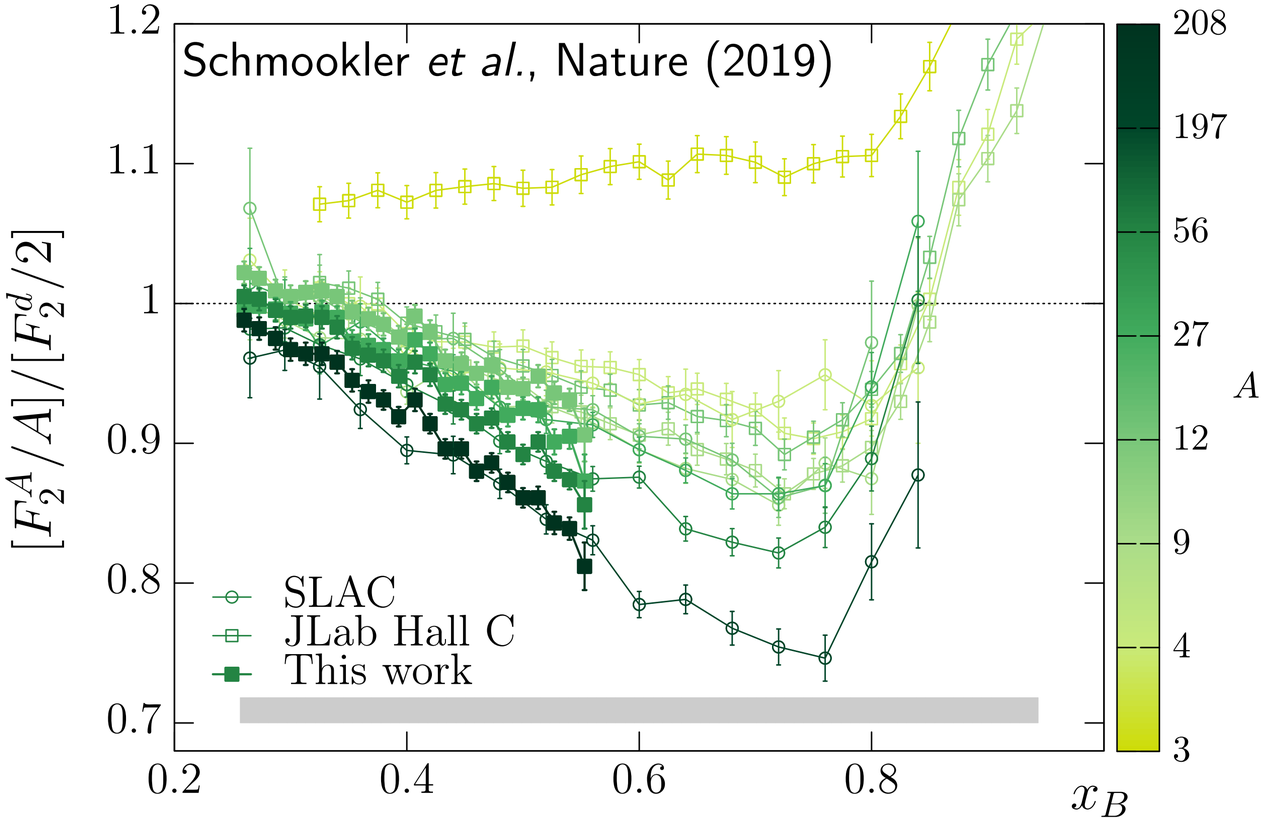
Bound proton structure with BAND

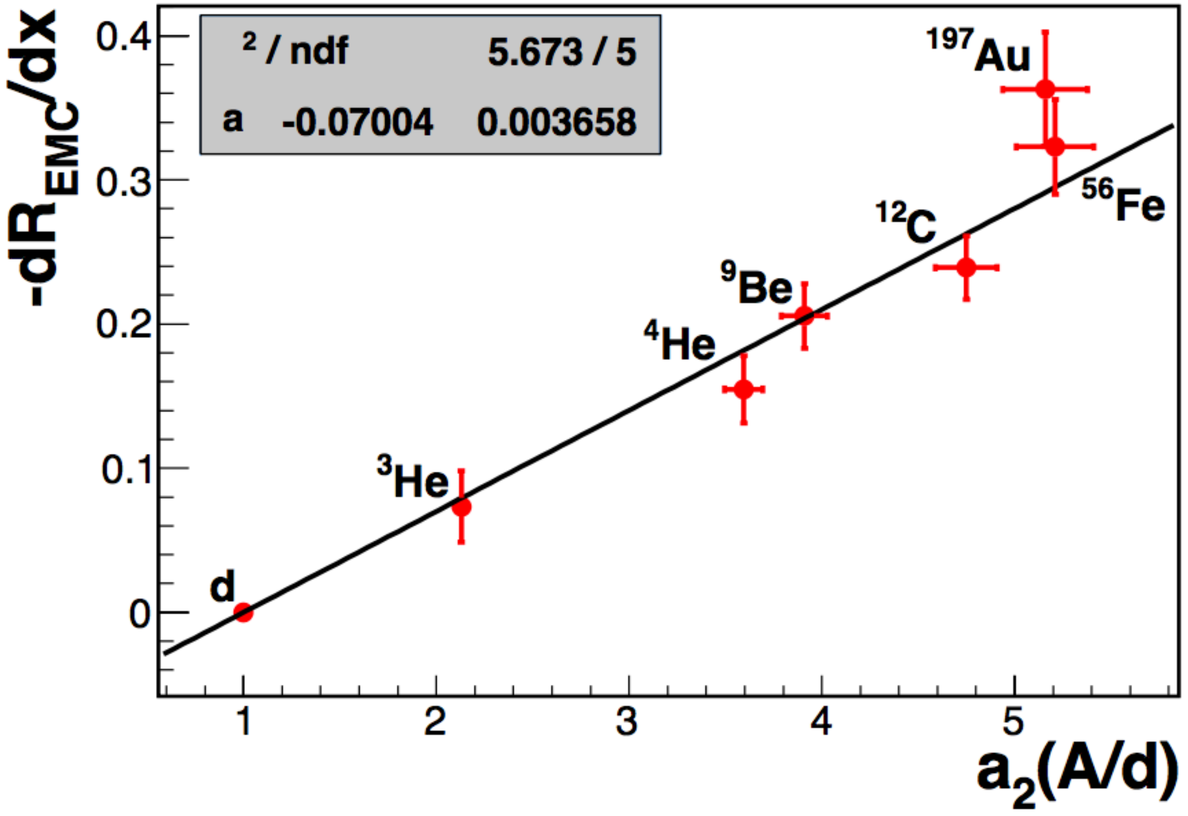
Tyler Kutz

Workshop on Short Range Correlations at the
Intersect of Nuclear and Nucleon Structures

August 3, 2022

Inclusive DIS measurements suggest connection between SRCs and EMC effect

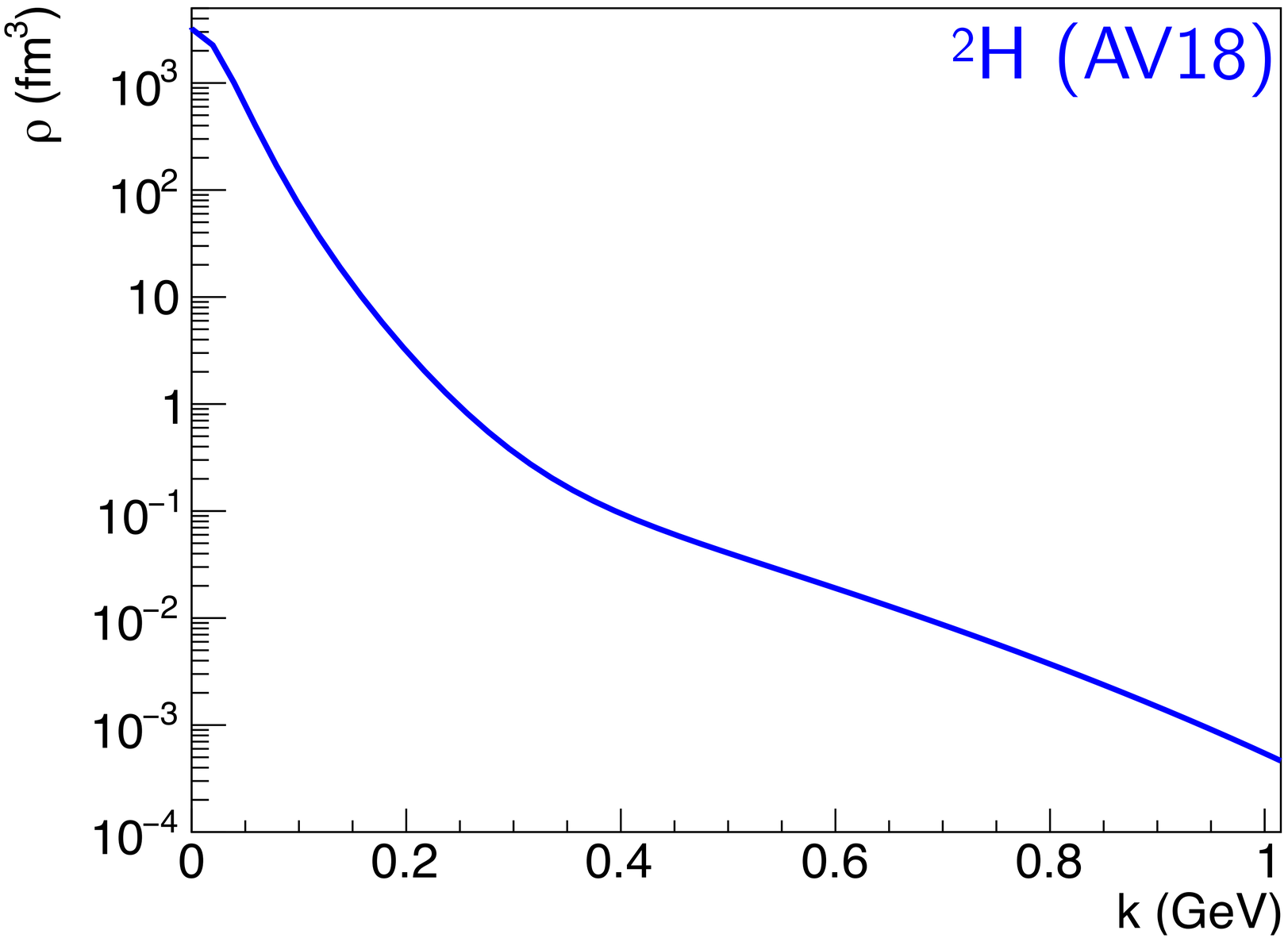




SRC-EMC hypothesis:

EMC effect driven by modification of nucleons in SRC pairs

Test SRC-EMC hypothesis with tagged DIS



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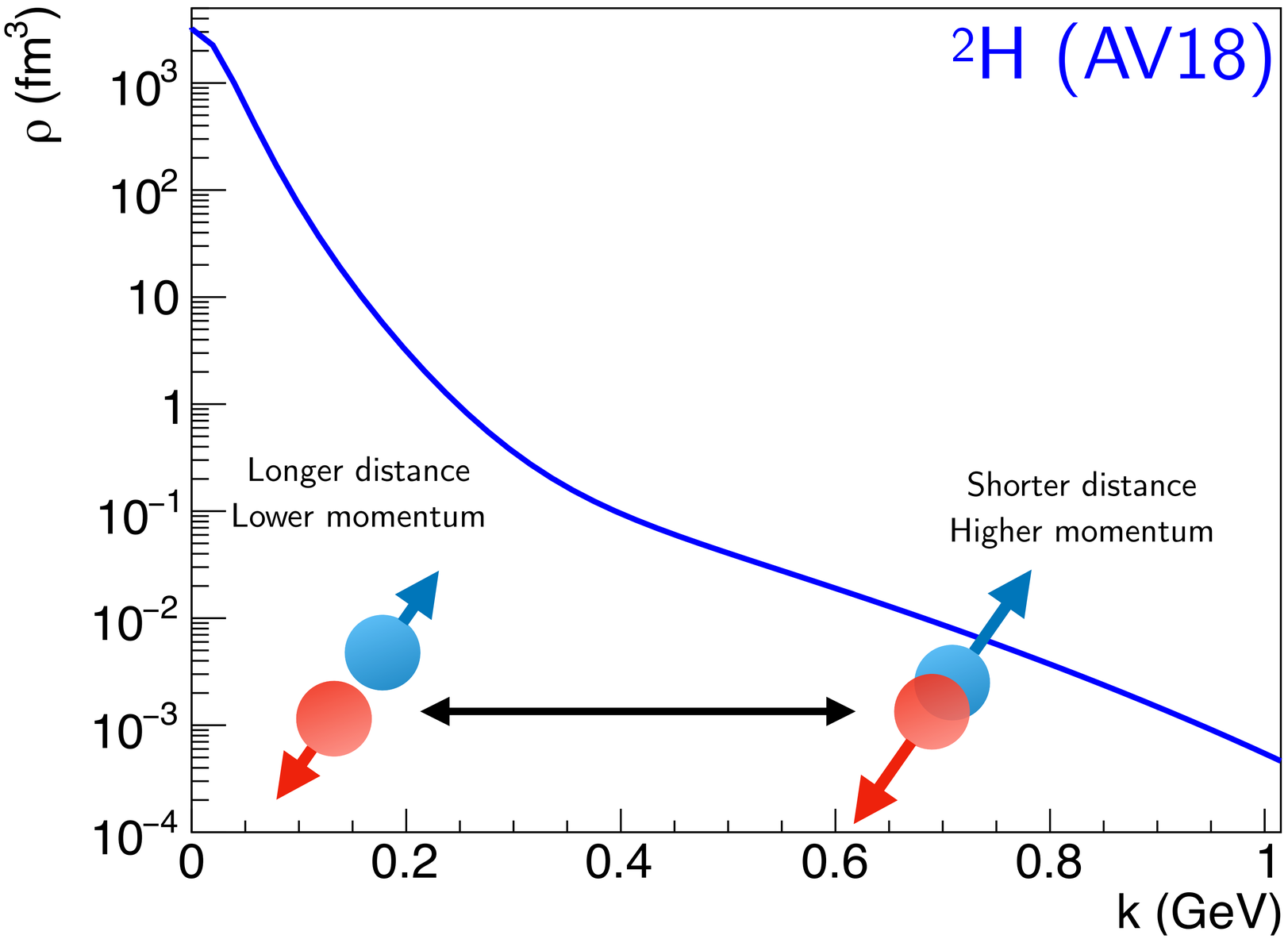

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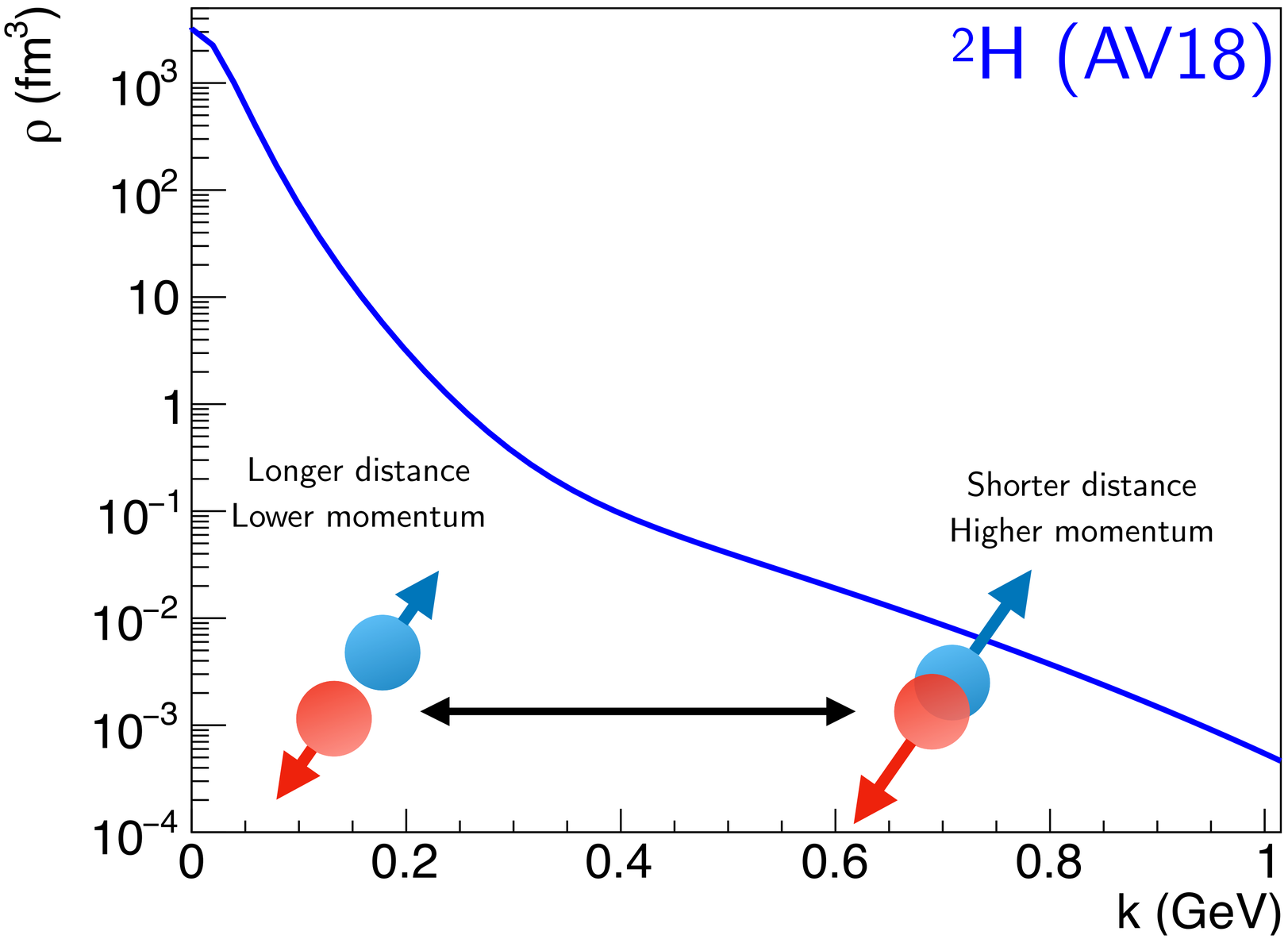

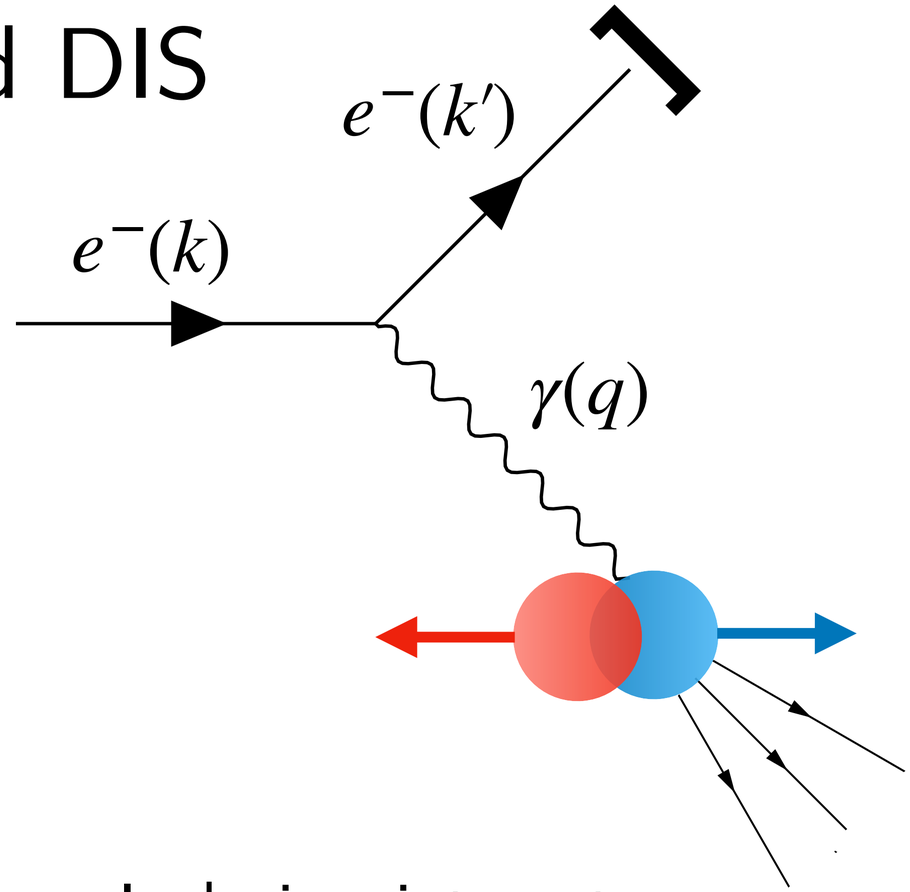

- Inclusive: integrate over all momentum

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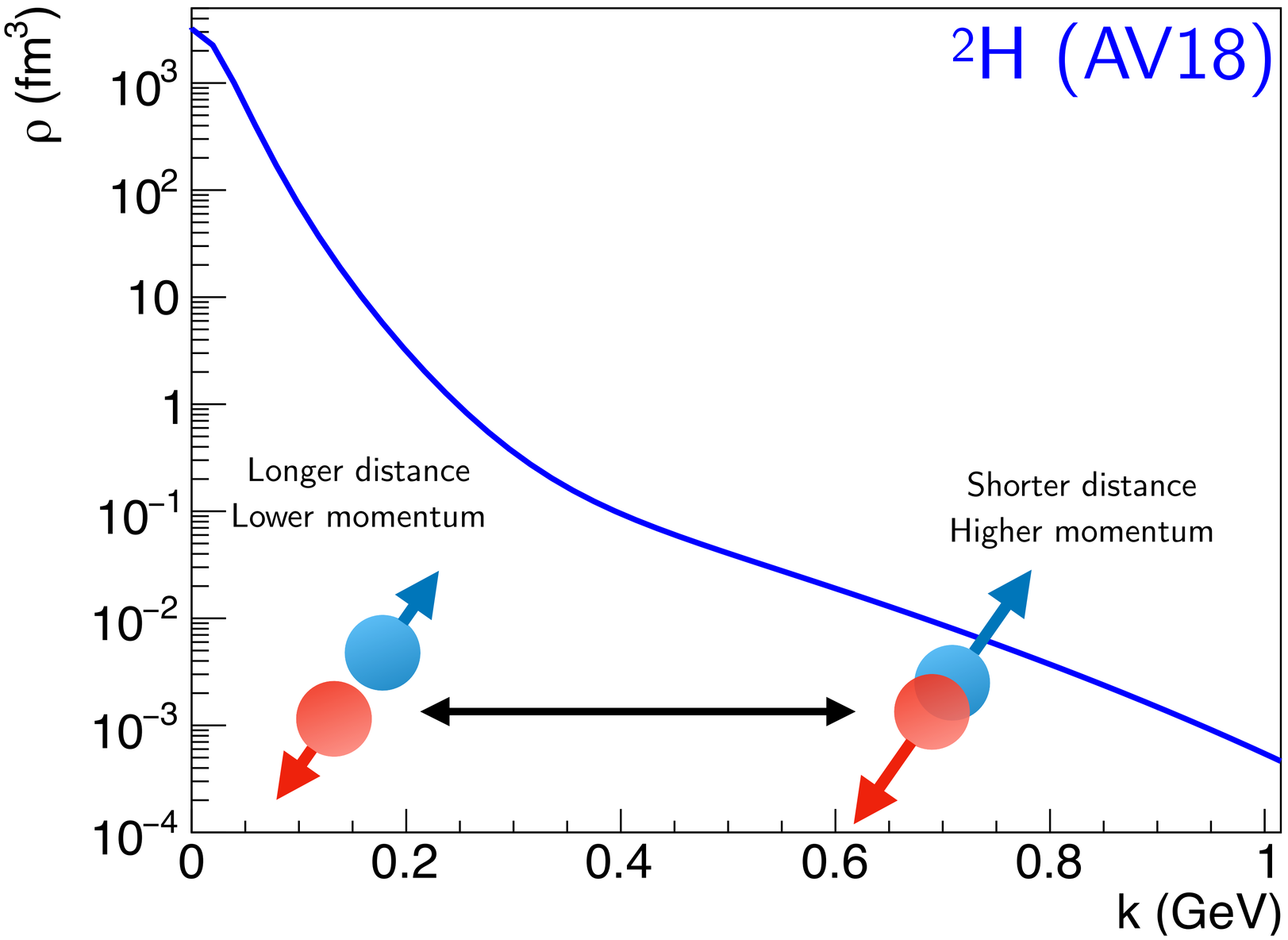
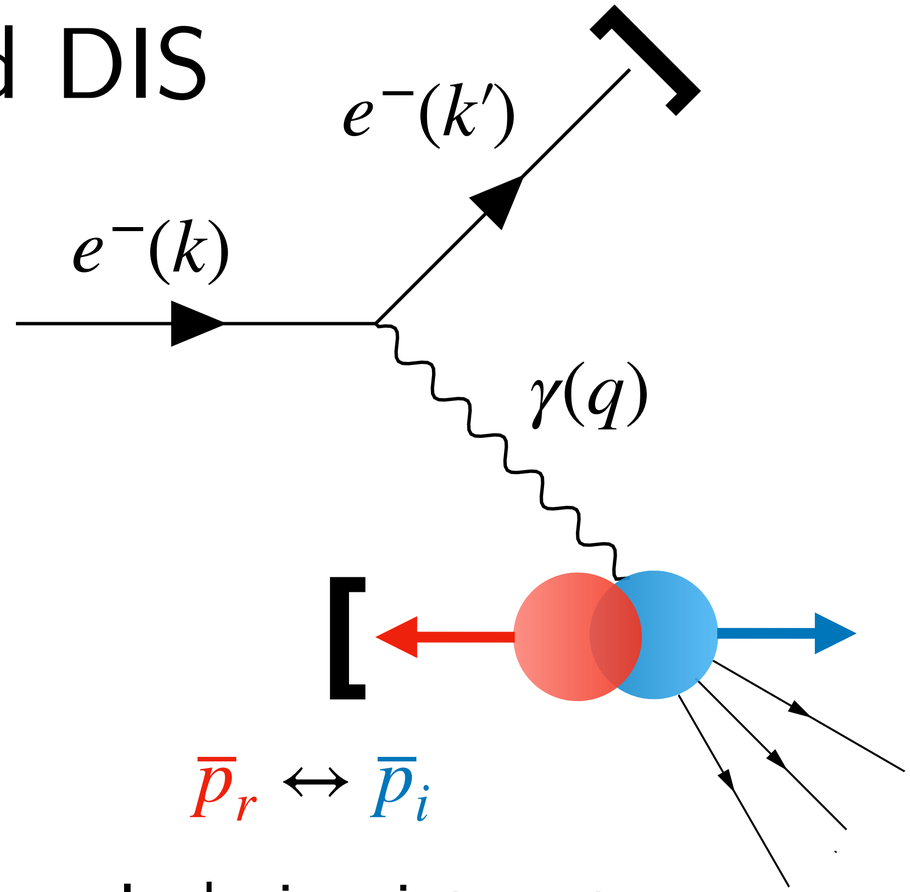
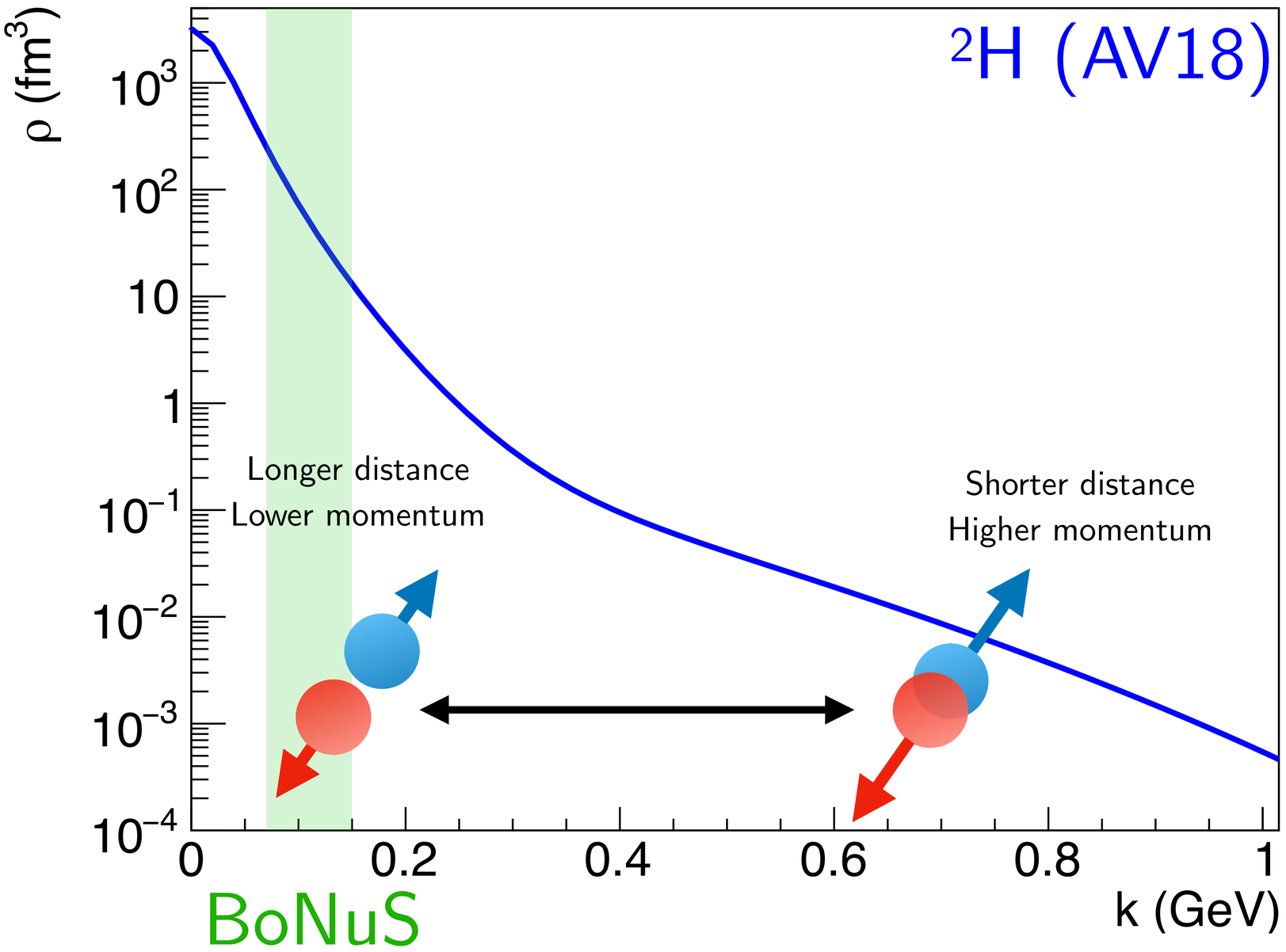
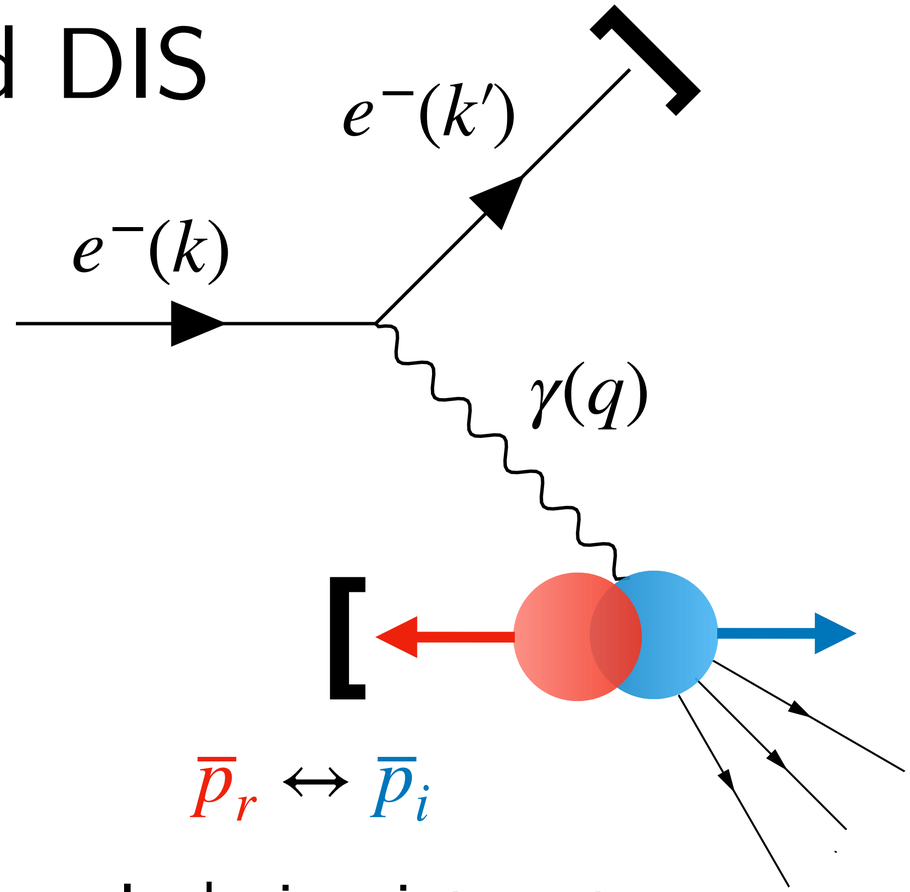




- Inclusive: integrate over all momentum
- Tagged: detect spectator nucleon to reconstruct initial momentum

Test SRC-EMC hypothesis with tagged DIS





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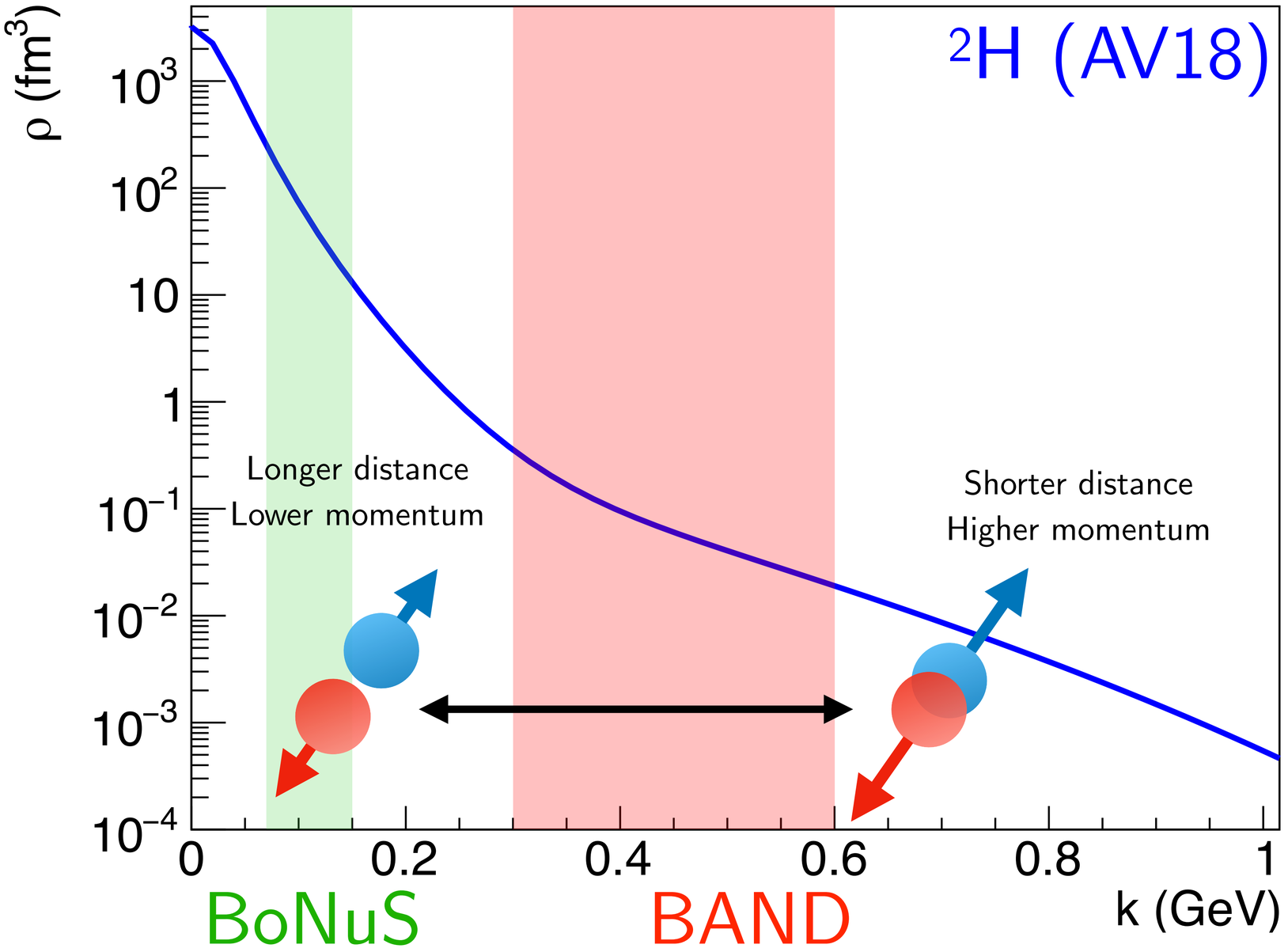
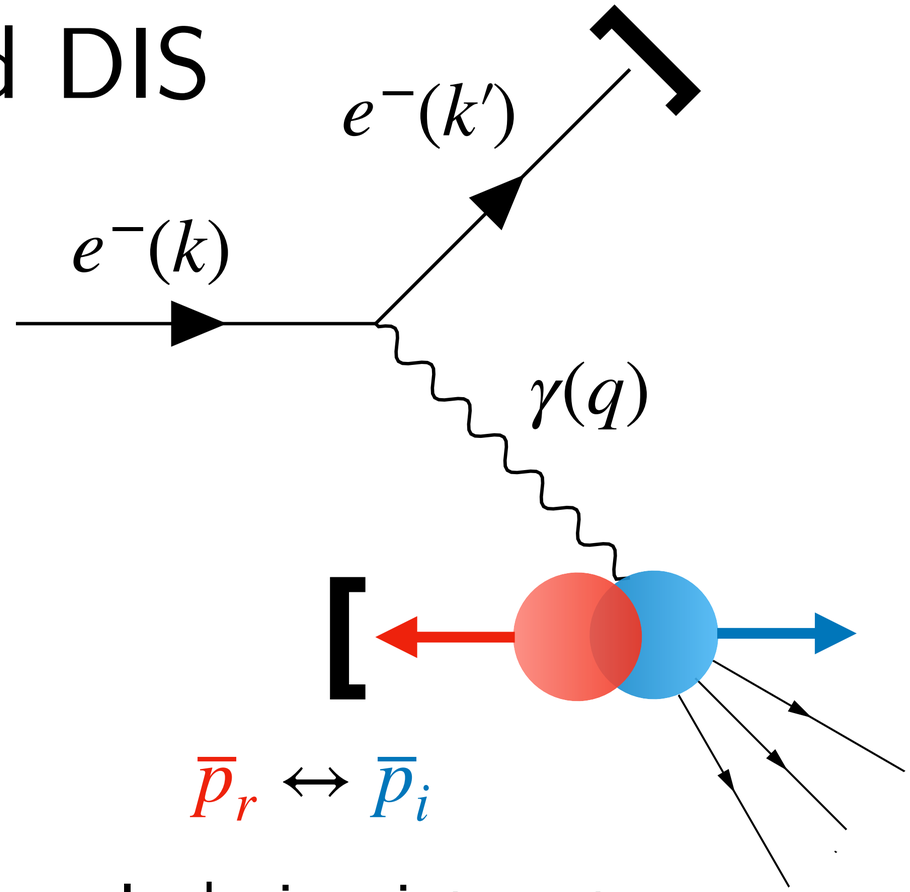
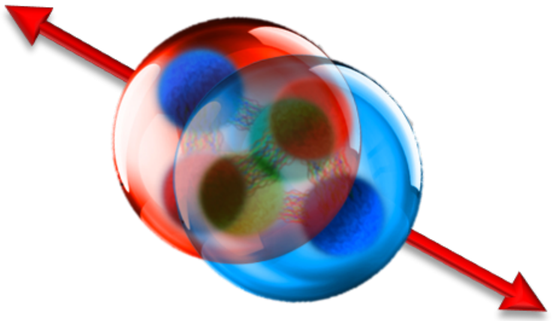




- Inclusive: integrate over all momentum
- Tagged: detect spectator nucleon to reconstruct initial momentum

Deuterium ideal nucleus for tagged DIS

- Know which nucleon was struck (n or p)
- "Simple" two-body system *always correlated*



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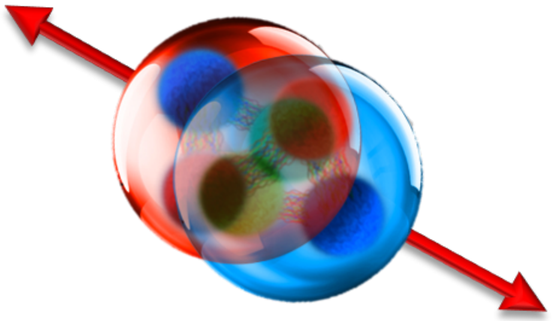
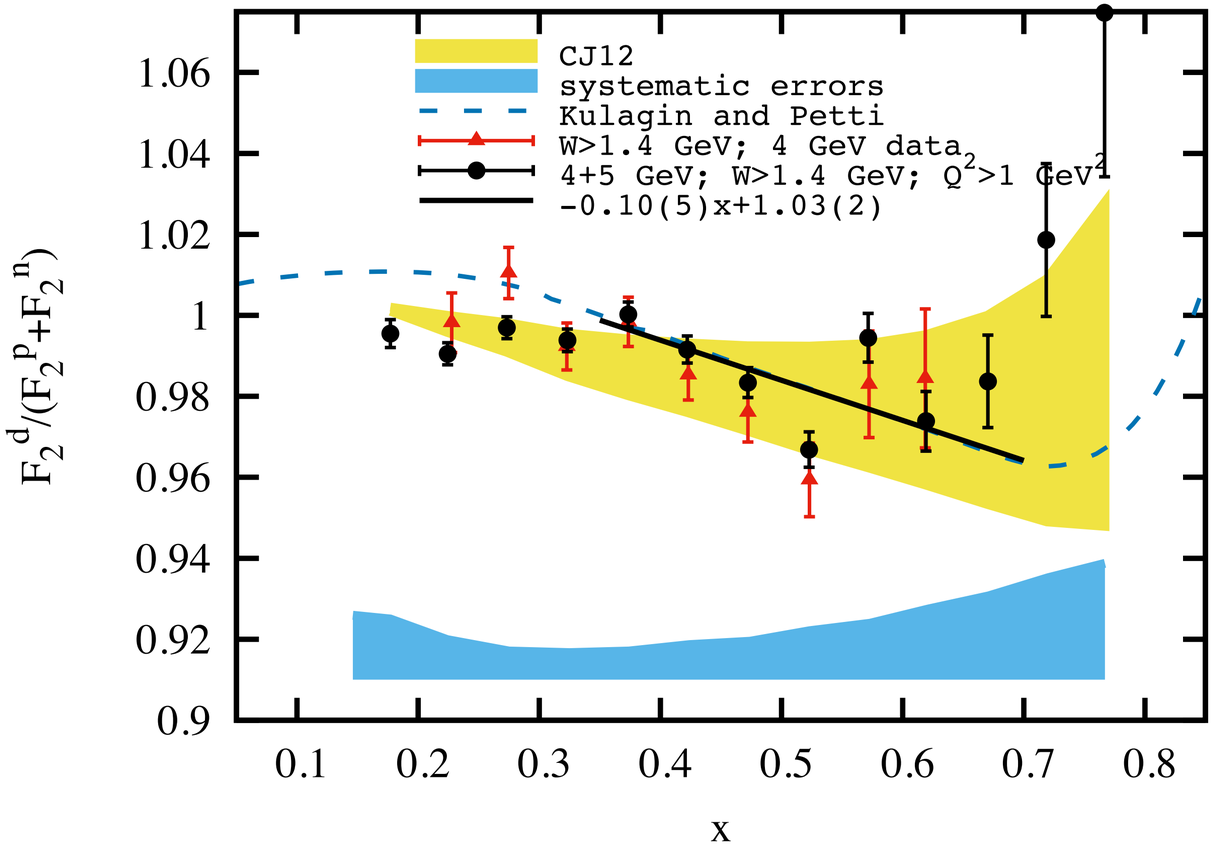
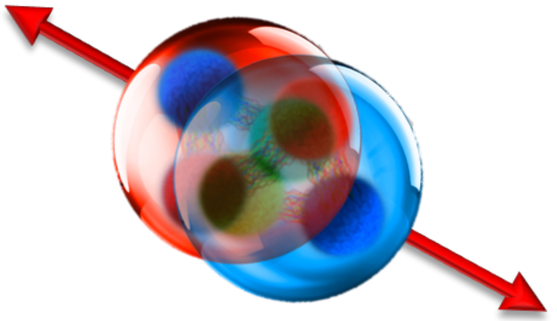


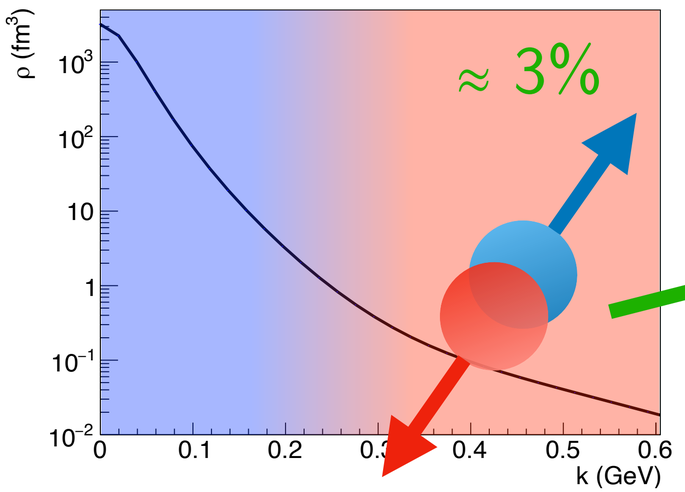
Griffioen *et al.*, PRC (2015)



Deuterium ideal nucleus for tagged DIS

- Know which nucleon was struck (n or p)
- "Simple" two-body system *always correlated*
- But EMC effect is *small*
- *SRC hypothesis predicts large modification of (rare) SRC states!*





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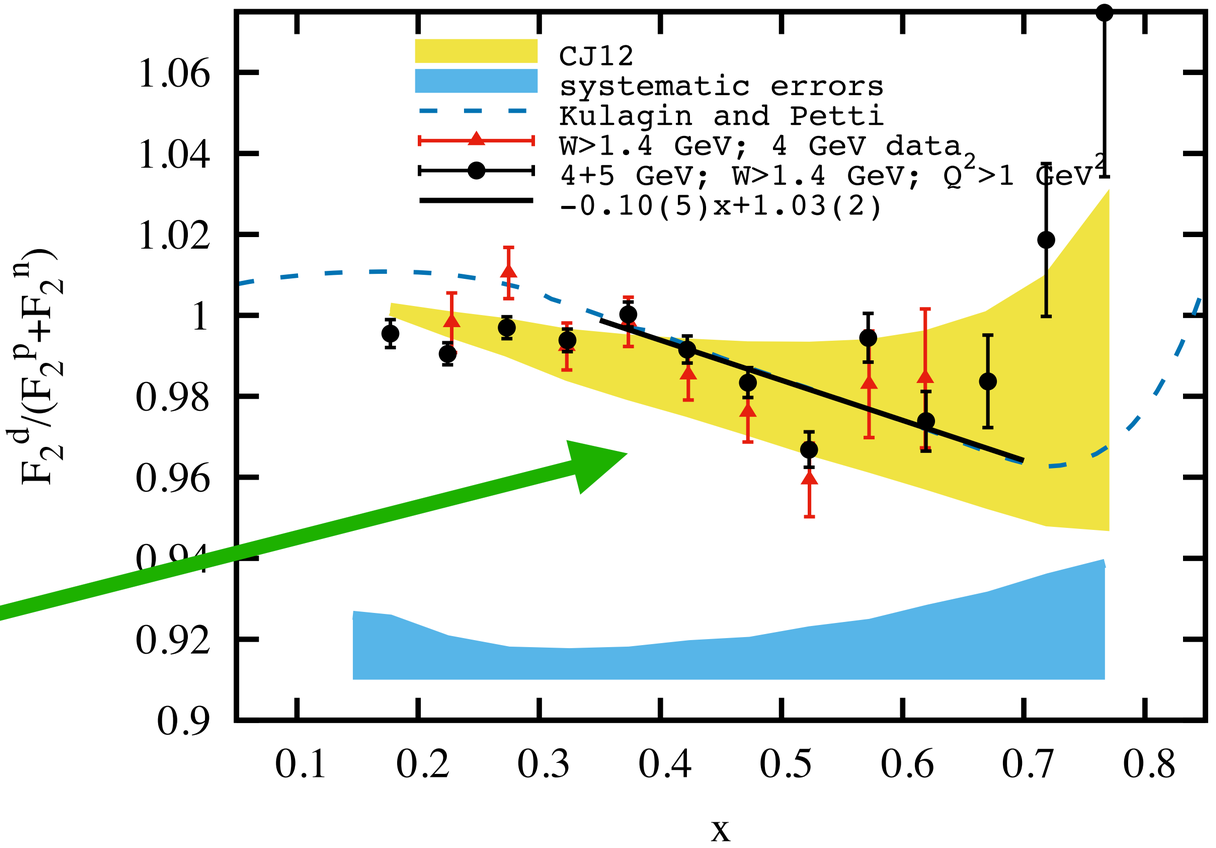


Overview

- Monte Carlo
- Inclusive DIS analysis
- Tagged DIS analysis
- Outstanding issues

BAND technical note is published online

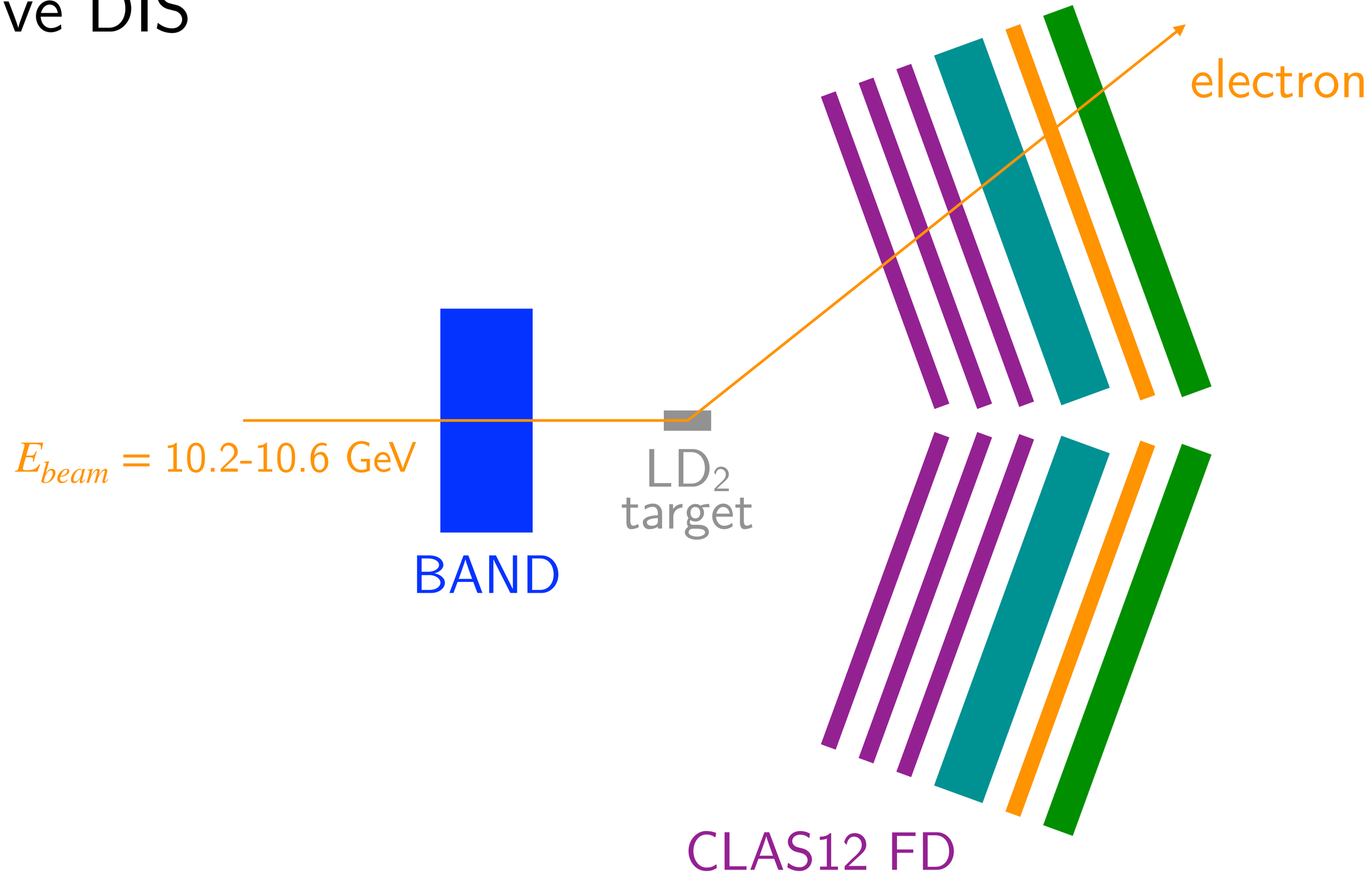
CLAS12 Note 2022-003 covers technical parts of the BAND analysis

- Software & framework
- Calibrations
  - Gain matching
  - Time-walk, time offset, global time calibration
  - Stability of calibrations with run periods
  - Energy calibration
- Good run selection (BAND only)

Monte Carlo

- Event generators
  - PWIA for tagged DIS (using *free* F_2^p and F_2^n)
    1. Model in DIS limit ($Q^2 \to \infty$)
    2. Model with exact expressions (no DIS limit) Strikman & Weiss, PRC 97, 035209 (2018)
    3. Independent generator from W. Cosyn Cosyn & Sargsian, PRC 84, 014601 (2011)
  - Standard inclusive generator (using F_2^d)
  - Various checks performed to ensure reasonable consistency in expected rates between generators
- GEANT4 simulation of detector
  - Standard implementation of CLAS12 in GEMC 4.4.1
  - Implemented geometry for:
    - BAND
    - Upstream material (beam pipes, electronics boxes, etc.)

Inclusive DIS

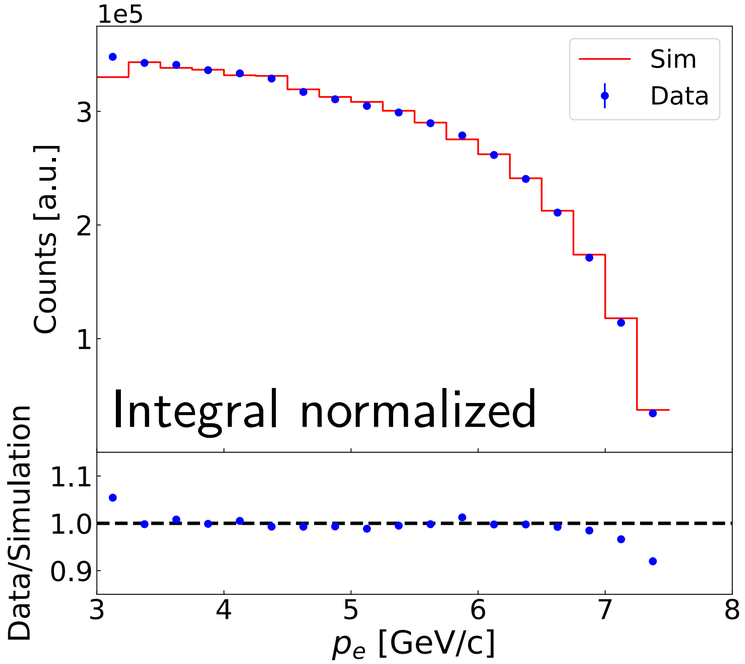


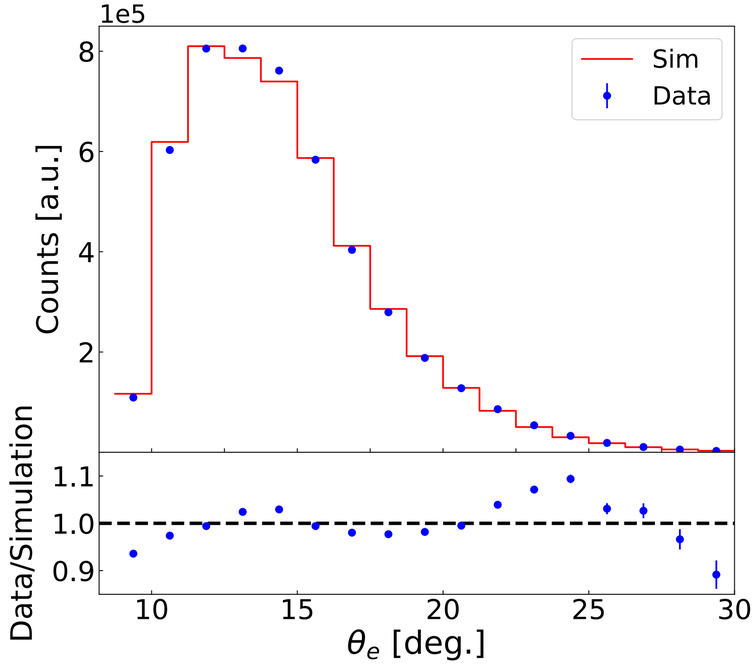
CLAS12 (electron) event selection

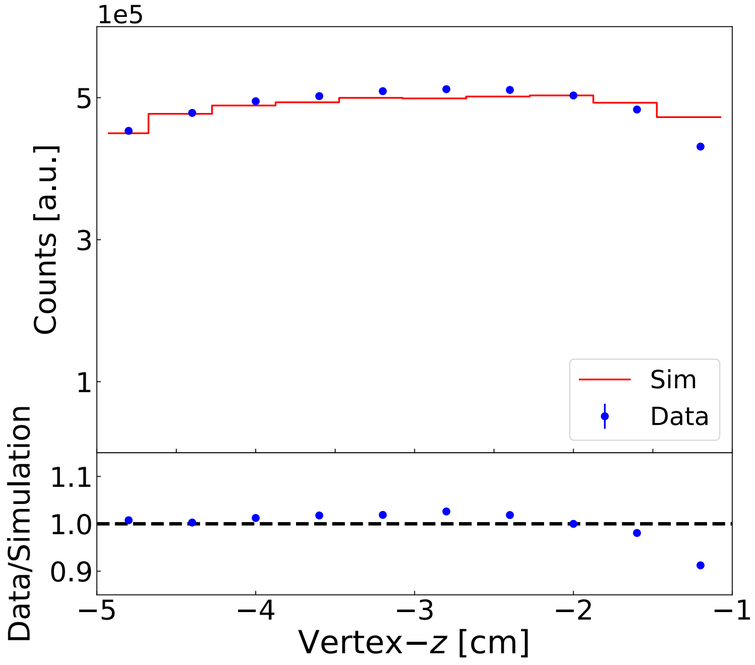
- Electron ID & fiducials
  - Charge & event builder PID
  - 5σ sampling fraction cut on E_{PCAL}, p
  - Additional E/p cut for $p >$ 4.5 GeV
  - DC fiducial cuts
  - ECAL fiducial cuts
  - -5 cm $< z_{vtx} <$ -1 cm
- Additional electron/inclusive DIS cuts
  - $p_e >$ 3 GeV
  - $Q^2 >$ 2 GeV^2.
  - $W^2 >$ 4 GeV^2.

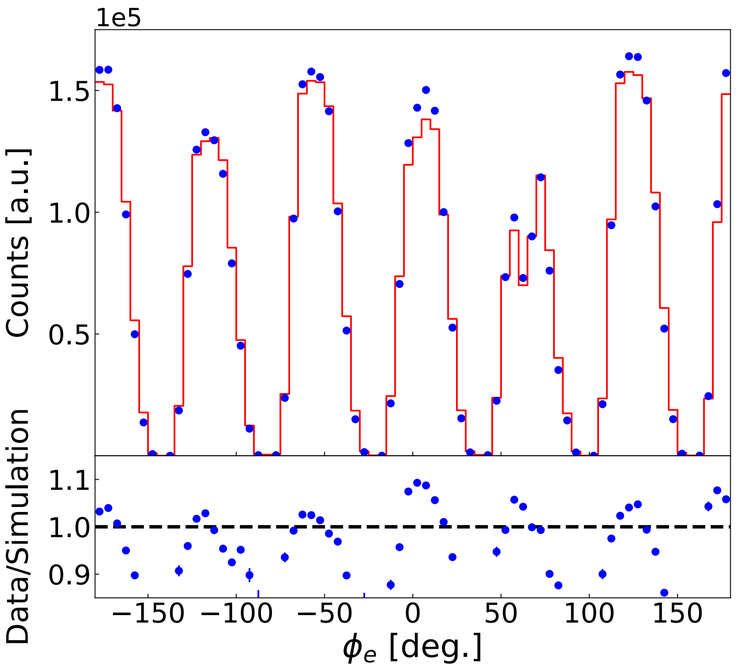
Inclusive analysis (electron quantities)

10% or better agreement in electron quantity distributions

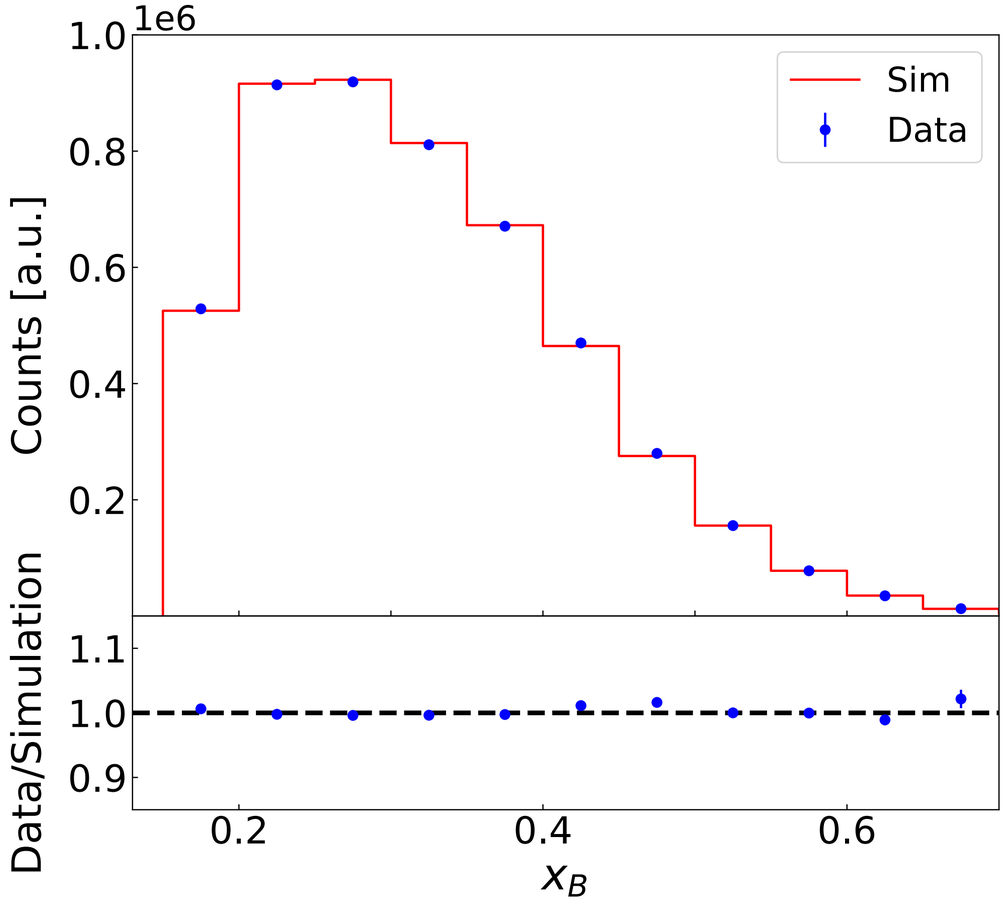


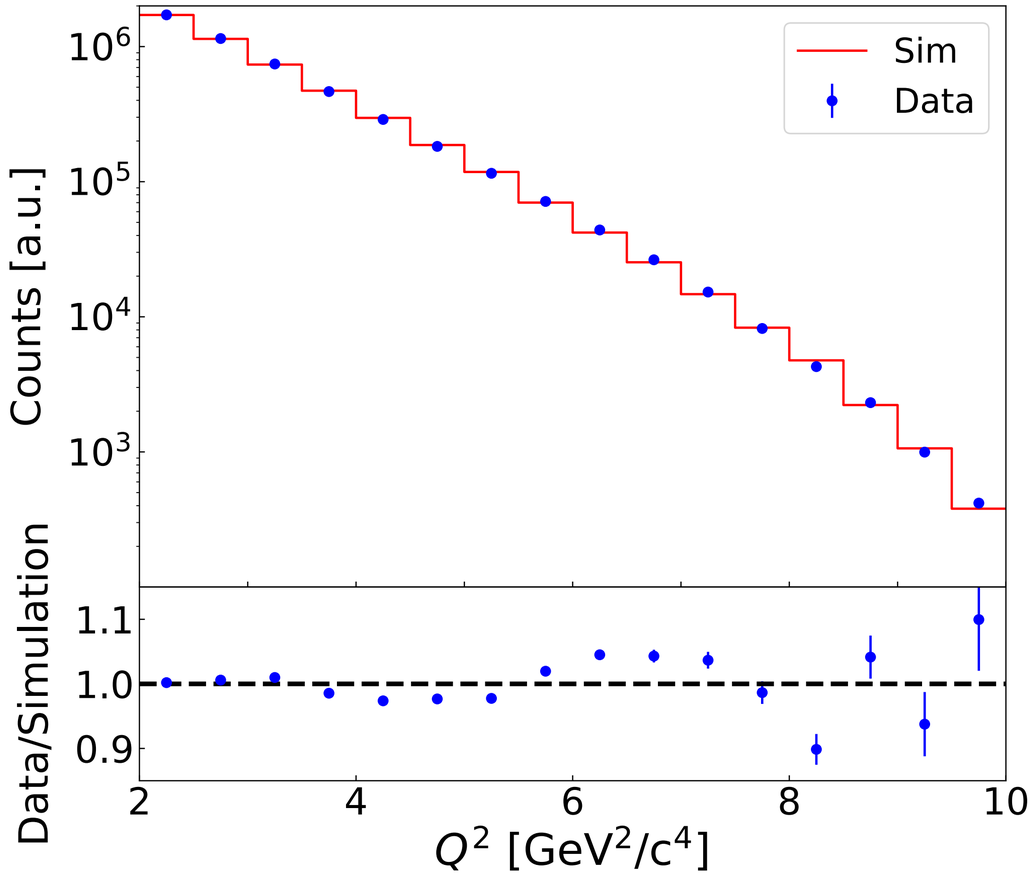






Inclusive analysis (DIS quantities)





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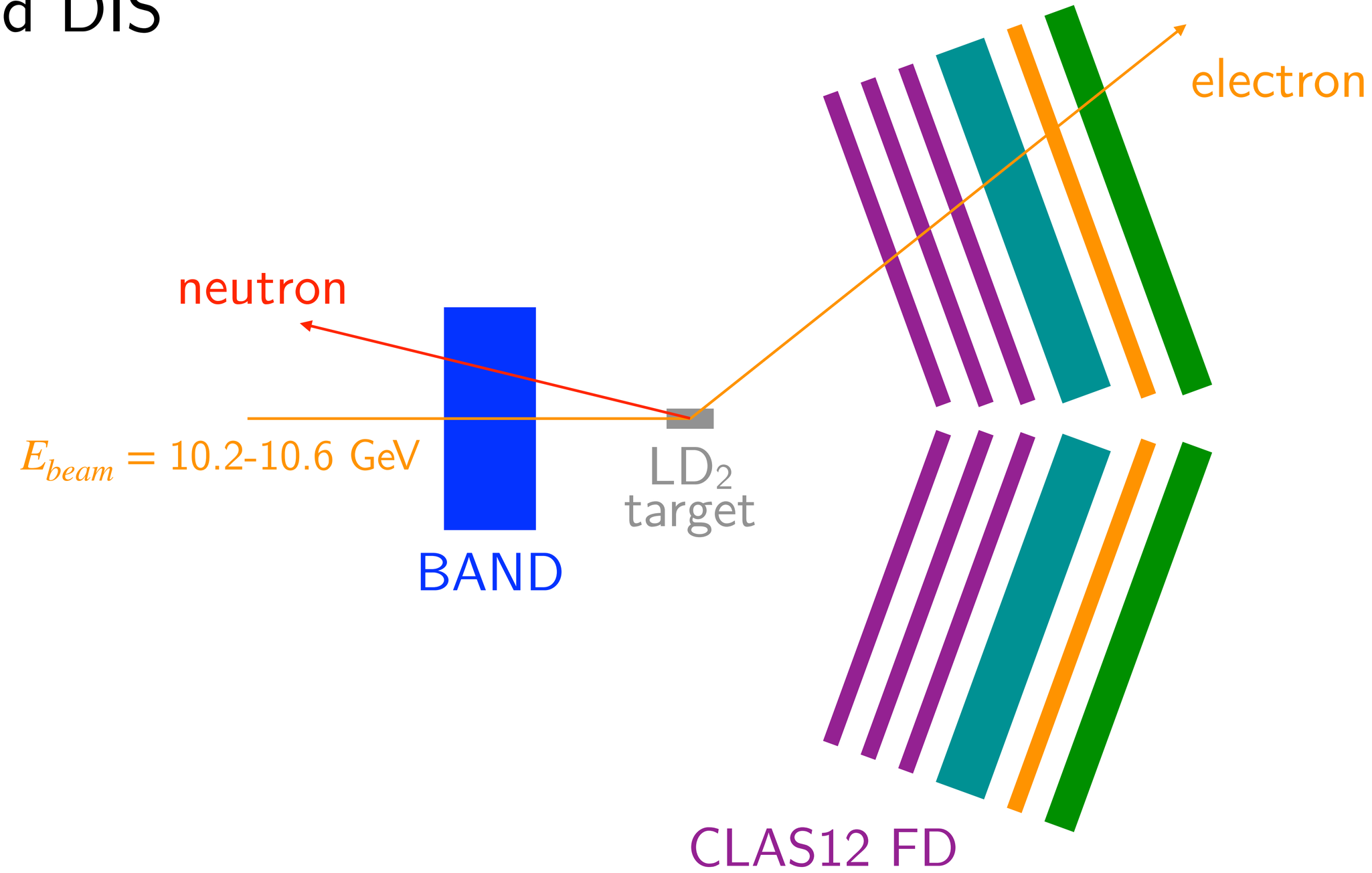
Tagged DIS


electron
neutron
E_{beam} = 10.2-10.6 GeV
LD_2 target
BAND
CLAS12 FD

Tagged double ratio

$$\sigma_{exp}^{Born} = \frac{Y_{exp}}{Y_{sim}} \sigma_{theory}^{Born} \quad \rightarrow \quad \frac{\sigma_{exp}^{Born}}{\sigma_{theory}^{Born}} = \frac{Y_{exp}}{Y_{sim}}$$

$$R_{tag} = \frac{Y_{exp}(x')/Y_{exp}(x' = x'_0)}{Y_{sim}(x')/Y_{sim}(x' = x'_0)} = \frac{\sigma_{exp}(x')/\sigma_{exp}(x' = x'_0)}{\sigma_{theory}(x')/\sigma_{theory}(x' = x'_0)}$$

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- Exact cancellation of luminosity (separately for data & MC)
- Large cancellation of BAND neutron detection efficiency
- Mitigation of FSI

Tagged double ratio

$$\sigma_{exp}^{Born} = \frac{Y_{exp}}{Y_{sim}} \sigma_{theory}^{Born} \quad \rightarrow \quad \frac{\sigma_{exp}^{Born}}{\sigma_{theory}^{Born}} = \frac{Y_{exp}}{Y_{sim}}$$

$$R_{tag} = \frac{Y_{exp}(x')/Y_{exp}(x' = x_0')}{Y_{sim}(x')/Y_{sim}(x' = x_0')} = \frac{\sigma_{exp}(x')/\sigma_{exp}(x' = x_0')}{\sigma_{theory}(x')/\sigma_{theory}(x' = x_0')}$$

- Choose to normalize to $x_0' = 0.3$
- Under traditional assumptions, $\sigma_A/\sigma_B = F_2^A/F_2^B$

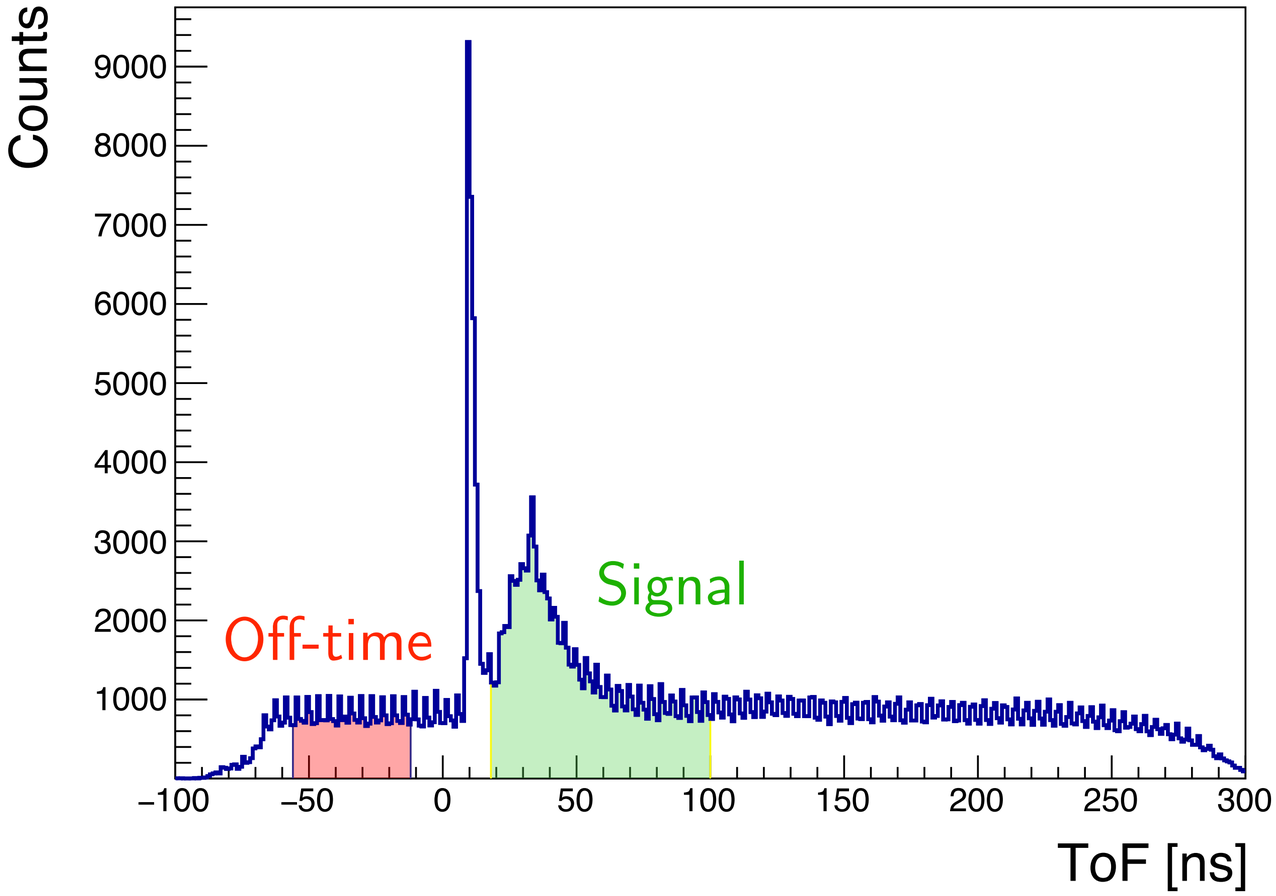
$$R_{tag} \propto \frac{F_2^* \left(Q^2, p_T, \alpha_S, x'\right) / F_2 \left(Q^2, p_T, \alpha_S, x'\right)}{F_2^* \left(Q^2, p_T, \alpha_S, x' = x_0\right) / F_2 \left(Q^2, p_T, \alpha_S, x' = x_0\right)}$$

BAND (neutron) event selection

- Neutron candidate ID & fiducials
  - Charged track veto algorithm applied to events with 2+ hits with $E_{dep} > 2$ MeVee
    - Kills <10% of events...majority have single BAND hit
  - Fiducial cut on BAND edges/select bars
  - TOF cut applied *after* background subtraction

- Additional neutron/tagged DIS cuts:
  - $E_{dep} > 10$ MeVee
  - $p_n > 0.25$ GeV
  - $\theta_n < 168.5^{\circ}$
  - $W' > 1.8$ GeV
  - $\alpha_s > 1.2$
  - $\cos\theta_{nq} <$ -0.8

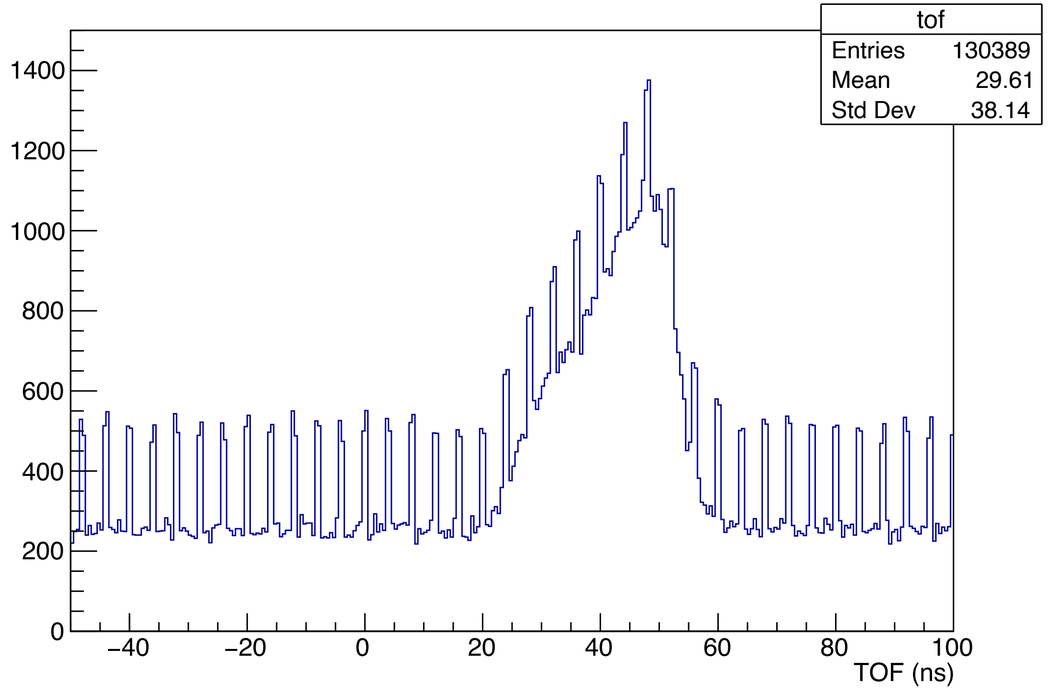
BAND background subtraction

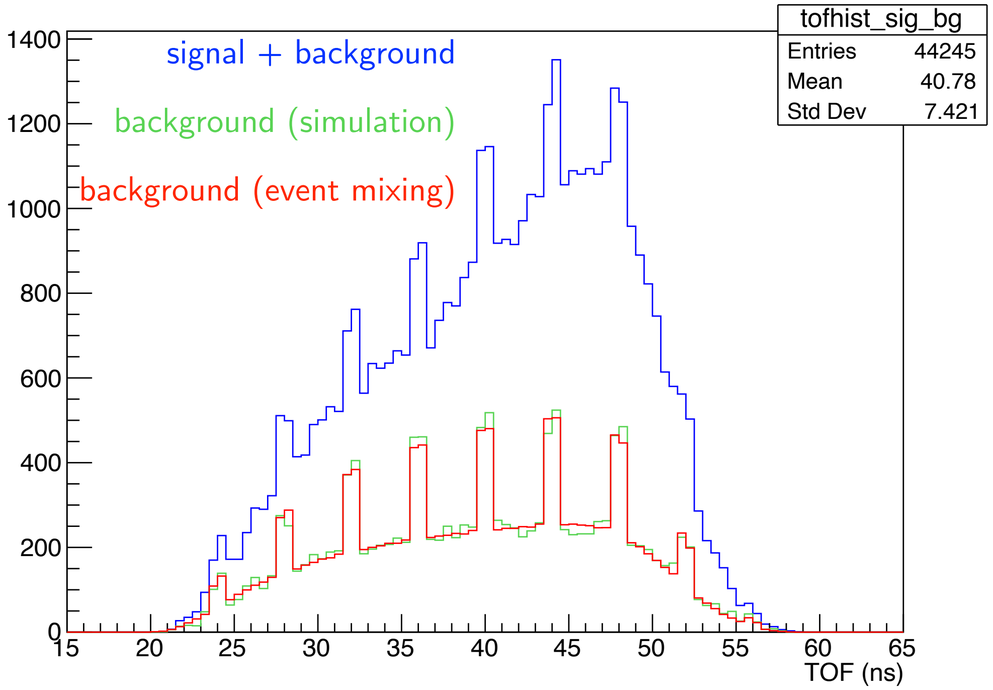


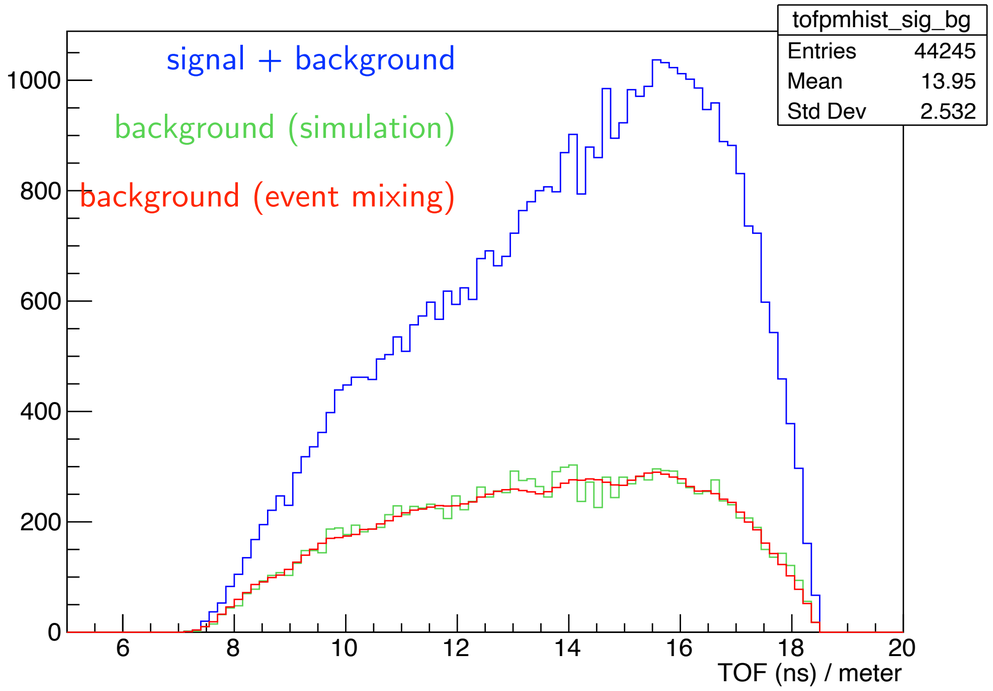
- Event-mix off-time neutrons with inclusive electrons
- Account for 4.008 beam bunch structure
- Normalize event-mixed sample to number of off-time background events

BAND event mixing validation

Simulated signal + background events in GEMC

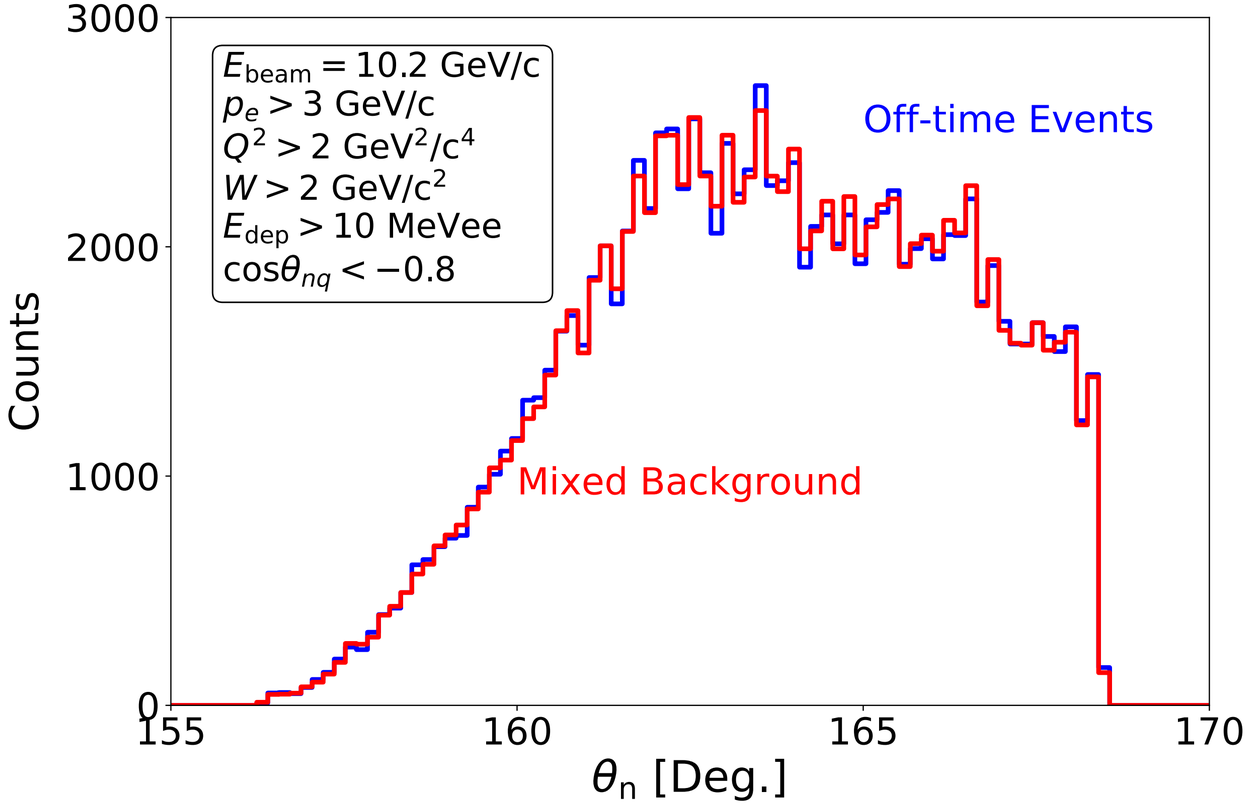


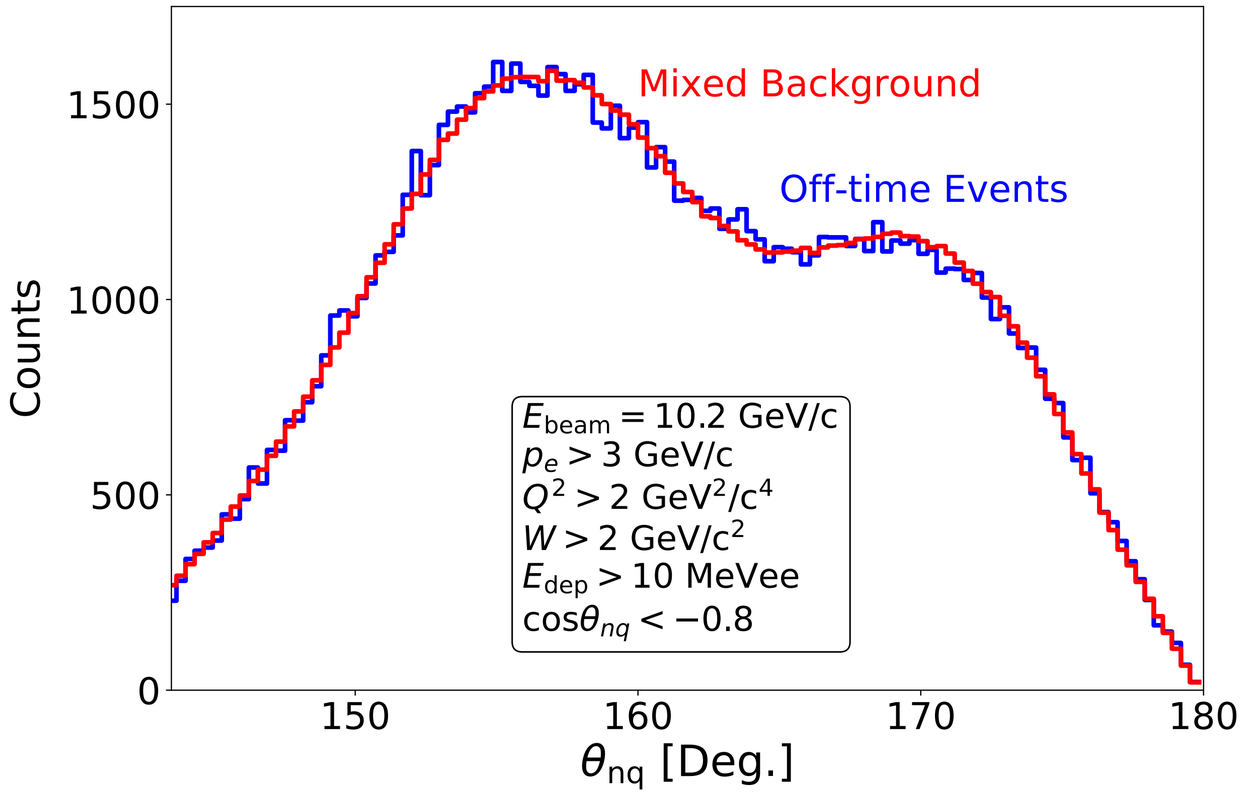




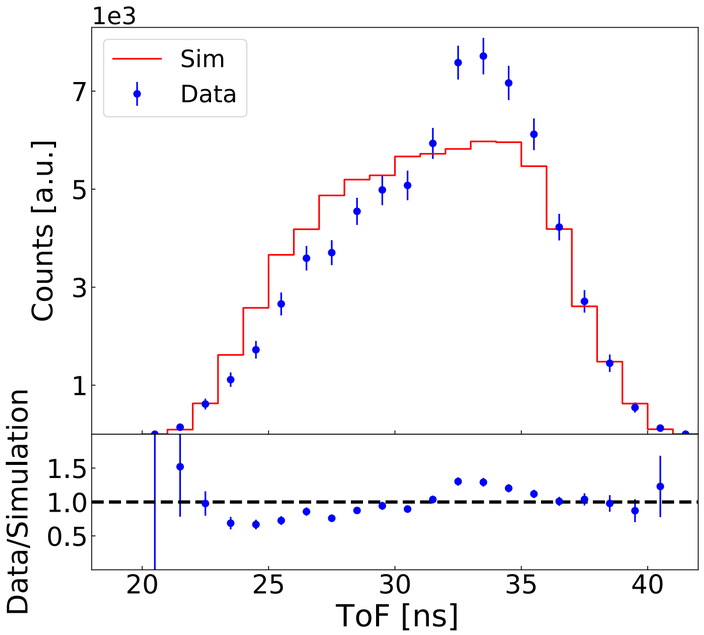
BAND event mixing validation

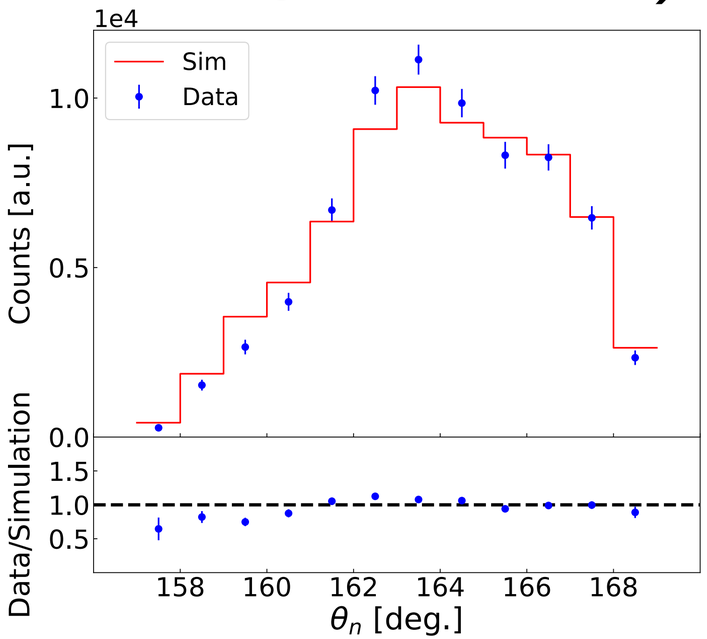
Direct comparison of variables
not sensitive to TOF

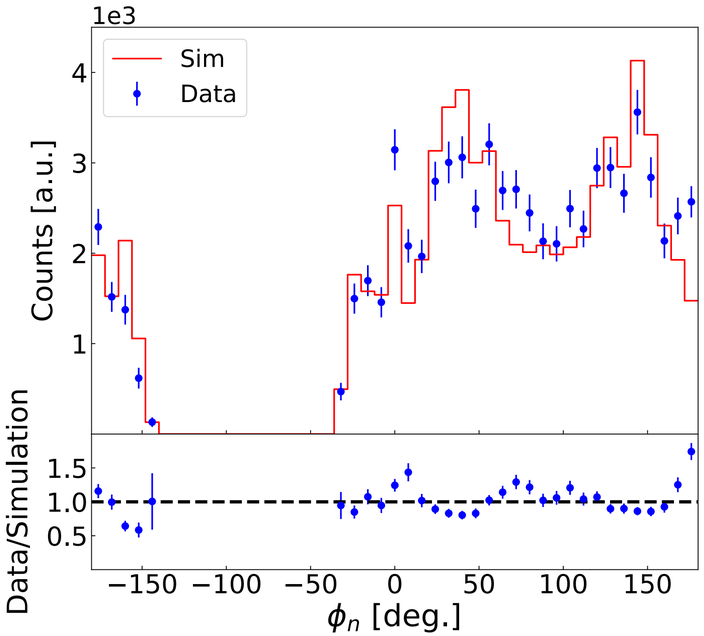


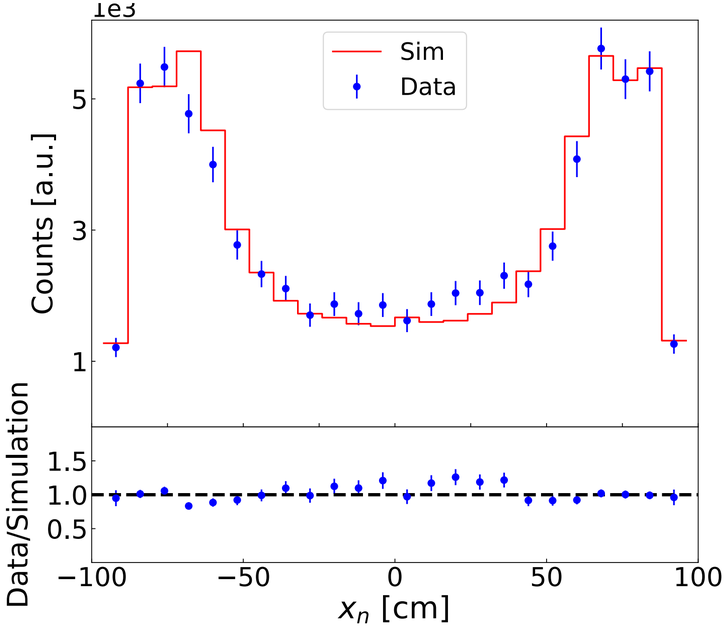


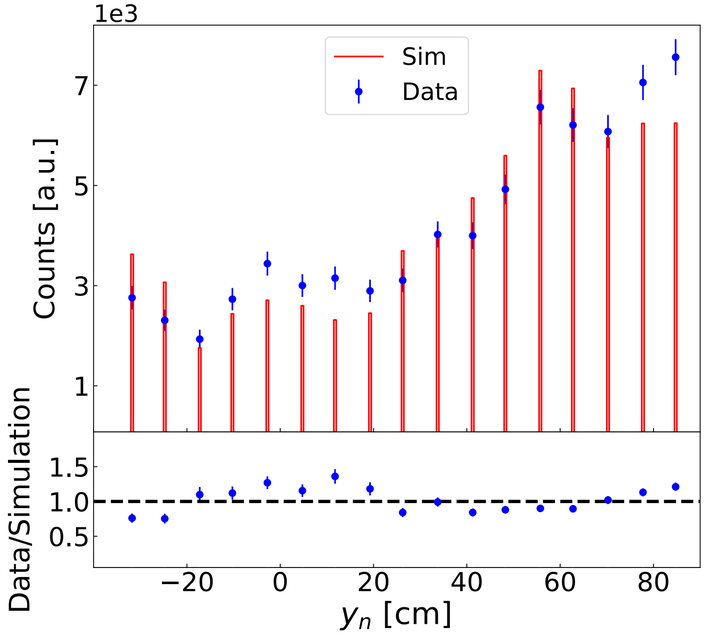
Tagged analysis (neutron quantities)

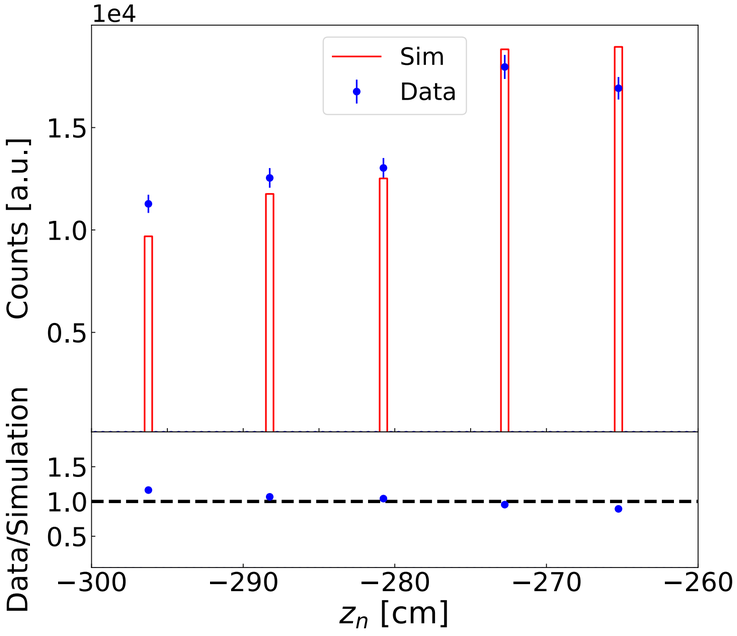




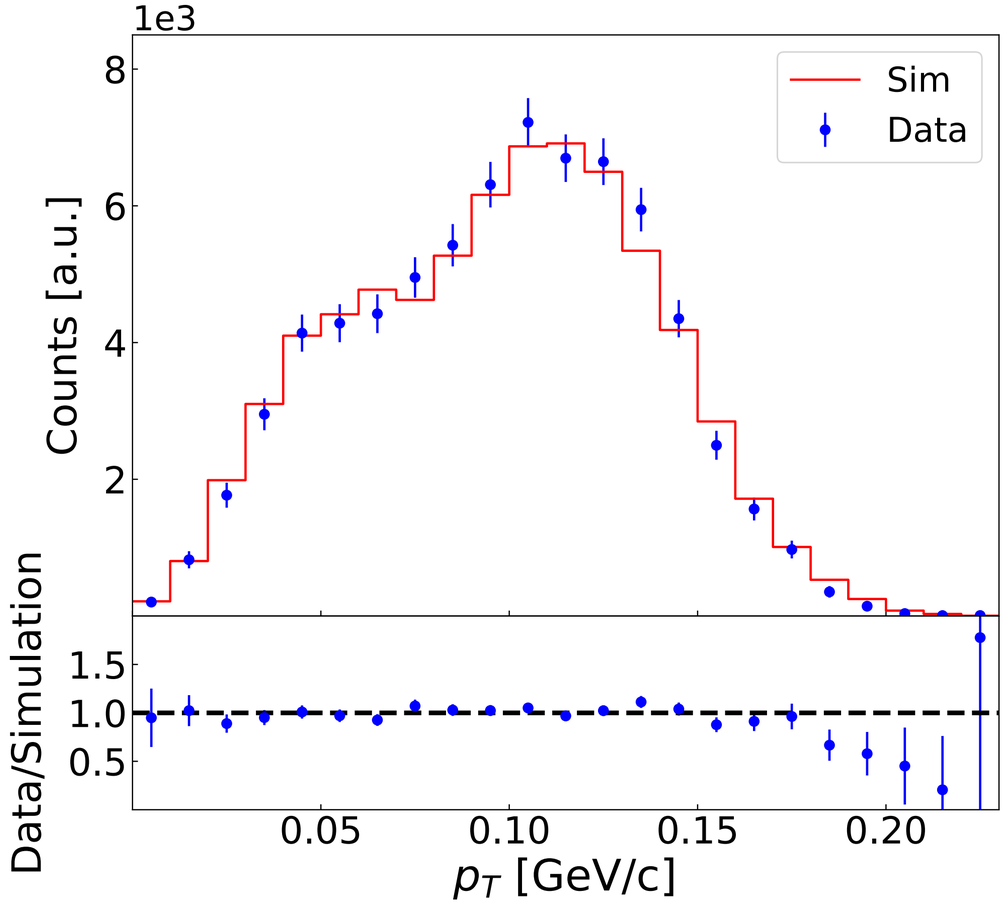


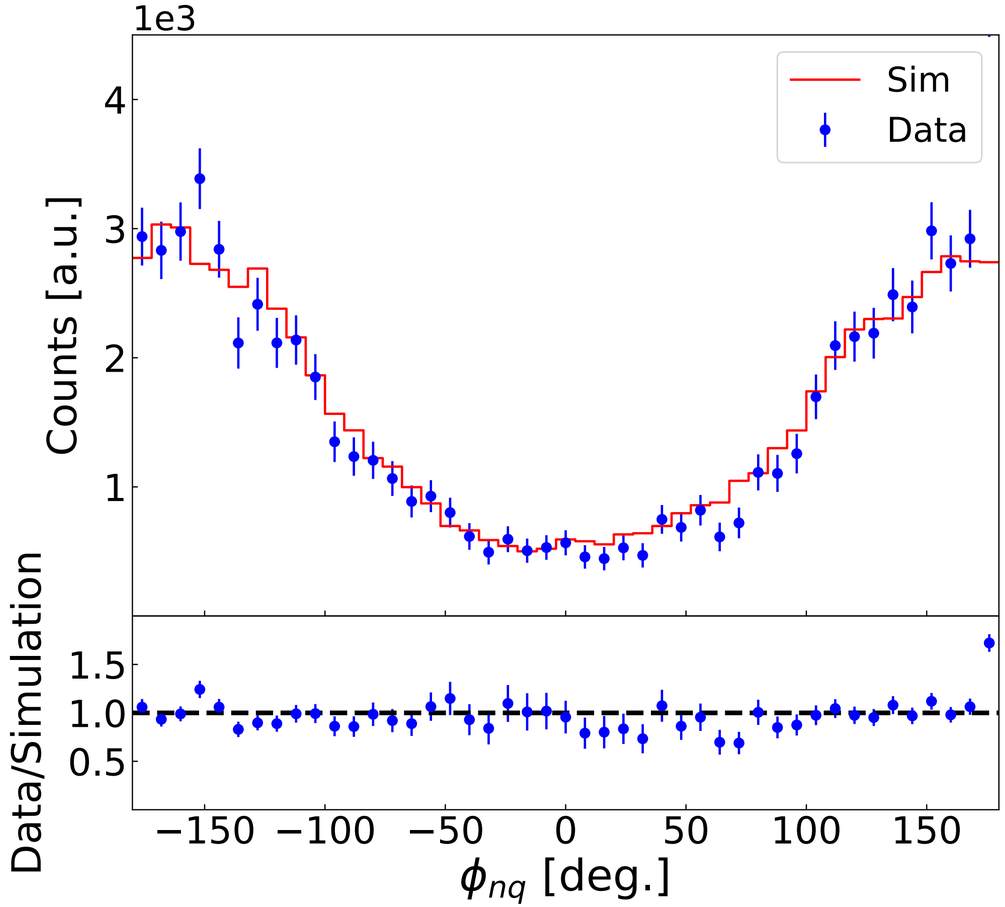




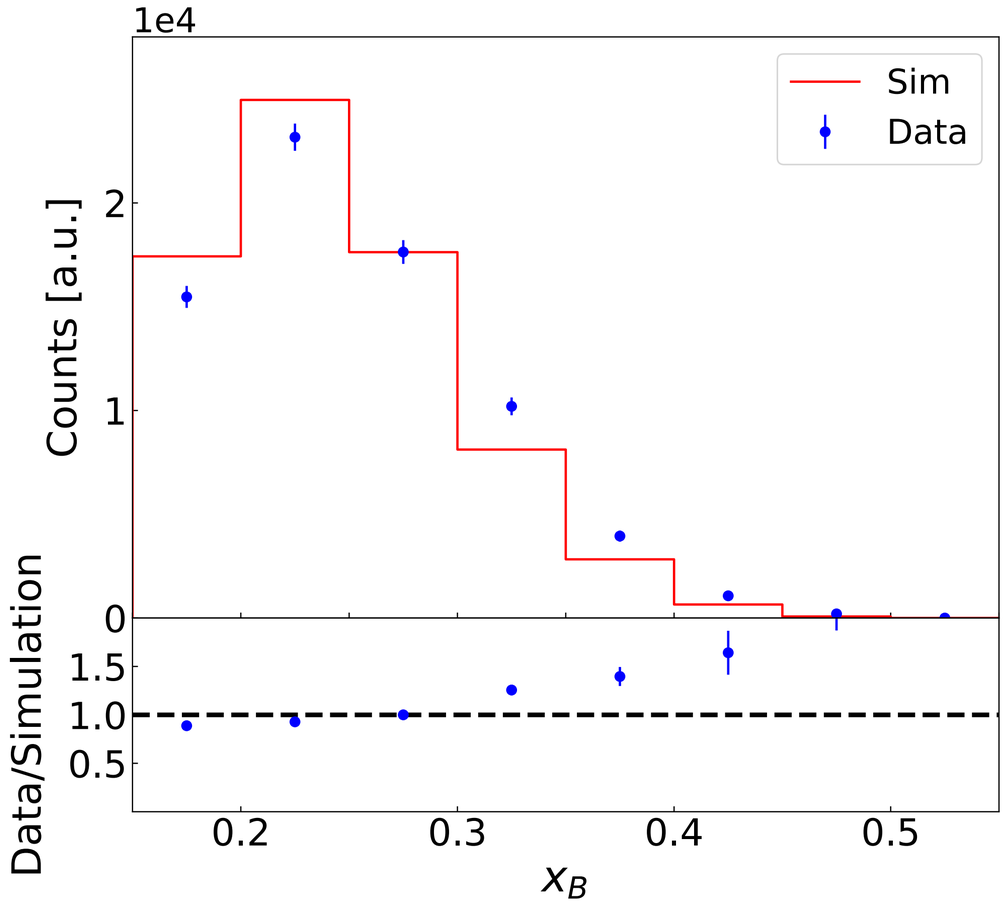


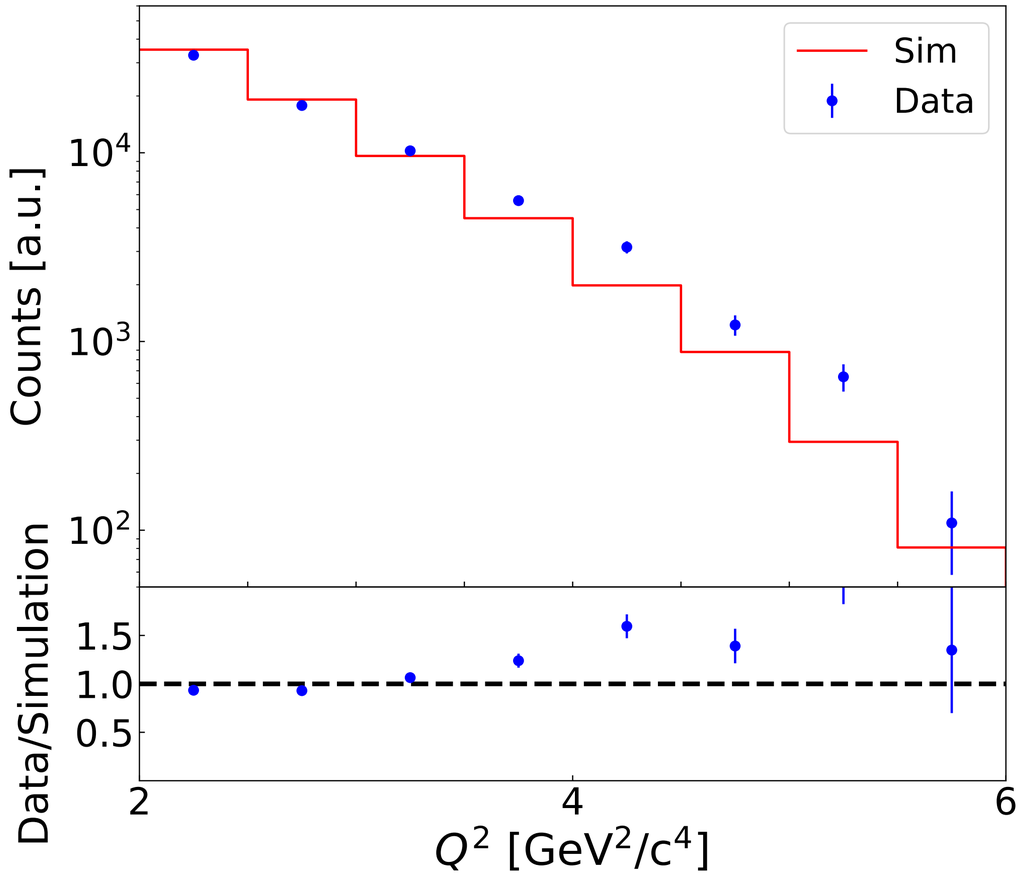
Tagged analysis
(electron + neutron quantities)





Tagged analysis (DIS quantities)





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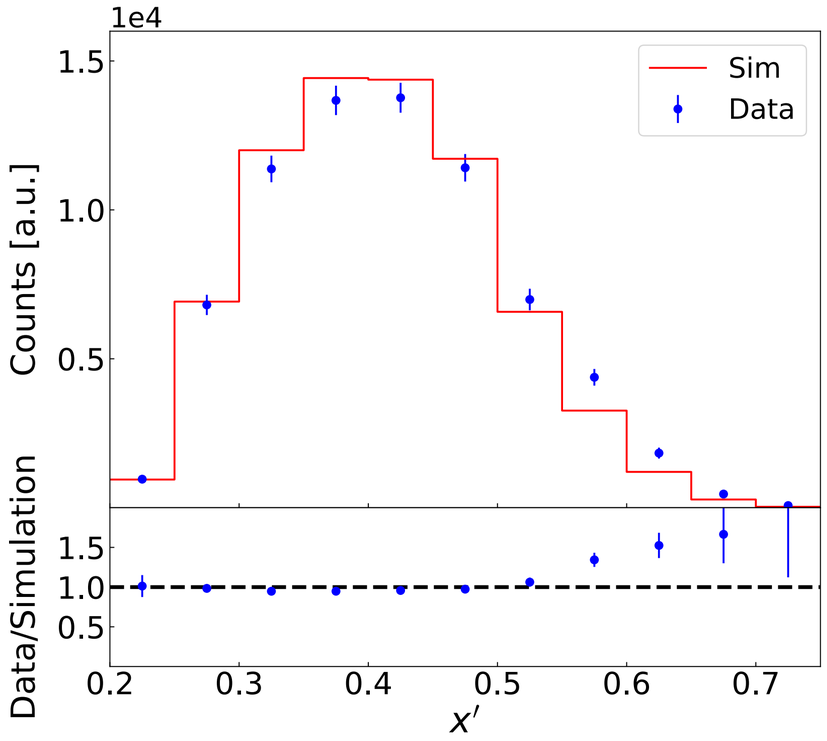
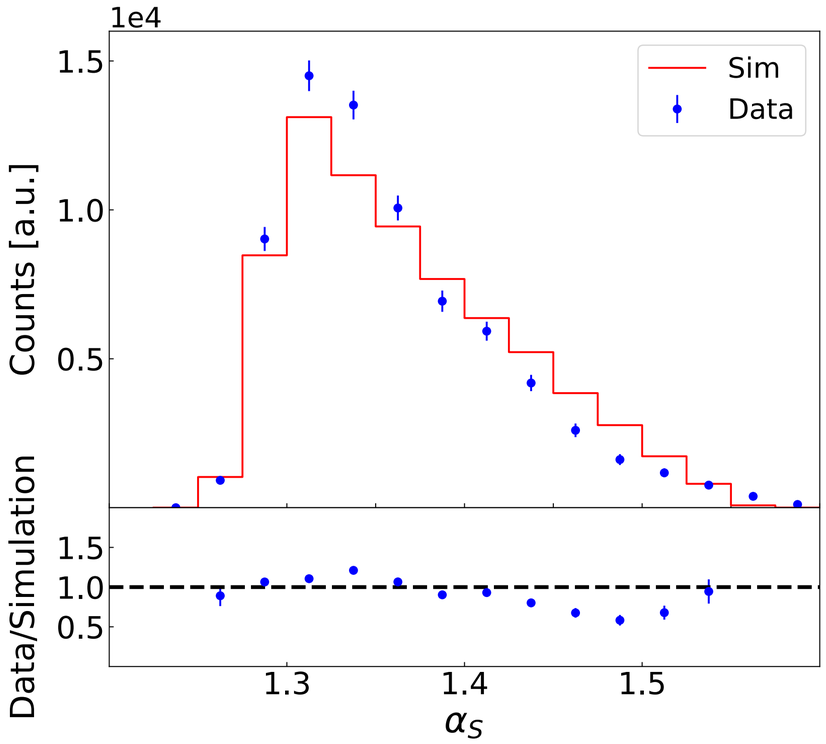
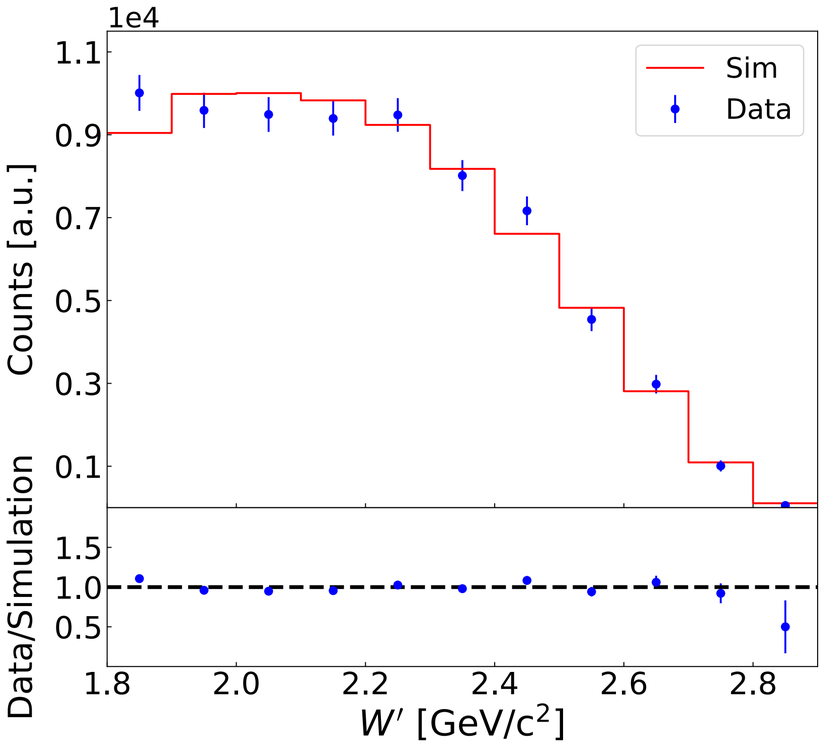
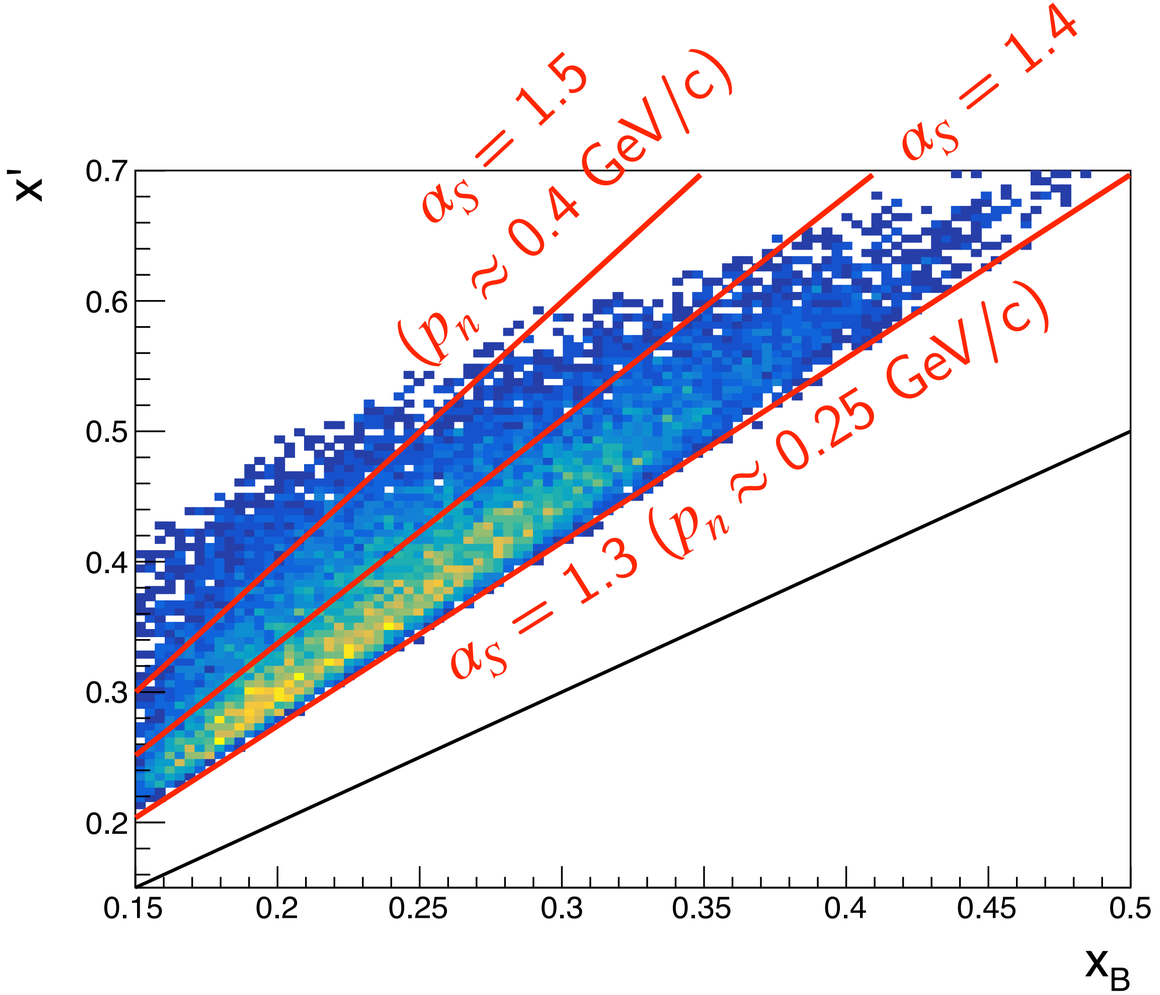
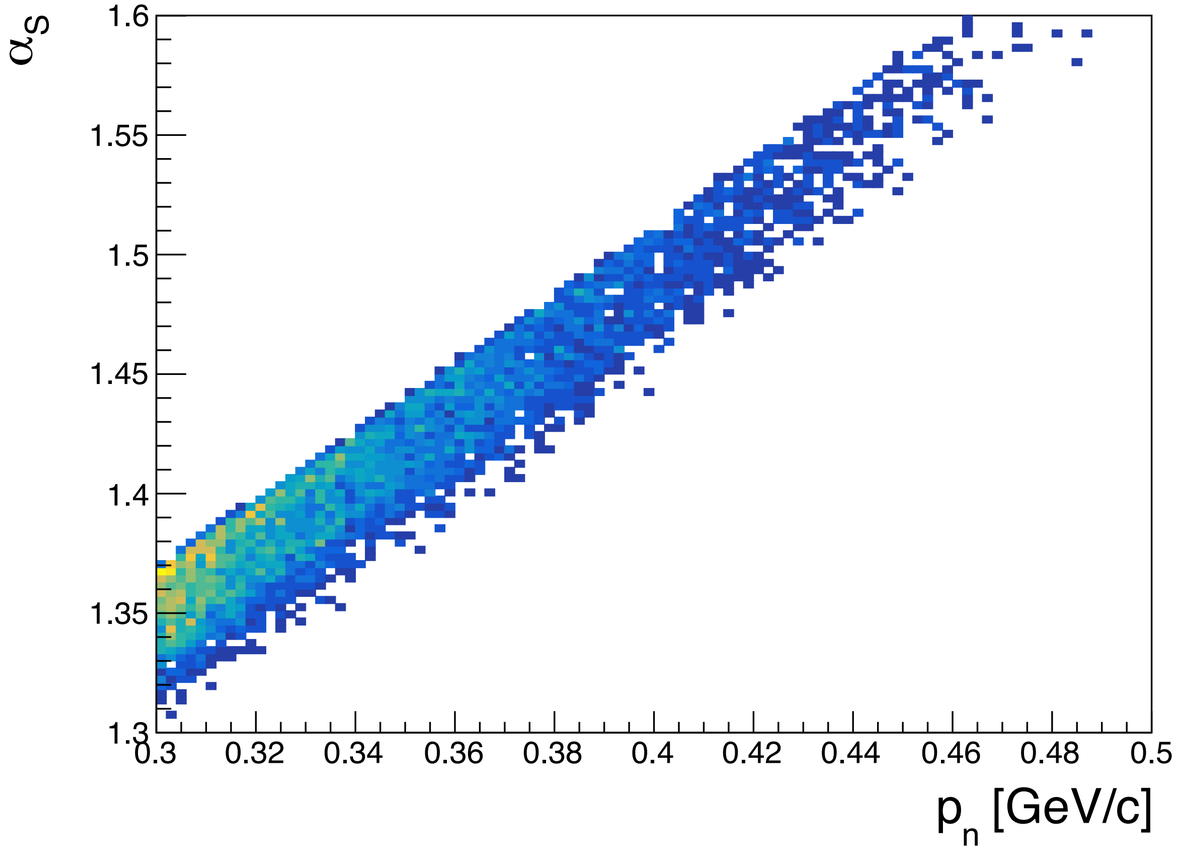






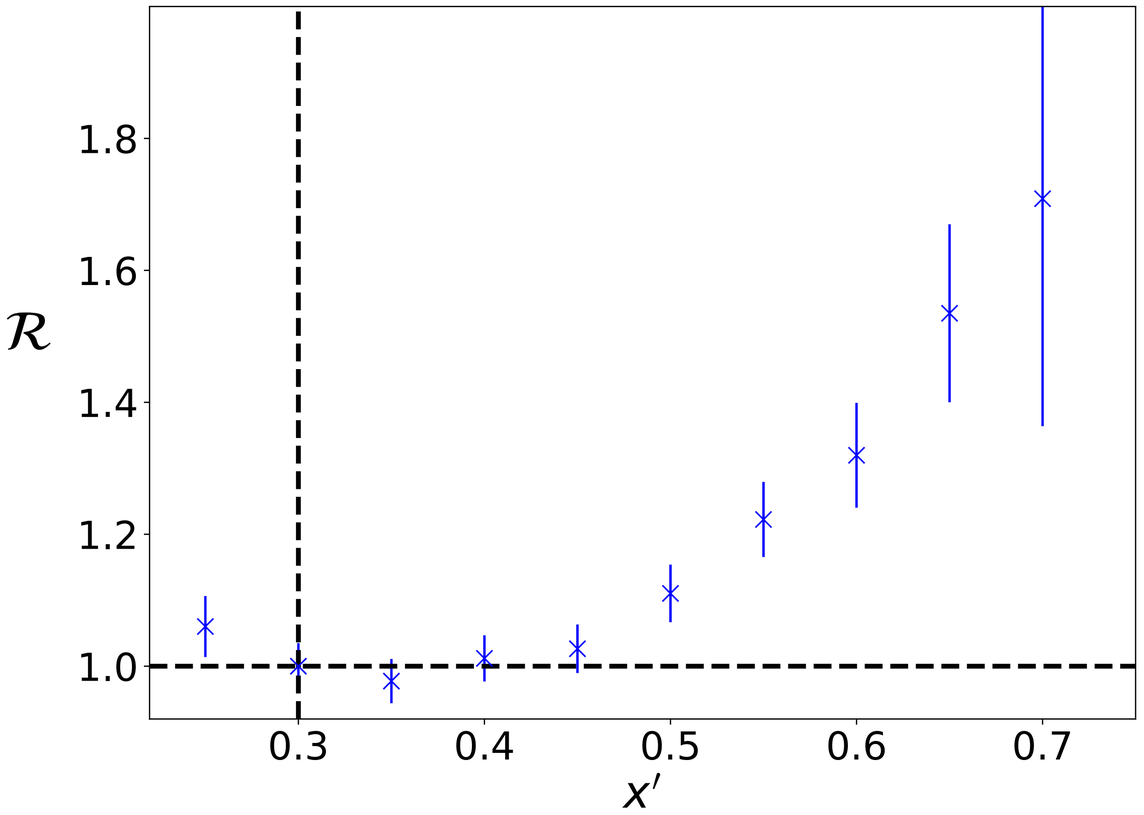
Tagged kinematics



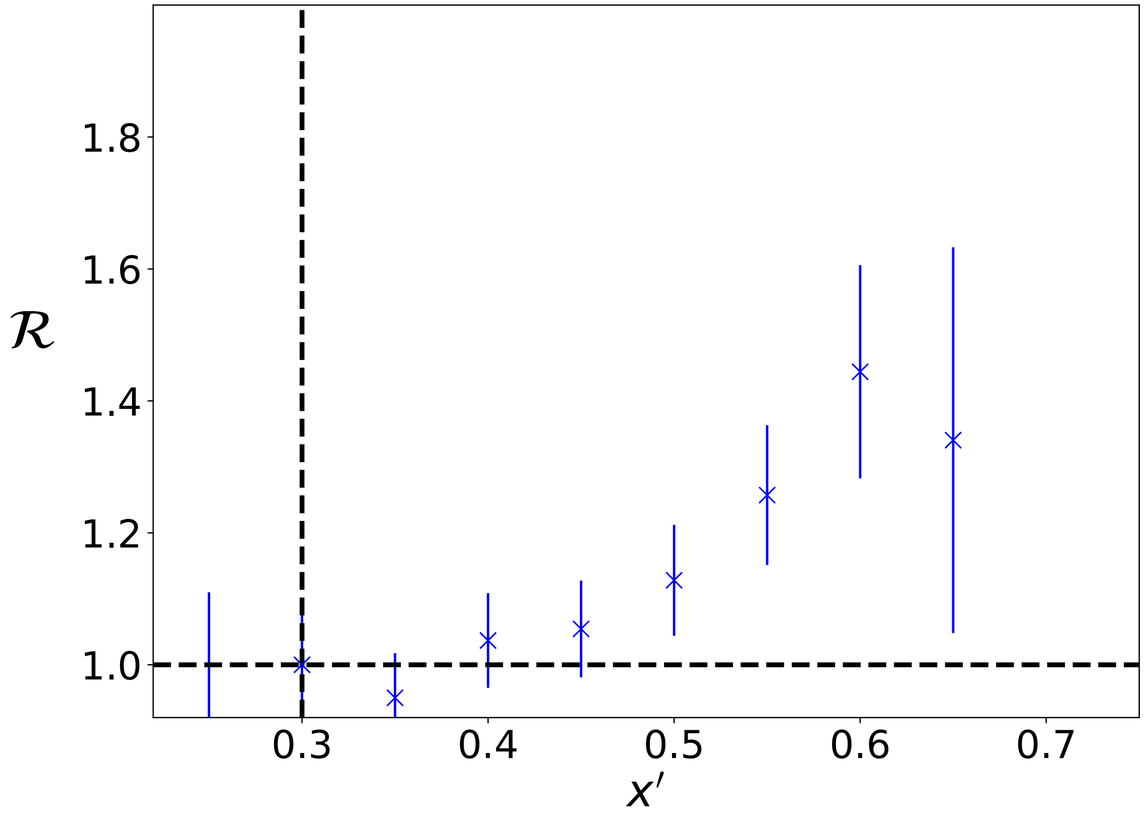


Tagged double ratio

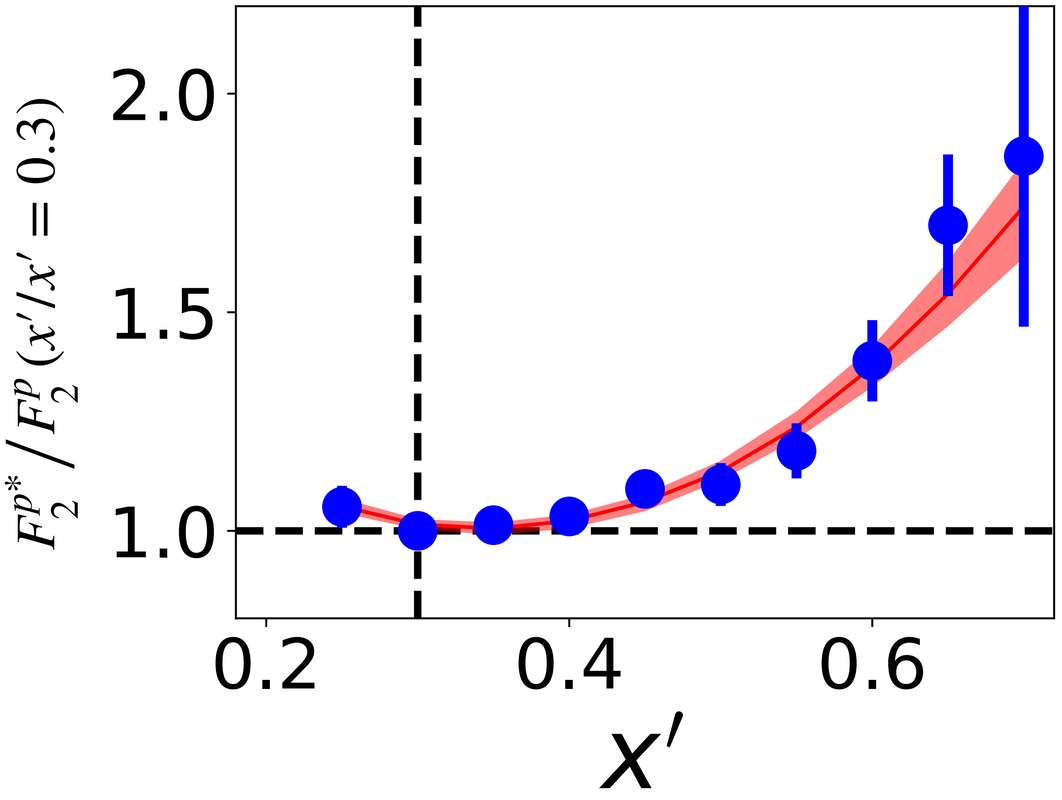
$1.3 < \alpha_s < 1.4$

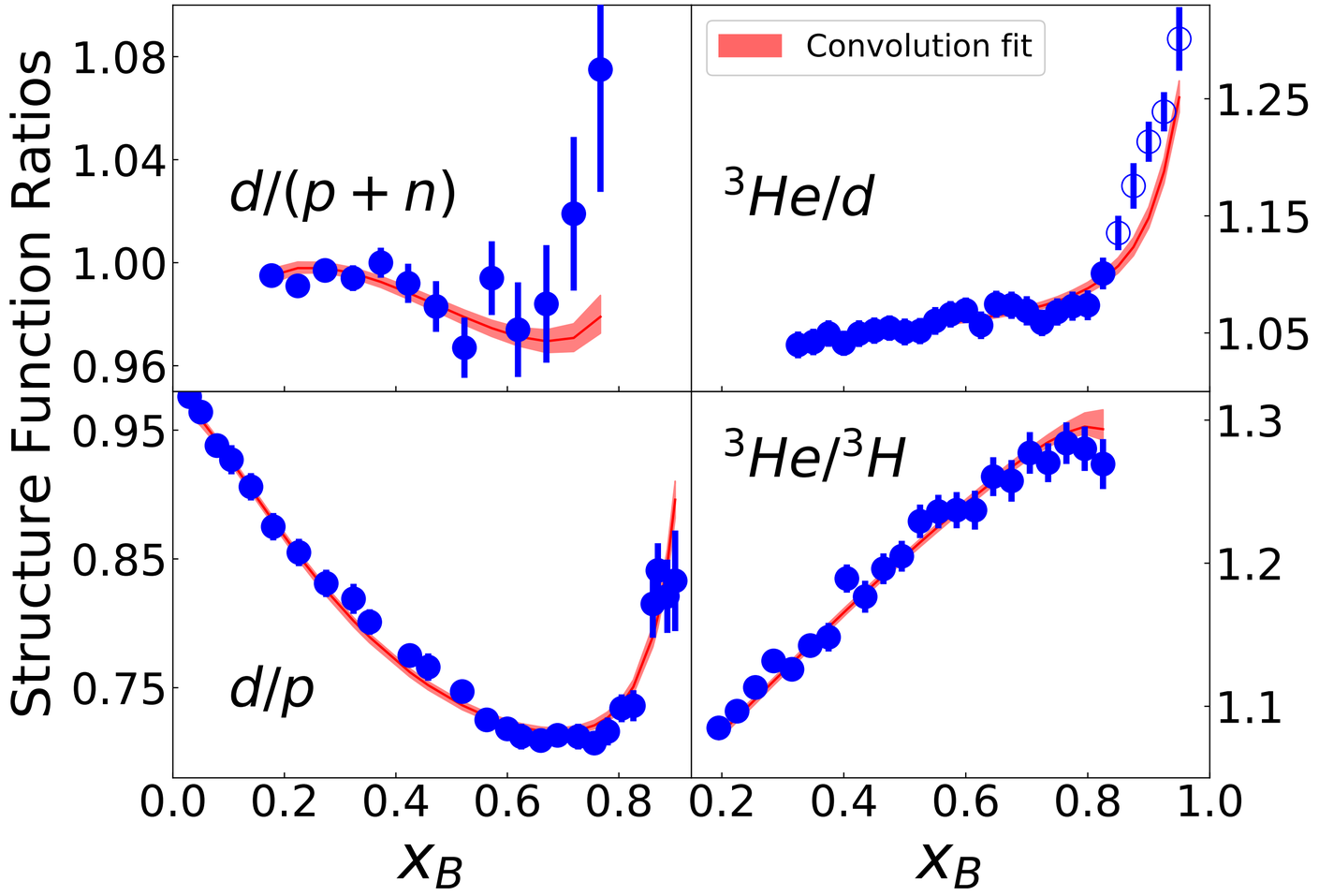


$1.4 < \alpha_s < 1.5$

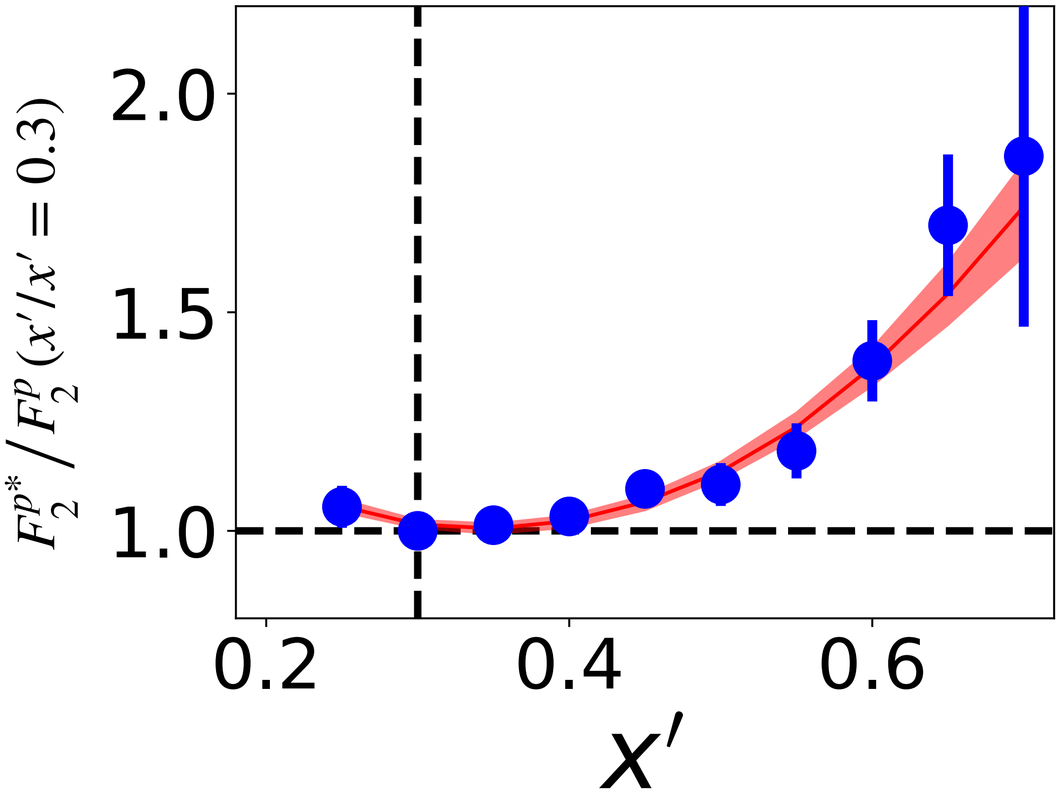


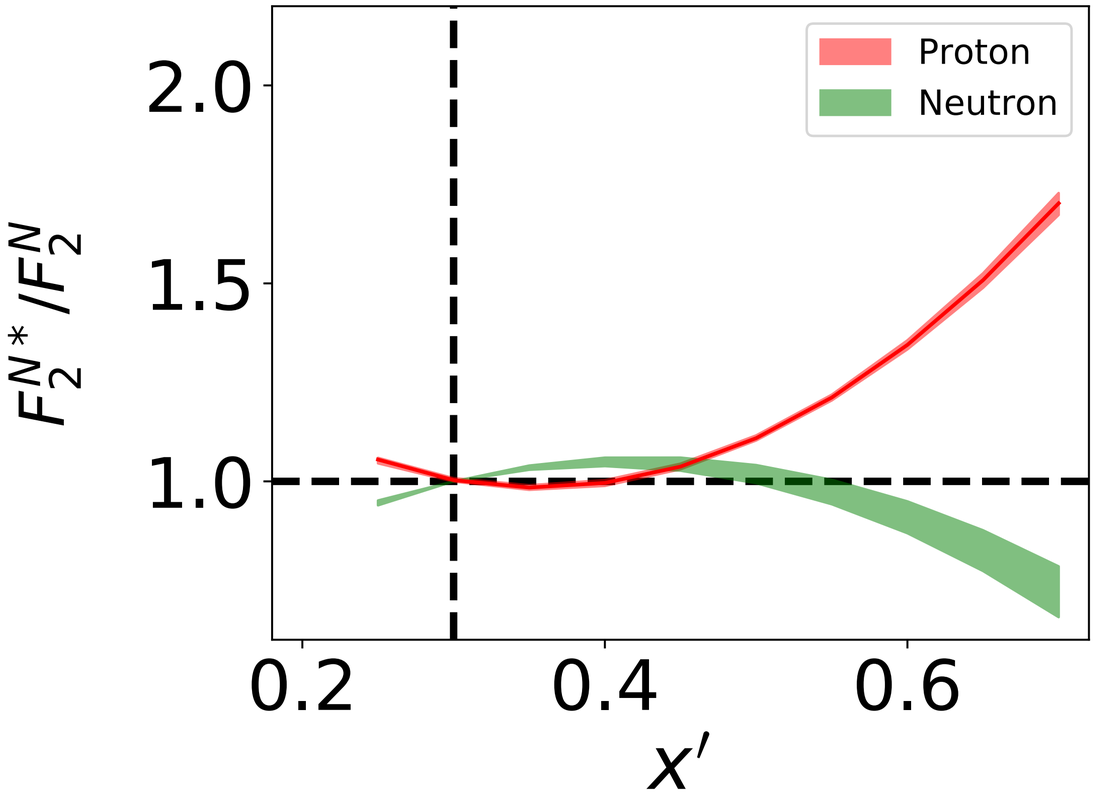
This result is consistent with existing (inclusive) measurements of light nuclei...





...and gives a prediction for bound *neutron* structure!





Overview

- Monte Carlo
- Inclusive DIS analysis
- Tagged DIS analysis
- Outstanding issues

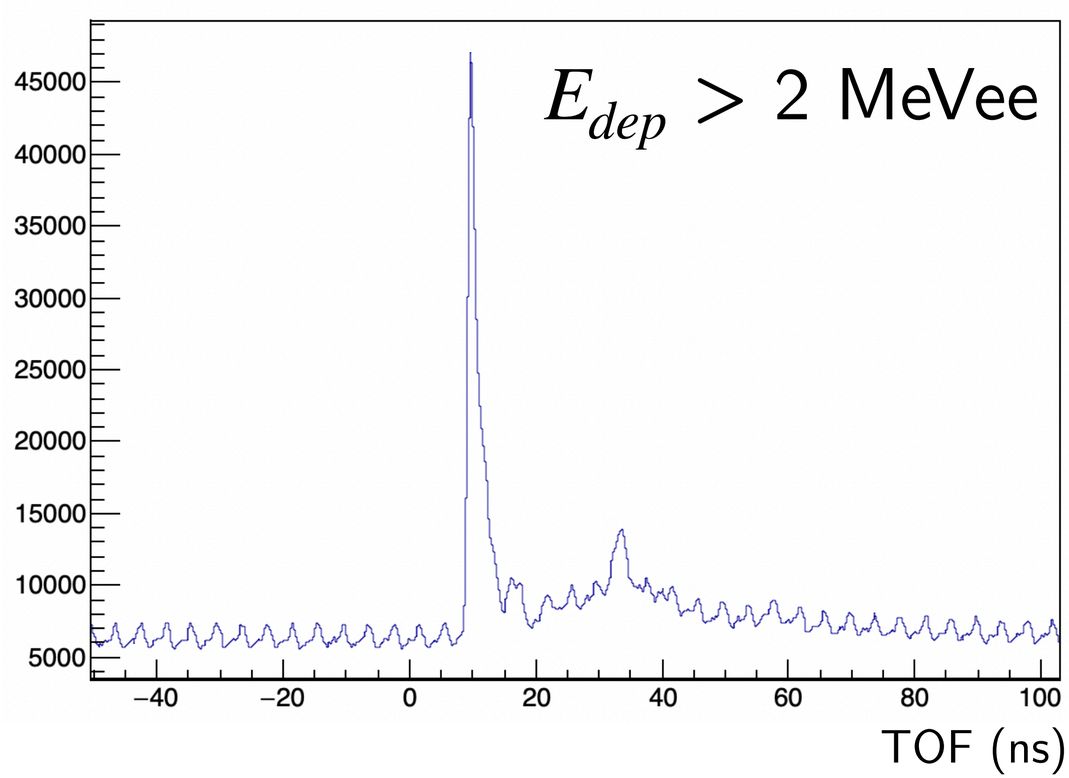
Outstanding issues (and what has been/is being done)

- Lower BAND efficiency from RG-B data than expected from simulation
  - Studied impact of efficiency on double ratio
  - Use higher-statistics RG-M data to map efficiency across BAND acceptance (ongoing)

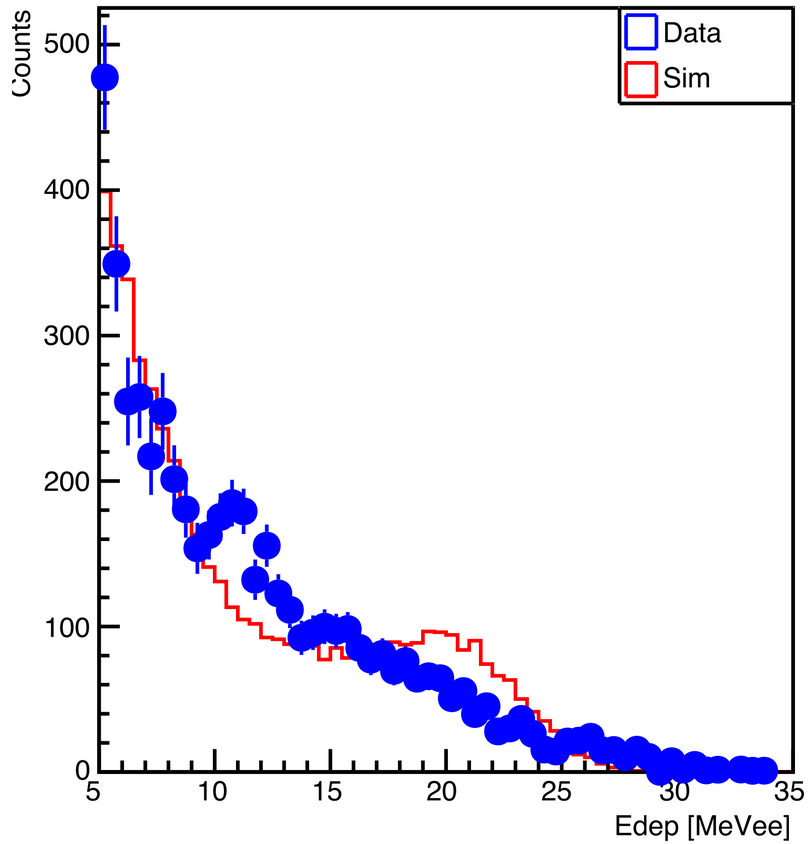
- Data/MC discrepancy in absolute rate
  - Compared multiple reactions
    - Inclusive data/MC $\approx$ 0.6-0.7
    - Tagged data/MC $\approx$ 7-10
  - Compared multiple event generators
  - Double ratio minimizes sensitivity to absolute rate

Outstanding issues (and what has been/is being done)

- Peak in TOF spectrum around 34 ns
  - Spatial dependence...suppressed by eliminating top bars
  - Suppressed by higher E_{dep} cut
  - Compare to empty target data



- Peak in E_{dep} distribution around 10 MeVee
  - Occurs only for $0.25 < p_n < 0.275$ GeV
  - Compare to empty target data

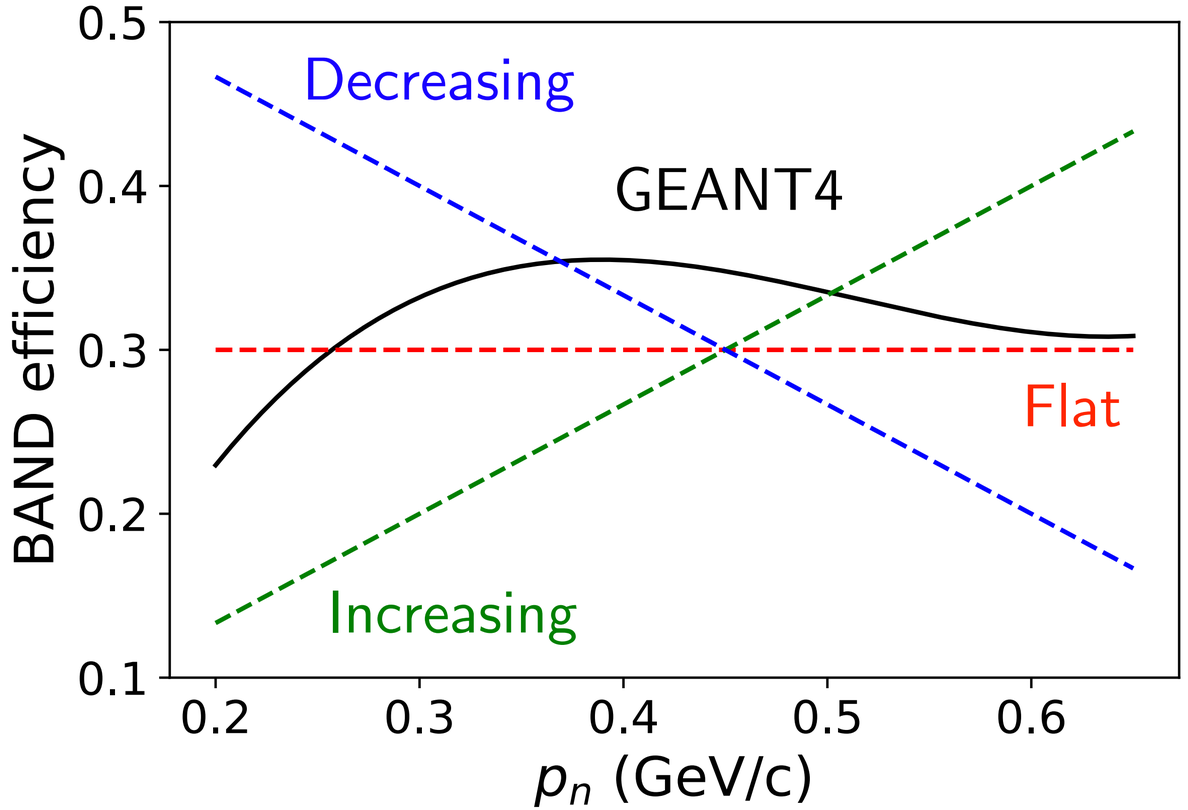


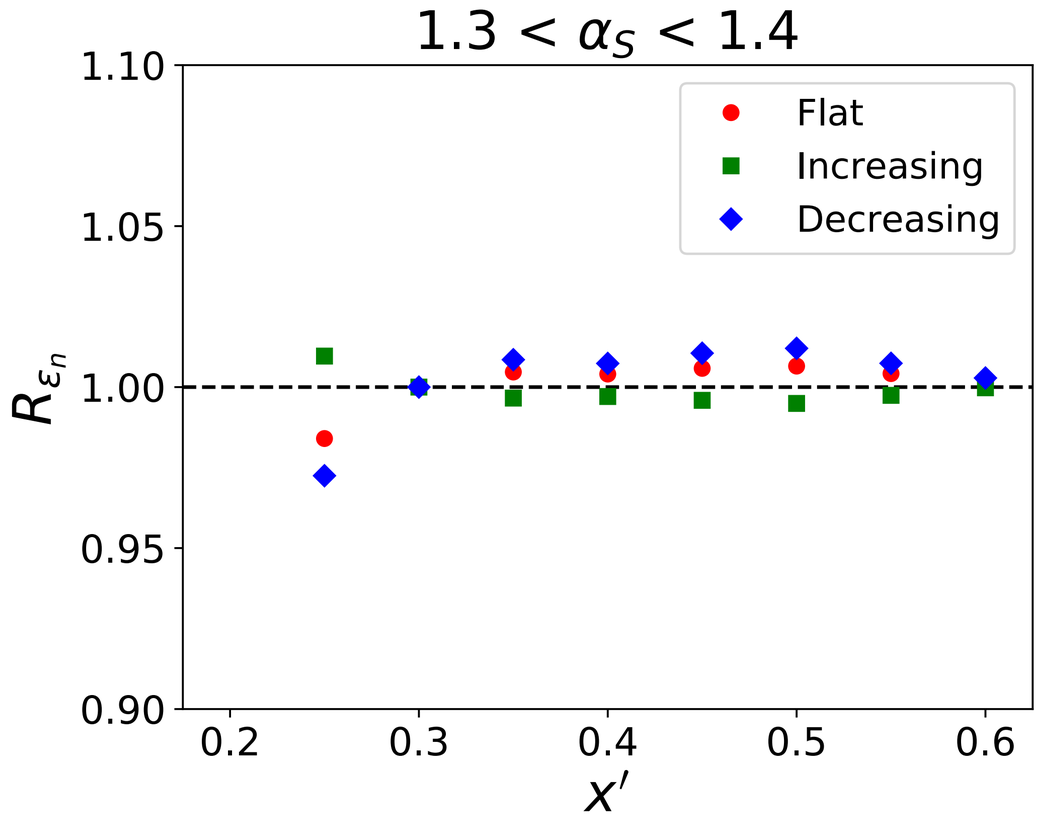
Impact of BAND efficiency on double ratio

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

Standard MC events

Events reweighted based on true p_n to assess range of efficiency curves





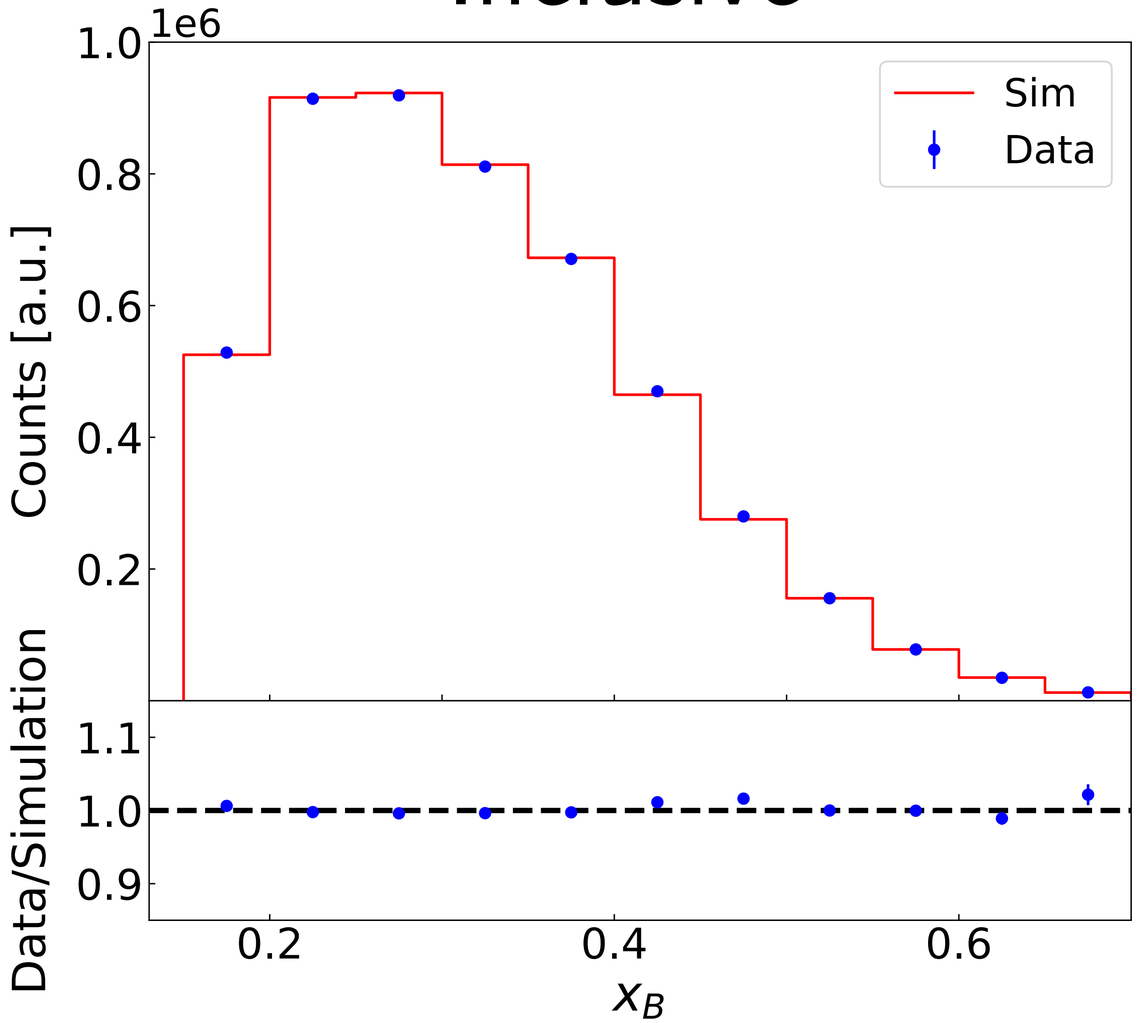
Summary

- First results from BAND show *large* modification of high-momentum, deeply-bound protons
- These results are consistent with existing (inclusive) measurements of light nuclei
- Some open issues remain, though we have chosen an observable that largely mitigates their effects
- CLAS12 analysis review underway

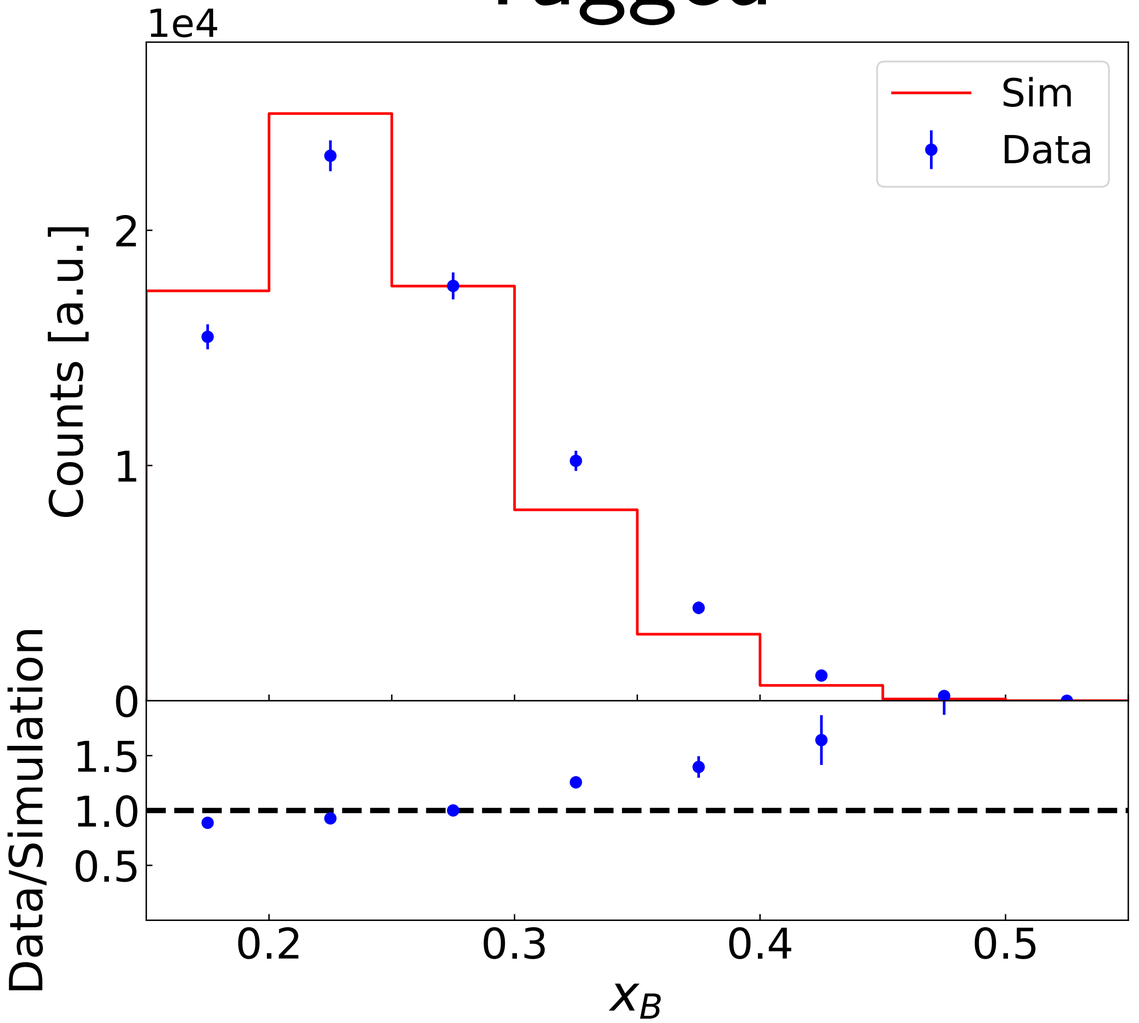
Backup

x_B and x'

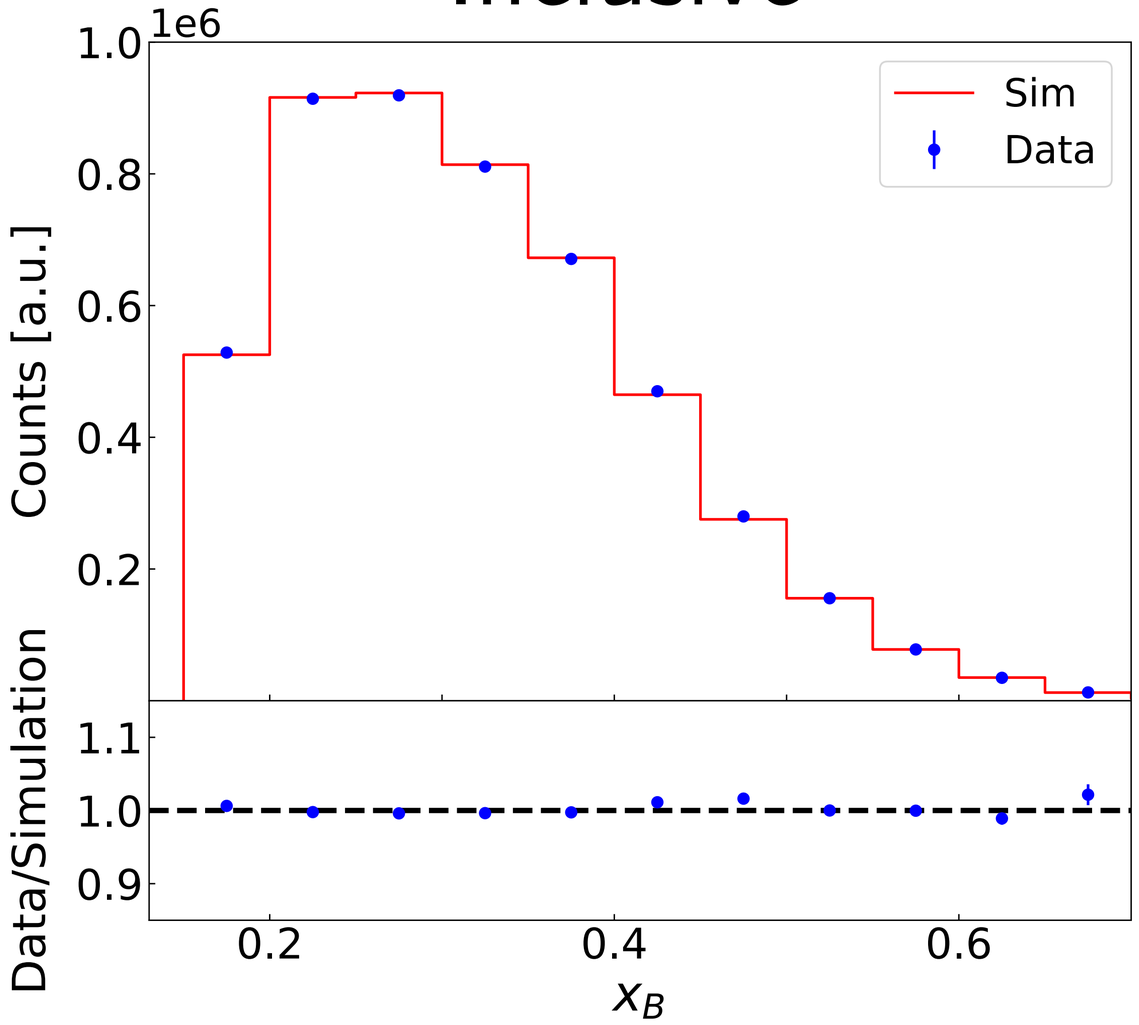
Inclusive



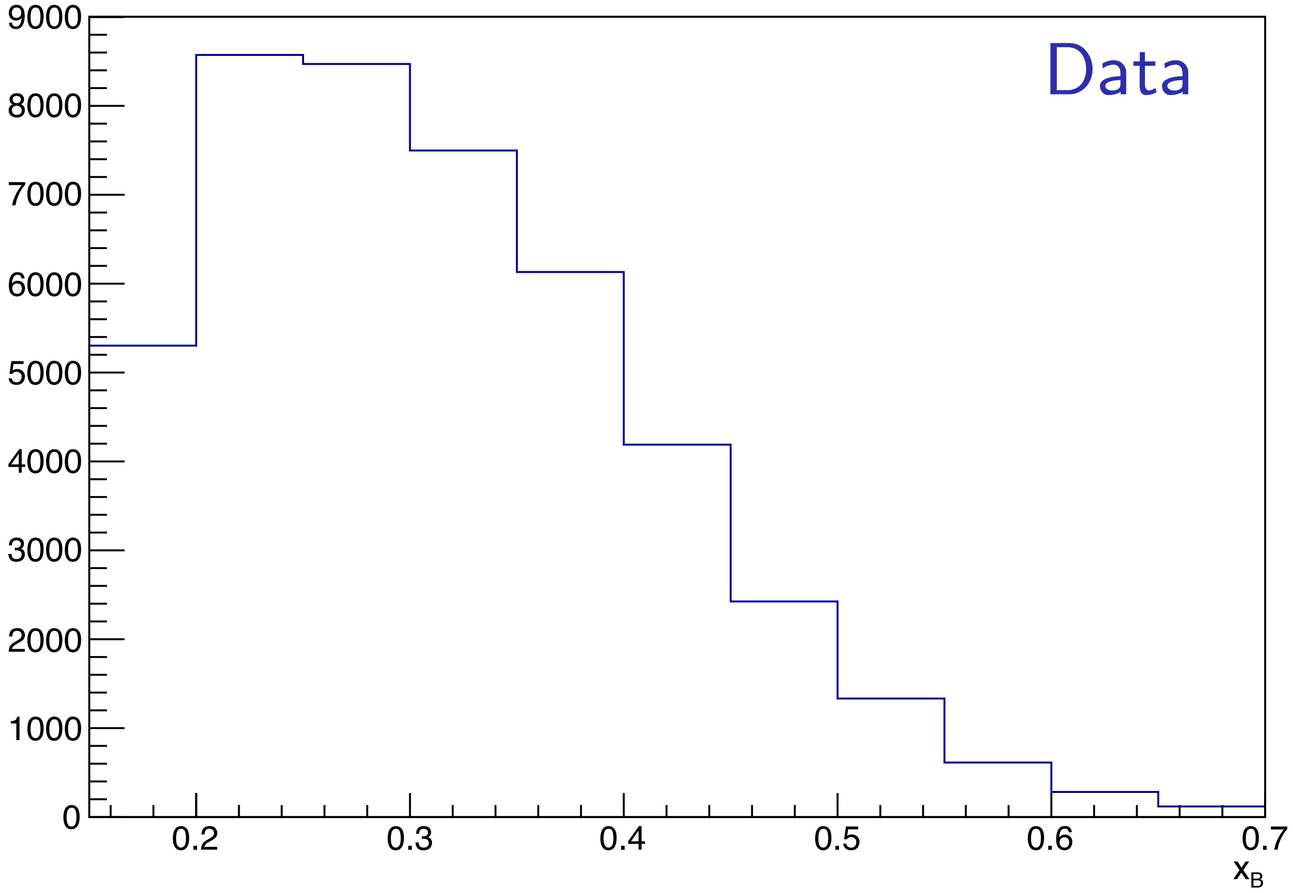
Tagged



Inclusive



Tagged (off-time neutron)

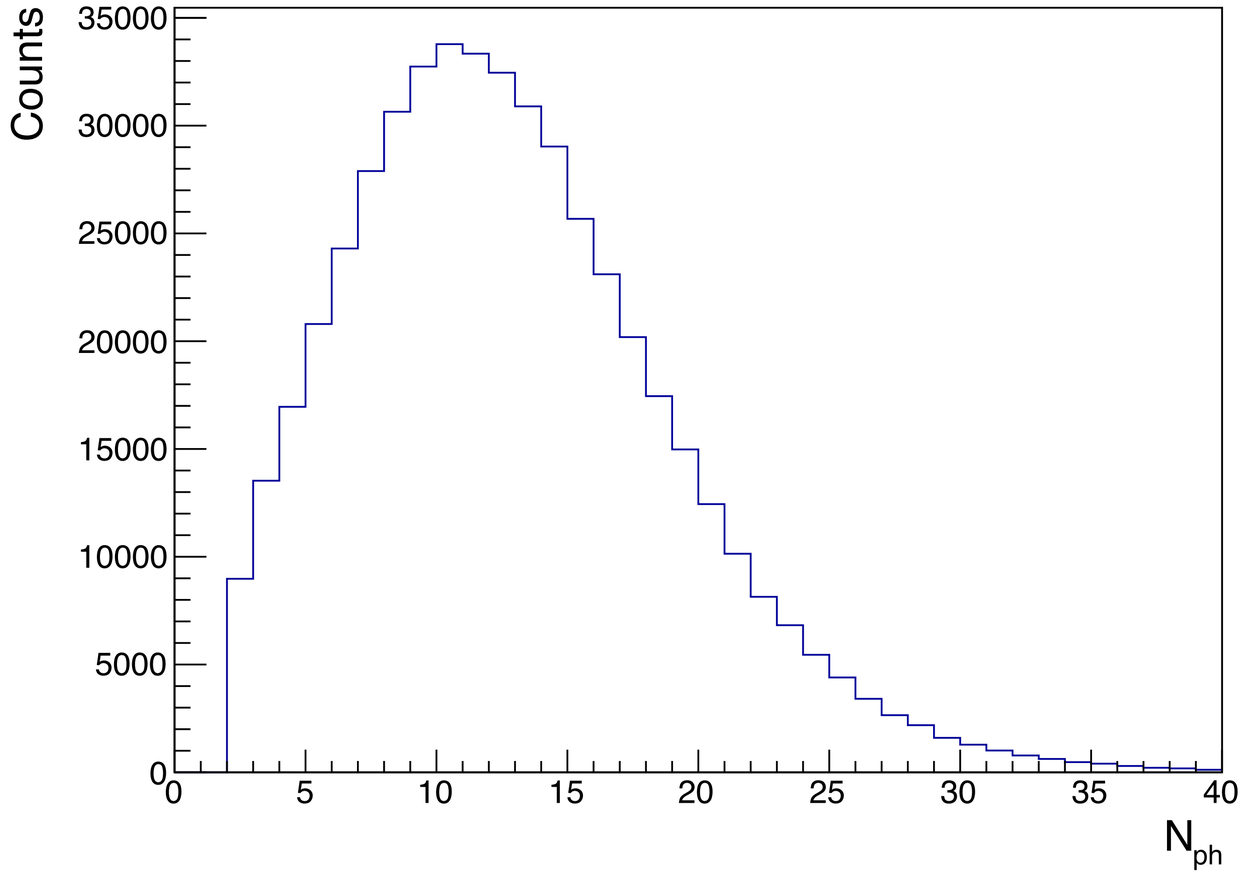


CLAS12 event selection

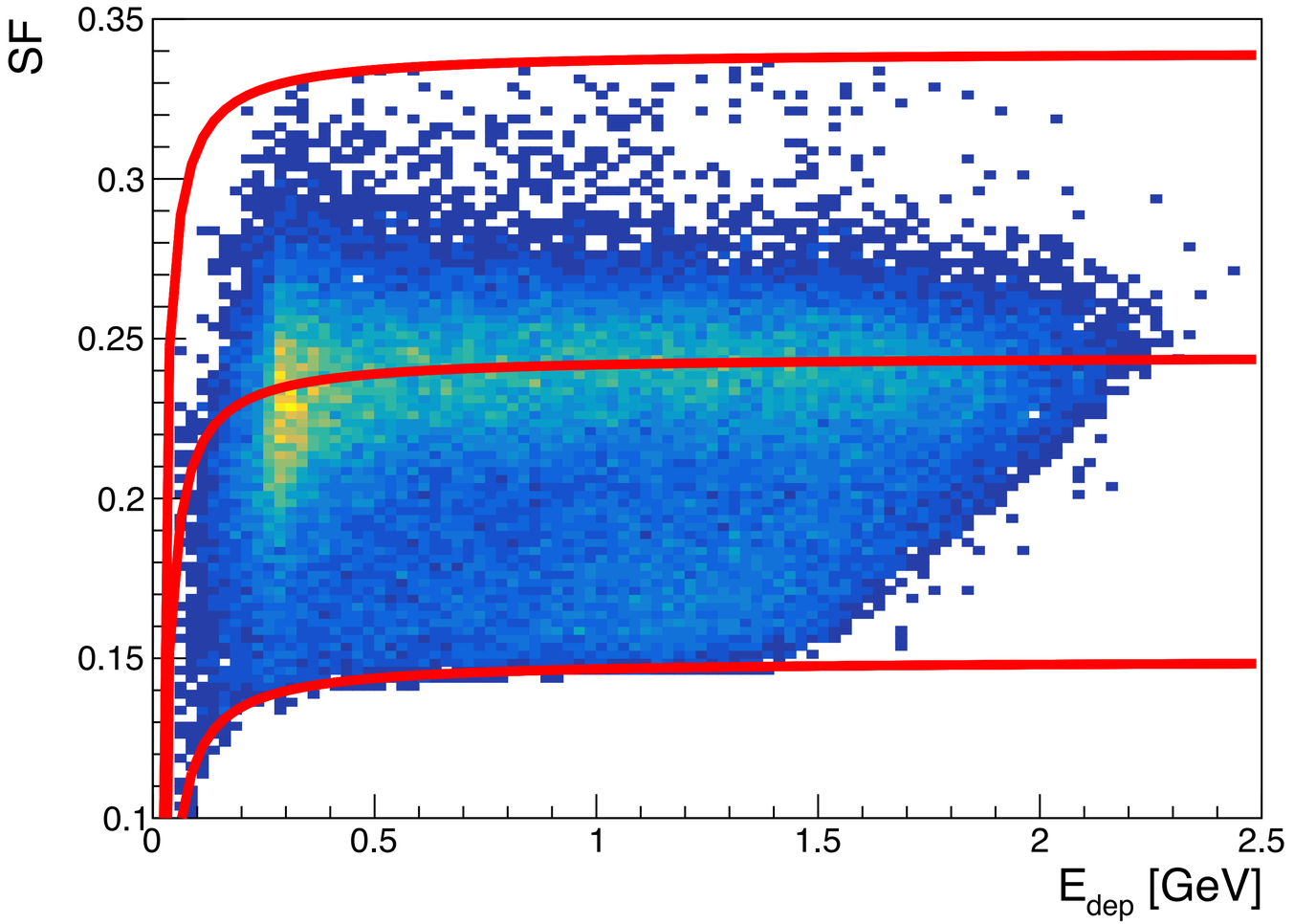
EB electron

- Negatively-charged track in DC with associated ECAL shower
- Minimum energy deposition in PCAL of 60 MeV
- Measured sampling fraction within 5σ of calibrated parameterization
- For $p < 4.9$ GeV, minimum number of photo-electrons (N_{ph}) greater than 2 correlated with DC track

N_{ph} requirement



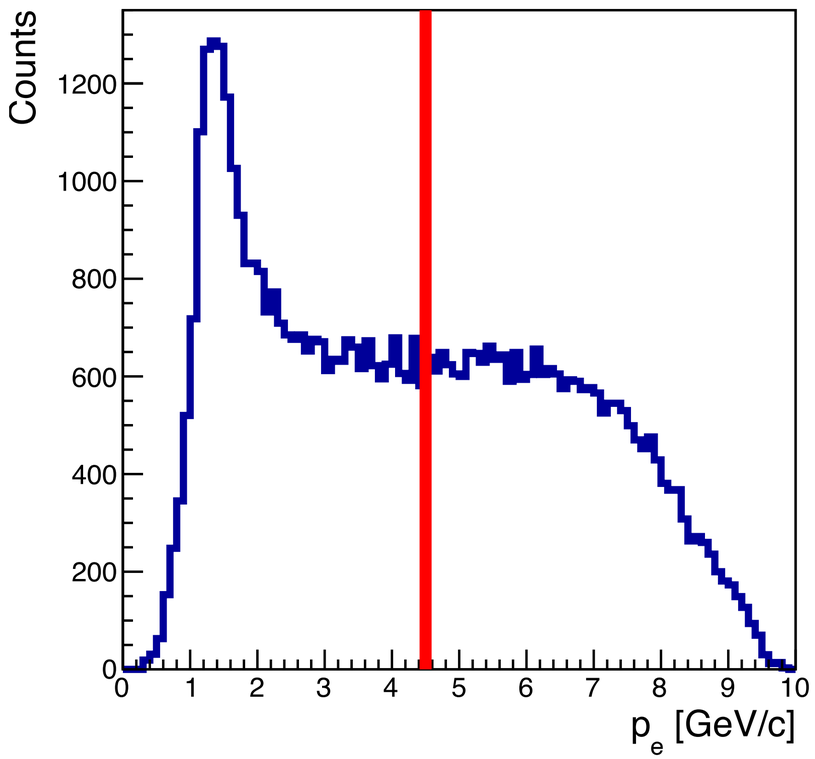
SF requirement

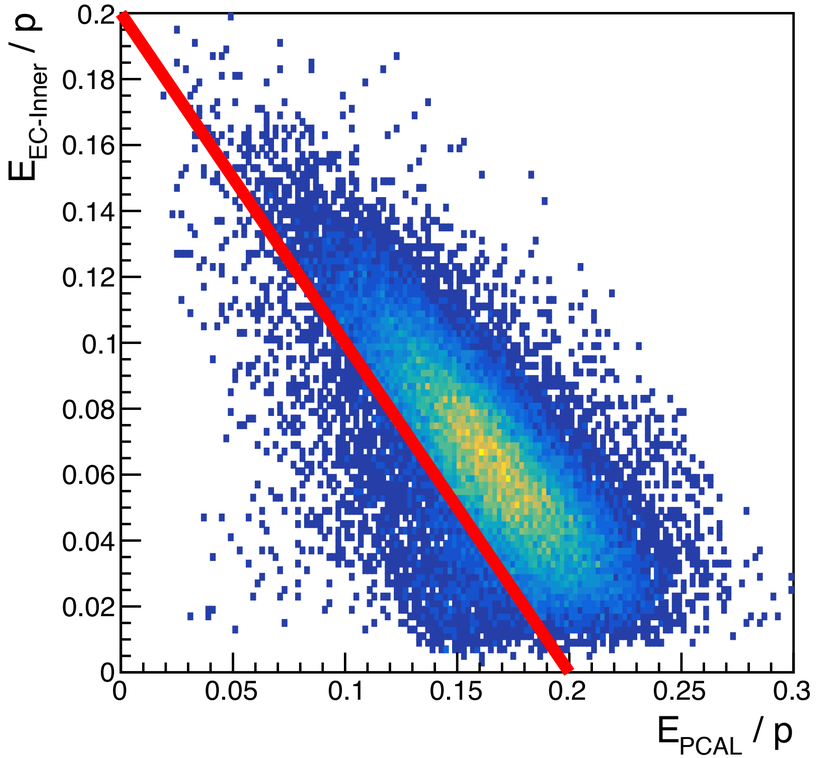


Refinement PID

- SF diagonal cut
- Minimum energy deposition in PCAL of 70 MeV
- SF vs. momentum
- SF vs. PCAL energy deposition
- Vertex

Diagonal cut

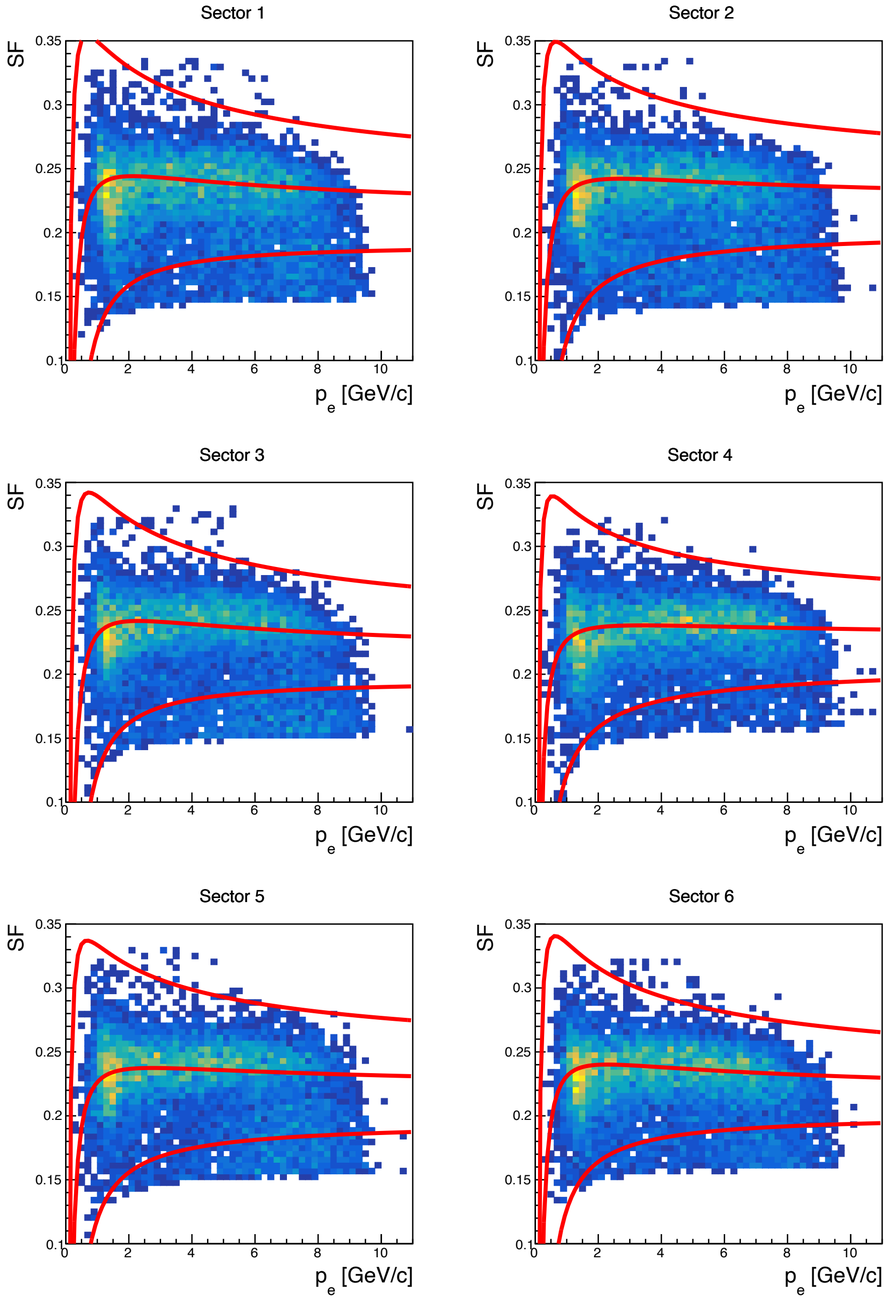




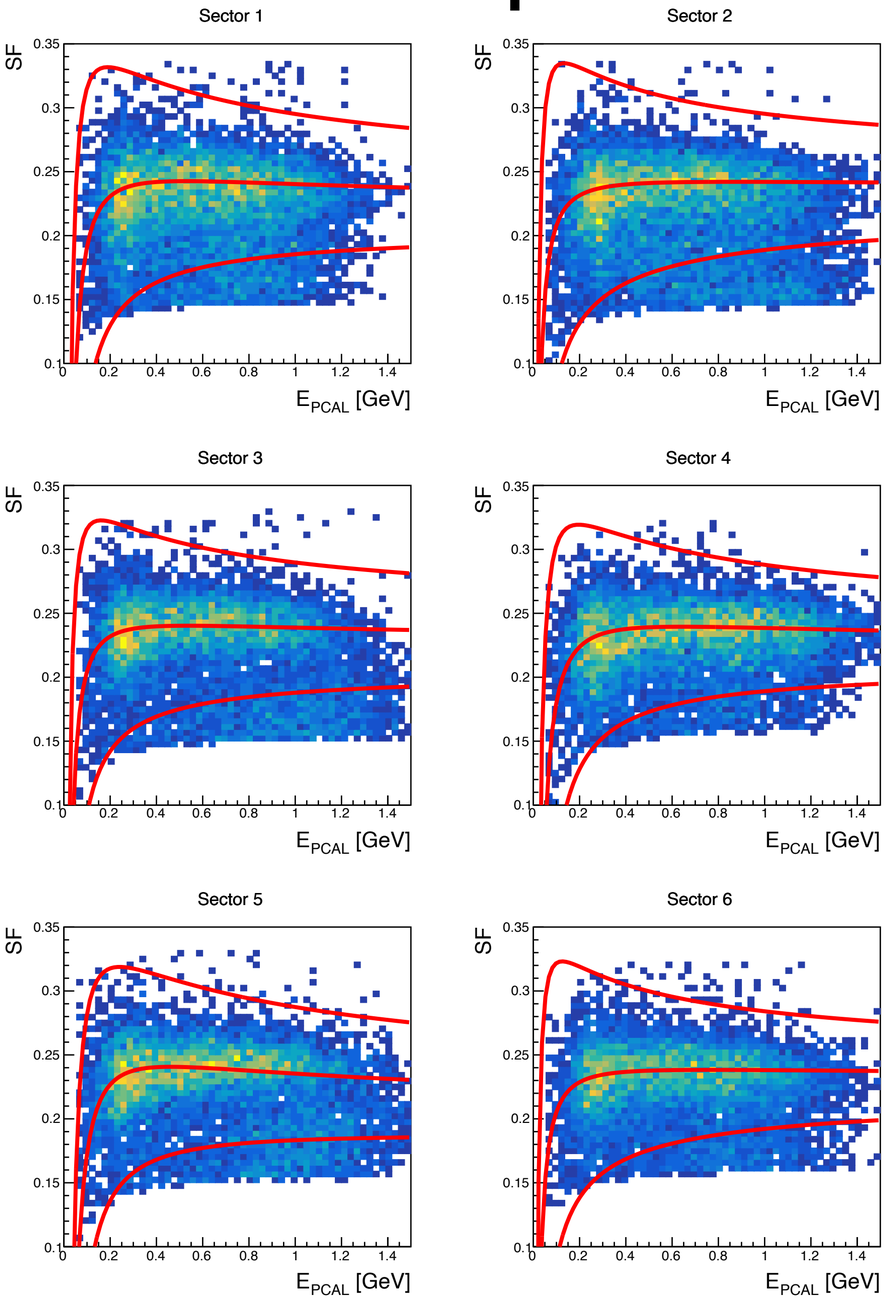
$$p > 4.5 \text{ GeV}: \quad \frac{E_{\text{dep,EC-inner}}}{p} < 0.2 - \frac{E_{\text{dep,PCAL}}}{p}$$

Pion contamination < 2%

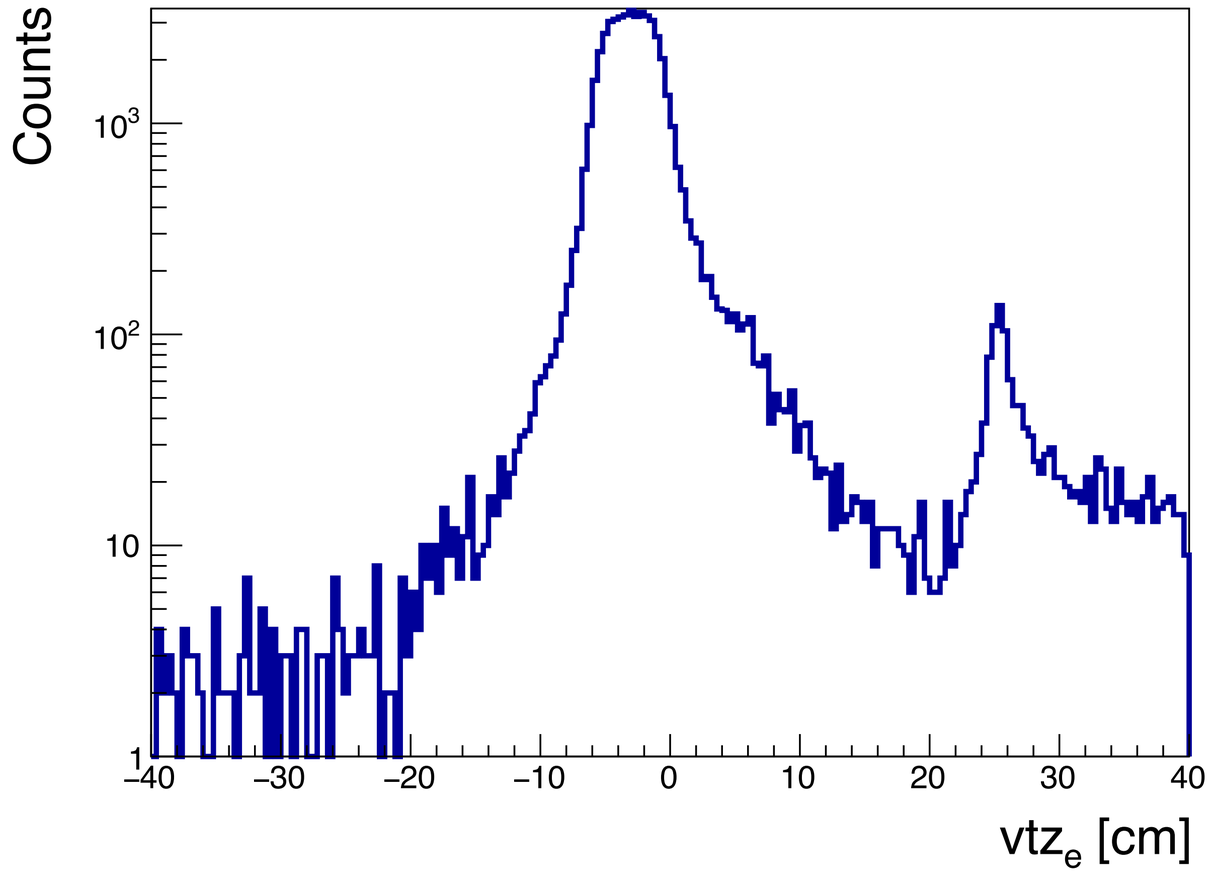
Momentum



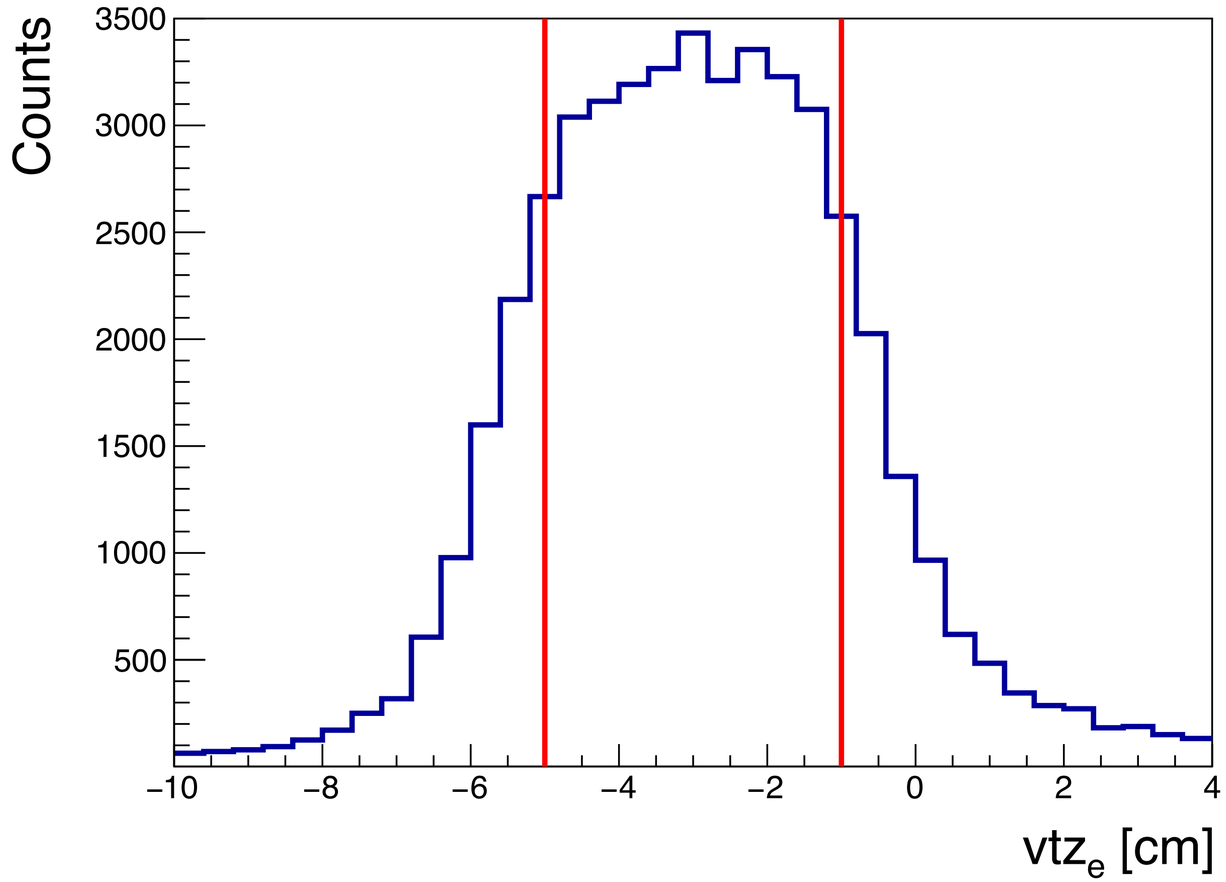
Edep



Vertex



Vertex



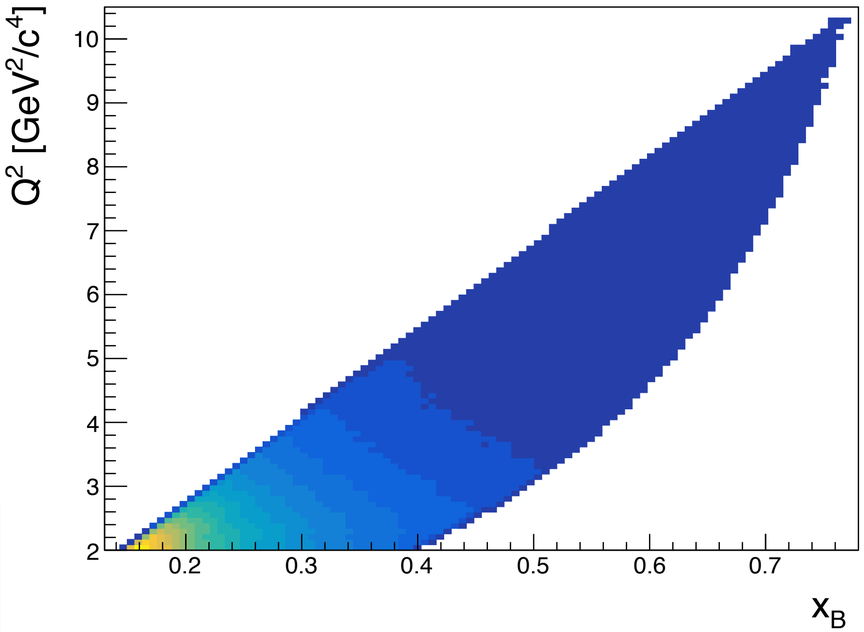
Survival rates

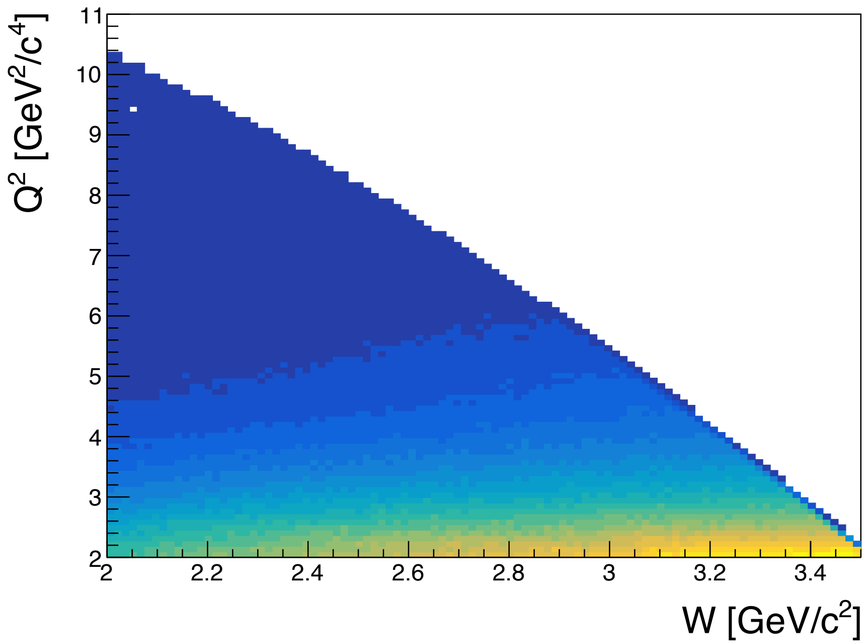
Electron refinement cut	**Fraction of EB electrons**
Minimum $E_{\mathrm{dep,PCAL}}$ cut	99.9%
"Diagonal" SF cut	81.8%
SF vs p cut	86.6%
SF vs $E_{\mathrm{dep,PCAL}}$ cut	87.2%
Vertex cut	60.4%
Total	48.0%

(Applied independently, except **total**)

DIS kinematics

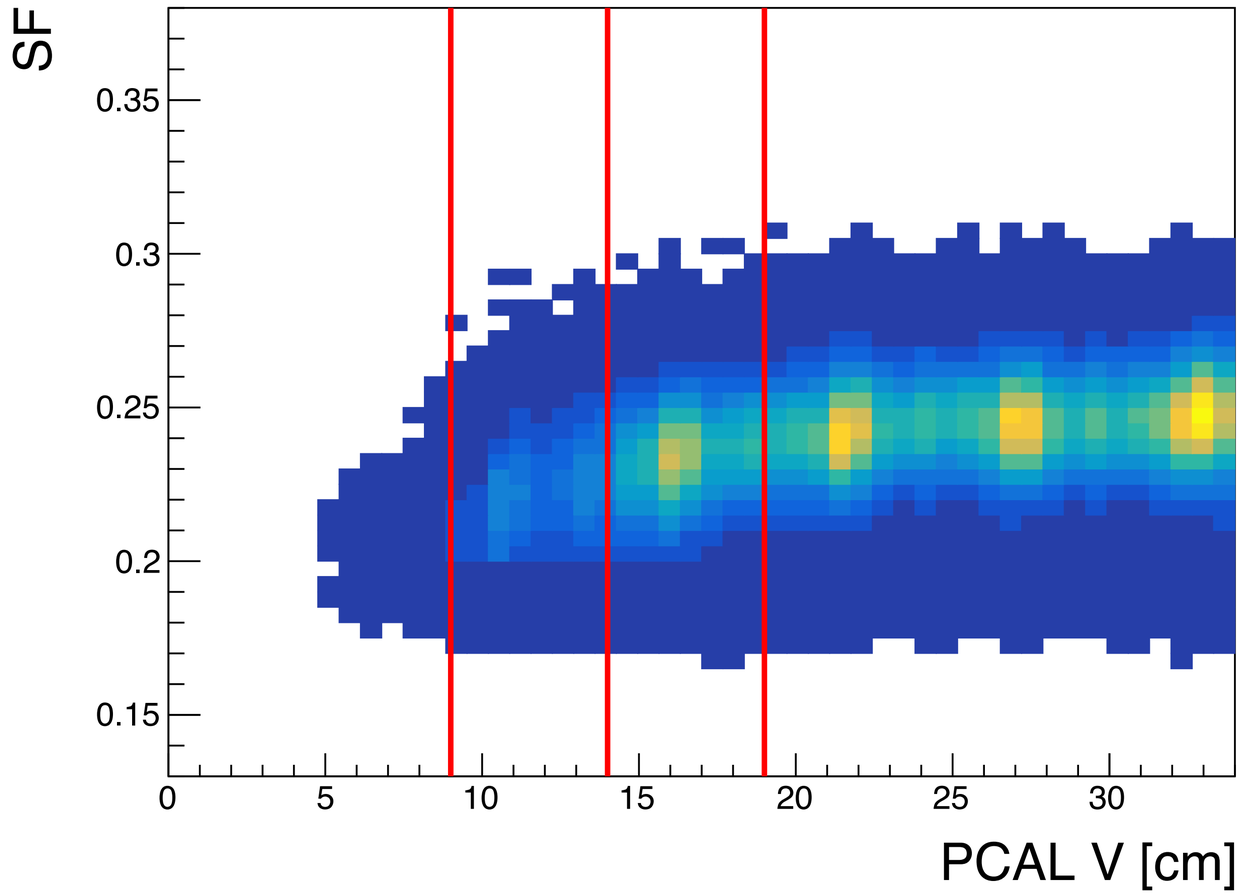
- $Q^2 > 2$
- $W > 2$
- $p > 3$





The rest of the discussion will be using electrons with these cuts

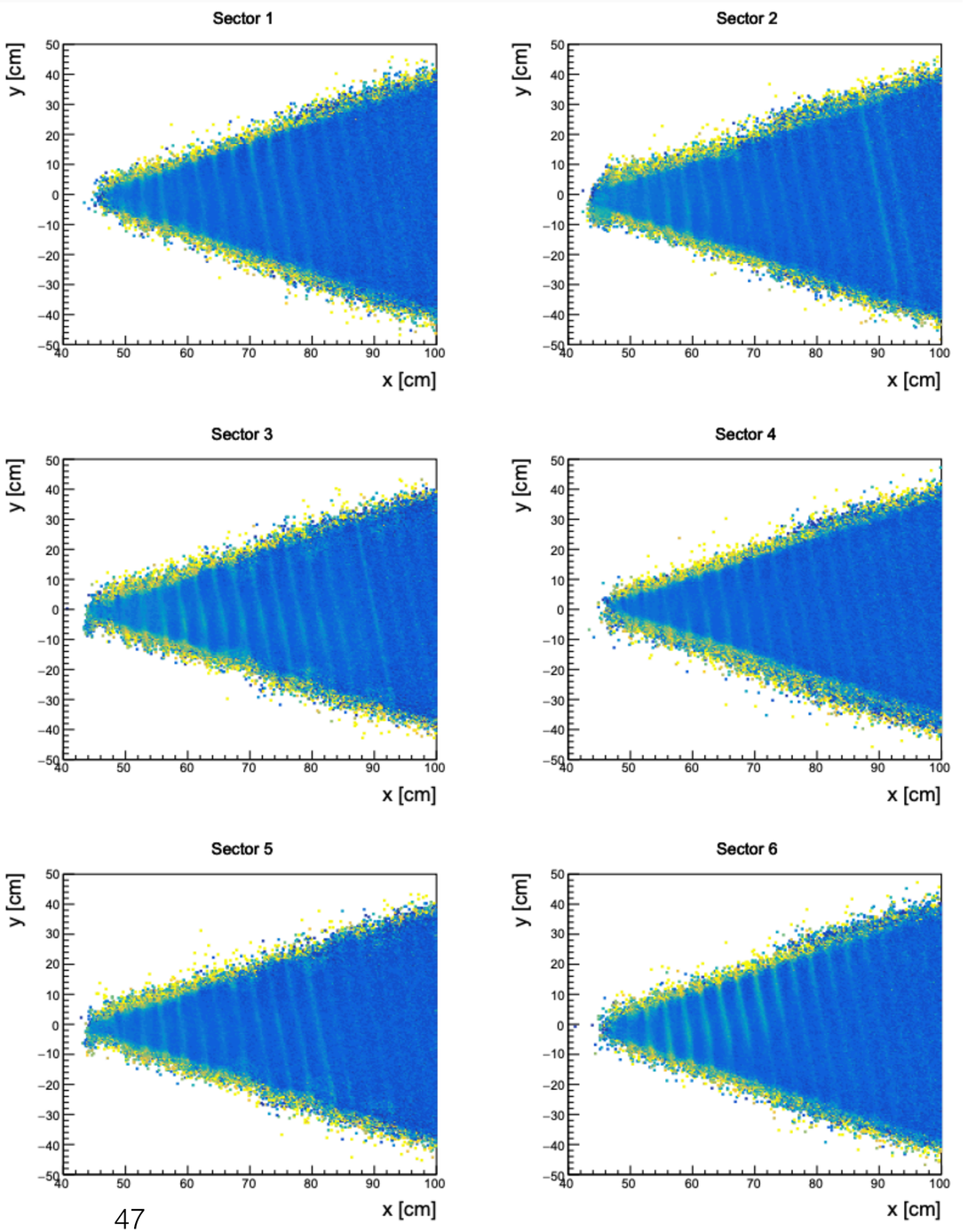
PCAL fiducial



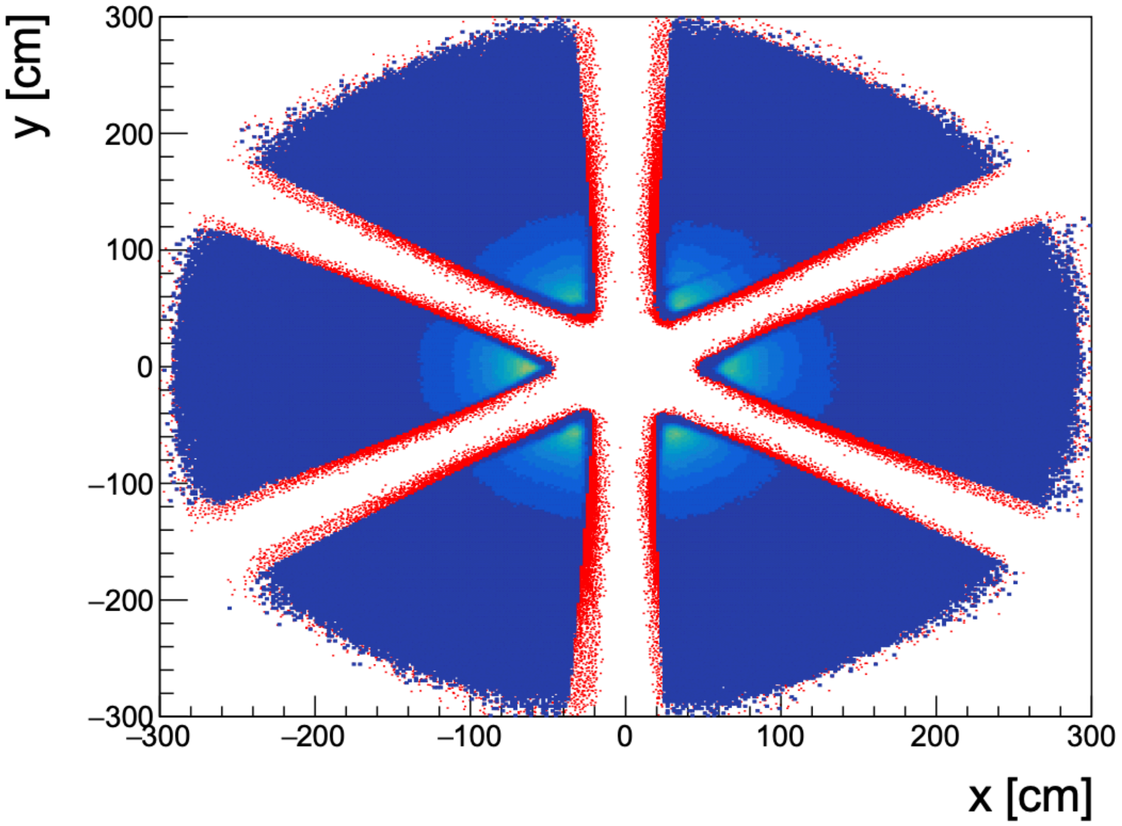
Medium cut: $V, W > 14$ [cm] $\rightarrow 92\,\%$ survival

DC Fiducial

Remove areas with large χ^2/dof



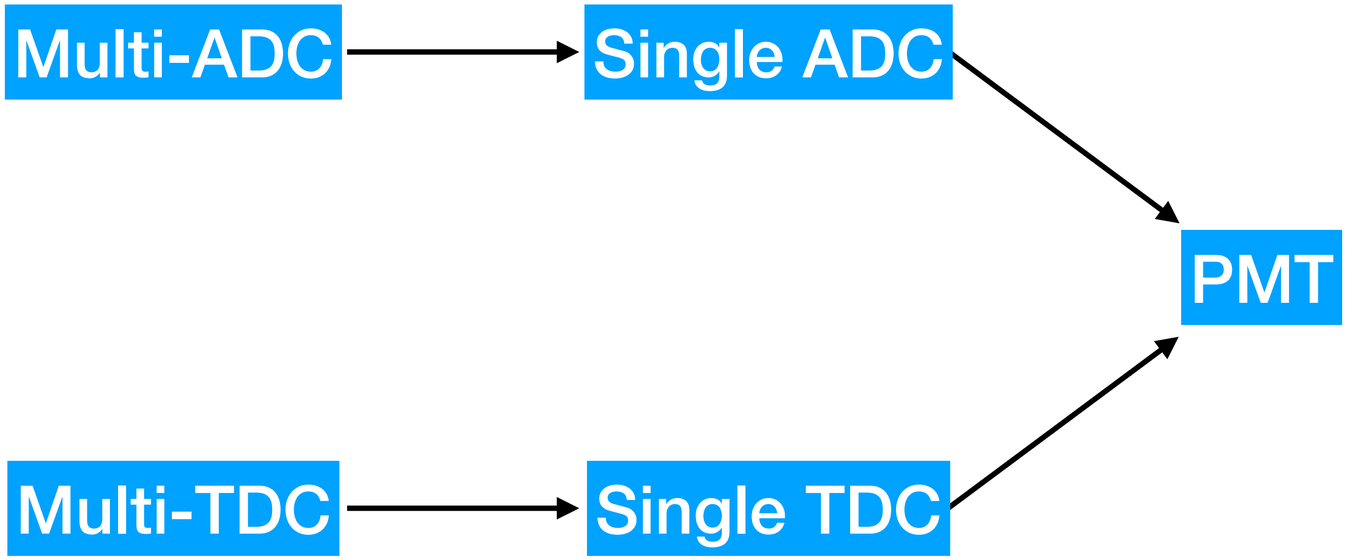
Result of DC



	RGA (%)	RGB(10.2 GeV) (%)	RGB(10.6 GeV) (%)	GEMC (%)
Region 1	97.7	97.6	97.5	97.6
Region 2	98.4	98.3	98.3	97.7
Region 3	95.7	94.9	94.7	93.9

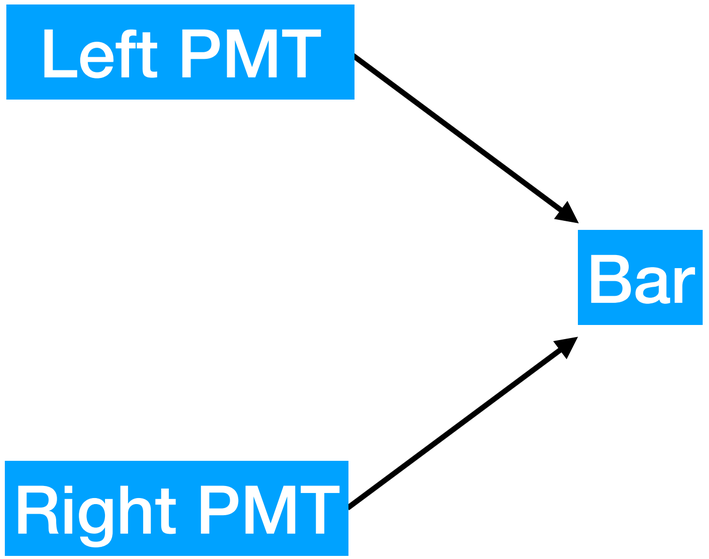
BAND neutron candidate selection

PMT reconstruction



Any ADCs/TDCs with null information are through away

Bar reconstruction

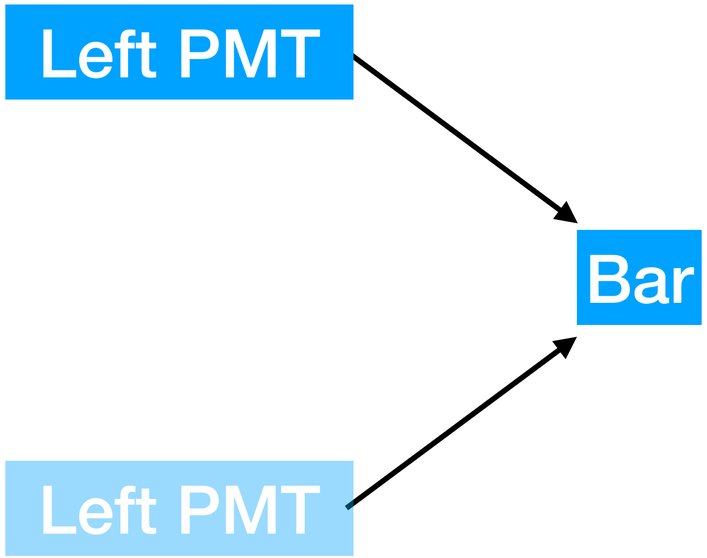


(except veto layer)

Needs to pass $t_L - t_R$ requirement

Only stored if $E_{dep} > 2$ MeVee

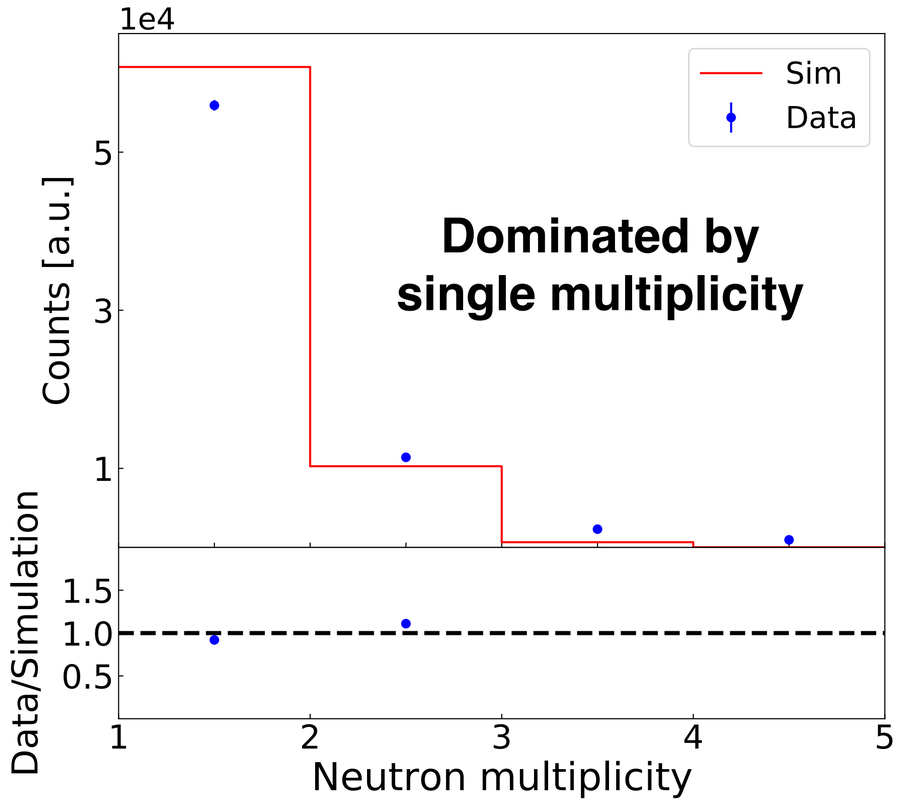
Veto bar reconstruction



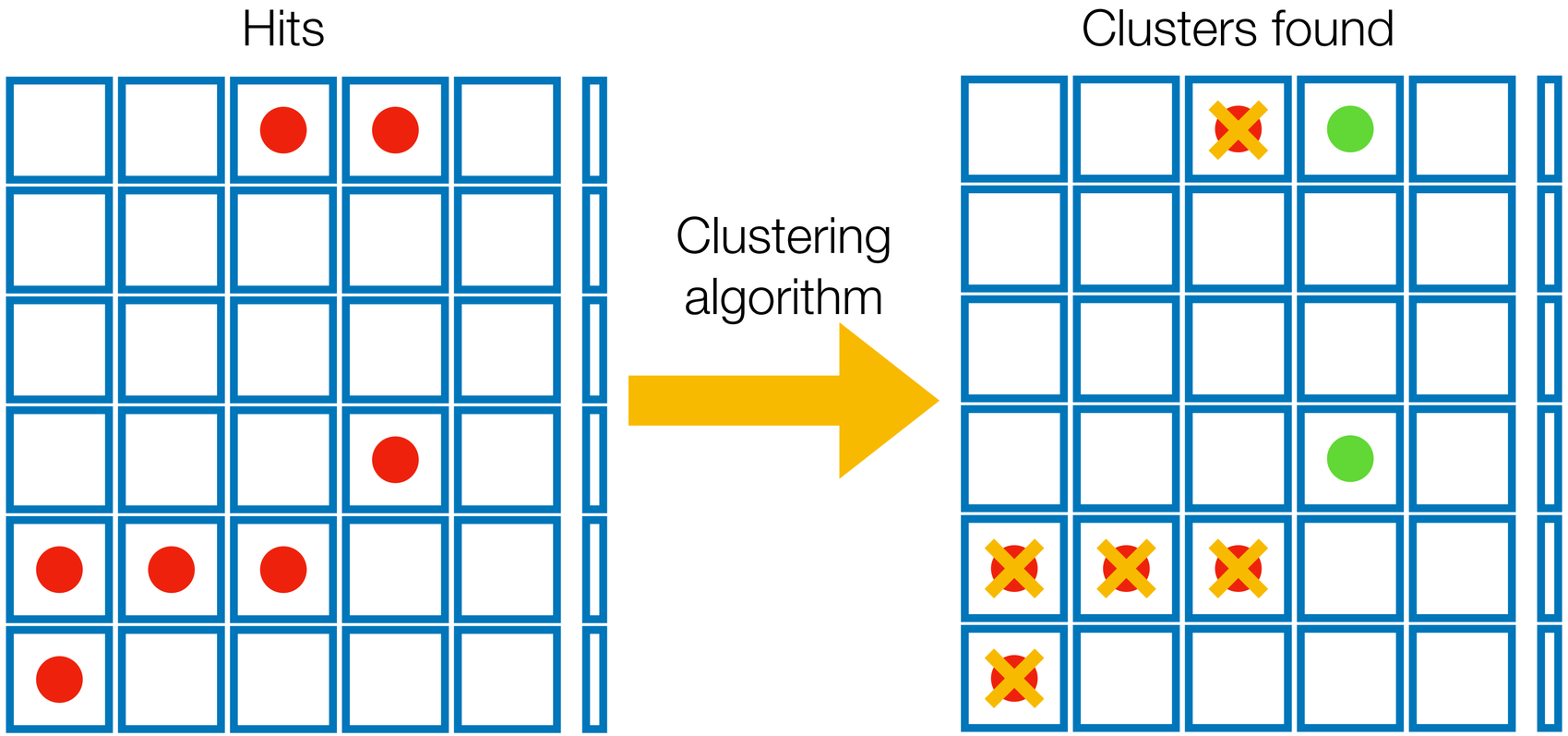
Only stored if $E_{dep} > 0.55$ MeVee

At the end, we have a collection of hits

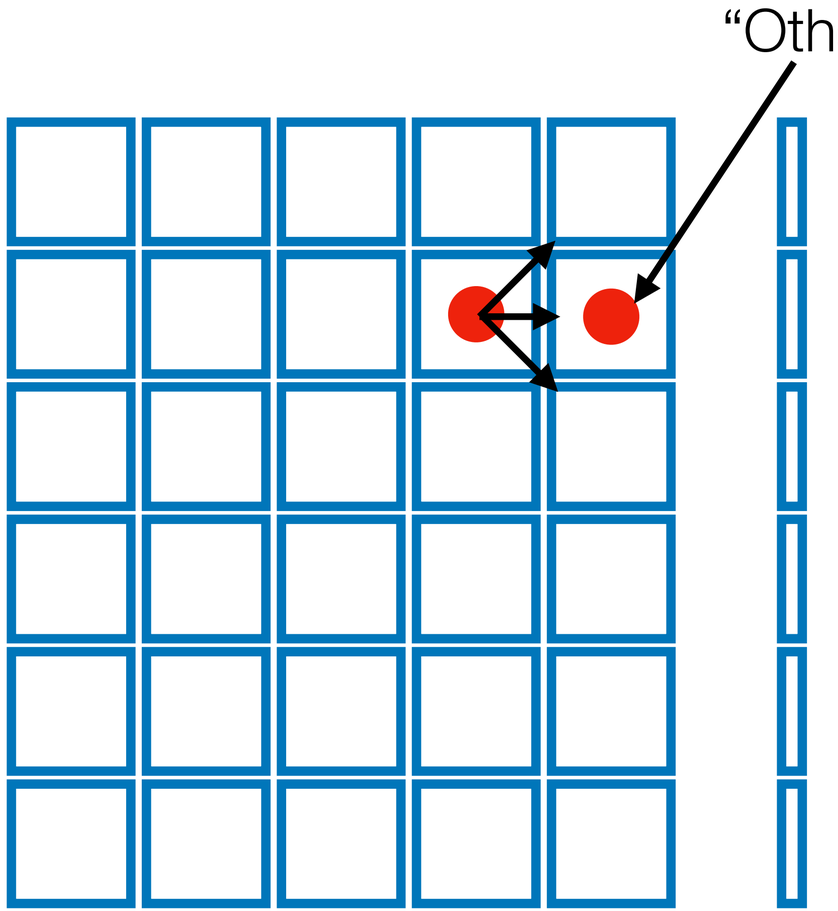
- Look at hit pattern to identify events with neutral hit
- If exists, pick the “lead” hit for the analysis



Lead hit identification

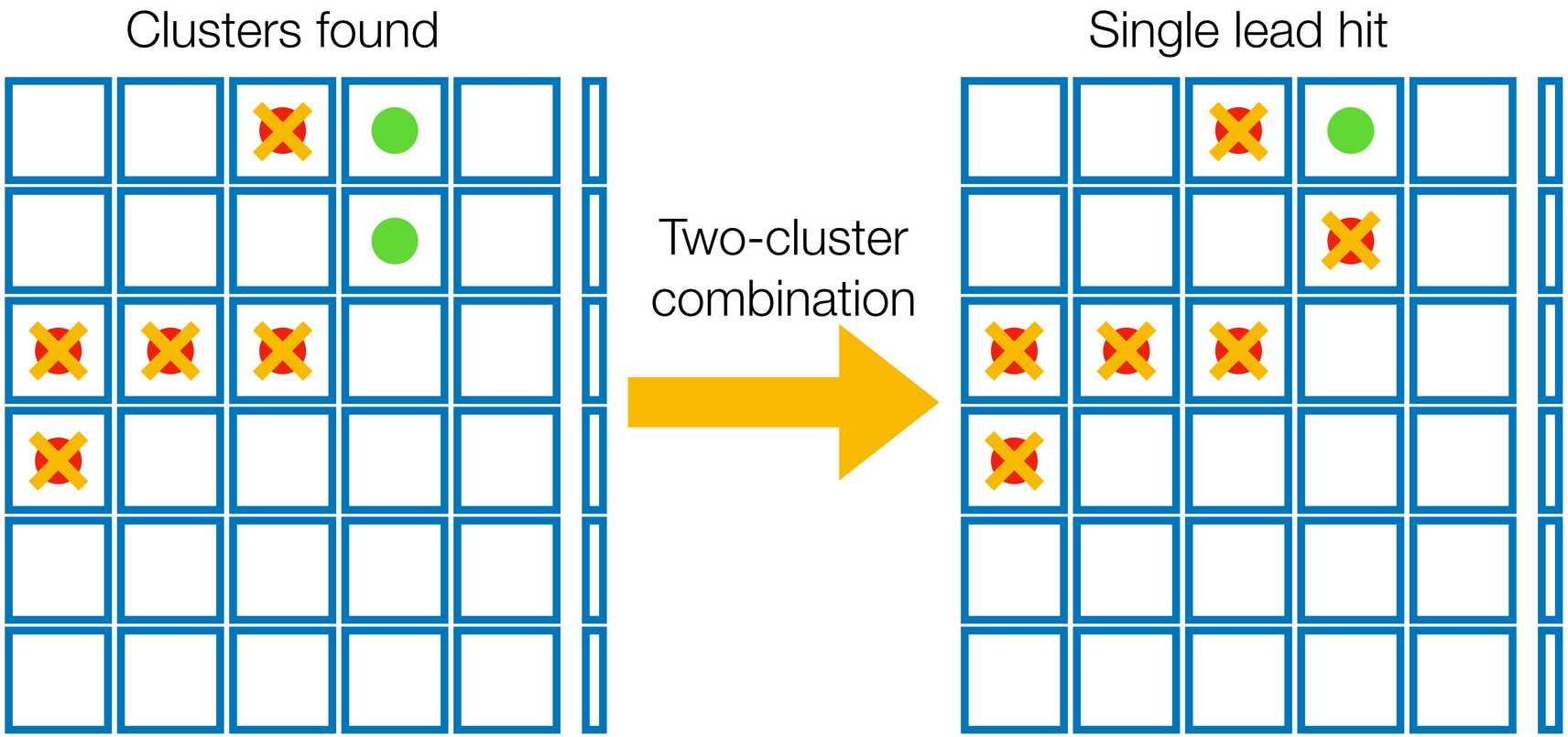


Blocking conditions



- $\text{layer}_{\text{other}} = \text{layer}_{\text{me}} + 1$
- $y_{\text{other}} = y_{\text{me}} \pm 8$ [cm]
- $x_{\text{other}} = x_{\text{me}} \pm 15$ [cm]
- $\text{ToF}_{\text{other}} = \text{ToF}_{\text{me}} \pm 3$ [ns]

Cluster reduction



Only treats cases with 2 clusters

Cases we throw out

- More than 2 clusters
- If 2 clusters cannot be combined
- If the remaining “lead” hit is a veto bar

$\sim 9\,\%$ of data is thrown away
Less simulation is thrown away

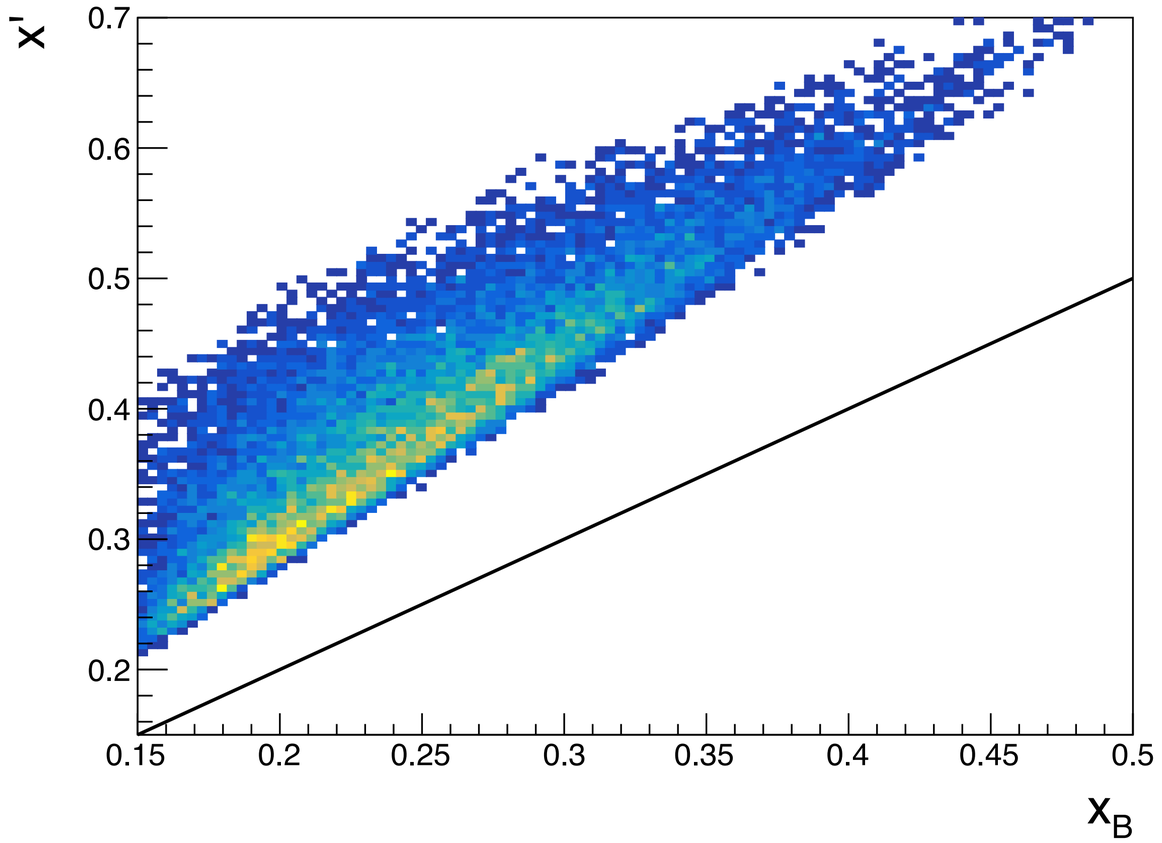
Using electron and neutron

- Form tagged hits (simulation uses smeared electron)

$$E_{dep} > 10$$
$$p_n > 0.25$$
$$W' > 1.8$$
$$\alpha_S > 1.2$$
$$\cos\theta_{nq} < -0.8$$

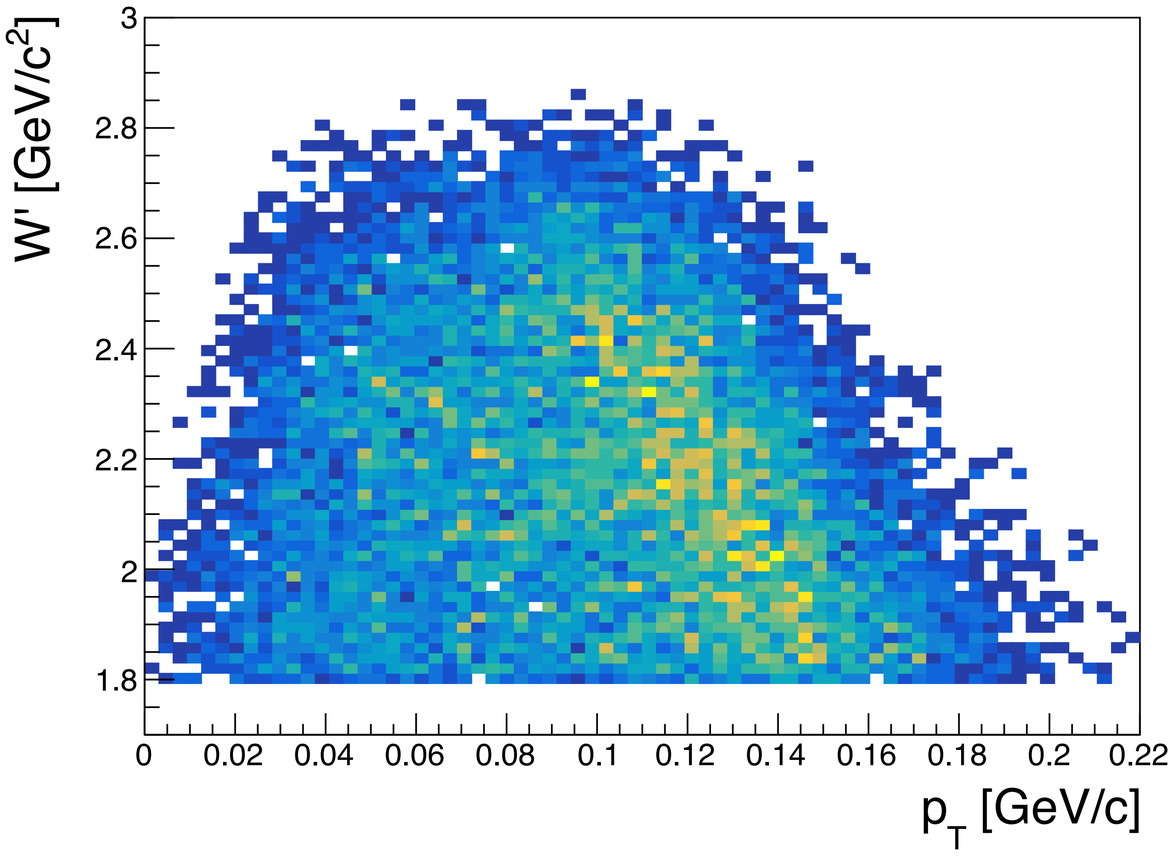
Using electron and neutron

- Form tagged hits (simulation uses smeared electron)



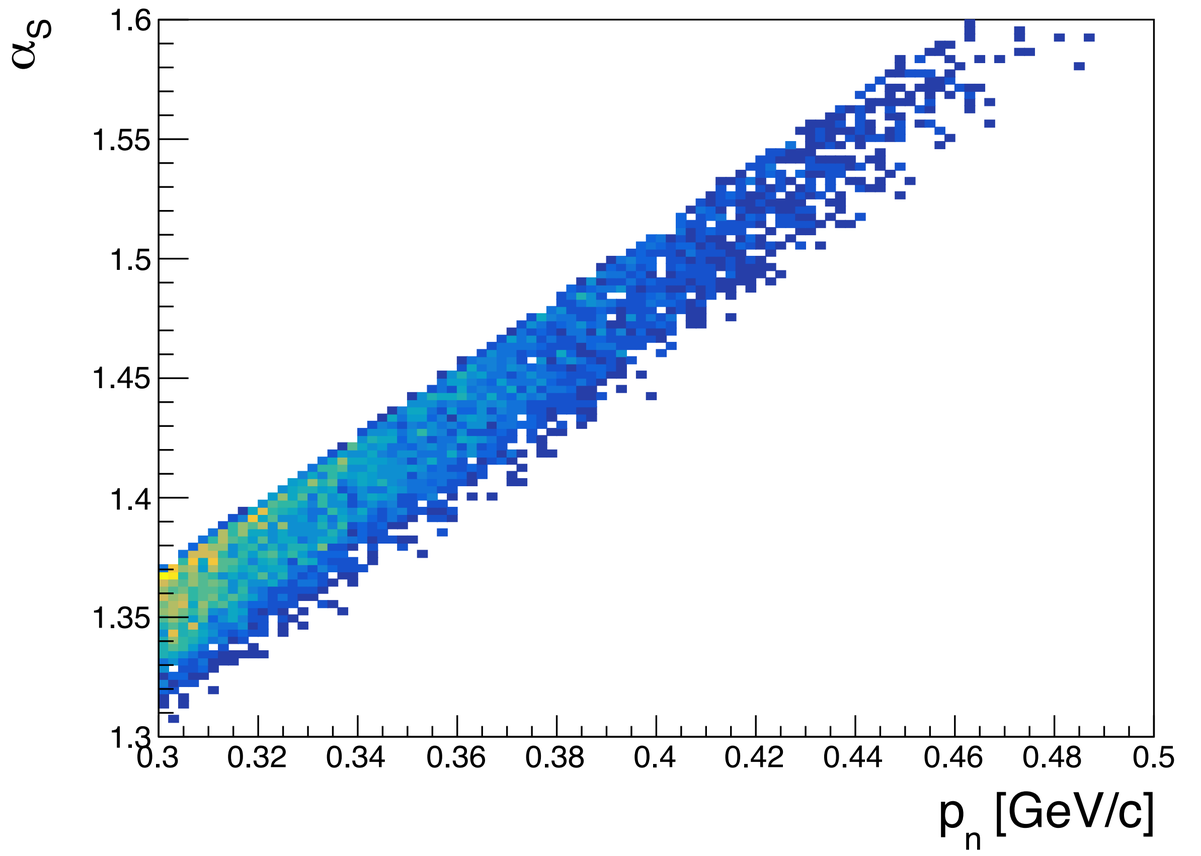
Using electron and neutron

- Form tagged hits (simulation uses smeared electron)



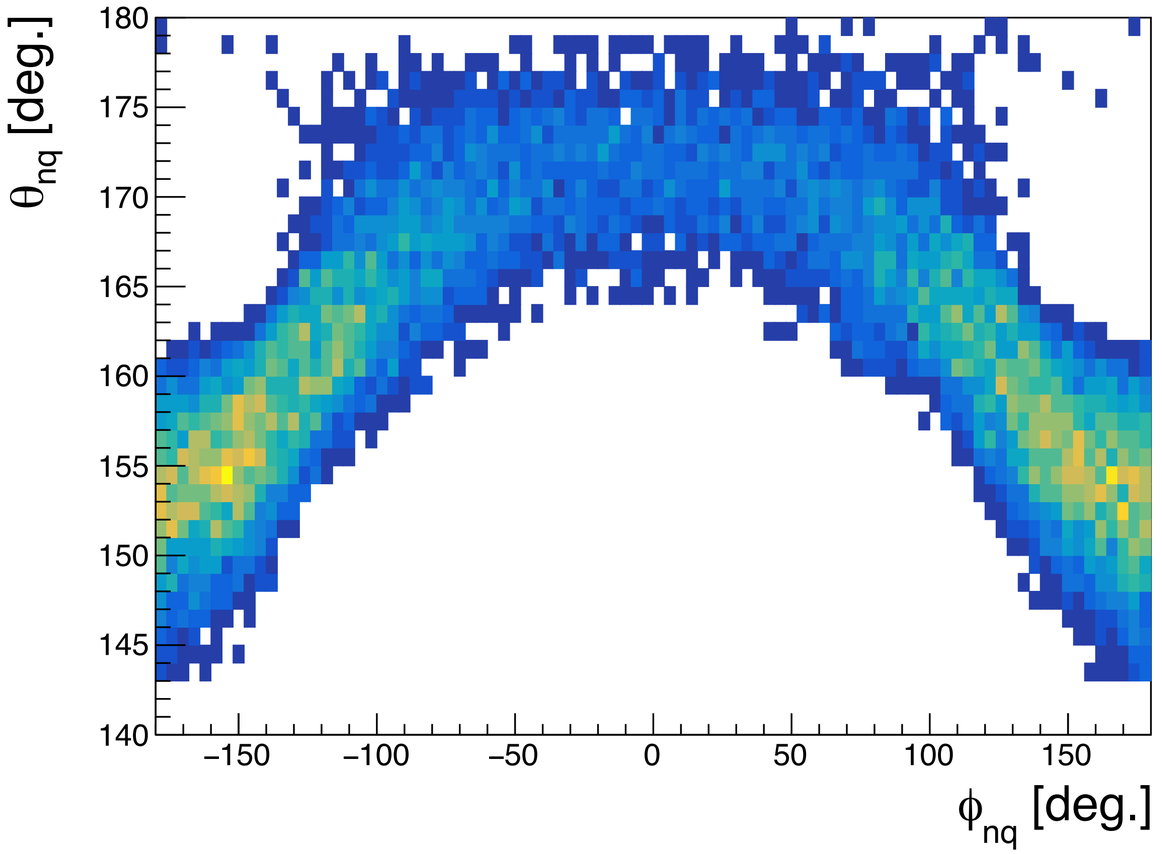
Using electron and neutron

- Form tagged hits (simulation uses smeared electron)



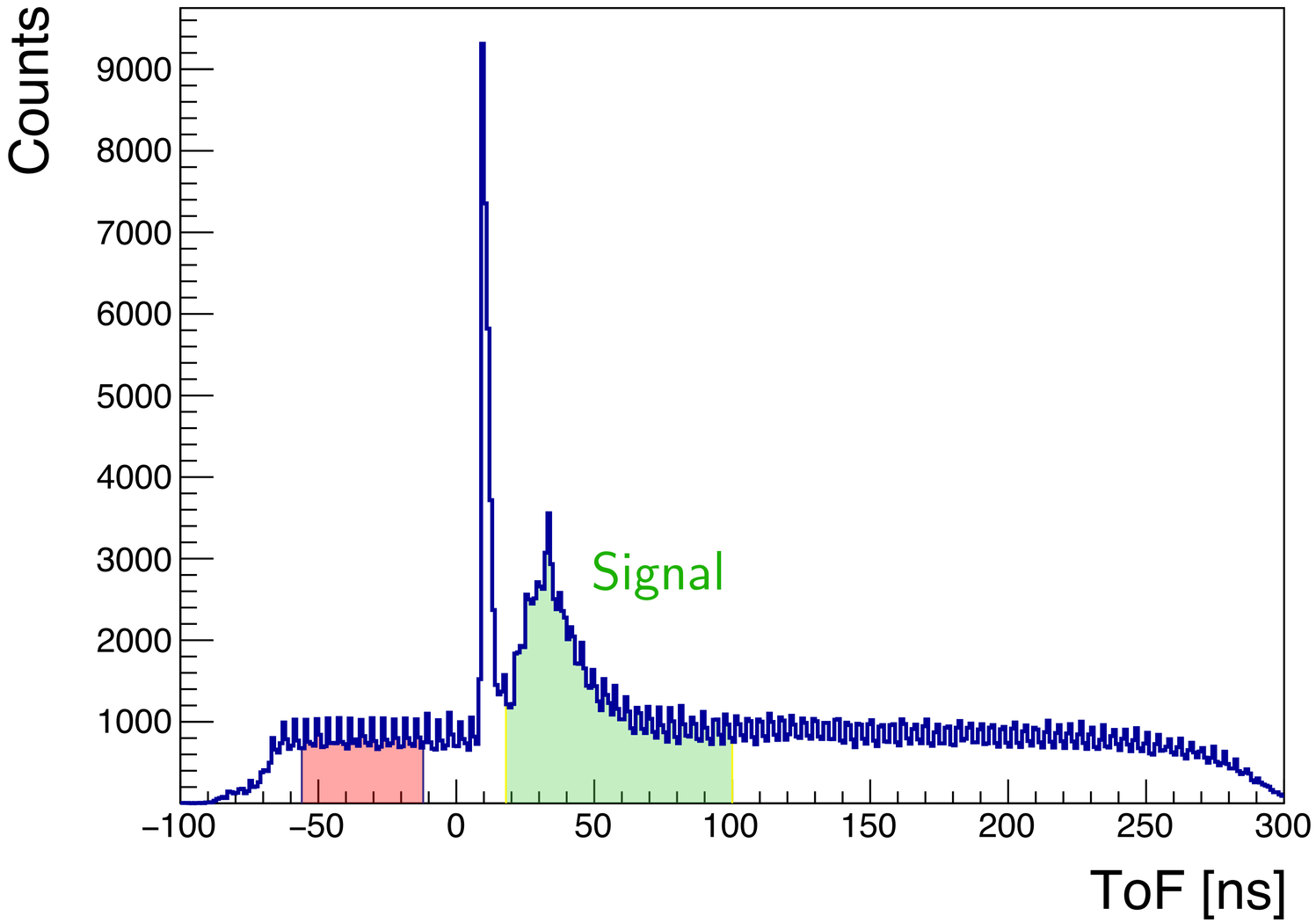
Using electron and neutron

- Form tagged hits (simulation uses smeared electron)



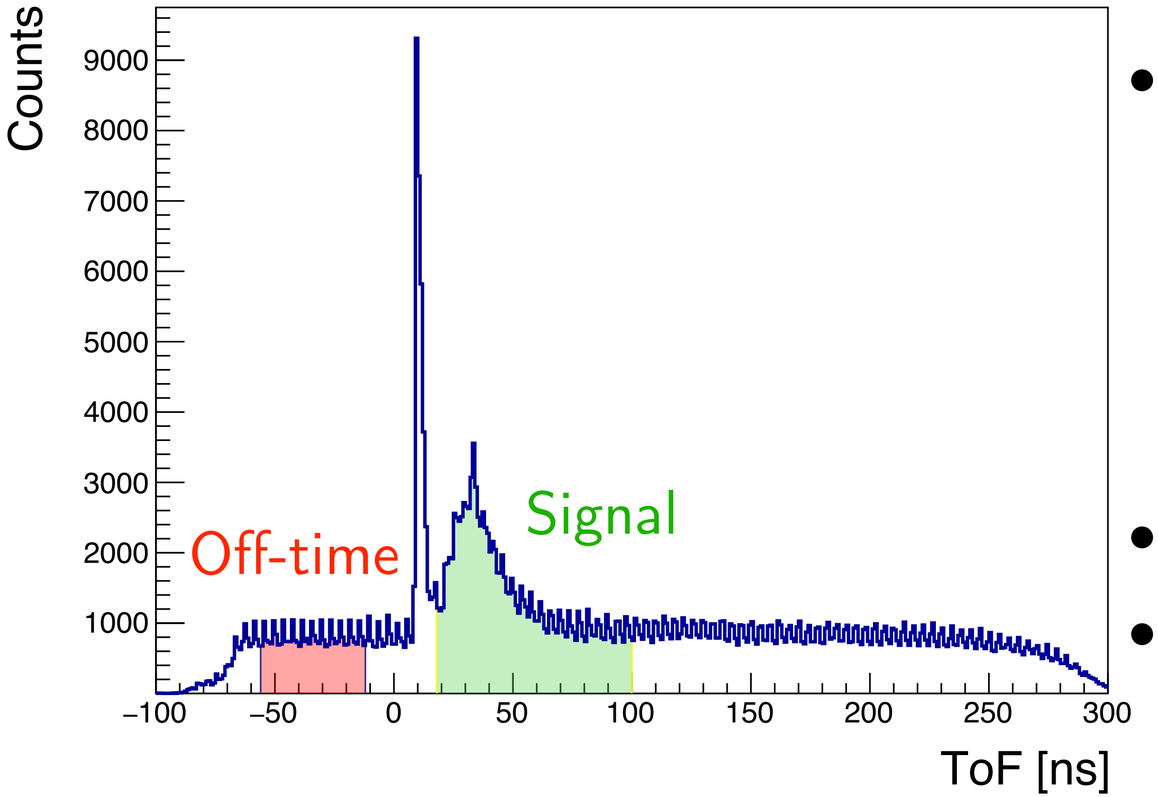
BAND background subtraction

BAND background



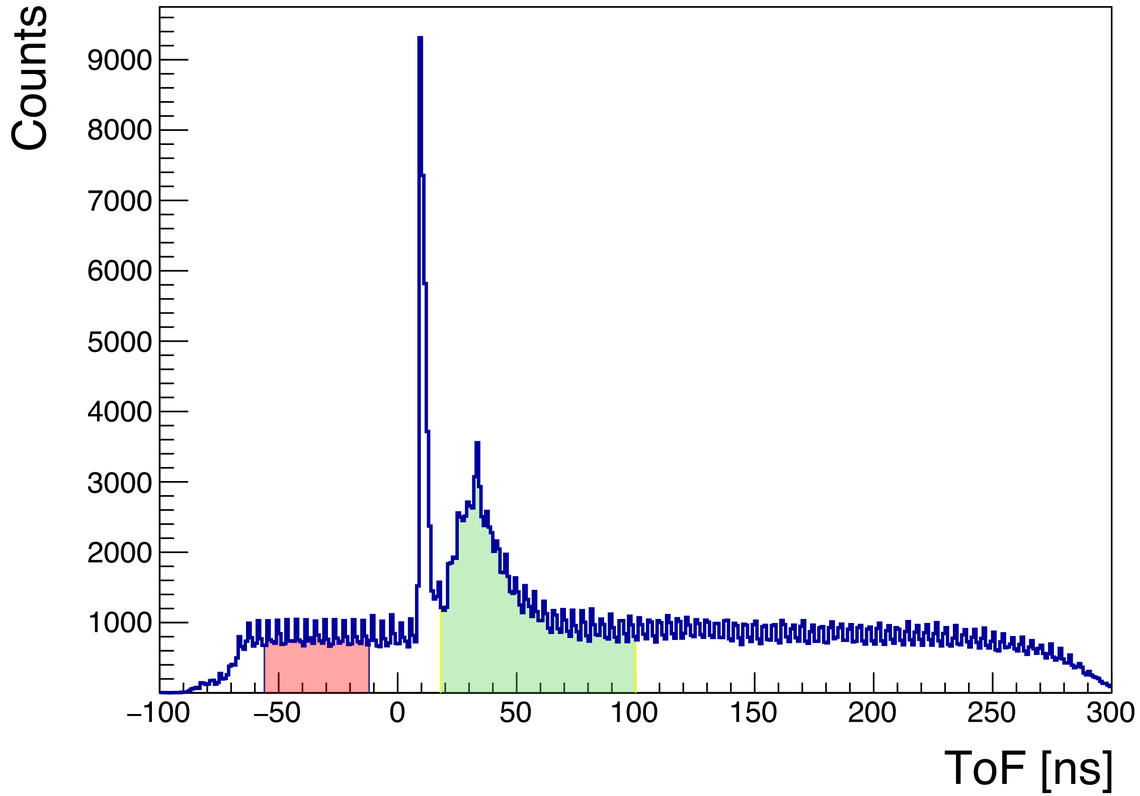
- Signal neutron peak sits atop random coincidence background
- Background has time structure associated with 4 ns beam bunches

Event mixing procedure



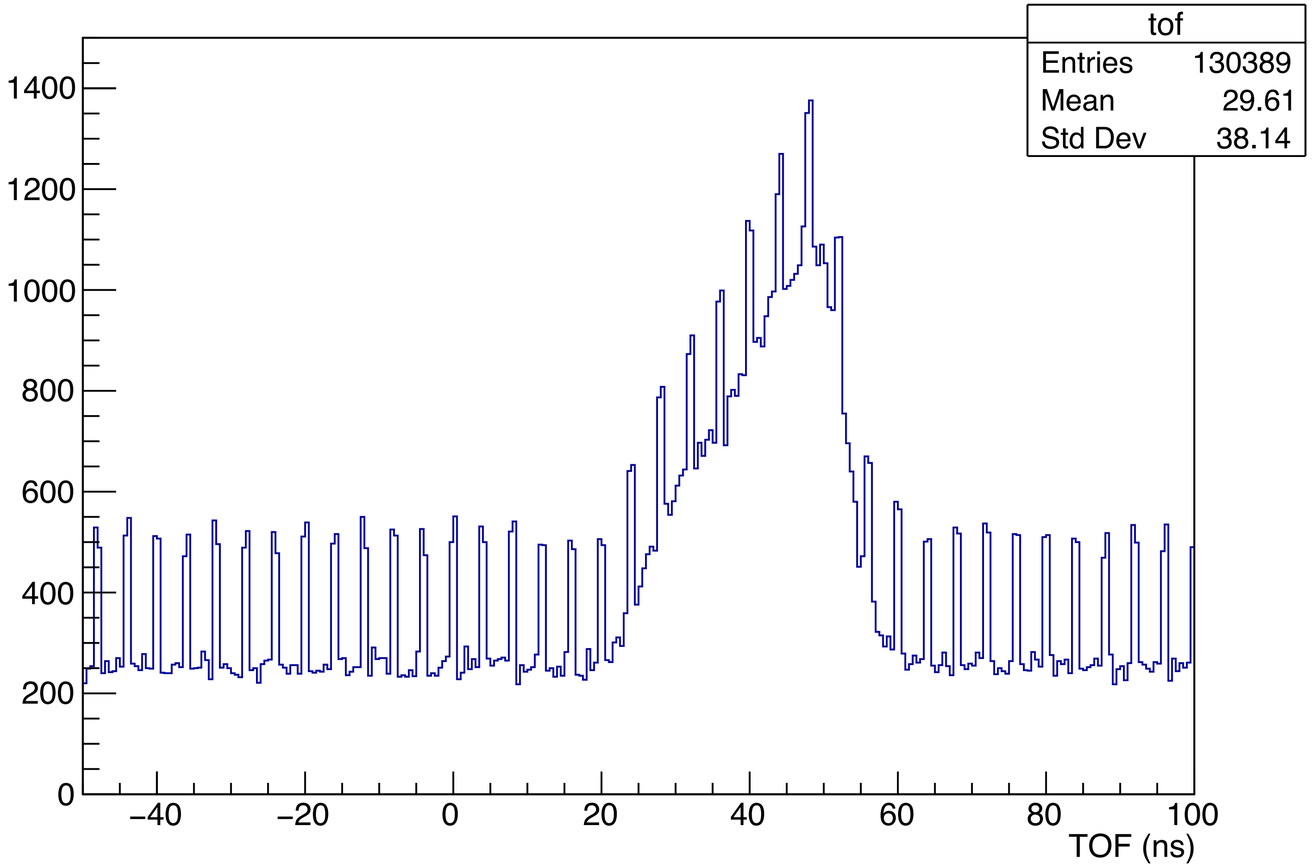
- For each neutron in specified off-time region:
  1. Randomly select inclusive electron
  2. Shift neutron TOF by 4 ns increments until in signal region
  3. Calculate tagged variables and save mixed event
- Repeat steps 2-3 for each 4 ns interval in signal region
- Repeat steps 1-3 for 10 electrons per off-time neutron

Normalization



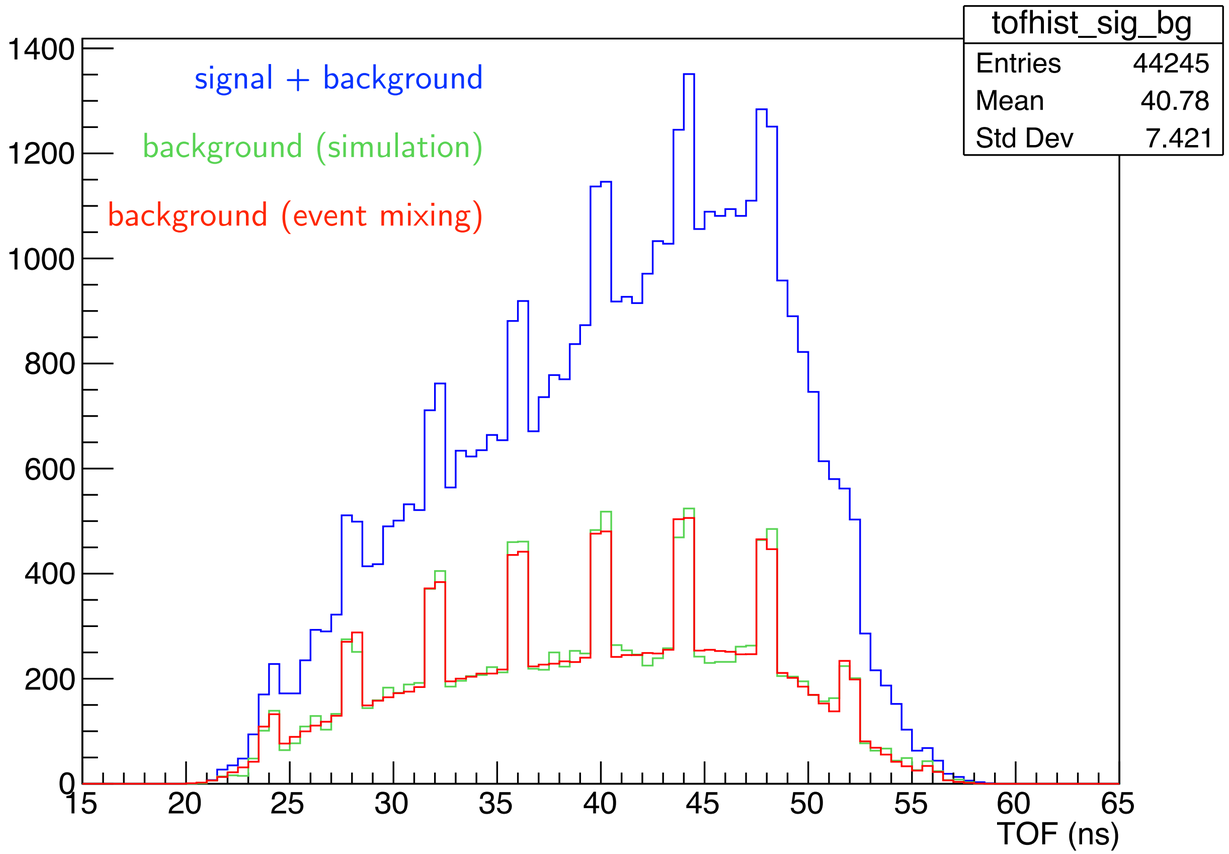
- Event mixing generates high-statistics sample N_{mix} that far exceeds the actual number of background events N_{BG}
- When skimming tagged data files, record number of background events N_{BG} in off-time region
- When filling histograms, subtract event-mixing counts (scaled by N_{BG}/N_{mix}) from data (i.e. signal + background) counts

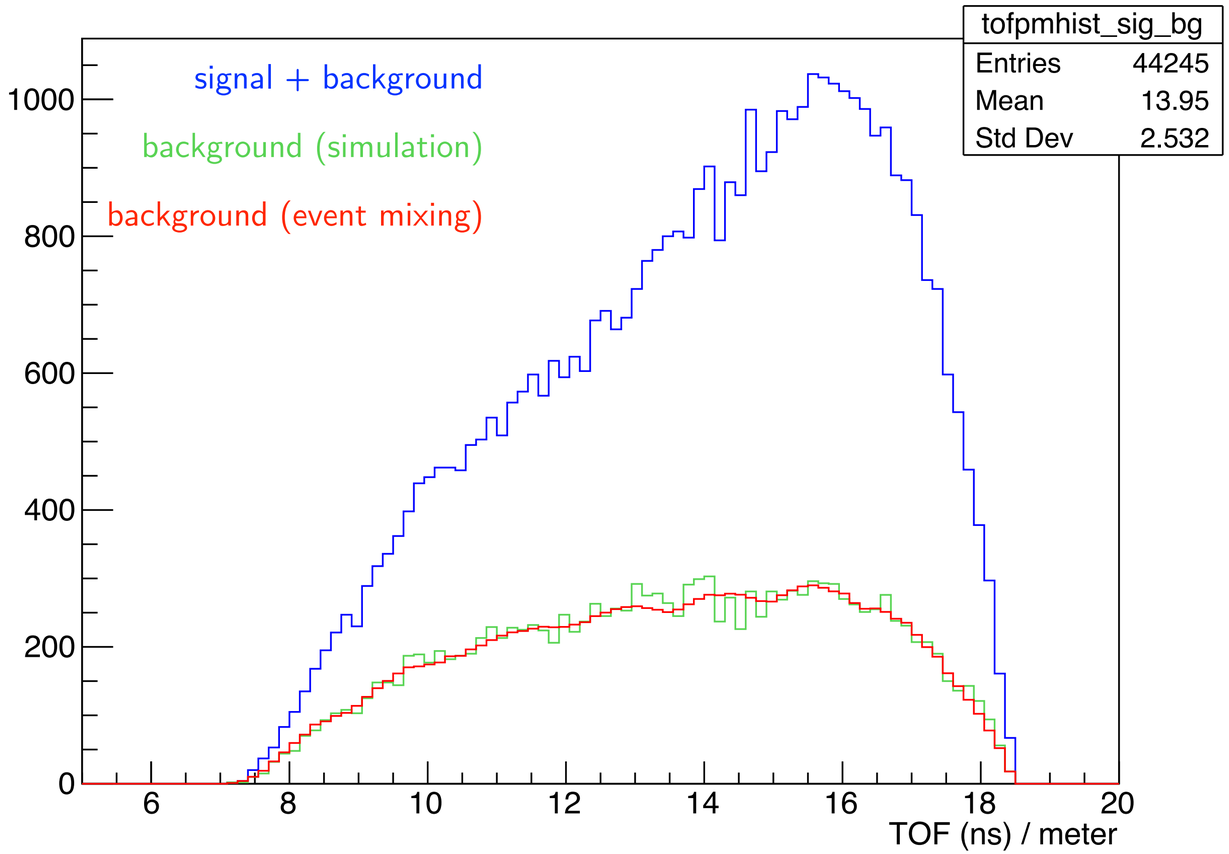
Simulation closure test



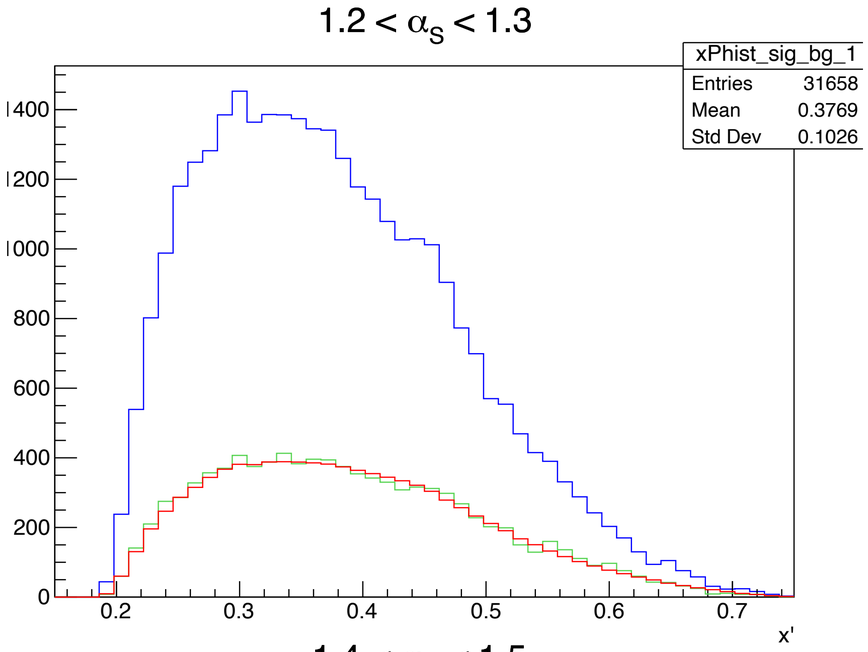
- Simulate background neutrons (flat TOF with square wave pulses) in GEMC
- Merge background neutrons with inclusive electrons to create simulated background events
- Merge background events with signal events to get simulated signal + background file
- Run through event mixing and compare background samples

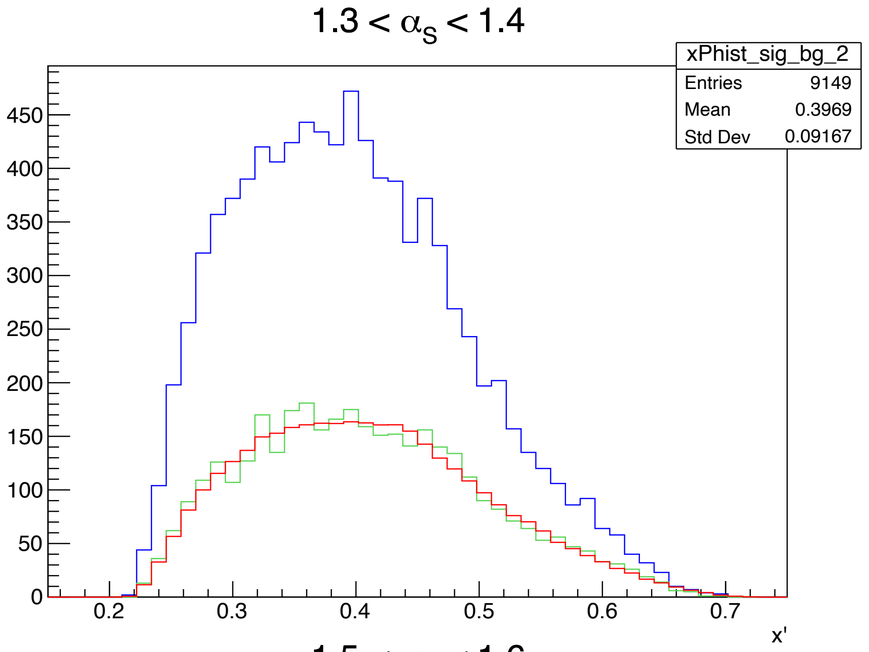
Simulation closure test

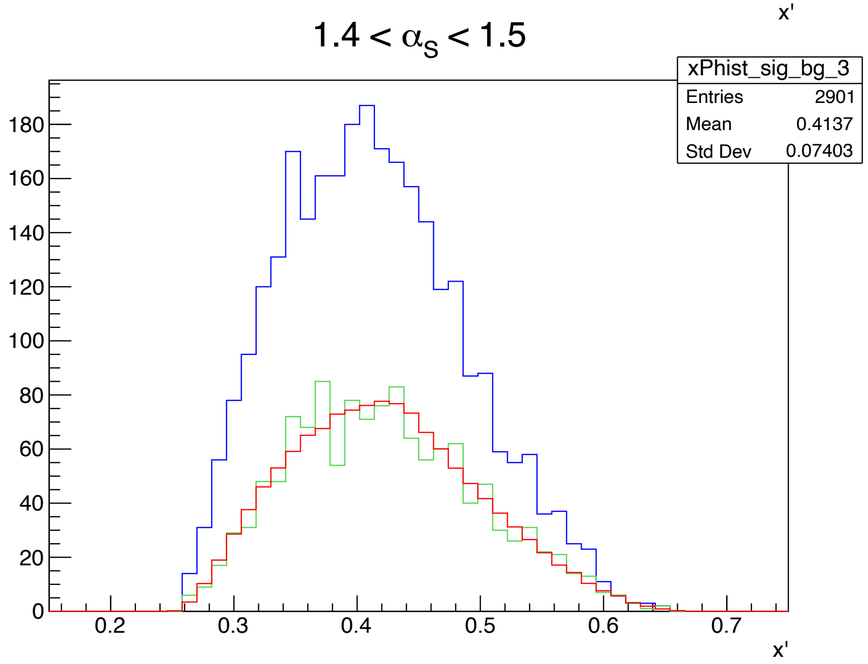


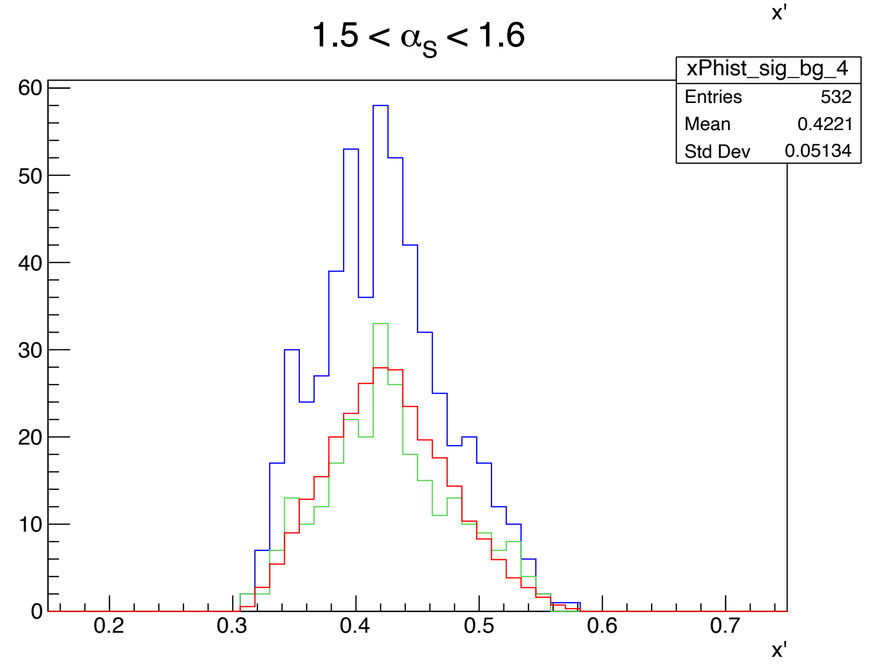


Simulation closure test

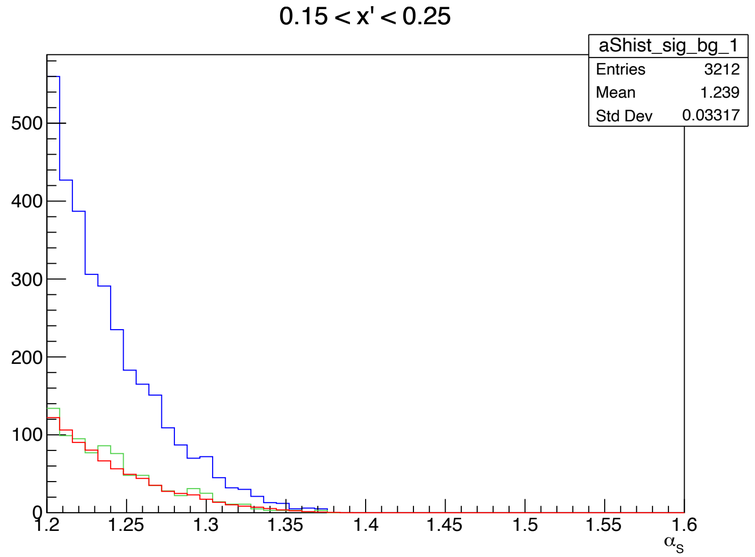


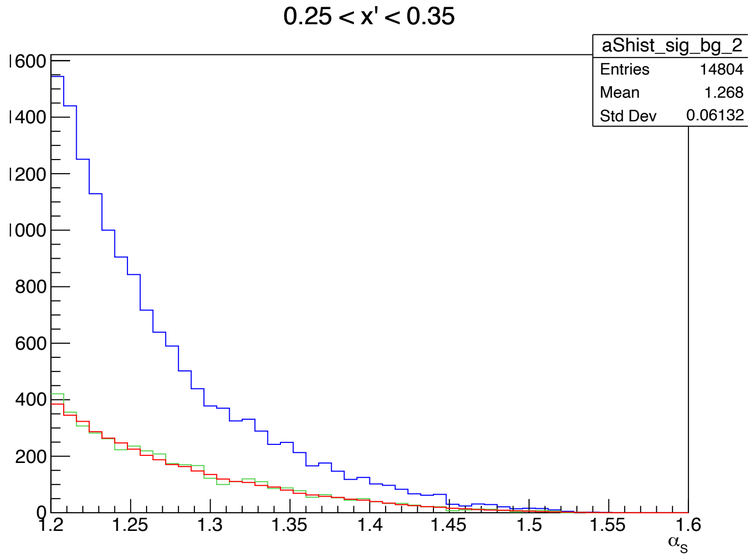


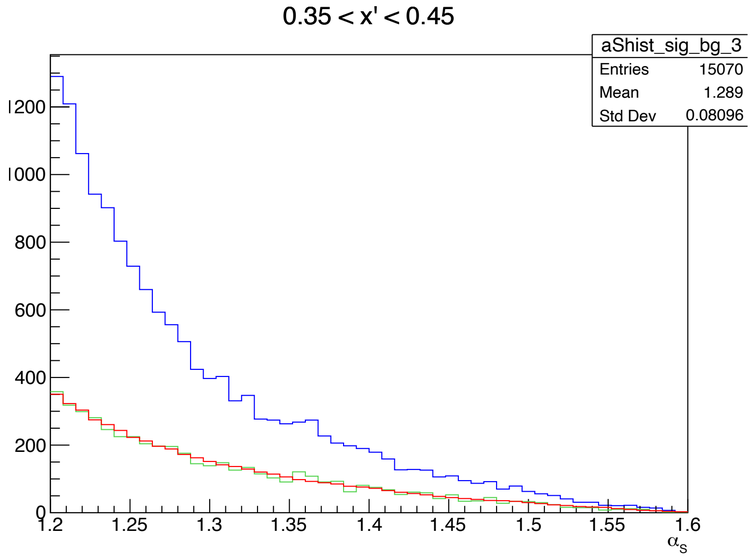


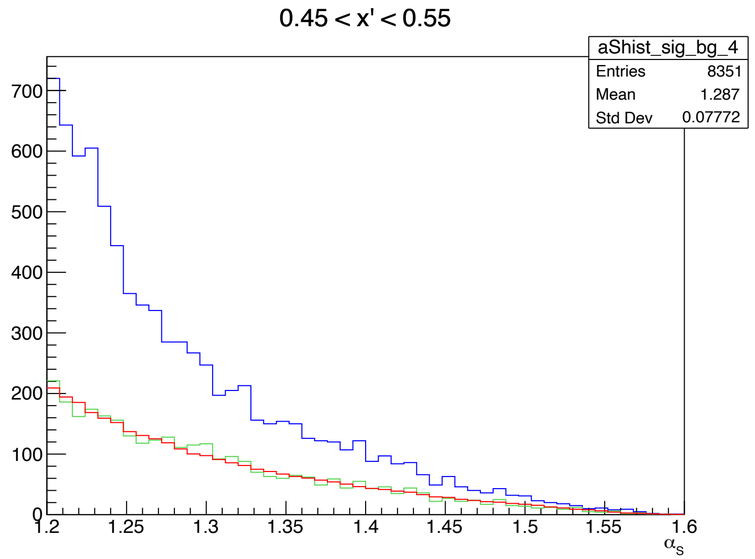


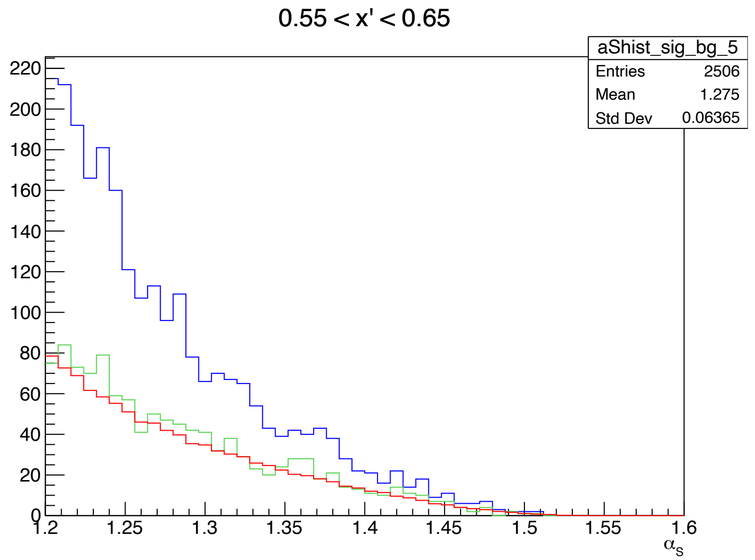
Simulation closure test

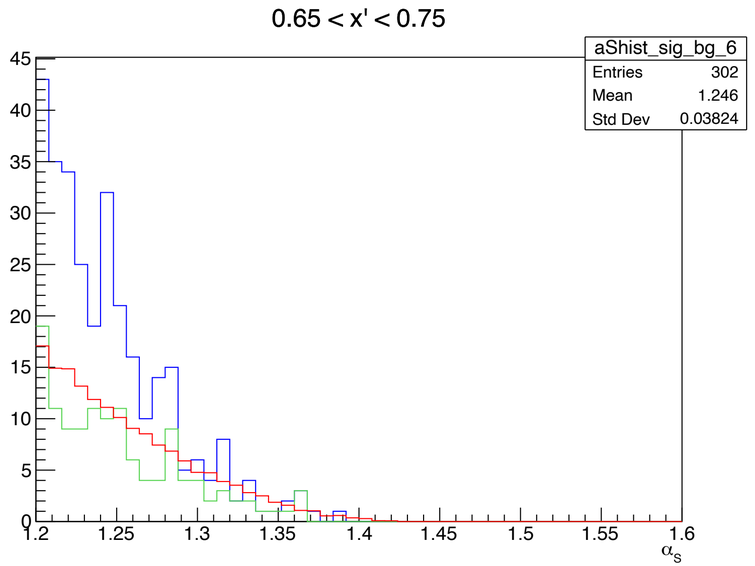




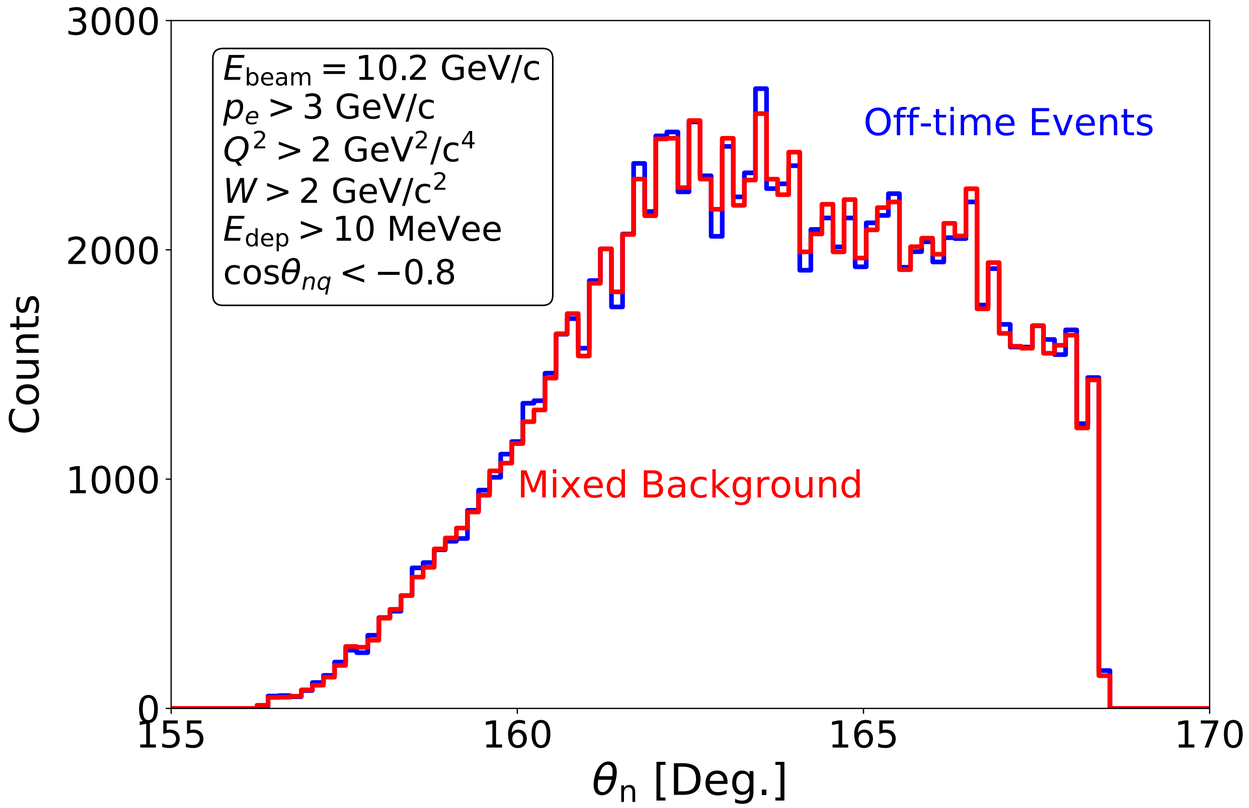


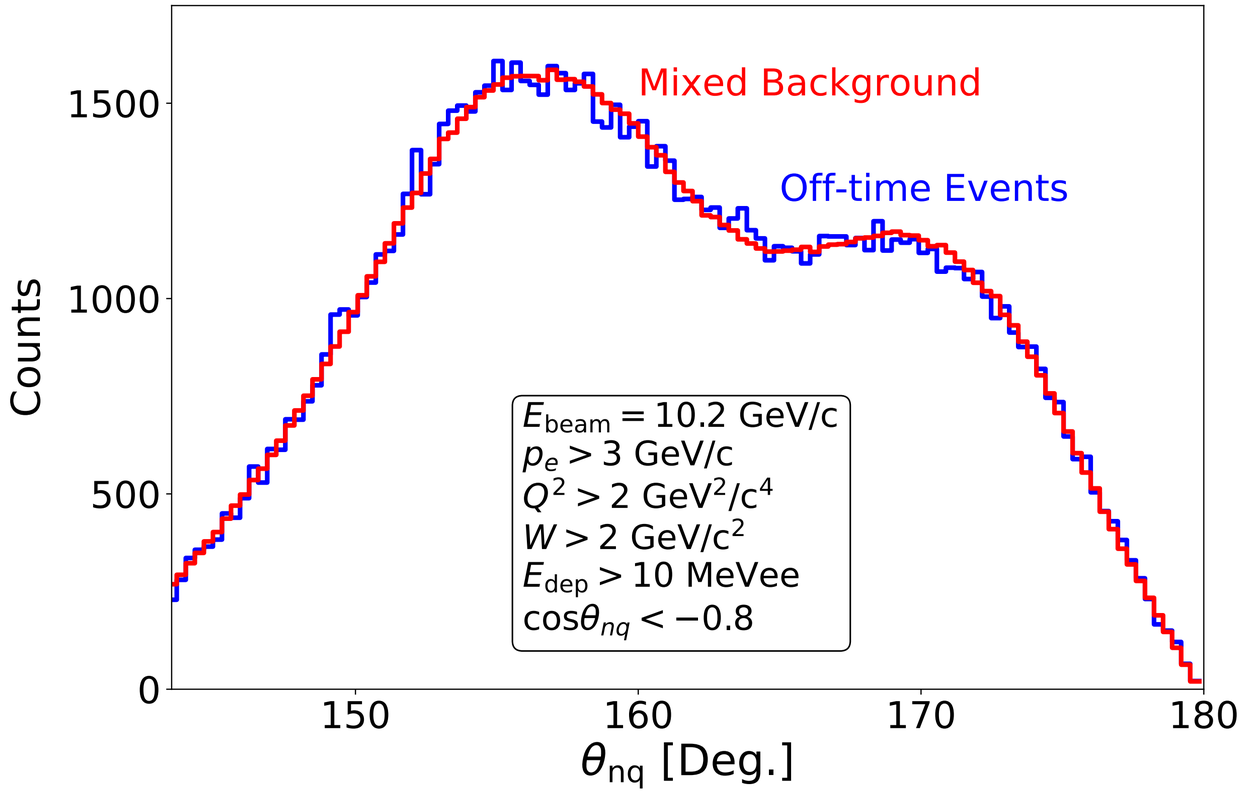






Direct off-time/event mixed comparison

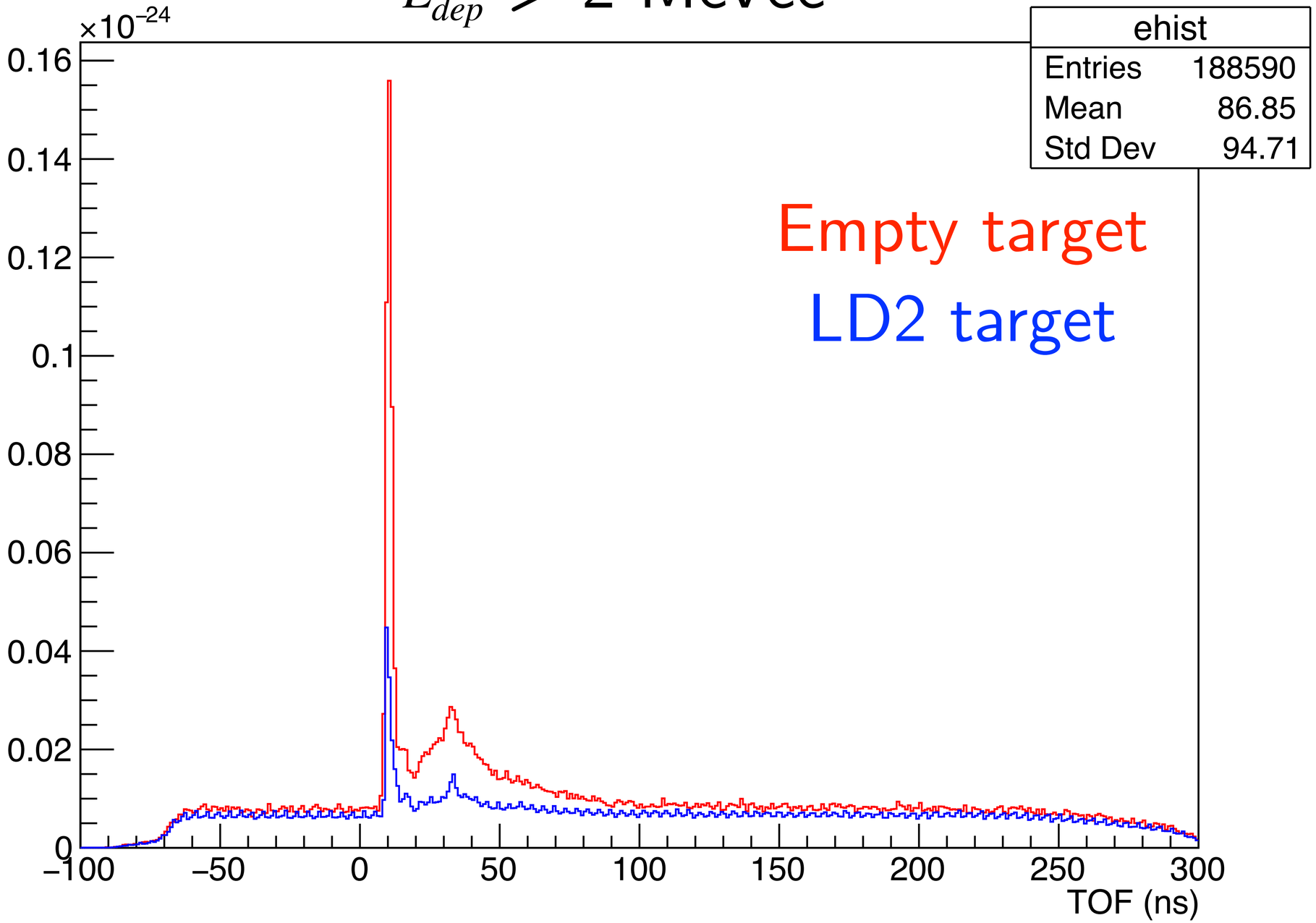




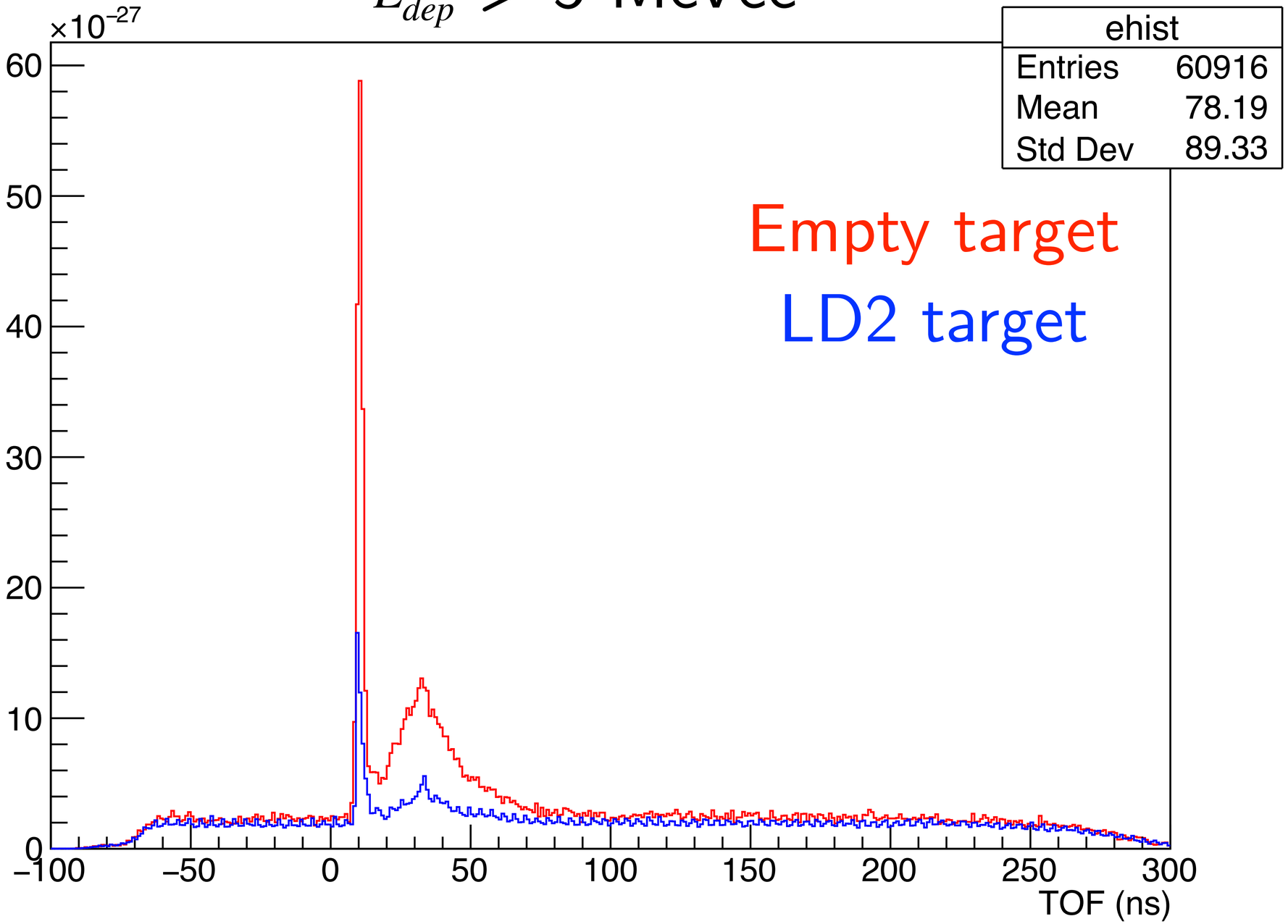
- Can directly compare event-mixed to background distributions of variables *not sensitive to time of flight*
- This provides a pure data validation of event-mixing procedure and normalization

Empty target analysis

$E_{dep} > 2$ MeVee


×10⁻²⁴
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
−100
−50
0
50
100
150
200
250
300
TOF (ns)
ehist
Entries 188590
Mean 86.85
Std Dev 94.71
Empty target
LD2 target

$E_{dep} > 5$ MeVee


×10⁻²⁷
60
50
40
30
20
10
0
−100
−50
0
50
100
150
200
250
300
TOF (ns)
ehist
Entries 60916
Mean 78.19
Std Dev 89.33
Empty target
LD2 target

$E_{dep} > 10$ MeVee