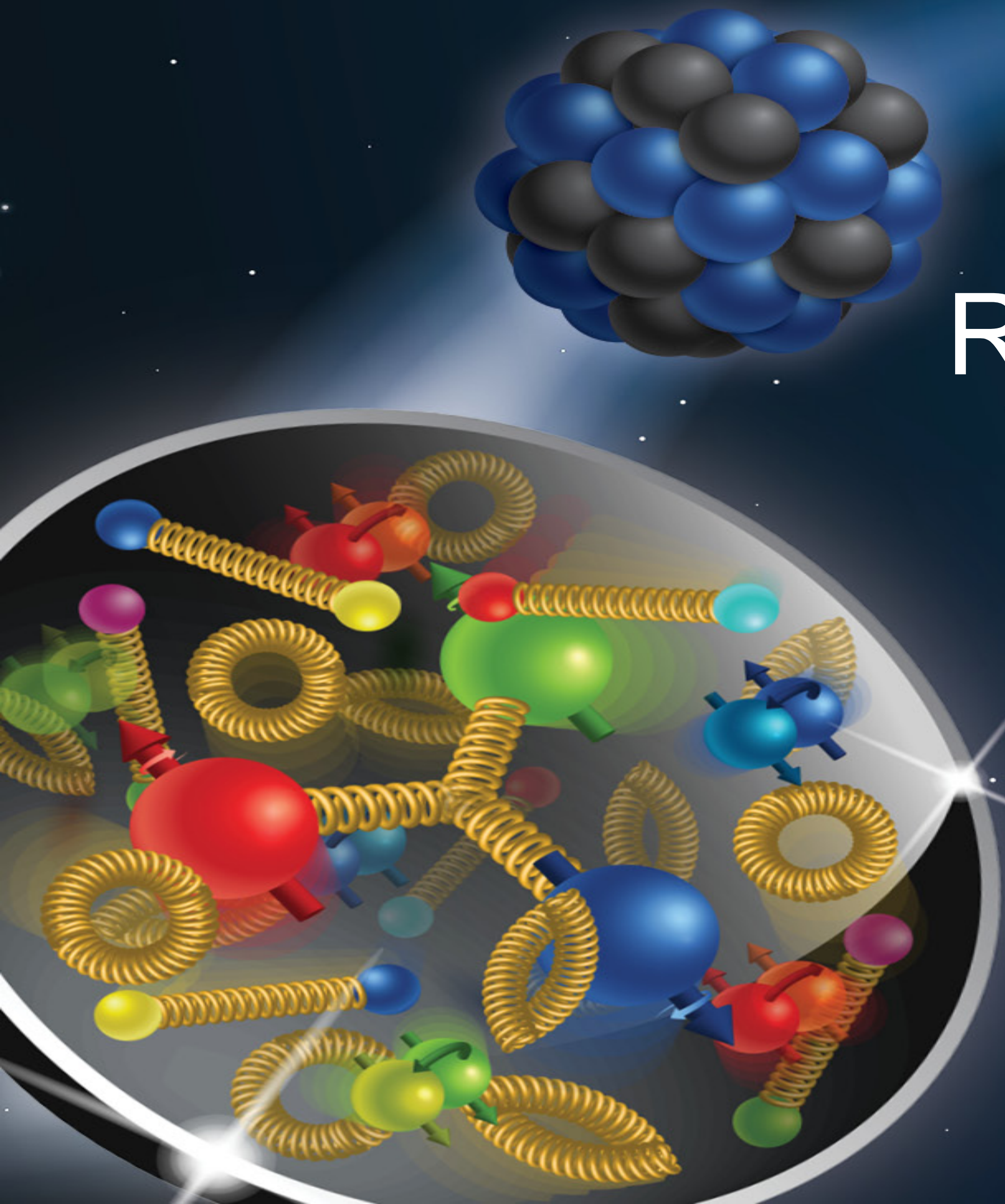


Roman Pots and other LGAD Applications at the EIC

LGAD Consortium Meeting

Feb. 3rd, 2021

Alex Jentsch (Brookhaven National Laboratory)

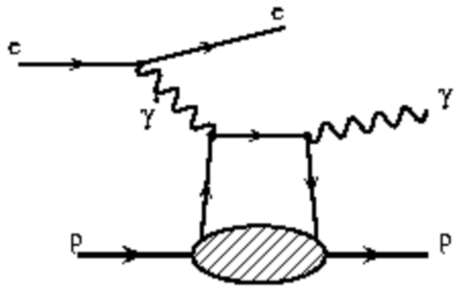
Electron Ion Collider

BROOKHAVEN NATIONAL LABORATORY

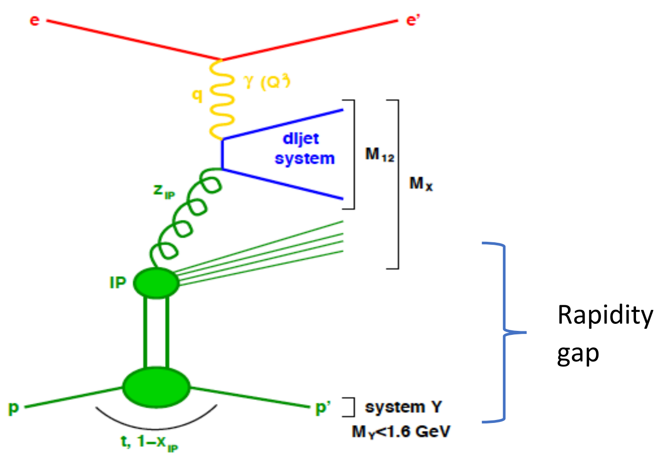
U.S. DEPARTMENT OF ENERGY | Office of Science

Far-forward physics at EIC

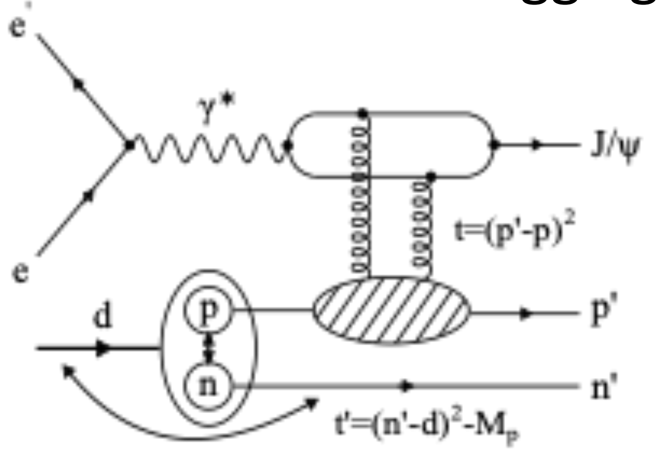
e+p DVCS events with proton tagging.



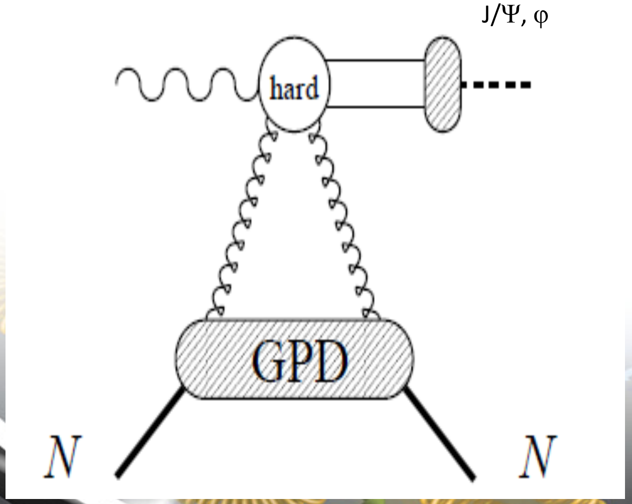
Diffraction



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

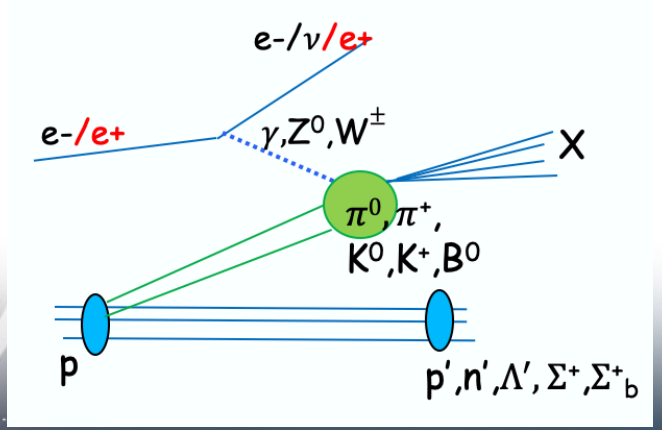


Saturation (coherent/incoherent J/ψ production)



Meson structure:

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



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 proton tagging

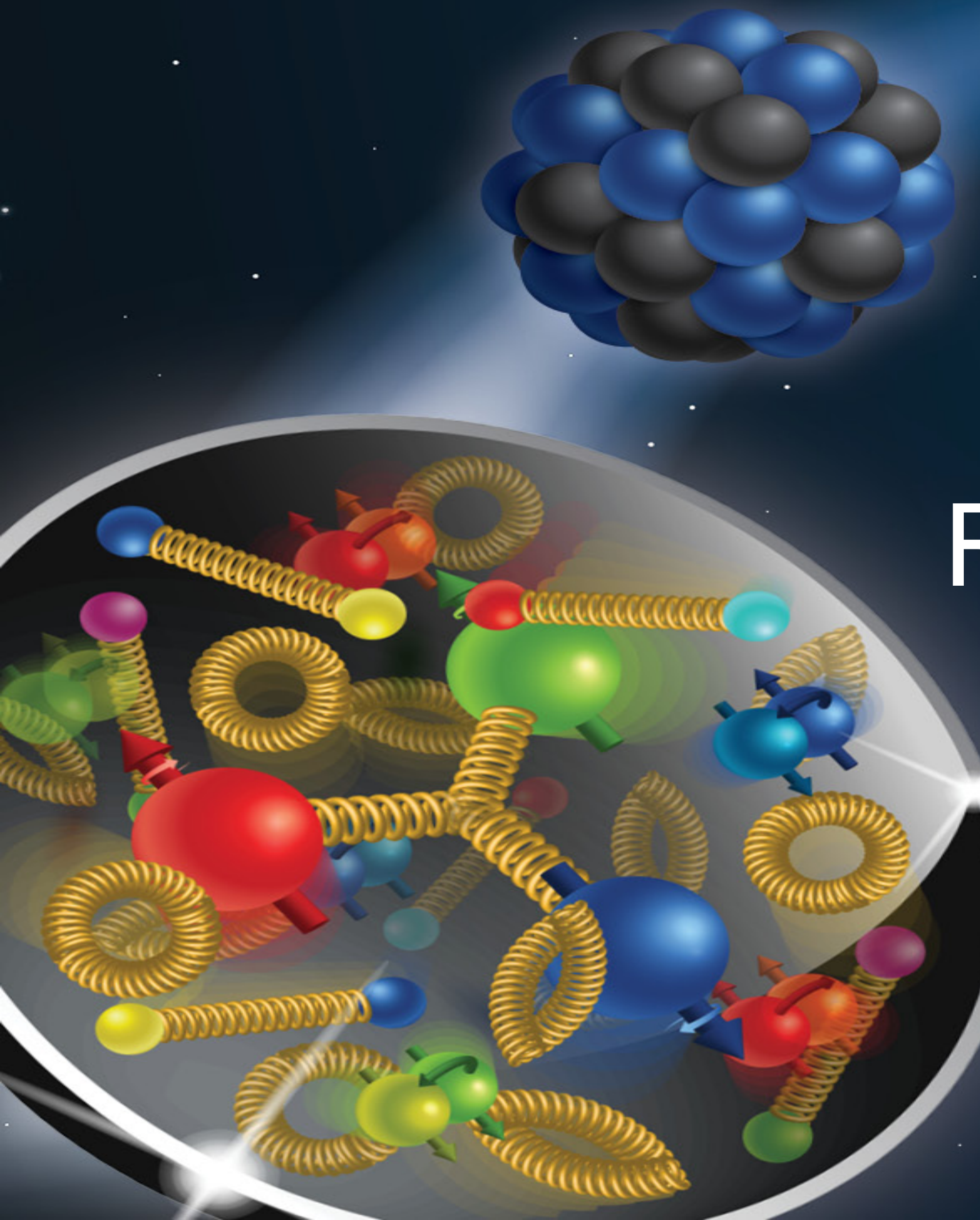
Diffraction

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.

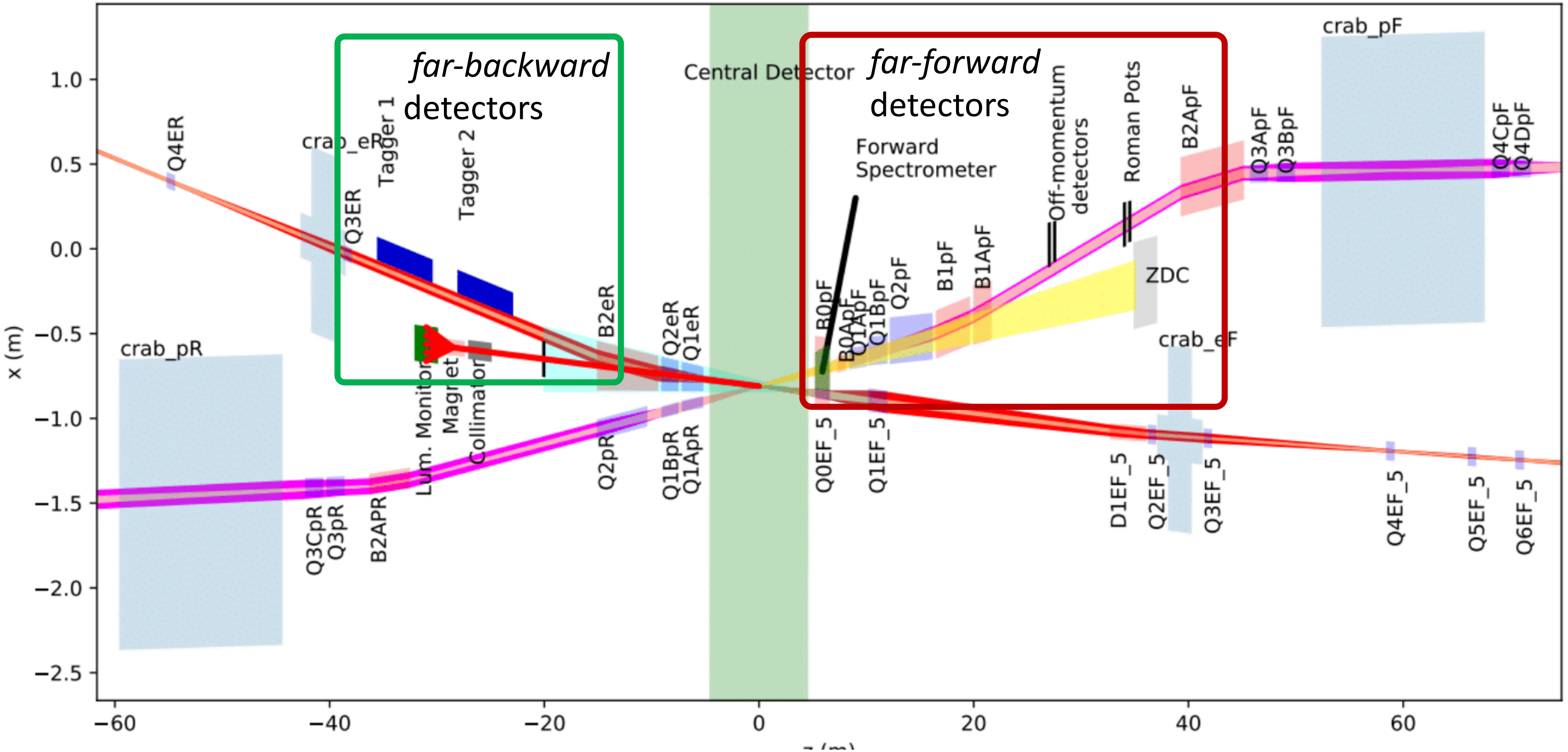
acceptance.

....



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

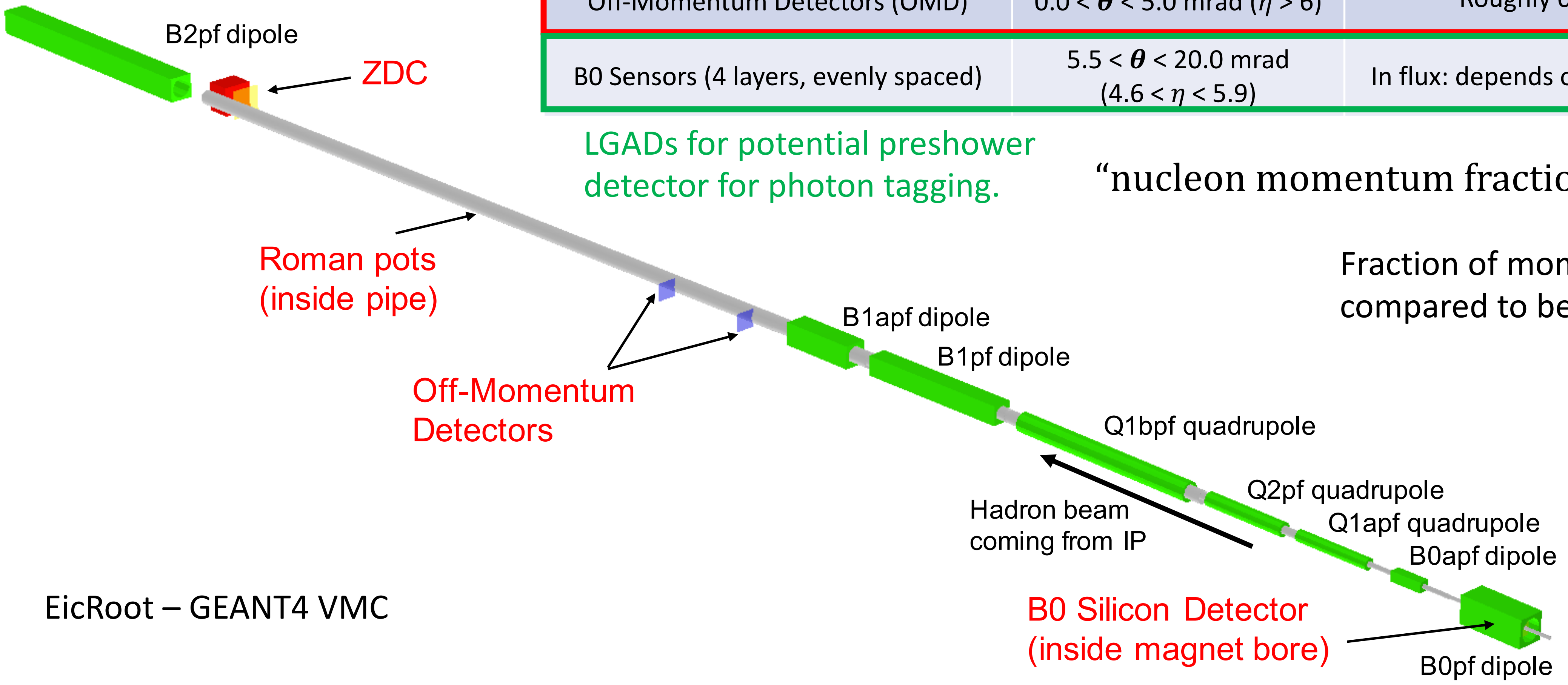
LGADs for proton/nuclear fragment/charged particle tagging.

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.

LGADs for potential preshower detector for photon tagging.

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

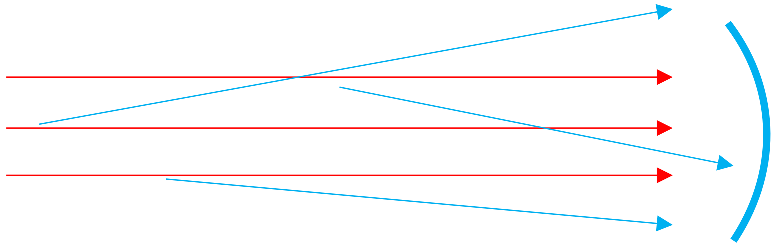
Fraction of momentum for nucleon compared to beam.

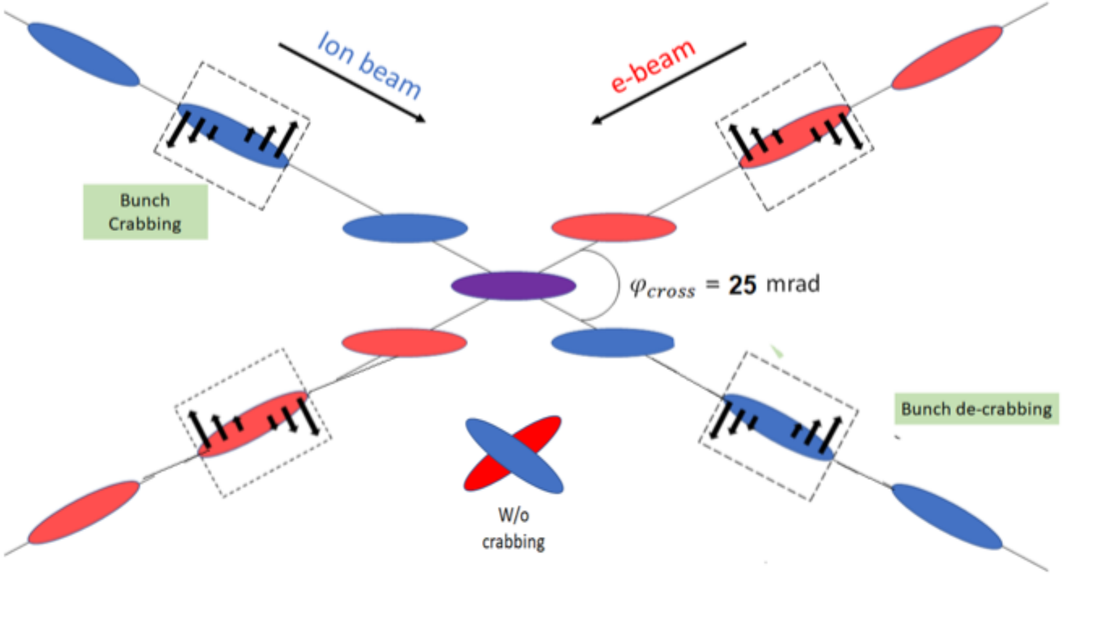


EicRoot – GEANT4 VMC

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.

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.

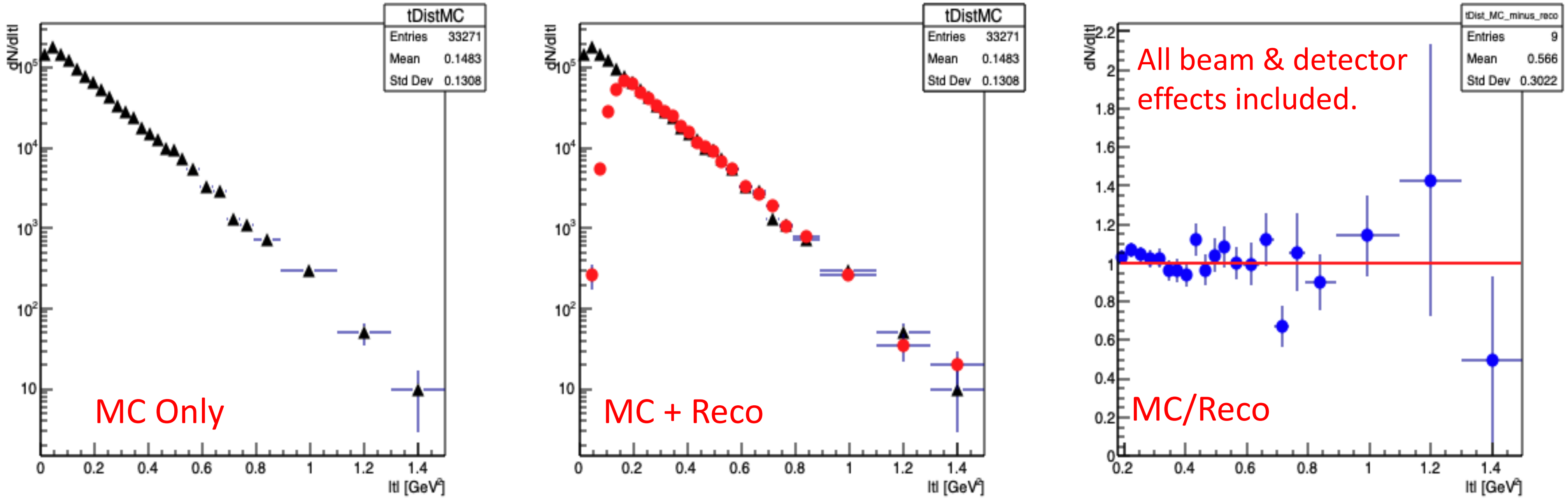
	Ang Div. (HD)	Ang Div. (HA)	Vtx Smear	250um pxl	500um pxl	1.3mm pxl
$\Delta p_{t,total}$ [MeV/c] - 275 GeV	40	28*	20	6	11	26
$\Delta p_{t,total}$ [MeV/c] - 100 GeV	22	11	9	9	11	16
$\Delta p_{t,total}$ [MeV/c] - 41 GeV	14	-	10	9	10	12

- **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**

e+p DVCS

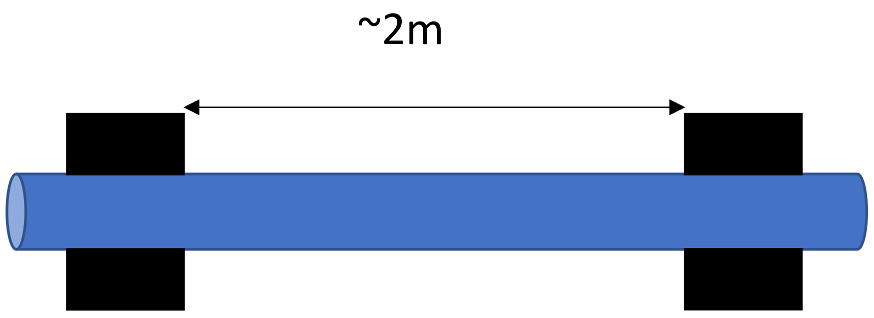
- Full GEANT4 simulations with Roman Pots carried out.
- All acceptance & smearing effects included.

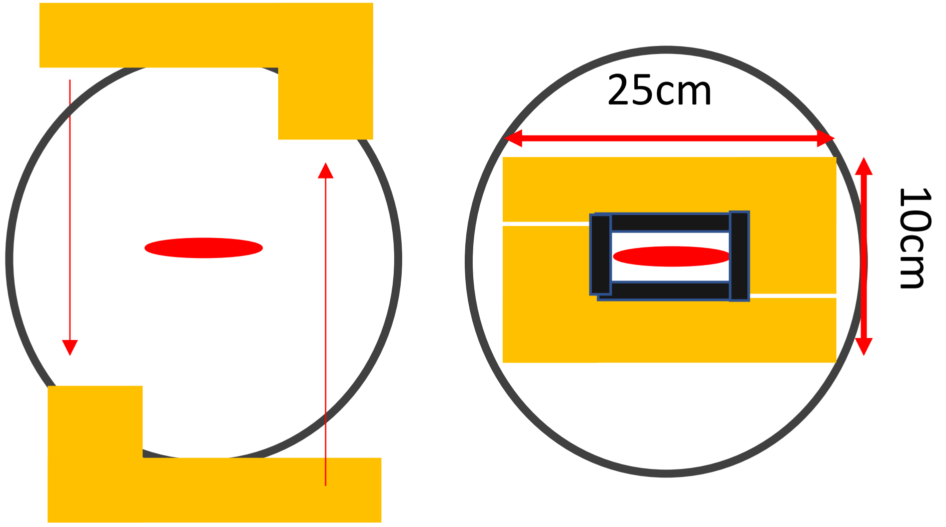
18x275 GeV e+p DVCS events generated with MILOU.



- ➢ **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.**

Roman Pots

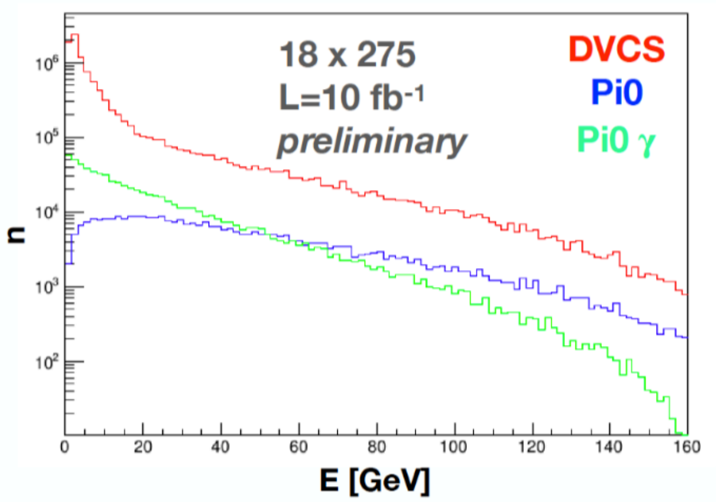




- <u>Requirements:</u>
  - Fast timing (~35ps) to remove vertex smearing effect from crab rotation.
  - 500um x 500um pixels.
  - Radiation hardness (although not as stringent as LHC).
  - Large active area (25cm x 10cm).
- **AC-LGADs cover these requirements in one package.**

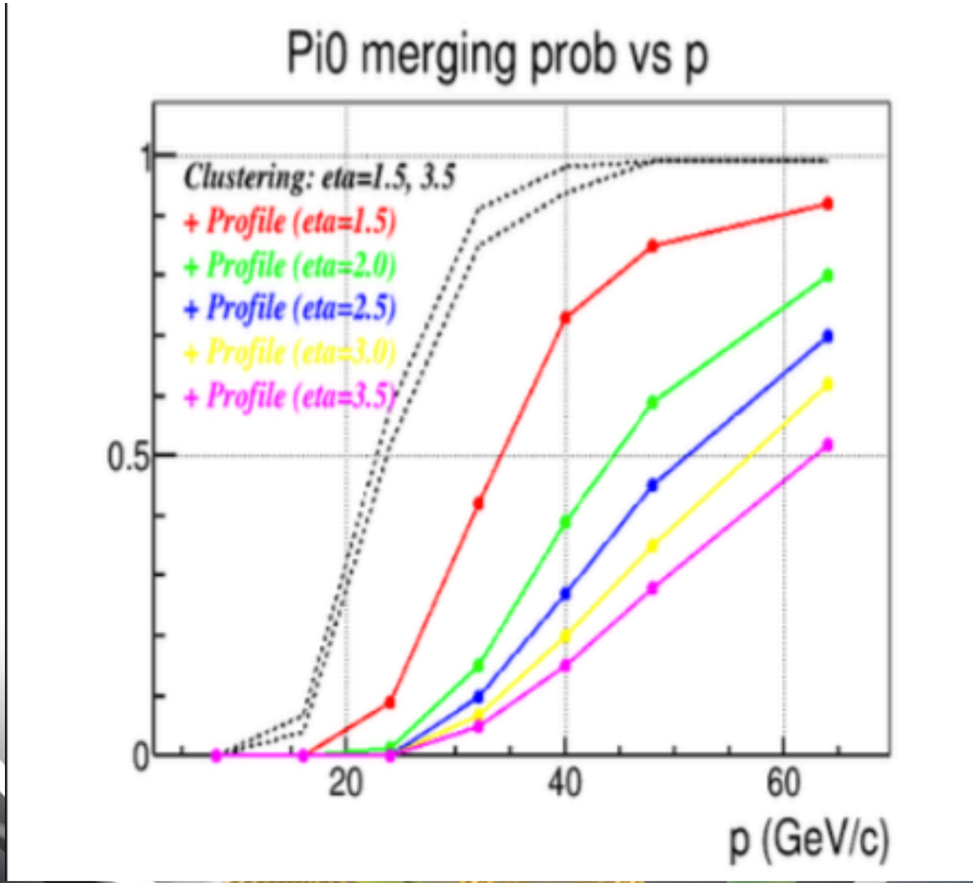
Expanding the Scope: Application for a Preshower Detector

DVCS and exclusive $\pi0$



High granularity/density h-endcap EMCal:
2.5×2.5 cm² granularity at z=3m

Need to discriminate $\pi0 \to \gamma\gamma$ up to ~150 GeV/c



Limited EMCal Performance

- Particularly for non-projective geometry.

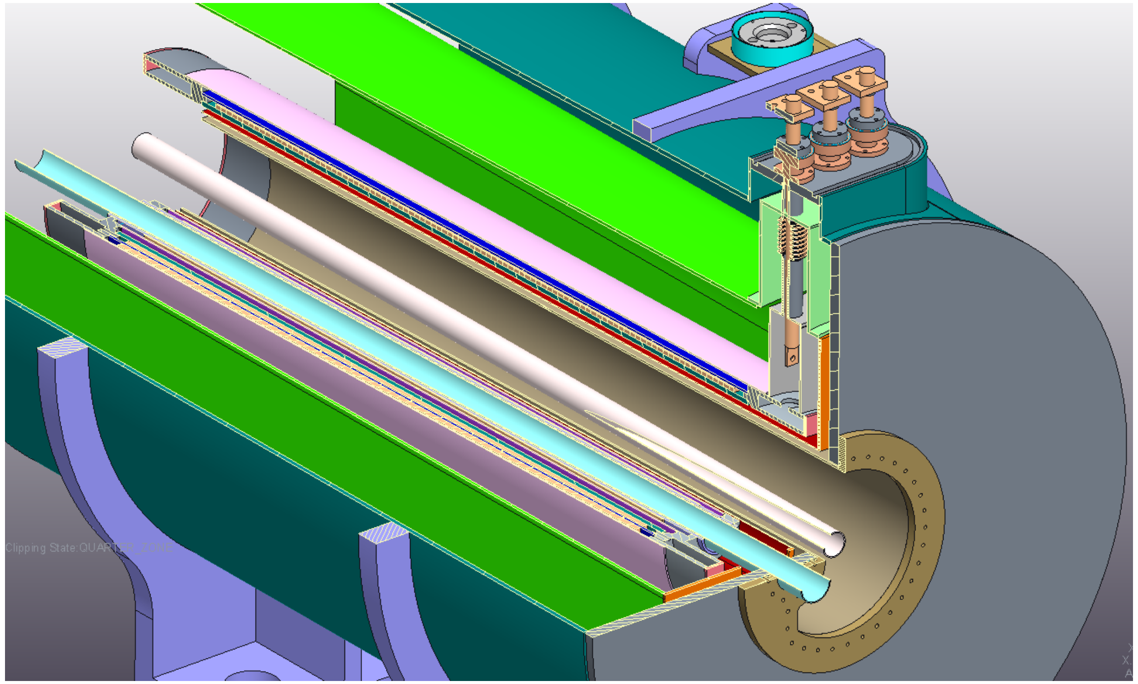
Preshower with granularity < 3mm would do the job

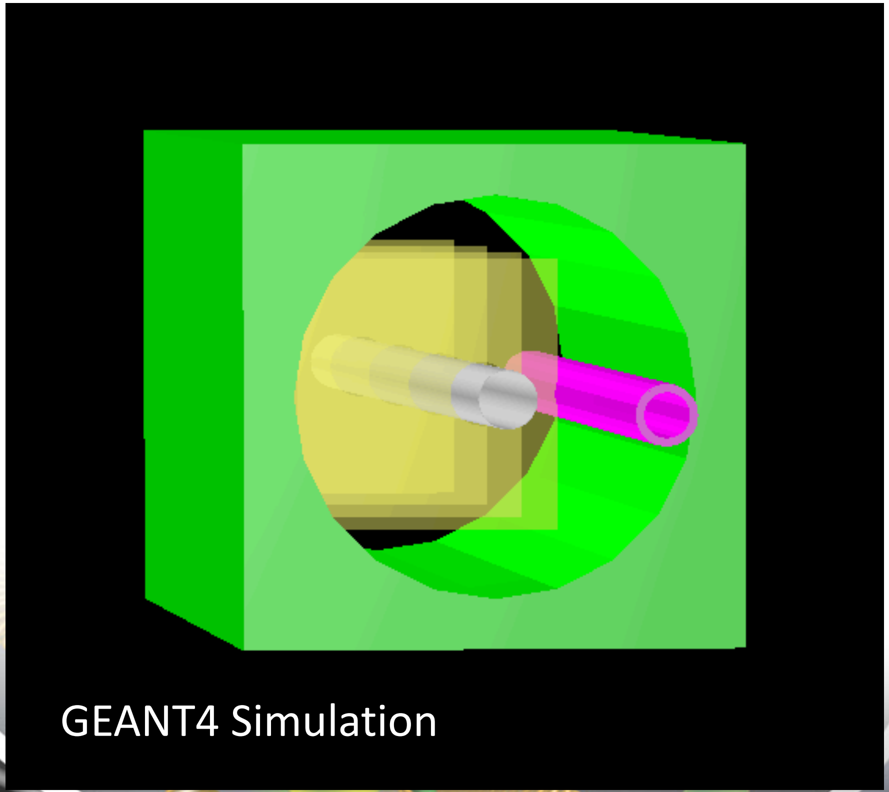
- Two photons from 150 GeV/c $\pi0$ are separated by ~5.5 mm in the EMCal.
- Also improves photon position resolution and e/h separation.
- Working on optimization of converter thickness.

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

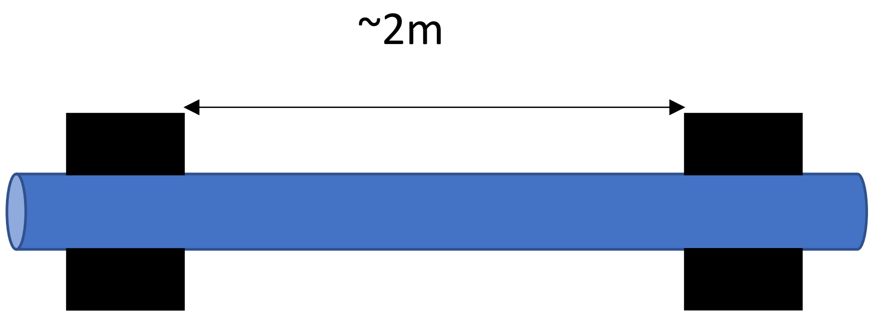
- ➢ Tagging photons is important for differentiating between coherent and incoherent heavy-nuclear scattering.
- ➢ Potential inclusion of small EMCAL or **preshower detector** in the B0 bore.
- ➢ Further study needed to assess.
- ➢ Tagging photons further down-stream (ZDC) highly technically challenging.

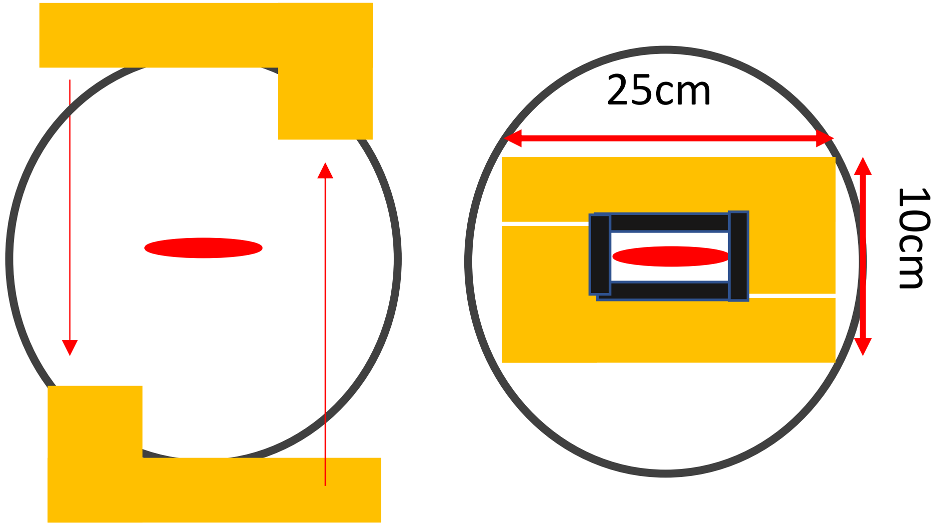
Takeaways

- Requirements for FF detectors are well-established.
  - LGADs suit the needs of the Roman Pots and Off-Momentum Detectors.
  - Could also be used as a timing layer in the B0.
- The idea for a preshower using LGADs has been floated, and would be especially useful in the B0 after the tracking layers for tagging photons.
  - More detailed studies underway.

Backup

Roman Pots





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

- <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.***

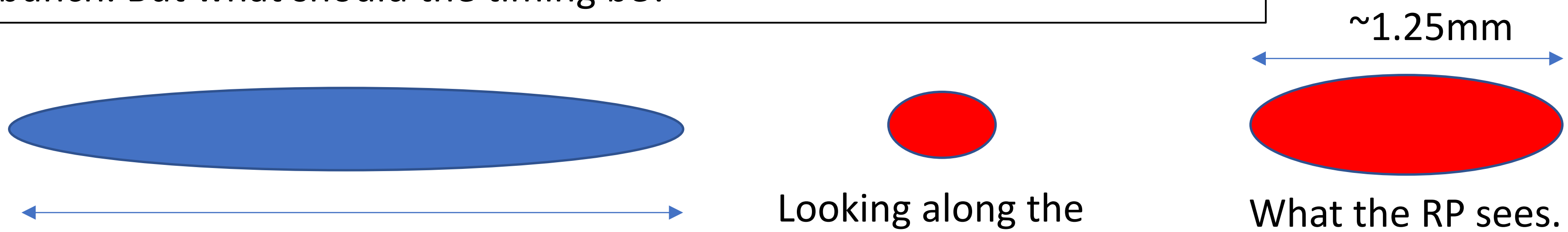
0.0* (10σ cut) < $\boldsymbol{\theta}$ < 5.0 mrad

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

Details/requirements studied using MILOU DVCS and e+He3 events from various MC generators.

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.

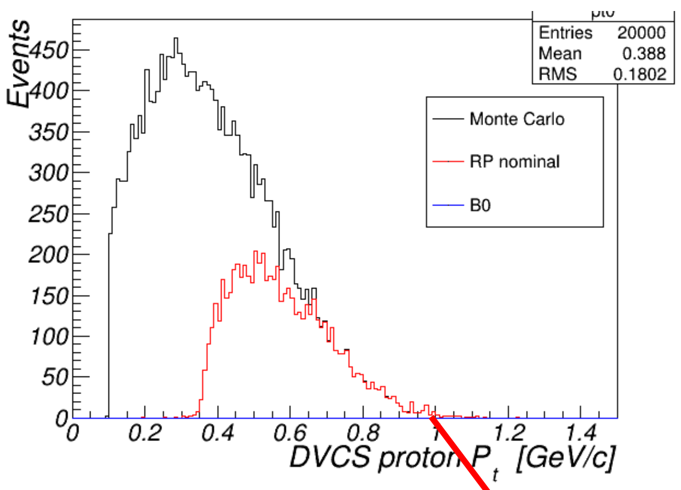
What the RP sees.

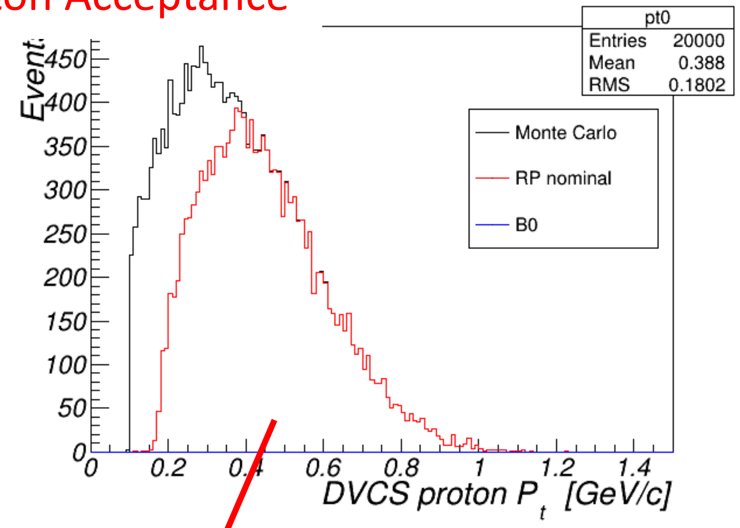
- Because of the rotation, the Roman Pots see the bunch crossing **smeared in x**.
- Vertex smearing = 12.5mrad (half the crossing angle) * 10cm = **1.25 mm**
- If the effective vertex smearing was **for a 1cm bunch**, we would have **0.125mm** vertex smearing.
- The simulations were done with these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

Roman Pots & Machine Optics

18x275 GeV DVCS Proton Acceptance





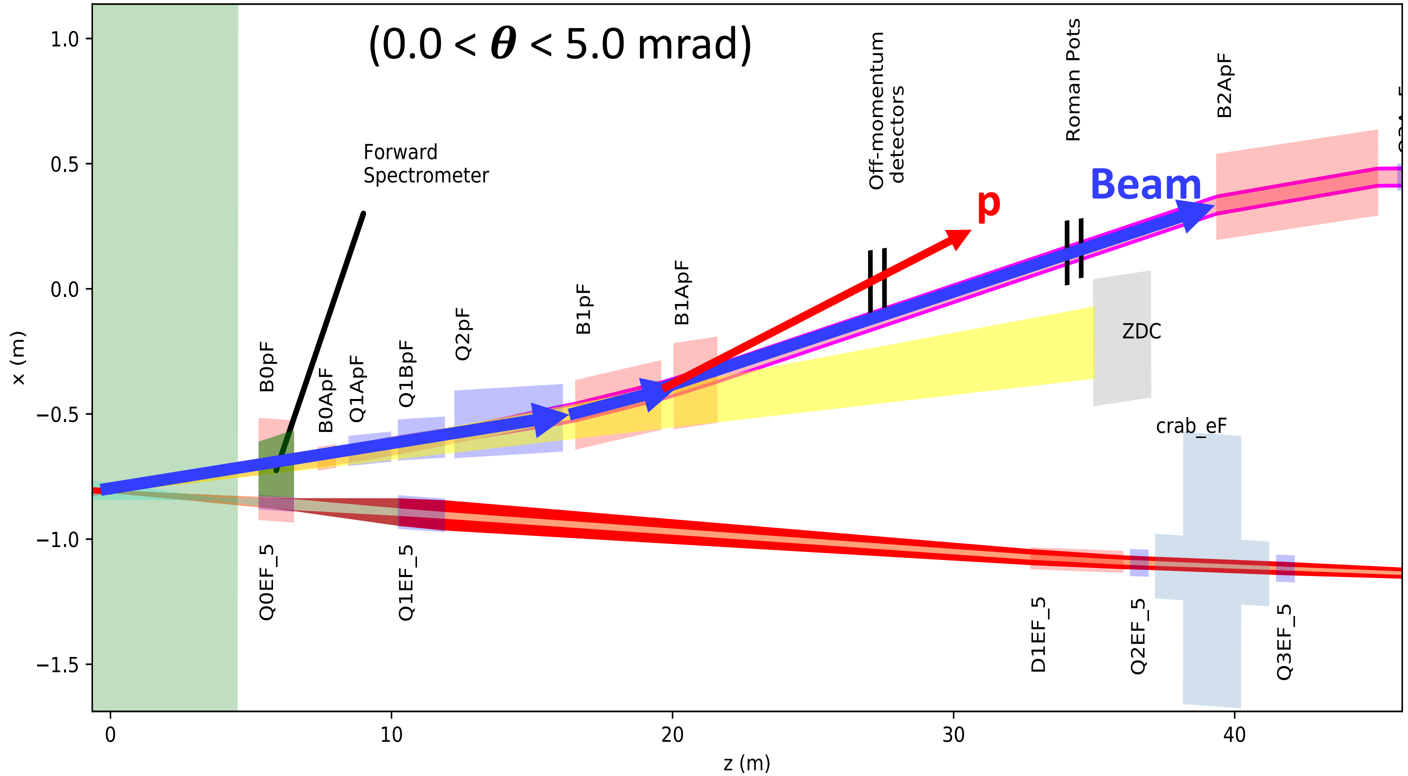
e+p Beam Energy	Option 1 (high luminosity)	Option 2 (high acceptance)
18x275 GeV	pT > 0.35 GeV/c	pT > 0.2 GeV/c
10x100 GeV	pT > 0.2 GeV/c	pT > 0.1 GeV/c (or better)
5x41 GeV	pT > 0.1 GeV/c	N/A

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.

Off-Momentum detectors

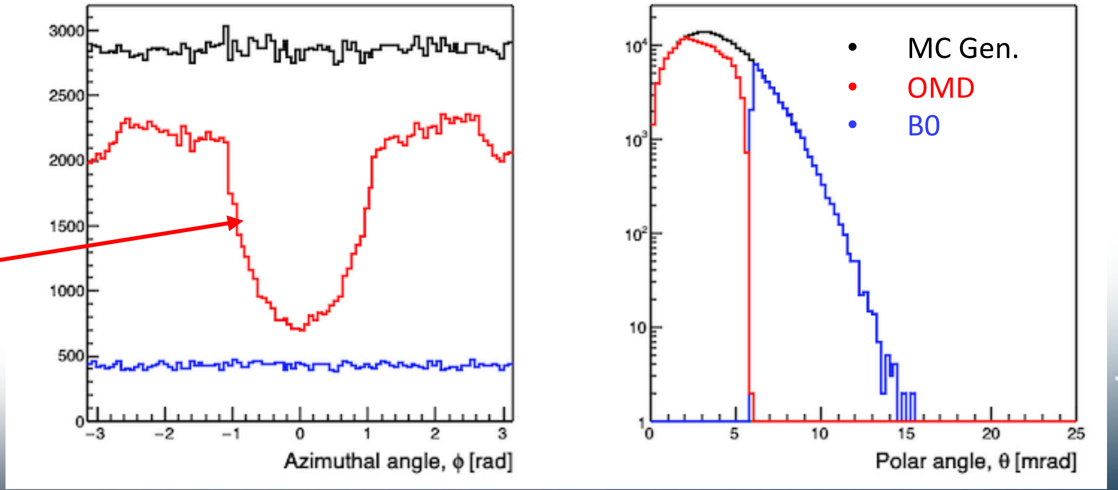


- Off-momentum detectors used for tagging protons from nuclear breakup and decay products (e.g. $\pi^{-}$and protons).
- Placed outside the beam pipe after the B1apf dipole (last dipole before long drift section that leads to the Roman Pots).

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

Neutron spectator/leading proton case.

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



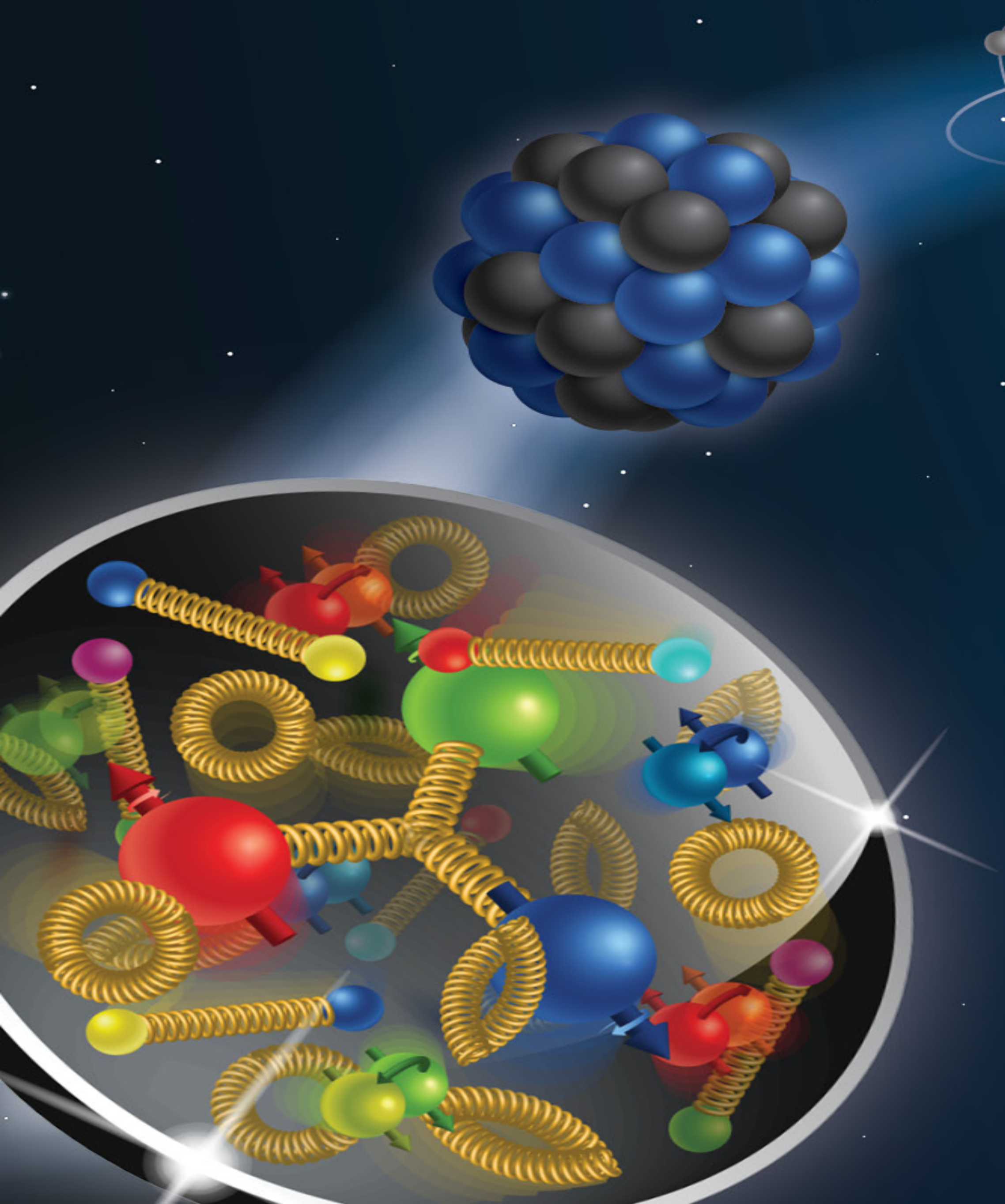
Geometric Acceptances

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%



Selected Physics Impact Studies

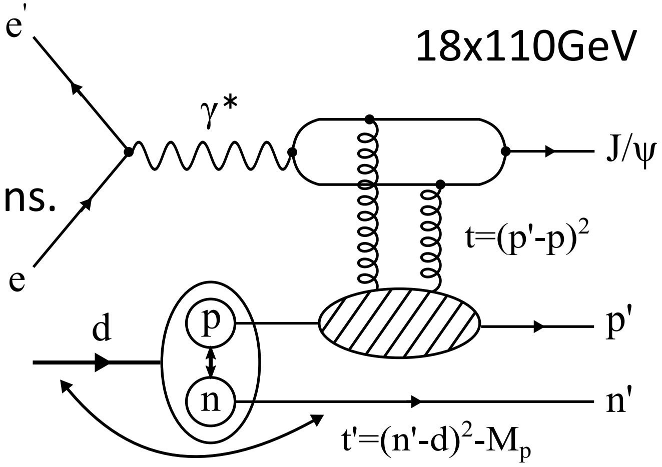
e+d Spectator Tagging

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

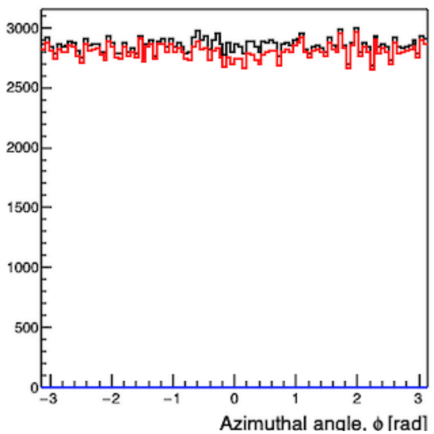
Proton spectator case.

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

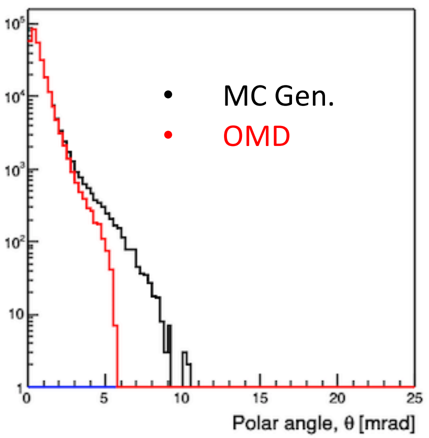
18x110GeV

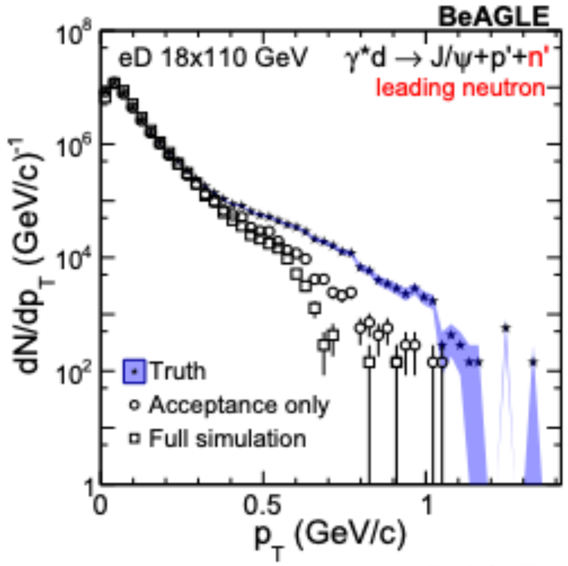


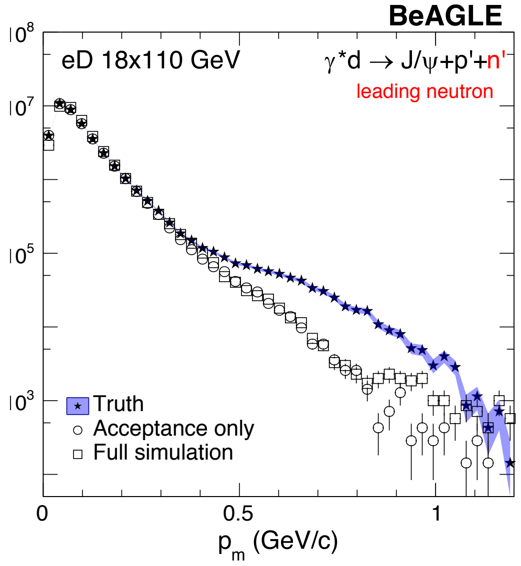
Protons

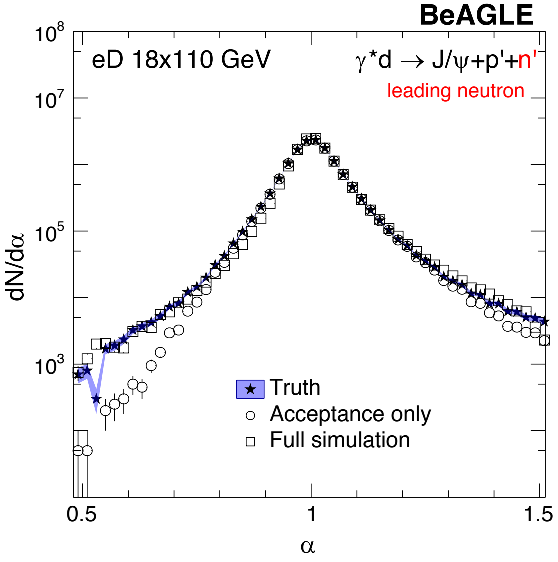


Protons









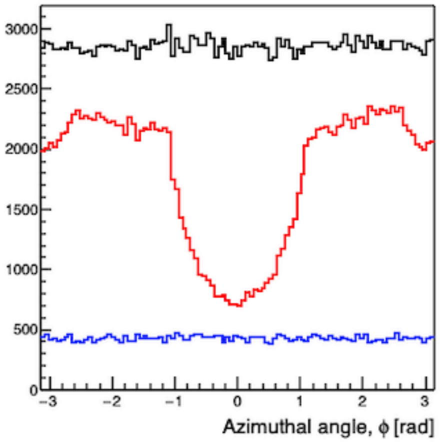
Spectator kinematic variables reconstructed over a broad range. Bin migration is observed due to smearing in the reconstruction. Each plot shows the MC (closed circles), acceptance effects only (open circles), and full reconstruction (open squares).

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

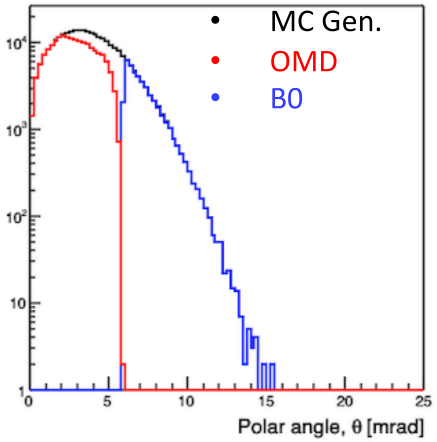
e+d Spectator Tagging

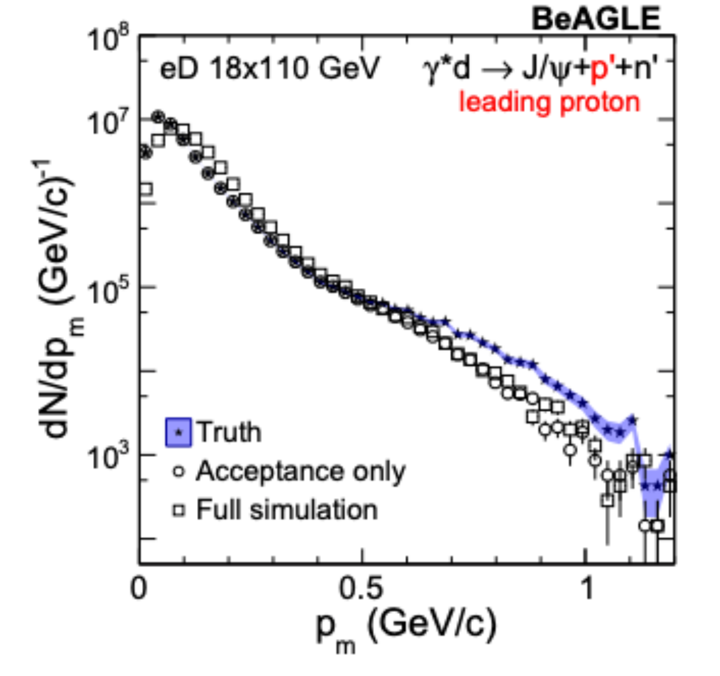
Z. Tu, A. Jentsch *et al.*, Phys. Lett. B, **811** (2020)

Protons



Protons

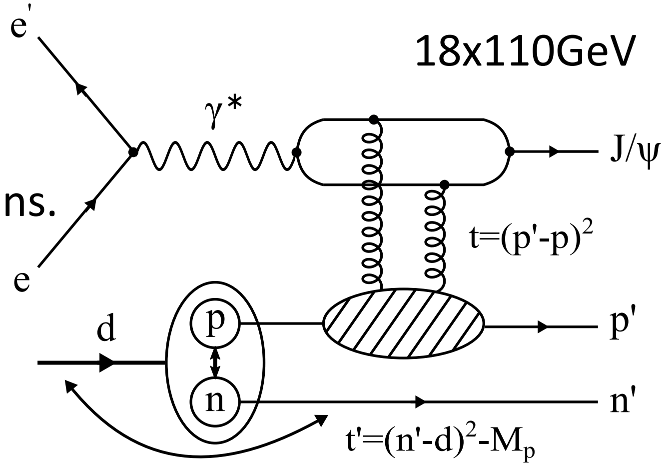


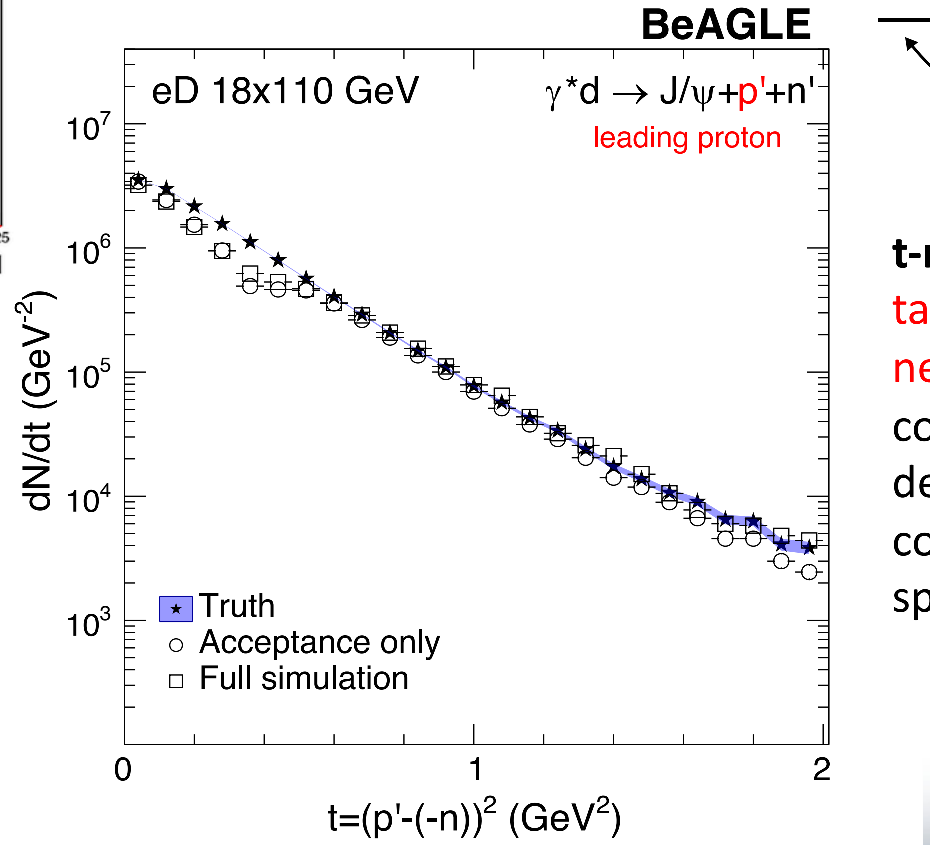


Neutron spectator case.

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

18x110GeV

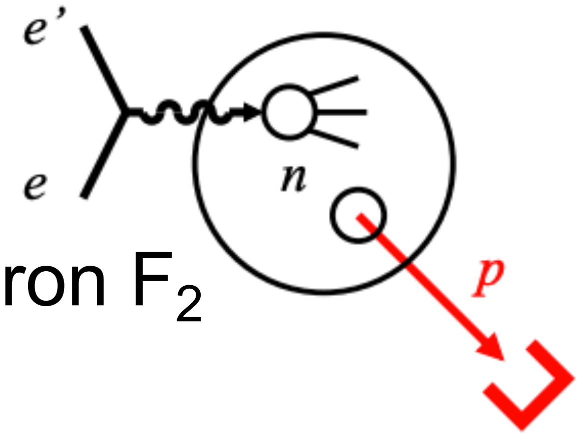




t-reconstruction using double-tagging (both proton and neutron). Takes advantage of combined B0 + off-momentum detector coverage. Better coverage in the neutron spectator case.

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

Ongoing Studies – Free Neutron Structure and Modifications.



- e+d spectator proton tagging yields access to free-neutron F_2 via on-shell extrapolation.
- Further studies ongoing to examine nuclear modifications and effect of detector smearing.