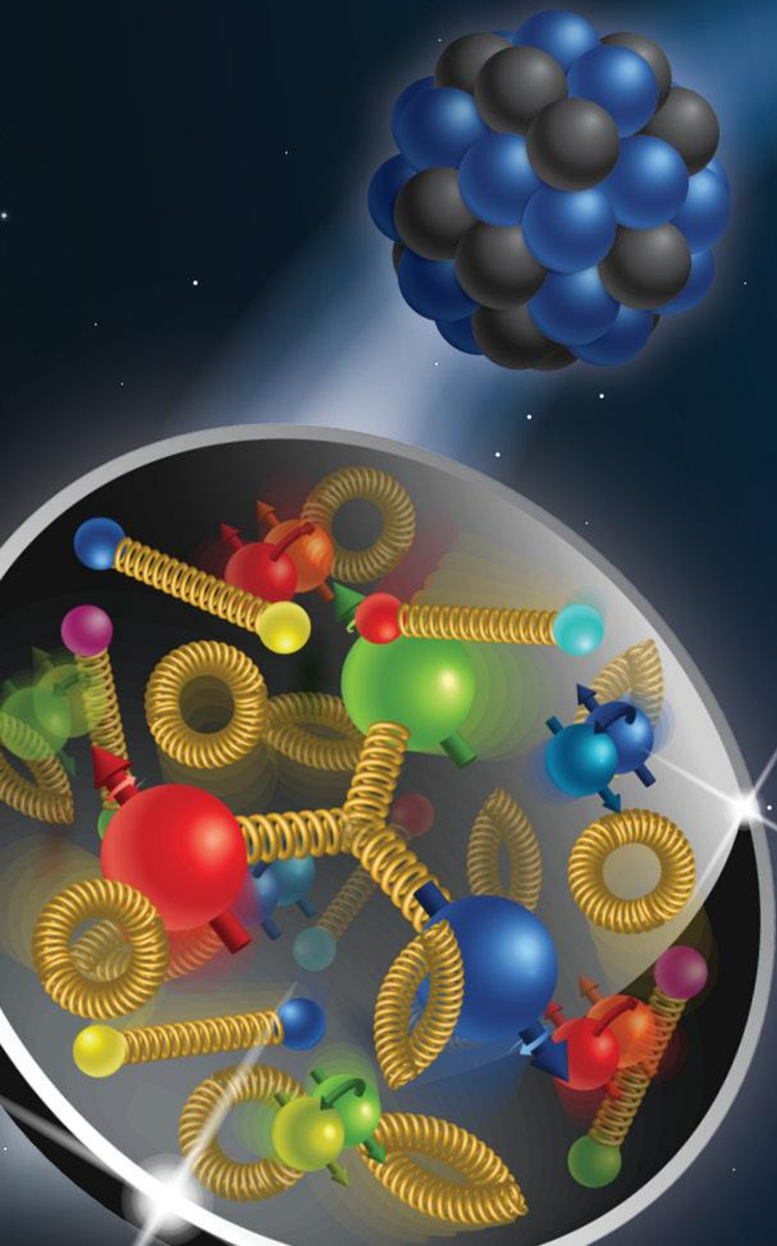

Far-Forward area and IR Integration

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ECCE meeting

July 8 , 2021

Electron-Ion Collider

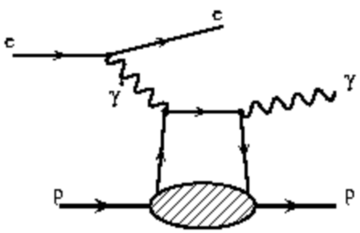
BROOKHAVEN NATIONAL LABORATORY Jefferson Lab U.S. DEPARTMENT OF ENERGY Office of Science

Outline

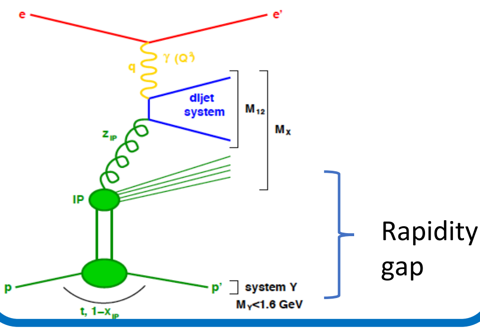
- Physics motivation and IR-requirements
- Far-forward IP6
- Far-forward IP8
- Far-backward regions
- Summary

Far-forward physics at EIC

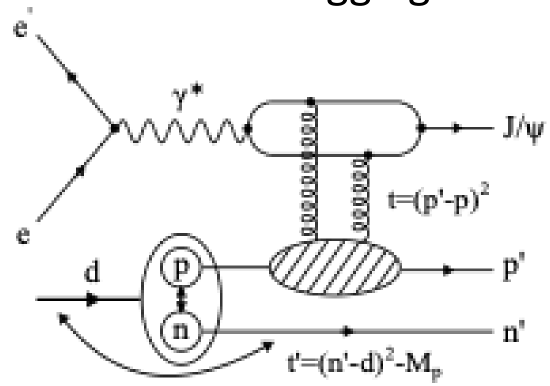
e+p DVCS events with proton tagging.



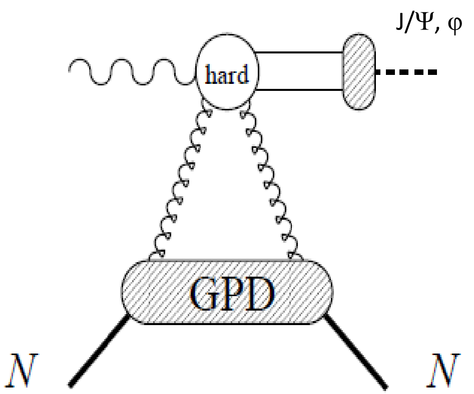
Diffraction



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

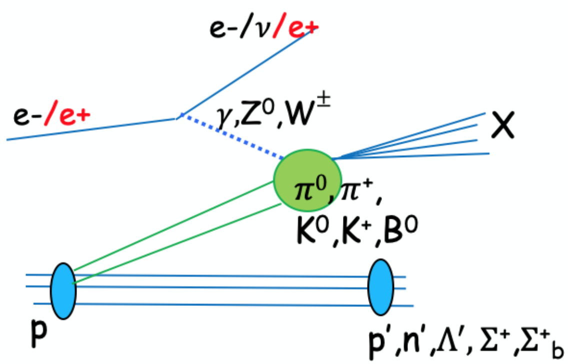


Saturation (coherent/incoherent J/ψ production)



Meson structure:

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

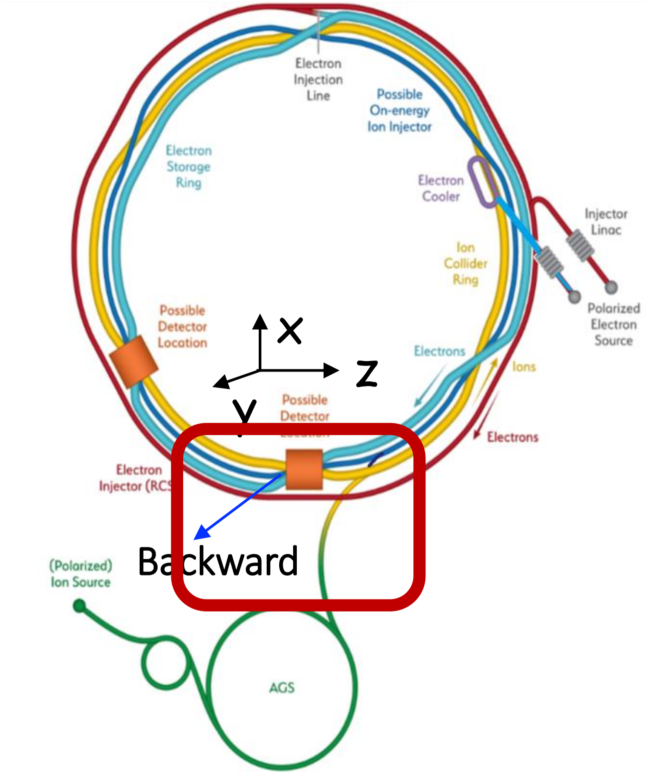
....

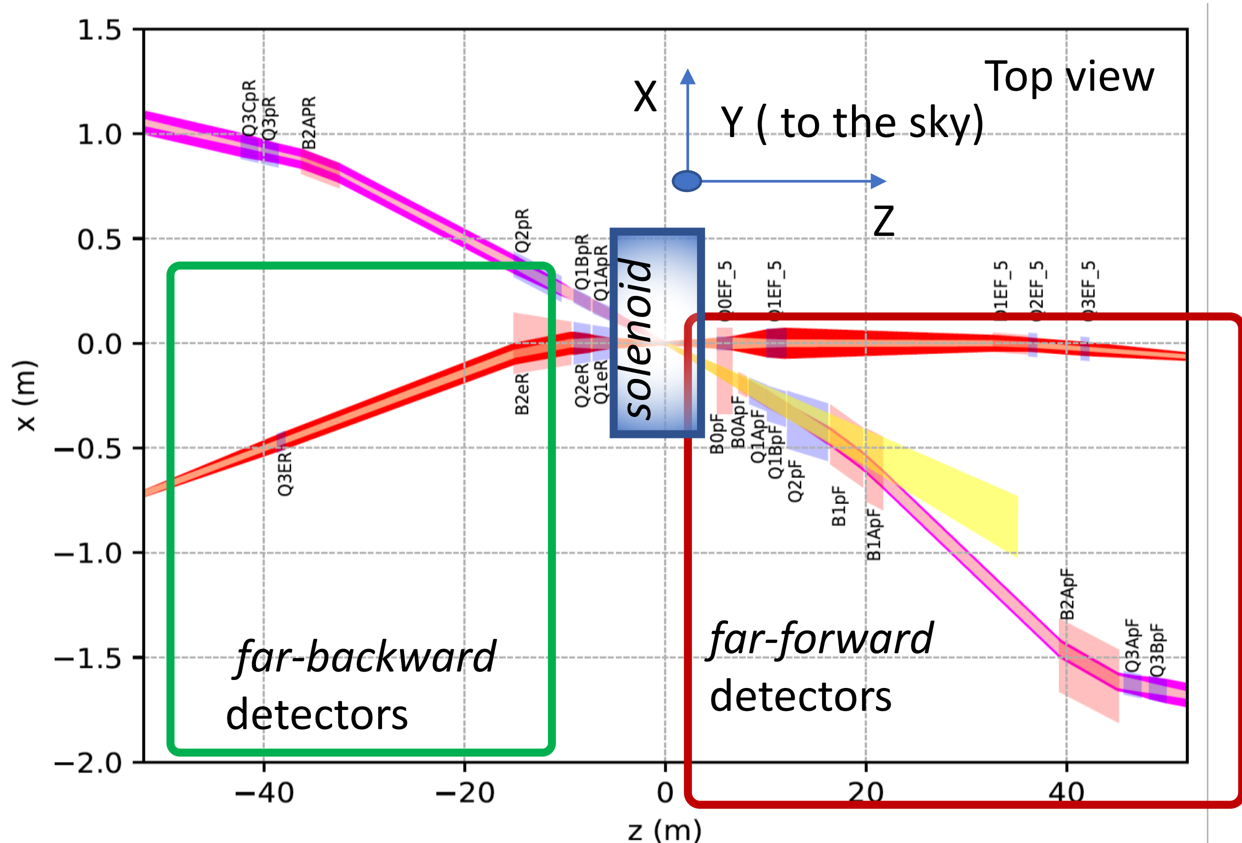
IR-related physics requirements

Table 2.2: Summary of the requirements from the physics program on the overall IR design.

	Hadron	Lepton
Machine element free region	± 4.5 m main detector beam elements $< 1.5^\circ$ in main detector volume	
Beam Pipe	Low mass material, i.e. Beryllium	
Integration of detectors	Local Polarimeter	
Zero Degree Calorimeter	60cm x60cm x 2m $@s = 30$ m	
scattered proton/neutron acc. all energies for e+p	Proton: $0.18\,\mathrm{GeV/c} < p_T < 1.3\,\mathrm{GeV/c}$ $0.5 < x_L < 1 (x_L = E'_p / E_{Beam})$ Neutron: $p_T < 1.3\,\mathrm{GeV/c}$	
scattered proton/neutron acc. all energies for e+A	Proton and Neutron: $\theta < 6$ mrad (for $\sqrt{s} = 50$ GeV) $\theta < 4$ mrad (for $\sqrt{s} = 100$ GeV)	
Luminosity	Relative Luminosity: $R = L^{++/--} / L^{+-/-+} < 10^{-4}$	
		γ acceptance: ± 1 mrad $\rightarrow \delta L / L < 1\%$
Low Q^2-Tagger		Acceptance: $Q^2 < 0.1$ GeV

EIC Interaction Region layout (IP6)

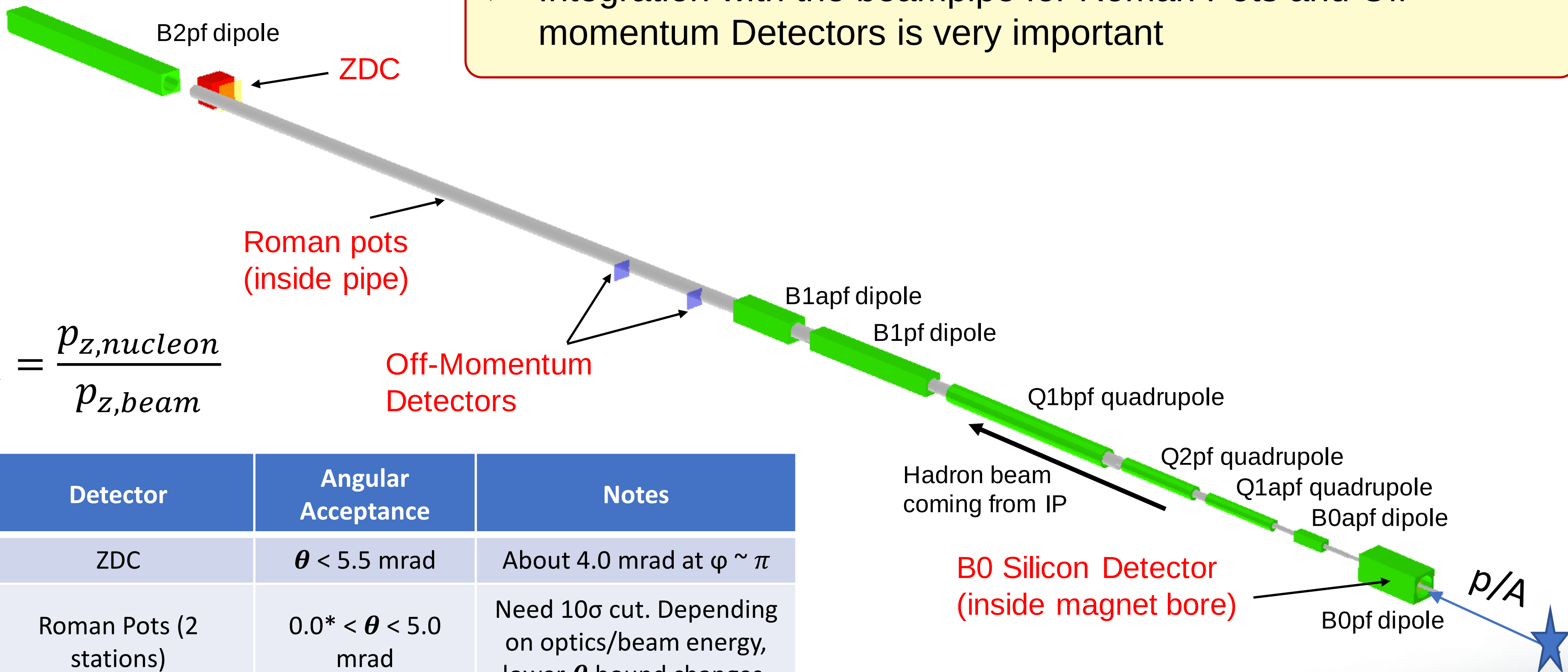




- ~9 m around the IP is reserved for the *central* detector
- But the *far forward* and *far backward* detector components are distributed along the beam line within ±35 m
- Design should be able to operate with different beam energy and high luminosity
- Very important to keep full detector integration in sync with the accelerator design from the early stages on

Far forward (hadron going) region

- From the installation / integration point of view, this area is completely independent from the Central detector
- Integration with the beampipe for Roman Pots and Off-momentum Detectors is very important



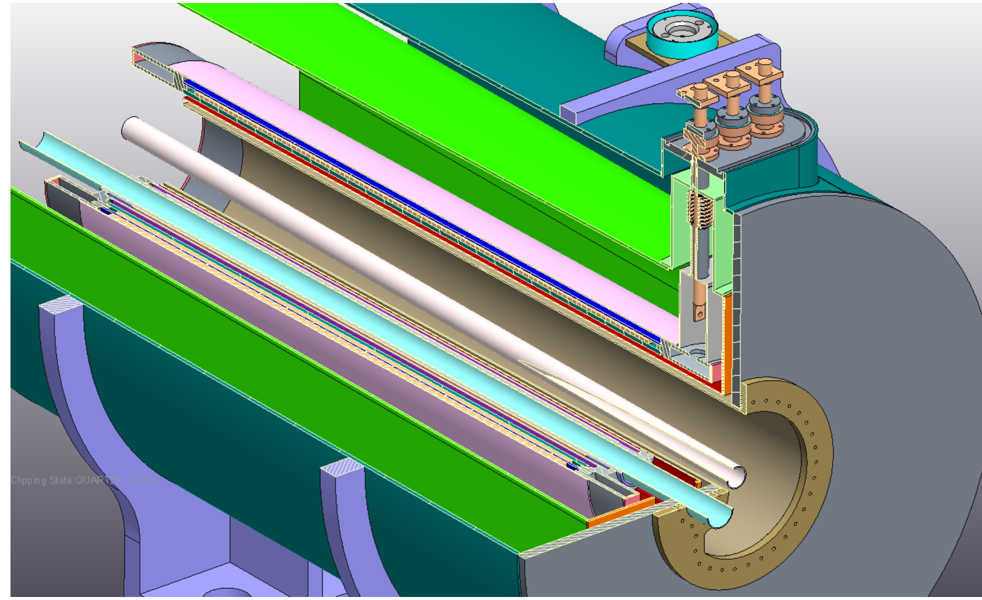
$$x_L = \frac{p_{z,nucleon}}{p_{z,beam}}$$

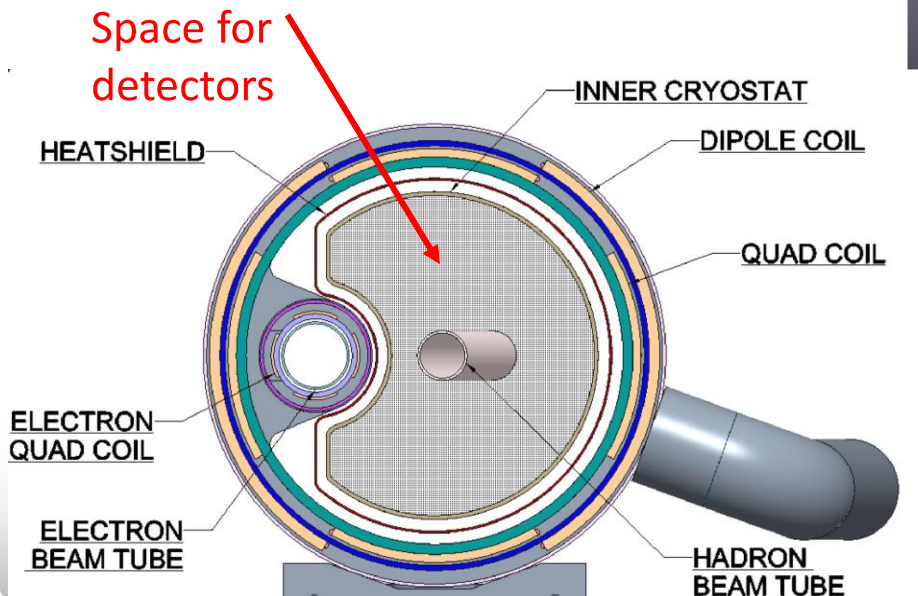
Detector	Angular Acceptance	Notes
ZDC	θ < 5.5 mrad	About 4.0 mrad at φ ~ π
Roman Pots (2 stations)	0.0* < θ < 5.0 mrad	Need 10σ cut. Depending on optics/beam energy, lower θ bound changes.
Off-Momentum Detectors	0.0 < θ < 5.0 mrad	Roughly 0.4 < x_L < 0.6
B0 Sensors (4 layers, evenly spaced)	5.5 < θ < 20.0 mrad	Could change a bit depending on pipe and electron quad

B0-detectors

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

- Create zero field line at electron beam axis by overlapping large diameter main quadrupole and dipole coils.
- Warm space for detector package insert located inside a vacuum vessel to isolate from insulating vacuum.

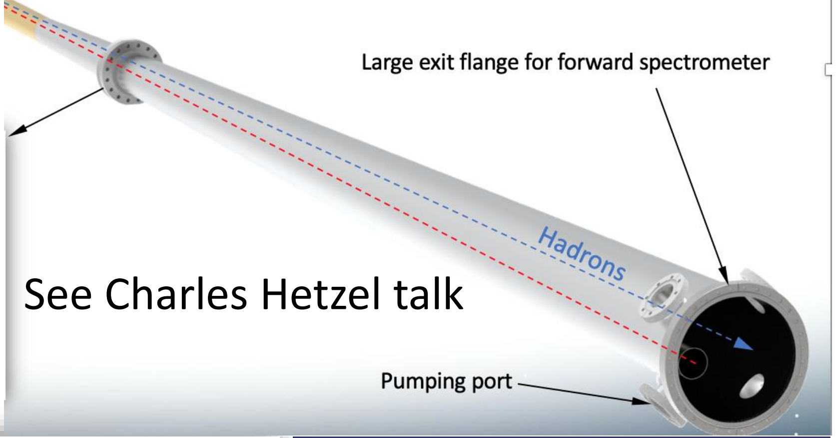


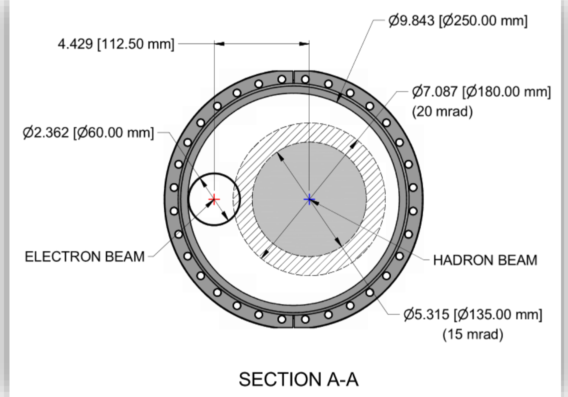


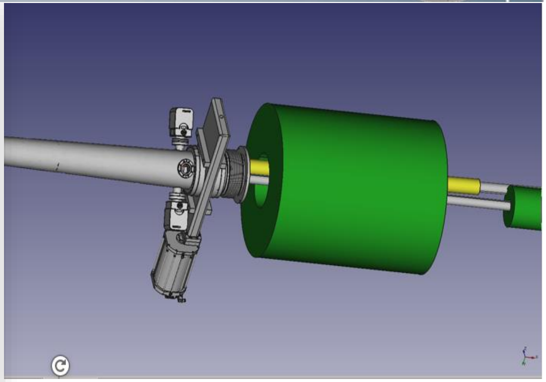
- ➢ Shape and coverage of B0 tracker needs to be further evaluated
- ➢ Higher granularity detectors needed in this area (MAPS) with layers of fast-timing detectors (LGADs)

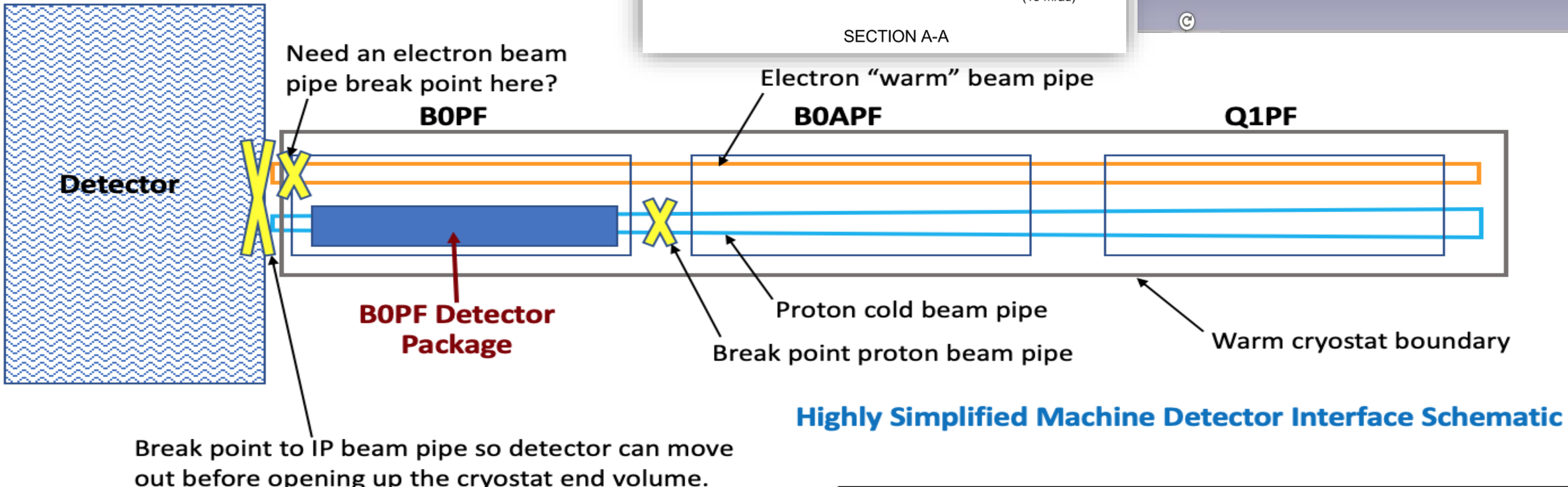
B0 integration

- Beampipe: exit window
- HCAL and vacuum pumps in front of B0 tracker => high background area
- Detector integration and maintenance

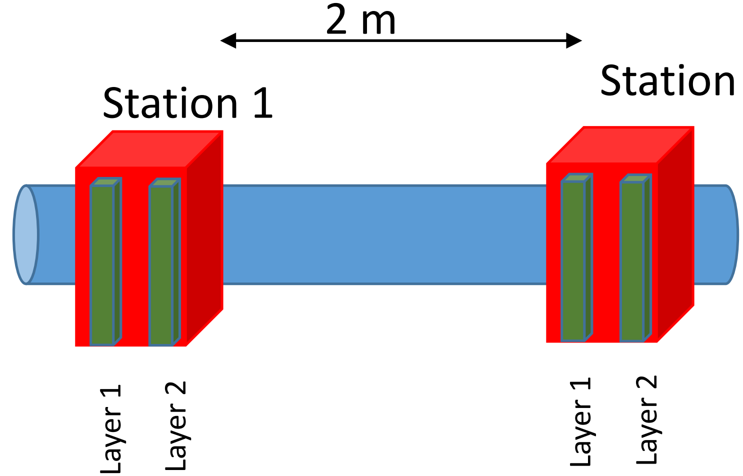




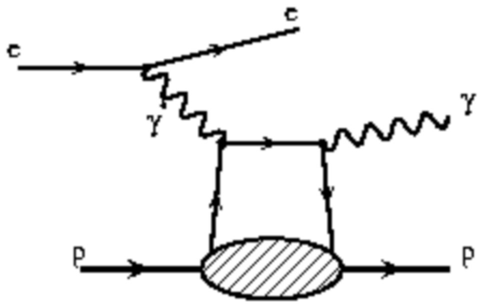




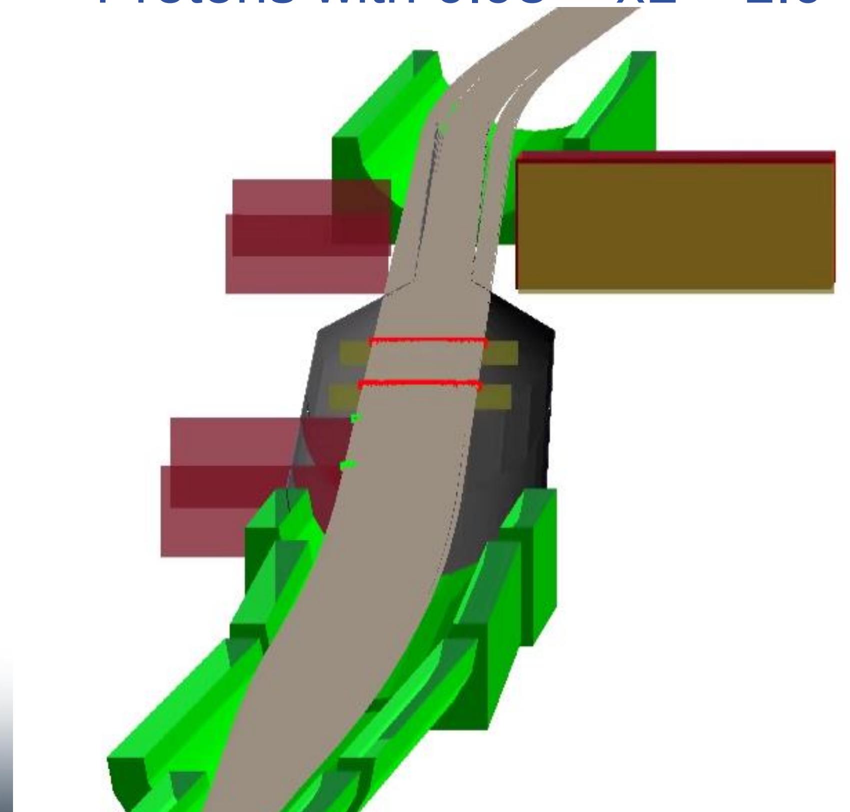
Roman Pots



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

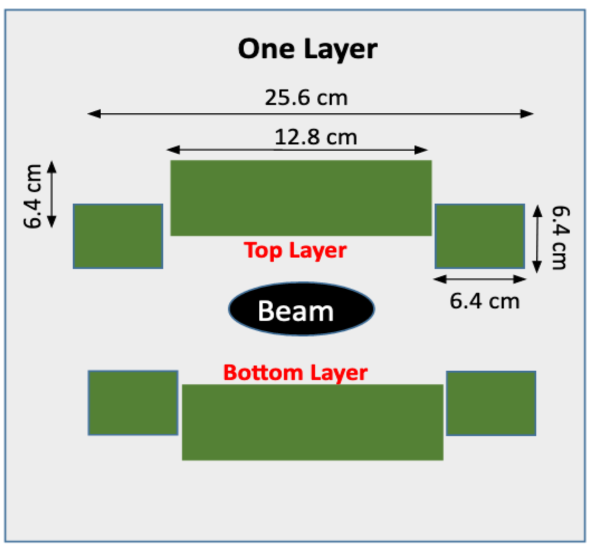


Protons with 0.98 < xL < 1.0



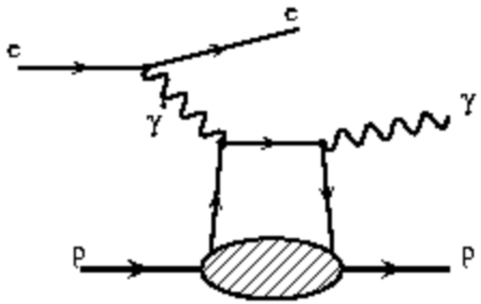
$\sigma(z)$ is the Gaussian width of the beam,
$\beta(z)$ is the RMS transverse beam size.
ε is the emittance.

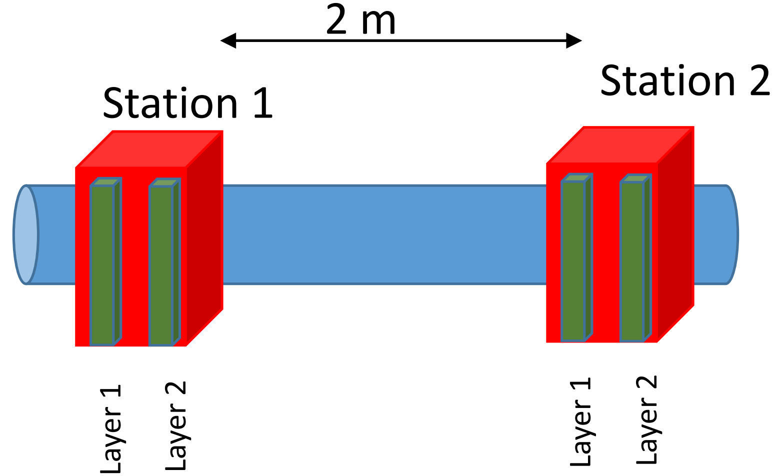
$$\sigma(z) = \sqrt{\varepsilon \cdot \beta(z)}$$



Roman Pots

0.0* (10σ 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 emittance.

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

Low Gain Avalanche Detectors (LGADs):

Gain 5-100, Large S/N ratio, 30-50 mm thickness

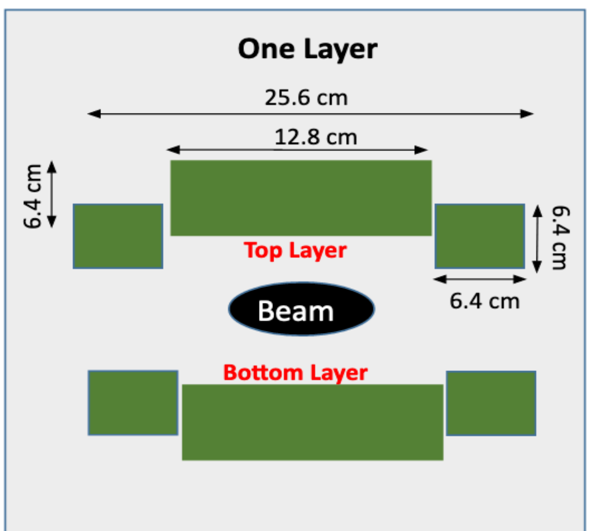
Fast-timing: ~30-50 ps per hit, dominated by Landau fluctua

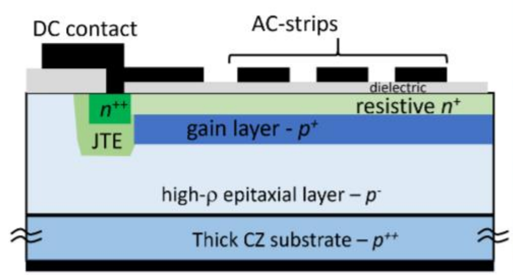
AC-coupling allows fine segmentation

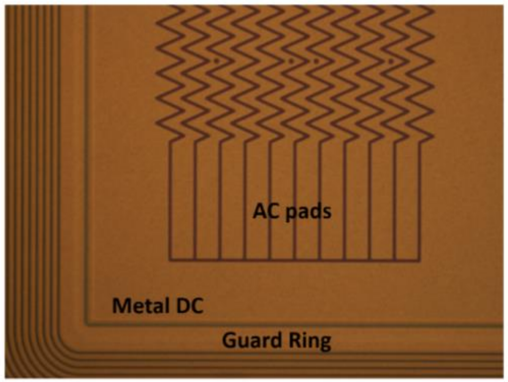
100% fill factor

AC-LGAD 2mmx2mm strip sensor.

Strip pitch = 100um







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

Roman Pots resolution

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

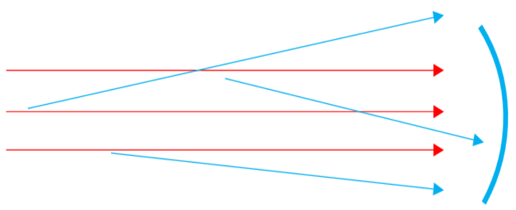
$$\Delta p_{t,total} = \sqrt{(\Delta p_{t,AD})^2 + (\Delta p_{t,CC})^2 + (\Delta p_{t,pxl})^2}$$

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

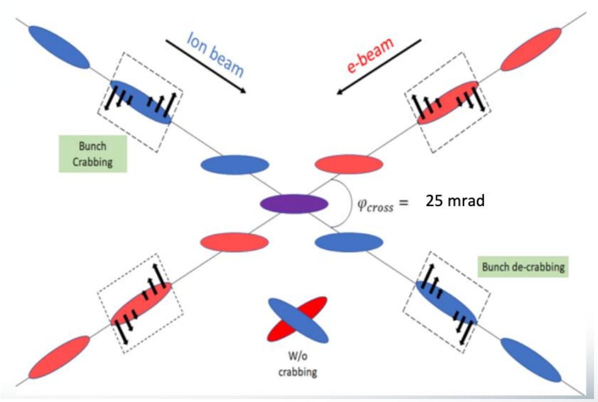
These studies based on the "ultimate" machine performance with strong hadron cooling.

	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

Angular divergence

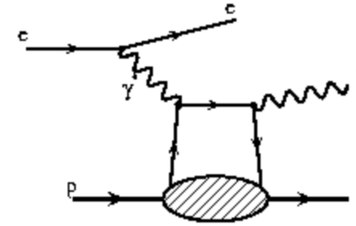


Primary vertex smearing from crab cavity rotation

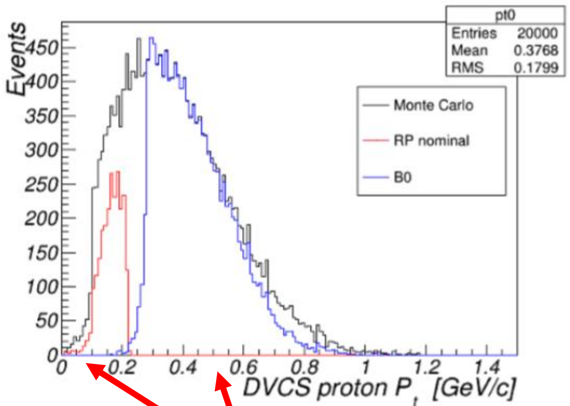


- **Beam angular divergence**
  - Beam property, can't correct for it – sets the lower bound of smearing.
  - Subject to change (i.e. get better) – beam parameters not yet set in stone
    - *using symmetric divergence parameters in x and y at 100urad.
- **Vertex smearing from crab rotation**
  - Correctable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

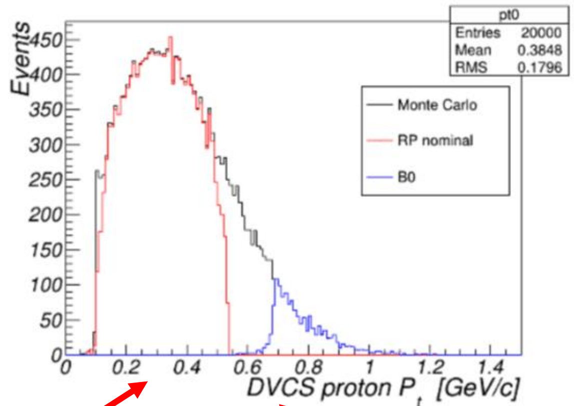
Forward Proton Acceptance



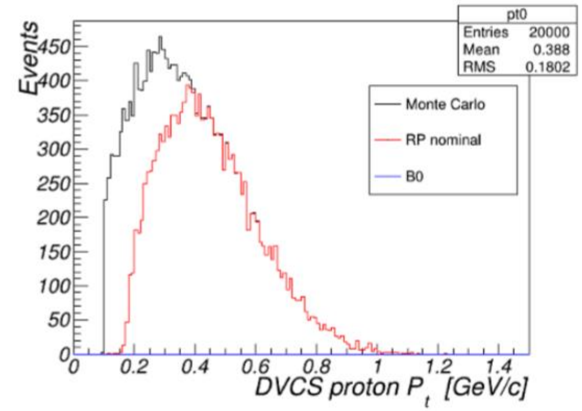
5 GeV x 41 GeV



10 GeV x 100 GeV



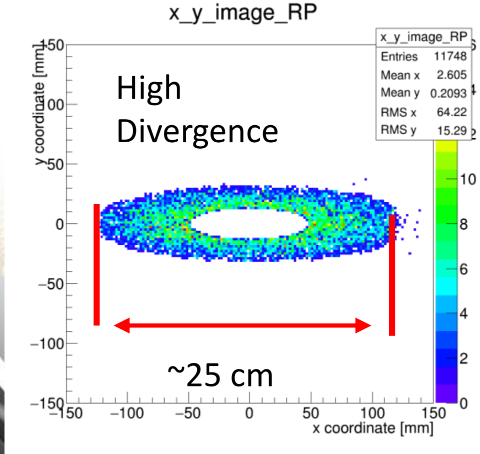
18 GeV x 275 GeV

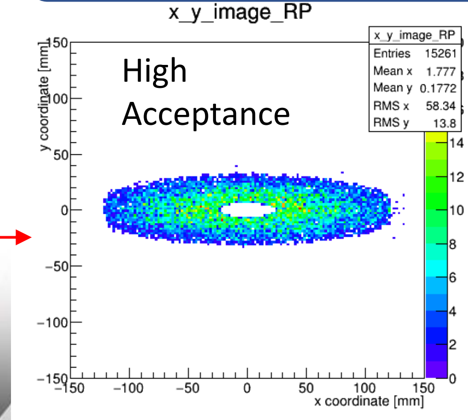


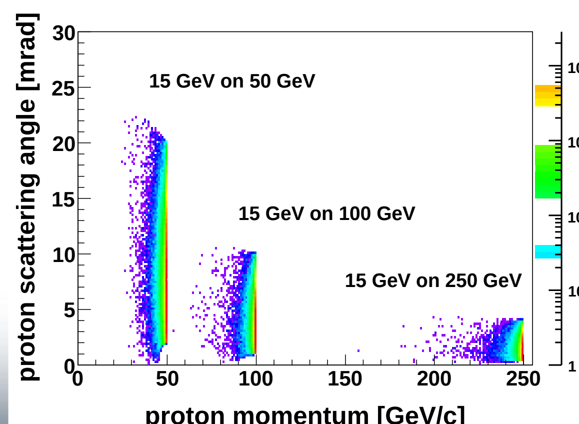
Need both detector systems together here!

High Divergence: smaller β^* at IP, but bigger $\beta(z = 30m)$ -> higher lumi., larger beam at RP

High Acceptance: larger β^* at IP, smaller $\beta(z = 30m)$ -> lower lumi., smaller beam at RP

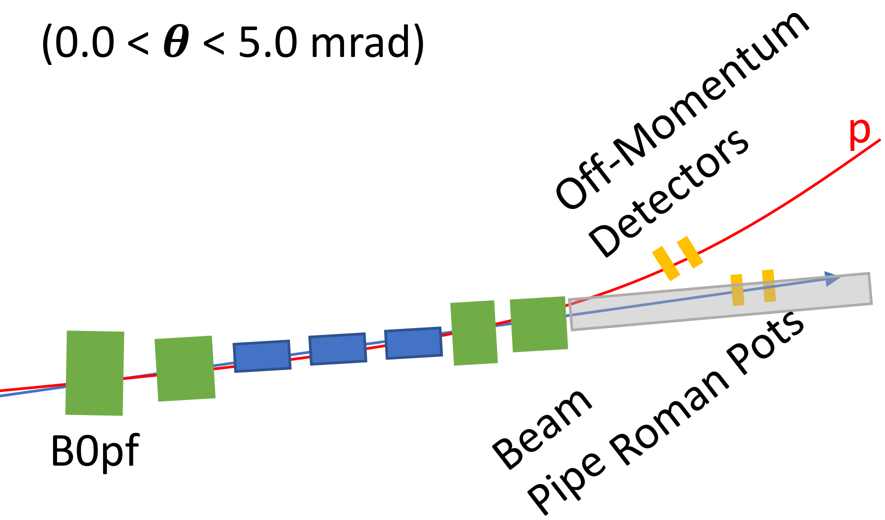


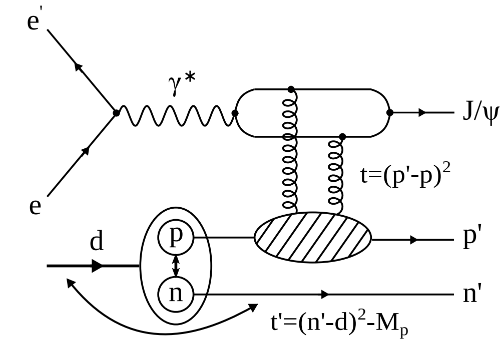


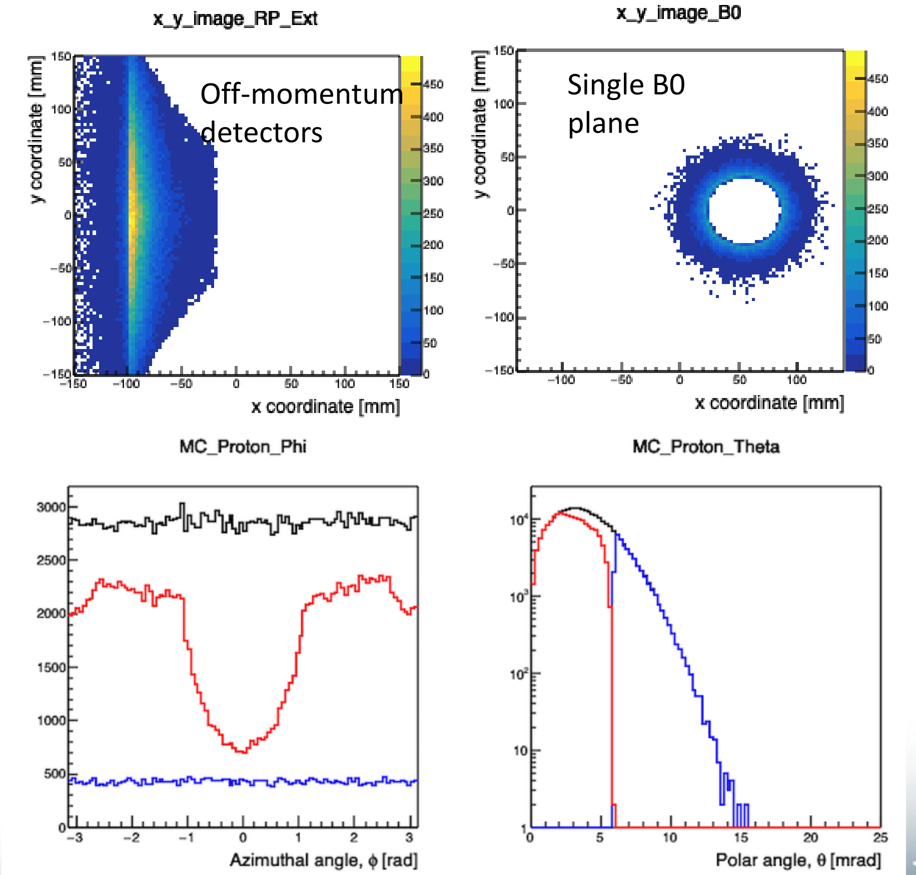


Off-Momentum detectors

(0.0 < θ < 5.0 mrad)







- Protons that come from nuclear breakup have a different magnetic rigidity than their respective nuclear beam (x_L<1)
- This means the protons experience more bending in the dipoles.
- As a result, small angle (θ < 5mrad) protons from these events will not make it to the Roman Pots, and will instead exit the beam pipe after the last dipole.
- Detecting these requires "off-momentum detectors".

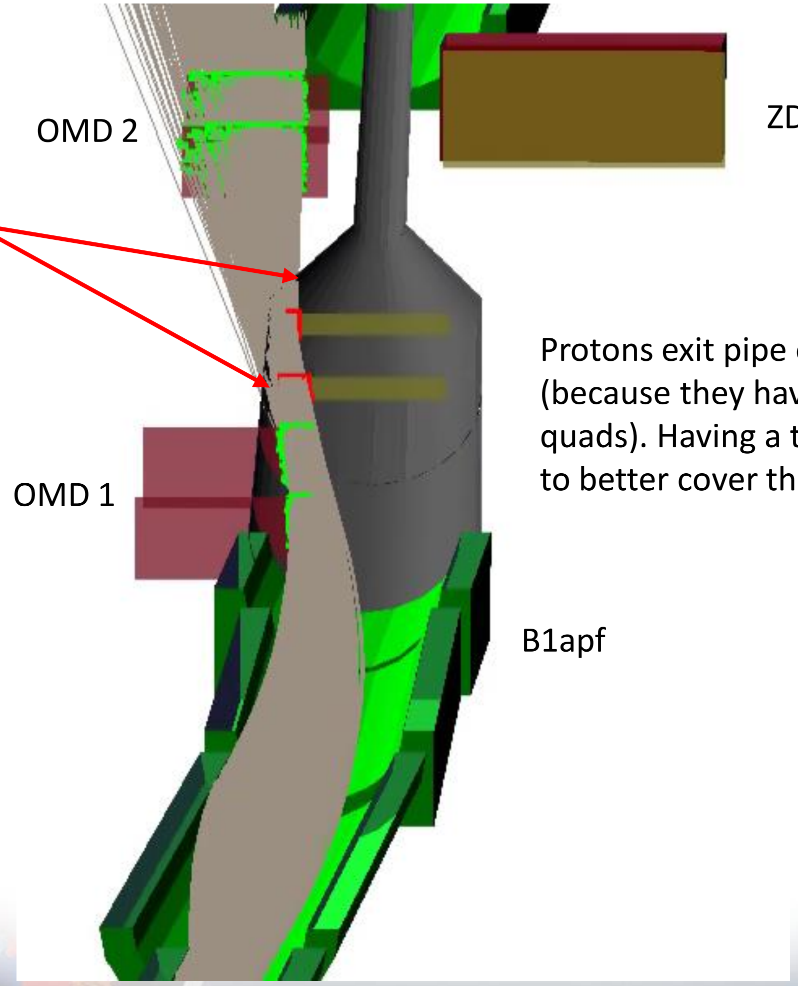
Neutron spectator/leading proton case.

ed (18x110GeV)

Protons with 0.45 < xL < 0.55

123.75 < p < 151.25 GeV/c
0.0 < theta < 4.0 mrad

As with neutrons, hope is to maximize protons impinging at big angles to minimize effective material length. Sharp taper, exit window, etc.



Protons exit pipe over a much smaller length in z (because they have a weak focal point from the quads). Having a two-step OMD system allows us to better cover the gaps between the OMD and RP.

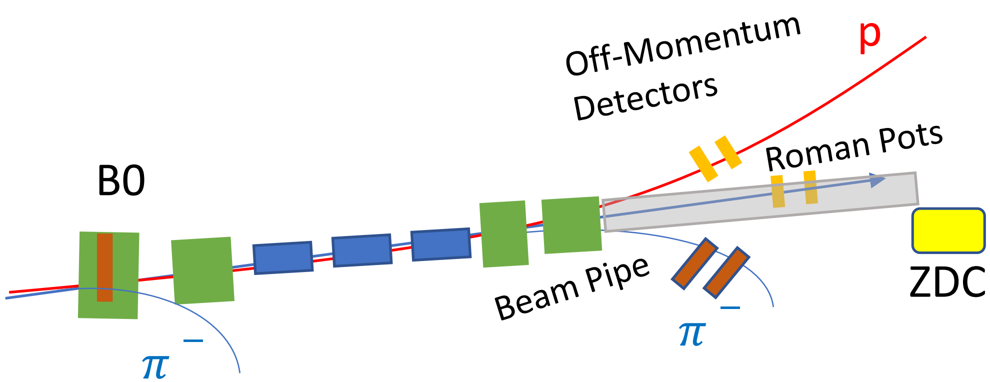
Lambda decays

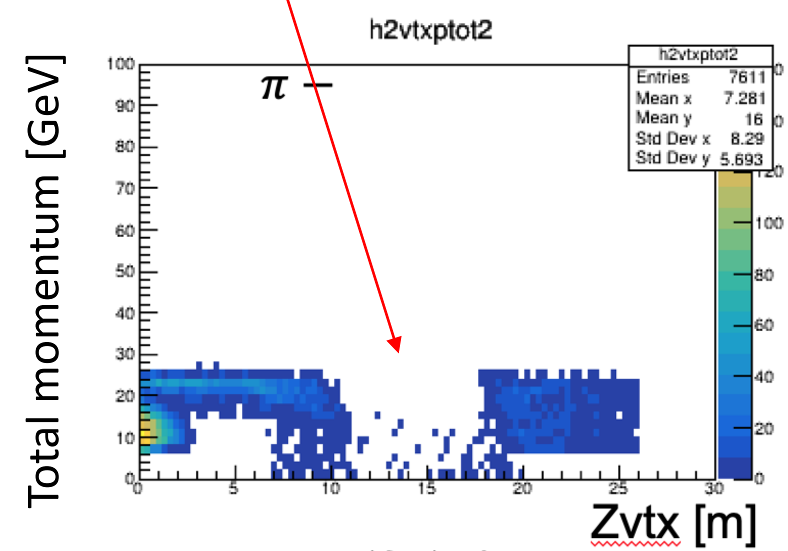
e p -> (K) -> e' + Λ + X

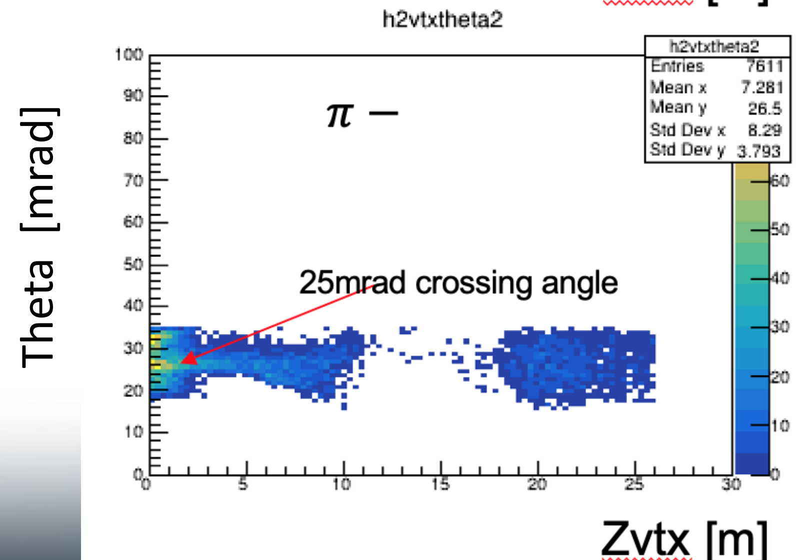
↳ p + π^- (Br~64%)

↳ n+ π^0 (Br ~36%)

Example (10x100 GeV): ~100% detection for protons from Lambda. Significant loss π^- along the beam line (FFQs) due to low momentum of those pions.







- ➢ Detecting Lambda's decays in the target fragmentation area is very hard, due to a very large decay length (meters).
- ➢ Would require in addition detection of negative charged particles (pi-) at the OFF-momentum detector location

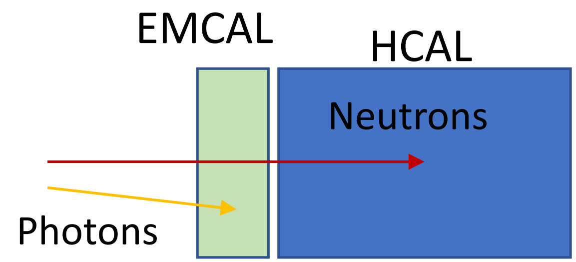
Zero-degree Calorimeter

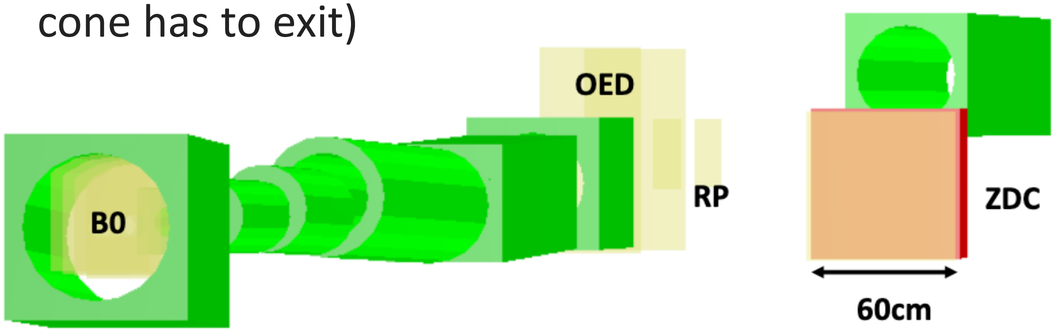
For detection of neutrons and photons

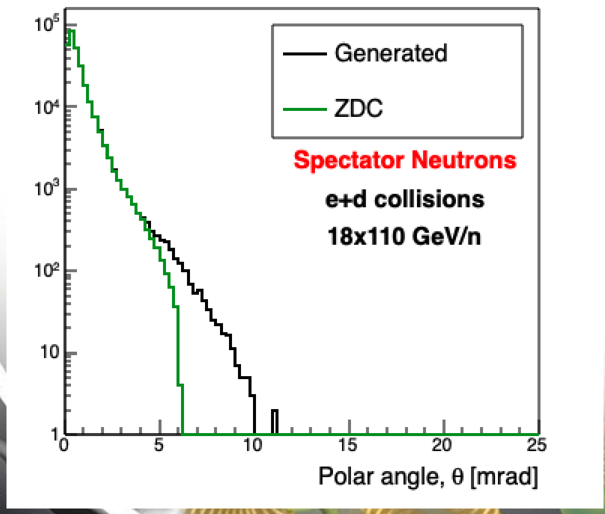
<u>Acceptance:</u>

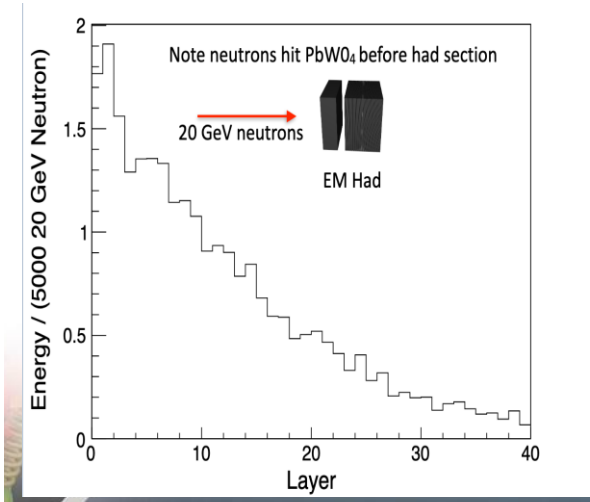
0<θ<5.5 mrad

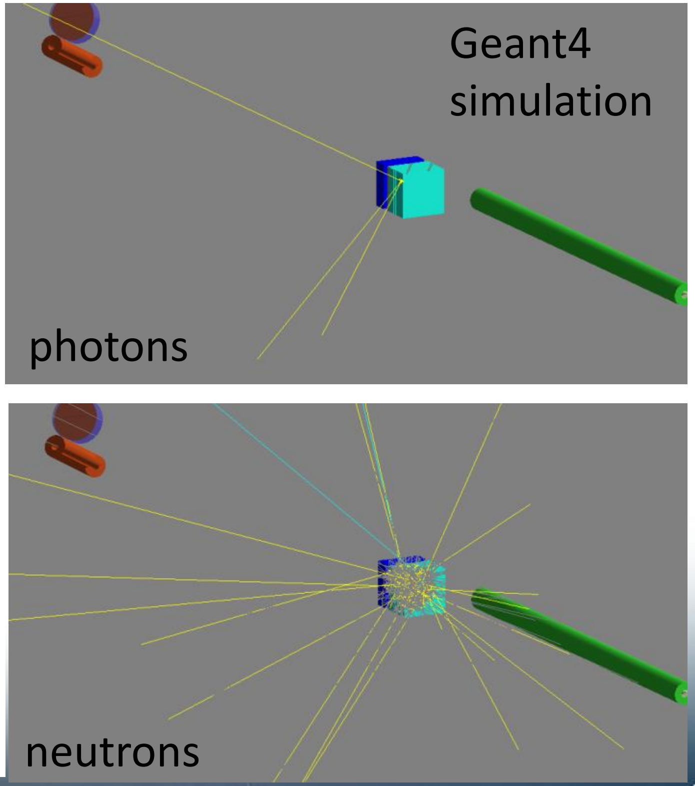
(Limited by bore of magnet where the neutron cone has to exit)





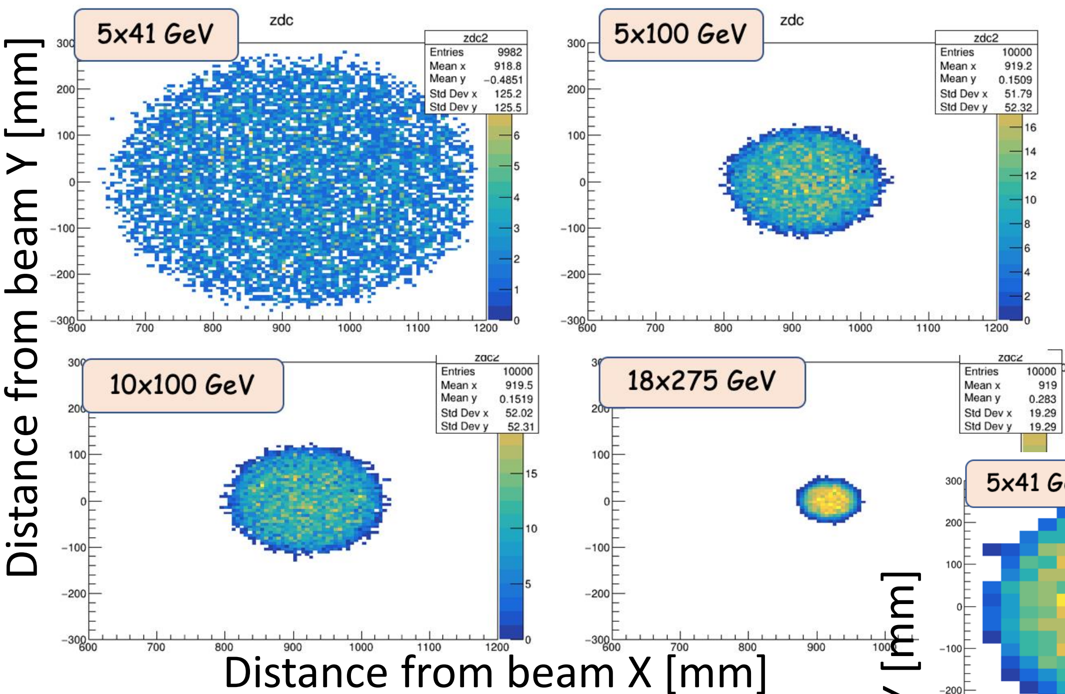


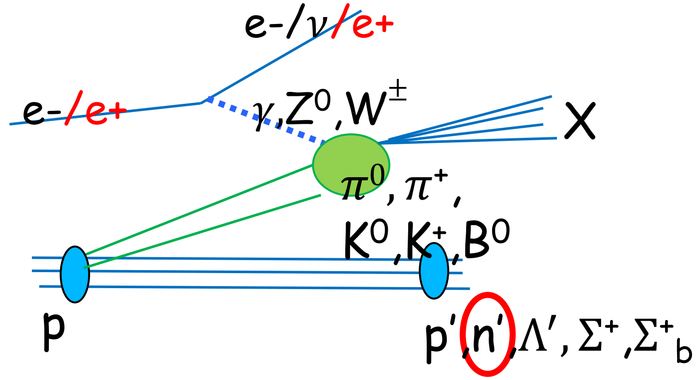




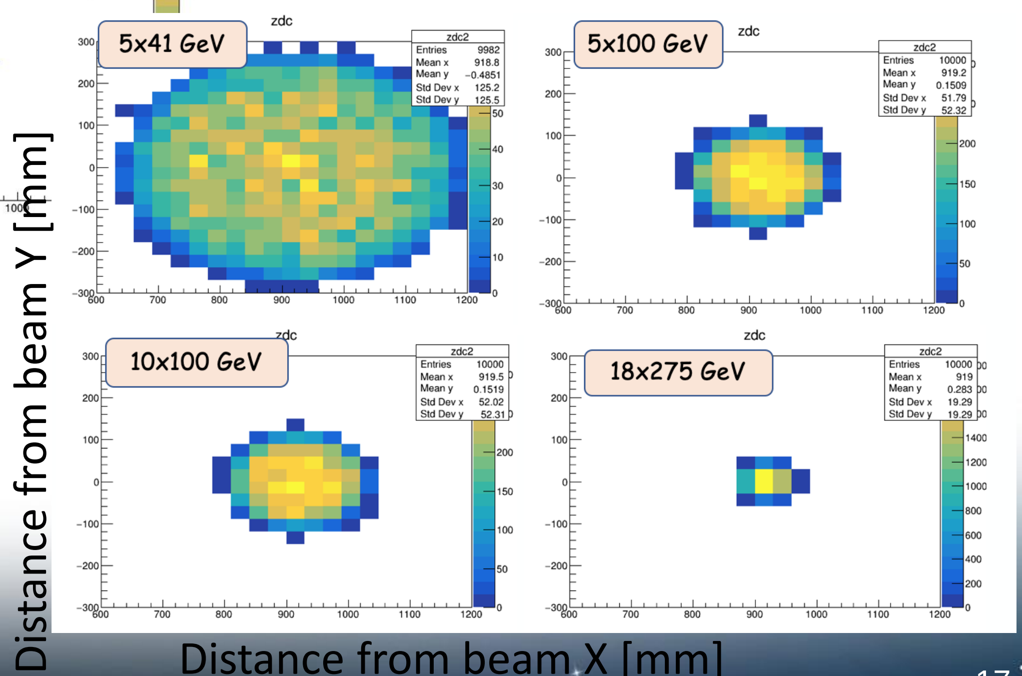
ZDC resolution

e p -> (π) -> e' + n + X



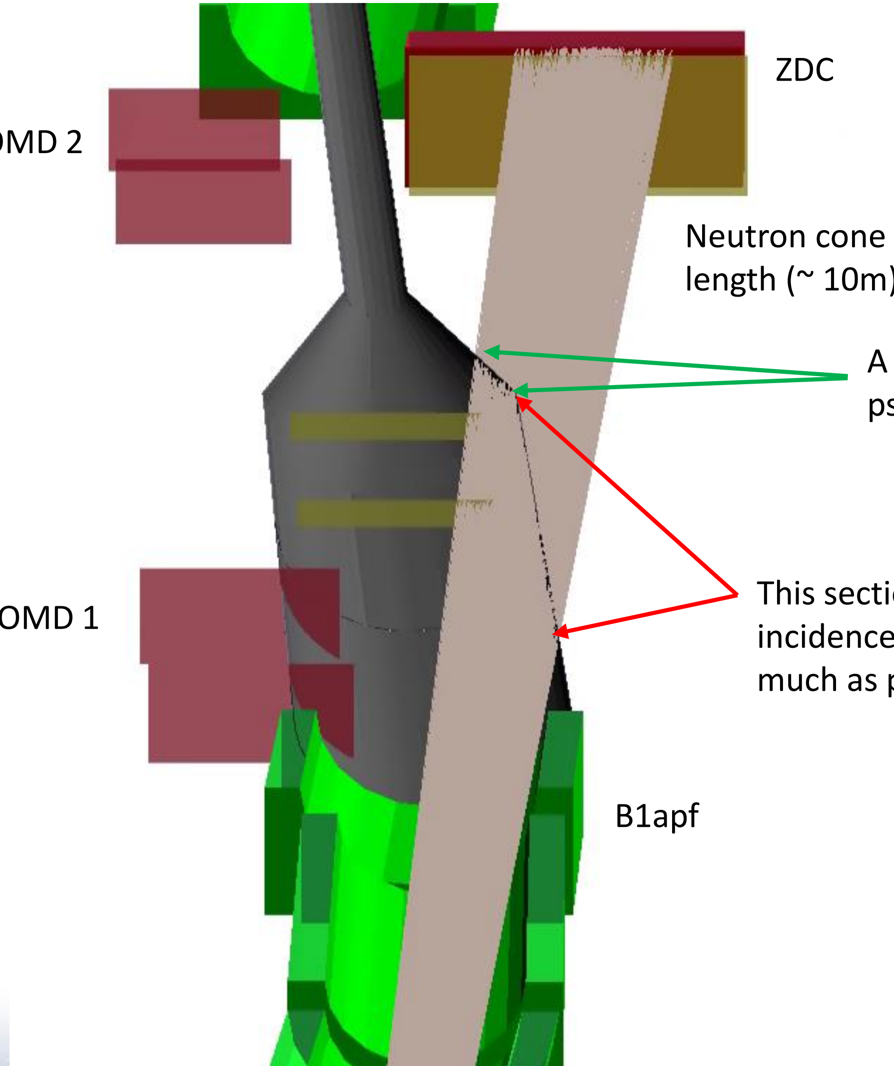


Size of 60x60 cm should be sufficient, high granularity is very important for high-energy operations

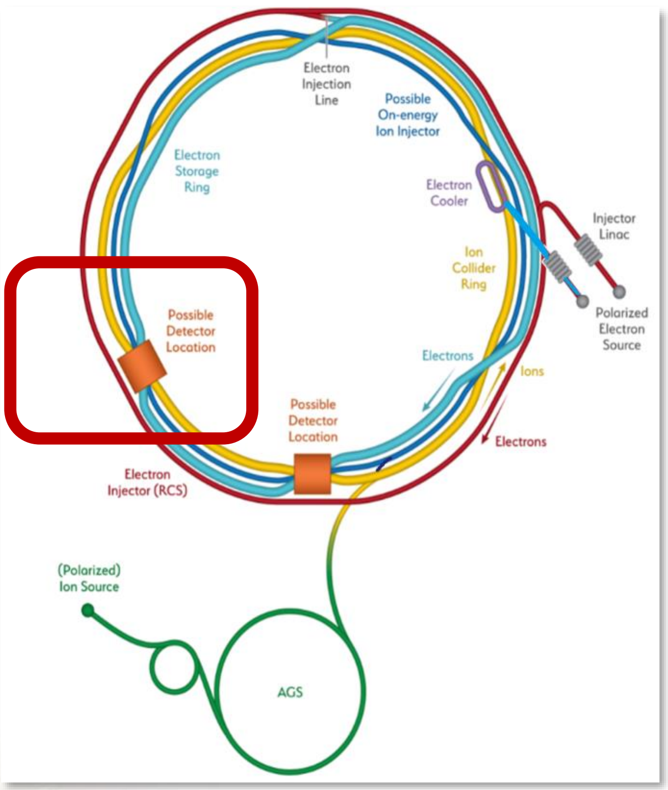


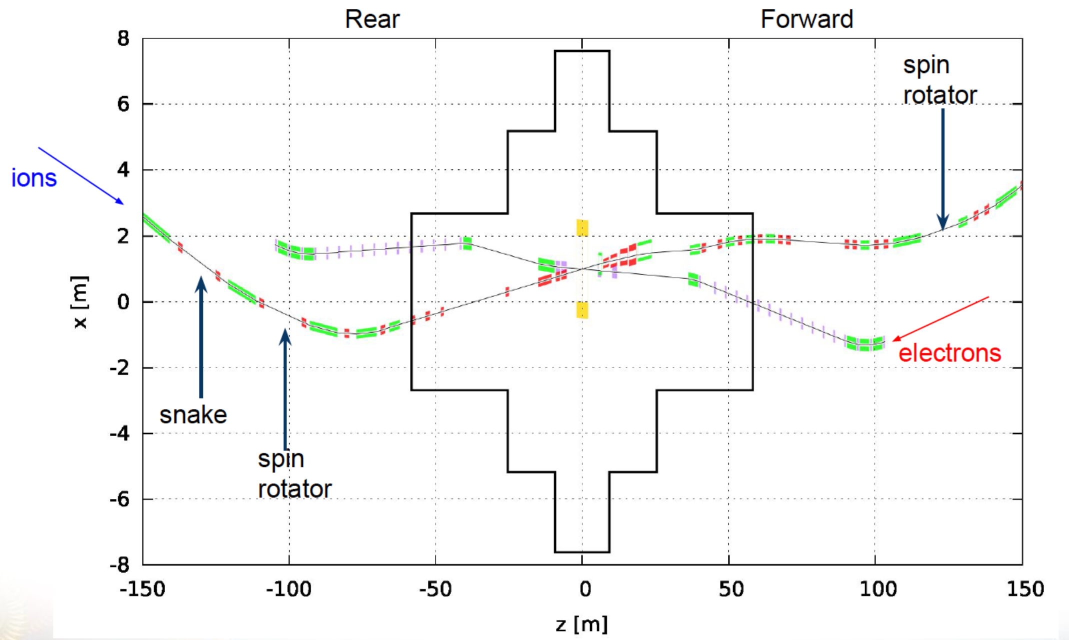
Neutron samples from Meson structure group (for different energies and ZDC granularity/spacial resolution 0.6 cm vs 3cm):

Neutrons


ZDC
OMD 2
OMD 1
B1apf
p = 135.0 GeV/c
0.0 < theta < 3.8 mrad
Neutron cone impinges pipe over long length (~ 10m) in z.
A short taper could serve as a pseudo exit-window.
This section is not ideal – shallow incidence angle – want to minimize as much as possible.

IP8





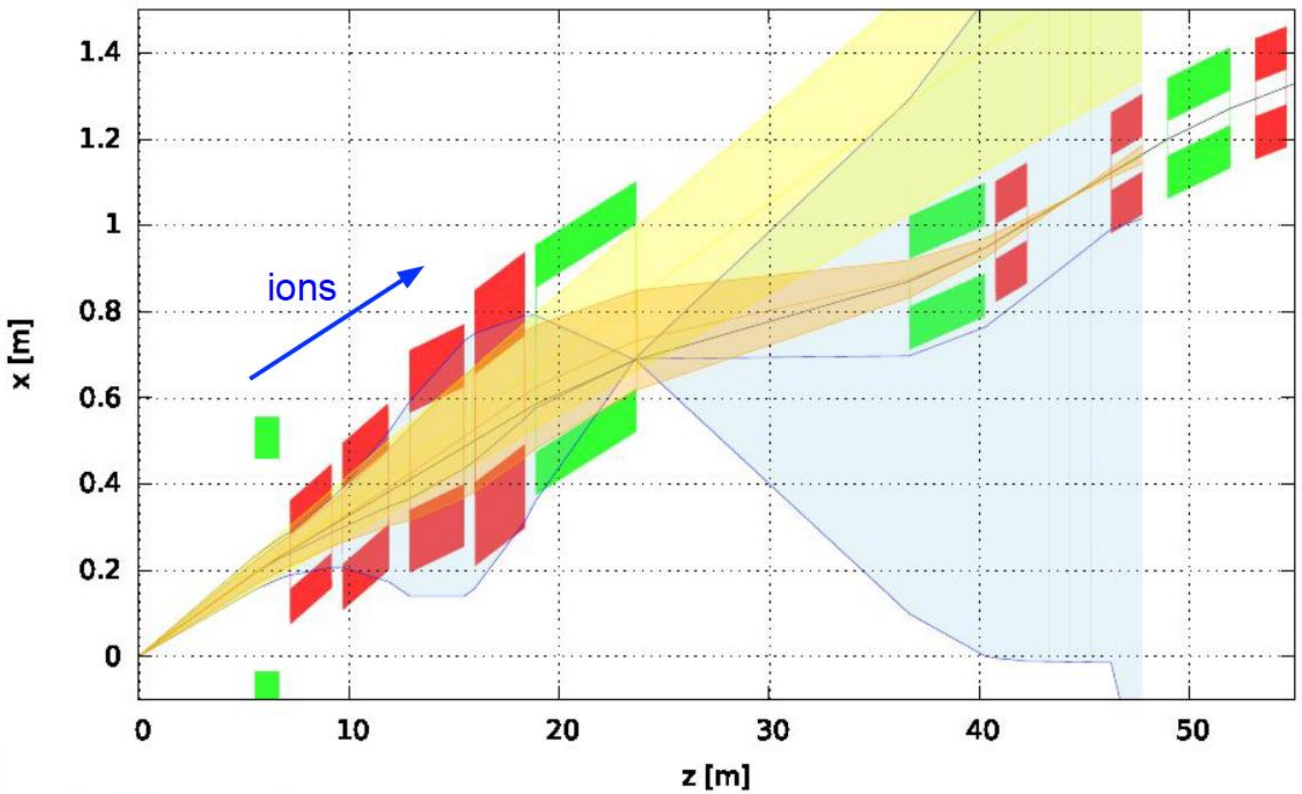
Coordinate system for detector at IP8 /accelerator needs to be adjusted to a similar as for IP6 (?)

IR8 forward layout after 15% bore reduction

Neutrons ±7mrad

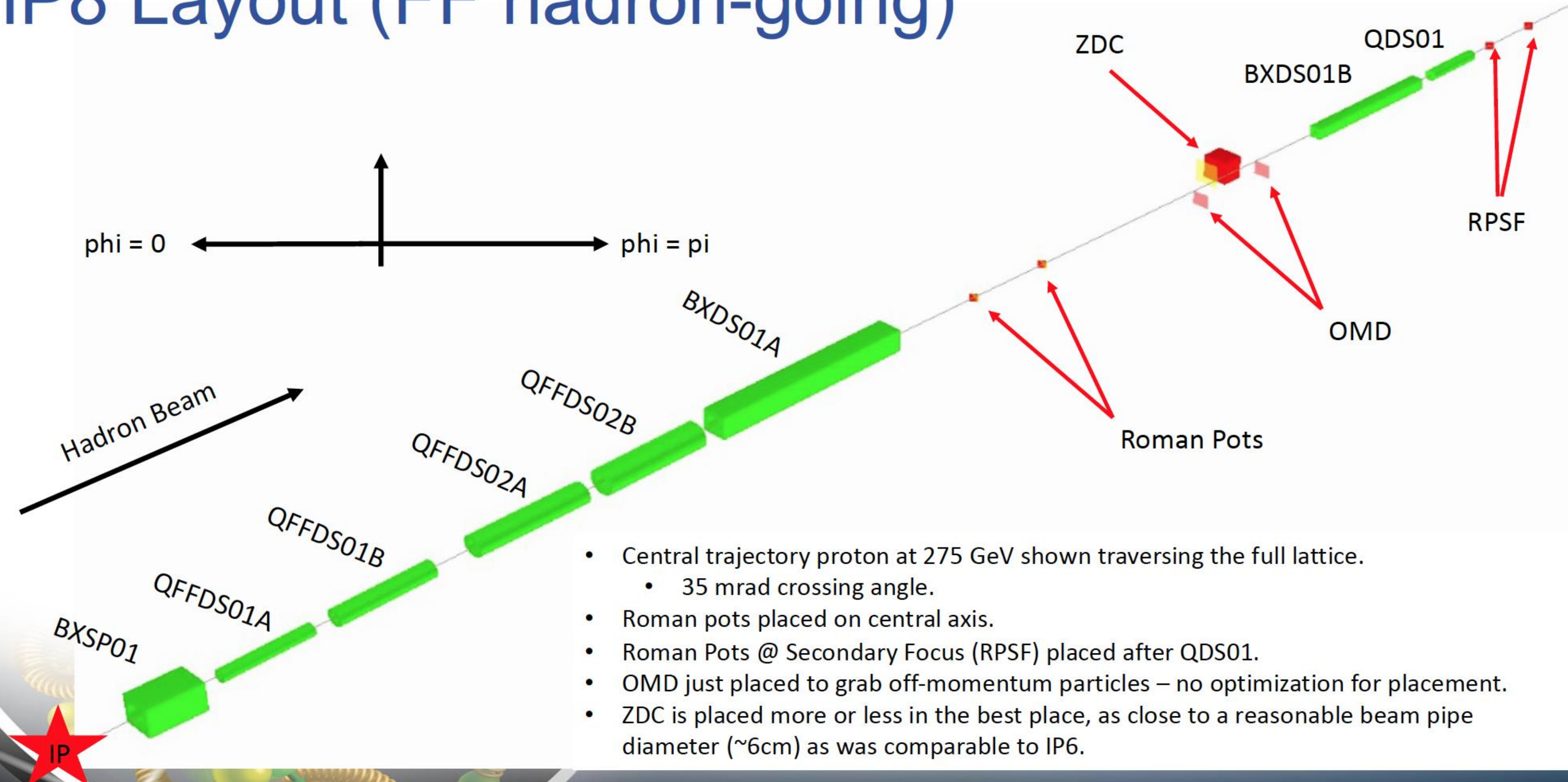
Protons ±5mrad
$\Delta p/p = 0$
p_T = 1.37 GeV, x_L=1

Protons ±7mrad
$\Delta p/p = -0.5$
p_T = 0.96 GeV, x_L=0.5



IP8

IP8 Layout (FF hadron-going)

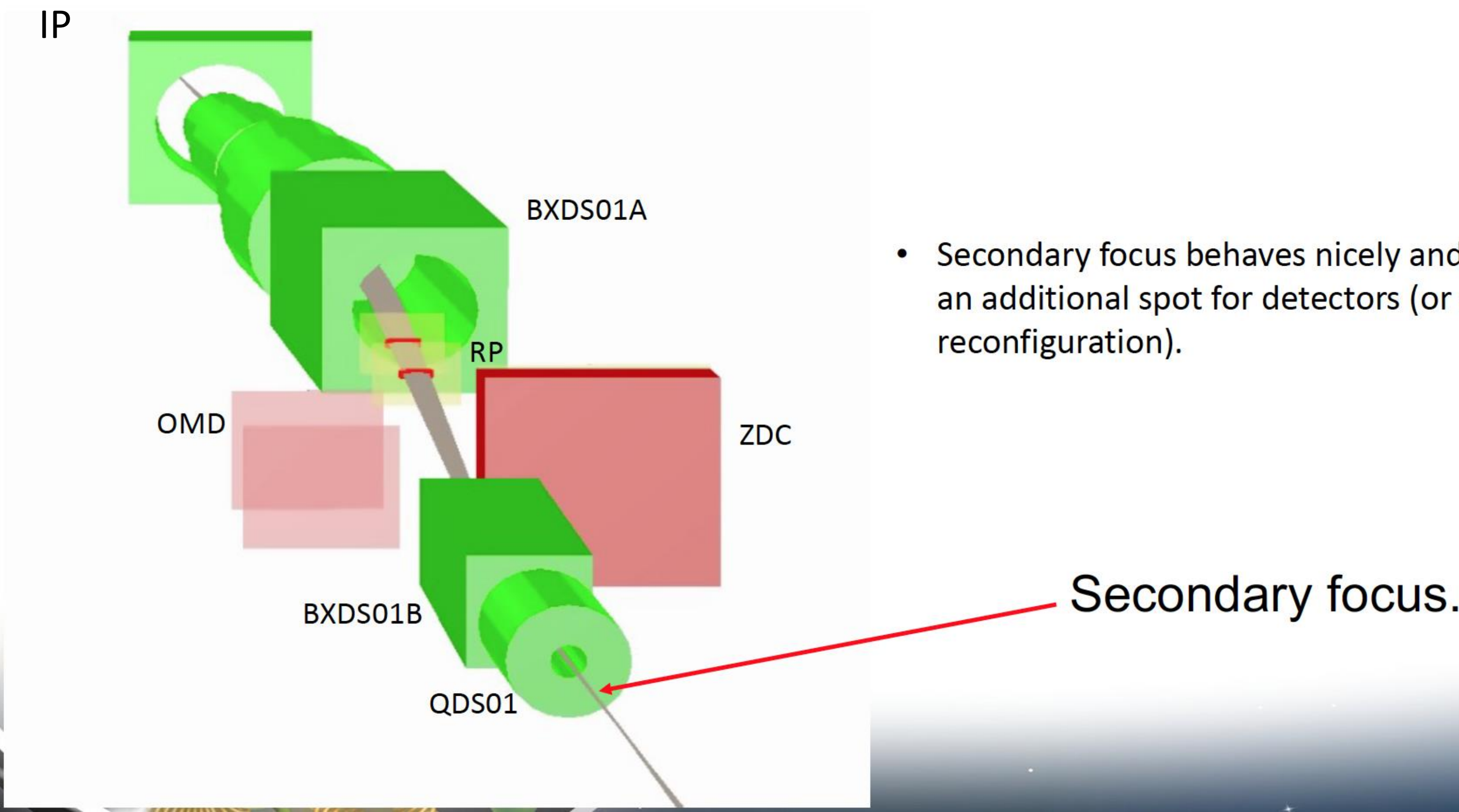


- Central trajectory proton at 275 GeV shown traversing the full lattice.
  - 35 mrad crossing angle.
- Roman pots placed on central axis.
- Roman Pots @ Secondary Focus (RPSF) placed after QDS01.
- OMD just placed to grab off-momentum particles – no optimization for placement.
- ZDC is placed more or less in the best place, as close to a reasonable beam pipe diameter (~6cm) as was comparable to IP6.

IP8

Secondary Focus

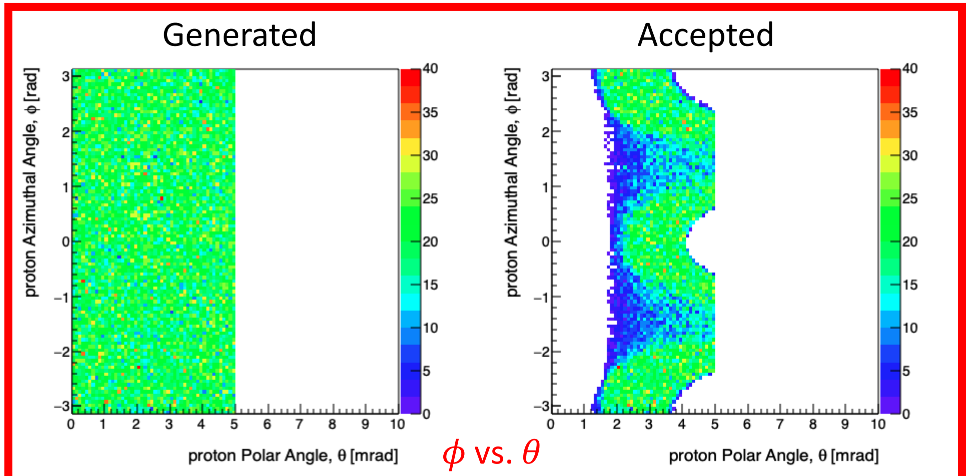
- p = 275 GeV protons
- 0 < theta < 2 mrad

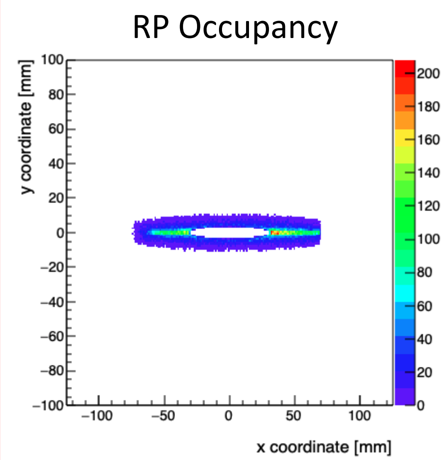


- Secondary focus behaves nicely and allows for an additional spot for detectors (or a complete reconfiguration).

Drift Roman Pots (z = 26m)

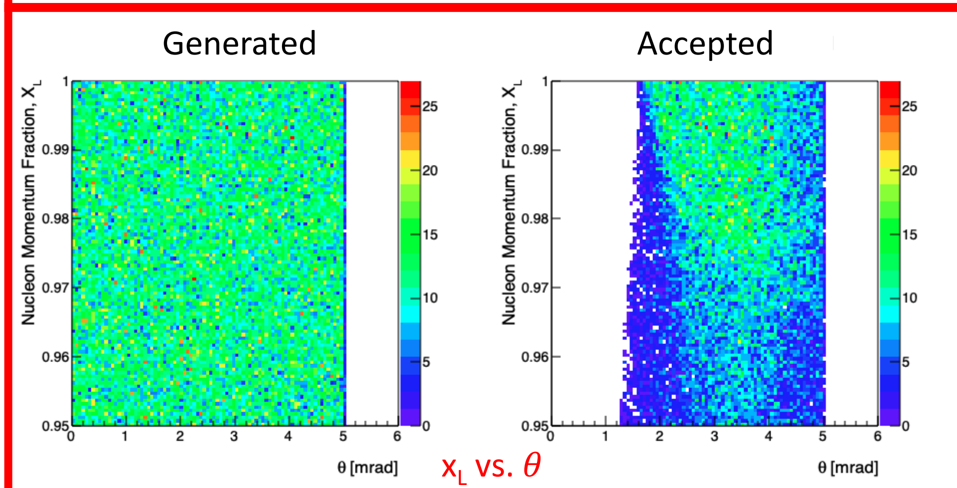
protons (275 GeV settings)
$0 < \theta < 5$ mrad
$0.95 < x_L < 1.0$

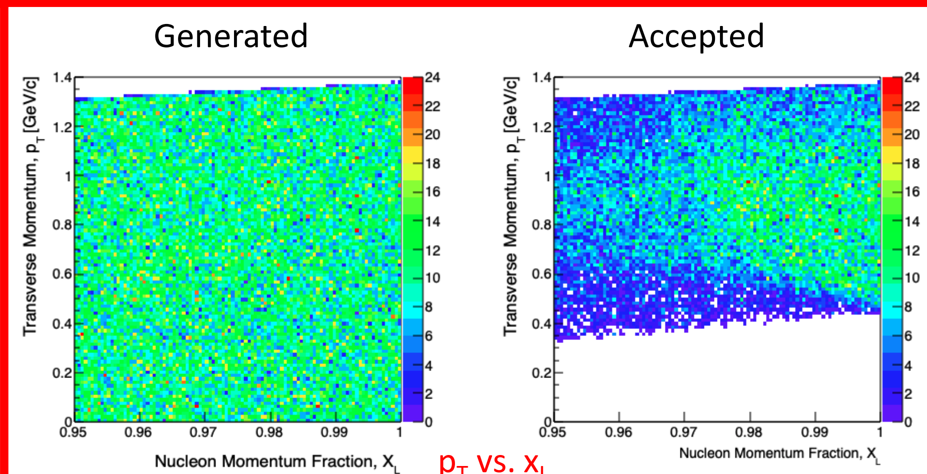




$\beta_x\ (z = 25.7m)$ = 548 m
β_y (z = 25.7m) = 87 m
$D_x = 0.126$

σ_x @ RP = 3.10607 mm
σ_y @ RP = 0.372664 mm





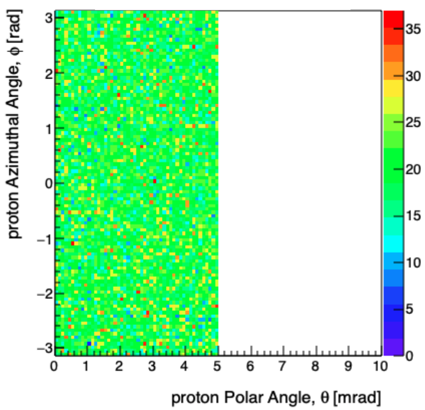
Drift Roman Pots (z = 30m)

protons (275 GeV settings)
$0 < \theta < 5$ mrad
$0.95 < x_L < 1.0$

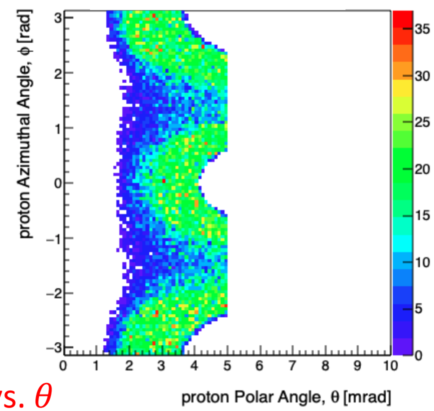
$\beta_x\ (z = 29.7m)$ = 338 m
β_y (z = 29.7m) = 55 m
$D_x = 0.204$

σ_x @ RP = 2.44373 mm
σ_y @ RP = 0.297106 mm

Generated

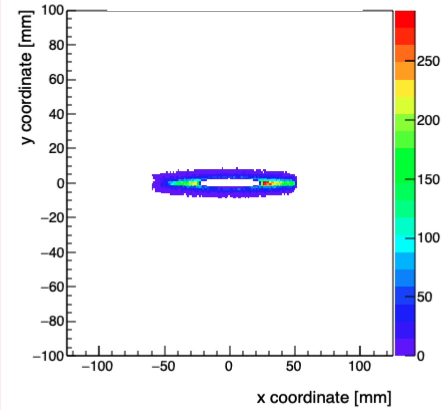


Accepted



ϕ vs. θ

RP Occupancy



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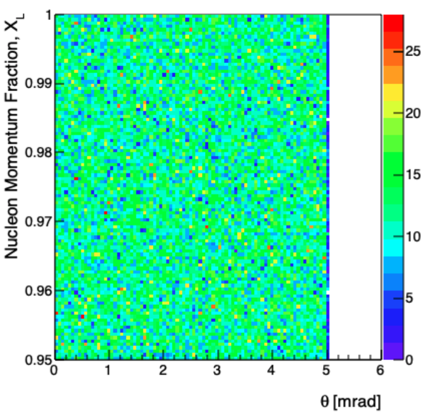
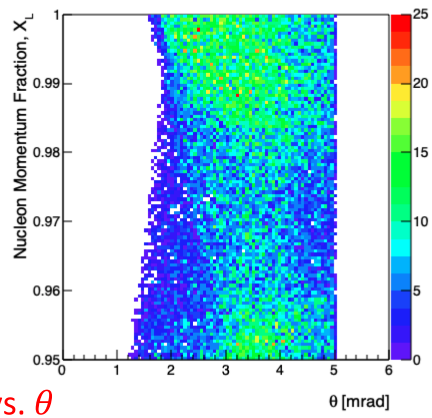
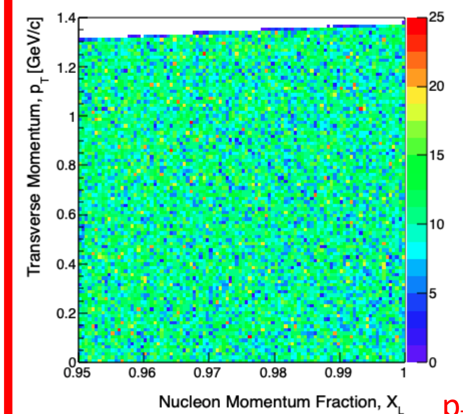


Accepted

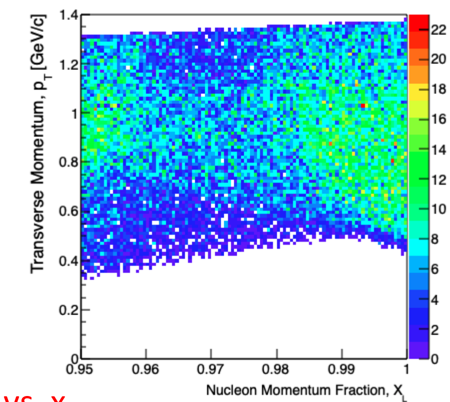


x_L vs. θ

Generated



Accepted



p_T vs. x_L

Roman Pots @ SF

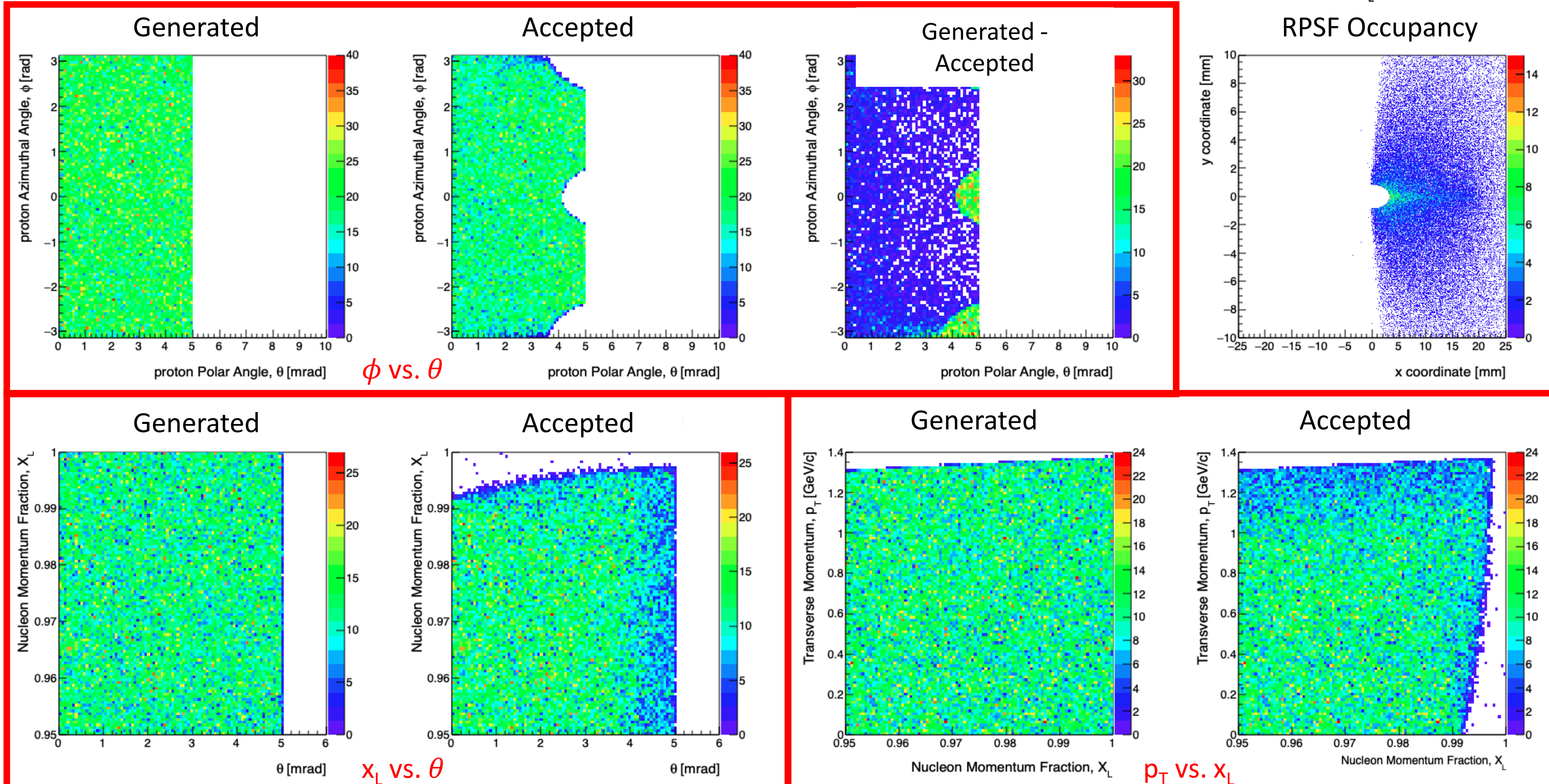
σ_x @ RPSF = 0.328283 mm.

σ_y @ RPSF = 0.085217 mm.

protons (275 GeV settings)

$0 < \theta < 5$ mrad

$0.95 < x_L < 1.0$

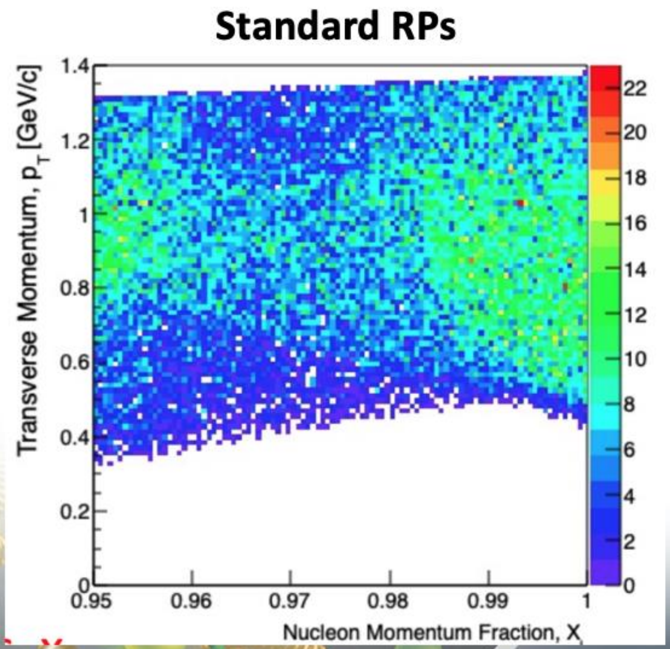


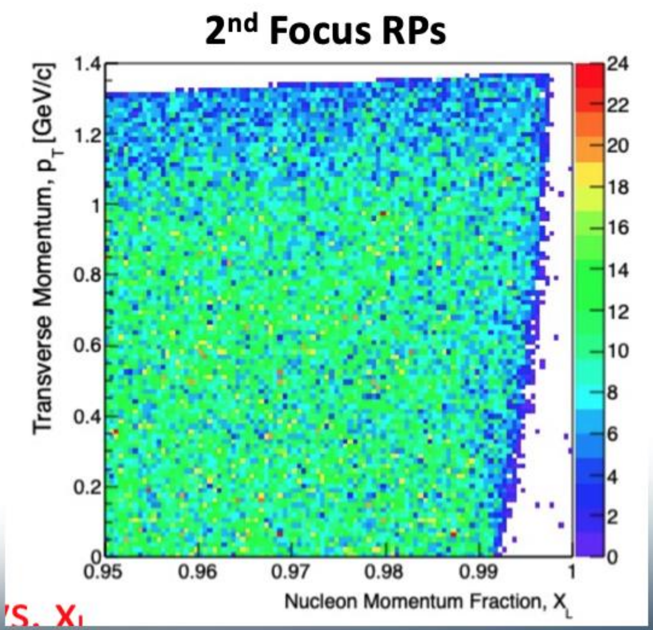
All material to simulate physics at 18 GeV x 275 GeV has been posted at
https://indico.bnl.gov/event/10974/contributions/51160/

- Detailed Read-Me how to use all the provided information

x_L acceptance at IP-8:

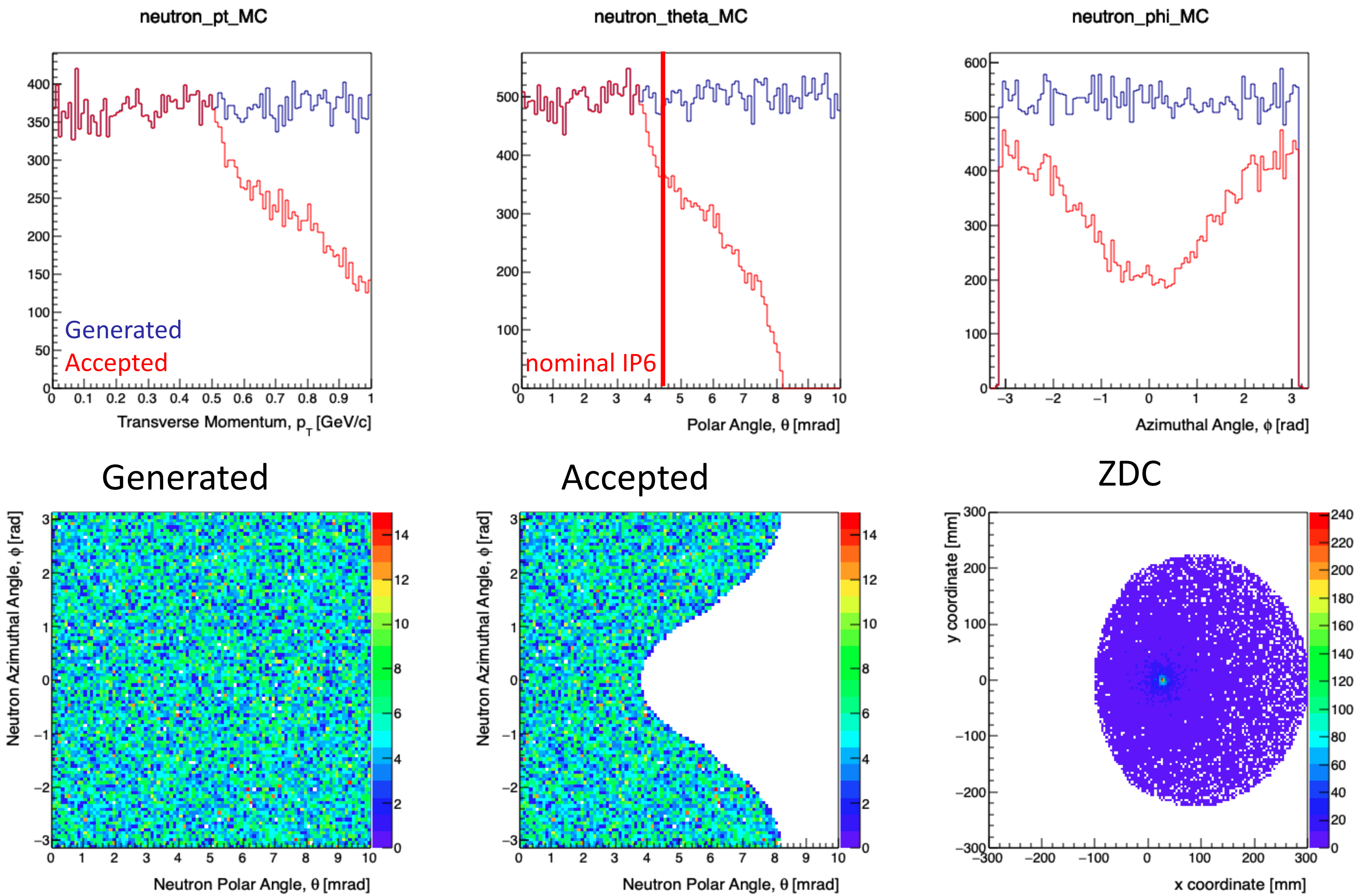
the most recent optics info was used





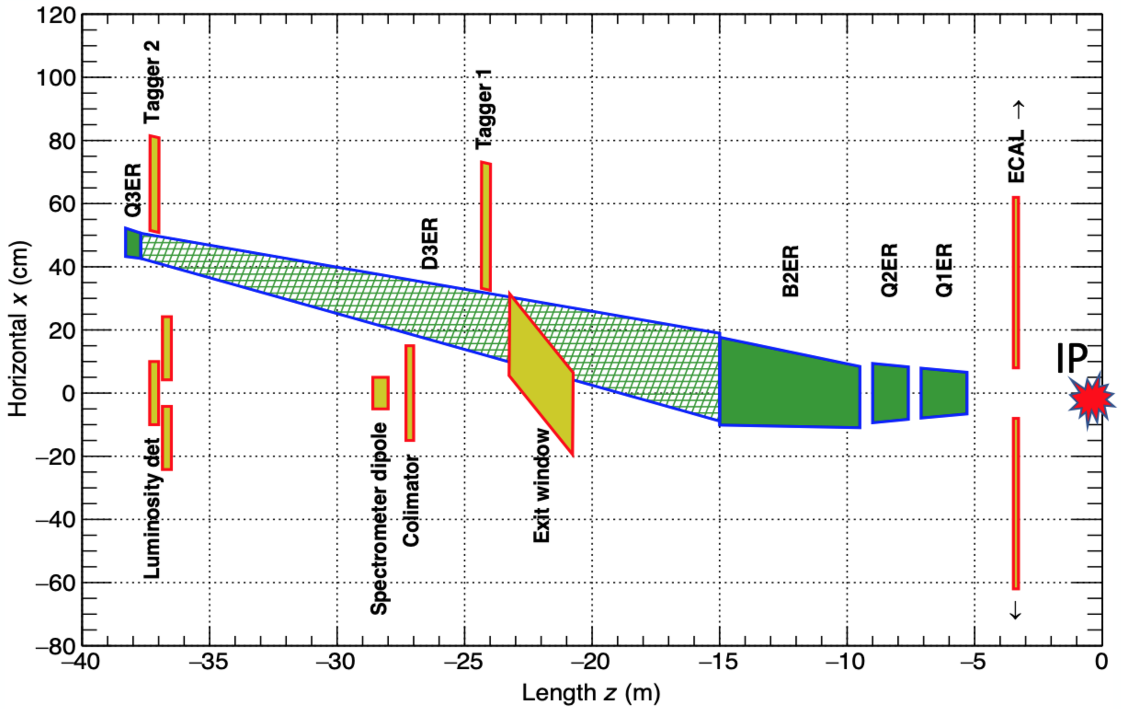
Neutrons

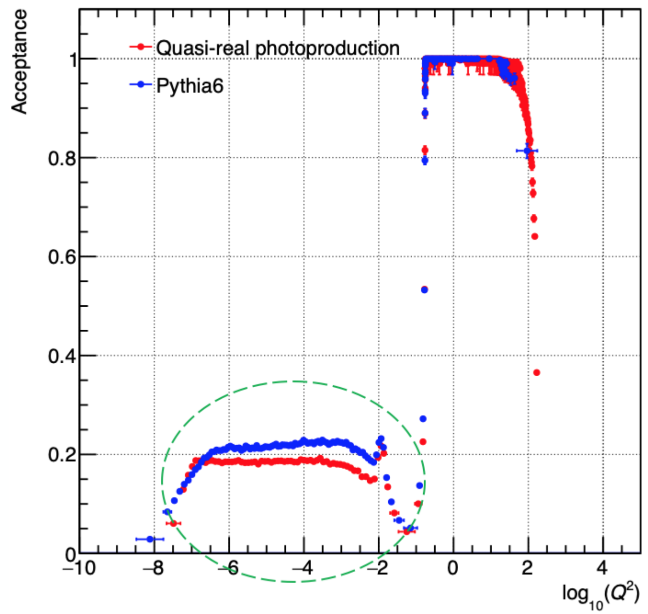
- p = 135 GeV protons
- 0 < theta < 10 mrad



Far-backward (electron-going) region

Far-backward (electron-going) region





❑ Q^2 acceptance up to ~10^{-6}

- ➢ This area is designed to provide coverage for the low-Q^2 events (photoproduction)
- ➢ And luminosity detector (ep -> e'pγ bremsstrahlung photons)

Low-Q2 coverage

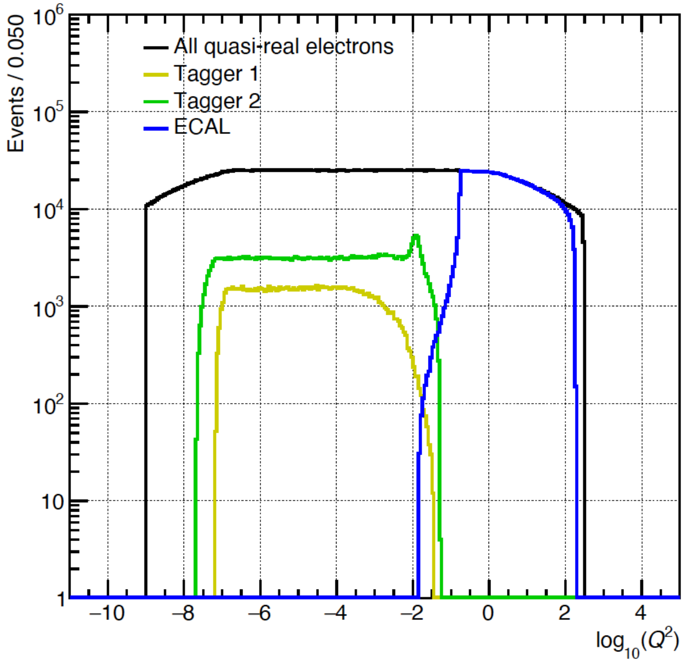
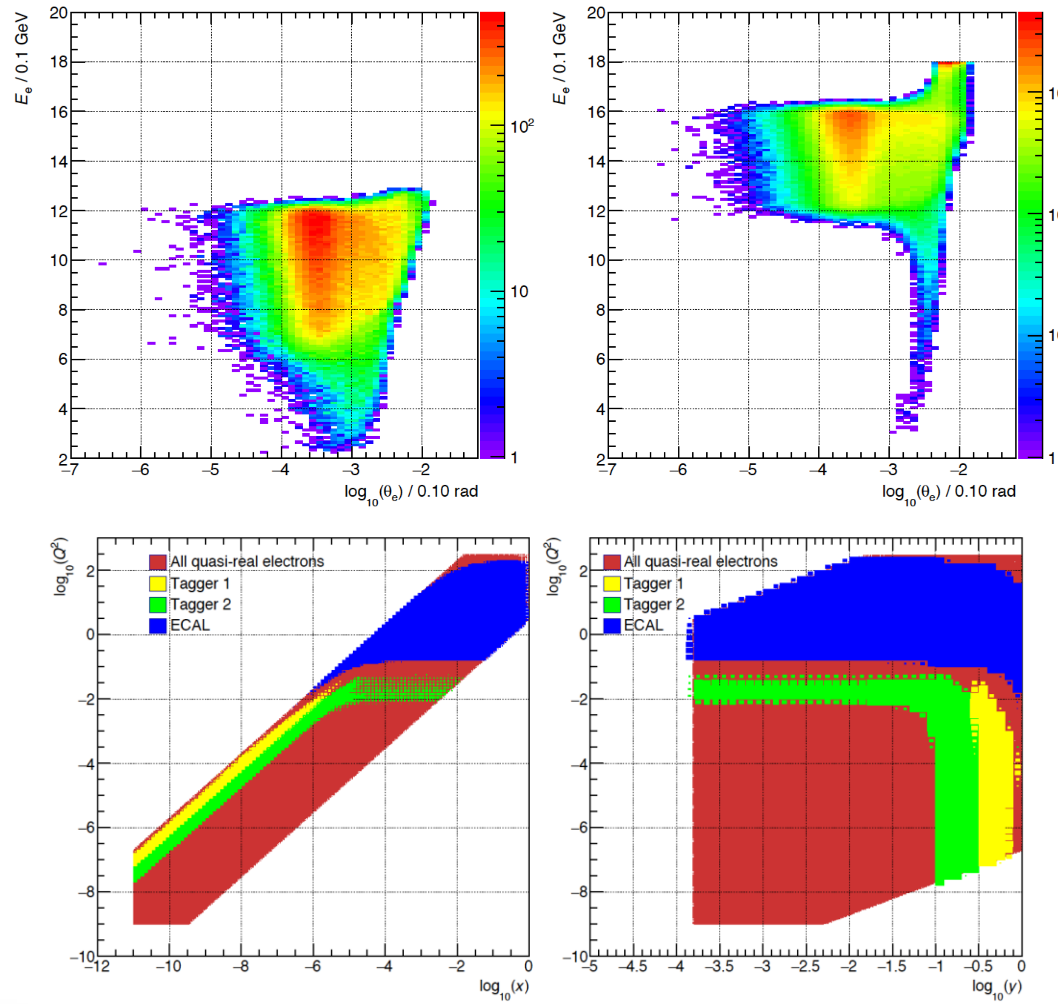


FIG. 16: Coverage in Q^2 for tagger detectors and ECAL.

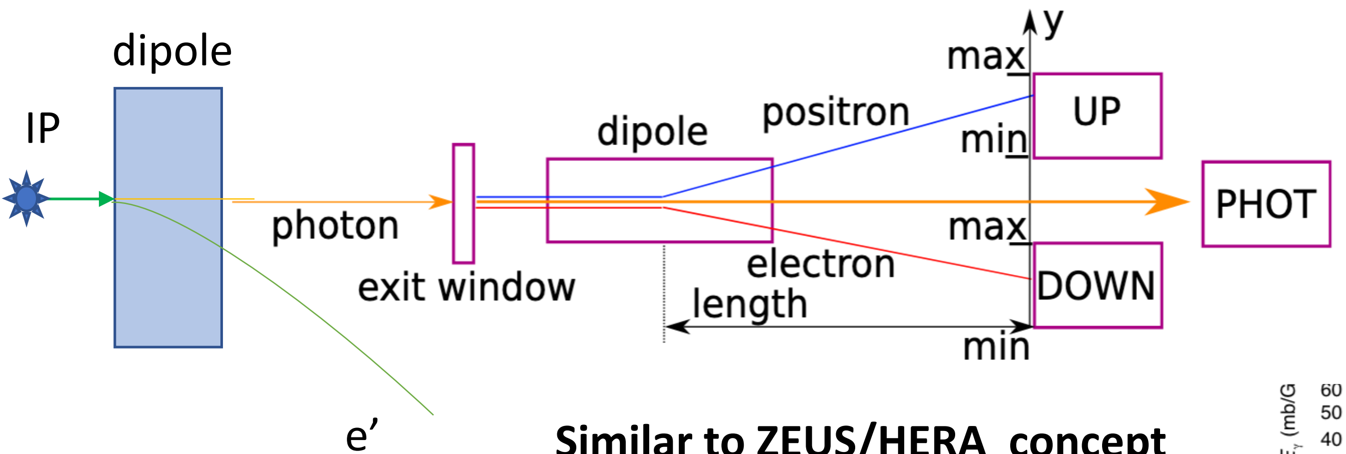


(a) Coverage in x and Q^2

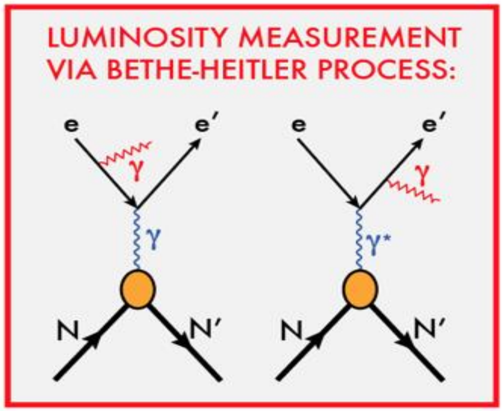
(b) Coverage in y and Q^2

FIG. 18: Coverage in x, y and Q^2 for tagger detectors and ECAL.

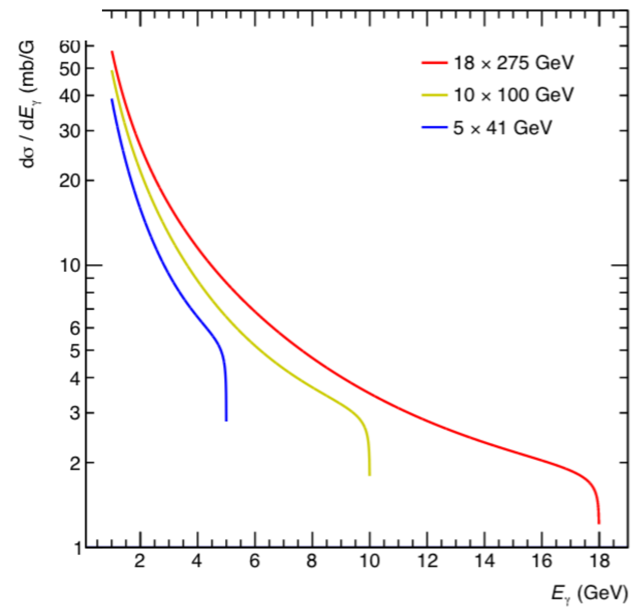
Luminosity monitor



Similar to ZEUS/HERA concept



- Luminosity measurements via Bethe-Heitler process
- Photons from IP collinear to e-beam
- First dipole bends electrons
- Photon conversion to e-/e+ pair
- Pair-spectrometer
- Synchrotron photons collimation scheme needs to be further refined



(a) Bremsstrahlung cross section as a function of photon energy.

Summary

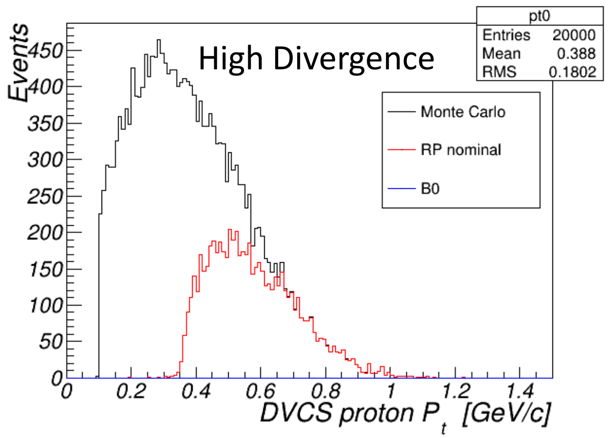
- IP6 and IP8 have many acceptance overlaps, and places where they enhance each other. The two IPs together will provide an incredibly strong, complementary physics program for the EIC!

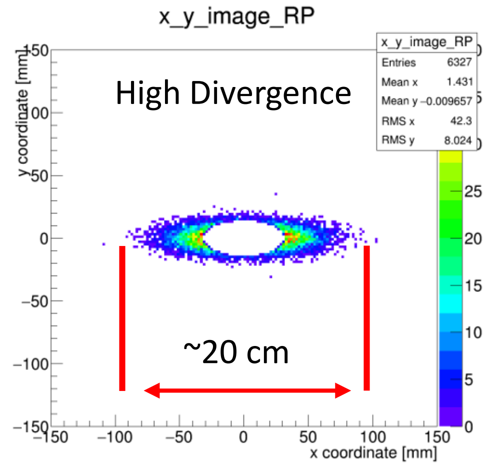
- First IP8 layout provides good acceptance to both protons and neutrons.
  - Almost the same coverage for RP protons as IP6 (theta ~ 4 mrad full coverage).
  - About the same azimuthally symmetric coverage for neutrons (~4 mrad), but more
    acceptance for neutrons at phi = 0.
- Secondary focus is observable in GEANT.
  - preliminary checks has been performed
  - some optics information still needed (beta functions, emittance, etc.) to do a more careful look.
- Off-momentum protons have a different overall behavior than in IP6 - will impact detector placement/usage. In general, may want to re-think the basic layout of detectors w.r.t. Roman Pots. vs. Roman Pots @ secondary focus, and the OMD.
- Space for B0 detector equivalent needs to be understood.

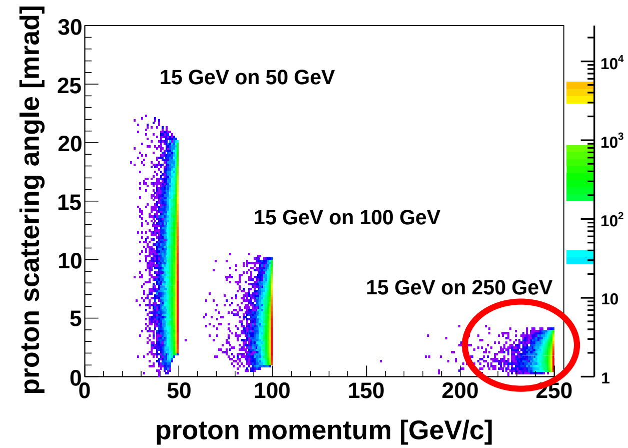
20

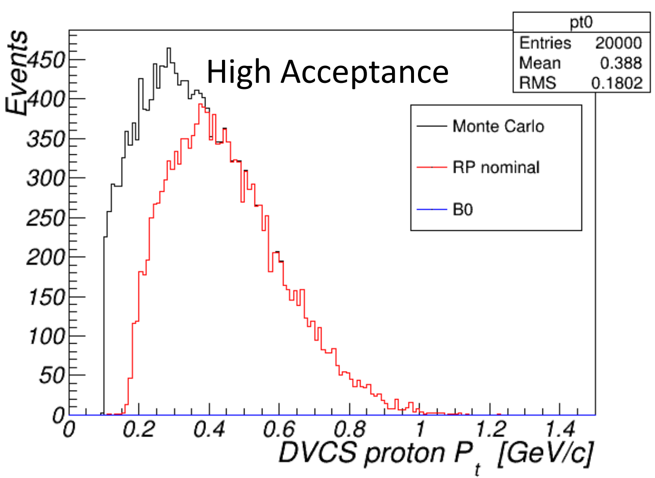
Backup

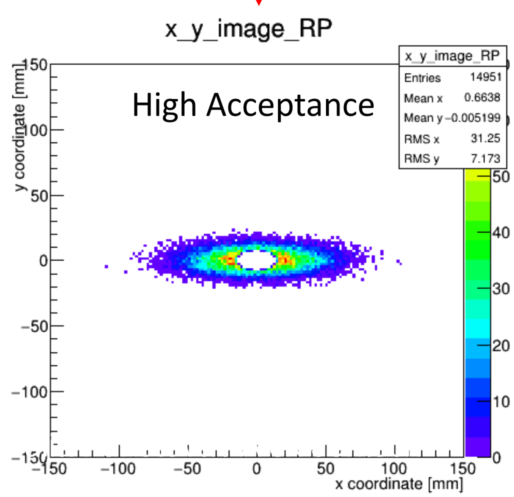
275 GeV DVCS Proton Acceptance







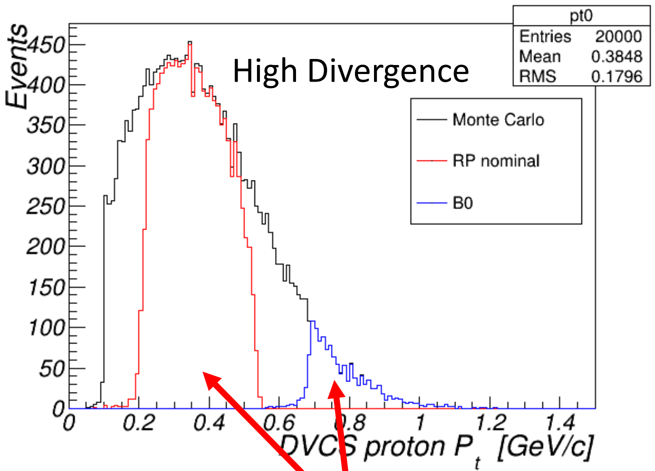


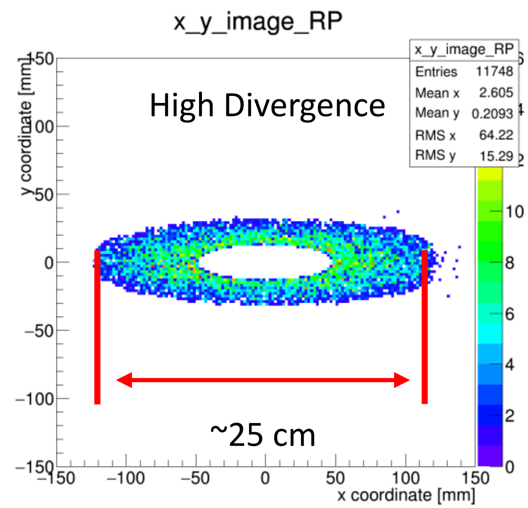


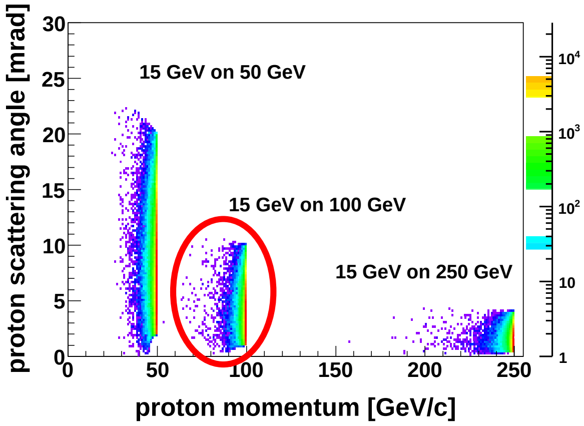
High Divergence: smaller β^* at IP, but bigger $\beta(z = 30m)$ -> higher lumi., larger beam at RP

High Acceptance: larger β^* at IP, smaller $\beta(z = 30m)$ -> lower lumi., smaller beam at RP

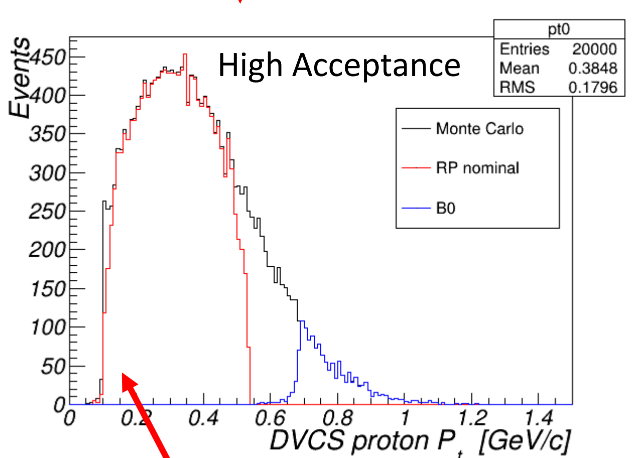
100 GeV DVCS protons

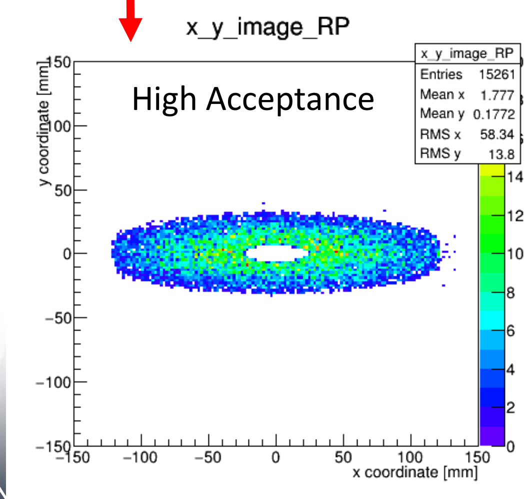






Need both detector systems together here!

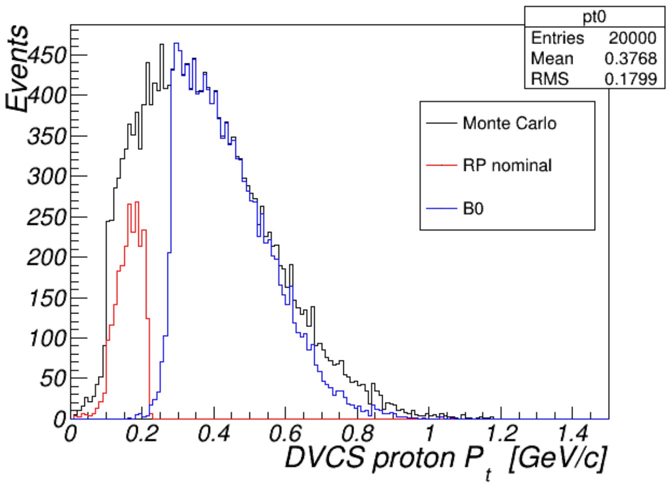


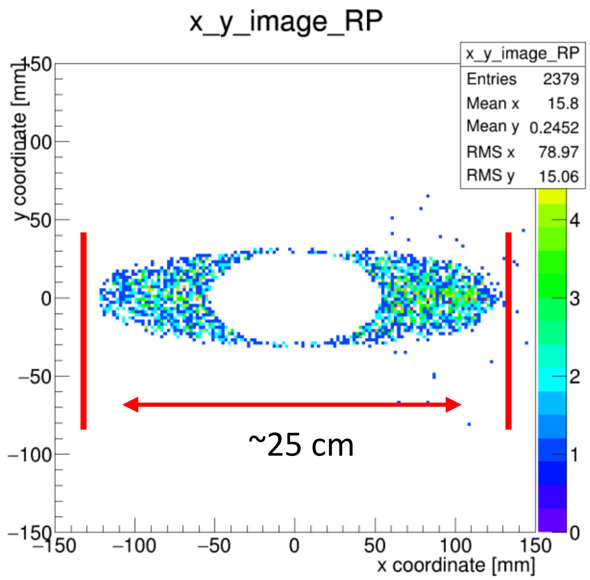


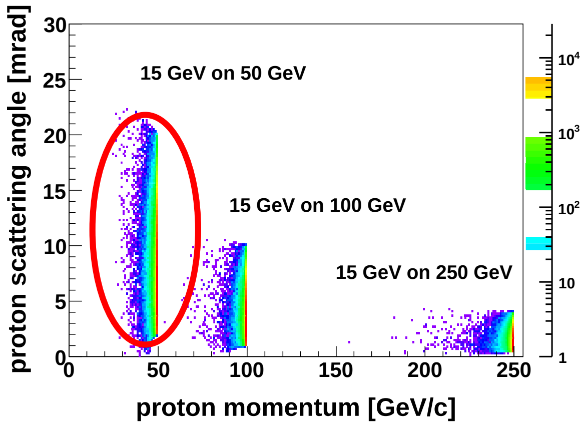
Improves low p_t acceptance.

35

41 GeV DVCS protons







- Only one beam configuration for now.
- Acceptance gap still observed.
- Lower acceptance at high p_t.
- B0 plays largest role at this beam energy.