MACHINE INDUCED BACKGROUNDS IN THE FCC-ee MDI REGION AND BEAMSTRAHLUNG RADIATION

Andrea Ciarma

Thanks to: E. Perez, D. Shatilov, F. Fransesini, A. Abramov, M. Boscolo, G. Ganis

FCC-ee MDI background studies

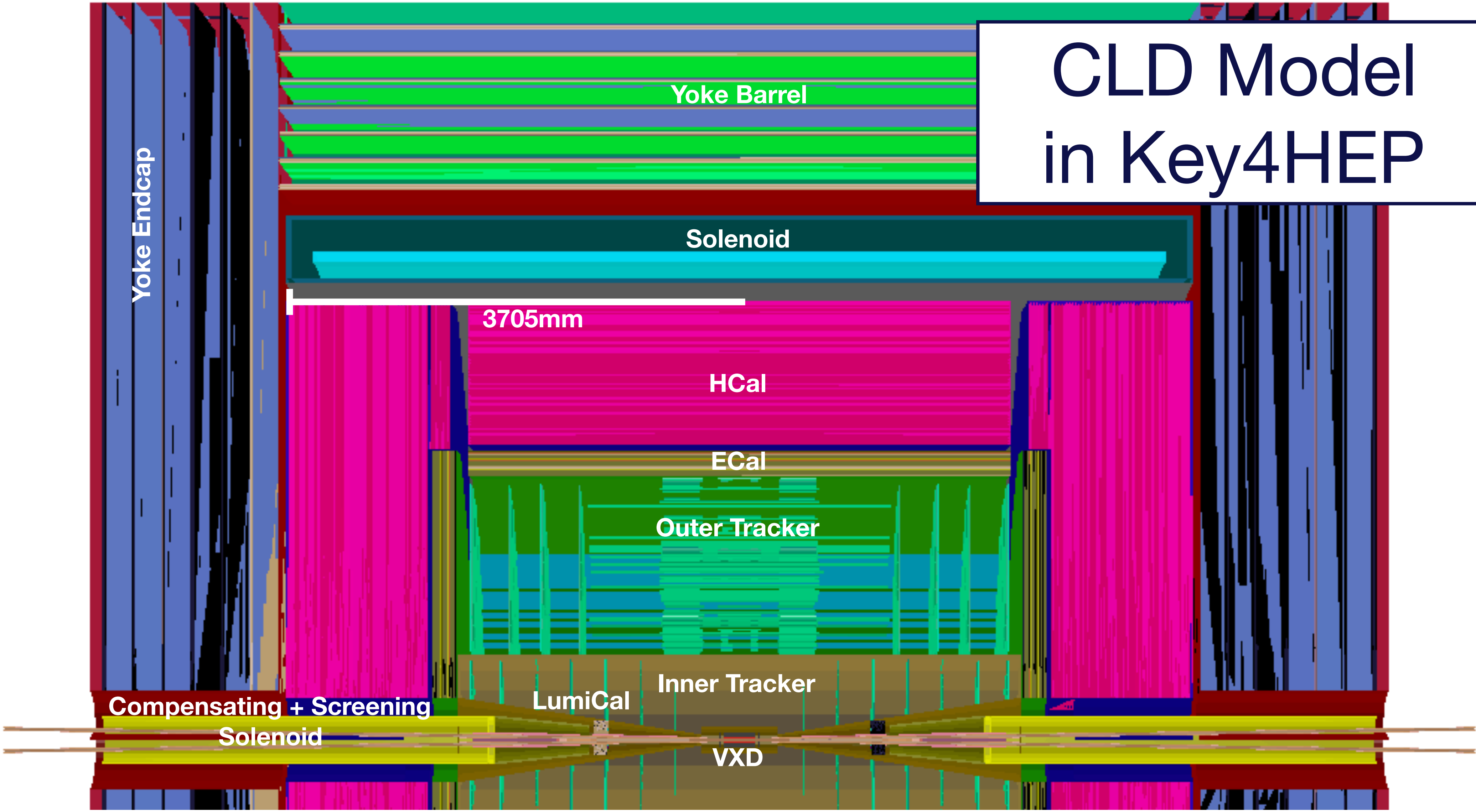
Machine induced background studies were performed for the CDR and included the beam losses in the IR, pairs production and the development of Synchrotron Radiation masks and shieldings.

After the design of the **new 4IP lattice** and the migration to the **turnkey software Key4HEP**, it is necessary to repeat and extend these studies. Currently ongoing work includes:

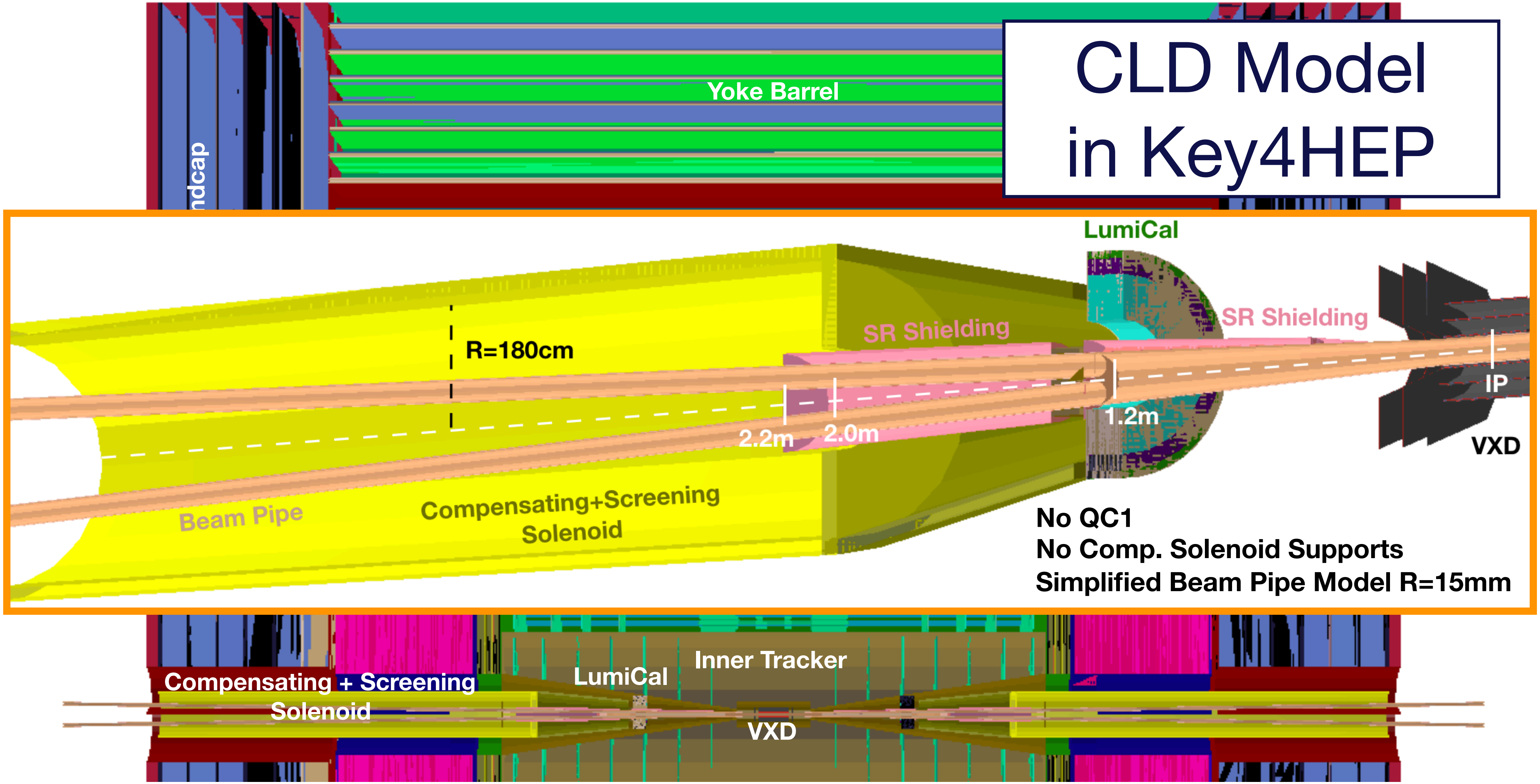
- The evaluation of the VXD/TRK occupancy due to **Incoherent Pair Creation (IPC)**
- Preliminary tracking of **beam losses** in CLD during failure scenarios
- Characterization of the **beamstrahlung radiation** produced at the IP

The tracking of the background particles in the **FCCSW model of the CLD detector** in order to estimate the related hit densities has been performed using the **turnkey software Key4HEP.**

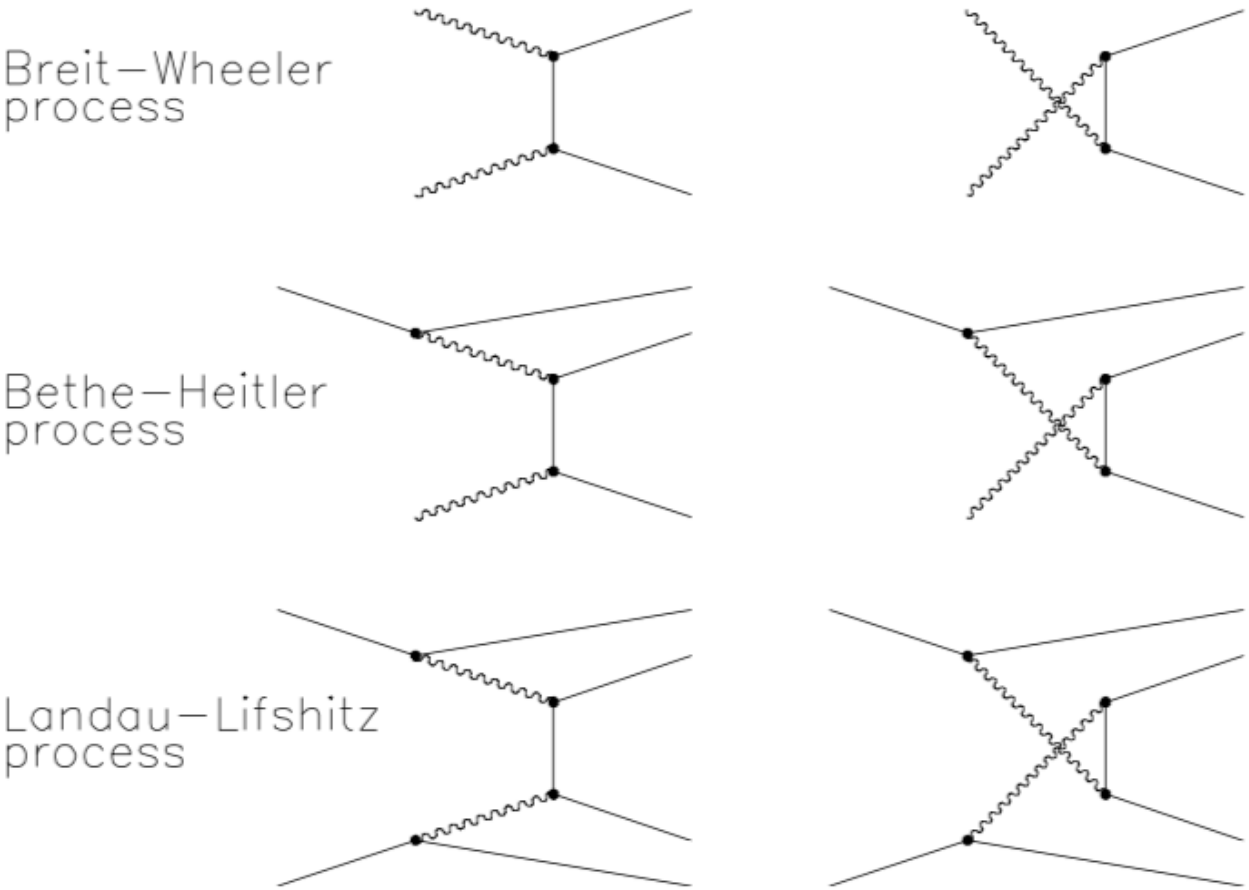
CLD Model in Key4HEP



CLD Model in Key4HEP



Incoherent Pairs Creation (IPC)



Secondary $e^- e^+$ pairs can be produced via the interaction of the beamstrahlung photons with real or virtual photons emitted by each particle of the beam during bunch crossing.

These particles might enter the **first layer of the VXD barrel** if produced with a transverse momentum $p_T > 5\,MeV$ and an azimuthal angle of $\theta > 8\,deg$ from the detector axis.

This process has been simulated using as generator **GuineaPig++** and tracking in the CLD detector using **Key4HEP**

CDR* @45.6GeV **4IP**

Study performed considering the most recent **beam parameters for the 4IP lattice** with $\beta_x^* = 0.10\,m$

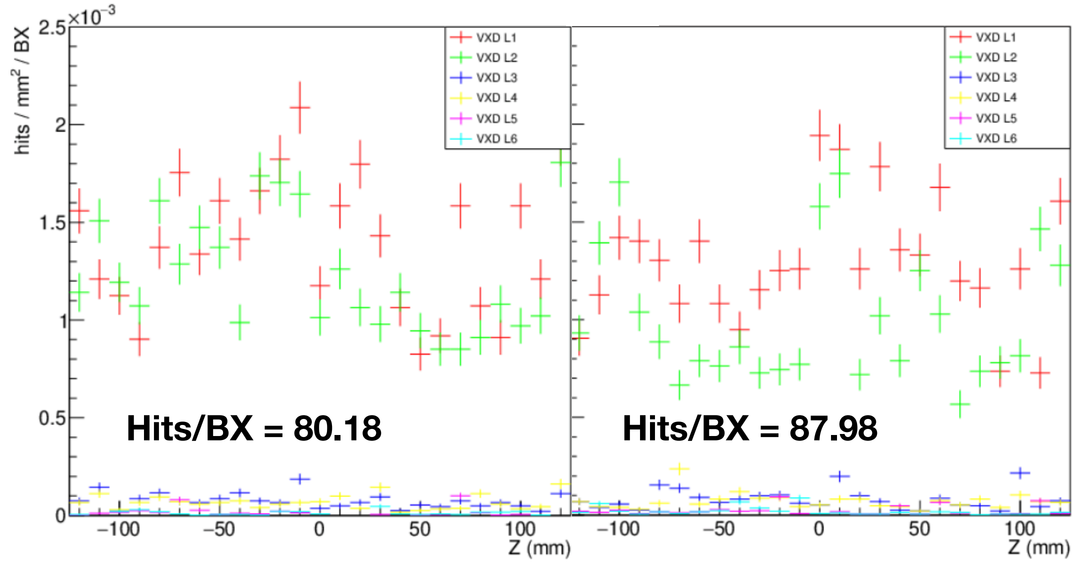
Comparing with the results obtained using the CDR beam parameters, a **slight increase** in the VXD hit densities can be observed using the 4IP parameters, due to the **higher bunch population** resulting in a higher number of pairs produced per bunch crossing (e.g. @Z: $N_{CDR} = 862, N_{4IP} = 1276$)

$$occupancy = hits/mm^2/BX \cdot size_{sensor} \cdot size_{cluster} \cdot safety$$

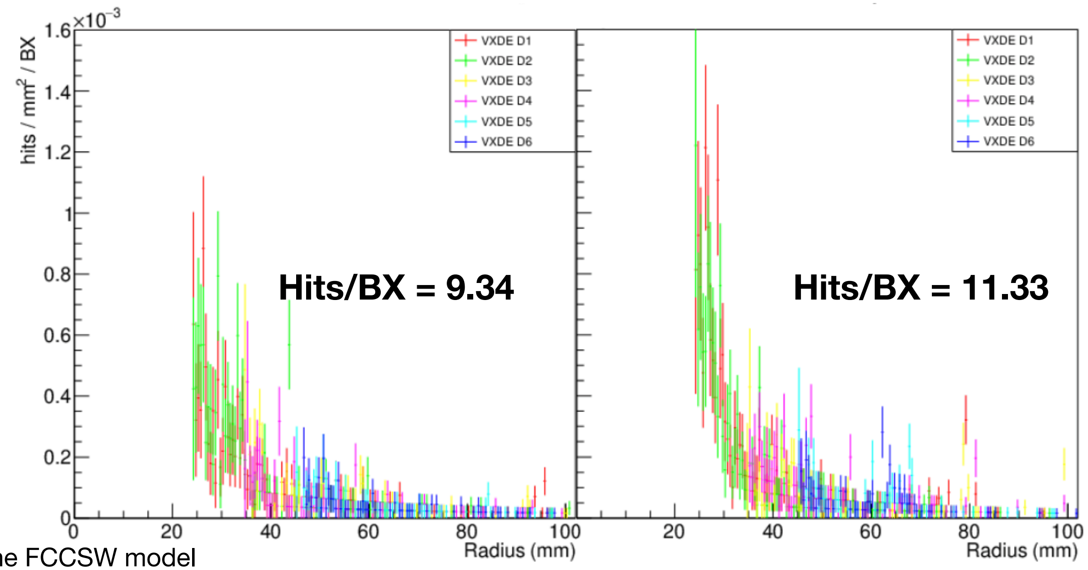
$$size_{sensor} = \begin{matrix} 25\mu m \times 25\mu m\ (pixel) \\ 1mm \times 0.05mm\ (strip) \end{matrix} \qquad size_{cluster} = \begin{matrix} 5\ (pixel) \\ 2.5\ (strip) \end{matrix}$$

$$safety = 3$$

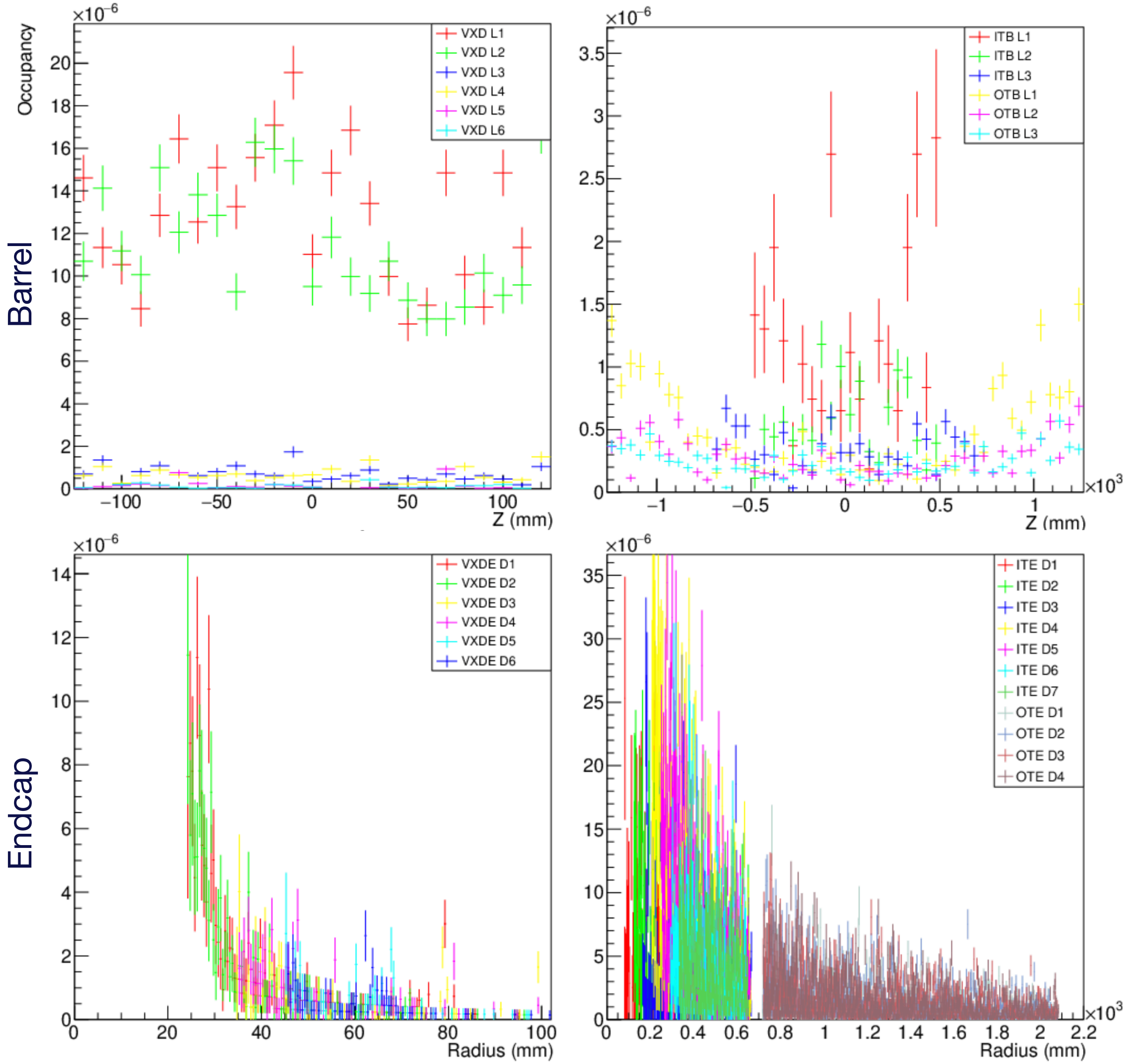
VXD BARREL



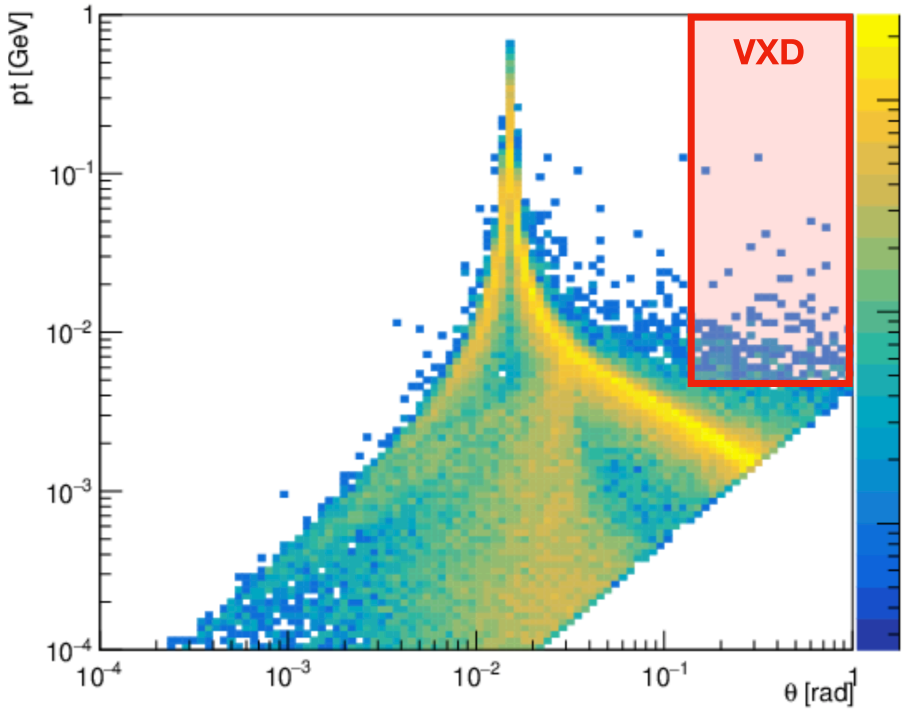
VXD ENDCAP

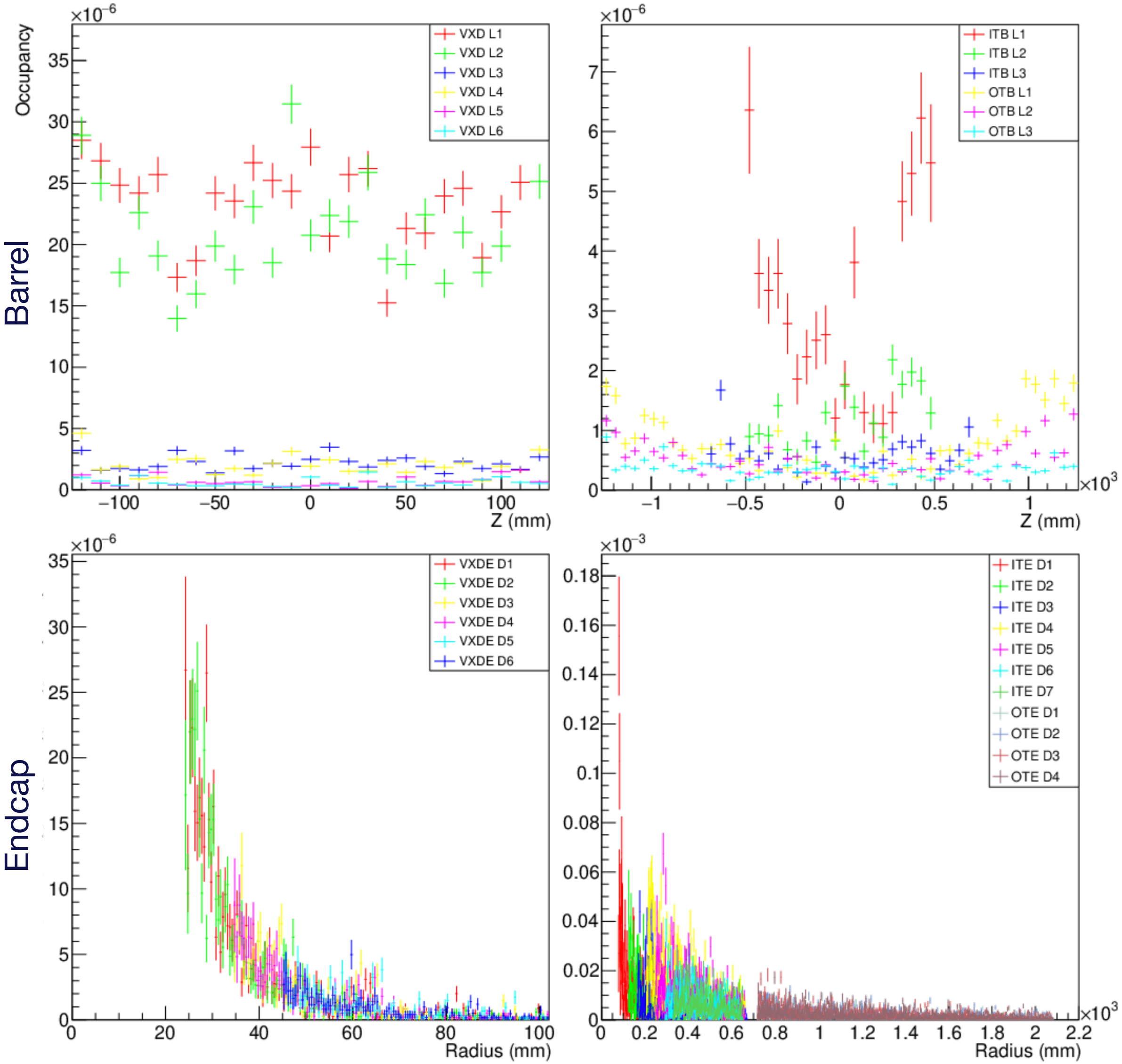


*CDR beam parameters, tracking performed in the FCCSW model

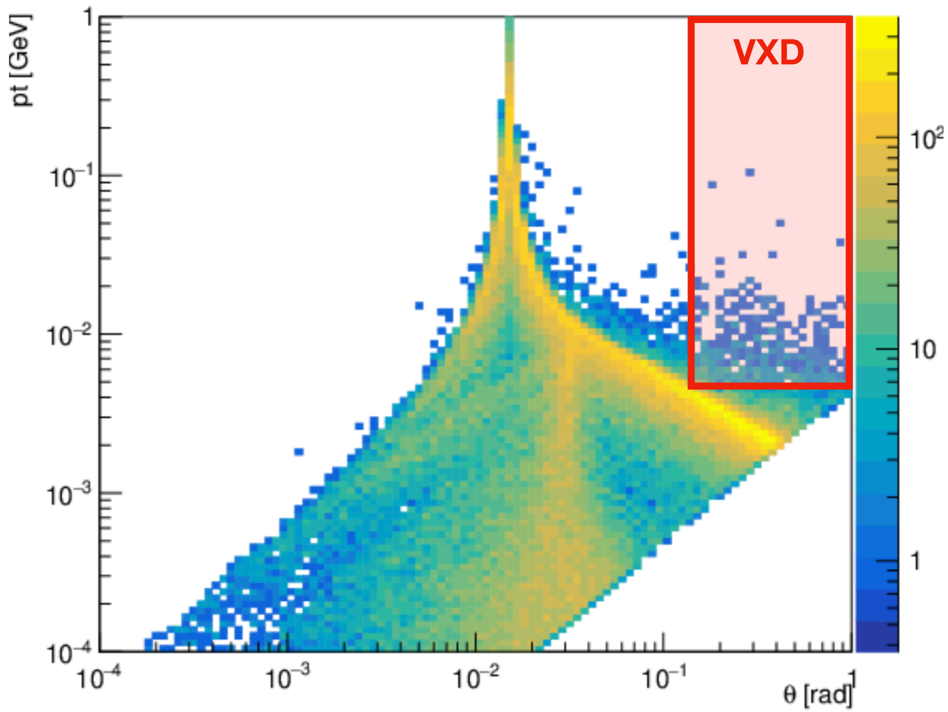


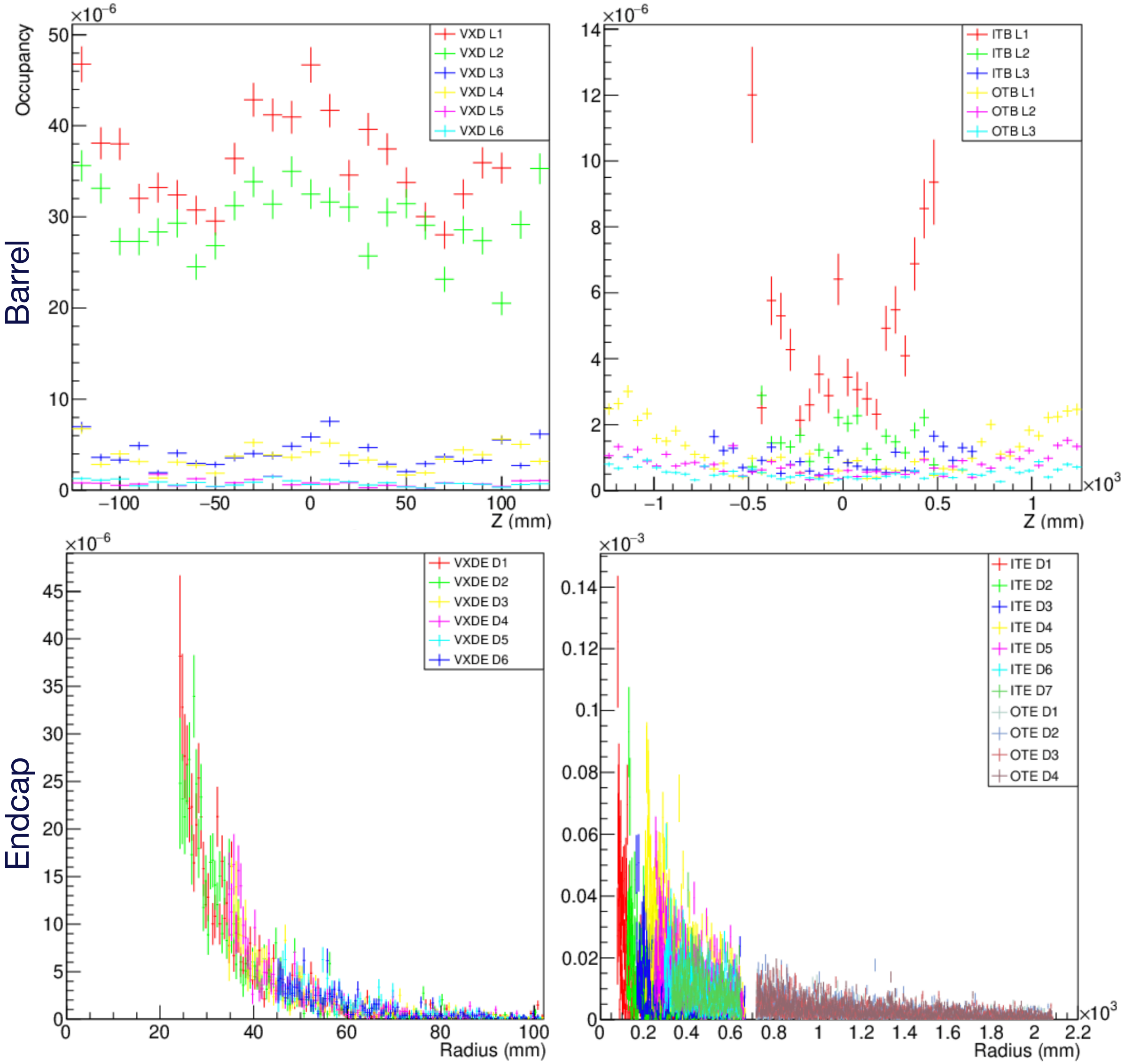
	Z	WW	ZH	Top
Pairs/BX	1300			
Max occup. VXDB	19.5e-6			
Max occup. VXDE	11.5e-6			
Max occup. TRKB	2.8e-6			
Max occup. TRKE	28e-6			



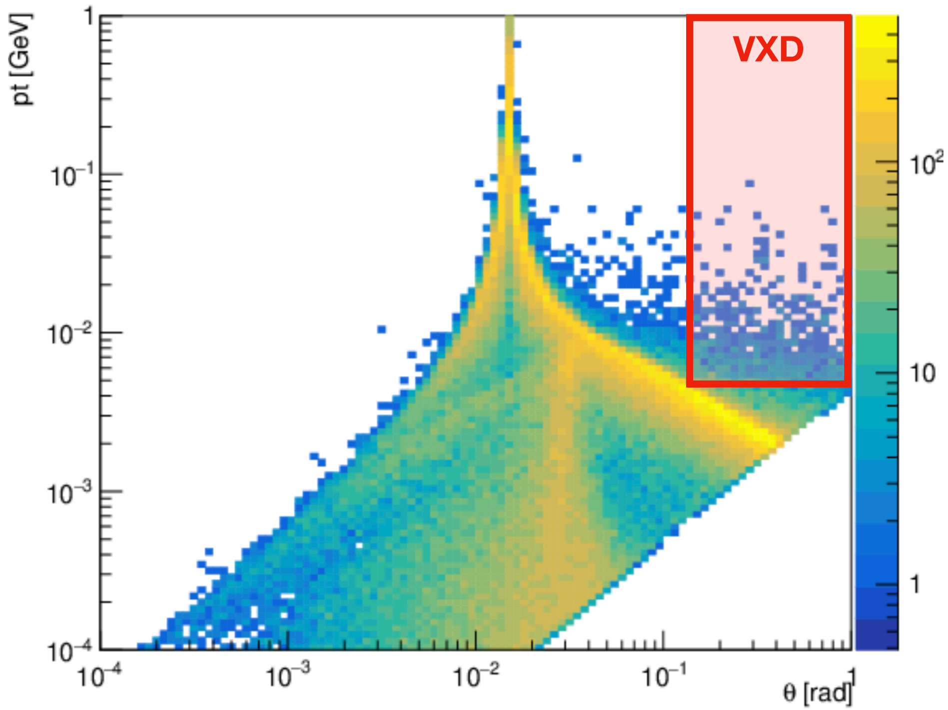


	Z	WW	ZH	Top
Pairs/BX	1300	1800		
Max occup. VXDB	19.5e-6	33e-6		
Max occup. VXDE	11.5e-6	27e-6		
Max occup. TRKB	2.8e-6	6.4e-6		
Max occup. TRKE	28e-6	155e-6		



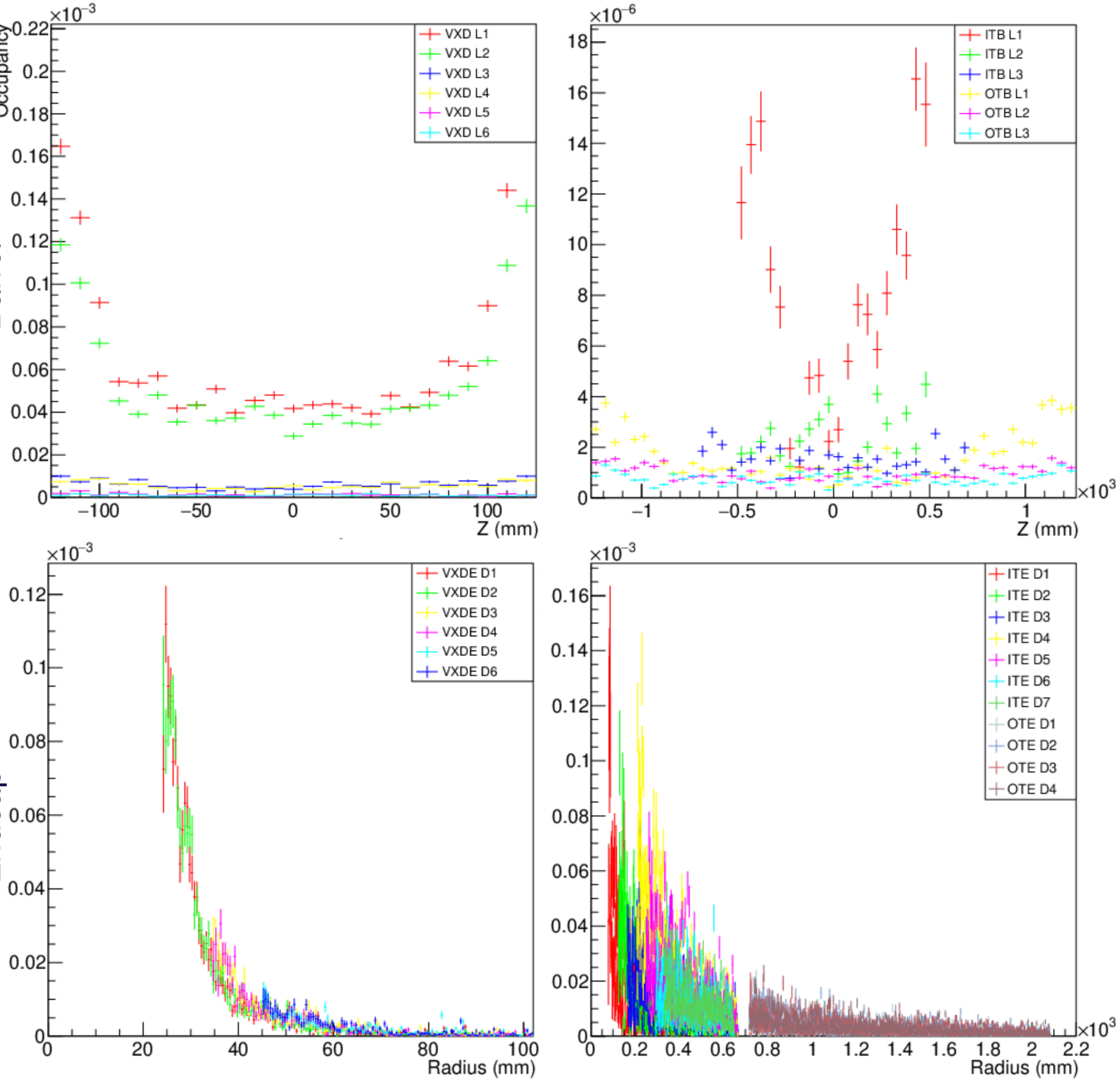


	Z	WW	ZH	Top
Pairs/BX	1300	1800	2700	
Max occup. VXDB	19.5e-6	33e-6	47e-6	
Max occup. VXDE	11.5e-6	27e-6	38e-6	
Max occup. TRKB	2.8e-6	6.4e-6	12e-6	
Max occup. TRKE	28e-6	155e-6	122e-6	

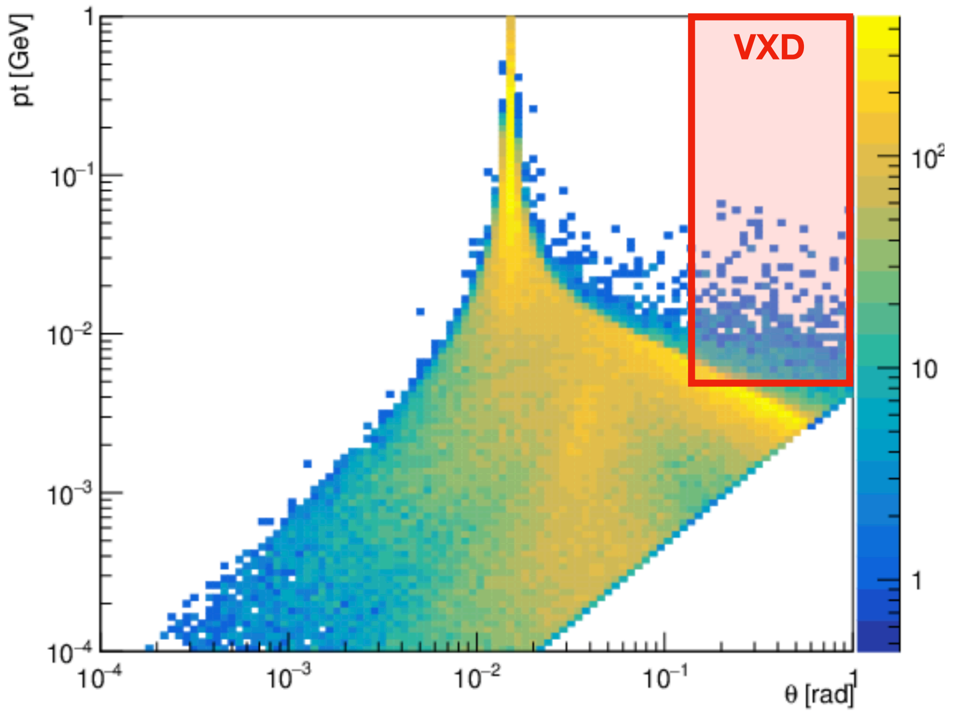


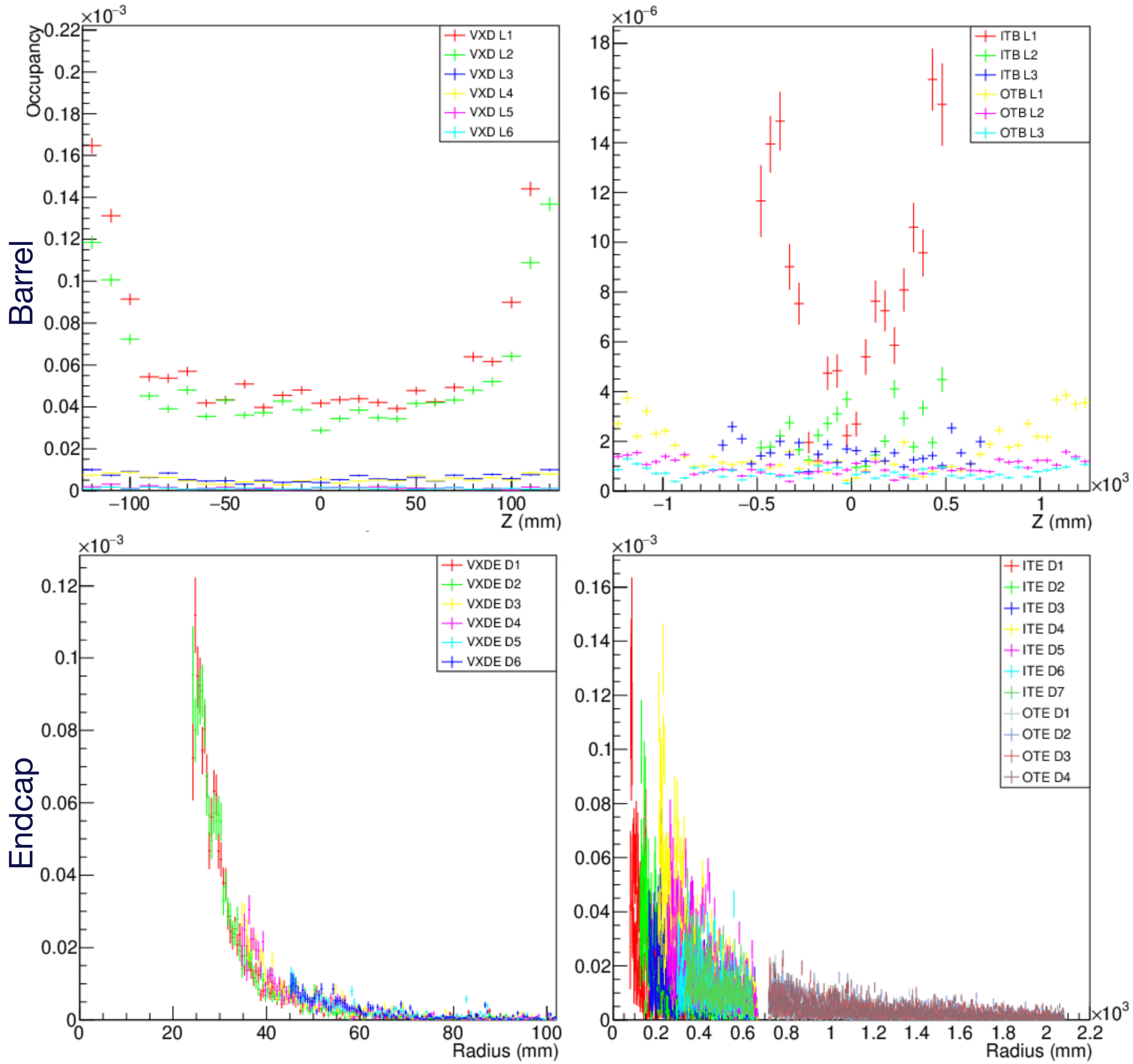
Barel

Endcap



	Z	WW	ZH	Top
Pairs/BX	1300	1800	2700	3300
Max occup. VXDB	19.5e-6	33e-6	47e-6	180e-6
Max occup. VXDE	11.5e-6	27e-6	38e-6	112e-6
Max occup. TRKB	2.8e-6	6.4e-6	12e-6	16.5e-6
Max occup. TRKE	28e-6	155e-6	122e-6	135e-6





	Z	WW	ZH	Top
Pairs/BX	1300	1800	2700	3300
Max occup. VXDB	19.5e-6	33e-6	47e-6	180e-6
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Max occup. TRKB	2.8e-6	6.4e-6	12e-6	16.5e-6
Max occup. TRKE	28e-6	155e-6	122e-6	135e-6

According to the electronics **readout time**, the sensors may integrate over more BXs.

Even considering a $10\mu s$ window, the occupancies will remain **below the 1%**

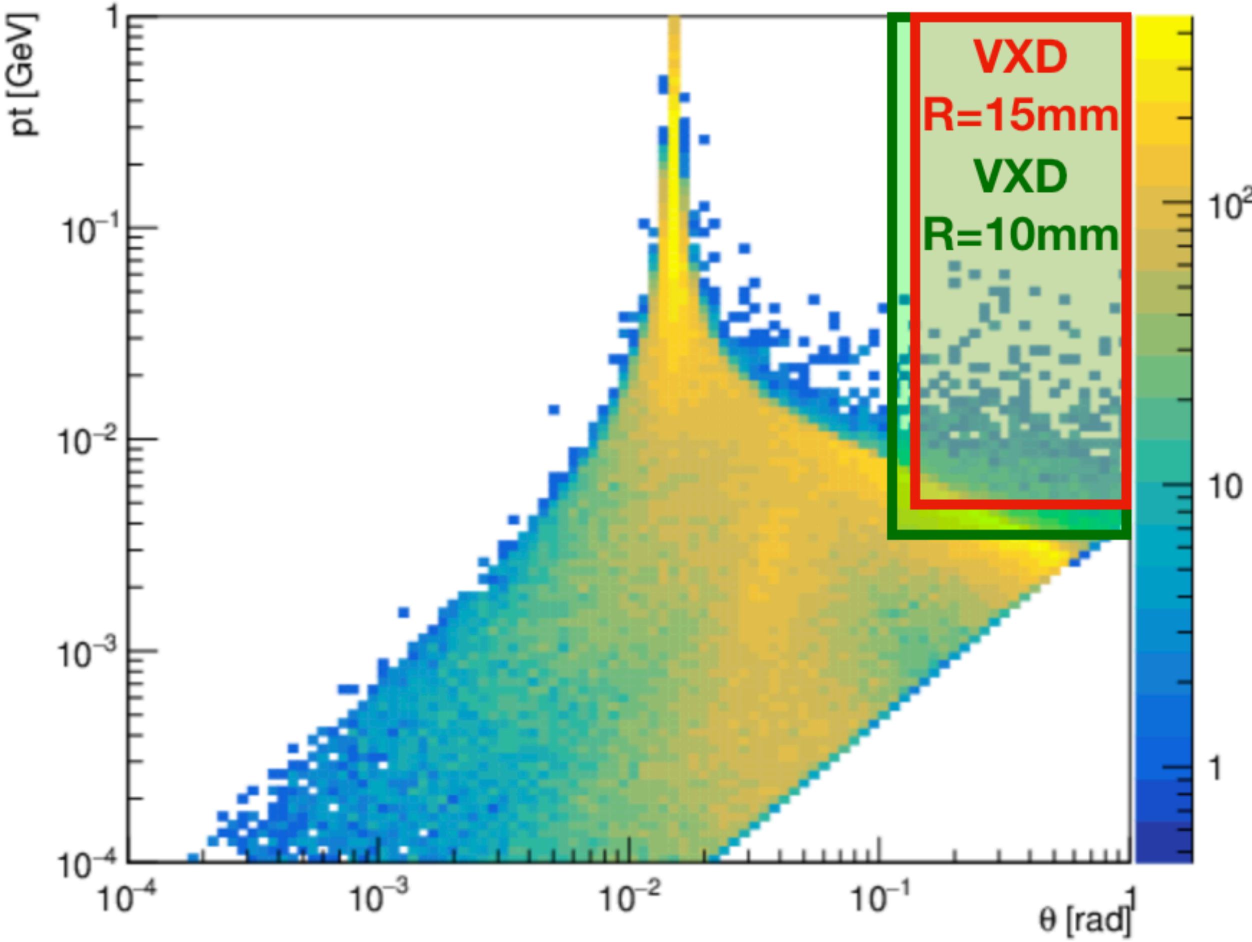
Bunch spacing [ns]	30	345	1225	7598
Max VXD occ. 1us	0.65e-3	0.09e-3	47e-6	180e-6
Max VXD occ.10us	6.50e-3	0.95e-3	383e-6	237e-6
Max TRK occ. 1us	0.93e-3	0.45e-3	122e-6	135e-6
Max TRK occ.10us	9.33e-3	4.50e-3	996e-6	177e-6

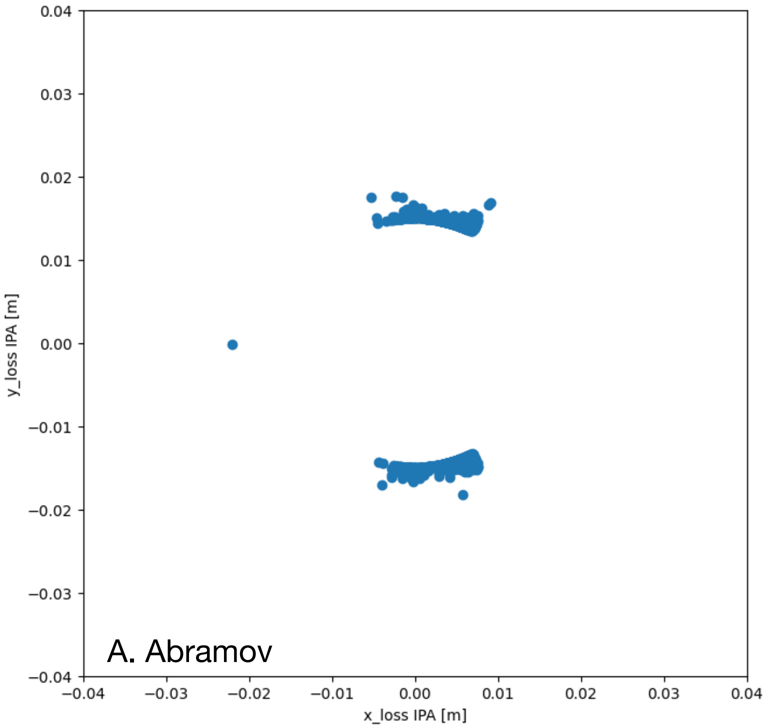
IPC - smaller beam pipe

A **smaller beam pipe** with radius $R = 10\,mm$ is currently under study. This will allow to have the first layer of the VXD **closer to the IP** and possibly improve the tagging efficiency.

Anyway this will also mean that more IPC particles will enter the VXD as its acceptance increases.

Previous studies estimated a x2 occupancy increase (negligible), but **dedicated simulations** using the smaller beam pipe and closer VXD are up next.





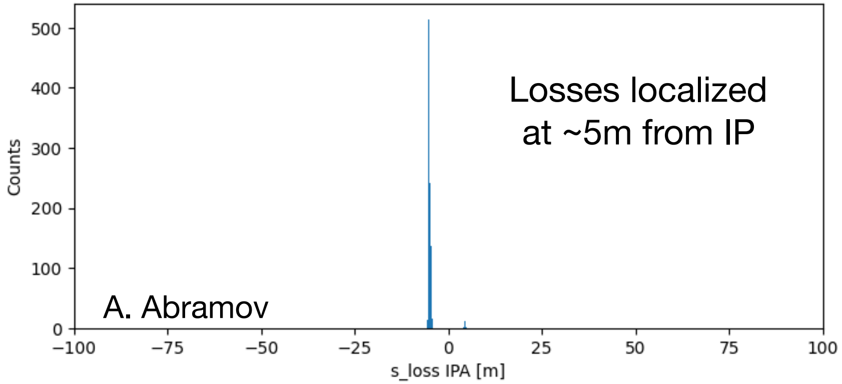
Beam Losses Background

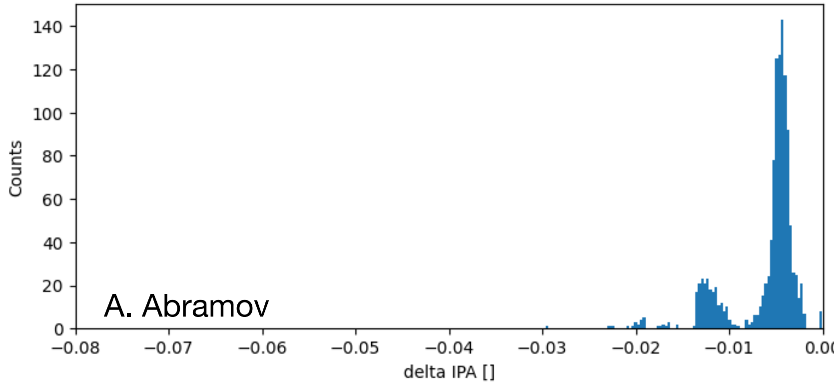
The background induced by **beam losses due to failure** which reduced the beam **lifetime to 5min** (nominal: 18min) has been studied in CLD

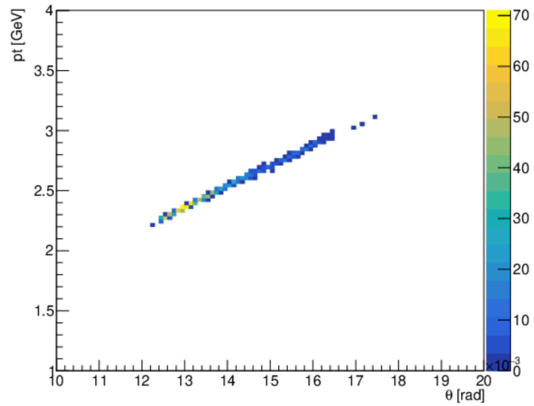
- CDR beam parameters - lattice **v217 @182.5GeV**
- No SR or optics tapering
- No SR collimators
- **15 mm** inner beamipe radius
- Only betatron collimation
- Beam halo impacting the **horizontal primary collimator** TPC.A.B1

Particles tracked in the lattice using **XTrack** (thanks to A. Abramov - talk 01/06) and tracked in the CLD detector using **Key4HEP**

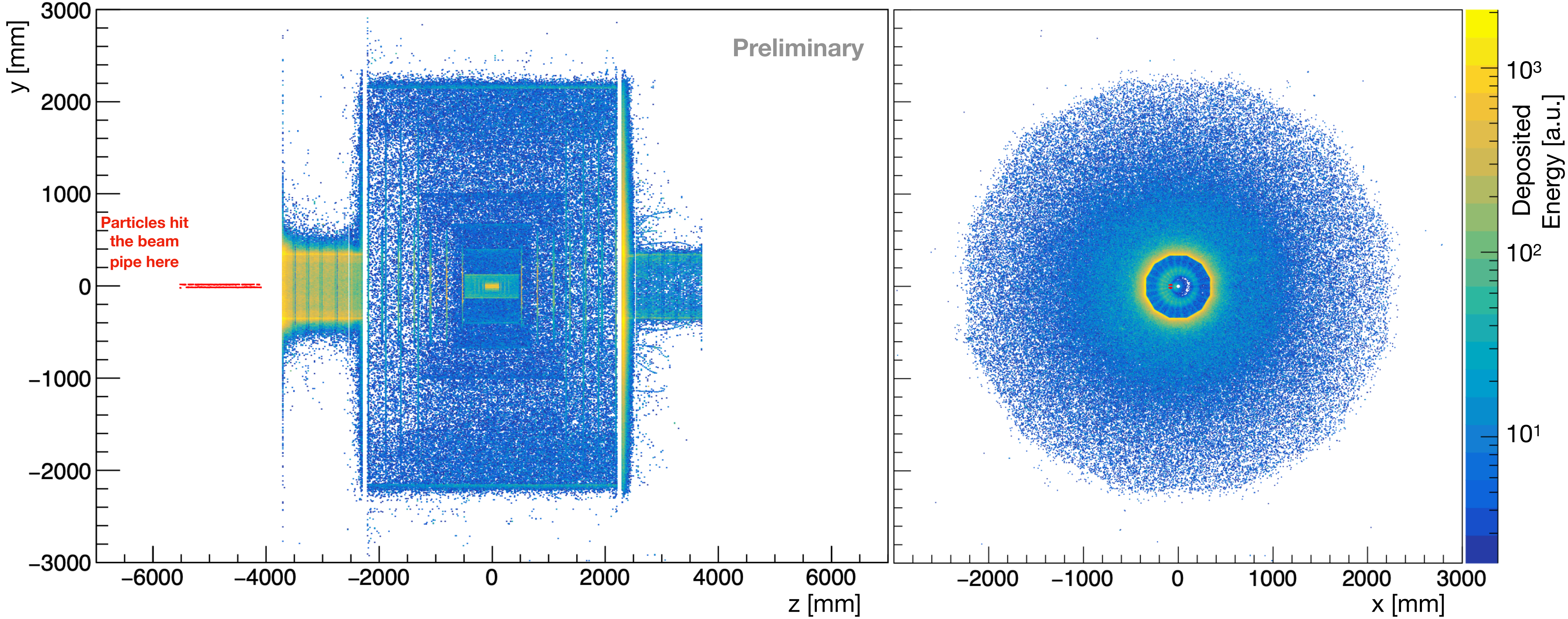
Preliminary study to setup the required tools







For this failure scenario the **estimated loss rate** in the MDI region is $61.2\ e^{-}/BX/beam$. A **first tracking** in CLD showed that hits are observed in all the sub-detectors. The large number of hits is due to the **shower** caused by the **interaction of the primaries with the material** of the beam pipe and compensating solenoid.



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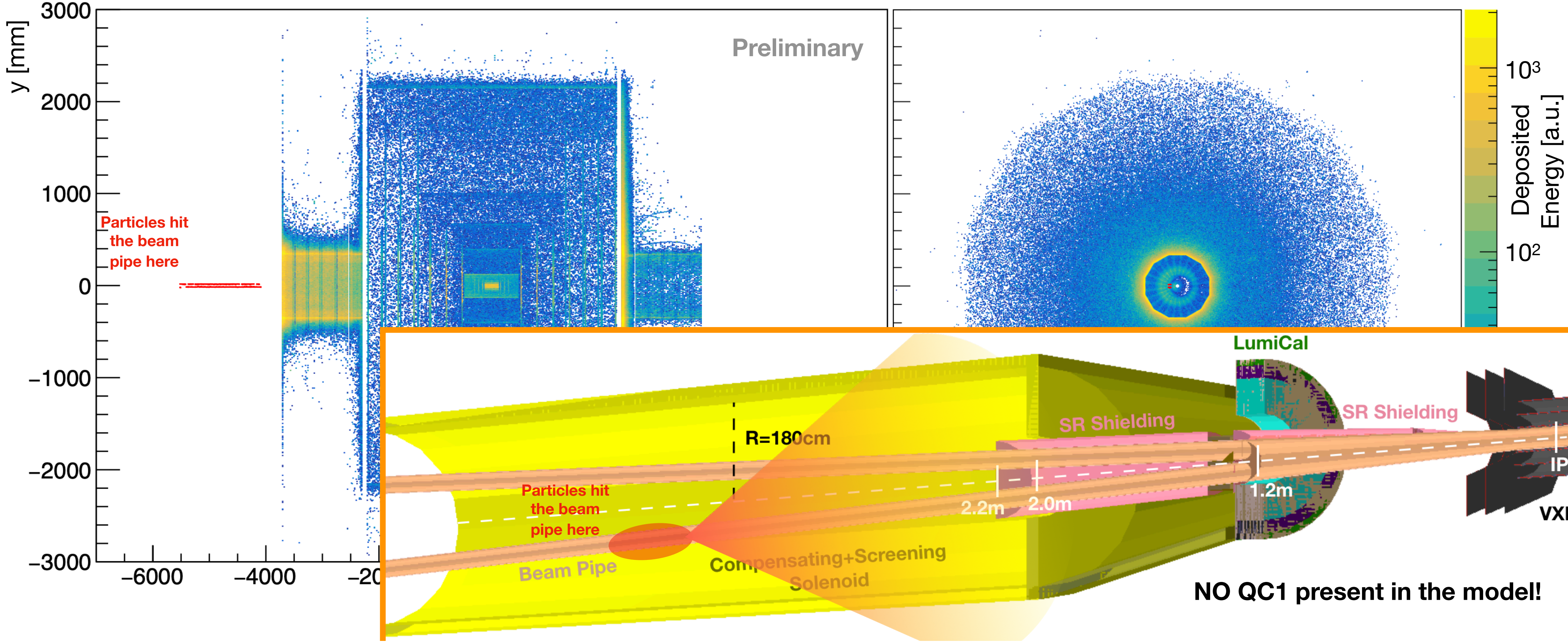
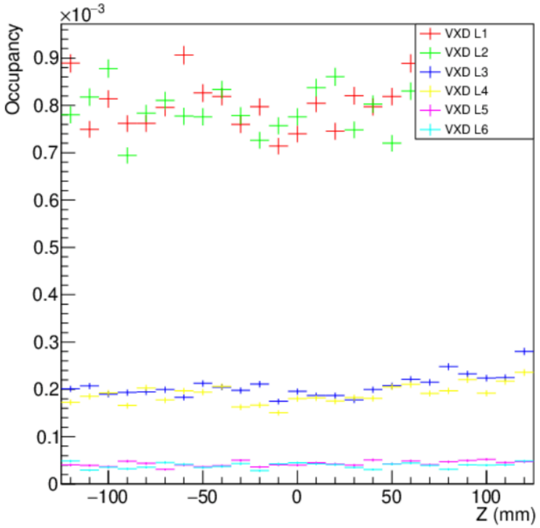
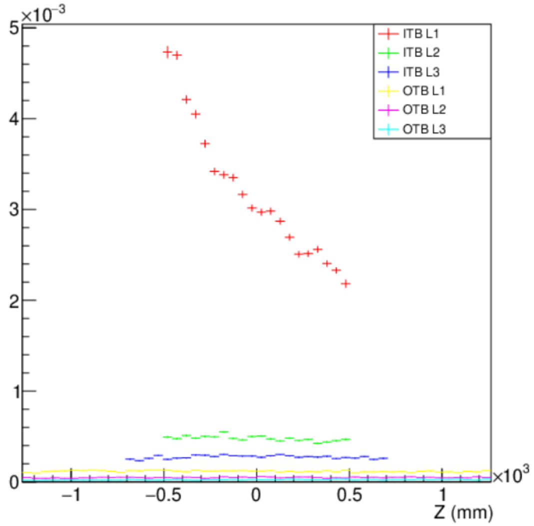


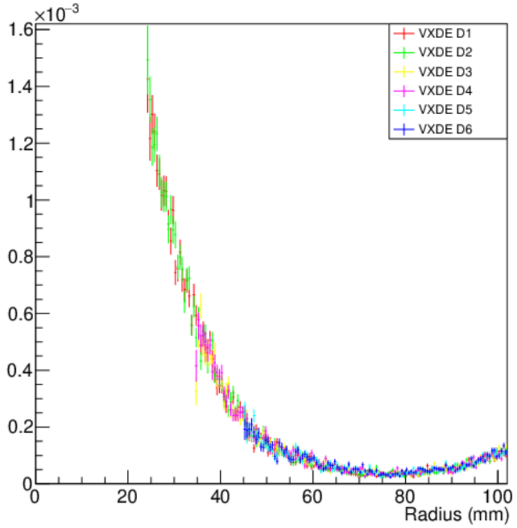
VXD Barrel



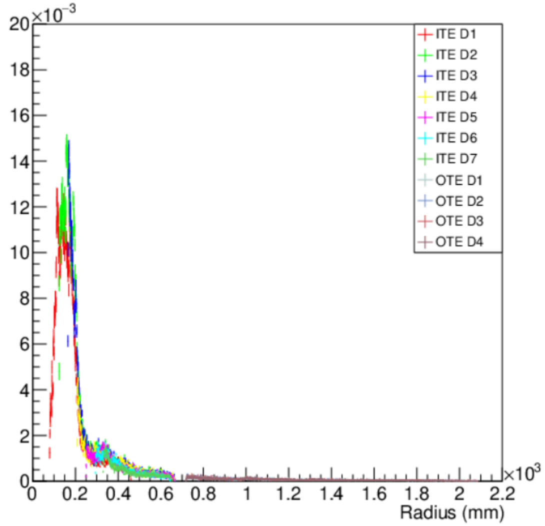
TRK Barrel



VXD Endcap



TRK Endcap



From this **preliminary** study, the occupancies in the VXD and trackers can get **up to 1%.** Further studies (i.e. overlapping with a physics signal) are required to estimate the **detector response** under such background.

The same study can be repeated for other **failure scenarios**, **beam energies**, **lattices** and for the **10mm beam pipe.** The possibility to implement a **shielding** to absorb the shower should also be considered and studied when the occupancies are too high. The effect of the **first FFQ** (s=2.2-5.4m) should be evaluated by including its model in the current **FCCSW detector model**.

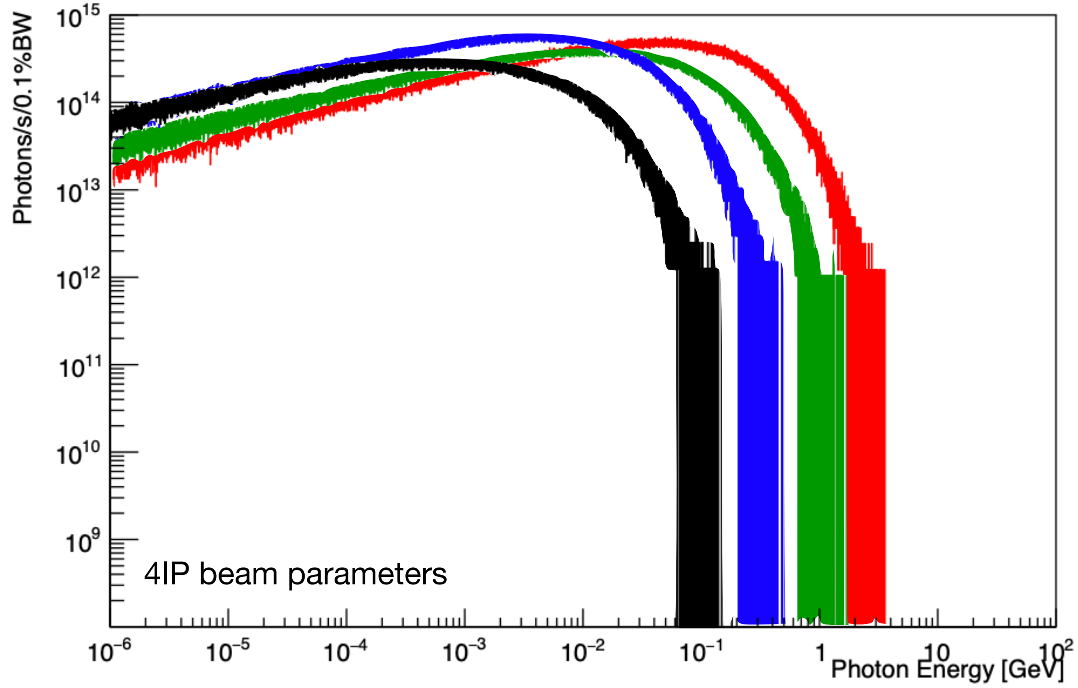
Beamstrahlung radiation Characterisation

Beamstrahlung is a **dominant process** for the lifetime at FCCee due to the small beam size and high population.

$$< E_\gamma > \sim E \times 0.462\Upsilon$$

$$\Upsilon \sim \frac{5}{6}\frac{r_e^2 \gamma N_e}{\alpha \sigma_z(\sigma_x + \sigma_y)}$$

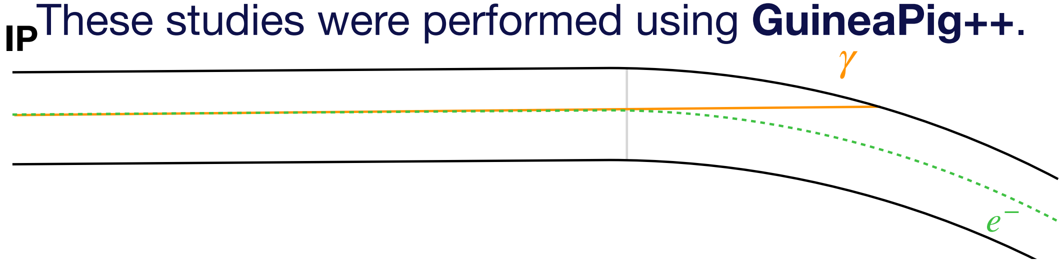
$$n_\gamma \sim 2.54 \left[\frac{\alpha^2 \sigma_z}{r_e \gamma}\Upsilon\right] \frac{1}{[1 + \Upsilon^{2/3}]^{1/2}}$$



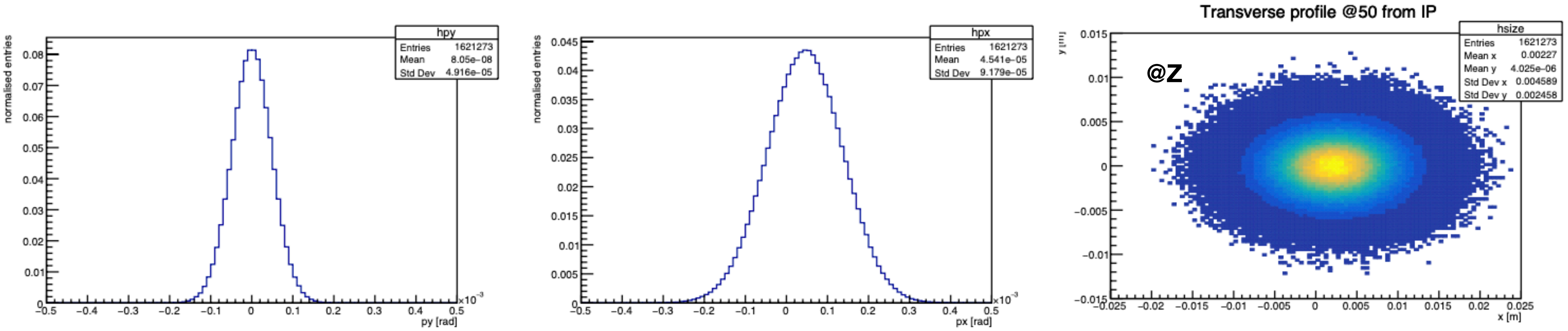
The photons are emitted **collinear to the beam** with an angle proportional to the beam-beam kick. This radiation is extremely intense **O(100kW)** and **hits the beam pipe** at the end of the first downstream dipole.

	Total Power [kW]	Mean Energy [MeV]
Z	370	1.7
WW	236	7.2
ZH	147	22.9
Top	77	62.3

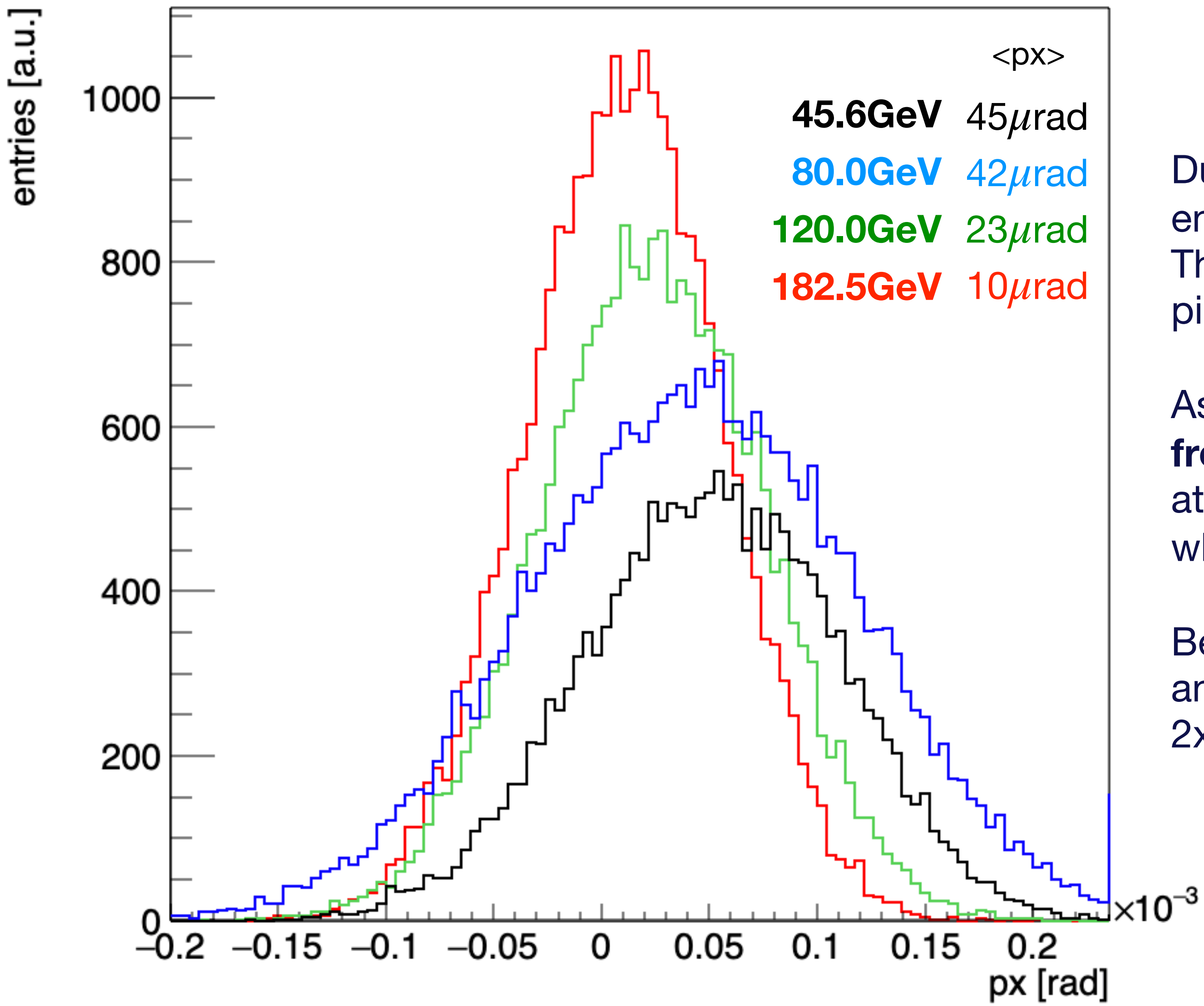
These studies were performed using **GuineaPig++**.



Photons are emitted in a **very narrow cone** ($\propto 1/\gamma$) in the direction of the particle which produced them. As the beam divergence is $O(10 \sim 100\mu rad)$, the **transverse spot size** at few hundred meters from the IP will remain in the order of $O(cm^2)$



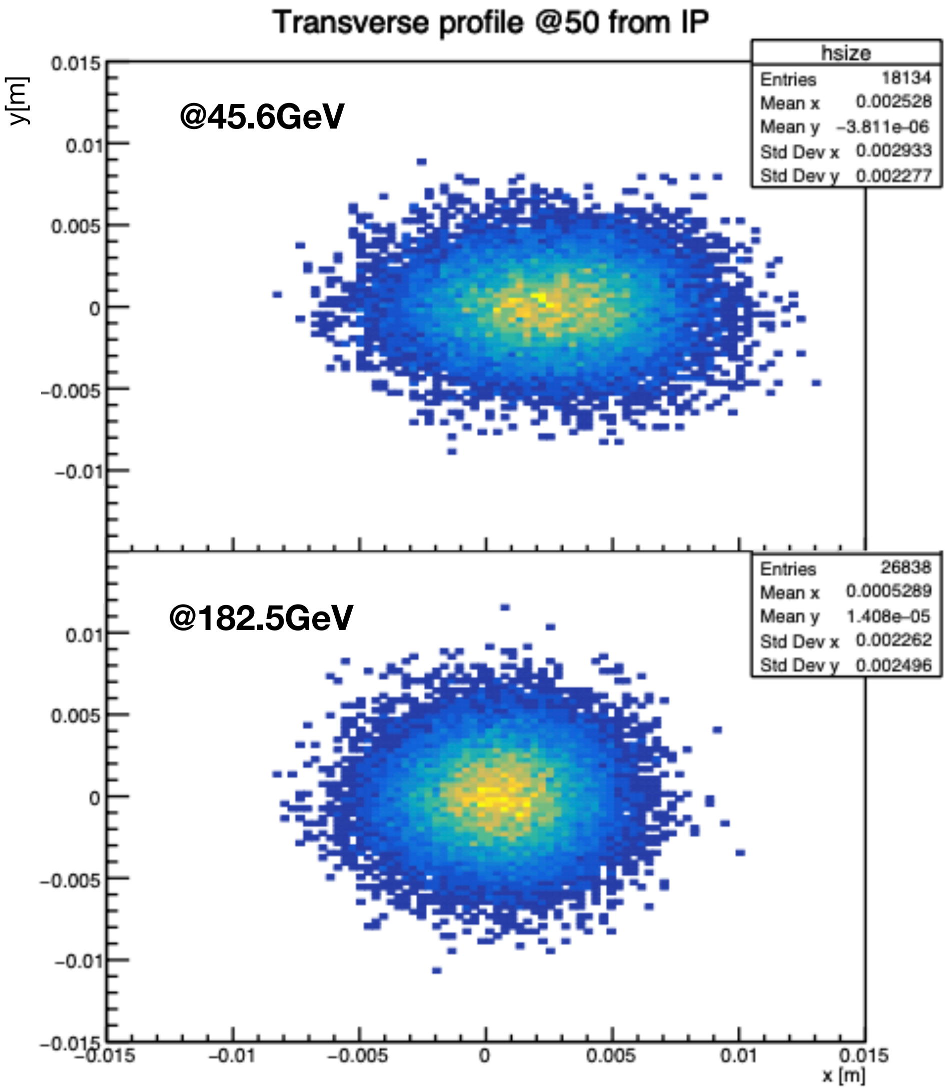
	$\sigma_{px}(\gamma)\ [\mu rad]$	$\sigma_{py}(\gamma)\ [\mu rad]$	$\sigma_{px}(e^-)\ [\mu rad]$	$\sigma_{py}(e^-)\ [\mu rad]$	$\sigma_x(\gamma)\ [mm] @ 50m$	$\sigma_y(\gamma)\ [mm] @ 50m$
Z	91.8	49.2	84.3	42.1	4.59	2.46
WW	110	73.0	103.4	65.7	5.50	3.65
ZH	51.7	41.3	46.2	35.9	2.58	2.06
Top	44.6	50.3	38.6	43.2	2.23	2.51



Due to the **different magnetic rigidity**, less energetic particles will receive a stronger kick. This means that the photon beam will hit the pipe in different positions.

As an example, on a transverse plane **@50m from the IP**, the photon distribution produced at the Z will be centered 2mm further than what happens at the ttbar energy.

Being the spot sizes of the order of $1x1cm^2$ anyway, all the spots are well contained in a $2x2cm^2$ region.



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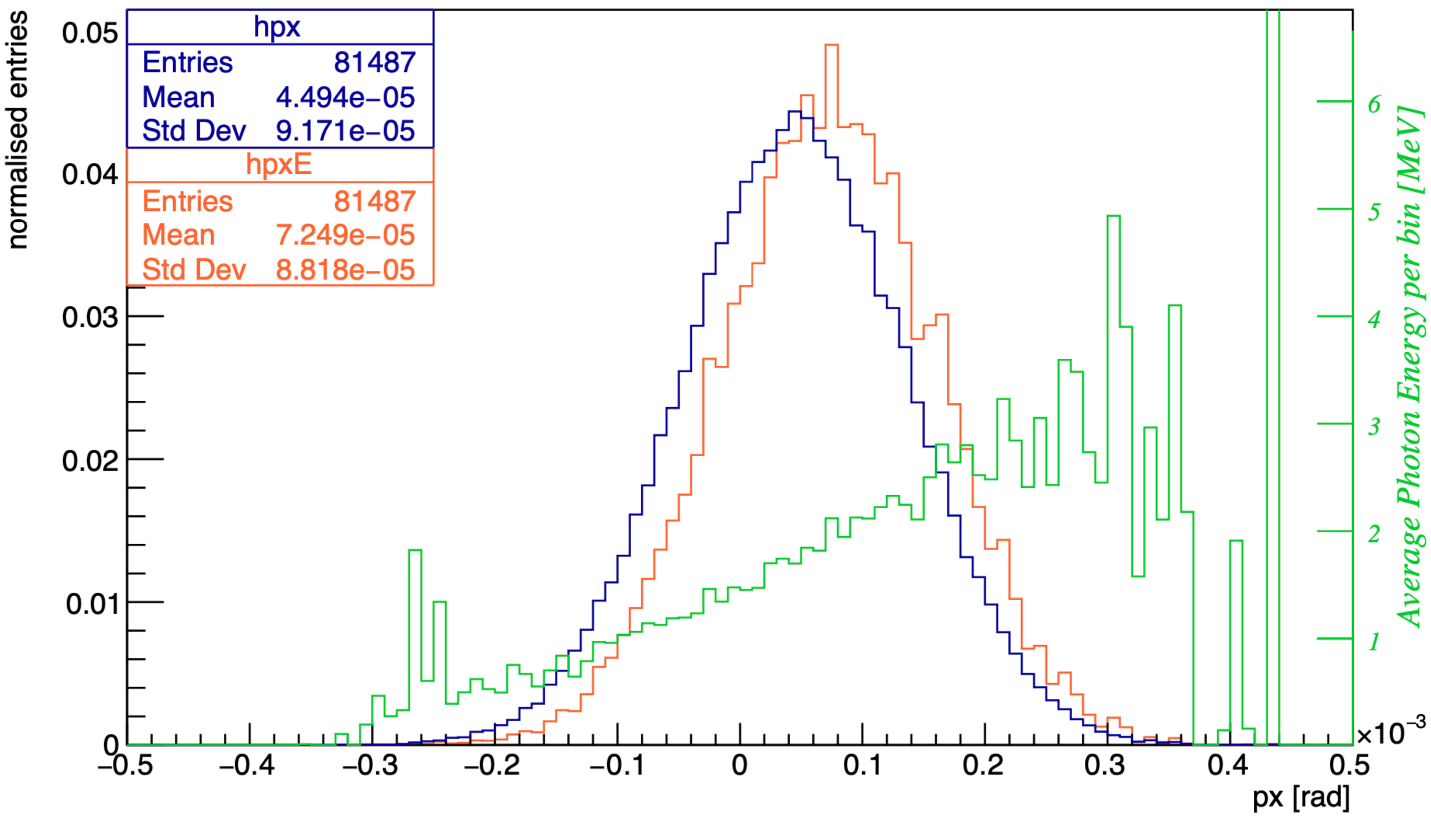
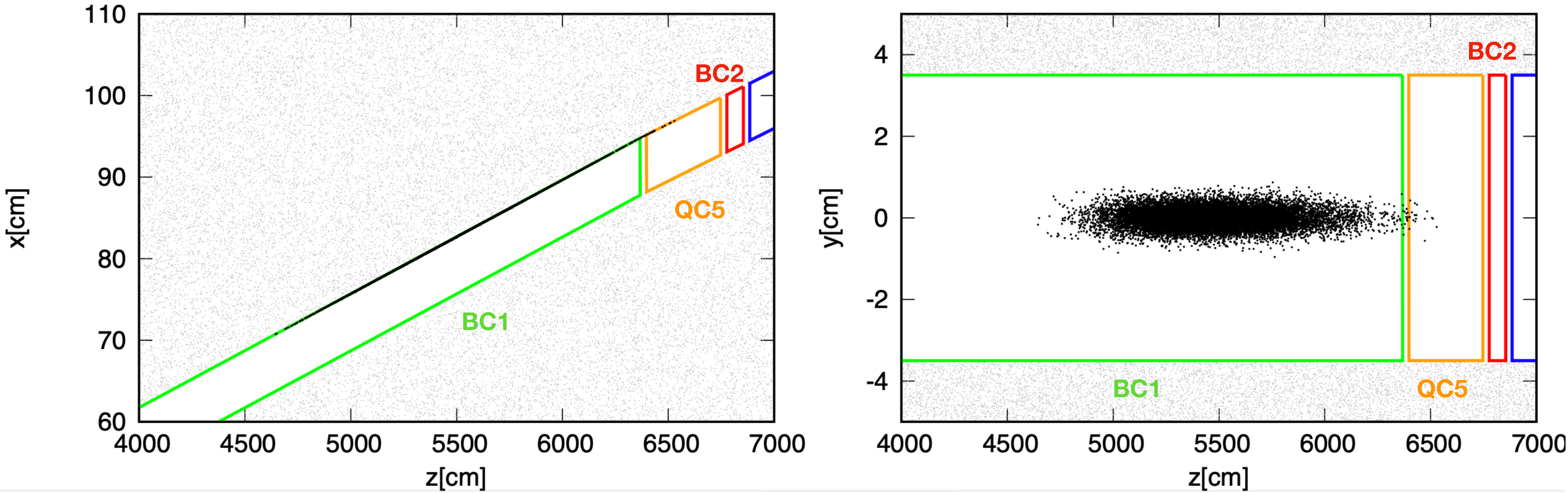
Being the spot sizes of the order of 1x1cm^2 anyway, all the spots are well contained in a 2x2cm^2 region.

Please note that the **power peak is slightly shifted** w.r.t. the flux peak. This because the photon energy is directly proportional to the intensity of the beam-beam kick (and therefore the photon horizontal momentum).

This shift means that the position of the power peak will be shifted of **O(mm) at O(100m)** from the IP



Thanks a lot to D. Shatilov for the extremely useful discussions

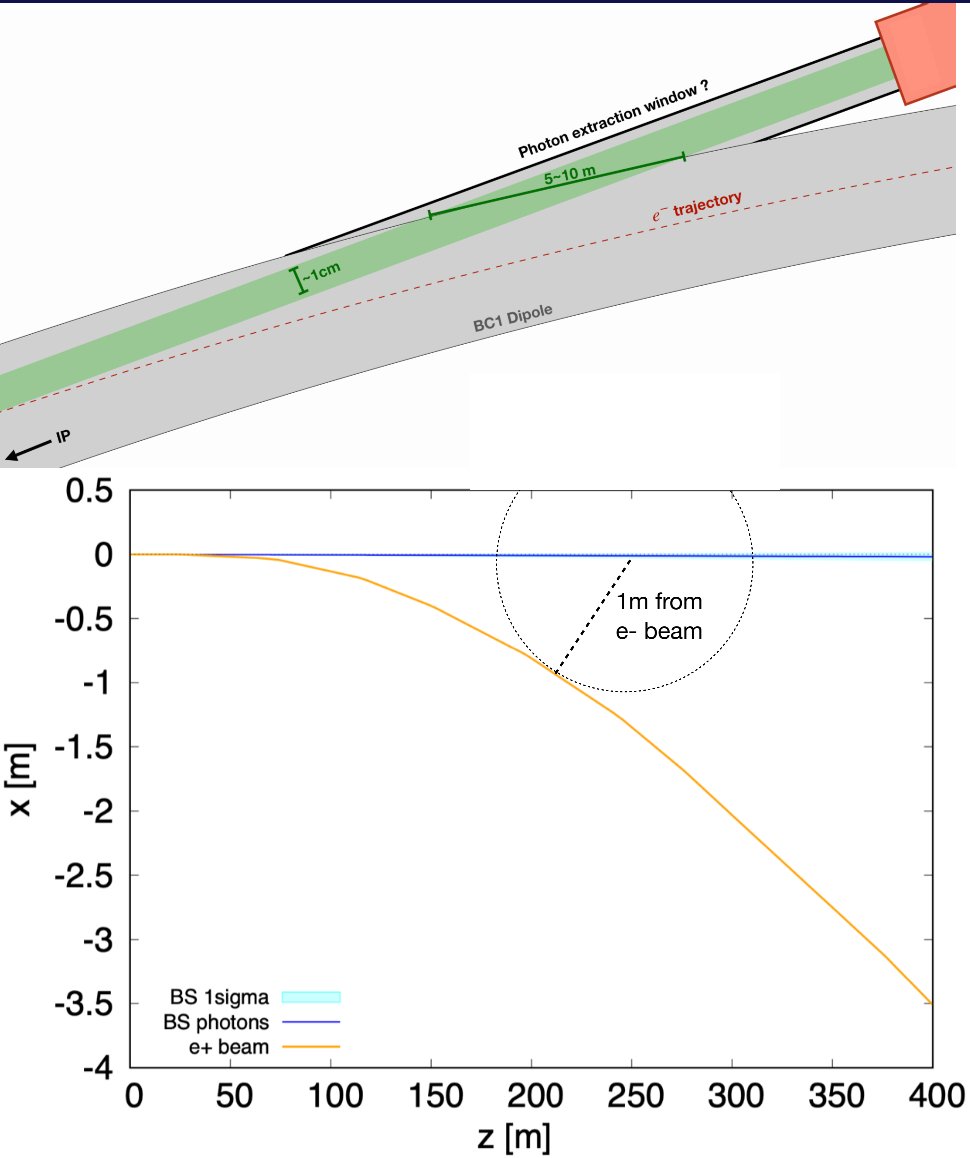


BS photons @Z tracking in the GDML description of lattice 217 - 2IPs. Photons hit the pipe mostly in **BC1**.

Drift spaces between elements in this part of the lattice is 30cm

No tracking performed yet on the latest lattice v530 - 4IPs (no GDML description available), but small changes are expected:

- BC1 ends at s=64.25m instead of s=63.70
- bending angle might be slightly different - to be checked

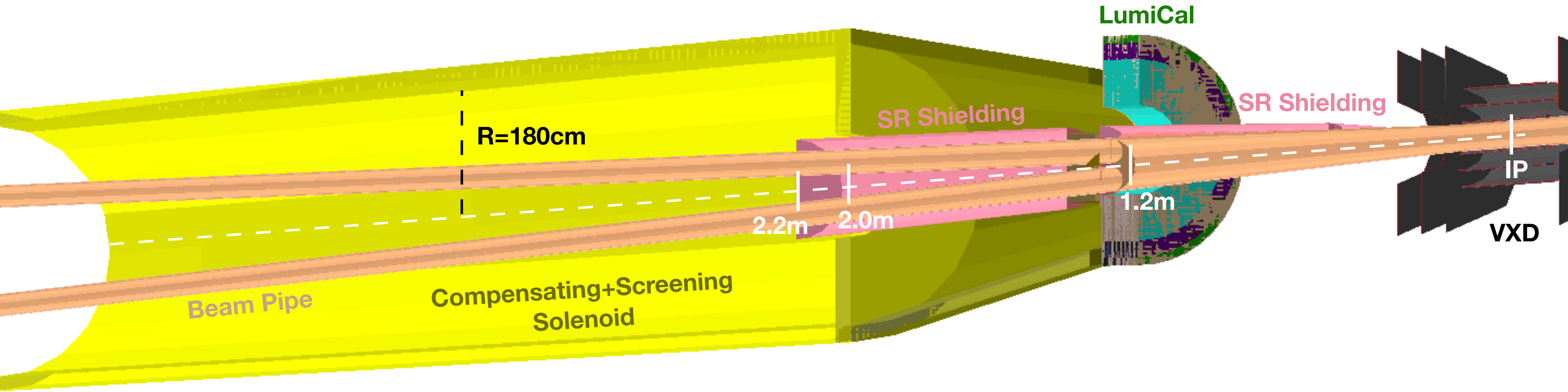


Beam dump for Beamstrahlung photons

Due to the very high power $O(100kW)$ it is necessary to have a **beam dump** for the beamstrahlung photons.

Several constraints like the long **extraction line** window, the **distance** of the dump from the beam pipe, and the **placement into the cavern** are all currently under study (see talk by M. Calviani 02/06).

Also the possibility to have an **instrumented beam dump** to measure properties of the colliding beams at the IP is under investigation.



MDI model description: Work in Progress and TODOs

- upgrade to the **engineered beam pipe model** (see F. Fransesini talk 02/06)
- implement the models of the **FFQs** (see M. Koratzinos talk 02/06)
- adapt the **VXD for the 10mm beam pipe**
- optimisation studies on the **SR tungsten shielding**
- study the necessity of shielding for **upstream beam losses**

Conclusions and Next Steps

- **IPC induced occupancy** in the CLD VXD is **below the 1%** also using the 4IP lattice beam parameters
  - Next: study the effect of the **smaller beam pipe** (R=10mm) and closer VXD

- Preliminary studies on the **beam losses** show a possible high occupancy as the primaries shower in the beam pipe material
  - repeat the study for different **failure scenarios** and **beam parameters**
  - study the **detector efficiency** under such background
  - consider implementing a **shielding**

- **Beamstrahlung** radiation can reach up to **>300kW** with a divergence of $O(10 \sim 100\mu rad)$
  - photons will hit the beam pipe at the **first downstream dipole** (~60m from IP)
  - a dedicated **beam dump** must be designed to absorb all this power
  - possibility to have an **instrumented beam dump** is also under investigation

- Several improvements can be done to the **model description of the MDI region**, like implementing **engineered models** of beam pipe and **FFQs**, and **updating the VXD** to the small beam pipe

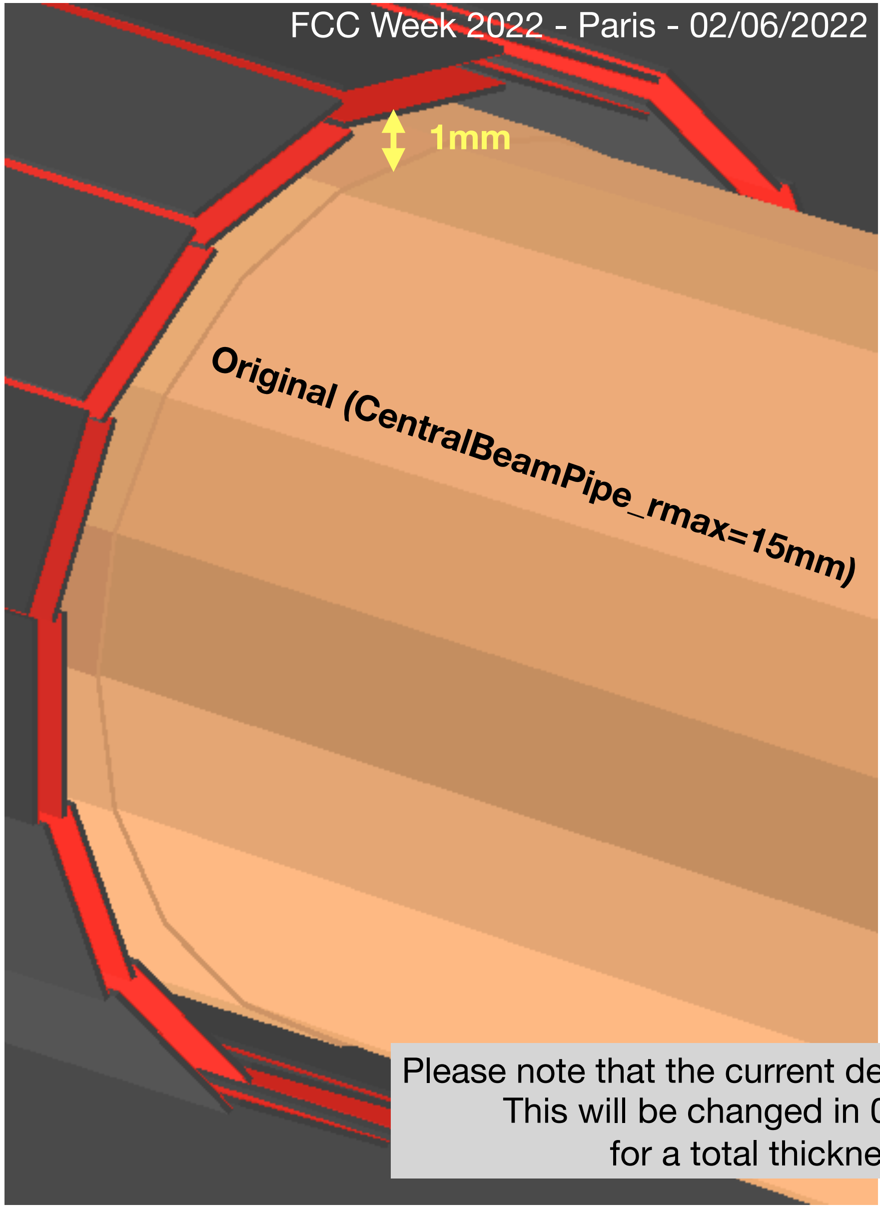
- Tracking of the **SR photons** coming from upstream in the detector to evaluate the induced background and optimise the SR shieldings in the IR

THANK YOU FOR YOUR ATTENTION

BACK-UPS

		CDR parameters				4IP PA31-1.0 (mar '22)			
[GeV]	**E**	45,6	80	120	182,5	45,6	80	120	182,5
[m.rad]	**emitt_x**	2,70E-10	8,40E-10	6,30E-10	1,46E-09	7,10E-10	2,16E-09	6,40E-10	1,49E-09
[m.rad]	**emitt_y**	1,00E-12	1,70E-12	1,30E-12	2,90E-12	1,42E-12	4,32E-12	1,29E-12	2,98E-12
[m]	**beta_x**	0,15	0,2	0,3	1	0,1	0,2	0,3	1
[m]	**beta_y**	0,0008	0,001	0,001	0,0016	0,0008	0,001	0,001	0,0016
[m]	**sigma_x**	6,364E-06	1,296E-05	1,375E-05	3,821E-05	8,426E-06	2,078E-05	1,386E-05	3,860E-05
[m]	**sigma_y**	2,828E-08	4,123E-08	3,606E-08	6,812E-08	3,370E-08	6,573E-08	3,592E-08	6,905E-08
[rad]	**sigma_px**	4,243E-05	6,481E-05	4,583E-05	3,821E-05	8,426E-05	1,039E-04	4,619E-05	3,860E-05
[rad]	**sigma_py**	3,536E-05	4,123E-05	3,606E-05	4,257E-05	4,213E-05	6,573E-05	3,592E-05	4,316E-05
[m]	**sigma_z**	1,21E-02	6,00E-03	5,30E-03	2,54E-03	1,54E-02	8,01E-03	6,00E-03	2,80E-03
[1]	**Ne**	1,70E+11	1,50E+11	1,80E+11	2,30E+11	2,43E+11	2,91E+11	2,04E+11	2,37E+11
[1]	**nbunch**	16640	2000	328	48	10000	880	248	40

4IP lattice - see K. Oide https://indico.cern.ch/event/1118299/



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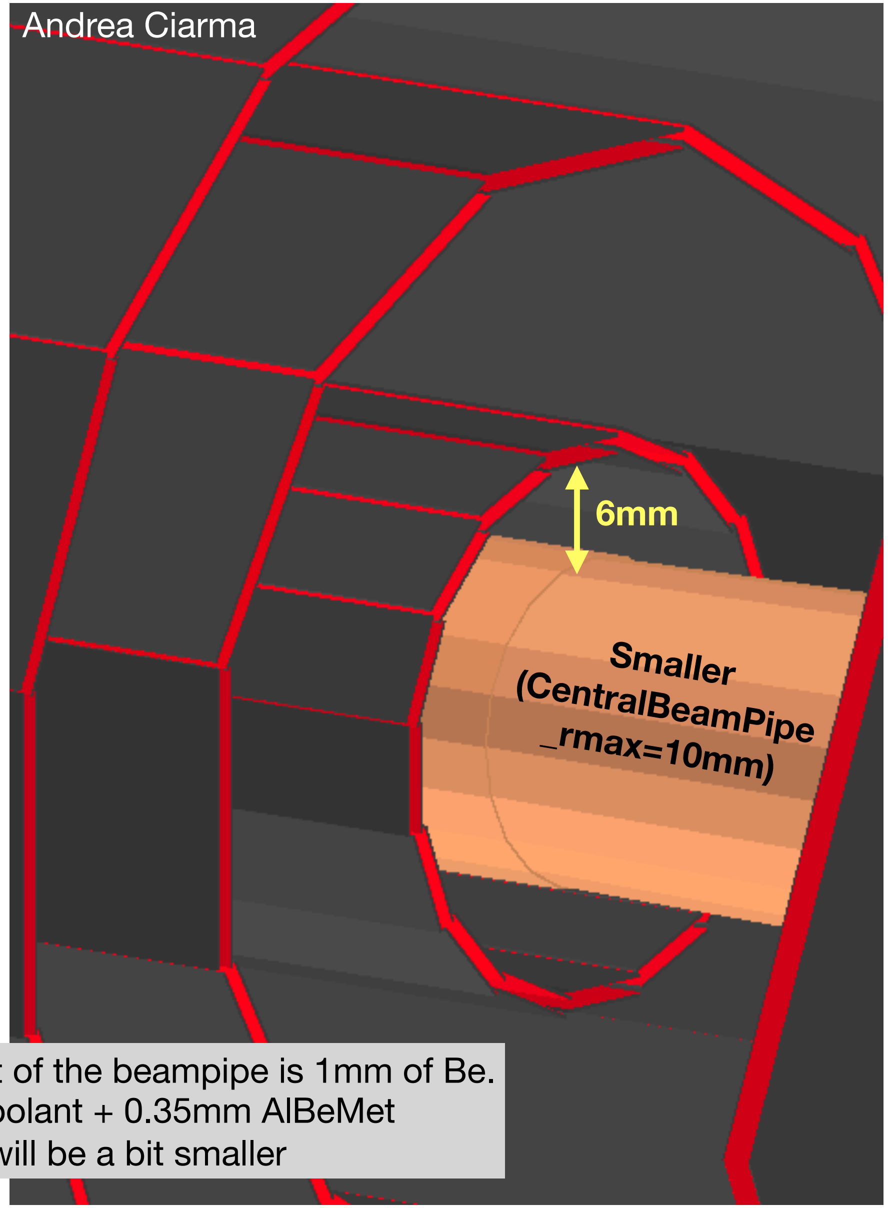
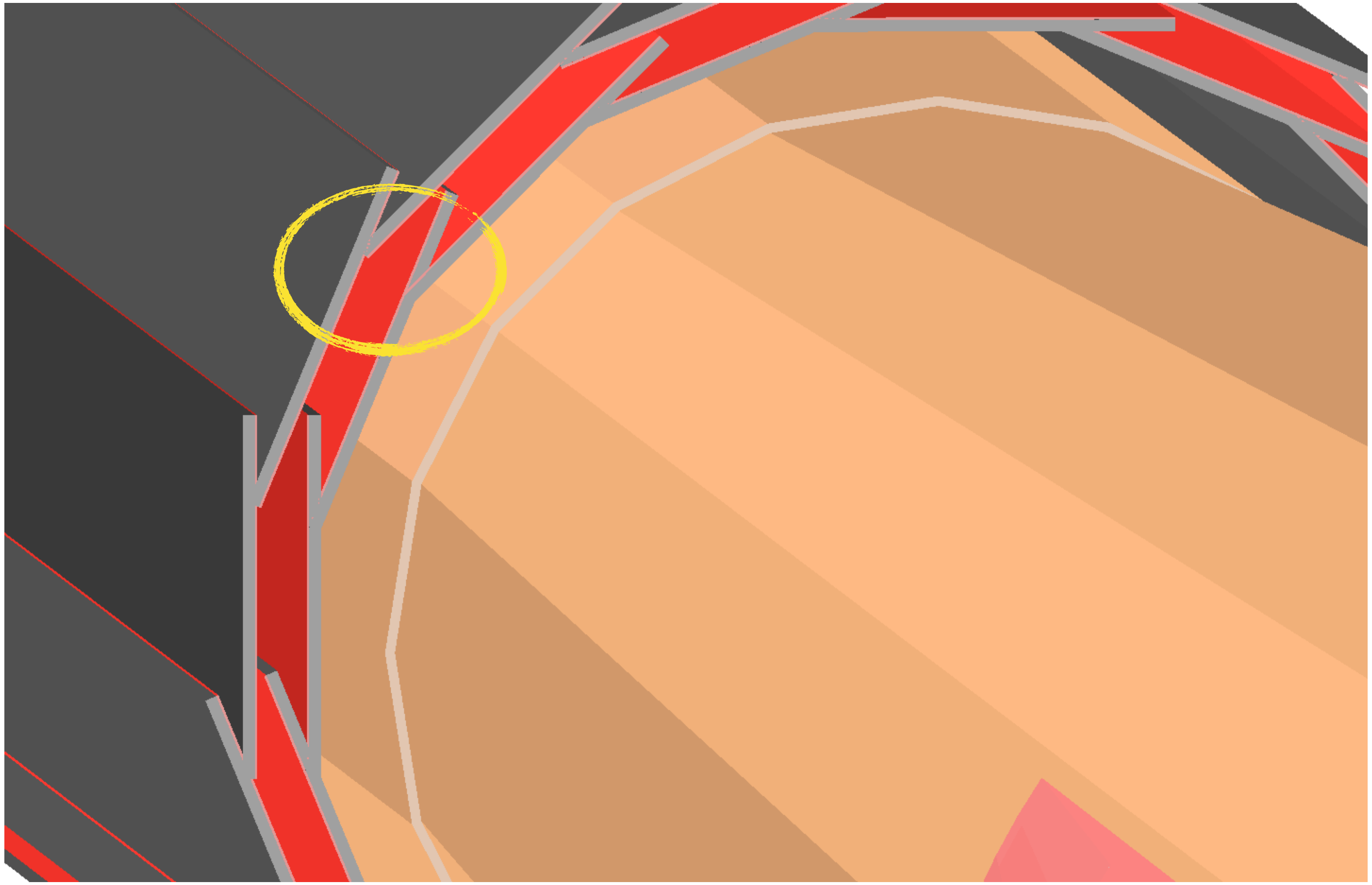


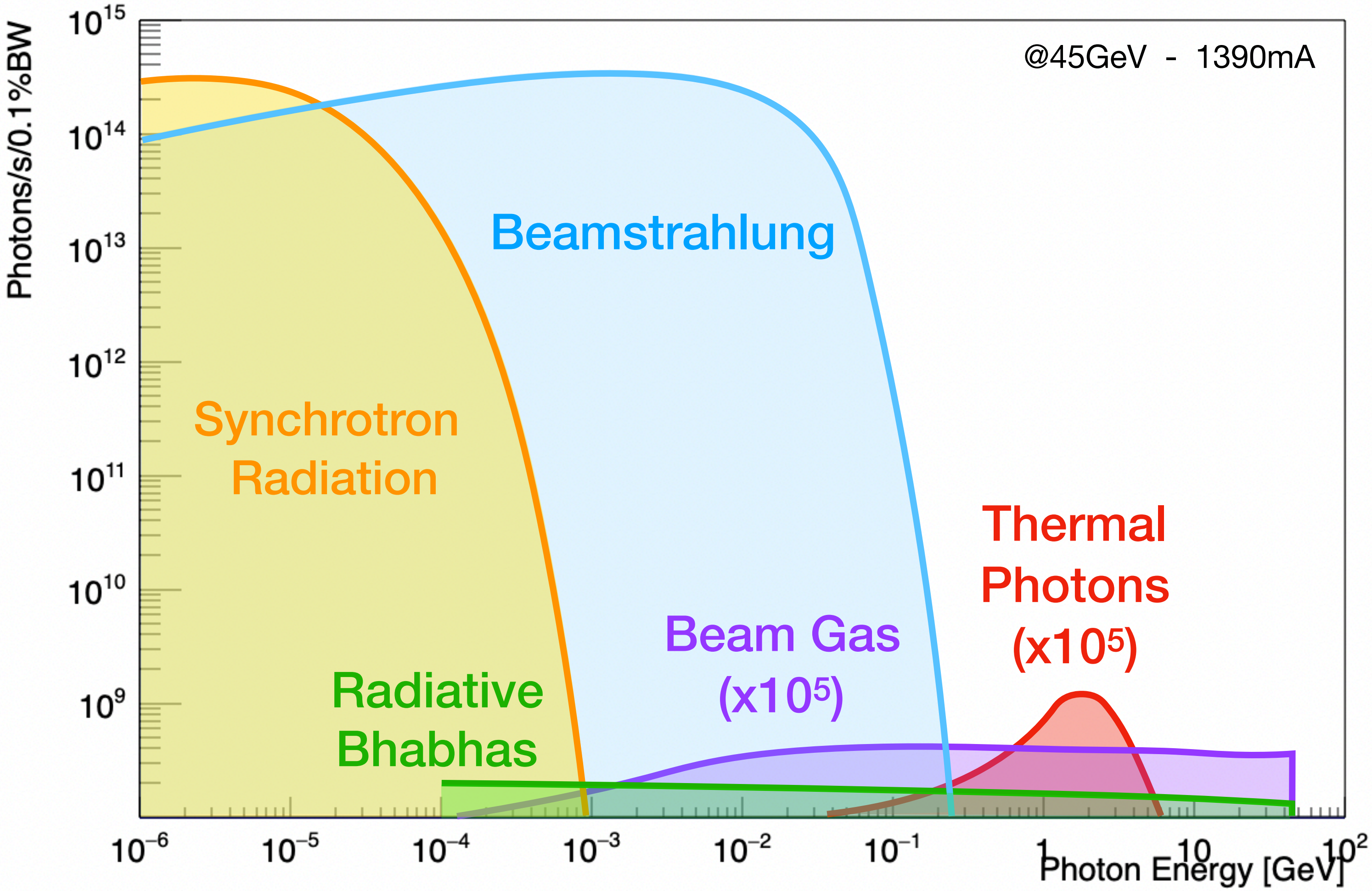
Please note that the current description of the central part of the beampipe is 1mm of Be.
This will be changed in 0.35mm AlBeMet + 1mm coolant + 0.35mm AlBeMet
for a total thickness of 1.70 mm so the gap will be a bit smaller



Simply reducing the radius of the innermost barrel won't suffice, as the staves will overlap.

Therefore, also a reduction of the staves width is necessary.

Sources of radiation collinear to the beam axis

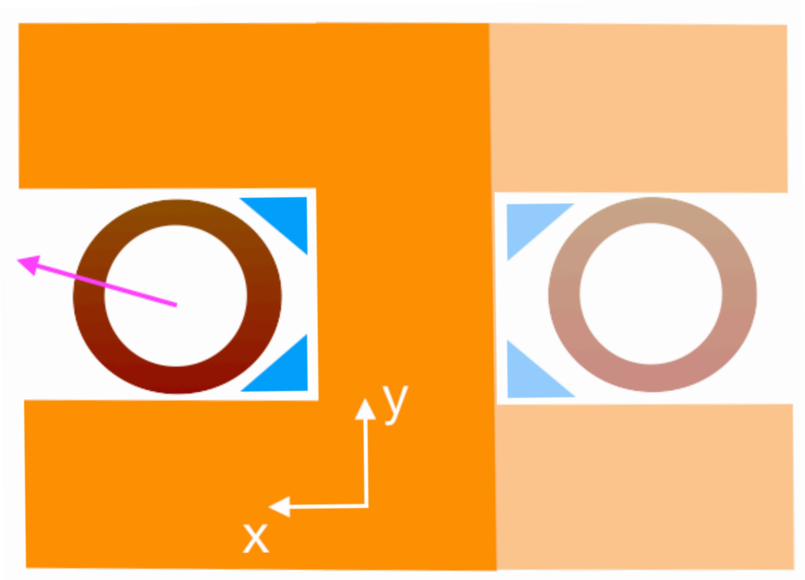


Other than beamstrahlung, there are **other sources of radiation** which can hit the beam pipe at the same downstream spot.

The comparison of the photon flux for the different sources shows that **beamstrahlung** is by far the most intense source by several orders of magnitude.

The yoke of the dipoles and quadrupoles has a "flipped-H" shape that does not go in the way of the BS radiation, in particular for the dipoles.

Could this be exploited for the photon extraction line?



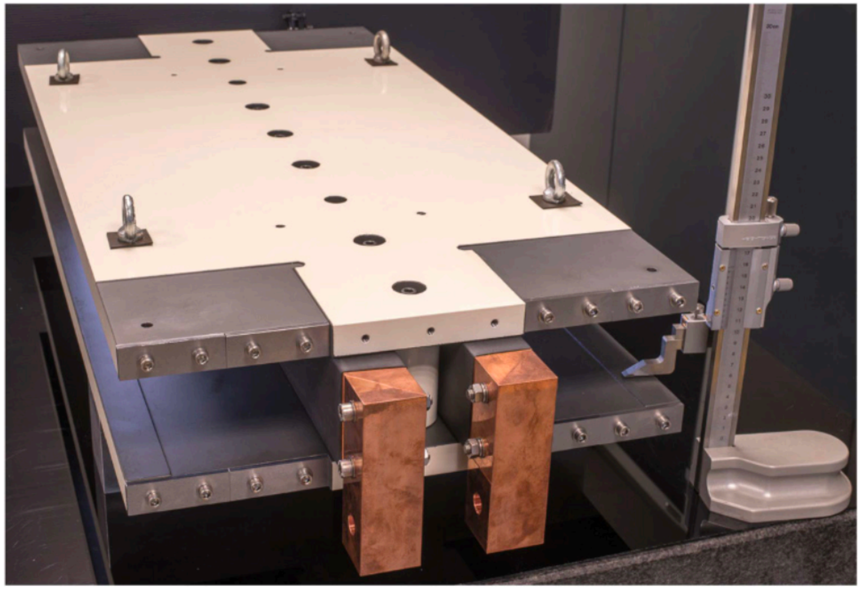


Fig. 3.2. One of the ca. 1 m long model dipole magnets manufactured at CERN.

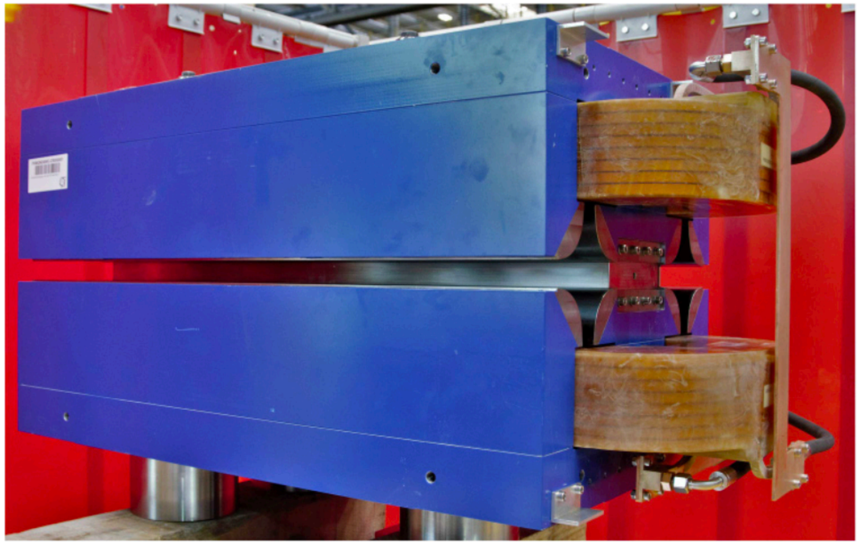
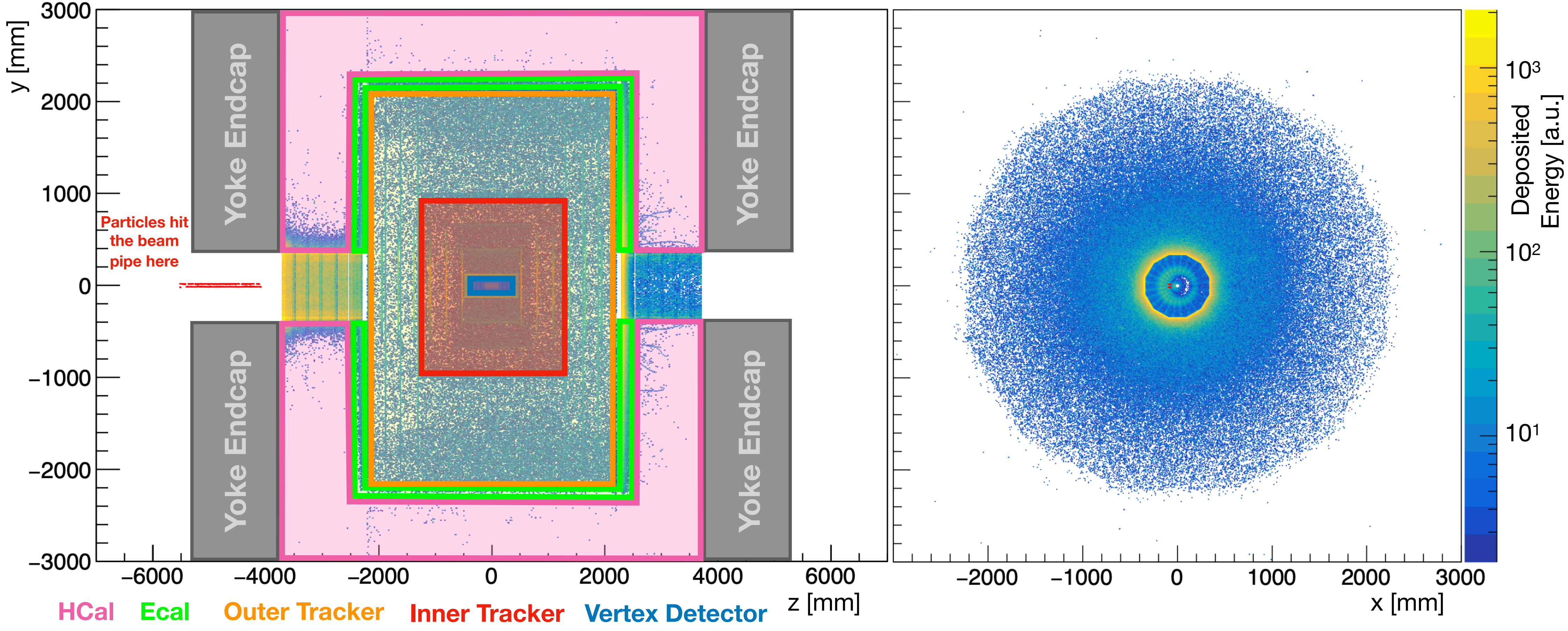


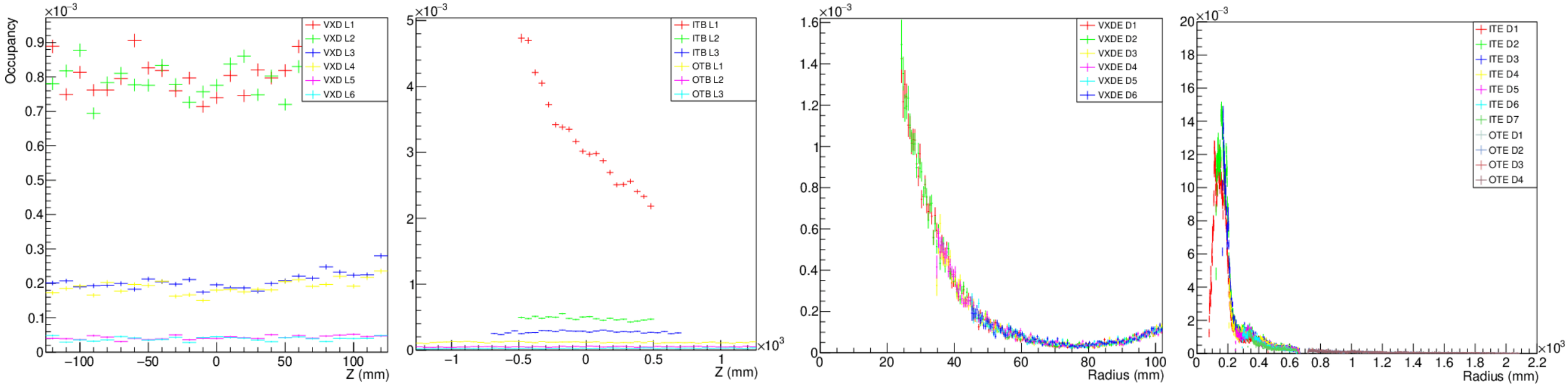
Fig. 3.5. Picture of a 1 m long quadrupole prototype magnet for the FCC-ee.


y [mm]
3000
2000
1000
0
−1000
−2000
−3000
−6000
−4000
−2000
0
2000
4000
6000
z [mm]
Yoke Endcap
Yoke Endcap
Yoke Endcap
Yoke Endcap
Particles hit the beam pipe here
−2000
−1000
0
1000
2000
3000
x [mm]
10^3
10^2
10^1
Deposited Energy [a.u.]
HCal
Ecal
Outer Tracker
Inner Tracker
Vertex Detector

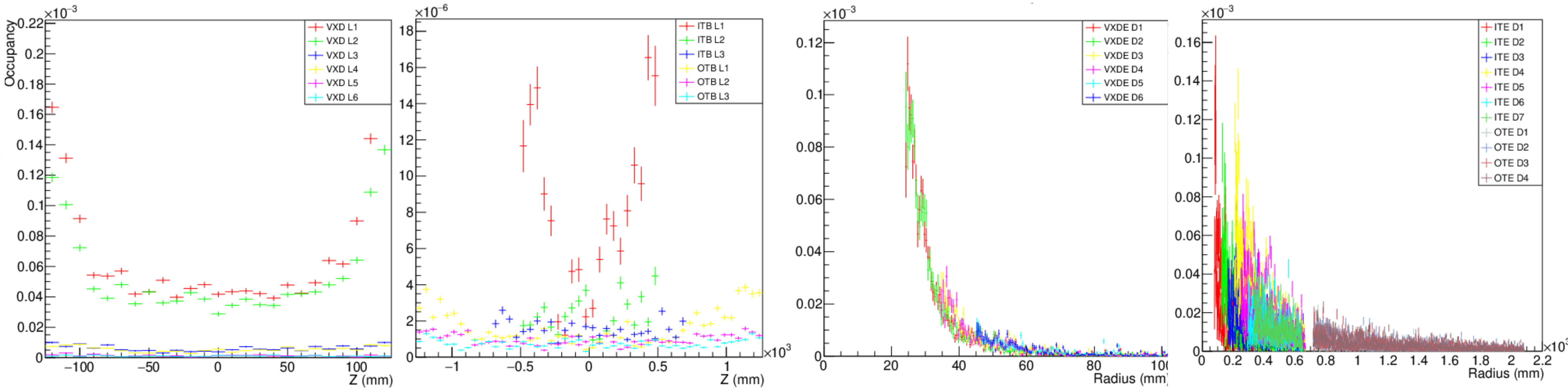
```
7.64e6*1184./1204. /40. *97756./3e8
(double) 61.204133 losses/BX

the expected rate is    = 61.2041 e-/BX!

Total Energy:
Enom*n_true:  11169.8 GeV
allGenParticles:11092.4 GeV
------------------------------------
VXD Endcap:0.0490684 GeV
VXD Barrel:0.440091 GeV
IT  Endcap:1.29874 GeV
IT  Barrel:0.833012 GeV
OT  Endcap:0.447468 GeV
OT  Barrel:0.349568 GeV
EcalEndcap:11.1994 GeV
EcalBarrel:2.7846 GeV
HcalEndcap:11.0037 GeV
HcalBarrel:0.043706 GeV
------------------------------------
Total Edep:28.4494 GeV
```

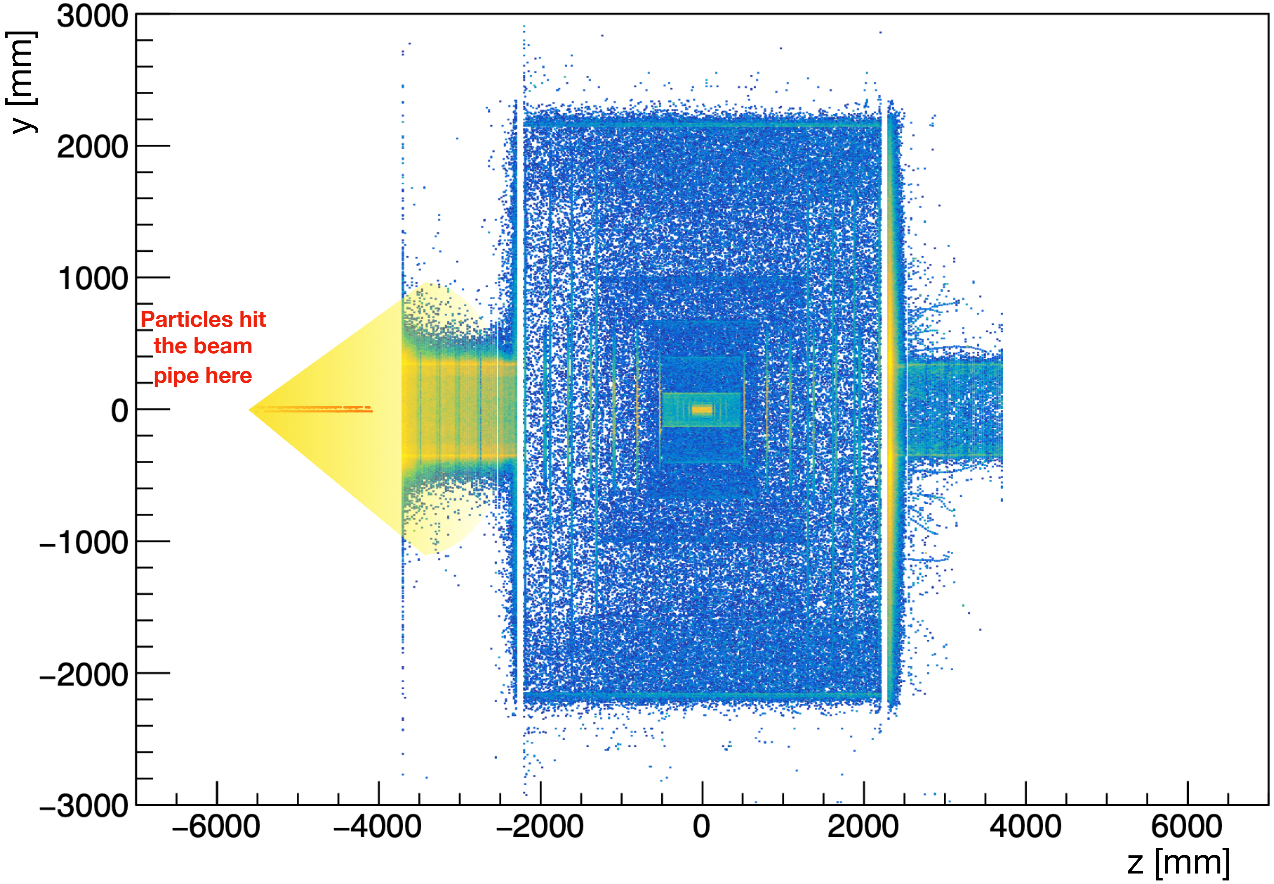
```
 Hits/BX above threshold

 VXD barrel
VXD L1 2523.6
VXD L2 2465.14
VXD L3 1336.02
VXD L4 1226.17
VXD L5 423.142
VXD L6 384.457
Total hits in VXD barrel: 8358.53

 VXD endcap
VXD D1 988.568
VXD D2 993.753
VXD D3 634.764
VXD D4 638.322
VXD D5 440.324
VXD D6 444.187
Total hits in VXD endcap: 4139.92

 TRK barrel
TRK L1 6512.09
TRK L2 3101.48
TRK L3 4282.2
TRK L4 5039.63
TRK L5 3264.25
TRK L6 2390.11
Total hits in TRK barrel: 24589.8

 TRK endcap
TRK D1 8034.31
TRK D2 9912.93
TRK D3 7320.14
TRK D4 4443.14
TRK D5 3400.54
TRK D6 2789.92
TRK D7 2072.55
TRK D8 3749.87
TRK D9 3812.9
TRK D10 3667.01
TRK D11 3815.34
Total hits in TRK endcap: 53018.7
Peak Occupancy/BX VXDE D1  0.001875
Peak Occupancy/BX VXDB L1  0.0046875
```

Losses

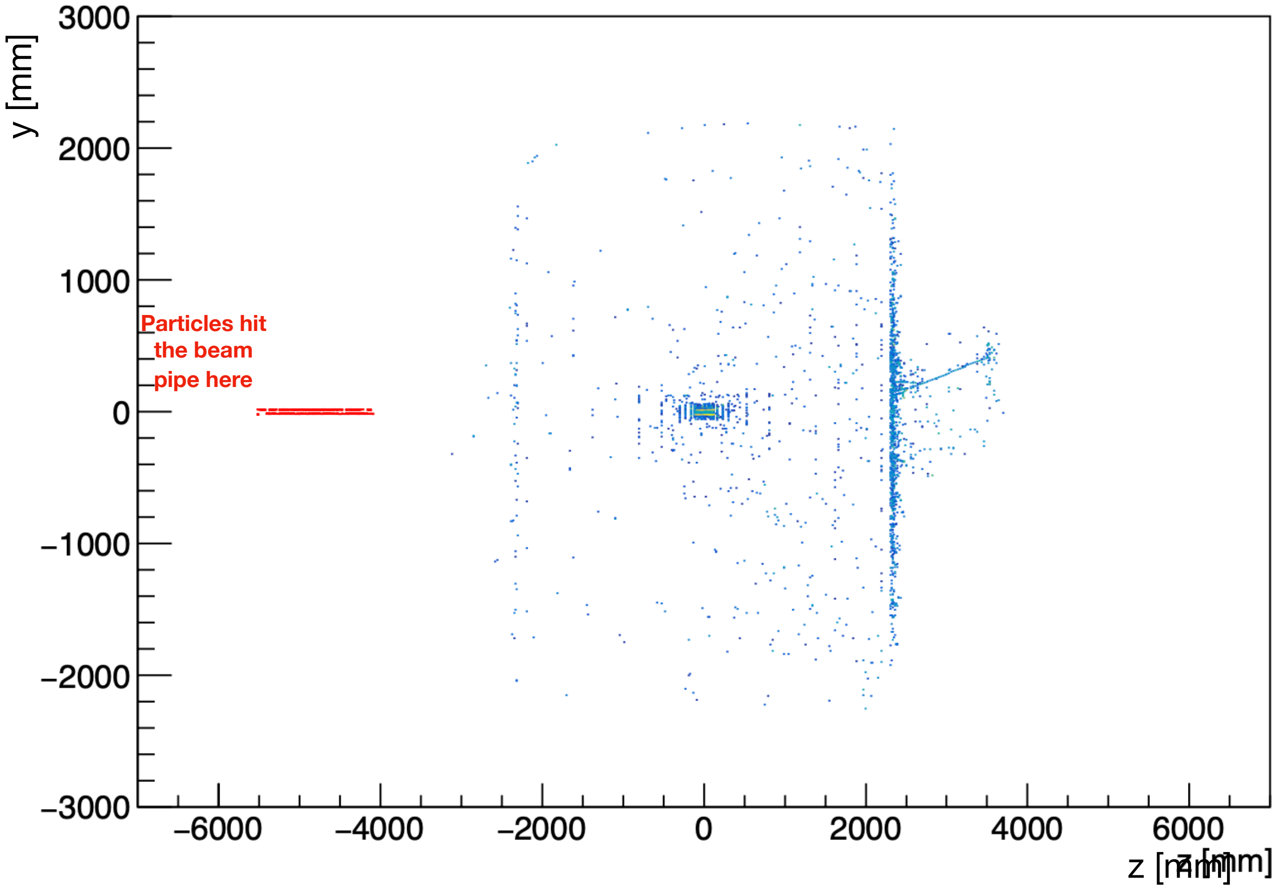

Occupancy
Z (mm)
Radius (mm)
VXD L1
VXD L2
VXD L3
VXD L4
VXD L5
VXD L6
ITB L1
ITB L2
ITB L3
OTB L1
OTB L2
OTB L3
VXDE D1
VXDE D2
VXDE D3
VXDE D4
VXDE D5
VXDE D6
ITE D1
ITE D2
ITE D3
ITE D4
ITE D5
ITE D6
ITE D7
OTE D1
OTE D2
OTE D3
OTE D4

IPC


Occupancy
Z (mm)
Radius (mm)
VXD L1
VXD L2
VXD L3
VXD L4
VXD L5
VXD L6
ITB L1
ITB L2
ITB L3
OTB L1
OTB L2
OTB L3
VXDE D1
VXDE D2
VXDE D3
VXDE D4
VXDE D5
VXDE D6
ITE D1
ITE D2
ITE D3
ITE D4
ITE D5
ITE D6
ITE D7
OTE D1
OTE D2
OTE D3
OTE D4

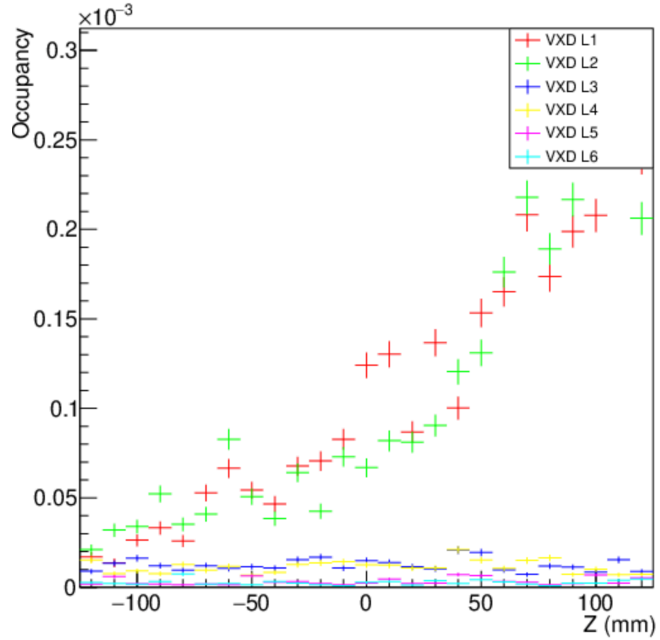


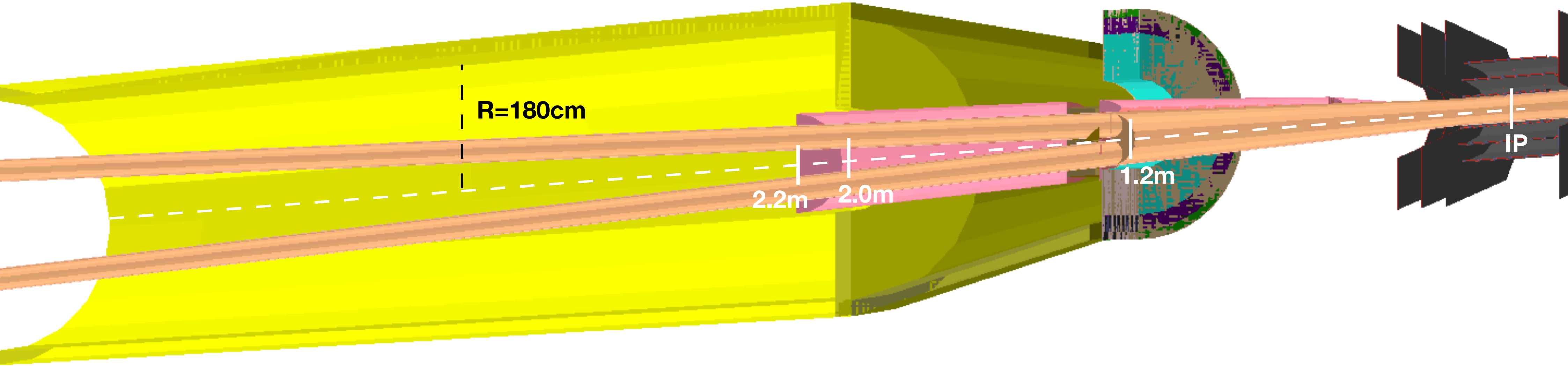
The large number of hits is due to the primaries **interacting with the material** from the beam pipe and compensating solenoid, producing a **large shower**.

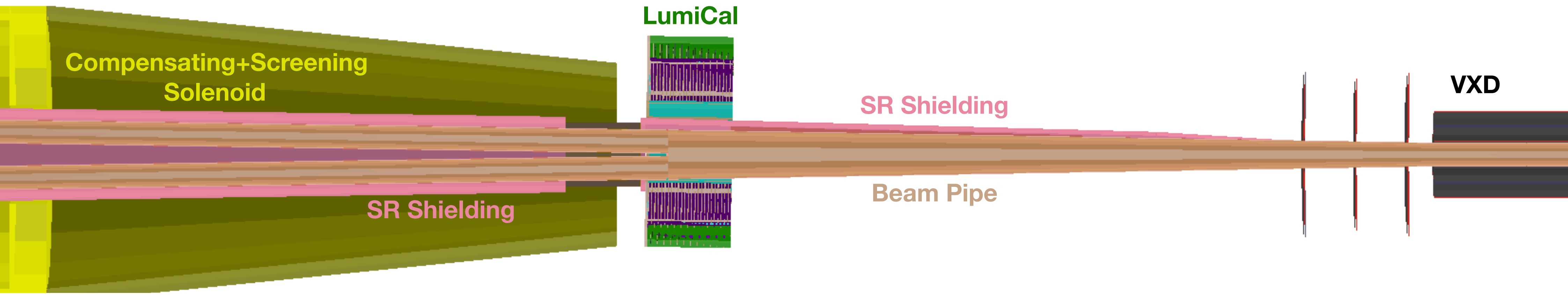


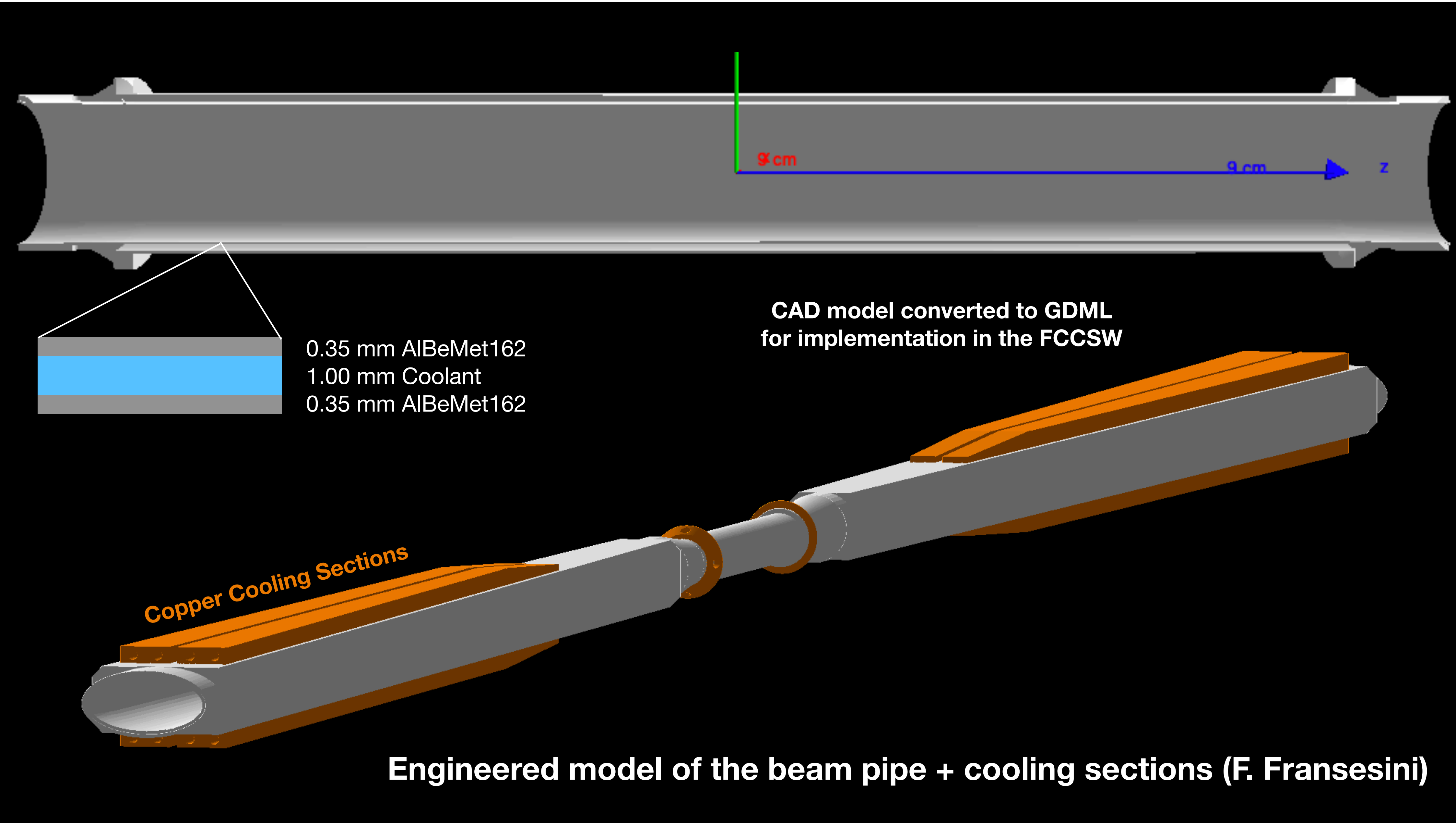
The large number of hits is due to the primaries **interacting with the material** from the beam pipe and compensating solenoid, producing a **large shower**.

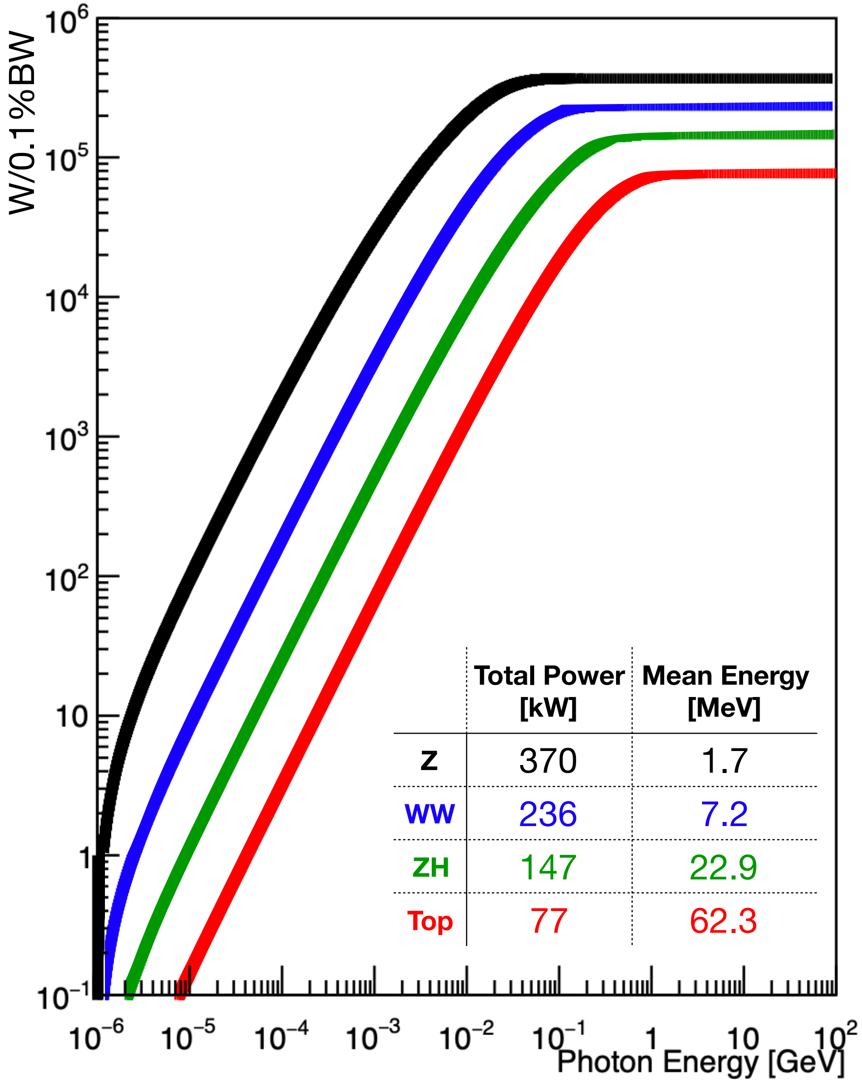
Removing these elements from the model the number of hits in the external regions of the detector largely decreases, but some of the particles still hit the VXD directly.




R=180cm
2.2m
2.0m
1.2m
IP


LumiCal
Compensating+Screening
Solenoid
SR Shielding
VXD
SR Shielding
Beam Pipe


9 cm
z
0.35 mm AlBeMet162
1.00 mm Coolant
0.35 mm AlBeMet162
CAD model converted to GDML
for implementation in the FCCSW
Copper Cooling Sections
Engineered model of the beam pipe + cooling sections (F. Fransesini)

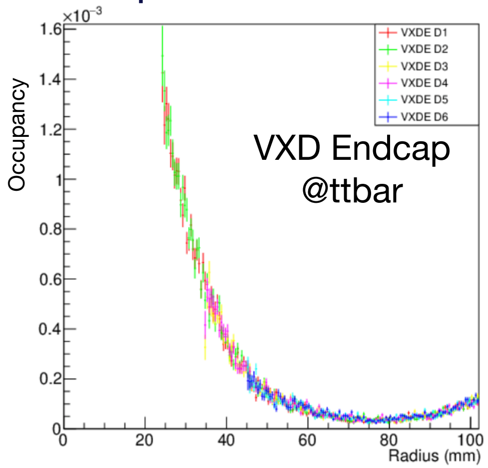


	Total Power [kW]	Mean Energy [MeV]
Z	370	1.7
WW	236	7.2
ZH	147	22.9
Top	77	62.3

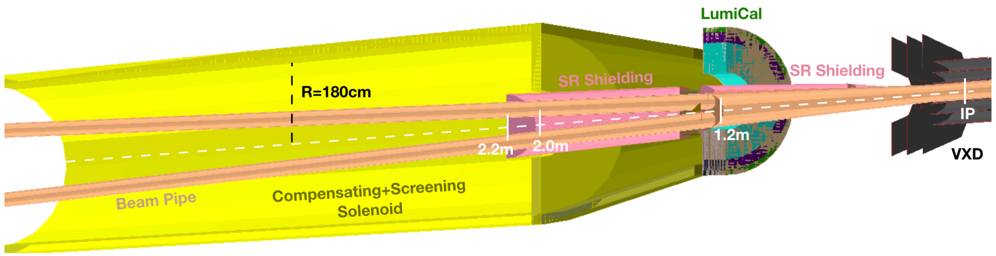
Tracking of the machine induced background in the FCCSW CLD detector model to evaluate the **occupancy in the VXD/TRK**

- Incoherent Pairs Creation (IPC) - using 4IP beam parameters
- Beam Losses near IP - preliminary to setup tools

IPCs occupancies are <1%, the beam losses hitting the beam pipe cause **secondaries showers** which may result in higher occupancies. Further studies will follow.



In order to have more realistic results, the **MDI description** in the current FCCSW model should be updated: **engineered beam pipe model** r=10mm, **FFQs**, VXD for small beam pipe, etc.



Beamstrahlung radiation will hit the beam pipe at BC1 (~60m downstream) and can carry up to **400kW**.

A **beam dump** is currently under study together with the option to have it **instrumented.**