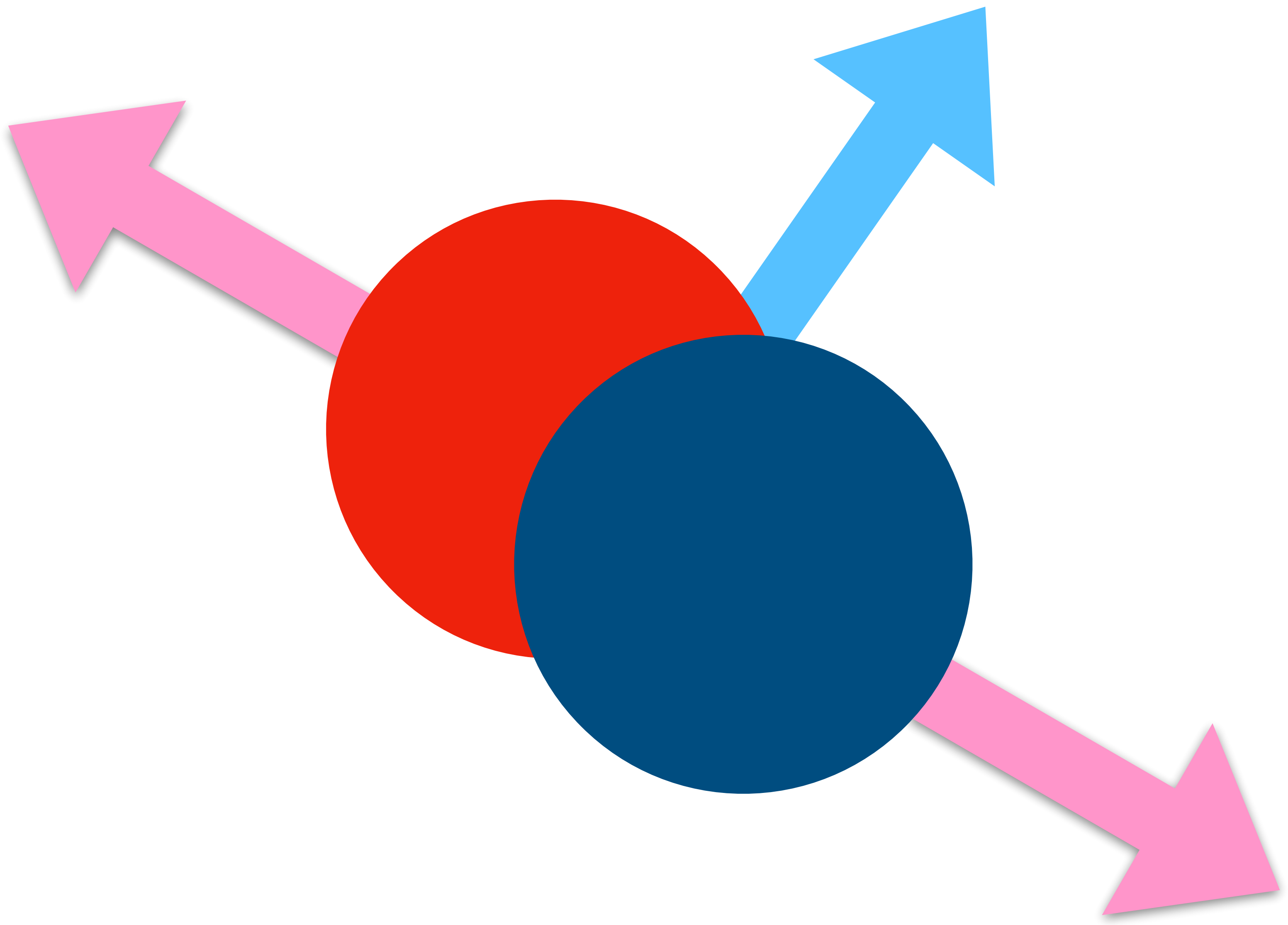
BAND Analysis Update

Jason Phelan (MIT), Nov 20, 2025

Short Range Correlated Nucleons

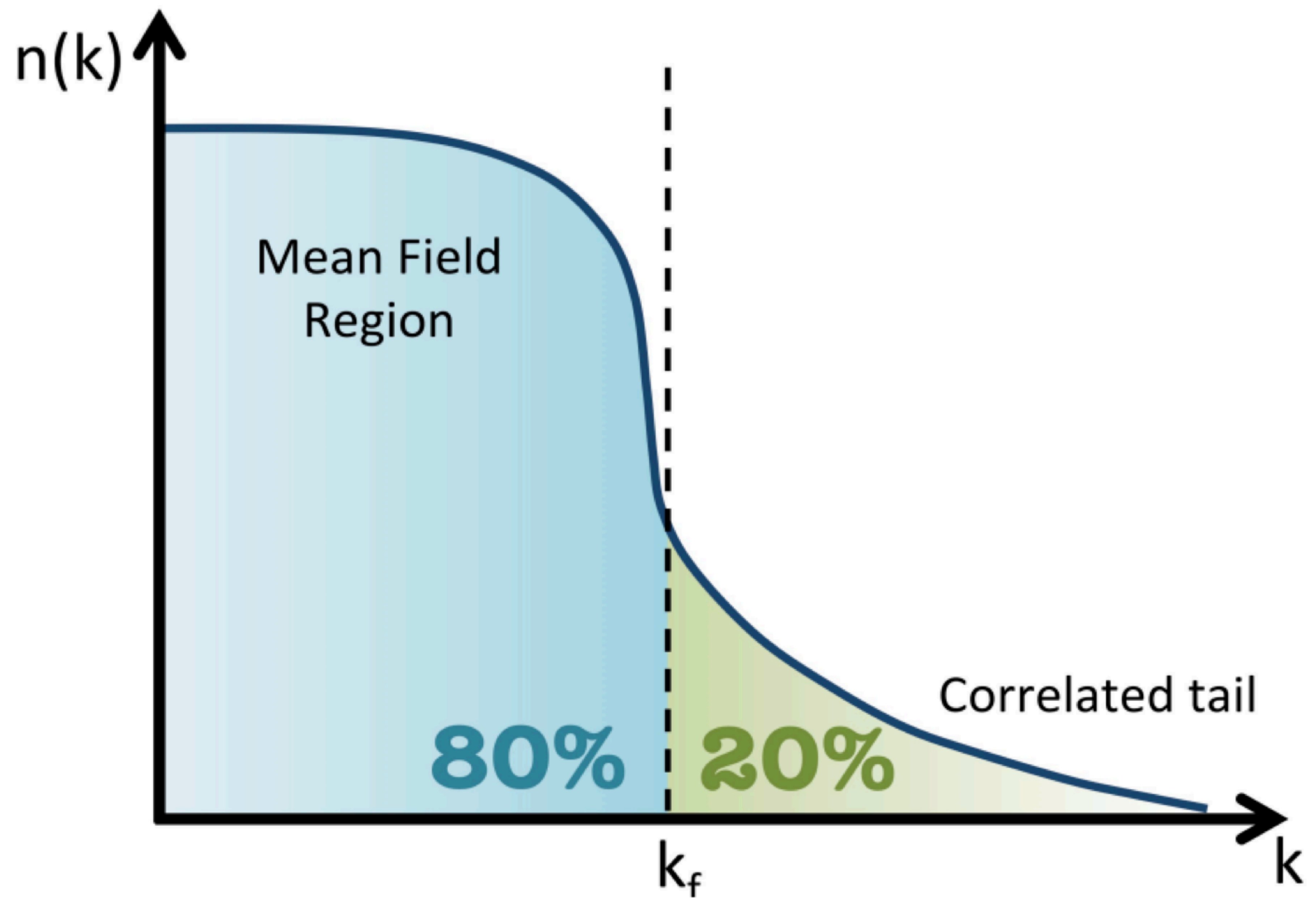


Nucleon pairs with:

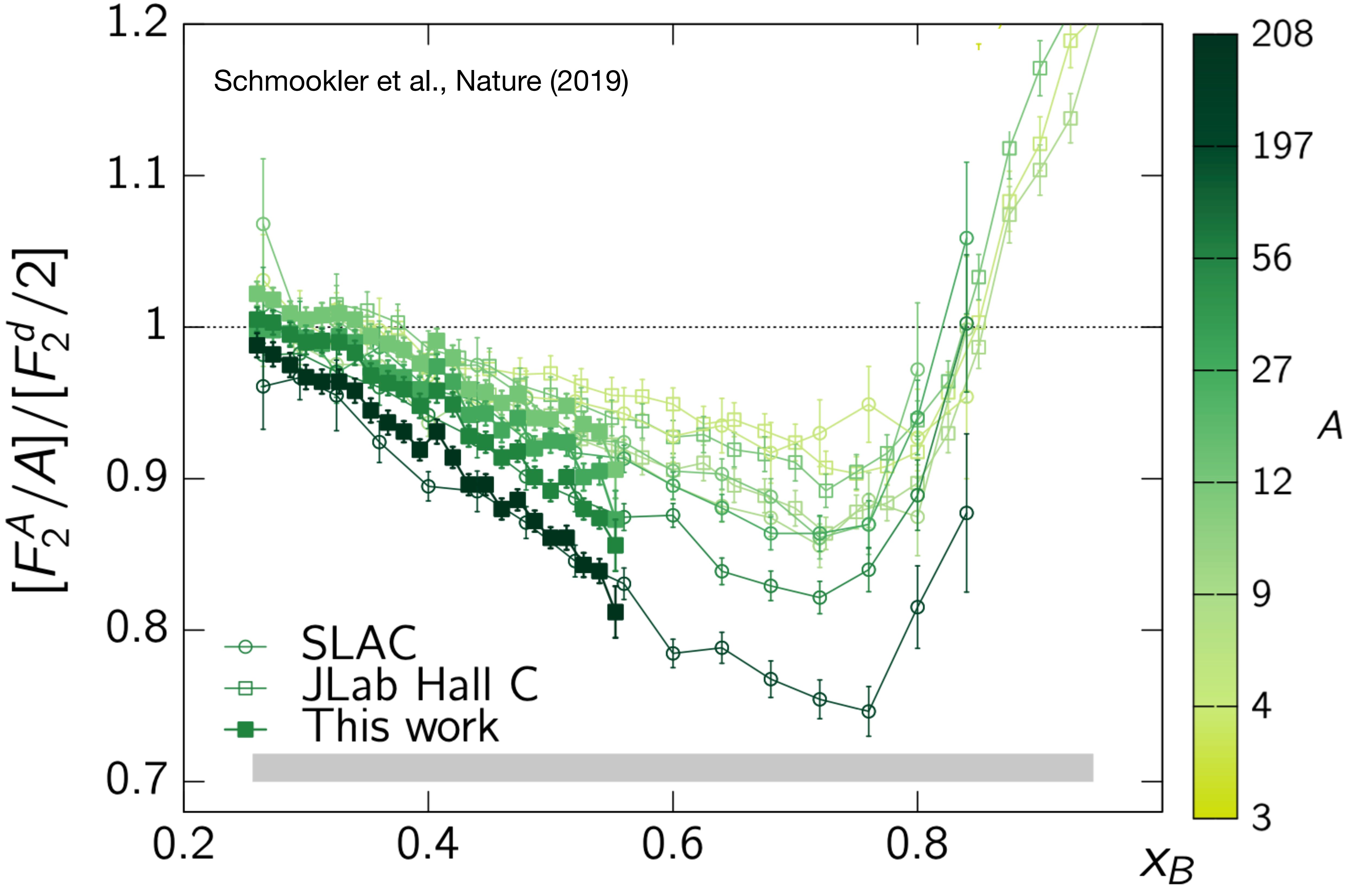
Small spatial separation

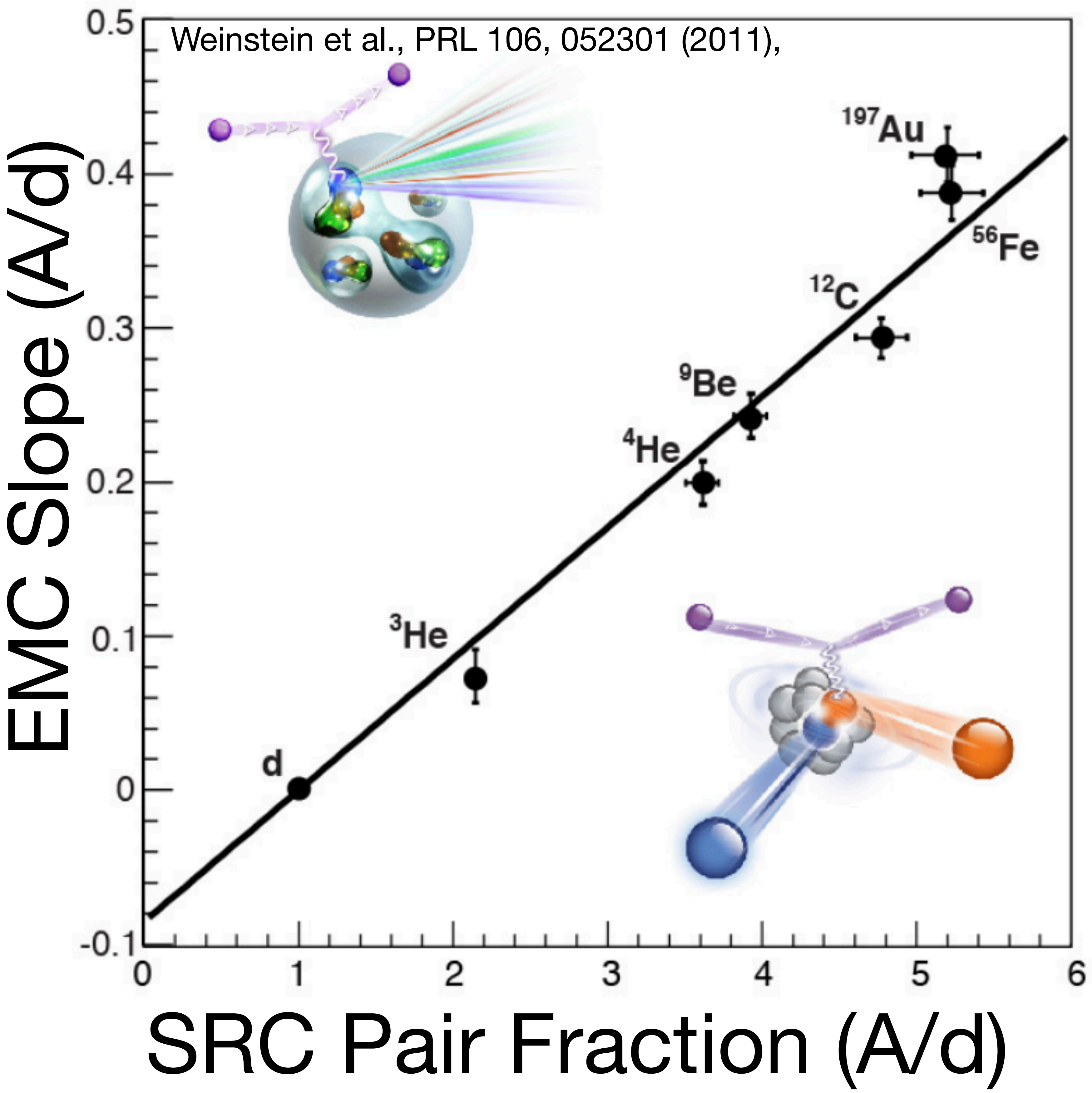
High relative and low CM momentum compared to k_F

Significant contribution to nuclear momentum distribution $p > k_F$

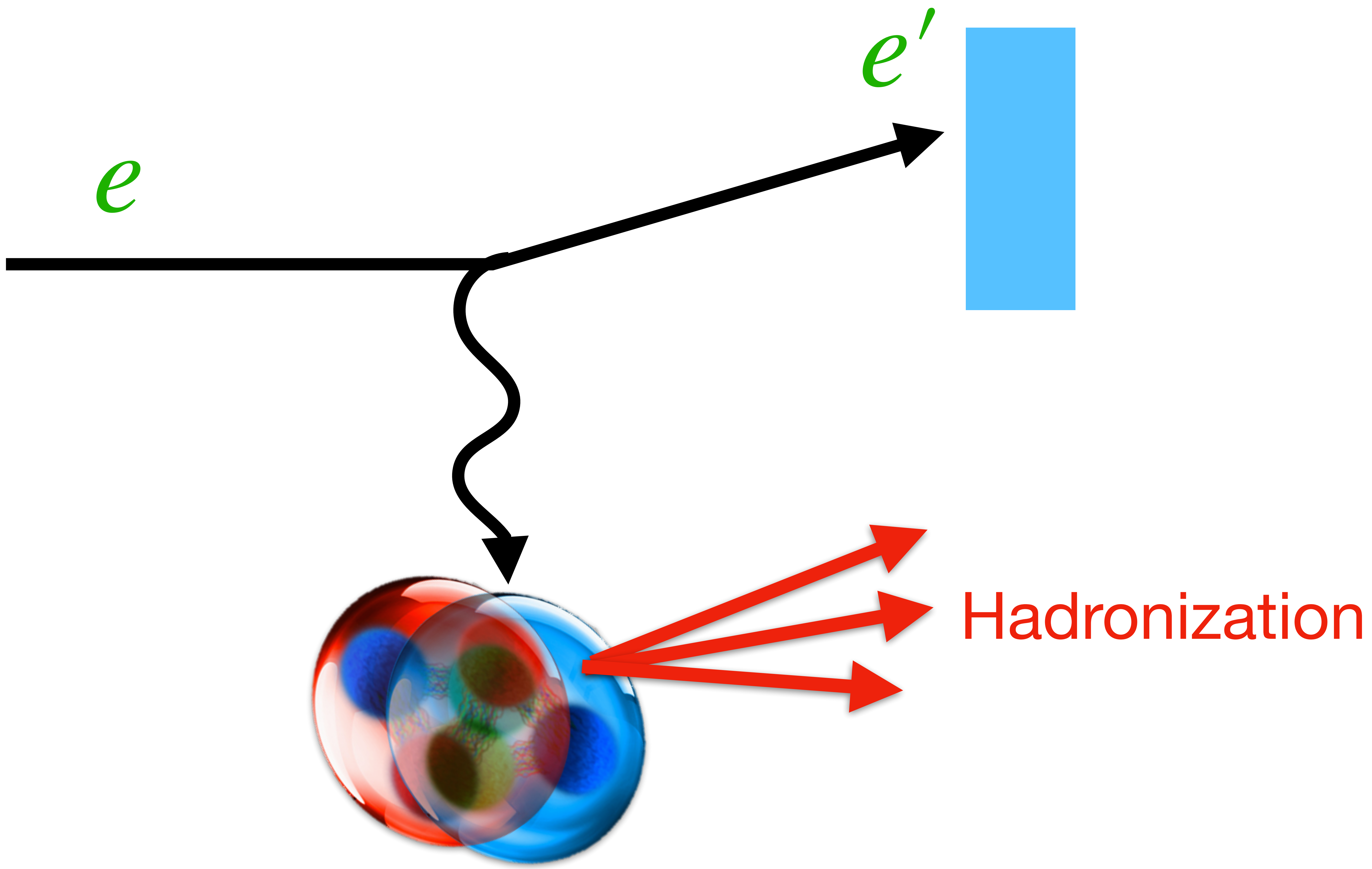


EMC-SRC Hypothesis





How do we bridge the EMC-SRC gap?



Standing nucleon target:

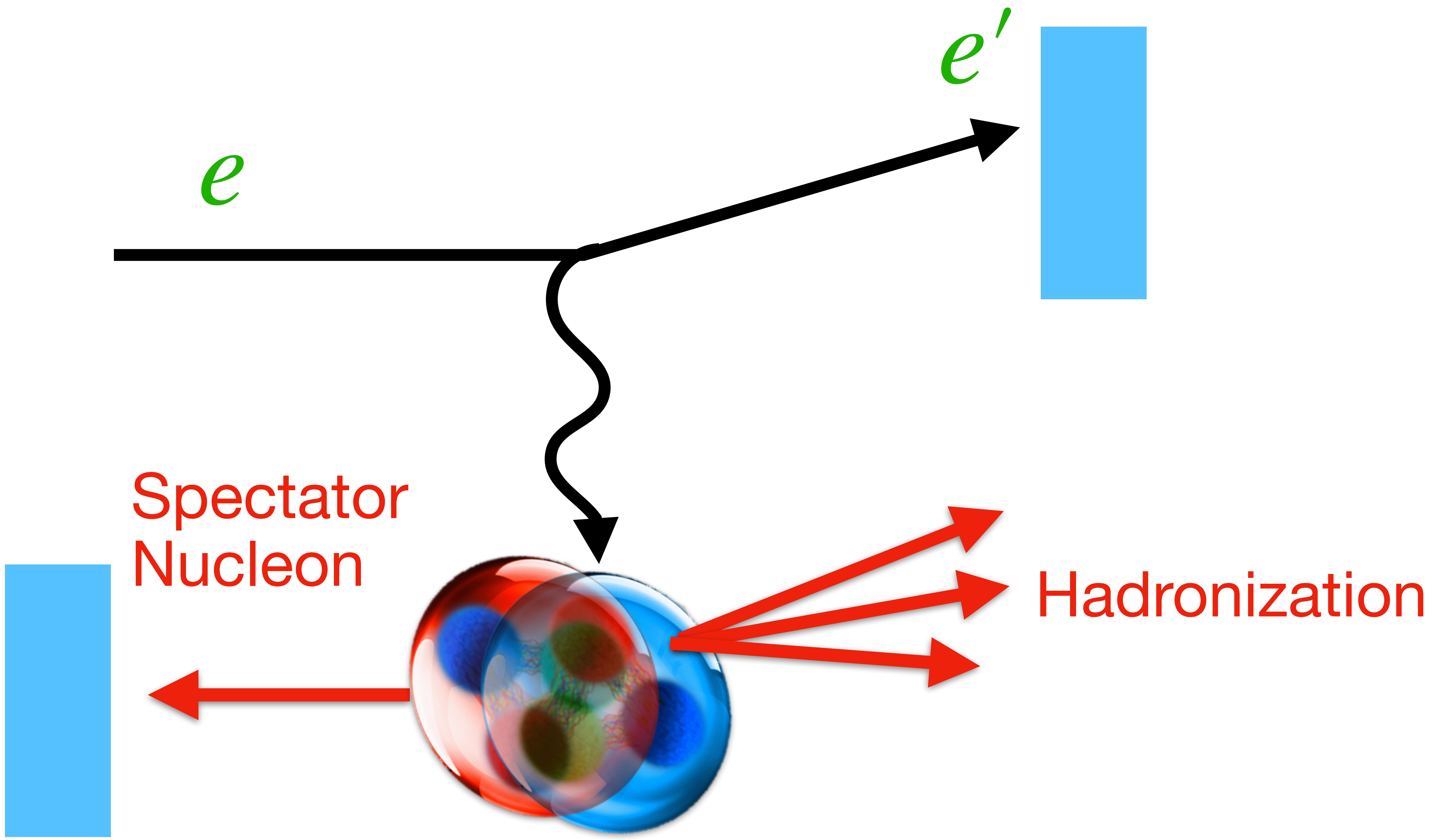
$$p_0 = (m_n\ ,\ 0)$$

$$W^2 = (p_0 + q)^2$$

$$x_B = \frac{Q^2}{2m_n\omega}$$

No information on initial nuclear state

How do we bridge the EMC-SRC gap?



Moving nucleon target:

$$p_\mu = (E, \; -p_s \;)$$

$$(W')^2 = (p_\mu + q)^2$$

$$x' = \frac{Q^2}{(W')^2 - m_n^2 + Q^2}$$

$$\alpha_S = \frac{E_s - p_s \cos\theta_{sq}}{m_n}$$

Tagging the spectator allows us to reconstruct the initial nuclear state

Constructing an observable

PWIA Tagged DIS Cross Section (struck proton):

$$\frac{d\sigma_{tag}}{dx dQ^2 d\alpha dp_\perp} = K(x, Q^2) \cdot S(\alpha, p_\perp) \cdot F_2^{p^*}(x', Q^2, \alpha, p_\perp)$$

Kinematic term **Spectral function** **Tagged structure function**

Constructing an observable

PWIA Tagged DIS Cross Section:

$$\frac{d\sigma_{tag}}{dx dQ^2 d\alpha dp_\perp} = K(x, Q^2) \cdot S(\alpha, p_\perp) \cdot \boxed{F_2^{p^*}(x', Q^2, \alpha, p_\perp)}$$

What we want to determine

Constructing an observable

PWIA Tagged DIS Cross Section:

$$\frac{d\sigma_{tag}}{dxdQ^2d\alpha dp_\perp} = K(x, Q^2) \cdot \boxed{S(\alpha, p_\perp)} \cdot F_2^{p^*}(x', Q^2, \alpha, p_\perp)$$

Normalize σ_{tag} to
$x' = 0.3$ to cancel S
dependence

Constructing an observable

PWIA Tagged DIS Cross Section:

$$\frac{d\sigma_{tag}}{dx dQ^2 d\alpha dp_\perp} = \boxed{K(x, Q^2)} \cdot S(\alpha, p_\perp) \cdot F_2^{p*}(x', Q^2, \alpha, p_\perp)$$

Compare σ_{tag} to simulation to cancel K dependence

Constructing an observable

$$\mathscr{R} = \frac{\sigma_{tag}^{meas.}(x', Q^2, \alpha, p_\perp)}{\sigma_{tag}^{meas.}(.3, Q^2, \alpha, p_\perp)} \Big/ \frac{\sigma_{tag}^{theory}(x', Q^2, \alpha, p_\perp)}{\sigma_{tag}^{theory}(.3, Q^2, \alpha, p_\perp)} = \frac{Y_{tag}^{meas.}(x')}{Y_{tag}^{meas.}(.3)} \Big/ \frac{Y_{tag}^{theory}(x')}{Y_{tag}^{theory}(.3)}$$

$$\mathscr{R} \approx \frac{F_2^{p*}(x') \,/\, F_2^{p}(x')}{F_2^{p*}(.3) \,/\, F_2^{p}(.3)}$$

Measured **bound** proton structure function

Simulated **free** proton structure function

Constructing an observable

$$\mathscr{R} = \frac{\sigma_{tag}^{meas.}(x', Q^2, \alpha, p_\perp)}{\sigma_{tag}^{meas.}(.3, Q^2, \alpha, p_\perp)} \Bigg/ \frac{\sigma_{tag}^{theory}(x', Q^2, \alpha, p_\perp)}{\sigma_{tag}^{theory}(.3, Q^2, \alpha, p_\perp)} = \frac{Y_{tag}^{meas.}(x')}{Y_{tag}^{meas.}(.3)} \Bigg/ \frac{Y_{tag}^{theory}(x')}{Y_{tag}^{theory}(.3)}$$

$$\mathscr{R} \approx \frac{F_2^{p^*}(x') \,/\, F_2^{p}(x')}{F_2^{p^*}(.3) \,/\, F_2^{p}(.3)}$$

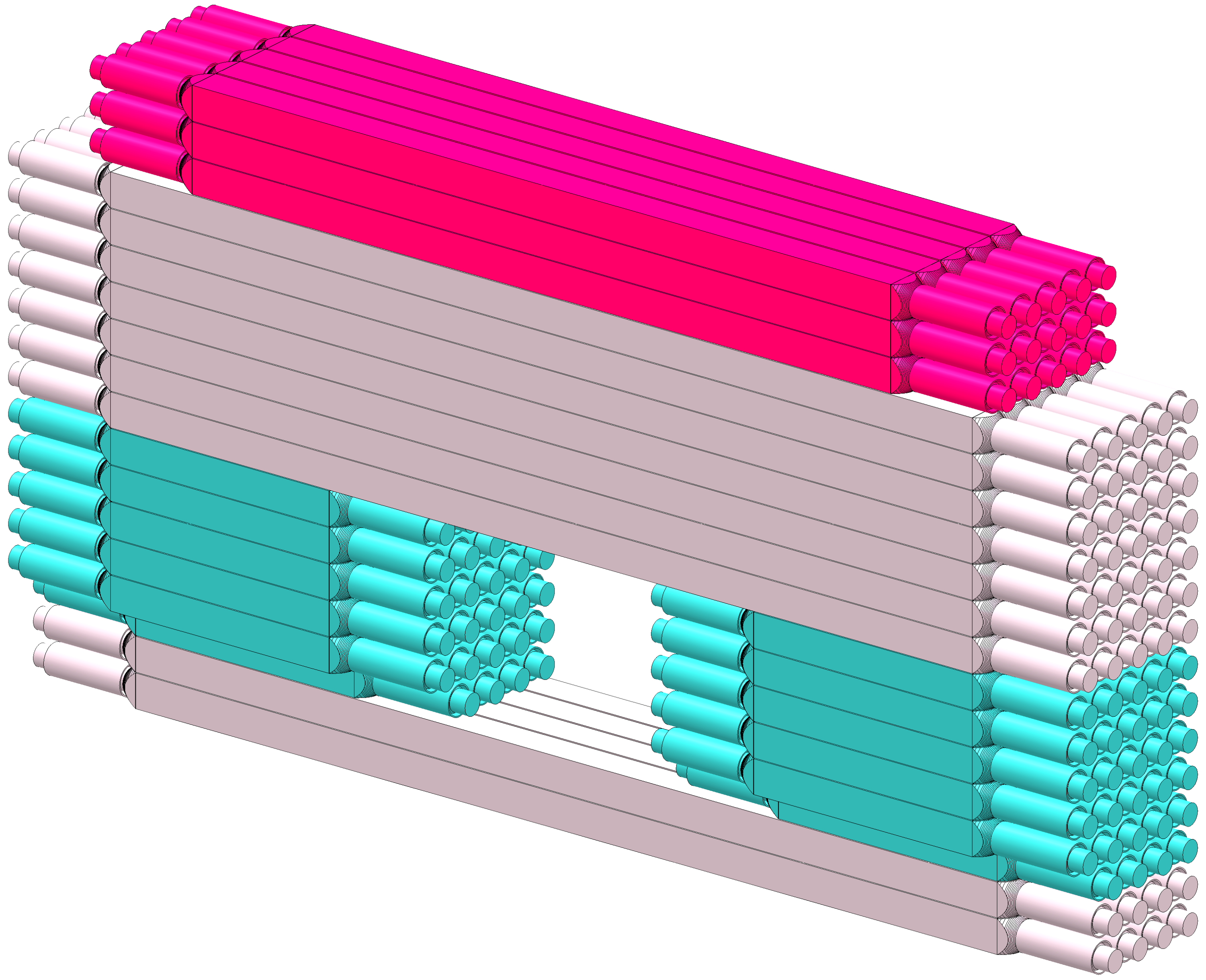
Measured **bound** proton structure function

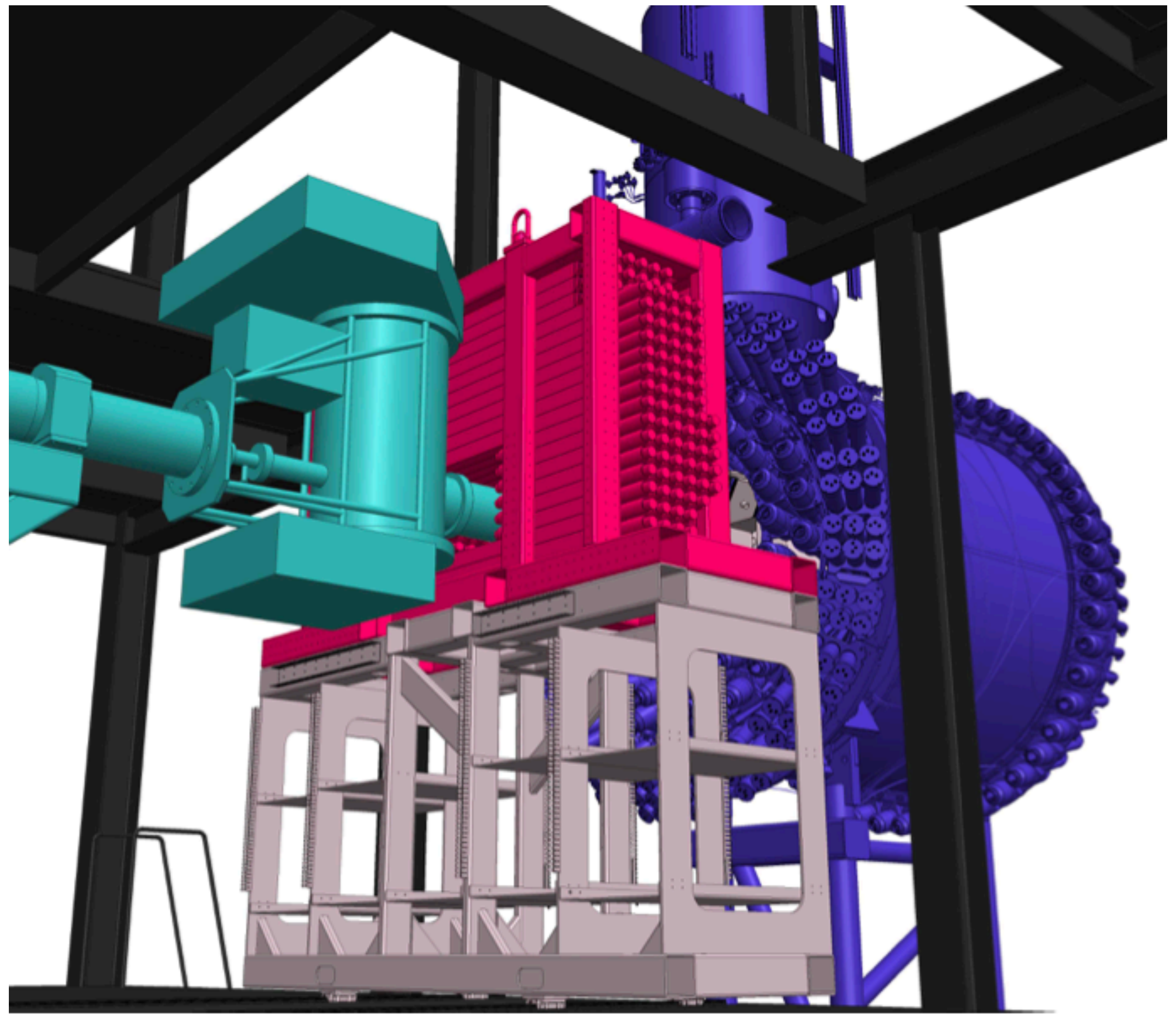
Simulated **free** proton structure function

We will study $\mathscr{R}$ as a function of α and x' with BAND using $d(e, e'n_{spectator})$ reactions

Backwards Angle Neutron Detector (BAND)

Time of flight (TOF) detector installed upstream of CLAS12 detector to measure backward recoiling neutrons from $d(e, e'n)X$ DIS scattering

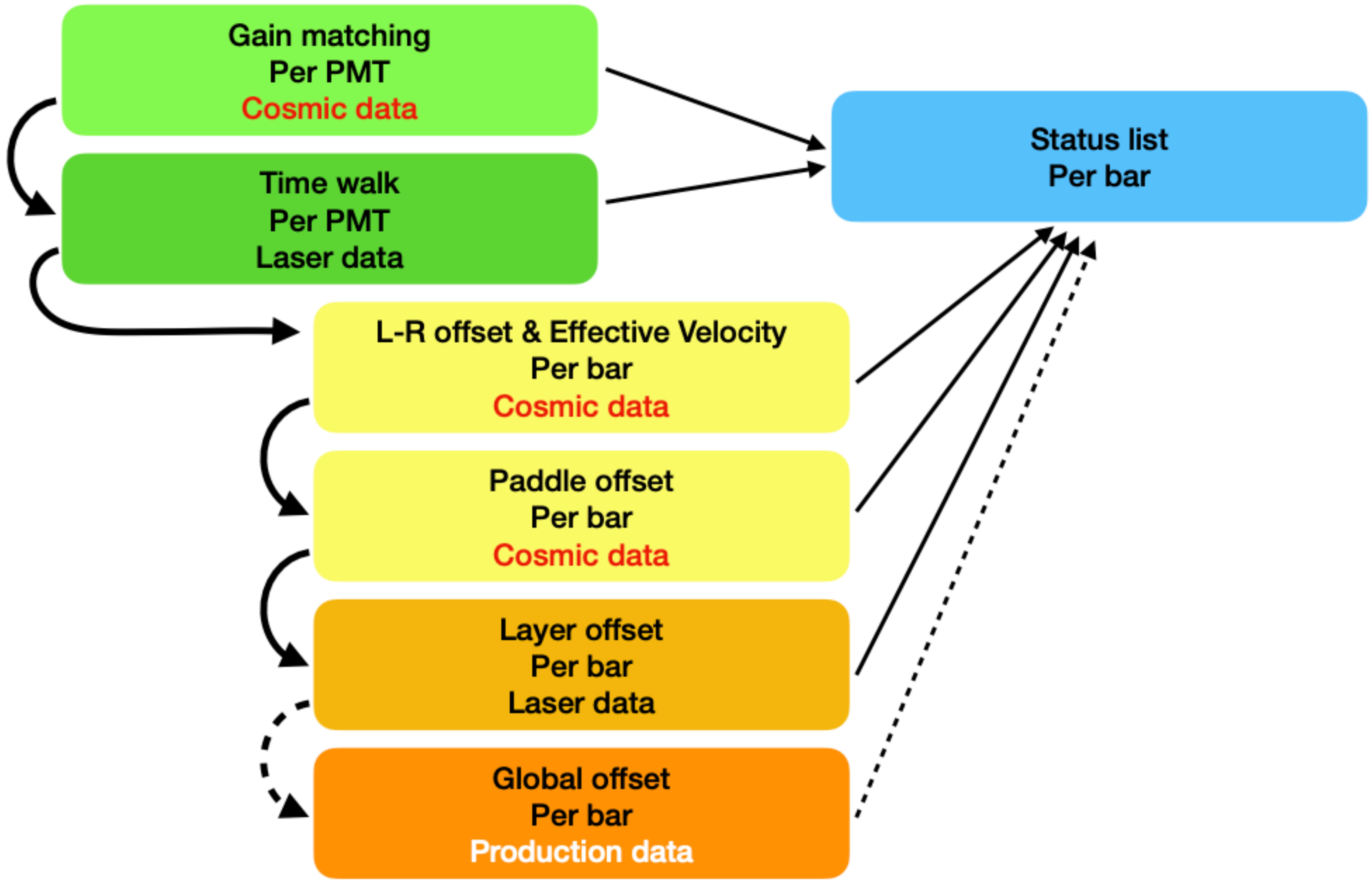




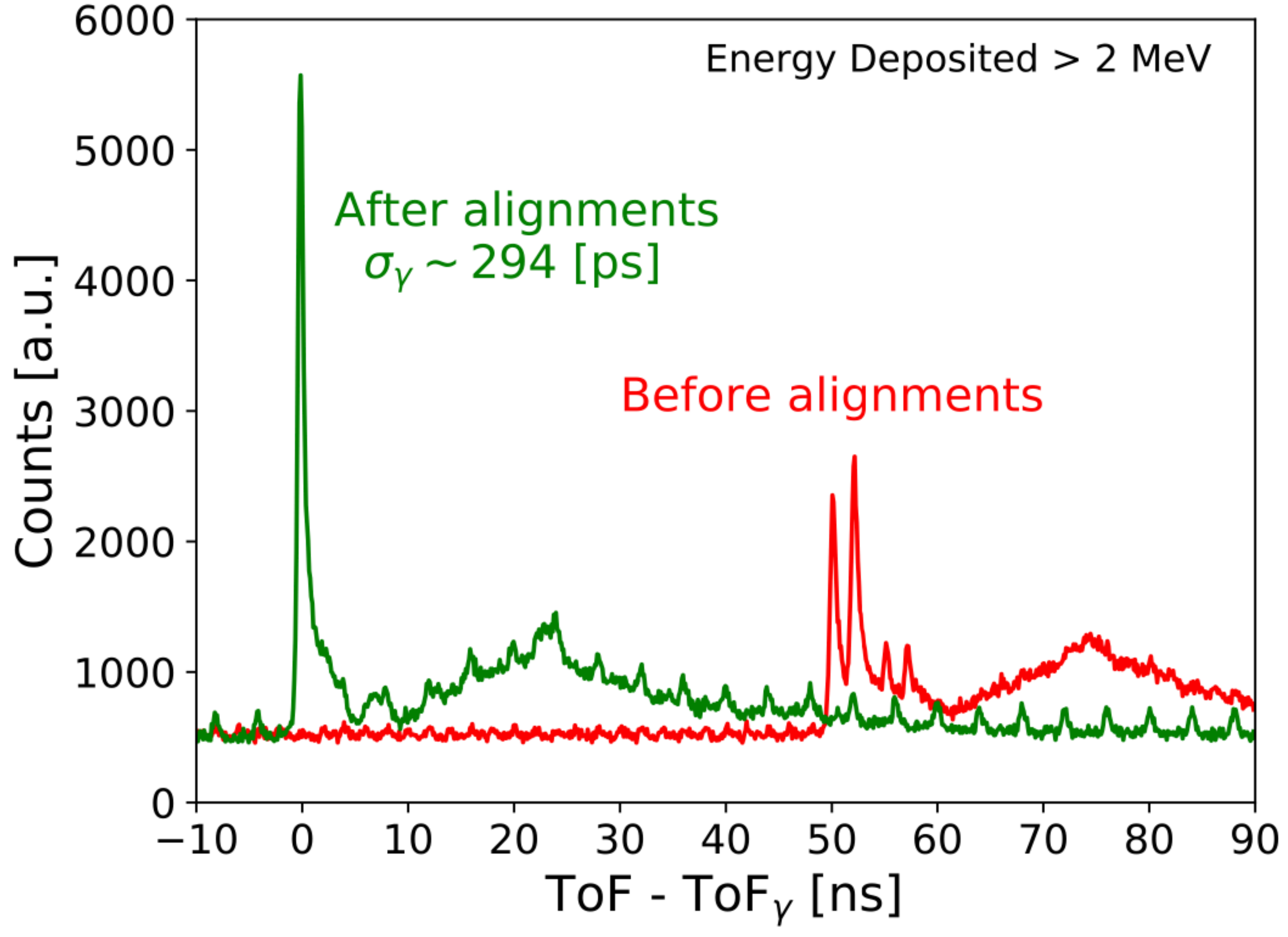
- 5×18 scintillator array with PMT readouts
- Veto layer and lead shield
- Laser calibration and control systems

- Spans polar angles $\theta_n \in (155^\circ, 175^\circ)$
- Sensitive to momenta $0.2 \le p_n \le 0.6$ GeV/c

Calibrations

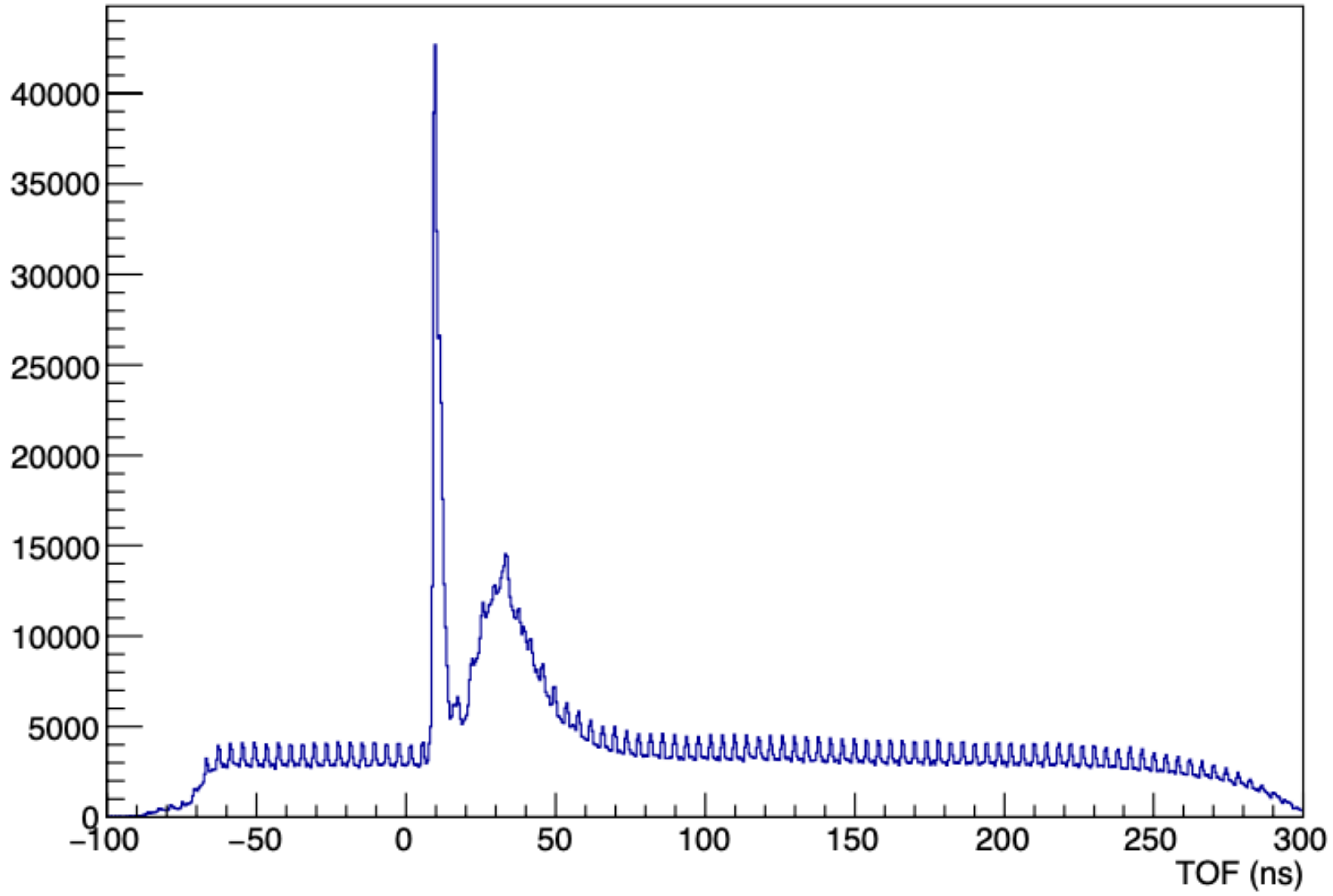


Obtain photon peak with width $\sigma \sim 294$ ps, which matches design resolution



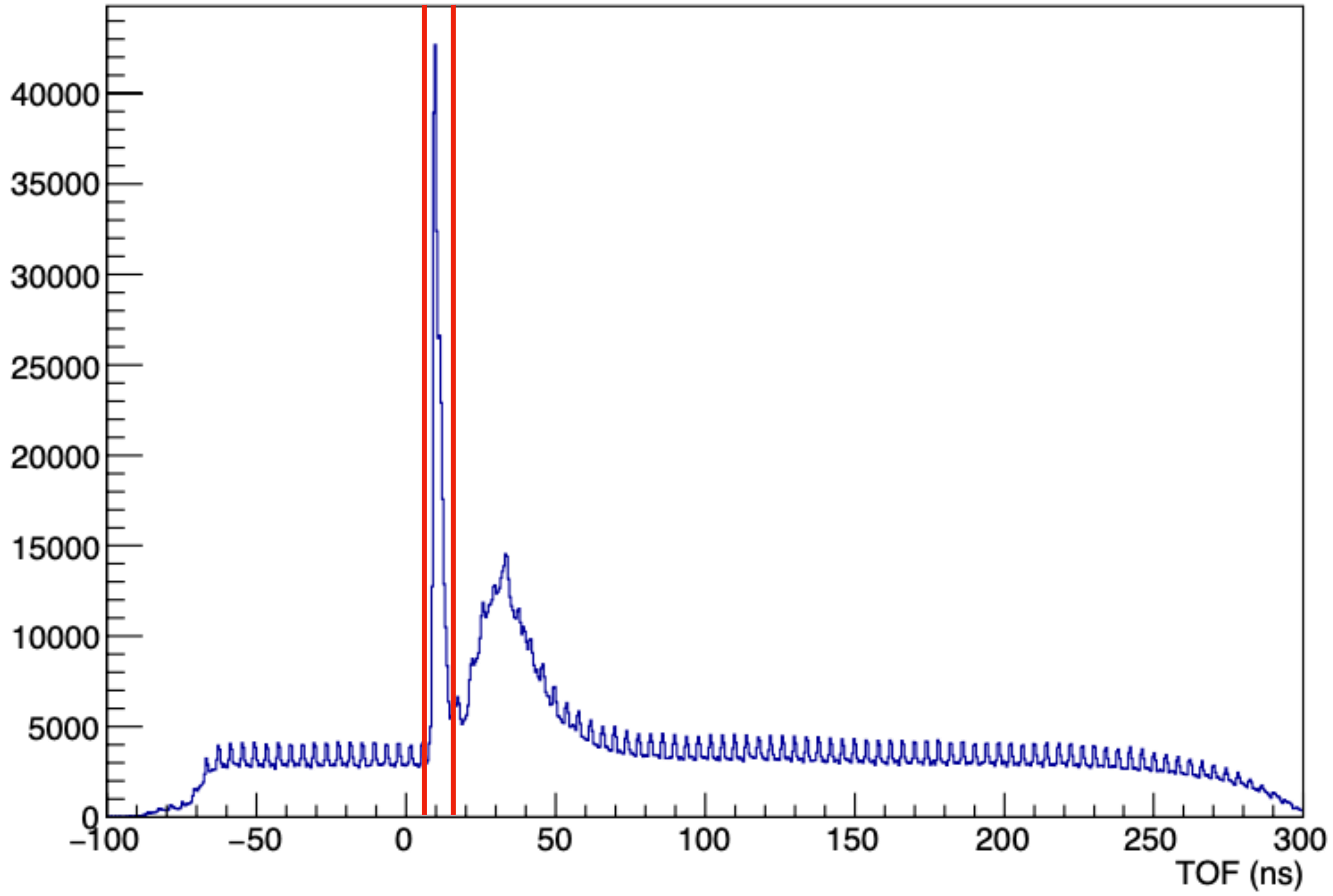
See the NIM paper: E.P Segarra et al., NIM-A 978, 164356 (2020), [arXiv:2004.10339]

After Calibrations and Neutron Reconstruction…



Key Features:

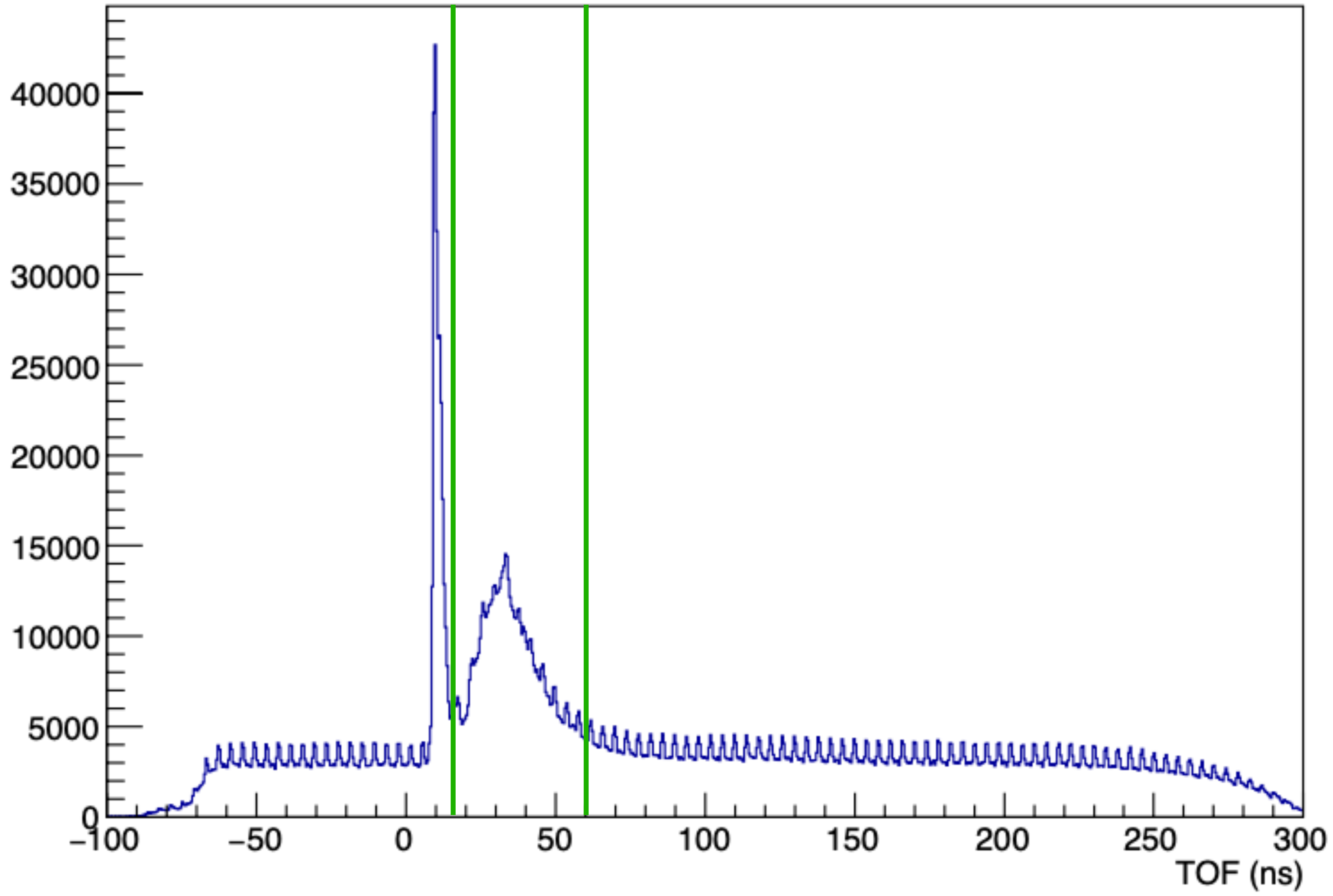
After Calibrations and Neutron Reconstruction…



Key Features:

Photon peak (10 < ToF < 16 [ns])

After Calibrations and Neutron Reconstruction…

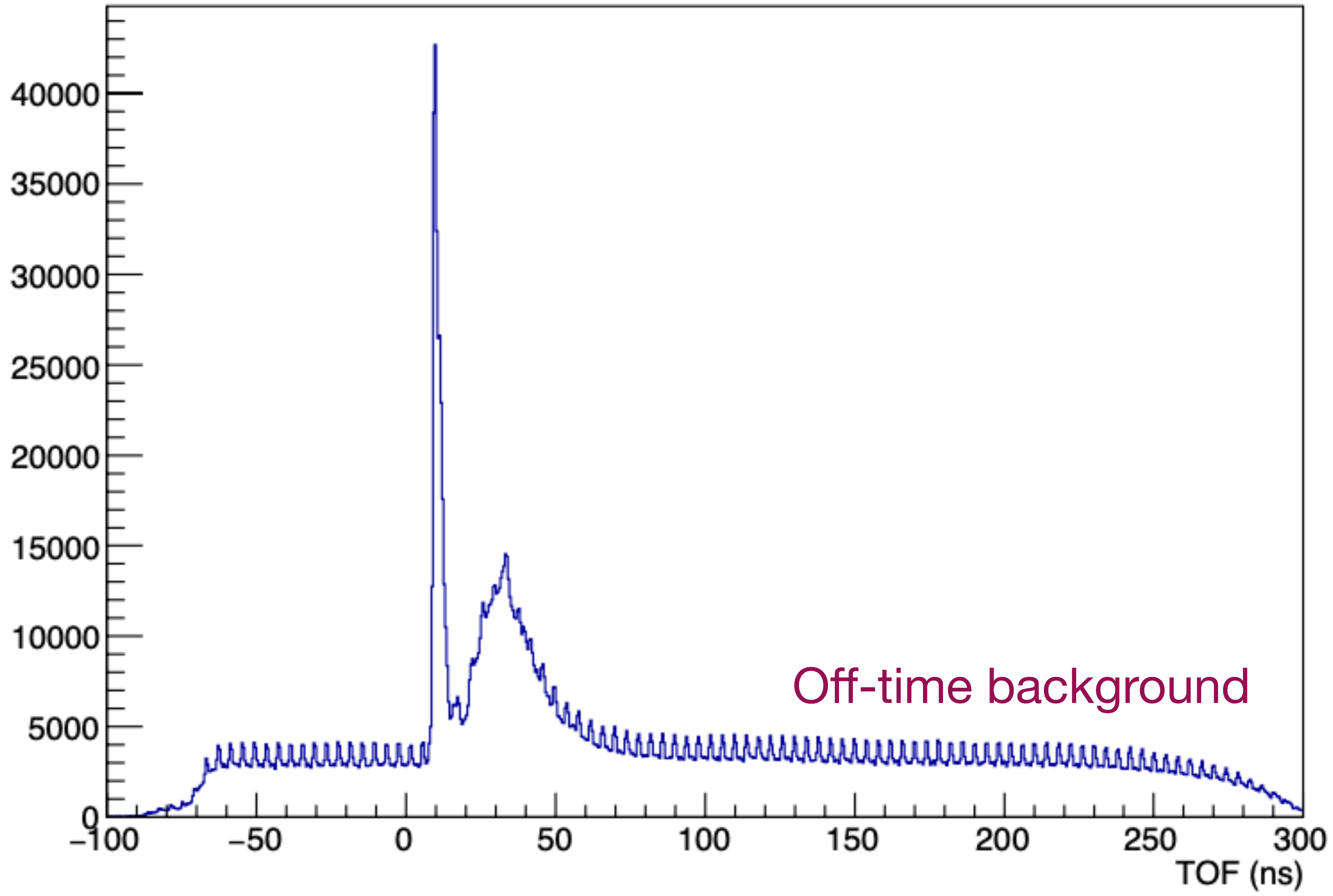


Key Features:

Photon peak (10 < ToF < 16 [ns])

Neutron peak (16 < ToF < 60 [ns])

After Calibrations and Neutron Reconstruction…



Key Features:

Photon peak (10 < ToF < 16 [ns])

Neutron peak (16 < ToF < 60 [ns])

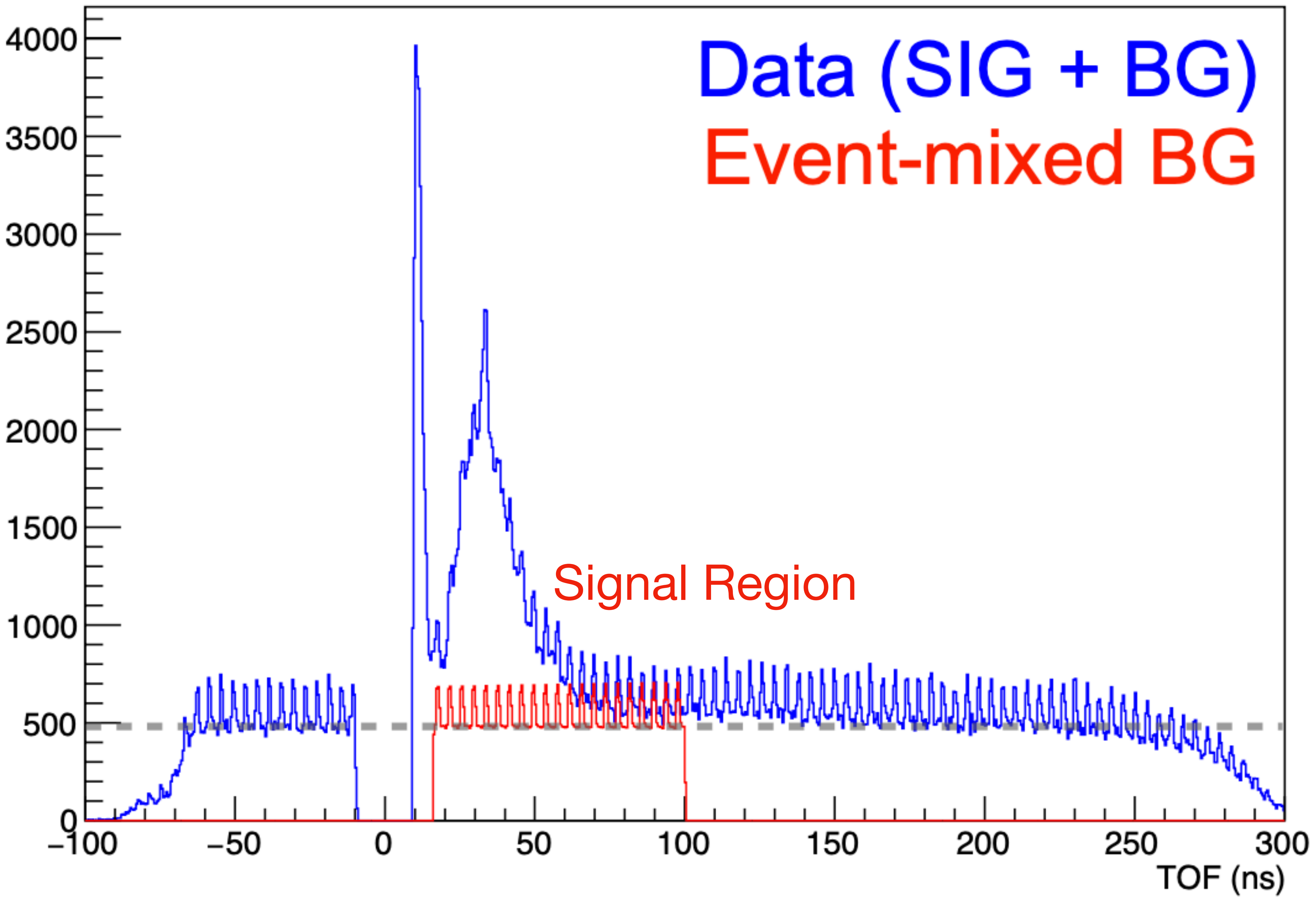
Off-time background

Off-time Neutron Background Subtraction

Event mixing procedure

1. Select neutrons from off-time region (-60 < ToF < -16 ns)
2. Adjust neutron timing to be in signal region (16 < ToF < 100 ns) in 4 ns increments
3. Pair neutron with inclusive electron to create pseudo event
4. Repeat with new electrons
5. Repeat with same neutron shifted by 4 ns

Negligible statistical uncertainty!



Tagged DIS with BAND at RG-B

RG-B: $d(e, e'n)$ at 10.2-10.6 GeV

Electron:

$Q^2 > 2$ GeV^2

$W > 2$ GeV

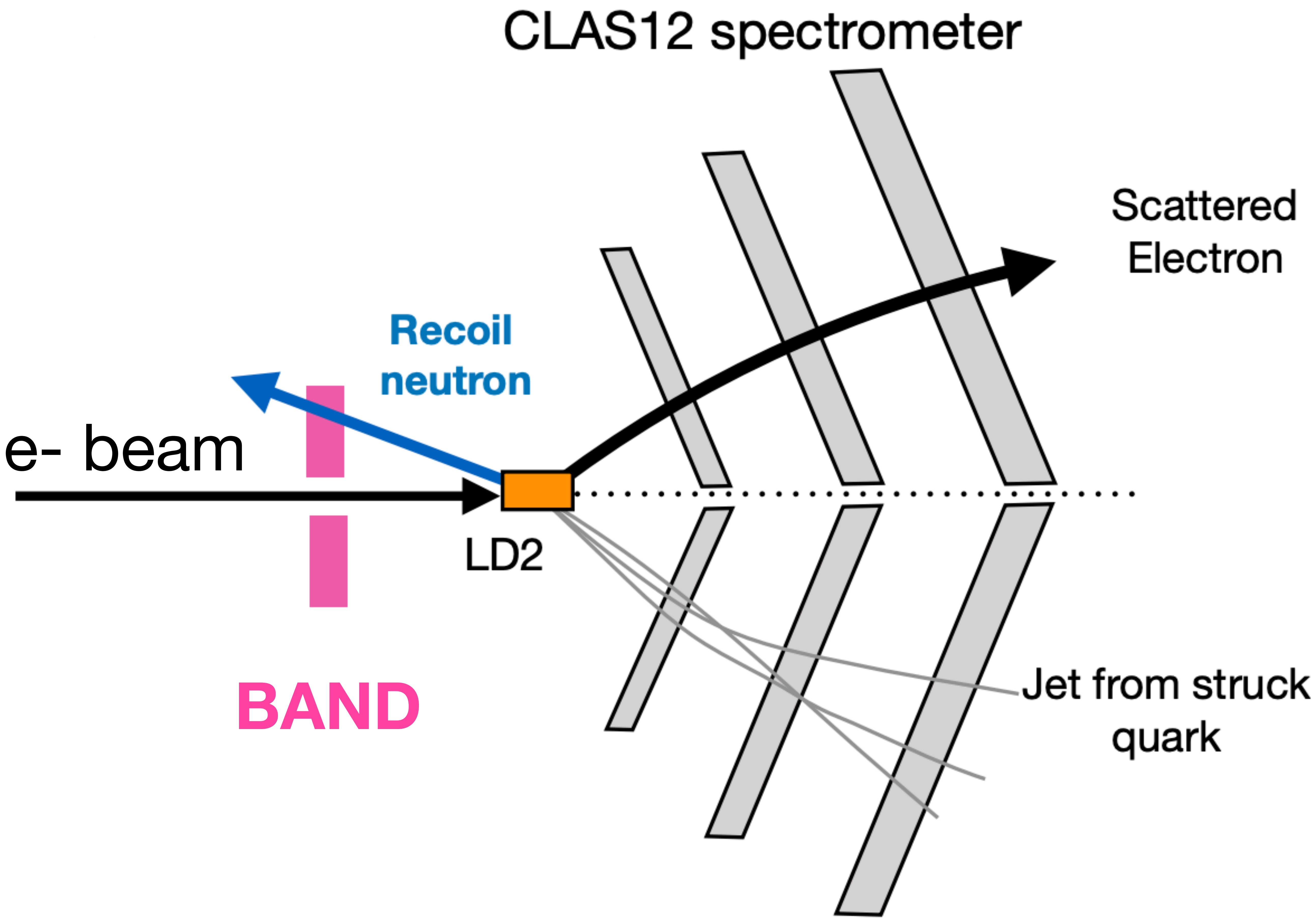
$p_e > 3$ GeV/c

Neutron:

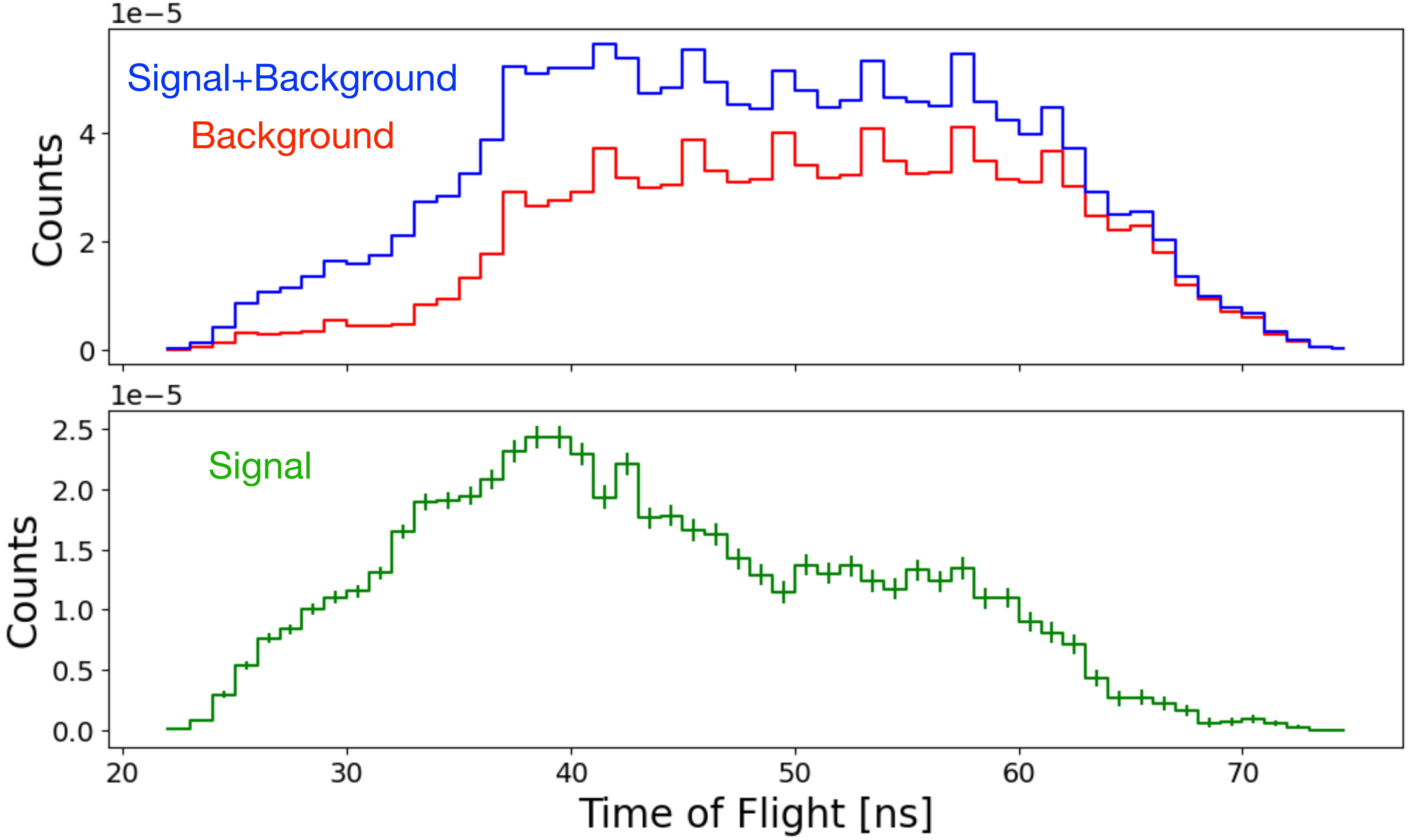
$W' > 1.8$ GeV

$.2 < p_n < .6$ GeV/c

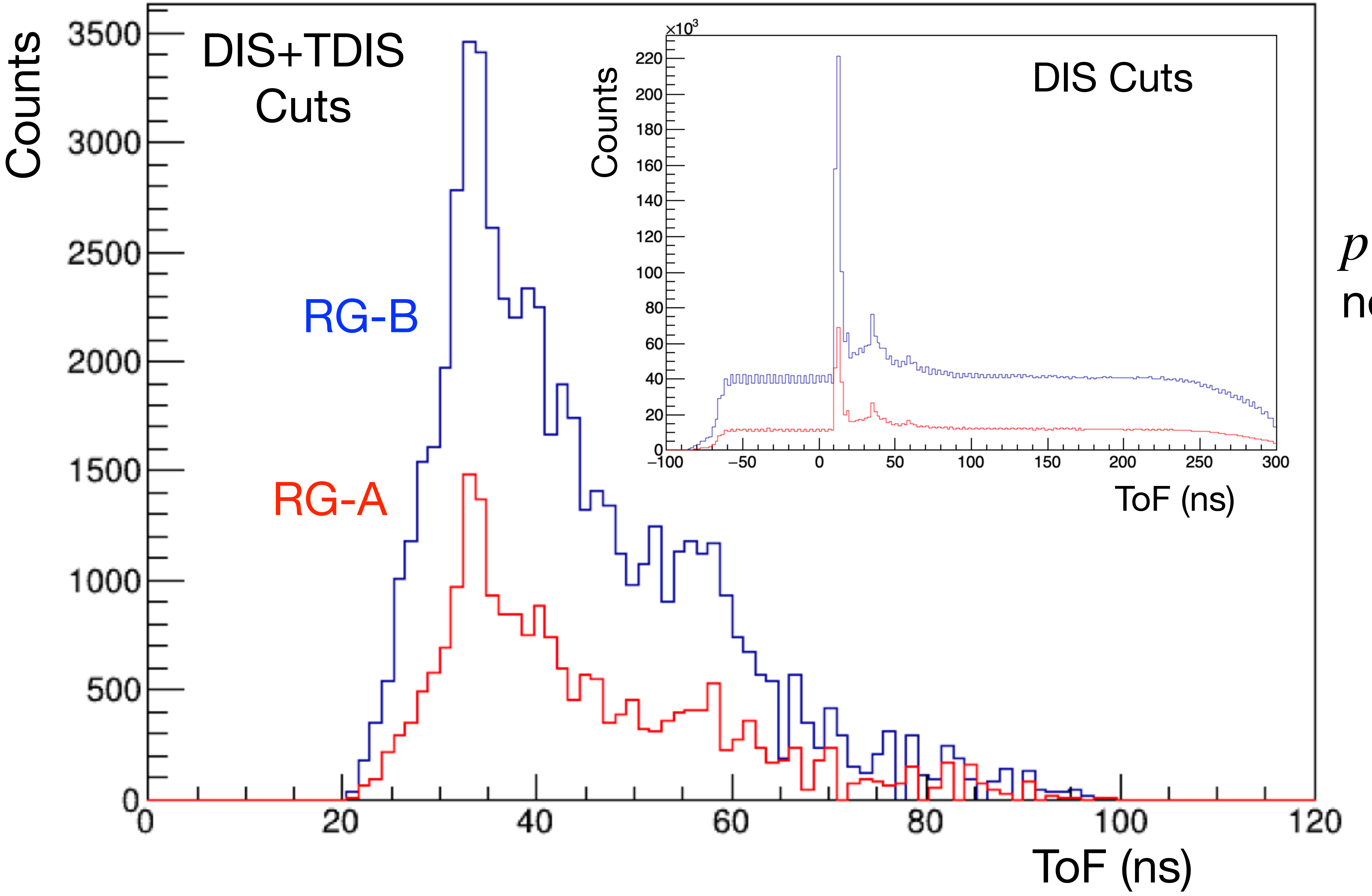
$E_{dep} > 5$ MeVee



After TDIS Cuts…



Non-TDIS Background Subtraction



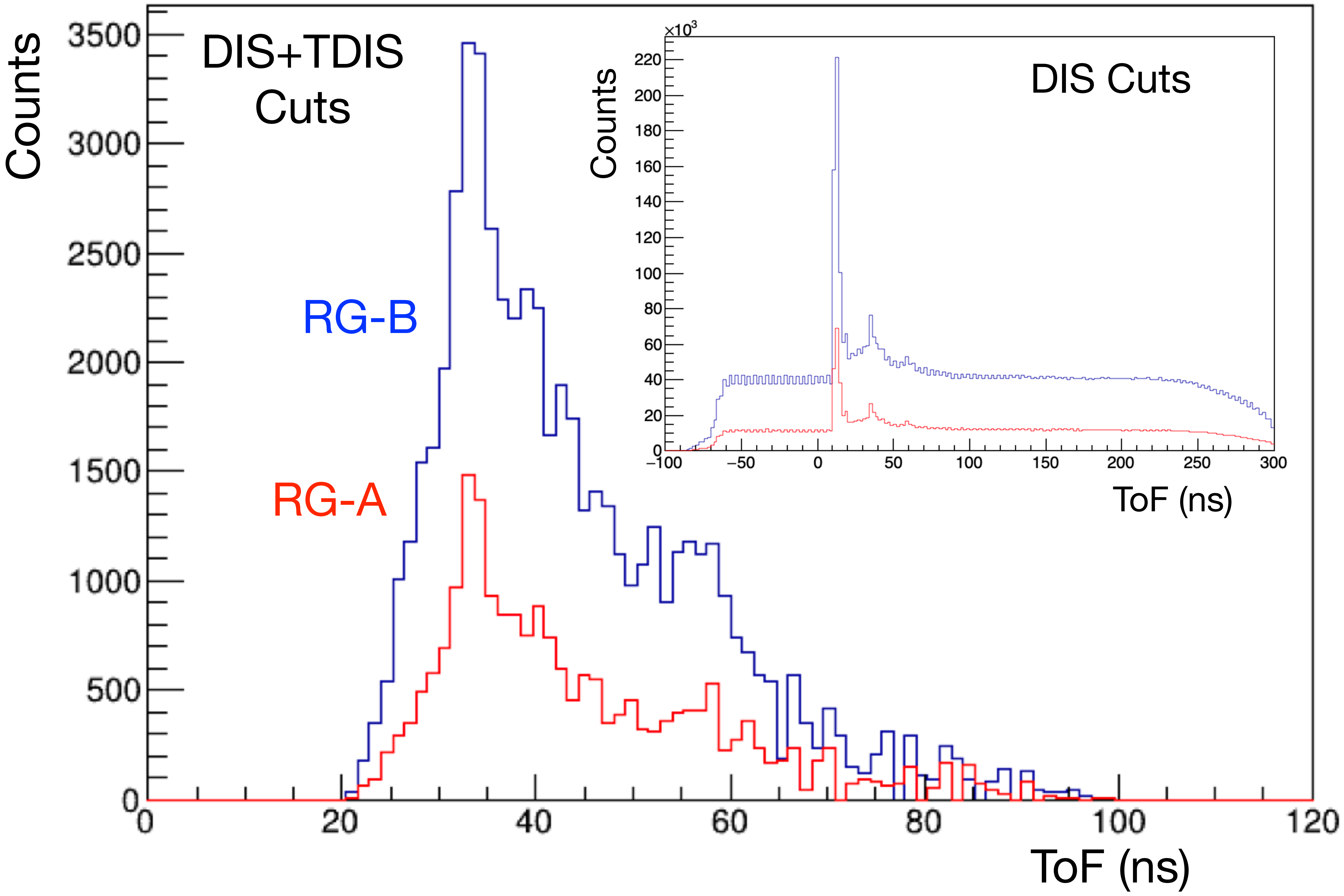
$p(e, e'n)$ data (RG-A) shows a non-negligible, non-TDIS background in BAND

Natalie Wright

Note: Distributions are charge normalized

Non-TDIS Background Subtraction

What we know:



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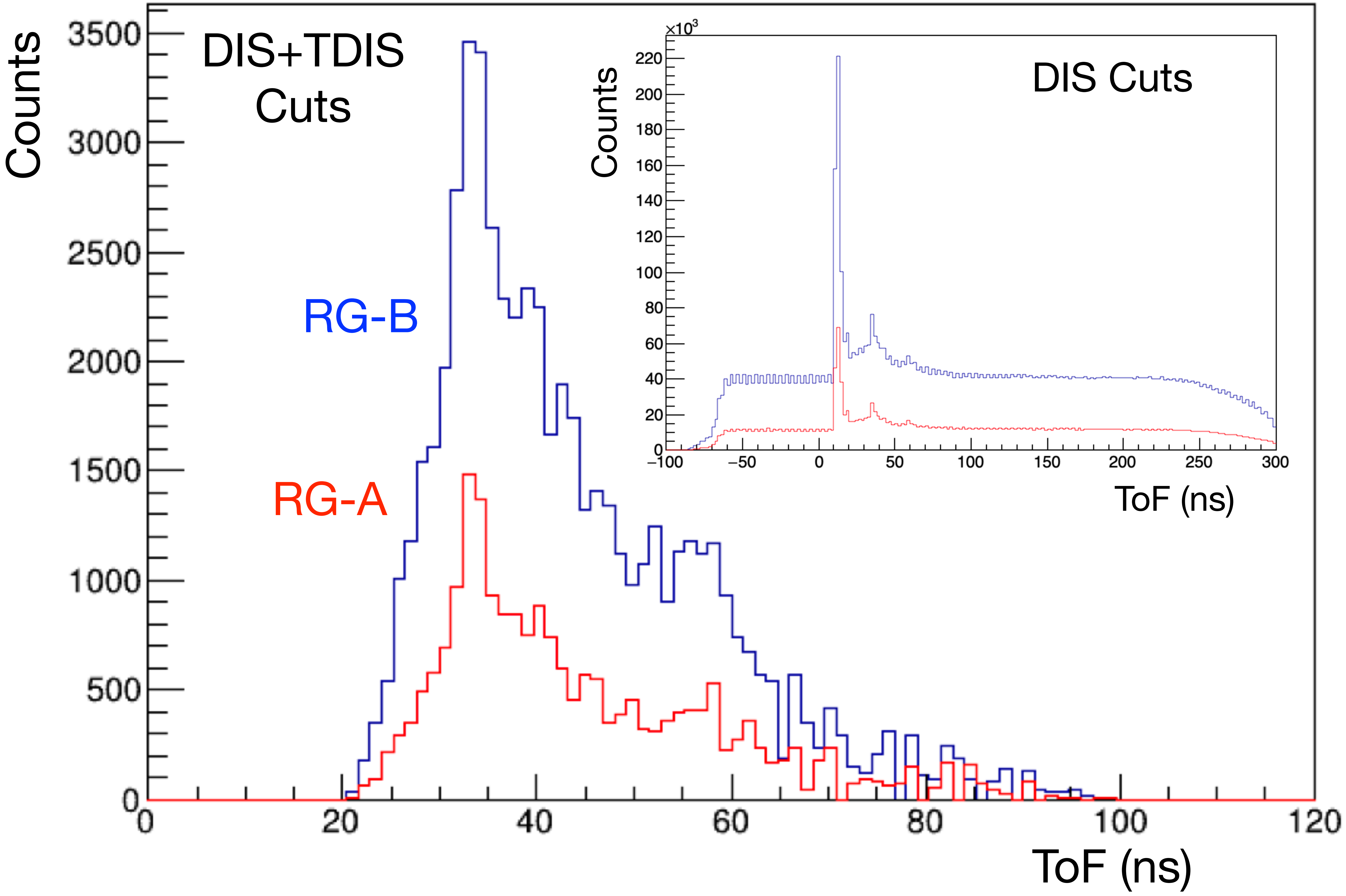

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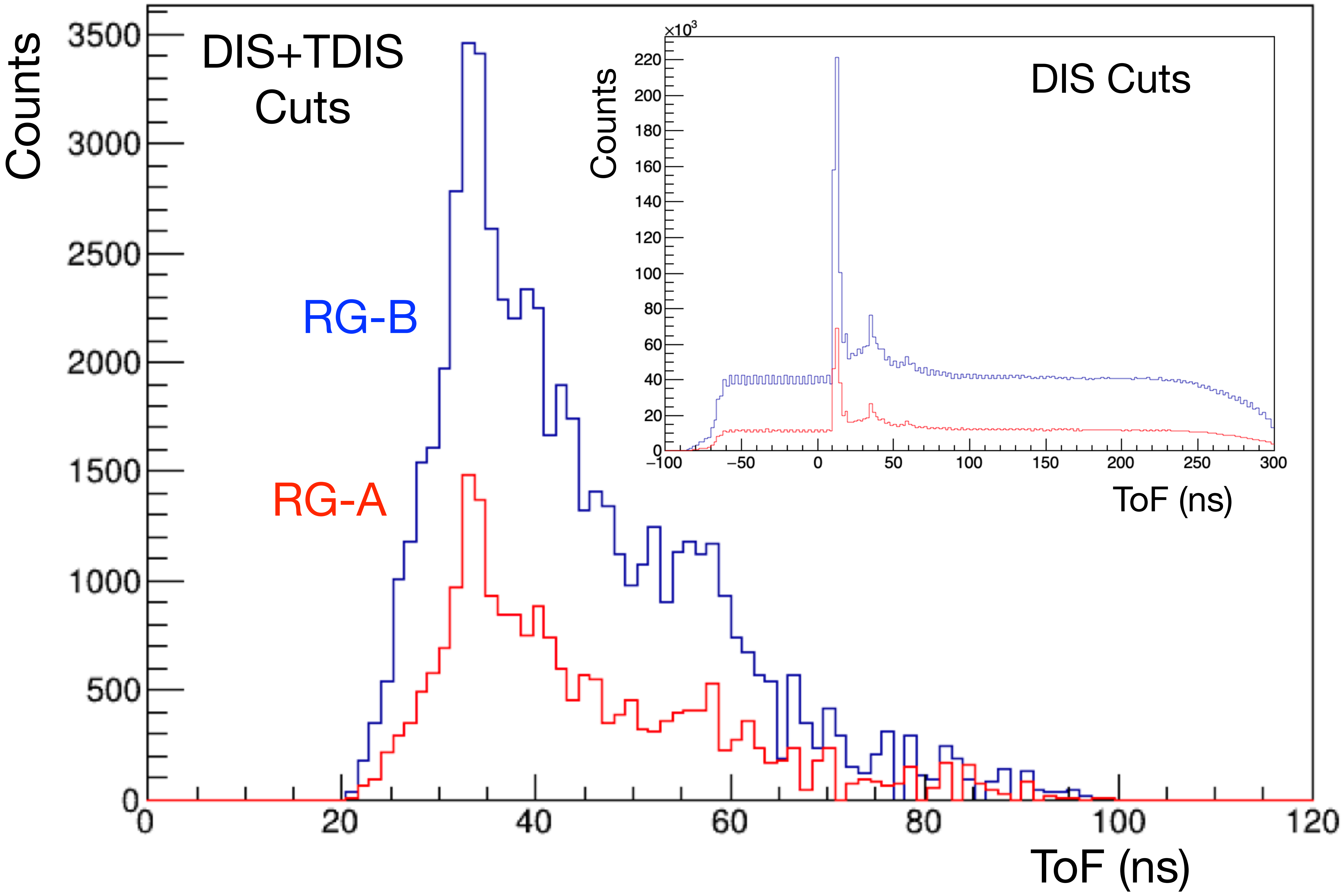
What we know:

- Background is prompt and associated with a DIS electron

Natalie Wright

Non-TDIS Background Subtraction



What we know:

- Background is prompt and associated with a DIS electron
- Background is NOT a prompt neutron
  - $p(e, e'n_{back})$ kinematically forbidden

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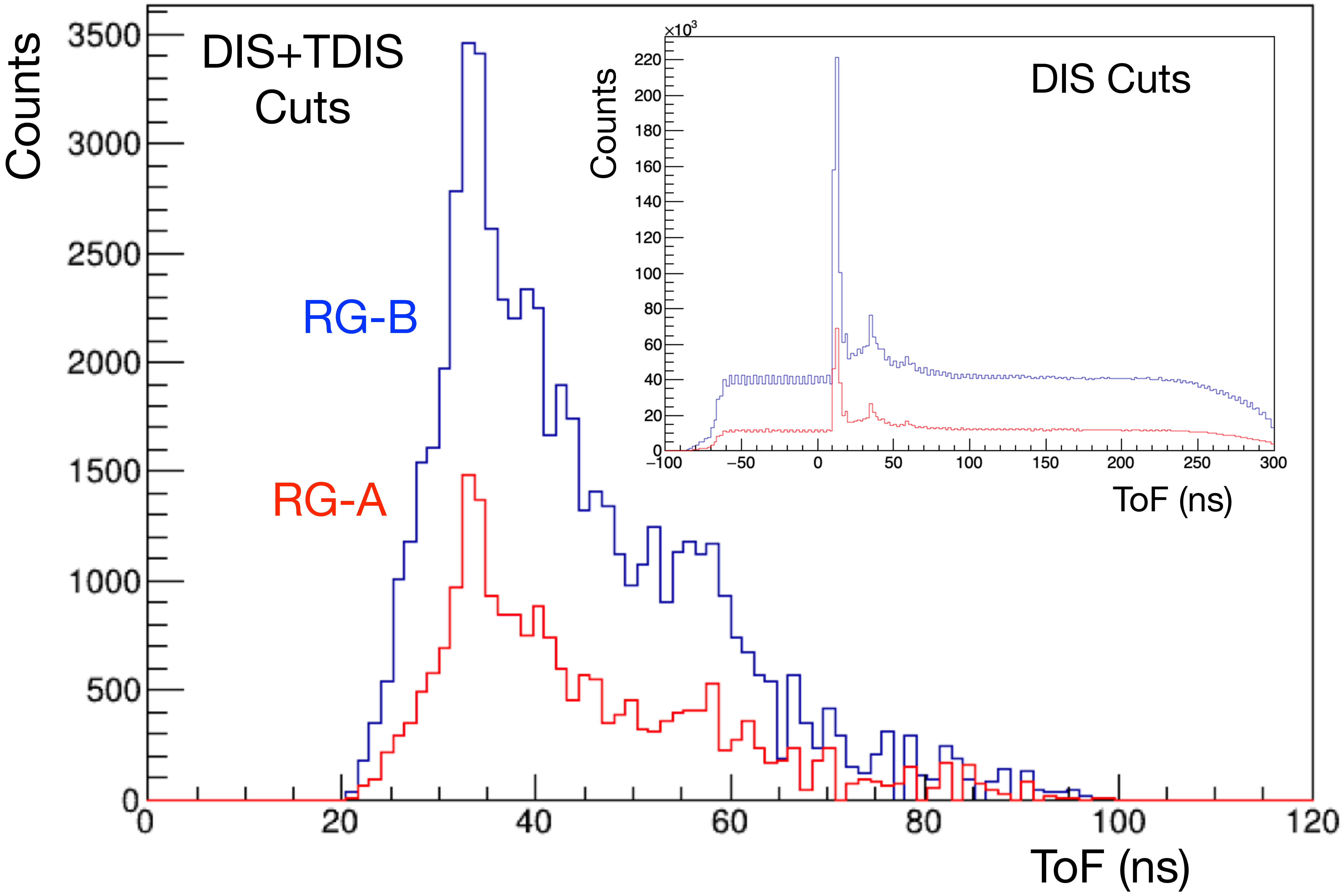

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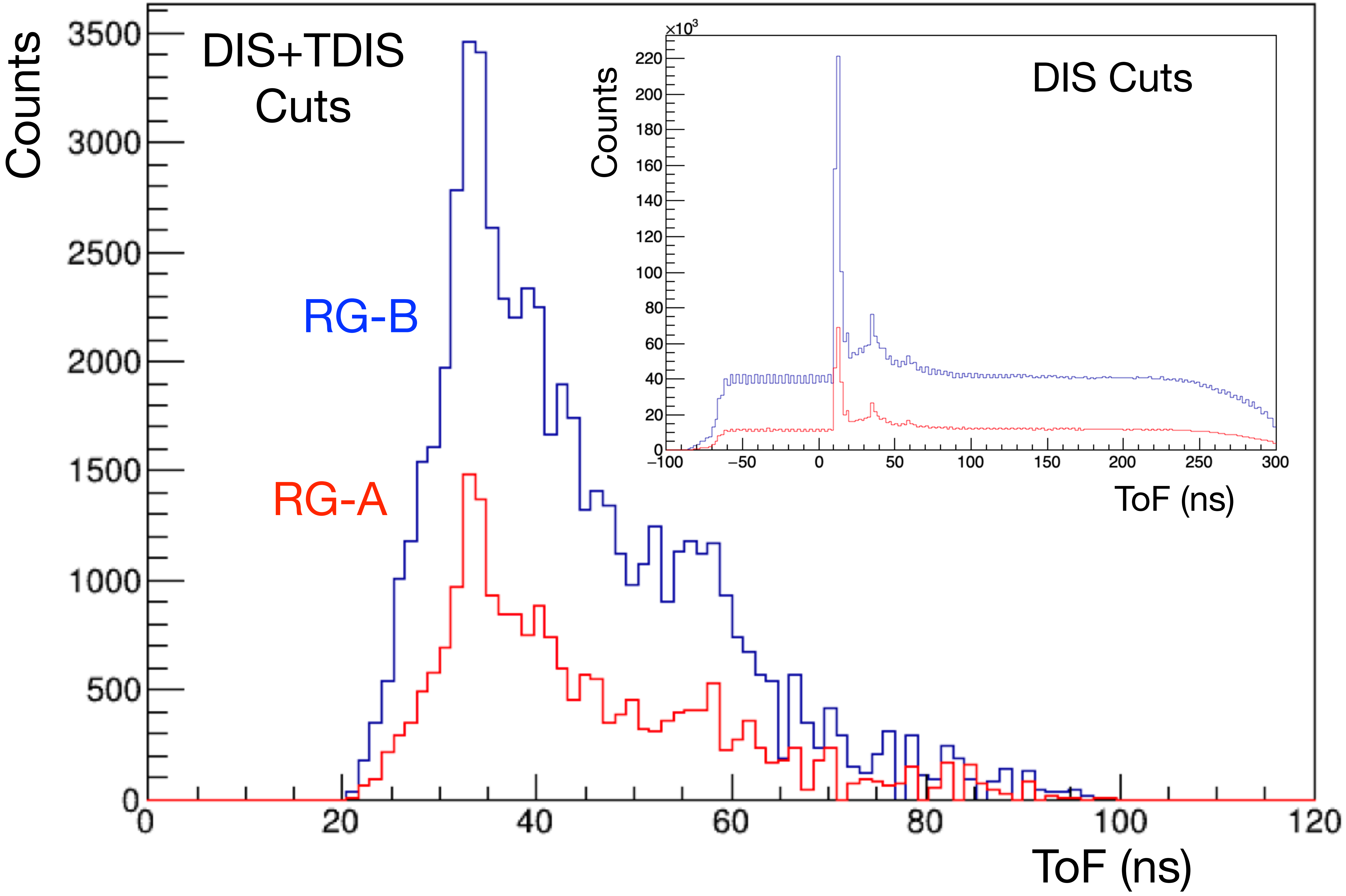
- Likely due to late arriving γ from forward-going particles hitting CLAS12 structure
  - Misidentified due to arrival time

Natalie Wright

Non-TDIS Background Subtraction



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- Background can either come from scattering off proton or neutron

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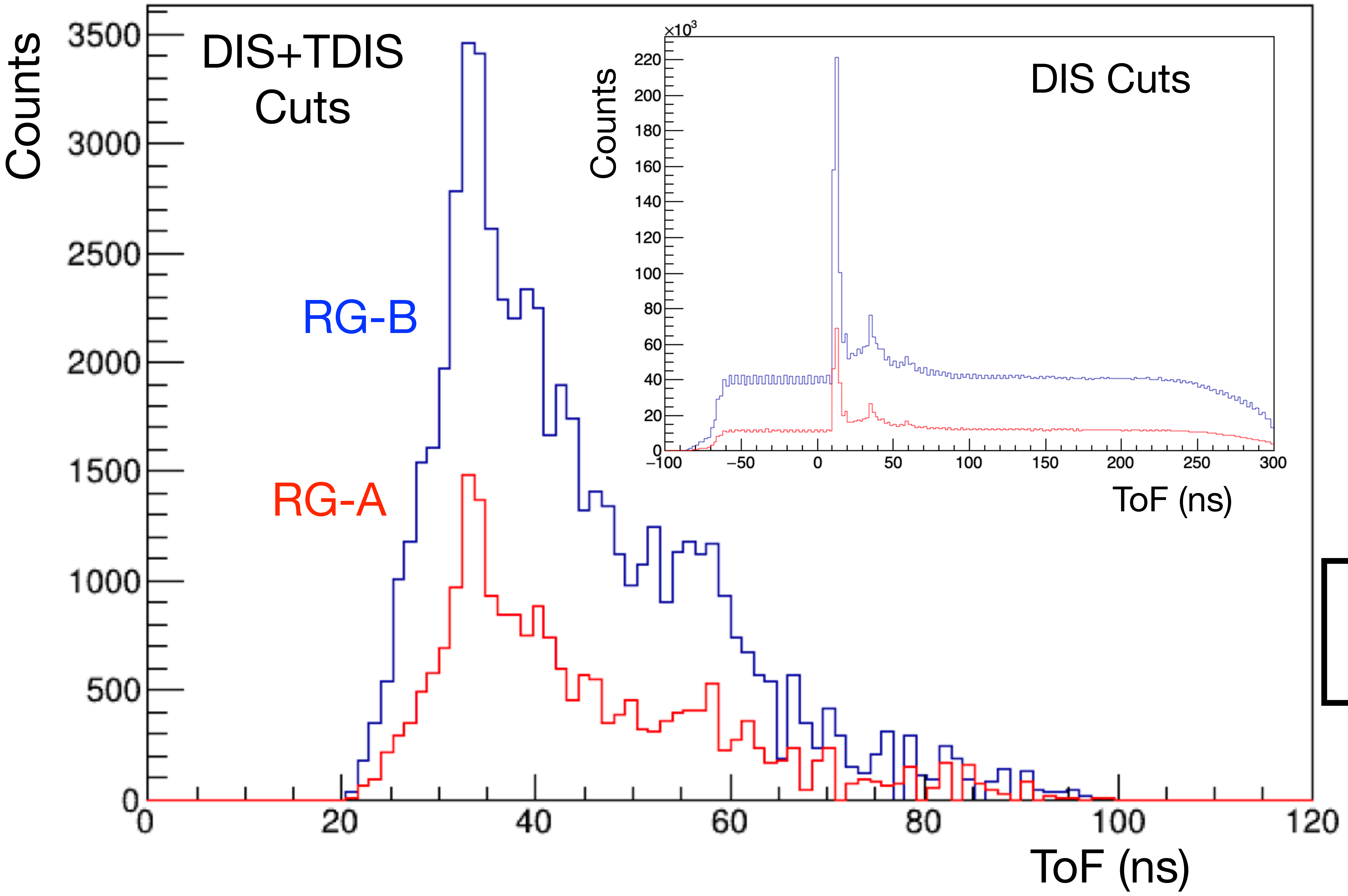

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Natalie Wright

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Scaling $p(e, e' \text{ neutral})$ to Deuterium Target

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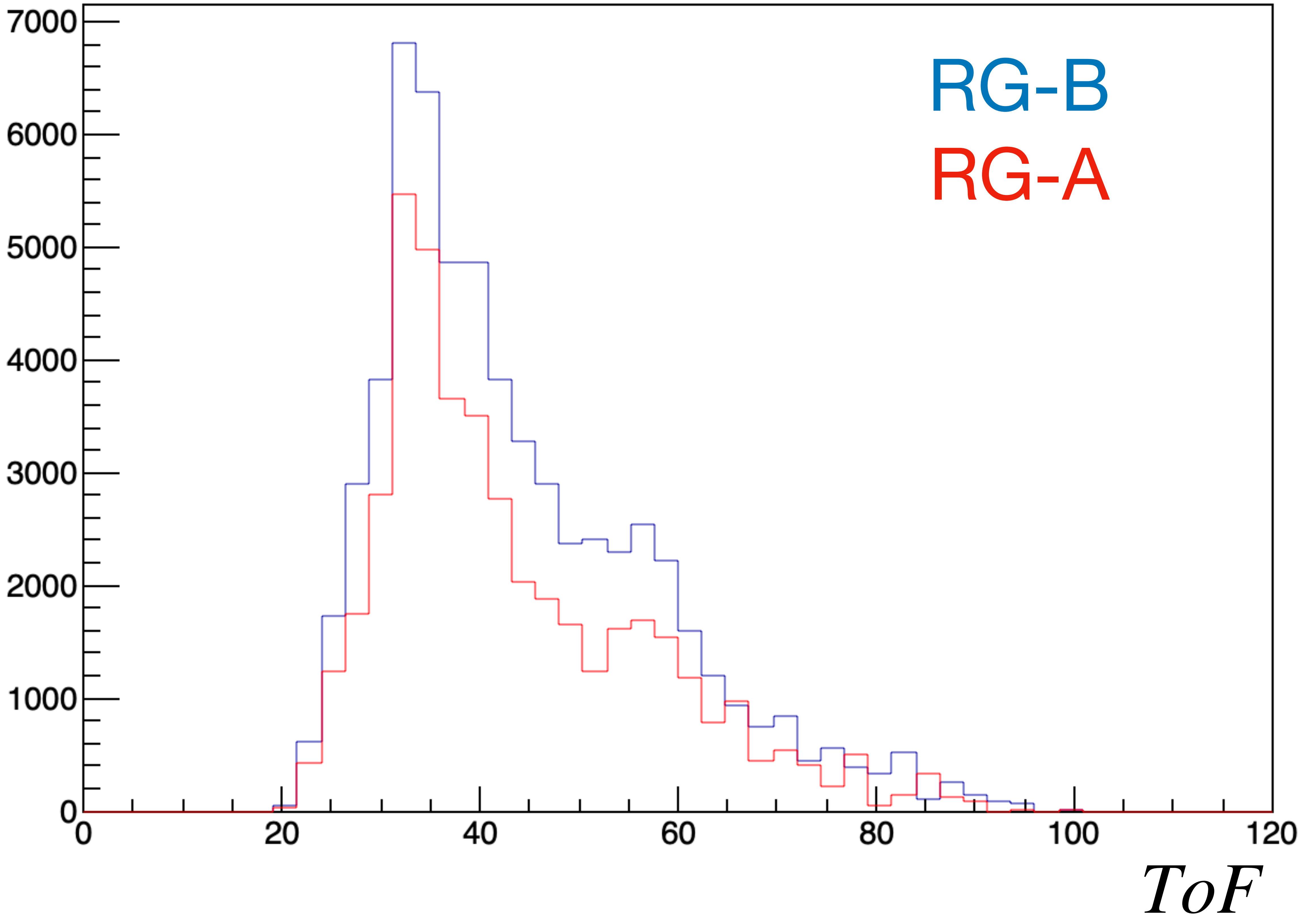
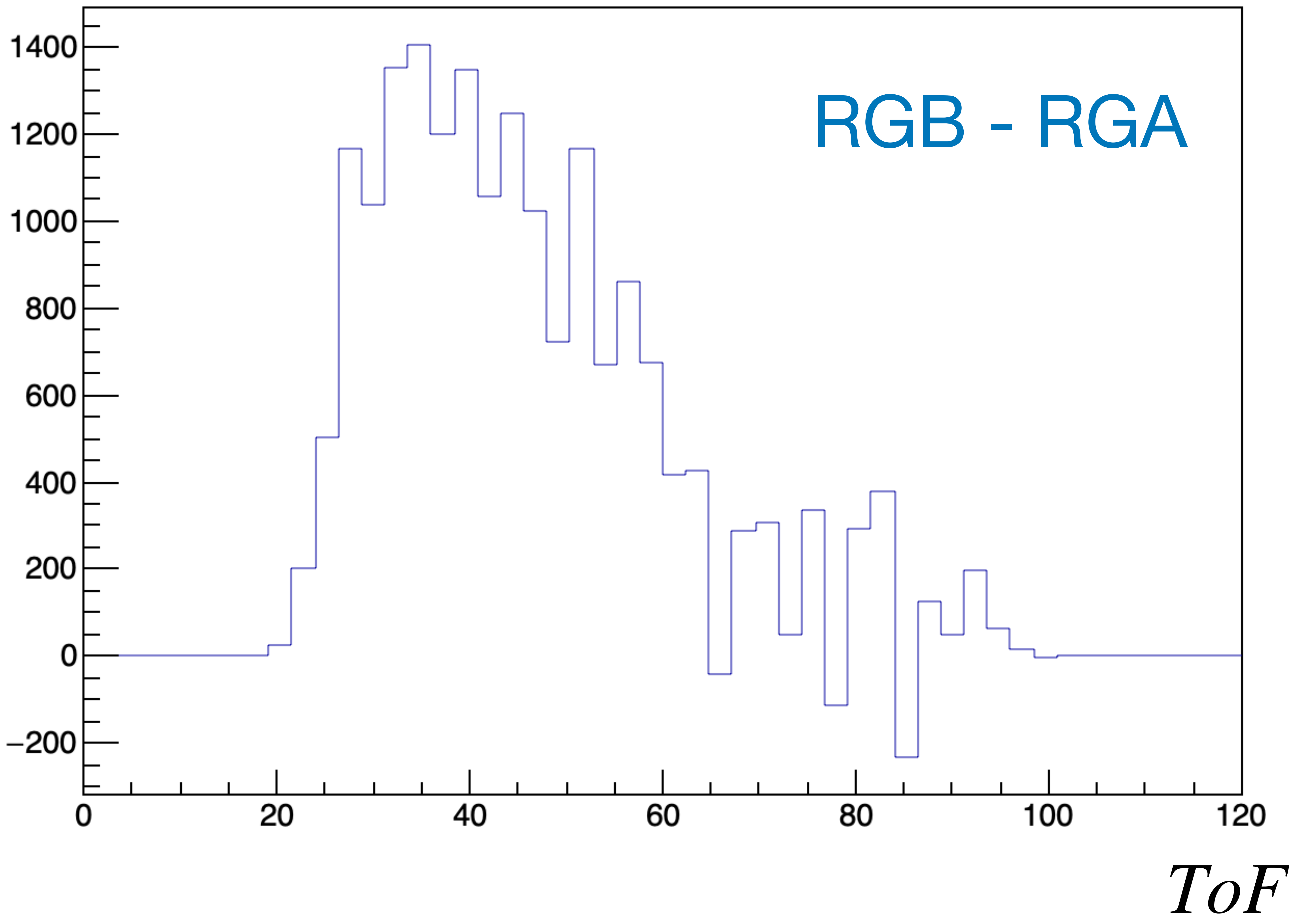
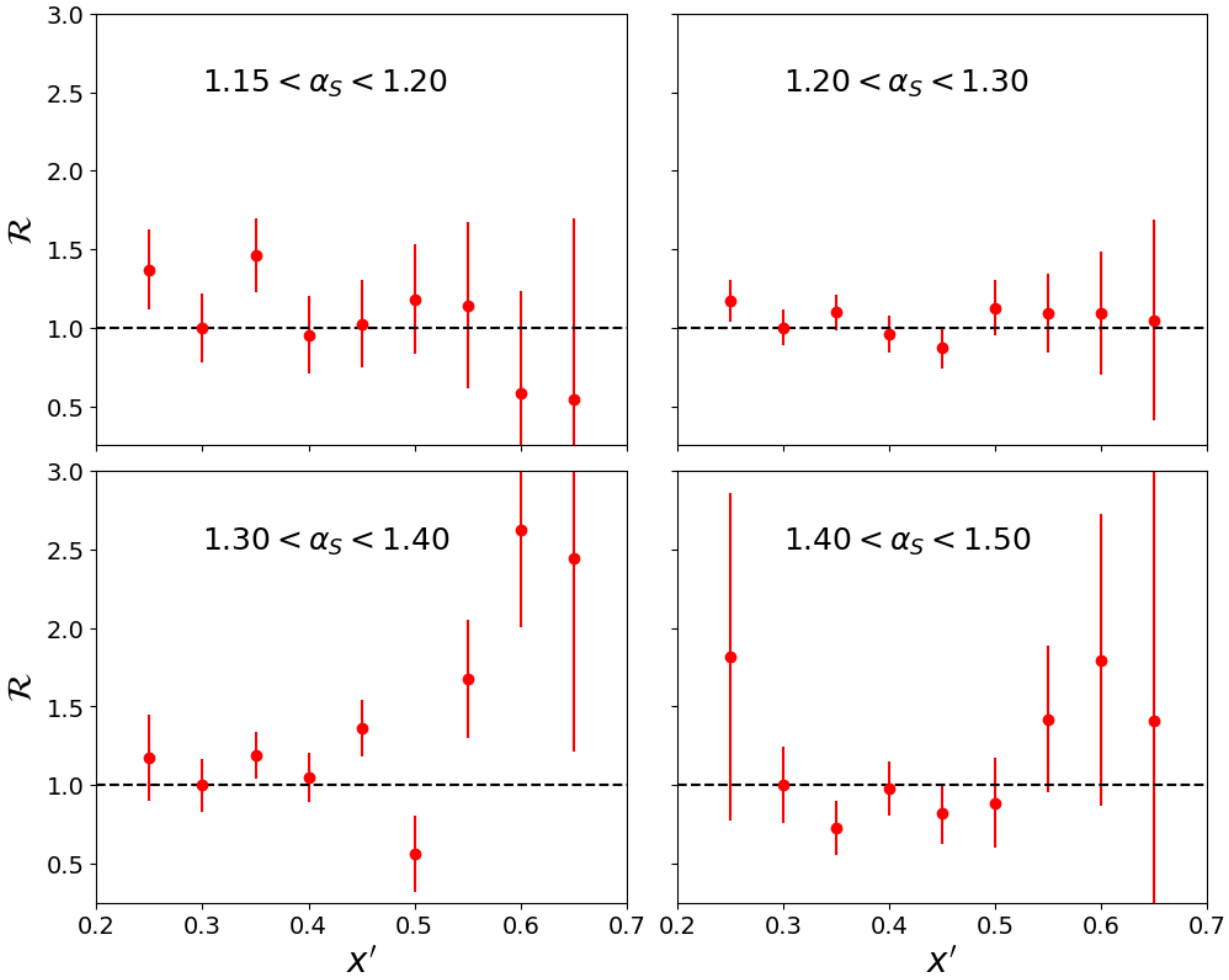
Scaled by inclusive electron yield

$Y_e(\text{RG-B})/Y_e(\text{RG-A}) \approx F_2^d/F_2^p$





Results at $E_{beam} = 10.2$ GeV!



$\mathscr{R}$ appears to be modified at larger α_S and x'!

Systematics

- Stability with beam energy
- Definition of x'
- BAND efficiency
- Finite Q^2 effects
- Neutron E_{dep} cut

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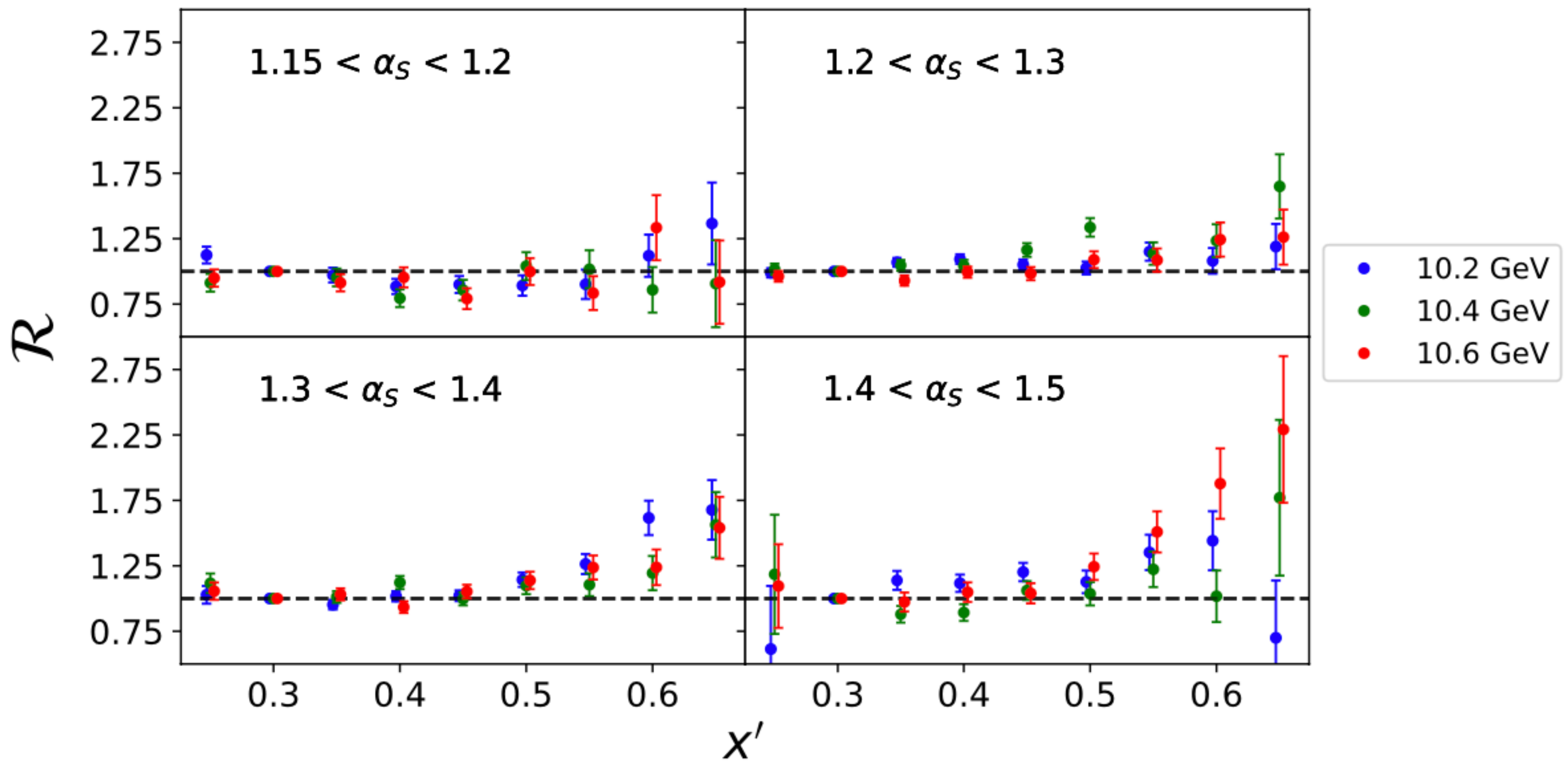

Note: Systematic tests done before RG-A background subtraction

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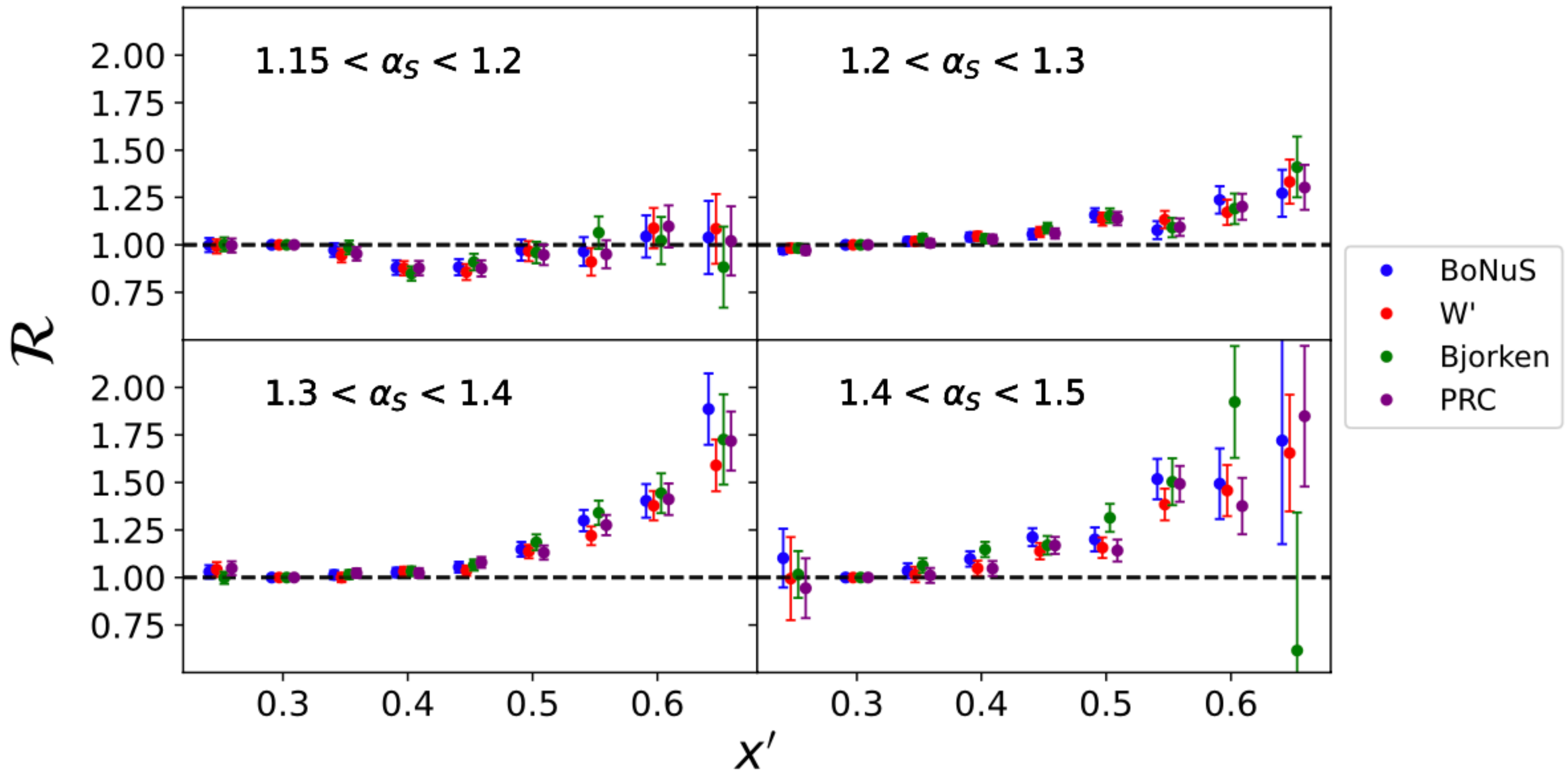

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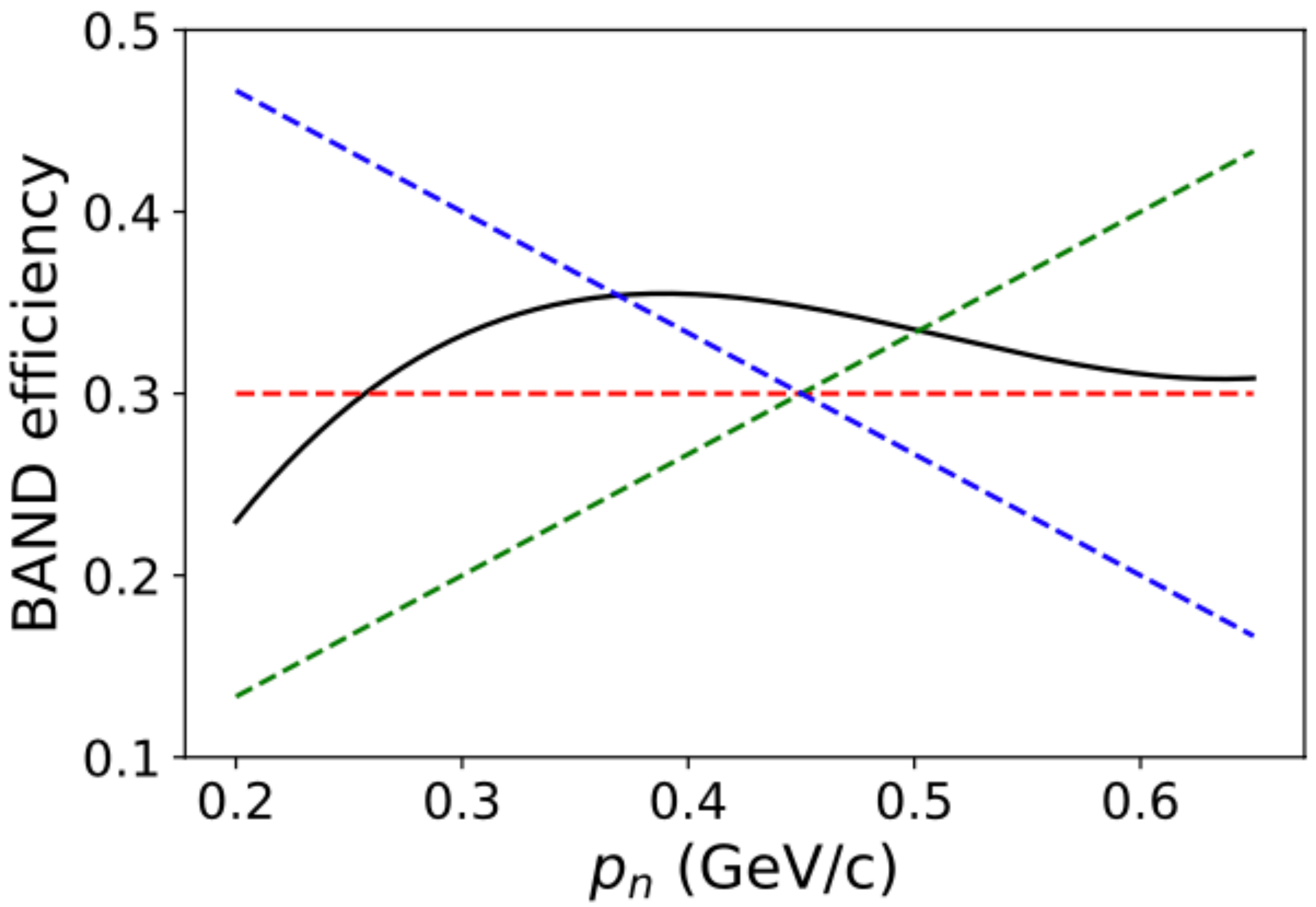

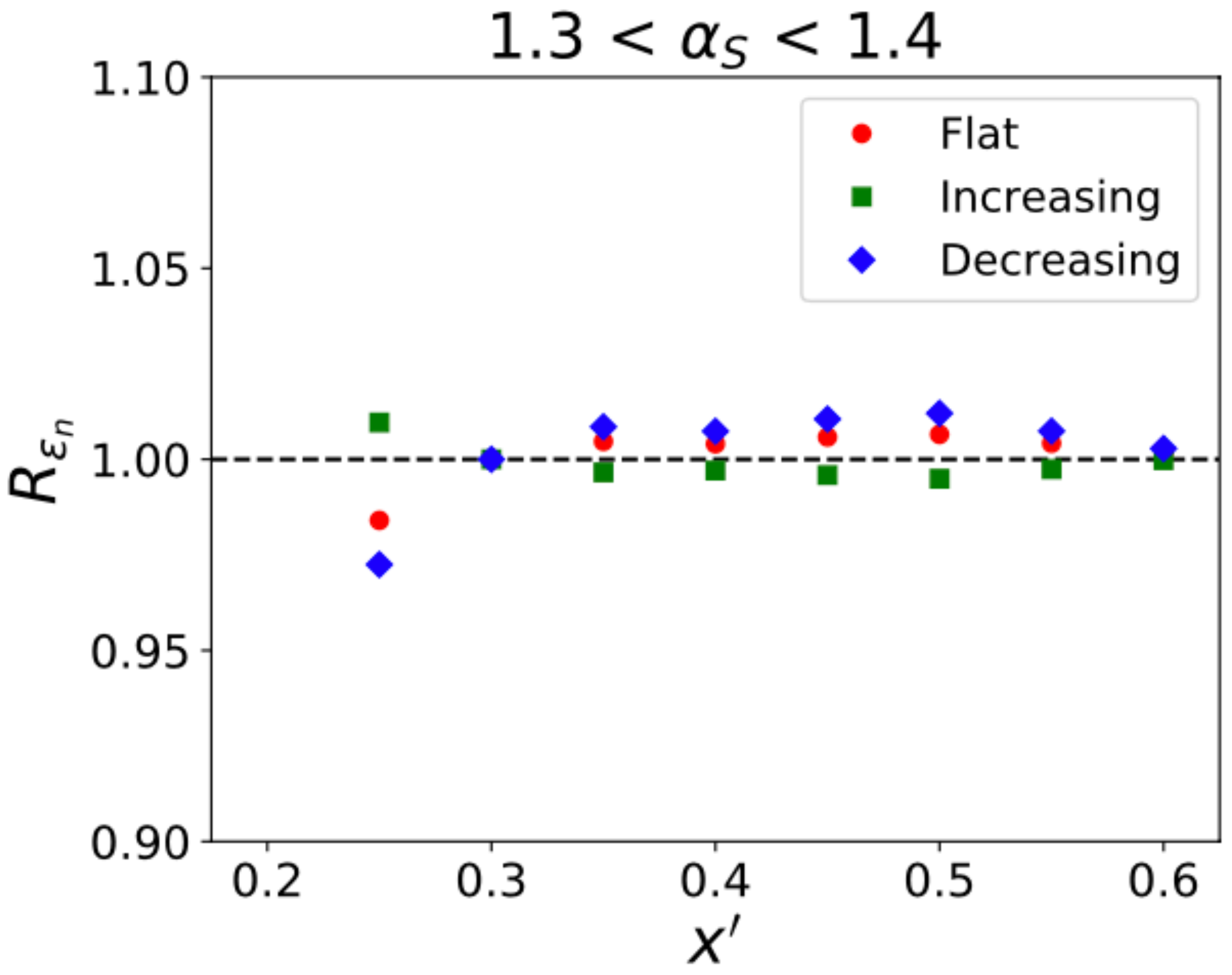

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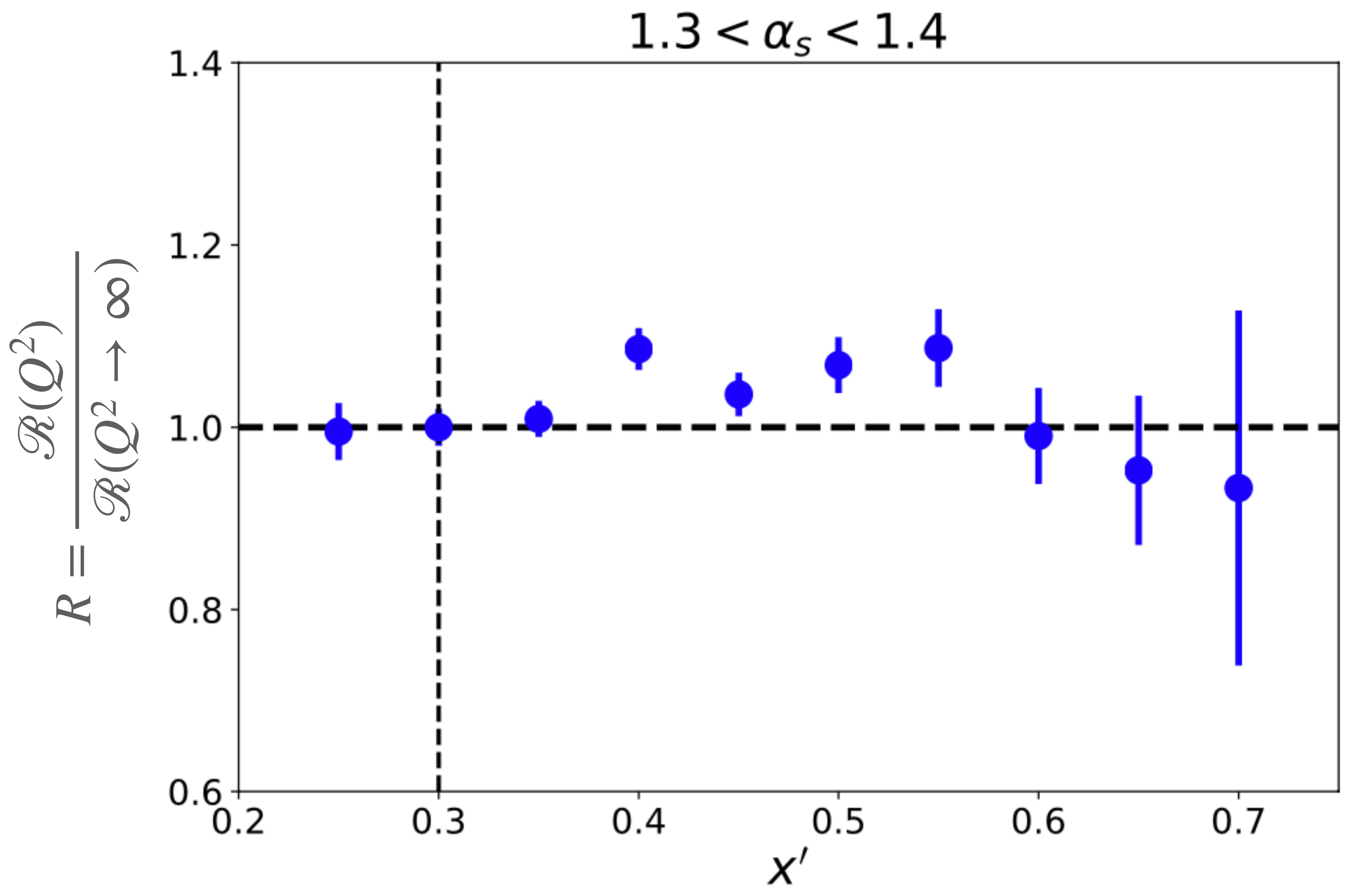

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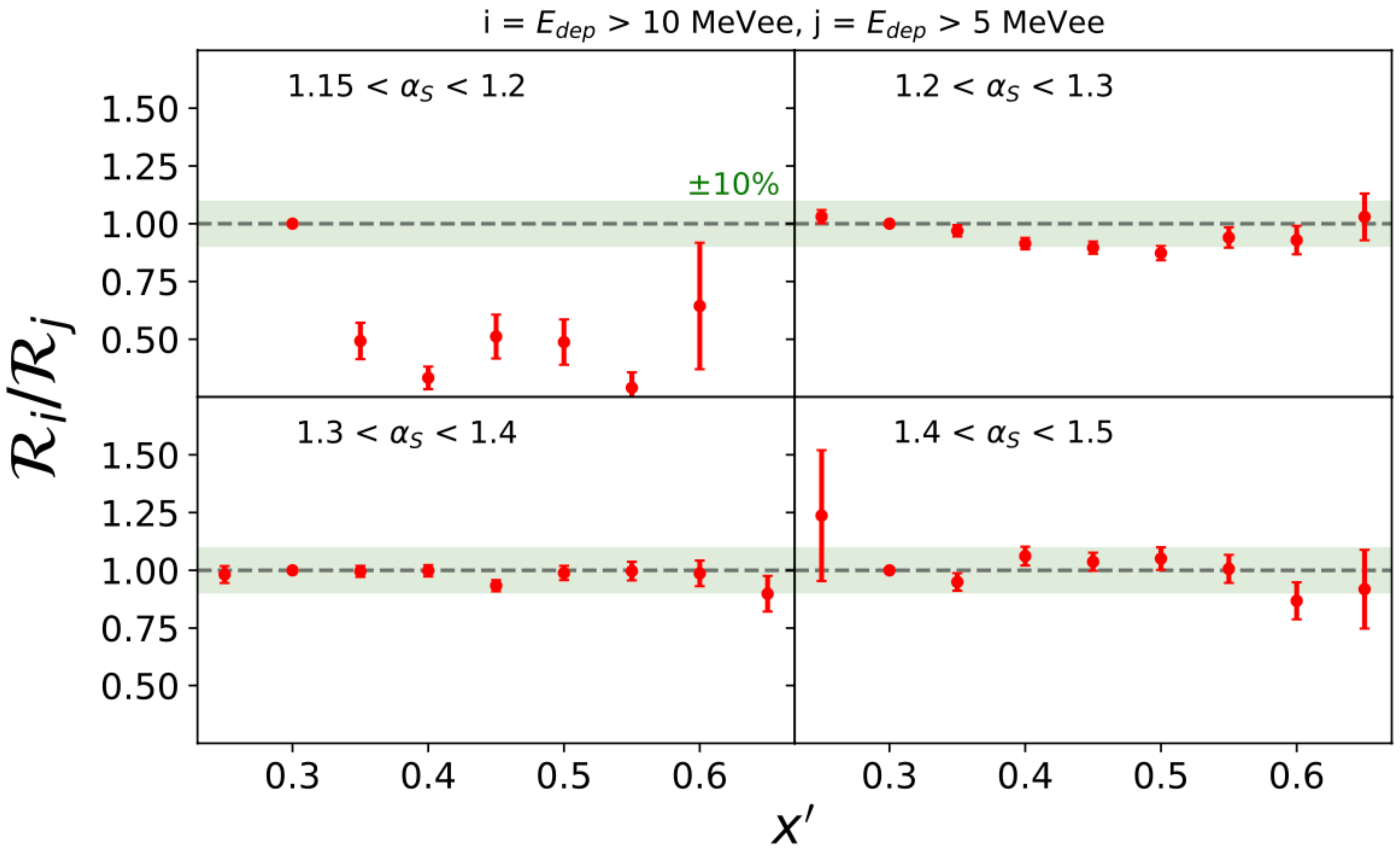


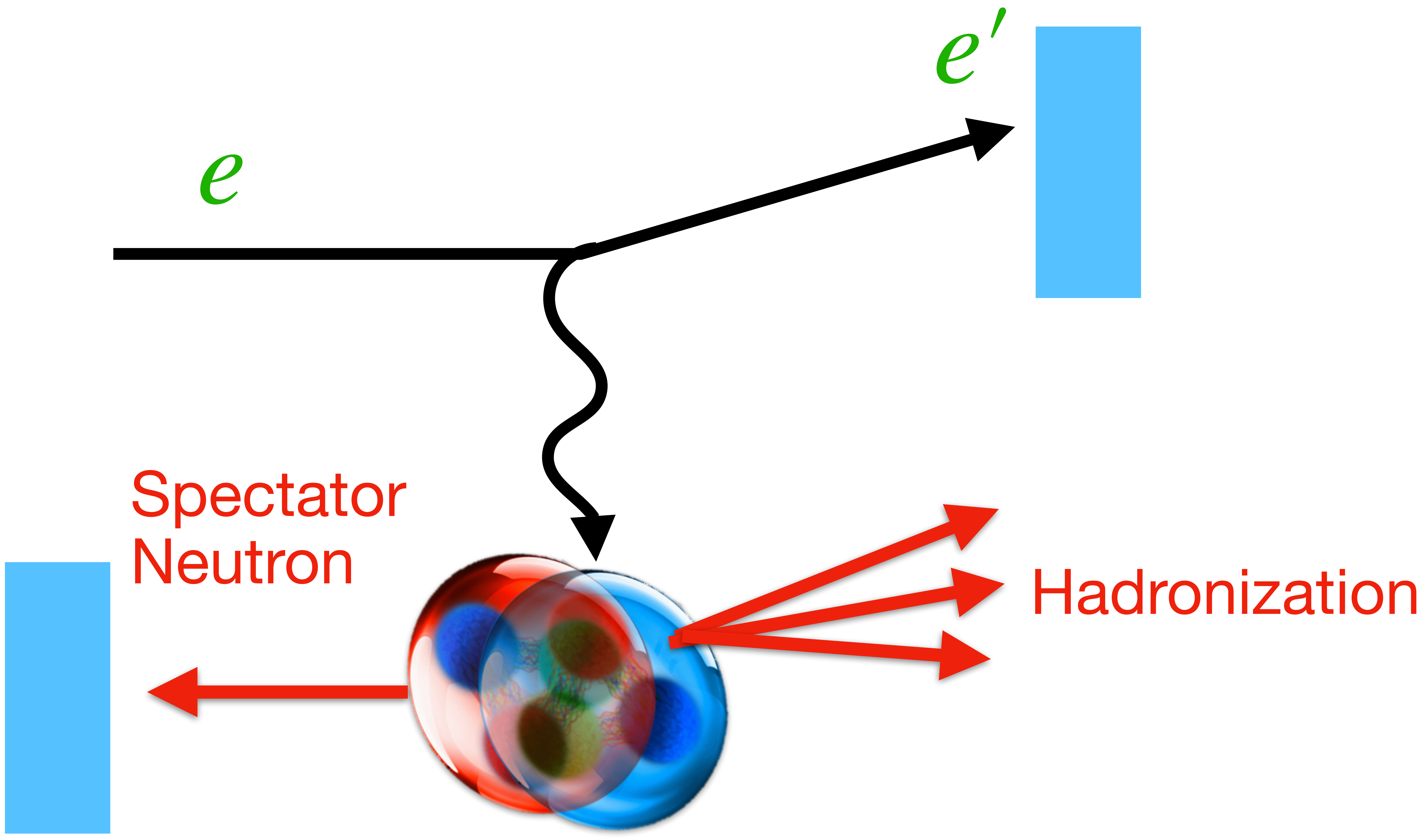
Note: Systematic tests done before RG-A background subtraction

Outlook

- Analysis note in review
    - Working to include 10.4 GeV and 10.6 GeV data in our analysis
    - Finalizing systematic uncertainties including subtraction of $p(e, e'$ neutral$)$ background

Backup

How can we confirm that we detect **neutrons**?



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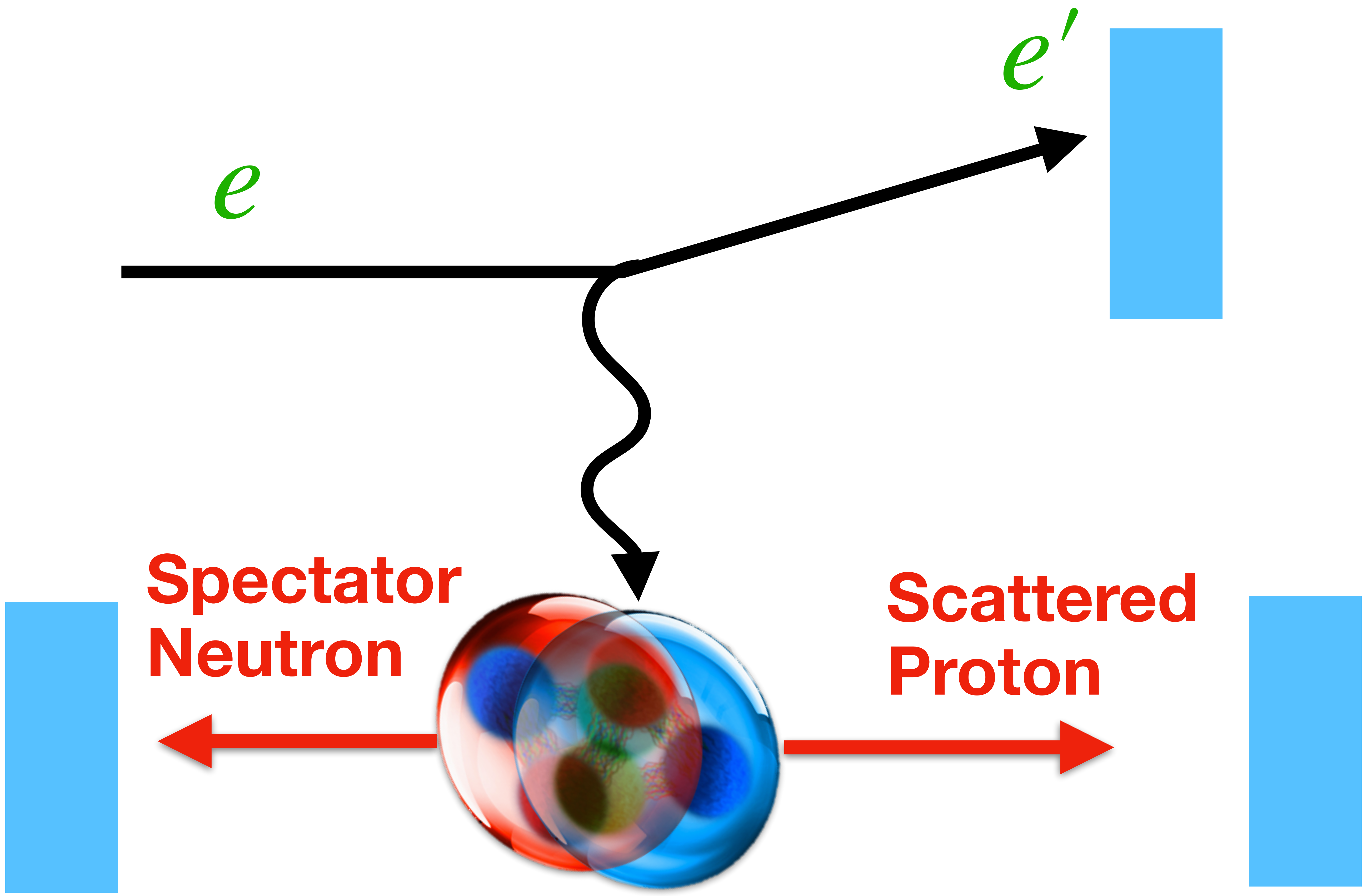
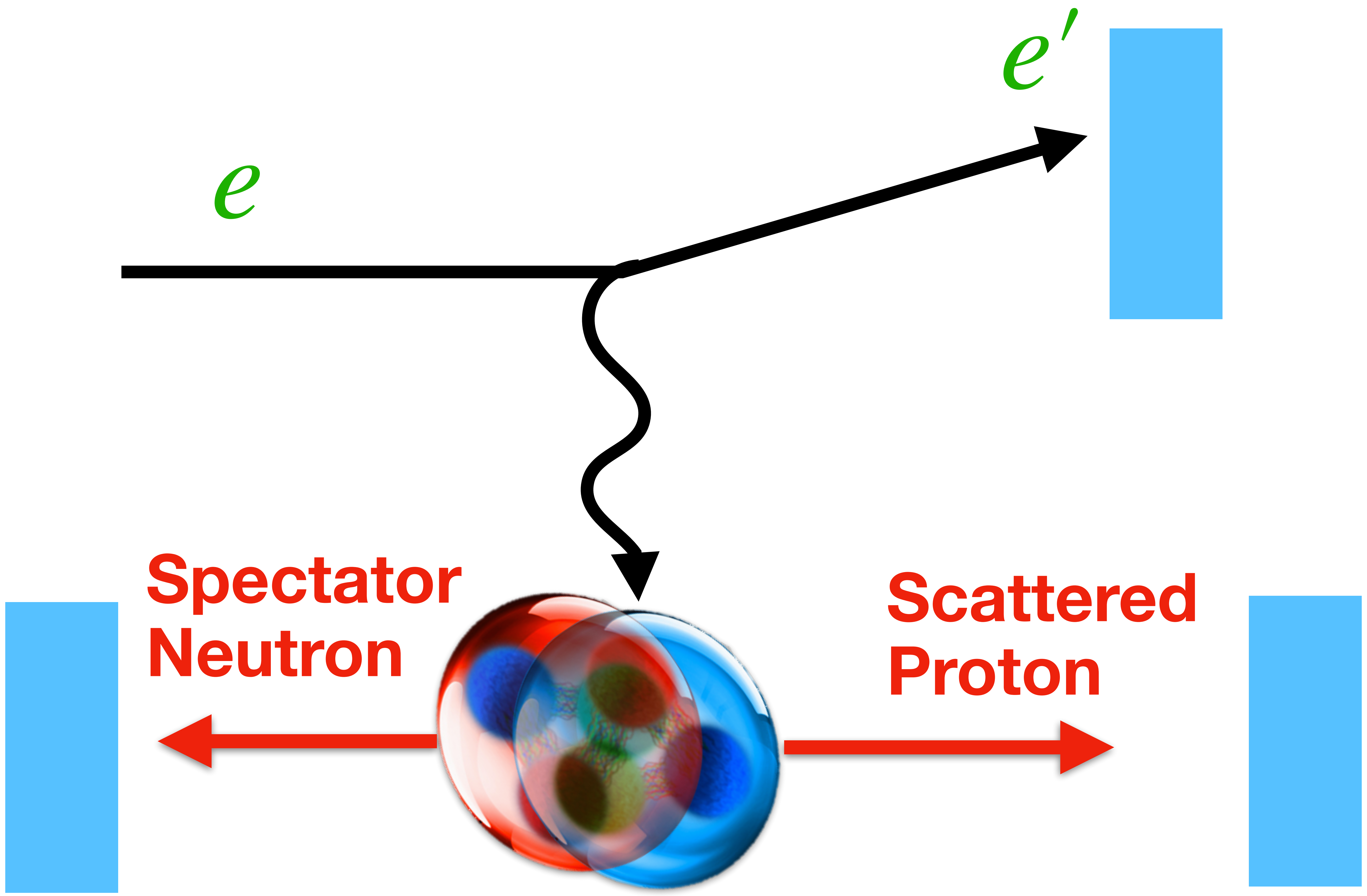


By identifying $d(e, e'pn)$ QE events (with 2GeV RG-M data), we can confirm that BAND is sensitive to neutrons

Natalie Wright

How can we confirm that we detect <u>neutrons</u>?



$$[W'(p)]^2 = [M_d + q - p]^2$$
$$[W'(n)]^2 = [M_d + q - n]^2$$

Natalie Wright

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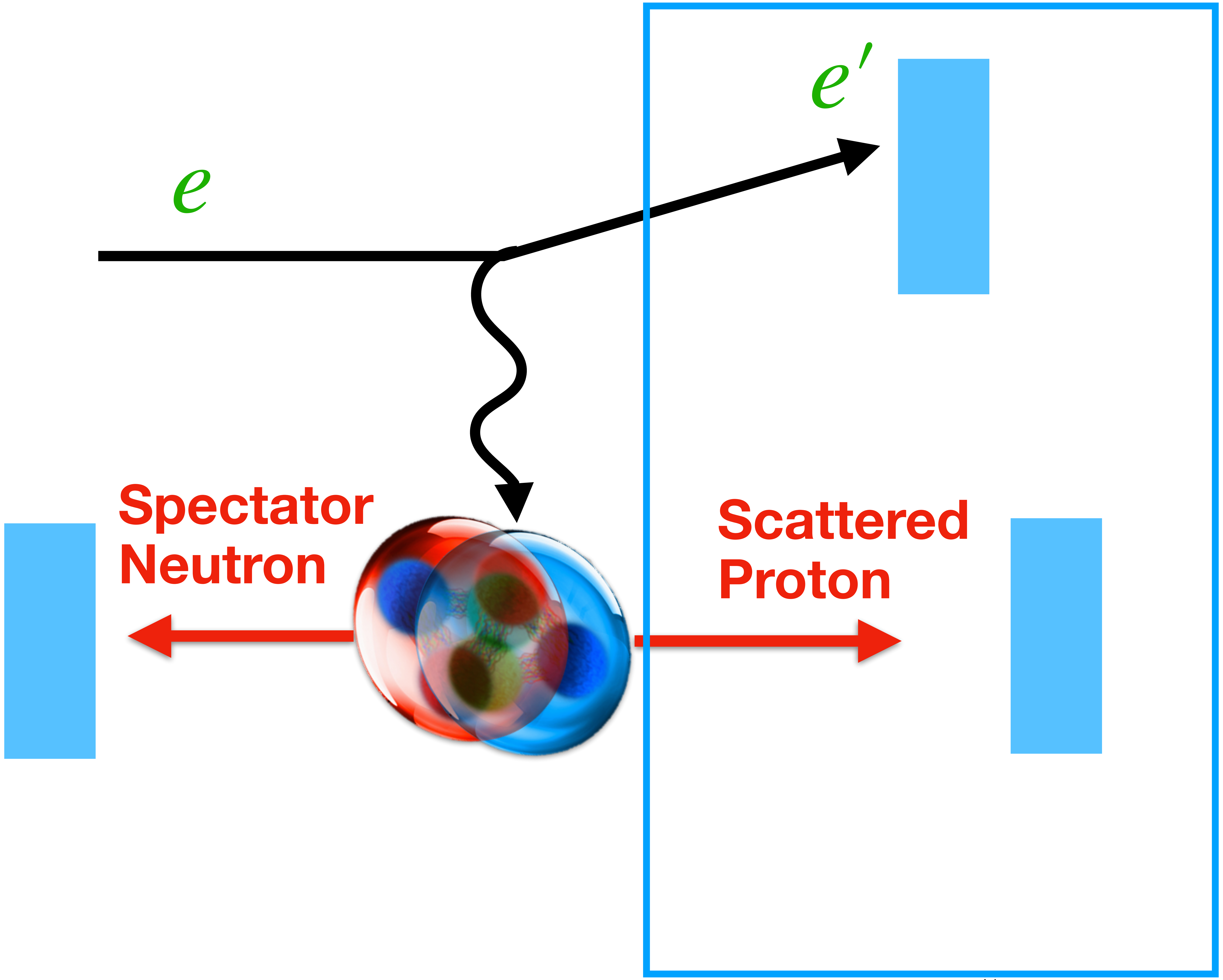

$$\boxed{[W'(p)]^2 = [M_d + q - p]^2}$$

$$[W'(n)]^2 = [M_d + q - n]^2$$

In a QE interaction, $W'(p)$ is the invariant mass of the spectator

Natalie Wright

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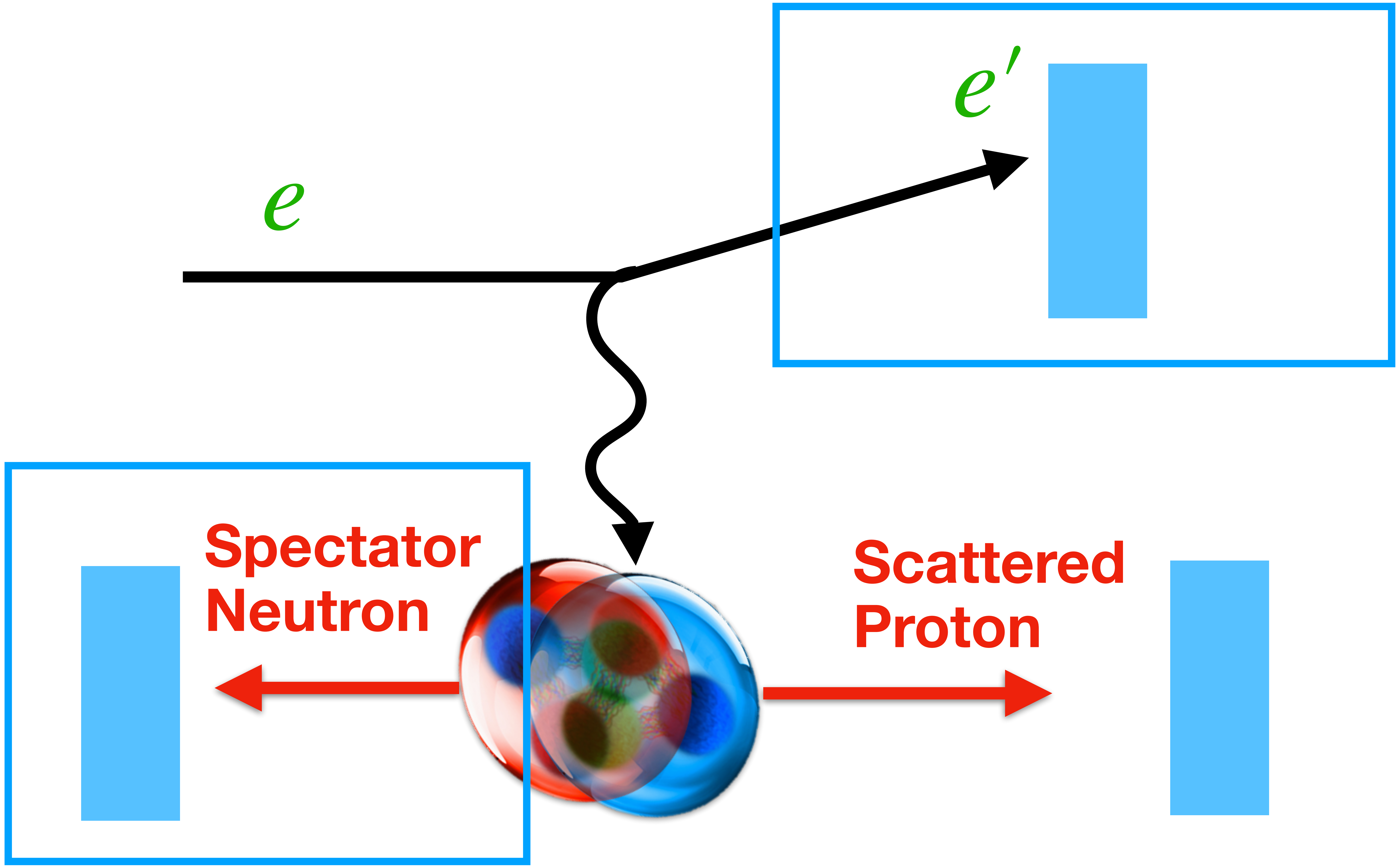

$$[W'(p)]^2 = [M_d + q - p]^2$$

$$\boxed{[W'(n)]^2 = [M_d + q - n]^2}$$

In a QE interaction, $W'(n)$ is the invariant mass of the struck particle

Natalie Wright

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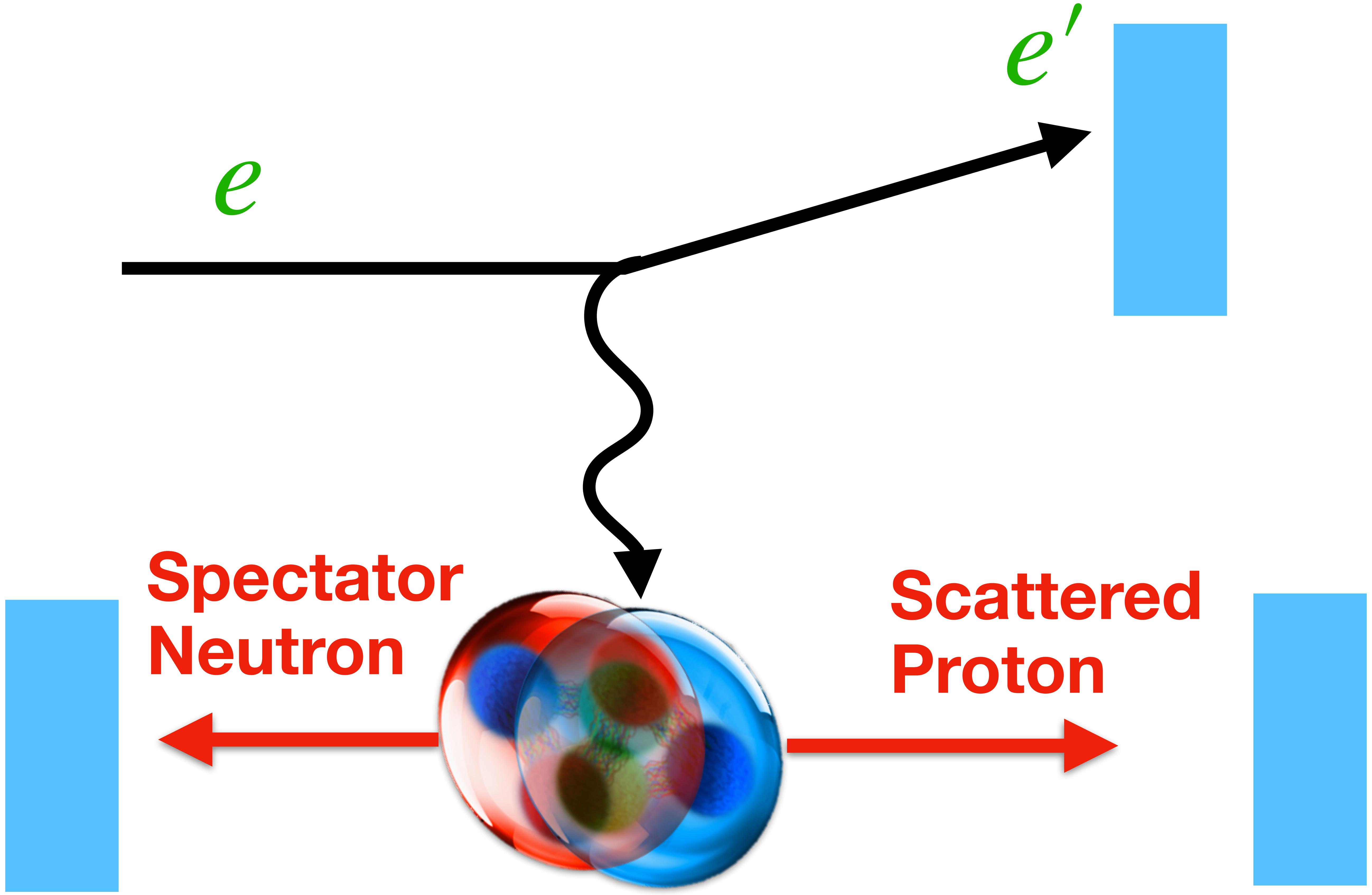


$$[W'(p)]^2 = [M_d + q - p]^2$$
$$[W'(n)]^2 = [M_d + q - n]^2$$

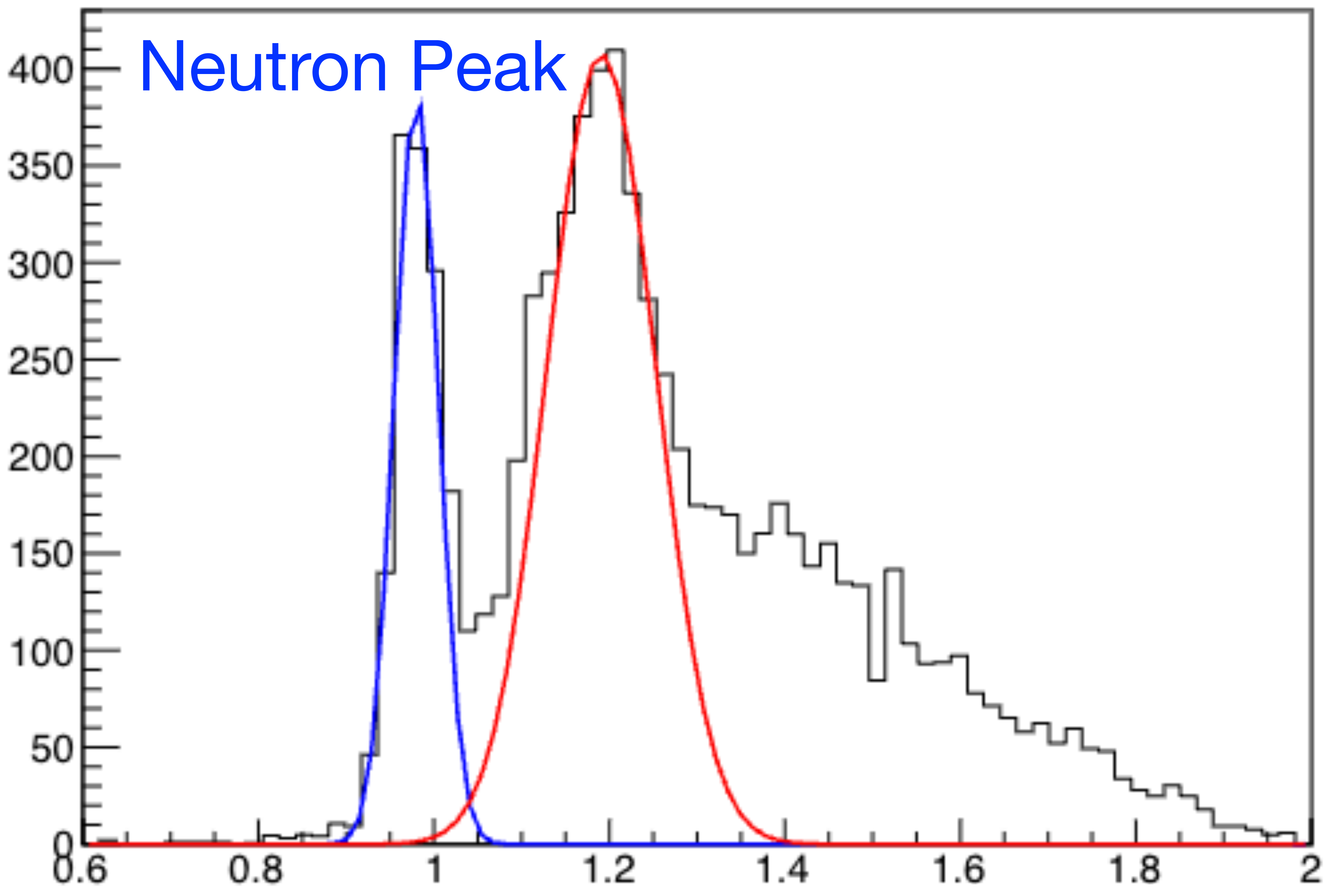
If BAND is sensitive to neutrons, there should be corresponding $W'(n)$ and $W'(p)$ QE peaks at $W'(n) \approx W'(p) \approx 938$ MeV

Natalie Wright

QE Results: Corresponding Nucleon Peaks!

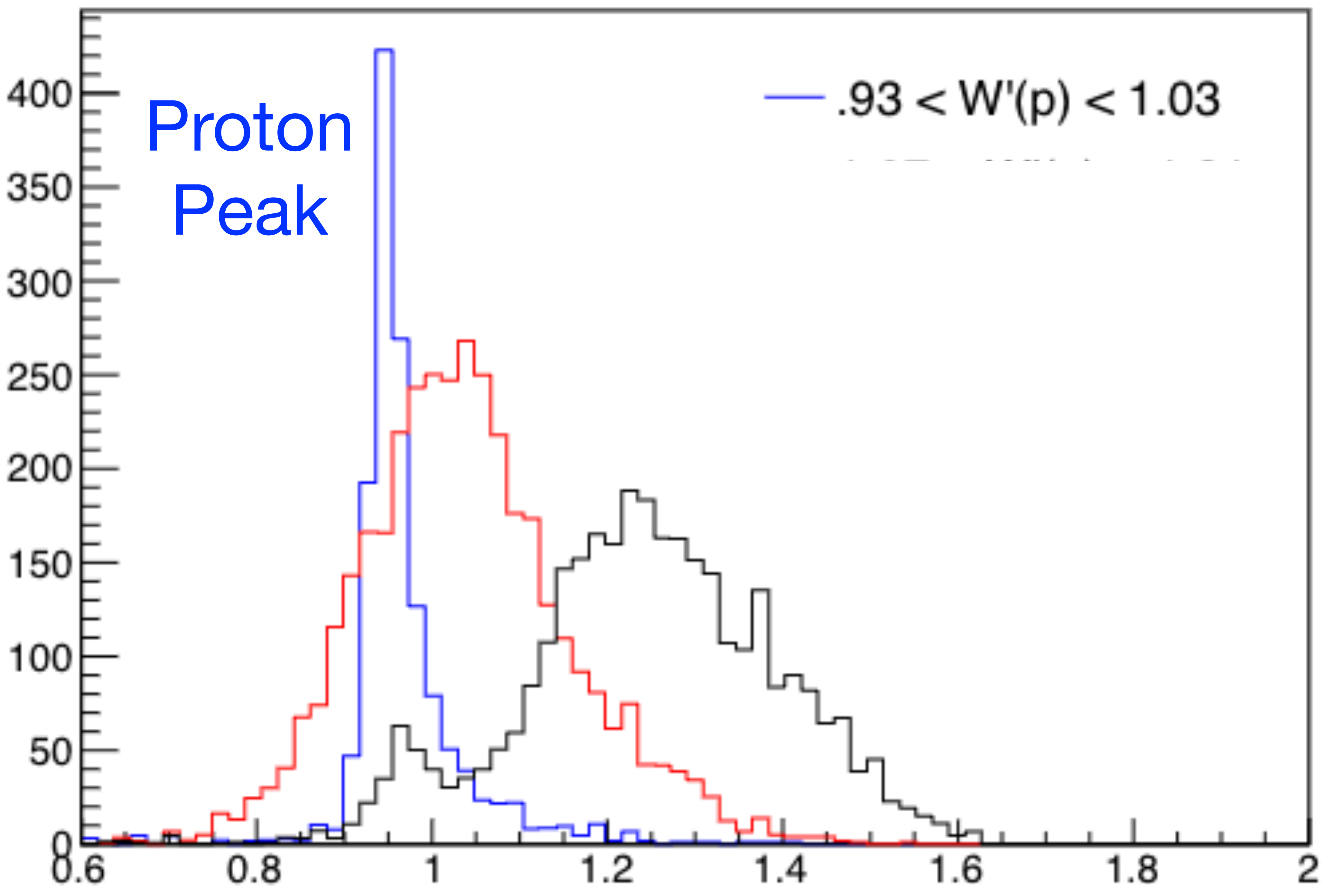
$$e + d \rightarrow e' + n + p$$

$1.30 < \alpha_S < 1.40$



$W'(p)$ [GeV/c^2]

$1.30 < \alpha_S < 1.40$



$W'(n)$ [GeV/c^2]

Selecting neutron peak in $W'(p)$ yields a corresponding proton peak in $W'(n)$ in 2 GeV data

Data / Sim Ratio after RGA Subtraction

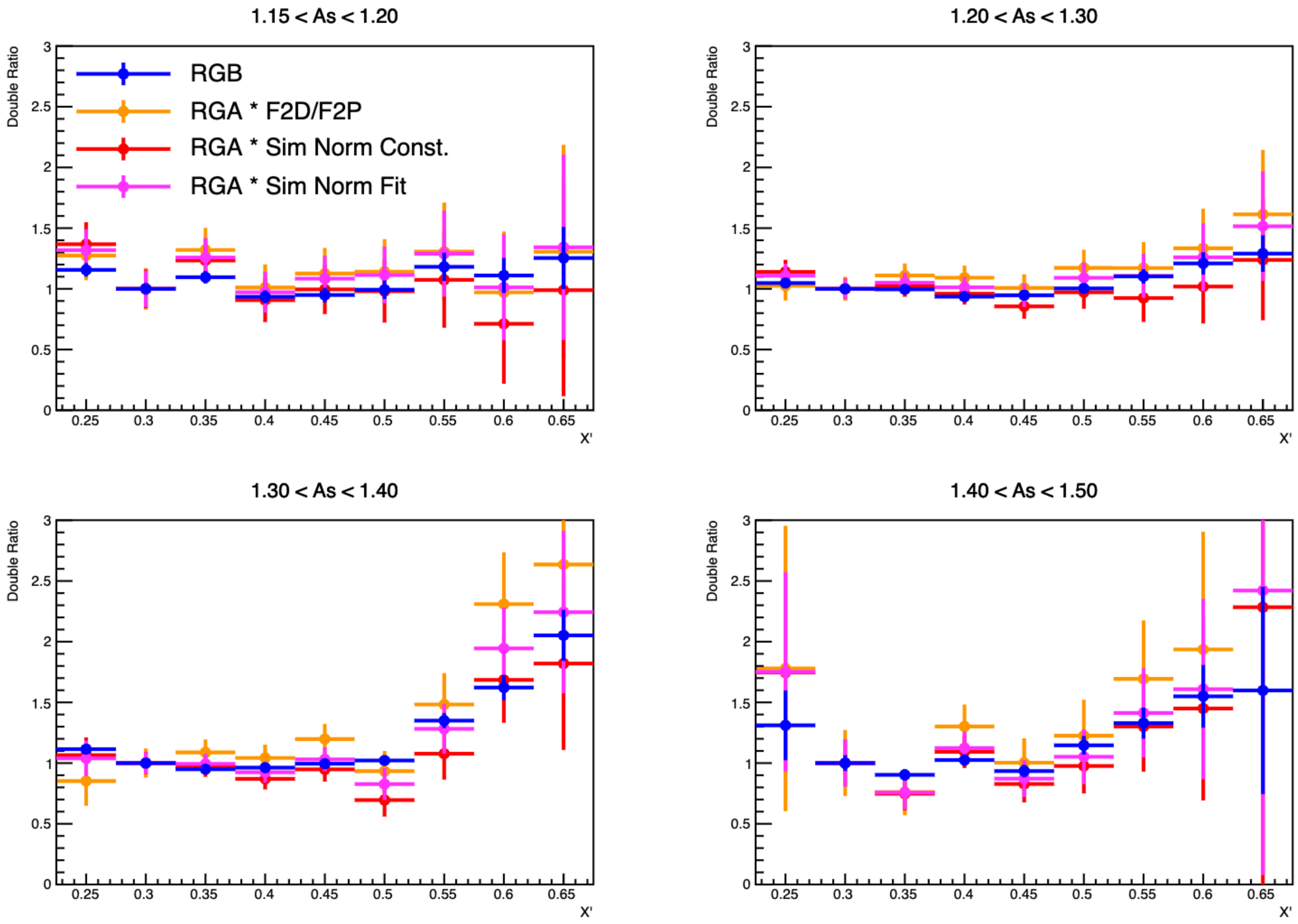
1. RGB events (before RGA subtraction): 6.68e4
2. RGA background events (F2n/F2p scaling): 3.86e4
3. RGB events (after RGA subtraction): 2.82e4

In the analysis note, the data/MC ratio for 10.2 GeV was 4.62 (using line 1 above)

The number of data events after subtraction is 42.2% of line 1

After RGA subtraction, the new data/MC ratio is 1.95

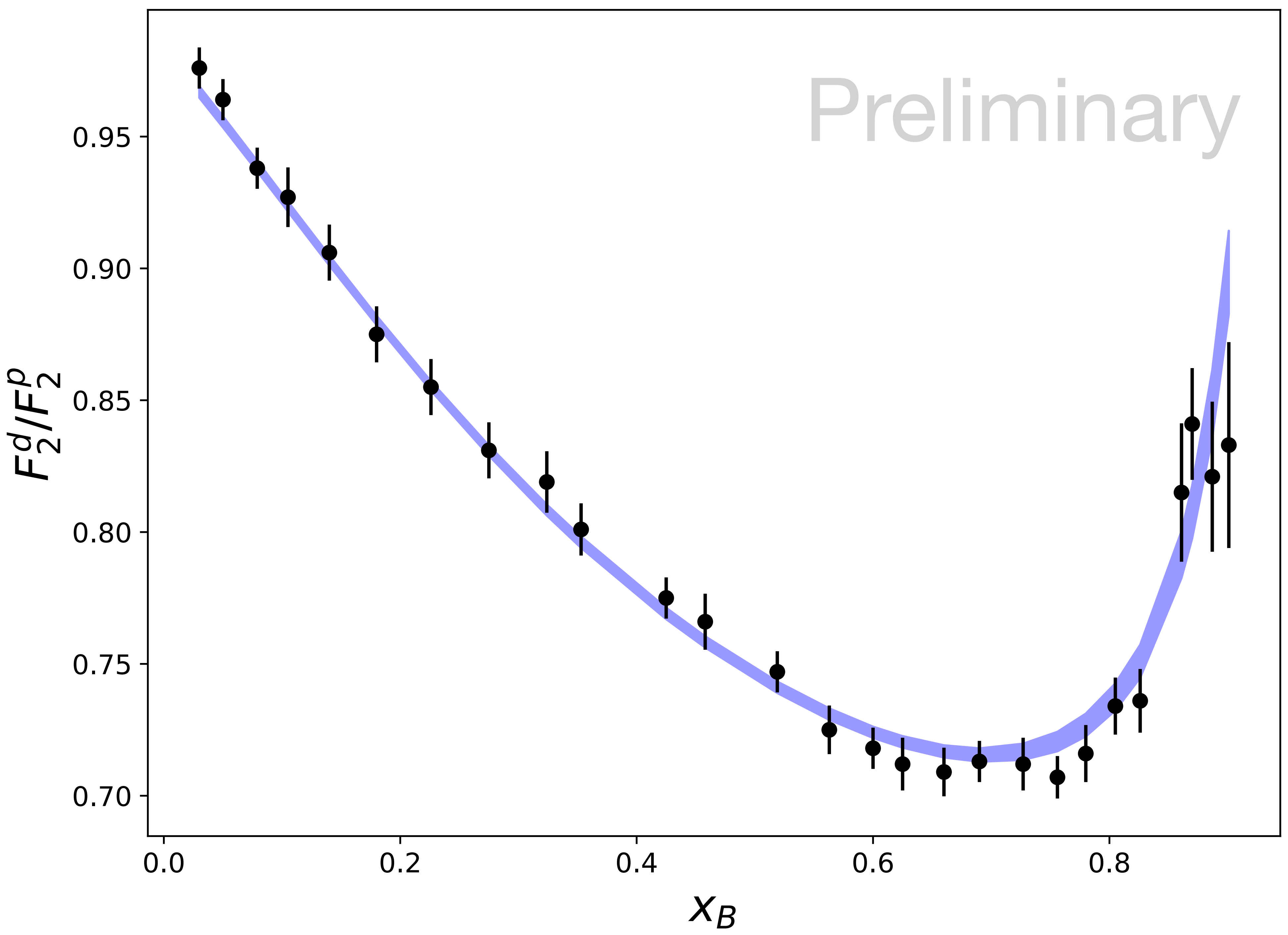
Subtracted double ratio with each RGA norm



Measurement compatible with DIS data

Convolution formalism:

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



$$F_2^p(x) = \frac{4}{9}u(x) + \frac{1}{9}d(x)$$

$$F_2^{*p}(x) = \frac{4}{9}u(x)\left(1 + \nu f_u^{off}(x)\right) + \frac{1}{9}d(x)\left(1 + \nu f_d^{off}(x)\right)$$

$\nu =$ Virtuality

$f_q^{off}(x) =$ Flavor-dept off-shell modification function

Measurement compatible with DIS data

Data used for fitting:

F_2^d / F_2^p (Global re-analysis, Arrington et al., J. Phys. G 36, 025005 (2009))

$F_2^{^3He} / F_2^d$ (Hall C, Seely et al., Phys. Rev. Lett. 103, 202301 (2009))

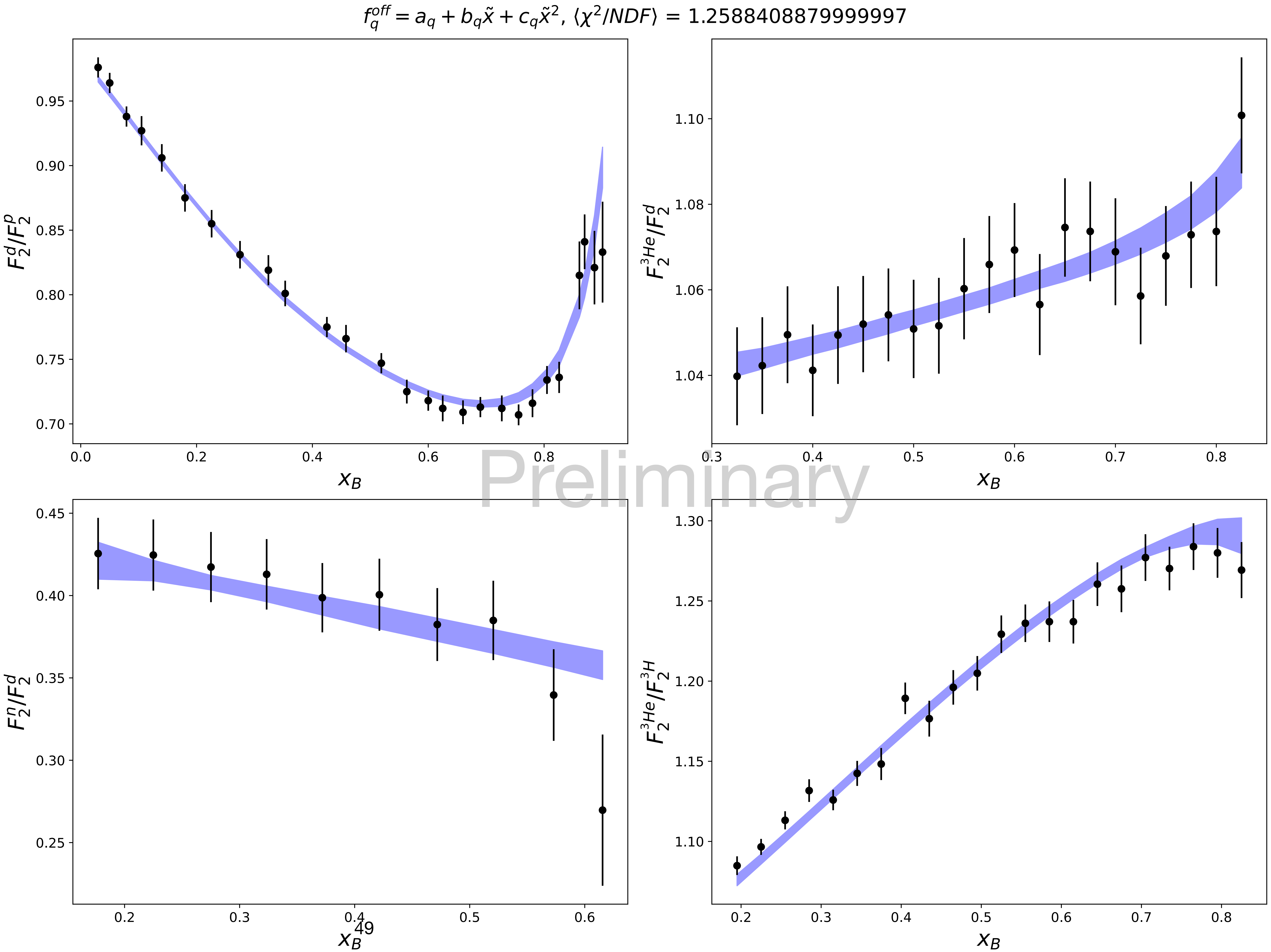
$F_2^d / (F_2^p + F_2^n)$ (BoNuS, Tkachenko et al., Phys. Rev. C 89, 045206 (2014))

$F_2^{^3He} / F_2^{^3H}$ (Marathon, D. Abrams et al., Phys. Rev. Lett. 128, 132003 (2022))

+Tagged: $F_2^{p,tagged} / F_2^p$ (BAND)

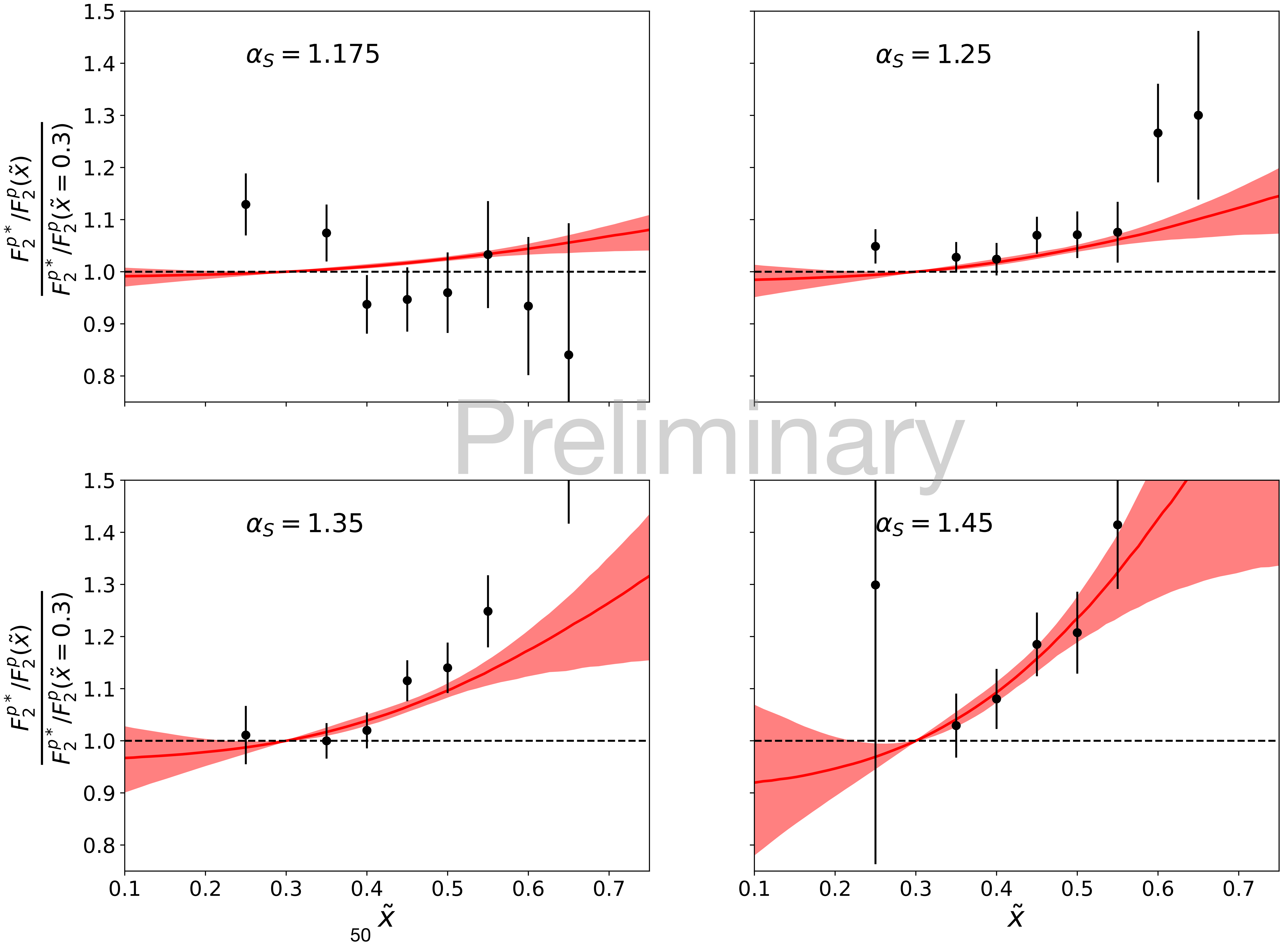
Measurement compatible with DIS data

Inclusive simultaneous fit results:



Measurement compatible with DIS data

BAND tagged simulataneous fit results:



Data vs. Simulation (No RG-A Subtraction)