Far-Forward Detectors in the EIC

EIC CFNS Target Fragmentation Workshop

Sept. 28th - 30th, 2020

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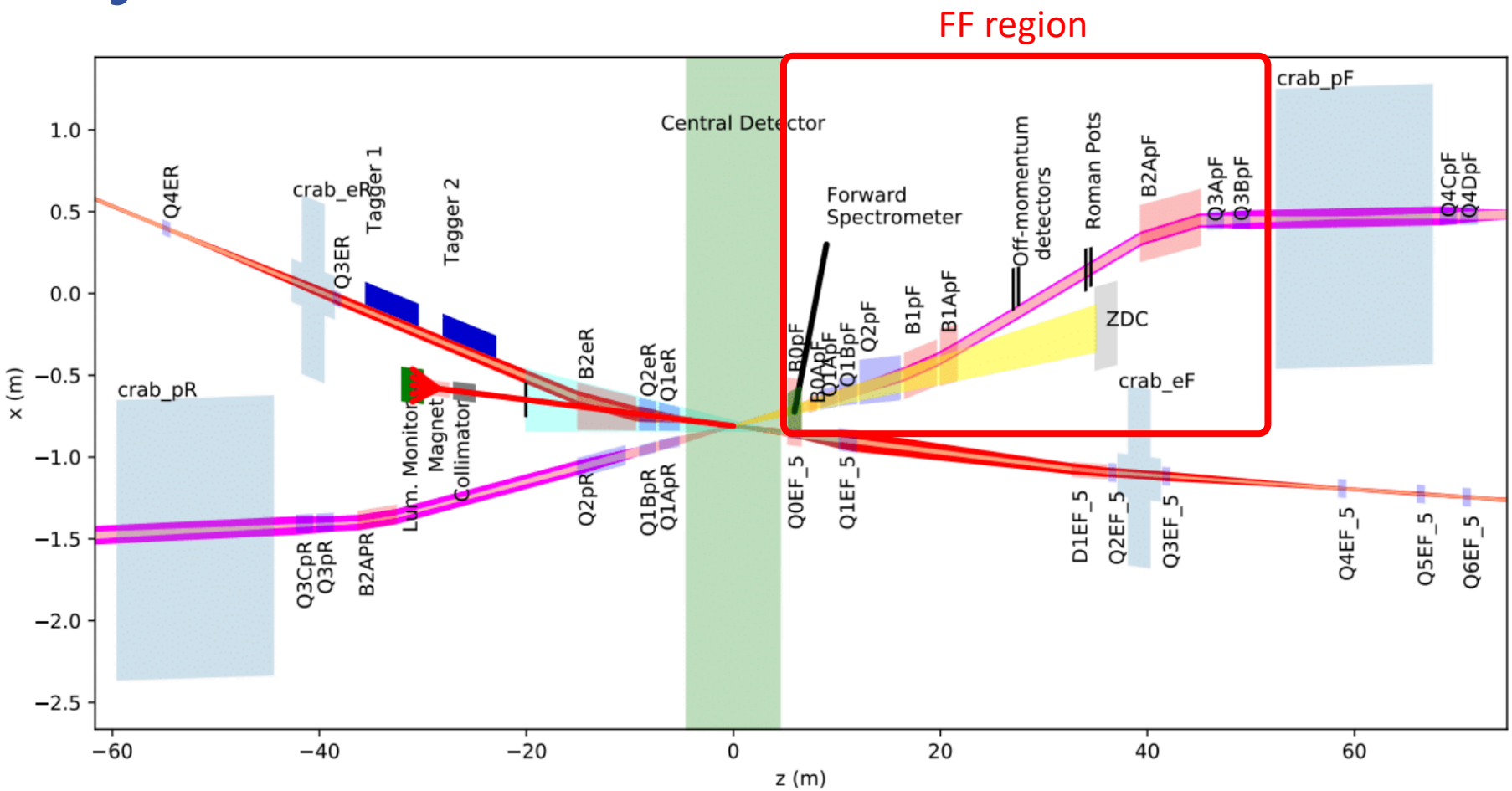
Co-Convener for YR FF Subgroup

Electron Ion Collider

BROOKHAVEN NATIONAL LABORATORY

U.S. DEPARTMENT OF ENERGY | Office of Science

Layout of Full IR

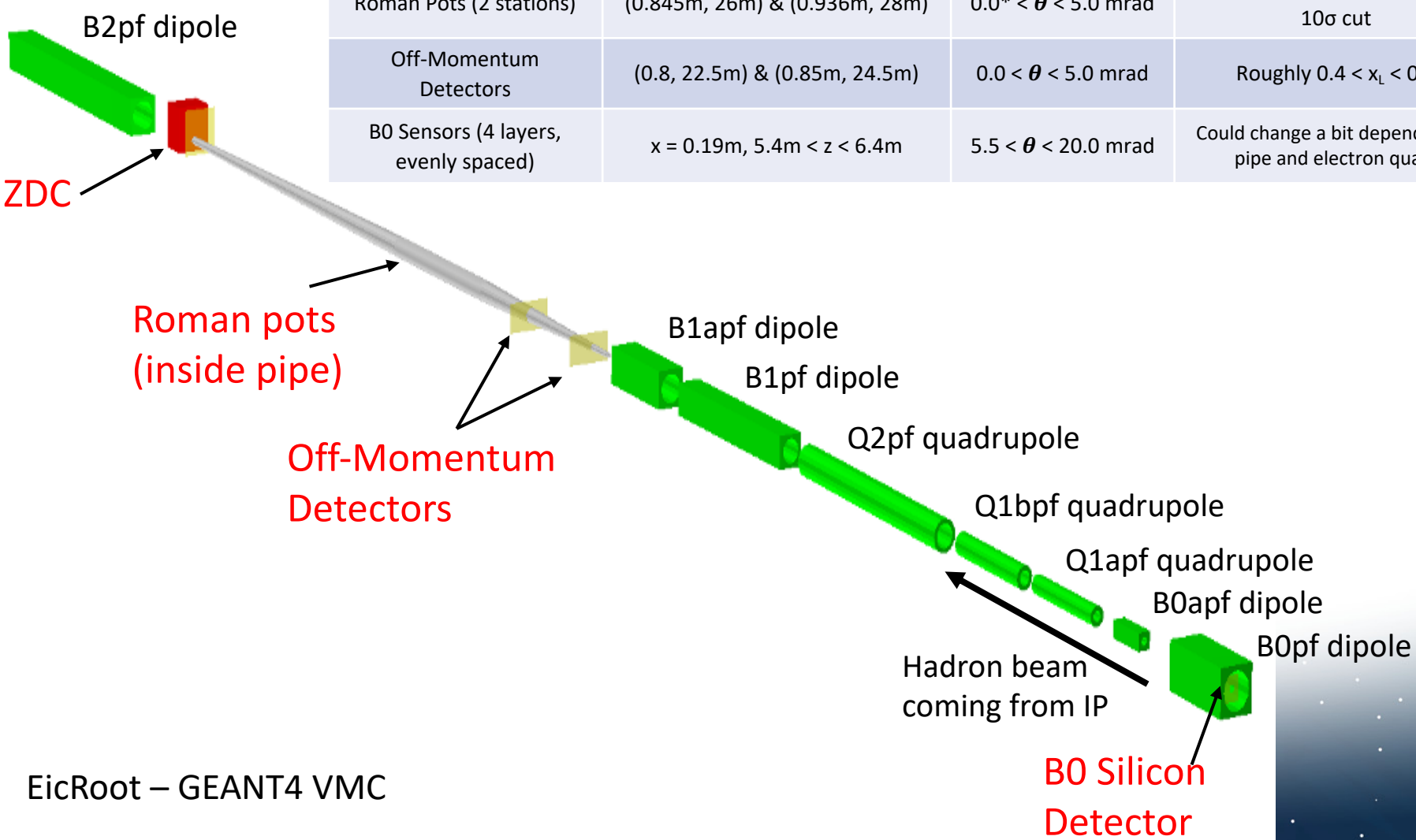


- ~9 m around the IP is reserved for the *central* detector
- But the *far forward* and *far backward* detector components are distributed along the beam line within $\pm$35 m
- FF detectors constrained by machine design.

Layout of Far-Forward Region

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

Detector	Detector Position (x,z)	Angular Acceptance	Notes
ZDC	(0.96m, 37.5m)	$\boldsymbol{\theta}$ < 5.5 mrad	About 4.0 mrad at $\varphi \sim \pi$
Roman Pots (2 stations)	(0.845m, 26m) & (0.936m, 28m)	0.0* < $\boldsymbol{\theta}$ < 5.0 mrad	$0.65 < x_L < 1.0$ 10σ cut
Off-Momentum Detectors	(0.8, 22.5m) & (0.85m, 24.5m)	0.0 < $\boldsymbol{\theta}$ < 5.0 mrad	Roughly $0.4 < x_L < 0.6$
B0 Sensors (4 layers, evenly spaced)	x = 0.19m, 5.4m < z < 6.4m	5.5 < $\boldsymbol{\theta}$ < 20.0 mrad	Could change a bit depending on pipe and electron quad.

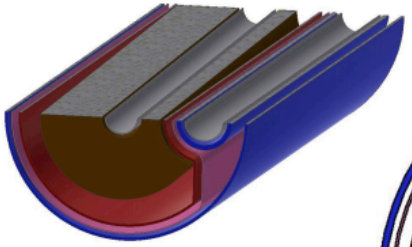


EicRoot – GEANT4 VMC

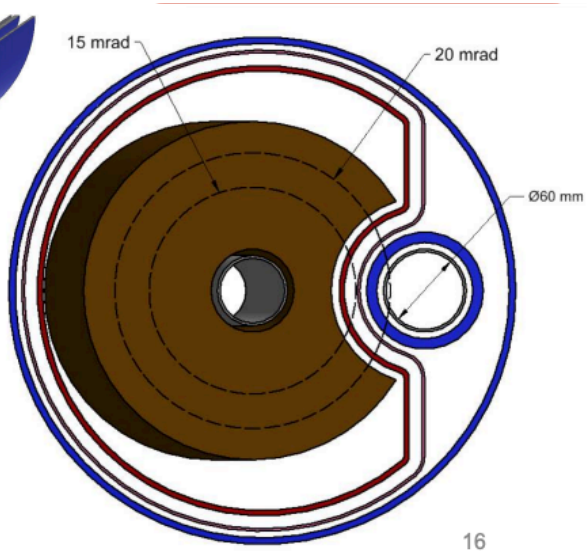
What has been studied so far?

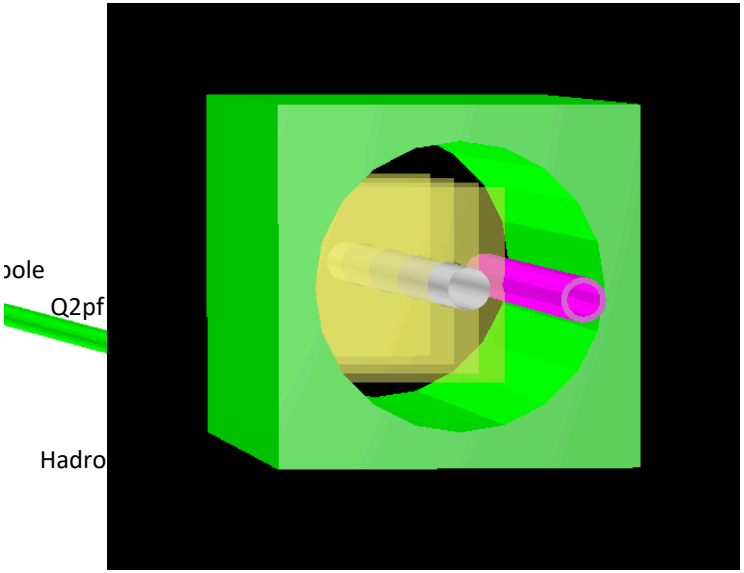
- e+p DVCS events with proton tagging.
- e+d exclusive J/Psi events with proton or neutron tagging.
- e+Au events with neutron tagging to veto breakup and photon acceptance.
- Meson structure with neutron tagging (ep→ (π) →e' n X) .
- Currently in progress
  - e+He3 with spectator proton tagging
  - Meson structure with Lambda decays ($\Lambda \rightarrow p\pi^-$ and $\Lambda \rightarrow n\pi^0$)
  - e+He4 coherent He4 tagging.

Aside: B0 Detector



Borrowed from Holger Witte.





B0 detector

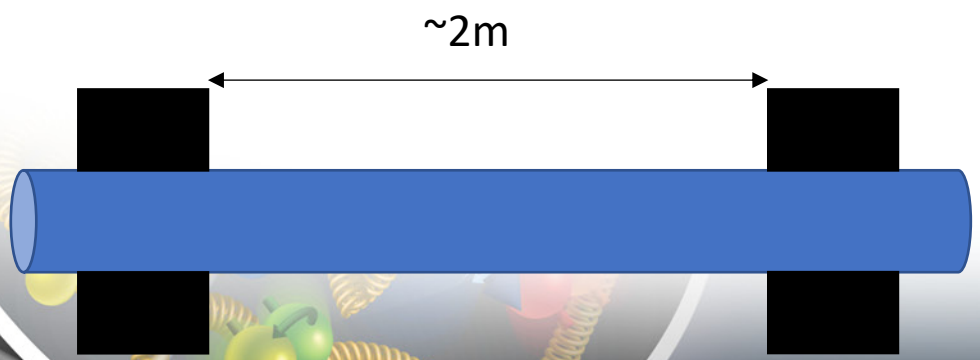
- Acts as a conventional spectrometer – allowing for tracking of charged particles in a dipole field.
- Can also be used for photon detection with pre-shower.
- 1.2 meters of total available longitudinal space – potential space for both a silicon tracker and EMCAL.
- Detects particles that are scattered with high enough angle to leave the beam pipe.
- Limitations include beam pipe size and spatial asymmetry.

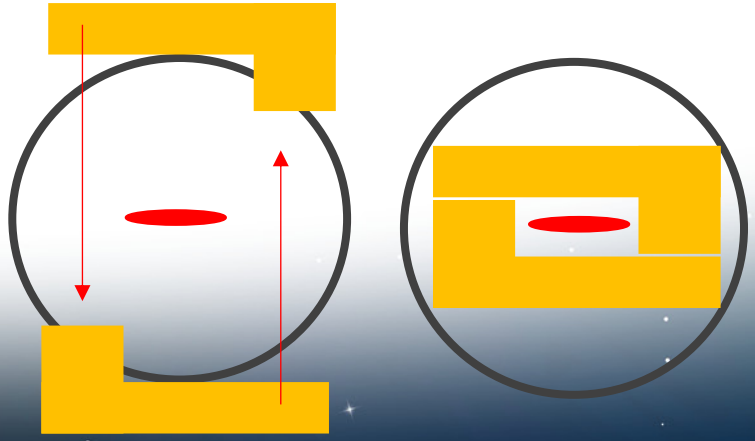
Aside: Roman Pots

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

- $\beta(z)$ is the RMS transverse beam size.
  - $\sigma(z)$ is the Gaussian width of the beam, ε is the emittance.
- General rule of thumb is to keep Roman Pot sensors at ~10σ distance from beam to limit exposure.
  - 275 GeV – 1σ = 1.79 mm (HA) / 3.58 mm (HD)
  - 100 GeV – 1σ = 2.45 mm (HA) / 5.13mm (HD)
  - 41 GeV – 1σ = 6.14 mm

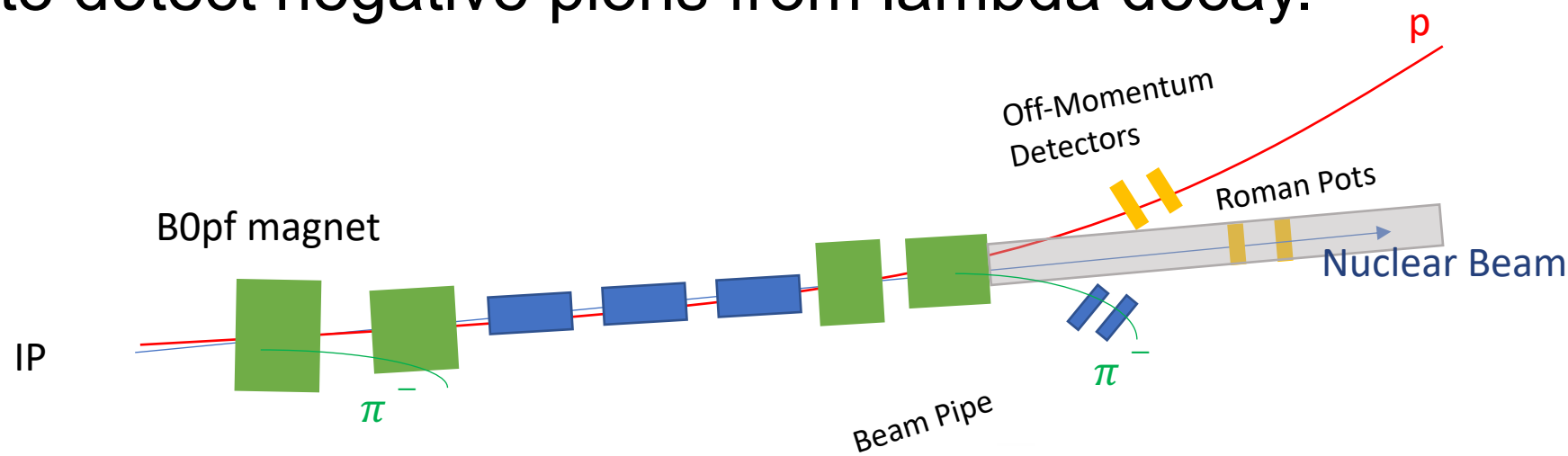
10σ cut places a limit on low-p_T acceptance.





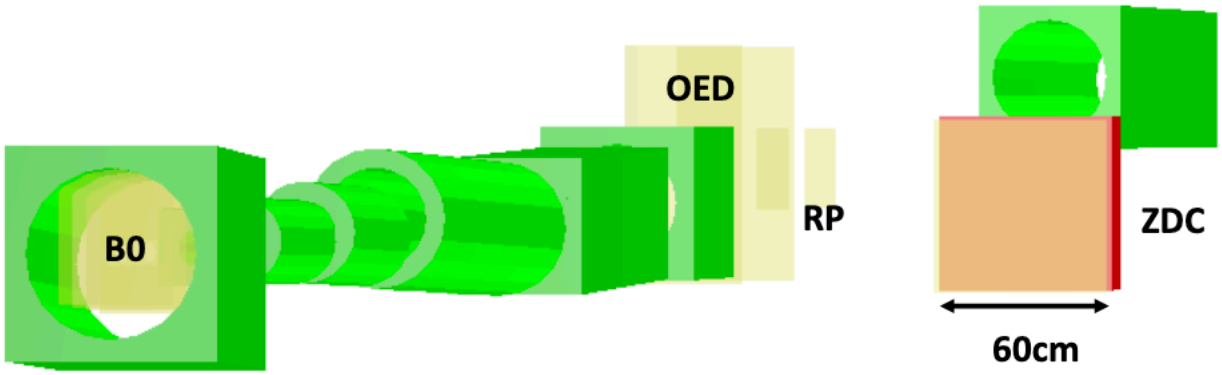
Aside: Off-Momentum Detectors

- Needed for measuring protons from nuclear breakup.
- Another set of sensors on the other side can be used to detect negative pions from lambda decay.

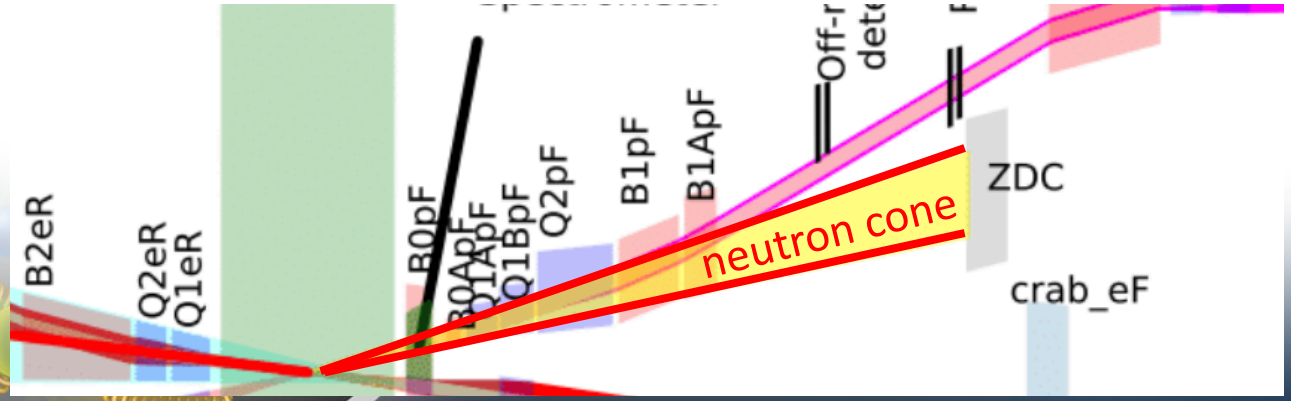


- No low-p_T cutoff - sensors are outside the beam pipe.
- Very off-momentum particles can be lost in the quads.

Zero-Degree Calorimeter (ZDC)



- For detecting neutral forward-going particles (neutrons and photons)
- Acceptance limited by bore of magnet where the neutron/photon cone has to exit.



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 $\sigma_\theta=(3 \text{ mrad})/\sqrt{E}$

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Protons:

- Assume uniform acceptance for $6 < \theta < 13$ mrad (20mrad on the other side) – "B0 spectrometer"

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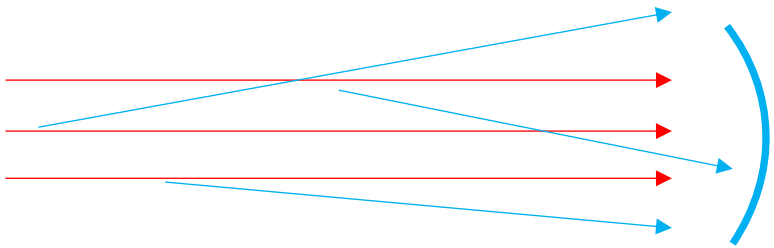
Protons:

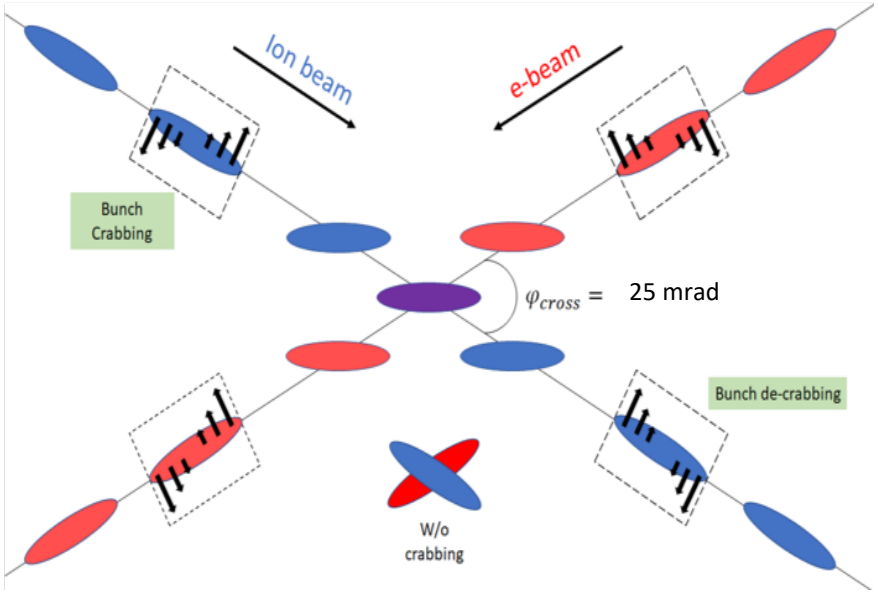
- Assume uniform acceptance for $6 < \theta < 13$ mrad (20mrad on the other side) – "B0 spectrometer"
- For protons with p_z/(beam momentum) > 0.6 – "Roman pots"
  - 275 GeV: Assume uniform acceptance for $0.5<\theta<5.0$ mrad
  - 100 GeV: Assume uniform acceptance for $0.2<\theta<5.0$ mrad
  - 41 GeV: 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%

Resolution: 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.

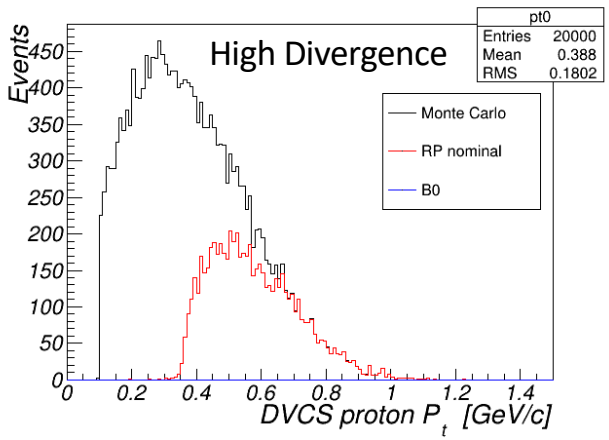


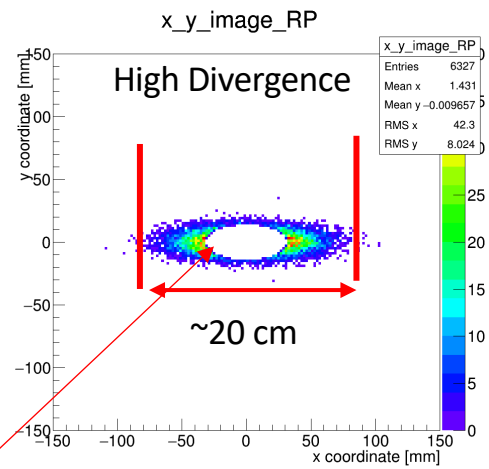
- Detector Choices
  - Pixel size, transfer matrix, etc.

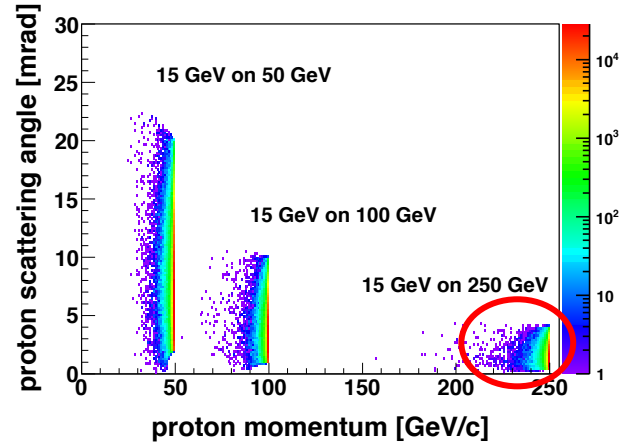
These effects introduce smearing in our momentum reconstruction.

DVCS Snapshot – 275 GeV

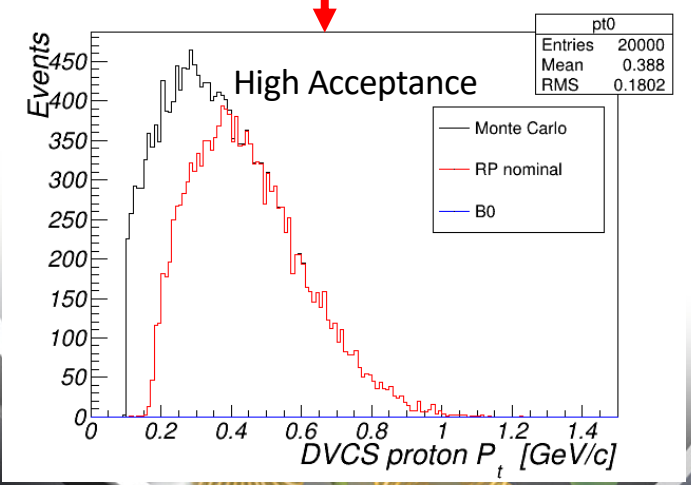
- 275 GeV DVCS Proton Acceptance
- Relevant detectors: Roman Pots and B0

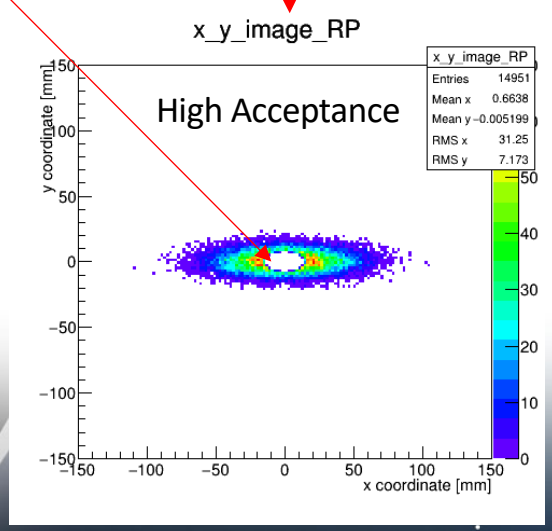






10σ cut



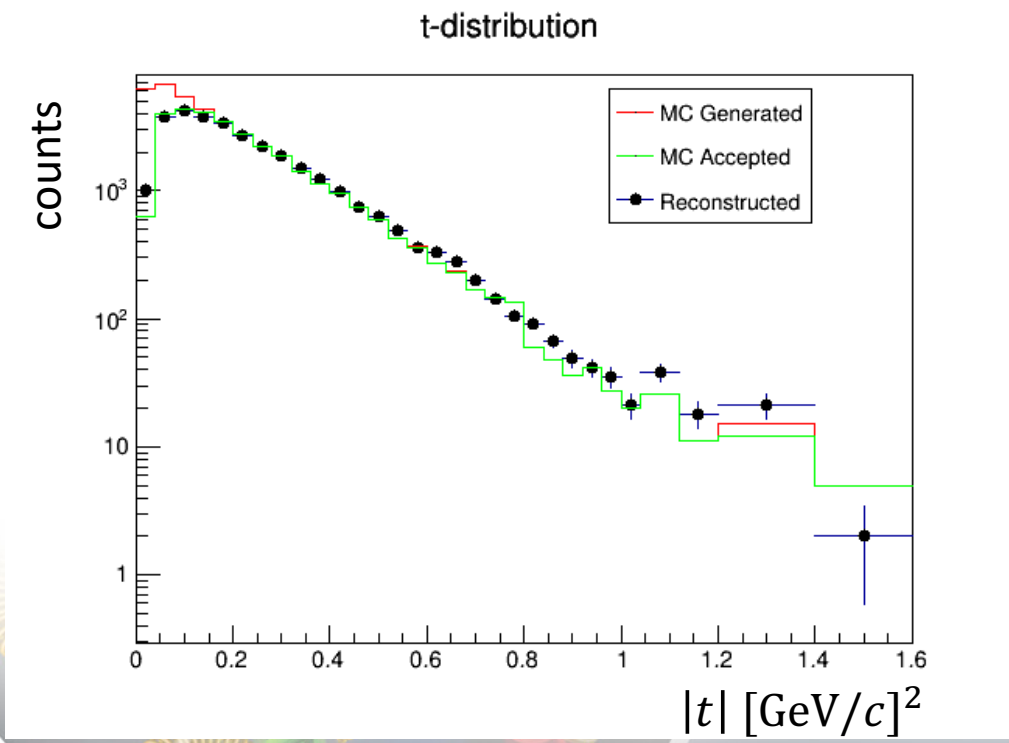


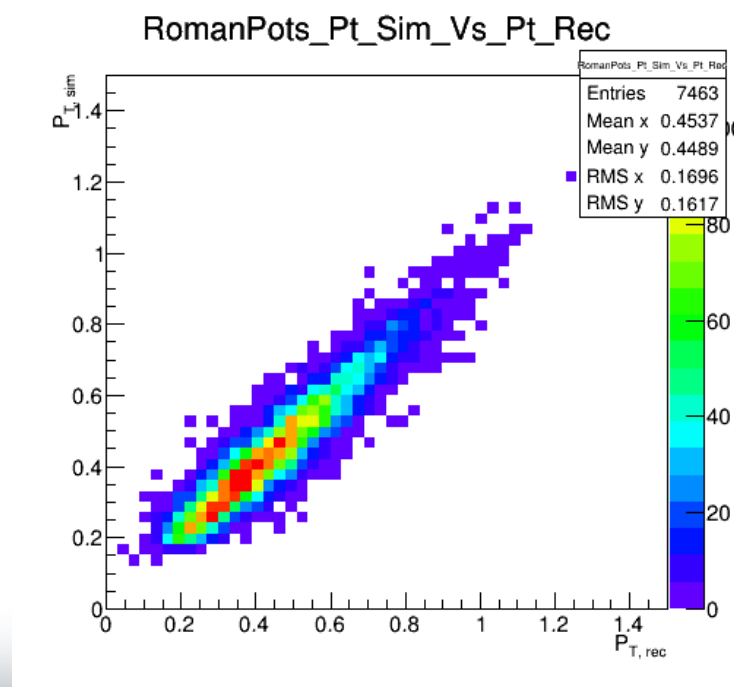
<u>High Divergence:</u> smaller β^* at IP, but bigger $\beta(z = 30m)$ -> higher lumi., larger beam at RP

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

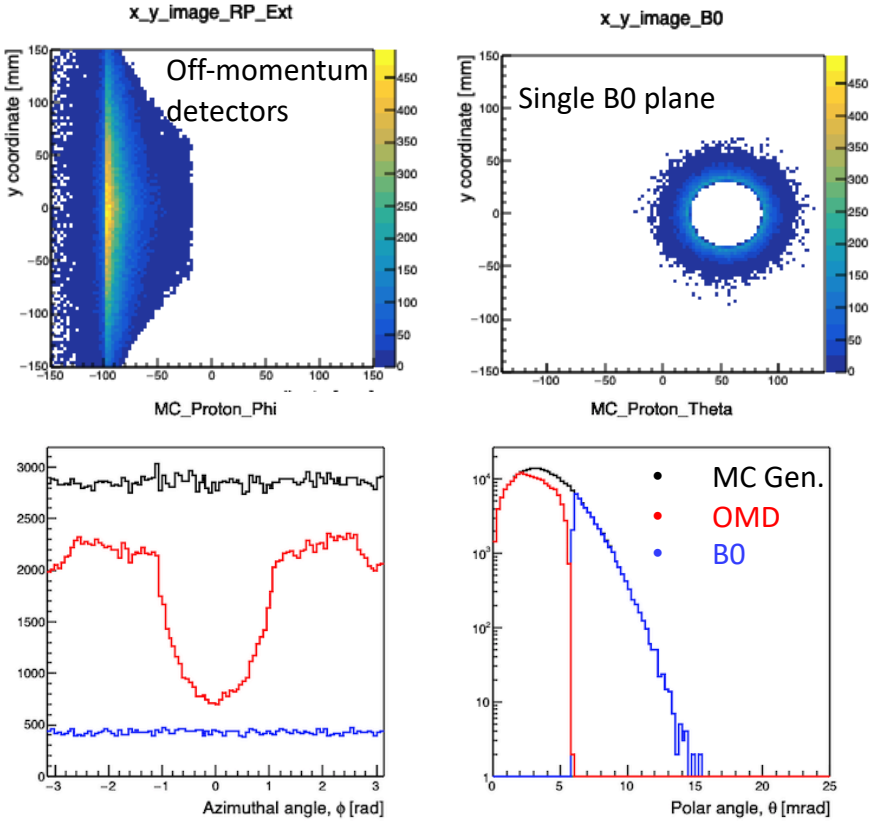
DVCS Snapshot – 275 GeV

- Reconstruction includes all smearing effects.
- Bin migration present, but the slope can still be accurately extracted.





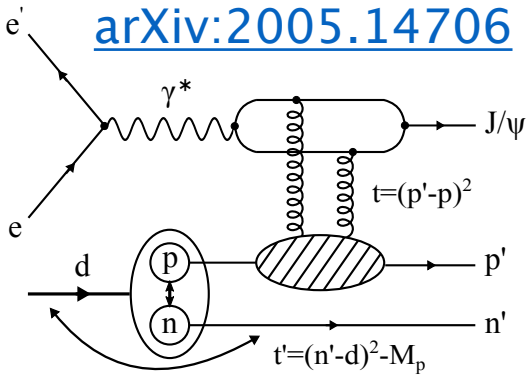
e+d -> p + n + j/Psi



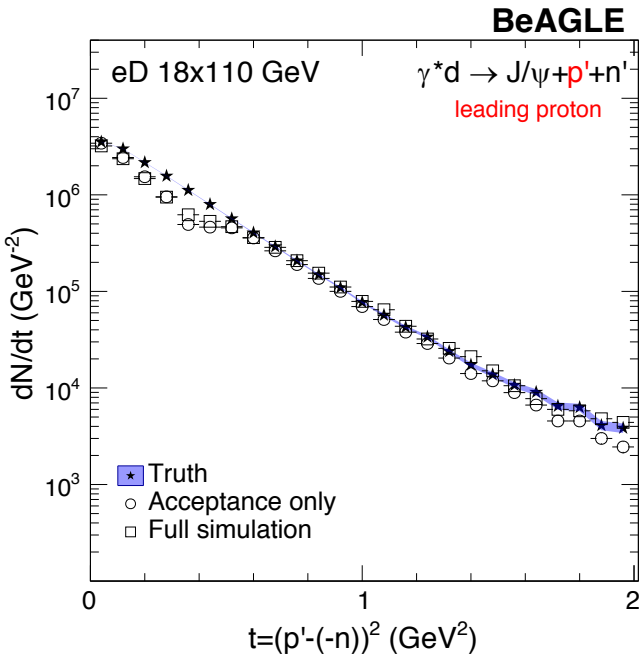
Neutron spectator/leading proton case.

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

arXiv:2005.14706



18x110GeV

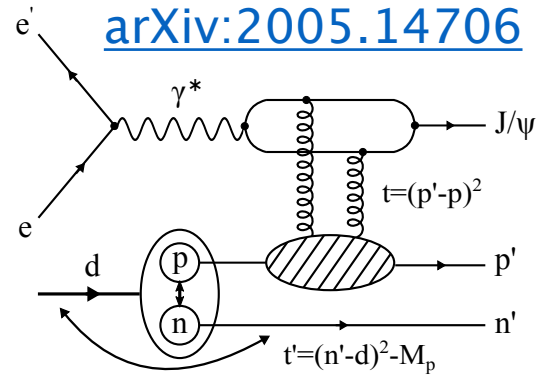


Good timing is assumed here (i.e. vertex smearing removed). If this contribution was not removed, the slope would be distorted.

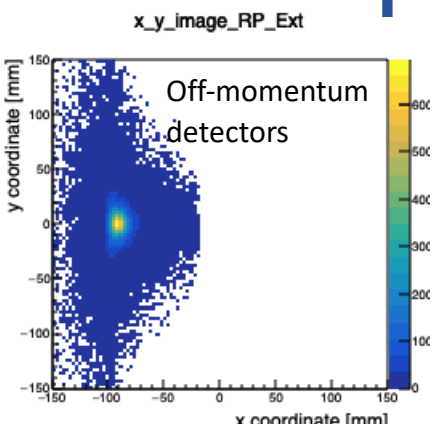
t-reconstruction using double-tagging (both proton and neutron). Takes advantage of combined B0 + off-momentum detector coverage.

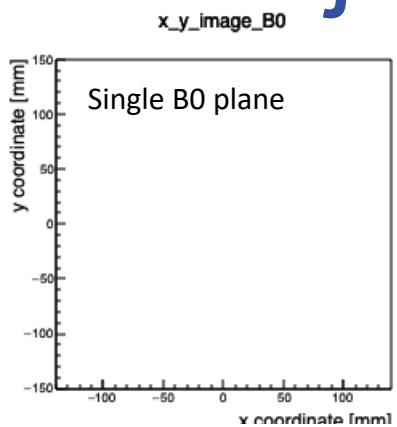
e+d -> p + n + j/Psi

arXiv:2005.14706

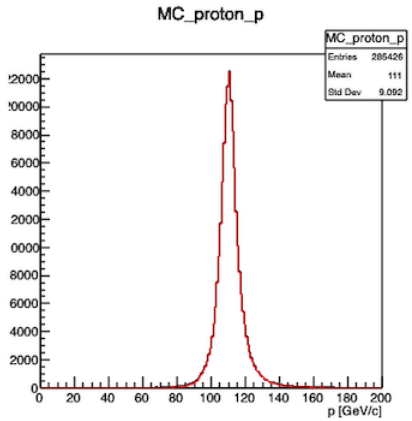


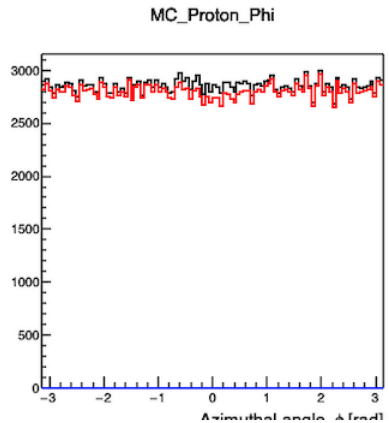
18x110GeV

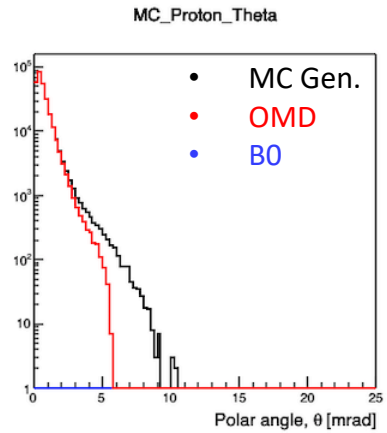




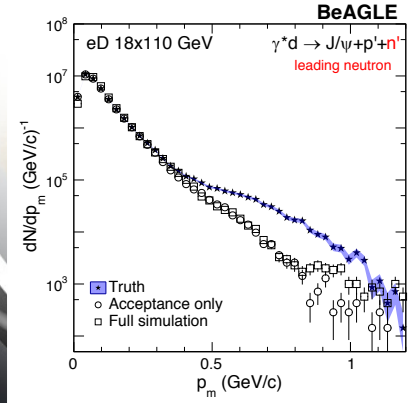
Particular process in BeAGLE: incoherent diffractive J/psi production off bounded nucleons.

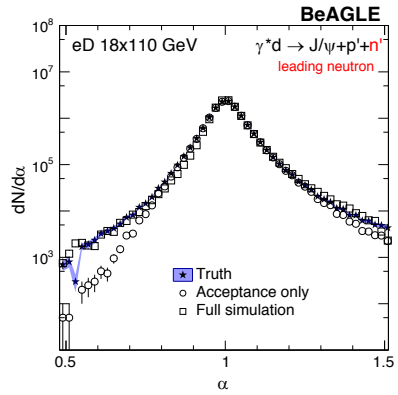






Proton spectator case.

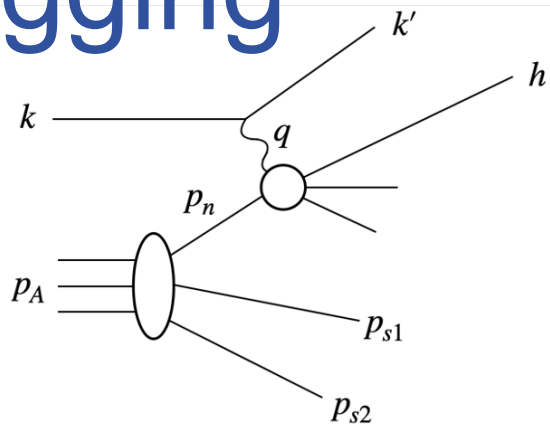


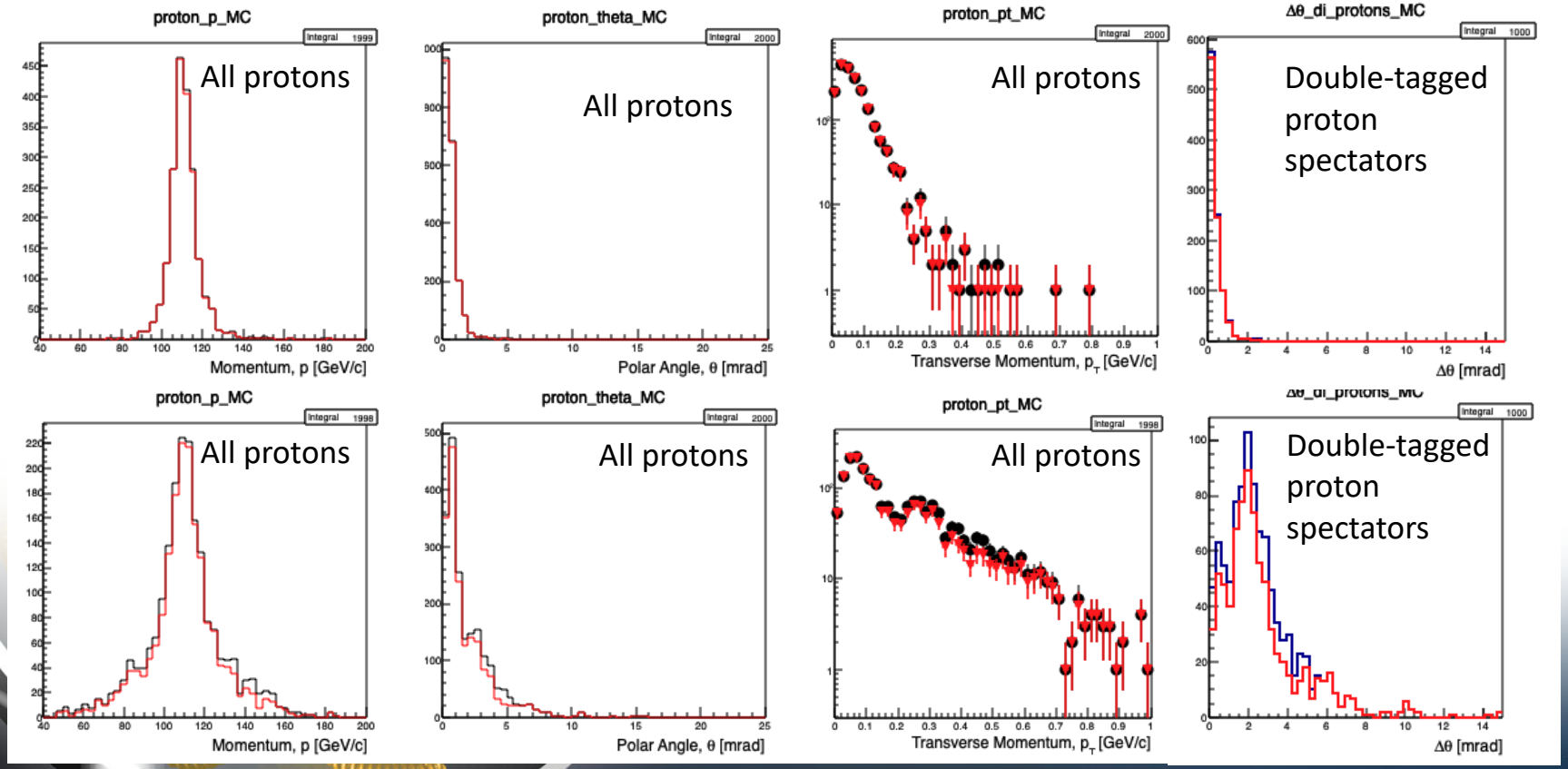


Some examples of observables (light-cone momentum fraction, α), and missing-momentum (p_m).

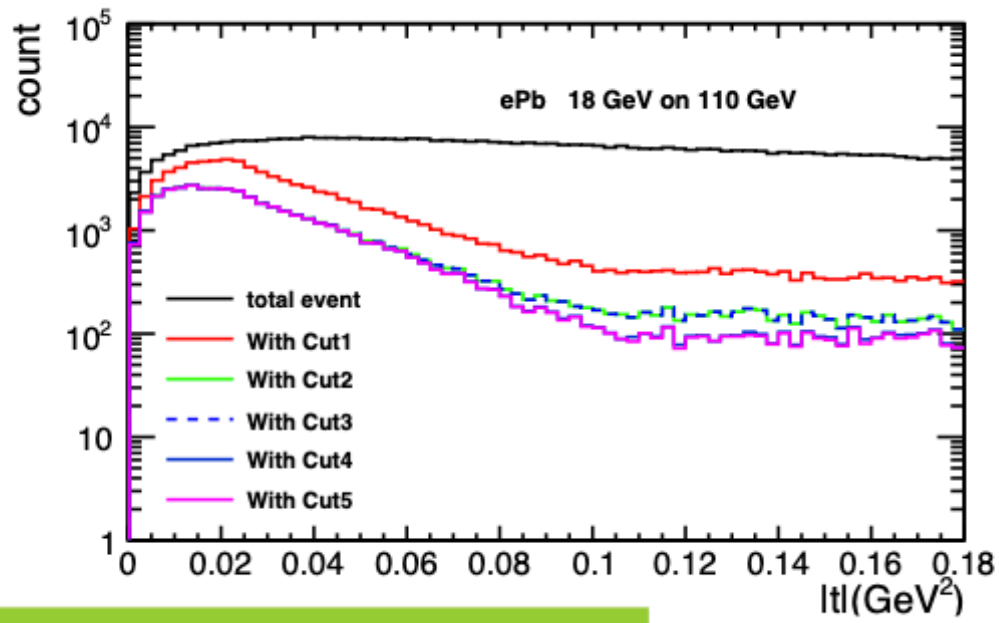
e+^{3}He spectator proton tagging

- Acceptance looks good for double tagging the protons.
- More detailed study underway.
  - Top row: 10x110GeV/n BeAGLE DIS
  - Bottom row: 10x110 GeV/n SRC





e+Pb Collisions in BeAGLE



The impact of the different detectors is studied by adding one requirement / cut after the other.

Cut1:
- no neutron in ZDC

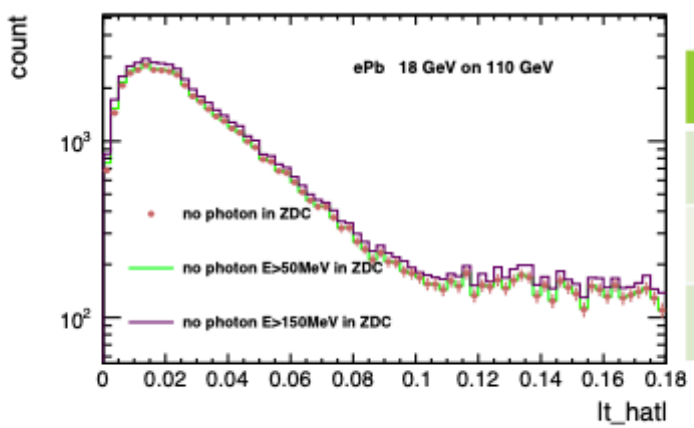
Cut2 :
- Cut1 + no photon ***E>50MeV*** in ZDC

Cut3:
- Cut2 + no proton in Roman Pots

Cut4:
- Cut3 + no proton in off-energy detector

Cut5:
- Cut4 + no proton in B0

Survived event count	
Total events	1000000
Cut1	132127
Cut2	66101
Cut3	66099
Cut4	61487
Cut5	55792



The survived events count after Cut2 with different energy cut on photon:

Survived event count	
E>150 MeV	71773
E>50MeV	66101
E>0 MeV	65278

Wan Chang

Lambda Decays

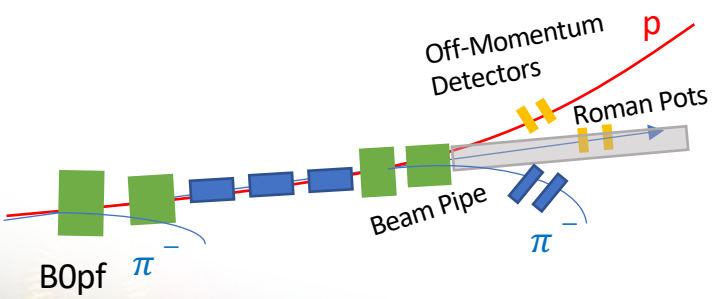
Example (10x100 GeV): ~100% detection for protons from Lambda. Significant loss $\pi -$along the beam line (FFQs) due to low momentum of those pions.

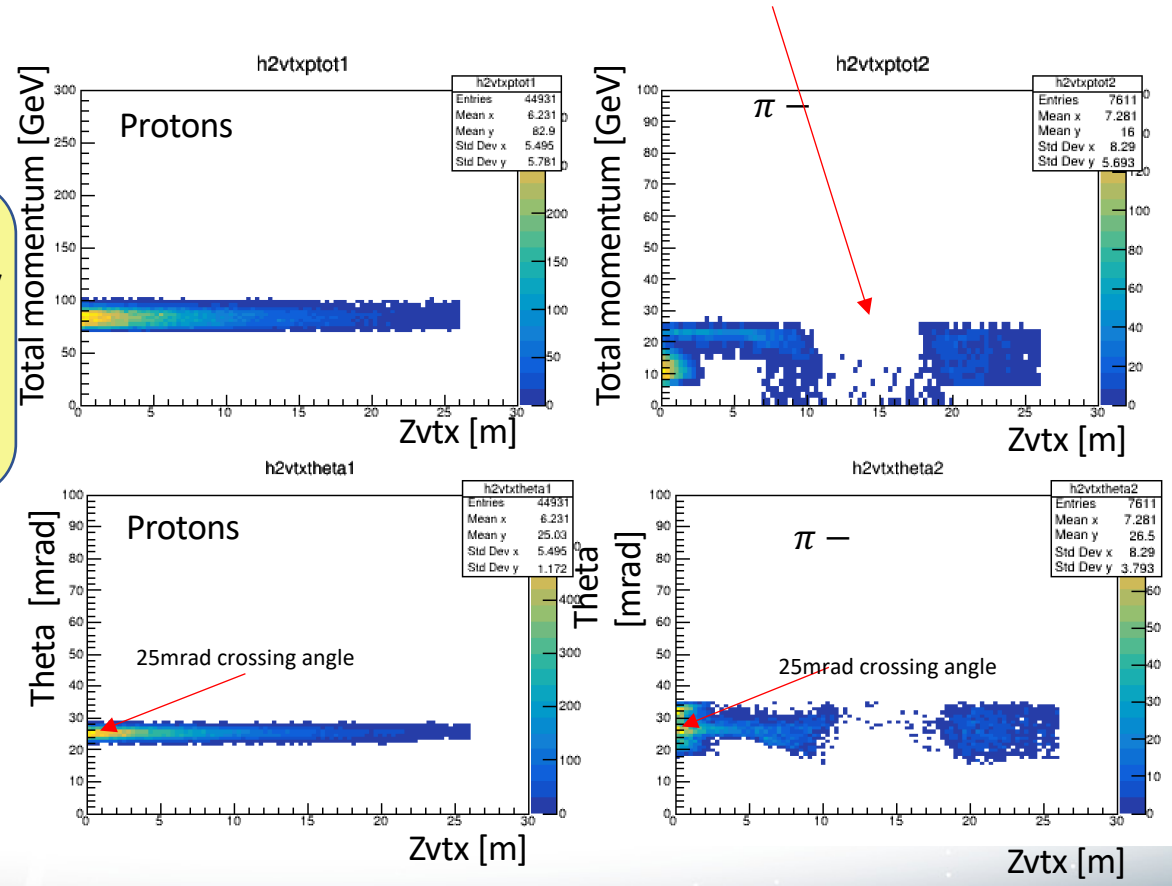
e p -> (K) -> e' + Λ + X

↳ p + π^-(Br~64%)

↳ n+ π^0 (Br ~36%)

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





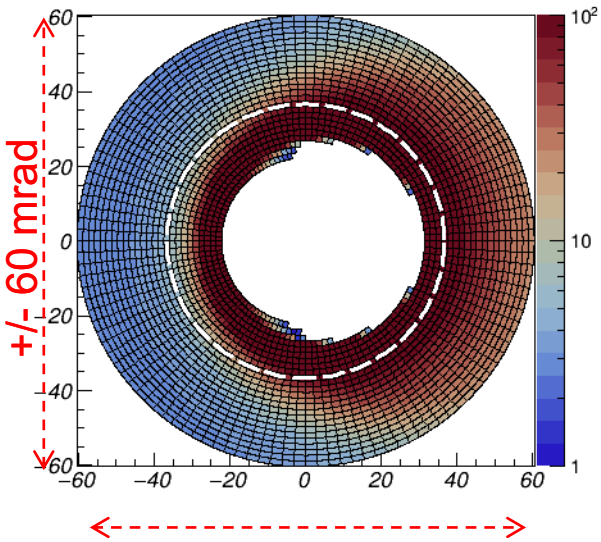
All plots: accepted particles

Slide credit: Julia Furletova

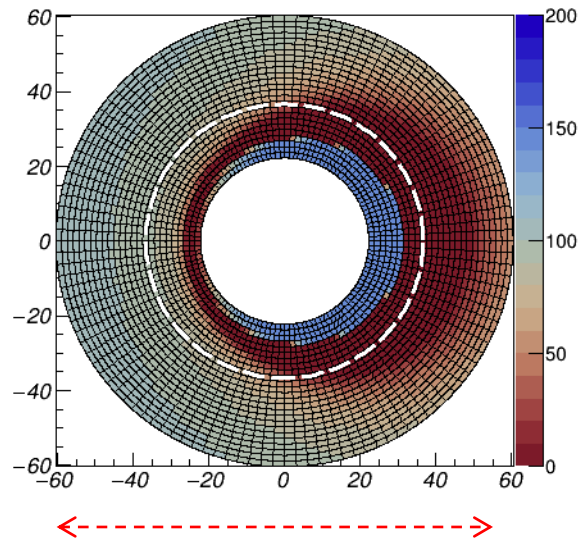
Some comments on the “less far” Forward Region

Hadron endcap acceptance & the beam pipe

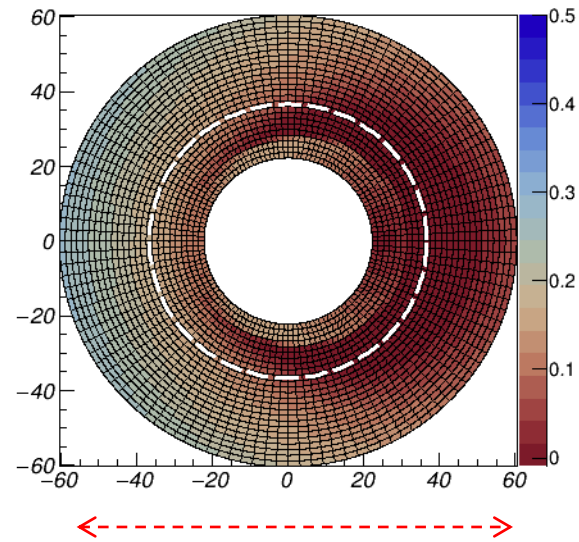
Material in acceptance, [%]



Max space available for Si tracker, [cm]

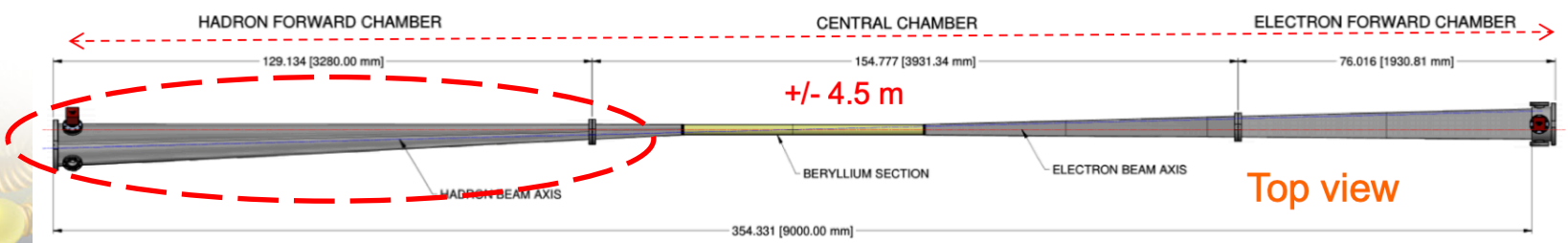


Max B*dl for Si tracker, [T*m]



- Plots: $3.5 < \eta < 4.5$; white circle: $\eta = 4.0$
- What can be the realistic η reach is a good question

Slide credit: A. Kiselev



Also: do not forget about the fiducial volume cut and lateral leakage close to the beam pipe

$\lvert\eta\rvert$ = 3.00	$\lvert\eta\rvert$ = 3.50	$\lvert\eta\rvert$ = 4.00	$\lvert\eta\rvert$ ~ 4.38	$\lvert\eta\rvert$ = 4.50
~99.5 mrad	~60.4 mrad	~36.6 mrad	25.0 mrad	~22.2 mrad

Azimuthal acceptance asymmetry in the h-endcap

remember: η in the h-endcap is counted relative to the hadron beam axis!

- Single axis solenoid:
  - Aligned with the incoming electron beam (want to minimize the synchrotron radiation) …
  - … therefore 25 mrad field axis slope in the h-endcap …
  - … therefore dramatically different bending for $\phi \sim 180^0$ and $\phi \sim 0^0$ at large η

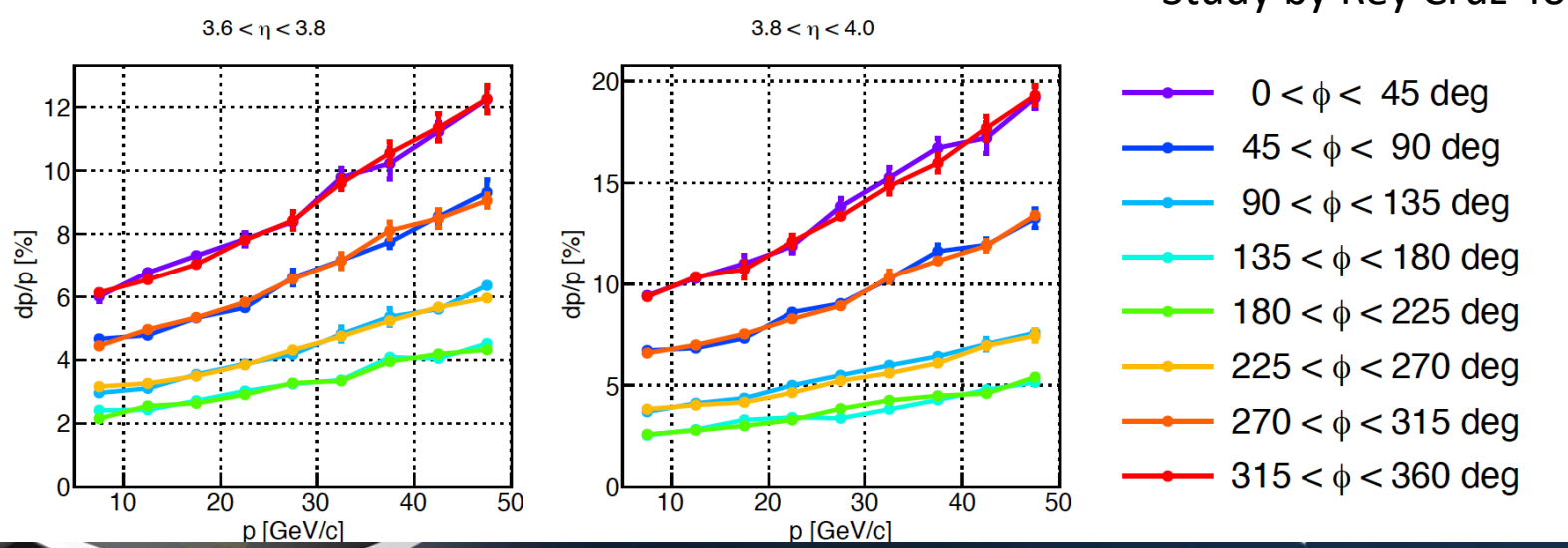
- A two-coil solenoid (with the halves aligned relative to the [eh]-going directions) is presently out of consideration:
  - Must be a very challenging design
  - Inevitable (and large) energy-dependent vertical excursion of the incoming electron beam
  - Certainly not an option for the existing BaBar magnet

Slide credit: A. Kiselev

Study by Rey Cruz-Torres

Forward silicon tracker momentum resolution study

Assume 5 ITS2-like stations, 3T field and 1m lever arm



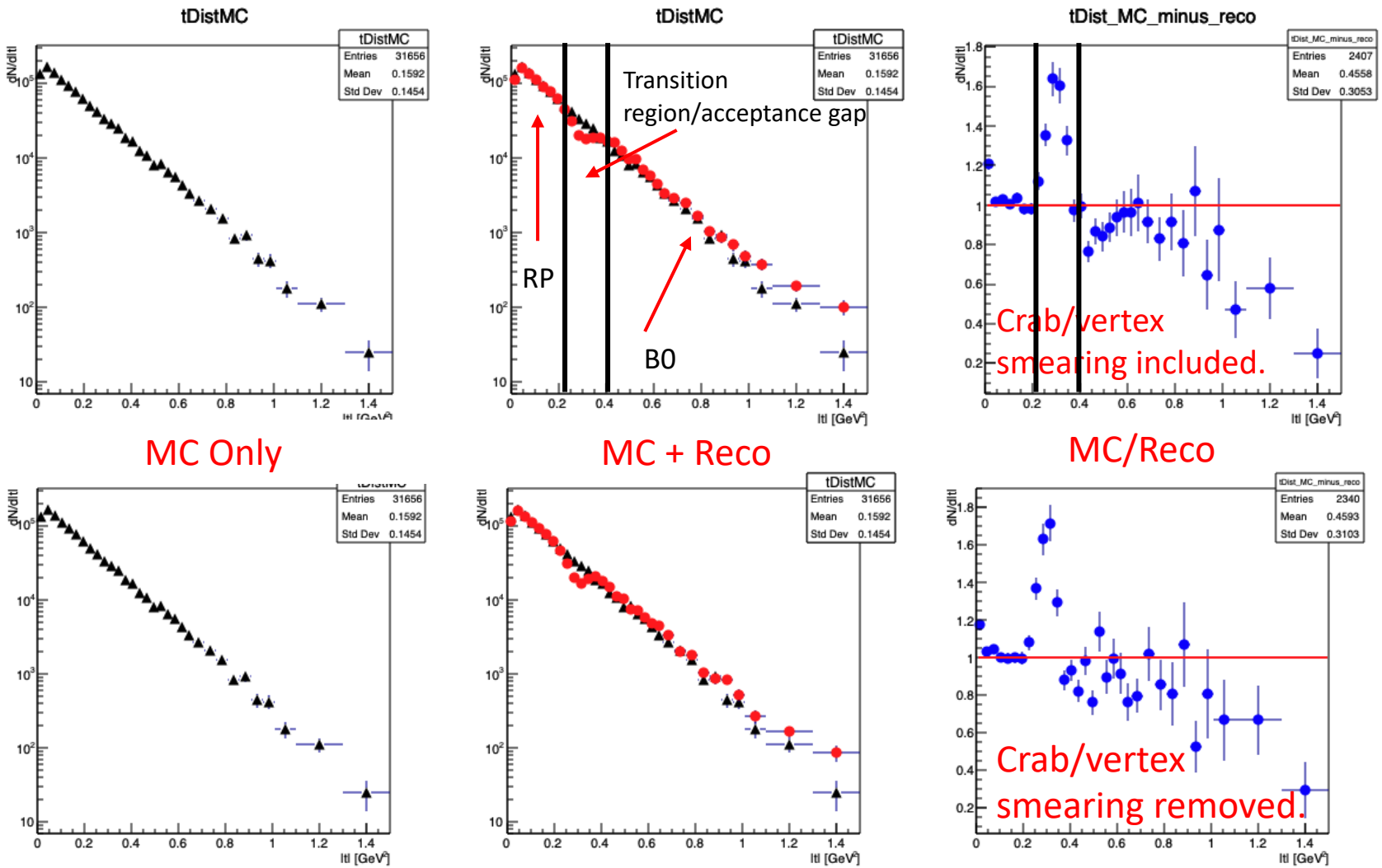
Takeaways

- Acceptances in the FF region of the EIC IR are well-understood.
  - Changes at this point will be minor and mostly to do with the addition of the final vacuum design.
- Resolutions for FF detectors look very good.
  - Not the limiting factor in performing analysis.
  - Several studies done, most comprehensive is on the arXiv:2005.14706.
- EIC R&D groups studying detector technologies for the FF region.

Backup

How does the crab smearing affect reconstruction of t?

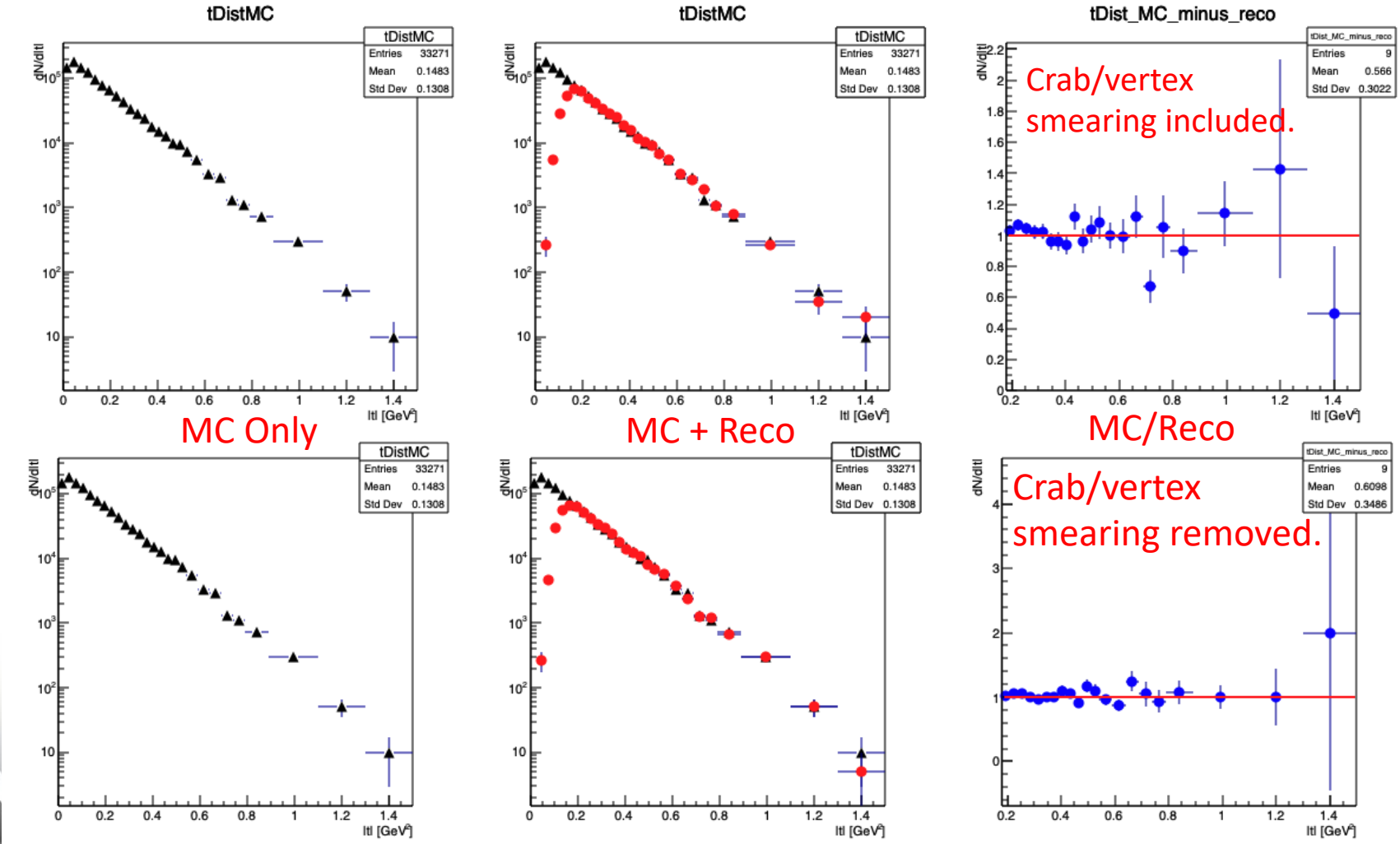
5x100 GeV
0.016 < x < 0.025
HA



Notes: 1) Above |t|= 0.2, B0 begins to be mainly used. 2) the peak at 0.35 is due to the acceptance gap between the Roman Pots and B0.

How does the crab smearing affect reconstruction of t?

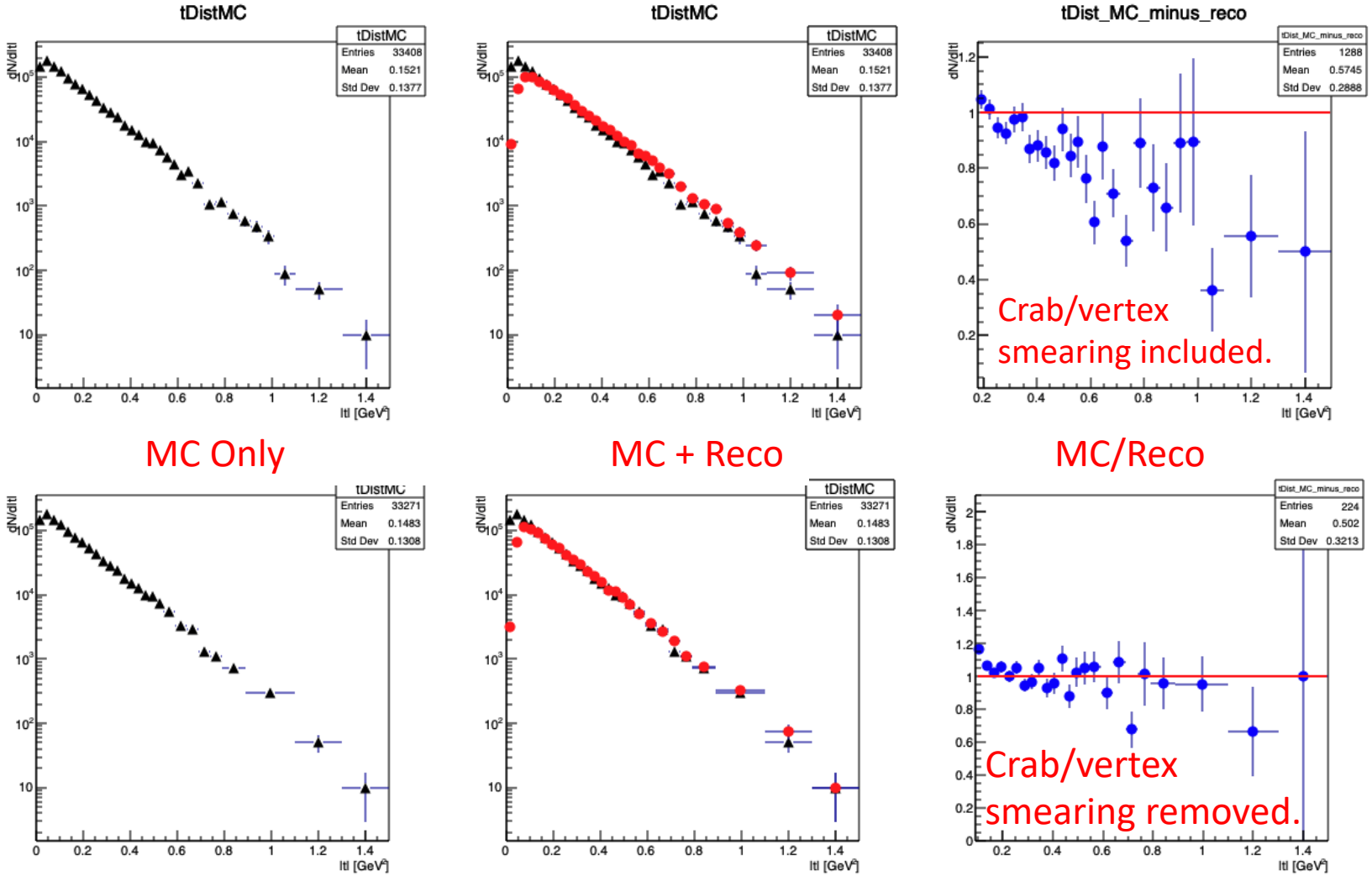
18x275 GeV
$0.9 < Q^2 < 50\ GeV^2$
$0.0016 < x < 0.0025$
HD (v2) – new parameters from C-AD



Note: The first few bins are cutoff, where the ratio is dominated by acceptance.

How does the crab smearing affect reconstruction of t?

18x275 GeV
$0.9 < Q^2 < 50\ GeV^2$
$0.0016 < x < 0.0025$
HD (v2) – new parameters from C-AD
crossing angle = 50 mrad

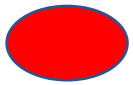


Reminder: Timing

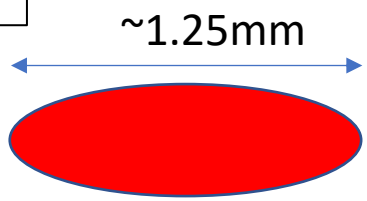
For exclusive reactions measured with the Roman Pots we need good timing to resolve the position of the interaction within the proton bunch. But what should the timing be?

RMS hadron bunch length ~10cm*.

*based on "ultimate" machine performance.



Looking along the beam with no crabbing.



What the RP sees.

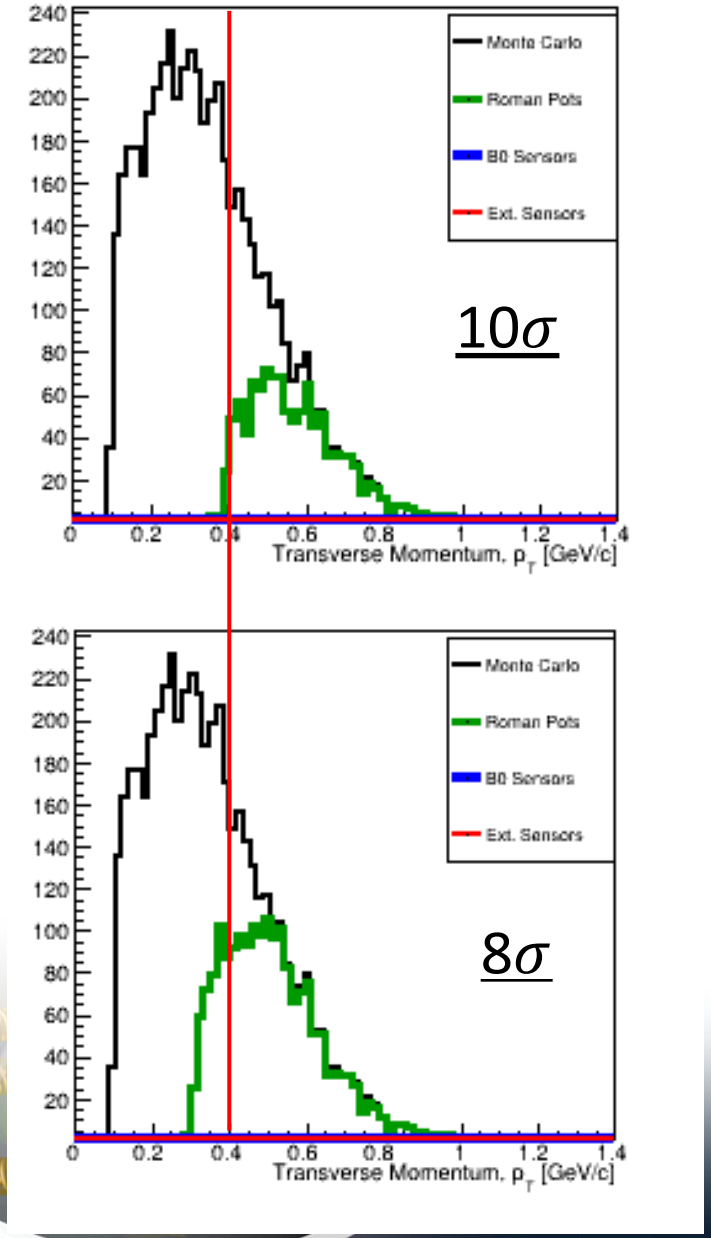
- Because of the rotation, the Roman Pots see the bunch crossing **smeared in x**.
- Vertex smearing = 12.5mrad (half the crossing angle) * 10cm = **1.25 mm**
- If the effective vertex smearing was **for a 1cm bunch**, we would have **0.125mm** vertex smearing.
- The simulations were done with these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

Conclusions from Timing

- With improved optics, the angular divergence and vertex smearing contributions become comparable.
  - Note: we expect improved optics for the Roman Pots for both the HD and HA configurations – we need the resolution to be good for both since the HD configuration helps populate the tails.
- A larger crossing angle (up to 50 mrad) is under consideration.
  - This would make the vertex smearing the dominant contribution, and it has a clear effect on the t-resolution.
- Timing will also be required for background rejection, which is being investigated now.

Some Comparisons – High Divergence



Move sensors closer to beam in increments of "1σ".

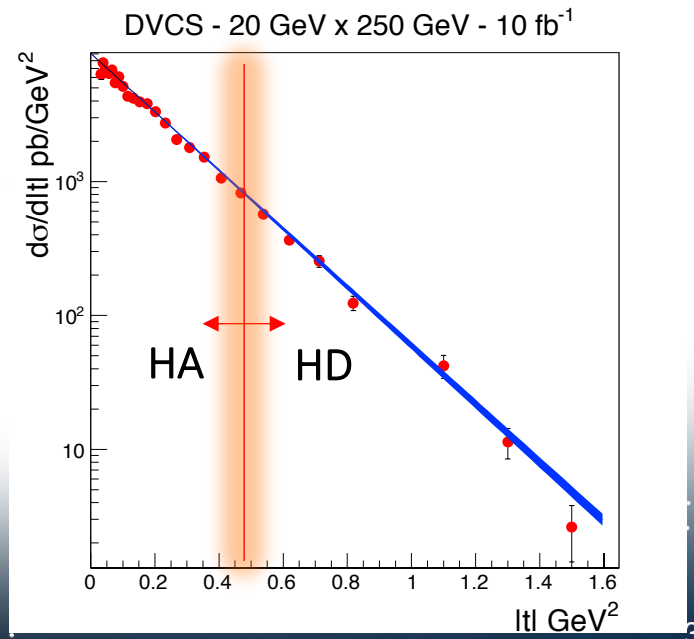
1σ = 3.58 mm
(for the high divergence optics)

Moving the sensors ~7.2 mm closer (from 10 to 8σ) gains about 100 MeV in pt-acceptance.

Reminder: Divergences and Optics Parameters

- Two configurations
  - **High divergence (HD)** – beta functions tuned such that small beam at IP (higher luminosity), at the cost of larger beam at Roman Pots (meaning worse low-pt acceptance).
  - **High acceptance (HA)** – Larger beam at IP, lower luminosity, better low-pt acceptance at the Roman Pots.

	18x275 GeV		10x100 GeV	
	HA	HD	HA	HD
RMS $\Delta\theta_H$, (urad)	65	133	180	203
RMS $\Delta\theta_V$, (urad)	277	251	243	227
Luminosity 10^{33} $cm^{-2}s^{-1}$	0.94	1.93	4.07	4.35



Note: there are ongoing discussions with C-AD about different configurations that significantly reduce divergence. One of those test cases was used previously to see what it did to the smearing.

Reminder: Comparison

- 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

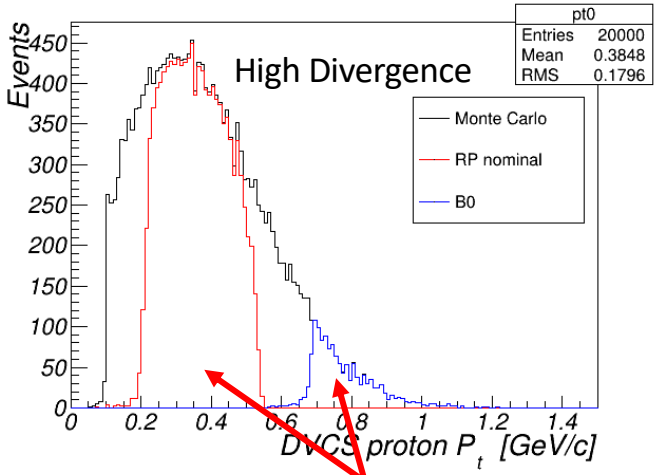
Current Parameters in Use

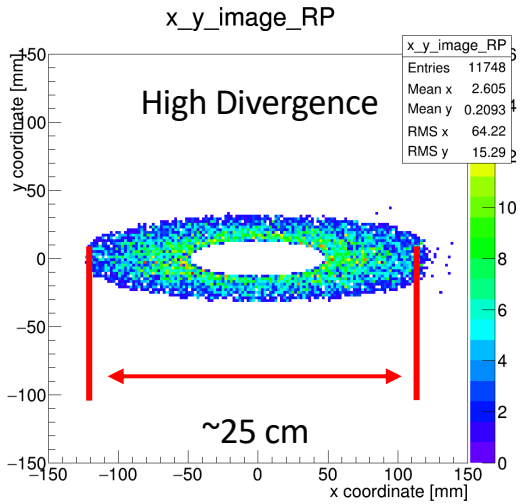
	275GeV	275GeV	275GeV		100GeV	100GeV
Configuration	**HA**	**HD**	**HD v2**		**HA**	**HD**
RMS $\Delta\theta_H$, (urad)	65	132	119		180	203
RMS $\Delta\theta_V$, (urad)	229	253	119		243	227

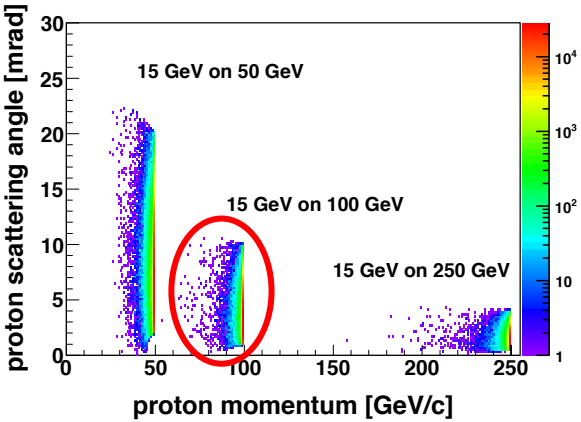
Angular Divergence

- The above divergences are essentially unchanged compared to what was studied previously.
  - ”HD v2” is a new set of parameters we are using to evaluate the effect of symmetric divergences, and smaller divergences.
- 500um x 500um pixels used for the Roman Pots.
- 20um x 20um pixels used for the B0 sensors (in backup).
- The smaller angular divergence configuration(s) cause the overall smearing contribution from divergences and crab cavity/vertex smearing to be comparable in magnitude.

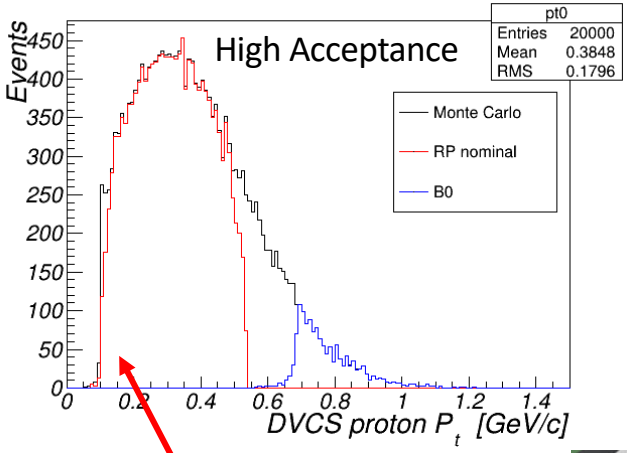
100 GeV DVCS protons

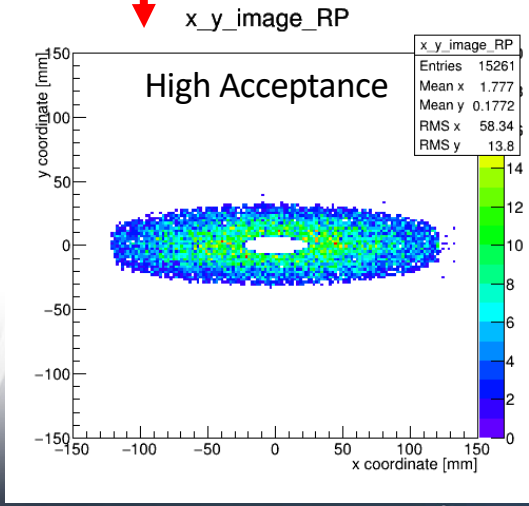






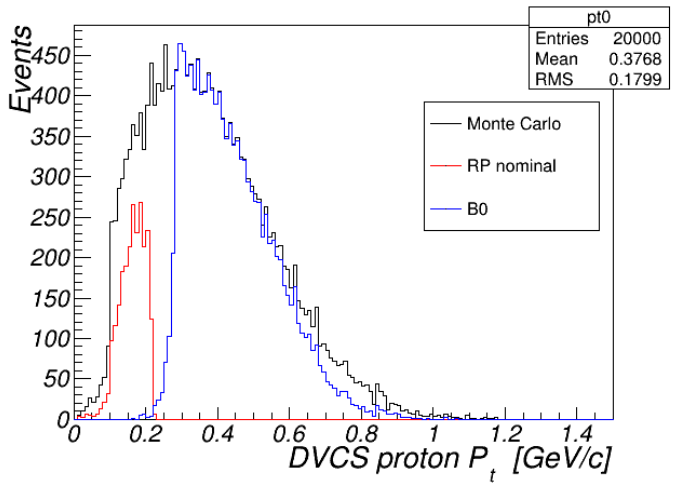
Need both detector systems together here!

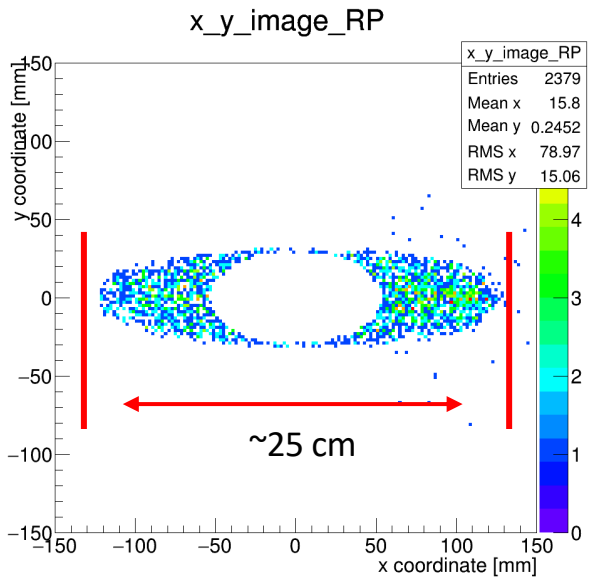


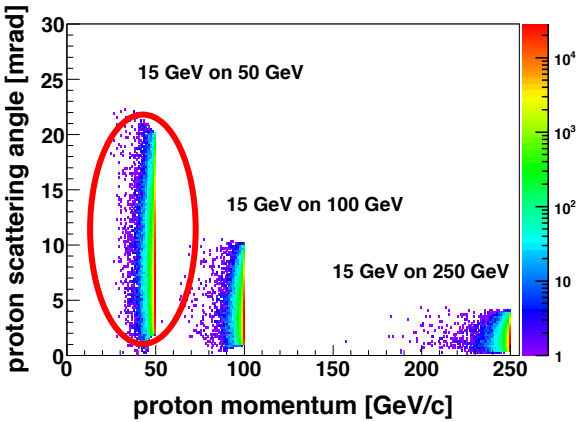


Improves low p_t acceptance.

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.