Target Fragmentation and Fracture Function Observables at the Electron-Ion Collider

@ HP2026 Satellite Workshop on Jets and Heavy Flavor Physics

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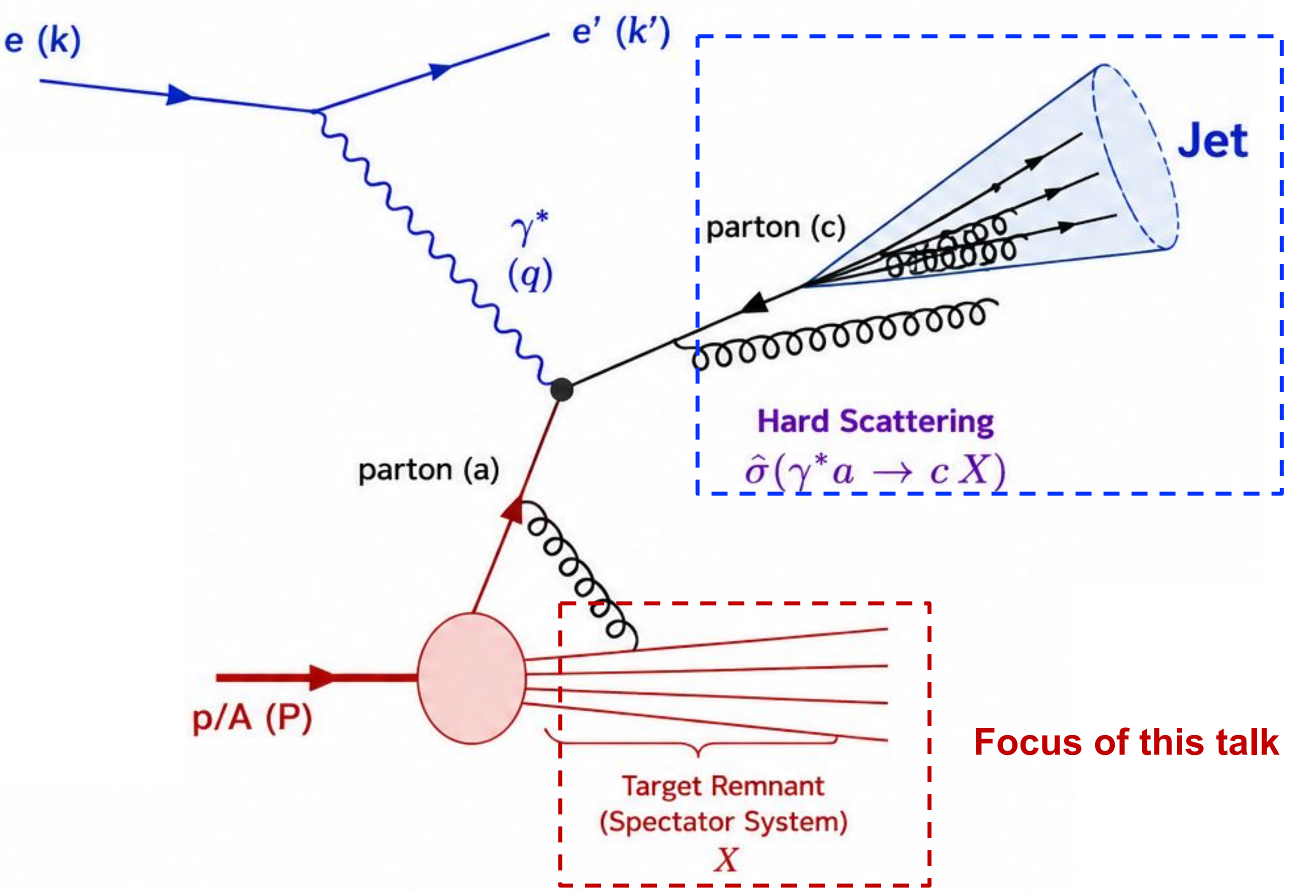
Center for Frontiers in Nuclear Science

Jet Production vs **Target Fragmentation**



Primary focus of the community
&
This workshop

Focus of this talk

"Is this soft structure? how do we measure this?"

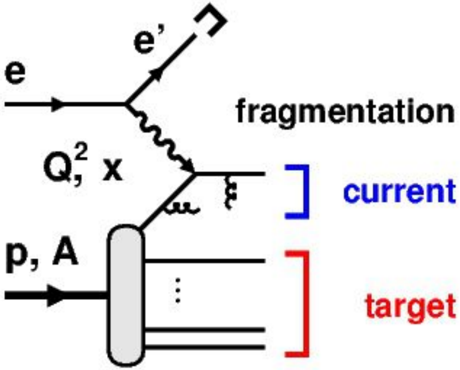
Outline and Disclaimer

- **A very superficial coverage for the theory**
  - Target fragmentation
  - Fracture function: (subset process description)

- **Experimental concerns at the EIC**
  - Current design (project) ePIC instrumentation limitation for detecting the target fragmentation
  - Possible future upgrade

Archaeology: CFNS Target Fragmentation Workshop in 2020

Image credit by C. Weiss



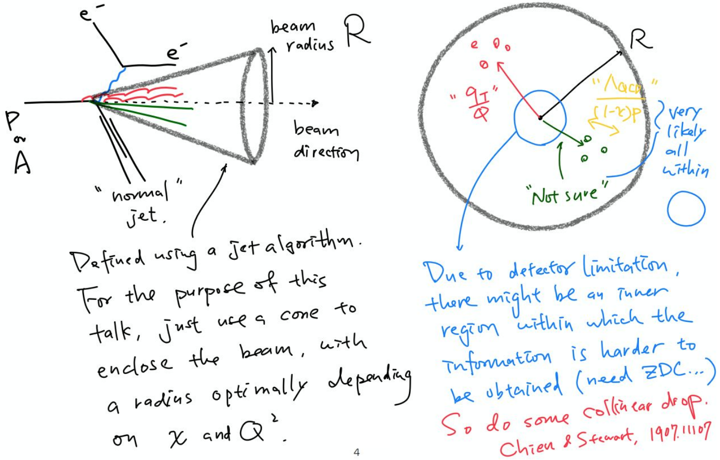


Image credit by Yang-Ting Chien, Soft-Collinear Effective Theory and target fragmentation, https://indico.bnl.gov/event/14009/

CFNS Adhoc Workshop: Target Fragmentation Physics with EIC

28 Sept 2020, 09:30 → 30 Sept 2020, 15:30 US/Eastern

Description

Measurements of target fragmentation in DIS have great potential for studying nucleon structure and nonperturbative QCD but have been little explored so far. Target fragmentation gives access to the nucleon's multiparton structure and correlations, which are the next frontier after the single-parton densities. The theory of target fragmentation in DIS is well developed, employs leading-twist QCD factorization and distributions, and is in some respects simpler than that of current fragmentation (TMD factorization). The use of spin/flavor quantum numbers in target fragmentation offers new ways to study nucleon spin structure, intrinsic strangeness, and quark-antiquark correlations related to dynamical mass generation in QCD.

Target fragmentation measurements represent a new opportunity for the EIC and could significantly extend the reach of the 3D nucleon structure program. This initiative needs a concise formulation of the physics case, development of simulation tools, and assessment of the requirements for forward/far-forward detectors. It is expected that target fragmentation measurements would be feasible with the baseline EIC detector specifications assumed in the on-going Yellow Report studies. The concepts and tools can also be tested by analyzing the archived HERA data on forward proton/neutron production and x_F distributions, which are now available in a database.

Target fragmentation is also important for understanding/modeling nuclear breakup in DIS on nuclei in measurements of spectator tagging and diffractive processes. Final-state interactions of the spectator nucleons with the slow DIS hadrons in the nucleon fragmentation region influence the nuclear breakup pattern. The lack of data and theoretical models on nucleon fragmentation has been a major impediment in this field. Conversely, nuclear breakup measurements can be used to explore the space-time picture of hadron formation and quantify the relevant time/distance scales. Such studies need joint discussions and exchanges between researchers working on DIS fragmentation and low-energy nuclear breakup (cascade models).

Objectives

- Review physics of target fragmentation at fixed-target and collider energies
- Develop plan for target fragmentation measurements at EIC
- Initiate analysis of archived HERA data for pre-EIC target fragmentation studies
- Stimulate theoretical research in nucleon fragmentation and nuclear final-state interactions

Topics

- QCD description of target fragmentation in DIS
- Dynamical models of nucleon fragmentation and fracture functions
- HERA forward proton/neutron data and future analyses
- Spin/flavor and multiparton correlations in target fragmentation
- Target fragmentation in fixed-target experiments JLab12/COMPASS
- Nucleon fragmentation and nuclear breakup in DIS
- Cascade models of nuclear final-state interactions
- Target fragmentation with EIC forward detectors and Yellow Reports

Workshop link: https://indico.bnl.gov/event/9287

Archaeology: CFNS Target Fragmentation Workshop in 2020

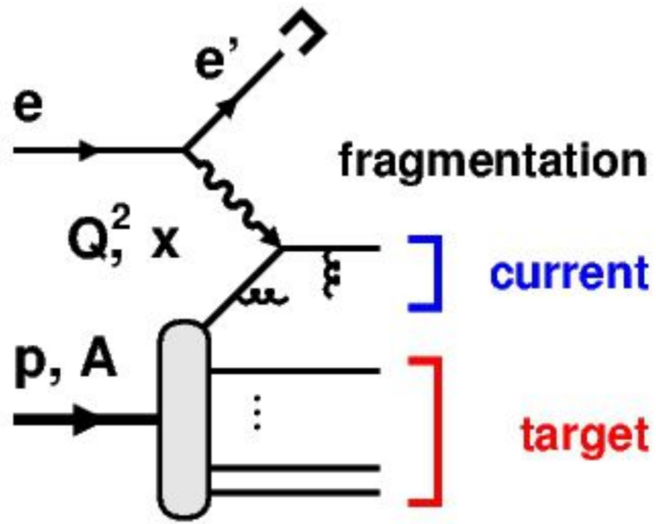
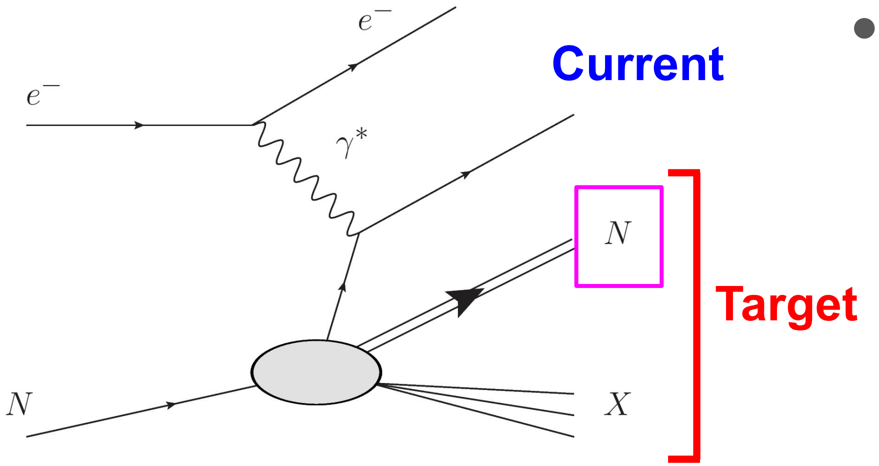


Image credit by C. Weiss

- **When we have a DIS scattering**
  - e + p → e' + Current Fragments + Target Fragments
- **Fragmentation function** is often the interest
  - Final-state hadronization
  - Easy to tag experimentally (SIDIS): simultaneous detection of e' and current fragments (mesons, jets, mesons within the jets)
  - Well defined formulasm
- **Can we also study the target?**
  - Largely unknown, exploratory stage
  - An Improved Description of Inclusive Hard Processes in QCD, , by L. Trentadue and G. Veneziano, https://arxiv.org/abs/hep-ph/9506324

Fracture Function Formalism



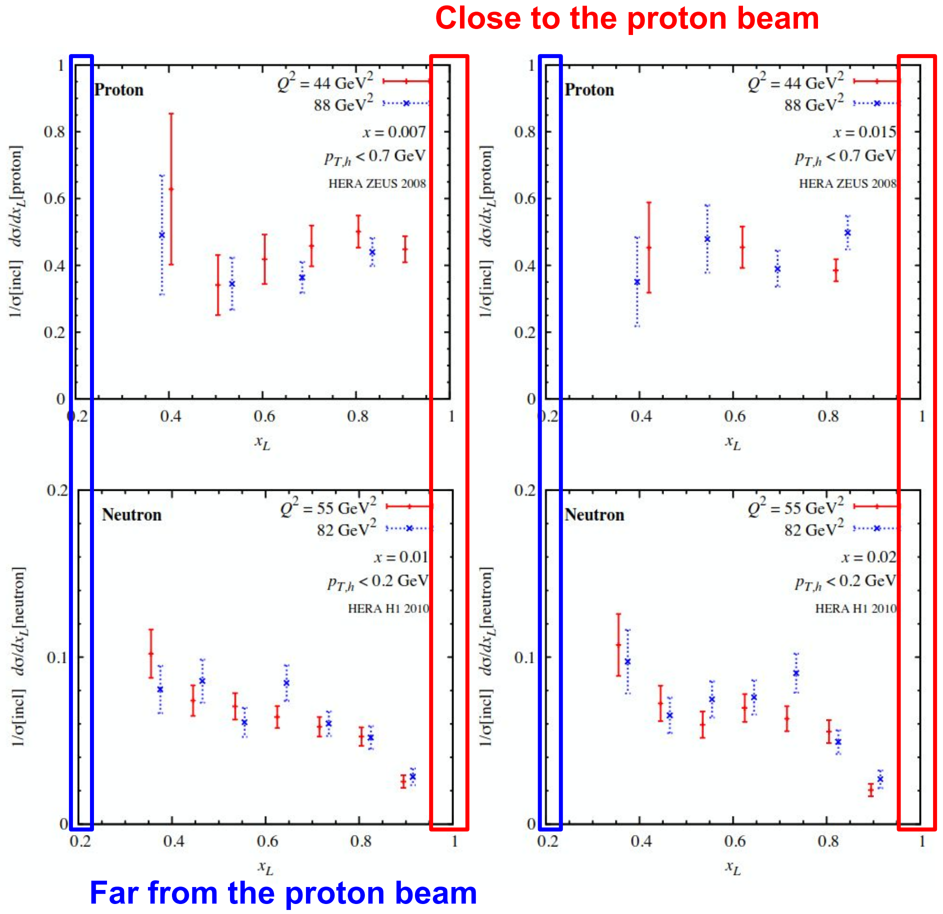
- **Fracture function:** A fracture function describes semi-inclusive deep-inelastic scattering when an identified hadron is produced from the target remnant

$$M^{h}_{i/N}(x, z, Q^2)$$

i: probability density for finding a parton of flavor
x: target momentum fraction
h: produced hadron carrying momentum fraction z

- **Skepticism:** why do we need to invent formulation for a this very specific case?
  - Subset of the target-fragmentation process
- **Data drive phenomenology effort:**
  - Similar to Silvers and Collins fragmentation function, later become a component of TMD

Key Results on Target Fragmentation from HERA



- **Final state/beam proton momentum ratio**

$$x_L \equiv \frac{p_{L,\text{baryon}}}{p_{L,\text{incoming proton}}} \simeq -x_F$$

- $\boldsymbol{x_L \to 1}$**:** the baryon stays close to the proton beam (original target)
- Probability of finding a leading baryon near the beam (x_L>0.3) is only 60-70%, 30-40% of the baryon number is lost away from the proton beam!
- Weak Q^2 dependence

Fracture Function Formalism

- The general one-particle-inclusive SIDIS cross section mechanism:

$$d\sigma^h = \boxed{\underbrace{\sum_i M^h_{i/N} \otimes d\hat{\sigma}_i}_{\text{target fragmentation}}} + \boxed{\underbrace{\sum_{i,j} f_{i/N} \otimes d\hat{\sigma}_{ij} \otimes D^h_j}_{\text{current fragmentation}}}.$$

- Formalism:

$$\boxed{M^h_{i/N}(x, z, Q^2)}$$

  - i: probability density for finding a parton of flavor
  - x: target momentum fraction
  - h: produced hadron carrying momentum fraction z

- Hybrid approach that combines the PDF and fragmentation function

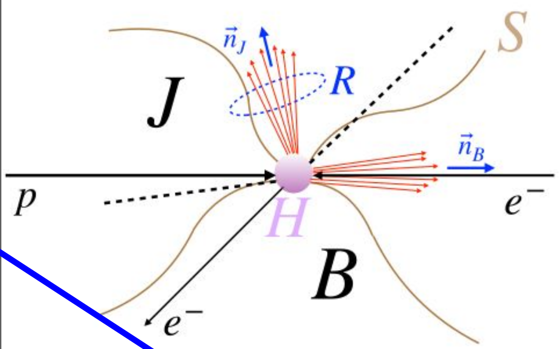
$$\underbrace{f_{i/N}(x, Q^2)}_{\text{PDF}} \quad \text{and} \quad \underbrace{D^h_i(z, Q^2)}_{\text{fragmentation function}} .$$

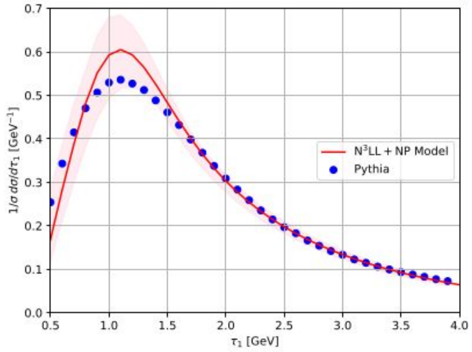
- Otherwise, the SIDIS proton in the target fragmentation region cannot be described in either formalism.

Fracture Function linked to the Beam Function?

Generalized fracture function?

1-Jettiness: Factorization





- Results known at N^{3}LL+$\mathcal{O}(\alpha_s^2)$:

[Cao, Kang,Liu, SM]
arXiv: 2008.00655 (PRD 2024)

- 1-Jettiness factorization formula:

$$d\sigma_{\text{resum}}\left[\tau_1, P_{J_T}, y_J\right] \sim H \otimes \boxed{B} \otimes J \otimes \mathcal{S} \qquad B \sim \mathcal{I} \otimes f$$

From Sonny’s talk

Physics Significance of the HERA data

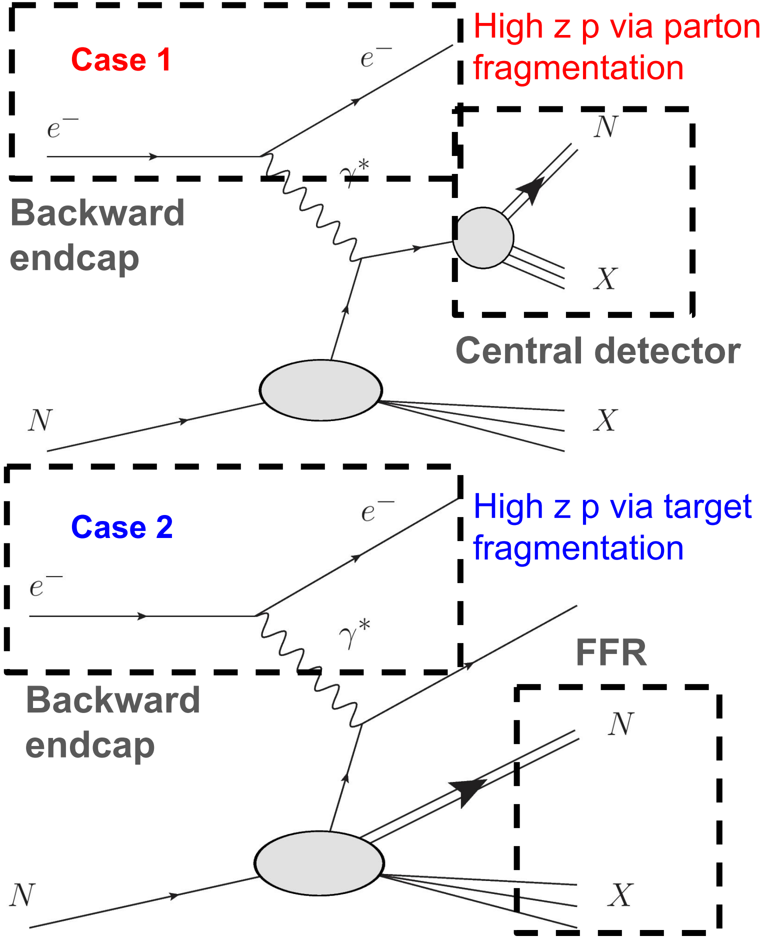
- **Weak Q2 dependence, proofs factorization !?**

$$d\sigma(ep \to eBX) \sim \text{hard DIS scattering} \times \text{target-fragmentation function}$$

- **Baryon number found far away from the beam? x_B~0.007−0.02 ?**
  - Baryon number transport mechanism
  - Fuse the discussion on who carries the baryon number? Quarks or Gluons?

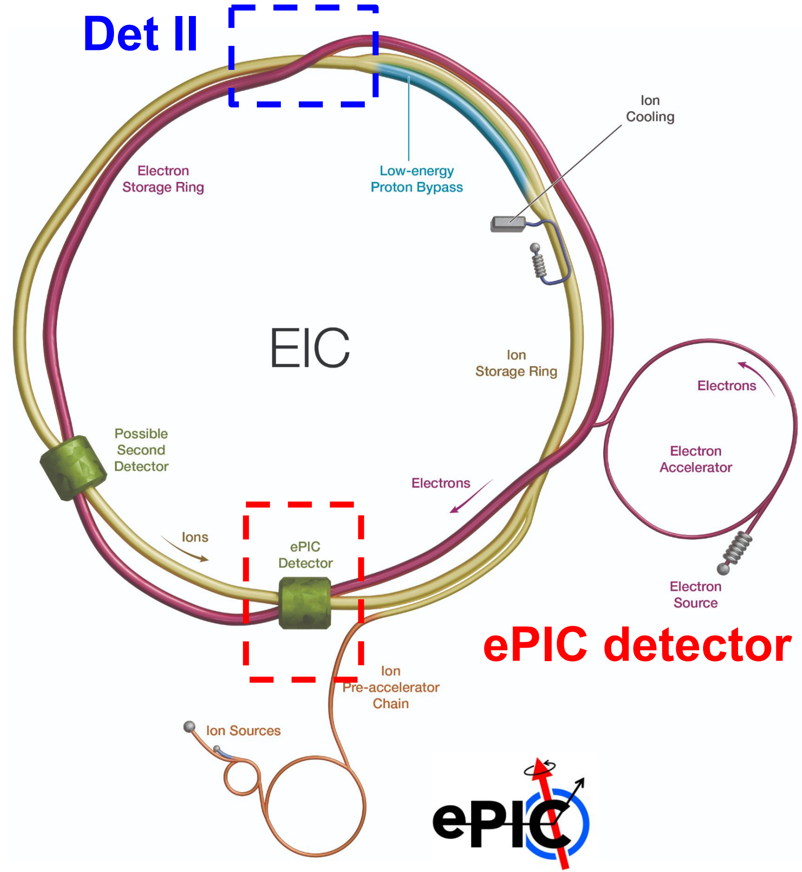
- **Criticism:**
  - Fracture function gives no specific model prediction
  - x_L study is not a Lorentz independent observable
  - Too little data to support any systematic study

Semi-inclusive scattering (inspired by Alessandro Bacchetta)



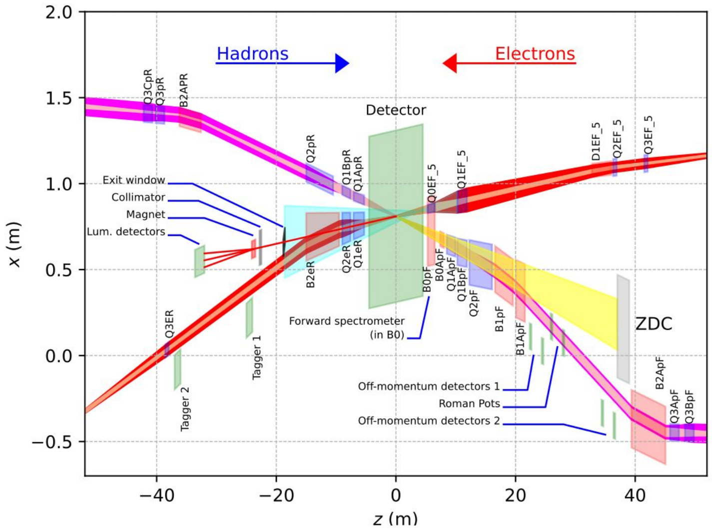
- **Where is the high-z proton coming from?**
- **Two possibilities**
  - Case 1: From the fragmented parton region, which can be described by proton fragmentation function (can be integrated into the TMD formalism)
  - Case 2: From the target fragmentation region, collinear factorization approach. Fracture function.
- **PDF vs Fragmentation Function (FF) vs Fracture Function**
  - **PDF:** what parton is struck?
  - **FF:** how does the struck quark hadronize?
  - **Fracture function:** what parton is struck **while the spectator remnant produces a tagged baryon**? (L. Trentadue and G. Veneziano, *Fracture functions*, **Phys. Lett. B 323**, 201–211 (1994).)
- **Misconception:** George Sterman (with W. Vogelsang and D. De Florian) derived the fragmentation probability for high momentum proton production 30 years ago.
  - True for case 1
  - **George Sterman**: "Case 2 is where he study stopped, "target fragmentation" is a new problem requires new sets of theoretical and experimental approaches, perhaps at the future EIC."

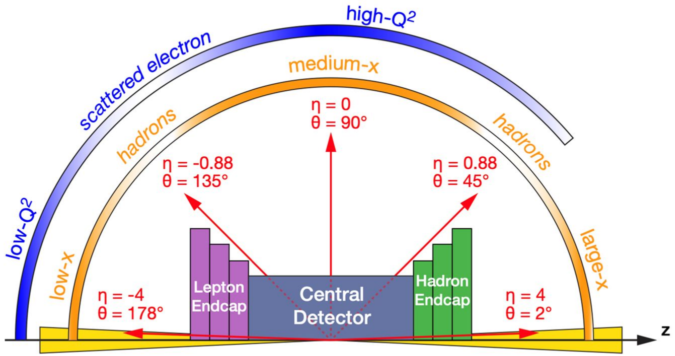
Latest Update on EIC and ePIC

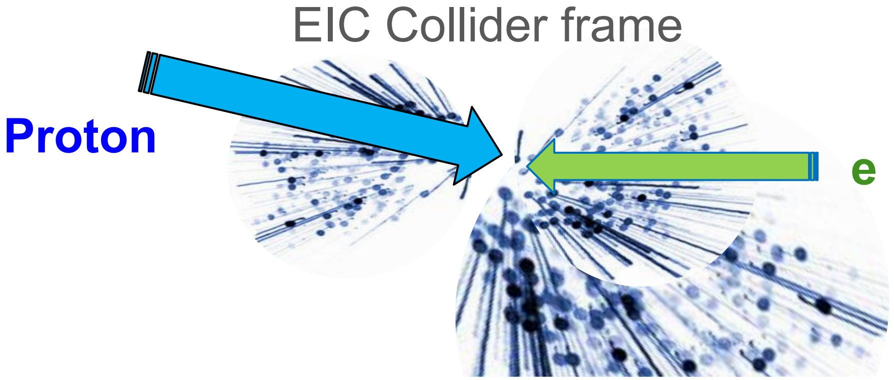


- **Beam Energy:**
  - **e beam:** 5-10 GeV
  - **p beam:** 130 GeV or higher
- **Initial running condition:**
  - **Year 1:** 10 GeV e×115 GeV/A Ru or Cu, W = 67.8 GeV
  - **Year 2:** 10×130 GeV/A deuteron, W = 72.1 GeV
  - **Late Year 2:** 10×130 GeV proton, W = 72.1 GeV
- **Luminosity:** 10^{33}–10^{34} $cm^{-2}s$
- Measuring fracture function is absolutely a day 1 measurement.
  - But not a easy one

ePIC Detector Detail



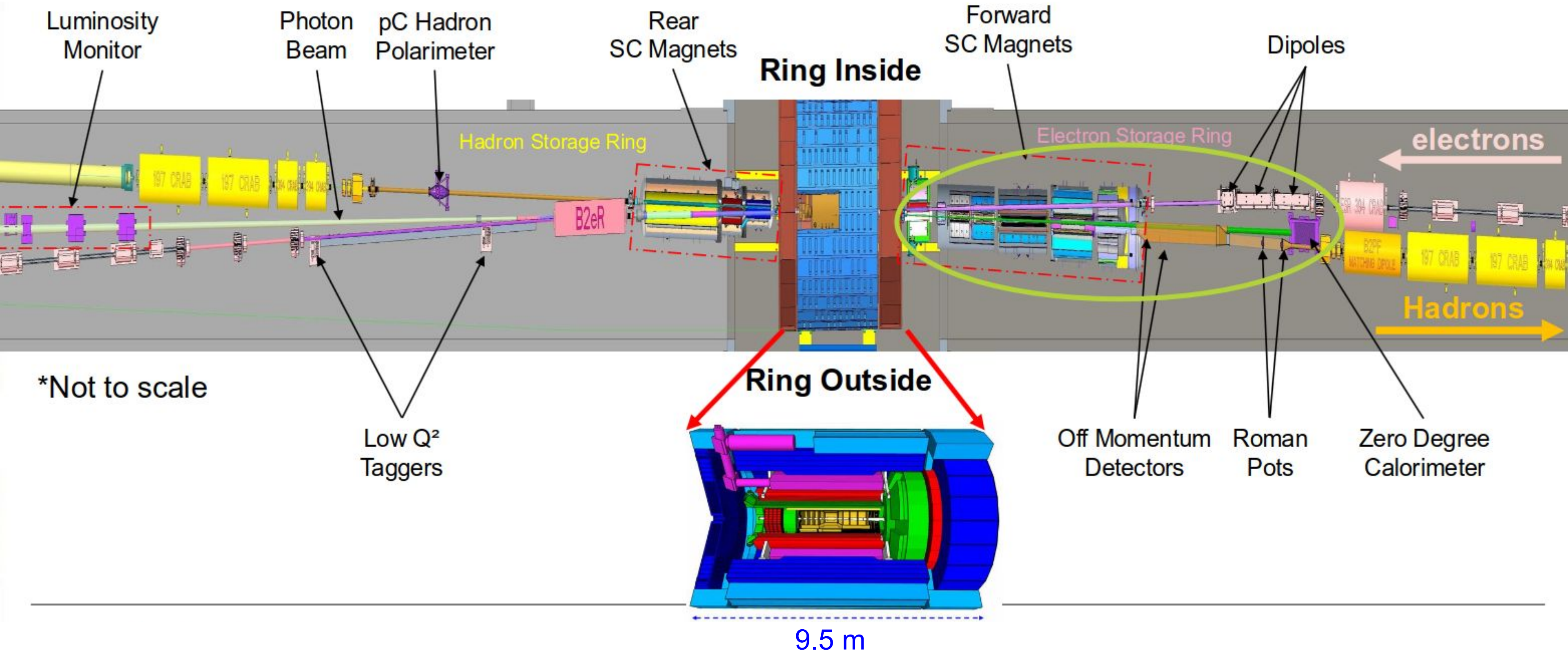




ePIC detector features:

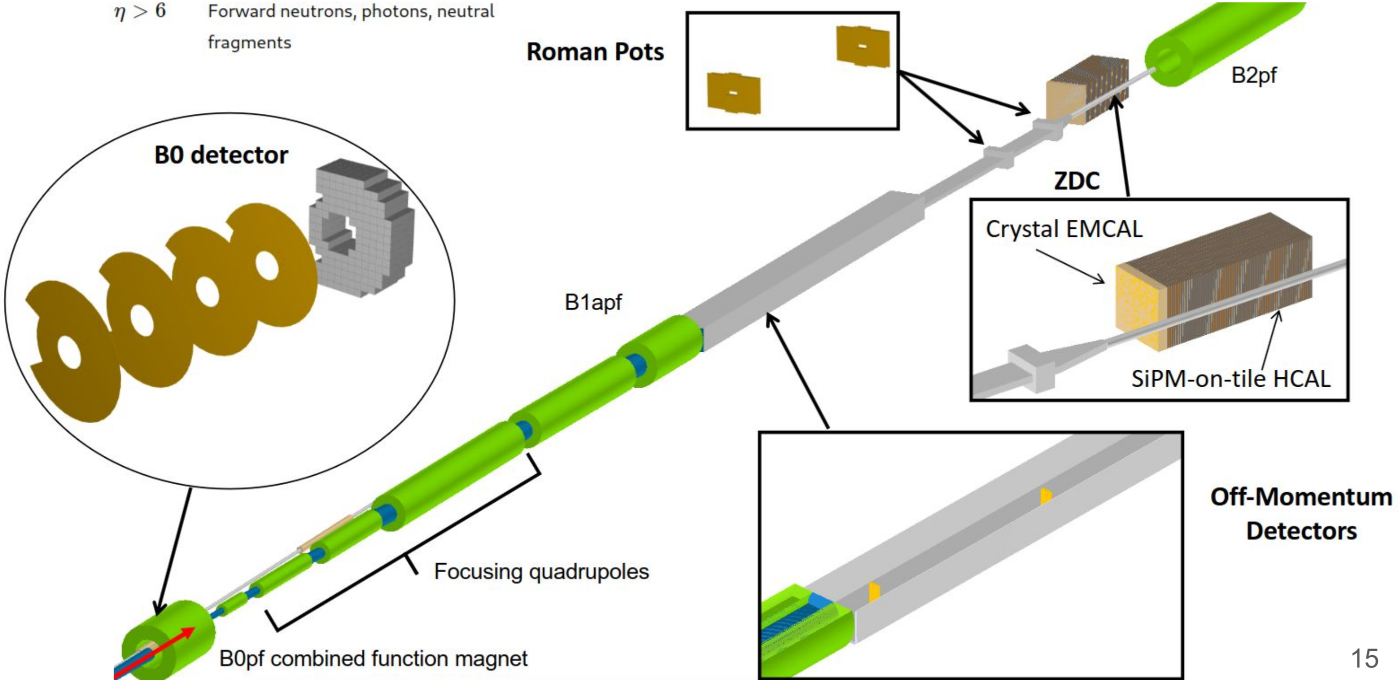
- A hermetic detector stack (almost 4π coverage)
- Asymmetrical collision frames (highly boosted in favors of proton)
- 25 mRad crossing angle: accessing η~6 for charged particles, η~ ∞ for neutral particles (Accessing small *-t* or p_T).

Full ePIC Stack



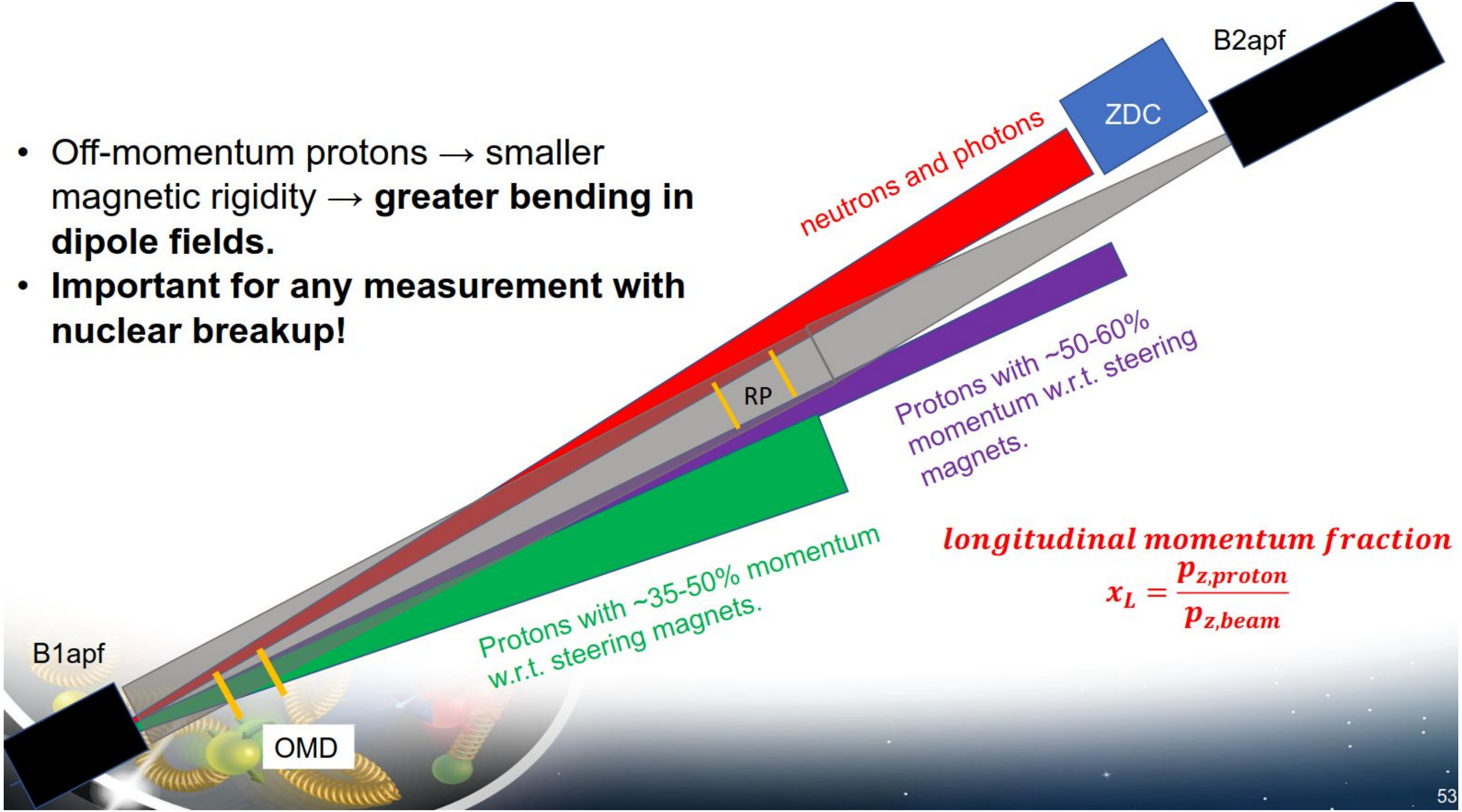
Far Forward Detector Layout

	Angular coverage	η coverage	Main role
B0 tracker + B0 EMCal	$5.5 < \theta < 20$ mrad	$4.6 < \eta < 5.9$	Forward charged particles + photons
Roman Pots	$0 < \theta < 5$ mrad	$\eta > 6$	Leading protons / intact fragments
Off-momentum detectors	$\theta < 5$ mrad	$\eta > 6$	Low-rigidity charged fragments
ZDC	$\theta < 5.5$ mrad	$\eta > 6$	Forward neutrons, photons, neutral fragments



Where Does Particle Go After the Interaction?

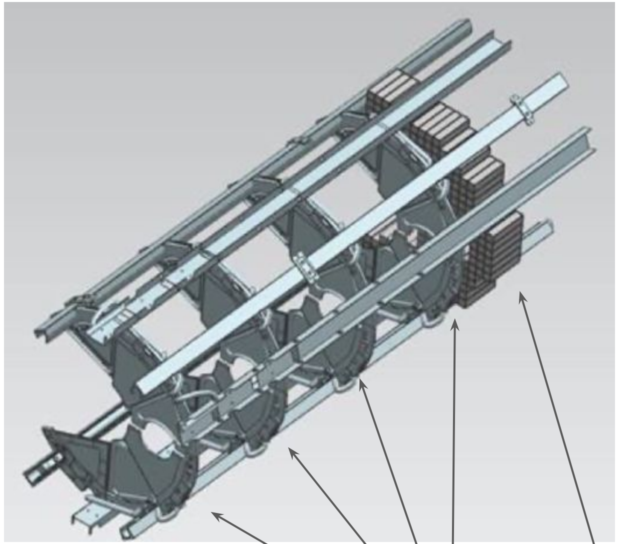
- Off-momentum protons → smaller magnetic rigidity → **greater bending in dipole fields.**
- **Important for any measurement with nuclear breakup!**

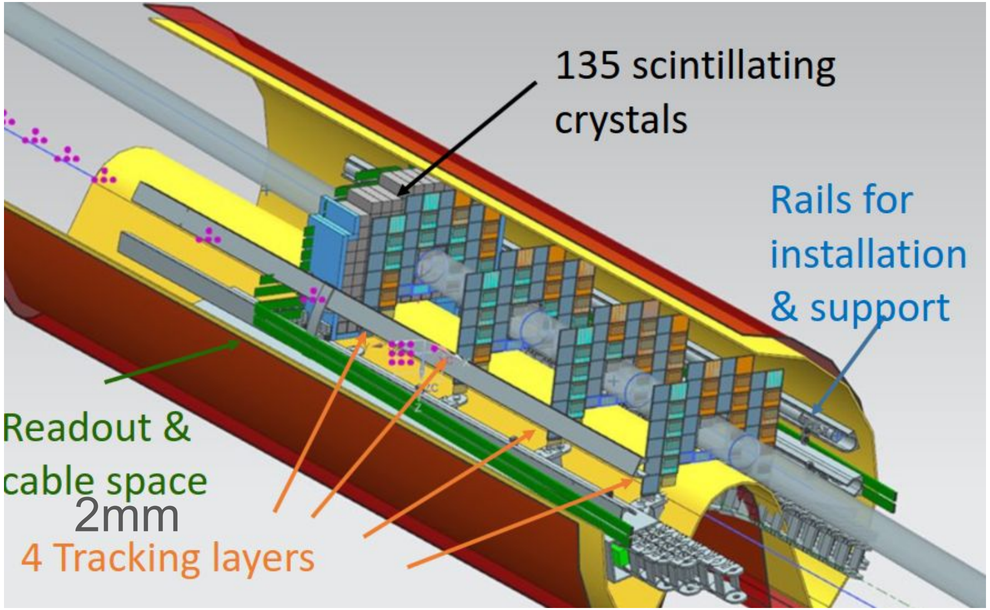


longitudinal momentum fraction

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

Integrated B0 Magnetic/Detector Stack



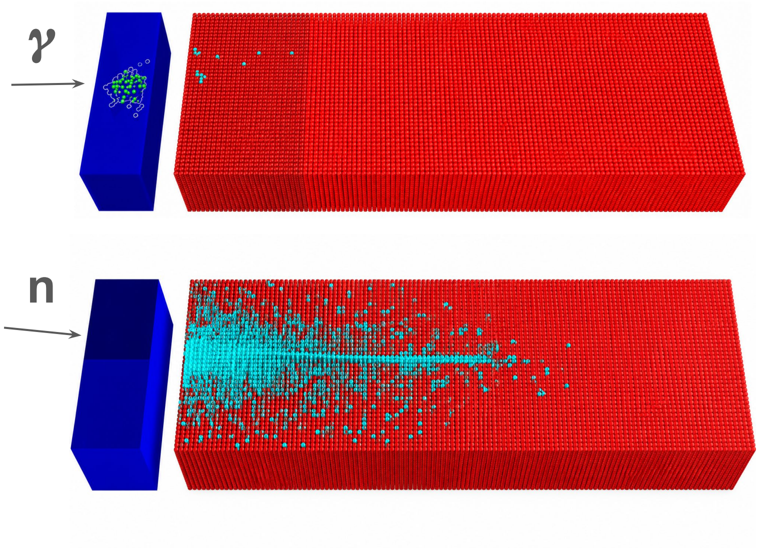


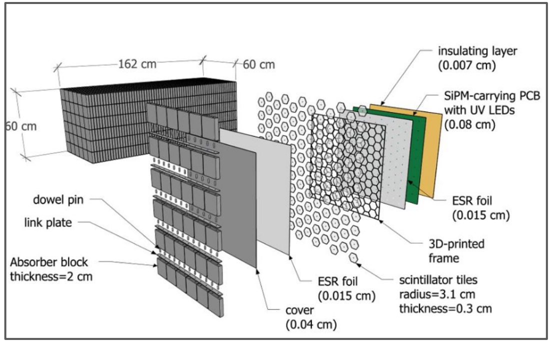
LYSO Calorimeter ~ 6-7% energy resolution

AC-LGAD Tracker

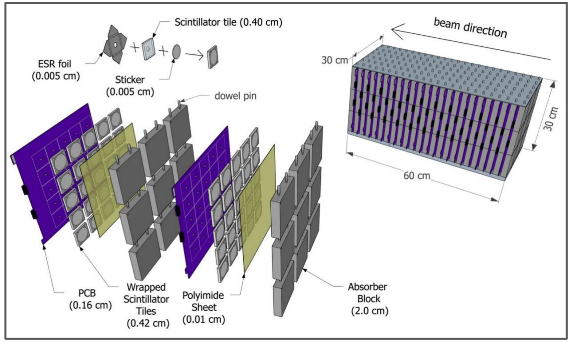
What do we need calorimeter there?

Zero Degree Calorimeter (ZDC)





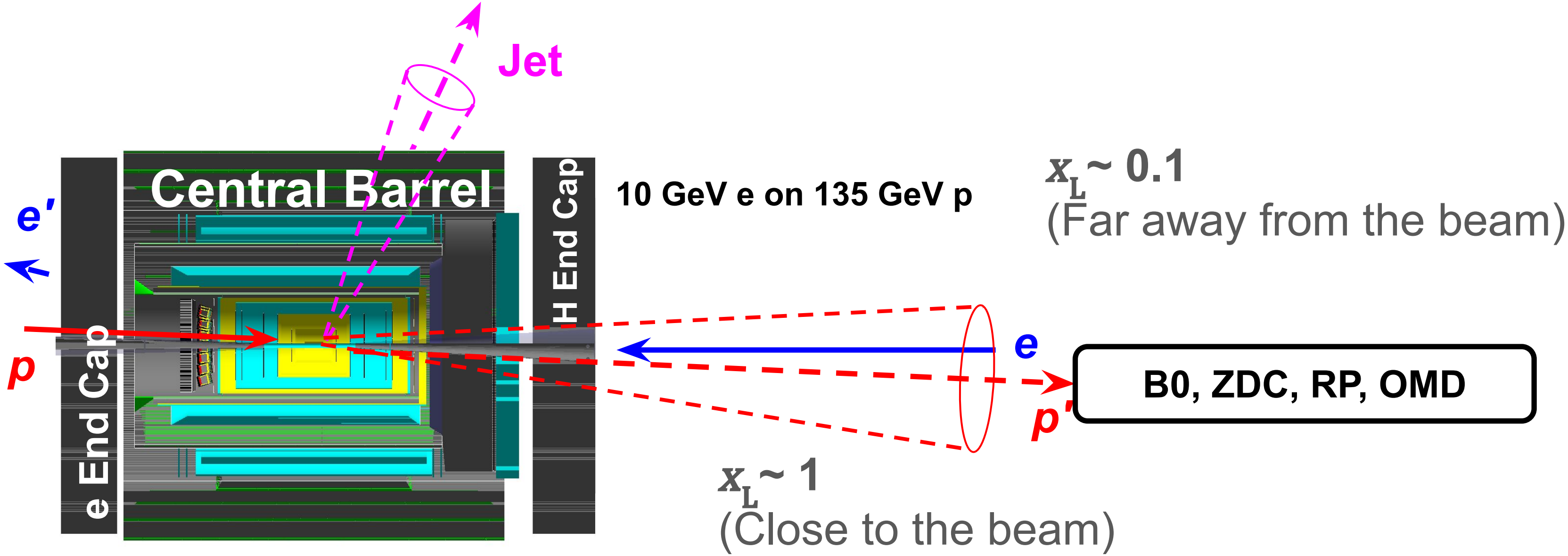
Old hexagon tile design



New square tile design
(a small scale mockup is shown)

- **ZDC**
  - LYSO Layer +Hadron Calorimeter layer
  - Photon and Neutron detection
  - Photon energy resolution: 6-7%
  - Hadron energy resolution: 20%

Fracture Function at EIC



Two definitions of being far from the beam:

- $x_L \sim 0.1$, small longitudinal momentum fraction
- Large rapidity gap

Proton Detection Coverage in Forward Region

- Assuming ep scattering of 10x135 GeV collision

Detector region	Approx. x_L sensitivity	Angular / η coverage	Rapidity information	Detection method
Hadron endcap	No fixed x_L interval; most useful for lower x_L or larger p_T	$1.2 \lesssim \eta \lesssim 3.5$, approximately 3.5°–34°	Typically $y \lesssim 3.5$	Tracking, dRICH PID, EMCal and LFHCal
B0 spectrometer	Optics-dependent	5.5–20 mrad; $4.61 \lesssim \eta \lesssim 5.90$	Typically $y \sim 4.3$–5.6	Charged-particle tracking
Off-momentum detectors	Approximately $0.4 \lesssim x_L \lesssim 0.6$	Mostly below 5 mrad; $\eta \gtrsim 6$	$y \simeq 4.75$–5.15 near zero angle	Magnetic-rigidity measurement
Roman Pots	Approximately $0.8 \lesssim x_L < 1$	Below roughly 5 mrad; $\eta \gtrsim 6$	$y \simeq 5.44$–5.66 near zero angle	Leading-proton tracking

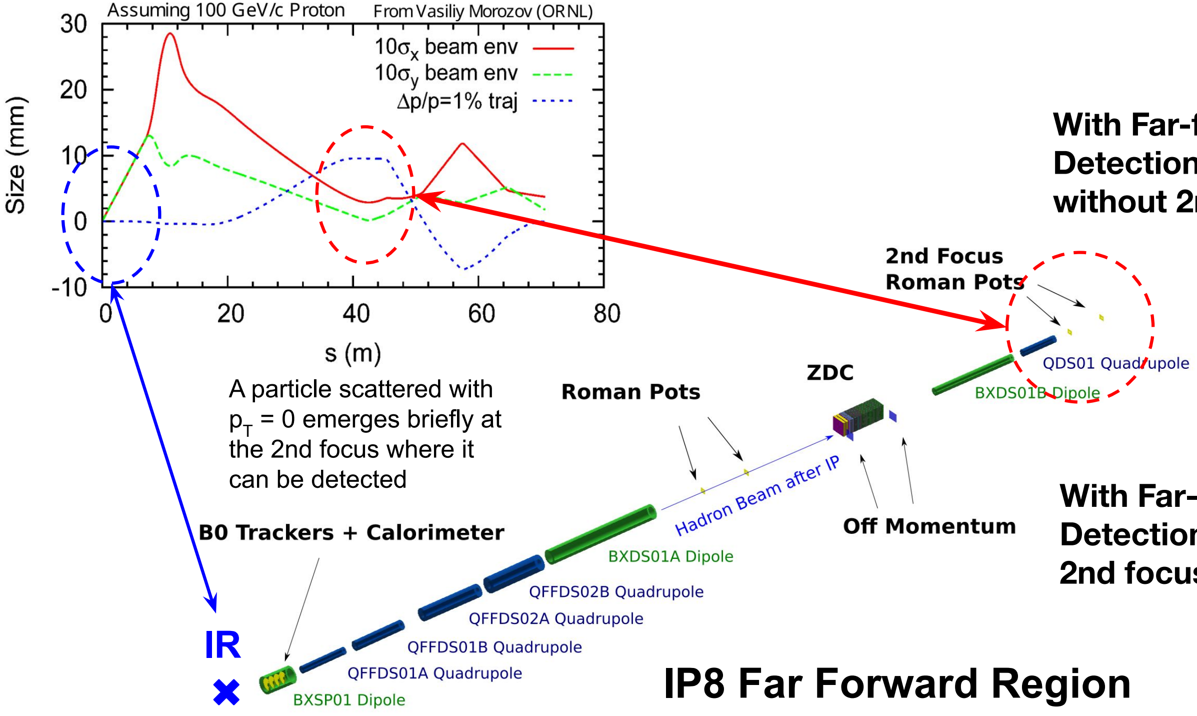
- Coverage is not detector
- Main issue: PID in the B0 track

Neutron Detection Coverage in Forward Region

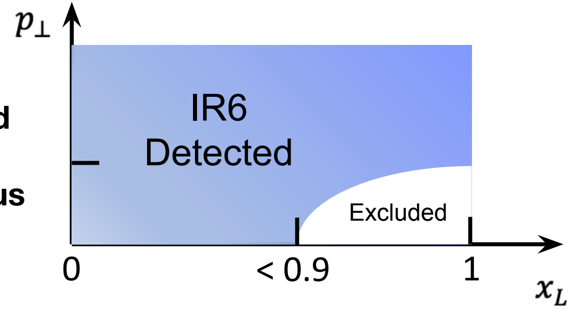
- **Neutron coverage**

Detector region	Approx. x_L sensitivity	Angular / η coverage
Hadron endcap LFHCal		$1.2 \lesssim \eta \lesssim 3.5$, approximately 3.5°–34°
ZDC	Practical working range $0.2 \lesssim x_L \lesssim 1$	$\theta \lesssim 5.5$ mrad; $\eta \gtrsim 5.90$

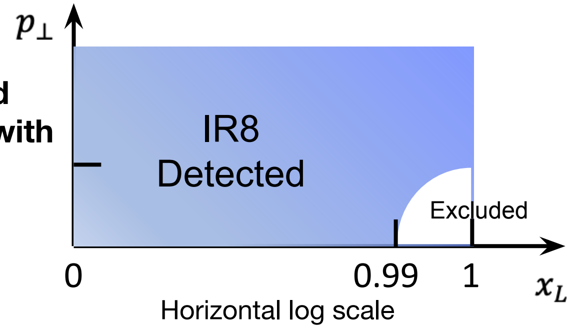
Second Focus at Detector II



With Far-forward Detection (RP), without 2nd focus

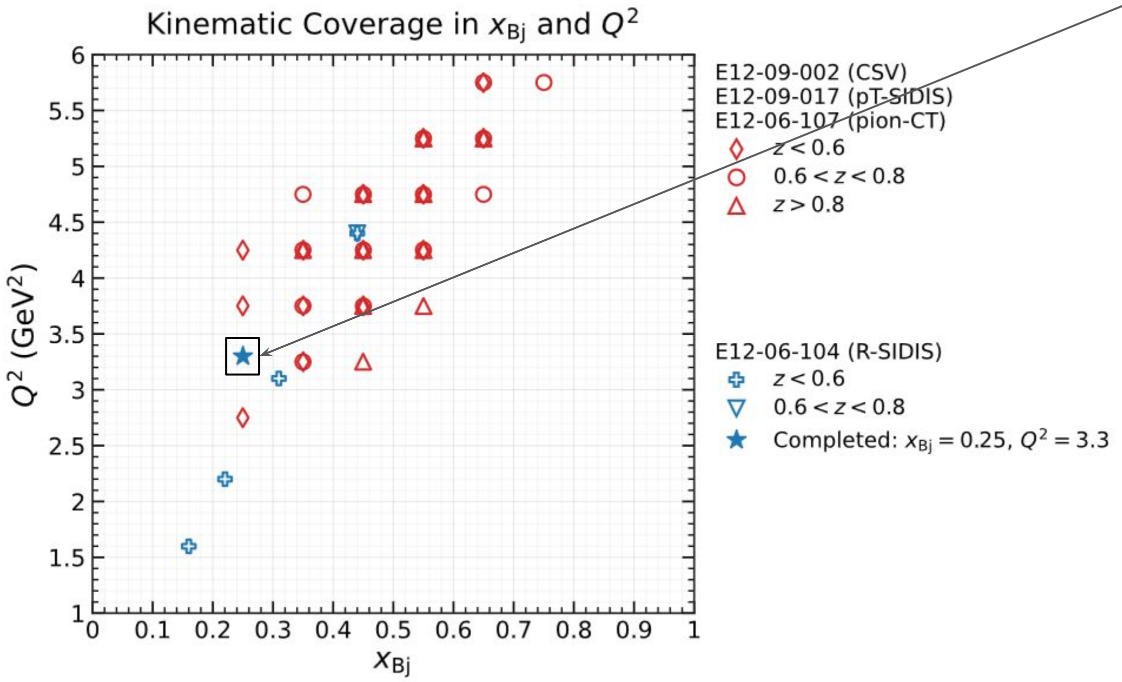


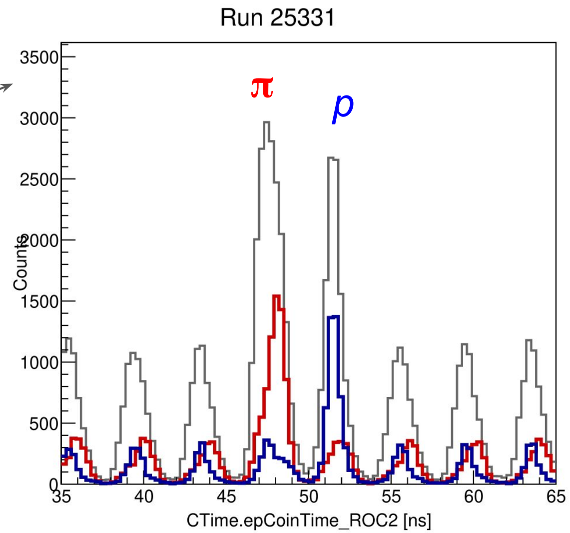
With Far-forward Detection (RP), with 2nd focus



Fracture function at Jefferson Lab

- Proton SIDIS Kinematics at Jefferson Lab





- **In progress:** extracting the p_T or η dependent cross section

Summary & Thank you !

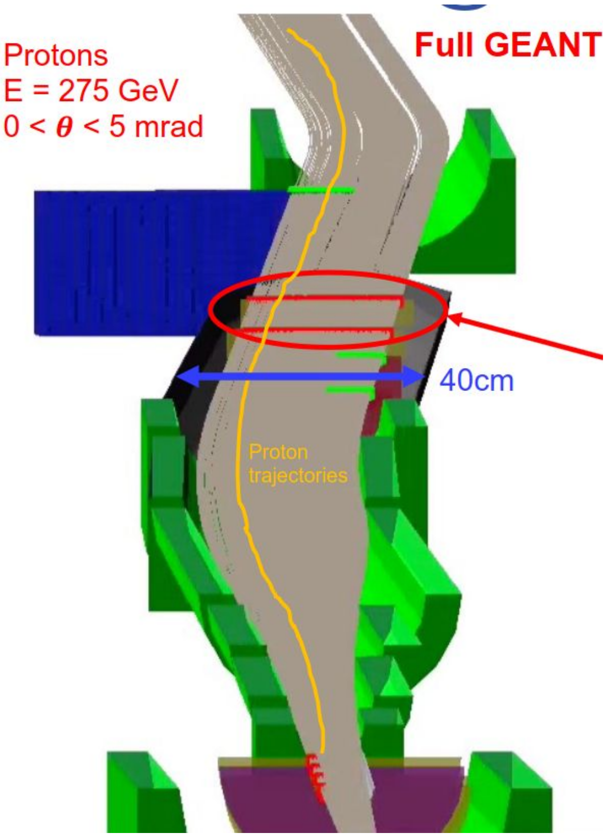
- Fracture Function will be a new focus area

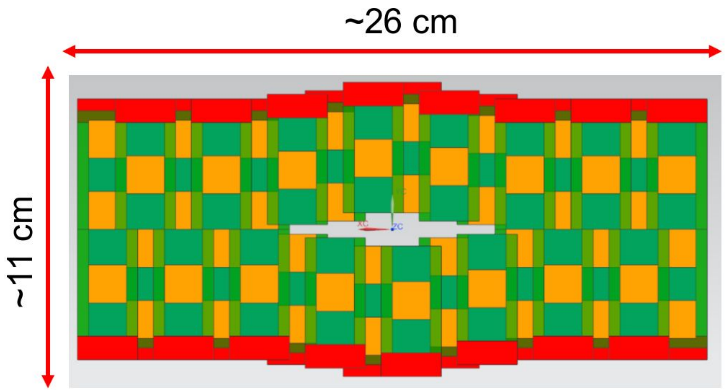
- Clear path from JLab to the EIC

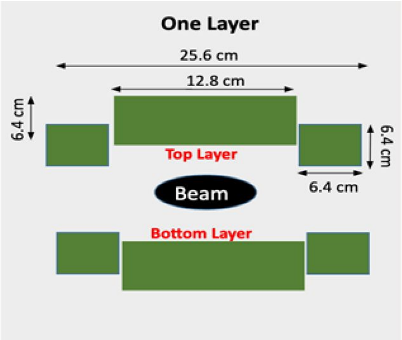
- Much detailed study can be performed than at HERA

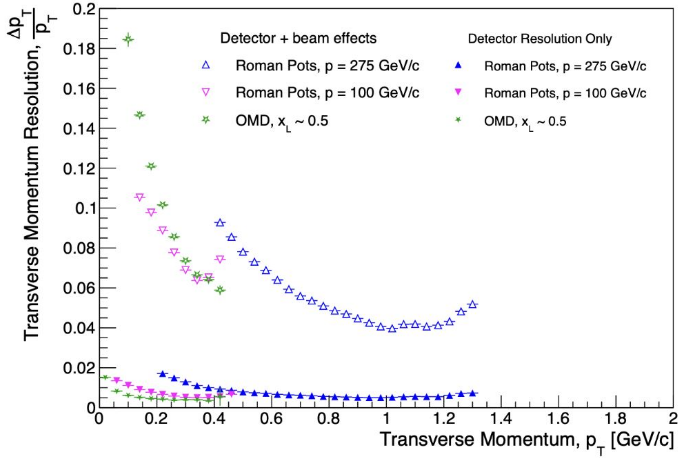
As People Requested: picture of Pancho the dog

Roman Pot (RP) and Off-Momentum Detector

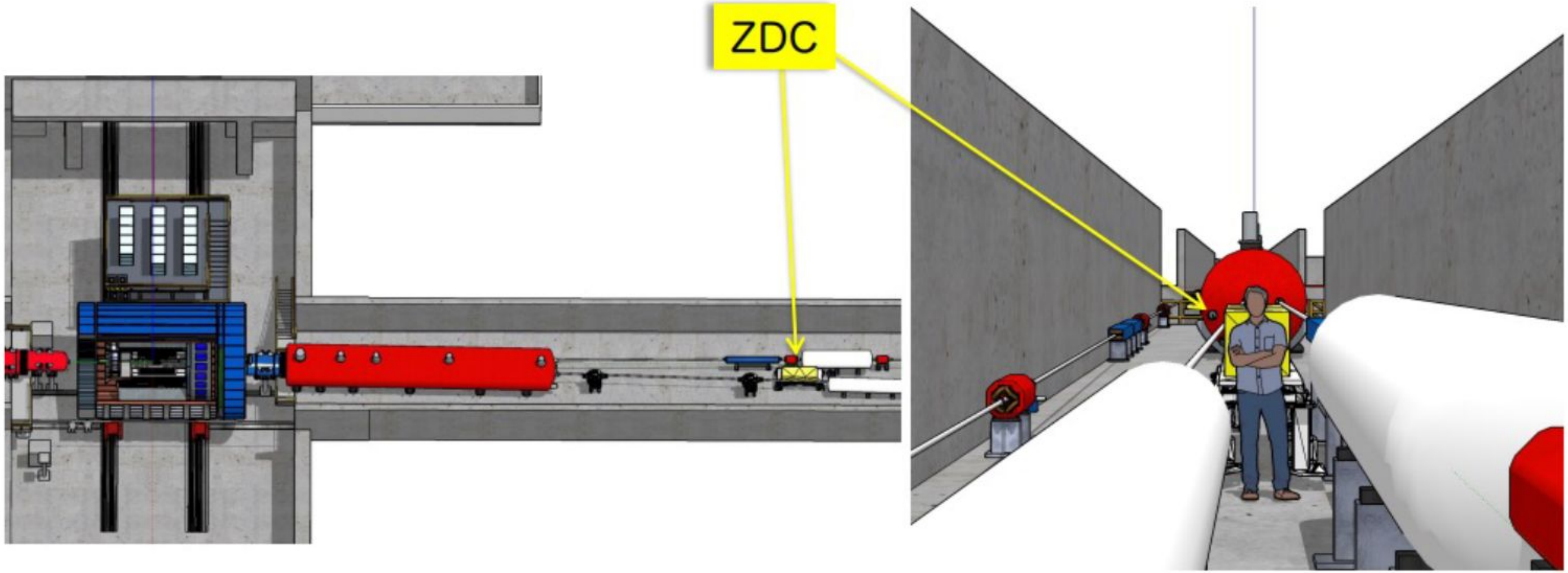




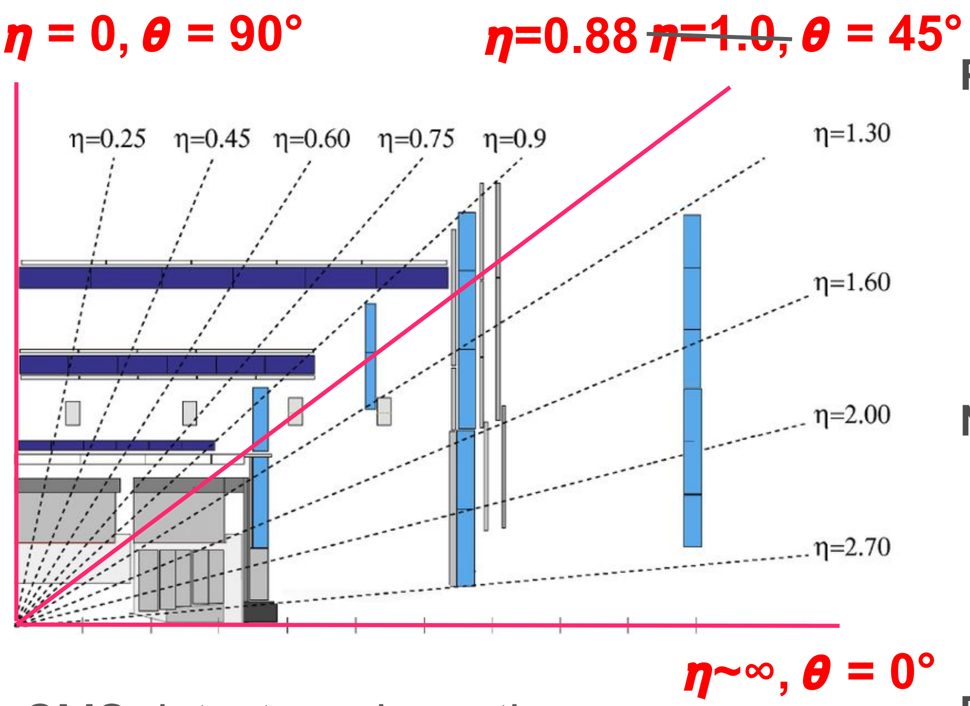




Zero Degree Calorimeter (ZDC)



Pseudorapidity In EIC and ePIC



CMS detector schematics is used as an example

Pseudorapidity is easy at the EIC!

- Defined with respect to the proton beam
- η=0 when particle is at θ = 90°
- η=1 when particle is at θ = 45°
- $\eta\sim\infty$ when particle is at θ = 0°
- Easy to remember!

Now read the ePIC detector coverage again:

- Central detector: $\eta \leq |3.5|$
- Forward endcap: $+1.5 \leq \eta \leq +3.5$
- Backward endcap: $-3.5 \leq \eta \leq 1.5$
- Far-forward/far-backward systems: $|\eta| > 6$

Forbidden question:

- Why ePIC is not designed to use $\eta\sim1$ (θ = 45°) as detector system boundary.