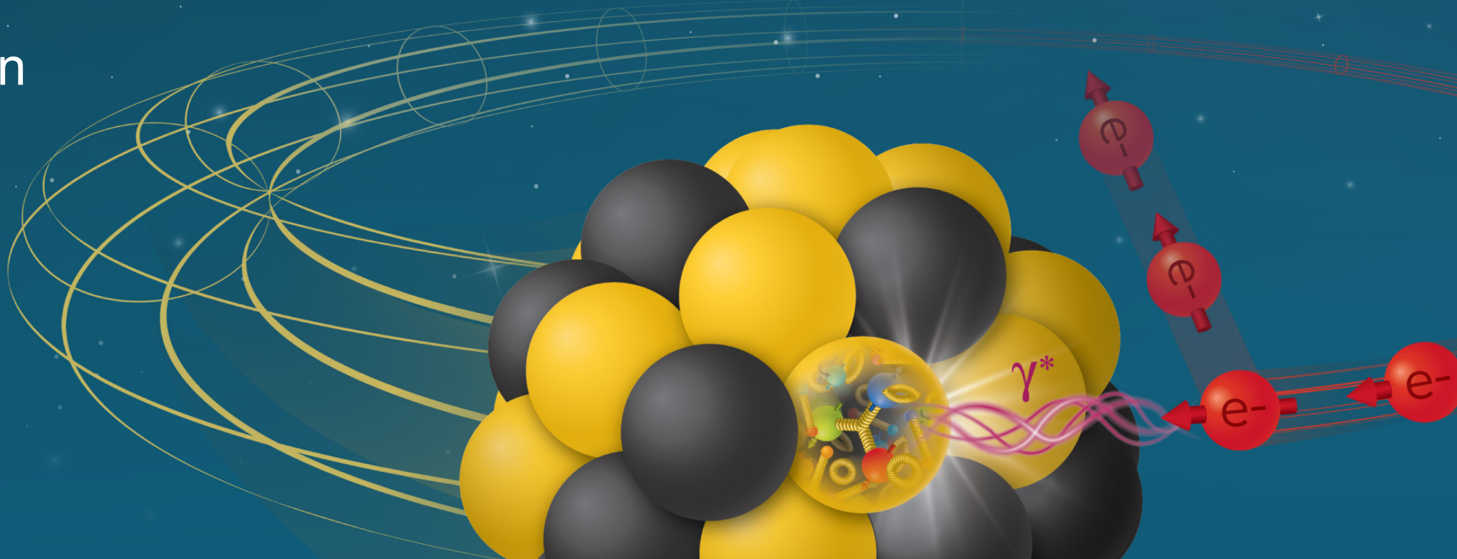
Partonic Imaging at the EIC

Alex Jentsch (BNL)

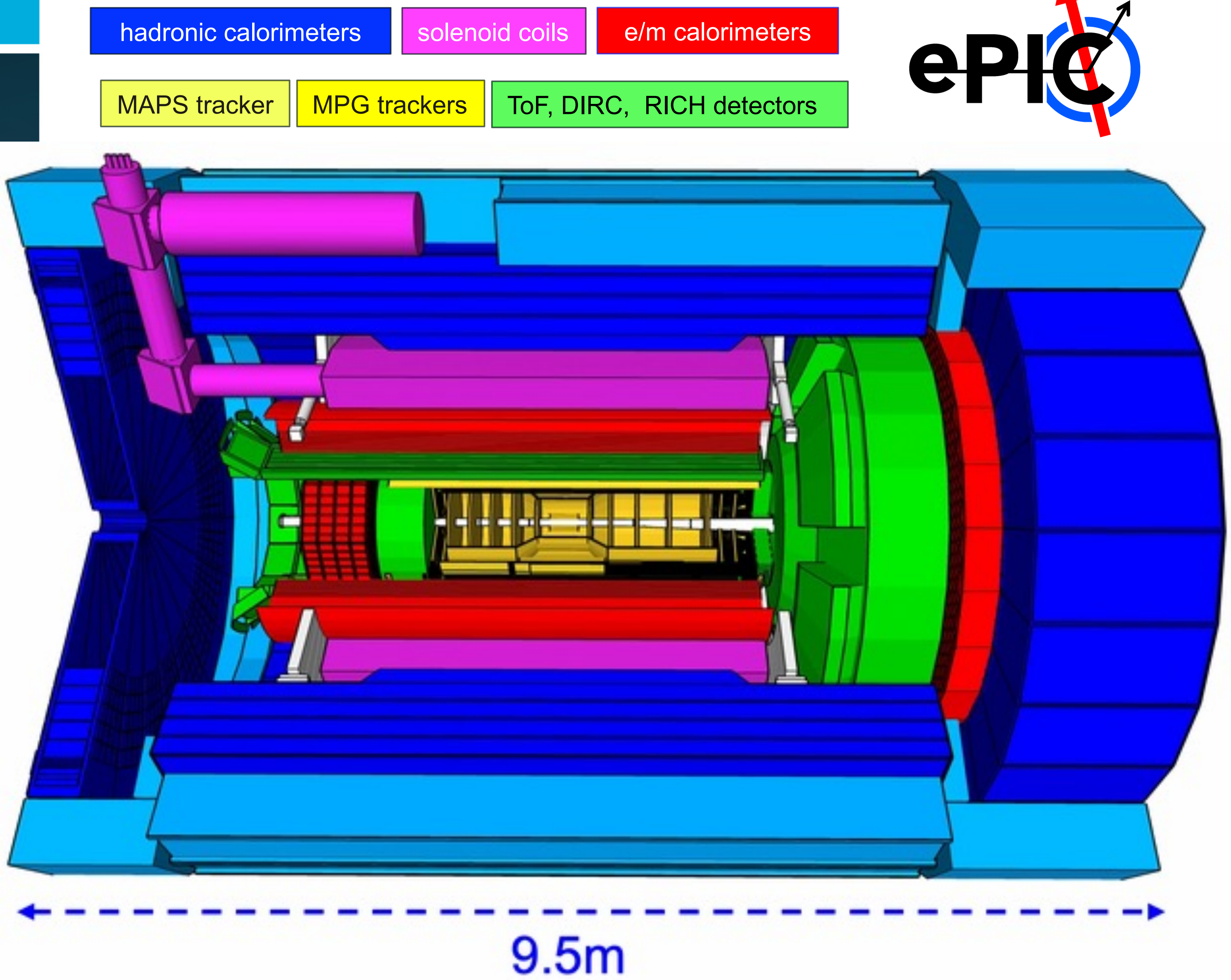
Towards Improved Hadron Femtography in Hard Exclusive Reactions

August 6th, 2024
ECT*, Trento, Italy (remote)

Electron-Ion Collider

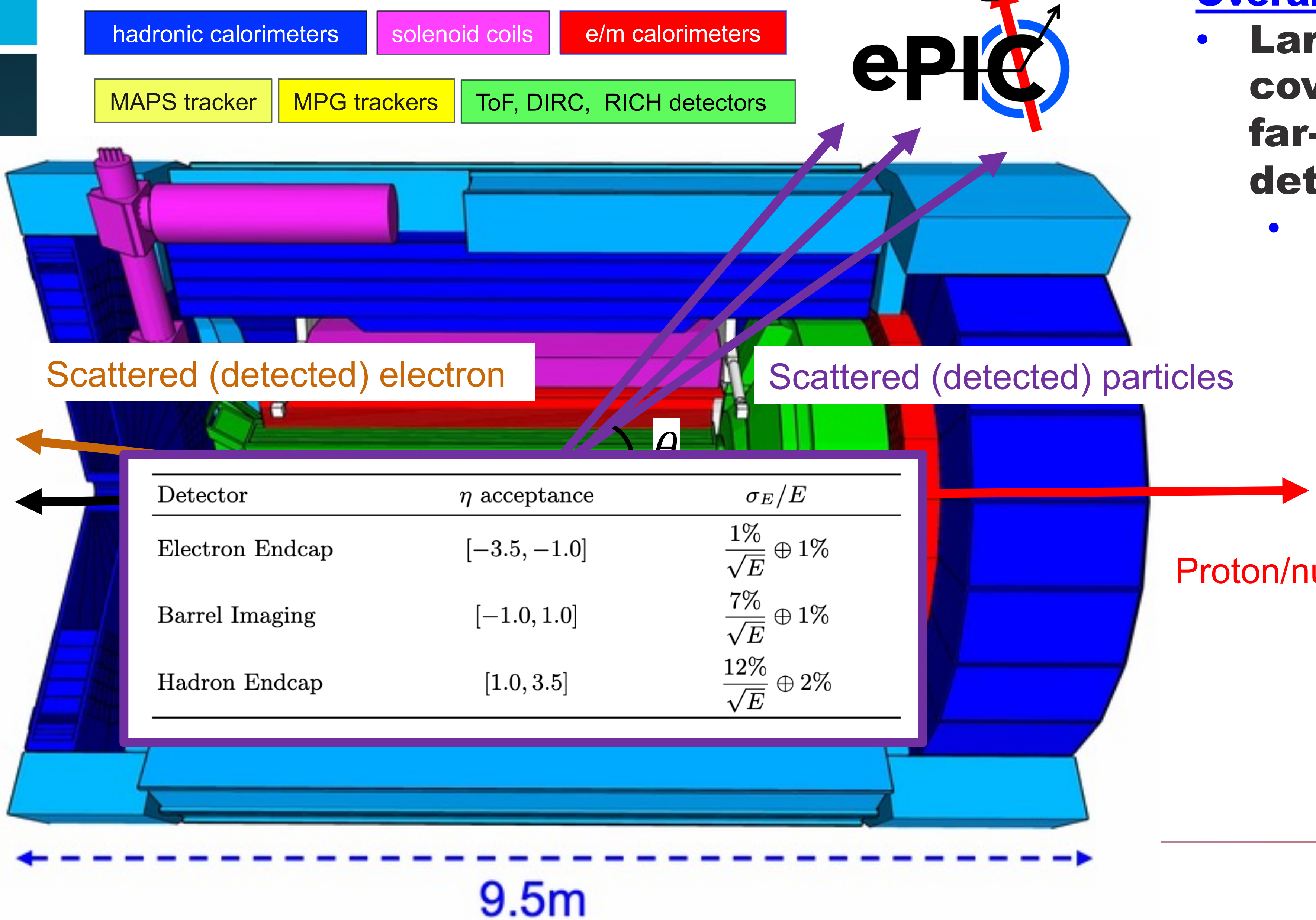


Accessing Exclusive Reactions at the EIC



See Talk from Charlotte for full discussion of ePIC!

Accessing Exclusive Reactions at the EIC

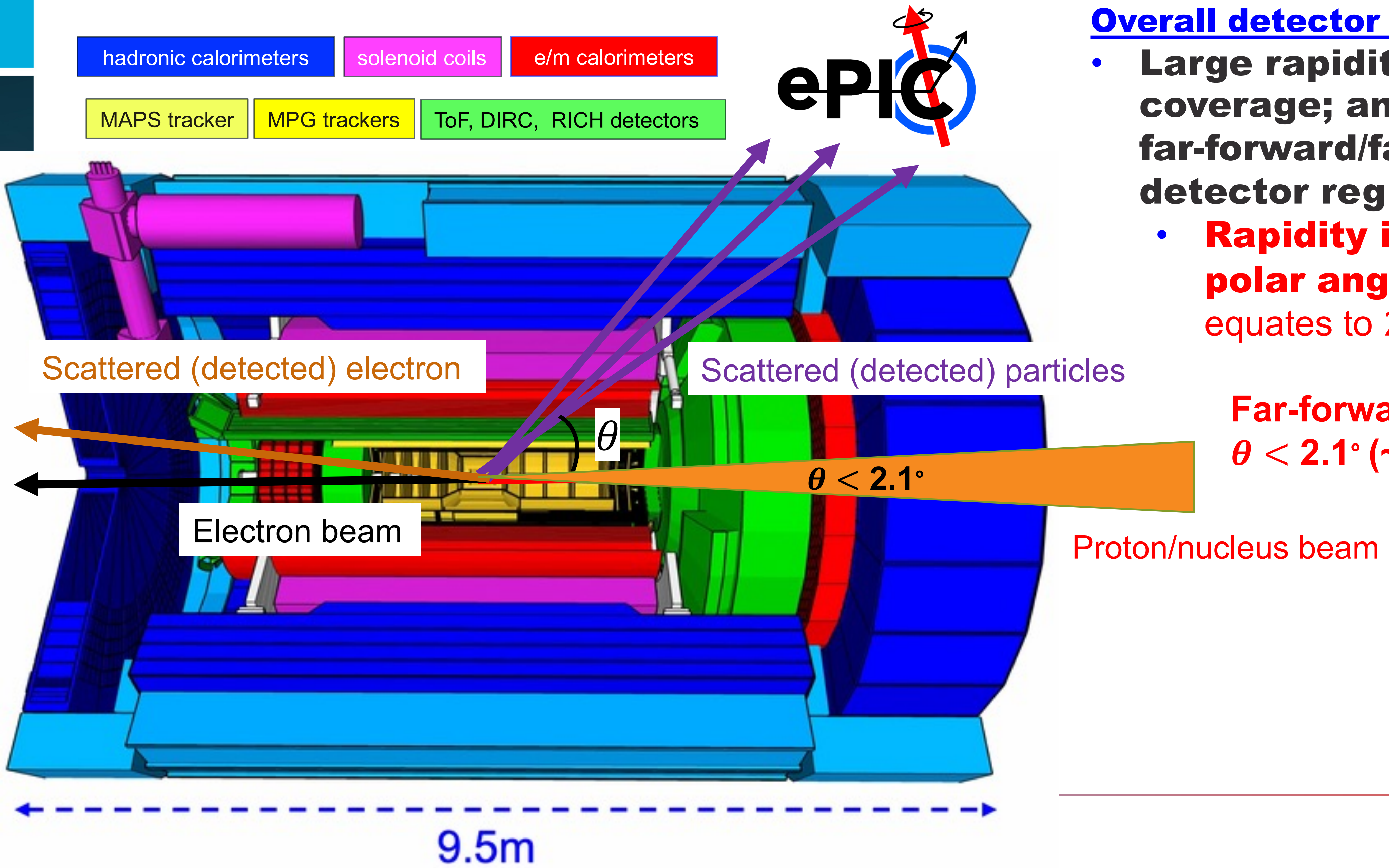


Detector	η acceptance	σ_E/E
Electron Endcap	$[-3.5, -1.0]$	$\frac{1\%}{\sqrt{E}} \oplus 1\%$
Barrel Imaging	$[-1.0, 1.0]$	$\frac{7\%}{\sqrt{E}} \oplus 1\%$
Hadron Endcap	$[1.0, 3.5]$	$\frac{12\%}{\sqrt{E}} \oplus 2\%$

Overall detector requirements:

- **Large rapidity (-4 < η < 4) coverage; and far beyond in far-forward/far-backward detector regions**
  - **Rapidity is related to the polar angle → 0 < η < 4** equates to $2.1^\circ < \theta < 90^\circ$

Accessing Exclusive Reactions at the EIC



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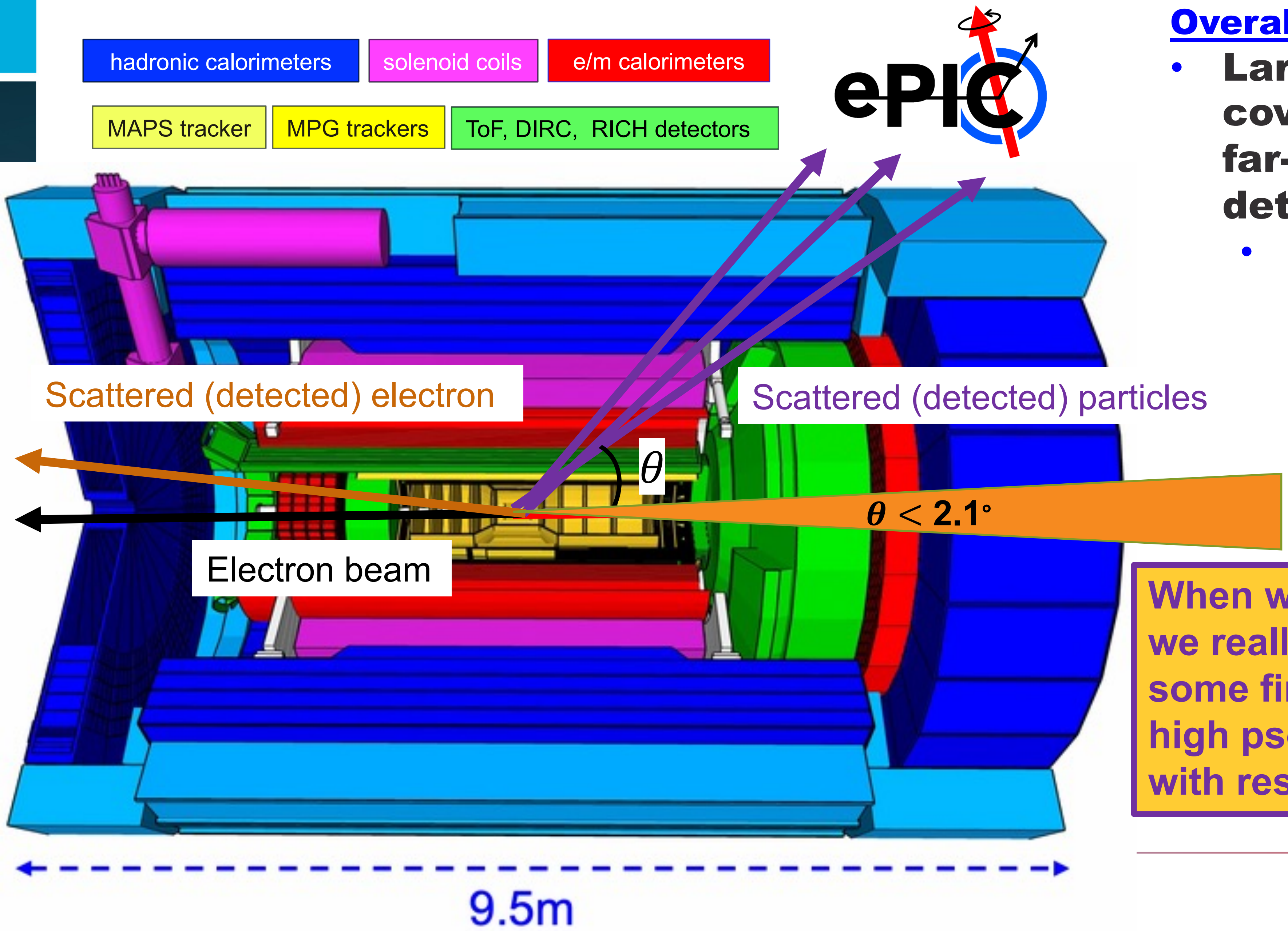
Far-forward here means $\theta < 2.1^{\circ}$ (~37 mrad)

Accessing Exclusive Reactions at the EIC



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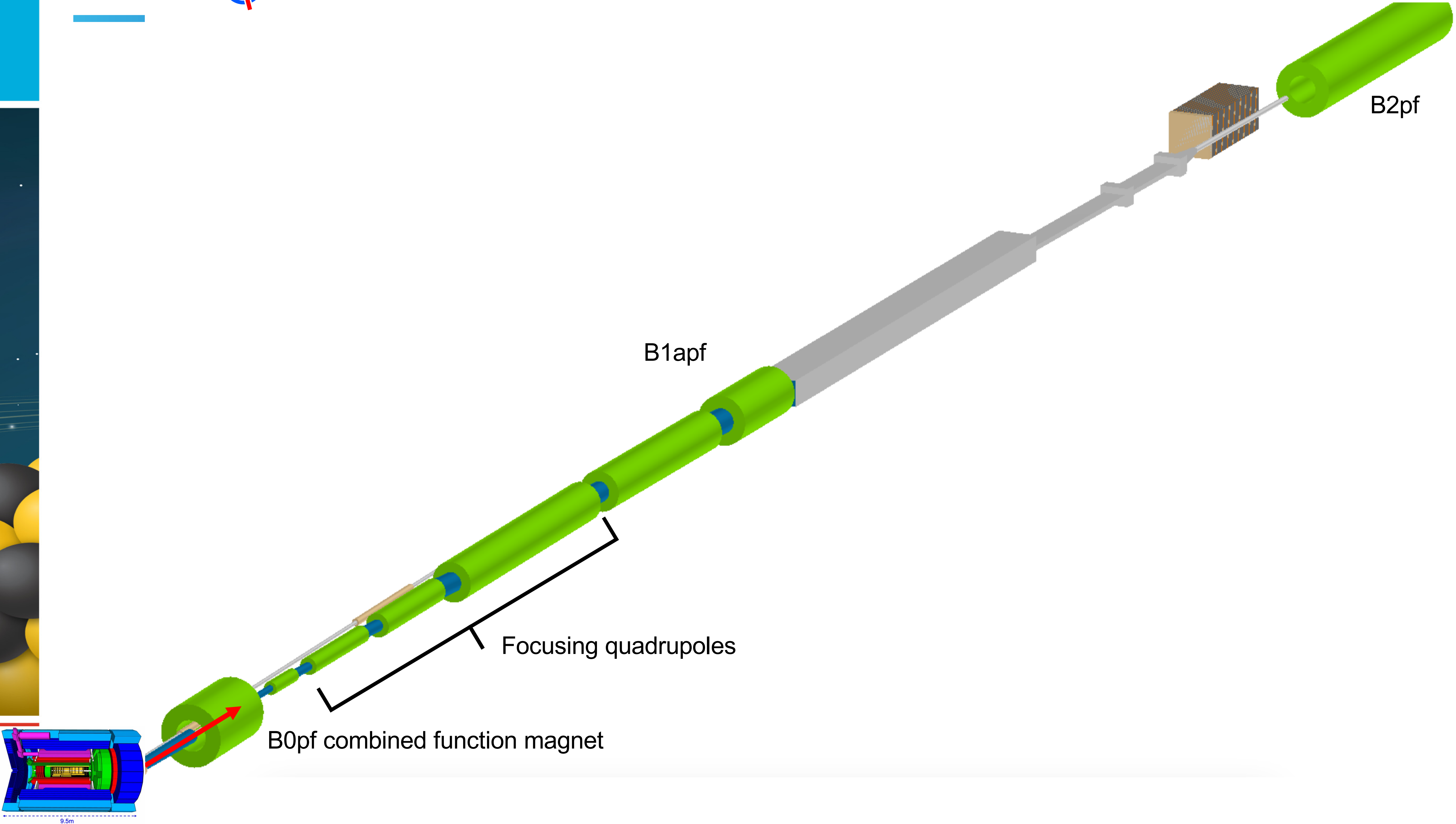
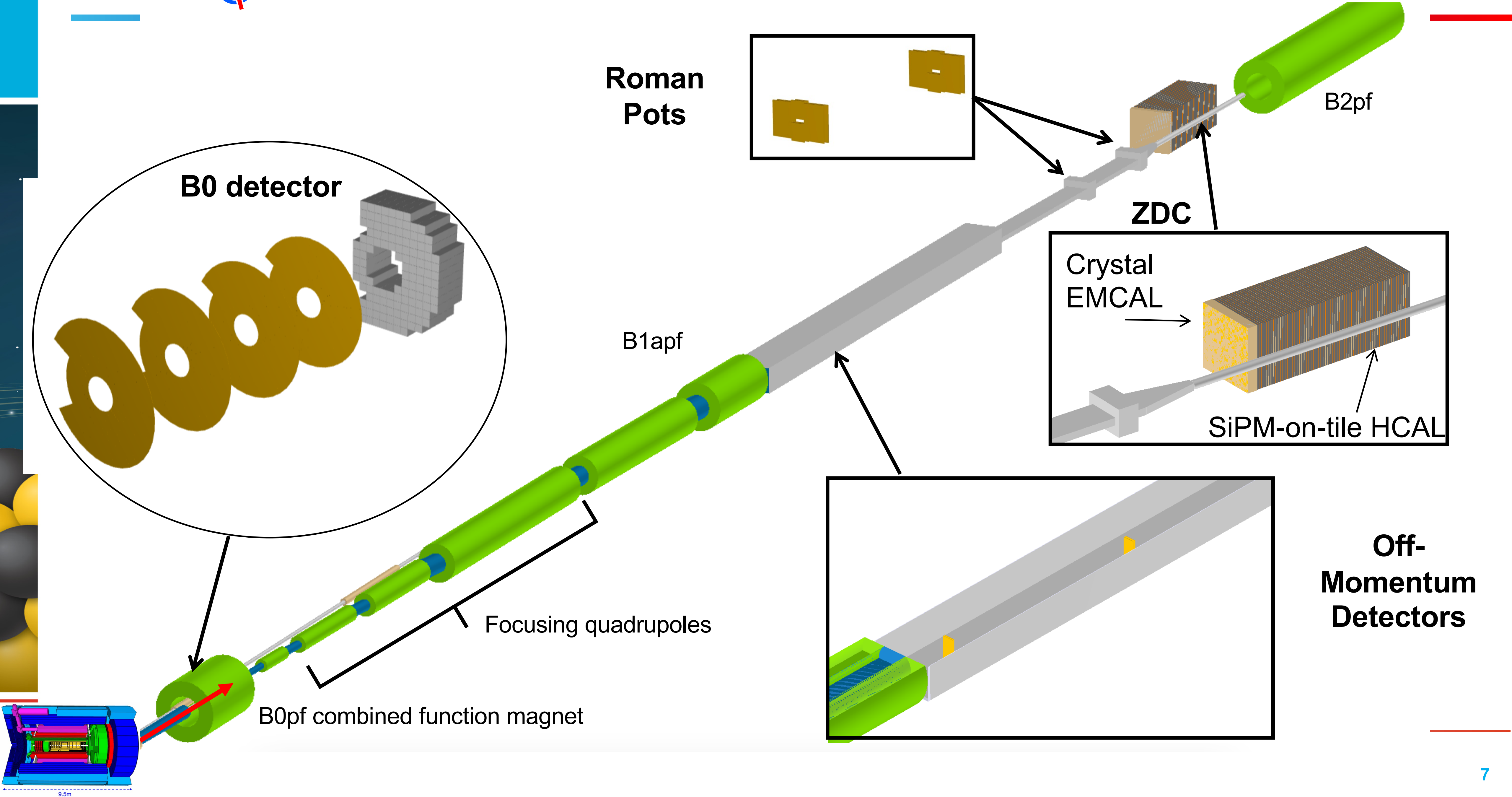
Far-forward here means θ < 2.1° (~37 mrad)

When we say "far-forward" physics, we really just mean interactions with some final state particles at very high pseudorapidity (or small angle with respect to the beam).

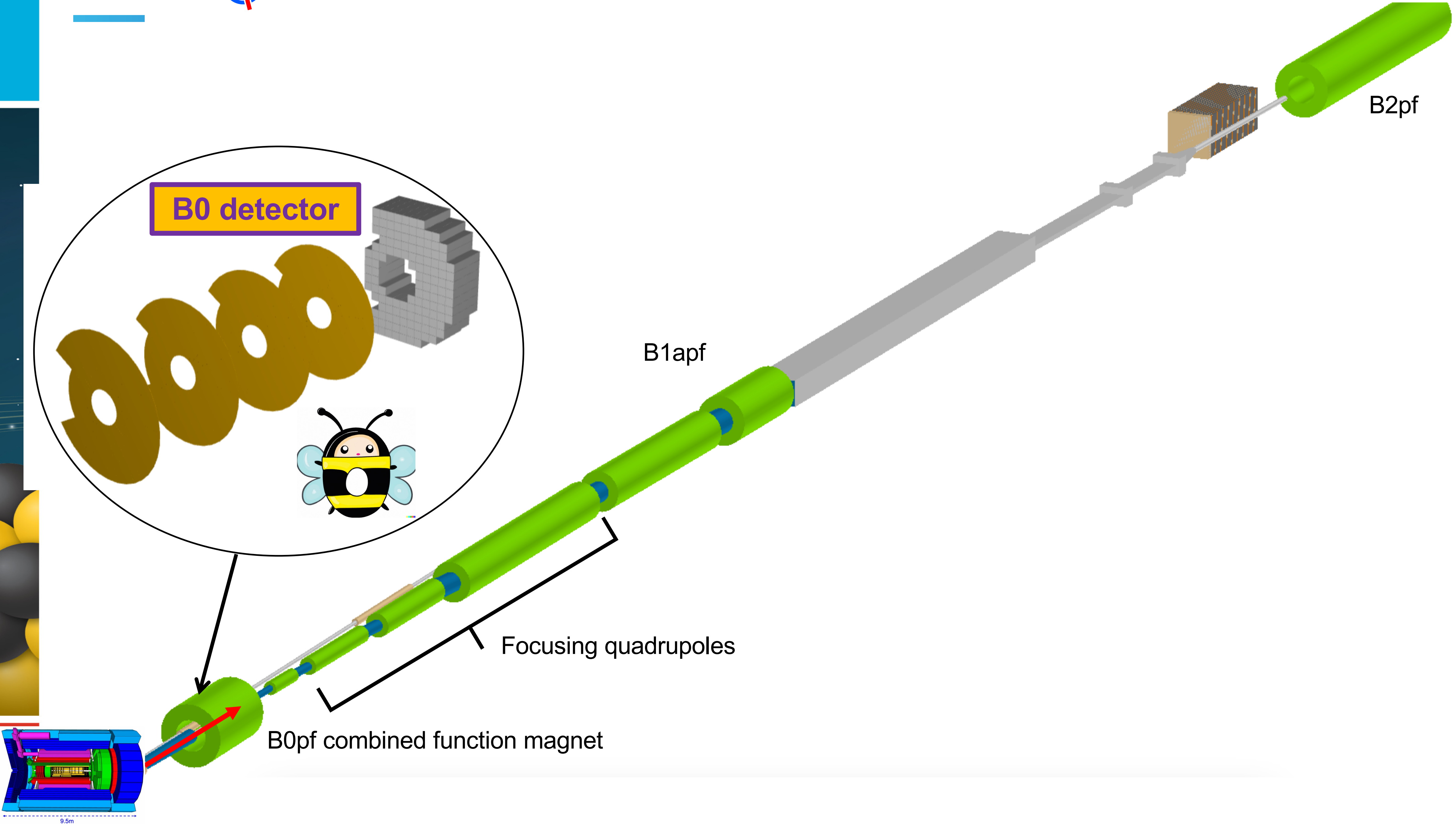
The ePIC Far-Forward Detectors



The ePIC Far-Forward Detectors

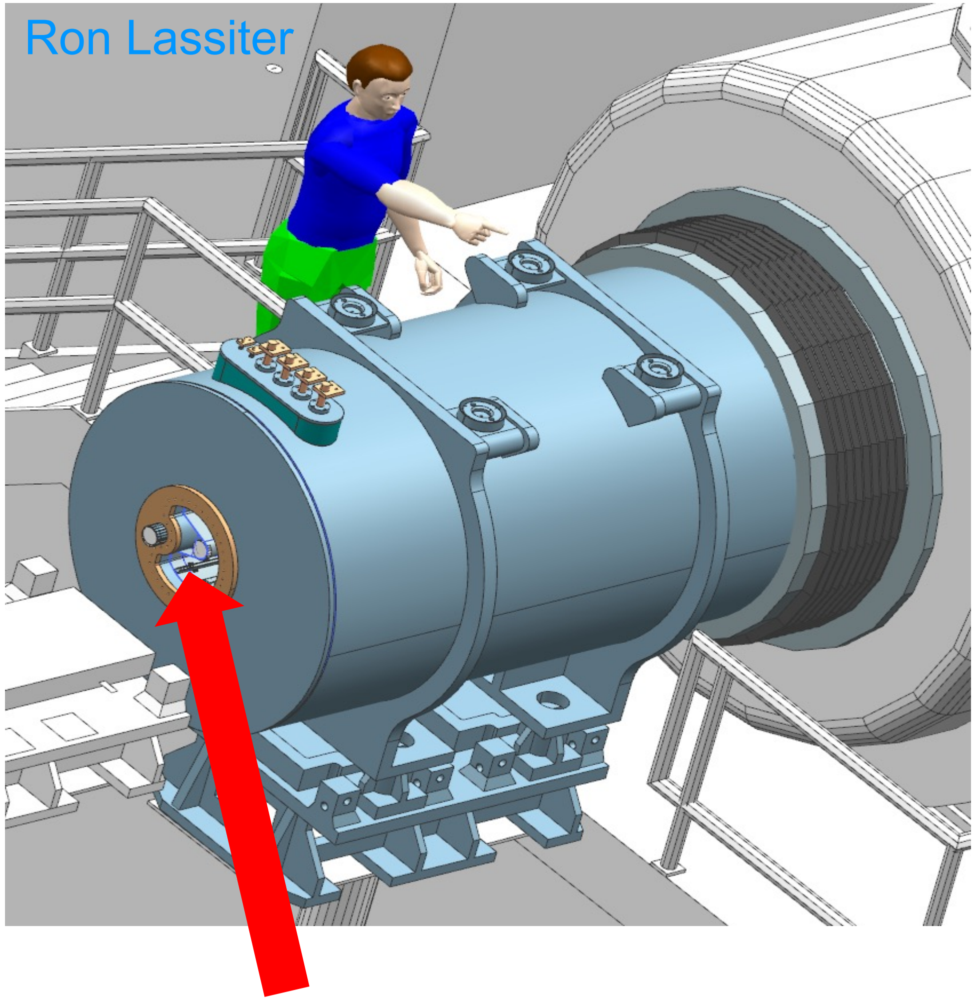


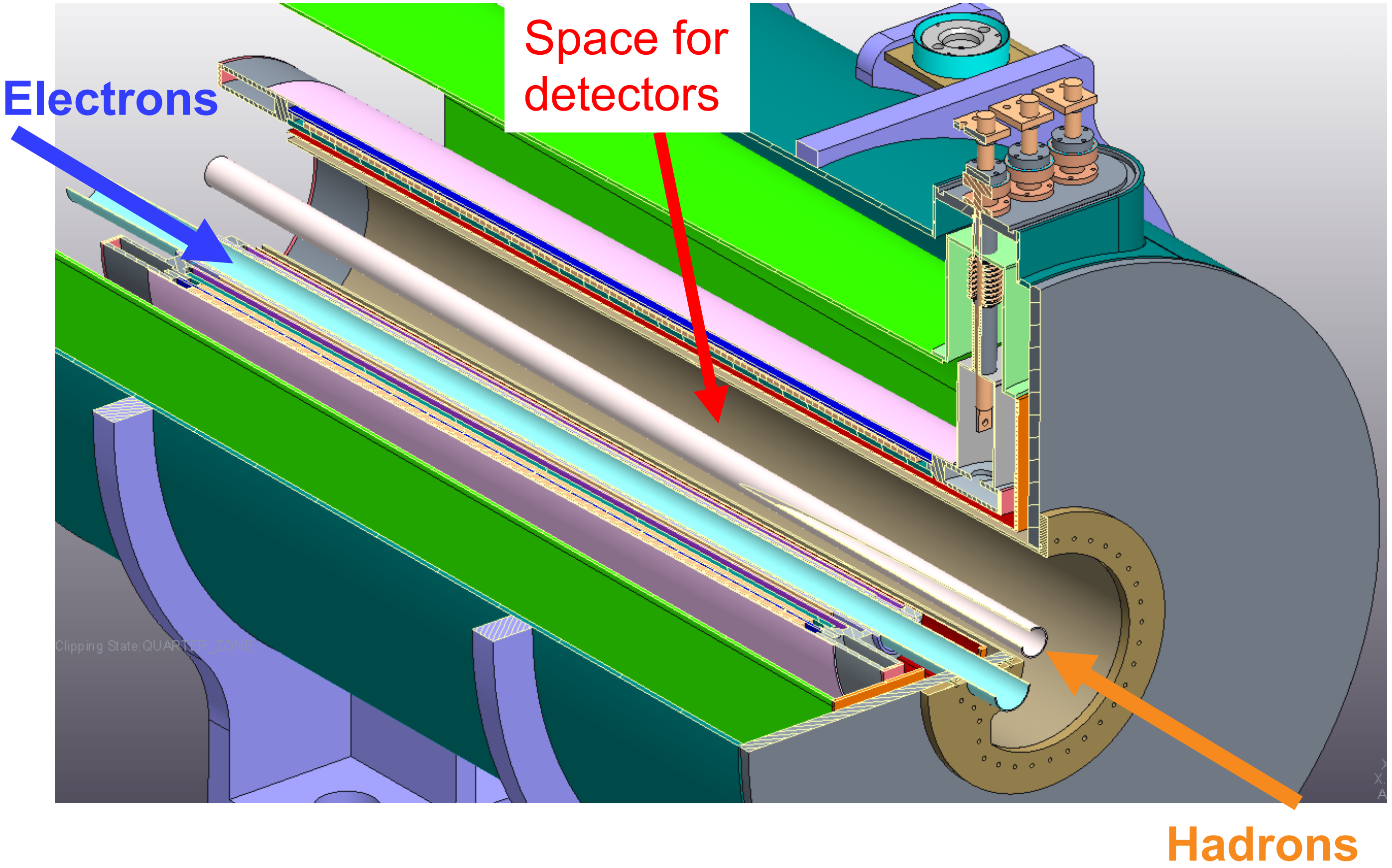
The ePIC Far-Forward Detectors



B0 Detector(s)

- Detector subsystem(s) embedded in an accelerator magnet.

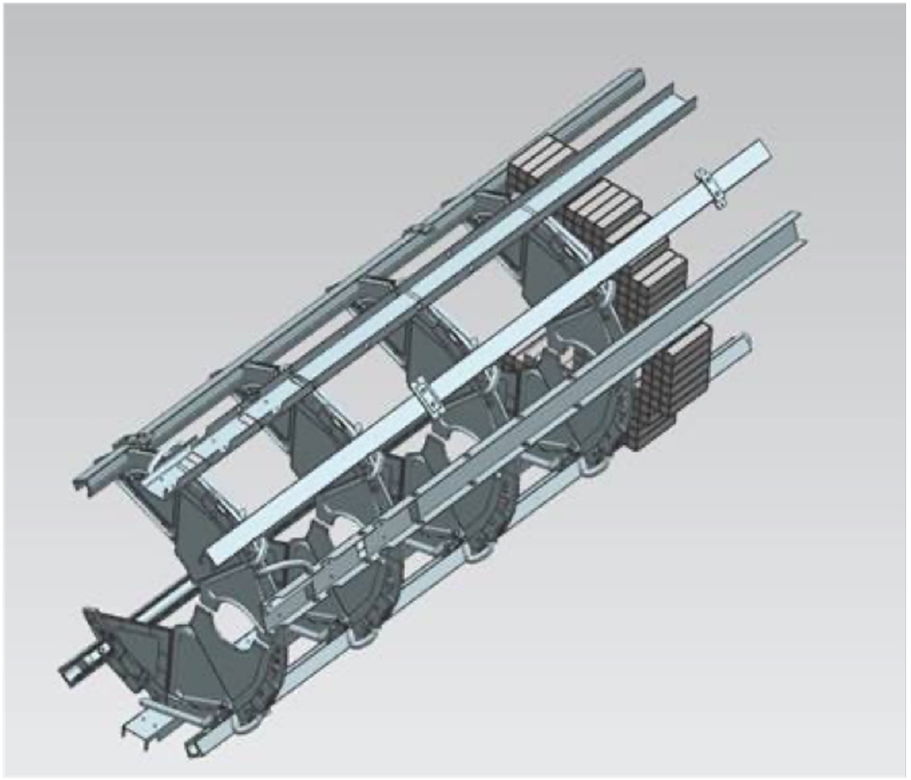




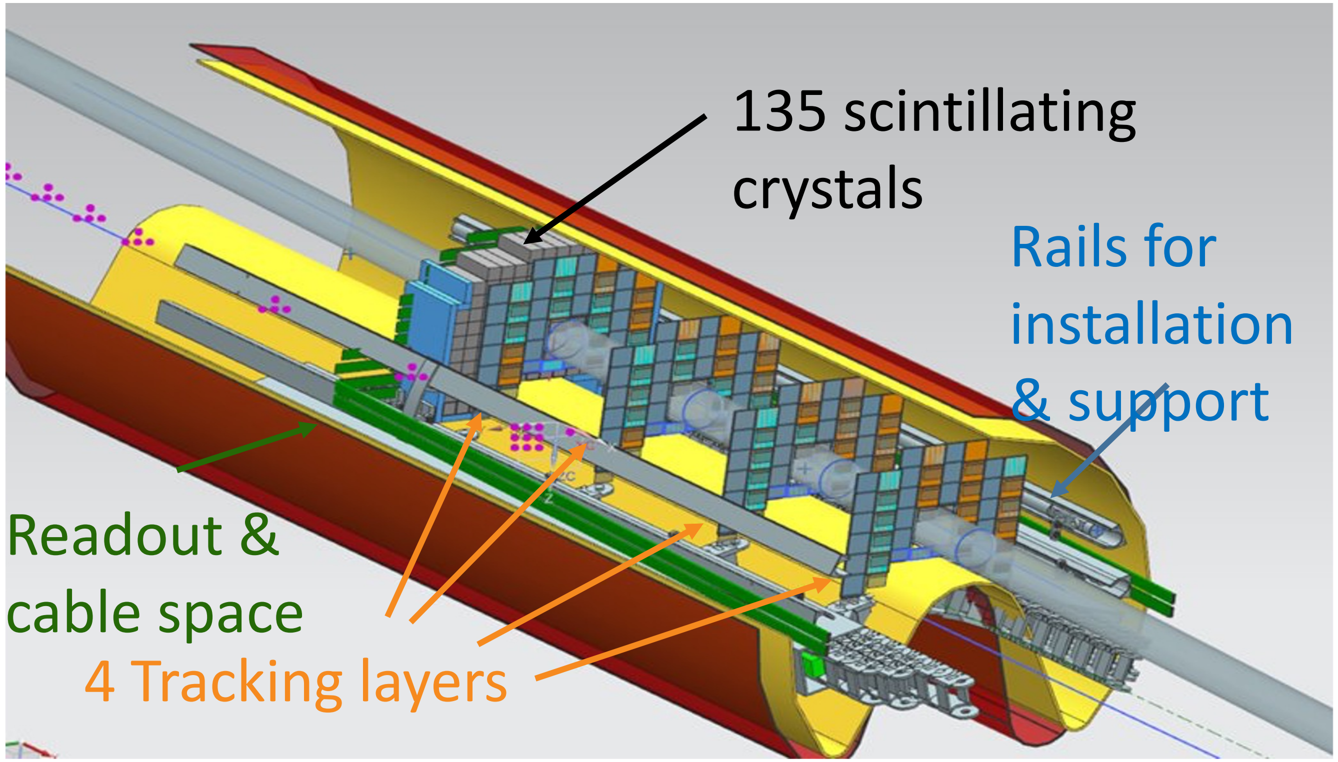
This is the opening where the detector planes will be inserted

B0 Detector(s)

Karim Hamdi

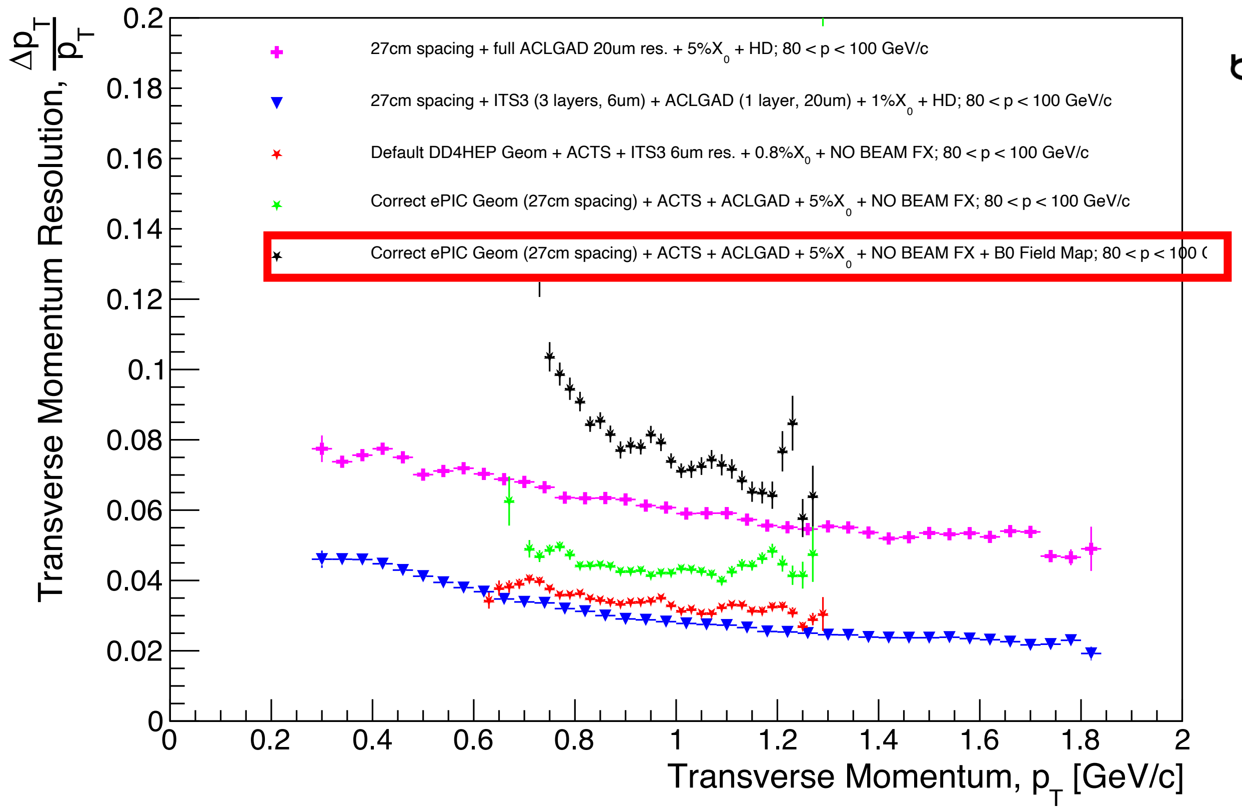


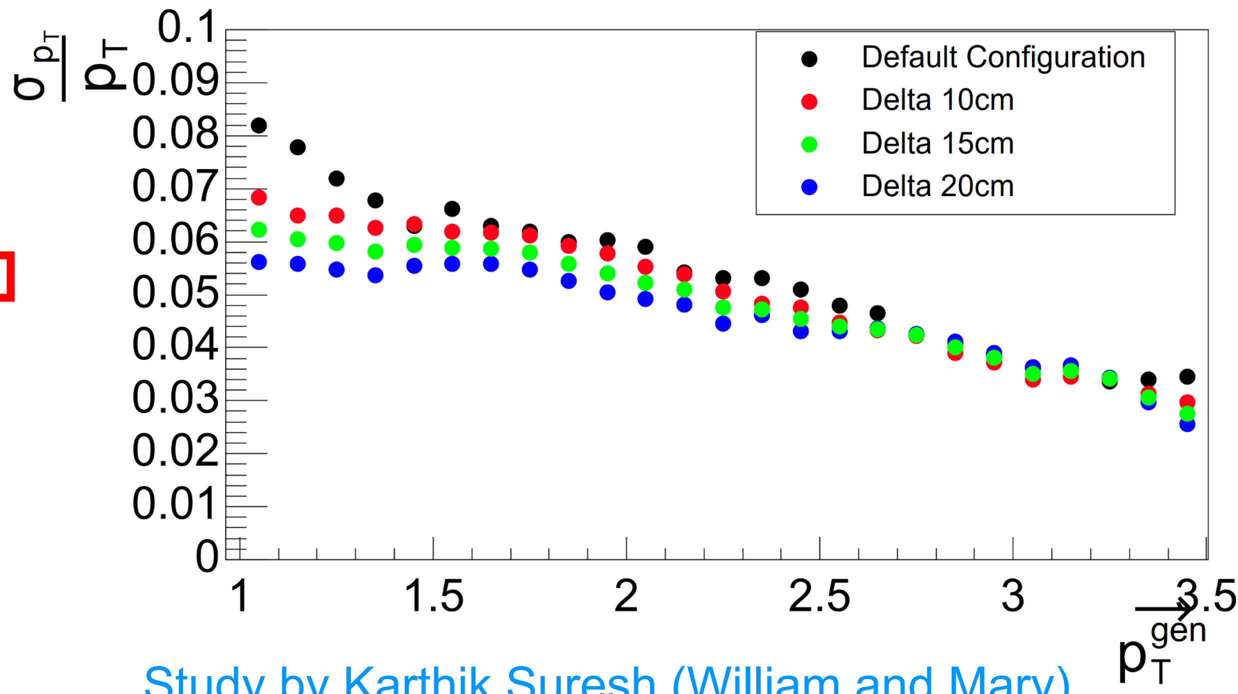
Jonathan Smith



- **Two detectors**:
  - AC-LGAD based silicon tracking detector.
  - PbWO4 EM calorimeter
- Primary challenges are related to integration with the machine (detector fully embedded in machine dipole magnet), and achieving required performance of tracking detector.

B0 Silicon Tracker

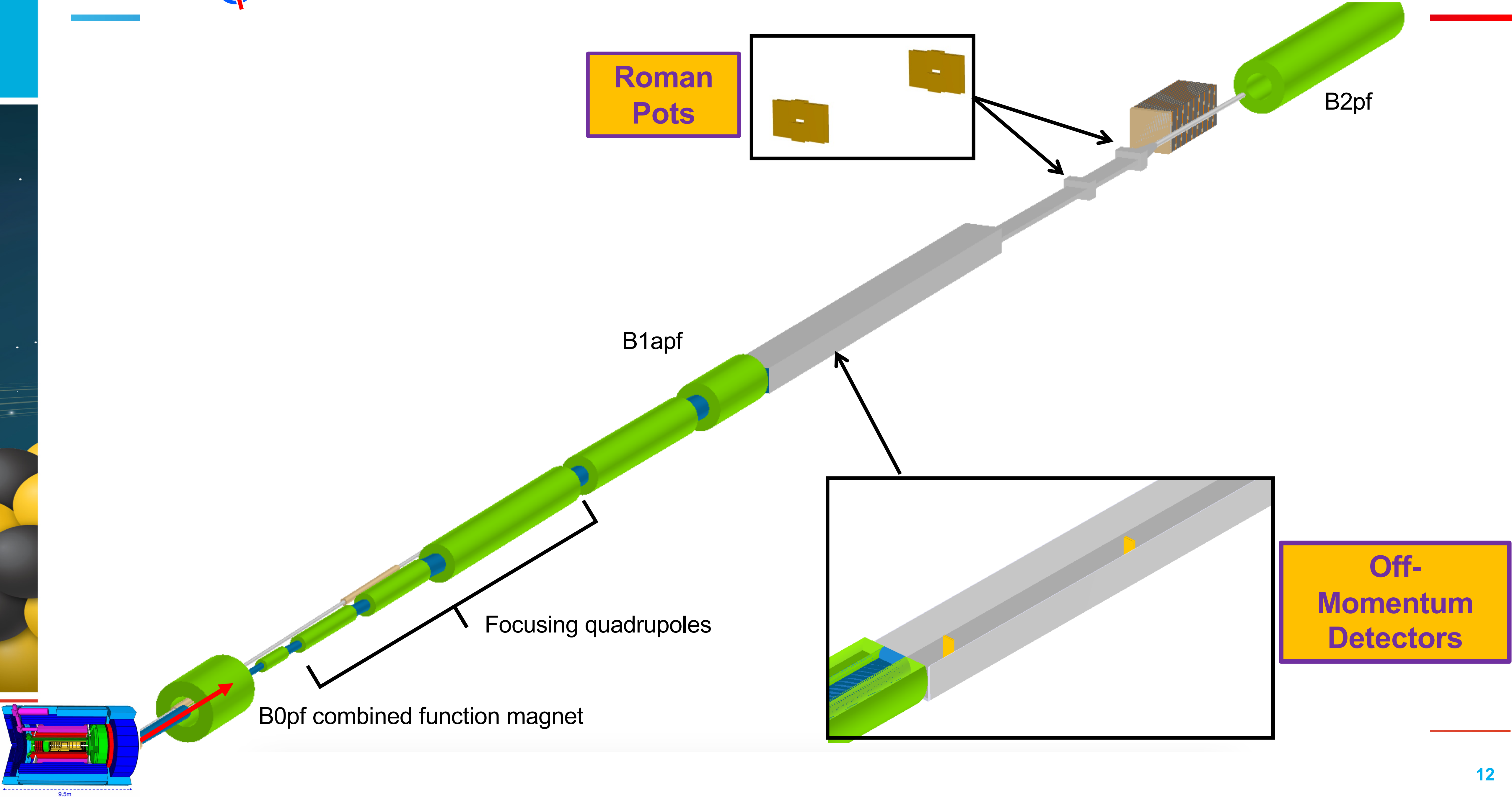




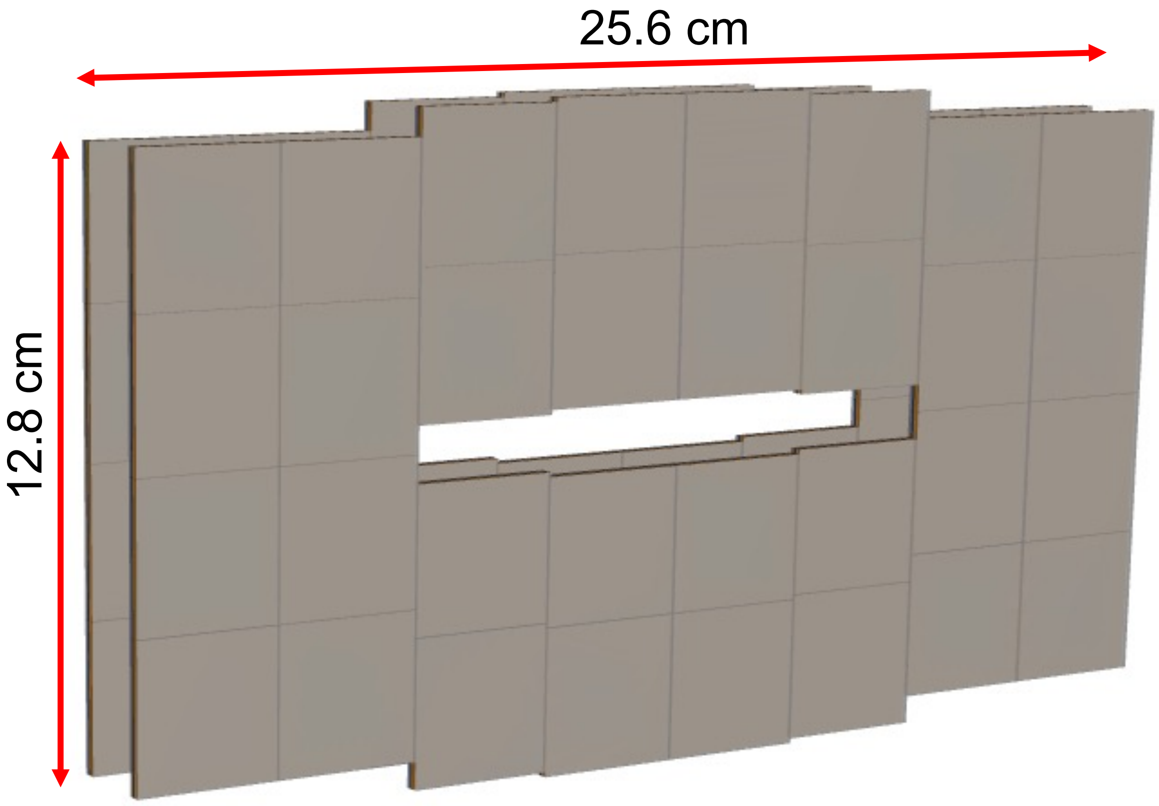
Study by Karthik Suresh (William and Mary)

- Inclusion of full B0 field map caused tracking performance to worsen → optimization work underway to place tracking layers in position with maximum (and flattest) field.

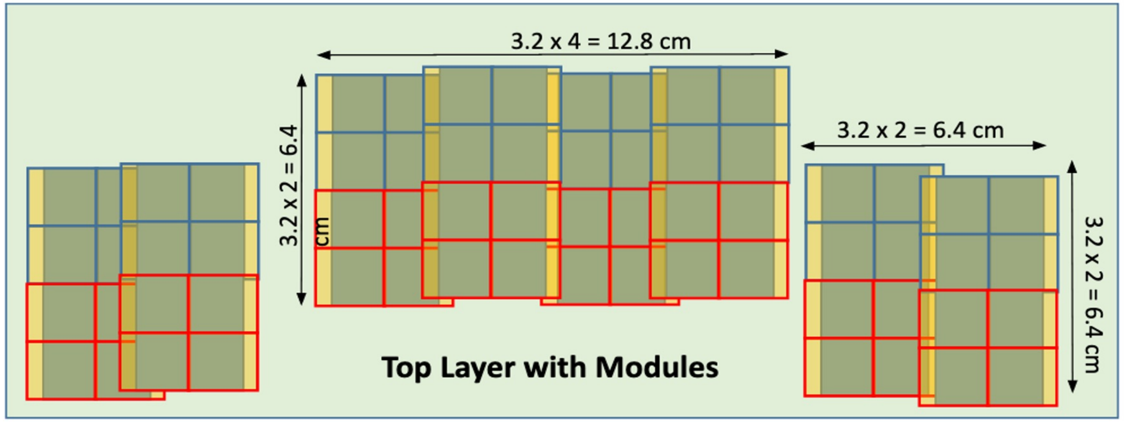
The ePIC Far-Forward Detectors



Technology: AC-LGAD



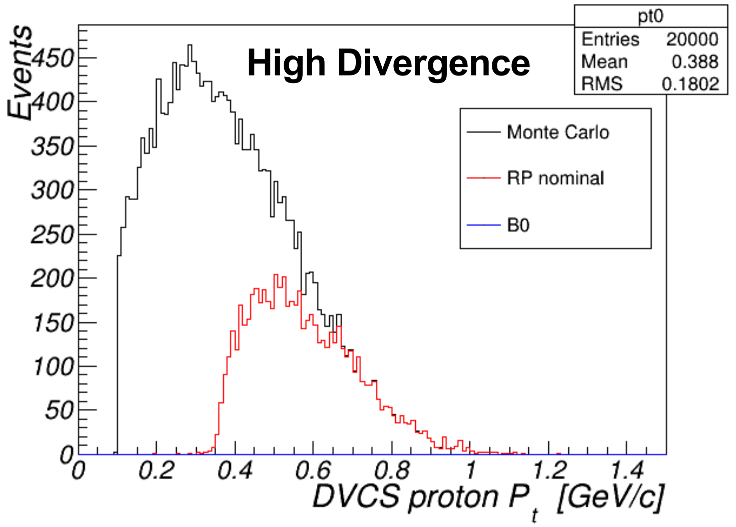
ePIC Simulation

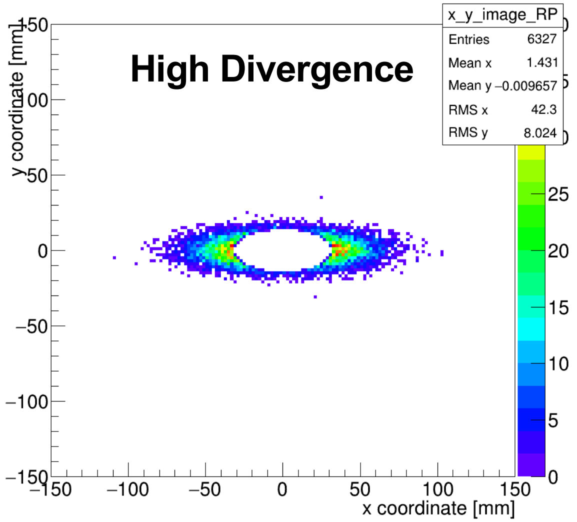


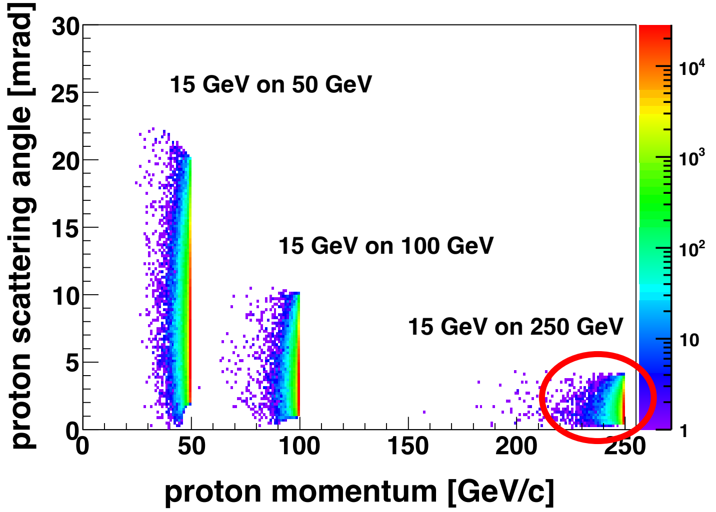
- AC-LGAD sensor provides both **fine pixilation** (500um square pixels), and **fast timing** (~30ps).
  - Based on extensive work from EIC generic R&D (eRD24) to establish needs for the Far-Forward detectors and evaluate usage of AC-LGADs.

Digression: Machine Optics Impact

275 GeV DVCS Proton Acceptance







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

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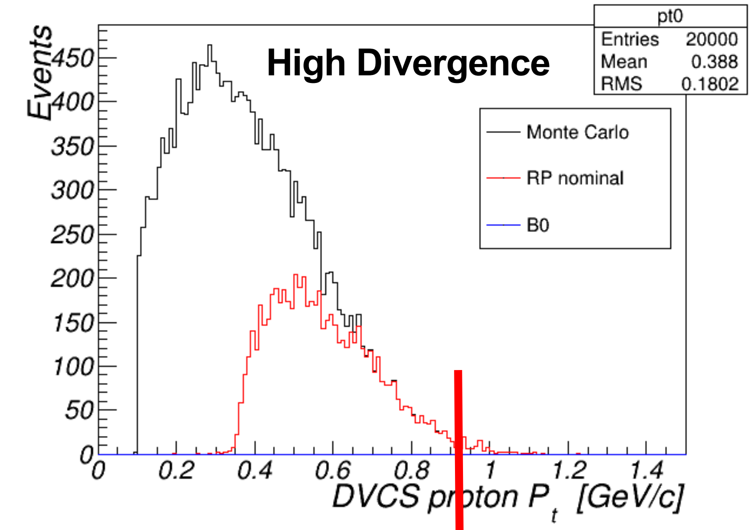

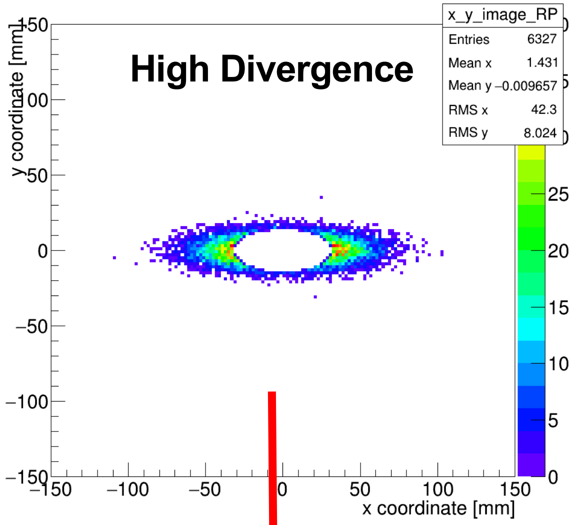

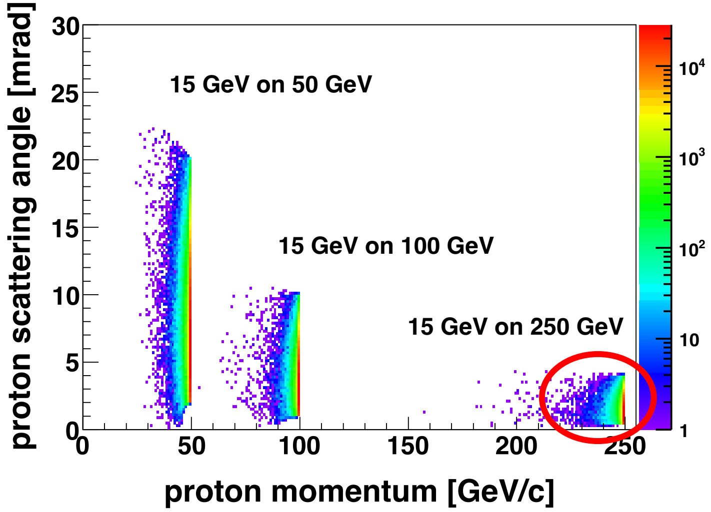

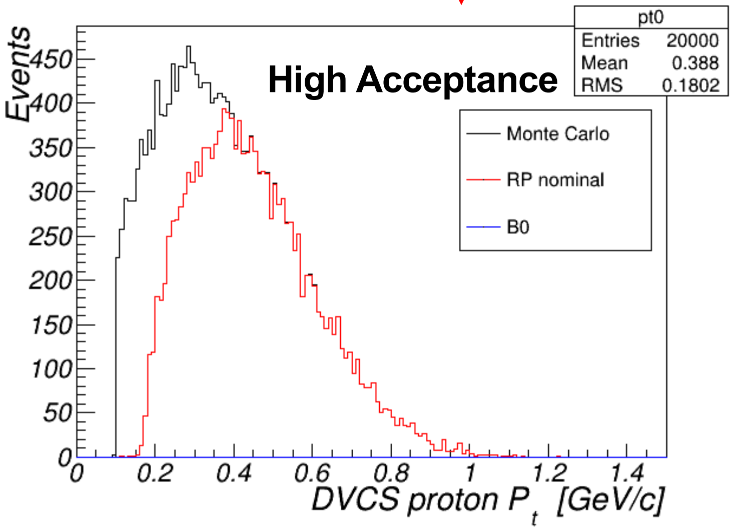

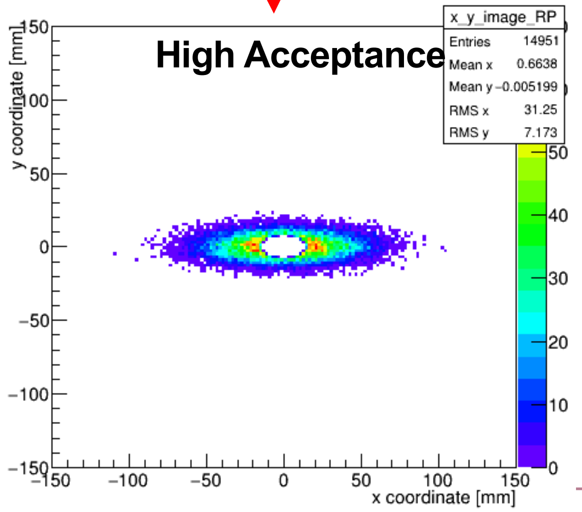

<u>High Divergence:</u> smaller β^* at IP, but bigger $\beta(z = 30m)$ -> higher lumi., larger beam at RP

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

Digression: Machine Optics Impact

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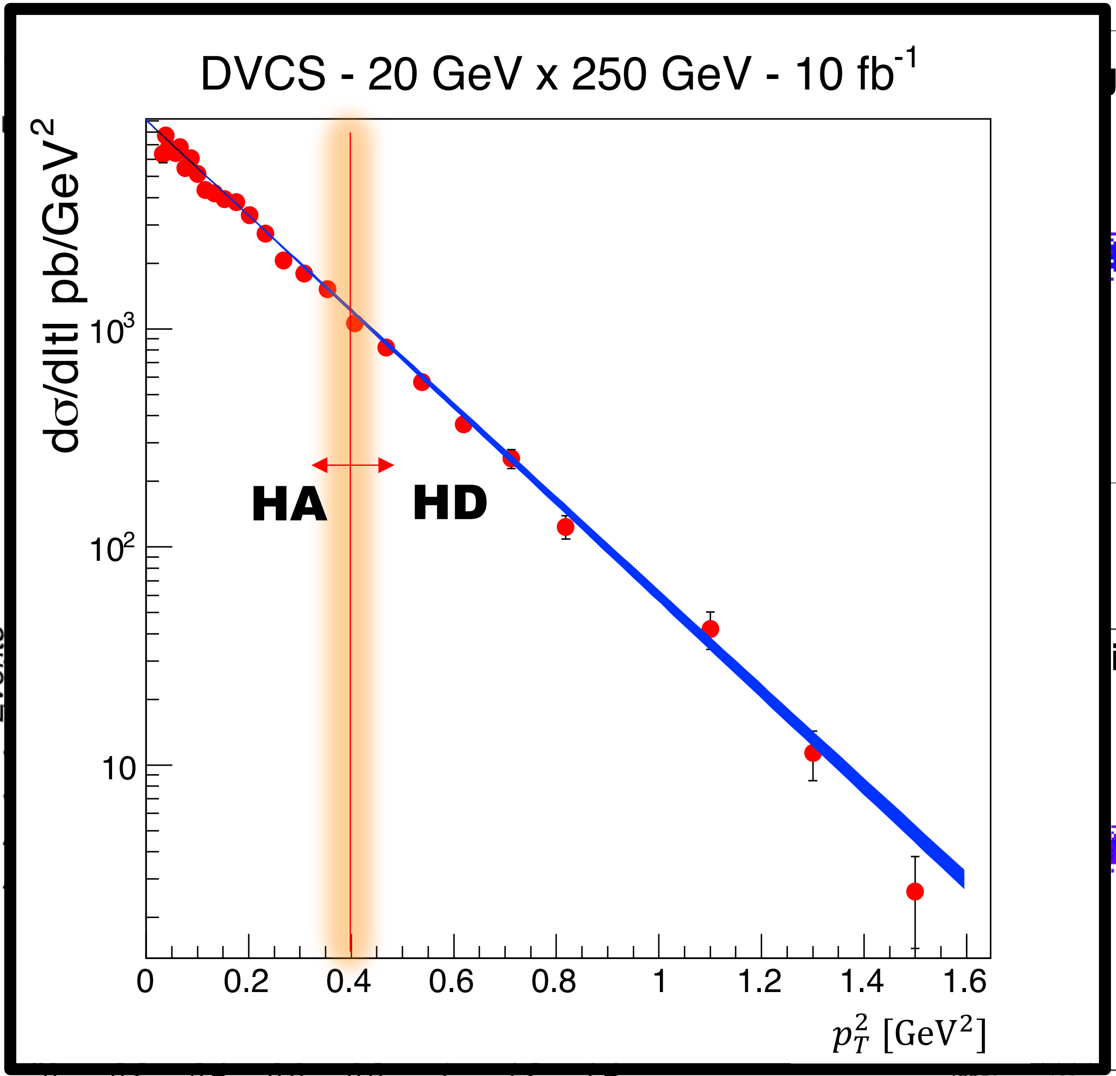


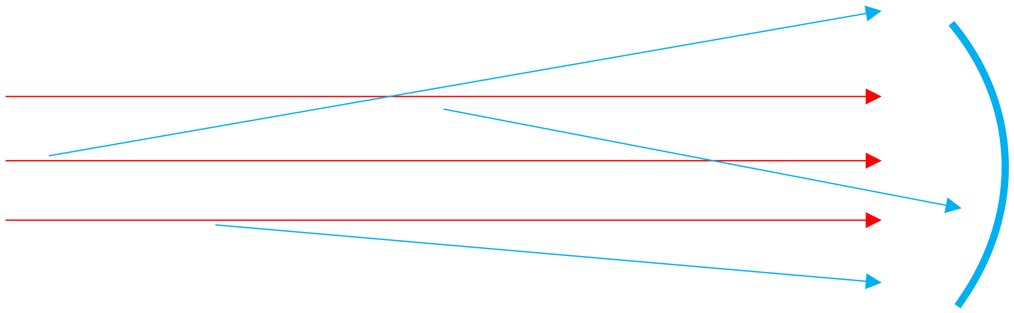
Using the two configurations, we are able to measure the low-p_T region (with better acceptance) and high-t tail (with higher luminosity).

Detectors need to be able to move to different positions for different optics configurations.

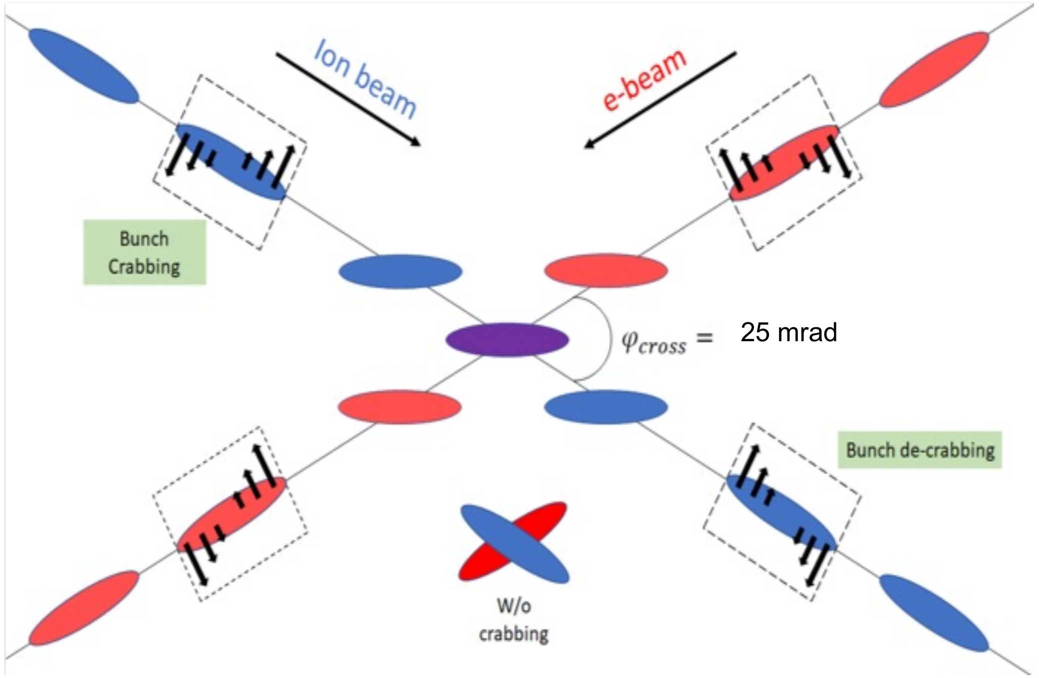
RP

Soapbox: Quick Reminder on Beam Effects

- Angular divergence
  - Angular “spread” of the beam away from the central trajectory.
    - Transverse momentum kick to the beam particles.

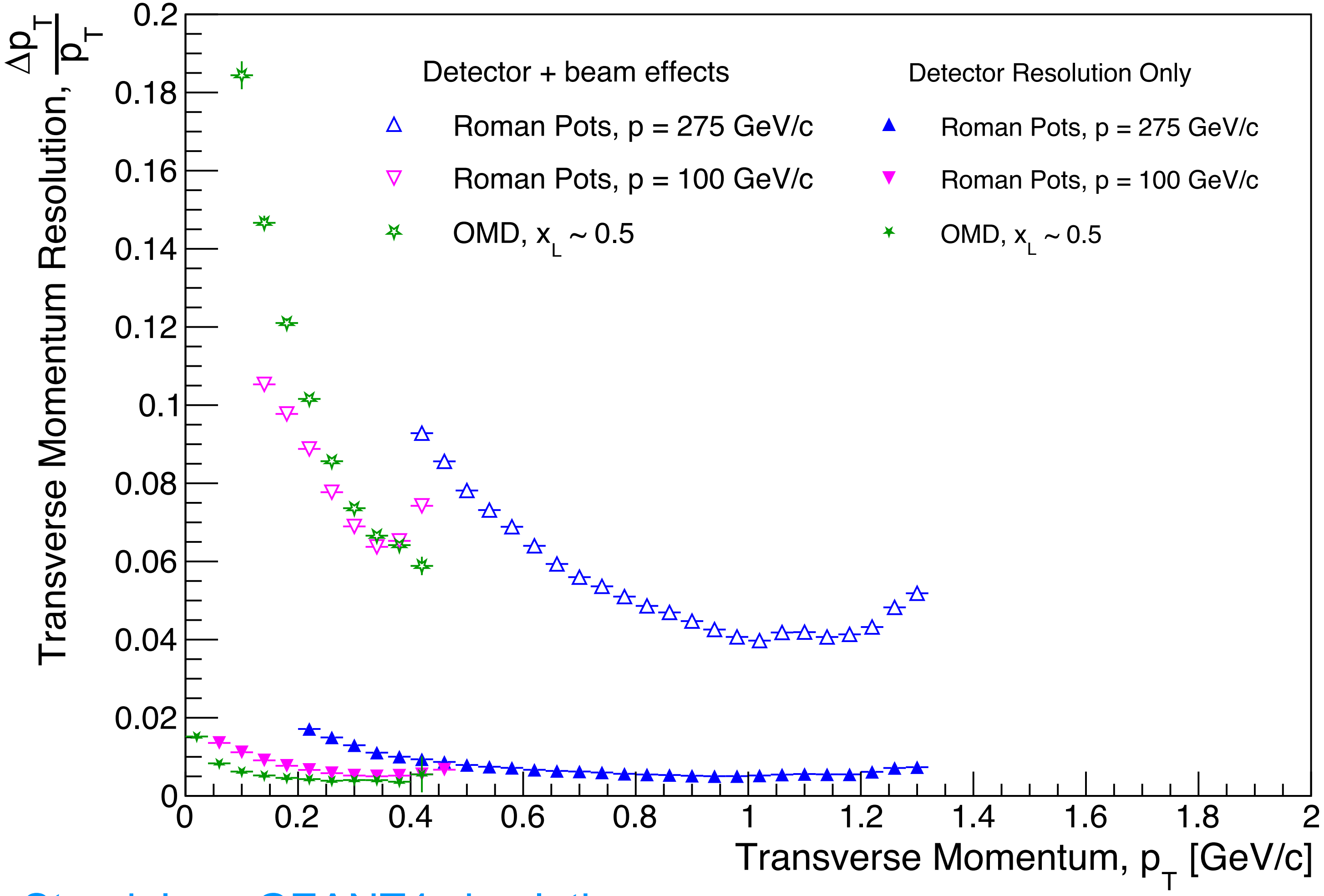


- Crab cavity rotation
  - Rotates beam bunches in 2D.
  - Used to account for the luminosity drop due to the crossing angle – allows for head-on collisions to still take place.
  - **Induces effective vertex smearing.**



These effects introduce smearing in our transverse momentum reconstruction.

Summary of Detector Performance



Standalone GEANT4 simulations

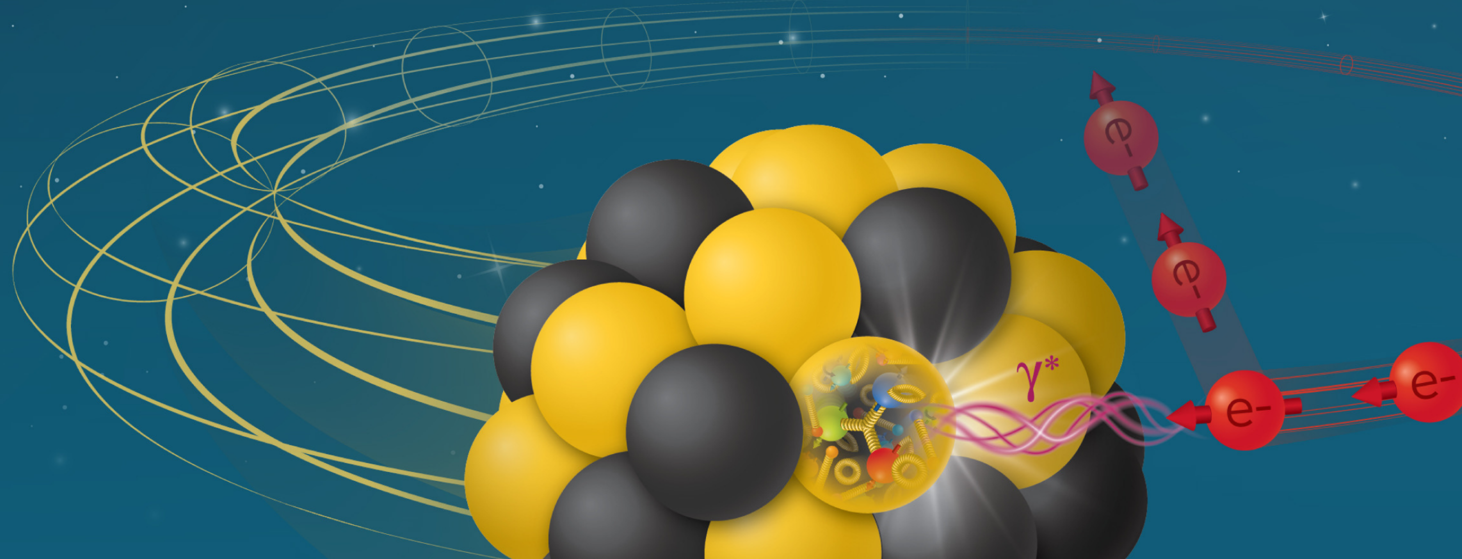
- Work being done now to ensure we can evaluate this in the ePIC software stack.
  - https://github.com/eic/EICrecon/pull/1492
  - "post-burner" ready to go to handle removal of afterburner (beam effects, crossing angle) effects needed for simulation.
  - This step has to be done to separate the components and see if previous assumptions are still valid.

Brookhaven National Laboratory

Jefferson Lab

U.S. DEPARTMENT OF ENERGY

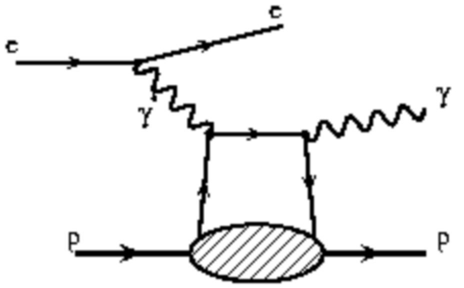
Now for the PHYSICS…



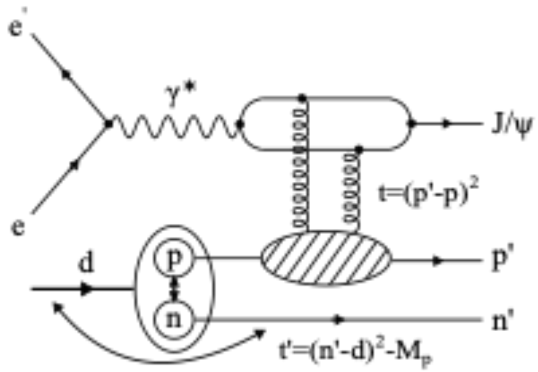
Electron-Ion Collider

Far-Forward Processes at the EIC

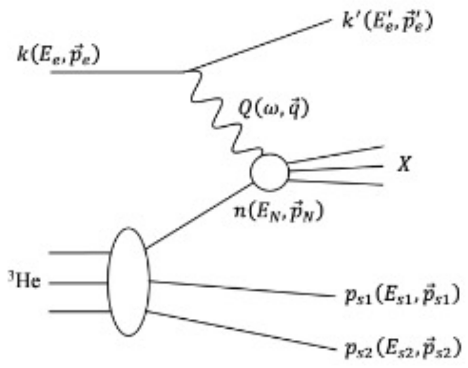
e+p DVCS



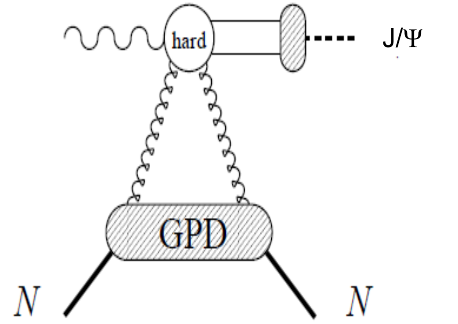
e+d exclusive J/Psi with p/n tagging



e+He3 spectator tagging

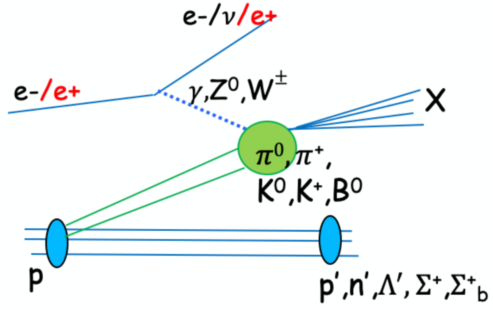


coherent/incoherent J/ψ production in e+A

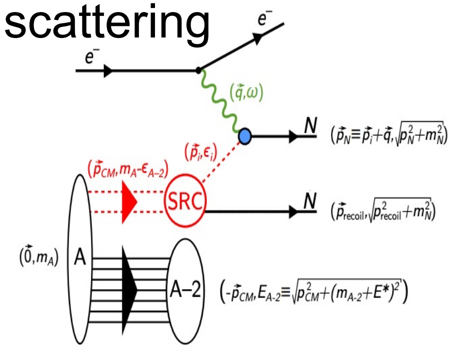


Meson structure:

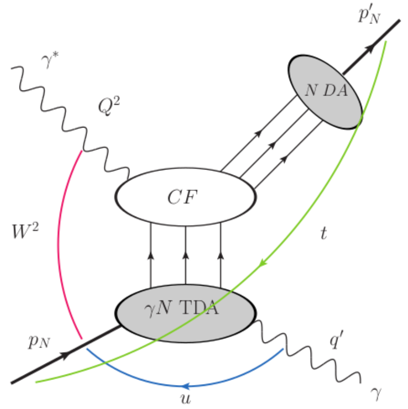
- ep→ (π) →e' n X
- Λ →pπ^- and Λ → nπ^0



Quasi-elastic electron scattering



u-channel backward exclusive electroproduction

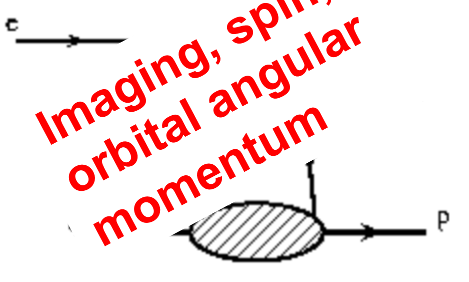


…and MANY more!

Far-Forward Physics at the EIC

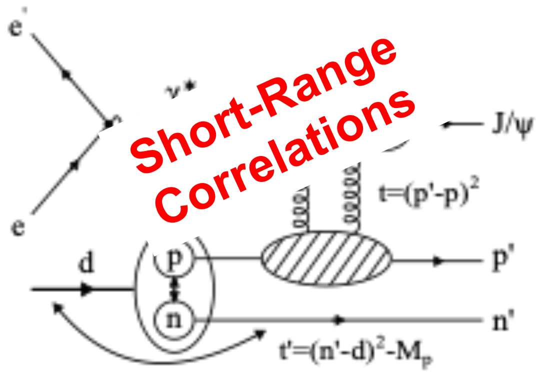
e+p DVCS

Imaging, spin, orbital angular momentum



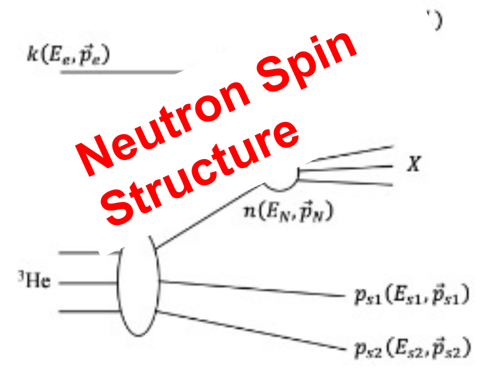
e+d exclusive J/Psi with p/n tagging

Short-Range Correlations



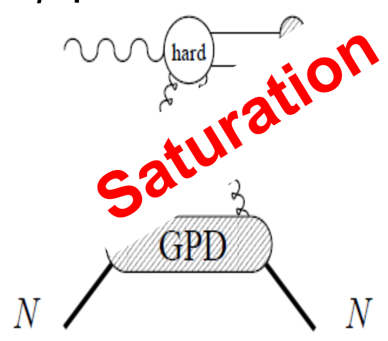
e+He3 spectator tagging

Neutron Spin Structure



coherent/incoherent J/ψ production in e+A

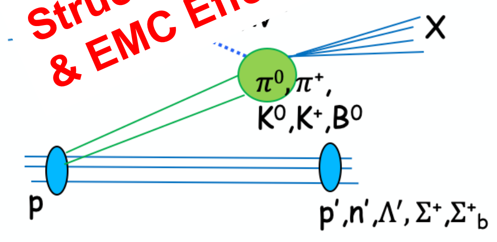
Saturation



Meson structure:

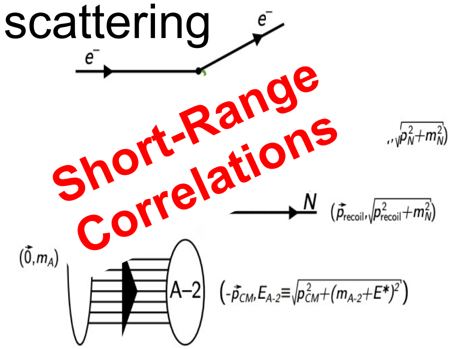
- ep→ (π) →e' ...
- Λ →pπ

Free Neutron Structure Functions & EMC Effect



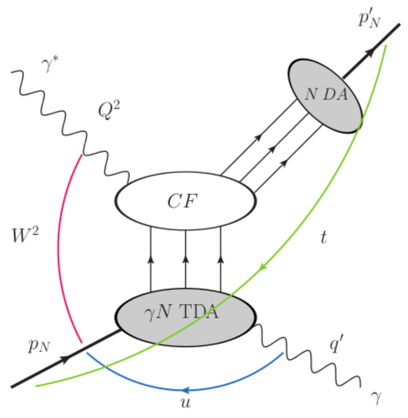
Quasi-elastic electron scattering

Short-Range Correlations



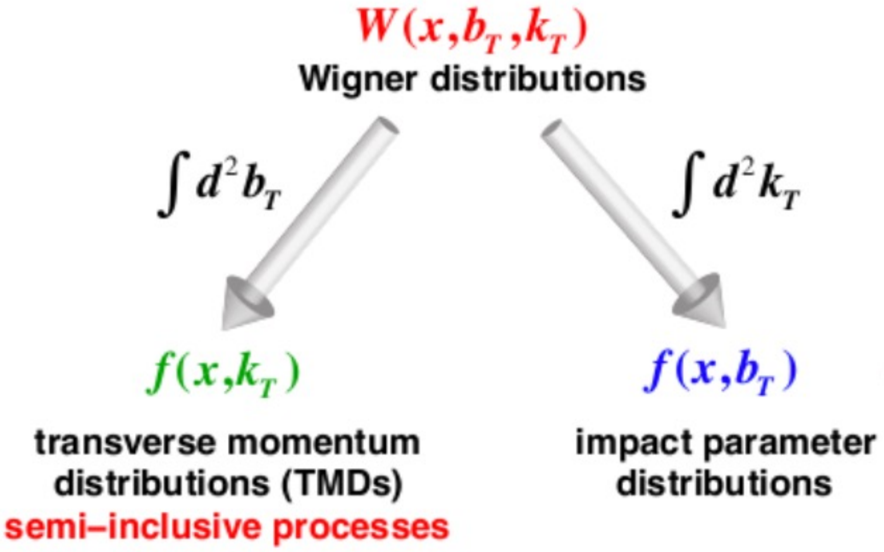
[1] Z. Tu, A. Jentsch, et al., Physics Letters B, (2020)
[2] I. Friscic, D. Nguyen, J. R. Pybus, A. Jentsch, *et al.,* Phys. Lett. B, **Volume 823**, 136726 (2021)
[3] W. Chang, E.C. Aschenauer, M. D. Baker, A. Jentsch, J.H. Lee, Z. Tu, Z. Yin, and L.Zheng, Phys. Rev. D **104**, 114030 (2021)
[4] A. Jentsch, Z. Tu, and C. Weiss, Phys. Rev. C **104**, 065205, (2021) **(Editor's Suggestion)**

u-channel backward exclusive electroproduction



…and MANY more!

Partonic Imaging of Nucleons



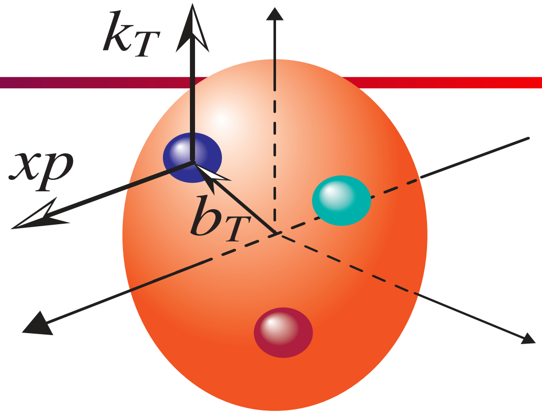
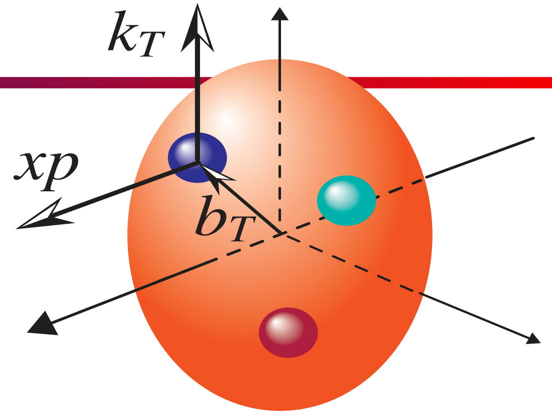


Fig. 2.2 from the EIC White Paper

Partonic Imaging of Nucleons



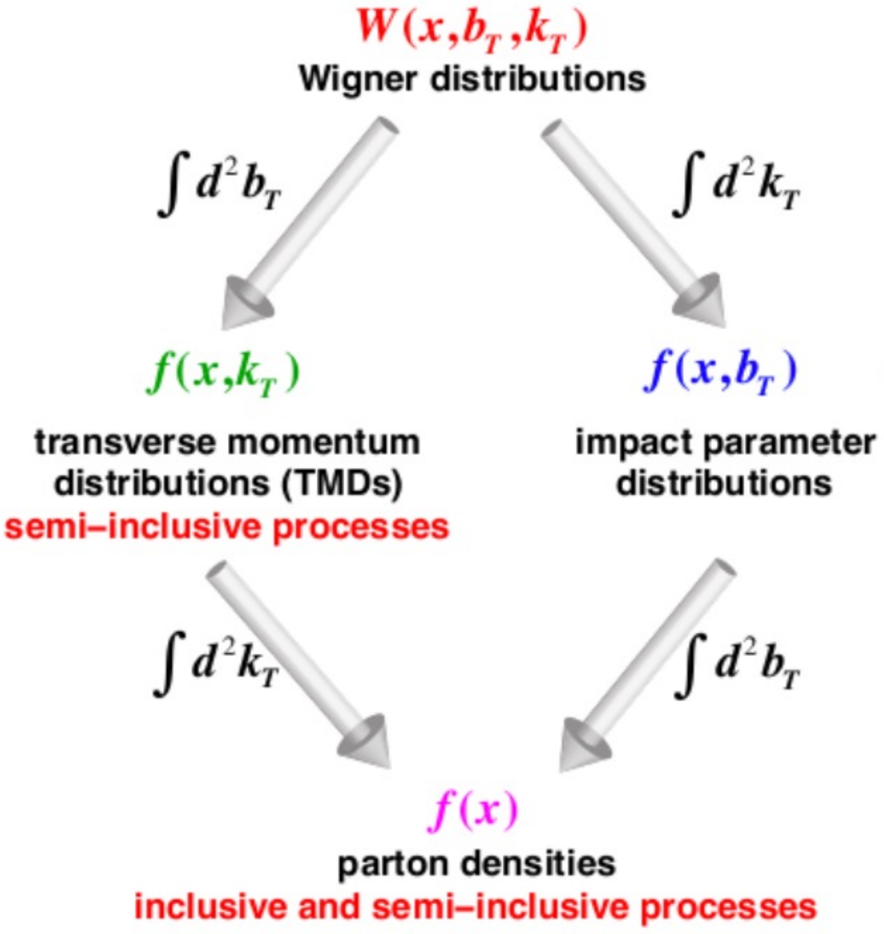
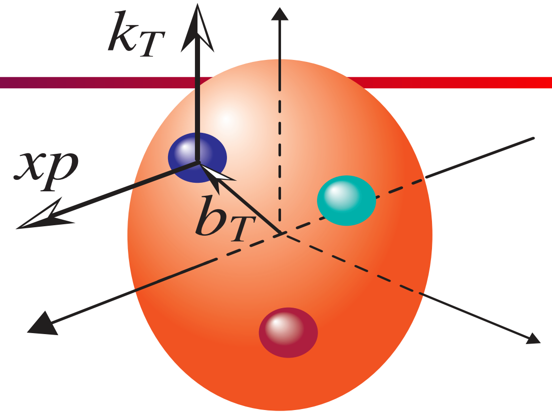


Fig. 2.2 from the EIC White Paper

Partonic Imaging of Nucleons



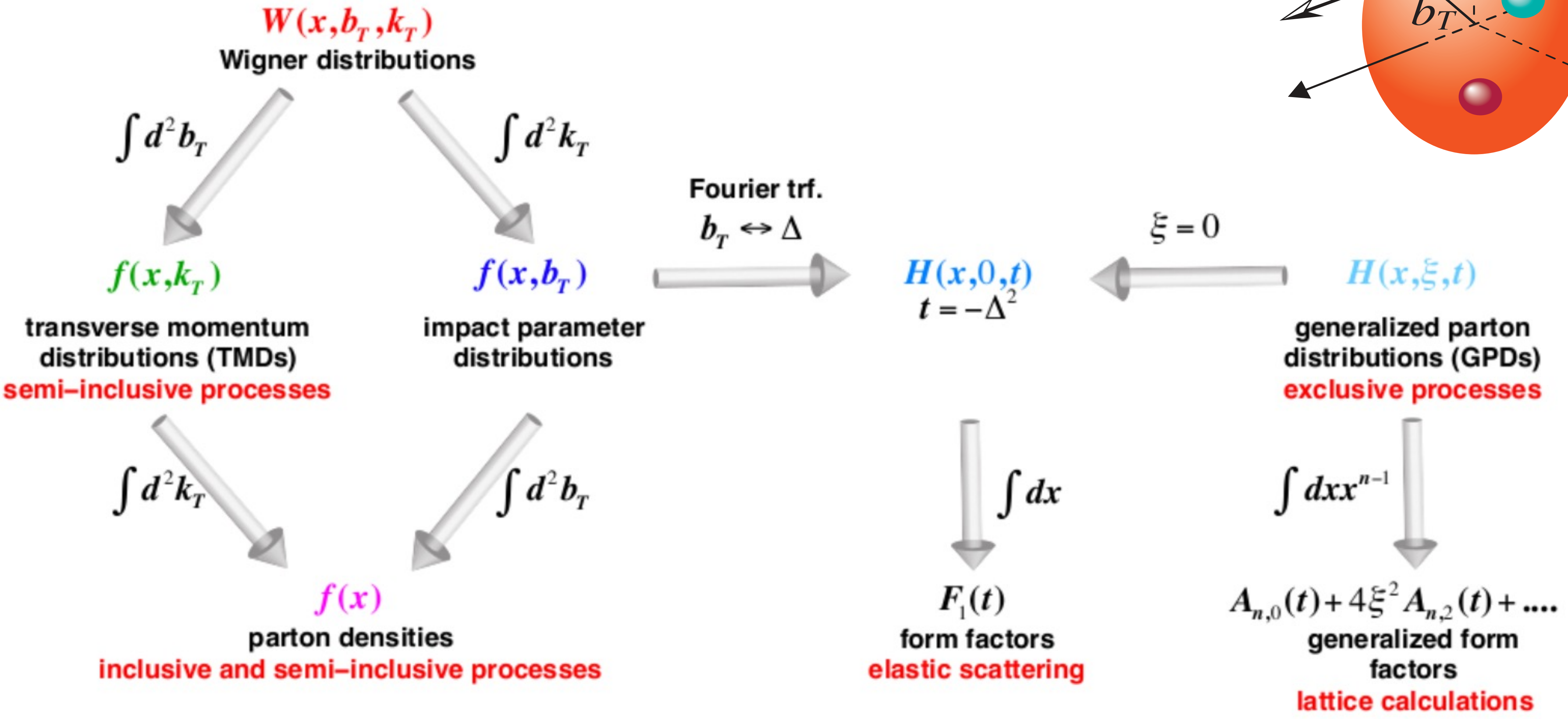
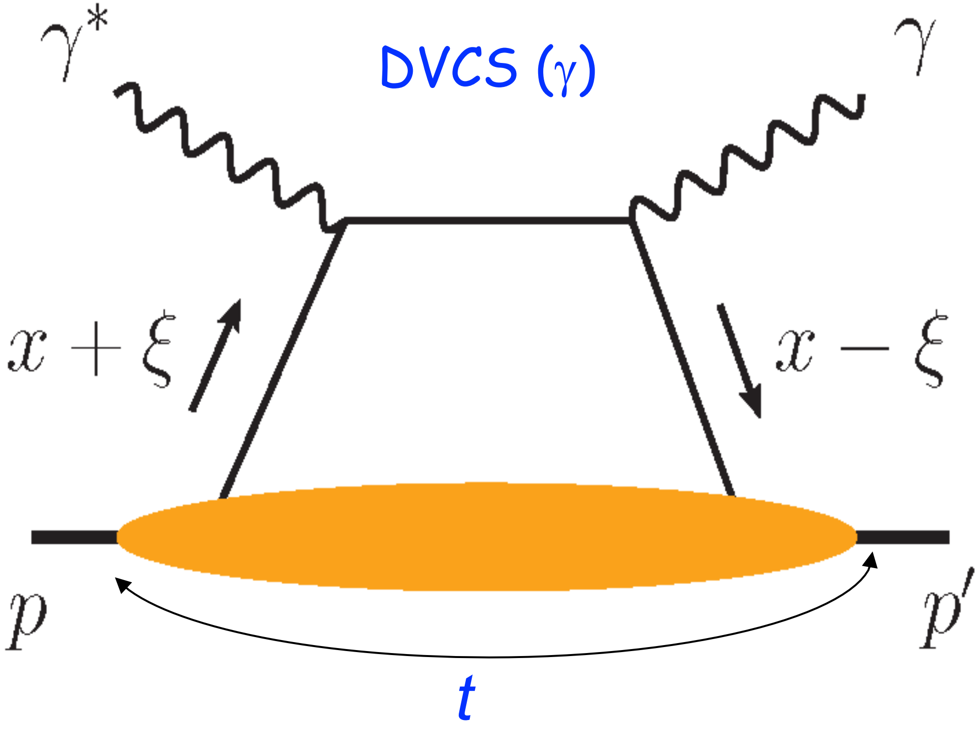


Fig. 2.2 from the EIC White Paper

Deeply Virtual Compton Scattering (DVCS)



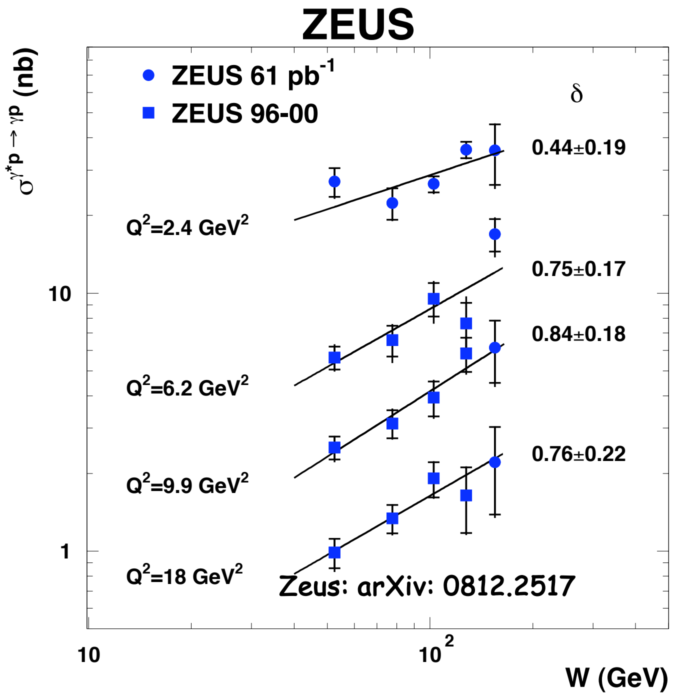
- Exclusive process with all final state particles detected in the event.
- Sensitive to the proton GPD.

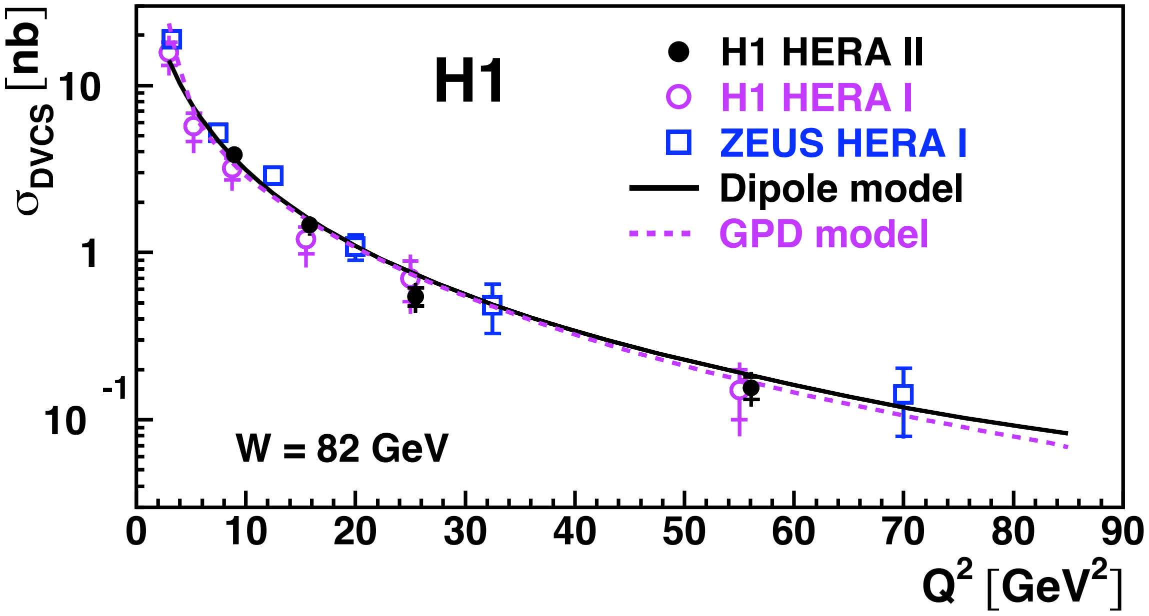
$$t = -(p - p')^2 \approx -{p'}_t^2$$

p_T and b_T are conjugate variables!

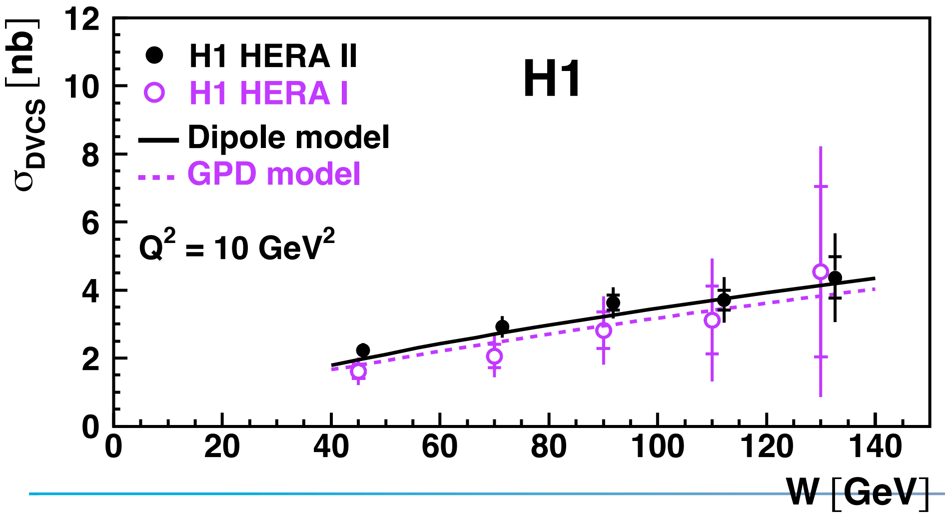
Measuring the cross-section differential on the momentum transfer yields access to spatial imaging!!

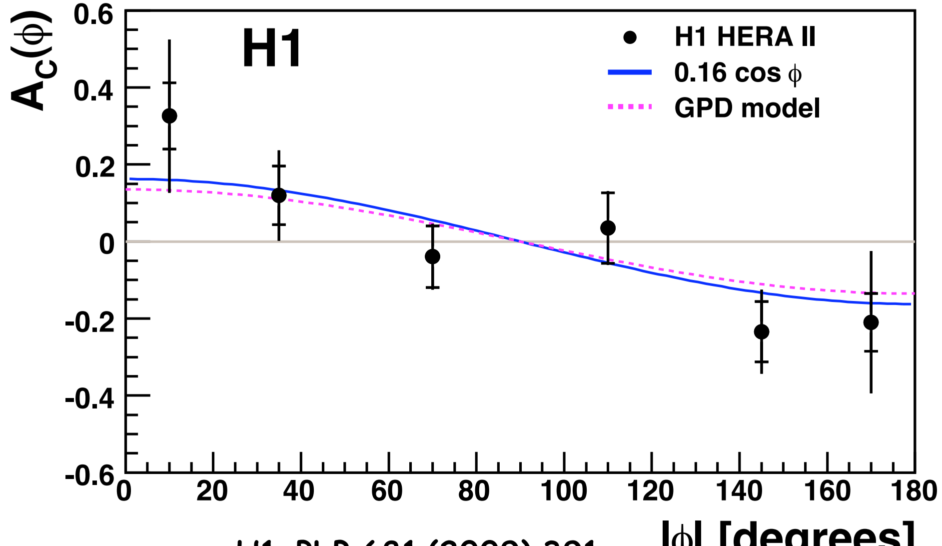
Results from HERA





- Not enough data or acceptance to differentiate GPD models from others.
- No proton beam polarization to study spin-dependence!

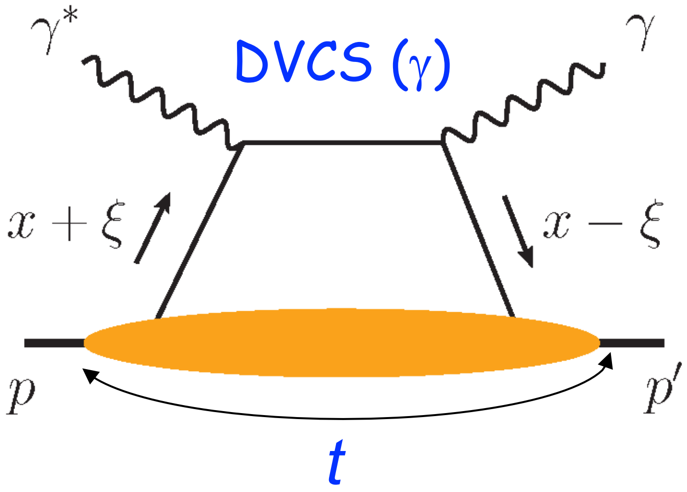




H1: PLB 681 (2009) 391

EIC gives us the tools to solve both problems!!

Deeply Virtual Compton Scattering @ the EIC



- Exclusive process with all final state particles detected in the event.
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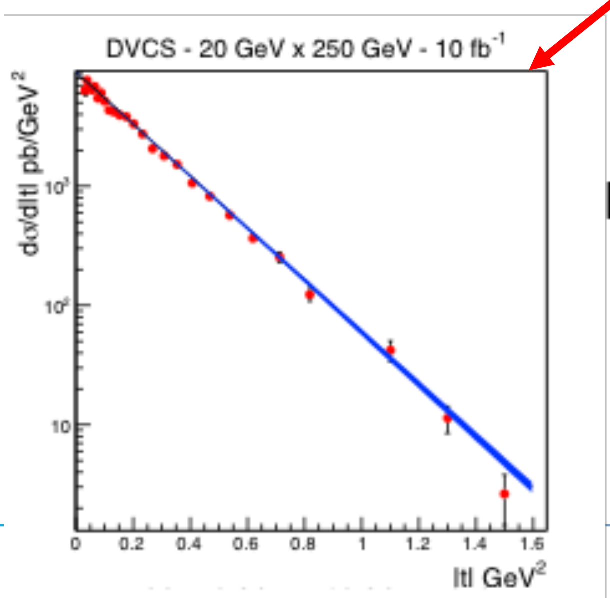
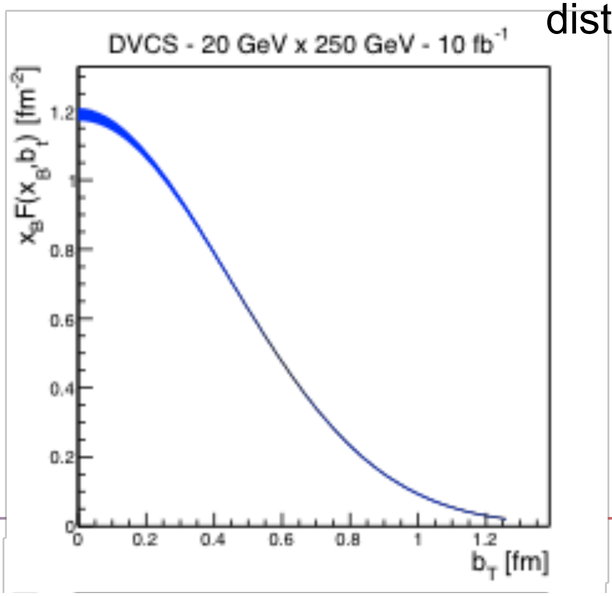
Measurement



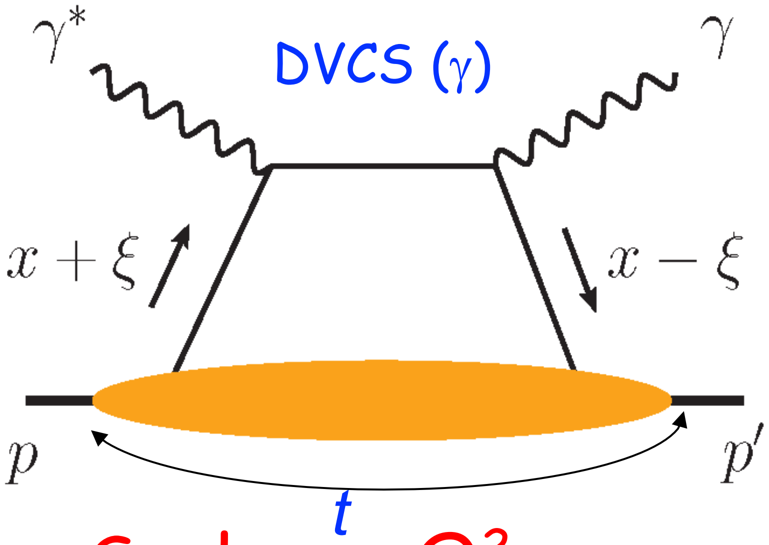
Plots from EIC White Paper:

Fourier transform

Physics observable (Impact parameter distribution)

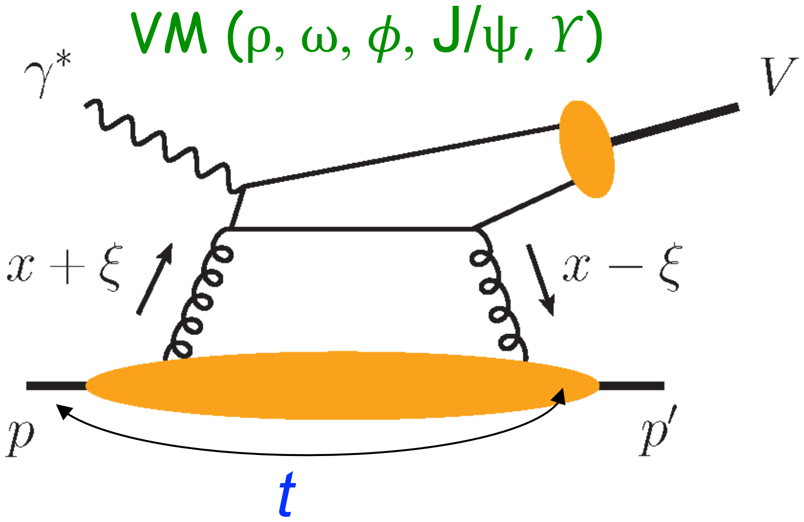


Exclusive Vector Meson and Real Photon Production



Scale: Q^2

square 4-momentum at *p*-vertex: *t=(p'-p)*^{2}



$Q^2 + M^2$

DVCS:

- Very clean experimental signature
- No VM wave-function uncertainty
- Hard scale provided by Q^2
- Sensitive to both quarks and gluons Q^2 dependence of cross section

VMP:

- Uncertainty of wave function
- J/Psi → direct access to gluons, c+cbar pair production
- Light VMs → quark-flavor separation

Small GPD Primer

How are GPDs characterized?

unpolarized | polarized

$H^q(x,\xi,t)$ $\tilde{H}^q(x,\xi,t)$

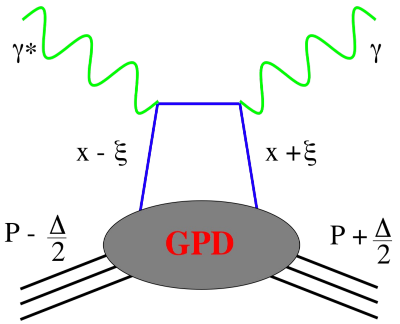
$E^q(x,\xi,t)$ $\tilde{E}^q(x,\xi,t)$

conserve nucleon helicity

$$H^q(x,0,0) = q, \tilde{H}^q(x,0,0) = \Delta q$$

flip nucleon helicity not accessible in DIS

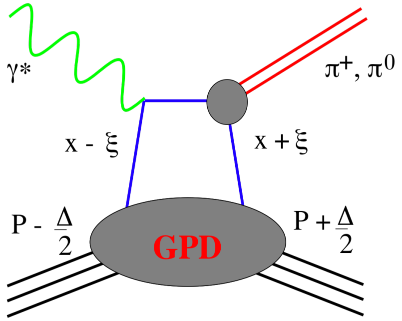
quantum numbers of final state ⟹ select different GPD



DVCS

H^q E^q $\tilde{H}^q$ $\tilde{E}^q$

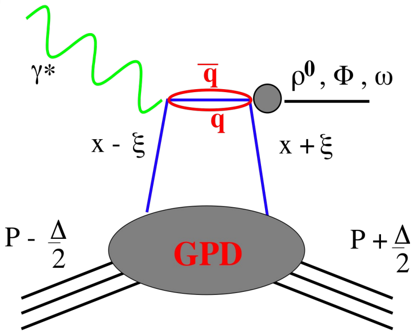
- $Q^2 = 2E_eE_{e'}(1-\cos(q_{e'}))$
- $x_B = Q^2/2Mn$ $n = E_e - E_{e'}$
- $x+\xi$, $x-\xi$ long. mom. fract.
- $t = (p-p')^2$
- $x \cong x_B/(2-x_B)$



pseudo-scaler mesons

$\tilde{H}^q, \tilde{E}^q$

π^0	$2\Delta u+\Delta d$
η	$2\Delta u-\Delta d$



vector mesons

H^q, E^q

ρ^0	2u+d, 9g/4
ω	2u–d, 3g/4
ϕ	s, g
ρ^+	u–d
J/ψ	g

Small GPD Primer

$H^{q,g}(x,\xi,t)$	$E^{q,g}(x,\xi,t)$	*for sum over parton helicities*
$\widetilde{H}^{q,g}(x,\xi,t)$	$\widetilde{E}^{q,g}(x,\xi,t)$	*for difference over parton helicities*
nucleon helicity conserved	*nucleon helicity changed*	

?

$$\frac{d\sigma}{dt} \sim A_0 \left[|H|^2 (x,t,Q^2) - \frac{t}{4M_p^2} |E^2| (x,t,Q^2) \right]$$

Dominated by H
slightly dependent on E

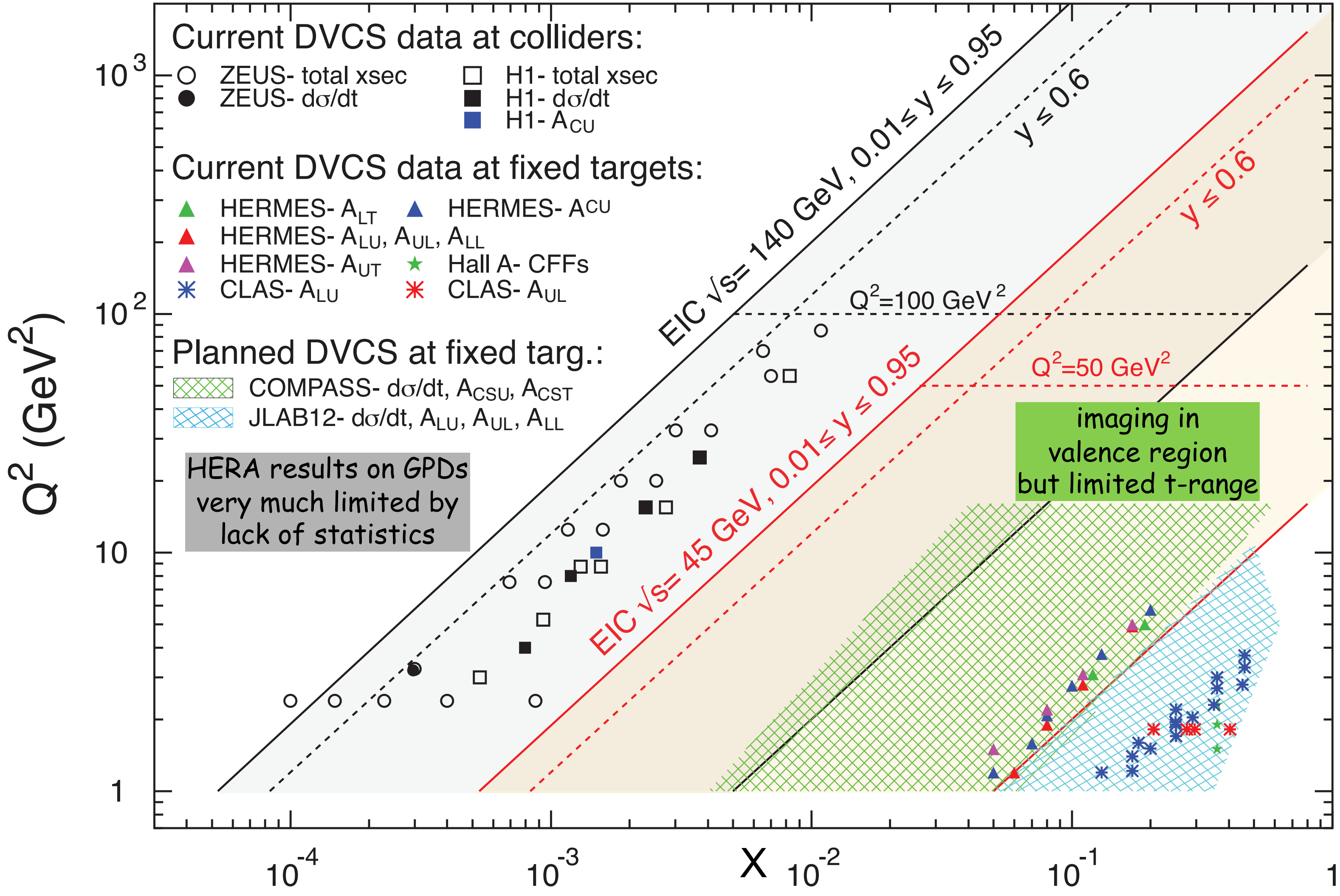
$$A_{UT} \propto \sqrt{\frac{-t}{4M^2}} \left[F_2(t) H(\xi,\xi,t,Q^2) - F_1(t) E(\xi,\xi,t,Q^2) + \ldots \right]$$

→ ***sin(Φ$_T$−ϕ$_N$)***
governed by E and H

Requires a polarized proton-target

responsible for total orbital angular momentum through Ji sum rule
a window to the SPIN physics

The DVCS Phase Space – What does the EIC add?

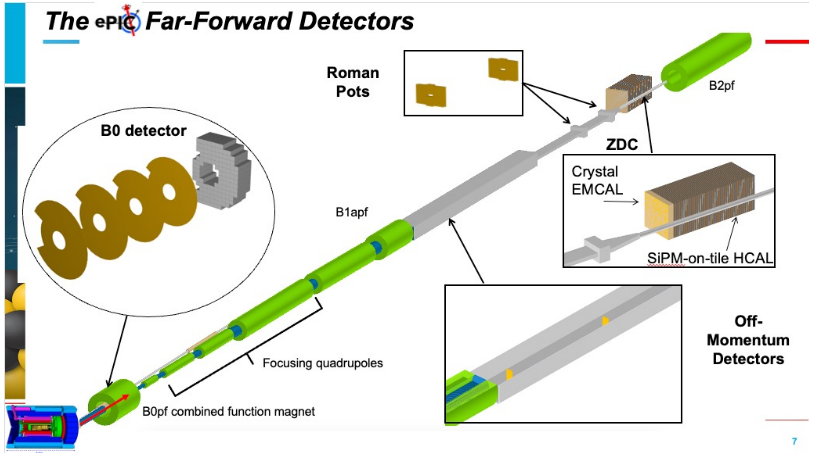


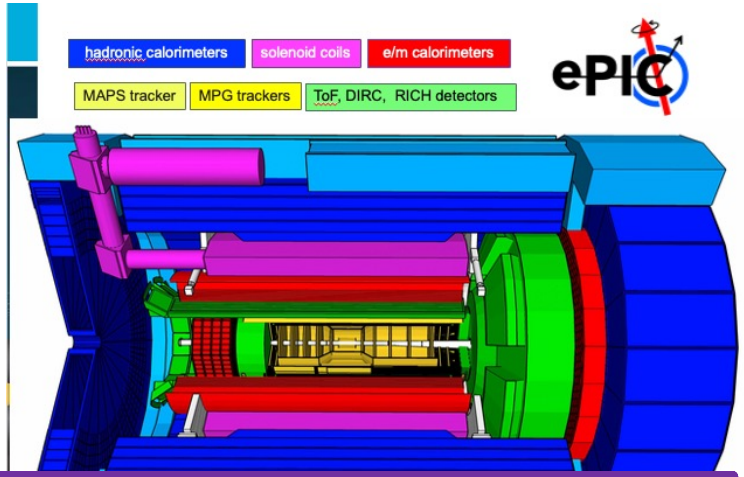
quantum numbers of final state → selects different GPD

DVCS: wide range of observables (σ, A_{UT}, A_{LU}, A_{UL}, A_C) to disentangle GPDs

A modern DVCS study for EIC

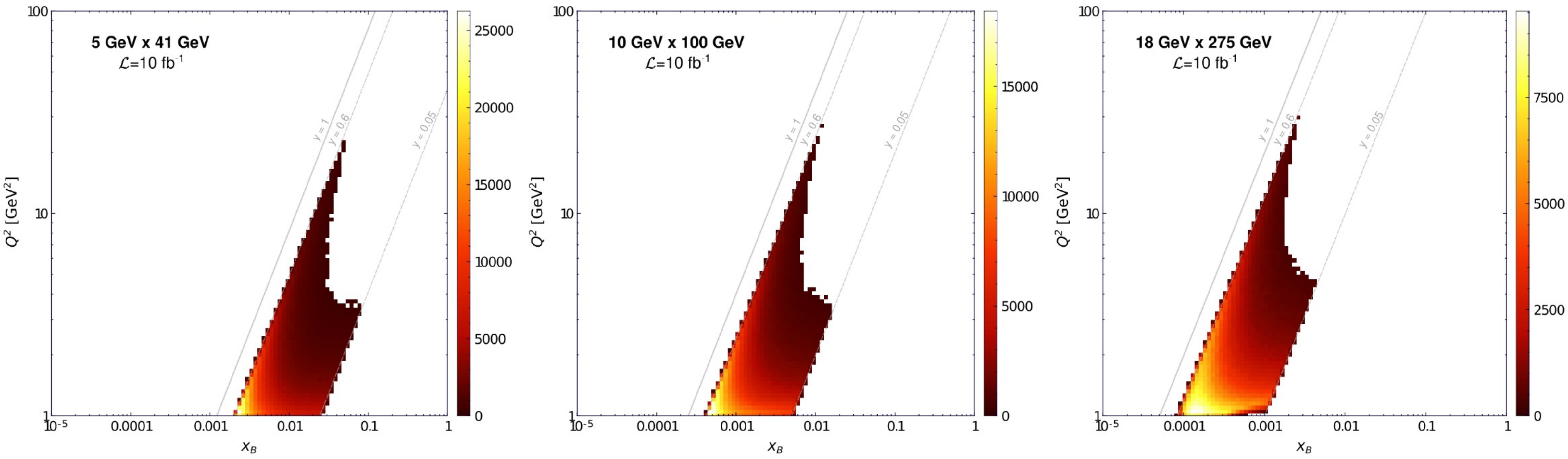
- Use the EpIC generator (Euro. Phys. Journal C, **Vol. 82,** 819 (2022)) to produce DVCS events at three EIC beam energies (18x275 GeV^2, 10x100 GeV^2, 5x41 GeV^2).
- Process events through hybrid simulation using EICROOT (used for all Yellow Report studies).
  - **Far-Forward region** – full simulations with all beam effects.
  - **Central region (main ePIC detector)** – fast simulations using understood acceptances, efficiencies, and detector resolutions.
- Use reconstructed DVCS events to perform study of nucleon tomography.





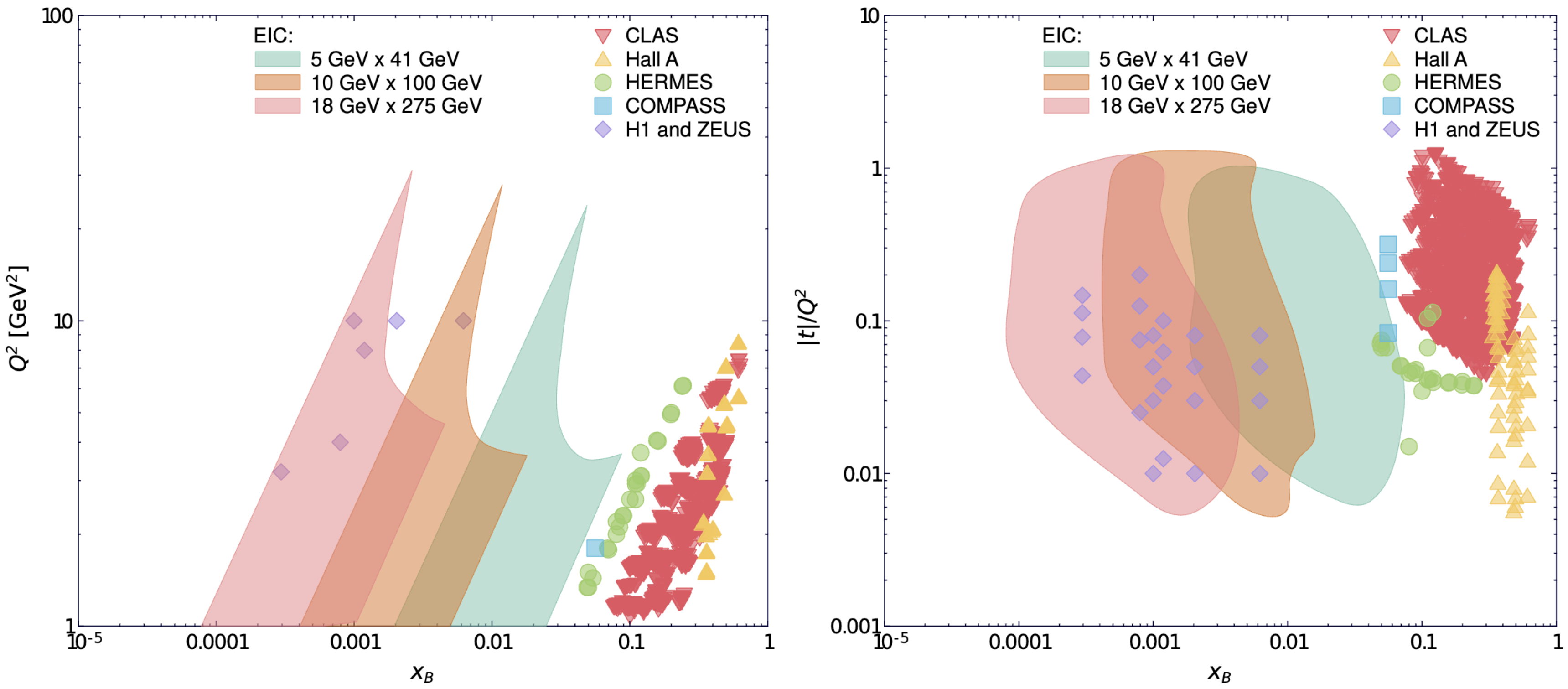
Detector	η acceptance	σ_E/E
Electron Endcap	$[-3.5, -1.0]$	$\frac{1\%}{\sqrt{E}} \oplus 1\%$
Barrel Imaging	$[-1.0, 1.0]$	$\frac{7\%}{\sqrt{E}} \oplus 1\%$
Hadron Endcap	$[1.0, 3.5]$	$\frac{12\%}{\sqrt{E}} \oplus 2\%$

DVCS phase space for this study



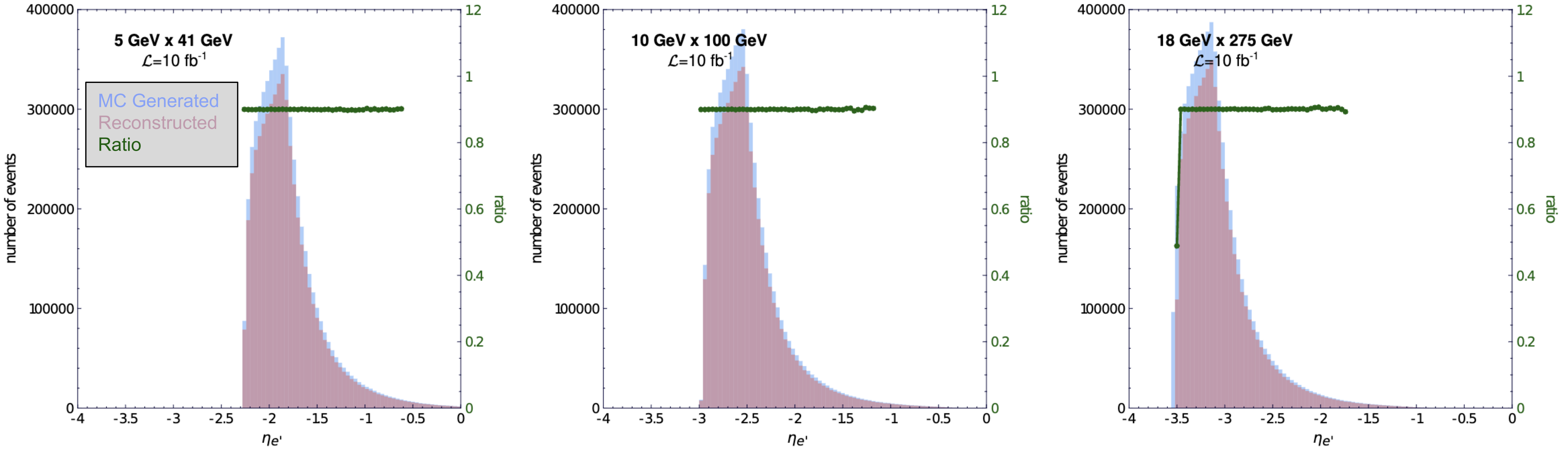
- EIC beam energy ranges enable broad coverage in x and Q^2 – one of the major EIC capabilities.
- Integrated luminosity assumed here is 10 fb^{-1}, arguably moderate for expected EIC luminosities, but realistic for the early years of running.

DVCS phase space for this study



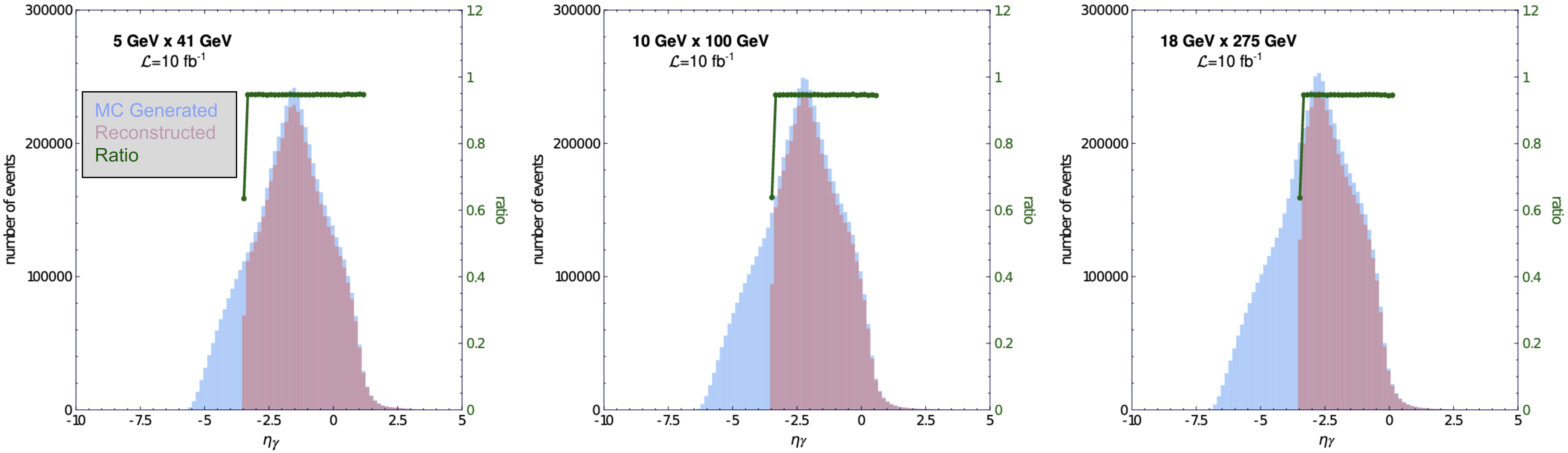
- Most DVCS measurements to date come from fixed-target experiments, with collider measurements (HERA) having fairly limited statistics and coverage in |t|.

Scattered Electron Reconstruction



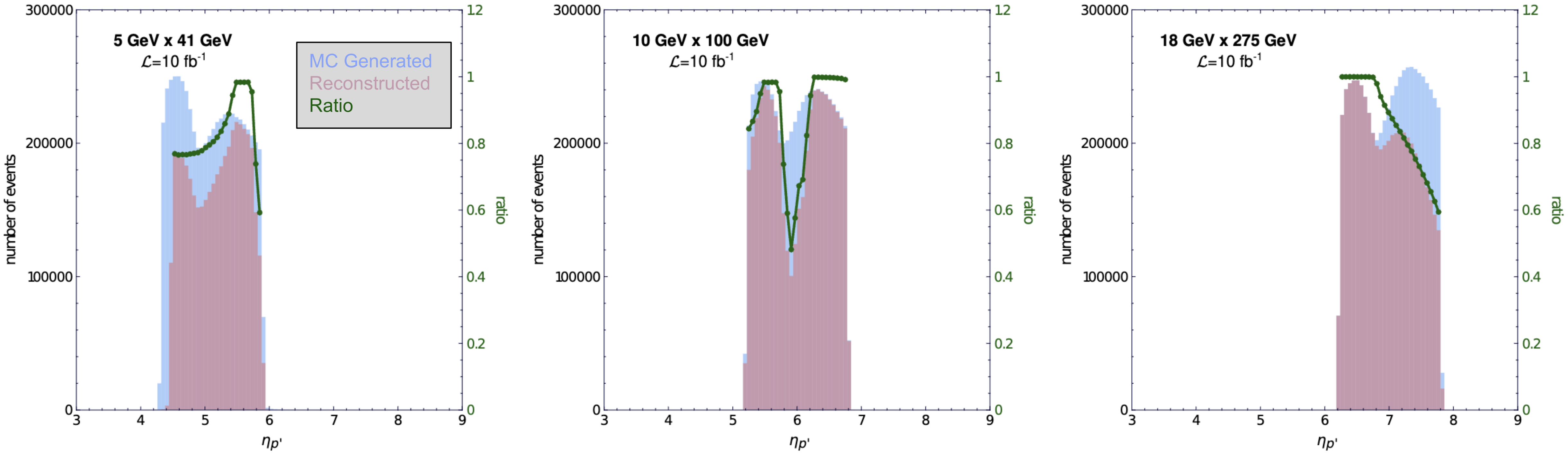
- Scattered electron tagging and reconstruction paramount for any DIS experimental apparatus.
- The ePIC detector has comprehensive coverage down to η ~ -3.5, with high-resolution tracking and calorimetry used to perform full reconstruction.

DVCS photon reconstruction



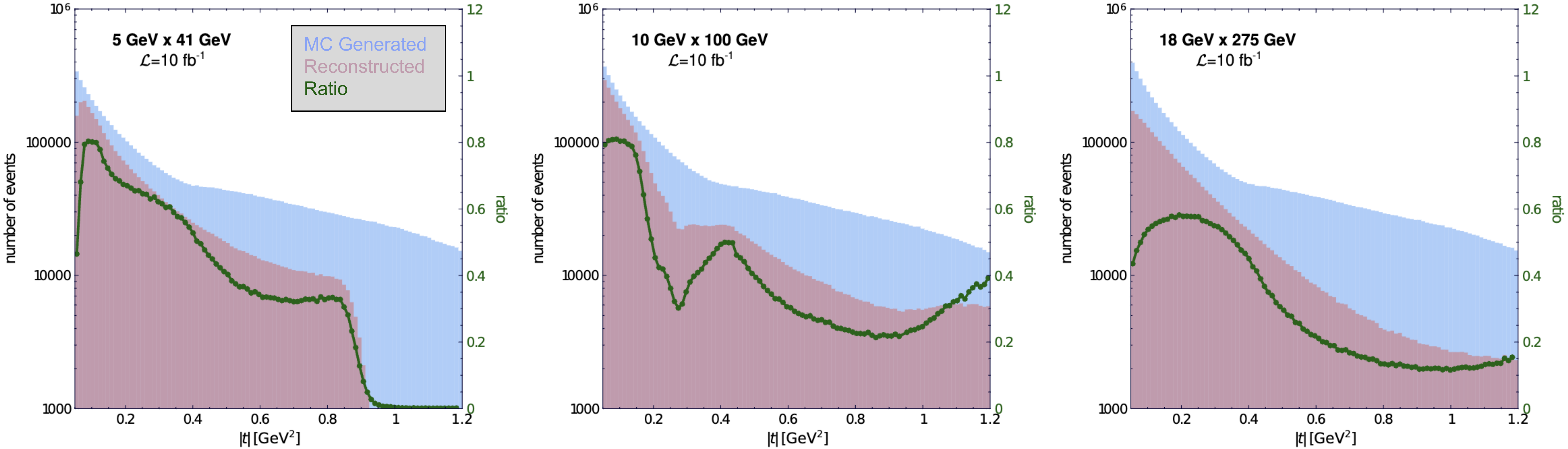
- DVCS photons reconstructed using only the EMCALs.
- Events with an extra photon (from FSR) are excluded – don't pass exclusivity constraint.

Scattered proton reconstruction



- Reconstruction highly dependent on beam energy – this is why we have multiple FF subsystems!
- At top beam energy, Roman pots are the dominate detector.
- At lower energies, the B0 tracking system takes up an increasingly dominant role in the reconstruction.

|t|-reconstruction



- |t| reconstruction is dependent on the reconstruction of the scattered proton for the kinematics, but the full distribution is also driven by the exclusivity requirement for the entire DVCS event.

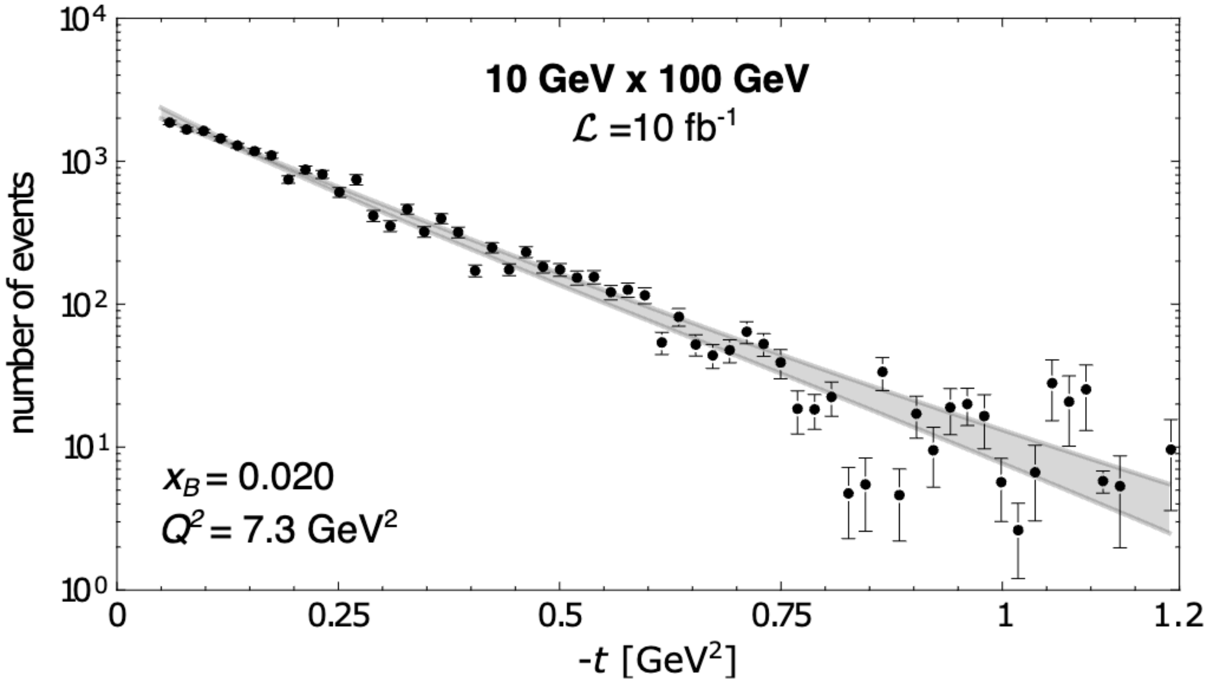
Radiative Corrections

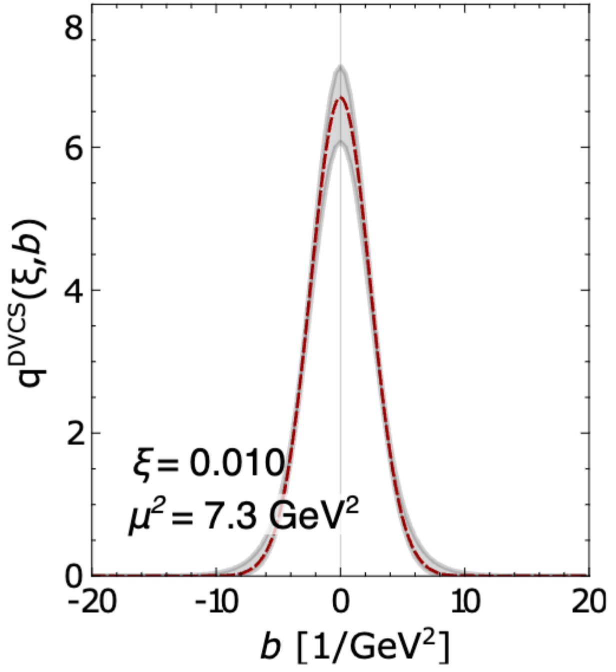
- Initial and final-state radiation is included in the EpIC MC events fed into the full simulations.
- For FSR, the radiated photon often falls within the detector acceptance, leading to a 4-particle final-state → event is rejected.
  - In cases where the FSR photon is “missed” by the detector, there would be a modification to the calculated x and Q^2 obtained from the scattered electron. → **impact found to be negligible in this study.**
- For ISR, the photon is never seen in the detector, but the initial electron kinematics are altered, and the experiment would never know.
  - **This could alter the shape of the |t|-distribution, in principle, but an enhanced treatment of the ISR would be needed to fully evaluate the effect.**
- Overall radiative effects do not produce a major impact on this study compared to other effects (e.g. full detector reconstruction).

π^0 background

- Previous experiments have shown exclusive π^0 production to be a significant source of background for DVCS measurements.
- Full simulations of exclusive π^0 production with the EpIC generator were run to study the capability to correctly identify, and reject, π^0 events.
- The issue stems from the misidentification of $\pi^0 \to \gamma\gamma$ as a single photon event due to the small opening angle between the daughters, and lack of angular resolution of the measuring sub-detector.
  - ePIC (collider) kinematics mean the $\pi^0 \to \gamma\gamma$ system is not highly boosted.
  - With the angular resolution of the various ePIC EMCALs, it is rare that the $\gamma\gamma$ showers cannot be disentangled.
  - Overwhelming majority of $\pi^0 \to \gamma\gamma$ events can be seen with both photons (it’s very rare one is lost).
- Overall, our study indicates less than < 10% contamination for the 5x41 GeV beam energy, and ~10x less contamination for the other beam energies.

The Punchline – Nucleon Tomography





Red curve is the reference from GK model.

- Extraction of shape of |t|-distribution enables Fourier transform and subsequent study of parton distribution as a function of impact parameter.
- See Krešimir's talk tomorrow for a discussion on CFF extraction.

Summary

- Lots of work on-going to finalize the baseline choices for the EIC detectors – preTDR due at the end of the year!
- Physics studies are part of the detector design process – we use the results of these studies to inform changes and study the impact of updates to the machine and detector design.
- This modern DVCS study improves upon previous studies by taking full detector simulations into account and uses a modern GPD model as input.
  - **Will be on the Arxiv this week!!**
  - It's clear the versatility of the EIC + the comprehensive beamline detector (far-forward) systems will drastically improve the reach of the partonic imaging program compared to previous experimental efforts – exciting times ahead!

Backup

Generic Performance Requirements

- Spatial resolution requirement → **140um or less**.
  - Angular divergence largest contributor, reduces impact of detector choice.
- Crab cavity rotation of the bunches → transverse “kick” to the particles, dependent on the location along the bunch.
  - Results in effective vertex smearing, disentangled with fast timing → **35ps to remove the full effect**.
- Timing also needed for background rejection.
- Technologies need to be radiation hard → expected radiation load on the RP and OMD ~ 100x less than at the LHC.
  - Radiation damage has impact on **timing resolution** and **spatial resolution (when charge sharing is used)**.
  - Radiation studies carried out for ePIC indicate that doses delivered to AC-LGADs for RP/OMD will not lead to reduction in performance during life of experiment.

Generic Performance Requirements

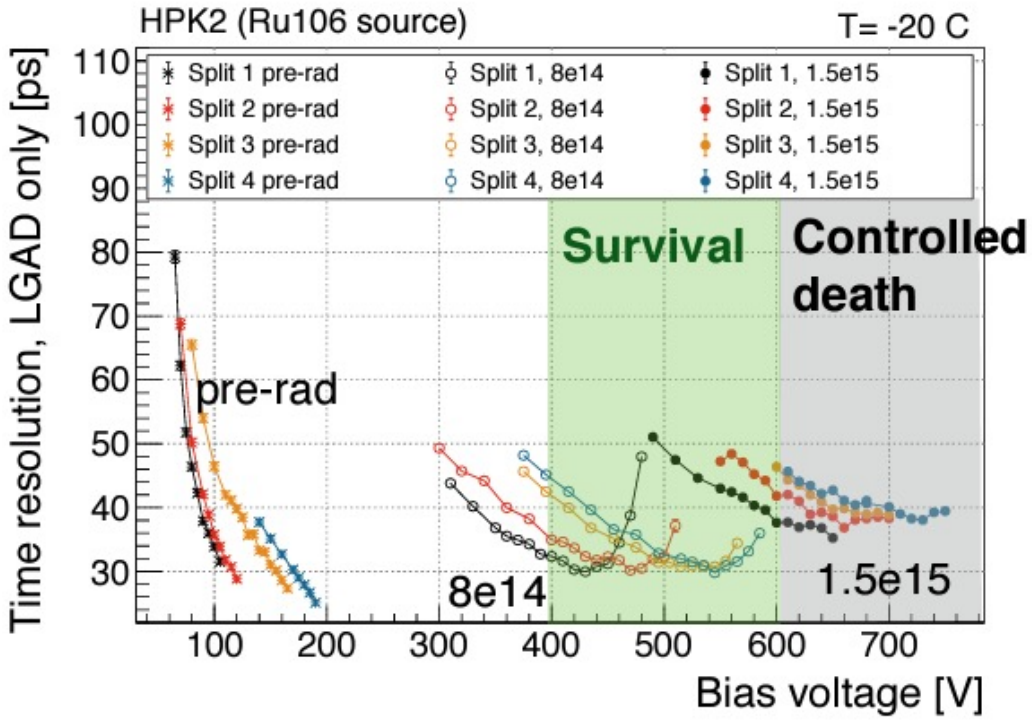
From:
https://indico.cern.ch/event/1029124/contributions/4411270/attachments/2269713/3854416/heller_LGAD_mortality_RD50.pdf

Plot shows time resolution as a function of bias voltage for various levels of irradiation of a batch HBK DC-LGADs used by ATLAS and CMS.

Split 1 — Split 4 (lowest to highest operating voltage)

Radiation: n_{eq} = 8e14 and 1.5e15 n/cm^2

***Note: the fluences shown here are ~ 2-3 orders of magnitude higher than what is expected at ePIC.



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Generic Performance Requirements

Study from eRD24 effort

- 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.

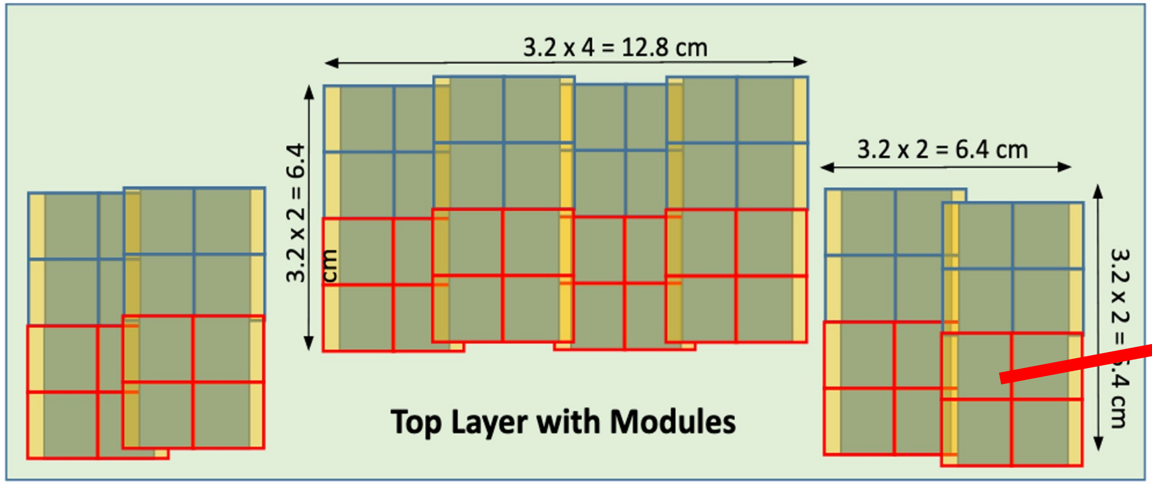
	Ang Div. (HD)	Ang Div. (HA)	Vtx Smear	250µm pxl	500µm pxl	1.3mm pxl
$\Delta p_{t,total}$ [MeV/c] - 275 GeV	40	28*	20	6	11	26
$\Delta p_{t,total}$ [MeV/c] - 100 GeV	22	11	9	9	11	16
$\Delta p_{t,total}$ [MeV/c] - 41 GeV	14	-	10	9	10	12

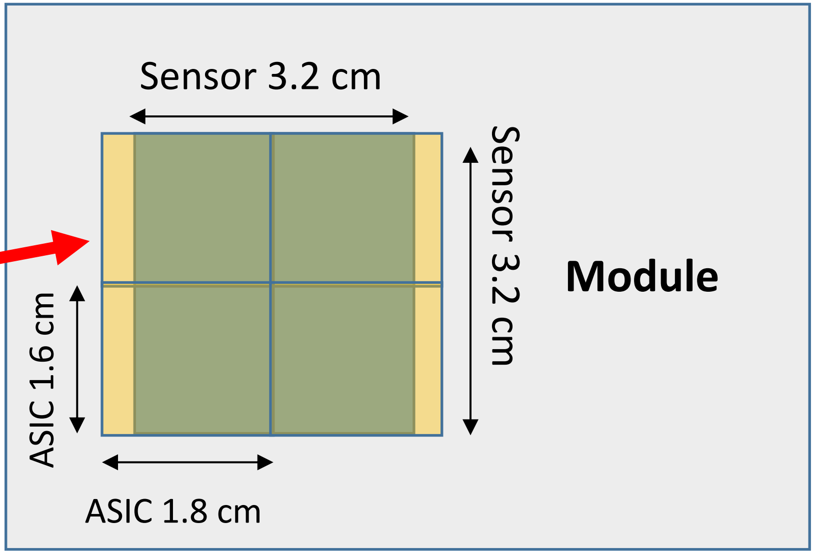
- **Beam angular divergence**
  - Beam property, can't correct for it – sets the lower bound of smearing.
- **Vertex smearing from crab rotation**
  - Correctable with precise timing (~35ps).
- **Finite pixel size on sensor**
  - 500µm seems like the best compromise between potential cost and smearing.

These requirements can be met by the new **AC-coupled LGAD sensor technology** (eRD24 was focused on applications of this technology to the far-forward detectors).

Technology: AC-LGAD

- Updated layout for the **Roman Pots** with current design for AC-LGAD sensor + ASIC.



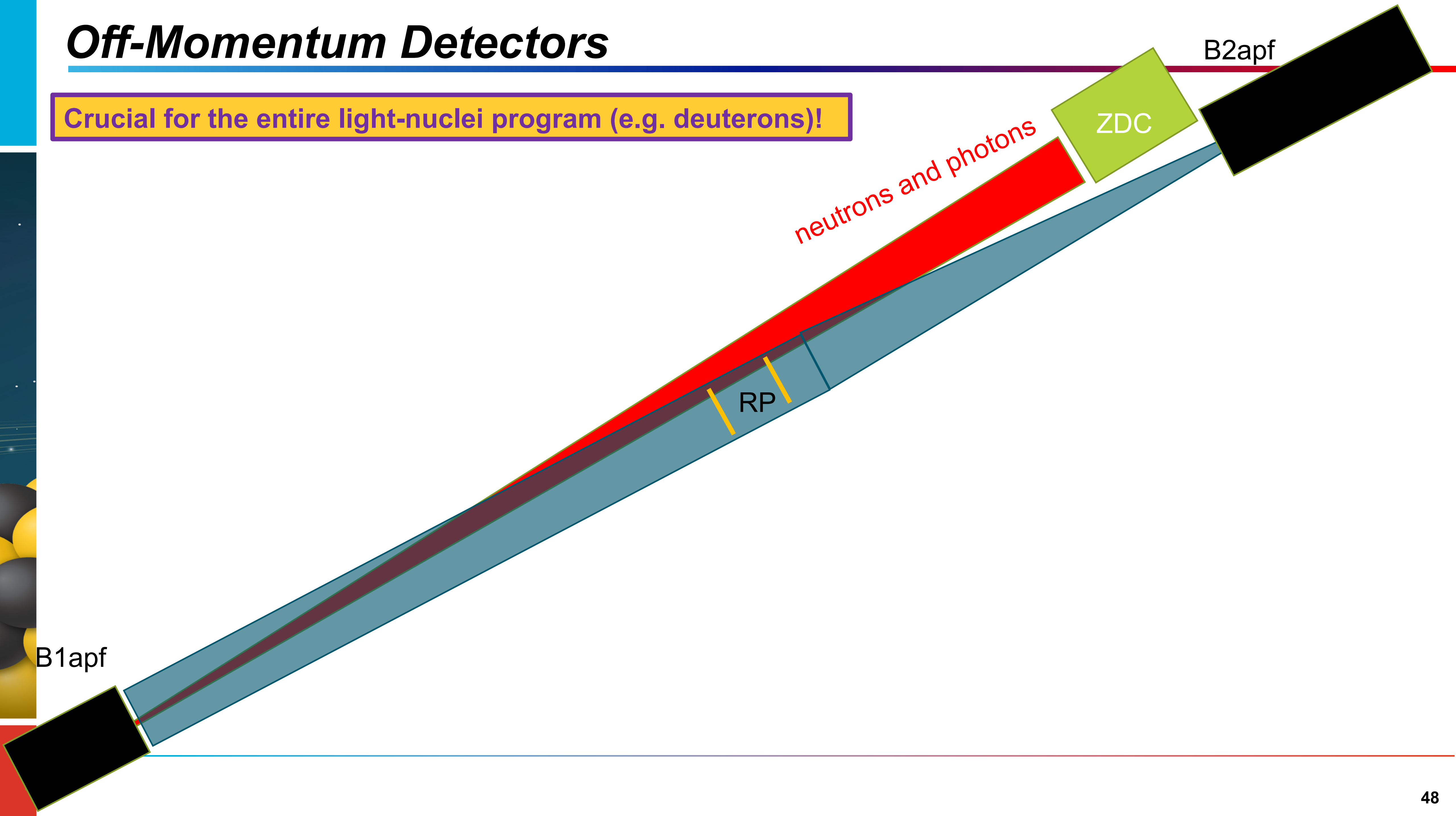


- Approach based on bump-bonding four custom ASICs to a single AC-LGAD sensor to make a “module”.
  - This is being re-evaluated now.

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

Off-Momentum Detectors

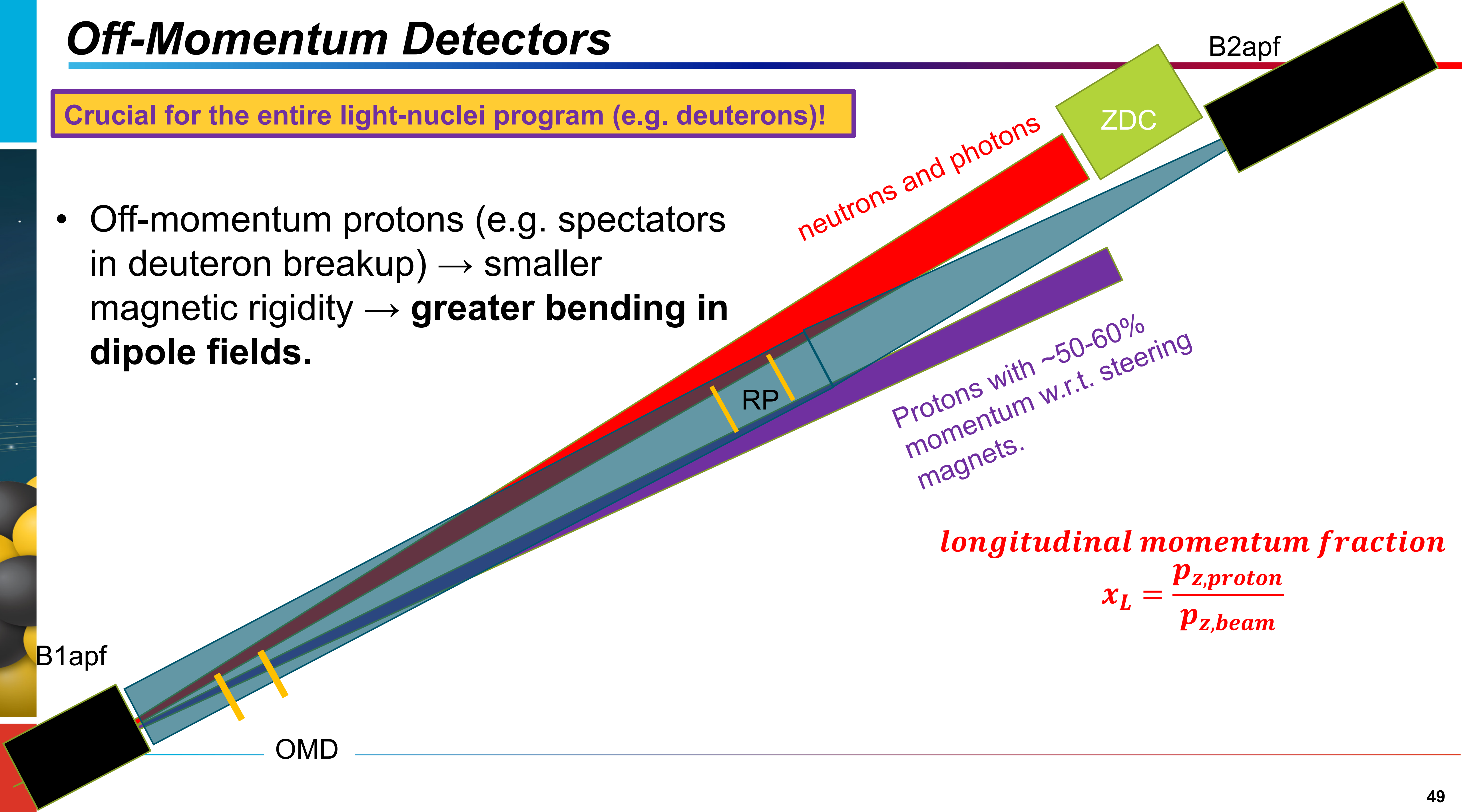
Crucial for the entire light-nuclei program (e.g. deuterons)!



Off-Momentum Detectors

Crucial for the entire light-nuclei program (e.g. deuterons)!

- Off-momentum protons (e.g. spectators in deuteron breakup) → smaller magnetic rigidity → **greater bending in dipole fields.**



longitudinal momentum fraction

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

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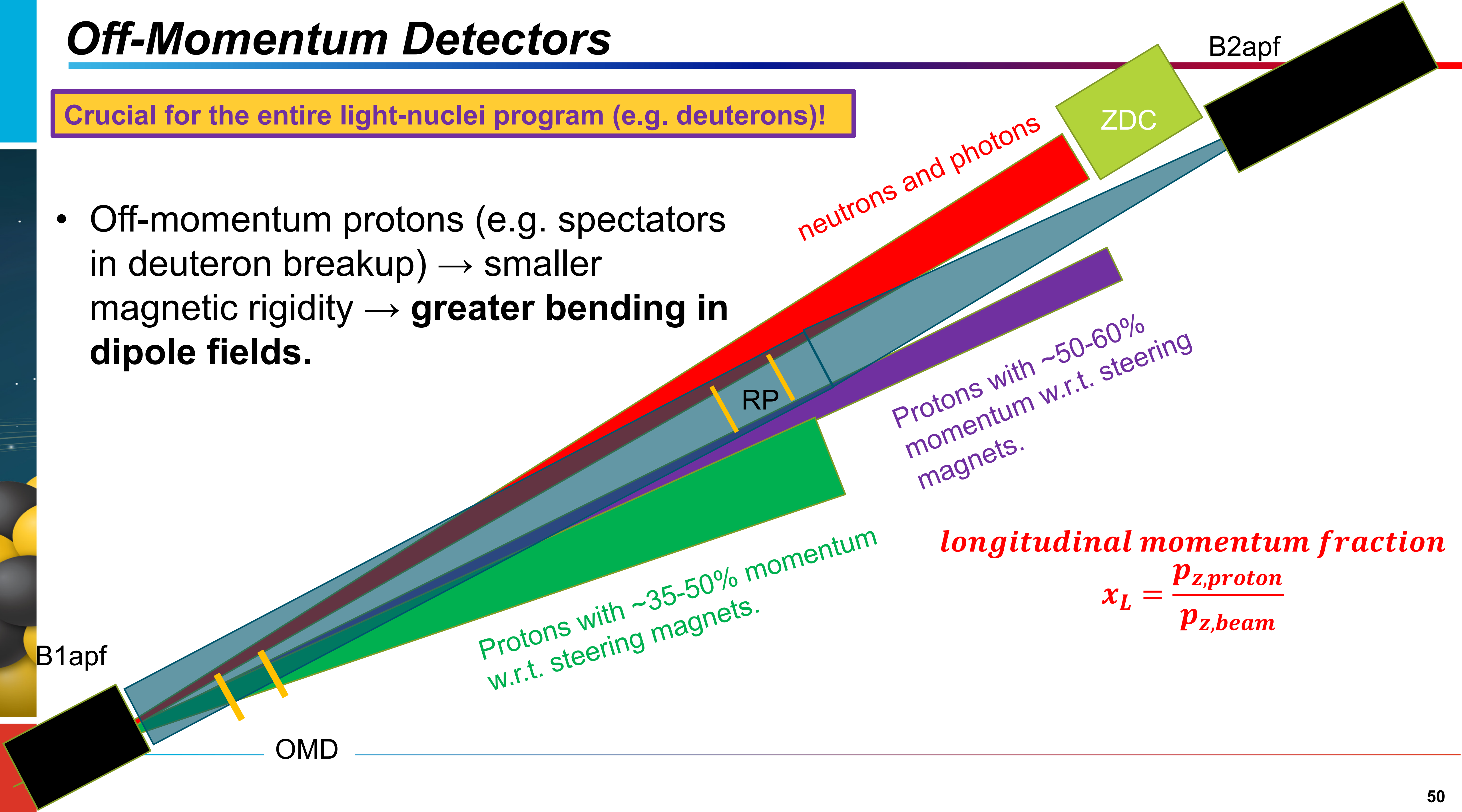

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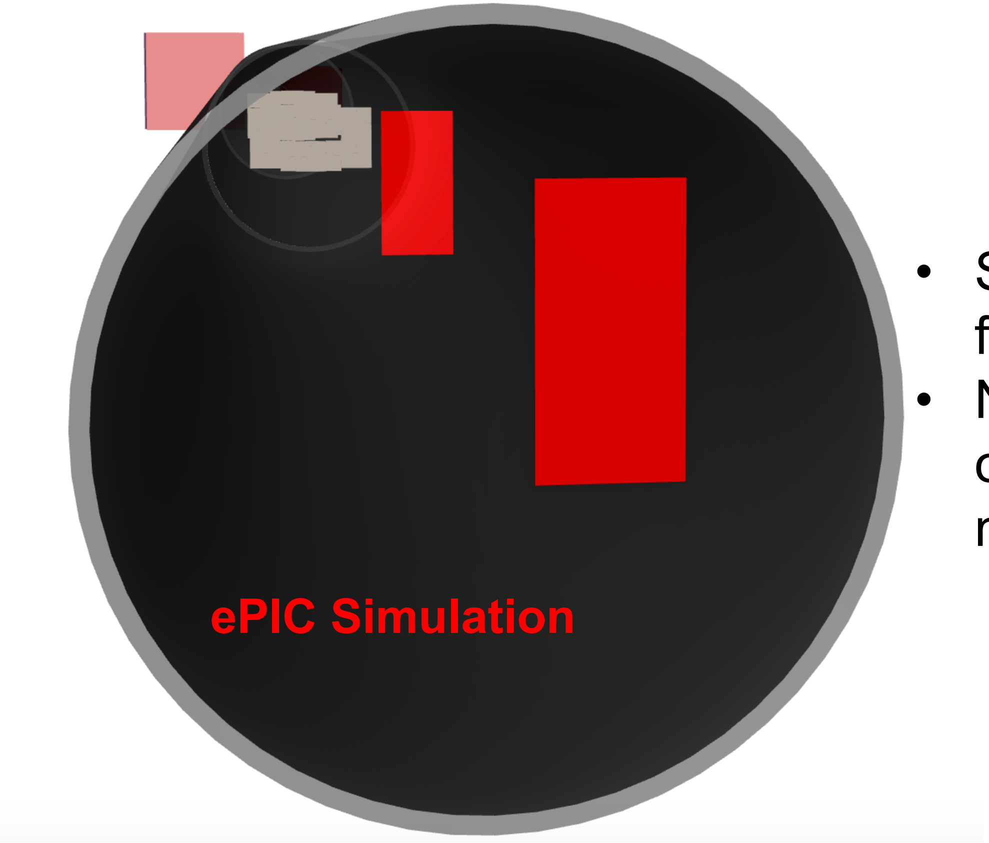
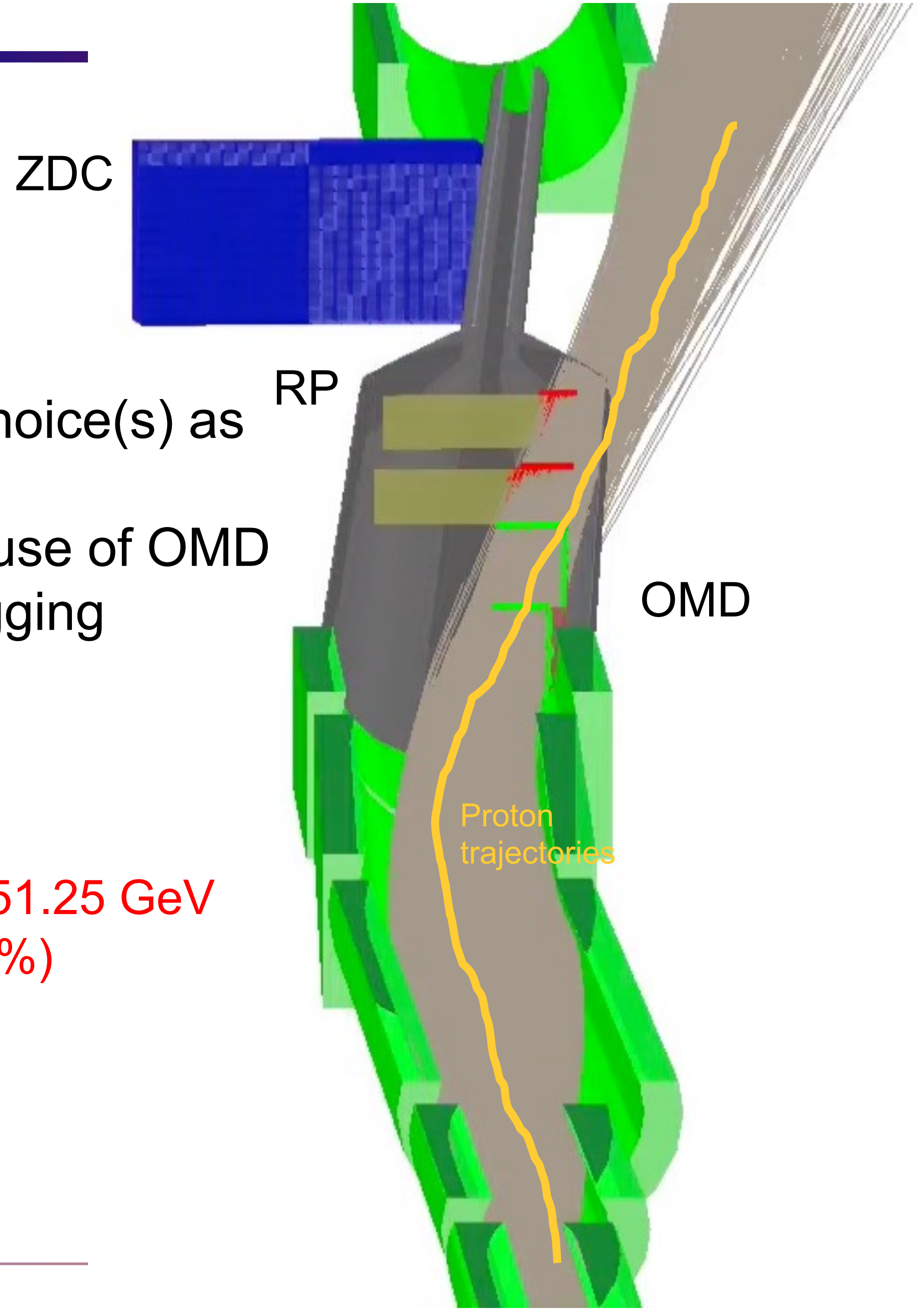
Off-Momentum Detectors



Off-momentum detectors implemented as horizontal ”Roman Pots” style sensors.

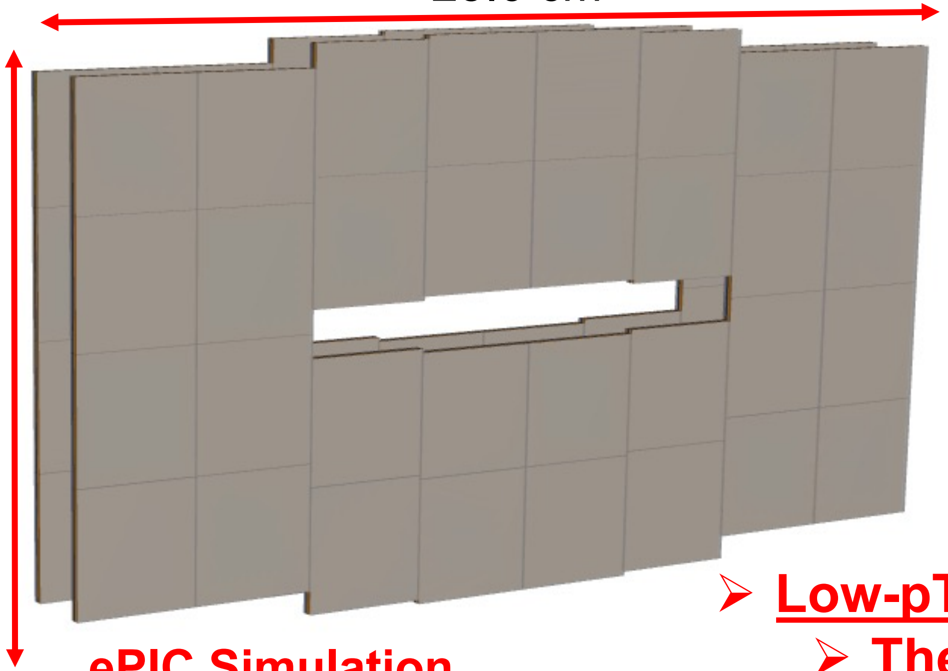
- Same technology choice(s) as for the Roman Pots.
- Need to also study use of OMD on other side for tagging negative pions.

Protons
123.75 < E < 151.25 GeV
(45% < xL < 55%)
0 < θ < 5 mrad



EICROOT GEANT4 simulation.

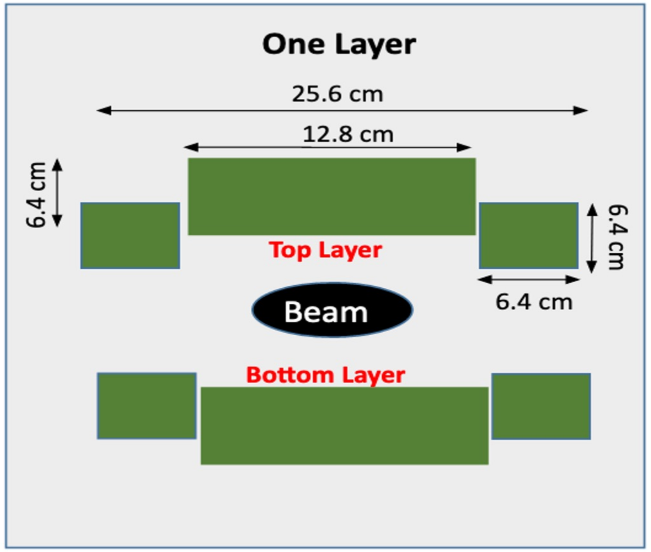
Roman Pots @ the EIC



ePIC Simulation

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

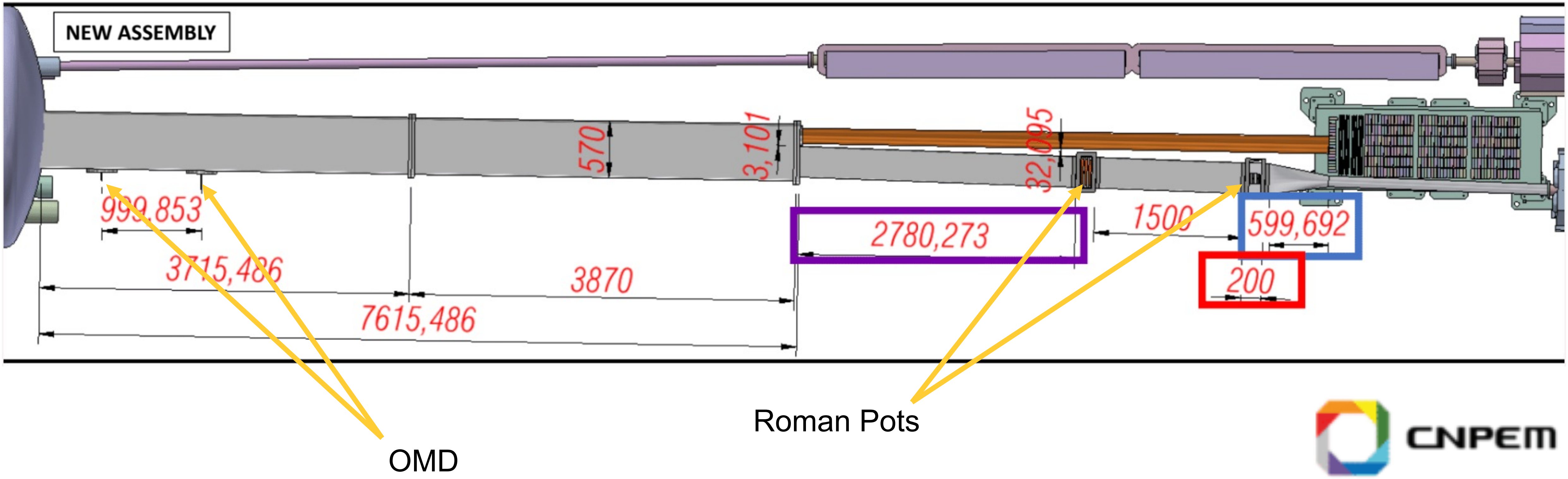
$$\sigma(z) \sim \sqrt{\varepsilon \cdot \beta(z)}$$



- **Low-pT cutoff determined by beam optics.**
  - **The safe distance is ~10σ from the beam center (1$\sigma \sim 1$mm).**
- **Optics change with energy**
  - **Can also be changed within a single energy to maximize *either acceptance at the RP, or the luminosity.***

- **Detectors need to be able to move to different positions for different optics configurations.**

Preliminary design of RP and OMD Pipe and Supports



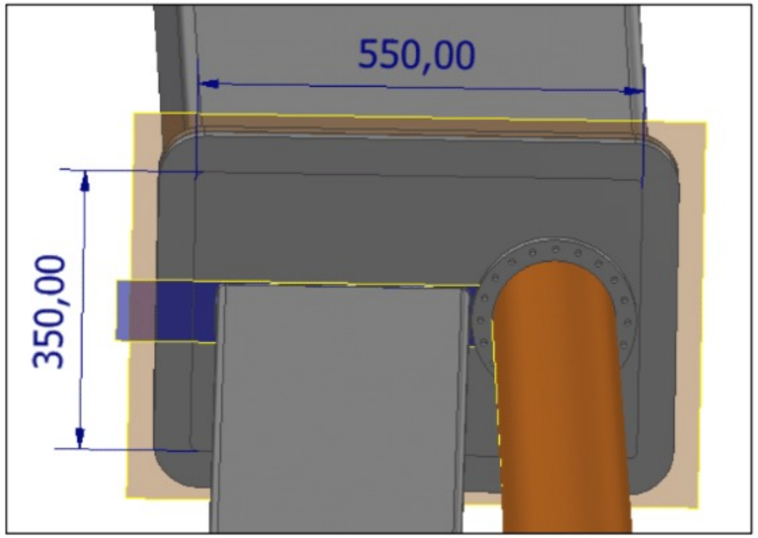
CNPEM

MINISTRY OF SCIENCE TECHNOLOGY AND INNOVATION

BRAZILIAN GOVERNMENT BRASIL UNITING AND REBUILDING

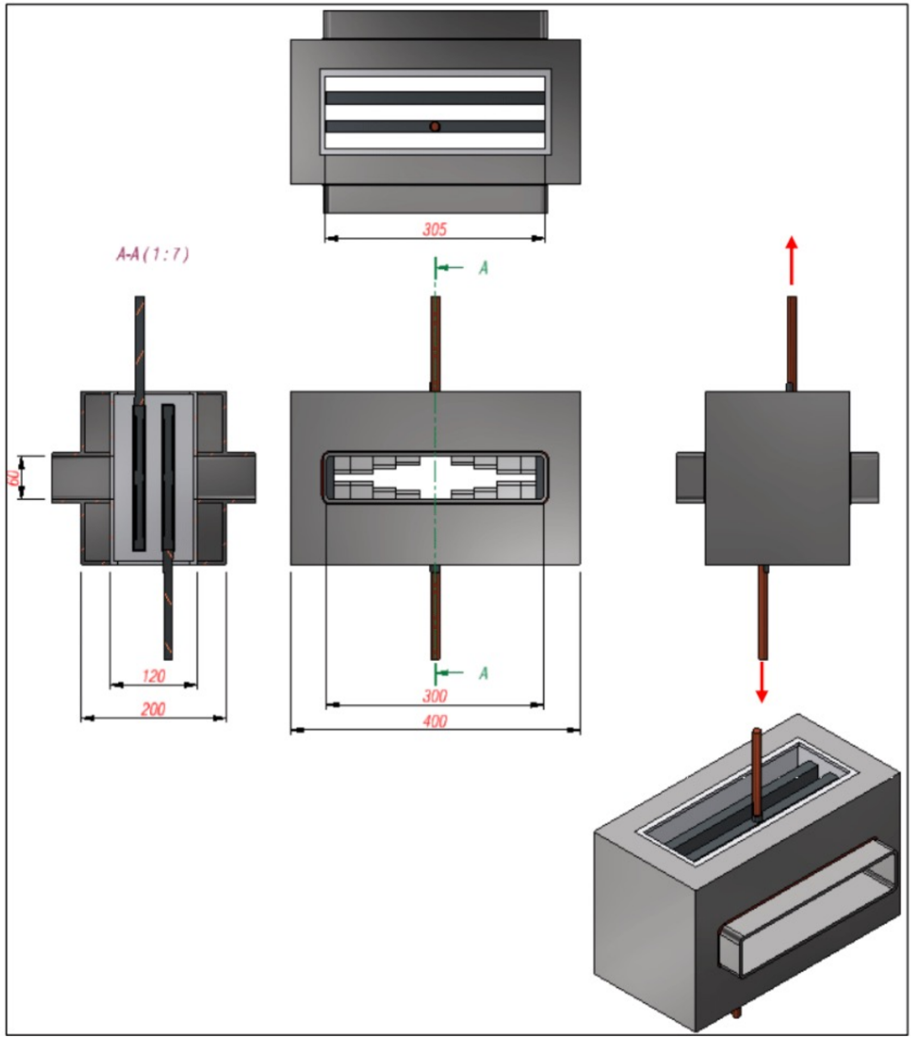
Preliminary design of RP and OMD Pipe and Supports

New 550x350 mm inner dimensions chamber



Transition region from larger beam pipe containing OMD to smaller pipe containing RP (left) and exit window for neutrals (right).

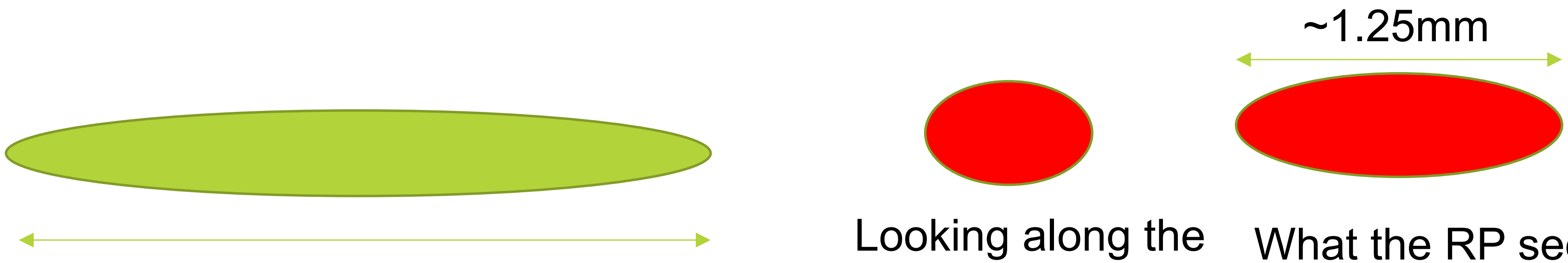
New Concept



Scattering chamber design for RP sensor packages.

Momentum Resolution – 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.

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 **.125mm** vertex smearing.
- The simulations were done with these two extrema and the results compared.

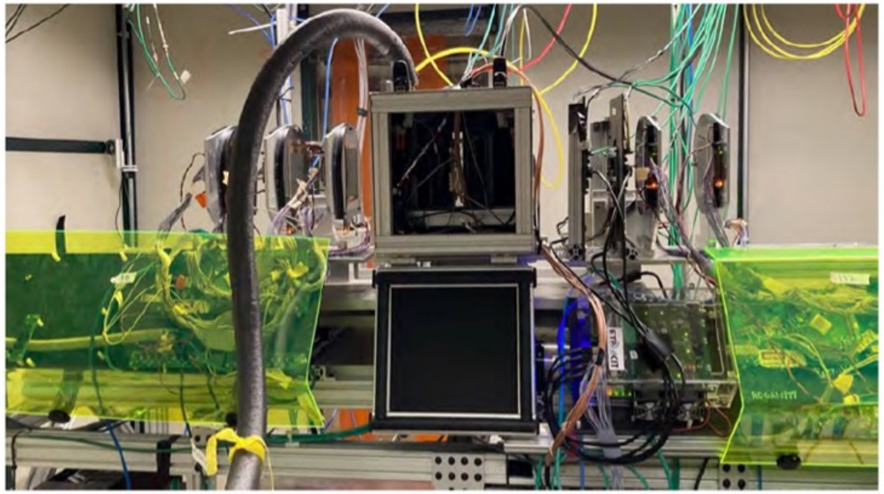
> - **From these comparisons, reducing the effective vertex smearing to that of the 1cm bunch length reduces the momentum smearing to negligible from this contribution.**
> - **This can be achieved with timing of ~ 35ps (1cm/speed of light).**

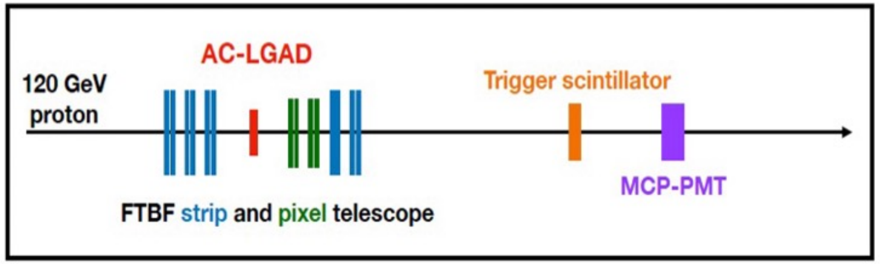
AC-LGADs

- Sensors with different configurations produced by BNL-IO and HPK, and tested with 120GeV protons
- Prototype strip sensors with ~35 ps time resolution and <15 um spatial resolution (more in the next talk).
- Prototype pixel sensors with ~20 ps time resolution and ~20* um spatial resolution.

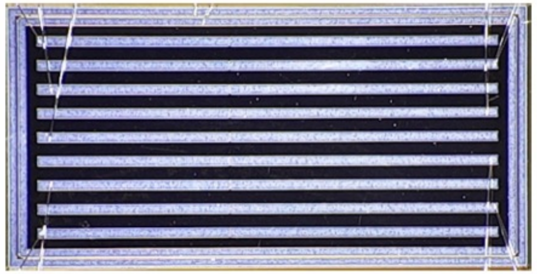
* ~50 um under metal electrodes. To be improved

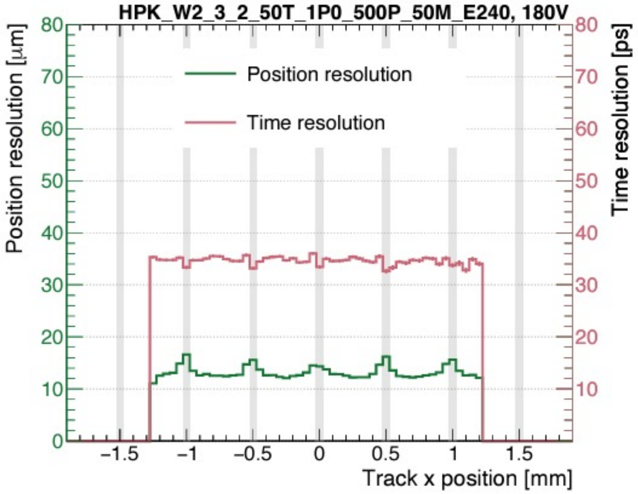
Fermilab Test Beam Setup



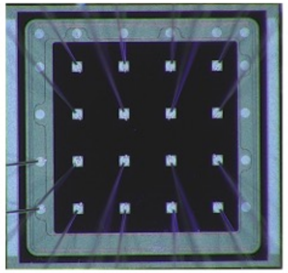


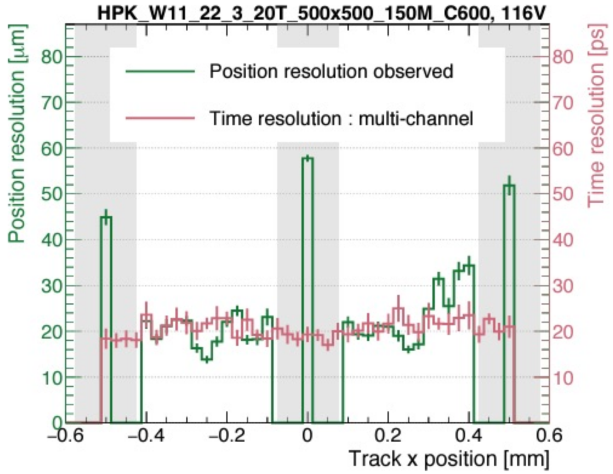
HPK Strip Sensor (4.5x10 mm²)



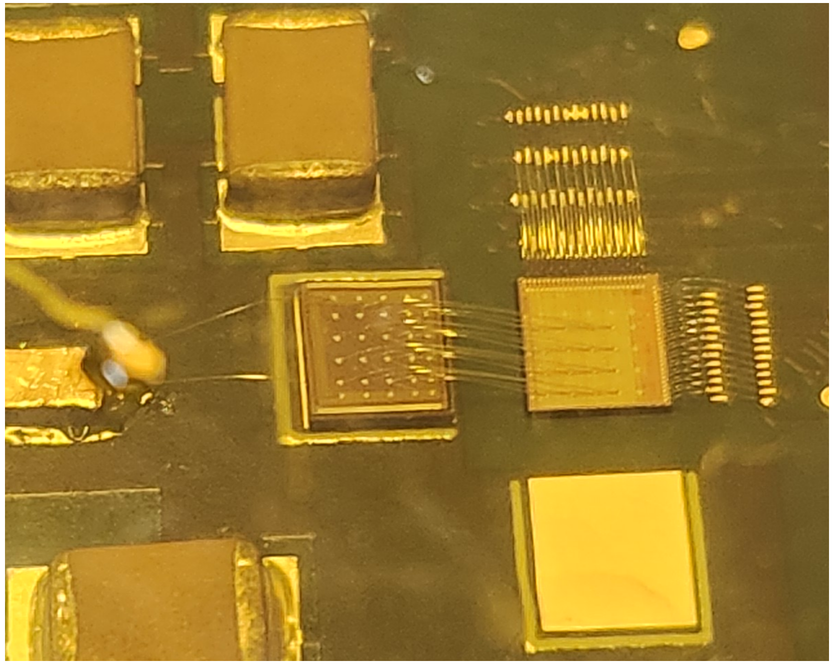


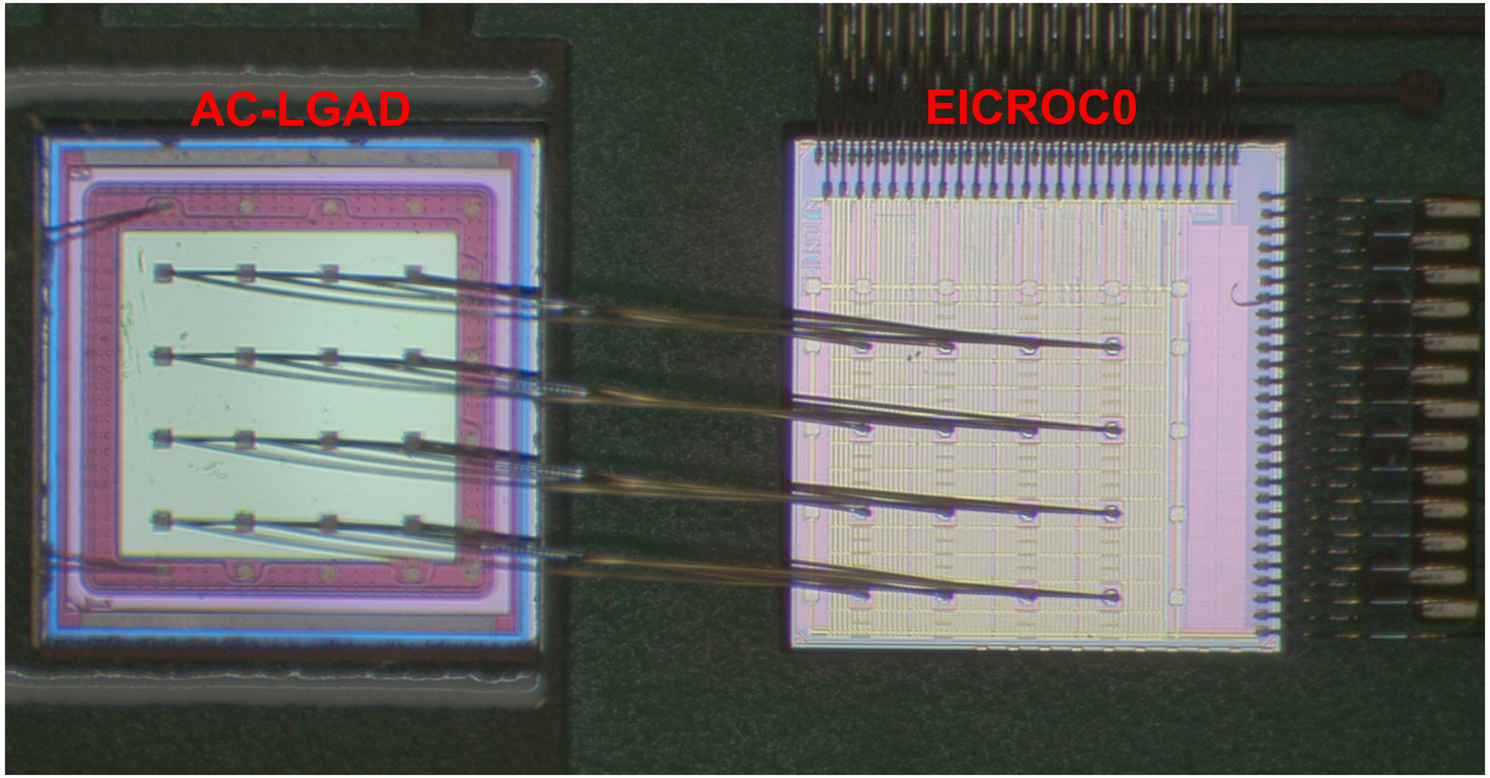
HPK Pixel Sensor (2x2 mm²)





Tests of AC-LGAD sensor with EICROC (version 0) ASIC





- AC-LGAD sensor (BNL) wire-bonded to EICROC0 (OMEGA/ICJLab) for testing on custom test board produced by OMEGA.

<u>BNL AC-LGAD:</u>

- 500x500 um^2 pixel pitch
- 100x100 um^2 metal electrode
- 30um active thickness

- Setup is presently wire-bonded for initial tests, bump bonding to follow very soon – both at BNL.
- Two other similar boards with EICROC0 were produced and sent to IJCLab and Hiroshima U. for testing.