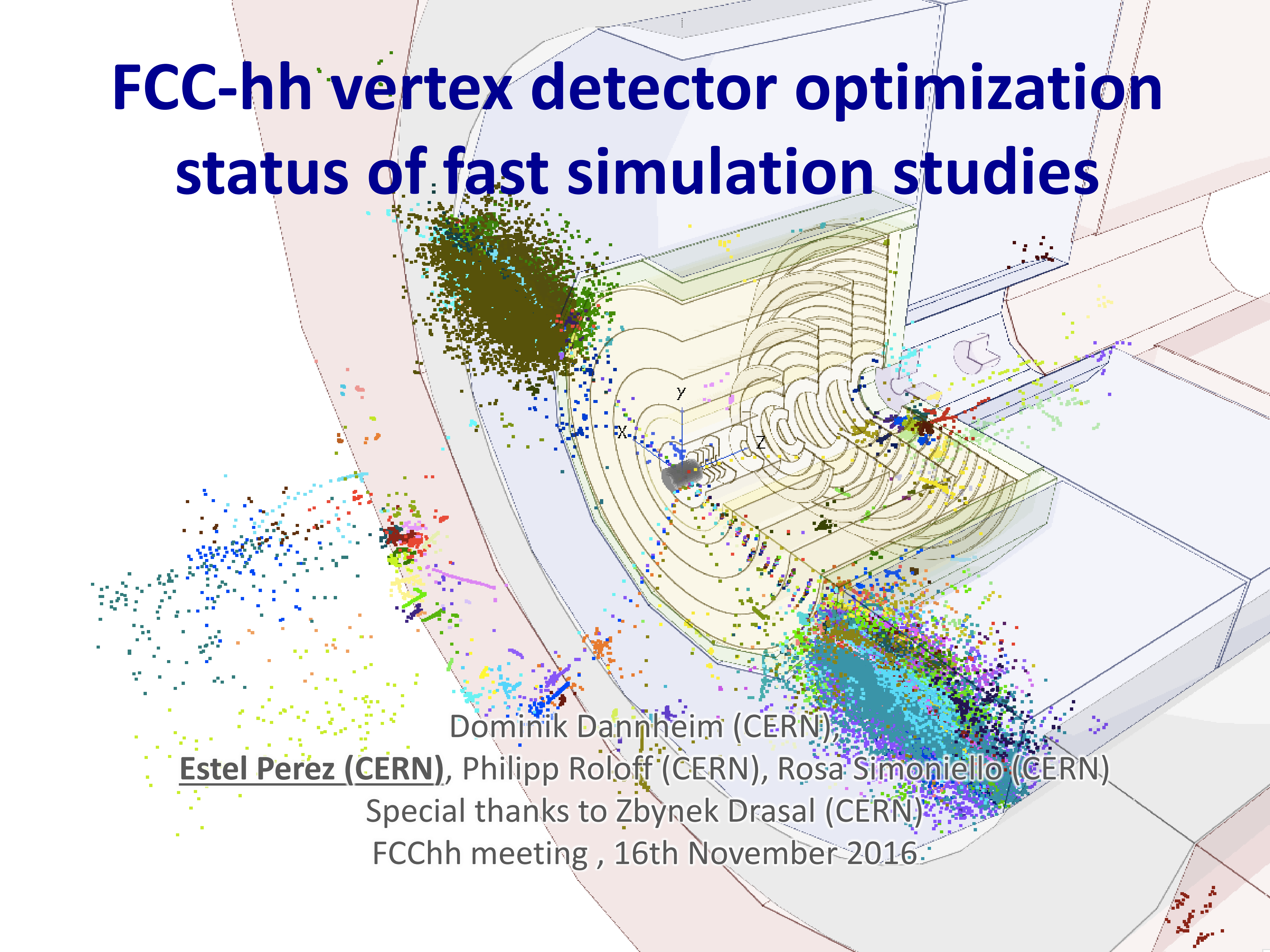
FCC-hh vertex detector optimization status of fast simulation studies



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Special thanks to Zbynek Drasal (CERN)
FCChh meeting , 16th November 2016

Outline

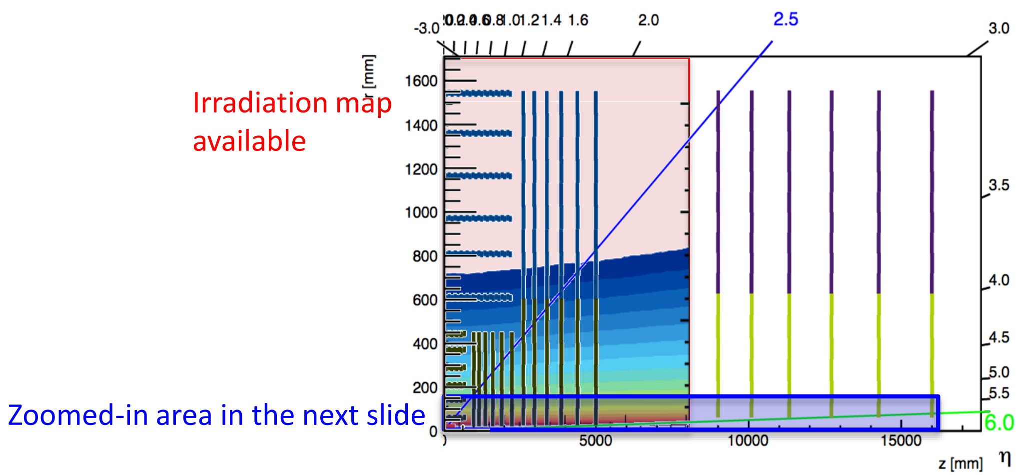
Constraints of the background occupancy on:

1. Detector's granularity (pixel size)
2. Pattern recognition
   - Trade-off between number of layers and single point resolution

Fluence map

Provided by M. Ilaria Besana

- Number of particles per pp collision per unit area
- For B field = 4 T
  - (scaled from the 6T map used by Zbynek in his past studies)
  - Does not include tracker material (small effect)
  - Includes EM calorimeter (acts as source of back scattered particles)
  - Assumes HAD calorimeter absorbs all particles
- Up to z=8m
  - Fluence in forward region not available: depends on the layout which is not yet fixed



1) Constraints from fluence on detector granularity

Given the fluence map, what is the minimum granularity needed in each part of the detector, to make sure there will be only one particle firing a pixel?

particles per unit area, per pp collision

Occupancy = Fluence * Pile up * PixelArea

per Bunch Crossing   # of pp collisions per Bunch Crossing (BC)

Assume we need the **occupancy <=0.01** (for consistency with prev. results, to be reviewed)
Assume # Pile up interactions per bunch crossing **=1100**
Assume no diffusion (cluster size for a perpendicular track = 1)
if we **Assume squared pixels and no charge sharing**, can express the area in terms of σ:

PixelArea = $(\text{PixelPitch})^2$ = $(\text{single point resolution} * \sqrt{12})^2$

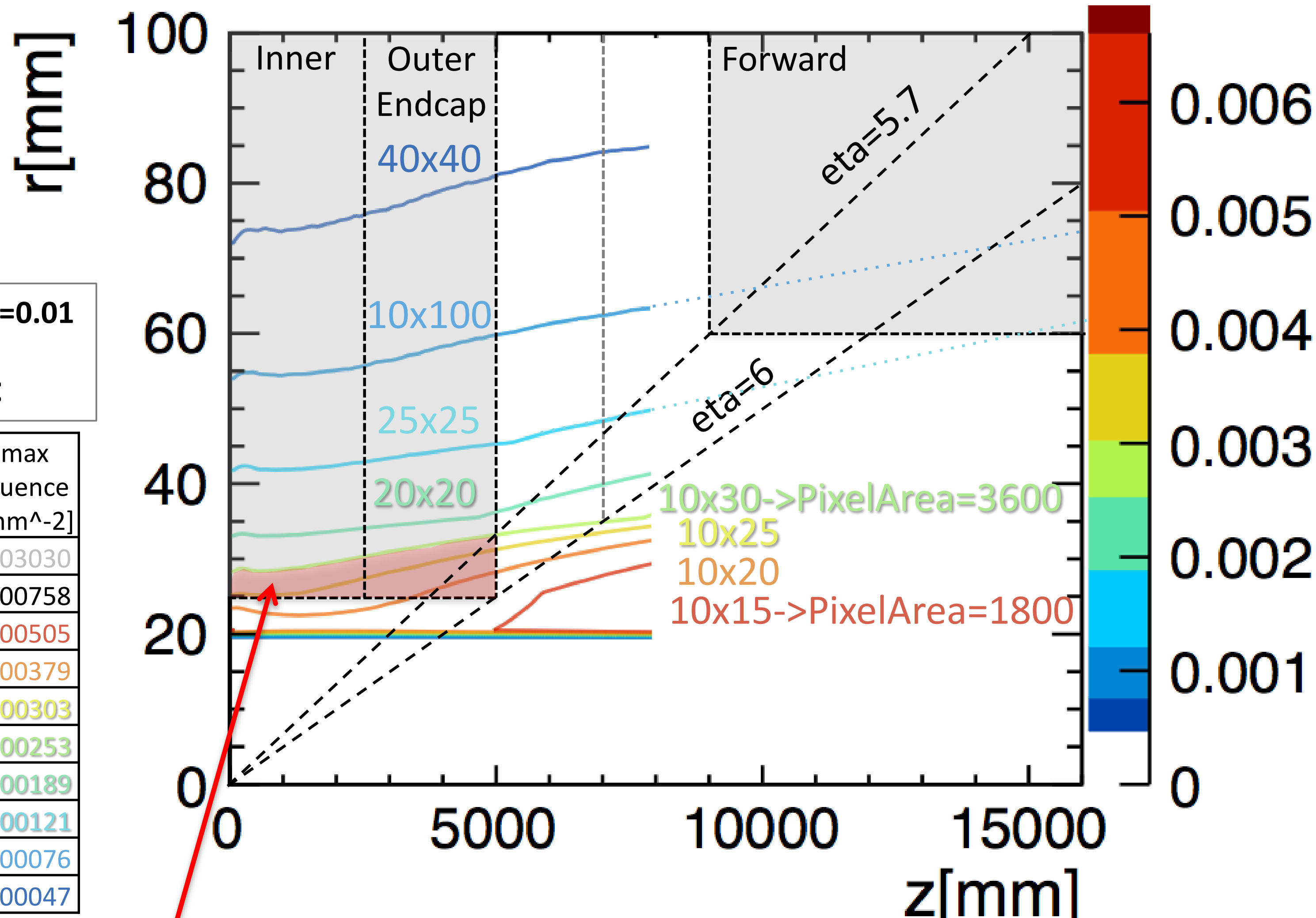
For a given single point resolution, how close to the beampipe can we go?
maximum **Fluence**= **0.01**/**1100** /$(\sigma * \sqrt{12})^2$
→ Draw constant fluence curves in the R vs Z plane

1) Constraints from occupancy on detector granularity

Which single point resolution is needed in each part of the tracker?

 # particles in a pixel <=0.01
σ = Pitch/√12
#PU =1100 int. per BC

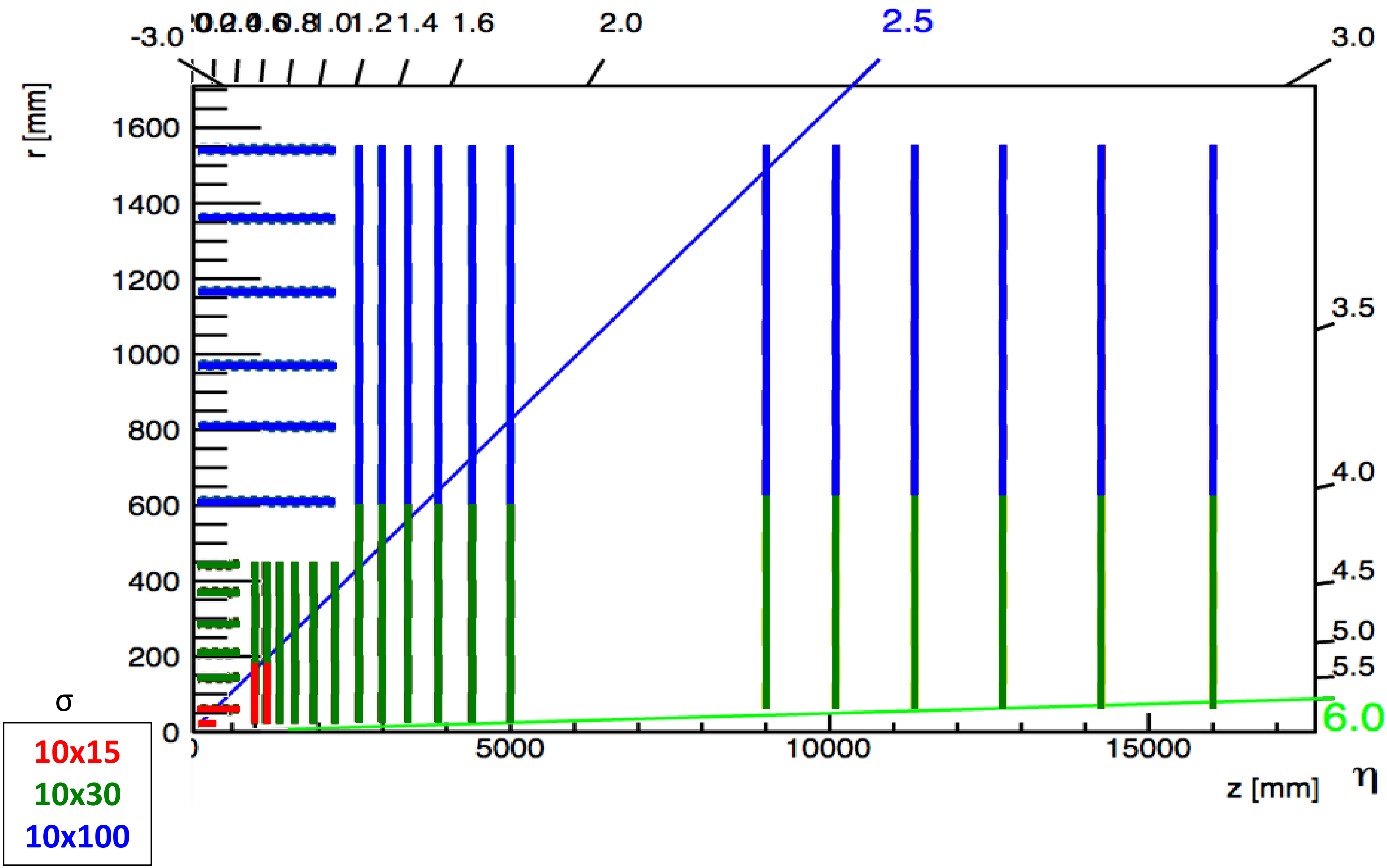
single point res σ [µm]	**pitch*** [µm]	pixel area [µm^2]	max Fluence [mm^-2]
5x5	**17.3**	300	0.03030
10x10	**34.6**	1200	0.00758
10x15	**42.4**	1800	0.00505
10x20	**49.0**	2400	0.00379
10x25	**54.8**	3000	0.00303
10x30	**60.0**	3600	0.00253
20x20	**69.3**	4800	0.00189
25x25	**86.6**	7500	0.00121
10X100	**109.5**	12000	0.00076
40x40	**138.6**	19200	0.00047



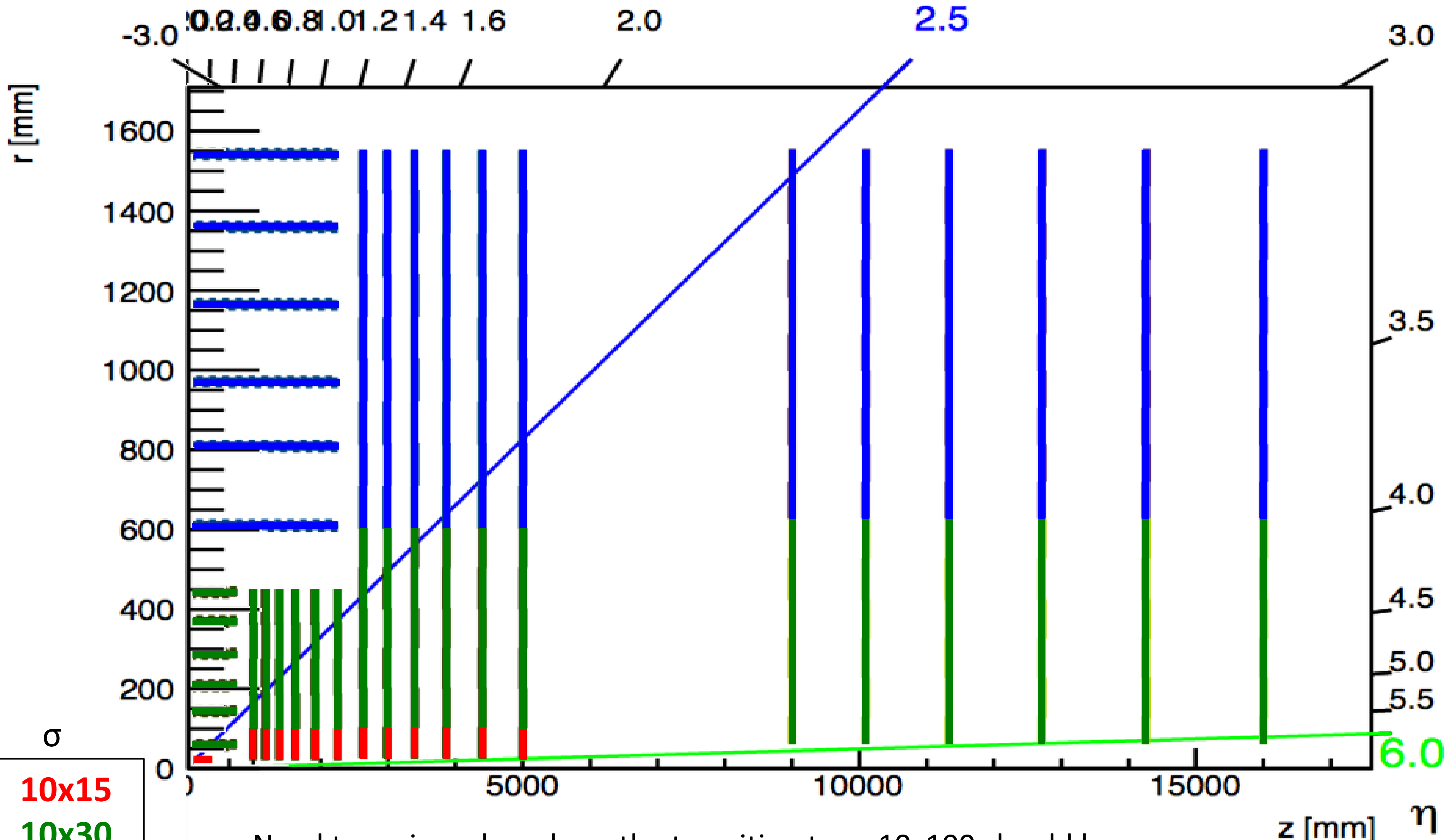
- For layers and rings with **R<35mm**, pixel area should go down to 1800µm^2 -> single point resolution =**10x15 µm** (for first inner barrel layer and innermost ring of **all** endcap disks)

* pitch = sqrt(pixel area), even for non-squared pixels

Current baseline



Proposal 1 (from occupancy point of view)



σ

10x15
10x30
10x100

Need to review also where the transition to σ=10x100 should happen
(consider also z0 and d0 resolution)

1) Constraints from occupancy on detector granularity - requests

- Do we have a baseline estimate of **max occupancy** and cluster size, for FCChh envisaged technologies?
  - Assuming 1% occupancy is probably not realistic:
  - **HL-LHC already requires to go down to 0.2%**
    - RD53 aims at 50x50µm pixel pitch coping with 3 GHz/cm^2
      - Sensors of area= 50x50µm = 2500 µm^2
      - 3 GHz/cm^2 = 75 KHz/pixel -> in 25 ns: 0.0019 particles
  - Propose to use occupancy **0.2% as benchmark** for the future
    - Factor of 5 in the max occupancy -> factor of 2.2 in the single point resolution
    - Go down to **7x5 µm single point resolution** for the innermost layers and disks

- Would need an estimation of the fluence values up to z=16000mm to realistically assess the minimum granularity in the forward part of the detector.

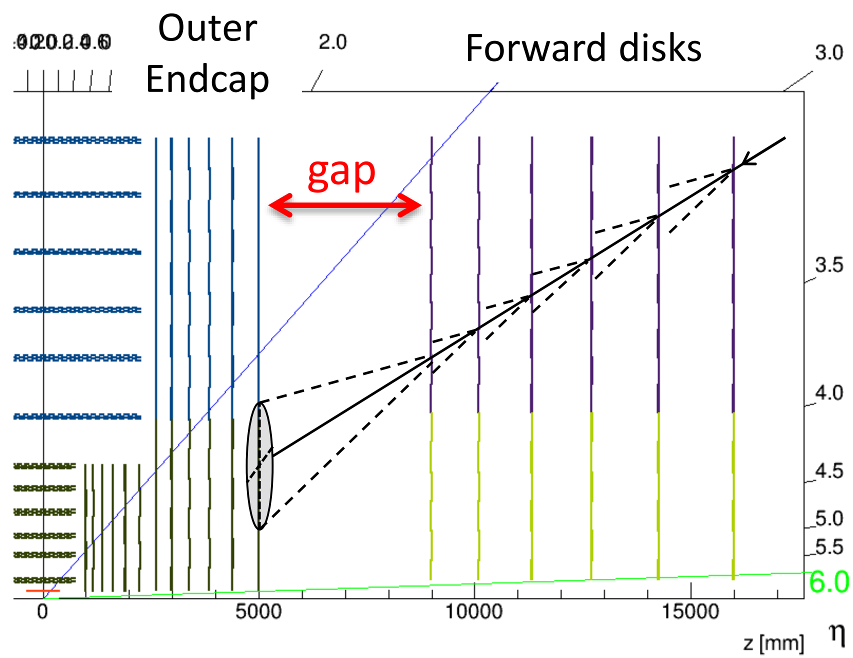
2) Pattern recognition

- How does the single point **resolution** of the **forward disks** and the **gap** distance affect pattern recognition

Steps:

1. Project track covariance matrix on the last encap disk
2. Calculate fluence at such position

If there is another particle in the error ellipse area, it will cause confusion in the tracking algorithms



LiC Toy uses outside-in tracking

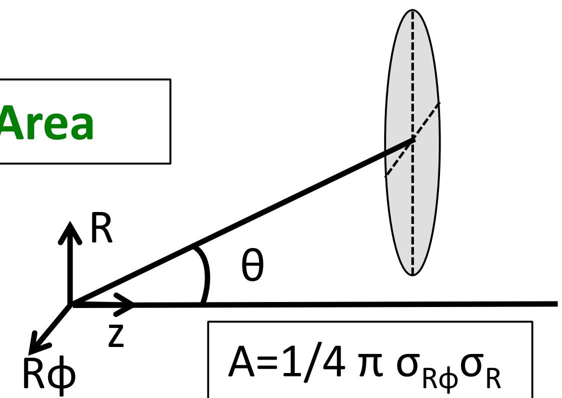
of background particles in the error ellipse ?

1. Area of the error ellipse projected at the last endcap disk:

   $$\textbf{EllipseArea} = \tfrac{1}{4}\ \pi\ \sigma_{R\phi}\ \sigma_z\ \tan\theta$$

1. Multiply by fluence at the last endcap disk

 # bkg particles in error ellipse = Fluence * Pile up * EllipseArea

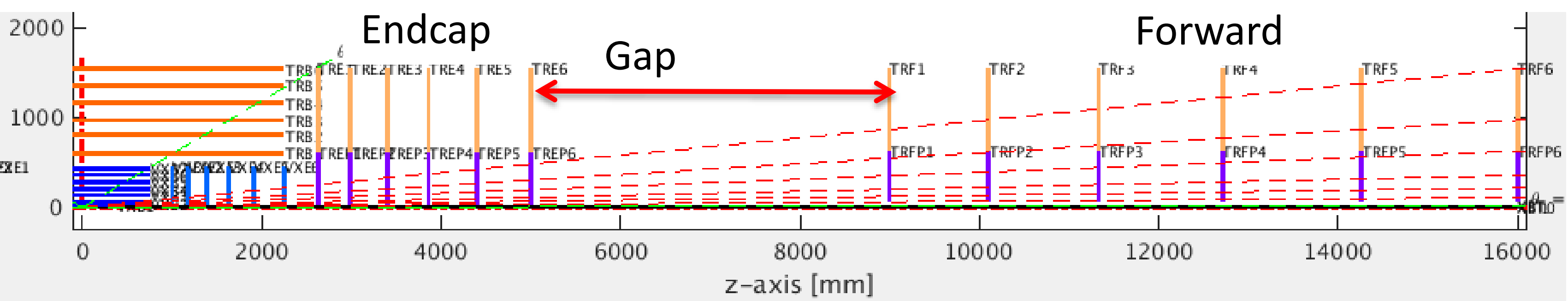


$A=1/4\ \pi\ \sigma_{R\phi}\sigma_R$

$\sigma_R=\sigma_z \tan\theta$

Study, for **forward tracks**: (going through all fwd layers)

- **Area as a function of the single-point resolution** of the forward layers
- **Area as a function of the gap distance** (endcap – forward)



θ=5.49 deg; η=3

θ=0.39 deg; η=5.7

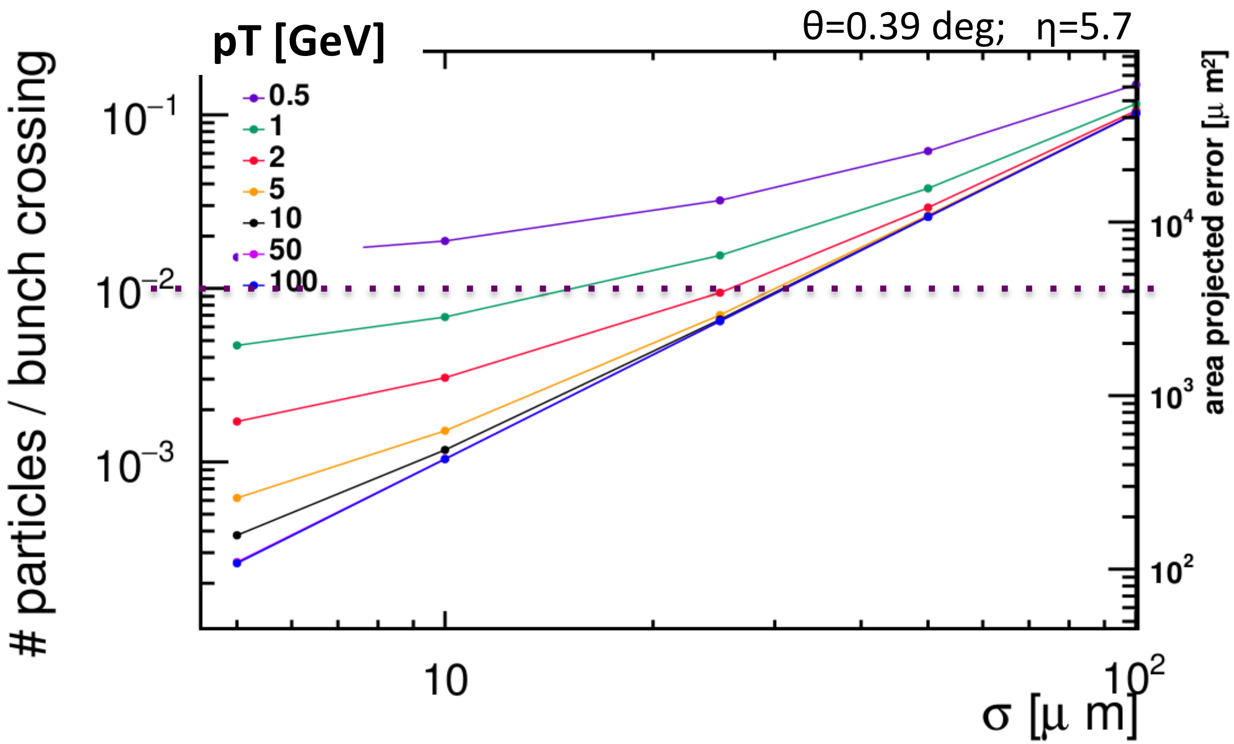
Note: In this study the upper and lower part of the disks have the same material budget and resolution

Bkg in error area vs single-point resolution

Assume we need the **# bkg particles in the error ellipse to be <=0.01**, which **single point resolution** is required for the **forward layers?**

 # bkg particles in error ellipse = Fluence * Pile up * EllipseArea

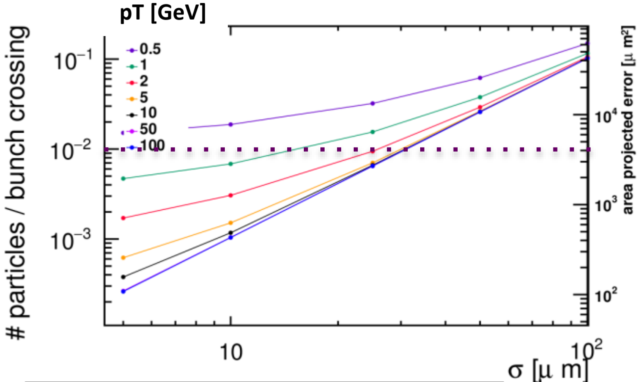
Assume # Pile up interactions per bunch crossing **=1100**
Assume squared pixels (single point resolution: 5x5, 10x10, 25x25, 50x50 100x100 µm)
Show results for the forward-most angle that hits all layers (**theta = 0.39 deg; eta=5.7**)



In order to have less than **0.01 particles per bunch crossing** in the error ellipse area, **would need σ=10x10µm.**
Not possible to go below pT=0.5 GeV with this layout

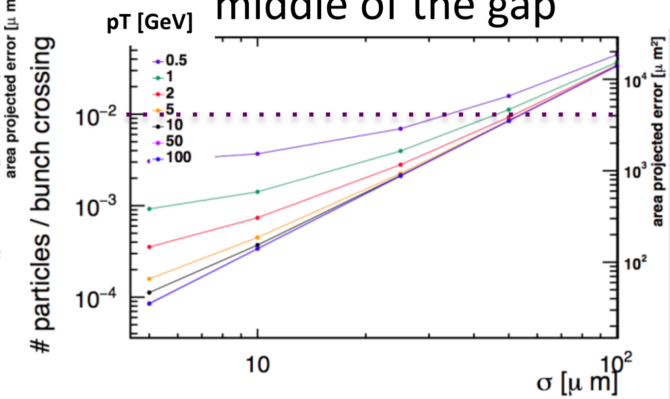
Adding an extra disk in the middle of the gap

Baseline



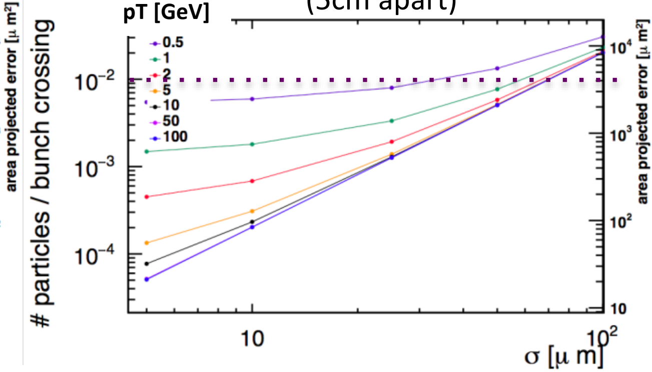
θ=0.39 deg; **η=5.7**
Line at max **# particles in the error ellipse** area per BC = **0.01**
Assume #PU/BC = 1100

extra disk in the middle of the gap



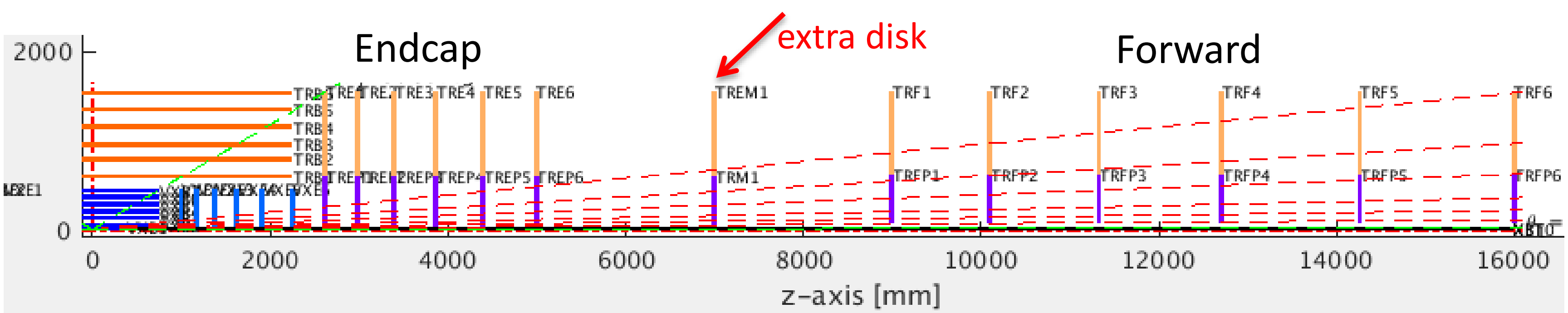
→ factor of 5 less background

pair of extra disks in the middle of the gap
(5cm apart)



→ extra material is counter-productive for low pT tracks

If we add one(two) **extra layer**(s) in the middle of the gap, we can go down to **σ=25x25 μm single point resolution for the forward disks** and down to **pT=0.5 GeV** tracks.



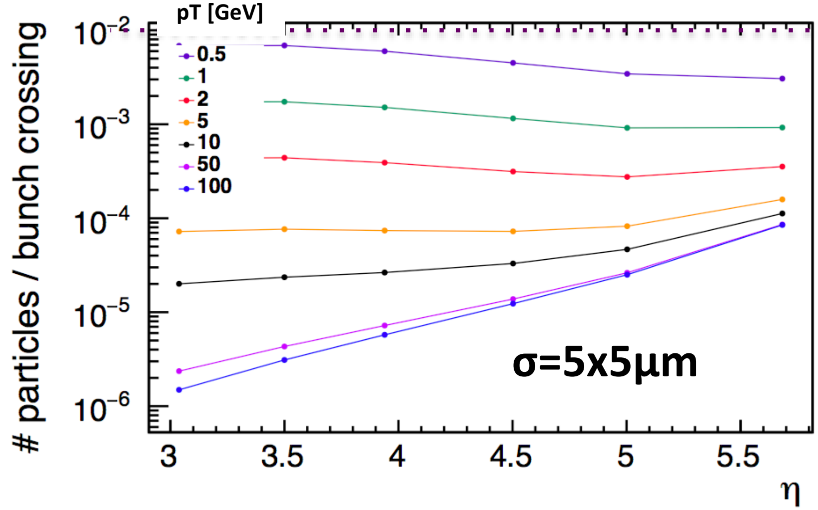
Dependance on track η

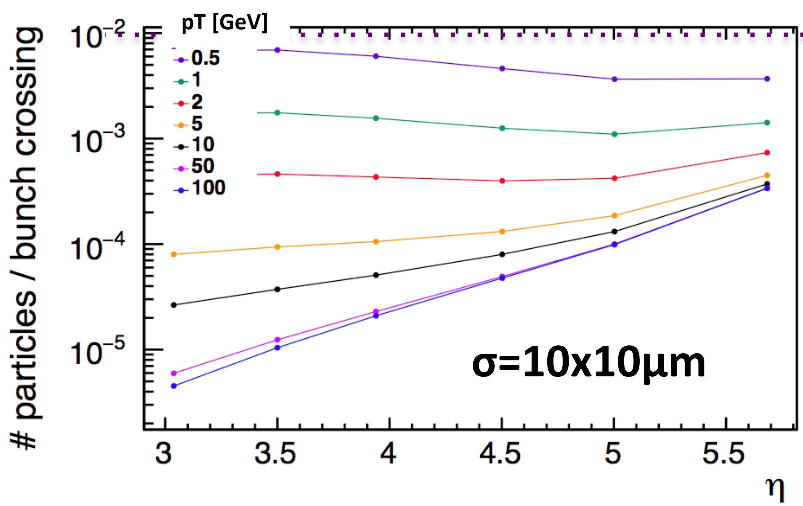
Would σ=25x25μm work for every η?

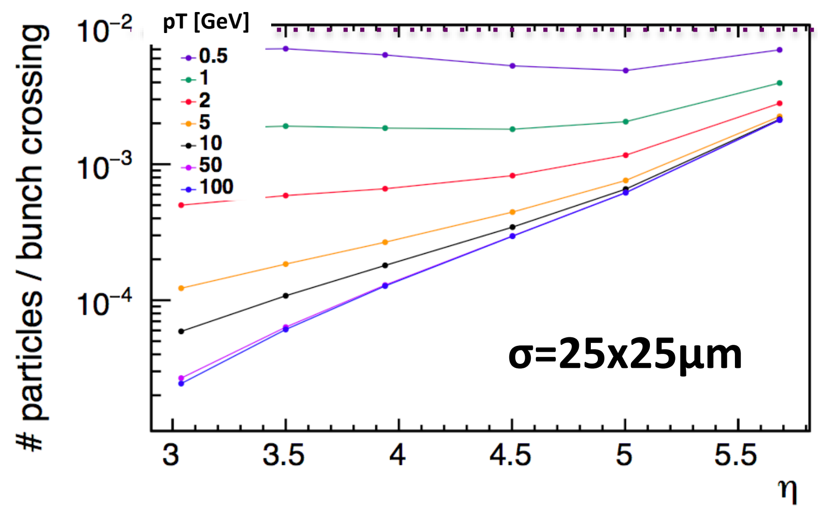
Show # particles per BC vs η for different single point resolutions (σ) of the **forward disks**.

Line at max **# particles in the error ellipse** area per BC = **0.01**
Assume #PU/BC = 1100
1 extra disk in the middle of the gap

Yes, even if highest η does not always mean highest #particles

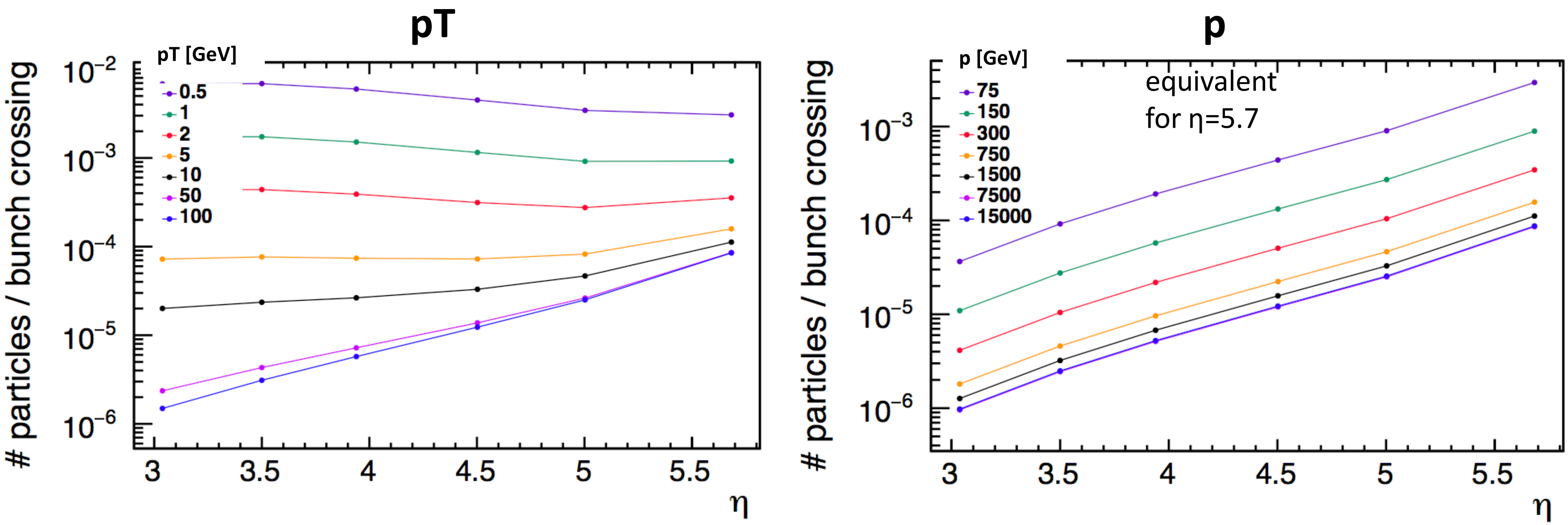






Dependance on track η

σ=5x5µm
1 extra disk in the middle of the gap
Assume #PU/BC = 1100



At high η the higher fluence is compensated by smaller ellipse area
(less multiple scattering: at constant pT, higher η means much higher p)

Conclusions

- Detector granularity close to the beampipe driven by fluence, while at larger R the limitations of the pattern recognition will start to play a role
- Need **finer granularity** in the area **close to the beampipe**
  - For layers and rings with R<35mm, single point resolution should be about 10x15 (7x5) µm for occupancy<1% (0.2%)
- Need at least **one extra disk** between the endcap and the forward disks
  - Decreases background in the error ellipse by a factor of 5

Next steps

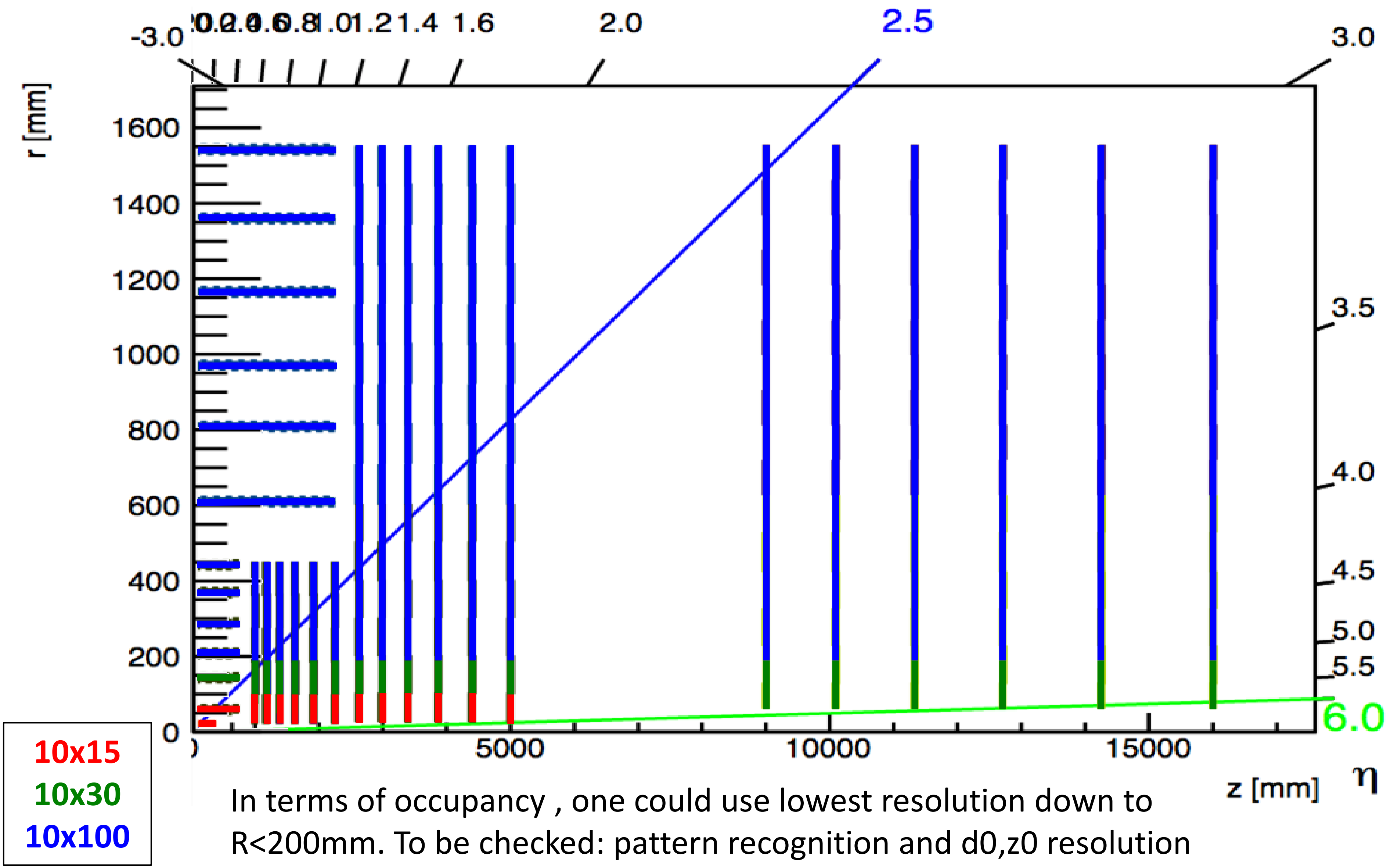
- Plan to also check pattern recognition constrains between
  - inner and outer barrel
  - inner and outer endcap

Note:

- Having time resolution of the order of 0.1 ns would allow to decrease background for pattern recognition.

Backup

Proposal 1b (from occupancy point of view)

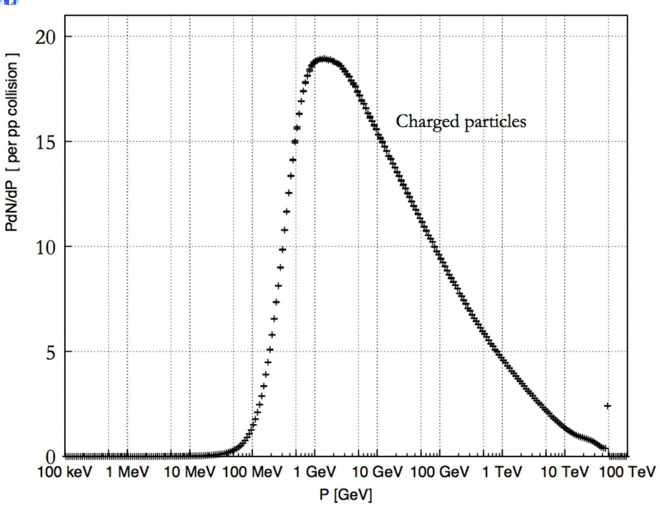


In terms of occupancy , one could use lowest resolution down to R<200mm. To be checked: pattern recognition and d0,z0 resolution

Occupancy

Occupancy map from Ilaria

```
# Simulation program: FLUKA devel
# Simulation run: FCC-hh pp 100TeV
# Simulation type: All Charged Particles fluence
# Data type: Fluence per collision
# Data unit: cm^-2
# Data arrangement: (Z x R) mesh
# R unit: mm
# R min: 0.0
# R max: 2500.0
# R bin width: 10
# R number of bins: 250
# Z unit: mm
# Z min: 0
# Z max: 8100
# Z bin widt
# Z number (
# Reference
# Author: M.
# Created: 2
```



below you can find the charged particles fluence values in the tracker per p-p collision.
The values have been obtained averaging on the azimuthal angle. In the header you can find some information concerning the binning in R and Z.
Each number is the value in one zXR bin. The loop is done on R for each z bin value. So value 251 is the fluence in the first radial bin for z = [10-20 cm].
For this simulation, I have rescaled the old magnetic field map to have a 4 T field in the tracker.
There are no layers in the tracker volume, just air. I have included the EM calorimeter in the simulation not to miss the back-scattering into the tracker.
We have forced a complete absorption at the level of the hadronic calorimeter to speed up the simulations.

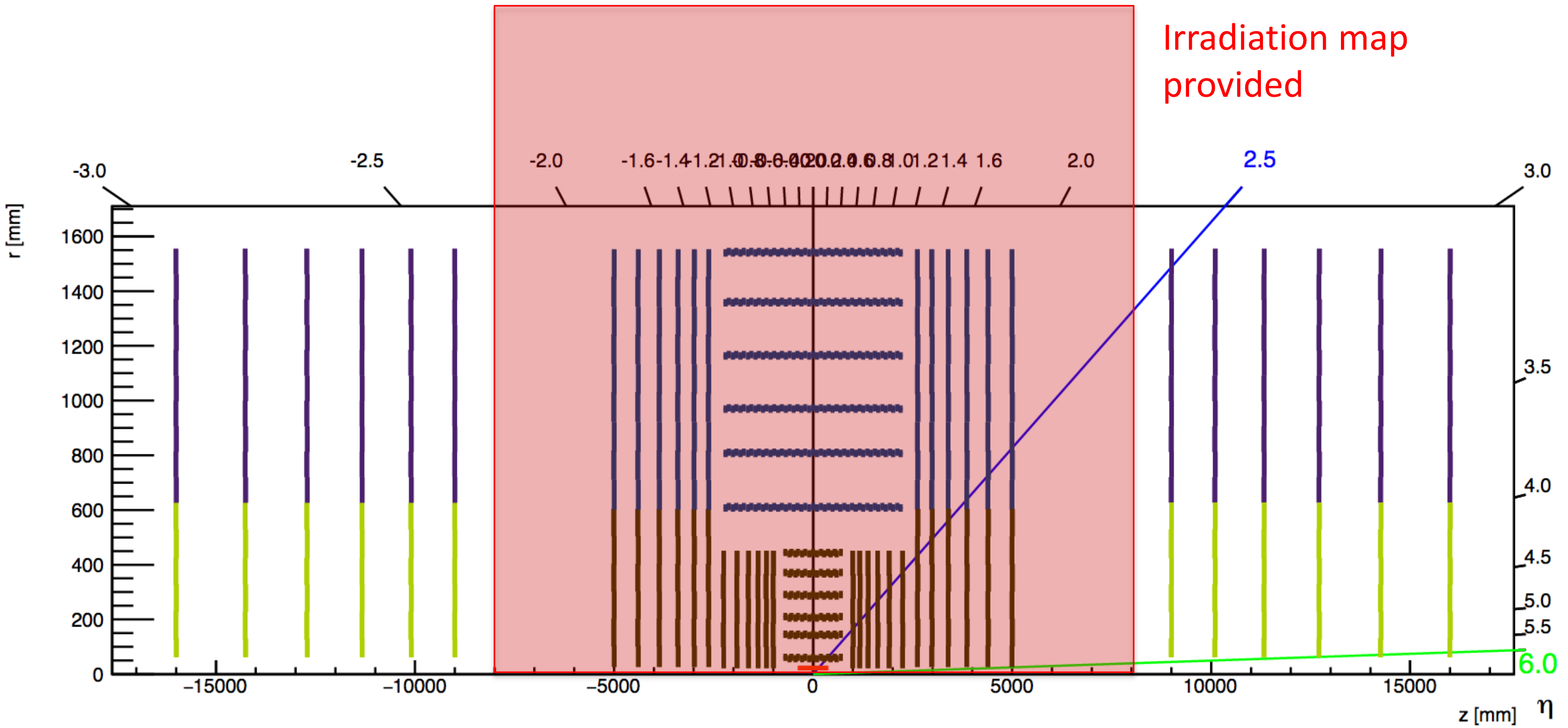
Beside this, I have performed a separate simulation to see the P and Pt distributions of collision debris particles. These plots have been obtained averaging on a sphere around the IP with a radius of 5 mm.

'hh/hh_IP_Detector/2016_sep_06_EMon

Independent of the orientation of the surface
http://www.fluka.org/content/course/NEA/lectures/Scoring.pdf

$$\Phi = \lim_{\Delta V \to 0} \frac{\Sigma_i L_i}{\Delta V}$$

Original map interpolated to obtain more precise values



1) Constraints from fluence on detector granularity

Given the fluence map, what is the minimum granularity needed in each part of the detector, to make sure there will be only one particle firing a pixel?

\# particles per unit area, per pp collision (→ Fluence)

\# hit pixels per perpendicular particle (→ ClusterSize)

Occupancy = Fluence * Pile up * PixelArea * ClusterSize(Diffusion)

per Bunch Crossing (→ Occupancy)

\# of pp collisions per Bunch Crossing (BC) (→ Pile up)

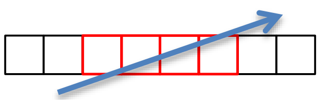
Assume we need the **occupancy <=0.01** (to be reviewed)

Assume cluster size due to difussion = 1

Assume # Pile up interactions per bunch crossing **=1100**

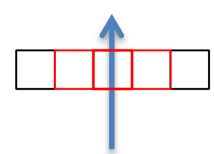
Cluster size has 2 components:

geometric:



included in the fluence calculation

diffusion:

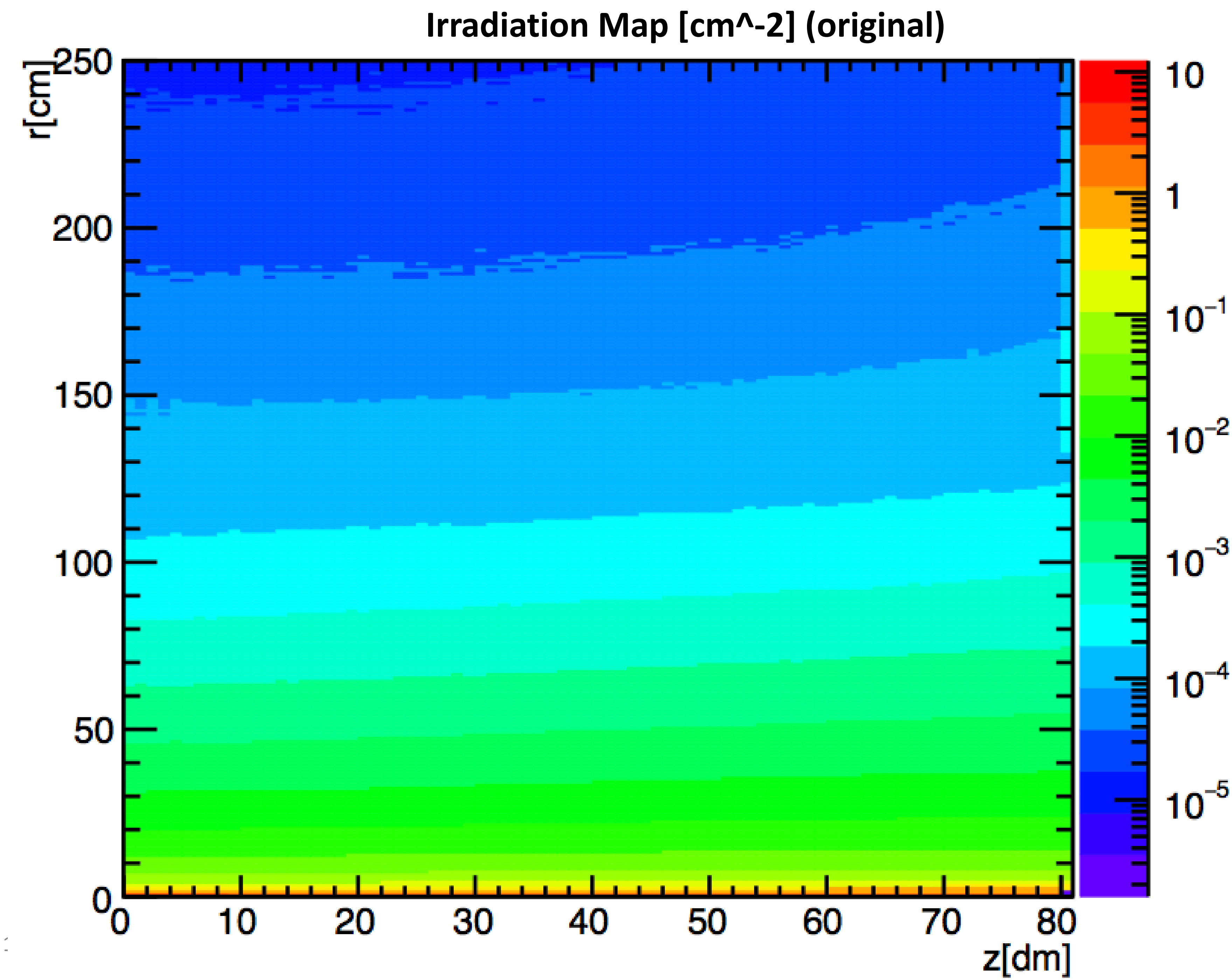


assumed to have no diffusion (size=1)

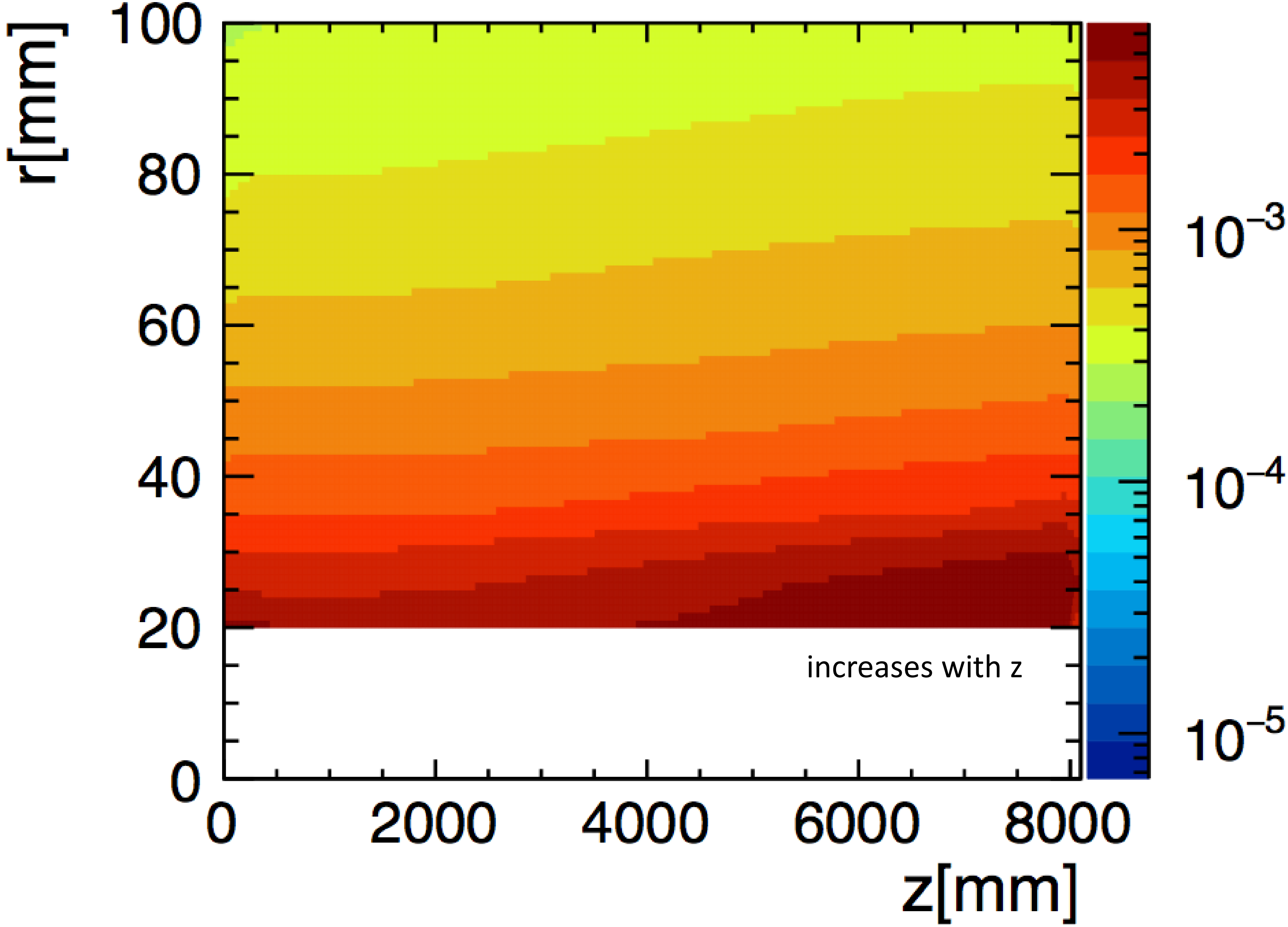
RD53

https://indico.cern.ch/event/527359/contributions/2158545/attachments/1278486/1898346/LHCC_status_report_2016_v5.pdf

- Extremely challenging requirements for HL-LHC:
  - Small pixels: 50x50um^2 (25x100um^2) and larger pixels
  - Large chips: ~2cm x 2cm (~1 billion transistors)
  - Hit rates: 3 GHz/cm^2
  - Radiation: 1Grad, 2 10^{16} neu/cm^2 over 10 years (unprecedented)
  - Trigger: 1MHz, 10us (~100x buffering and readout)
  - Low power - Low mass systems

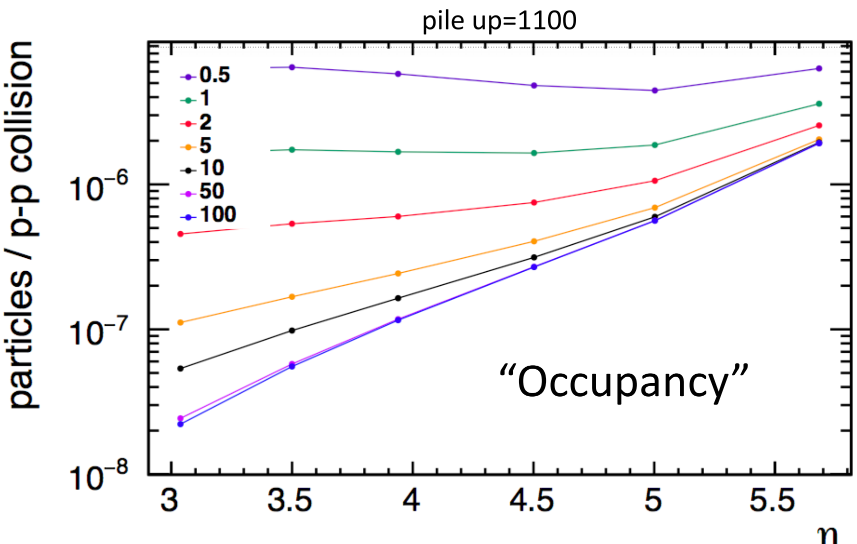

Irradiation Map [cm^-2] (original)
r[cm]
250
200
150
100
50
0
0
10
20
30
40
50
60
70
80
z[dm]
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}

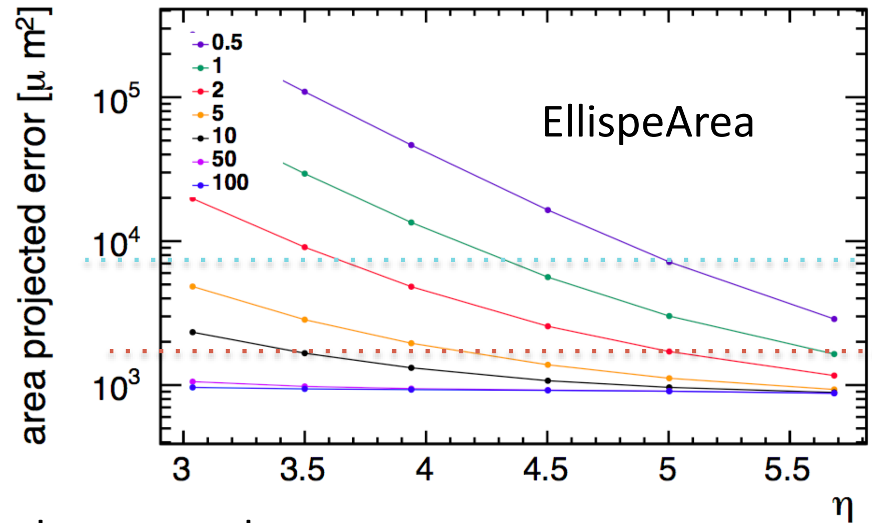
Interpolated Irradiation Map [mm^-2] (zoom in low R, full Z, removed beampipe area)



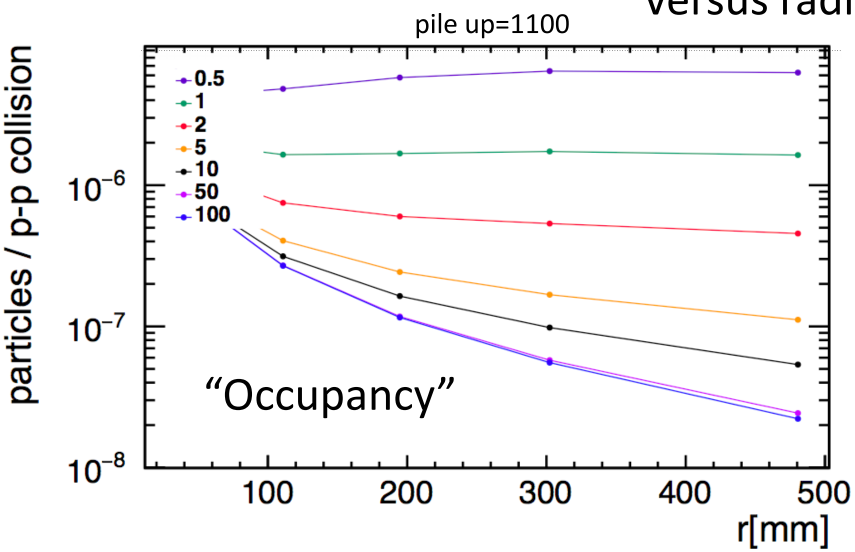
σ(fwd layers)=25x25 1 middle layer

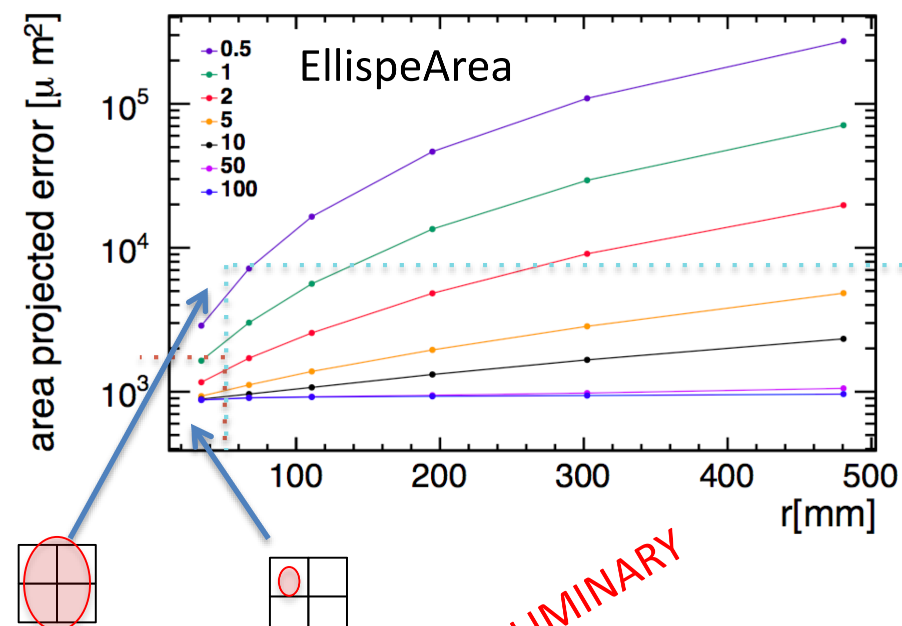
versus eta





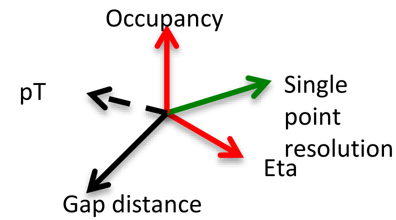
versus radius at last encap layer

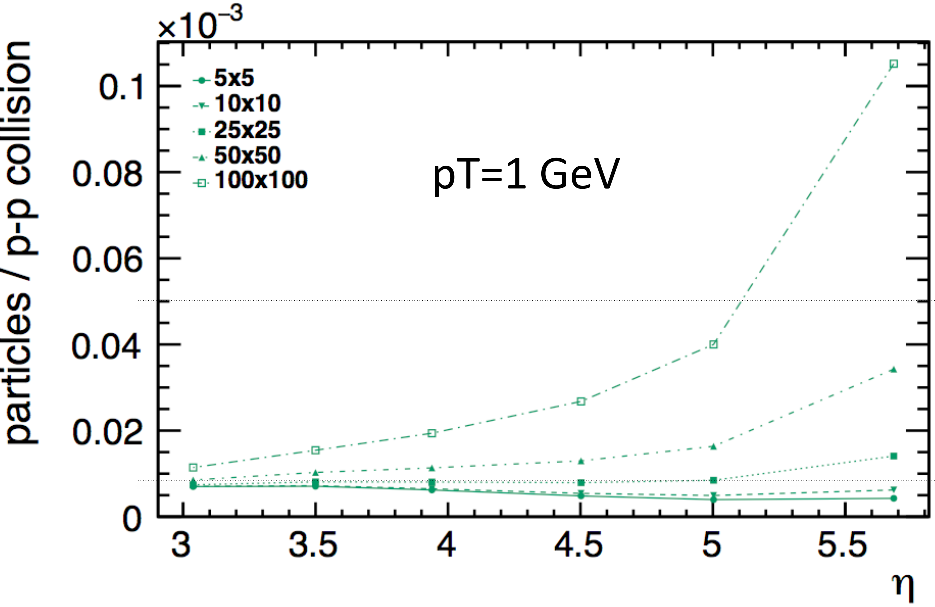


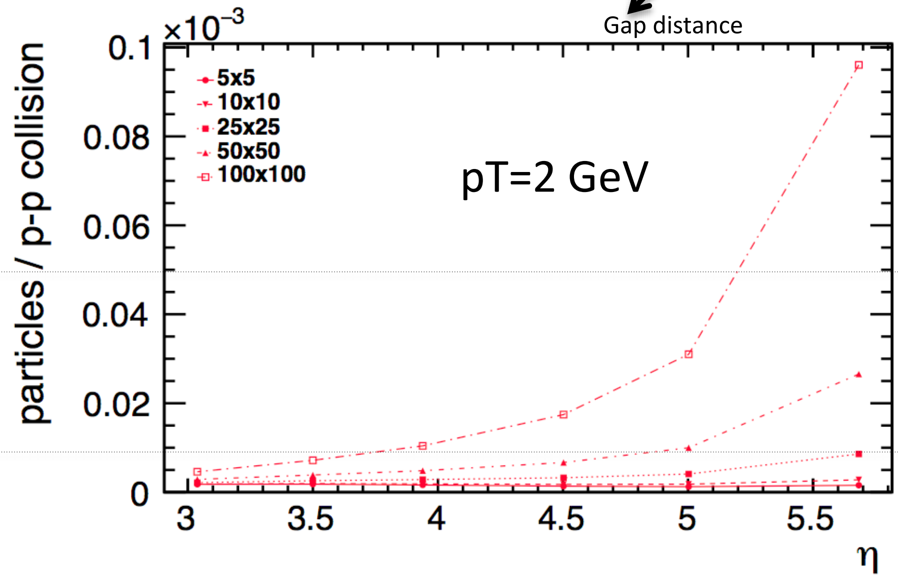


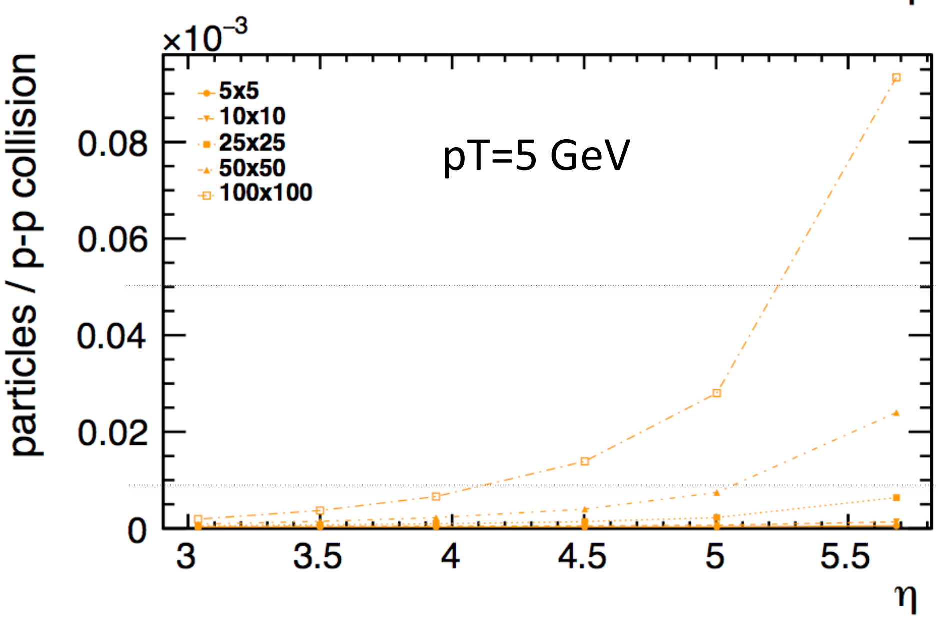
PRELIMINARY

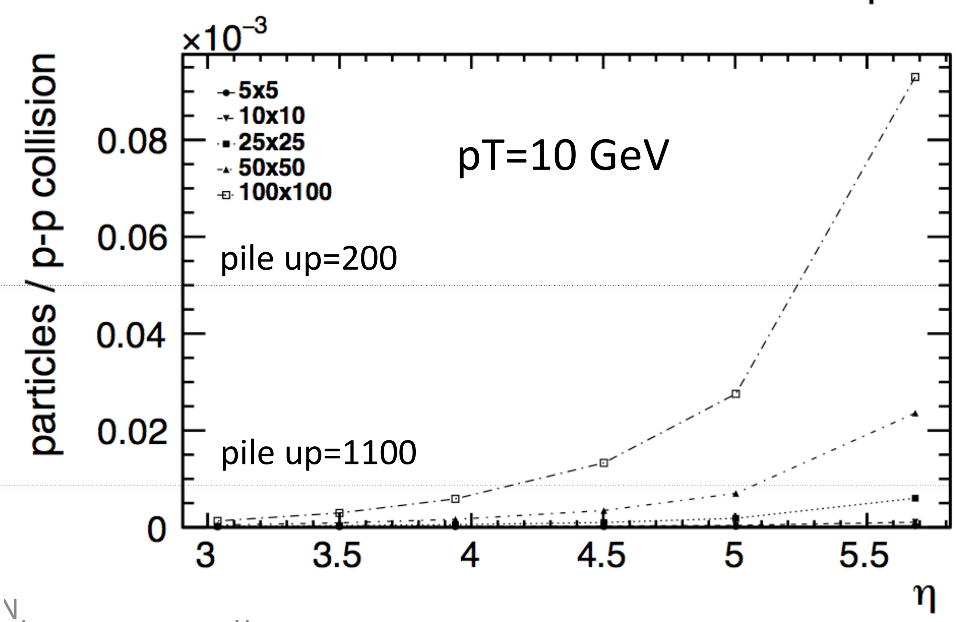
occupancy dependence with the angle





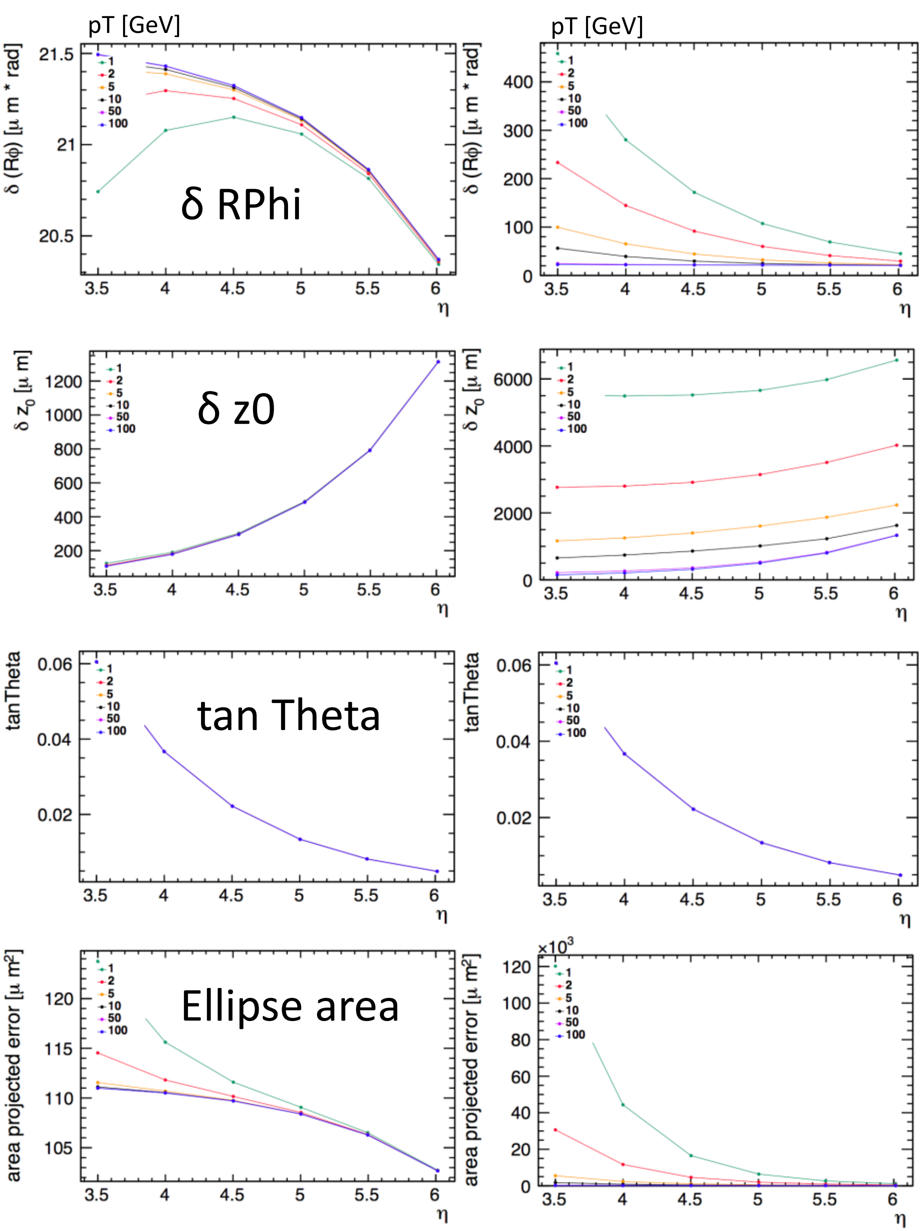






Cross-checking area and occupancy calculations

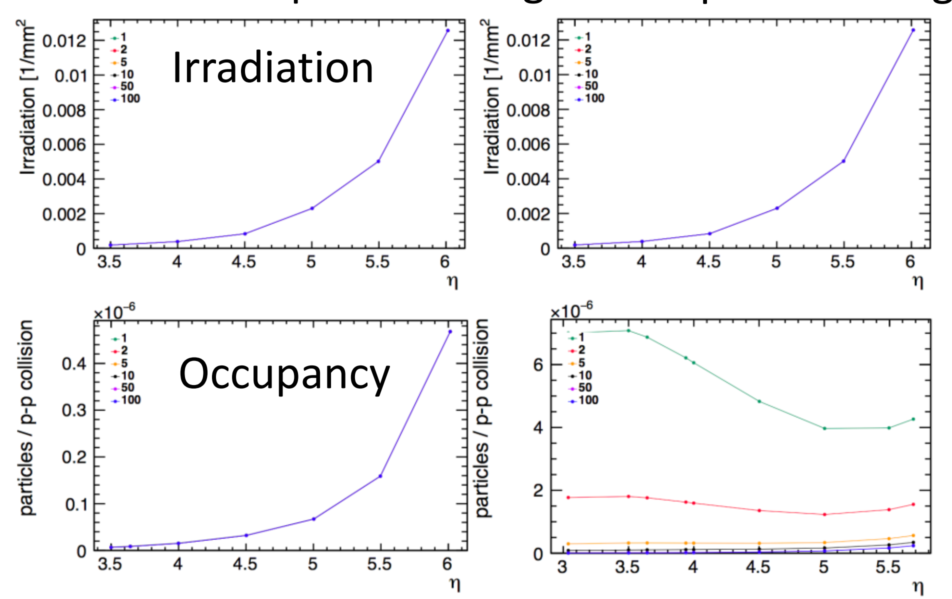
NO MultipleScattering MultipleScattering



A= ¼ * π * res(Rphi) * res(z) * tan(theta)

Occupancy = Irradiation[mm^-2] * 10^-6 [mm^2 / um^2] * Area [um^-2]

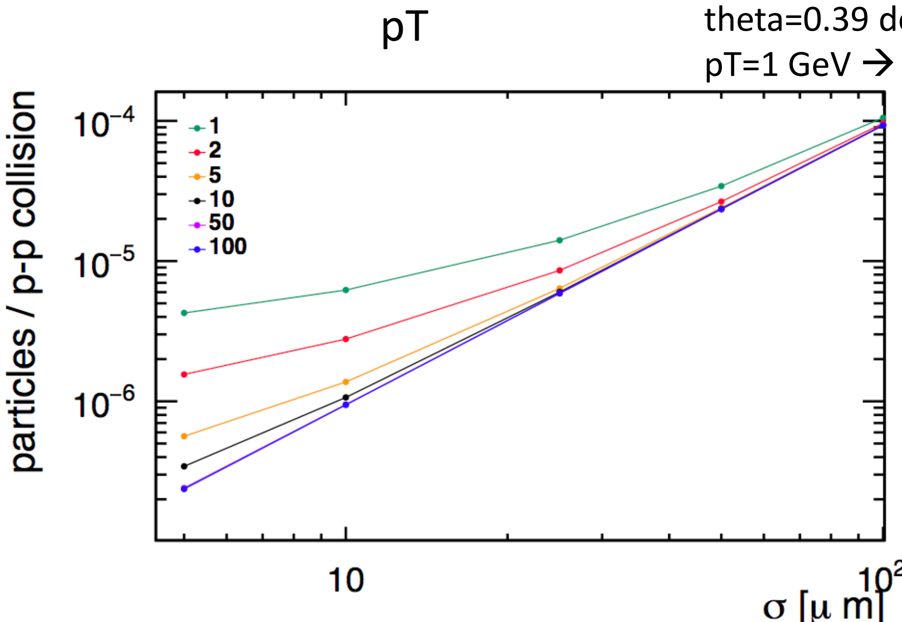
NO MultipleScattering MultipleScattering

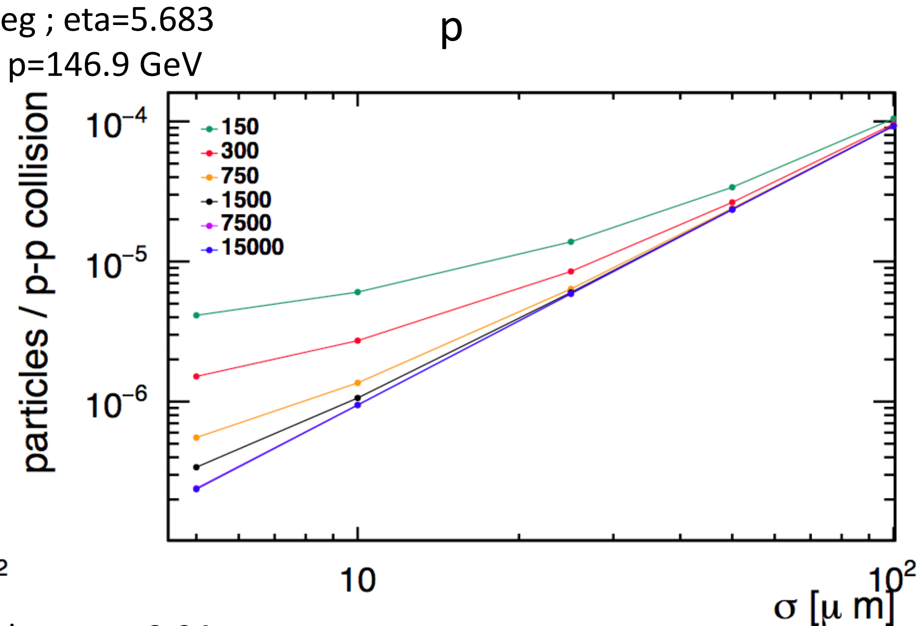


Cross-checking area and occupancy calculations

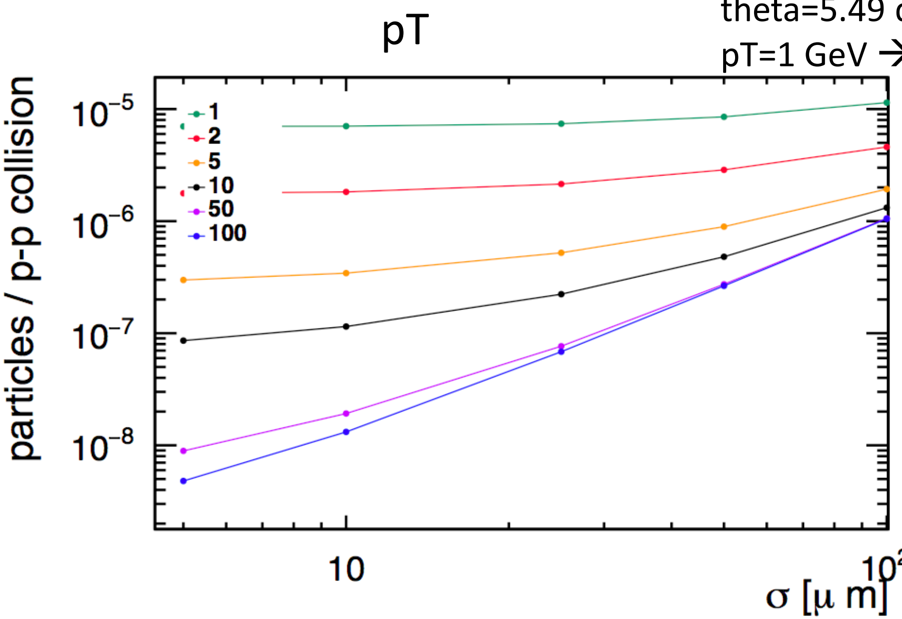
eta=-ln[tan(theta/2)] ;
p=pT*cosh(eta)

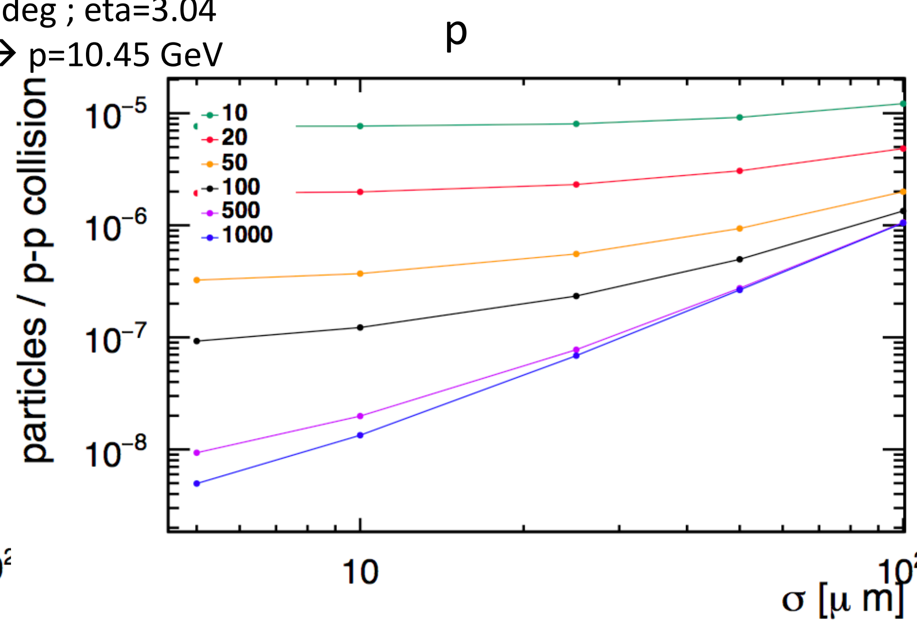
theta=0.39 deg ; eta=5.683
pT=1 GeV → p=146.9 GeV





theta=5.49 deg ; eta=3.04
pT=1 GeV → p=10.45 GeV



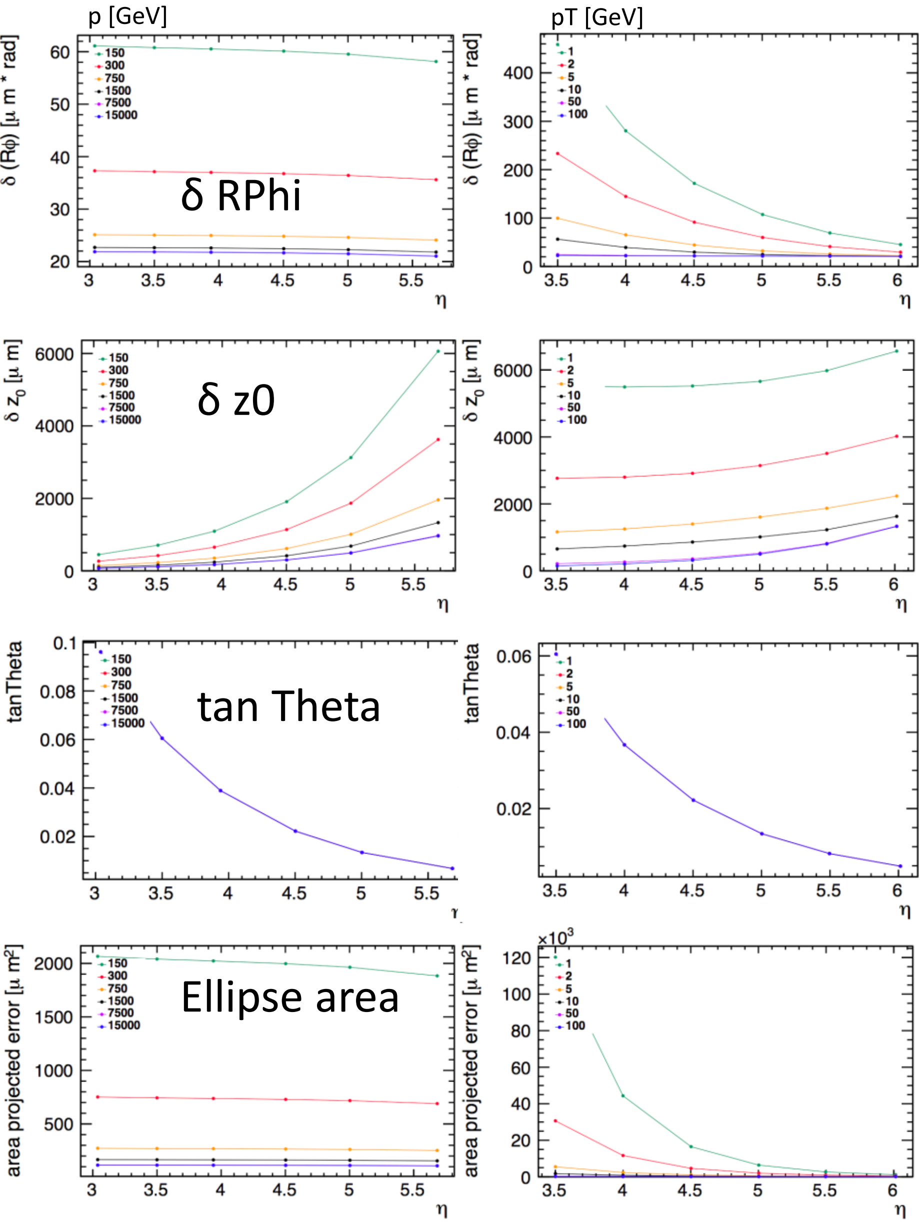


Cross-checking area and occupancy calculations

p

equivalent for eta=5.7

pT

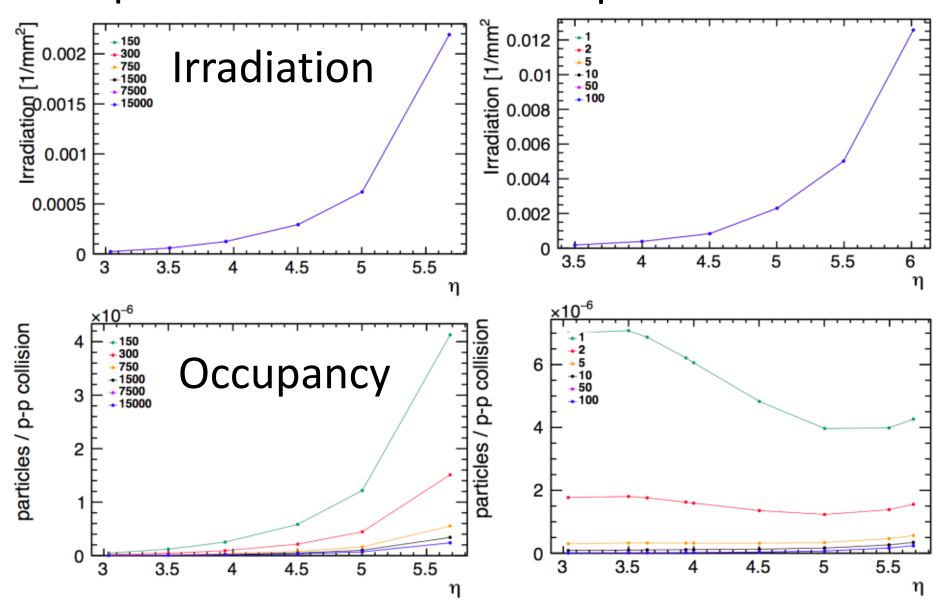


A= ¼ * π * res(Rphi) * res(z) * tan(theta)

Occupancy = Irradiation[mm^-2] * 10^-6 [mm^2 / um^2] * Area [um^-2]

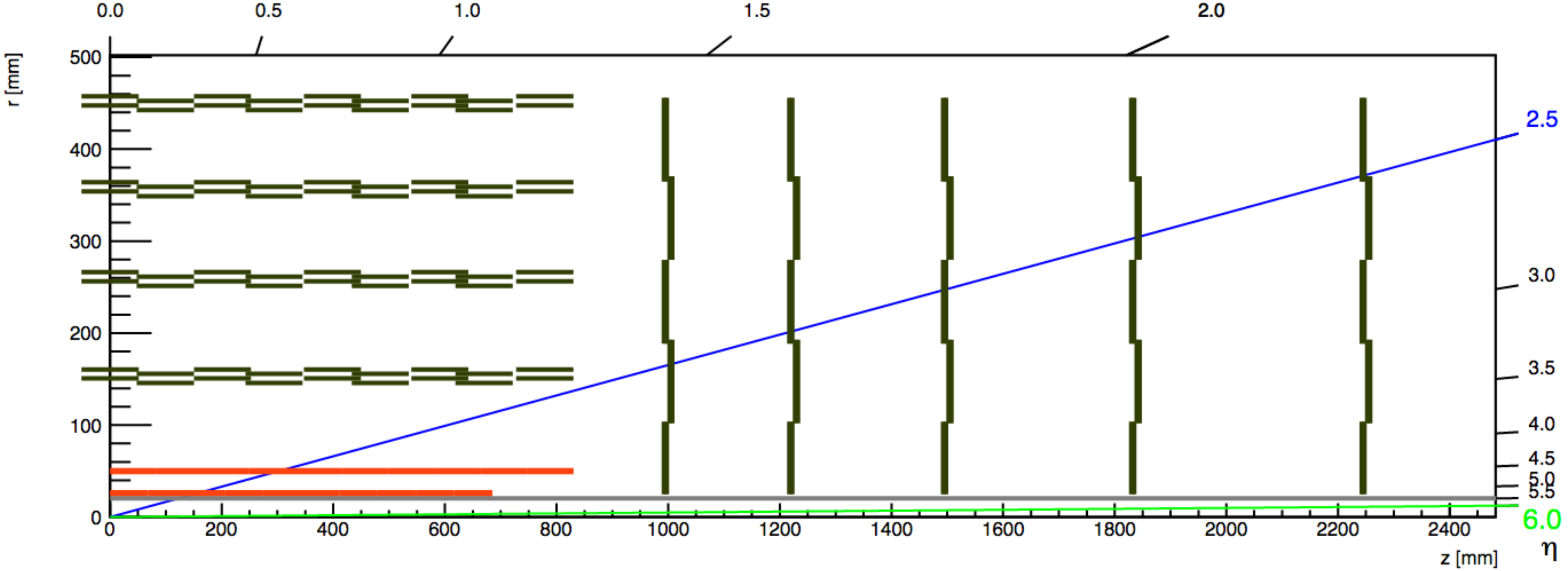
p

pT



- # New baseline geometry from Zbynek:

http://fcc-tklayout.web.cern.ch/fcc-tklayout/FCChh_Option3.v01



Layer no :	1	2	3	4	5	6
Average radius [mm] :	25.02	48.31	151.05	257.52	355.50	449.22
Radius-min [mm] :	23.66	46.94	142.48	248.94	346.93	440.65
Radius-max [mm] :	27.16	51.30	161.66	267.32	364.98	458.51
Z-min [mm] :	-685.0	-830.0	-830.0	-830.0	-830.0	-830.0
Z-max [mm] :	685.0	830.0	830.0	830.0	830.0	830.0

Module in:	Barrel	Barrel	Endcap	Barrel	Endcap	Endcap	Endcap	Endcap	Endcap
Position:	BRL_Inner0_L01	BRL_Inner0_L02	ECAP_R05D1 ECAP_R05D2 ECAP_R05D3 ECAP_R05D4 ECAP_R05D5	BR_Inner1_L01 BR_Inner1_L02 BR_Inner1_L03 BR_Inner1_L04	ECAP_R04D1 ECAP_R04D2 ECAP_R04D3 ECAP_R04D4 ECAP_R04D5	ECAP_R01D1 ECAP_R01D2	ECAP_R01D3 ECAP_R01D4 ECAP_R01D5	ECAP_R03D1 ECAP_R03D2 ECAP_R03D3 ECAP_R03D4 ECAP_R03D5	ECAP_R02D1 ECAP_R02D2 ECAP_R02D3 ECAP_R02D4 ECAP_R02D5
Type:	pixelFirst	pixelFirst	pixel	pixel	pixel	pixel	pixel	pixel	pixel
Sensor area [mm^2]:	876.8	2124.8	4191.0	5242.9	4210.8	2541.8	2541.8	4164.4	4137.9
Total area [m^2]:	0.2	0.6	2.3	13.5	1.9	0.1	0.2	1.3	0.8
Number of modules:	280	280	560	2584	440	48	72	320	200
Number of sensors:	280	280	560	2584	440	48	72	320	200
Number of channels (M):	36.70	36.70	73.40	2709.52	57.67	6.29	9.44	41.94	26.21
Min-Max R-Phi resolution (μm):	10-10	10-10	10-10	10-10	10-10	10-10	10-10	10-10	10-10
Min-Max Z(R) resolution (μm):	15-15	15-15	30-30	30-30	30-30	15-15	30-30	30-30	30-30

longer inner barrel layer,
lighter 1st and 2nd barrel ($X/X0=0.5\%$, others 1.5%)
worse single point resolution assumed