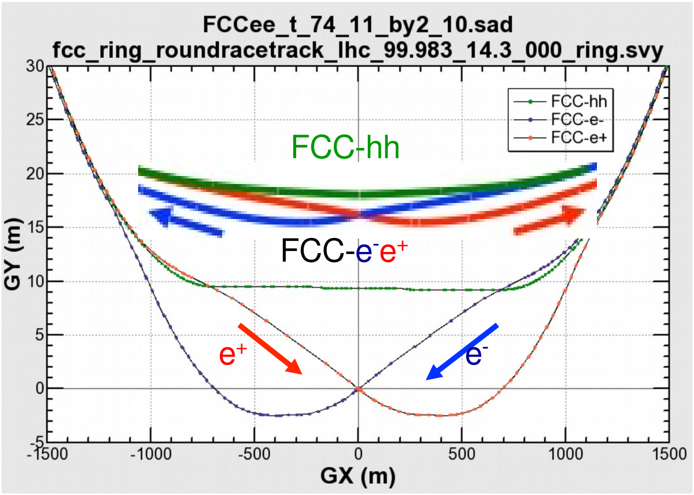

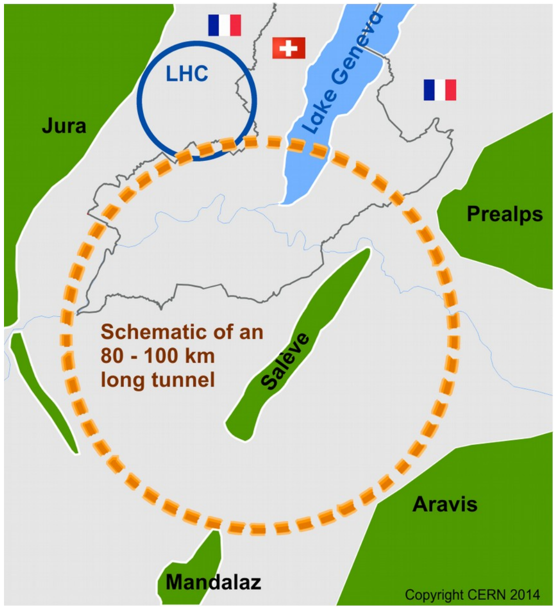

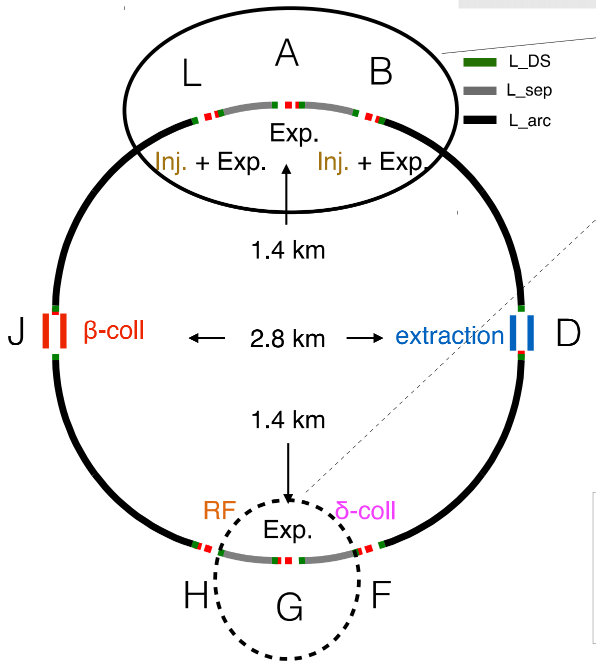

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Key FCC-hh parameters

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

- **Baseline** (phase 1): 10 yrs of operation @ $L_{peak} = 5x10^{34}cm^{-2}s^{-1}$ → **2.5 ab^{-1}** per detector
- **Ultimate** (phase 2): 15 yrs of operation @ $L_{peak} \leq 30x10^{34}cm^{-2}s^{-1}$ → **15 ab^{-1}** per detector

→ **Total: O(20)ab^{-1} per experiment**

Understanding FCC-hh parameters

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14TeV → 100 TeV

$\sigma_{inelastic}$: 80mb → 108mb

average p_T: 0.6 → 0.8 GeV/c

$\text{multiplicity}_{\text{charged/unit }\eta}$: 5.4 → 8

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5x increase in pile-up wrt HL-LHC

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6x increase in luminosity wrt HL-LHC

→ the minimum bias events @FCC are quite similar to ones @HL-LHC, but ...

→ pile-up per bunch crossing **O(1000)** is a big challenge → keeping 5ns (versus 25ns) operation scheme as an option

→ FCC-hh represents an extremely high luminosity machine → expecting huge particle/data rates & significantly higher rad. level in the inner/fwd detector

Physics Requirements on Detector Design

- **Design strongly depends on outcome of future LHC discoveries:**
  - **In case of new discoveries** → precise understanding of new physics will motivate the design
  - **In case no new physics is discovered** → mass scale of new physics may be beyond LHC reach or final states are too elusive → **higher mass reach, high luminosity machine & precise det. are the key!**

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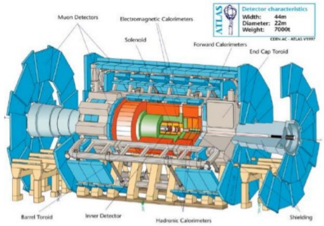
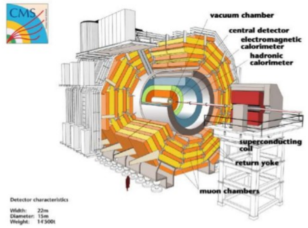
  → either way **a very general purpose detector** is a way to go (as ATLAS or CMS)





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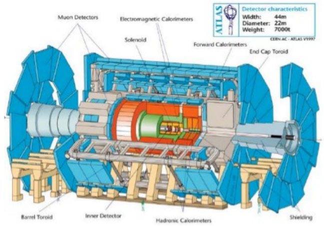
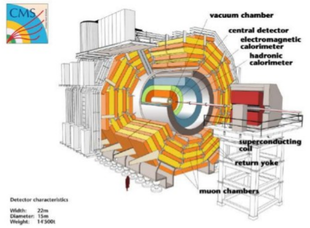
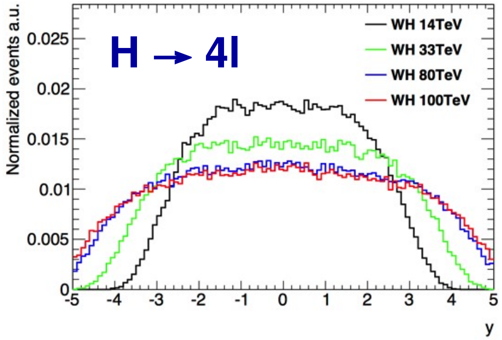




- The key benchmarks: Higgs & EWSB phenomena → FCC opens us a new kinematic & dynamical regime
  - e.g. **W(H → 4l)**

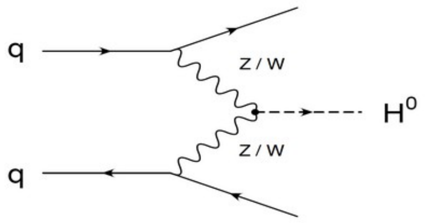


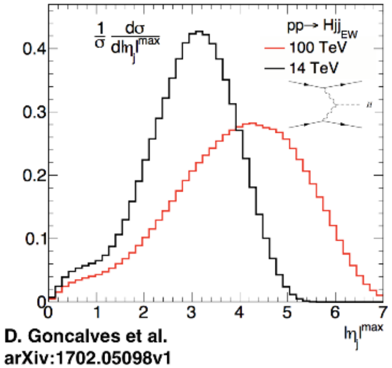
	14 TeV		100 TeV	
	2.5	4	2.5	4
ggF	0.74	0.99	0.56	0.88
WH	0.66	0.97	0.45	0.77
ZH	0.69	0.98	0.48	0.8
ttH	0.84	1	0.56	0.9
VBF	0.75	0.98	0.55	0.87

→ Need **extended** tracking & ECAL coverage **up-to |η|~4** (c.f. |η|~2.5 for LHC exp.)

Physics Requirements on Detector Design

– e.g. **VBF**





D. Goncalves et al.
arXiv:1702.05098v1

→ Need for efficient VBF jet measurement **up-to |η|~6**

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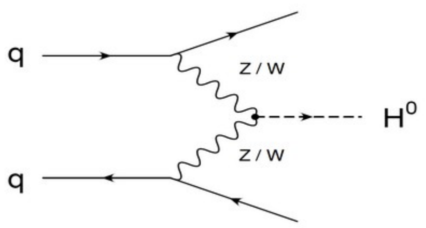

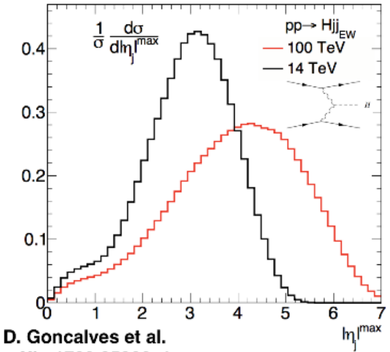

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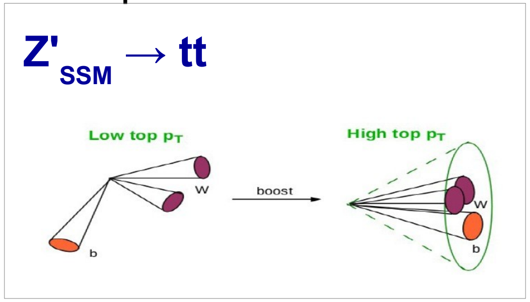
- FCC immensely increases **the mass reach** ~ E/14TeV (by factor of 5-7 increase, depending on $L_{integr.}$)
  - e.g. **Z' → μμ** or **Z' → tt**

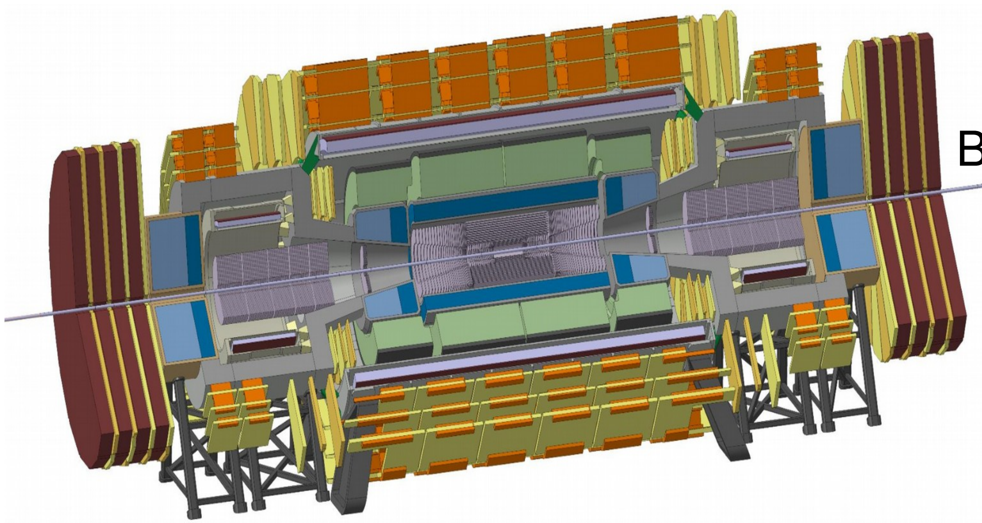
→ Need for **high p_T resolution ~10-20% @ 10TeV** (cf. LHC: 10% @1TeV), but **keep sensitivity to low p_T tracks**



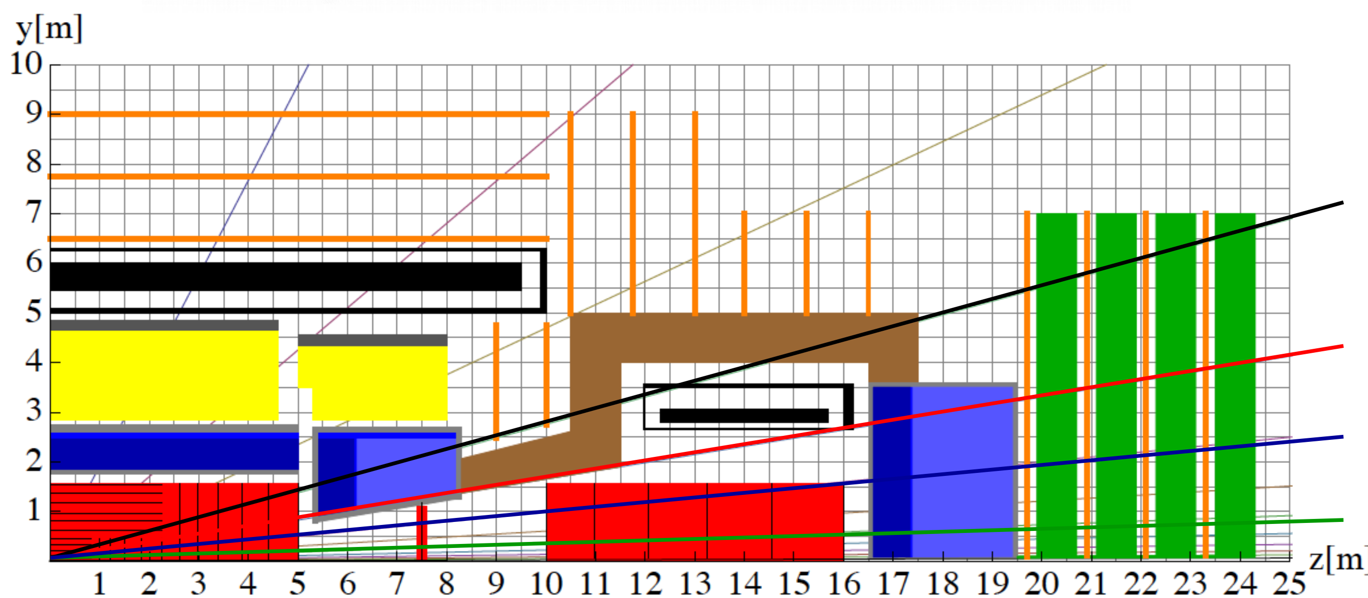
Expected highly-collimated final states – boosted decay products (min distance between 2 partons ~ m/p_T)

→ **High Tracker, E/HCAL granularity essential** to resolve jet-substructure (E/HCAL), reject bkg,...

Reference Detector Layout



Be beam-pipe @R=20+0.8mm



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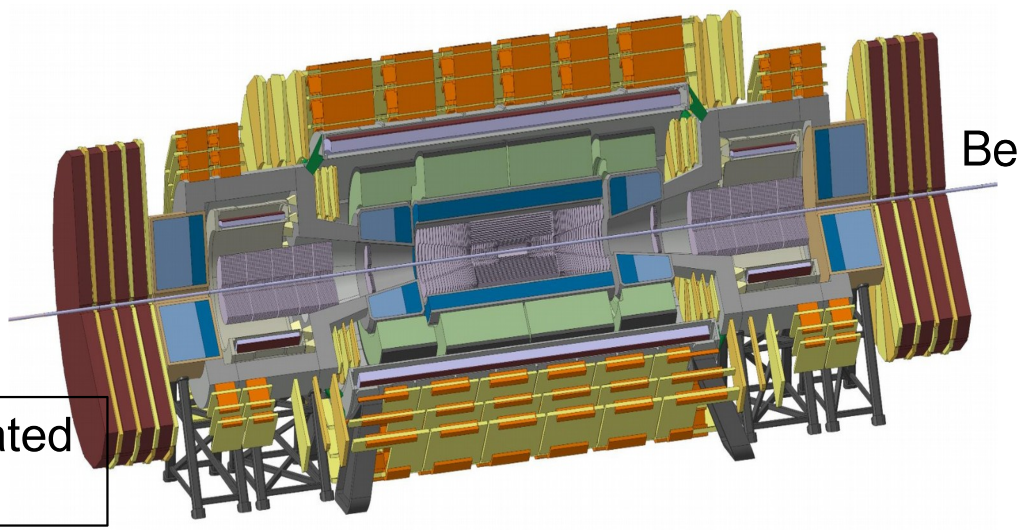

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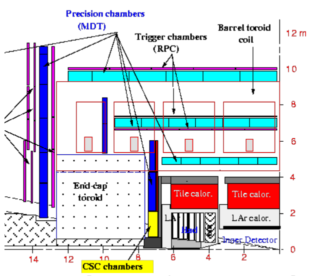
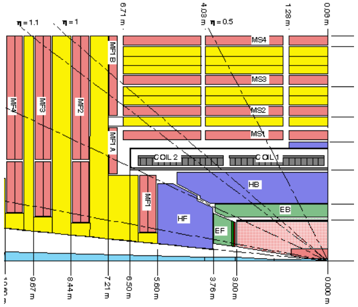
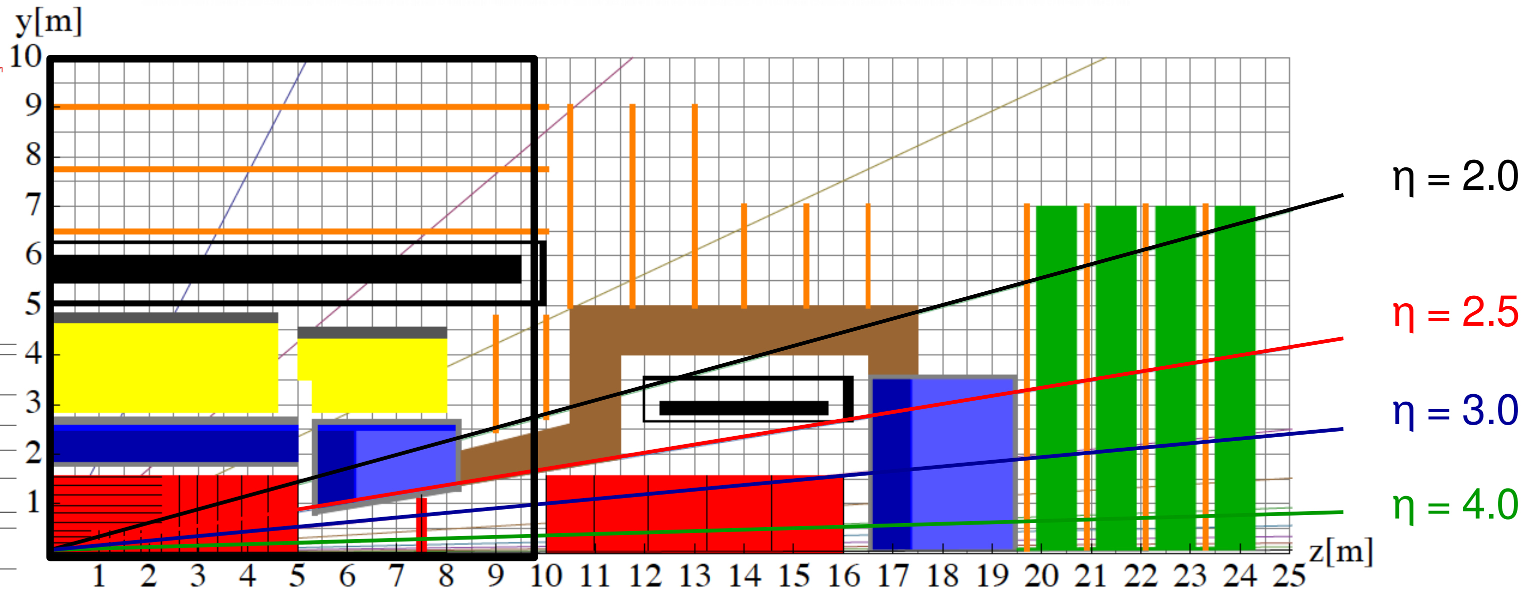
Central region motivated by ATLAS/CMS







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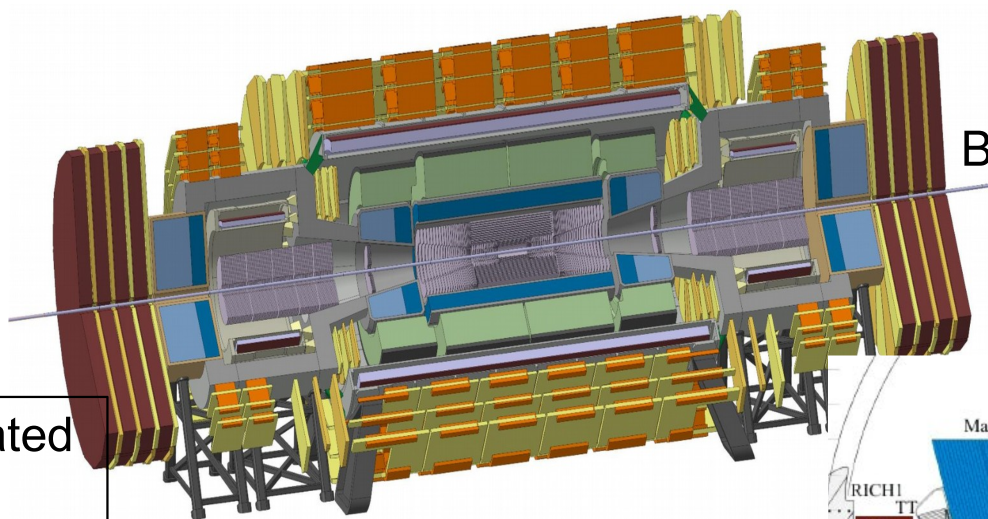

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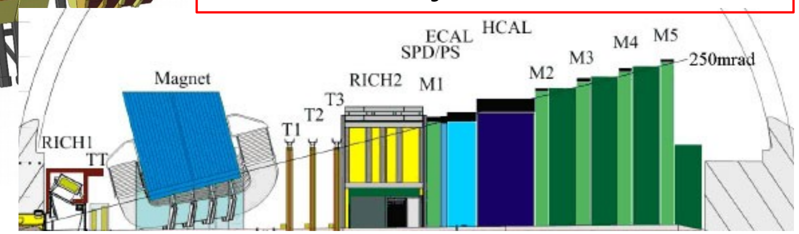
Forward region motivated by LHCb



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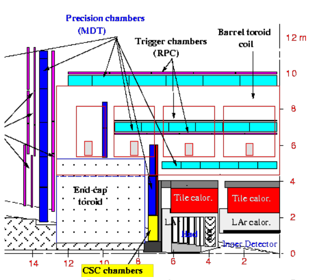

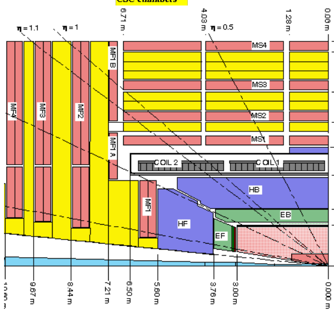

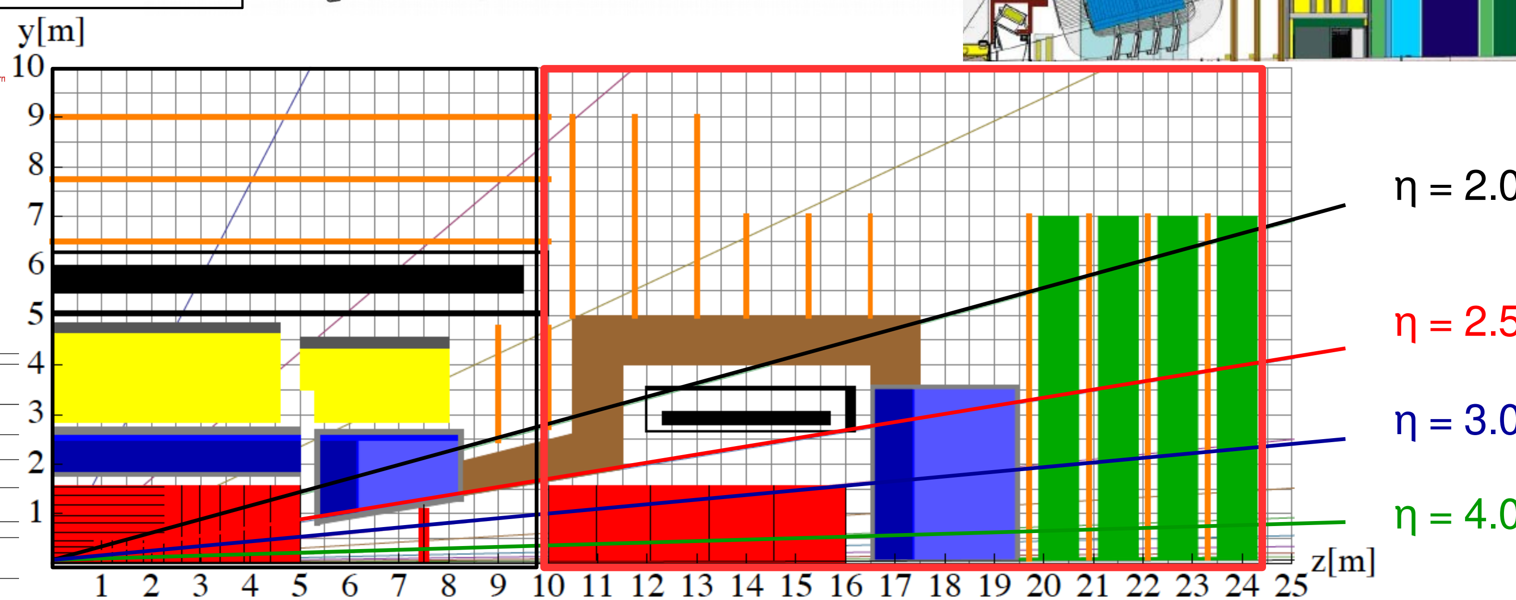

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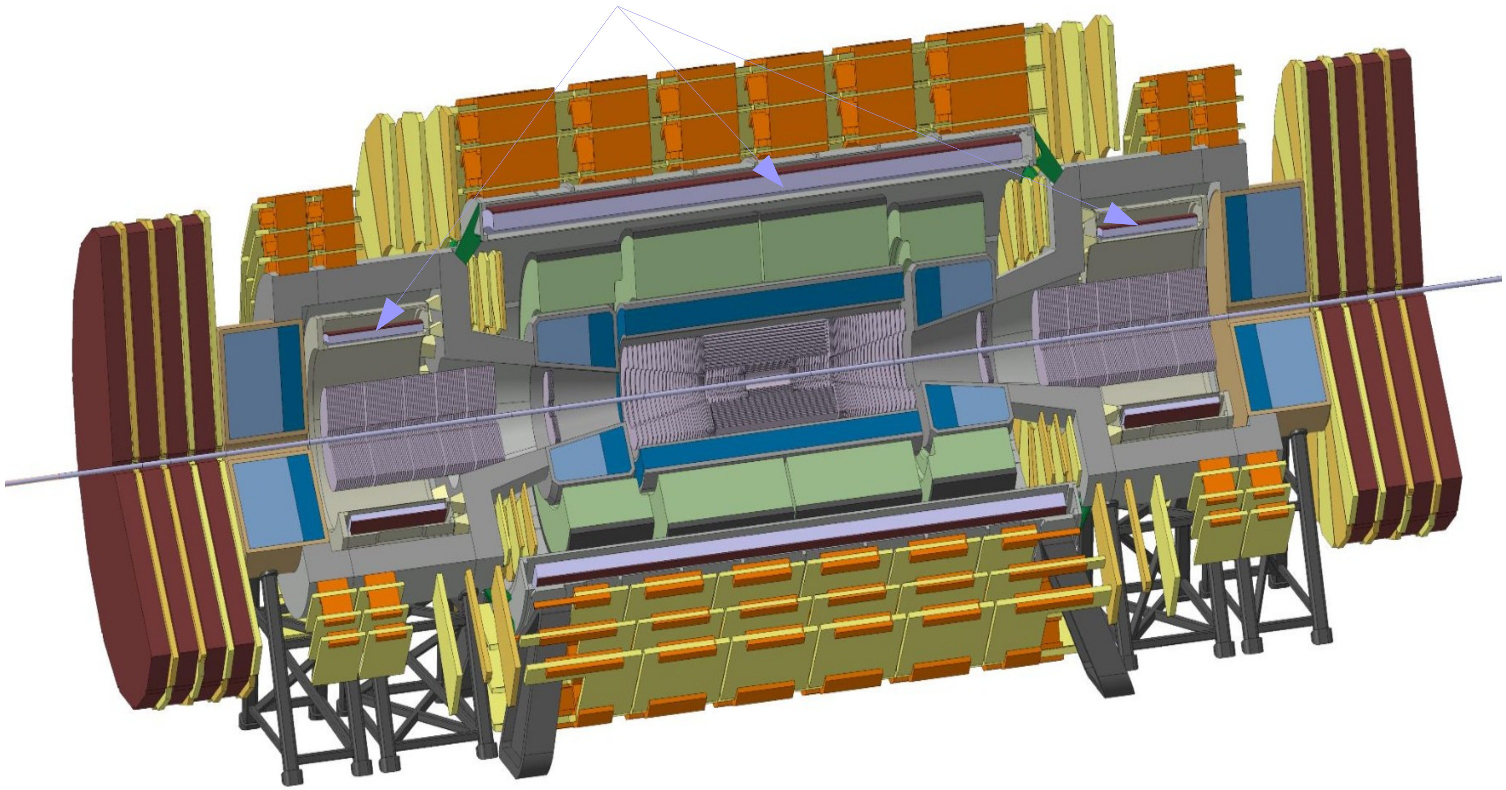
4T solenoid (10m free bore) + 2x 4T Fwd solenoids (no shielding)



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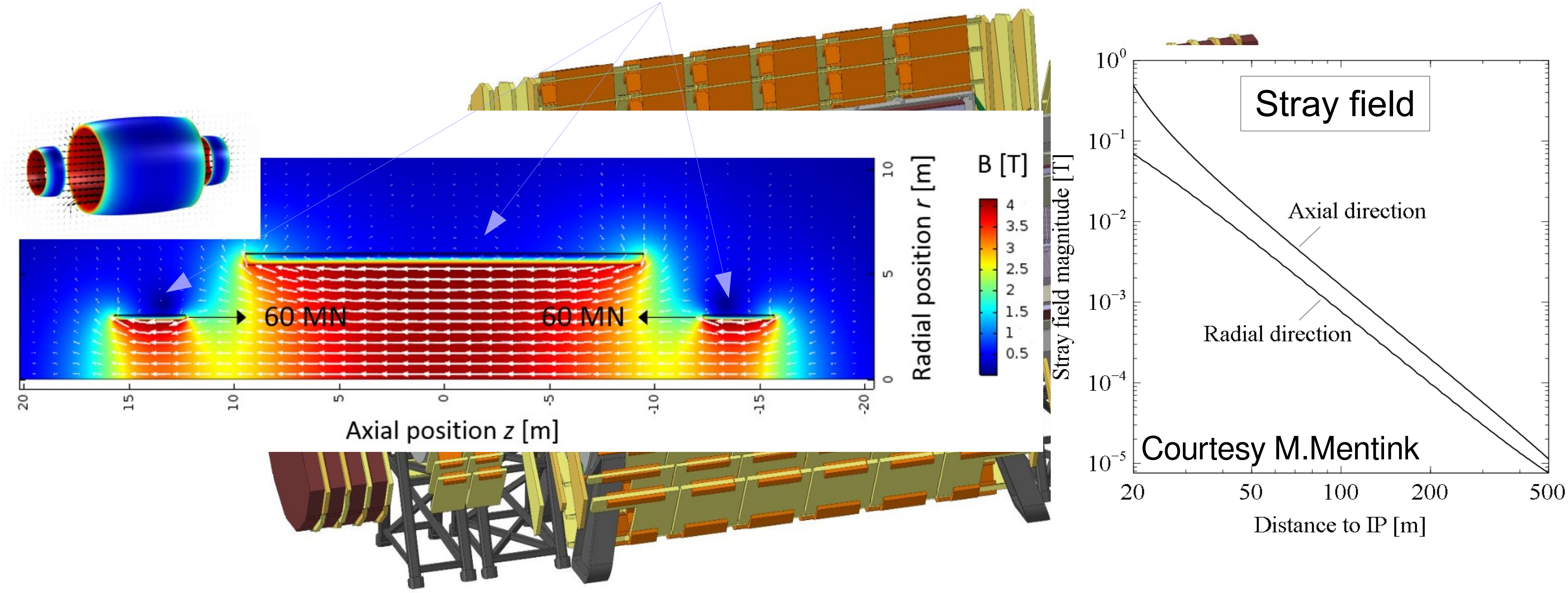

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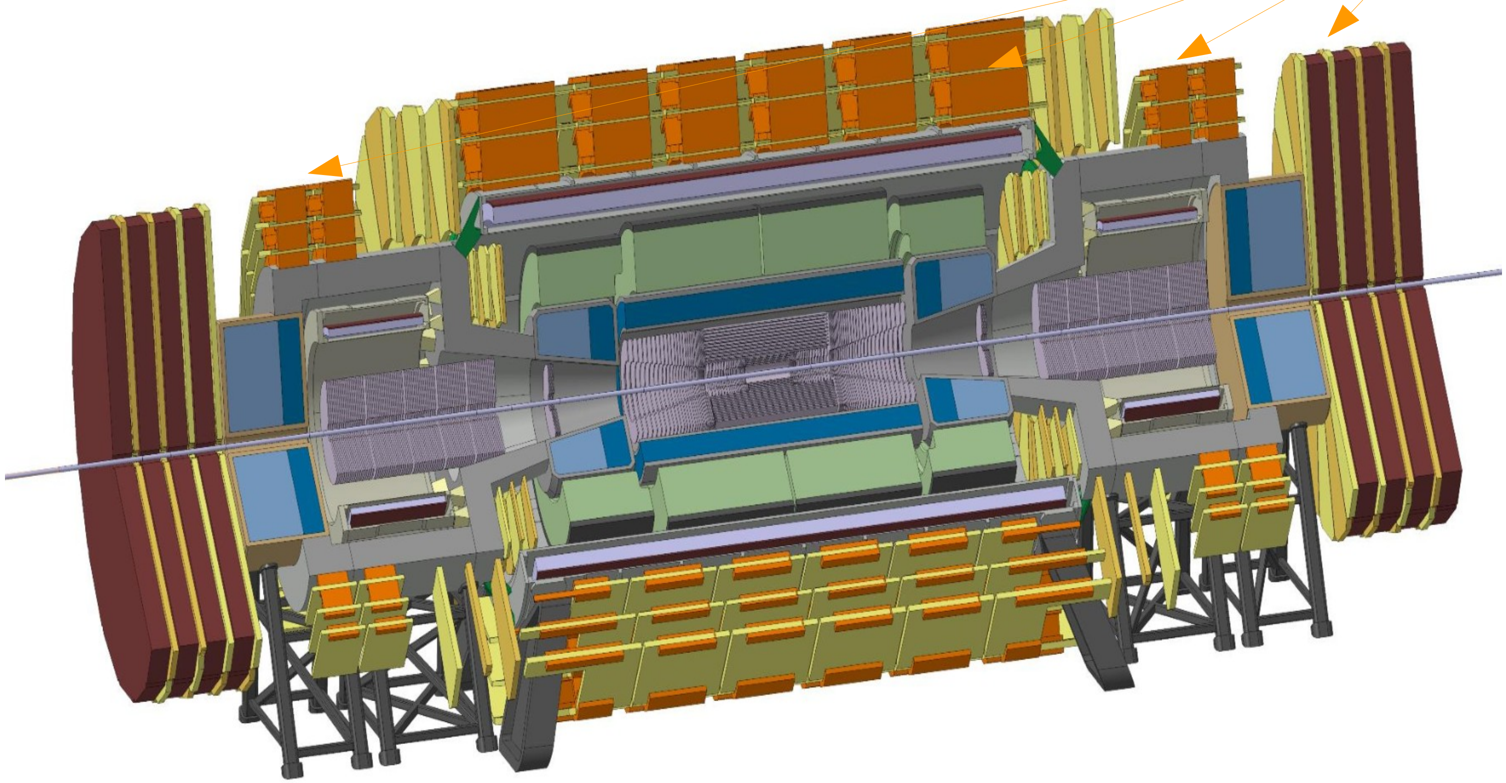

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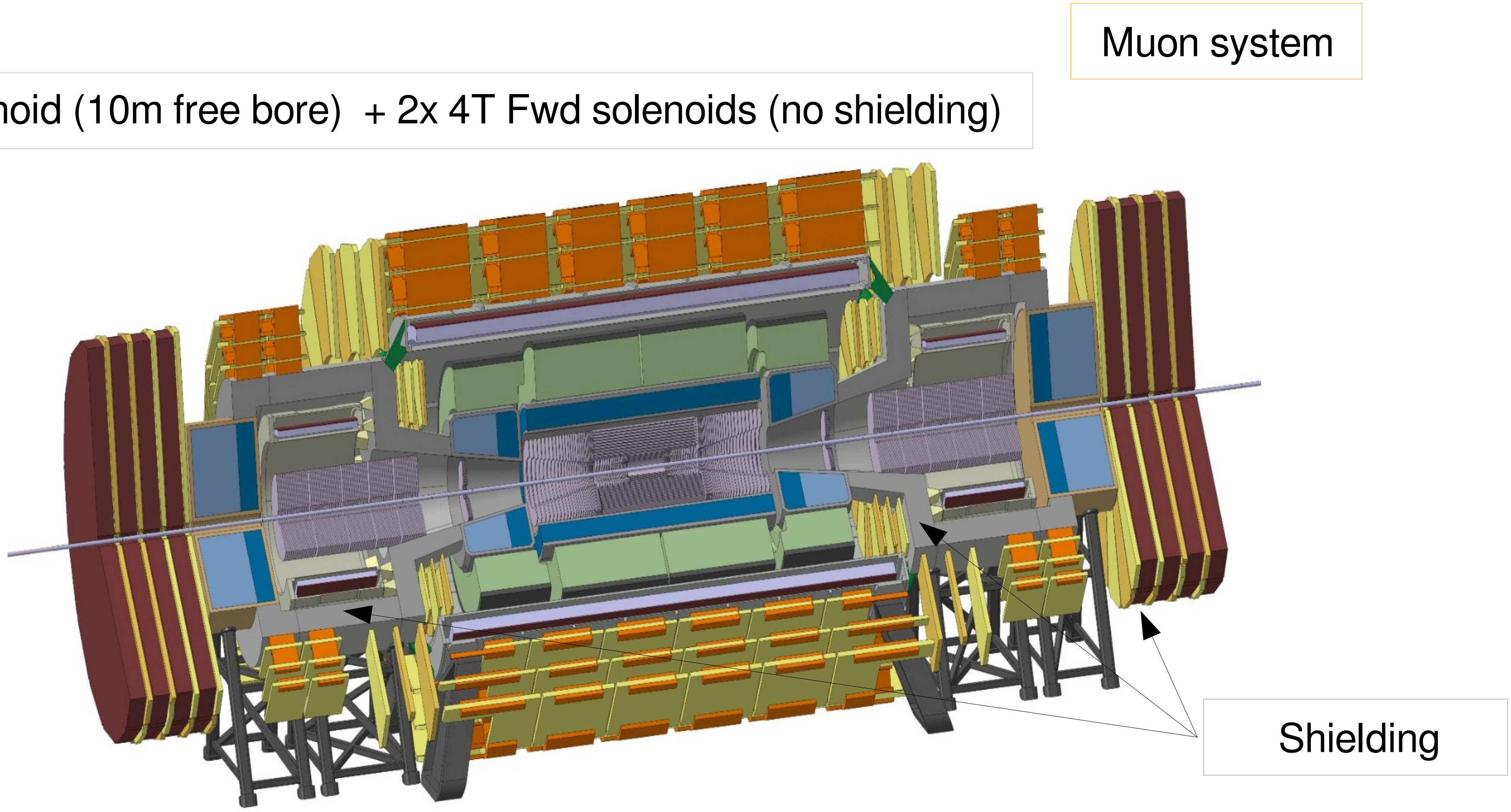

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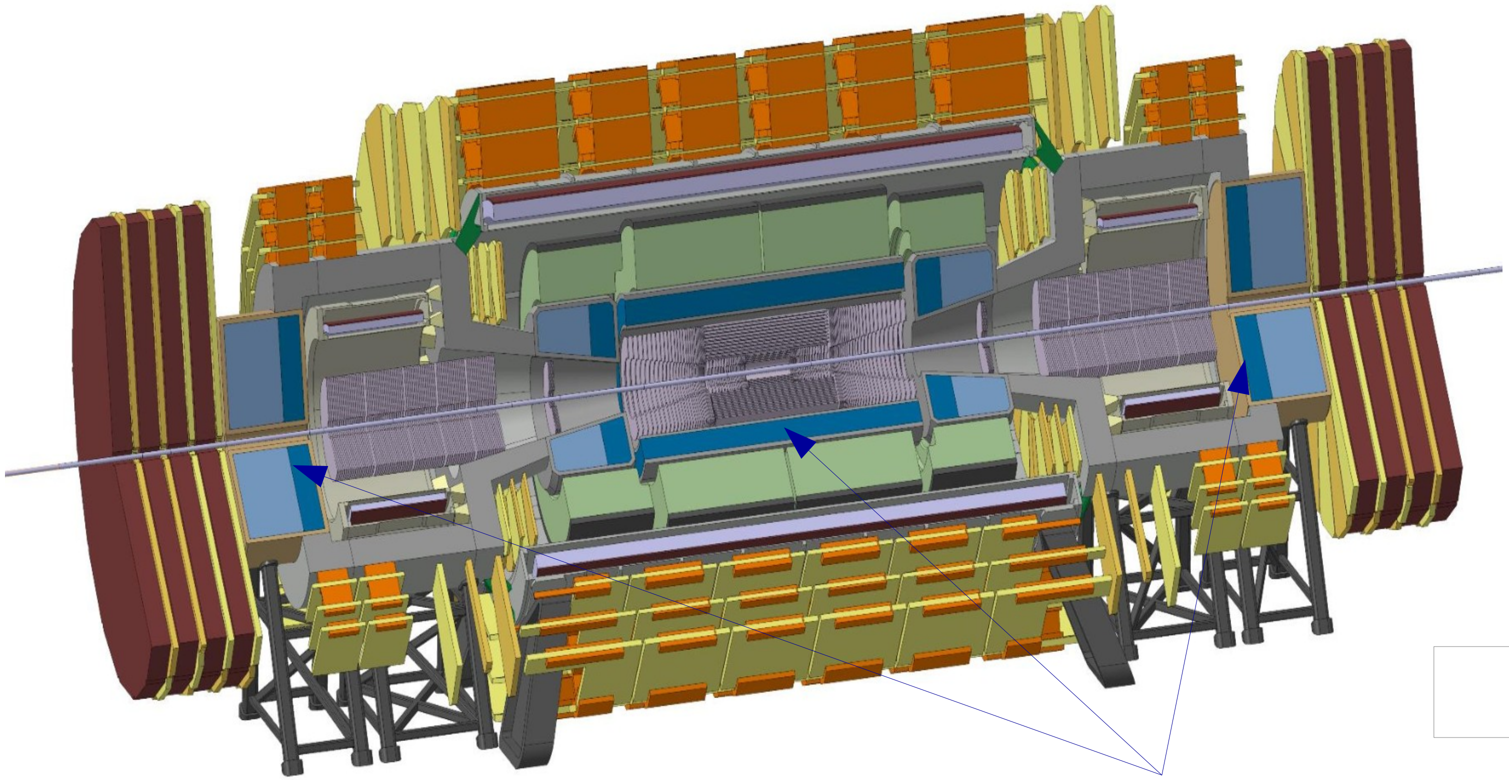

Shielding

Electromag. Calorimeter (Pb/LAr)

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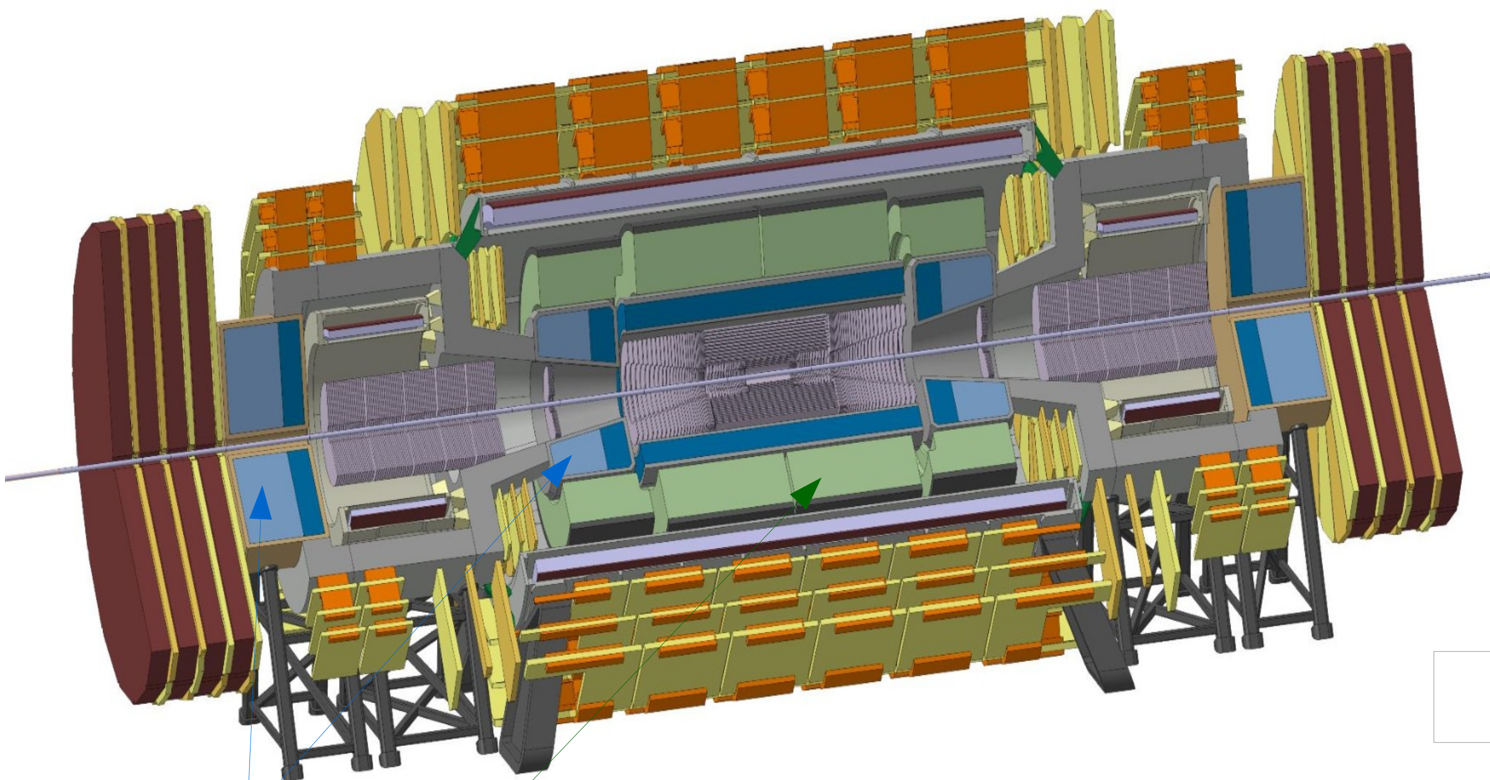

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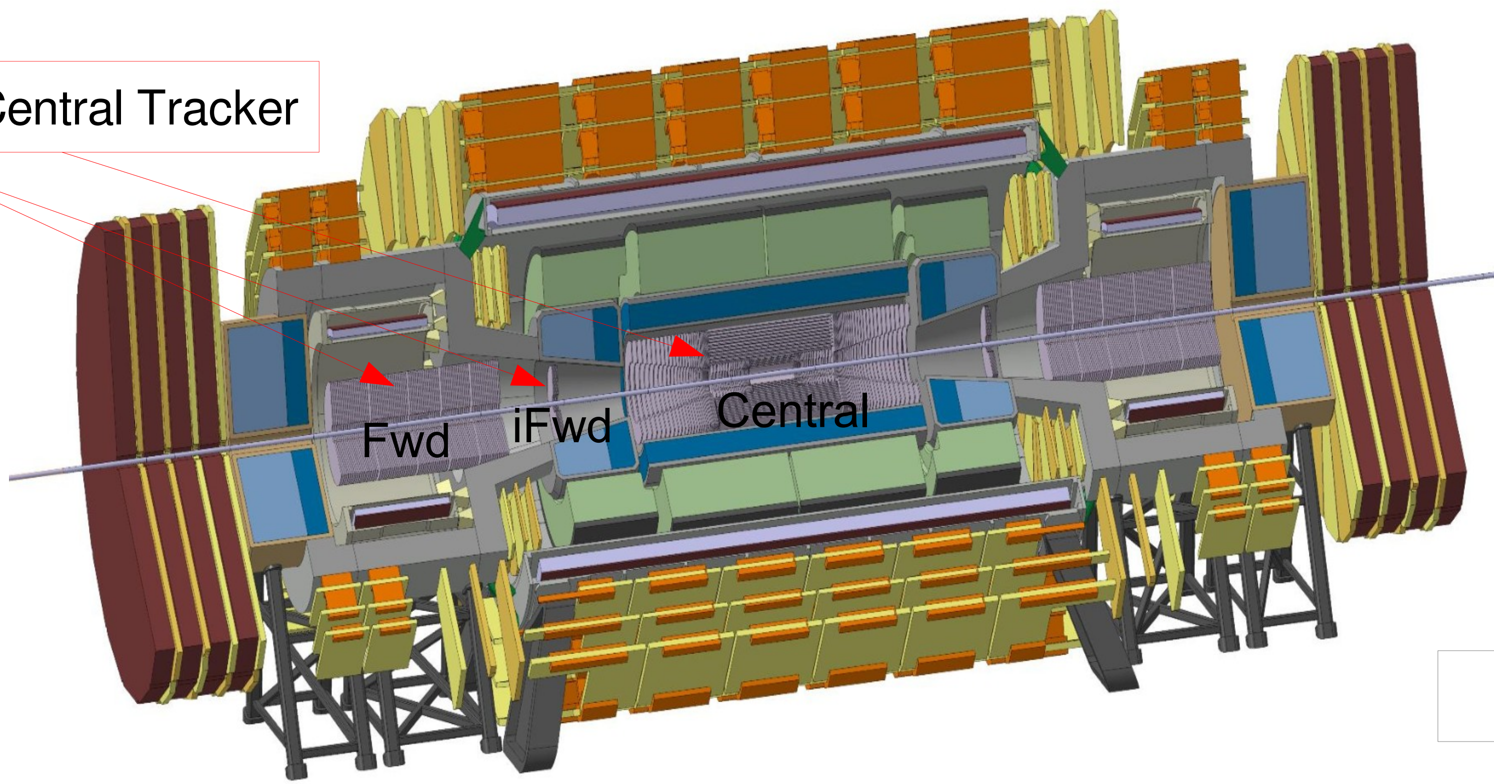
(i)Fwd + Central Tracker



Shielding

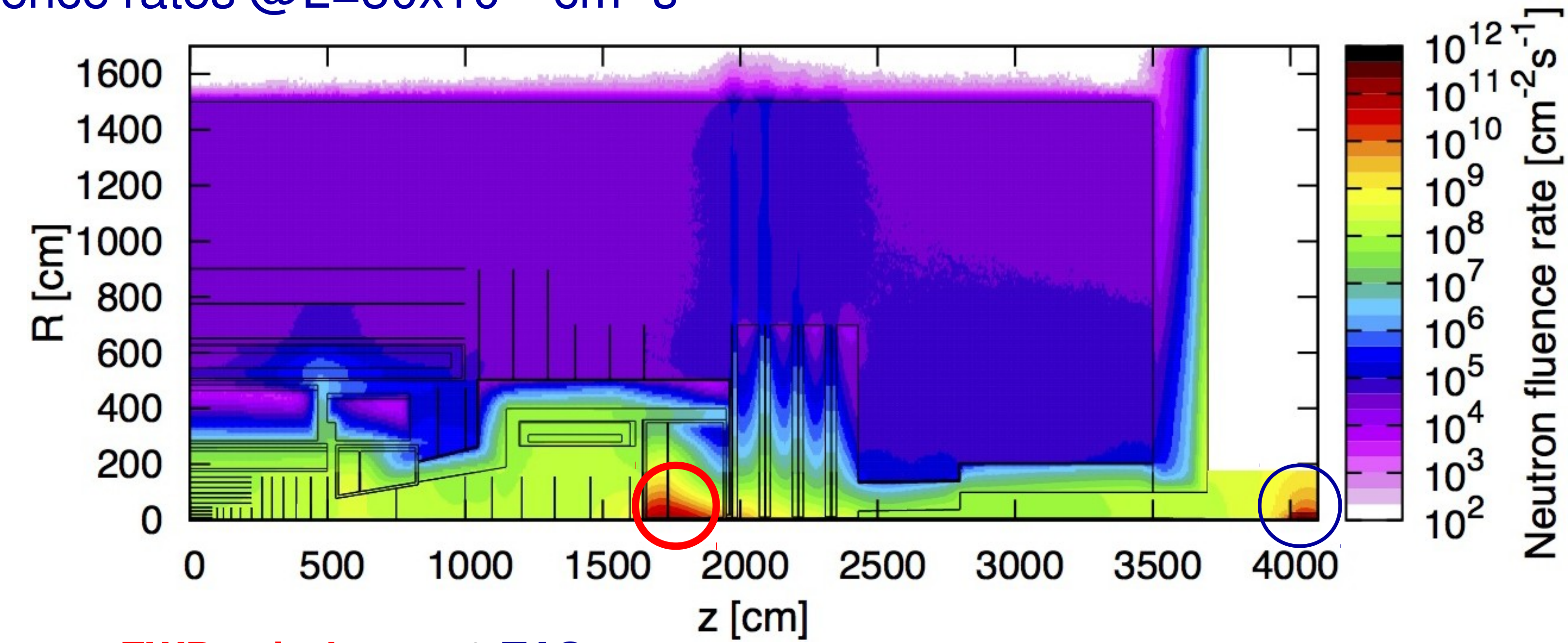
Electromag. Calorimeter (Pb/LAr)

Hadr. Calorimeter **Fwd** (Pb/LAr), **BRL**(Fe/Sci)

FCC-hh & Radiation Rates?

Courtesy of M.I.Besana

- Neutron fluence rates @L=30x10^{34} cm^{-2}s^{-1}



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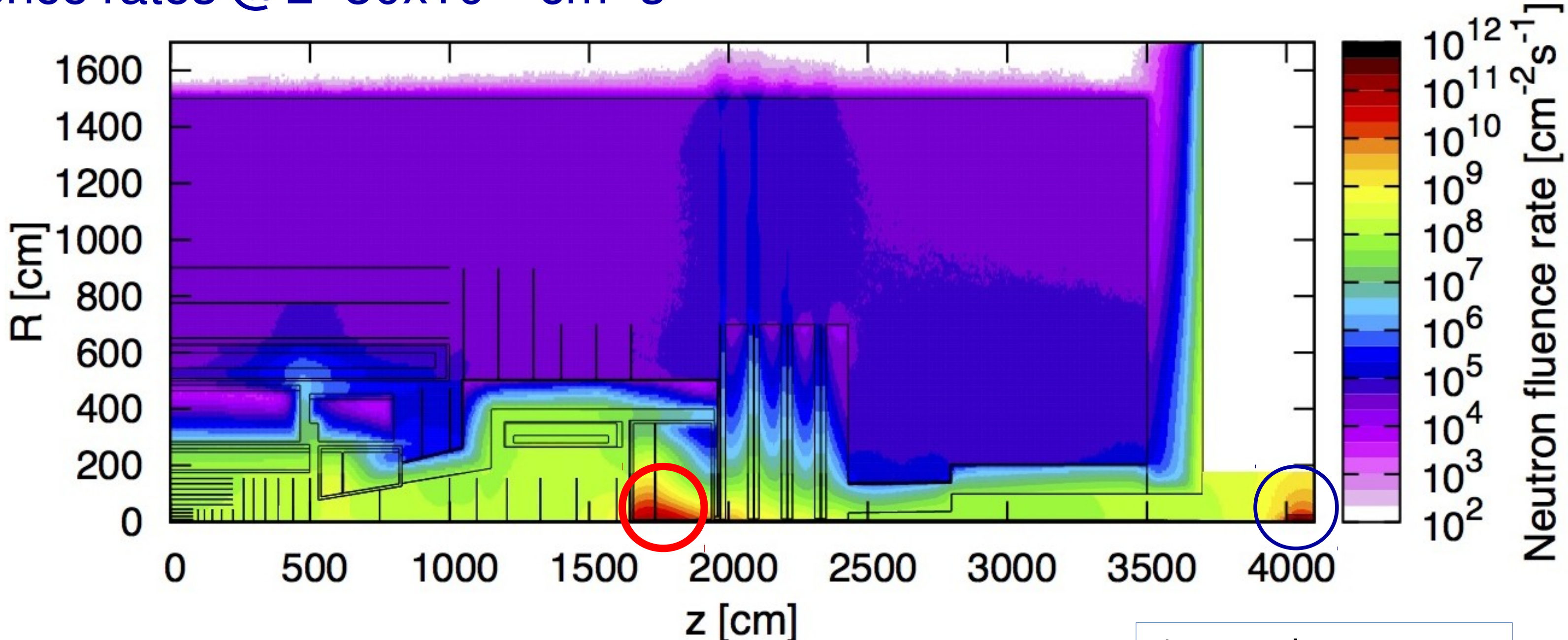

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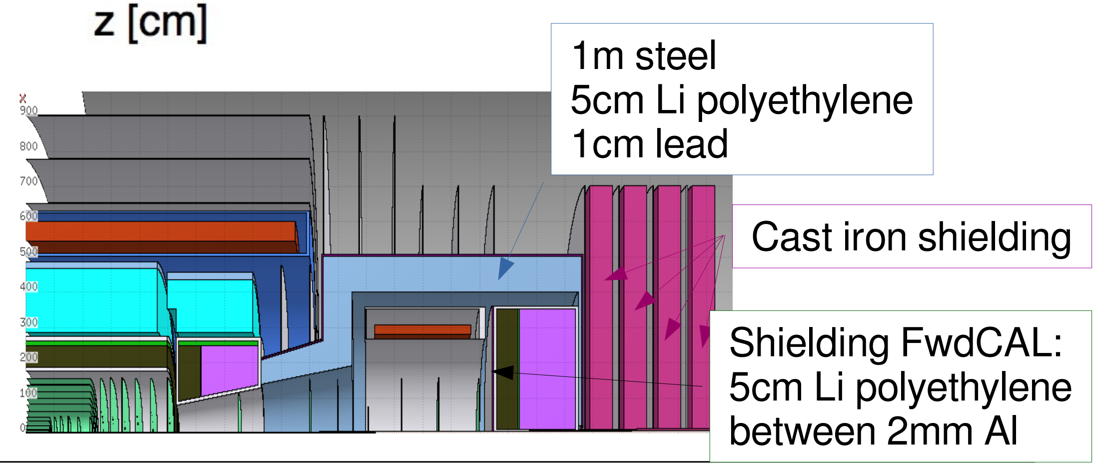

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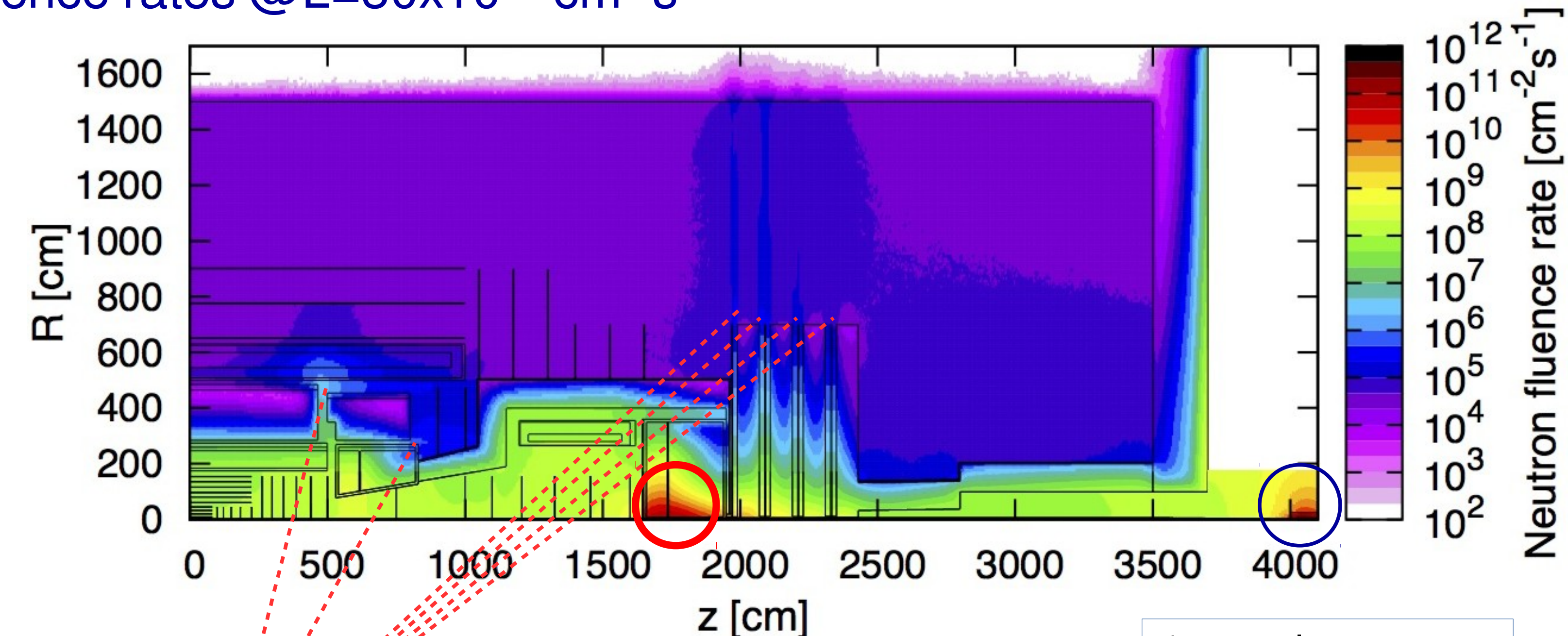

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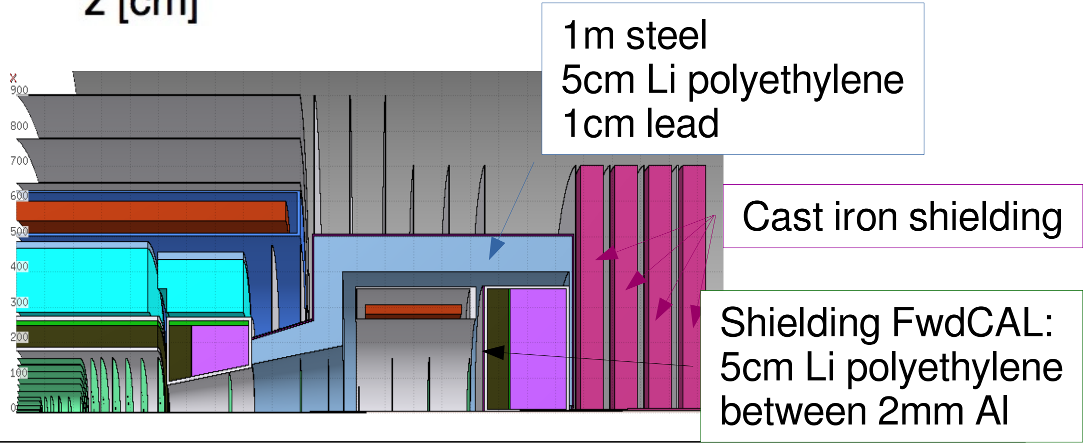
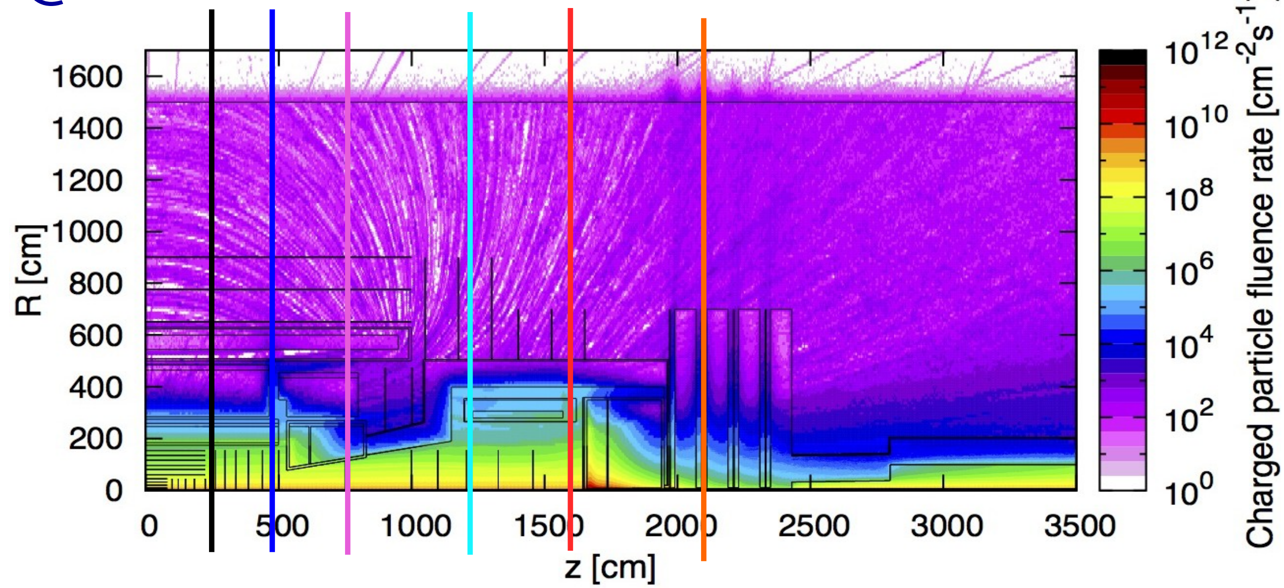
- → Shielding scheme effective, **but…**
- → **Several leakage channels appear** due to service channels etc.



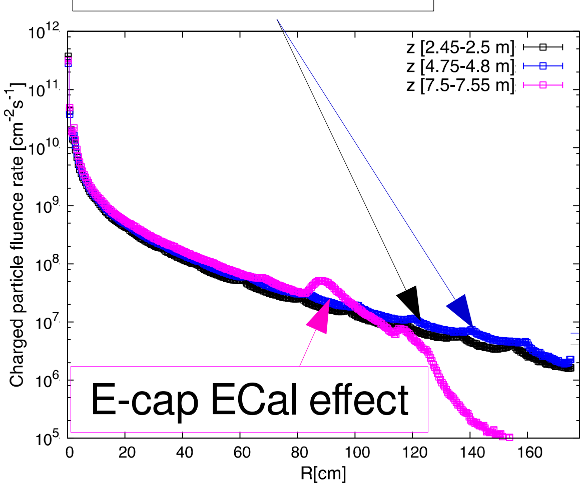
Radiation Rates in Tracker

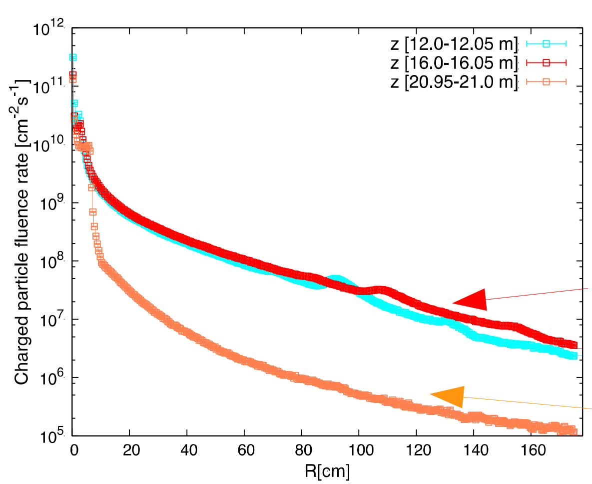
Courtesy of M.I.Besana

- Charged particle fluence rates @L=30x10^{34} $cm^{-2}s^{-1}$



- Layer structure
- ECal effect





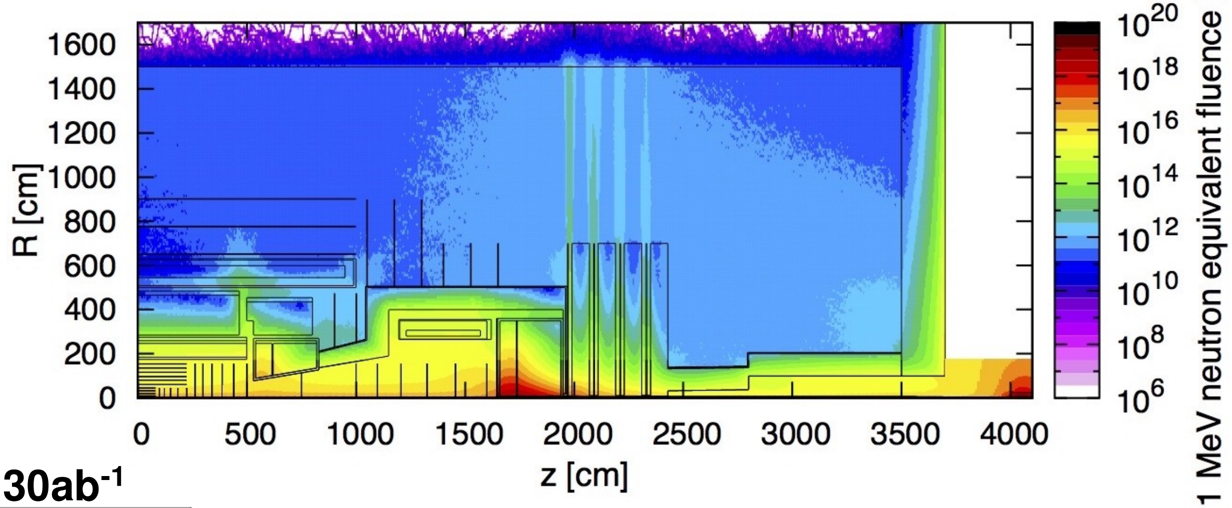
Closer to the FwdCAL hotspot

Effect of shielding in muon chamber

Tracker & Long-term Damage after 30ab^{-1}

- 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**

Tracker & Long-term Damage after 30ab^{-1}

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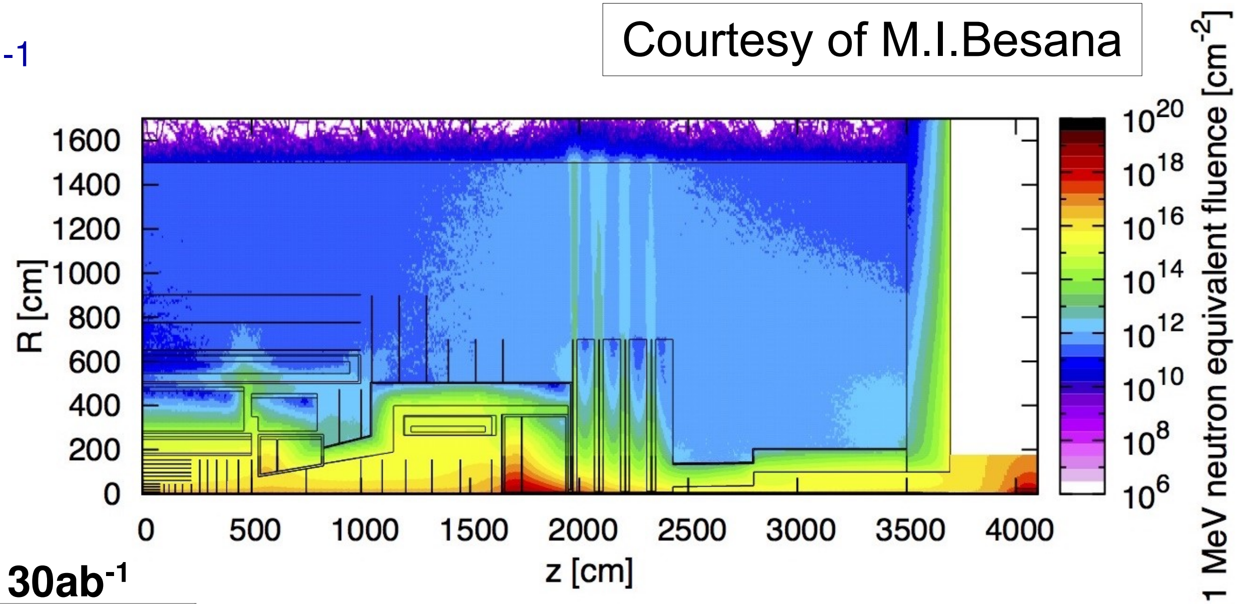
Courtesy of M.I.Besana



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

Tracker Layout & Design Driving Principles

- Key tracker parameters:
  - **Granularity in R-Φ →** driven by requirement on dp_T/p_T res.

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

L: 1.55m
B: 4T
$\sigma_{R\text{-}\Phi}$: 10(7.5)um
N_{layers}: 12

} **~ 20% @ 10TeV/c**

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  - **Number of layers N** → driven by dp_T/p_T res. & pattern recognition capabilities
    Note: res. improves as $\mathbf{1/\sqrt{N_{layers}}}$, but material budget (MB) increases as $\mathbf{N_{layers}}$

} **Low MB Important!**

Tracker Layout & Design Driving Principles

- Key tracker parameters:
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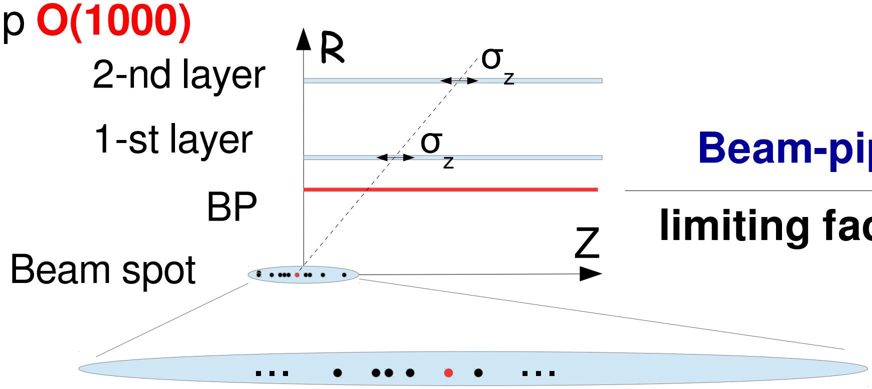
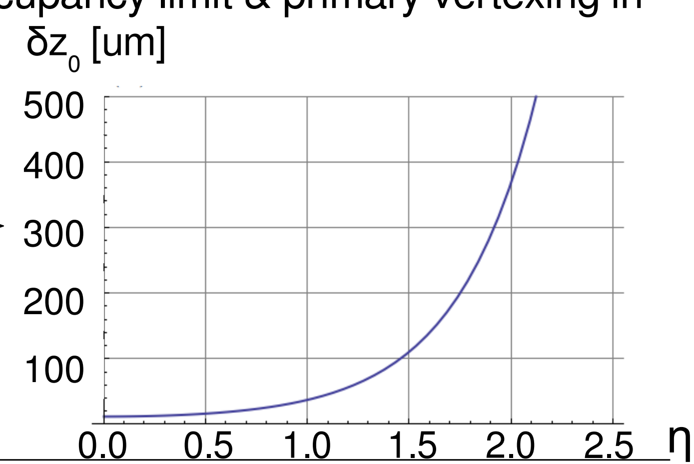
    Note: res. improves as **$1/\sqrt{N_{layers}}$**, but material budget (MB) increases as **N_{layers}**

} **Low MB Important!**

  - **Granularity in Z** → driven by pattern recognition capabilities, occupancy limit & primary vertexing in given pile-up **O(1000)**



Beam-pipe
limiting factor!

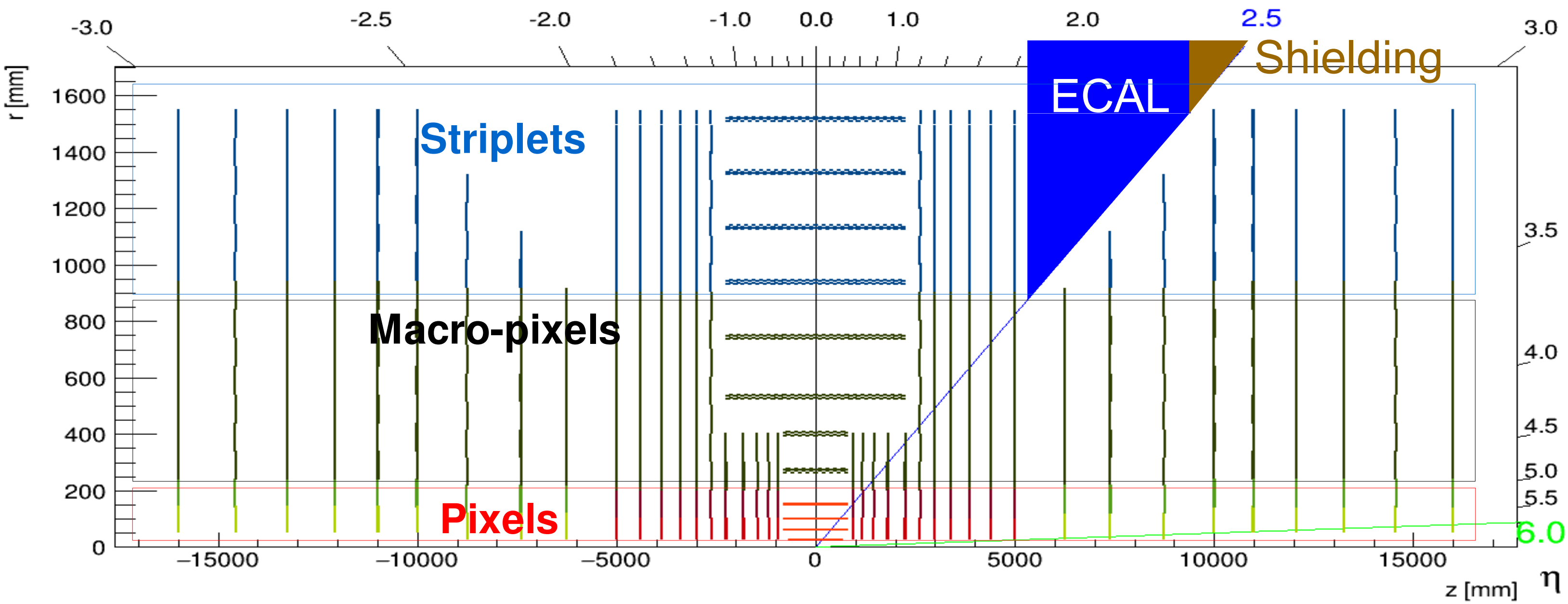


Reference Tracker Layout (v3.03)

Surface: ~430m²
#Channels: **489.4M**
9964.4M
5460.9M

Pixel R↗0.9 m
due to occupancy

4 (seed) BRL layers



Pixels : 25x50um² (1-4th BRL layers, EC R1), 100/3x100um² (R2), 100/3x400um² (R3,R4)

Macro-pixels: 100/3x400um²

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

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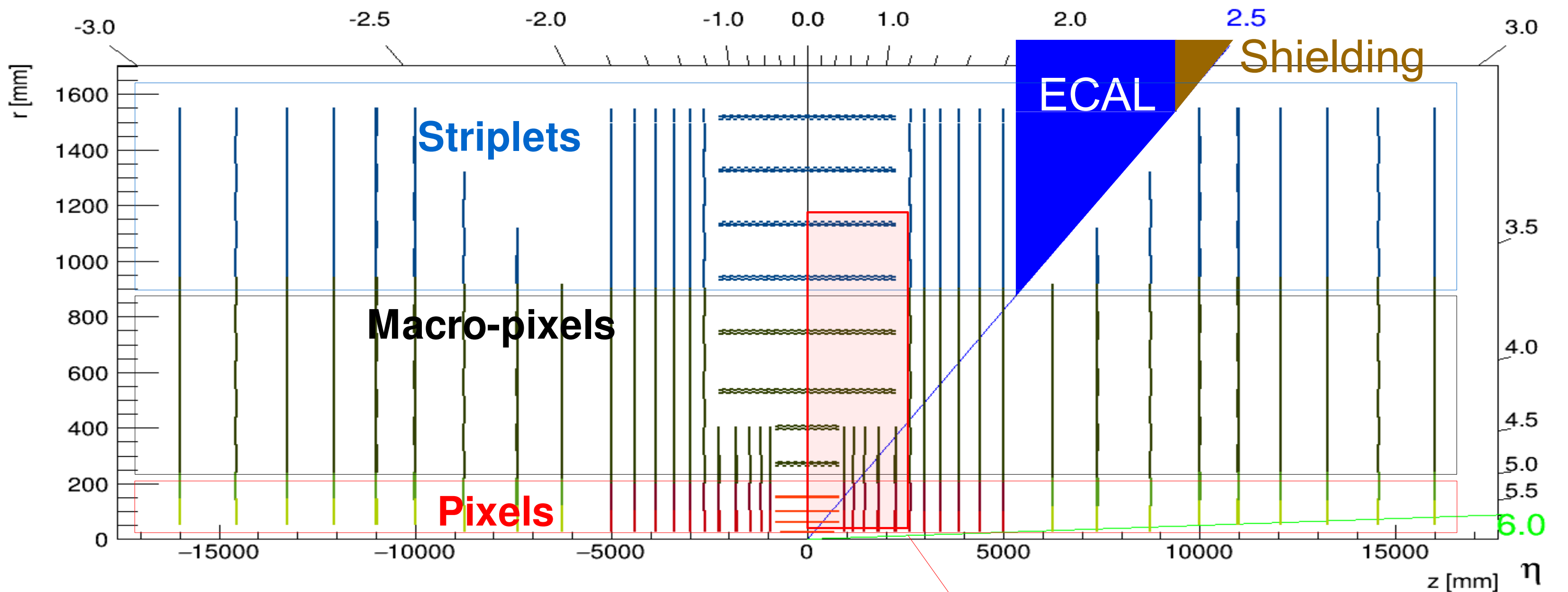

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Macro-pixels: $100/3x400um^2$

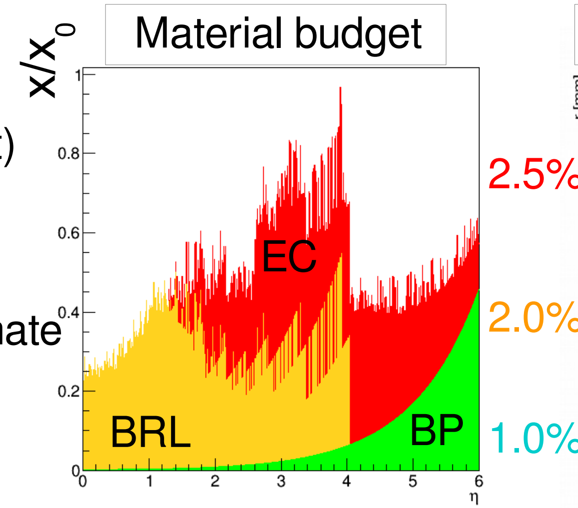
Strips : 100/3umx50mm (BRL),
100/3umx10mm (EC)

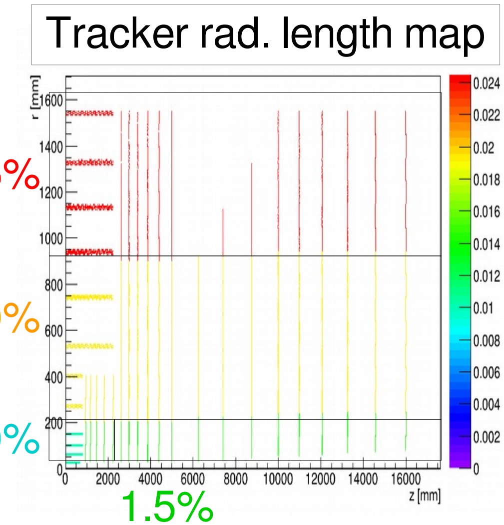
Huge increase in #pixel channels wrt LHC experiments due to requirements on tracking up to **η=6** & resilience to **high rad. levels** generated by FCC-hh!

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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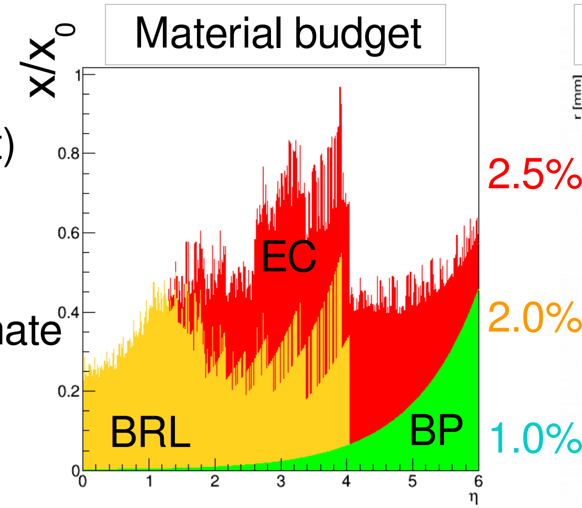
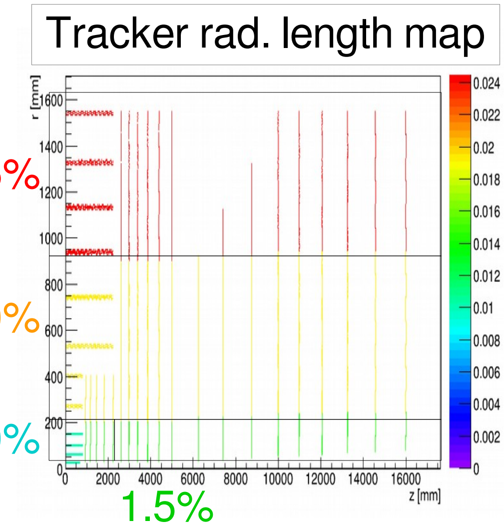
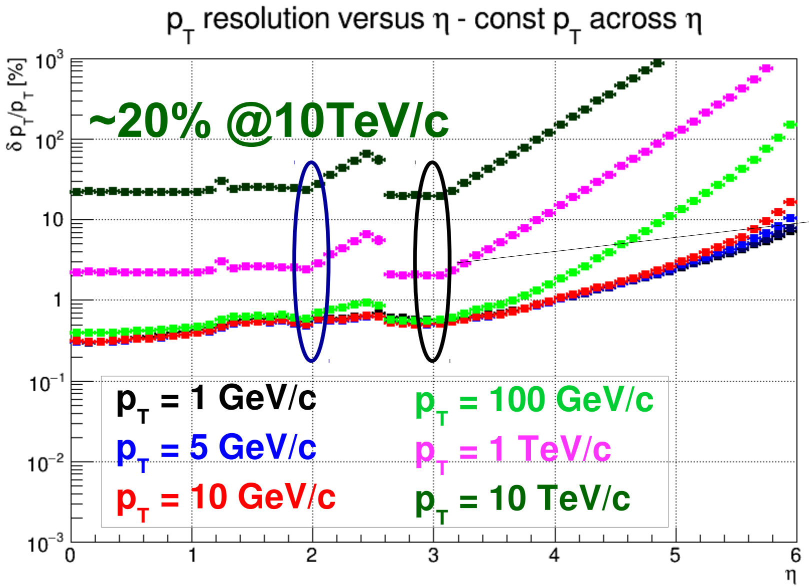
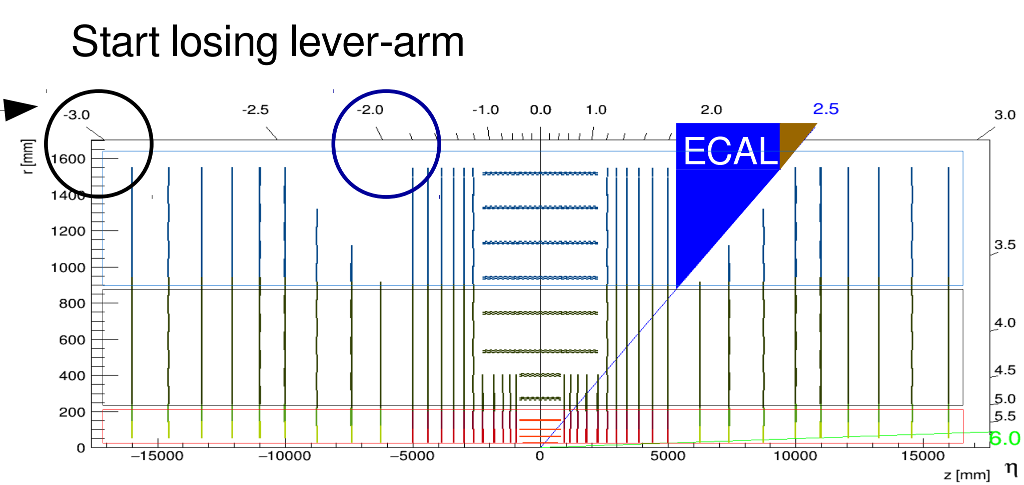




- Tracking resolution:

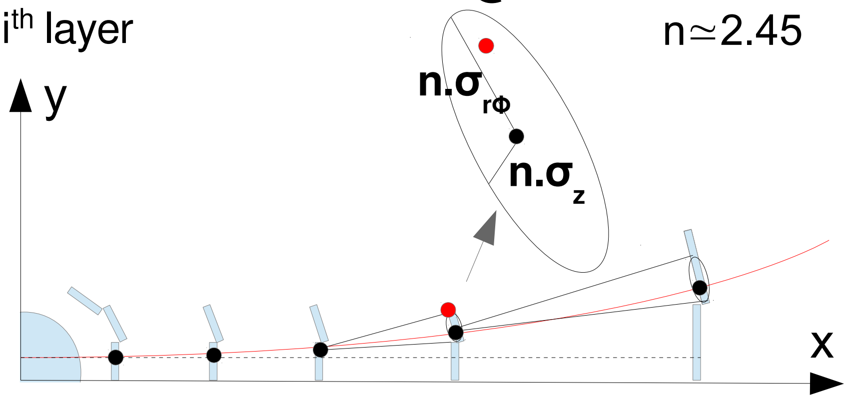




Pattern recognition (PR) Capabilities

- 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 $\boldsymbol{\sigma_{r\Phi}}$, $\boldsymbol{\sigma_z}$ to i[th] 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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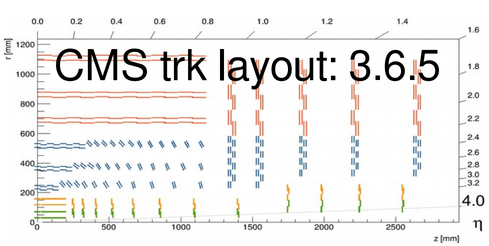
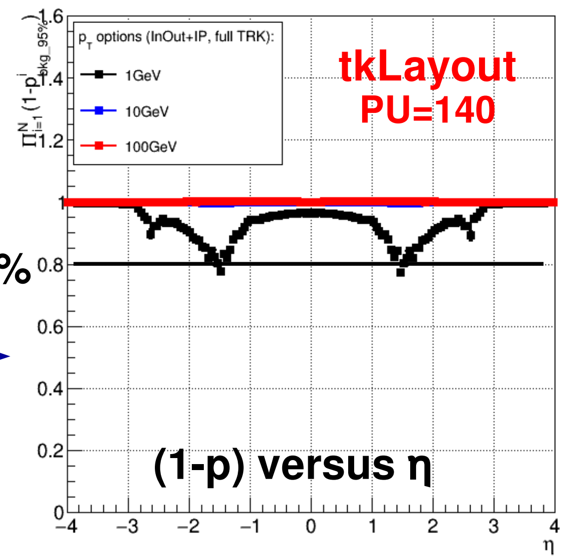
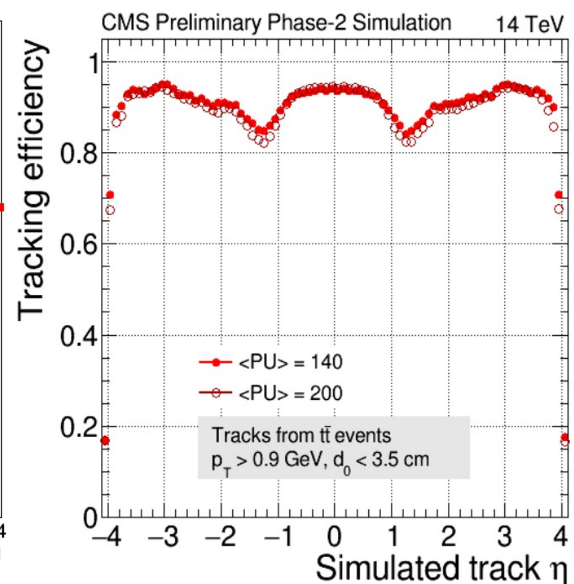
- **How to “qualitatively” interpret *p* ?**
  c.f. CMS Ph2 layout @PU~140...



(1-p) ~ 80%



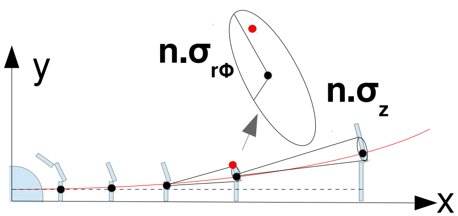


E.Brondolin: CMS DP-2017/010

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

Understanding Track Propagator in Pattern Recognition

- 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**



$$
\begin{aligned}
\sigma^2_{\rm MS} &\approx \langle \vartheta^2_{p_T} \rangle \frac{d/X_0}{\sin(\vartheta+\alpha)} \Delta r^2 f_{\rm proj} \\
\langle \vartheta^2_{p_T} \rangle &= \left(\frac{13.6\,\mathrm{MeV}}{\beta p_T c}\right)^2 \left(1 + 0.038 \ln \frac{d/X_0}{\sin(\vartheta+\alpha)}\right)^2 \\
f_{\rm proj} &= \left(\frac{1}{\sin(\vartheta+\alpha)}\right)^2 \quad \text{proj. in Z} \\
f_{\rm proj} &= 1 \quad \text{proj. in R–}\Phi
\end{aligned}
$$

$$
\begin{aligned}
\sigma_{R\Phi} &= \sqrt{\sigma^2_{R\Phi_{\rm loc}} + (A/\sqrt{1-A^2}\,\sin\alpha)^2 \sigma^2_{Z_{\rm loc}}} \\
A &= \Delta r / 2R
\end{aligned}
$$

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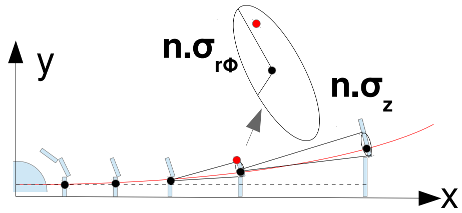

$$\sigma^2_{\mathrm{MS}} \approx \langle \vartheta^2_{p_T} \rangle \frac{d/X_0}{\sin(\vartheta+\alpha)} \Delta r^2 f_{\mathrm{proj}}$$

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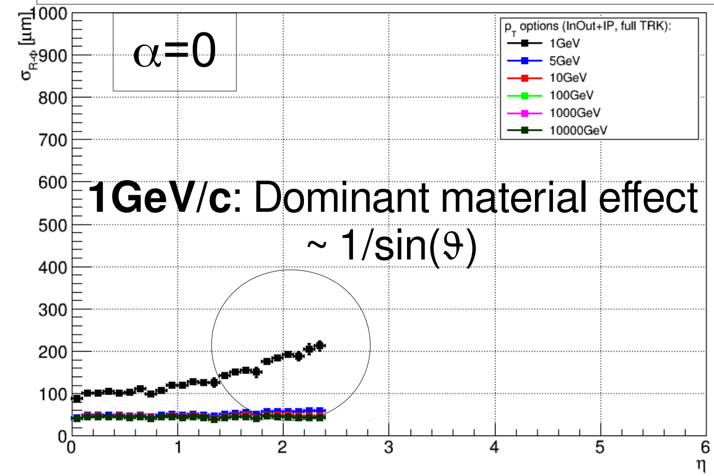
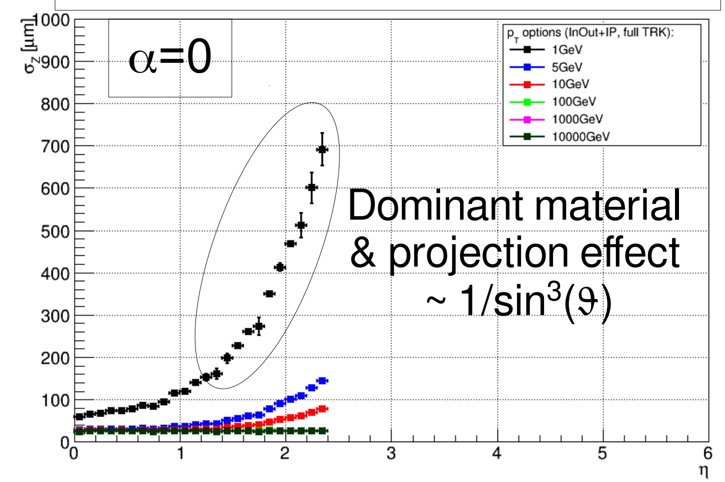
Propagated $\sigma_{R\text{-}\Phi}$ on 4th BRL layer



Propagated σ_Z on 4th BRL layer



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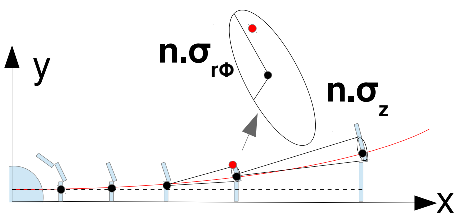

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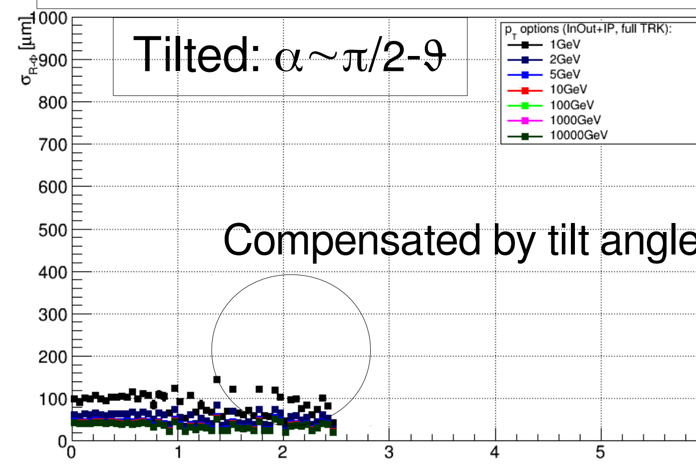
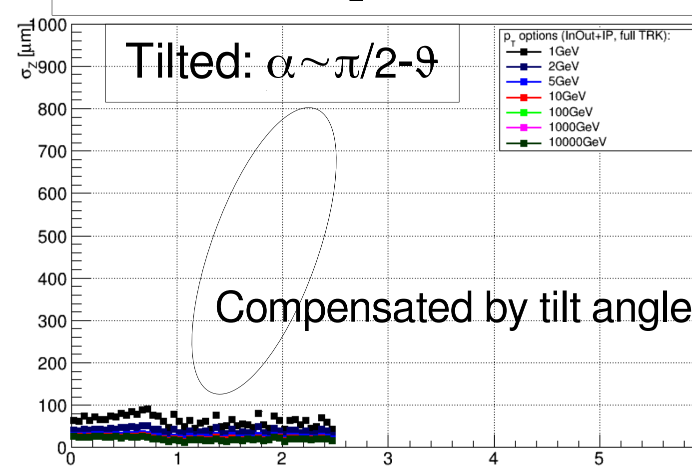
Propagated $\sigma_{R\text{-}\Phi}$ on 4th BRL layer

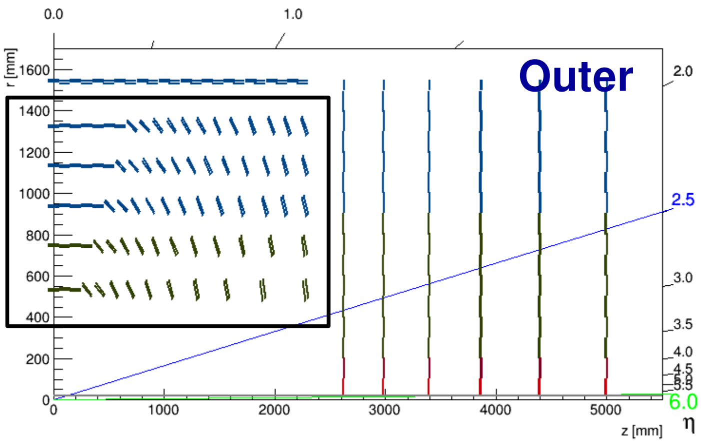


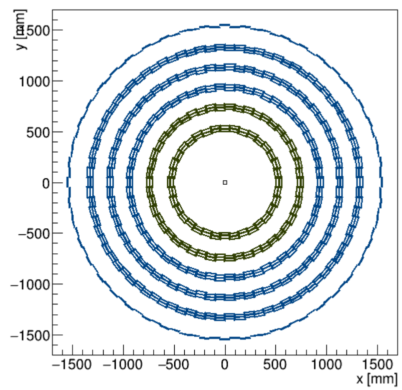
Propagated σ_Z on 4th BRL layer



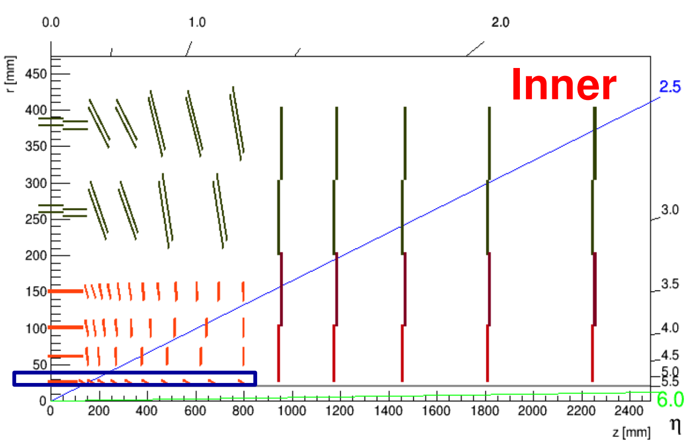
- **To min. mat. effects, tracker in tilted layout advantageous!**

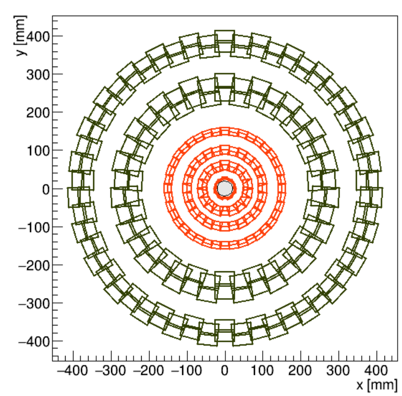
Tilted Geometry: Design Proposal v4.01





- 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)

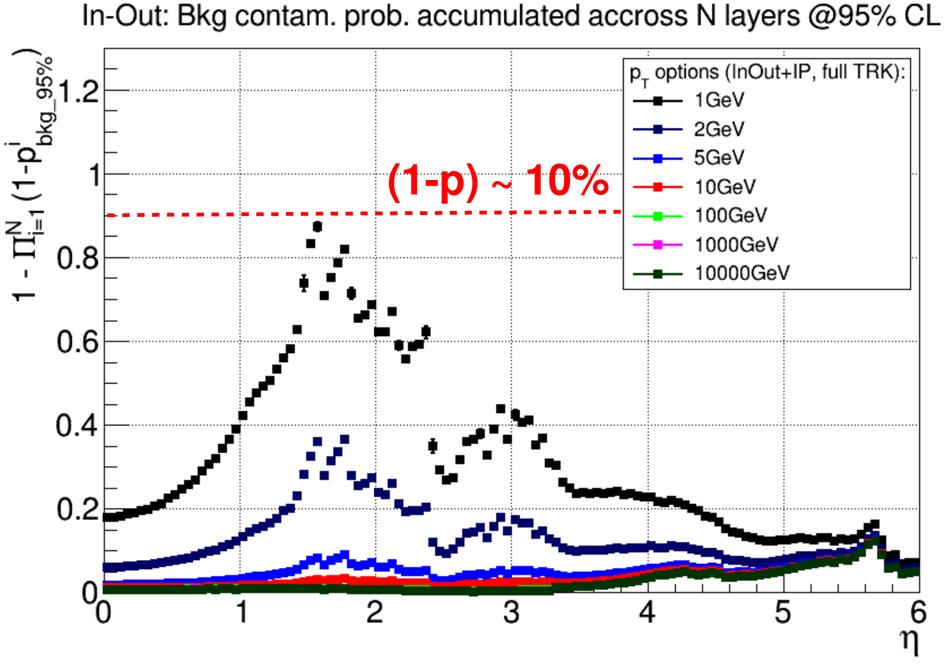




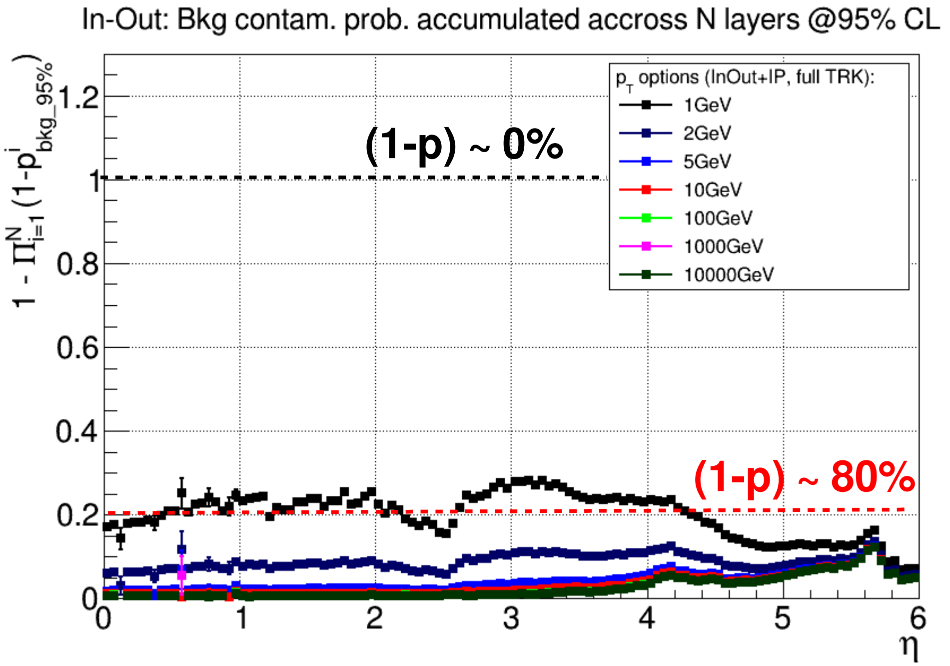
- Tilted layout of **inner tracker** driven by ~0.2 BCL in PR & **highest achievable z0 res.** (to deal with primary vertexing @PU~1000):
  - → tilt angle of 1st layer: $\vartheta_{tilt} \simeq 10^{\circ}$ optimized to achieve a compromise between low MB & higher radial position

Tilted Layout & Pattern Recognition

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



Tilted layout v4.01: in→out approach

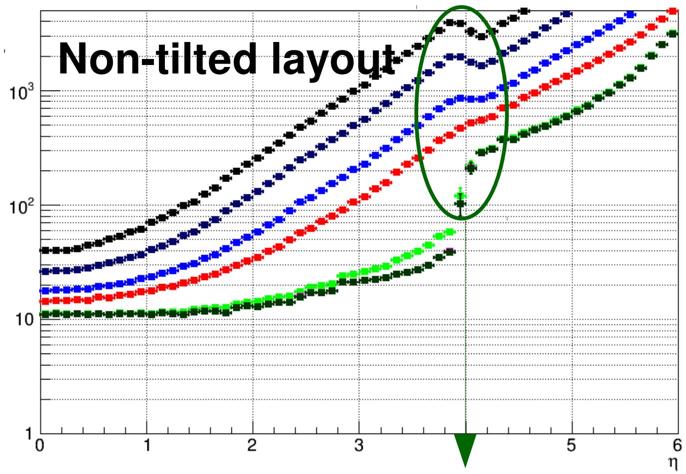


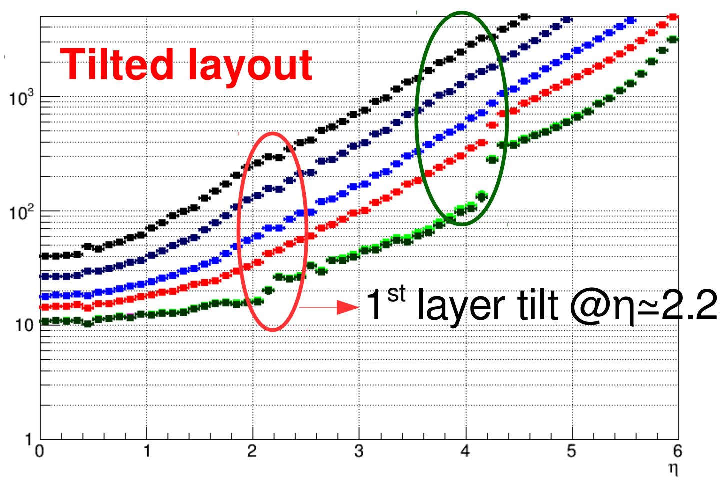
→ **With tilted layout the bkg. contam. level @~20% achievable in PU~1000 for p_T=1GeV/c** (limit value driven by HL-LHC scenario with PU~140 & CMS Phase 2 upgrade tracker layout)

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

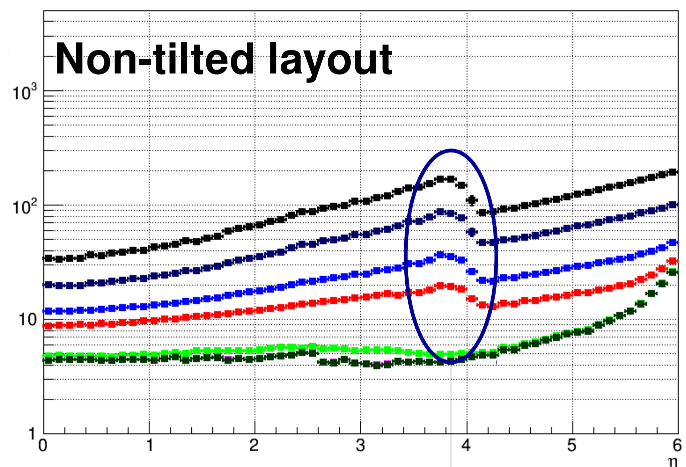
Tilted Layout: Improvement in Tracking Performance

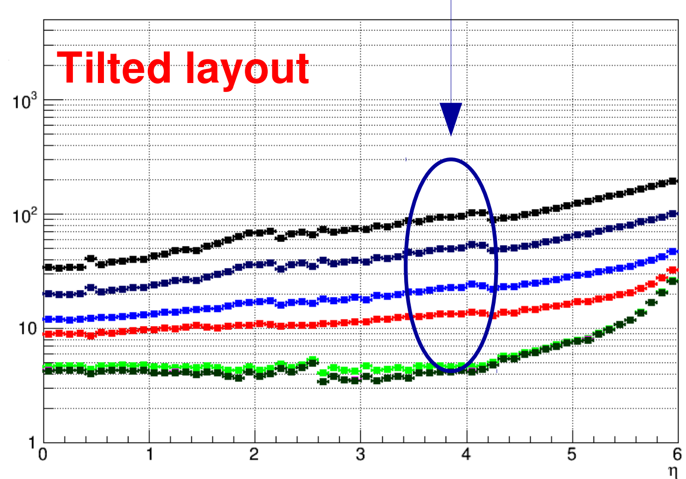
δz0 [um] versus η





δd0 [um] versus η



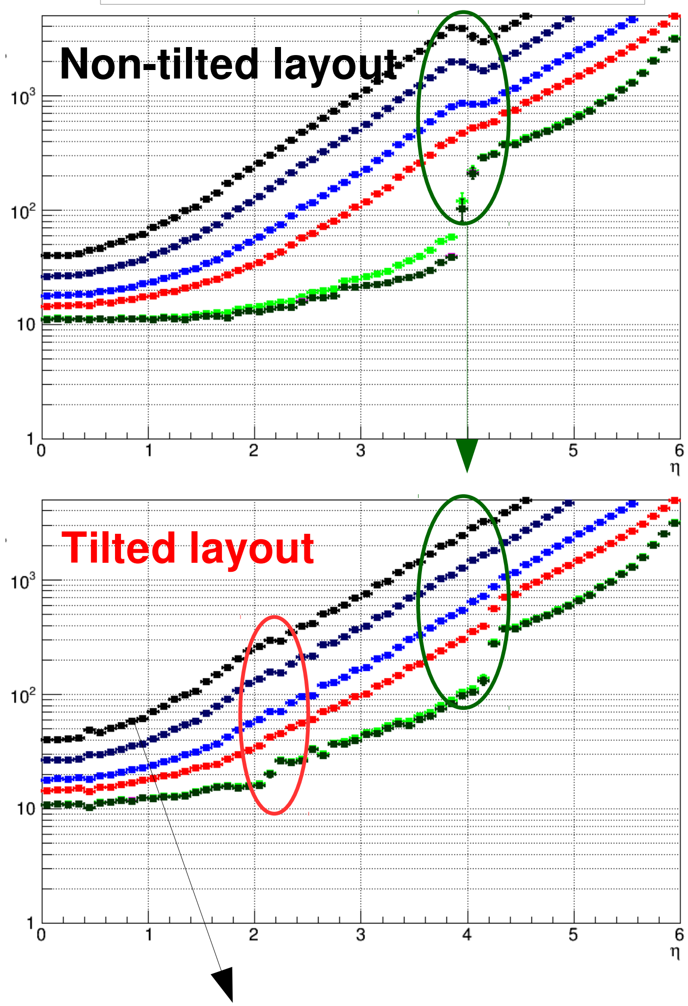


p_T = 1 GeV/c
p_T = 5 GeV/c
p_T = 10 GeV/c
p_T = 100 GeV/c
p_T = 1 TeV/c
p_T = 10 TeV/c

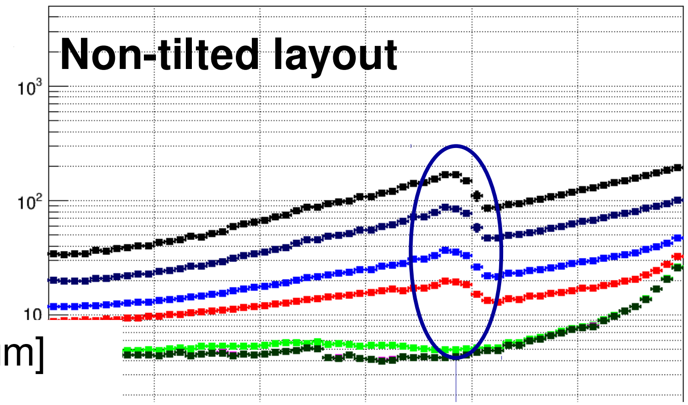
Similar dp_T/p_T res. for both tilted & non-tilted

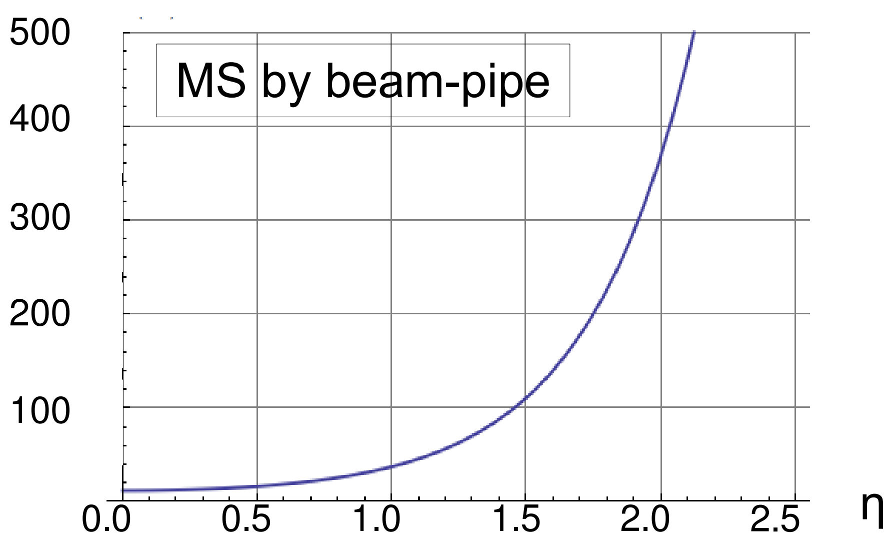
Tilted Layout: Improvement in Tracking Performance

δz0 [um] versus η



δd0 [um] versus η





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

Similar dp_T/p_T res. for both tilted & non-tilted

→ **For tilted layout, the dominant effect for 1GeV/c curve shape is beam-pipe material!**

Vertexing @ PU=1000 & Timing Information

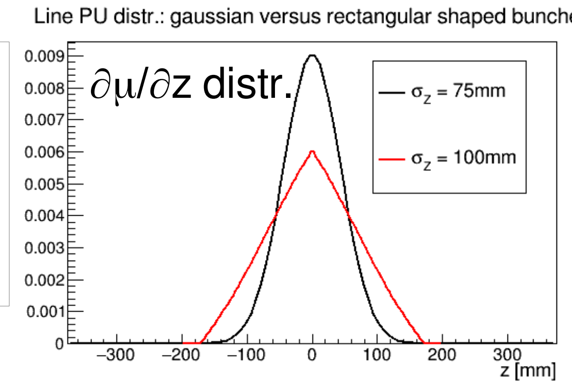
- How the pile-up (PU)~1000 degrades primary vertexing? Does the timing info help?

→ 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: $\frac{1}{\sqrt{2\pi}\sigma_z} e^{-\frac{1}{2}\left(\frac{z}{\sigma_z}\right)^2}$

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

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



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

Vertexing @ PU=1000 & Timing Information

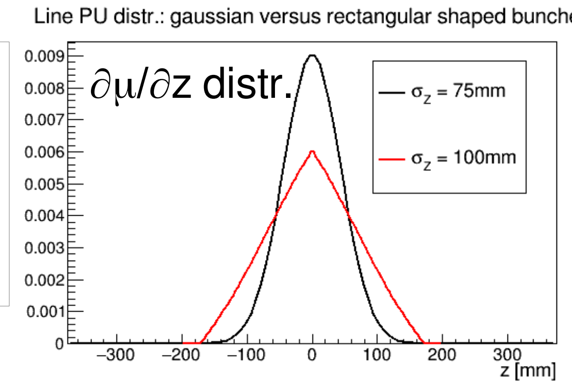
- How the pile-up (PU)~1000 degrades primary vertexing? Does the timing info help?

→ 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: $\frac{1}{\sqrt{2\pi}\sigma_z} e^{-\frac{1}{2}\left(\frac{z}{\sigma_z}\right)^2}$

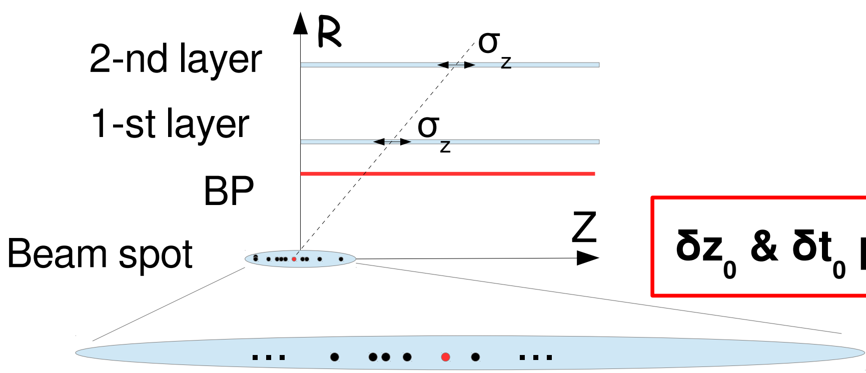
Line PU: $\frac{\sqrt{1+\phi^2}}{\sqrt{\pi}\sigma_z} e^{-(1+\phi^2)\left(\frac{z}{\sigma_z}\right)^2}$

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



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)

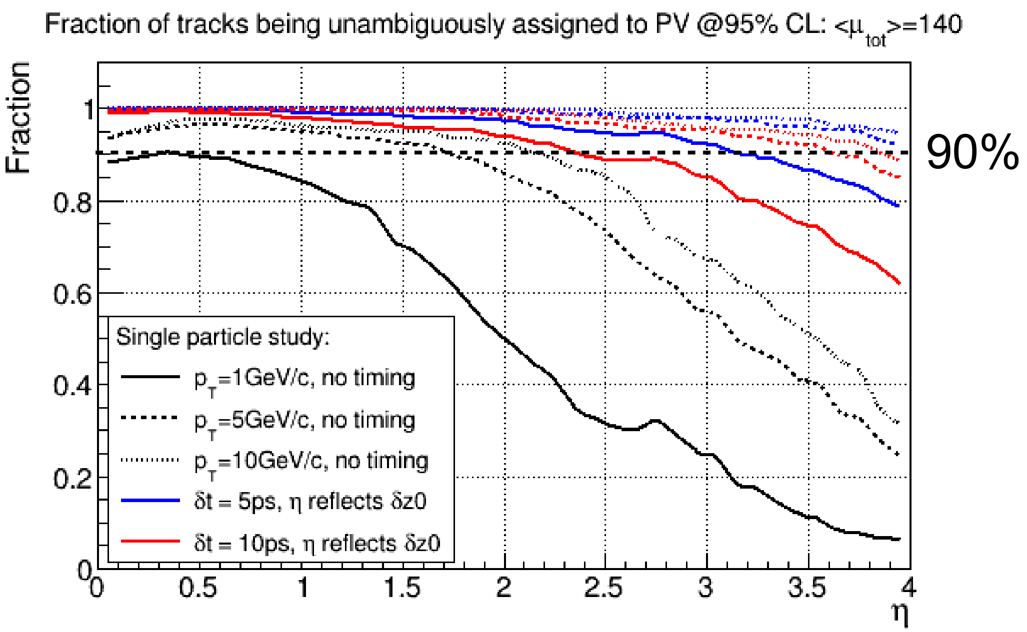


δz_0 & δt_0 play the crucial role!

Vertexing @ PU=1000 & Timing Information

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

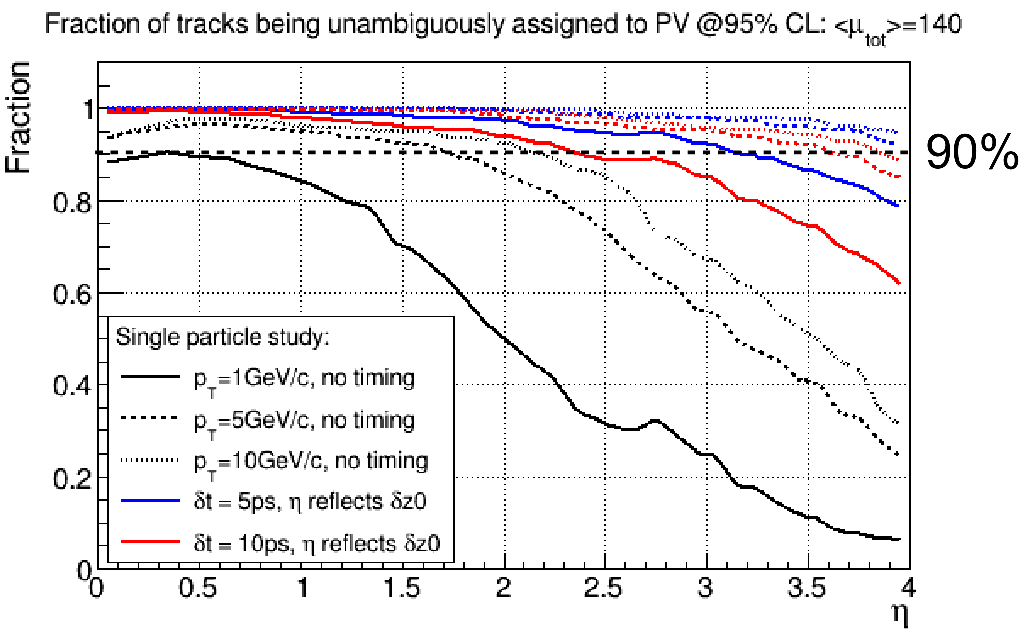
HL-LHC scenario @ PU=140
CMS Ph2 Upgr. tracker



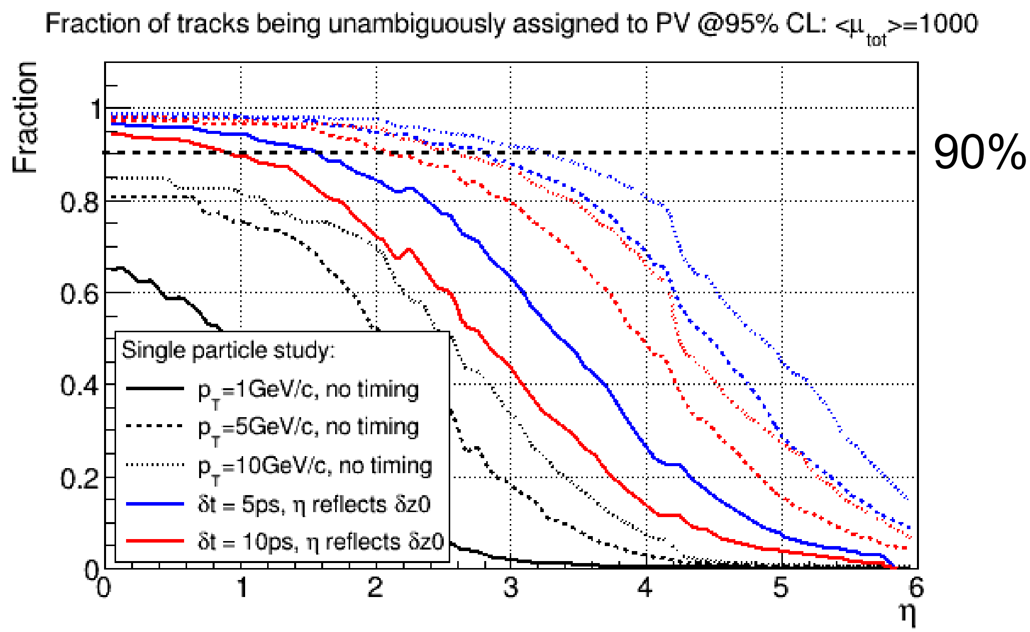
Vertexing @ PU=1000 & Timing Information

→ 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



→ @PU~1000 avg. distance between vertices (Φ~0.67) **~110um @z=0m**, hence the error due to mult. scattering in beam-pipe is for η>1.5 already larger than the avg. vertex distance → **timing essential**

→ With current FCC-hh scheme & need for eta coverage up-to 6 **the primary vertexing @ PU~1000 seems very difficult for η>4.0**, even **with timing res. ~5ps** (several time measur. per track)

Occupancy & Expected Data Rates @ PU=1000

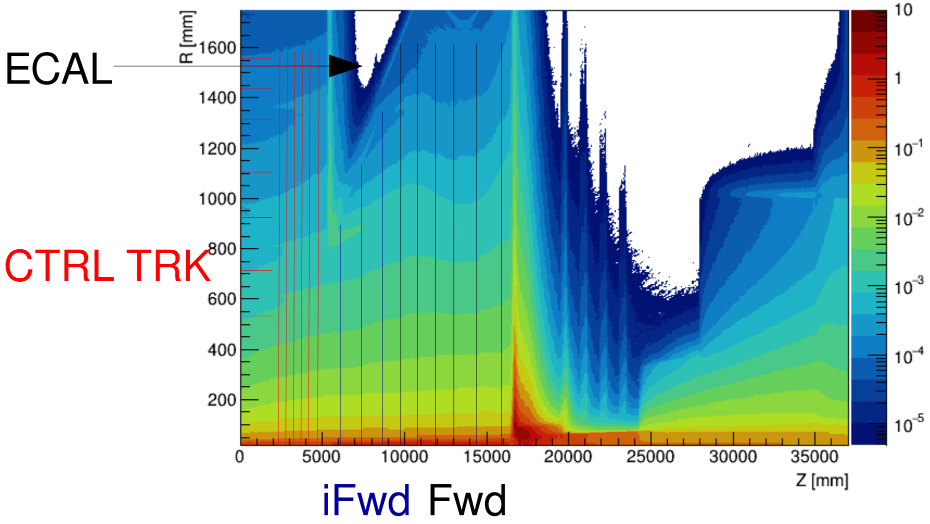
- Have a look at the tracker granularity in a view of hit occupancy (~ <1%), what data rates may we expect at **PU~1000**?

→ **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)
  - Assume binary read-out (spars. read-out scheme)

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



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	

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

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

Outer & Fwd: 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	

Summary & Challenges

- **The key tracker parameters have been studied & optimized:**
  - → **Current layout:** ~430m² (391m² 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%**
  - → The **granularity in Z driven by prim. vertexing** & **pattern recognition** capabilities @PU=1000:
    - Due to minimized material budget **tracker in tilted layout very advantageous** (even for the vertex detector) to achieve similar pattern recognition performance as with PU~140 & HL-LHC conditions → realistic engineering (technology input) with services, cooling & support structure important!
    - **Primary vertexing & correct PV assignment @PU=1000 seems feasible up-to η~4**, but only with precise timing information σ_t~10ns (2D vertexing) → the limiting factor for **high η coverage is beam-pipe material**
  - → Expected data rates (**766 TB/s untriggered**, **19 TB/s triggered @1MHz**) implicate need for new read-out technologies (high speed, low power optical links) & dedicated trigger design!
  - → Expected **1MeV neq fluence ~5x10^{17}cm^{-2}** & **TID ~0.4GGy** @ **R=25mm** (up to R~270mm) represent **new challenges** for the tracker (vertex detector) technologies

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→ **Dedicated R&D is a key to success!**