Detectors in the Far-Forward Region at the EIC

RHIC/AGS Annual User's Meeting

June 8th - June 11th, 2021

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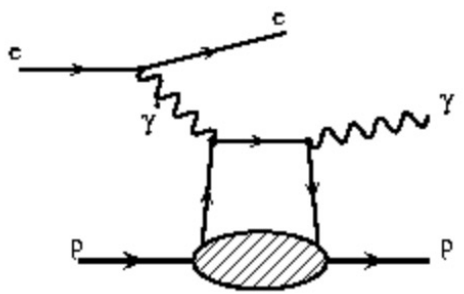
Electron Ion Collider

BROOKHAVEN NATIONAL LABORATORY

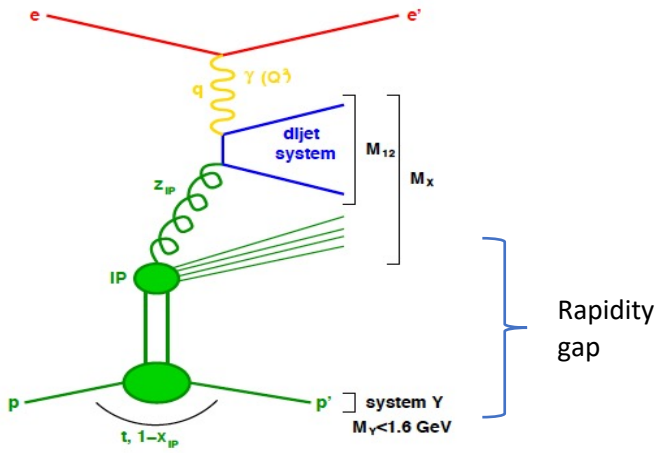
U.S. DEPARTMENT OF ENERGY | Office of Science

Far-forward physics at EIC

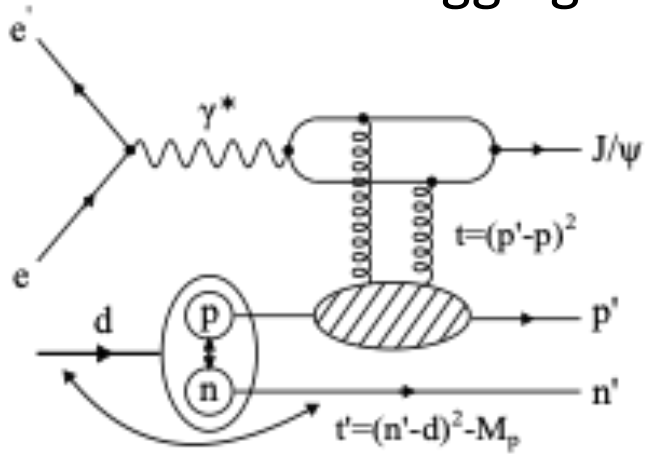
e+p DVCS events with proton tagging.



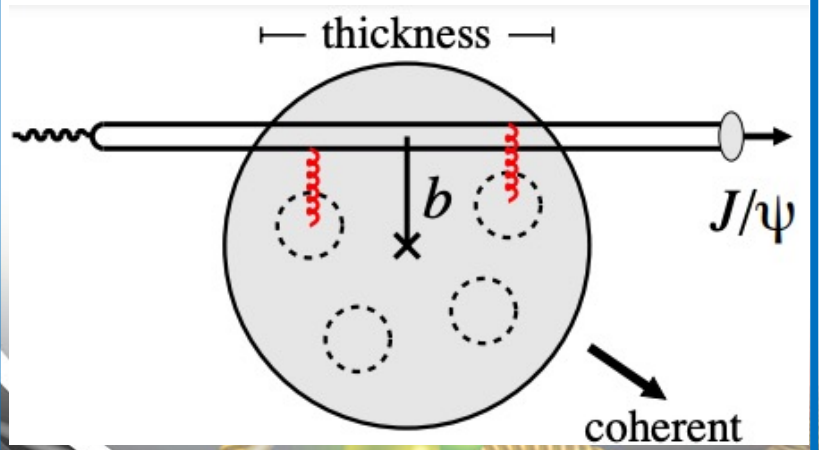
Diffraction



e+d incoherent J/Psi events with proton or neutron tagging

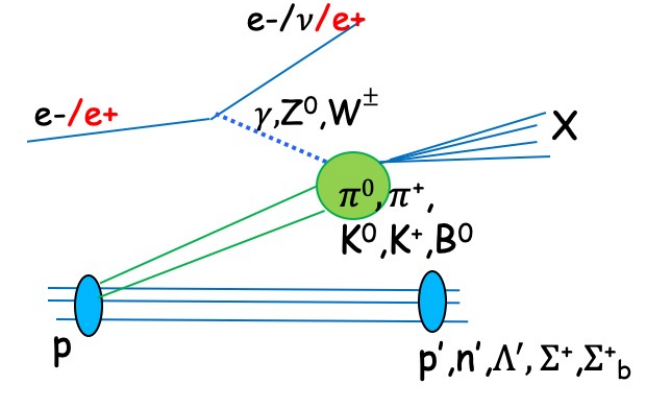


Saturation (coherent/incoherent J/ψ production)



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.

Tagging of coherent light ions (d, He3, He4) from coherent scattering.

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

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Far-forward physics at EIC

e+p DVCS events with proton tagging

Diffraction

e+d exclusive J/Psi 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 constraint, apertures, etc.

acceptance.

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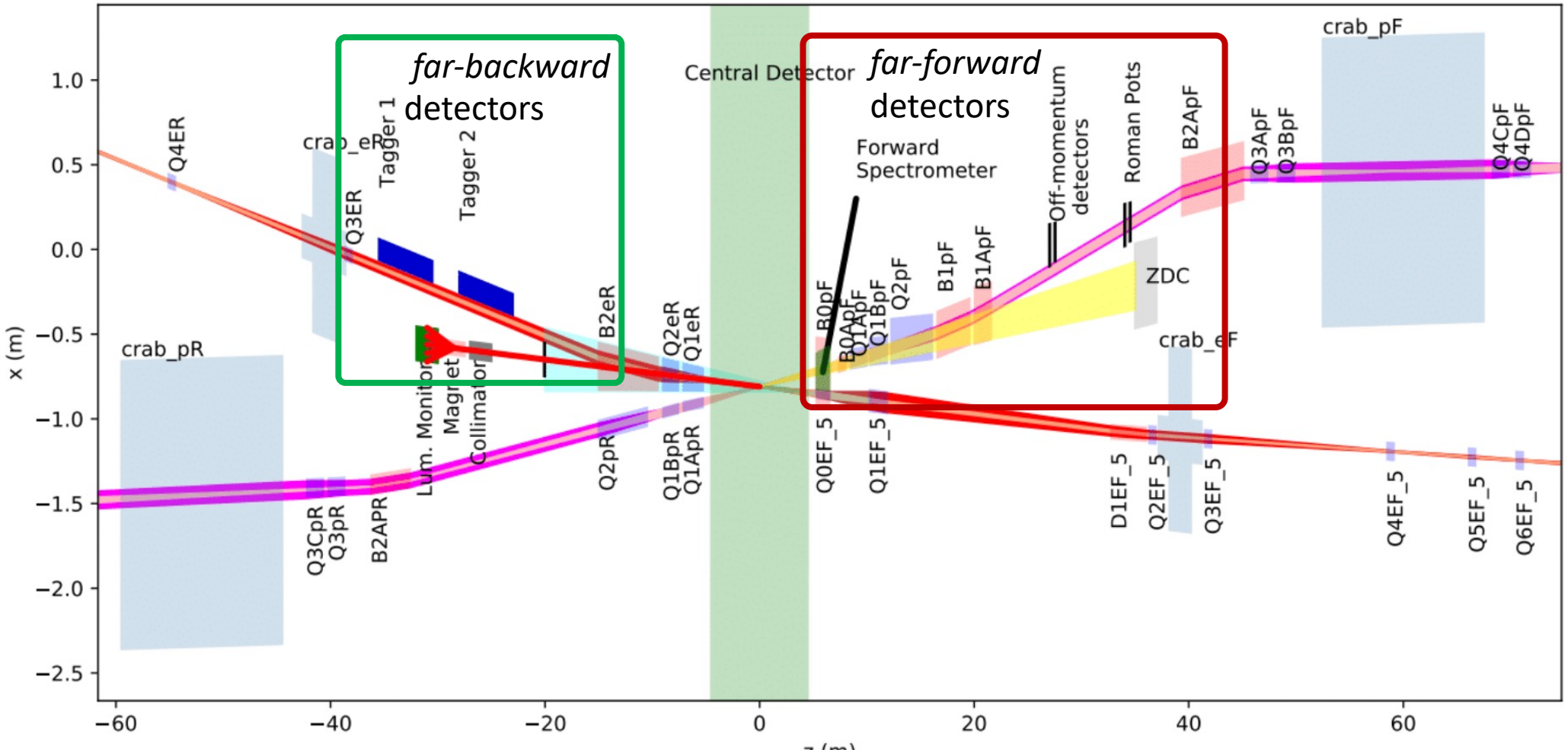
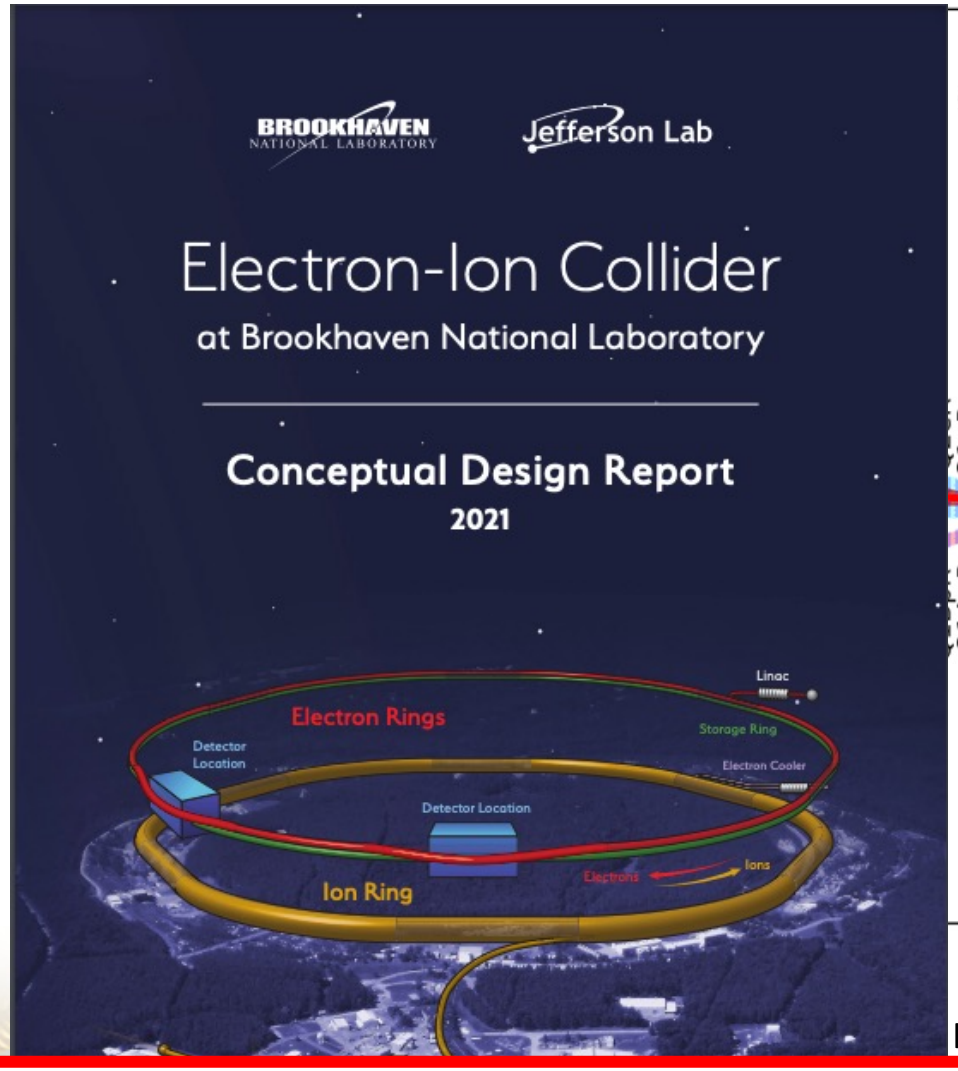
Far-Forward Interaction Region Design and Detectors

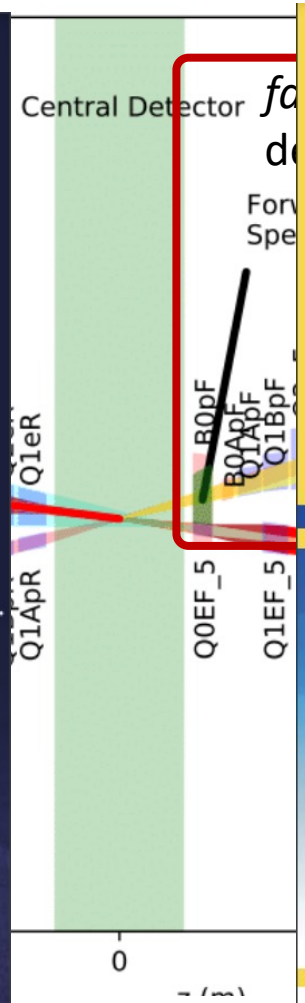
EIC Interaction Region Layout

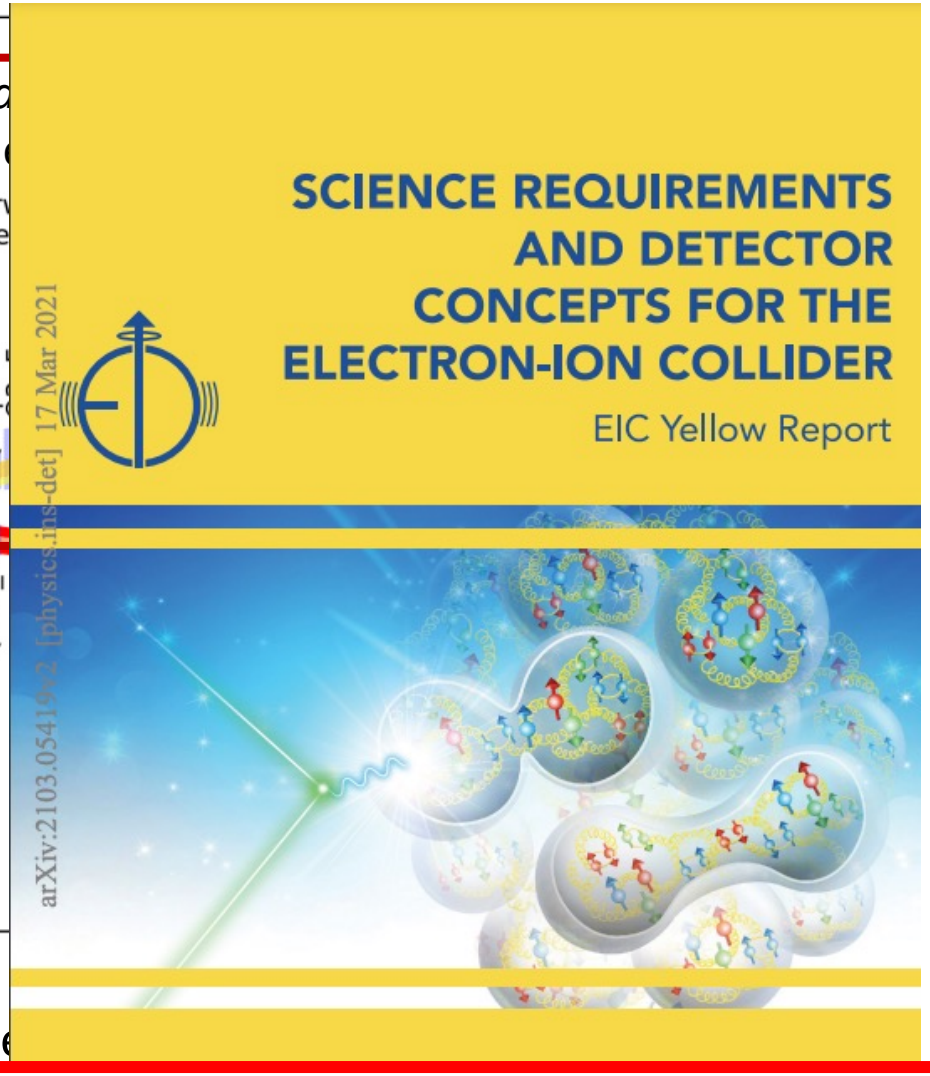


- Central detector spans 9 meters and is machine-component free (except for beam pipe).
- Hadron-going and electron-going directions after central detector fully instrumented.
- Hadron and electron beam cross with an angle of 25 mrad.

EIC Interaction Region Layout







EIC CDR:
https://www.bnl.gov/ec/files/EIC_CDR_Final.pdf

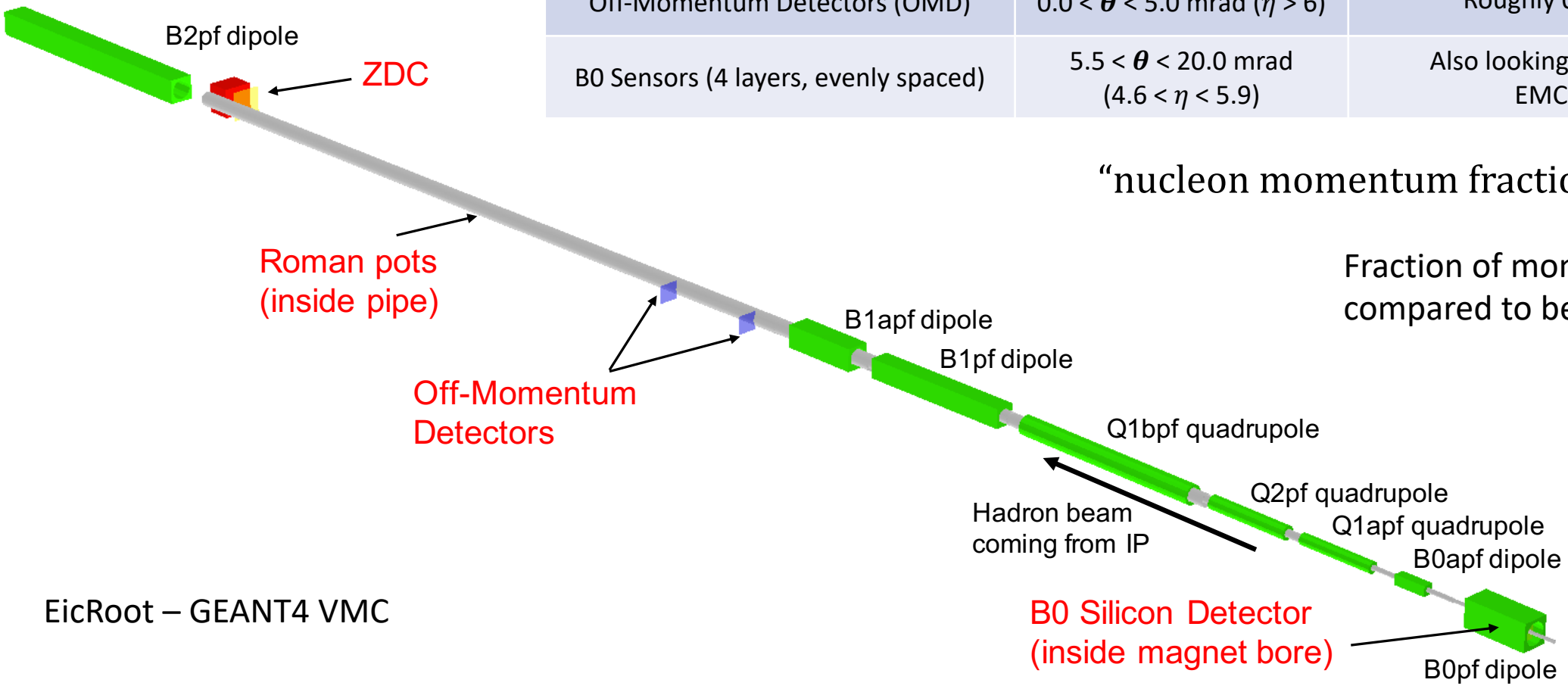
EIC Yellow Report:
https://arxiv.org/pdf/2103.05419.pdf

FF Hadron-Going Direction & Acceptance

Detector	Acceptance	Notes
Zero-Degree Calorimeter (ZDC)	$\boldsymbol{\theta} < 5.5$ mrad ($\eta > 6$)	About 4.0 mrad at $\varphi \sim \pi$
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
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 ($4.6 < \eta < 5.9$)	Also looking at photon tagging via EMCAL/preshower.

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

Fraction of momentum for nucleon compared to beam.

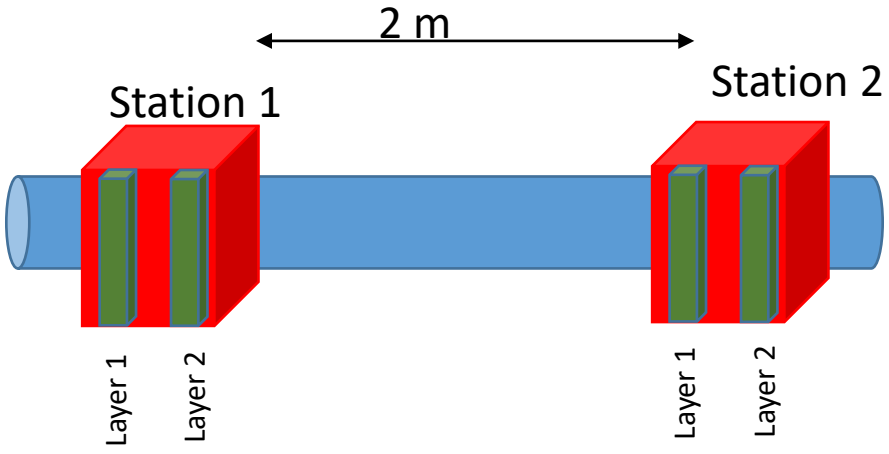


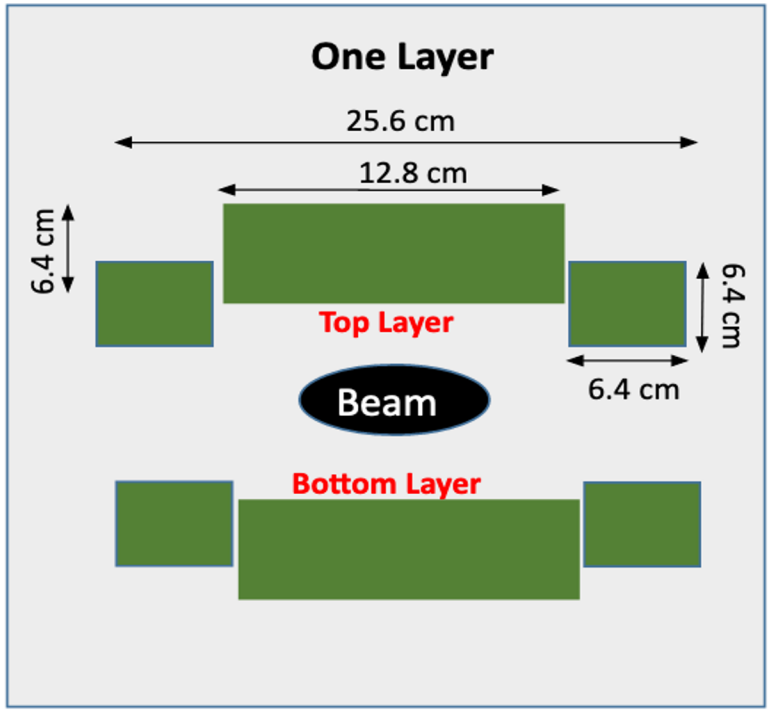
EicRoot – GEANT4 VMC

Details of Individual Detector Requirements (based on IP6 studies)

Roman Pots

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





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

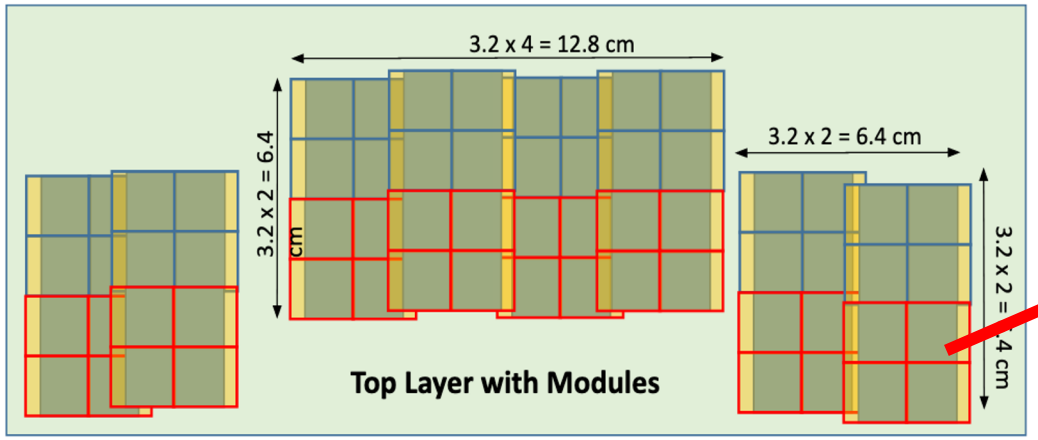
$$\sigma(z) = \sqrt{\varepsilon \cdot \beta(z))}$$

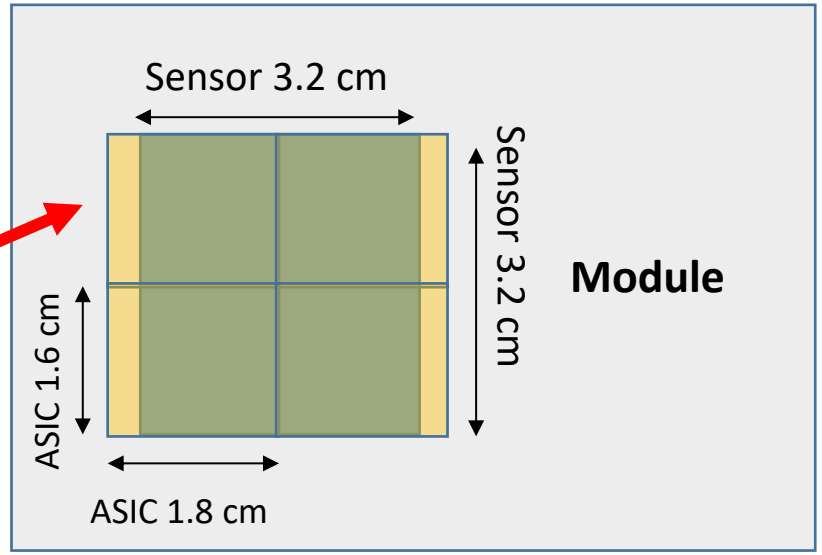
- Requirements:
  - Fast timing (~35ps) to remove vertex smearing effect from crab rotation.
  - 500um x 500um pixels.
  - Radiation hardness (not as stringent as LHC).
  - Large active area (25cm x 10cm).
- **AC-LGADs cover these requirements in one package.**

- **Low-pT cutoff determined by beam optics.**
  - **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.***

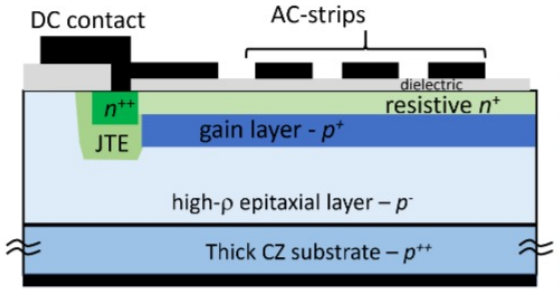
Roman Pots

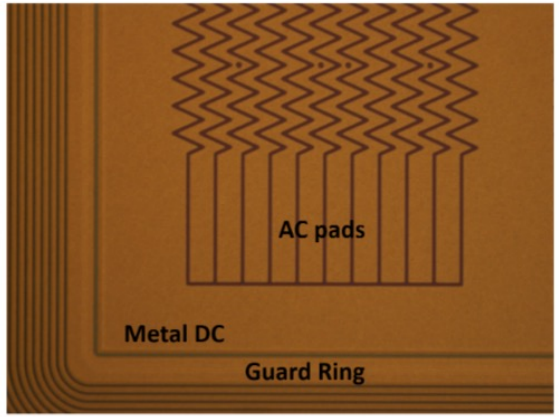
- Updated strawman layout with current design for LGAD sensor + ASIC.





AC-coupled Low Gain Avalanche Detectors (AC-LGADs)



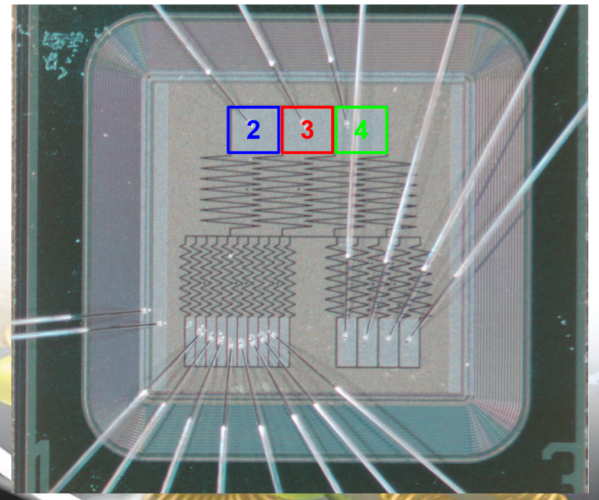


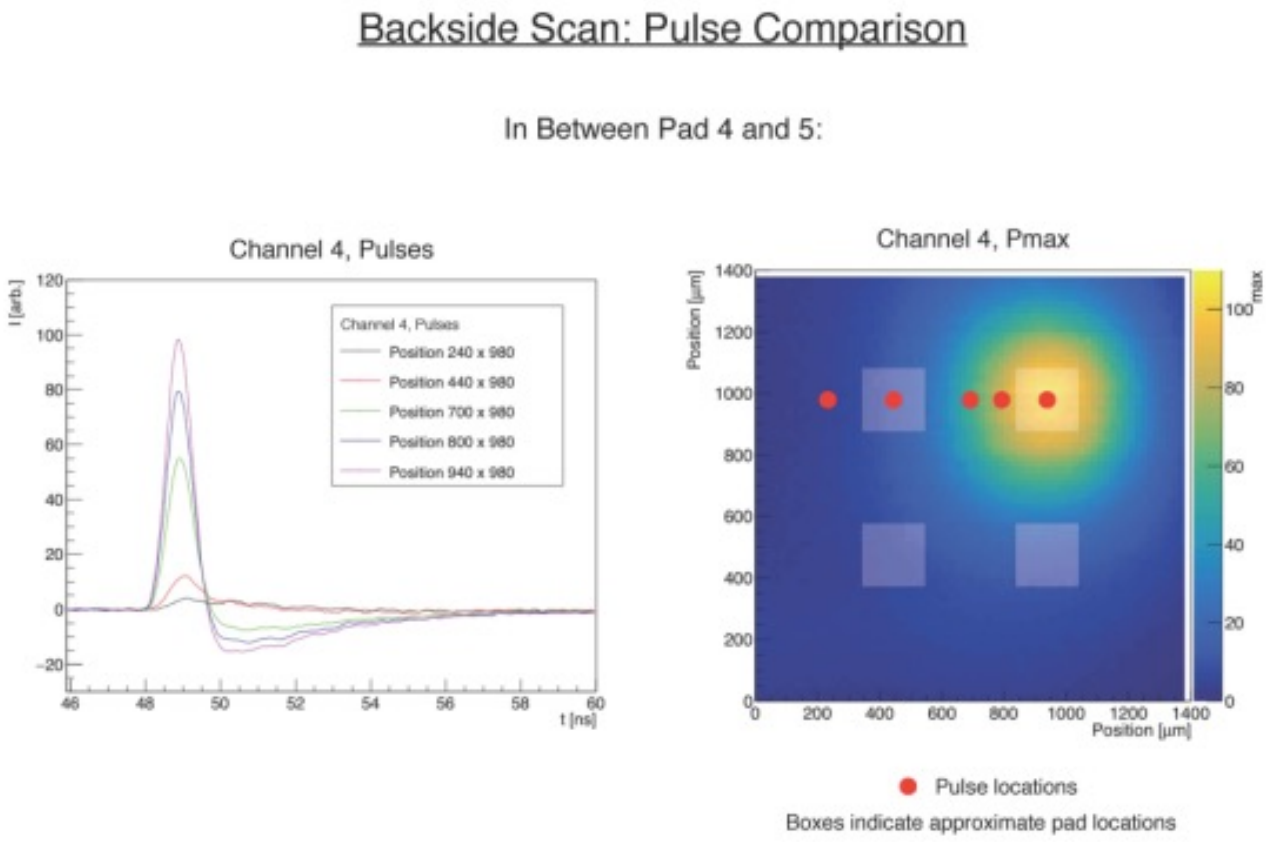
- Problems to be solved:
  - Full engineering layout with insertion tooling.
  - Cooling scheme needed to go with “potless” design.

ASIC size	ASIC Pixel pitch	# Ch. per ASIC	# ASICs per module	Sensor area	# Mod. per layer	Total # ASICs	Total # Ch.	Total Si Area
1.6x1.8 cm^2	500 μm	32x32	4	3.2x3.2 cm^2	32	512	524,288	1,311 cm^2

Roman Pots

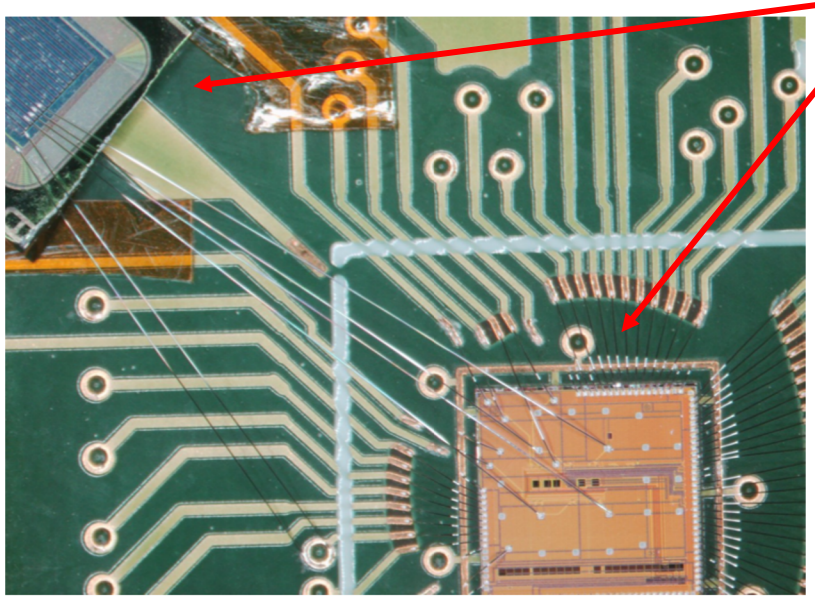
- Study of ultimate spatial resolution:
  - Strips with variable pitches and geometry (e.g. zig-zag, hexagonal, crosses)
  - Produced to test dependence of signal sharing (space resolution) on geometry - tested at test-beams.
  - Different geometrical patterns optimized for spatial resolution could allow for larger overall pixel size, and therefore less total pixels per sensor -> **leads to reduced number of channels and power consumption, and less cooling!**



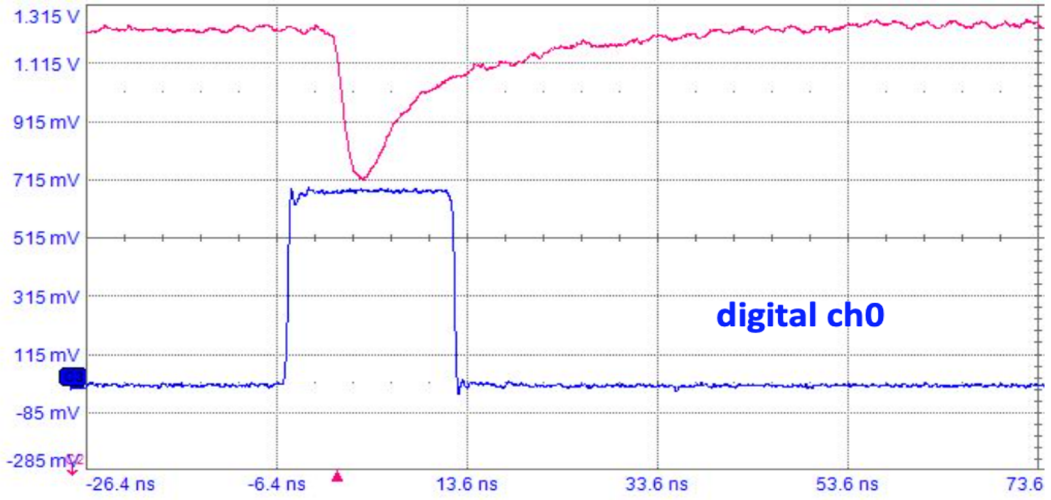


- **<u>Test-beam at FNAL with 120 GeV protons shows that AC-LGADs meet requirements</u>**
  - 30-35 ps time resolution
  - < 15 µm space resolution with strip sensor: 100 µm pitch, 20 µm gap
  - ~100% particle detection efficiency
  - See: https://indico.fnal.gov/event/46746/contributions/210254/attachments/141193/177718/Apresyan_4D-trackers.pdf

Roman Pots



- **Assembly:** ALTIROC0 v1 prototype (4 channels) + strip AC-LGAD with pitch 100 µm, and inter-strip gap of 20 µm.
  - ALTIROC0 chip: analog readout after the preamplifier, 2 TDCs (Time-Of-Arrival and Time-Over-Threshold) and threshold discriminator. Time jitter smaller than 20 ps for input charge larger than 5 fC
  - ALTIROC1 + AC-LGAD already assembled for studying the Constant Fraction Discriminator. To be studied next period.

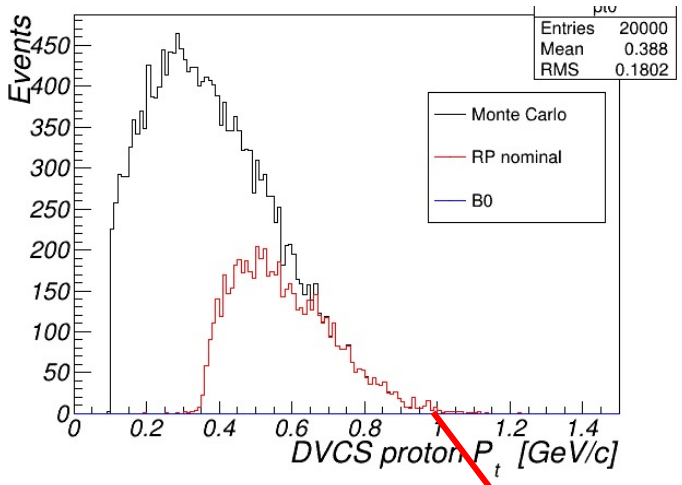


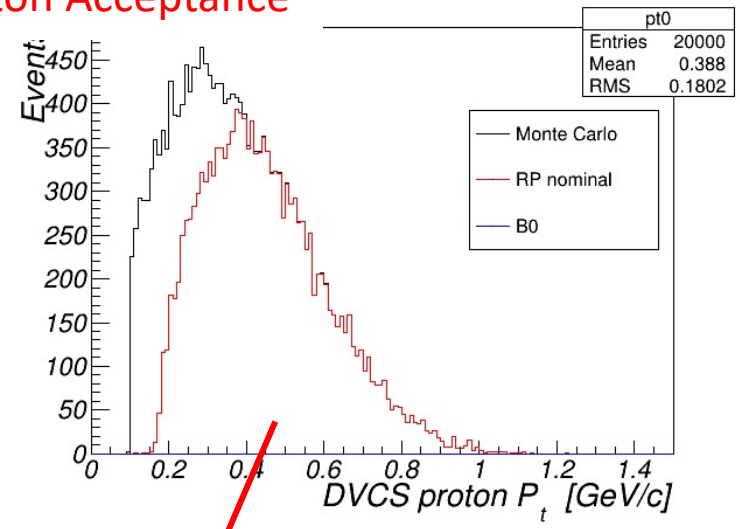
- Signal from beta-particles from 90Sr source.
- **Clear signal with negative and positive polarity.**
- Fast (~5 ns) signal compatible with published results for (DC-)LGAD sensors read-out via ALTIROC0 [JINST 15 P07007 (2020)]

- **Main modifications have been identified to reduce pixel pitch from 1.3 mm to 500 µm**
- ASIC power dissipation of a 32x32 channel ASIC
  - Per pixel power dissipation of 3 mW (assuming 10% occupancy - very conservative!, as expected occupancy <<01%)
    - **3.072 W per chip, including the peripheral electronics**
    - **1.067 W/cm² power density**
    - **total power dissipation in the whole detector of 1.573kW (Strawman layout)**
      - For comparison ALTIROC for HGTD: 1.2 W/chip (300 mW/cm2) and 19.3kW total power dissipation

Roman Pots & Machine Optics

18x275 GeV DVCS Proton Acceptance





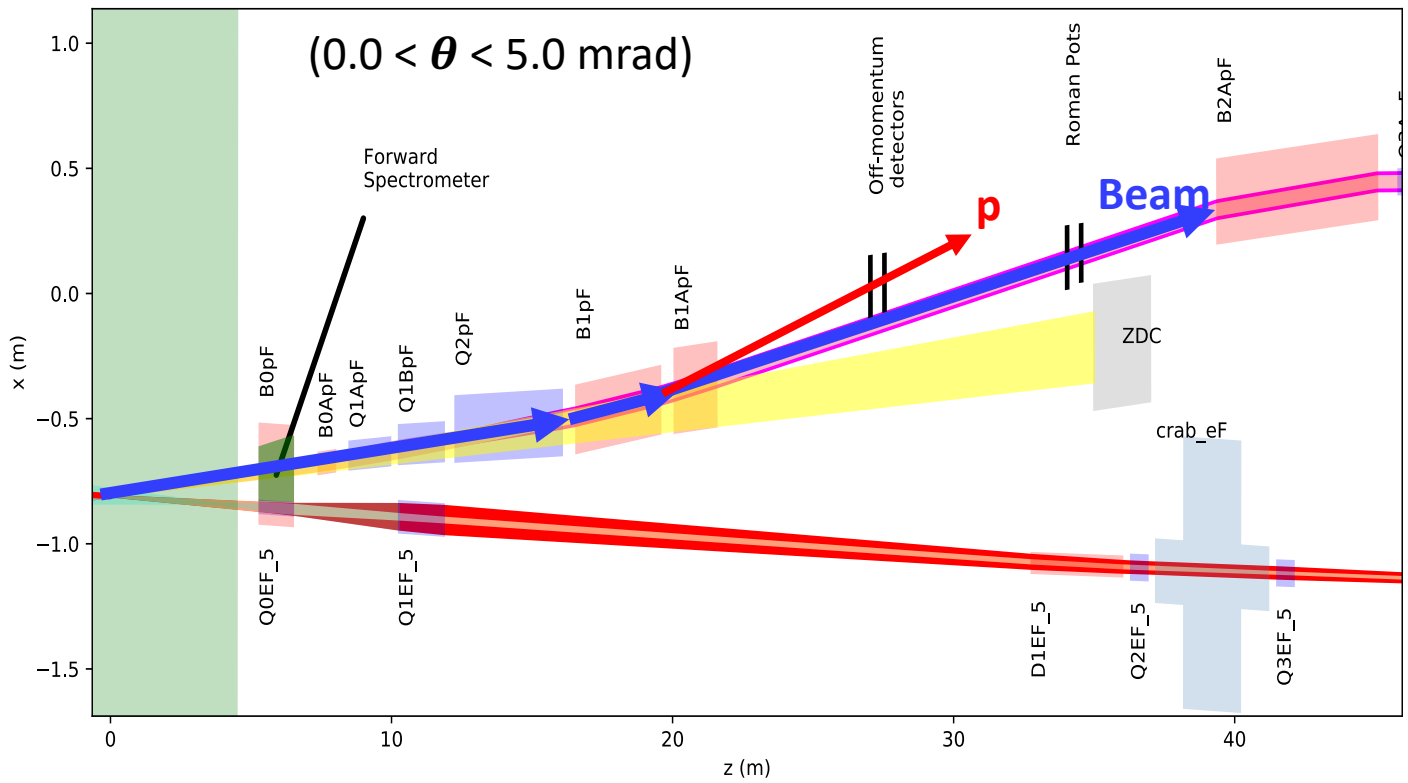
e+p Beam Energy	Option 1 (high luminosity)	Option 2 (high acceptance)
18x275 GeV	pT > 0.35 GeV/c	pT > 0.2 GeV/c
10x100 GeV	pT > 0.2 GeV/c	pT > 0.1 GeV/c (or better)
5x41 GeV	pT > 0.1 GeV/c	N/A

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

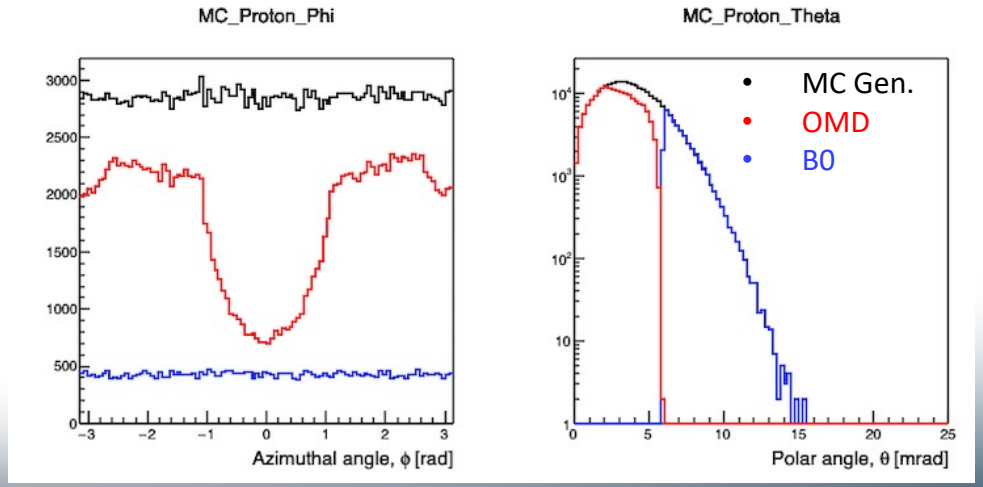


- Acceptance mostly limited by losses of very off momentum particles in quadrupoles.

- Off-momentum detectors used for tagging protons from nuclear breakup and decay products (e.g. π^- and protons).
- Can use same technology as Roman Pots system.
- 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)

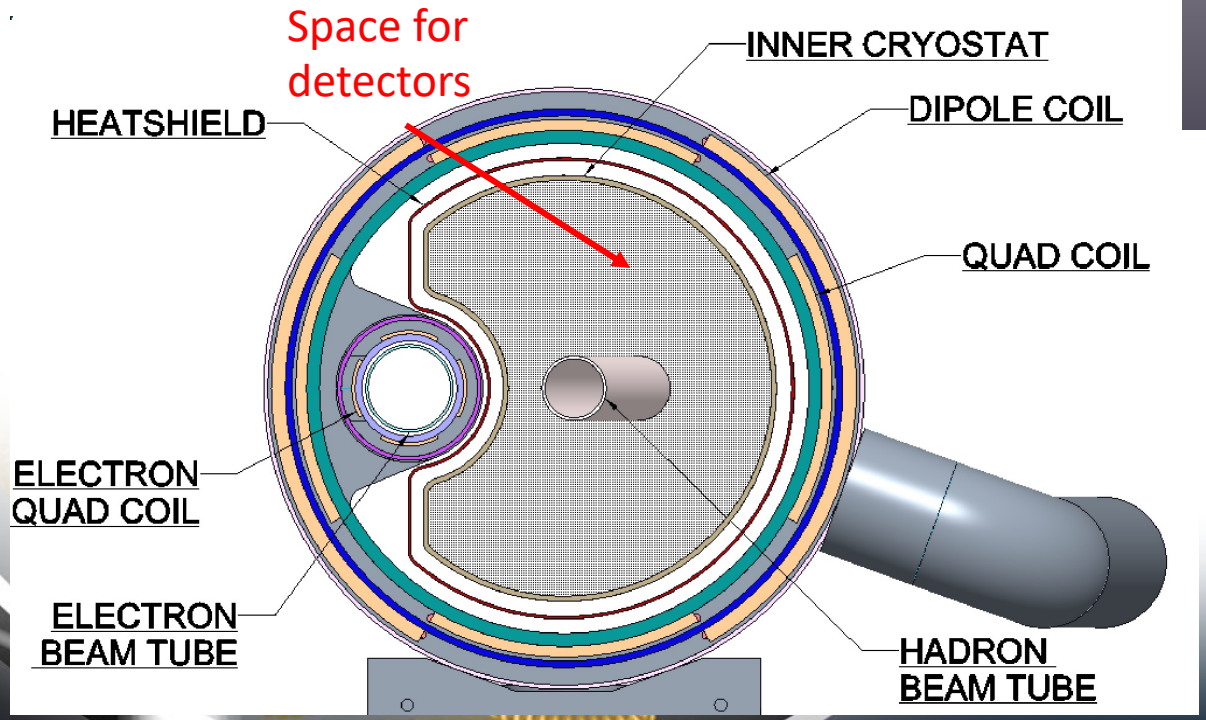
Neutron spectator/leading proton case.

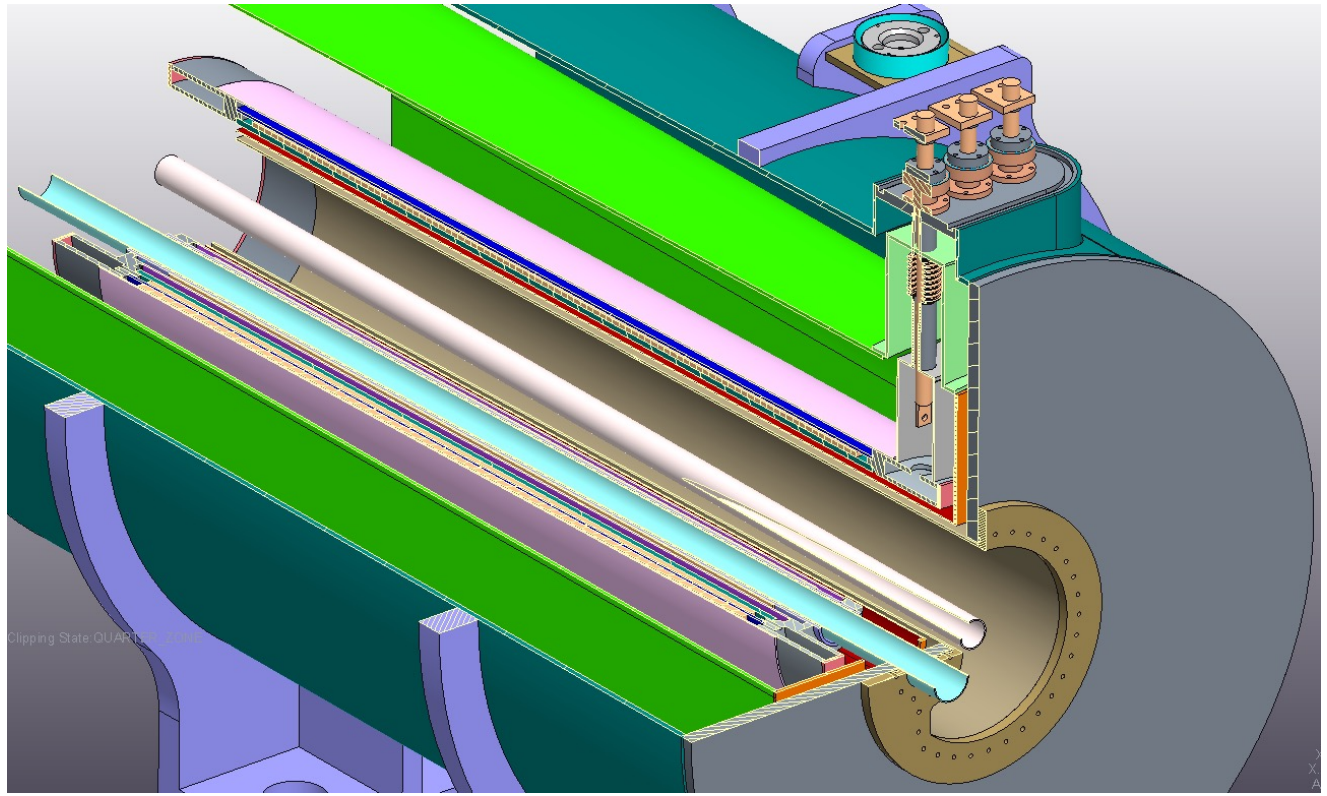


B0-detectors

(5.5 < θ < 20.0 mrad)

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



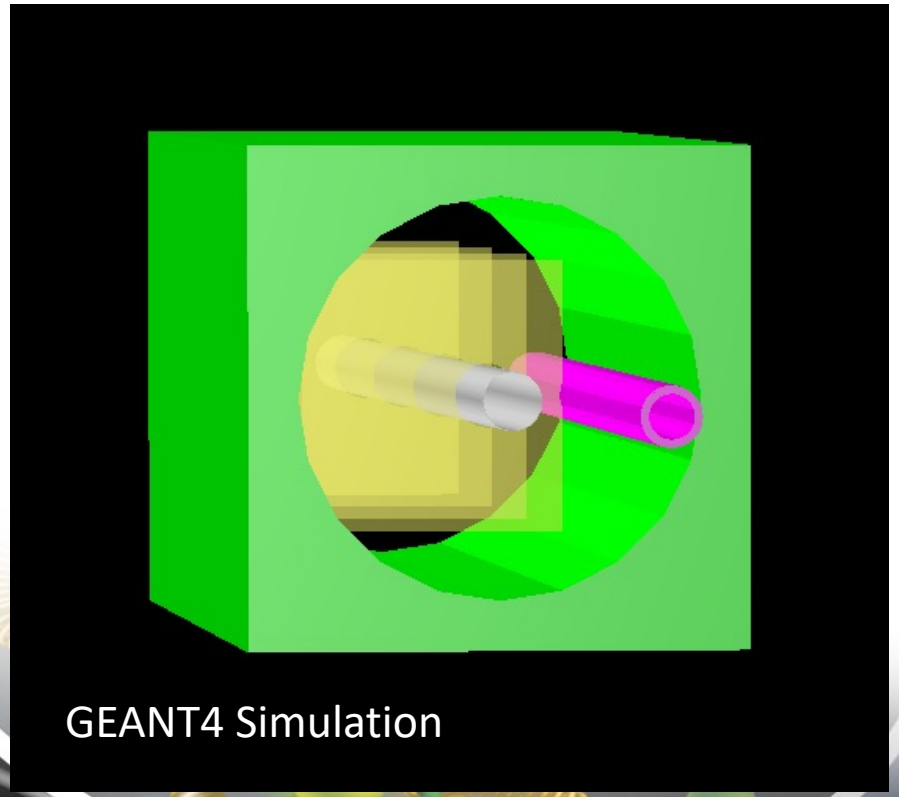


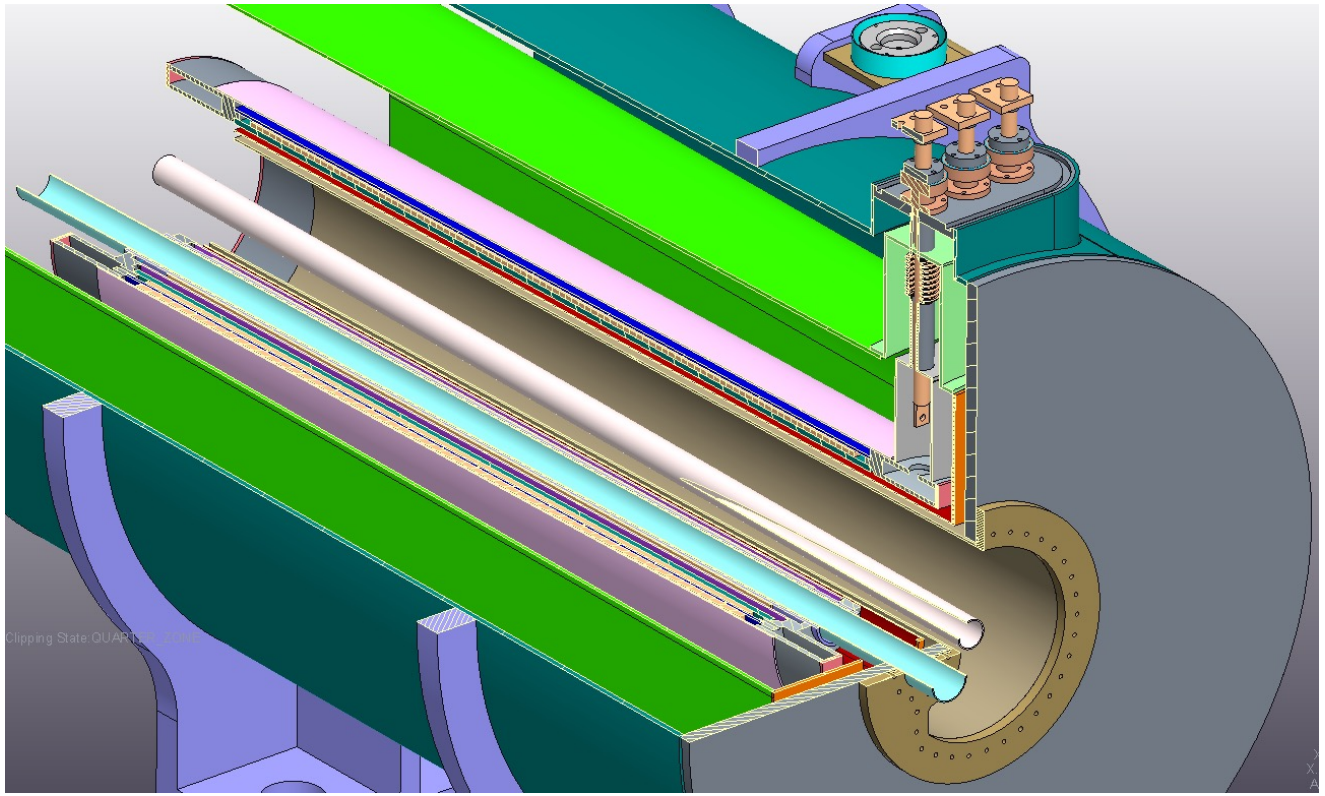
- Higher granularity detectors needed in this area (MAPS, or something similar) with layers of fast-timing detectors (e.g. LGADs), or timepix (provides high resolution space and timing information), depending on sensor layout and size.

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).

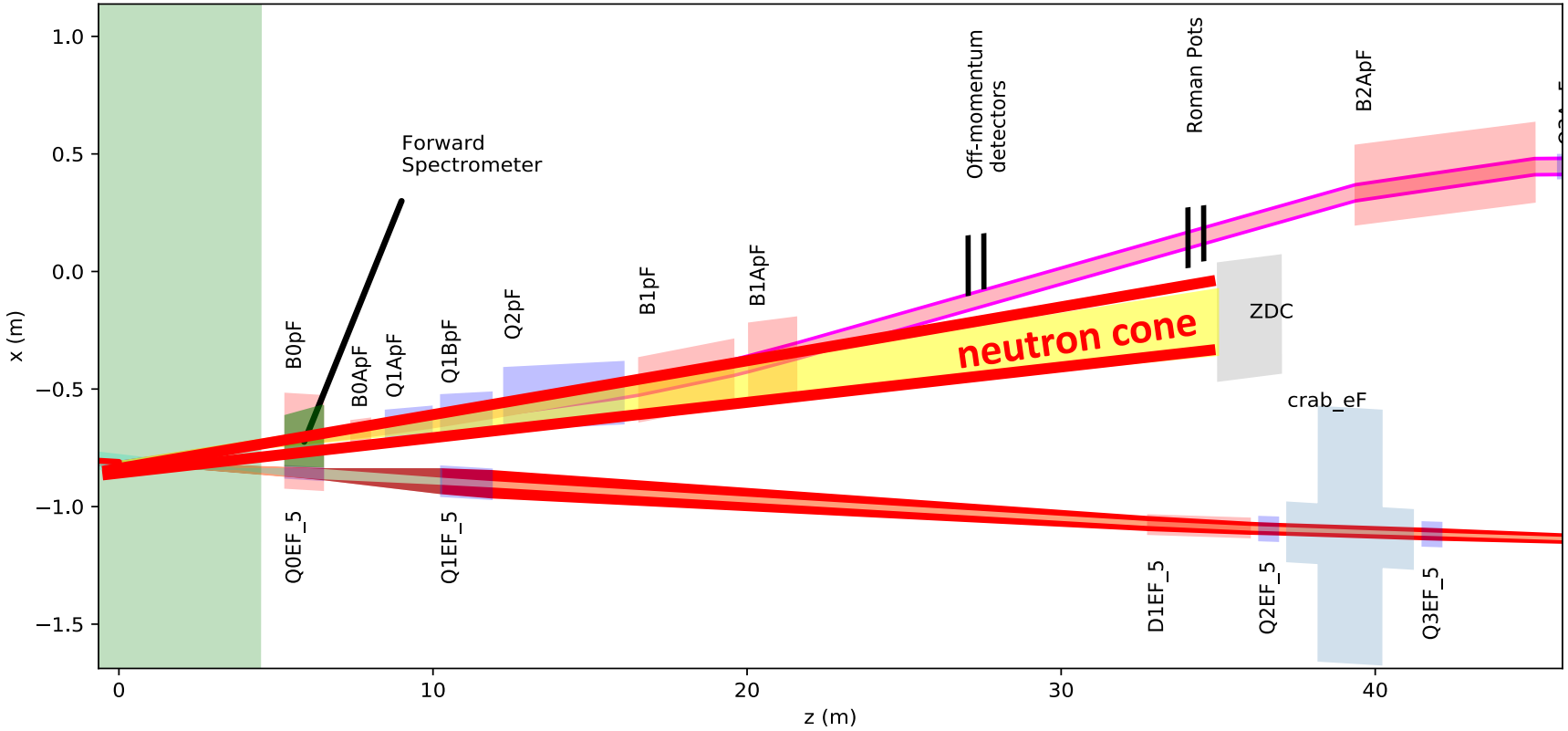




- Tagging photons is also important in differentiating between coherent and incoherent heavy-nuclear scattering.
- Potential inclusion of small EMCAL or preshower detector in the B0 bore.
- Further study needed to assess.
- Tagging photons further down-stream (ZDC) highly technically challenging.

Zero-Degree Calorimeter

- High resolution HCAL + EMCAL for detecting neutral forward-going particles (neutrons and photons) – using ALICE FoCal as starting point.
- Acceptance limited by bore of magnet where the neutron/photon cone exits.
  - $0.0 < \theta < 4.5$ mrad



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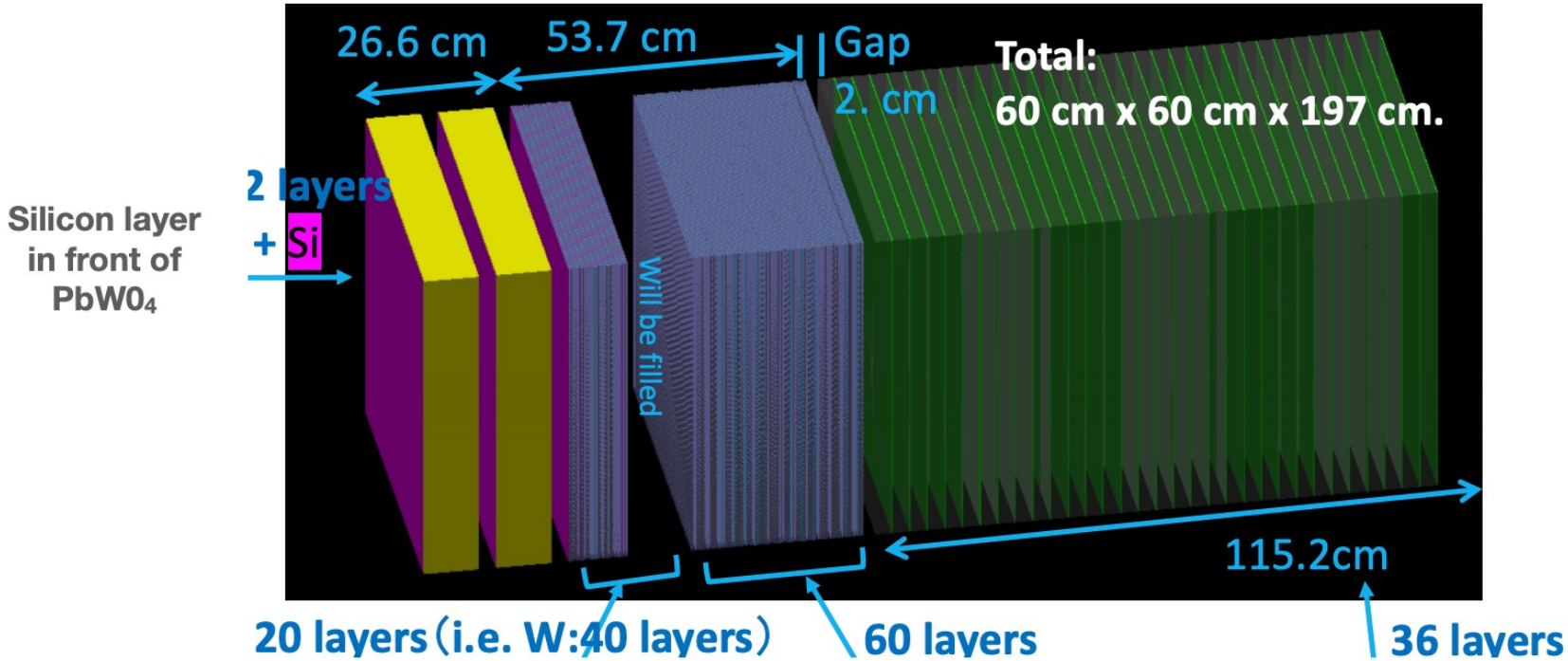
ZDC uses Silicon/PbW04 for EM followed Silcion/W for Hadronic Section



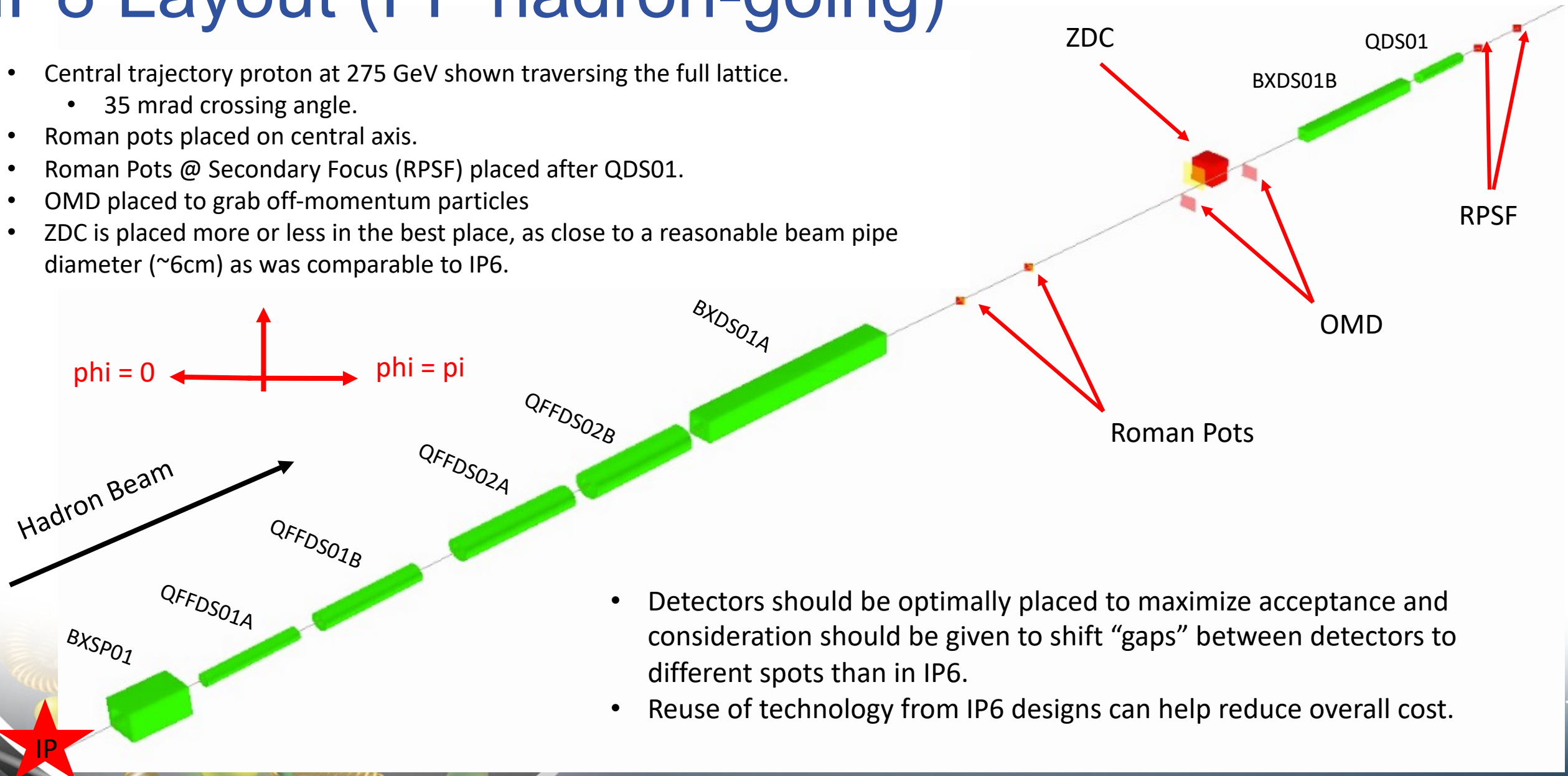
What about the second IR?

Some thoughts on IP8

- Most of the technology and detector concepts can be also used for IP8.
- There is (always) a desire for more acceptance!
  - Proposed secondary focus at RP location to improve low-pt acceptance.
  - Altered bending direction for separation of beam and breakup neutrons to try and improve neutron cone acceptance.
  - Different placement of between-detector gaps @ IP6/IP8 so combined measurements cover full phase-space.
- While the same basic ideas from IP6 can be used for the detector solutions, the optimization problem for the different subsystem needs careful thought.
- A first version of the IP8 design was released to the EIC proto-collaborations this week!

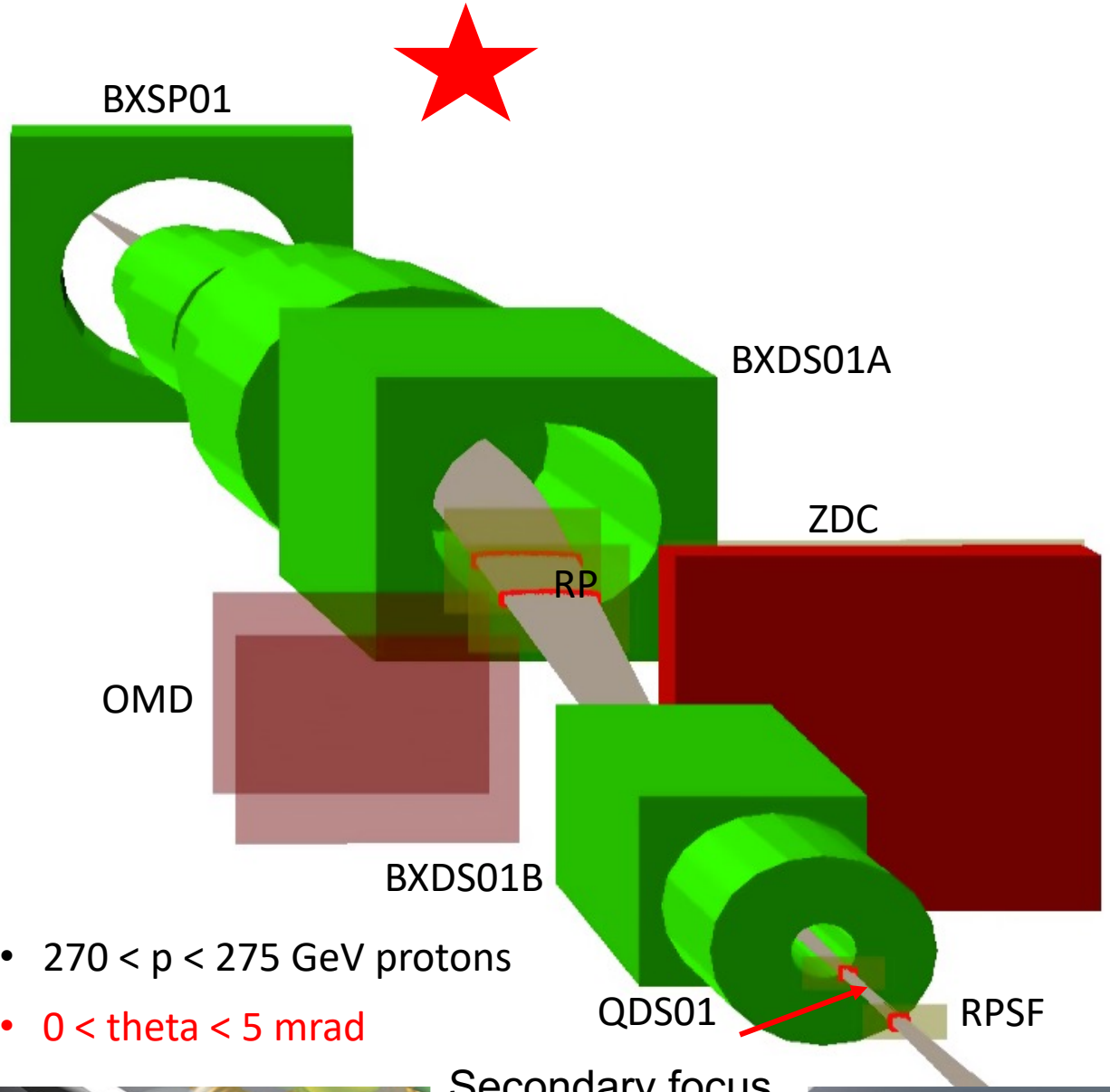
IP8 Layout (FF hadron-going)

- Central trajectory proton at 275 GeV shown traversing the full lattice.
  - 35 mrad crossing angle.
- Roman pots placed on central axis.
- Roman Pots @ Secondary Focus (RPSF) placed after QDS01.
- OMD placed to grab off-momentum particles
- ZDC is placed more or less in the best place, as close to a reasonable beam pipe diameter (~6cm) as was comparable to IP6.



- Detectors should be optimally placed to maximize acceptance and consideration should be given to shift “gaps” between detectors to different spots than in IP6.
- Reuse of technology from IP6 designs can help reduce overall cost.

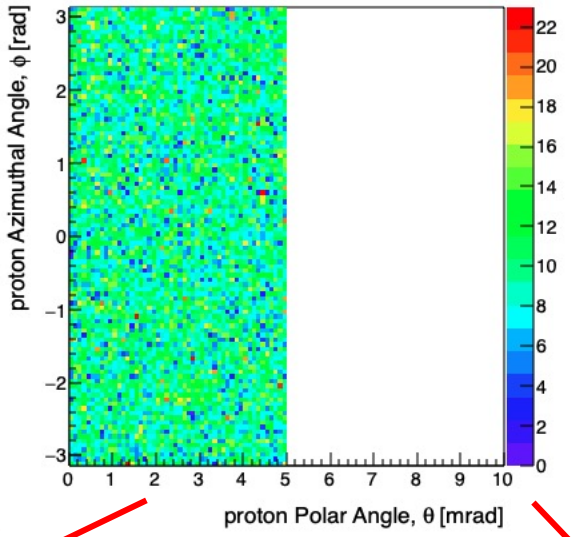
Secondary Focus



- 270 < p < 275 GeV protons
- 0 < theta < 5 mrad

Secondary focus.

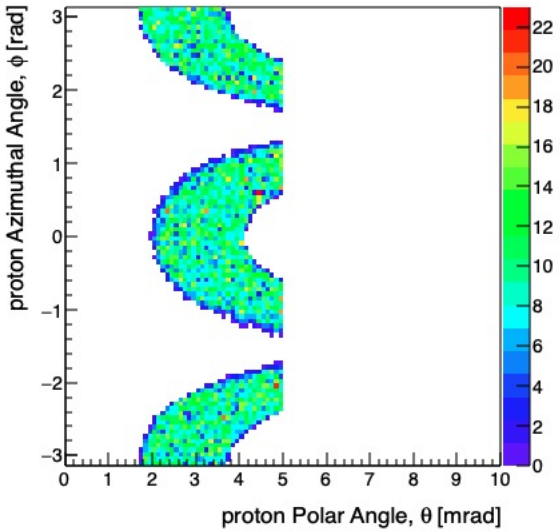
Generated



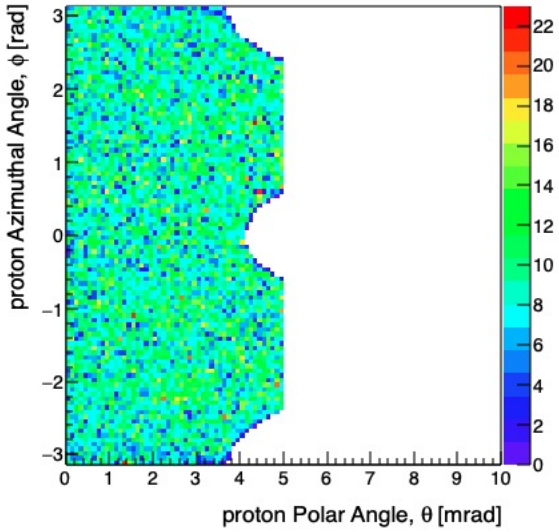
10σ cut.

10σ cut.

Acceptance – RP drift



Acceptance – RPSF



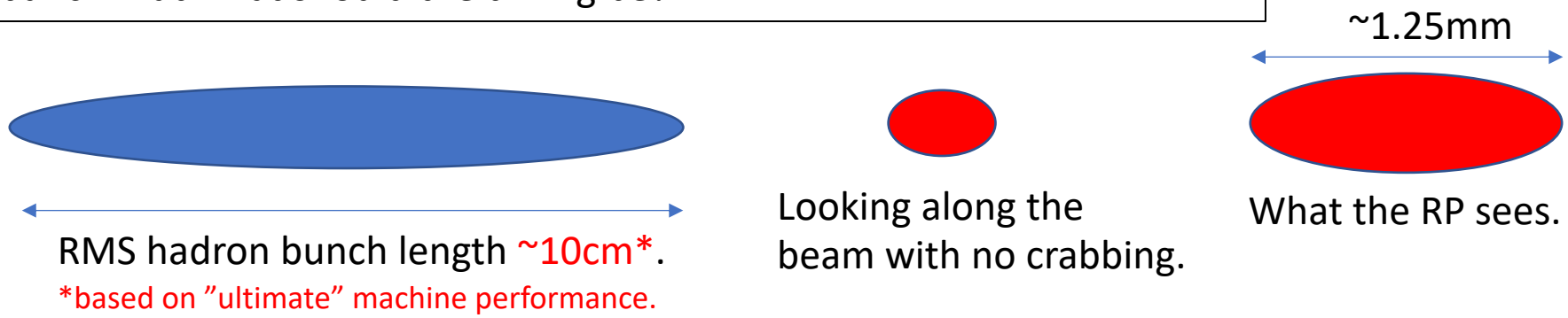
Takeaways

- Much has been achieved during the YR in understanding the physics reach possible with IP6.
  - Many of these studies provide crucial benchmarks for deciding on options for IP8!
- Things are rapidly moving past the YR era as the proto-collaborations (ATHENA, CORE, ECCE) look at more-detailed material considerations and cost.
- Many of the lessons learned from studies in IP6 are very beneficial to the continued development of IP8.
- The far-forward region of both IPs is extremely important to the entire exclusive/diffractive physics program at the EIC!

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?

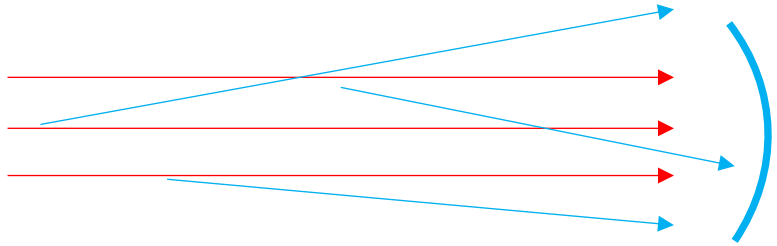


- Because of the rotation, the Roman Pots see the bunch crossing **smeared in x**.
- Vertex smearing = 12.5mrad (half the crossing angle) * 10cm = **1.25 mm**
- If the effective vertex smearing was **for a 1cm bunch**, we would have **0.125mm** vertex smearing.
- The simulations were done with these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

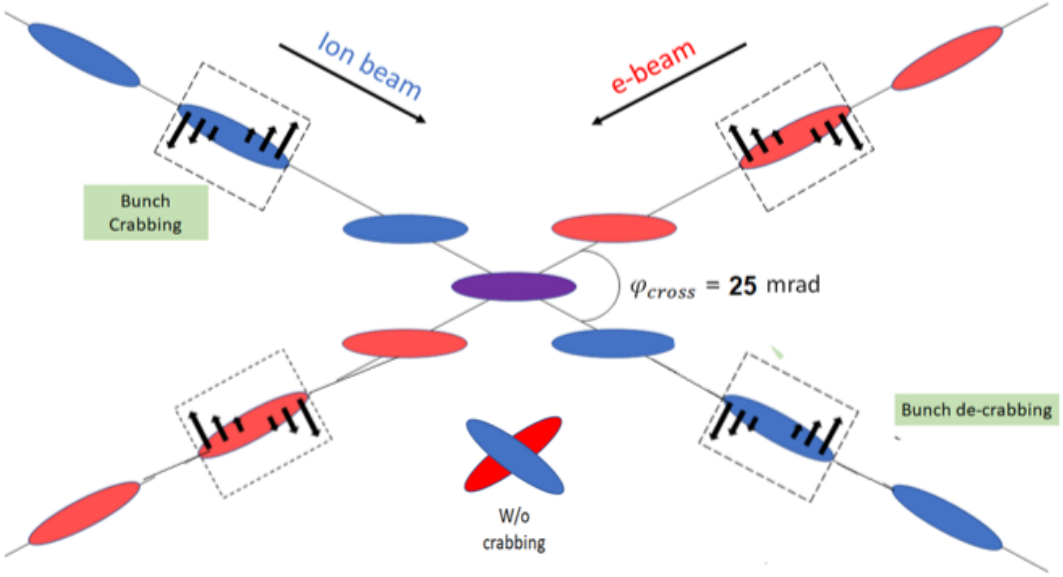
- **From these comparisons, reducing the effective vertex smearing to that of the 1cm bunch length reduces the momentum smearing to a negligible amount from this contribution.**
- **This can be achieved with timing of ~ 35ps (1cm/speed of light).**

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.



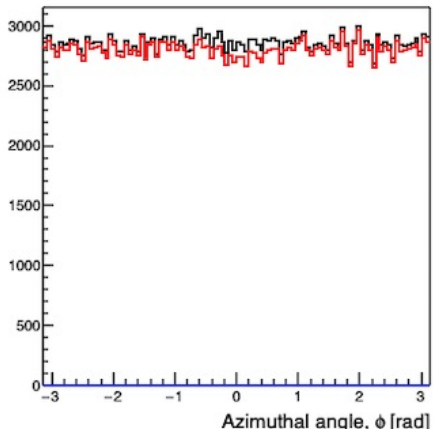
- Detector Choices
  - Pixel size, RP transfer matrix, etc.

These effects introduce smearing in our momentum reconstruction.

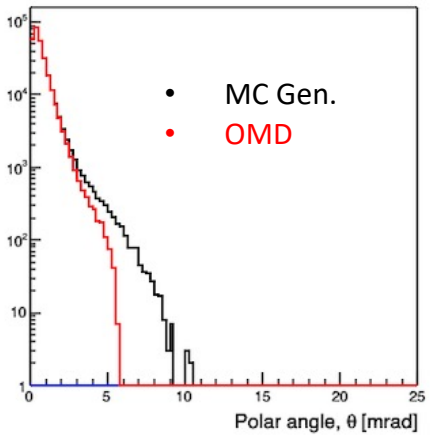
e+d Spectator Tagging

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

Protons

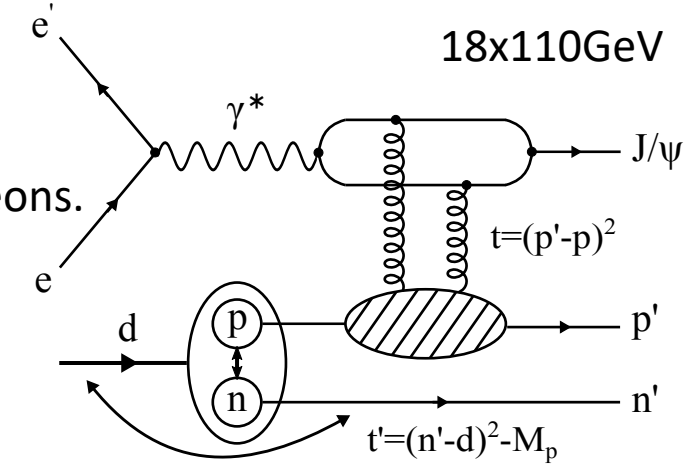


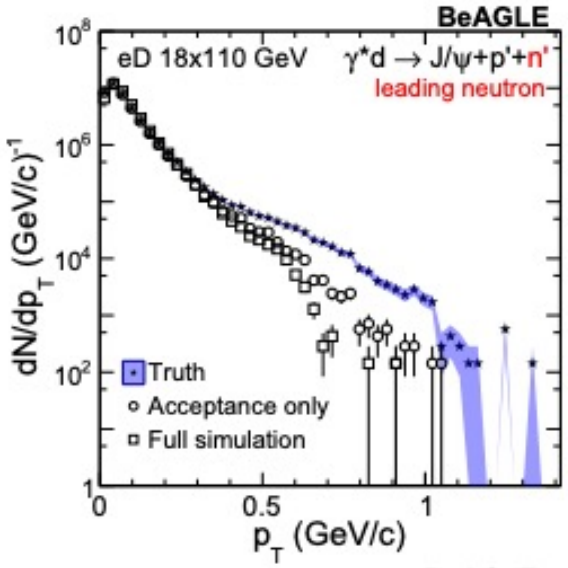
Protons

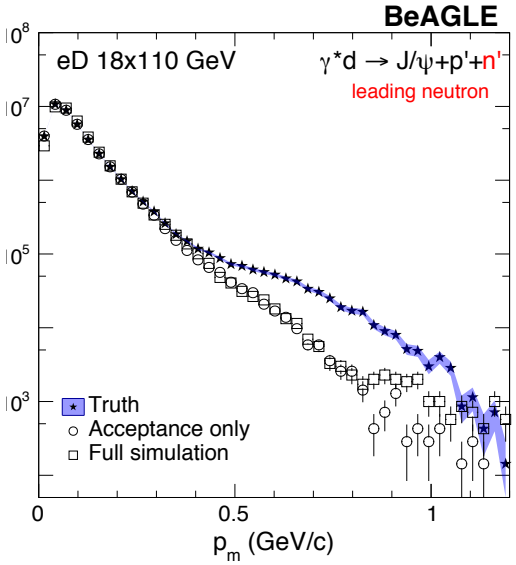


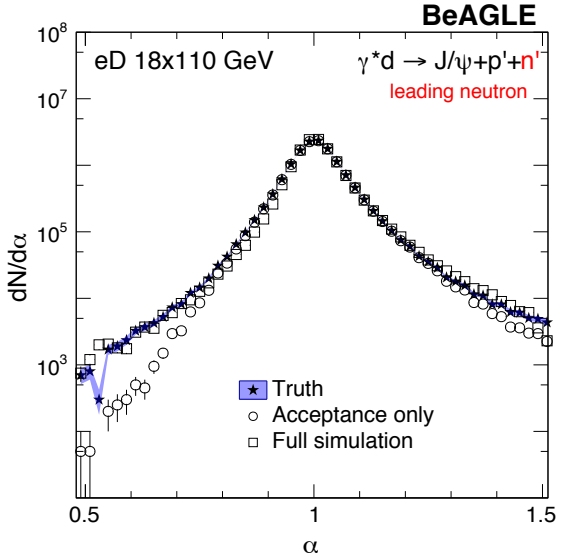
Proton spectator case.

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









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).

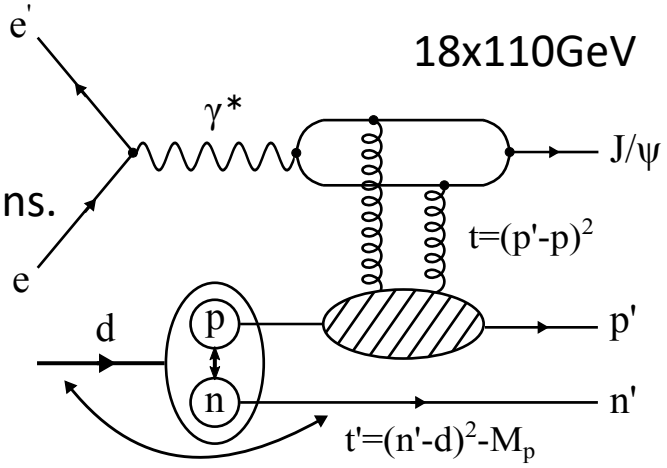
- **In the proton spectator case, essentially all spectators tagged.**
- **Active neutrons only tagged up to 4.5 mrad.**

e+d Spectator Tagging

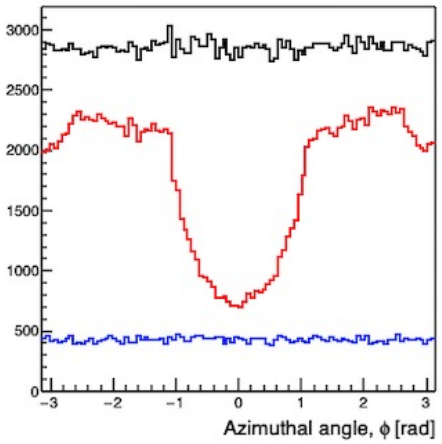
Z. Tu, A. Jentsch *et al.*, Phys. Lett. B, **811** (2020)

Neutron spectator case.

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



Protons



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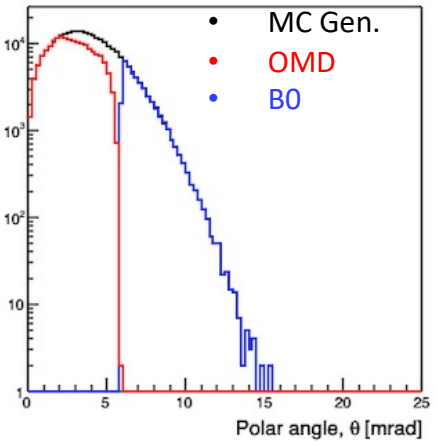
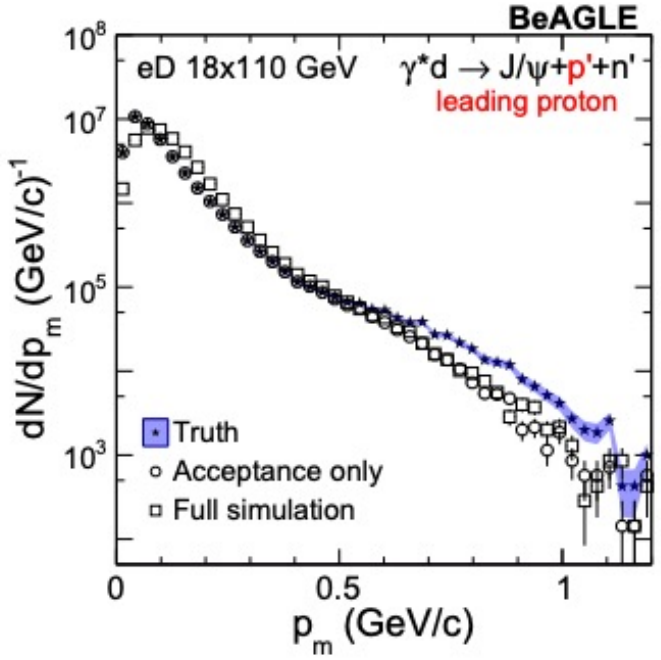
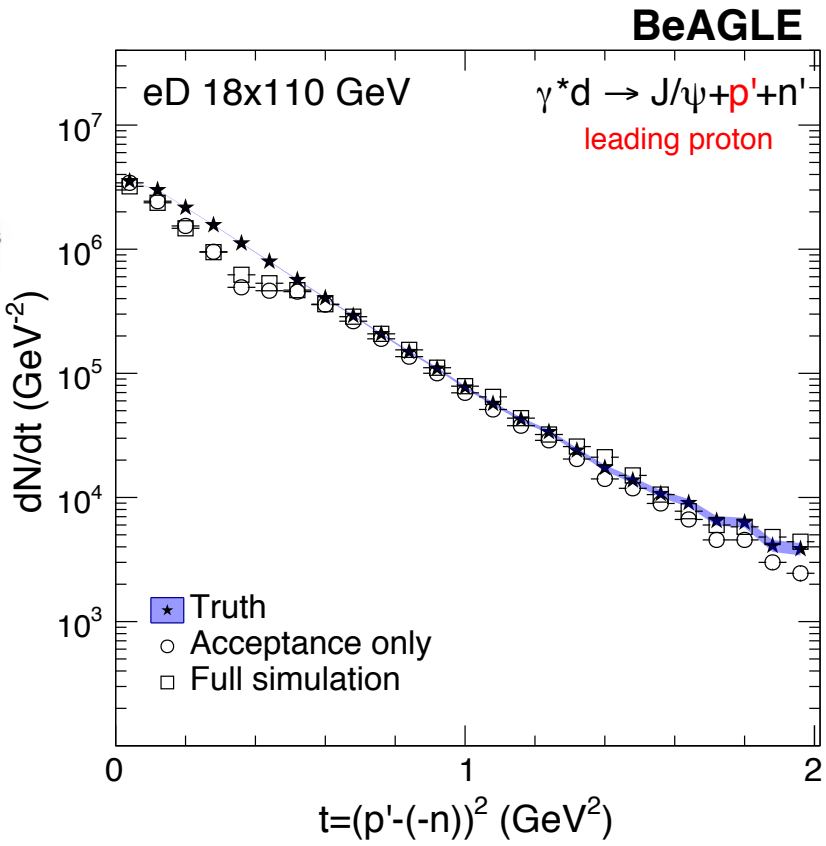


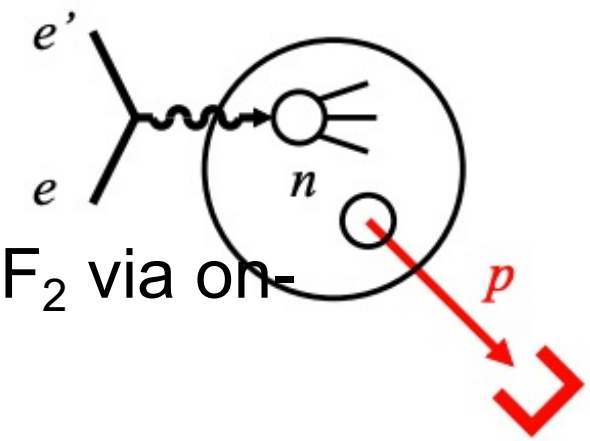




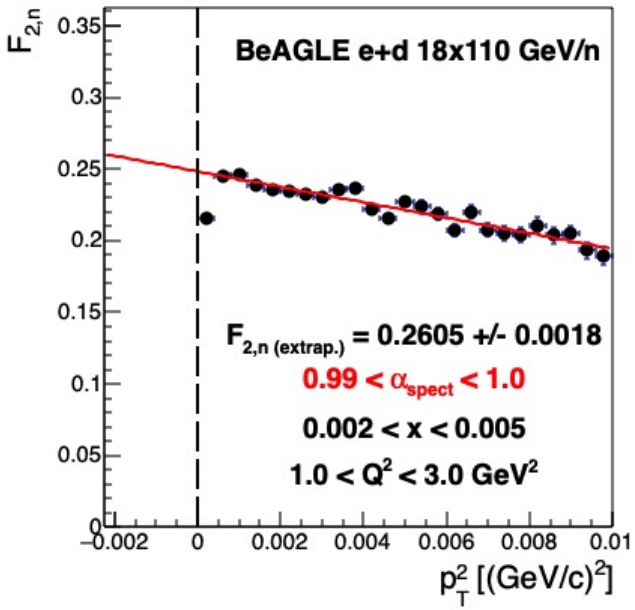
t-reconstruction using double-tagging (both proton and neutron). Takes advantage of combined B0 + off-momentum detector coverage. Better coverage in the neutron spectator case.

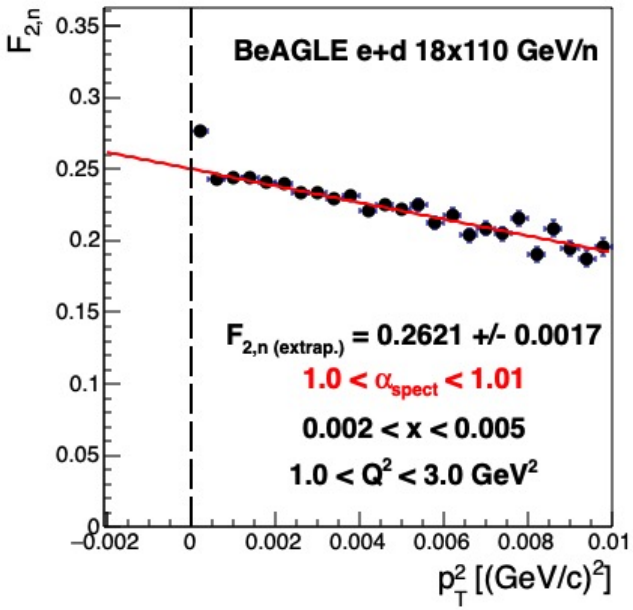
➢ **Spectator information is the "dial" for the SRC region.**

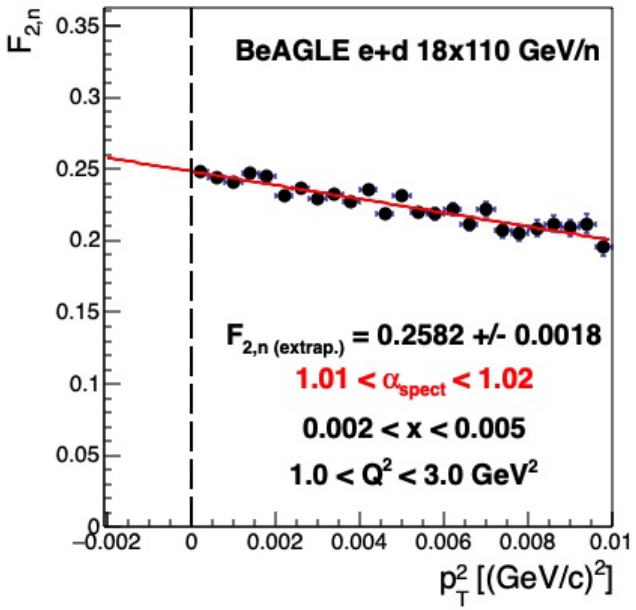
Ongoing Studies – Free Neutron Structure and Modifications.



- e+d spectator proton tagging yields access to free-neutron F_2 via on-shell extrapolation.
  - Paper will be on the ArXiv in a few weeks.
- Further studies ongoing to examine nuclear modifications and effect of detector smearing.

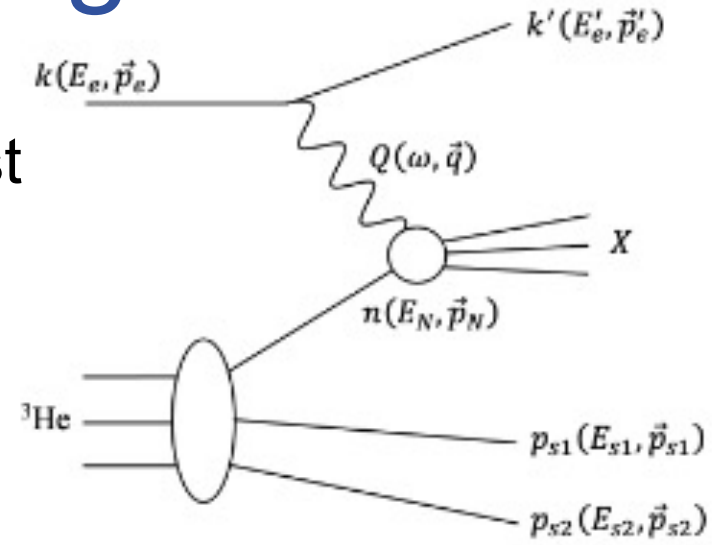


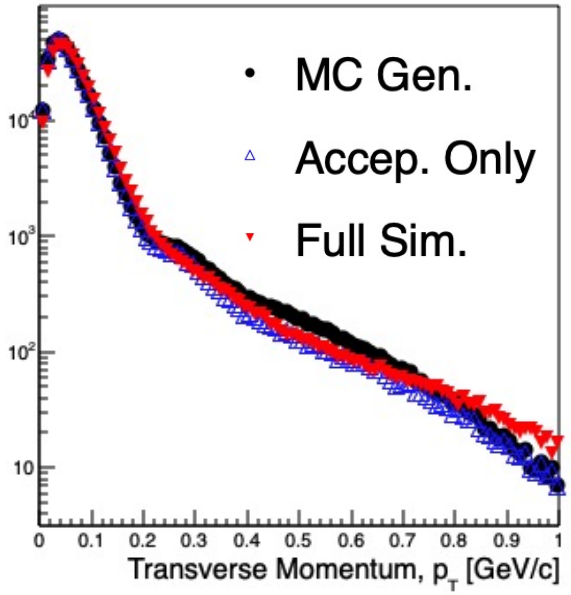


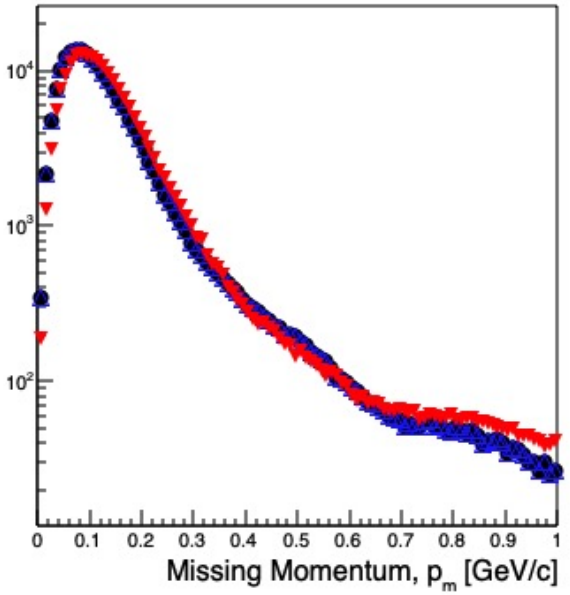


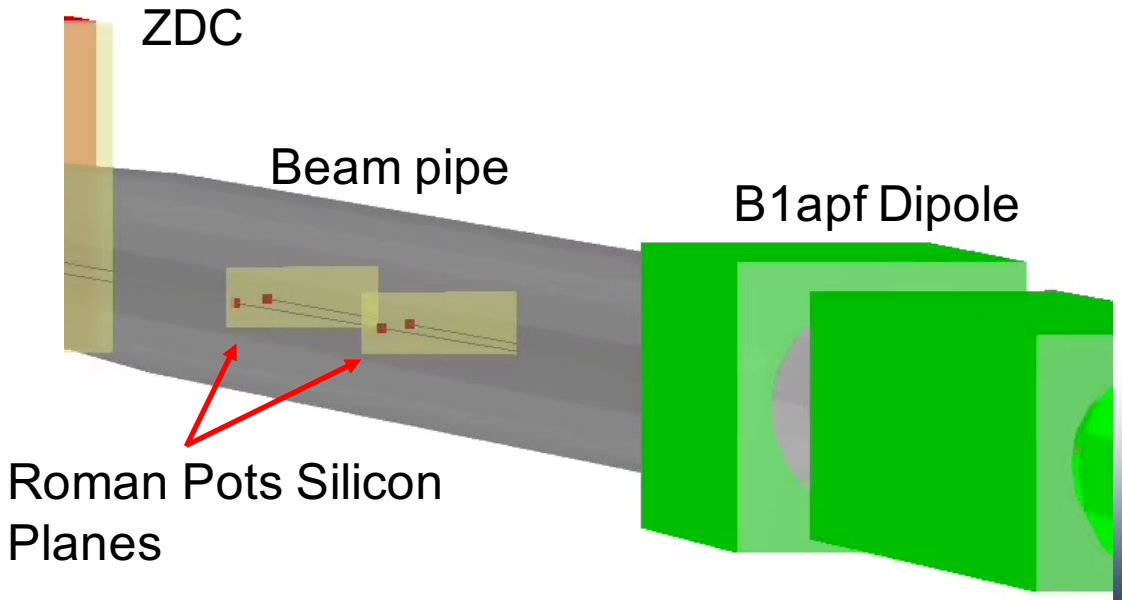
Ongoing Studies – e+He3 scattering.

- Studies of neutron structure with a *polarized* neutron.
- More challenging final state tagging since *both* protons must be tagged in the FF region.
- MC events generated with CLASDIS in fixed-target frame, and then boosted to collider frame.
- Paper on the ArXiv soon.





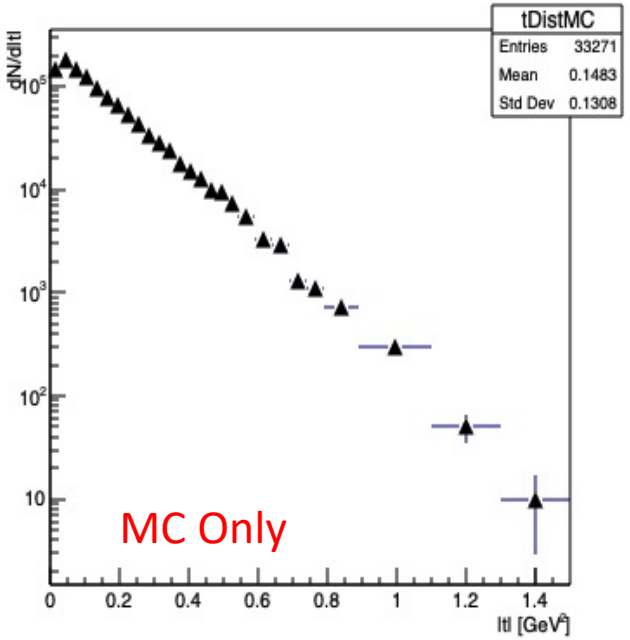


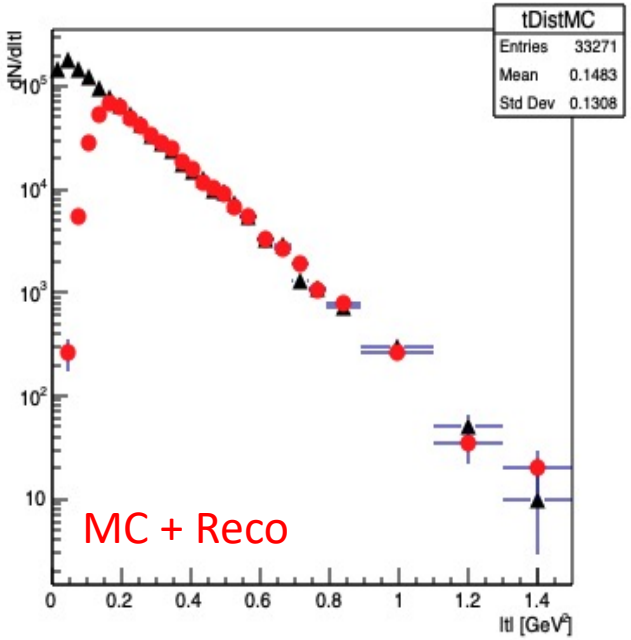


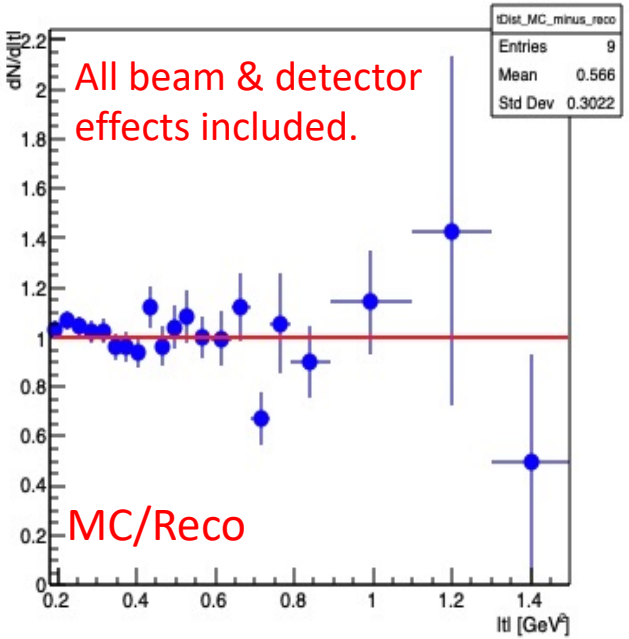
e+p DVCS

- 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.**