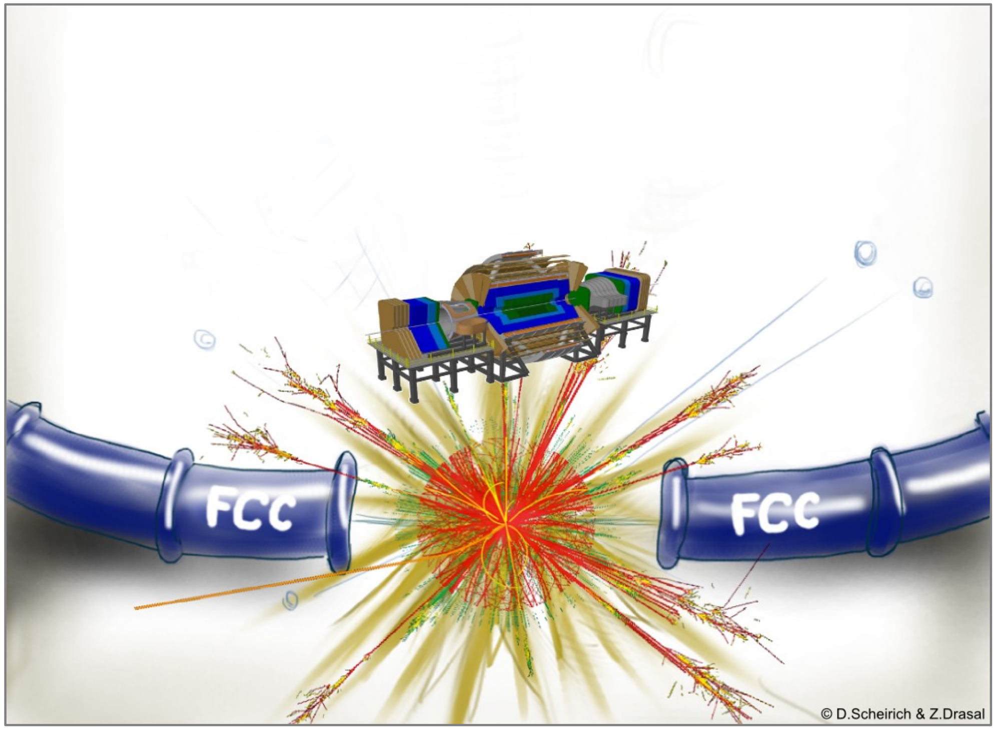
Tracker Optimization: Pile-up & Vertex Finding



Zbyněk Drásal
CERN

With Marcello Mannelli

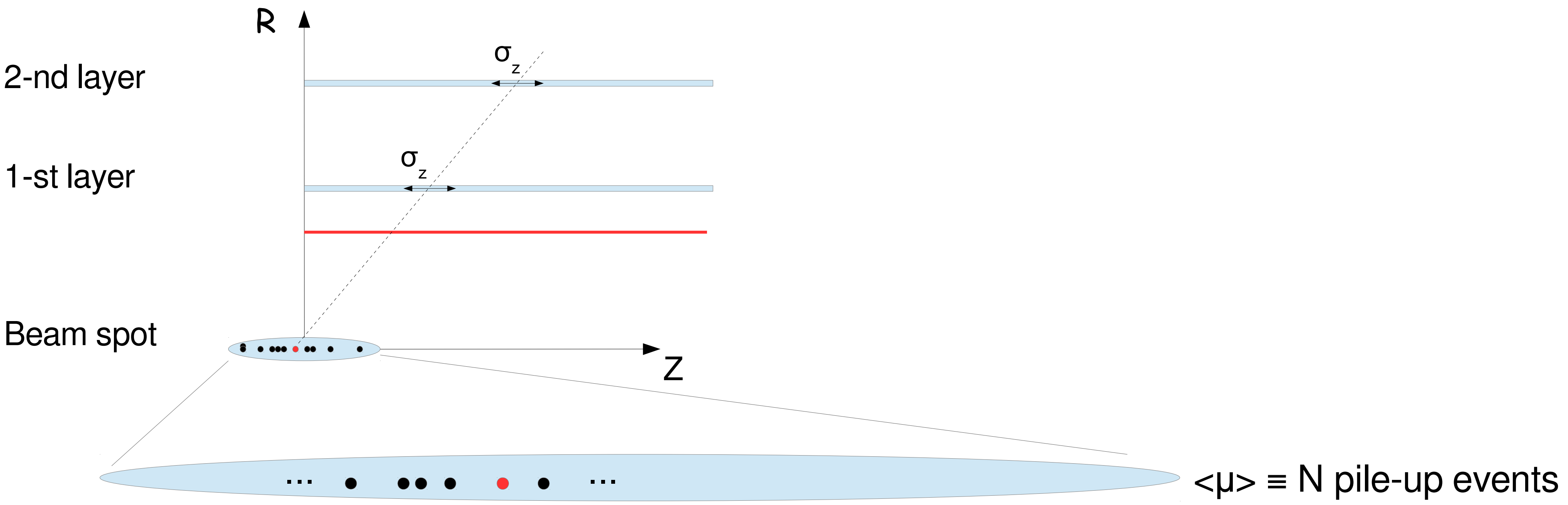
Introduction

- Pile-up & Z_0 res. : update & corrections on the study presented on FCC-hh (Sep 28^{th})
  - Different scenarios of bunch structure simulated:
    - Gaussian-shaped bunches
    - Rectangular-shaped bunches
  - Pile-up scenarios compared to HL-LHC environment & CMS performance
  - Maths beyond Z_0 res. → possible improvements with tilted geometry, etc.
- Conclusions & Outlook

Pile-up & Requirements on Z Resolution

- dp_T/p_T resolution given by tracker granularity in R-Φ, what defines the granularity in Z?

→ one of the key requirements on the tracker layout: **to find the primary vertex in a huge pile-up**



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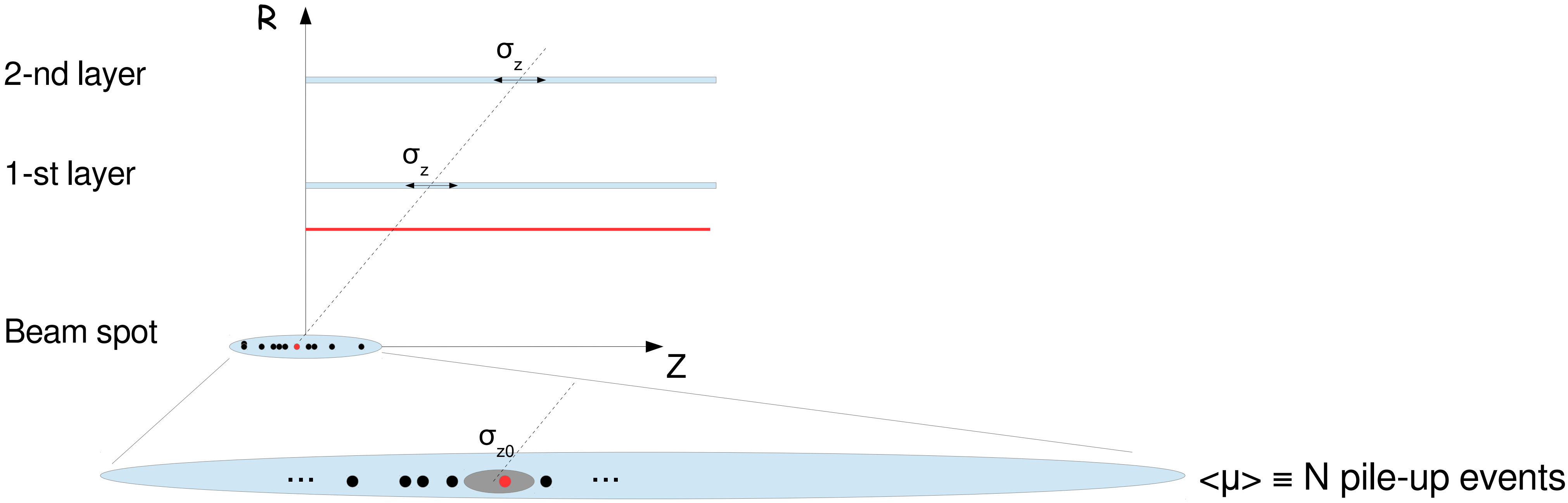

→ **Z_0 res. needs to be "sufficiently small" in order not to cover several pile-up vertices**

Pile-up Estimation

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

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

- σ_{inel} ~ 85mb @ 14TeV (LHC) → ~ **108mb @ 100TeV (FCC-hh)**
- **n_B = 2808** → N bunches (nominal LHC)
- **f_r = 11.245kHz** → revolution frequency (nominal LHC)
- **L = 5 (20-30) x 10^{34}** $cm^{-2}s^{-1}$ → HL-LHC or FCC-hh Phase1 (FCC-hh Phase2)

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  - **Pile-up: μ is Poisson distributed**

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  - affected by spread of luminosity → ~ a few % (?)
  - **Pile-up: μ is Poisson distributed** → quantify **limits** by 95% confidence interval (σ~1.96√N)

→ <μ> = 135 ± 23 (HL-LHC)

→ <μ> = 170 ± 26 (FCC-hh phase 1) → ~ **200 pile-up events** as a limit

→ <μ> = 1026 ± 63 (FCC-hh phase 2) → **~1100 pile-up events** as a limit (NOT 1000 pile-ups)

Beam-spot Simulation

- How to estimate the pile-up distribution in Z?
  - **Procedure:**

    → simulate N piled-up vertices according to relevant Line PU Density distr. in 2 scenarios (for ref. see: http://journals.aps.org/prab/pdf/10.1103/PhysRevSTAB.17.111001)

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

versus

Rectangular bunches: $\frac{1}{2L}\Theta(1-|z|/L)$ → $\frac{\sqrt{\pi}}{2RL\psi}\mathrm{Erf}[\psi(1-|z|/L)]\Theta(1-|z|/L)e^{-(\frac{\phi z}{L})^2}$

where ϕ (**Piwinsky angle**) corresponds to **crab cavity effect** (ϕ=0 → full crabbing) & ψ (“**time**” **Piwinsky angle**) to crab “kissing” (ψ=0 → no kissing)

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  - **Comment:** Correction to previous results → Colliding bunches ~ 2 waves with phases: (ct+z), (ct-z)
    Hence, in scenario with ϕ=0 one gets $\sigma_{collision} = \sigma_z/\sqrt{2}$ (NOT σ_z)

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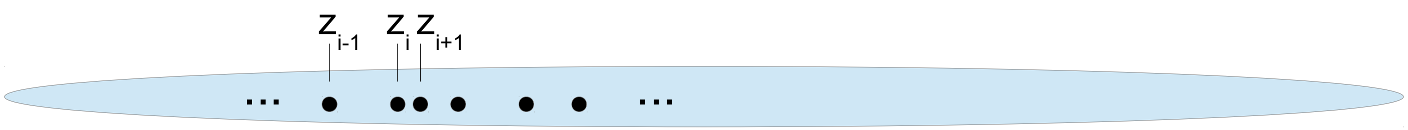

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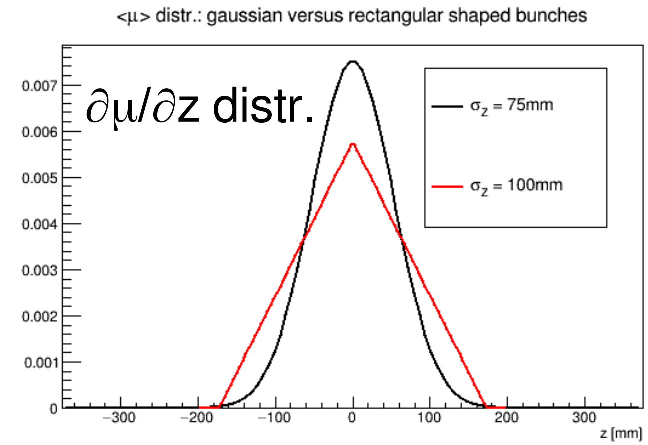
→ use quantiles **to quantify** the required Z_0 resolution: $\delta(Z_0)$ → "purity" estimate

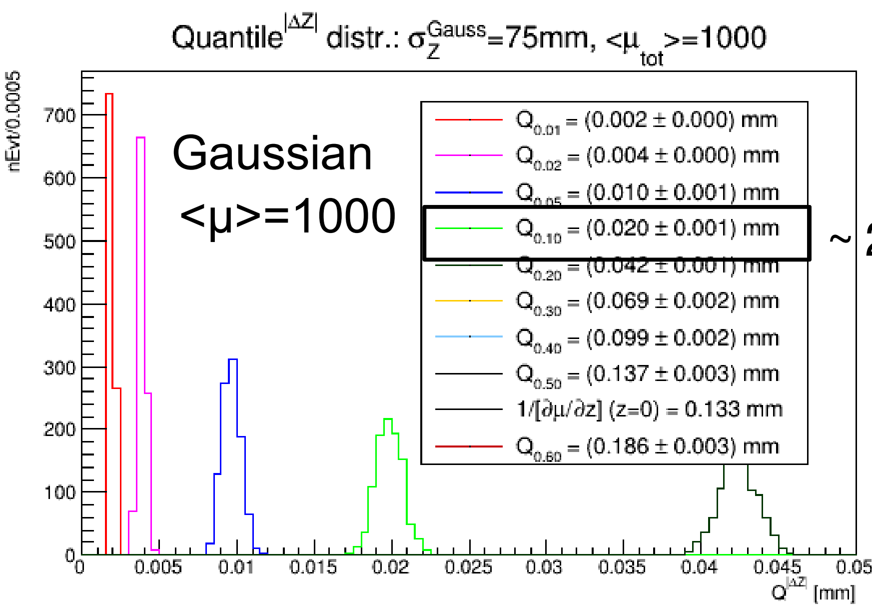
Comments:

- Quantiles are not directly related to "events loss" (only correlated) → in events with more than 1 vertex being assigned to a bunch of tracks, one may naturally expect an increase in combinatorial bkg, efficiency decrease etc. (only full simulation & physics use case studies can estimate the overall effect)
- An average particle p_T is <1GeV/c → one naturally expects to measure only a small fraction of p_T spectrum → so the final requirements on vertexing/triggering capabilities may be much softer

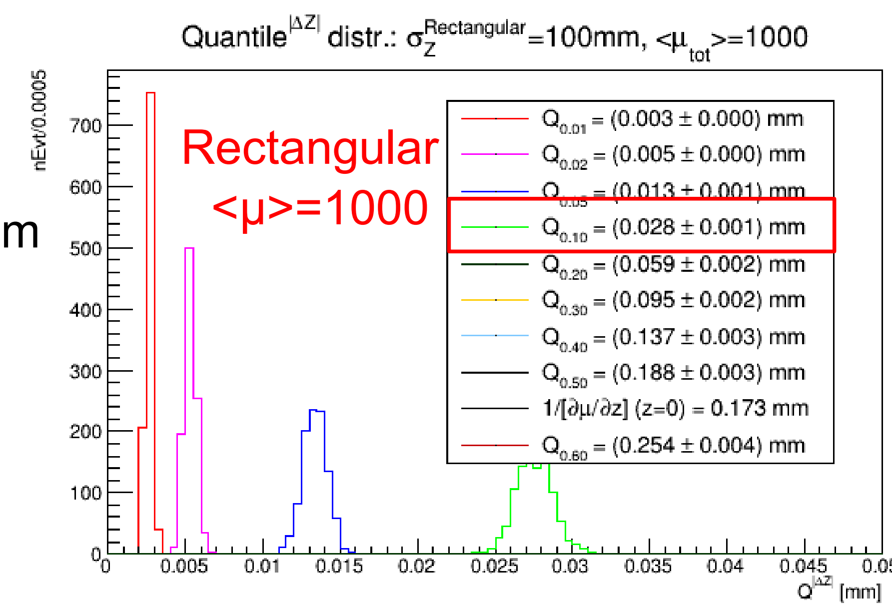
FCC Scenario: Gaussian versus Rectangular

- Pile-up distribution for full crabbing (ϕ=0), no kissing (ψ=0)





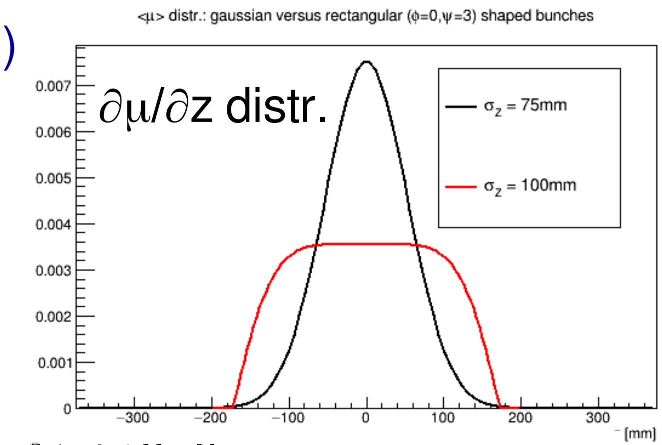
~ 20μm

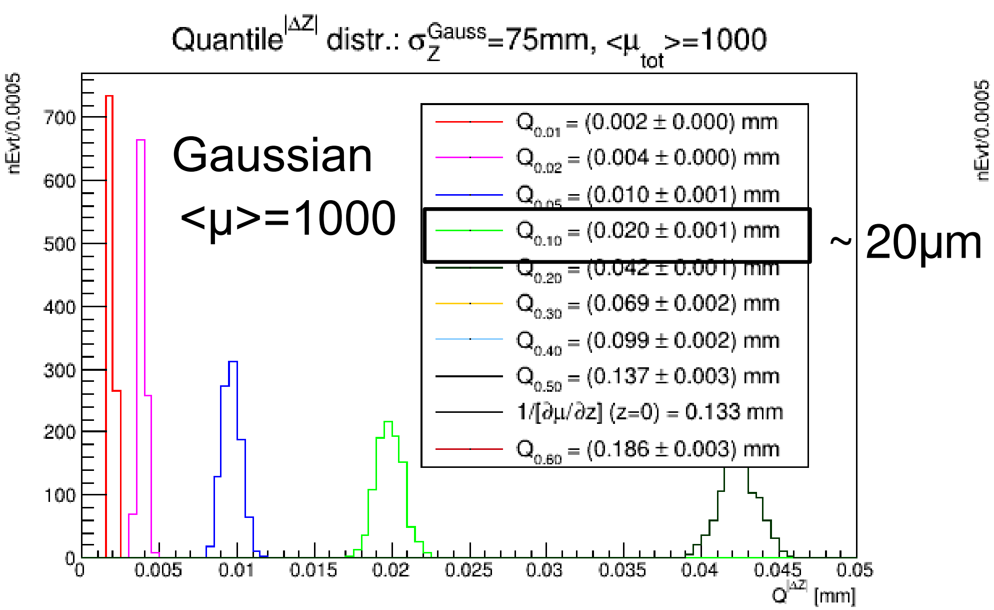


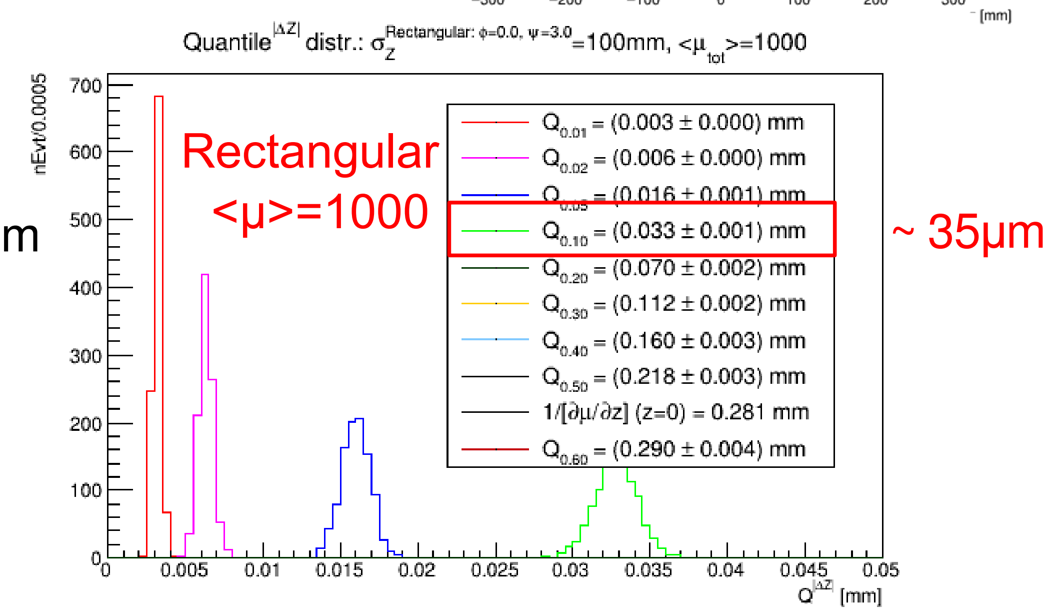
~ 30μm

FCC Scenario: non-zero Time-Piwinsky Angle

- Pile-up distr. for full crabbing (ϕ=0), crab-kissing (e.g. $\psi \sim 3.0$)

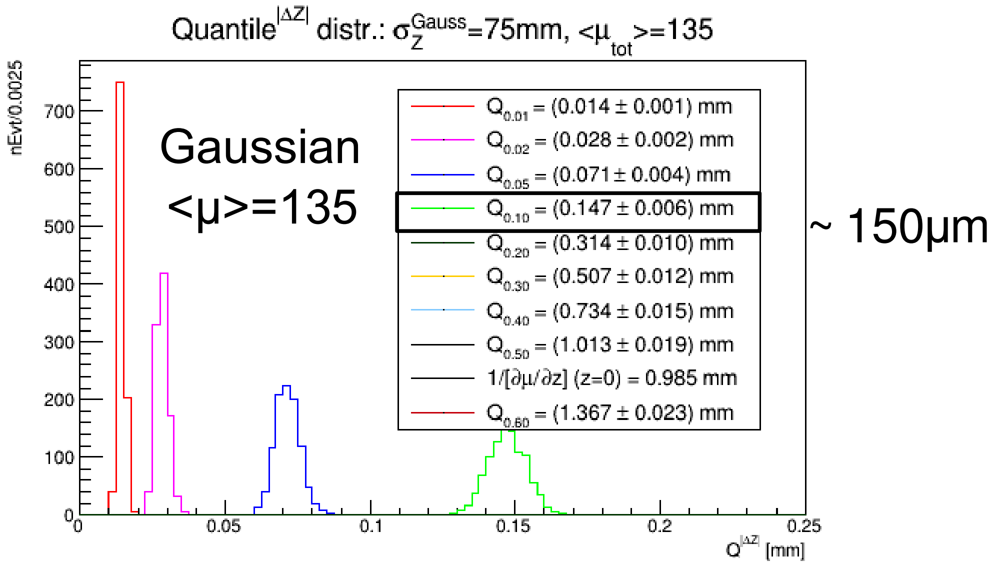


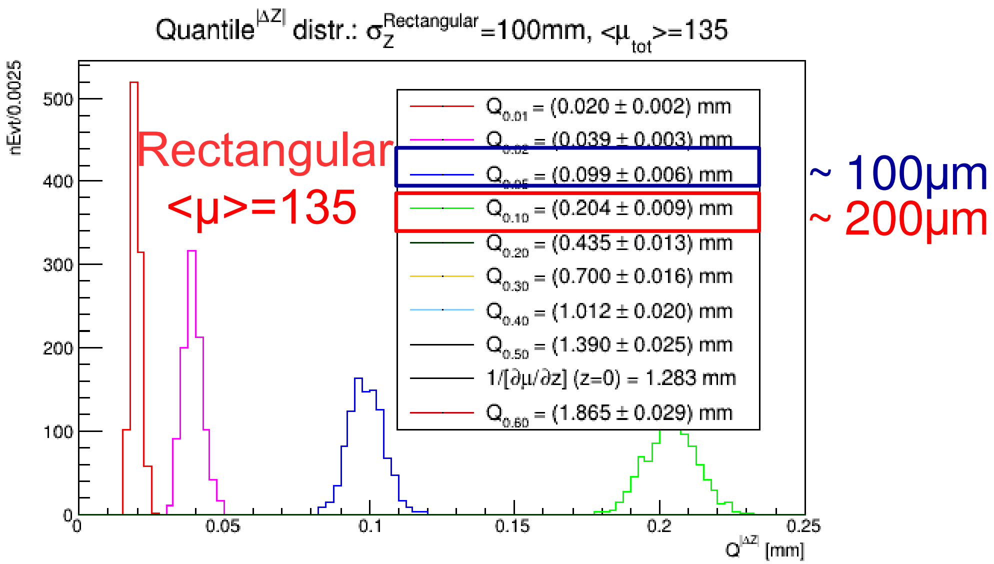




→ **bunch structure have a non-negligible effect on the pile-up distribution (~ factor of 2)**

Compare to HL-LHC Scenario for Reference





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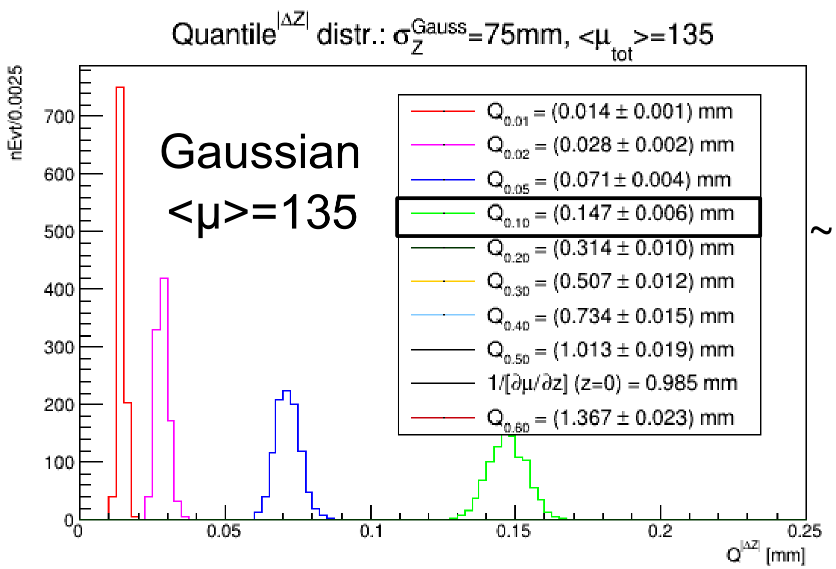
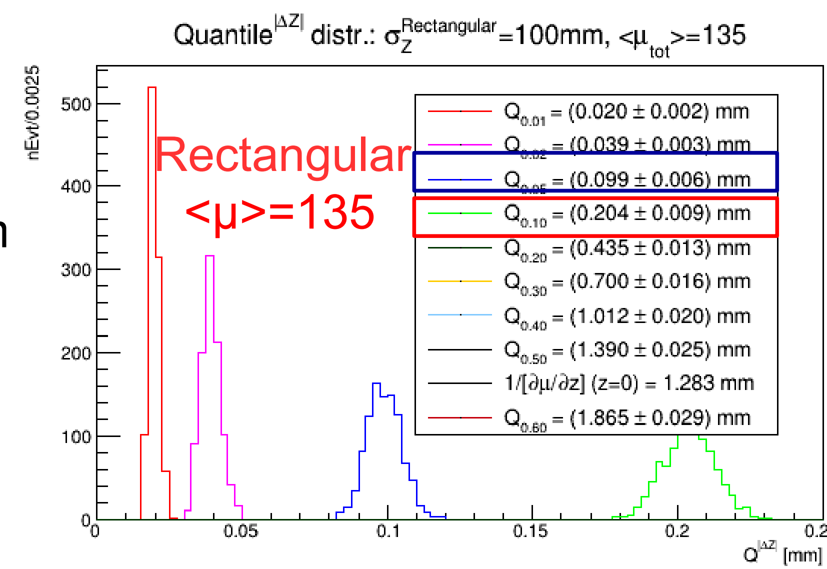
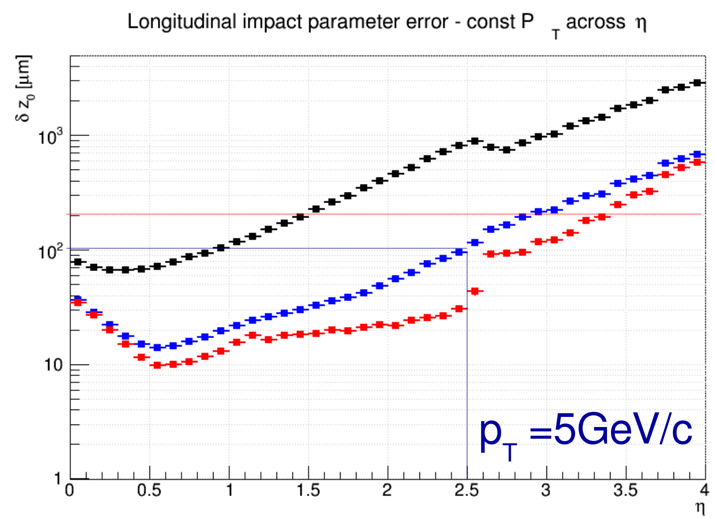


~ 150μm



~ 100μm
~ 200μm

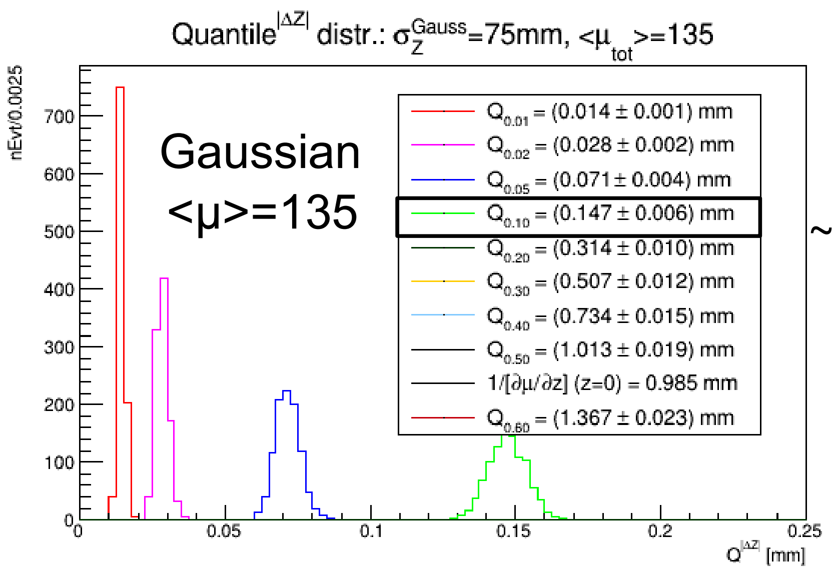
CMS Phase 2 tracker $\delta(z_0)$:



~ 200μm
~ 100μm

→ Rule of thumb: Apply **Q_5-Q_{10} limits**

Compare to HL-LHC Scenario for Reference



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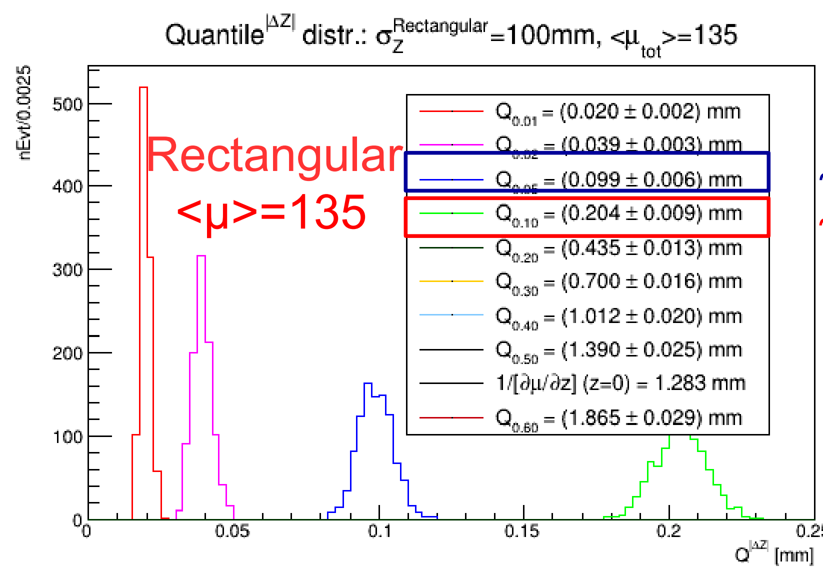

~ 100μm
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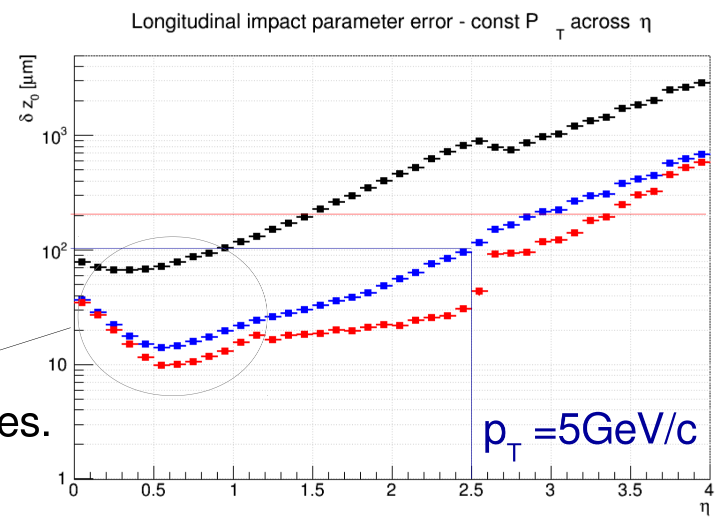
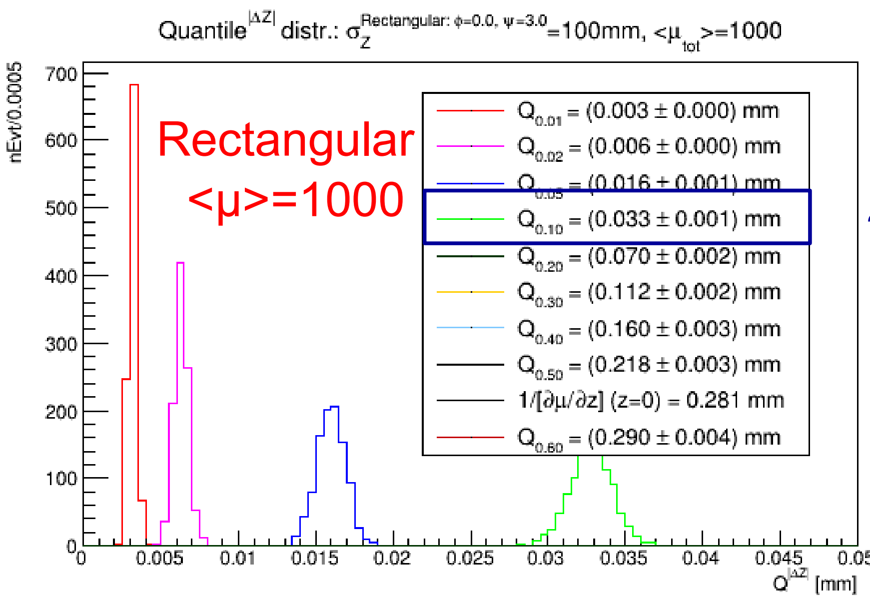


Effect of cluster size on det. res.

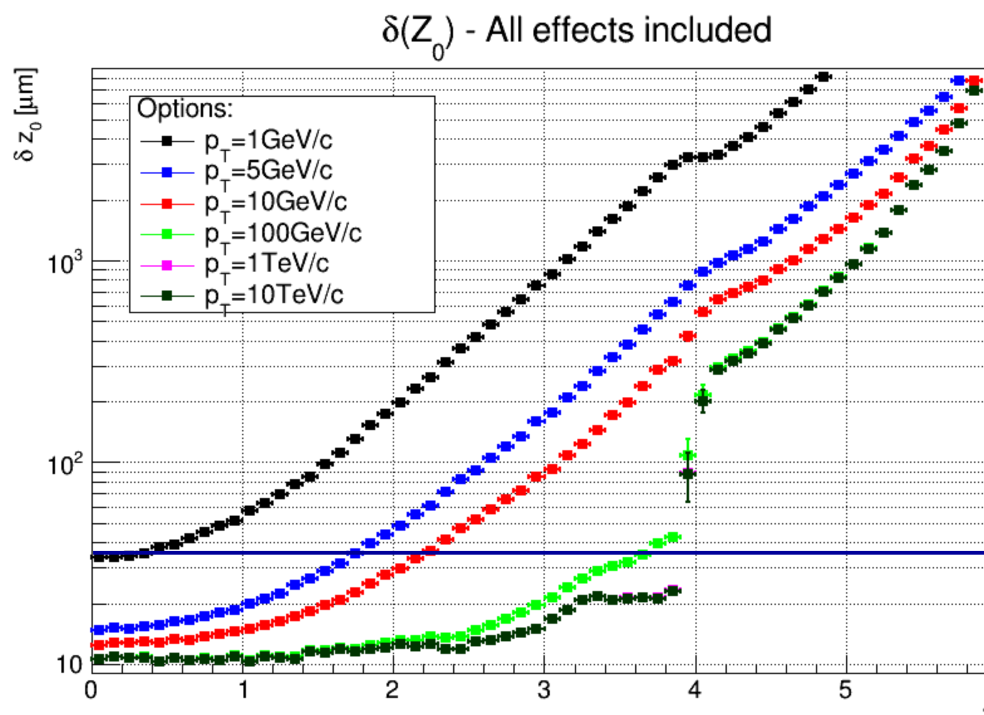
~ 200μm
~ 100μm

► Rule of thumb: Apply **Q_5-Q_{10} limits**

FCC-hh Detector & Impact Parameter Resolution



~ 35μm



~ 35μm

Problem!!!

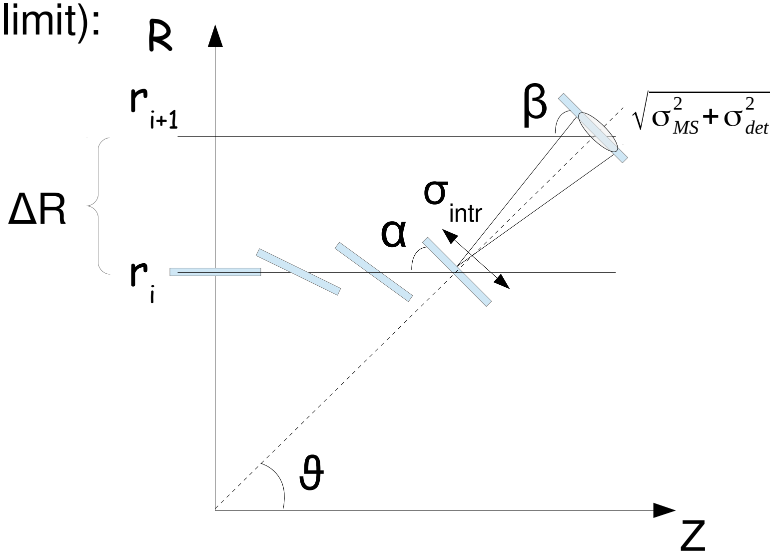
- Is there anything one can do to improve the resolution (degraded by MB)?

Detector Resolution versus Multiple-scattering

- $\delta(z_0) \rightarrow$ 2 main effects playing an opposite role in overall performance in Z:
  - **Detector resolution** propagated to Z direction (in r_i/R_{helix} ~ 0 limit):

$$\sigma^2_{\mathrm{det}} \approx (\cot\vartheta \sin\alpha + \cos\alpha)^2 \sigma^2_{\mathrm{intr}}$$

→ For **non-zero tilt** & high η, det. res. degrades ~ $\frac{1}{\sin^2\vartheta}$



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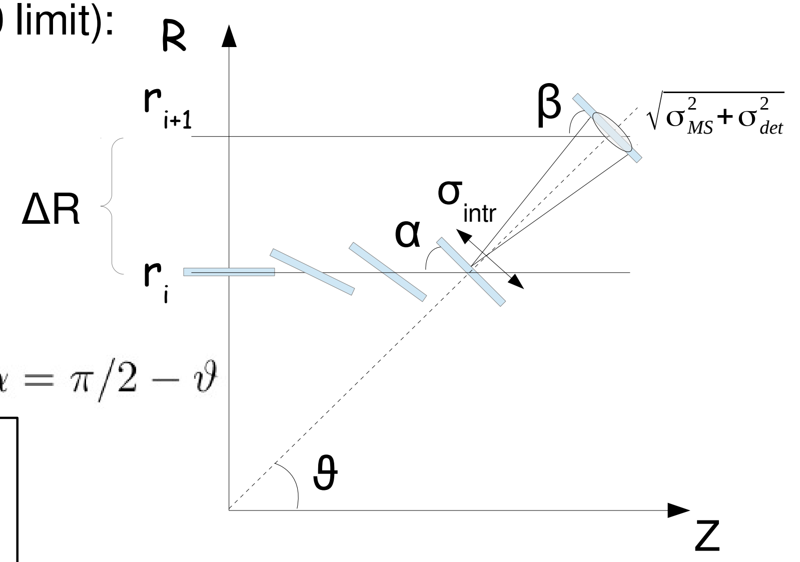

  - **Multiple scattering:**

Tilt of previous layer ~ 1 for $\alpha = \pi/2 - \vartheta$

$$\sigma_{\text{MS}}^2 \approx \langle\vartheta_{p_T}^2\rangle \frac{d/X_0}{\sin(\vartheta+\alpha)} f_L$$

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

$$f_L = \left(\frac{\Delta R}{\sin\vartheta}\right)^2$$

→ MS path length for BRL

→ lower effect for BRL+Disc (or tilted)

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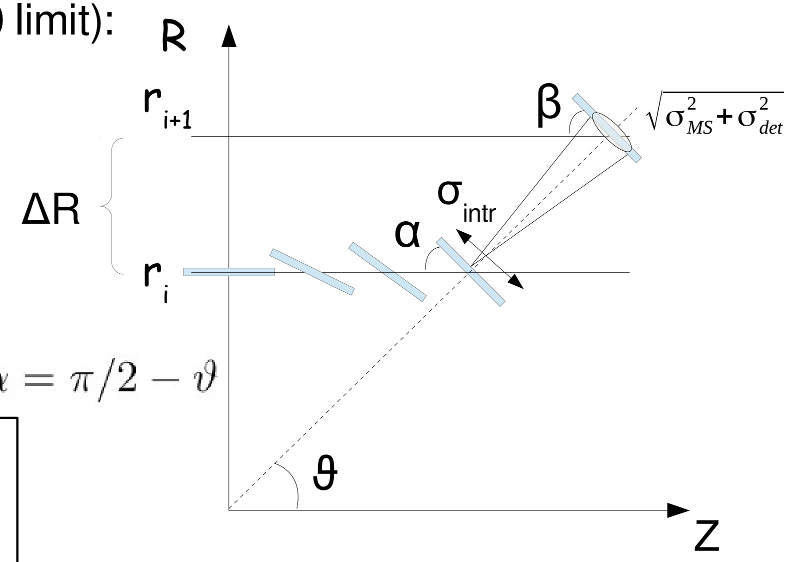

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→ Combination of BRL+Disc structure in tilted geometry decreases MS effect: $\sim \dfrac{1}{\sin^3\vartheta} \rightarrow\ < \dfrac{1}{\sin^2\vartheta}$

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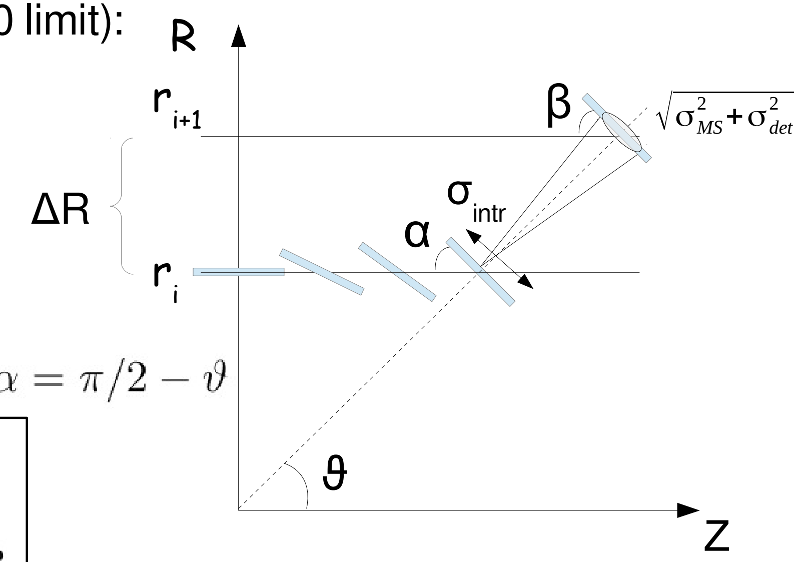

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→ **Tilted geometry + "clever" beam-pipe may give us a possible solution (η~4-6 still difficult)!**

Conclusions & Outlook

- 1000 pile-up (PU) events represent a real challenge to tracking & vertexing @ FCC-hh
  - Moreover, due to Poisson nature of **μ distr.** one should even consider **1100 PU as the worst limit**
  - Applying the same quantiles on Δz primary vertex distr. as for the CMS Ph 2 scenario, we come up to the requirement on **$\delta(Z_0)$ ~ 30-40 μm (correction to previous results) up-to full tracker coverage**
  - The main limitation on the tracker performance is the material budget visible by particle @ high η
- There are several effects, which may "compensate" for the material budget increase @ η:
  - **Clever beam-pipe (BP) design** → need to start a general discussion on possible BP designs
  - **Beam parameters** → 25 (5ns) option
  - **Beam bunch structure** → studied (~ factor of 2 improvement applying the current HL-LHC scenarios)
  - **Tracker with tilted geometry** → under study (complex optimization needed ~ 2months of work)