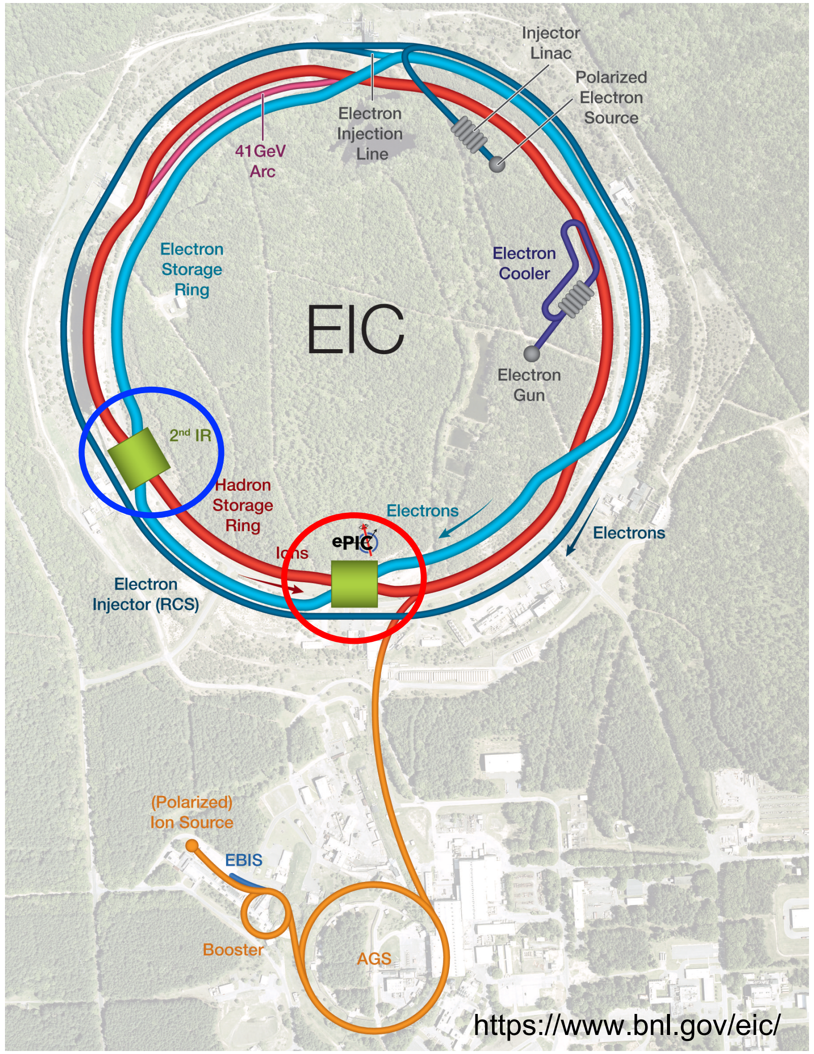
Update on EIC 2nd Detector Study – Far-Forward Focus

Jihee Kim (jkim11@bnl.gov)

2024/05/09

Brookhaven National Laboratory

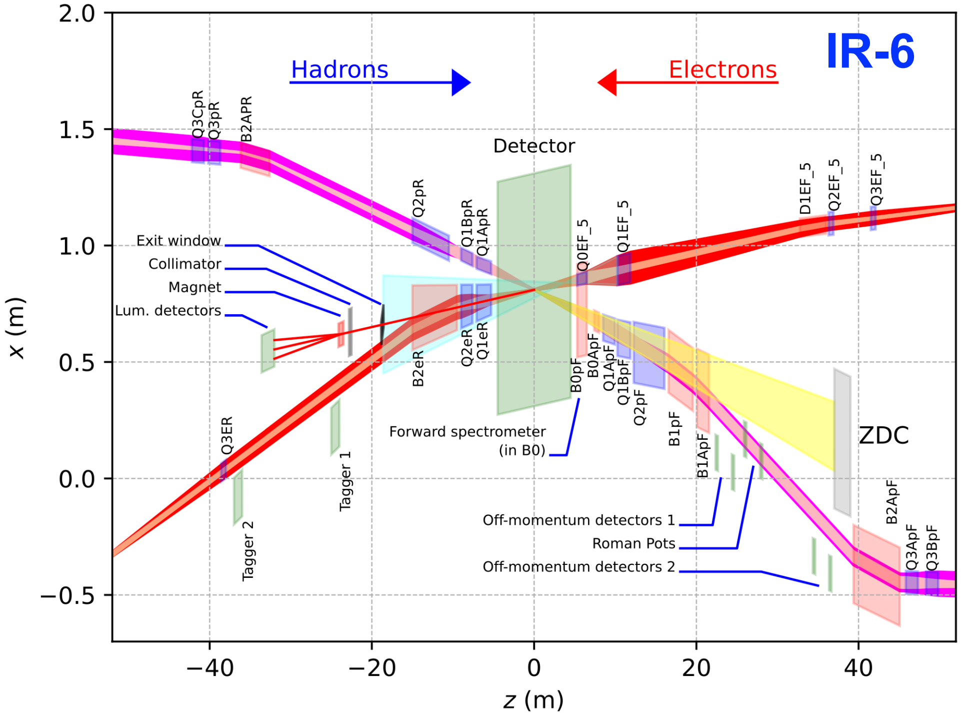
EIC 2nd Detector Motivation



- EIC Design
  - Two interaction points (IP-6 and IP-8)
  - Two interaction regions (IR-6 and IR-8)
- **Detector 1,** called **ePIC,** locates at **IP-6**
- Favors to accommodate the **second detector** and a **second interaction region**
- **A general-purpose collider detector** to support full EIC program (**complementarity**)
  - **Cross-checks & control of systematics**
  - Subdetector technologies
  - Magnetic field
  - **Broaden physics program (different physics focuses)**

EIC Interaction Regions

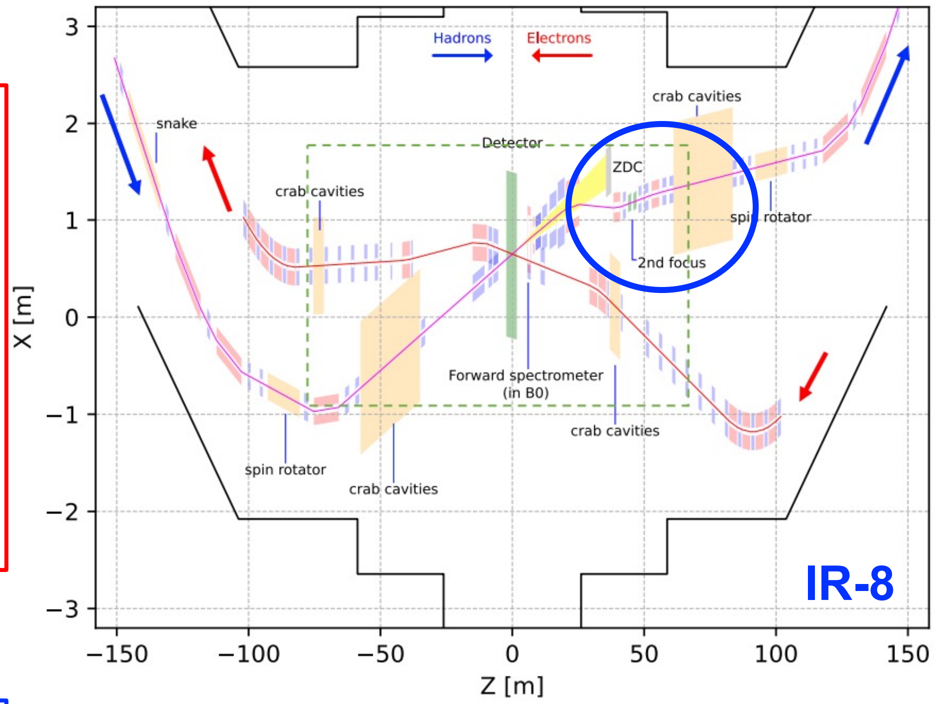
Requires specialized detectors integrated in the interaction region over 80 m



Same
Accelerator highlights and challenges

Luminosity at both IRs

Center-of-mass energy coverage



Crossing angle: **25 mrad**

IR-Design:
0.2 GeV < p_T < 1.3 GeV

Different
Blind spots

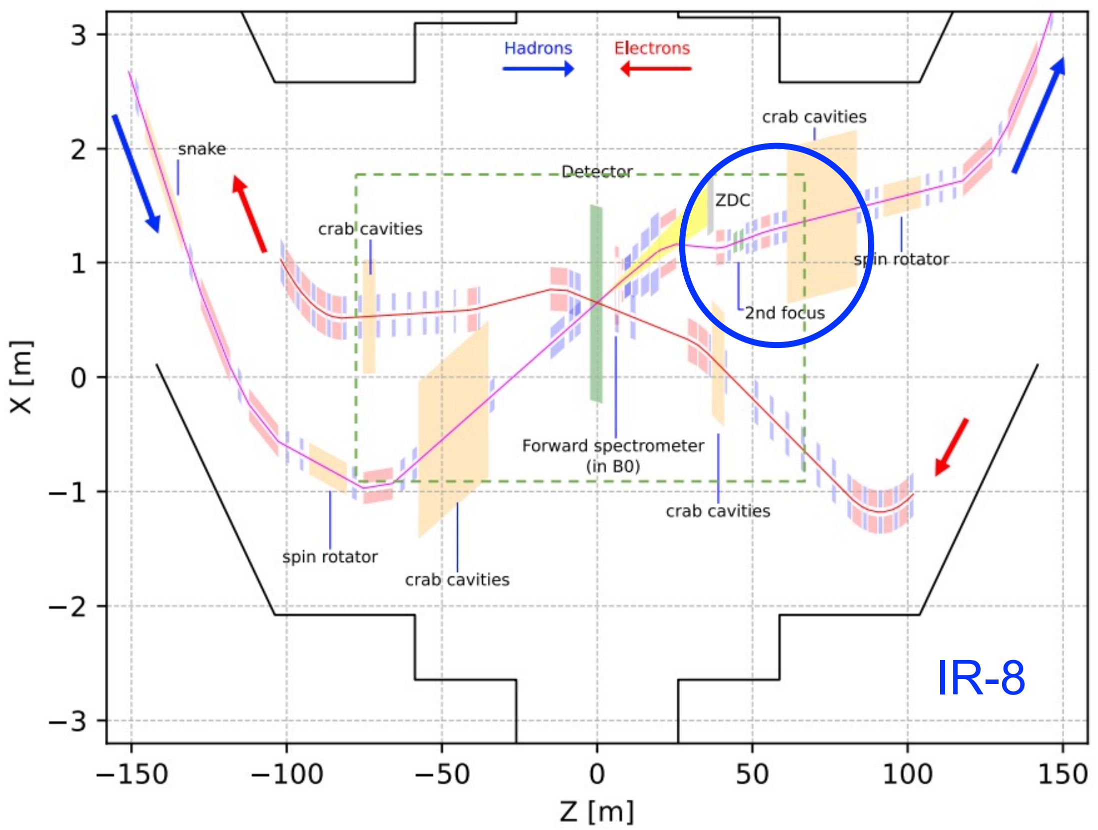
Far-forward detector acceptances

Crossing angle: **35 mrad**

IR-Design:
2nd "beam optics" focus
comes with challenges (ex. magnet design) in accelerator machine

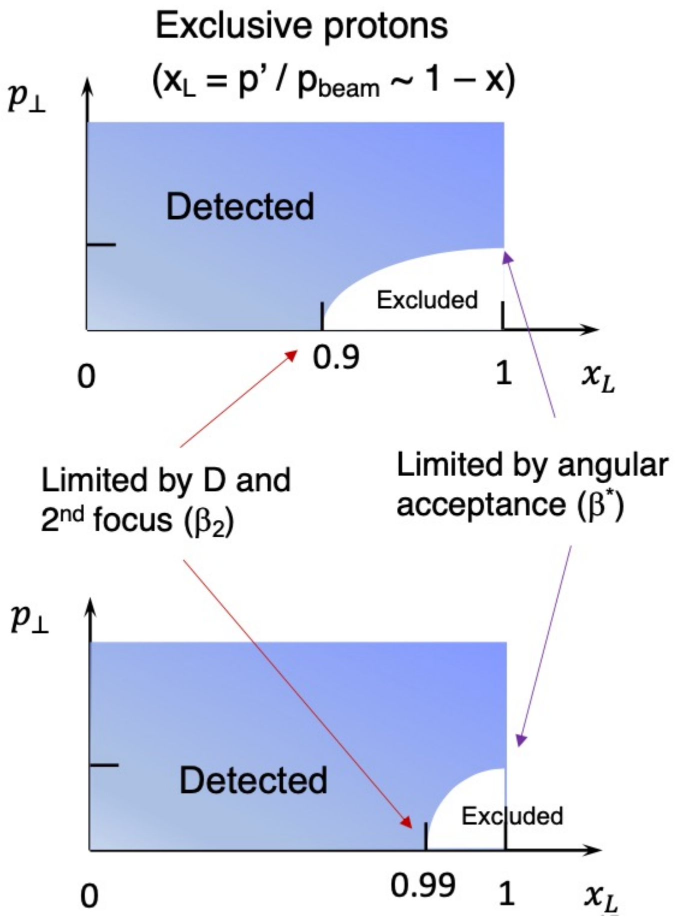
IR Concept – 2nd Focus in Far-Forward

- By adding additional magnet to focus beam ~ 45 m downstream from interaction point
- This is NOT detector design, but it is **machine design that detector can be benefit from**
- 2nd focus enables
  - Higher probability to **detect low p_T (< 250 MeV) particles**
  - Detects near-beam particles where get out beam envelop
- **Complementary to ePIC: exclusive, tagging, and diffractive physics analysis**



Physics Opportunities with 2nd Focus

- 2nd focus in IR8 greatly improves **forward acceptance**
- Complementarity with Detector 1 (ePIC) @ IR-6
- **Excellent low-p_T acceptance** for protons and light nuclei from exclusive reactions **at very low t**
- **Detection of target fragments** makes it possible
  - To veto breakup to study coherent process
  - To study final state when breakup occurs
- Coherent diffraction on heavy nuclei by vetoing breakups
- Rare isotopes detection and identification of heavy fragments



Order-of-magnitude improvement in forward acceptance

Physics Opportunities with 2nd Focus

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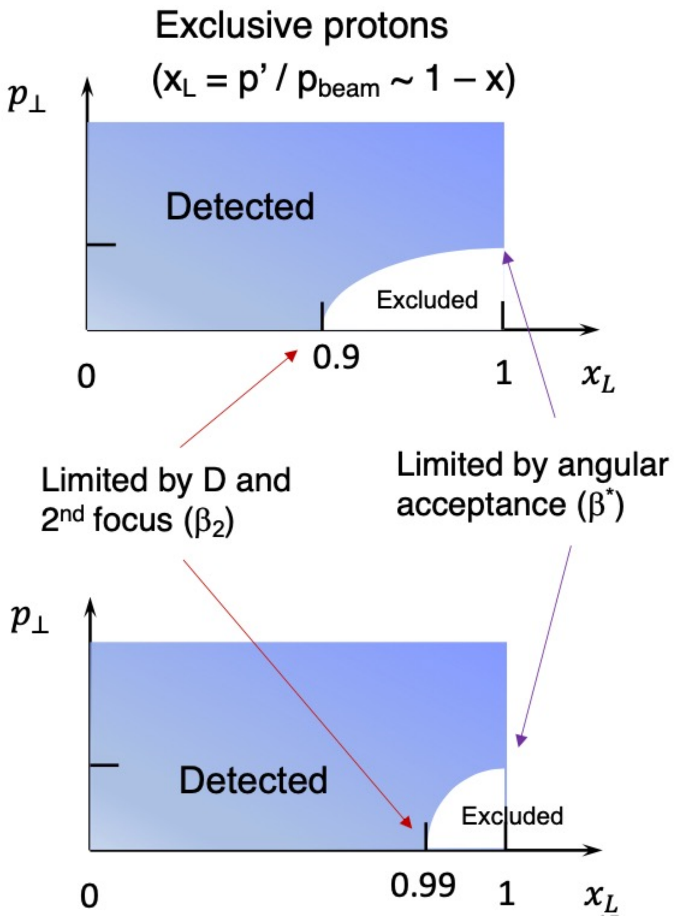
  - To study final state when breakup occurs
- Coherent diffraction on heavy nuclei by vetoing breakups
- Rare isotopes detection and identification of heavy fragments
- **Today, show study on capabilities of separating coherent from incoherent diffractive events by tagging far-forward nuclear fragments**

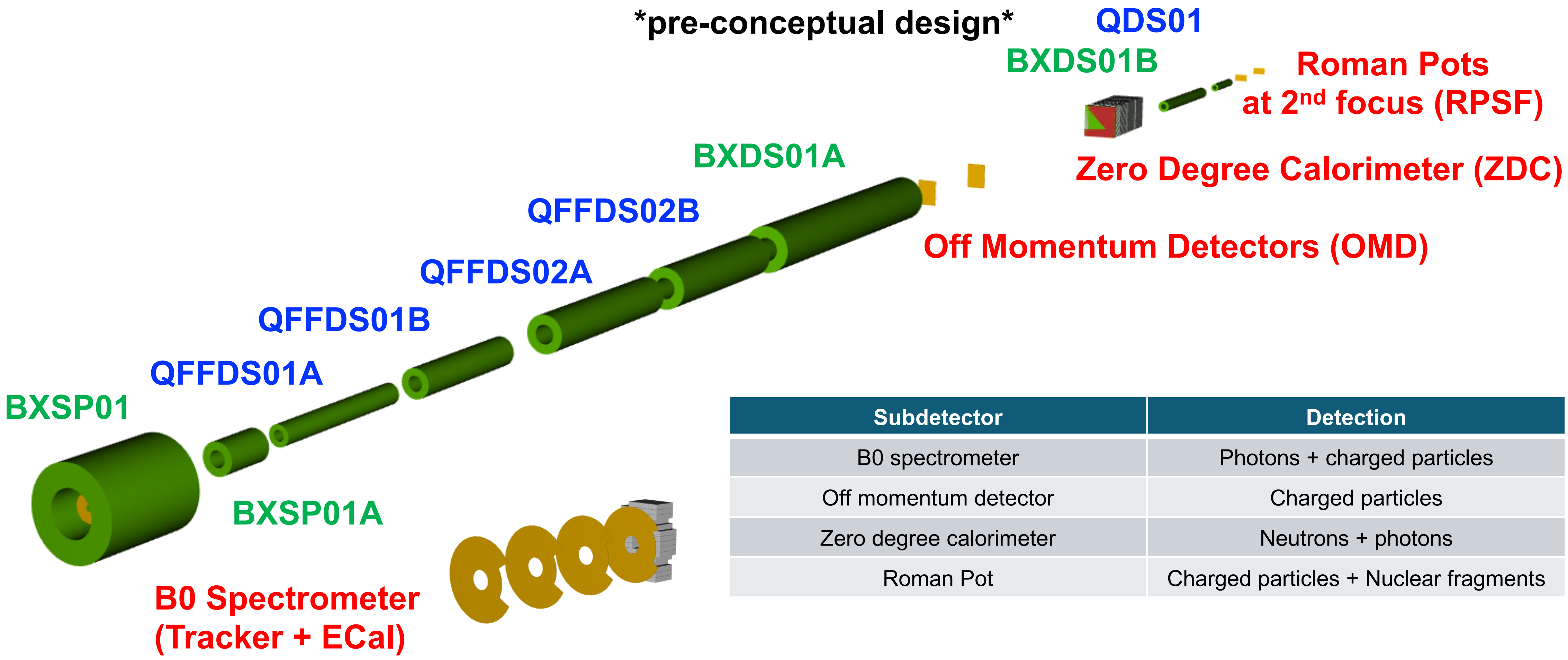


Order-of-magnitude improvement in forward acceptance

Far-Forward Detector – Layout

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

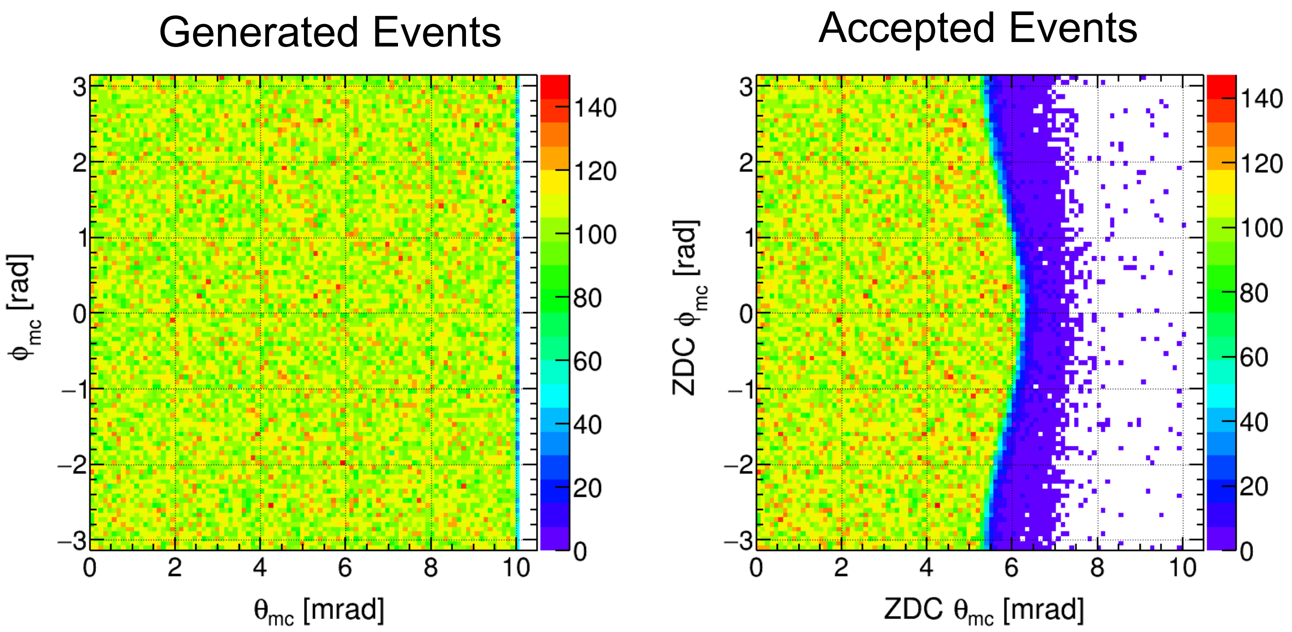
pre-conceptual design



Subdetector	Detection
B0 spectrometer	Photons + charged particles
Off momentum detector	Charged particles
Zero degree calorimeter	Neutrons + photons
Roman Pot	Charged particles + Nuclear fragments

Far-Forward Detector – Acceptance

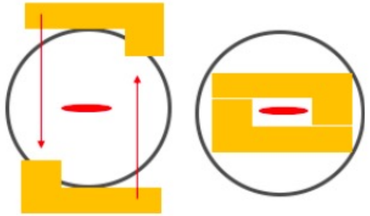
Zero Degree Calorimeter

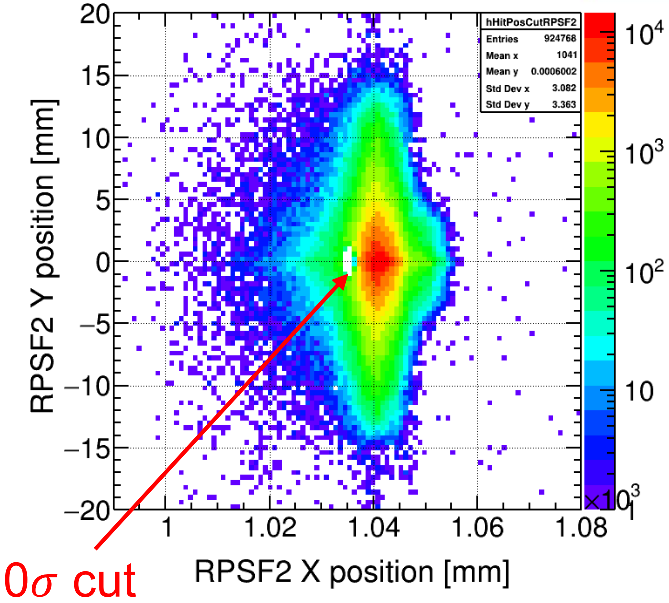


- ZDC < 5.5 mrad uniformly ~100 %
- <u>Needs to evaluate beam pipe impact on neutrons</u>

Roman Pot (@ 2nd focus)

Roman Pot concept





ep DVCS
18×275 GeV^2

- Windows on pots depending on the **beam optics (transverse beam size)**

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

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

☺ RPSF: Roman Pot at Secondary Focus

Approach – Vetoing Efficiency

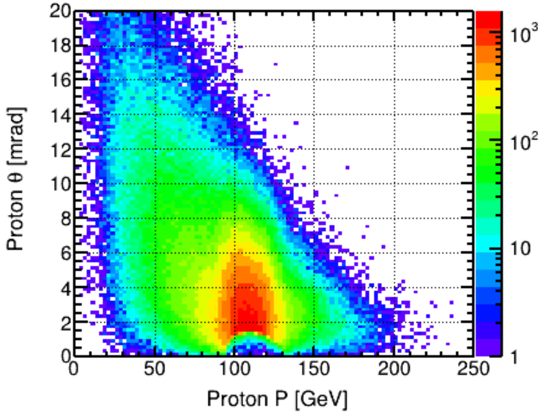
- To understand **impact of 2nd focus on suppression of incoherent contribution** (background to coherent J/ψ production)
- Used **BeAGLE** v1.03.02 ePb 18×110 GeV^2 J/ψ production (**$1 < Q^2 < 10$**)
  - **Incoherent events** $ePb \rightarrow e' + J/\psi(ee/\mu\mu) + X$
- Applied **10σ safe distance cut** based on **eAu @ IR-8 Roman Pot at 2nd focus**
- **Tagged events for nuclear breakups tagging purpose**
  - 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**

Nuclear Breakups Distribution

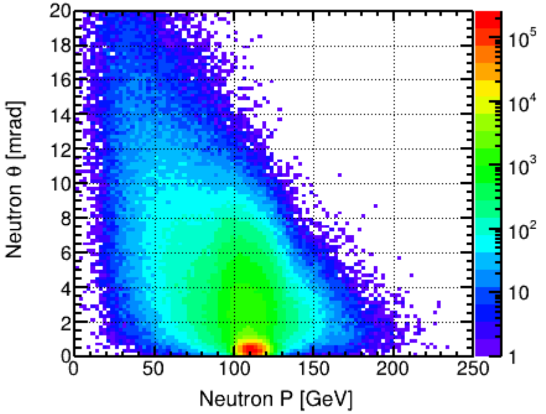
Nuclear Breakups at Final State	Number of Events
Only Neutrons	7.86 %
Only Protons	0.0001 %
Only Photons	3.45 %
Neutrons + Protons	3.18 %
Neutrons + Photons	45.41 %
Protons + Photons	1.85 %
Neutrons + Protons + Photons	38.25 %

About **95 %** of events have **neutrons**

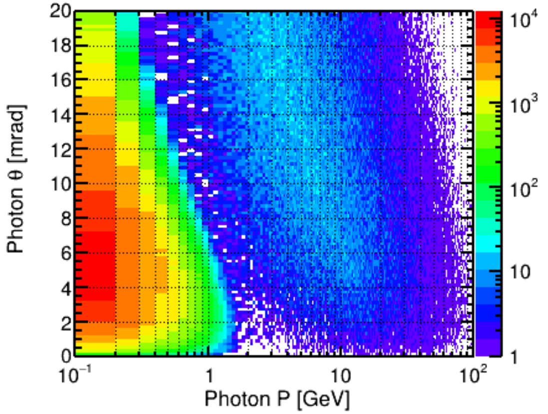
Proton



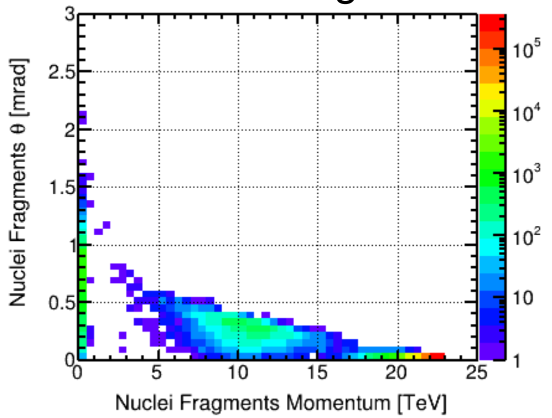
Neutron



Photon

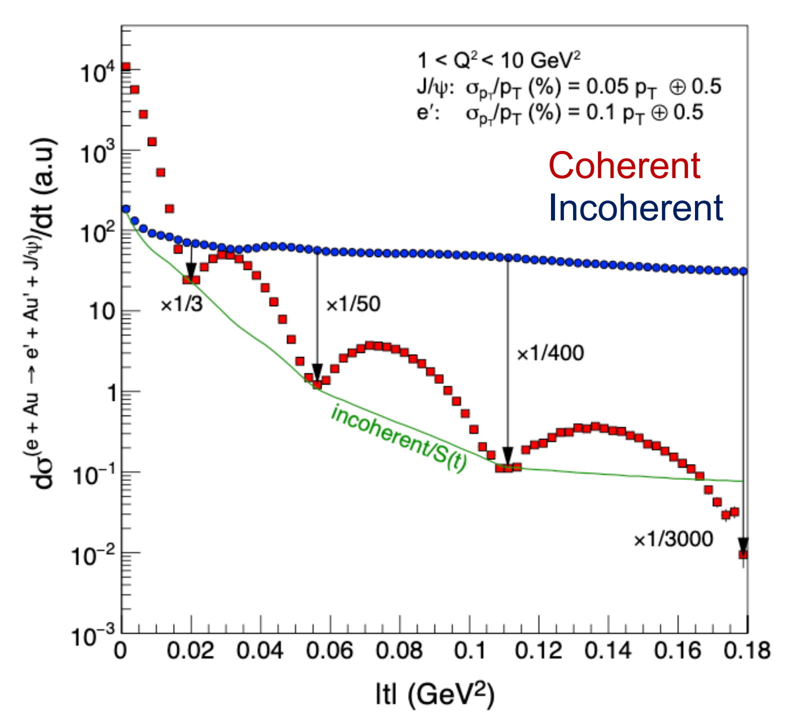


Nuclear Fragments



Far-Forward Detector – Incoherent Veto

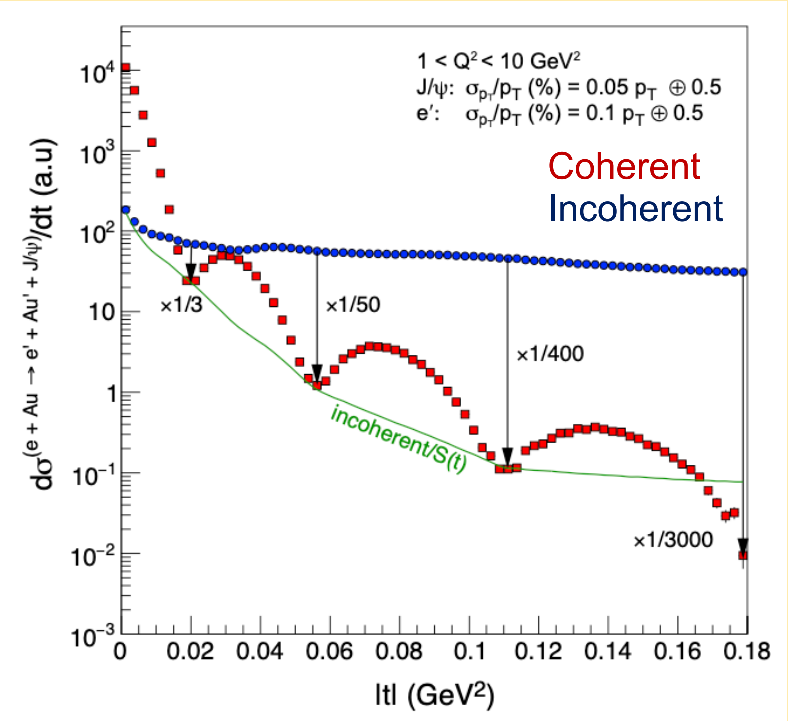
Reference from EIC YR p.352



At position of third diffractive minimum, **rejection factor for incoherent event better than 400:1 must be achievable (0.0025 % inefficiency)**

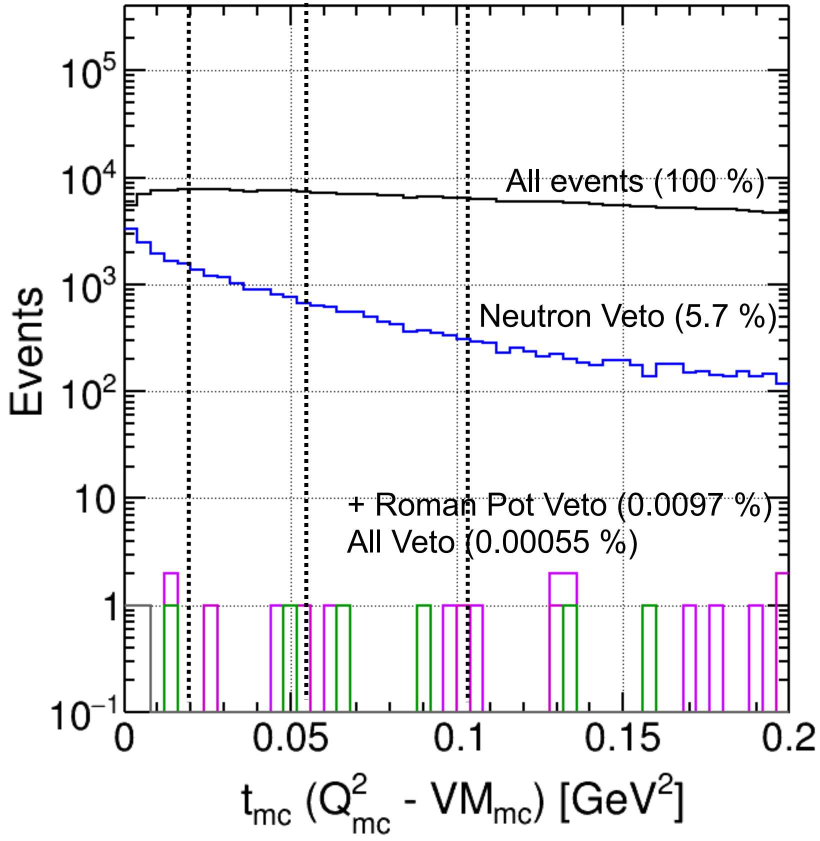
Far-Forward Detector – Incoherent Veto

Reference from EIC YR p.352



At position of third diffractive minimum, **rejection factor for incoherent event better than 400:1 must be achievable (0.0025 % inefficiency)**

Veto inefficiency for incoherent events



ZDC hcal tagged
(neutrons)
RPSF tagged
(protons, nuclear fragments)
OMD tagged
(charged particles)
B0 tracker tagged
(charged particles)
B0 ecal tagged
(photons)
ZDC ecal tagged
(photons)

Vetoing power $> 10^3$

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

Summary and Next Step

- To explore physics opportunities by taking full advantage of 2nd focus
  - Implemented IR-8 hadron beamline geometry and its field configuration
  - Implemented required far-forward detectors
- Using BeAGLE incoherent events, Evaluated vetoing power by tagging nuclear fragments using far-forward detectors
  - Found to be enough to suppress incoherent contribution at three diffractive minima
  - Vetoing power reaches > 10^3

Next steps

- Investigate beampipe impact on vetoing efficiency
- Further look into possible physics cases (at very low t) with far-forward 2nd focus by t reconstruction from scattered protons

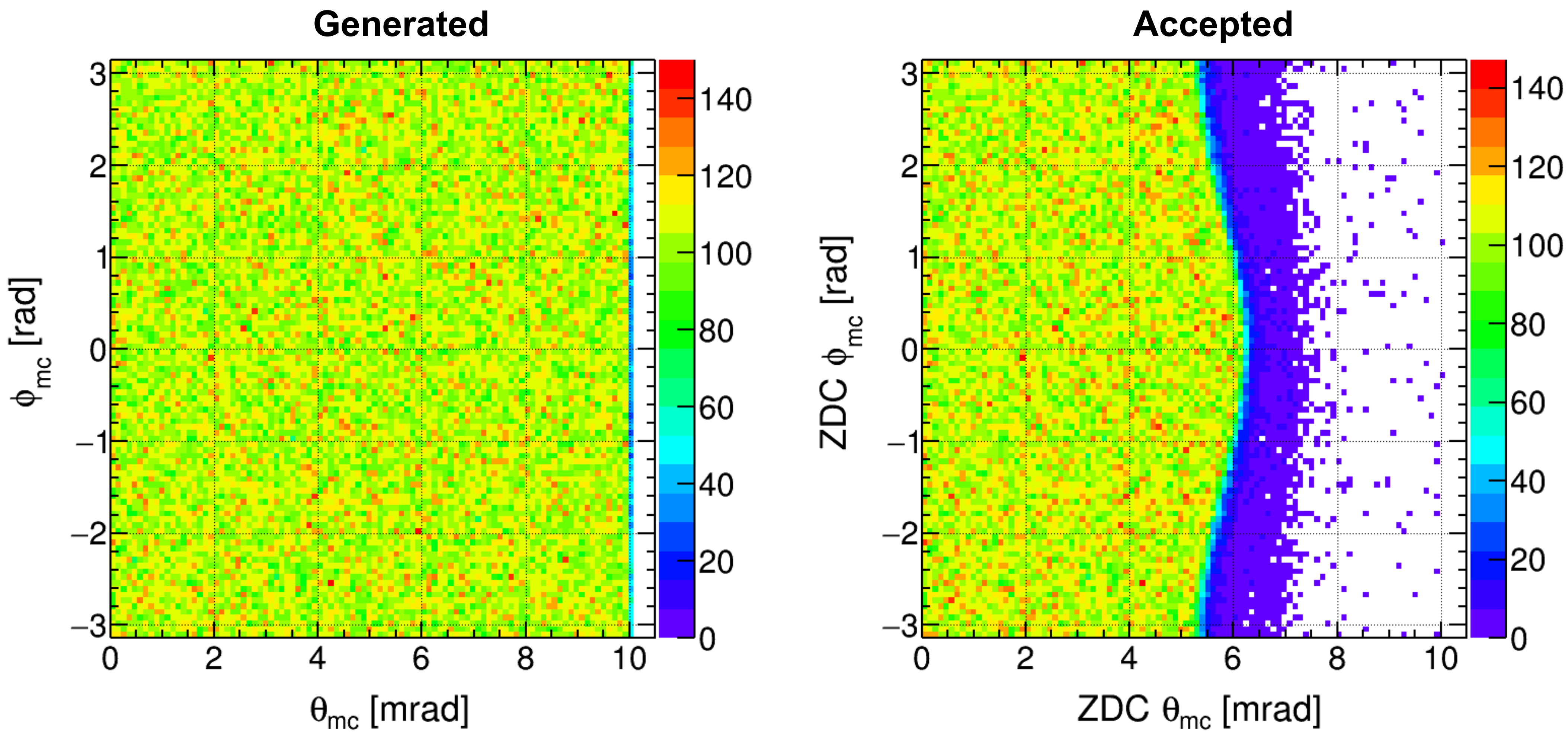
Backup Slides

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

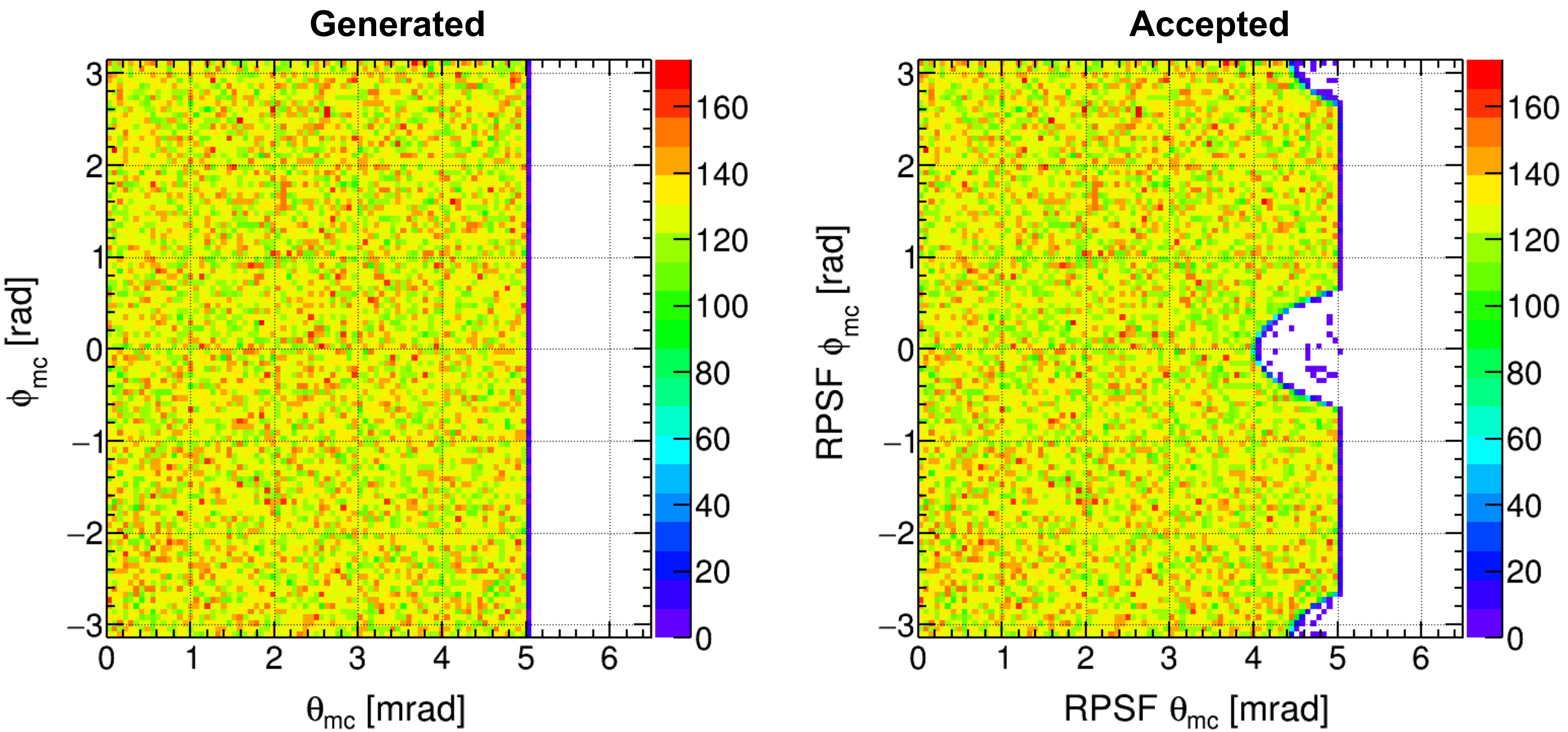
Single Neutron
E = 275 GeV
$0 < \theta_{MC} < 10$ mrad



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)

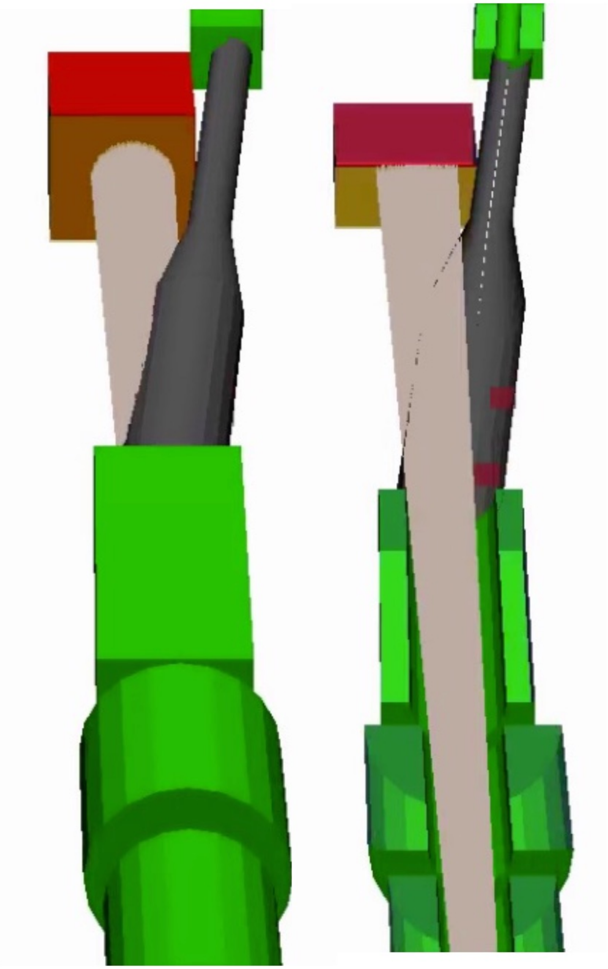
Clipping occurs in quadrupoles for protons

Clipping on Acceptance of Far-Forward

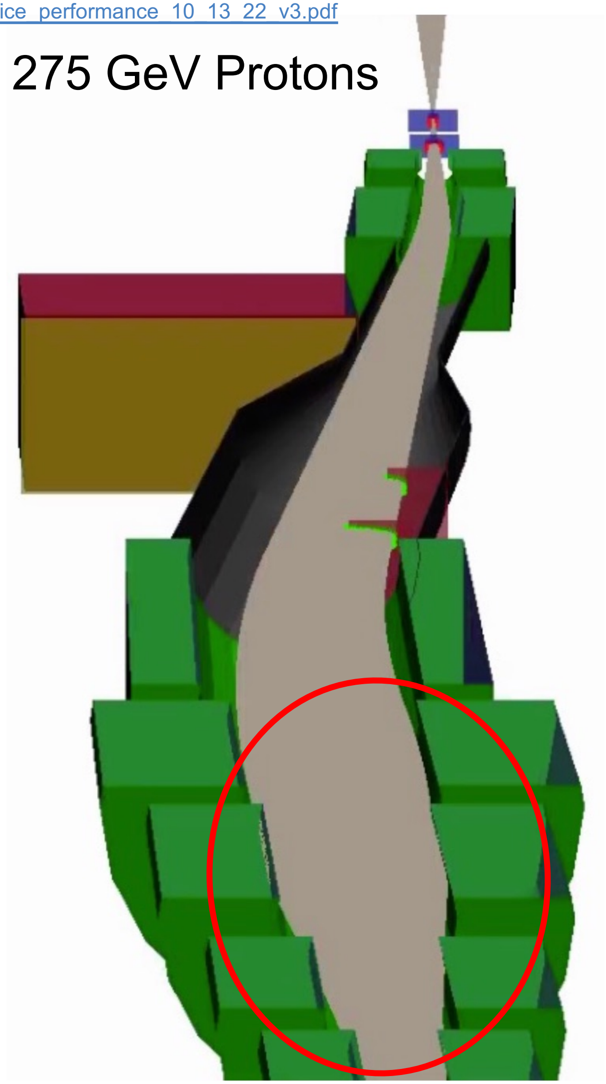
Kindly Provided by Alex Jentsch using EicRoot Simulation Event Display

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

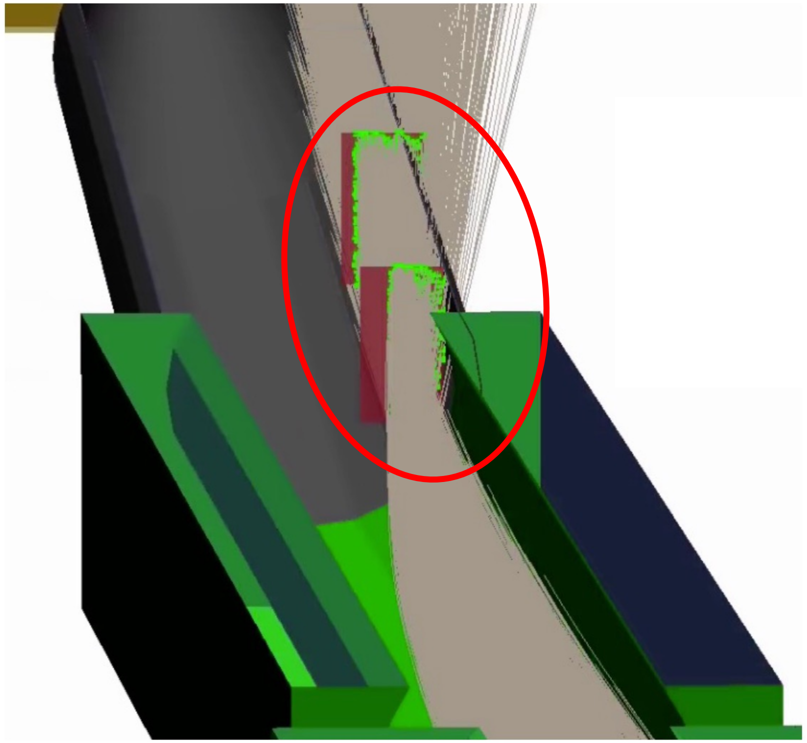
275 GeV Neutrons



275 GeV Protons



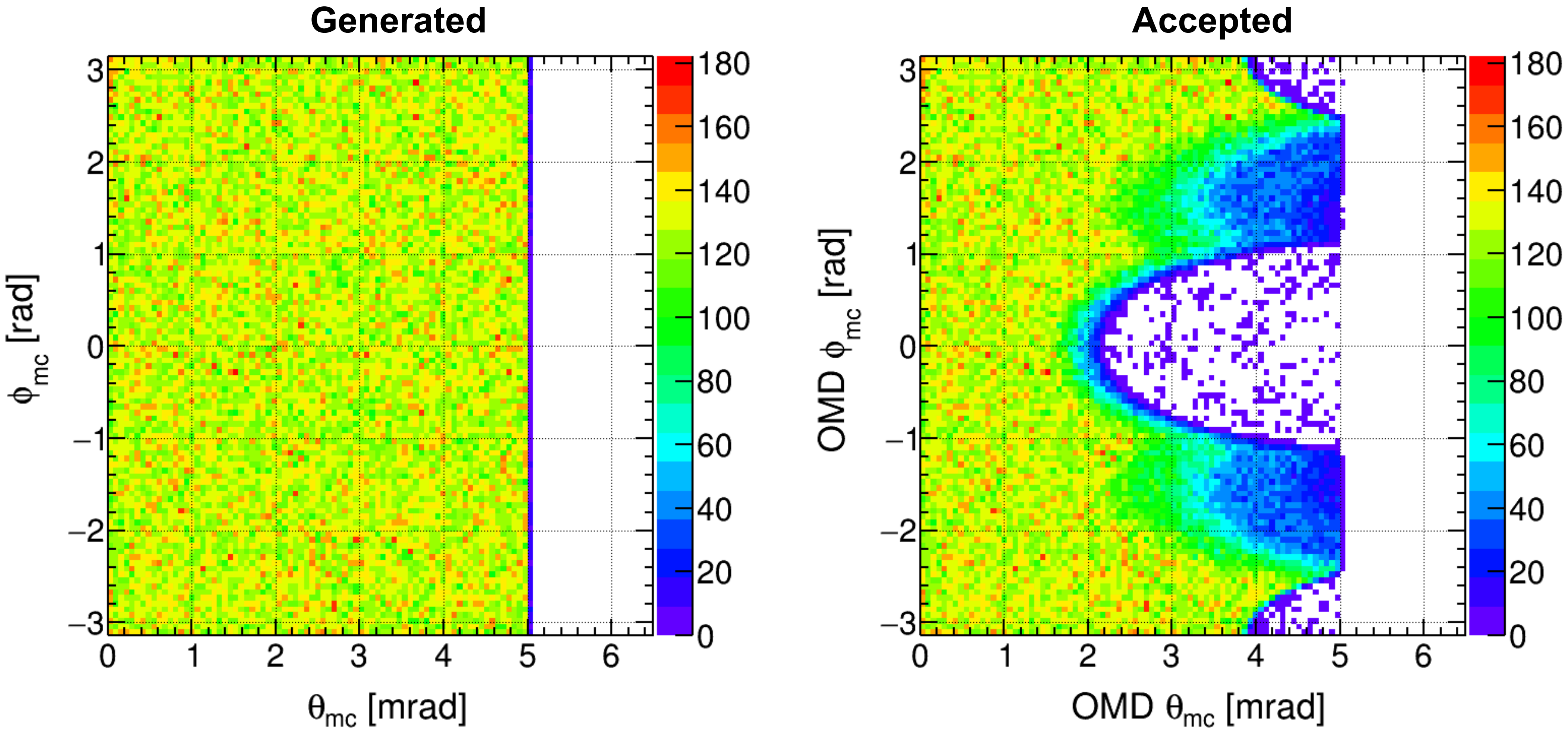
123.75 – 151.25 GeV Protons



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

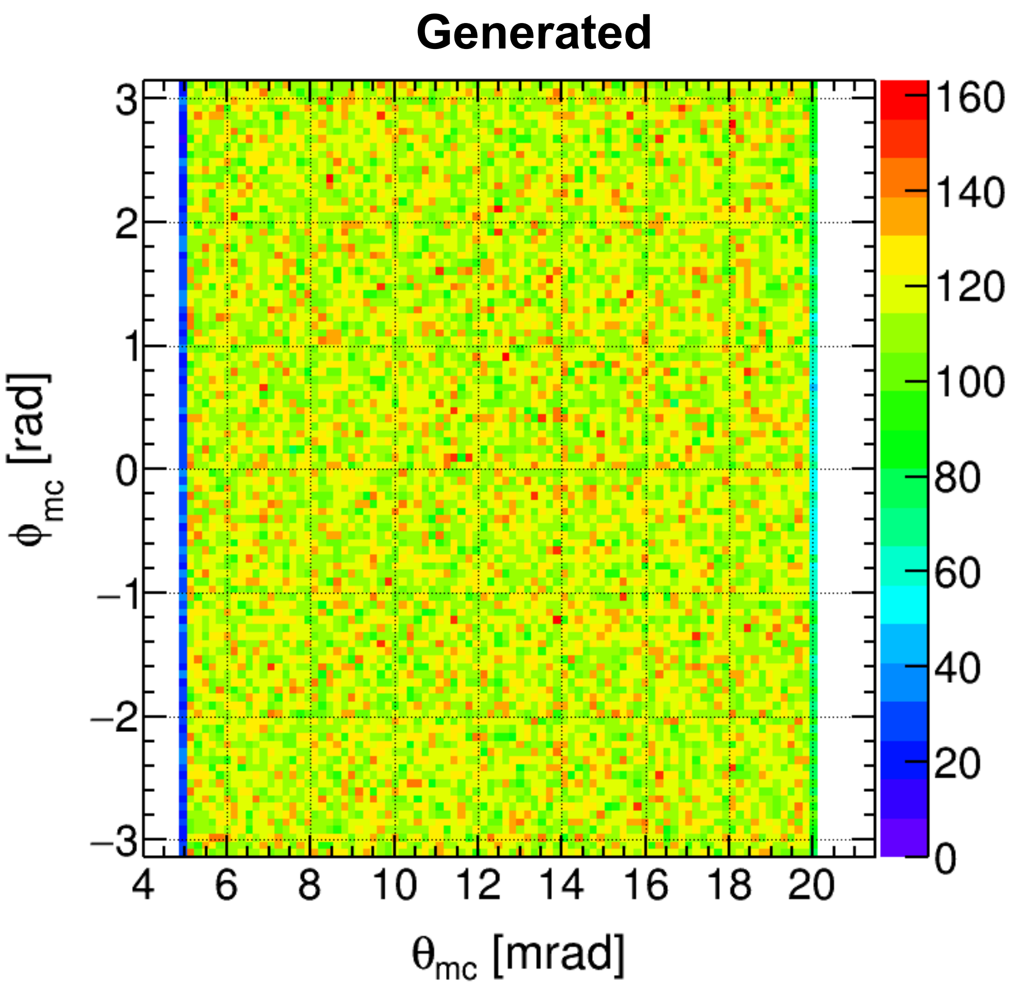


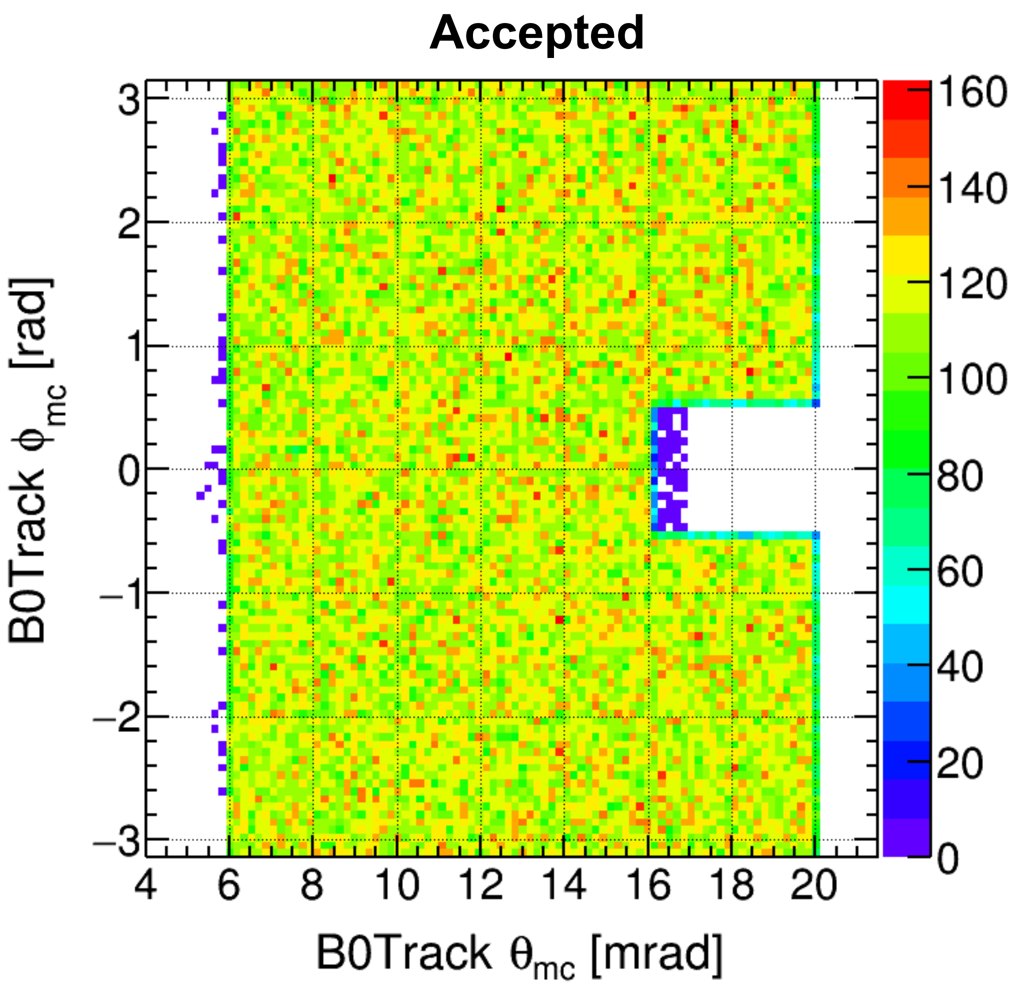
About 67.42 % events were accepted

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





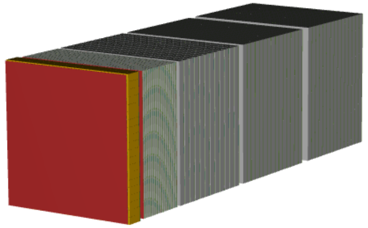
About **88.94 (93.6) %** events were **accepted requiring four layers (more than two layers)**

IP-8 Far-Forward Detectors

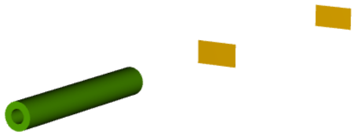
Implemented in **IP-6 detector configuration**

- **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)

pT Acceptance from EIC YR

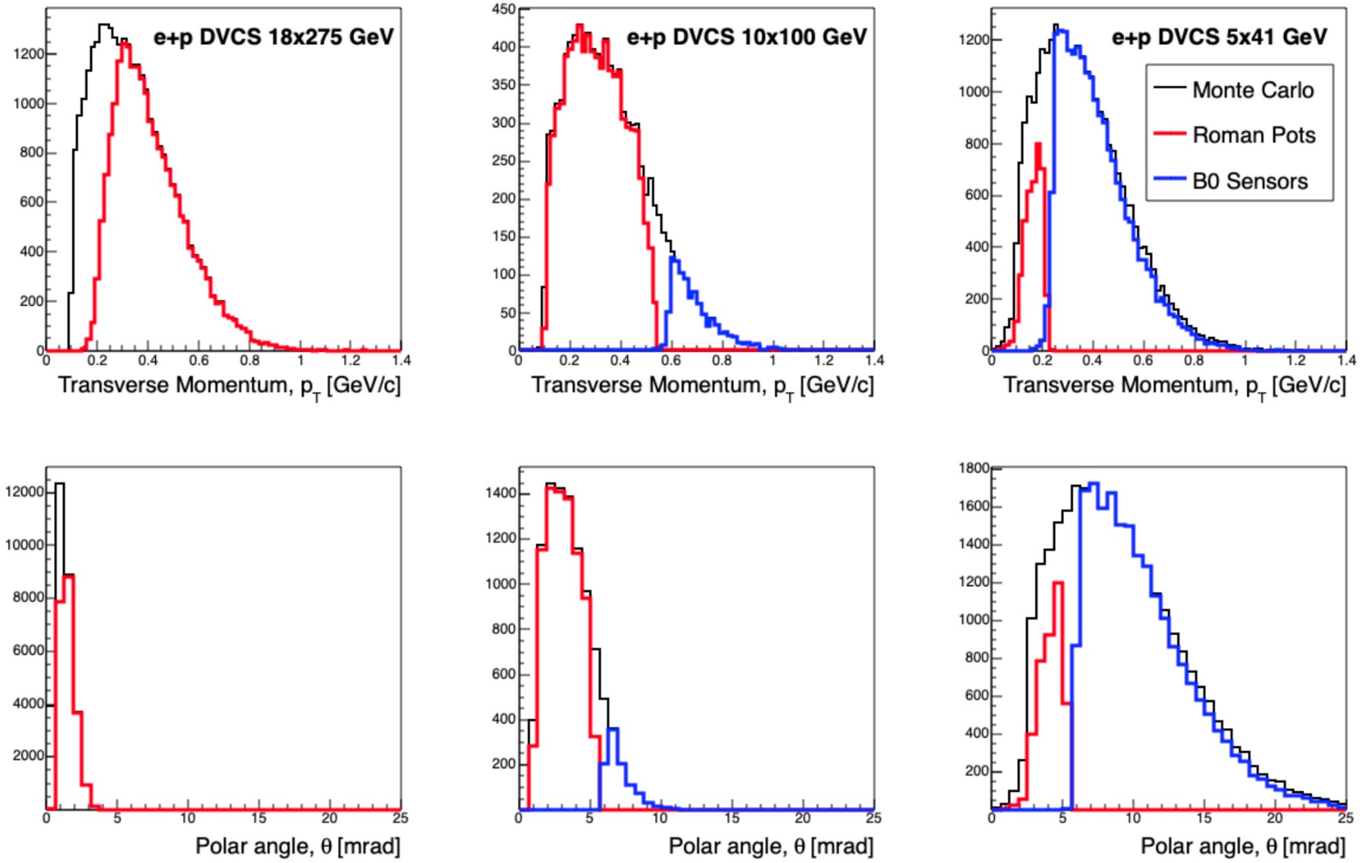
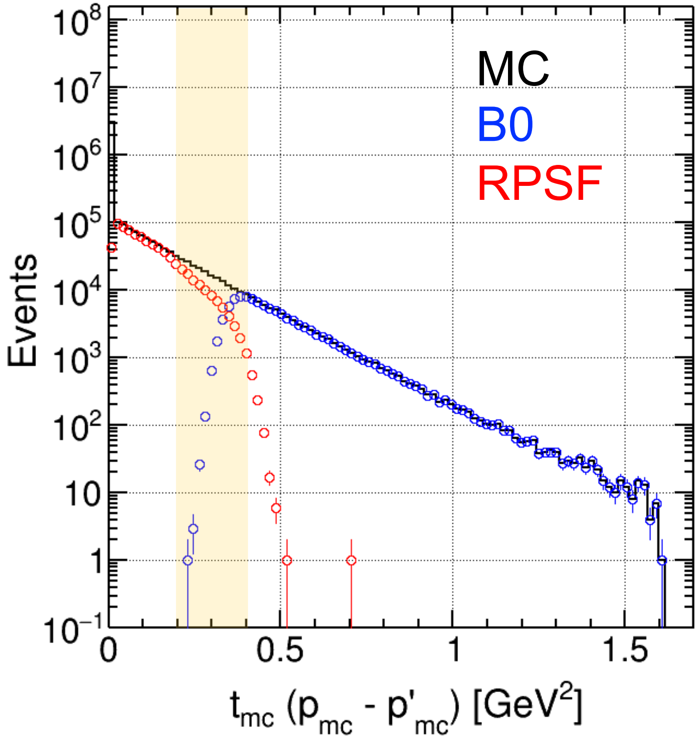


Figure 11.98: p_T (top row) and polar angle (bottom row) acceptance for three different beam energy configurations: 18x275 GeV (left), 10x100 GeV (middle), and 5x41 GeV (right). The black data in each figure represent the MC information from MILOU, the red lines are the accepted particles in the Roman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

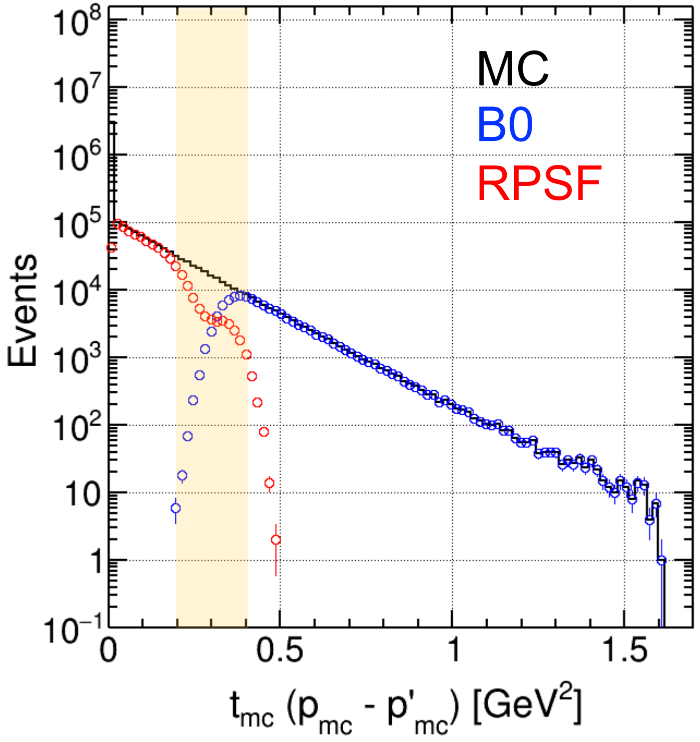
From EIC YR p.564

DVCS 10 GeV on 100 GeV

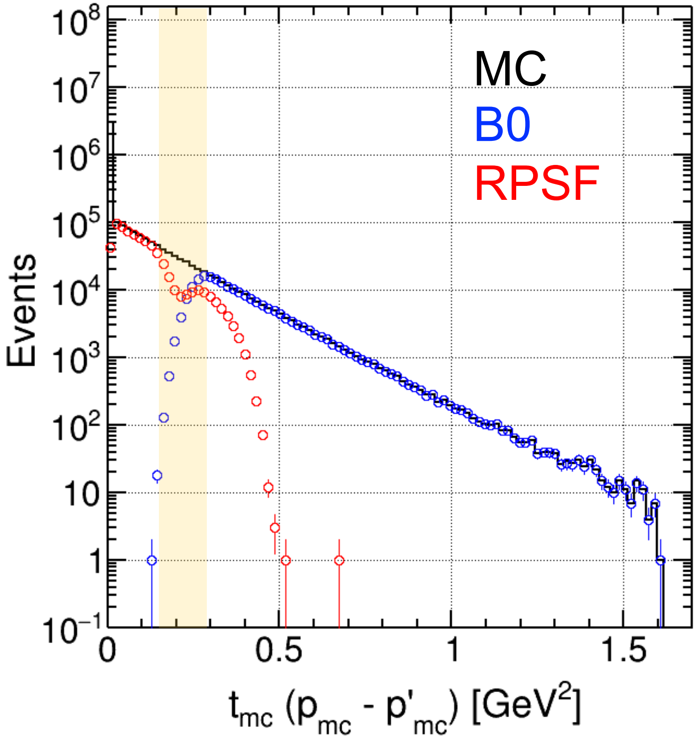
W/O Beampipe at B0



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

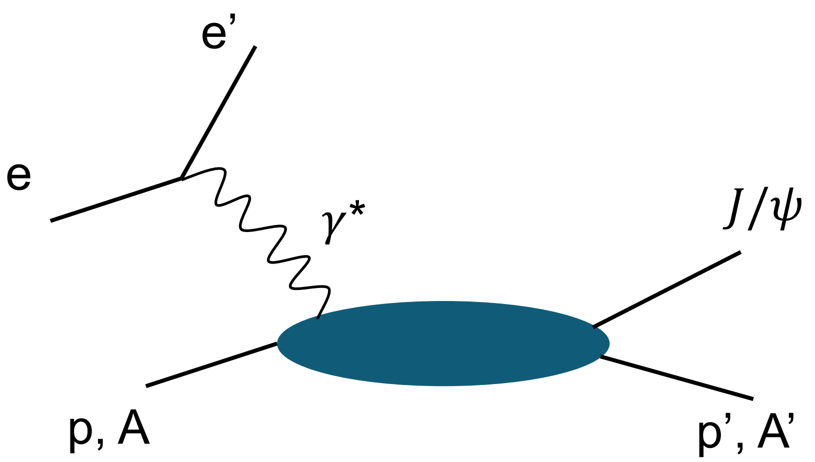


W/ Beampipe ($r_{beampipe\ outer}$ = 3.0 cm) at B0

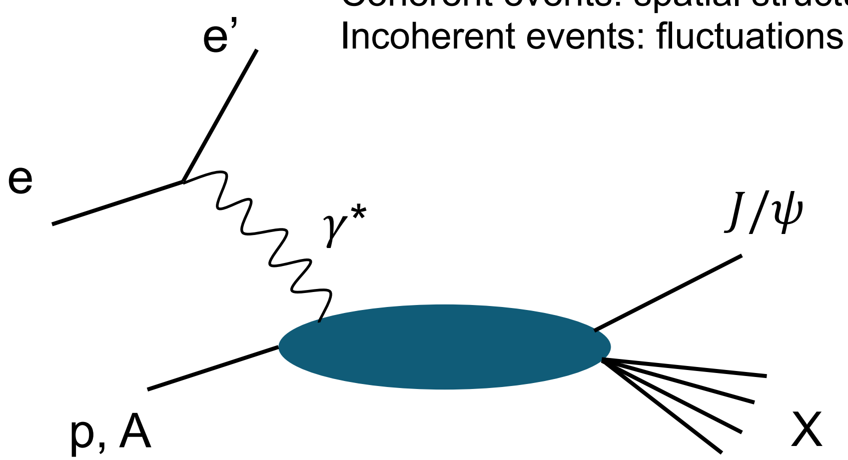


Diffractive Physics Program

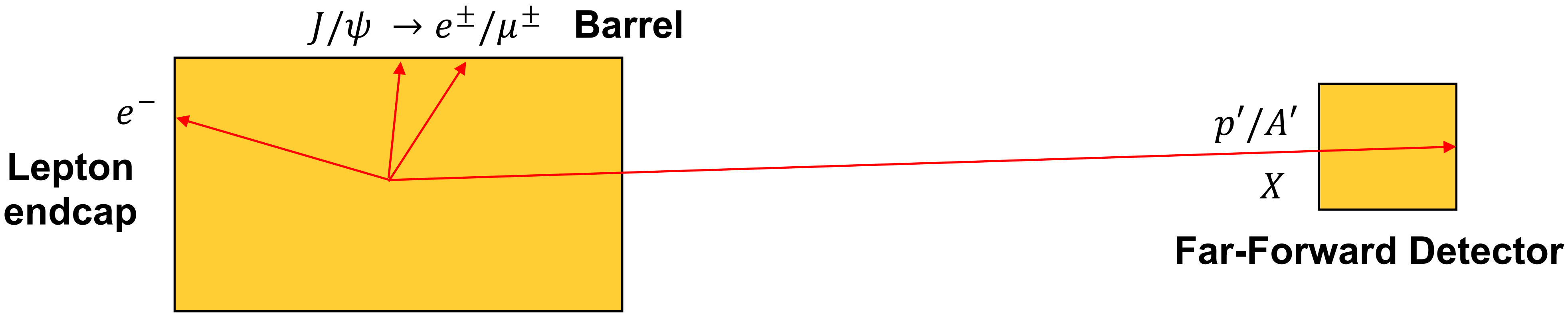
Coherent events: spatial structure of gluons (mean)
Incoherent events: fluctuations



Coherent – Target stays intact



Incoherent – Target breaks up



Central Detector

$$t = (\boldsymbol{p}_A - \boldsymbol{p}_{A'})^2 = (\boldsymbol{p}_{\mathrm{VM}} + \boldsymbol{p}_{e'} - \boldsymbol{p}_e)^2$$

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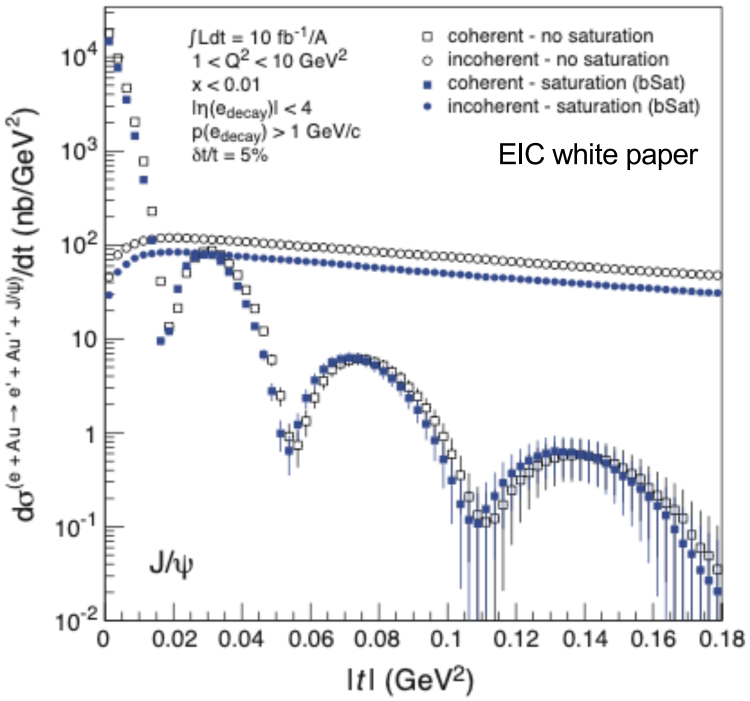
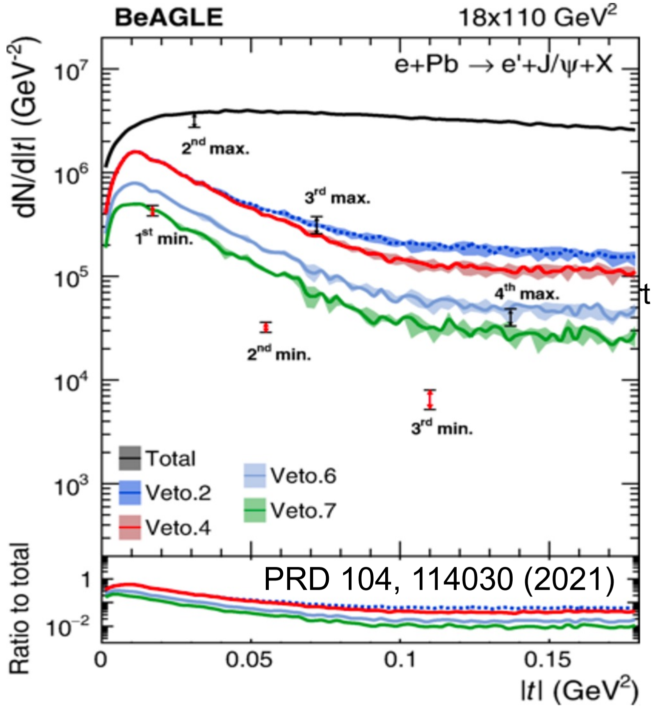
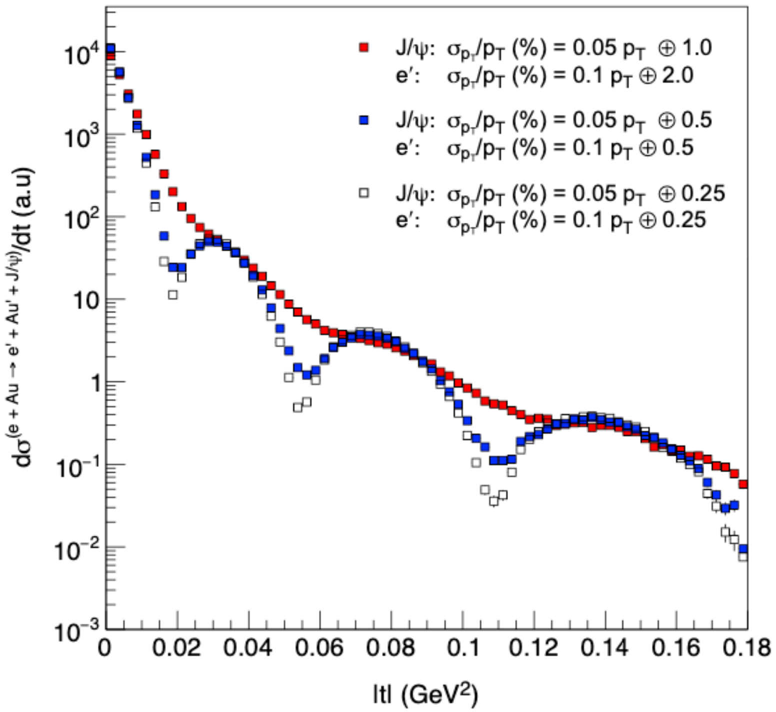
Diffractive Physics Program

- Experimentally, **measured spectra** in vector meson production contain **sum of coherent and incoherent processes**
  - Low t – coherent events dominate, but **higher t – incoherent events dominate**
  - Measuring coherent events is **very challenging → tagging nuclear breakups and vetoing incoherent events instead**
  - **Tracking resolution (p_T in particular)** allows to measure position of dip patterns







IP-8 Beam Parameters and 10σ Cut

From EIC CDR table 3.5 and Randy's eAu study

☺ RPSF: Roman Pot at Secondary Focus

eAu 18 GeV on 110 GeV	Momentum Dispersion ($D_{secondary\ focus}$)	Emittance X (ϵ_x*) [mm]	Emittance Y(ϵ_y*) [mm]	Beta function X (β_x secondary focus) [mm]	Beta function Y (β_y secondary focus) [mm]	Momentum spread ($\Delta p/p$)*
Old ep 18 on 275 GeV^2	0.382	43.2e-6	5.8e-6	2289.454596	4538.713168	6.2e-4
New ep 18 on 275 GeV^2	**0.465446718**	43.2e-6	5.8e-6	**498.013008**	**3392.376638**	6.2e-4
New eAu 18 on 110 GeV^2	**0.467582853**	43.2e-6	5.8e-6	**565.292559**	**1870.555797**	6.2e-4

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

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

1σ calculation	1σ_x	1σ_y
ep β @ IR-8 RPSF (Old)	0.314867	0.1629770
ep β @ IR-8 RPSF (new)	**0.146677**	**0.140271**
eAu β @ IR-8 RPSF (new)	**0.156271**	**0.104160**

Nuclear Breakups Distribution

BeAGLE **v1.01.01**

Phys. Rev. D 104, 114030

produced particle	rate
only neutron	7.66%
only proton	0%
only photon	3.25%
neutron and proton	3.19 %
neutron and photon	44.24 %
proton and photon	2.27 %
neutron, proton and photon	39.39 %

TABLE II. Summary of particles produced in incoherent J/ψ production in BeAGLE.

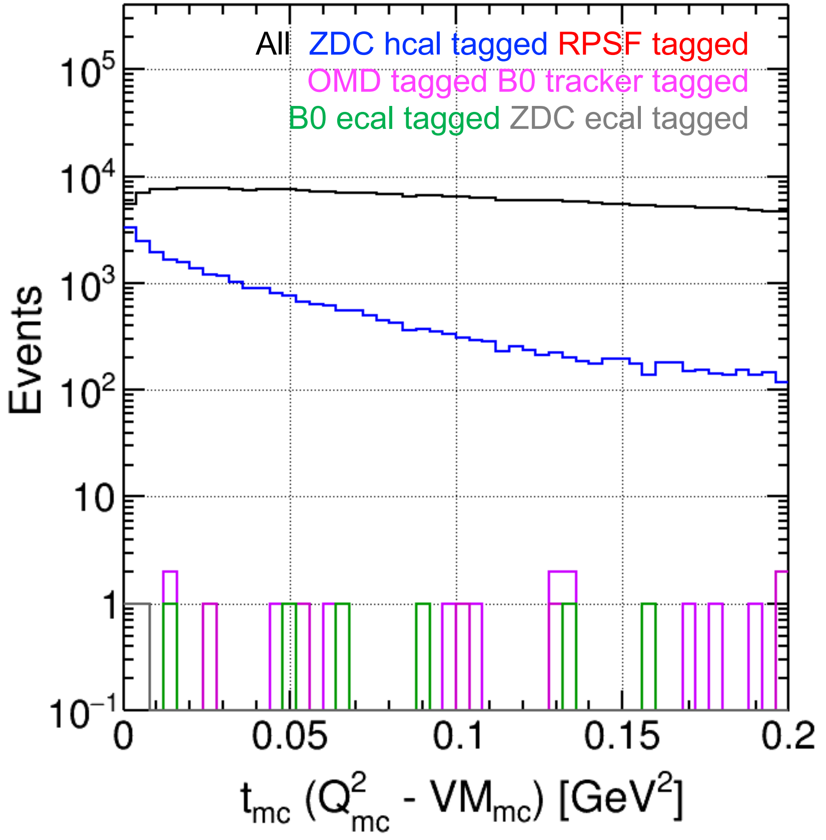
BeAGLE **v1.03.02**

Nuclear Breakups at Final State	Number of Events
Only Neutrons	7.86 %
Only Protons	0.0001 %
Only Photons	3.45 %
Neutrons + Protons	3.18 %
Neutrons + Photons	45.41 %
Protons + Photons	1.85 %
Neutrons + Protons + Photons	38.25 %

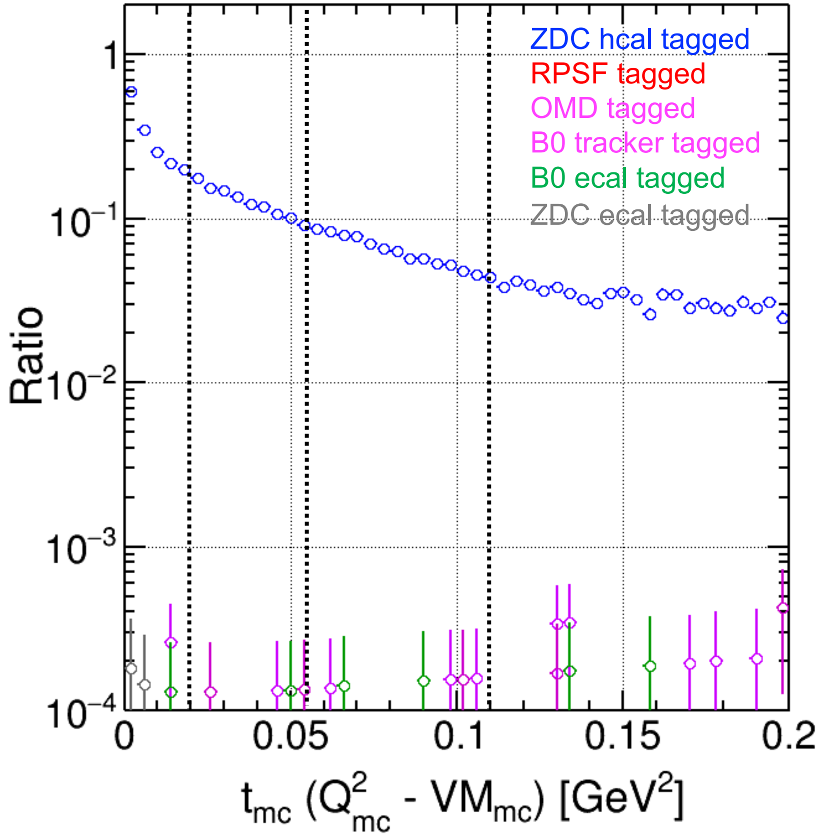
About **95 %** of events have **neutrons**

t Distribution and Vetoing Efficiency

Veto inefficiency for incoherent events



Coherent diffractive minima



Found to be enough to suppress incoherent contribution at three minima

Vetoing efficiency is > 99.99% at all three minima

Remaining (Non-Vetoed) Events

Veto Selections	Surviving Events	
	ep β @ IR-8 RPSF	eAu β @ IR-8 RPSF
All events	998,161	997,820
Events with one scattered electron identified and $\|\eta_{J/\psi}\| < 4$ and 1 < Q^2 < 10	732,707 (100.0 %)	732,455 (100 %)
ZDC HCAL tagged	41,880 (**5.71579 %**)	41,848 (**5.71339 %**)
+ RPSF tagged	94 (**0.0128291 %**)	71 (**0.00969343 %**)
+ OMD tagged	93 (0.0126927 %)	71 (0.00969343 %)
+ B0 tracker tagged	51 (0.00696049 %)	30 (0.00409581 %)
+ B0 ecal tagged	27 (0.00368497 %)	17 (0.00232096 %)
+ ZDC ECAL tagged	15 (**0.0020472 %**)	4 (**0.000546109 %**)

With 10σ safe distance cut based on ***eAu β @ IP-8 RPSF (New)***

4 of 997,820 events were NOT vetoed

Remaining (Non-Vetoed) Events

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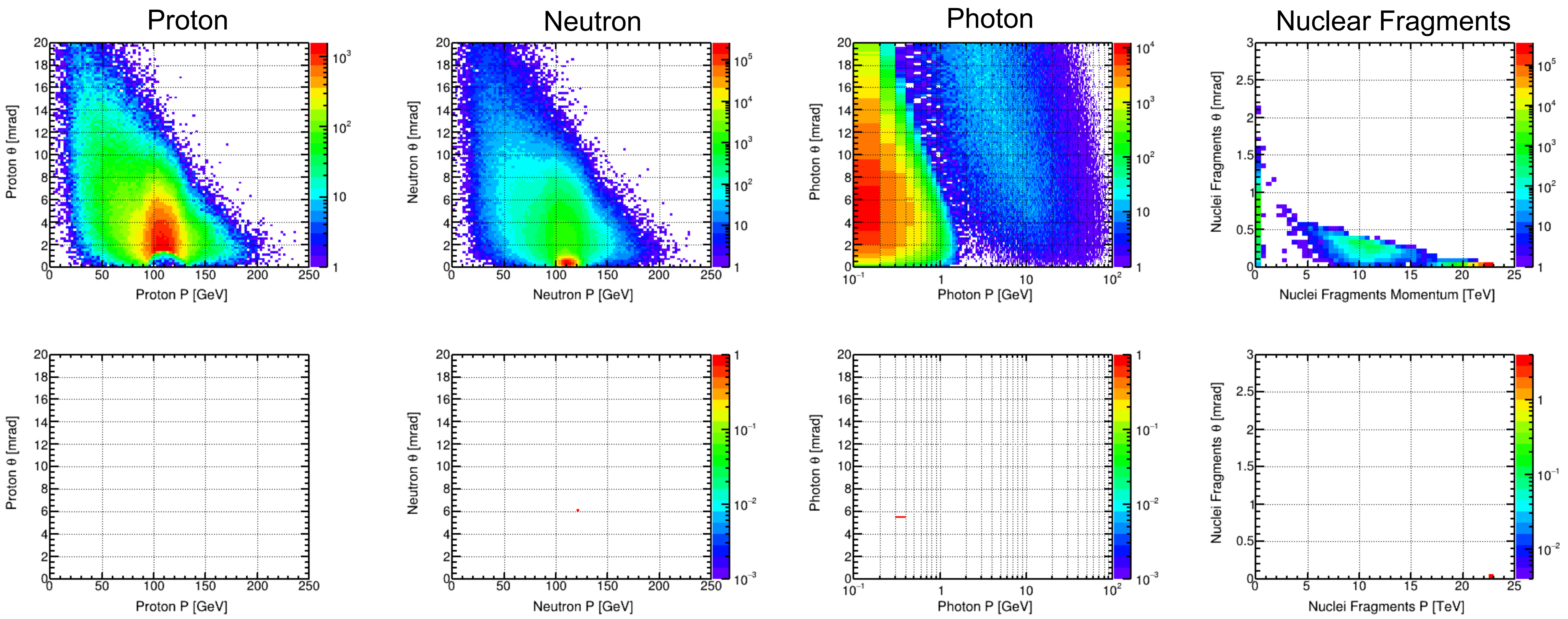
- Veto.1: no activity other than e^- and J/ψ in the main detector ($|\eta| < 4.0$ and $p_T > 100$ MeV/c) ;
- Veto.2: Veto.1 and no neutron in ZDC;
- Veto.3: Veto.2 and no proton in RP;
- Veto.4: Veto.3 and no proton in OMDs;
- Veto.5: Veto.4 and no proton in B0;
- Veto.6: Veto.5 and no photon in B0;
- Veto.7: Veto.6 and no photon with $E > 50$ MeV in ZDC.

Survived Event Ratio				
Material	Without beam pipe	Beryllium	Aluminum	Stainless Steel
Total events	100 %	100 %	100%	100%
Veto.1	86.9%	86.9%	86.9%	86.9 %
Veto.2	5.81%	9.73%	9.85%	17.2%
Veto.3	5.81%	9.73 %	9.85%	17.2%
Veto.4	5.09%	8.77%	8.89%	15.73%
Veto.5	4.32%	6.22%	5.97%	10.18%
Veto.6	2.29%	3.32%	3.18%	5.68%
Veto.7 ($E_{\text{photon}} > 50$ MeV)	1.06%	2.05%	2.46%	5.58%
Veto.7 ($E_{\text{photon}} > 100$ MeV)	-	2.18%	-	-

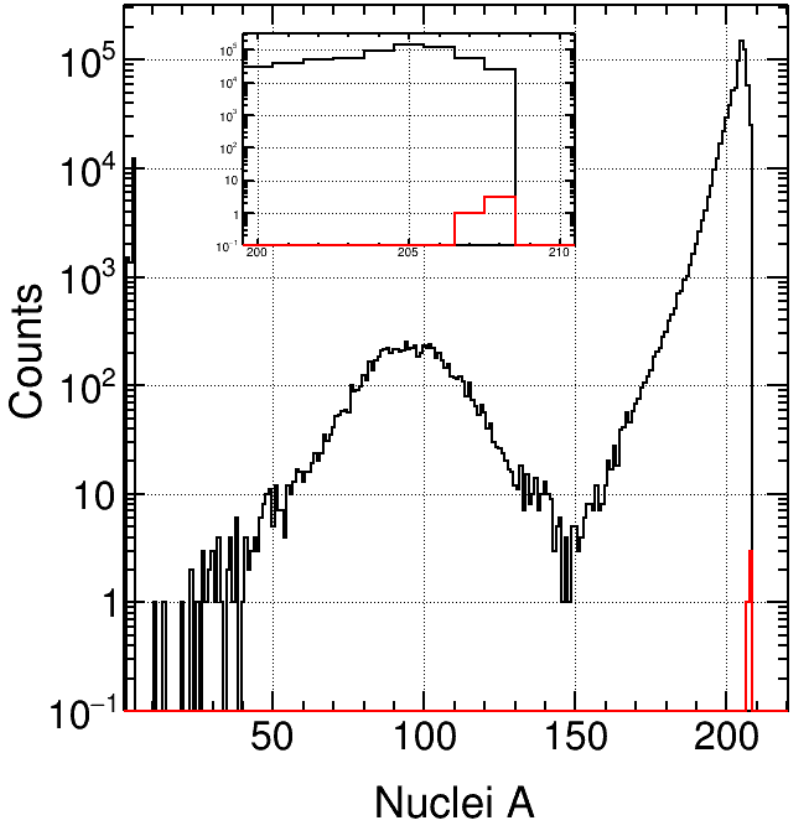
TABLE III. Summary of the percentage of events surviving the different vetoing steps for incoherent events assuming no beam pipe and different beam pipe materials of beryllium, aluminum, and stainless steel.

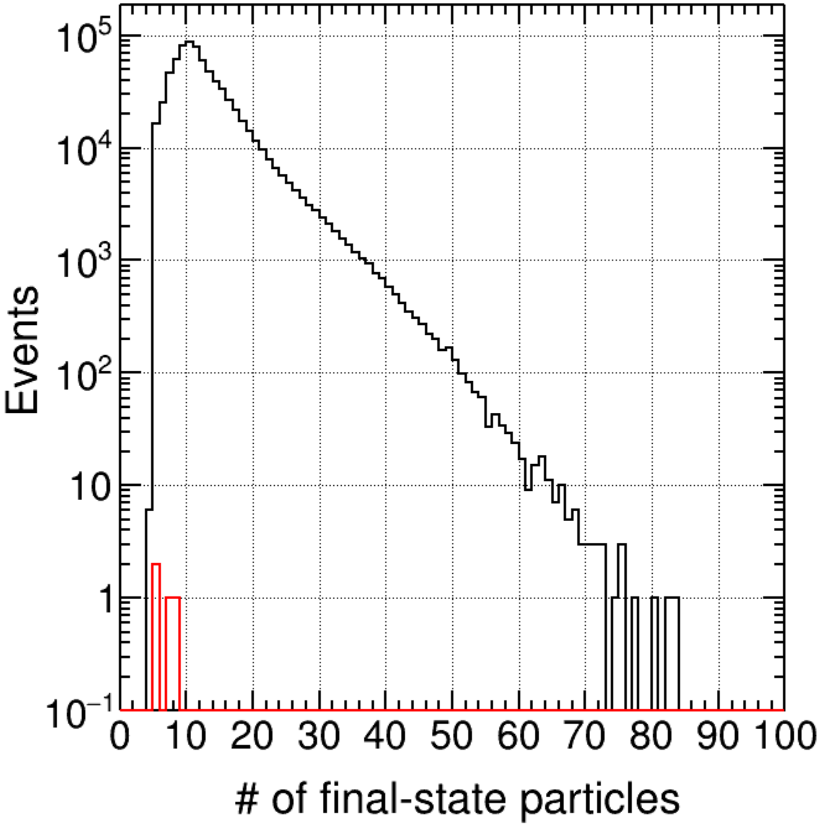
Veto Selections	Surviving Events eAu β @ IR-8 RPSF
All events	997,820
Events with one scattered electron identified and $|\eta_{J/\psi}| < 4$ and 1 < Q^2 < 10	732,455 (100 %)
ZDC HCAL tagged	41,848 (**5.71339 %**)
+ RPSF tagged	71 (**0.00969343 %**)
+ OMD tagged	71 (0.00969343 %)
+ B0 tracker tagged	30 (0.00409581 %)
+ B0 ecal tagged	17 (0.00232096 %)
+ ZDC ECAL tagged	4 (**0.000546109 %**)

Remaining (Non-Vetoed) Events



Remaining (Non-Vetoed) Events





Remaining events have high mass nuclear remnants (A = 208 and 207 for Pb) and low particle multiplicity