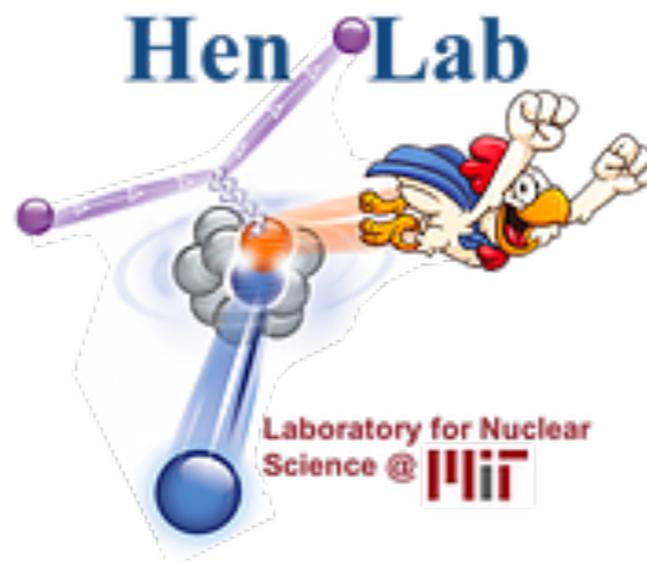


Neutron-tagged DIS at Jefferson Lab with CLAS12 and BAND

Efrain Segarra



May 4, 2022

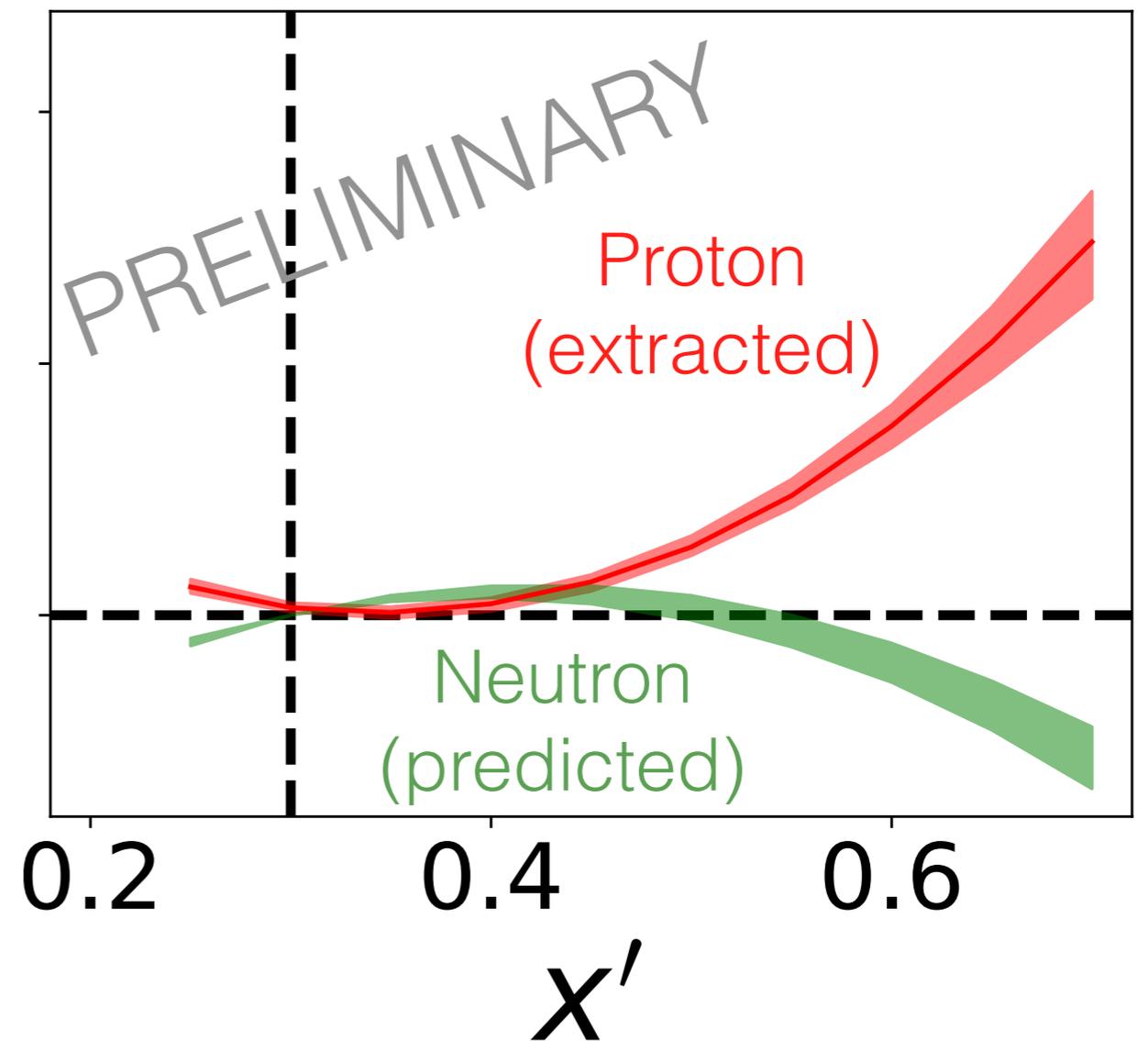
DIS2022

First measurement of strongly interacting bound proton structure

Outline today

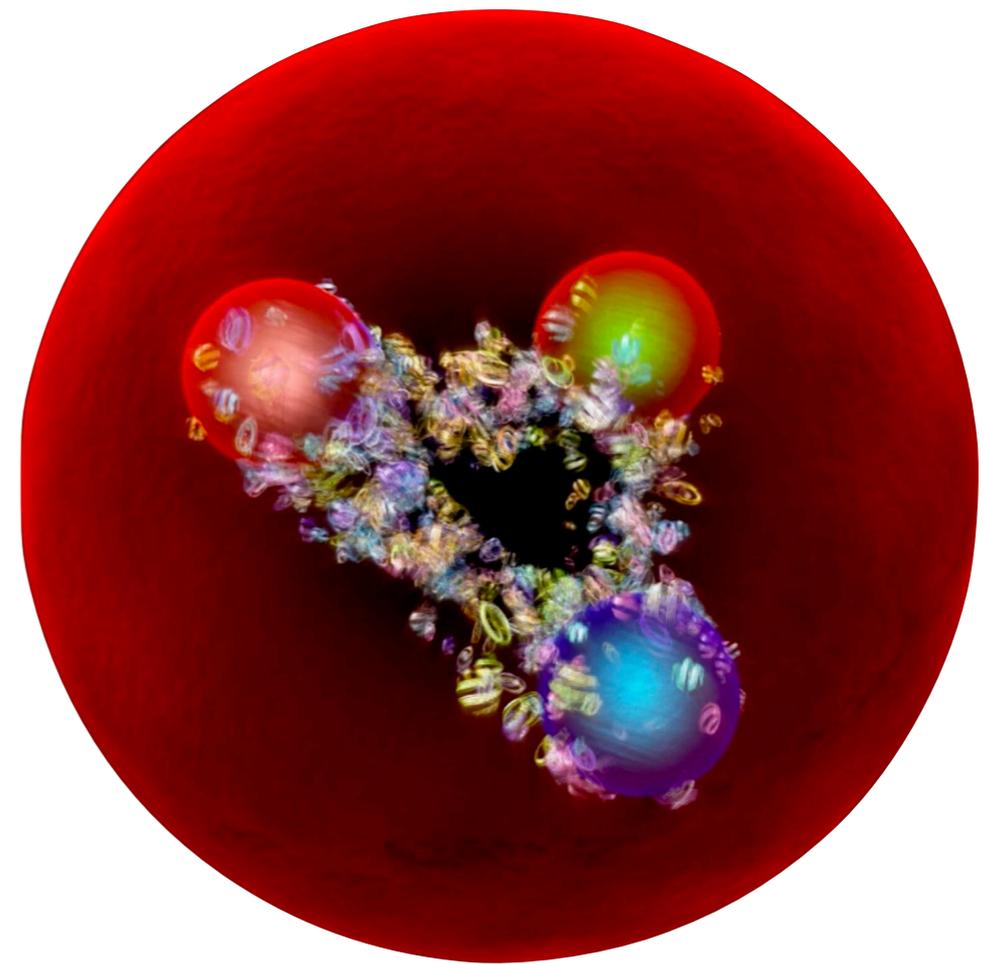
- EMC effect
- Tagged DIS
- CLAS12 + BAND
- Bound proton structure

$$F_2^{N^*} / F_2^N$$

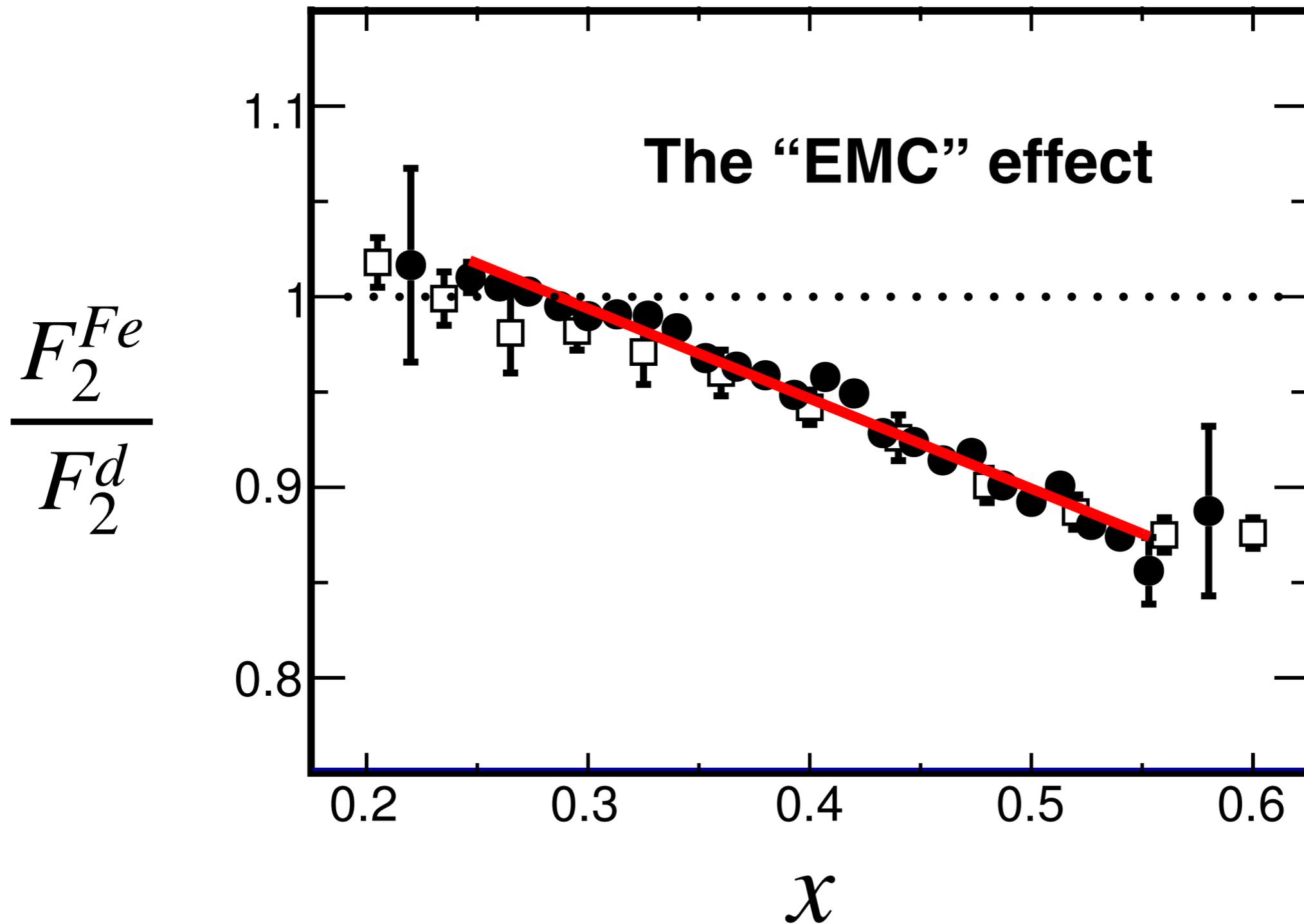


How does the strong nuclear force affect quark distributions

Comparing quark distributions in a bound and free proton



Quarks modified heavily in nuclear environment



Puzzled for decades... until now?

- No solution to the EMC effect for decades

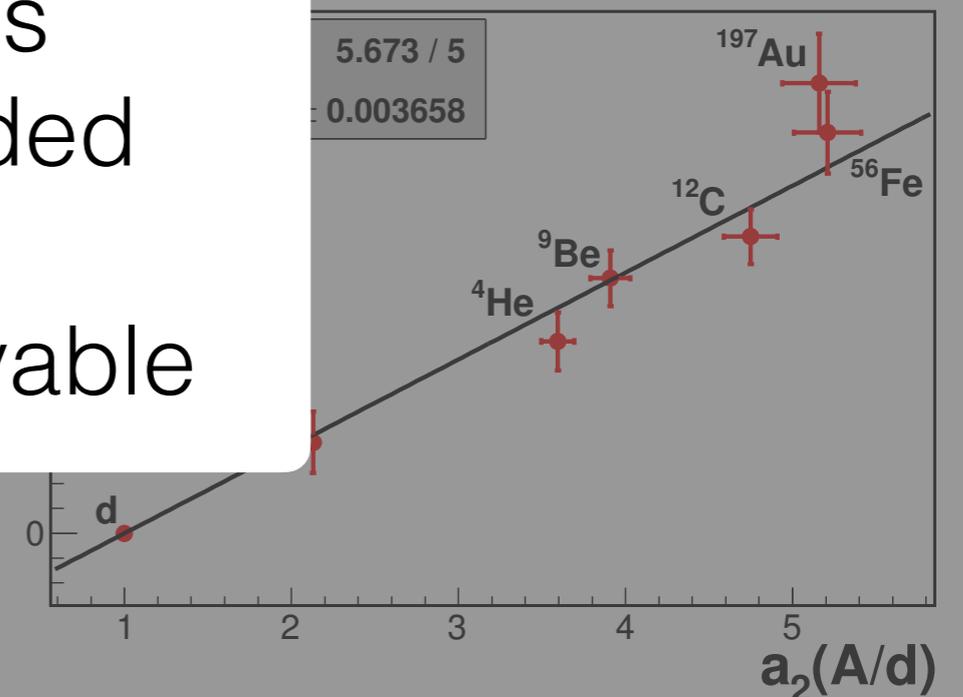
- **Novel** Drell-Yan experiment changed our understanding

- Phenomenological gaps in recent years

> 1000 publications, only thing agreed upon is modification is needed

Need a **new** observable

Strongly interacting nucleons correlate EMC strength!



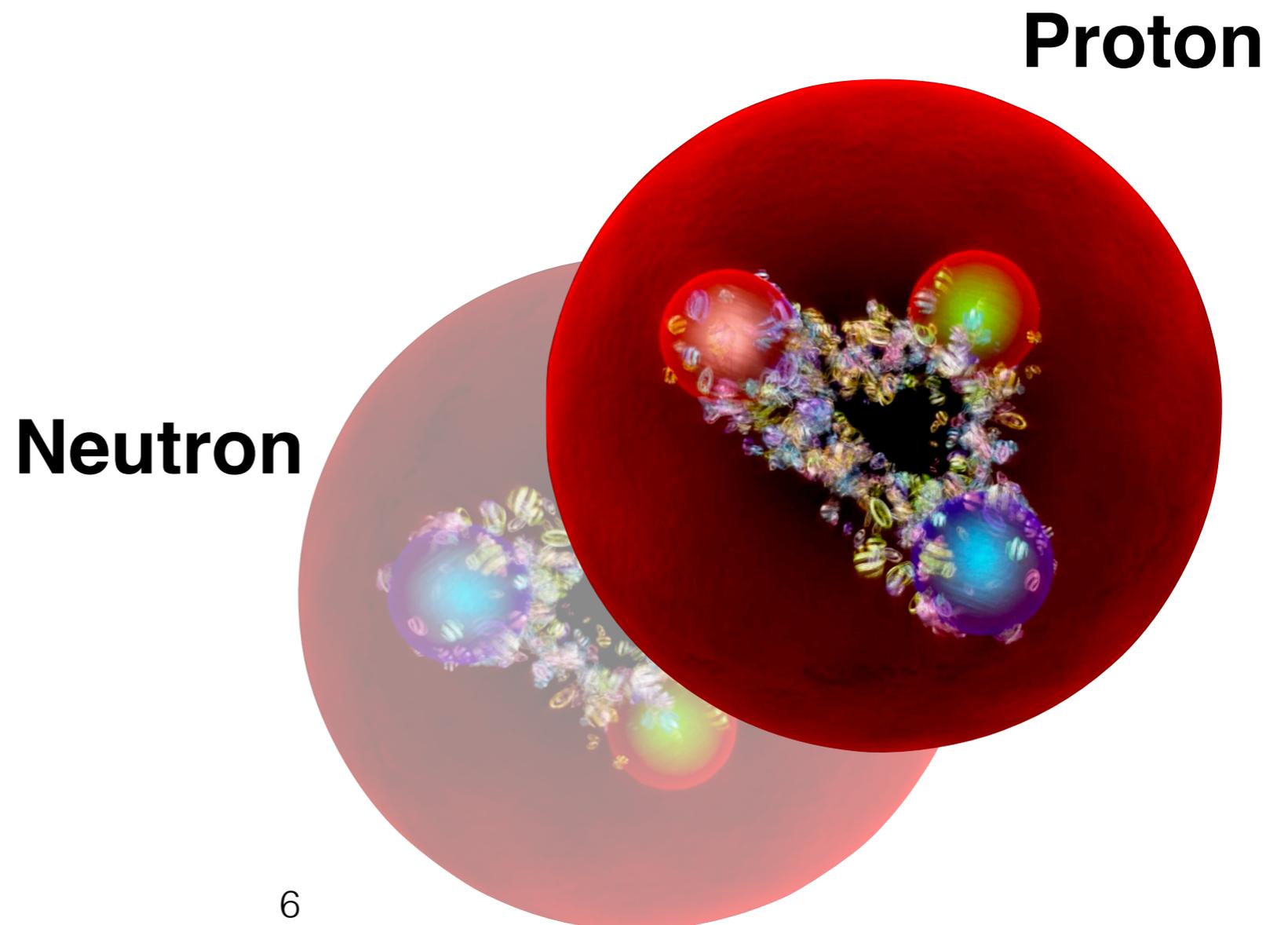
E.P. Segarra et al., [PRL \(2020\)](#)

E.P. Segarra et al., [Phys. Rev. Research \(2021\)](#)

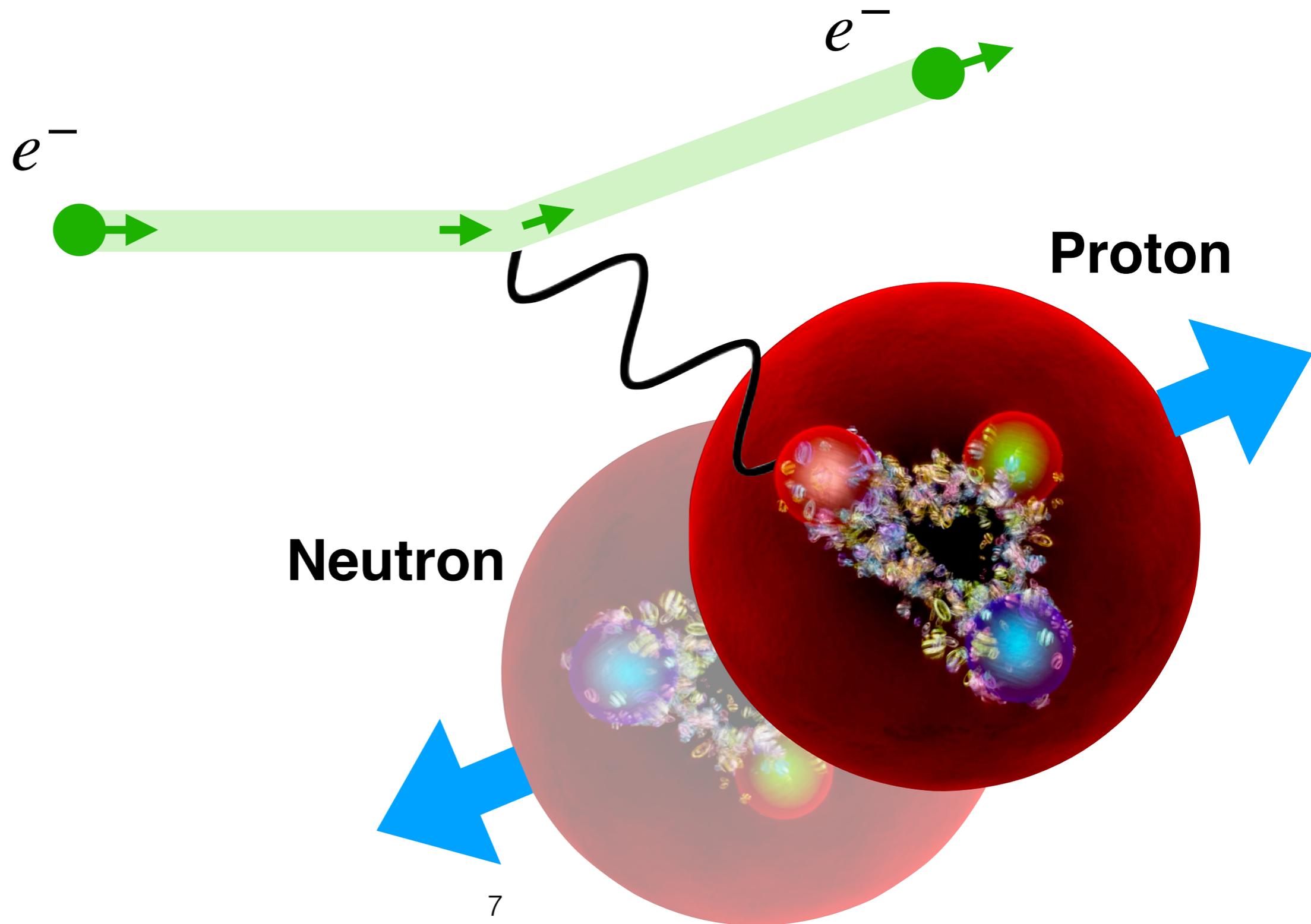
E.P. Segarra et al., [arXiv: 2104.07130 \(submitted, 2021\)](#)

Today: spectator tagging to study the EMC effect

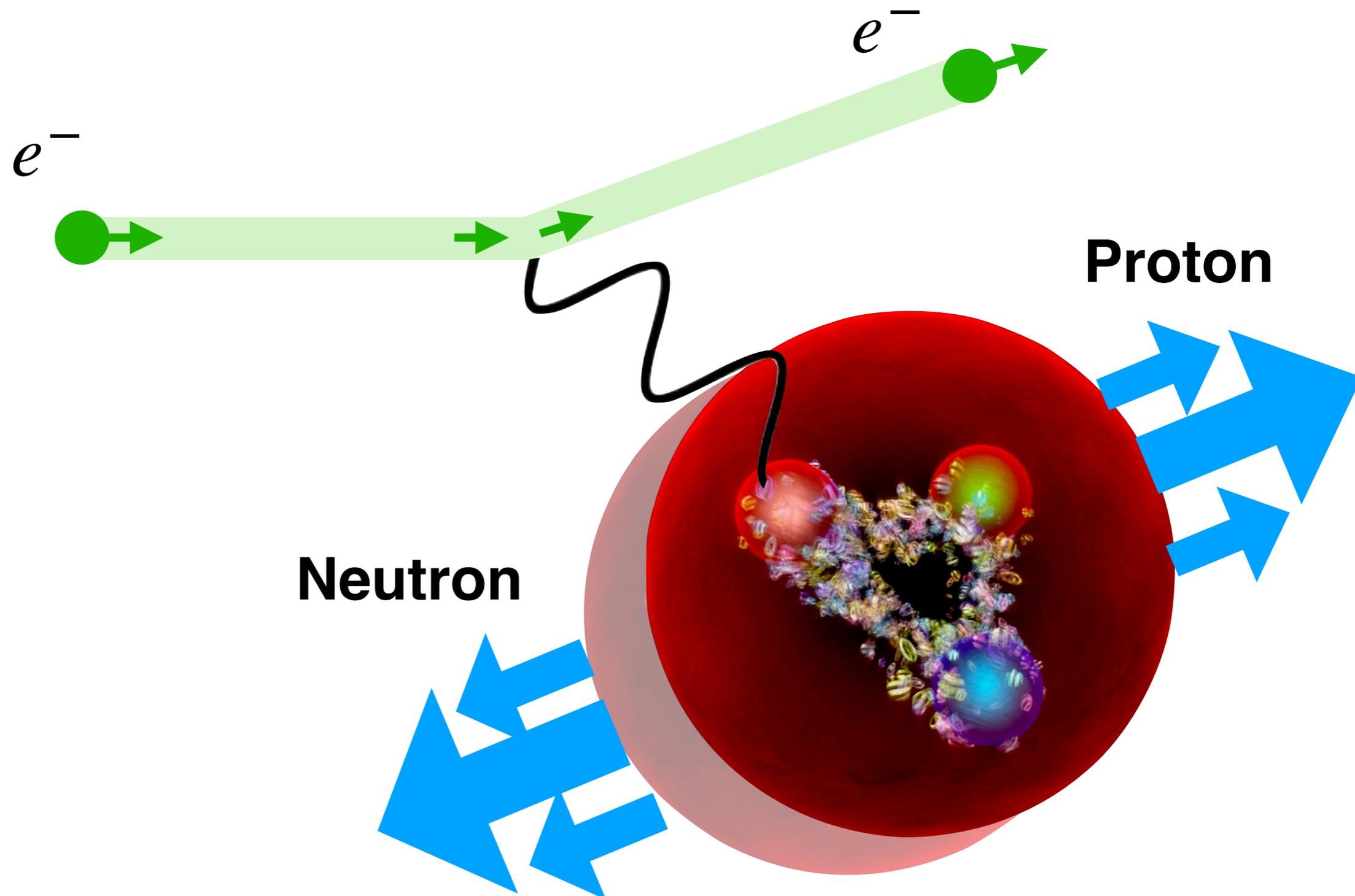
Goal is to investigate modification effects in strongly interacting systems



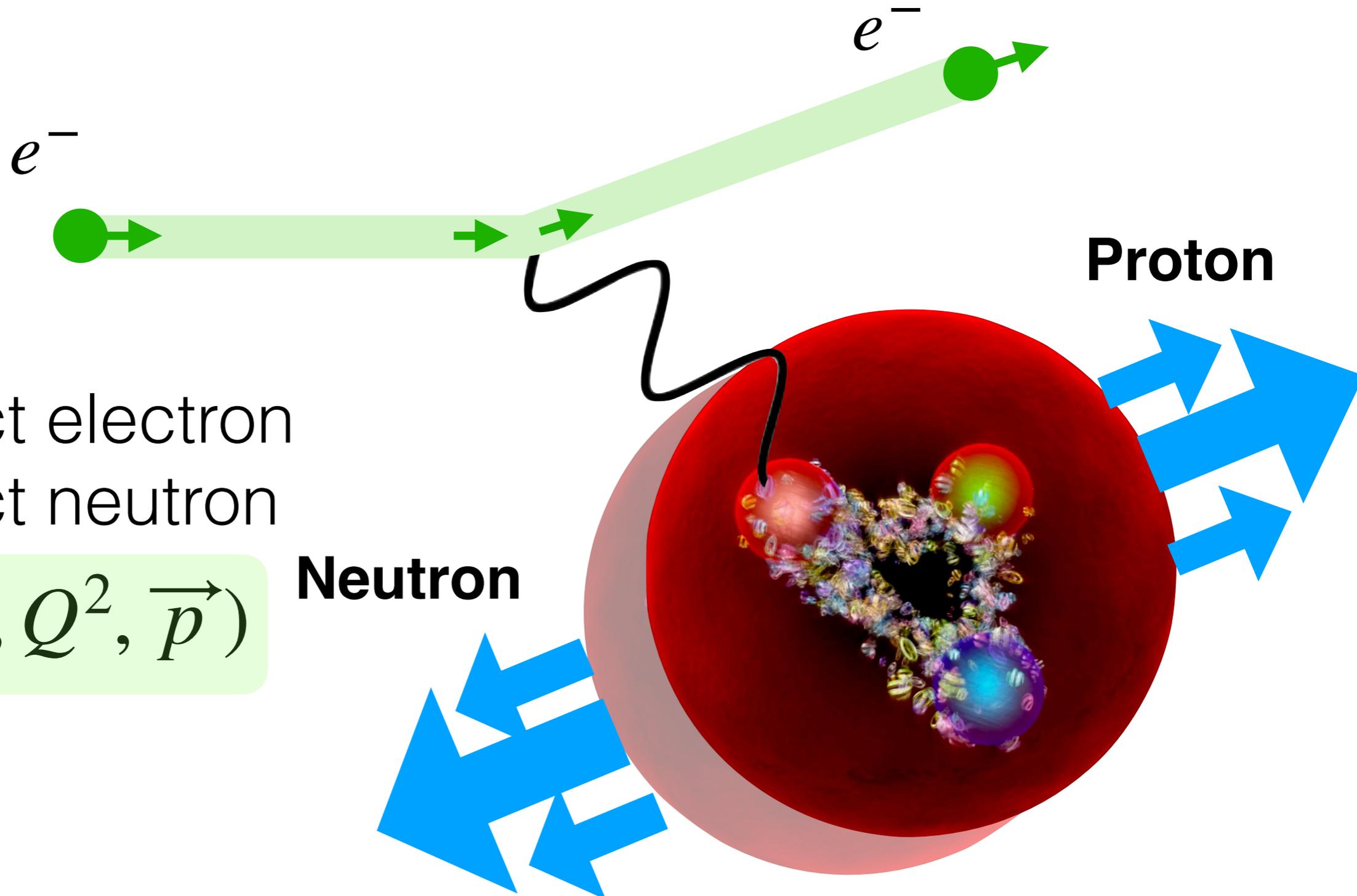
Spectator tagging in deuterium:
study EMC effect as a function of \vec{p}



Spectator tagging in deuterium:
study EMC effect as a function of \vec{p}



Spectator tagging in deuterium: study EMC effect as a function of \vec{p}



- Detect electron
- Detect neutron

$$F_2^{p*}(x, Q^2, \vec{p})$$

Neutron

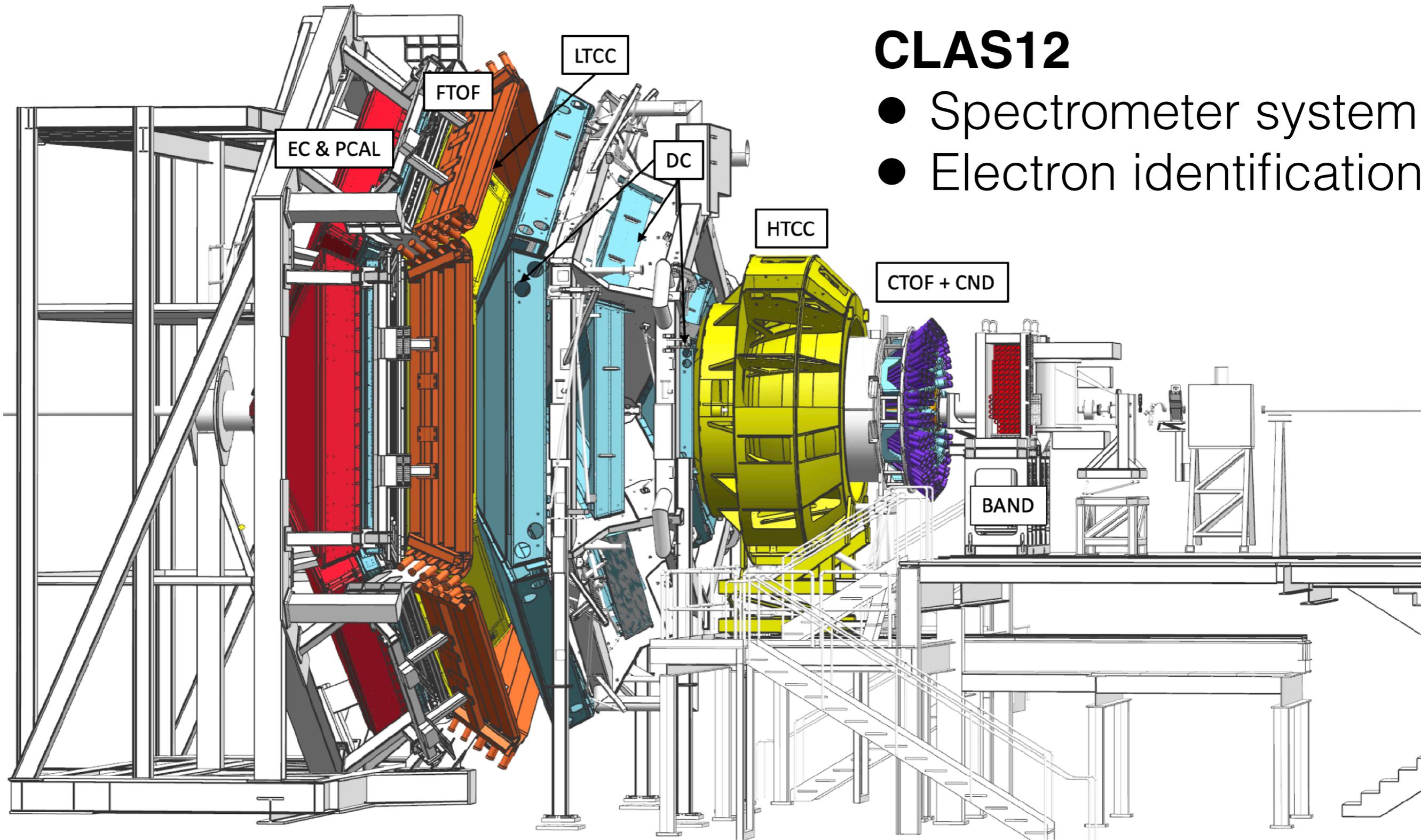
Spectator tagging at JLab



Jefferson Lab,
12 GeV e^- beam

Hall B

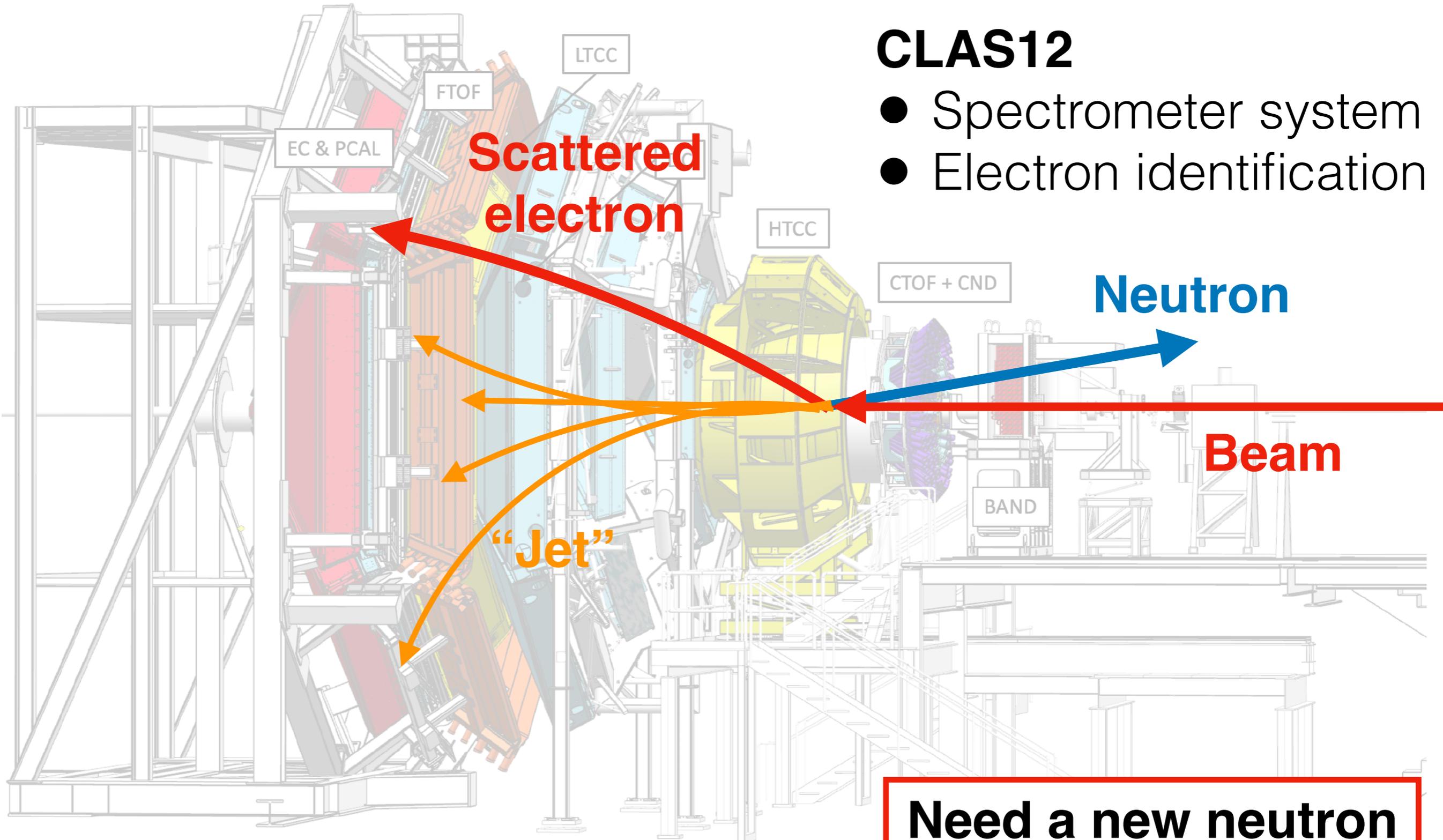
Hall B at Jefferson Lab



CLAS12

- Spectrometer system
- Electron identification

Hall B at Jefferson Lab

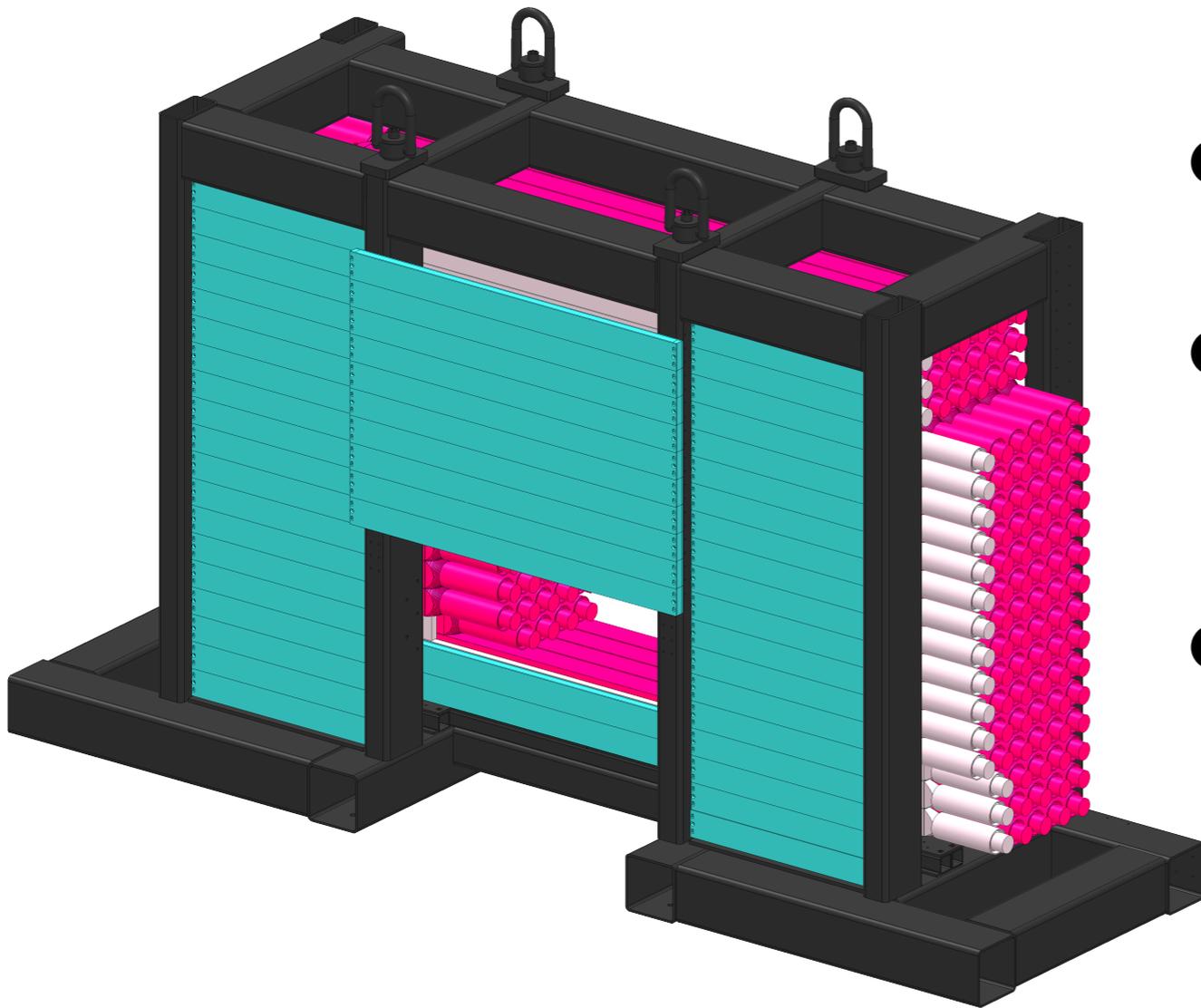


CLAS12

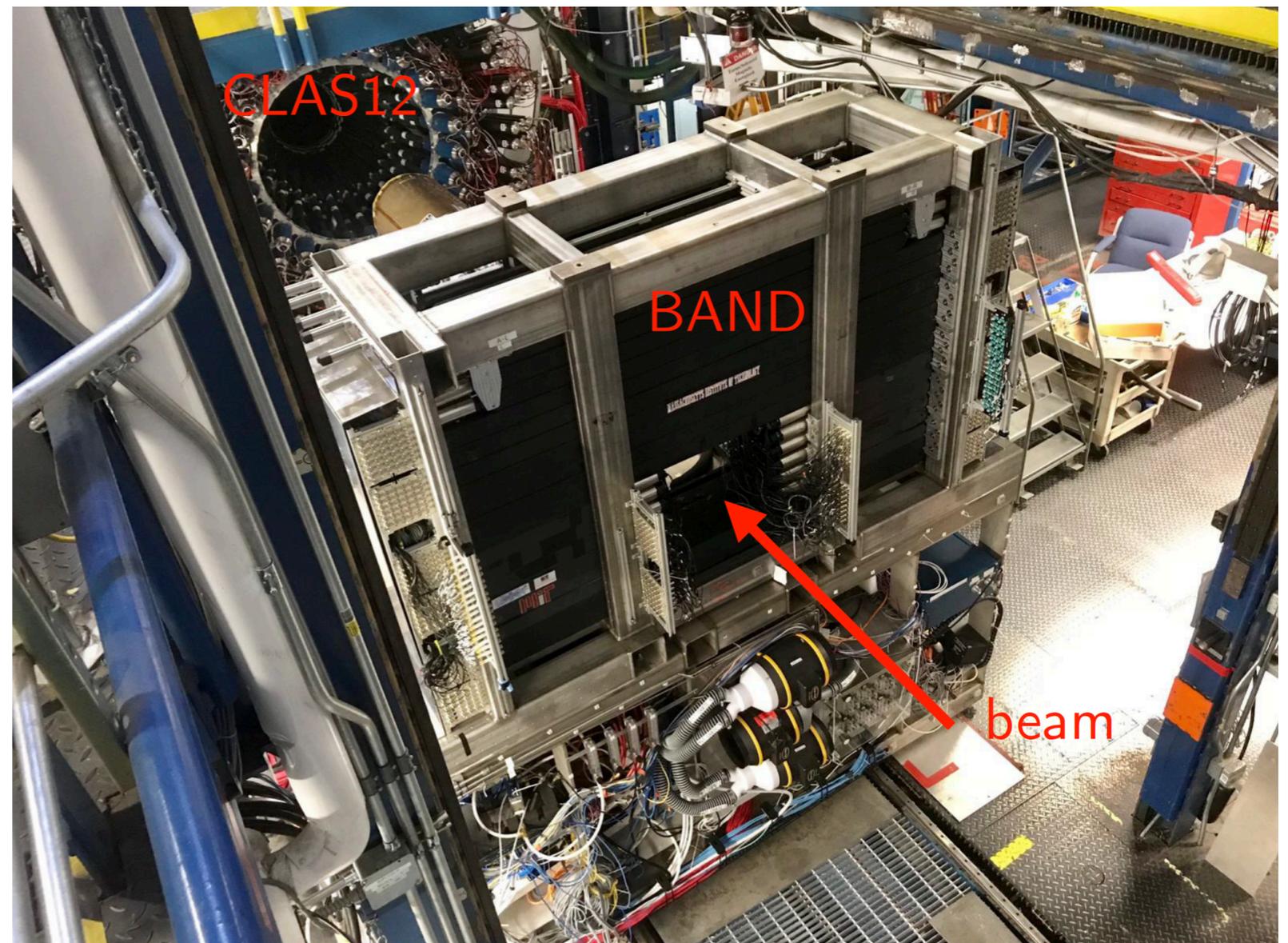
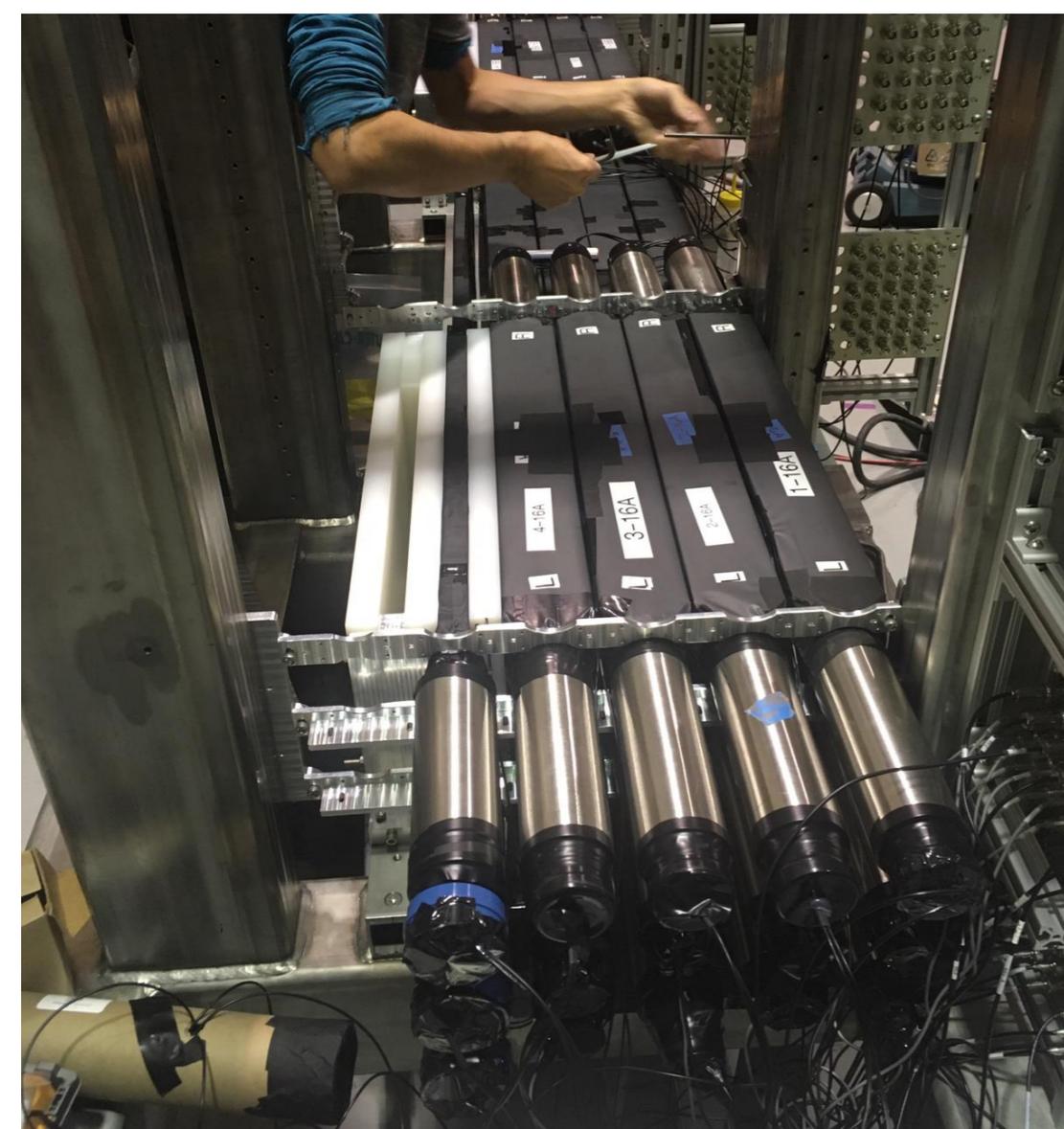
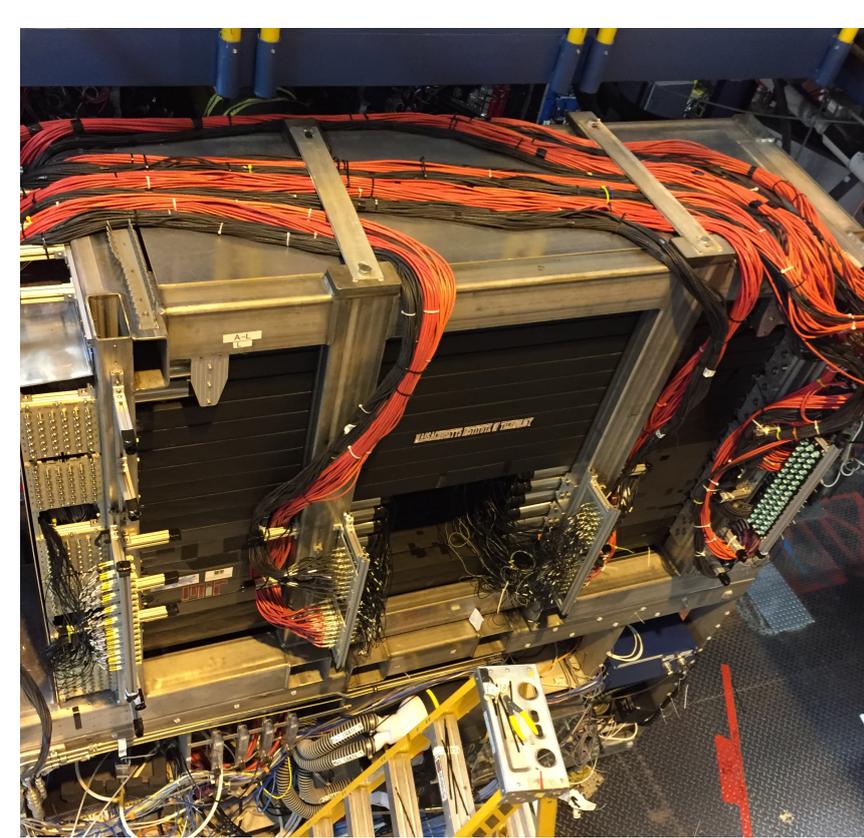
- Spectrometer system
- Electron identification

Need a new neutron detector (BAND)

Design of the Backward Angle Neutron Detector (BAND)

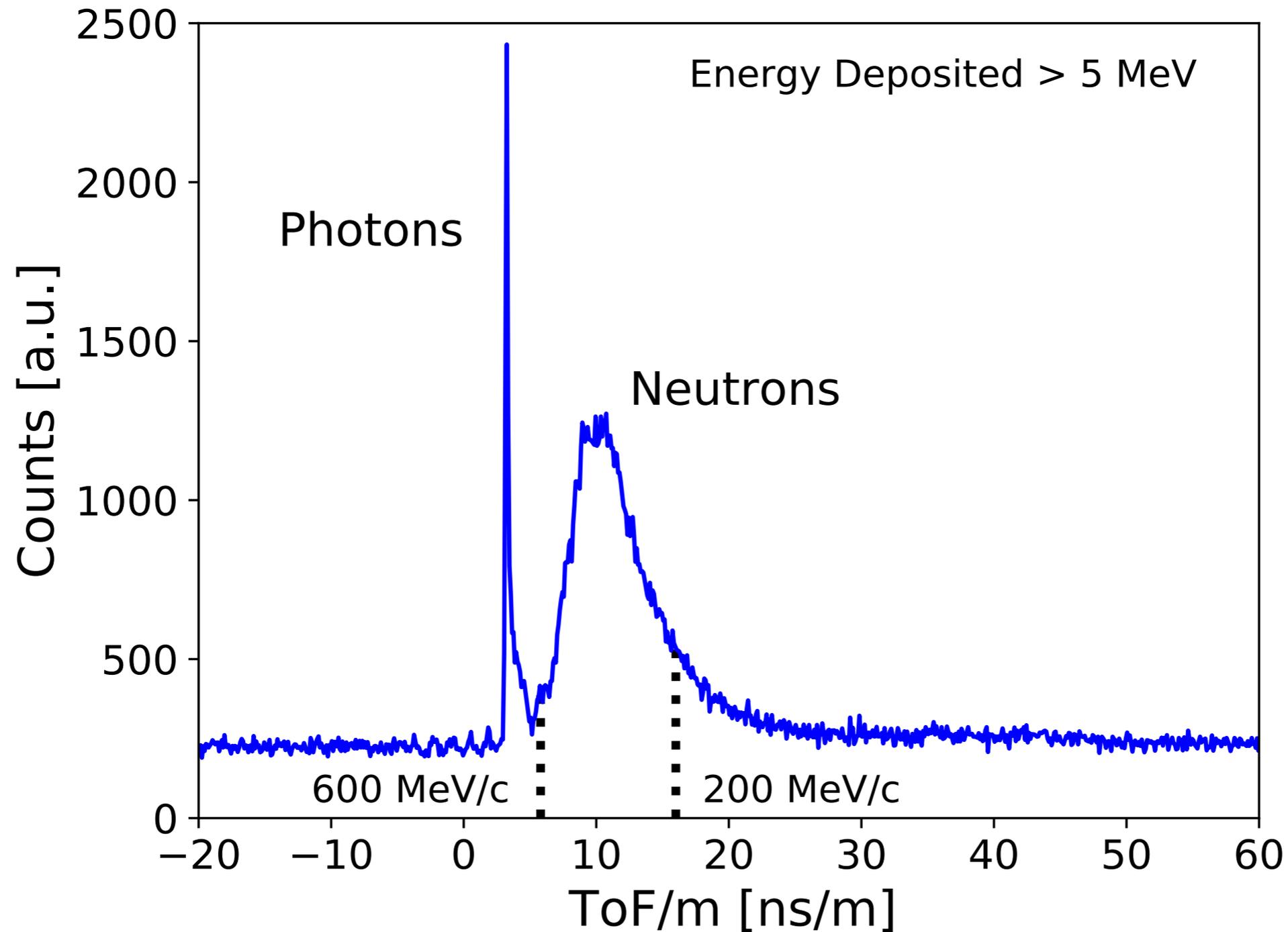


- 140 scintillator bars
- 5 layers (36cm) + veto layer
- ToF resolutions < 250 ps at 2 MeVee
- 3 meters upstream of target, coverage in $\theta \sim 155 - 176^\circ$



At the end of the day, the result!

BAND response in $d(e, e'n_{BAND})X$

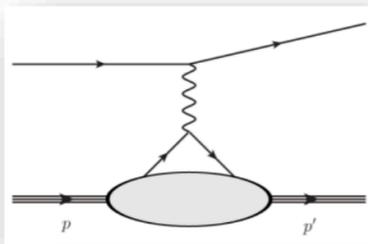


Data taken for Run-Group B

Data taking 2019-2020

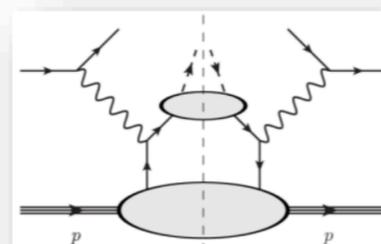
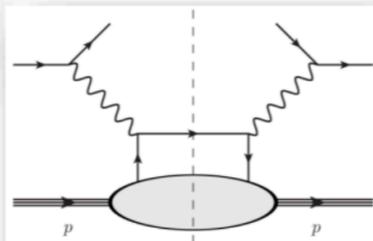
- ~90 days
- 10.2, 10.4, 10.6 GeV beam
- Liquid deuterium target

CLAS12 Run Group B: experiments & analyses/PhDs

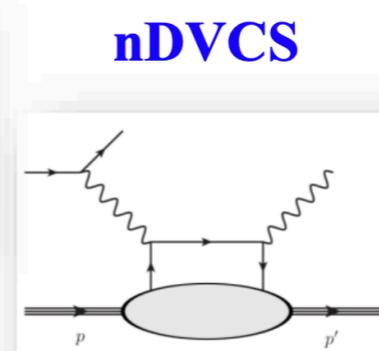


Elastic Scattering
 (G_M^n)

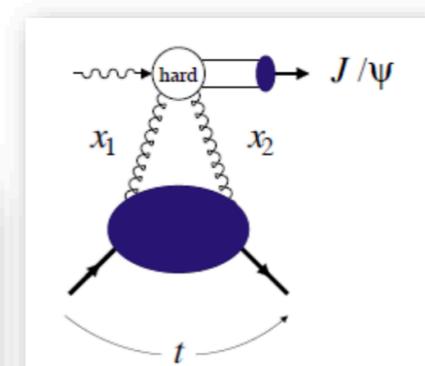
DIS (for SRC and EMC effect)



SIDIS (for PDFs and TMDs)



nDVCS



J/psi photoproduction

Run-Group B aims to measure FFs, PDFs, TMDs, GPDs, using **deuteron** as a **neutron target**
→ **Quark-flavor separation, combining with proton results**

Observable to study bound structure

Bound proton:

$$F_2^{p^*} \sim \frac{d^4\sigma_{d(e,e'n)X}}{dQ^2 d\alpha_S dp_T dx'}$$

Observable to study bound structure

Bound proton:

$$F_2^{p^*} \sim \frac{d^4\sigma_{d(e,e'n)X}}{dQ^2 d\alpha_S dp_T dx'}$$

Relative to
free proton
(simulated):

$$F_2^{p^*} / F_2^p \sim \sigma_{exp}(x') / \sigma_{sim}(x')$$

Observable to study bound structure

Bound proton:

$$F_2^{p^*} \sim \frac{d^4\sigma_{d(e,e'n)X}}{dQ^2 d\alpha_S dp_T dx'}$$

Relative to
free proton
(simulated):

$$F_2^{p^*}/F_2^p \sim \sigma_{exp}(x')/\sigma_{sim}(x')$$

Luminosity
normalized
(double ratio):

$$R_{tag} \equiv \frac{\sigma_{exp}(x')/\sigma_{exp}(x'_{ref})}{\sigma_{sim}(x')/\sigma_{sim}(x'_{ref})} \sim \frac{F_2^{p^*}(x')/F_2^{p^*}(x'_{ref})}{F_2^p(x')/F_2^p(x'_{ref})}$$

Observable to study bound structure

Bound proton:

$$F_2^{p^*} \sim \frac{d^4\sigma_{d(e,e'n)X}}{dQ^2 d\alpha_S dp_T dx'}$$

Relative to
free proton
(simulated):

- Detect electron
- Detect neutron
- Compare to simulation

Luminosity
normalized
(double ratio):

$$R_{tag} \equiv \frac{\sigma_{exp}(x')/\sigma_{exp}(x'_{ref})}{\sigma_{sim}(x')/\sigma_{sim}(x'_{ref})} \sim \frac{F_2^{p^*}(x')/F_2^{p^*}(x'_{ref})}{F_2^p(x')/F_2^p(x'_{ref})}$$

Observable to study bound structure

$$R_{tag} \equiv \frac{\sigma_{exp}(x')/\sigma_{exp}(x'_{ref})}{\sigma_{sim}(x')/\sigma_{sim}(x'_{ref})} \sim \frac{F_2^{p*}(x')/F_2^{p*}(x'_{ref})}{F_2^p(x')/F_2^p(x'_{ref})}$$

Double ratio to simulation:

- Luminosity cancels
- Electron & neutron detection effects partially cancel

Need reliable simulation

Theoretical PWIA calculation

Cross section model from Strikman & Weiss PRC (2018):

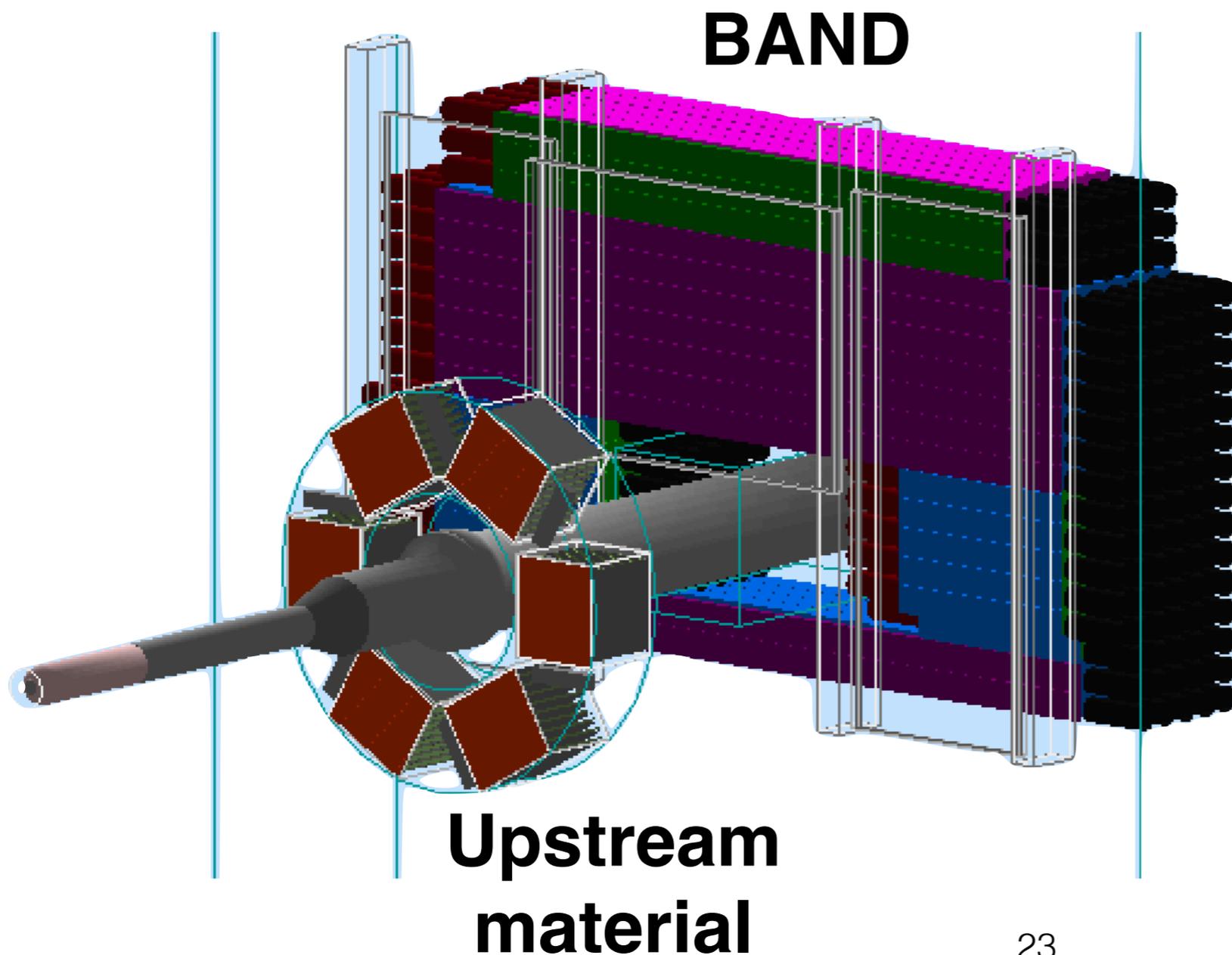
$$d\sigma[D(e, e'n_s)X] \sim K \frac{2S(\alpha_S, p_T)}{2 - \alpha_S} \cdot F_2$$

- Kinematic factor
- Spectral function of proton in deuterium
- Bound proton structure function
- Includes finite Q^2 effects

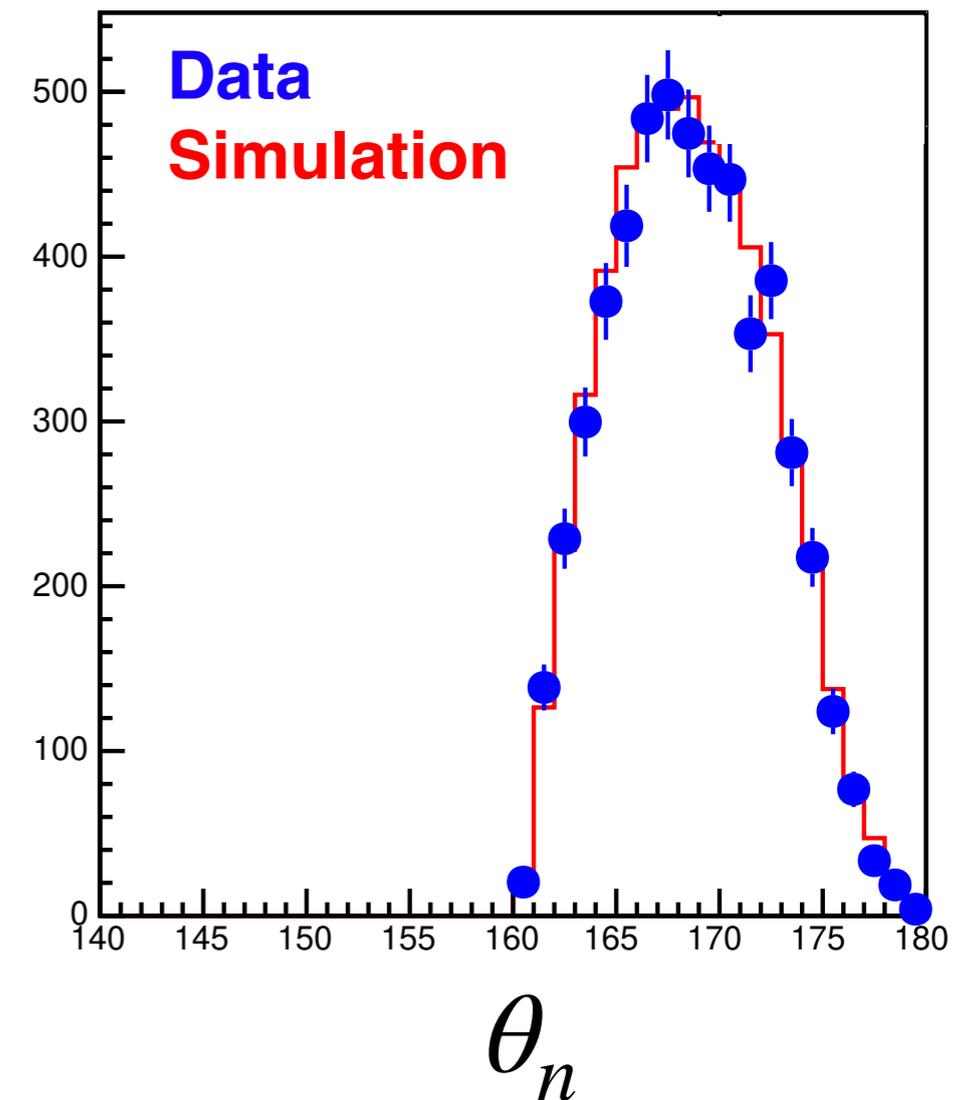
Simulate generated events (include QED radiation) in GEANT4

Simulation

- Created BAND & upstream material in Geant4
- Designed detector response, digitization, reconstruction

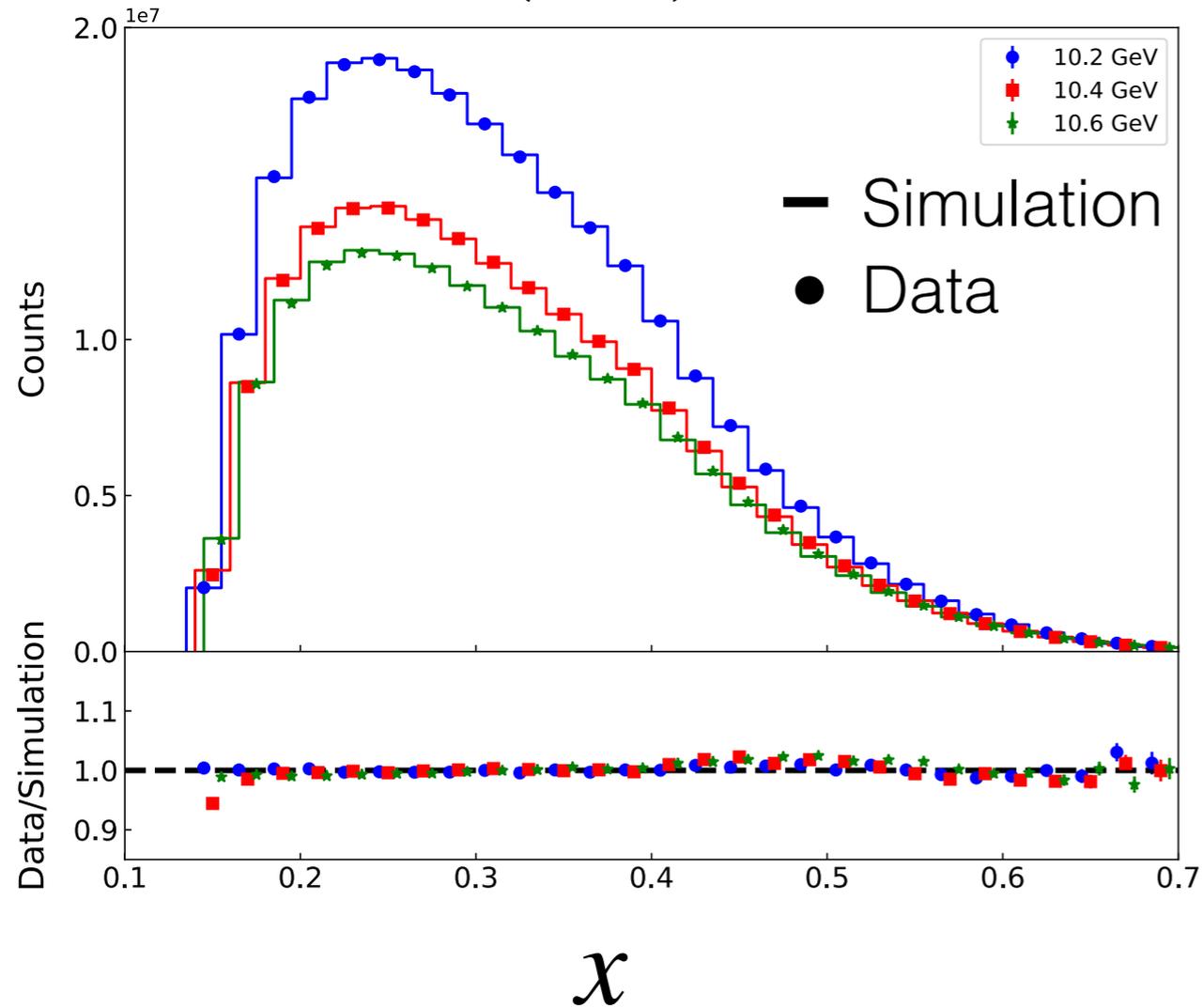


Large validation effort



Validated detector response over wide phase space

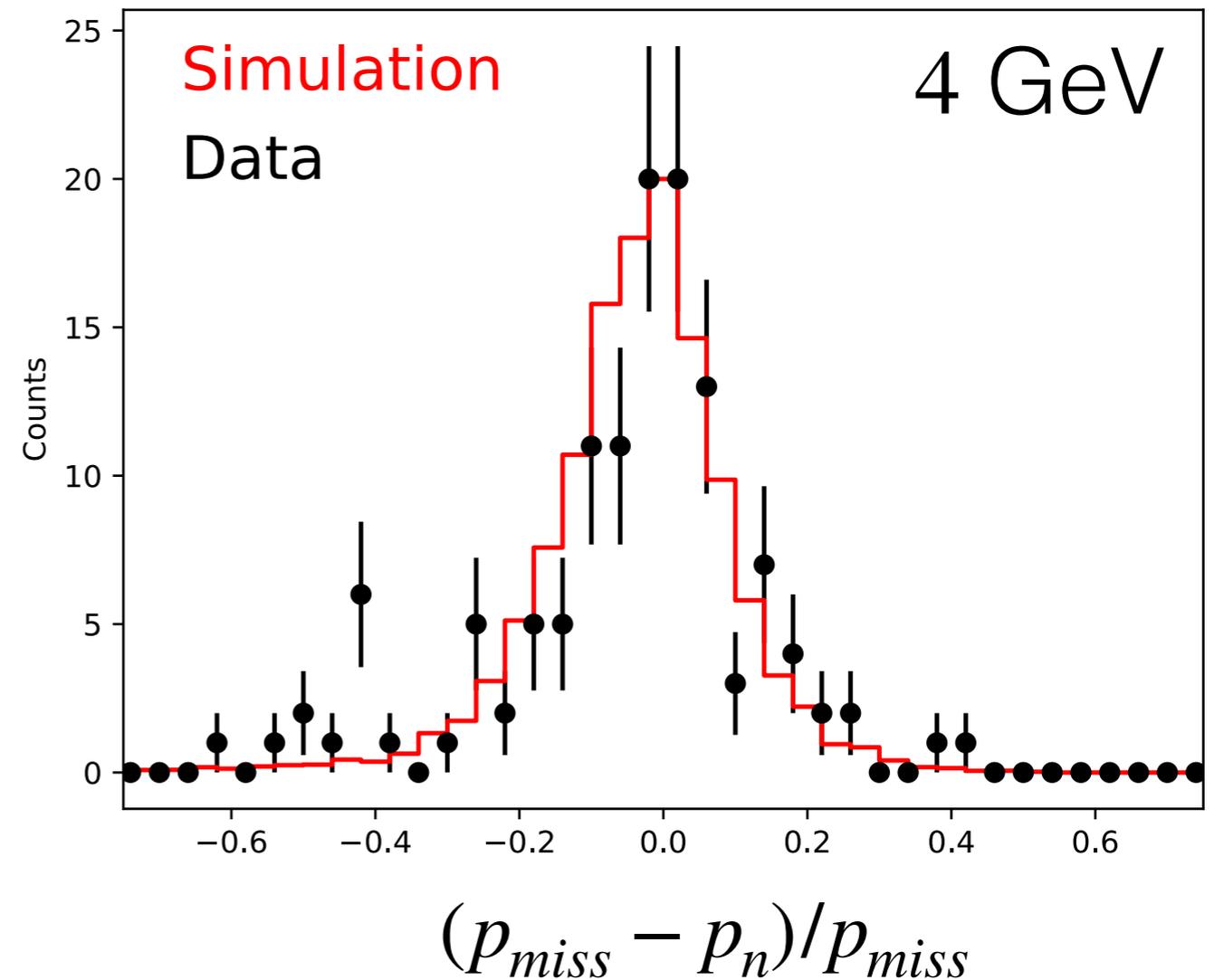
$d(e, e')X$



Simulated
electron in
CLAS12



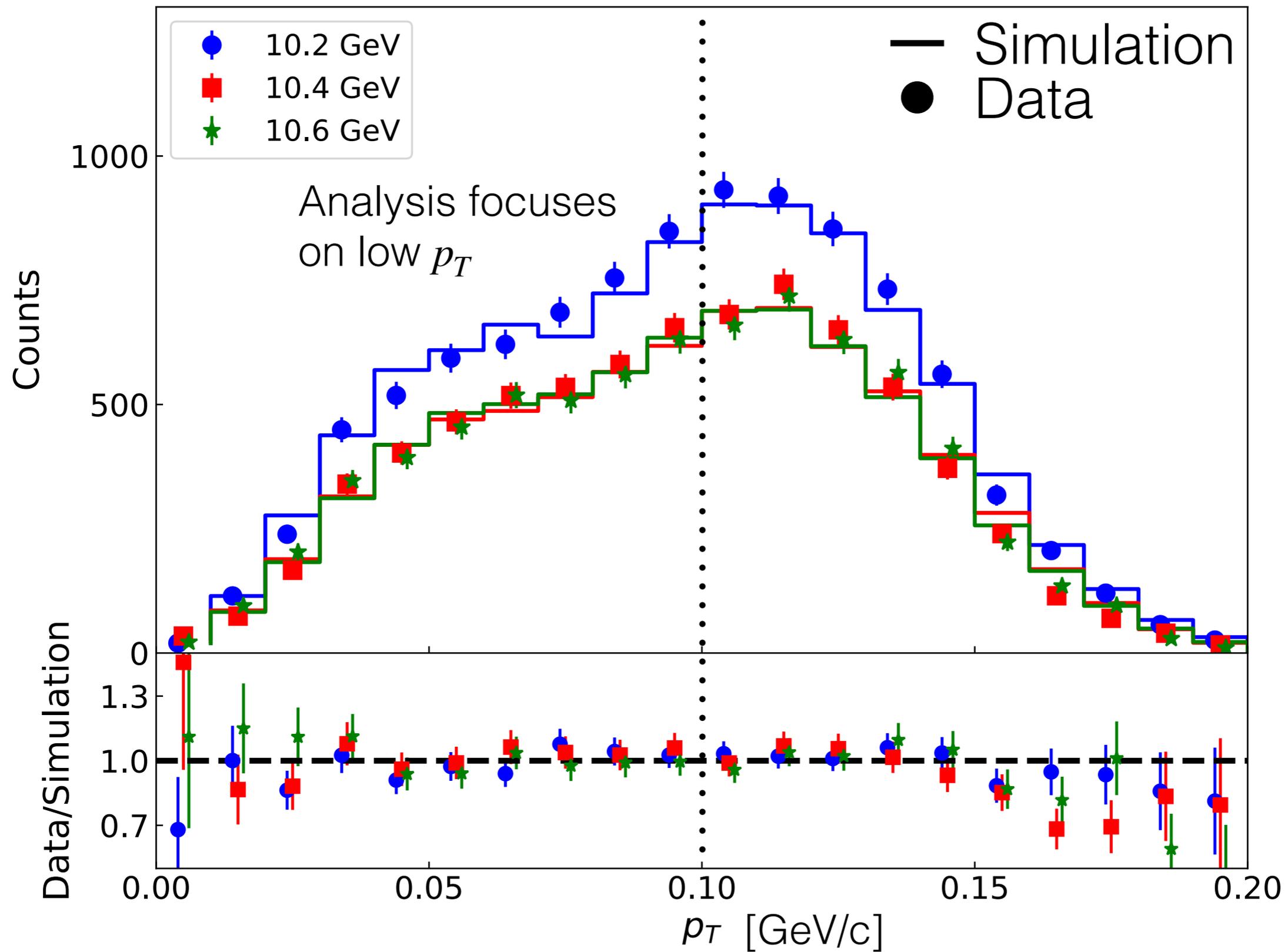
$d(e, e'pn)$



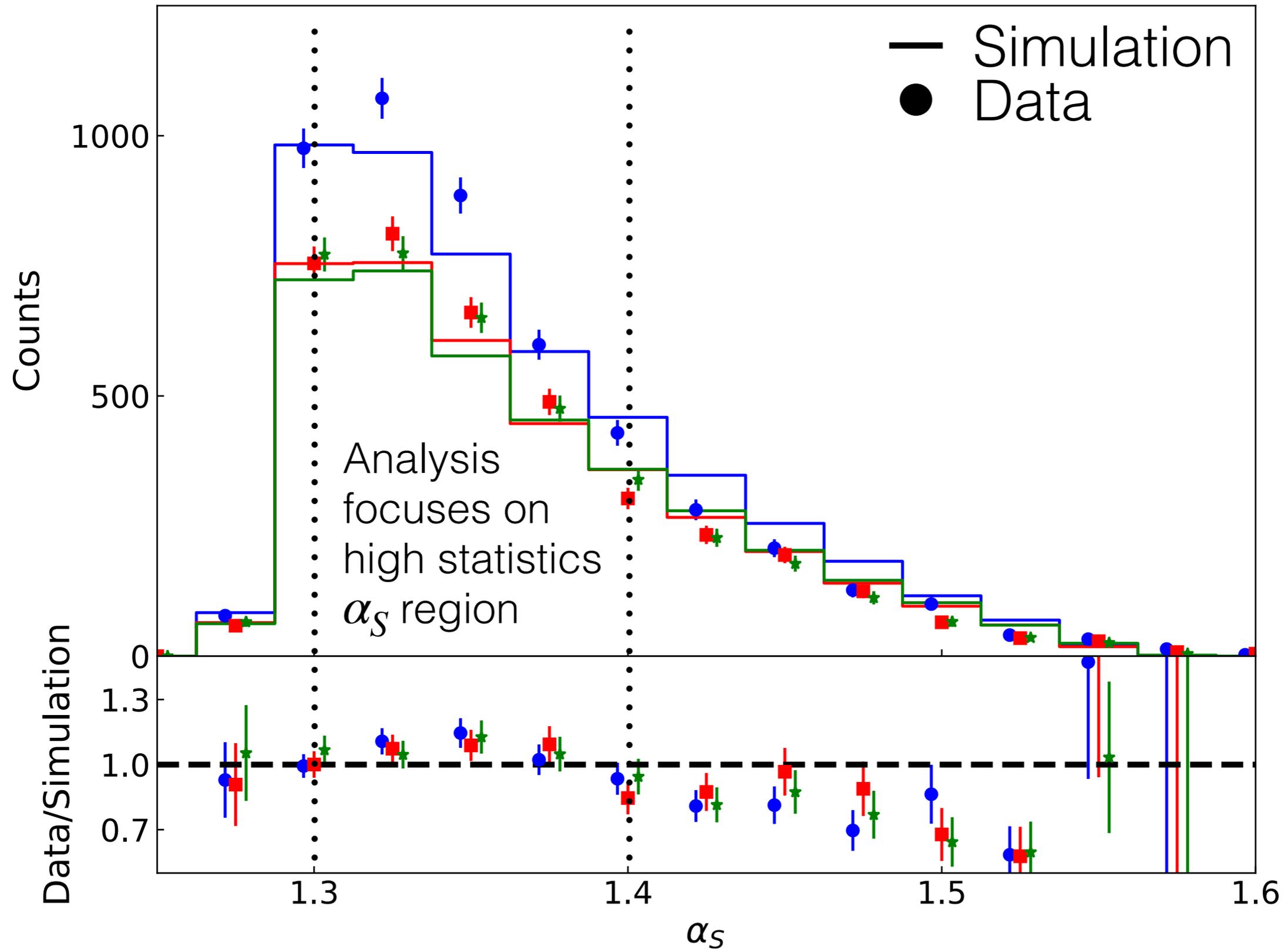
Simulated
neutron in
BAND



Spectator tagging $d(e, e'n)X$ with BAND



Spectator tagging $d(e, e'n)X$ with BAND



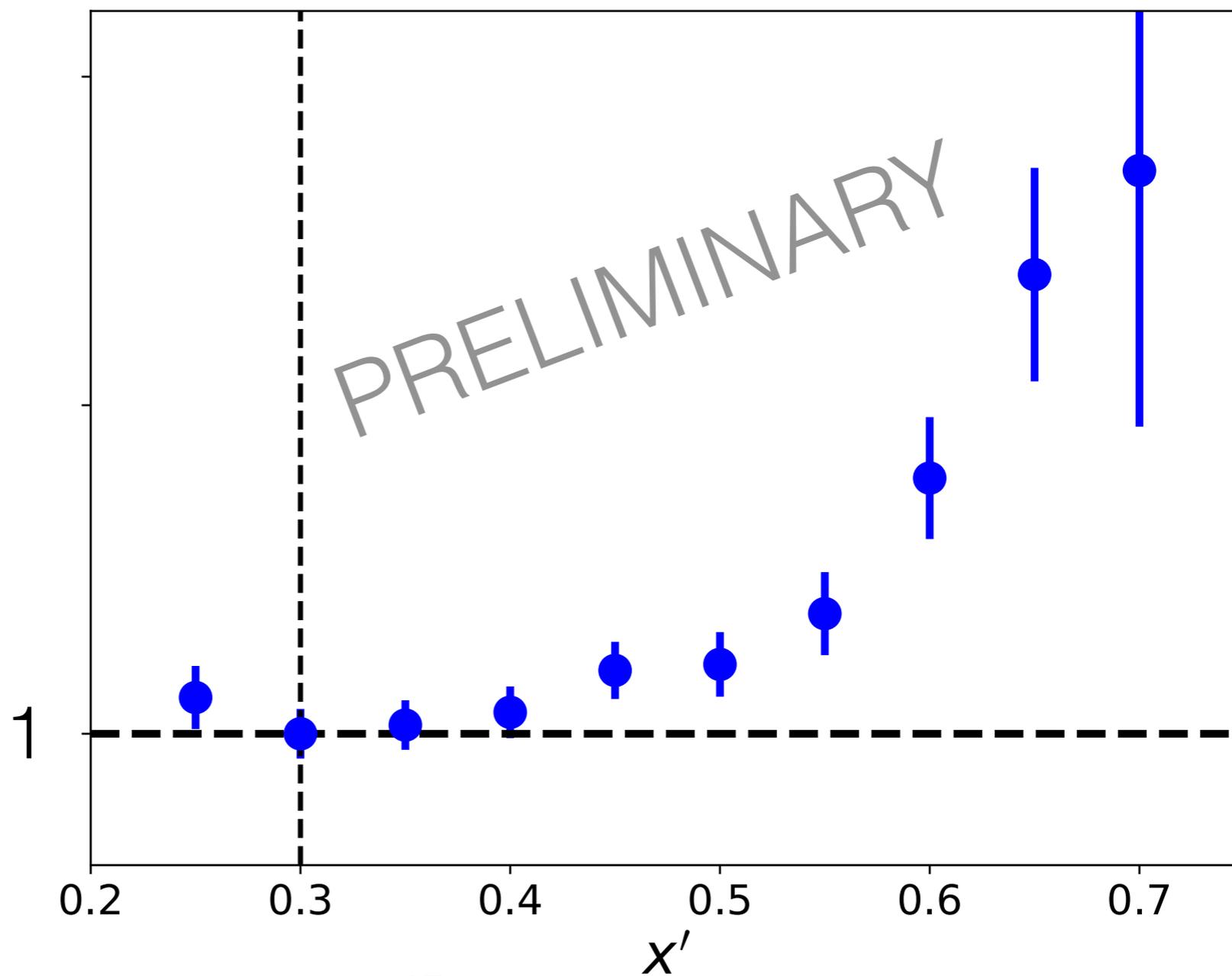
Preliminary bound proton structure

$$R_{tag} \equiv \frac{\sigma_{exp}(x')/\sigma_{exp}(x'_{ref})}{\sigma_{sim}(x')/\sigma_{sim}(x'_{ref})} \sim \frac{F_2^{p*}(x')/F_2^{p*}(x'_{ref})}{F_2^p(x')/F_2^p(x'_{ref})}$$

$$2 < Q^2 < 6$$

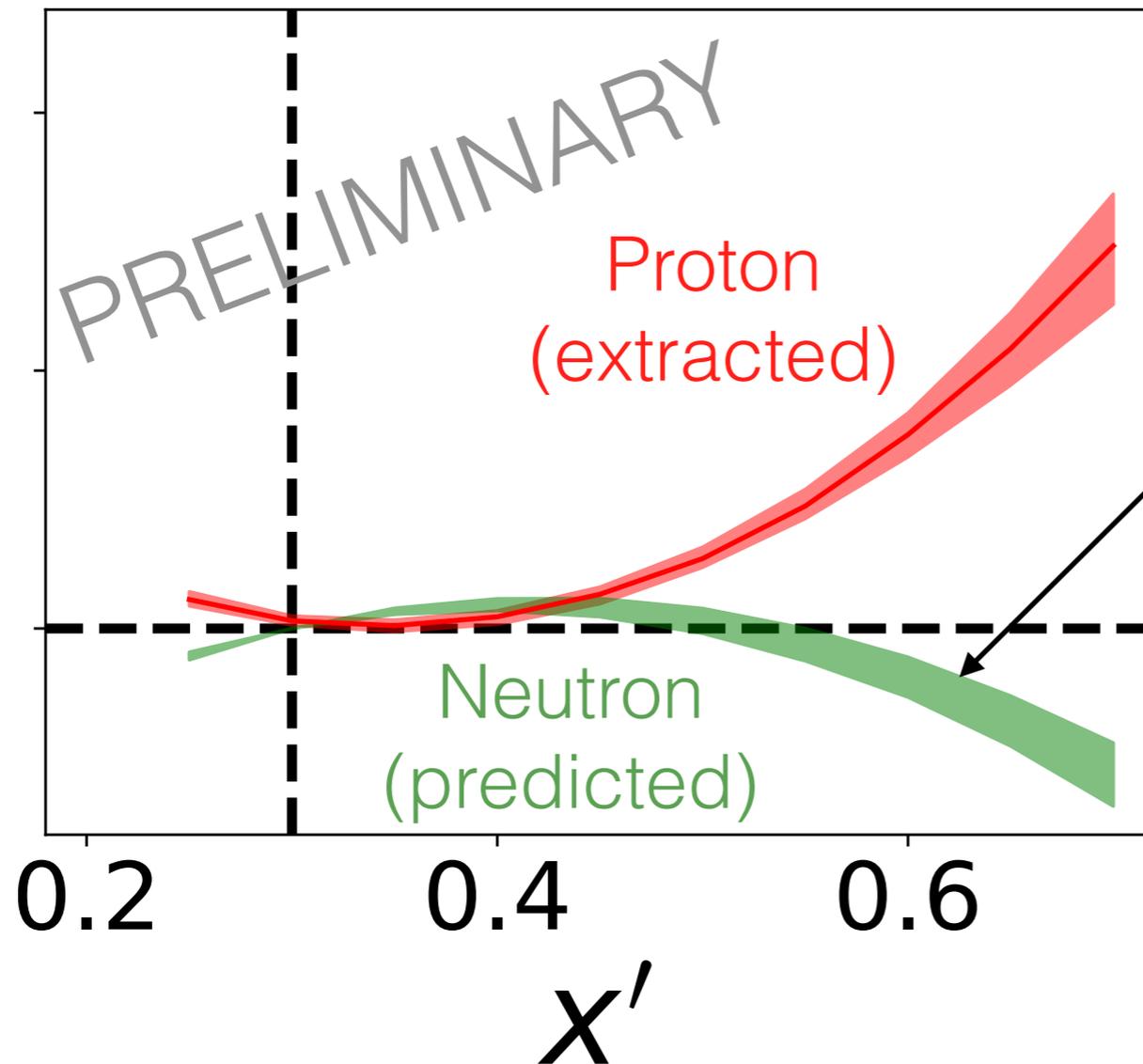
$$p_T < 0.1$$

$$1.3 < \alpha_S < 1.4$$

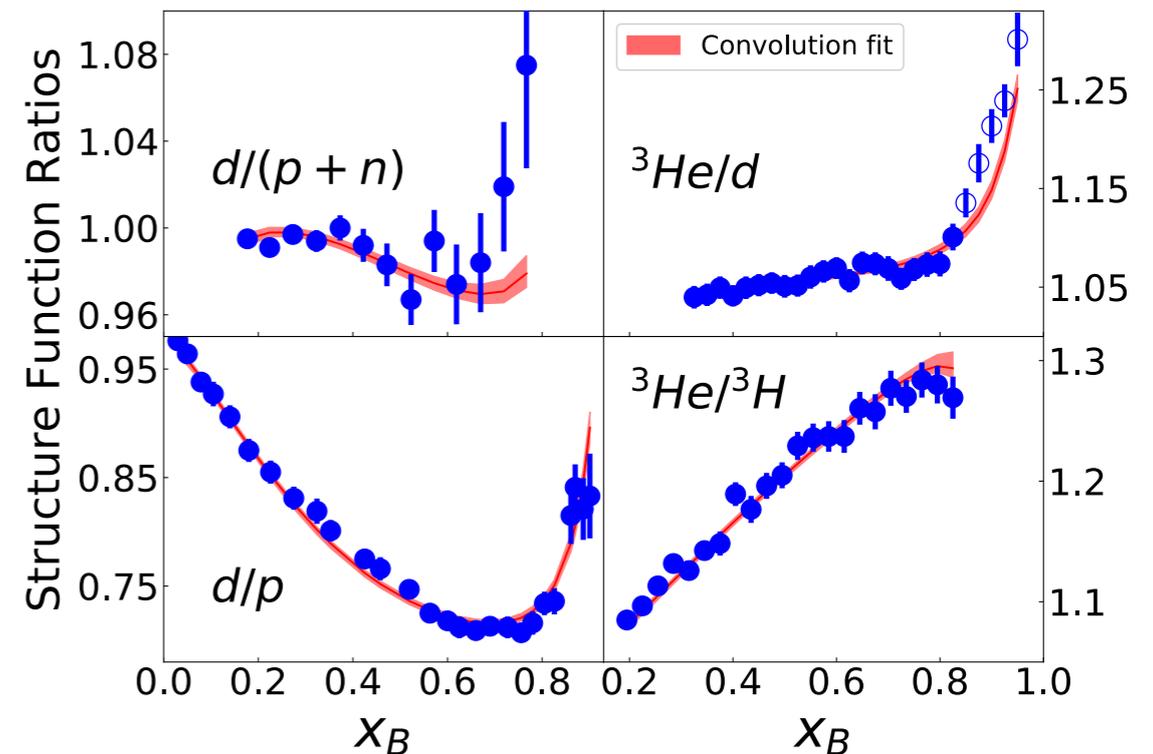


What does BAND mean for bound nucleon structure

$$F_2^{N^*} / F_2^N$$



Predicts opposite and large neutron modification



Conclusion

- First measurement of strongly interacting bound proton structure using spectator tagging
- **Preliminary** results show large modification
 - consistent with inclusive measurements
 - predicts large & opposite neutron modification (will be tested with LAD)
 - future analysis to examine quark modification
- Completing analysis prior to collaboration review

E.P. Segarra et al., [PRL \(2020\)](#)

E.P. Segarra et al., [NIMA \(2020\)](#)

A. Denniston, **E.P. Segarra** et al." [NIMA \(2020\)](#)

E.P. Segarra et al., [Phys. Rev. D \(2021\)](#)

E.P. Segarra et al., [Phys. Rev. Research \(2021\)](#)

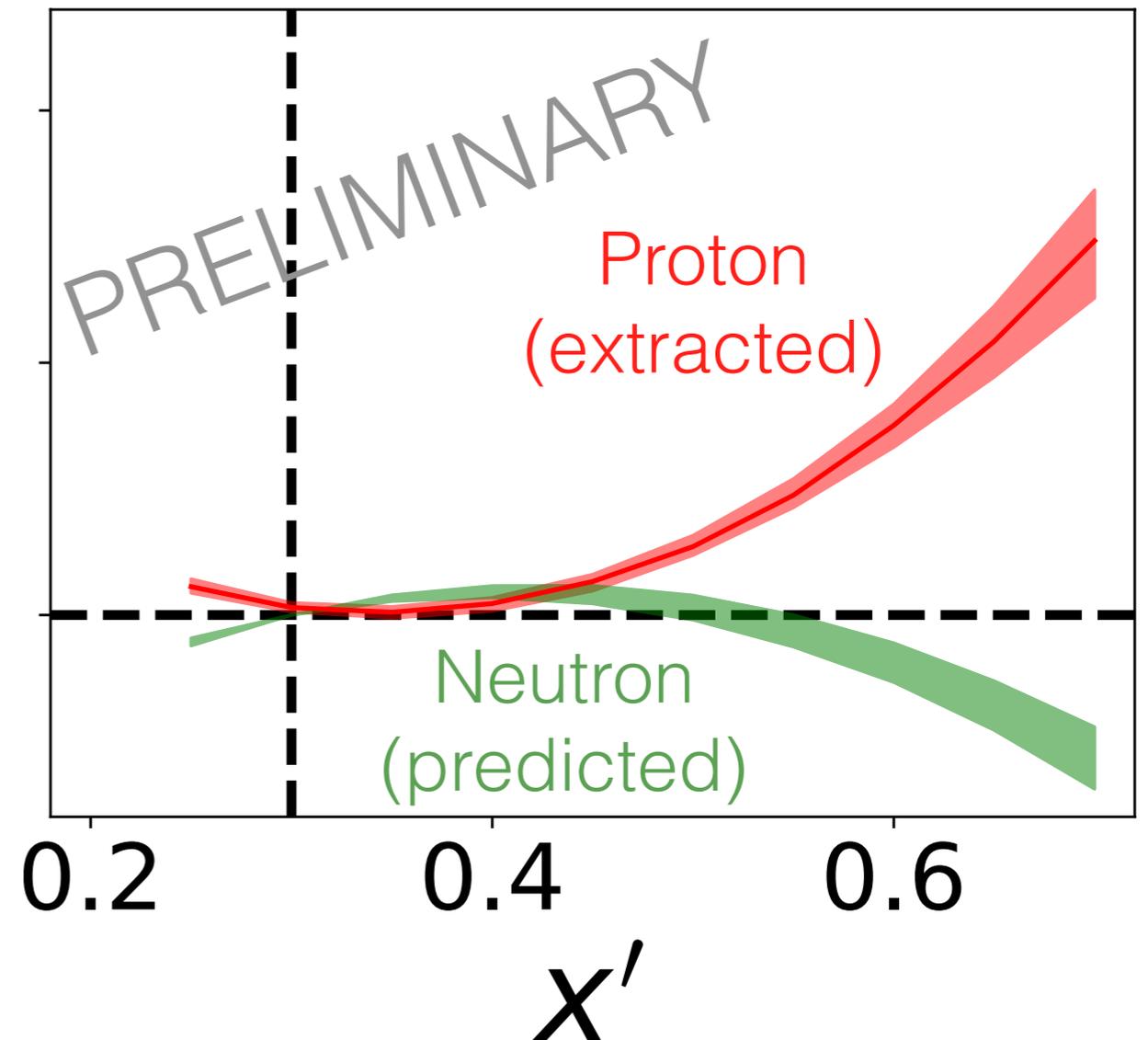
E.P. Segarra et al., [arXiv: 2104.07130 \(submitted, 2021\)](#)

Thank you!

Comments, questions?



$$F_2^{N^*} / F_2^N$$



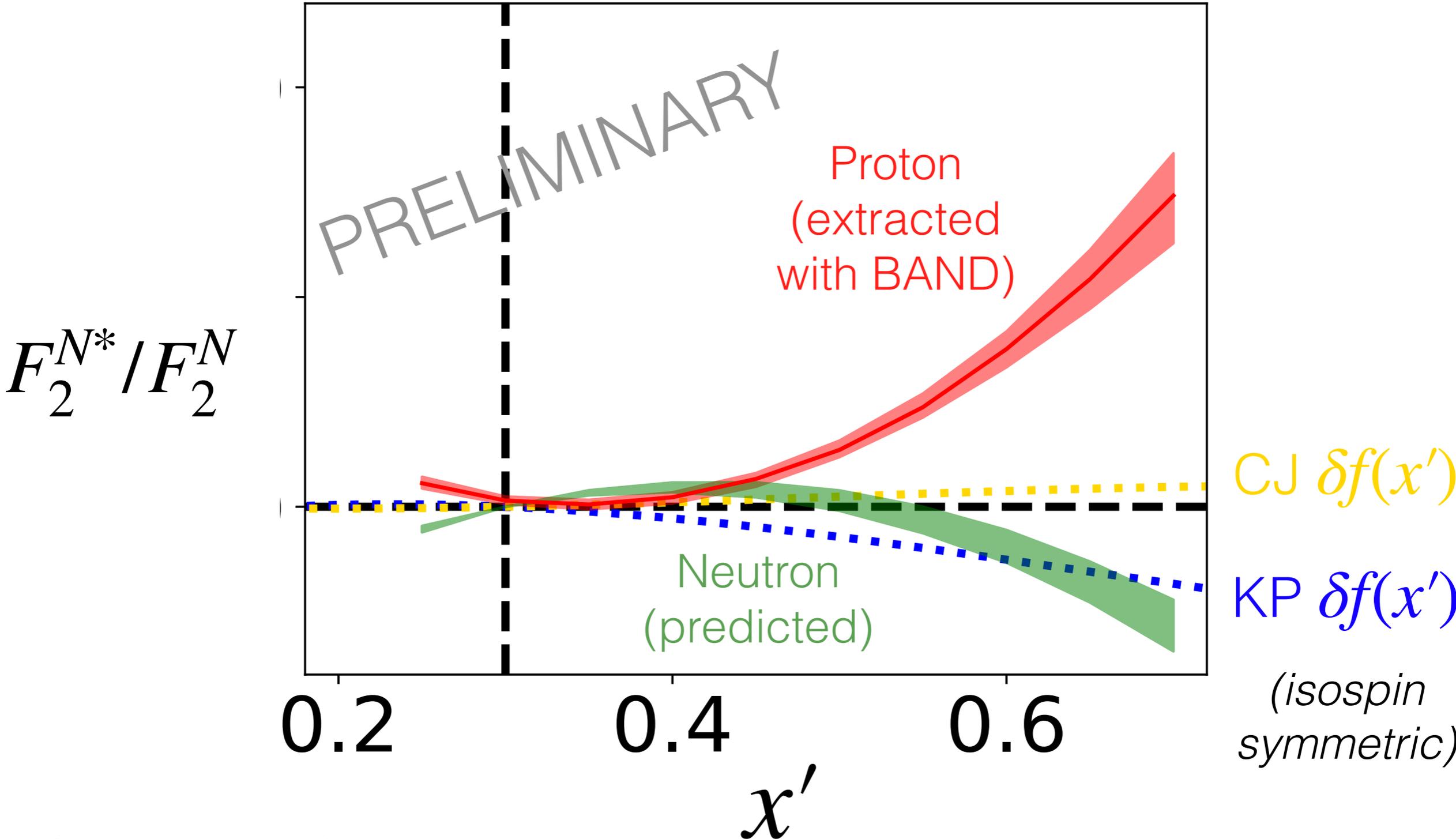
Backups

What does BAND mean for bound nucleon structure

$$F_2^A = \int_{x_B}^A \frac{d\alpha}{\alpha} \int_{-\infty}^0 d\nu \left[ZF_2^{p*}(x', \alpha, \nu) \rho_p^A(\alpha, \nu) + NF_2^{n*}(x', \alpha, \nu) \rho_n^A(\alpha, \nu) \right]$$

Use inclusive DIS data + BAND tagged DIS data

Comparing extraction with other efforts



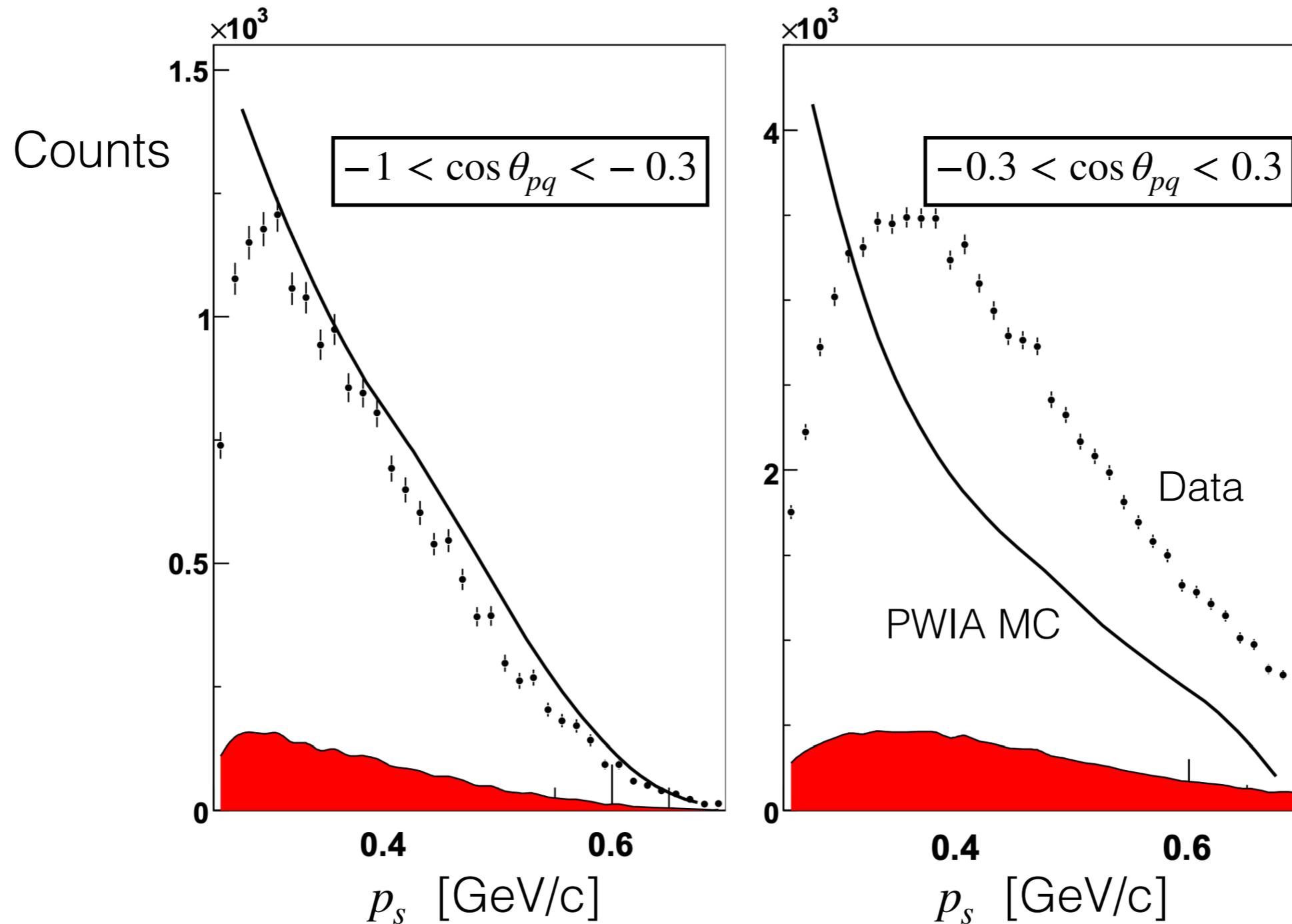
E.P. Segarra et al., [PRL \(2020\)](#)

E.P. Segarra et al., [Phys. Rev. Research \(2021\)](#)

E.P. Segarra et al., [arXiv: 2104.07130 \(2021\)](#)

Theory

Similar previous experiment $d(e, e'p_s)X$



FSI effects prominent around $\theta_{nq} \sim 90$ deg

Puzzled for decades... until now?

- No solution to the EMC effect for decades

Binding, motion,
pion clouds?

Puzzled for decades... until now?

- No solution to the EMC effect for decades
- **Novel** Drell Yan measurements changed our understanding

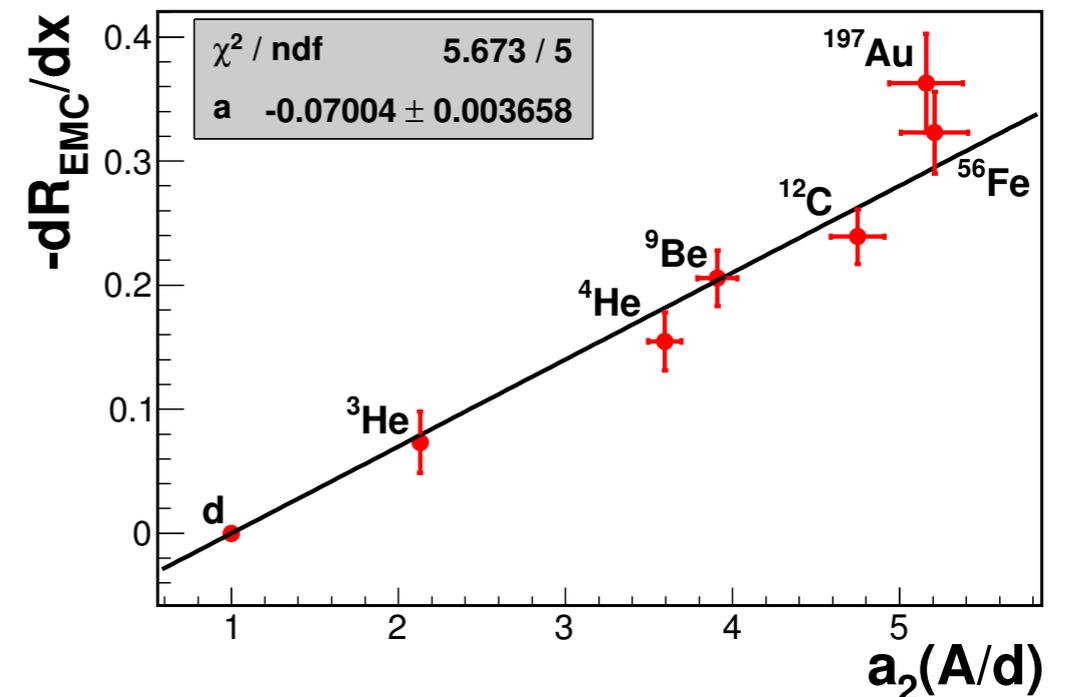
Binding, motion,
pion clouds?



Puzzled for decades... until now?

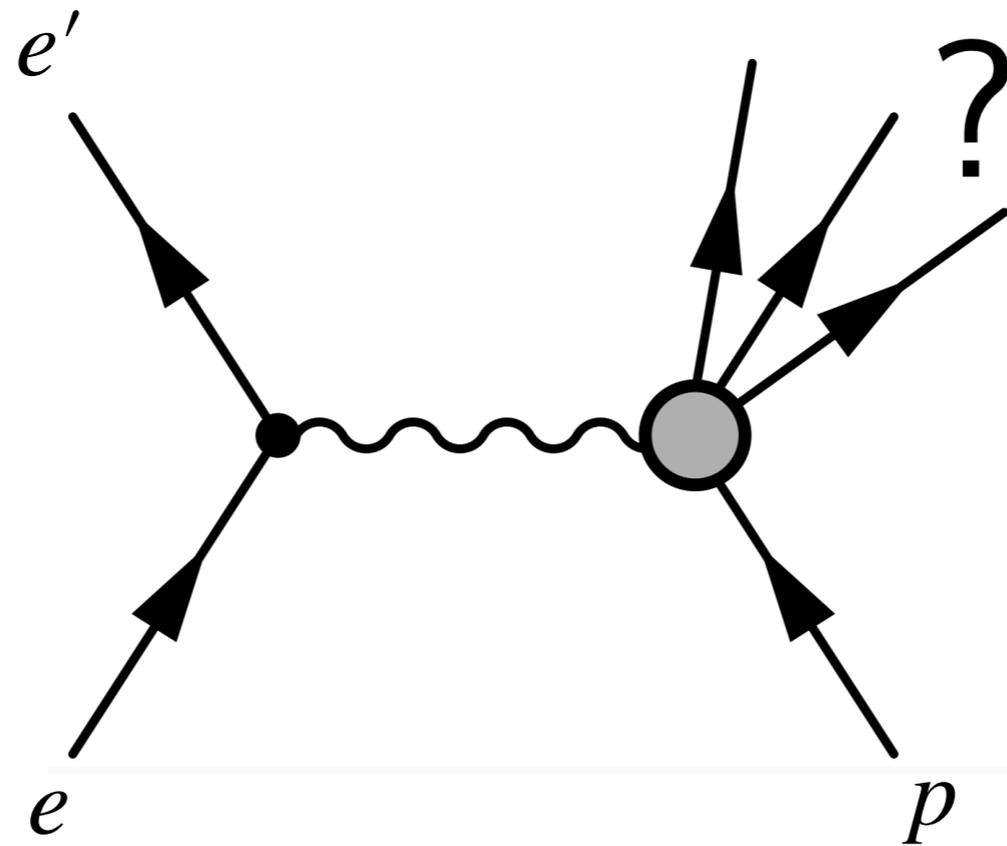
- No solution to the EMC effect for decades
- **Novel** Drell Yan measurements changed our understanding
- Phenomenology bridged some gaps in recent years

Strongly interacting nucleons correlate with EMC strength!



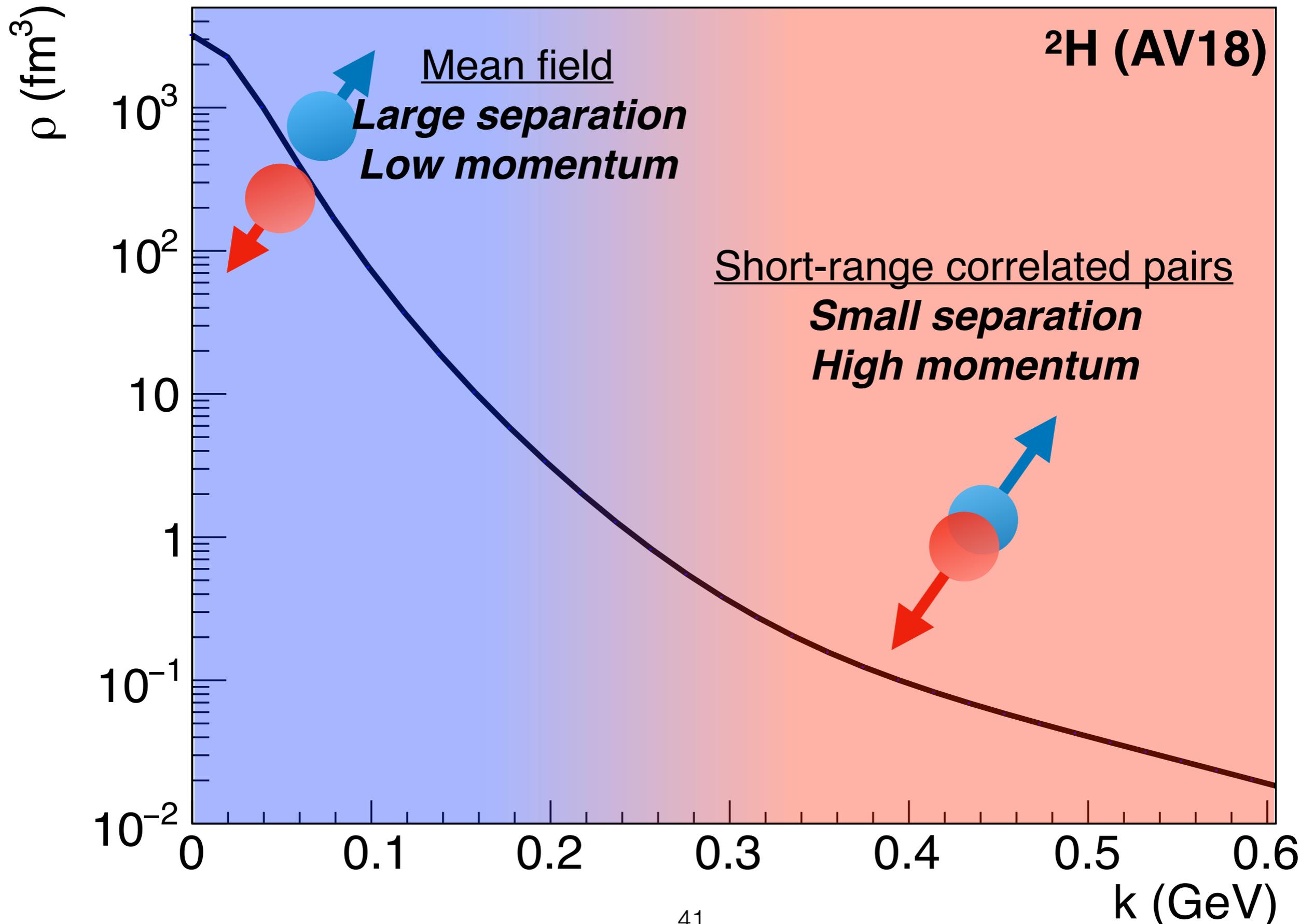
E.P. Segarra et al., [PRL \(2020\)](#)
E.P. Segarra et al., [Phys. Rev. Research \(2021\)](#)
E.P. Segarra et al., [arXiv: 2104.07130 \(submitted, 2021\)](#)

Structure Functions of a free proton



$$\frac{d\sigma}{dx dQ^2} = \frac{4\pi\alpha^2}{Q^4} \left[\left(1 - y - \frac{m_p^2 y^2}{Q^2} \right) \frac{F_2(x, Q^2)}{x} + y^2 F_1(x, Q^2) \right]$$

Which nucleons are modified?



Theoretical PWIA calculation

Cross section model from Strikman & Weiss PRC (2018):

$$d\sigma[D(e, e'n_s)X] = K \frac{2S(\alpha_S, p_T)}{2 - \alpha_S} \cdot F_2$$

- Kinematic factor
- Spectral function of bound protons in deuterium
- Bound proton structure function
- Includes finite Q^2 effects

Simulate generated events (include QED radiation) in GEANT4

Convolution framework

$$F_2^d \sim F_2^p + F_2^n$$

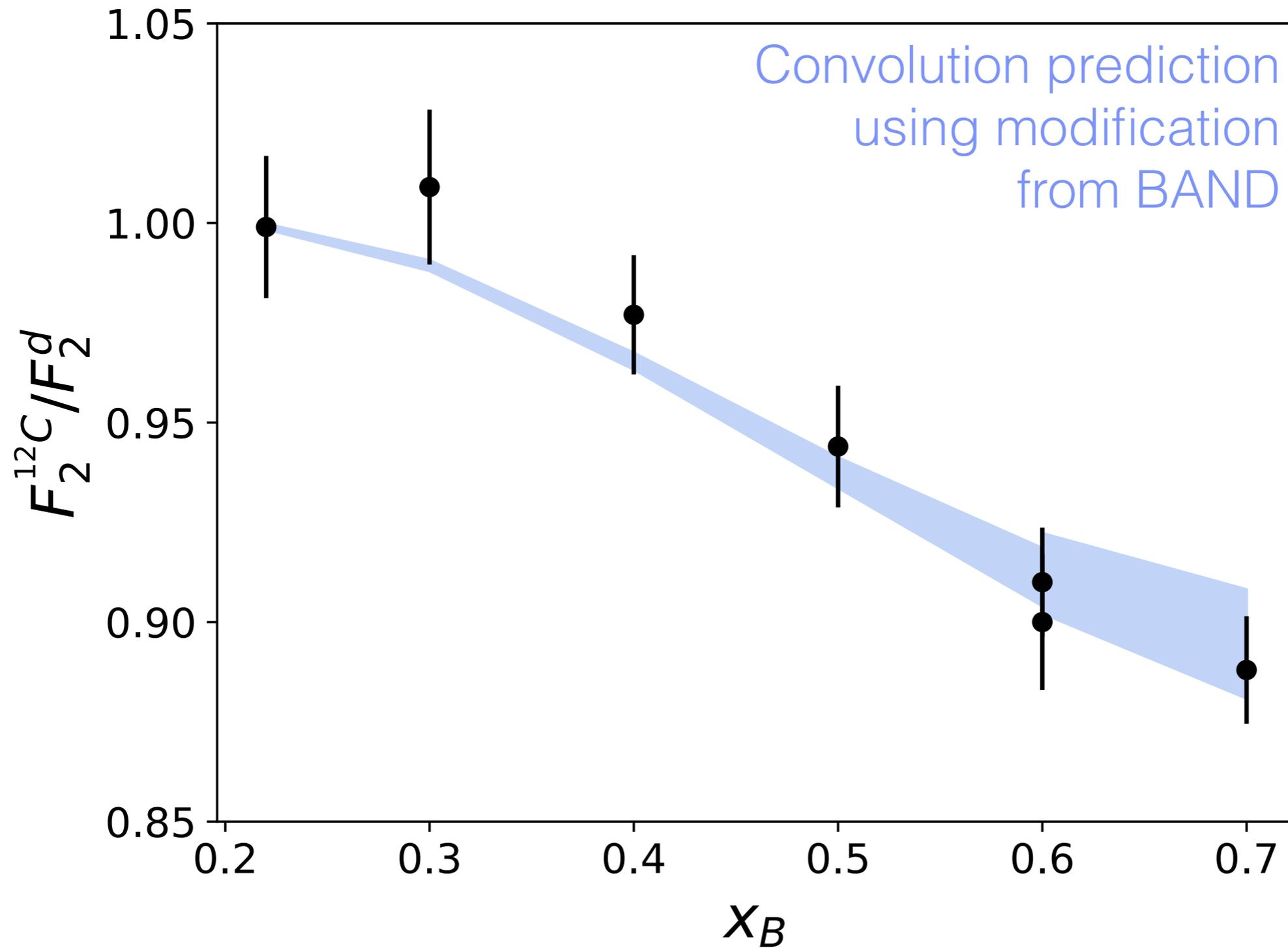
$$F_2^d = \int_{x_B}^2 \frac{d\alpha}{\alpha} \int_{-\infty}^0 d\nu \left[F_2^{p*}(x, \tilde{\alpha}, \nu) \rho_p^d(\alpha, \nu) + F_2^{n*}(\tilde{x}, \alpha, \nu) \rho_n^d(\alpha, \nu) \right]$$

Assume:

$$F_2^{p*} = F_2^p (1 + \nu f^{off}(x'))$$
$$F_2^{n*} = F_2^n (1 + \nu f^{off}(x'))$$

- How well do we know the free neutron structure?
- Is this the right functional form?
- Is modification same for protons and neutrons?
- Is modification same in all nuclei?

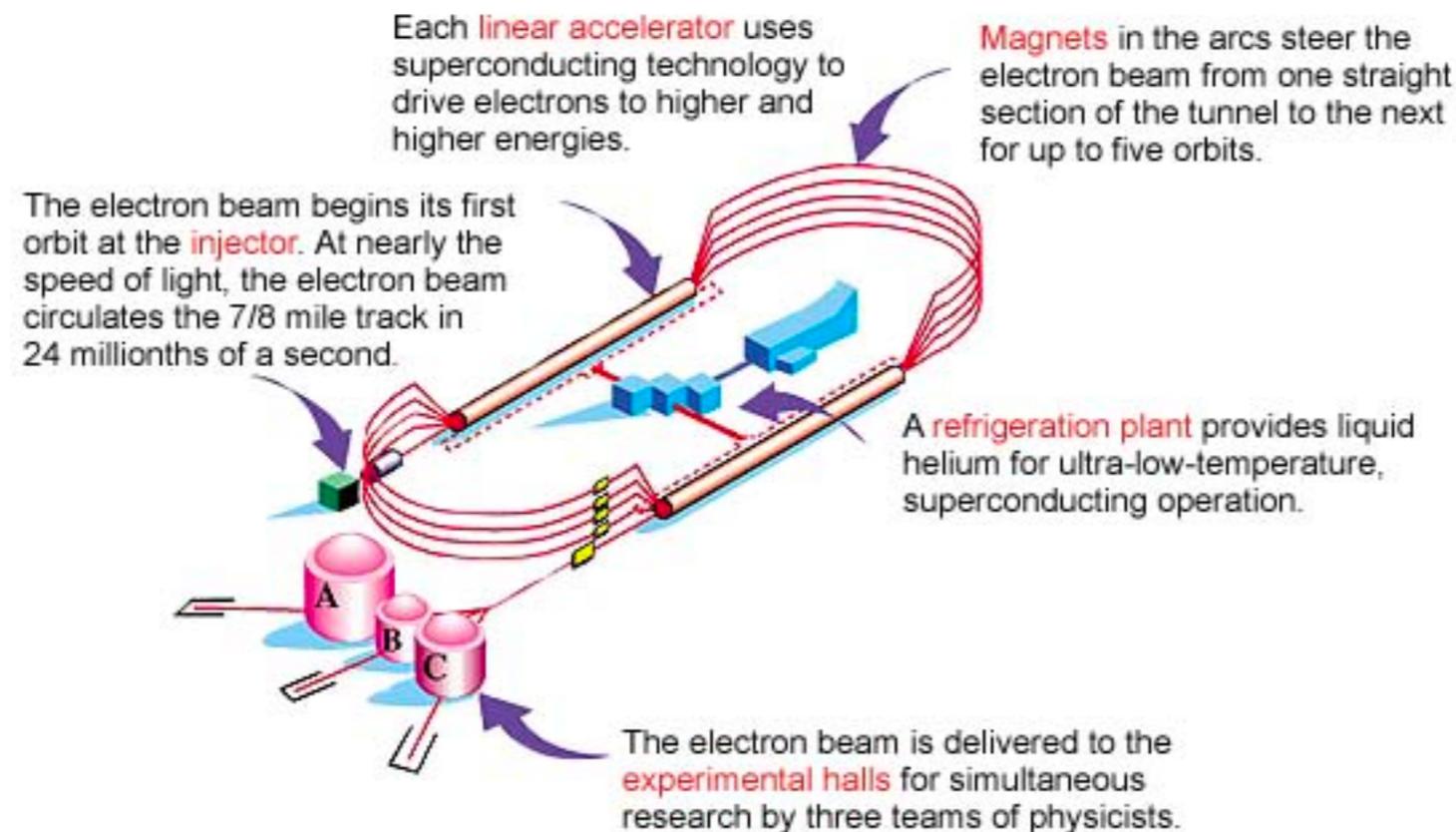
Modification effects consistent even in Carbon



Jefferson Lab

Electron beam

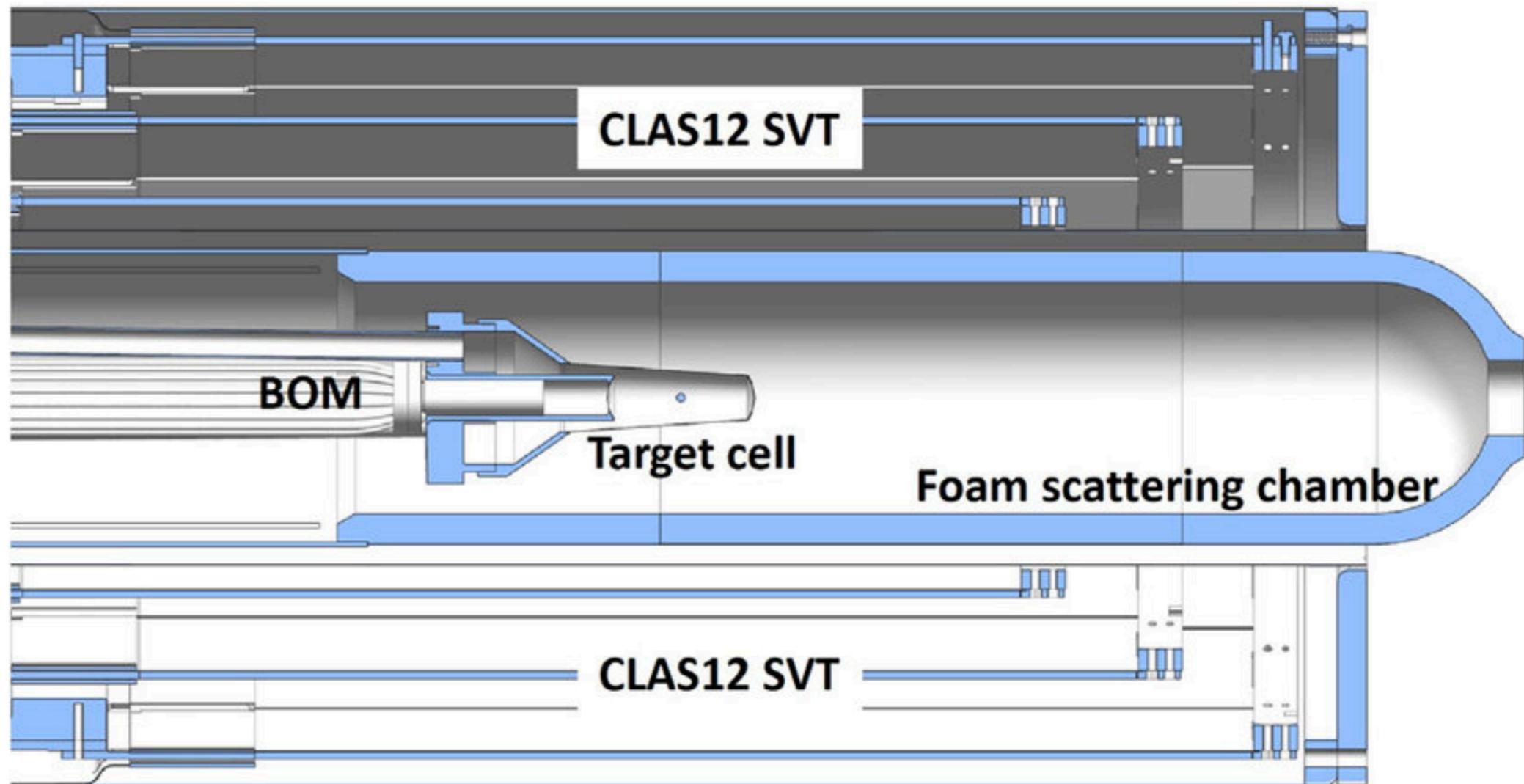
- Produced from laser light on photocathode lattice with high polarization
- Continuous-wave beam, electrons bunched every 2 or 4 ns.



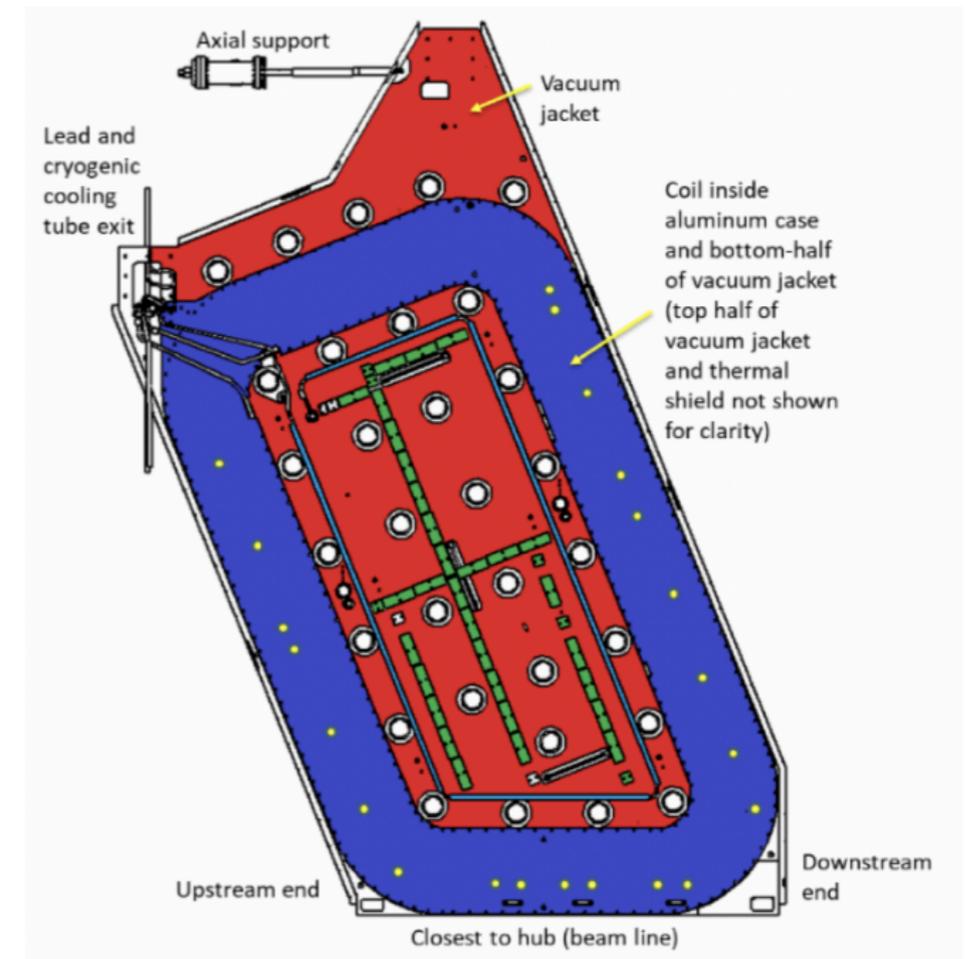
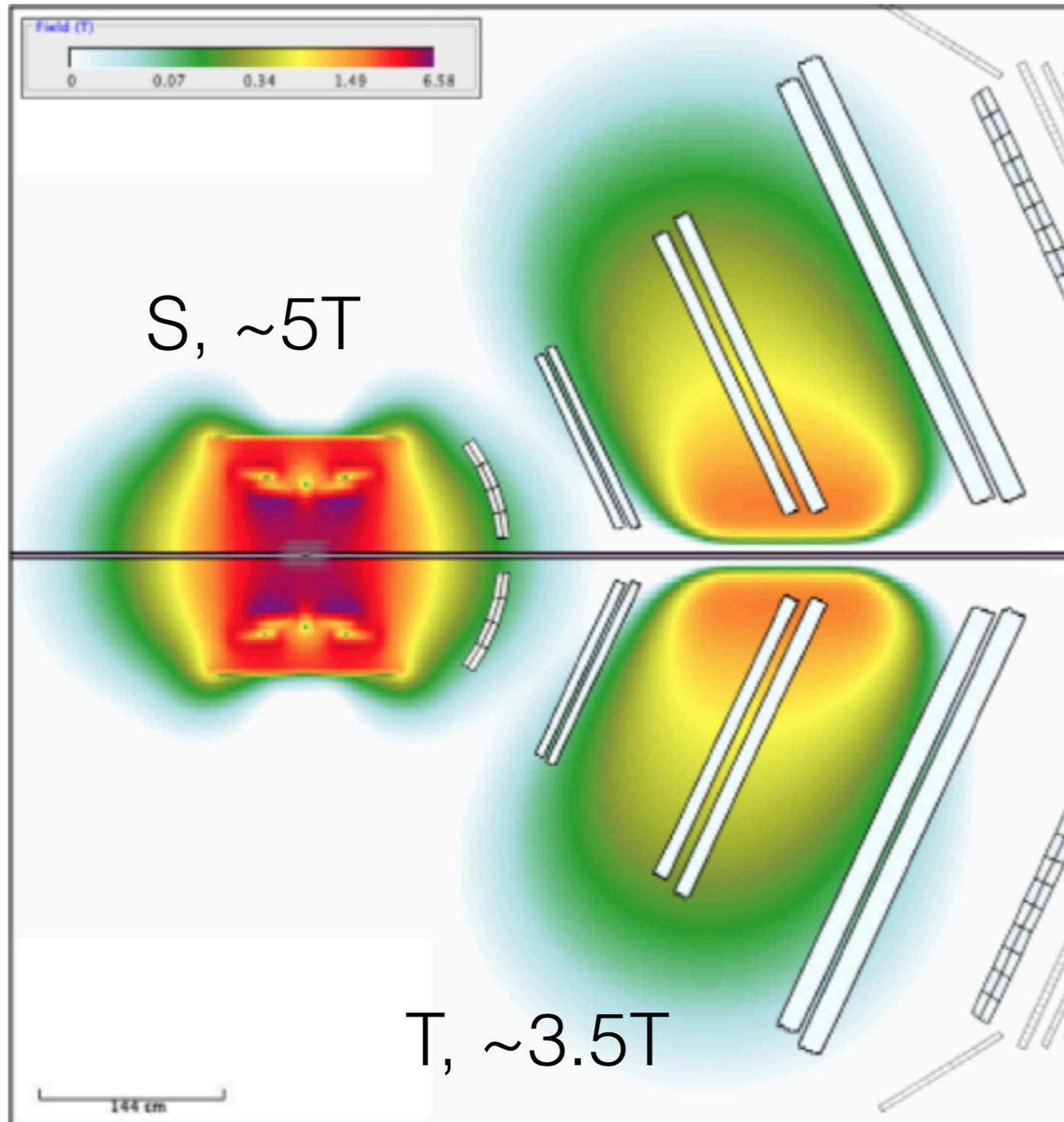
CLAS12

CLAS12 target

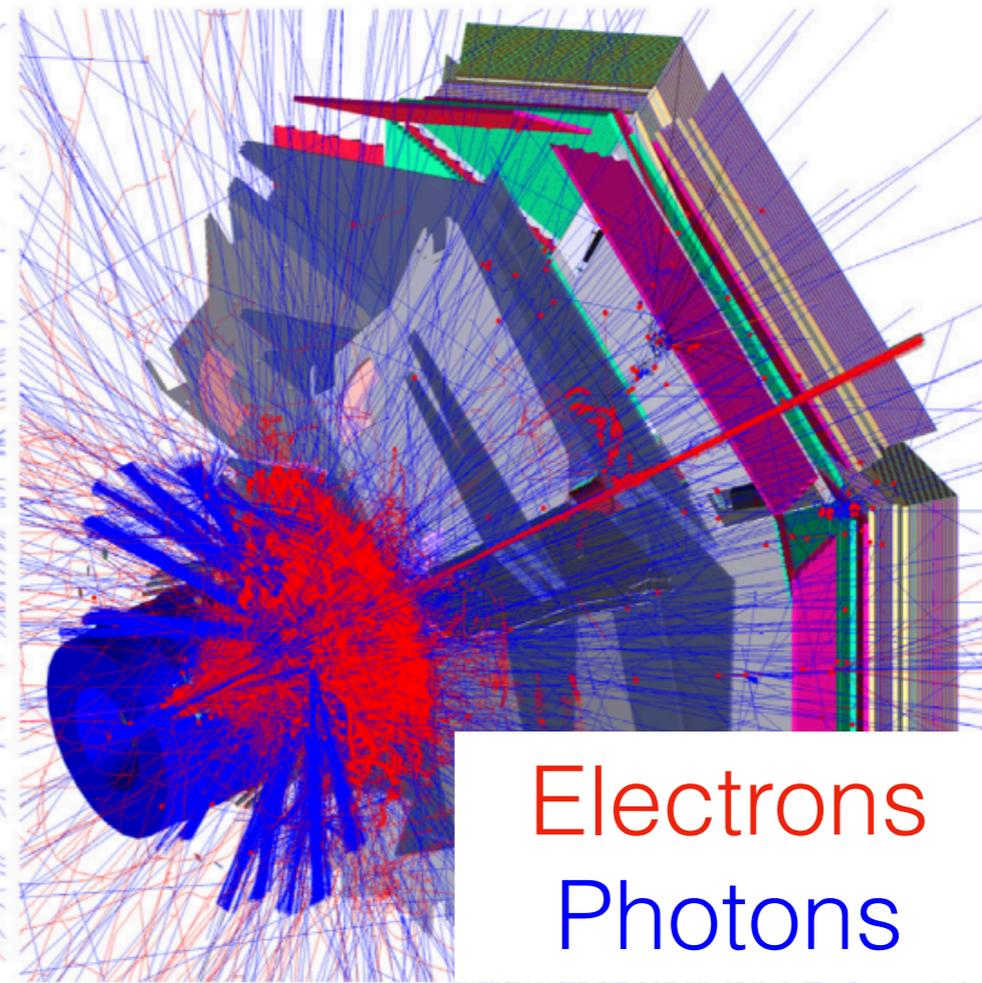
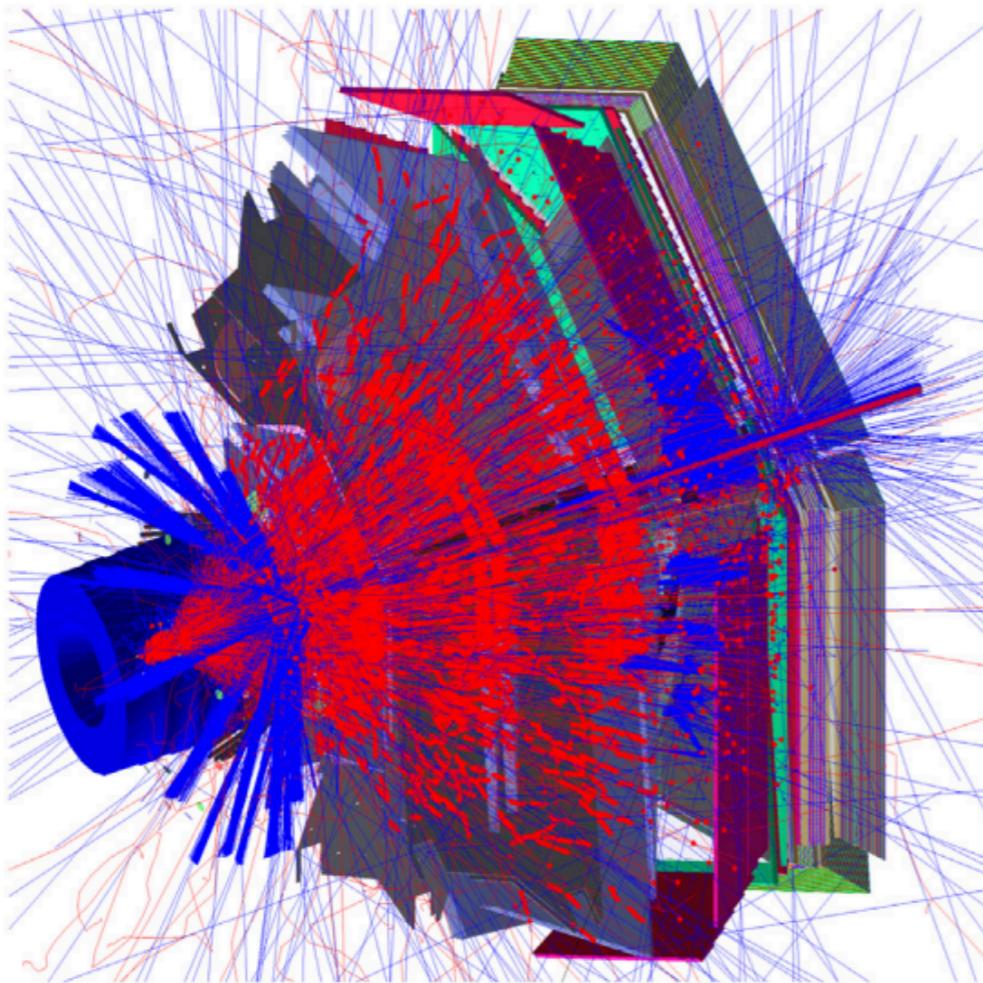
- 5cm LD2 target



CLAS12 magnets

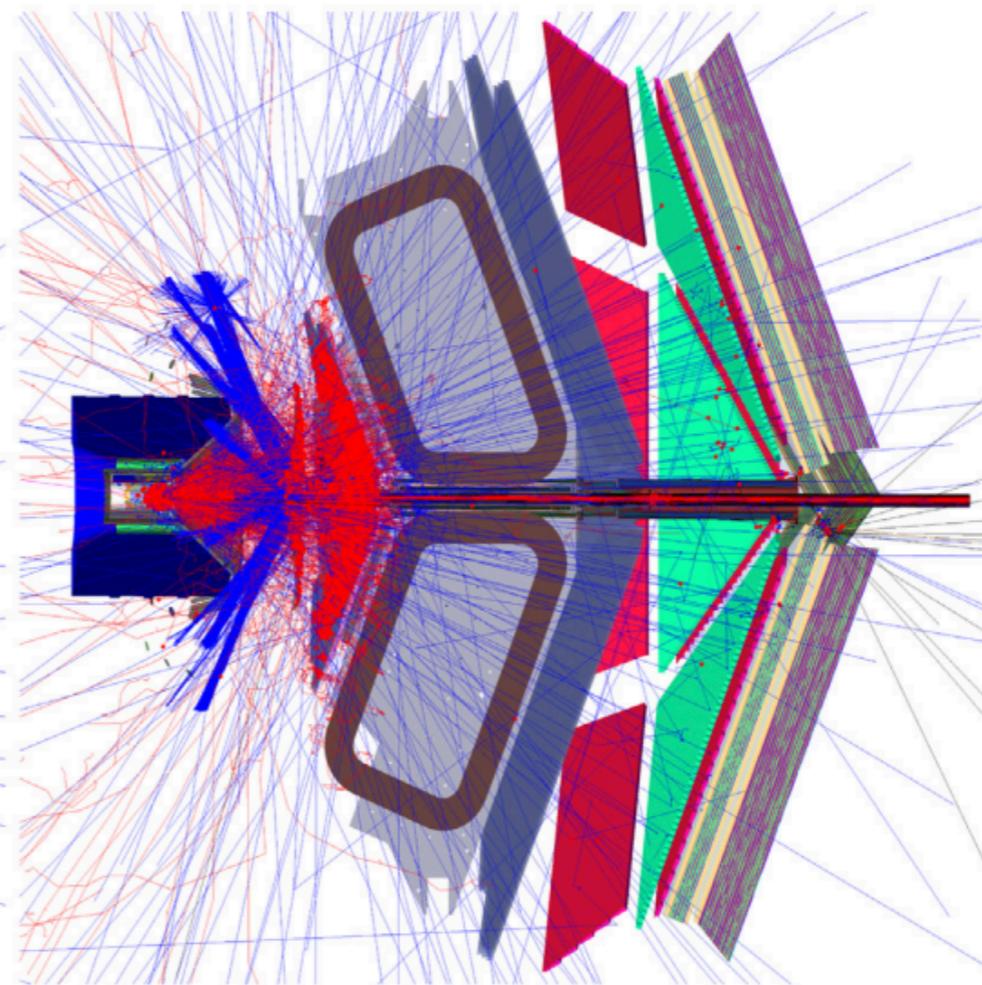
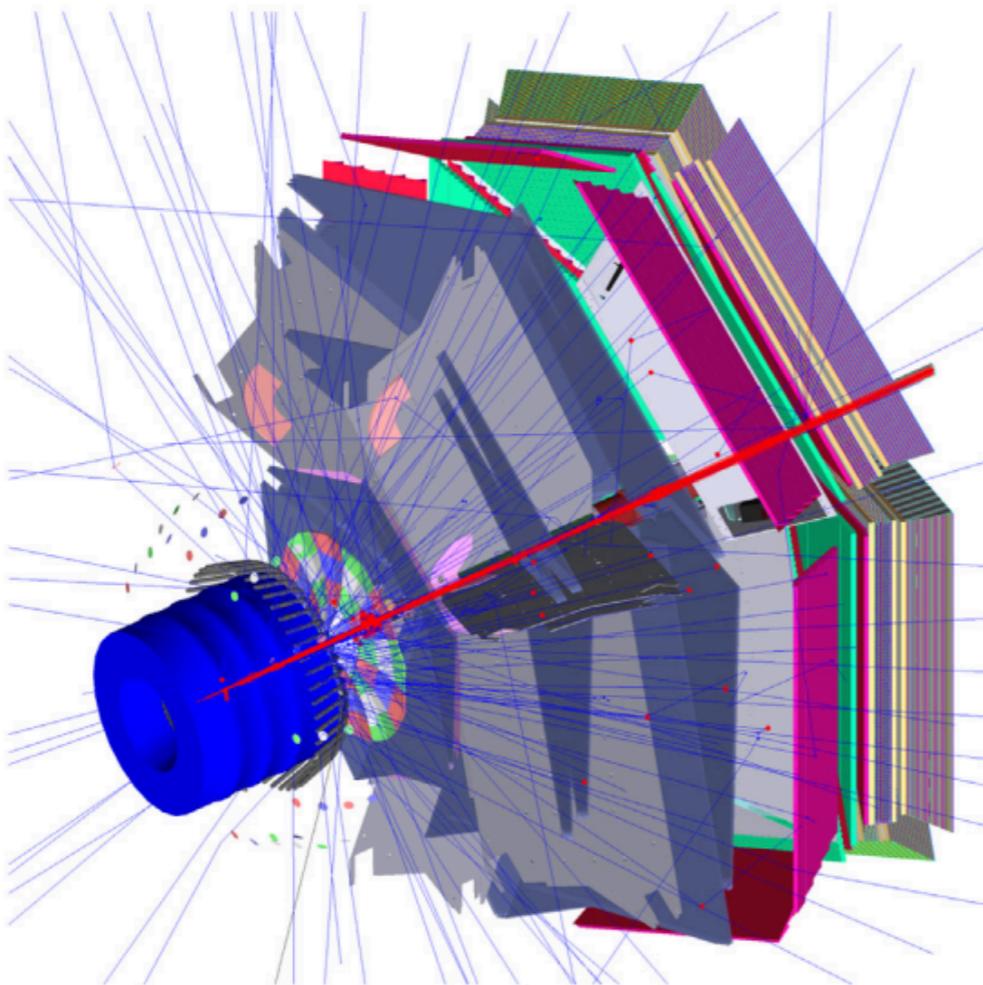


S: 0
T: 0



S: 0
T: -1

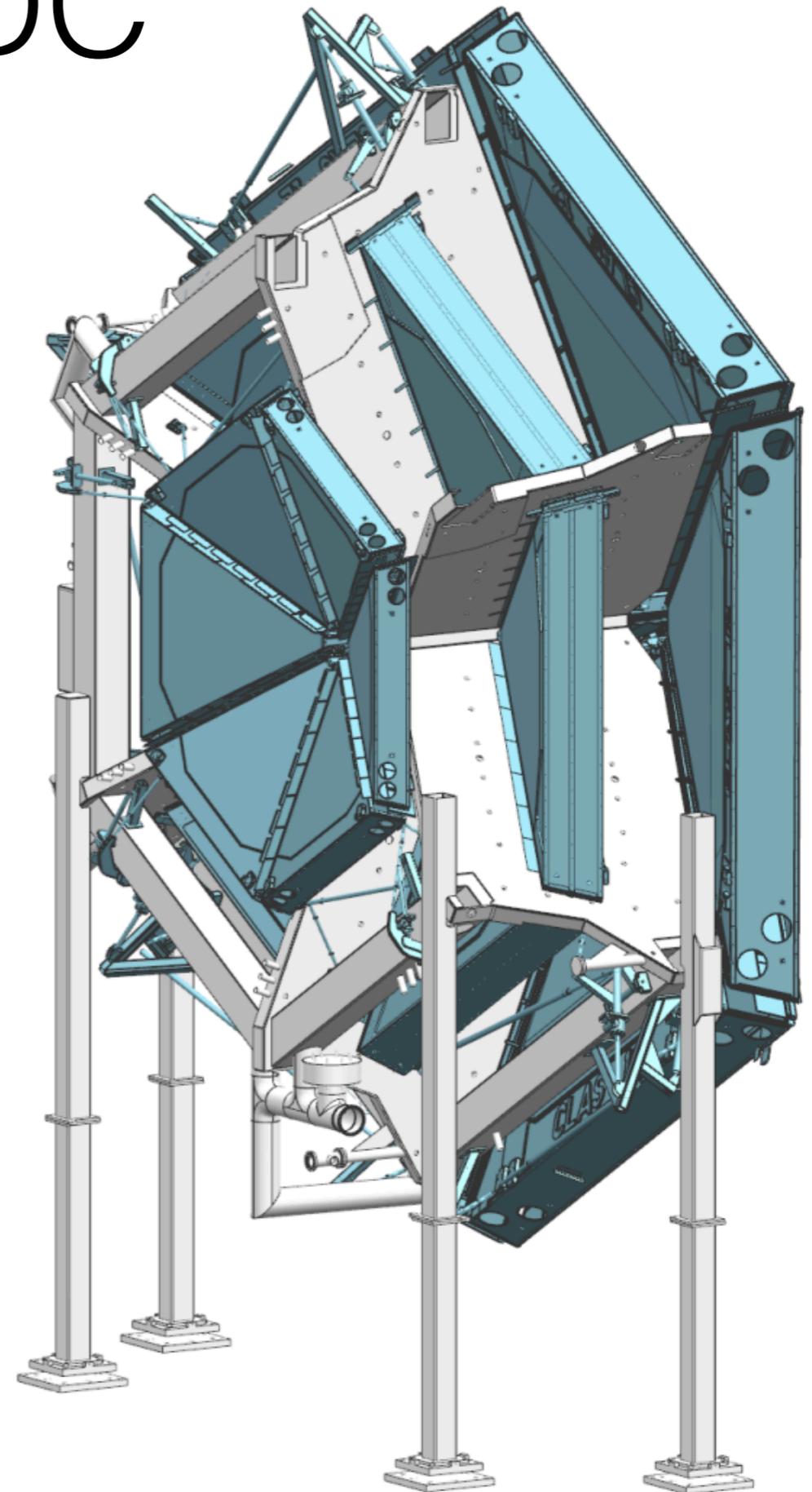
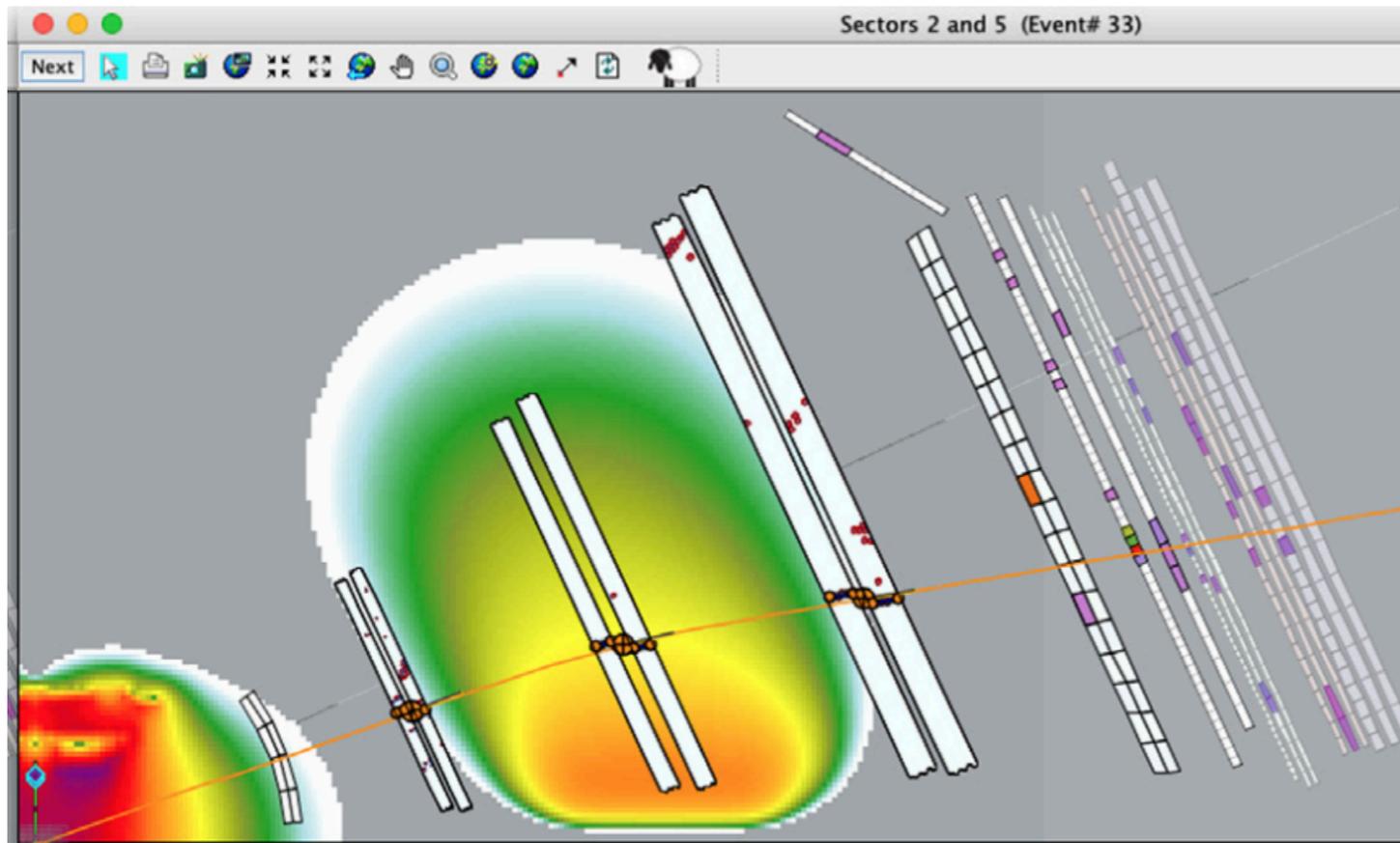
S: -1
T: -1



S: 0
T: -1

CLAS12 DC

- Argon/CO₂ mixture (90-10)
- 3 regions, each with 12 layers, each with 112 sense wires



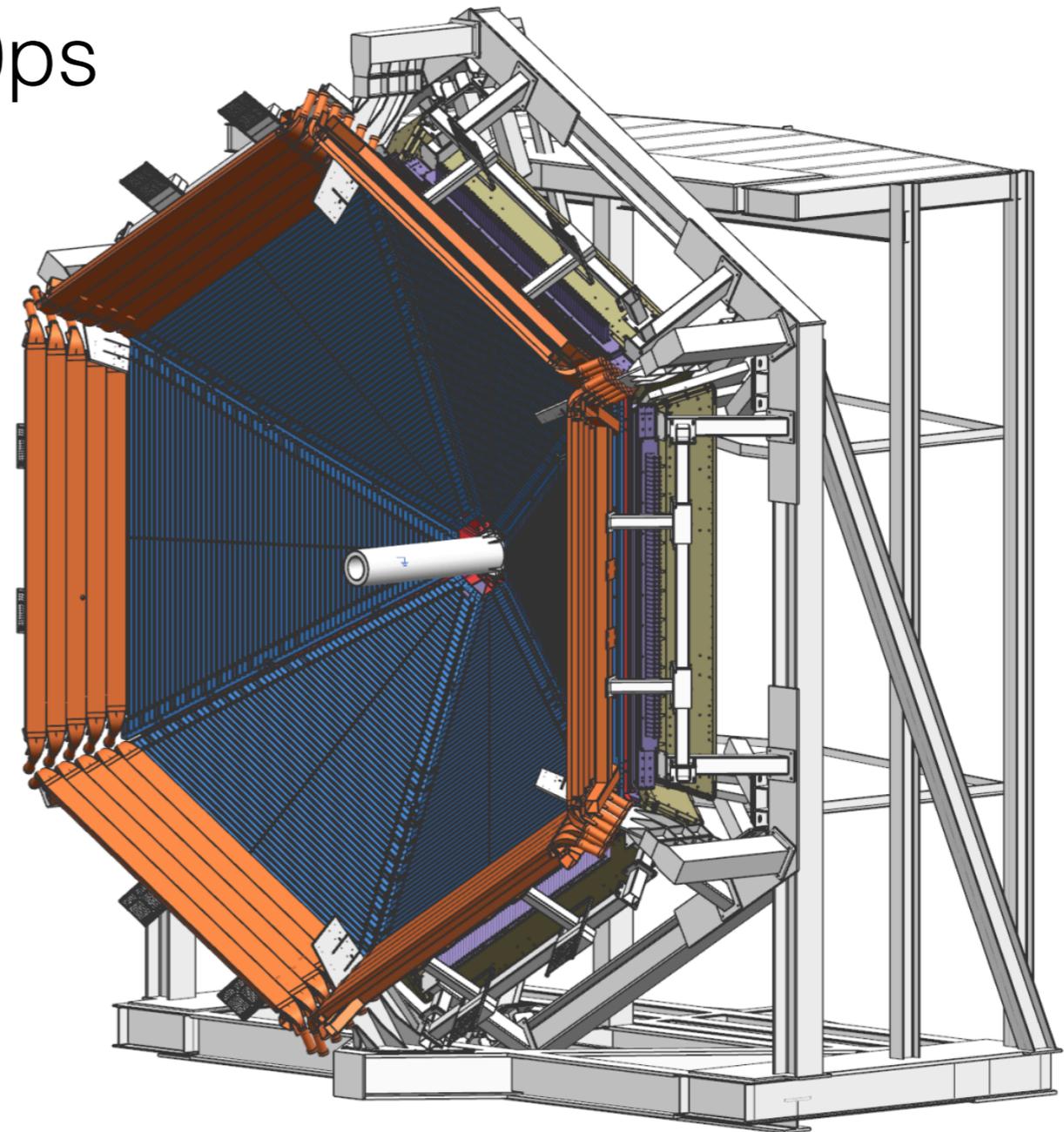
HTCC

- Electrons with $< 4.9 \text{ GeV}/c$ separation from pion/kaon/proton
- CO₂ mixture, full coverage, 48 mirrors focus on PMT readout



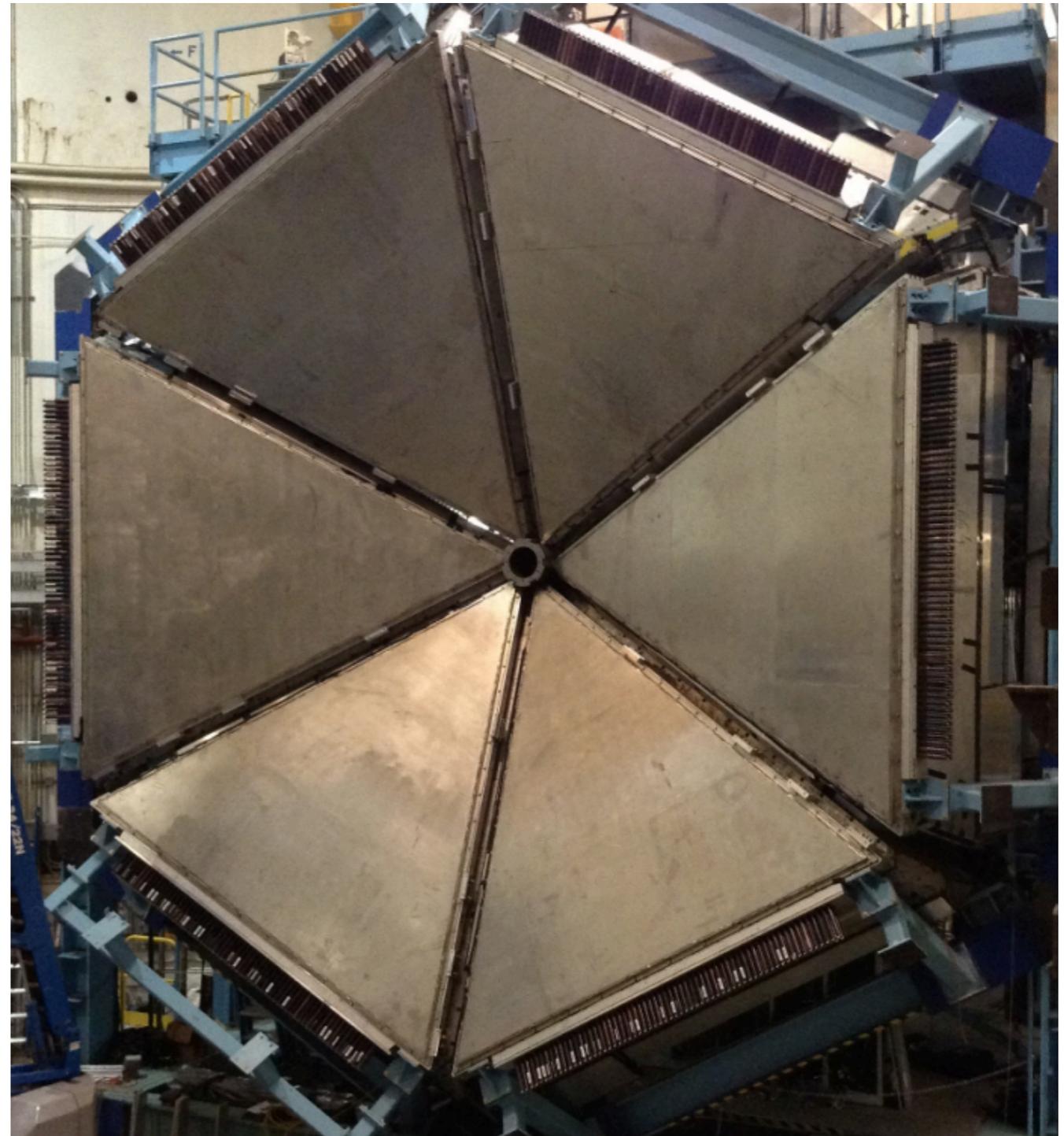
FTOF

- Scintillator bars read out with PMTs
- ToF resolution from 80ps - 150ps



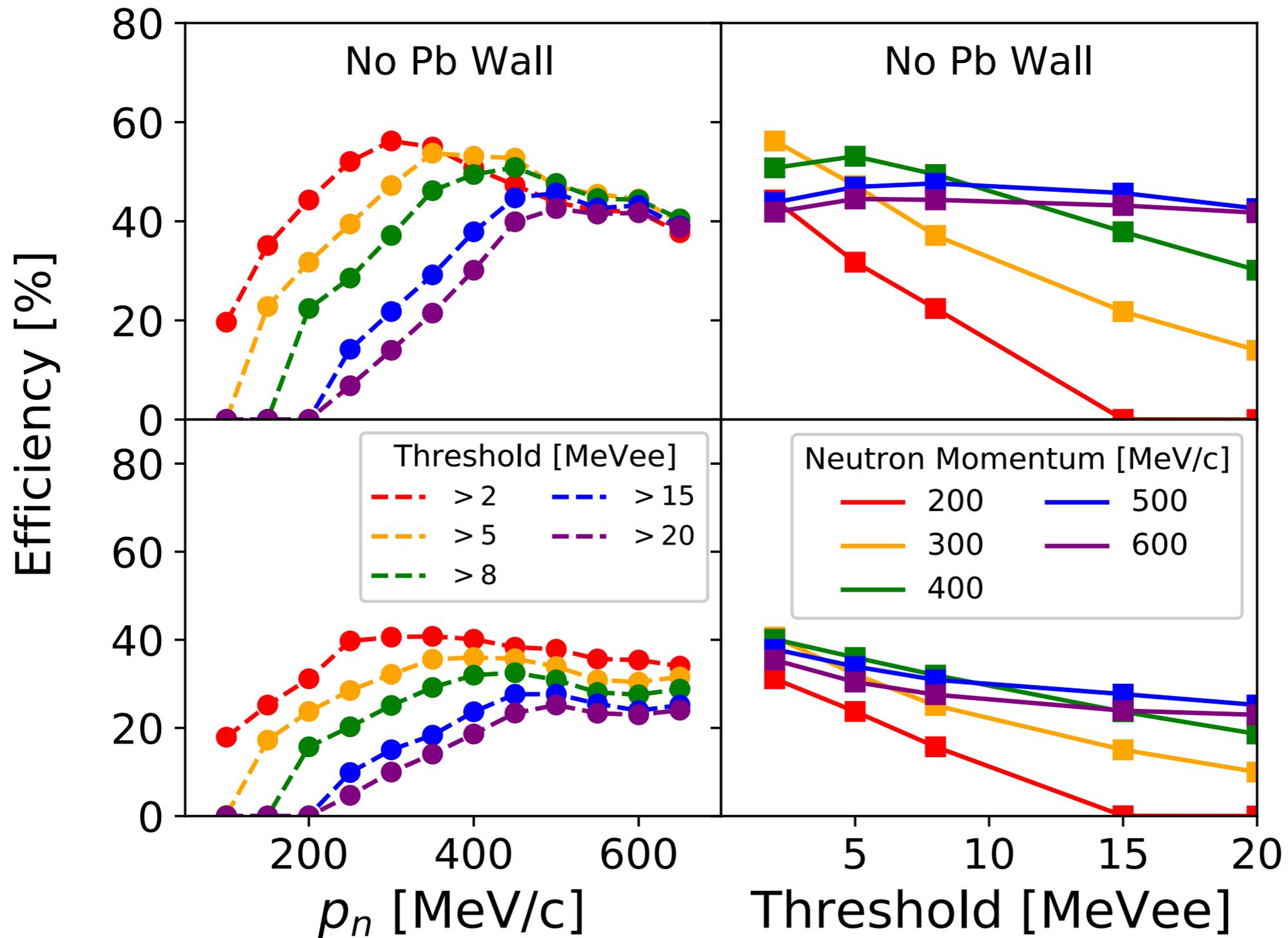
Calorimeters

- “Pre-shower” and “EC”
- Pre-shower added to improve spatial resolution and have full EM shower containment
- Sampling calorimeters (plastic scintillators sandwiched between lead sheets)

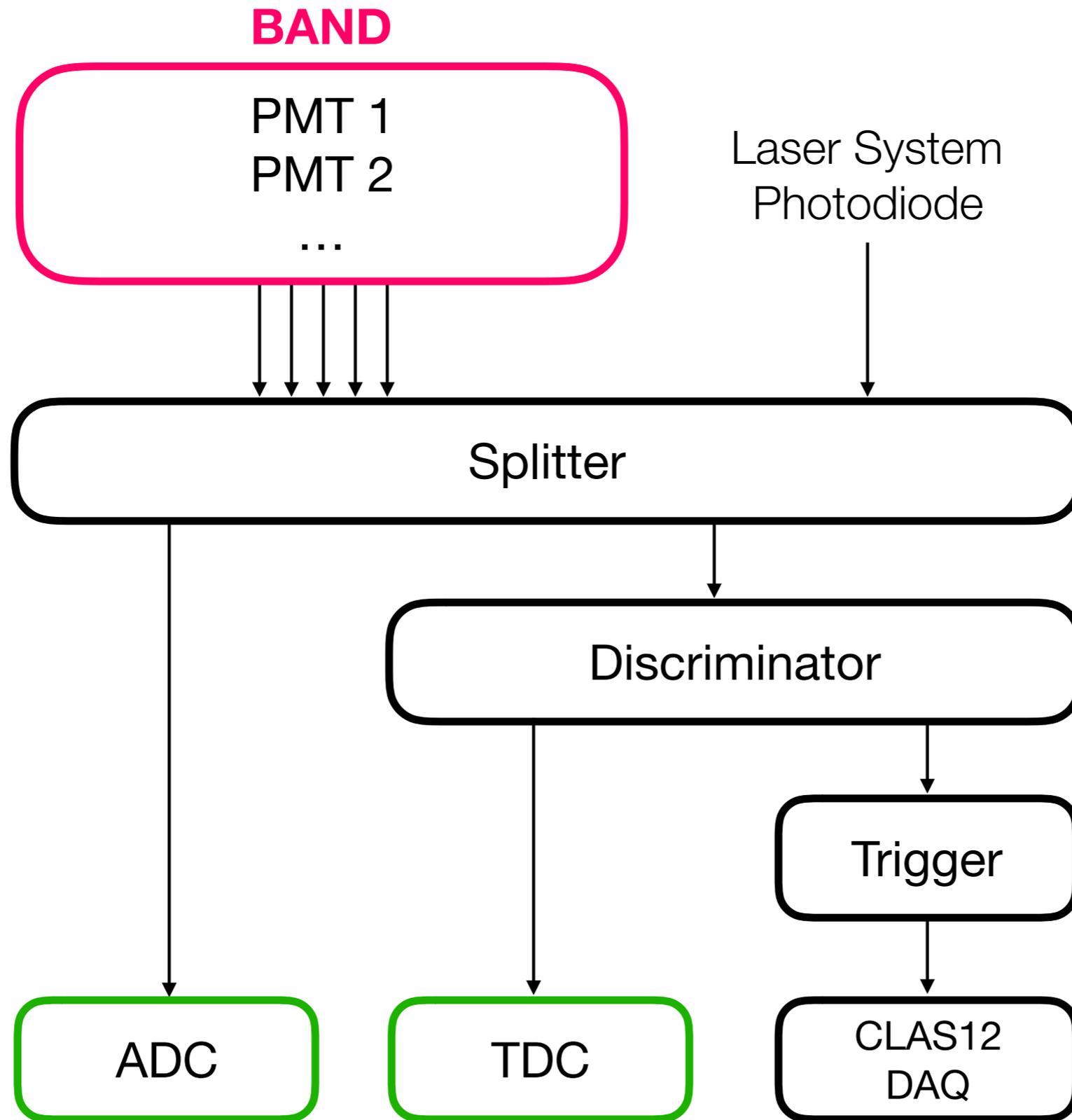


BAND

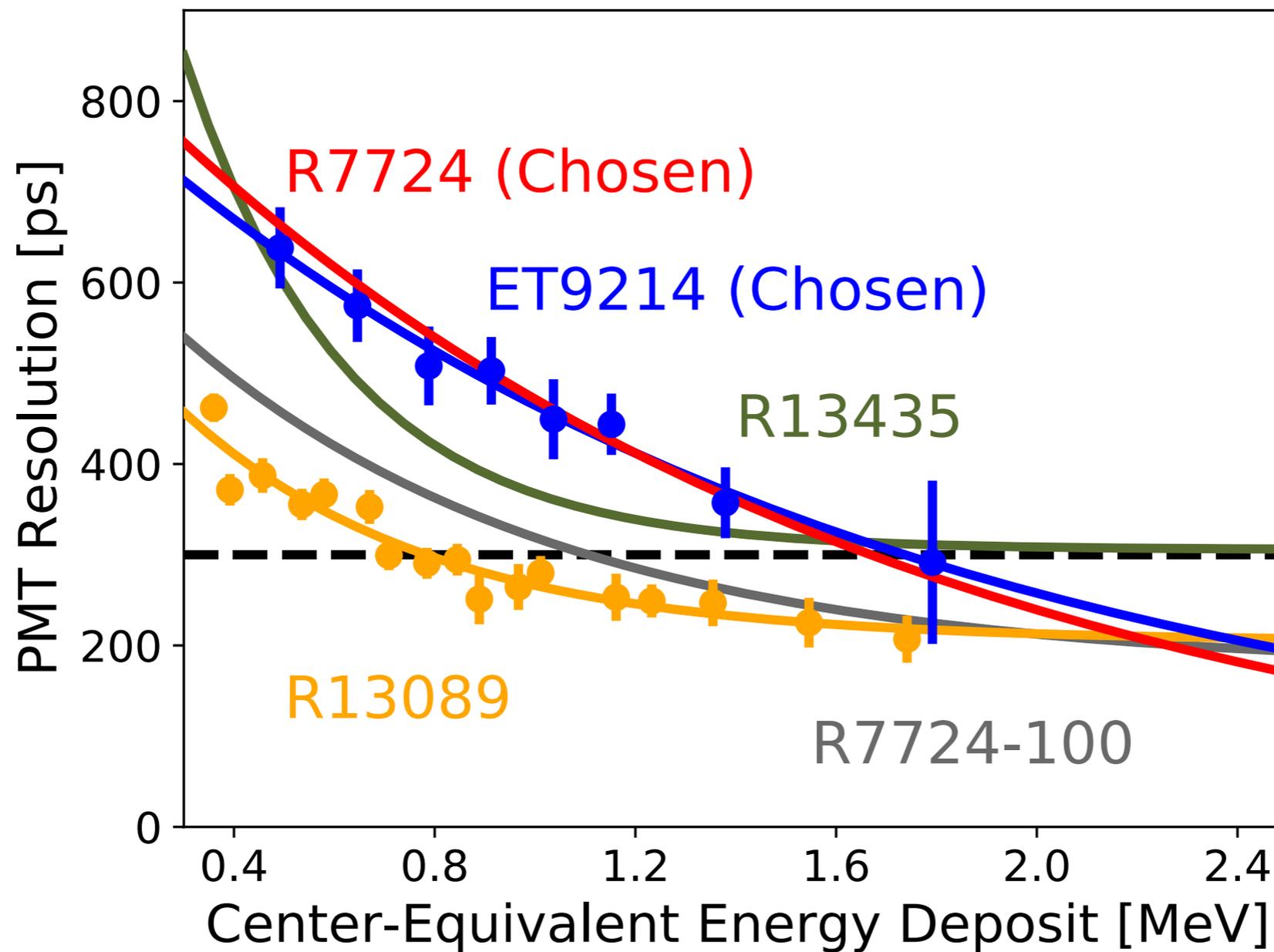
Geant4 efficiency



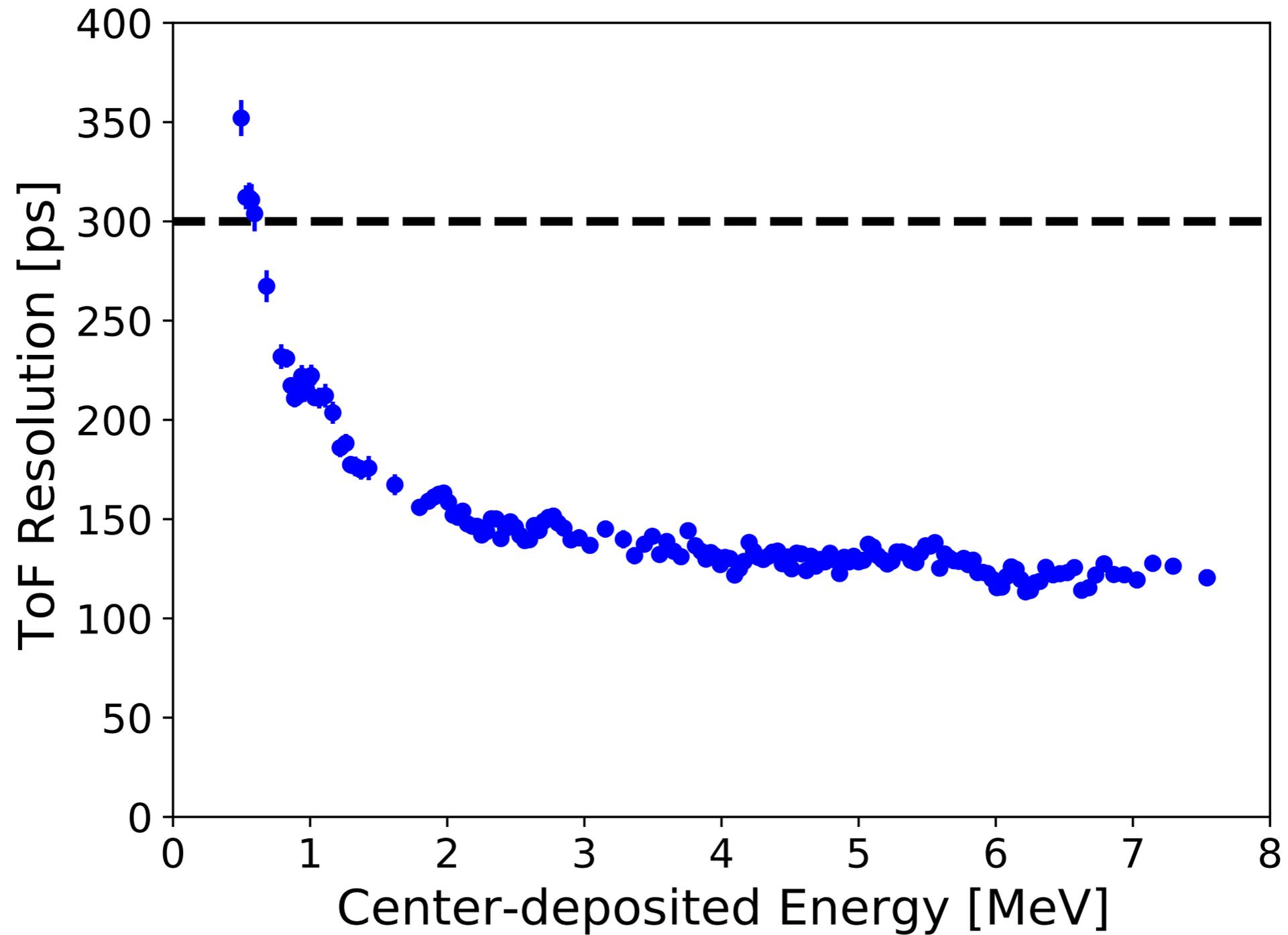
Electronic readout



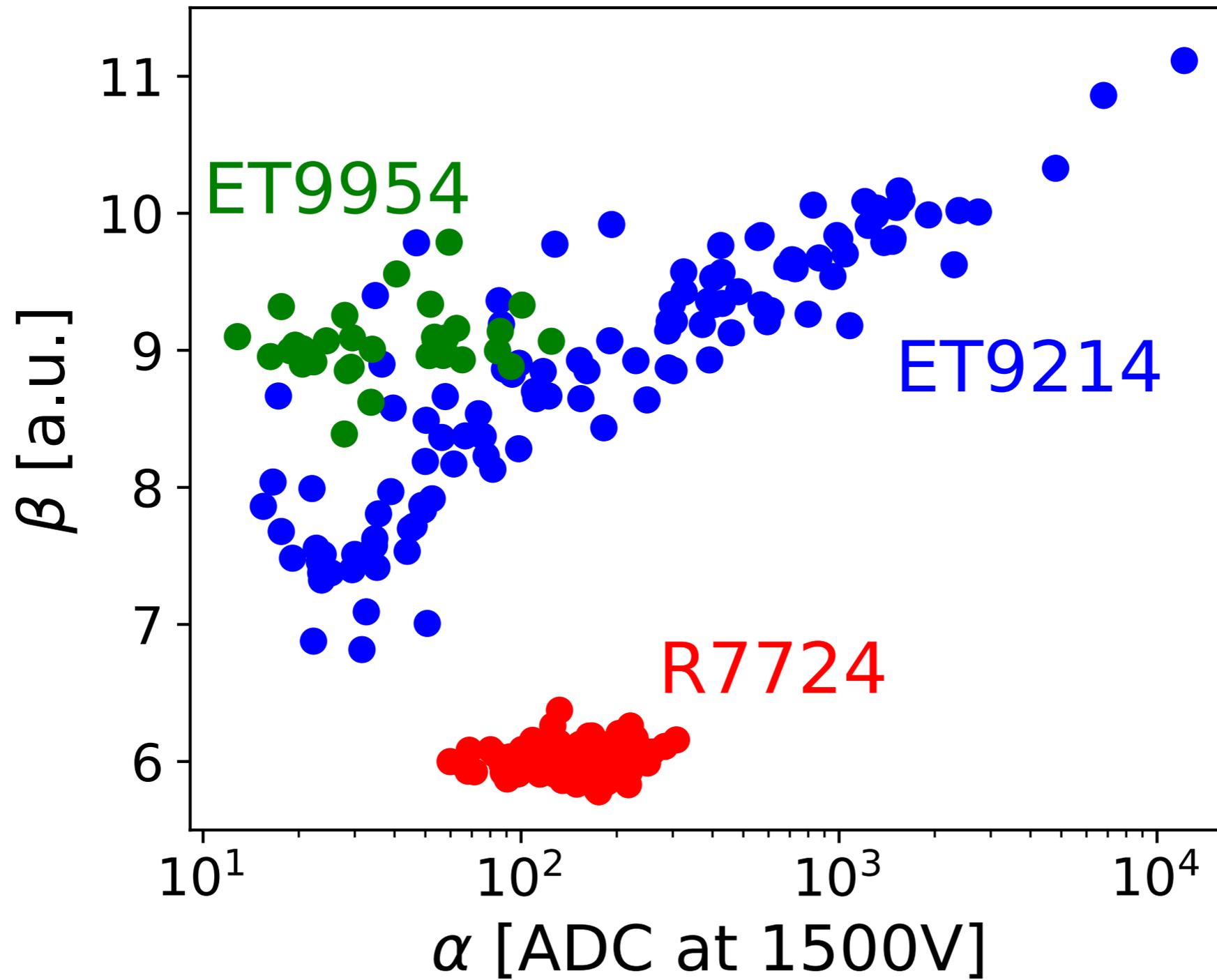
PMT Optimization



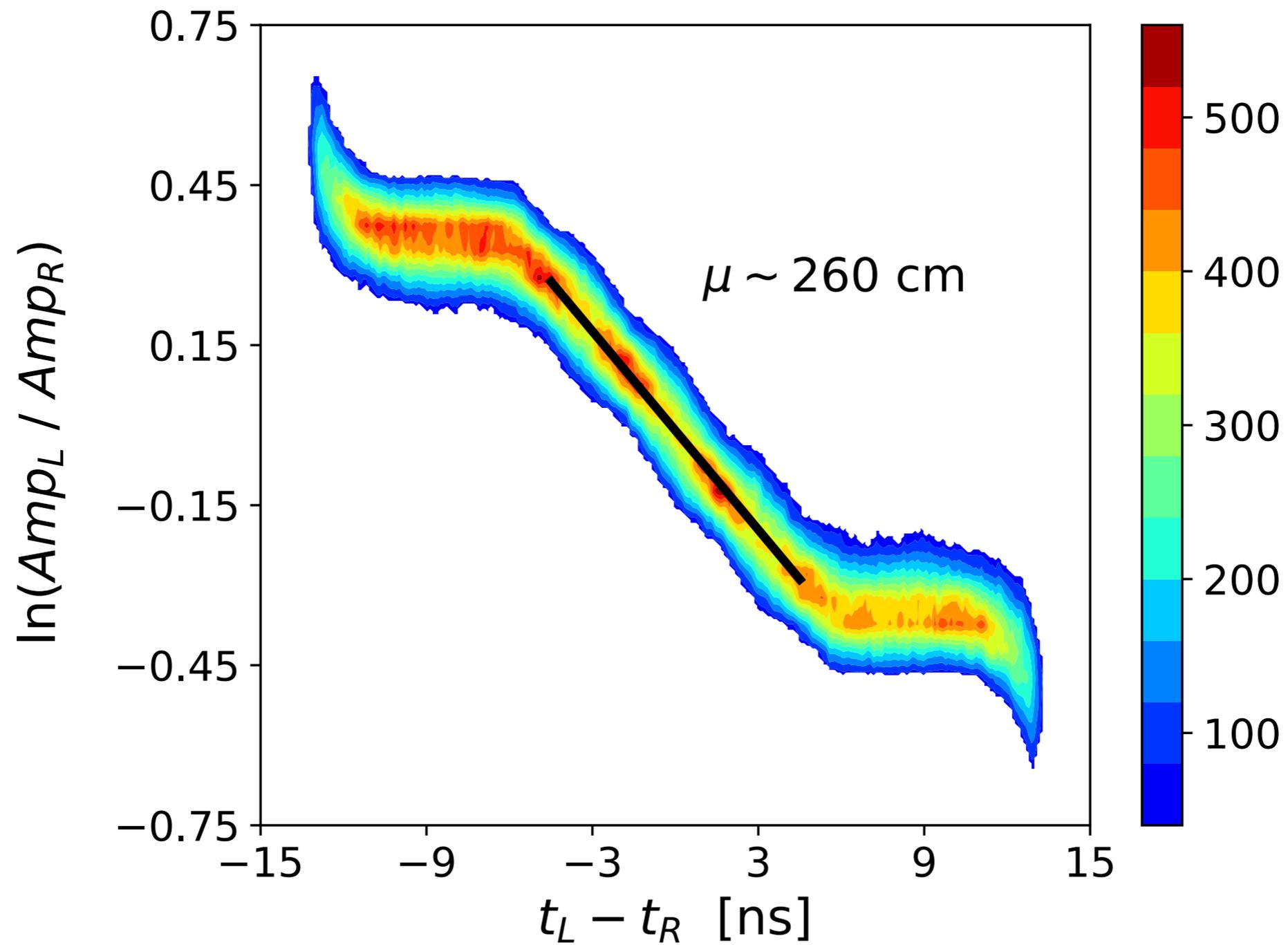
ToF with laser system



QC PMT testing



Bar attenuation lengths

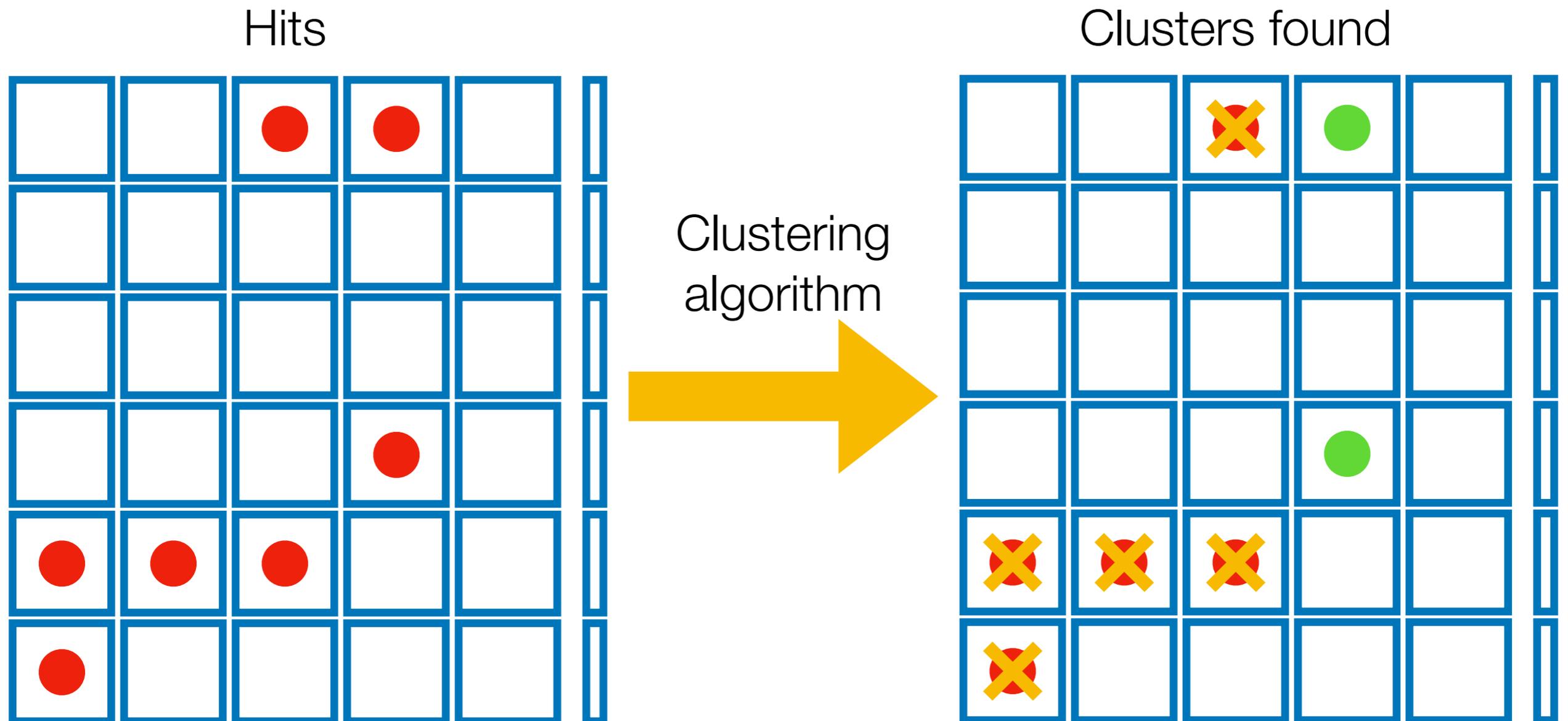


Final construction procedure

1. Select pair of matched PMTs
2. Wrap scintillator with ESR, leaving window-flap for laser fiber
3. Glue PMTs to light guides with RTV615 silicone rubber compound
4. Glue one light-guide PMT assembly to each end of bar with UV curing glue
5. Wrap with light-tight foil
6. Glue optical fiber to center of the bar and seal window
7. Install mu-metal shields
8. Search for light leaks
9. Install bar in BAND
10. Connect fibers, HV, and signal cables
11. Final test for leaks

Hit algorithm

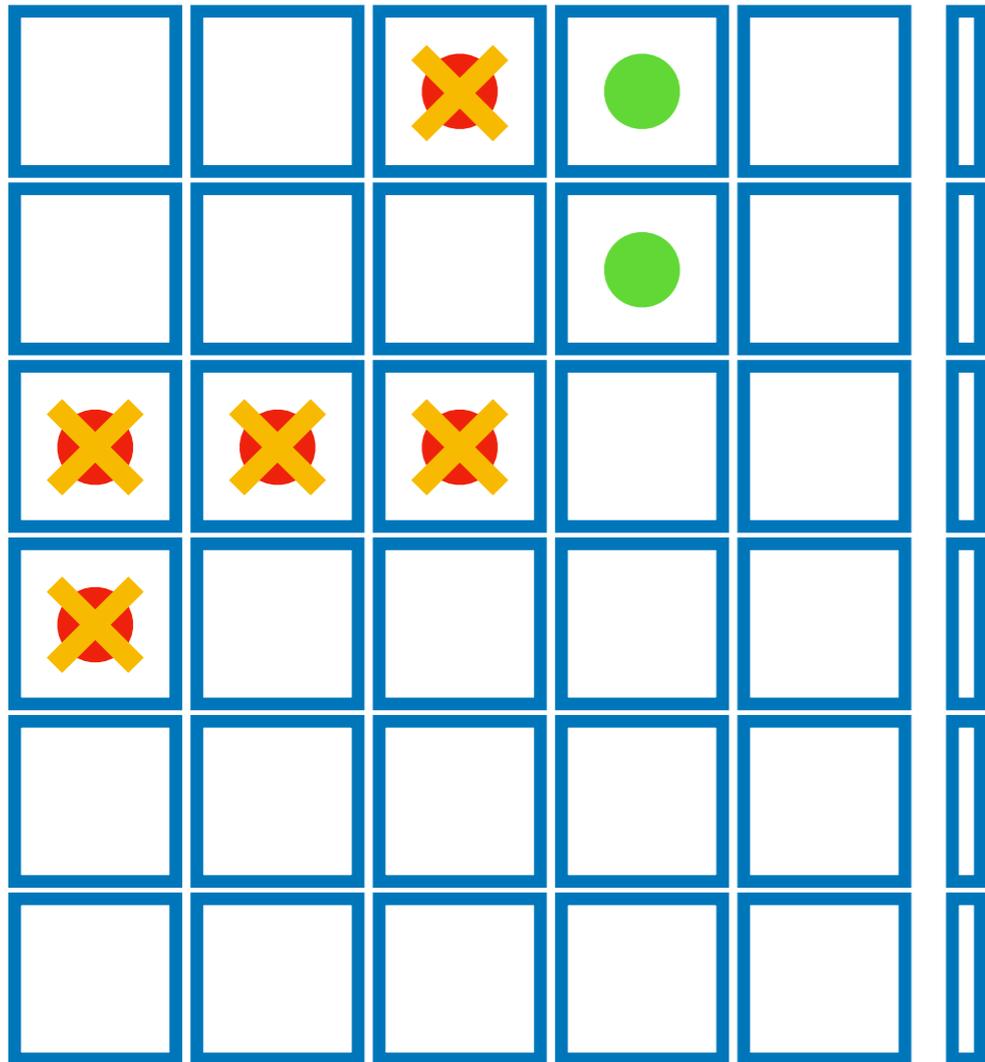
1. Find clusters
2. Try to group clusters
3. Cut on cluster hit multiplicity



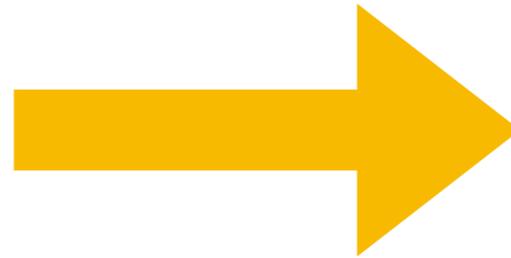
Hit algorithm

1. Find clusters
2. Try to group clusters
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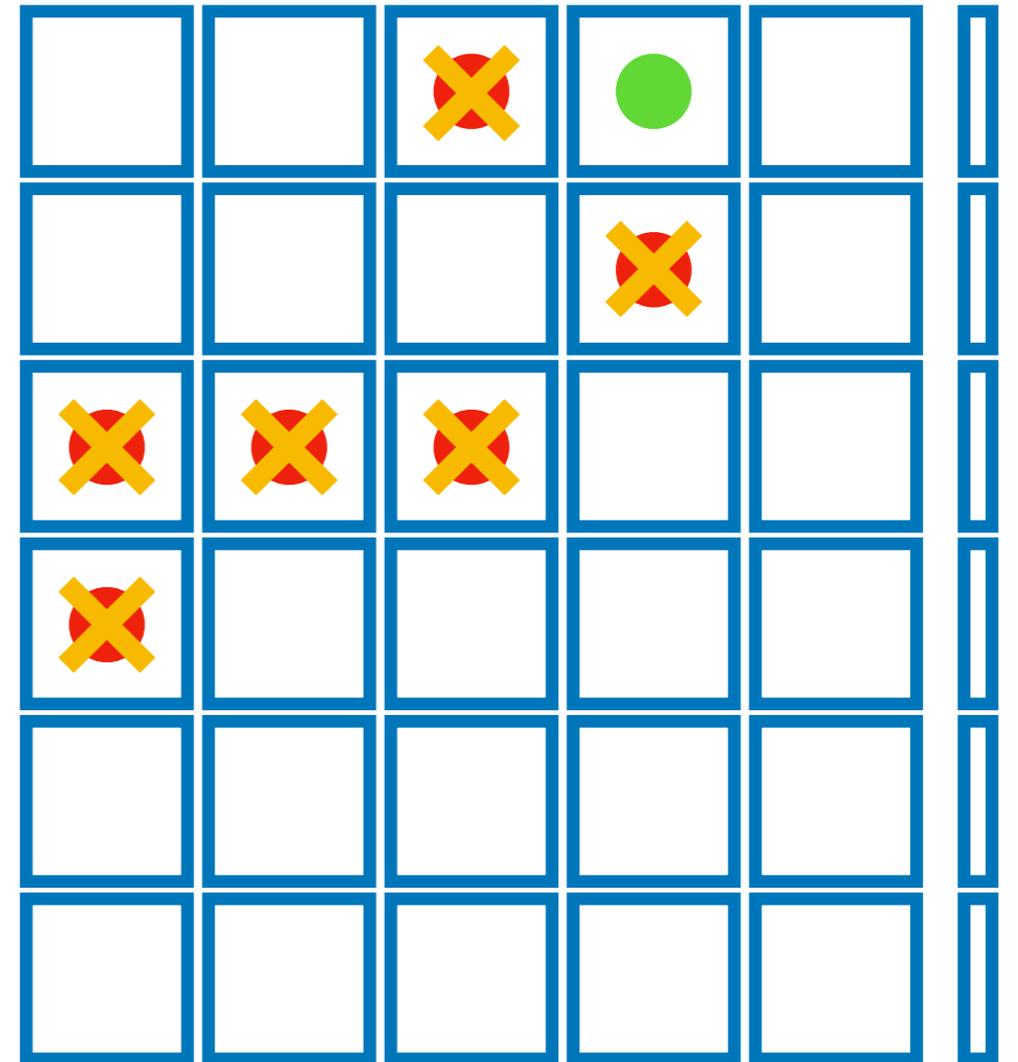
Clusters found



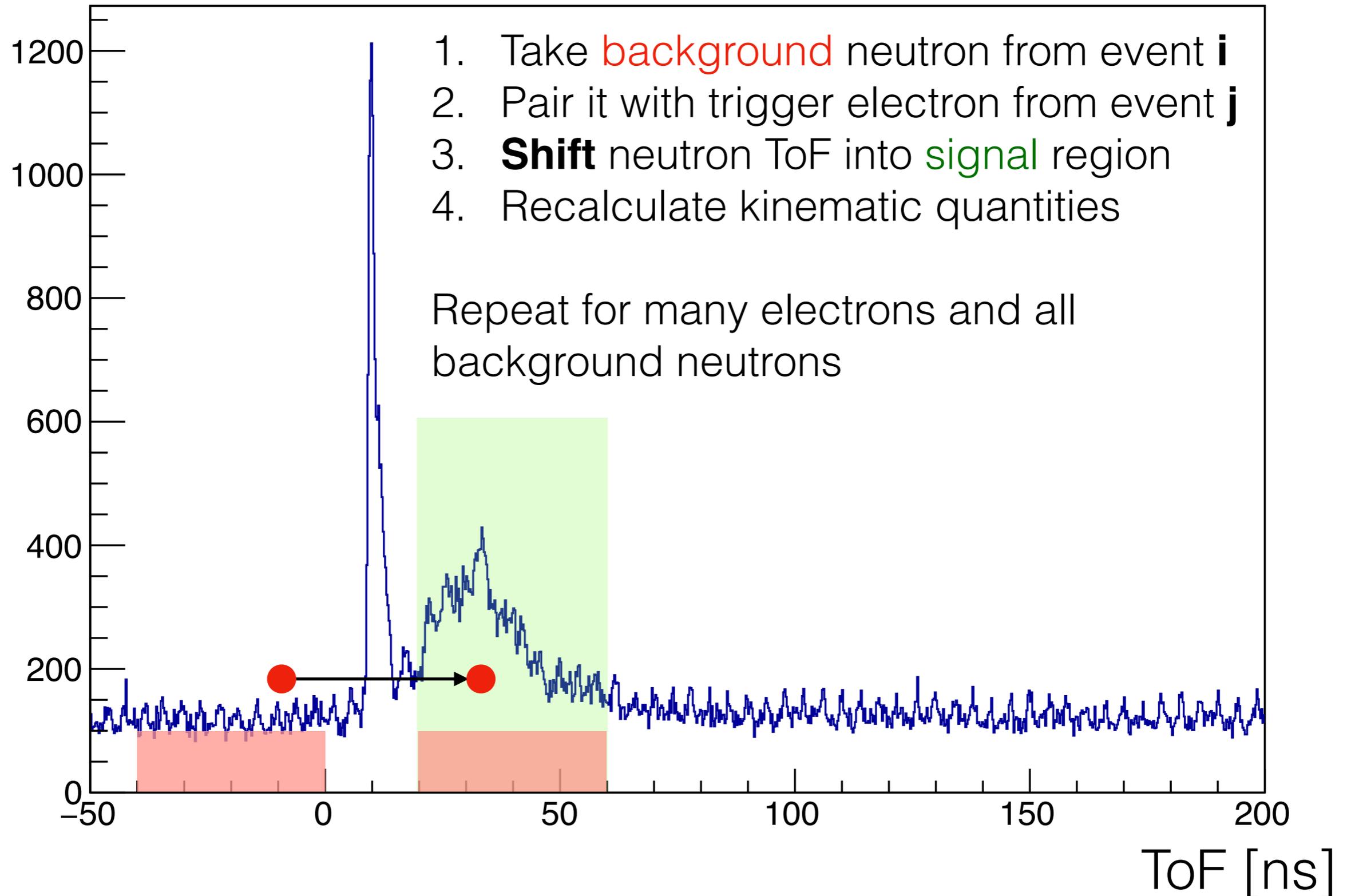
Two-cluster
combination



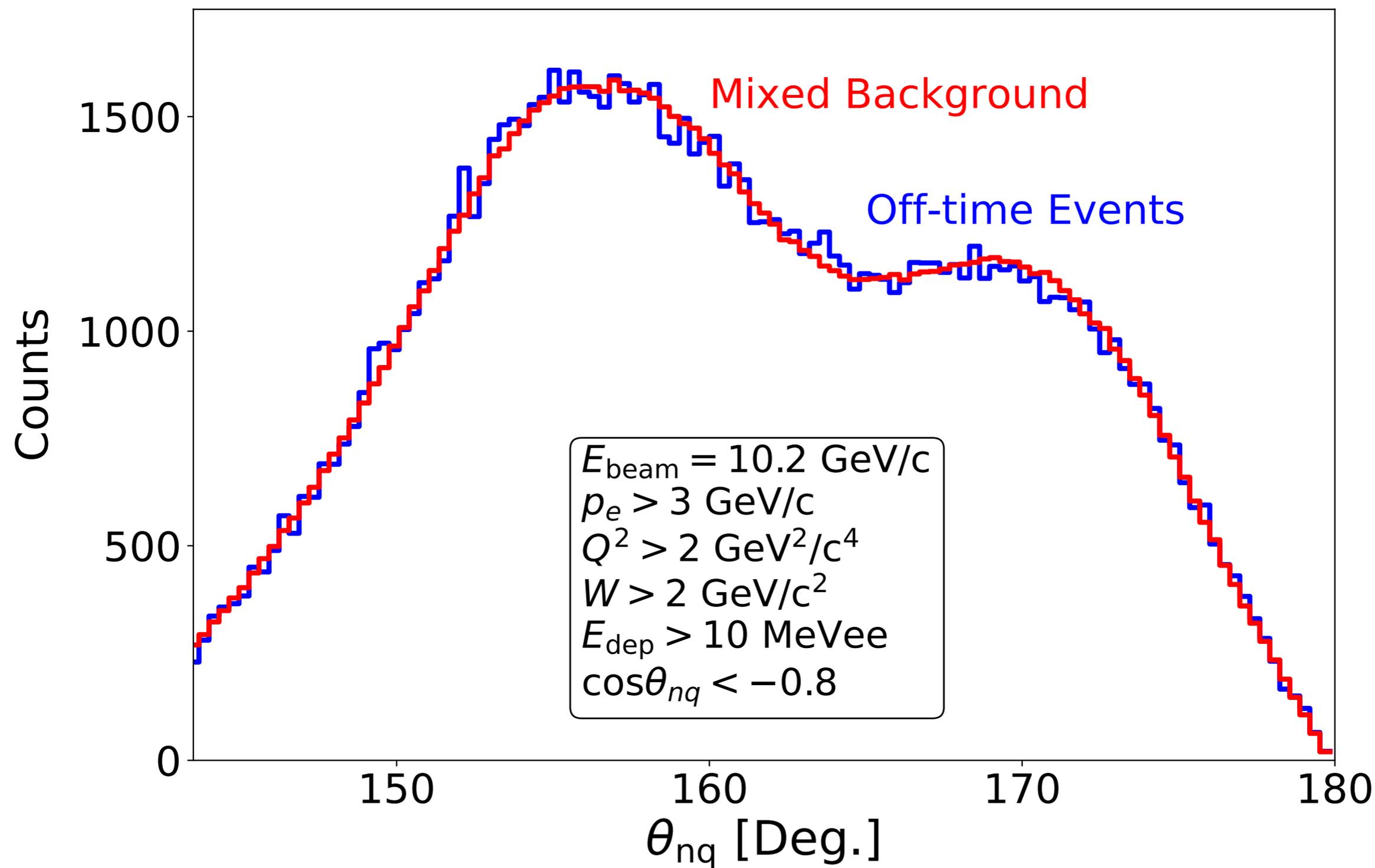
Single lead hit



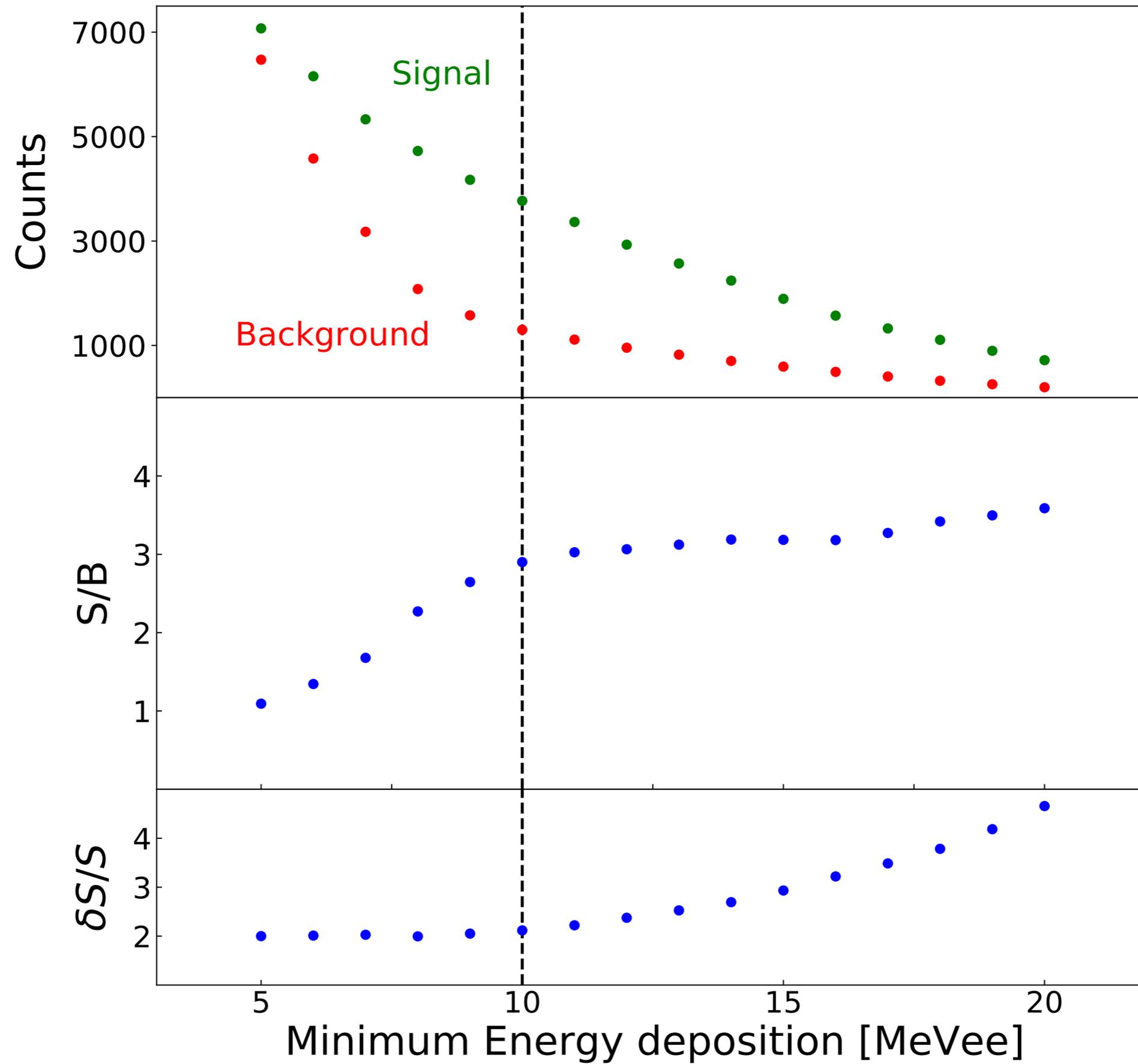
Event-mixing procedure



Can check consistency with real off-time neutrons

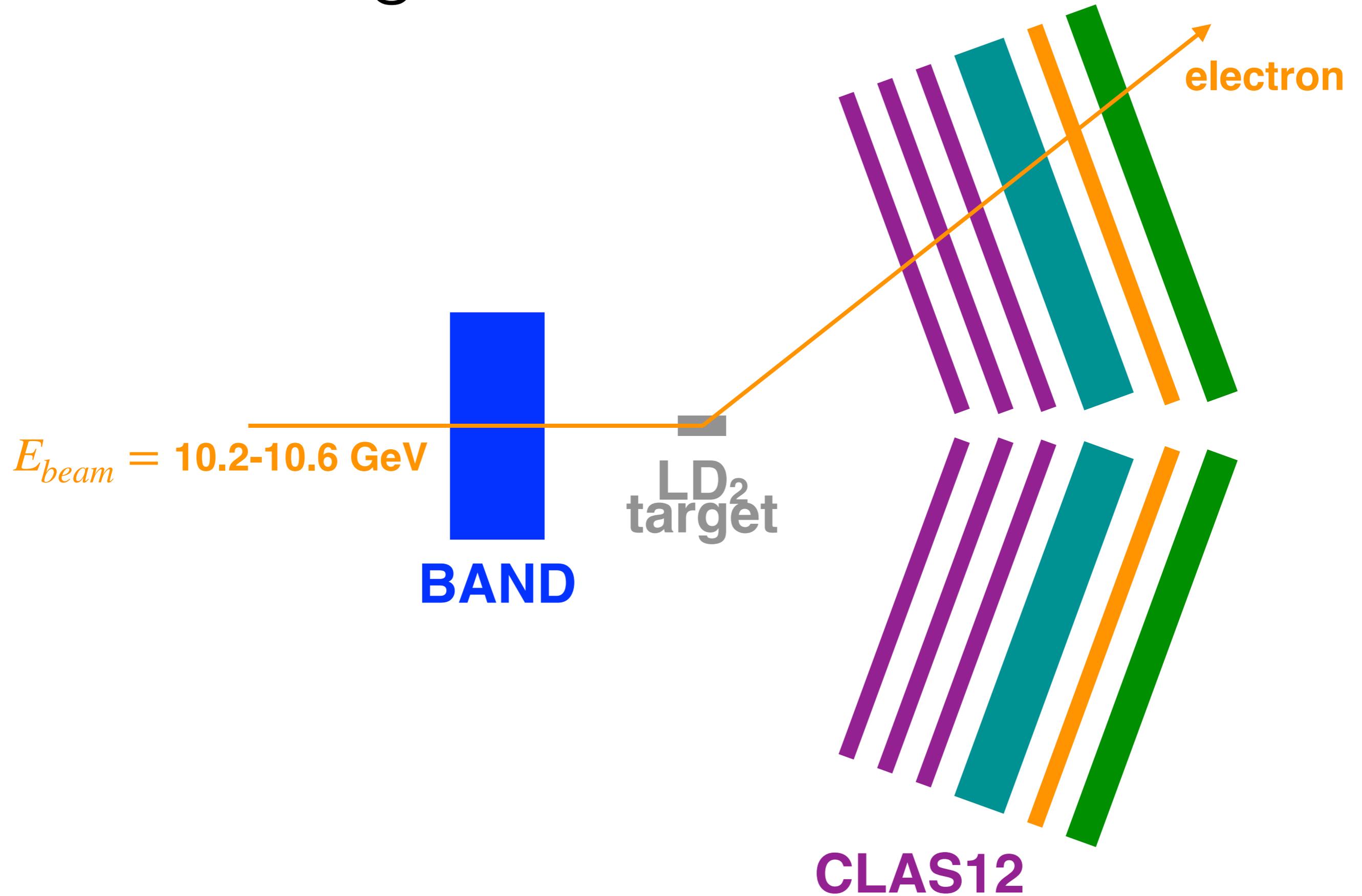


Minimizing off-time neutron contribution

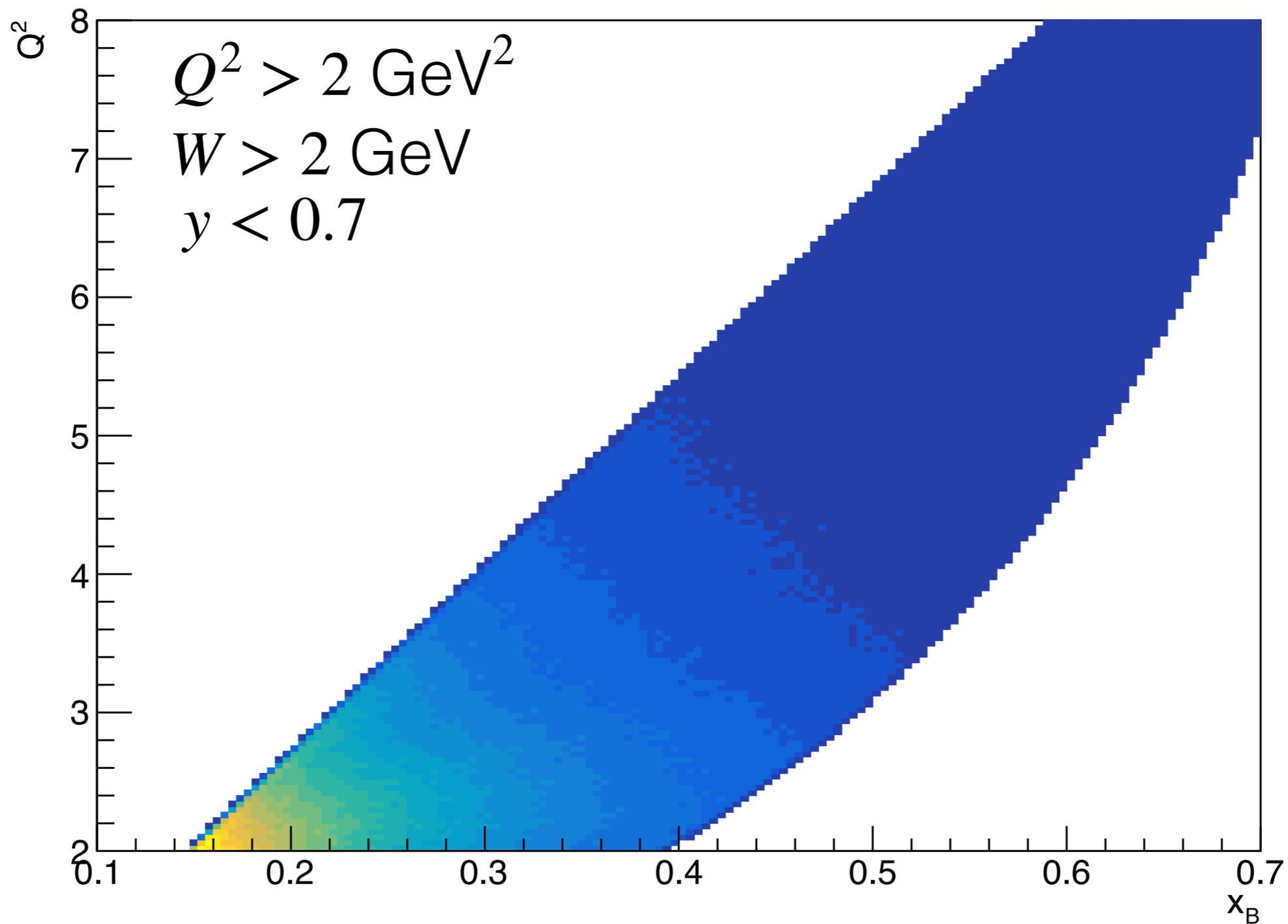


Validating analysis with different channels

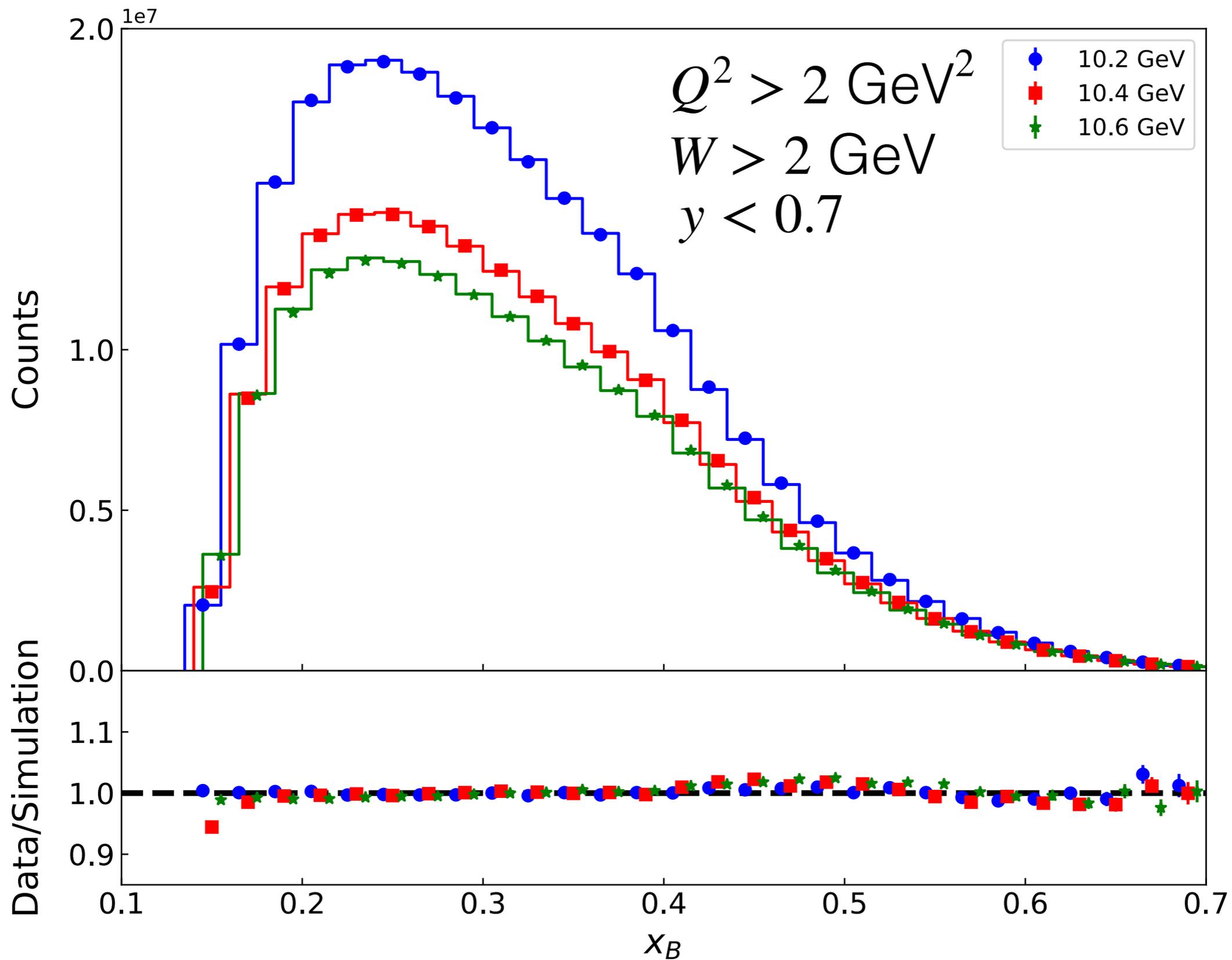
Testing CLAS12: Inclusive DIS



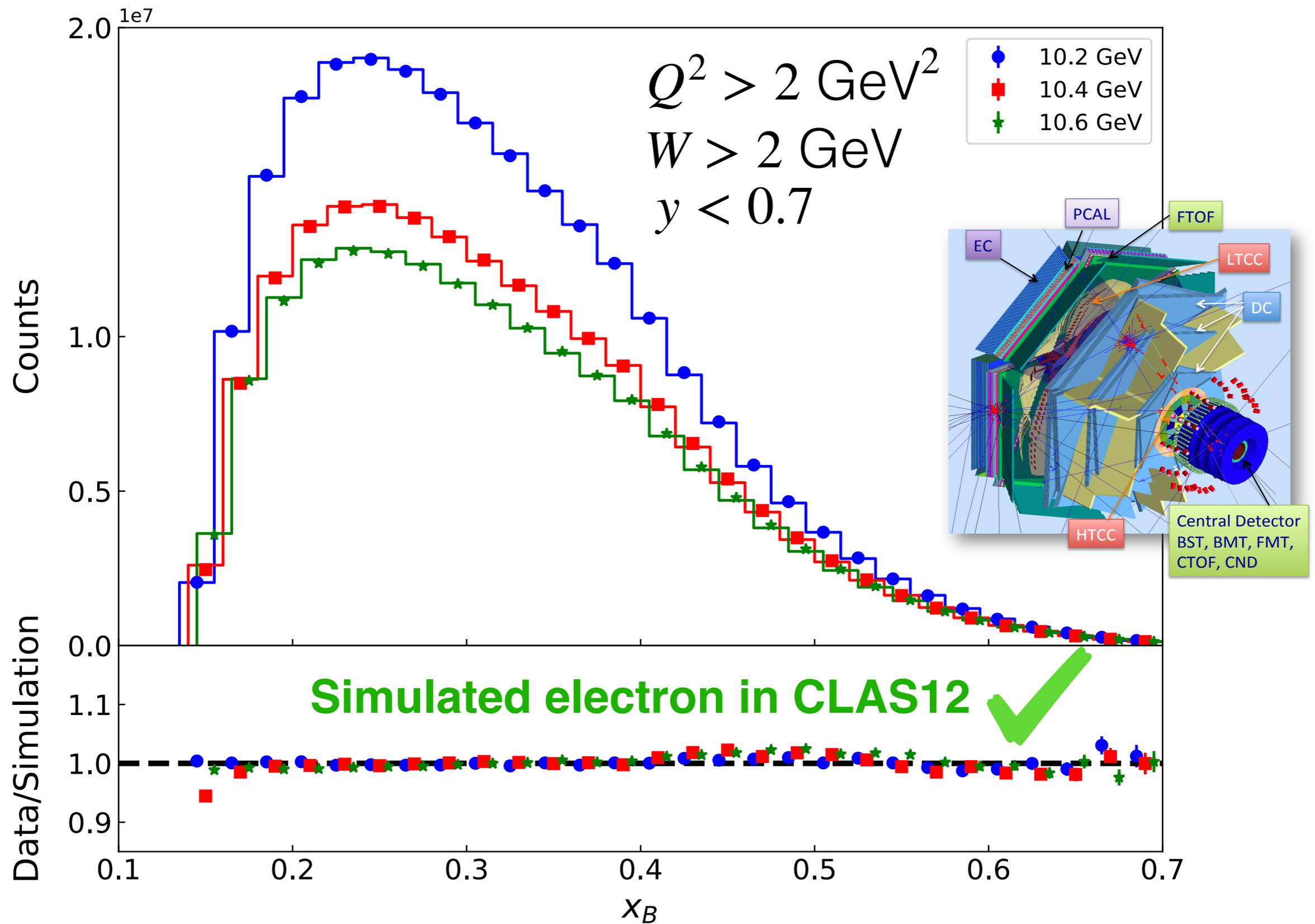
Inclusive $d(e, e')X$ data



Inclusive $d(e, e')X$ comparison

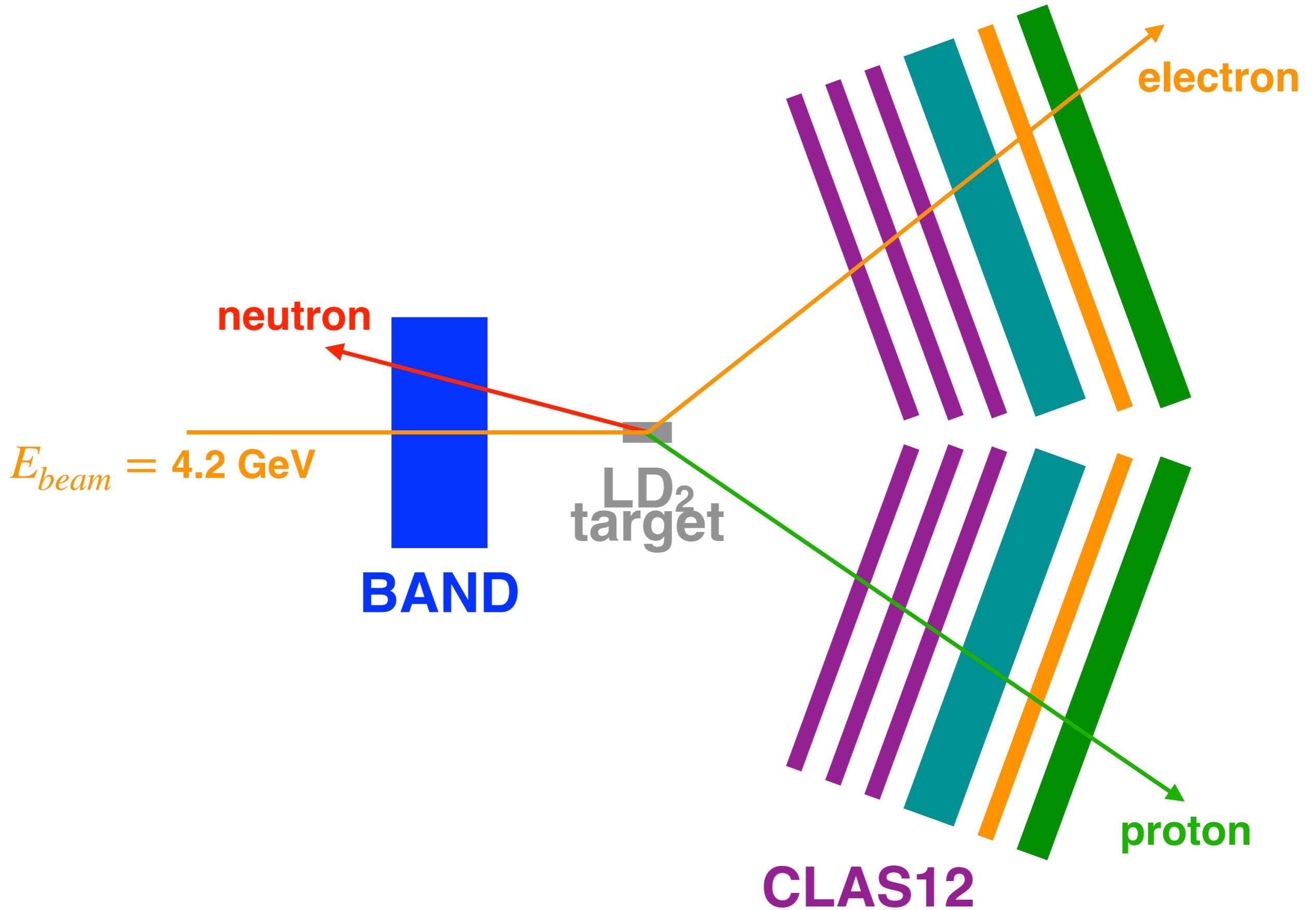


Inclusive $d(e, e')X$ comparison

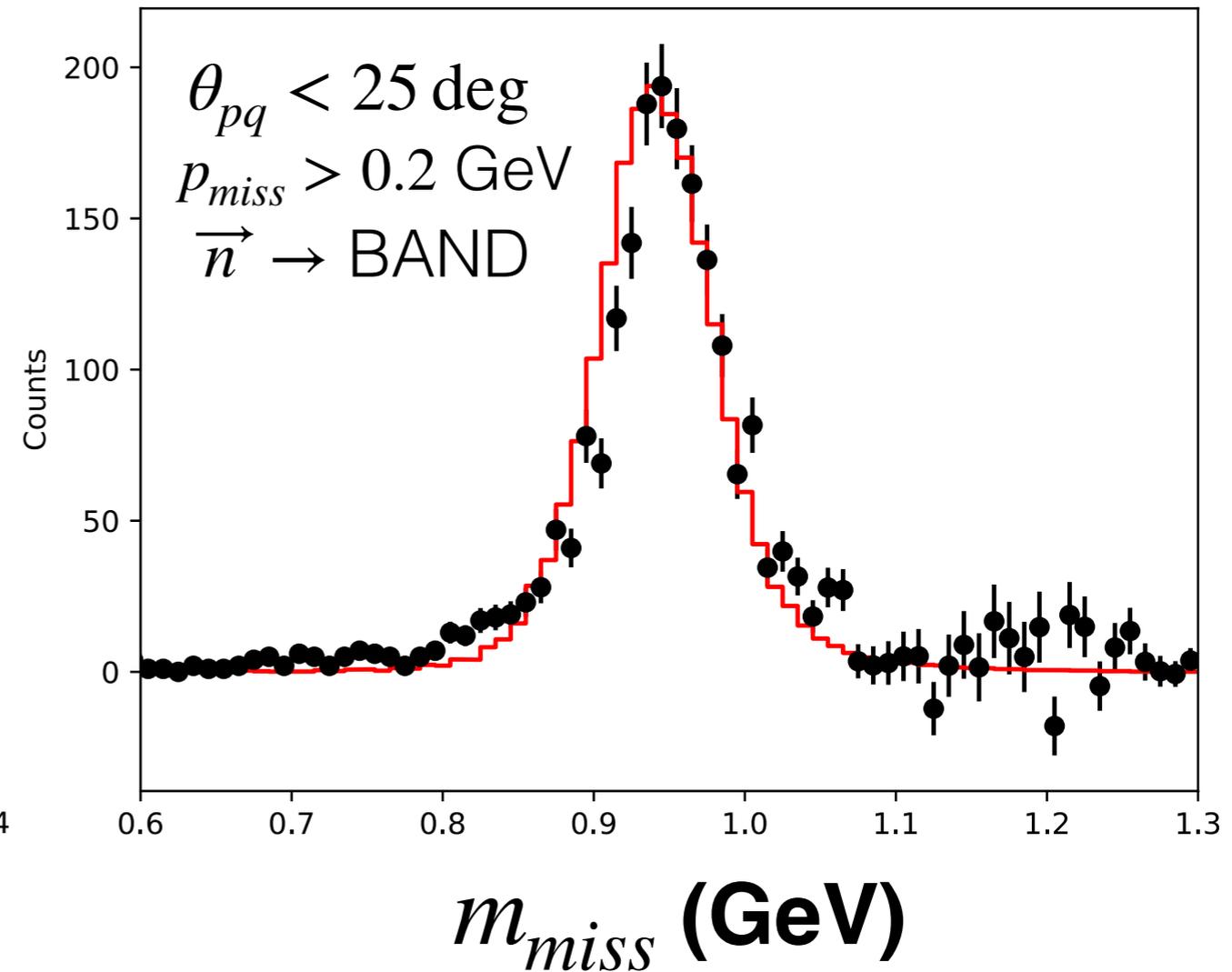
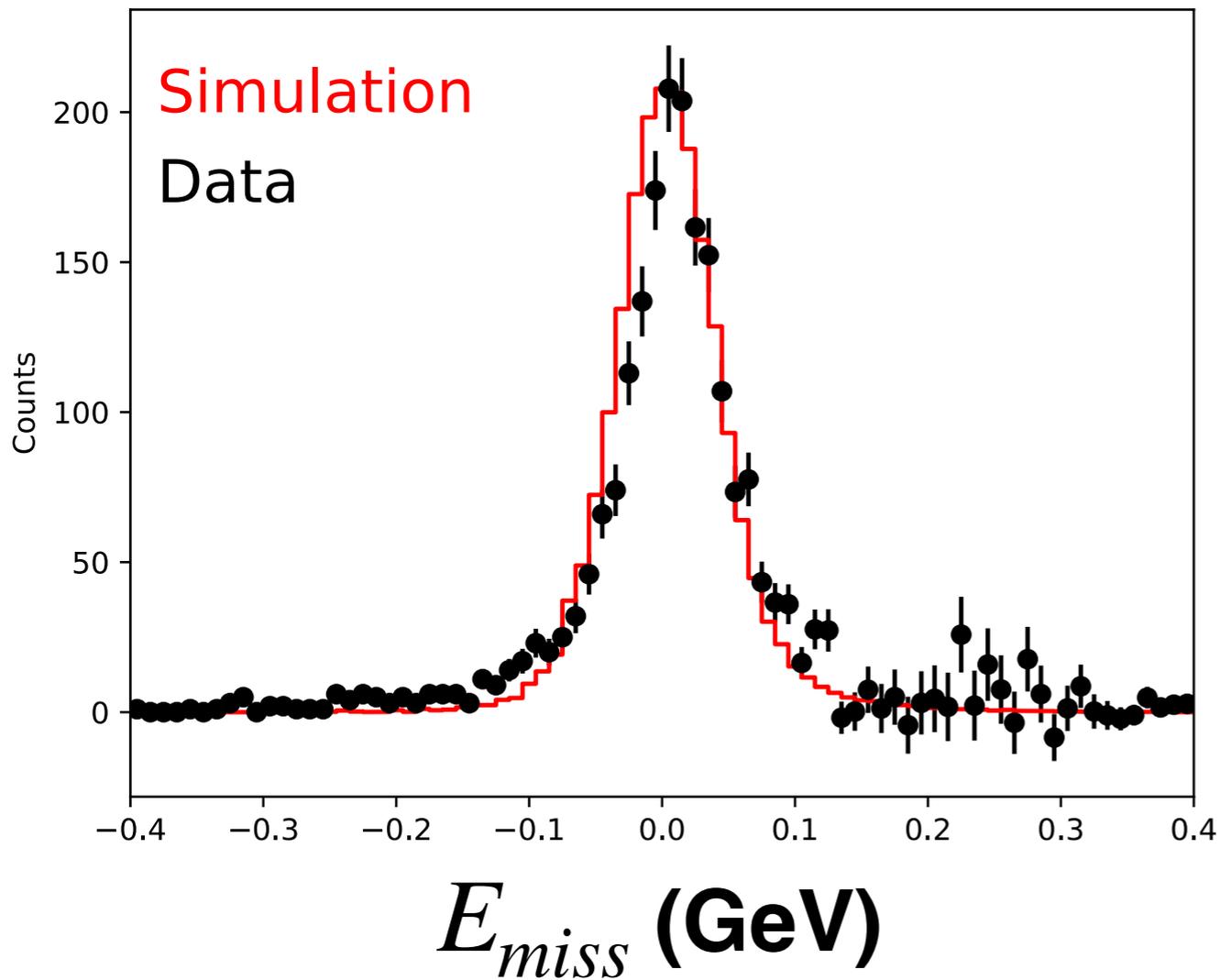


+e PID, fiducial cuts

Testing CLAS12 + BAND: quasi-elastic $d(e, e'pn)$



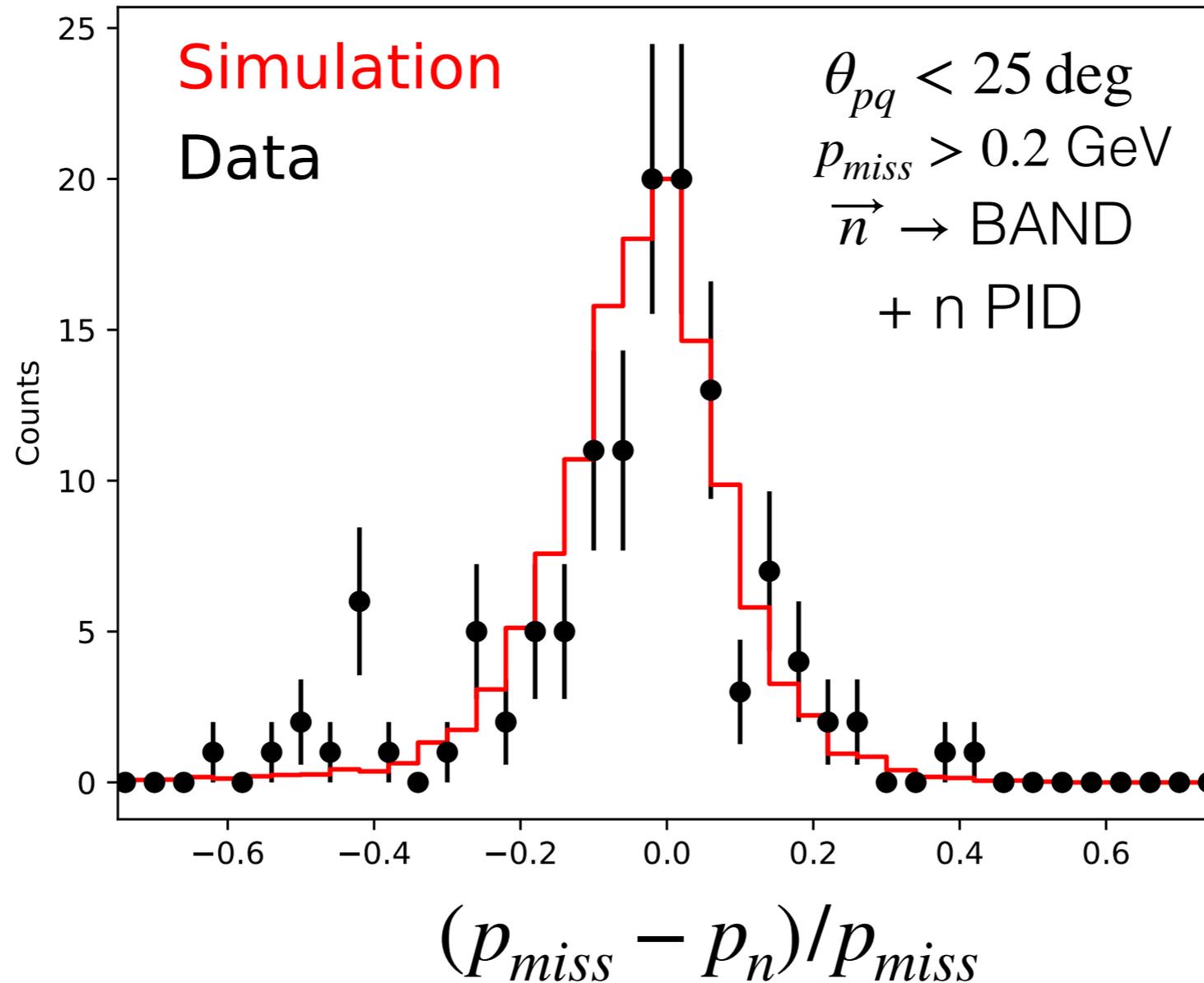
Quasi-elastic $d(e, e'p)n$



Simulated electron & proton in CLAS12



Quasi-elastic $d(e, e'pn)$



Simulated electron & proton in CLAS12

Simulated neutron in BAND



Tagged DIS with BAND

$$Q^2 > 2 \text{ [GeV}^2\text{]}$$

$$W > 2 \text{ [GeV]}$$

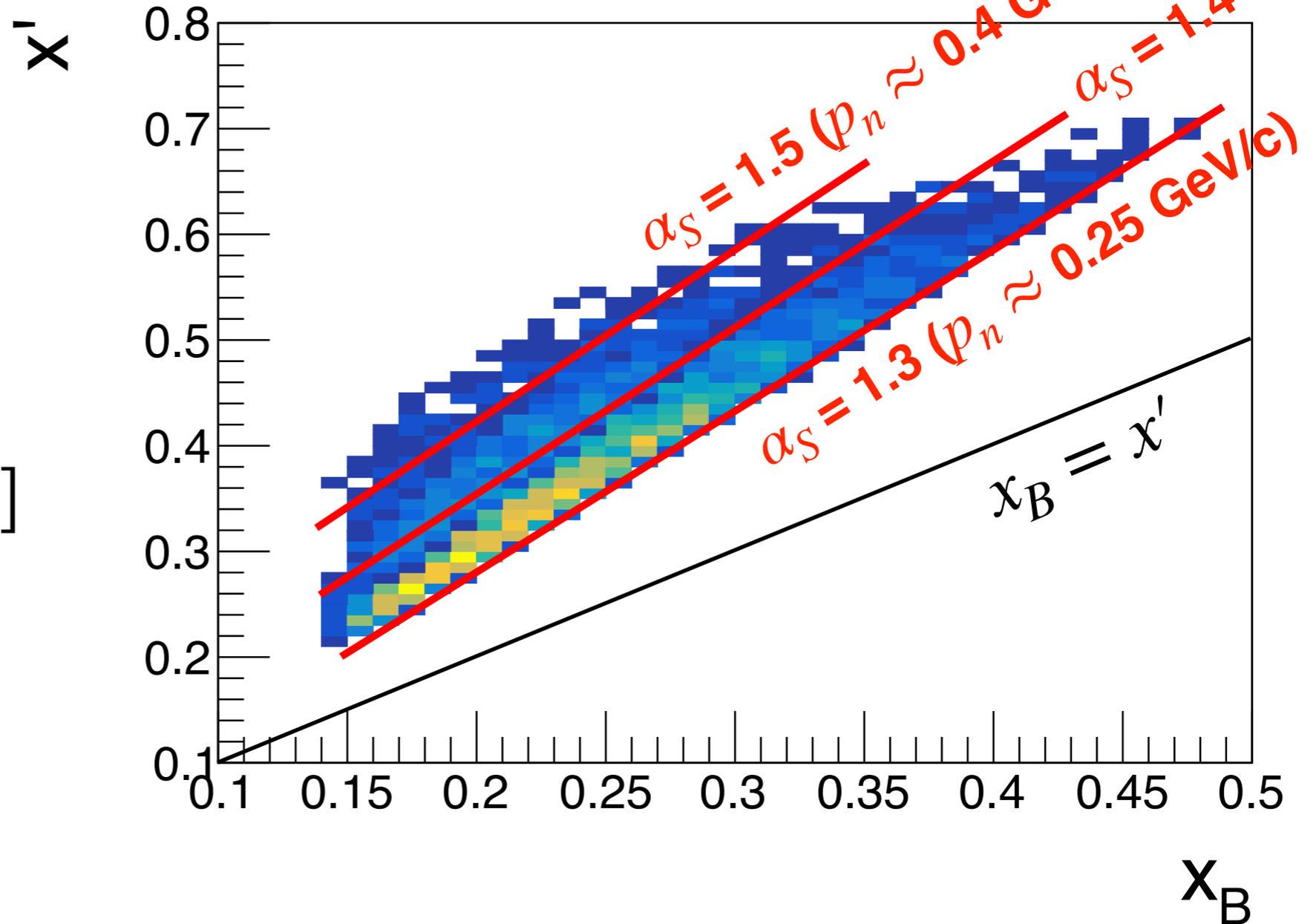
$$p_e > 3 \text{ [GeV]}$$

$$p_n > 0.25 \text{ [GeV]}$$

$$E_{dep} > 10 \text{ [MeVee]}$$

$$W' > 1.8 \text{ [GeV]}$$

$$p_T < 0.1 \text{ [GeV]}$$



Systematic studies

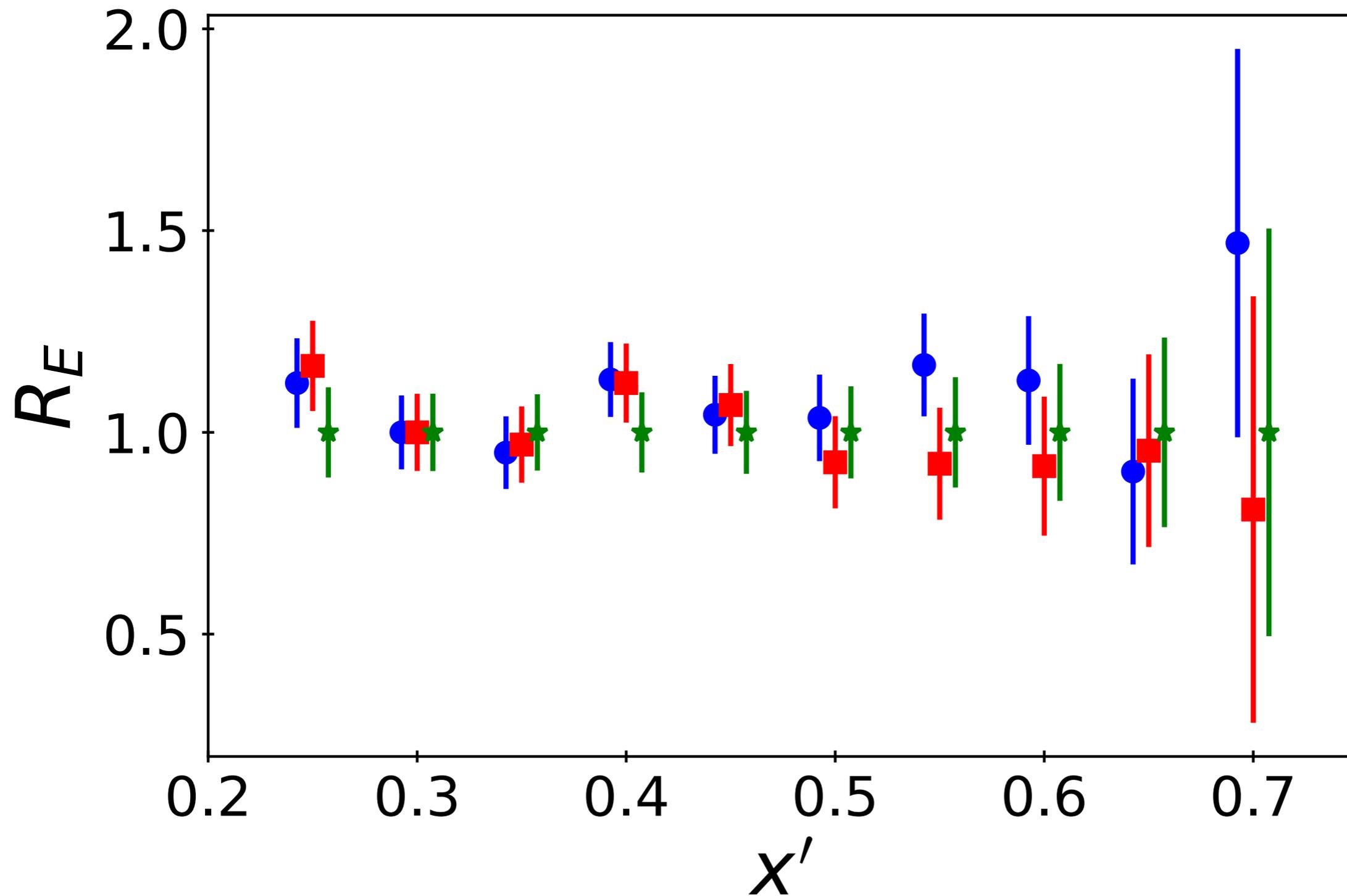
Variations with run period

Theoretical assumptions in model cross section

Neutron efficiency cancellation

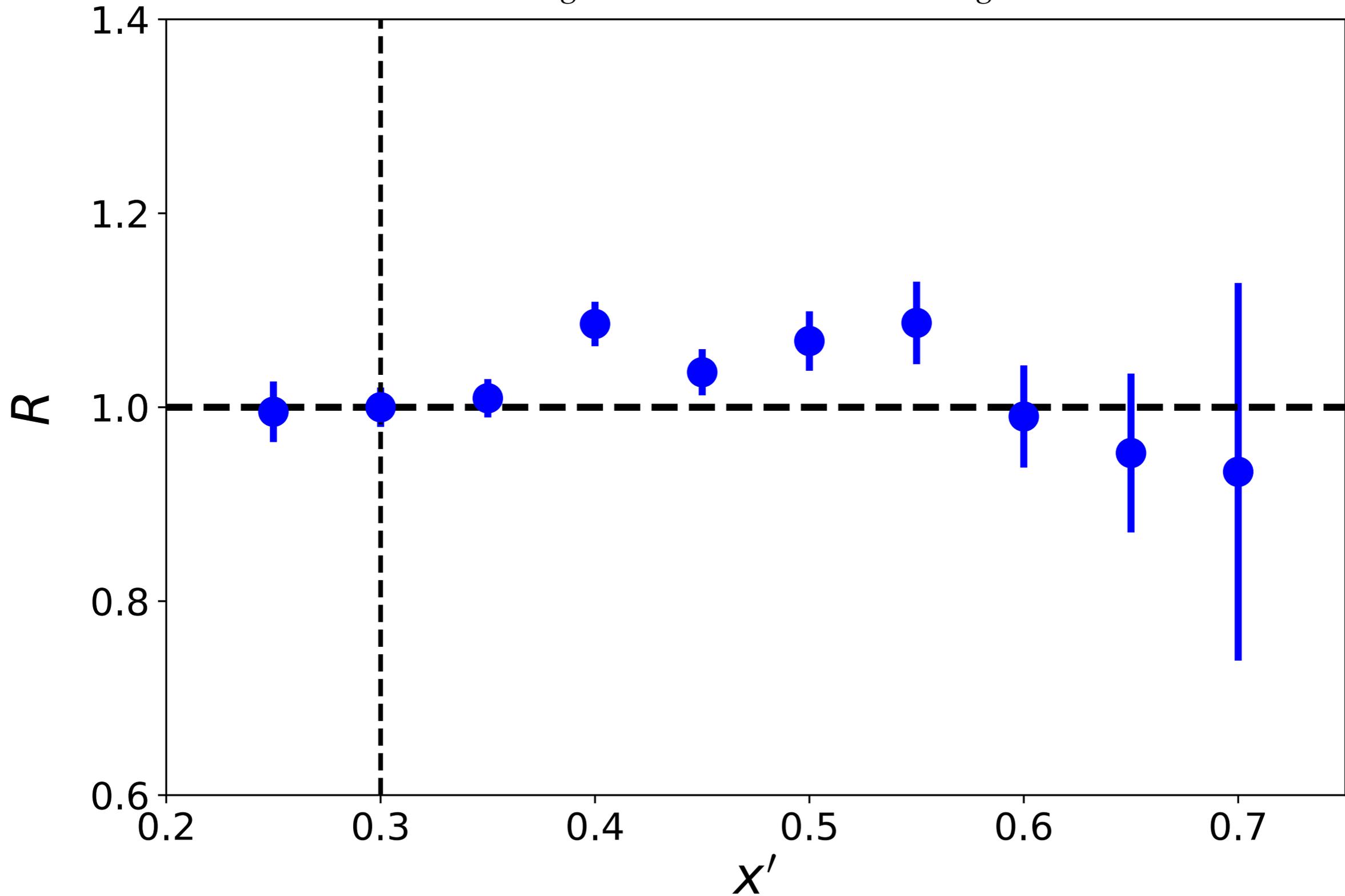
Stability with run period

$$R_E = R_{tag}(E)/R_{tag}(E = 10.6 \text{ GeV})$$



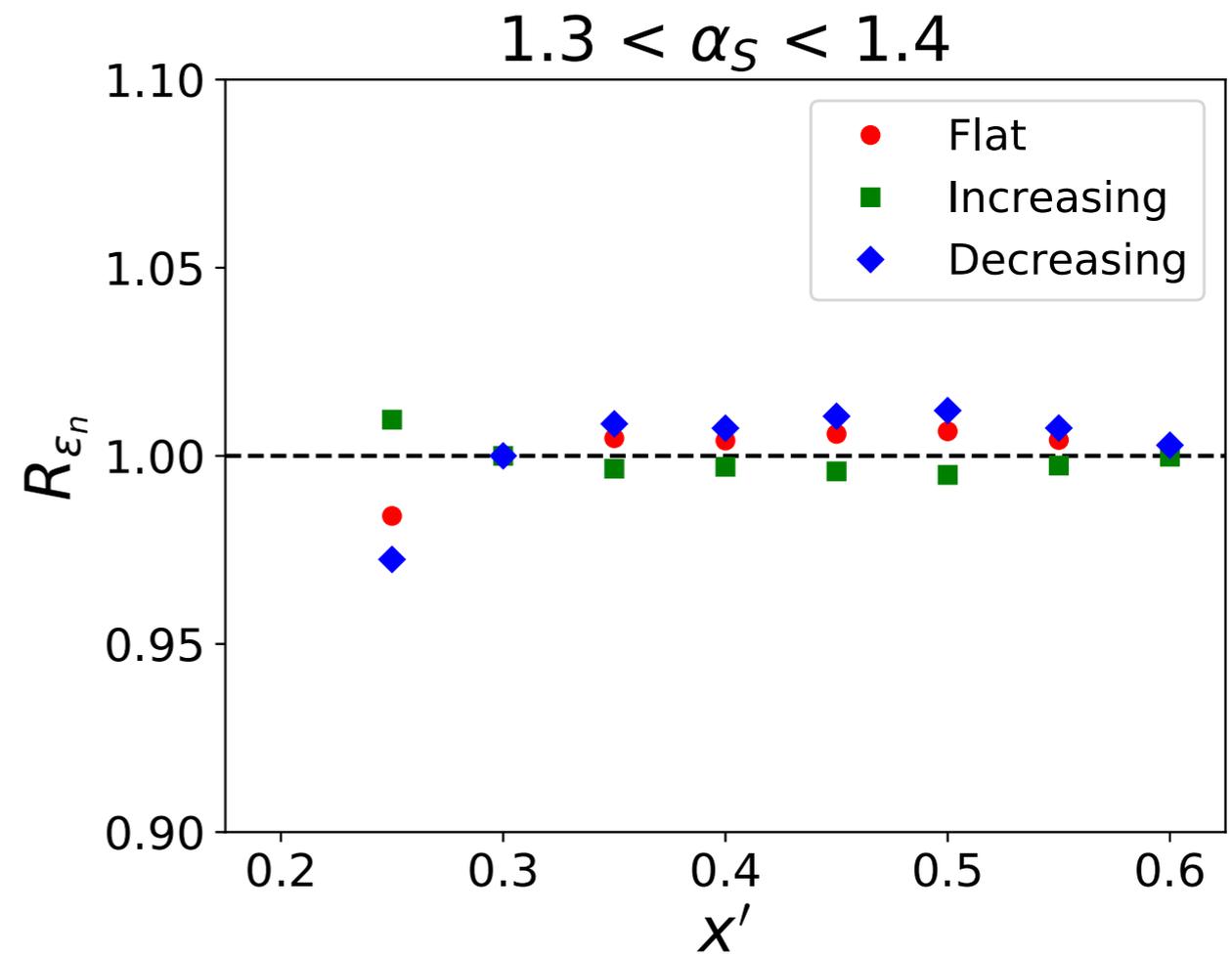
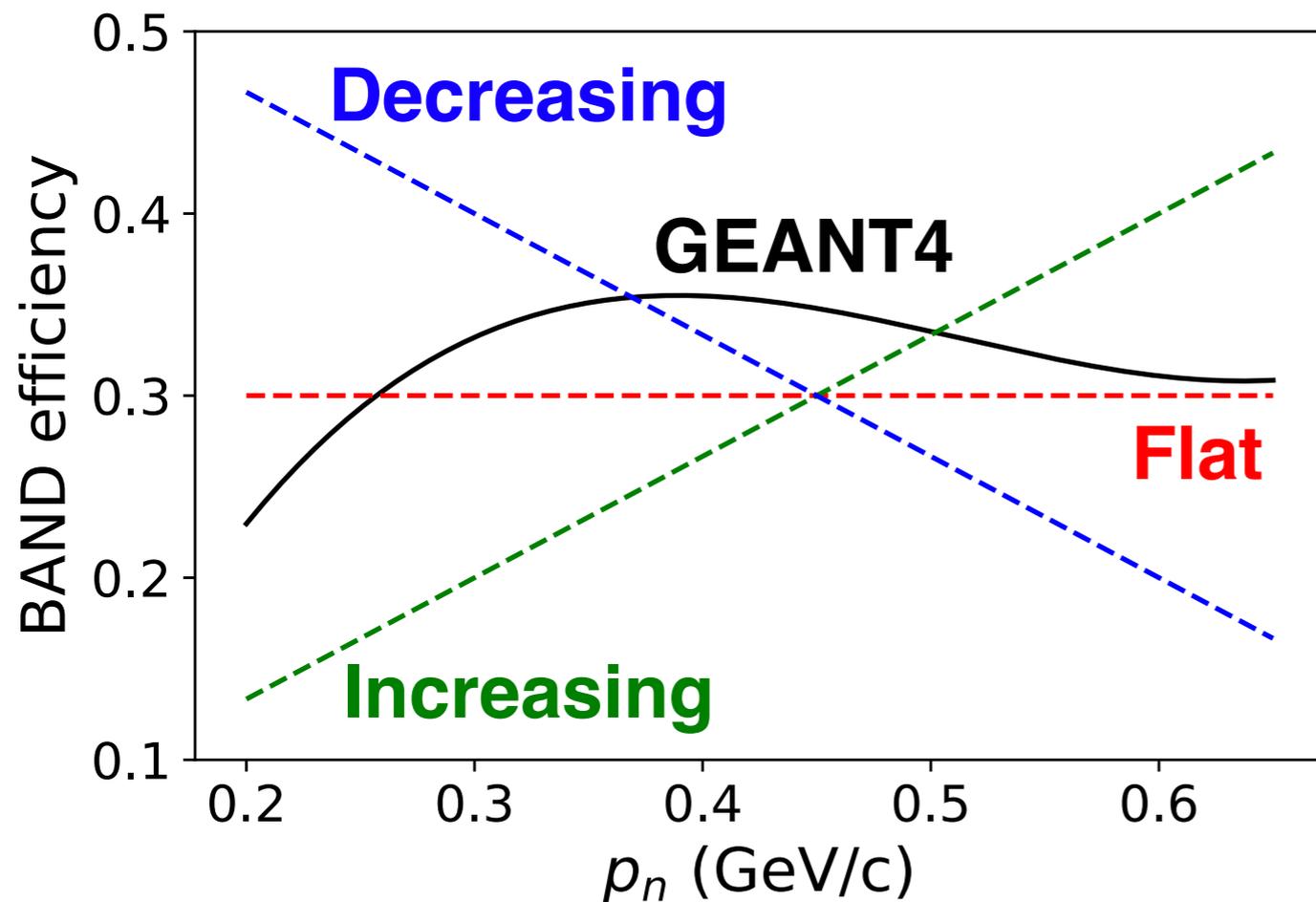
Assessing theory assumptions

$$R = R_{tag}(Asymptotic)/R_{tag}(Full)$$



Neutron efficiency

$$R_{\epsilon_n} = \frac{N_{standard}(x') / N_{standard}(x' = x_0)}{N_{reweight}(x') / N_{reweight}(x' = x_0)}$$



Pheno work

Many approaches to extract F_2^n , but all depend on modeling off-shell modification

Use all nuclear DIS

$$F_2^A = \left[\begin{array}{l} \text{Free nucleons} \\ (Z - n_{SRC}^A) F_2^p \\ + (N - n_{SRC}^A) F_2^n \end{array} \right] + n_{SRC}^A \left(\begin{array}{l} \text{Modified high-} \\ \text{momenta nucleons} \\ F_2^{p*} + F_2^{n*} \end{array} \right)$$

Many approaches to extract F_2^n , but all depend on modeling off-shell modification

Use all nuclear DIS

$$F_2^A = \left[\begin{array}{l} \text{Free nucleons} \\ (Z - n_{SRC}^A) F_2^p \\ + (N - n_{SRC}^A) F_2^n \end{array} \right] + \text{Modified high-momenta nucleons} \left(F_2^{p*} + F_2^{n*} \right)$$

Use ${}^3\text{He}$, ${}^3\text{H}$

$$\frac{F_2^n}{F_2^p} = \frac{2\mathcal{R} - F_2^{3\text{He}} / F_2^{3\text{H}}}{2F_2^{3\text{He}} / F_2^{3\text{H}} - \mathcal{R}}$$

Measured

Theoretical input

Many approaches to extract F_2^n , but all depend on modeling off-shell modification

Use all nuclear DIS

$$F_2^A = \left[\begin{array}{l} \text{Free nucleons} \\ (Z - n_{SRC}^A) F_2^p \\ + (N - n_{SRC}^A) F_2^n \end{array} \right] + \text{Modified high-momenta nucleons} \left(F_2^{p*} + F_2^{n*} \right)$$

Use ${}^3\text{He}$, ${}^3\text{H}$

$$\frac{F_2^n}{F_2^p} = \frac{2\mathcal{R} - F_2^{3\text{He}} / F_2^{3\text{H}}}{2F_2^{3\text{He}} / F_2^{3\text{H}} - \mathcal{R}}$$

Measured

Theoretical input

Use light nuclei

$$F_2^A = \int_{x_B}^A \frac{d\alpha}{\alpha} \int_{-\infty}^0 d\nu \left[Z F_2^p(\tilde{x}) \rho_p(\alpha, \nu) + N \rho_n(\alpha, \nu) F_2^n(\tilde{x}) \right] \cdot (1 + \nu f^{off}(\tilde{x}))$$

F_2^n dependent on motion, off-shell structure, and data used

$$F_2^A = \int_{x_B}^A \frac{d\alpha}{\alpha} \int_{-\infty}^0 d\nu F_2^P(\tilde{x}) \left[Z\rho_p(\alpha, \nu) + N\rho_n(\alpha, \nu) \frac{F_2^n(\tilde{x})}{F_2^P(\tilde{x})} \right] \cdot \underbrace{\left(1 + \nu f^{off}(\tilde{x}) \right)}_{\text{off-shell modification}}$$

Diagram annotations:

- Arrows from "nucleon motion" point to $Z\rho_p(\alpha, \nu)$ and $N\rho_n(\alpha, \nu)$.
- An arrow from "free structure" points to $F_2^P(\tilde{x})$.
- An arrow from "free structure" points to $F_2^n(\tilde{x})$.
- An arrow from F_2^A points to "compare to data".

Toggle options:

- **Data used**
- **Nuclear motion**
- **Off-shell parameterization**