Probing SRC via deuteron breakup at an EIC

Kong Tu

BNL

09.25.2019

Short-Range Correlations

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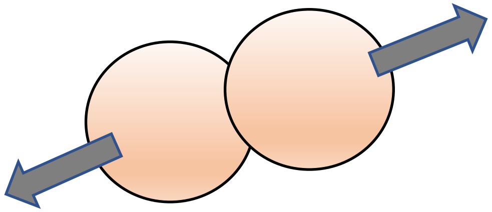
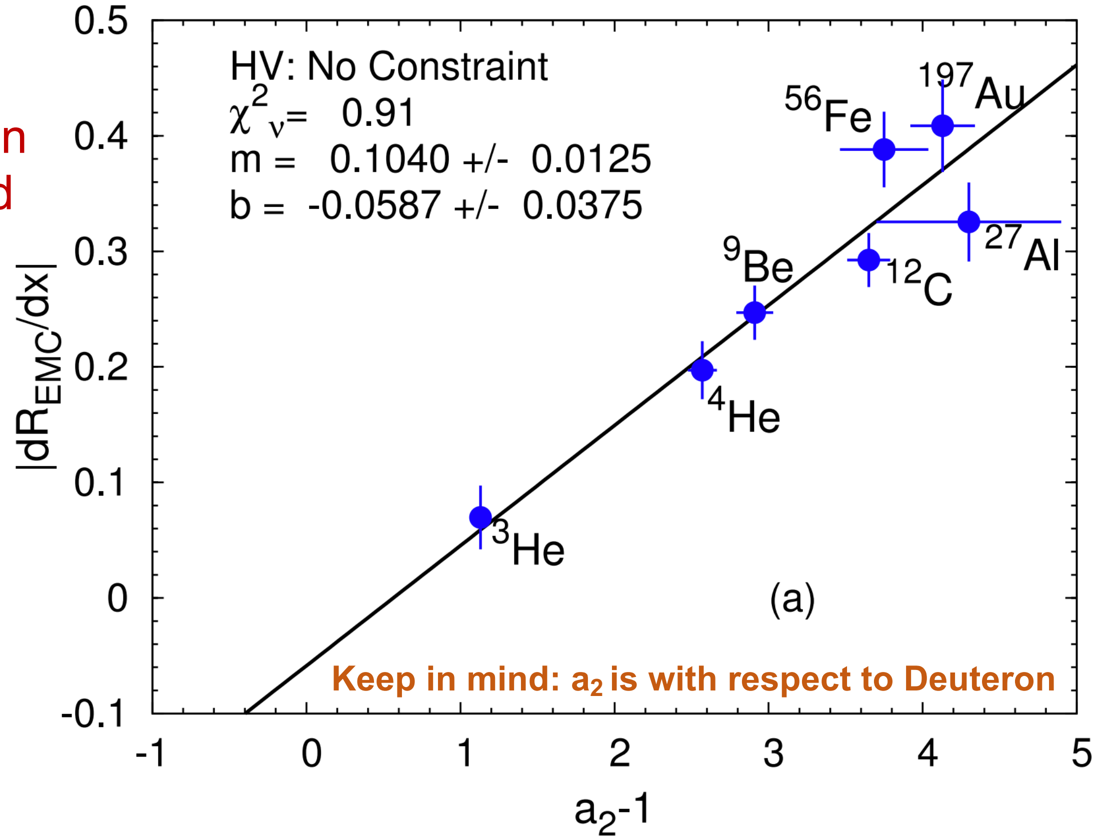
- What is Short-Range Correlations, aka, **SRC**?
  - Nucleon-Nucleon interaction at very short distance;
  - *High momentum nucleon* in the nucleus rest frame; a small fraction of the cross section, but could impact many aspects of nuclear effects.
  - pp, pn, nn pairs.



EMC vs SRC

How much nucleon PDF gets modified



Effect of nuclear density?

How strong (many) the SRCs (pairs) are

(e.g., the probability of selecting a pair of SRC nucleons in A)

A strong correlation between the two effects

One hypothesis

- SRC is the ultimate cause of the EMC effect.
    - Experiments (Jlab) have shown it is an universal ~20% of nucleons are in SRC pairs, starting from A > 12.

    - These SRC pairs have high momentum (e.g., > 400-600 MeV/c), and spatially very close to each other.
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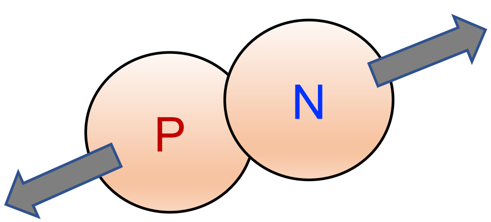
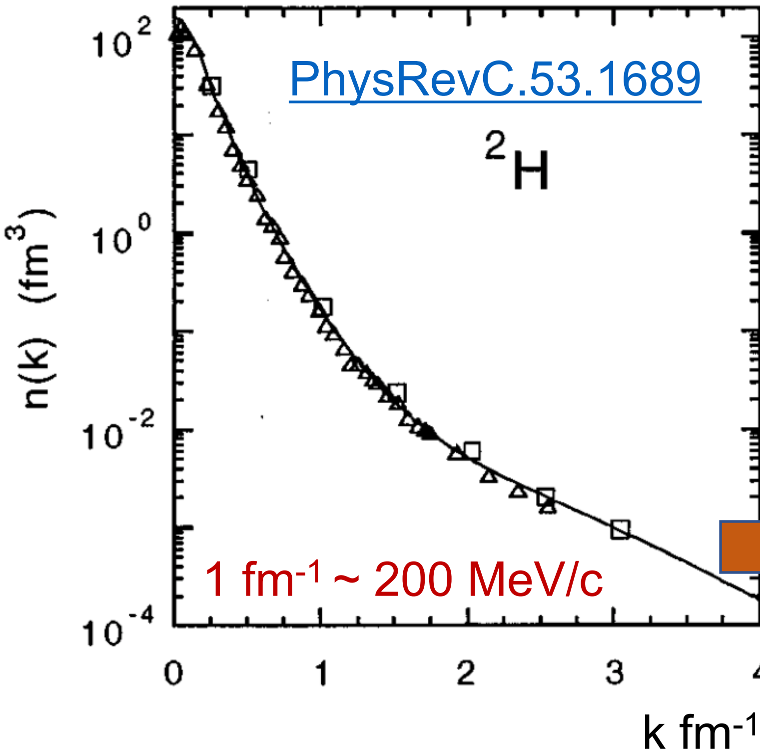
  - Almost all (>90%) of these SRC pairs are found to be similar to a quasi-deuteron at its high momentum tail.

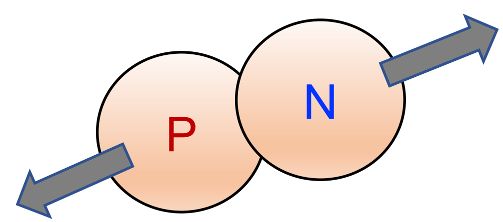


➢ How well do we understand the baseline, **deuteron**?
➢ "Simplest" SRC pair to be studied.

Deuteron – a “simple” pn system



- Deuteron n(k) distributions have been measured decades ago, via inclusive scattering measurements
- k > 2-3 fm^{-1} it is the high momentum tail region, or SRC region



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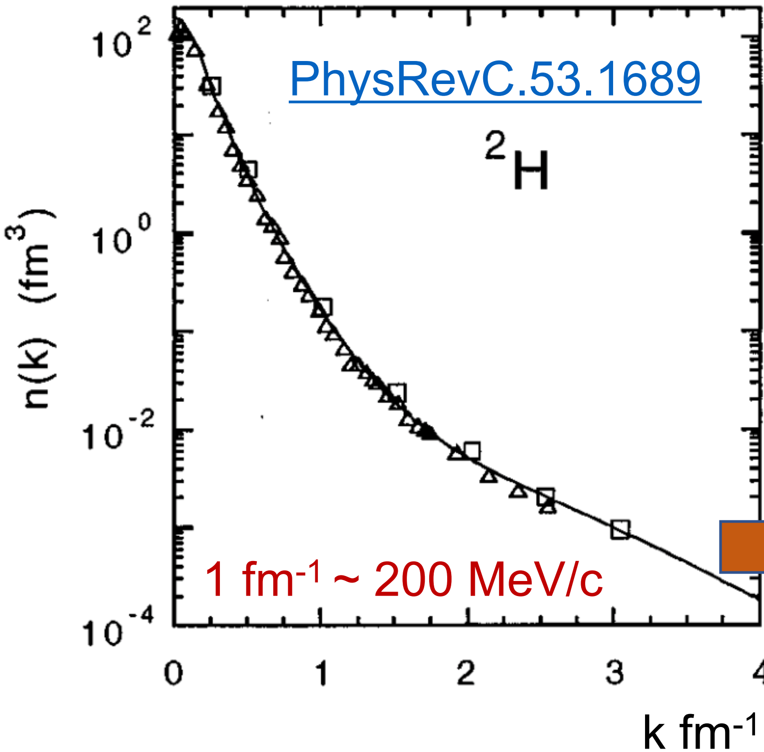

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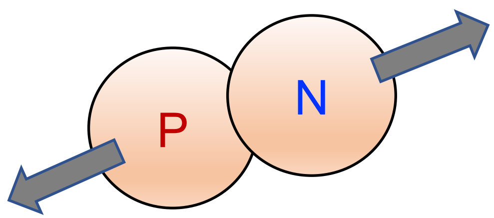


In order to understand the whole SRC picture, the baseline needs to be clear:

- What is the NN potential at high k?
- What are the dynamics at such short distance? Quarks exchange? **Gluons** exchange? Different potential via different processes?
- Are those nucleons PDF modified?

What can we do using Deuteron?

“Diplon” disintegration

First deuteron disintegration measurement in history

A ‘Nuclear Photo-effect’: Disintegration of the Diplon by γ-Rays

By DR. J. CHADWICK, F.R.S., and M. GOLDHABER

BY analogy with the excitation and ionisation of atoms by light, one might expect that any complex nucleus should be excited or ‘ionised’, that is, disintegrated, by γ-rays of suitable energy. Disintegration would be much easier to detect than excitation. The necessary condition to make disintegration possible is that the energy of the γ-ray must be greater than the binding energy of the emitted particle. The γ-rays of thorium C″ of $h\nu = 2{\cdot}62 \times 10^6$ electron volts are the most energetic which are available in sufficient intensity, and therefore one might expect to produce disintegration with emission of a heavy particle, such as a neutron, proton, etc., only of those nuclei which have a small or negative mass defect; for example, D^2, Be^9, and the radioactive nuclei which emit α-particles. The emission of a positive or negative electron from a nucleus under the influence of γ-rays would be difficult to detect unless the resulting nucleus were radioactive.

Heavy hydrogen was chosen as the element first to be examined, because the diplon has a small mass defect and also because it is the simplest of all nuclear systems and its properties are as important in nuclear theory as the hydrogen atom is in atomic theory. The disintegration to be expected is

$$_1D^2 + h\nu \rightarrow {_1H^1} + {_0n^1} \quad \ldots\ldots\ldots (1).$$

Since the momentum of the quantum is small and the masses of the proton and neutron are nearly the same, the available energy, $h\nu - W$, where W is the binding energy of the particles, will be divided nearly equally between the proton and the neutron.

strong γ-ray of thorium C″), the mass of the neutron must lie between $1{\cdot}0058$ and $1{\cdot}0086$; if the γ-ray of radium C of $1{\cdot}8 \times 10^6$ electron volts is ineffective, the mass of the neutron must be greater than $1{\cdot}0077$. If the energy of the protons liberated in the disintegration (1) were measured, the mass of the neutron could be fixed very closely. A rough estimate of the energy of the protons was deduced from measurements of the size of the oscillograph kicks in the above experiments. The value obtained was about 250,000 volts. This leads to a binding energy for the diplon of $2{\cdot}1 \times 10^6$ electron volts, and gives a value of $1{\cdot}0081$ for the neutron mass. This estimate of the proton energy is, however, very rough, and for the present we may take for the mass of the neutron the value $1{\cdot}0080$, with extreme errors of $\pm\, 0{\cdot}0005$.

Previous estimates of the mass of the neutron have been made from considerations of the energy changes in certain nuclear reactions, and values of $1{\cdot}007$ and $1{\cdot}010$ have been derived in this way[2,3]. These estimates, however, depend not only on assumptions concerning the nuclear processes, but also on certain mass-spectrograph measurements, some of which may be in error by about $0{\cdot}001$ mass units. It is of great importance to fix accurately the mass of the neutron and it is hoped to accomplish this by the new method given here.

Experiments are in preparation to observe the disintegration of the diplon in the expansion chamber. These experiments should confirm the nuclear process which has been assumed, and therewith the assumption that the diplon consists

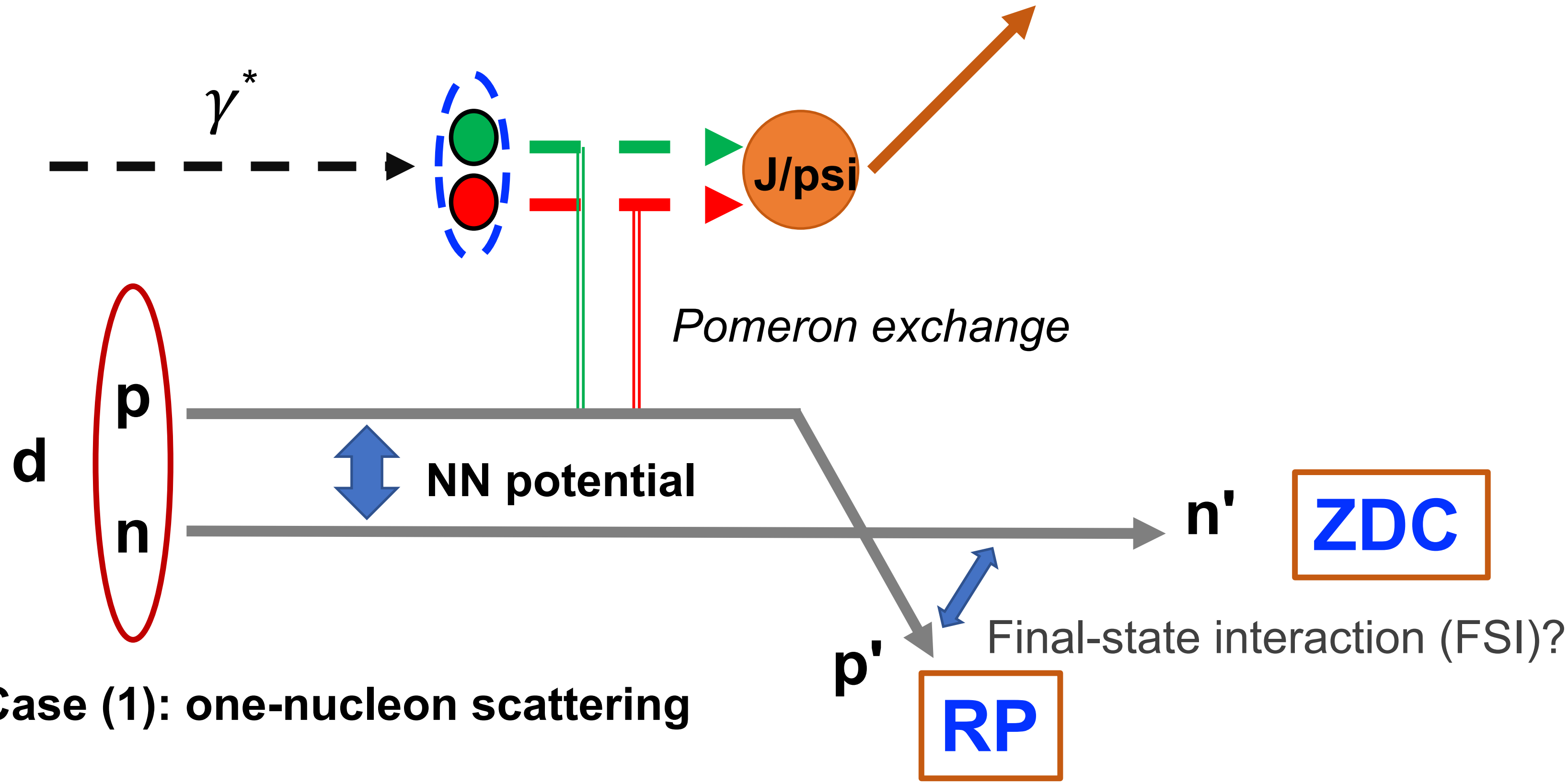
Maurice Goldhaber

James Chadwick

There are still unknowns!

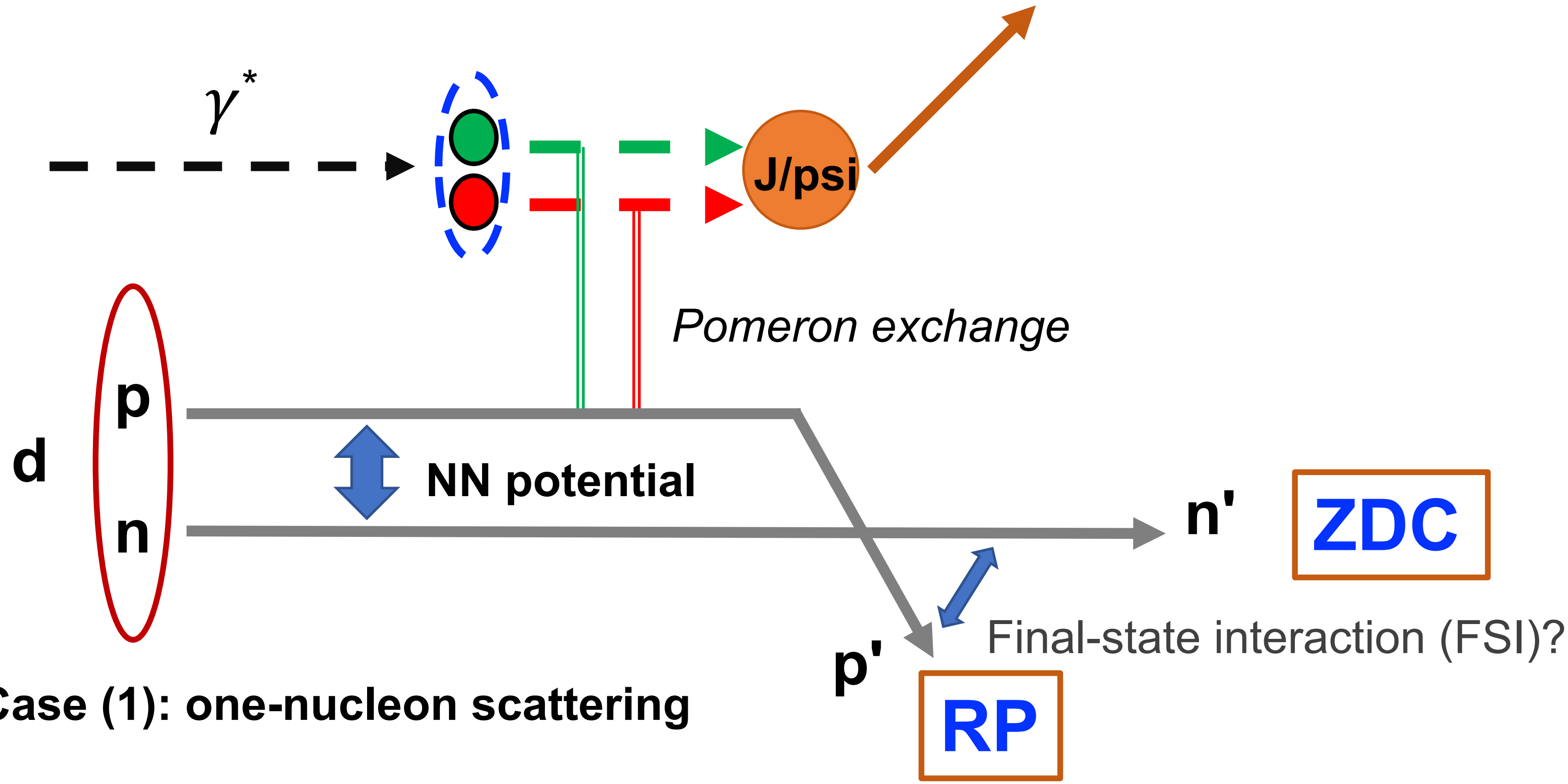
80-90 years later, we could continue to measure “Diplon” breakups

(1) Diffractive VM production



Case (1): one-nucleon scattering

(1) Diffractive VM production



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Experimentally, we are looking for signatures, e.g.,

1) p_T balance between proton (or neutron) and the q - Jpsi
2) Coincidence with a spectator nucleon, e.g., ZDC neutron
3) Need neutron's energy and position to obtain four-momentum.

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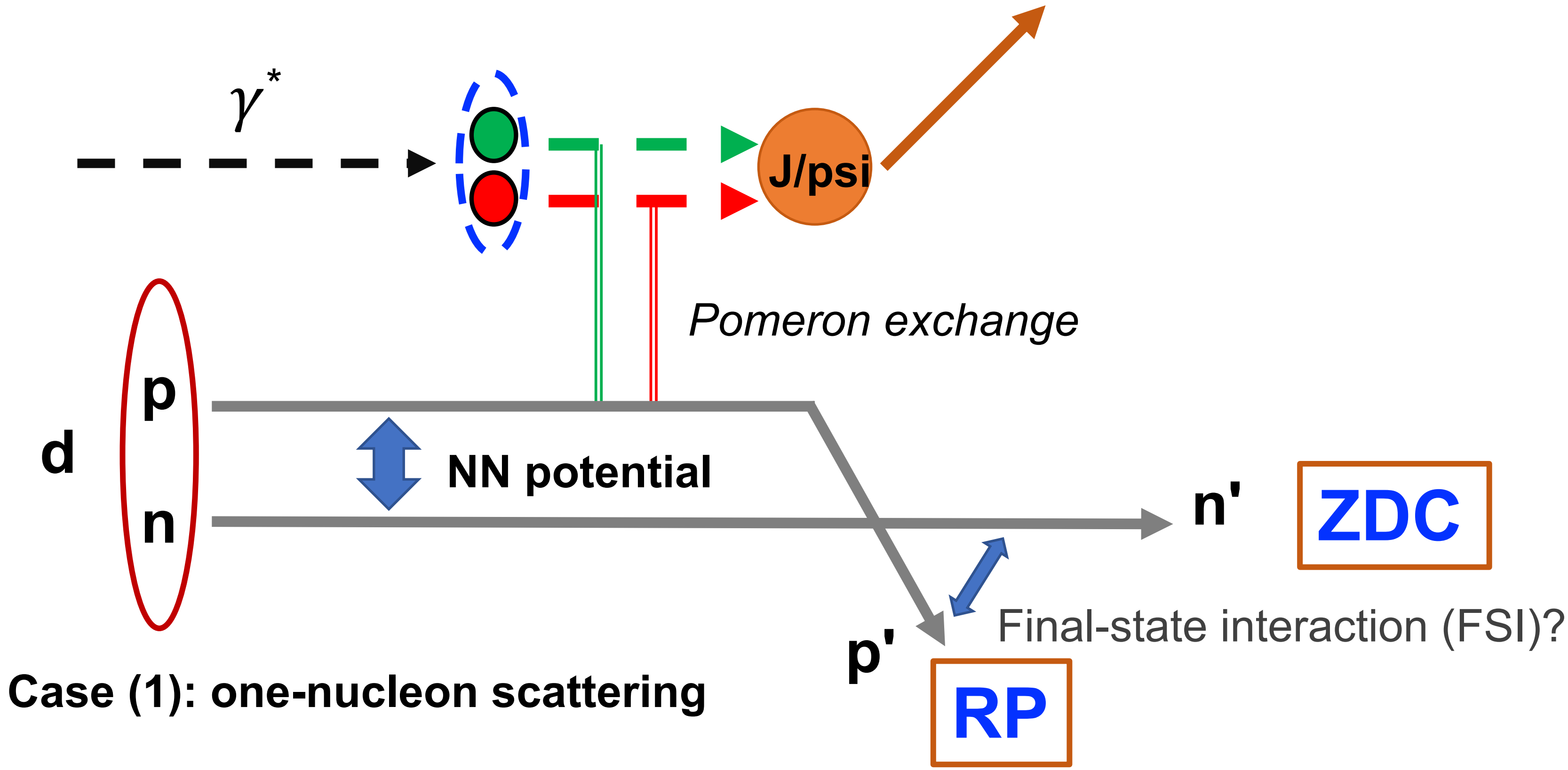

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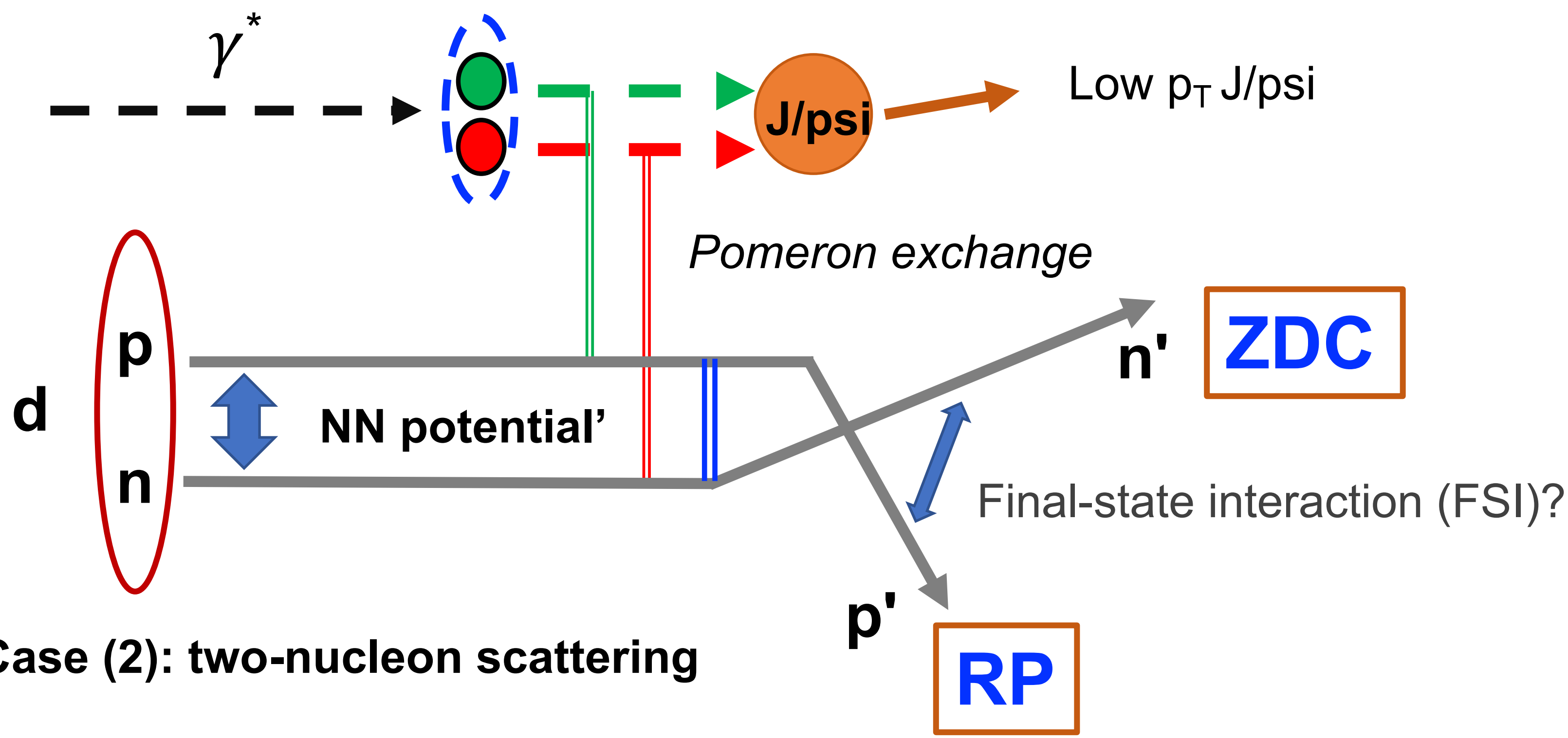
Would this process provides a different NN potential?

(2) Diffractive VM production

Miller, Sievert, and *Venugopalan* (2016)



Case (2): two-nucleon scattering

(2) Diffractive VM production

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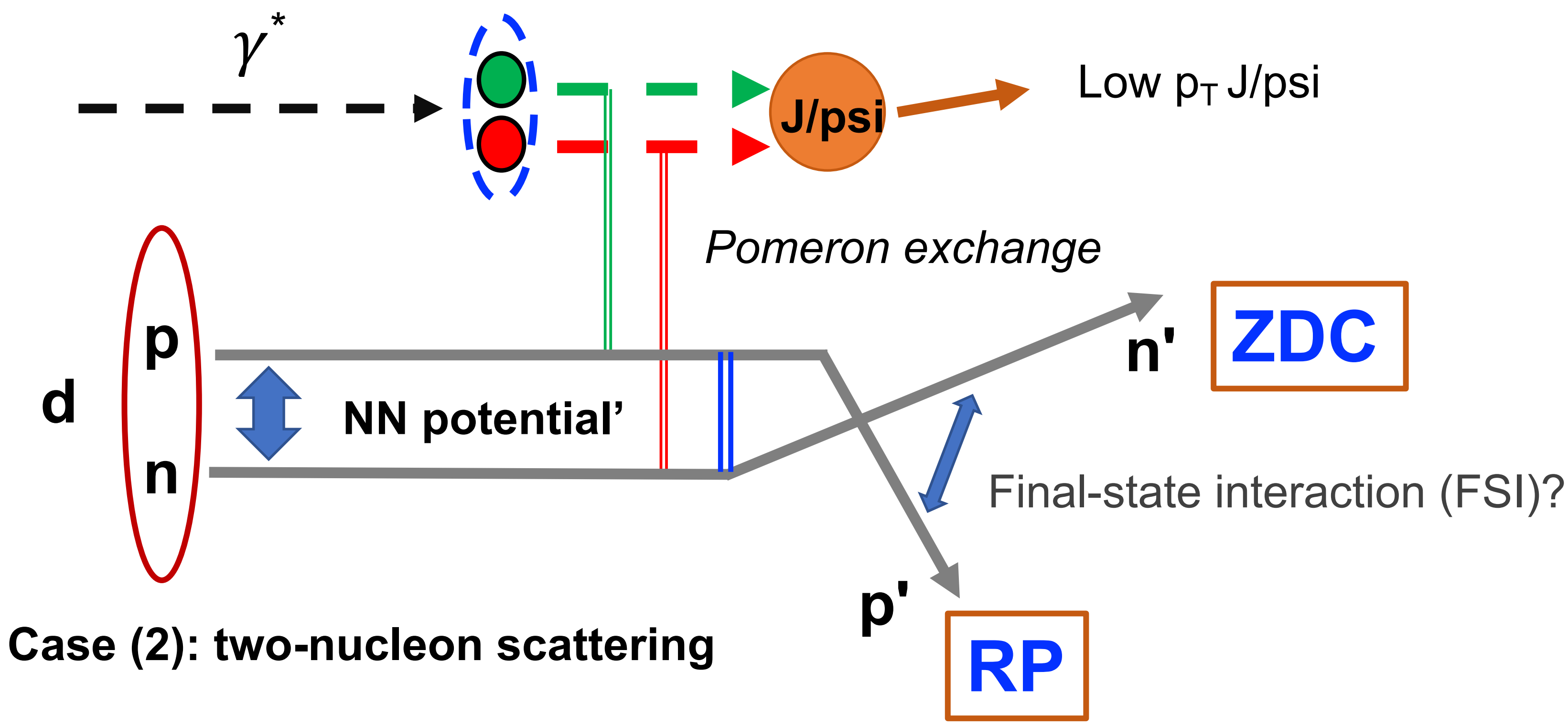

Experimentally, we are looking for signatures, e.g.,

1) Low p_T J/psi but high p_T back-to-back ***pn*** system: $p_{T,J} \sim 0 < p_{T,p} = p_{T,n}$

We have to reconstruct full kinematics.

(can we measure n(k) via this process? Not trivial to me)

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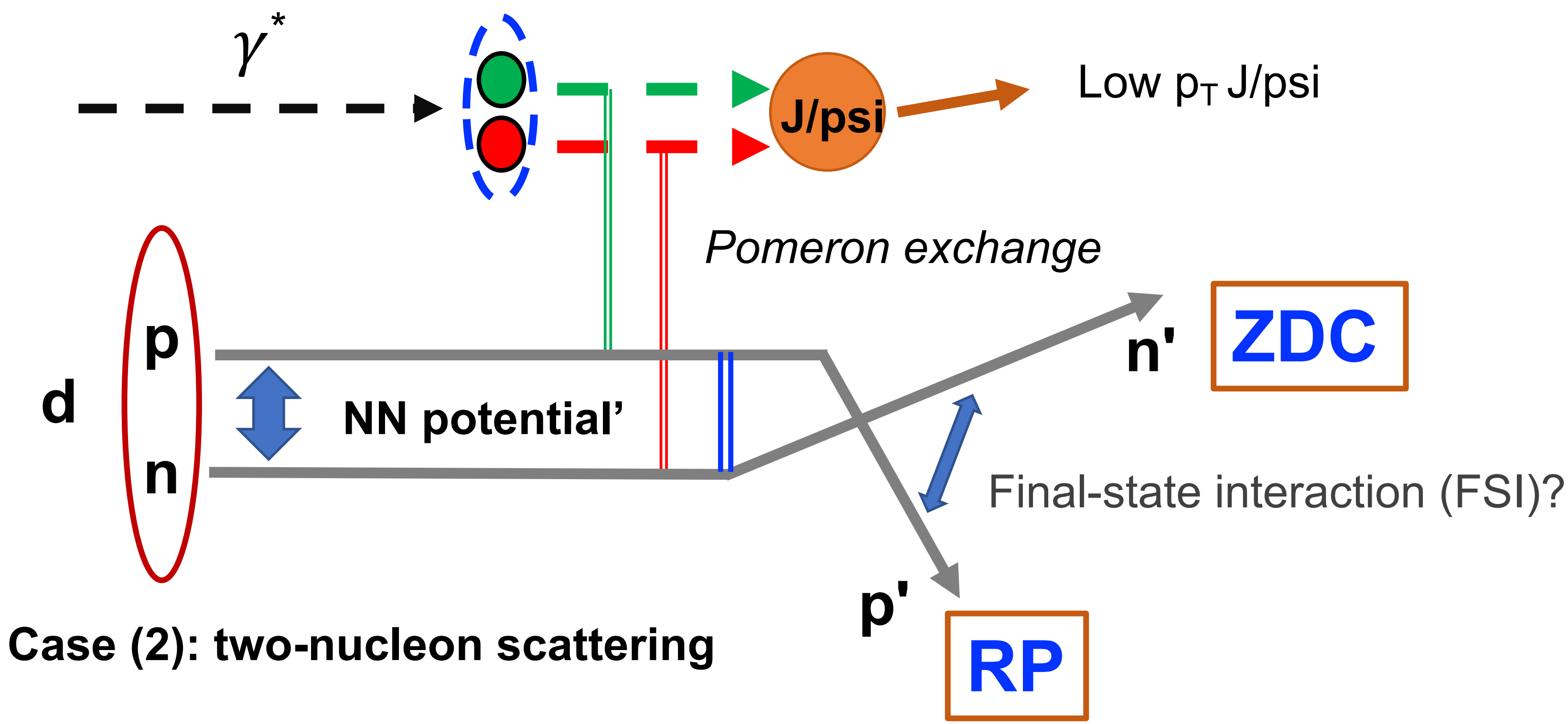

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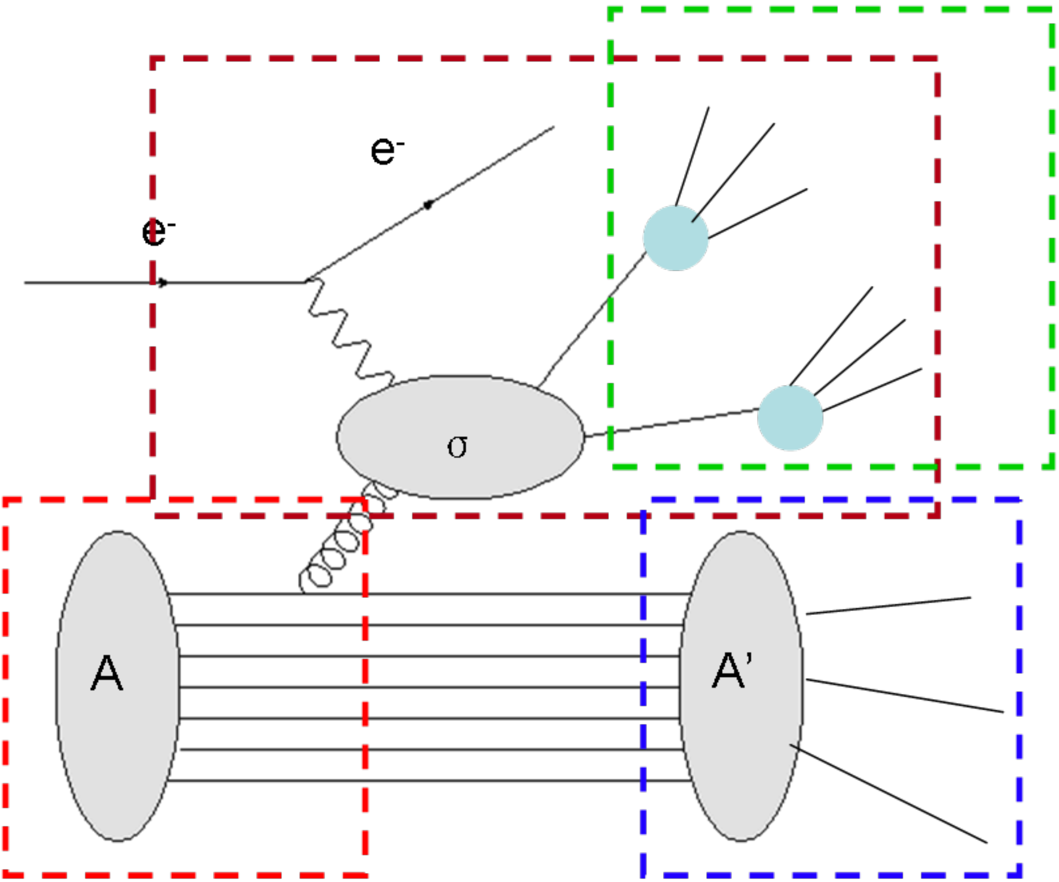
Sensitive to gluonic configuration, might result in a different NN potential?

BeAGLE: Benchmark eA Generator for LEptoproduction



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.

Nuclear evaporation (gamma dexcitation/nuclear fission/fermi break up) treated by DPMJet

Energy loss effect from routine by Salgado&Wiedemann to simulate the nuclear fragmentation effect in cold nuclear matter

BeAGLE is soon be published with version 1.0. Extremely useful for eA simulation study

See talk by M.Baker and W.Chang

BeAGLE - Incoherent diffractive J/psi

$$q + (p + n) = J' + p' + n'$$

- Realistic n(k) momentum distribution of Deuteron

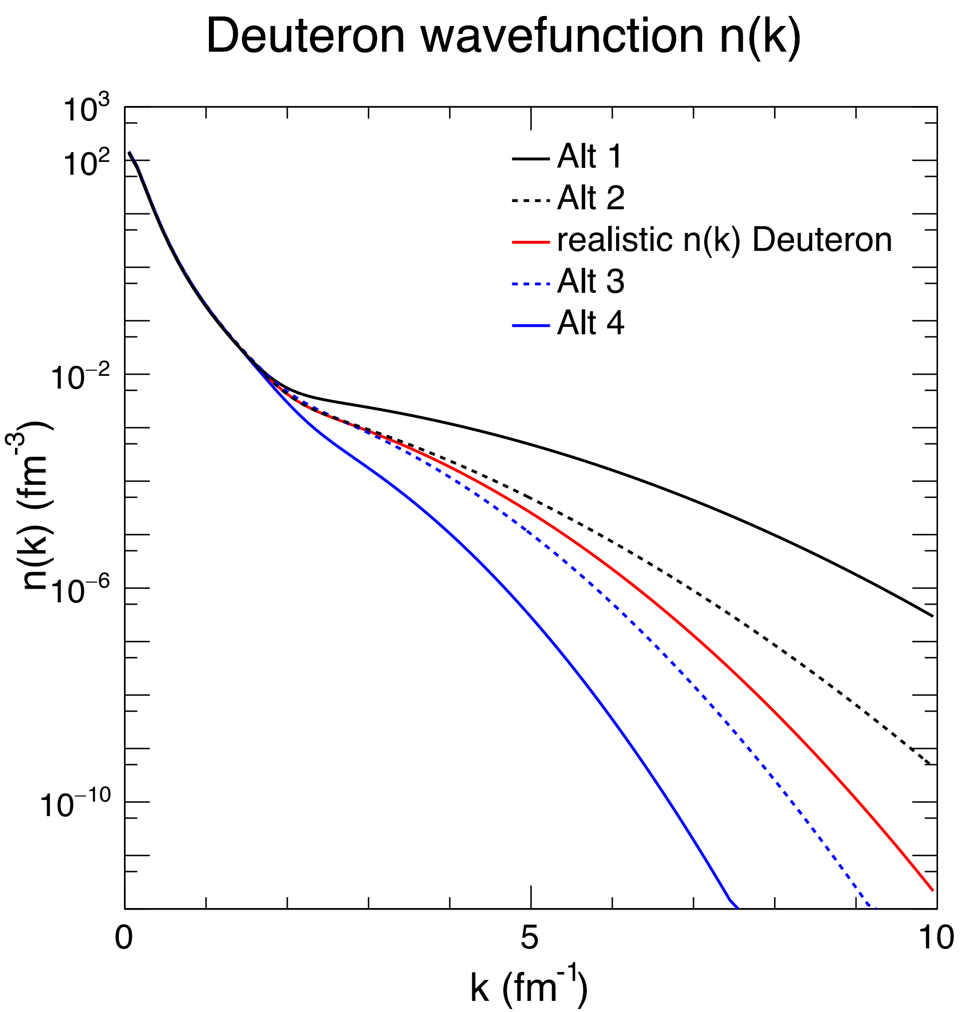
(BeAGLE: A>2 nucleus also have realistic n(k) distributions now)

- Diffractive J/psi production based on elementary process e+N using Pythia 6.

(therefore, momentum and energy are not conserved due to on-shell mass of proton and neutron in Deuteron)

- Deuteron breakup kinematics are needed to be fixed before looking at detector requirements
- No GEANT simulations are attempted yet

Deuteron n(k) in BeAGLE



For exotic configurations, we don't know the potential. Alternatives are artificial.

kinematics

Exclusive process for both cases (1) and (2)

$$q + (p + n) = J' + p' + n'$$

We cannot assume we know the beam particles. We do know deuteron as a whole (experimentally also with uncertainties),

but we don't know the momentum k for proton and neutron, and their off-shell mass

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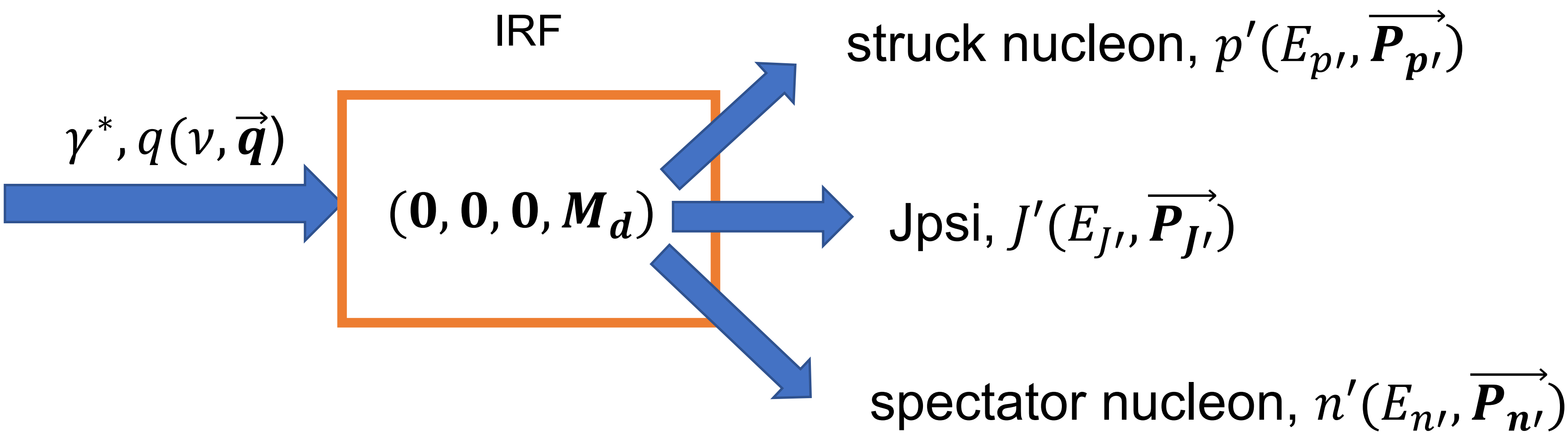

Momentum equations:

1) $q_x = P_{p',x} + P_{J',x} + P_{n',x}$

2) $q_y = P_{p',y} + P_{J',y} + P_{n',y}$

3) $q_y = P_{p',z} + P_{J',z} + P_{n',z}$

Energy equations:

$$\nu + M_d = E_{J'} + E_{p'} + E_{n'}$$

Kinematics in details

BeAGLE can do Case (1) by default with an ad-hoc solution of conserving energy and momentum.

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"This study":
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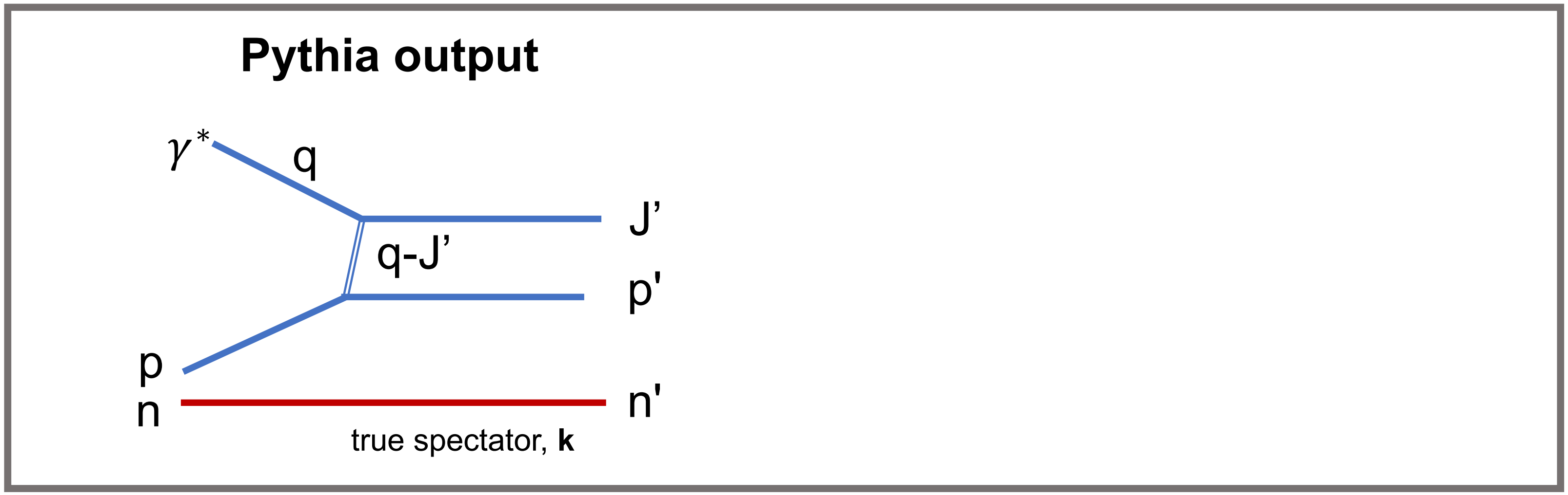

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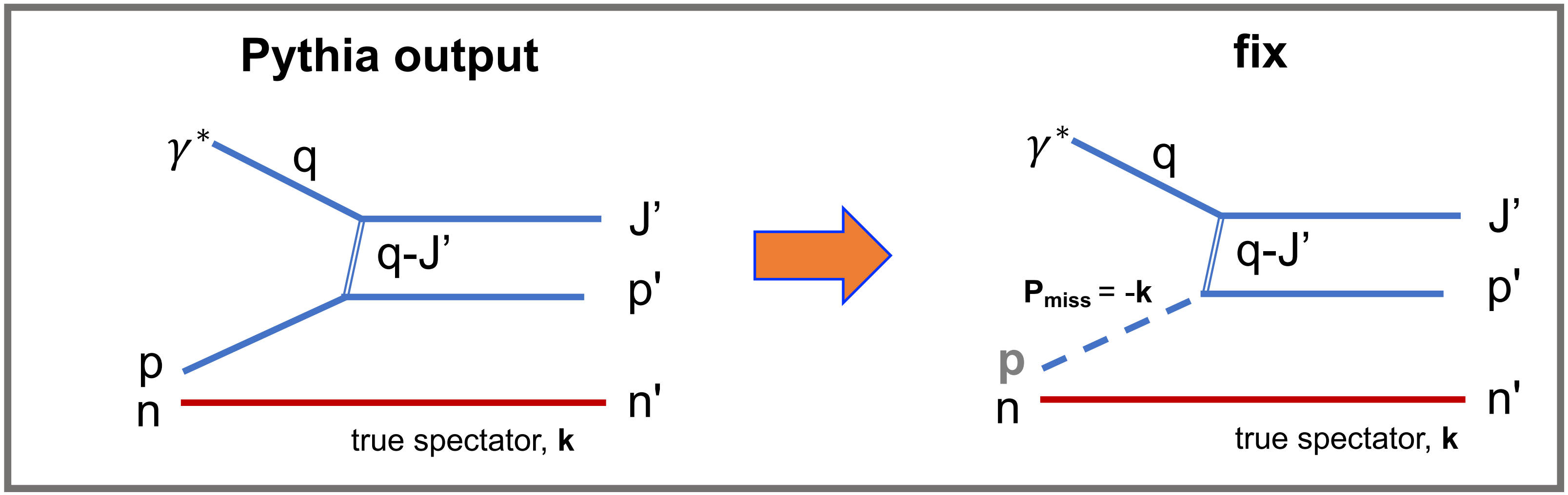

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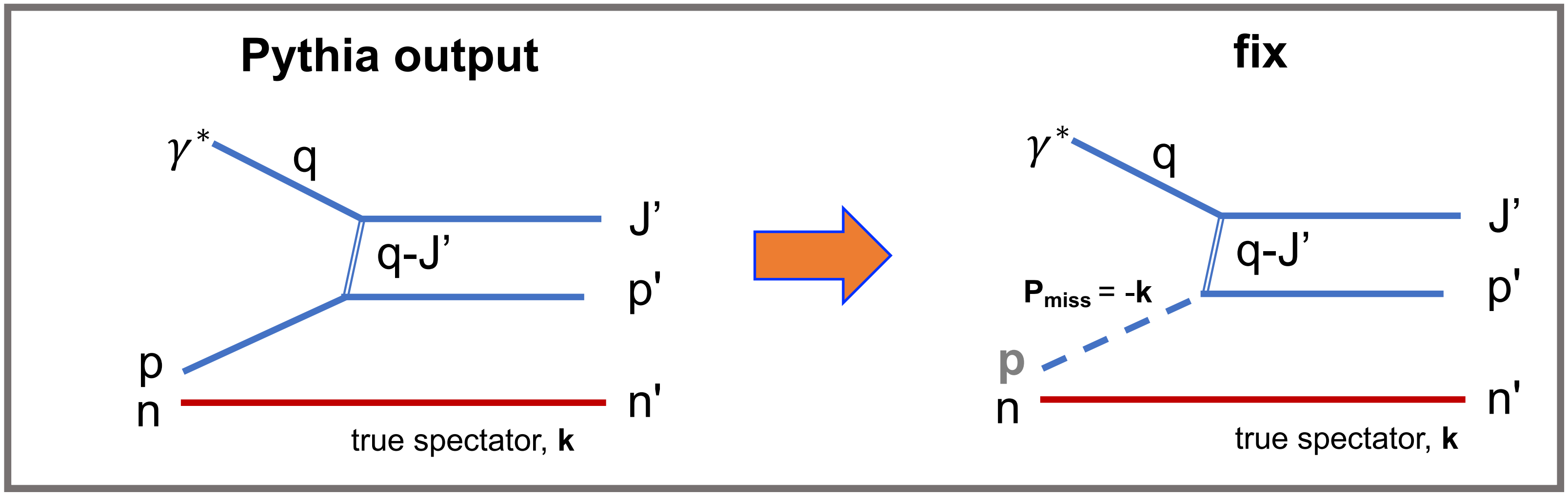

Case (2) two-nucleon scattering:

- Similar to case (1) - evenly distribute the "Pomeron" between both nucleons

No approximation – exact solutions

```
P_{J',z} = (qzkz*(TMath::Power(jx,2) + TMath::Power(jy,2) + TMath::Power(Mj,2) - TMath::Power(Mp,2) + TMath::Power(Md +
numn,2) -
       TMath::Power(px,2) - TMath::Power(py,2) - TMath::Power(qzkz,2)) -
    sqrt(TMath::Power(Md + numn,2)*(TMath::Power(jx,4) + TMath::Power(jy,4) + TMath::Power(Md,4) -
        2*TMath::Power(Md,2)*TMath::Power(Mj,2) + TMath::Power(Mj,4) - 2*TMath::Power(Md,2)*TMath::Power(Mp,2) -
        2*TMath::Power(Mj,2)*TMath::Power(Mp,2) + TMath::Power(Mp,4) + 4*TMath::Power(Md,3)*numn -
        4*Md*TMath::Power(Mj,2)*numn - 4*Md*TMath::Power(Mp,2)*numn +
        6*TMath::Power(Md,2)*TMath::Power(numn,2) - 2*TMath::Power(Mj,2)*TMath::Power(numn,2) -
        2*TMath::Power(Mp,2)*TMath::Power(numn,2) + 4*Md*TMath::Power(numn,3) + TMath::Power(numn,4) -
        2*TMath::Power(Md,2)*TMath::Power(px,2) - 2*TMath::Power(Mj,2)*TMath::Power(px,2) +
        2*TMath::Power(Mp,2)*TMath::Power(px,2) - 4*Md*numn*TMath::Power(px,2) -
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        2*(TMath::Power(Mj,2) + TMath::Power(Mp,2) - TMath::Power(Md + numn,2) + TMath::Power(px,2) +
          TMath::Power(py,2))*TMath::Power(qzkz,2) + TMath::Power(qzkz,4) -
        2*TMath::Power(jy,2)*(-TMath::Power(Mj,2) + TMath::Power(Mp,2) + TMath::Power(Md + numn,2) +
          TMath::Power(px,2) + TMath::Power(py,2) - TMath::Power(qzkz,2)) +
        2*TMath::Power(jx,2)*(TMath::Power(jy,2) + TMath::Power(Mj,2) - TMath::Power(Mp,2) -
          TMath::Power(Md + numn,2) - TMath::Power(px,2) - TMath::Power(py,2) + TMath::Power(qzkz,2)))))/
    (2.*(Md + numn - qzkz)*(Md + numn + qzkz))
```
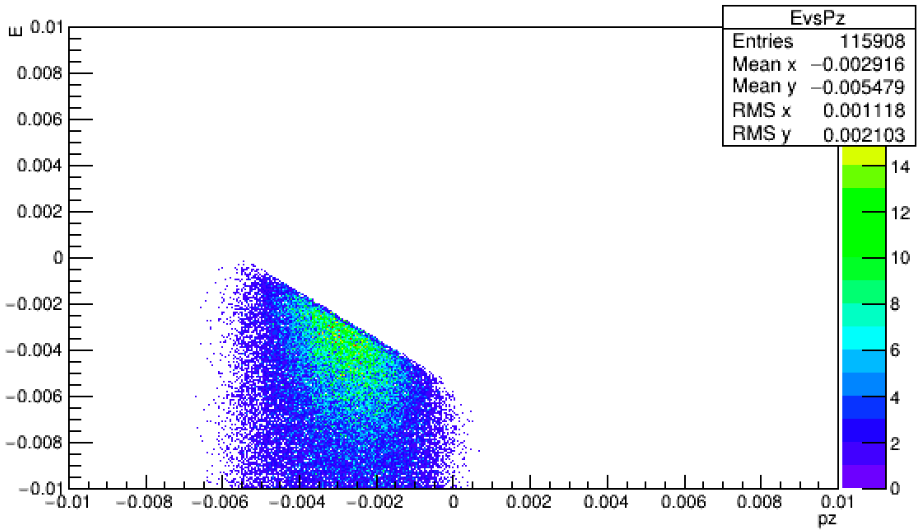

Similarly for Pz' of struck nucleon

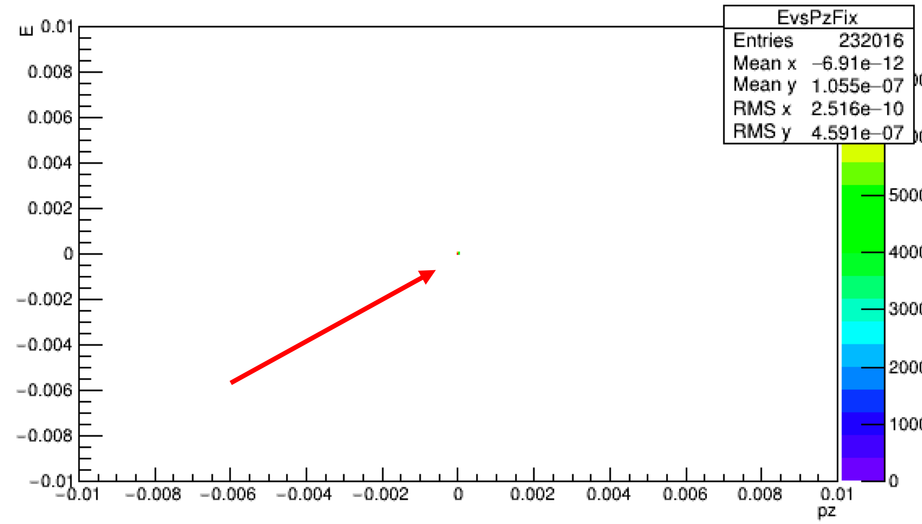
PS: there are some change of variables needed. But the solutions are in the same forms.

Energy and momentum conservation

E_{in}-E_{out} vs $P_{z,in}$- $P_{z,out}$



Before fix, BeAGLE

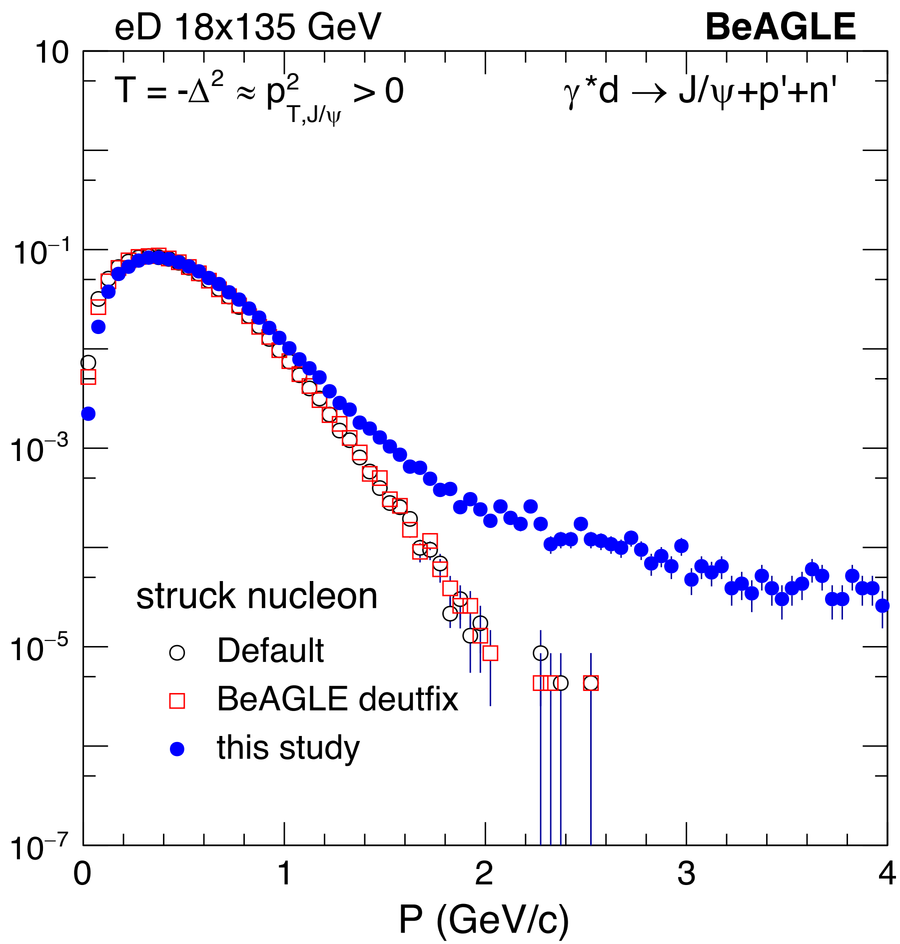


After fix, soon in BeAGLE

All following results are energy and momentum conserved.

Struck nucleon momentum

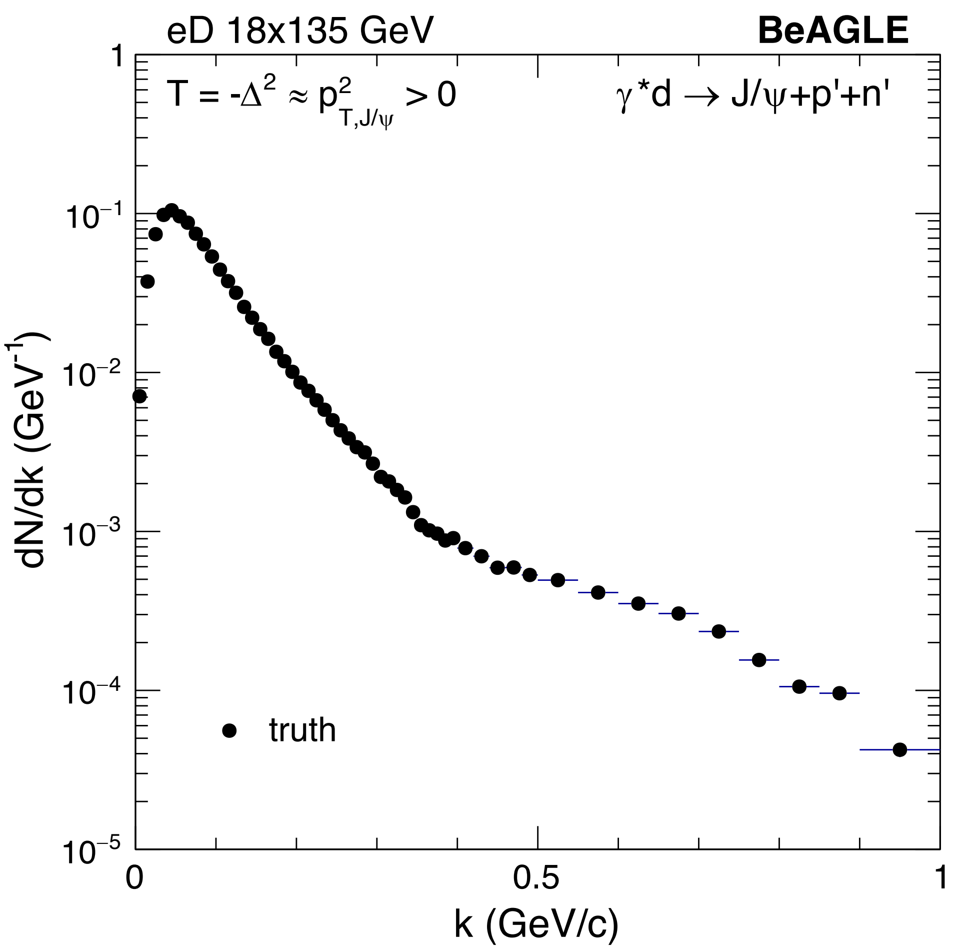
IRF: Ion rest frame



IRF: struck nucleon can be either proton or neutron. Their kinematics are modified after the fix in this study. Will use for later studies.

(BeAGLE ad-hoc deutfix does not change the kinematics of the struck nucleon much)

n(k) reconstructions



n(k) intrinsic momentum distribution from spectator. Same as input

- Only Case (1) can be used to reconstruct n(k)
- Case (2) would not tell us n(k), at least not directly.

Detector assumptions

- RP+B0:
  - Perfect resolution
  - 0-5 mrad and 7-22 mrad 100% efficient within these acceptance

(not realistic but effort is on-going, see A. Jentsch's talk)

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- ZDC:
  - Acceptance: 4 mrad
  - Energy resolution:
    1. **(85%/sqrt(E)+9.1%) STAR ZDC**
    2. **(35%/sqrt(E)+2%) ZEUS ZDC**
  - Position resolution: ~ 10cm/sqrt(E) @ 28.8 meter away from IP

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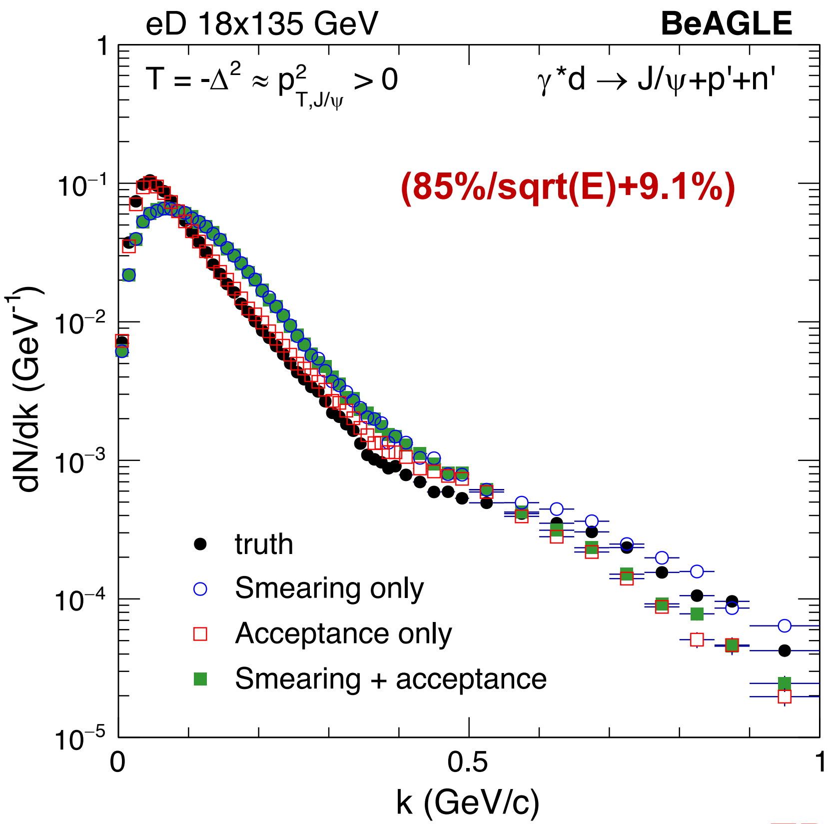
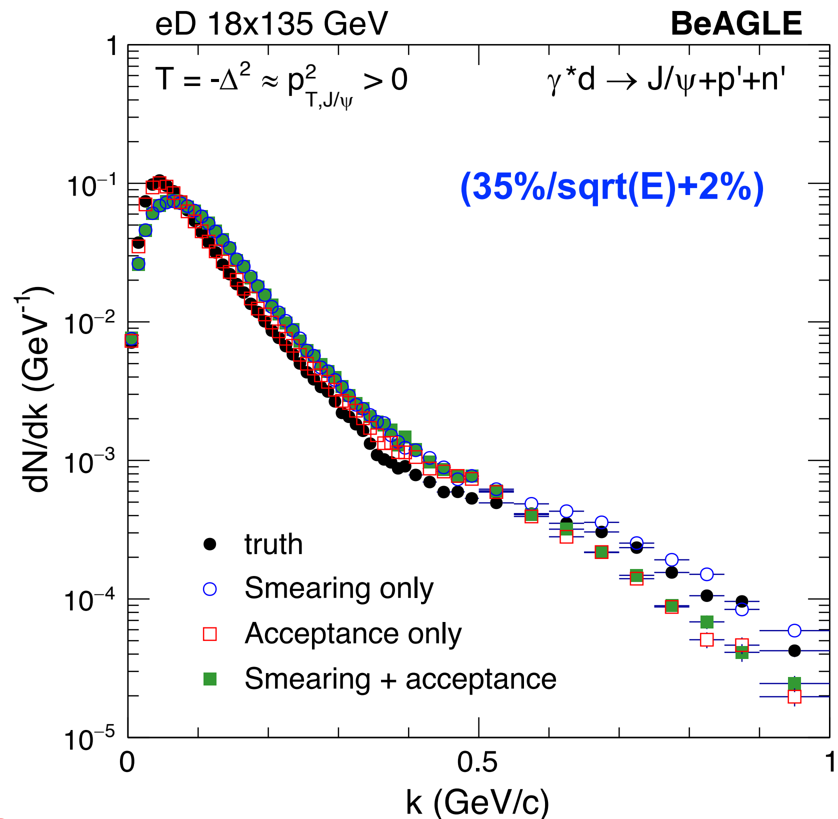
- Other things not considered:
  - Jpsi reconstruction resolution, scattered electron, beam divergence, beam momentum, … and many more

Acceptance and resolution



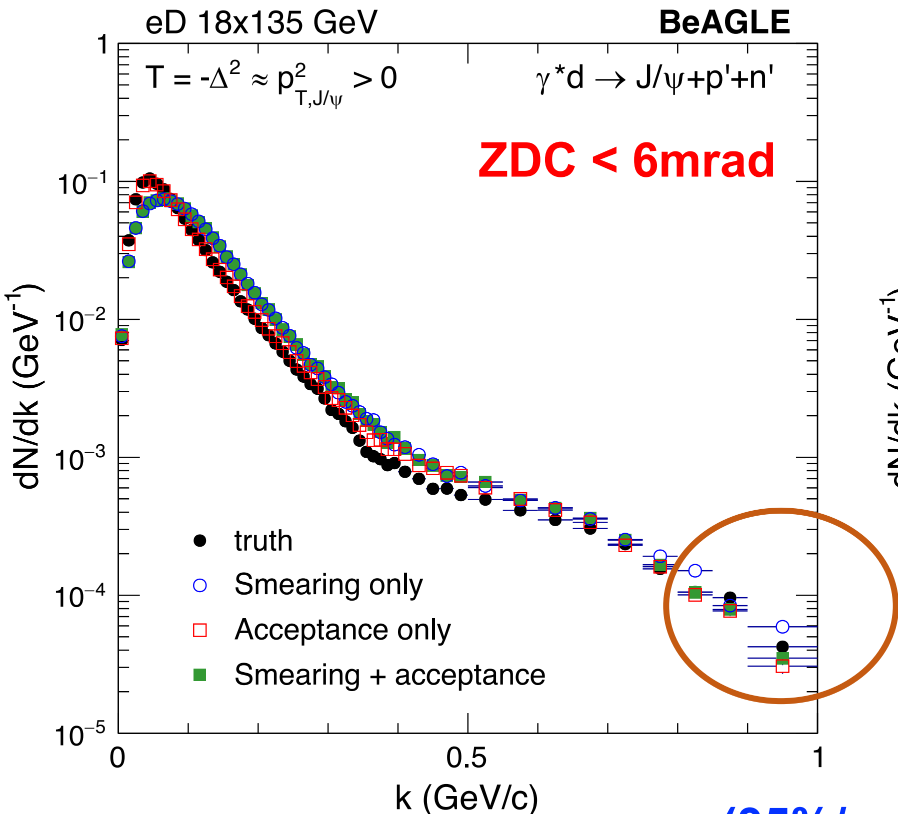


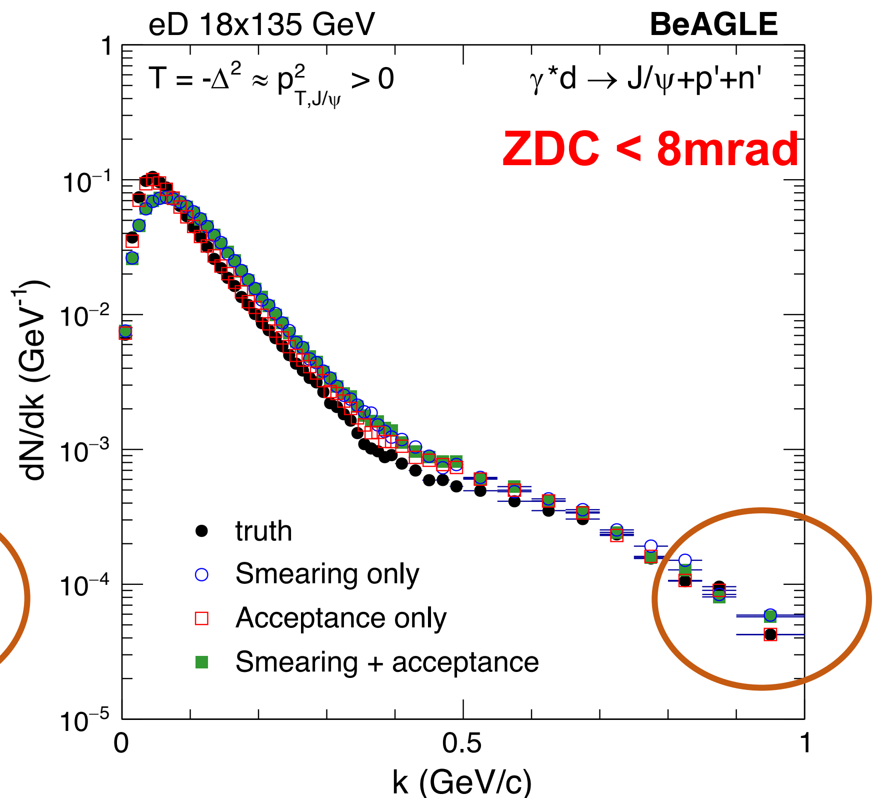
ZDC < 4mrad

"STAR-like" ZDC "ZEUS-like" ZDC

- Large resolution effect at low k, and large acceptance effect at high k
- Bottle neck for resolution is the constant term.

Acceptance and resolution





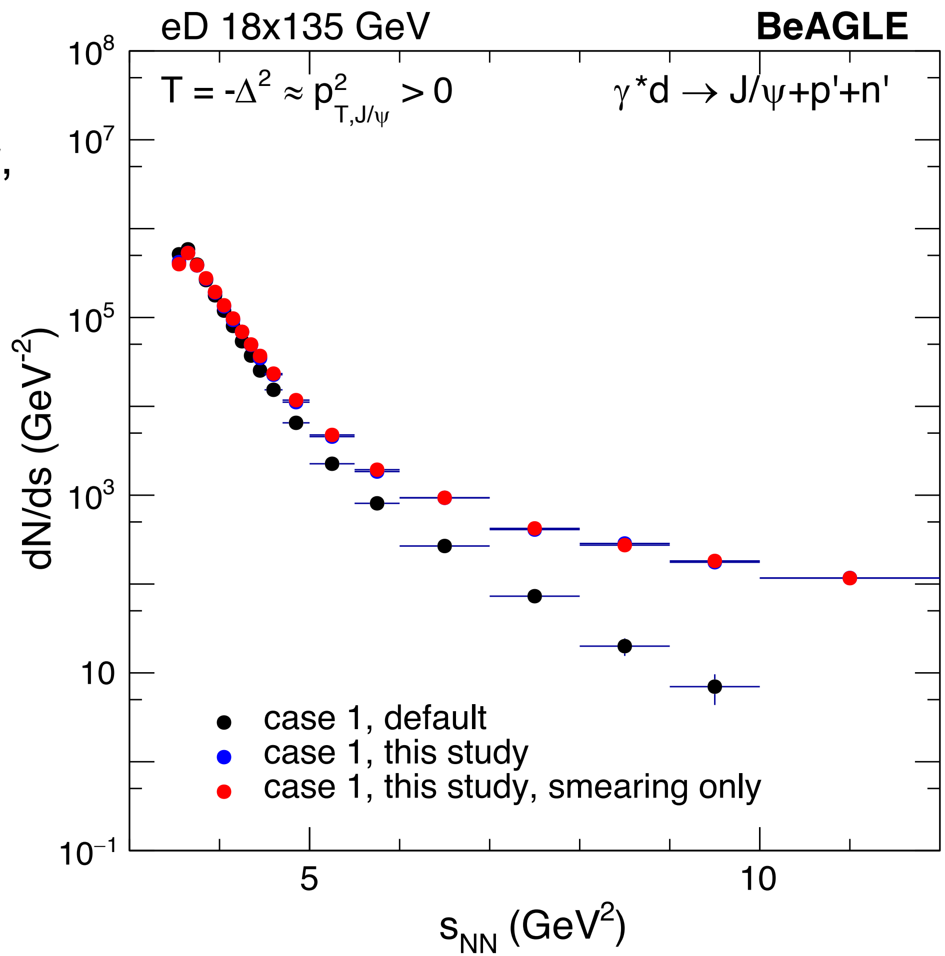
(35%/sqrt(E)+2%)

“ZEUS-like” ZDC

6 mrad and 8 mrad are not different until 0.8-0.9 GeV.

S_{NN} in IRF

Case 1: *One nucleon scattering*, but it can be on proton or neutron.



$s_{NN} = (p' + n')^2$, ~ center of mass energy squared in the *pn* system

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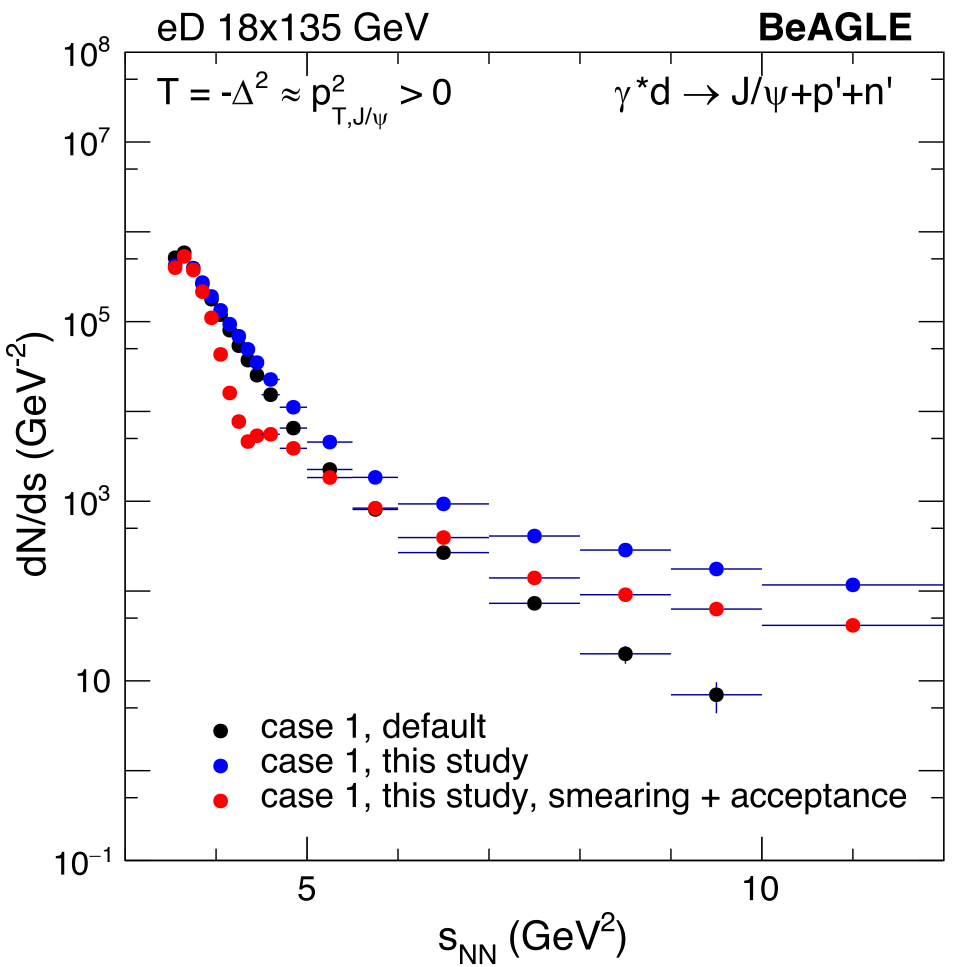
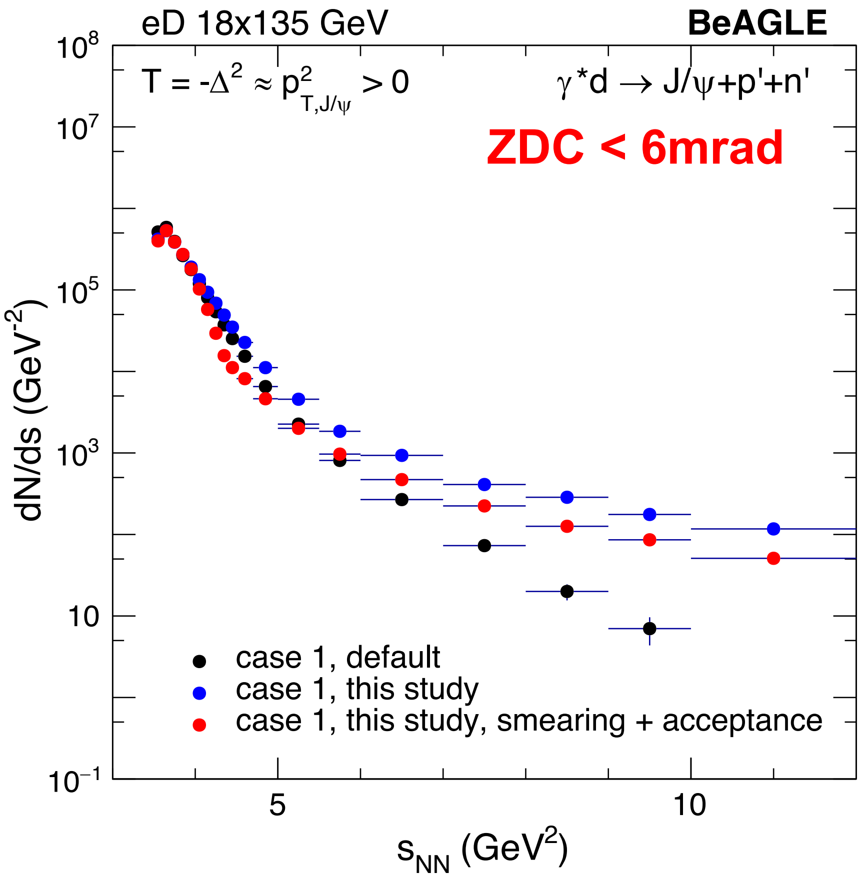
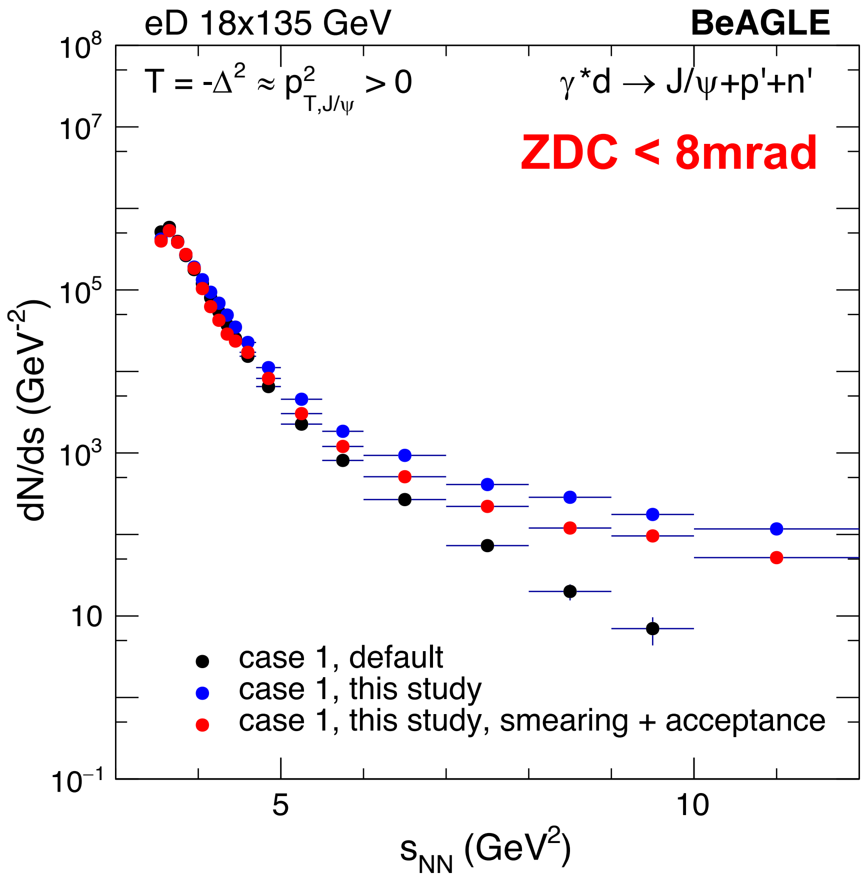


For this observable, the acceptance effect is more significant. (ZDC: <4mrad)

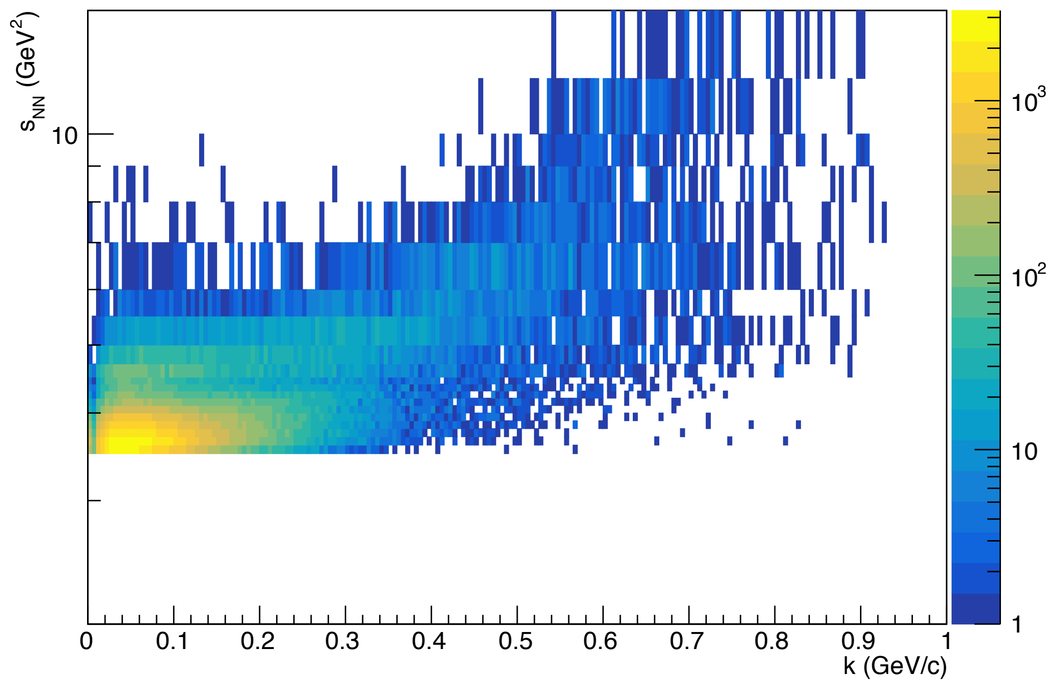
s_{NN} in IRF





ZDC < 6 or 8mrad can improve significantly. RP+B0 is kept the same

s_{NN} vs k in IRF

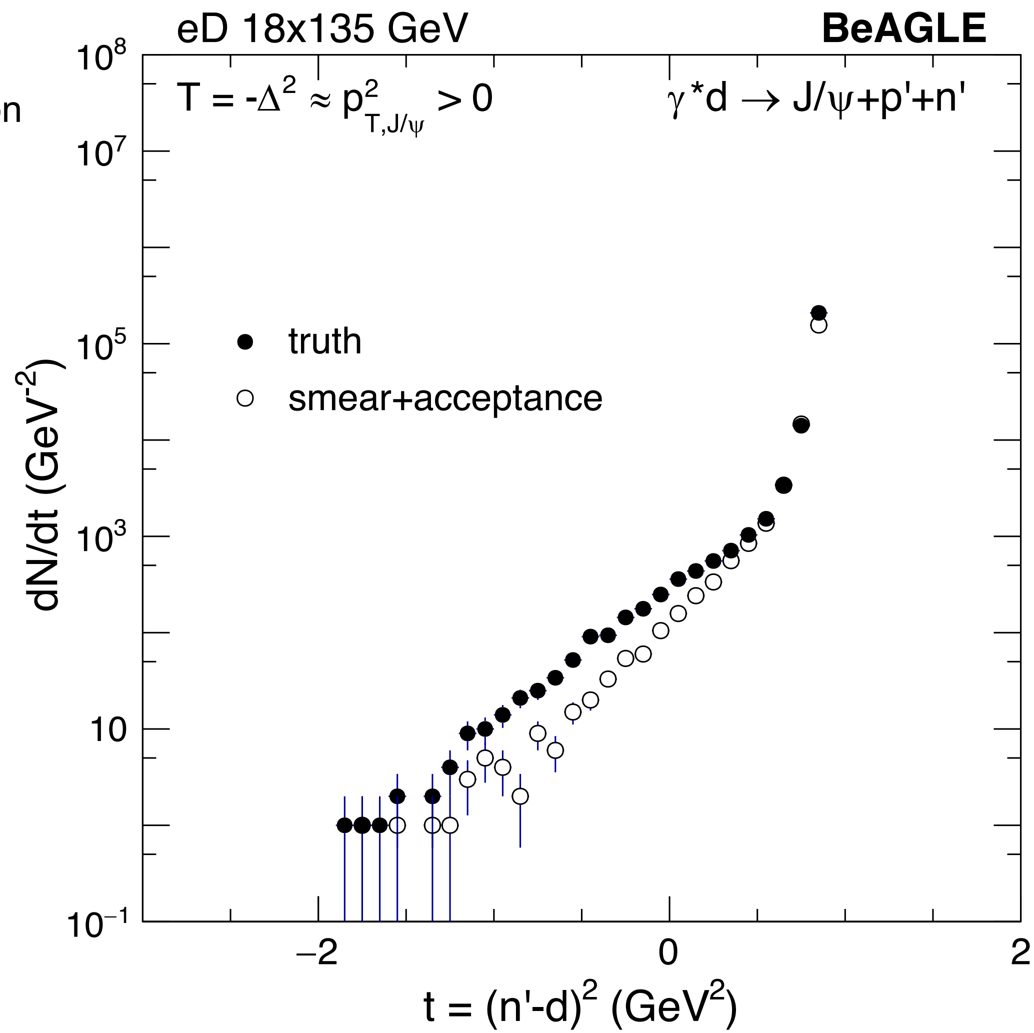


Case 1 one-nucleon scattering:

- s_{NN} vs k momentum, where k momentum is the intrinsic nucleon momentum.

t=(spectator-deuteron)^2

See *Christian's* talk for extrapolating free neutron structure function using condition $t-M_N{**}2 = 0$

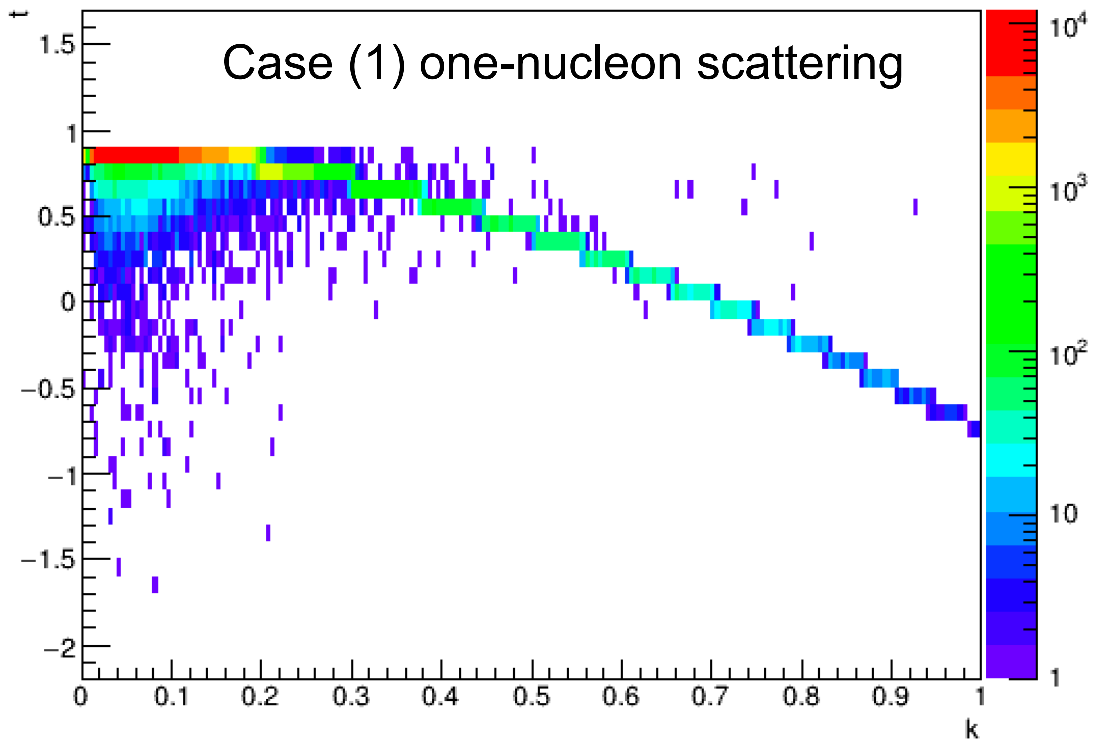


(35%/sqrt(E)+2%)

ZDC < 4mrad

n' is the four-momentum of the spectator.

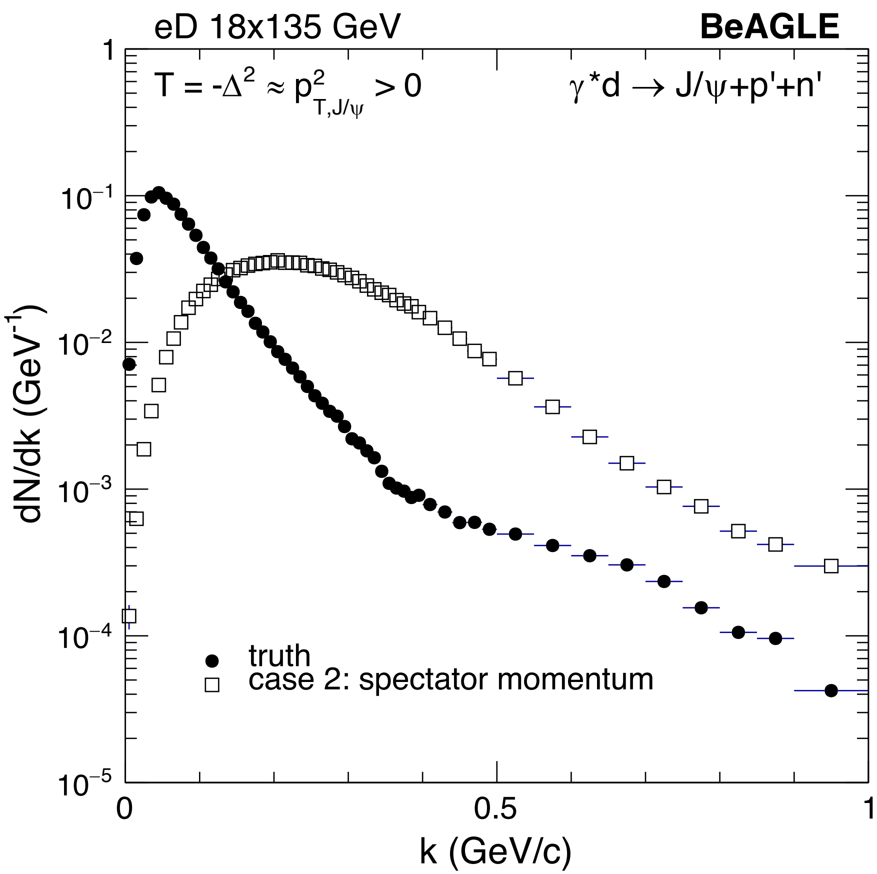
t vs k



- t measures how off-shell the spectator nucleon is, and as expected, correlated with k

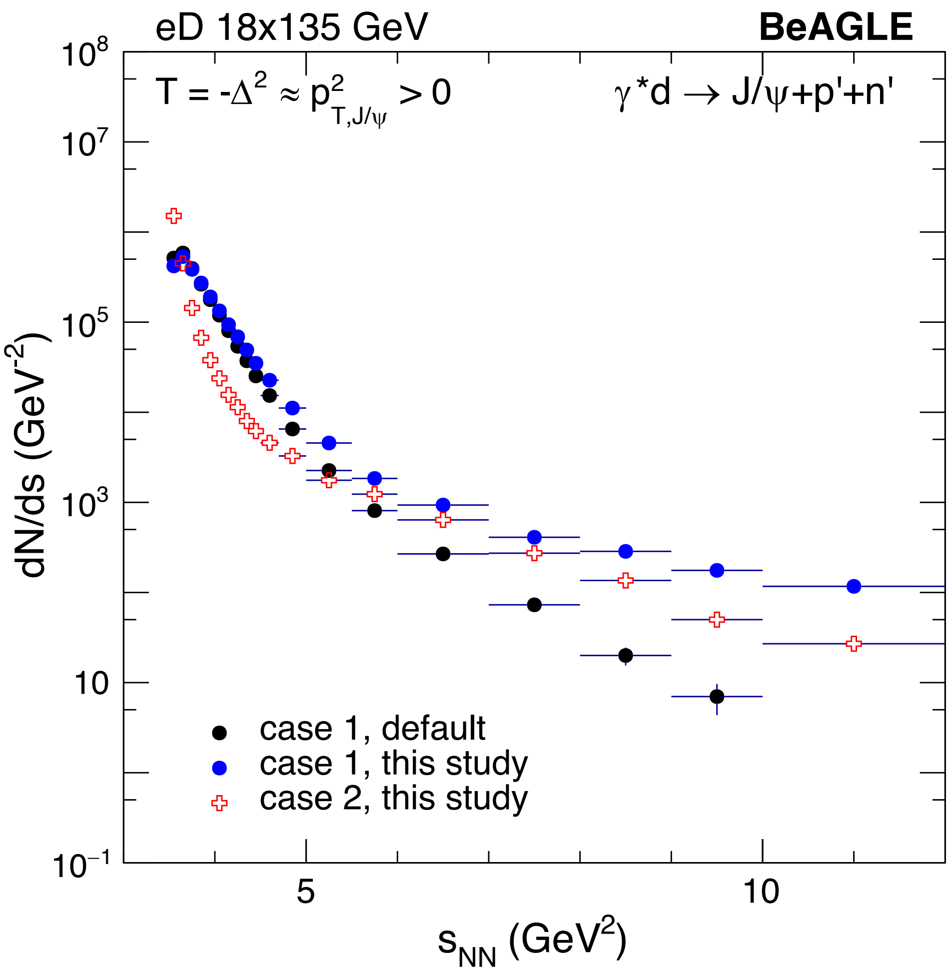
Case 2 – two-nucleon scattering

- Neutron momentum distribution is no longer n(k) distribution.



The intrinsic momentum information is lost if both nucleons are hit. (Similar to FSI?)

Case 1 vs Case 2



- Is this an observable to distinguish case 1 and case 2?
- More theoretical developments are needed.

Summary

- Forward physics at an EIC would be an very important aspect of the program. Good forward detection is essential!
- Forward proton and neutron detections for light nuclei are (in some way) more challenging.

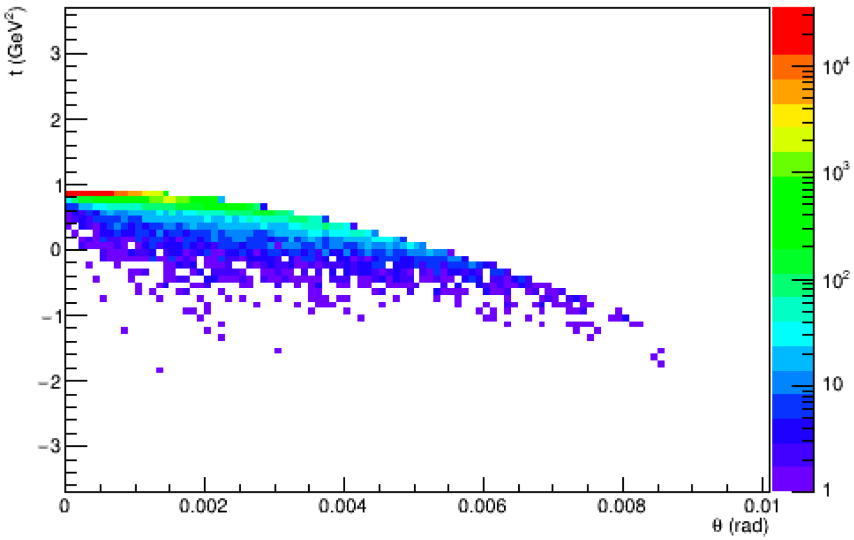
- For theorists, it is more important NOW to get the kinematics first, a rough estimate of resolutions on your observables (before… a lot of details).

Detectors are being designed!

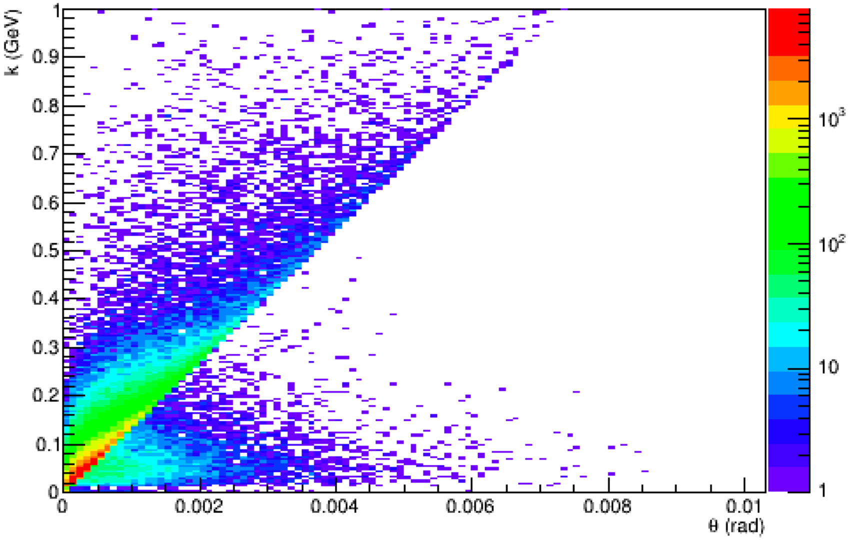
- For experimentalists, should try to make some measurements using ZDC (or RP) with existing data and detector. **Find out more info with realistic conditions.**

Backup

Case (1)



t (GeV^2)
3
2
1
0
−1
−2
−3
0
0.002
0.004
0.006
0.008
0.01
θ (rad)
10^4
10^3
10^2
10
1



k (GeV)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.002
0.004
0.006
0.008
0.01
θ (rad)
10^3
10^2
10
1