Geometry tagging with heavy ions at the EIC

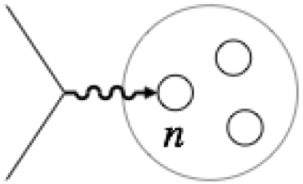
P. Nadel-Turonski, A. Accardi, M. Baker, W. Brooks, R. Dupre, M. Ehrhart, C. Fogler, K. Hafidi, C. Hyde, V. Morozov, K. Park, J. Stukes, A. Sy, T. Toll, G. Wei, L. Zheng

POETIC8, 19–23 March 2018, Regensburg, Germany

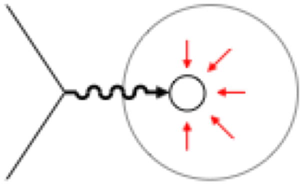
eA physics is a central part of the EIC program

- The EIC will be the first eA collider
- Physics with light and heavy ions will drive the requirements for the near-beam ion / hadron detection

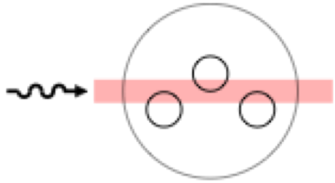
EIC physics opportunities with nuclei



- Neutron structure
  - Flavor decomposition of quark spin, Δg, etc



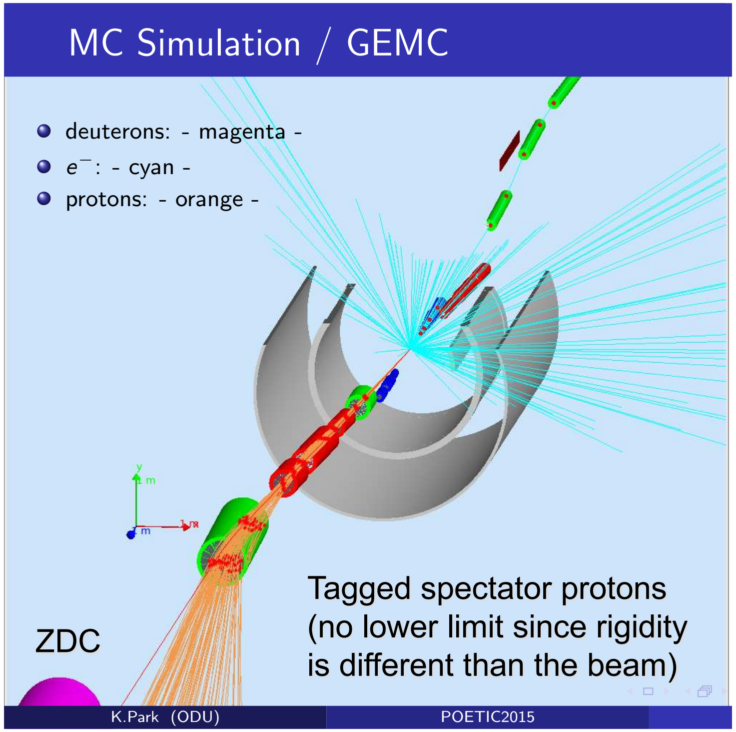
- A bound nucleon in QCD
  - Modification of the quark/gluon structure by the nuclear medium

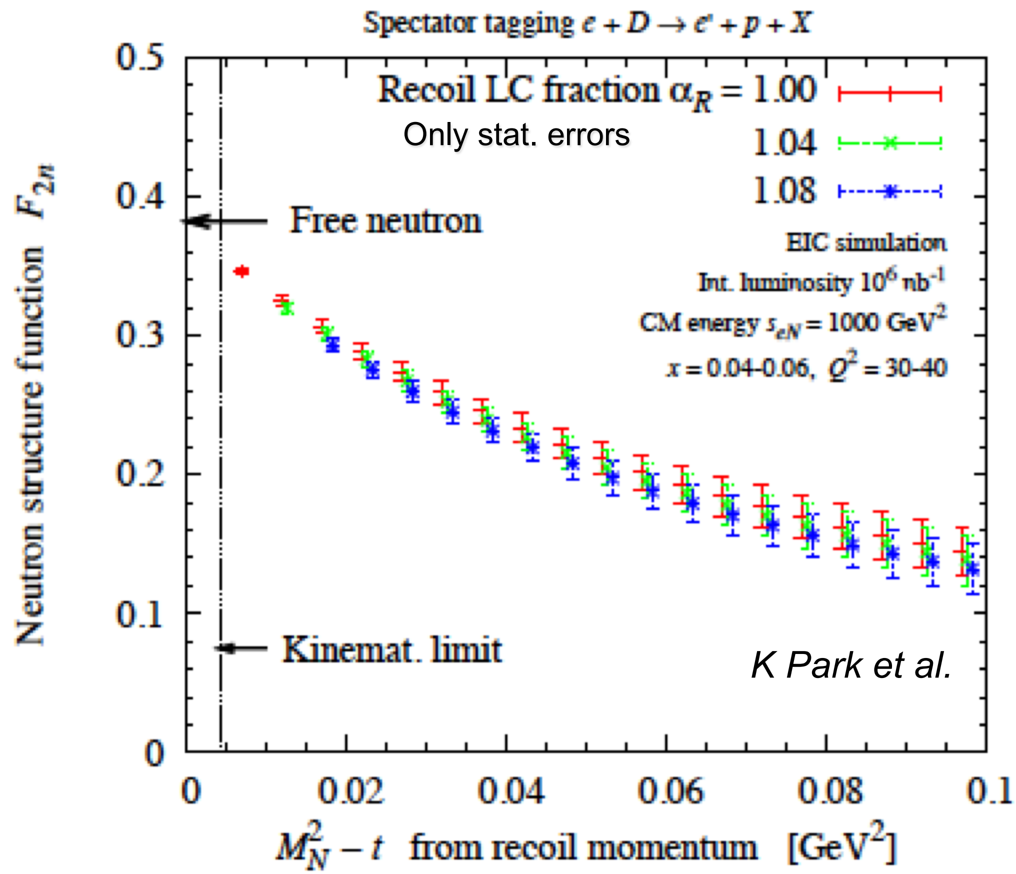


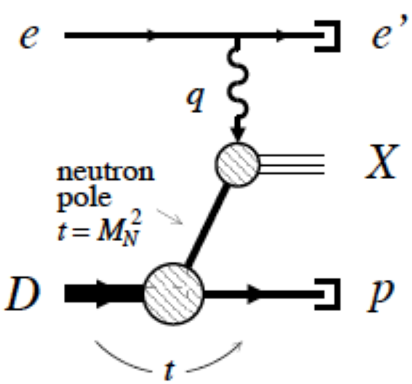
- Coherence and signature of gluon saturation
  - Interaction of a high-energy probe with coherent quark-gluon fields

[Nucleus rest frame view]

Example for light ions: "free" neutron structure at an EIC







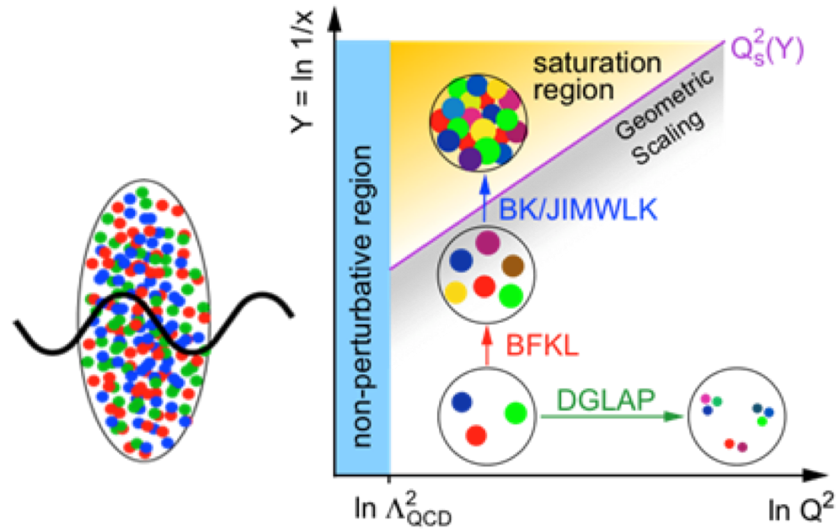
On-shell extrapolation of F_{2n}

- Free neutron at pole. Value not affected by final-state interactions!
- Requires:
  - resolution ~ Fermi momentum
  - acceptance for spectator protons (half beam rigidity + p_T)

Key EIC measurements with heavy nuclei

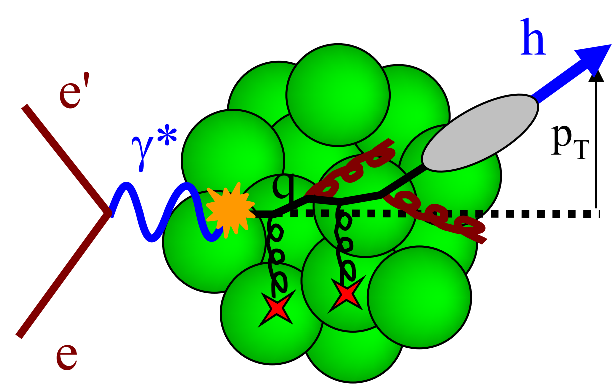
Coherence and gluon saturation

- At low x and Q^2, the probe interacts coherently with all gluons in its path
- The gluon density can be increased by going to lower x (higher cm energy), or increasing the nuclear thickness
  - Heavy nuclei + selection of large path lengths through geometry tagging
  - Extra boost from non-spherical nuclei?



Quark propagation and hadronization

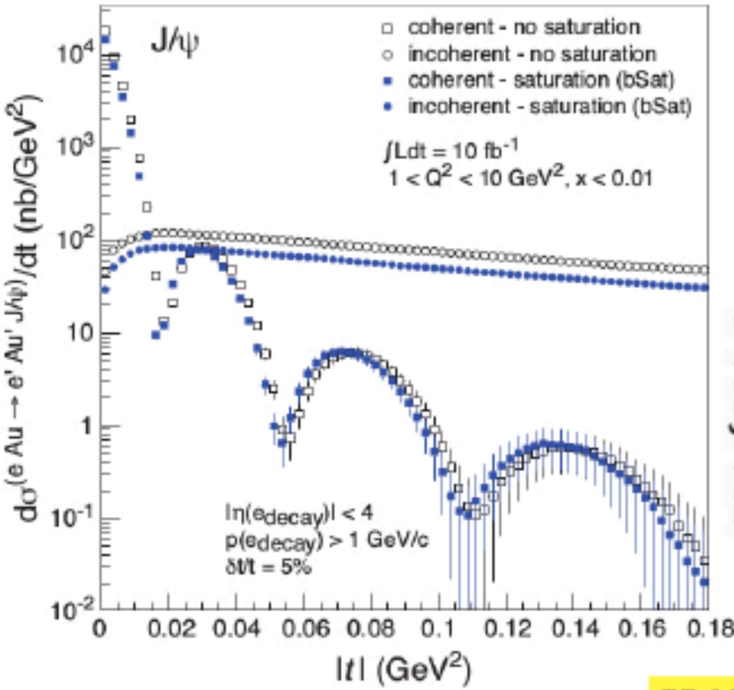
- Knowing the path length will greatly improve our understanding of what happens when a quark propagates through nuclear matter.
  - Energy loss, p_T broadening, etc



Spatial gluon distribution from coherent diffraction

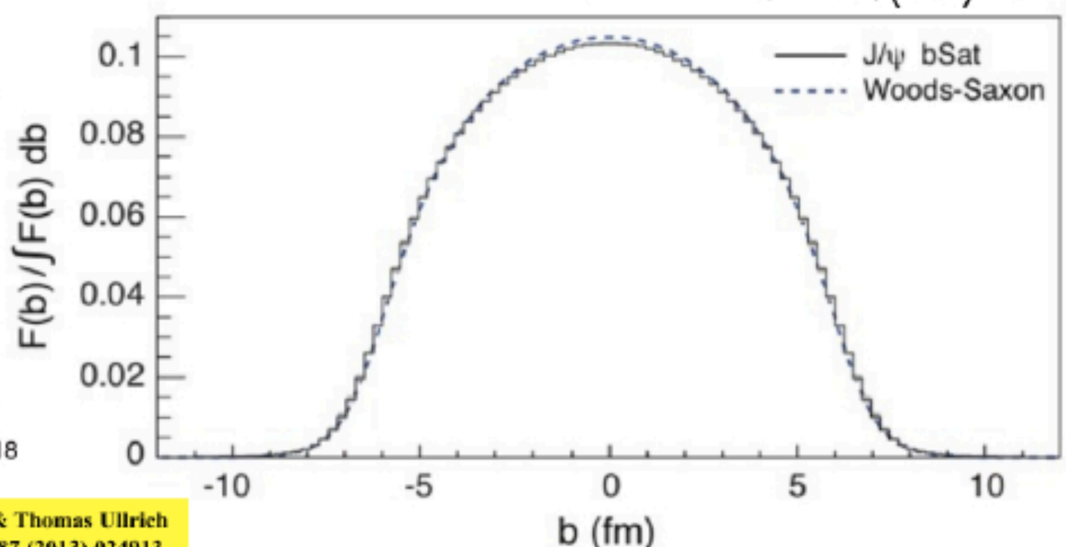
Momentum transfer t conjugate to transverse coordinate b

T. Toll, T. Ullrich



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

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

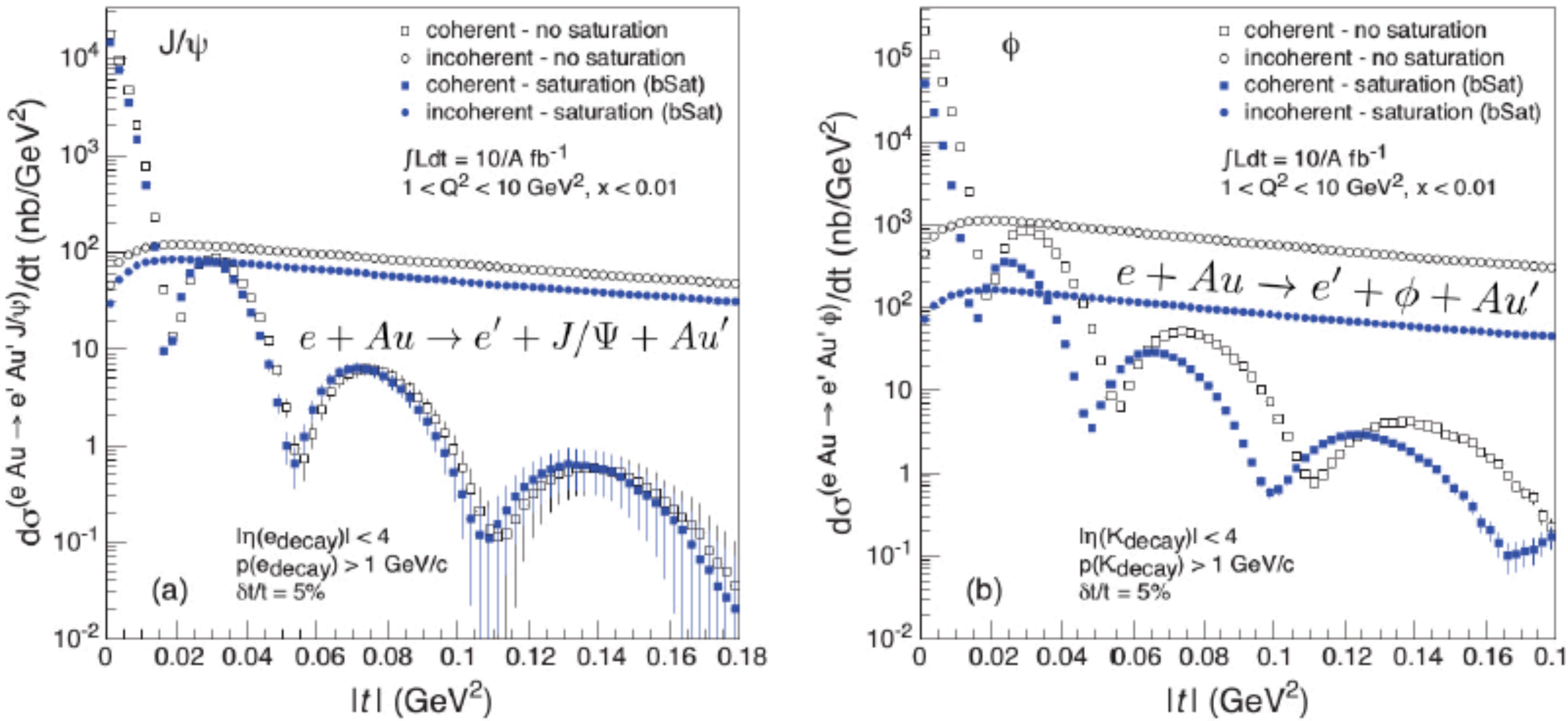


T.T. & Thomas Ullrich
PRC 87 (2013) 024913

Coherent diffraction may be the only way to image the transverse gluon distribution in nuclei, but the incoherent background is large. Veto needed!

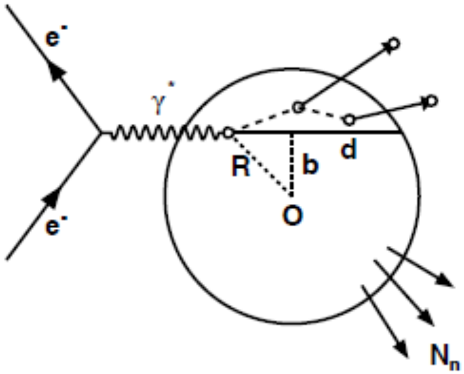
Sensitivity to gluon saturation

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



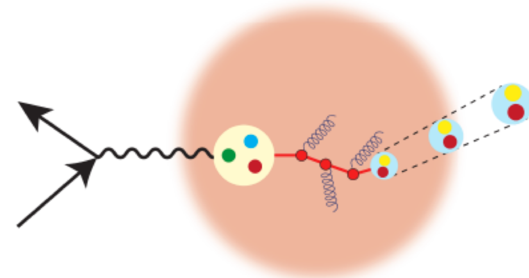
- In addition to providing a transverse spatial image of the gluon distribution, coherent diffraction is also sensitive to gluon saturation
- The (smaller) J/psi shows little sensitivity and can serve as a reference for the (larger) phi, which shows a significant sensitivity to saturation (at moderate Q^2)

Collision geometry reconstructed from final state

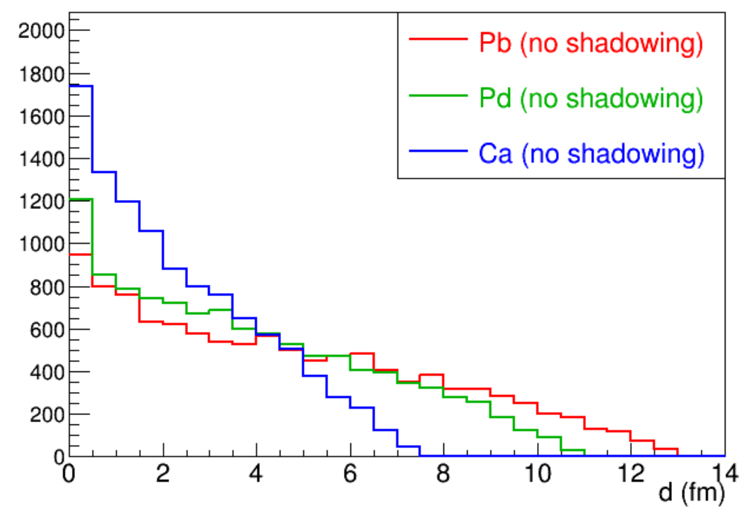


Intra-nuclear cascading increases with d (forward)

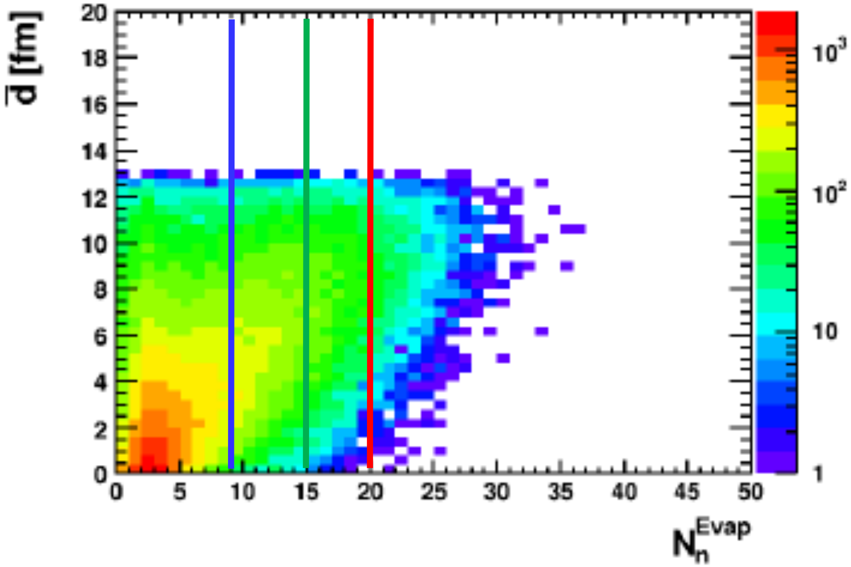
Evaporation of nucleons from excited nucleus (very forward)

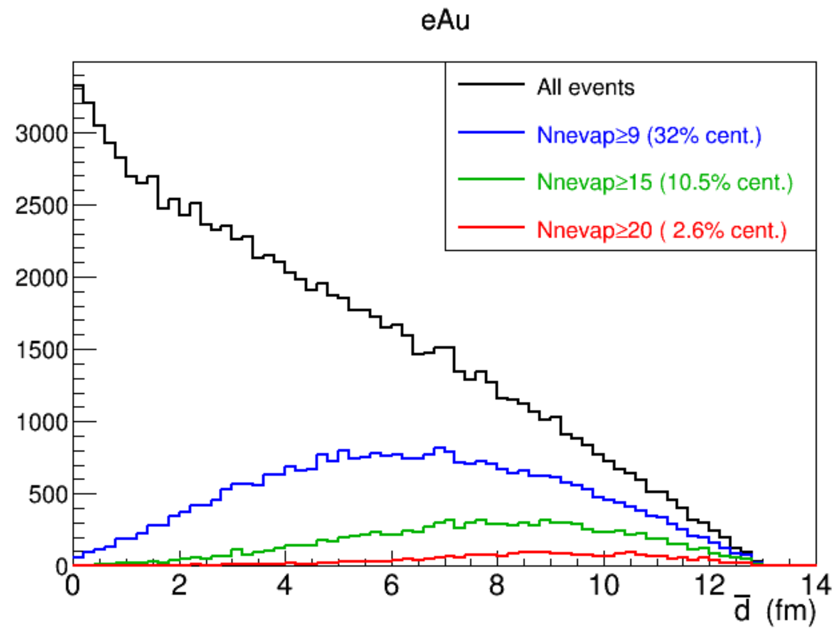


- Geometry tagging allows us to determine the impact parameter *b* and the effective nuclear thickness *T(b)* at lower x, and at higher x the path length *d* in the nucleus after the primary interaction, by detecting the final state
  - Nuclear fragments & particles in ion direction
- Without tagging, the average d in a nucleus scales as the radius ($A^{1/3}$)
  - Plot shows 40 < A < 197
- Tagging allows us to select events for which the average d is very different from that for the entire nucleus



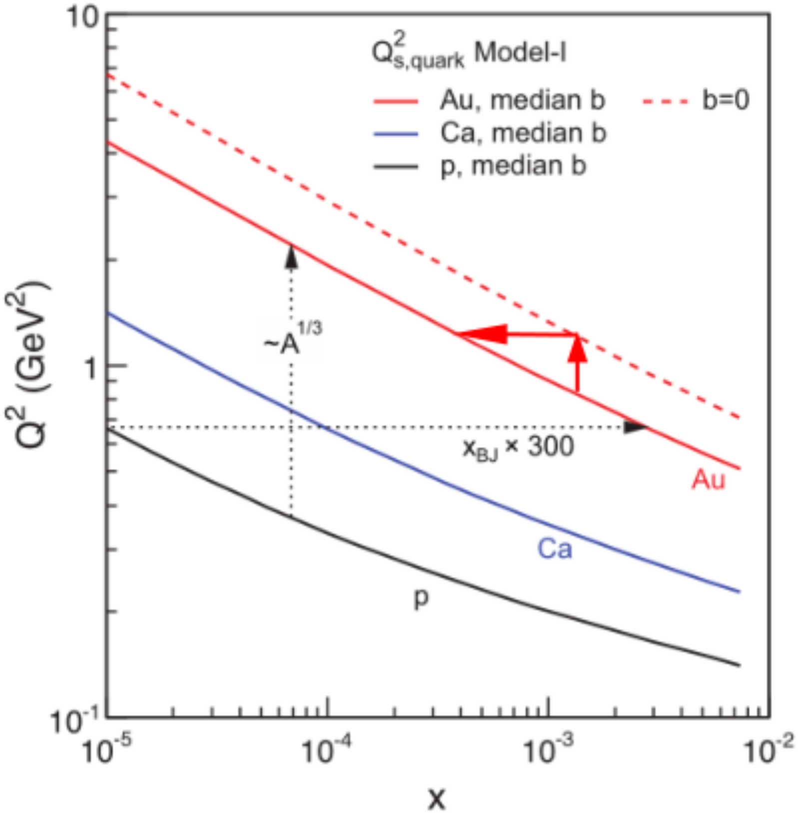
Geometry tagging with evaporation neutrons

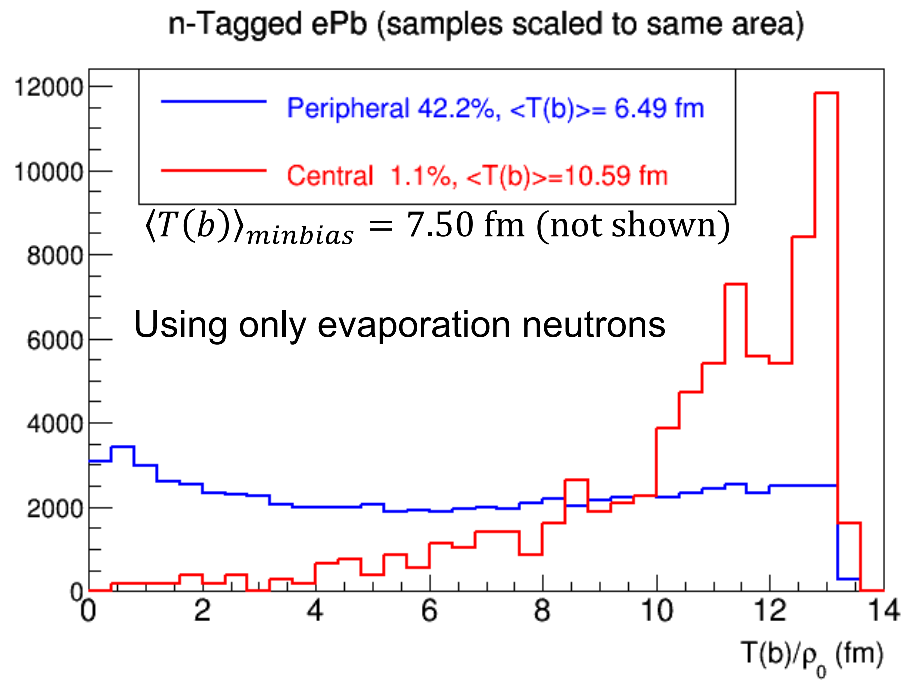




- Geometry tagging using only evaporation neutrons and spherical nuclei has been studied as part of the EIC R&D program (eRD17)
- Selecting higher multiplicities gives, on the average, longer path lengths (at the cost of lower statistics).

Tagging the nuclear thickness increases kinematic reach



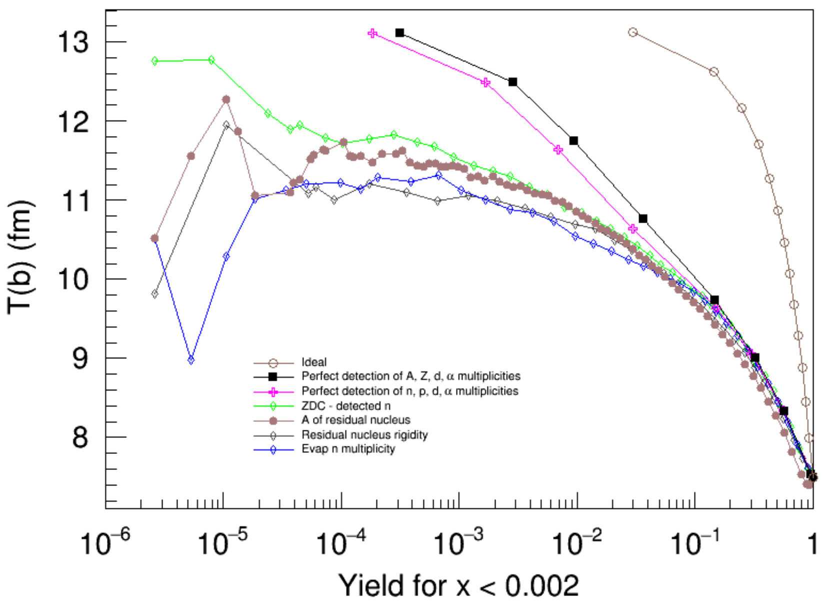


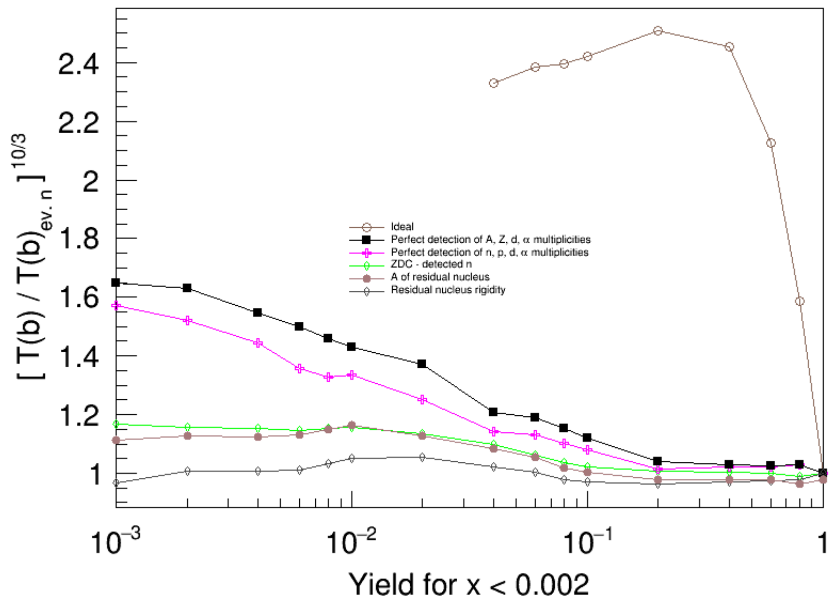
$Q_s^2 \sim A^{1/3} / x^{0.3} \sim T(b) * (E_e E_A)^{0.3}$

$$F_E = \left(\frac{\langle T(b)\rangle_{cent}}{\langle T(b)\rangle_{minbias}}\right)^{10/3} = 3.2$$

- Selecting 1.1% of events with the largest average nuclear thickness (measured by evaporation neutrons only) is equivalent to increasing the accelerator energy by a factor 3.2

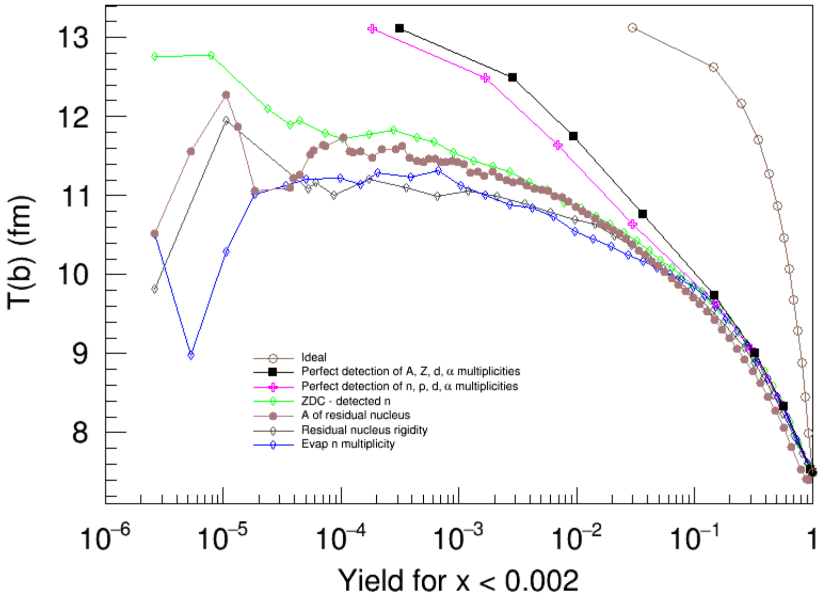
What if we also detect the charged particles?

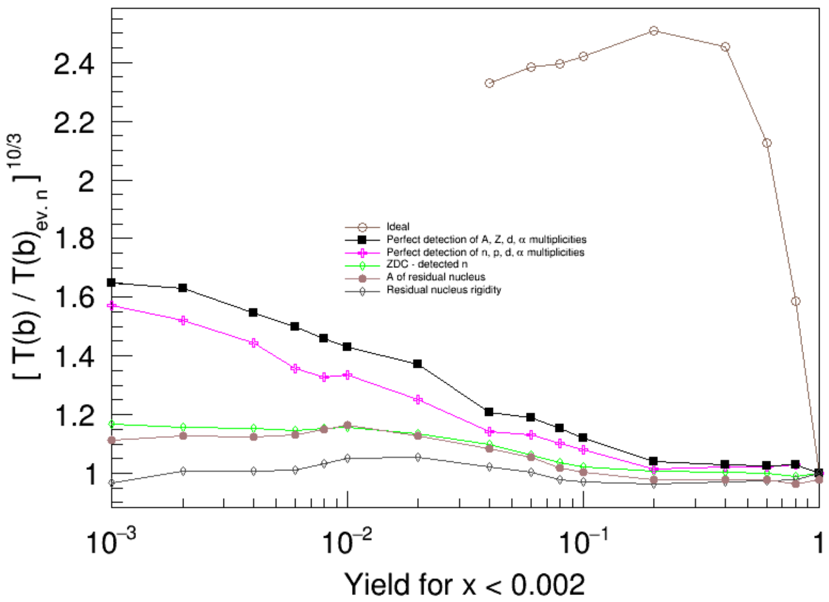




- Detecting protons and light ions (d and ^{4}He) in addition to neutrons increases the selectivity in b and the effective nuclear thickness T(b).
- For a 1% yield cut, the increase in equivalent collision energy is about 40% (magenta curve on the right) compared with using evaporation neutrons only.
- Compared with no geometry tagging, the a total factor is then 4.5

What if we detect the residual ion?

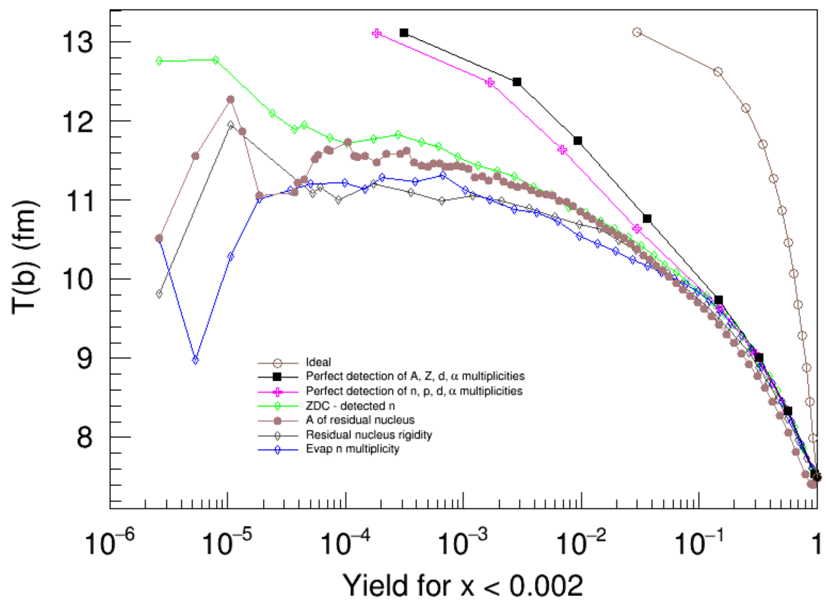


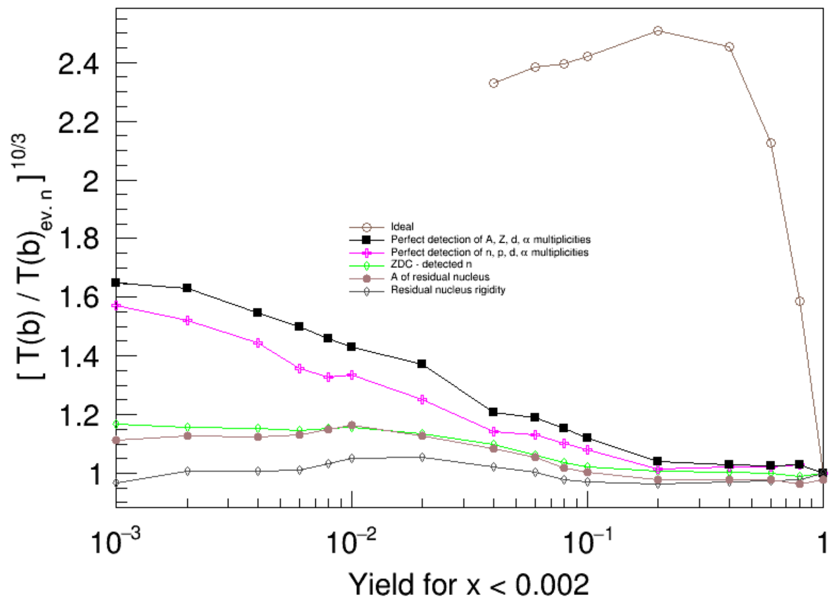


- An alternative method to measuring the evaporation neutrons is to detect the residual nucleus. Measuring its magnetic rigidity (~ A/Z), is straightforward as it changes substantially for nuclei that evaporate many neutrons. Detection extremely close to the beam is not needed.

- Selecting T(b) based only on the rigidity of the scattered ion has about the same selectivity as using evaporation neutrons, but it is easier to precisely detect a single ion than ~20 neutrons in the ZDC.

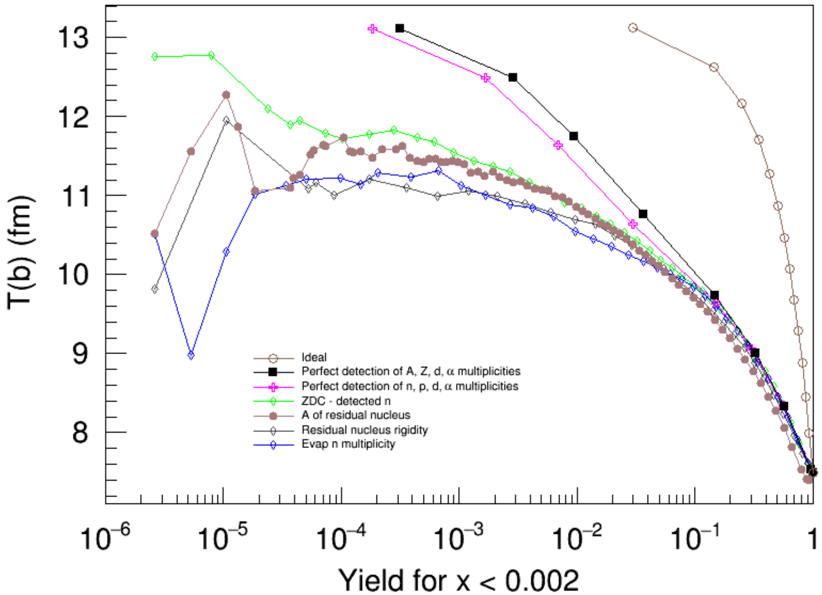
What if we also identify the residual ion?

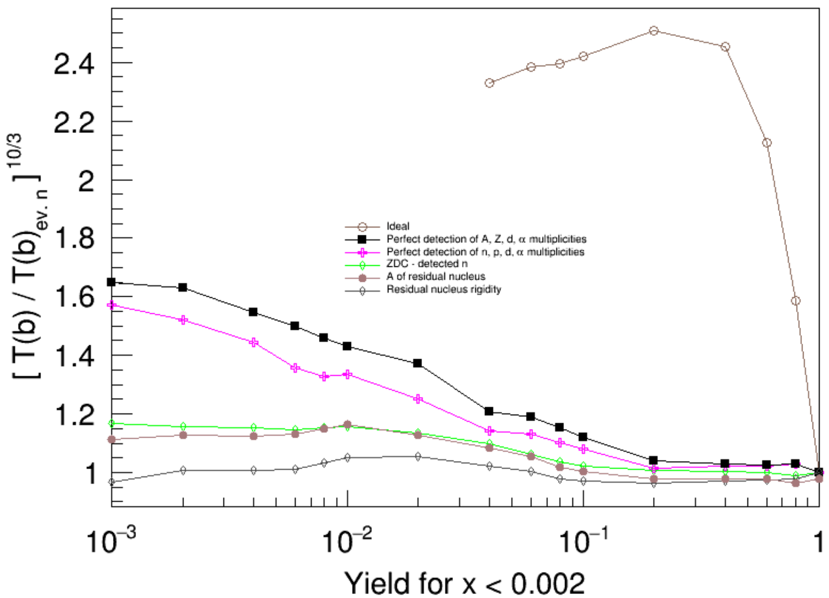




- As in the case of evaporation neutrons, the kinematic reach can be extended by detecting the residual ion together with charged particles.
- The best result can be obtained if one in addition to measuring A/Z also could measure Z and infer A. This would require a PID system for the ion (e.g., additional dE/dx if the dE/dx from the tracker is insufficient)
- Using A, Z, and light ions, one obtains the maximum kinematic reach (black curve). Detection of light ions is straightforward.

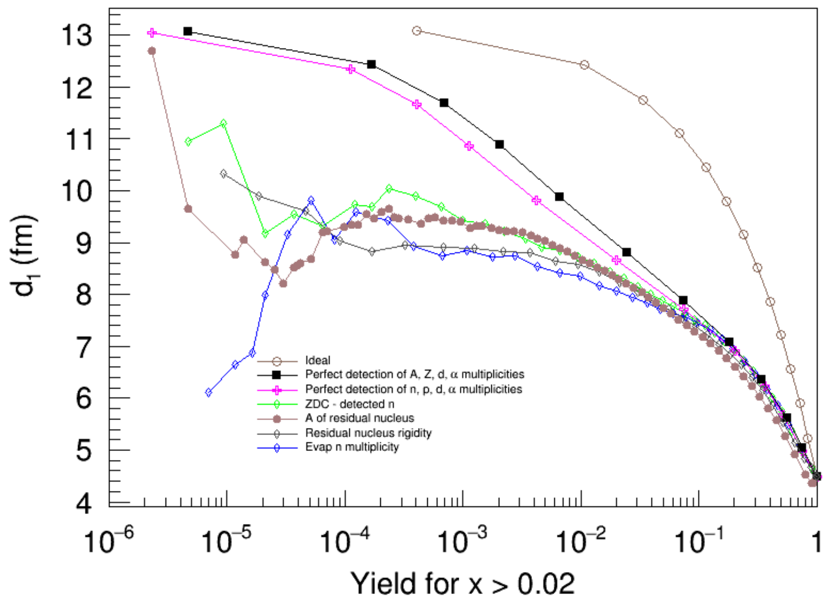
Detection requirements

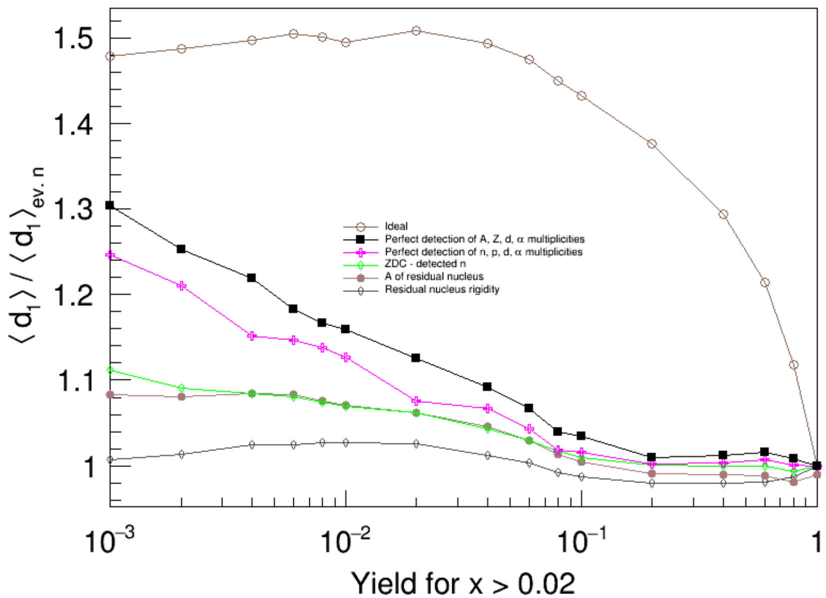




- The best results can be obtained by detecting the residual ion (tracking + dE/dx) and light ions (easy for all except Z = N nuclei).
- A neutron ZDC can provide a useful cross check but is not critical.
- If one nevertheless wants to rely on neutrons, it is beneficial to detect not only the neutrons and light ions but also the protons. The latter requires larger magnet apertures as the protons bend more in the magnetic field, but it is required for spectator tagging with light nuclei

Tagging of the path length d at higher x



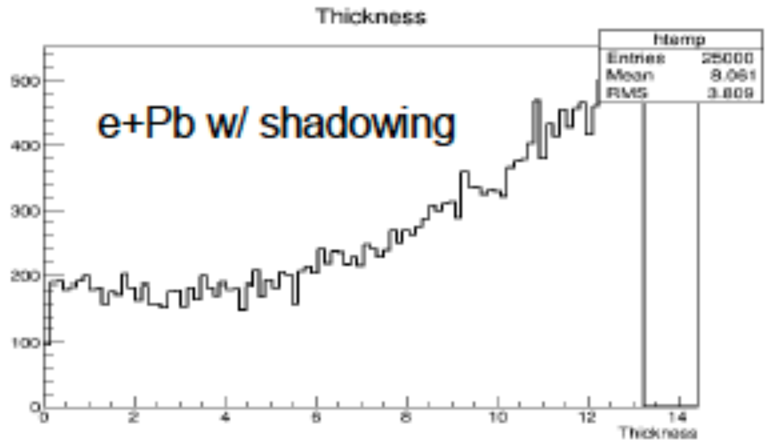


- For quark propagation and hadronization studies, it is more important to know the path length than to maximize it, but the plots for d above illustrate the sensitivity. Binning for different values of average d is straightforward.

- The same detection criteria apply

Further increasing the effective thickness: ^{208}Pb vs ^{238}U

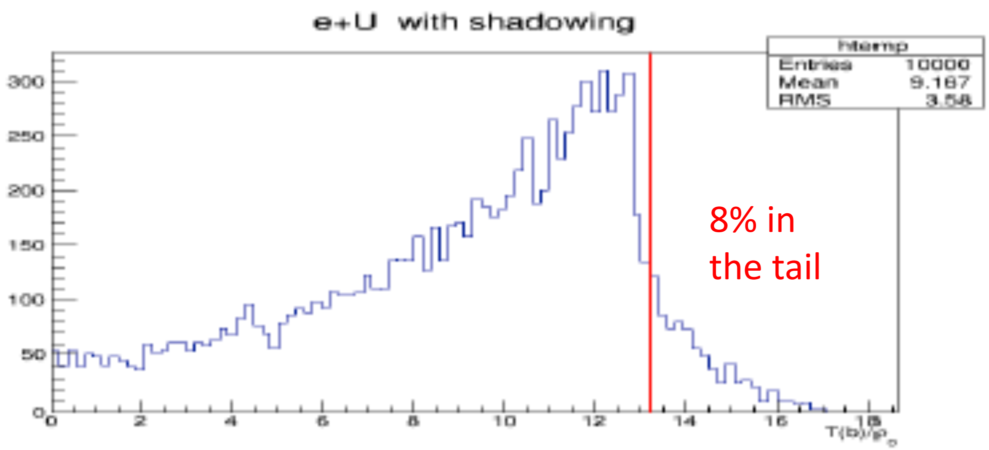
M. Baker, 2017

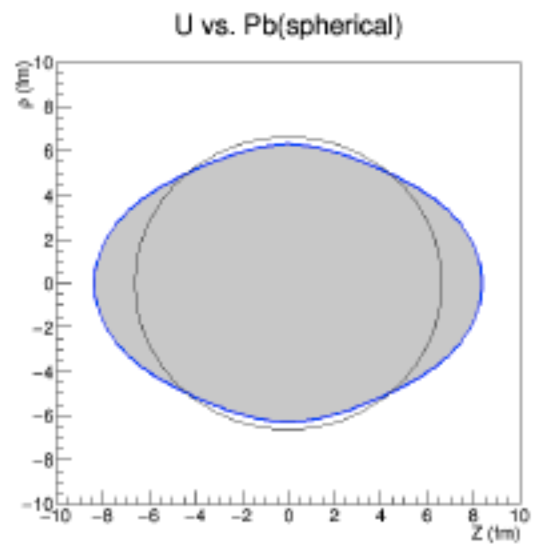


$T(b)$ = thickness in nucleons/fm^2

ρ_0 = Pb density 0.17 nucleons/fm^3

T/ρ_0 is effective-Pb thickness in fm

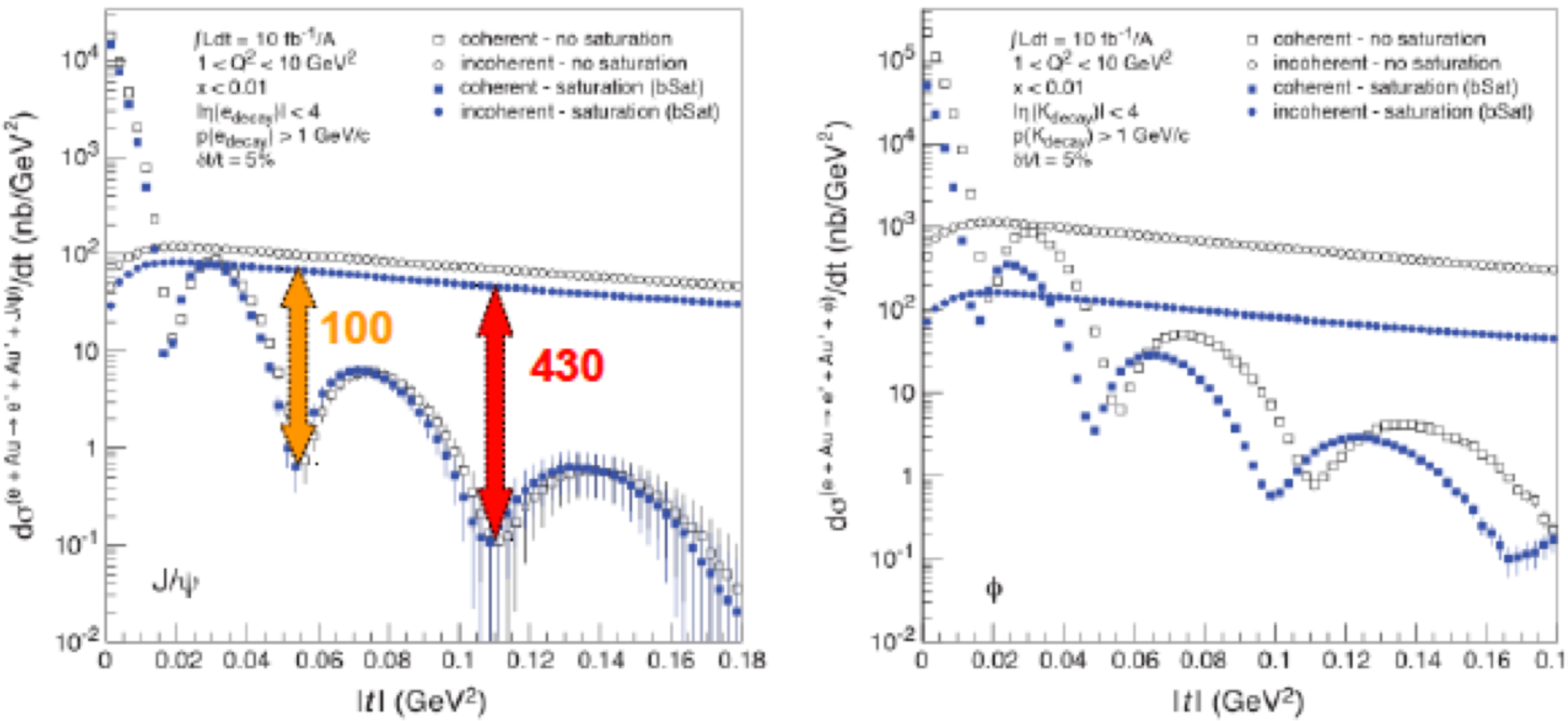




- e on U is easier than U on U since only one axis needs to be aligned
- Study not yet finished, but large tail suggest a significant improvement

Coherent nuclear diffraction

M. Baker, 2017

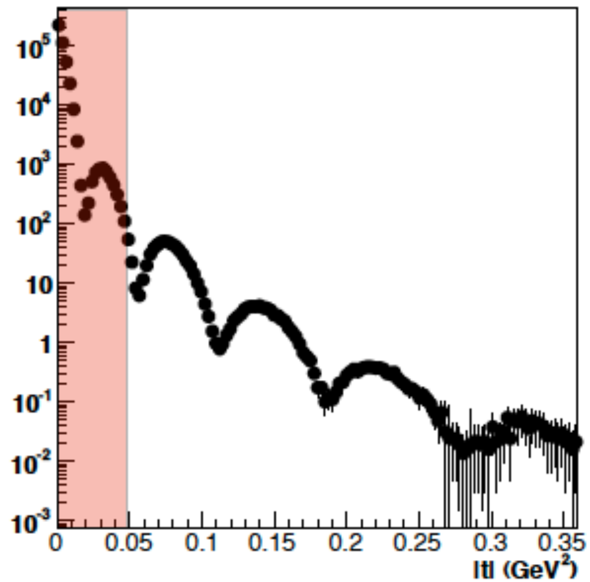


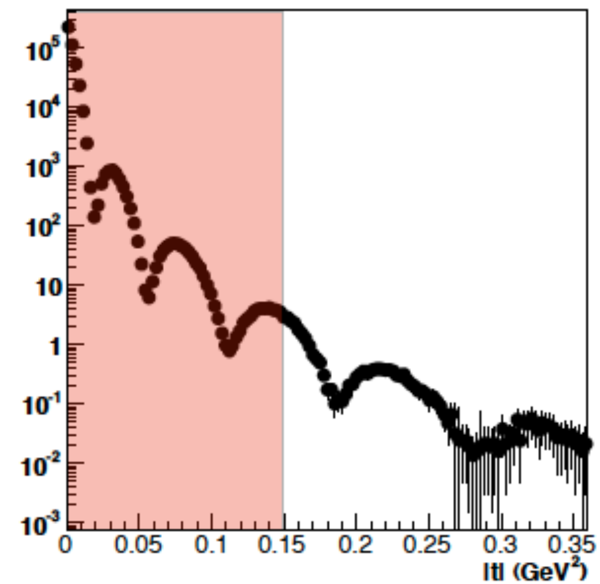
- The challenge for coherent diffraction is not to increase the kinematic reach by using geometry tagging or deformed nuclei or, but to suppress the incoherent backgrounds by vetoing with high efficiency any outgoing particles indicating a breakup of the nucleus. This requires a combination of detection methods.
- Signal-to-noise of 2:1 at the 3rd dip requires a veto efficiency of 99.9%.

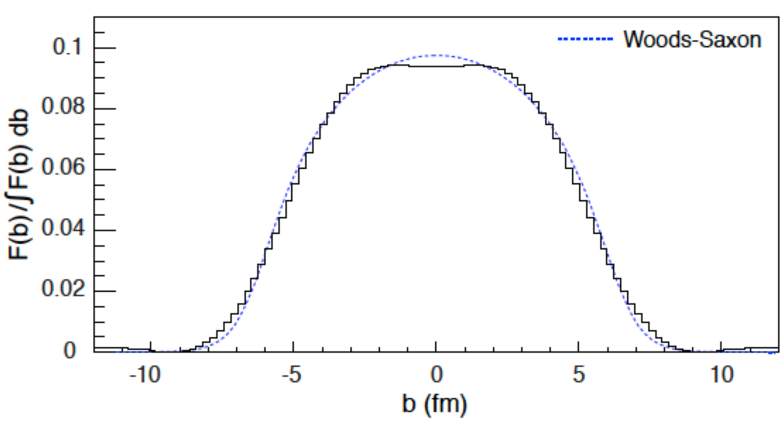
How far in t do we need to measure?

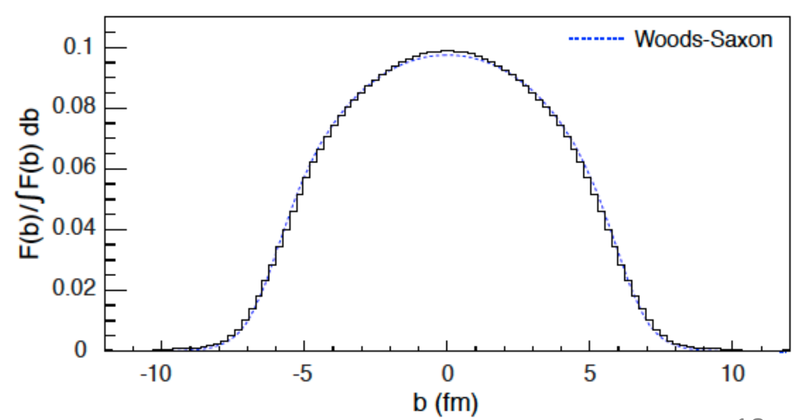
T. Ullrich, T. Toll

Fourier: large t ⇔ small b





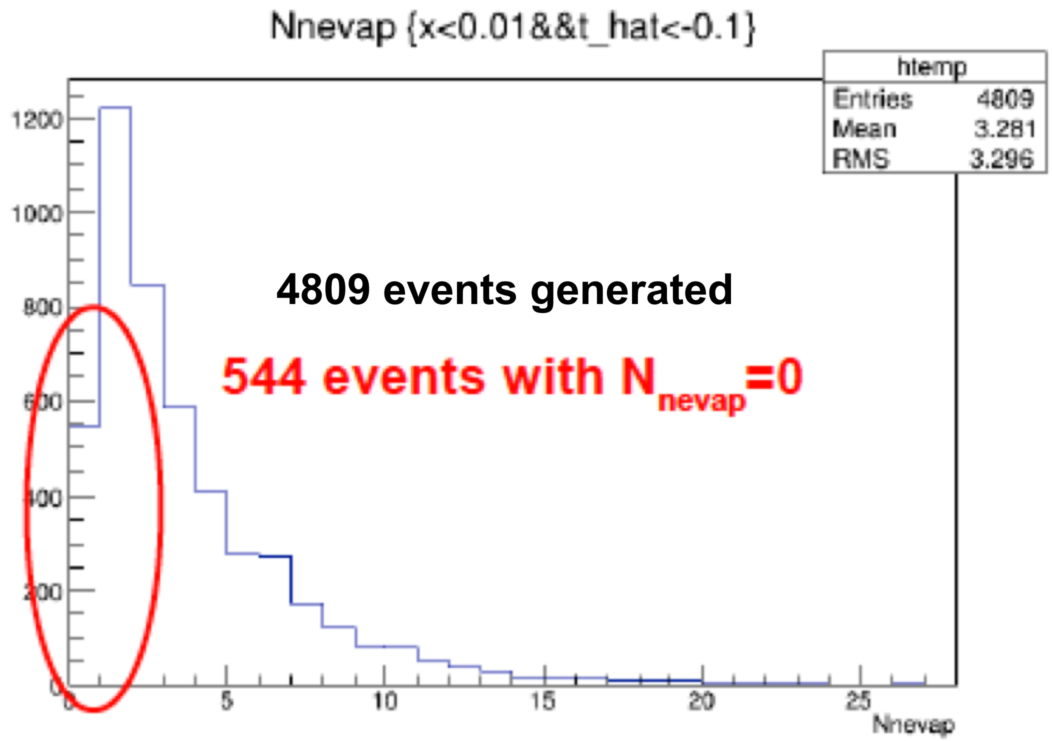




First look at a veto for incoherent diffraction

M. Baker, 2017

Exclusive vector meson incoherent diffraction for 10x40 GeV ePb in BeAGLE



Sample included any vector meson (J/psi, phi, rho, omega)

τ_0=9 fm

$\sigma_{dipole}=<\sigma(J/\psi)>_{Sartre}$=5.7 mb

$P(N_n=0)$=11.3%

ε_{veto}=88.7%

Rej.Factor ~ 9

- Even assuming that a ZDC can detect and count neutrons with 100% efficiency, the rejection factor using a ZDC alone is two order of magnitudes too low, since a significant fraction of the incoherent background events does not have an evaporation neutron.

Adding detection of A-1 nuclei (very near beam)

544/4809 events w/ N_{nevap}=0, t<-0.1

Beam Remnant	Z=80 Hg	Z=81 Tl	Z=82 Pb	Z=83 Bi
A=208		1 Tl-208	**6** **Pb-208**	3 Bi-208
A=207	1 Hg-207	**303** **Tl-207**	**226** **Pb-207**	
A=206	1 Hg-206	3 Tl-206		

- Out of the 544 events where proton or neutron was knocked out but not evaporated, detecting the residual nucleus leaves only 6 ambiguous events where a nucleon was struck, but reabsorbed.
- This corresponds to a rejection factor of 6/4800 = 802,
or a veto efficiency of 99.9%

Detection requirements for coherent diffraction

Detection of A-1 nuclei

- Detection of the residual nuclei, including ones that only lose one proton or neutron (rigidity change of 0.5%) allows to reach the desired veto efficiency. Identification of the ions is not needed.
- Incorporating a far-forward spectrometer for very low p_T ions (equivalent to a 0.5% change in rigidity) into the collider design is highly beneficial.

A ZDC is necessary but not sufficient to suppress backgrounds

- Even with perfect detection, a ZDC would not provide a veto efficiency for neutrons that is high enough to suppress the incoherent backgrounds. But it is important for achieving the desired S:N with realistic detectors

Photon detection

- Detection A-1 nuclei and photons from nuclear de-excitations can possibly further improve the S:N ratio. Using only photons and the ZDC would be more challenging considering the backgrounds

Detection requirements for light and heavy ions

Light Ions (LI)

- Need to detect spectator nucleons over a wide range in p_T and rigidity (a spectator proton from deuterium has half the rigidity of the beam, in addition to any p_T it picks up from the interaction).
- Need good resolution for spectator to suppress final-state interactions

Heavy Ions (HI)

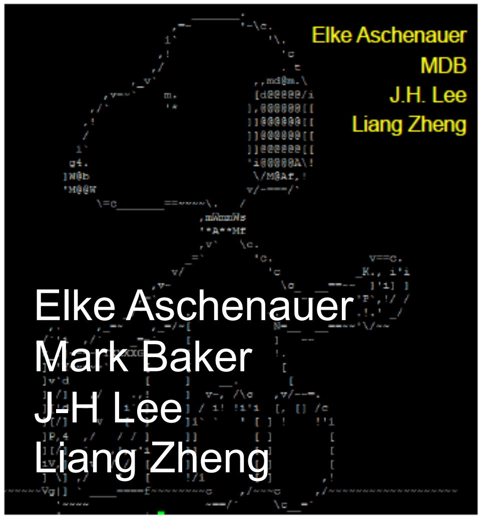
- Need to detect protons and light ions, but the resolution and high-p_T acceptance is driven by tagging requirements for light ions.
- Detection of the residual ions, preferably with PID (determination of A), is important for extending the effective kinematic reach of the EIC.
- Near-beam detection (w/o PID) of A-1 nuclei can provide a sufficient veto efficiency for studying coherent diffraction

LI+HI define the forward detection requirements (DVCS is a subset)

Event generators and simulations

BeAGLE

Benchmark **eA** **G**enerator for **LE**ptoproduction



26-June-2017

Sartre

Exclusive diffractive vector meson production and DVCS in *ep* and *e*A collisions based on the dipole mode

Tobias Toll
Thomas Ullrich
Pia Zurita
Heikki Mäntysaari

Talk by M. Baker on Friday at 17:15

We also want to thank M. Ungaro for adding support for the event generator formats in the GEMC (Geant4) package.

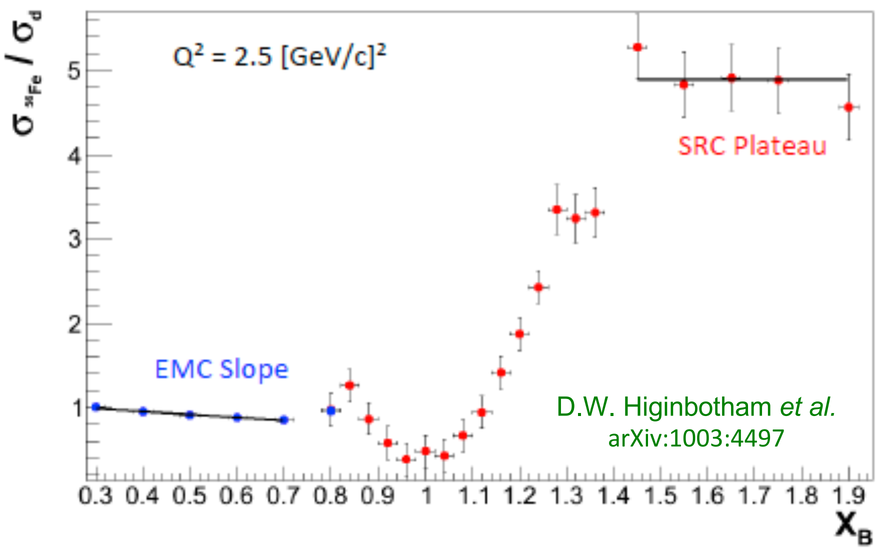
2018-LDRD-4: Geometry Tagging for Heavy Ions at JLEIC (Continuation of 2017-LDRD-6)

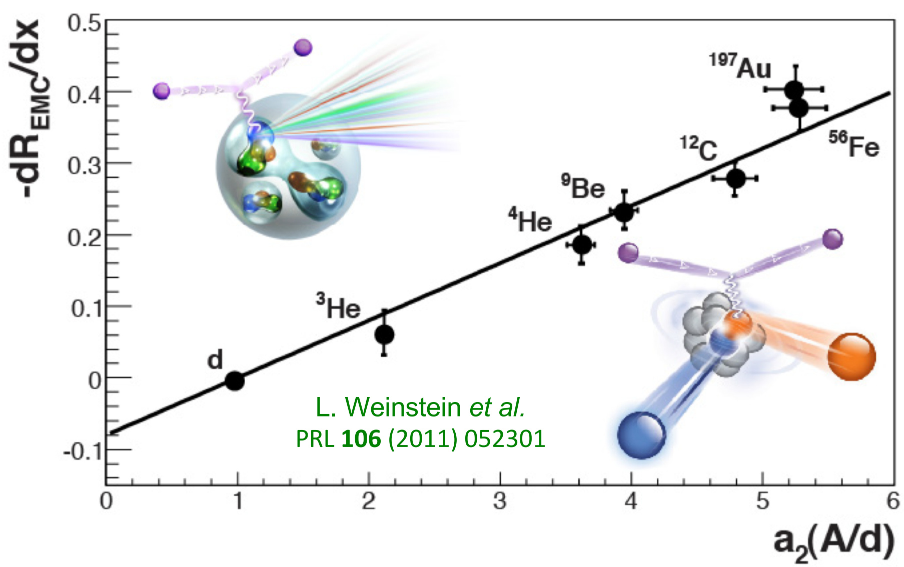
A. Accardi, M. Baker, W. Brooks, R. Dupre, M. Ehrhart, C. Fogler, K. Hafidi, C. Hyde, V. Morozov (PI), P. Nadel-Turonski, K. Park, T. Toll, G. Wei, L. Zheng

JLab LDRD Public Review Session

June 28, 2017

Next steps: SRCs and the in-medium nucleon?





- Short-range nucleon correlations (SRCs) in nuclei are responsible for the high-momentum tail not described by mean-field models
- SRCs sometimes give partons a momentum fraction x > 1, *i.e.*, more than that of a nucleon
- SRCs are strongly correlated with the EMC effect:
  - EMC slope of the cross section ratio
  - vs. mass ratio (scaled density)
- Can detecting the final state at an EIC help us understand the FSI in heavy nuclei?

Summary and Outlook

- By selecting 1% of events with the smallest impact parameter, geometry tagging can enhance the effective nuclear thickness by an amount equivalent to more than a five-fold increase in the accelerator energy. This increase in kinematic reach is important for studies of gluon saturation in heavy nuclei.
- For coherent diffraction, a sufficient suppression of incoherent backgrounds can be achieved through detection of nuclear fragments and residual (A-1) nuclei.
- Requirements for near-beam detection are driven by eA physics.

Thank you!

Backup

Energy Impact Factor

$Q_s^{\,2} \sim A^{1/3}/x^{\lambda}$ $\lambda \sim 0.3$

$A_{eff}^{\,1/3} \sim T(b)$ $x \sim Q^2/(ys)$ $s/A \sim 4E_eE_A/A$

$Q_s^{\,2} \sim T(b)*(E_eE_A)^{0.3}$

$<T(b)>_{cent}/\rho_0 = 10.71$ fm $<T(b)>_{minbias}/\rho_0 = 7.52$ fm

$$E_{enhancement} \sim [T(b)_{cent}/T(b)_{minb}]^{10/3}$$
$$\sim [10.62 / 7.52]^{10/3}$$
$$\sim \mathbf{3.2!}$$