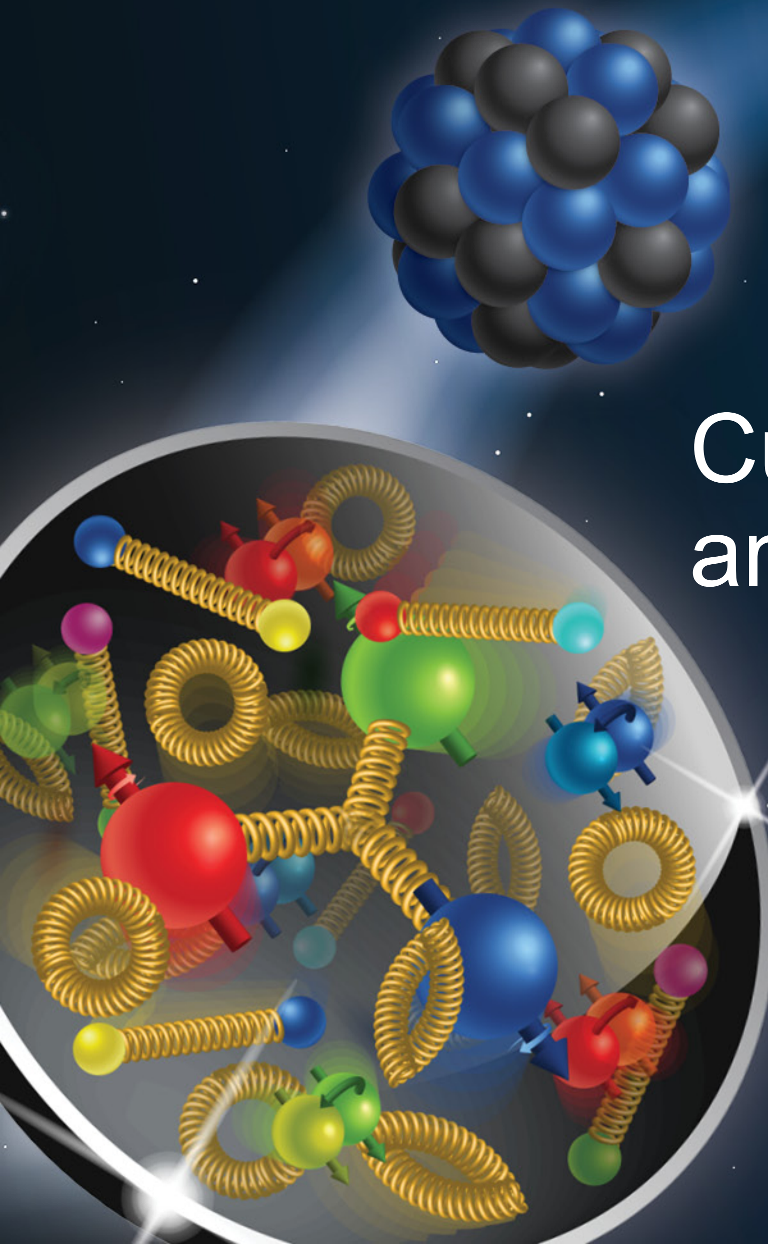


Current Far-Forward Design and Potential Alternatives

Alex Jentsch (BNL), Julia Furletova (JLAB),
and Michael Murray (KU)

4th EIC Yellow Report Meeting
@ Berkeley (remote)

Electron-Ion Collider

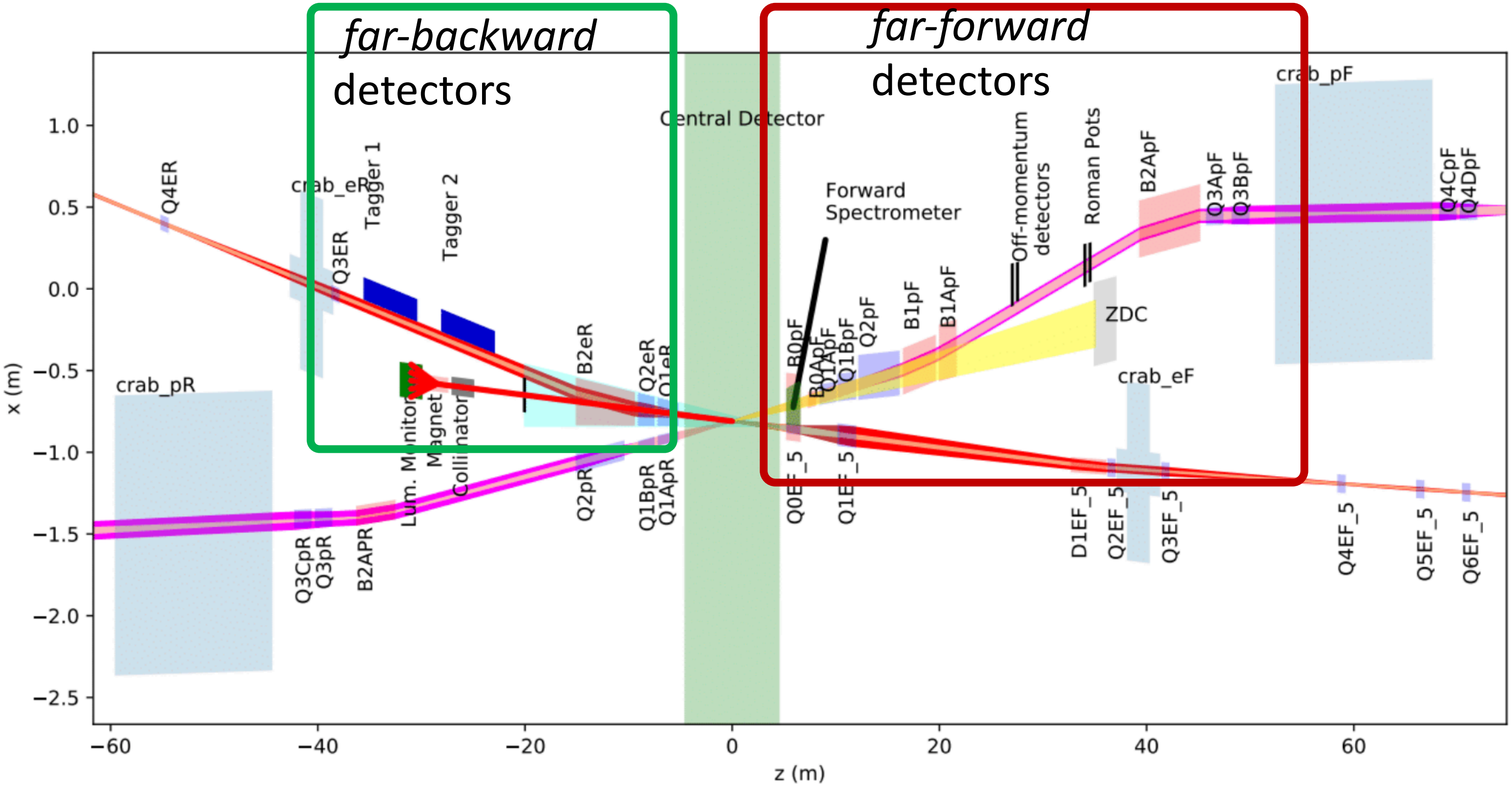
BROOKHAVEN NATIONAL LABORATORY · Jefferson Lab · U.S. DEPARTMENT OF ENERGY | Office of Science

What are the goals of the FF region?

- Tag protons and light nuclei from exclusive reactions.
- Tag protons/neutrons from nuclear breakup events.
- Capture hadrons from lambda decay for meson structure studies.
- Measure low-energy photons from heavy nuclear reactions.
- Far-backward (electron-going) for tagging low-Q2 electrons.

➢ **Requires coverage in an area with lots of physical constraints!**

EIC Interaction Region layout

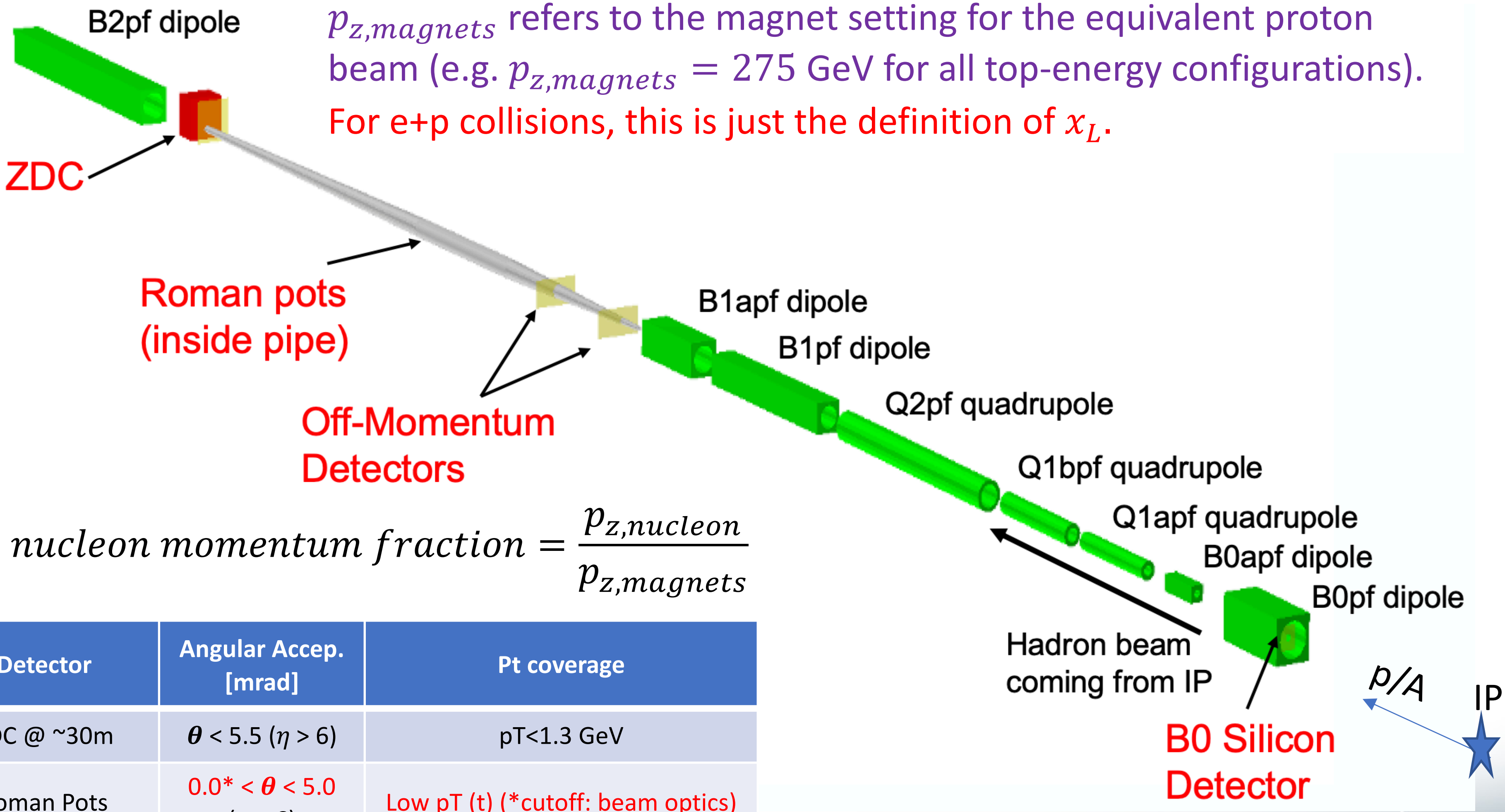


- ~9 m around the IP is reserved for the *central* detector
- But the *far forward* and *far backward* detector components are distributed along the beam line within ±35 m
- Design should be able to operate with different beam energy and high luminosity
- Very important to keep full detector integration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

Far forward (hadron going) region

$p_{z,magnets}$ refers to the magnet setting for the equivalent proton beam (e.g. $p_{z,magnets} = 275$ GeV for all top-energy configurations).

For e+p collisions, this is just the definition of x_L.



$$nucleon\ momentum\ fraction = \frac{p_{z,nucleon}}{p_{z,magnets}}$$

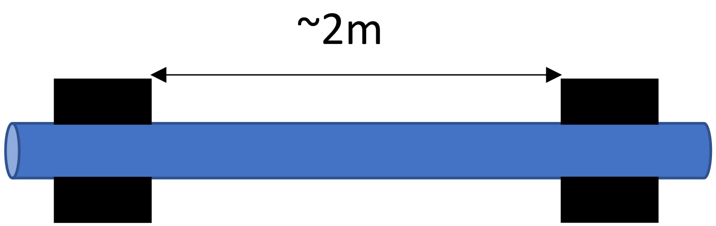
Detector	Angular Accep. [mrad]	Pt coverage
ZDC @ ~30m	$\boldsymbol{\theta} < 5.5$ ($\eta > 6$)	pT<1.3 GeV
Roman Pots	$0.0^* < \boldsymbol{\theta} < 5.0$ ($\eta > 6$)	Low pT (t) (*cutoff: beam optics)
Off-Momentum Detectors	$0.0 < \boldsymbol{\theta} < 5.0$ ($\eta > 6$)	Low-rigidity particles from nuclear breakup
Forward spectrometer	$5.5 < \boldsymbol{\theta} < 20.0$ ($4.6 < \eta < 5.9$)	High pT (t)

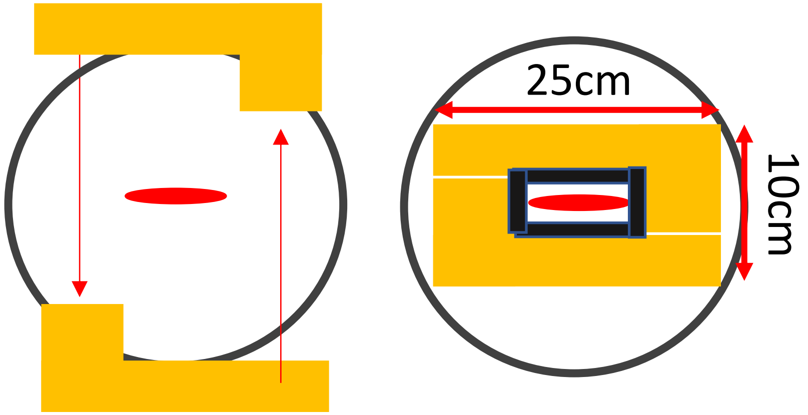
How can we classify “alternatives”?

- **Detector Technology**
  - Are there multiple technologies that really provide a reasonable set of choices, or is one choice obviously best-suited?
- **Detector Layout and Placement**
  - Can sub-systems be laid out differently to better optimize acceptance/performance?
  - How does this affect other constraints?
- **Machine optics**
  - Can different configurations of beam optics, energy, etc. have a major impact on different physics channels?

In principle, the answer to each of these questions is yes*, but as the asterisk implies, there are many caveats to each of these possibilities.

Detector Technology: 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.**

Low Gain Avalanche Detectors (LGADs):

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

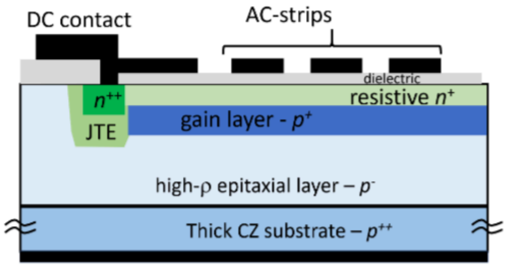
Fast-timing: ~30-50 ps per hit, dominated by Landau fluctuation

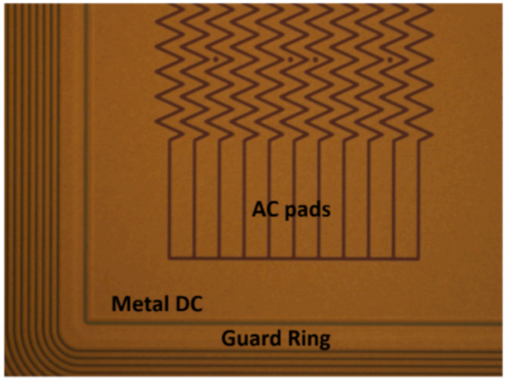
AC-coupling allows fine segmentation

100% fill factor

AC-LGAD 2mmx2mm strip sensor.

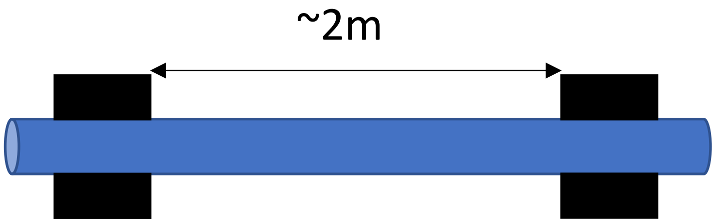
Strip pitch = 100um





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

Machine Optics: Roman Pots

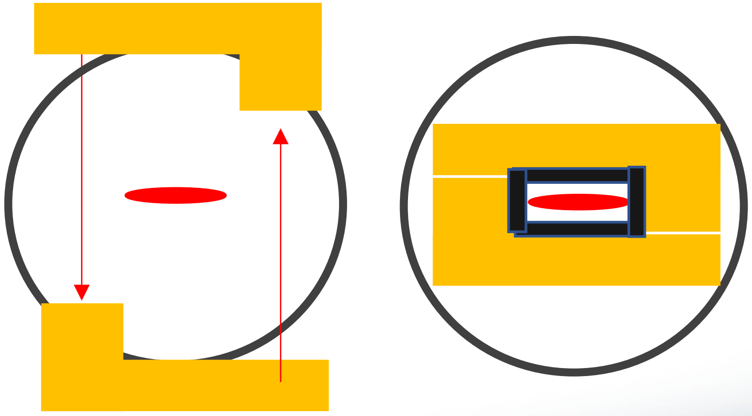


0.0* (10σ cut) < $\boldsymbol{\theta}$ < 5.0 mrad

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

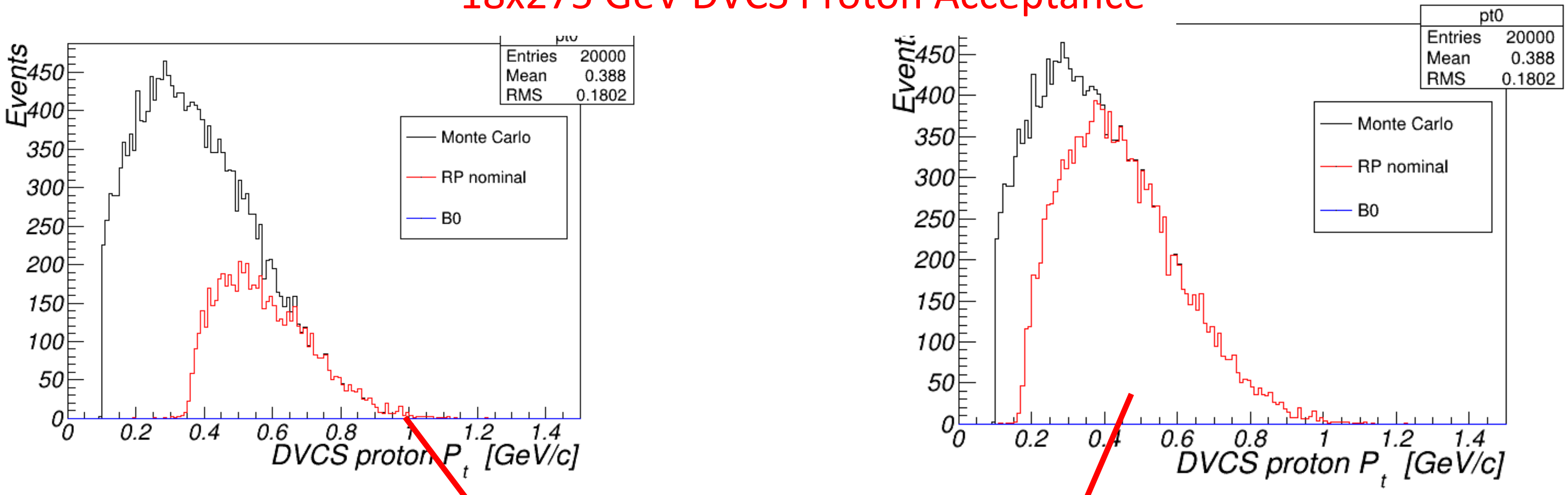
$$\boxed{\sigma(z) = \sqrt{\varepsilon \cdot \beta(z))}}$$

- **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.***



Machine Optics: Roman Pots

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**

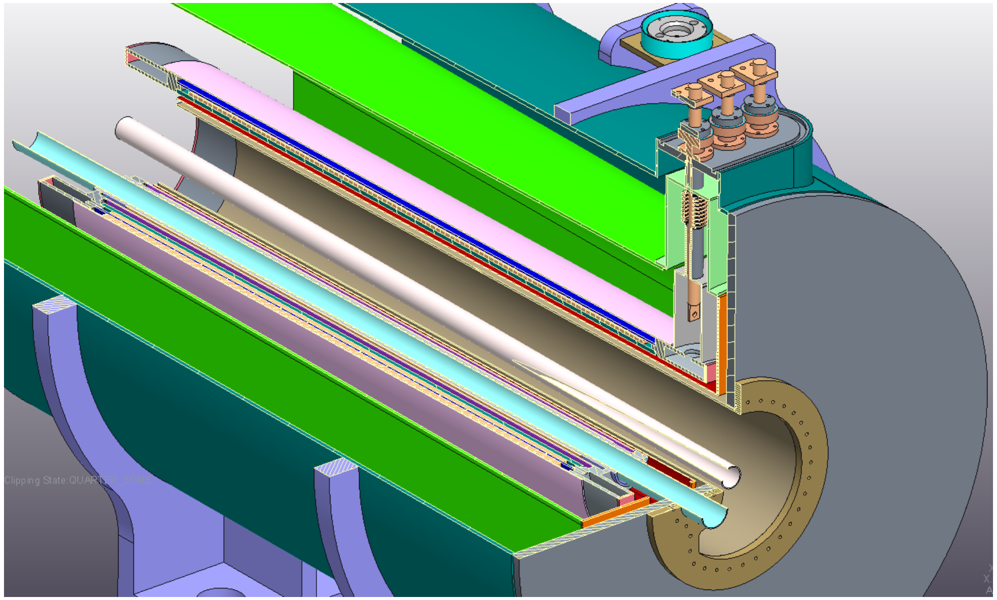
Option 2: lower lumi., **smaller beam at RP**

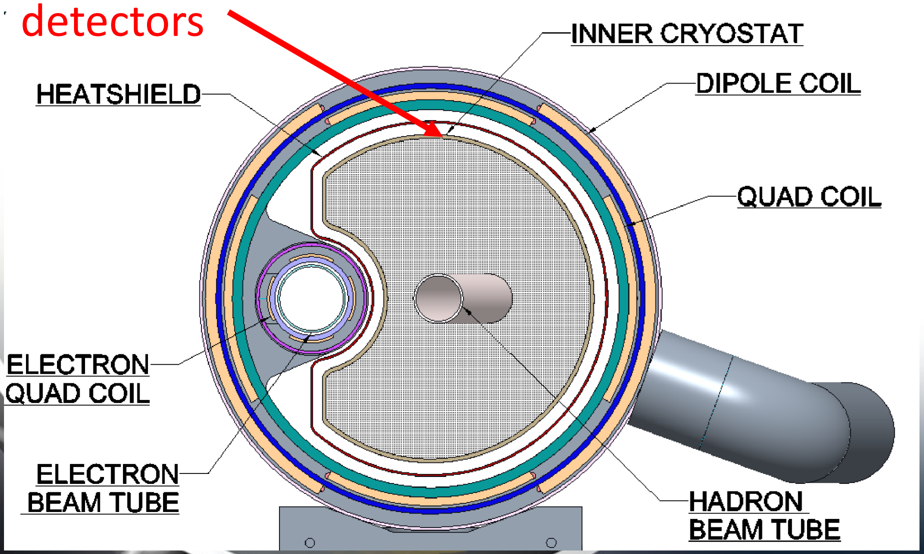
The luminosity trade-off is about a factor of 2 between the different configurations.

Layout: B0-detectors (silicon tracking)

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

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





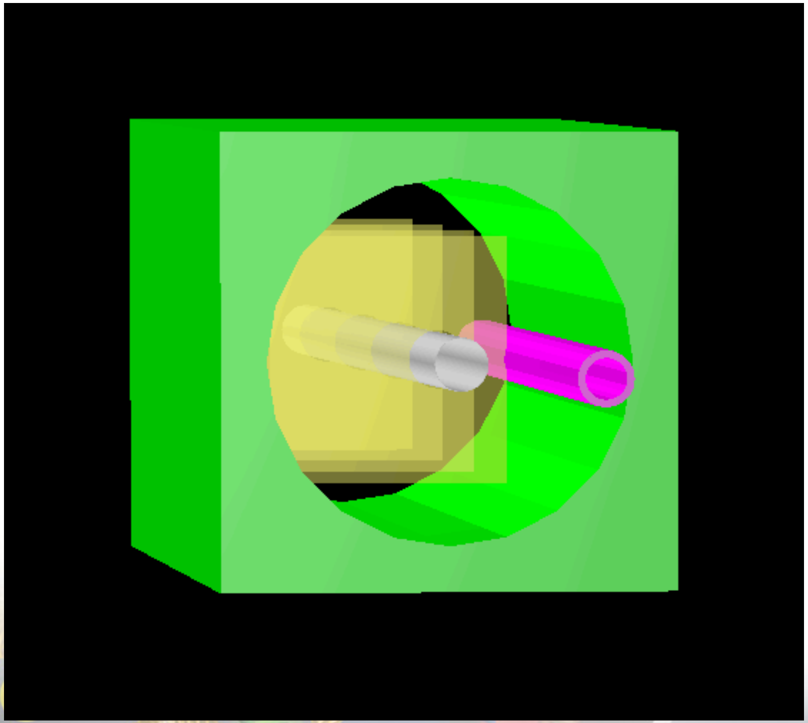
Space for detectors

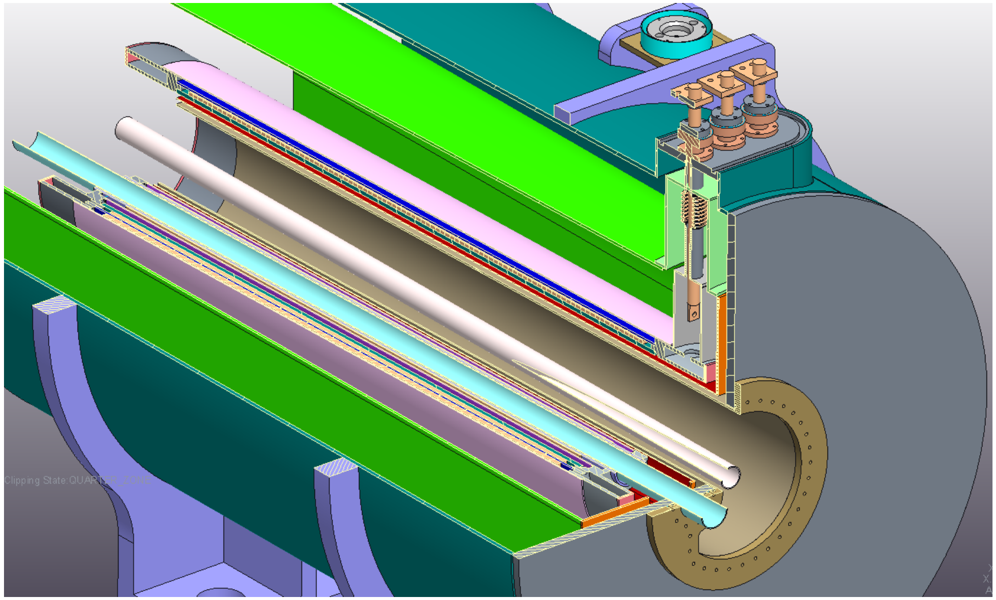
- Higher granularity detectors needed in this area (MAPS, or something similar) with layers of fast-timing detectors (e.g. LGADs), or timepix (provides high resolution space and timing information), depending on sensor layout and size.

Layout: B0-detectors (calorimetry)

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

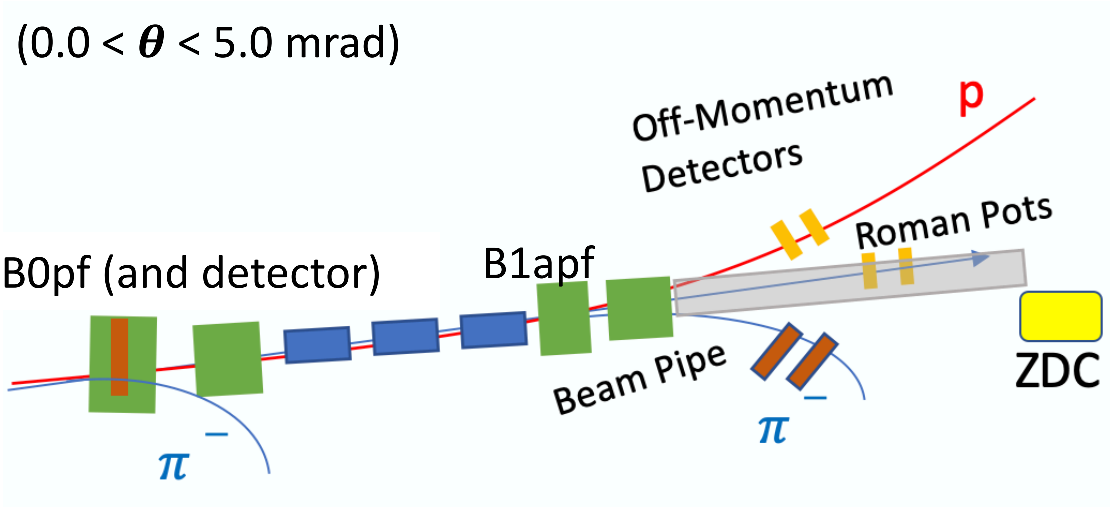
- ~1.2 meters of longitudinal space in bore.
- Could potentially have several layers of silicon for tracking, and a few layers after for some EM calorimetry (compact).





- ➢ 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.

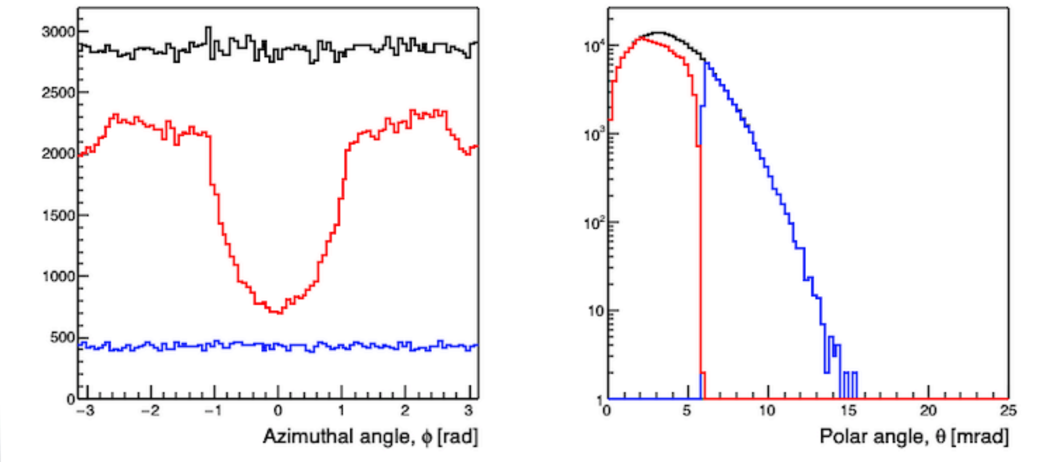
Layout: Off-Momentum detectors



- 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).

- Acceptance mostly limited by losses of very off momentum particles in quadrupoles.
- Can use LGAD technology here too.

Neutron spectator/leading proton case.



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

Technology + Machine: ZDC

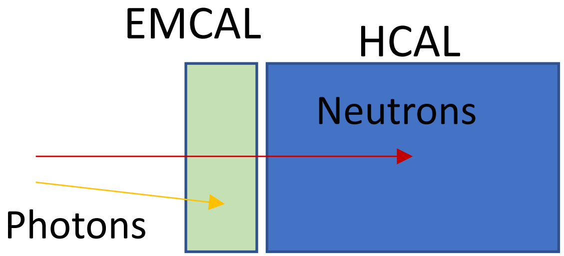
For detection of neutrons and photons

Acceptance:

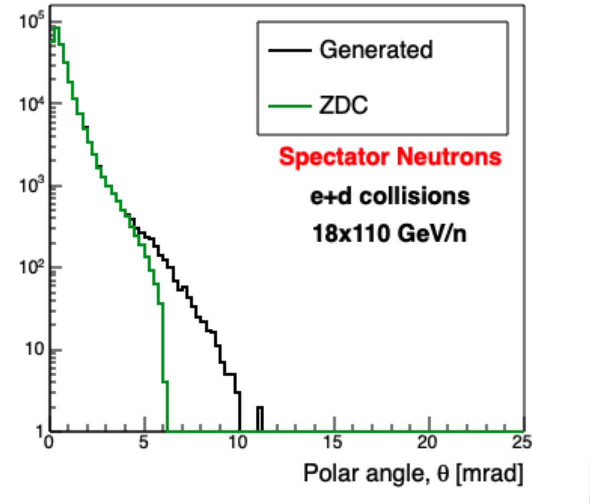
$0 < \theta < 5.5$ mrad

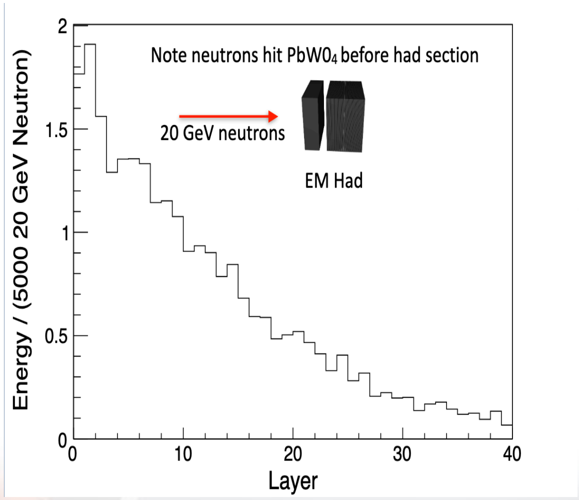
(Limited by bore of magnet where the neutron cone has to exit)

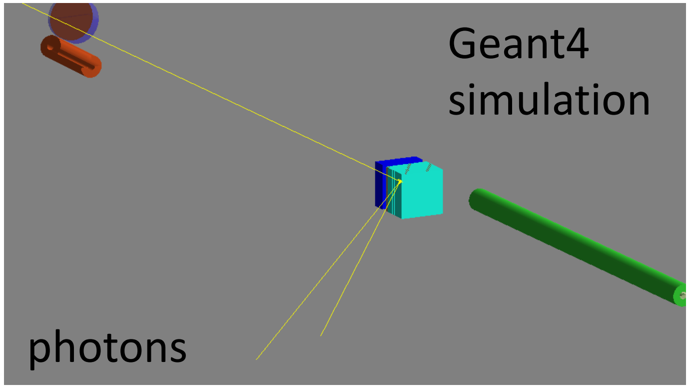
- HCAL: $\sim 50\%/\sqrt{E}$ & $3\ \mathrm{mrad}/\sqrt{E}$ or better
- EMCAL: $\sim 25\%/\sqrt{E} \oplus 2\%$ or better (EM)

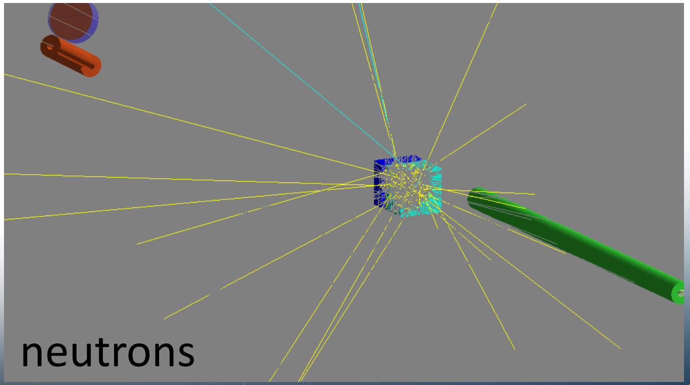


~2 meters of longitudinal space available, which will help achieve better HCAL resolution.



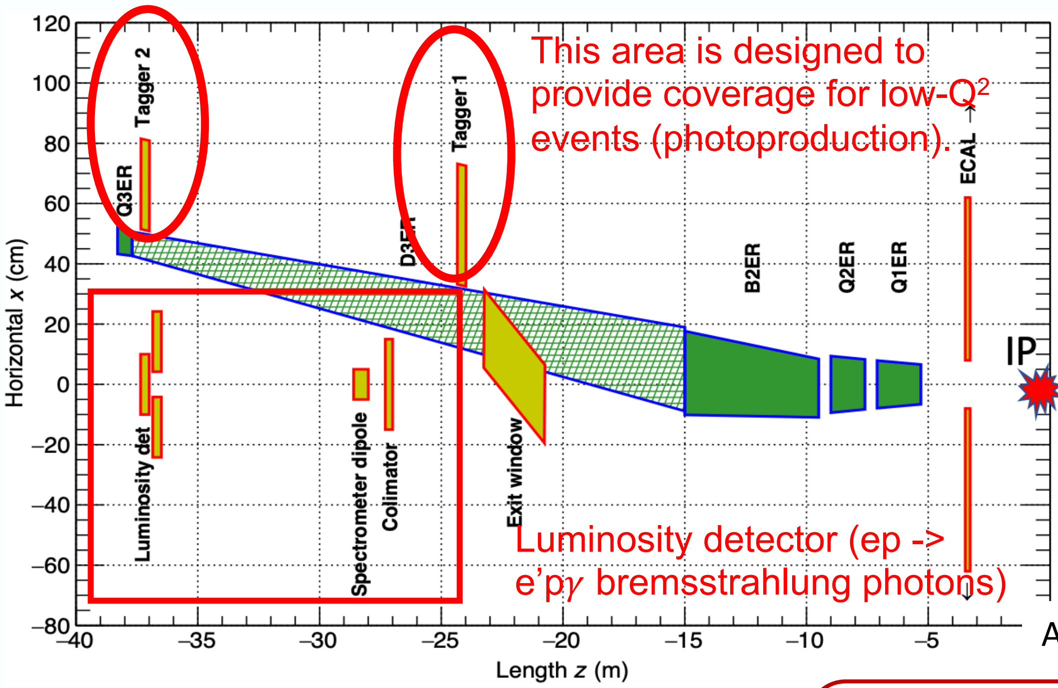






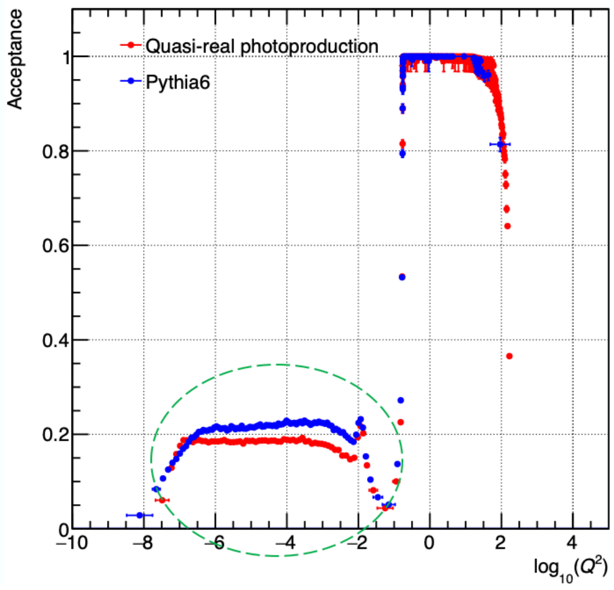
EIC R&D Contact: Michael Murray

Far-backward (electron-going) region

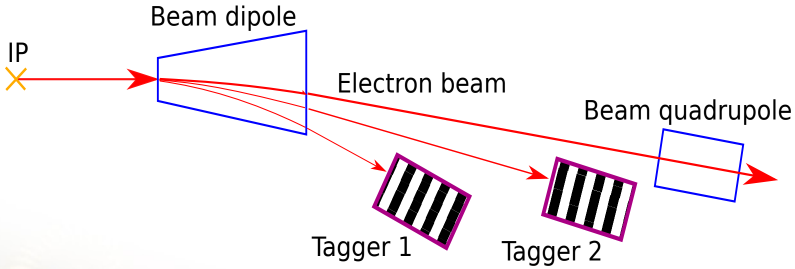


This area is designed to provide coverage for low-Q^2 events (photoproduction).

Luminosity detector (ep -> e'pγ bremsstrahlung photons)



Acceptance up to ~10^{-4} with smearing (not shown).



- Needs to be fast enough to detect each bunch crossing (<10 ns).
- High radiation and temperature loads due to beam proximity and synchrotron radiation.
- Angular divergence makes the lowest Q^2 coverage challenging.
- Various technologies on the table, including diamond or silicon sampling calorimetry.

Complementarity/Second IR

- Separate group dedicated to complementarity.
  - Different location of “gap region” between the B0 and RP/Off-Momentum Detectors (different beam pipe size in the equivalent B0pf magnet in IR 2, for example).
  - Different crossing angle (will also increase crab-induced smearing).

Summary and Takeaways

- Many issues have been considered during this Yellow Report effort, but a few things **must be included**.
  - e.g. timing, maximal acceptance, precision.
- Tagging low energy photons is the most demanding task.
  - More study is needed with detailed material considerations and beam backgrounds.
- <u>Alternatives should be considered when:</u>
  - required by physics (i.e. technology choice doesn’t meet requirements) → Reflected in the YR.
  - if the cost for a technology is excessive when a final design materializes.

The Yellow Report serves as a foundational starting point for the collaboration(s). As the machine design is iterated and refined, and as new R&D is completed, new alternatives may present themselves that improve on previous work!

IR-related physics requirements

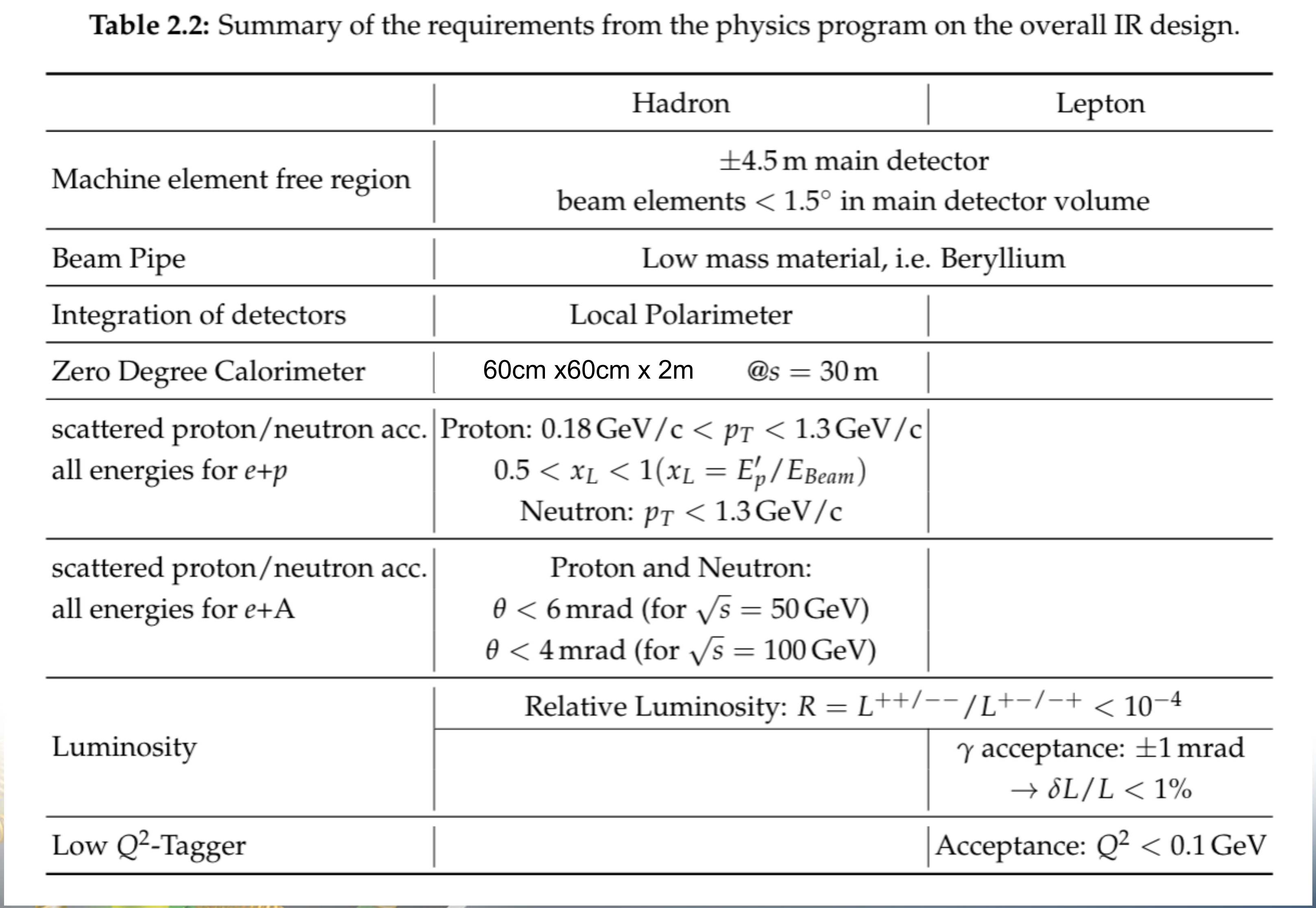
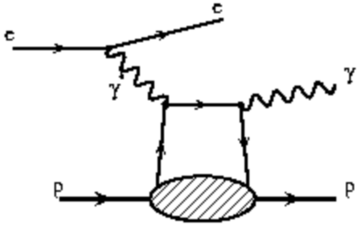


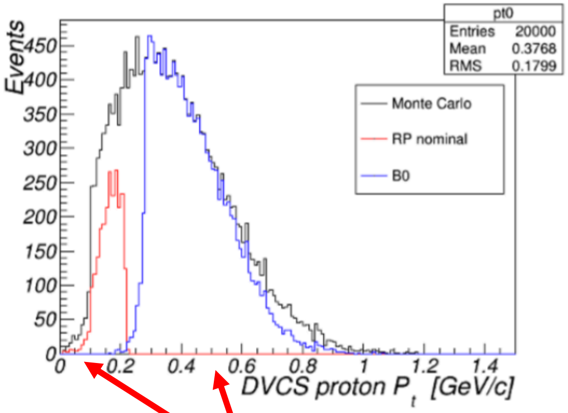
Table 2.2: Summary of the requirements from the physics program on the overall IR design.

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

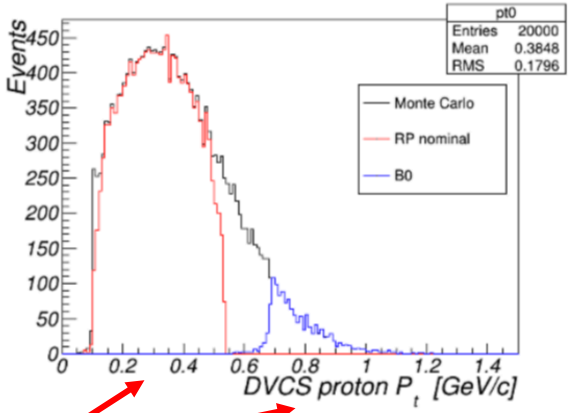
Forward Proton Acceptance



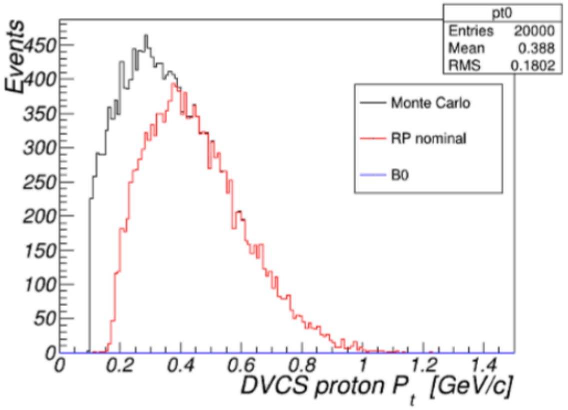
5 GeV x 41 GeV



10 GeV x 100 GeV



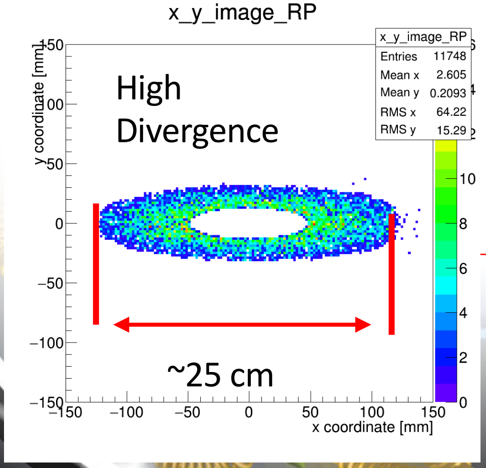
18 GeV x 275 GeV

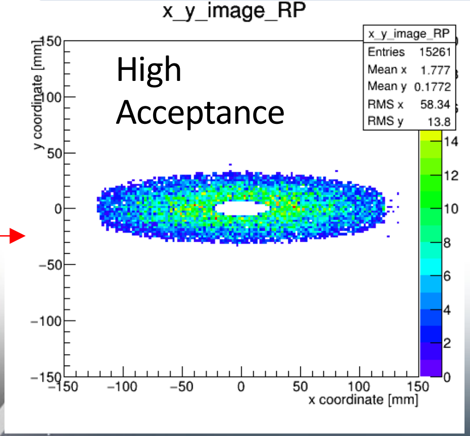


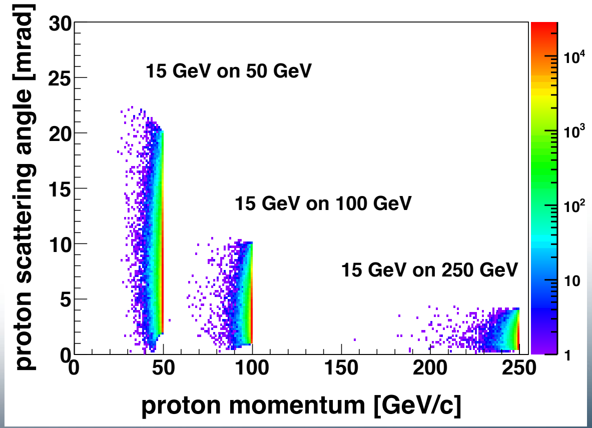
Need both detector systems together here!

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

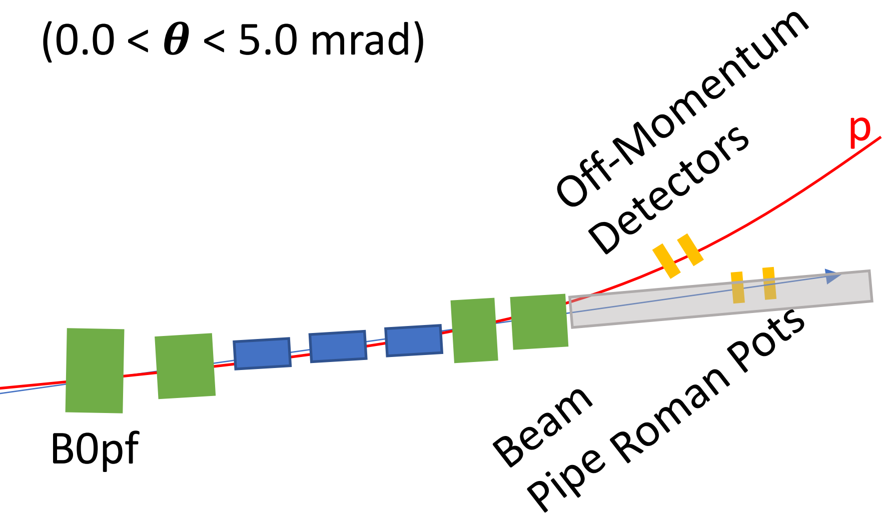


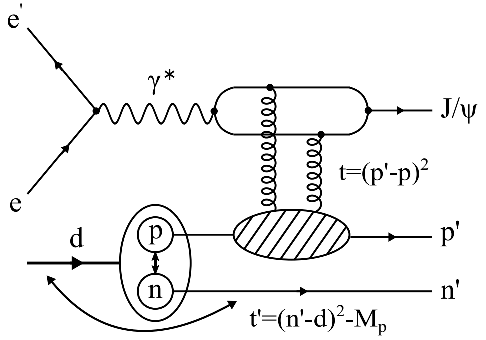


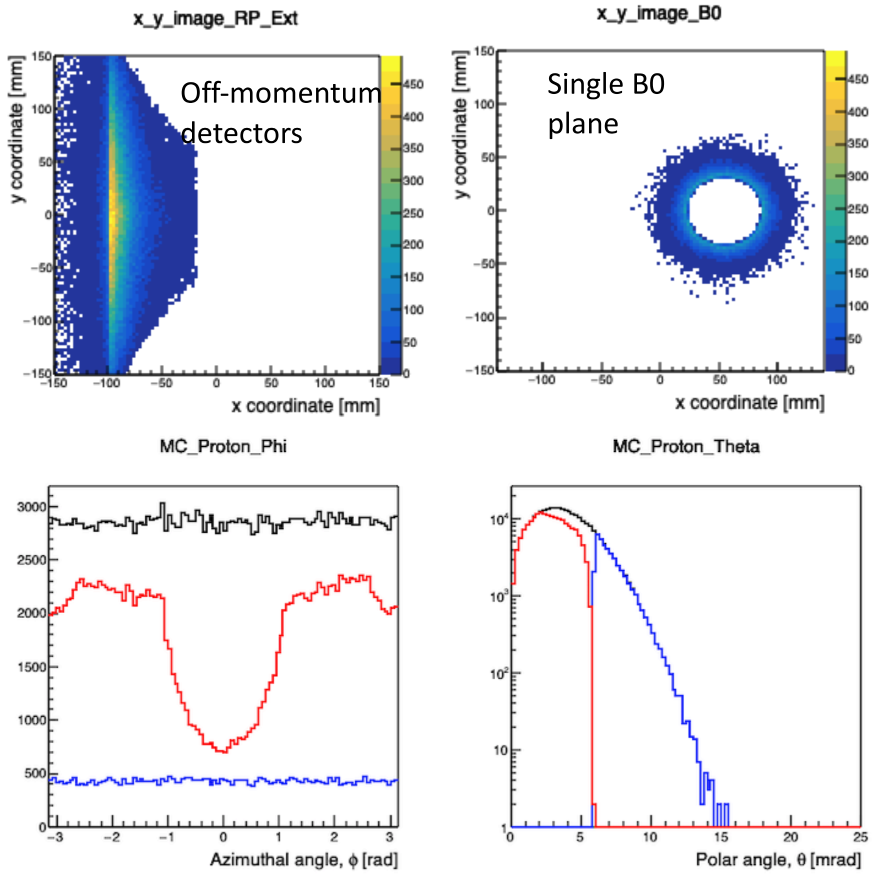


Off-Momentum detectors

(0.0 < $\boldsymbol{\theta}$ < 5.0 mrad)





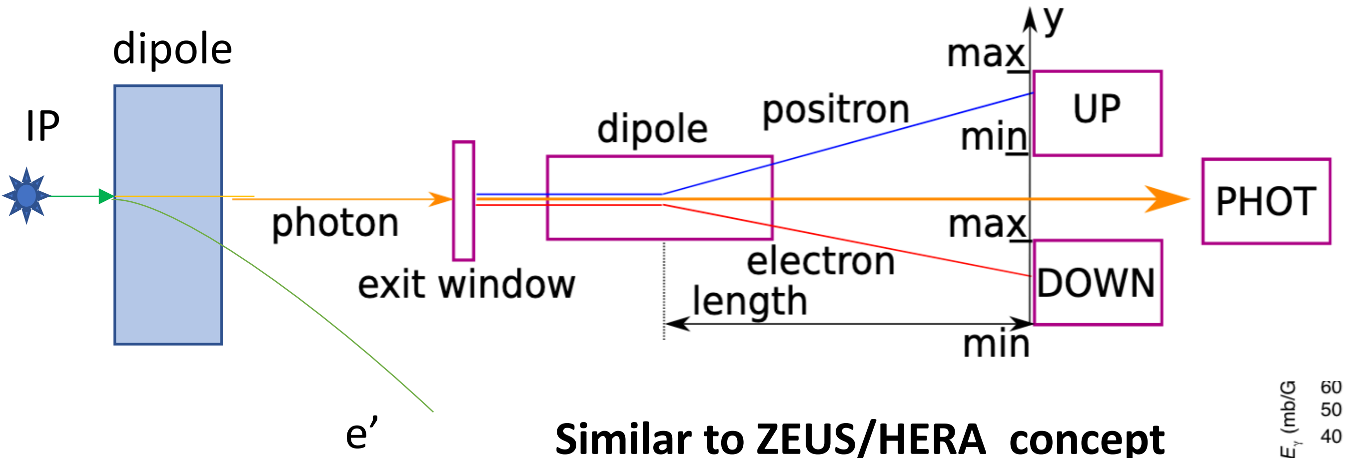


- Protons that come from nuclear breakup have a different magnetic rigidity than their respective nuclear beam (x_L<1)
- This means the protons experience more bending in the dipoles.
- As a result, small angle (θ < 5mrad) protons from these events will not make it to the Roman Pots, and will instead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

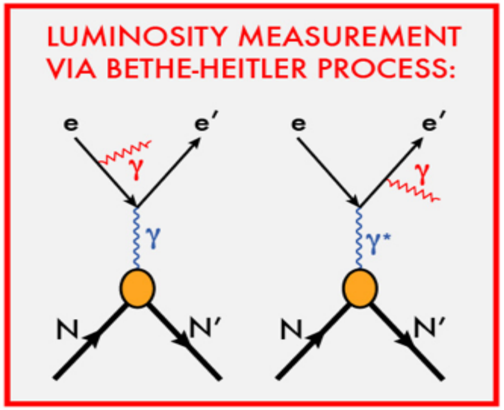
Neutron spectator/leading proton case.

ed (18x110GeV)

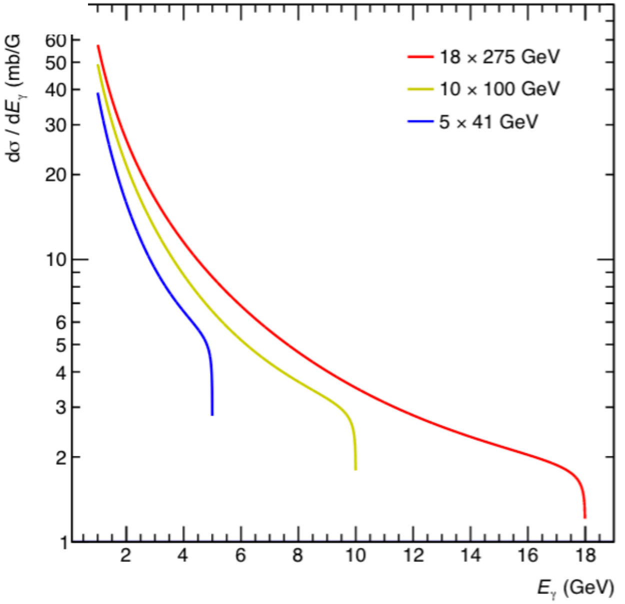
Luminosity monitor



Similar to ZEUS/HERA concept



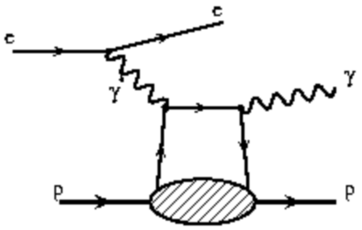
- ➢ Luminosity measurements via Bethe-Heitler process
- ➢ Photons from IP collinear to e-beam
- ➢ First dipole bends electrons
- ➢ Photon conversion to e-/e+ pair
- ➢ Pair-spectrometer
- ➢ Synchrotron photons collimation scheme needs to be further refined



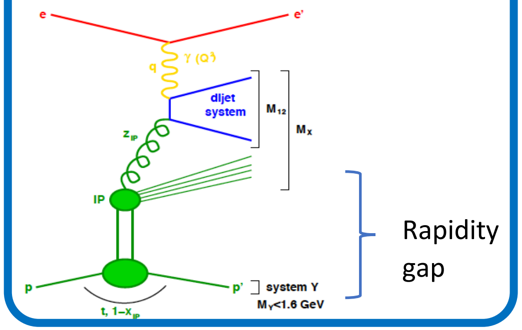
(a) Bremsstrahlung cross section as a function of photon energy.

Far-forward physics at EIC

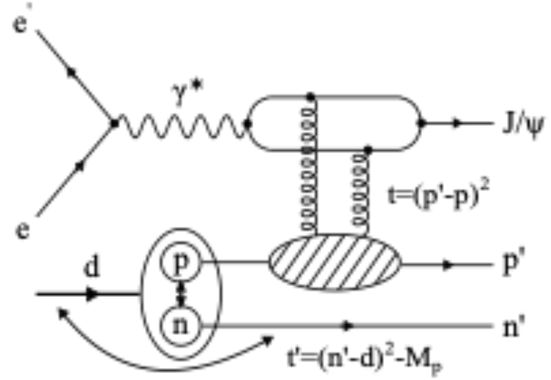
e+p DVCS events with proton tagging.



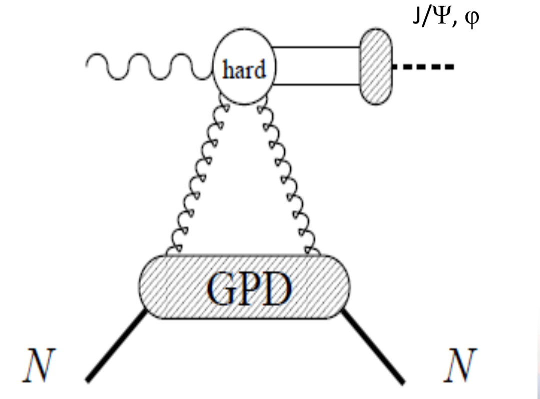
Diffraction



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

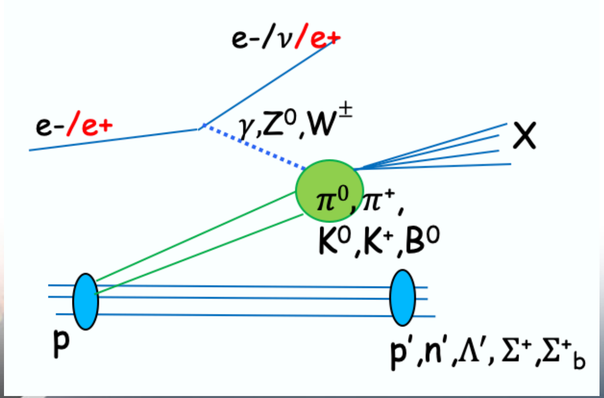


Saturation (coherent/incoherent J/ψ production)



Meson structure:

- with neutron tagging ($ep \to (\pi) \to e'\, n\, X$) .
- Lambda decays ($\Lambda \to p\pi^-$ and $\Lambda \to n\pi^0$)



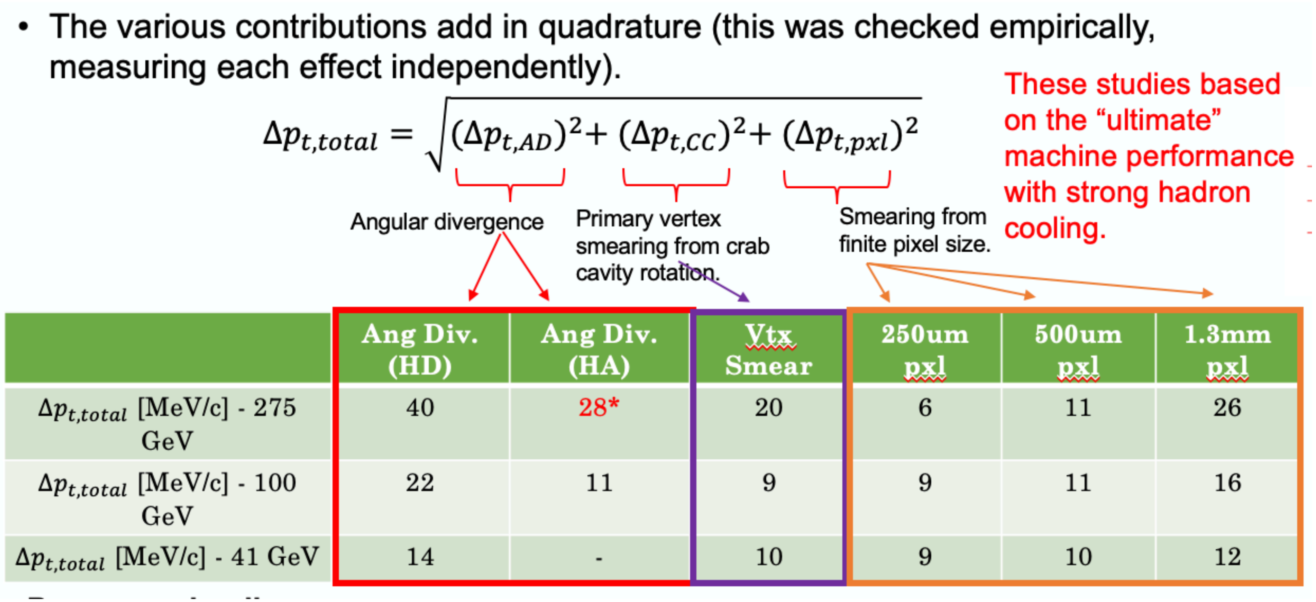
e+He3 with spectator proton tagging.

e+He4 coherent He4 tagging.

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

….

Roman Pots resolution



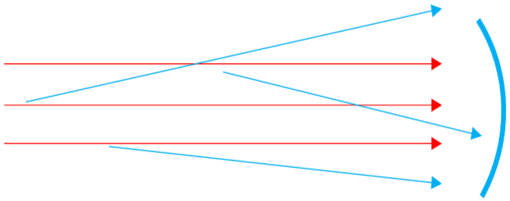
- The various contributions add in quadrature (this was checked empirically, measuring each effect independently).

$$\Delta p_{t,total} = \sqrt{\underbrace{(\Delta p_{t,AD})^2}_{\text{Angular divergence}} + \underbrace{(\Delta p_{t,CC})^2}_{\text{Primary vertex smearing from crab cavity rotation.}} + \underbrace{(\Delta p_{t,pxl})^2}_{\text{Smearing from finite pixel size.}}}$$

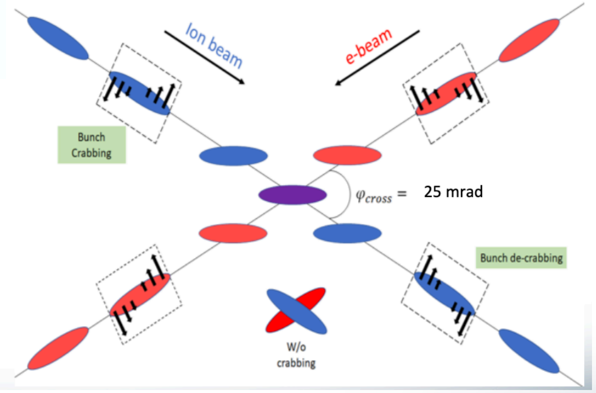
These studies based on the "ultimate" machine performance with strong hadron cooling.

	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



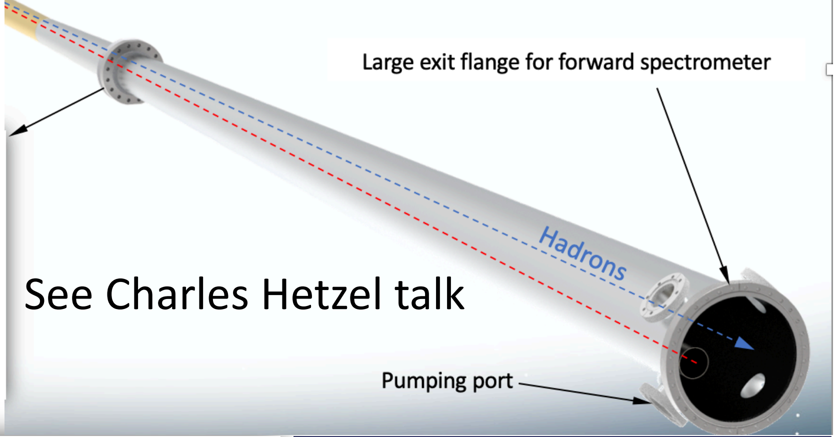
Primary vertex smearing from crab cavity rotation



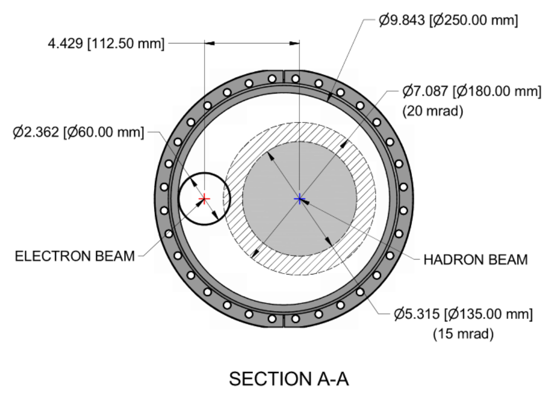
- **Beam angular divergence**
  - Beam property, can't correct for it – sets the lower bound of smearing.
  - Subject to change (i.e. get better) – beam parameters not yet set in stone
    - *using symmetric divergence parameters in x and y at 100urad.
- **Vertex smearing from crab rotation**
  - Correctable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

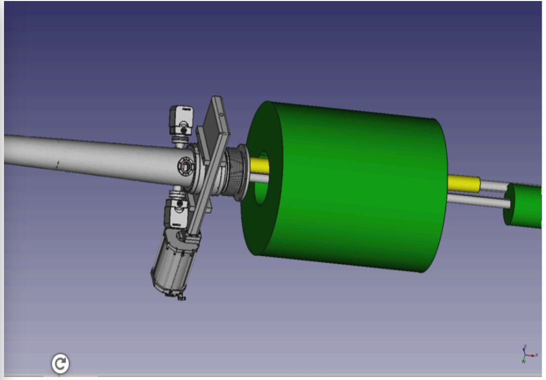
B0 integration

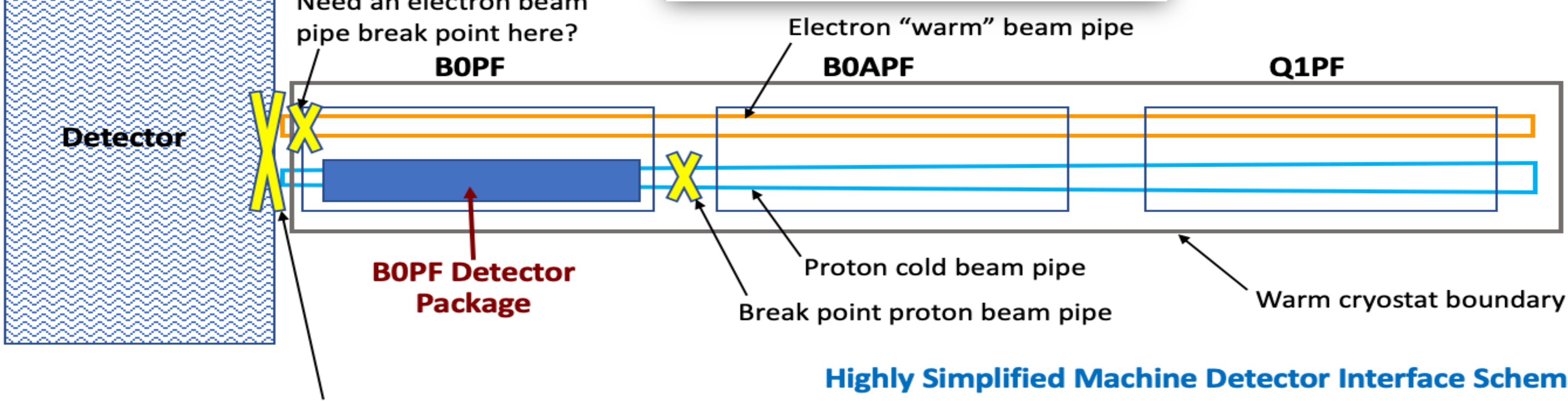
- Beampipe: exit window
- HCAL and vacuum pumps in front of B0 tracker => high background area
- Detector integration and maintenance



See Charles Hetzel talk







Detector

Need an electron beam pipe break point here?

B0PF

Electron “warm” beam pipe

B0APF

Q1PF

B0PF Detector Package

Proton cold beam pipe

Break point proton beam pipe

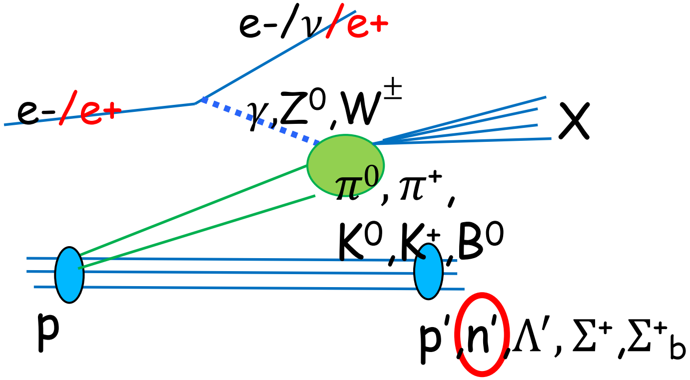
Warm cryostat boundary

Highly Simplified Machine Detector Interface Schematic

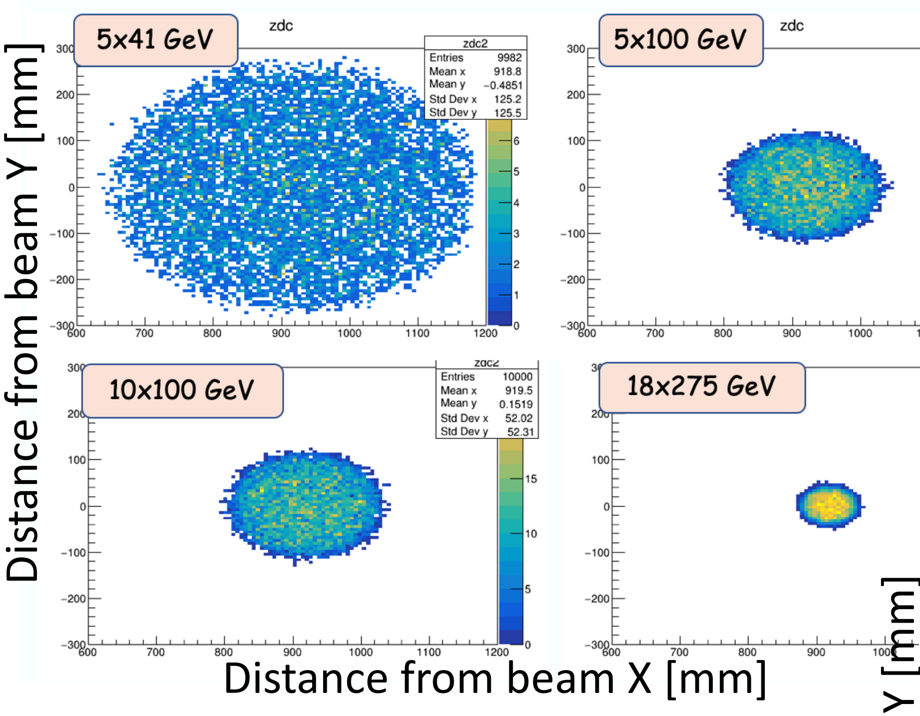
Break point to IP beam pipe so detector can move out before opening up the cryostat end volume.

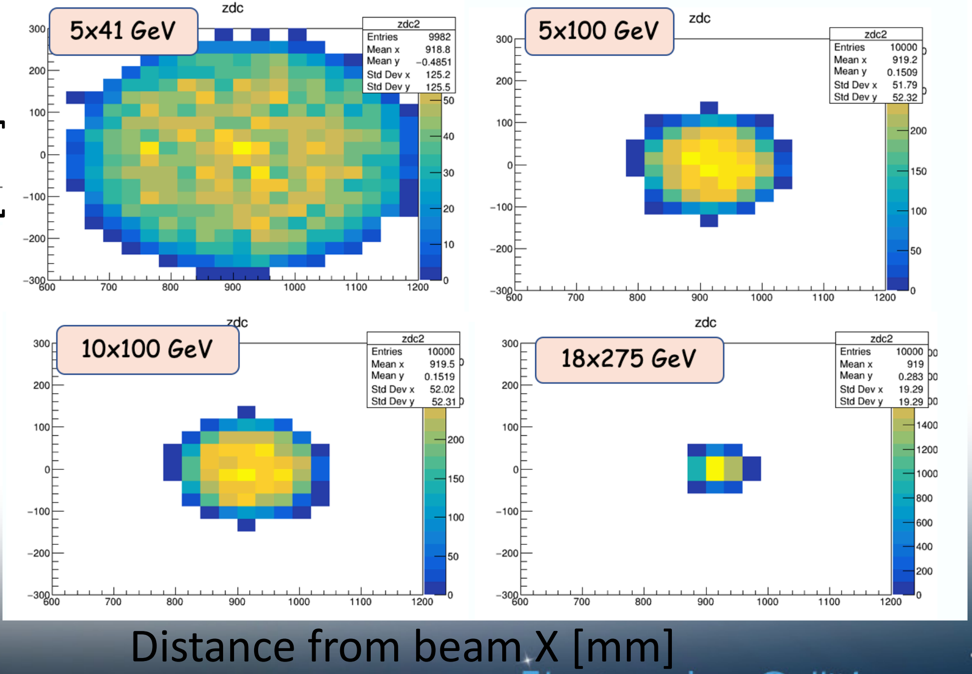
ZDC resolution

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):

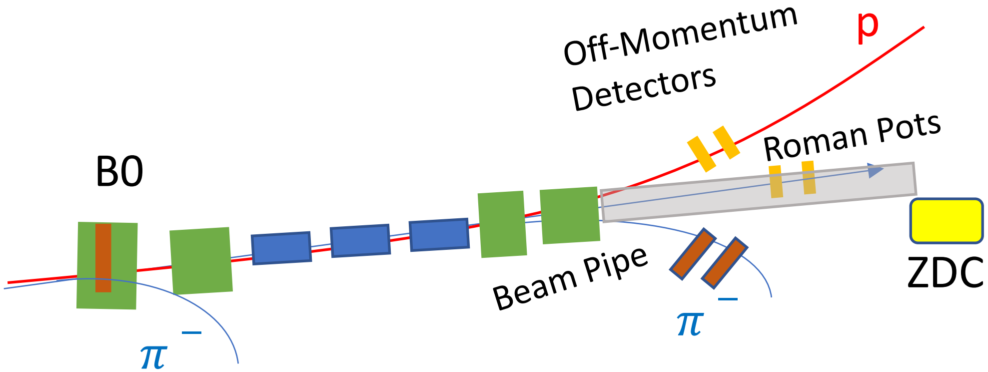
Lambda decays

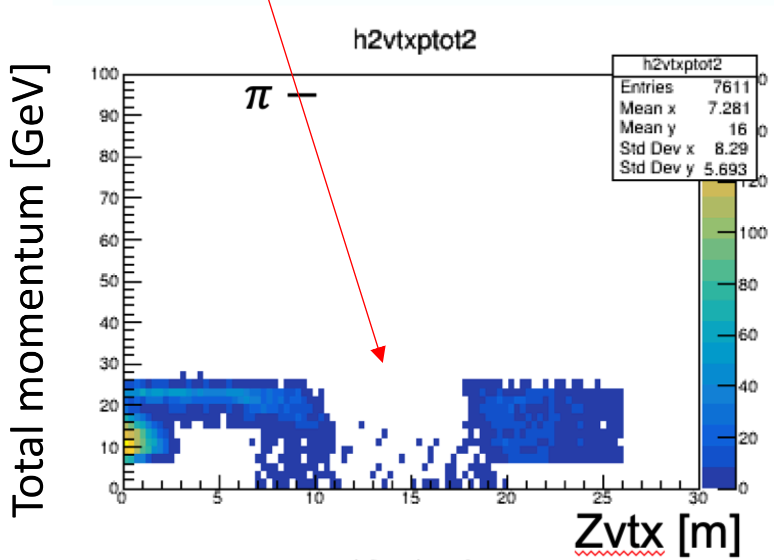
e p -> (K) -> e' + $\Lambda + X$

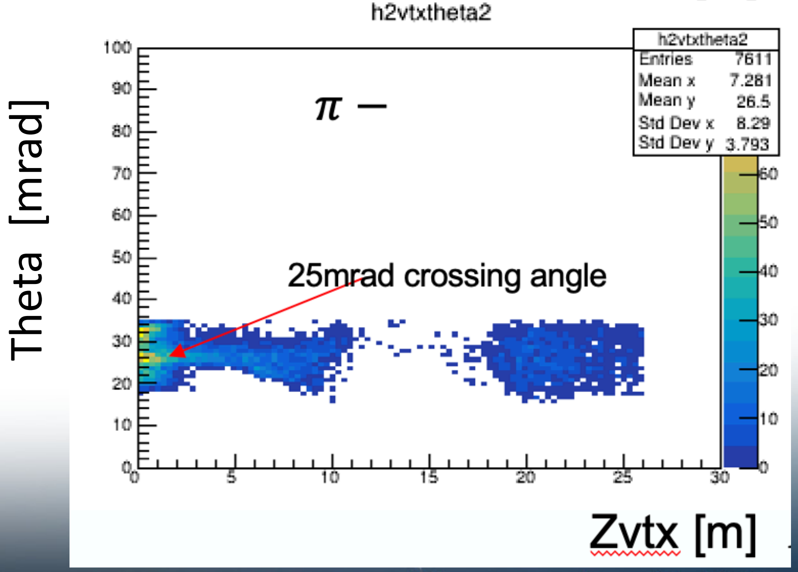
↳ p + π^- (Br~64%)

↳ 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.



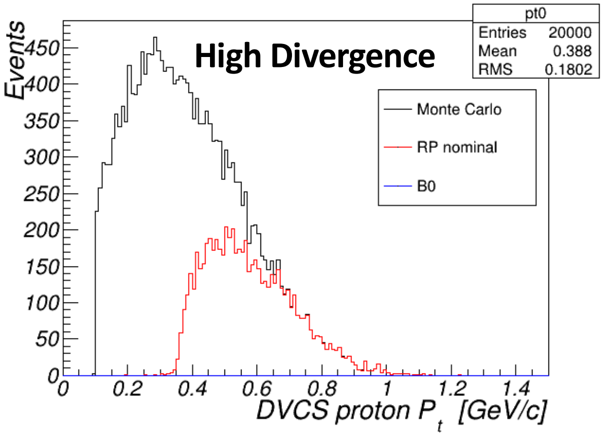


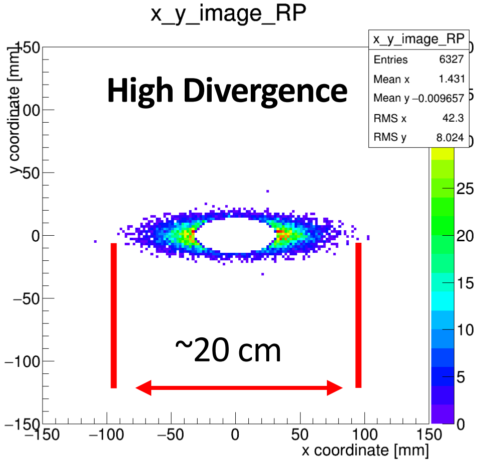


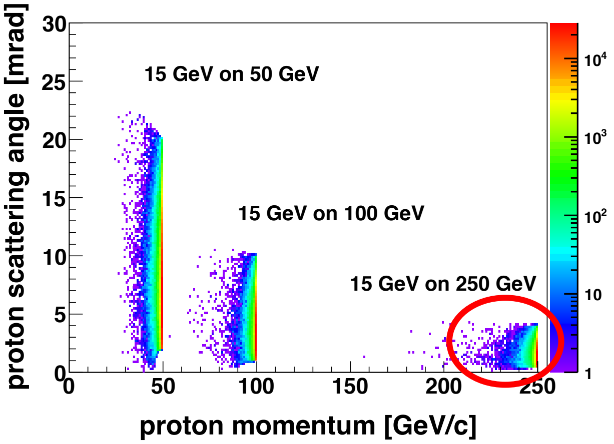
- ➢ Detecting Lambda's decays in the target fragmentation area is very hard, due to a very large decay length (meters).
- ➢ Would require in addition detection of negative charged particles (pi-) at the OFF-momentum detector location

Machine Optics: Roman Pots

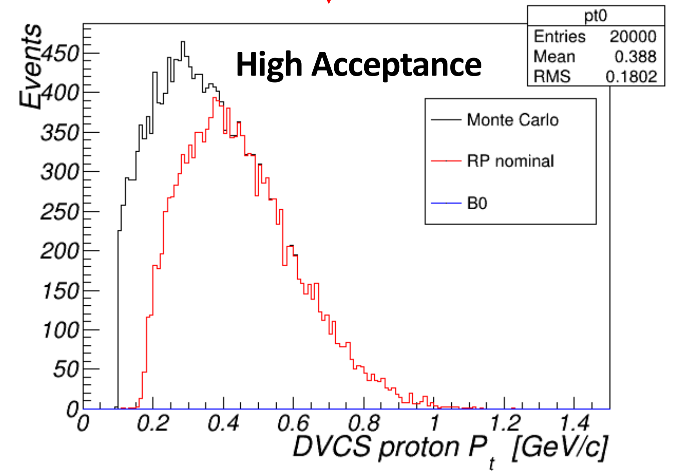
275 GeV DVCS Proton Acceptance

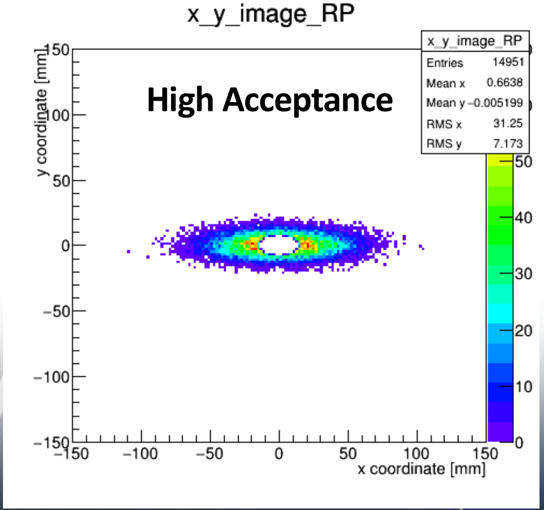






High Divergence: smaller β^* at IP, but bigger $\beta(z = 30m)$ -> higher lumi., larger beam at RP

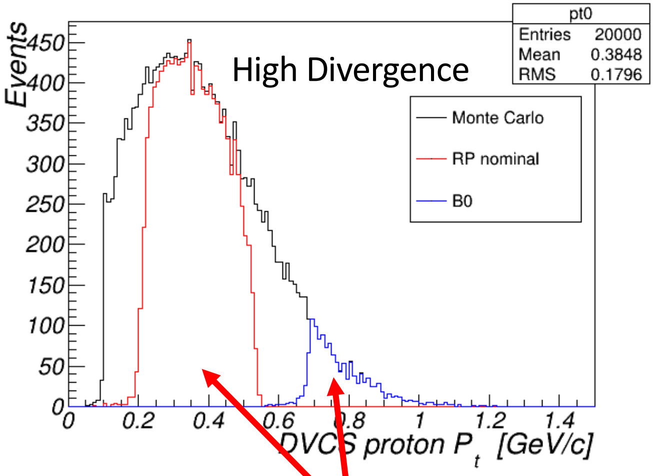


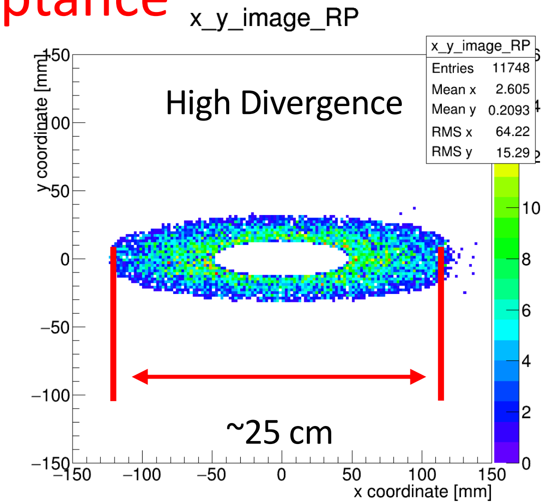


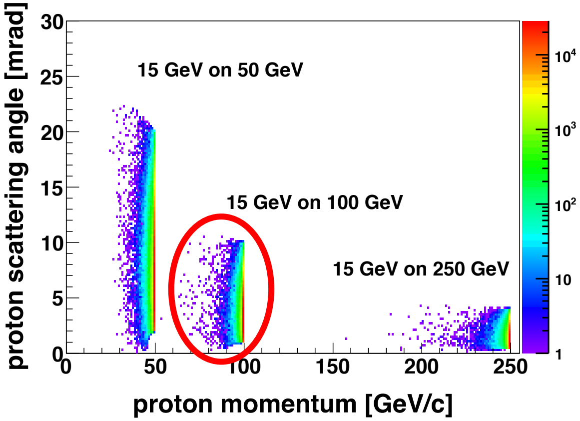
High Acceptance: larger β^* at IP, smaller $\beta(z = 30m)$ -> lower lumi., smaller beam at RP

Machine Optics: Roman Pots

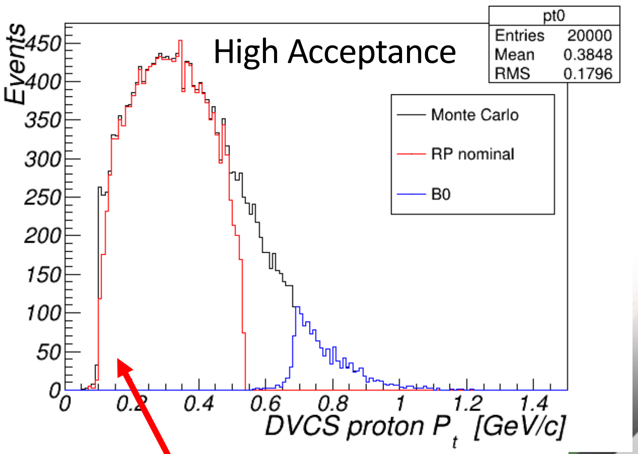
100 GeV DVCS Proton Acceptance

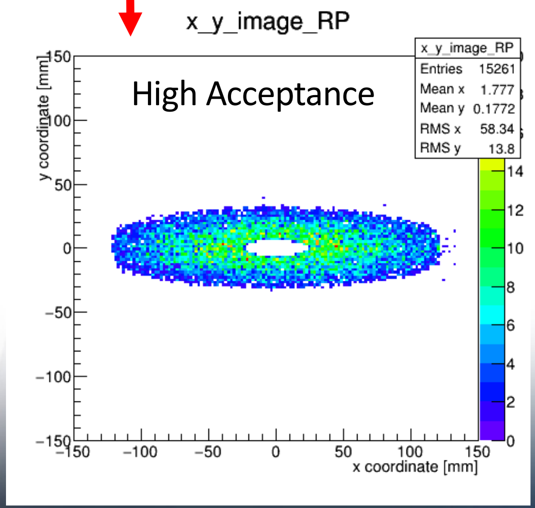






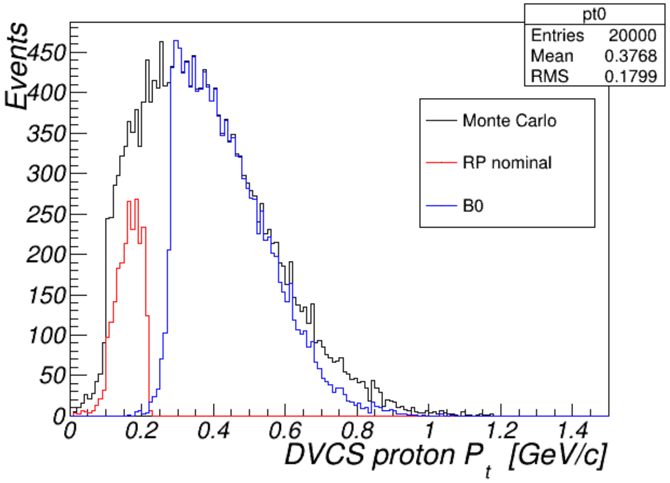
Need both detector systems together here!

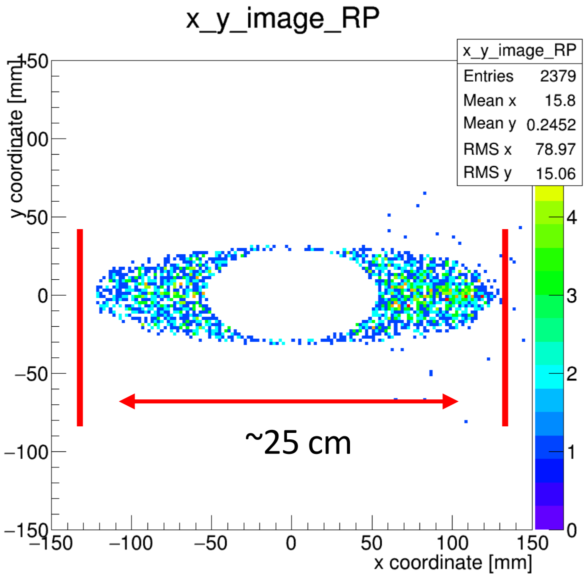


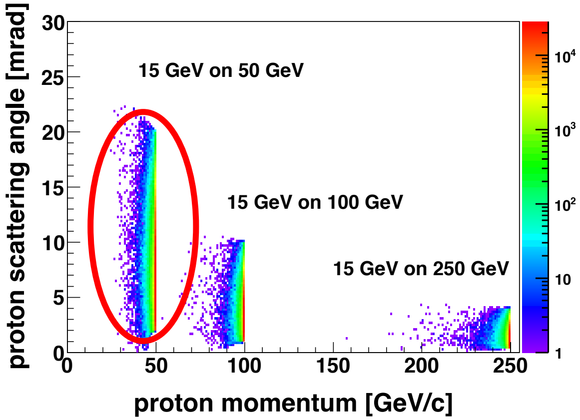


Improves low p_t acceptance.

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.