Deuteron breakup kinematics in BeAGLE event generator

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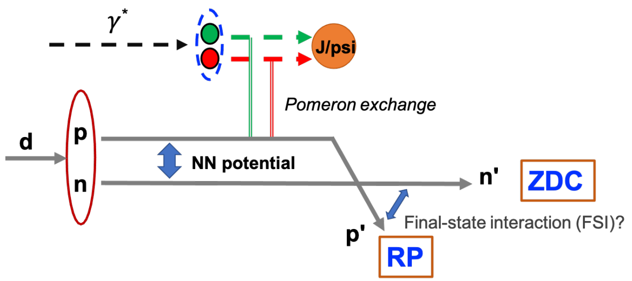
Status

- One process:

$$e+D = e'+J/psi+p'+n'$$



was implemented in BeAGLE, which consists of realistic deuteron wavefunction and LF kinematics of the struck and spectator nucleons.

- Useful for both EIC physics and detector requirements studies with spectator tagging.
  - Short-range nuclear correlations in deuteron.
  - Incoherent diffractive VM production.
  - DVCS on deuteron (incoherent)
  - …
- Replace J/psi with any particle of one's interest, the tagging is still valid.
- This study overlaps with other subgroups of YR effort. *Take what you need and/or tell us what you need.*

- In this talk, the study is done with ***J/psi***, but it can apply to any VM or photon or dijet or …

Observables and detectors

Physics observables:

Observables	SRC	DVCS	VMP
p_m (GeV) p_T ,p_z (GeV)	✓		✓
t (GeV^2) = $(e'-e+V)^2$		✓	✓
alpha (LC mom. frac.)	✓		✓
S_{PN} (GeV^2) (s btw. p' and n')	✓		✓
t' (GeV^2) = $(p'/n'-d)^2$	✓	✓	✓
theta' (p'/n' polar angle w.r.t gamma*)	✓		
p_T of VM (e.g., J/psi, photon, dijets)	…	✓	✓

Toy EIC forward detectors

Detectors	Neutron det.	Proton det.
Energy reso.	$\frac{50\%}{\sqrt{E}} + 5\%$	
Angular reso. (mrad)	0.3	
Momentum reso.		$\frac{dp_T}{p_T} = 3\%$
Acceptance (mrad)	5	$(0,5)$ $(7,22)$

BeAGLE parameters

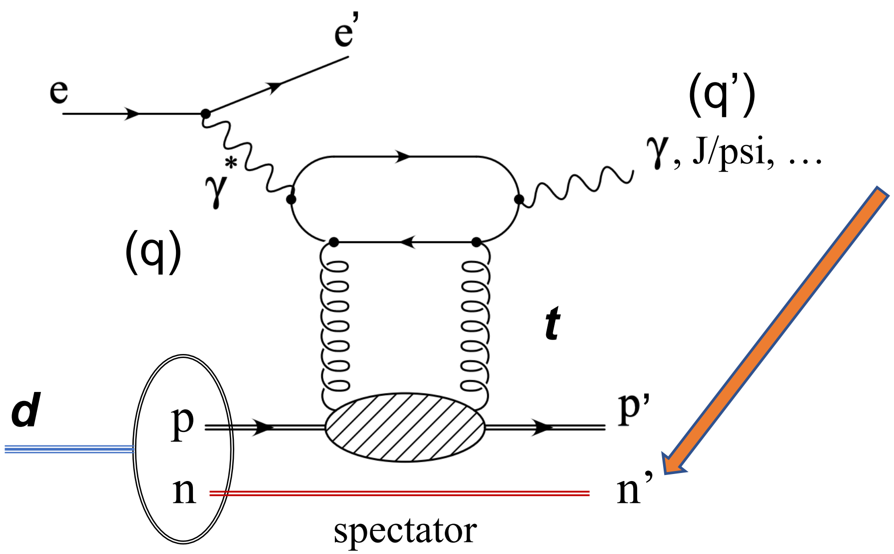
- 18 GeV electron scattering off 135 GeV deuteron
- Other available energy configurations for EIC, e,g., 5x20, 10x50 GeV
- Deuteron wavefunction for ***k***, where ***k*** is momentum of nucleon in p+n frame. Taken from [Phys. Rev. C 53, 1689]
- LC kinematics of nucleons in deuteron, taken from Strikman & Weiss [Phys.Rev. C97 (2018) no.3, 035209]

- 1M events with incoherent diffractive J/psi production

(optional, BeAGLE can keep J/psi decay or not decay to lepton pairs)

- $Q^2 > 1$ GeV^2
- $0.05 < y < 0.85$

Kinematic variables

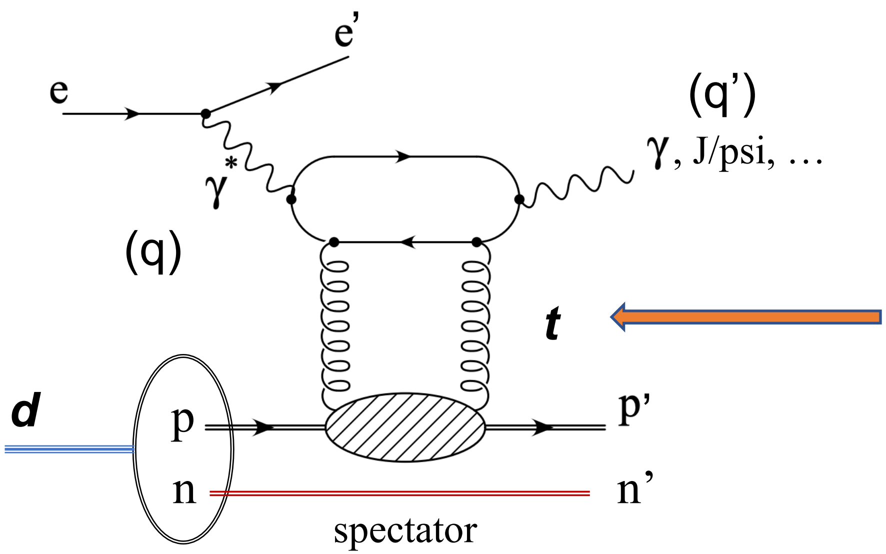


Observables	SRC	DVCS	VMP
p_m (GeV) p_T ,p_z (GeV)	√		√
t (GeV^2) = $(e'-e+V)^2$		√	√
alpha (LC mom. frac.)	√		√
S_{PN} (GeV^2) (s btw. p' and n')	√		√
t' (GeV^2) = $(p'/n'-d)^2-M^2$	√	√	√
theta' (p'/n' polar angle w.r.t gamma*)	√		
p_T of VM (e.g., J/psi, photon, dijets)		√	√

p_m ,p_t ,p_z :

Total, transverse, and longitudinal momentum of spectator nucleon in ***d*** rest frame

Kinematic variables



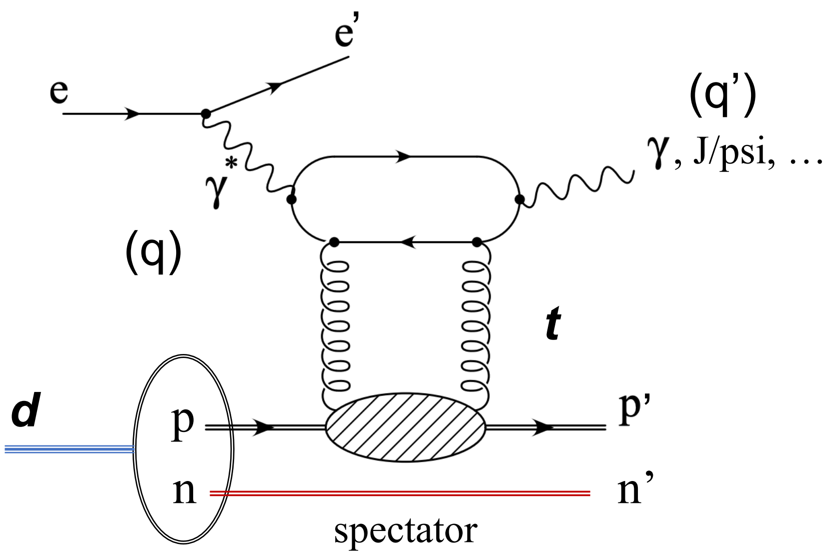
$t = (e'-e+V)^2 = (p' - (-n''))^2$

Momentum transfer from virtual photon to the struck nucleon

-n'' = p, the initial momentum of the struck nucleon

Observables	SRC	DVCS	VMP
p_m (GeV) p_T, p_z (GeV)	√		√
t (GeV^2) = $(e'-e+V)^2$		√	√
alpha (LC mom. frac.)	√		√
S_{PN} (GeV^2) (s btw. p' and n')	√		√
t' (GeV^2) = $(p'/n'-d)^2-M^2$	√	√	√
theta' (p'/n' polar angle w.r.t gamma*)	√		
p_T of VM (e.g., J/psi, photon, dijets)		√	√

Kinematic variables



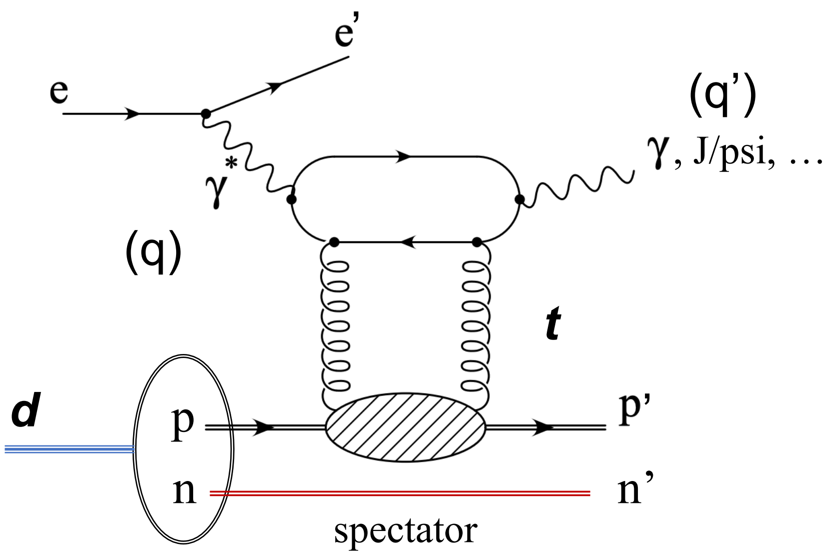
Observables	SRC	DVCS	VMP
p_m (GeV) p_T ,p_z (GeV)	√		√
t (GeV^2) = (e'-e+V)^2		√	√
alpha (LC mom. frac.)	√		√
S_{PN} (GeV^2) (s btw. p' and n')	√		√
t' (GeV^2) = (p'/n'-d)^2-M^2	√	√	√
theta' (p'/n' polar angle w.r.t gamma*)	√		
p_T of VM (e.g., J/psi, photon, dijets)		√	√

alpha:

Light cone momentum fraction

$$\alpha = \frac{2p^+_{n'}}{p^+_d}$$

Kinematic variables

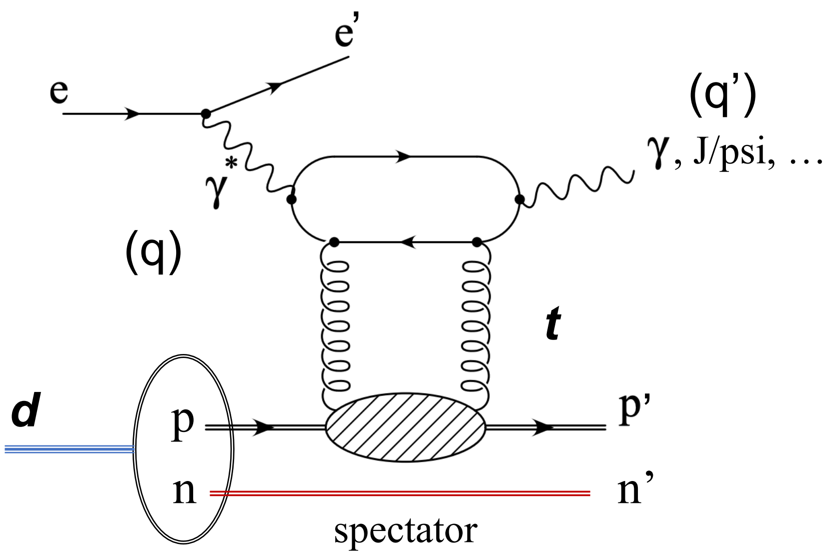


s_{PN}:

Center-of-mass energy between proton and neutron squared $(p' + n')^2$

Observables	SRC	DVCS	VMP
p_m (GeV) p_T ,p_z (GeV)	✓		✓
t (GeV^2) = $(e'-e+V)^2$		✓	✓
alpha (LC mom. frac.)	✓		✓
S_{PN} (GeV^2) (s btw. p' and n')	✓		✓
t' (GeV^2) = $(p'/n'-d)^2-M^2$	✓	✓	✓
theta' (p'/n' polar angle w.r.t gamma*)	✓		
p_T of VM (e.g., J/psi, photon, dijets)		✓	✓

Kinematic variables

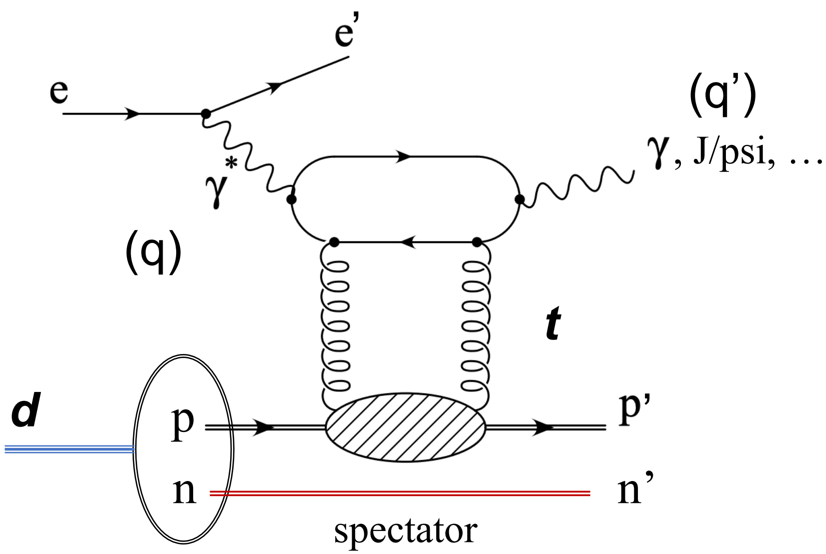


$t' = (n'-d)^2 - M^2$:

effective struck nucleon off-shellness

Observables	SRC	DVCS	VMP
p_m (GeV) p_T, p_z (GeV)	✓		✓
t (GeV^2) $= (e'-e+V)^2$		✓	✓
alpha (LC mom. frac.)	✓		✓
S_{PN} (GeV^2) (s btw. p' and n')	✓		✓
t' (GeV^2) $= (n'-d)^2-M^2$	✓	✓	✓
theta' (p'/n' polar angle w.r.t gamma*)	✓		
p_T of VM (e.g., J/psi, photon, dijets)		✓	✓

Kinematic variables

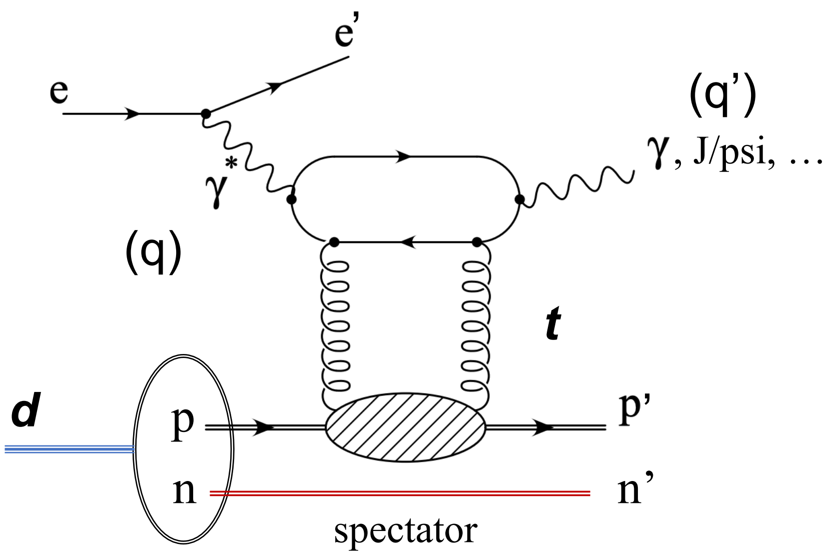


theta':

Spectator nucleon polar angle w.r.t virtual photon direction in target rest frame

Observables	SRC	DVCS	VMP
p_m (GeV) p_T ,p_z (GeV)	√		√
t (GeV²) = (e'-e+V)²		√	√
alpha (LC mom. frac.)	√		√
S_{PN} (GeV²) (s btw. p' and n')	√		√
t' (GeV²) = (p'/n'-d)²-M²	√	√	√
theta' (p'/n' polar angle w.r.t gamma*)	√		
p_T of VM (e.g., J/psi, photon, dijets)		√	√

Kinematic variables

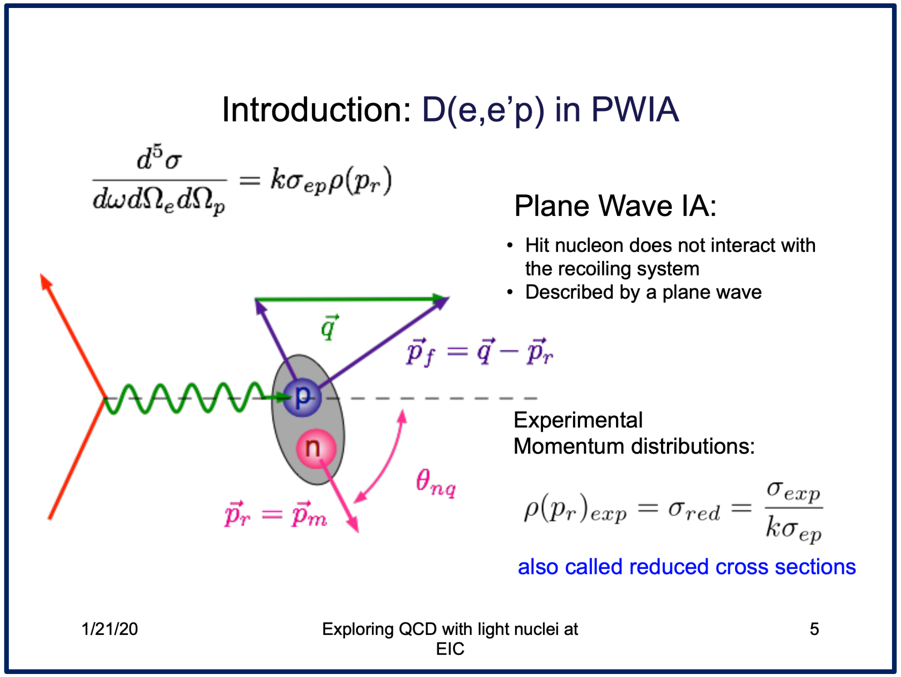


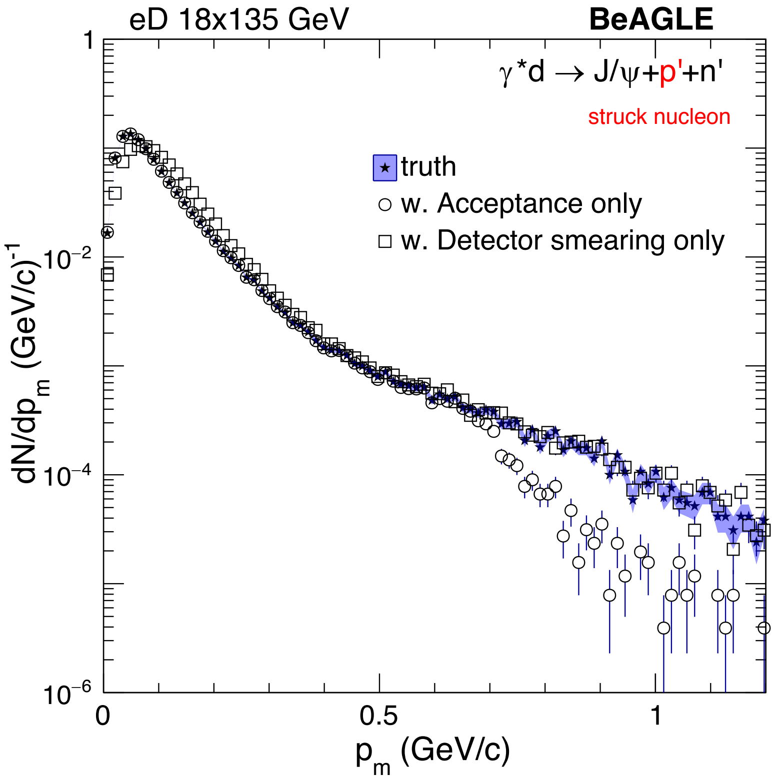
p_T of VM:

Transverse momentum of VM, e.g., J/psi, rho0, or other particles like real photon ..

Observables	SRC	DVCS	VMP
p_m (GeV) p_T ,p_z (GeV)	✓		✓
t (GeV^2) = $(e'-e+V)^2$		✓	✓
alpha (LC mom. frac.)	✓		✓
S_{PN} (GeV^2) (s btw. p' and n')	✓		✓
t' (GeV^2) = $(p'/n'-d)^2-M^2$	✓	✓	✓
theta' (p'/n' polar angle w.r.t gamma*)	✓		
p_T of VM (e.g., J/psi, photon, dijets)		✓	✓

PWIA



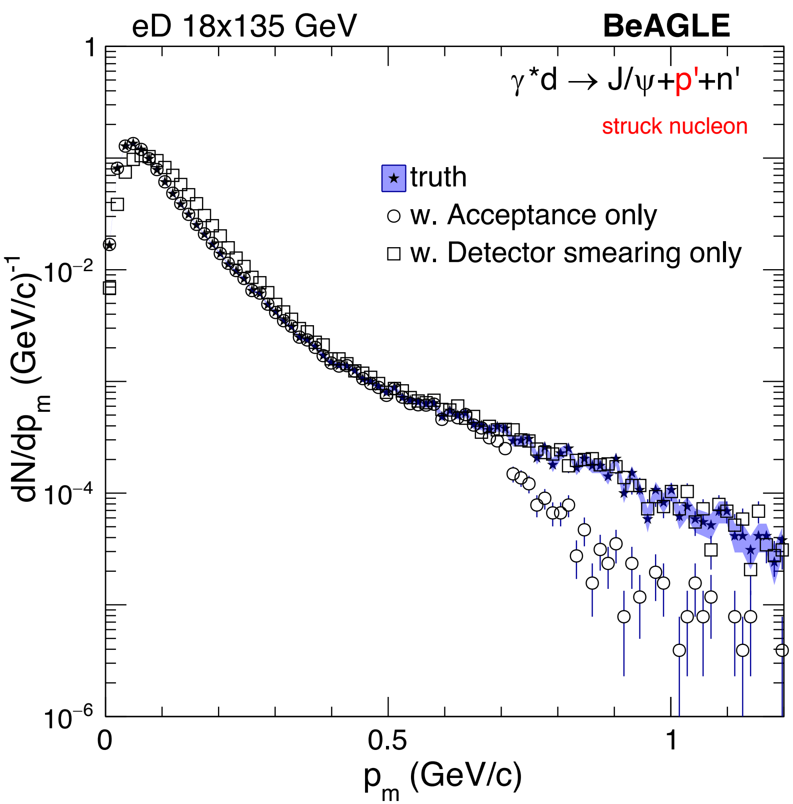


Deuteron SRC 101 by W. Boeglin
Workshop on Light Ion (CFNS)

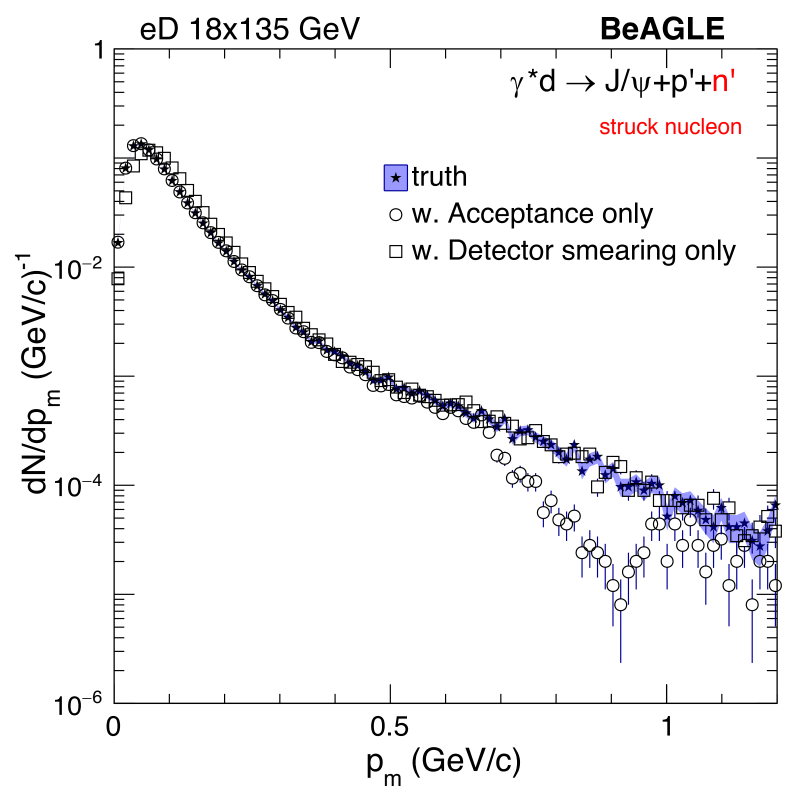
- Low momentum limited by resolution
- High momentum limited by acceptance

Shown this before, next is to compare each observables by tagging protons or neutrons

P_m



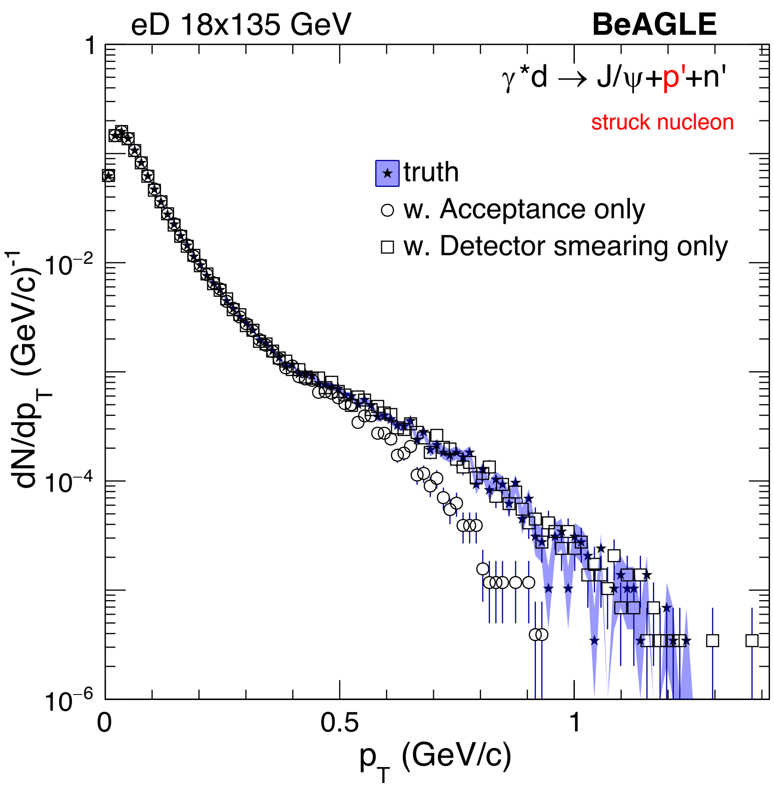
Neutron spectator tagging



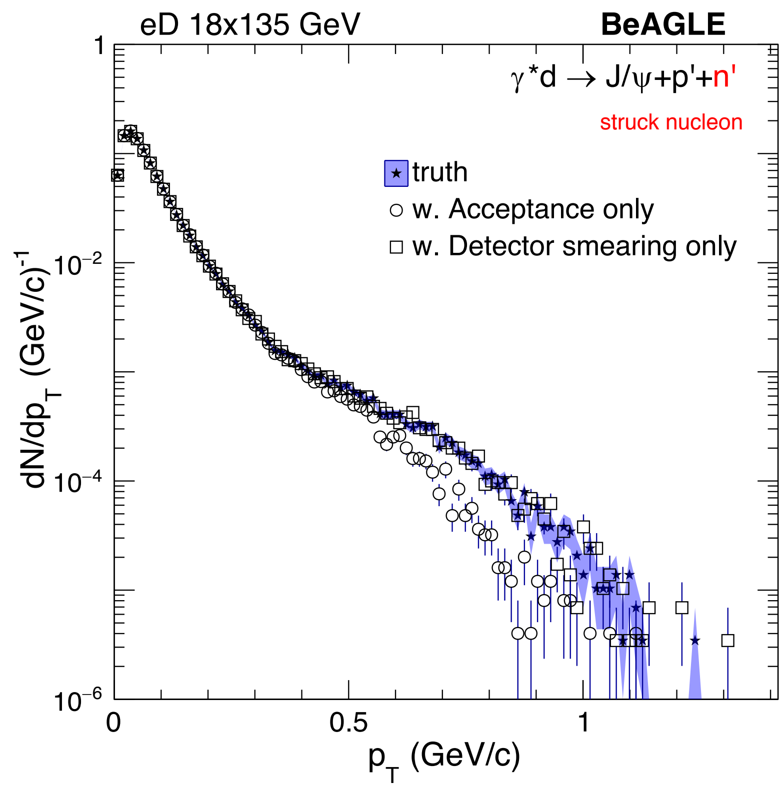
Proton spectator tagging

- Both acceptance and detector resolutions are checked, separately.
- Given the current assumption of detector, tagging proton seems to be better

P_T



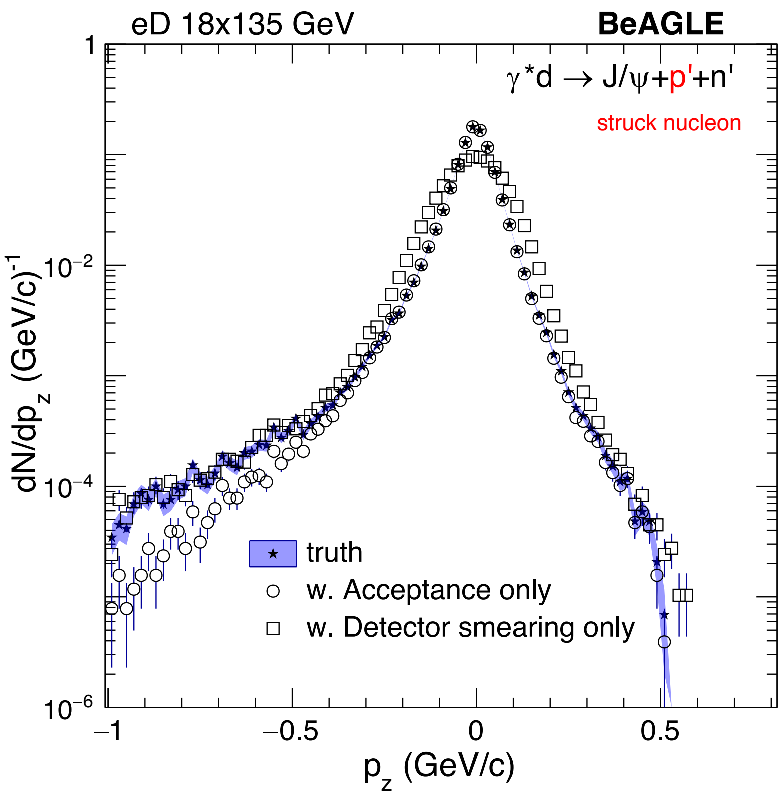
Neutron spectator tagging



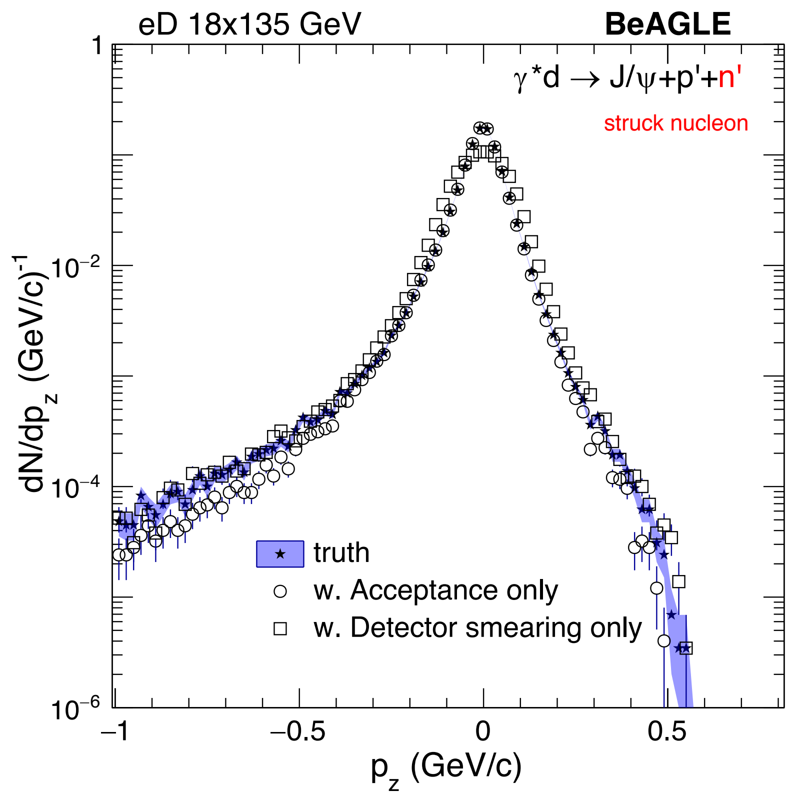
Proton spectator tagging

- There is no significant difference, and the transverse momentum is much less sensitive to detector resolution

p_z



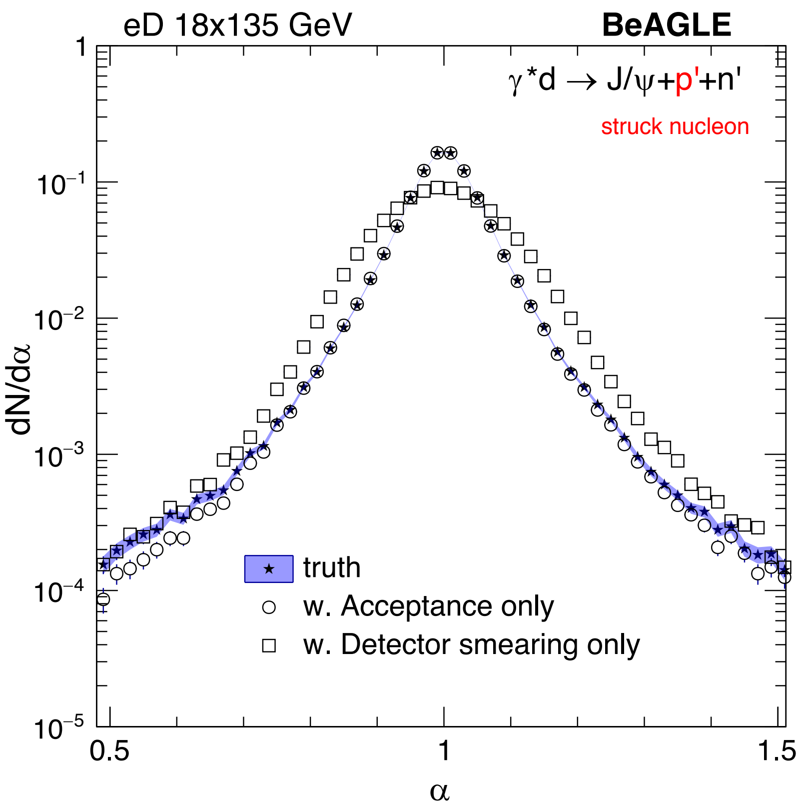
Neutron spectator tagging



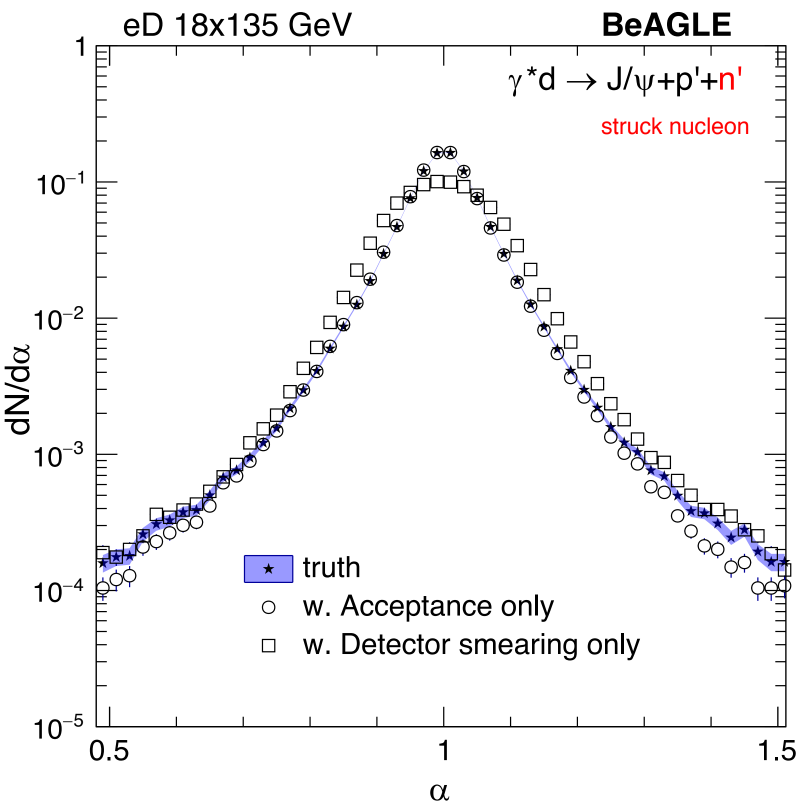
Proton spectator tagging

- Given the current assumption of detector, tagging proton seems to be better

alpha



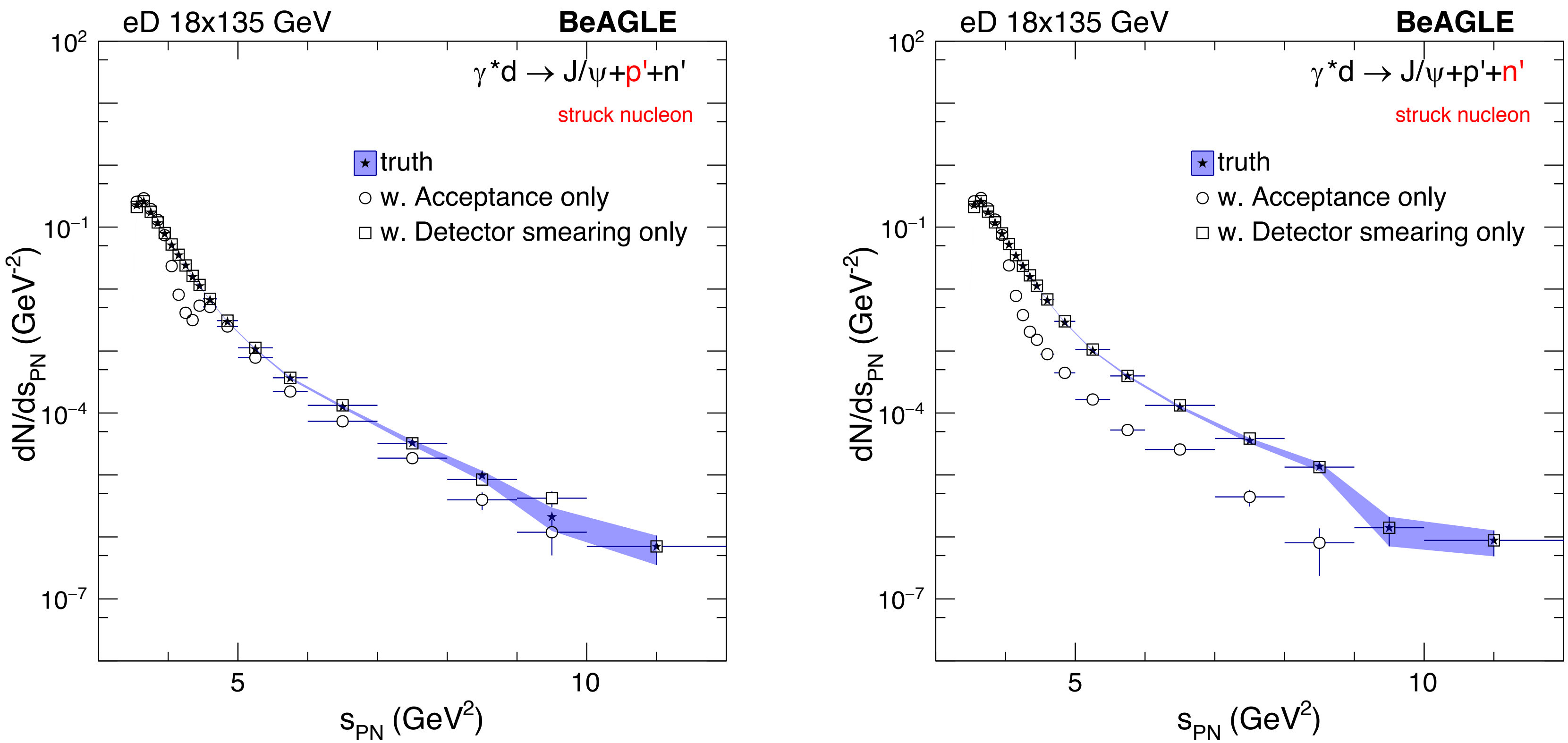
Neutron spectator tagging



Proton spectator tagging

- Given the current assumption of detector, tagging proton seems to be better but not much..

s_{PN}

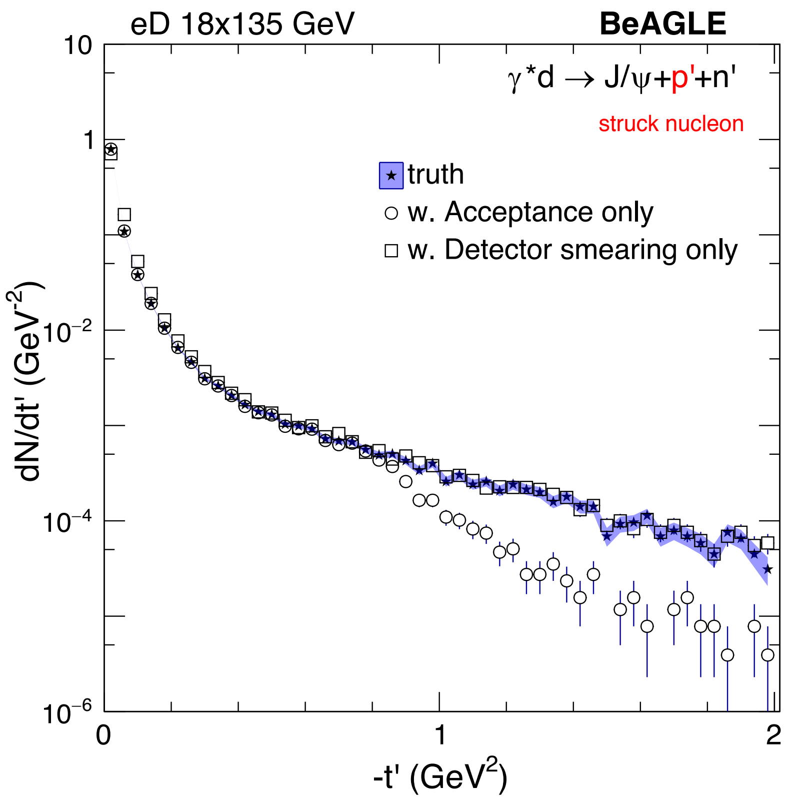


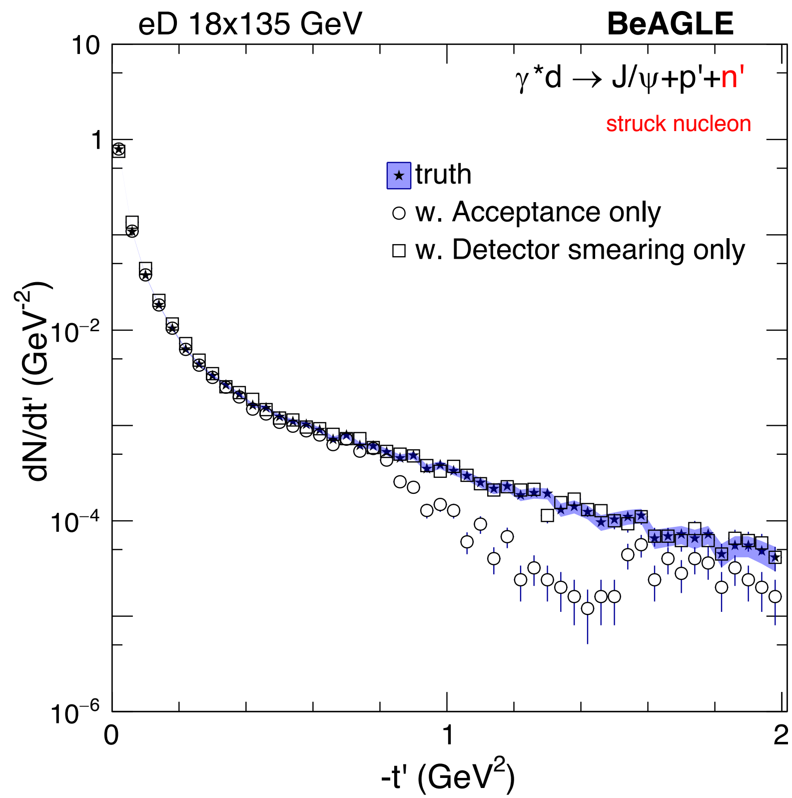
Neutron spectator double tagging

Proton spectator double tagging

- This observable is not so sensitive to the resolution because the lower bound starts at (Mp+Mn)**2, so ~ 100 MeV smearing is not dominant at low s.

t'



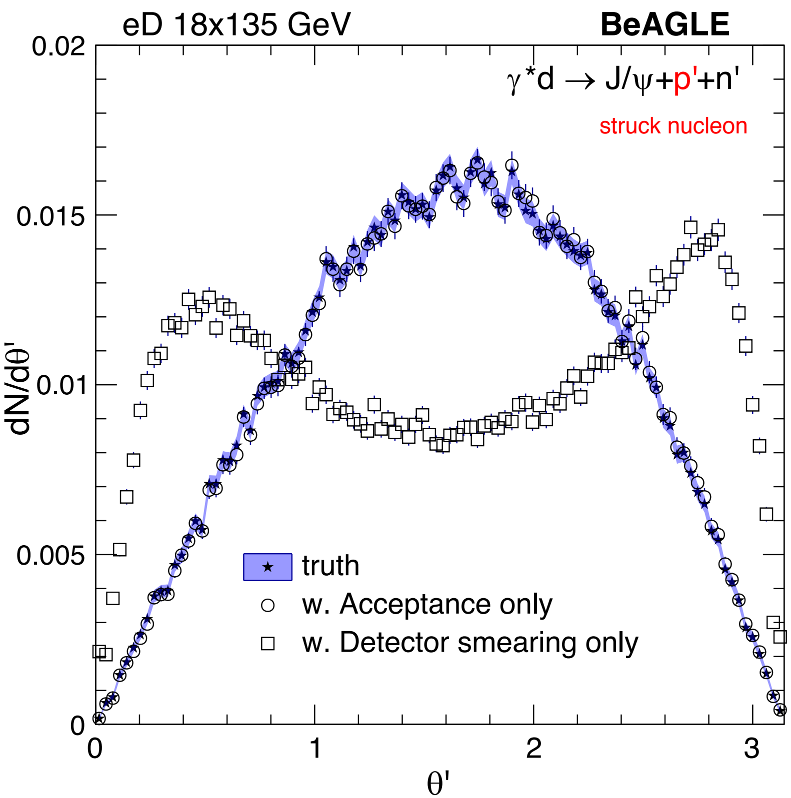


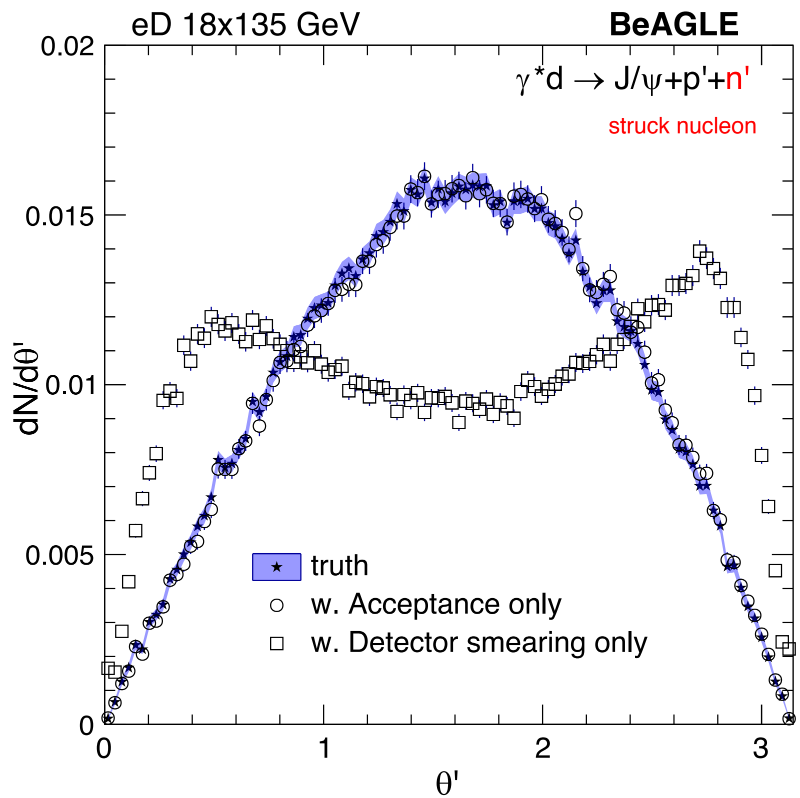
Neutron spectator tagging

Proton spectator tagging

- Important observable to extract free neutron xxx (PDF, GPD, ..)
- Intuitively, this is the struck nucleon off-shellness, and on-shell extrapolation will be needed for certain analysis, so low-***t’*** is essential.

theta'





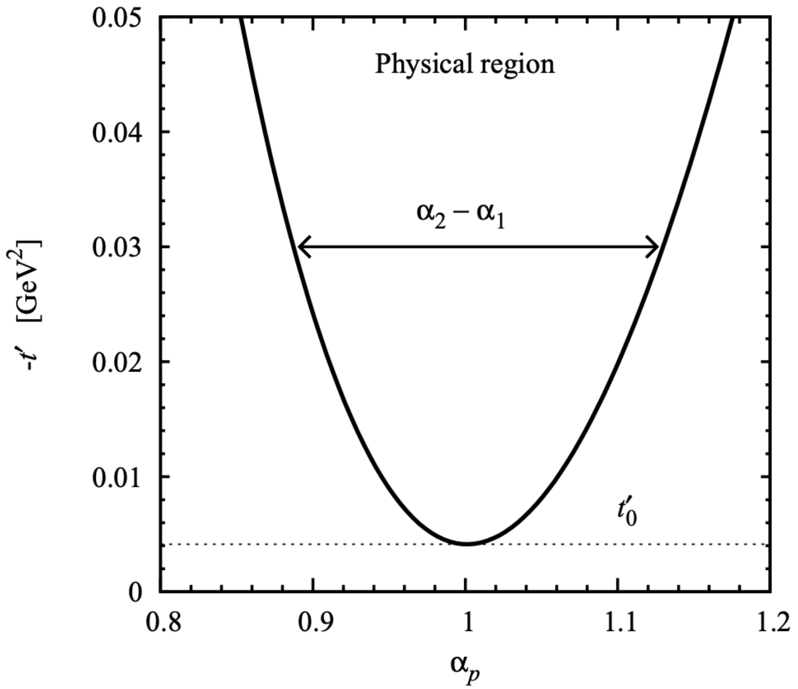
Neutron spectator tagging

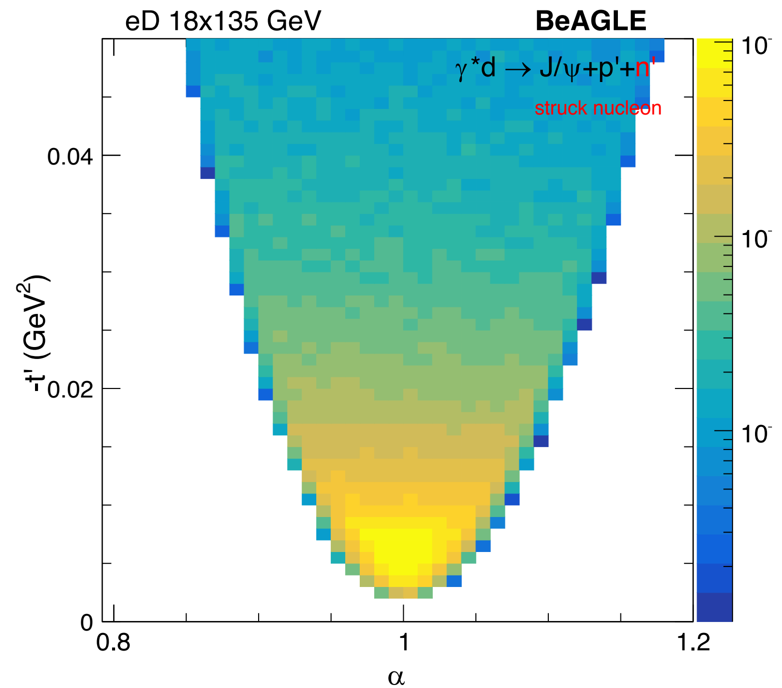
Proton spectator tagging

- Most dramatic smearing in this observable. Is this quantity the right one to look at?
- In the ***d*** rest frame, the angle between photon and spectator nucleon.

Definition found in **PRL 98, 262502 (2007)**

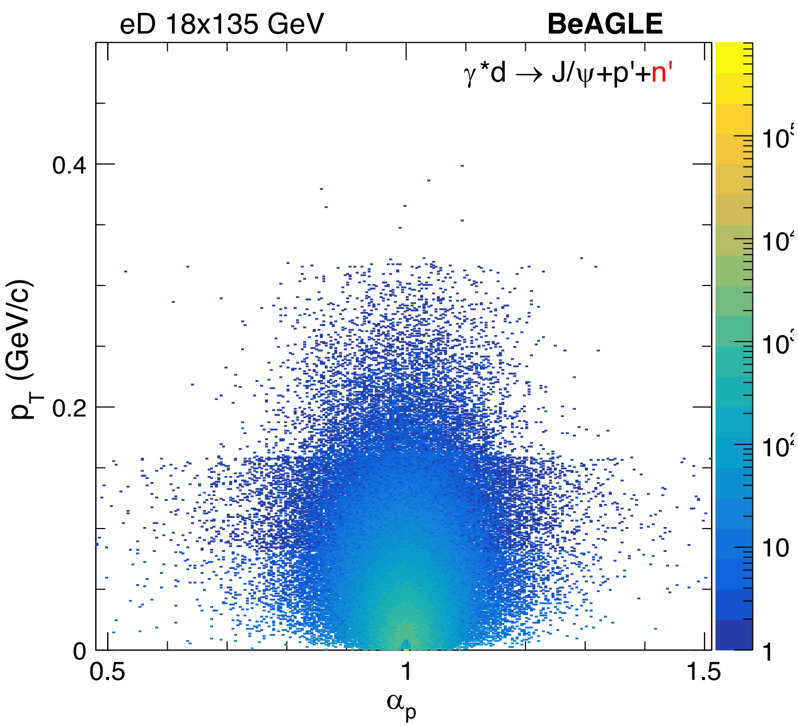
t’ vs alpha





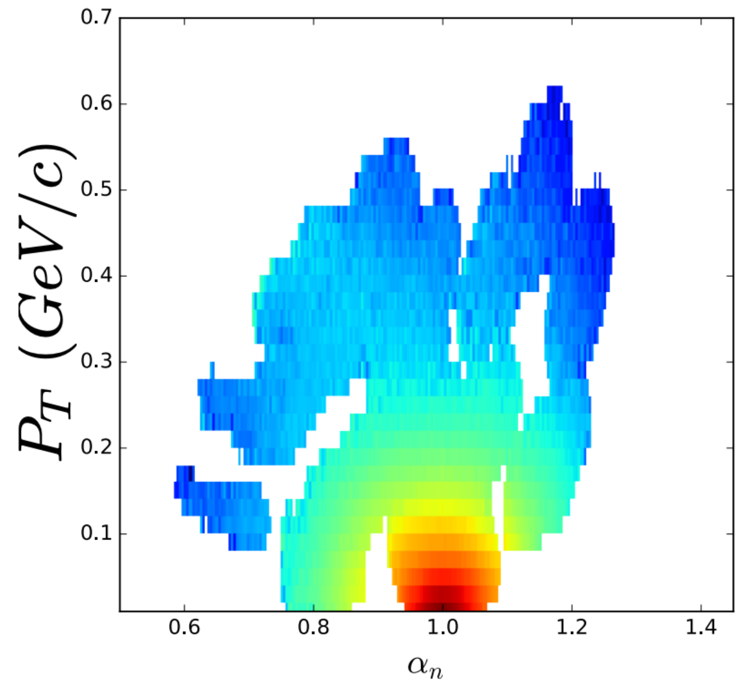
Kinematic limits and physical regions are well reproduced! t_{min} ~ 0.004
Based on Strikman & Weiss paper, https://arxiv.org/abs/1706.02244

Spectral function $S_d(\alpha, p_T)$



Proton spectator tagging
Acceptance only

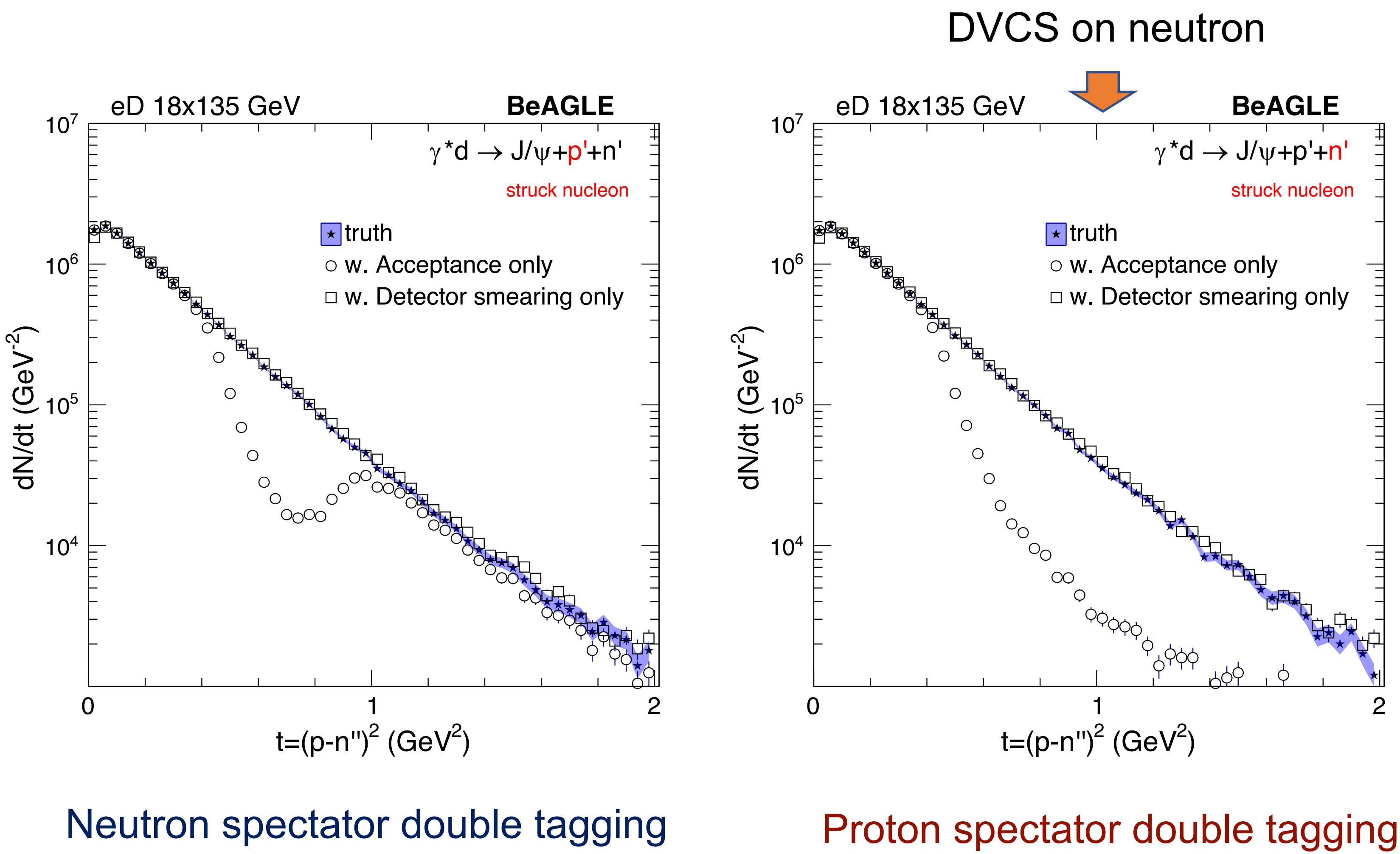
$$0.8\ (GeV/c)^2$$



New results from Jlab preliminary data

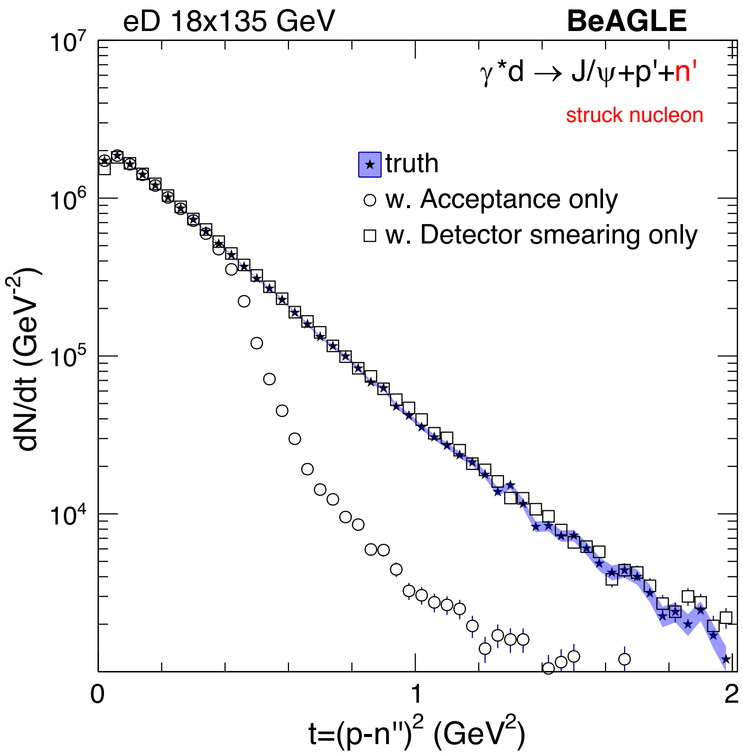
Seems to have a better acceptance for alpha comparing to fixed target experiment?

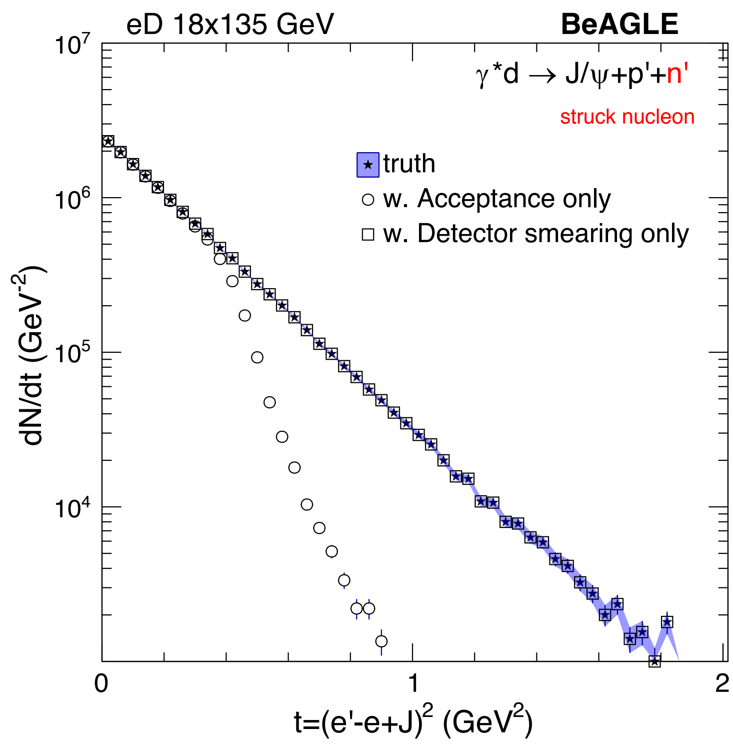
t



- Acceptance is much more important than detector resolution. This method requires double tagging, most of high ***t*** is lost by acceptance.
- A dip structure is observed at low ***t***, might be related to the difference between this method and $t = (e'-e+J)^2$ in BeAGLE.

t compare



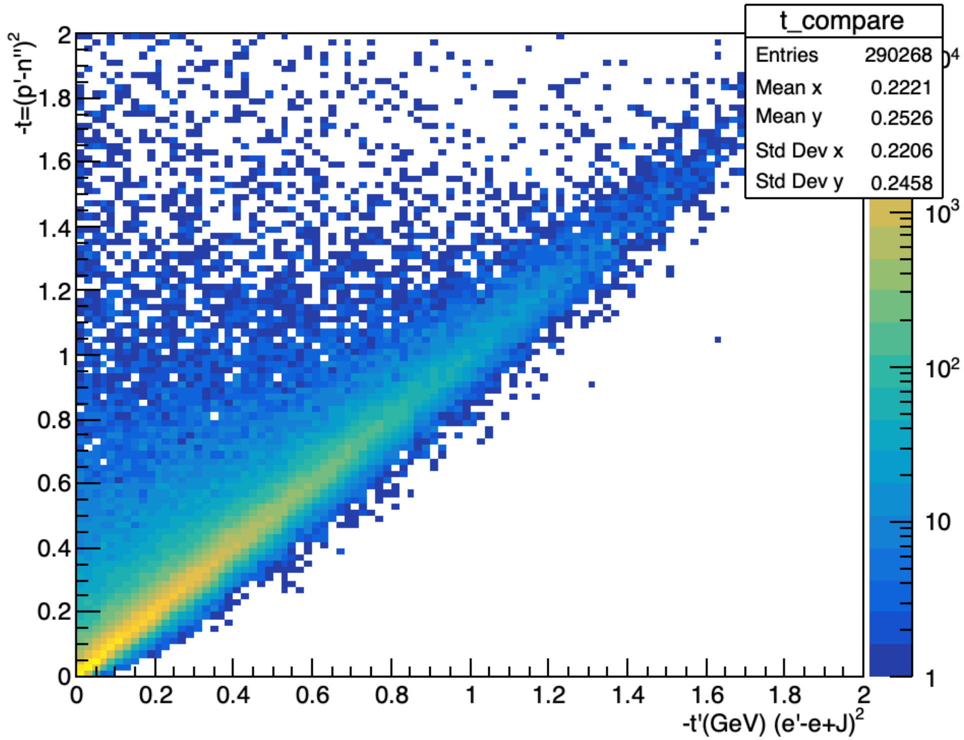


Proton spectator double tagging

- The true ***t*** in BeAGLE is not the physical ***t*** ! The kinematics was given by Pythia, ignoring the fact that nucleon has fermi motion/SRC
- Correcting this kinematics is not so trivial, need to think about it.

- The slopes of these two are slightly different.

t compare



- This is not a resolution effect, it's because of inconsistency in BeAGLE.
- However, for detector requirements, it doesn't matter much.

Comparison

- Neutron detector

Neutron Det.	Default	V1	V2
Acceptance	5 mrad	6 mrad	7 mrad
Energy reso.	$\frac{50\%}{\sqrt{E}} + 5\%$	$\frac{30\%}{\sqrt{E}} + 5\%$	$\frac{100\%}{\sqrt{E}} + 5\%$

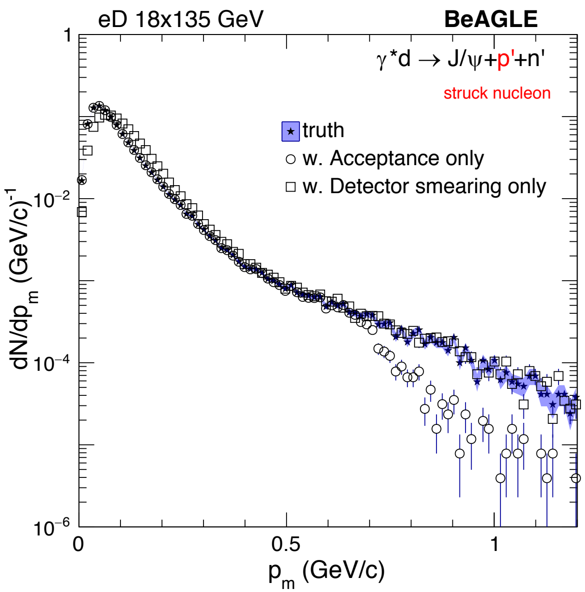
- Proton detector
  - Acceptance: (0,5) + (7-22) mrad (default)

Proton Det.	Default	V1	V2
Momentum reso.	$\frac{dp_T}{p_T} = 3\%$	$\frac{dp_T}{p_T} = 5\%$	$\frac{dp_T}{p_T} = 10\%$

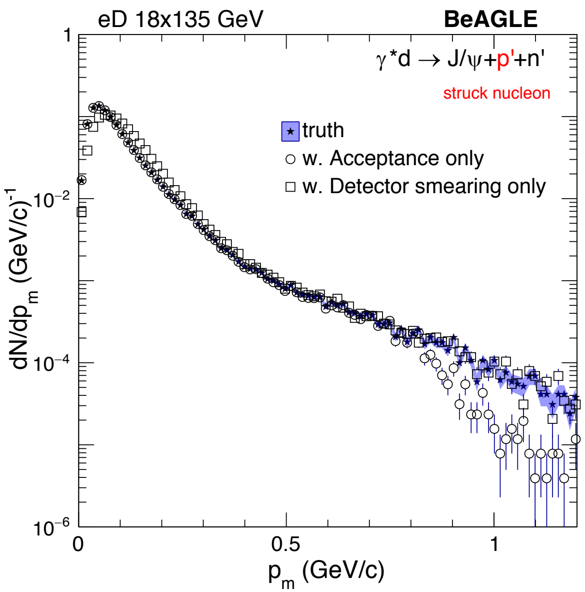
- Energy configurations:
  - 18 x 135 GeV (default)
  - 10 x 50 GeV
  - 5 x 20 GeV

Neutron detector acceptance

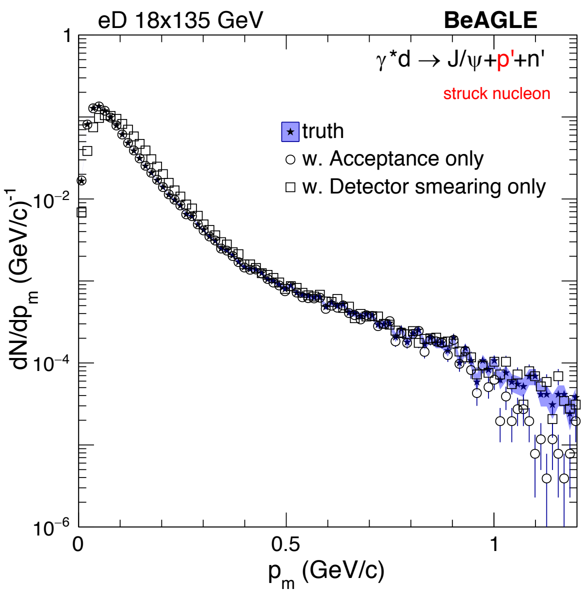
Neutron detector acceptance - p_m



5 mrad



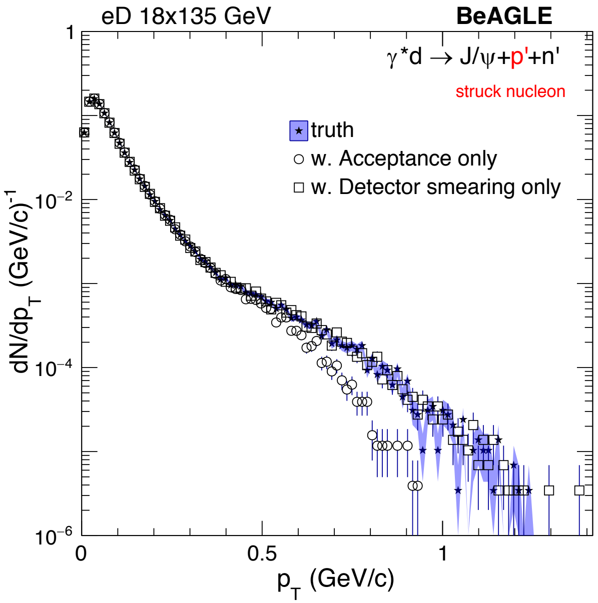
6 mrad



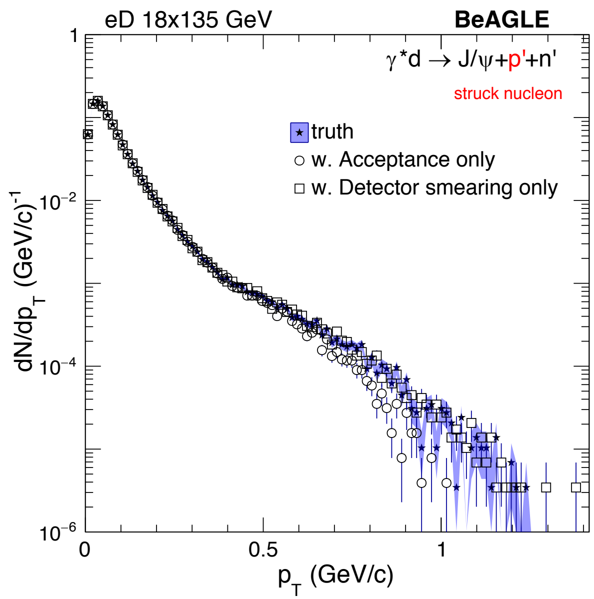
7 mrad

High momentum tail gradually comes back when increase the size of neutron detector

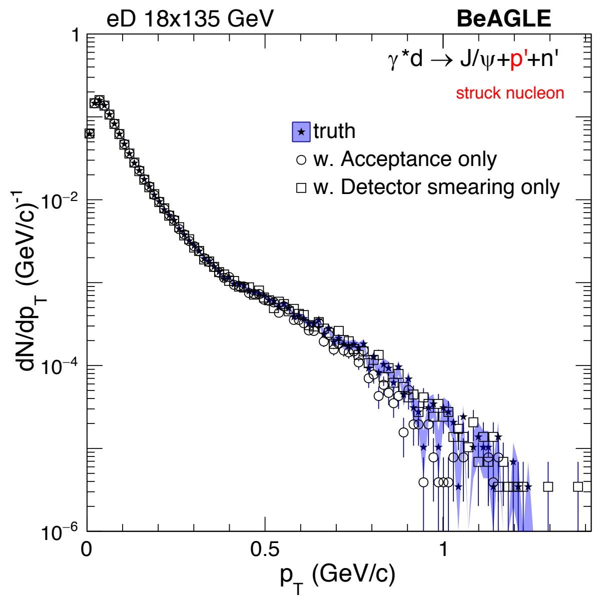
Neutron detector acceptance - p_t



5 mrad



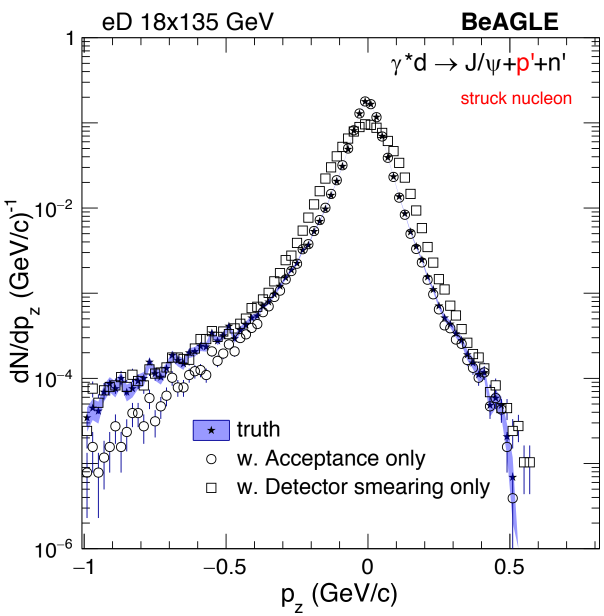
6 mrad



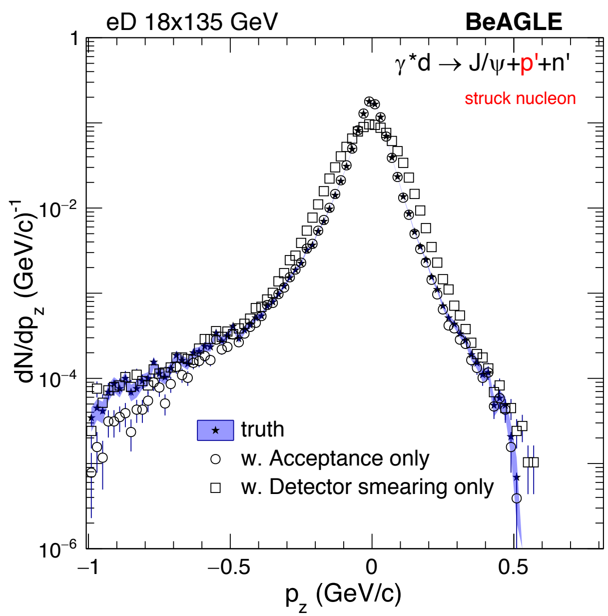
7 mrad

High momentum tail gradually comes back when increase the size of neutron detector

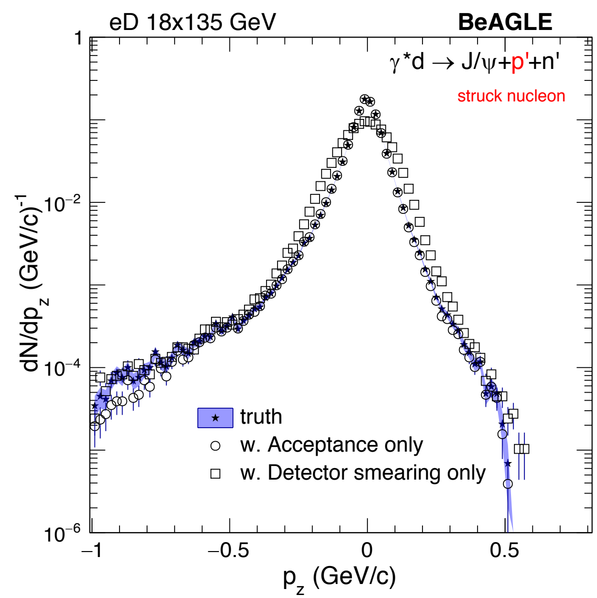
Neutron detector acceptance - p_z



5 mrad



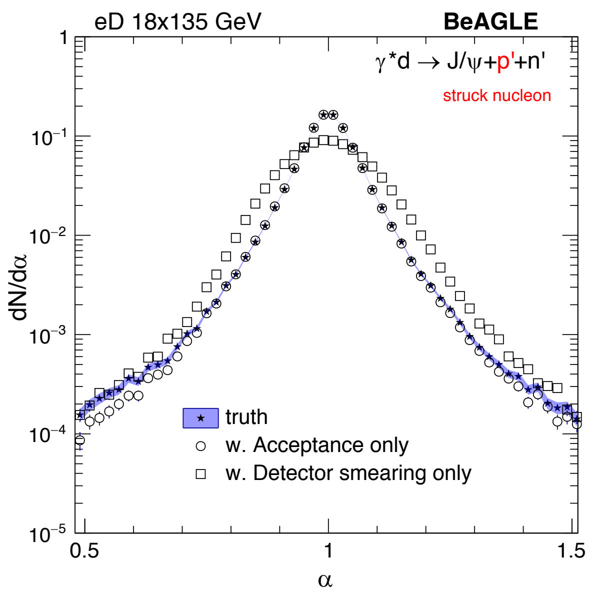
6 mrad



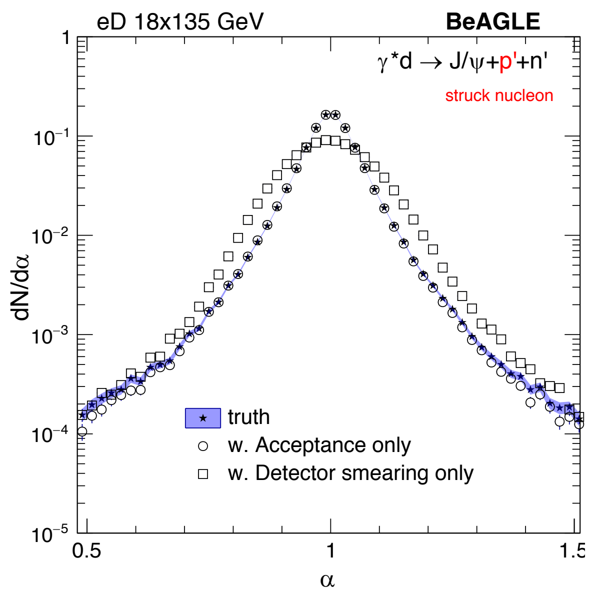
7 mrad

High momentum tail gradually comes back when increase the size of neutron detector

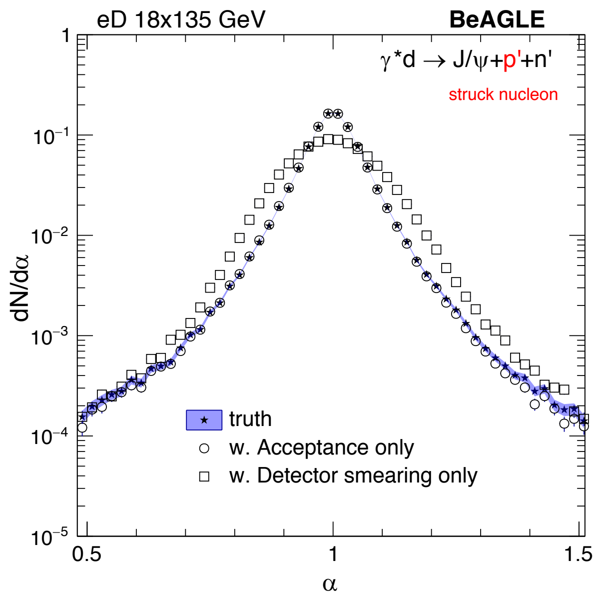
Neutron detector acceptance - alpha



5 mrad



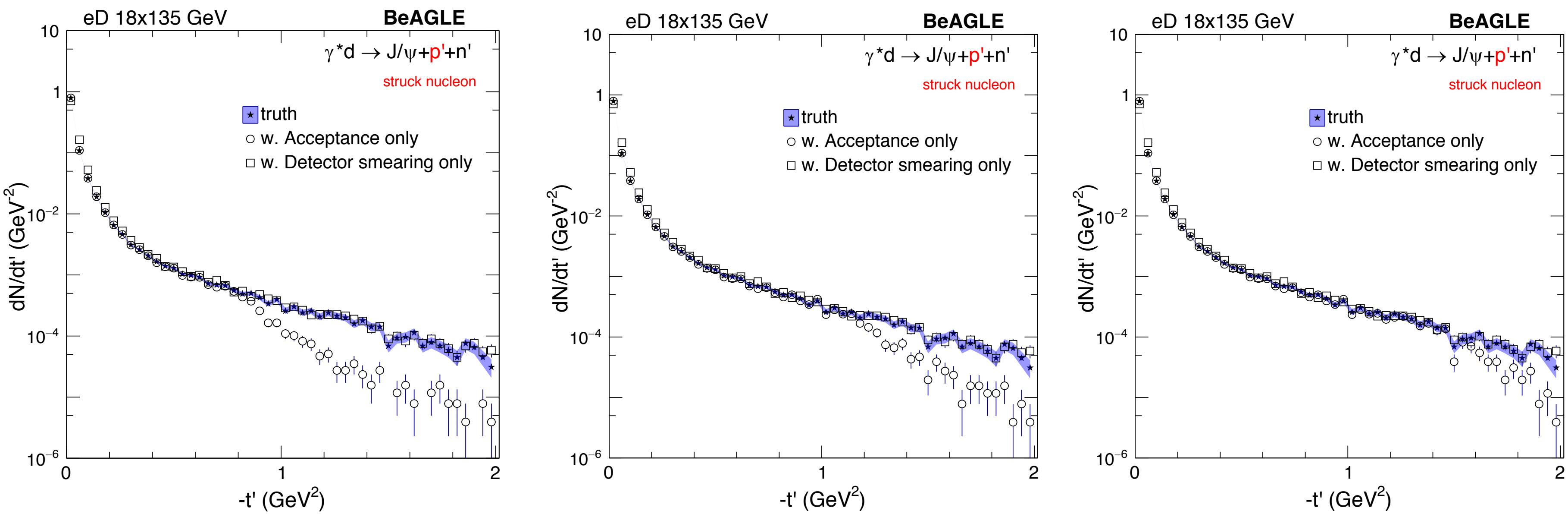
6 mrad



7 mrad

High momentum tail gradually comes back when increase the size of neutron detector

Neutron detector acceptance – t'

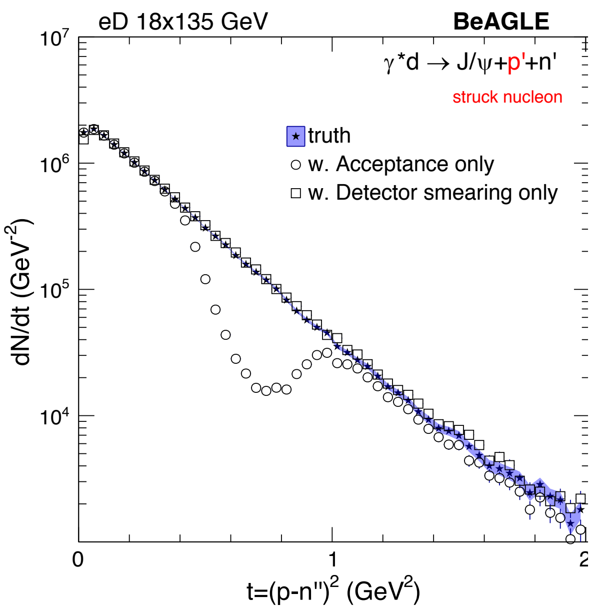


5 mrad 6 mrad 7 mrad

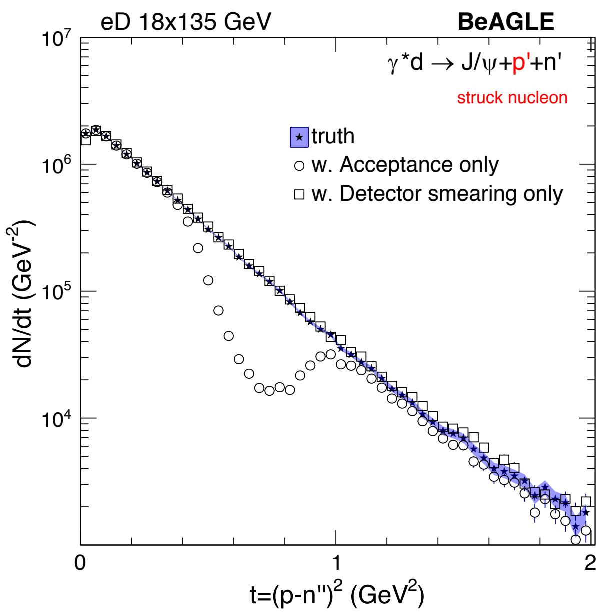
Neutron spectator tagging

High t' gradually comes back when increase the size of neutron detector

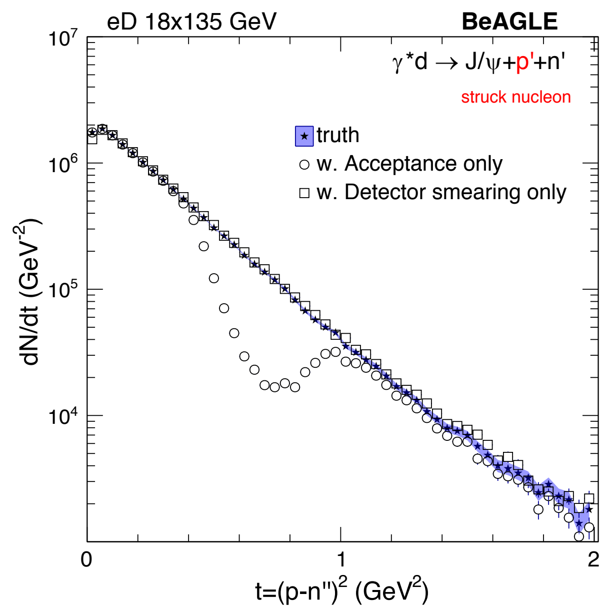
Neutron detector acceptance – t



5 mrad



6 mrad

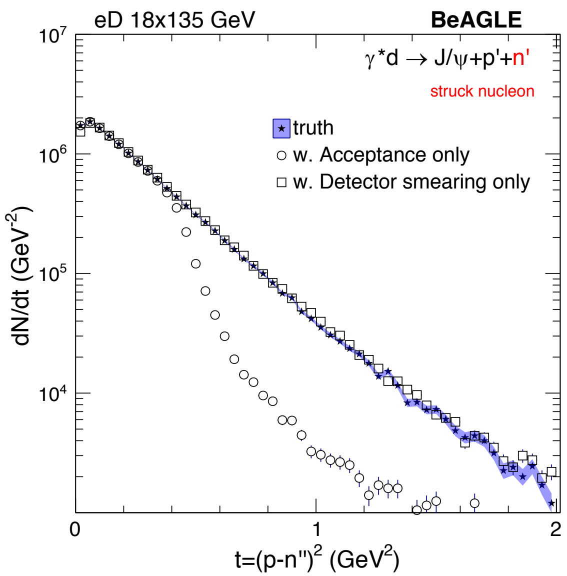


7 mrad

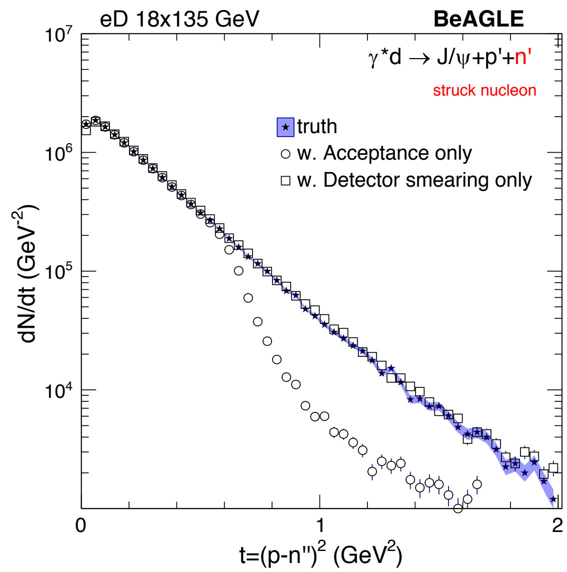
Neutron spectator double tagging

- Very small differences, because most of spectator neutron are within acceptance of 5 mrad, only gain at some very high momentum tail.
- For DVCS, we are interested in hitting neutron. See next slide.

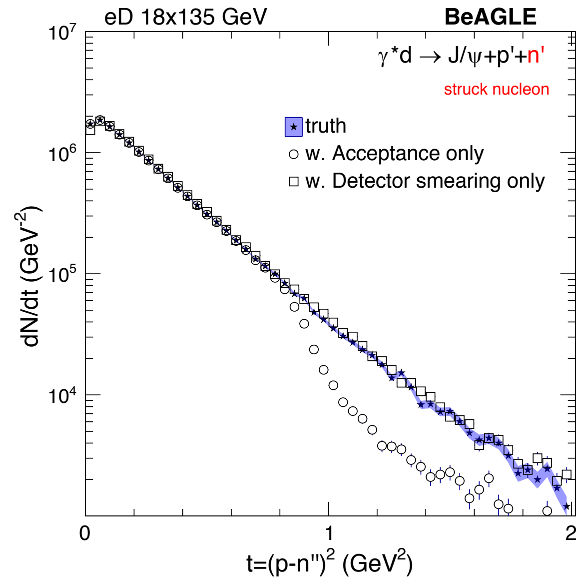
Neutron detector acceptance – t



5 mrad



6 mrad



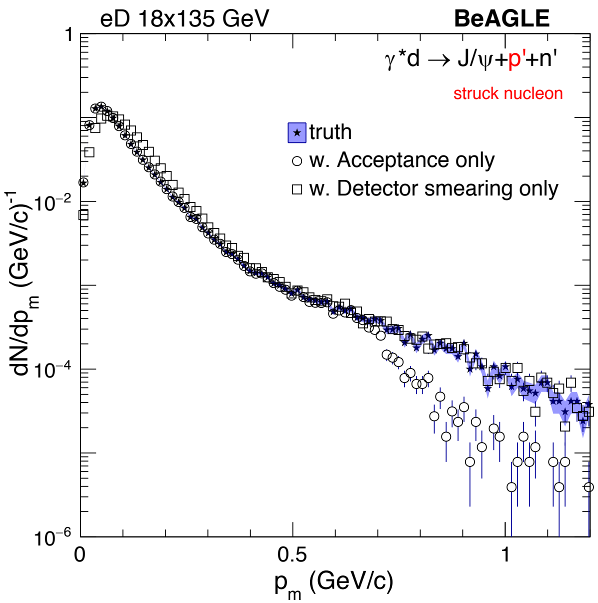
7 mrad

Proton spectator double tagging

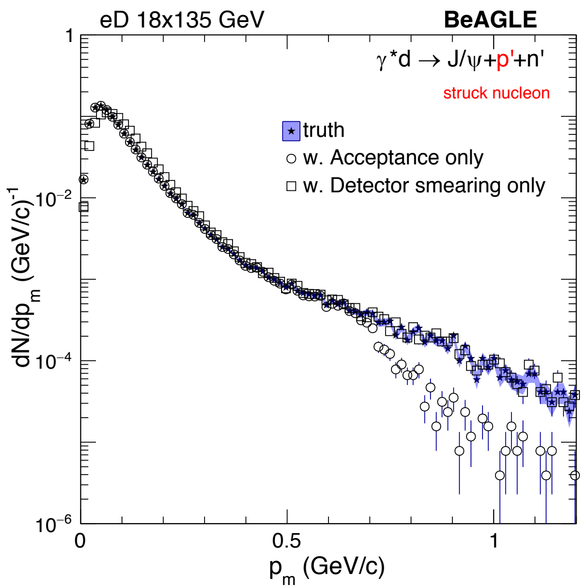
- Significant differences are observed. Full acceptance in t up to 800 MeV**2 for 7 mrad.
- More physics impact studies might be needed to justify for large neutron detector?

Neutron detector energy resolution

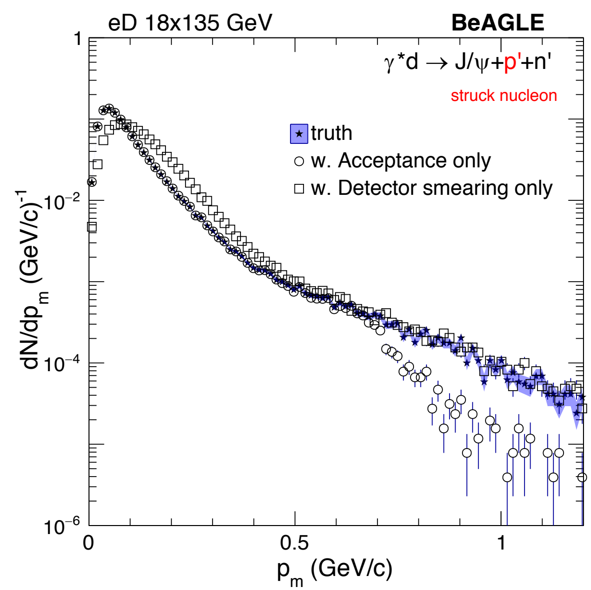
Neutron detector energy resolution - p_m



50%/sqrt(E)



30%/sqrt(E)

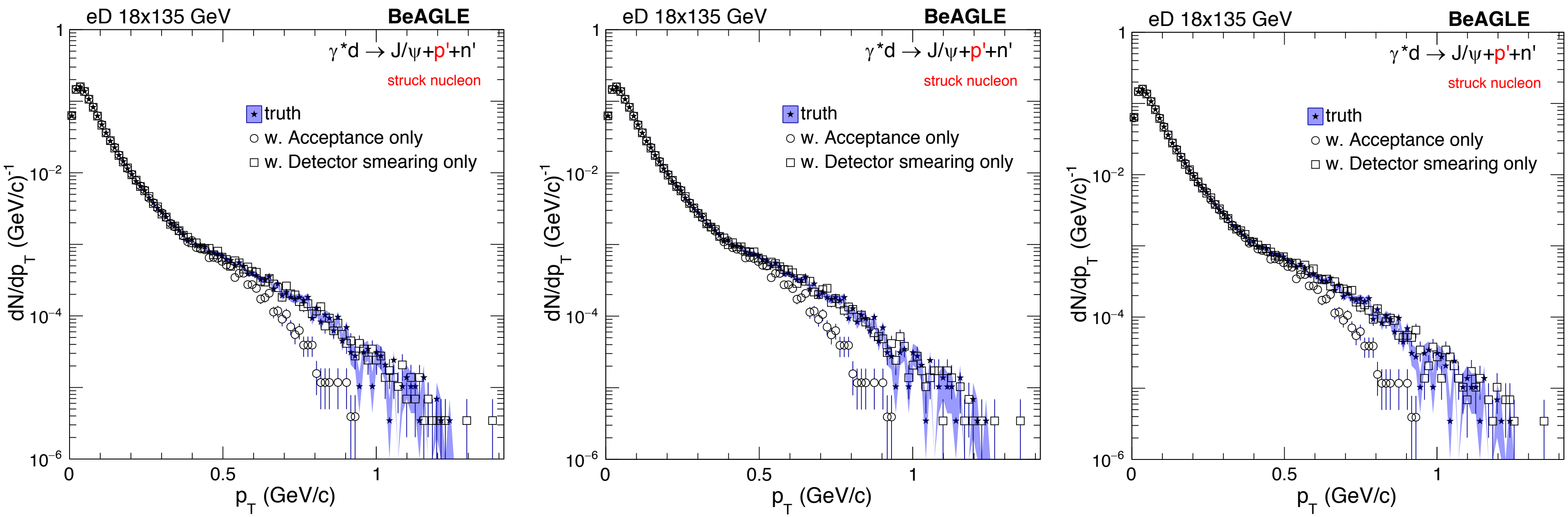


100%/sqrt(E)

- The worst scenario is still better than the STAR ZDC since the constant term here is 5%. The STAR ZDC has ~ 10% for the constant term.

- Low momentum has stronger smearing for poorer resolution.
- High momentum tails are fine.

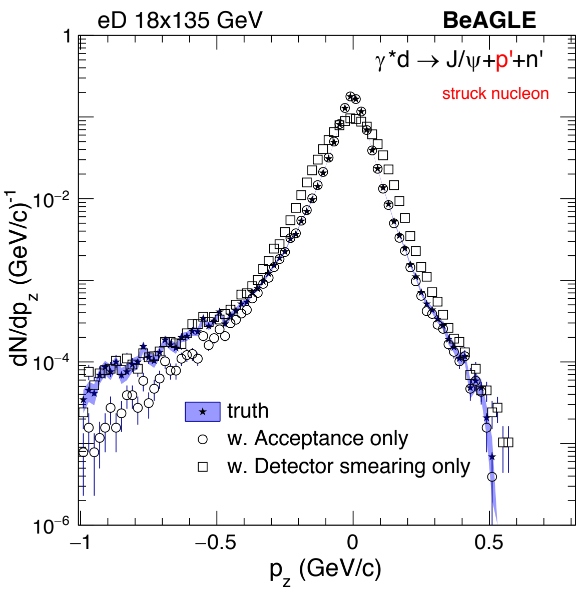
Neutron detector energy resolution - p_T



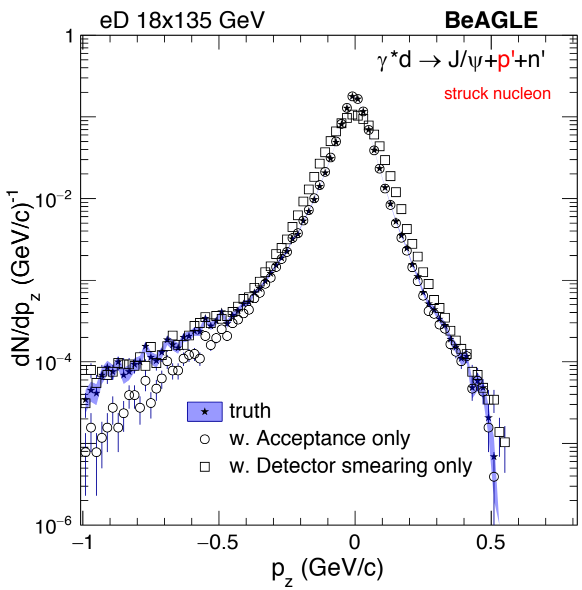
50%/sqrt(E) 30%/sqrt(E) 100%/sqrt(E)

- No difference is observed for p_T

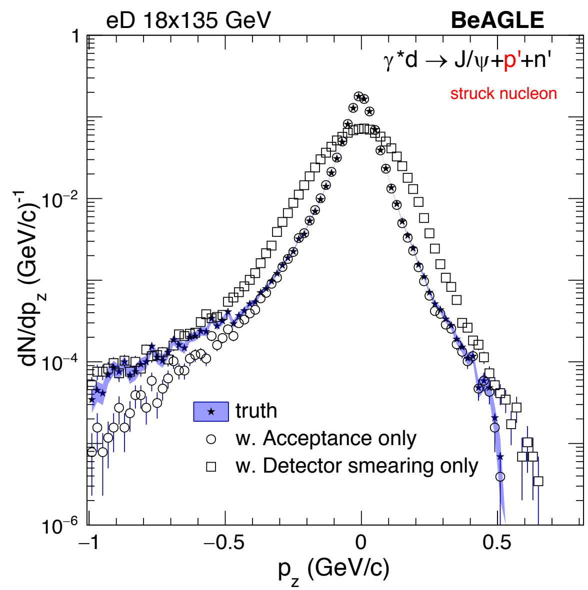
Neutron detector energy resolution - p_z



50%/sqrt(E)



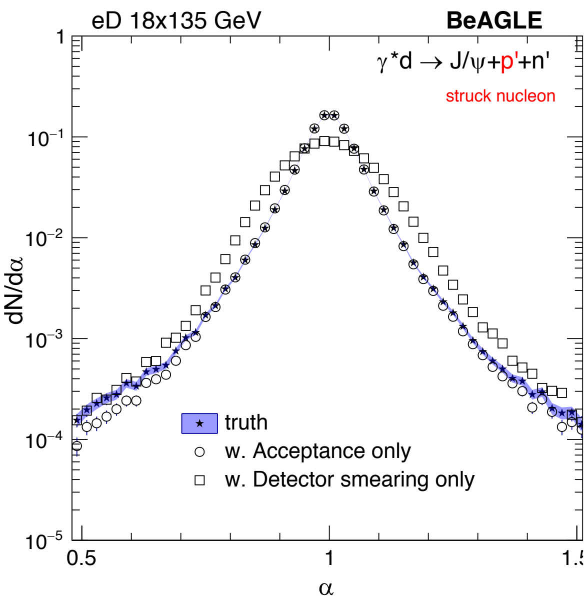
30%/sqrt(E)



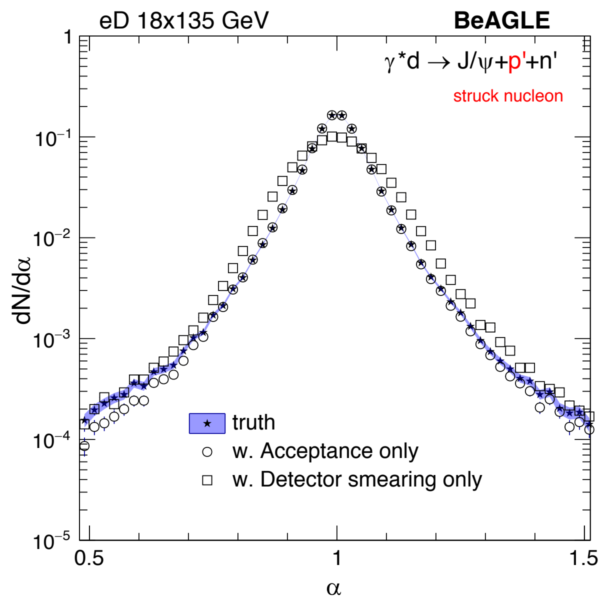
100%/sqrt(E)

- Like p_m where difference is obvious.

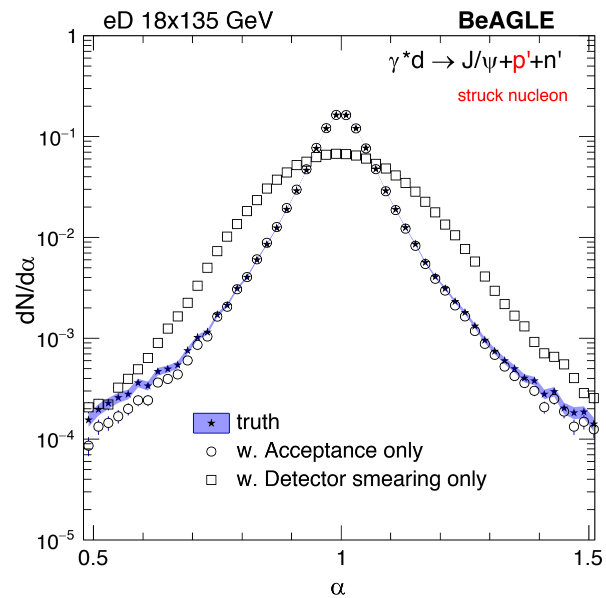
Neutron detector energy resolution - alpha



50%/sqrt(E)



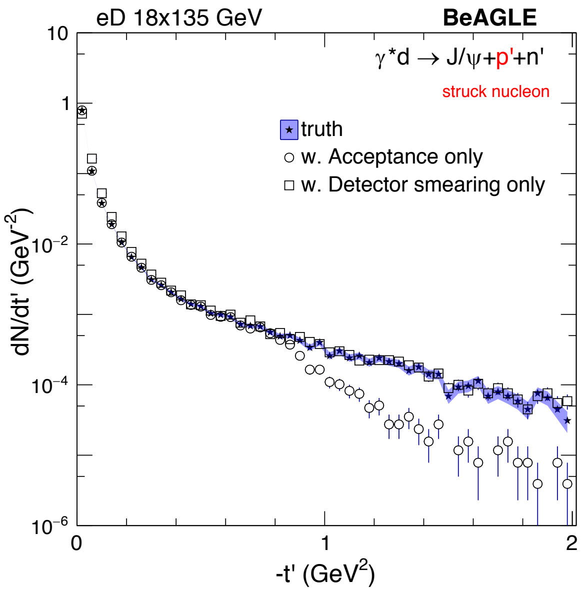
30%/sqrt(E)



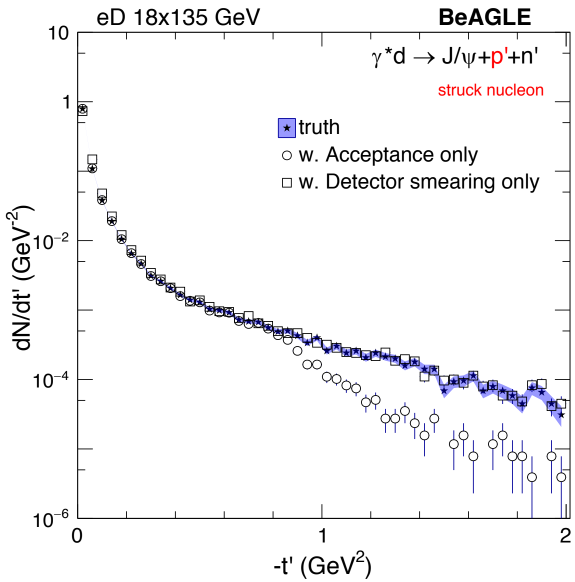
100%/sqrt(E)

- Like p_m where difference is obvious.

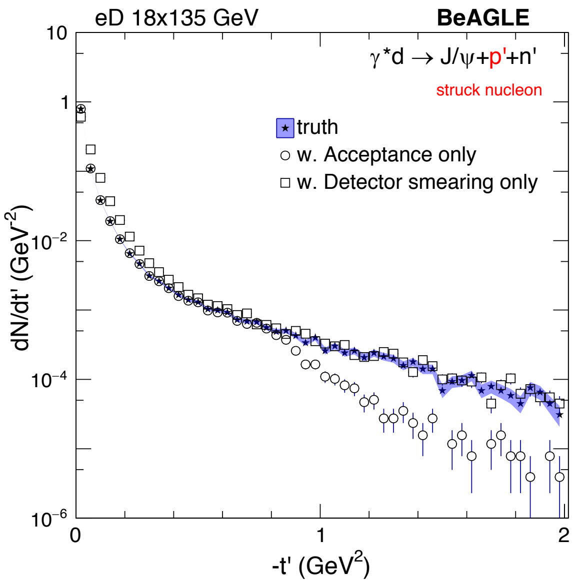
Neutron detector energy resolution – t’



50%/sqrt(E)



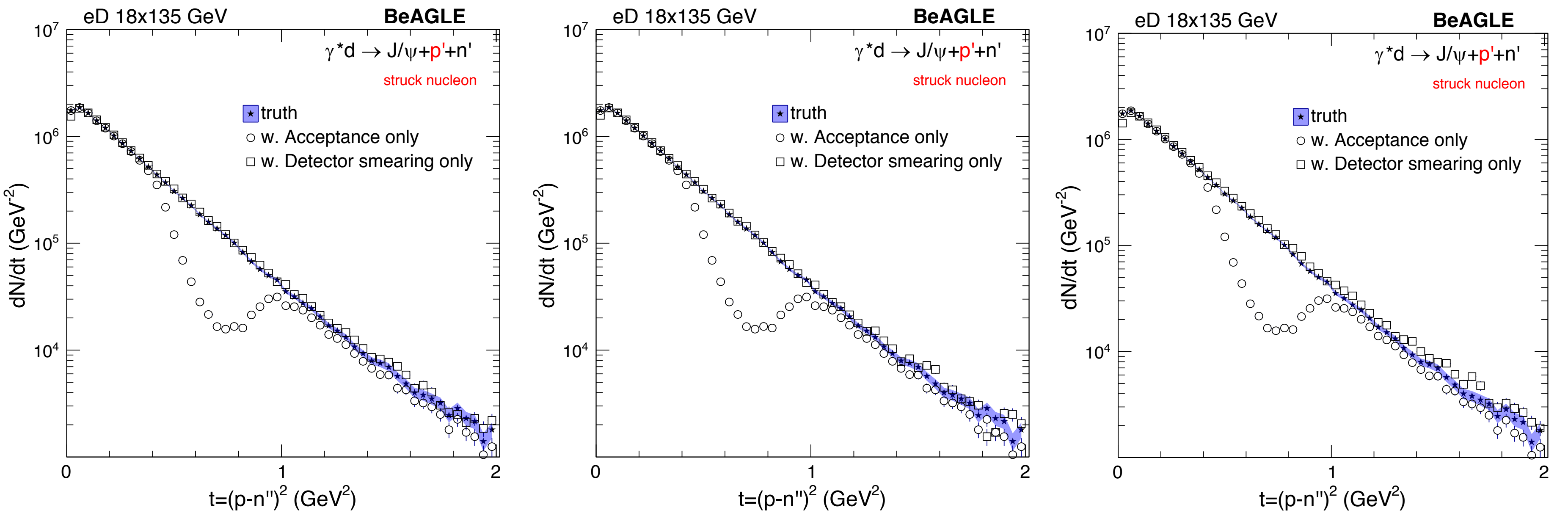
30%/sqrt(E)



100%/sqrt(E)

- See some difference at low t’. This will significantly affect the low t’ extrapolation. Unfolding technique needs to be applied for analysis anyway, but its uncertainty is correlated to how good the resolution is

Neutron detector energy resolution – t



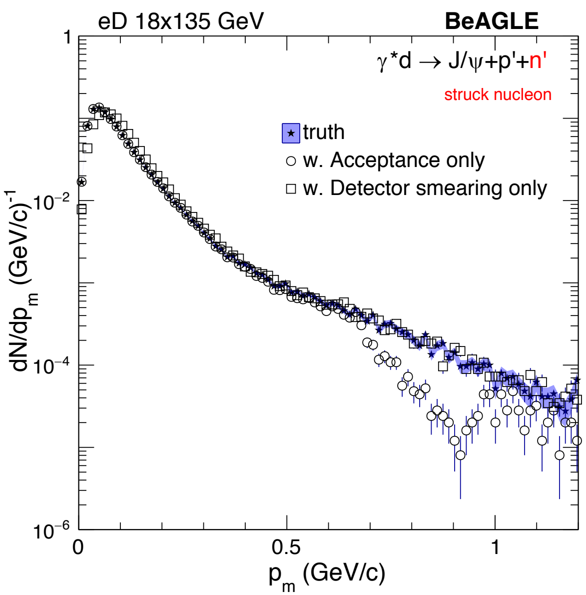
50%/sqrt(E) 30%/sqrt(E) 100%/sqrt(E)

Neutron spectator double tagging

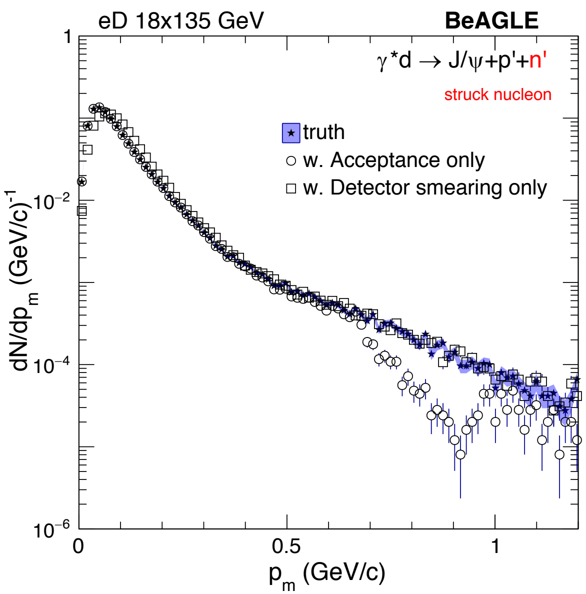
- Some small difference can be seen.
- In the resolution study, proton spectator double tagging case is just the same.

Proton detector momentum resolution

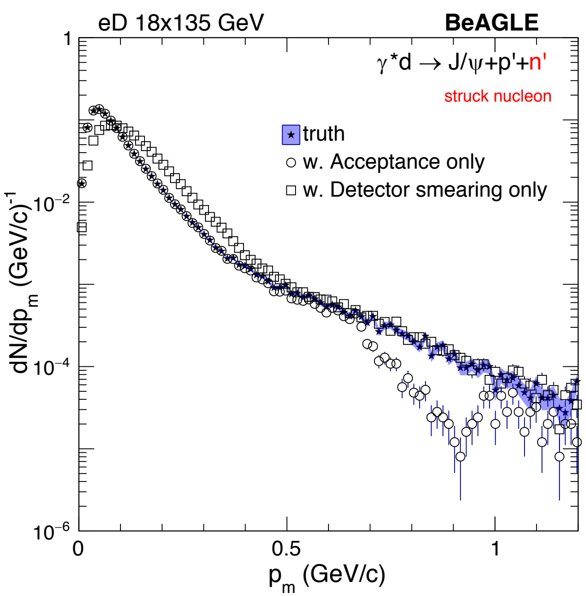
Proton detector momentum resolution - p_m



dpt/pt = 3%



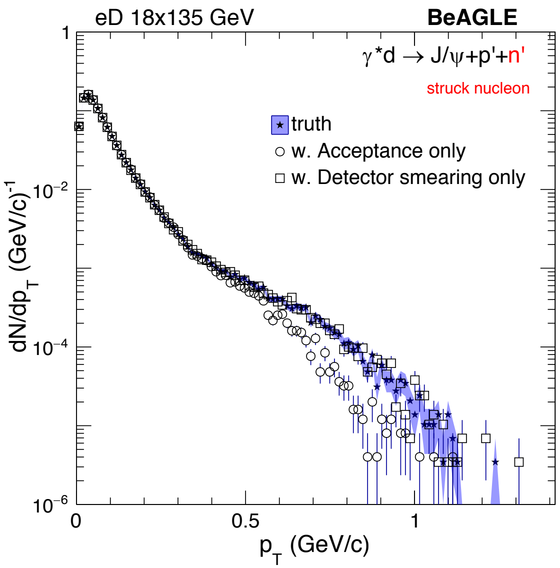
dpt/pt = 5%



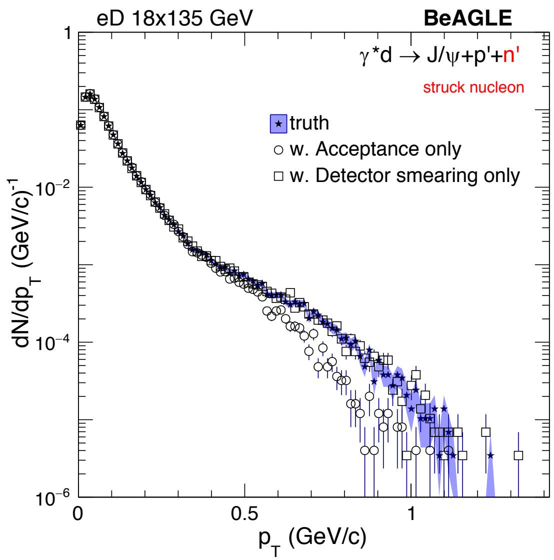
dpt/pt = 10%

- Same conclusion as for neutron detector energy resolution study

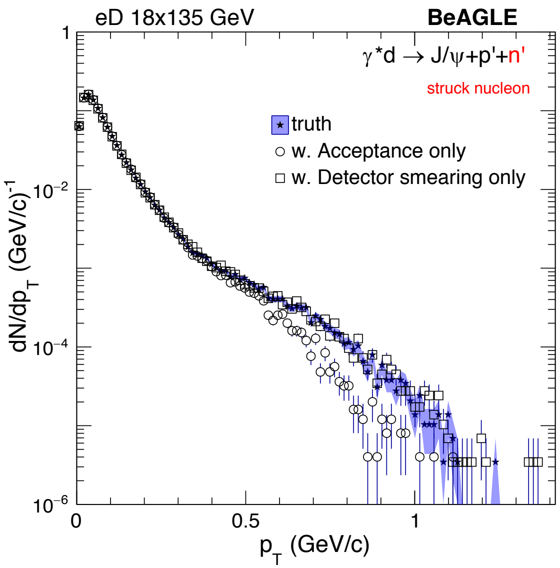
Proton detector momentum resolution - p_T



dpt/pt = 3%



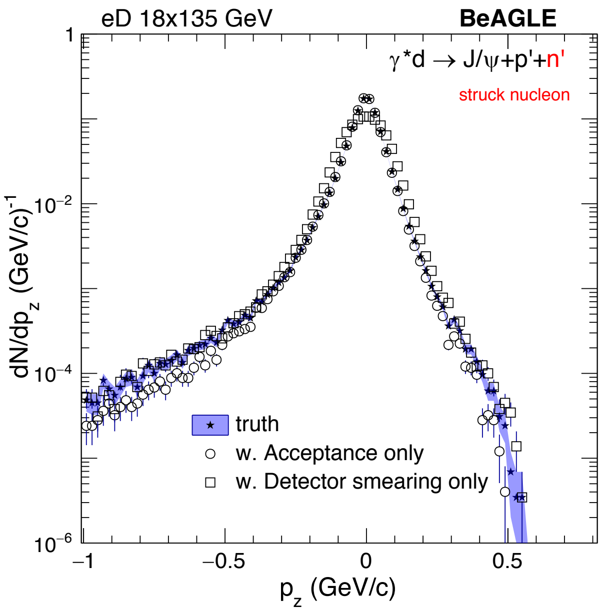
dpt/pt = 5%



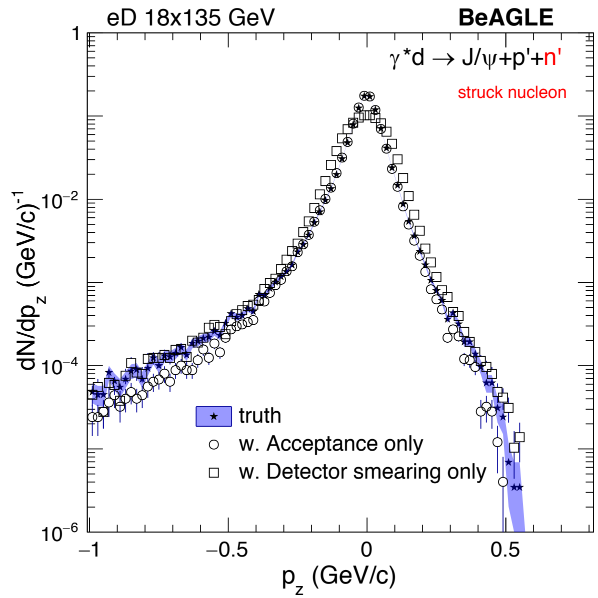
dpt/pt = 10%

- Still very robust on the p_T

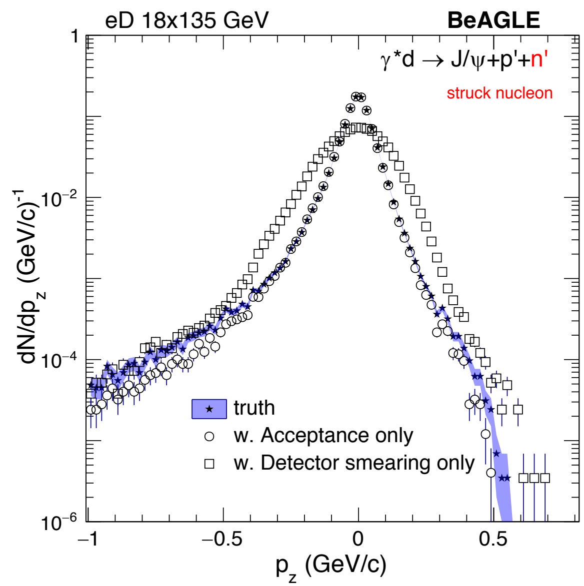
Proton detector momentum resolution - p_z



dpt/pt = 3%



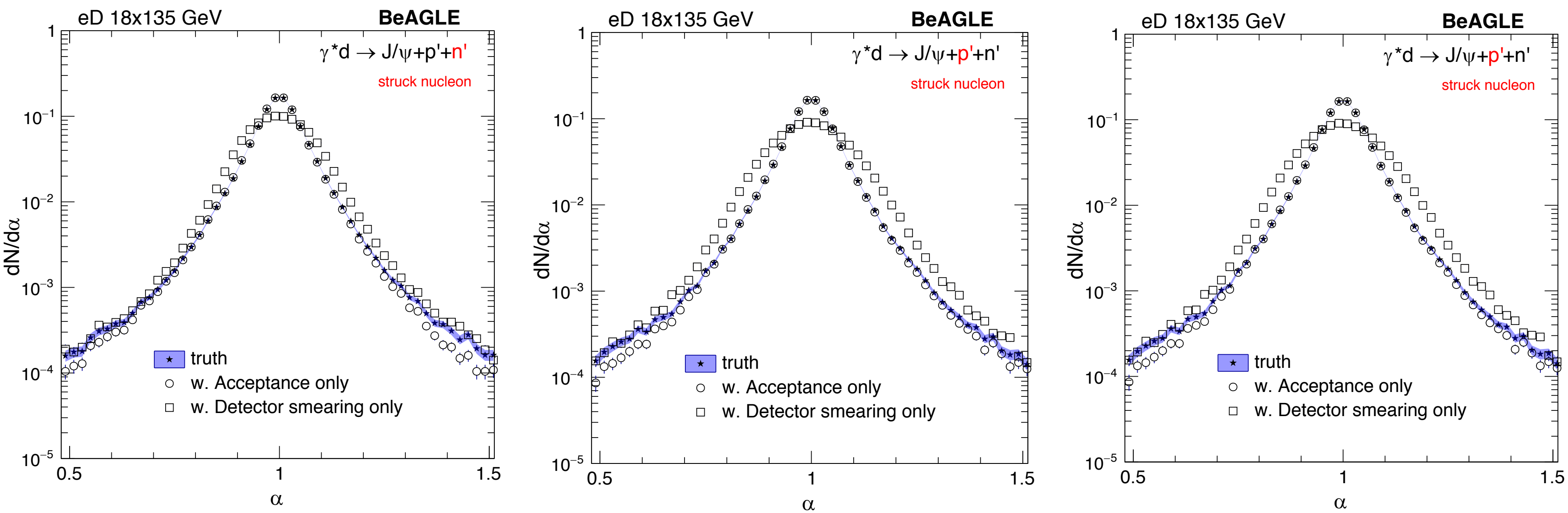
dpt/pt = 5%



dpt/pt = 10%

- Same conclusion as for neutron detector energy resolution study

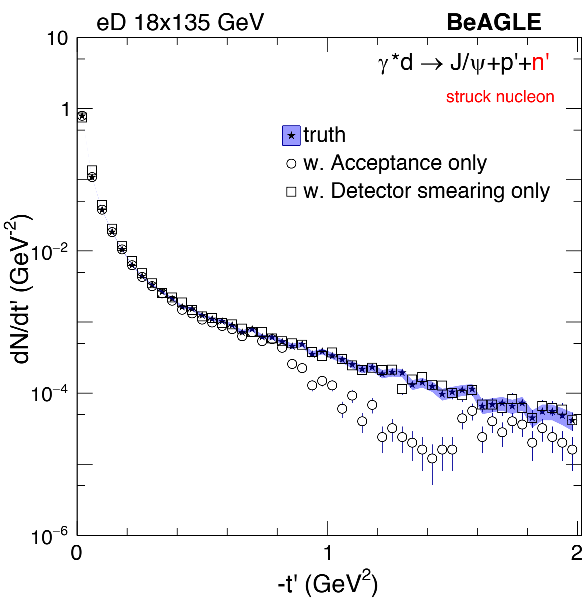
Proton detector momentum resolution - alpha



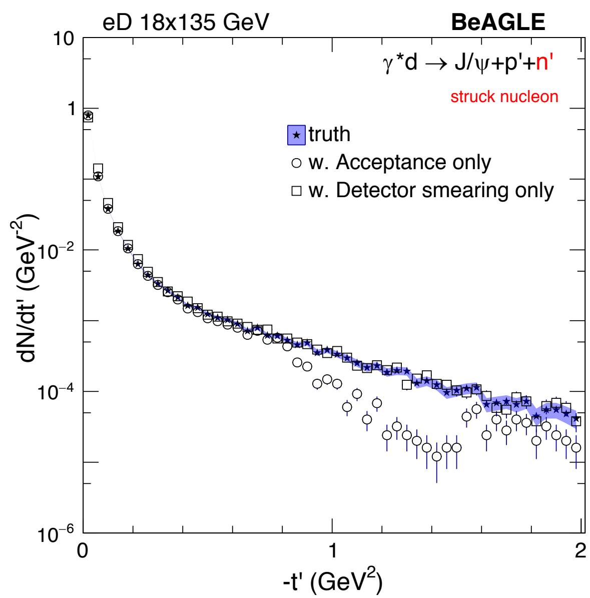
dpt/pt = 3% dpt/pt = 5% dpt/pt = 10%

- Same conclusion as for neutron detector energy resolution study

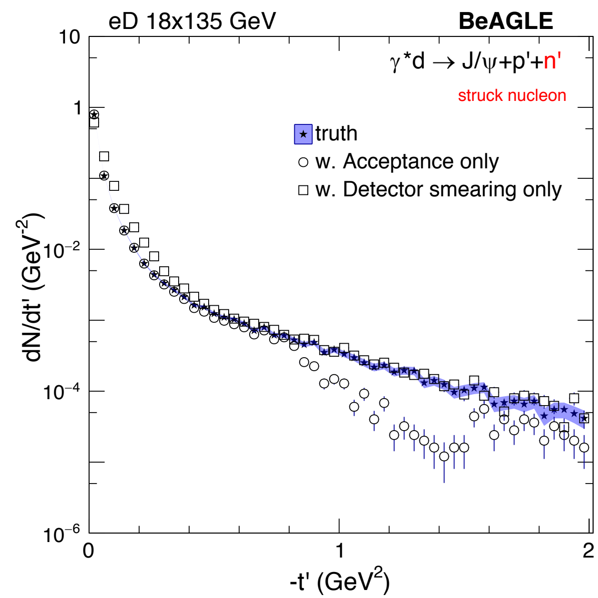
Proton detector momentum resolution – t'



dpt/pt = 3%



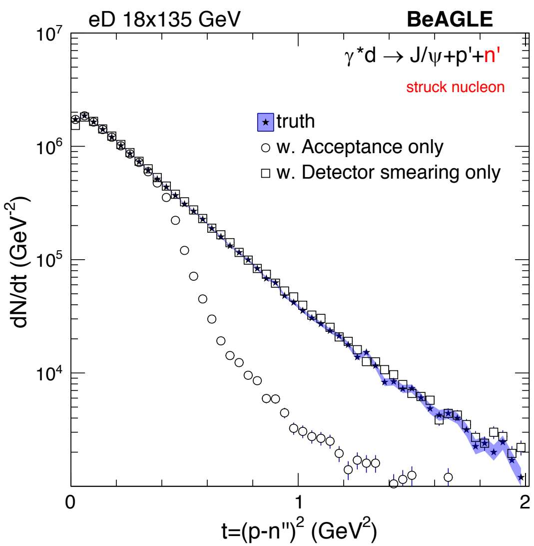
dpt/pt = 5%

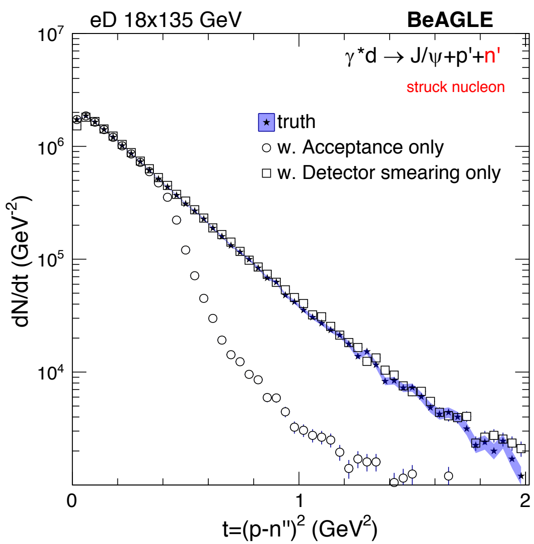


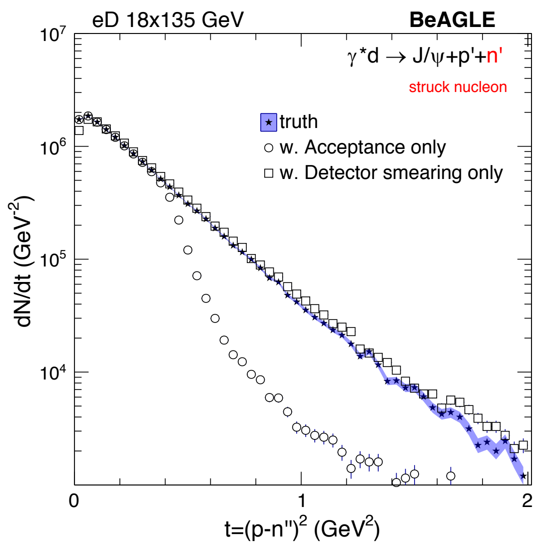
dpt/pt = 10%

- Same conclusion as for neutron detector energy resolution study

Proton detector momentum resolution – t





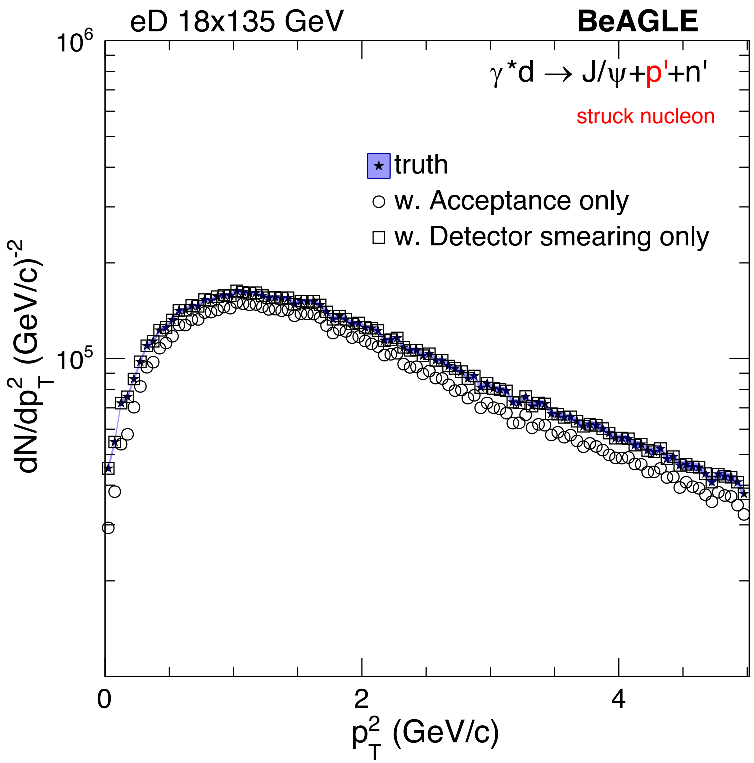


dpt/pt = 3%   dpt/pt = 5%   dpt/pt = 10%

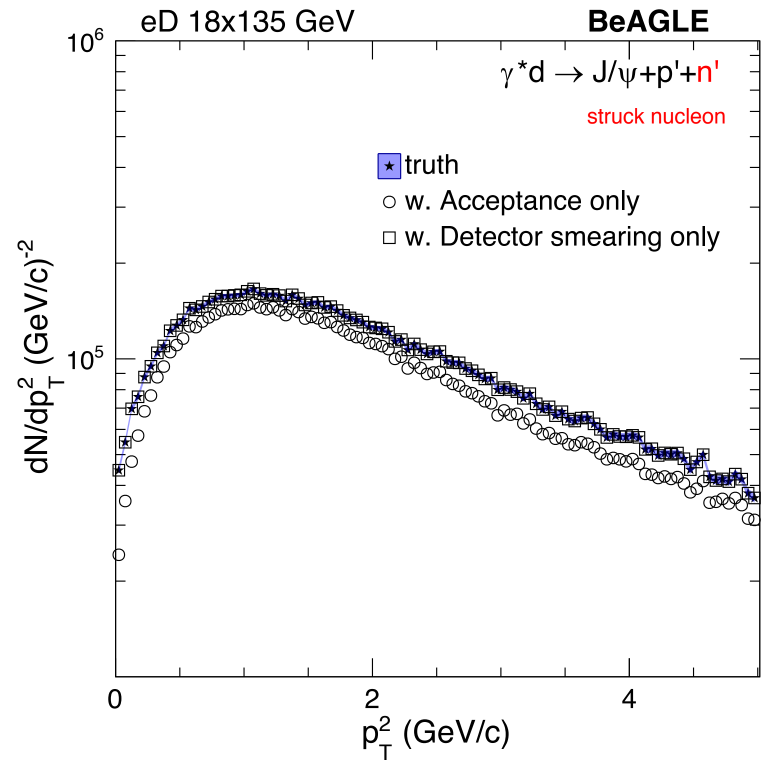
Proton spectator double tagging

- Same conclusion as for neutron detector energy resolution study

Jpsi distributions – no detector effect



Neutron spectator double tagging



Proton spectator double tagging

- Acceptances are on protons and neutrons only, the shift is due to requirement of double tagging

Energy configurations comparisons

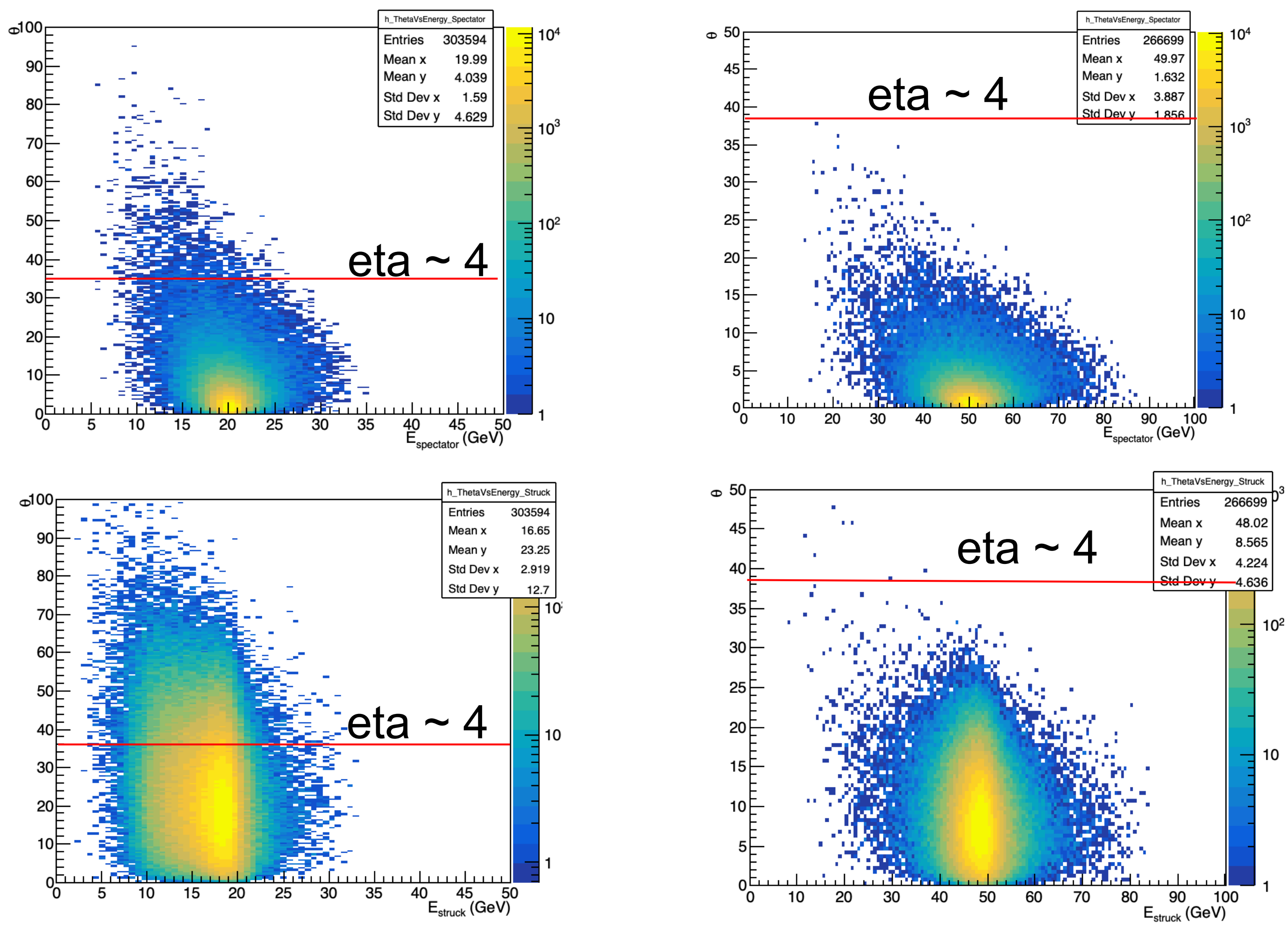
Disclaimer:

- No central detector is included
- Proton and neutron detectors use default settings

where are protons and neutrons

5x20 GeV

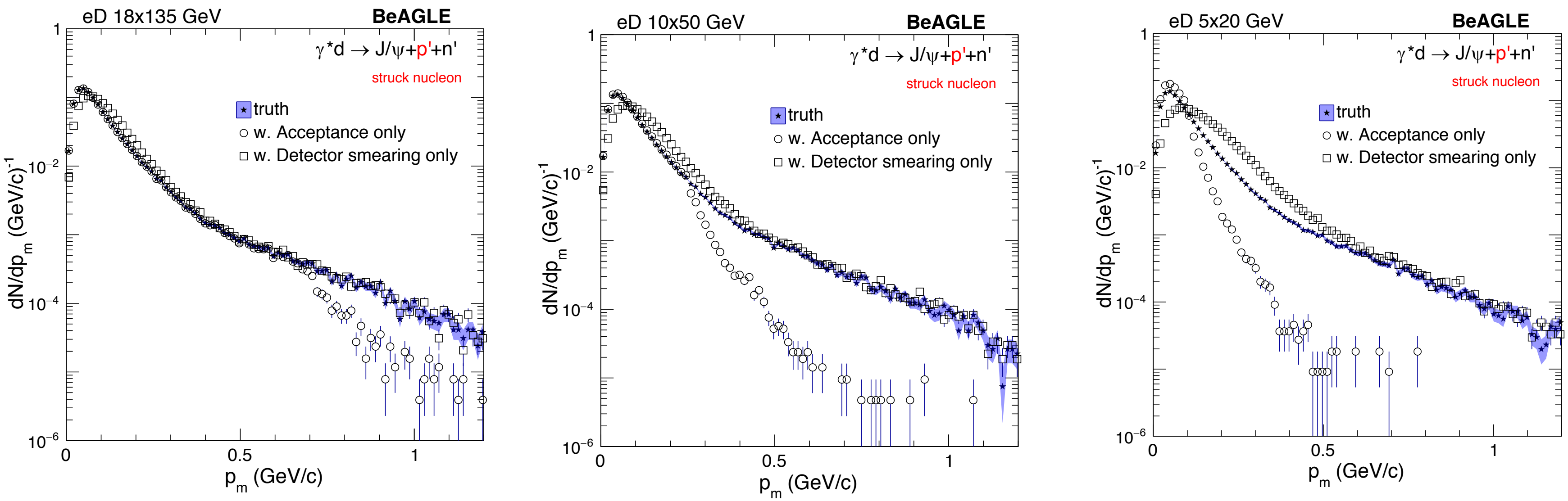
10x50 GeV



- For low enough energy, nucleons could be in the central tracker!
- Might be a benefit for extreme SRC studies?

Neutron spectator

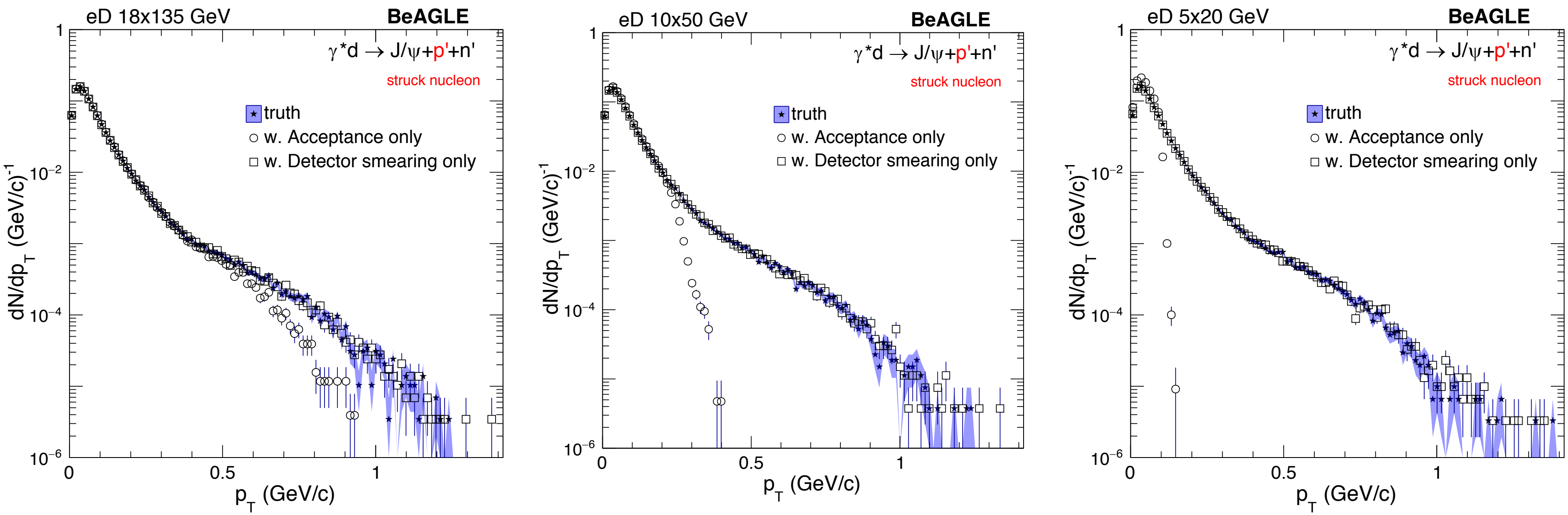
Neutron spectator - p_m



18x135 GeV | 10x50 GeV | 5x20 GeV

- Significant difference towards low energies.
- SRC studies seem to be better off with higher energy configuration

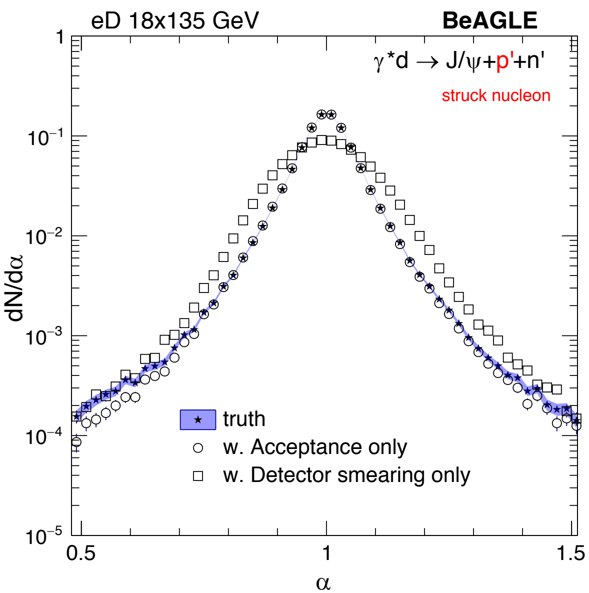
Neutron spectator - p_T



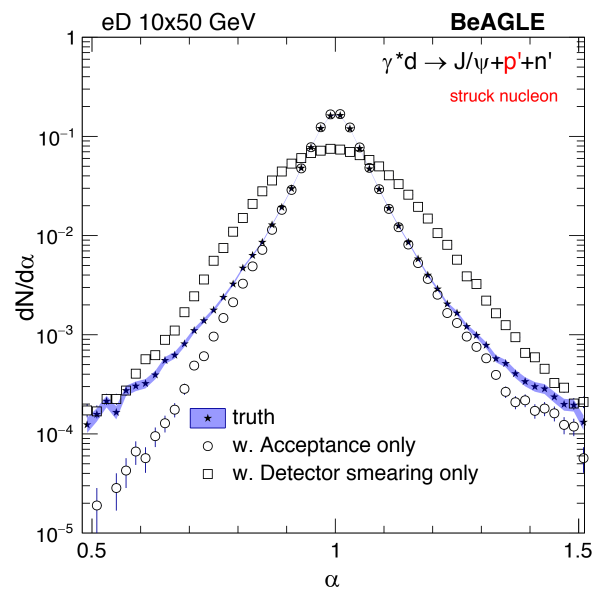
18x135 GeV | 10x50 GeV | 5x20 GeV

- Significant difference towards low energies.
- SRC studies seem to be better off with higher energy configuration

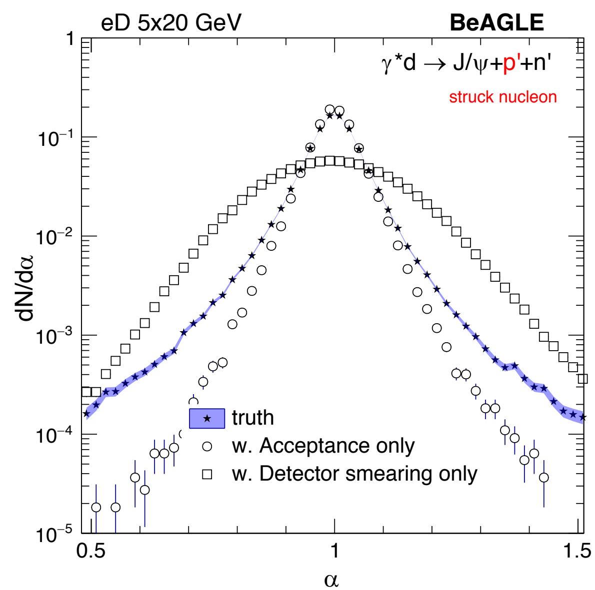
Neutron spectator - alpha



18x135 GeV



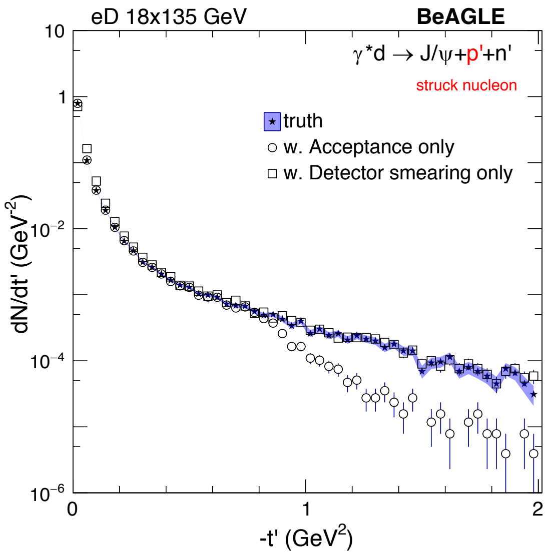
10x50 GeV



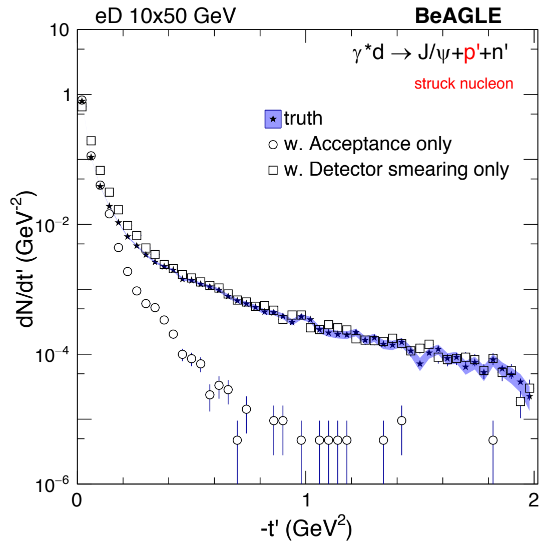
5x20 GeV

- Significant difference towards low energies.
- SRC studies seem to be better off with higher energy configuration

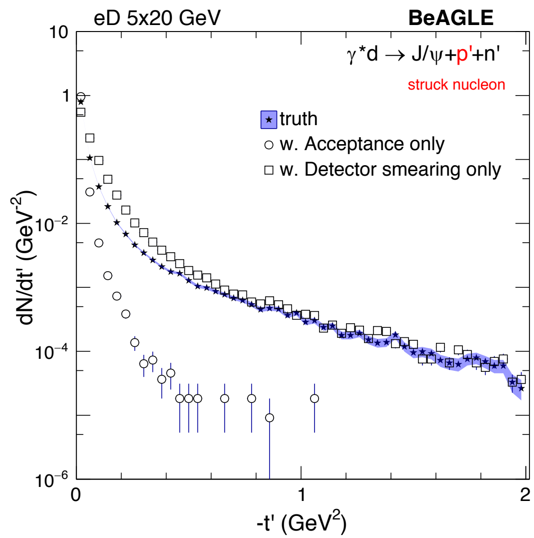
Neutron spectator – t'



18x135 GeV



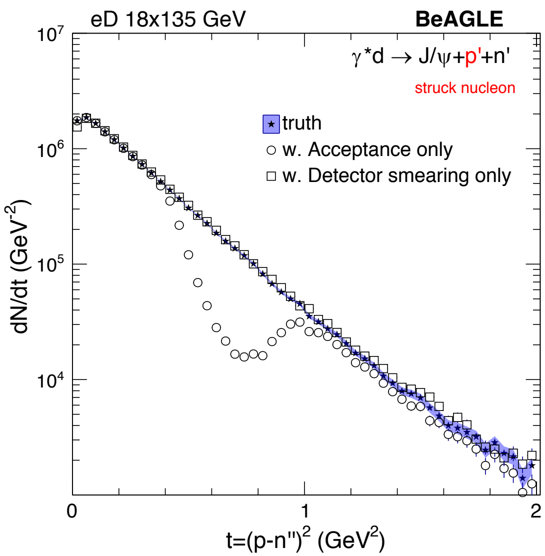
10x50 GeV



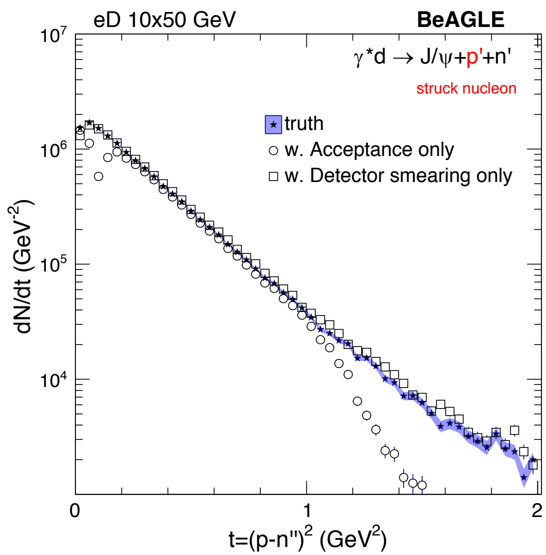
5x20 GeV

- Significant difference towards low energies.
- SRC studies seem to be better off with higher energy configuration

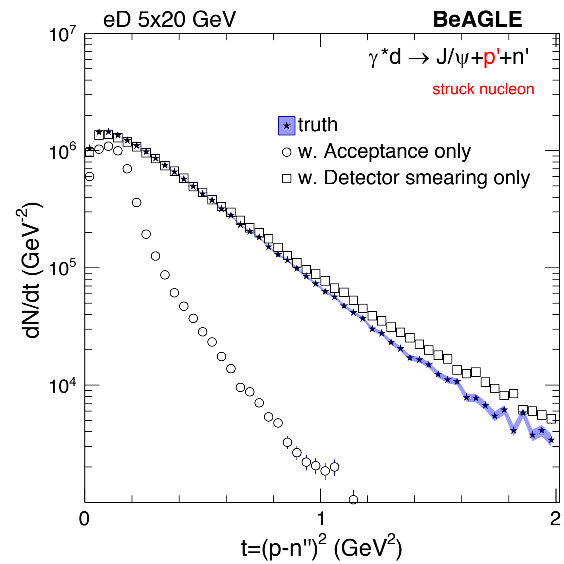
Neutron spectator – t



18x135 GeV



10x50 GeV

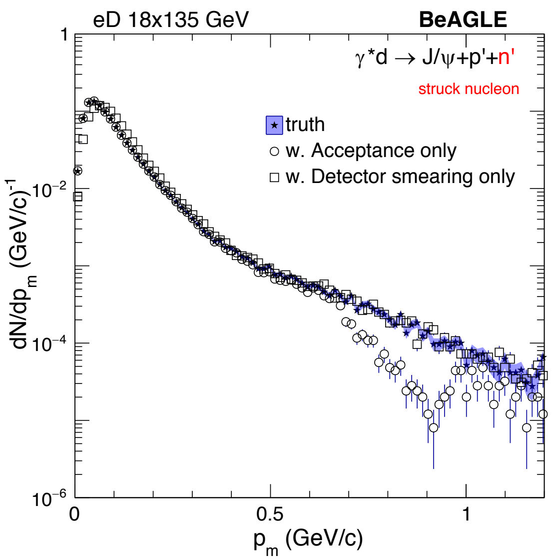


5x20 GeV

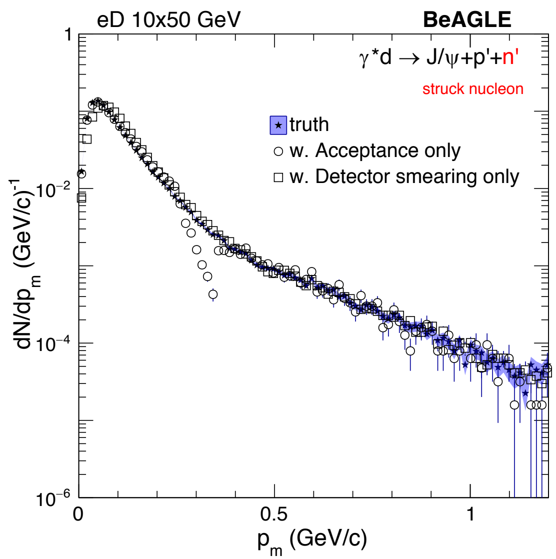
- Significant difference towards low energies.

Proton spectator

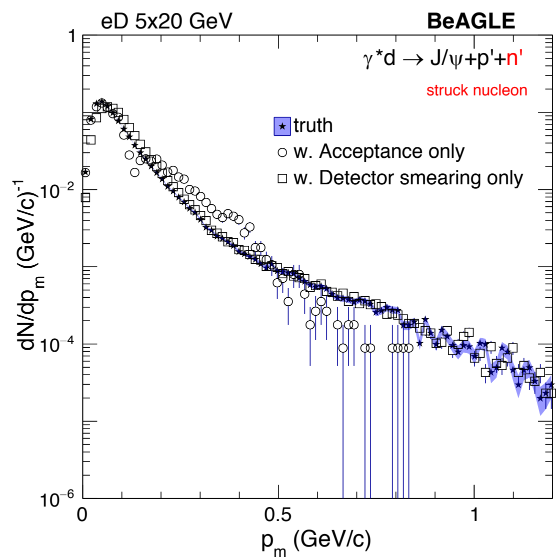
Proton spectator - p_m



18x135 GeV



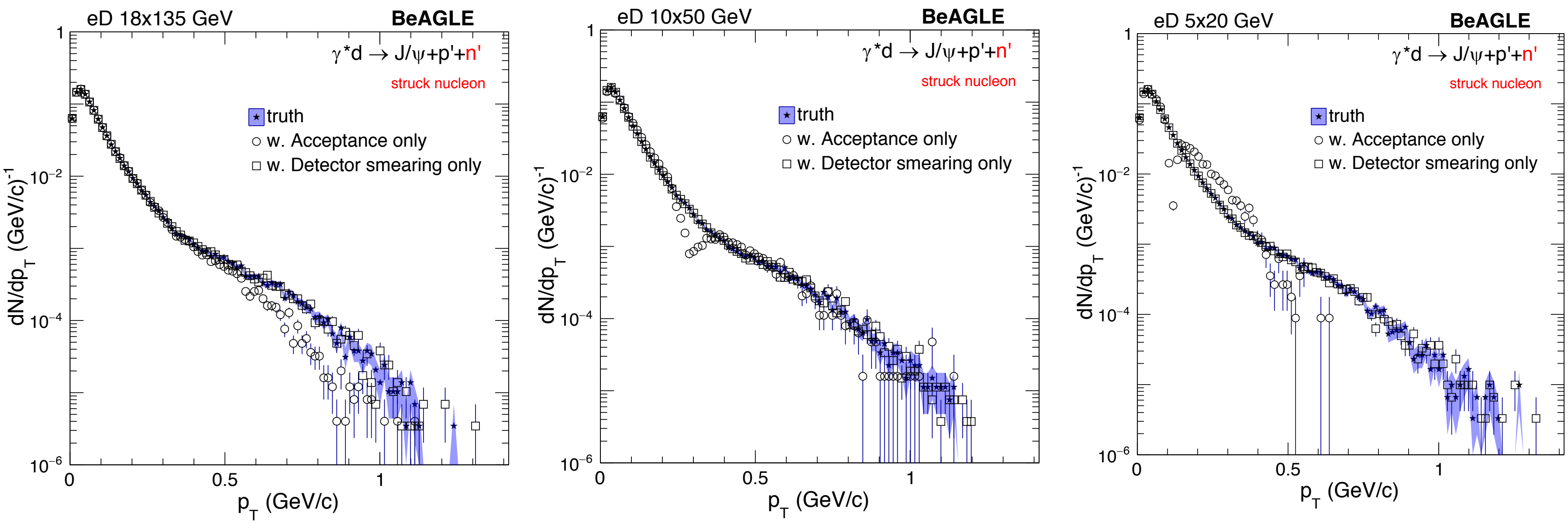
10x50 GeV



5x20 GeV

- Significant difference towards low energies.
- SRC studies seem to be better off with higher energy configuration

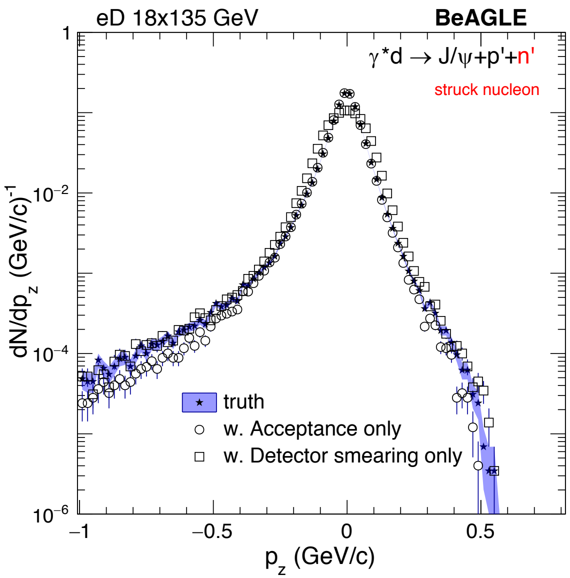
Proton spectator - p_T



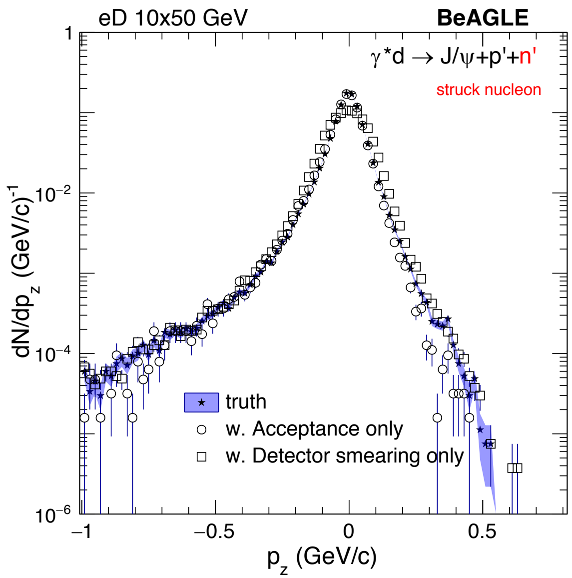
18x135 GeV | 10x50 GeV | 5x20 GeV

- Significant difference towards low energies.
- SRC studies seem to be better off with higher energy configuration

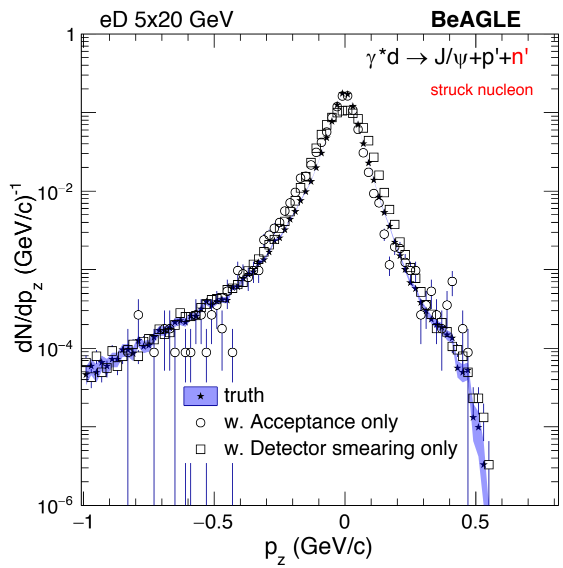
Proton spectator - p_z



18x135 GeV



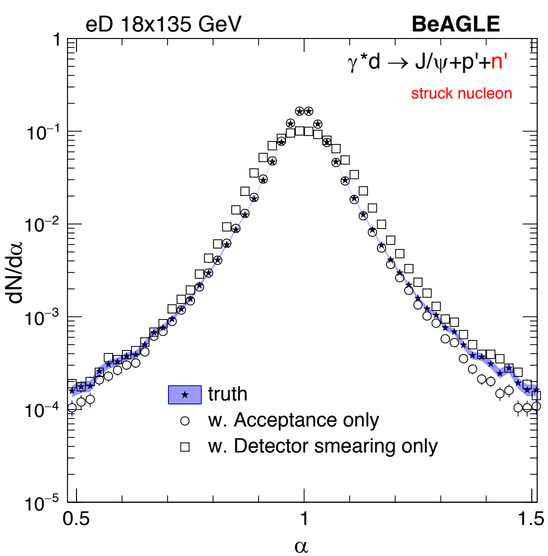
10x50 GeV



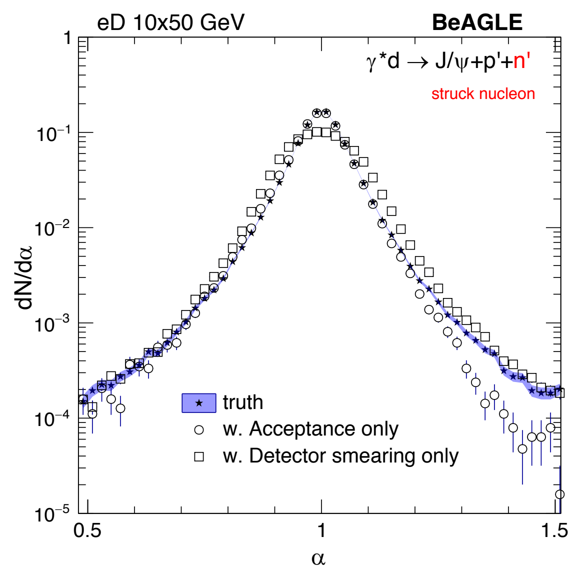
5x20 GeV

- Significant difference towards low energies.
- Starting to see more asymmetries for lower energies.
- SRC studies seem to be better off with higher energy configuration

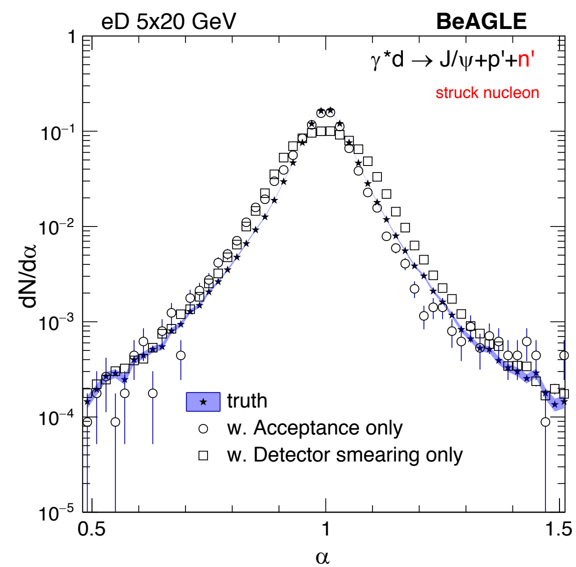
Proton spectator - alpha



18x135 GeV



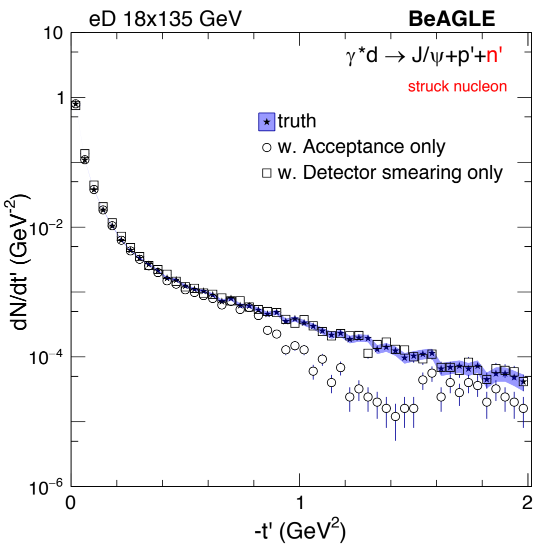
10x50 GeV



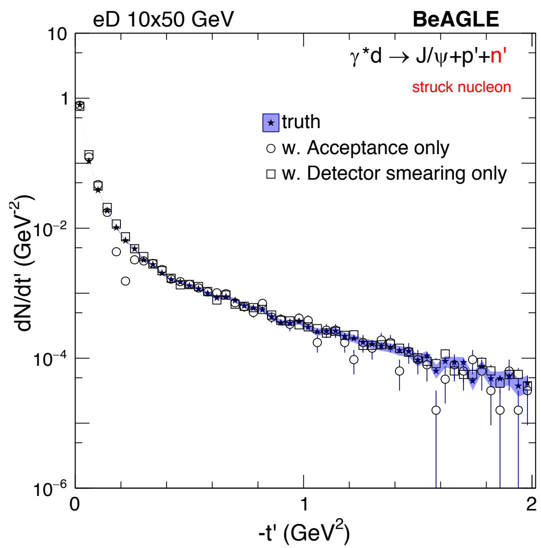
5x20 GeV

- Significant difference towards low energies.
- SRC studies seem to be better off with higher energy configuration

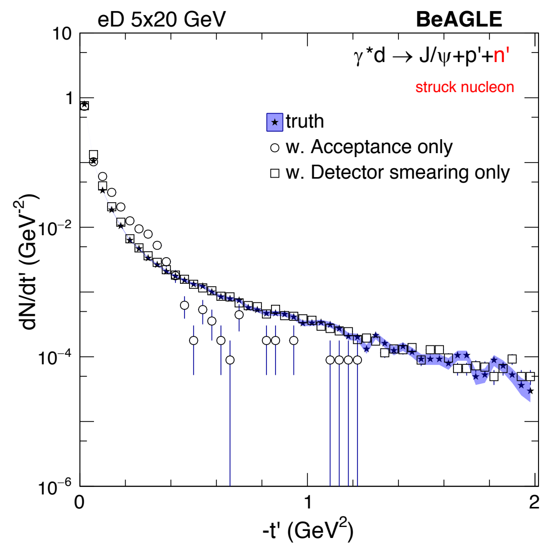
Proton spectator – t'



18x135 GeV



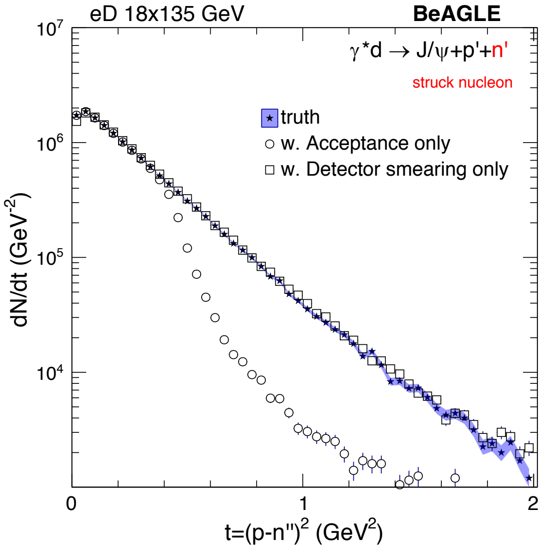
10x50 GeV

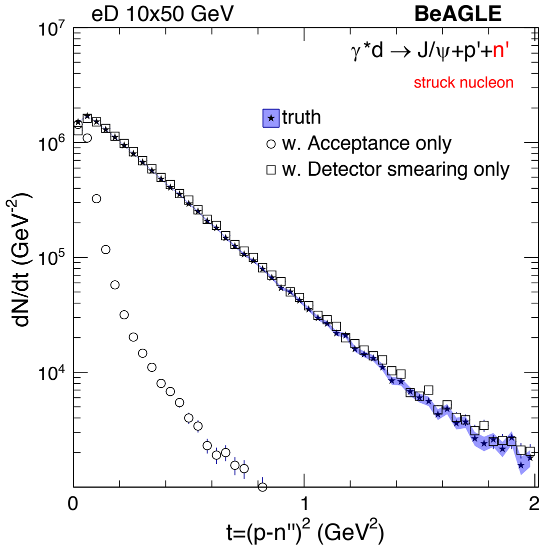


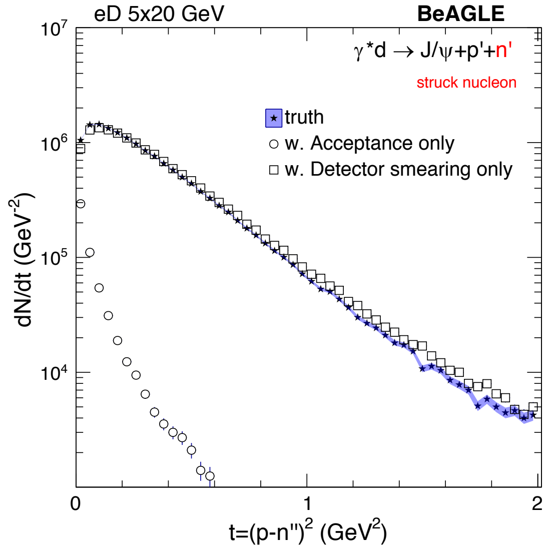
5x20 GeV

- Significant difference towards low energies.
- SRC studies seem to be better off with higher energy configuration

Proton spectator – t







18x135 GeV　　10x50 GeV　　5x20 GeV

- Significant difference towards low energies.
- Very bad acceptance at low energy but don't forget this might be recovered by main detector

Summary

- Spectator tagging in deuteron breakups have been investigated with toy forward detectors.
- Tagging spectator protons and neutrons are done separately.
- Some observables are more sensitive to energy/momentum resolutions, while some are more acceptance hungry.
- Many more physics cases can be studied using BeAGLE, however for coherent VMP off deuteron, it might be easier to go to *Satre.* Will need more investigations.

- *Will need to think about what and how to combine all above information*

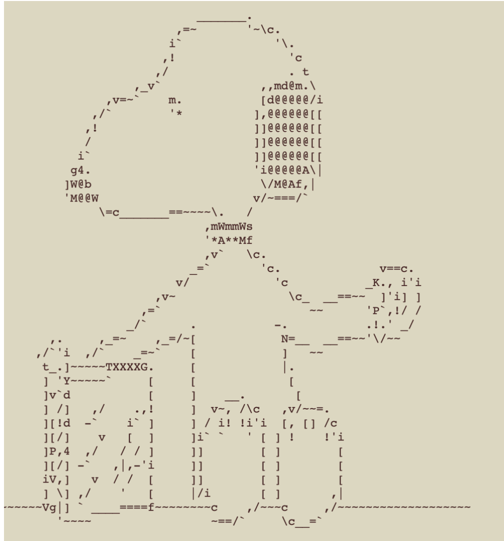
- Realistic simulations are done by Alex Jentsch et al, which includes more effects for the detector and IR/Machine designs, e.g., momentum spread of the beam, crab cavity, angular divergence, etc.

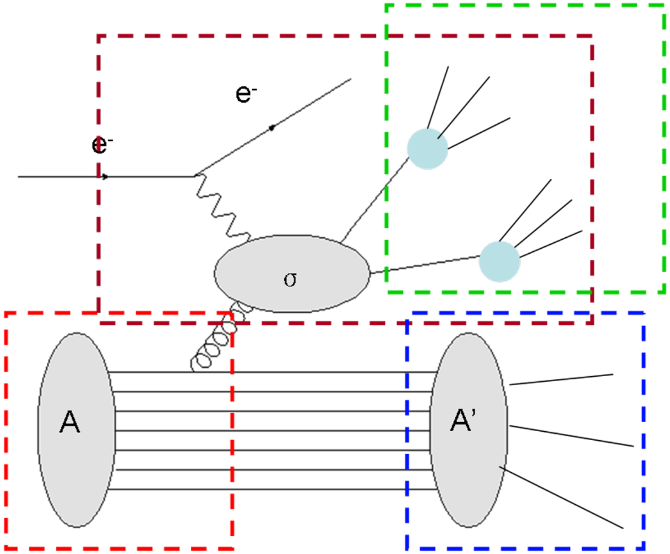
Backup

BeAGLE

- Initiated by M.Baker, E. Aschenauer, JH. Lee, Z. Liang.
- Now new developers/maintainers, e,g., Kong Tu, Mathieu Ehrhart, …
- Many users from Jlab, BNL, and other institutes, and becoming more.

- Pythia 6 + DPMJet + Fluka - embed an elementary eN collision into a nuclear environment, https://wiki.bnl.gov/eic/index.php/BeAGLE





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

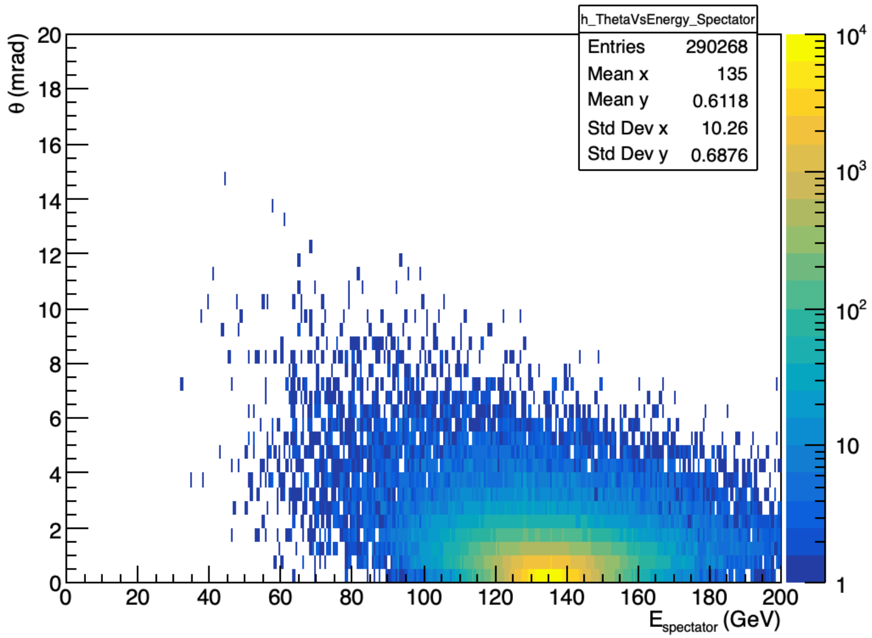
Nuclear geometry by DPMJet and nPDF provided by EPS09.

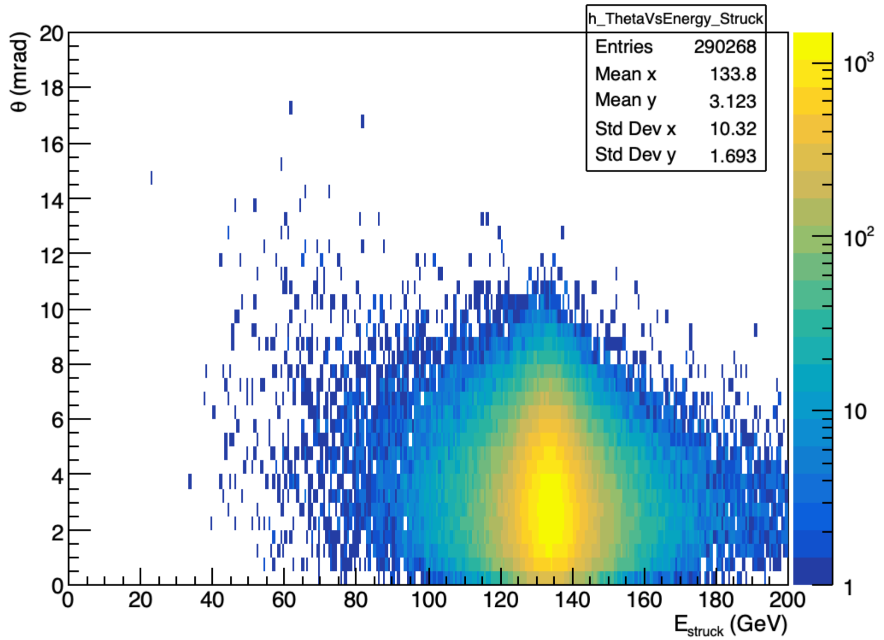
Parton level interaction and jet fragmentation completed in PYTHIA.

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

theta vs E





No detector acceptance or resolution was applied.