PAC 54

(PR12-26-009)

FSI Studies at the Nuclear Core

Spokespeople: C. Yero* (CUA), W. U. Boeglin, M.K. Jones (JLab),

Theory Collaborators: M. Sargsian (FIU), S. Jeschonnek (OSU)

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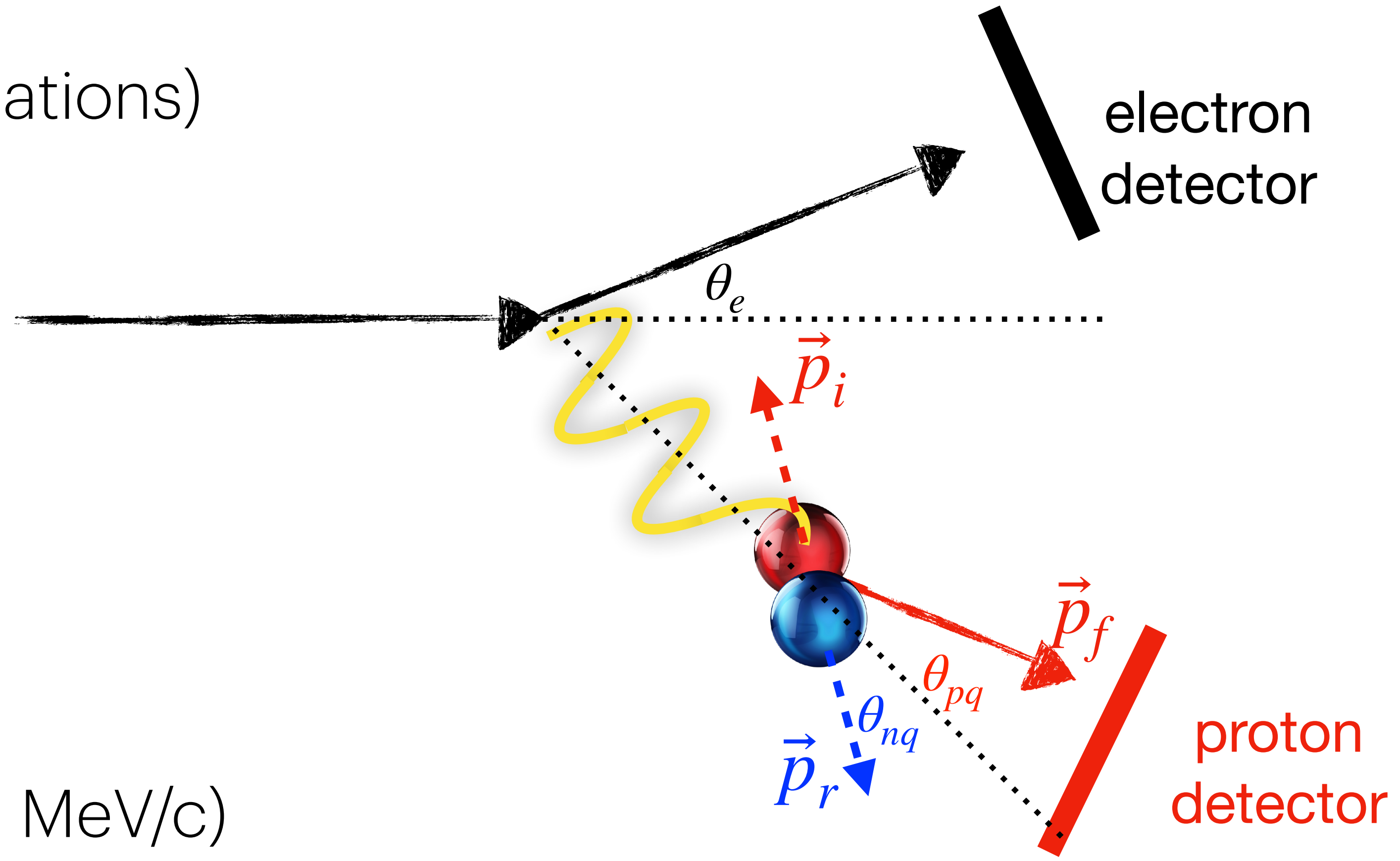
Why Study the Deuteron ?

$d(e, e'p)n$ ideal for nuclear core studies

- most simple *np* bound system
  (no 3*N* forces or additional complications)

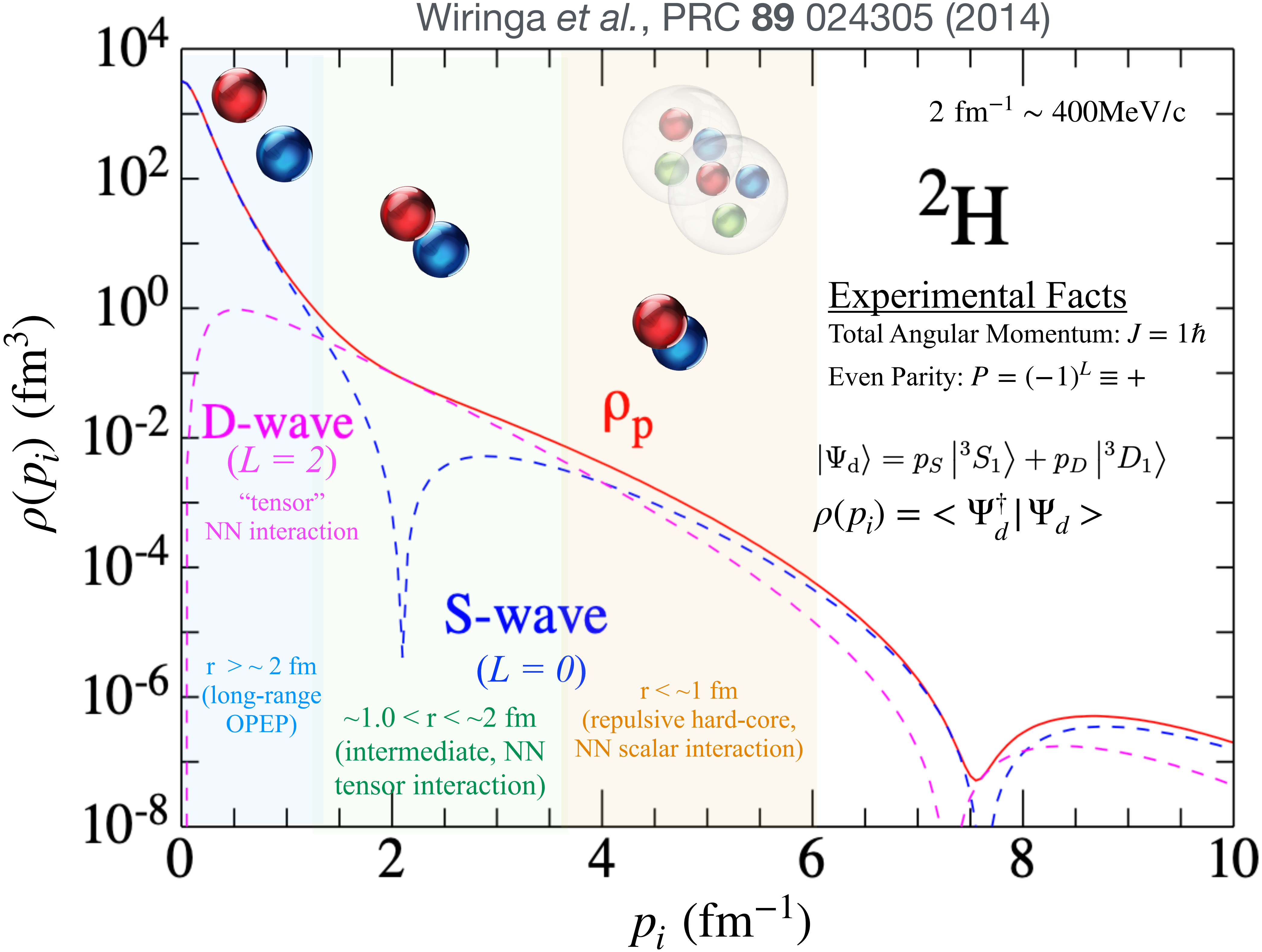
- foundation for short-range
  correlations in heavier nuclei
  (*np*-dominance, scaling in *A*>2)

- reliable FSI calculations (up to ~550 MeV/c)
  compared to heavier nuclei



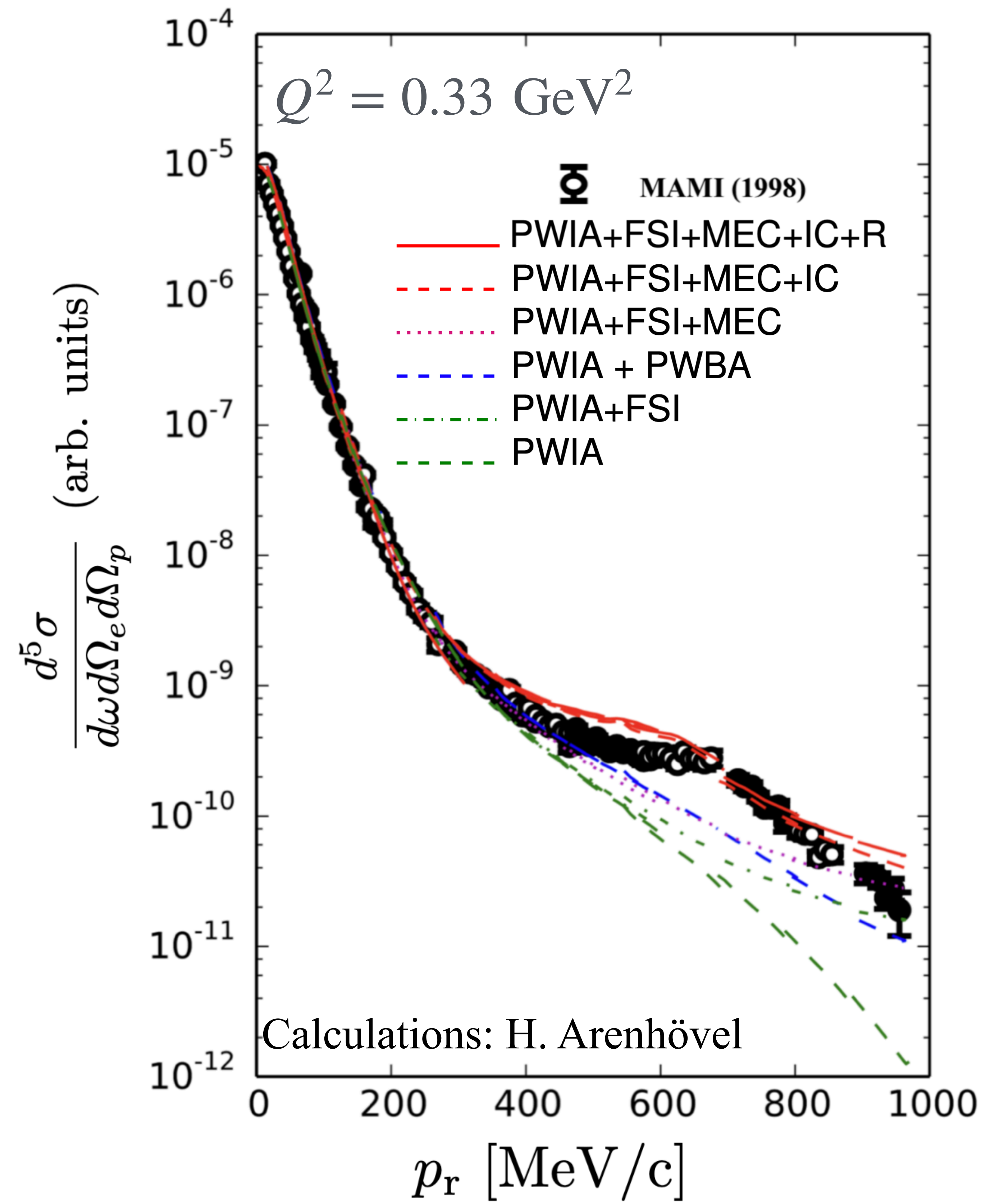
Momentum Distribution

Wiringa *et al.*, PRC **89** 024305 (2014)



Difficulty in Probing the Nuclear Core

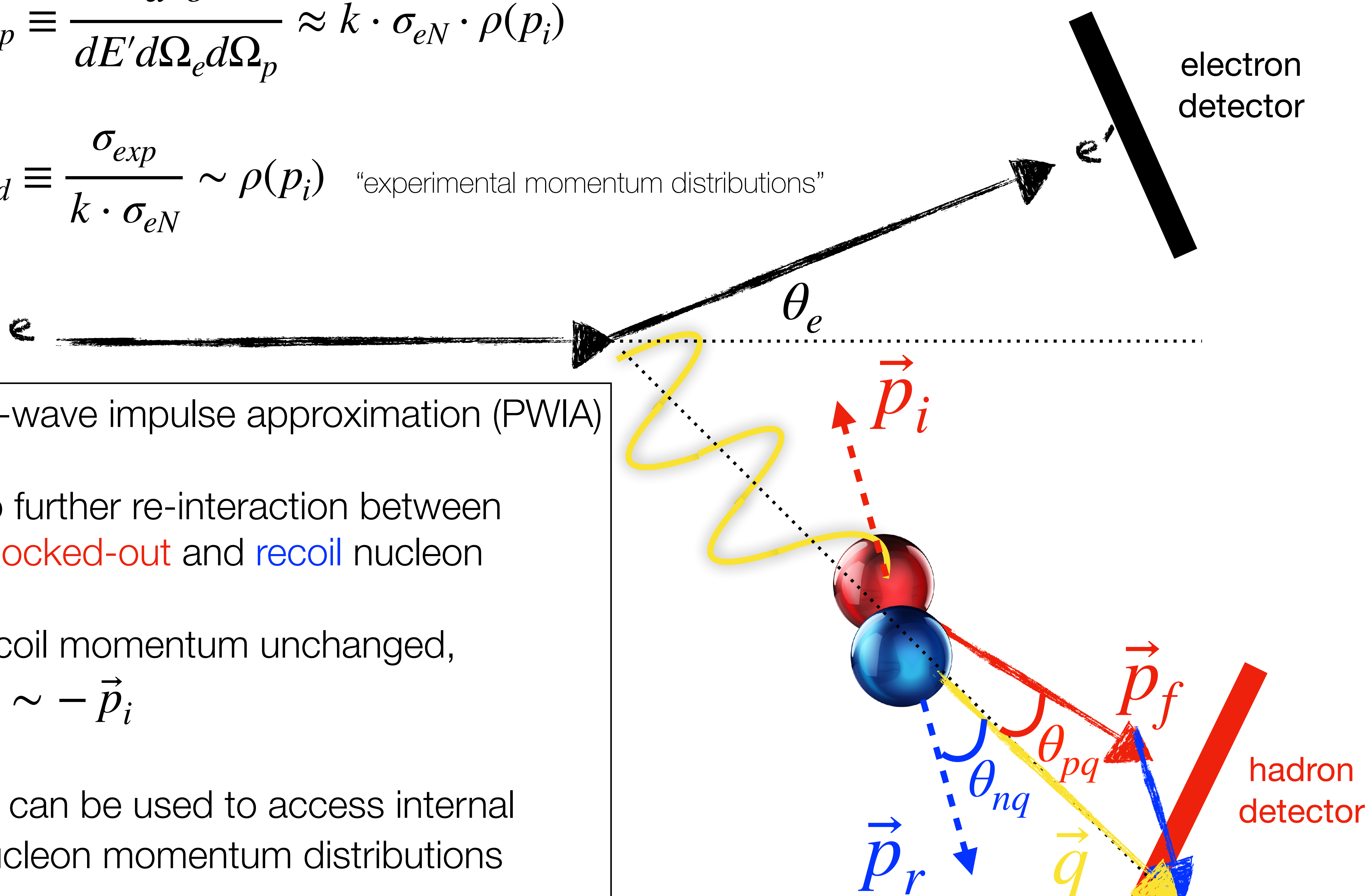
Blomqvist, Boeglin *et al.*, PLB **424** 33 (1998)



Probing the High-Momentum Structure

$$\sigma_{exp} \equiv \frac{d^5\sigma}{dE' d\Omega_e d\Omega_p} \approx k \cdot \sigma_{eN} \cdot \rho(p_i)$$

$$\sigma_{red} \equiv \frac{\sigma_{exp}}{k \cdot \sigma_{eN}} \sim \rho(p_i)$$ "experimental momentum distributions"



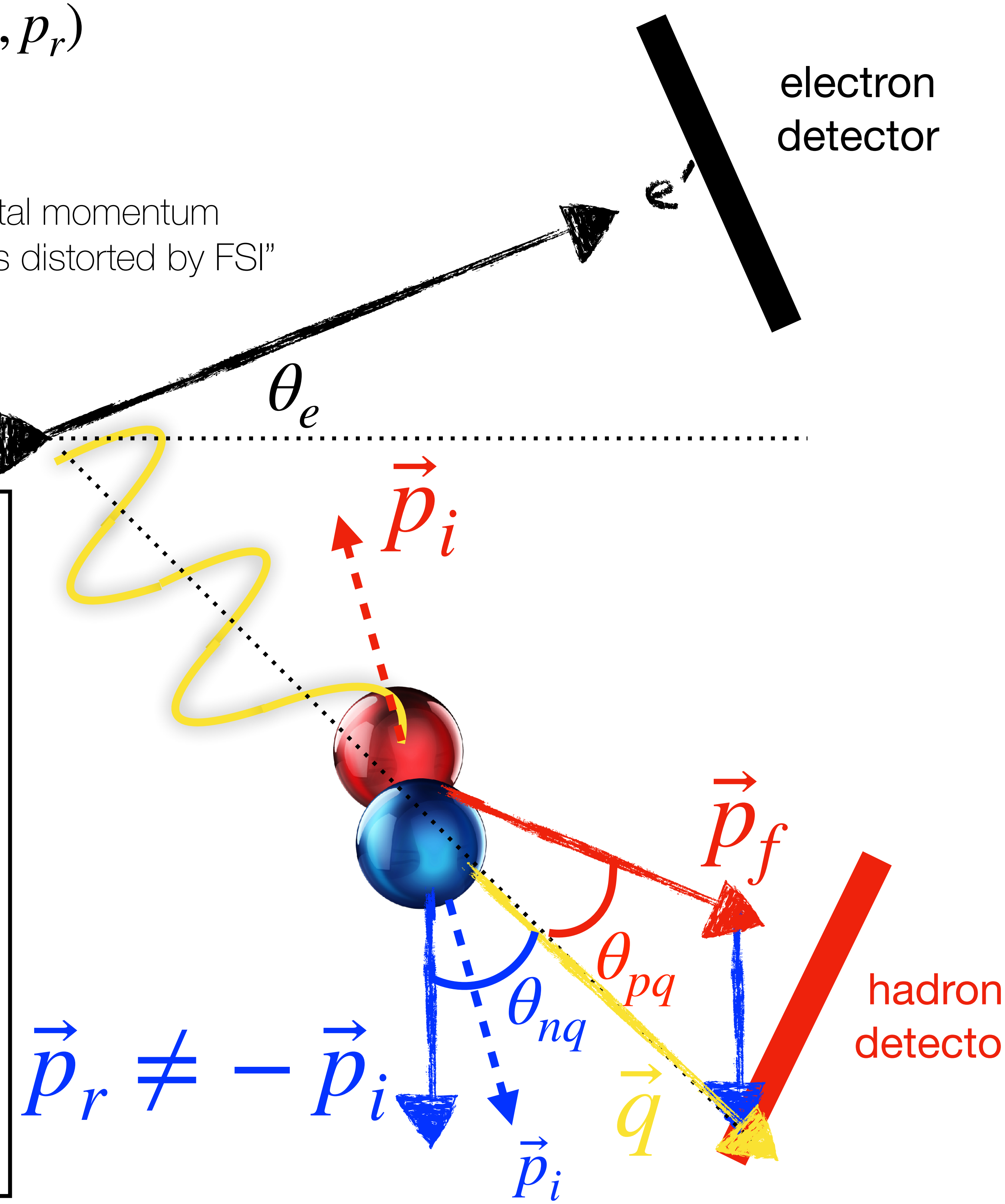
- plane-wave impulse approximation (PWIA)
  - no further re-interaction between knocked-out and recoil nucleon
  - recoil momentum unchanged, $\vec{p}_r \sim -\vec{p}_i$
  - $\vec{p}_r$ can be used to access internal nucleon momentum distributions

Probing the High-Momentum Structure

$$\sigma_{exp} \equiv \frac{d^5\sigma}{dE' d\Omega_e d\Omega_p} = k \cdot \sigma_{eN} \cdot \rho_D(p_i, p_r)$$

$$\sigma_{red} \equiv \frac{\sigma_{exp}}{k \cdot \sigma_{eN}} \sim \rho_D(p_i, p_r)$$

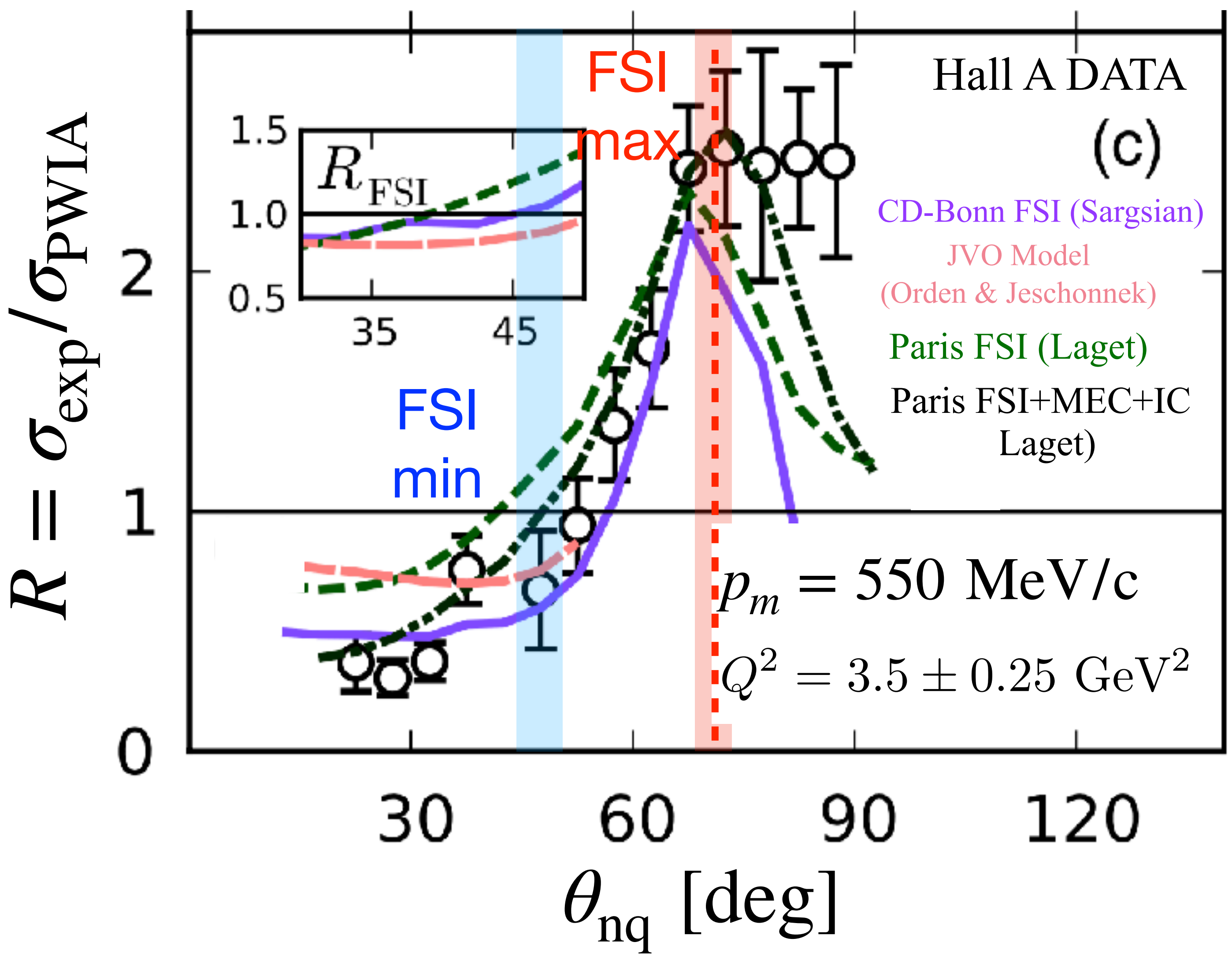
"experimental momentum distributions distorted by FSI"



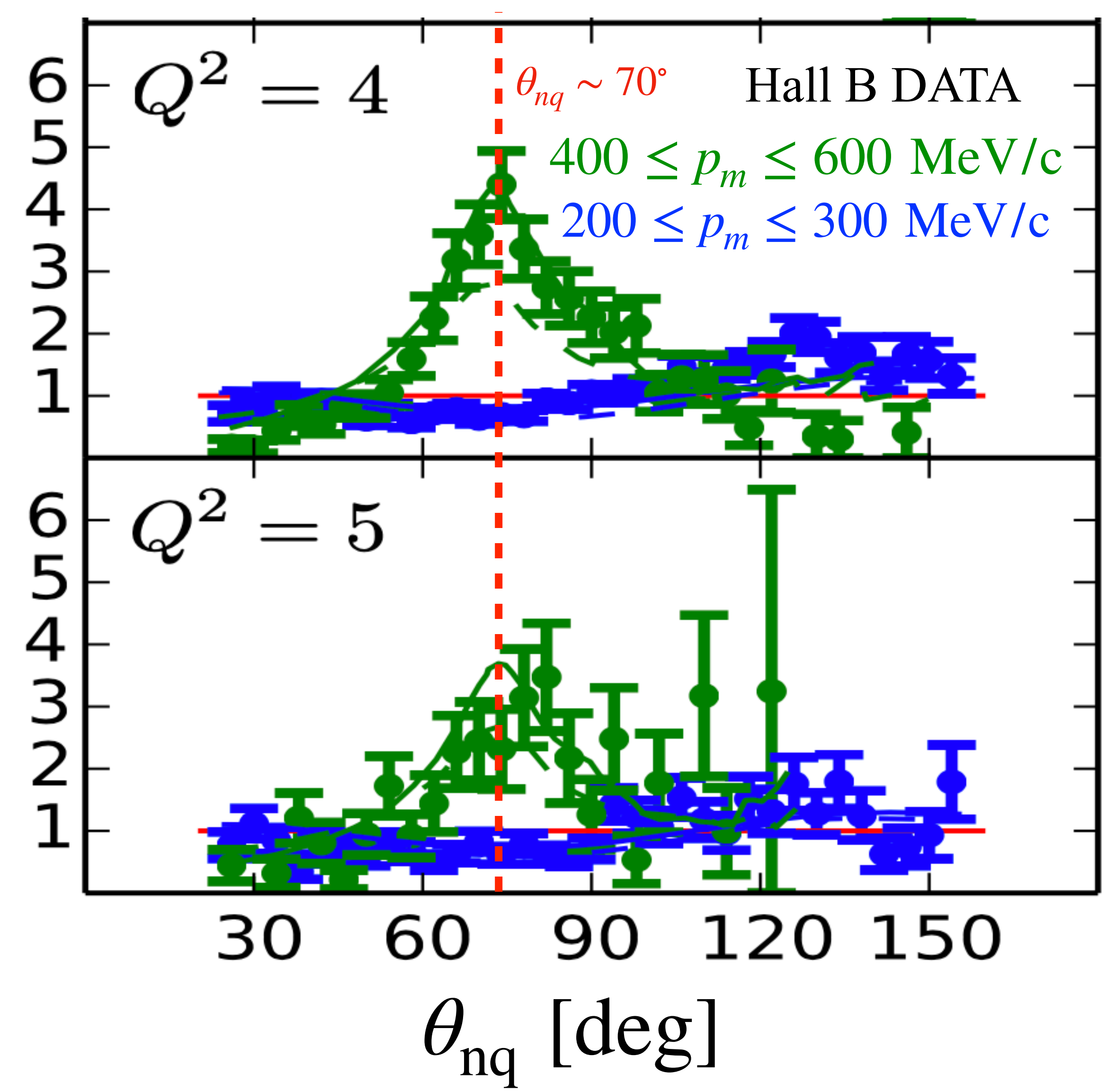
- Final-state interactions (FSI):
  - recoil nucleon re-interacts with knocked-out nucleon
  - recoil momentum modified, $\vec{p}_r \neq -\vec{p}_i$
  - $\vec{p}_r$ cannot be used to access internal nucleon momentum distributions

Controlling Final-State Interactions

Boeglin et al. (Hall A) PRL **107**, 262501 (2011)



Egiyan et al. (CLAS) PRL **98**, 262502 (2007)



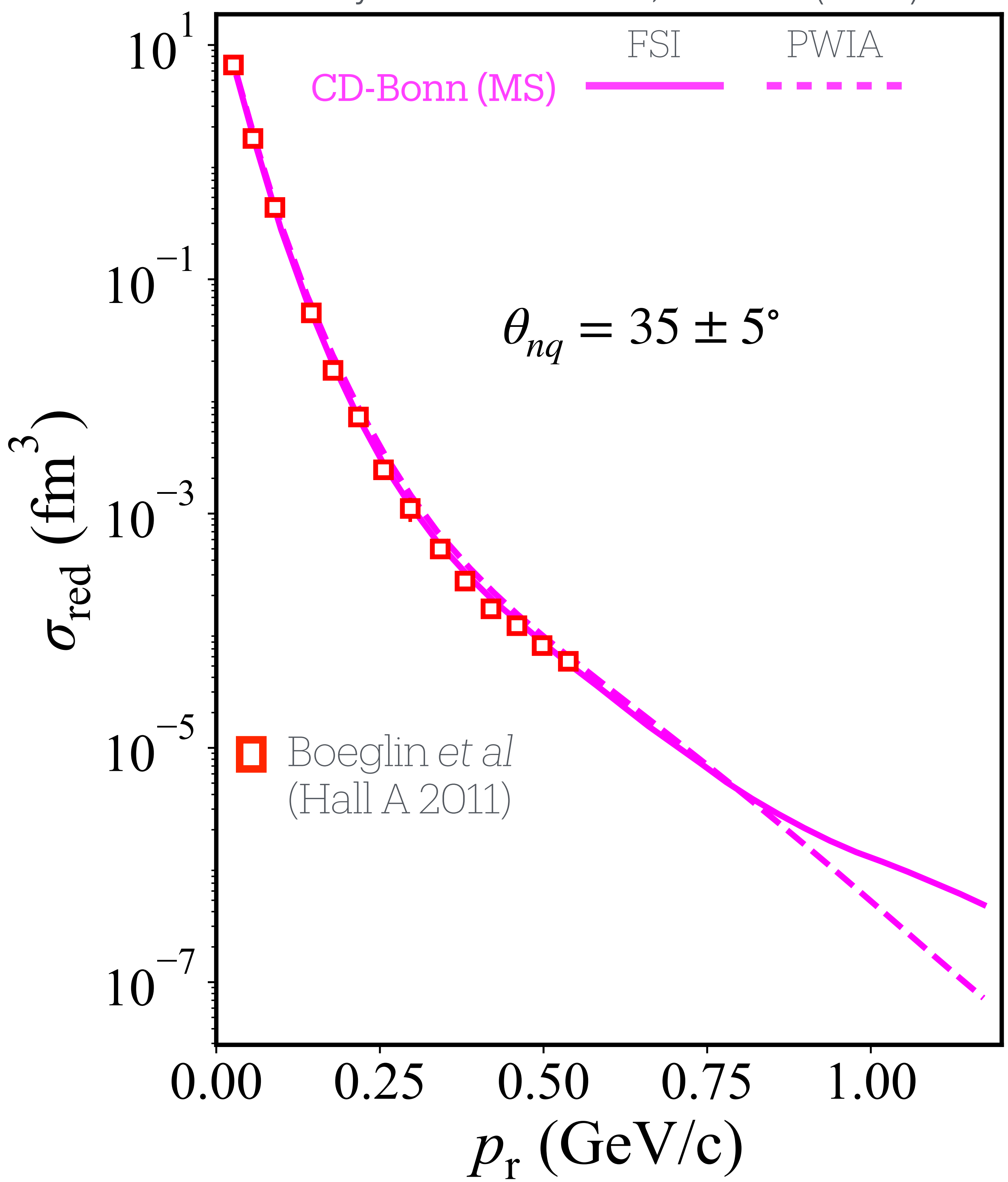
Phys. Rev. B **609**, 49 (Laget 2005)

Phys. Rev. C **78**, 014007 (Orden & Jeschonnek 2008)

Phys. Rev. C **82**, 014612 (Sargsian 2010)

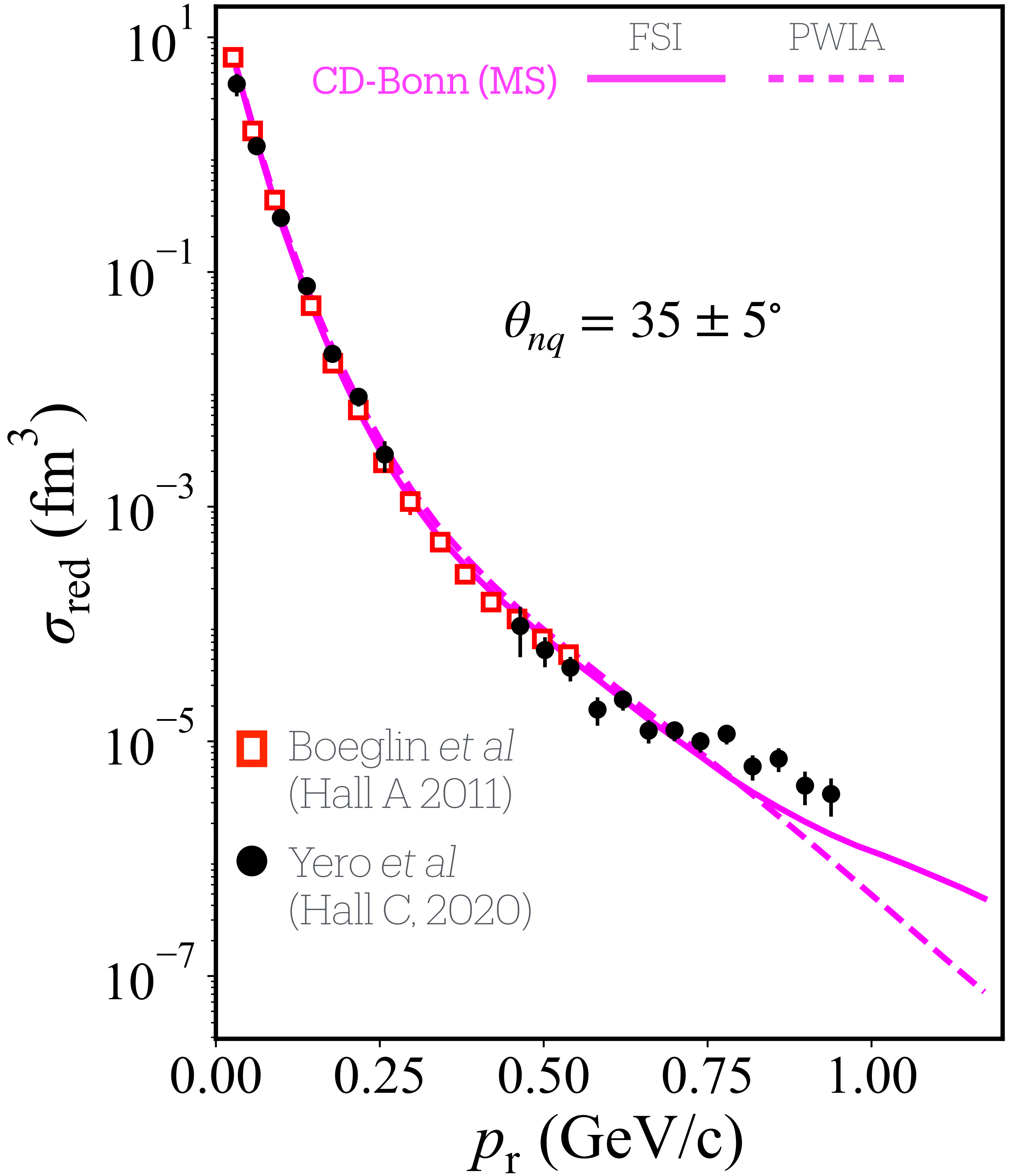
Probing the NN Repulsive Core

Phys. Rev. Lett. **125**, 262501 (2020)



Probing the NN Repulsive Core

Phys. Rev. Lett. **125**, 262501 (2020)



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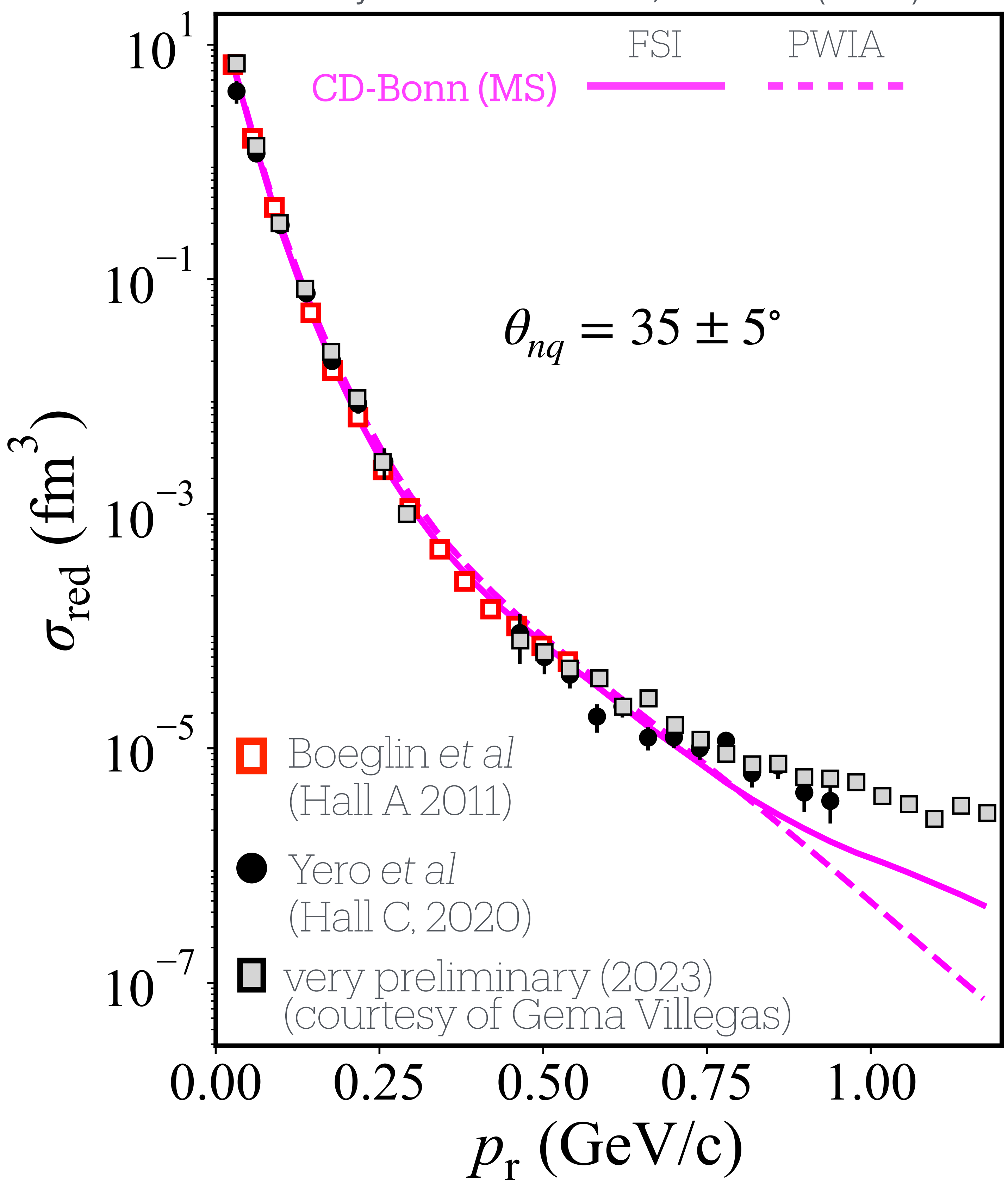
Phys. Rev. Lett. **125**, 262501 (2020)



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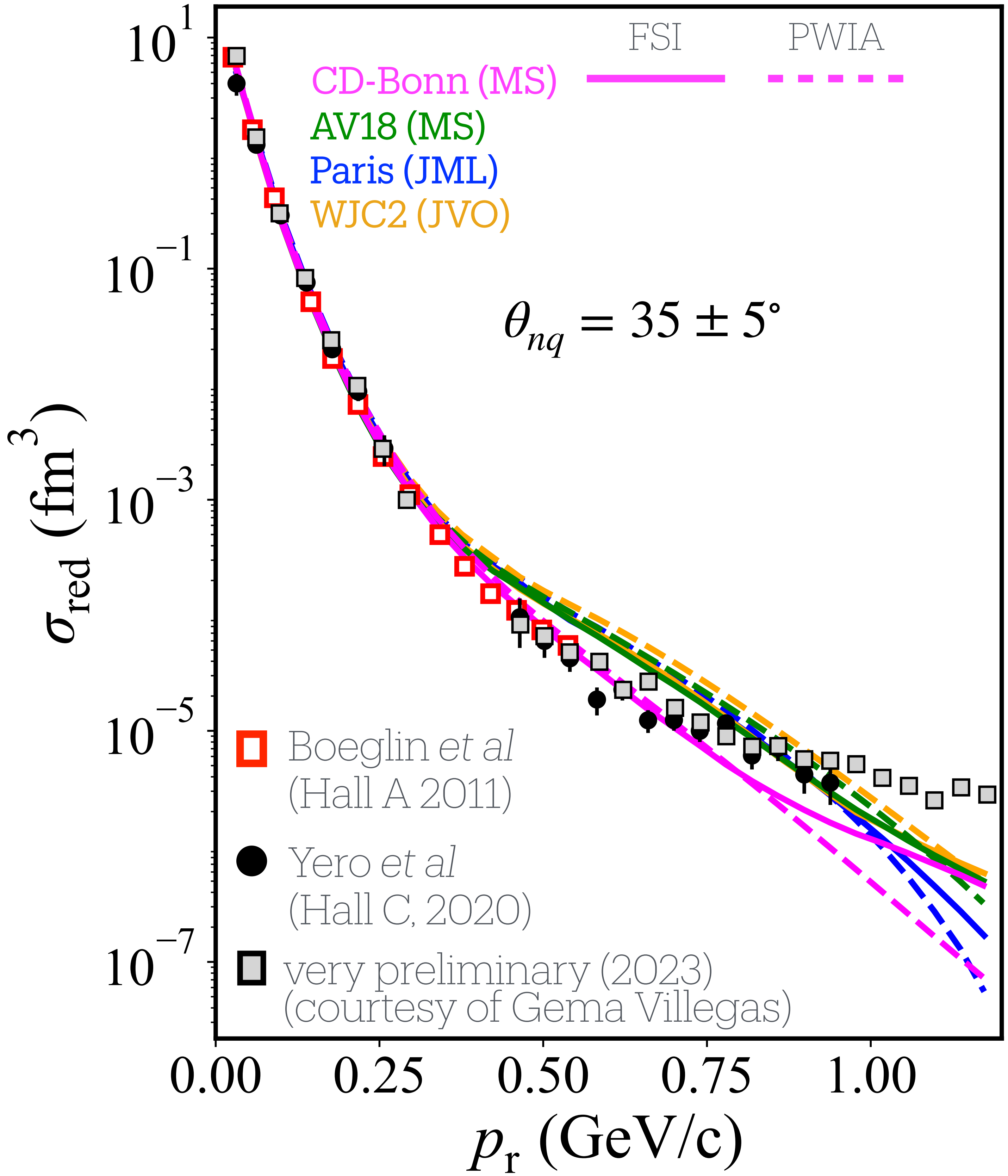
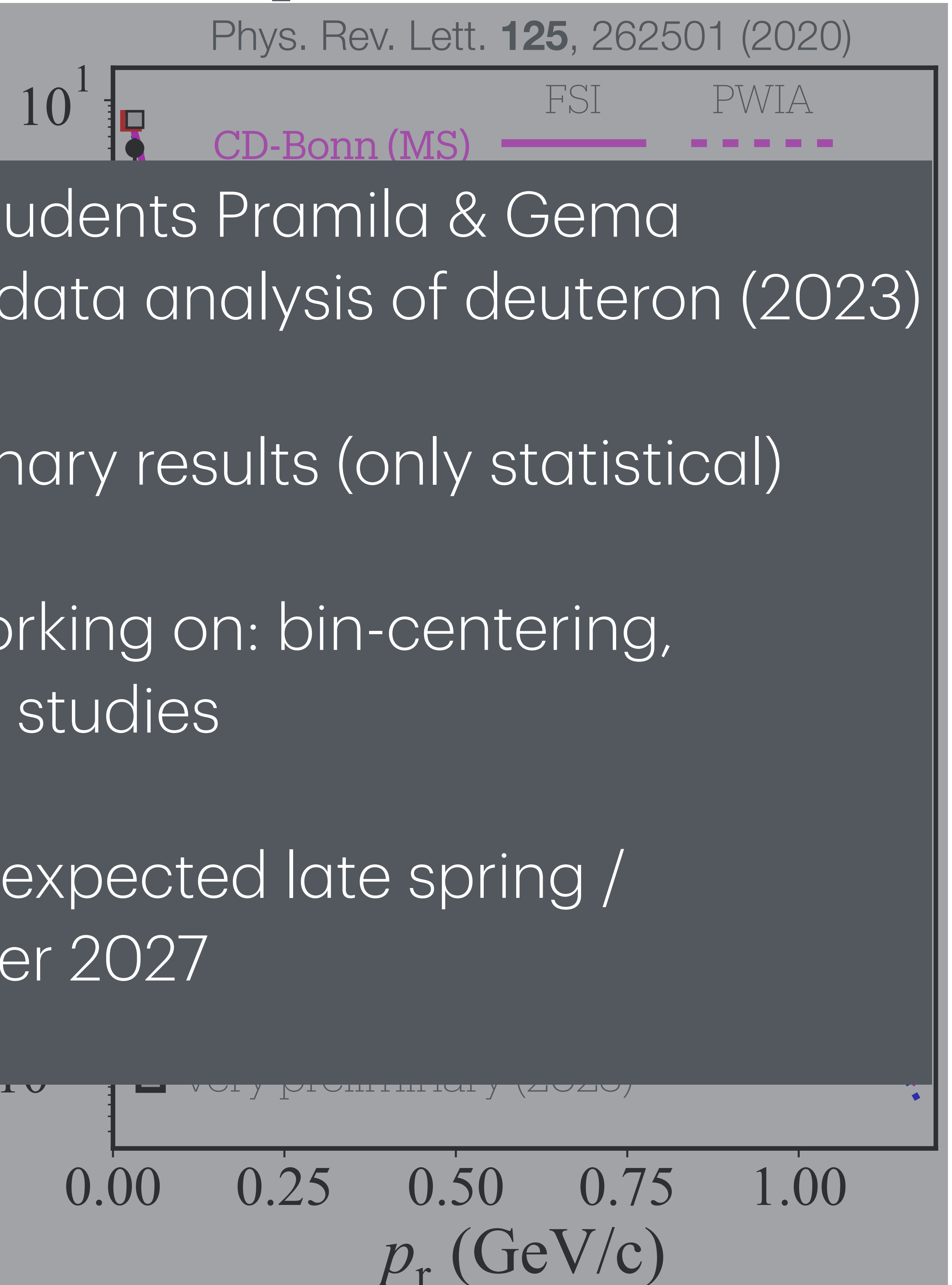


Probing the NN Repulsive Core



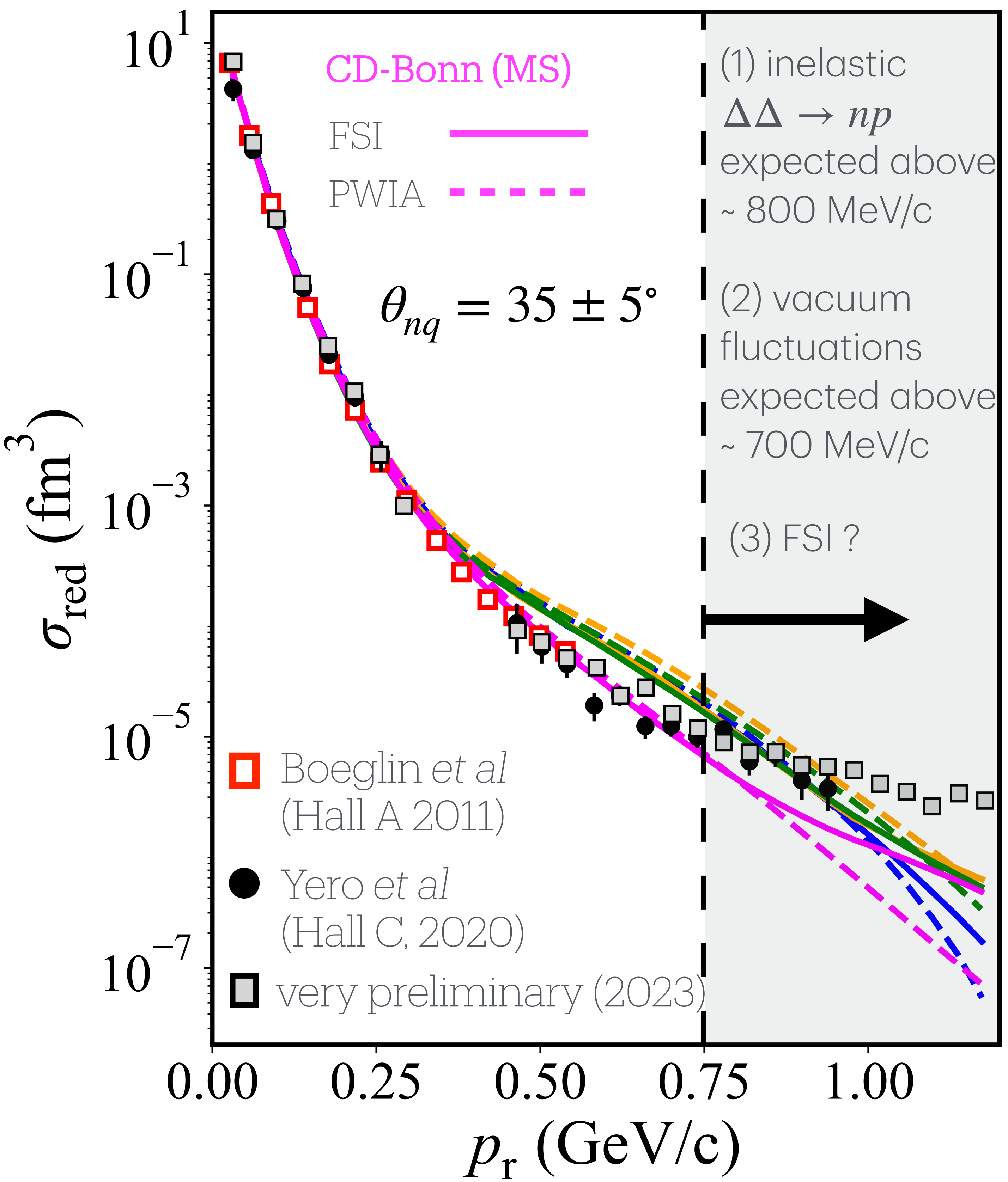
- Graduate students Pramila & Gema working on data analysis of deuteron (2023)
- very preliminary results (only statistical)
- currently working on: bin-centering, systematics studies
- publication expected late spring / early summer 2027

Pramila Pokhrel (CUA)

Gema P. Villegas (FIU)

Probing the NN Repulsive Core

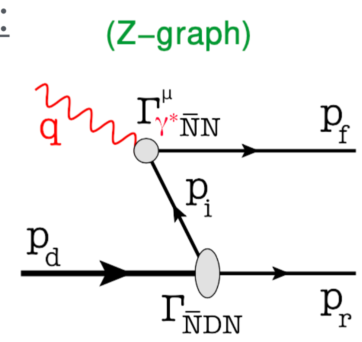
Phys. Rev. Lett. **125**, 262501 (2020)



Virtual Nucleon Approximation (VNA) Theoretical Framework (Sargsian 2010)

- only $pn \rightarrow pn$ transitions (non-nucleonic parts excluded)
- dynamics of $\gamma^* N$ and FSI (GEA) are relativistic
- vacuum fluctuations neglected; $\Psi_d = \Psi_d^{NR} \times f_{corr}^{rel.}$ (below p_r ~ 700 MeV/c VF are expected to be small)

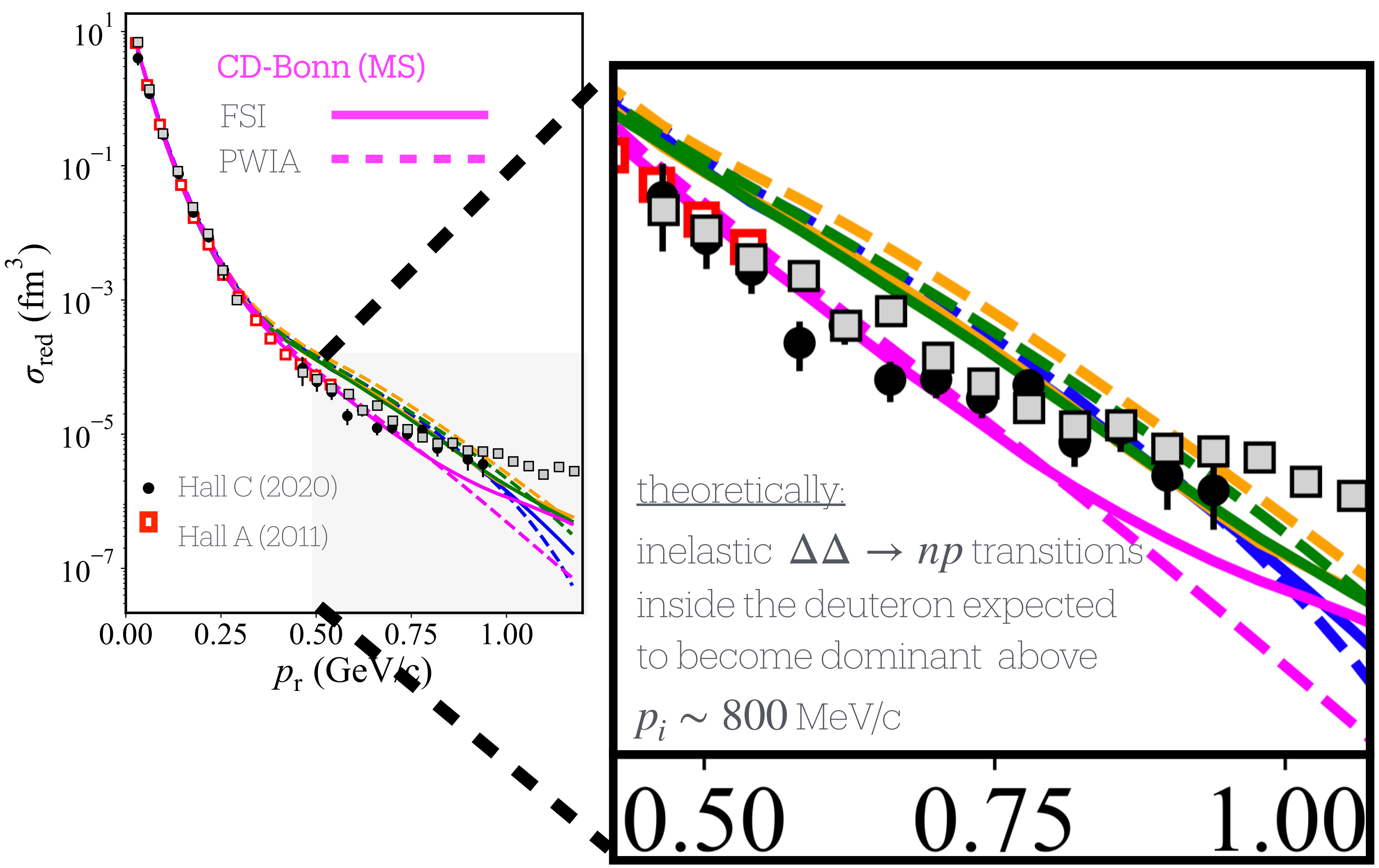
vacuum fluctuations diagram:



F. Vera Thesis (2021)

PRC **82**, 014612 (Sargsian 2010)

Probing the NN Repulsive Core



NO theory calculation reproduces data trend above ~750 MeV/c

"anomaly" in data starts very close to the threshold of non-nucleonic transitions (~800 MeV/c) of the *NN* system

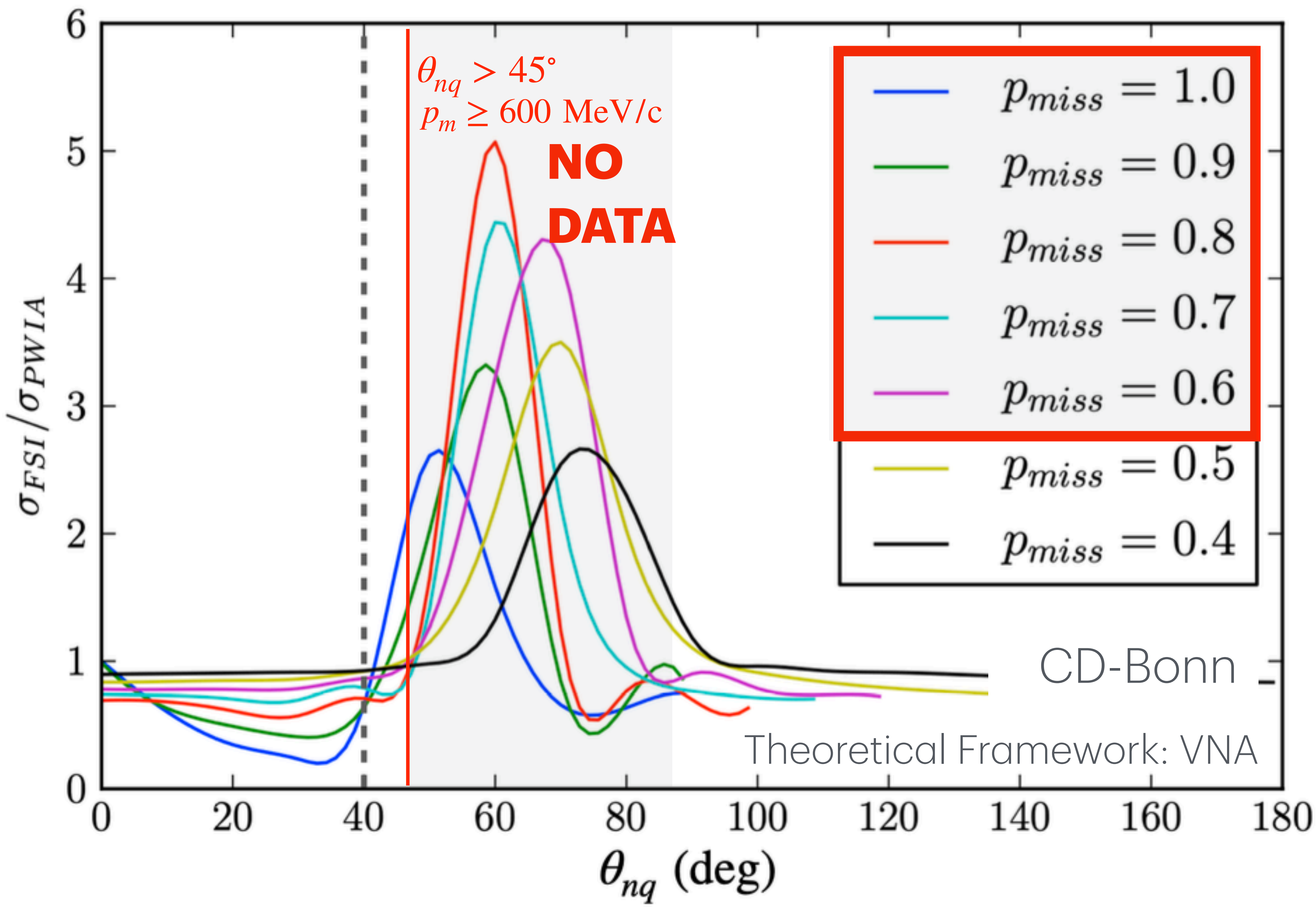
How to dis-entangle **FSI** + **relativistic** + **non-nucleonic(?)** effects at high missing momenta ?

PRC **82**, 014612 (Sargsian 2010)

PRL **130**, 112502 (Sargsian 2023)

NN Repulsive Core Sensitivity to FSI

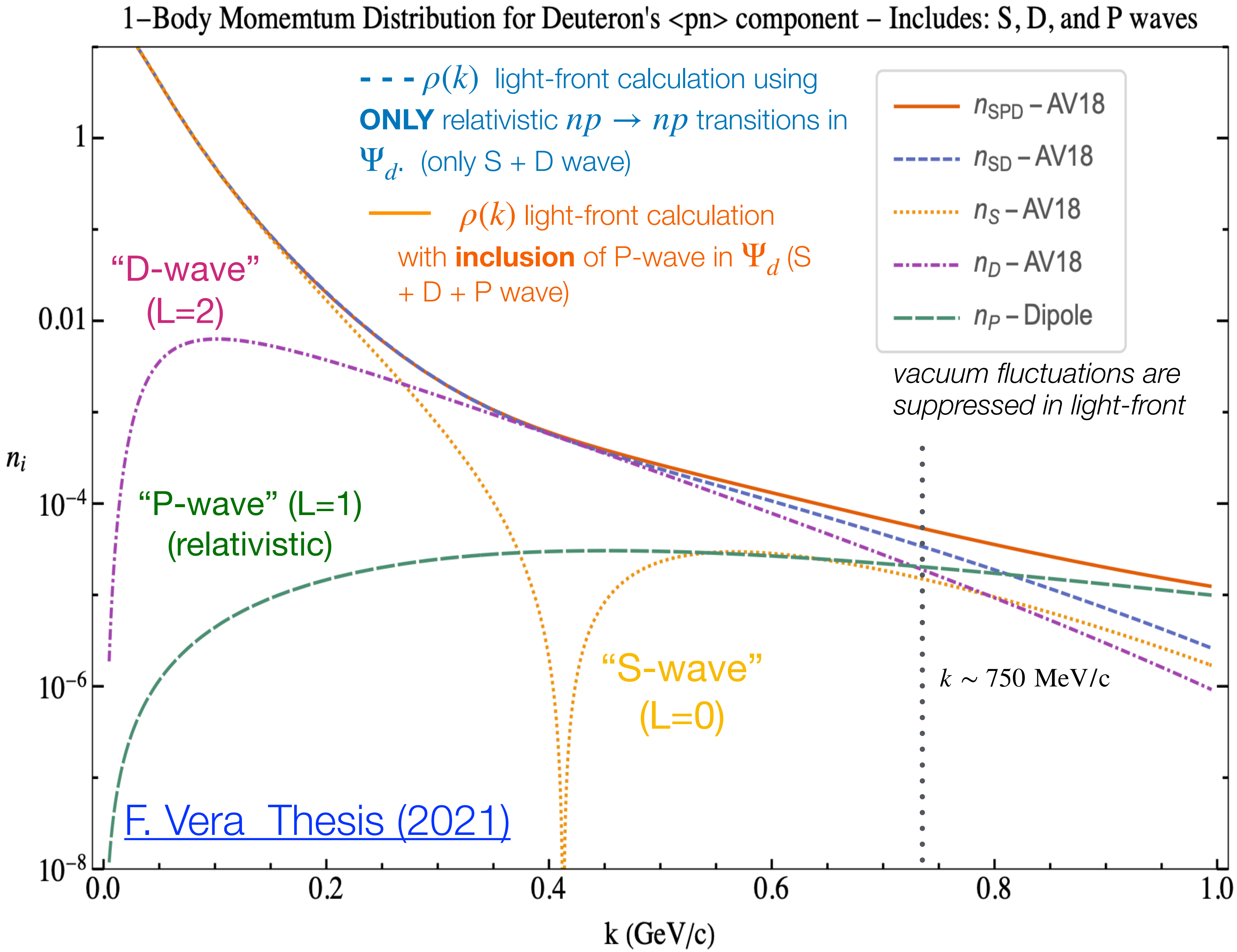
IJMP E Vol. **24**, No. 03, 1530003 (Boeglin & Sargsian, 2015)



*GEA predict FSI peak shifts towards lower θ_{nq} with increasing p_m

*generalized eikonal approximation: relativistic theoretical framework for FSI calculations

Deuteron on the Light-Front



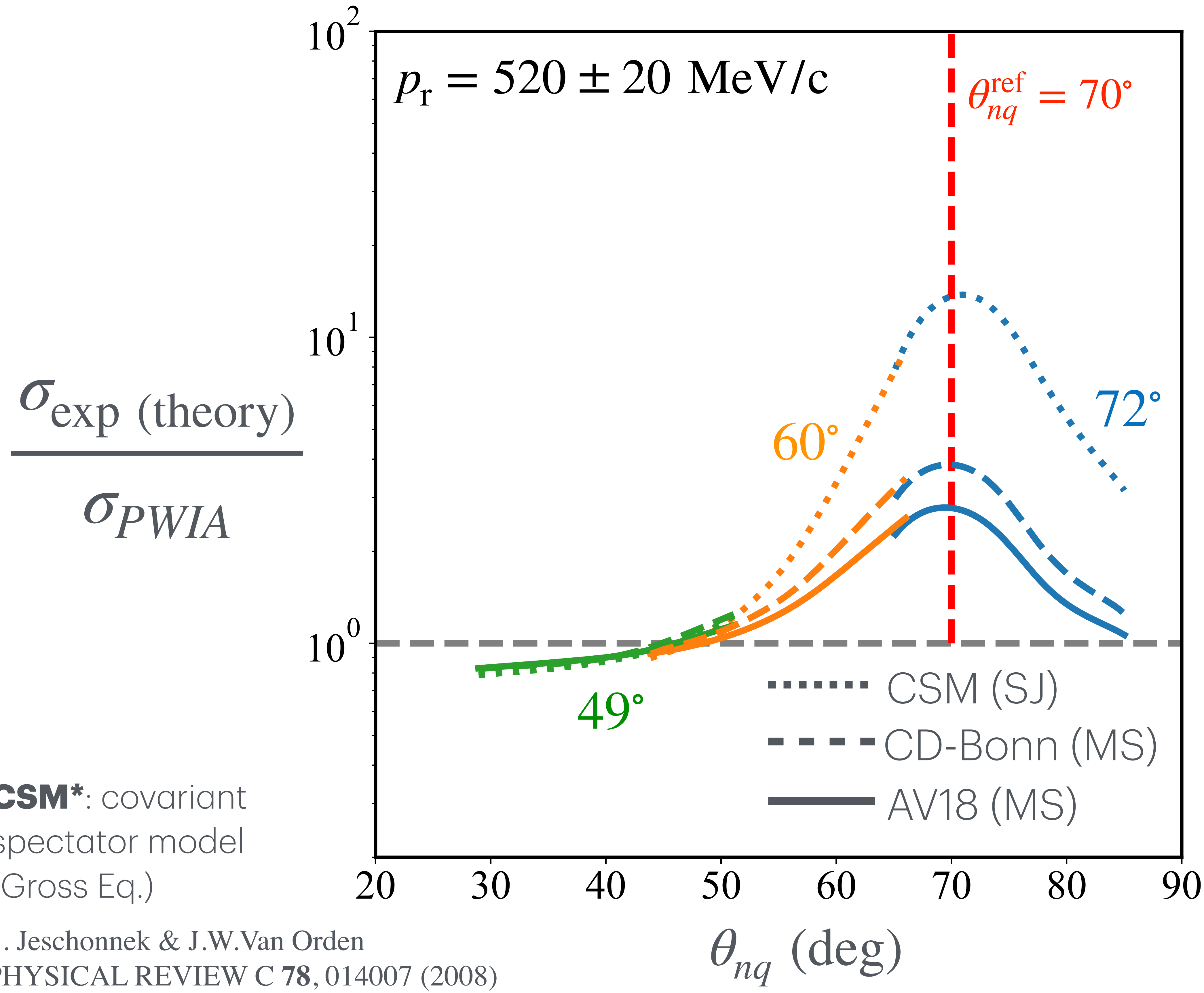
- calculation of Ψ_d in the light-front give rise to a 'P-wave' -like component (in violation of angular condition)
- P-wave starts to dominate at $k \sim 750$ MeV/c, characterized by a 'flattening trend';
- published data Yero et al. 2020 anomaly starting at 750 MeV/c has a similar trend (but origin not clear)
- LF calculation (PWIA+FSI) in progress by M. Sargsian

M. Sargsian & F. Vera Phys. Rev. Lett. 130, 112502 (2023)

relativistic (np) relativistic (non-nucleonic)

$$\Psi_d = \boxed{\Psi_{pn}} + \boxed{\Psi_{\Delta\Delta} + \Psi_{NN^*} + \Psi_{hc} + \Psi_{NN\pi} \cdots}$$

Proposed Measurement

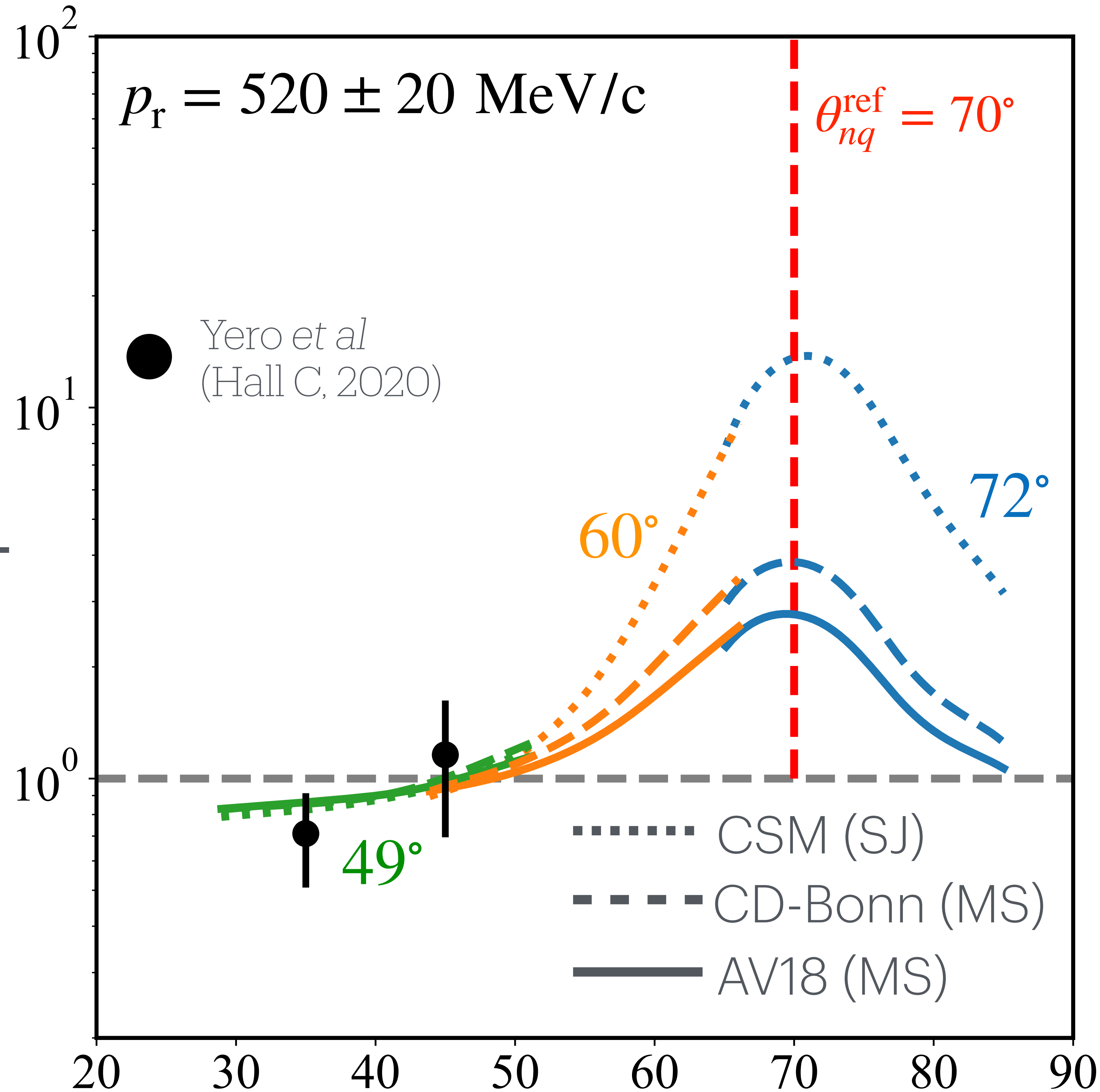


CSM*: covariant spectator model (Gross Eq.)

S. Jeschonnek & J.W.Van Orden
PHYSICAL REVIEW C **78**, 014007 (2008)

Proposed Measurement

$\frac{\sigma_{\text{exp (theory)}}}{\sigma_{PWIA}}$



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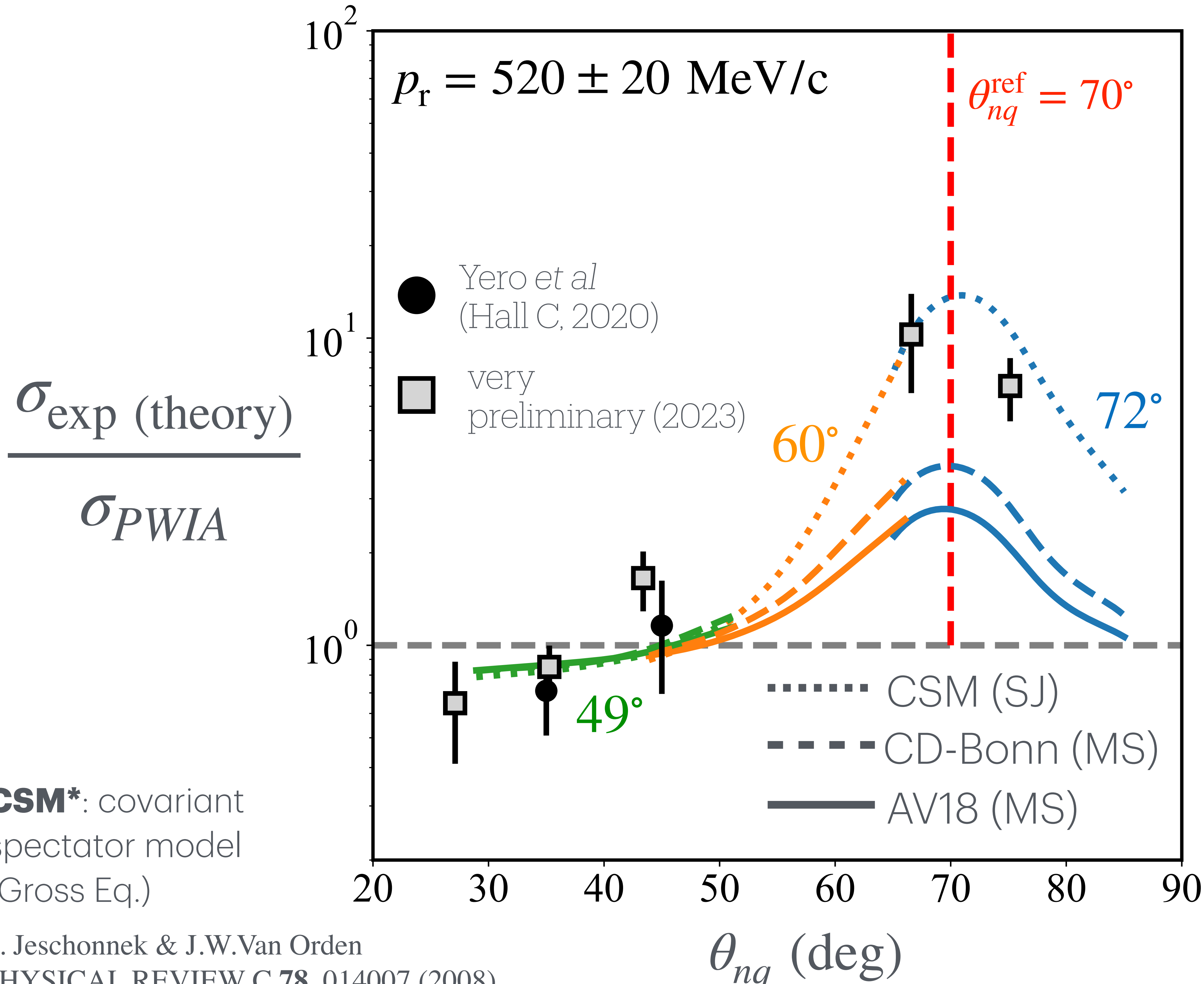

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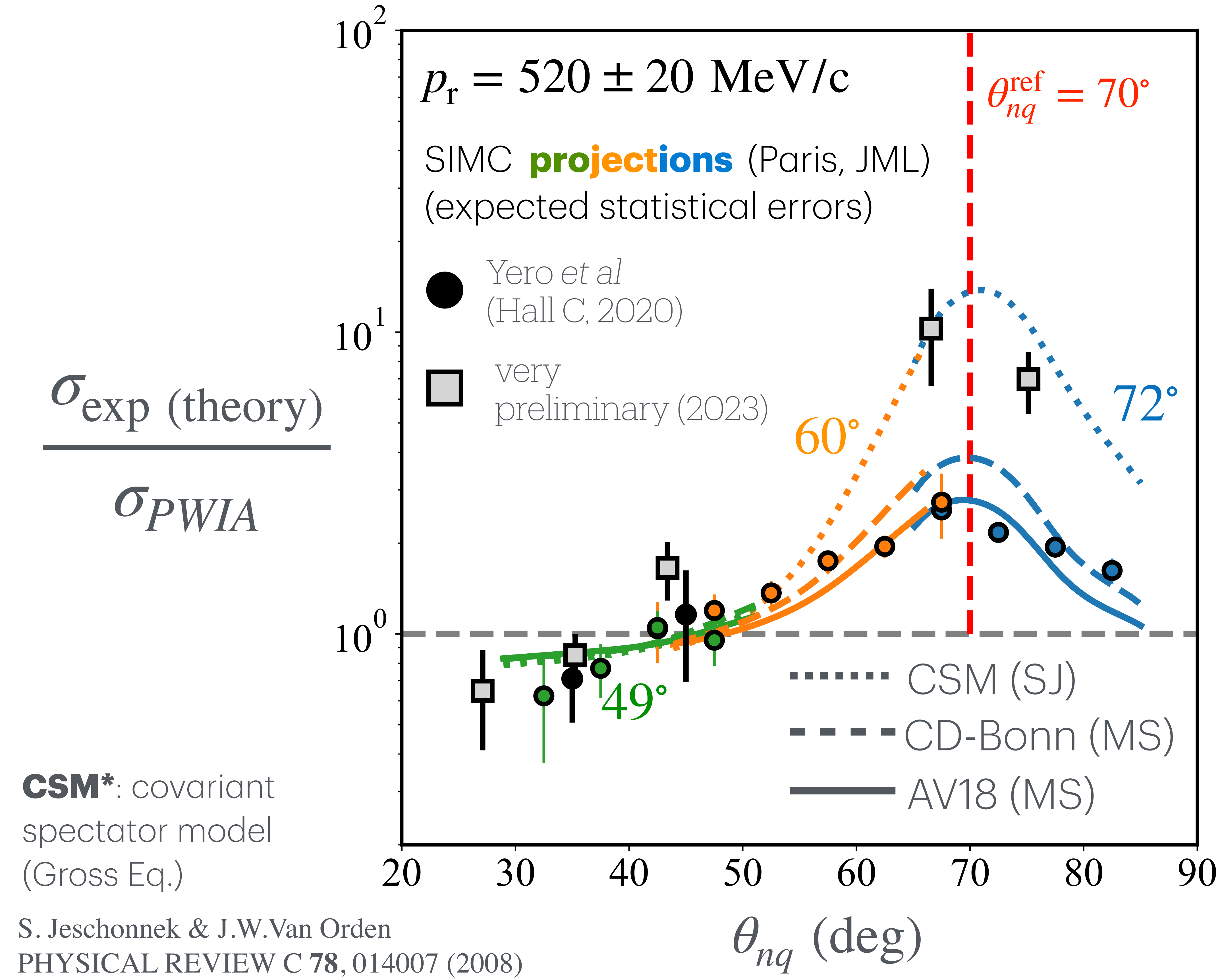

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PHYSICAL REVIEW C **78**, 014007 (2008)

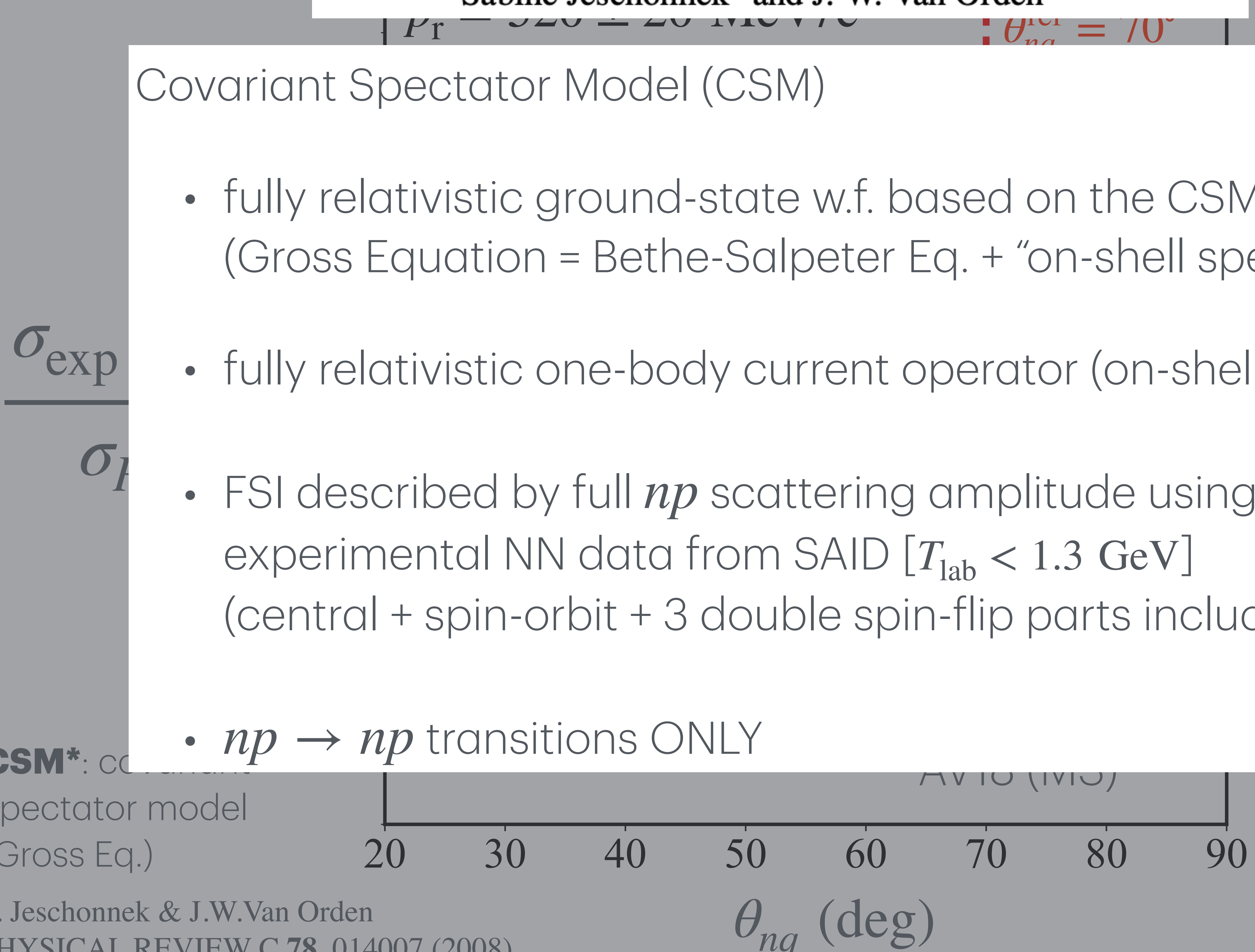
PHYSICAL REVIEW C **78**, 014007 (2008)

New calculation for ^{2}H(e, $e'p$)n at GeV energies

Sabine Jeschonnek[1] and J. W. Van Orden[2,3]

Covariant Spectator Model (CSM)

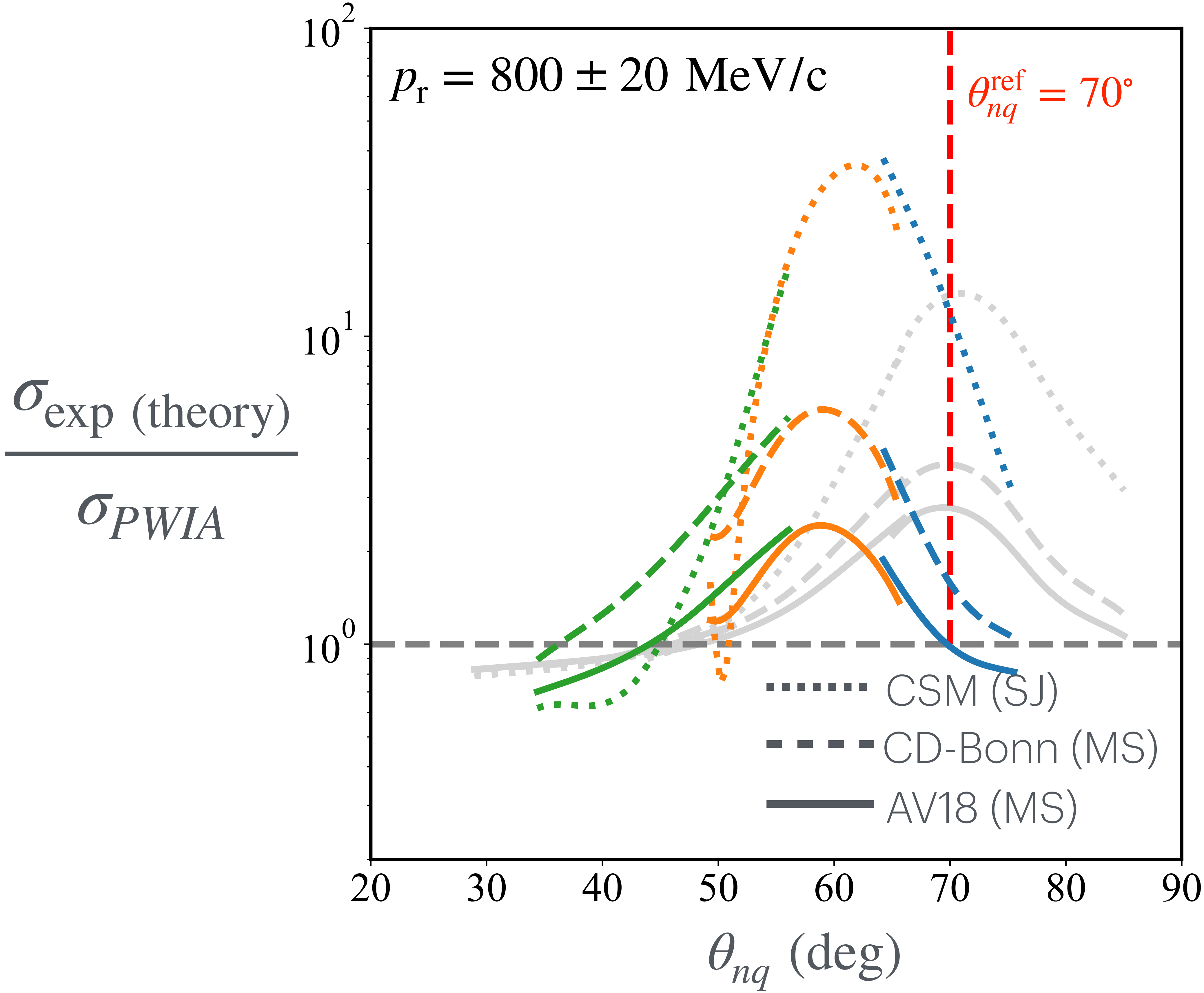
- fully relativistic ground-state w.f. based on the CSM (Gross Equation = Bethe-Salpeter Eq. + “on-shell spectator”)
- fully relativistic one-body current operator (on-shell nucleon)
- FSI described by full *np* scattering amplitude using experimental NN data from SAID [$T_{\mathrm{lab}} < 1.3$ GeV] (central + spin-orbit + 3 double spin-flip parts included)
- $np \rightarrow np$ transitions ONLY



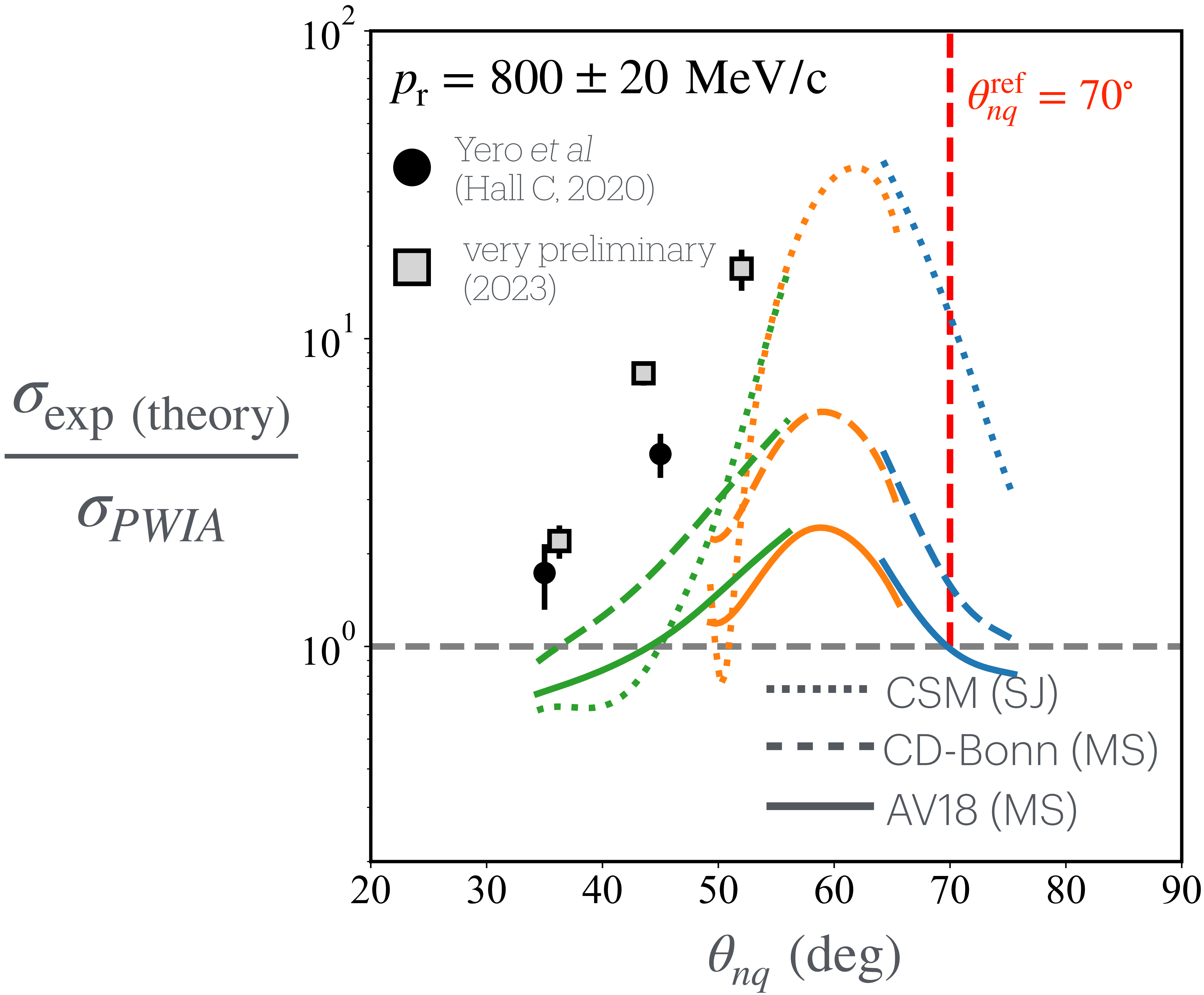
CSM*: covariant spectator model (Gross Eq.)

S. Jeschonnek & J.W.Van Orden
PHYSICAL REVIEW C **78**, 014007 (2008)

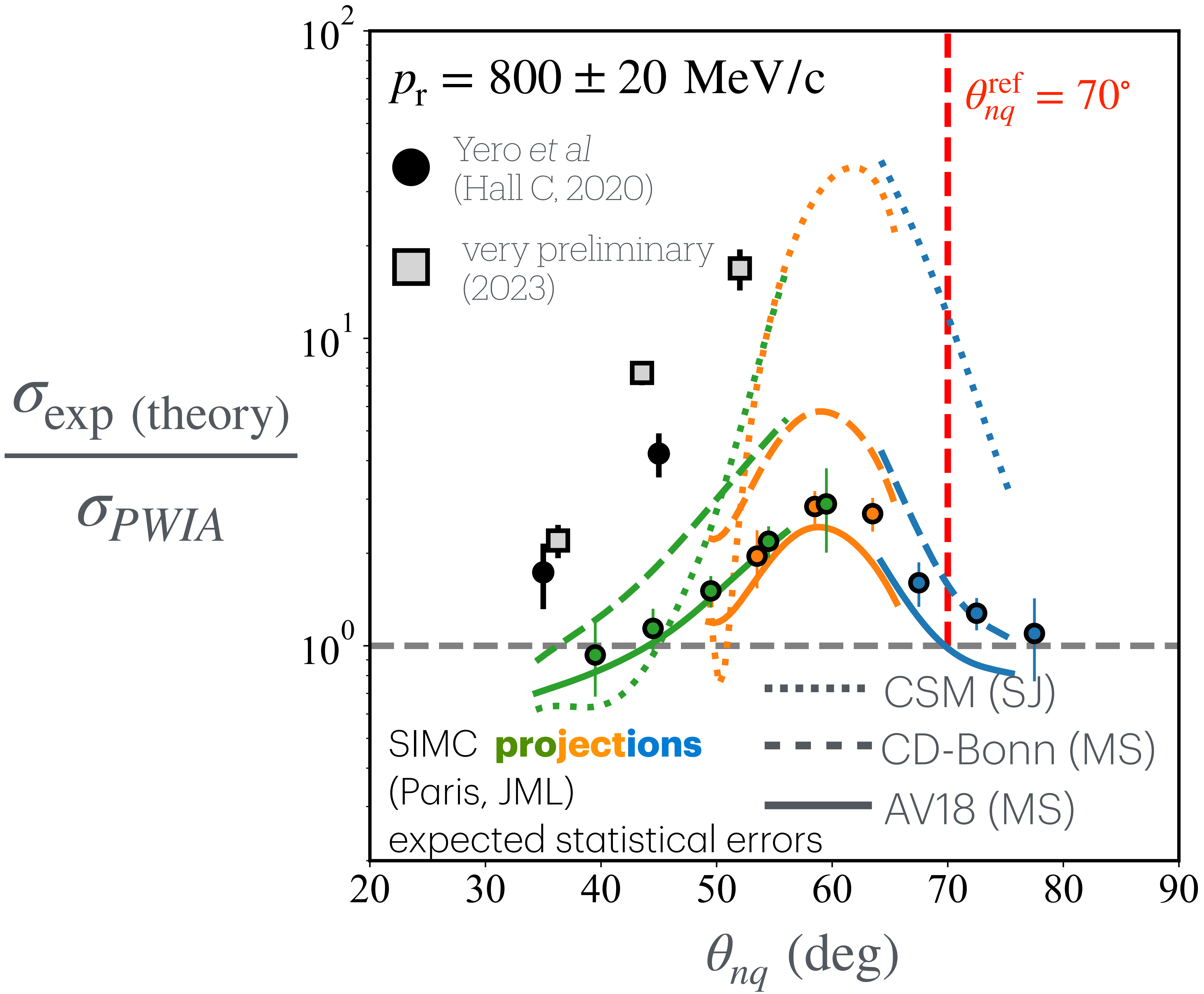
Proposed Measurement



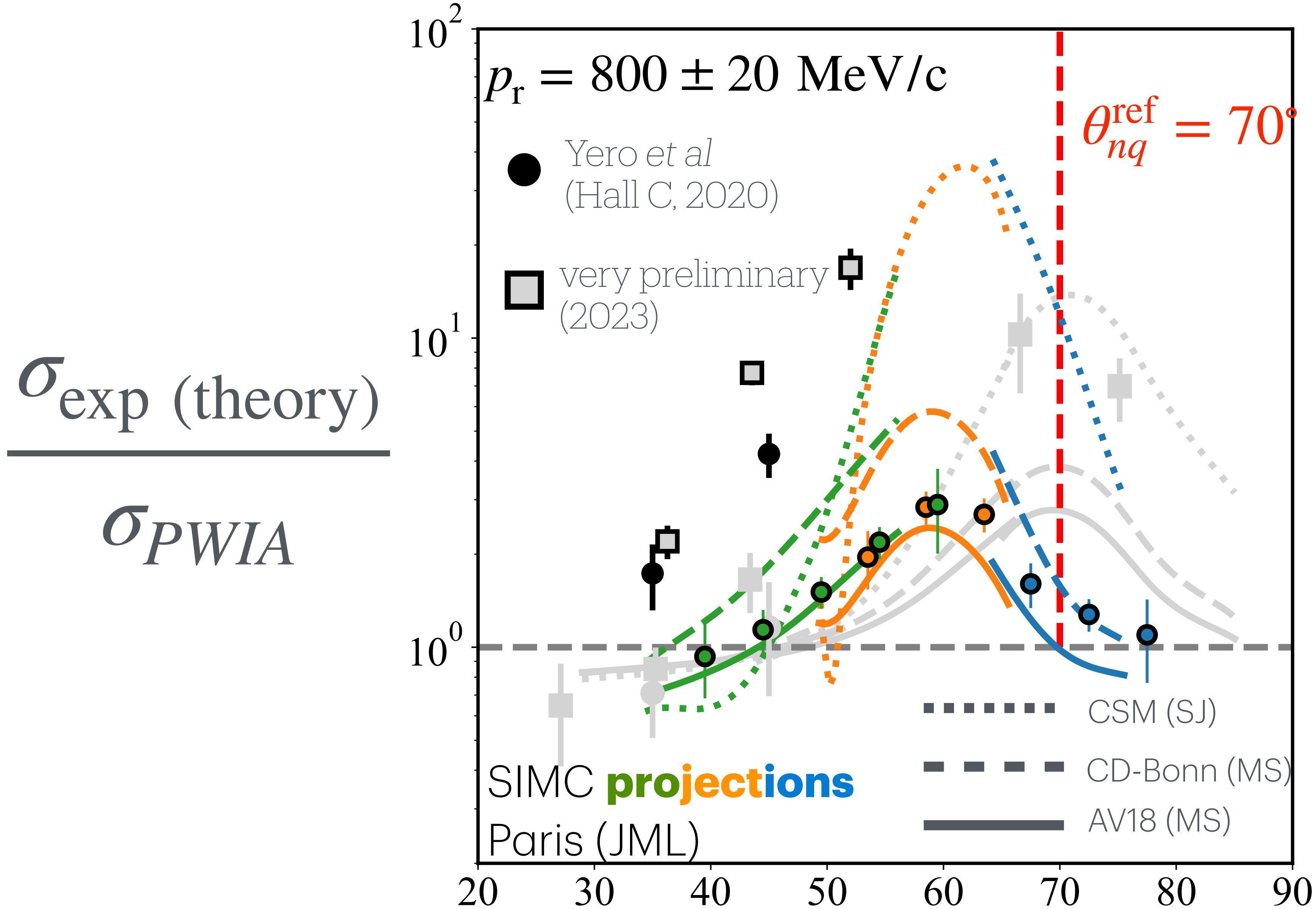
Proposed Measurement



Proposed Measurement



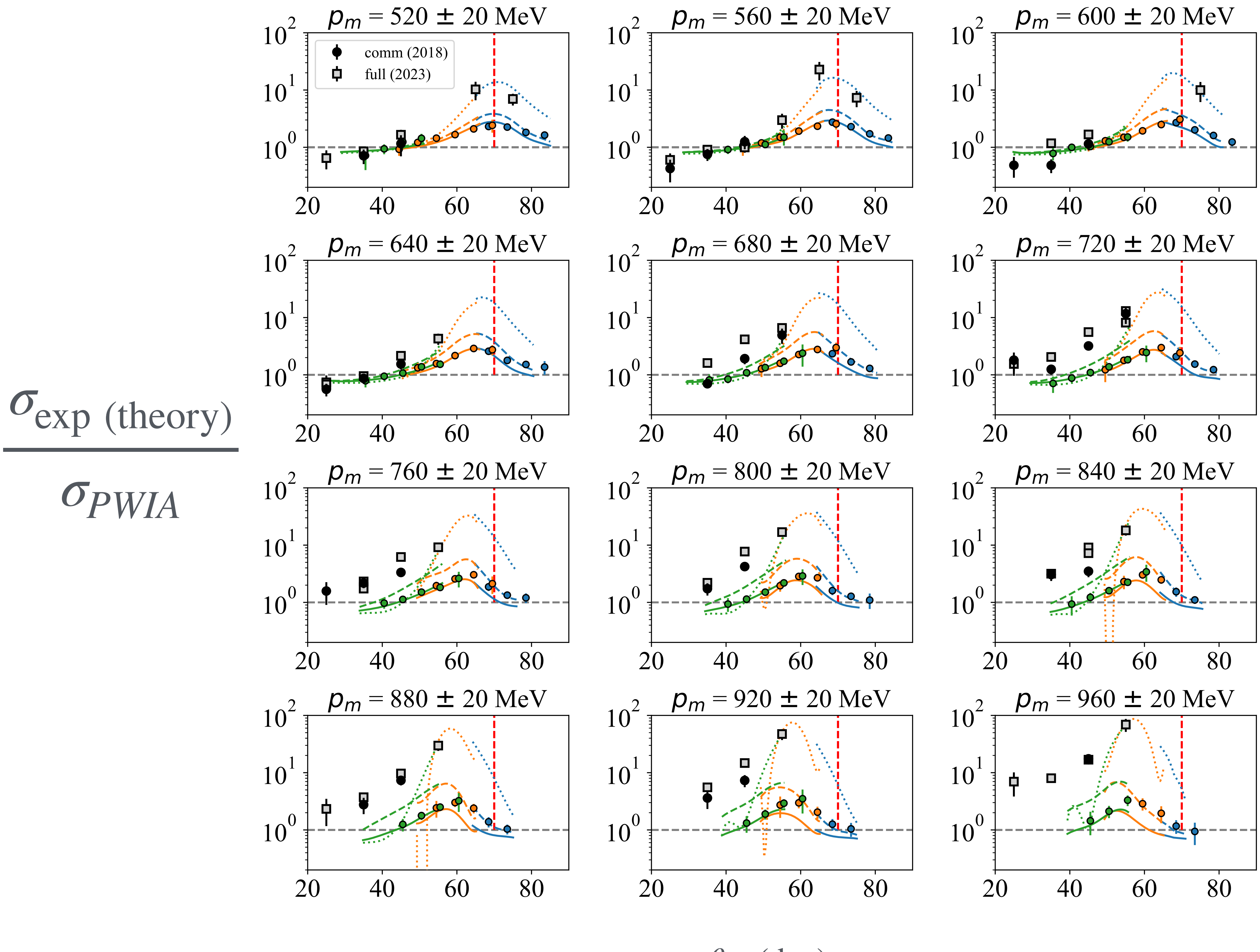
Proposed Measurement



NEW proposed measurement will address the following:

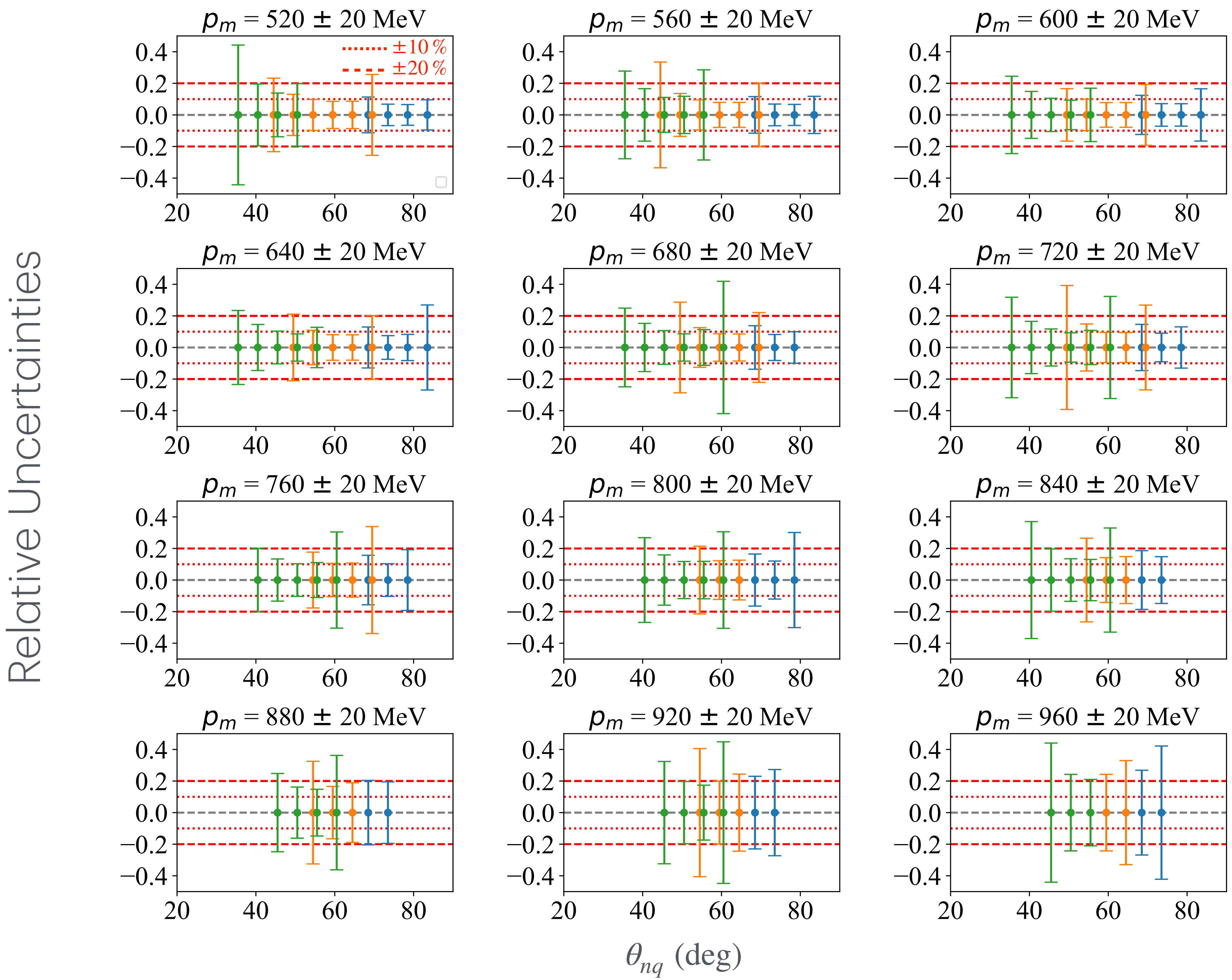
- **check reliability** of FSI calculations for $p_r > 500$ MeV/c; (required for *NN* core studies) over the full angular range
- **disentangle** FSI + relativistic + non-nucleonic effects

This Proposal: Projected Angular Distributions



theory calculations predict FSI peak will shift toward smaller θ_{nq} with increasing p_m (data from this proposal will be able to validate this prediction)

This Proposal: Projected Uncertainties



This Proposal: Expected Uncertainties

Statistical: $\sim 10 - 15\,\%$

Systematics:

Normalization: $\sim 3 - 4\,\%$ (BCM calibration, dead time, target boiling, proton absorption)

Kinematical: $\leq 6.5\,\%$ (beam energy, spectrometers momentum / angle)

Our previous $d(e, e'p)n$ measurements at Hall C (Yero 2020 *et al.*), covered the same range of missing momentum as presented in this proposal (~800 MeV/c), in which the **major sources of systematic uncertainties were well below 10 %.** We expect overall systematics to be similar in this proposal, given the similarities in both kinematics and small coincidence event rates (< 1 Hz)

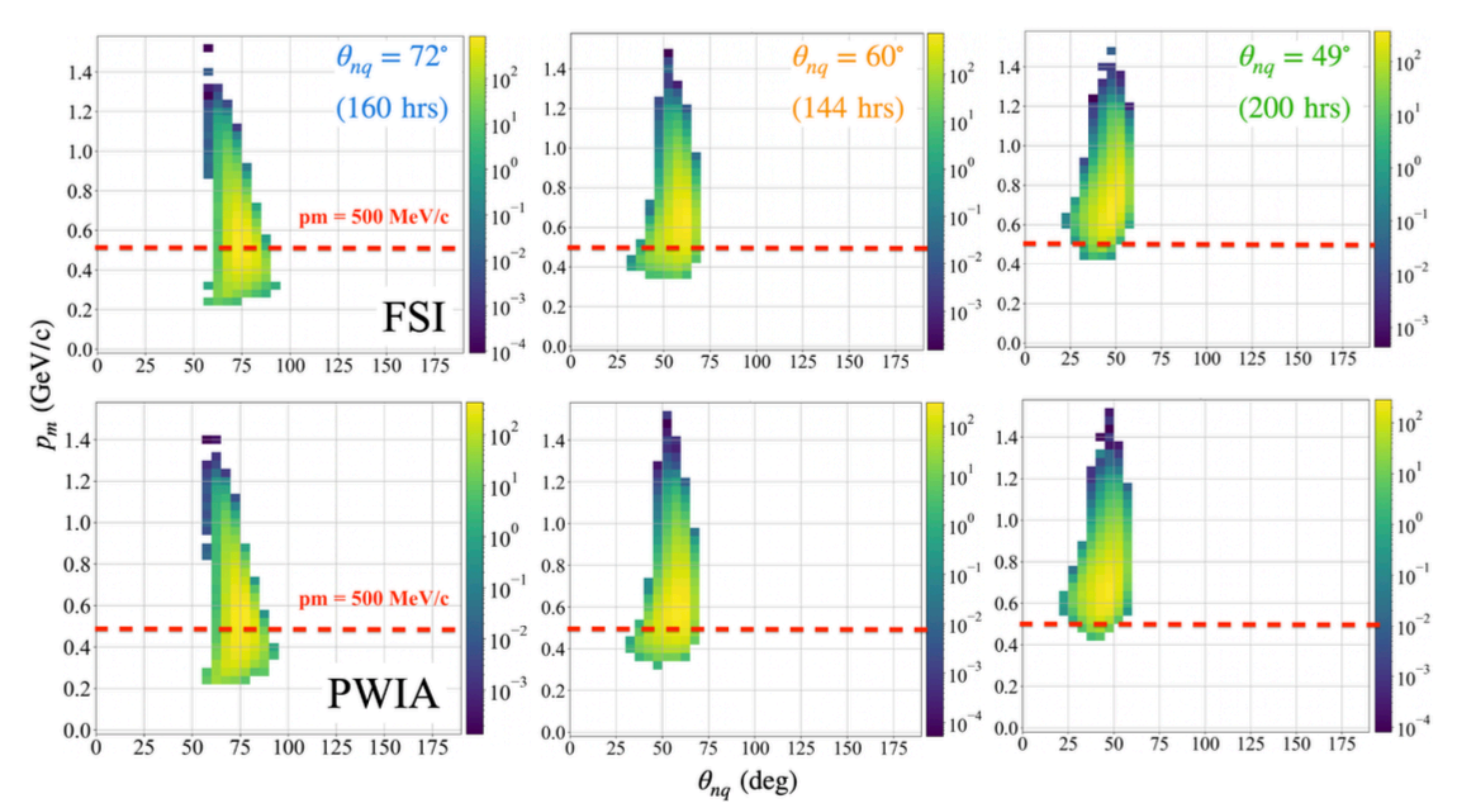
PRL **125**, 262501 (2020)

This Proposal: Beam Time Request

target	current (μA)	p_m (MeV/c)	θ_{nq} (deg)	data-taking (hrs)	overhead (hrs)	
~~LD2~~	~~65~~	~~500~~	~~70~~	~~24~~	~~2~~	Removed
LD2	65	800	49	200	2	
			60	144	2	
			72	160	2	
LH2	65	^{1}H$(e, e'p)$ elastic		8		
C12/LD2/LH2	10-70	target boiling		2		
C12 (2 foil)	50	SHMS optics		8		
no target	0-70	BCM calibration		2		
		total		524	6	**530 hrs** (22 PAC days)

We request a total of **530 hrs (22 PAC days)**

This Proposal: Beam Time Request



We request a total of **530 hrs (22 PAC days)**

Conclusion and Outlook

- deuteron w.f. (Ψ_d) well-understood up to ~550 MeV / c (Boeglin 2011)

- anomaly observed in high-momentum component ($\geq$ ~750 MeV/c)
is **<u>NOT</u>** yet understood ; how to disentangle FSI + relativistic + non-nucleonic ? (measure θ_{nq} angular distributions centered at ~800 MeV/c)

- light-front deuteron calculations (including FSI) are in progress (Sargsian)

<u>test validity of FSI models:</u>

(i) will FSI peak shift towards smaller recoil angles (θ_{nq}) with increasing p_m as predicted by theory ?

(ii) will the deuteron Ψ^{LC}_{np} (S+D only) fix the anomaly observed above $p_m \sim 750$ MeV/c ?
Or will it persist ? In which case, it would be a possible first indication of non-nucleonic components.

<u>Novelty of the proposed measurement:</u>

The proposed experiment seeks to improve our understanding of FSI at high-p_m, a crucial step that will provide a unique opportunity to explore the possibility of discovering non-nucleonic components in the deuteron.

Back-up: This Proposal (PAC Comments / Reply)

1. If the new angular distributions remain inconsistent with the present calculations, what conclusions would the proponents regard as experimentally justified, and how would they distinguish between missing FSI or relativistic effects and explicit non-nucleonic components?

[Sargsian]: If the new angular distribution remains inconsistent with the current virtual nucleon approximation, the theoretical analysis should be focused on identifying two possible reasons of such inconsistency: First: the emerging role of vacuum fluctuations, in which case virtual photon transforms to $p\bar{p}$ pair with a subsequent absorption of $\bar{p}$ by the deuteron. This contribution can be calculated in the Light-Front approximation (which is currently in progress with both PWIA and FSI terms included). If the LF calculation is able to describe the data, then the conclusion will be that the experiment observed measurable contribution from vacuum fluctuations and one will be able to extract LF momentum distribution $n_d(k)$, consisting of proton and neutron. If $n_d(k)$ will be independent on measured angle then it will conclude that it indeed represents the *pn* component of the deuteron. However if one observes distinguishable angular dependence of $n_d(k)$ then this will be first indication that one probed also non-nucleonic component in the deuteron.

In particular, given that the FSI peak is predicted to shift to $\theta_{nq} \leq 60^\circ$ at $p_m \sim 800$ MeV/c while non-nucleonic anisotropy is expected to peak near 90°, can the proponents sketch (even qualitatively) what the measured angular distribution would need to look like in each scenario, and whether the proposed angular coverage and statistical precision are sufficient to discriminate between them?

[Sargsian]: Preliminary calculation within Light-Front approximation indicate that the angular distribution is less steeper than the one predicted within Virtual Nucleon approximation and presented in the proposal. Such an observation will be indicative of the dominance of the light-cone dynamics in the scattering process. However to go beyond and conclude that non-nucleonic component is being observed one needs to extract $n_d(k)$ and check its angular independence. See Ref. Phys. Rev. Lett. 130, 112502 (2023)

2. The (72^{o}) setting extends into $x < 1$, where the proposal notes that isobar-current contributions may become important. Can the proponents estimate whether such contributions could significantly distort the angular dependence? Specifically, would it be possible to apply a dedicated x cut within the 72^{o} acceptance to bound or isolate the isobar-current contribution, rather than treating it as an unquantified systematic?

[Sargsian]: In addition to kinematic suppression one expects the intermediate Δ contribution to be suppressed dynamically due to the spin-flip nature of the $\gamma^{*}N \to \Delta$ transition. This was observed experimentally from the analysis of SLAC [Stoler] and Jlab [Ungaro] data. The PACs idea of an additional suppression can work too if one manipulates the mass created from the stationary nucleon defined as $m_x^2 = m_N^2 + Q^2(1/x_N - 1)$, where $x_N = (m_D - E_R)q_0 + p_R q \cos(\theta_{rq})$.

Finally, since there is high quality measurement of M1 form-factor of N-Delta transition [Ungaro], the Δ production can be calculated within the same approach in which quasi-elastic disintegration is calculated.

The dynamical-suppression argument is well taken. Could the proponents provide an order-of-magnitude estimate of the residual isobar-current contribution after dynamical suppression at $Q^2 = 4 - 5$ GeV^2, so that the PAC can assess whether it constitutes a significant and quantifiable systematic uncertainty for the (72°) setting?

As the figure from Ref. https://inspirehep.net/literature/360093) shows, the $\gamma^* N \to \Delta$ transition form-factor is suppressed almost by factor of 2 as compared to the elastic $\gamma^* N \to N$ form factor. This results in a factor of 4 in the suppression of the re-scattering cross section as compared to diagonal $NN \to NN$ re-scattering contribution. Note that since $N\Delta \to NN$ re-scattering amplitude does not interfere with diagonal $NN \to NN$ amplitude, the former is predominantly real (because of pion exchange nature of scattering) while the latter is imaginary because of dominance of the Pomeron exchange at these energies.

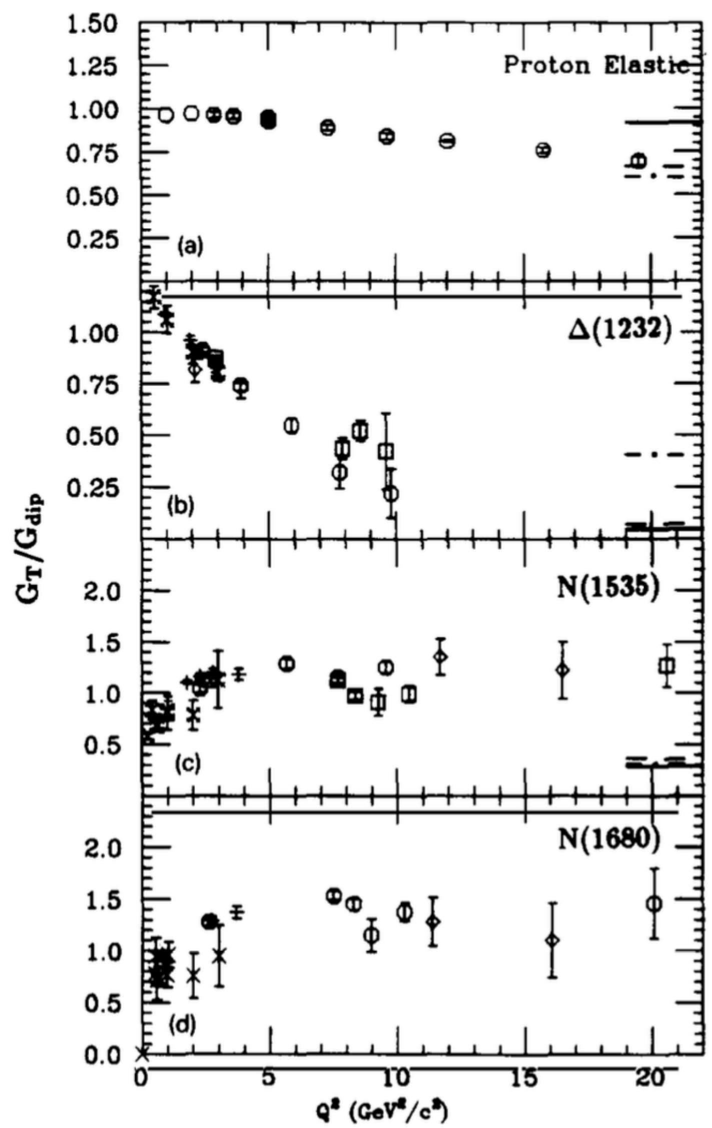


Fig. 19. (a) The absolute value of the proton elastic magnetic form-factor divided by the dipole shape, G_M/G_{dipole}, versus Q^2, where $G_{dipole} = \mu_P(1 + Q^2/0.71)^{-2}$. The data are from ref. [Ar-86]. The curves at the right of the figure are the results of calculations [Ji-87] at $Q^2 = 20$ GeV$^2/c^2$ using the proton distribution functions C-Z (solid), G-S (dot–dashed), and K-S (dashed). (b)–(d) The quantity G_T/G_{dipole} versus Q^2 for transitions to the first, second and third resonances, respectively, with $G_{dipole} = 3(1 + Q^2/0.71)^{-2}$. The first resonance (b) is the Δ(1232). The second resonance (c) at $Q^2 = 0$ consists of contributions from the $D_{13}(1520)$ and $S_{12}(1535)$, but at $Q^2 \sim 3$ GeV$^2/c^2$ it is mainly due to the $S_{12}(1535)$. The third resonance (d) at low Q^2 is dominated by the $F_{15}(1680)$. The resonance form-factor G_T is defined in the text (eq. 9). The fits for G_T were based on inclusive data reconstructed from refs. [Br-76] (+), [Ro-92] (○), [Po-74, Bo-79, Ri-73] (□, ◇). Also shown at lower Q^2 denoted by (×) are form-factors derived from amplitudes obtained from exclusive (e, e′p)π° and (e, e′p)η data obtained from refs. [Br-84, PDG-92, Bu-91]. The errors shown are statistical. Estimated systematic errors are discussed in the text.

It is worth nothing that the Δ form factor is larger than elastic form factor at $Q^2 < 0.5\ \mathrm{GeV}^2$ which is why intermediate Δ contribution is important for low energy electro-disintegration processes (e.g. https://inspirehep.net/literature/134355).

In addition, there is a kinematical suppression, due to the fact that the Δ production threshold is at

$$x_\Delta = \frac{1}{1 + \frac{m_\Delta^2 - m_N^2}{Q^2}}$$

while the peak of the FSI takes place at x = 1. As a result the deuteron wave function in the case of intermediate Δ production has an additional longitudinal component of the momentum $\approx m_N(x - x_\Delta)$ for $x > x_\Delta$

3. Radiative effects are included in SIMC. Can the proponents quantify their impact on the reconstructed angular distribution around p_m =760-840 MeV/*c*, particularly on the position and magnitude of the FSI maximum? Given that the FSI peak is predicted to shift with missing momentum, even a modest smearing of the reconstructed \theta_nq or p_m from radiative effects could affect the interpretation of the peak position, and a quantitative estimate would strengthen confidence in the projected results.

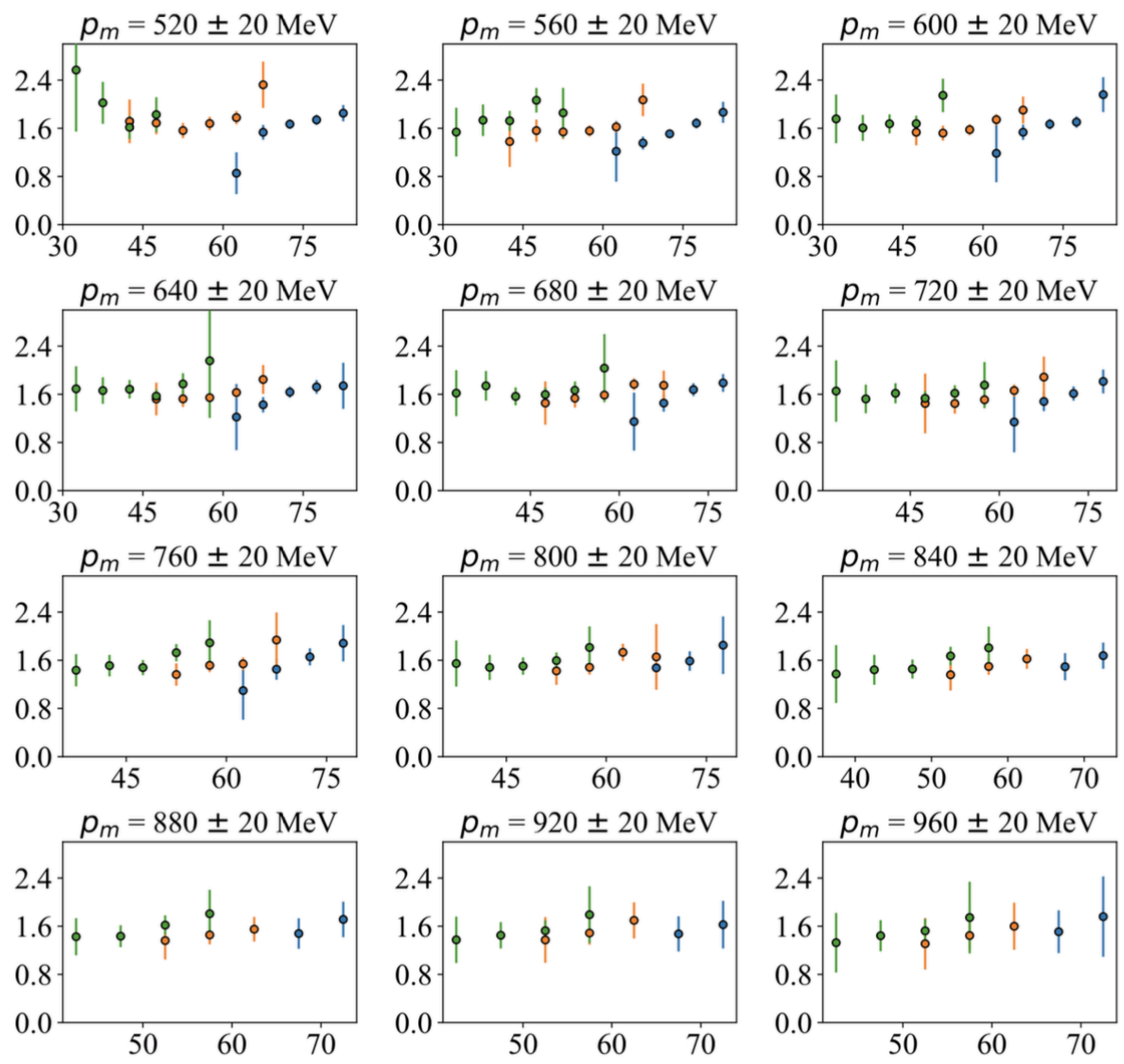
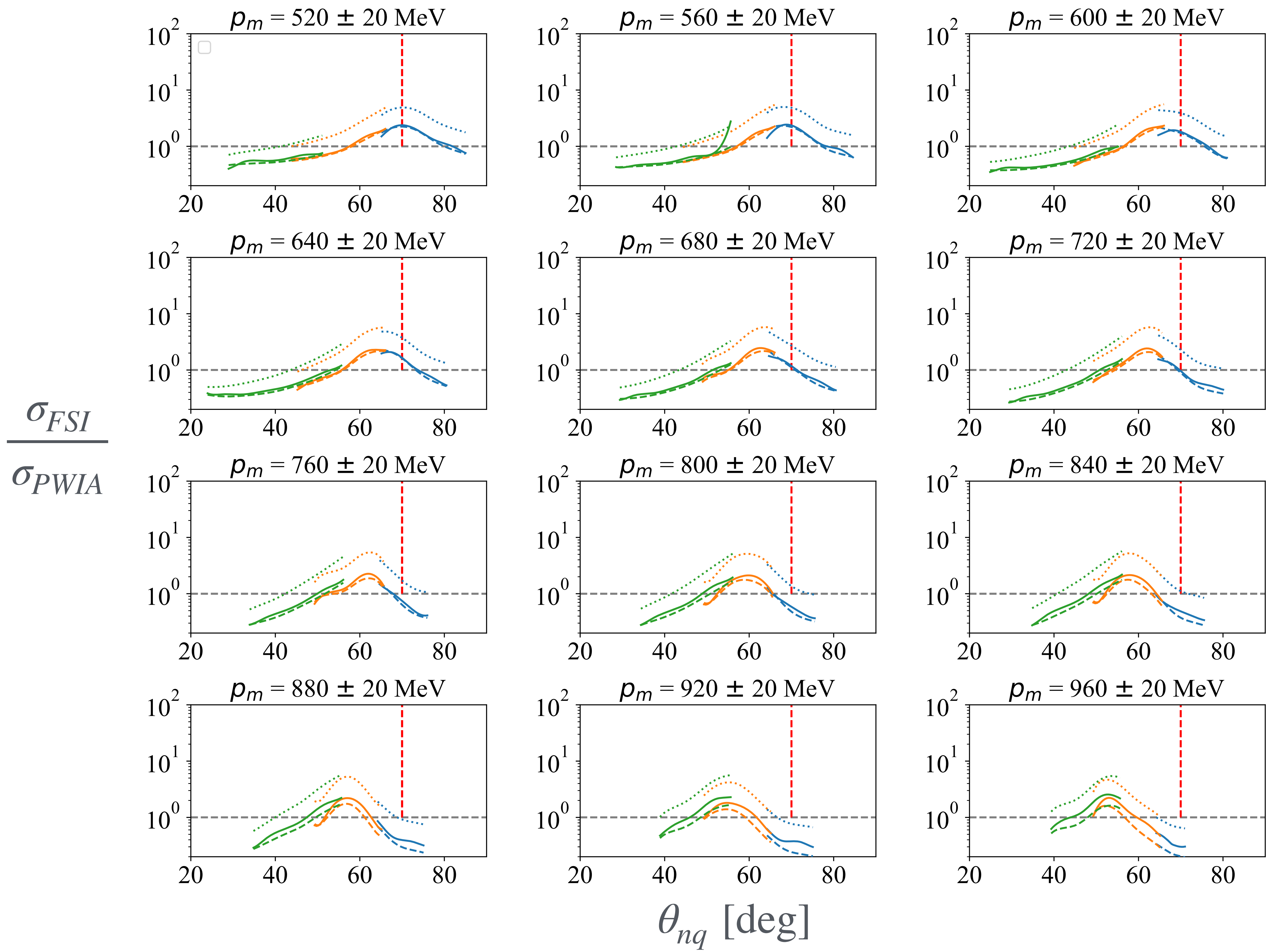


Fig. 1 Radiative corrections (y-axis) versus recoil angles θ_{nq} (x-axis) taken from the ratio of the non-radiative to radiative SIMC yields using the Laget FSI model. The ratios are stable over the full angular range for every missing momentum bin, with an average correction factor of about ~1.6

4. The results are often presented as ratios to a PWIA calculation. Which features of the angular distribution (the peak position, width, or relative variation) are expected to remain robust against the choice of PWIA denominator, and will the absolute cross sections be presented as the primary experimental result?

[Sargsian]: Since off-shell effects are model specific, the ratio should be represented as a measured cross section divided by PWIA calculation. However it is important to have the absolute cross section, for detailed theoretical analysis. We have successful comparison of theory to absolute cross section measured for the same reaction at $p_m \leq 500$ MeV/c.

Yes, the absolute cross sections will be presented as the primary results, and from these we calculate the cross section ratios for the angular distributions.



The curves are the ratio of FSI CD-Bonn (MS) to :
JML Paris PWIA [solid], MS AV18 (dashed), SJ CSM (dotted)
The angular distribution seems to remain robust in shape and peak position against different models presented in this proposal.

5. The 200 hours allocated to the 49^{o} setting represents the largest single block of beam time in the request. The prior Hall C measurement already provides 2-3 data points at \theta_nq <= 50^{o} across the relevant p_m range, as shown by the open squares in Figure 14. Can the proponents clarify what the 49^{o} setting adds beyond the existing data, given that the most novel angular coverage in this proposal lies at 60^{o} and 72^{o} where no prior measurements exist at high missing momentum? How much physics sensitivity would be lost if the 200-hour allocation were redistributed towards the 60^{o} and 72^{o} settings, and has this reallocation been considered?

[Yero]: While it is true that the previous data provides ~2-3 data points, it would be favorable to have additional data points to fill up the gap left by the previous measurements and be able to properly assess the observed anomaly starting at $p_r \sim 750$ MeV/c. Our motivation for the 49 deg point was to have the low θ_{nq} side of the peak so that in one experiment (this proposal) we would cover the full range of θ_{nq} so as to map out the FSI contribution. The currently proposed measurement at the 49 deg kinematics would allow overlap with the previous measurement and to independently verify the previous experimental results.

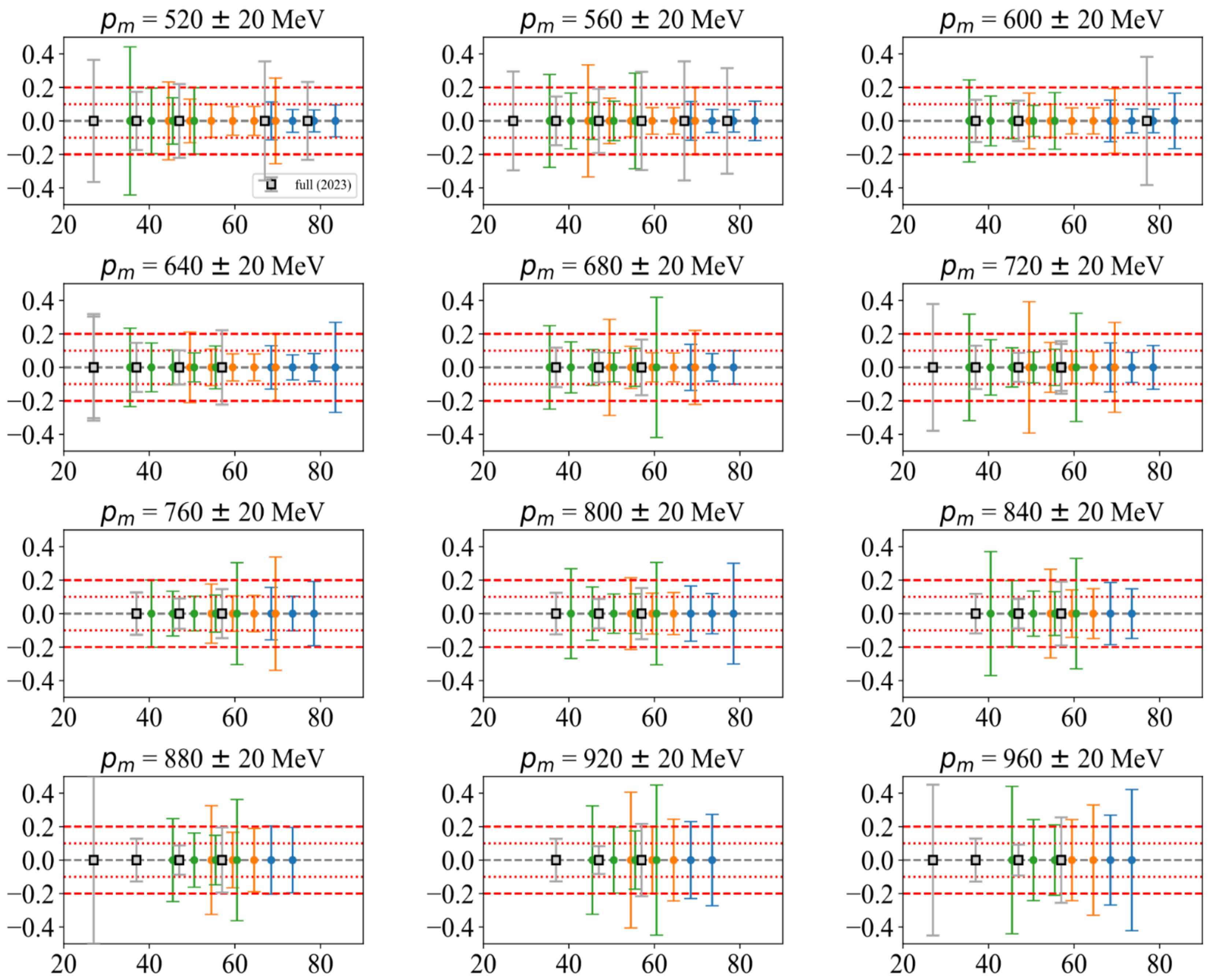


Fig.3 Relative statistical errors (y-axis) of the angular distributions versus neutron recoil angle (deg). The colored circles show the SIMC projections for each setting INCLUDING the 49 deg setting (in green). The gray squares show the very preliminary 2023 deuteron measurement (only statistical errors). The published commissioning data have been omitted for clarity.

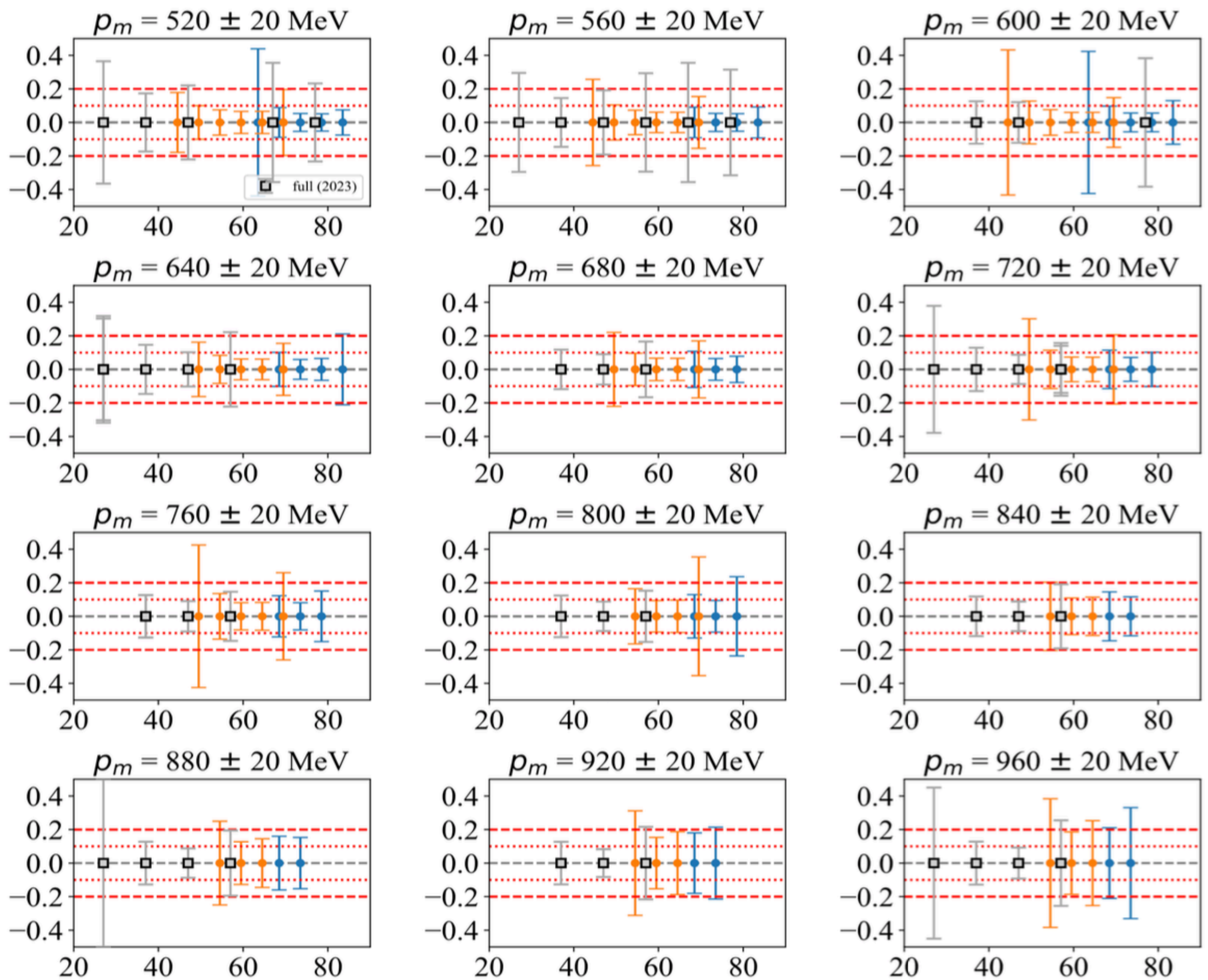


Fig.4 Relative statistical errors (y-axis) of the angular distributions versus neutron recoil angle (deg). The colored circles show the SIMC projections for each setting EXCLUDING the 49 deg setting. The 200 hrs from the 49 setting were evenly allocated to the 60 (orange) and 72 (blue) settings. The gray squares show the very preliminary 2023 deuteron measurement (only statistical errors). The published commissioning data have been omitted for clarity.

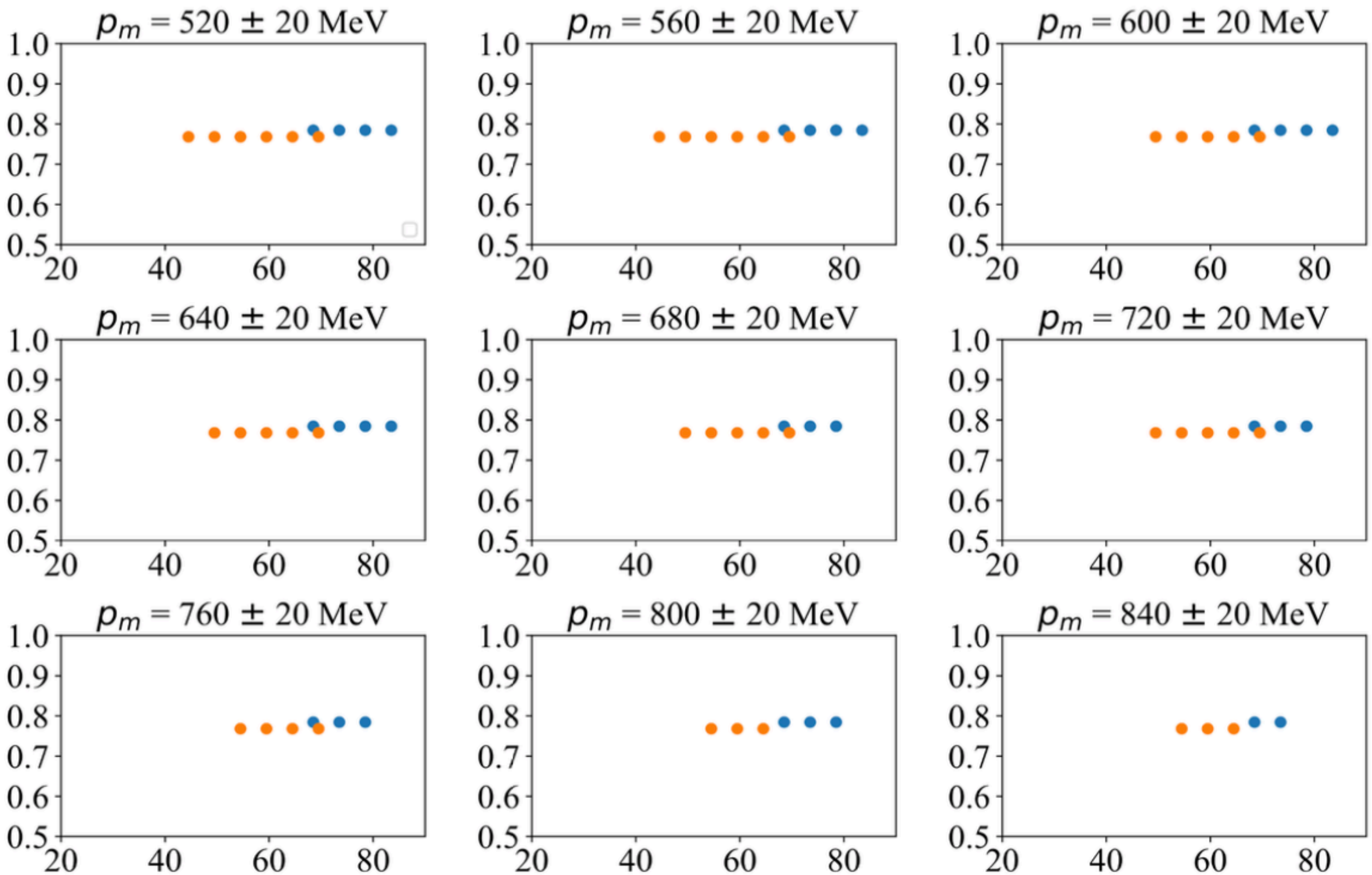


Fig.5 Ratio of the relative statistical error (y-axis) --> rel_error_without49_setting / rel_error_with49_setting. That is, the numerator represents the projected relative errors with the 200 hrs allocated evenly between the 60, 72 settings, and the denominator is the relative error using the original allocated hrs from the proposal. This way, we can see the reduction in the relative error. The value of the ratio is around 0.75 which means that the new errors are 25 % smaller than the original relative error after the 200 hr re-allocation.

6. The proposal allocates 12 hours to the normalization run at p_m = 500 MeV/c, \theta_nq = 70o for comparison with the existing Hall A data. Given that the absolute cross sections are identified as the primary experimental result (see also question 4 above), can the proponents quantify the normalization precision achievable in this time, and demonstrate that it is sufficient to make the 800 MeV/c absolute cross sections meaningful at the level of the claimed systematic uncertainties? In particular, if the normalization carries a 5-10% uncertainty, how does this propagate into the model comparisons at high missing momentum?

   [Yero]: We do not have any new data for 70 degree at pm = 500 MeV/c except the old Hall A experiment at 3.5 GeV/c and an additional data point there would be useful. At high missing momenta (pm > 0.8 GeV/c) calculations differ by much more than a few % and a 5 - 10% normalization uncertainty is irrelevant especially if the statistical precision is of the same order or larger.

   As a separate point, examining our kinematic coverage more carefully at Pm = 800 central setting (see attached), it does seem to cover the Pm = 500 MeV point, for each of the three recoil angles, 49, 60, 72 deg.   This means, we can perhaps simply drop the Pm=500 central setting (that means 24 hours or 1 day of beam time less). I did also, *perhaps erroneously*, write in the proposal, that this could be a calibration point, but I was just thinking in terms of the reproducibility of the data in a kinematic region we understand, i.e., pm = 500 MeV/c setting.

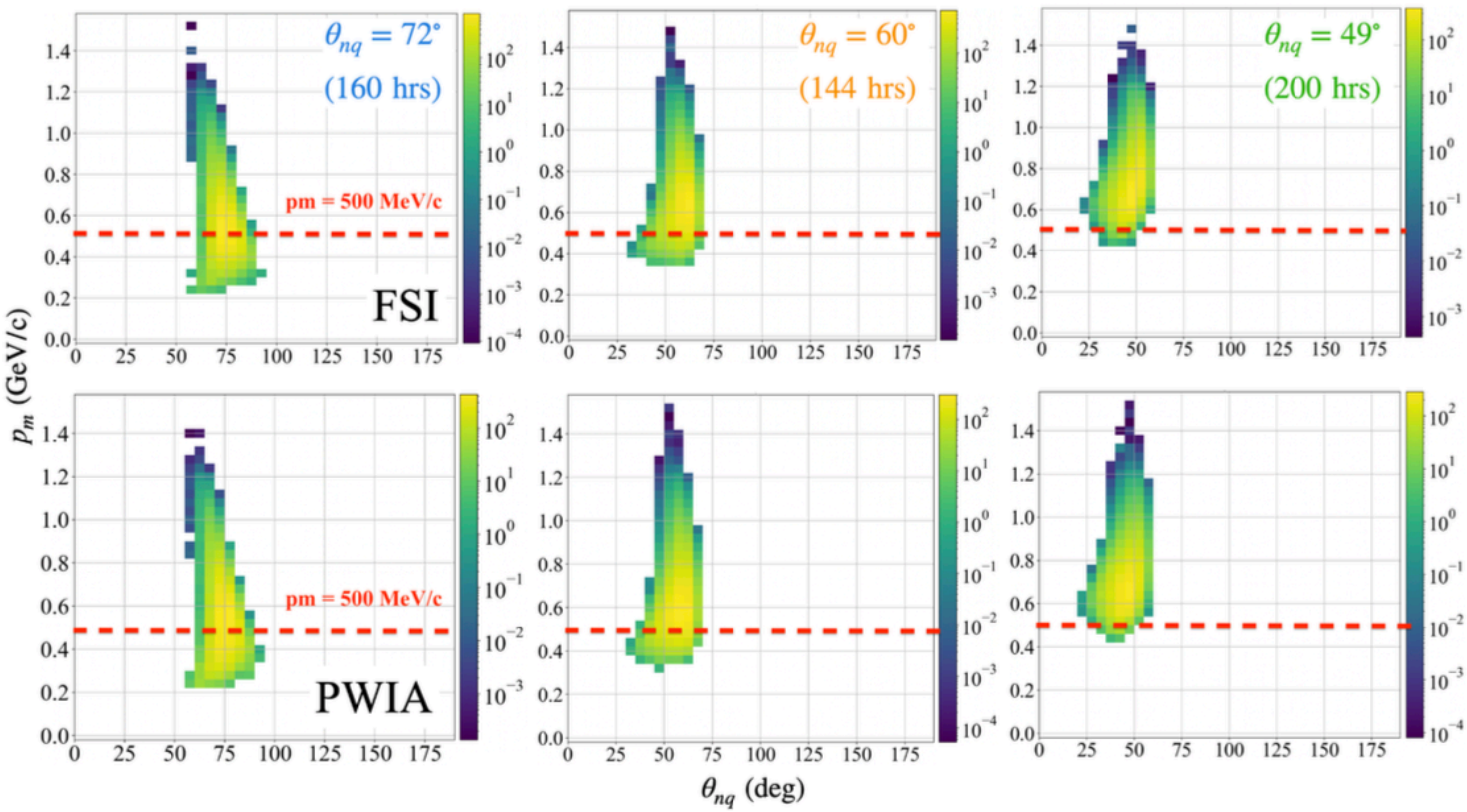


Fig.6 Kinematic coverage for the pm=800 MeV/c central setting shows a kinematic region where p_m= 500 MeV/c for each of the central angle settings, which makes it possible to take data in this region at this setting, without having to take a dedicated 500 MeV/c set

7. The projected count rates in Table 3 and the statistical projections in Figure 15 are derived using the Laget FSI model with the Paris potential as the SIMC event weight. Since the proposal motivates itself partly by the fact that different theoretical models already diverge significantly above 750 MeV/c, can the proponents comment on how sensitive the projected yields and statistical uncertainties are to this choice of weighting model? Specifically, would the projected count rates change materially if the Sargsian CD-Bonn or AV18 models were used instead, and does this introduce a model-dependent uncertainty in the beam time estimate that is not currently reflected in Table 3?

   [Yero]: It is true that we have used a model (Laget FSI) whose general trend already deviates from the measured data starting at ~ 300 MeV/c. However, if one looks closely at the comparisons in Fig. 3 (or Fig. 8 on this reply), even though the general trend differs, the data points actually are closer to the Laget than the CD-Bonn calculations at that particular momentum ~750 - 900 MeV/c. Therefore, we believe the rate estimates closely match those of the actual existing data in this high-pm region, even though the general trend is different.

   Given the similarities between the AV18 (MS) and Paris (Laget) calculations, the projected count rates would not change between these two. However, if one were to have used the CD-Bonn (MS) calculation in the weights, since the cross section is smaller, it would produce actually smaller projected counts making our projected uncertainties larger. However, from the trend observed, using the CD-Bonn calculations in the weight to make the statistical projections will not be realistic as the data starts to deviate from it at ~750 MeV/c.

   As an illustrative example, we have scaled the Laget FSI projected yield by the CD-Bonn FSI / Paris FSI cross-section ratio to estimate the projected yield and corresponding uncertainties if we had used the Sargsian CD-Bonn calculation. In the figure below, we have overlaid the relative error for the original proposal relative errors (light gray) with the relative error after scaling to the CD-Bonn calculation (red).

   Given that the Sargsian CD-Bonn calculation cross sections are smaller than the either AV18 or Paris calculations, as expected, the error is slightly larger, by about ~ 1.4

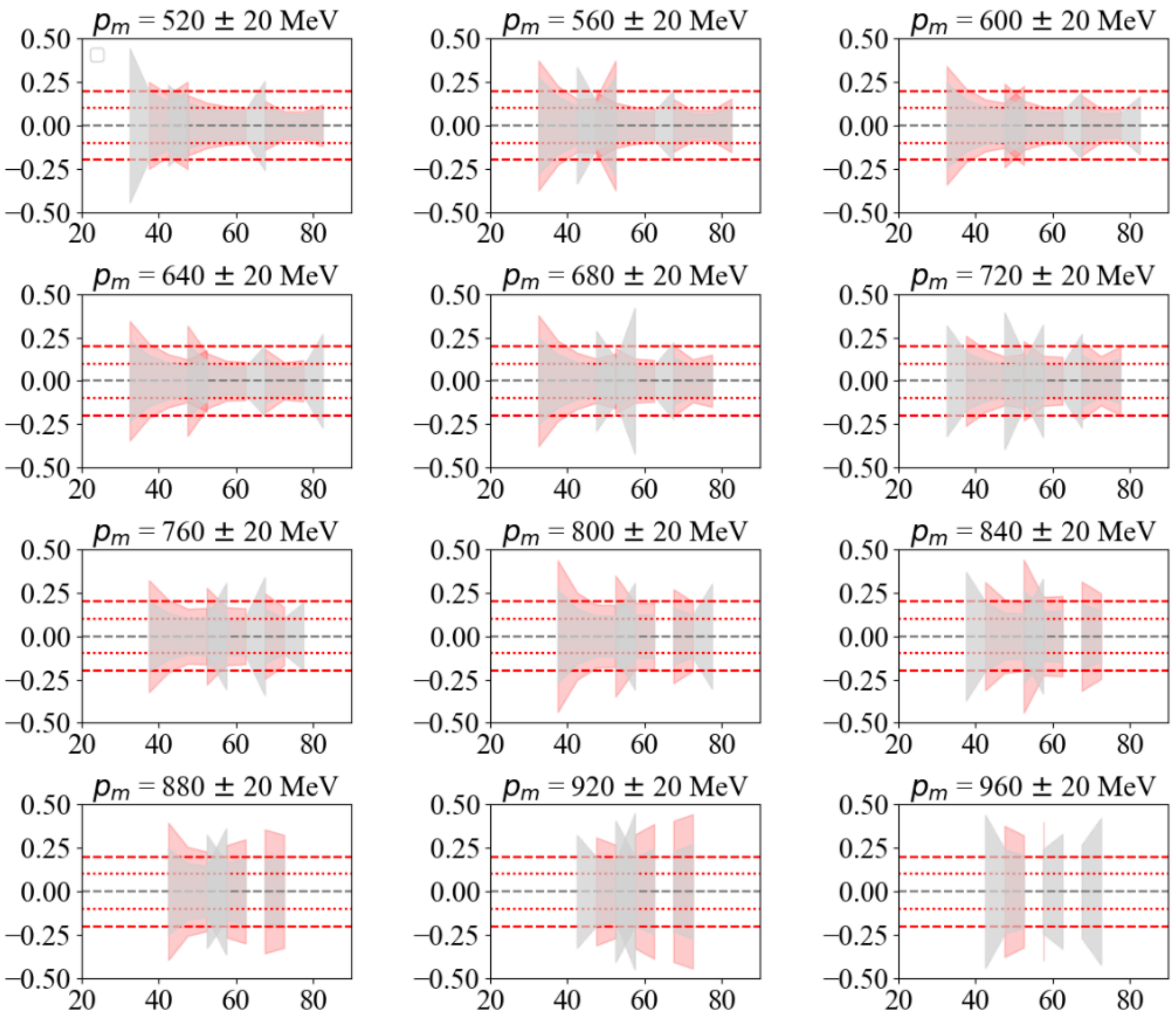


Fig. 7: Relative errors using the Laget Paris FSI model (original, light gray) and the relative errors after scaling the Laget Paris FSI to the Sargsian CD-Bonn FSI calculations. The relative errors typically increase by ~ 1.4. The outer dashed red lines are +/- 0.20 (or 20 % relative error) and the inner dotted red lines are +/- 0.10 (or 10 % relative error).

8. The experiment infers the neutron recoil angle \theta_nq from the measured electron and proton momenta, with the neutron reconstructed from momentum conservation. The scientific case rests substantially on resolving the position and shape of the FSI angular peak, which is predicted to shift towards smaller angles with increasing missing momentum. Can the proponents provide an estimate of the experimental resolution on \theta_nq at p_m = 800 MeV/c, and quantify the expected bin migration between the three central angle settings? In particular, is the angular resolution sufficient to track the predicted shift in the FSI peak position across the p_m bins shown in Figure 14, or could smearing wash out the discriminating features of the angular distribution?

[Yero]: The angular distributions from Fig. 14 of the proposal have a bin width of +/- 2.5 deg. To quantify the angular resolution and verify we are within the limits, we have histogrammed the difference between the reconstructed (smeared) and vertex recoil angles θ_{nq} and fitted a Gaussian to determine the angular resolution (sigma).

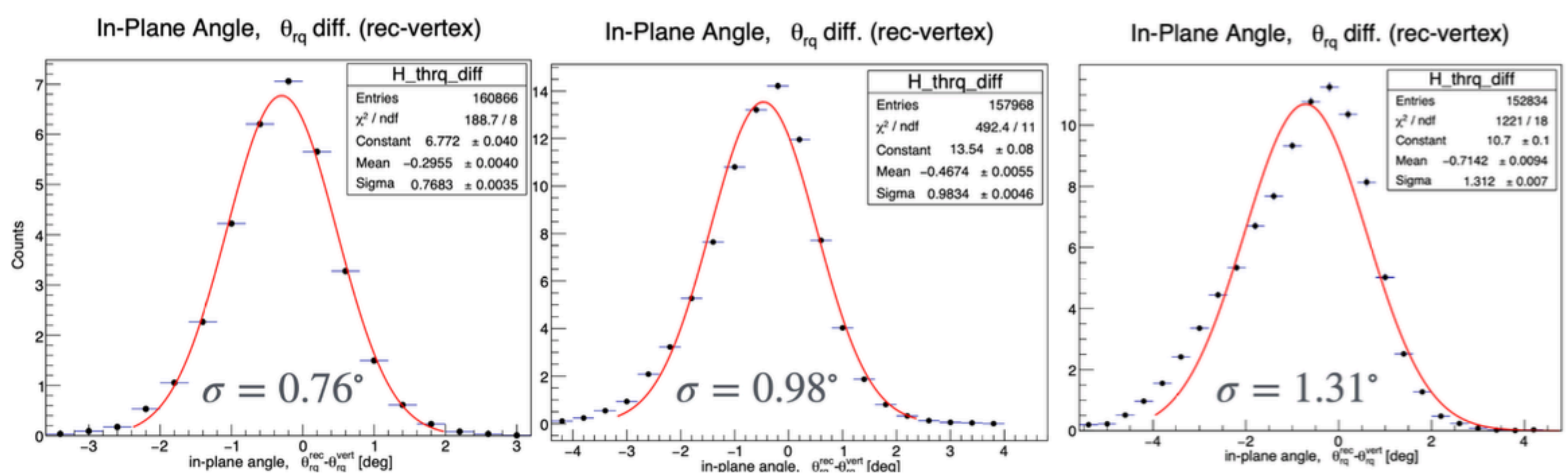


Fig. 8 : Angular resolution for neutron recoil angles, θ_{nq} = 49 (left), 60 (mid), 72 (right) deg central settings. The resolution is within the +/- 2.5 (or 5 deg) bin width.

Some additional minor questions.

3. Is Eq.(4) qualitative or a rigorous Fock expansion? If the latter is the case, how does one avoid double counting considering that the NN, NN*, and ΔΔ Fock components themselves have 6q contributions -- just like the hidden color component?

[Sargsian]: For high Q^2 reaction only two components of the wave functions dominate, since the $NN\pi$ component will be suppressed by extra power of Q^2. For the two component case, one takes the color singlet 6q Isospin=0, and Spin-1 state and expands by color, isospin and spin components. In this approach we do not require the individual three-quarks states to be color singlet. Such expansion was first done by Harvey in [https://inspirehep.net/literature/152167] and more elaborated by Brodsky and Ji [https://inspirehep.net/literature/221125]. This expansion results to:

$$\Psi_{6q}^{T=0,S=1} = \sqrt{\frac{1}{9}}\Psi_{NN} + \sqrt{\frac{4}{45}}\Psi_{\Delta\Delta} + \sqrt{\frac{4}{5}}\Psi_{CC}$$

Where Ψ_{NN} contains also NN* component, N* represents a radial excitation with same quantum number of nucleon. Ψ_{CC} – referred to as hidden color component corresponds to a two color octet baryonic sates that combine to color single 6q state. In such expansion there is no double counting since the states are mutually orthogonal. This indicated very large probability for the hidden color component. However until now no signatures for such a component have been observed since it is not known at which internal momenta such an excitation is possible. Note that the highest internal momenta measured in the deuteron so far is 550 MeV/c and not an indication of any other components other than pn component.

4. Out of curiosity, would it be feasible from experimental point of view and desirable from theoretical point of view to go above $|p_m| \sim 800$ MeV/c? And: hypothetically, if one was able to go to very large values of $|p_m|$, would things become "trivial" or "predictable" at some point?

[Sargsian]: Two main effects that these measurements can help to find, are vacuum fluctuations and non-nucleonic contributions. It will be very interesting if one will not find signatures for non-nucleonic component but discover large vacuum fluctuation effects for *pn* system. Moving up with missing momentum it will be possible to set the upper limit for closely separated *pn* system proximity that does not contain any inelastic component. This may resonate with current status of Neutron Star physics in which two solar mass neutron stars seemingly described by the *NN* component only with no signature for non-nucleonic component. However if one finds a non-nucleonic component at given p_{miss}, we will be able to predict at which densities of nuclear matter the picture of only *NN* component breaks down.

From the point of view of theory, these measurements will open up a new venue and most probably one single measurement will not settle the question of non-nucleonic components. However the description of the previously observed anomalous momentum distribution of the deuteron together with proposed measurement of angular distribution will provide an unprecedented opportunity for physics of high density nuclear matter.

Back-up: Kinematics

This Proposal: Kinematics

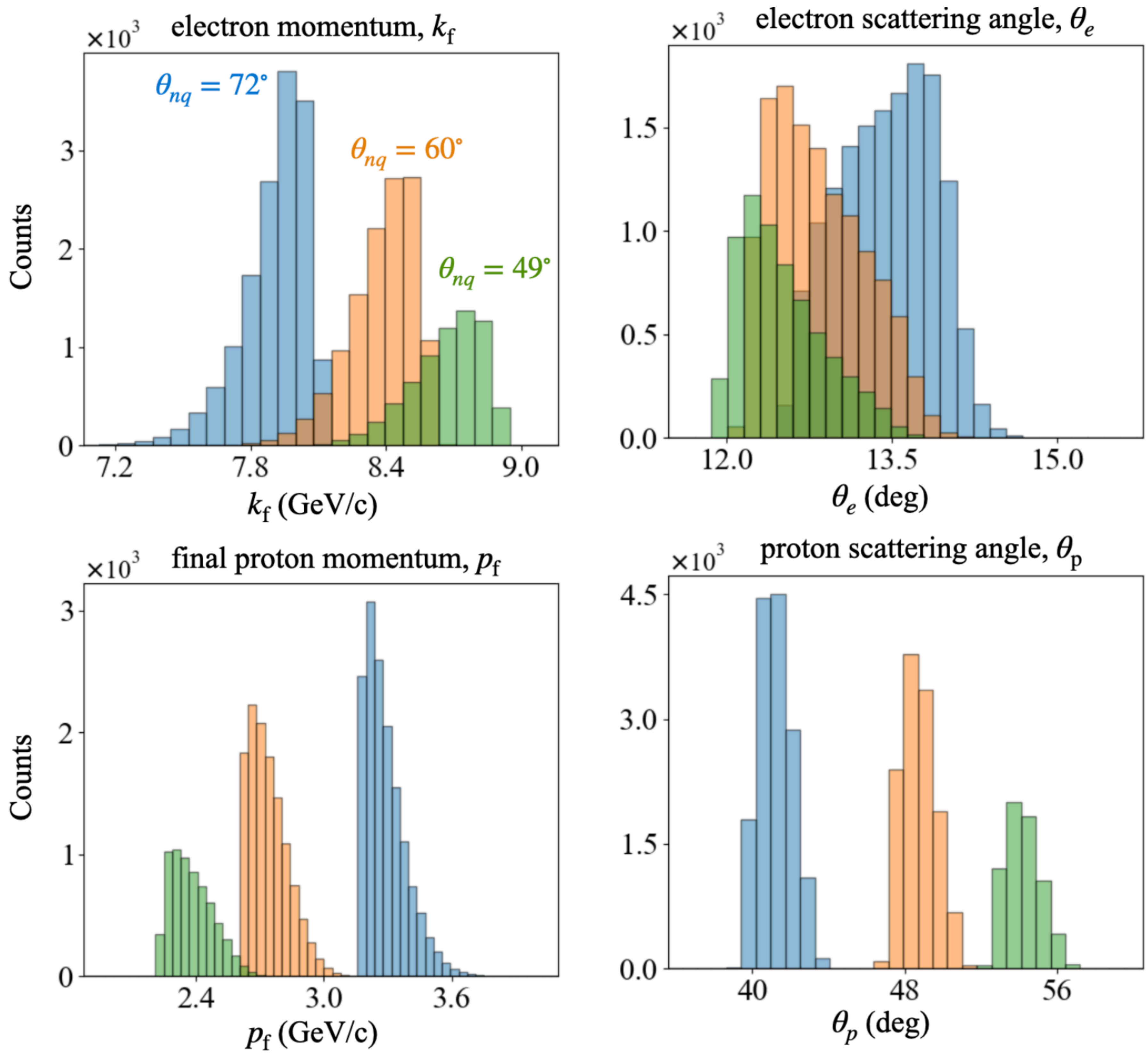


Figure 9: Simulated spectrometer kinematic distributions for SHMS (electrons) and HMS (protons) at 65 μA.

This Proposal: Kinematics

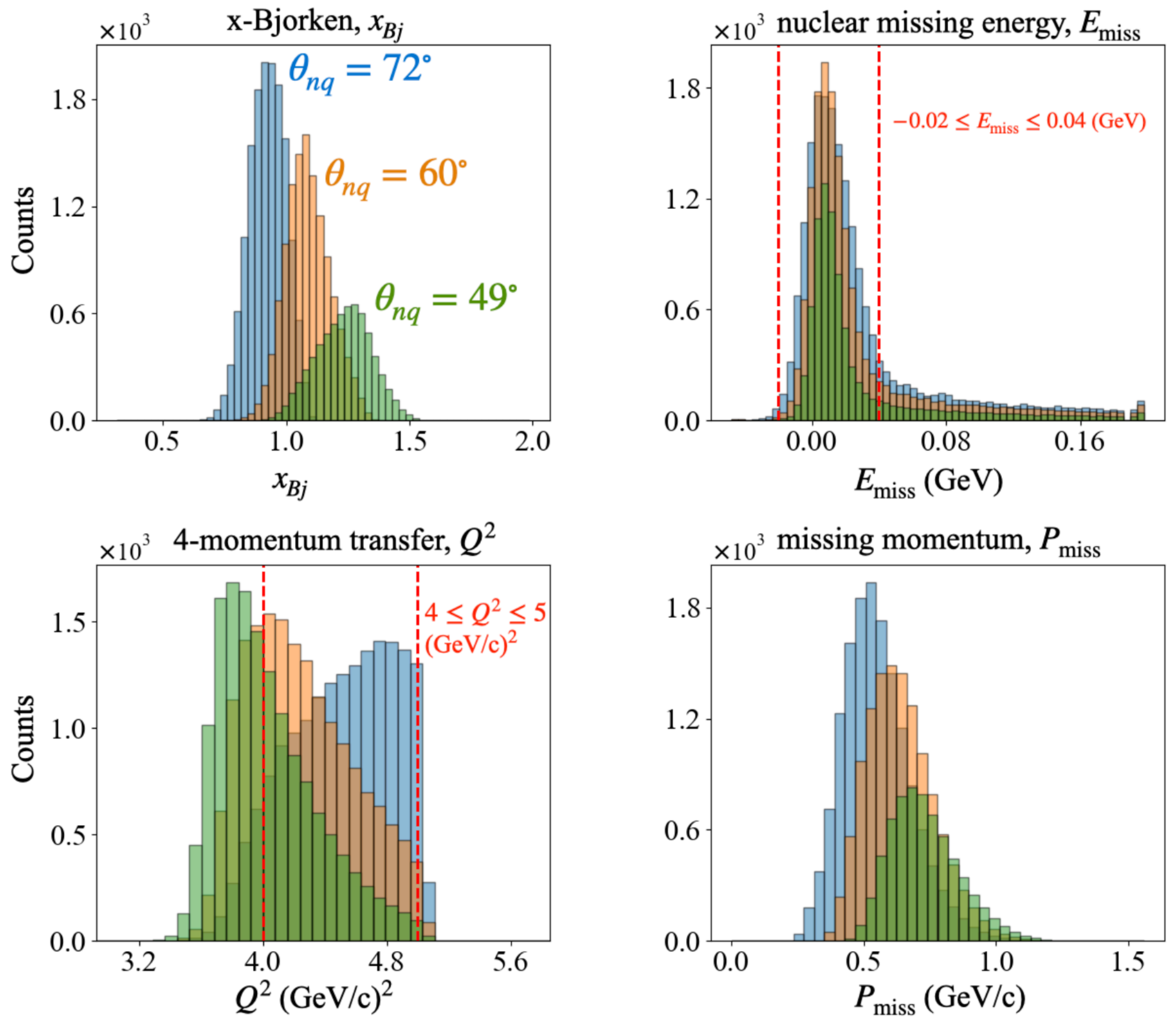


Figure 10: Additional kinematic distributions for x_{Bj} and Q^2

This Proposal: Kinematics

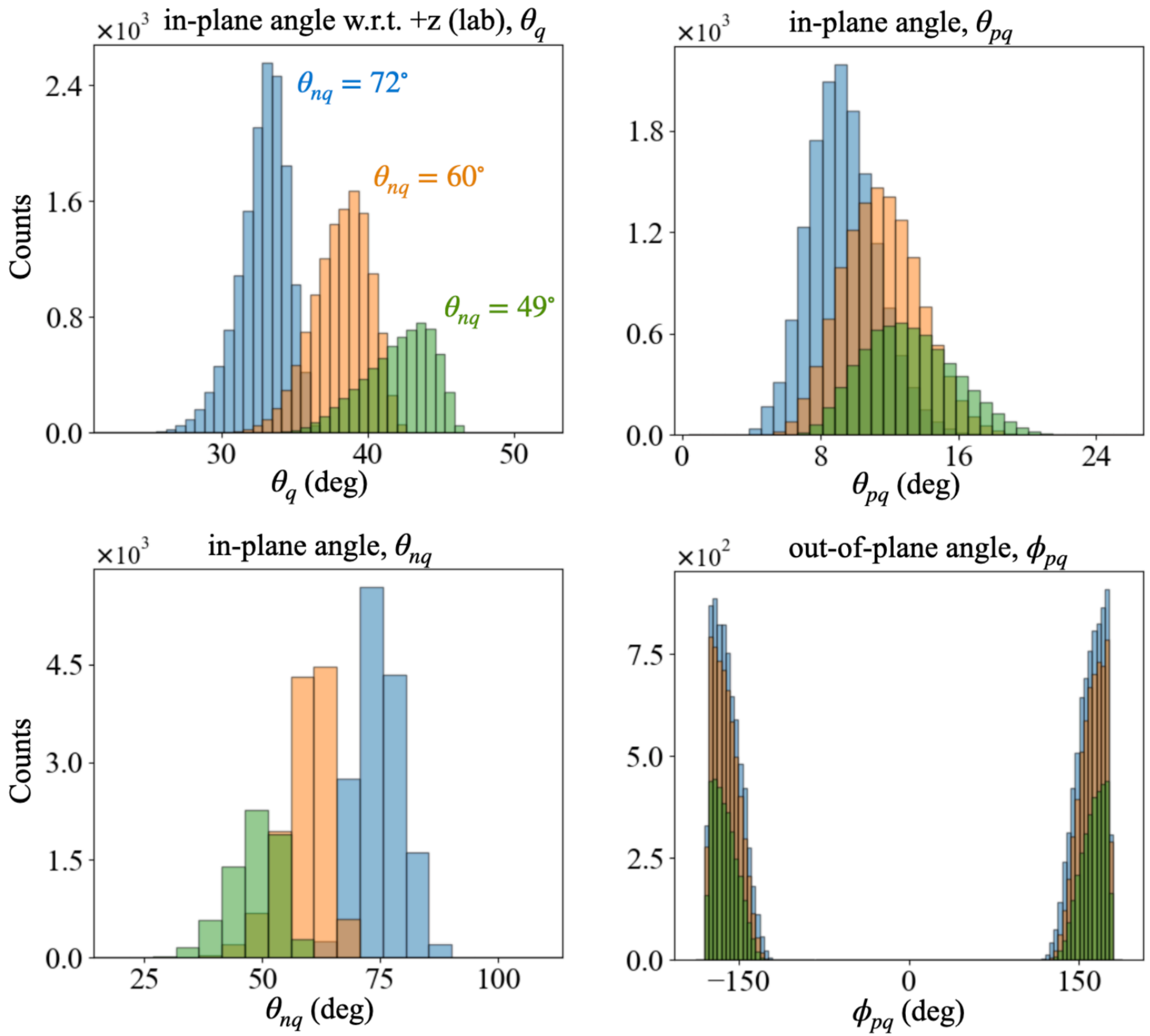


Figure 11: Angular kinematics showing the angles of $\vec{q}$ and the angles of the proton and neutron relative to $\vec{q}$ at 65 μA.

This Proposal: Acceptance

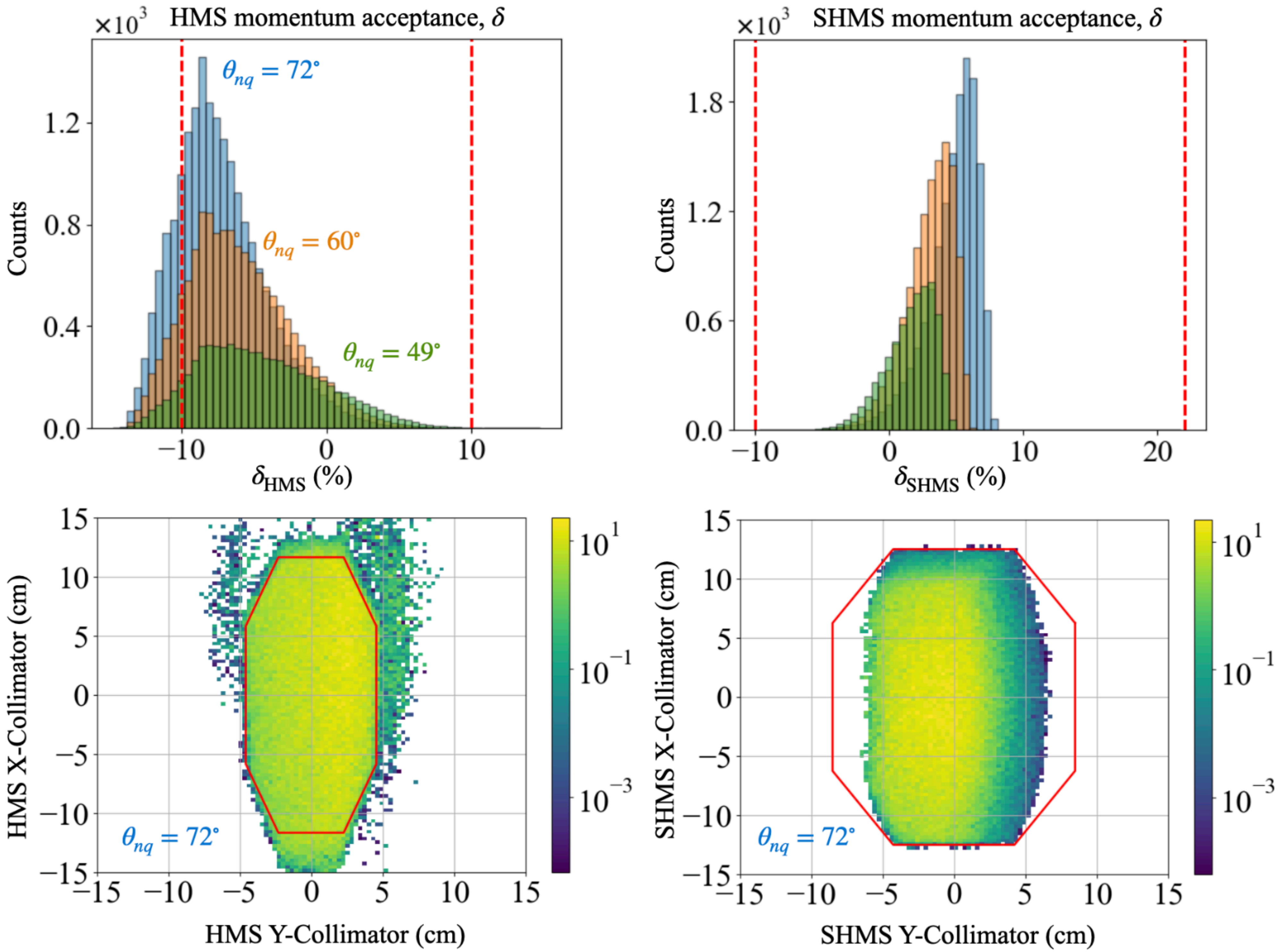


Figure 12: Momentum (top) and angular (bottom) acceptance distributions. The bottom panels show a contour line indicating the collimator geometry boundary; the HMS collimator determine the acceptance of the SHMS, as evidenced by most events in SHMS acceptance falling within the collimator geometry.

Back-up: Experimental

Expected Systematic Uncertainties

<u>Normalization</u>

- tracking efficiencies / boiling : ~ 1%
- proton loss in HMS : ~ 0.5 %
- total live time / charge : ~ 1-2 %
- target wall contributions : < 3%
- spectrometer acceptance : ~ 1.5 %

<u>total normalization:</u> $\lesssim$ 4 %

<u>Kinematic</u>

point-to-point uncertainty on:

- beam energy
- spectrometer angles/momentum

<u>total kinematic:</u> $\lesssim$ 6.5 %

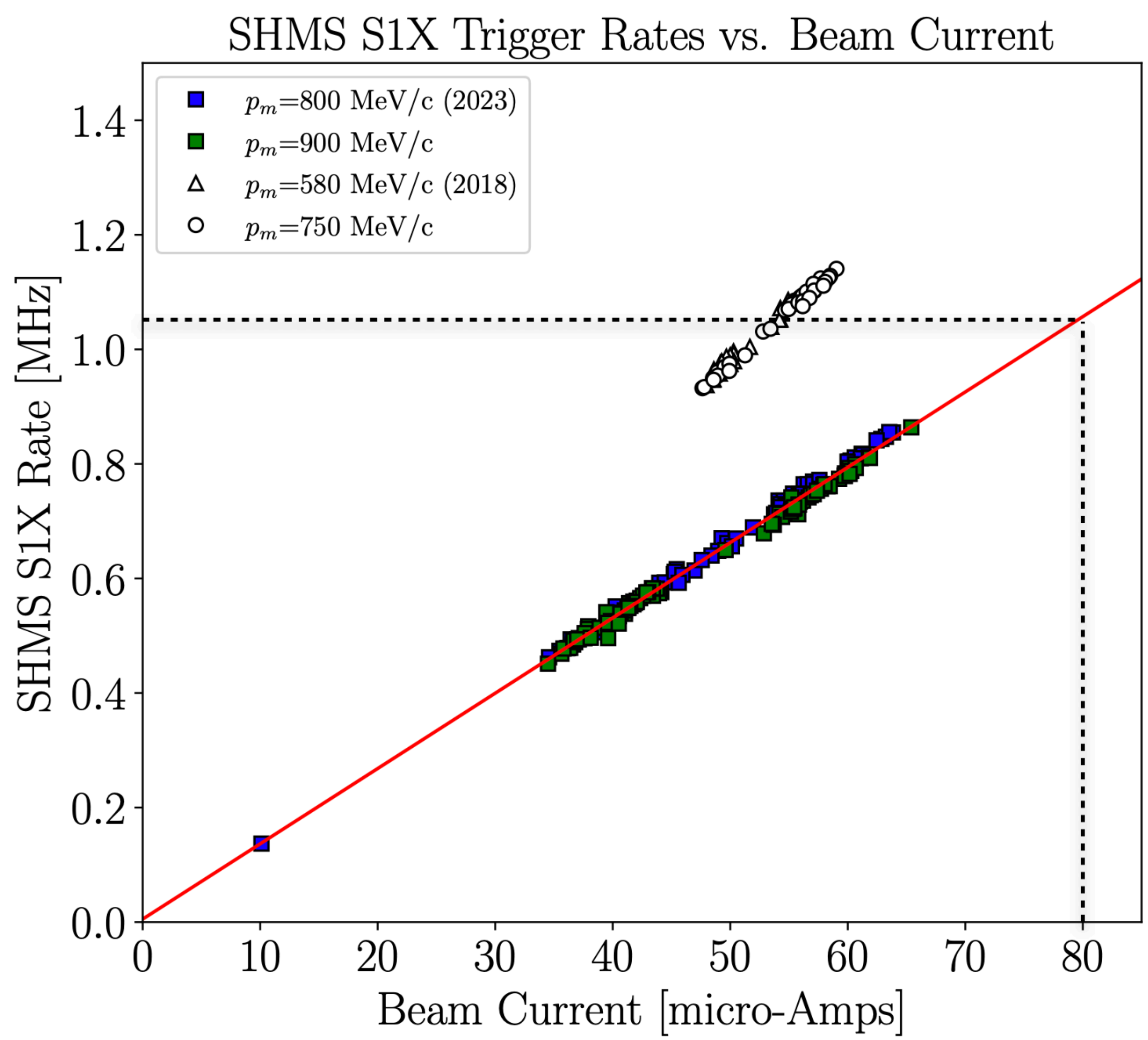
Total Systematic Uncertainty : ~ 7.6 %
(added in quadrature)

Overall Uncertainty: ~ 10-15 % (statistical) + 7.6 % (systematics) **~ 12- 16 %**
(added in quadrature)

systematics based on our published data (at very similar spectrometer settings)

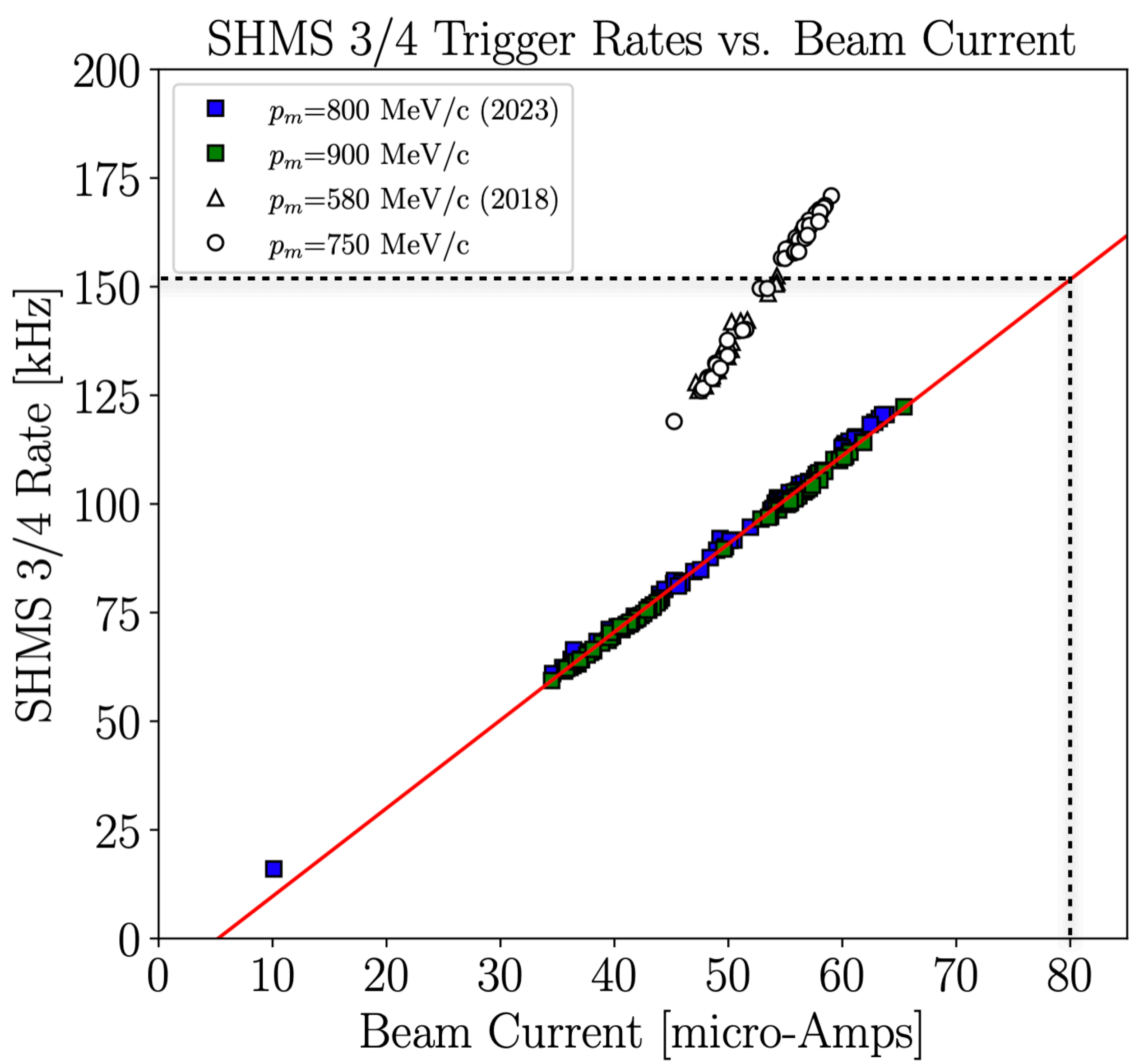
Phys. Rev. Lett. **125**, 262501 (2020)

Experimental Expectations



SHMS S1X rate vs. Beam Current for the deuteron experiment completed in 2018 [14], and the recently completed experiment in 2023 (under analysis).

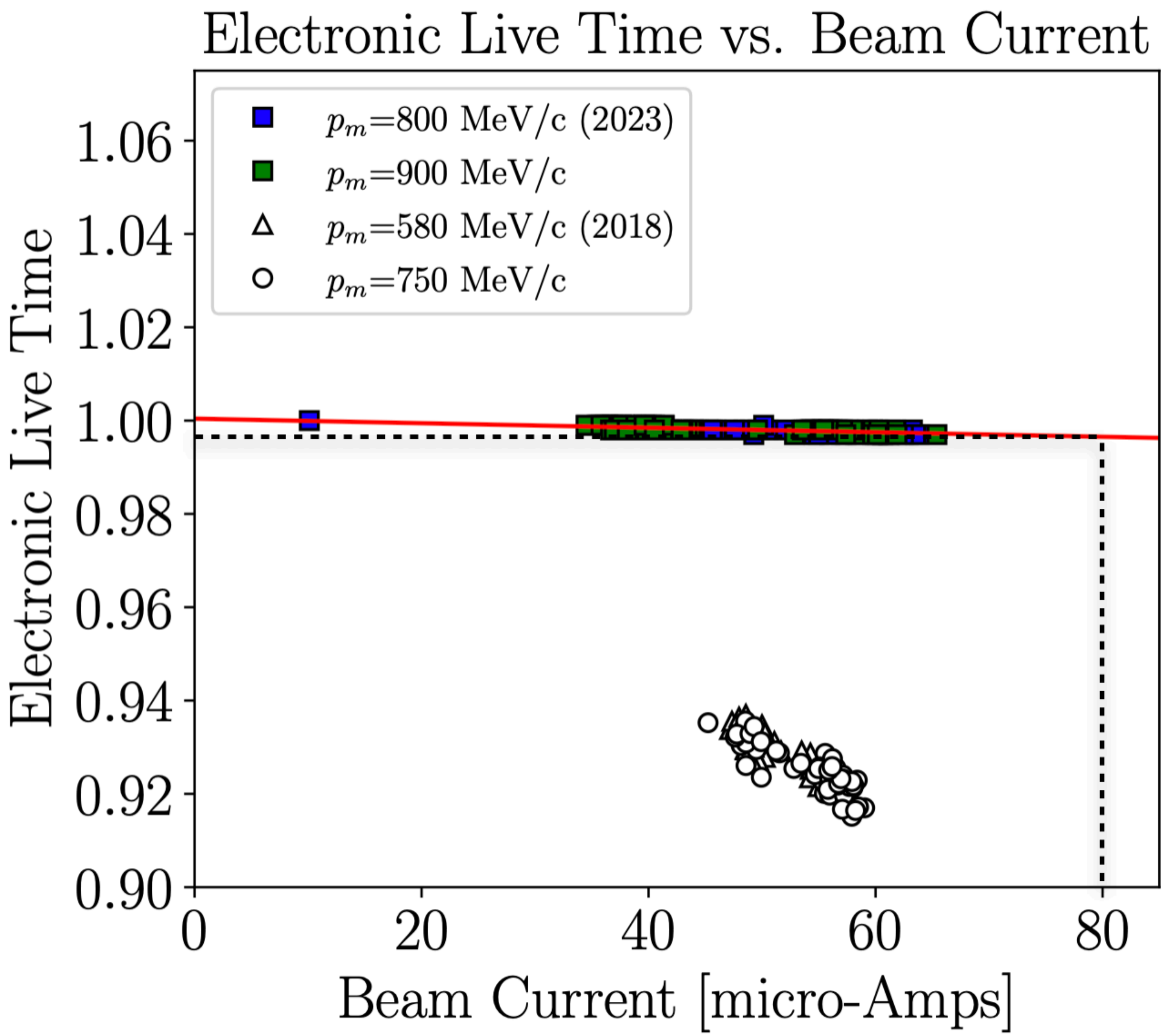
Experimental Expectations



SHMS 3/4 rate vs. Beam Current for the deuteron experiment completed in 2018 [14], and the recently completed experiment in 2023 (under analysis).

SHMS 3/4 is the Hall C standard event-selection criteria requiring at least any 3 of the 4 hodoscopes plane to produce a signal trigger.

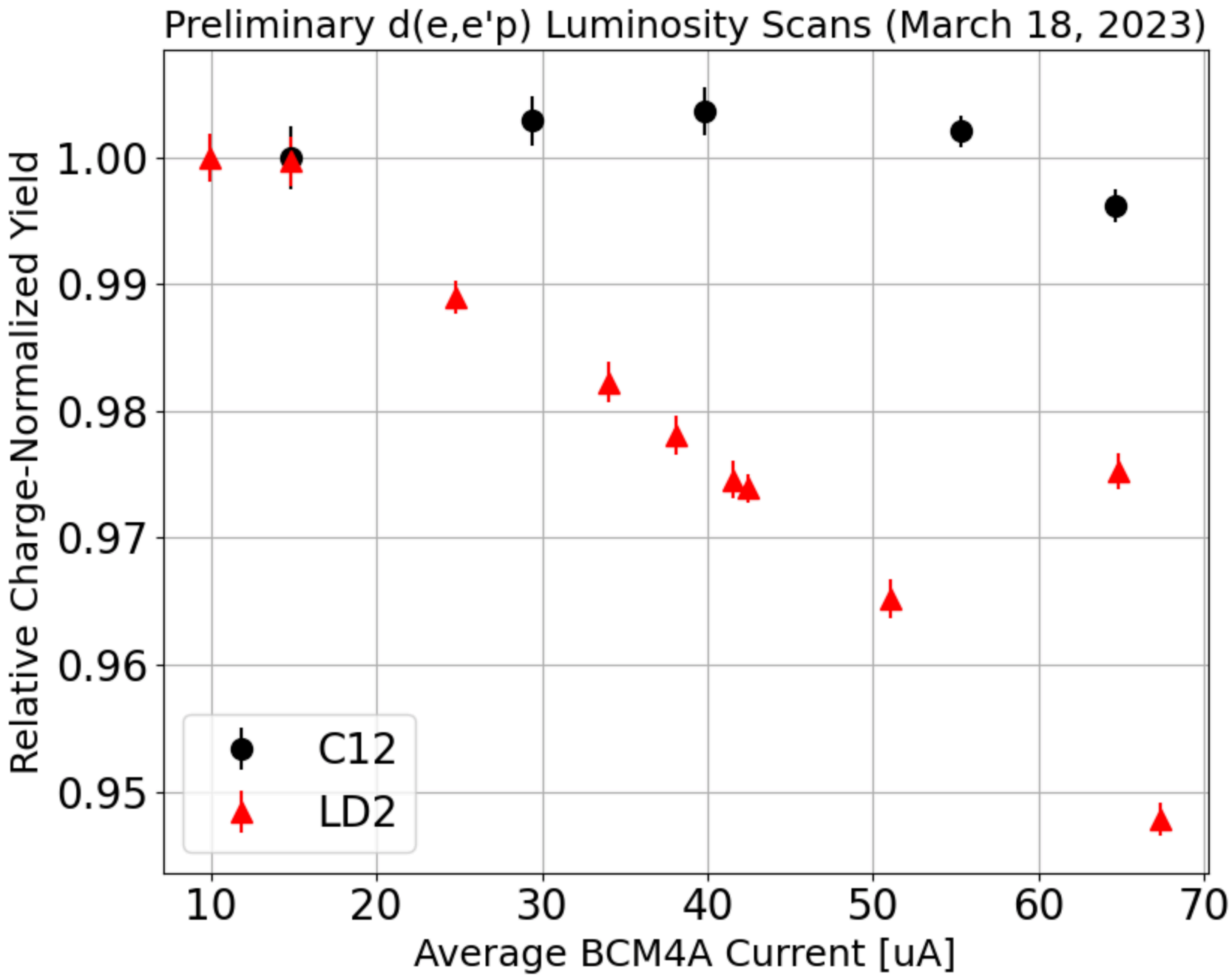
Experimental Expectations



$\tau_{\text{total.LT}} = \tau_{cpu} \text{ x } \tau_{\text{electronic}} \sim \tau_{\text{electronic}}$

$\tau_{cpu} = 1$ (coincidence trigger rates < 1 Hz)

Experimental Expectations



very preliminary target boiling studies for our completed d(e,e'p)n experiment in 2023.

Back-up: Theory Part

Back-up: Difficulty of Probing the NN Core

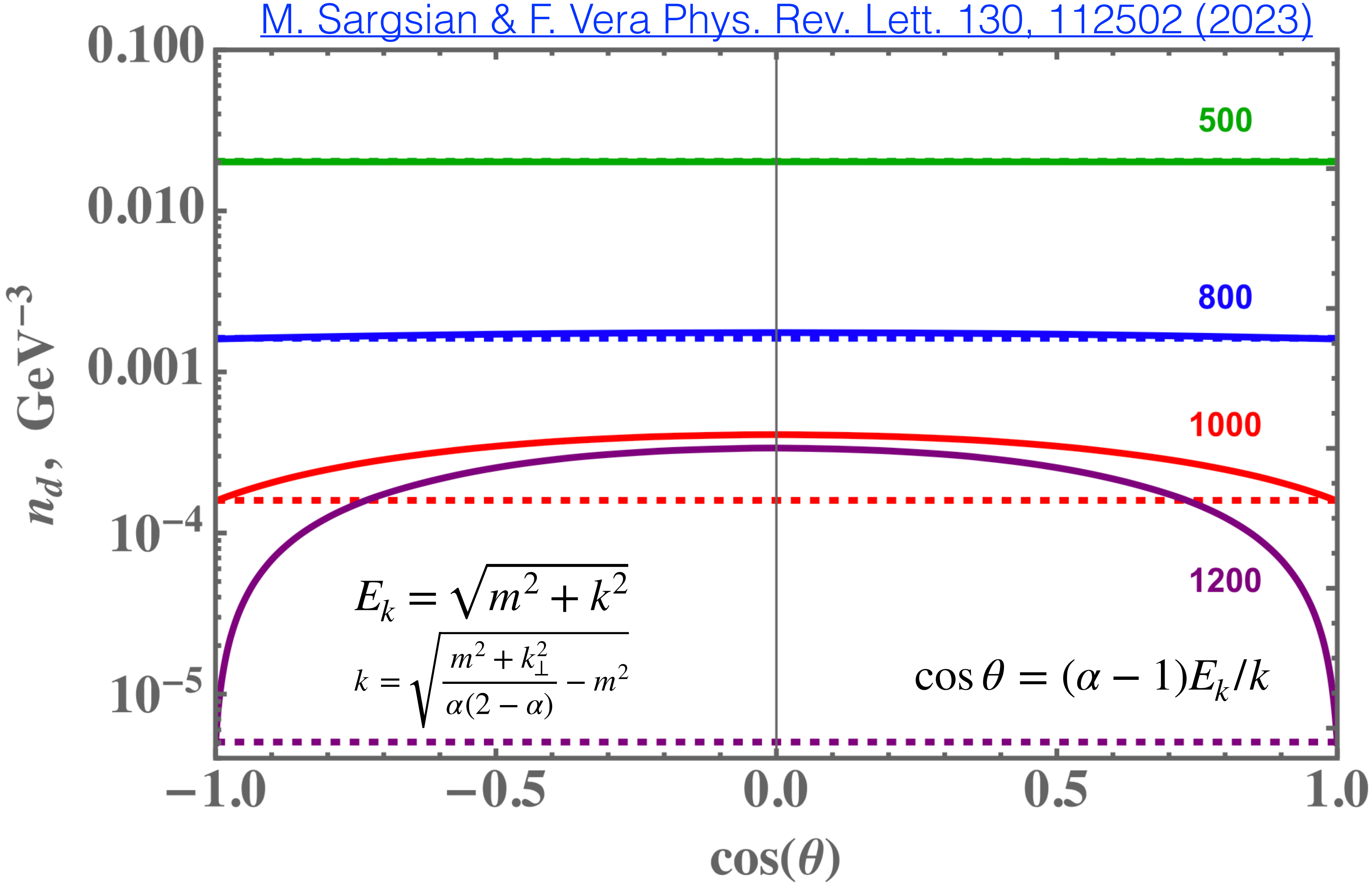
the nuclear core is responsible for the stability for atomic nuclei, without which the matter would collapse, however, since its introduction in the 1960's not much progress has been made

- the most modern *NN* phenomenological potentials based on phase-shift fits to *NN* scattering data use an ansatz for the repulsive core
- attempts to describe the core through vector-meson exchanges face conceptual difficulties, e.g. how to describe < 0.6 fm inter-nucleon distances by meson exchange with comparable or larger radii
- effective field theories faces the issue in which short-distance dynamics of the NN interaction are absorbed in the contact terms which are evaluated by comparing calculations w/ low-energy observables

Ref. "Hole in the Deuteron" (Sargsian 2024) arXiv:2410.08384

Probing the NN Repulsive Core: Recent Theoretical Advances

M. Sargsian & F. Vera Phys. Rev. Lett. 130, 112502 (2023)



Relativistic pn component

P-wave like non-nucleonic component (included)

exp. momentum distributions (light-cone)

$$\frac{d\sigma}{dE'd\Omega_e d\Omega_s} = K\sigma^{\rm LC}_{eN}(\alpha, p_t)\rho(\alpha, p_t),$$

$$\rho(\alpha, p_t) \approx \frac{\sigma_{exp}}{K\sigma^{LC}_{eN}(\alpha, p_t)}$$

$$\alpha = 2 - \alpha_n,\ \alpha_n = \frac{E_n - p_{n,z}}{M_d/2}$$

where α is the proton light-cone momentum fraction

- In the light-front, if only Ψ^{LC}_{pn} is considered, the momentum distribution only depends on the magnitude of the internal momenta $n_d(k)$, and the angular condition (L=0 or L=2), is satisfied
- Violation of the angular condition gives rise to an additional *P-wave* like (L=1) component, which could only be explained by the emergence of non-nucleonic components in the deuteron w.f. $\Psi^{LC}_{np+\Delta\Delta'}$ giving rise to an additional dependence, $n_d(k, k_\perp)$

Virtual Nucleon Approximation (a detailed description)

Within the VNA (Ref. Phys.Rev.C 82 (2010) 014612), the spectator nucleon is treated as on-shell and the virtuality is introduced into the electromagnetic current of bound nucleon. This current is relativistic and has a virtuality parameter. Also the deuteron wave function has a flux factor that allows to satisfy baryonic number conservation. If one explicitly introduces the $d \to N\bar{N}$ transition, then this approximation similar to the Gross approach in the relativistic description of the deuteron. However if one neglects $d \to N\bar{N}$ (vacuum fluctuation diagram) then one can express the deuteron wave function through the non-relativistic deuteron wave function with additional factor, since normalization of the wave function is defined from the condition that the charge form-factor of the deuteron at $Q^2 = 0$ is equal to 1. In short this is a relativistic approach, in which however we neglected the contribution from vacuum fluctuations. Justification of it is that one expects that vacuum fluctuations should be small for up to 700 MeV/c.

In our published article Phys. Rev. Lett. **125**, 262501 (2020), the theoretical calculations using the AV18 & CD-Bonn NN potentials by M. Sargsian were done within the VNA framework

Phys.Rev.C **82** (2010) 014612

Calculations of Inelastic Thresholds for $\Delta\Delta$, NN_{Roper}, NN^*

<u>particle mass (GeV)</u>

$$M_N = 0.938272$$

$$M_\pi = 0.139$$

$$M_\Delta = 1.232$$

$$M_{\mathrm{Roper}} = 1.440$$

$$M_{N^*} = 1.520$$

<u>Inelastic threshold momenta (GeV/c)</u>

$$k_\Delta = \sqrt{M_\Delta^2 - M_N^2} \sim 0.798$$

$$k_{\mathrm{Roper}} = \sqrt{\frac{(M_{\mathrm{Roper}} + M_N)^2}{4} - M_N^2} \sim 0.730$$

$$k_{NN^*} = \sqrt{\frac{(M_{N^*} + M_N)^2}{4} - M_N^2} \sim 0.793$$

($NN\pi$ not considered an inelastic threshold)

$$k_{NN\pi} = \sqrt{M_N M_\pi + \frac{M_\pi^2}{4}} \sim 0.368$$

pion production threshold is suppressed, the reason being that
(a) $NN\pi$ vertex is proportional to the momentum so slow pion production is suppressed and
(b) $NN\pi$ vertex is hard and gives little contribution.

We know this also from the fact that there are very little pions observed in the nuclear medium.