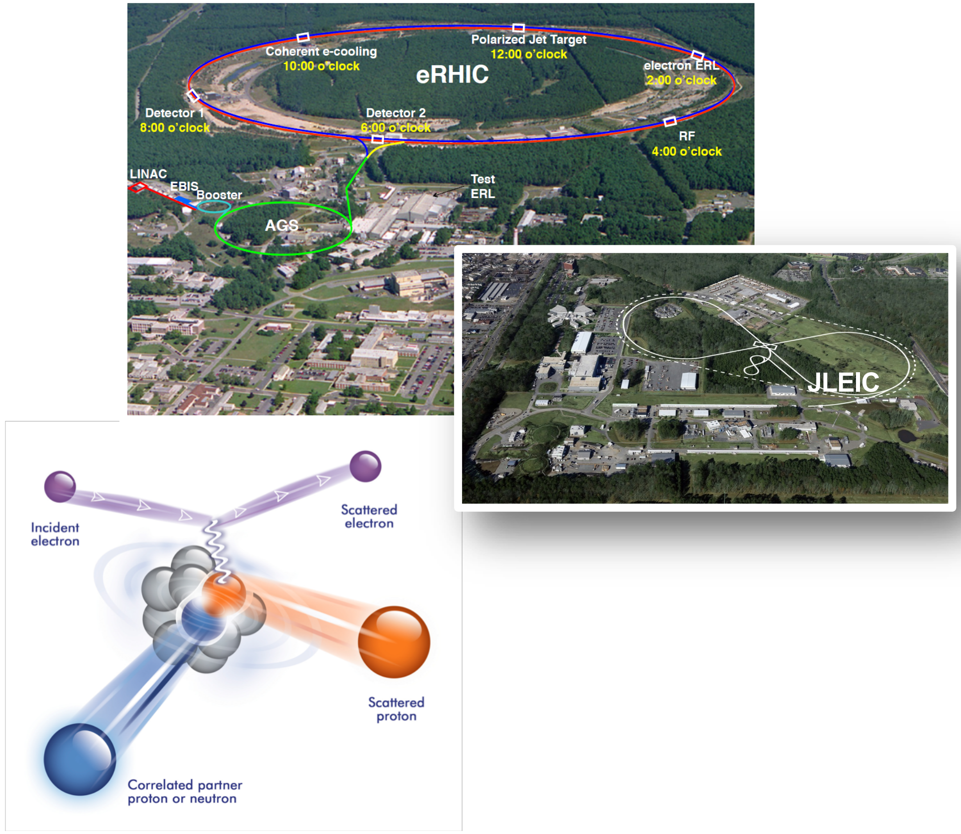
# Opportunities for SRC/EMC studies at the EIC




Pawel Nadel-Turonski

Stony Brook University

2nd Workshop on Quantitative Challenges in SRC and EMC Research, MIT, March 20-23, 2019

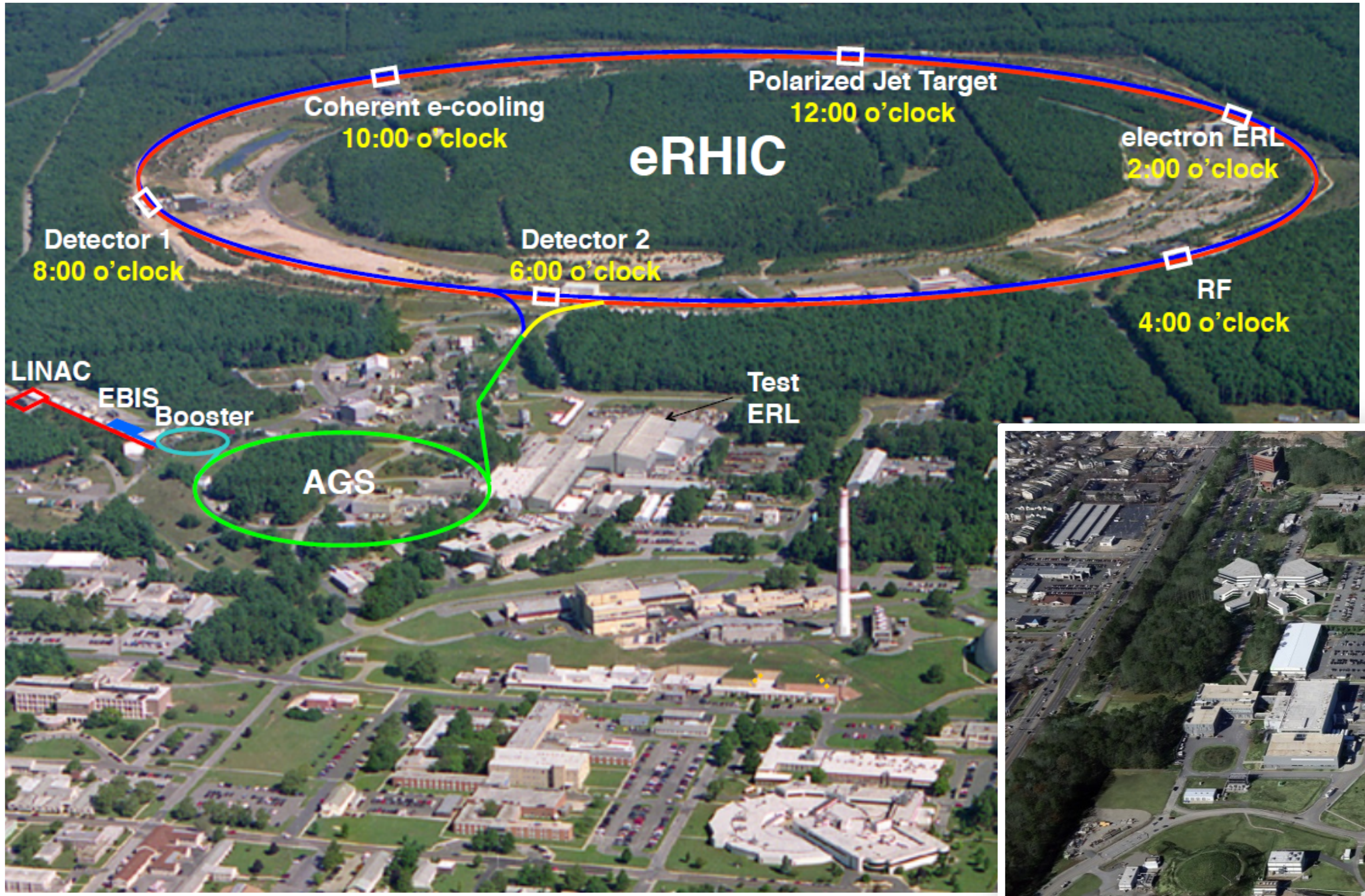
# The Electron-Ion Collider (EIC)

# The EIC in the 2015 NSAC LRP and the recent NAS review


**NSAC:** **"We recommend a high-energy high-luminosity polarized EIC as the highest priority for new facility construction following the completion of FRIB."**

**NAS:** **"The committee unanimously finds that the science that can be addressed by an EIC is compelling, fundamental, and timely."**

# Proposed EIC implementations at JLab and BNL



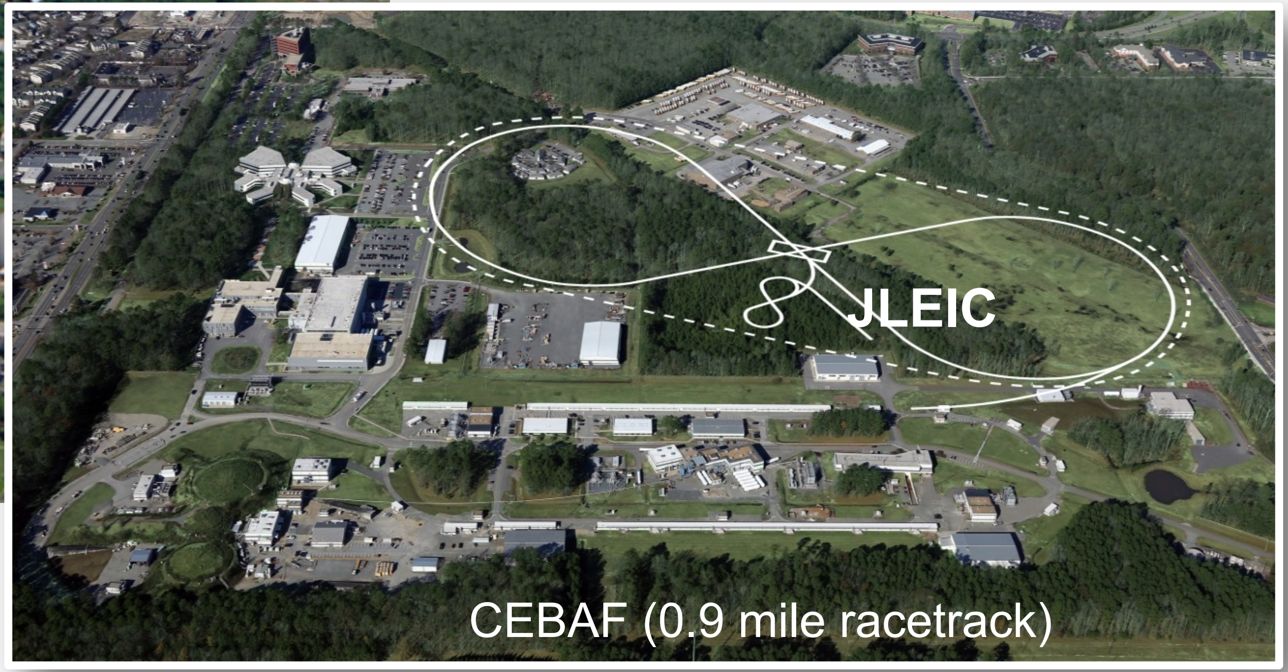

## BNL EIC at RHIC (eRHIC)

18 GeV e (10 GeV lumi max) on 275 GeV p

Parameters are similar

12 GeV e (5 GeV lumi max) on 200 GeV p

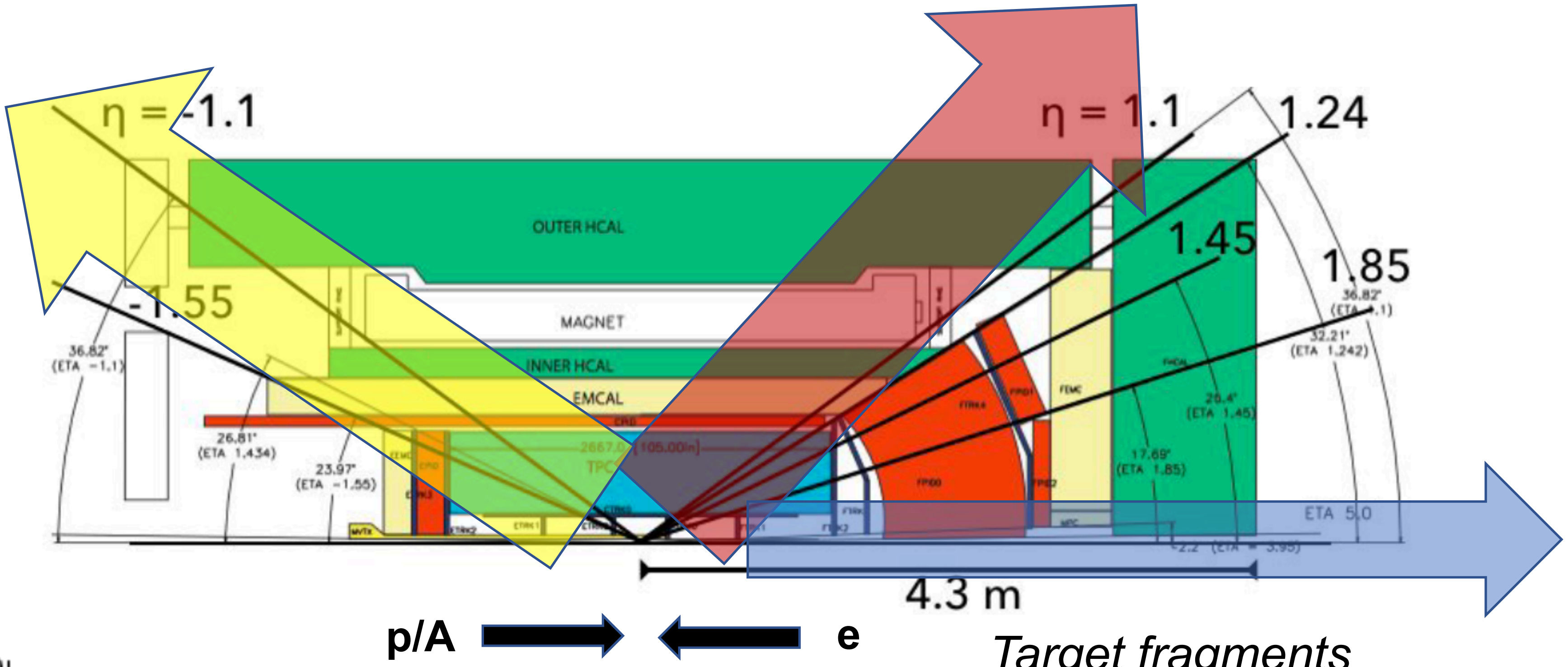
## JLab EIC (JLEIC)



# What do we measure?

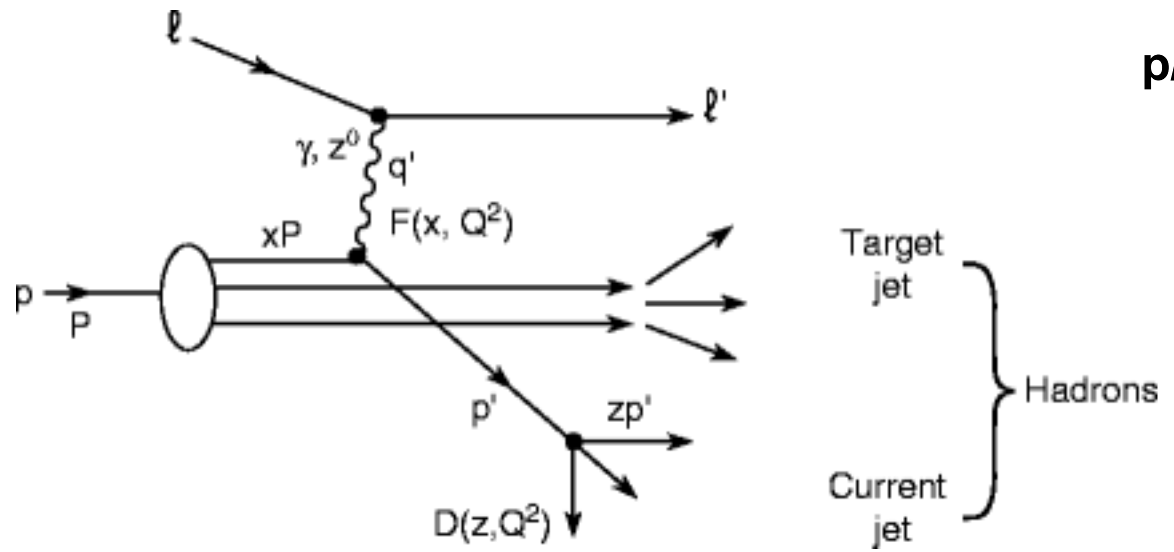
*Current jet (or hadron)*

*Scattered electron*




*Target fragments*

Lepton scattering on a proton

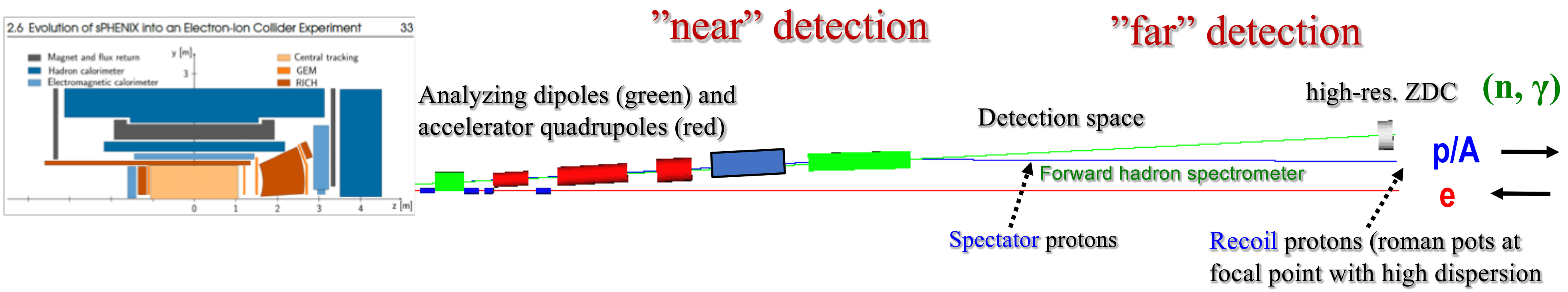



**Inclusive DIS:** only electron is detected

**Semi-Inclusive DIS (SIDIS):** electron and current jet (hadron) are detected.

**Exclusive reactions:** all particles are detected

# Detection of target fragments



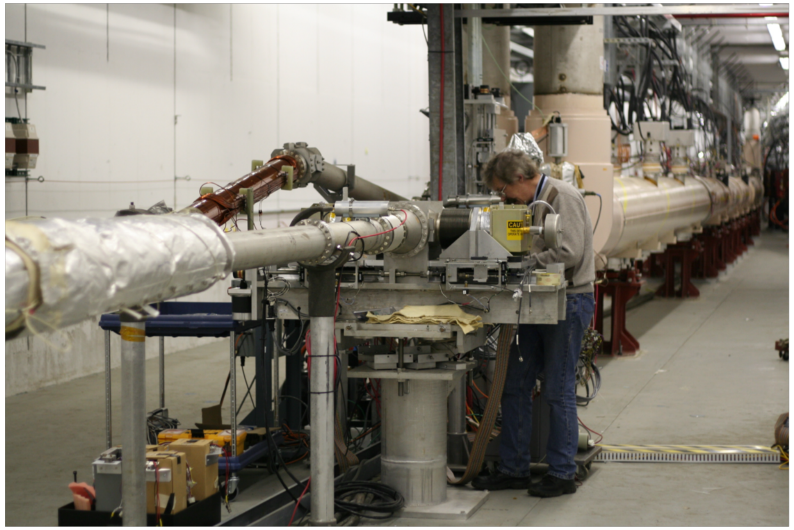

- A large part of the EIC program relies on detecting recoil baryons and target fragments
  - Spatial imaging through *exclusive* meson/photon production on the proton, and in coherent diffraction on nuclei
  - Neutron structure through spectator tagging in light nuclei
  - Various incoherent processes on heavy nuclei, including SRC and EMC studies

- Forward detection requirements for the EIC are very demanding
  - Need to detect particles very near the beam (down to $p_T = 0$ for $dp/p > 1\%$)
  - Need to detect protons with $p_T$ up to at least 1 GeV/c and spectators with A/Z very different from that of the beam (*e.g.*, spectator protons from deuterium)
  - Need excellent momentum resolution, detection of neutrals, and PID for ions

# Near-beam detection at JLab and BNL

- At JLab, a full forward spectrometer was always a key part of the MEIC (now JLEIC) concept since its introduction in 2009.
  - proton acceptance up to 99.8% of the $E_{beam}$ for *all* angles and down to 2 mrad for *all* energies

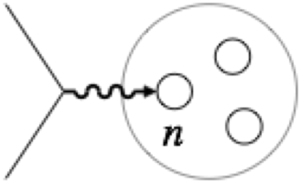
- At BNL, the eRHIC forward detection (not related to the RHIC one) currently only has a less-capable "near" part, restricting its potential for the eA program.
  - However, with similar max ion energy, BNL could have as good forward detection as JLab.
  - Implementation easier at BNL since a larger e-ring allows reversing the order of electron and ion quads.
  - But substantial changes to the forward detection cannot be made once the EIC is built.



Roman pots in STAR located ~50 m downstream from the collision point

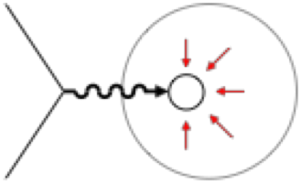
- **Input on from the eA community to both labs on the detection requirements is important and urgent**

# Key physics topics for nuclei at the EIC



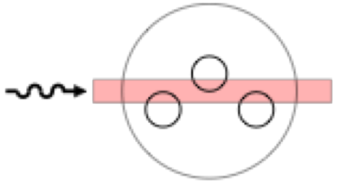

- Neutron structure
  - JLab “spectator tagging” LDRD project

-> talk by C. Weiss



- A bound nucleon in QCD
  - JLab “SRCs at an EIC” LDRD project

-> focus of this talk



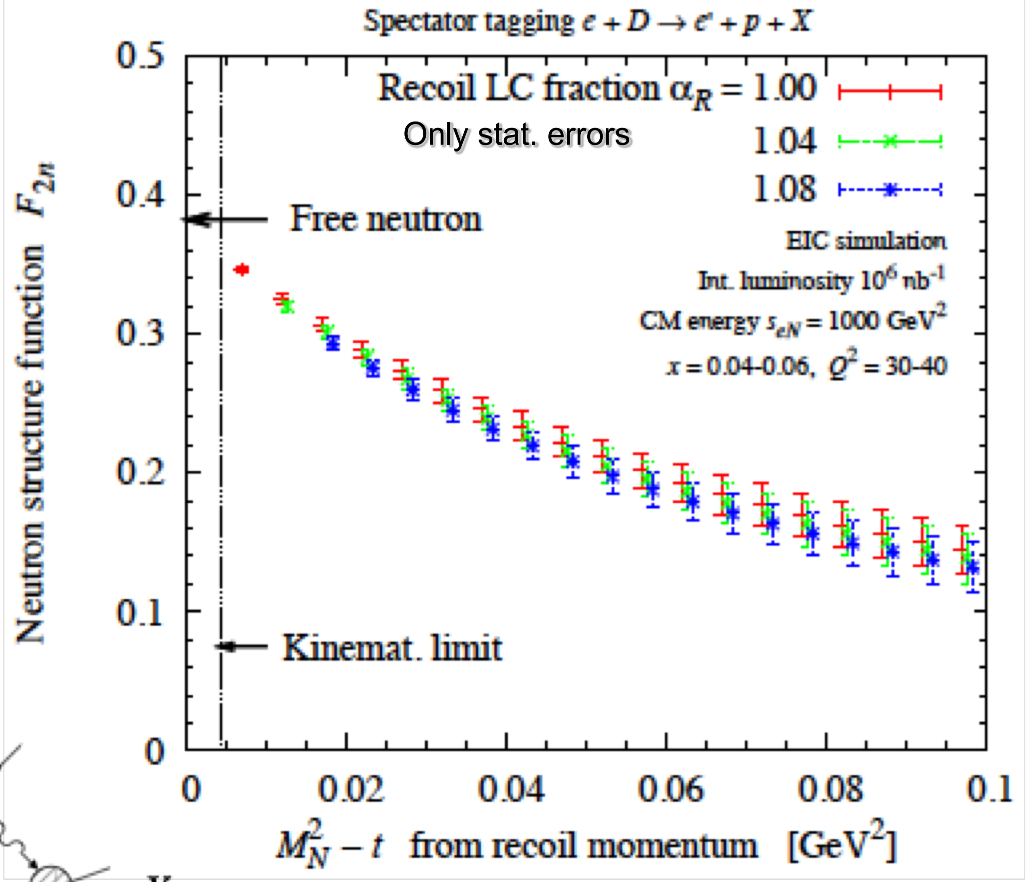
- Coherence and gluon saturation
  - JLab “geometry tagging” LDRD project

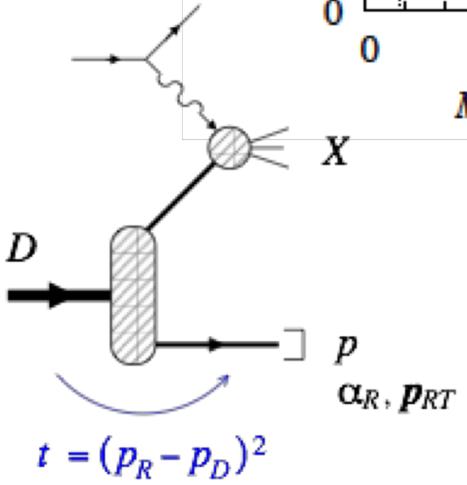
[Nucleus rest frame view]

# Neutron structure through spectator tagging

JLab “spectator tagging” LDRD: C. Weiss, W. Cosyn, V. Guzey, D. Higinbotham, C. Hyde, S. Kuhn, W. Melnitchouk, PNT. K. Park, M. Sargsian, M. Strikman

# Neutron structure through spectator proton tagging




Spectator tagging LDRD, Weiss, et al.

- Simplest case: tagged DIS on neutron
  - Recoil-proton light-cone momentum:

$$\alpha_R = (E_R + p_{R||})/(E_D + p_{D||}) \text{ and } \mathbf{p}_{RT}$$

  - Cross section in impulse approximation:

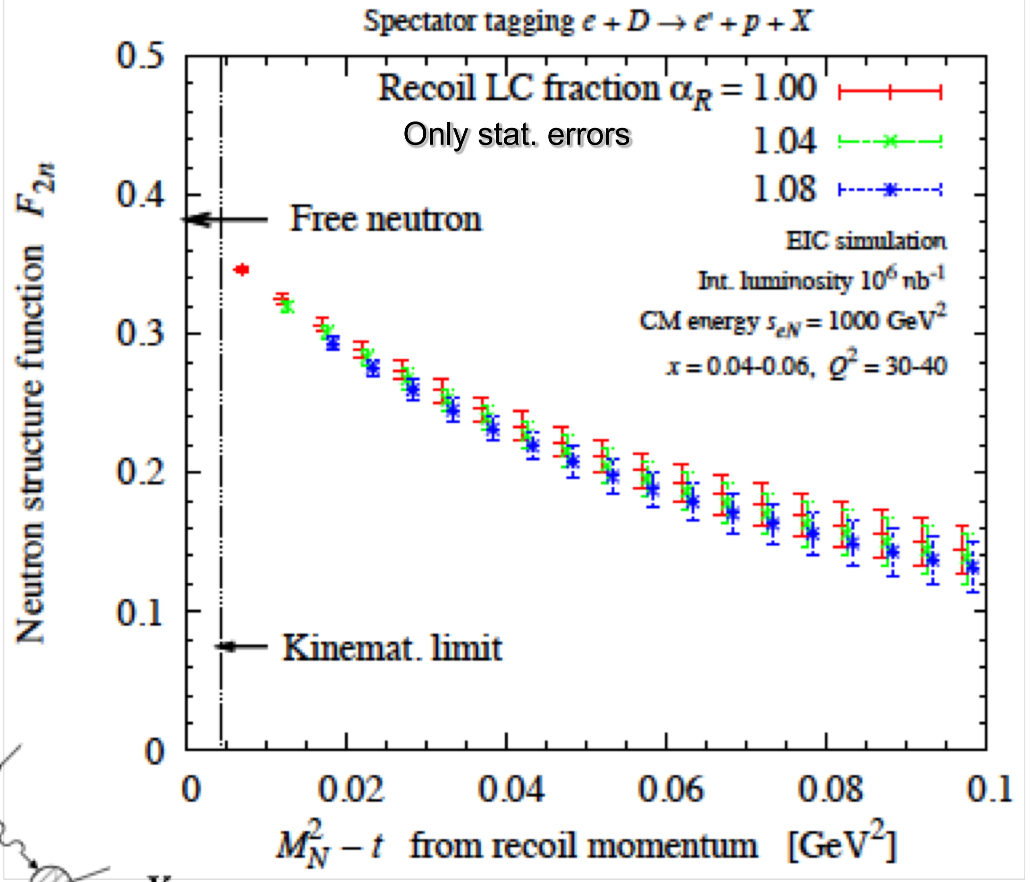
$$\frac{d\sigma}{dx\, dQ^2\, (d\alpha_R/\alpha_R)\, d^2 p_{RT}} \propto |\psi_D^{LC}(\alpha_R, p_{RT})|^2 F_{2n}[x/(2-\alpha_R), Q^2]$$

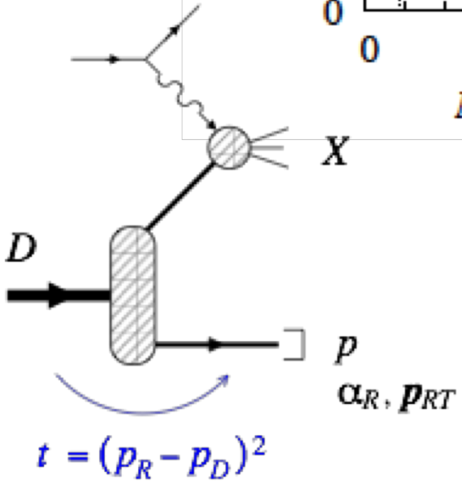
Deuteron LCWF — Neutron SF

Frankfurt, Strikman 1981

- Free neutron structure at pole
  - Not affected by final-state interactions!
- Exclusive processes like DVCS can be treated similarly
- Neutron structure can also be accesses by tagging the protons in He-3
  - Experimentally straightforward but theory more complicated

# Methods developed for the EIC are also helping the JLab fixed target




Spectator tagging LDRD, Weiss, et al.

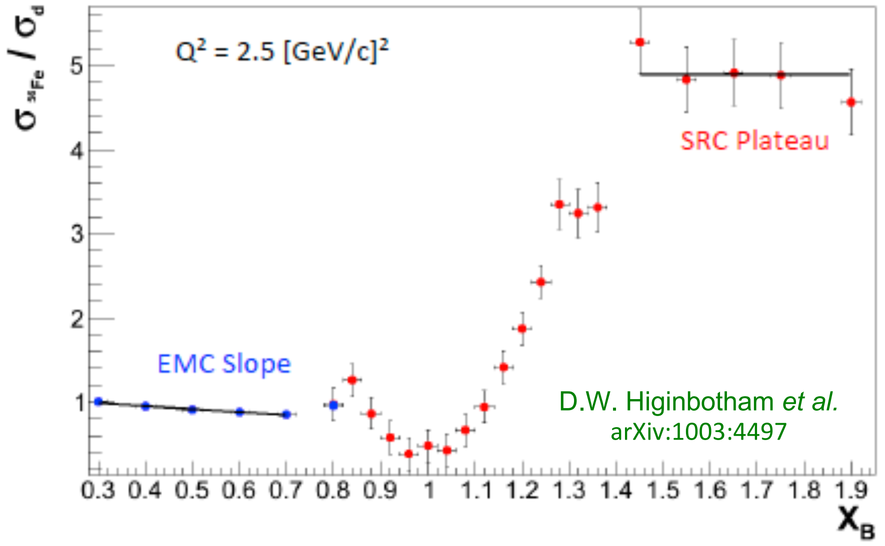
**Example: on-shell extrapolation in exclusive meson photoproduction**

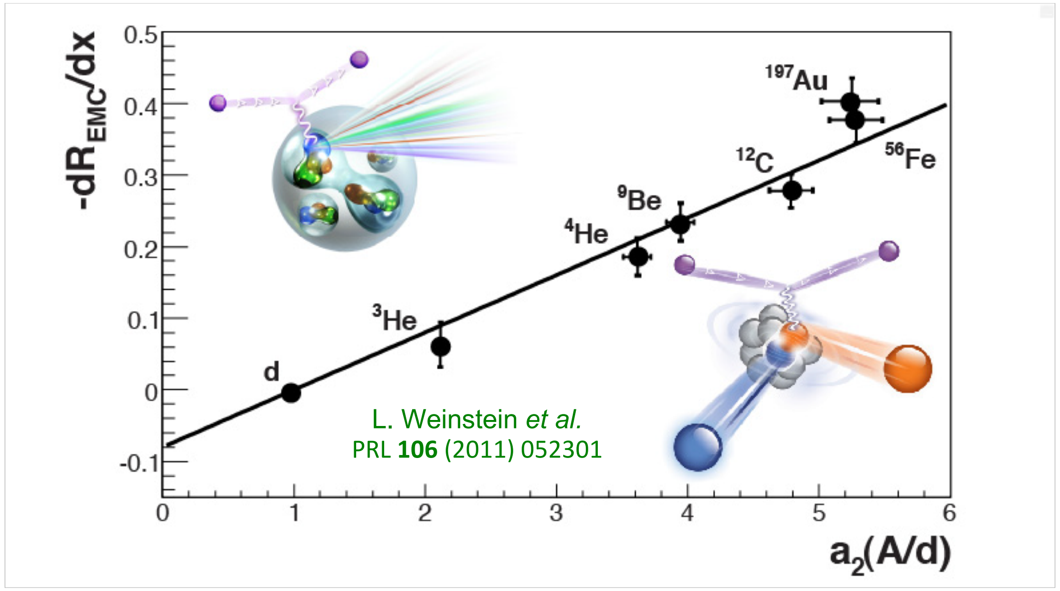
- CLAS experiment E06-103 collected 55 billion photoproduction events on deuterium
  - 30 billion with linearly polarized photons
- Beam asymmetry flat at low values of $M^2$-t
  - Reliable extrapolation to free neutron pole
  - Dilution at higher values understood
- Extraction of deuteron high momentum tail?

# SRCs in DIS at the EIC

JLab "SRC" LDRD1912: D. Higinbotham, M. Baker, F. Hauenstein, O. Hen, C. Hyde, V. Morozov, PNT, L. Zheng

# SRCs in DIS at high- and low (?) x




- The link between SRCs and the EMC effect is being investigated in fixed-target experiments.
- The EIC can provide a large lever arm in $Q^2$ at high x and detection of all target fragments
  - Caveat: event rates at high x are lower than at JLab

"New-ish"

- The EIC can also tell us to what extent SRCs will impact our understanding of nuclear DIS at lower x
  - Do the effects disappear, and if so - when?

"New"

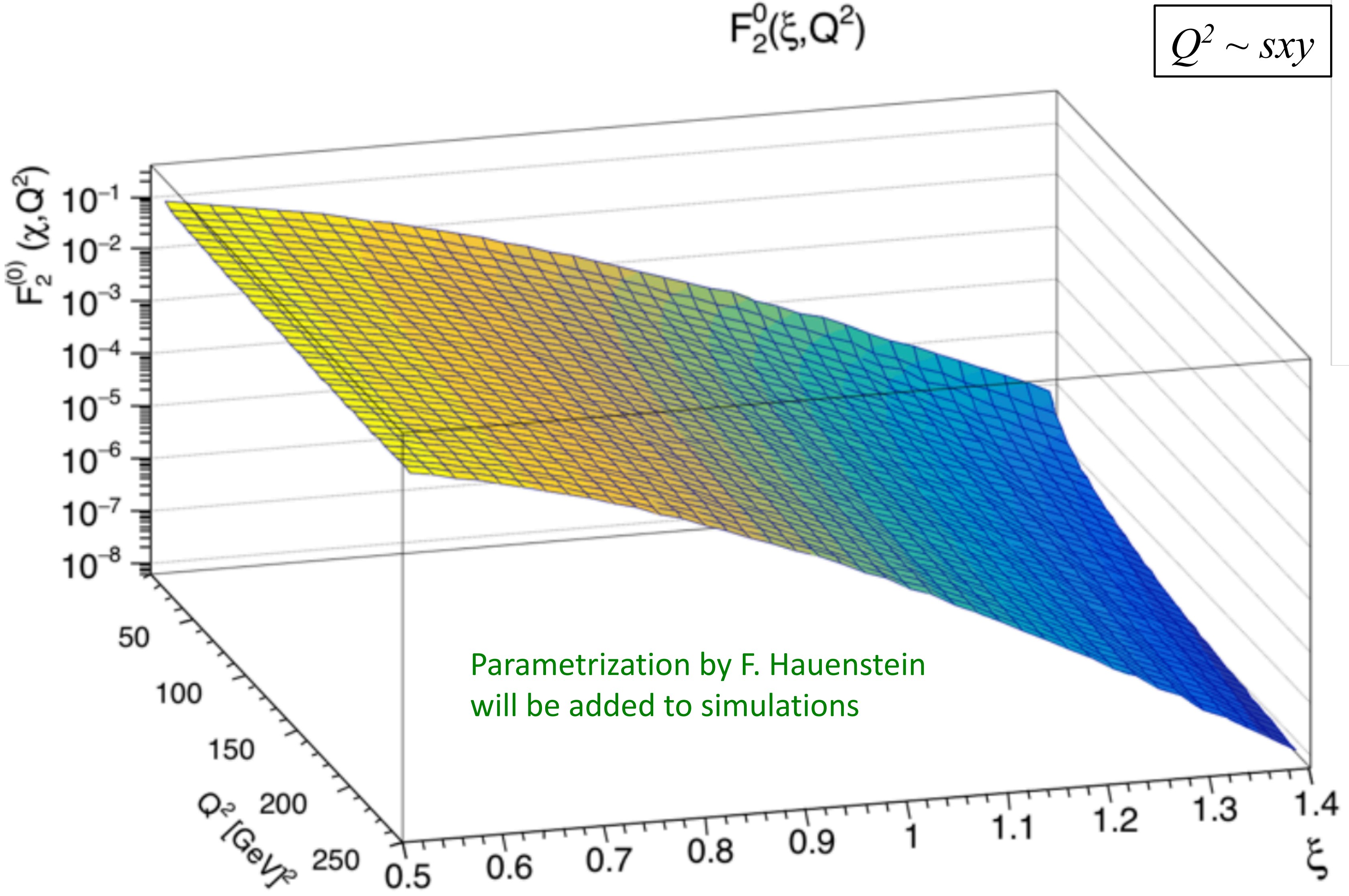
- Can we in the future get a new perspective on clusters and correlations in nuclei through incoherent diffraction?
  - Sensitive to fluctuations in partonic densities

"Exploratory"

# Ongoing JLab LDRD work

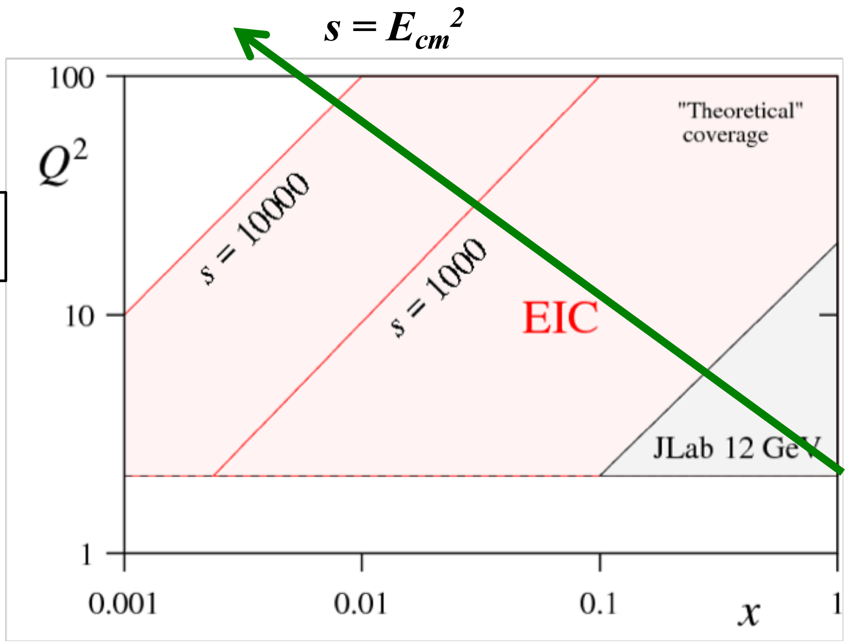
- Feasibility studies
    - Rates at high x
    - Resolution in x at high x
- Simulations, modeling, and detection requirements
    - BeAGLE – an eA event generator for the EIC
    - Incorporating SRCs into BeAGLE
    - Detection requirements
- Diffraction – in the next section

# Rate estimate: parametrization of modified $F_2$



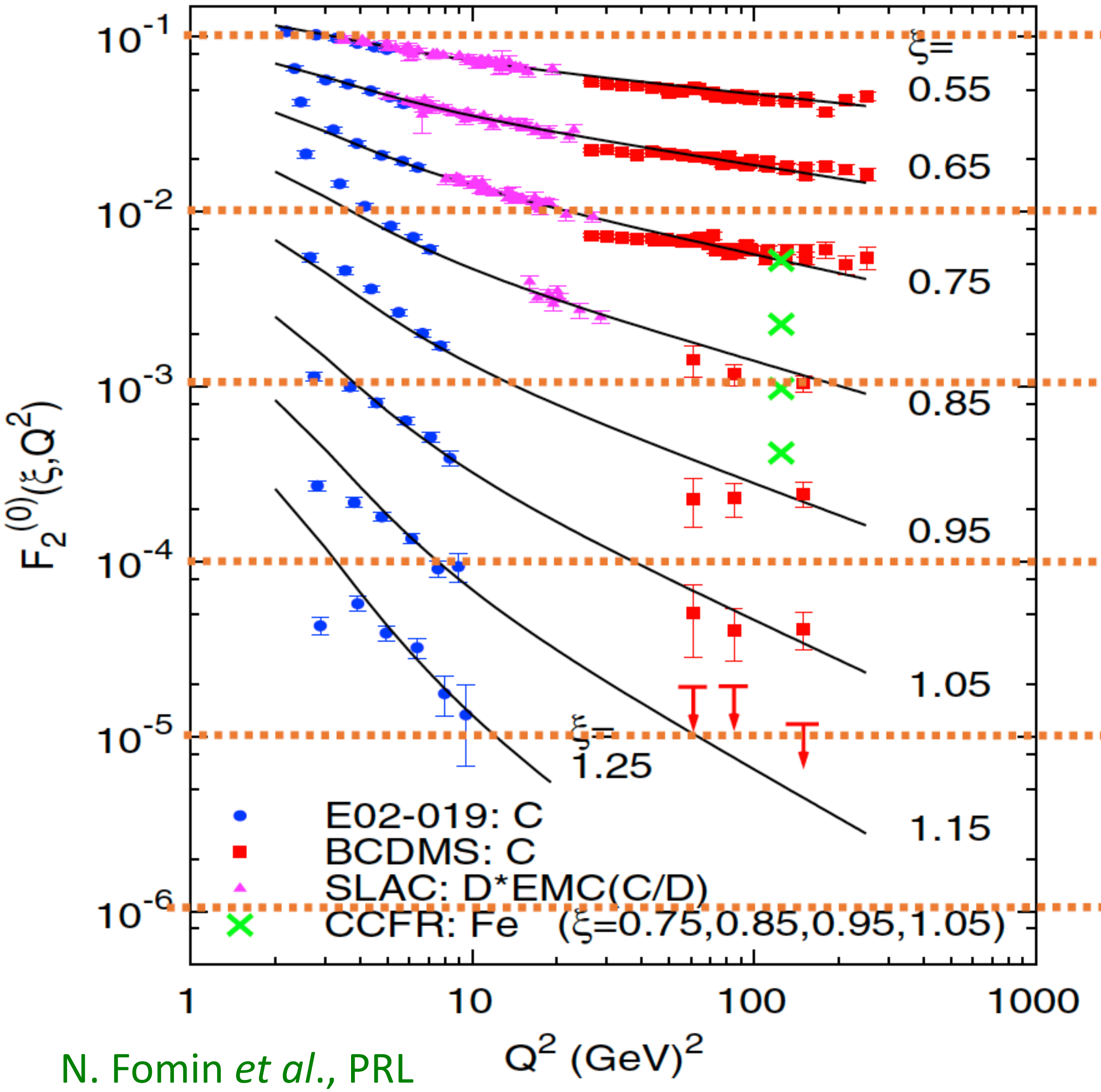

Parametrization by F. Hauenstein
will be added to simulations

$Q^2 \sim sxy$

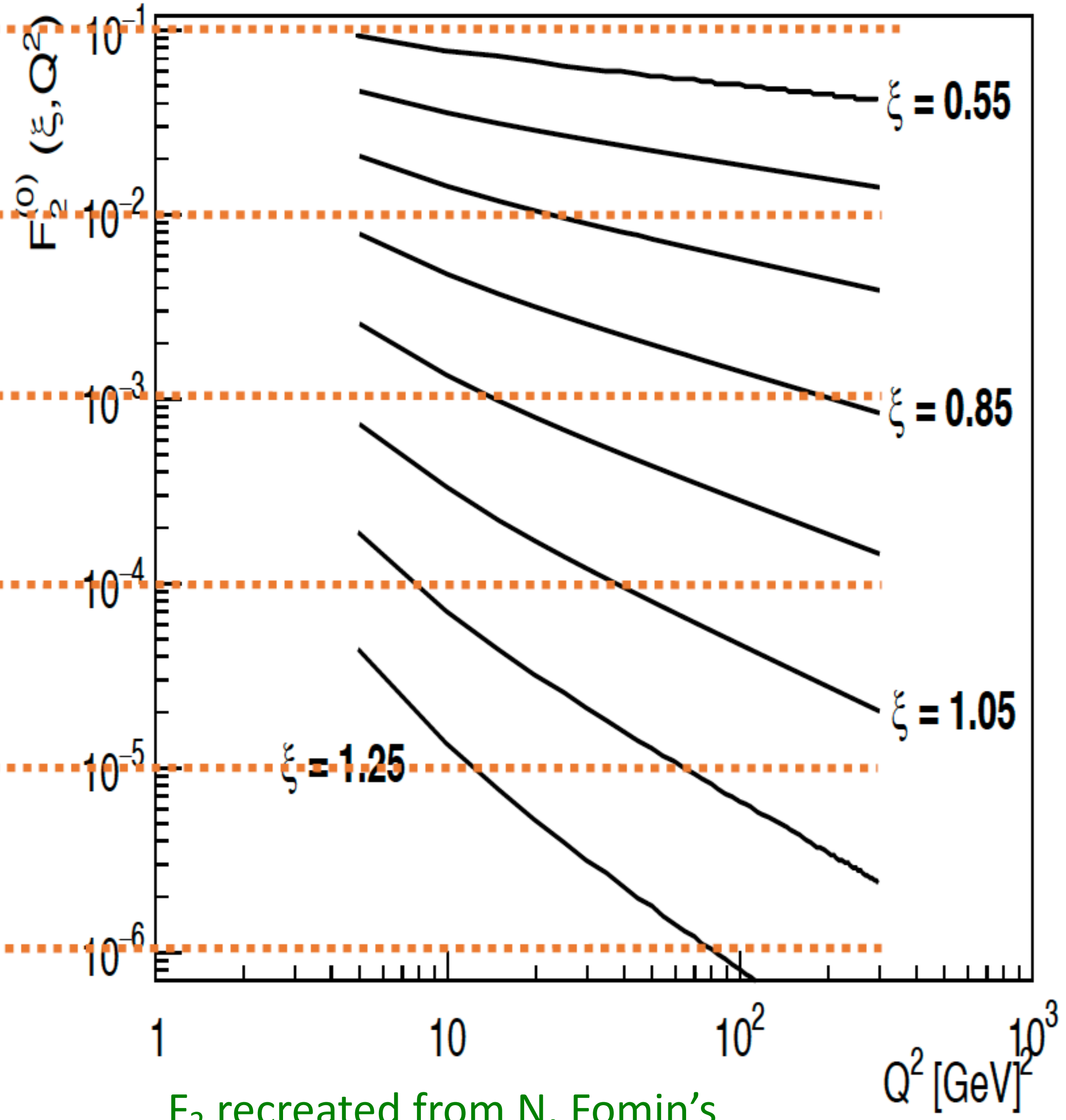



- To reach high x, the EIC would have to operate at low s and low y and/or high $Q^2$
  - Lower s reduces luminosity
  - Lower y reduces resolution
- At high x and $Q^2$, the value of $F_2$ is also low.
  - Rate is challenging
  - Running conditions need to be optimized

# A more detailed look at the modified $F_2$



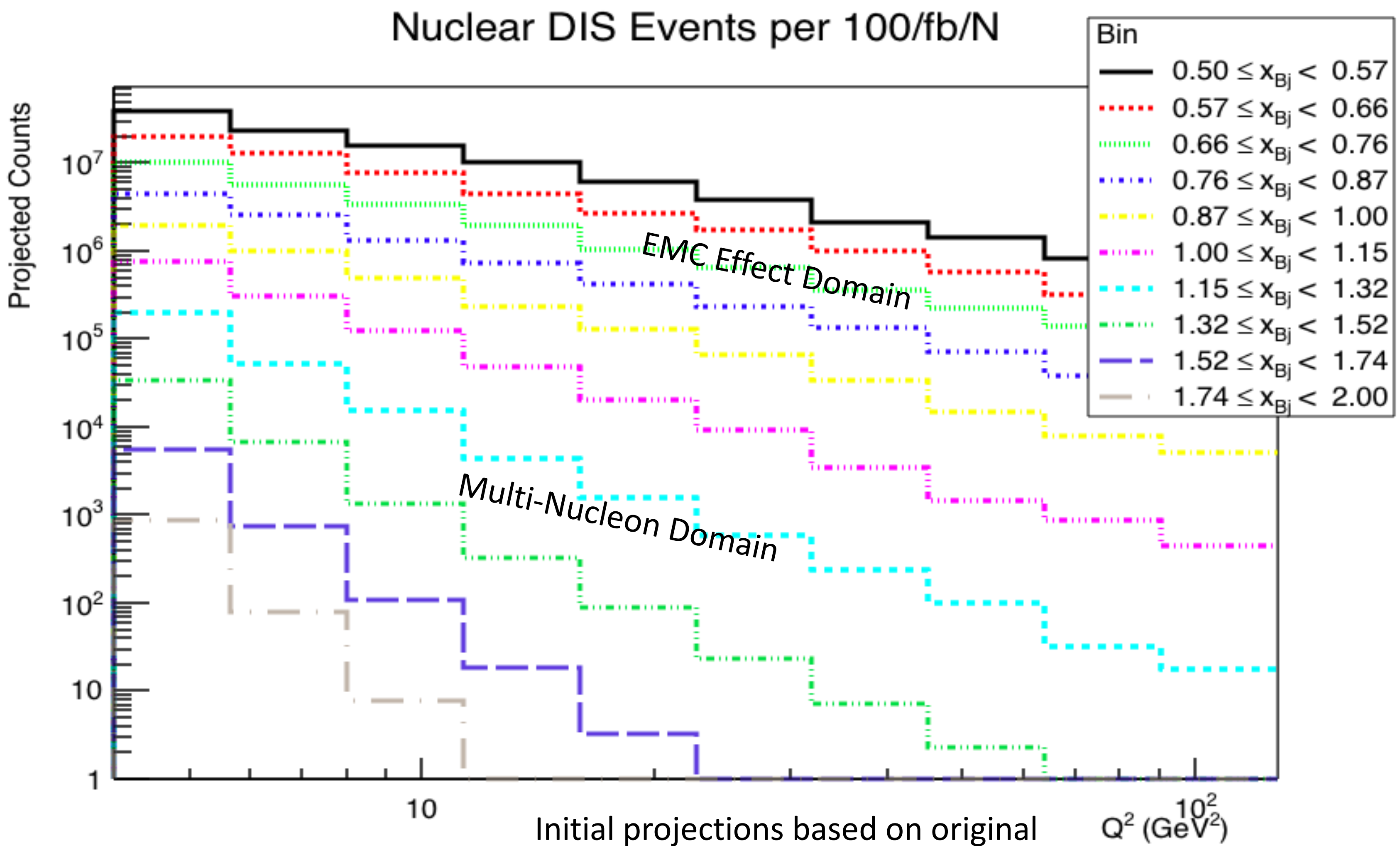

N. Fomin *et al.*, PRL 105, 212502 (2010)




$F_2$ recreated from N. Fomin's scripts by F. Hauenstein

# Initial rate estimates for high x (and $Q^2$)

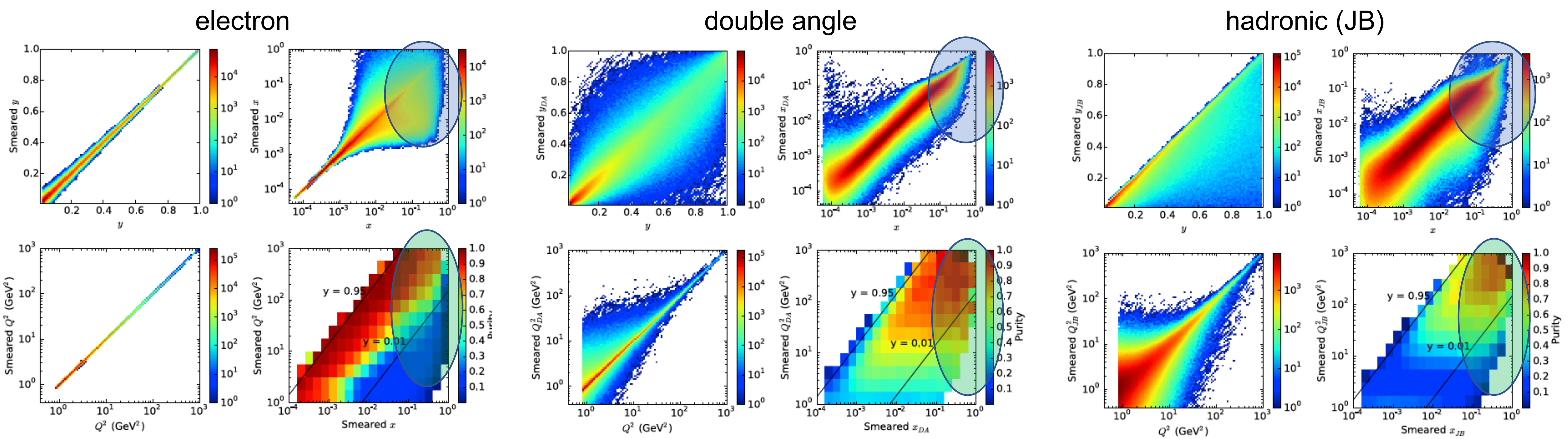
5x50 GeV e+C JLEIC with 6 weeks @ 100% eff. (at lower energy rates would be lower)




Initial projections based on original parameterization by N. Fomin et al., PRL **105** (2010) 212502

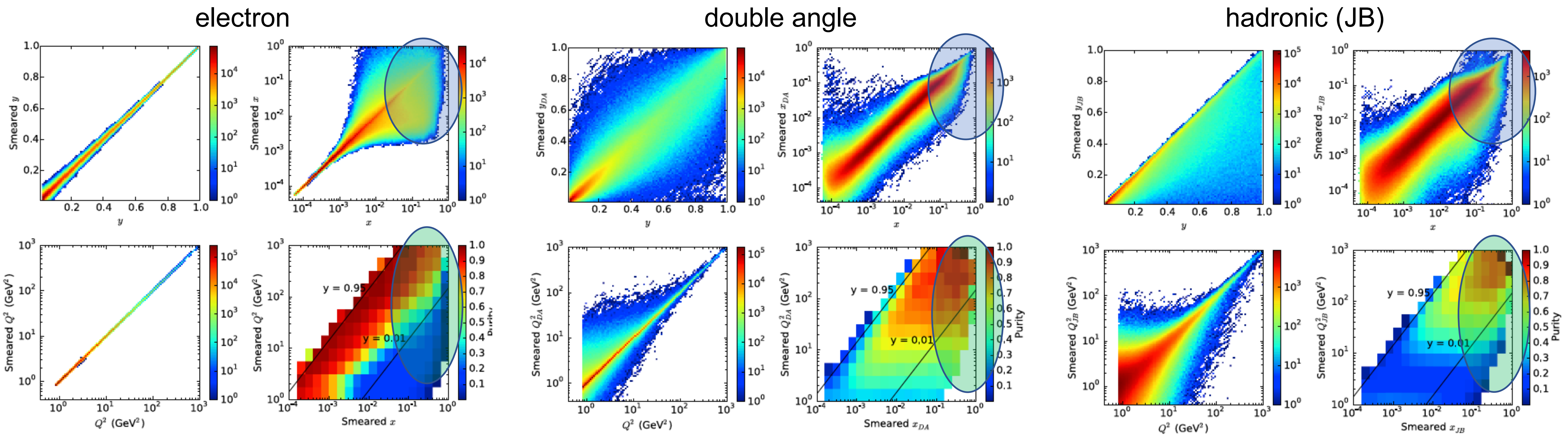
- Measuring the EMC effect at high $Q^2$ is straightforward
- Measuring SRCs at x>1 is challenging, but there will be some events.

# Resolution in x and $Q^2$ for ep scattering at high energy




- Using only the scattered electron, the x-resolution dx/x ~ 1/y
  - Limits how low in y you can go
- Using the produced hadrons produced on a proton works considerably better at small y (large x)
  - Does not work very well at low $Q^2$

# Resolution in x and $Q^2$ for ep scattering at high energy

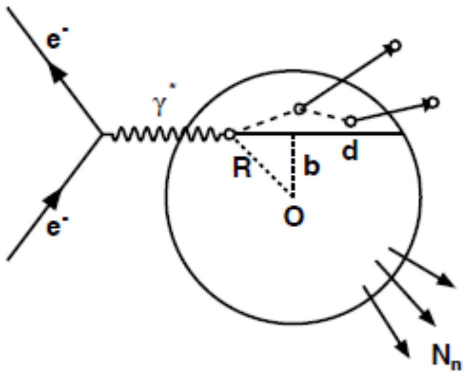



- Hadronic reconstruction does not work for scattering on a nucleon in a nucleus, which is not at rest in the initial state.
  - The motion is small in the rest frame of the nucleus, but the large boost significantly degrades the resolution
- For eA in general, and high x in particular, a more general approach is needed (*e.g.* kinematic fitting)
  - For high x, also need to evaluate how low in energy one needs to go even with such methods to retain a sufficient x-resolution

# BeAGLE - Benchmark eA Generator for LEptoproduction

Mark Baker, E. Aschenauer, J.H. Lee, L. Zheng

https://wiki.bnl.gov/eic/index.php/BeAGLE




Multistep process.

Hard interaction (DIS or diffractive) involving one or more nucleons (Glauber).

Intra Nuclear Cascade w/ Formation Zone

Excited nuclear remnant decays by:
 Fission &/or evaporation of nucleons
 De-excitation by gamma emission.

- Merger of
  - Pythia6: hard interaction (adding RAPGAP option)
  - Glauber + multinucleon shadowing
  - PyQM: Optional radiative jet quenching
  - DPMJET3-F (DPMJET3+Fluka) – nuclear response
- Tuned to
  - ZEUS forward nucleons
  - FNAL E665 (fixed target) slow neutrons
  - HERMES
  - Working on E665 e-by-e charged hadrons (SC)

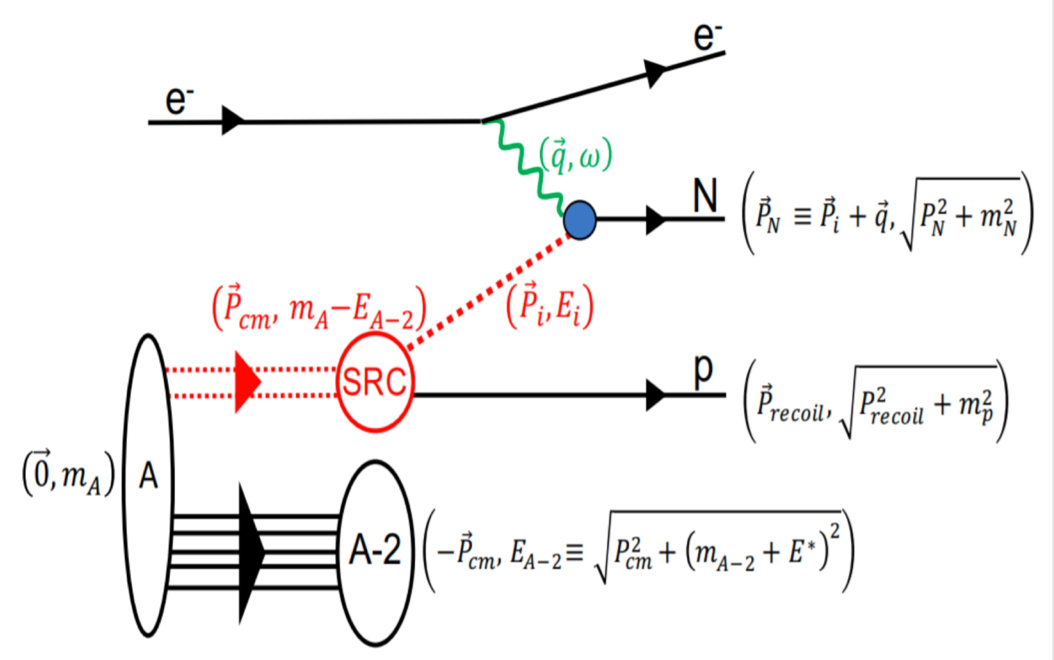
# Planned work as part of the LDRD

- We plan to extend BeAGLE to simulate SRCs in e+C and higher, as well as refine the current e+D simulations.

- Input QE events from the GCF event generator into BeAGLE, which can then apply (A-2)-FSI effects, including formation-zone intranuclear cascade and nuclear remnant evaporation and breakup.

- Implement a simplified SRC/EMC effect model for DIS events into BeAGLE.

# Generalized Contact Formalism (to be added to BeAGLE)

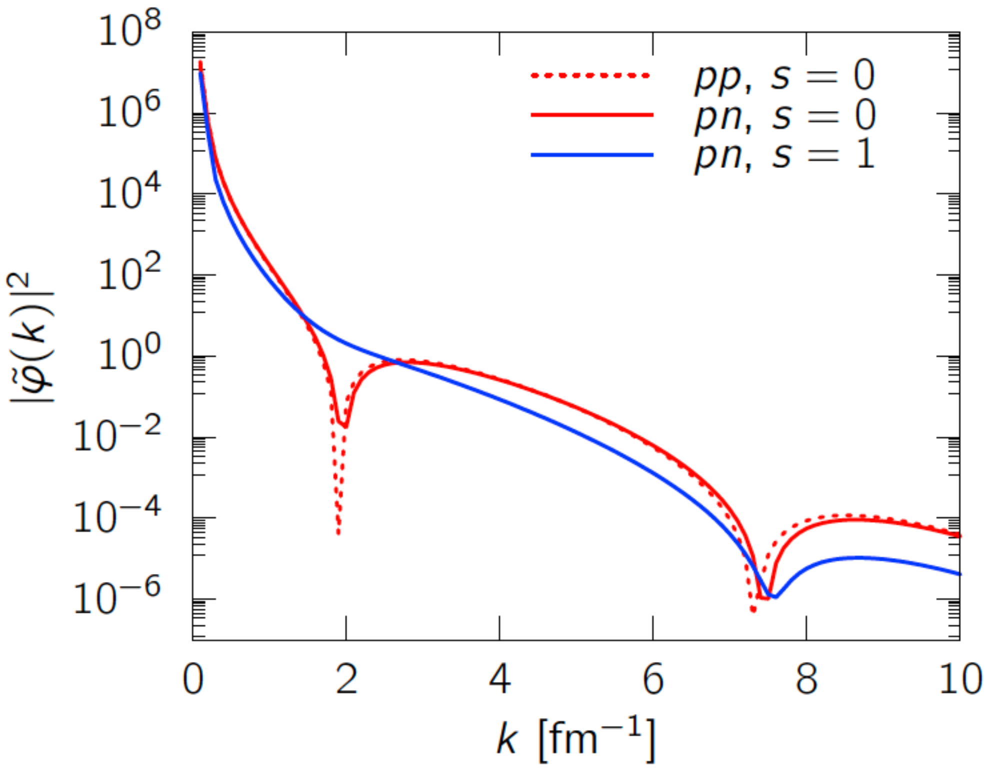



$$d\sigma \sim \sigma_{eN} \cdot n(\vec{p}_{CM}) \cdot \sum_{\alpha} C_\alpha |\tilde{\varphi}_\alpha(k)|^2$$

-> talk by Axel Schmidt

- Factorized cross section
- Scale separation:

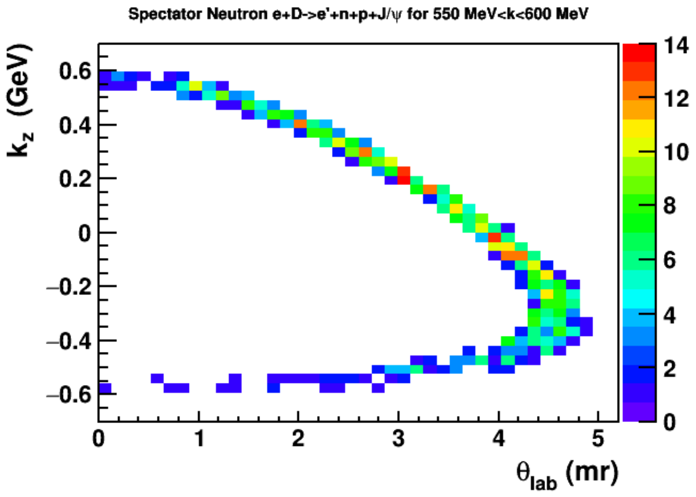
  $p_{CM} < p_{rel} < q$

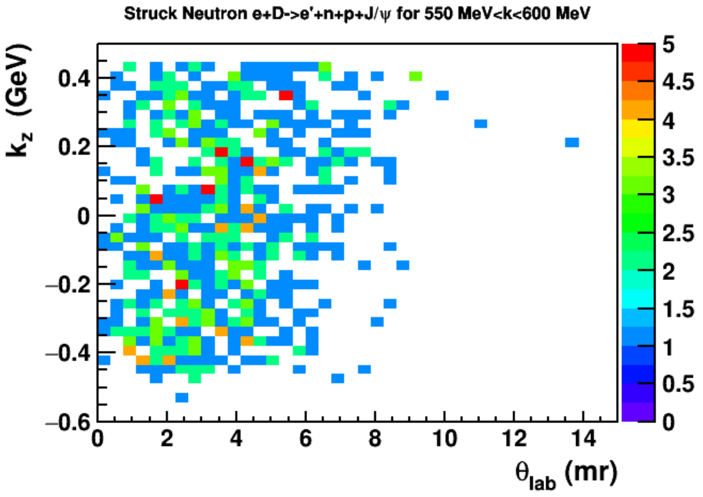


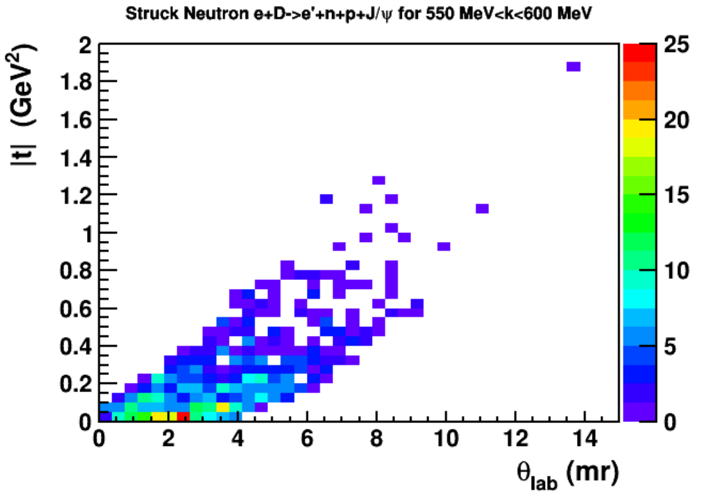
# Lab kinematics of spectator and struck neutrons at high energy

spectator n | struck n | struck n (vs t)

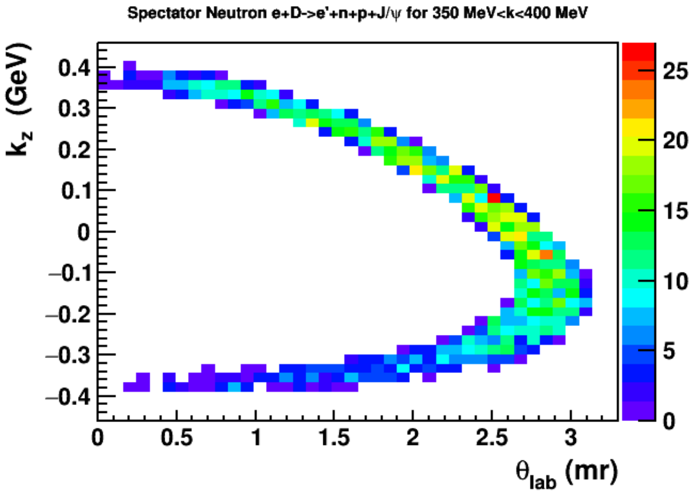
k ~ 575 (MeV)

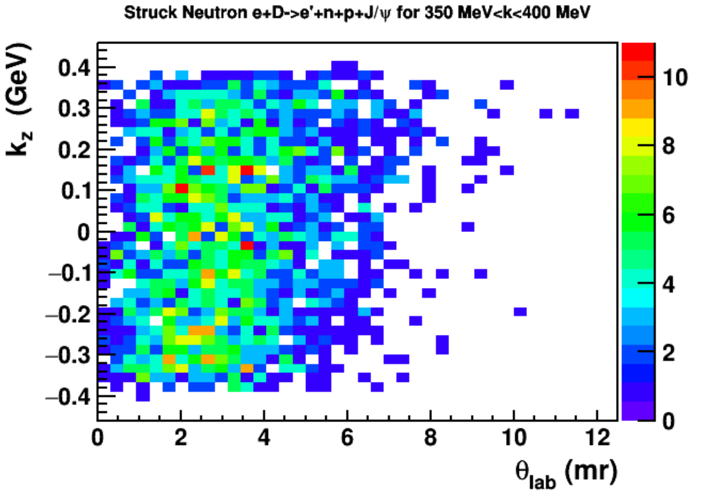


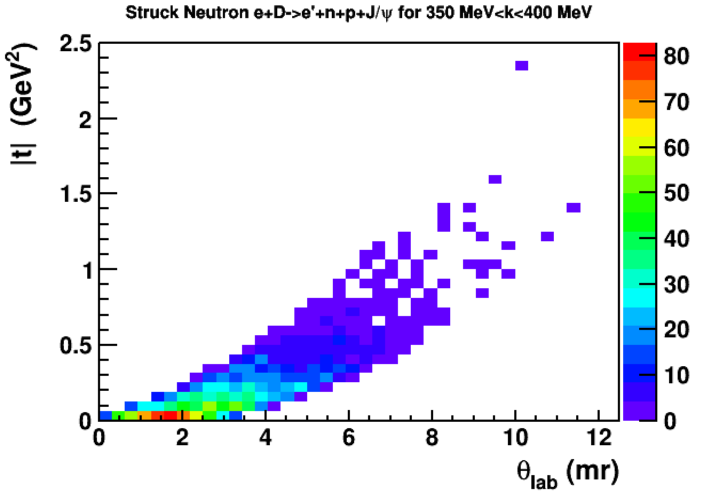




k ~ 375 (MeV)



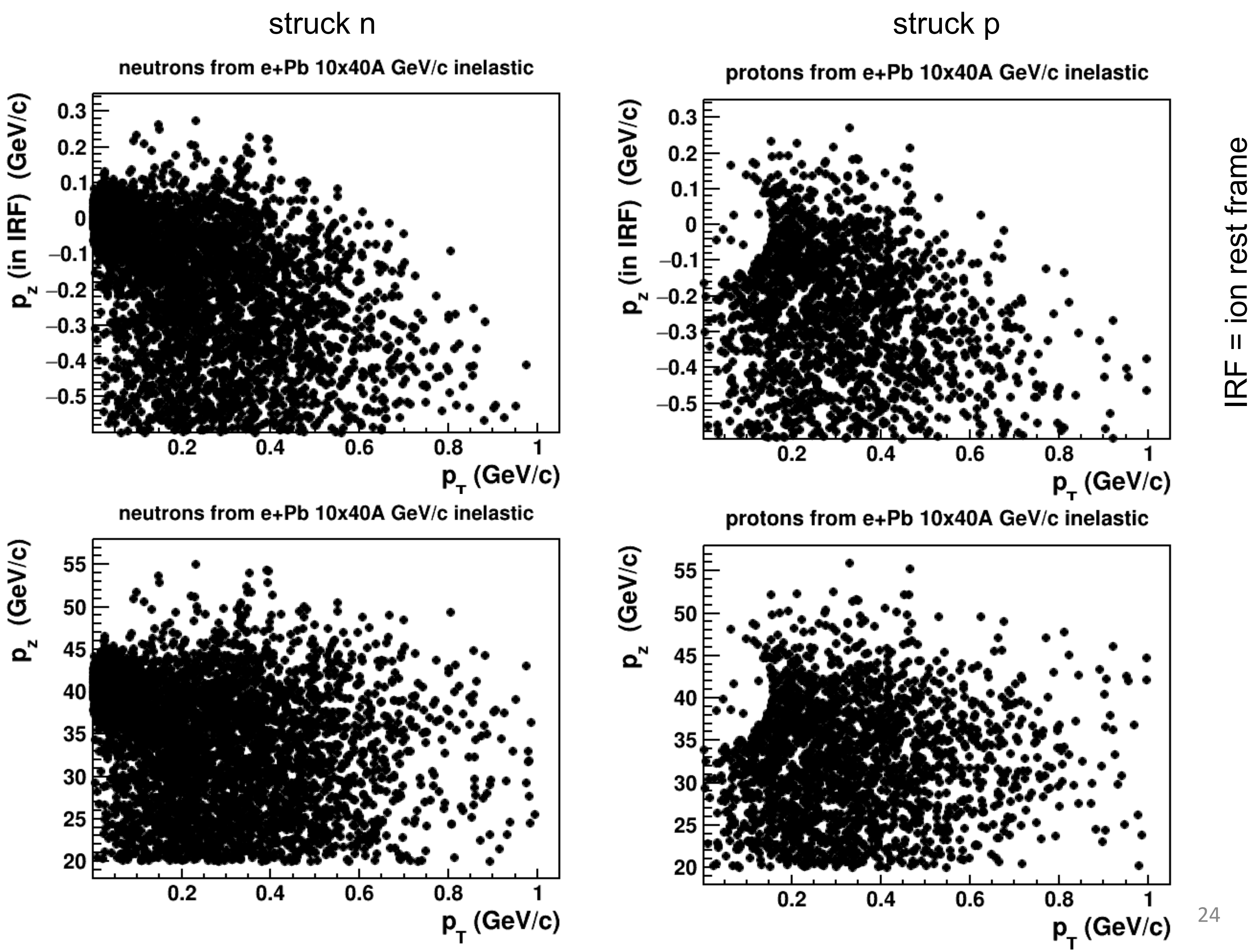



# And protons...

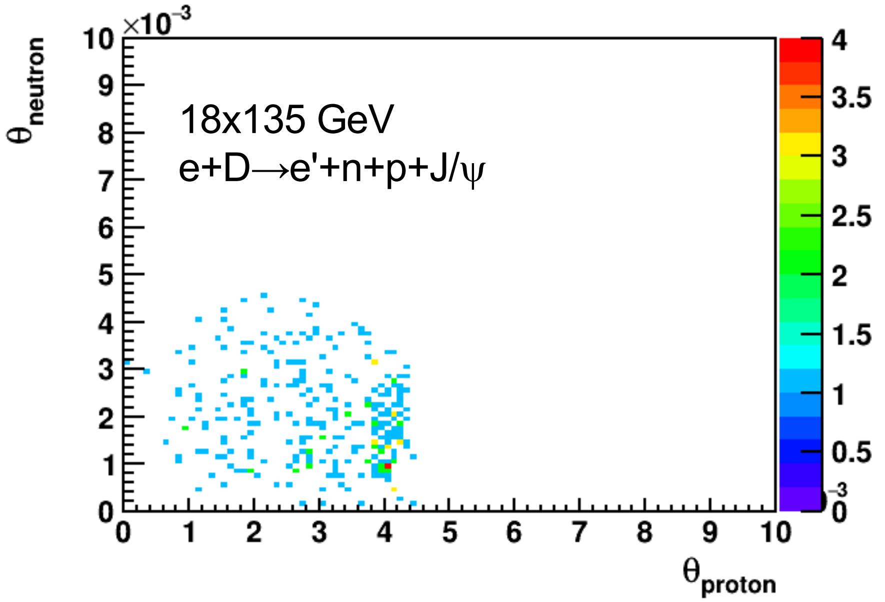
- For protons, Coulomb effects are not negligible.

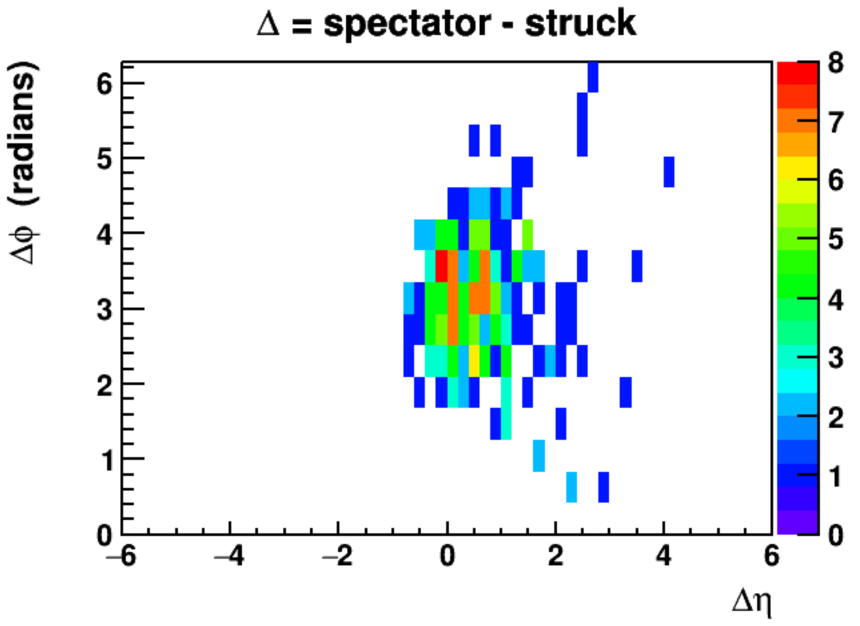
- We need to merge the primary process with a detailed simulation of the nuclear response (BeAGLE) to understand the measurements



# And correlations (deuteron breakup)...

struck neutron, spectator proton
$|t|<0.1$ GeV$^2$, $550 < k < 600$ MeV

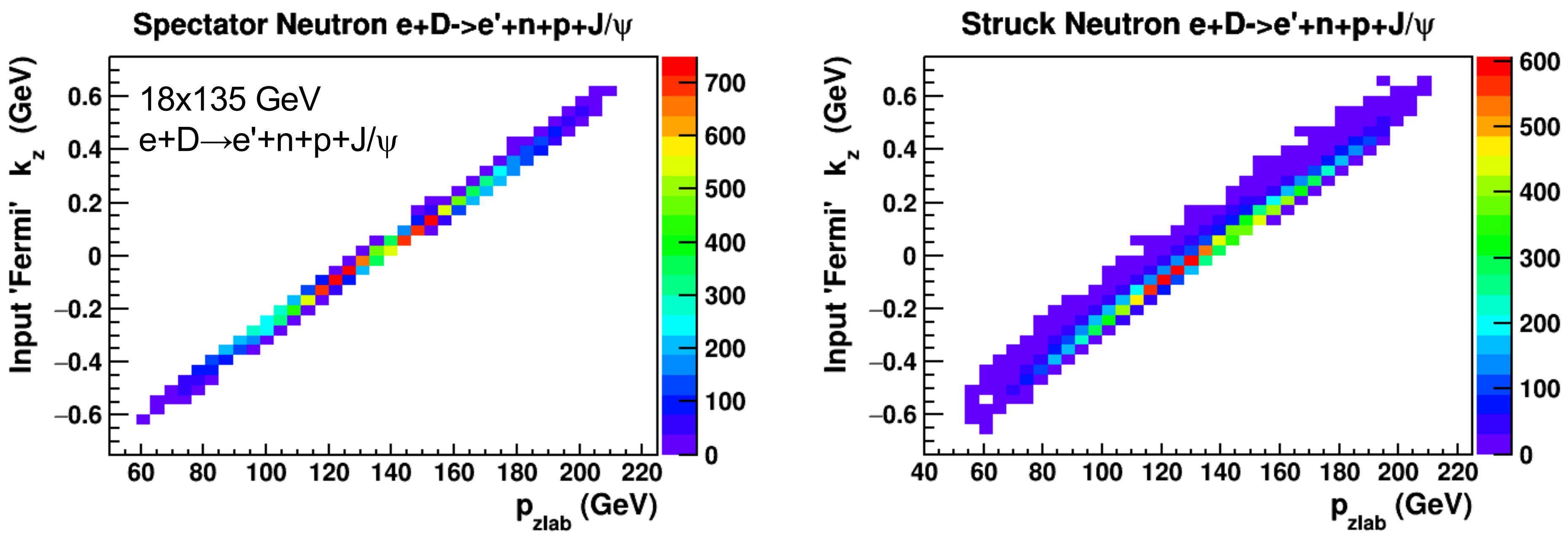



$\eta = -\ln\tan(\theta/2)$

- BeAGLE can be also be used to study spectator tagging

# Effect of boosting $k_z$ to the lab frame



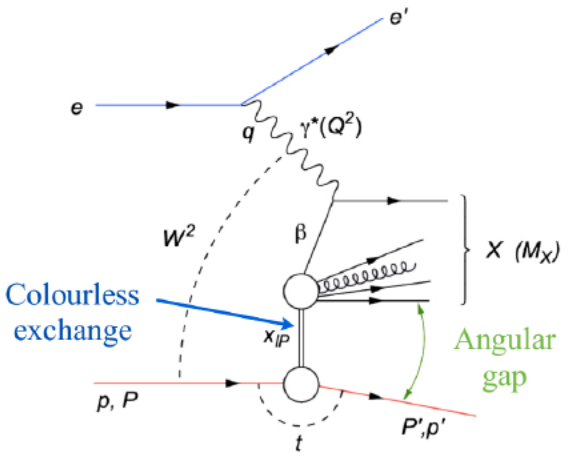

- The boost makes precision measurements of nucleons moving along the z-axis easier
  - It also makes precision gamma spectroscopy of photons from nuclear de-excitations in heavier nuclei possible.
- However, as noted earlier, this is also the reason why hadronic reconstruction methods do not work as well for eA as they do for pA.

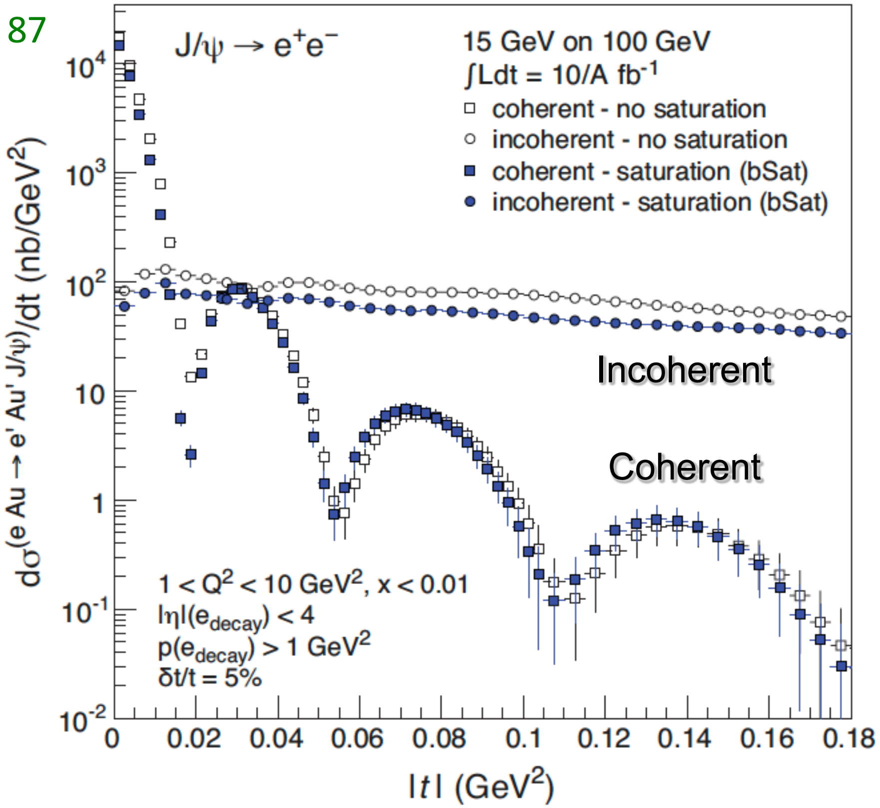
# Diffraction on Nuclei at the EIC

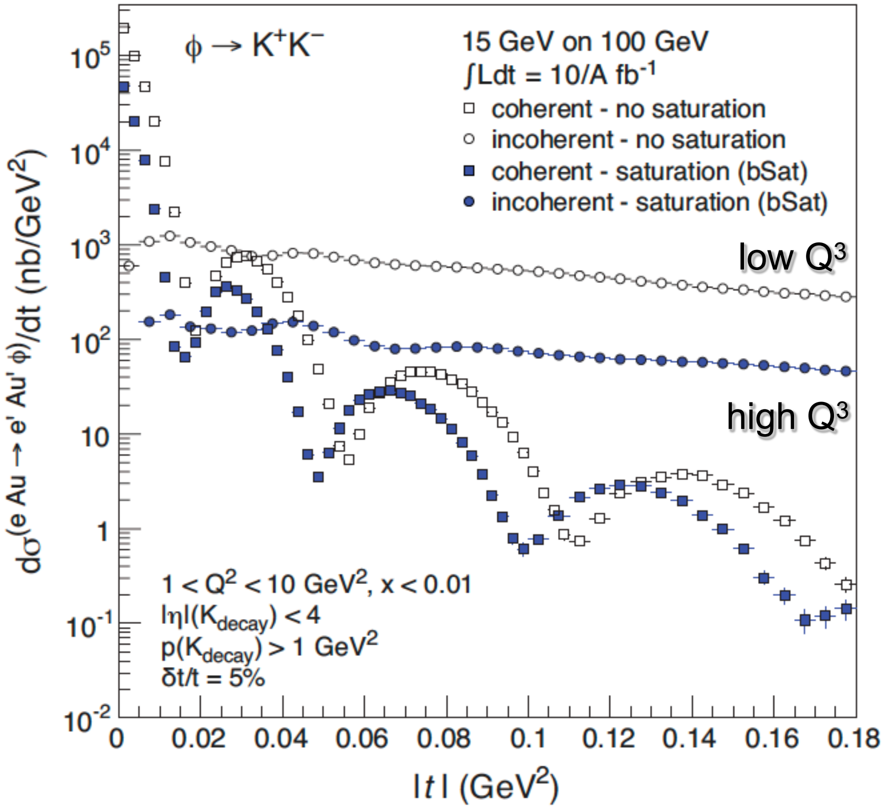
JLab "geometry tagging" LDRD: V. Morozov, A. Accardi, M. Baker, W. Brooks, R. Dupre, K. Hafidi, C. Hyde, PNT, T. Toll, L. Zheng

# Diffraction on nuclei in exclusive meson production ($M_x$ = meson)

T. Toll, T. Ullrich, PRC 87 (2013) 024913



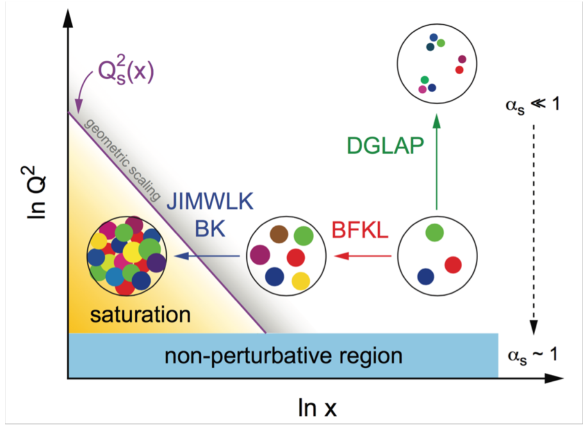



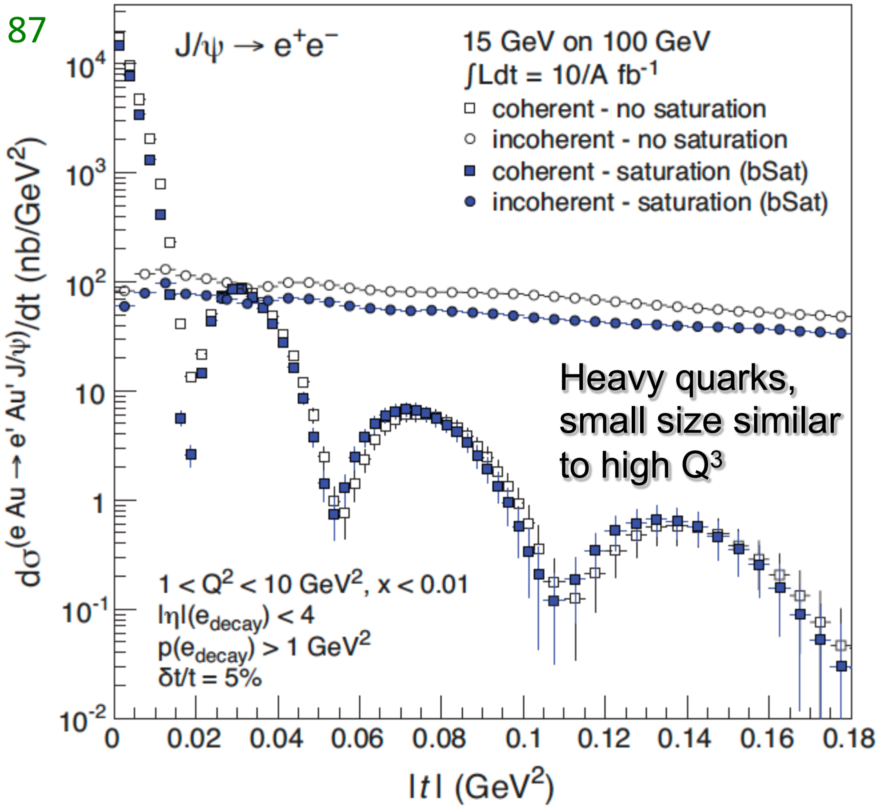



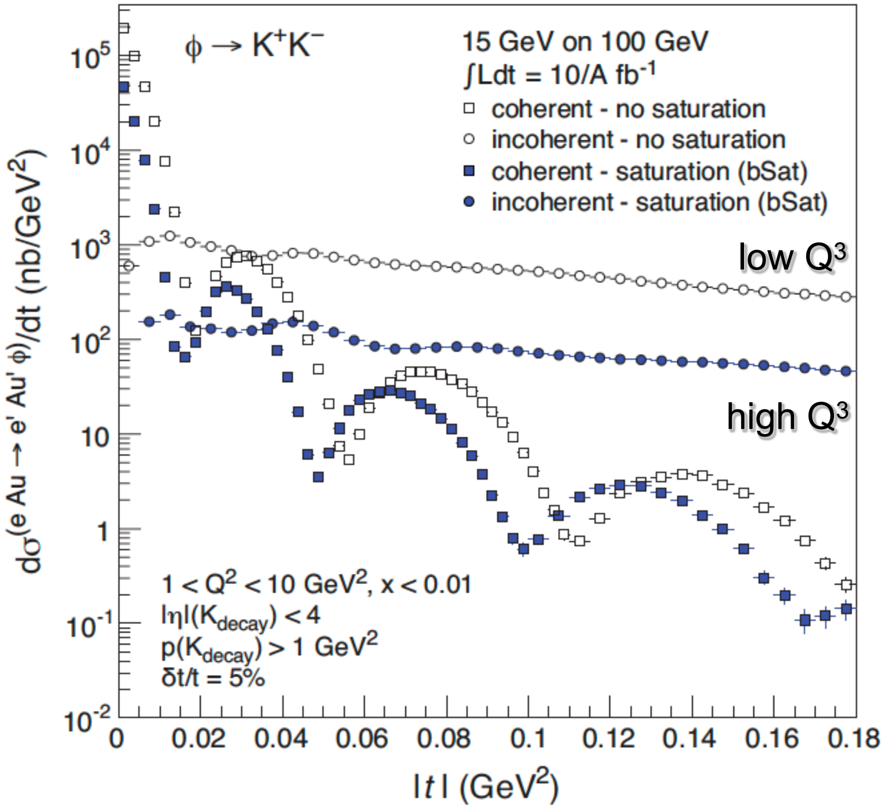

- At reasonably high energy and low x, there is a large probability for the target to stay intact
  - A rapidity gap clearly separates the current and target
  - In *coherent* diffraction the entire nucleus stays intact
  - In *incoherent* diffraction the stuck nucleon stays intact, but the nucleus breaks up

# Sensitivity to gluon saturation in heavy nuclei at very low x

T. Toll, T. Ullrich, PRC 87 (2013) 024913



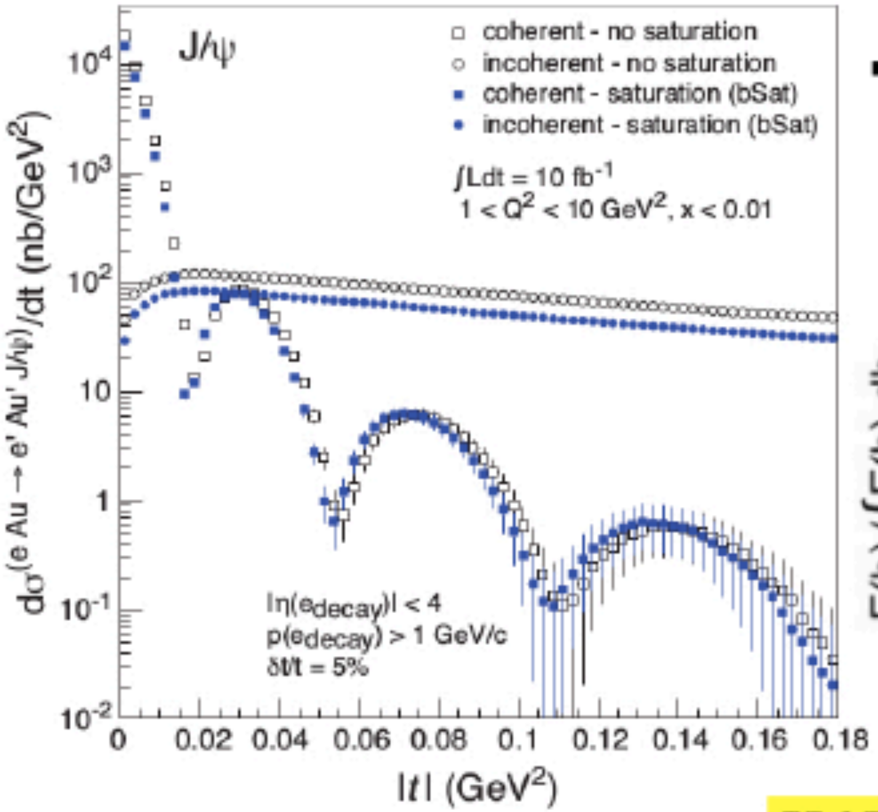




- $Q^2$-dependence of phi production shows sensitivity to gluon saturation
  - Needs to be “calibrated” to the $Q^2$-dependence in an intermediate range of x
  - The J/psi is always is always small, and thus shows little sensitivity to saturation at EIC energies

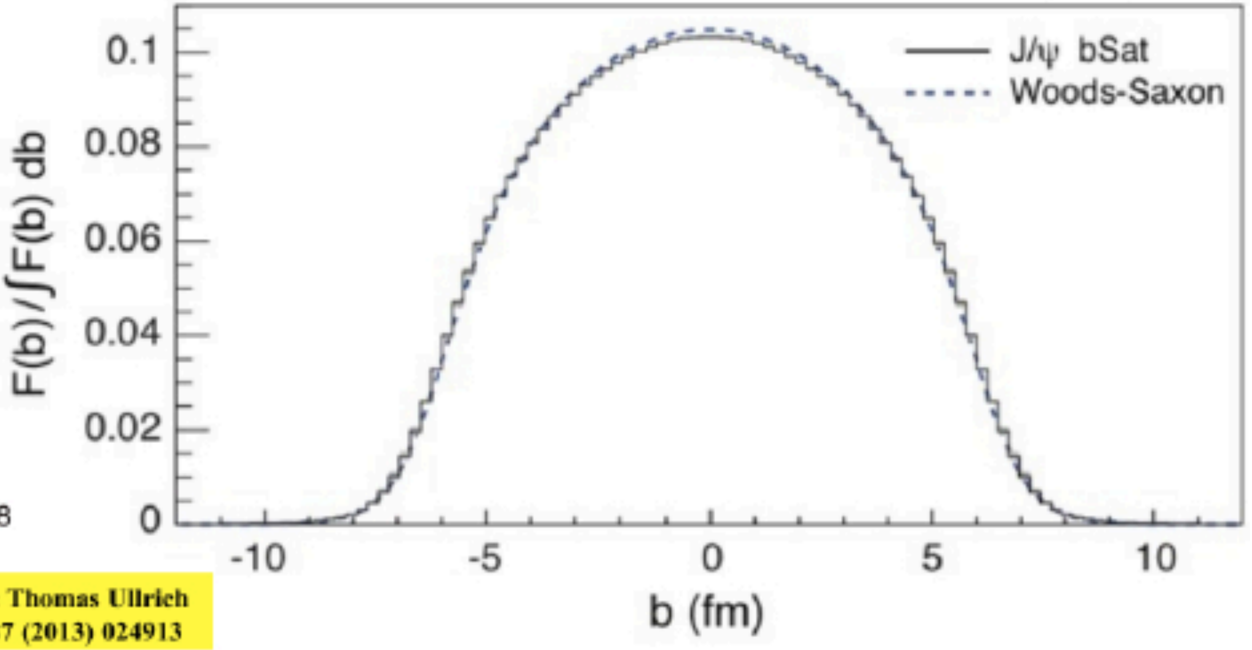
# Coherent diffraction can give us the transverse spatial gluon distribution

## Momentum transfer $t$ conjugate to transverse coordinate $b$




$$F(b) \propto \int \mathrm{d}\Delta \Delta J_0(\Delta b) \sqrt{\frac{\mathrm{d}\sigma}{\mathrm{d}t}}$$

$t = \Delta^2/(1-x) \approx \Delta^2$

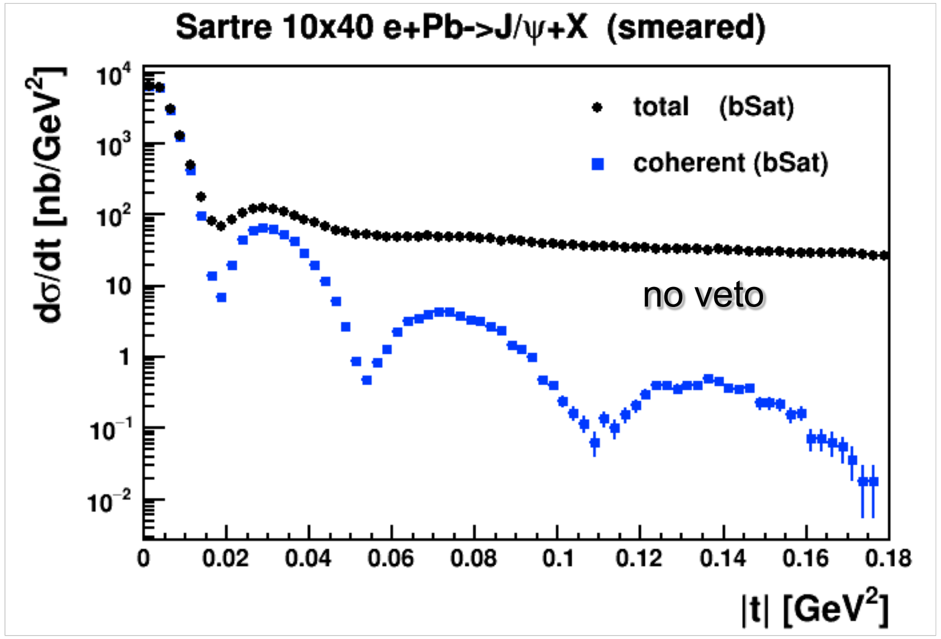



T.T. & Thomas Ullrich
PRC 87 (2013) 024913

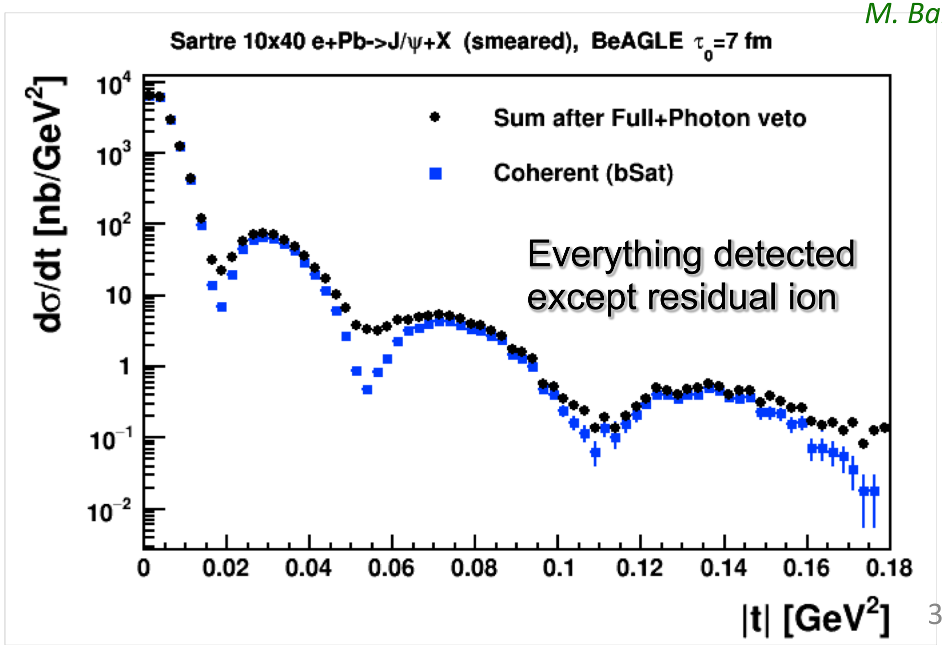
- Experimental challenge: veto the large incoherent background.

# BeAGLE was used to evaluate the veto efficiency of target fragment detection

- Intact heavy ions cannot be detected directly
  - The momentum transfer is too small to kick intact heavy ions out of the beam envelope
- Need high-efficiency veto of incoherent events
  - Detection of *all* produced particles required: protons, neutrons, light nuclei, and photons from nuclear de-excitations
  - Detection of the residual nucleus (from incoherent diffraction) is also helpful
- BeAGLE was used to simulate the incoherent part – in this case the background
  - The coherent simulation used Sartre




M. Baker



# Density fluctuations from incoherent diffraction

- Incoherent diffraction probes the variance of the density
  - Calculations at $x \sim 10^{-3}$ show "lumpiness" in the gluon distribution and suggest sensitivity to model assumptions
- Could we in the future see the imprint of correlations from nucleonic degrees of freedom in at the partonic level?
  - Experimentally straightforward, but a clear interpretation needs much more progress on the theory side

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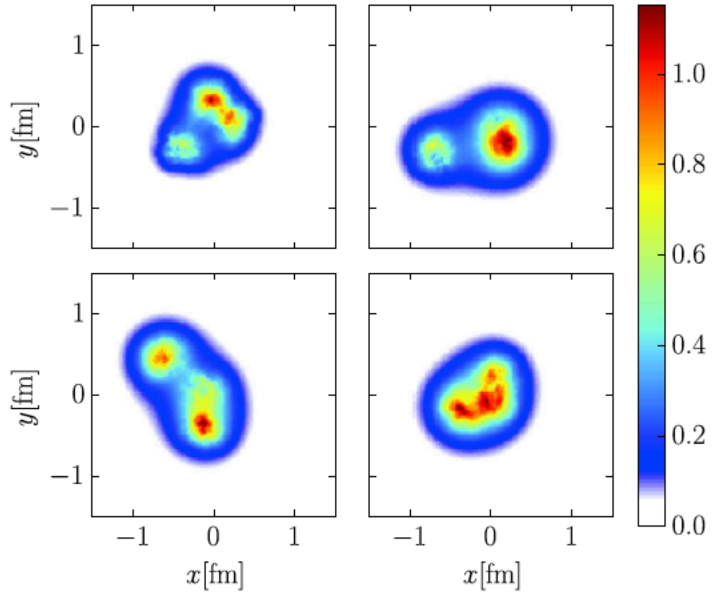
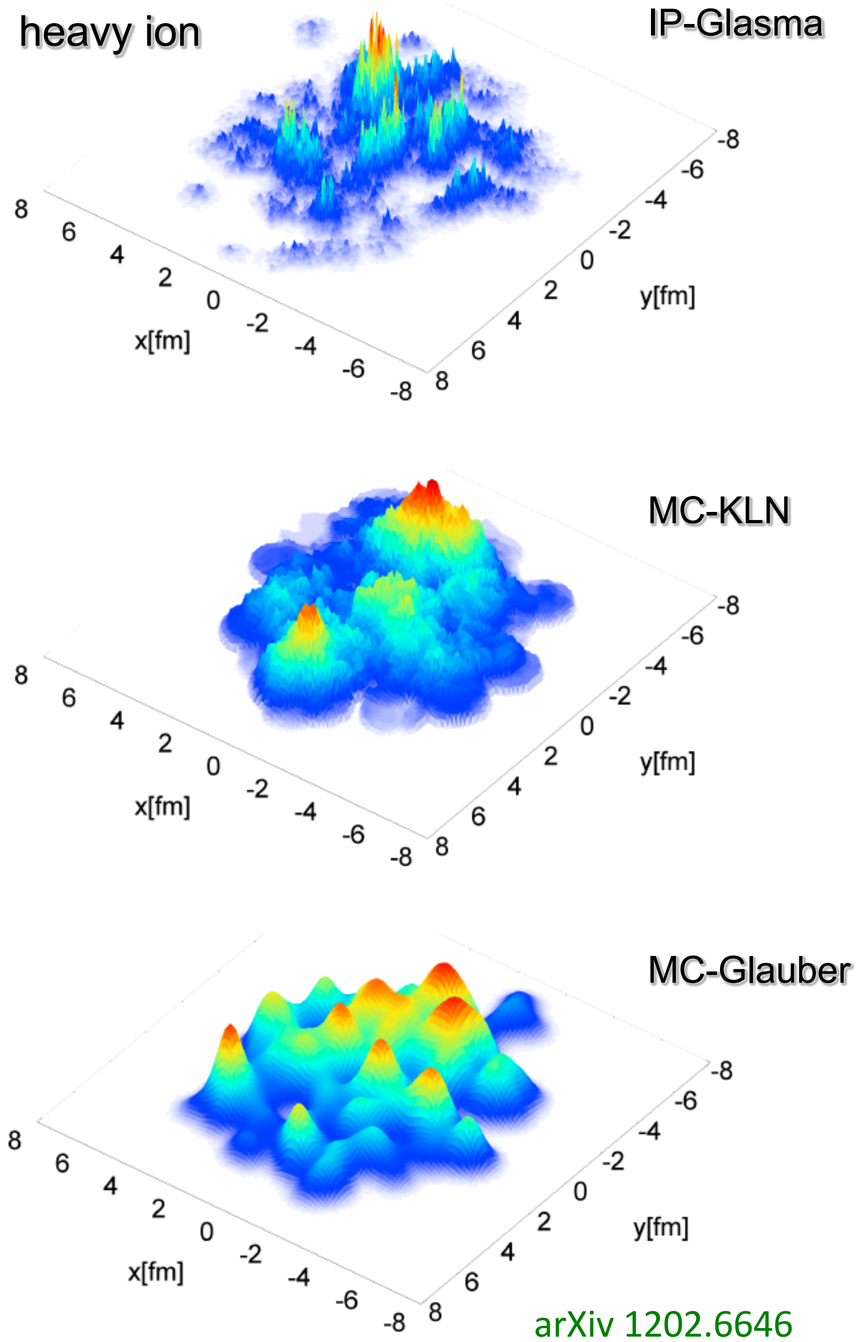



proton




arXiv 1202.6646

Thank you!

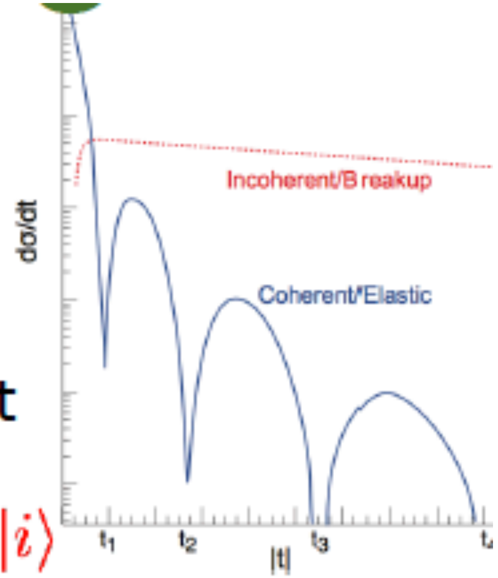
# Backup

# Incoherent diffraction

T. Toll

Good, Walker:

nucleus dissociates ($f \neq i$):




$$\sigma_{\text{incoherent}} \propto \sum_{f \neq i} \langle i|\mathcal{A}|f\rangle^\dagger \langle f|\mathcal{A}|i\rangle$$

complete set

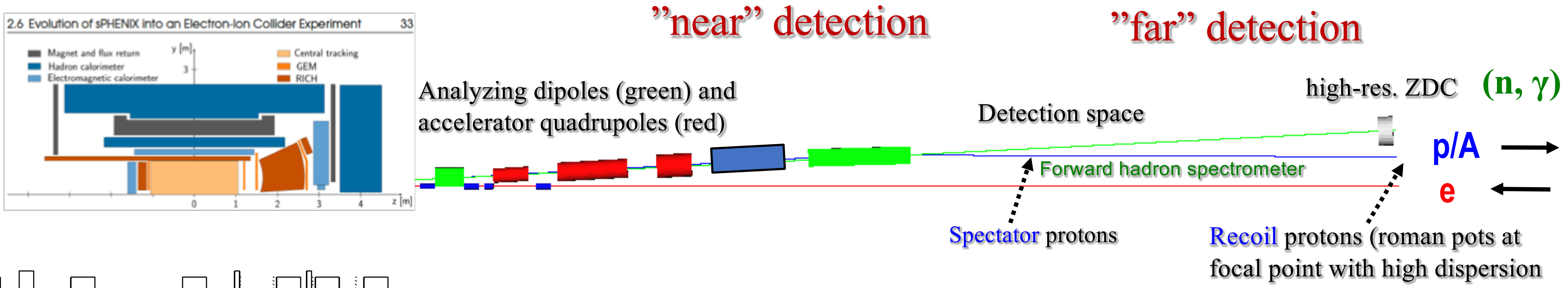
$$= \sum_{f} \langle i|\mathcal{A}|f\rangle^\dagger \langle f|\mathcal{A}|i\rangle - \langle i|\mathcal{A}|i\rangle^\dagger \langle i|\mathcal{A}|i\rangle$$

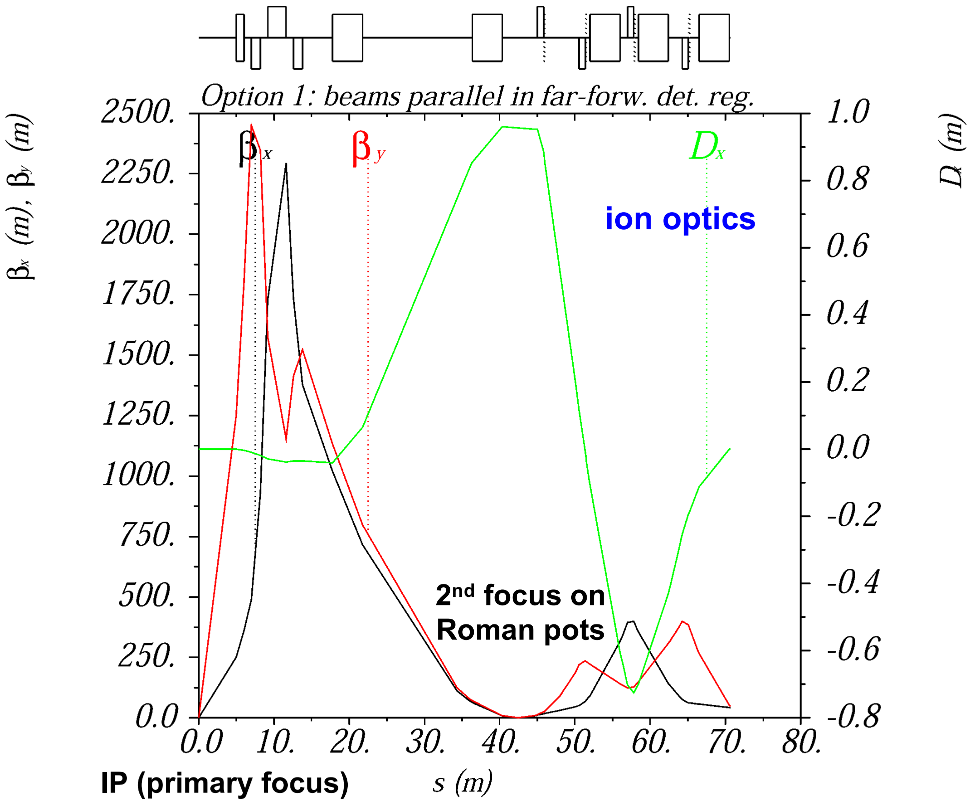
$$= \langle i \left| |\mathcal{A}|^2 \right| i\rangle - |\langle i|\mathcal{A}|i\rangle|^2 = \langle |\mathcal{A}|^2\rangle - |\langle \mathcal{A}\rangle|^2$$

the incoherent CS is the variance of the amplitude!!

$$\frac{d\sigma_{\text{total}}}{dt} = \frac{1}{16\pi}\left\langle |\mathcal{A}|^2 \right\rangle \qquad \frac{d\sigma_{\text{coherent}}}{dt} = \frac{1}{16\pi}|\langle \mathcal{A}\rangle|^2$$

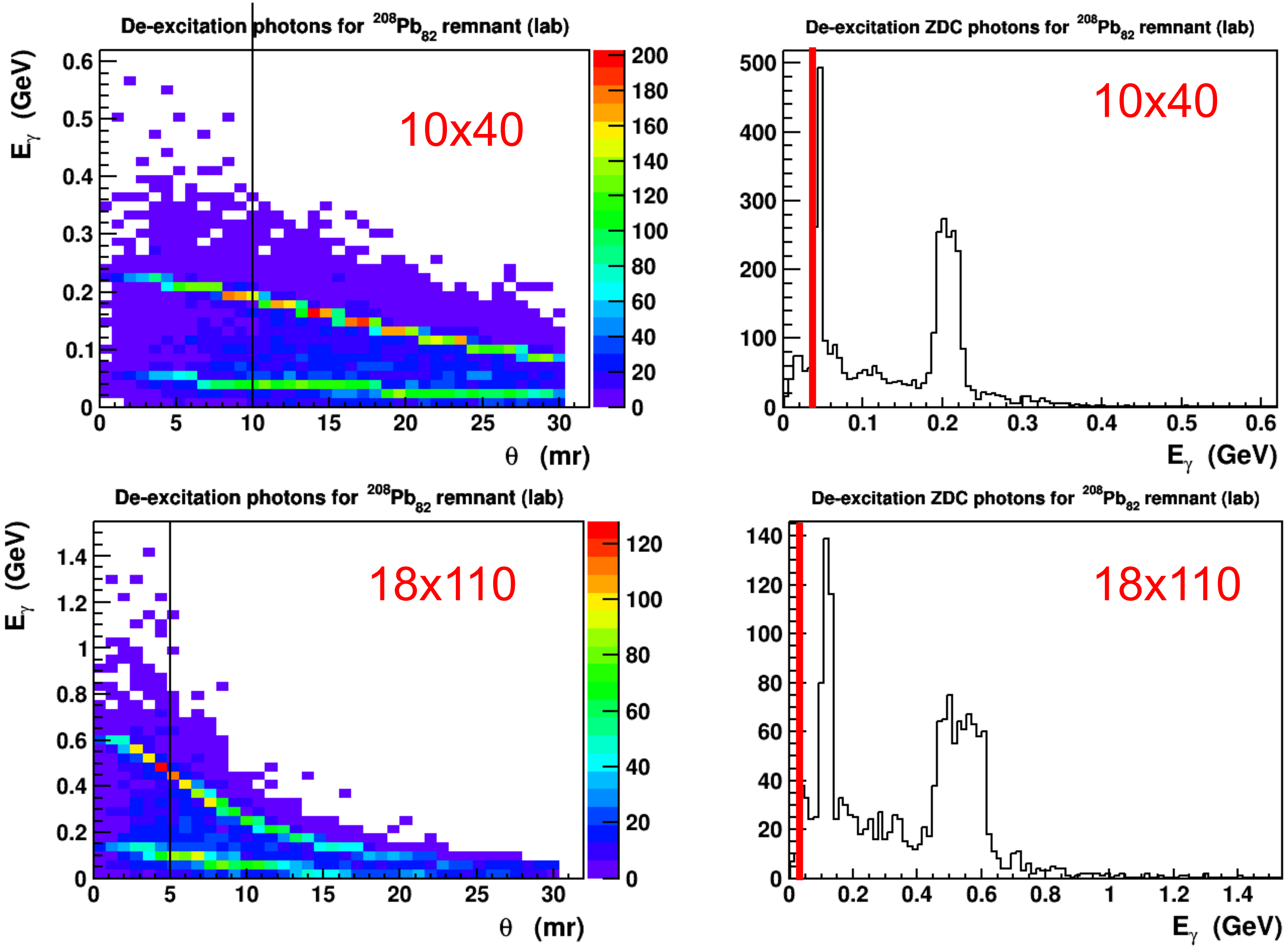
# Detection of target fragments – forward spectrometer




- Functionally, the forward detection is naturally separated into a ”near” and “far” parts
- “Near” detection:
  - *Goal*: off-momentum/rigidity particles or ones scattered at ”large” angles (high $p_T$)
  - *Requirement*: large magnet apertures
- “Far” detection (can be after a crab cavity):
  - *Goal*: small-angle particles with momentum/rigidity close to that of the beam
  - *Requirement*: large dispersion and small beam size

# Photons from $^{208}Pb_{82}$ in lab frame




Detailed studies ongoing.

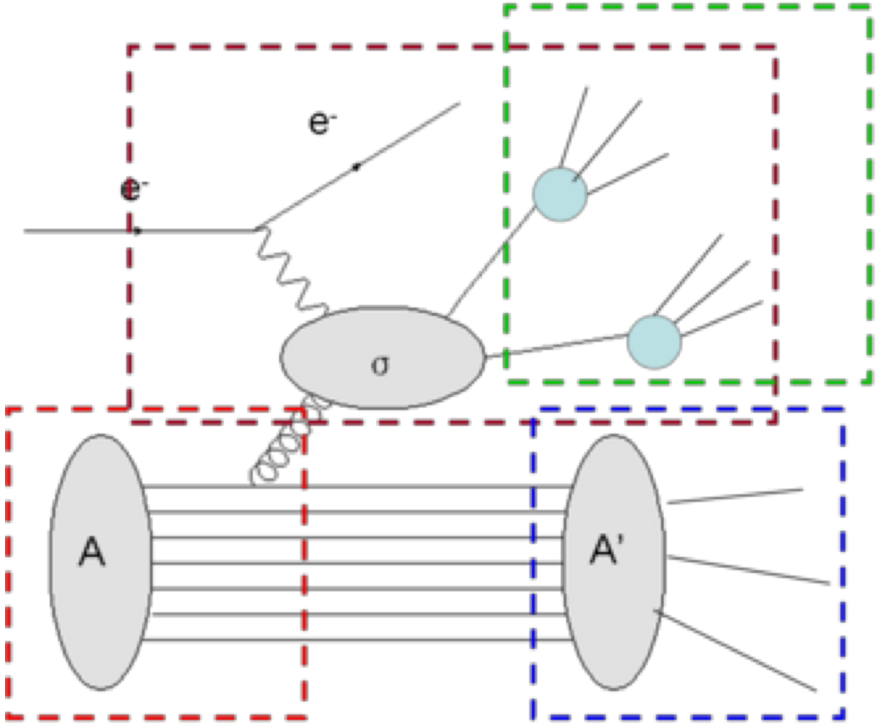
It is clear that $\gamma$'s will be needed for low |t|!

**w/ Morozov, Hyde, Turonski et al.**

# BeAGLE Structure

E. Aschenauer + M. Baker + J.H. Lee + L. Zheng

From: https://wiki.bnl.gov/eic/index.php/BeAGLE




A hybrid model consisting of DPMJet and PYTHIA with nPDF EPS09.

Nuclear geometry by DPMJet and nPDF provided by EPS09.

Parton level interaction and jet fragmentation completed **in Pythia** in PYTHIA.

**Intra Nuclear Cascade &**
Nuclear evaporation ( gamma dexcitation/nuclear fission/fermi break up ) treated by DPMJet **(Fluka)**

Energy loss effect from routine by **Accardi,** Salgado&Wiedemann to simulate the **Dupré** nuclear fragmentation effect in cold nuclear matter **is available.**