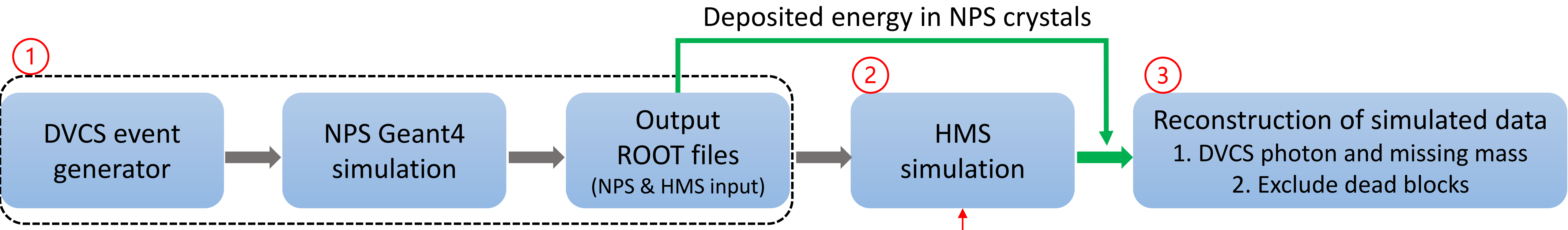
DVCS event simulation for NPS 2023-2024 experiment

Hao Huang, Yaopeng Zhang

NPS collaboration meeting
2025.05.06

Strategy of DVCS event simulation



Generate events and NPS simulation (original setup by Ho San KO)

- Done by the NPS Geant4 package
- Generated variables
  - Vertex position
  - Initial electrons (before vertex)
  - Scattered electrons
  - DVCS real photons
  - Q^2, x_B, t, ϕ
- Reconstructed variables
  - Initial electrons (beam electrons)
  - Deposited energy in NPS crystals (by Geant4)

Input for HMS simulation

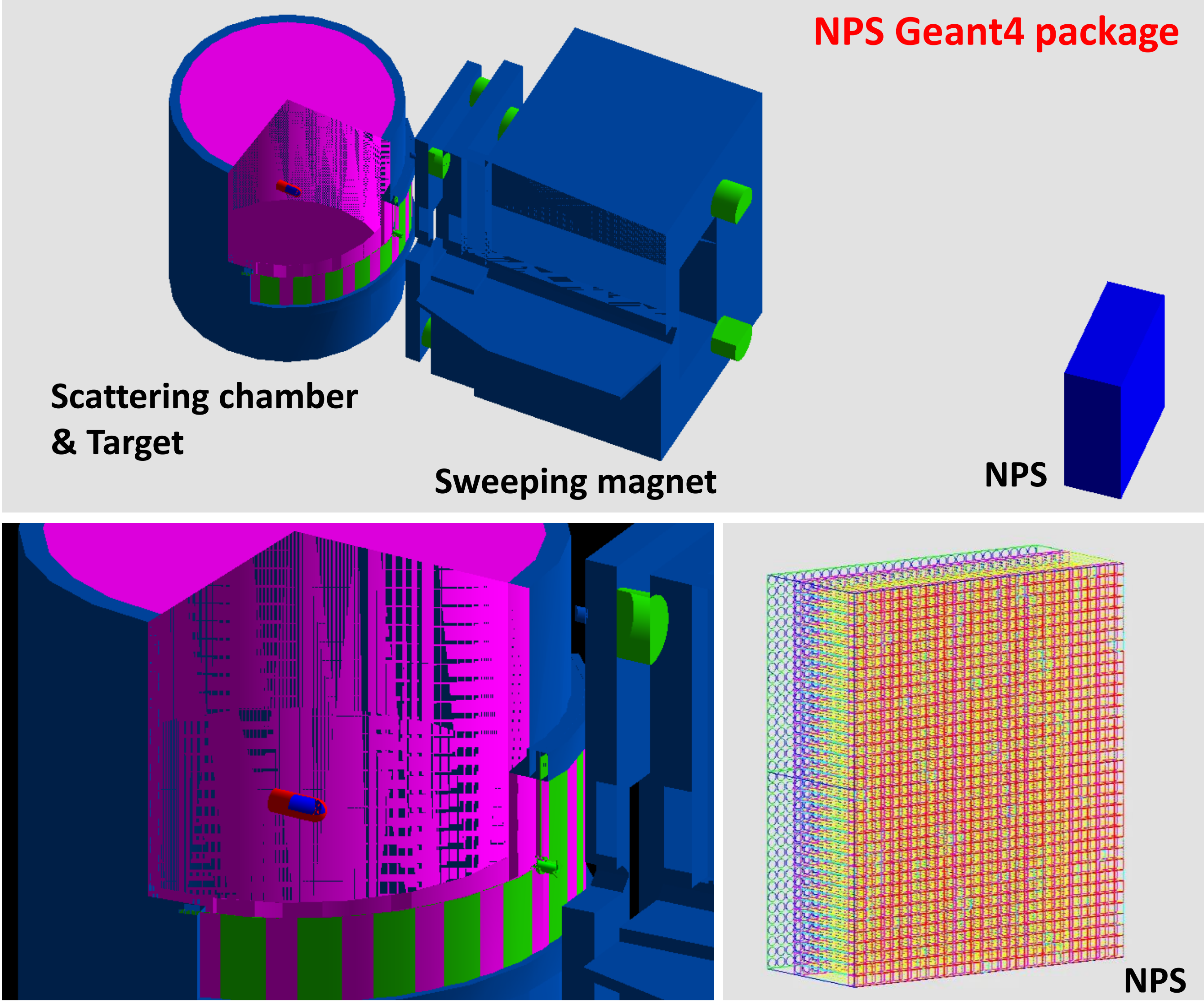
HMS simulation (credit: D. Gaskell, Y. Zhang)

- HMS single arm Monte-Carlo
- Input variables
  - Generated vertices & scattered electrons
  - HMS angle & central momenta
- Output variables
  - HMS focal plane variables for vertex reconstruction
  - Reconstructed scattered electrons

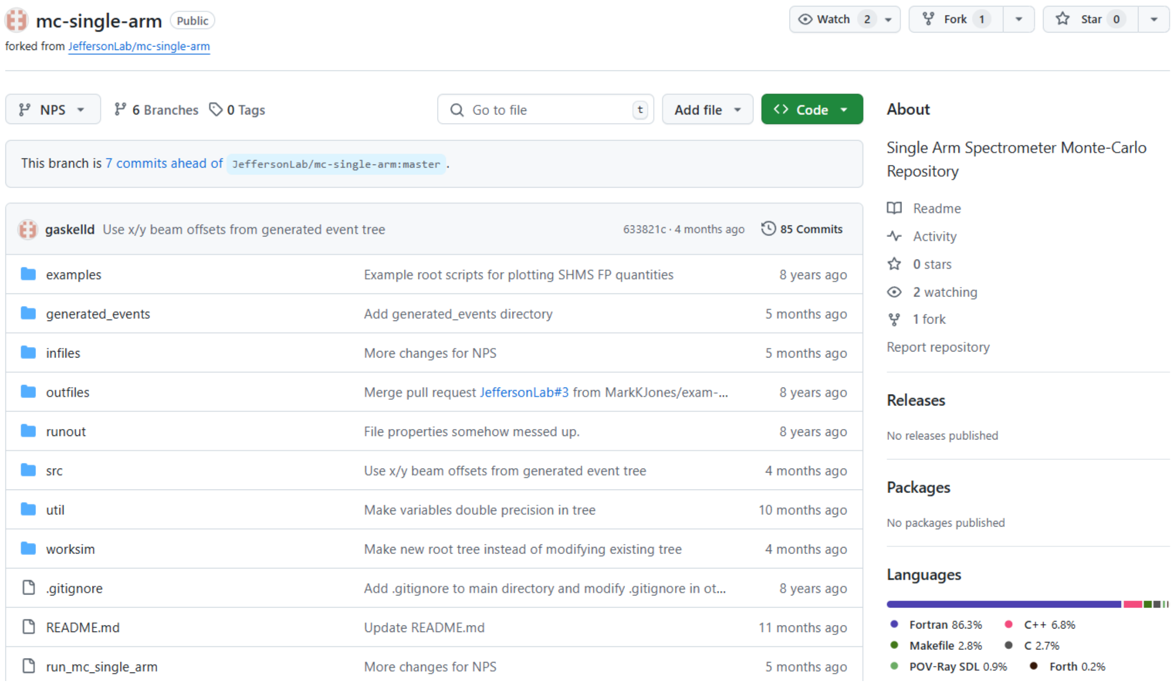
Reconstruction

- Output reconstructed variables
  - NPS Cluster information
  - DVCS real photons
  - Q^2, x_B, t, ϕ

Simulation packages



HMS single arm Monte-Carlo package



Finalized kinematic list

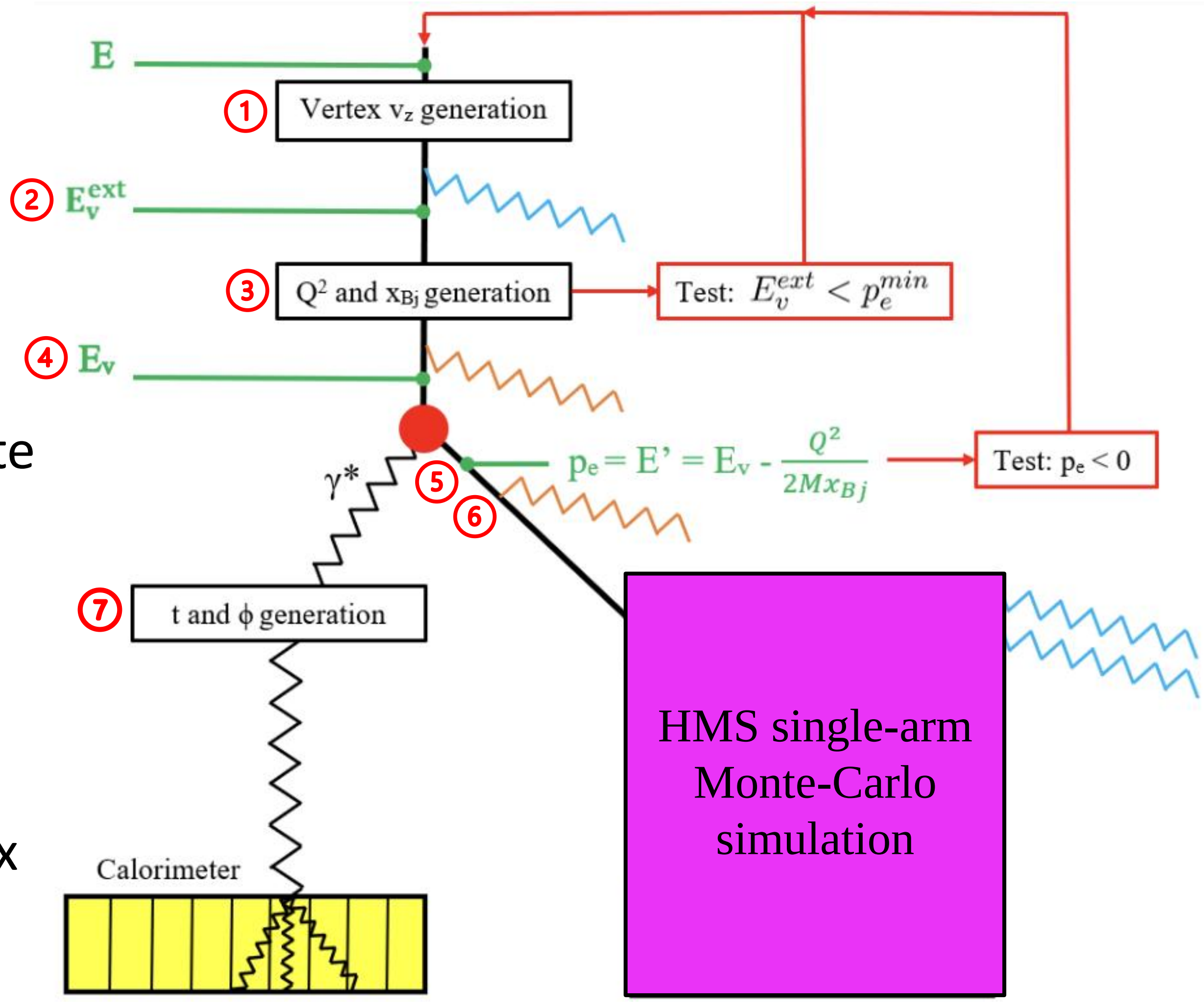
Incredible work from Yaopeng

- Corrected all the angles with the screenshots in hclog
- Most updated version "Kin_list_2.xlsx" in https://hallcweb.jlab.org/elogs/NPS-RG1a-Analysis/61
- Update angles are labeled yellow
- SHMS angles may have a big difference: split the kinematics (e.g., x25_4 → x25_4_1, x25_4_2)
- Number of kinematics: 33 → 53

KinC name old	KinC name new	Simulation name	begin of run	end of run	SHMS angle	E	HMS P	HMS angle	NPS angle	calo distance	HMS_pol
KinC_x25_1	x24_q21_p3	KinC_x25_1_1	5903	5975	25.616	6.372	1.734	25.13	9.316	357	-1
		KinC_x25_1_2	6733	6740	27.790	6.37	1.734	25.13	11.490	357	-1
KinC_x25_3	x26_q30_p4	KinC_x25_3	6570	6697	26.405	8.453	2.131	23.7	10.105	357	-1
KinC_x25_4	x26_q31_p5	KinC_x25_4_1	4966	5182	27.495	10.538	4.149	15.2	11.195	407	-1
		KinC_x25_4_2	6940	6953	28.000	10.538	4.149	15.2	11.700	357	-1
KinC_x36_1	x36_q30_p3	KinC_x36_1	5977	6142	27.795	6.37	1.956	28.34	11.495	357	-1
			6724	6732	27.790	6.37	1.956	28.34	11.490	357	-1
			6770	6827	27.805	6.37	1.956	28.345	11.505	357	-1
KinC_x36_2	x36_q30_p4	KinC_x36_2_1	3013	3062	30.665	8.457	4.042	17.015	14.365	307	-1
		KinC_x36_2_2	6874	6880	30.665	8.455	4.042	17.01	14.365	357	-1
KinC_x36_2p	x36_q30_p4	KinC_x36_2p	2973	3012	28.775	8.458	4.042	17.015	12.475	307	-1
			3106	3113	28.769	8.456	4.042	17.01	12.469	307	-1

Event generator workflow

1. Generate the vertex position (uniformly along z with beam offset and raster)
2. Apply the external radiation correction before vertex ($E \longrightarrow E_v^{ext}$)
3. Generate Q^2 and x_B uniformly (within $[Q^2_{min}, Q^2_{max}]$ and $[x_B^{min}, x_B^{max}]$)
4. Apply the internal radiative corrections before verte ($E_v^{ext} \longrightarrow E_v$)
5. Calculate the corresponding p_e and $\cos\theta_e$ of scattered electrons using Q^2, x_B and E_v
   - $p_e = Ev - \frac{Q^2}{2MxB}, \cos\theta_e = 1 - \frac{Q^2}{2peEv}$
6. Apply the internal radiative corrections after vertex
7. Generated t and ϕ uniformly for the real photons
   - $\phi \in [\,0, 2\pi\,]$; $t \in [\,-2, t_{min}(Q^2, x_B)\,]$



Simulation output variables

- TTree: MC_dvcs
- Branches (G: generated, R: reconstructed)
  - RIE_px (py, pz): momenta of initial beam electron
  - GIE_px (py, pz): momenta of initial beam electron momenta after external radiation correction
  - GV_x (y, z): vertex position
  - GSE_px (py, pz): momenta of scattered election after internal radiation correction
  - GQ2, GxB, Gt, Gphi: phase space variables
  - hms_stop_id: 0 if passed HMS simulation, > 0 when stopped in HMS

  hms_stop_id == 0 to look at reconstructed variables below

  - RV_z: Reconstructed vertex z position
  - hsxfp (yfp, xpfp, ypfp): HMS focal plane variables
  - hsxptar (ytar, yptar), hsdelta: HMS target variables and δp

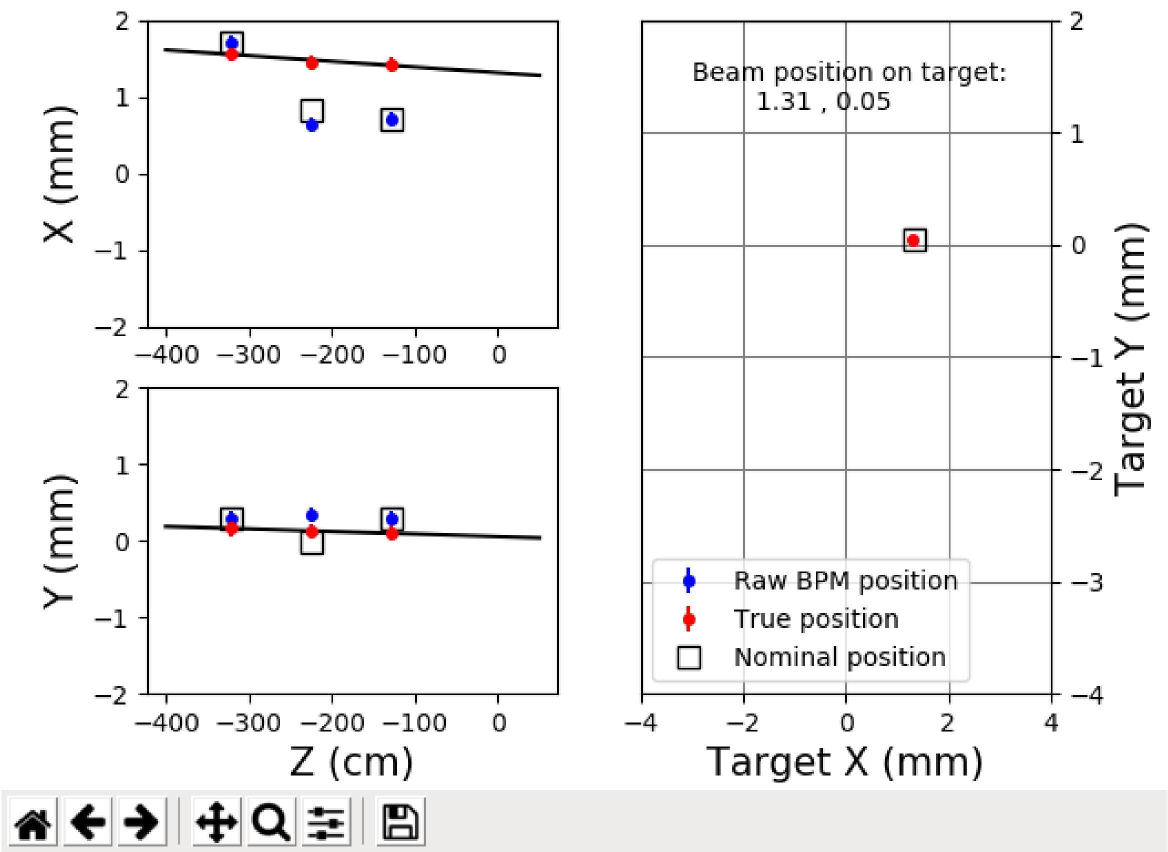
  hms_stop_id == 0 && cluster_ene > 0 to look at reconstructed NPS variables below

  - clust_ene, clust_x, clust_y, clust_size: cluster energy, position, size
  - RPh_px (py, pz): momenta of reconstructed photons
  - Mx2: Reconstructed missing mass square
  - RQ2, RxB, Rt, Rphi: phase space variables

Beam configuration for vertex generation

- Beam offsets (-1.31 mm, 0.05 mm): based on https://logbooks.jlab.org/entry/4254868
- Raster simulation: randomly generate uniform vertex (x, y) in 2x2 mm^2

Beam position on target after BPM calibration in 2024



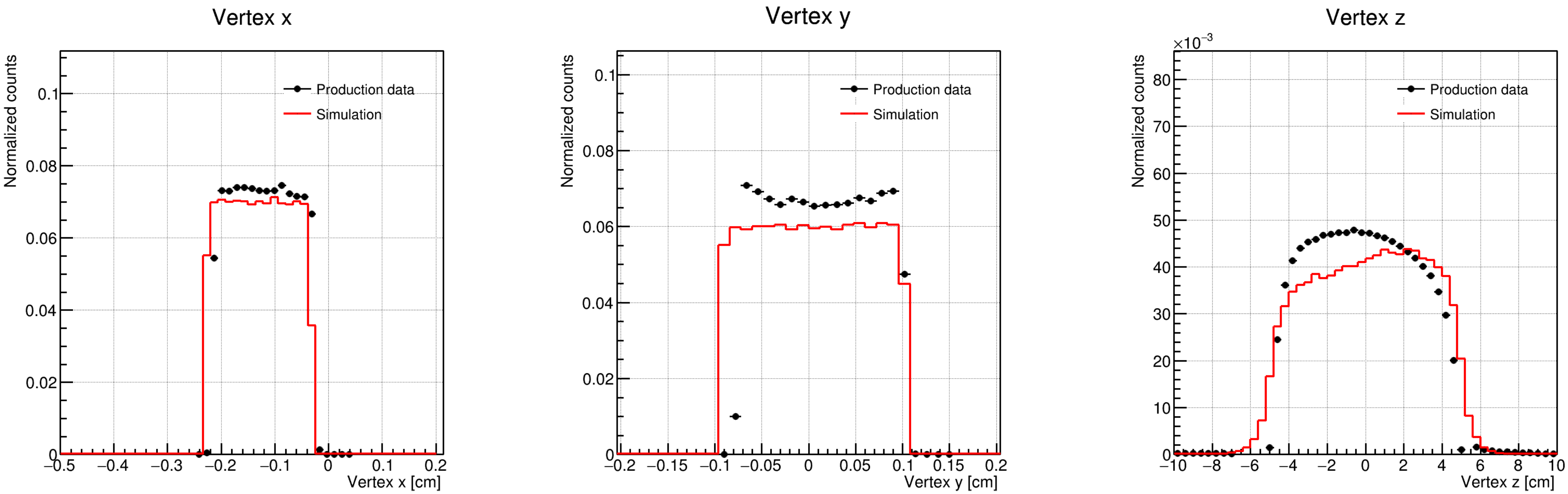
Comparison of vertex distributions

- Vertex distributions, simulation vs. production data (LD2)
- Nice results after including beam offsets and raster
- Discrepancies at the edge due to the property of raster
- Dummy subtracted for vertex z distribution

Simulation and real data
Reconstructed vs. production

$$vertex\ z = \frac{y_{tar} + y_{offset} - vertex\ x \cdot (cos\theta_{HMS} + y'_{tar} \cdot sin\theta_{HMS})}{sin\theta_{HMS} - y'_{tar} \cdot cos\theta_{HMS}}$$

set as 0



Scattered electrons in event generator

- Set up HMS angular acceptance based on the geometry of large collimator in the slit box

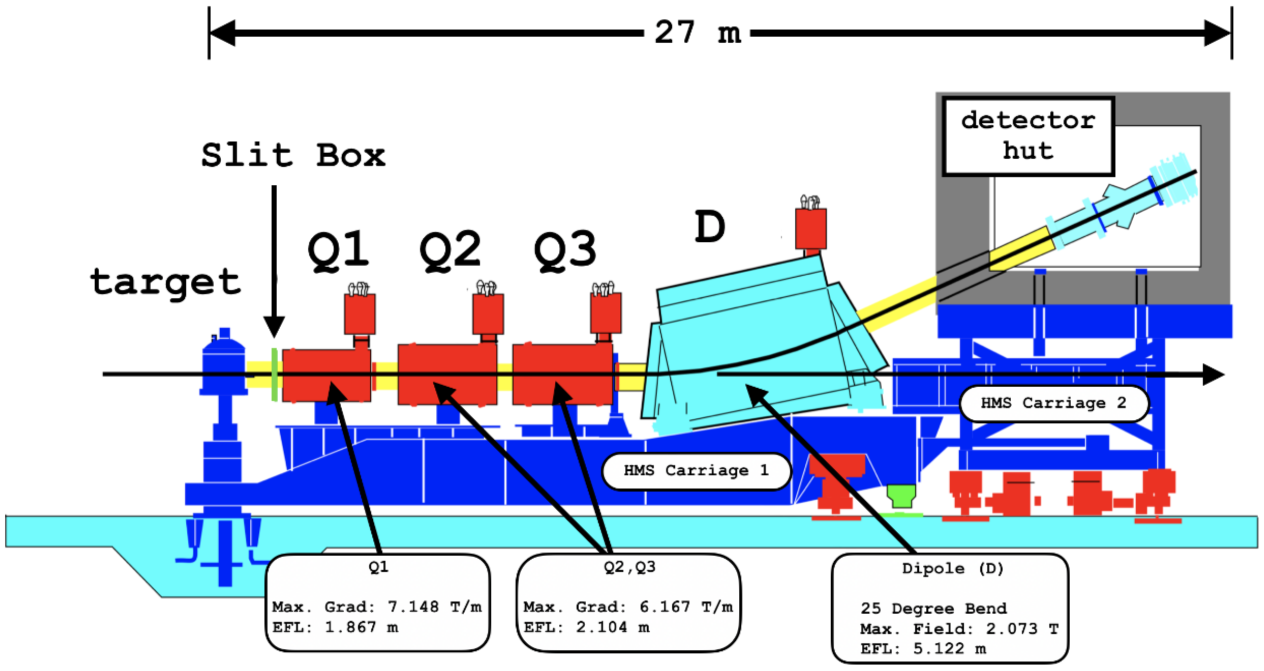
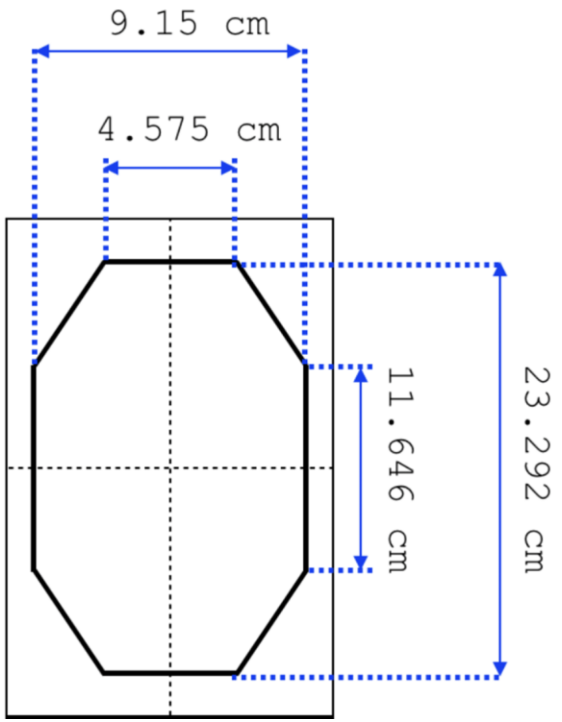


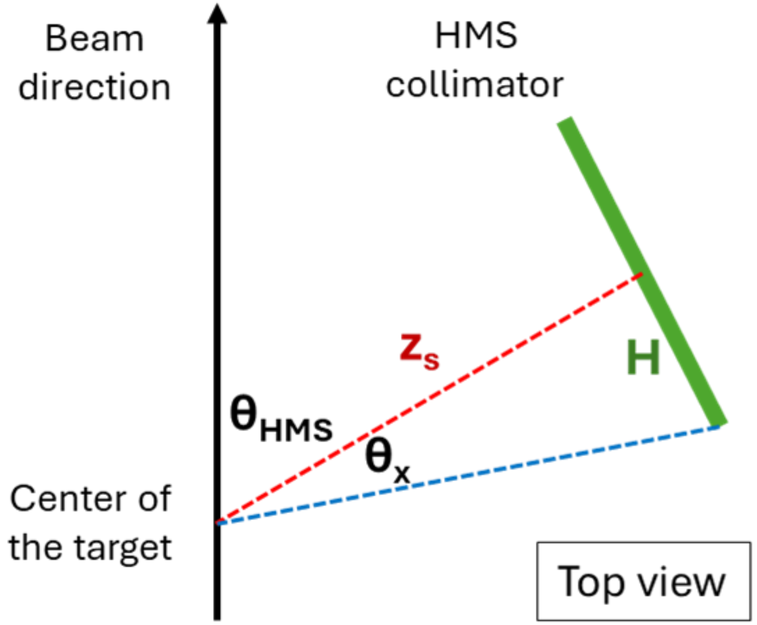
Figure 3.20: High Momentum Spectrometer (HMS) side view.

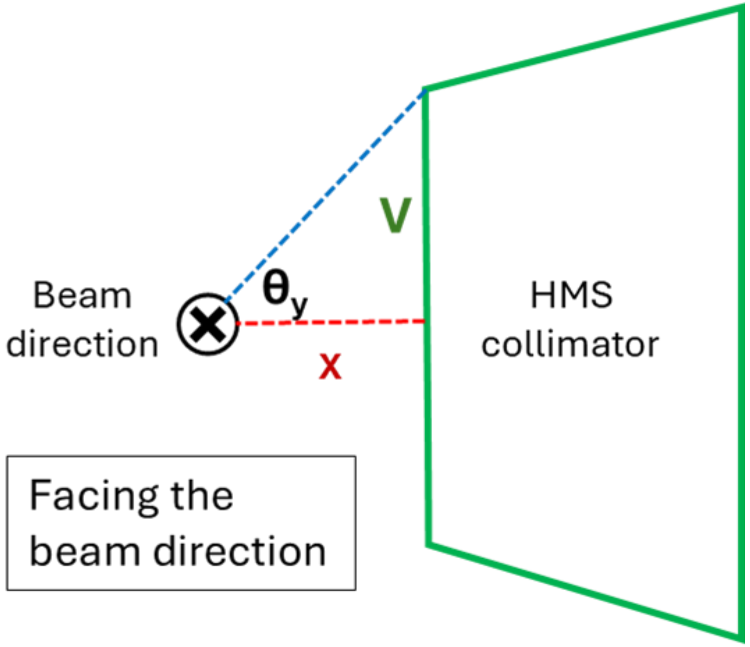
- **Large collimator**
  - **Entrance geometry**
    - 166.37 cm to the center of target
  - **Exit geometry**
    - (166.37+6.3) cm to the center of target
    - replace 4.575 with **4.759** and 11.646 with **12.114**



Scattered electrons (HMS acceptance)

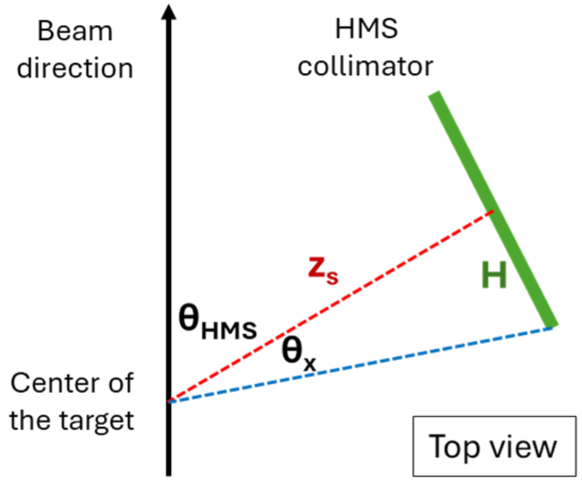
- Physical parameters based on collimator geometry
  - $H = 1.1 \times 4.759$ (cm): horizontal acceptance of HMS entrance
  - $V = 1.1 \times 12.114$ (cm): vertical acceptance of HMS entrance
  - $z_s = 166.37$ (cm): target center to collimator entrance
  - $X = -z_s \sin\theta_{HMS} + H \cos\theta_{HMS}$: distance from the beam line to the edge of collimator
- Calculate the angular acceptance θ_x and θ_y based on these parameters

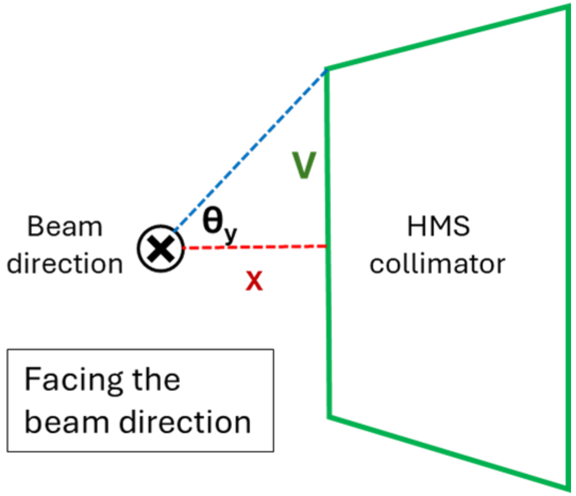




Scattered electrons (angular acceptance)

- Horizontal: $[\theta_e^{min}, \theta_e^{max}] = [\theta_{HMS} - \theta_x, \theta_{HMS} + \theta_x]$
  - $\theta_x = \mathrm{Tan}^{-1}(2H/z_s)$



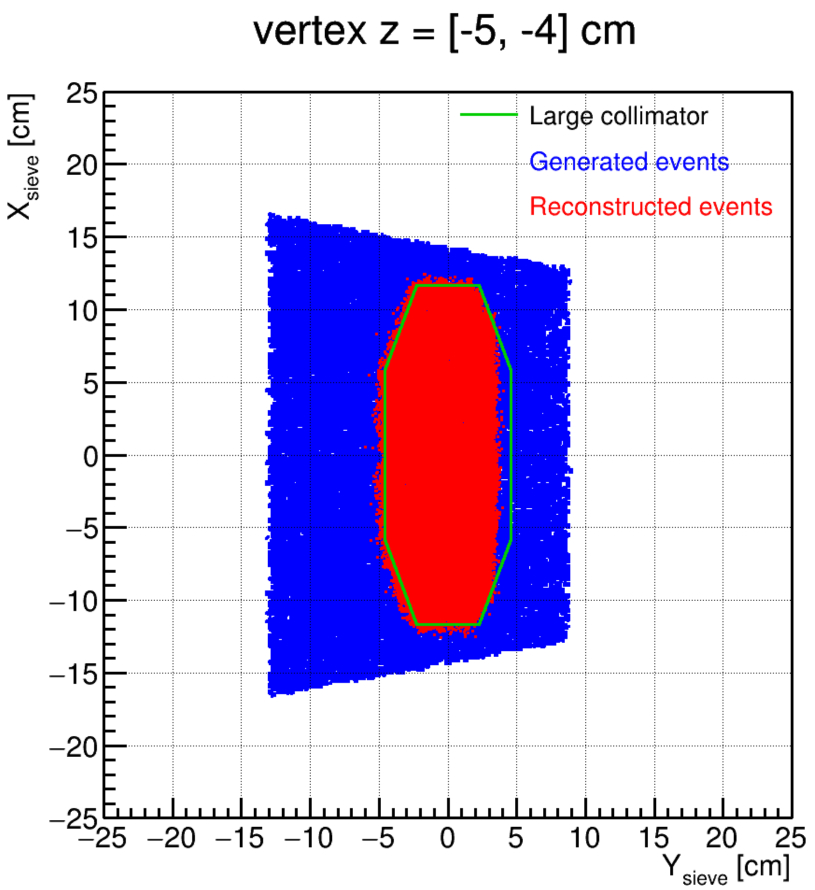


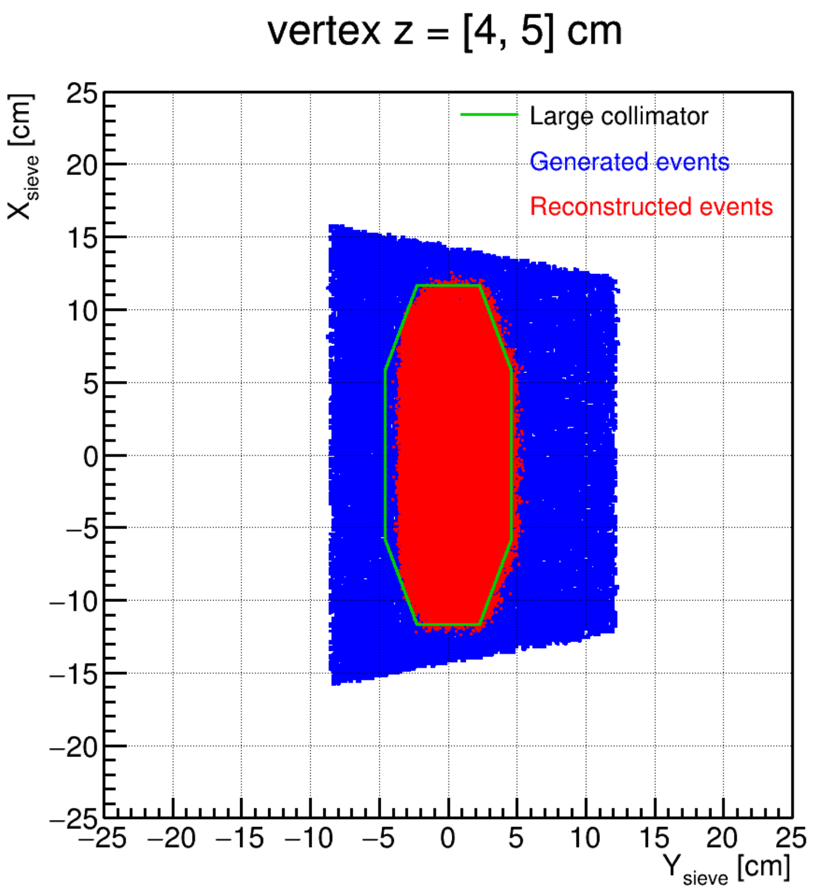
- Vertical: $[\phi_e^{min}, \phi_e^{max}] = [\pi - \theta_y, \pi + \theta_y]$
  - $\phi_e^{min} = \mathrm{Tan}^{-1}(V/X)$
  - $\phi_e^{max} = 2\pi + \mathrm{Tan}^{-1}(-V/X)$
- Momentum acceptance
  - $[p^{min}, p^{max}] = [p_{HMS} \times (1 - 15\%), p_{HMS} \times (1 + 40\%)]$
- The limits above are used to set the range of Q^2 and x_B
  - $Q^2_{min} = 2p_e^{min} E_v^{ext} (1 - \cos\theta_e^{min})$; $Q^2_{max} = 2p_e^{max} E_v^{ext} (1 - \cos\theta_e^{max})$
  - $x_B^{min} = \max\{ 0.05, \frac{Q^2_{min}}{2M(E_v^{ext} - p_e^{min})} \}$; $x_B^{max} = \min\{ \frac{Q^2_{max}}{2M(E_v^{ext} - p_e^{max})}, 0.95 \}$

Scattered electrons on the collimator plane

- Projection of scattered electrons to collimator plane
- Reconstructed electrons matched to the acceptance

Simulation
Generated vs. reconstructed

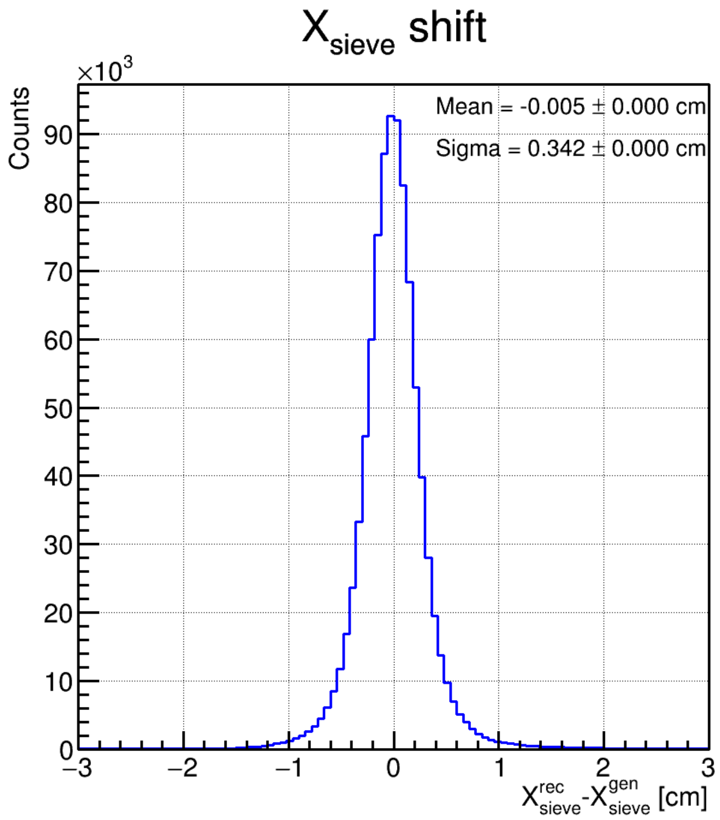


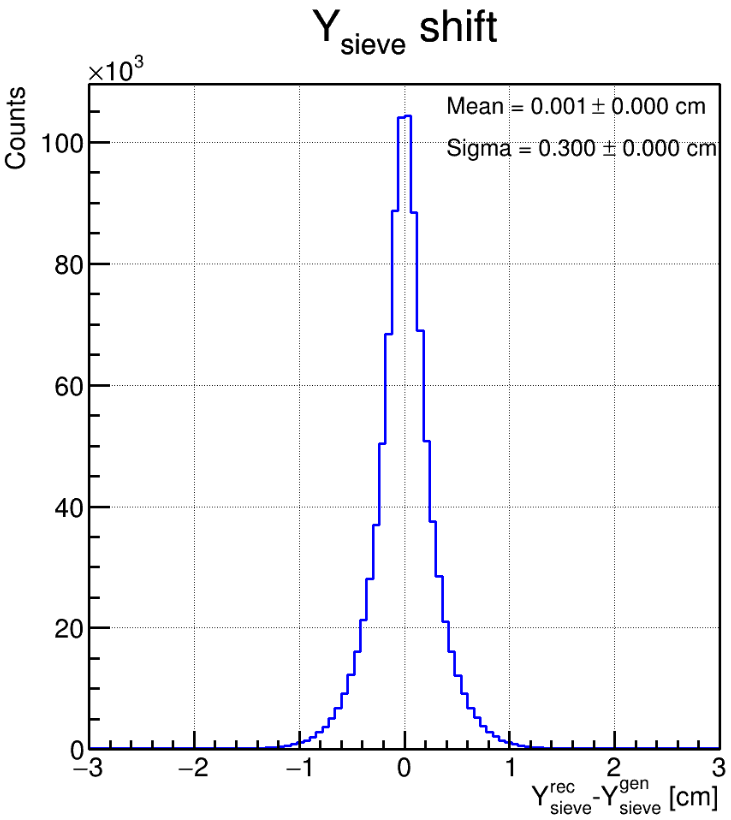


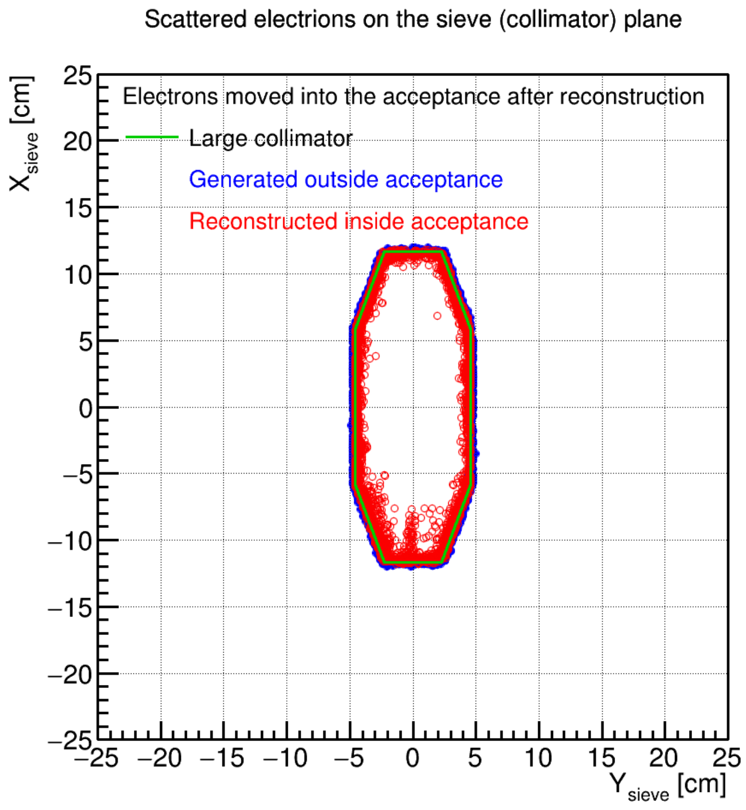
Scattered electrons on the collimator plane

- ➢Further investigation: Do electrons shift a lot after reconstruction?
- ➢Shift on collimator plane: less than 1 cm
- ➢Shifted electrons (reconstructed) only found close to the edge of physical acceptance

Simulation
Generated vs. reconstructed



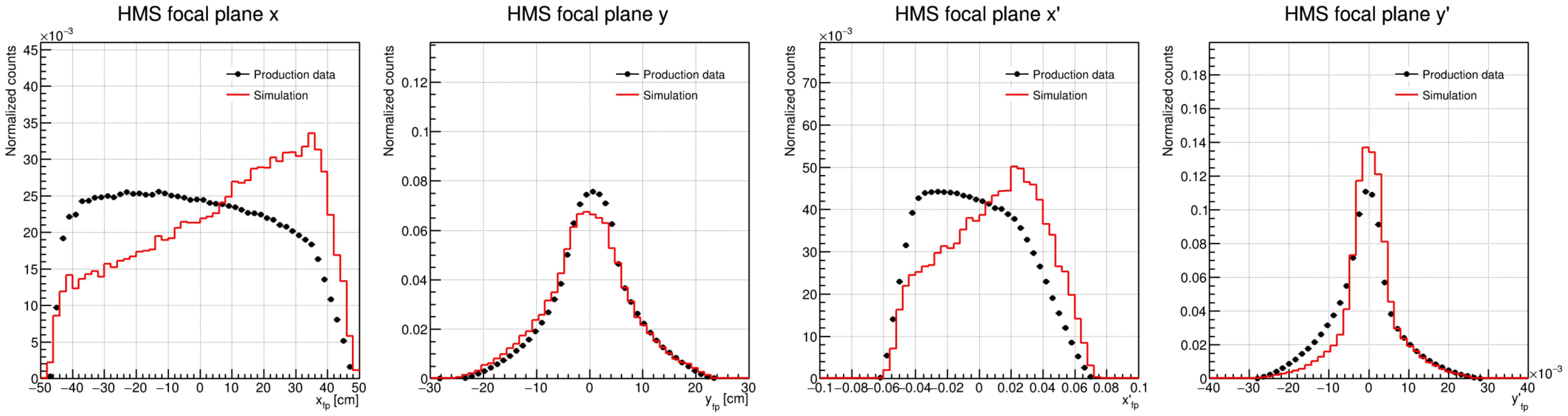




HMS focal plane variables

- ➢Discrepancies: no cross section in the simulation
- ➢Working on applying a weight from DIS cross section

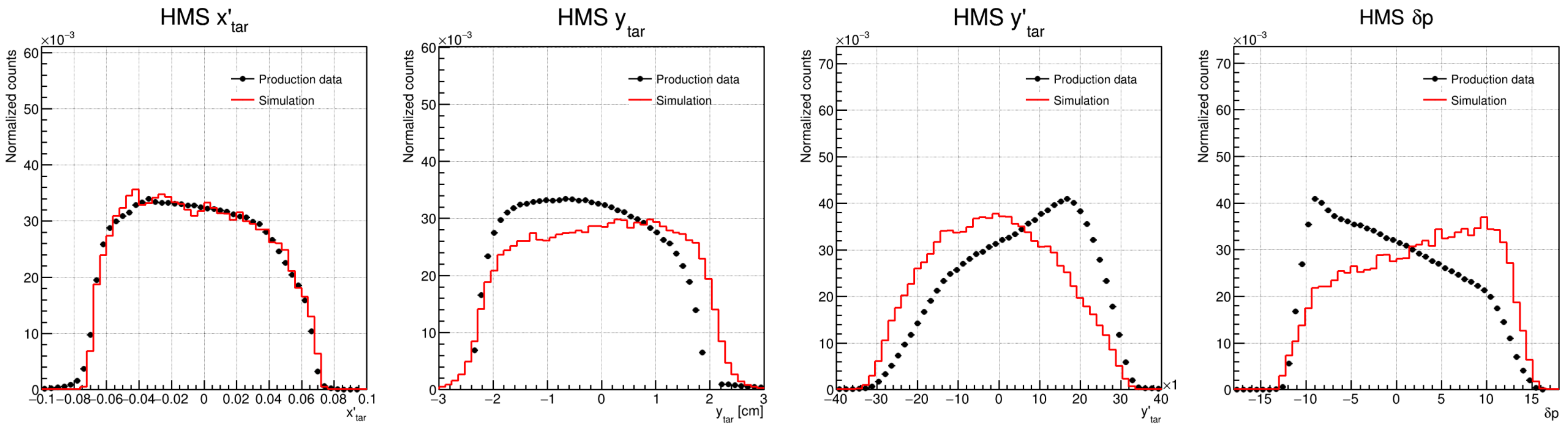
Simulation and real data
Reconstructed vs. production



HMS target variables

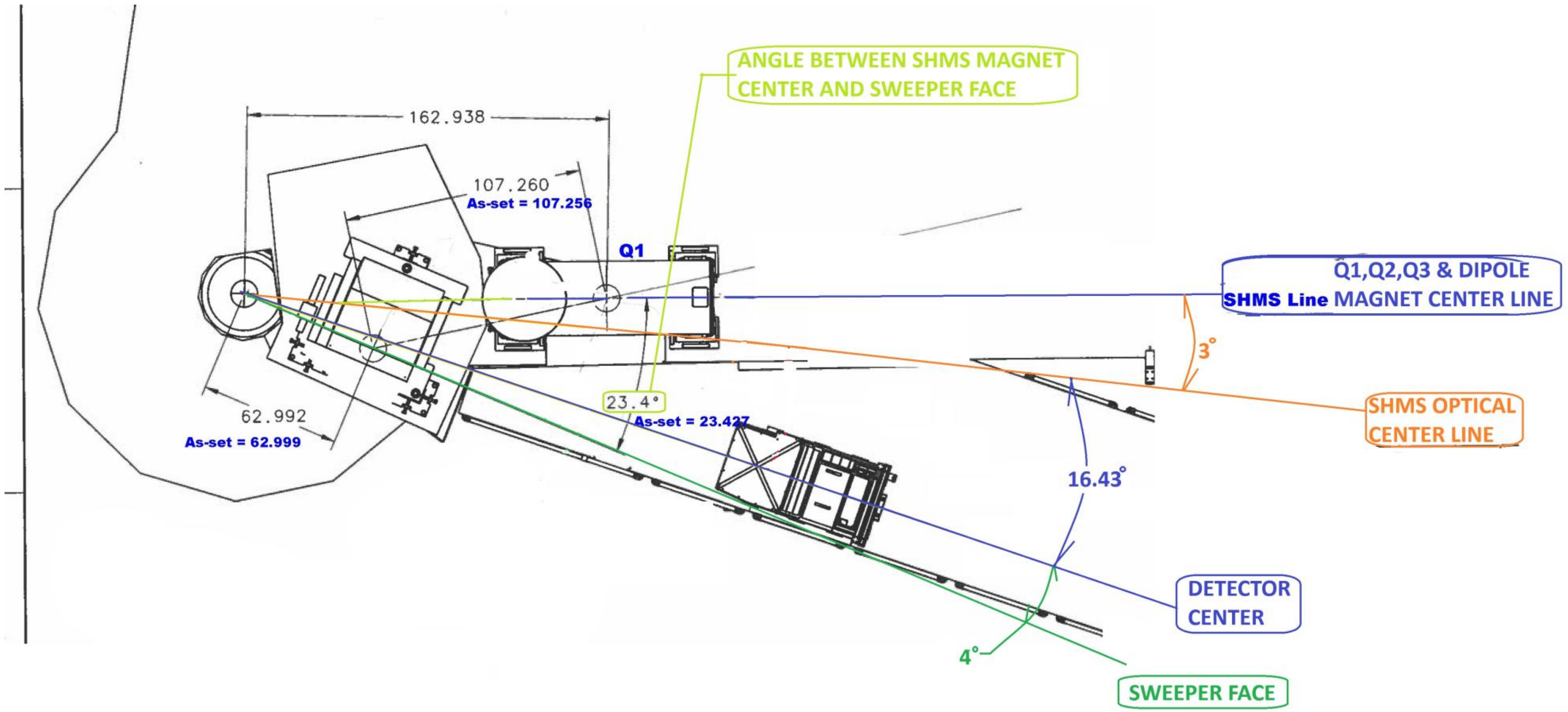
- Discrepancies: no cross section in the simulation
- Working on applying a weight from DIS cross section

Simulation and real data
Reconstructed vs. production



NPS acceptance: cluster x and y

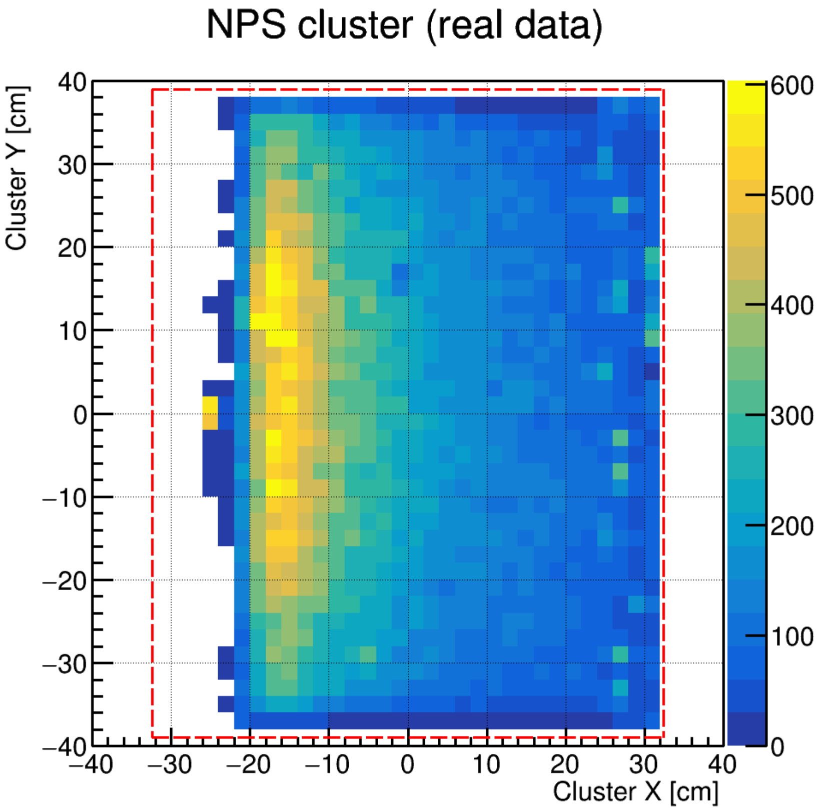
- Cluster energy > 2 GeV to reduce background
- Sweeping magnet: 4 degrees relative to NPS
- 4 kinematics with different NPS distance to check the shadow of the magnet

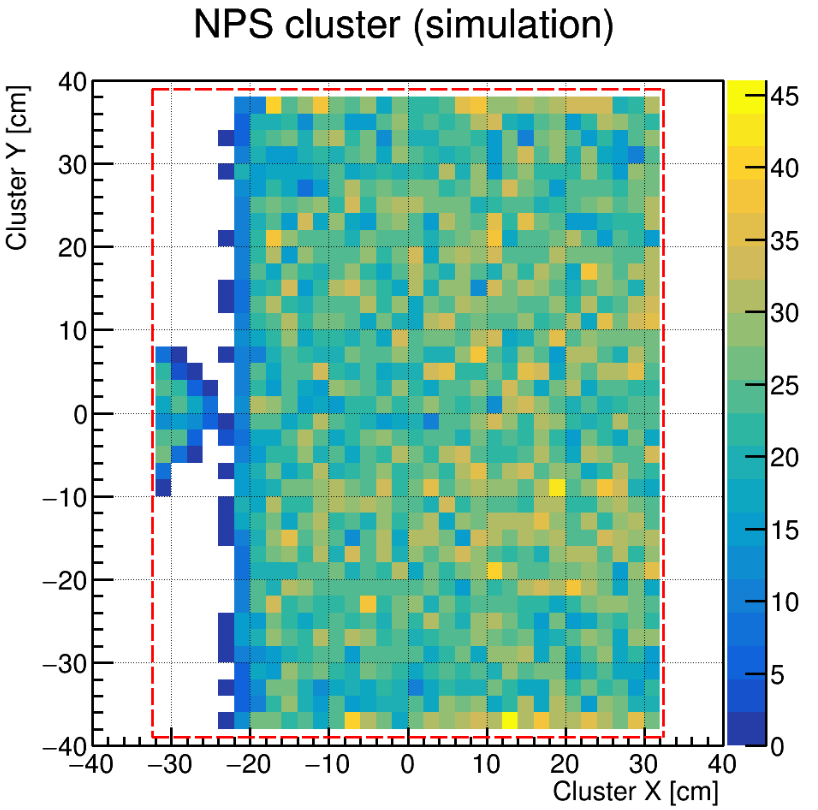


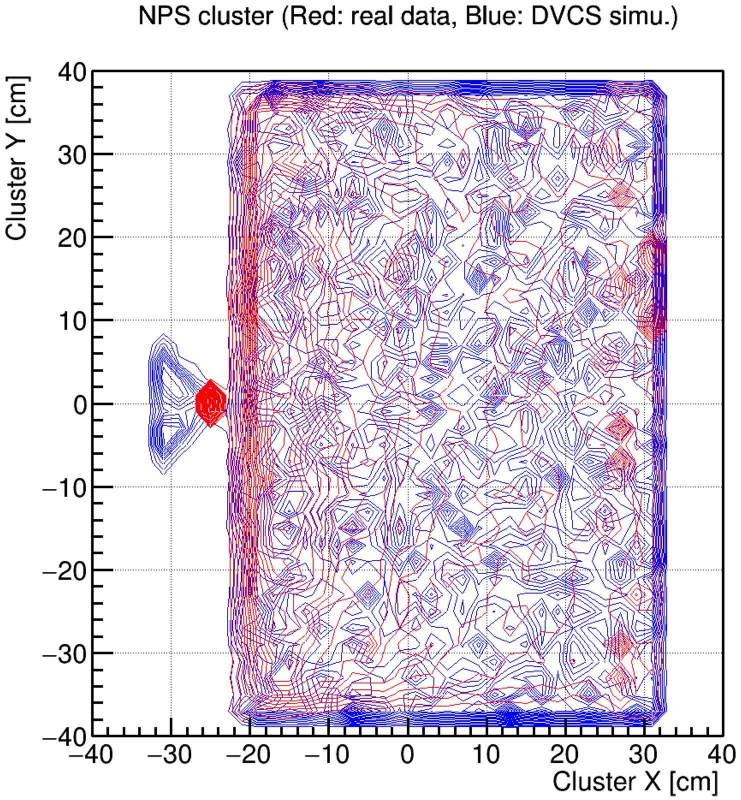
NPS at 3 meters (x50_0_1)

Simulation and real data
Reconstructed vs. production

- ➢ Shadow of the magnet matched very well
- ➢ Additional clusters around x = -30 cm in simulation will be cut out
  - photons went through the two wings of the magnet



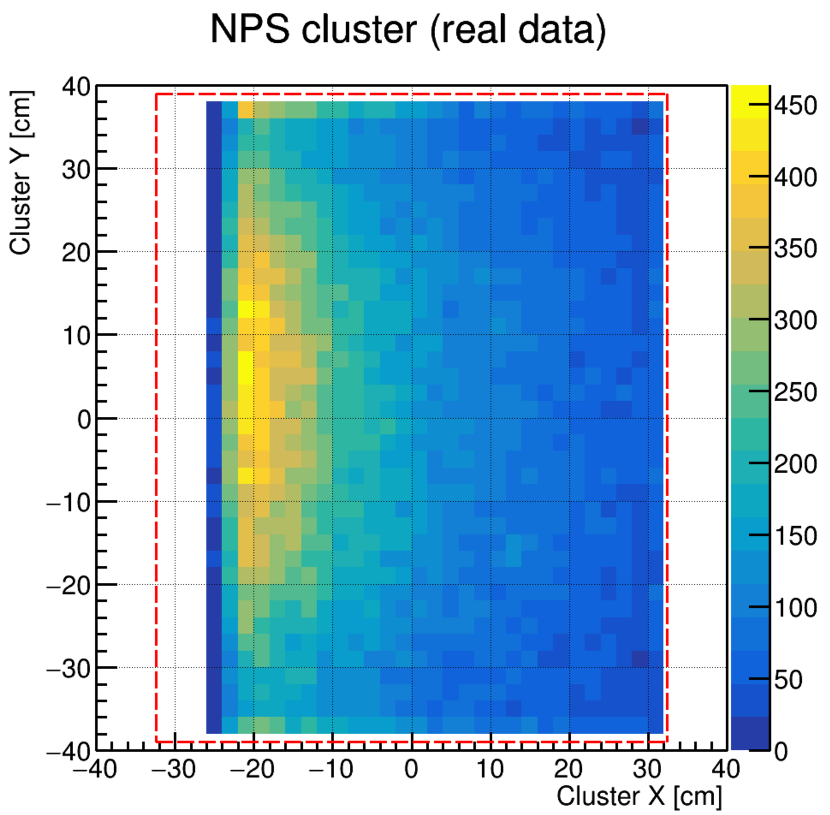


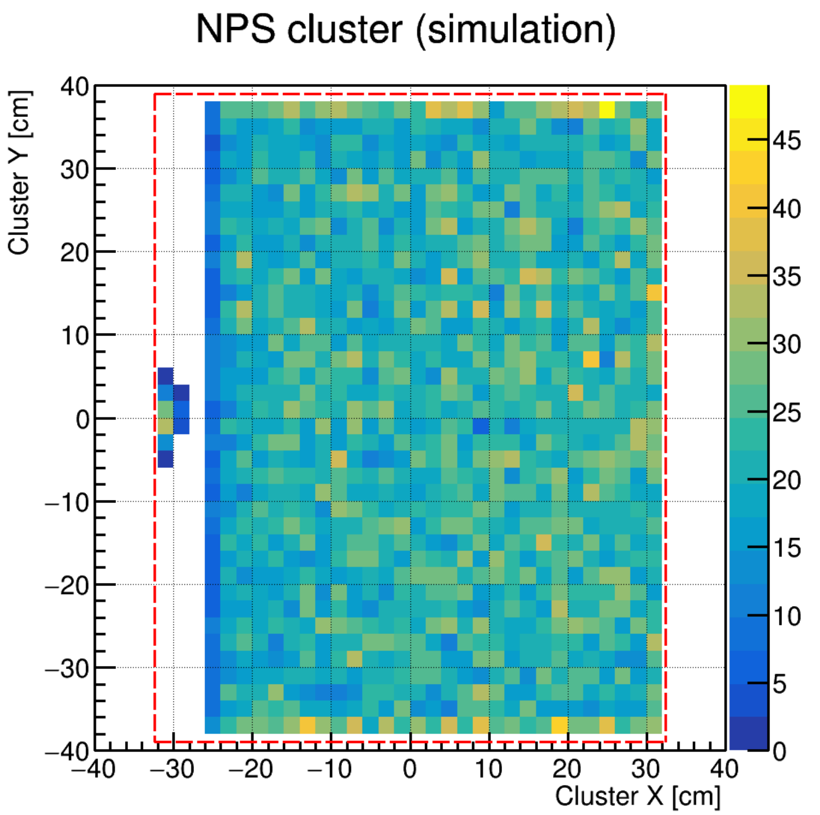


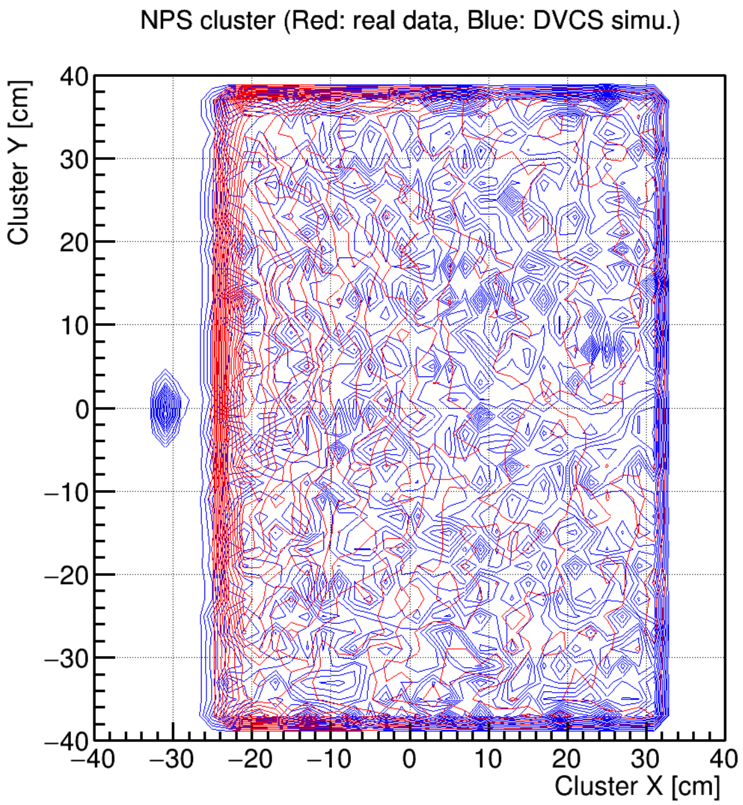
NPS at 3.5 meters (x36_4)

- ➢Shadow of the magnet matched very well
- ➢Additional clusters around x = -30 cm in simulation will be cut out
  - photons went through the two wings of the magnet

Simulation and real data
Reconstructed vs. production



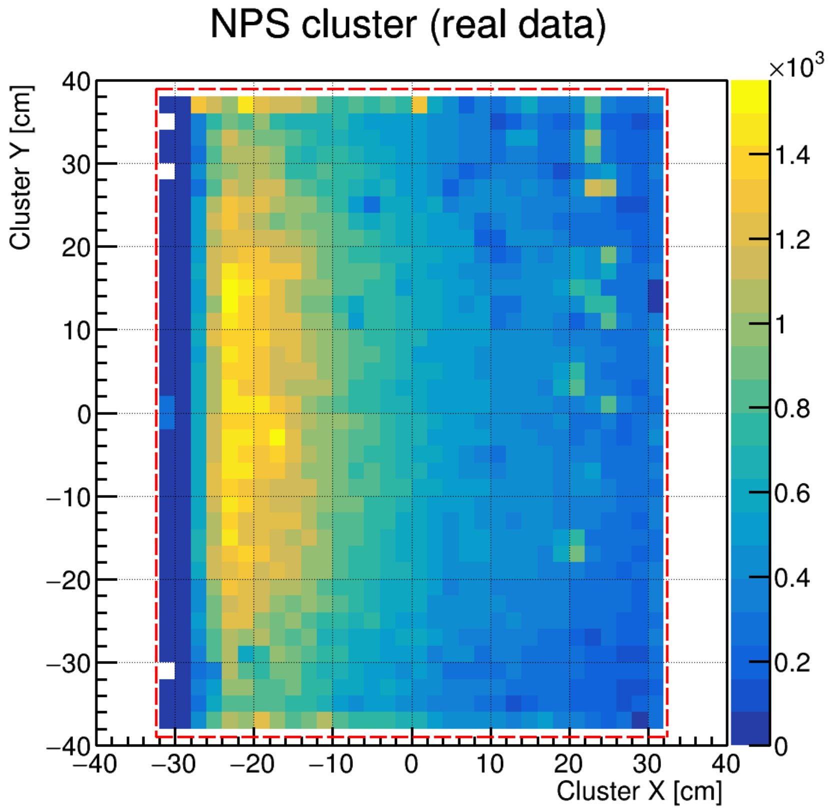


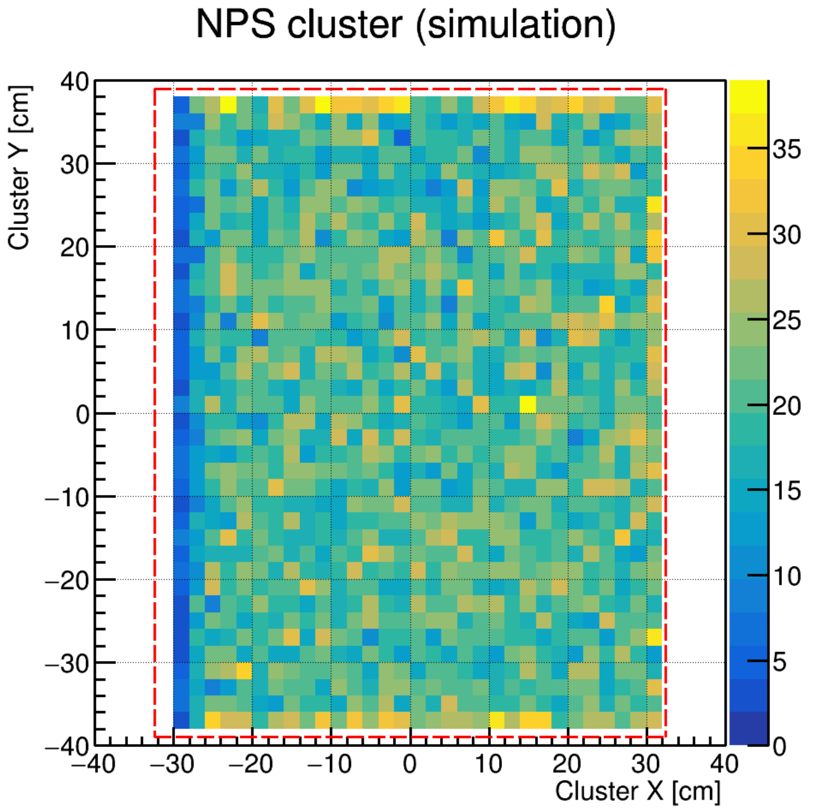


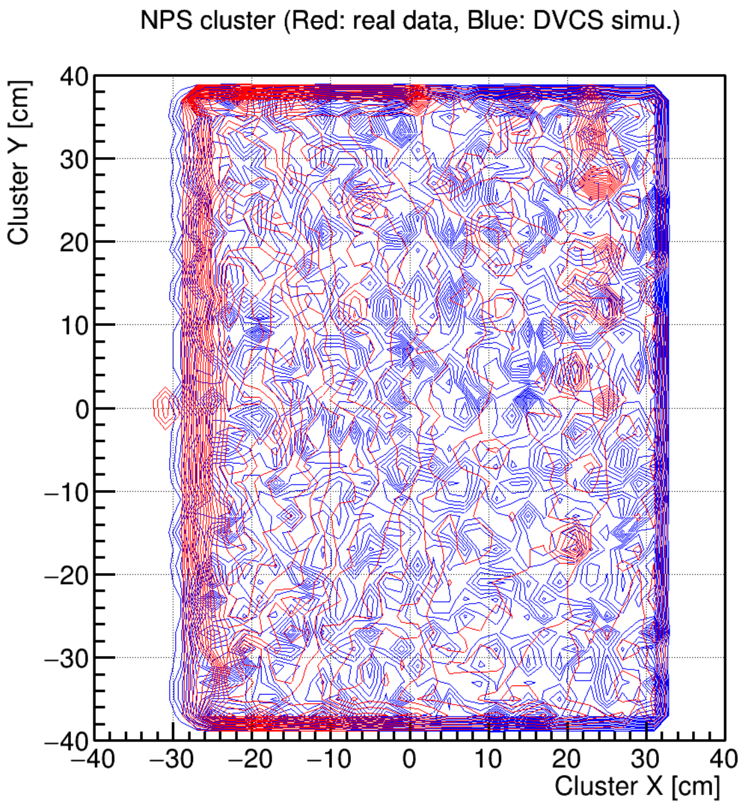
NPS at 4 meters (x25_0_1)

➢Shadow of the magnet matched very well

Simulation and real data
Reconstructed vs. production



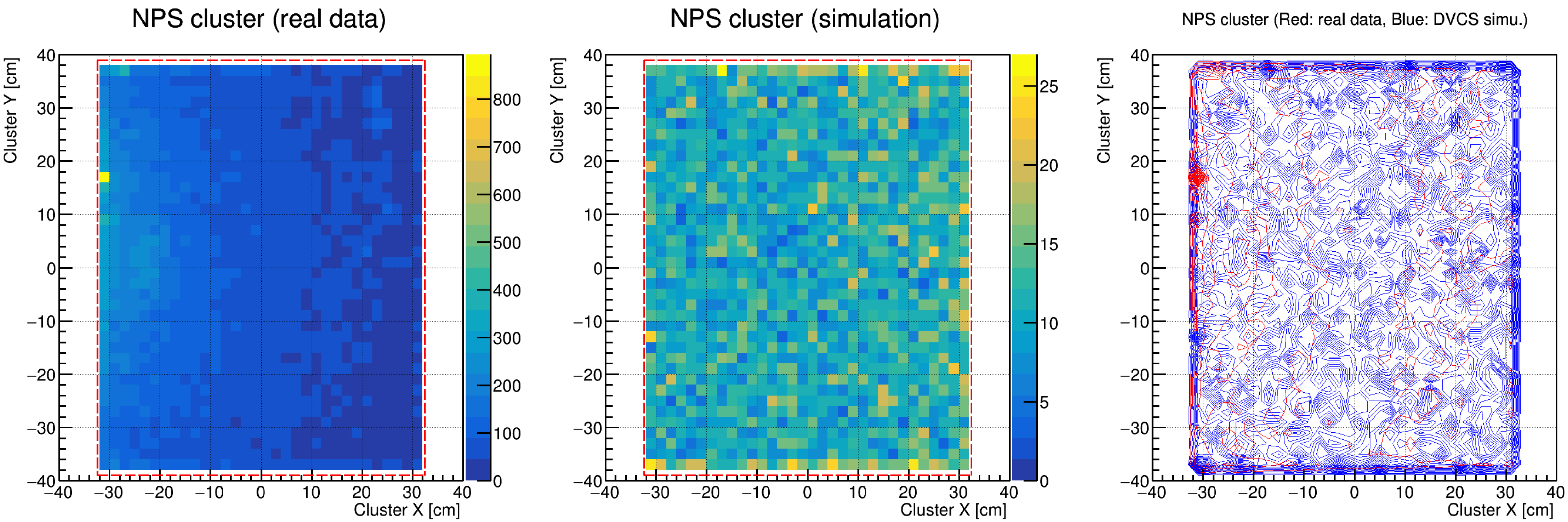




NPS at 6 meters (x36_6_2)

- ➢Shadow of the magnet matched very well

Simulation and real data
Reconstructed vs. production



Conclusion

- Modification of DVCS event generator and NPS-Geant4 simulation package
- HMS MC-single arm simulation adapted to the DVCS simulation
- Compared generated and reconstructed events in the simulation
  - Acceptance in the generator looked good
- Compared simulated results (reconstructed) with real data
  - Discrepancies of HMS related variables due to the lack of cross section in simulation
  - NPS acceptance and the shadow of magnet matched the real data

Future work

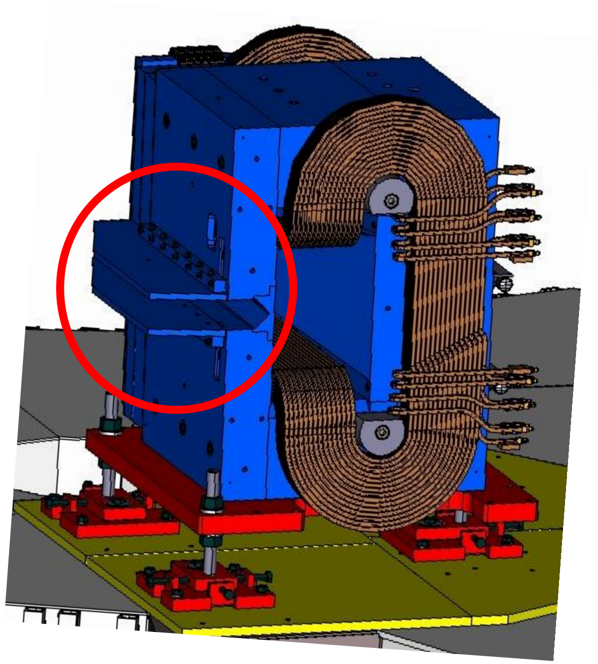
- Test the distribution of HMS variables by weighting with DIS cross section
- Remove NPS dead blocks
  - List of dead blocks in https://hallcweb.jlab.org/elogs/NPS-RG1a-Analysis/94
  - Remove all signals/pulses of these blocks in both simulation and data
  - Accumulated charge as a function of run number is required

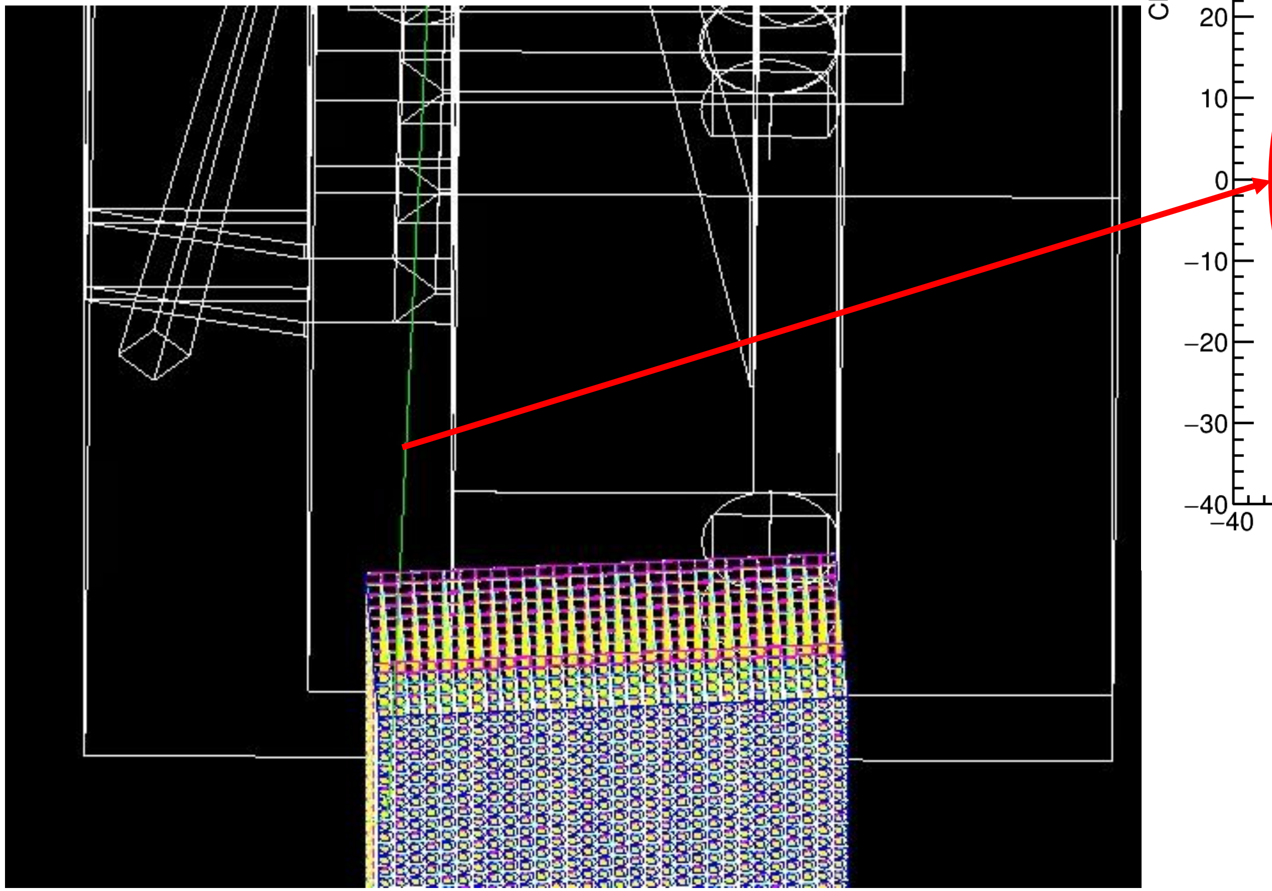
1	Start run	End run	Columns (Dead/OFF)			Blocks (Dead/Missing)												
20	2286	2300	0	1		542	572	482	632	422	452	392	602	332				
21	2301	2302	0	1		542	572	482	632	422	452	392	602	332	302			
22	2303	2337	0	1		542	572	482	632	422	452	392	602	332	302	662		
23	2338	2343	0	1		542	572	482	632	422	452	392	602	332	302	662	692	
24	2344	2349	0	1		542	572	482	632	422	452	392	602	332	302	662	692	842
25	2350	2376	0	1	2													
26	2377	2405	0	1	2	393												

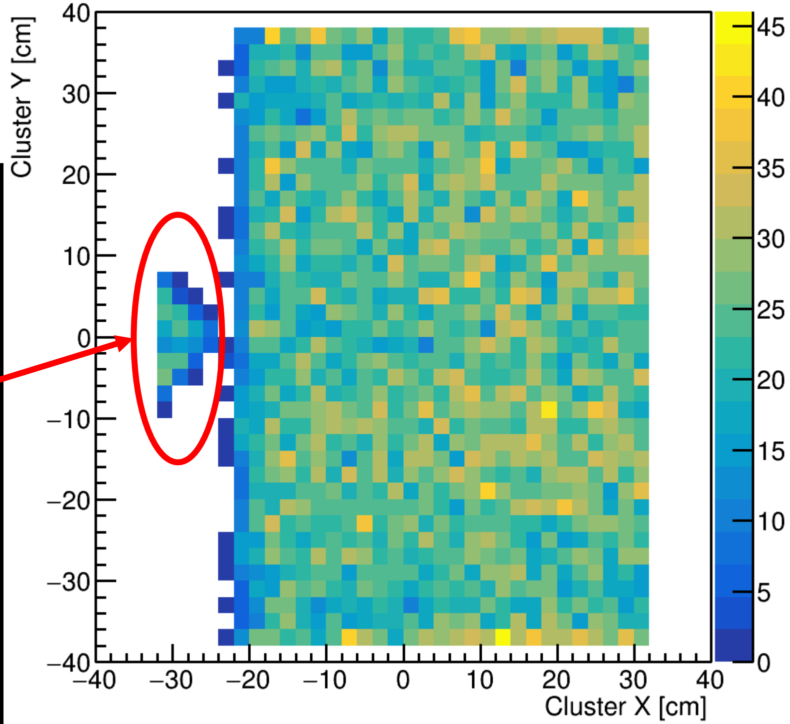
- Simulation calibration and smearing for photons
  - To have the same resolution as in the data
  - Requires extracted DVCS peak from real data (waveform analysis + pi0 calibration)
- A new version of simulation user manual

Backups

Additional clusters around x = -30 cm in simulation

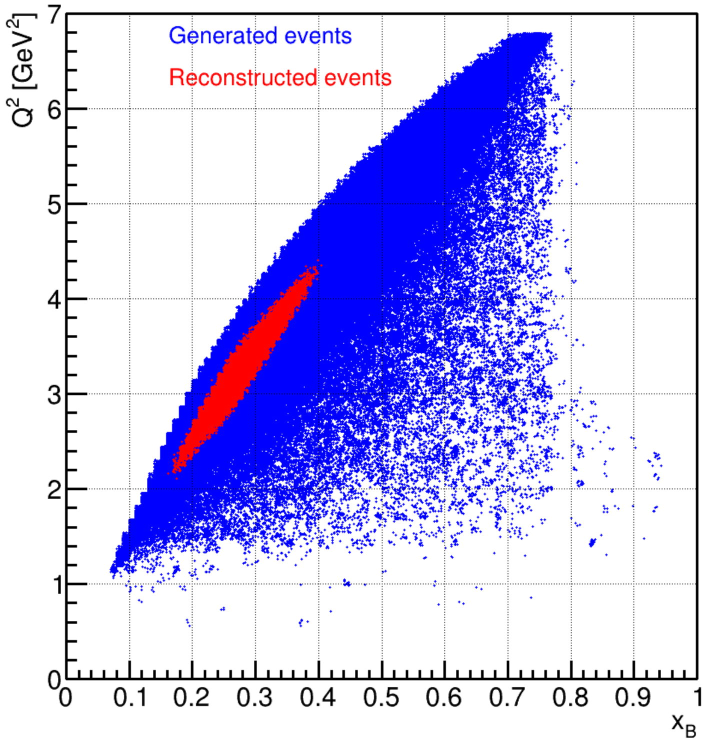




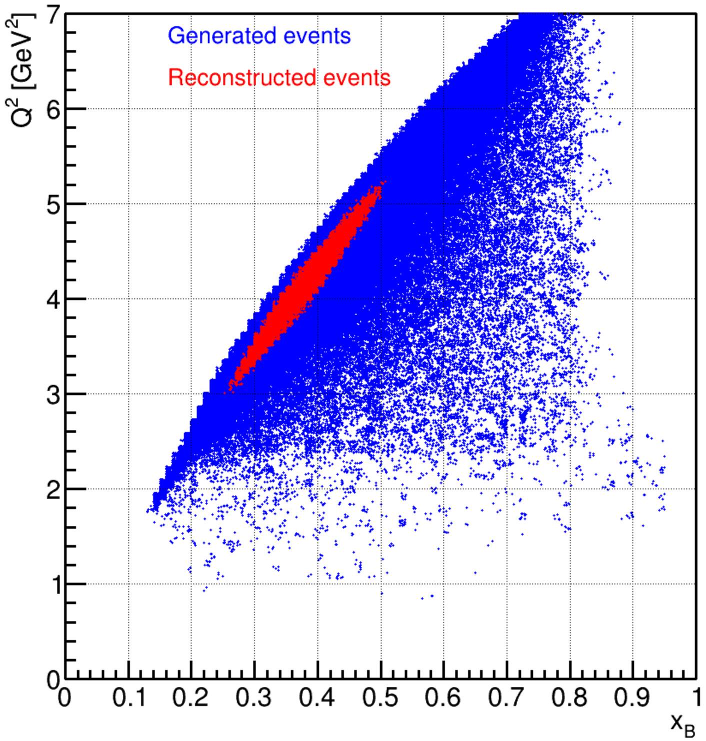


Q^2 vs. x_B

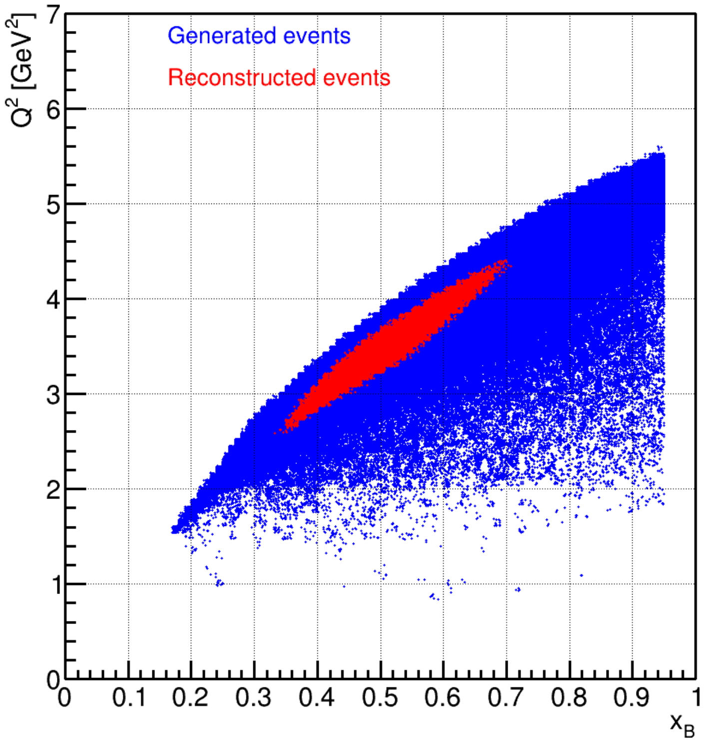
x25_4_1



x36_4

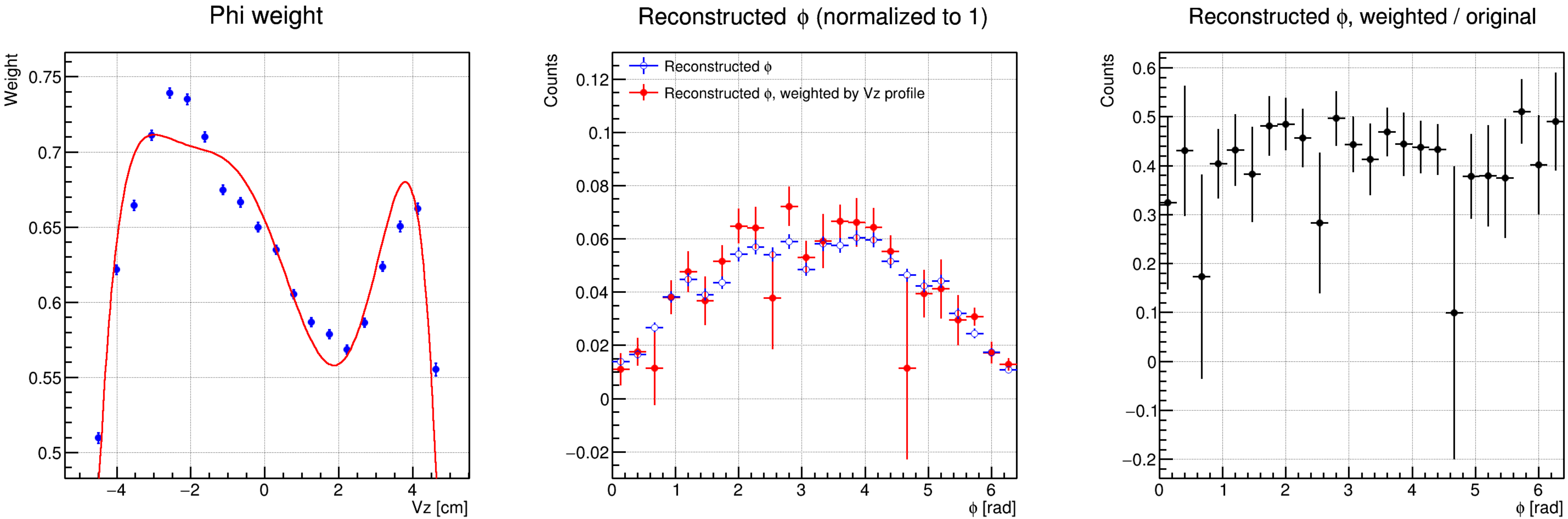


x50_0_1



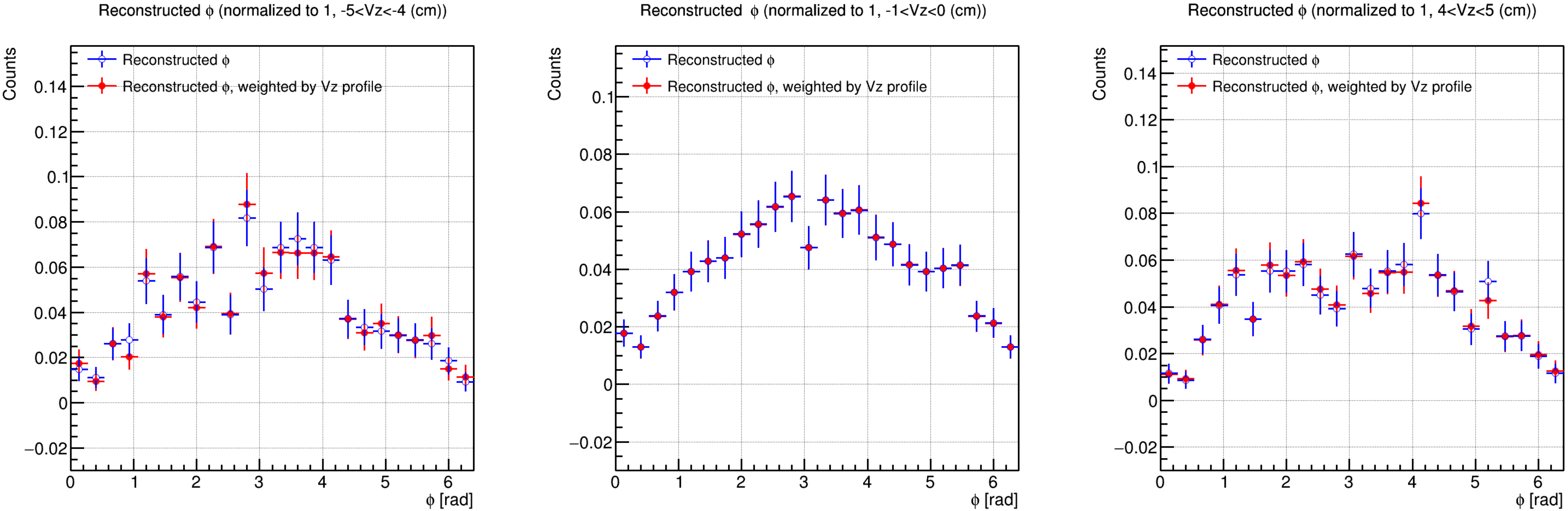
ϕ study with the target z profile

➢ϕ distribution from DVCS simulation, no cross section, origin vs. weighted



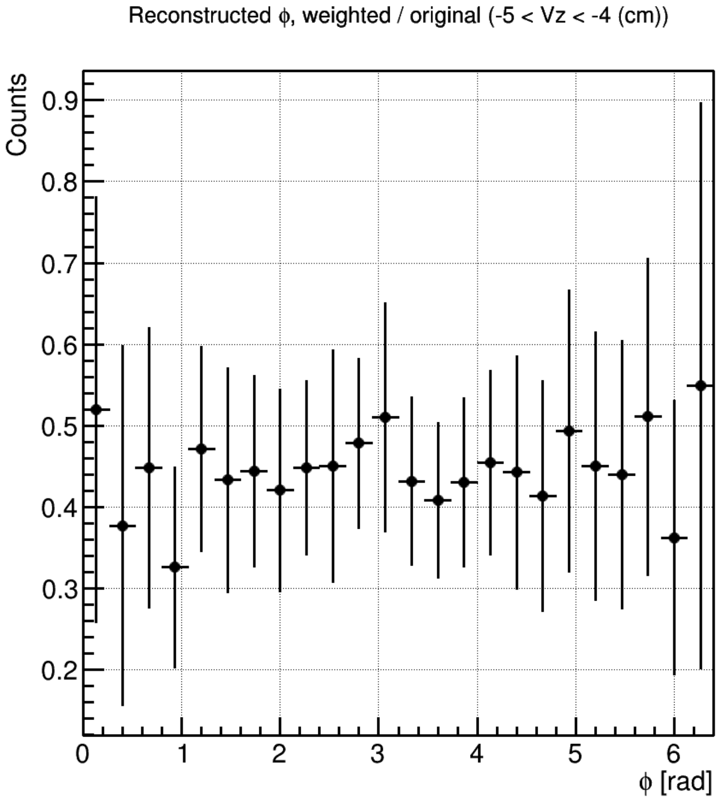
ϕ study with the target z profile

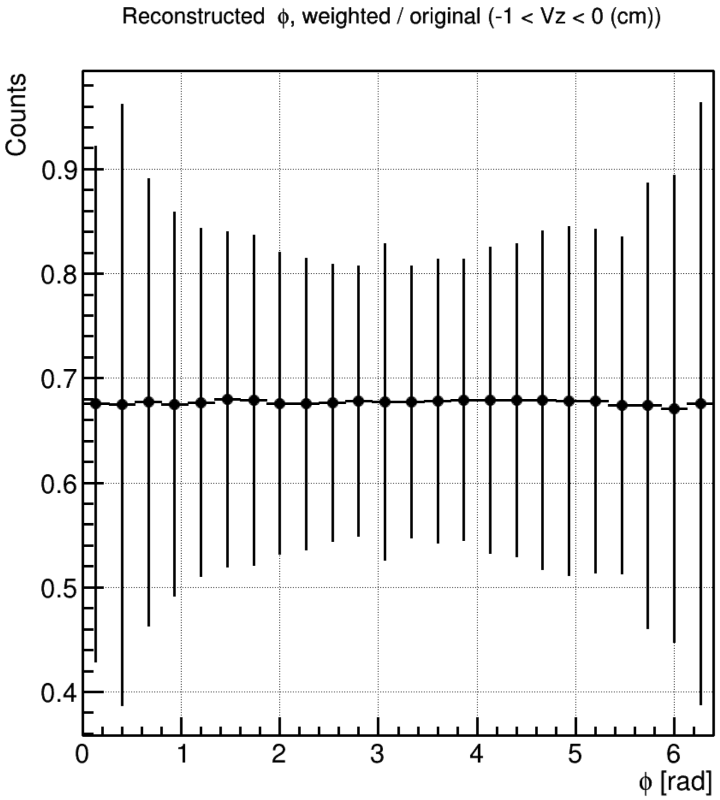
➤Different vertex range

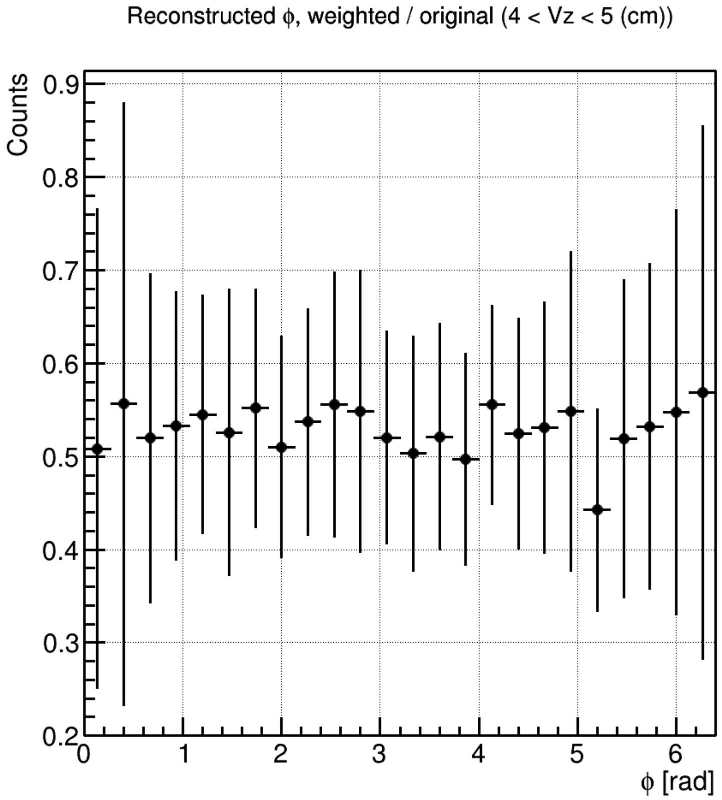


ϕ study with the target z profile

➢ Ratio with different vertex z range





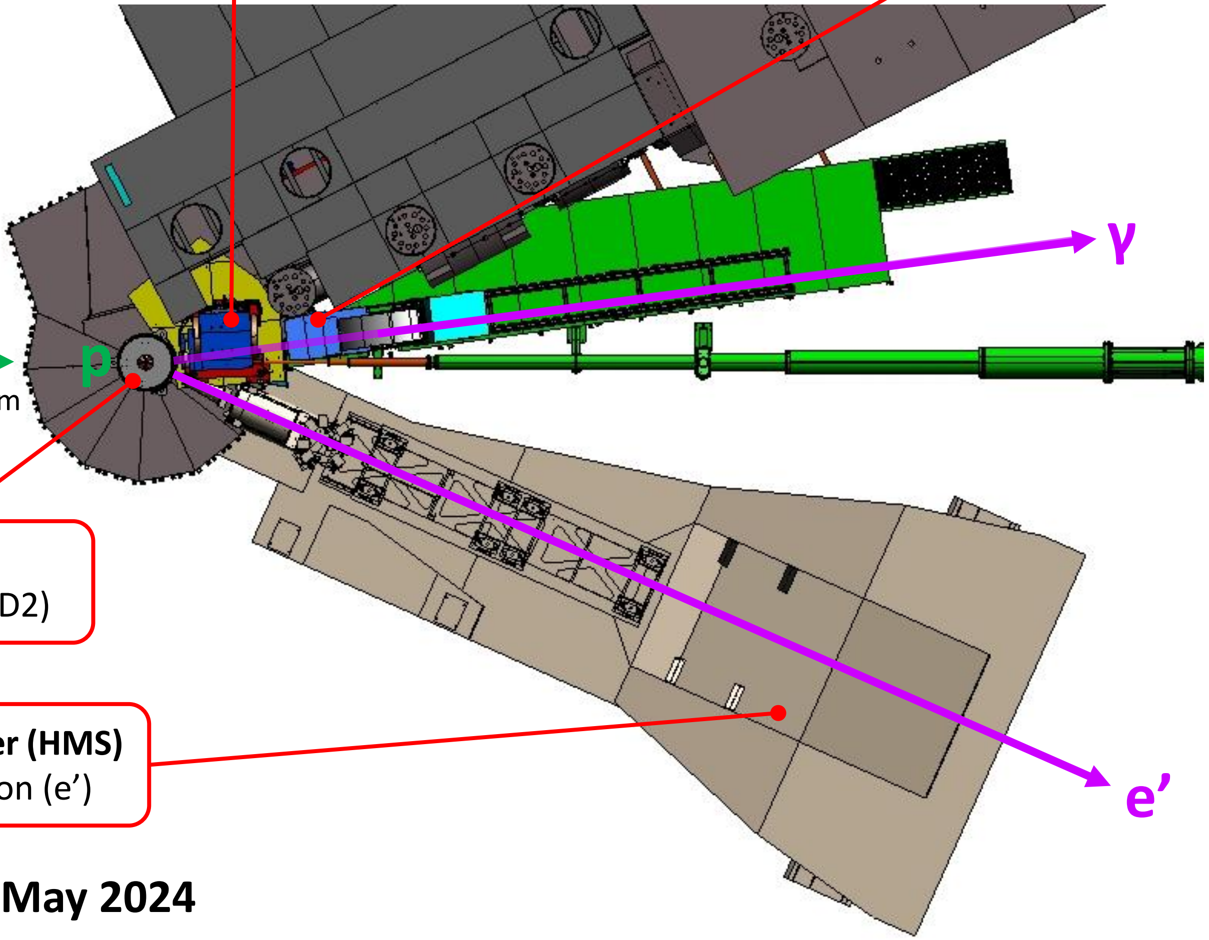


DVCS experimental setup in Hall C at Jefferson Lab

Sweep magnet
- 0.3 T·m of magnetic field
- Reduce the low energy background electrons

Neutral Particle Spectrometer (NPS) calorimeter
- Detect photon (γ) with an array of 1080 $PbWO_4$ crystals

e
from the **C**ontinuous **E**lectron **B**eam **A**ccelerator **F**acility (**CEBAF**)



Target chamber
- Liquid H_2 (LH2) or liquid D_2 (LD2)

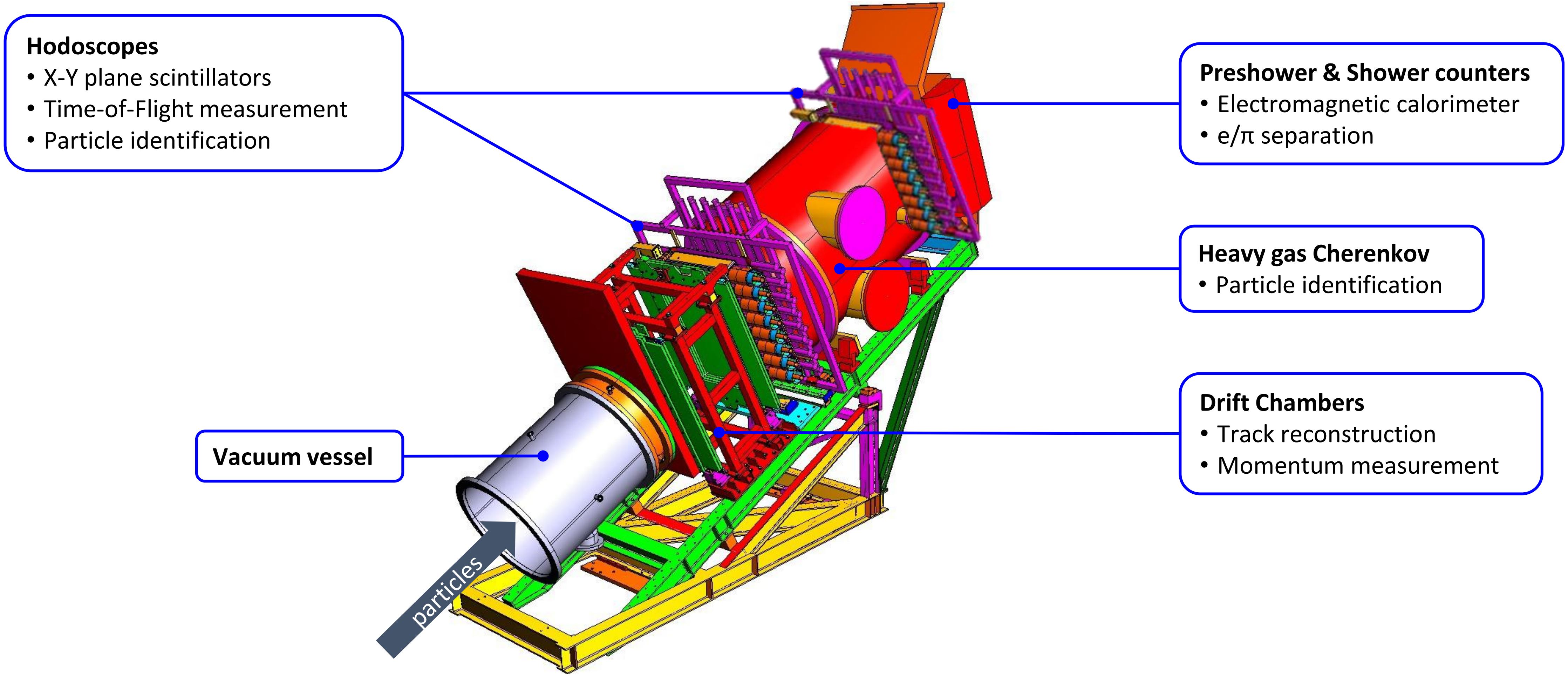
High Momentum Spectrometer (HMS)
- Detection of scattered electron (e’)

⬆ Front view of NPS crystal array

Run period: Sep. 2023 – May 2024

High Momentum Spectrometer

➢ Provides sufficient momentum reach for the separation of interference and |DVCS|^2 terms using beam energy dependance



HMS drift chambers and focal plane

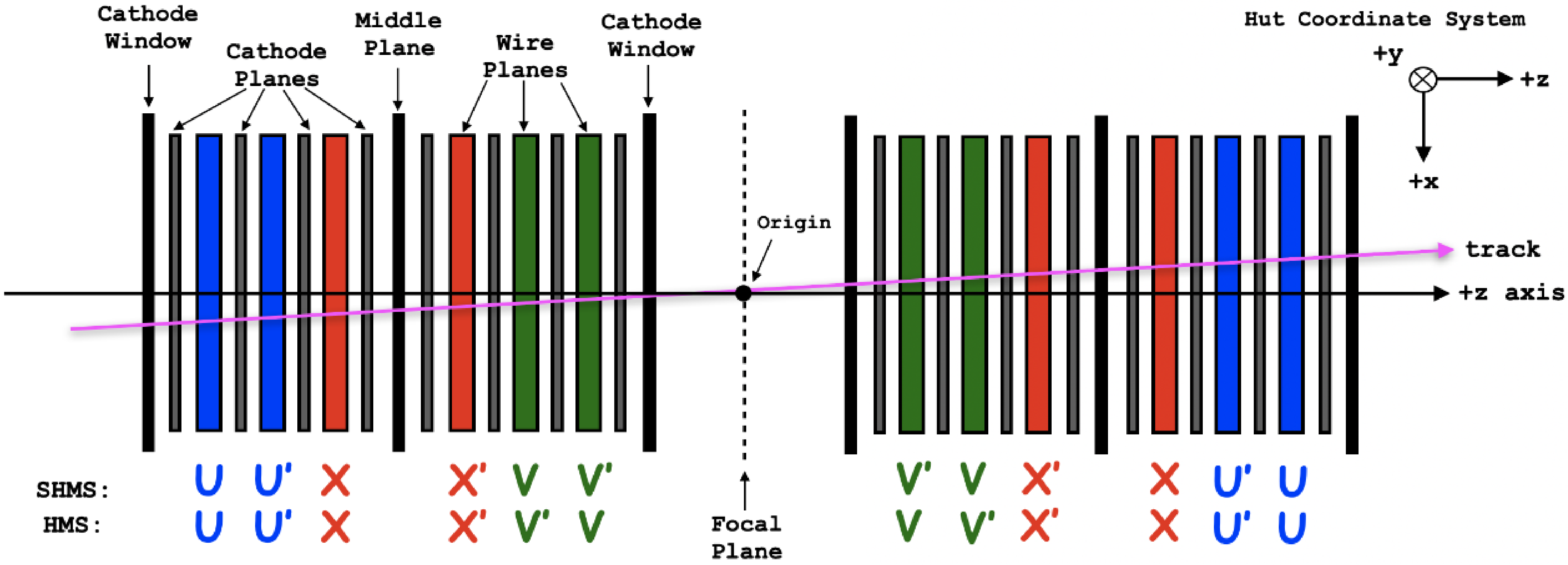


Figure 3.24: Side view of the plane orientation for the DC1 (left) where the colored planes represent the wire planes, and DC2 (right) which is identical in design to DC1 rotated by 180° about the x-axis (vertical) forming a mirror image along the z-axis.

Reconstruction of events

- From the Note on HMS optics

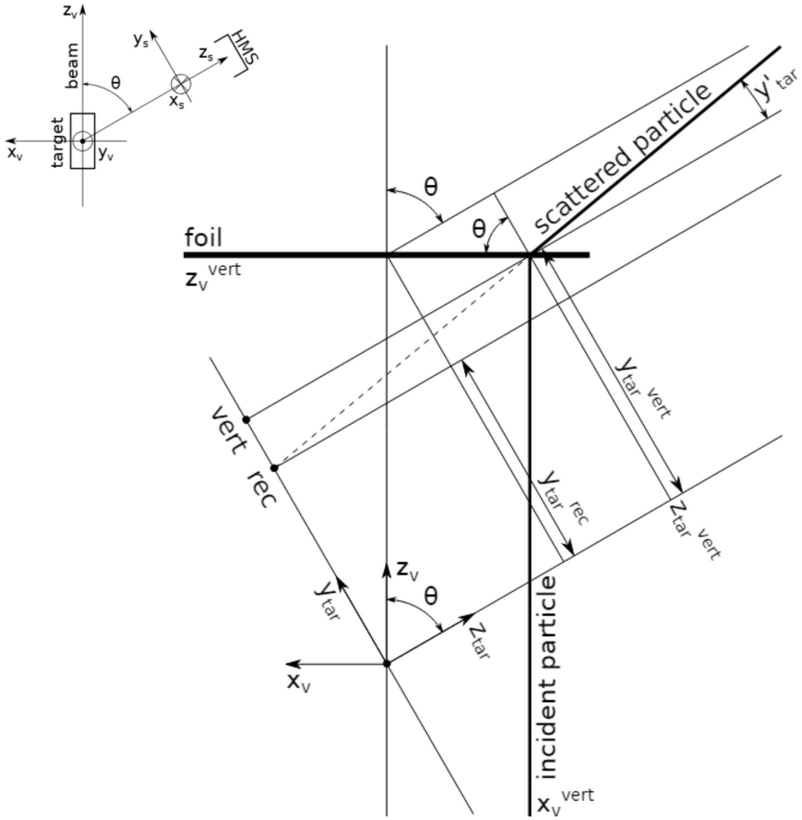


Figure 2: Detailed drawing of event coordinates. The subscript "v" denotes the vertex coordinate system while "tar" stands for target. The "vert" point marks the vertex projection of the interaction vertex onto the target coordinate system. On the other hand, the "rec" point is the reconstructed point as given by Equation 1. The vertex projection must be calculated from the reconstructed point.

$$x'_{\rm tar} = \sum_{i,j,k,l,m} X'_{i,j,k,l,m} \cdot x^i_{\rm fp}\, x'^j_{\rm fp}\, y^k_{\rm fp}\, y'^l_{\rm fp}\, x^m_{\rm tar} \tag{1a}$$

$$y^{\rm rec}_{\rm tar} = \sum_{i,j,k,l,m} Y_{i,j,k,l,m} \cdot x^i_{\rm fp}\, x'^j_{\rm fp}\, y^k_{\rm fp}\, y'^l_{\rm fp}\, x^m_{\rm tar} \tag{1b}$$

$$y'_{\rm tar} = \sum_{i,j,k,l,m} Y'_{i,j,k,l,m} \cdot x^i_{\rm fp}\, x'^j_{\rm fp}\, y^k_{\rm fp}\, y'^l_{\rm fp}\, x^m_{\rm tar} \tag{1c}$$

$$\delta_{\rm tar} = \sum_{i,j,k,l,m} D_{i,j,k,l,m} \cdot x^i_{\rm fp}\, x'^j_{\rm fp}\, y^k_{\rm fp}\, y'^l_{\rm fp}\, x^m_{\rm tar} \tag{1d}$$

$$z_{\rm v}^{\rm vert} = \frac{y^{\rm rec}_{\rm tar} + x^{\rm beam}(\cos(\theta) + y'_{\rm tar}\sin(\theta))}{\sin(\theta) - y'_{\rm tar}\cos(\theta)}$$

hms_stop_id

mc-single-arm > src > mc_single_arm.f

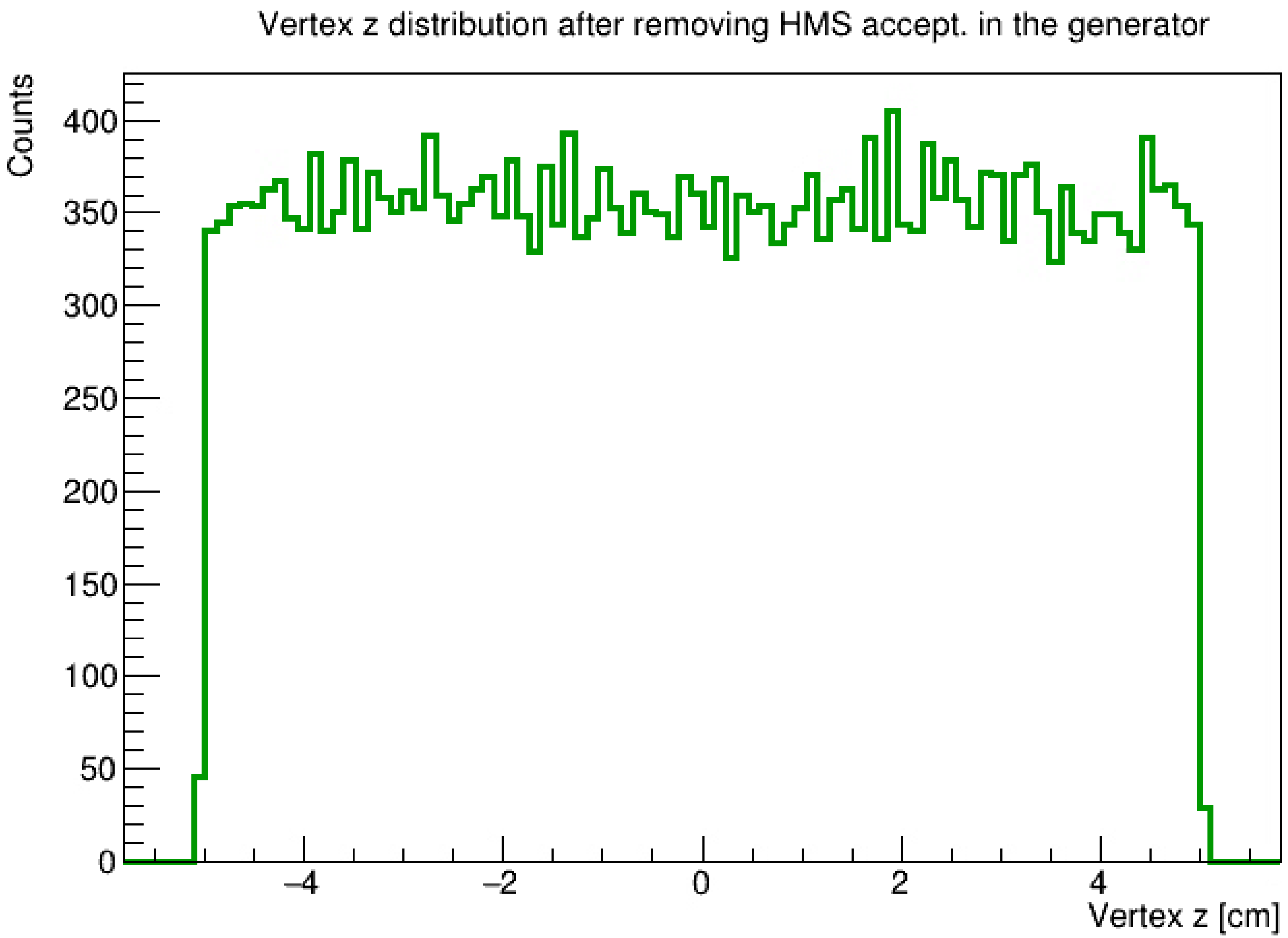
```
 1012    format(1x,16i4)

 1015    format(/,
     >      i11,' stopped in the TARG APERT HOR',/
     >      i11,' stopped in the TARG APERT VERT',/
     >      i11,' stopped in the TARG APERT OCTAGON',/
     >      i11,' stopped in the FIXED FRONT SLIT HOR (id=-1)',/
     >      i11,' stopped in the FIXED FRONT SLIT VERT (id=-1)',/
     >      i11,' stopped in HB ENTRANCE (id=1)',/
     >      i11,' stopped in HB MAG ENTRANCE (id=2)',/
     >      i11,' stopped in HB MAG EXIT (id=3)',/
     >      i11,' stopped in HB EXIT (id=4)',/
     >      i11,' stopped in the DOWN SIEVE SLIT (id=99)',/
     >      i11,' stopped in the COLLIMATOR HOR (id=5)',/
     >      i11,' stopped in the COLLIMATOR VERT (id=5)',/
     >      i11,' stopped in the COLLIMATOR OCTAGON (id=5)',/
     >      i11,' stopped in Q1 ENTRANCE (id=6)',/
     >      i11,' stopped in Q1 MAG ENTRANCE (id=7)',/
     >      i11,' stopped in Q1 MIDPLANE (id=8)',/
     >      i11,' stopped in Q1 MAG EXIT (id=9)',/
     >      i11,' stopped in Q1 EXIT (id=10)',/
```

Generate the vertices in the simulation

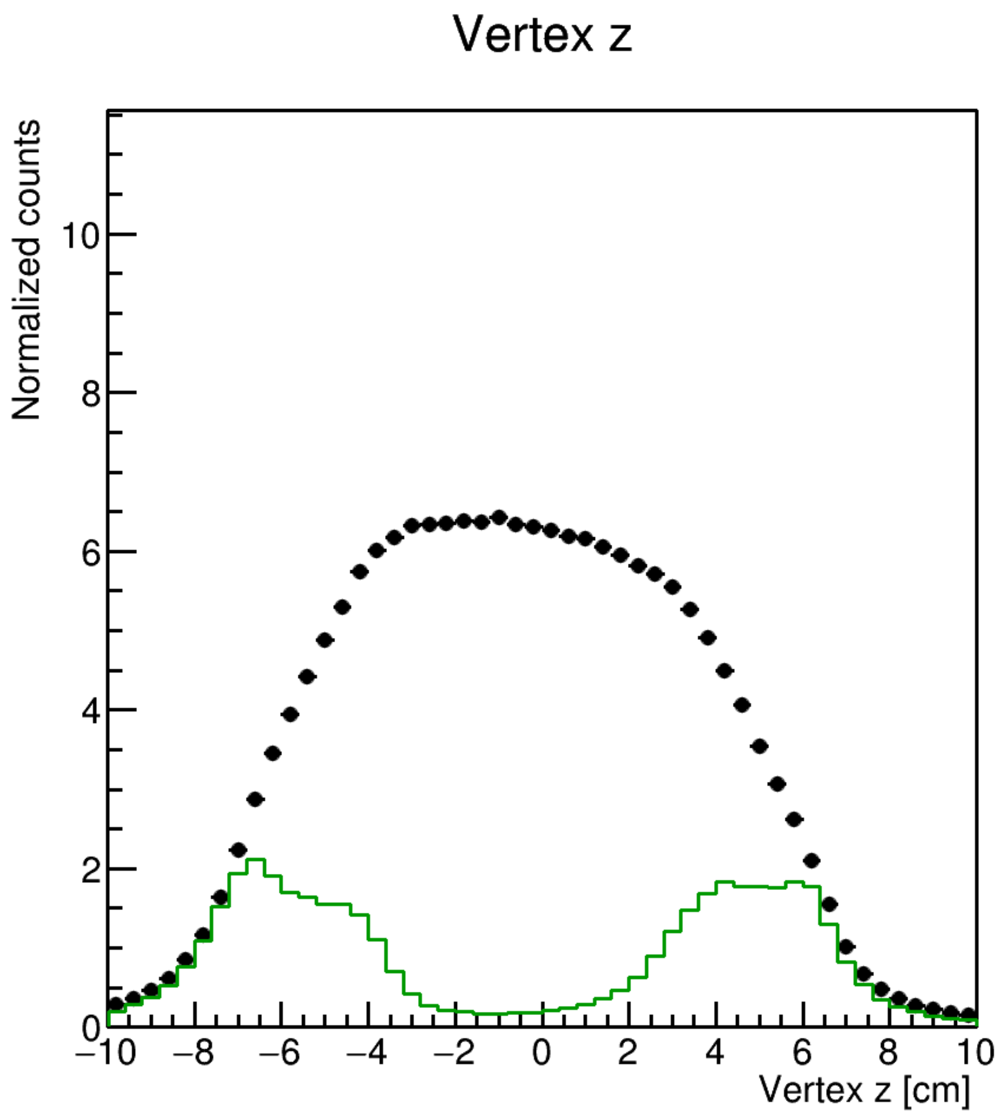
- Different versions here corresponds to the colored histograms of the vertex distributions in previous page

```
// Version 2
// Vertex with rasters (uniform 2x2 distribution on x-y plane)
SetVertex(0.2*fRan->Rndm()-0.1, 0.2*fRan->Rndm()-0.1, fTargLength*fRan->Rndm()-fTargLength/2.+fTargZoff);

// Version 3
// Vertex with beam offset and rasters
// Beam position (-1.31 mm, 0.05 mm) on target from https://logbooks.jlab.org/entry/4254868

Double_t x_offset = -1.31*0.1; // beam offset (cm)
Double_t y_offset = 0.05*0.1; // beam offset (cm)

Double_t x_raster = 0.2*fRan->Rndm()-0.1; // x raster, centered at 0
Double_t y_raster = 0.2*fRan->Rndm()-0.1; // y raster, centered at 0

SetVertex(x_offset+x_raster, y_offset+y_raster, fTargLength*fRan->Rndm()-fTargLength/2.+fTargZoff);

// Version 4
// Vertex with beam offset, beam width and rasters
// Beam position (-1.31 mm, 0.05 mm) on target from https://logbooks.jlab.org/entry/4254868
// Beam width (0.5481 mm, 0.1586 mm) (sigma from harp scan) from https://logbooks.jlab.org/entry/4254747
TRandom3 *r = new TRandom3(0);

Double_t x_offset = r->Gaus(-1.31*0.1, 0.5481*0.1); // randomly generate Vx based on the beam offset and width
(cm)
Double_t y_offset = r->Gaus(0.05*0.1, 0.1586*0.1); // randomly generate Vy based on the beam offset and width (cm)

Double_t x_raster = 0.2*fRan->Rndm()-0.1; // x raster, centered at 0
Double_t y_raster = 0.2*fRan->Rndm()-0.1; // y raster, centered at 0

SetVertex(x_offset+x_raster, y_offset+y_raster, fTargLength*fRan->Rndm()-fTargLength/2.+fTargZoff);
```

Generated vertex z distribution without HMS accept. cut



Vertex z (dummy vs. data)



Added energy loss from the entrance of target cell

- Material of target cell : aluminum alloy (AL7050)
- Radiation length of aluminum

```
//______________________________________________________________________
 Double_t TGenGeo::AlX0(void)
{
  // Returns the radiation length of the entrance window (Aluminium) of target

  if(fTargDens==0.) cout<<"Target not initialized !"<<endl;
  return 24.01/2.7 ; // Al radiation length in g/cm^-2/Al density
}
```

- Energy loss before vertex due to Bremsstrahlung: $\Delta E = E_0 R^{1/bt}$
- E_0: initial energy of electron beam
- t: material thickness in radiation length
- b: coefficient related to atomic number Z
- R: Random number between 0 and 1
- Target window thickness: 0.0132 cm (average of the 3 cells)

- Added energy loss of target window

```
//______________________________________________________________________
void TGenBase::ExtBrem(void)
{
  // Make external bremsstrahlung corrections before the vertex (straggling)
  // Uses \Delta E=E_0 * R^(1/b/t) with R randomly between 0 and 1.

  Double_t t=0; //Lengh of matter in radiation length
  Double_t eel=0.;
  fRadCor=kTRUE;

   if(fTargType!=0 && fTargType!=1 && fTargType!=2){
    cout<<" UNKOWN TARGET!"<<endl;
    exit(1);
  }
  if(fTargType==0){
    t=(fVertex->Pz()+fTargLength/2.)/PX0() + fTargetWindowThickness/AlX0();
  }else{
    t=(fVertex->Pz()+fTargLength/2.)/NX0() + fTargetWindowThickness/AlX0();
  }

    Double_t toto=TMath::Power(fRan->Rndm(),1./(b()*t));

    //cout<<"toto="<<toto<<endl;

    eel=fEbeam*(1.-toto);
    feini->SetPxPyPzE(0.,0.,eel,eel);
}
```

Geometry of NPS crystals

- Width of crystals: 20.5 mm
- Spaces between the crystals: ~ 1 mm

	Beam following system		
	X(mm)	Y(mm)	Z(mm)
C02_R18	-268.81	10.64	0.15
C14_R34	-10.63	354.76	0.19
C27_R18	268.84	10.77	0.19
C14_R02	-10.78	-332.83	0.14
C03_R18	-247.34	10.61	0.28
C14_R33	-10.65	333.15	0.16
C27_R17	268.77	-10.79	0.14
C14_R01	-11.00	-354.24	0.32
C03_R17	-247.30	-10.95	0.15
C15_R17	10.82	-10.81	0.03
C15_R18	10.73	10.85	-0.01
C14_R18	-10.73	10.78	0.02
C14_R17	-10.82	-10.82	-0.05

- Crystal wrapping
  1. Reflective sheet (65 µm, VM2000)
  2. Tedlar (30 µm of thickness, material: ?)
- Add 30 µm to the reflective sheet