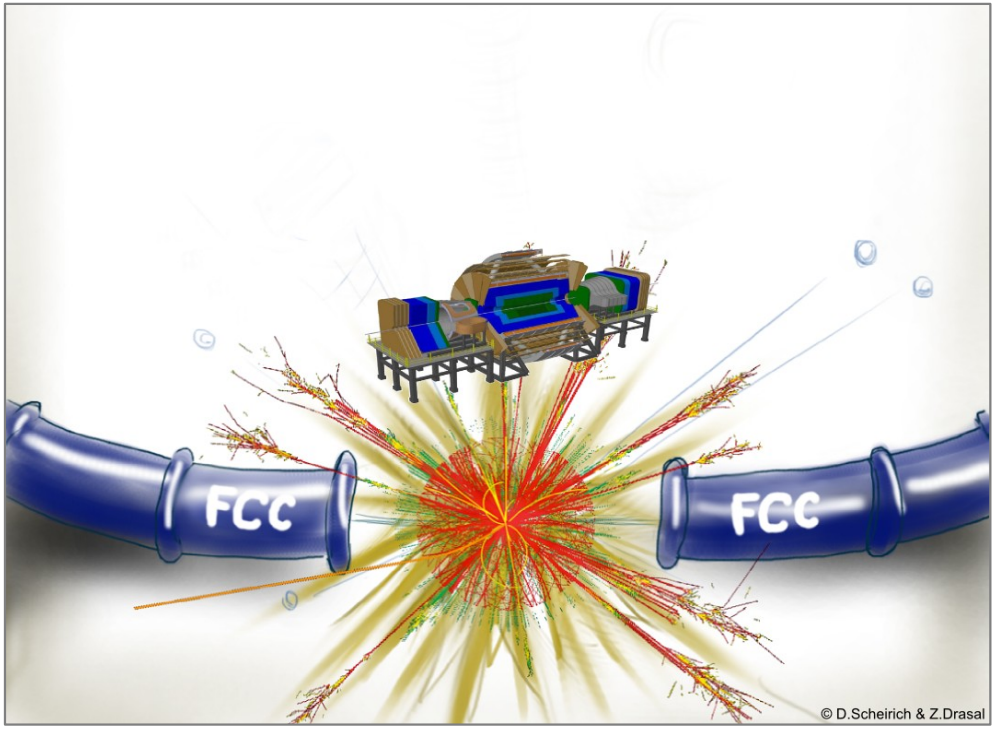
Pattern Recognition & Tracker with Tilted Layout



Zbyněk Drásal
CERN

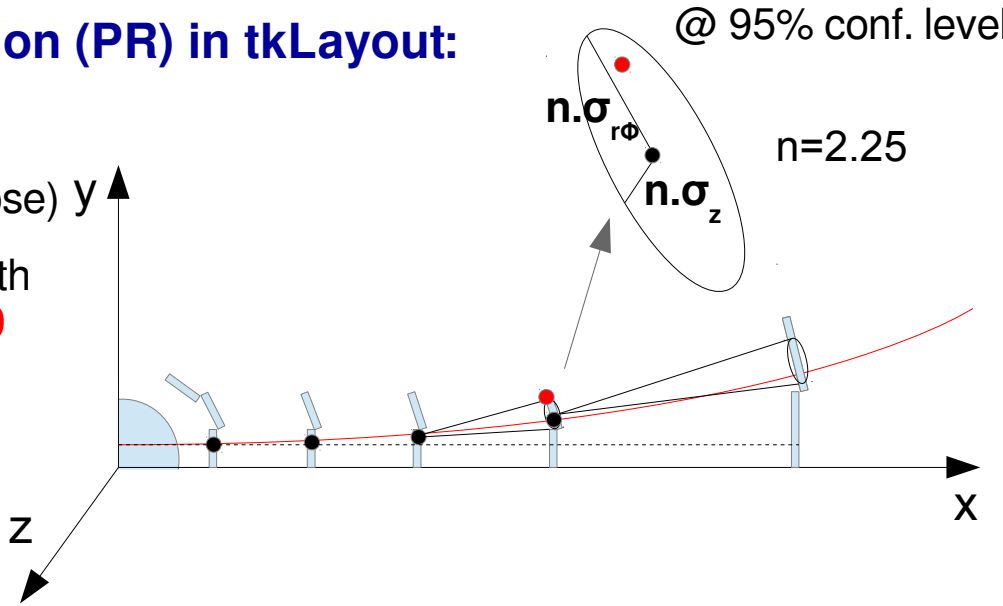
With many thanks to: G. Hugo & S. Mersi (CMS)

Overview

- Mathematical concept of tkLayout pattern recognition in a nutshell
  - Short recap of math. technique introduced 2 months ago
  - Interpretation of method results → comparison with CMS Ph2 tracker layout
- Non-tilted layout & pattern recognition capabilities
  - Drawbacks & solution
  - Details on individual layout parameters affecting particle propagation & pattern recognition
- First proposal of tilted layout
  - Study of pattern recognition performance
  - Improvement in track parameters resolution
- Summary & Outlook

TkLayout Pattern Recognition in a Nutshell

- **Mathematical concept of pattern recognition (PR) in tkLayout:**
  - → Start with a triplet assuming **perfect seeding**
  - → Propagate $\sigma_{r\Phi}$, σ_z to the **i-th layer** (use error ellipse)
  - → Calculate probability **p** to mis-match a **real hit** with a bkg hit @ 95% confidence level → **in PU=1000**



  - **To quantitatively evaluate the overall tracker performance**, calculate a probability that the track has been found with any ambiguity:

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

TkLayout Pattern Recognition in a Nutshell

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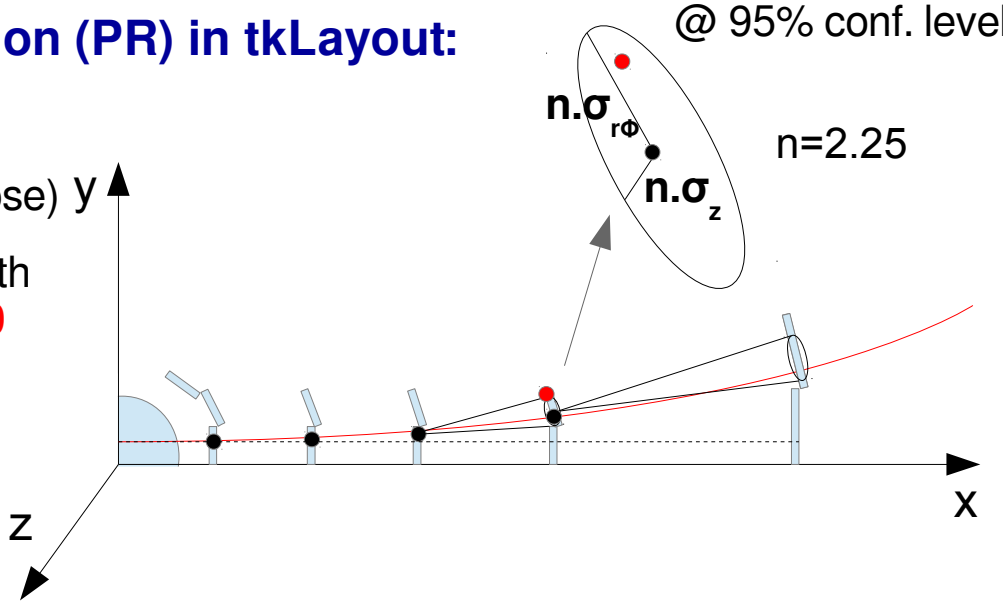


  - **To quantitatively evaluate the overall tracker performance**, calculate a probability that the track has been found with any ambiguity:

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

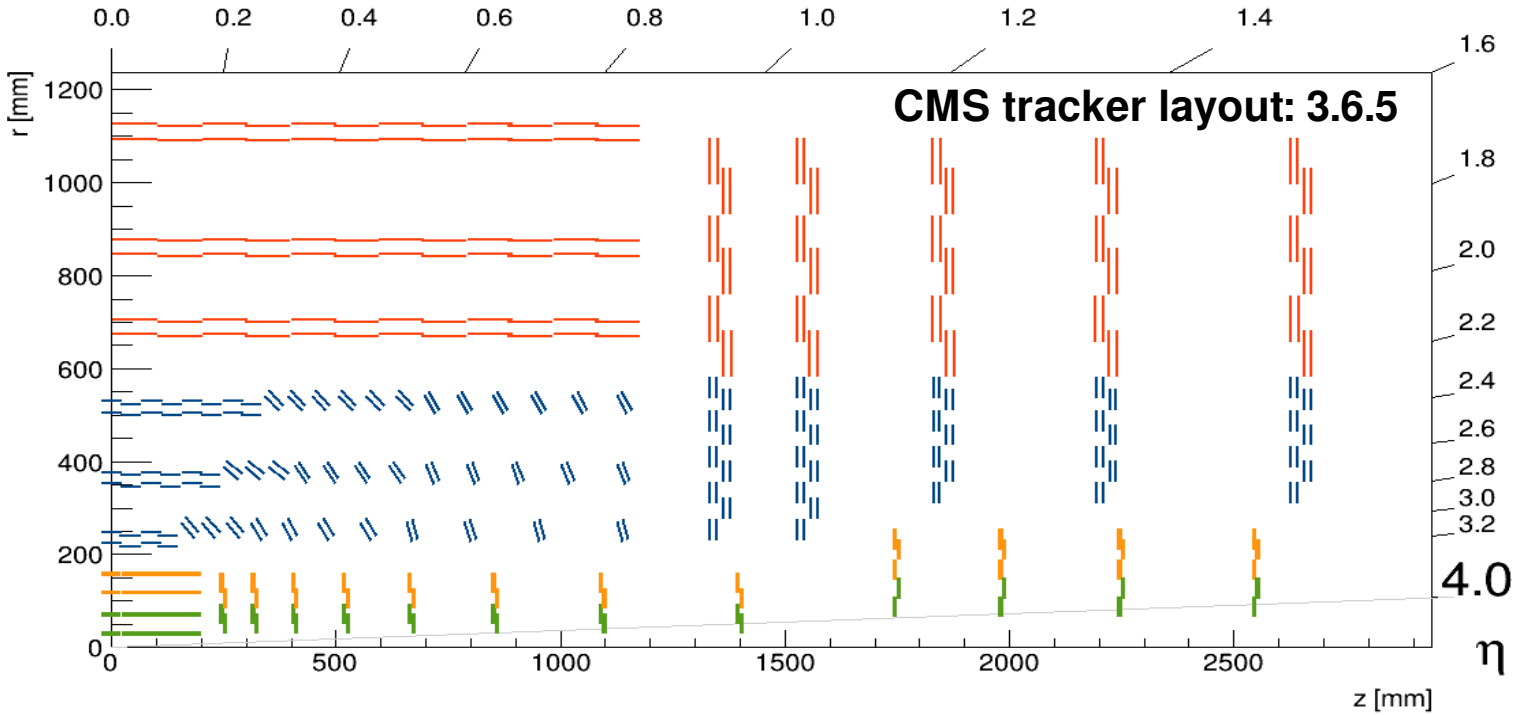
- **Strategy: Check "weak" spots in geometry & optimize:**
  - Module(s) resolution: $\sigma_{r\Phi}$, σ_z
  - Module(s) tilt (min. material budget) & layer-to-layer distance → limit Multiple scattering effect

Interpretation of tkLayout PR Results?

- **Natural question:** How results from such a technique relates to **real tracker pattern recognition capabilites?** Is there a way to **"evaluate" that & interpret the results?**
  - **Only by full simulations**, which is **NOT POSSIBLE** at the moment for FCC-hh tracker, **but...**

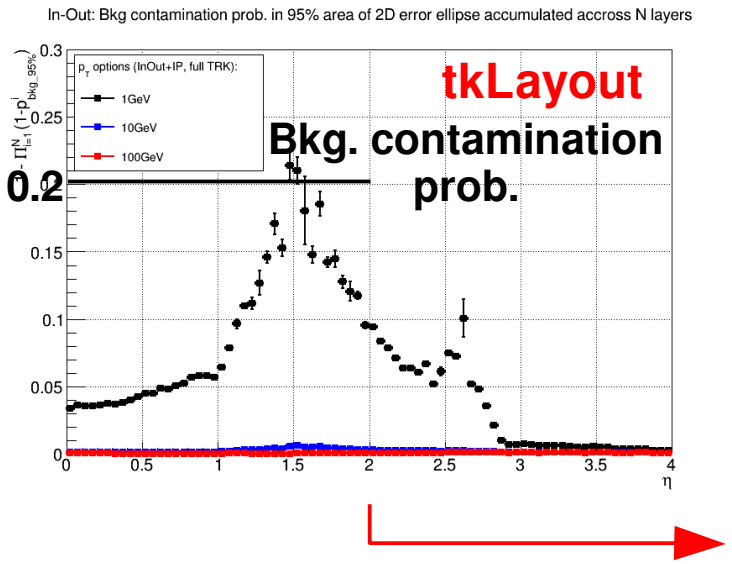
Interpretation of tkLayout PR Results?

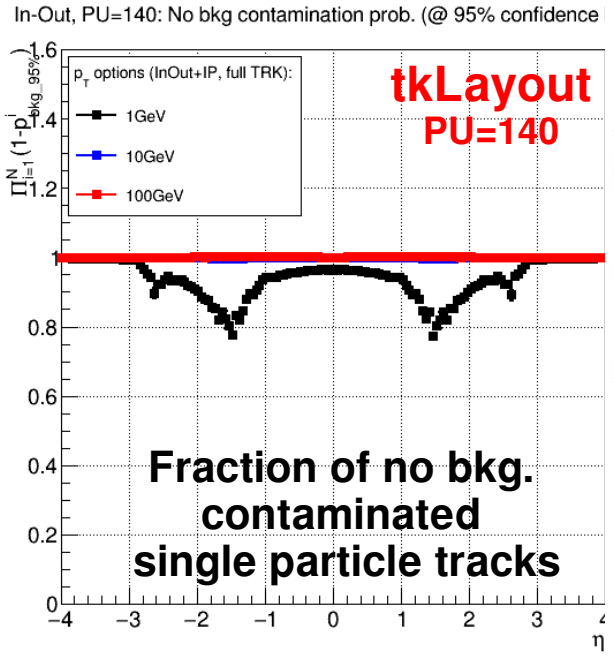
- **Natural question:** How results from such a technique relates to **real tracker pattern recognition capabilites?** Is there a way to **"evaluate" that & interpret the results?**
  - **Only by full simulations**, which is **NOT POSSIBLE** at the moment for FCC-hh tracker, **but...**
  - **We may apply the same technique to CMS Phase 2 upgrade tracker layout & "qualitatively" compare with CMSSW full simulation tracking performance (see results by E. Brondolin for CMS collab.: CMS DP-2017/010)**

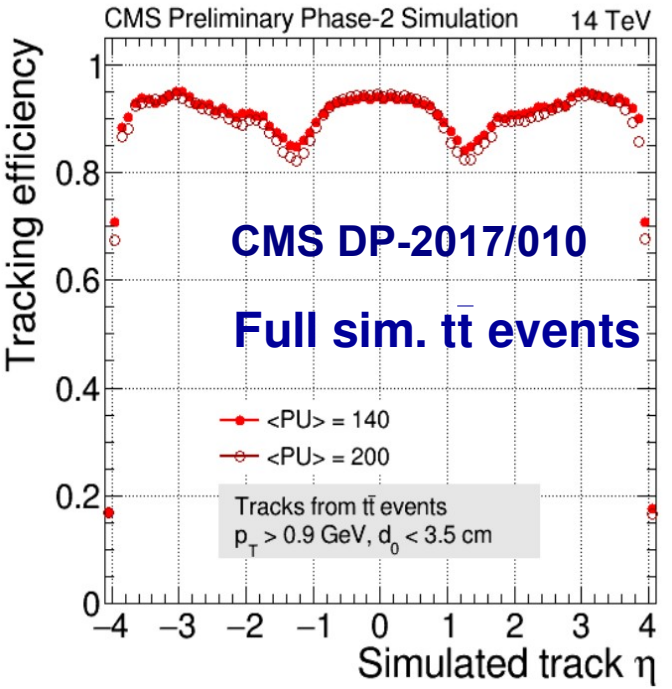


Interpretation of tkLayout PR Results?

→ **Qualitative comparison of single particle study (tkLayout) versus full sim. $t\bar{t}$ events study (CMS DP-2017/010)** to cross-check, whether the technique "sees" the same weak spots in geometry layout → **Follow the shape of tracking efficiency only!**







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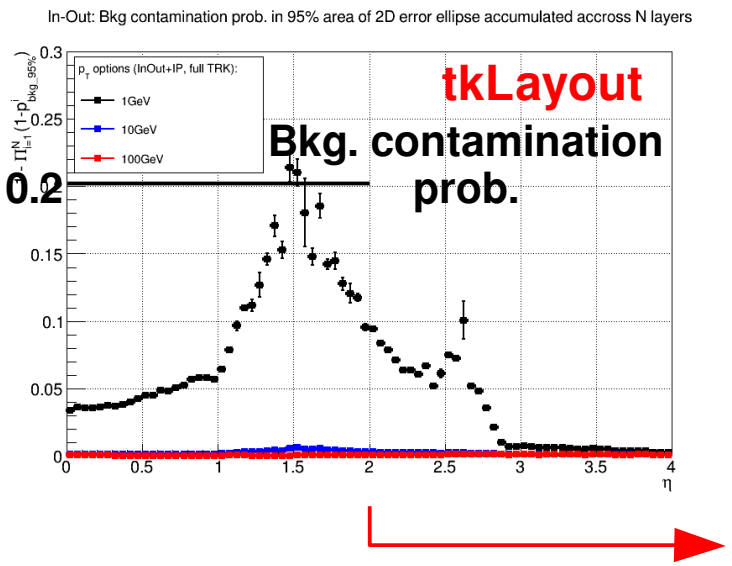
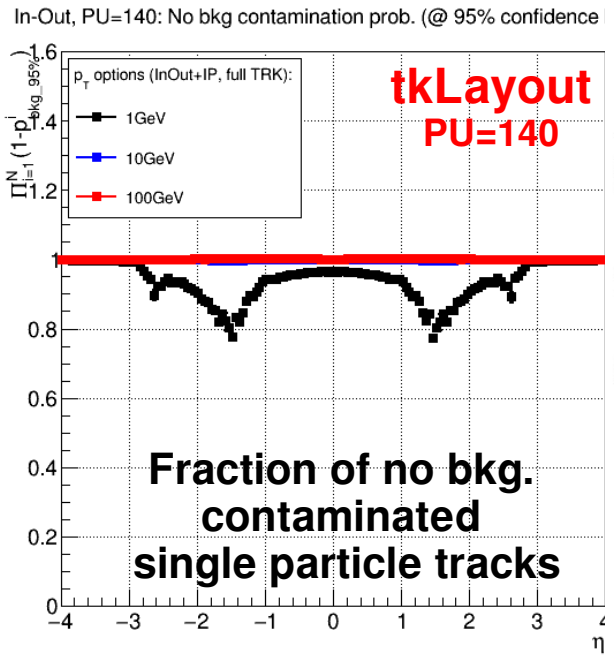
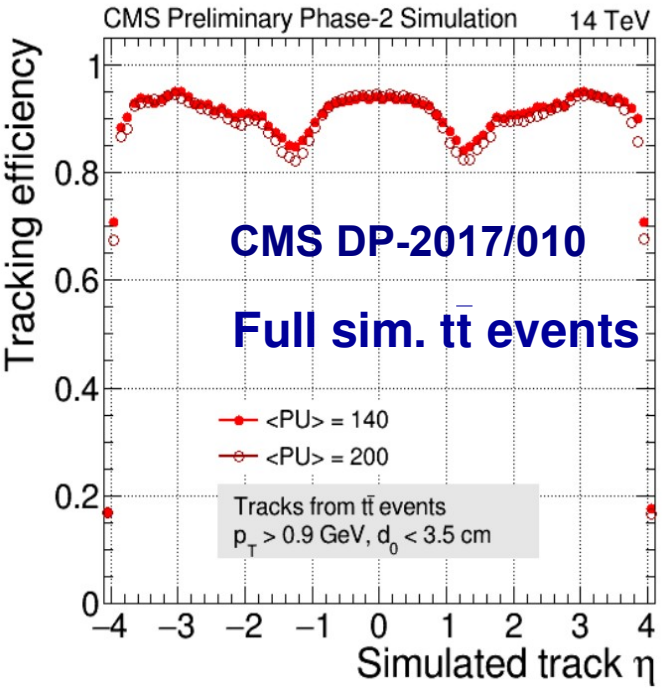


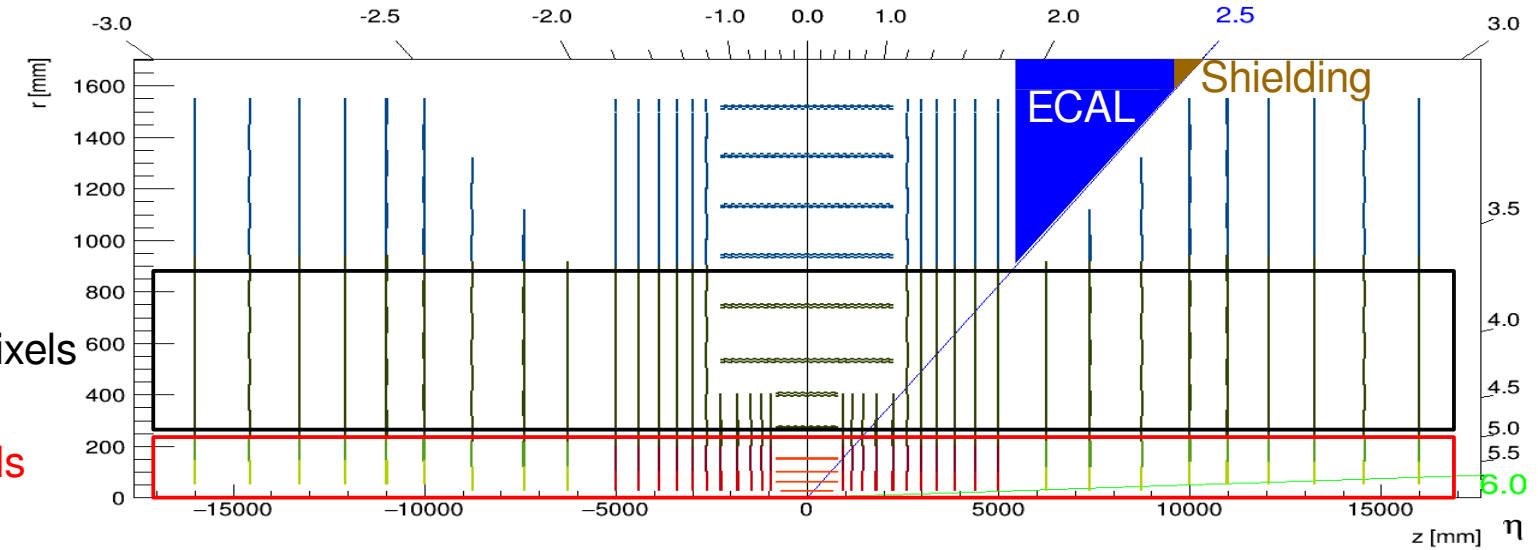




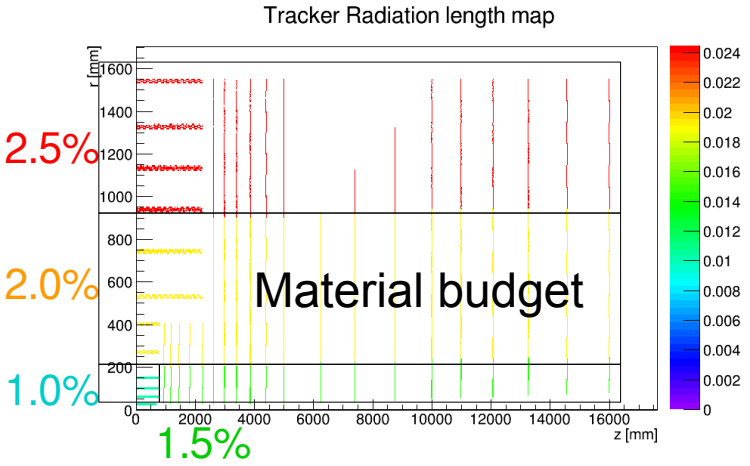
- **Conclusion:**
  - The method provides first quick insight into layout pattern recognition capabilities, **addressing qualitatively the same layout weak "spots" as full simulation analysis!**
  - In order to keep similar performance **@ PU=1000**, let's **set the bkg. prob. contamination @ ~0.2** and drive the layout optimization by that limit! **Cross-check by full. sim. in future necessary!!!**

Non-tilted Layout & Pattern Recognition

- **Geometry 3.v03:**

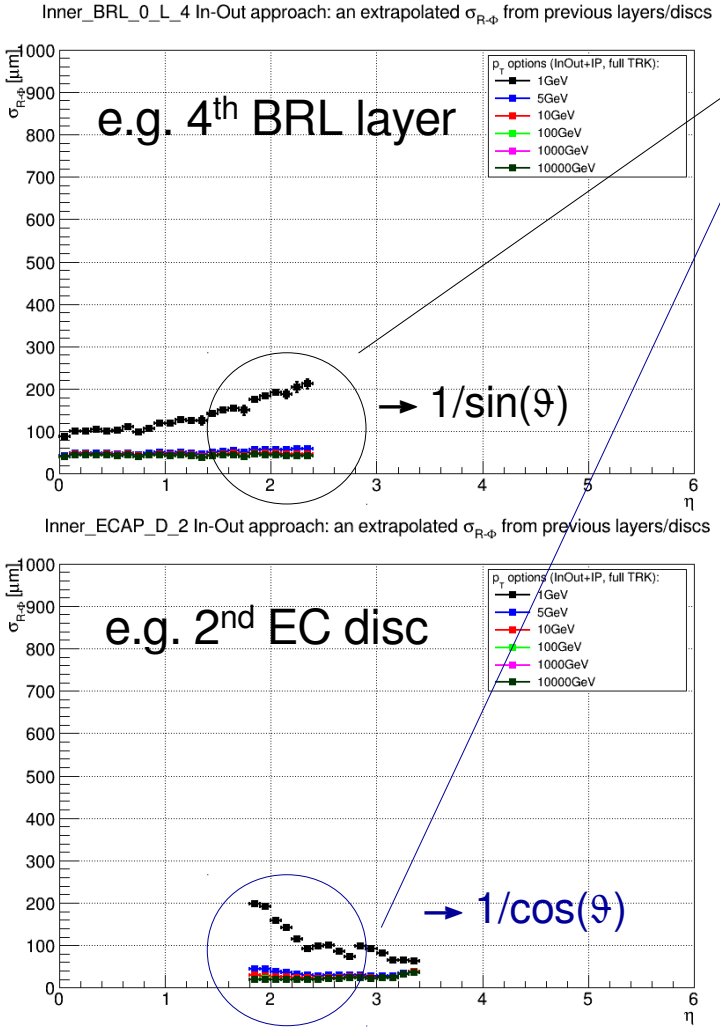


- **Pixels** (pitch)**:** 25x50um^2 (1-4th BRL layers, EC R1), 100/3x100um^2 (R2), 100/3x400um^2 (R3,R4)
- **Macro-pixels** (pitch)**:** 100/3x400um^2
- **Strips** (pitch)**:** 100/3umx50mm (BRL), 100/3umx10mm (EC)



R-Φ: Understanding Pattern Recognition

- Recapitulation of propagator in R-Φ (illustration of typical examples):



BRL: Why propagation **degrades** with higher η?
EC: Why propagation **improves** with higher η?

- σ_d depends on radial distance **Δr** only → **const. effect**, but...
- **Multiple scattering** depends on **material & module tilt** α!
  → α = 0 for BRL
  → α = π/2 for EC

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

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

$$f_L = \left(\frac{\Delta R}{1} \right)^2 \text{ proj. in } R\Phi$$

- **EC** modules → res. in R-Φ given by combination of R & Φ:

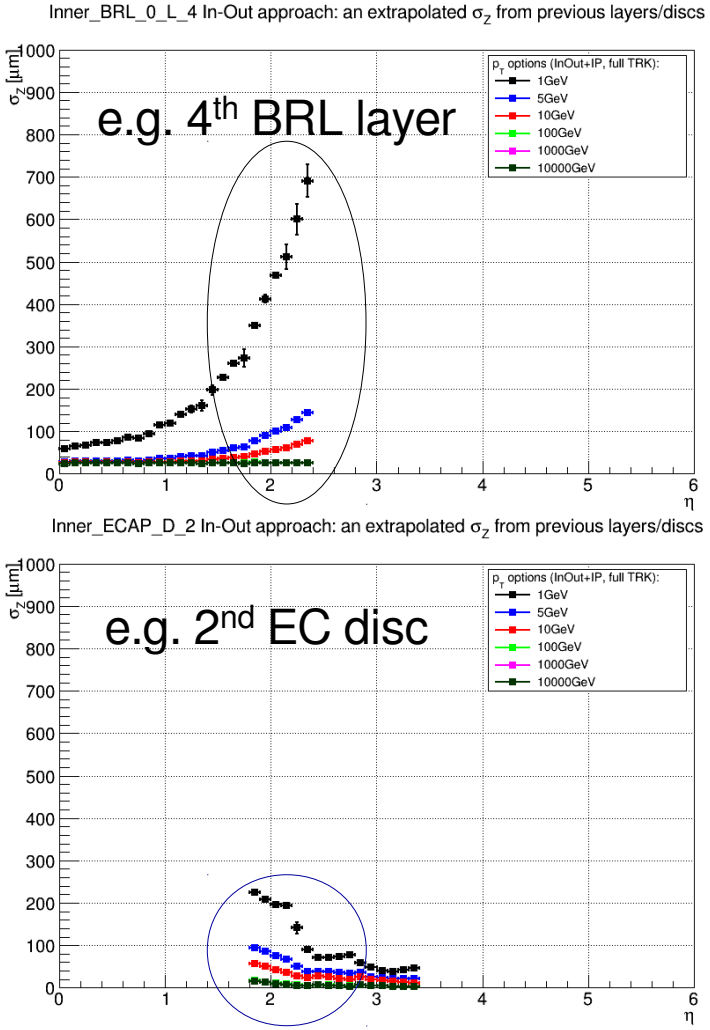
$$\sigma_{R\Phi} = \sqrt{\sigma^2_{R\Phi_{\mathrm{loc}}} + (A/\sqrt{1-A^2}\,\sin\alpha)^2 \sigma^2_{Z_{\mathrm{loc}}}}$$

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

Problem: "long" strips

Z: Understanding Pattern Recognition

- Recapitulation of propagator in Z (illustration of typical examples):



- **σ_z** depends on radial distance **Δr** only, but **projection necessary → ~ $1/\sin^2(\vartheta)$ factor for BRL**
- **Multiple scattering** depends on **material & module tilt α**!
  → $\alpha = 0$ for BRL
  → $\alpha = \pi/2$ for EC

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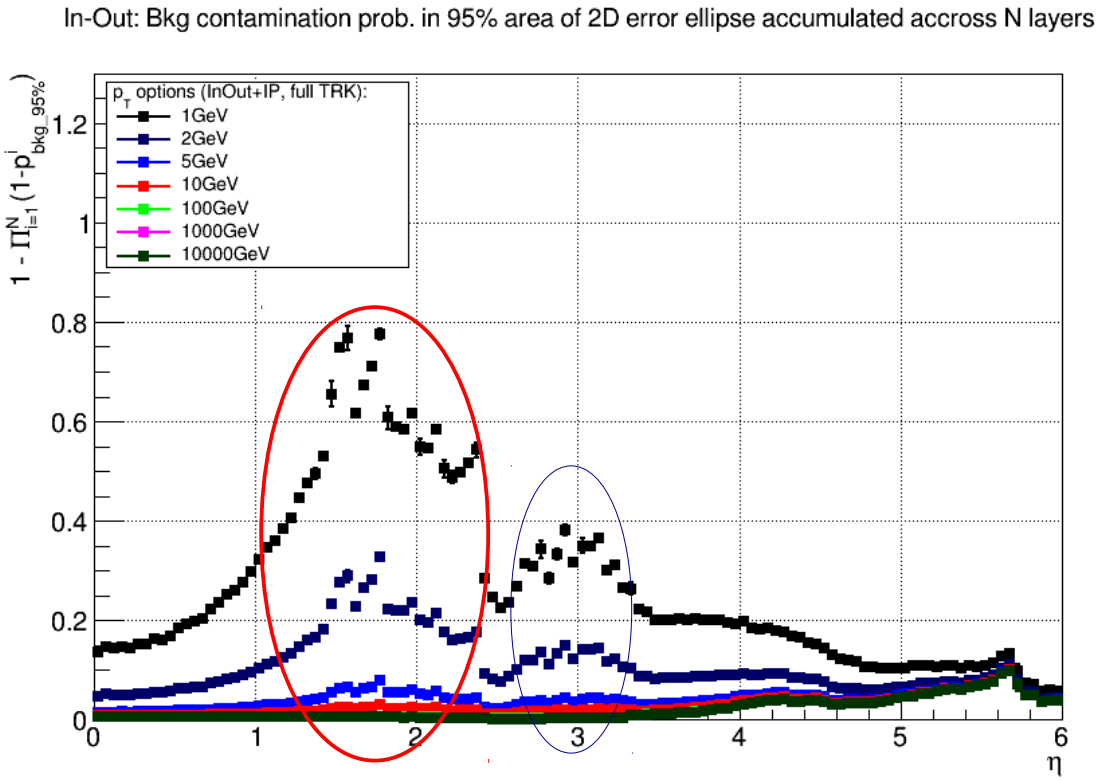
Non-tilted Layout & Pattern Recognition

- **Geometry 3.v03 → Results on pattern recognition:**

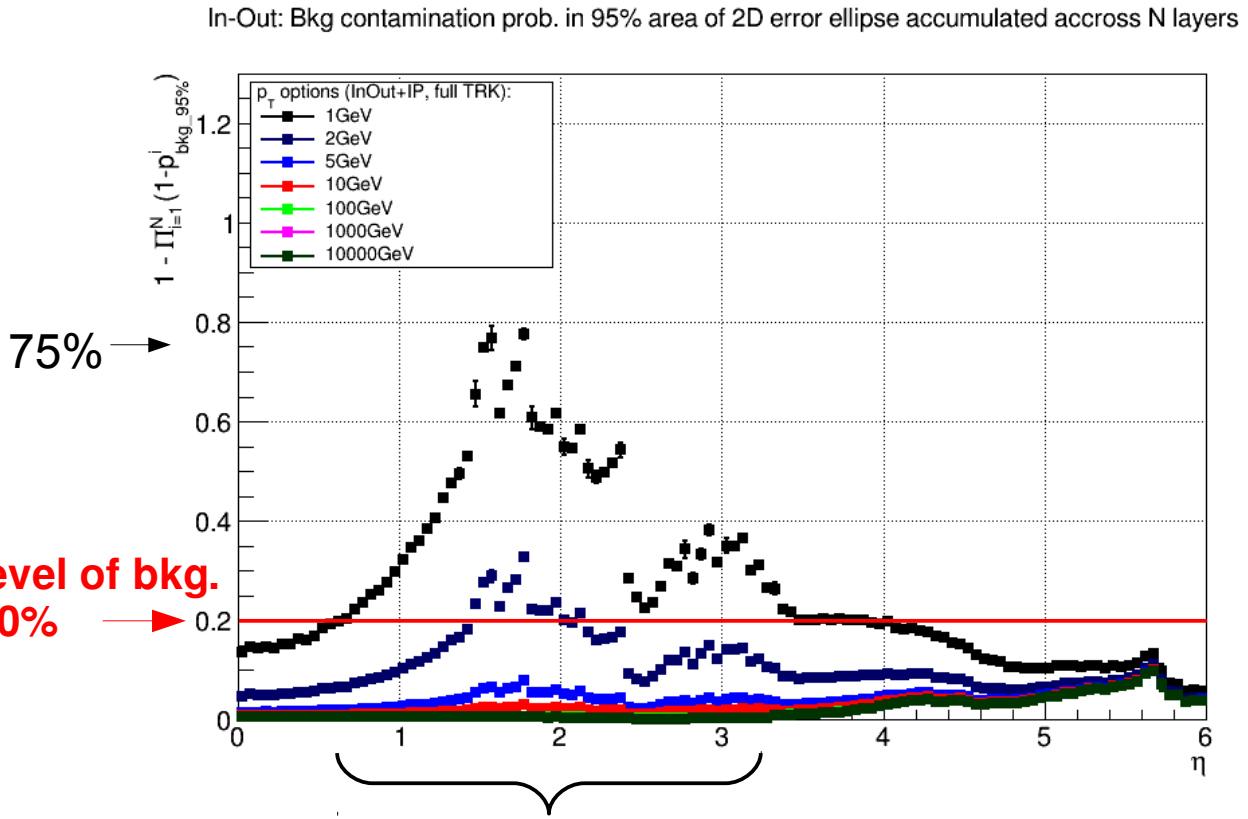


→ **EC: Effect of "long" strips along R** → R-ϕ measurement given by precise ϕ & radial pos. measur.

→ **Effect of barrel modules tilt & material:** Non-tilted modules increase it's material & "projection" effect with increasing eta! (Namely important for BRL & high occupancy region)

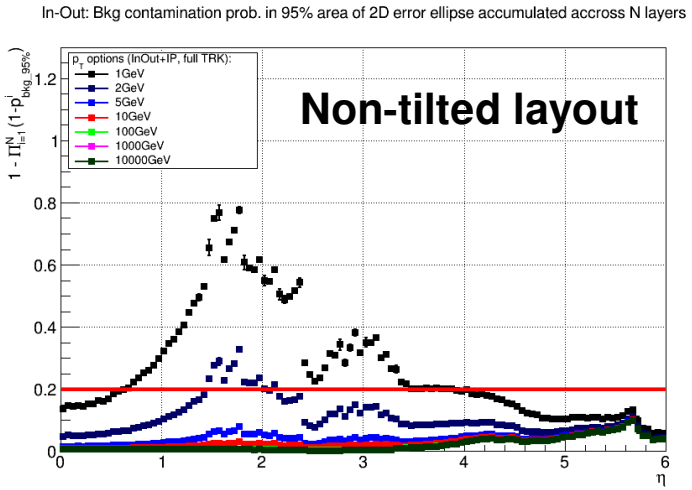
Non-tilted Layout & Pattern Recognition

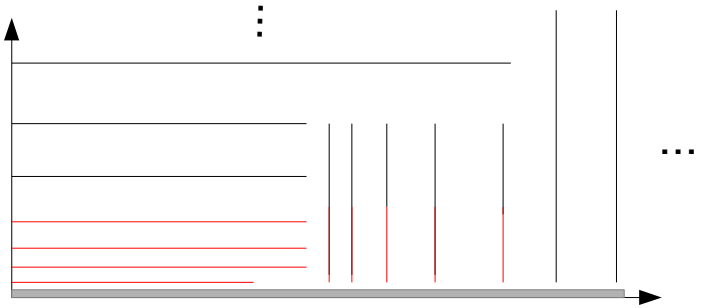
- **Geometry 3.v03 → Results on pattern recognition:**



Critical eta region: 0.5-2.5 (3.5) → transition area between BRL & EC

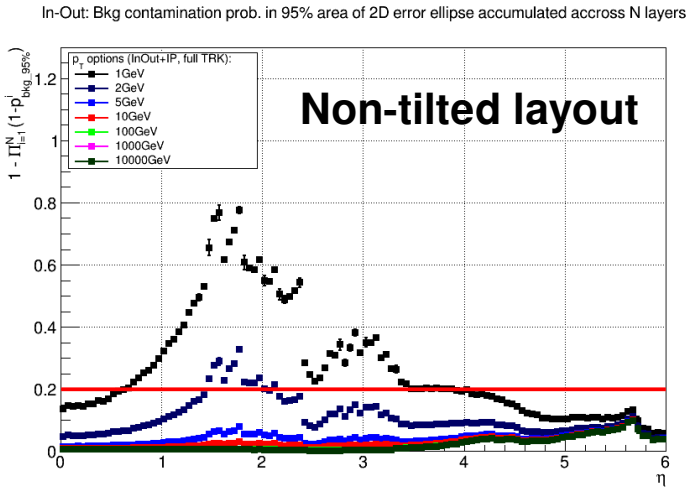
Non-tilted Layout x Tilted Layout

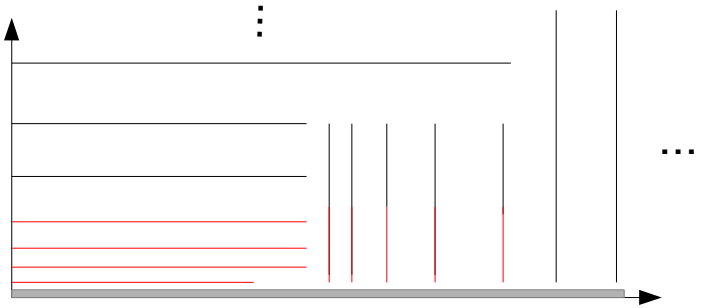




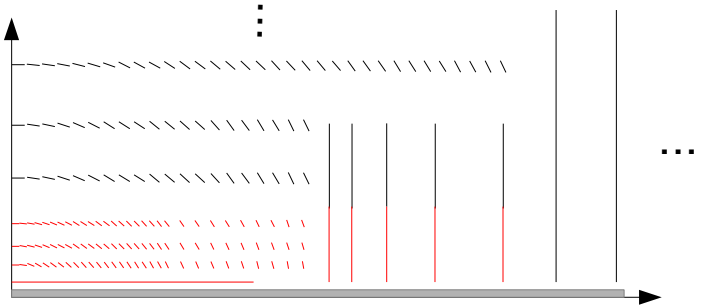
Solution?

Non-tilted Layout x Tilted Layout

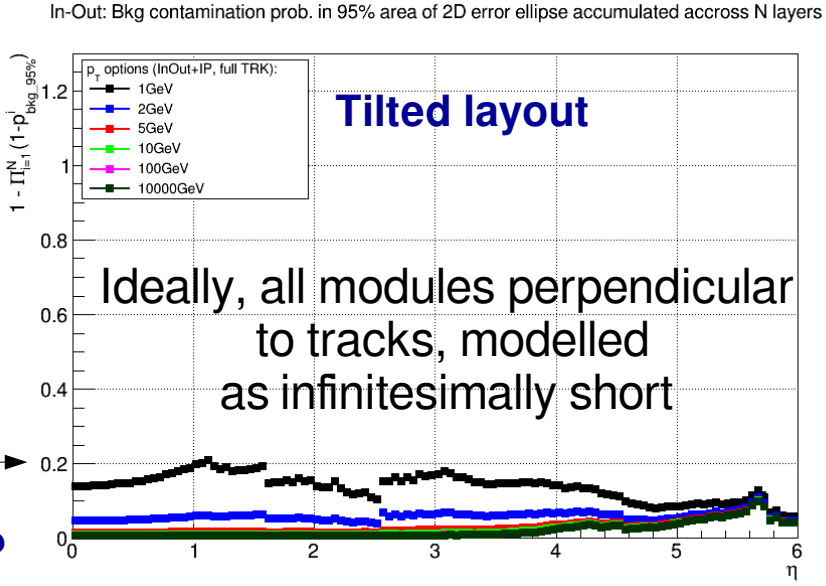




Solution? Go for tilted layout



20%



OK, but how to design tilted layout realistically?

Tilted Layout: Design Principles

- **Design principles:**
  - **Install tilted modules in barrel part only** (no tilting necessary in EC part)
    - → Non-tilted **(flat) part** arranged in rods, up-to **η≃0.5**
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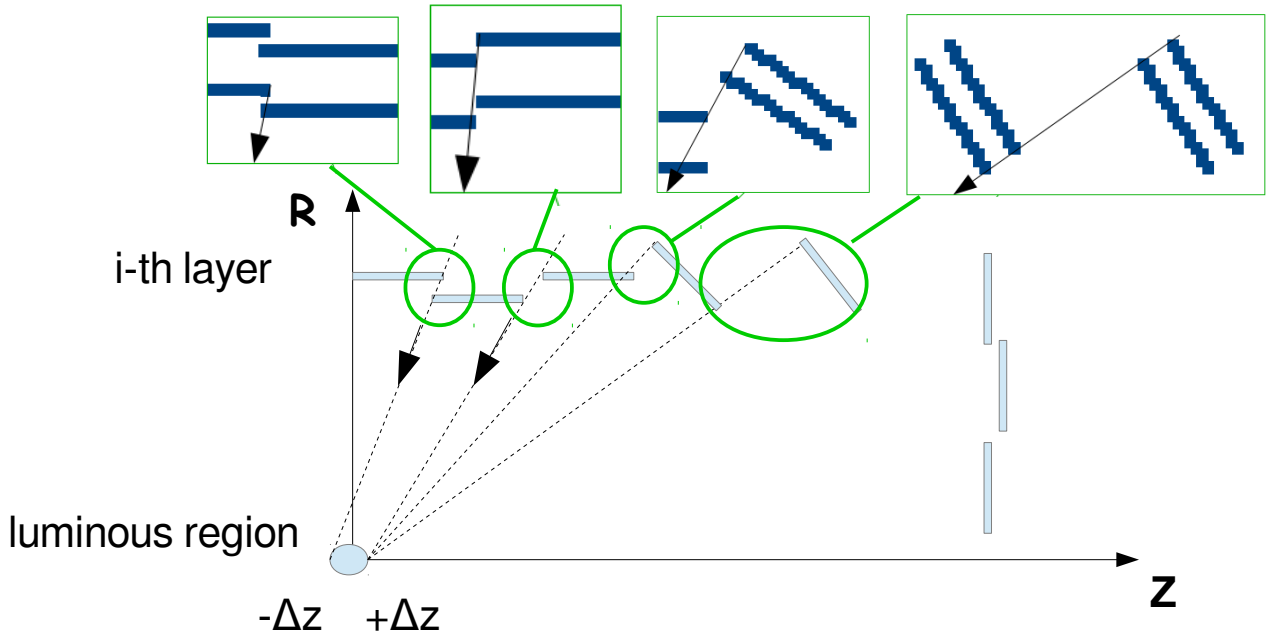

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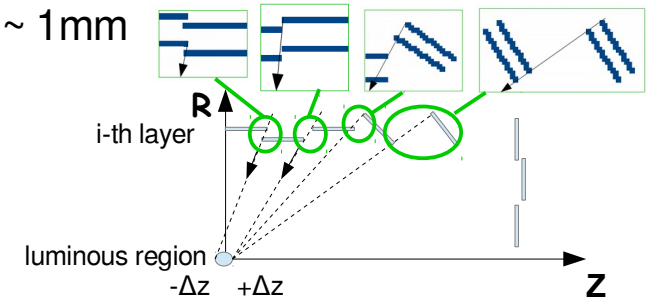

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    - → Module(s) tilting in uppermost layer has no effect on in-out PR + zig-zag structure affects lever-arm

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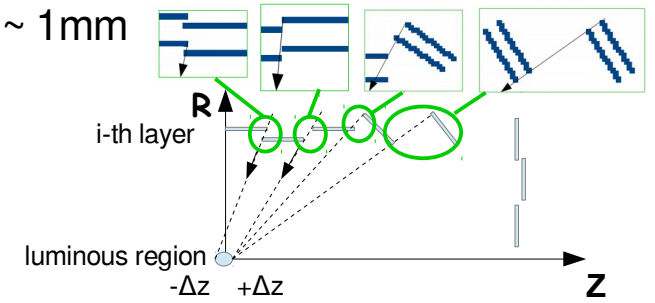
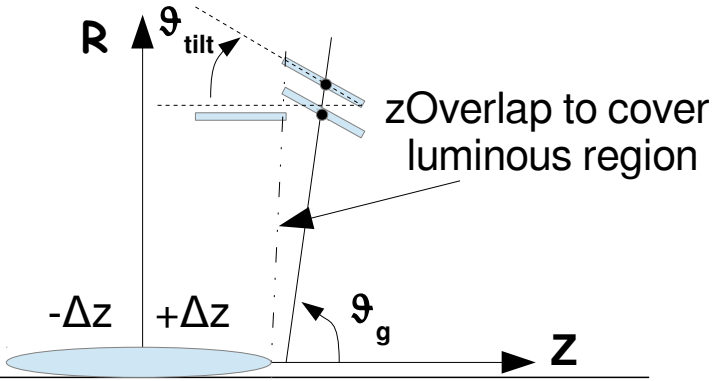
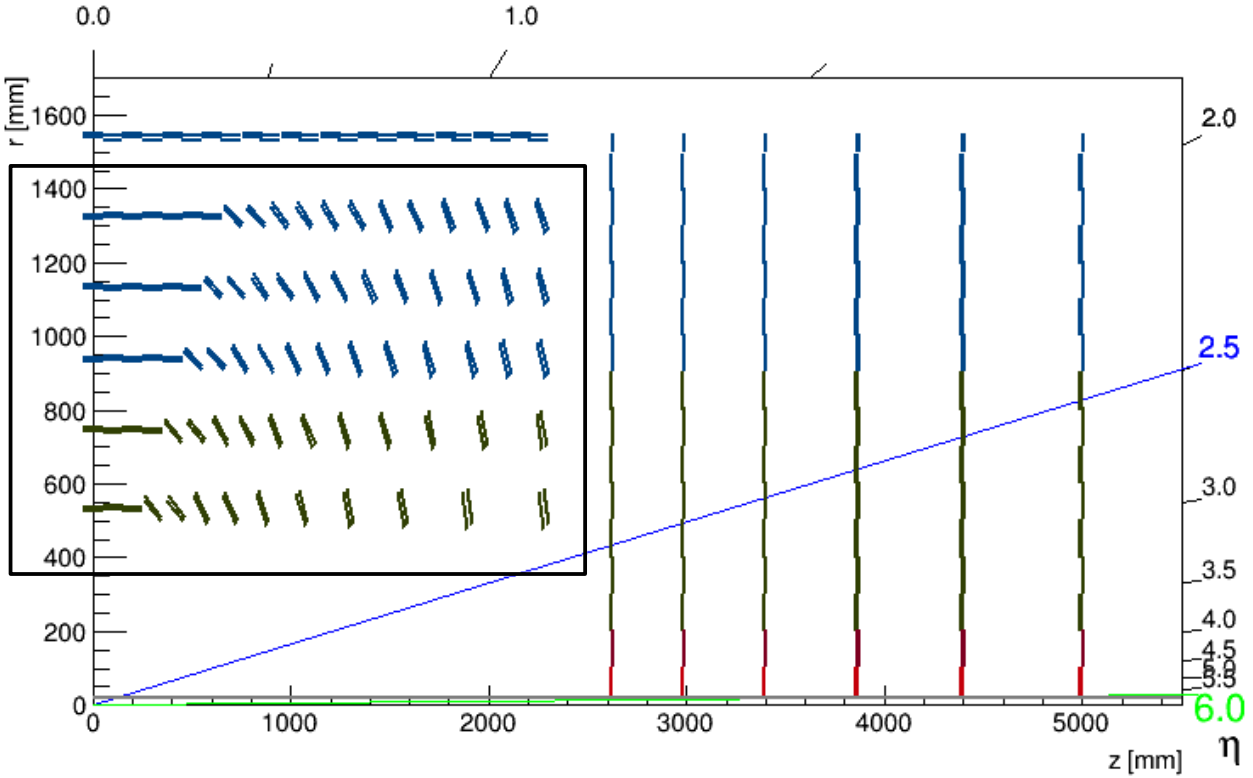


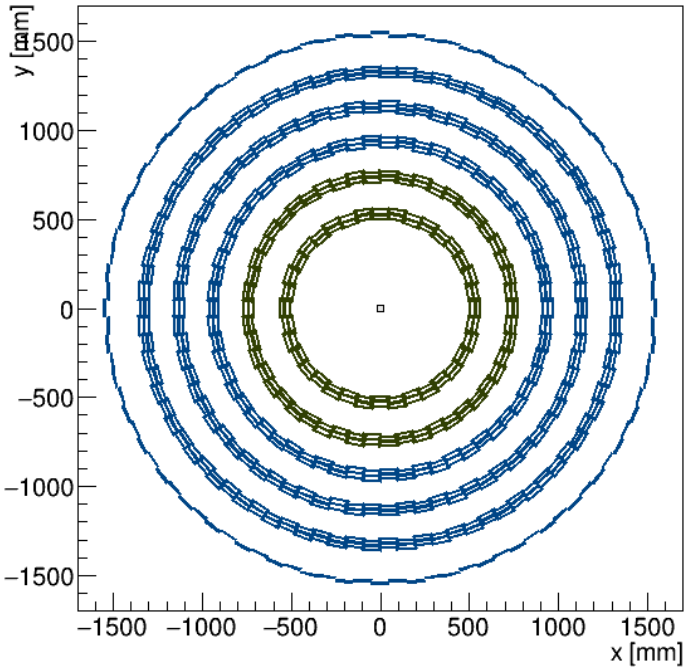
  - **Last barrel layer kept non-tilted → keep max available lever-arm ~ 1550mm!**
    - → Module(s) tilting in uppermost layer has no effect on in-out PR + zig-zag structure affects lever-arm
  - **Modules tilted geometry:**
    - → Algorithm kindly provided by CMS Ph2 Tracker group, (special thanks to **G.Hugo & S.Mersi**)
    - → **Main parameters affecting geometry: ϑ_{tilt}, ϑ_{g}, zOverlap**
    - → Same tilt used for a group of 2 rings (higher cls size & practical)



Tilted Geometry: Design Proposal

- **Geometry 4.v01 (tilted layout) → outer tracker**



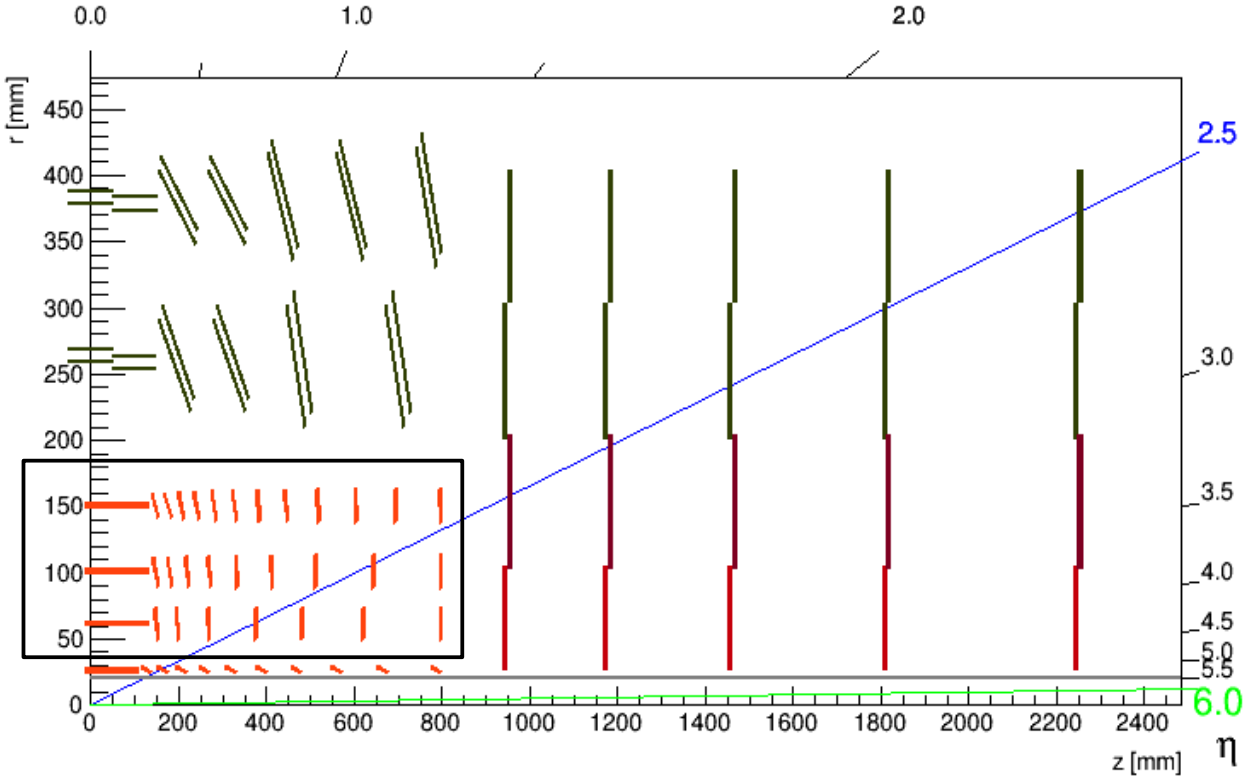


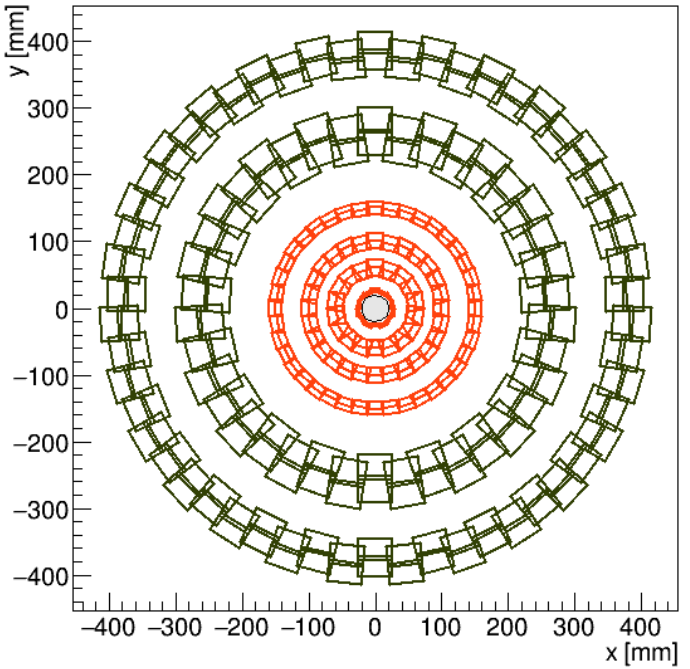
→ Drawback of tilted layout versus flat barrel geometry: res. in R-Φ given by combination of R & Φ → **long Z strips (50mm) not usable (res. ~14.4mm) → Z res. set to 500um** (up-to 1mm OK)

→ To achieve 0.2 bkg. contamination level Z res. of EC strips set to 500um too

Tilted Geometry: Design Proposal

- **Geometry 4.v01 (tilted layout) → inner tracker**

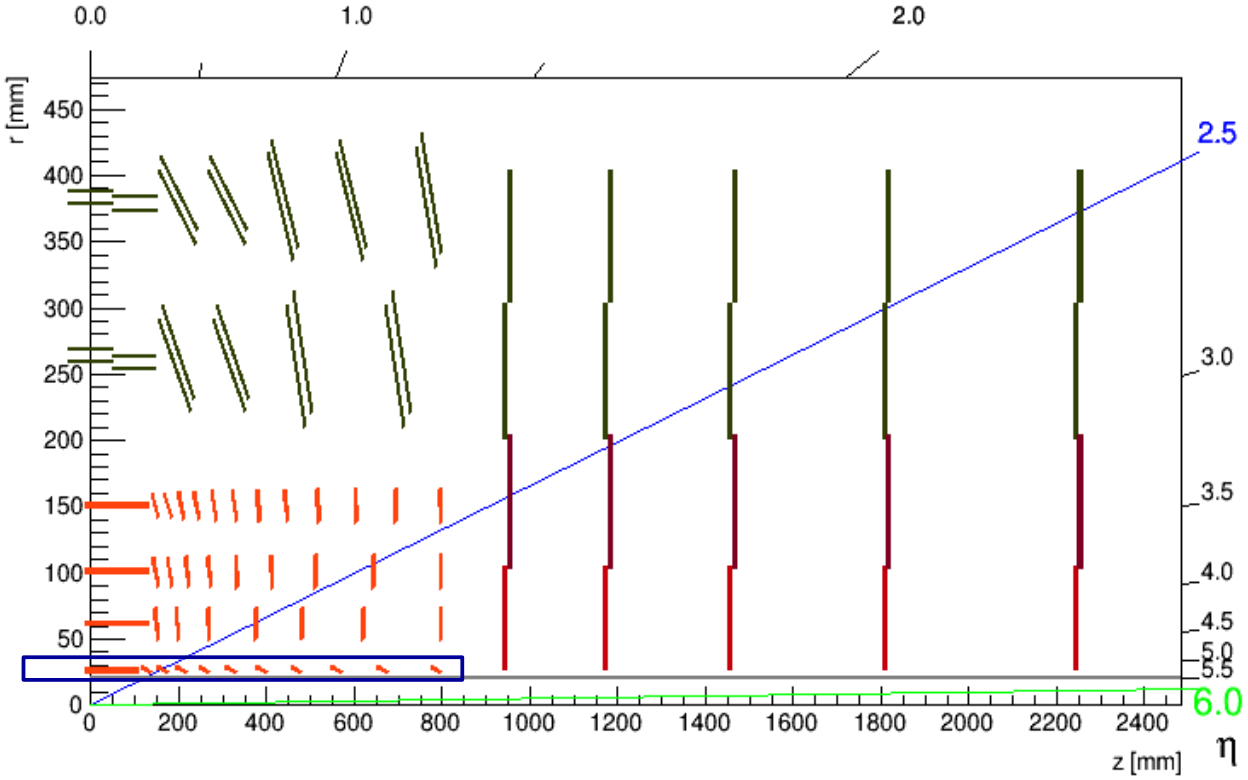


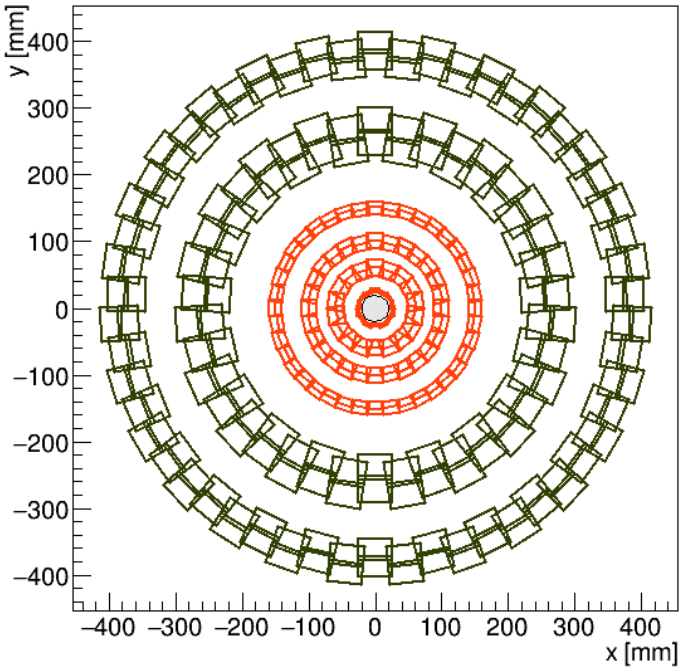


→ Tilted layout of vertex detector not directly driven by Pattern recognition (used for seeding), **but it improves Z0 resolution**, visible improvement in correct primary vertex assignment @ high pile-up

Tilted Geometry: Design Proposal

- **Geometry 4.v01 (tilted layout) → inner tracker**



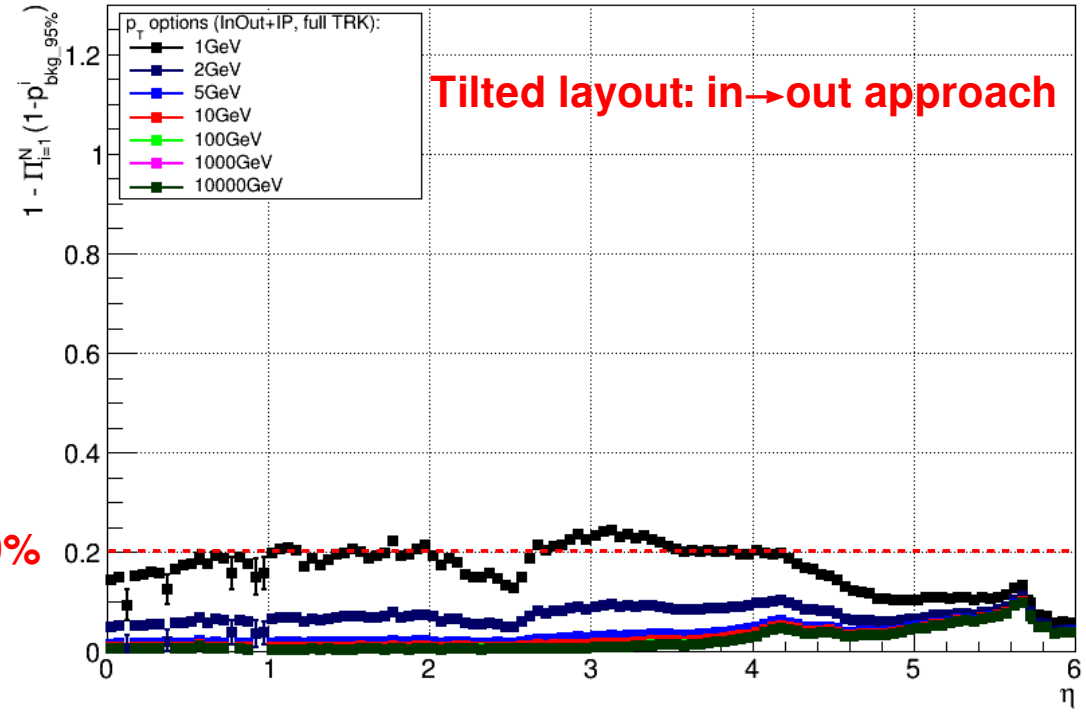


→ Tilted layout of vertex detector not directly driven by Pattern recognition (used for seeding), **but it improves Z0 resolution**, visible improvement in correct primary vertex assignment @ high pile-up

→ Tilt angle of first layer is given by compromise between **low material budget & higher radial pos. due to tilt → set $\vartheta_{tilt} \simeq 10^{\circ}$**

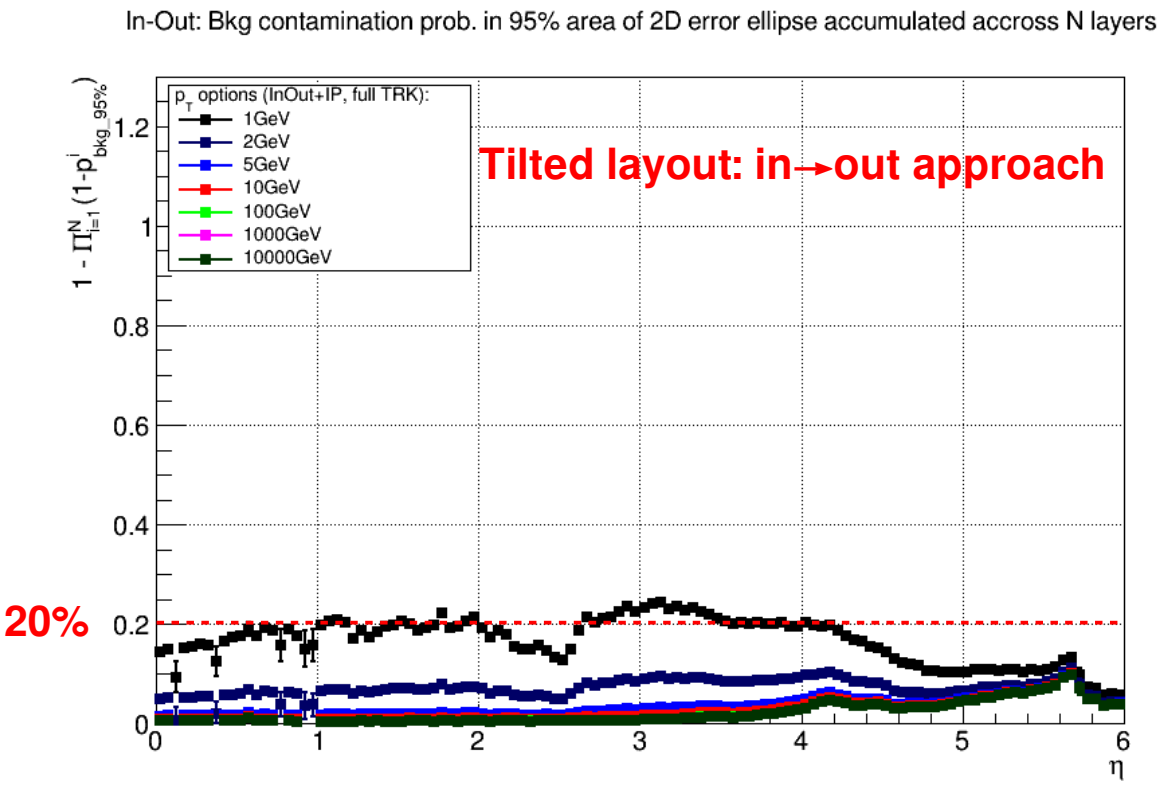
Tilted Layout & Pattern Recognition

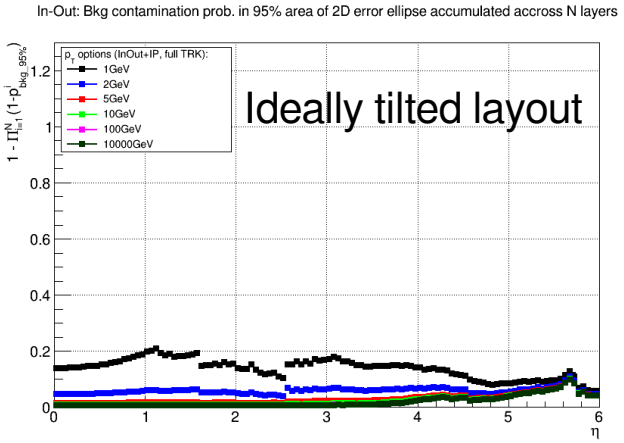
In-Out: Bkg contamination prob. in 95% area of 2D error ellipse accumulated accross N layers

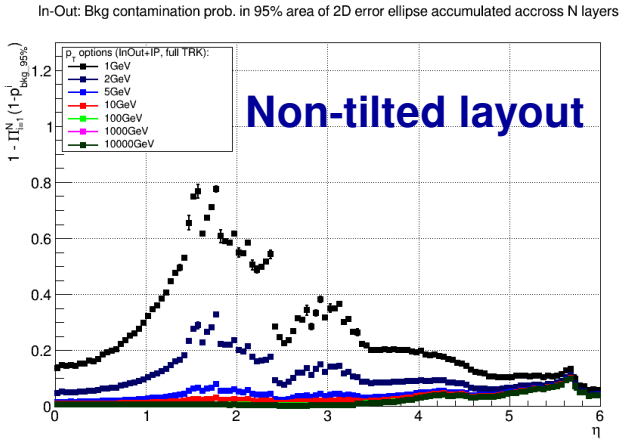


20%

Tilted Layout & Pattern Recognition



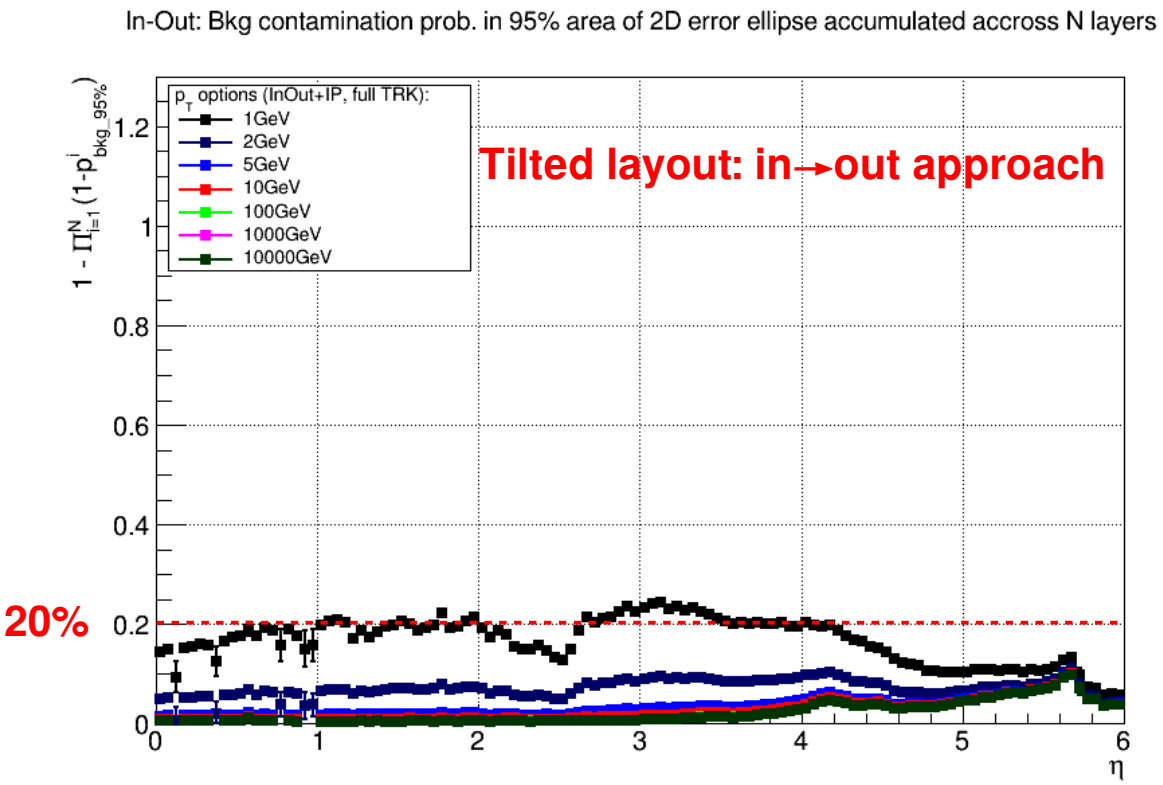


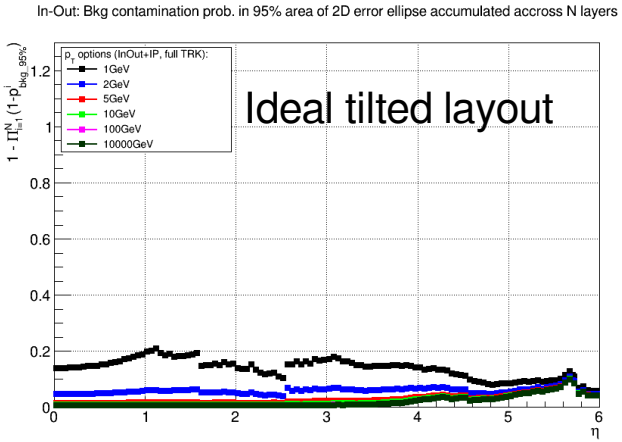


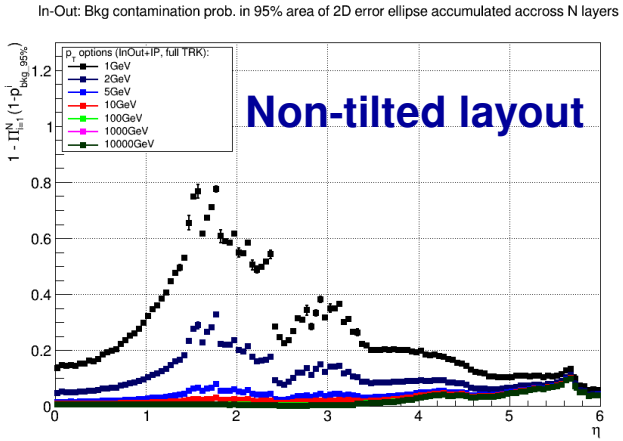
- **Conclusion:**

  → **Bkg. Contamination level @ 20% for p_T=1GeV/c** (limit driven by CMS Phase 2 upgrade tracker @ PU=140) **possibly achievable with tilted geometry @ PU=1000, but...**

Tilted Layout & Pattern Recognition



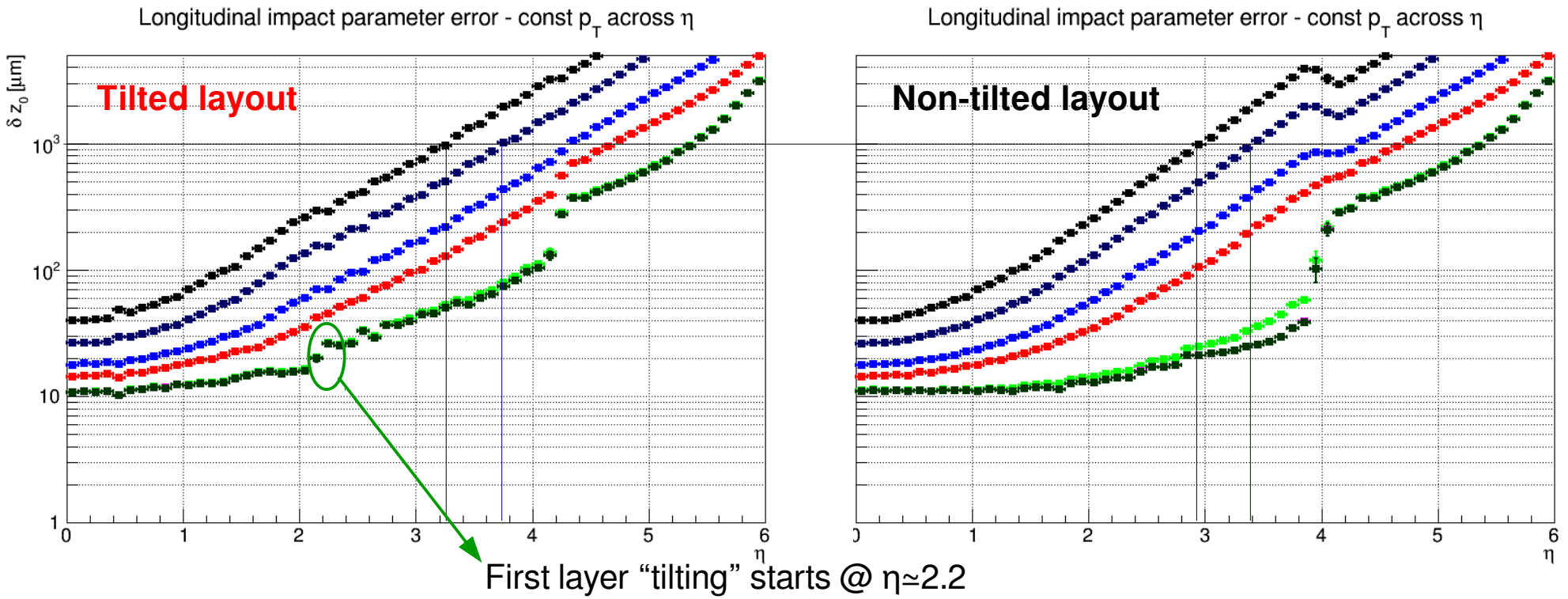




- **Conclusion:**
  - → **Bkg. Contamination level @ 20% for p_T=1GeV/c** (limit driven by CMS Phase 2 upgrade tracker @ PU=140) **possibly achievable with tilted geometry @ PU=1000, but...**
  - → Up-to now, mat. budget assumed per module → **NOT fully realistic for tilted layout, missing services & support structure!**

Tilted Layout & Tracking Performance

- Resolution of all track parameters remain similar, **except Z0 res. → important for primary vertex finding algorithm in high pile-up!**



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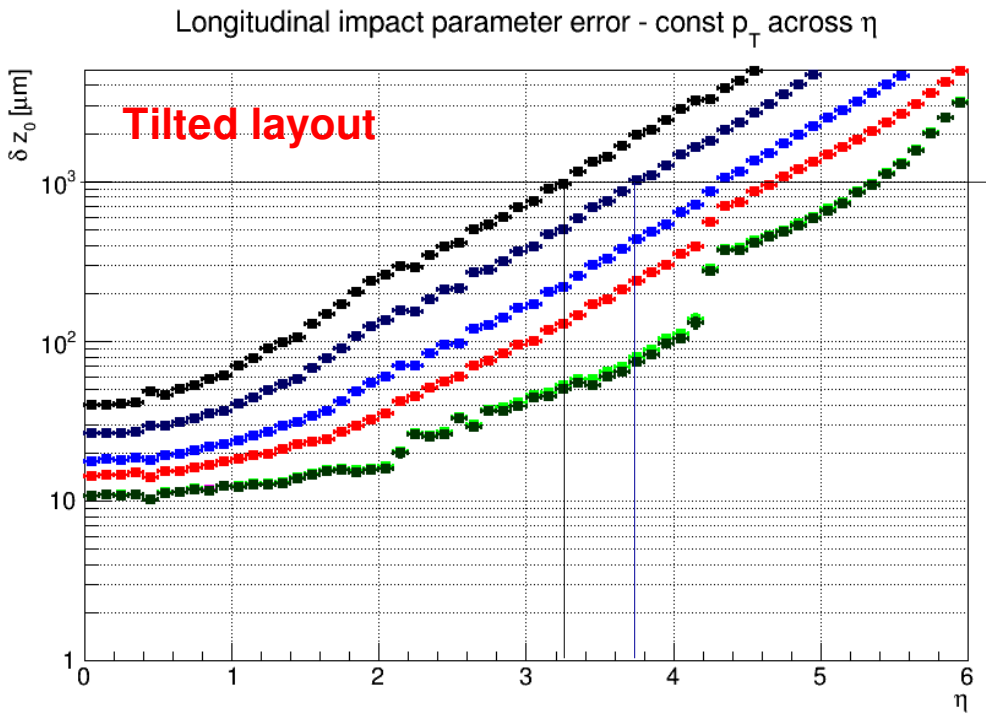

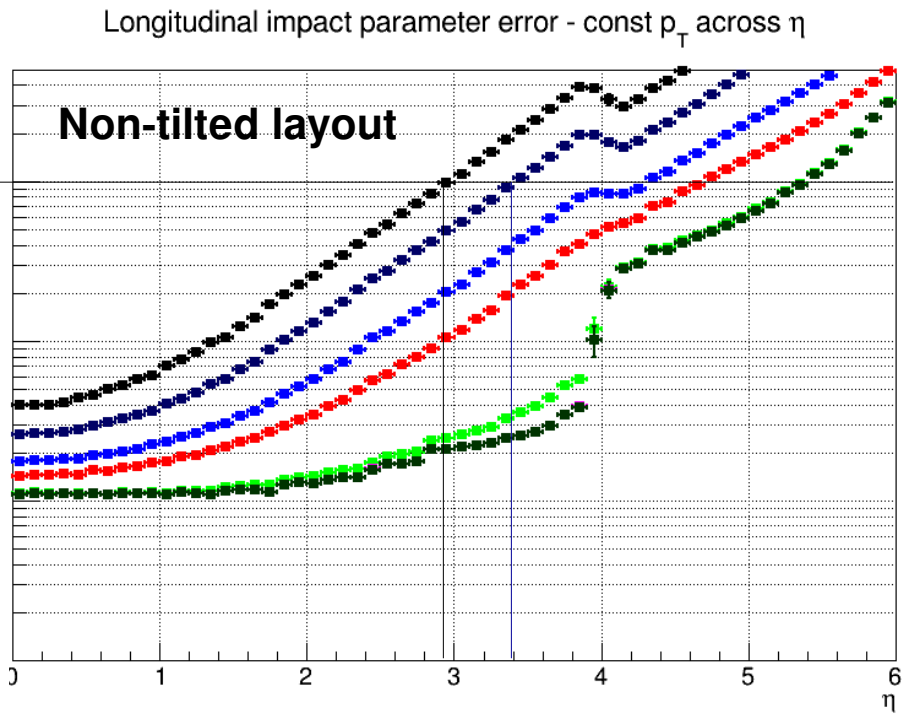

- **Conclusion: The remaining limiting factor for tilted layout is material budget of beam-pipe! Solution? Combine measurement with timing information?**

Summary & Outlook

- **Presented first tracker layout (tilted geometry) "optimized" by pattern recognition capabilities in high pile-up environment ~ 1000**
  - → modules tilt introduced **in critical eta region: 0.5-3.0 (transition area between BRL & EC)**
  - → **uppermost BRL layer designed untilted** to keep max available lever-arm @ 1550mm
  - → **first BRL vertex layer tilt optimized to $\vartheta_{tilt} \simeq 10^{\circ}$** to minimize mat. budget, but improve Z0 res

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- **An optimized tilted layout provides an overall improvement by factor of 3-4 in track finding purity & helps improving Z0 res.** (important for primary vertex finding in high PU)
- **Key features & limits**:
  - \+ **An analytical solution to estimate the weak "spots" in geom. layout in a view of pattern recognition** (Algorithms fully implemented in tkLayout SW)
  - \+ **Implemented algorithms to design tracker with tilted layout in tkLayout SW (G. Hugo & S. Mersi, CMS Ph2 upgrade tracker group)**
  - – **Current tracker design with tilted layout still lacks true services & supports, which need to be implemented!** On the other hand, tilted layout is very "transparent" for services, so one may achieve better performance versus material budget compared to "classical" design