Update on EIC 2nd detector study with Far-Forward Acceptance and Vetoing Efficiency

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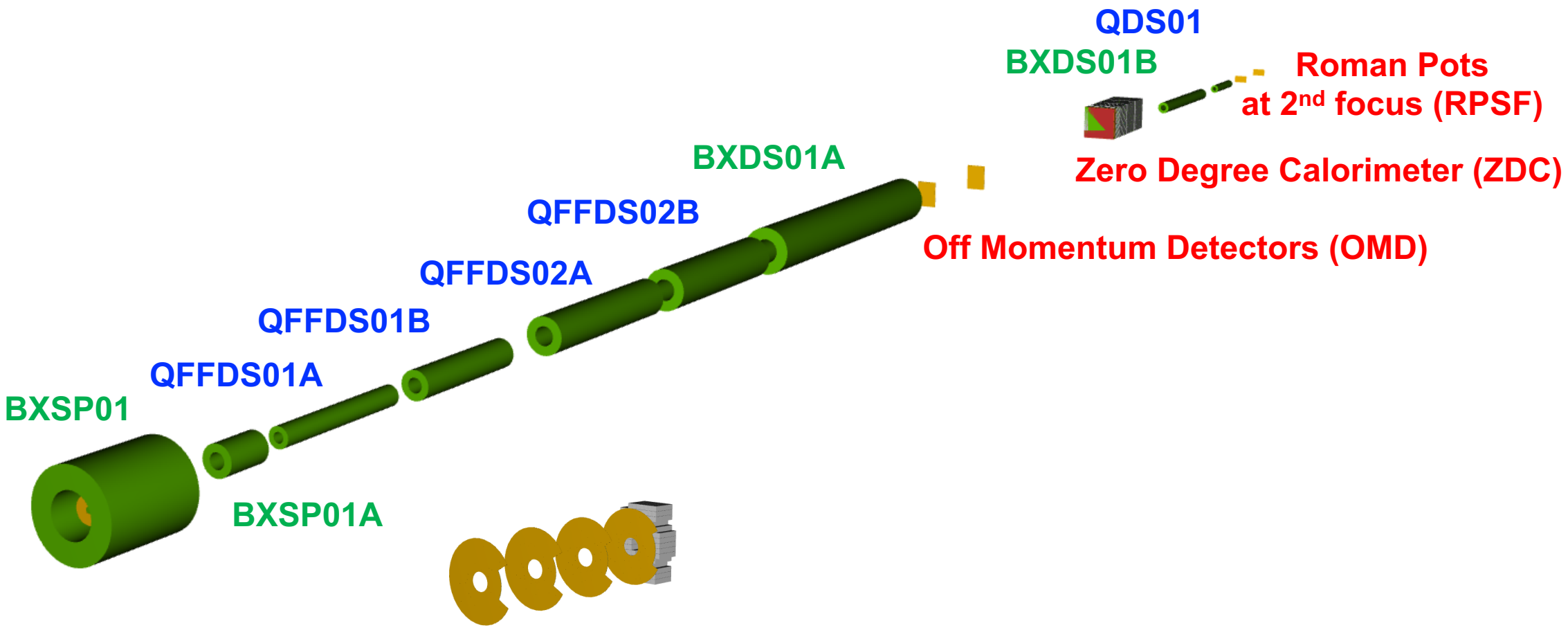
Introduction

- One of golden channels for EIC Detector-2 LDRD program
  - Study exclusive processes to access transverse spatial structure and fluctuations of gluons in target
  - Experimentally, measured spectra in vector meson production contain sum of coherent and incoherent processes
  - Separate coherent from incoherent process
    - By tagging nuclear fragments using far-forward detectors, understand background of coherent vector meson productions (ex. J/ψ)
- Looking into more details on
  - Far-forward detector acceptance
  - pT acceptance of scattered protons
  - Vetoing efficiency for incoherent events

IP-8 Far-Forward Layout

pre-conceptual design

Implemented in **IP-8 Forward Hadron Lattice** and IP-6 detector configuration



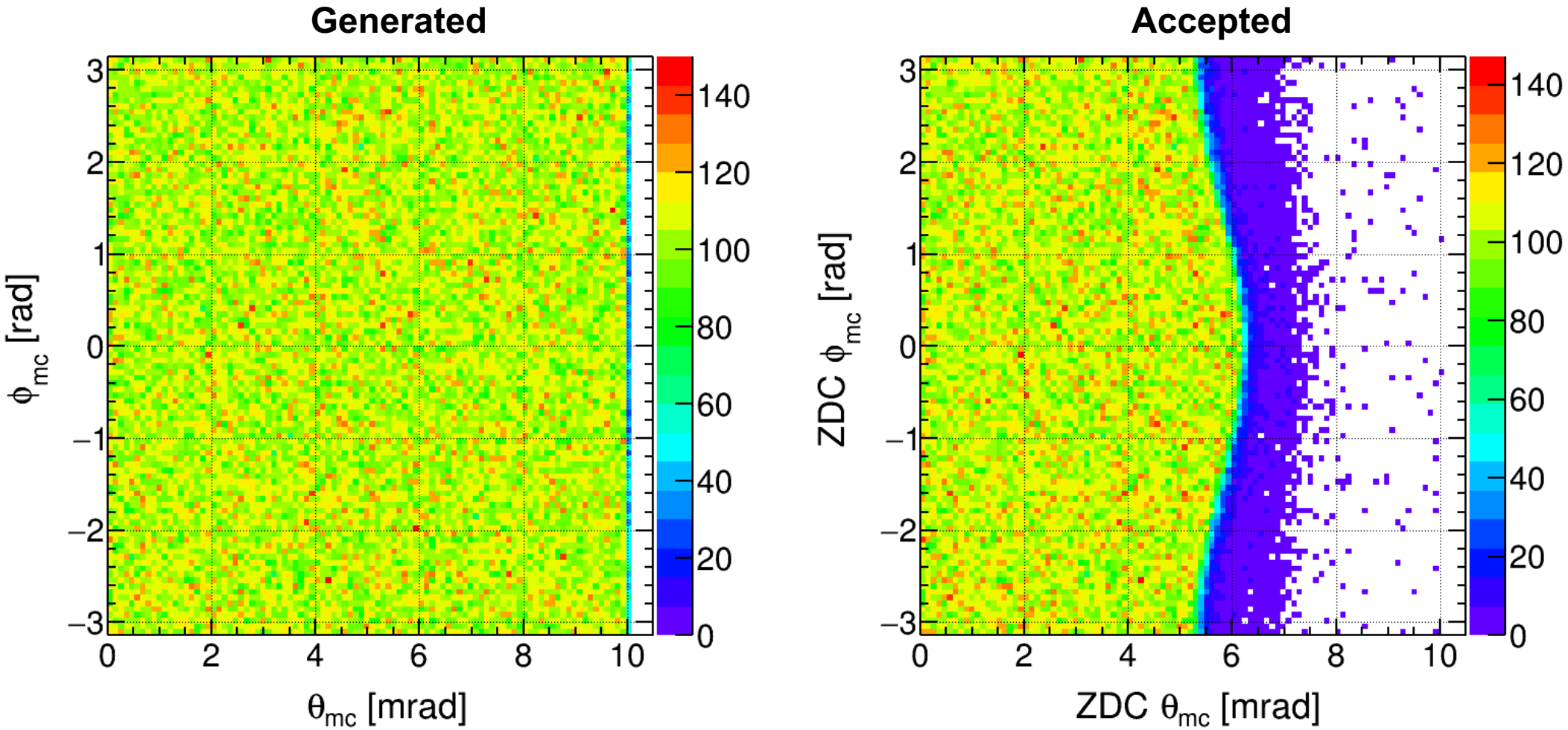
References from https://wiki.bnl.gov/eic-detector-2/images/d/de/IR8_magnet_layout_12052022.xlsx
https://wiki.bnl.gov/eic-detector-2/images/8/86/IP8_HSR_lattice_performance_10_13_22_v3.pdf

Approach – Detector Acceptance

- **Far-Forward region**
  - Particles with $\boldsymbol{\theta}$ **< ~ 37 mrad (2.1°)**
  - **Tag charged hadrons** (protons) or **neutral particles** (neutrons, photons)
  - IP8 has larger crossing angle (35 mrad) and secondary focus far downstream
- **Single particle simulation**
  - **B0 Tracker + Calorimeter** for detecting protons and photons
    - Proton energy: 80 GeV < E_p < 120 GeV and **5 < $\boldsymbol{\theta}_{MC}$ < 20 mrad**
  - **Off-Momentum Detector** for detecting protons from nuclear breakup
    - Proton energy: 123.75 GeV (45%) < E_p < 151.25 GeV (55%) and **0 < $\boldsymbol{\theta}_{MC}$ < 5 mrad**
  - **Zero Degree Calorimeter** for detecting photons and neutrons
    - Neutron energy: E_n = 275 GeV (***$\boldsymbol{\theta}_{MC}$ < 10 mrad**)
  - **Roman Pot at Secondary Focus** for detecting charged particles from nuclear breakup
    - Proton energy: E_p = 275 GeV and **0 < $\boldsymbol{\theta}_{MC}$ < 5 mrad**

Zero Degree Calorimeter

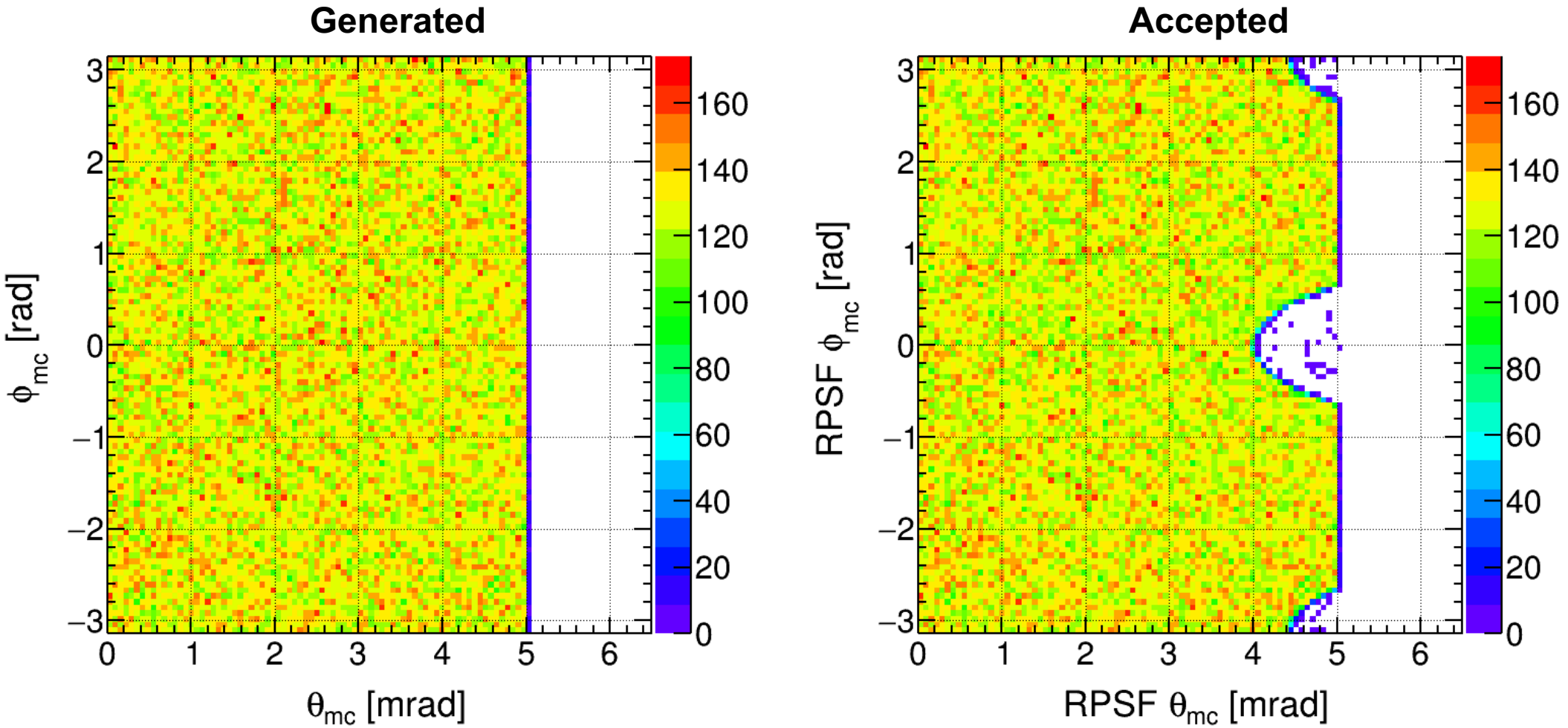
Single Neutron
E = 275 GeV
$0 < \theta_{MC} < 10$ mrad



About 99.98 % events were accepted (θ_{MC} upto 5 mrad)

Roman Pots at Secondary Focus

Single Proton
E = 275 GeV
$0 < \theta_{MC} < 5$ mrad



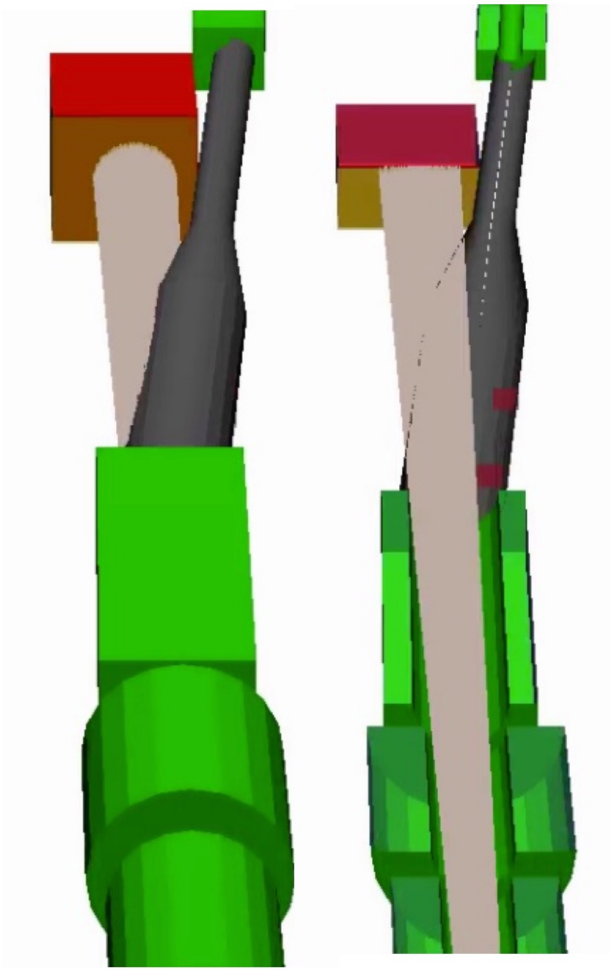
About 95.4 % events were accepted and observed losses at higher theta (polar angle)
Clipping occurs in quadrupoles for protons

Clipping on Acceptance of Far-Forward

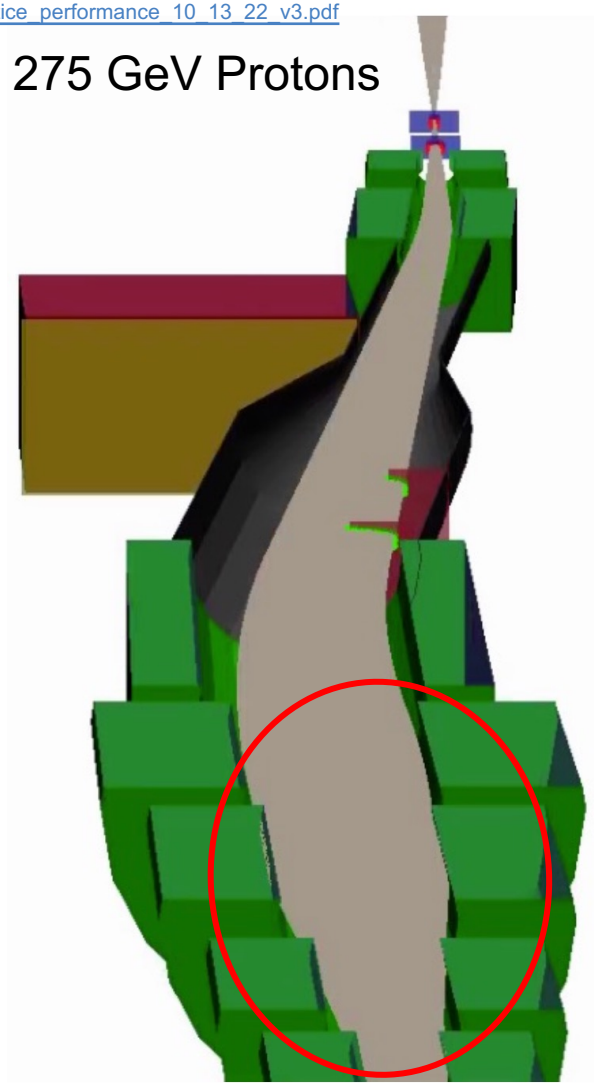
Kindly Provided by Alex Jentsch using EicRoot Simulation Event Display

Reference from https://wiki.bnl.gov/eic-detector-2/images/8/86/IP8_HSR_lattice_performance_10_13_22_v3.pdf

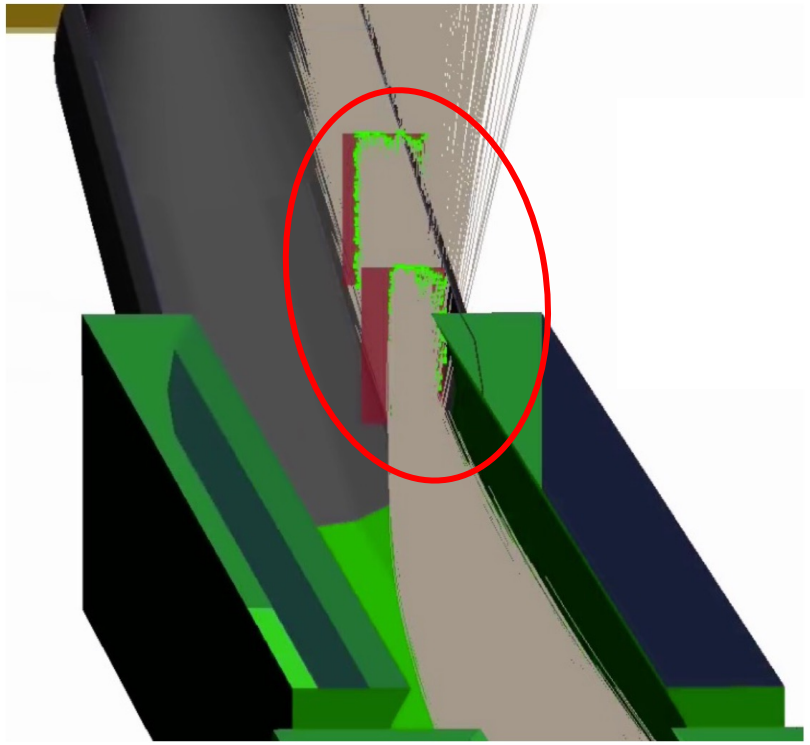
275 GeV Neutrons



275 GeV Protons



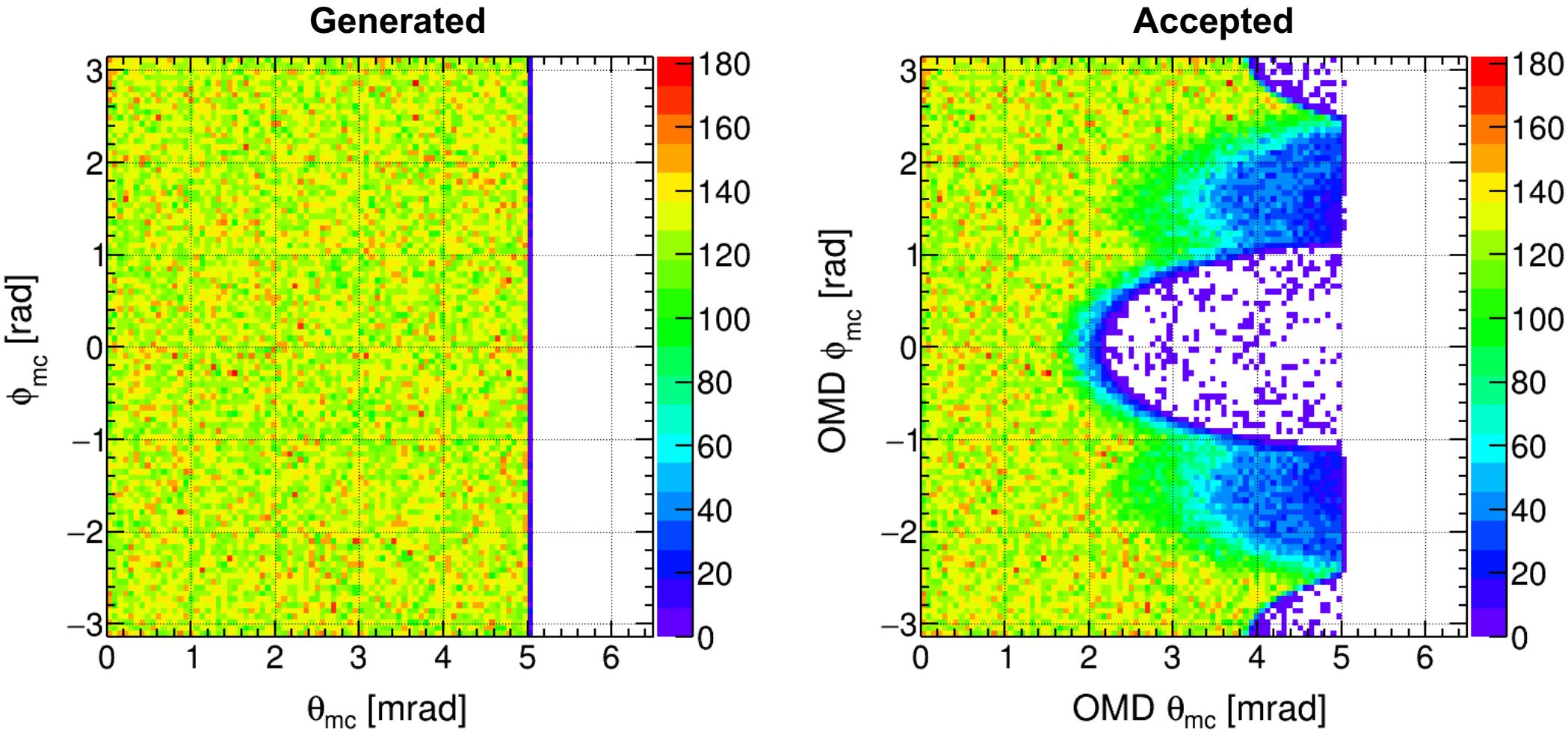
123.75 – 151.25 GeV Protons



DD4hep simulation event display was not successful…

Off Momentum Detectors

Single Proton
123.75 GeV (45%) < E < 151.25 GeV (55%)
$0 < \theta_{MC} < 5$ mrad

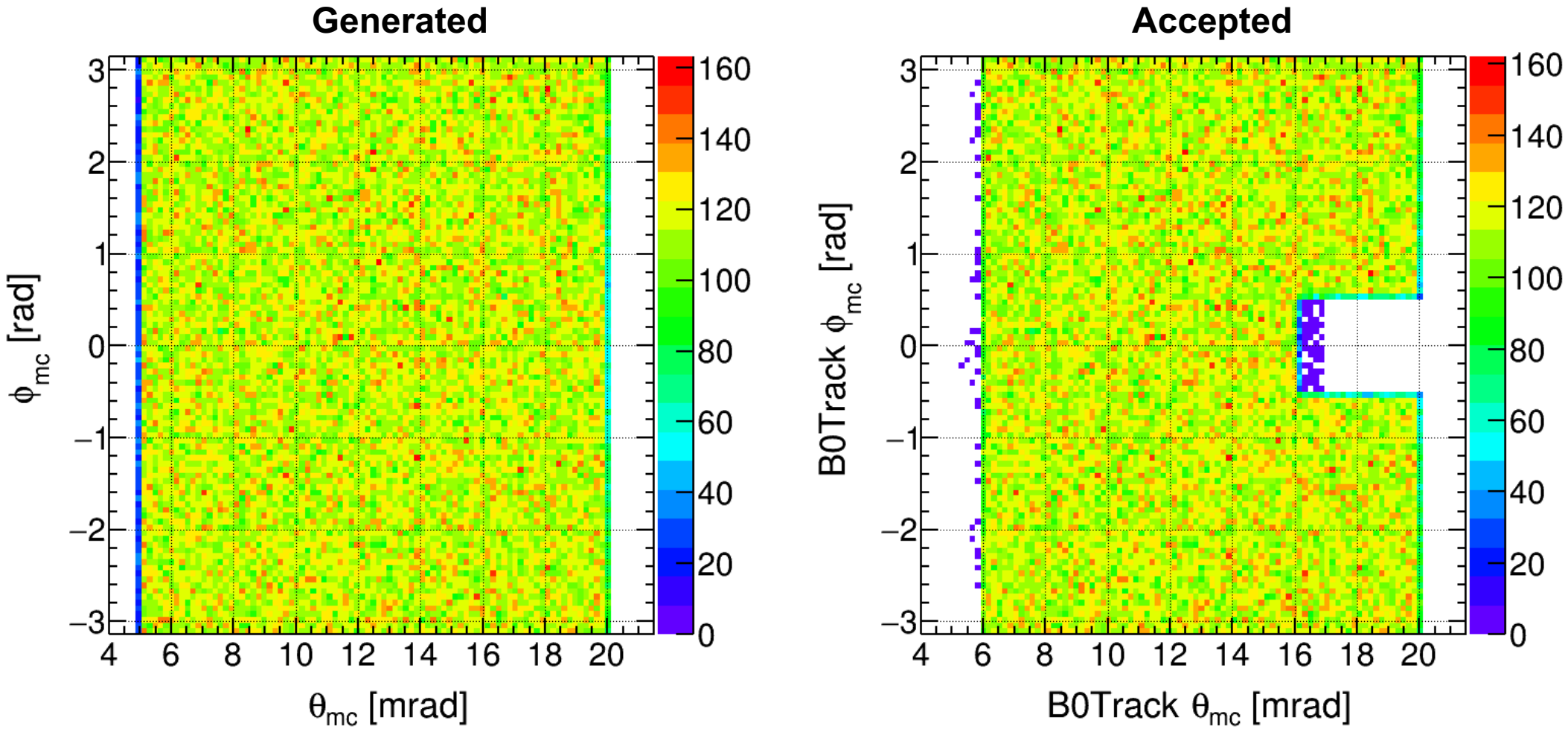


About 67.42 % events were accepted

Hadron lattice in simulation set to be 275 GeV proton and clipping occurs in quadrupoles for protons

B0 Tracker

Single Proton
80 GeV < E < 120 GeV
5 < θ_{MC} < 20 mrad



About **88.94 (93.6) %** events were **accepted requiring four layers (more than two layers)**

Approach – pT Acceptance

- By **tagging final-state proton**, it directly connects to **momentum transfer, t, measurement**
  - Investigate **pT acceptance at B0 and RPSF**
- Used simulated **ep DVCS* 1M** events each
  - Three beam energy combinations: ep 18×275, 10×100, and 5×41 GeV^2
- Passed through **afterburner IP-8 ep high divergence** configuration
  - IP-8 crossing angle (35 mrad) and IP-6 ep high divergence beam effects based on **EIC CDR table 3.3**
- **Accepted events for scattered protons <u>reconstruction purpose</u>**
  - B0 tracker: **all four layers** have hits
  - OMD: **two layers** (actual four layers as redundancy) have hits
  - RPSF: **two layers** have hits > 10σ safe distance based on **ep β @ IP8 RPSF**

*S3/eictest/EPIC/EVGEN/EXCLUSIVE/DVCS/18x275/DVCS.3.18x275.hepmc | *S3/eictest/EPIC/EVGEN/EXCLUSIVE/DVCS/10x100/DVCS.1.10x100.hepmc
*S3/eictest/EPIC/EVGEN/EXCLUSIVE/DVCS/5x41/DVCS.2.5x41.hepmc

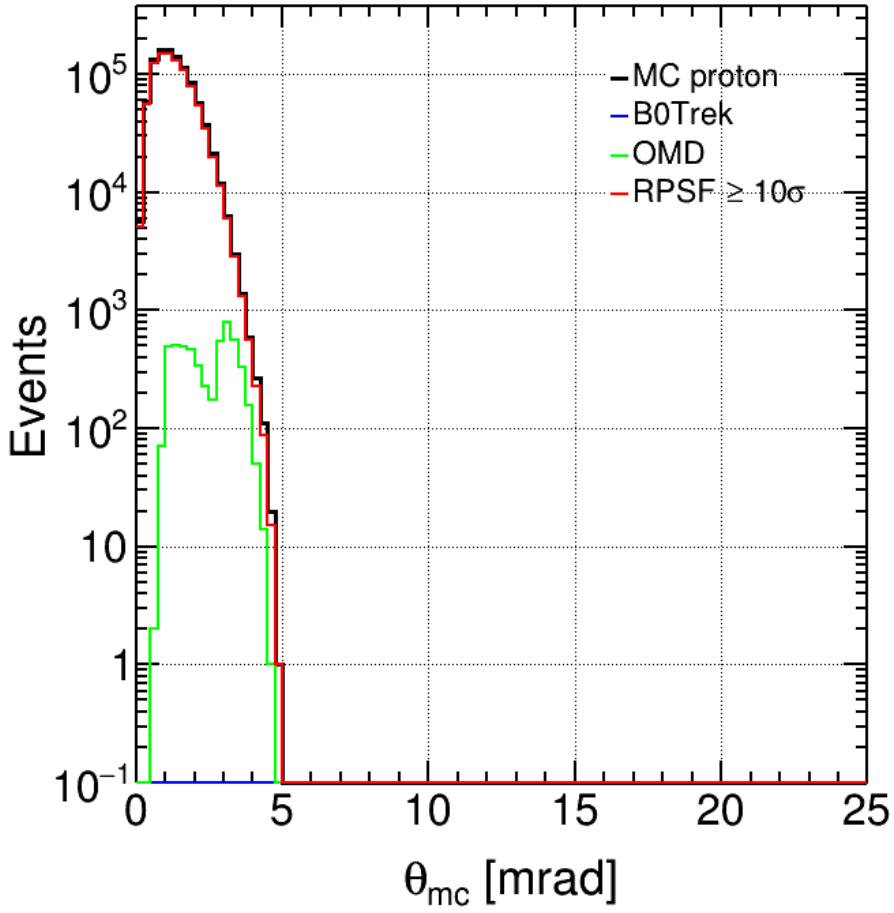
W/O Beampipe at B0

DVCS 18 GeV on 275 GeV

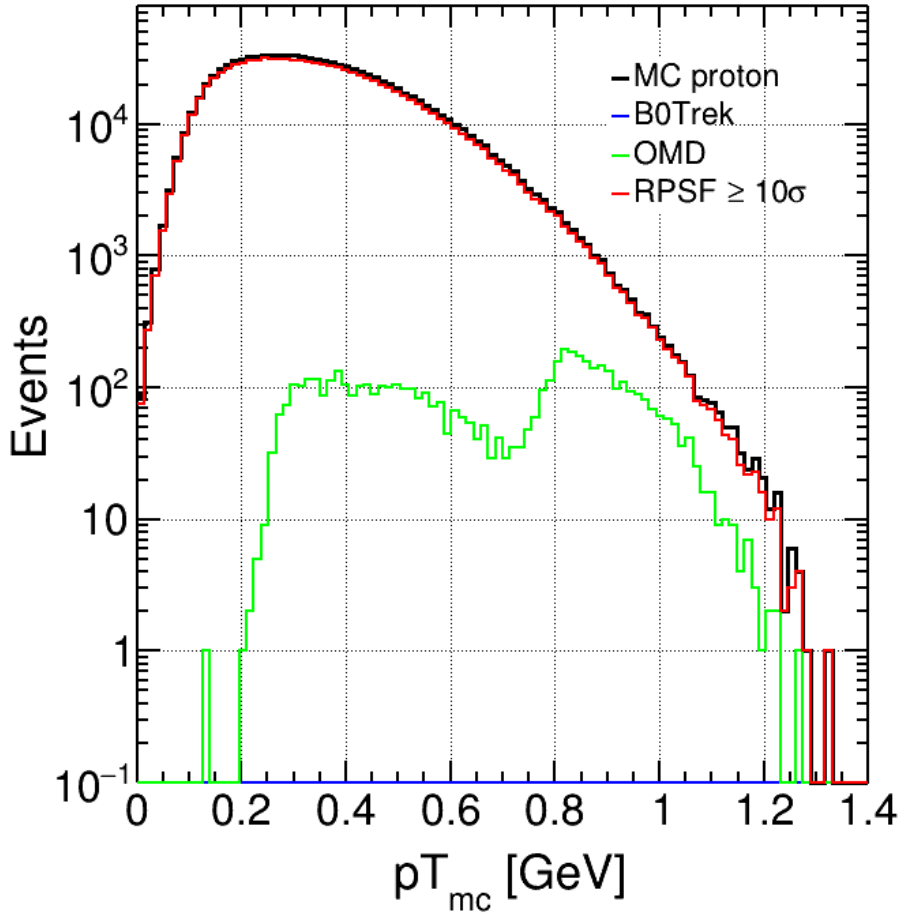
Log Scale

*Each histogram fills individually

Polar Angle



Transverse Momentum



MC
B0
OMD
RPSF

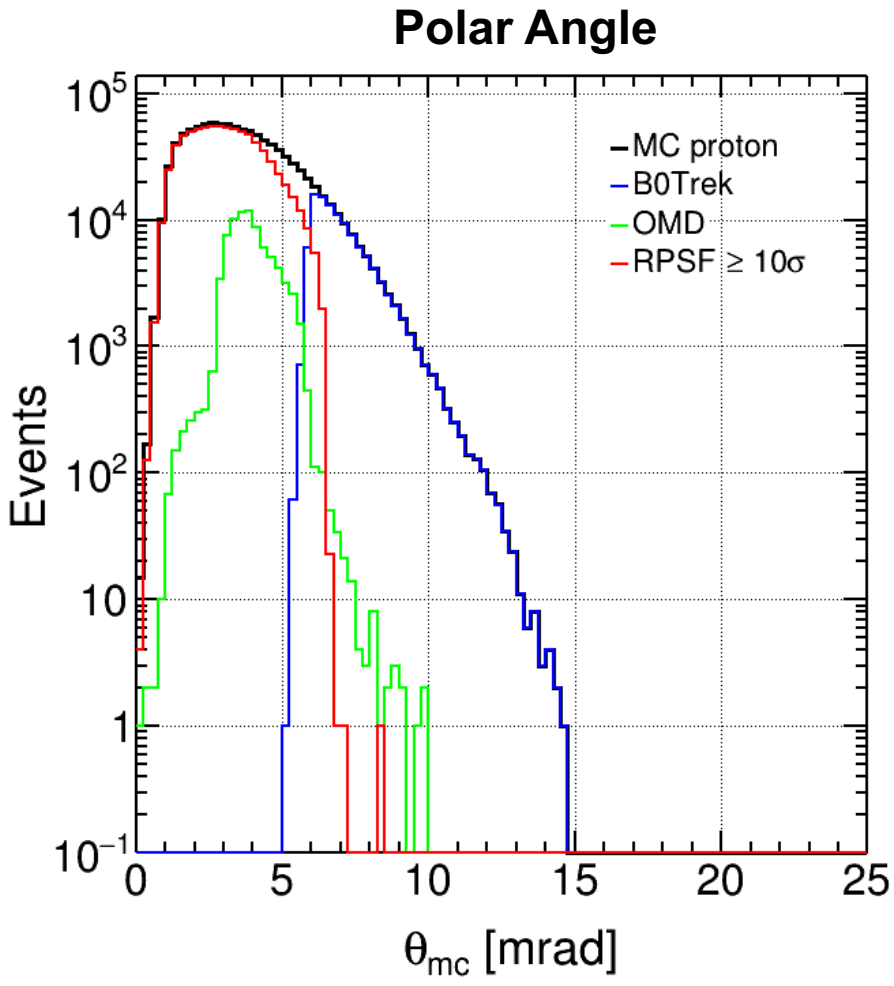
Scattered protons are very forward (< 5 mrad), measured in **Roman Pot at secondary focus**
(**93.33 %** events **accepted** with 10σ safe distance cut based on **ep 18 GeV on 275 GeV β @ IP-8 RPSF**)

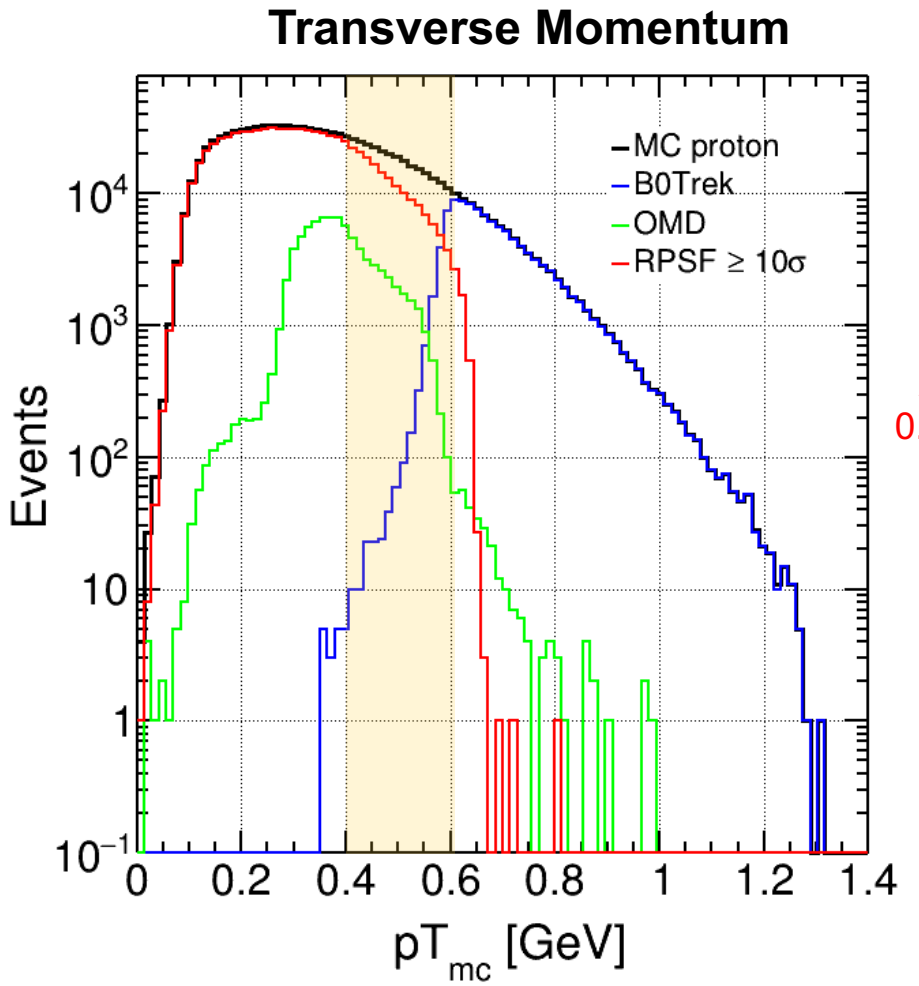
W/O Beampipe at B0

DVCS 10 GeV on 100 GeV

Log Scale

*Each histogram fills individually





MC
B0
OMD
RPSF

Acceptance gap
0.4 < pT < 0.6 GeV

Scattered protons measured in **both B0 and *Roman Pot at secondary focus** (**10.89 % and 77.71 %** events **accepted** with 10σ safe distance cut based on **ep 10 GeV on 100 GeV β @ IP-8 RPSF**)

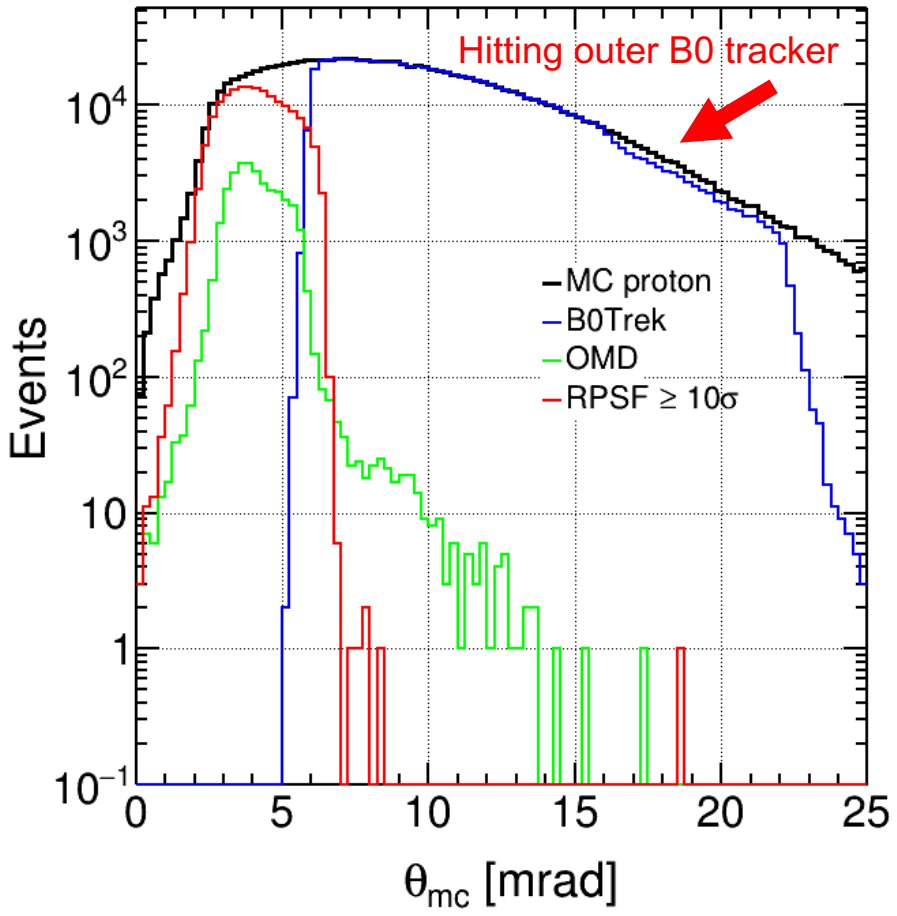
W/O Beampipe at B0

DVCS 5 GeV on 41 GeV

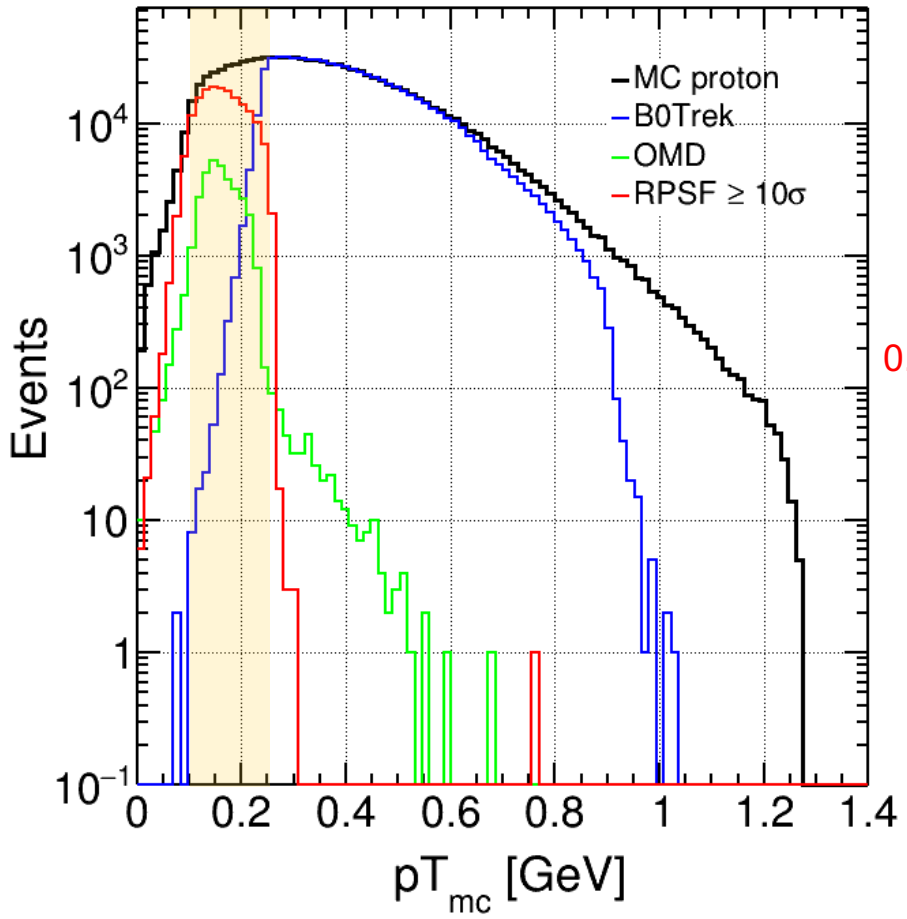
Log Scale

*Each histogram fills individually

Polar Angle



Transverse Momentum



MC
B0
OMD
RPSF

Acceptance gap
0.1 < pT < 0.25 GeV

Scattered protons measured in **both *B0 and Roman Pot at secondary focus** (**70.62 %** and **16.87 %** events **accepted** with 10σ safe distance cut based on **ep 5 GeV on 41 GeV β @ IP-8 RPSF**)

Approach – Beampipe Impact Study at B0

- How to estimate beampipe size: **15(20)σ-distance** based on **IP-6 beam parameters**
  - **Transverse beam size (σ)** is defined as

$$\sigma_{x,y} = \sqrt{\epsilon_{x,y}\beta(z)_{x,y} + (D_{x,y}\frac{\Delta p}{p})^2}$$

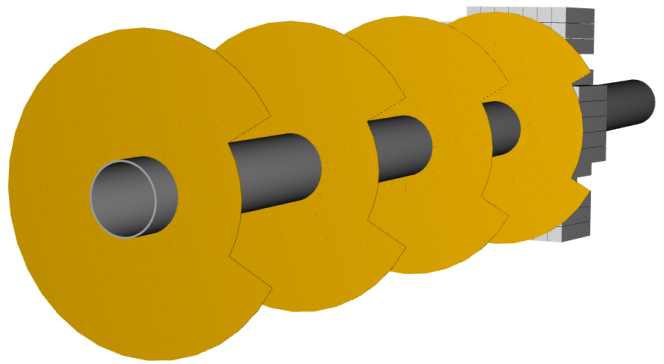
where ϵ : Emittance at z=0, $\boldsymbol{\beta}$ **: Beta function at z=B0** , D : Momentum dispersion at z=B0, $\frac{\Delta p}{p}$: Momentum spread at z=0

18 GeV on 275 GeV	σ_{1x} [mm] σ_{1y} [mm]	σ_{15x} [mm] σ_{15y} [mm]	σ_{20x} [mm] σ_{20y} [mm]
IP-6 ep High Divergence	0.96747121 0.95916659	**14.512068** **14.387499**	19.349424 19.183332

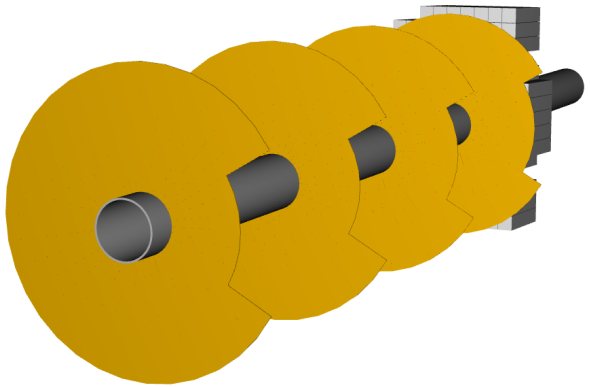
18 GeV on 110 GeV	σ_{1x} [mm] σ_{1y} [mm]	σ_{15x} [mm] σ_{15y} [mm]	σ_{20x} [mm] σ_{20y} [mm]
IP-6 eAu	1.4987997 1.8261984	**22.481996** **27.392976**	29.975994 36.523968

Beampipe thickness = 2 mm
Beampipe material = Beryllium

$r_{B0\ tracker\ inner}$ = 3.5 cm



$r_{B0\ tracker\ inner}$ = 3.0 cm



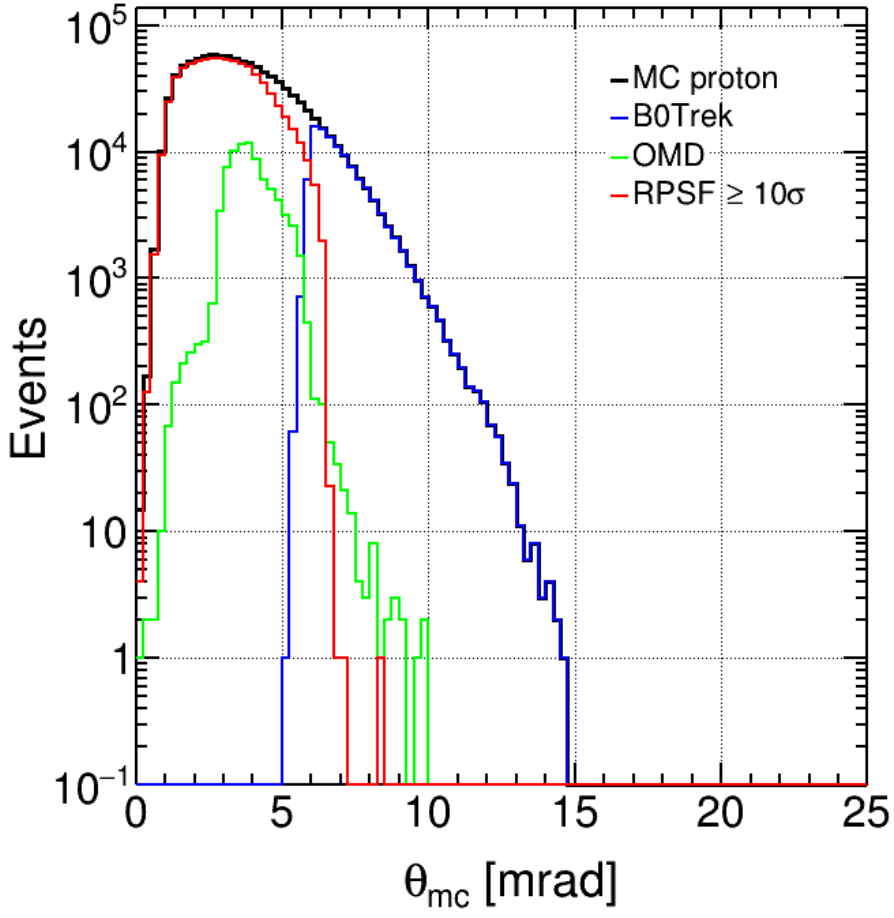
W/O Beampipe at B0

DVCS 10 GeV on 100 GeV

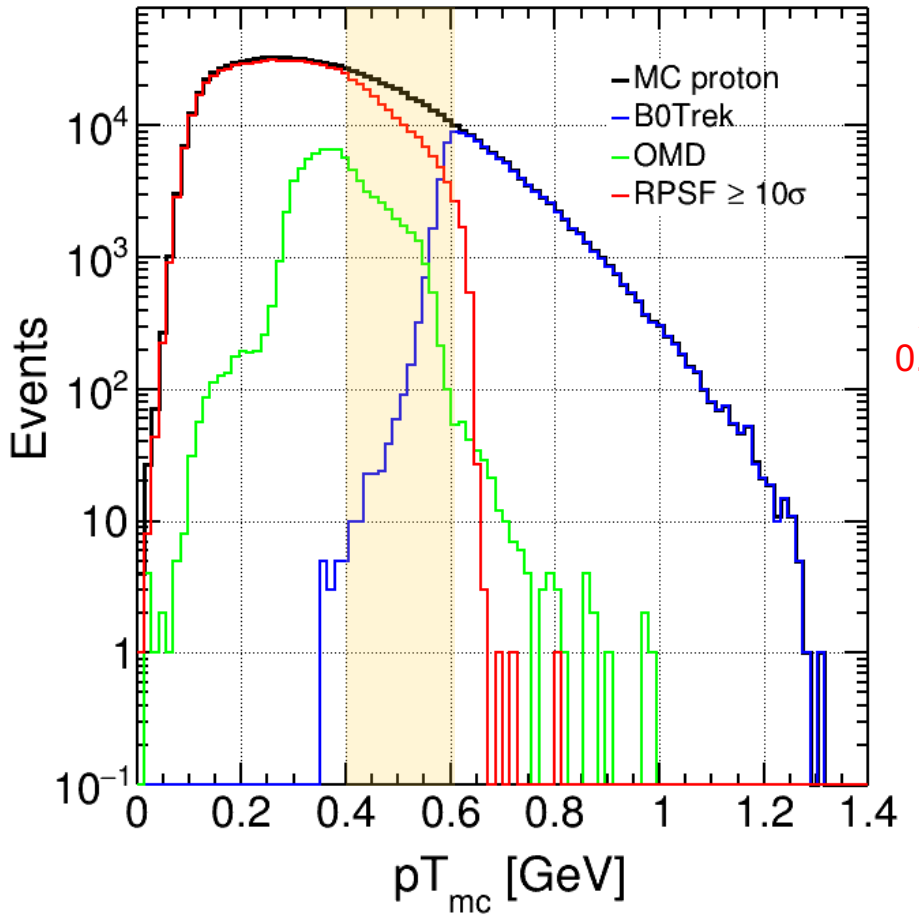
Log Scale

*Each histogram fills individually

Polar Angle



Transverse Momentum



MC
B0
OMD
RPSF

Acceptance gap
0.4 < pT < 0.6 GeV

Scattered protons measured in **both B0 and *Roman Pot at secondary focus** (**10.89 % and 77.71 %** events **accepted** with 10σ safe distance cut based on **ep 10 GeV on 100 GeV β @ IP-8 RPSF**)

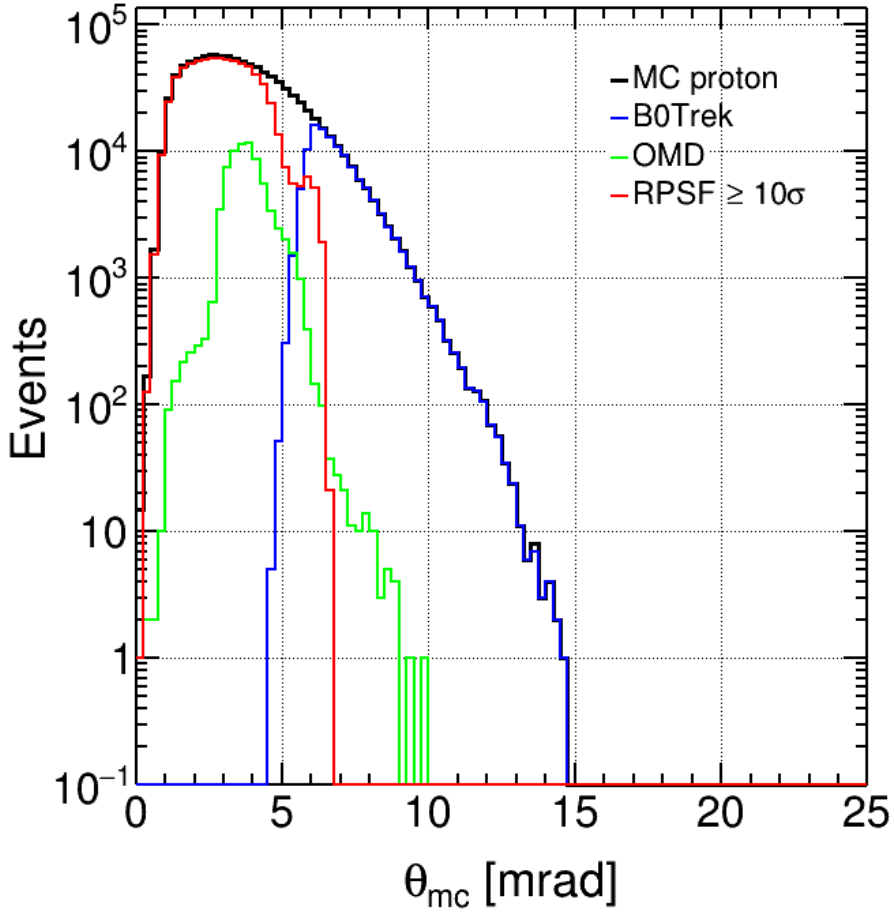
W/ Beampipe ($r_{B0\ tracker\ inner} = r_{beampipe\ outer} = 3.5$ cm) at B0

DVCS 10 GeV on 100 GeV

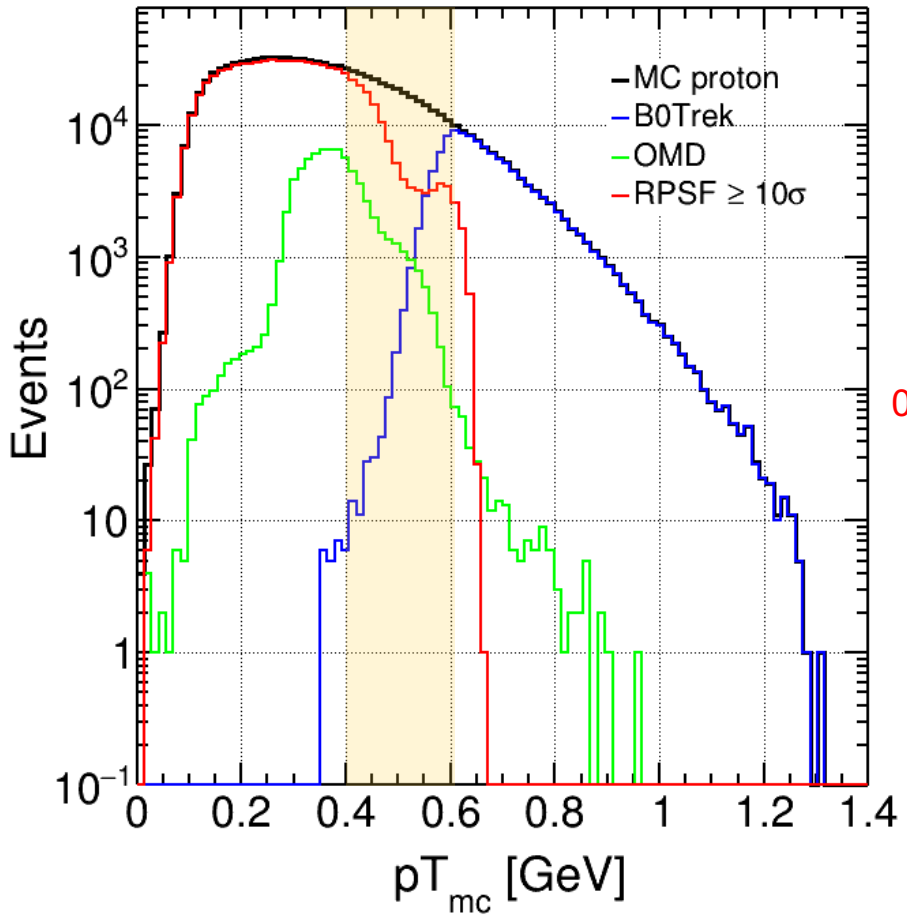
Log Scale

*Each histogram fills individually

Polar Angle



Transverse Momentum



MC
B0
OMD
RPSF

Acceptance gap stays SAME
0.4 < pT < 0.6 GeV,
But acceptance drops quite steep

Scattered protons measured in **both B0 and *Roman Pot at secondary focus** (**12.01 % and 73.32 %** events **accepted** with 10σ safe distance cut based on **ep 10 GeV on 100 GeV β @ IP-8 RPSF**)

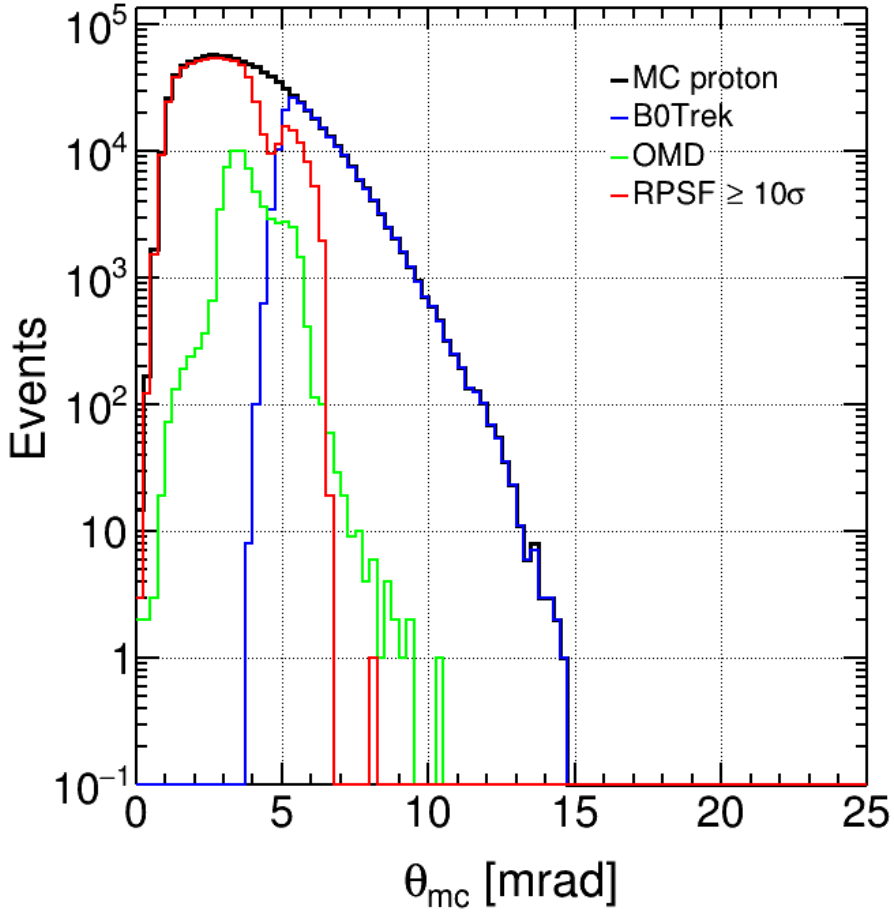
W/ Beampipe ($r_{B0\ tracker\ inner} = r_{beampipe\ outer} = 3.0$ cm) at B0

DVCS 10 GeV on 100 GeV

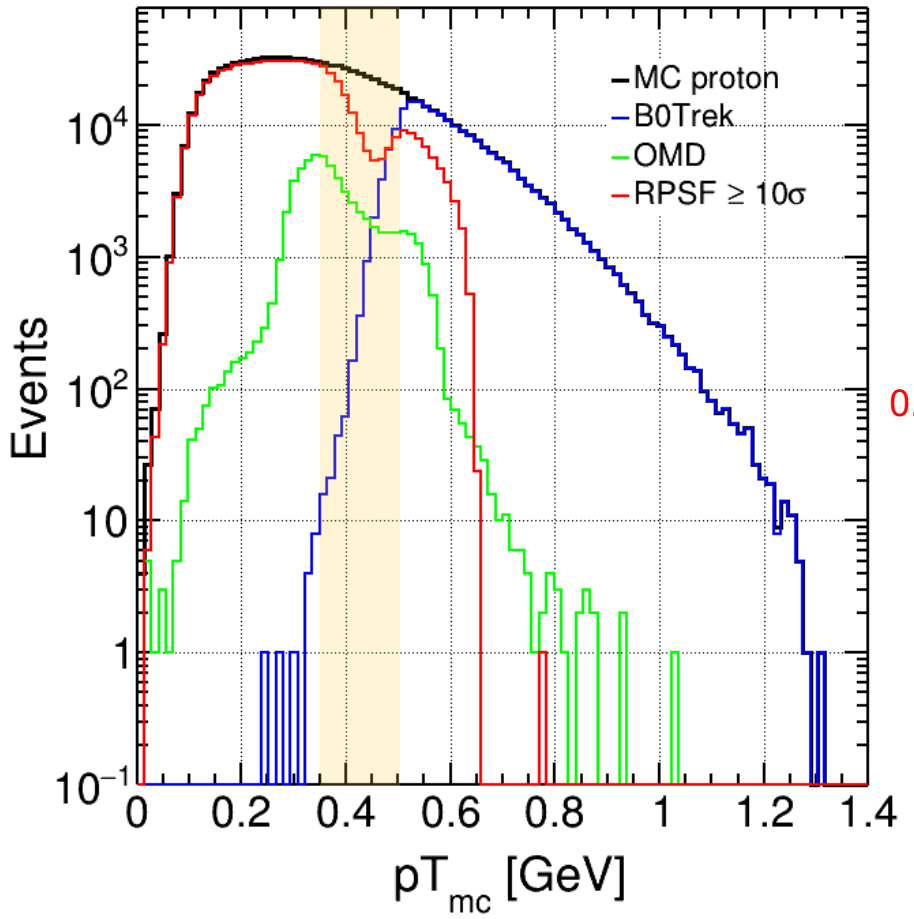
Log Scale

*Each histogram fills individually

Polar Angle



Transverse Momentum



MC
B0
OMD
RPSF

Acceptance gap moves lower pT
0.35 < pT < 0.5 GeV

Scattered protons measured in **both B0 and *Roman Pot at secondary focus** (**21.29 % and 69.62 %** events **accepted** with 10σ safe distance cut based on **ep 10 GeV on 100 GeV β @ IP-8 RPSF**)

Approach – Incoherent Vetoing Efficiency

- Understand background to coherent J/ψ production
- Used **BeAGLE** ePb 18×110 GeV incoherent $J/\psi(\mu\mu)$* 801k events with $1 < Q^2 < 10$
- Passed through **afterburner IP-8 eAu** configuration
  - IP-8 crossing angle (35 mrad) and IP-6 eAu beam effects based on **EIC CDR table 3.5**
- Discarded events having **more than one electron in final state with η < -1**
- Calculated **10σ safe distance cut** based on **eAu β @ IP-8 RPSF**
  - **Transverse beam size (σ)** is defined as $\sigma_{x,y} = \sqrt{\epsilon_{x,y}\beta(z)_{x,y} + (D_{x,y}\frac{\Delta p}{p})^2}$ where ϵ : Emittance at z=0, **β : Beta function at z=RPSF** , D : Momentum dispersion at z=RPSF, $\frac{\Delta p}{p}$: Momentum spread at z=0
- **Tagged events for nuclear breakups <u>tagging purpose</u>**
  - ZDC Hcal: **any registered RAW hits**
  - RPSF: **one layer (closet to 2nd focus)** has registered RAW hits outside **10σ** safe distance
  - OMD: **two layers** (actual four layers as redundancy) have registered RAW hits
  - B0 Tracker: **at least two out of four layers** have registered RAW hits
  - B0 Ecal: **energy** of all hits greater than **100 MeV**
  - ZDC Ecal**: energy** of all hits greater than **100 MeV**

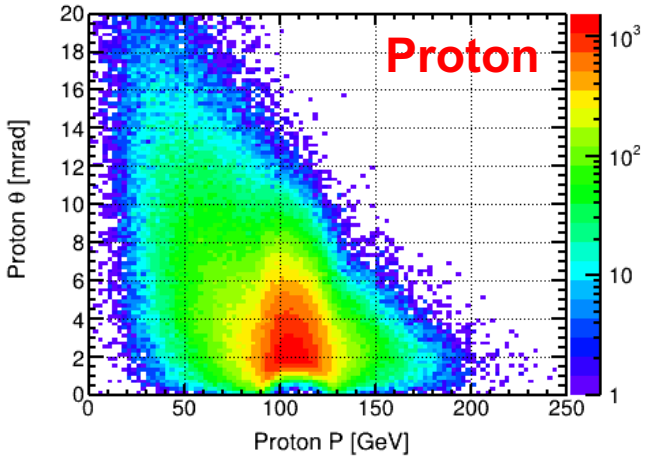
*S3/eictest/EPIC/EVGEN/EXCLUSIVE/DIFFRACTIVE_JPSI_ABCONV/BeAGLE/ePb_18x108.41_tau10_B1.1_Jpsi_highstats/ePb_18x108.41_tune3_tau10_B1.1_extracted_Jmu_1.hepmc

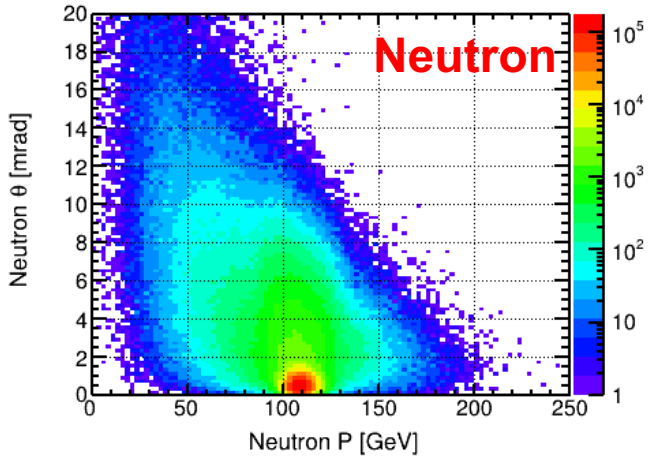
Nuclear Breakups Distribution

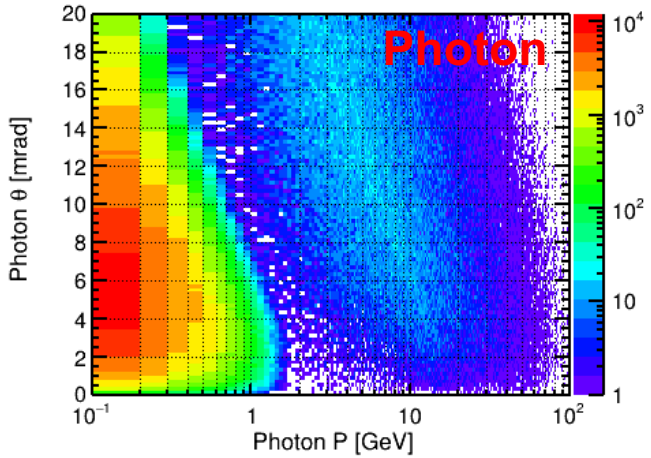
BeAGLE 18x110 GeV^2
Incoherent events
$ePb \rightarrow e' + J/\psi(\mu\mu) + X$

Generated Level	Nuclear Breakups at Final State	Number of Events
	Only Neutrons	7.55 %
	Only Protons	0.0004 %
	Only Photons	3.24 %
	Neutrons + Protons	3.28 %
	Neutrons + Photons	43.98 %
	Protons + Photons	2.24 %
	Neutrons + Protons + Photons	39.72 %

94.53 % of events have **neutrons** in nuclear breakups



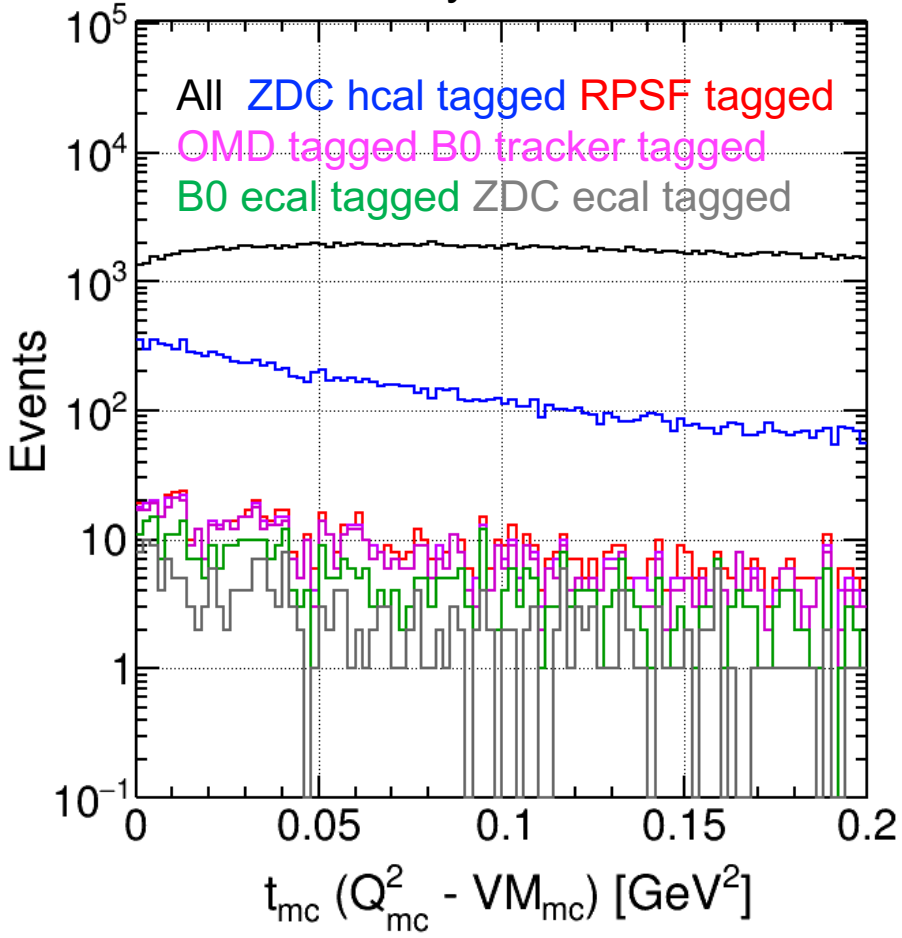




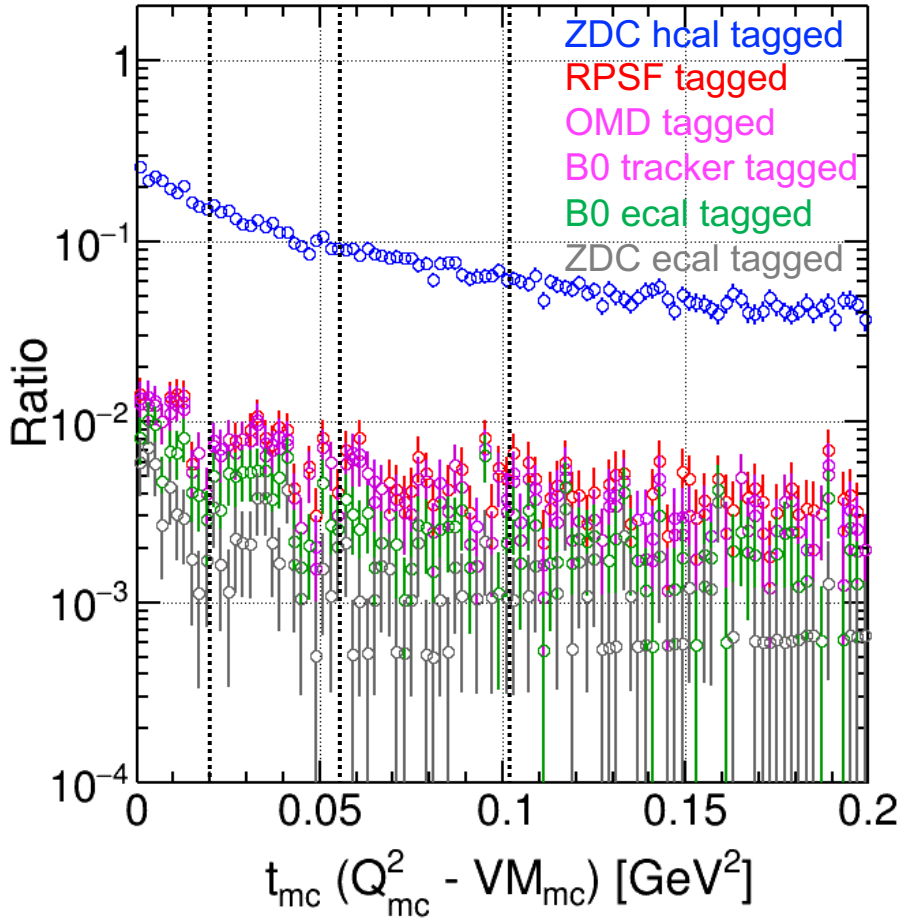
t distribution

BeAGLE 18x110 GeV^2
Incoherent events
$ePb \rightarrow e' + J/\psi(\mu\mu) + X$

Veto inefficiency for incoherent events



Coherent diffractive minima

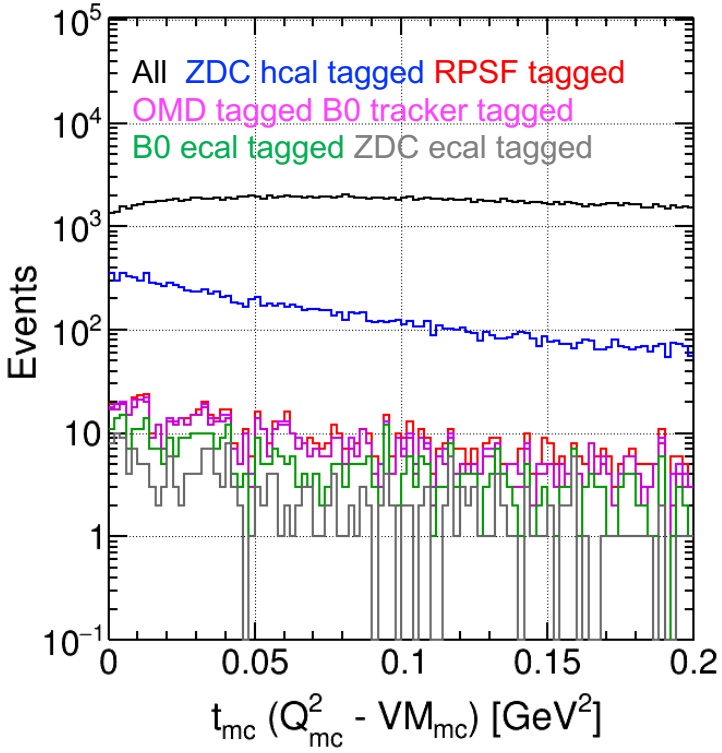


Found to be enough to suppress incoherent contribution at three minima
Vetoing efficiency is about 99.99%

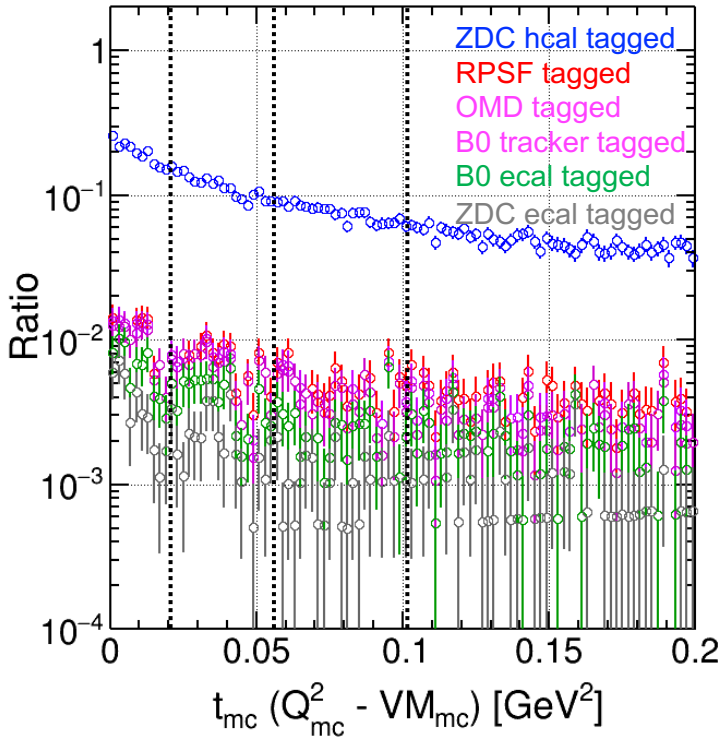
t distribution

BeAGLE 18x110 GeV^2
Incoherent events
$ePb \rightarrow e' + J/\psi(\mu\mu) + X$

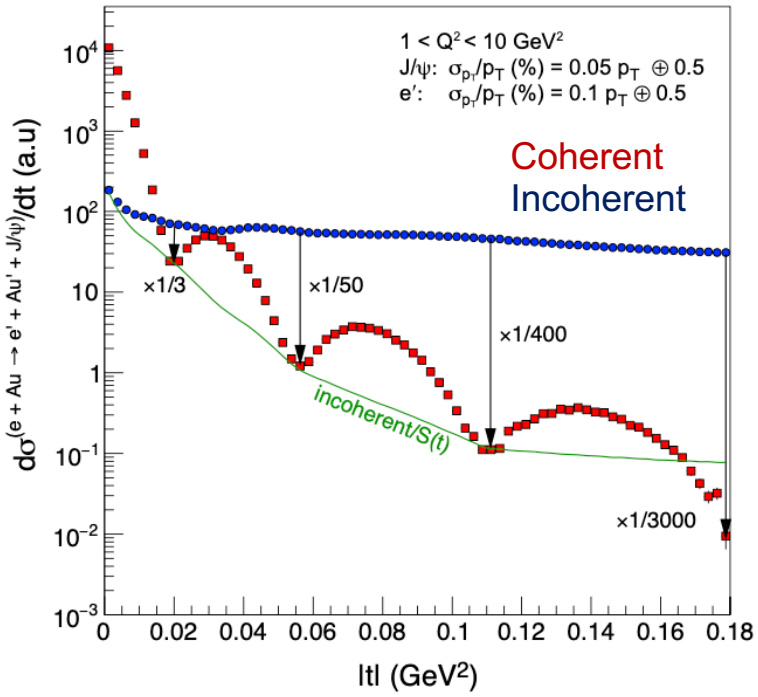
Veto inefficiency for incoherent events



Coherent diffractive minima



Reference from EIC YR p.352



At position of third diffractive minimum, rejection factor for incoherent event better than 400:1 must be achievable

Found to be enough to suppress incoherent contribution at three minima
Vetoing efficiency is about 99.99%

Remaining Events

BeAGLE 18x110 GeV^2
Incoherent events
$ePb \rightarrow e' + J/\psi(\mu\mu) + X$

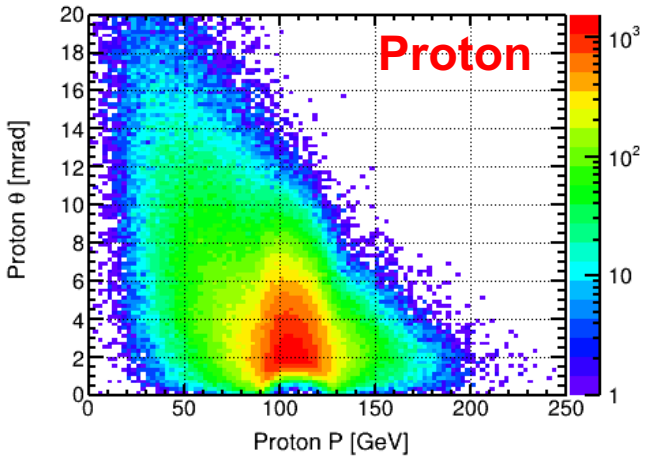
Veto Selections	Surviving Events
All events	801,464
Events with one scattered electron identified and $\lvert\eta_{J/\psi}\rvert < 4$	711,795 (100.0 %)
ZDC HCAL tagged	41,751 (5.86559 %)
+ RPSF tagged	2,785 (0.391264 %)
+ OMD tagged	2,484 (0.348977 %)
+ B0 tracker tagged	1,994 (0.280137 %)
+ B0 ecal tagged	1,257 (0.176596 %)
+ ZDC ECAL tagged	589 (**0.0827485 %**)

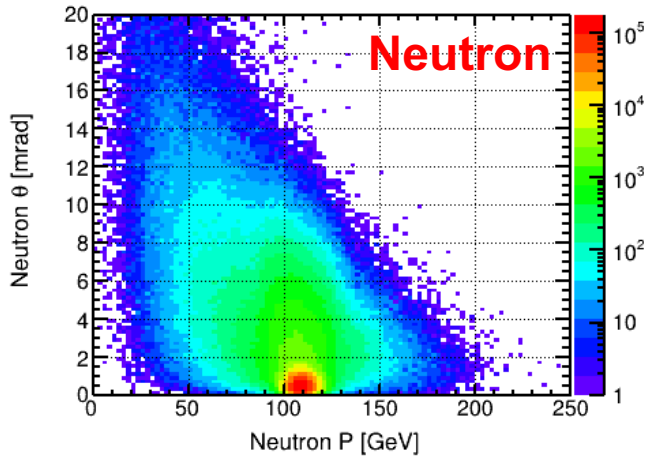
With 10σ safe distance cut based on ***eAu β @ IP-8 RPSF***
589 of 801,464 events were NOT vetoed

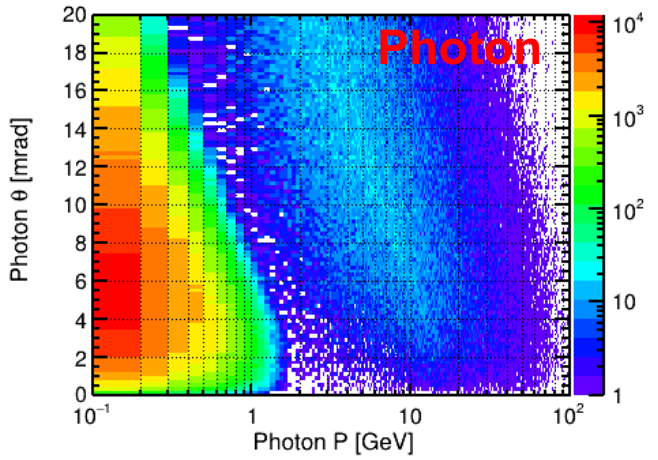
Remaining Events

BeAGLE 18x110 GeV^2
Incoherent events
$ePb \rightarrow e' + J/\psi(\mu\mu) + X$

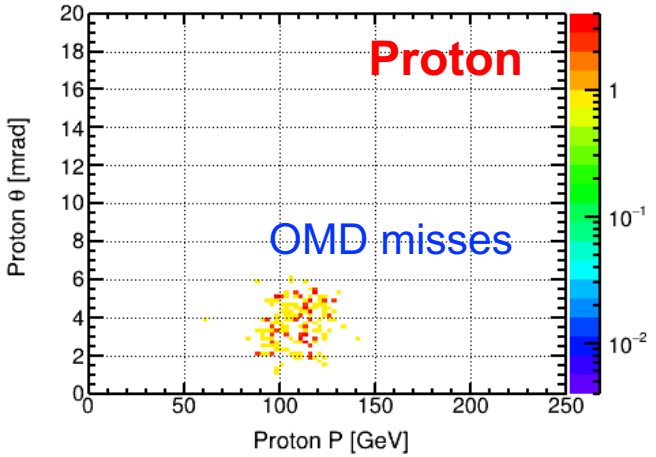
Generated level

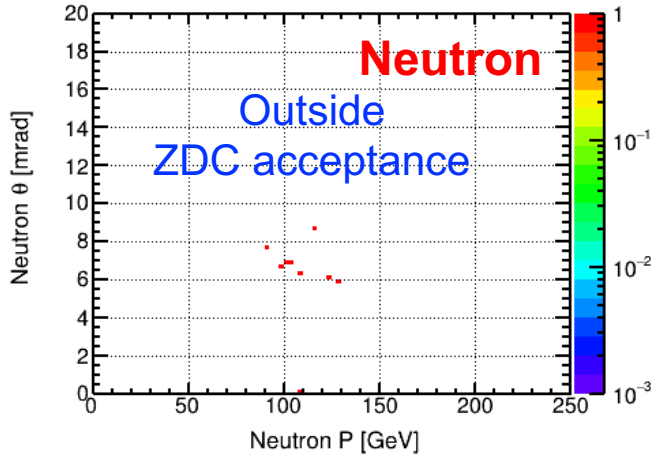


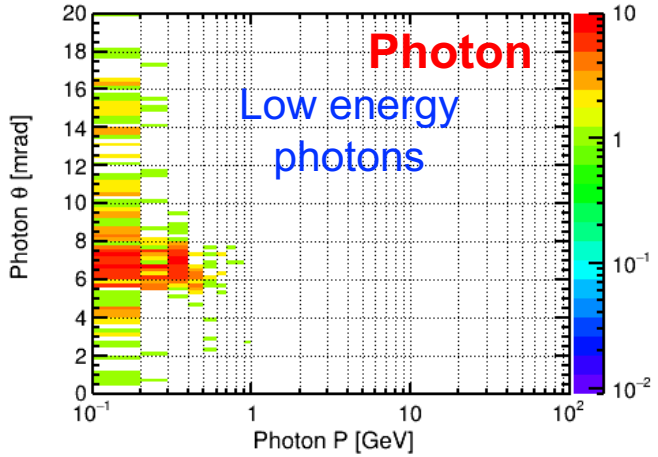




Remained level







Summary

- With basic components are in-place in EIC 2nd detector DD4hep simulation, checked IP8 acceptance on each far-forward detectors (B0, OMD, ZDC, and RPSF)
  - Acceptance and things can change as this is still pre-conceptual design (magnets, space, etc)
- Using exclusive DVCS events, understanding acceptance gap in pT between B0 and RPSF
  - Acceptance gap depends on aperture size
  - Difficult to remove acceptance gap, but complementary detector may make different acceptance gap region so that it covers all pT acceptance for scattered proton using both IP-6 and IP-8
- Using BeAGLE incoherent events, evaluating vetoing power to understand background to coherent events with $1 < Q^2 < 10$ and $t < 0.2$
  - Used latest beam optics study for IP8 ep(eAu) especially for secondary focus
  - Vetoing power reaches ~10^{-3} at three coherent diffractive minima

Next Steps

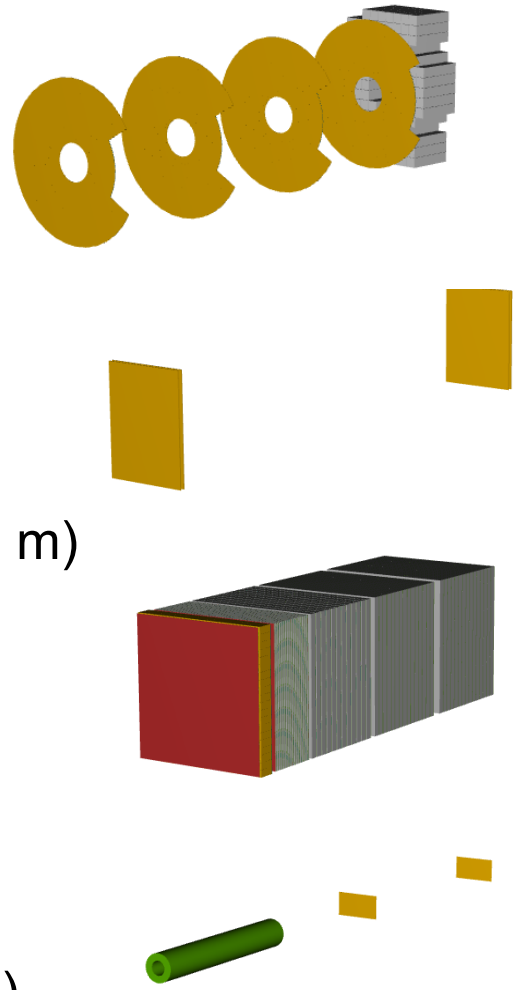
- Recently more realistic beam optics for IP-8 thanks to Randy
  - Update forward beamline – this will affect on detector acceptance
    - Coordinates of magnets and magnetic fields
    - Expect small impact in acceptance. Need to re-evaluate
    - eAu lattice study coming up (so far, ep lattice study with different beam configurations)
- Look into events without beam effects
  - Current sample with beam effects has more (transverse) momentum-kick
  - Evaluate vetoing power on detector response
- Implement beampipe between OMD-ZDC-RPSF to study beampipe impact

Backup Slides

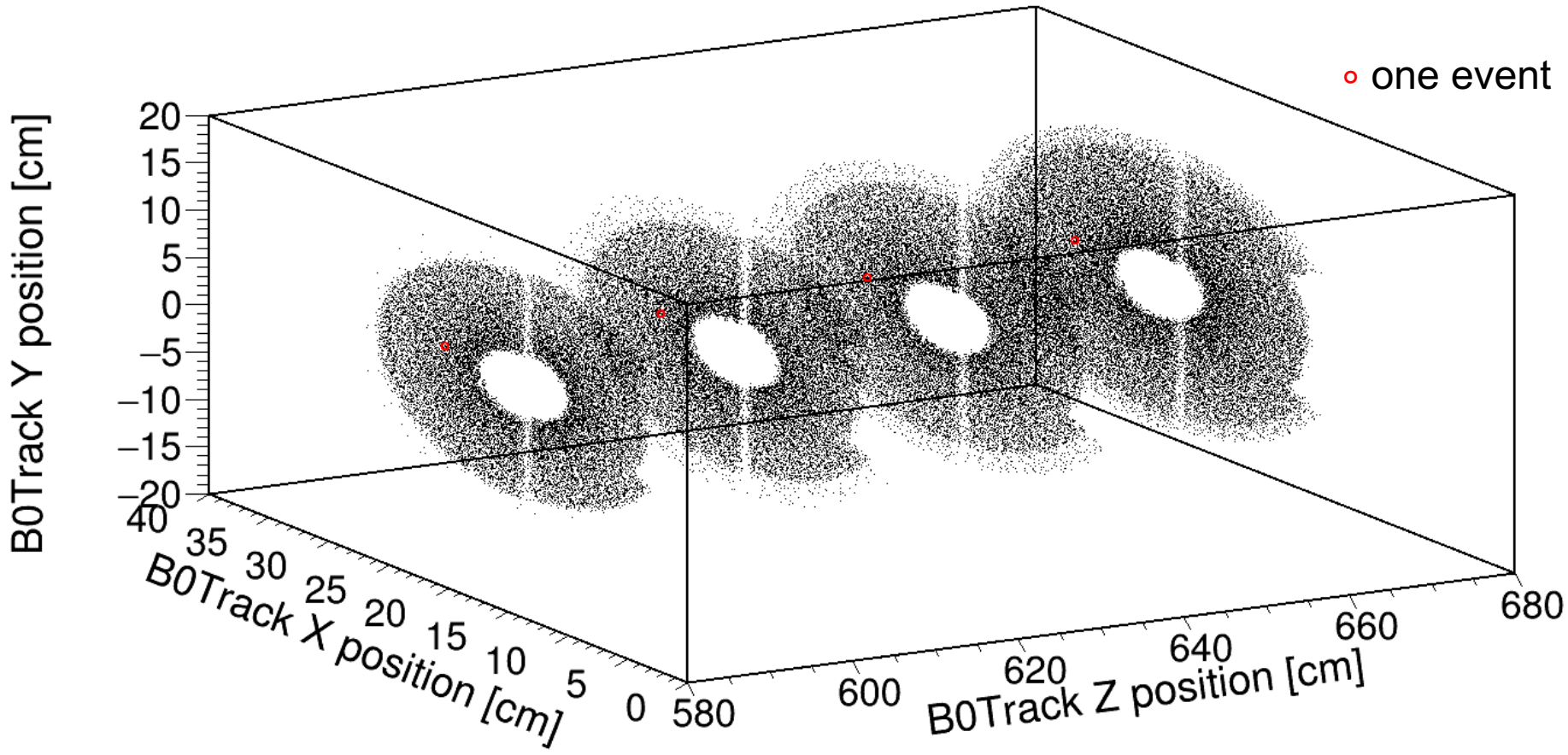
IP-8 Far-Forward Detectors

Implemented in **IP-6 detector configuration**

- **B0 Spectrometer (Tracker + Calorimeter)**
  - 4 tracker planes and 10 cm long crystal module
  - Placed at z = 0.06 m
- **Off Momentum Detector (OMD)**
  - 40 cm tall and 30 cm wide
  - Placed at (x, z) = (0.723133 m, 25.9359 m) and (0.702435 m, 27.9363 m)
- **Zero Degree Calorimeter (ZDC)**
  - 2 meter-long and 60 × 60 cm^2
  - Placed at (x, z) = (1.3798 m, 35.4293 m front)
- **Roman Pot at Secondary Focus (RPSF)**
  - 14 cam tall and 26 cm wide
  - Placed at (x, z) = (1.00603 m, 43.9339 m) and (1.03788 m, 45.4337 m)



B0 Tracker


one event
B0Track Y position [cm]
20
15
10
5
0
−5
−10
−15
−20
B0Track X position [cm]
40
35
30
25
20
15
10
5
0
B0Track Z position [cm]
580
600
620
640
660
680

pT Acceptance from EIC YR

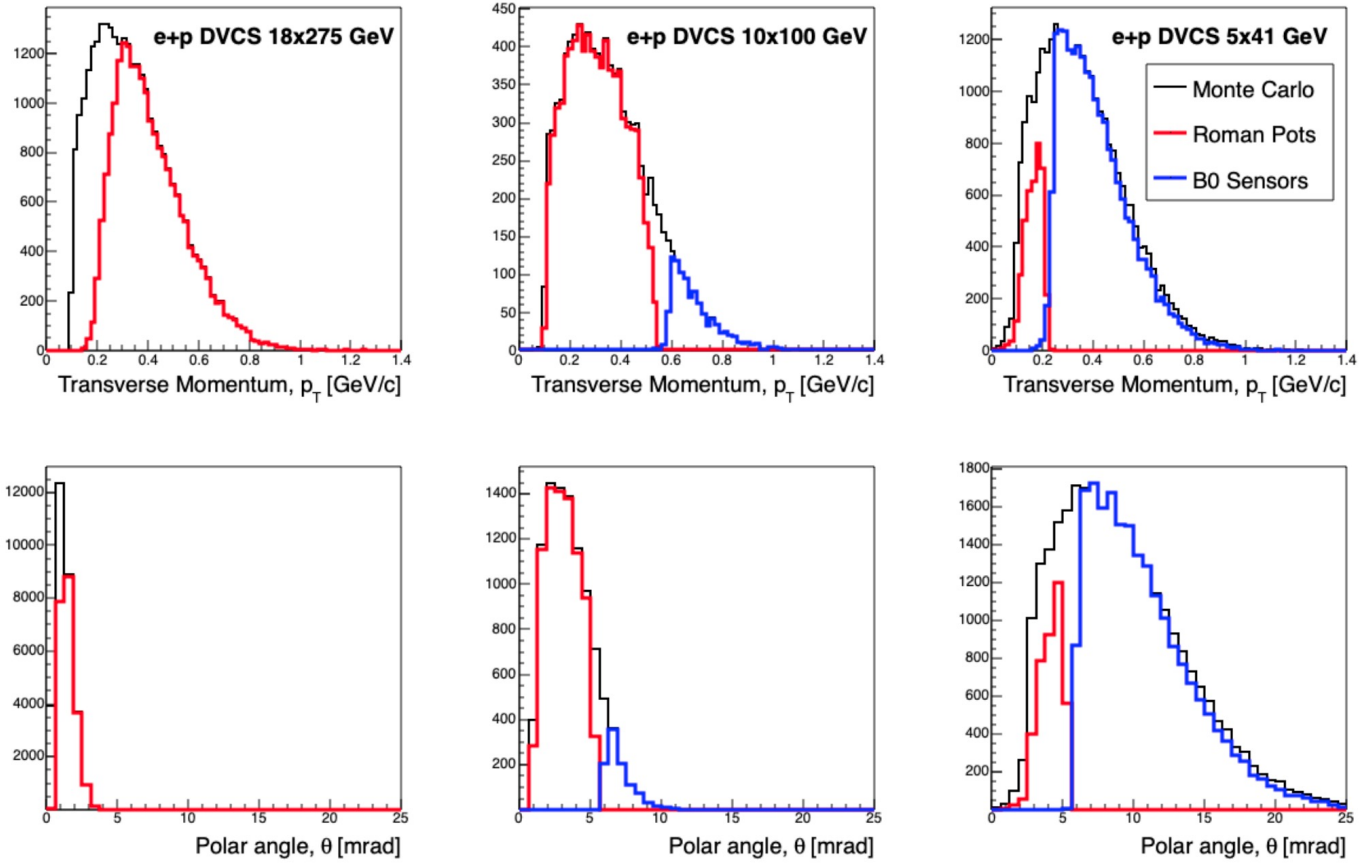
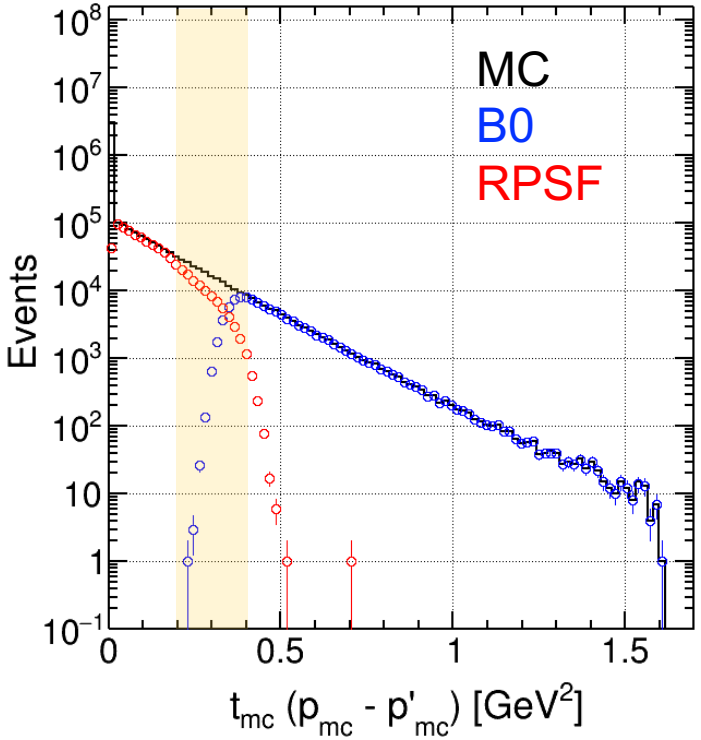


Figure 11.98: p_T (top row) and polar angle (bottom row) acceptance for three different beam energy configurations: 18x275 GeV (left), 10x100 GeV (middle), and 5x41 GeV (right). The black data in each figure represent the MC information from MILOU, the red lines are the accepted particles in the Roman Pots, and the blue lines are particles accepted in the B0 sensors.

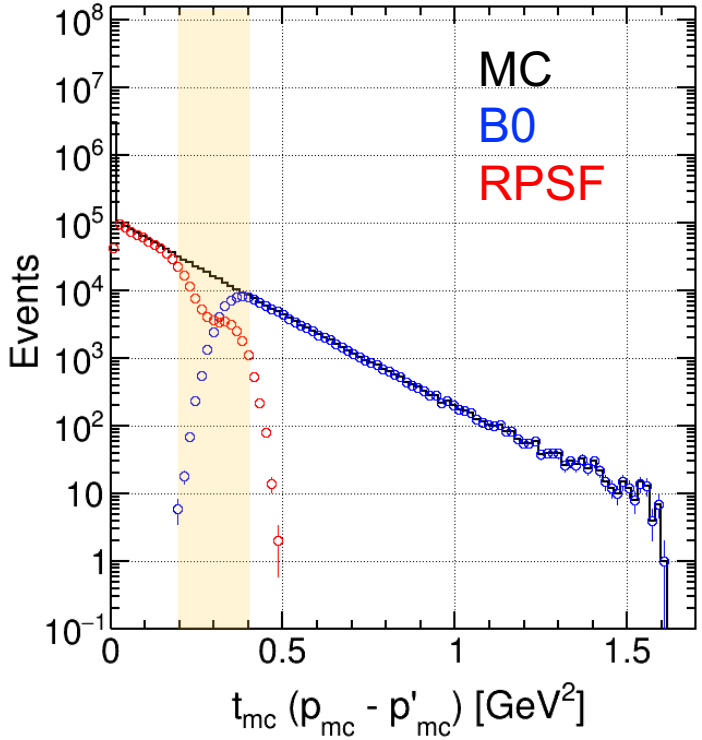
From EIC YR p.564

DVCS 10 GeV on 100 GeV

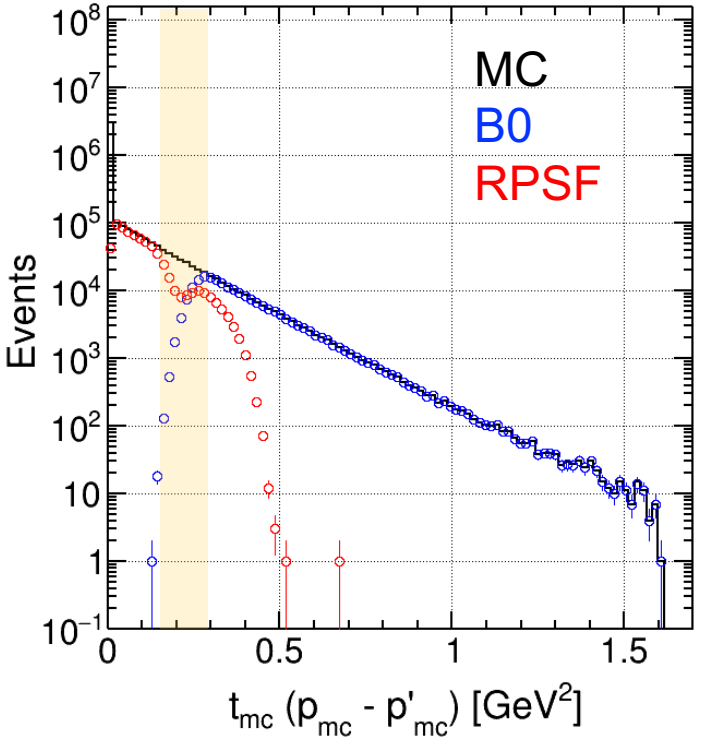
W/O Beampipe at B0



W/ Beampipe ($r_{beampipe\ outer}$ = 3.5 cm) at B0



W/ Beampipe ($r_{beampipe\ outer}$ = 3.0 cm) at B0



IP-8 Beam Parameter

- Randy sent IP-8 lattice study for ep 18GeV on 275 GeV configuration

18 GeV on 275 GeV	Momentum Dispersion ($D^{\text{secondary focus}}$)	Emittance X (ϵ_x*) [mm]	Emittance Y(ϵ_y*) [mm]	Beta function X ($\beta_x^{\text{secondary focus}}$) [mm]	Beta function Y ($\beta_y^{\text{secondary focus}}$) [mm]	Momentum spread ($\Delta p/p$)*
IP8 ep High Divergence	**0.465446718**	18.e-6	1.6e-6	**498.013008**	**3392.376638**	6.8e-4
18 GeV on 110 GeV	**Momentum Dispersion ($D^{\text{secondary focus}}$)**	**Emittance X (ϵ_x*) [mm]**	**Emittance Y(ϵ_y*) [mm]**	**Beta function X ($\beta_x^{\text{secondary focus}}$) [mm]**	**Beta function Y ($\beta_y^{\text{secondary focus}}$) [mm]**	**Momentum spread ($\Delta p/p$)***
IP8 eAu	**0.465446718**	43.2e-6	5.8e-6	**498.013008**	**3392.376638**	6.2e-4

- Transverse beam size (σ) calculation at secondary focus

$$\sigma_{x,y} = \sqrt{\epsilon_{x,y}\beta(z)_{x,y} + (D_{x,y}\frac{\Delta p}{p})^2}$$

where ϵ : Emittance at z=0, $\boldsymbol{\beta}$ **: Beta function at z=RPSF** , D : Momentum dispersion at z=RPSF, $\frac{\Delta p}{p}$: Momentum spread at z=0

	σ_{1x}	σ_{1y}
eAu β @ IP8 RPSF	**0.146677**	**0.140271**

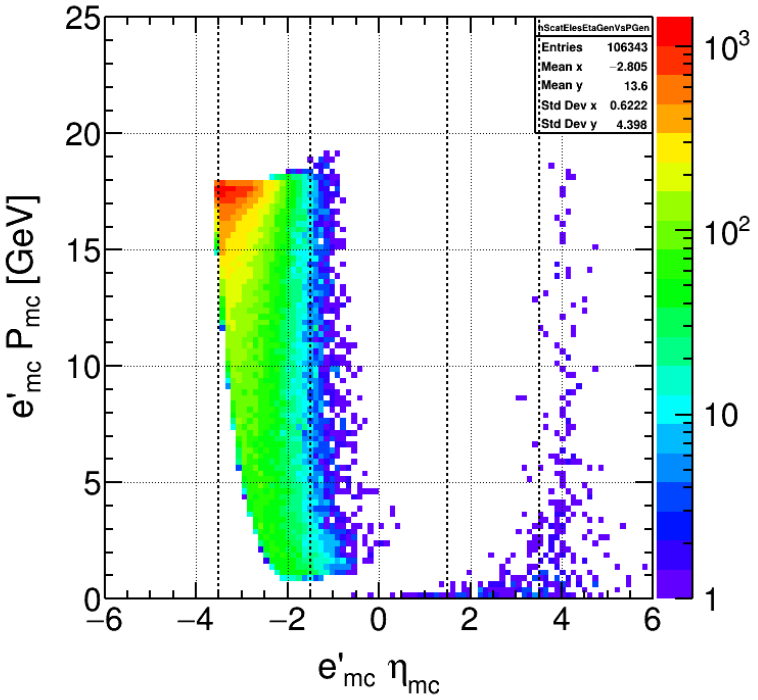
Candidates for e’

Final-state Electrons

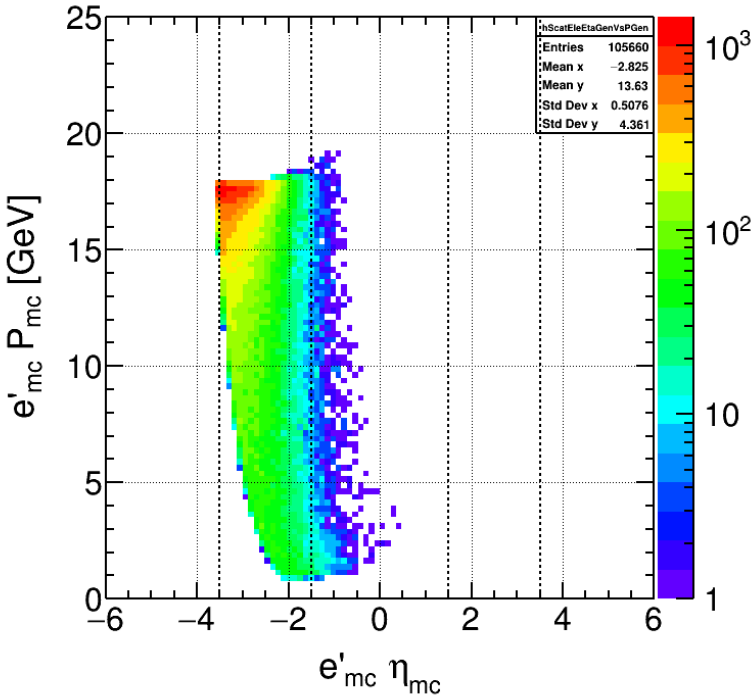
BeAGLE 18x110 GeV^2
Incoherent events
$ePb \rightarrow e' + J/\psi(\mu\mu) + X$

Within BeAGLE incoherent J/ψ events, there can be multiple electrons in final-state
If there are multiple electrons, take electron having less than -1 in rapidity
However, more than one electron heading backward (η < -1), then discard for now

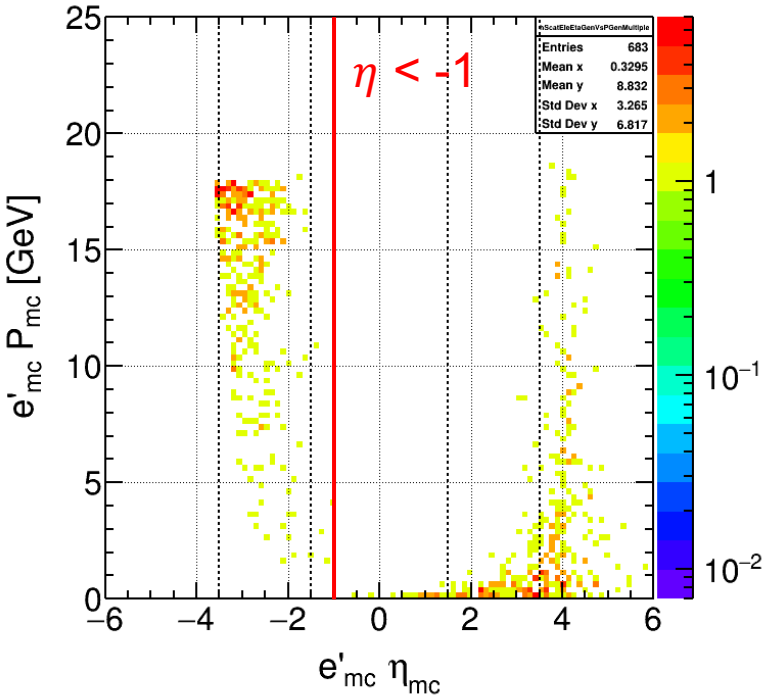
All Electrons



Only One Electron

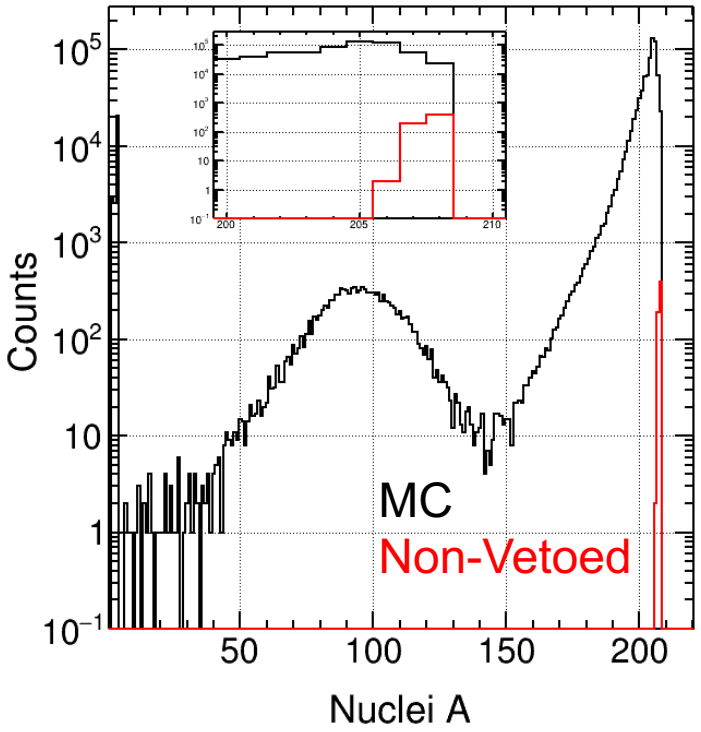


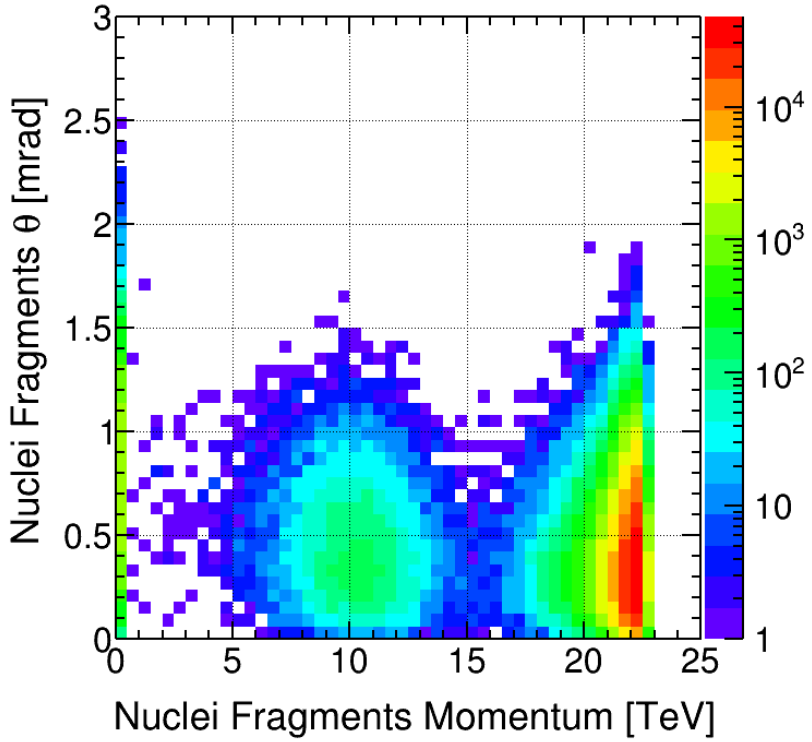
More than One Electron

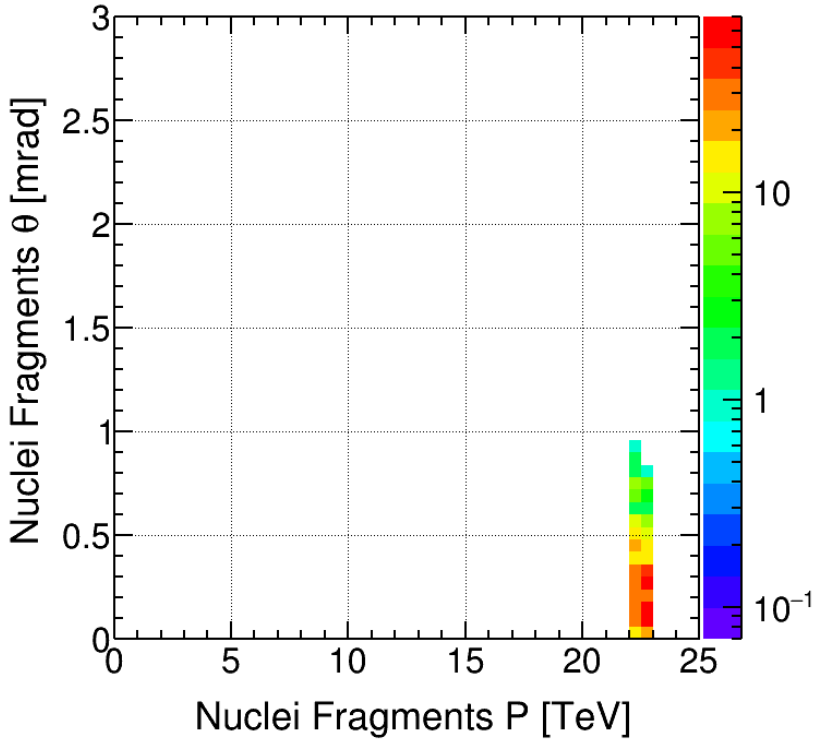


Remaining Events

BeAGLE 18x110 GeV^2
Incoherent events
$ePb \rightarrow e' + J/\psi(\mu\mu) + X$



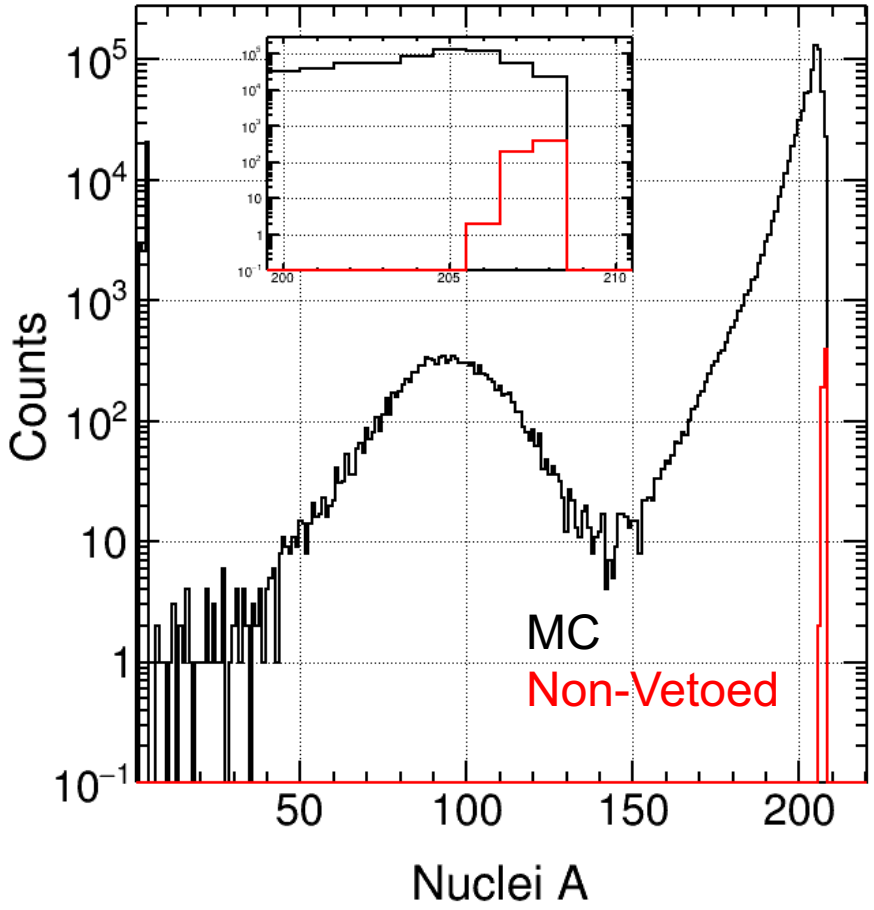


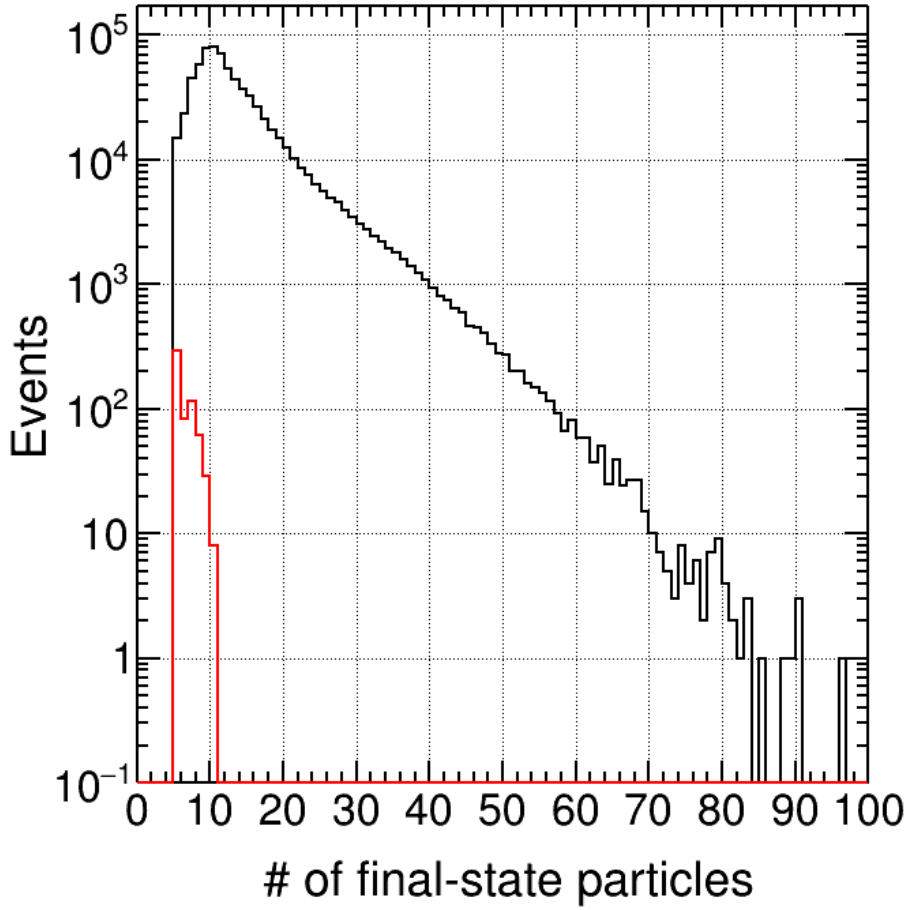


Remaining (surviving) events have higher mass nuclear remnants and low particle multiplicity

Remaining Events

BeAGLE 18x110 GeV^2
Incoherent events
$ePb \rightarrow e' + J/\psi(\mu\mu) + X$





Remaining (surviving) events have higher mass nuclear remnants and low particle multiplicity