Beam-induced backgrounds estimation at CEPC TPC

Xin She, **Huirong Qi, Yue Chang, Jinxian Zhang, Haoyu Shi, Jianchun Wang, Linghui Wu, Guang Zhao,Gang Li, Chengdong Fu**

Special thanks to Daniel Jeans/KEK

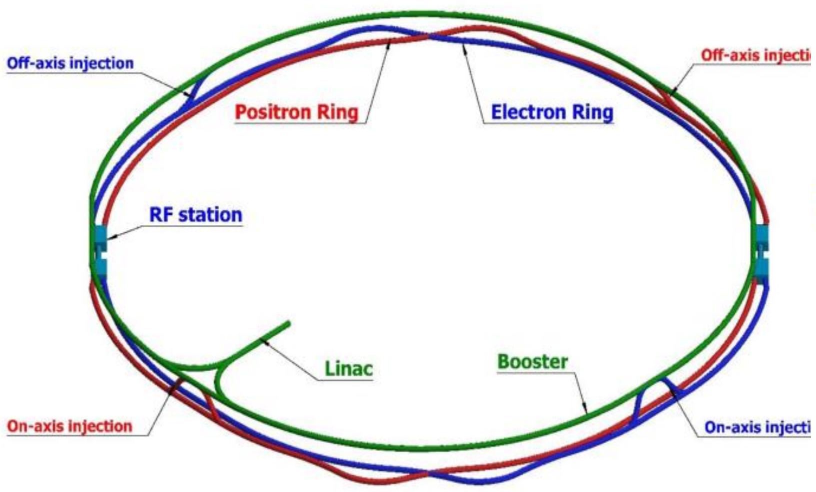
LCTPC Collaboration Meeting
January 30, 2025

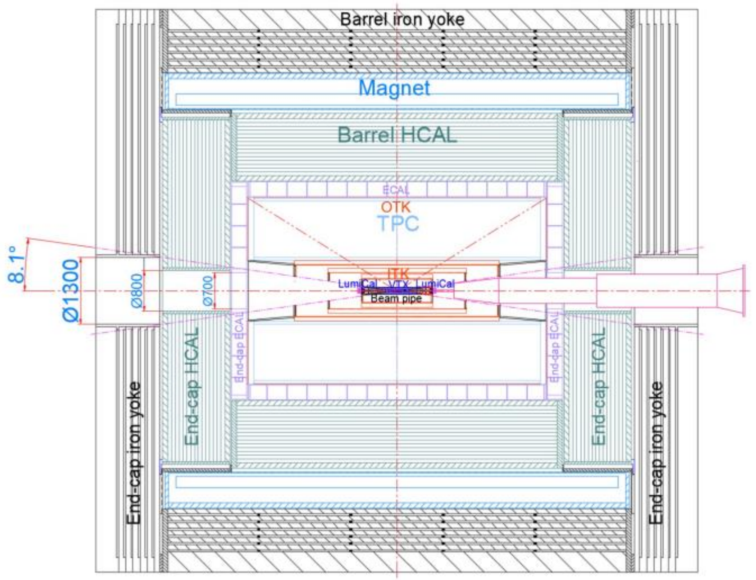
Content

- Motivation and Physics requirements
- Estimation the beam backgrounds at CEPC TPC
- Comparison with FCCee & ILC
- Summary

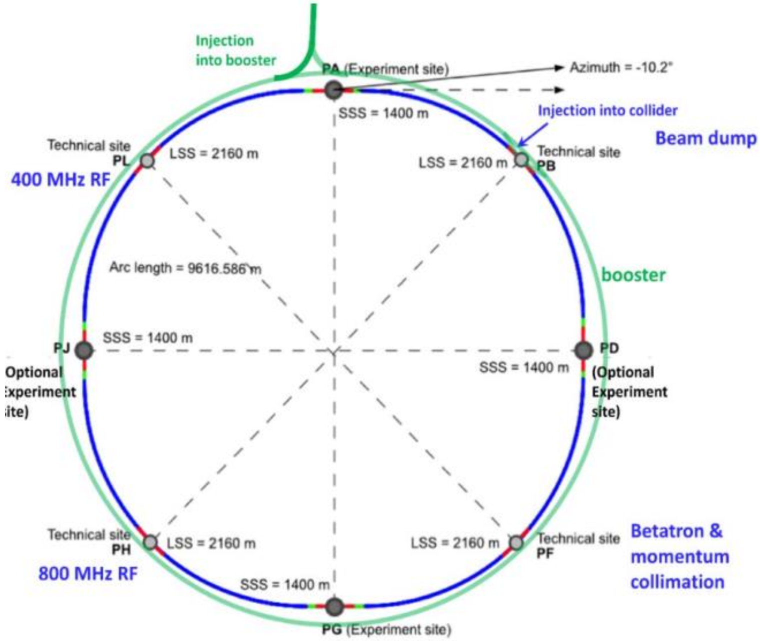
TPC detector for future e+e- colliders

- A TPC is a promising main tracking detector candidate for future e+e- colliders experiments
    - Baseline detector in CEPC CDR and ILD
    - **Pixelated TPC** has been selected as the baseline main track detector (MTK) in CEPC Ref-TDR
- Pixelated readout TPC is potential to **improve PID requirements of Flavor Physics** at e+e- collider.
- TPC technology can be interest for other future colliders (FCC-ee, EIC, KEKb…)





Circular Electron Positron Collider (CEPC)



Future Circular Collider (FCCee)

https://arxiv.org/abs/1811.10545

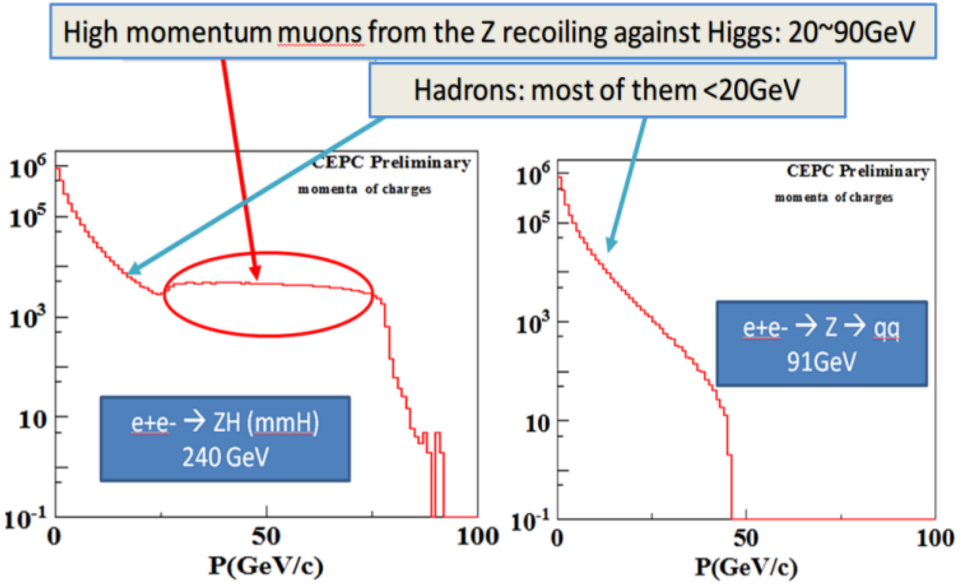
https://arxiv.org/abs/2203.08310

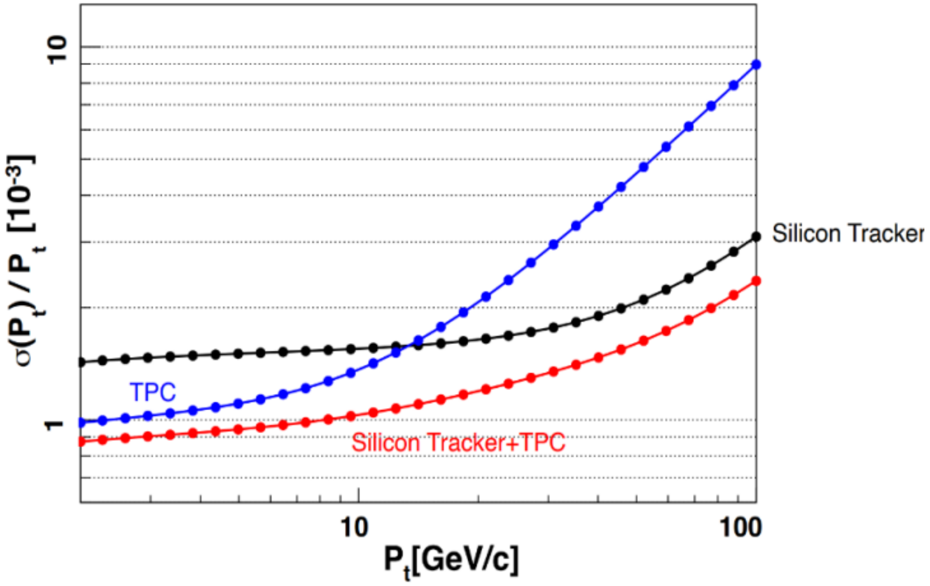
Motivation and physics requirements

- CEPC operation stages in Accelerator TDR: **10-years Higgs @3T** → 2-years Z pole@2T → 1-year W
- Physics Requirements for TPC
  - High momentum resolution for Higgs and low Lumi. Z run (~10^{-4} GeV/c^{-1})
  - Particle Identification (PID) for flavor physics and jet reconstruction

Calibration: Low luminosity Z at 3T
Approximately 10^{35}cm^{-2}s^{-1}
1%-20% of high luminosity Z

- Challenges:
  - Beam induced backgrounds
  - Space Charge effect and Distortion
  - …





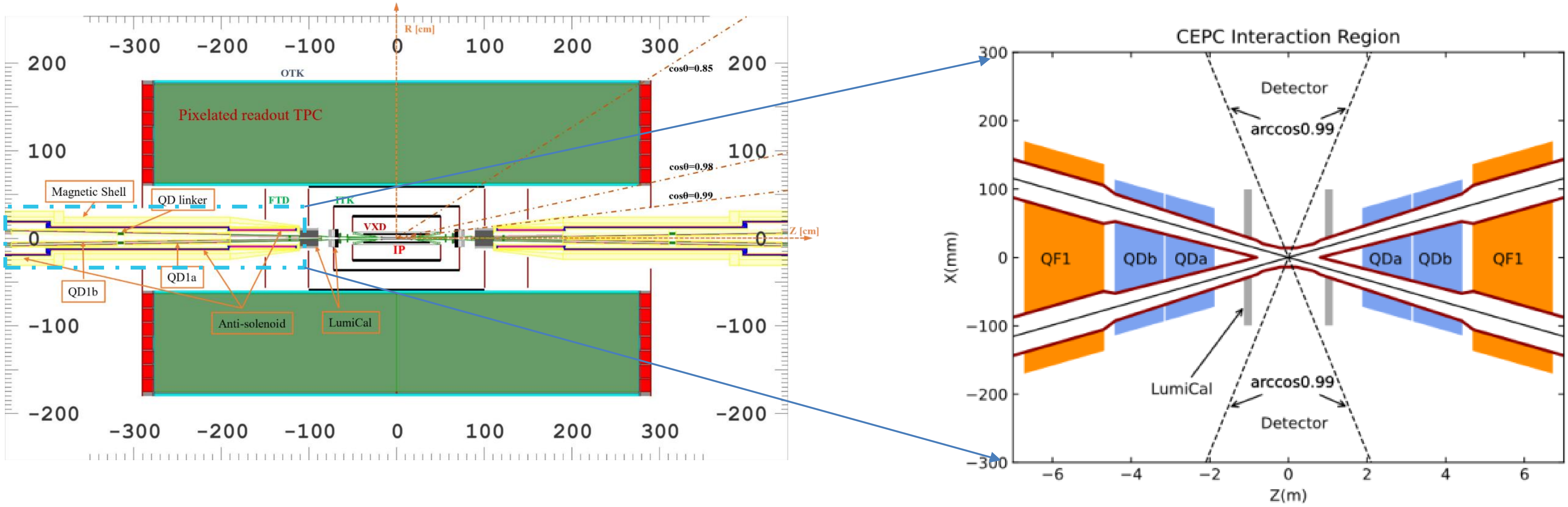
Estimation the beam backgrounds at CEPC TPC

- CEPC MDI design
- Beam-induced backgrounds simulation
- Low energy photon
- Space charge density caused by BG

CEPC MDI design and Tracker system in TDR

Sha Bai,Haoyu Shi

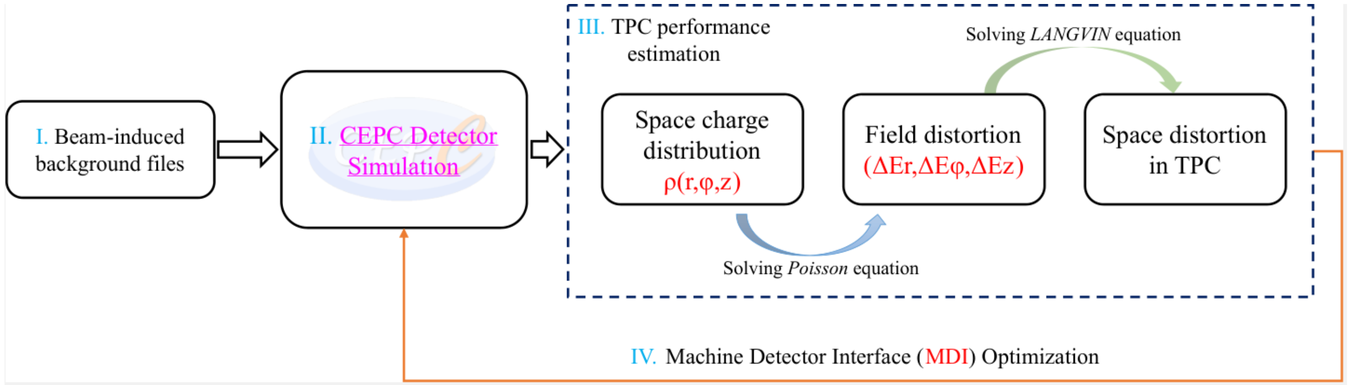
- MDI stands for “Machine-Detector Interface”
  - Interaction region, beam-pipe, QD,QF, cryo-modules and LumiCal → ±7m from the IP, cosθ>0.99
  - **33 mrad** Crossing angle, L*(distance from IP to last QD ~ 1.9m)
- CEPC tracker system consists of a large volume gaseous detector (TPC) and four types of silicon detectors (VXD, ITK, FTD, OTK)
  - TPC inner radius=0.6m, outer radius=1.8m, max. drift length~2.75m Total volume~52.48m^3



CEPC tracker system and One of Machine-Detector Interface design in CEPC ref-TDR

Simulation flow of beam backgrounds

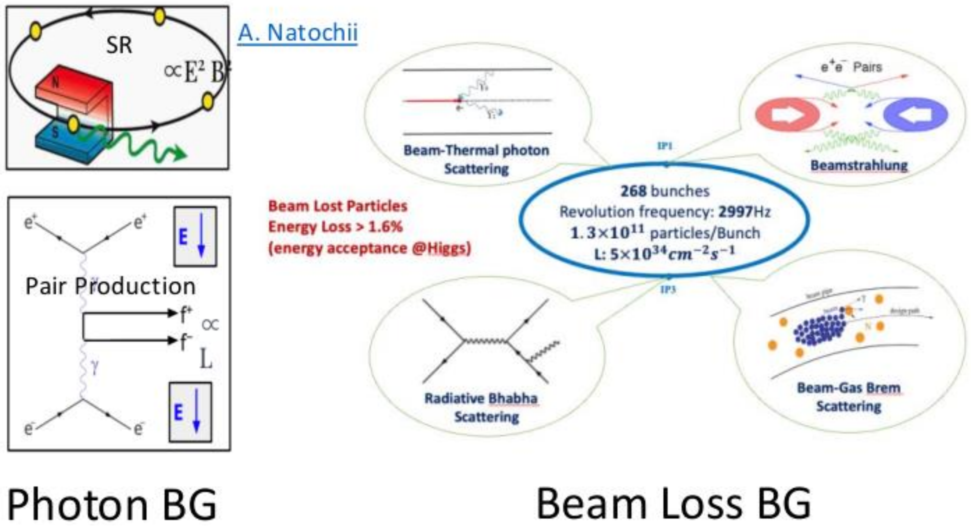
- Beam-induced backgrounds seeds generation
  - Pair production (beamstrahlung) → luminosity related
  - Single-Beam (BGC,BGB,BTH,TSC) → Single Beam
- Full Detector simulation in [CEPCSW](#) (based on Geant4)
  - [DD4hep](#): full detector description
  - Physic list: QGSP_BERT
- TPC space charge density and distortions estimation



estimate number of **primary ions** produced in the TPC per bunch crossing
→ geant4 energy deposit / effective ionisation potential of Ar [26 eV]

Backgrounds	Generation	Tracking	
Pair production	[Guinea-Pig++](#)	[SAD](#)	Luminosity related (BS files)
Beam-Gas Coulomb (BGC)	BGC in [SAD](#)		Single-Beam (Lost maps)
Beam-Gas Bremsstrahlung (BGB)	[PyBGB](#)		
Beam-Thermal Photon (BTH)	[PyBTH](#)		
Touschek Scattering (TSC)	TSC in [SAD](#)		

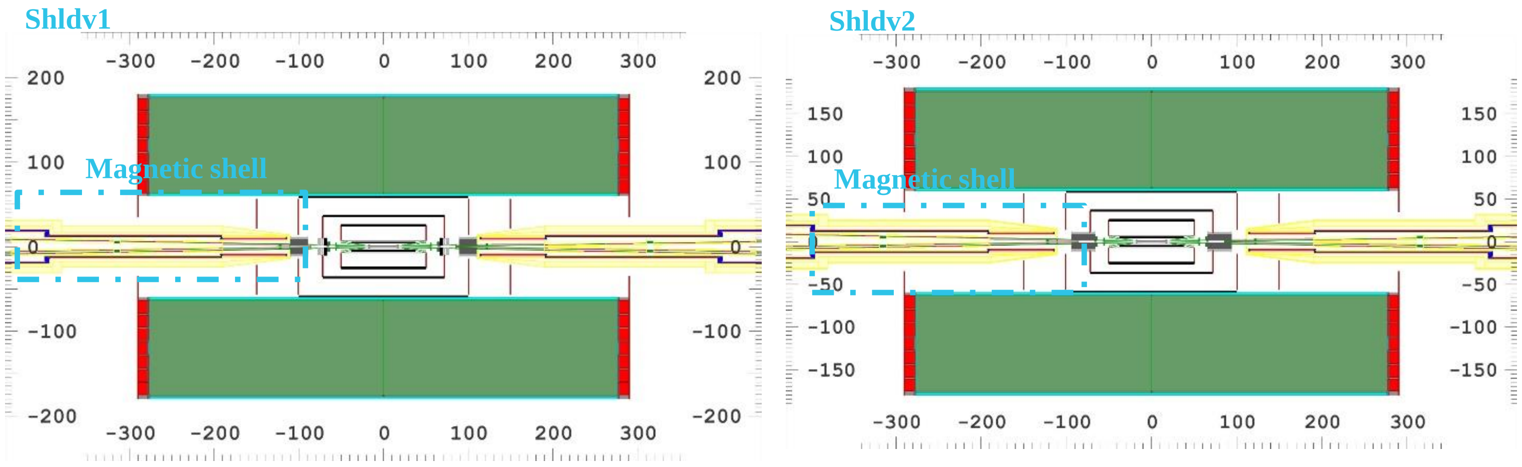
→ Haoyu Shi



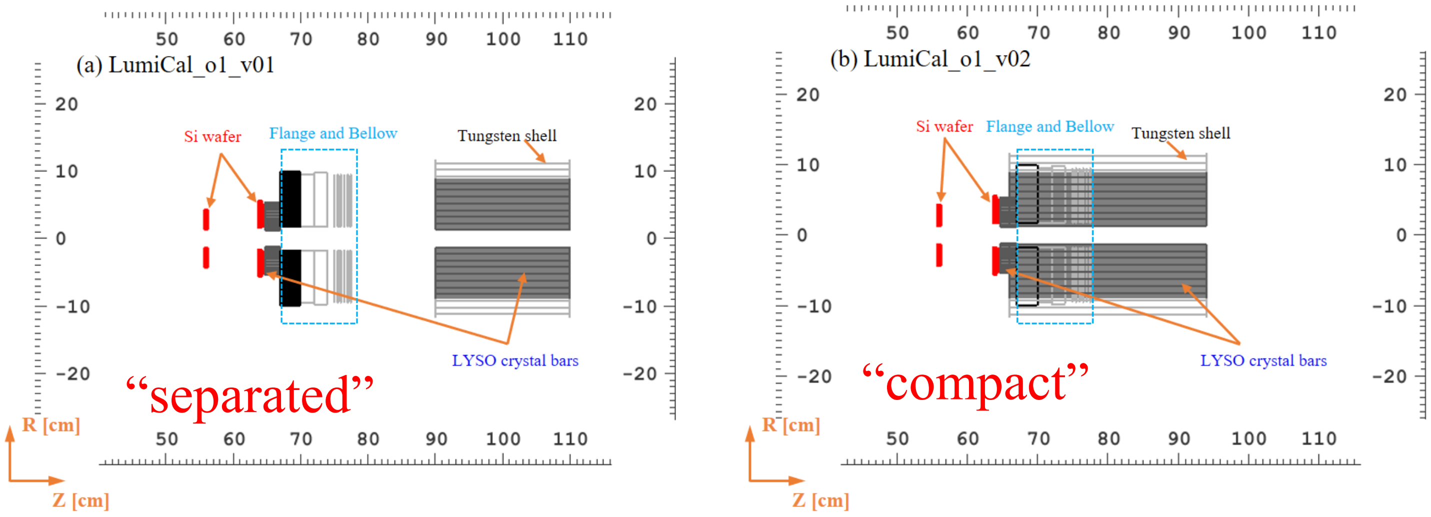
Different geometry models

- Four detector models have been used in our simulation
  - Two types of LumiCal design
  - Different shielding material of magnetic shell
  - Other sub-detectors remain the same
- Material of magnetic shell:
  - Different thickness of Ti, SS and Ti+Tungsten
- Lumi-Cal design:
  - Two part, one before the flange (Si-wafers, $2X_0$ LYSO)
  - One after the flange ($\sim 12X_0$ LYSO), wrapped by 2cm Tungsten

Models	LumiCal	Material of Magnetic Shell	Thickness
NoShield	LumiCal_v01	Ti	3mm
Shldv1	LumiCal_v01	Stainless Steels	65mm
Shldv2	LumiCal_v02	Stainless Steels	65mm
Shldv3	LumiCal_v02	Ti+Tungsten	3mm+10mm



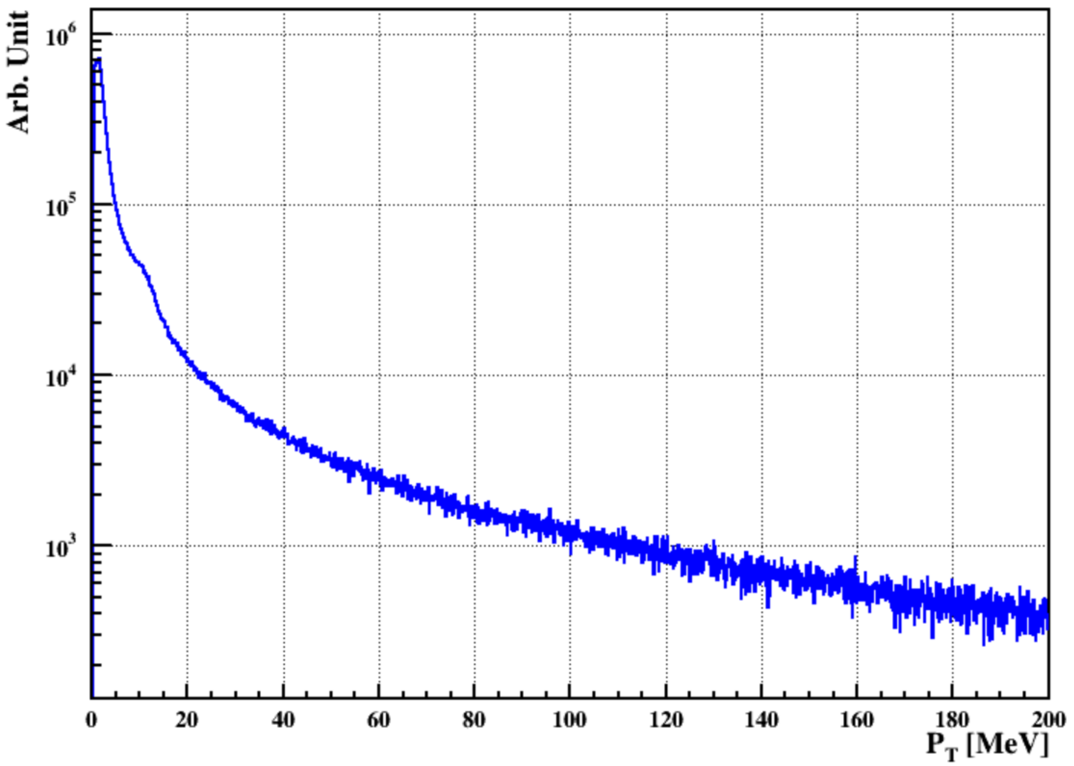
Two detector models, using two types of LumiCal



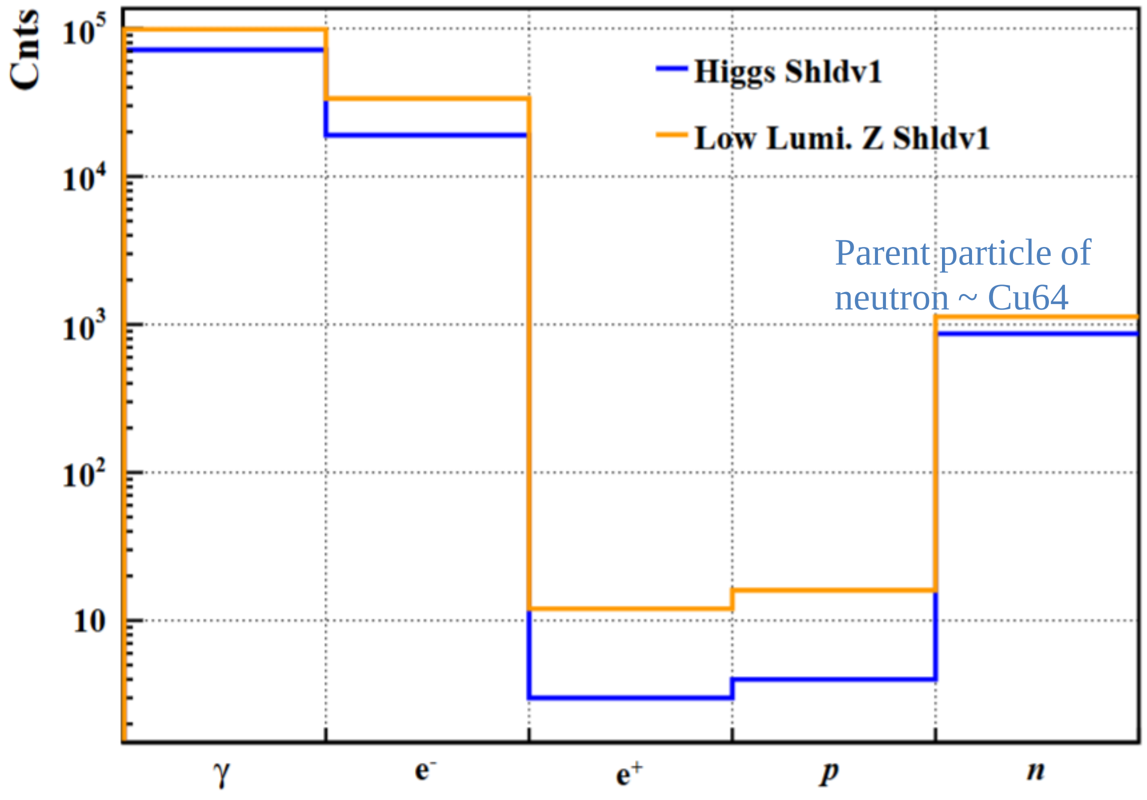
Two types of LumiCal design

Particles in TPC

- The momentum (Pt) of most primary particles (e+e-) is below 50 MeV (can not incident TPC directly under 3T B-field)
- Photons and electrons (produced by low energy photons) are the main components in the TPC volume
- Other type of particles (e+/Proton/Neutron) are negligible



Primary backgrounds momentum distribution



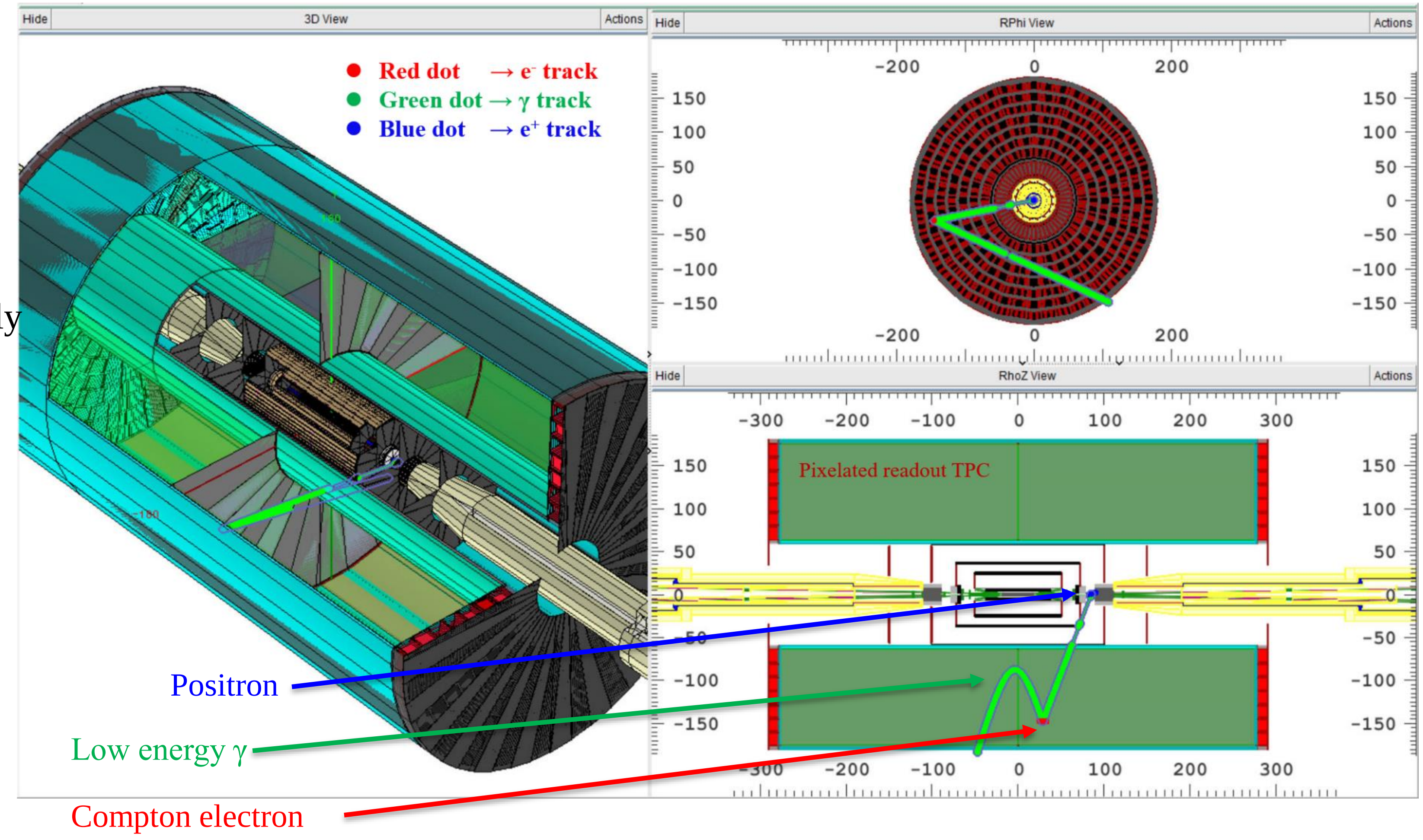
Particle type distribution in TPC under Higgs and Low Lumi. Z mode (CEPC_Shldv1 geometry)

Beam-induced Background events display

- Primary background particles (e^+e^-) can hardly incident TPC under 3T magnetic field
  - Photons aren't deflected under a B field
  - Low material budget of TPC barrel
- Typical event display:
  - e+ annihilation
  - Low energy (0.511 MeV) γ incident TPC and interact with T2K gas
  - generate secondary Compton electron
  - Secondary e- will deposit its energy totally in TPC and generate positive ions.

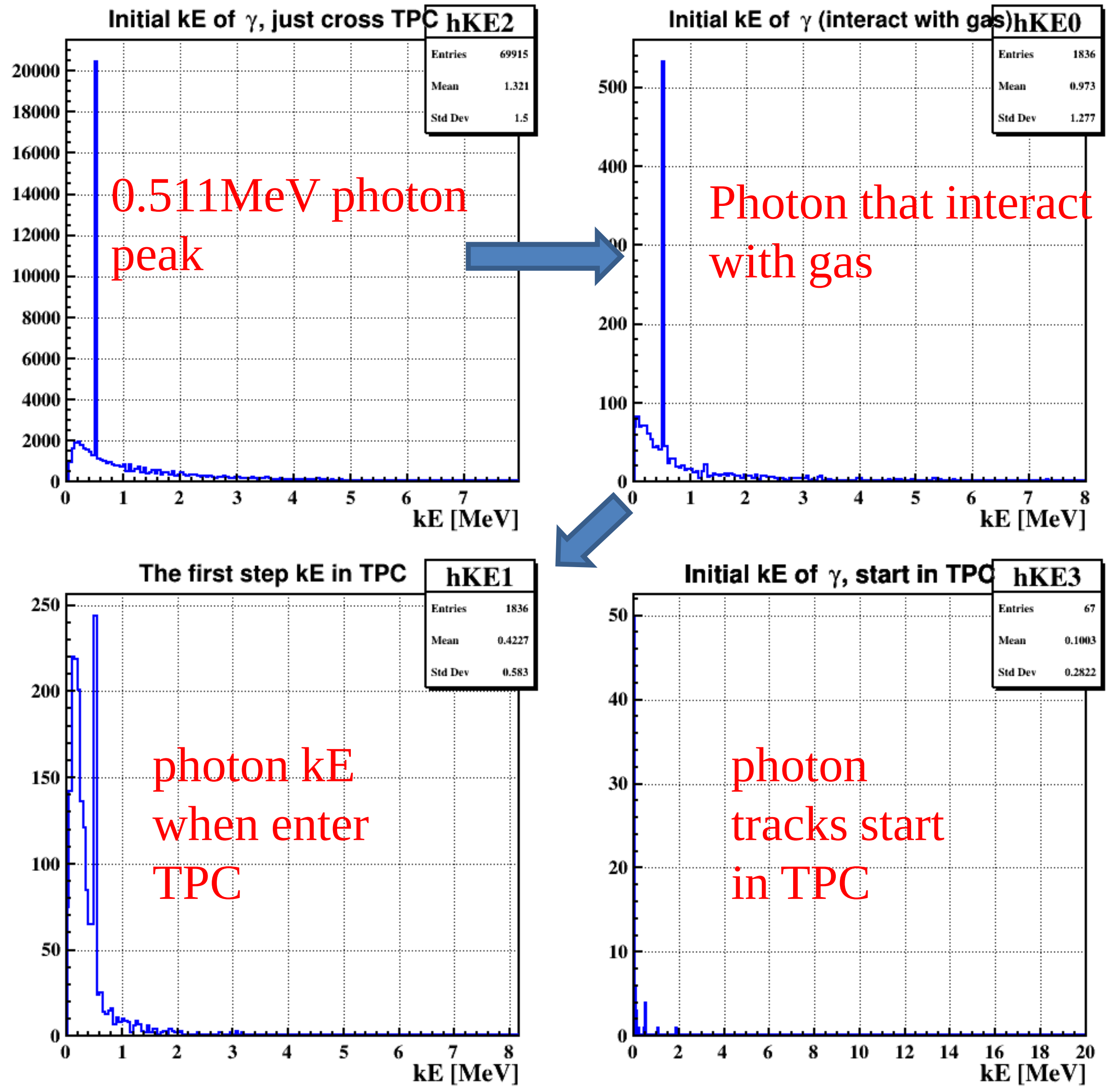
$$background\ e^+annihilation \rightarrow \gamma(0.511MeV) \rightarrow Compton\ e^-$$

Shldv1 model




```
Remark:
Due to limited computer memory,
only plot the Tracker system and
MDI region for visualization.
All sub detectors are included in
BG simulation.
```

Low energy photon energy distribution (Higgs 3T)

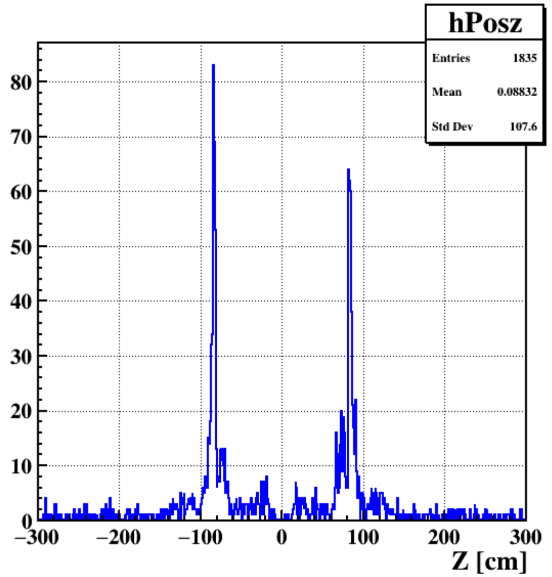


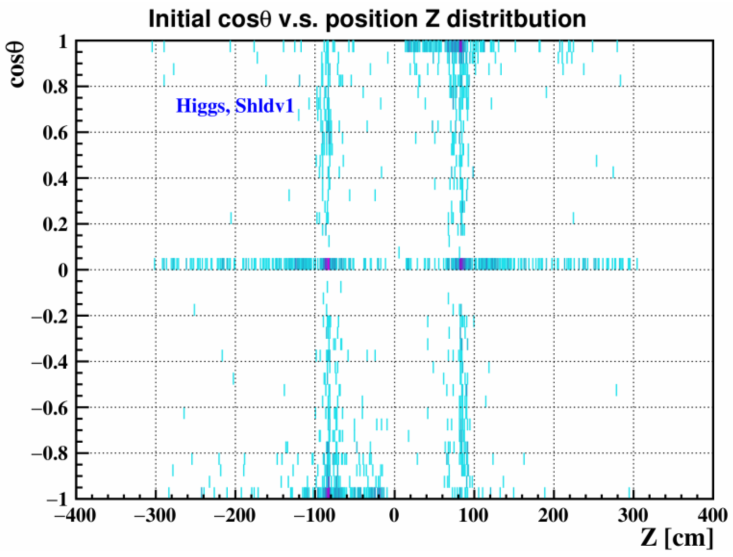
Photon energy distribution   (Shldv1 model)

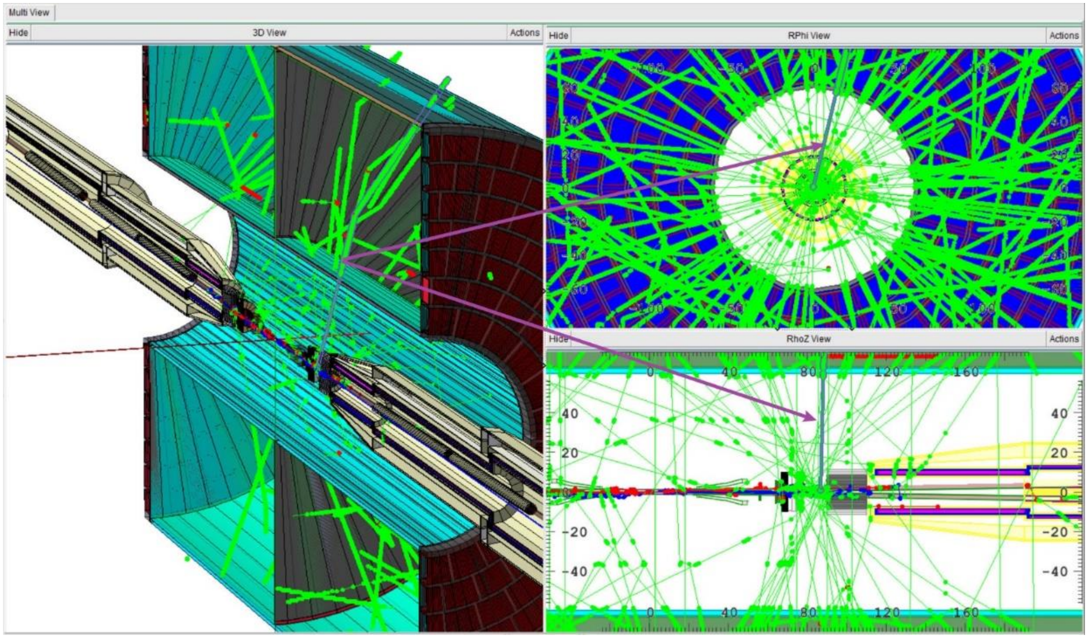
- 7.2e+4 photons will cross TPC and ~1836 photons will interact with T2K gas through “compt, phot, conv” process, 6.9e+4 γ just cross TPC without energy deposit after 10 Bunch Crossing
- ~0.07% photons energy > 10 MeV
- Large number of 0.511 MeV photons (through e+ annihilation)
- Average energy deposit： 16.14 MeV/BX by sum all secondary e- dE, small less than the result from .root file (17.5 MeV/BX)
- The results for the low-Lumi. Z-mode are essentially the same as for the Higgs mode.
- **Low energy photon is the main contributions of space charge in TPC**

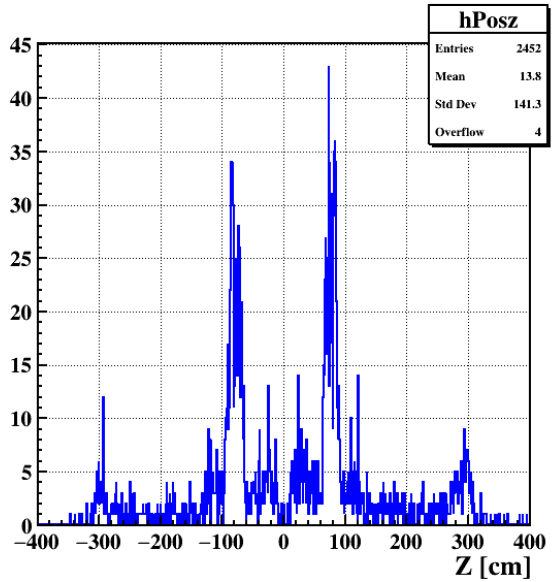
Photon position/direction distributions

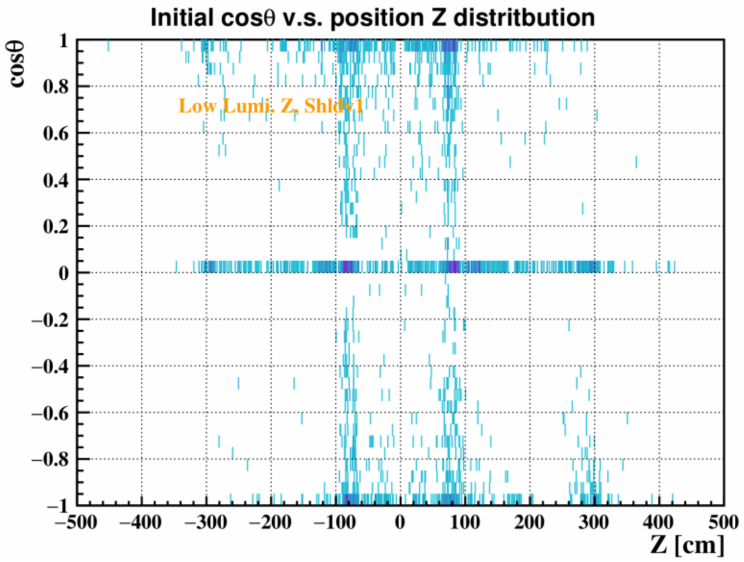
- Start point distribution of these photons (enter TPC and interact with gas) @ ***Shldv1*** Model
  - Two peaks at the gap of LumiCal for Higgs mode
  - Other two small peaks near ±3m for Low Lumi. Z mode
  - ***Cosθ*** vs ***Z*** distributions of these photons: Mostly along the beam-pipe or vertical beam-pipe emission







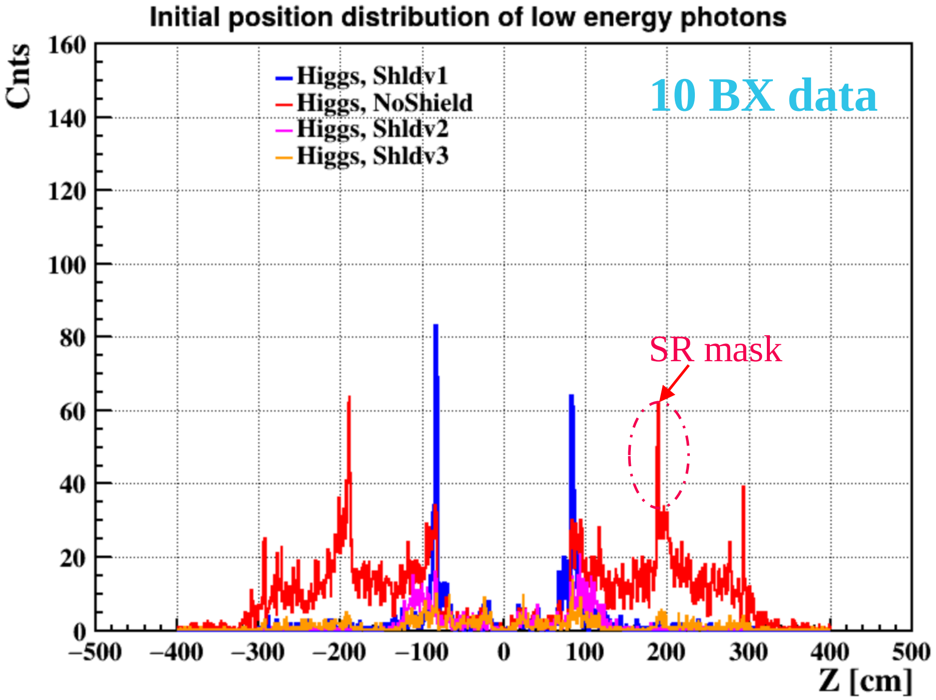


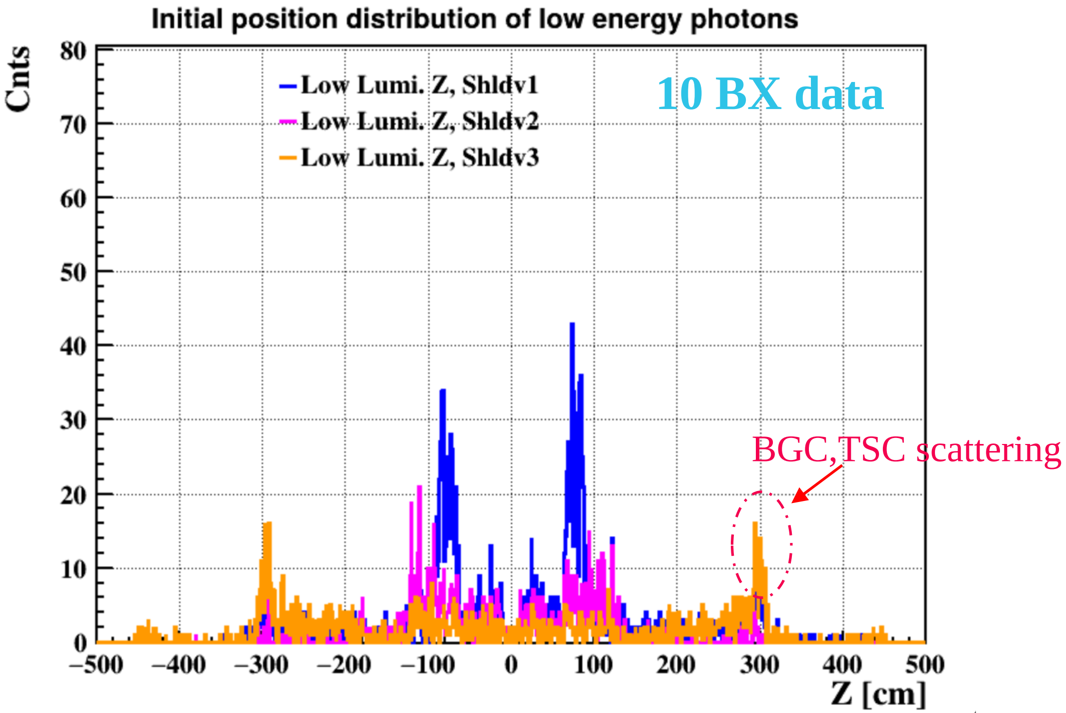


Comparison of different geometry models

- Initial position of low energy photons that incident and interact with TPC gas：
  - NoShield (LumiCal_v01, 3mm Ti of magnetic shell): photons are come from 1m<|Z|<3m, especially around LumiCal and SR mask
  - Shldv1 (LumiCal_v01, 65mm SS): two peaks at the gap of LumiCal, few photons after LumiCal
  - Shldv2 (LumiCal_v02, 65mm SS): two small peaks at the end of LumiCal, few photons after LumiCal
  - Shldv3 (LumiCal_v02, 3mm Ti + 10 mm Tungsten): two small peaks at the end of LumiCal and some come from 1m<|Z|<3m

> - **The LumiCal can absorb many low energy photons produced by primary beam-backgrounds → "compact" LumiCal**
> - **The amount of shielding after LumiCal is important to reduce beam-induced backgrounds in TPC → thicker magnet shell**





Initial position distribution of low energy photons, Higgs (Left) & Low Lumi. Z (Right)

Space charge density estimation

- TPC integrates over many collisions; maximum ion drift time ~ 2.75m/(5m/s)=0.55s
- Roughly estimate number of primary ions in the CEPC TPC volume at any time, taking account of different collision rates
  - Number of Ions ~Primary ion/BX · BX $frequency$ **max drift time** · 50% [ion already reached cathode] from Daniel Jeans
  - BX $frequency$ = 1/346ns @Higgs mode , 1/69ns @ Low Lumi. Z mode

IBF×Gain~1, Primary ion level

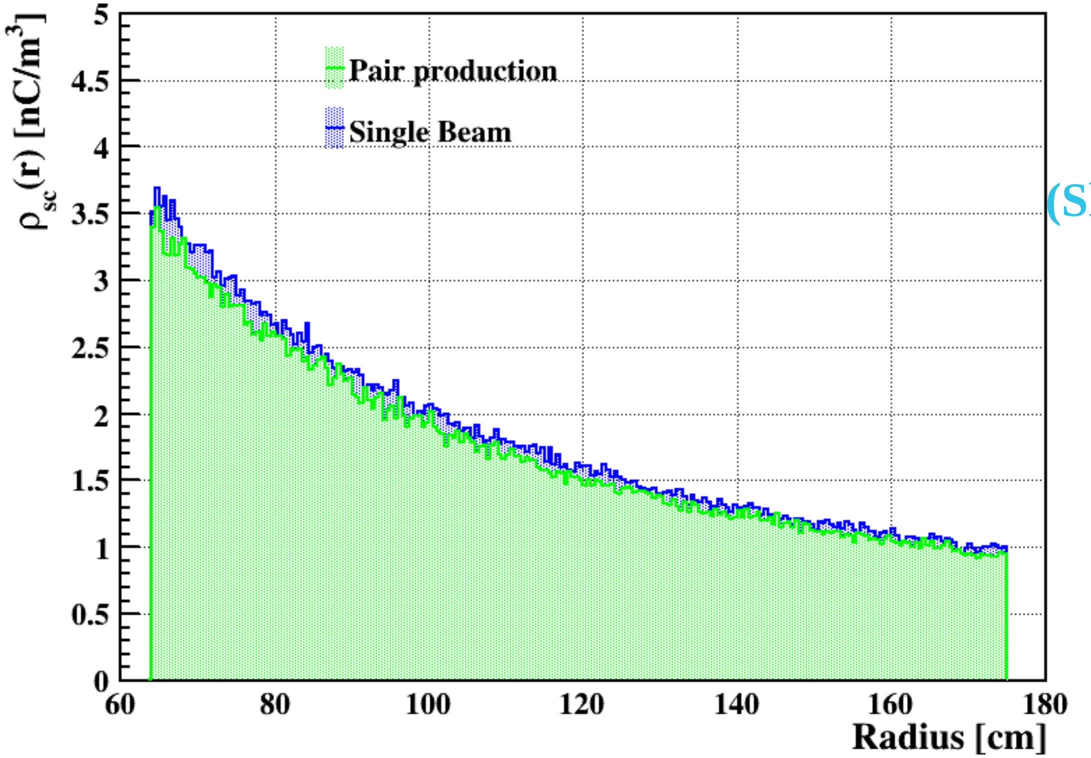
Run mode	Geometry	EDep/BX in TPC	Ave. space charge density (nC/m³)	BX. Freq.
Higgs mode	NoShield	68.65 MeV/BX	6.47	1/346ns
	Shldv1	17.50 MeV/BX	1.65	
	Shldv2	11.44 MeV/BX	1.07	
	Shldv3	12.94 MeV/BX	1.22	
Low Lumi. Z mode	NoShield	176.04 MeV/BX	83.14	1/69ns
	Shldv1	32.23 MeV/BX	15.22	
	Shldv2	21.27 MeV/BX	10.04	
	Shldv3	64.04 MeV/BX	30.25	

Preliminary results

- Compare to ALICE-TPC
  - The space charge density of ALICE TPC is about ~120 nC/m³
  - For Higgs run, the space charge is only ~1/20 of ALICE TPC
  - For Low Lumi. Z, the space charge in TPC → similar or probably larger than ALICE TPC without any MDI optimization

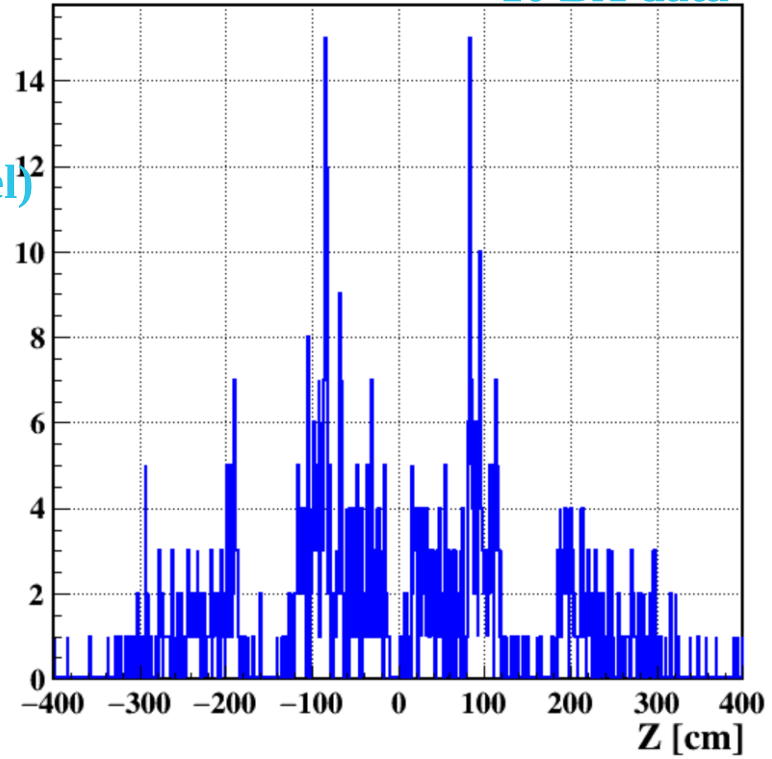
Space charge density of different BG components @ Higgs

- For Higgs run, Pair production background is dominated and hard to mitigate.
- ~96% positive ion charge comes from Pair production and Single Beam backgrounds (BGC+BGB+BTH+TSC) are much smaller than Pair production
- For Higgs, it is necessary to shield the low energy photons which come from 1m<|Z|<3m



(Shldv3 model)

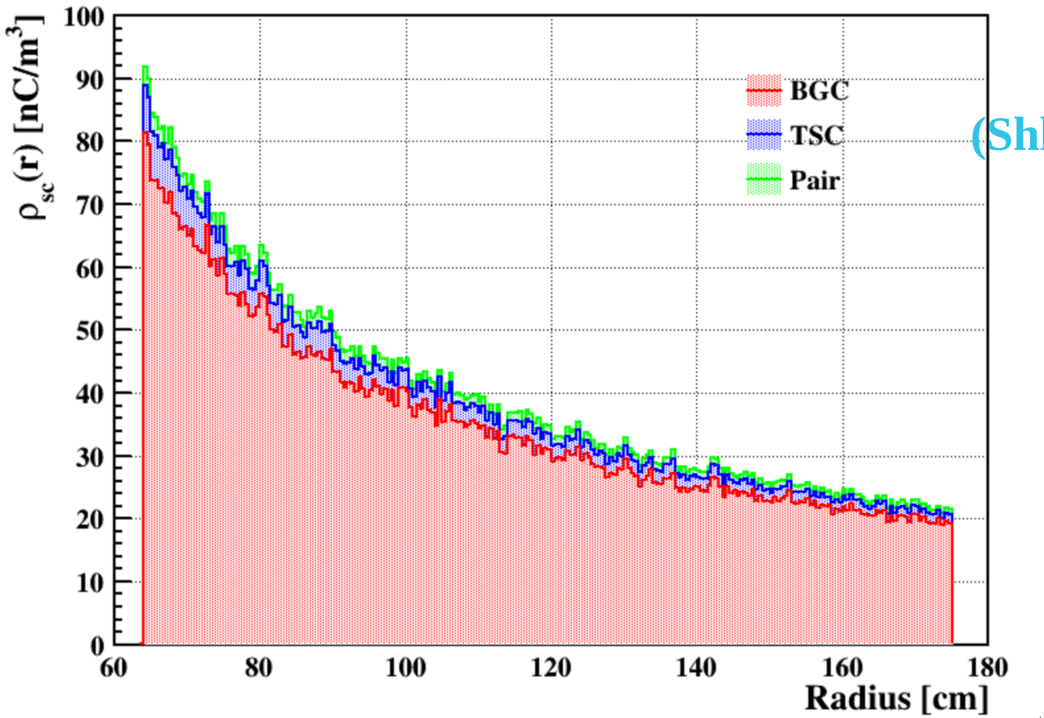
10 BX data



Space charge density caused by different BG components (left) and The initial position Z distribution of low energy photons (right)

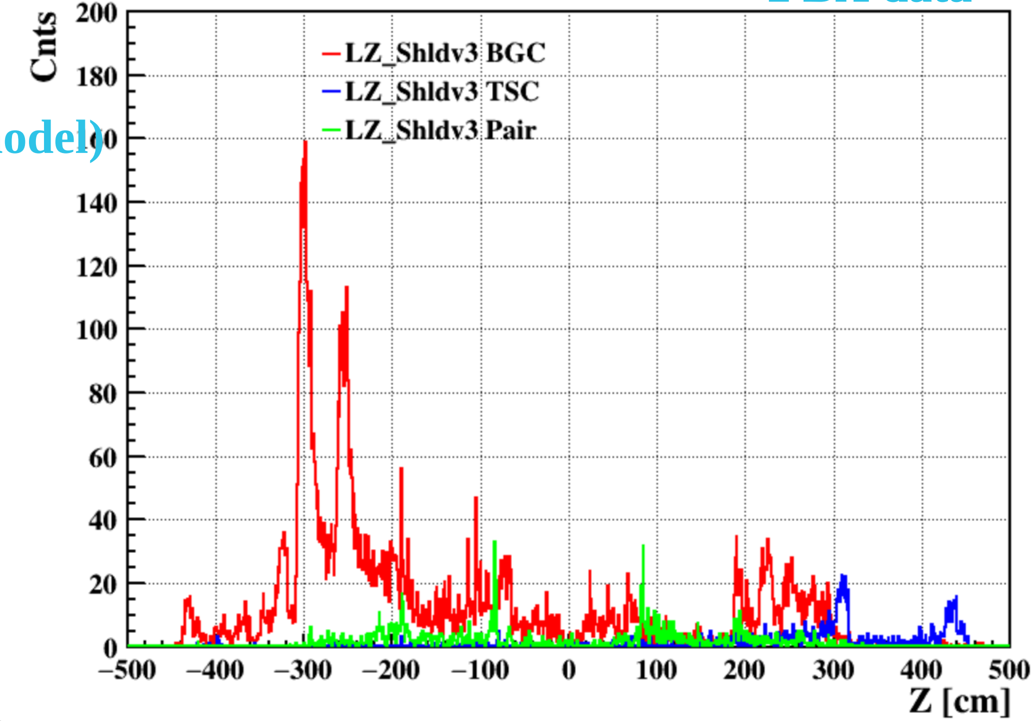
Space charge density of different BG components @ Low Lumi. Z

- For Low Lumi. Z run, Single-Beam backgrounds are dominated and the max. charge density is 25× larger than Higgs
  - BGC has contributed ~90% space charge, 7.2% from TSC and 3.7% from Pair production
  - BTH+BGB can be negligible
- Low-energy photon caused by BGC and TSC occurs mainly from 2m-3m, and a small portion of them can be backscattered into the TPC from as far as 4 m away.
- For Low Lumi. Z, it is necessary to control the beam loss and add more shield after LumiCal (|Z|>1m)



(Shldv3 model)

2 BX data



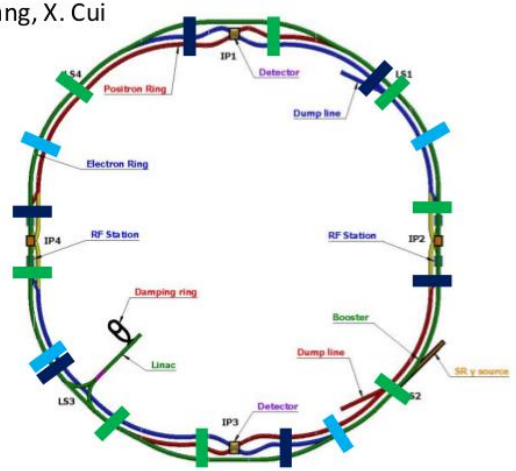
Space charge density caused by different BG components (left) and The initial position Z distribution of low energy photons (right)

Mitigation of the Single-Beam BGs

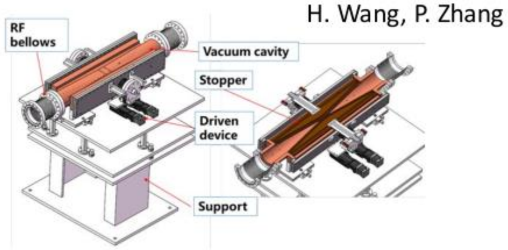
- Collimators were implemented to reduce Interact Region(IR) loss caused by Single-Beam
- With the implementation of collimators, single-beam backgrounds can be shielded effectively @ Low Lumi. Z run
  - ~20 sets of collimators were installed for passive machine protection and will also contribute to mitigate beam-backgrounds
  - After adding collimators, the beam loss rate can be reduced
  - The space charge density in TPC @ Low Lumi. Z is close to Higgs mode

Slides from Haoyu Shi

S. Bai, Y. Wang, X. Cui



H. Wang, P. Zhang



- for H betatron collimator
- for momentum collimator
- for vertical collimator

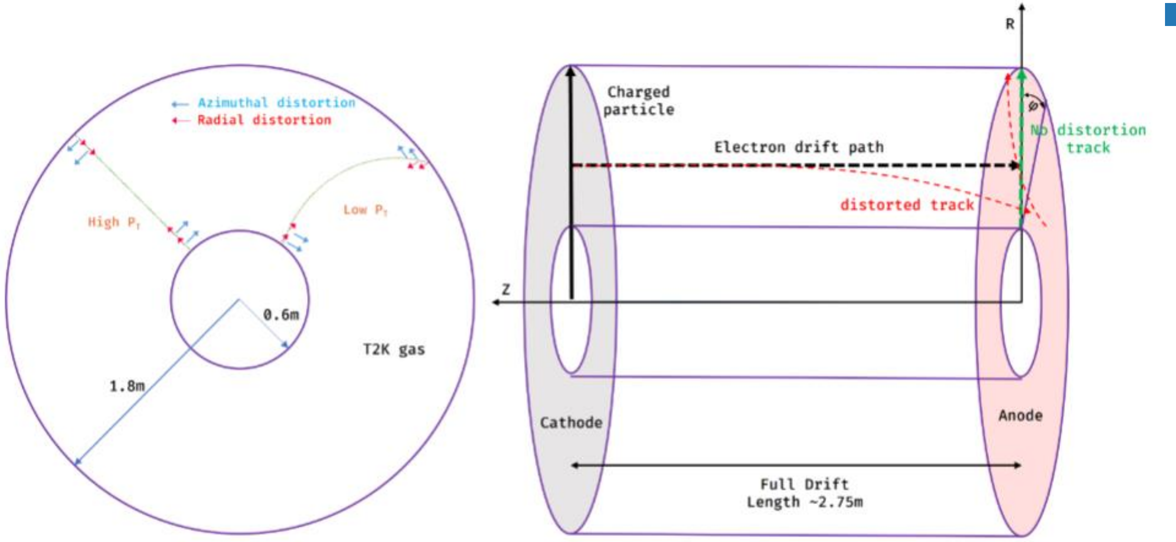
Run mode	Geometry	EDep/BX in TPC	Ave. space charge density (nC/m^3)	BX. Freq.
Higgs mode	Shldv4(15mm stainless steels)	37.75 MeV/BX	3.7	1/346ns
	Shldv5(5mm Ti + 10 mm Tungsten)	17.07 MeV/BX	1.67	
Low Lumi. Z mode	Shldv4(15mm stainless steels)	10.26 MeV/BX	5.03	1/69ns
	Shldv5(5mm Ti + 10 mm Tungsten)	4.88 MeV/BX	2.4	

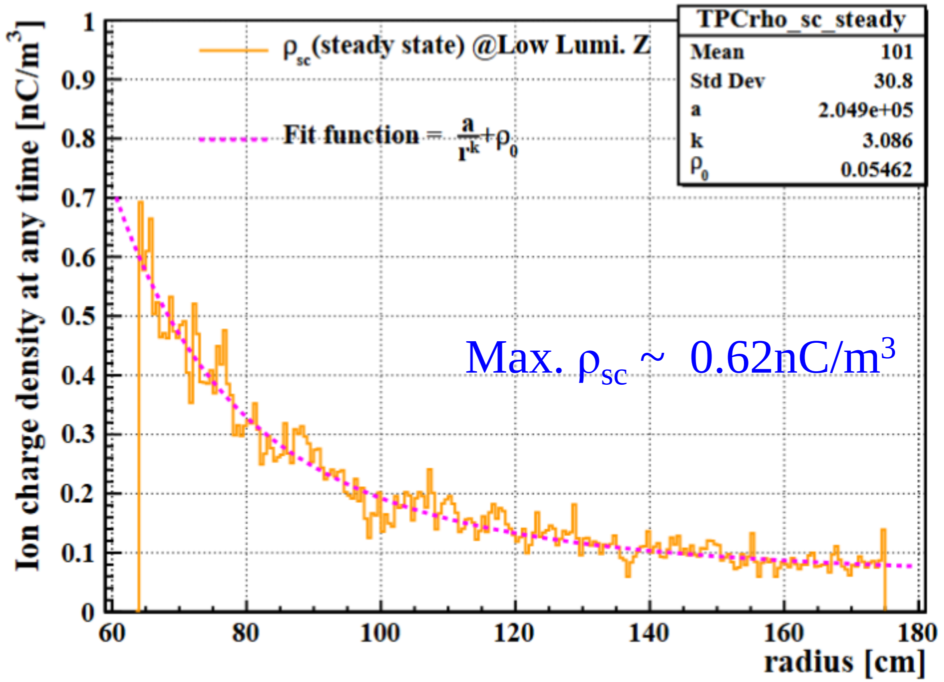
Preliminary results

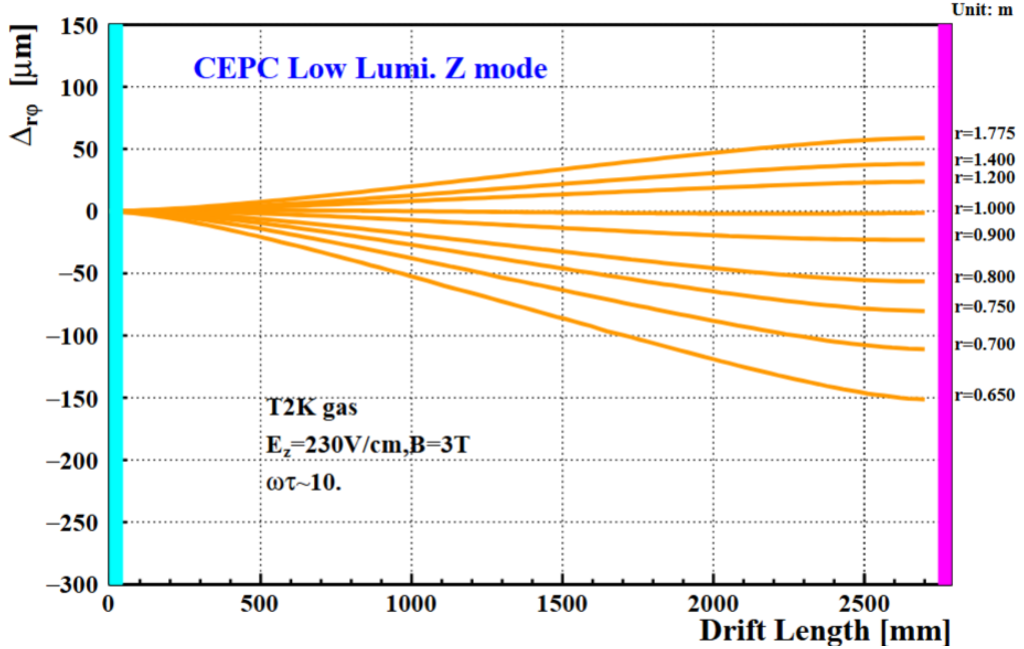
14/01/2025 IAS Program on FP 2025, HKUST, H.Shi(shihy@ihep.a

How about the distortions without low energy photons?

- The space charge density is only 0.62 nC/m^3 @Low Lumi. Z mode if we can shield all low energy photons(<10MeV) → **Ideal Situation**
- The max. r-phi distortion is about 150 um under 2.75m drift length.





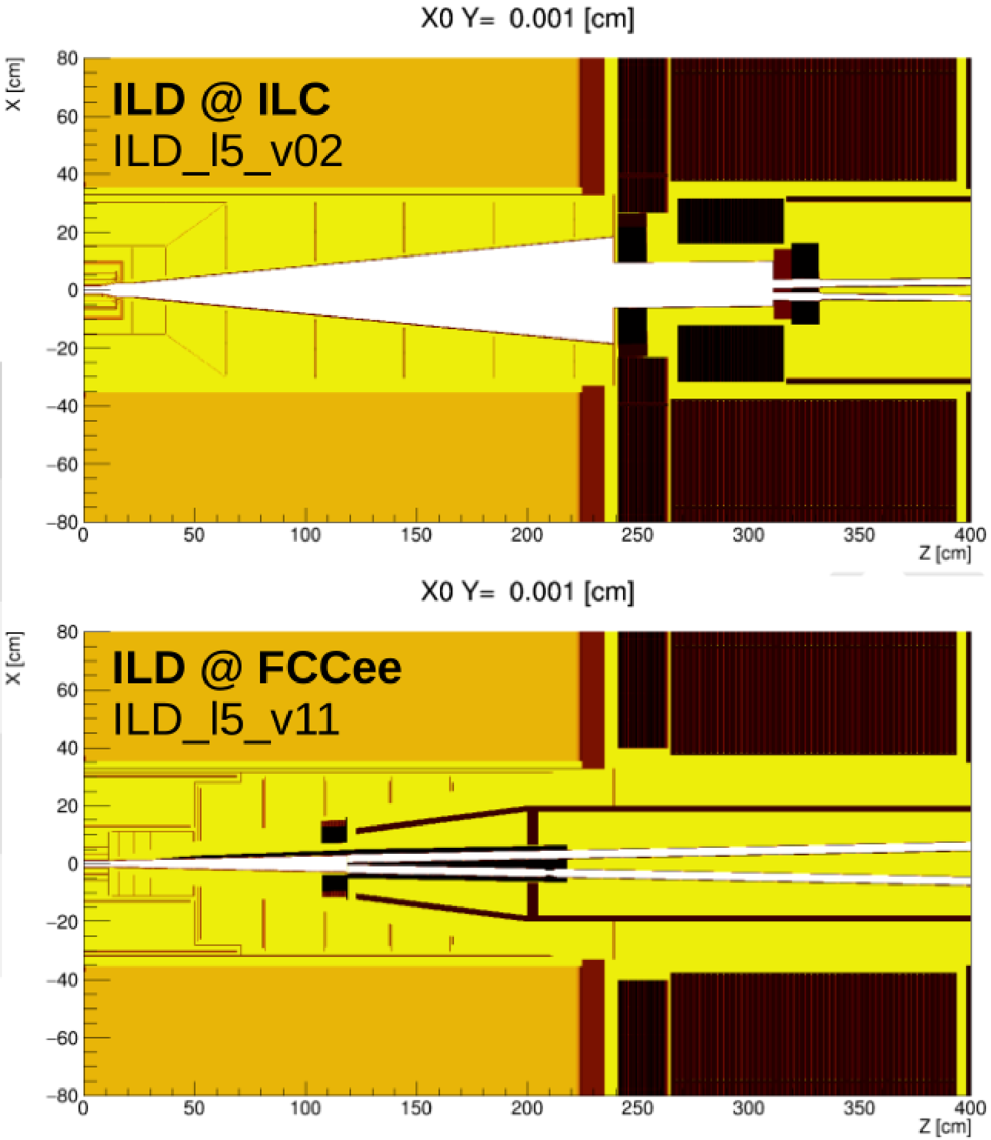


- **Comparison with FCCee & ILC (Slides from Daniel Jeans)**

Comparison with FCCee & ILC

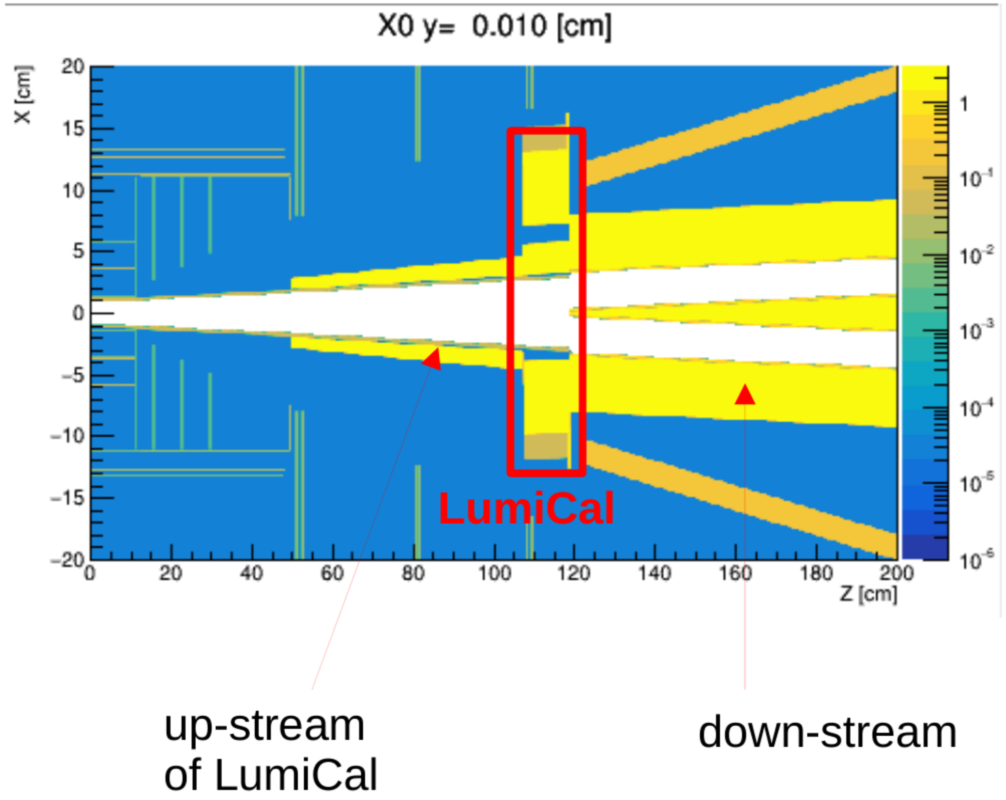
machine-detector interface

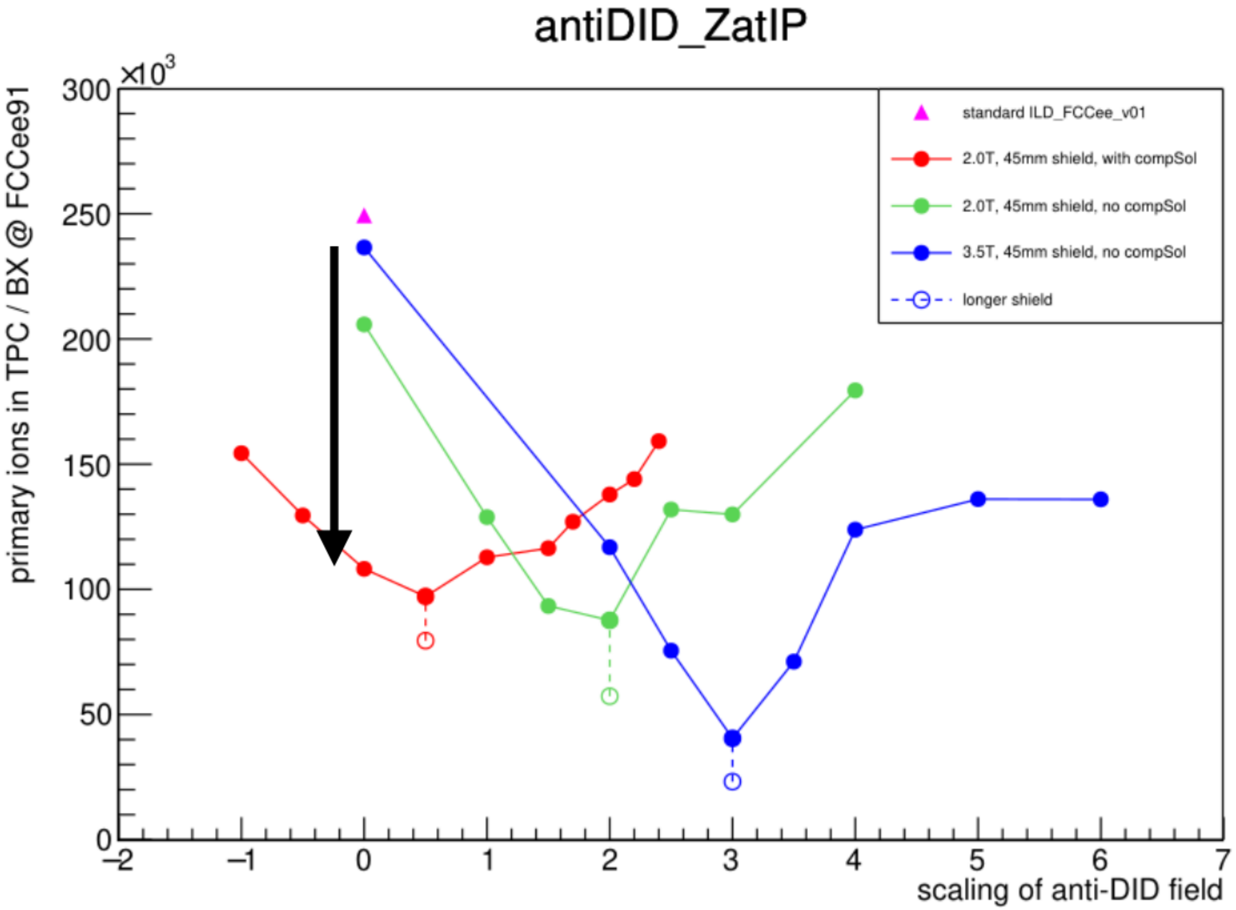
	ILC	FCCee
crossing angle	14 mrad	30 mrad
L* [distance from IP to last accel focusing quadupole magnet]	4.1 m	2.0 m
detector solenoid	3.5 T	2.0 T
additional B-fields	anti-DID (?)	- compensating - screening



Reducing BG @FCCee 1

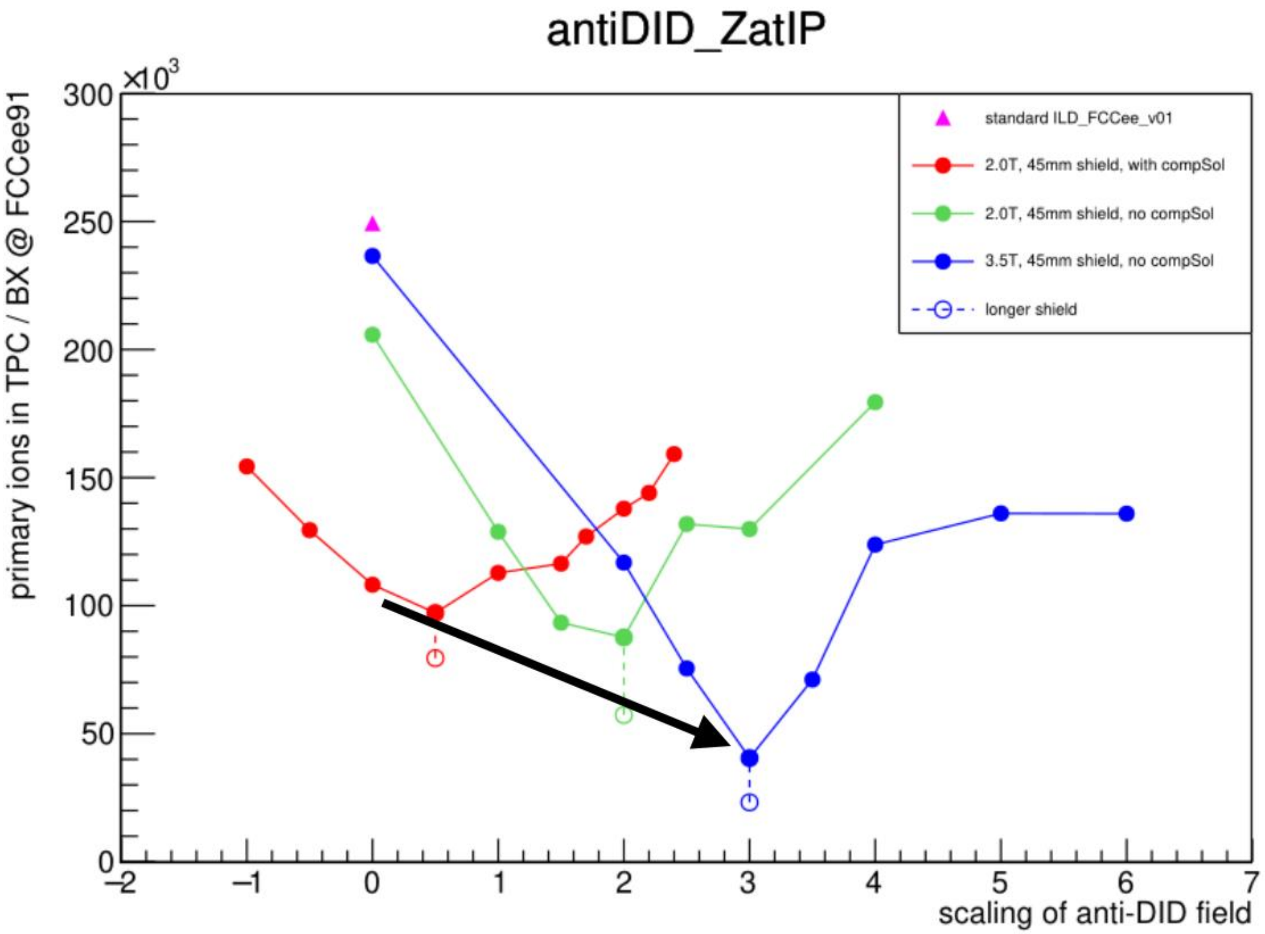
- Adding thicher shield after LumiCal → ~×1/2.5 reduction

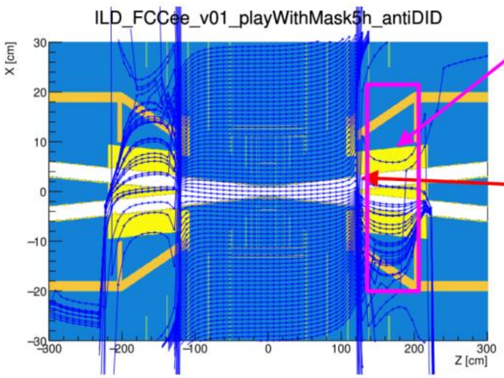




Reducing BG @FCCee 2

- 2.0 → 3.5 T + anti-DID → ~×1/2 reduction





compensating solenoid (–5T) ensures that integrated B_z seen by beam is 0

limited space available
→ strong compensating magnet, limited detector solenoid

transition between
+ 2T detector solenoid and
– 5T compensating solenoid
is essentially a magnetic wall for low p_T e^{+-}
→ steered into the shielding just behind LumiCal

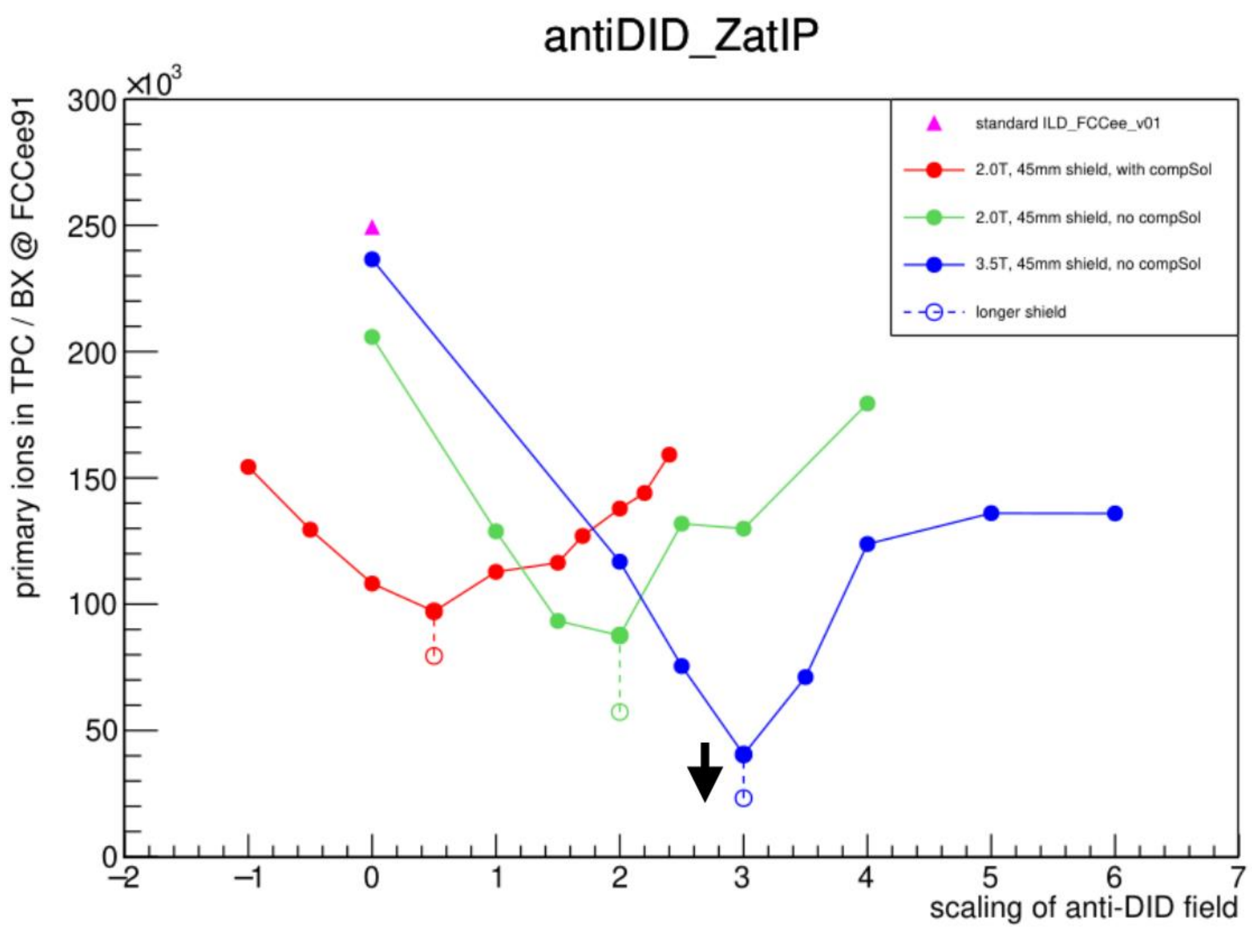
new proposal for alternative compensation scheme moves this strong compensating solenoid outside the detector

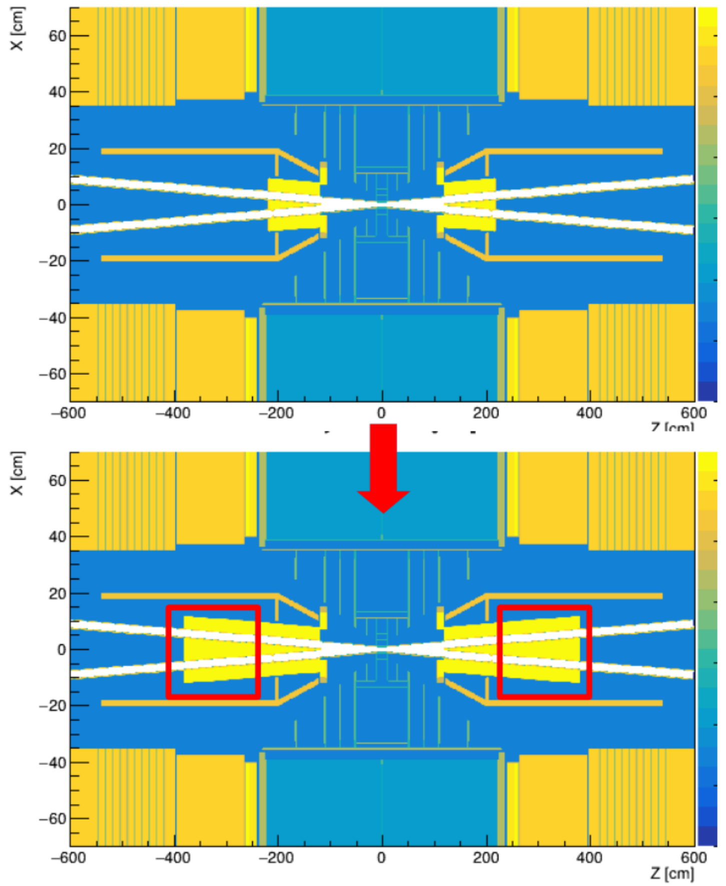
doi:10.18429/JACoW-IPAC2024-TUPC68

→ more space available for compensation → relaxed limit on detector solenoid strength

Reducing BG @FCCee 3

- Longer shield after LumiCal → ~×1/2 reduction (if space of MDI permits)





* just a toy model: eg QD0 needs space!

Comparison with FCCee & ILC

- Max. ion charge density **(steady state) in** CEPC TPC @ Higgs mode and Low Lumi. Z mode is close to FCC91 before MDI Optimization
- Further optimization work on the CEPC MDI region is in progress.

Only pair-production background, after MDI Optimization

Collider Detector model	FCC-91 ILD_FCCee_v01	FCC-240 ILD_FCCee_v01	ILC-250 ILD_l5_v05
average BX frequency	30 MHz	800 kHz	6.6 kHz
primary ions / BX	260 k	820 k	450 k
primary ions in TPC at any time	$1.7 \times 10^{\cancel{12}\ 11}$	$1.4 \times 10^{\cancel{11}\ 10}$	6.5×10^{8}
average primary ion charge density nC/m^3	~~6.4~~ 0.6	~~0.54~~ 0.05	0.0025

*rough estimates

primary ion density in TPC: ~~2500~~ 250 times higher at FCCee-91 than ILC-250
~~200~~ 20 times higher at FCCee-240 than ILC-250

CEPC TPC

Run mode	Geometry	EDep/BX in TPC	Ave. space charge density (nC/m^3)	BX. Freq.
Higgs mode	Shldv4(15mm stainless steels)	37.75 MeV/BX	3.7	1/346ns
	Shldv5(5mm Ti + 10 mm Tungsten)	17.07 MeV/BX	1.67	
Low Lumi. Z mode	Shldv4(15mm stainless steels)	10.26 MeV/BX	5.03	1/69ns
	Shldv5(5mm Ti + 10 mm Tungsten)	4.88 MeV/BX	2.4	

Summary

- The TPC had been selected as the baseline main track (MTK) detector in CEPC ref-TDR.
- Low-energy photons (~MeV) is the main source of positive ions in the TPC volume, both in the Higgs and Low Lumi. Z modes
  - For Higgs mode, Pair-production is dominated
  - For Low Lumi. Z mode, it is important to control the beam loss (single beam backgrounds)
- Preliminary results from CEPC TPC shows that adding more shield is important to reduce beam-induced backgrounds and the MDI region needs further optimization, especially the LumiCal and the Magnet Shell of the Beam-pipe.

Happy Chinese New Year!

Thanks for Listening!

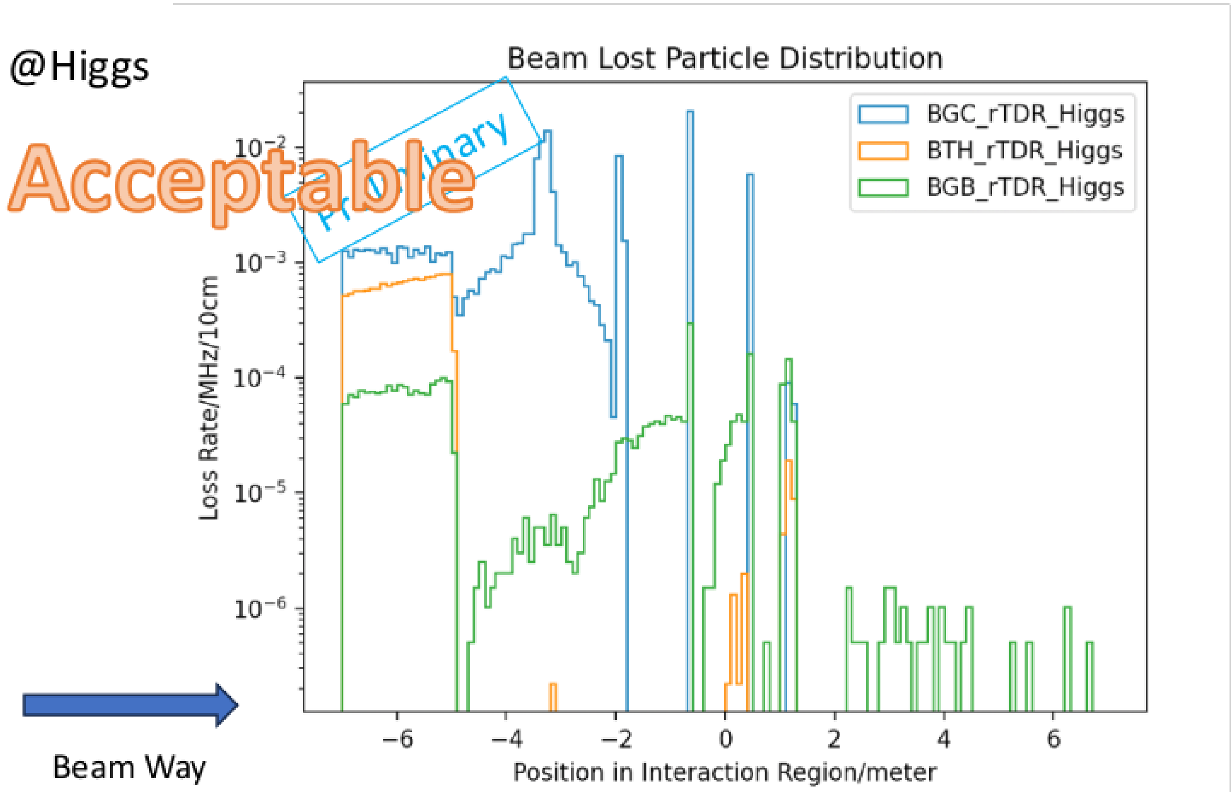
Lost Maps of Single Beam BGs

→ Haoyu Shi

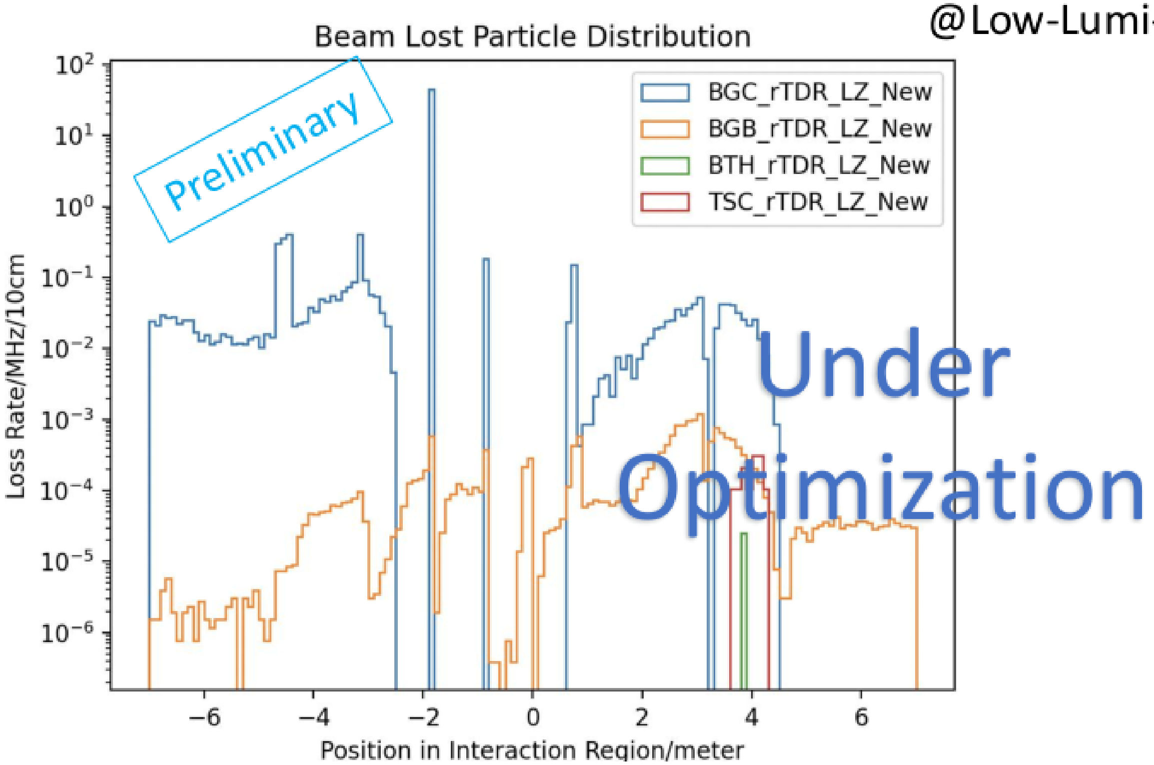
- Errors implemented
  - High order error for magnets
  - Beam-beam effect
- No Solenoid Currently

$$Loss\ Rate = \frac{Loss\ Number}{Loss\ Time} = \frac{Bunch\ number * Particles\ per\ Bunch * (1 - e^{-1})}{Beam\ Lifetime}$$

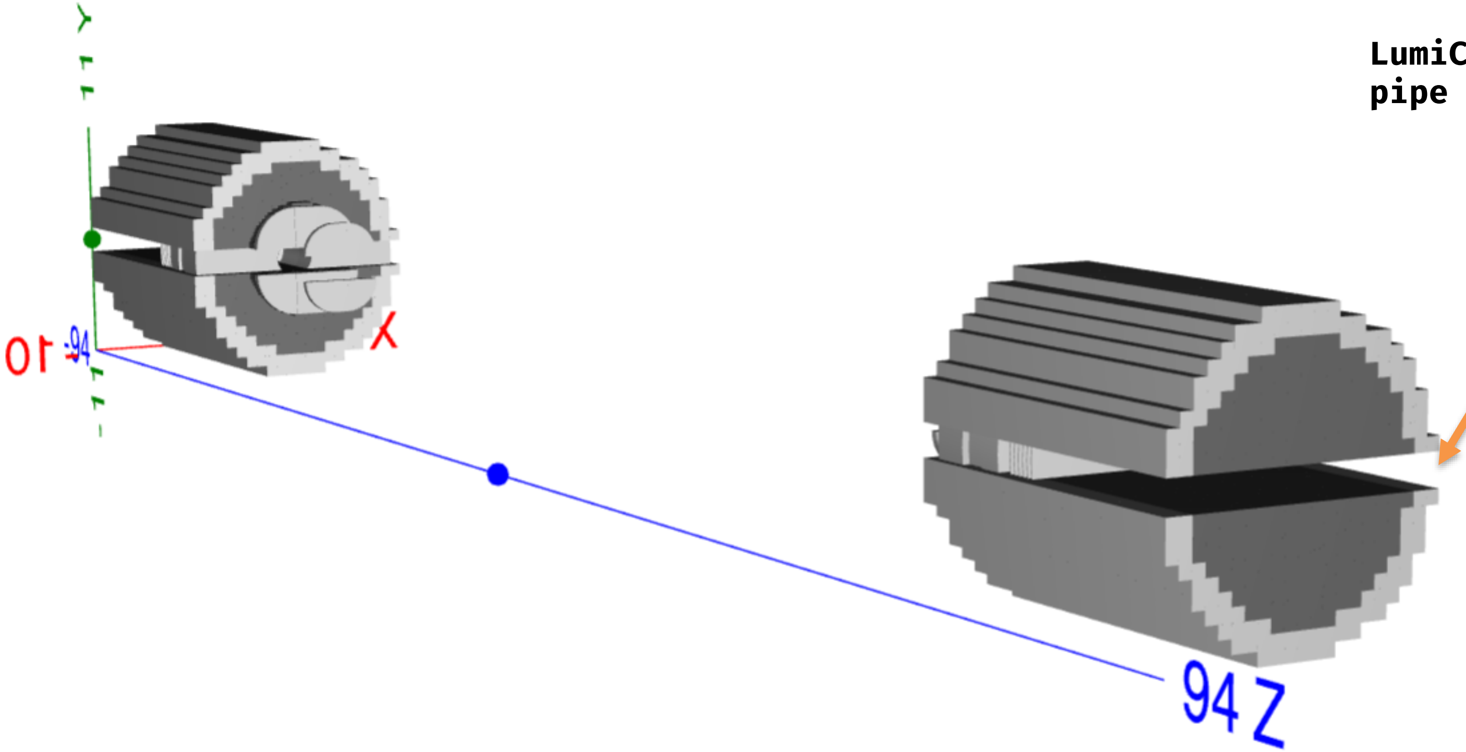
@Higgs



@Low-Lumi-Z



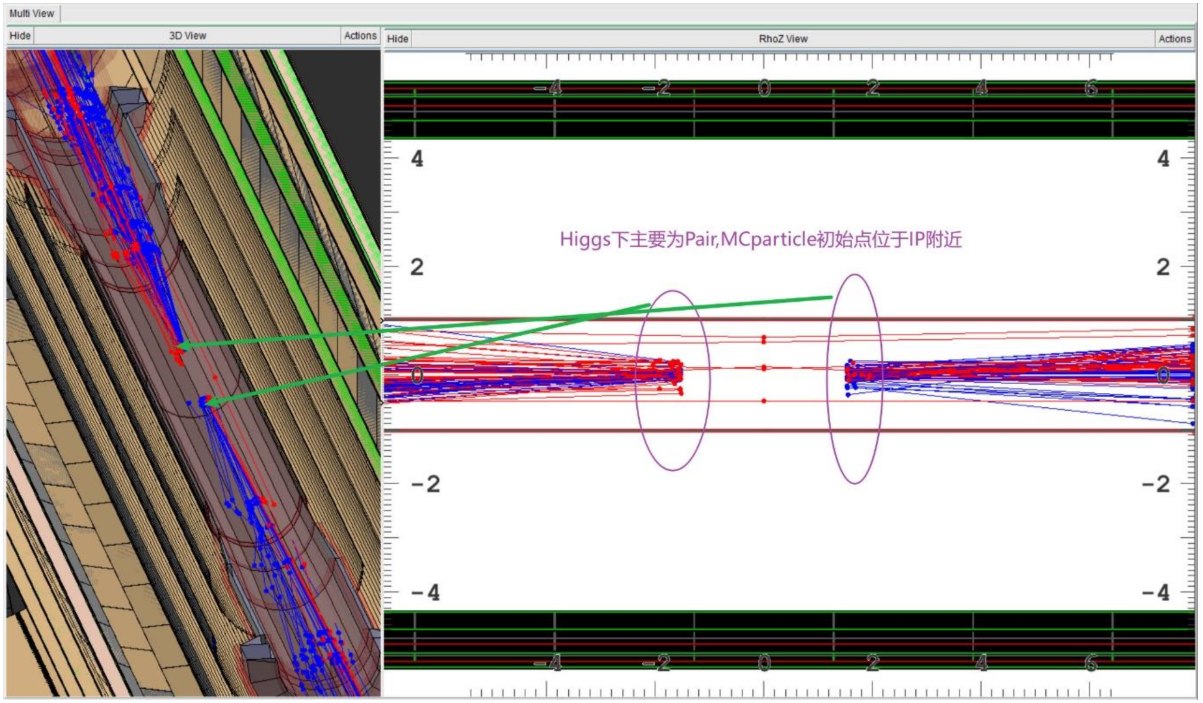
LumiCal geometry

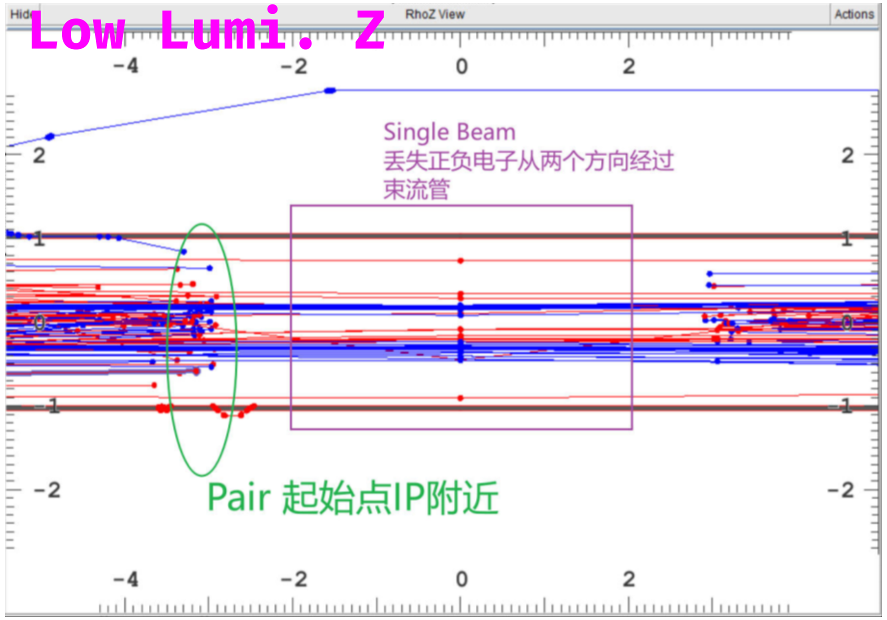


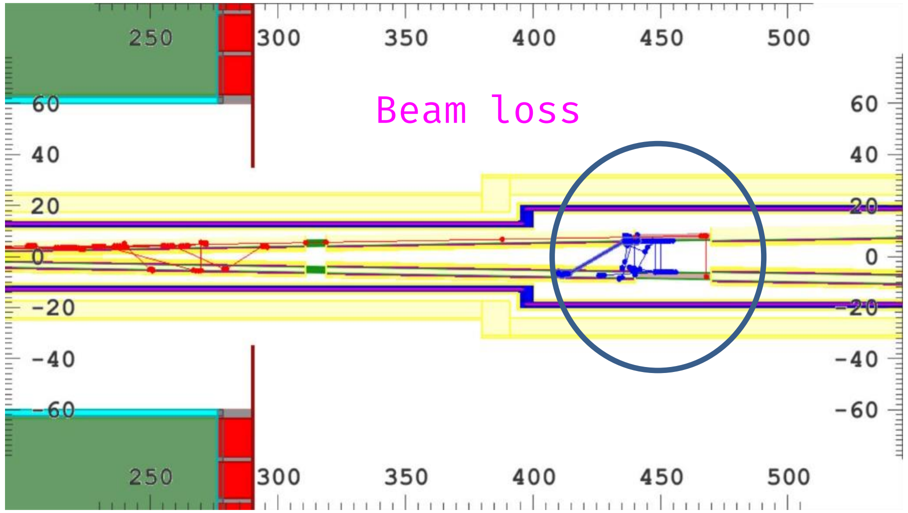
LumiCal didn’t cover the beam-pipe total in Φ direction

Low Lumi. Z / Higgs MCParticle tracks

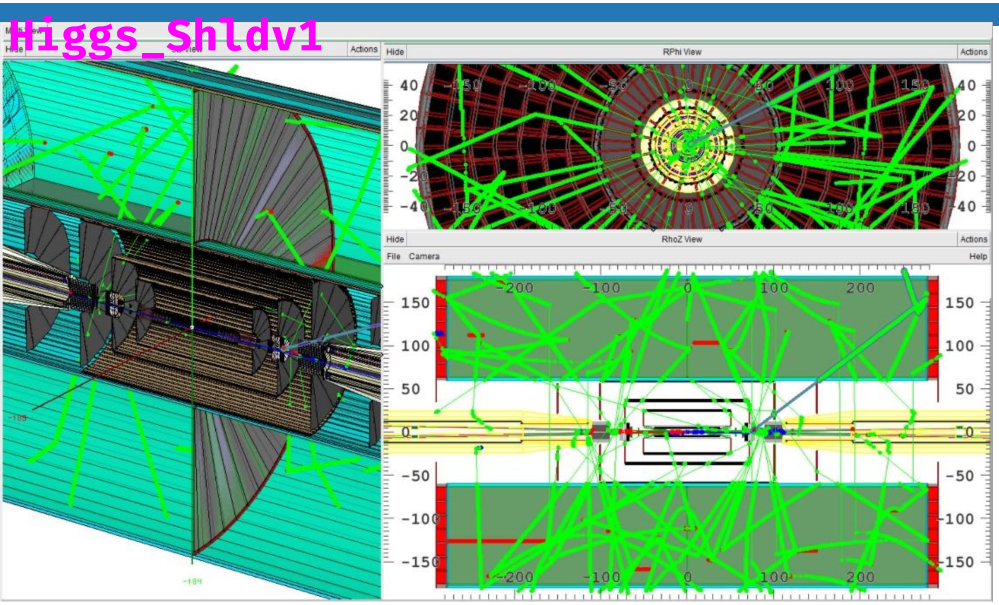
Higgs

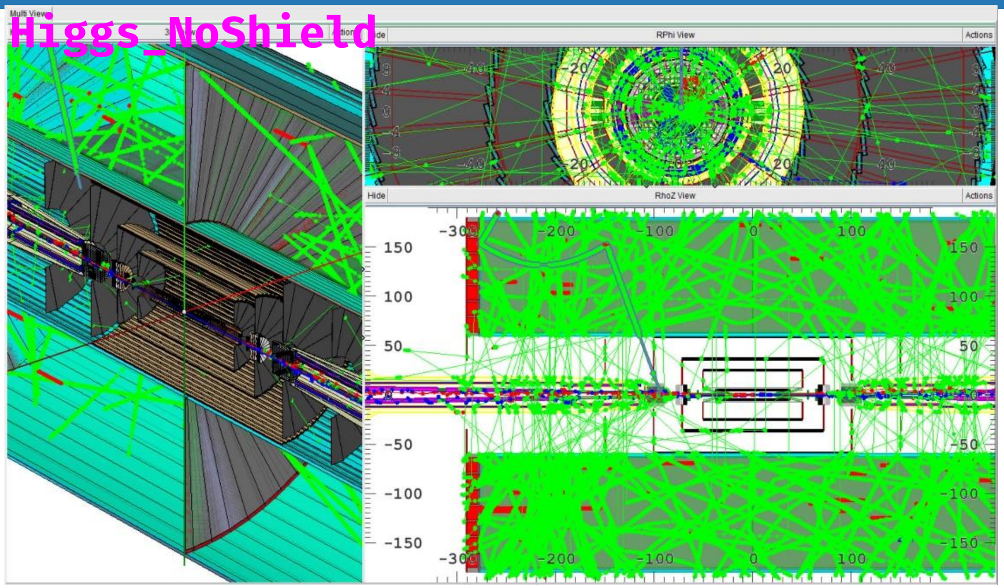


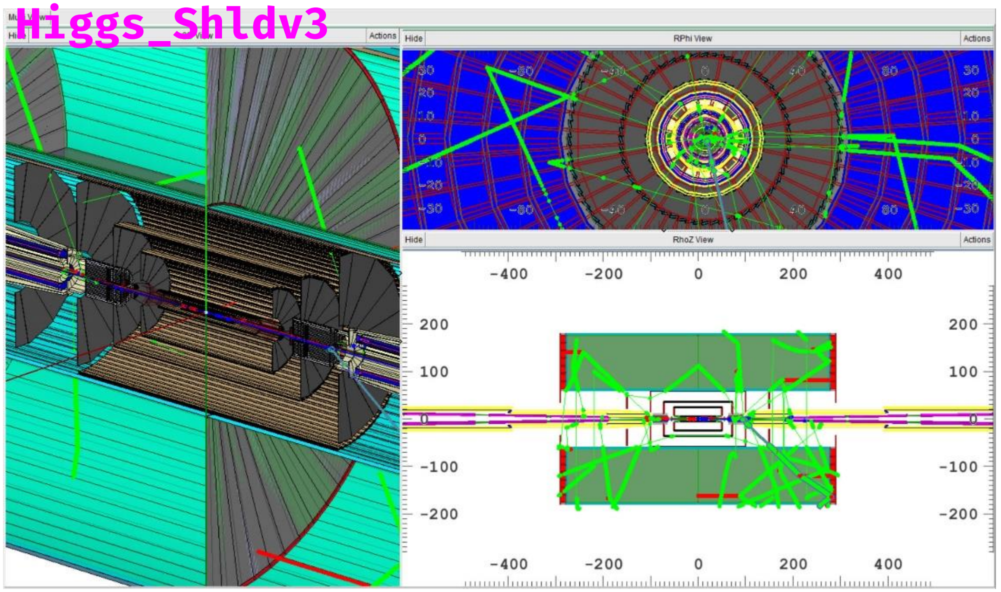


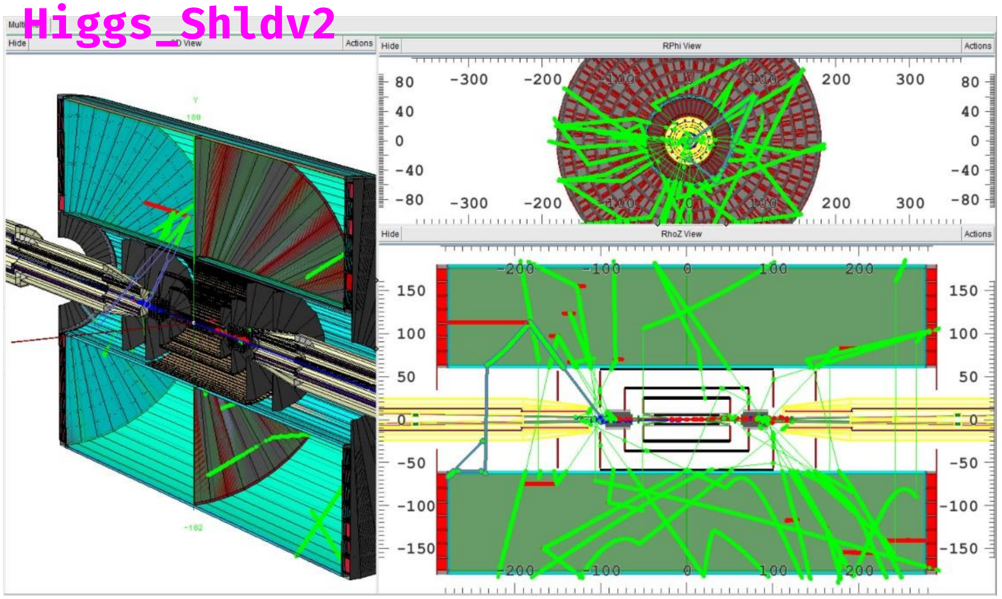


Event Display @Higgs Different Geo models



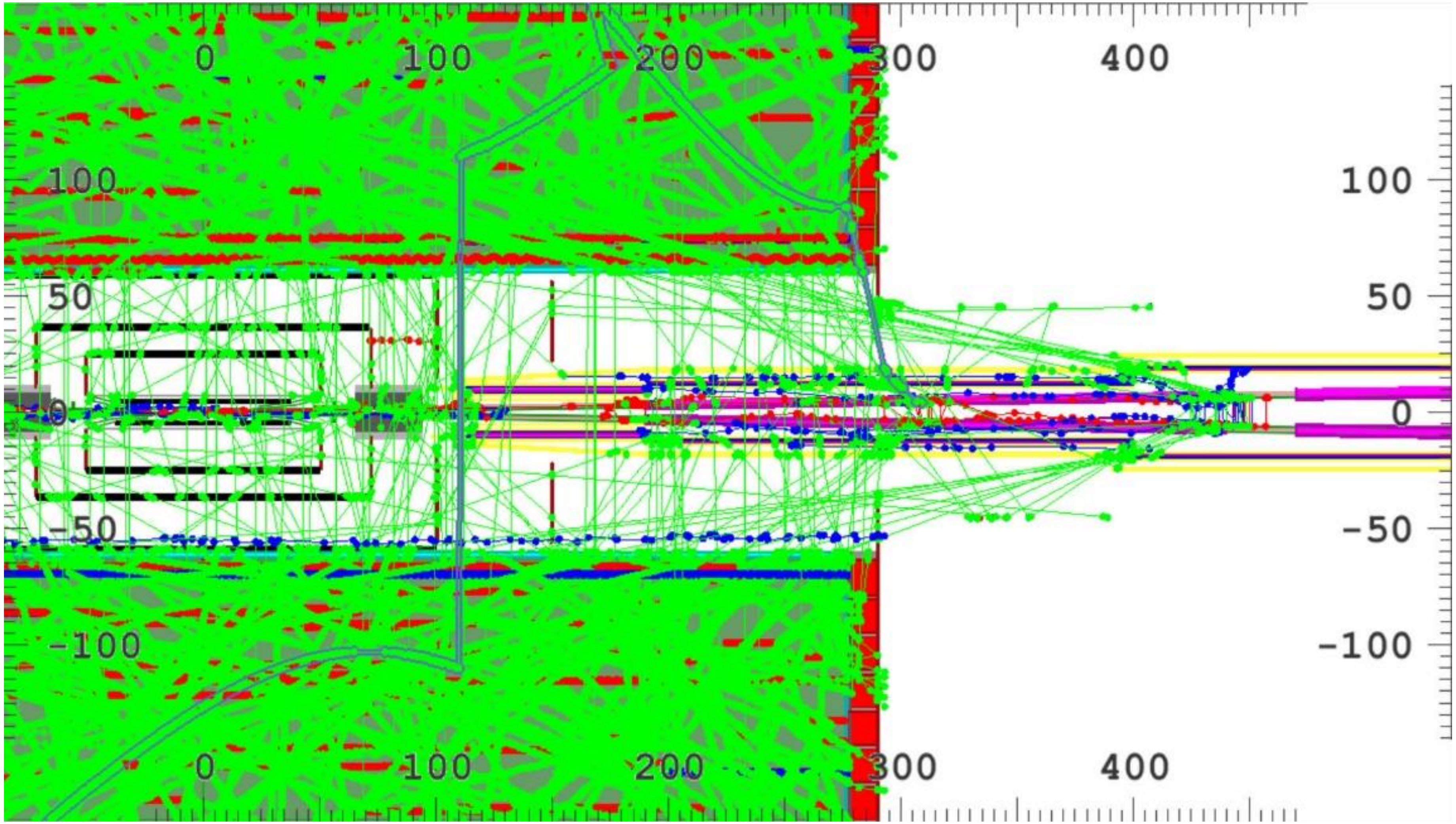






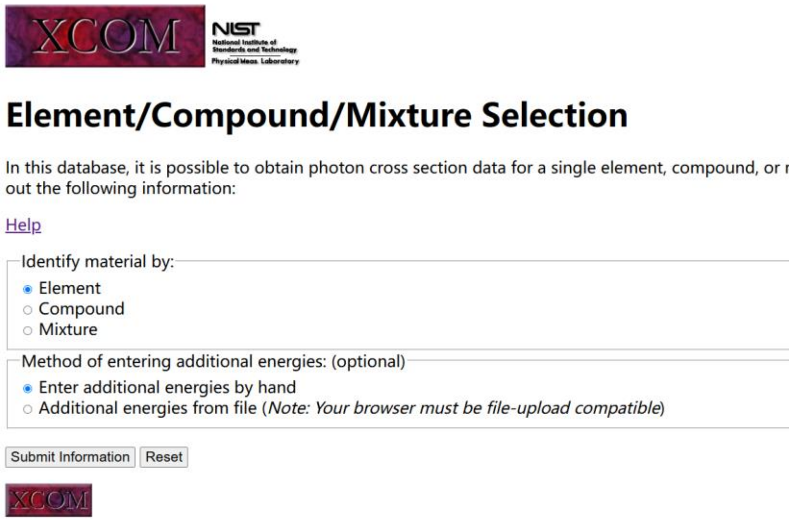
Remark:
2% gamma events of 10 BX data have been plotted

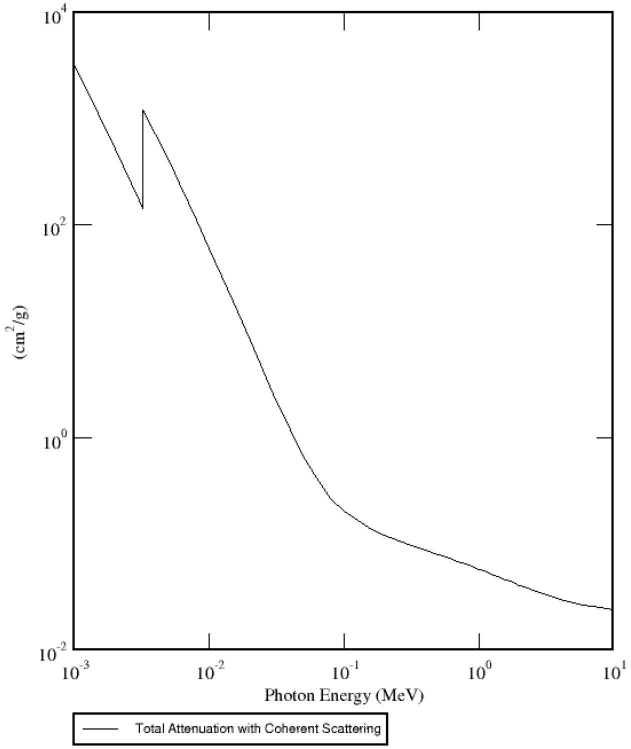
Event Display of Single Beam



Total attenuation coeff. of T2K gas

- Total Attenuation coeff. Of T2K gas (from XCOM)





(required) Photon Energy	Scattering		Photoelectric Absorption	Pair Production		Total Attenuation	
	Coherent	Incoherent		In Nuclear Field	In Electron Field	With Coherent Scattering	Without Coherent Scattering
MeV	cm²/g	cm²/g	cm²/g	cm²/g	cm²/g	cm²/g	cm²/g
4.000E-01	1.374E-03	8.622E-02	7.598E-04	0.000E+00	0.000E+00	8.835E-02	8.698E-02
5.000E-01	8.829E-04	7.884E-02	4.137E-04	0.000E+00	0.000E+00	8.014E-02	7.926E-02
5.110E-01	8.456E-04	7.814E-02	3.908E-04	0.000E+00	0.000E+00	7.937E-02	7.853E-02
6.000E-01	6.145E-04	7.300E-02	2.591E-04	0.000E+00	0.000E+00	7.388E-02	7.326E-02

- For 0.511 MeV γ
  - Photoelectric absorption ~3.908e-4 cm2/g
  - Pair Production 0
  - Incoherent Scattering ~7.814e-2 cm2/g
  - Compton Scattering dominated

- 0.511 MeV γ, Total attenuation coeff. ~7.853e-2 cm2/g
- u=7.853e-2 cm2/g × 1.73e-3 g/cm3 = 1.36e-4 /cm
- For x= 120cm thick T2K gas, I = I0exp(-ux) ~ 0.984I0