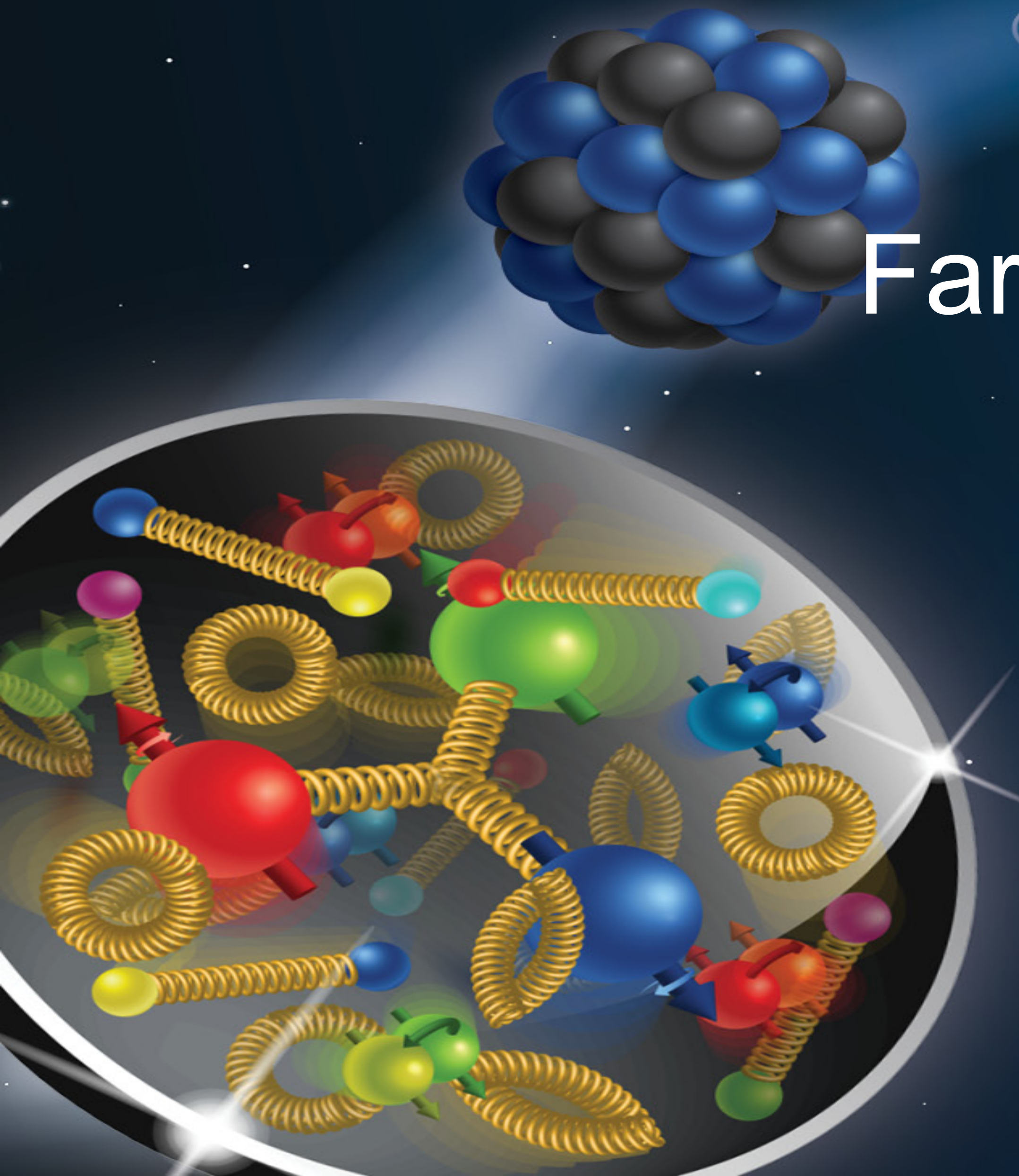


Far-Forward Particle Detection at the EIC

1st ECCE Workshop, Feb. 11th, 2021

Alex Jentsch (Brookhaven National Laboratory)

This work only possible via strong collaboration between the EIC physics & machine/accelerator community – and the significant input from the Yellow Report effort! Thanks to all who have contributed!

Fellow YR WG conveners: Yulia Furletova & Michael Murray

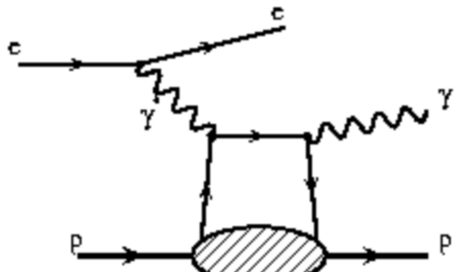
Electron Ion Collider

BROOKHAVEN NATIONAL LABORATORY

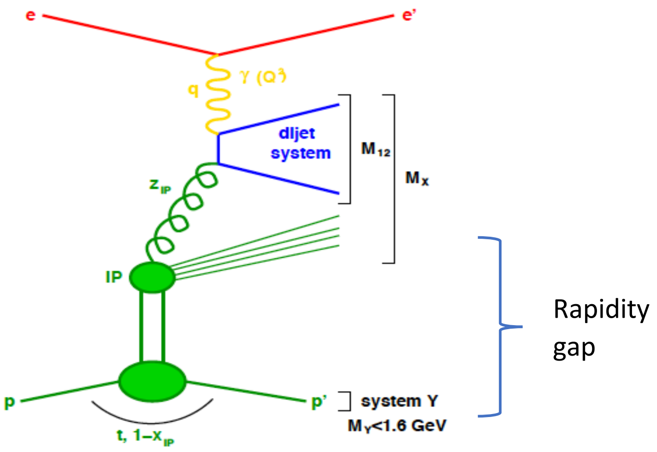
U.S. DEPARTMENT OF ENERGY | Office of Science

Far-forward physics at EIC

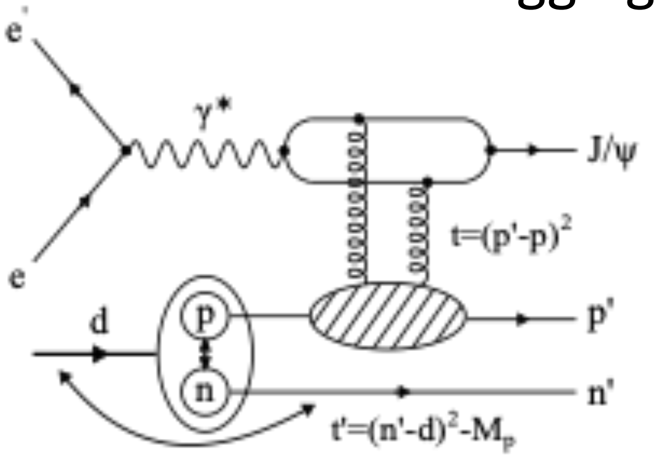
e+p DVCS events with proton tagging.



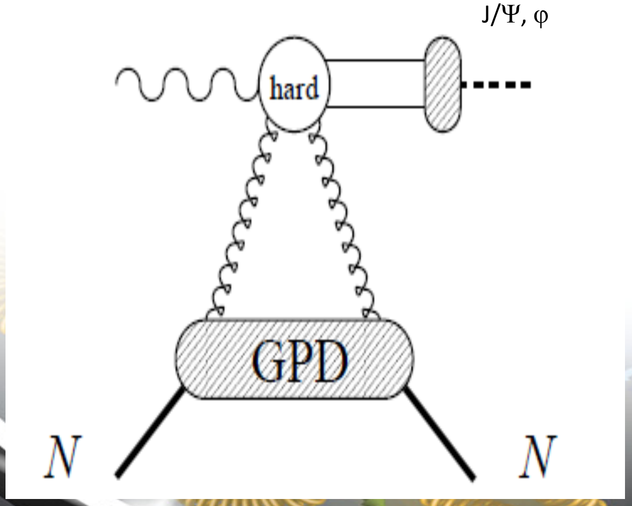
Diffraction



e+d exclusive J/Psi and DIS events with proton or neutron tagging

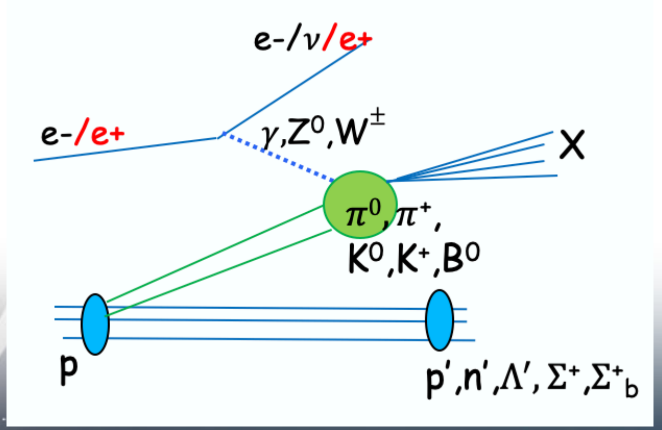


Saturation (coherent/incoherent J/ψ production)



Meson structure:

- with neutron tagging (ep→ (π) →e' n X)
- Lambda decays ($\Lambda \rightarrow p\pi^-$ and $\Lambda \rightarrow n\pi^0$)



e+He3 with spectator proton tagging.

e+He4 coherent He4 tagging.

e+Au events with neutron tagging to veto breakup and photon acceptance.

….

Far-forward physics at EIC

e+p DVCS events with

Diffraction

e+d exclusive J/Psi and DIS events with proton or neutron tagging

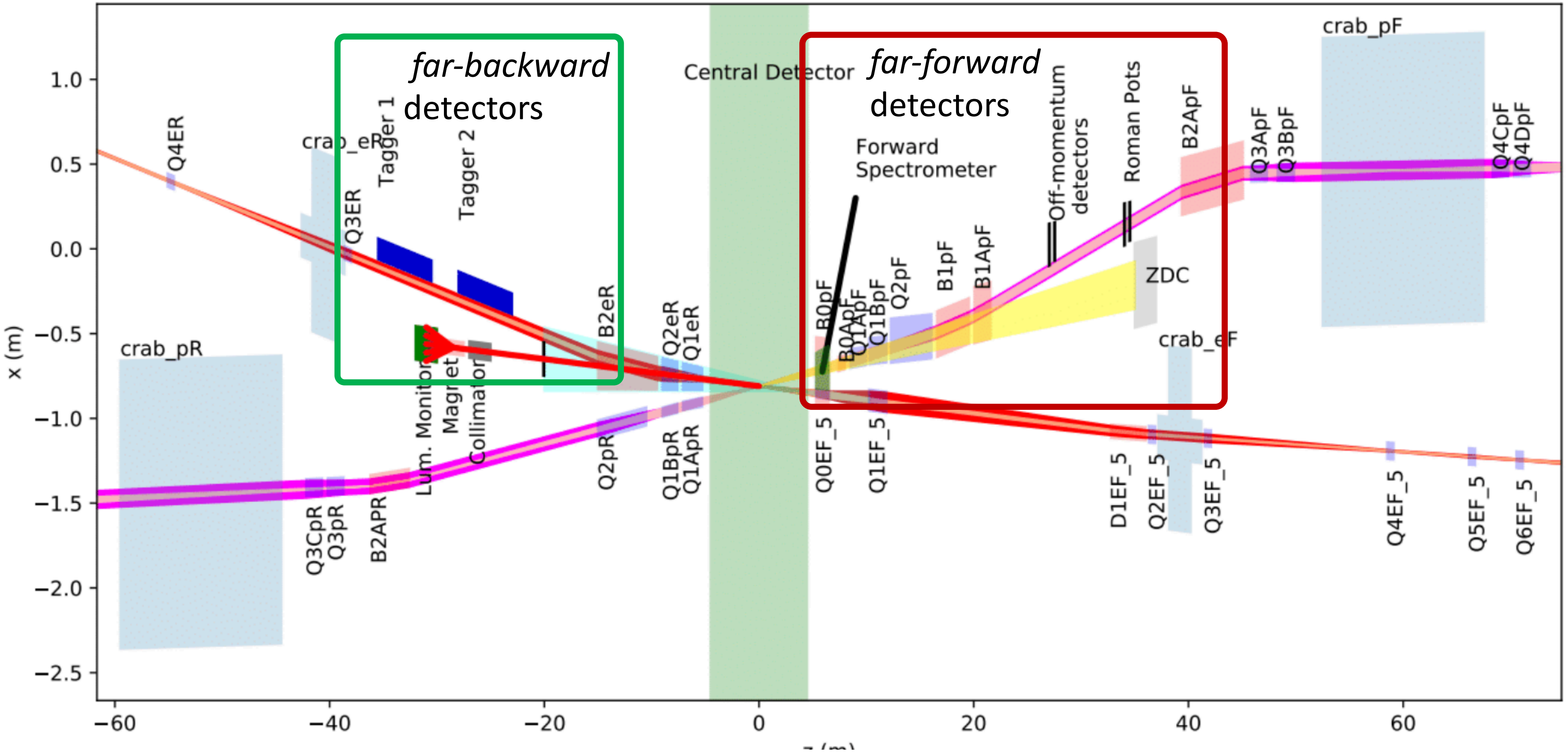
- ➢ The various physics channels require tagging of charged hadrons (protons, pions) or neutral particles (neutrons, photons) at very-forward rapidities ($\eta > 4.5$).
- ➢ Different final states require different detector subsystem for detection.
- ➢ Different collision systems provide unique challenges due to magnetic rigidity difference between beam and final-state particles.
- ➢ Placing far-forward detectors uniquely challenging due to presence of machine components, space constraints, apertures, etc.

acceptance.

....

Far-Forward Interaction Region Design and Detectors

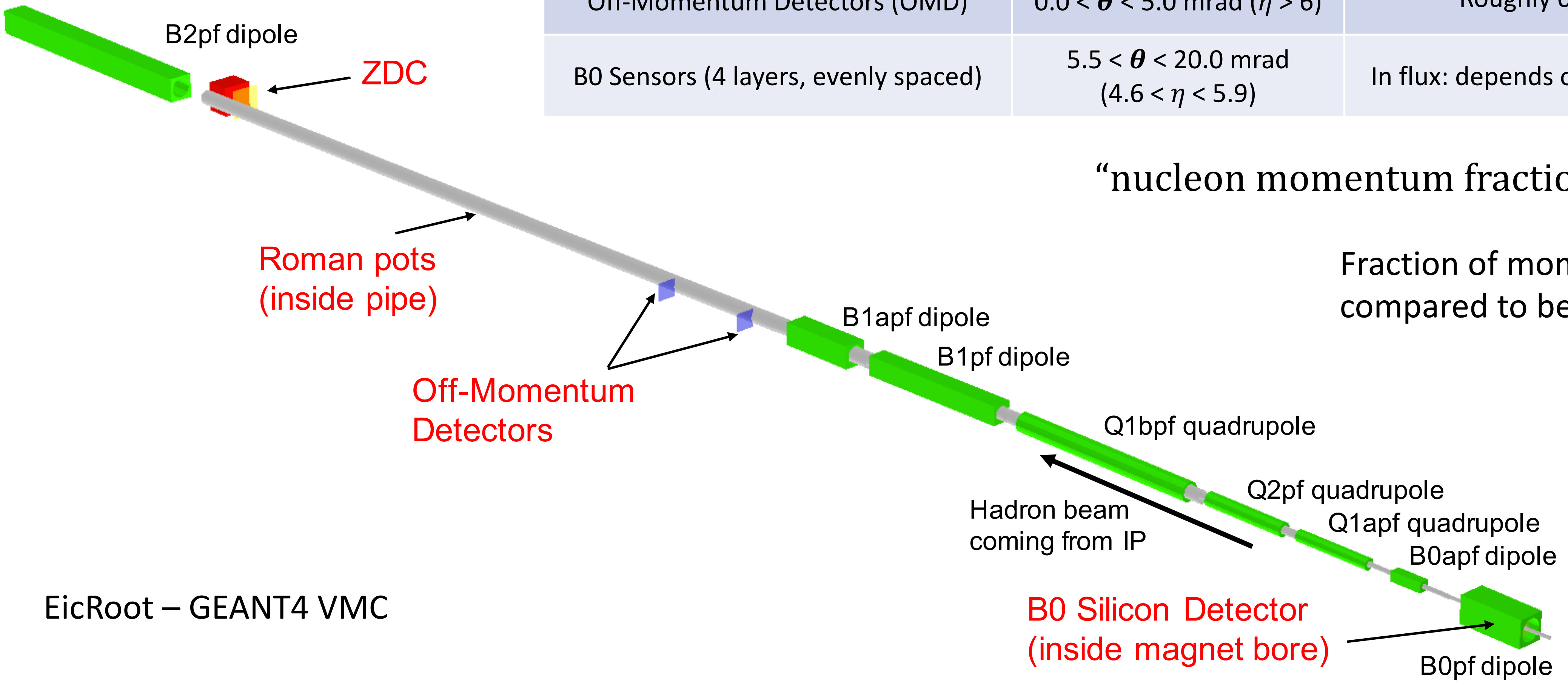
EIC Interaction Region Layout



- Central detector spans 9 meters and is machine-component free (except for beam pipe).
- Hadron-going and electron-going directions after central detector fully instrumented.
- Hadron and electron beam cross with an angle of 25 mrad.

FF Hadron-Going Direction & Acceptance

Detector	Acceptance	Notes
Zero-Degree Calorimeter (ZDC)	$\boldsymbol{\theta} < 5.5$ mrad ($\eta > 6$)	About 4.0 mrad at φ ~ π
Roman Pots (2 stations)	**0.0*** < $\boldsymbol{\theta} < 5.0$ mrad ($\eta > 6$)	$0.65 < \frac{p_{z,nucleon}}{p_{z,beam}} < 1.0$ ***10σ cut/beam optics change lower cutoff**
Off-Momentum Detectors (OMD)	$0.0 < \boldsymbol{\theta} < 5.0$ mrad ($\eta > 6$)	Roughly $0.3 < \frac{p_{z,nucleon}}{p_{z,beam}} < 0.6$
B0 Sensors (4 layers, evenly spaced)	$5.5 < \boldsymbol{\theta} < 20.0$ mrad ($4.6 < \eta < 5.9$)	In flux: depends on pipe and electron quad.



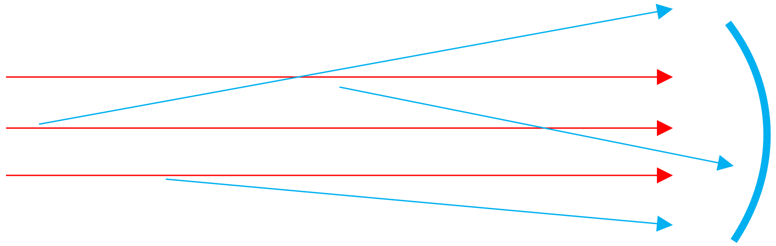
$$\text{“nucleon momentum fraction”} = \frac{p_{z,nucleon}}{p_{z,beam}}$$

Fraction of momentum for nucleon compared to beam.

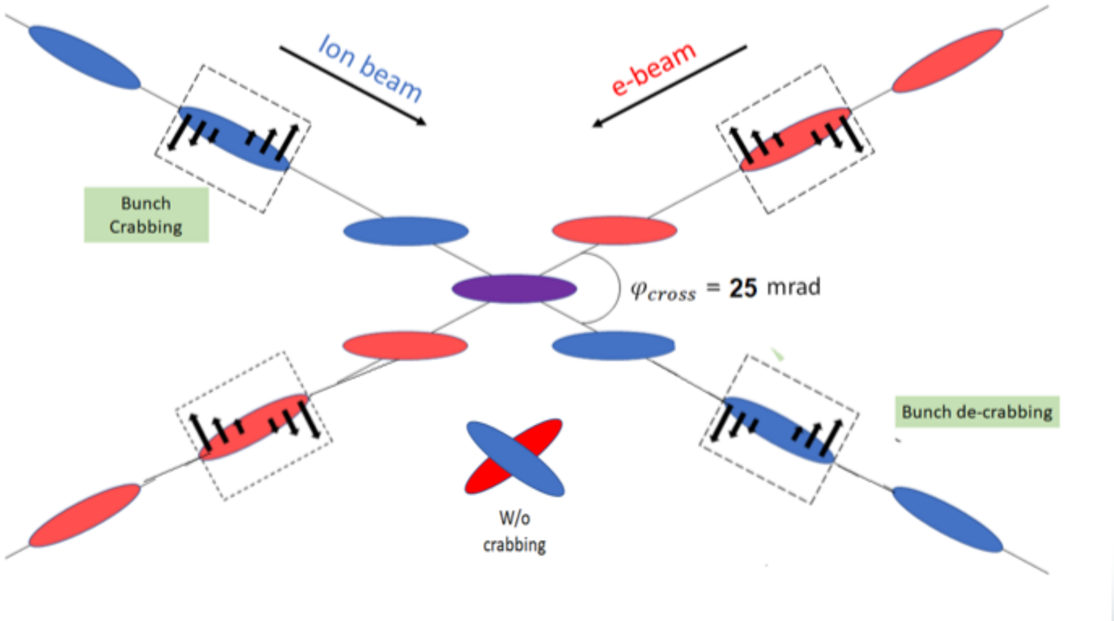
EicRoot – GEANT4 VMC

Reality of Particle Detectors: Smearing Contributions

- Angular divergence
  - Angular “spread” of the beam away from the central trajectory.
  - Gives some small initial transverse momentum to the beam particles.

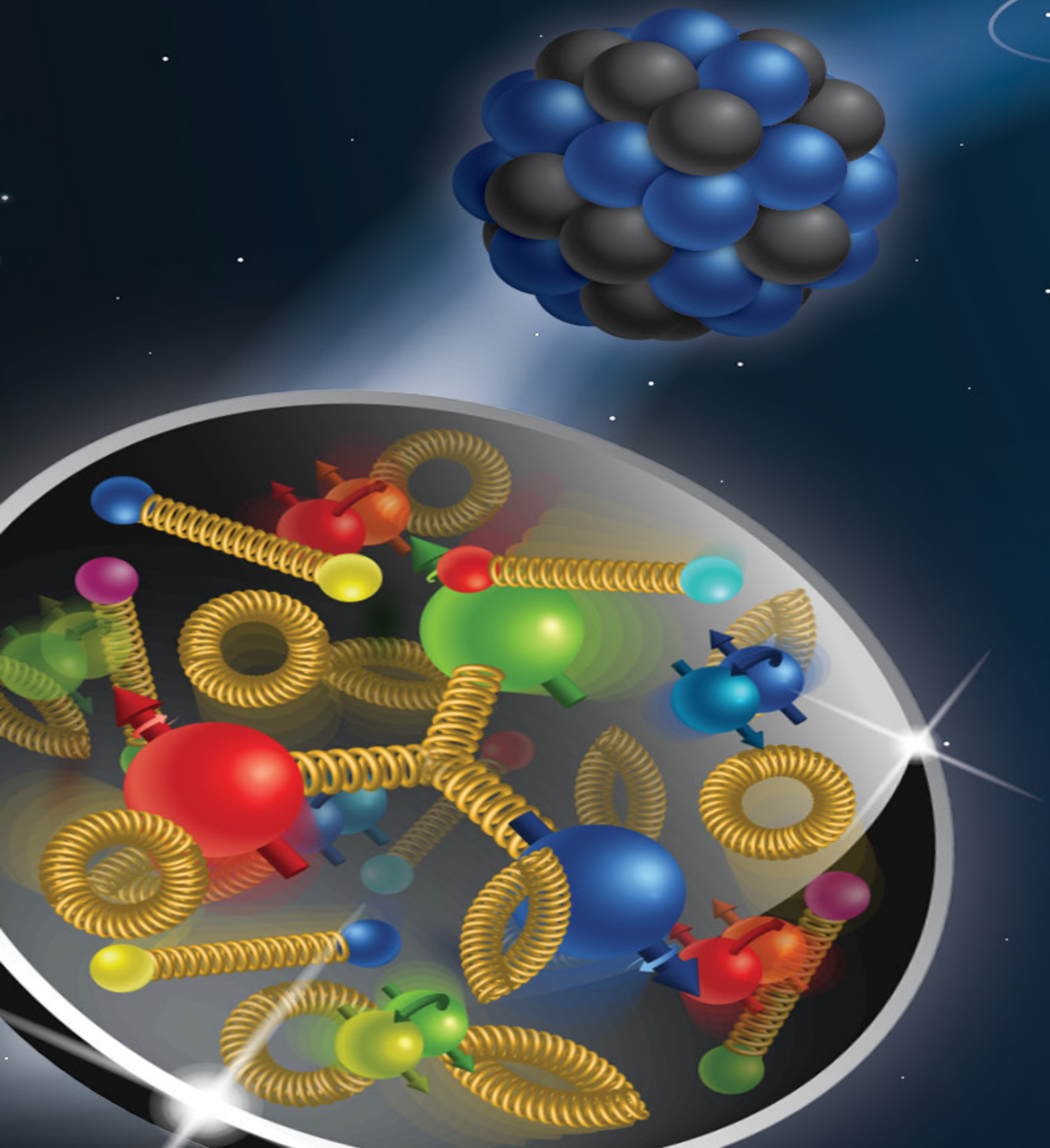


- Crab cavity rotation
  - Can perform rotations of the beam bunches in 2D.
  - Used to account for the luminosity drop due to the crossing angle – allows for head-on collisions to still take place.



- Detector Choices
  - Pixel size, RP transfer matrix, etc.

These effects introduce smearing in our momentum reconstruction.

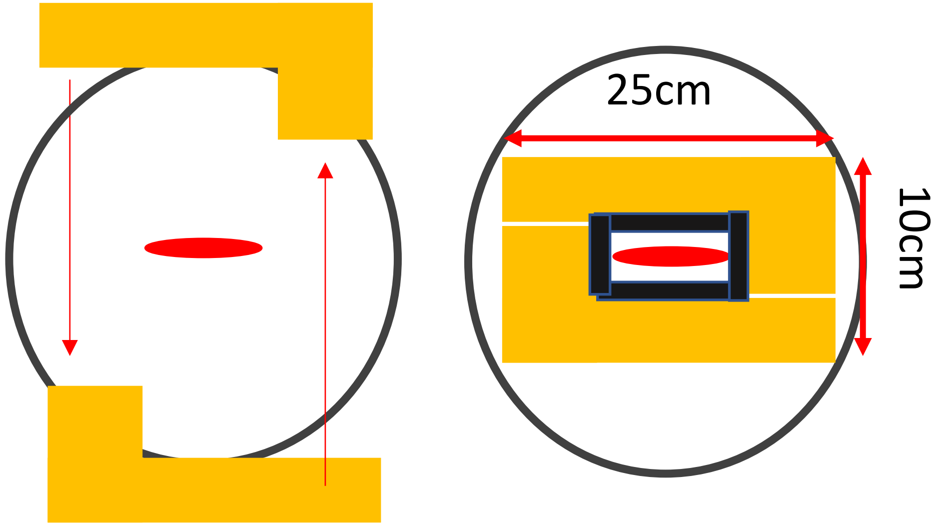


Details of Individual Detector Requirements

Roman Pots

- <u>Requirements:</u>
  - Fast timing (~35ps) to remove vertex smearing effect from crab rotation.
  - 500um x 500um pixels.
  - Radiation hardness (although not as stringent as LHC).
  - Large active area (25cm x 10cm).
  - Silicon sensor that provides timing and spatial information ideal (e.g. LGADs).
  - eRD24 + LGAD consortium actively doing R&D to this end.

- **<u>Low-pT cutoff determined by beam optics.</u>**
  - **The safe distance is 10σ from the beam center.**
- **These optics choices change with energy, but can also be changed within a single energy to maximize *either acceptance at the RP, or the luminosity.***



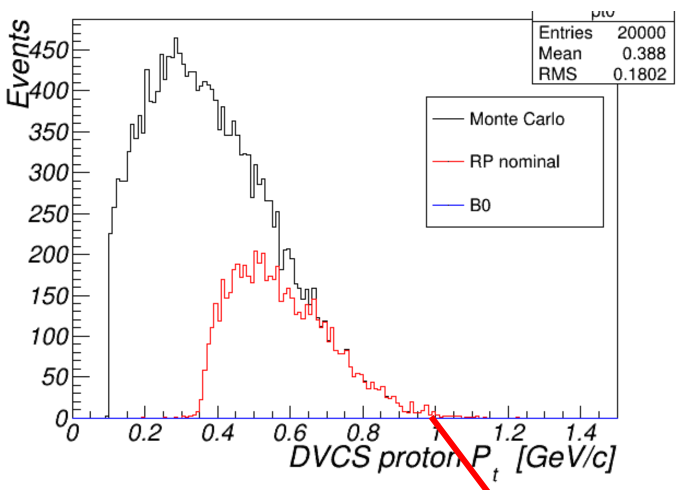
$\sigma(z)$ is the Gaussian width of the beam, $\beta(z)$ is the RMS transverse beam size.
ε is the beam emittance.

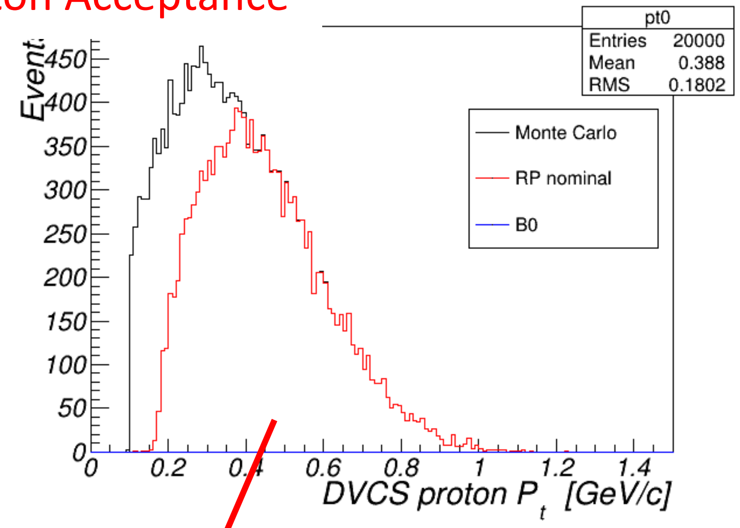
0.0* ($10\sigma\ cut$) < $\boldsymbol{\theta}$ < 5.0 mrad

$$\sigma(z) = \sqrt{\varepsilon \cdot \beta(z))}$$

Roman Pots & Machine Optics

18x275 GeV DVCS Proton Acceptance





e+p Beam Energy	Option 1 (high luminosity)	Option 2 (high acceptance)
18x275 GeV	pT > 0.35 GeV/c	pT > 0.2 GeV/c
10x100 GeV	pT > 0.2 GeV/c	pT > 0.1 GeV/c (or better)
5x41 GeV	pT > 0.1 GeV/c	N/A

Option 1: higher lumi., **larger beam at RP**

Option 2: lower lumi., **smaller beam at RP**

The luminosity trade-off is about a factor of 2 between the different configurations.

Impact of Smearing Contributions

- The various contributions add in quadrature (this was checked empirically, measuring each effect independently).

$$\Delta p_{t,total} = \sqrt{(\Delta p_{t,AD})^2 + (\Delta p_{t,CC})^2 + (\Delta p_{t,pxl})^2}$$

Angular divergence — Primary vertex smearing from crab cavity rotation. — Smearing from finite pixel size.

These studies based on the "ultimate" machine performance with strong hadron cooling.

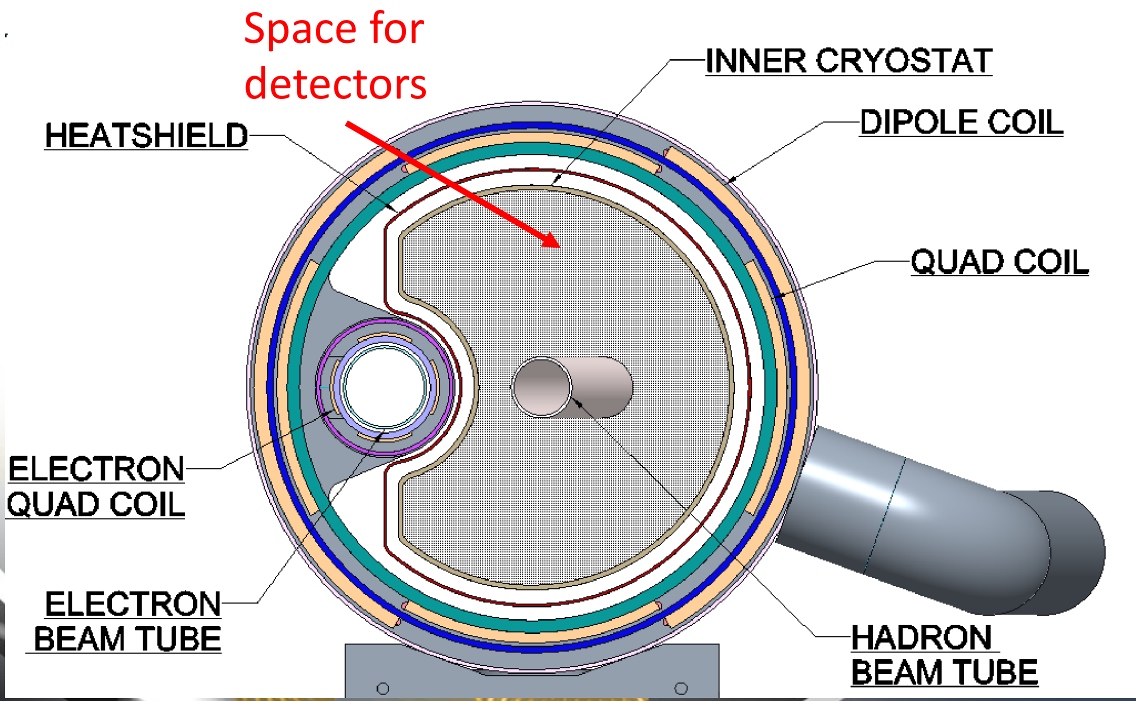
	Ang Div. (HD)	Ang Div. (HA)	Vtx Smear	250um pxl	500um pxl	1.3mm pxl
$\Delta p_{t,total}$ [MeV/c] - 275 GeV	40	28*	20	6	11	26
$\Delta p_{t,total}$ [MeV/c] - 100 GeV	22	11	9	9	11	16
$\Delta p_{t,total}$ [MeV/c] - 41 GeV	14	-	10	9	10	12

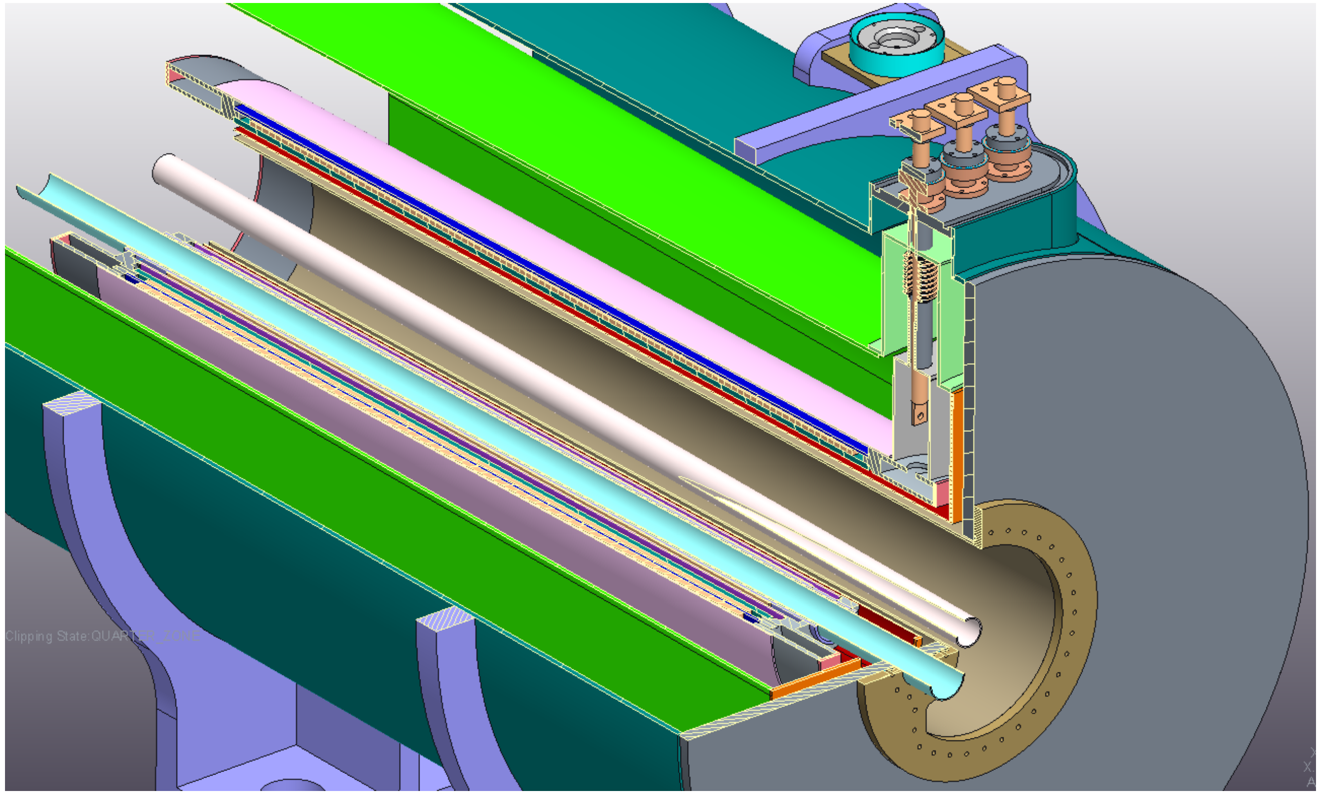
- **Beam angular divergence**
  - Beam property, can't correct for it – **sets the lower bound of smearing.**
  - Subject to change (i.e. get better) – beam parameters not yet set in stone
    - *using symmetric divergence parameters in x and y at 100urad.
- **Vertex smearing from crab rotation**
  - **Correctable with good timing (~35ps).**
  - With timing of ~70ps, effective bunch length is 2cm ->.25mm vertex smearing (~7 MeV/c)
- **Finite pixel size on sensor**
  - **500um seems like the best compromise between potential cost and smearing**

B0-detectors

(5.5 < $\boldsymbol{\theta}$ < 20.0 mrad)

- Charged particle reconstruction.
  - Precise tracking -> need smaller pixels (50um) than for the RP.
  - Require timing layer for the crab rotation effect and background rejection.
  - Shape and # of layers of B0 tracker needs to be further evaluated.



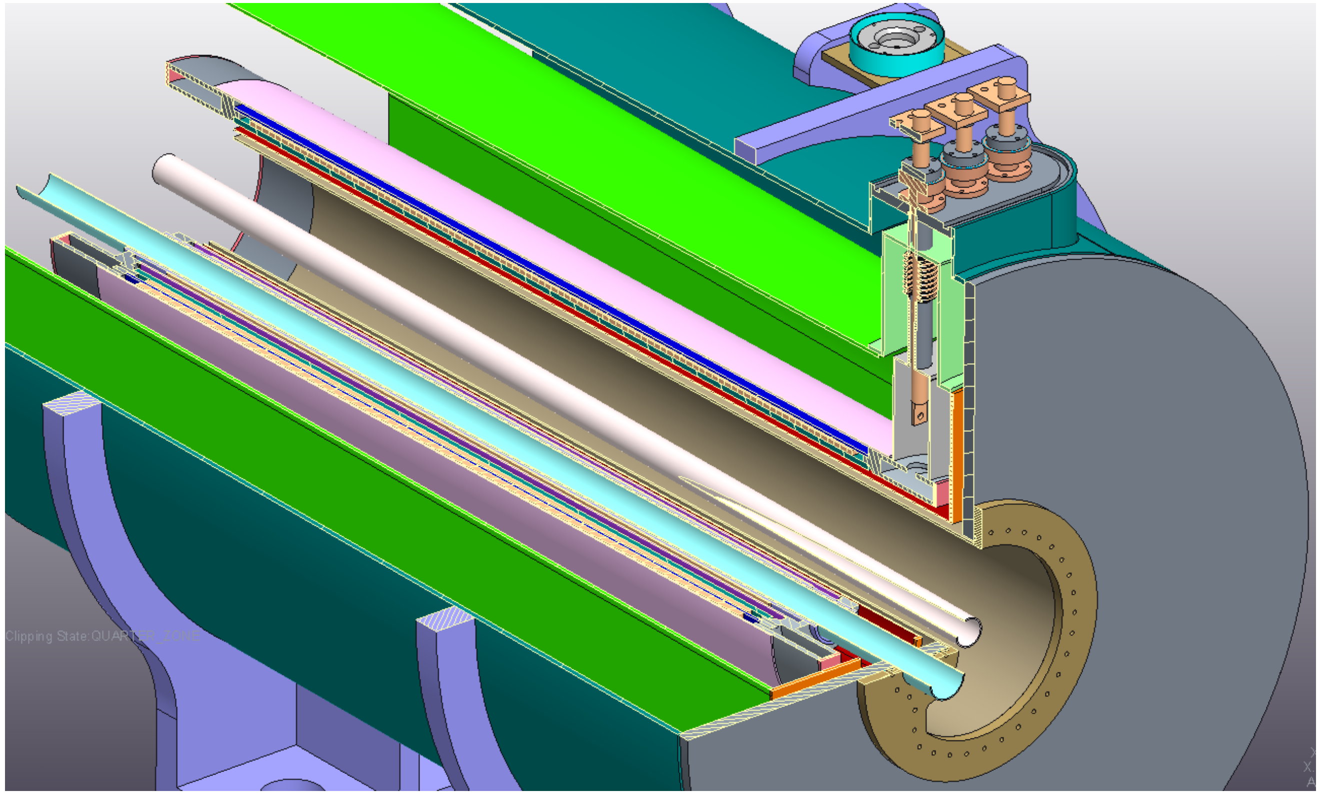


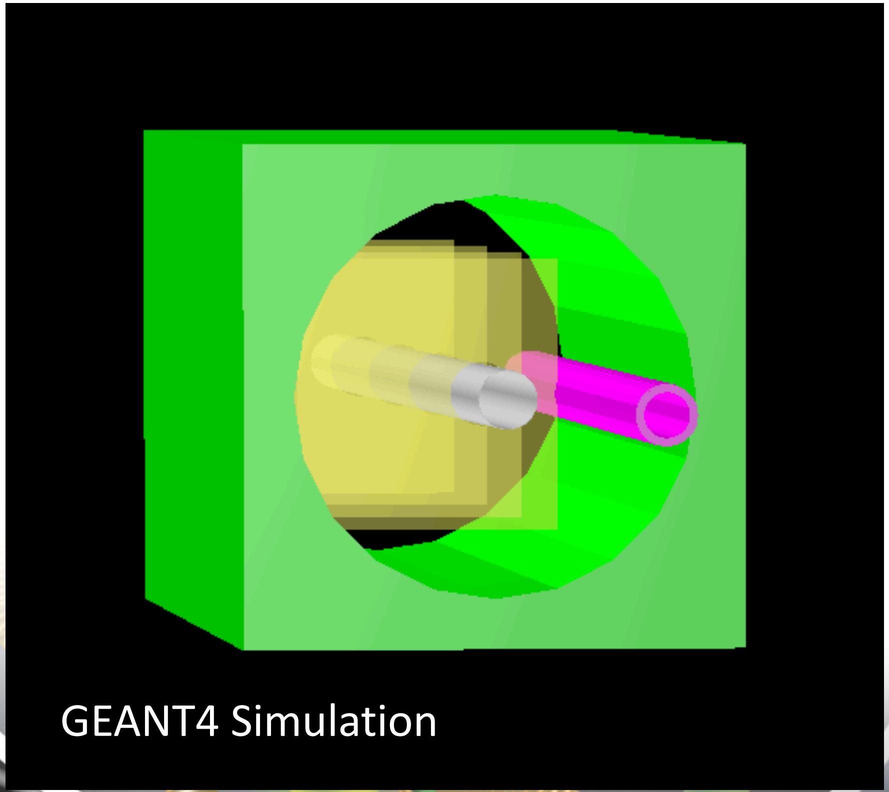
- Higher granularity detectors needed in this area (MAPS, or something similar) with layers of fast-timing detectors (e.g. LGADs), or timepix (provides high resolution space and timing information), depending on sensor layout and size.

B0-detectors

(5.5 < $\boldsymbol{\theta}$ < 20.0 mrad)

- ~1.2 meters of longitudinal space in bore.
- Could potentially have several layers of silicon for tracking, and a few layers after for some EM calorimetry (compact).

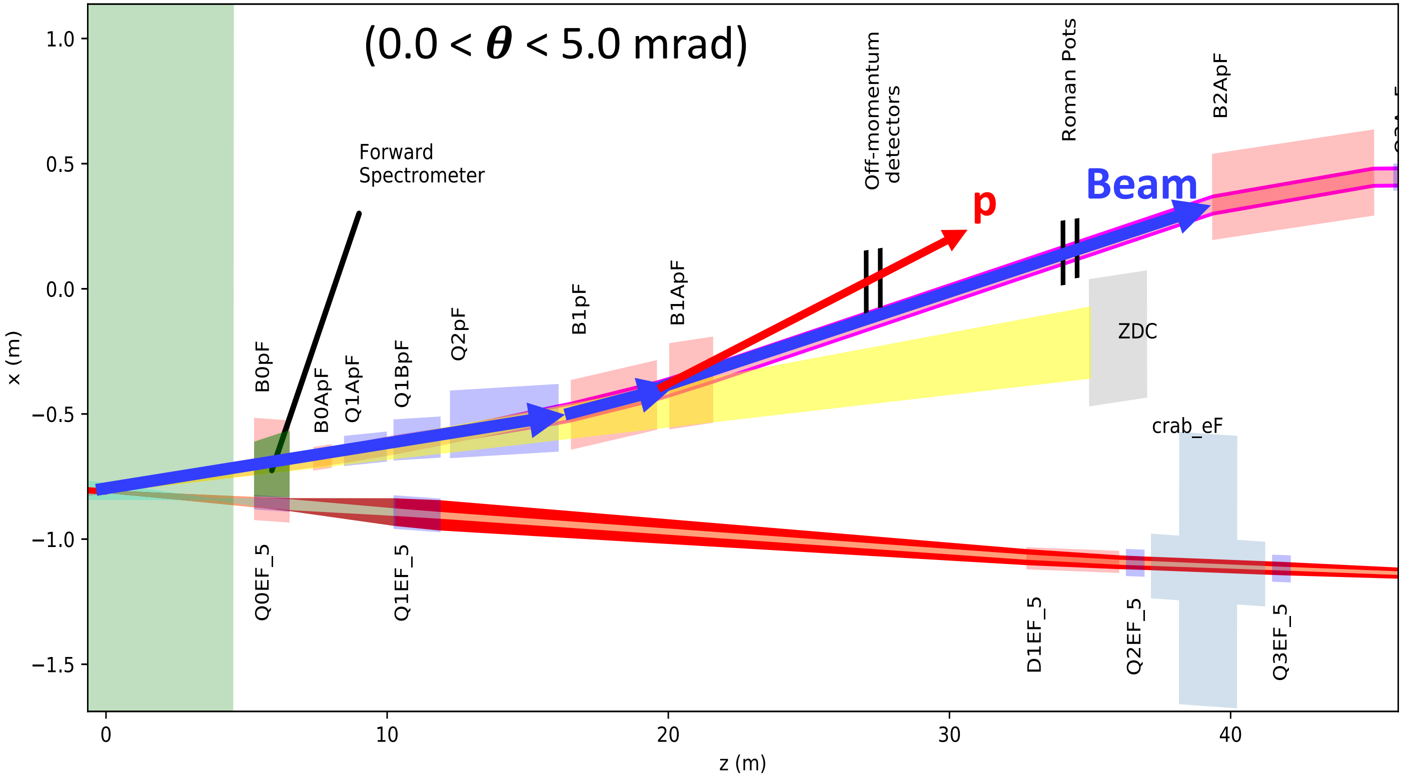




GEANT4 Simulation

- ➢ Tagging photons is also important in differentiating between coherent and incoherent heavy-nuclear scattering.
- ➢ **Potential inclusion of small EMCAL or preshower detector in the B0 bore.**
- ➢ Further study needed to assess.
- ➢ Tagging photons further down-stream (ZDC) highly technically challenging.

Off-Momentum detectors

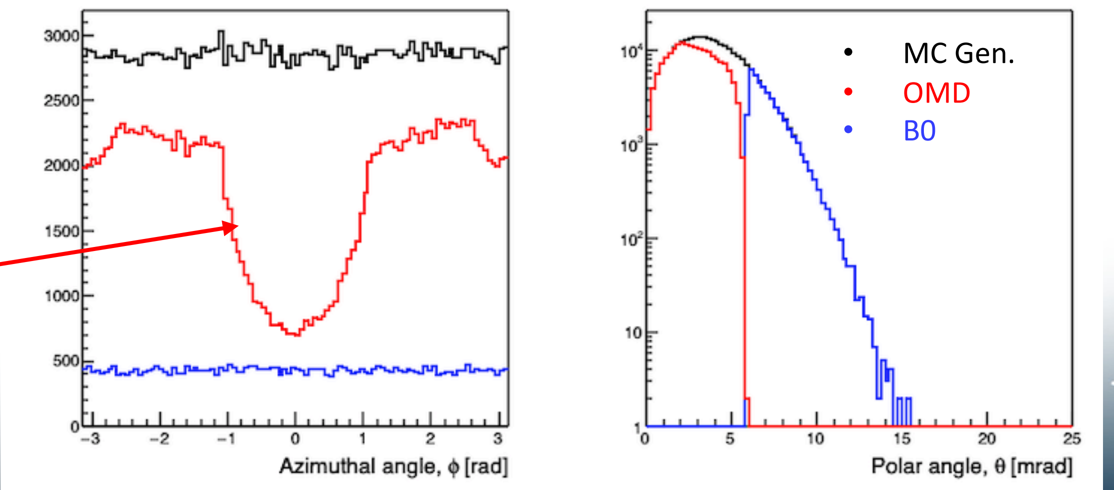


- Acceptance mostly limited by losses of very off momentum particles in quadrupoles.

- Off-momentum detectors used for tagging protons from nuclear breakup and decay products (e.g. π^- and protons).
- Placed outside the beam pipe after the B1apf dipole (last dipole before long drift section that leads to the Roman Pots).
- Same technology can be used as for the RP sensors.

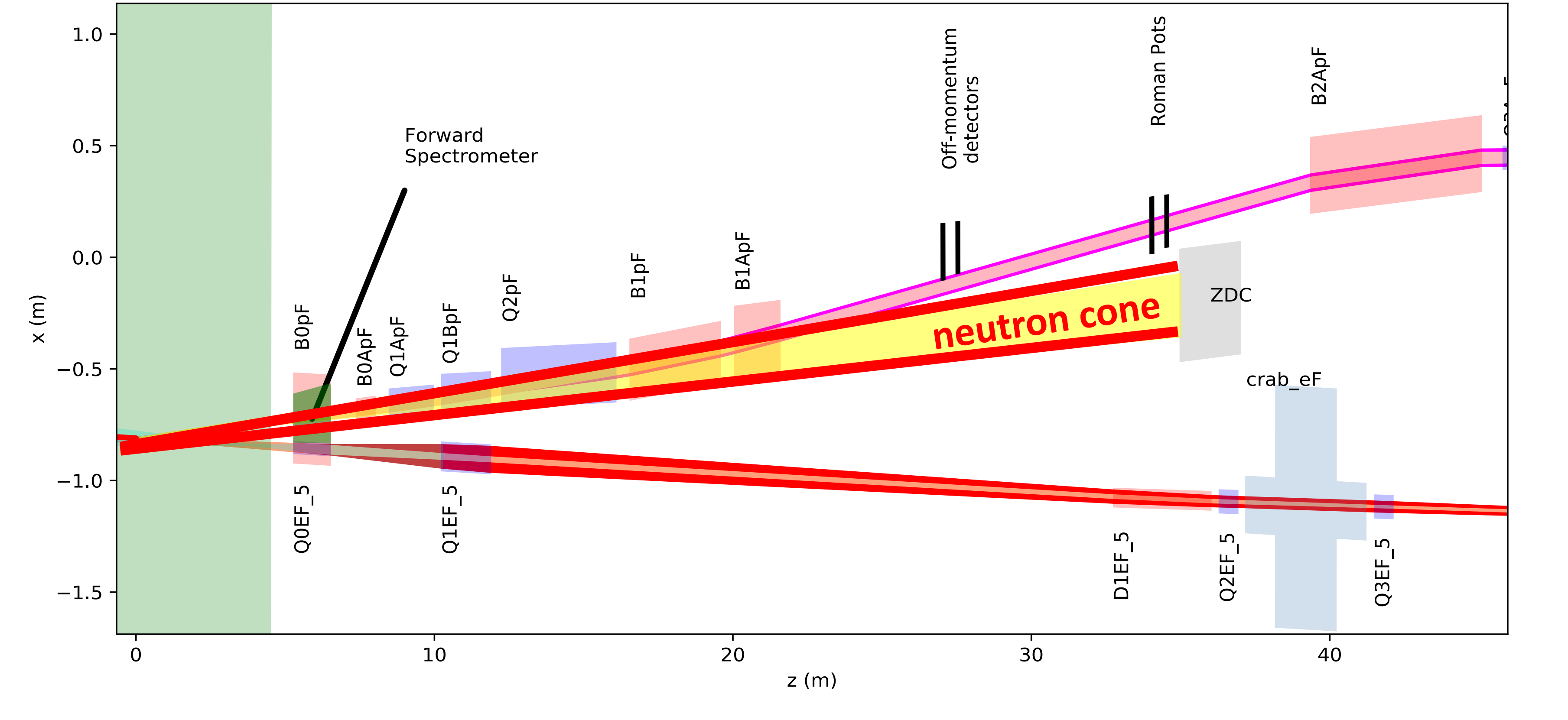
e+d -> J/Psi + p + n (18x110GeV)

Neutron spectator/leading proton case.



Zero-Degree Calorimeter

- High resolution HCAL + EMCAL for detecting neutral forward-going particles (neutrons and photons)
  - HCAL requires $\frac{\Delta E}{E} \sim \frac{50\%}{\sqrt{E}} \oplus 5\ \%$ and $\sigma_\theta \sim \frac{3\ \mathrm{mrad}}{\sqrt{E}}$, or better.
  - ALICE FoCal assumptions used for studies thus far (EIC R&D group started last summer).
  - Acceptance limited by bore of magnet where the neutron/photon cone exits ($0.0 < \theta < 4.5$ mrad).



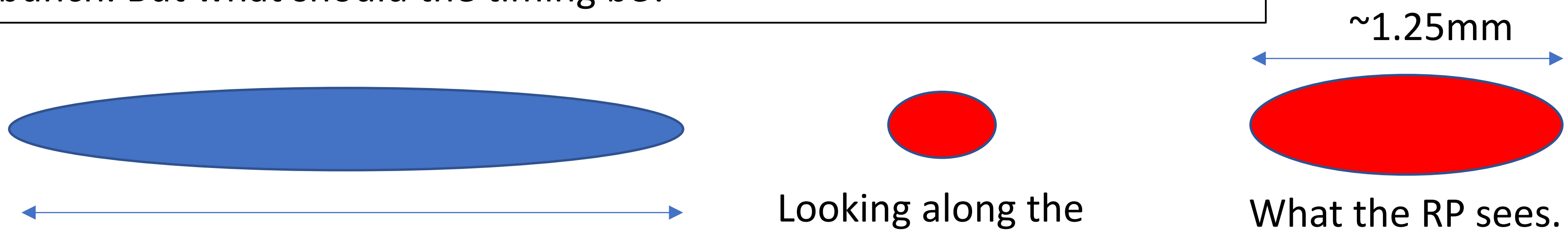
Takeaways

- Acceptances and resolutions in the FF region of the EIC IR are well-understood.
  - Multiple detector sub-systems, lots of engineering considerations affecting acceptance.
  - Major design challenge!
- As the design process continues, optimizations are being considered to provide better acceptance (e.g. beam optics configurations to allow better low-pt acceptance at the RP).
- Numerous physics impact studies carried out and detailed in the EIC Yellow Report and CDR (on the ArXiV soon).
- EIC R&D groups studying detector technologies for the FF region.
  - These studies have provided essential feedback the process of refining the EIC IR design, and the choice of detector technologies.
- In general, there is still much to study in terms of integration, material budget, etc. – stay tuned!

Backup

Reminder: Timing

For exclusive reactions measured with the Roman Pots we need good timing to resolve the position of the interaction within the proton bunch. But what should the timing be?



RMS hadron bunch length ~10cm*.
*based on "ultimate" machine performance.

Looking along the beam with no crabbing.

What the RP sees.

- Because of the rotation, the Roman Pots see the bunch crossing **smeared in x**.
- Vertex smearing = 12.5mrad (half the crossing angle) * 10cm = **1.25 mm**
- If the effective vertex smearing was **for a 1cm bunch**, we would have **0.125mm** vertex smearing.
- The simulations were done with these two extrema and the results compared.

➢ **From these comparisons, reducing the effective vertex smearing to that of the 1cm bunch length reduces the momentum smearing to a negligible amount from this contribution.**

➢ **This can be achieved with timing of ~ 35ps (1cm/speed of light).**

Geometric Acceptances

Neutrons:

- Assume uniform acceptance for $0<\theta<4.5$ mrad
  - Limited by bore of magnet where the neutron cone has to exit.
  - Up to 5.5 mrad on one side of the aperture.
- Resolutions (ZDC)
  - Assume an overall energy resolution of $\sigma_E/E=(50\%)/\sqrt{E} \oplus 5\%$
  - Assume angular resolution of $\sigma_\theta=(3\text{ mrad})/\sqrt{E}$

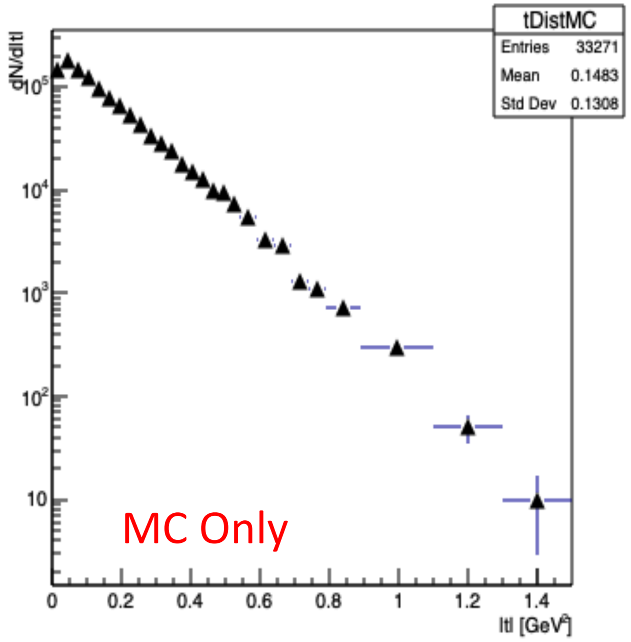
Protons:

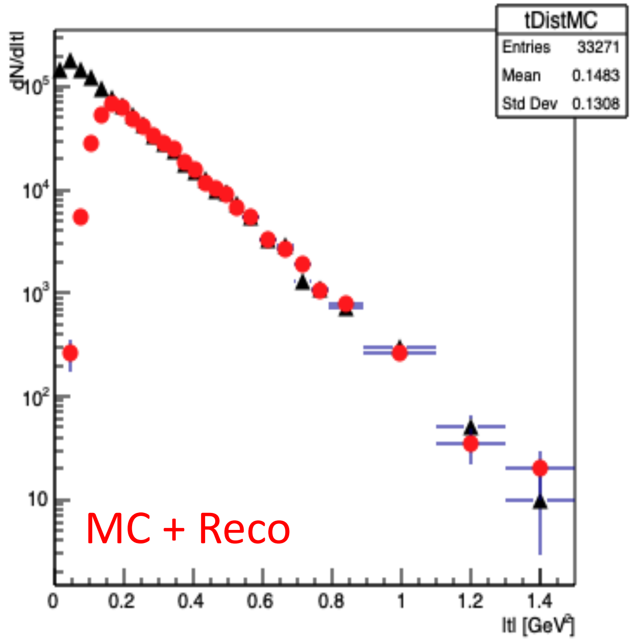
- Assume uniform acceptance for $6 < \theta < 13$ mrad (20mrad on the other side) – “B0 spectrometer”
- For protons with p_z/(beam momentum) > 0.6 – “Roman pots”
  - 275 GeV: Assume uniform acceptance for $0.5<\theta<5.0$ mrad
  - 100 GeV: Assume uniform acceptance for $0.2<\theta<5.0$ mrad
  - 41 GeV: Assume uniform acceptance for $1.0<\theta<4.5$ mrad
- For protons with $0.25<p_z$/(beam momentum)<0.6 – “Off-momentum Detectors”
- Assume uniform acceptance for $0.0<\theta<2.0$ mrad
- for $2.0<\theta<5.0$ mrad, only accepted for $|\varphi|>1$ radian
- Resolutions (silicon reconstruction with transfer matrix or conventional tracking).
  - pt ~ 3% for pt > 550 MeV/c, p ~ 0.5%

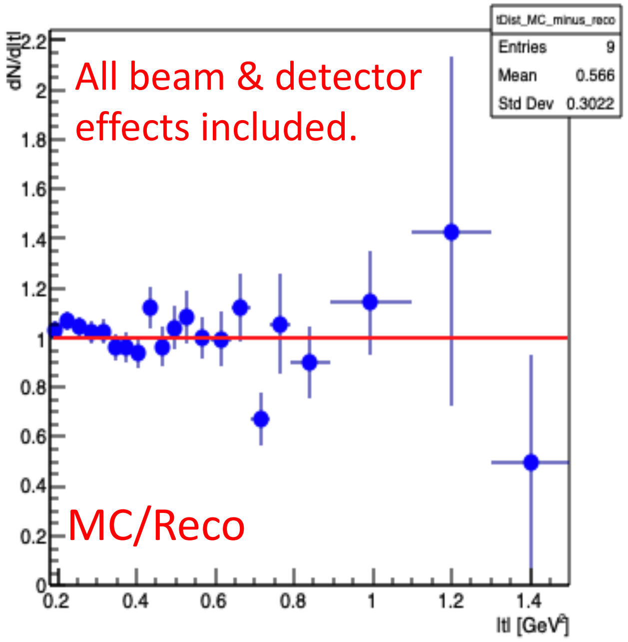
e+p DVCS

- Full GEANT4 simulations with Roman Pots carried out.
- All acceptance & smearing effects included.

18x275 GeV e+p DVCS events generated with MILOU.







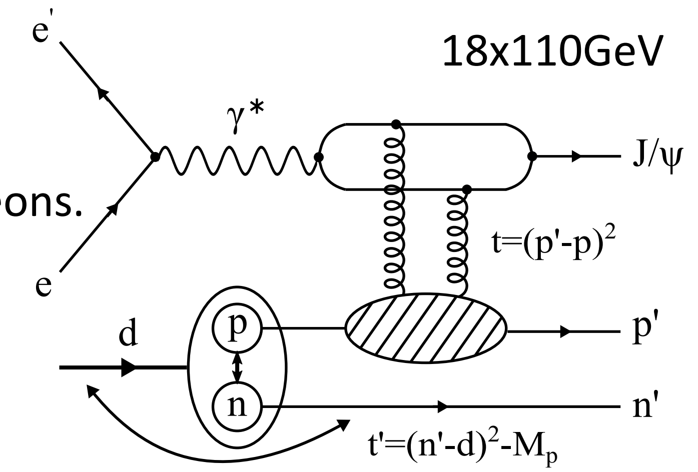
- ➢ **Low-|t| acceptance affected by beam optics/size of beam at Roman Pots – can be mitigated with different optics configurations.**
- ➢ **With all smearing effects included, extraction of slope for Fourier Transform straightforward.**

e+d Spectator Tagging

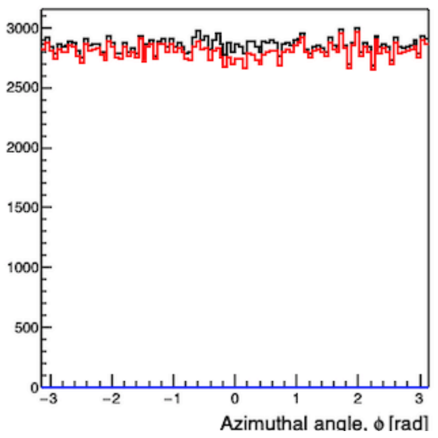
Z. Tu, A. Jentsch *et al.*, Phys. Lett. B, **811** (2020)

Proton spectator case.

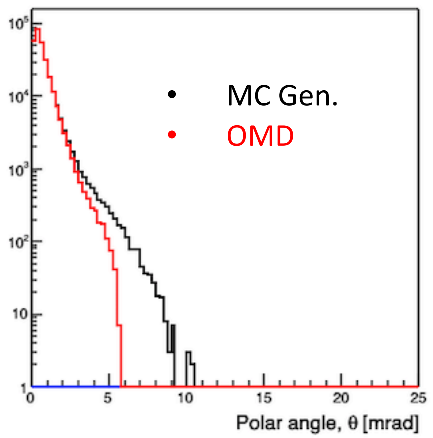
Particular process in BeAGLE: incoherent diffractive J/psi production off bounded nucleons.

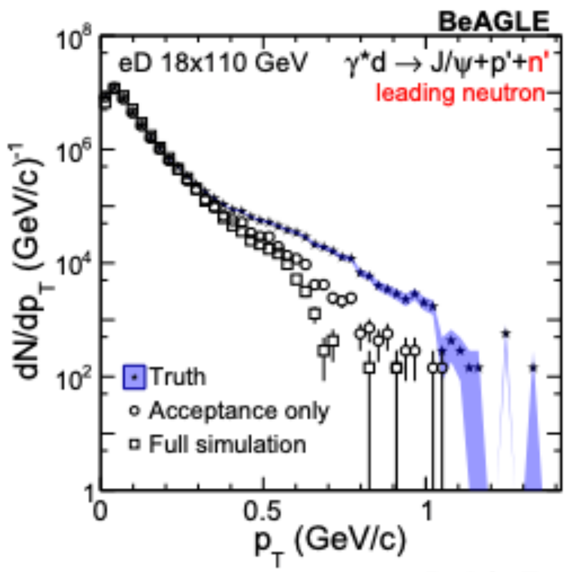


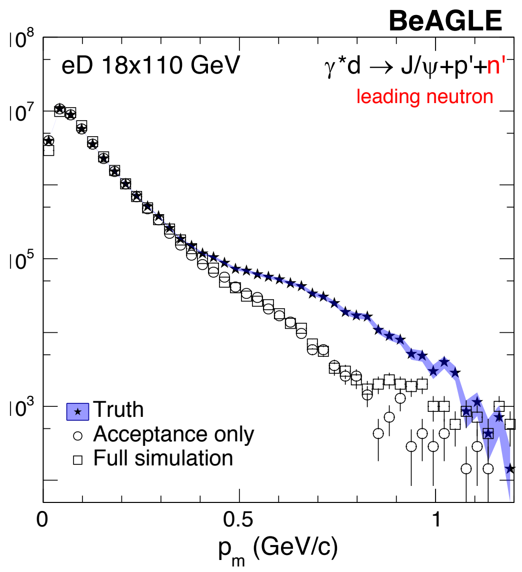
Protons

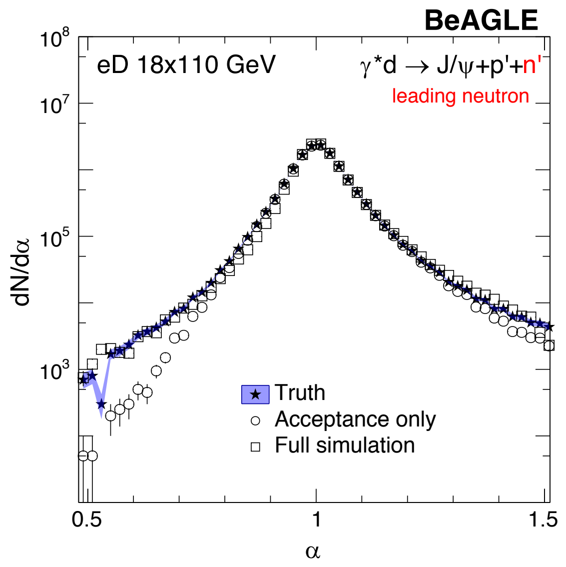


Protons









Spectator kinematic variables reconstructed over a broad range. Bin migration is observed due to smearing in the reconstruction. Each plot shows the MC (closed circles), acceptance effects only (open circles), and full reconstruction (open squares).

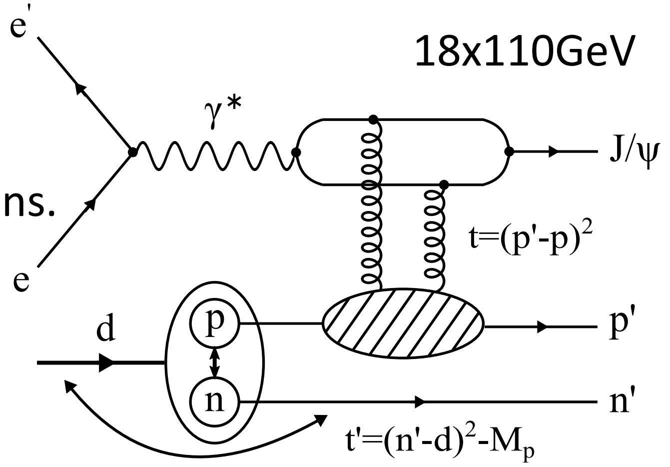
- **In the proton spectator case, essentially all spectators tagged.**
- **Active neutrons only tagged up to 4.5 mrad.**

e+d Spectator Tagging

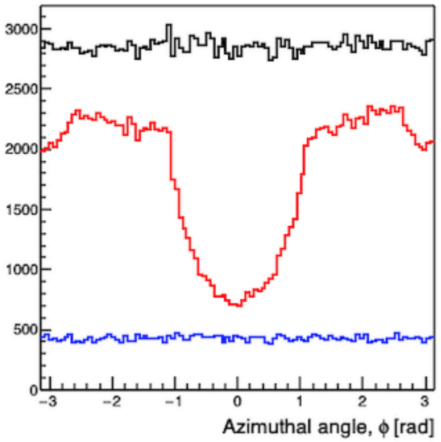
Z. Tu, A. Jentsch *et al.*, Phys. Lett. B, **811** (2020)

Neutron spectator case.

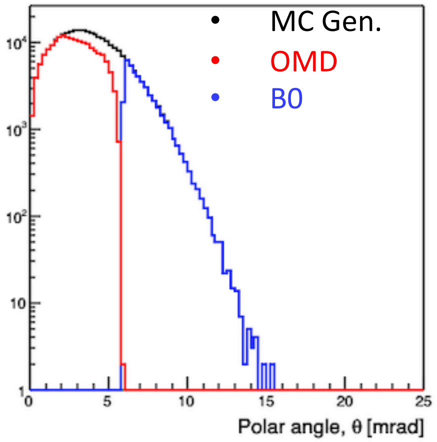
Particular process in BeAGLE: incoherent diffractive J/psi production off bounded nucleons.

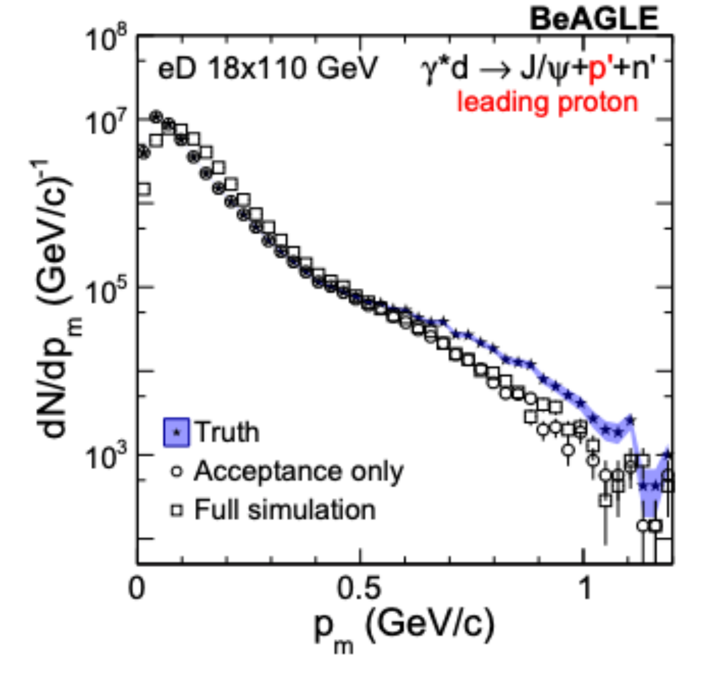


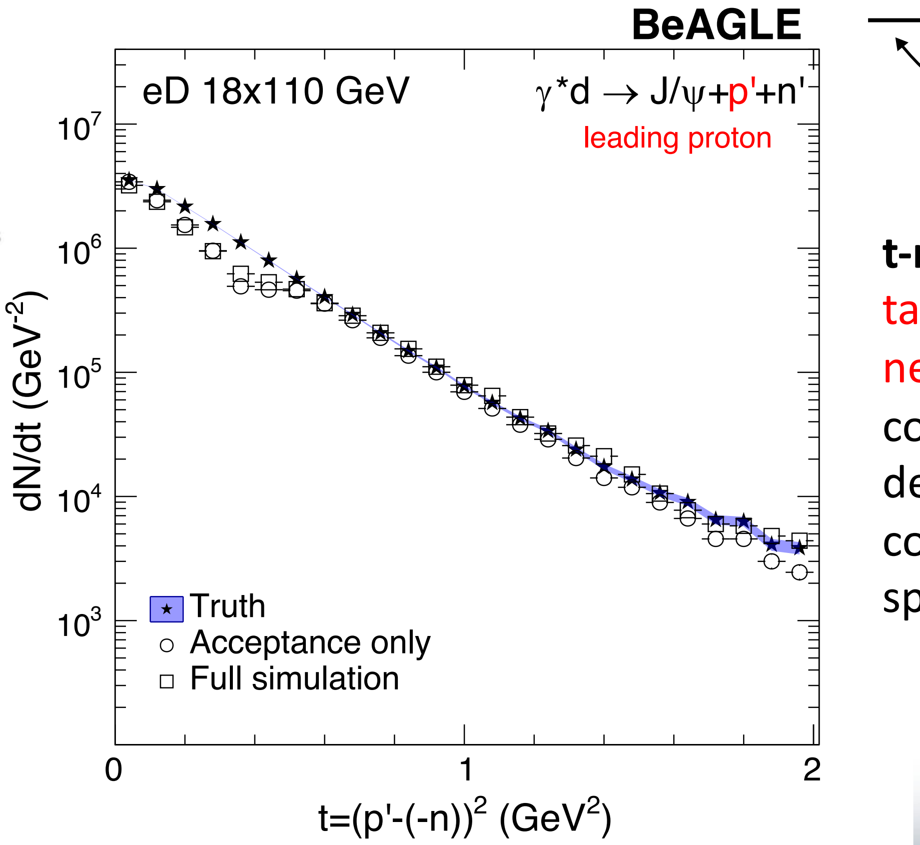
Protons



Protons







t-reconstruction using double-tagging (both proton and neutron). Takes advantage of combined B0 + off-momentum detector coverage. Better coverage in the neutron spectator case.

➢ **Spectator information is the "dial" for the SRC region.**