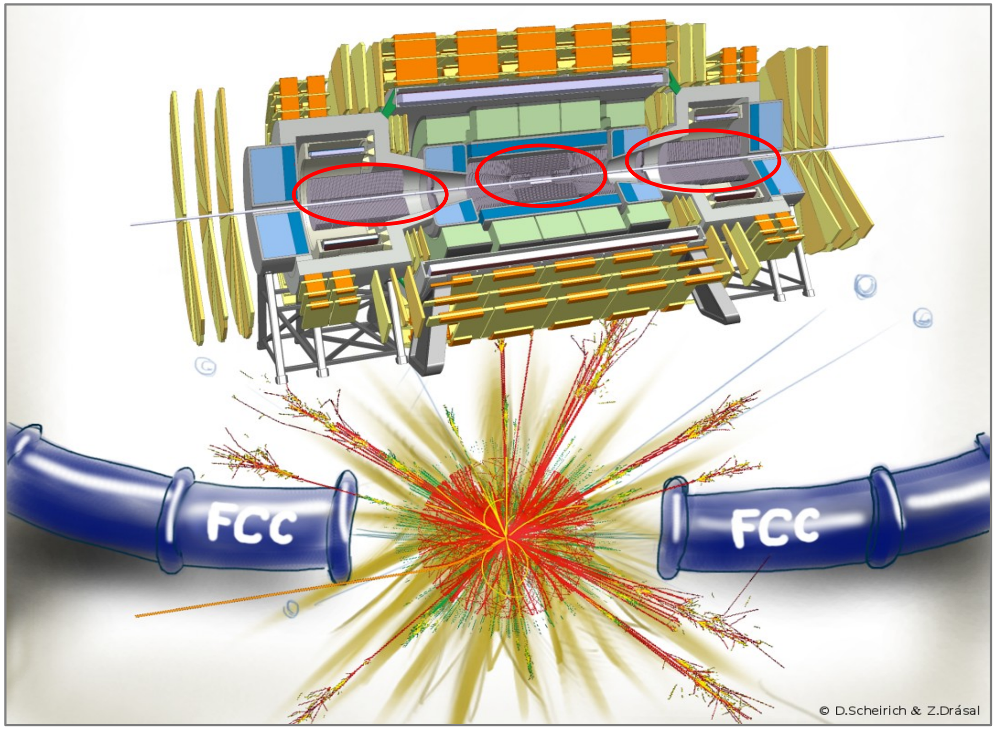
Status & Challenges of Tracker Design for FCC-hh



Zbyněk Drásal

CERN

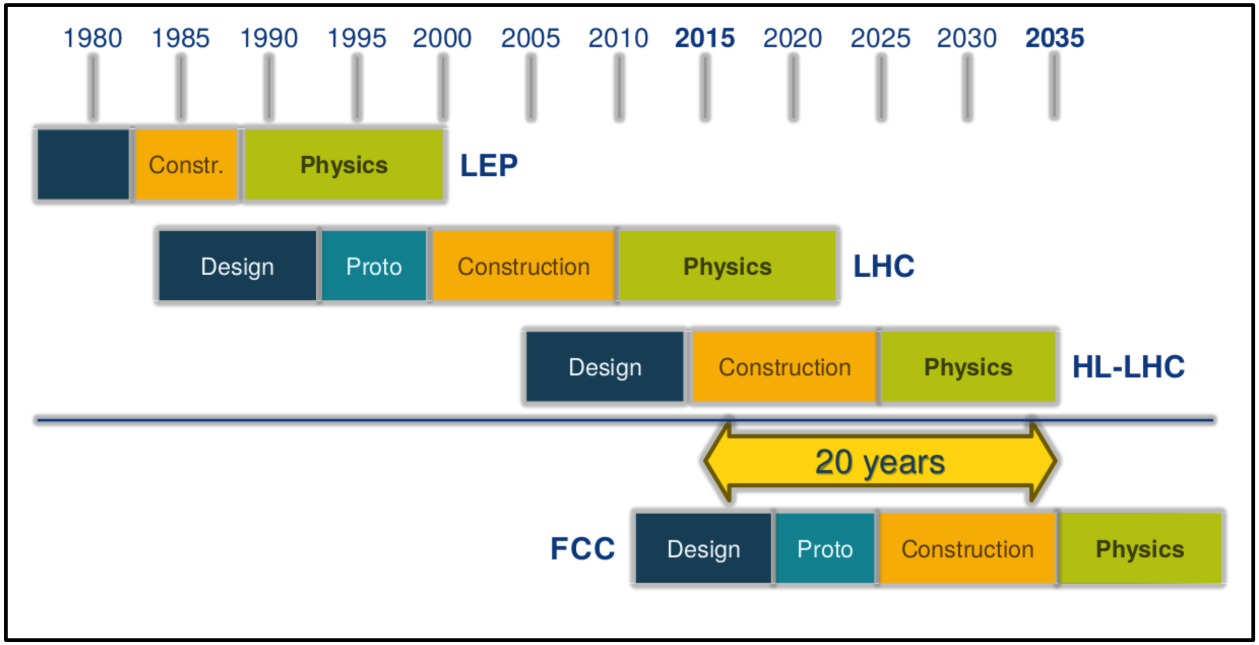
On behalf of the FCC-hh detector working group

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

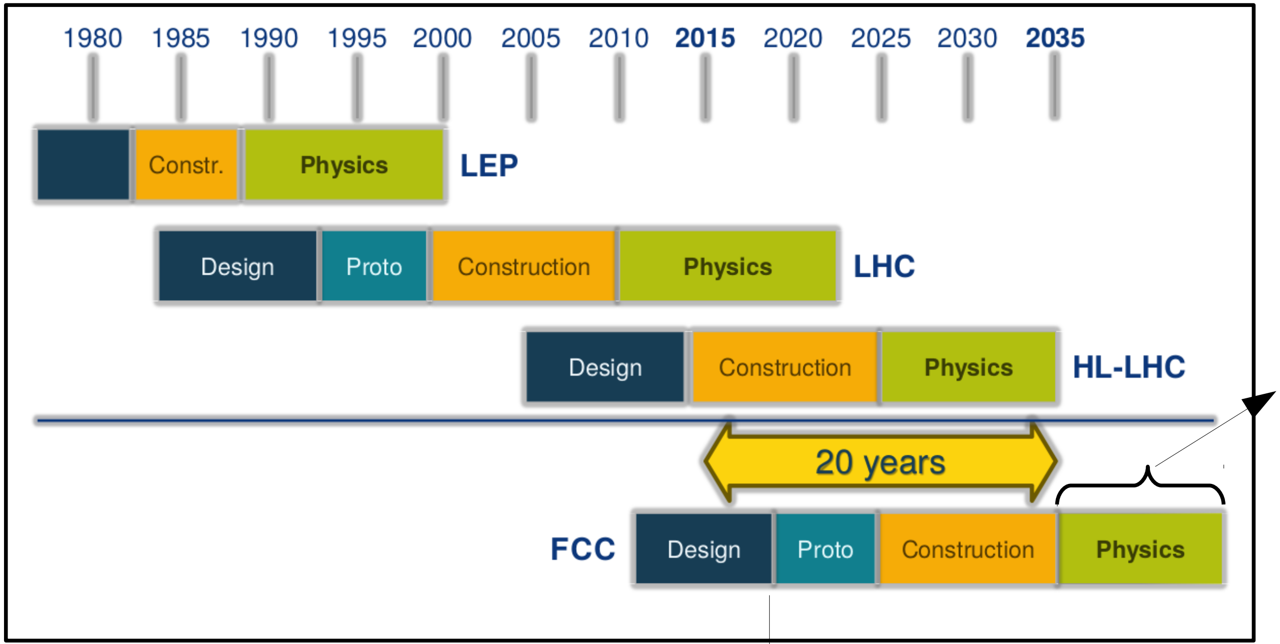
Road-map & Timescale

- LHC detector R&D started in the 1980's (HL-LHC in the 2000's)
  - **FCC R&D** will build on that for HL-LHC, but with more advanced technologies. That **requires long lead times**...



Road-map & Timescale

- LHC detector R&D started in the 1980's (HL-LHC in the 2000's)
  - **FCC R&D** will build on that for HL-LHC, but with more advanced technologies. That **requires long lead times**...

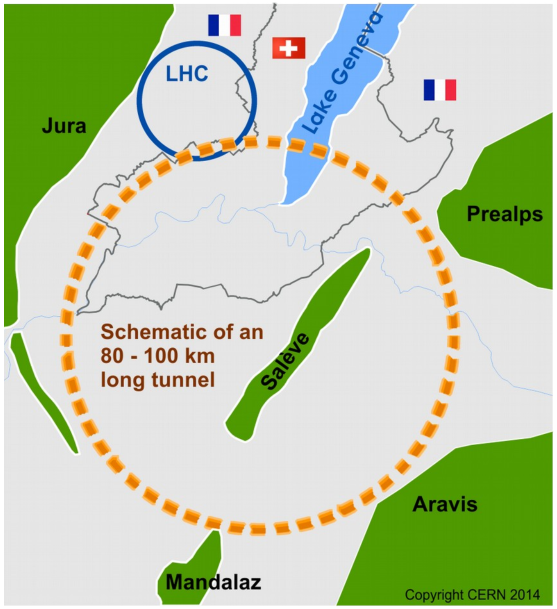


Planning for the period 2035-2040

1st milestone: prepare an FCC Conceptual Design Report by end of 2018 (for European Strategy Update in 2019/2020)

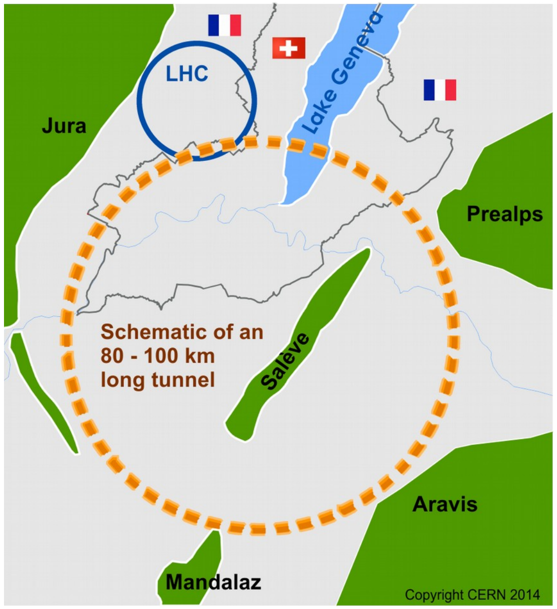
Future Circular Collider

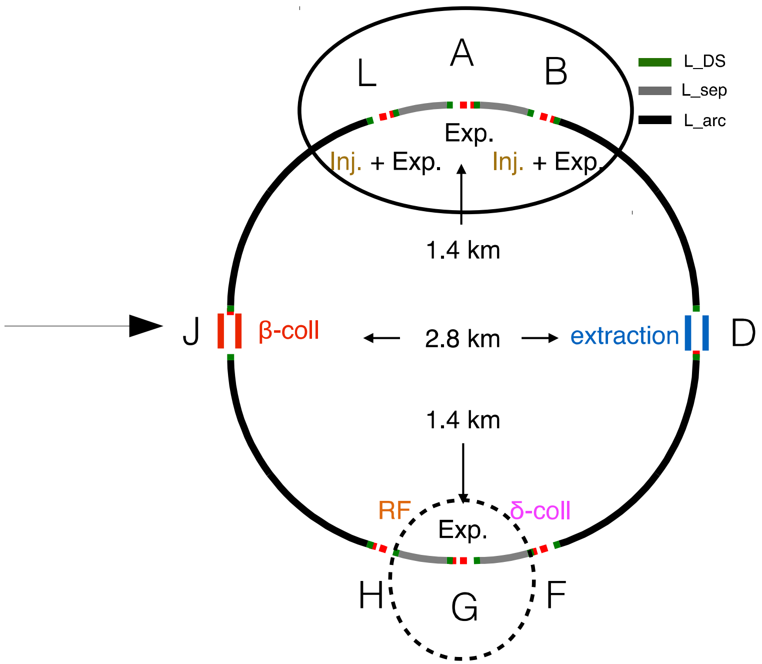
- **FCC machine:**
  - FCC-hh (pp collider): final goal defining the whole infrastructure
    → ~**16T** magnets → **100TeV pp** collider in **97.75km tunnel**
  - FCC-ee: as possible intermediate step
  - FCC-eh: as an option



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 possible intermediate step
  - FCC-eh: as an option





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

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

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

Understanding 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

14TeV → 100 TeV

$\sigma_{inelastic}$: 80mb → 108mb

average p_T: 0.6 → 0.8 GeV/c

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

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

Understanding 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

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

5x increase in pile-up 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

Understanding 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

14TeV → 100 TeV

$\sigma_{inelastic}$: 80mb → 108mb

average p_T: 0.6 → 0.8 GeV/c

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

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

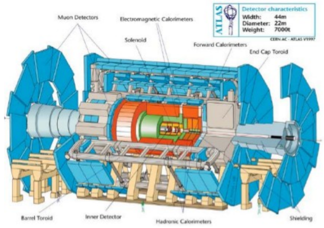
Physics Requirements on Detector Design

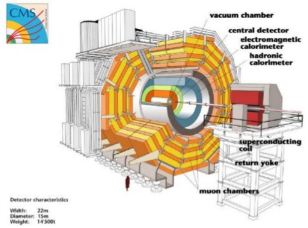
- **Design strongly depends on outcome of future LHC discoveries:**
  - **In case of new discoveries** → precise understanding of new physics will motivate the design
  - **In case no new physics is discovered** → mass scale of new physics may be beyond LHC reach or final states are too elusive → **higher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

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!**

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

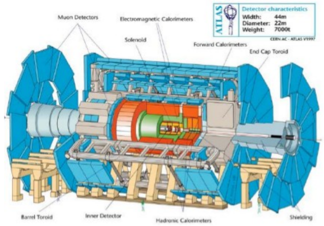


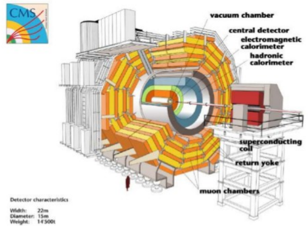


Physics Requirements on Detector Design

- **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!**

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





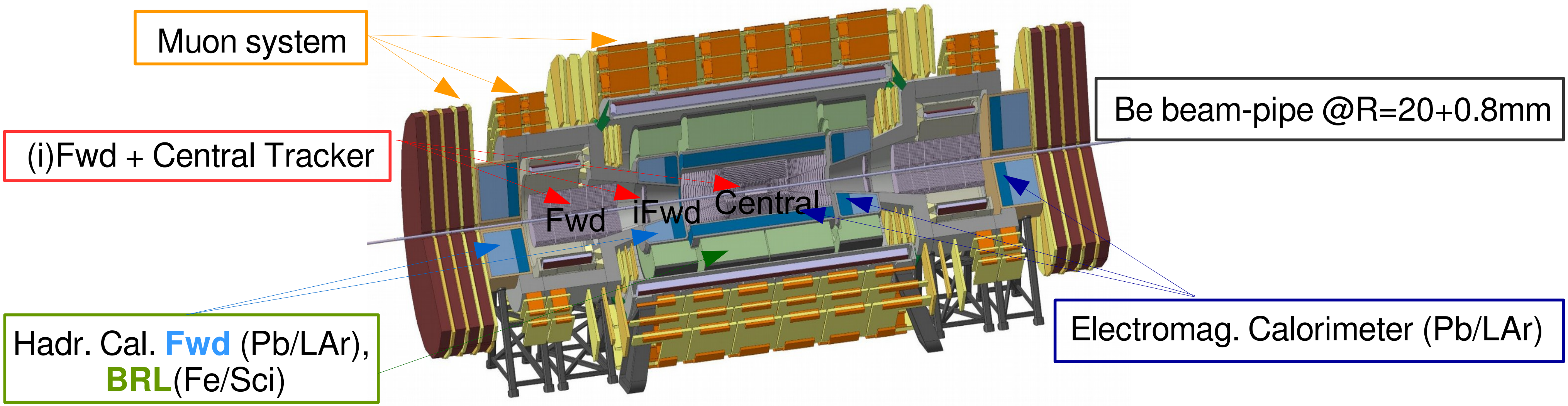
- **FCC opens us a new kinematic & dynamical regime, so requirements on tracker:**

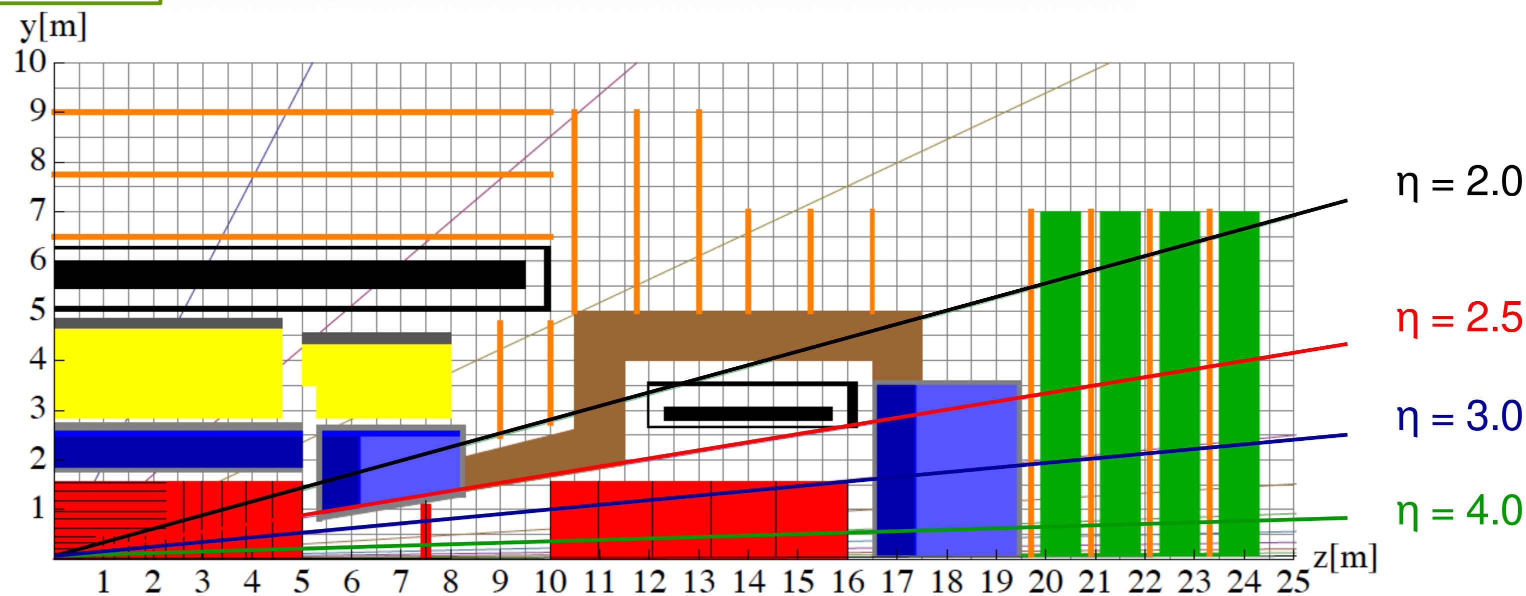
  → **Extended tracking up-to |η|~4** (c.f. |η|~2.5 for LHC exp.) + efficient **VBF jet** meas. **up-to |η|~6**

  → **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**

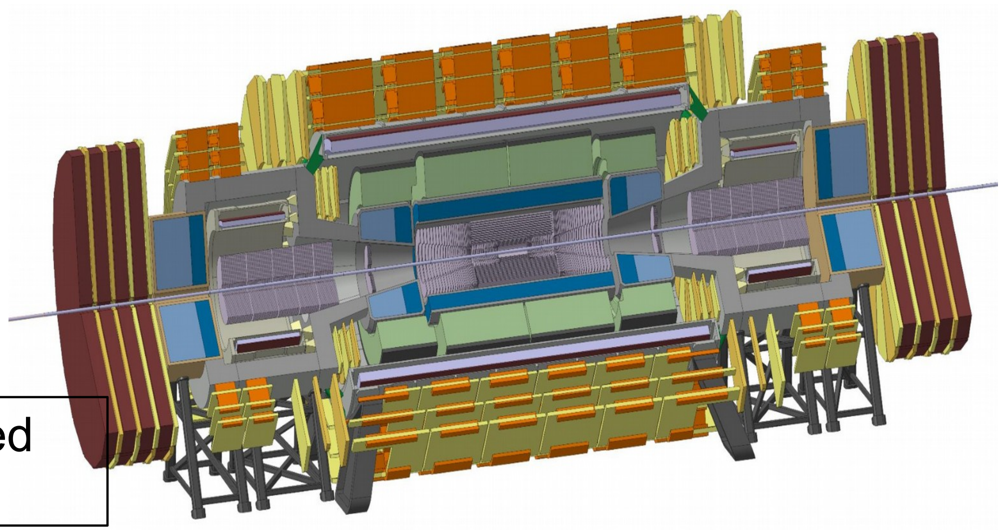
  → **High Tracker granularity essential** to resolve jet-substructure (E/HCAL), reject bkg,...

Reference Detector Layout

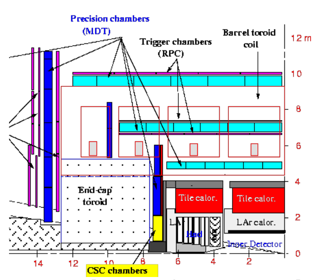


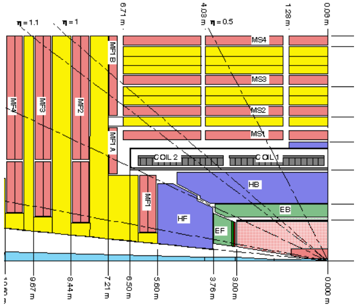


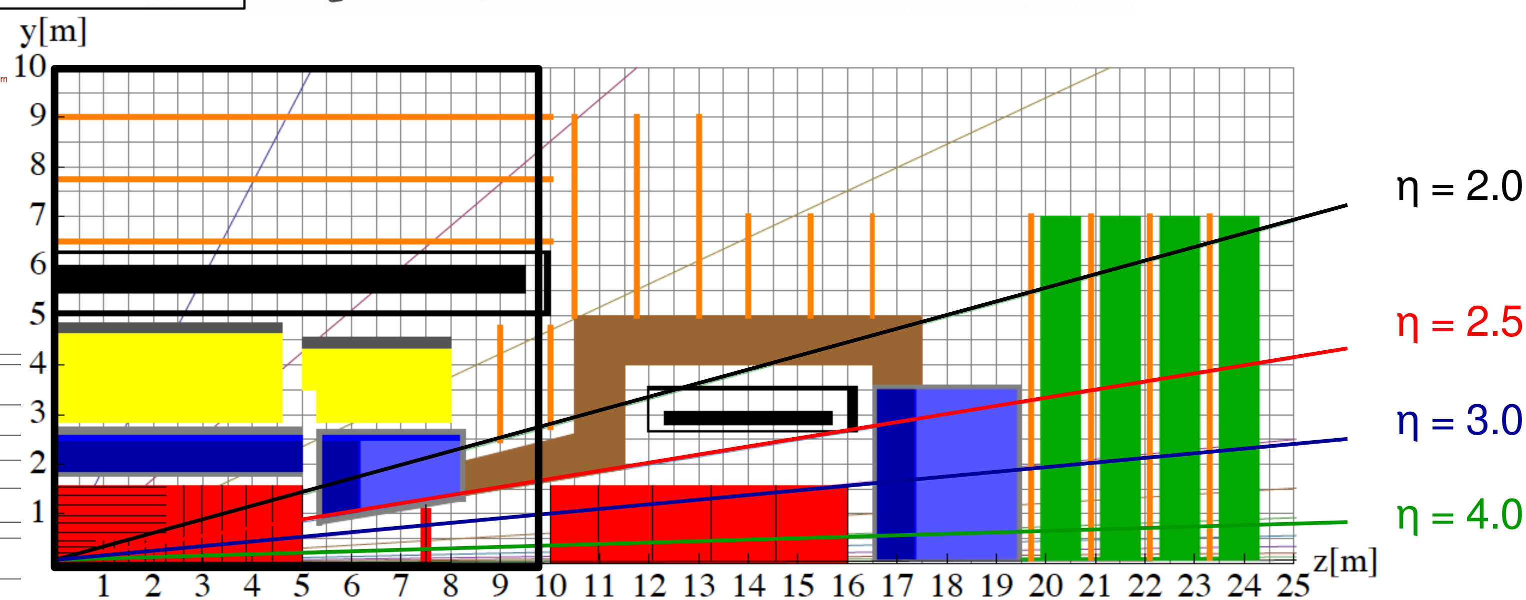
Reference Detector Layout



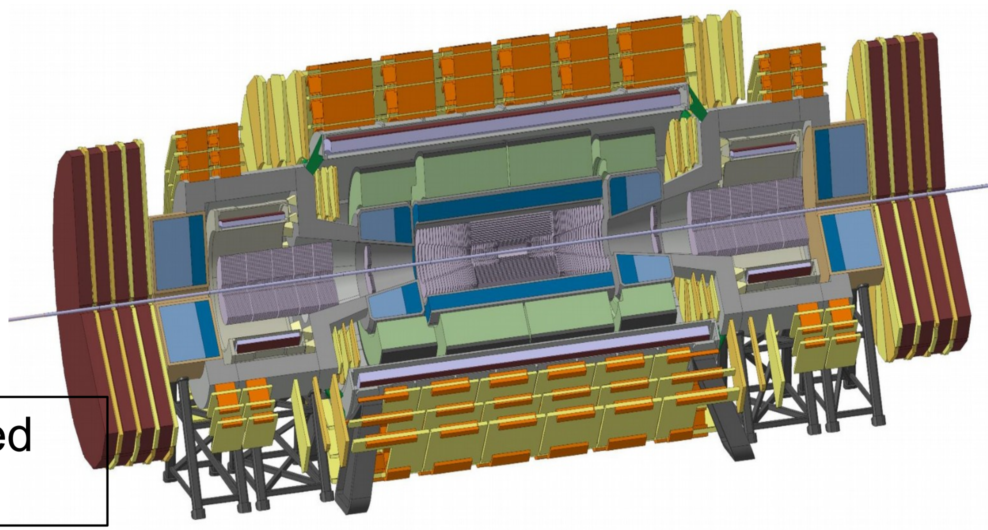
Central region inspired by ATLAS/CMS



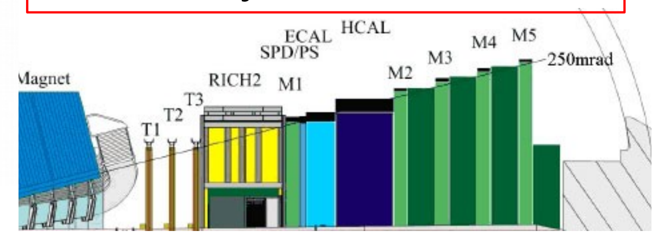




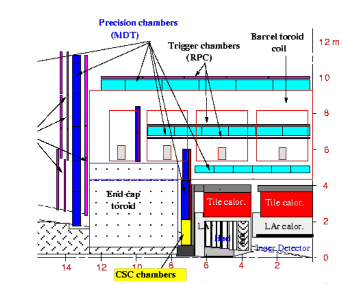
Reference Detector Layout

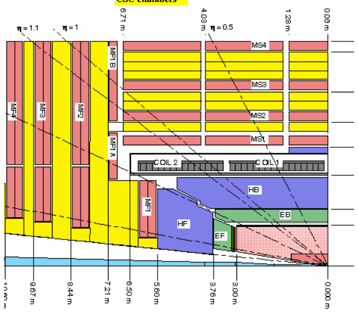


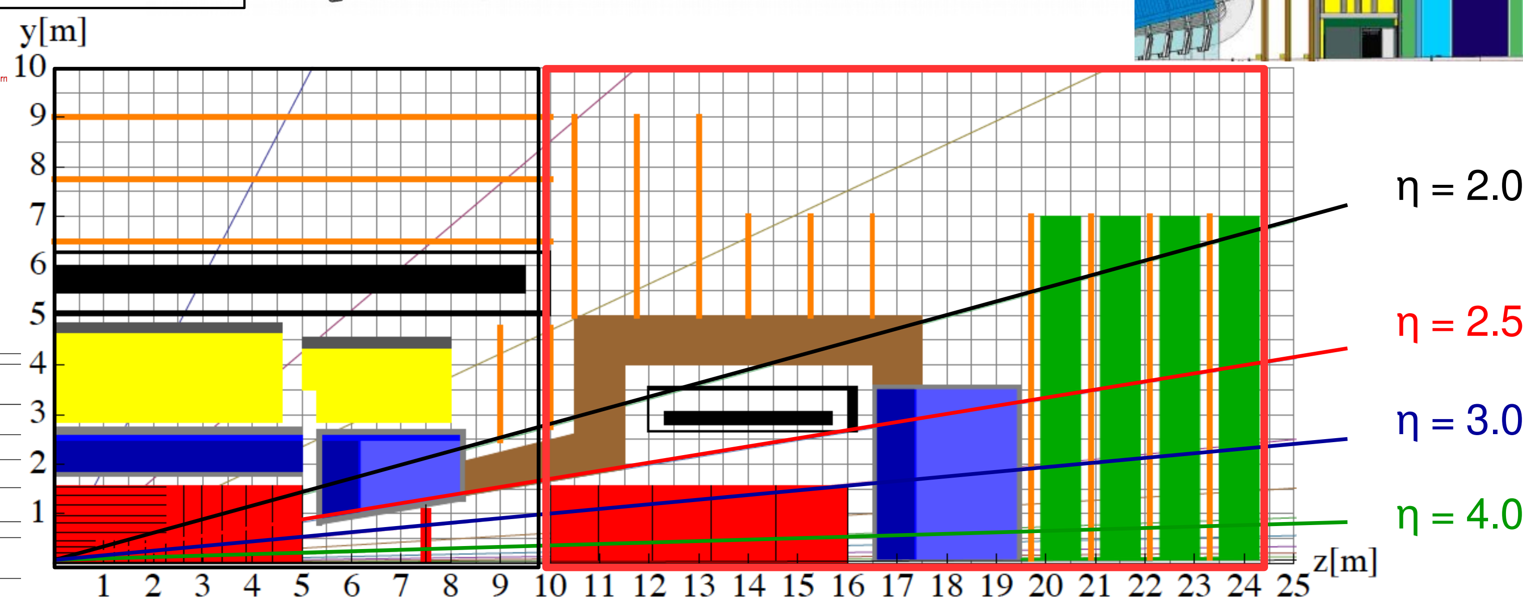
Forward region inspired by LHCb



Central region inspired by ATLAS/CMS

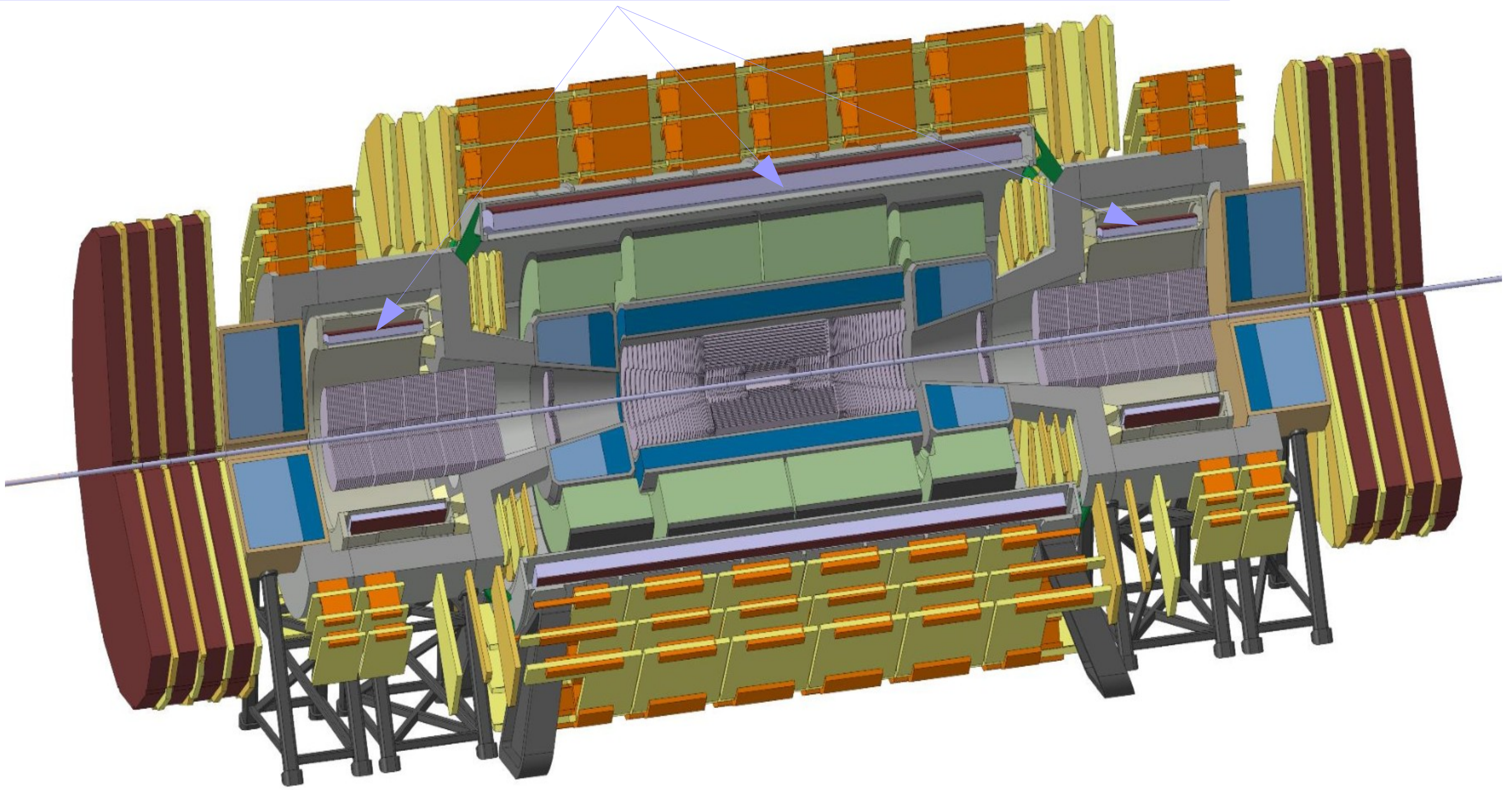






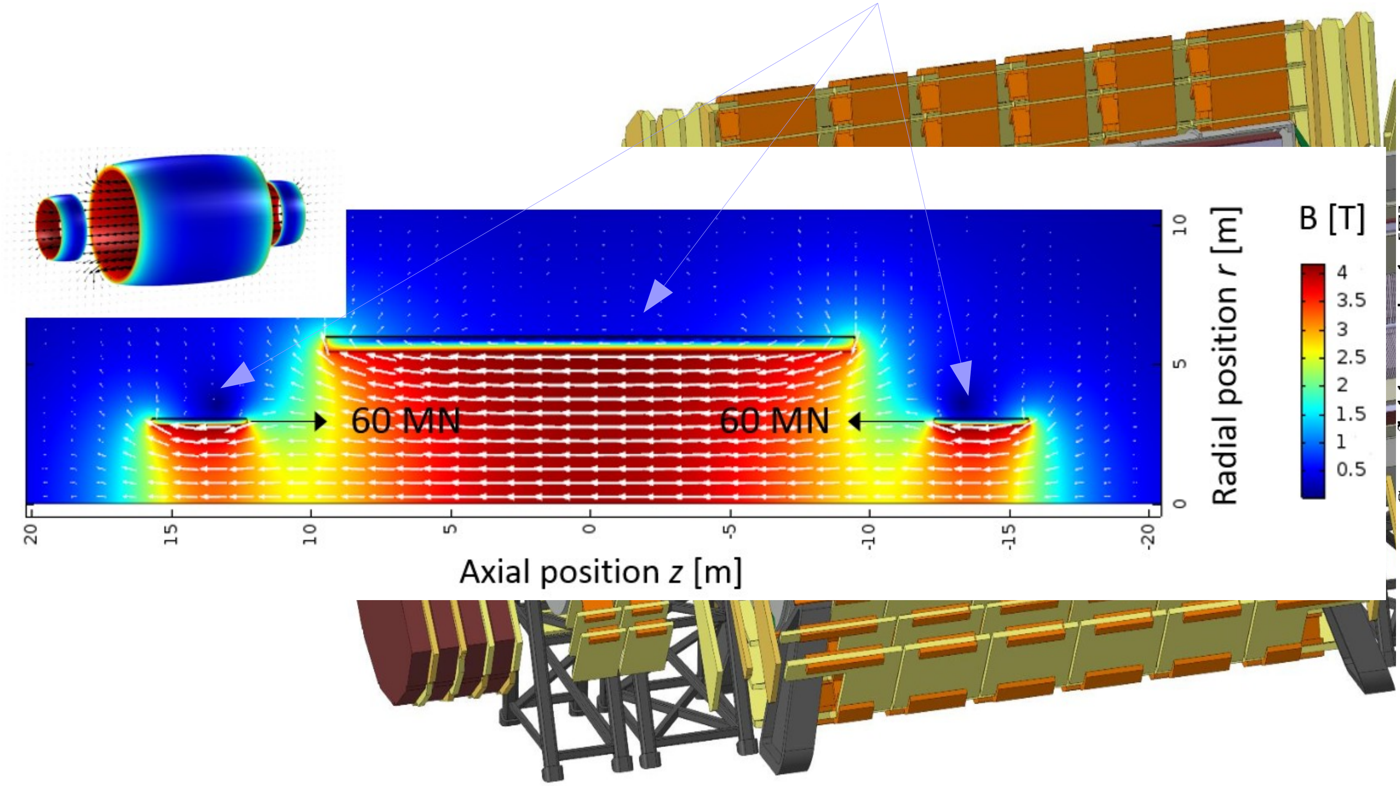
Reference Detector Layout & Magnet

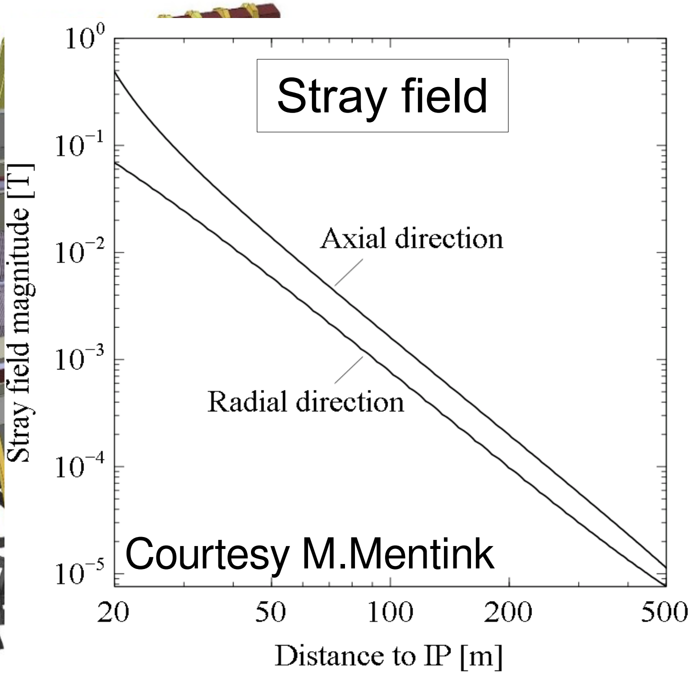
4T solenoid (10m free bore) + 2x 4T Fwd solenoids (no shielding)



Reference Detector Layout & Magnet

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

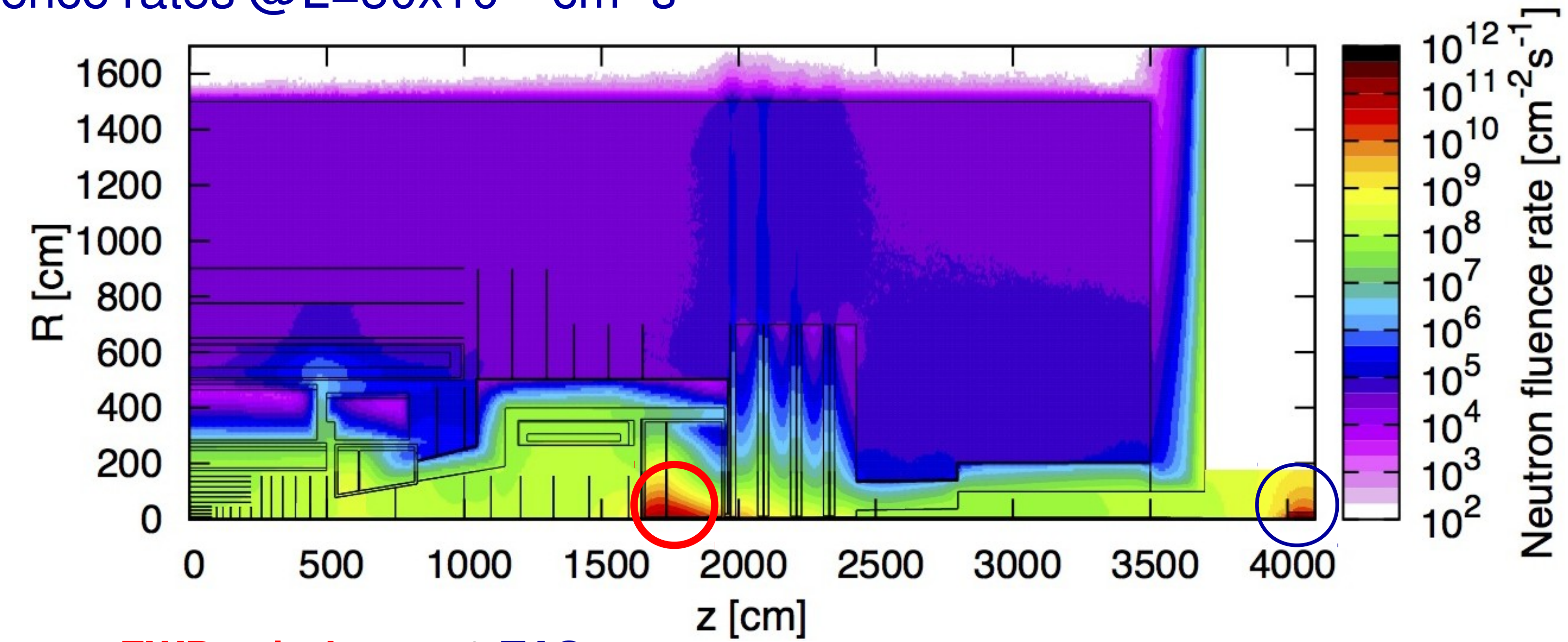




FCC-hh & Radiation Rates?

Courtesy of M.I.Besana

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

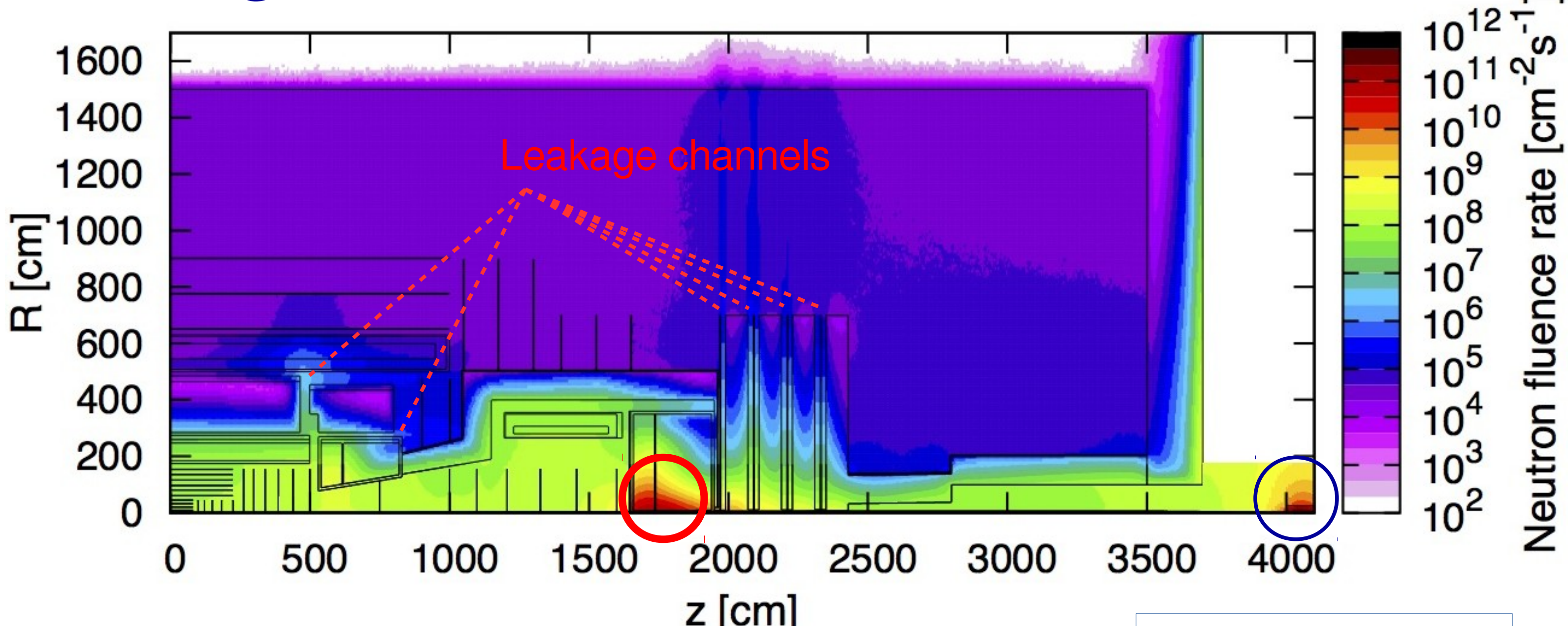


→ 2 main hot spots: **FWD calorimeter** & **TAS**

FCC-hh & Radiation Rates?

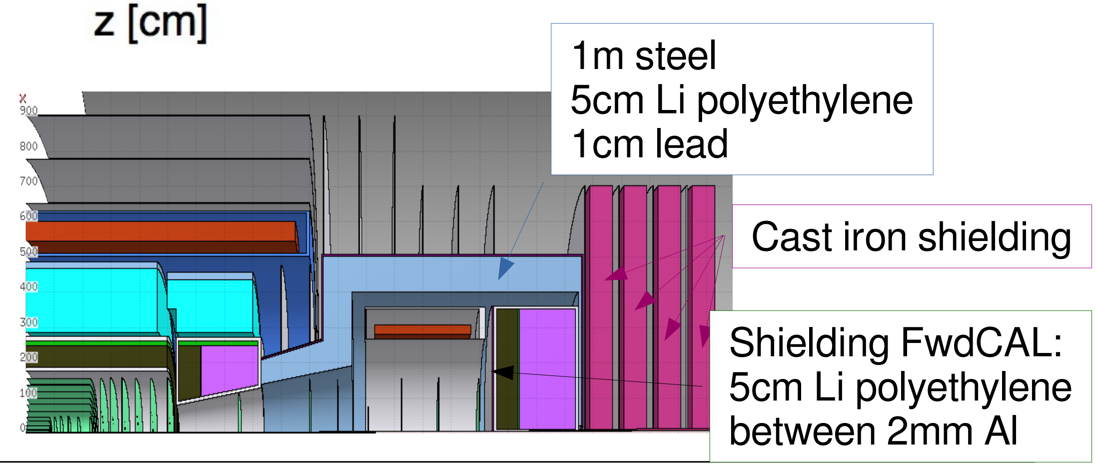
- Neutron fluence rates @L=30x10^{34} cm^{-2}s^{-1}

Courtesy of M.I.Besana



→ 2 main hot spots: **FWD calorimeter** & **TAS**

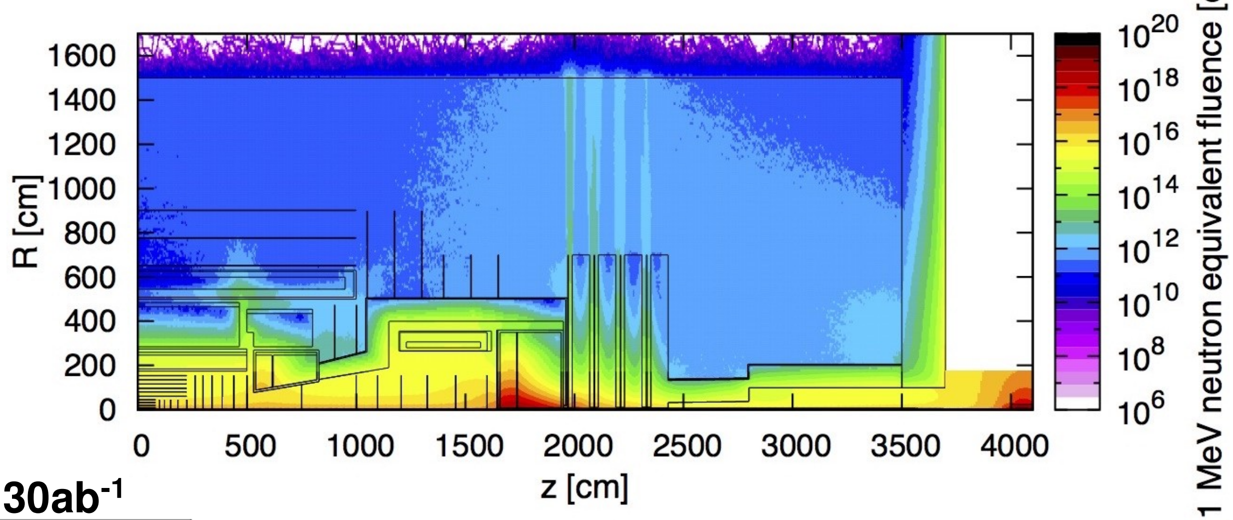
→ **Shielding scheme effective**, but several leakage channels appear due to service channels etc.



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

Courtesy of M.I.Besana

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



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:

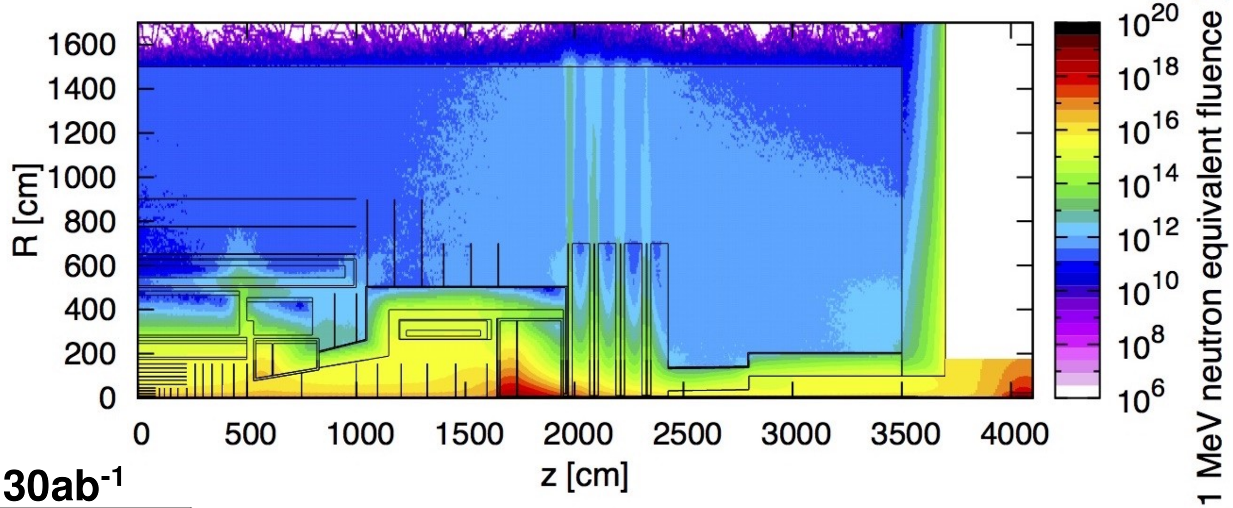
► @R=25mm: **~$6x10^{17}$ neq cm^{-2} ,TID~0.4GGy**

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

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

- 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 for z=0m (z-pos. dependent)

Tracker Layout & Design Driving Principles

- Key tracker parameters:
  - **Granularity in R-Φ →** driven by requirement on dp_T/p_T, efficient tagging of displ. vertices (d0) & 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: 4T
$\sigma_{R\text{-}\Phi}$: 10(7.5)um
N_{layers}: 12

~ 20% @ 10TeV/c

Tracker Layout & Design Driving Principles

- Key tracker parameters:
  - Granularity in R-Φ → driven by requirement on dp_T/p_T, efficient tagging of displ. vertices (d0) & occupancy limit (~1%)

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

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

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

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

} **Low MB Important!**

Tracker Layout & Design Driving Principles

- Key tracker parameters:
  - Granularity in R-Φ → driven by requirement on dp_T/p_T, efficient tagging of displ. vertices (d0) & occupancy limit (~1%)

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

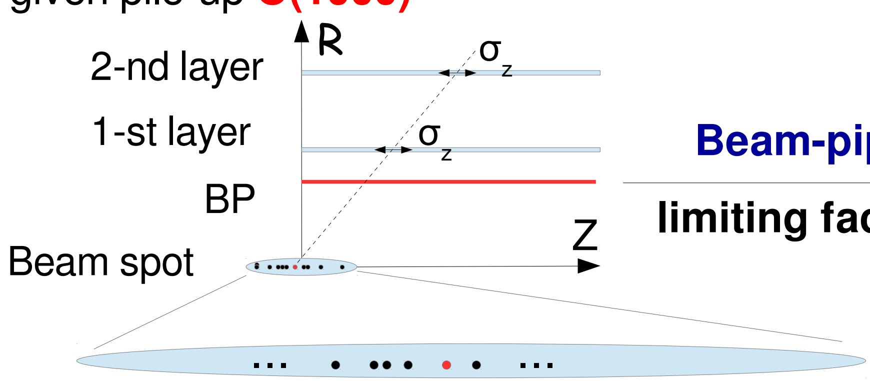
L: 1.55m
B: 4T
$\sigma_{R\text{-}\Phi}$: 10(7.5)um
N_{layers}: 12

~ 20% @ 10TeV/c

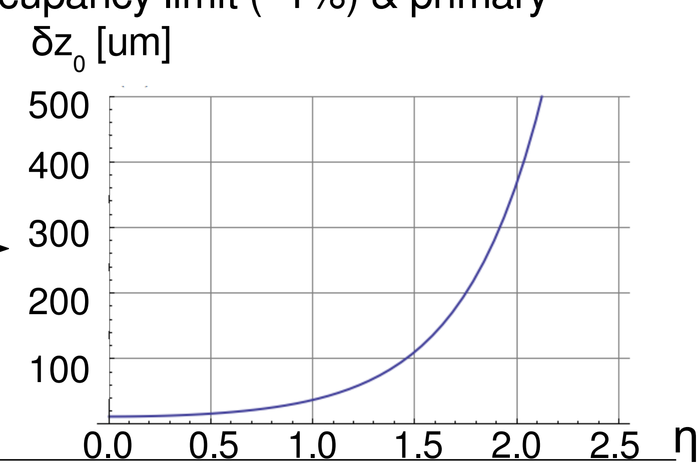
  - Number of layers N → driven by dp_T/p_T res. & pattern recognition capabilities
    Note: res. improves as $\mathbf{1/\sqrt{N_{layers}}}$, but material budget (MB) increases as $\mathbf{N_{layers}}$

Low MB Important!

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



Beam-pipe limiting factor!

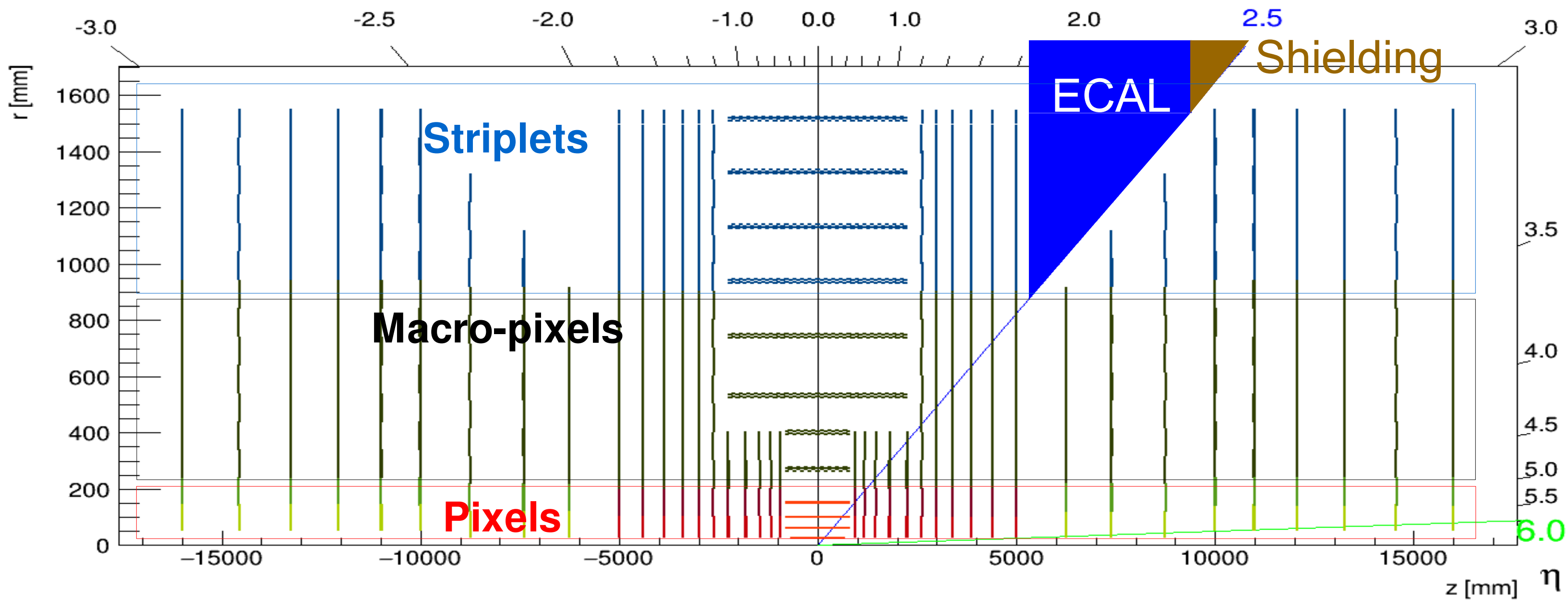


Reference Tracker Layout (v3.03)

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)

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

Reference Tracker Layout (v3.03)

Surface: ~430m^2

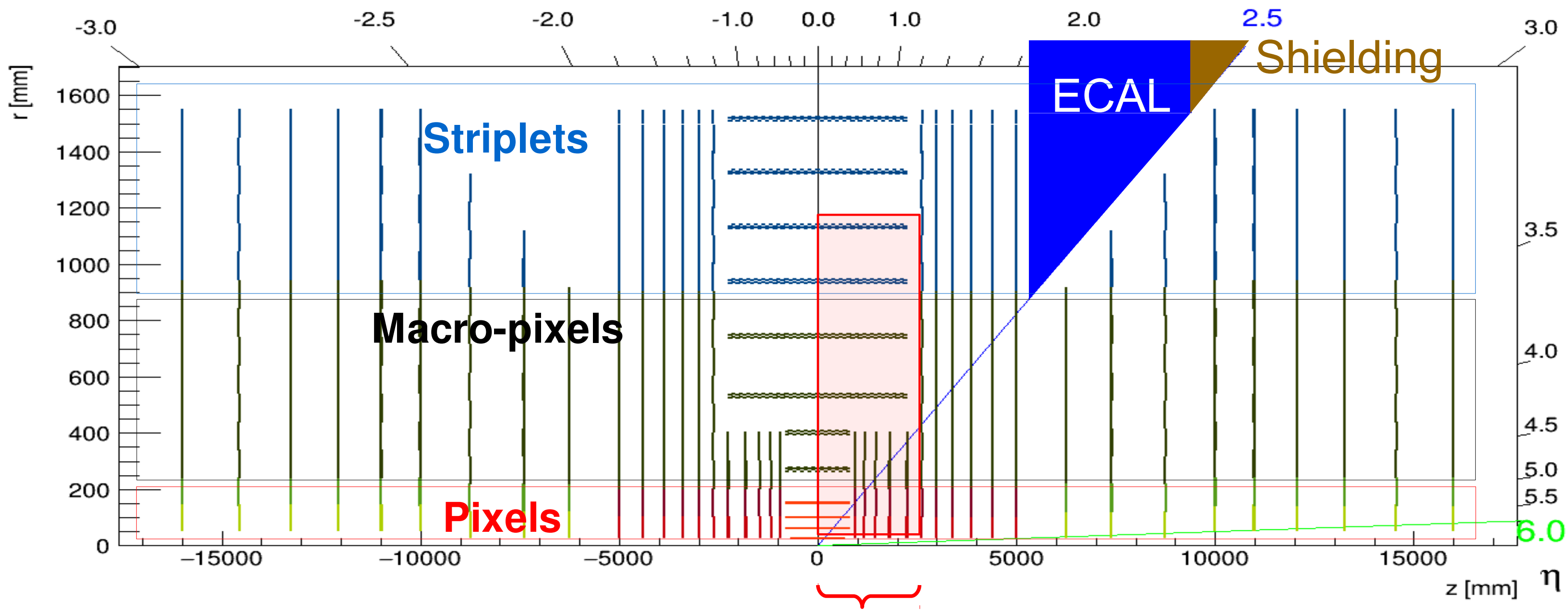
#Channels: **489.4M**

9964.4M

5460.9M

Pixel R↗0.9 m due to occupancy

4 (seed) BRL layers



~ Dimensions of CMS tracker

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:

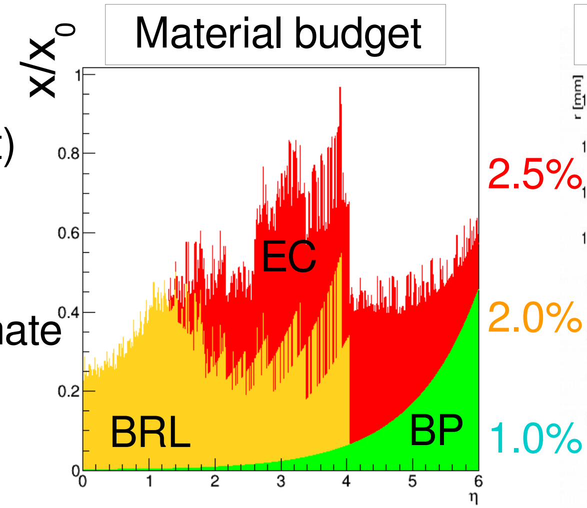
- requirements on tracking up to **η=6**
- resilience to **high rad. levels** generated by FCC-hh

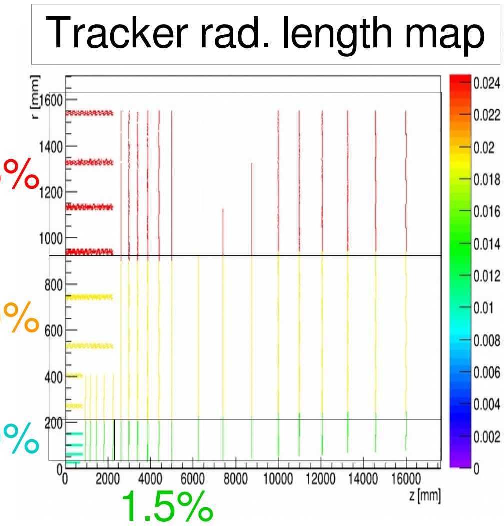
For details see http://fcc-tklayout.web.cern.ch

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

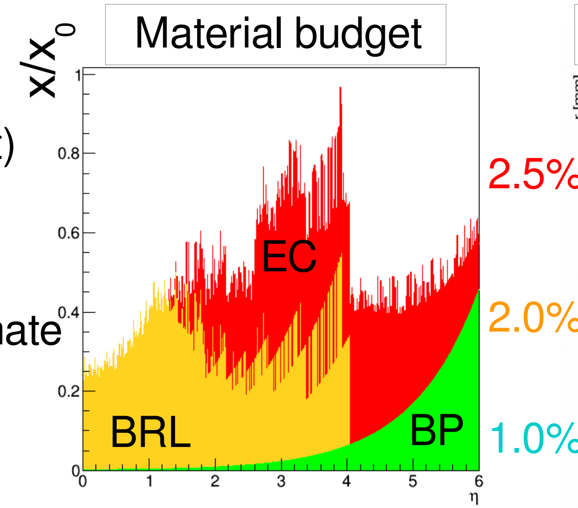


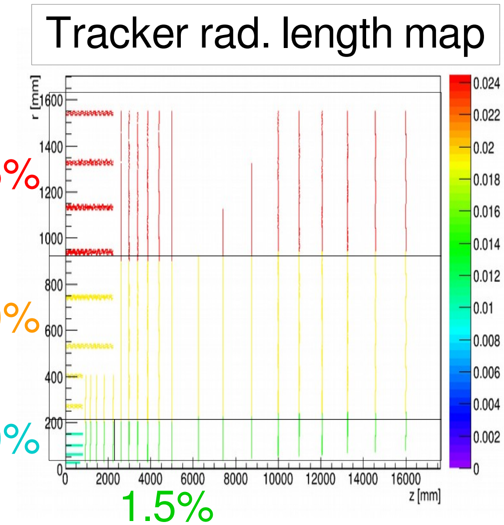


Material Budget & Tracking Resolution

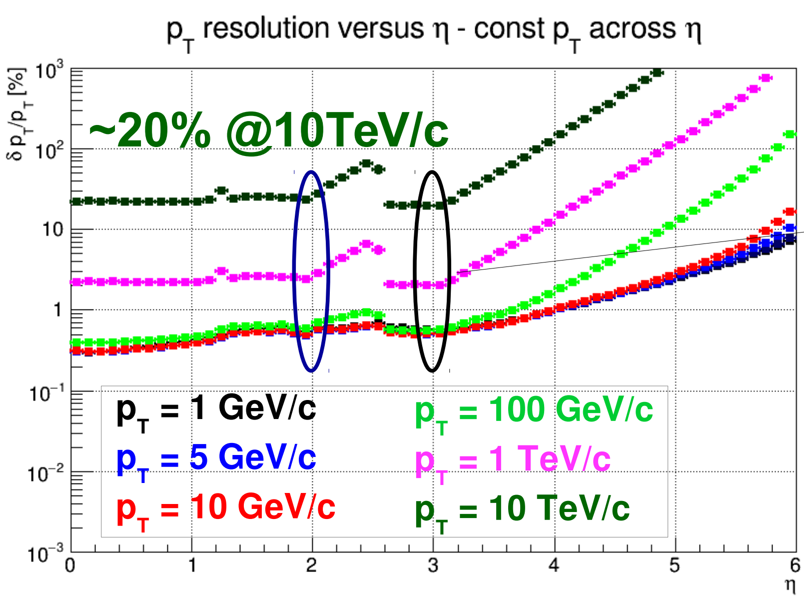
- A simplified model for MB assumed:
  - x/x0 ~1-2.5% per layer (services accumul. effect) (20% Si, 42% C, 2% Cu, 6% Al, 30% Plastic)

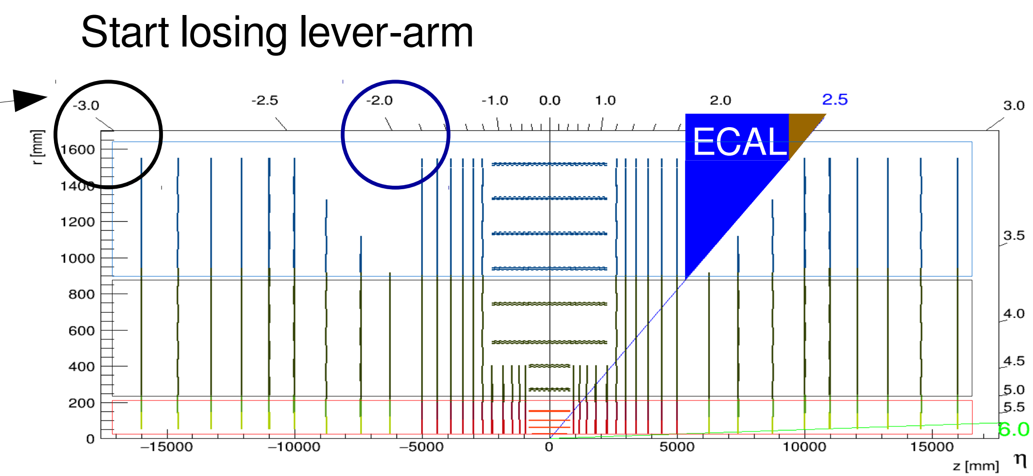
  → **technology input needed** for more real. estimate





- Tracking resolution (tkLayout SW):





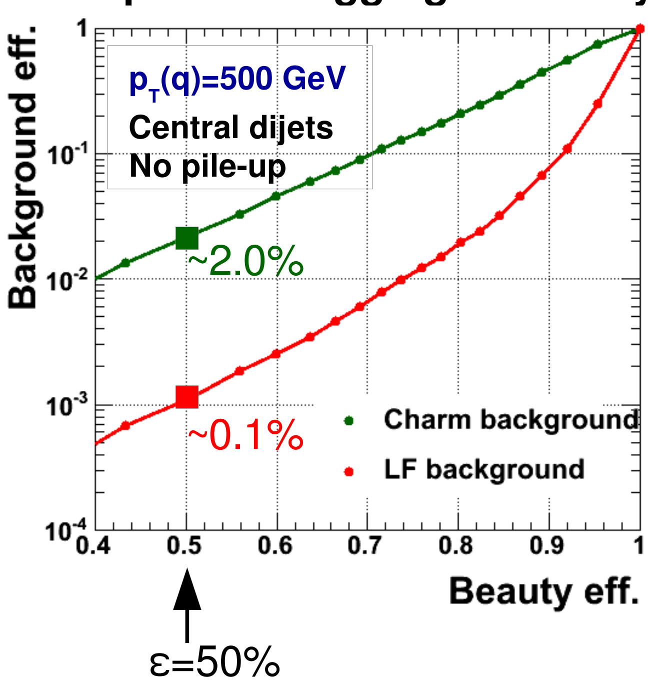
Vertex Detector & Flavour Tagging

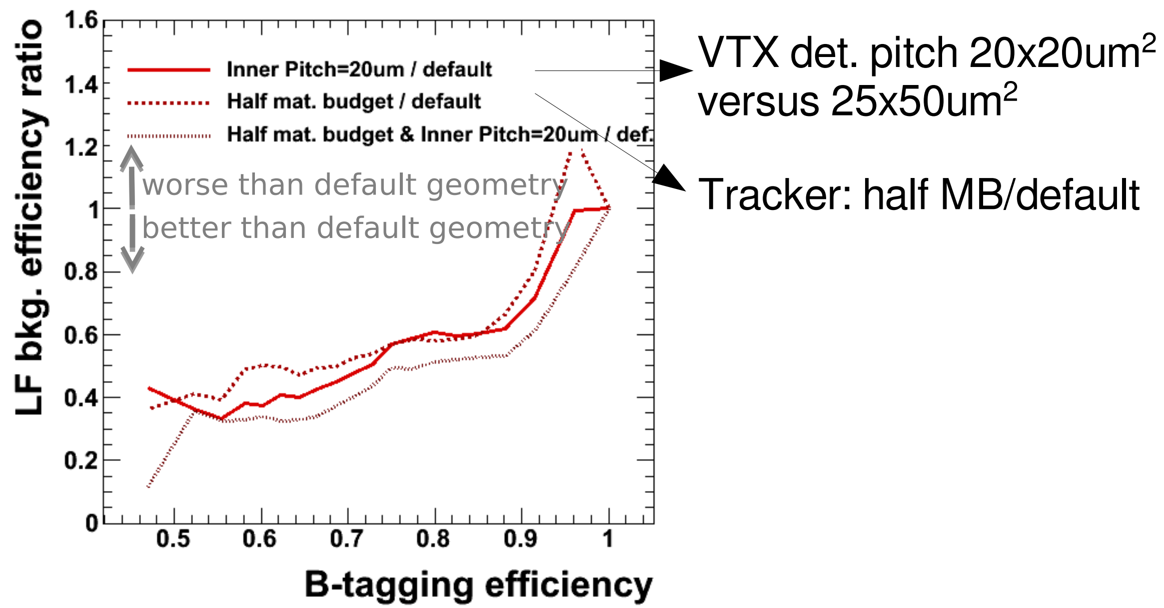
- Flavour tagging represents another important aspect of vertex detector & tracker design:

→ Tagging of very high-energy jets (p_T>1TeV/c) is extremely challenging, not only because of **very collimated particles**, but also due to **extremely long-lived hadrons** (displaced vertices):
E.g. 5TeV central b-jets → B-hadrons decay outside the vertex detector in ~50% cases

Courtesy of E. Perez Codina

→ **Example of B-tagging efficiency versus MB & granularity**





Pattern Recognition (PR) Capabilities

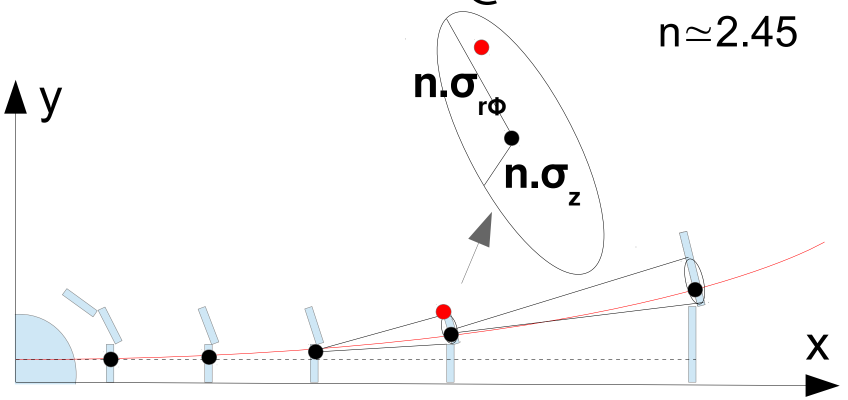
- **Tracker granularity in Z** is strongly affected by requirement on **PR capabilities!** How to study such effects analytically? Use **track propagator** & analyze **layout "weak" spots**:

  → Assume **perfect seeding** → propagate analytically $\sigma_{r\Phi}$, σ_z to ith layer in → out

  → Calculate probability **p** to mis-match a **real hit anywhere on the track** with a **bkg hit** @95% CL **in PU=1000**

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

@ 95% conf. level
n≃2.45



Pattern Recognition (PR) Capabilities

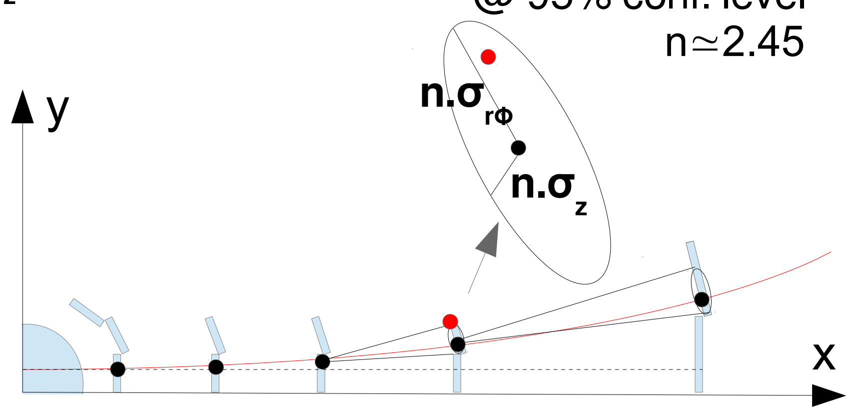
- **Tracker granularity in Z** is strongly affected by requirement on **PR capabilities!** How to study such effects analytically? Use **track propagator** & analyze **layout "weak" spots**:

→ Assume **perfect seeding** → propagate analytically $\sigma_{r\Phi}$, σ_z to i[th] layer in → out

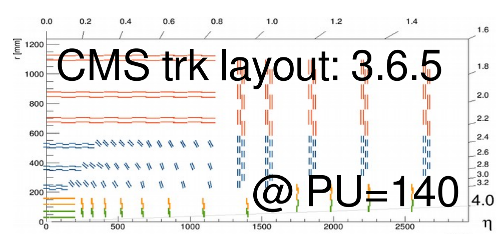
→ Calculate probability **p** to mis-match a **real hit anywhere on the track** with a **bkg hit** @95% CL **in PU=1000**

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

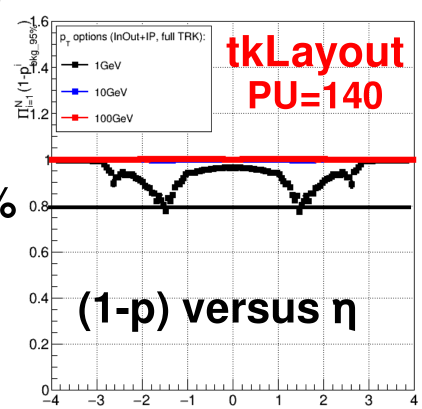
@ 95% conf. level
n≃2.45

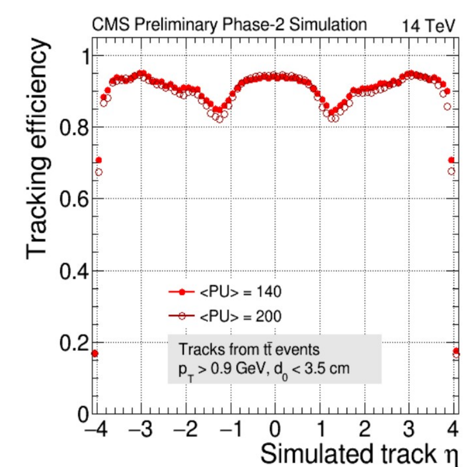


→ **How to interpret & set a limit value on p?**



(1-p) ~ 80%



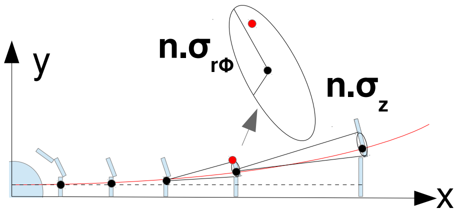


E.Brondolin: CMS DP-2017/010

→ **Try to achieve p ~20% for FCC-hh**

Understanding Track Propagator in PR

- 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**



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

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

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

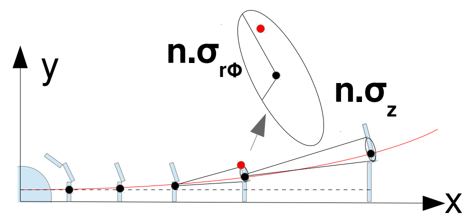
$$f_{\mathrm{proj}} = 1 \quad \text{proj. in R}-\Phi$$

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

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

Understanding Track Propagator in PR

- 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**



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

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

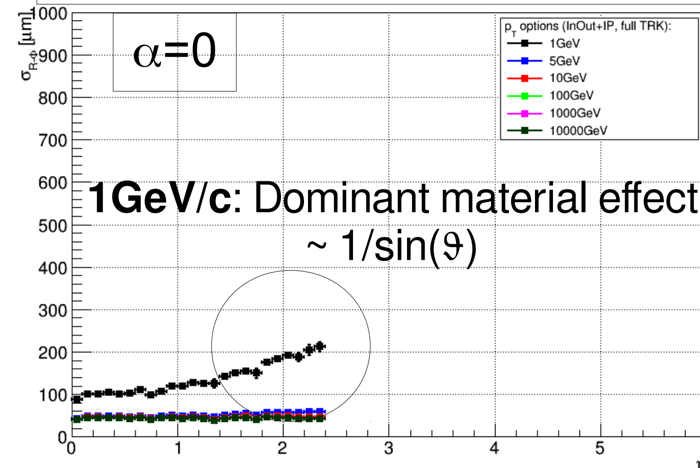
$$f_{\mathrm{proj}} = \left(\frac{1}{\sin(\vartheta+\alpha)}\right)^2 \quad \text{proj. in Z}$$

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

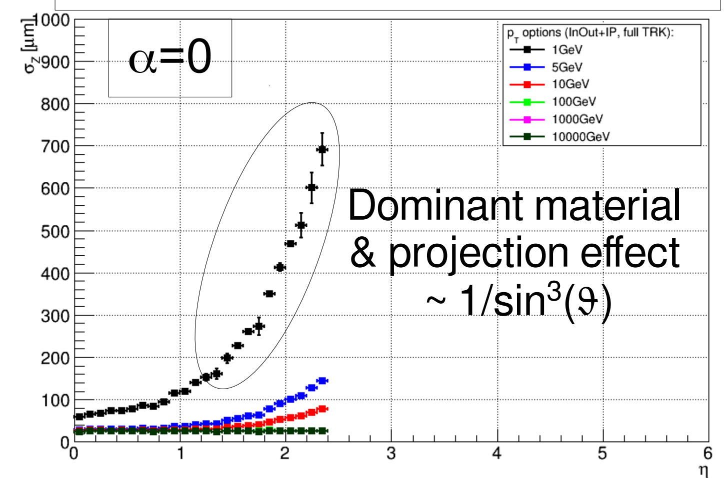
$$\sigma_{R\Phi} = \sqrt{\sigma^2_{R\Phi_{\mathrm{loc}}} + (A/\sqrt{1-A^2}\,\sin\alpha)^2\sigma^2_{Z_{\mathrm{loc}}}}$$

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

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

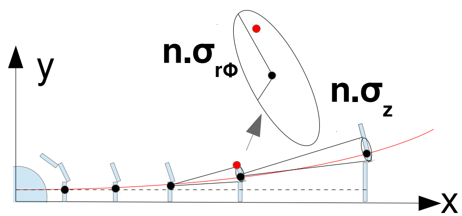


Propagated σ_Z on 4th BRL layer



Understanding Track Propagator in PR

- 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**



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

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

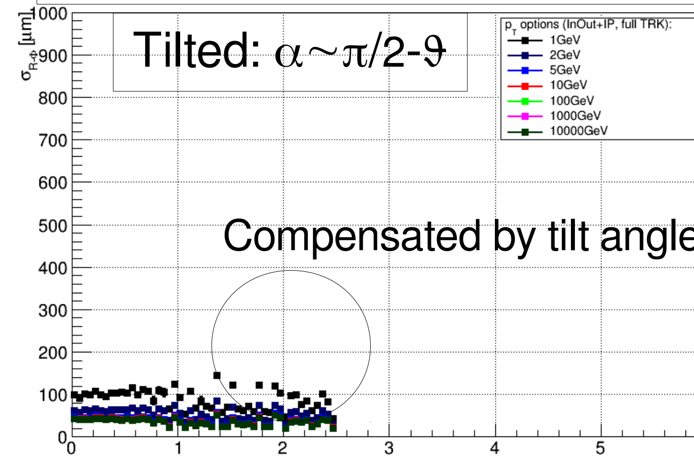
$$f_{proj} = \left(\frac{1}{\sin(\vartheta+\alpha)}\right)^2 \quad \text{proj. in Z}$$

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

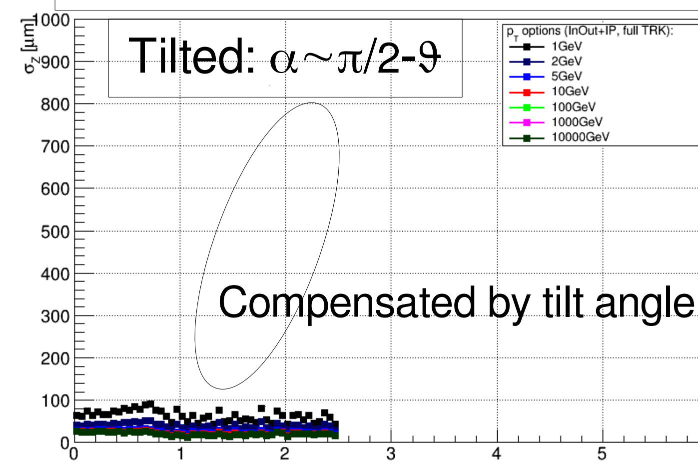
$$\sigma_{R\Phi} = \sqrt{\sigma_{R\Phi_{loc}}^2 + (A/\sqrt{1-A^2}\sin\alpha)^2 \sigma_{Z_{loc}}^2}$$

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

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

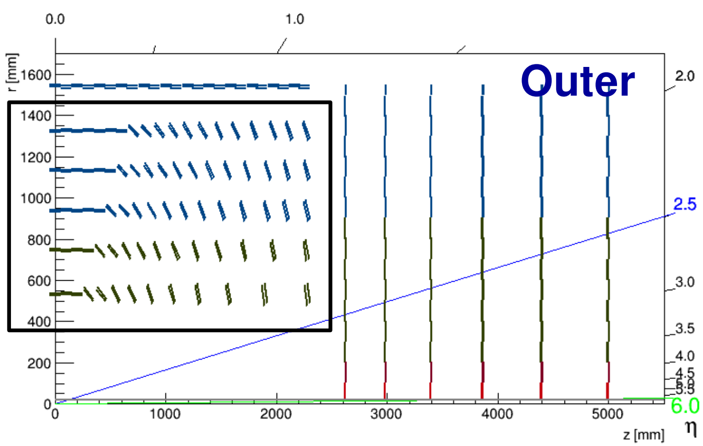


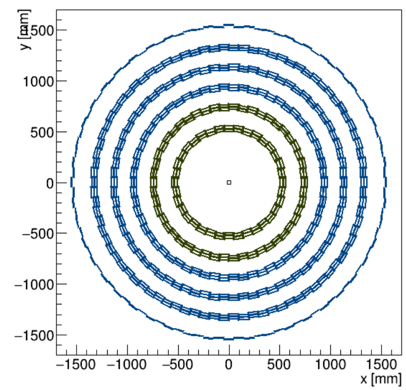
Propagated σ_z on 4th BRL layer



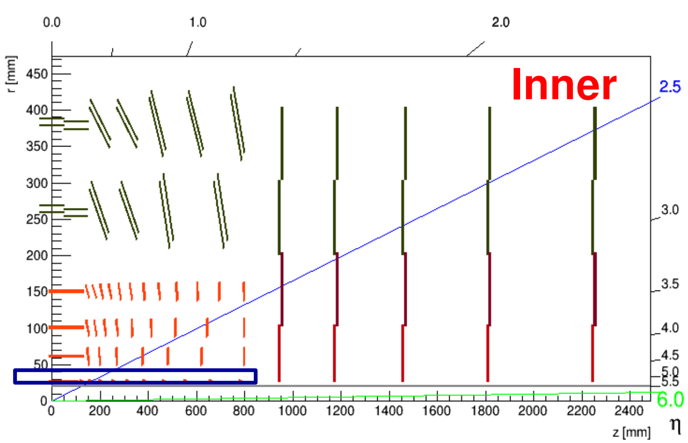
- **To min. mat. effects, tracker in tilted layout advantageous!**

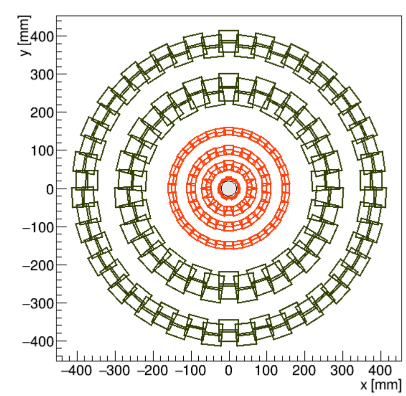
Tilted Geometry: Design Proposal v4.01





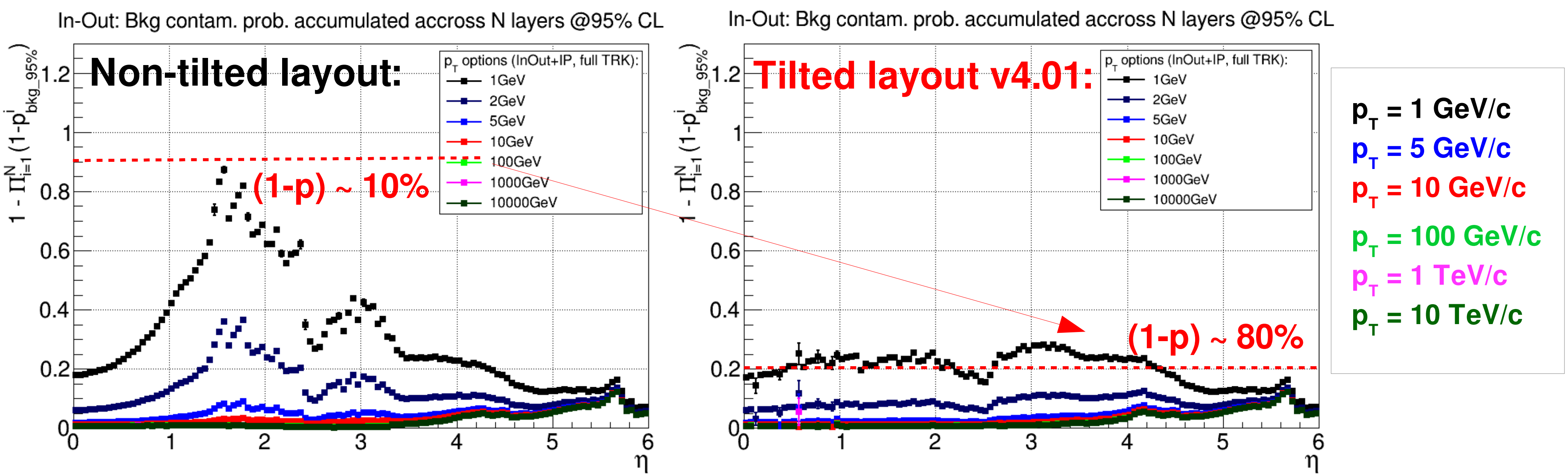
- Layout of **outer tracker** driven by requirement on **p~0.2**:
  - → uppermost layer designed non-tilted to keep the highest possible lever-arm
  - → modules positioned as to hermetically cover full luminous region





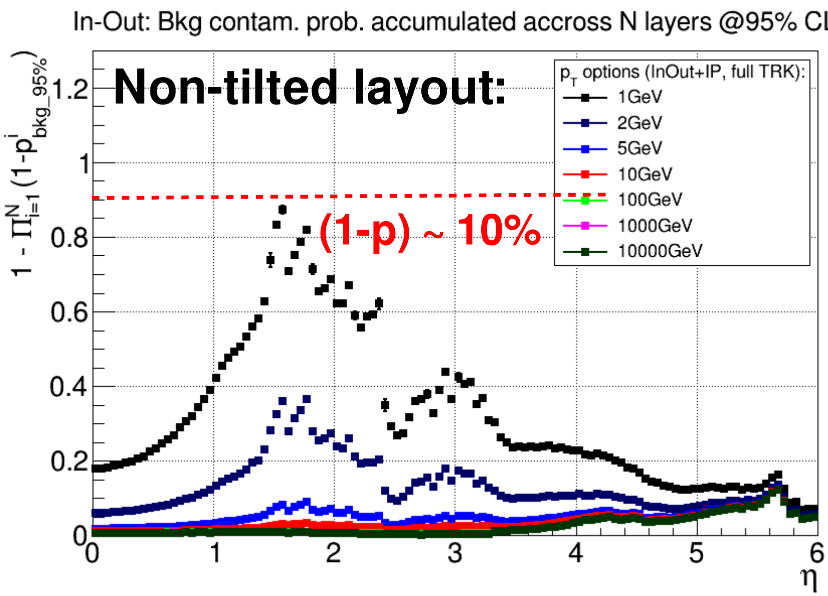
- Layout of **inner tracker** driven by **p~0.2** & **requirement on best z0 res.:** (to deal with primary vertexing @PU~1000):
  - → tilt angle of 1st layer: $\vartheta_{tilt} \simeq 10^{\circ}$ set as a compromise between low MB & high radius

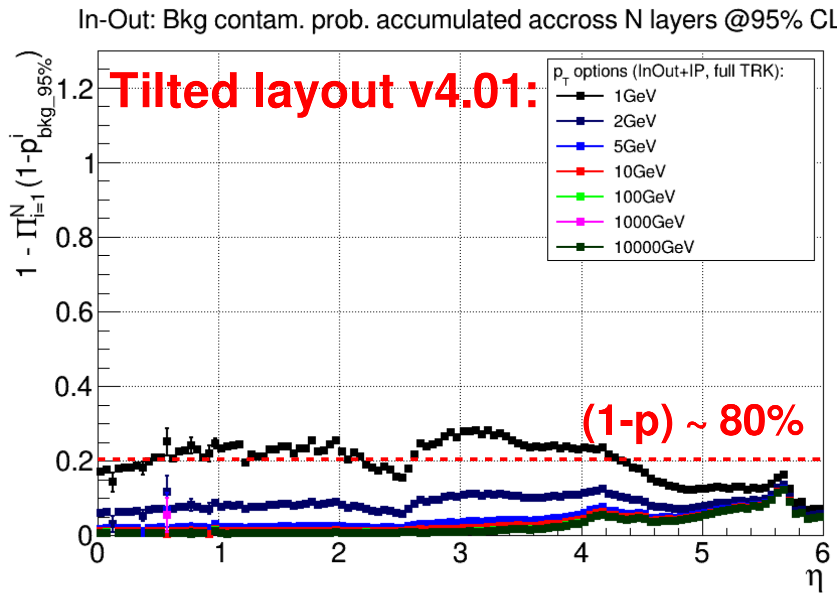
Tilted Layout: Improvement in Performance



→ **Approach constraint:** Mat. budget assumed per module → need to add realistic engineering: services etc.

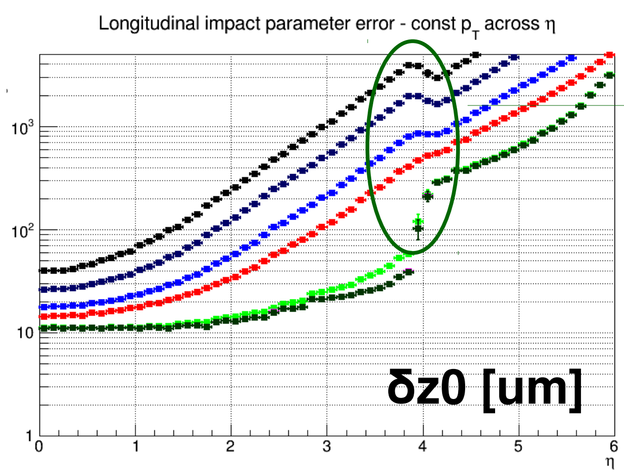
Tilted Layout: Improvement in Performance

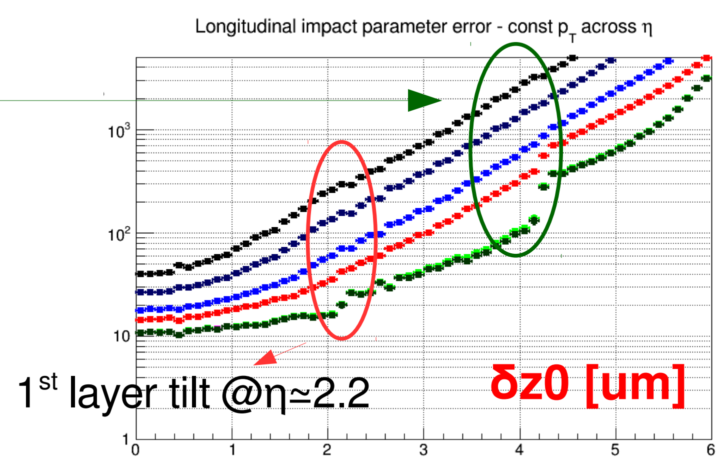




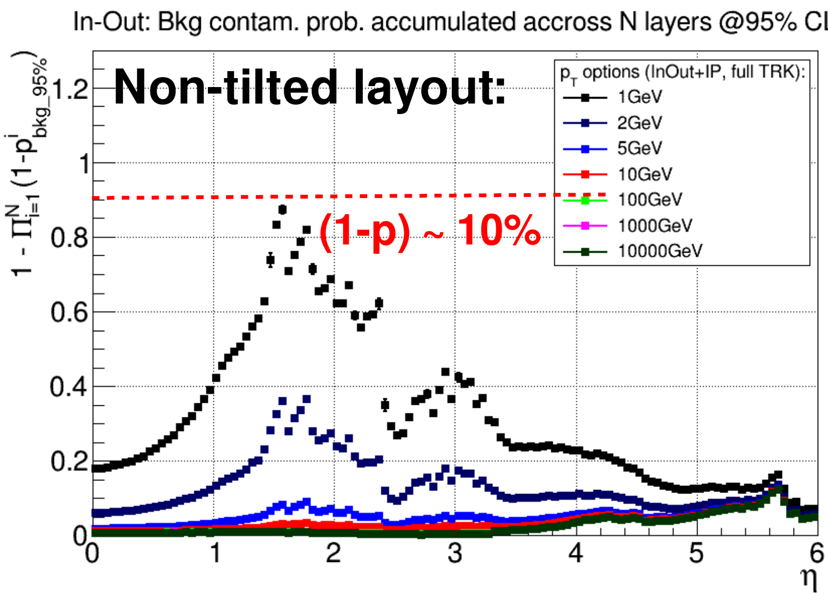
p_T = 1 GeV/c
p_T = 5 GeV/c
p_T = 10 GeV/c
p_T = 100 GeV/c
p_T = 1 TeV/c
p_T = 10 TeV/c

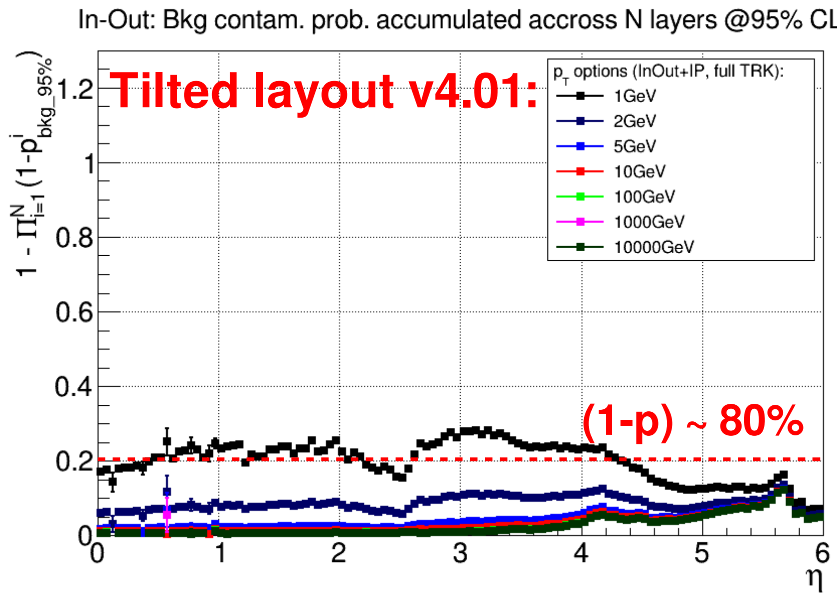
→ **Approach constraint:** Mat. budget assumed per module → need to add realistic engineering: services etc.





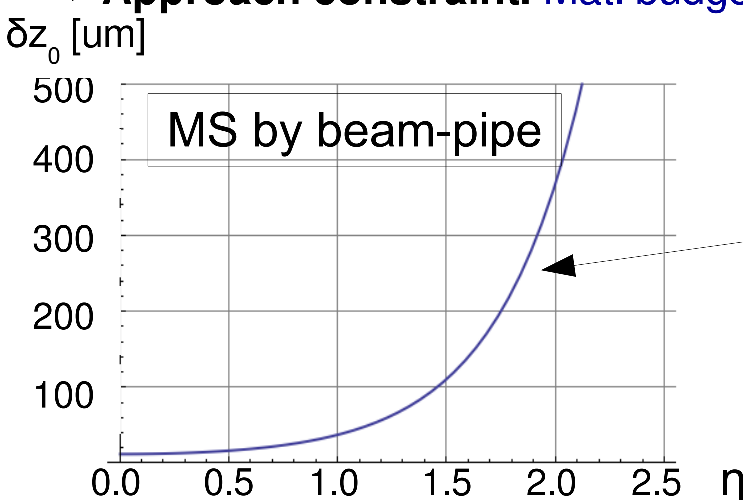
Tilted Layout: Improvement in Performance

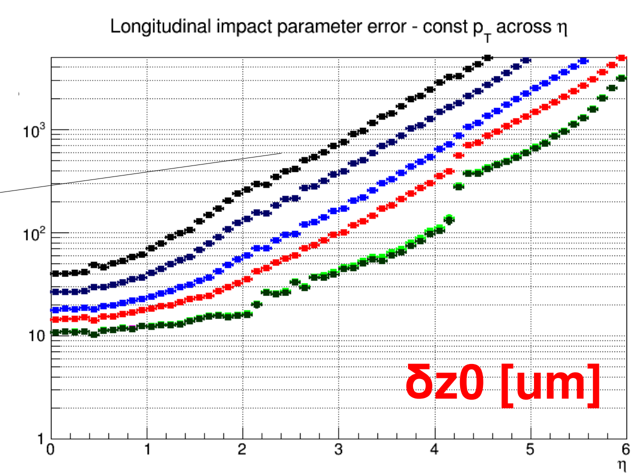




p_T = 1 GeV/c
p_T = 5 GeV/c
p_T = 10 GeV/c
p_T = 100 GeV/c
p_T = 1 TeV/c
p_T = 10 TeV/c

→ **Approach constraint:** Mat. budget assumed per module → need to add realistic engineering: services etc.





Tilted layout: The dominant effect for "low" p_T tracks is **beam-pipe mat.!**

Vertexing @ PU=1000 & Timing Information

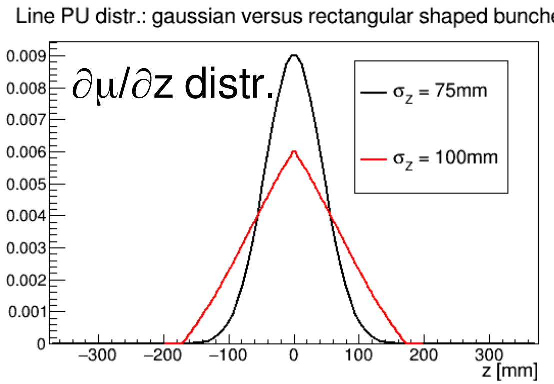
- How the pile-up (PU)~1000 degrades primary vertexing? Would the timing info help?

→ 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

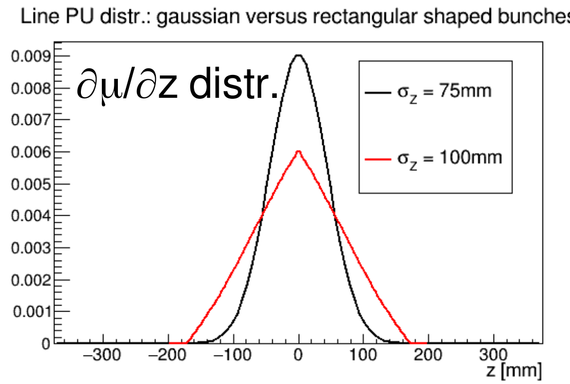
- How the pile-up (PU)~1000 degrades primary vertexing? Would the timing info help?

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

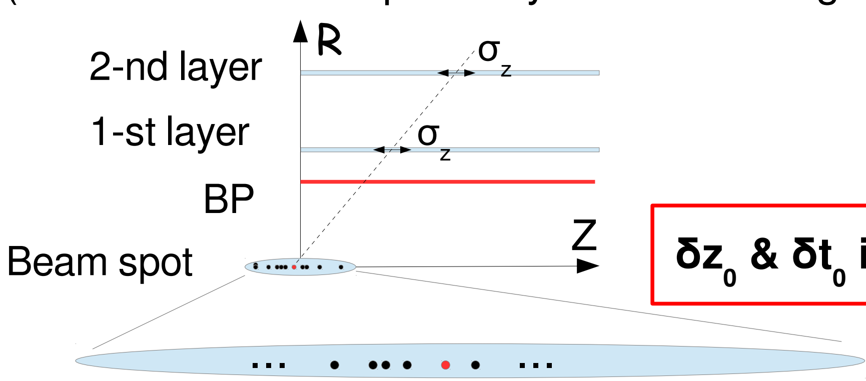
→ **Line PU:** $\frac{\sqrt{1+\phi^2}}{\sqrt{\pi}\sigma_z} e^{-(1+\phi^2)\left(\frac{z}{\sigma_z}\right)^2}$

→ **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

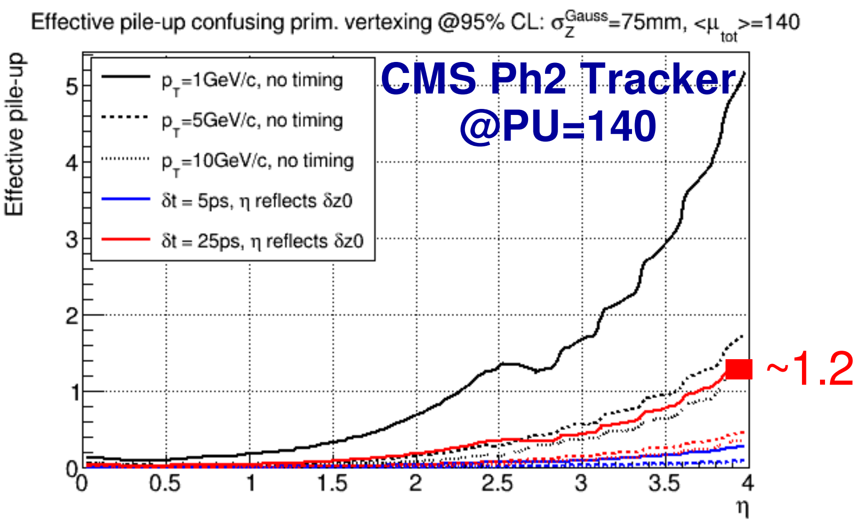
→ Study **what fraction of tracks may be unambiguously assigned to the primary vertex @ 95% CL? Use 2D info** (PV assumed to be “precisely” found from e.g. high p_T tracks)



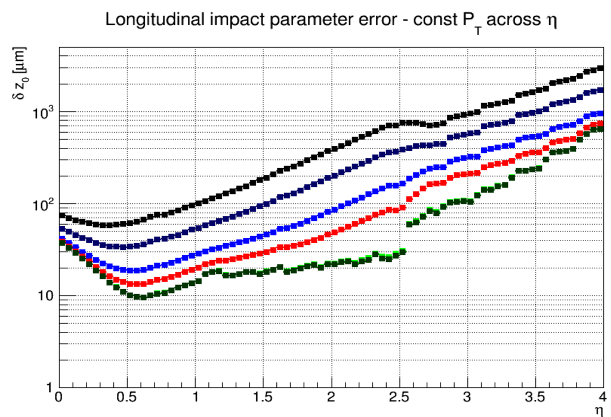
δz_0 & δt_0 interplay crucial!

Effective Pile-up Rate & Timing Information

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



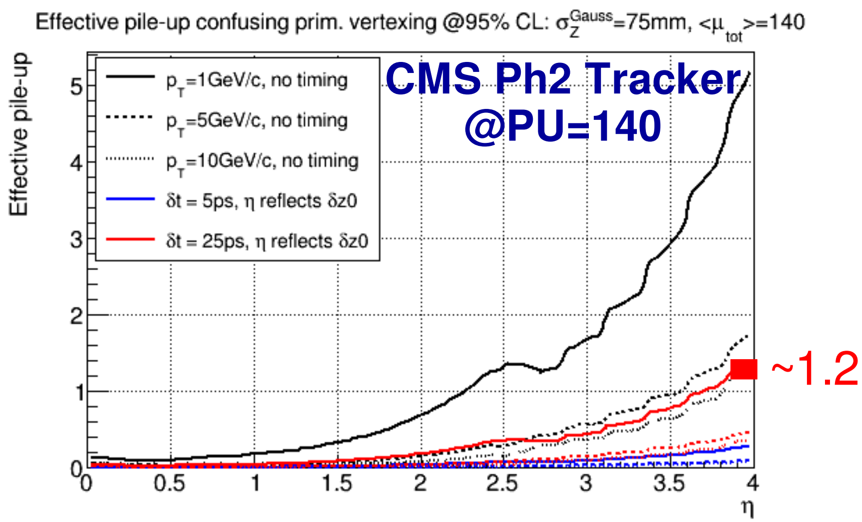
Why such shape? Follow z0 res. curve…



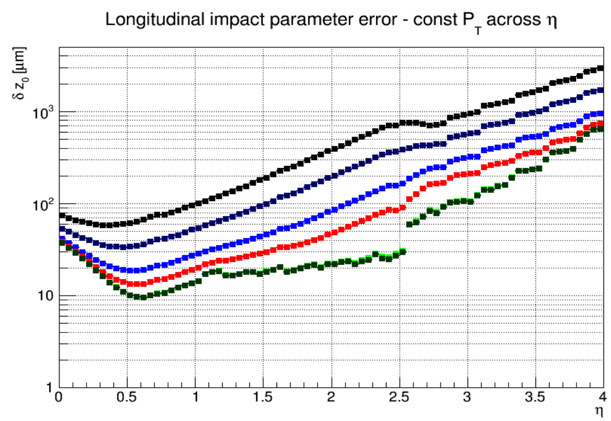
Decrease in δz0 needs to be "compensated" by extra timing info (in FWD)

Effective Pile-up Rate & Timing Information

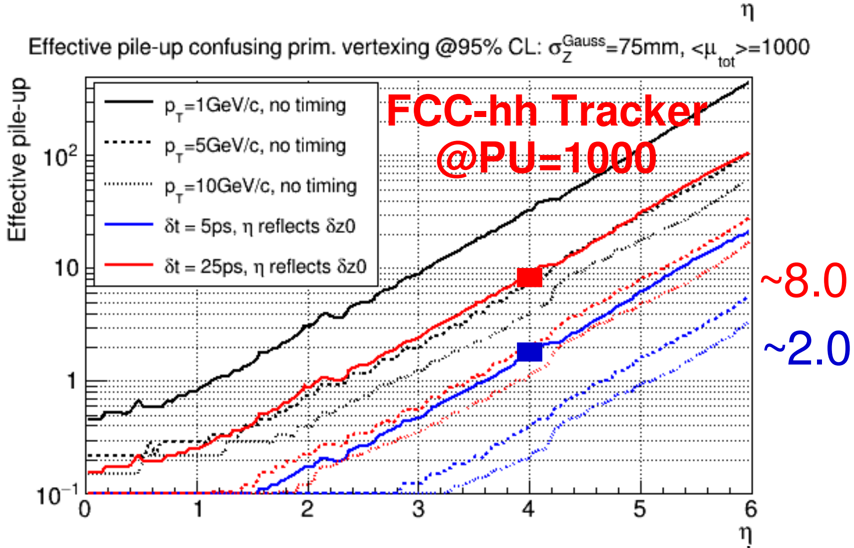
→ Compare **FCC-hh** to **HL-LHC** conditions **(PU~140)**, using e.g. CMS Ph2 upgrade layout



Why such shape? Follow z0 res. curve...



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



FCC-hh: 2D vertexing (time & z) essential, but may not be sufficient to mitigate the PU effect, namely for η>4.0

Occupancy & Expected Data Rates @ PU=1000

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

  → use **Fluka sim. charged particles fluence** & calculate hit occupancy (binary R/O):

- **E.g. inner tracker:**

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	
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 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

→ Expected **huge tracker data rates: 766 TB/s** (untrig. @40MHz), **19 TB/s** (trig. @1MHz)

→ Expected **extreme data flows>>10Gb/s/module** (from innermost layers/discs, even when being triggered **@1MHz)**

Summary & Challenges

- **The key tracker parameters have been studied & optimized:**

→ **Layout:** ~430m^2 (391m^2 in tilted layout) of Si, with: 5461M (pixels), 9964M (macropixels), 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 mat. budget **the tracker (even vertex detector) in tilted layout very advantageous** 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~5ps (2D vertexing, several timing layers assumed) → 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!

→ **1MeV neq fluence ~6x10^{17}cm^{-2}** & **TID ~0.4GGy @ R=25mm** represent **new challenges** for the tracker (vertex detector) technologies

→ **Dedicated R&D is needed to meet the challenging requirements!**