Deuteron series

Episode 3:

Exploring the origin of the EMC effect with electron-deuteron DIS at the EIC

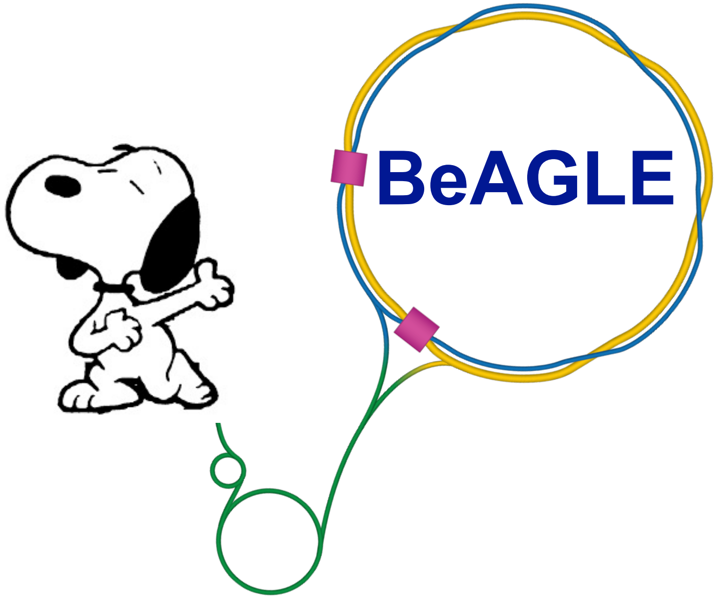
Kong Tu

BNL

02. 28. 2022

Collaboration with A. Jentsch, M. Strikman, and C. Weiss

Status



BeAGLE has been developing actively, especially the light ion.

Deuteron series

Episode 1:
Gluon distribution and its modification in deuteron, what role does SRC play in gluons?
[*Phys. Lett. B 811 (2020) 135877]*

Episode 2:
Minimizing nuclear effect in deuteron – pathway towards free nucleon structure
[*Phys.Rev.C 104 (2021) 6, 065205 Editor's Suggestion]*

Episode 3:
Origin of the EMC effect and its connection to the off-shell nucleons.
[Focus of this talk]

Extra credit:
Gluonic structure of the deuteron from UPC in d+Au at STAR
[accepted in PRL]

Heavy nuclei series

Episode 1:
Incoherent VM production and nuclear breakups in Pb.
[*Phys.Rev.D 104 (2021) 11, 114030]*

Episode 2:
Forward particle productions in nuclear breakup and eA centrality
[submission in < 2 weeks]

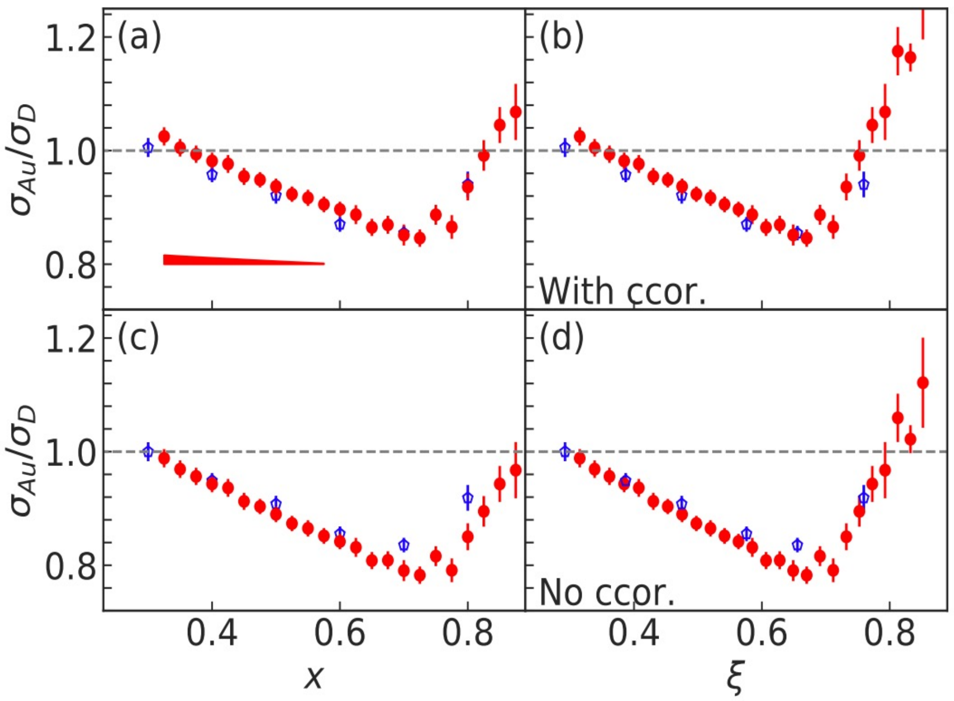
Episode 3:
Parton energy loss (PyQM) in eA
[submission in < 2 weeks]

EMC effect and SRC

~40 years of EMC puzzle in nuclear physics

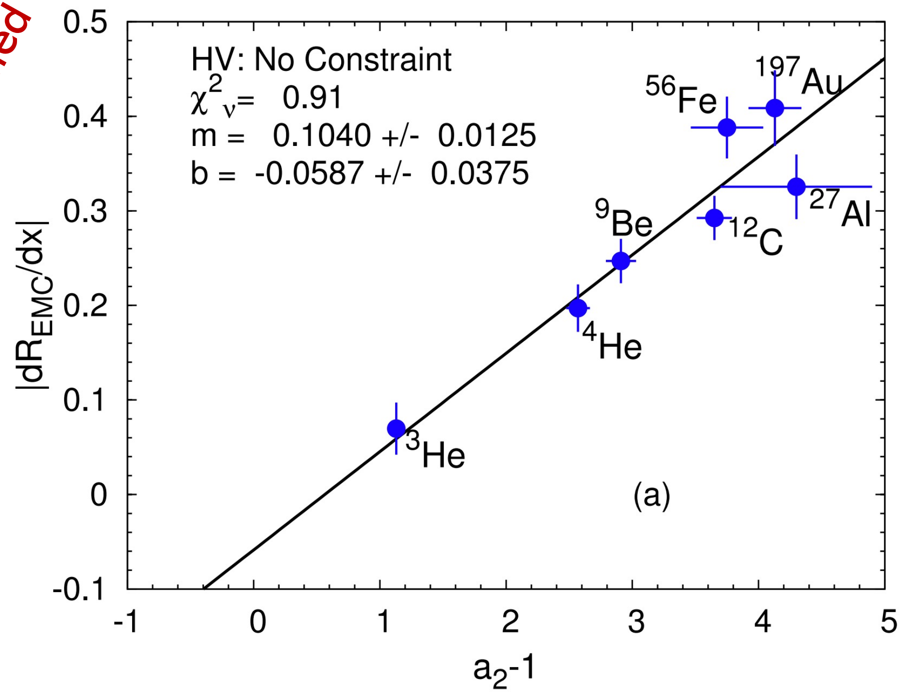
Effect of nuclear density?

Inclusive DIS cross section ratio to D



Example of EMC measurements

How much nucleon PDF gets modified



How strong (many) the SRCs (pairs) are

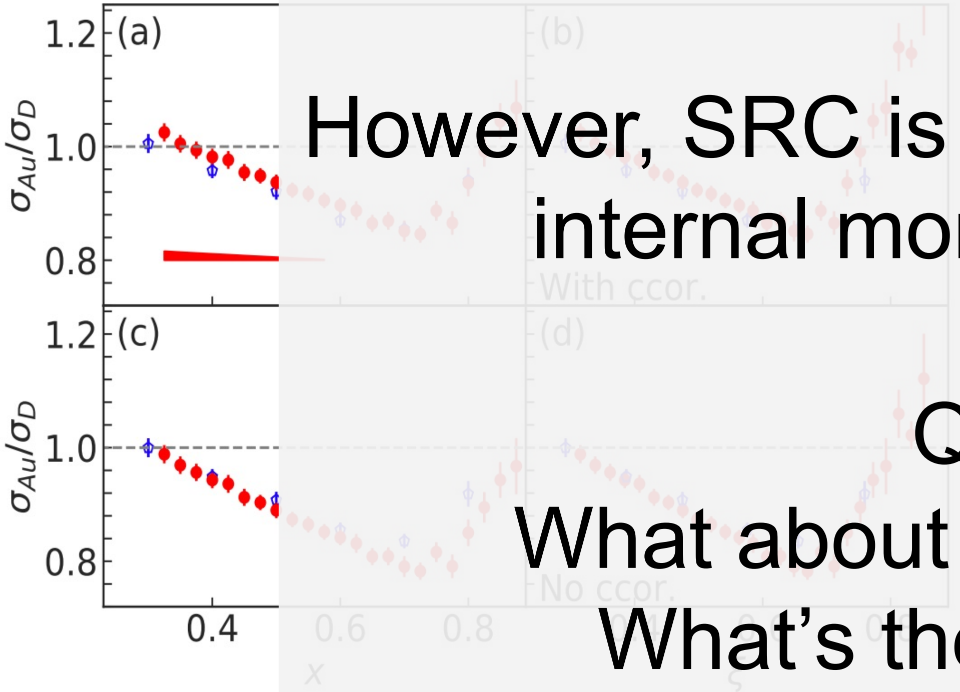
(e.g., the probability of selecting a pair of SRC nucleons in A)

Recent experiments have revealed the EMC might be caused by SRC

EMC effect and SRC

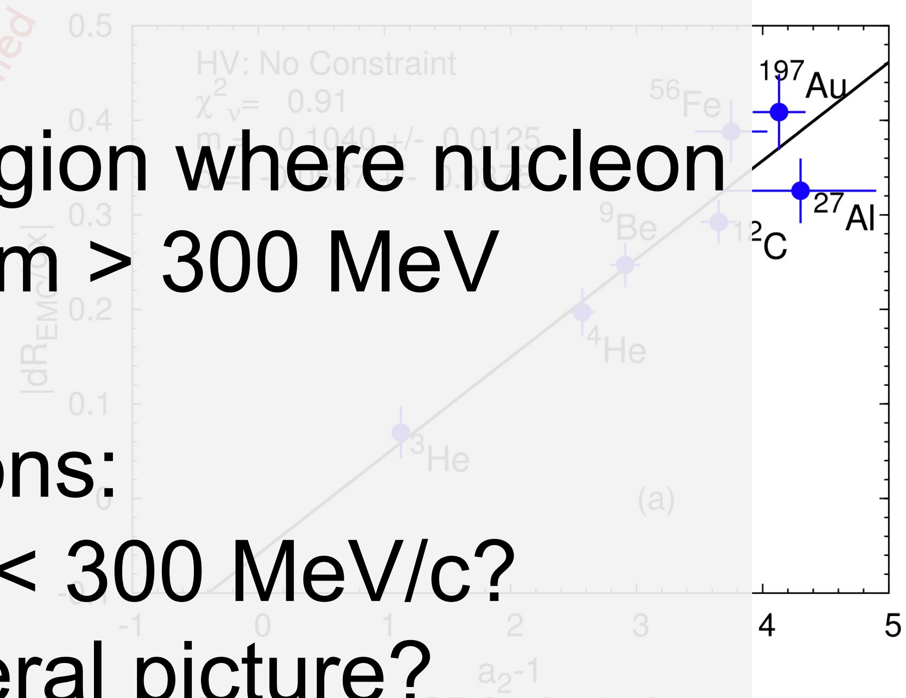
~40 years of EMC puzzle in nuclear physics

Inclusive DIS cross section ratio to D



Example of EMC measurements

Effect of nuclear density?



How strong (many) the SRCs (pairs) are
(e.g., the probability of selecting a pair of SRC nucleons in A)

SRC seems to *explain* the EMC

However, SRC is the region where nucleon internal momentum > 300 MeV

Questions:
What about 0 < p < 300 MeV/c?
What's the general picture?

Recent experiments have revealed the EMC might be caused by SRC

EMC ("Everyone's Model is Correct")

PHYSICS REPORTS (Review Section of Physics Letters) 160, Nos. 5 & 6 (1988) 235–427. North-Holland, Amsterdam

HARD NUCLEAR PROCESSES AND MICROSCOPIC NUCLEAR STRUCTURE

Leonid FRANKFURT and Mark STRIKMAN

Leningrad Nuclear Physics Institute, Gatchina, Leningrad District, 188350 USSR

Received April 1987

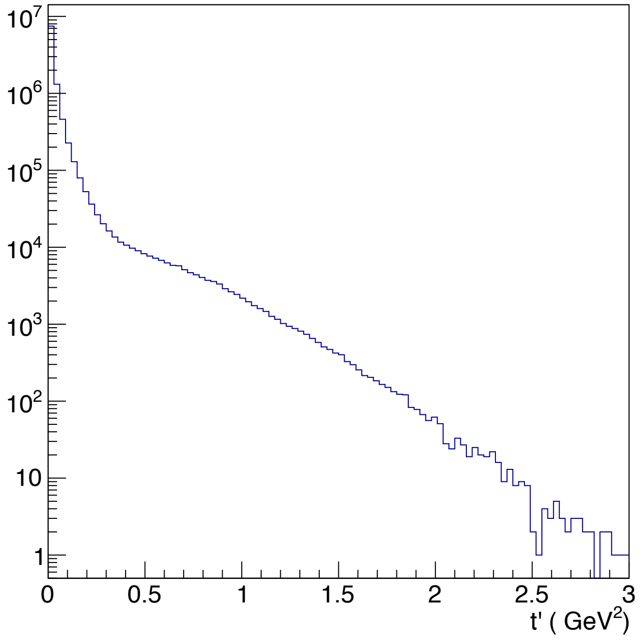
Contents:

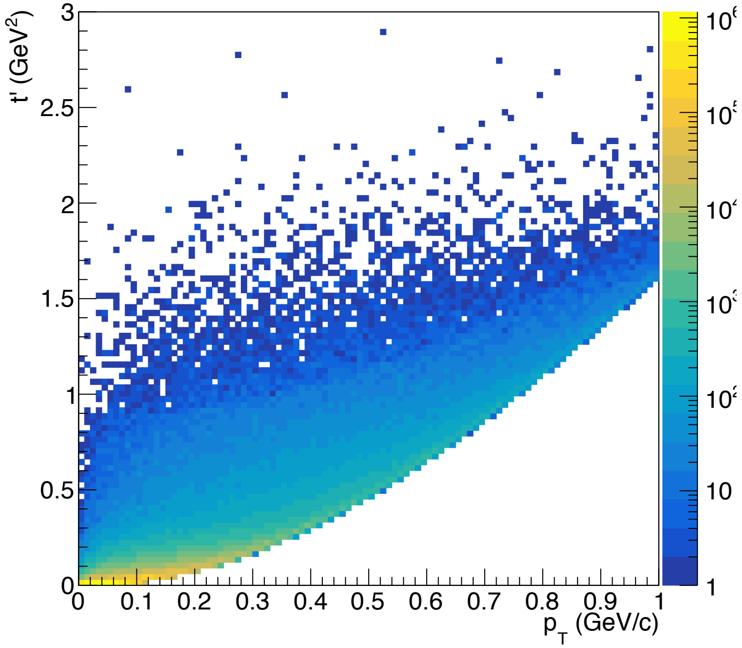
Frankfurt and Strikman had summarized EMC models (1988)

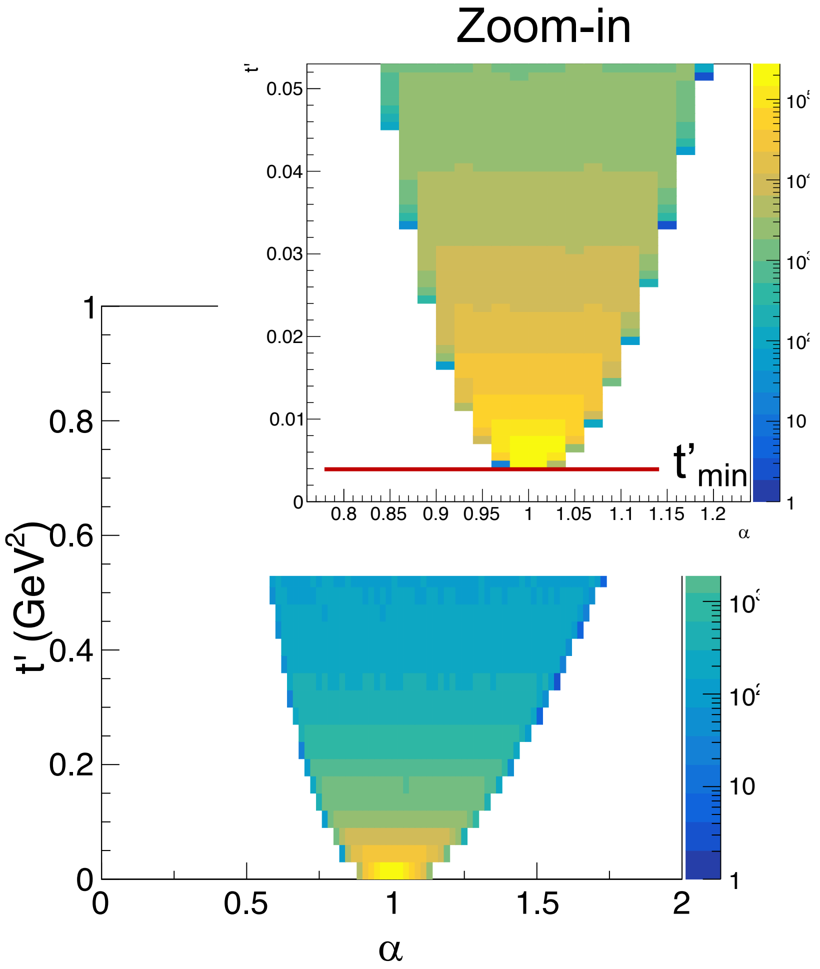
This study - we explore the EMC effect in terms of nucleon off-shellness, which has the following features:

1. The EMC effect is universal and only determined by how much the nucleon is off the mass shell.
2. Light nuclei have an average smaller "off-shellness" while heavy nuclei have higher average "off-shellness". Qualitatively consistent with data.
3. Off-shellness is closely related to the momentum of the bound nucleon, which is connected to the Short-Range Nucleon Correlations (SRC)
4. **Deuteron** is a perfect testing ground.

"Off-shellness" – t'







Toy MC

Based on Ciofi et al. parametrization for ***d*** wavefunction (same as in BeAGLE)

- $t' = M_N{}^{**}2 - (p_d - p_p)^2$
- Raw distributions (left), and p_T (middle) and alpha (right) dependence.
- Zoom-in t' vs alpha reproduced [Strikman & Weiss] and the minimum t' ~ 0.004 GeV^2

One-parameter parametrization

- Minimal parametrization [Frankfurt, Strikman 80's]

$$\frac{F_{2n,\text{bound}}(x_n, t')}{F_{2n,\text{free}}(x_n)} = 1 - \Delta(t')\, f(x_n)$$

$t' \equiv t'(\alpha_p, p_{pT}) = m_N^2 - (p_d - p_p)^2$ neutron virtuality

$x_n = x/(2 - \alpha_p)$ effective Bjorken variable

General procedure:

Find relation btw. EMC slope and virtuality (t') (DATA) → Fits ~ parametrization → Derive weights per [x_N, t'] bin → Apply to DIS event-by-event. (BeAGLE) → Observables

Useful References:

1. Ciofi et al. https://arxiv.org/abs/0706.2937, includes all virtuality calculations.
2. Many EMC measurements, https://arxiv.org/abs/2110.08399
3. Nature paper, https://www.nature.com/articles/s41586-019-0925-9.pdf
4. Data spread sheet on google, https://docs.google.com/spreadsheets/d/1OVPSfLvtQTHq5eg54fXi8-__O4WsMsAYC6TYTA5iltI/edit?usp=sharing

Parametrization

- Nucleon virtuality from Ciofi. et al. (07) $t' = \langle V_{NR} \rangle 2M_N$ (Dimensional analysis → multiply by mass)
- Deuteron virtuality t' can be inferred from Toy MC. average is ~ 0.03 GeV^2

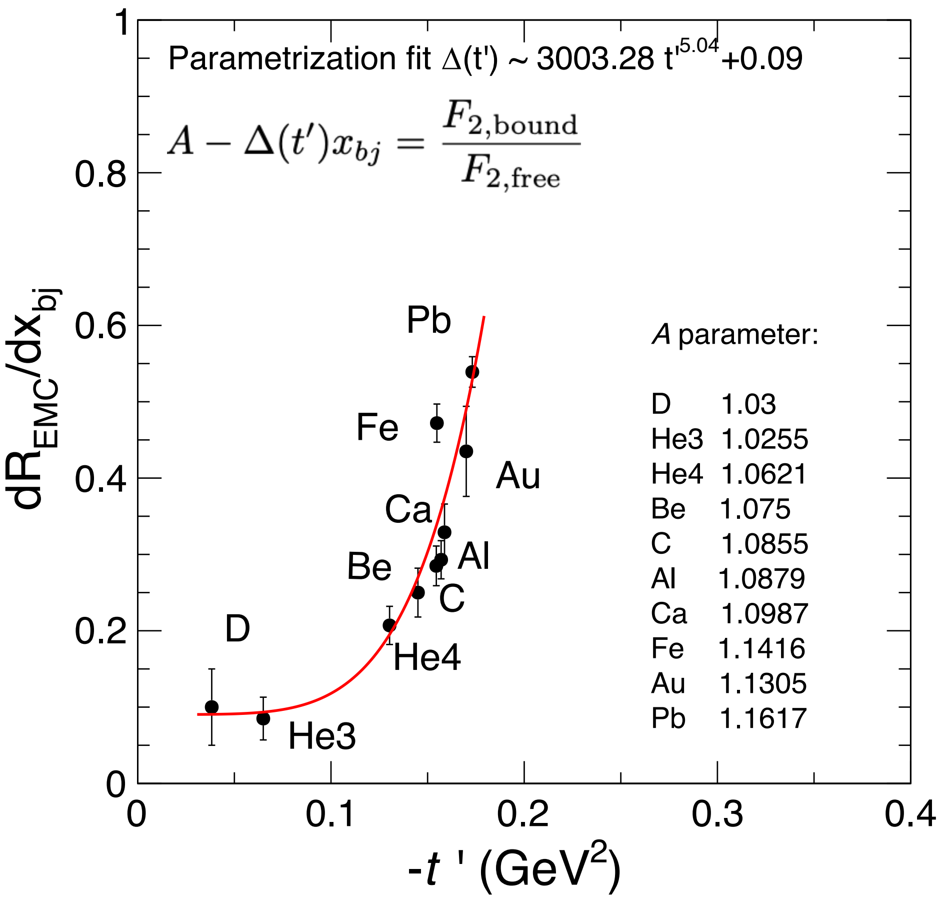
A	$\langle v_{NR}^{(0)} \rangle$	$\langle v_{NR}^{(1)} \rangle$	$\langle v_{NR} \rangle$
^3He	-7.15	-27.44	-34.59
^4He	-26.82	-42.58	-69.40
^{12}C	-33.17	-49.11	-82.28
^{16}O	-31.40	-48.28	-79.68
^{40}Ca	-35.00	-49.54	-84.54
^{56}Fe	-31.66	-50.76	-82.44
^{208}Pb	-32.87	-59.33	-92.20

(MeV)

Table. IV

1. EMC slope from various of data (Jlab, SLAC, etc.)
2. Firstly, we should focus on t' < 0.2 region, constrained by data.
3. *Quick comment: deut t' can be > 0.2. However, this parametrization goes too *fast*. Should think about another parametrization for region t' > 0.2

Best fit found (so far) is a power function, while linear extrapolation clearly is insufficient



BeAGLE implementation

✓ Goal:

1. Use parametrization to generate a "look-up" table on the flight, for each x_{bj} and deuteron configuration (t');
2. Obtain an event weight, which accounts for the EMC effect for every corresponding deuteron configuration; Easy to process. [No need to do complicated "after-burner" on the analysis level]
3. Users only need to apply this event weight, nothing else is needed. Easy to compare w/o weight and with different alpha, pT dependence.
4. (Hopefully) Easier for later detector simulations plugin.

- Status/Properties:

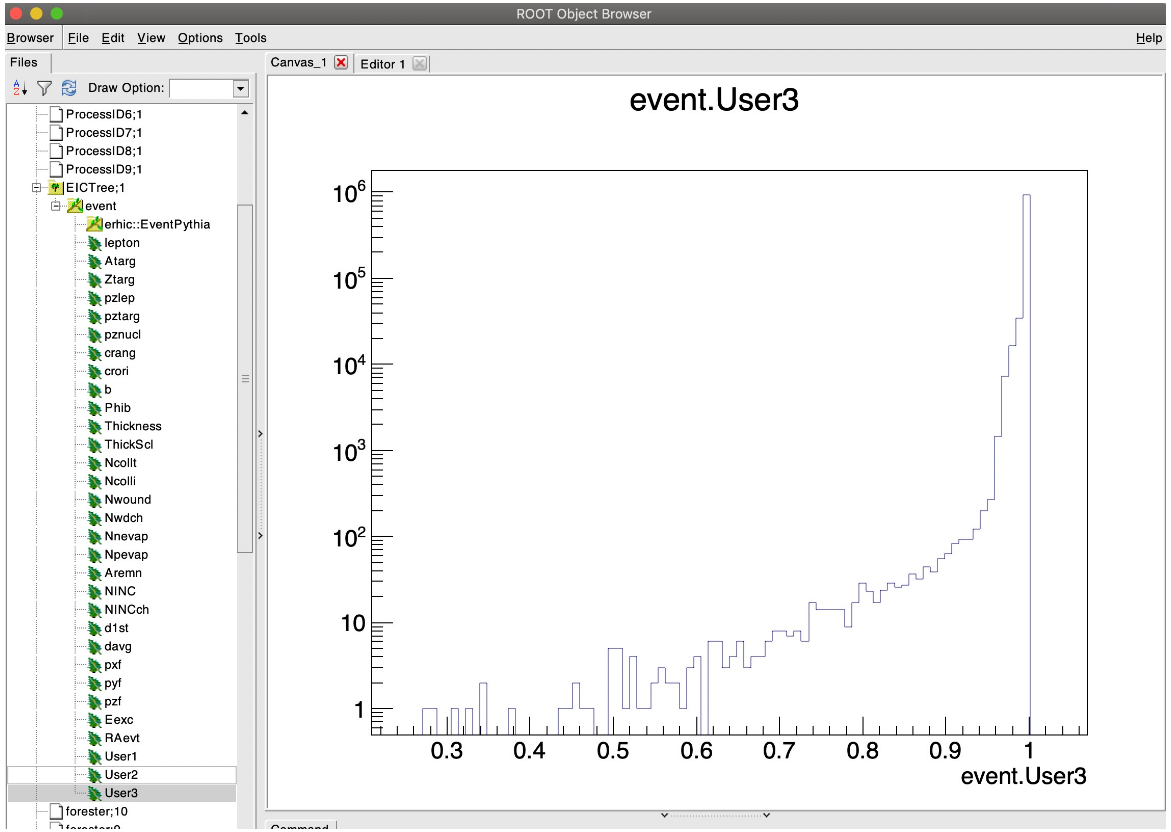
1. Q^2 independent, only [x_{bj},t'] dependent.
2. Only apply to 0.3 < x < 0.7, everywhere else the weight = 1.0;
3. The EMC slope cannot be exceeded -2.5 ($F_{2,bound}/F_{2,free}$ cannot be less than zero at x=0.7)
4. BeAGLE **v1.01.05** (will be updated with master when done with tests), test codes live under "/gpfs02/eic/ztu/BeAGLE/BeAGLE_devK_TaggedEMC_2022-01-13/BeAGLE"
5. 100M events – 5x41 eD DIS events are produced and ready to be analyzed. (/gpfs02/eic/ztu/Analysis/BeAGLE/eD_Tagged_DIS/5x41_Q2_10/batch_2_output/*.root)

EMC factor

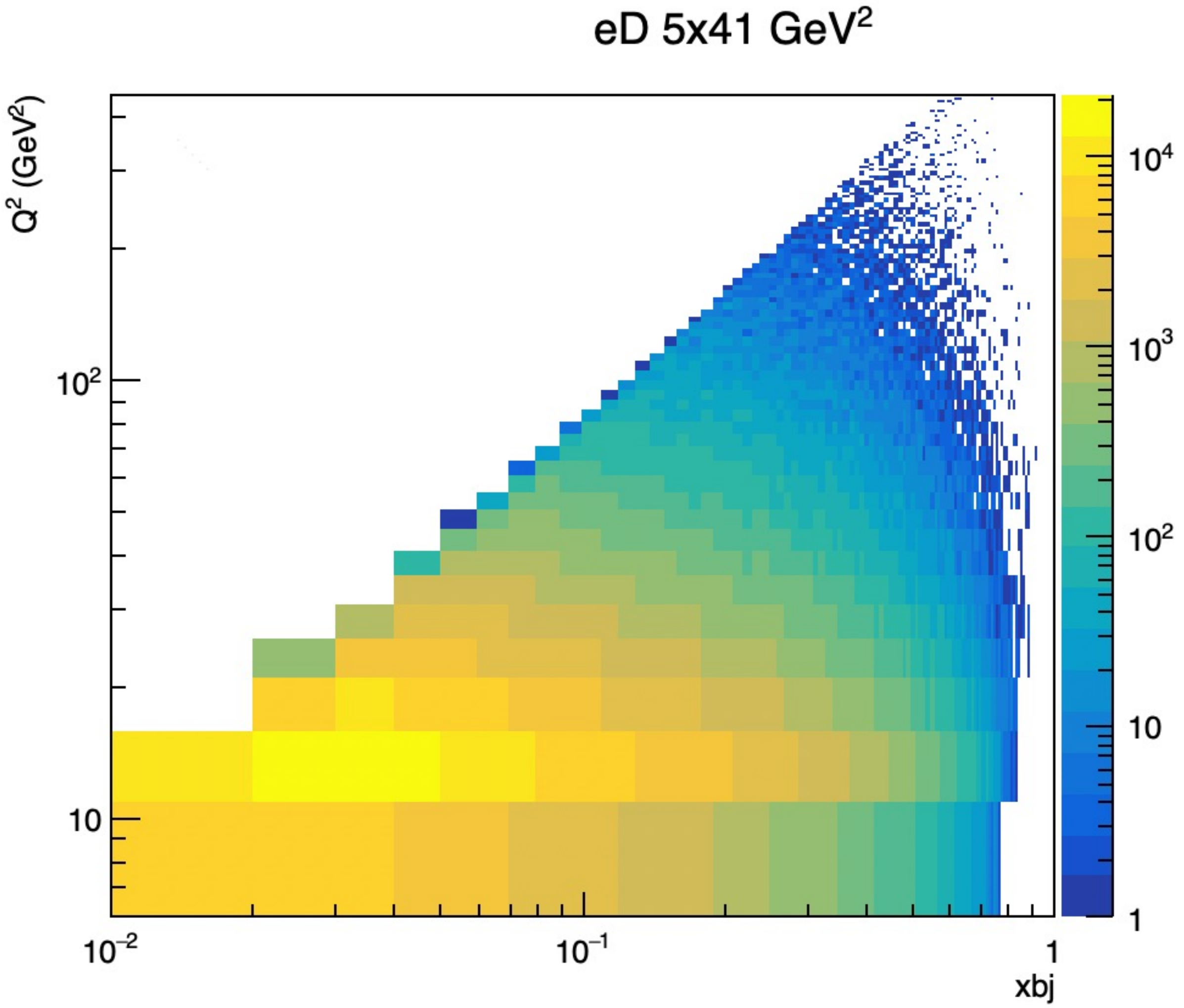
- When running BeAGLE, there is one switch to turn this on. → FERMI line, fourth argument = 2

- Set USERSET = 17
  1. User1 = t'
  2. User2 = $\Delta(t')$
  3. User3 = EMC weight in terms of $F_{2,bound}/F_{2,free}$

- Event-by-event weight. For any distribution, this weight can be applied, e.g., reduced cross section.



Phase space

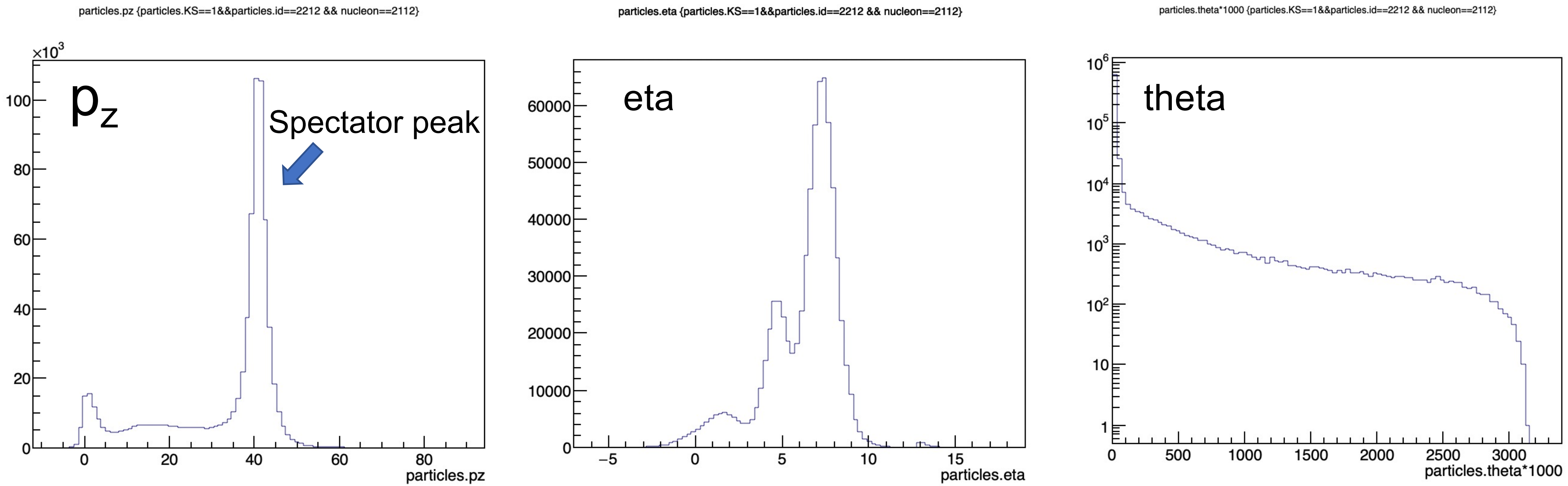


- Lowest EIC energy setting can reach the EMC region with $Q^2 > 10$ GeV^2
- Statistics should not be a problem, but it depends on how differential the measurements are.
- We should pick our binning from the start (lessons learned from last paper)

e.g.,
- Q2[]={10,20,40,100,above)
- x[]={0.08,0.12,0.2,0.25,0.3,0.35,0.4,0.45,0.5 ,0.55,0.6,0.65,0.7,0.75}

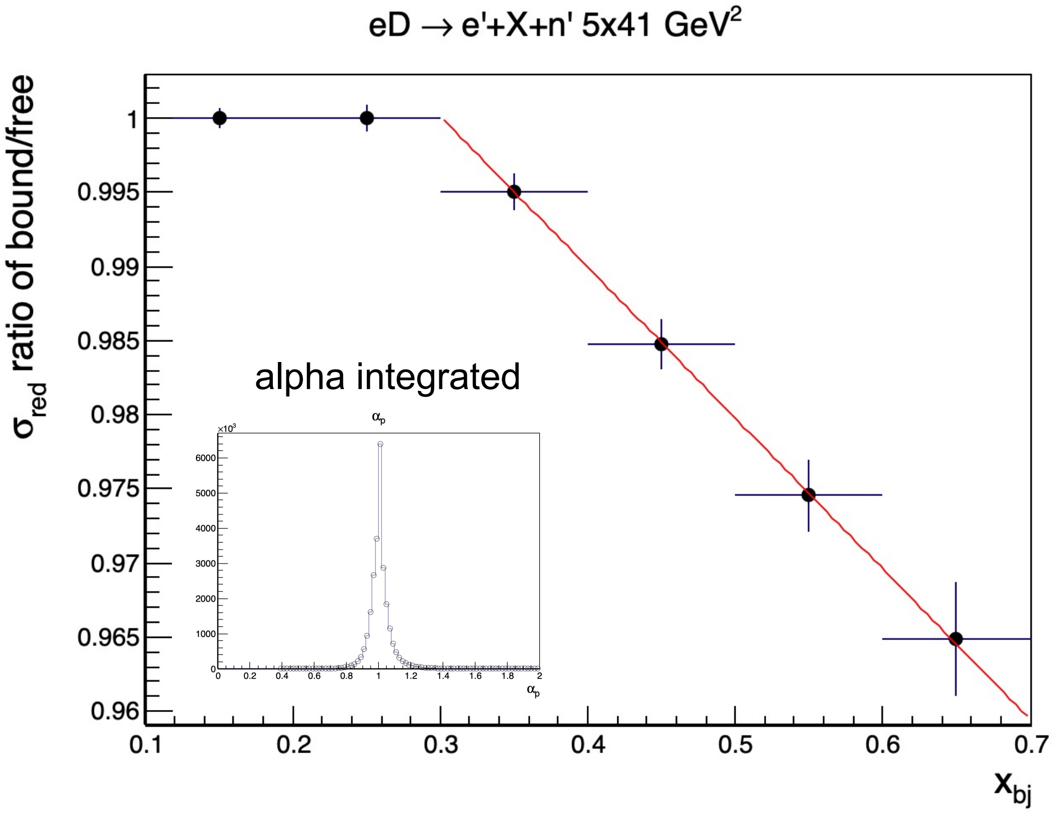
(just an example)

Proton distributions when neutron is hit.



- Very different acceptance is needed in this phase space in terms of spectator tagging
- Full simulations will be of great help

Results (1)

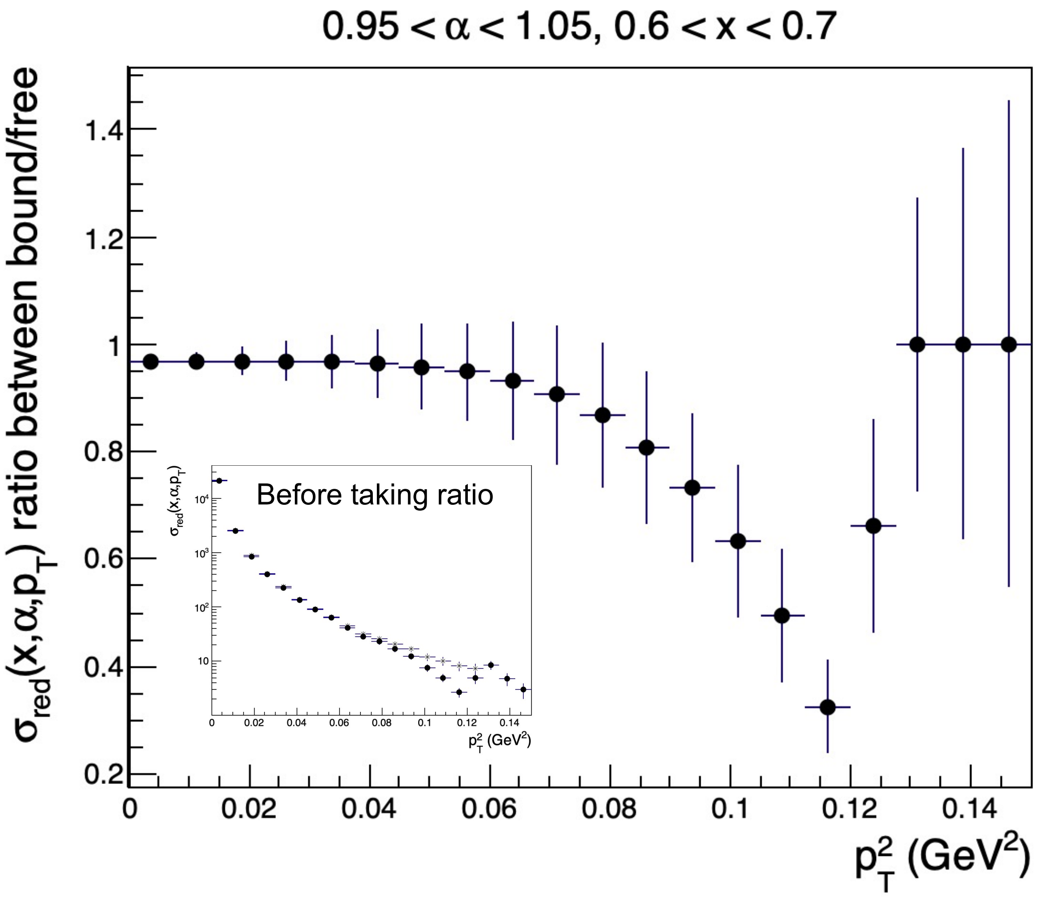


BeAGLE v1.01.05 (test version)

Ratio = With/without weight

- Inclusive tagged DIS measurement with neutron spectator – average deuteron configuration.
- $10 < Q^2 < 15$ GeV^2, $0.01 < y < 0.95$, 100M events in total. (Error bar is currently overestimated due to correlation)
- DIS reduced cross section was measured, and compare w. and without weight (bound vs free)
- The slope gives -0.1, consistent with our parametrization. [closure test]

Results (2)



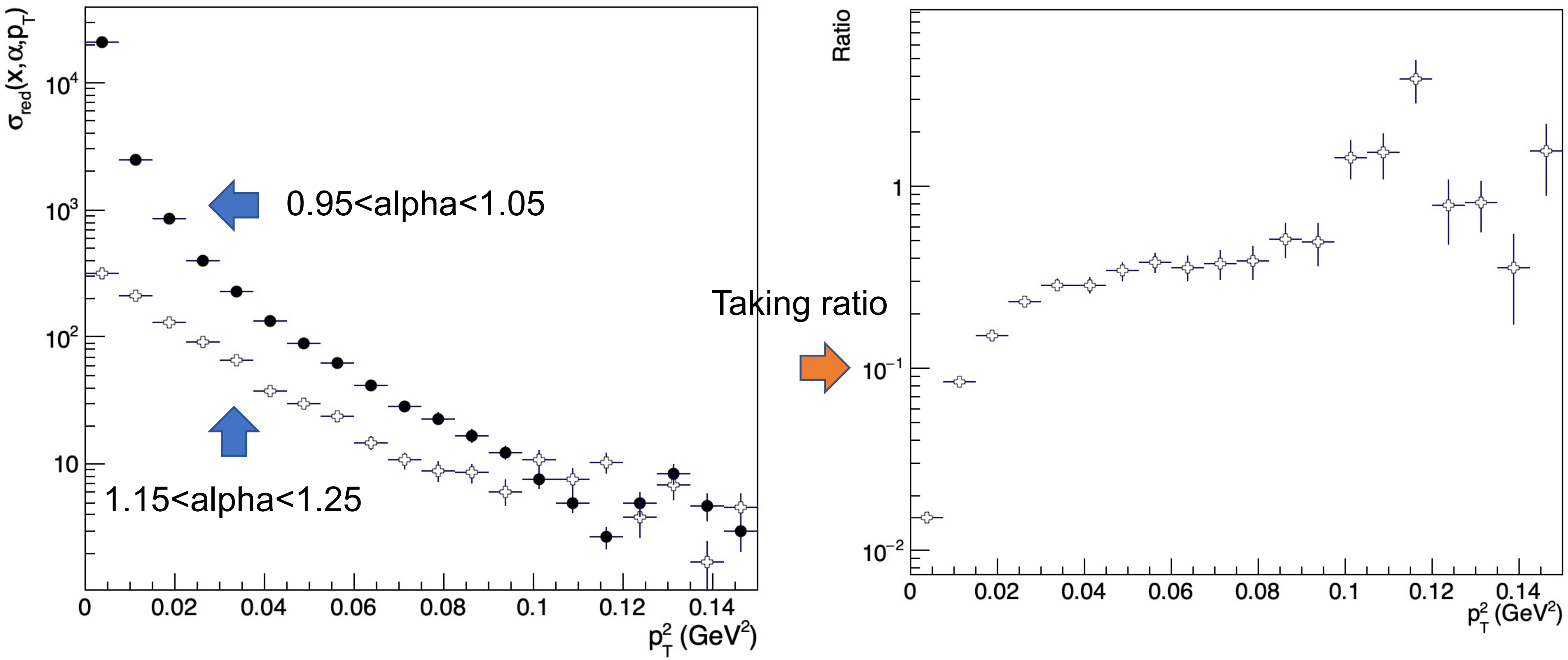
Ratio = With/without weight

- Differential measurement on reduced cross section ratio as a function of p_T^2 of spectator;
- $10 < Q^2 < 15$ GeV^2, $0.01 < y < 0.95$, 0.95<alpha<1.05, 0.6<x<0.7 [One bin]
- The sudden dip around 0.12 is because the parametrization runs out, and the slope becomes too steep. Currently I put the EMC factor back to 1.

Result (3)

0.6<x<0.7

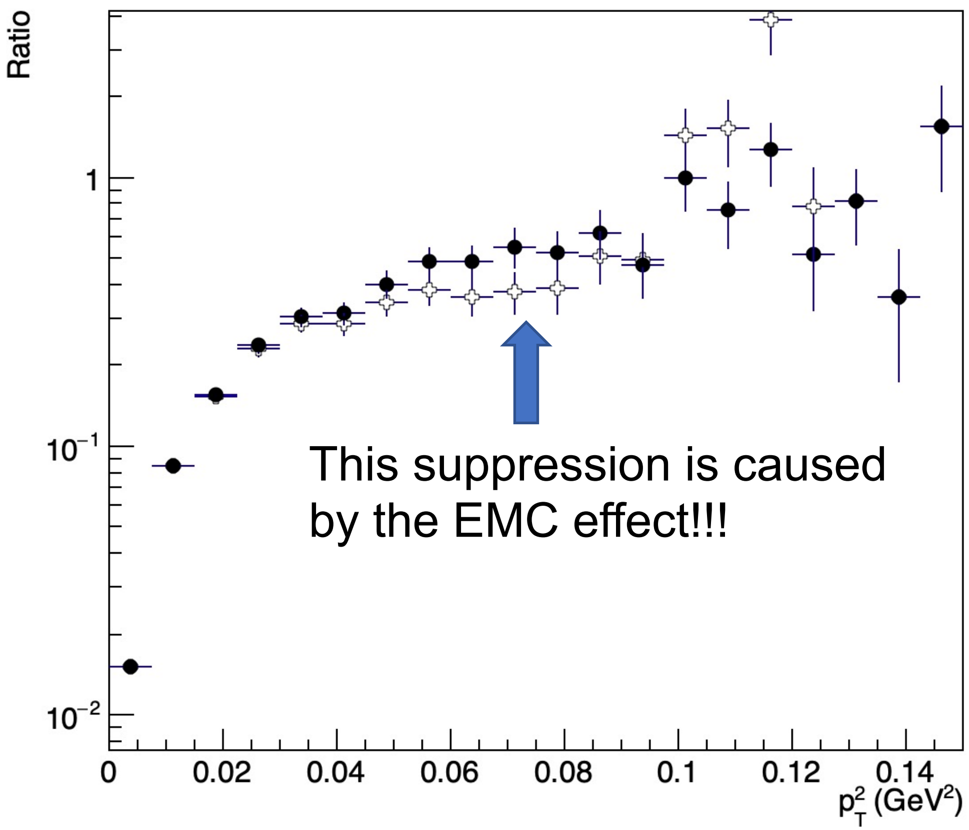
With EMC weights applied



- Difference in magnitude on reduced cross section due to alpha distribution. Cross section formula was used from our PRC paper, i.e., up to the step before we remove the pole.

Result (3) cont.

0.6 < x < 0.7

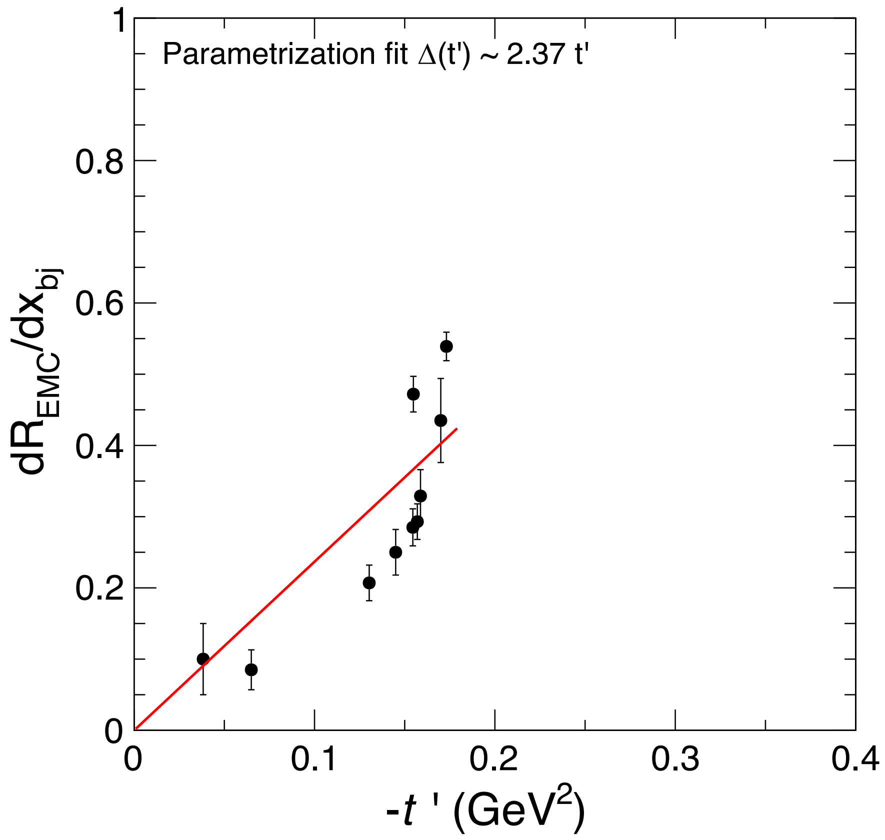


- Ratio = 1.15<alpha<1.25 / 0.95<alpha<1.05 in terms of reduced cross section (**same as previous slide**)

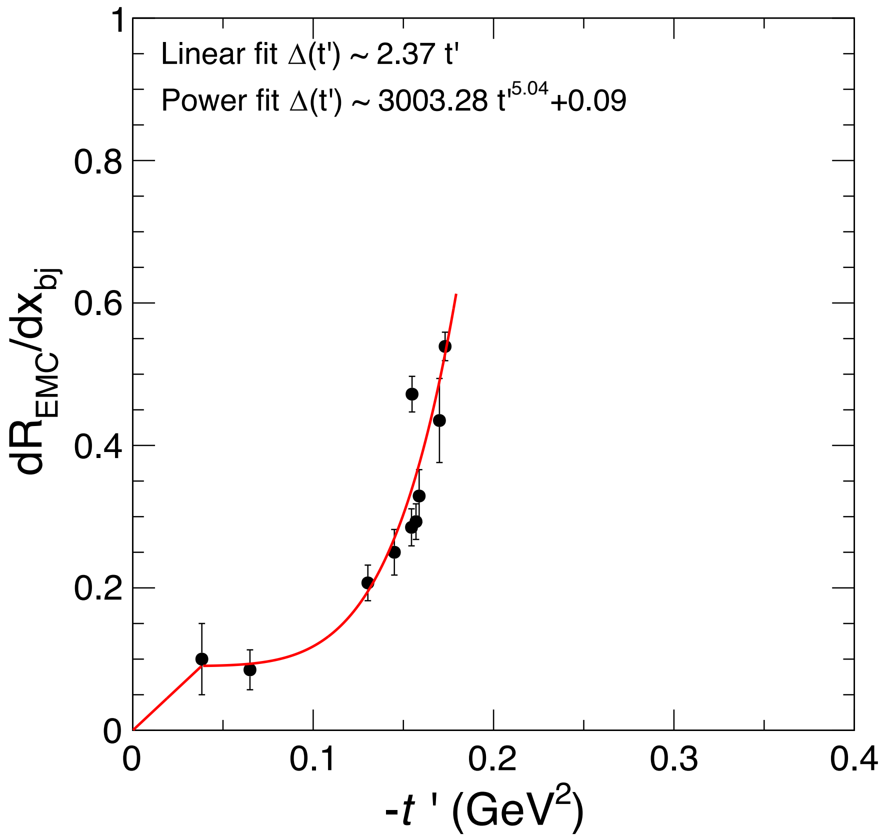
- Solid = without weight (default BeAGLE)
- Open = w. weight**, same as previous slide**

- Taking another ratio (double ratio) would be the effect of EMC.

New parametrizations



Linear



Linear + Power law

Summary

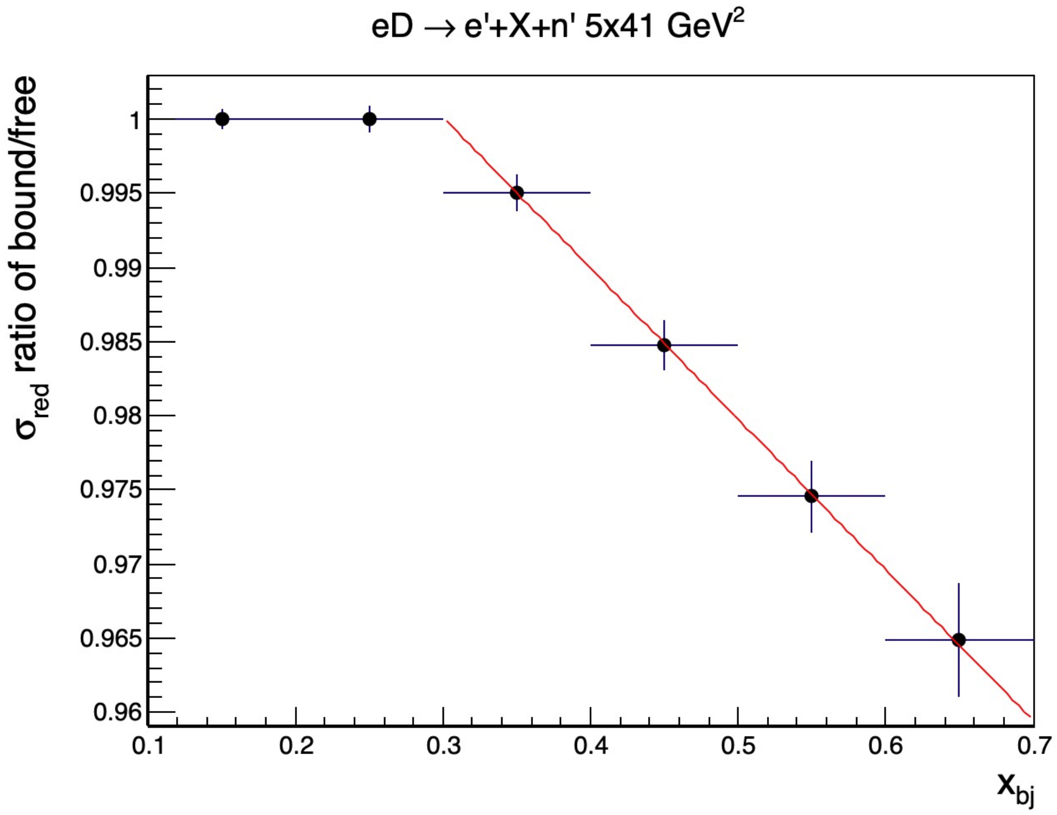
- Simple parametrization on the EMC effect has been done. Power law function is being used. *Alternative parametrization to higher t' would be needed.*

- This has been implemented in BeAGLE as a new feature. Easy to use for analyzers as an event weight (v1.01.05)

- 3x(100M) 5x41 eD new BeAGLE has been generated and ready for more rigorous analyses.

- First look at the results - very interesting. Now it's time to think more on what observables we would like to measure.

Deuteron EMC feature



BeAGLE v1.04.05 (test version)