PAC 54

(PR12-25-003)

Deuteron FSI Studies

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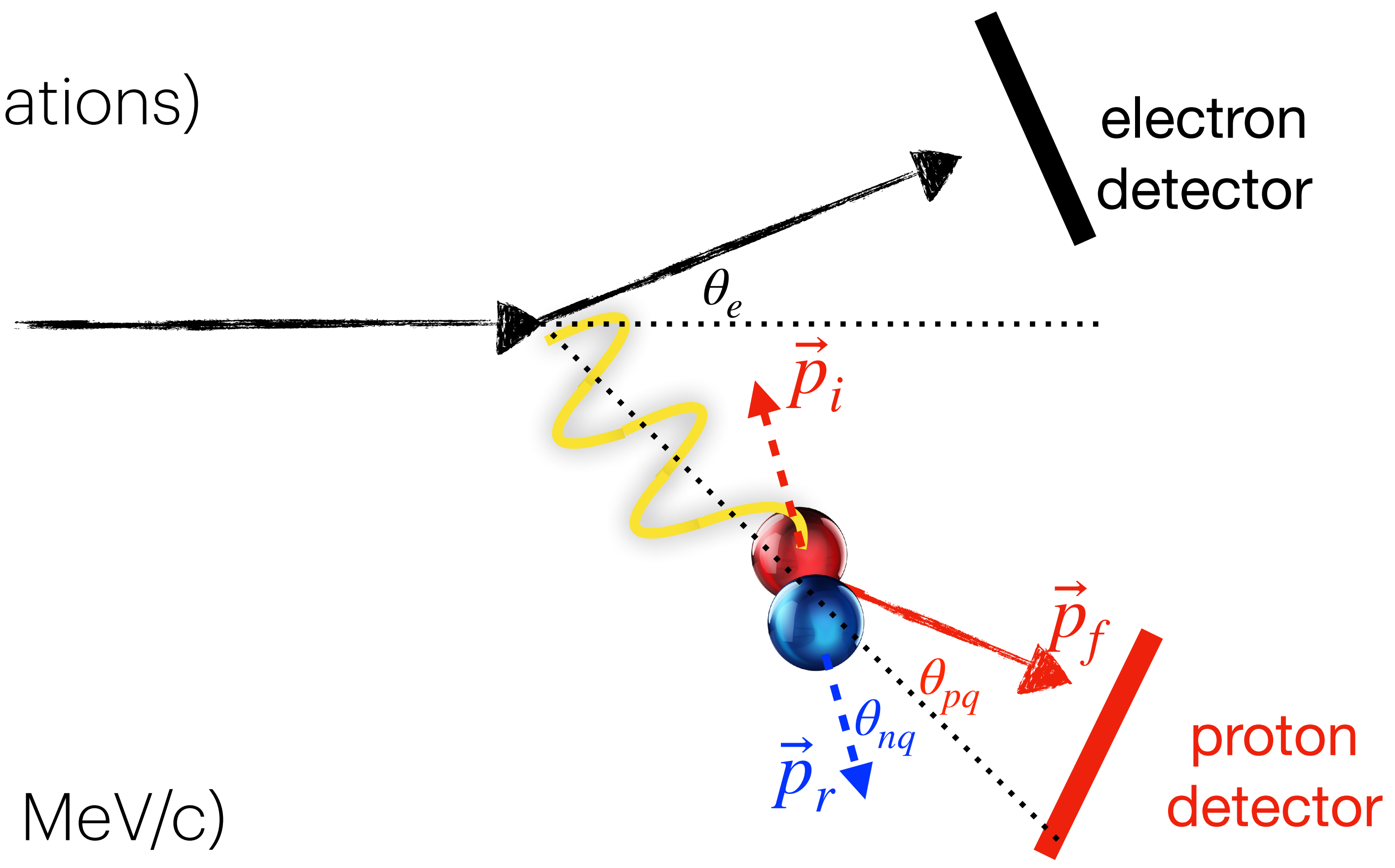
Why Study the Deuteron ?

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

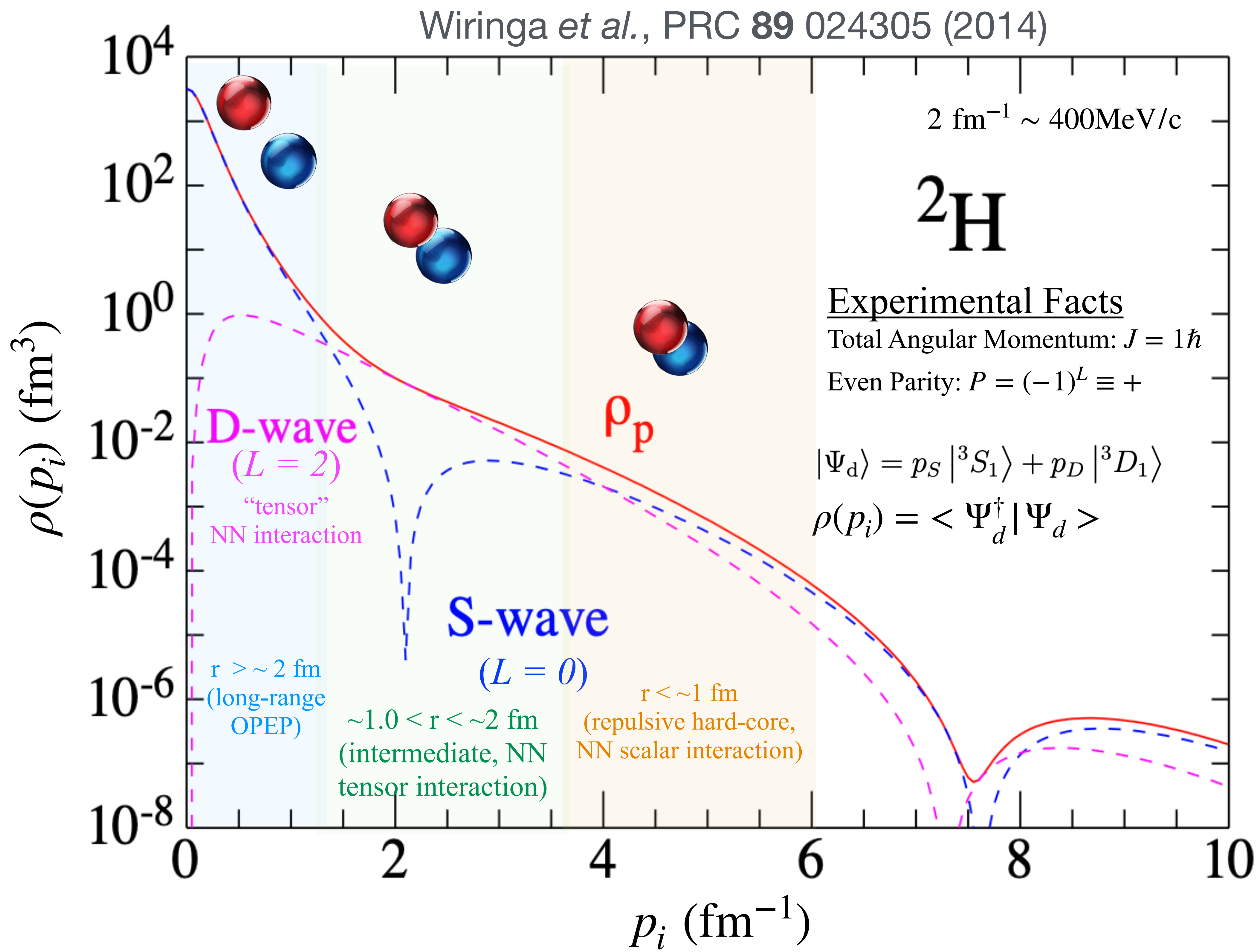
- most simple *np* bound system
  (no 3*N* forces or additional complications)

- 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

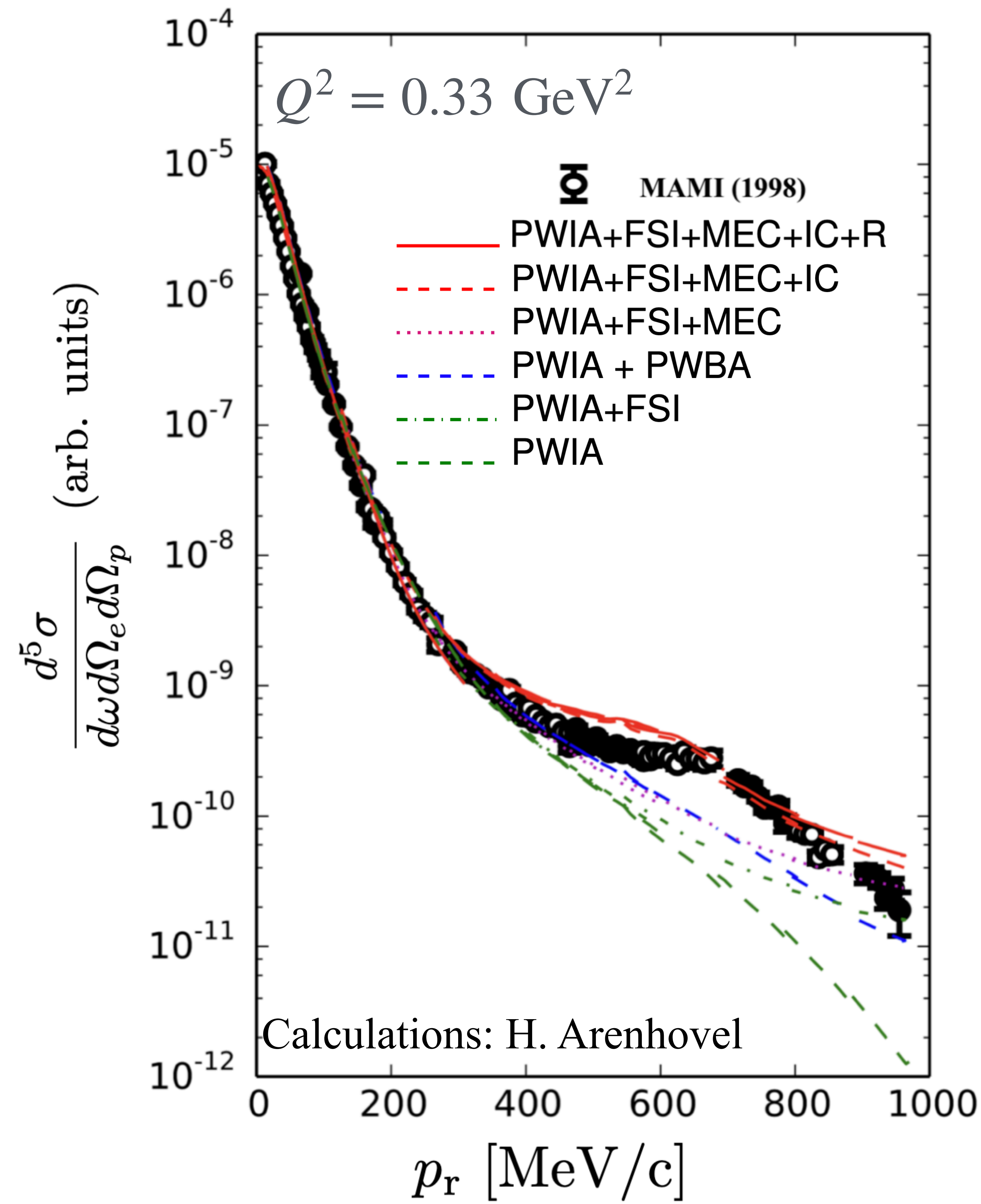


Momentum Distribution



Difficulty in Probing the Nuclear Core

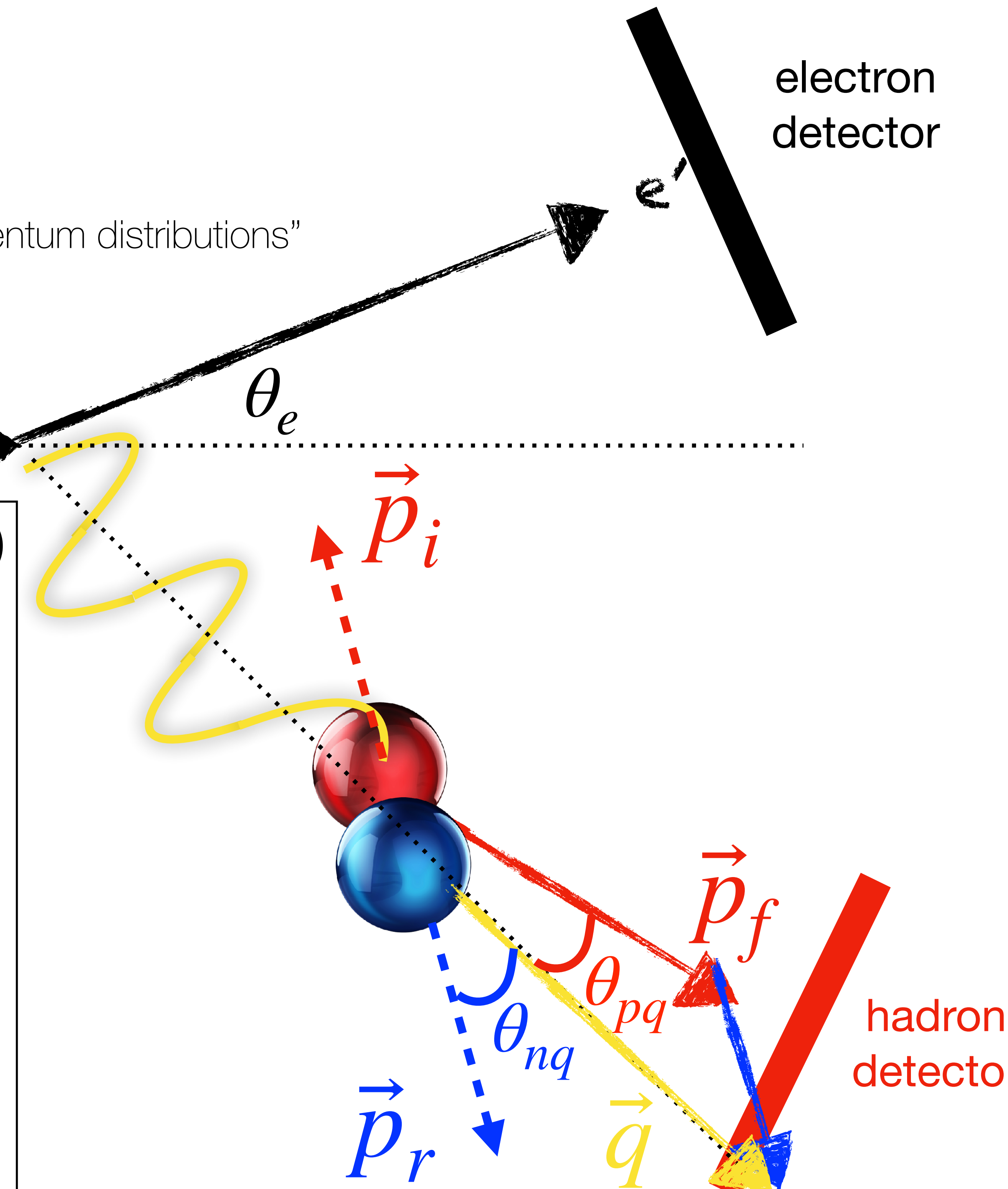
Blomqvist, Boeglin *et al.*, PLB **424** 33 (1998)



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"



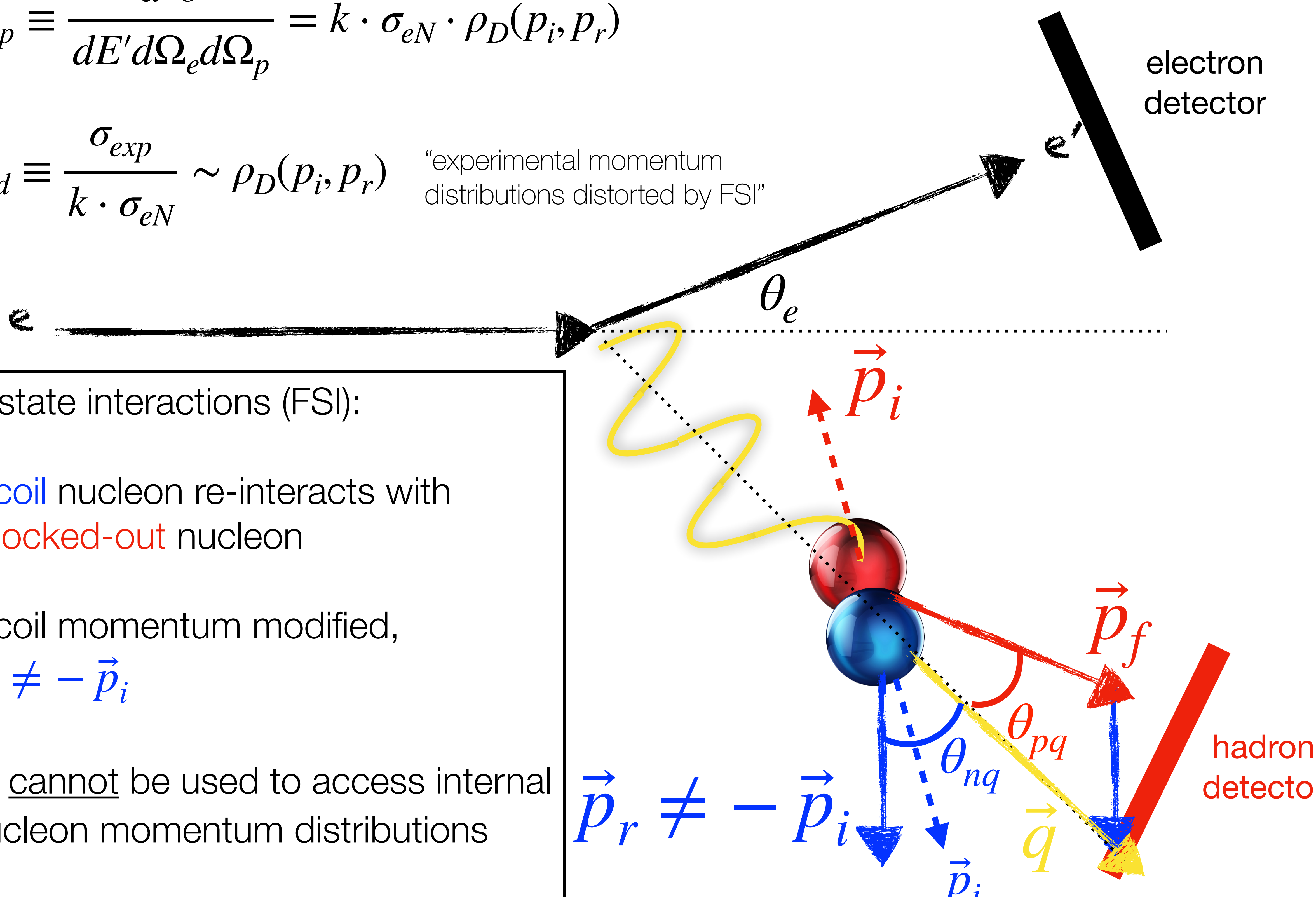
- plane-wave impulse approximation (PWIA)
  - no further re-interaction between knocked-out and recoil nucleon
  - recoil momentum unchanged, $\vec{p}_r \sim -\vec{p}_i$
  - $\vec{p}_r$ can be used to access internal nucleon momentum distributions

Probing the High-Momentum Structure

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

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

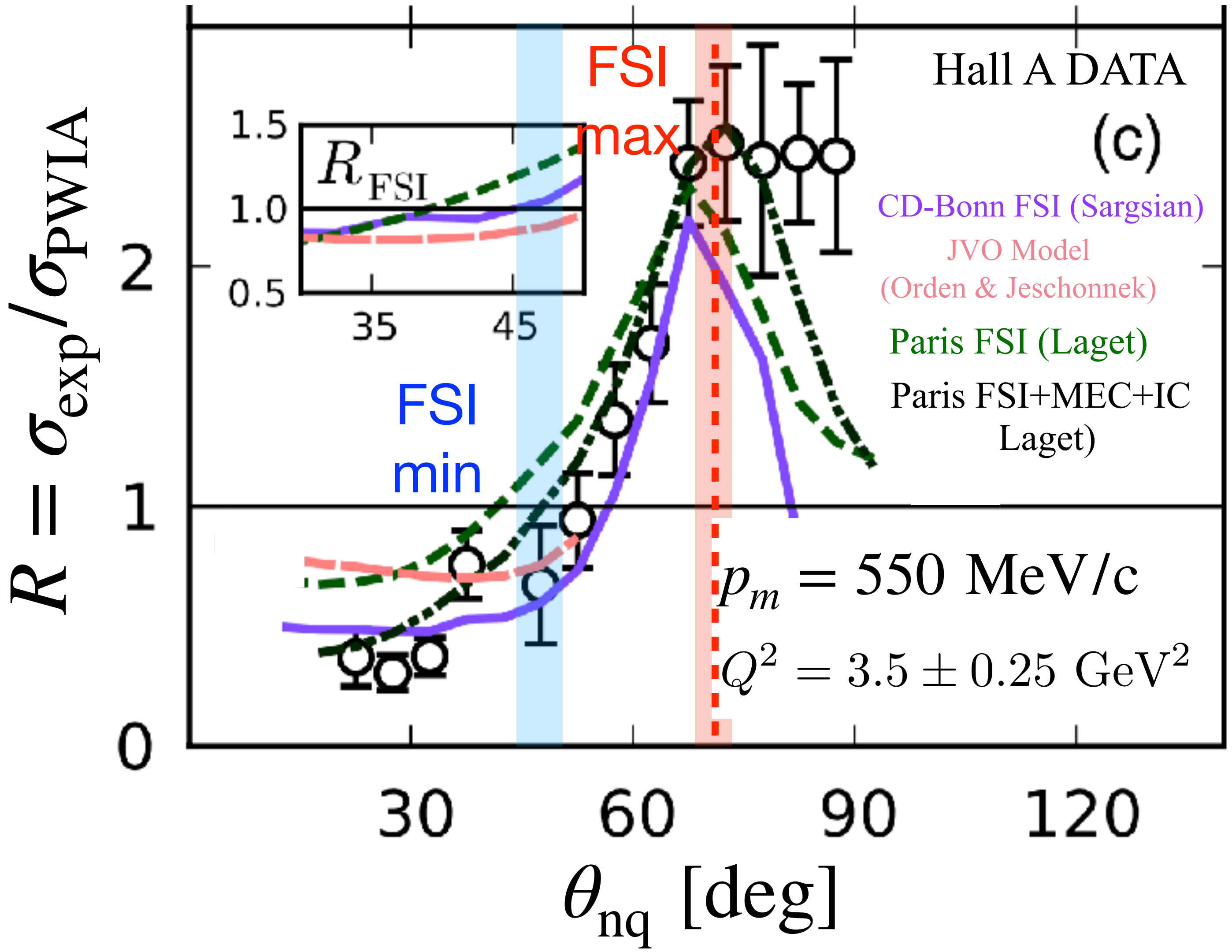
"experimental momentum distributions distorted by FSI"



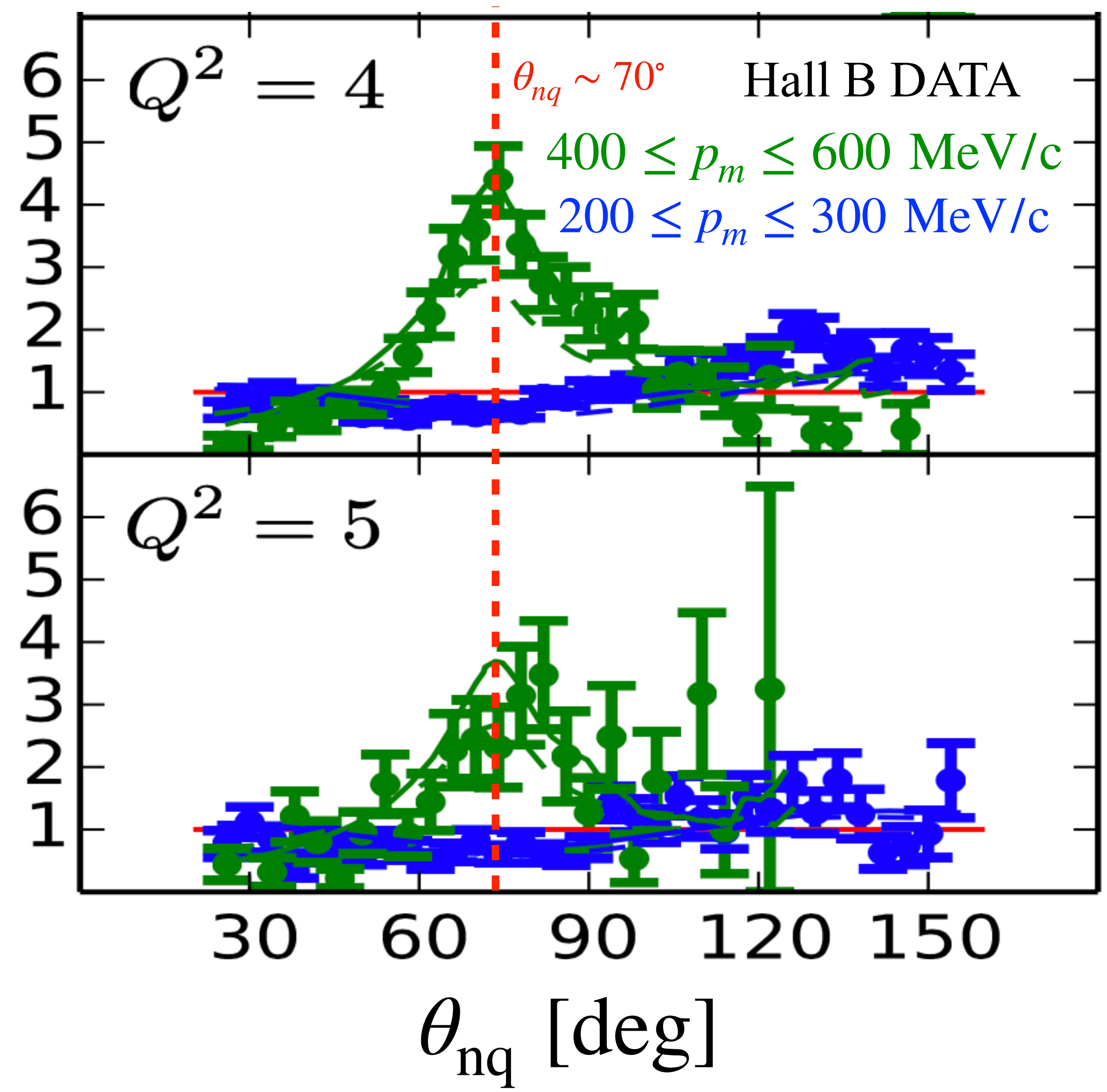
- Final-state interactions (FSI):
  - recoil nucleon re-interacts with knocked-out nucleon
  - recoil momentum modified, $\vec{p}_r \neq -\vec{p}_i$
  - $\vec{p}_r$ cannot be used to access internal nucleon momentum distributions

Controlling Final-State Interactions

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



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



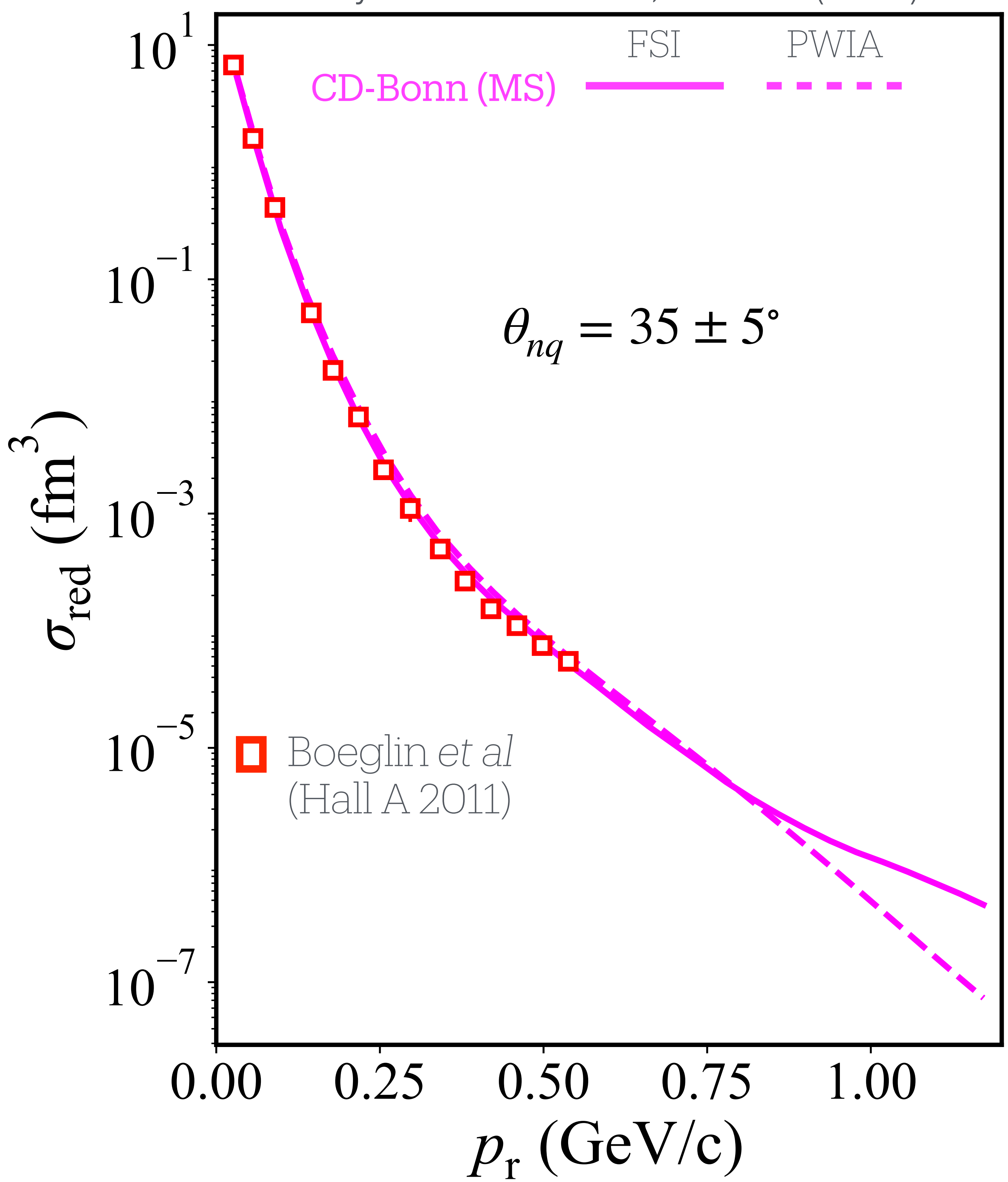
Phys. Rev. B **609**, 49 (Laget 2005)

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

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

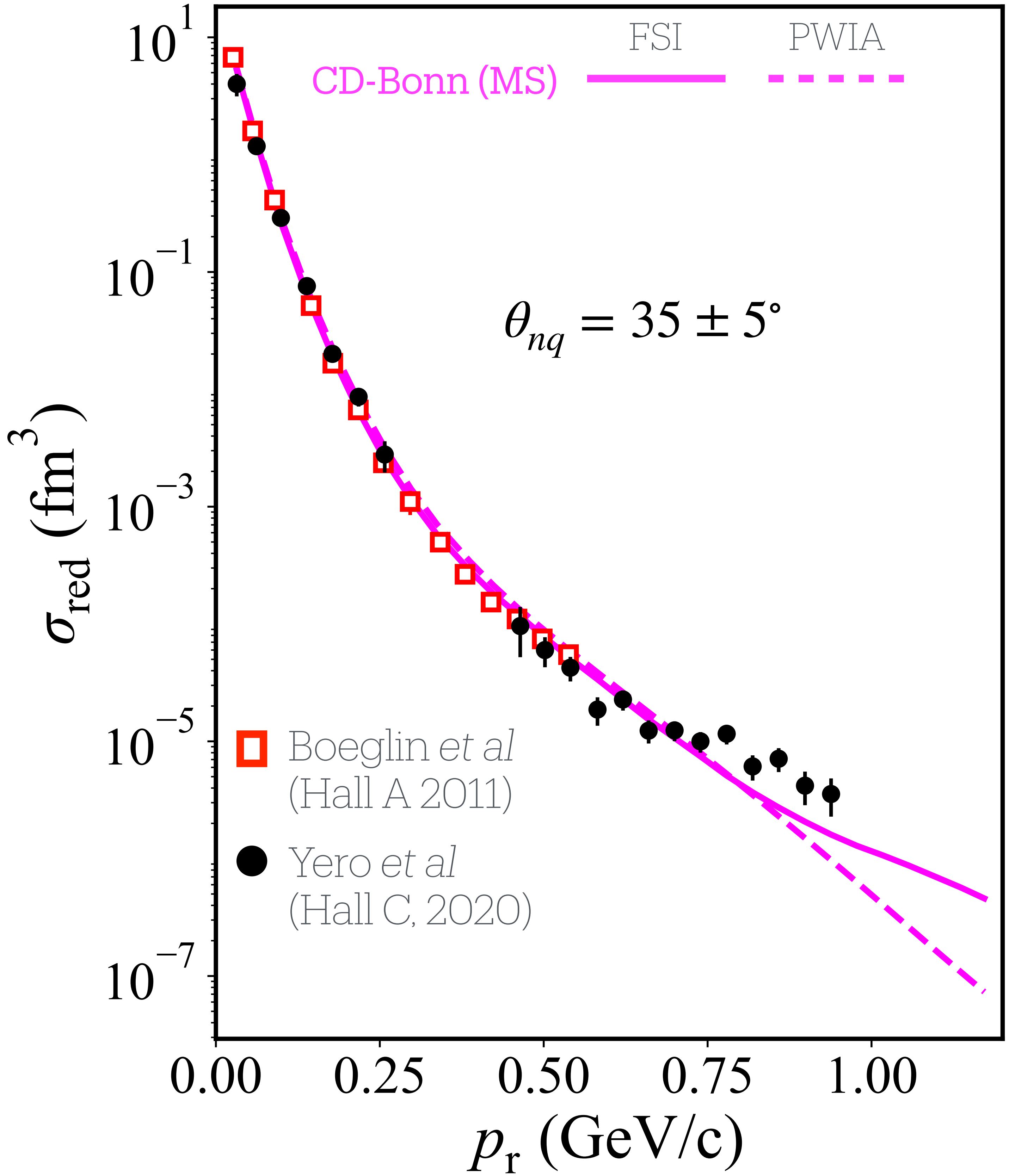
Probing the NN Repulsive Core

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



Probing the NN Repulsive Core

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



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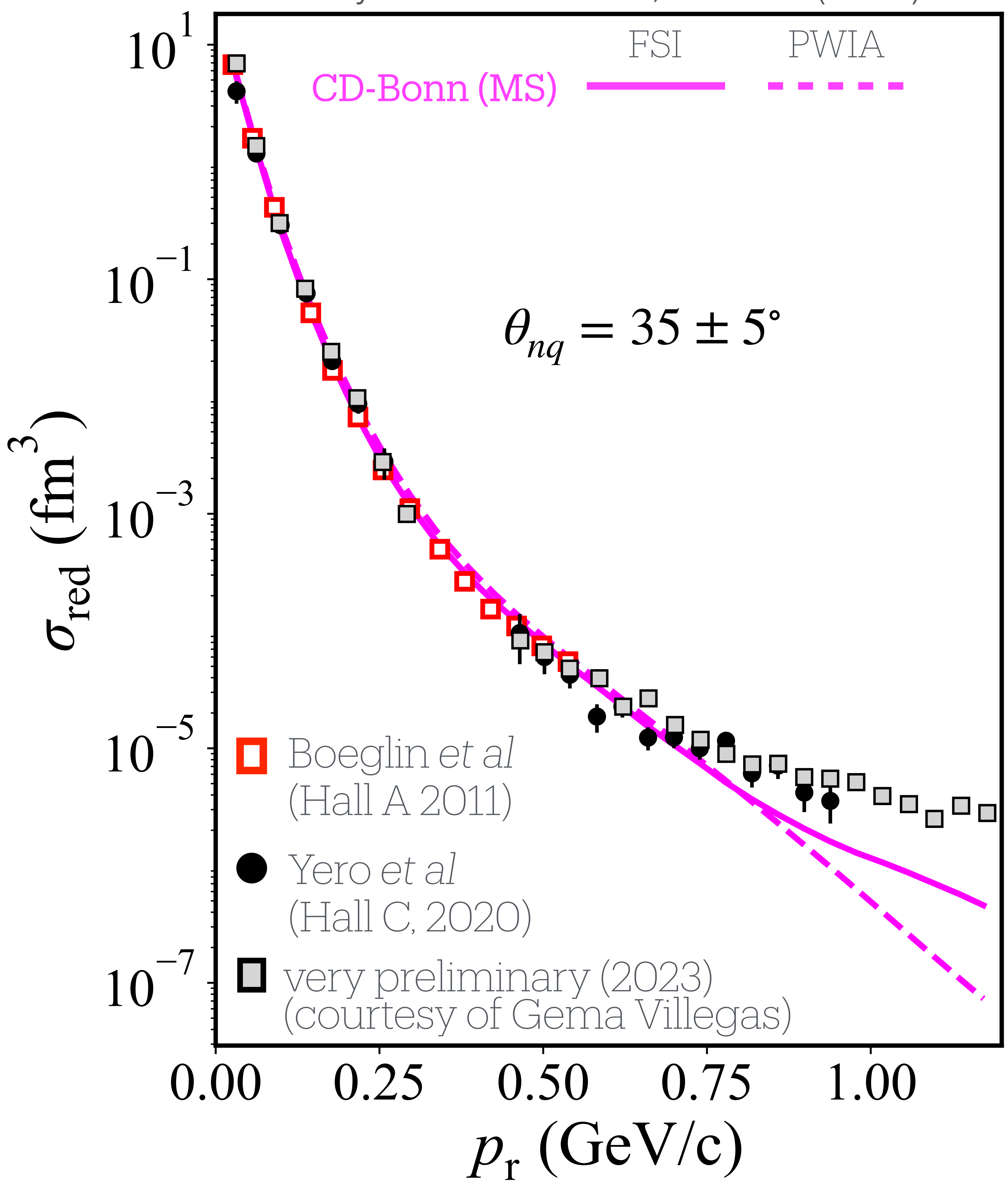

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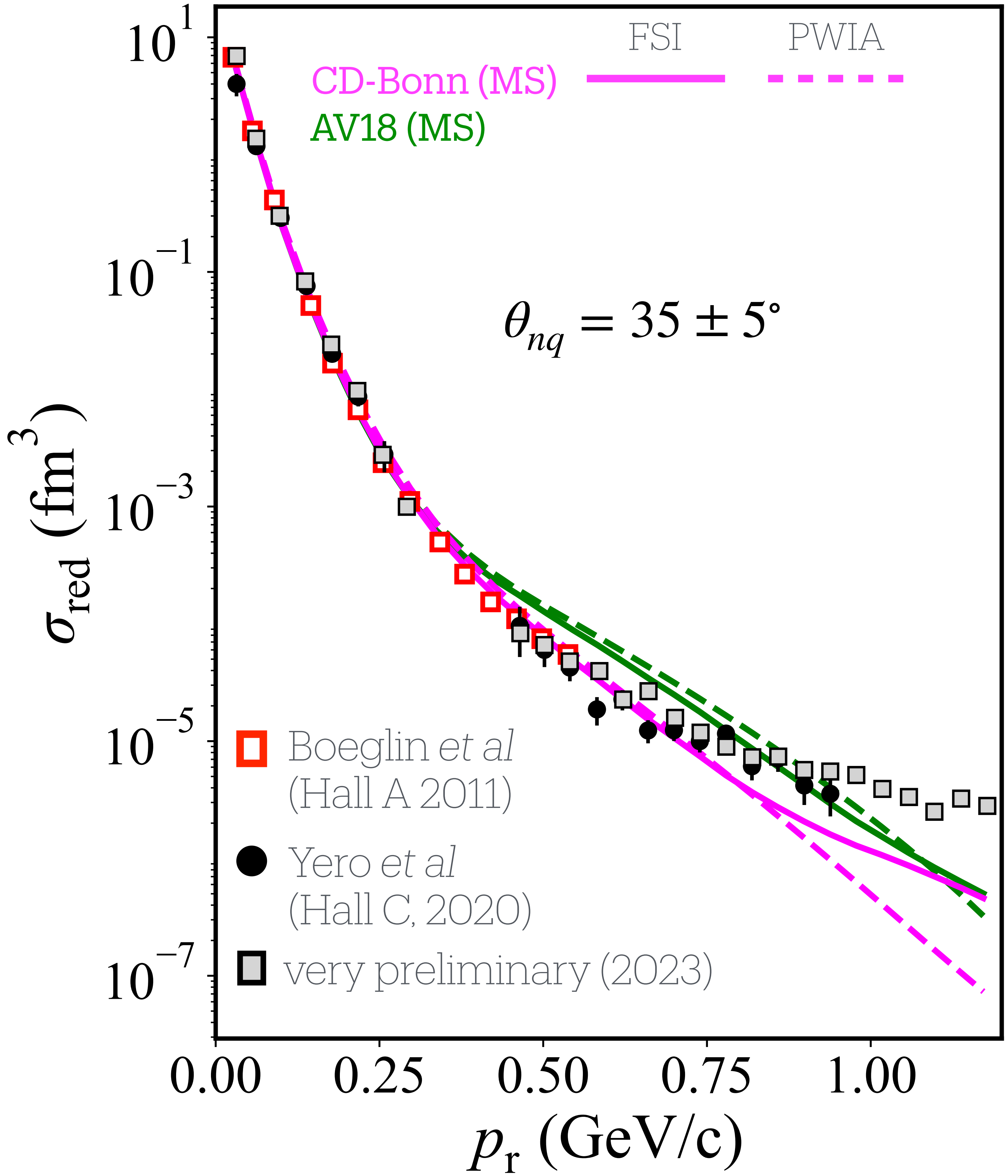

Probing the NN Repulsive Core

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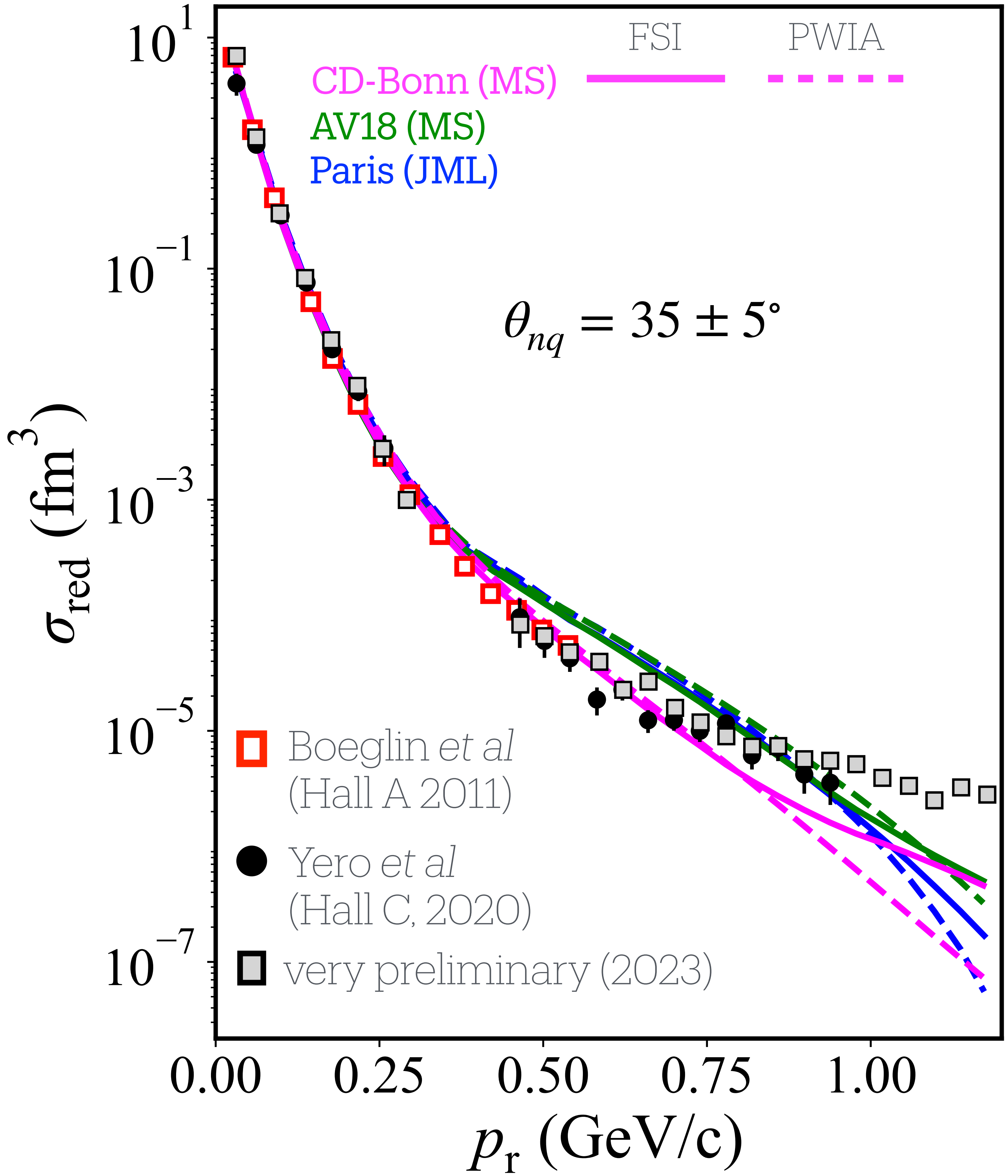
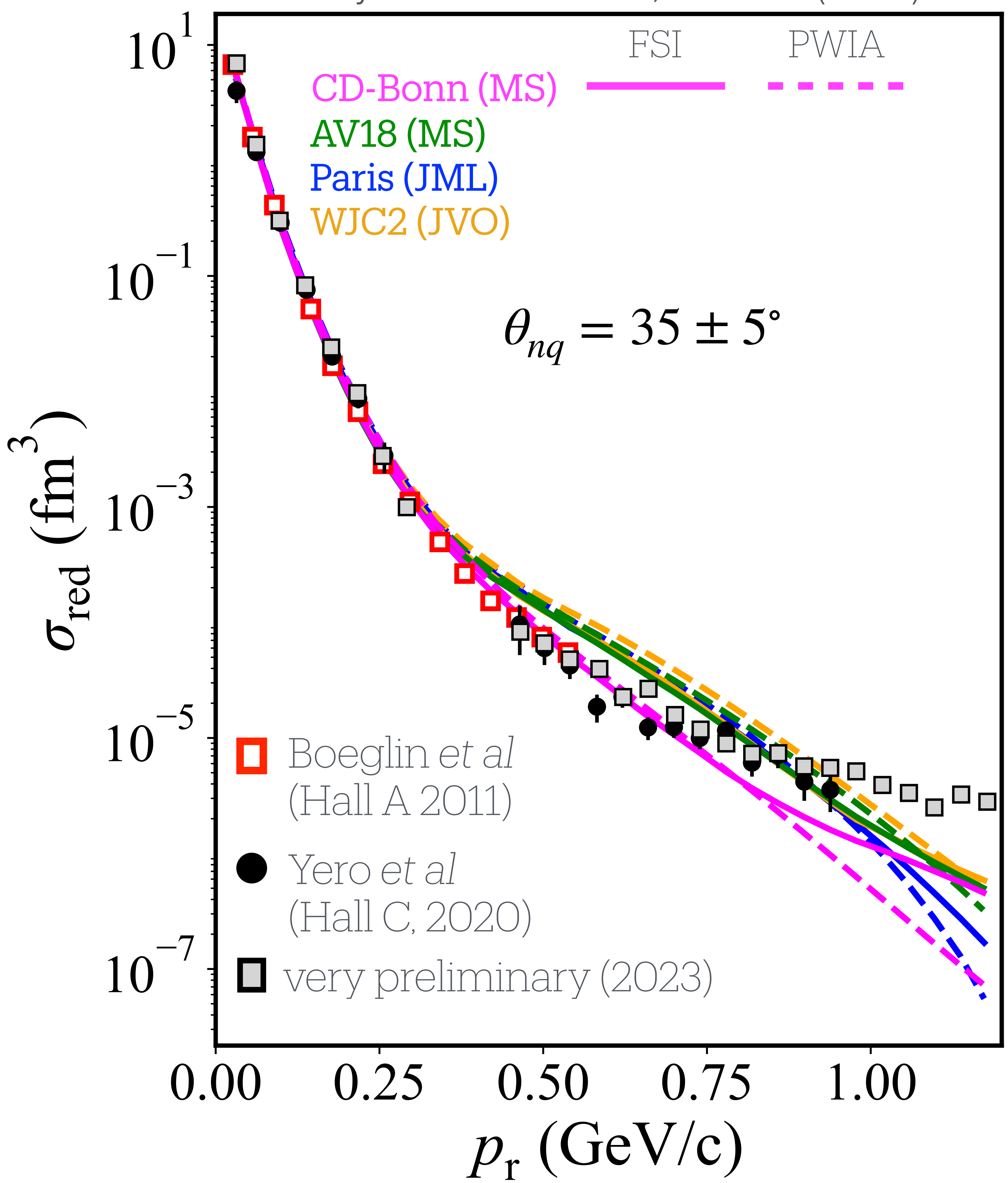


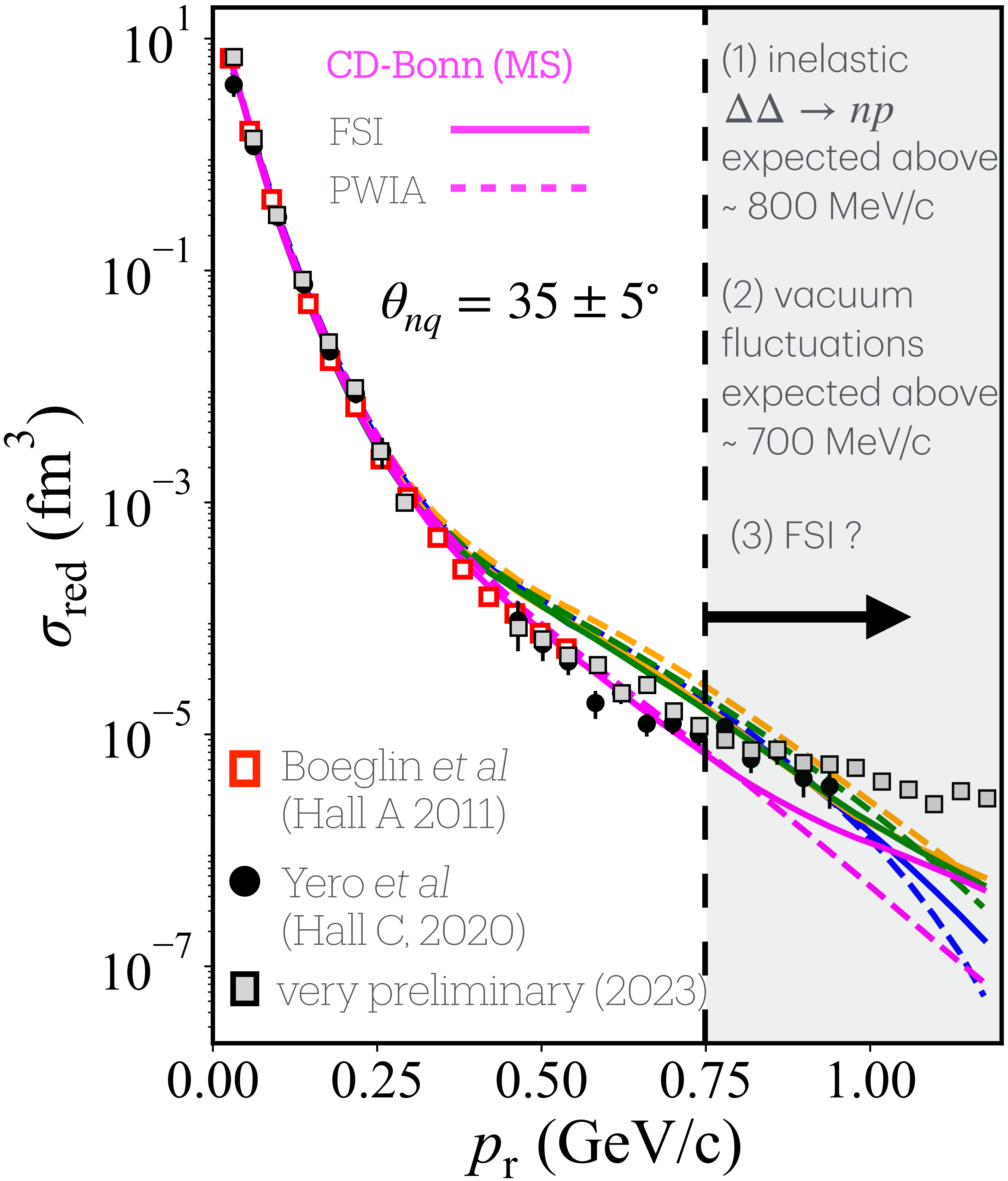
Probing the NN Repulsive Core

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



Probing the NN Repulsive Core

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



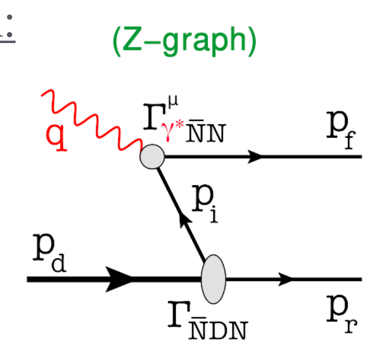
Virtual Nucleon Approximation (VNA) Theoretical Framework (Sargsian 2010)

- only $pn \rightarrow pn$ transitions (non-nucleonic parts excluded)
- dynamics of $\gamma^* N$ and FSI (GEA) are relativistic
- vacuum fluctuations neglected;

$$\Psi_d = \Psi_d^{NR} \times f_{corr}^{rel.}$$

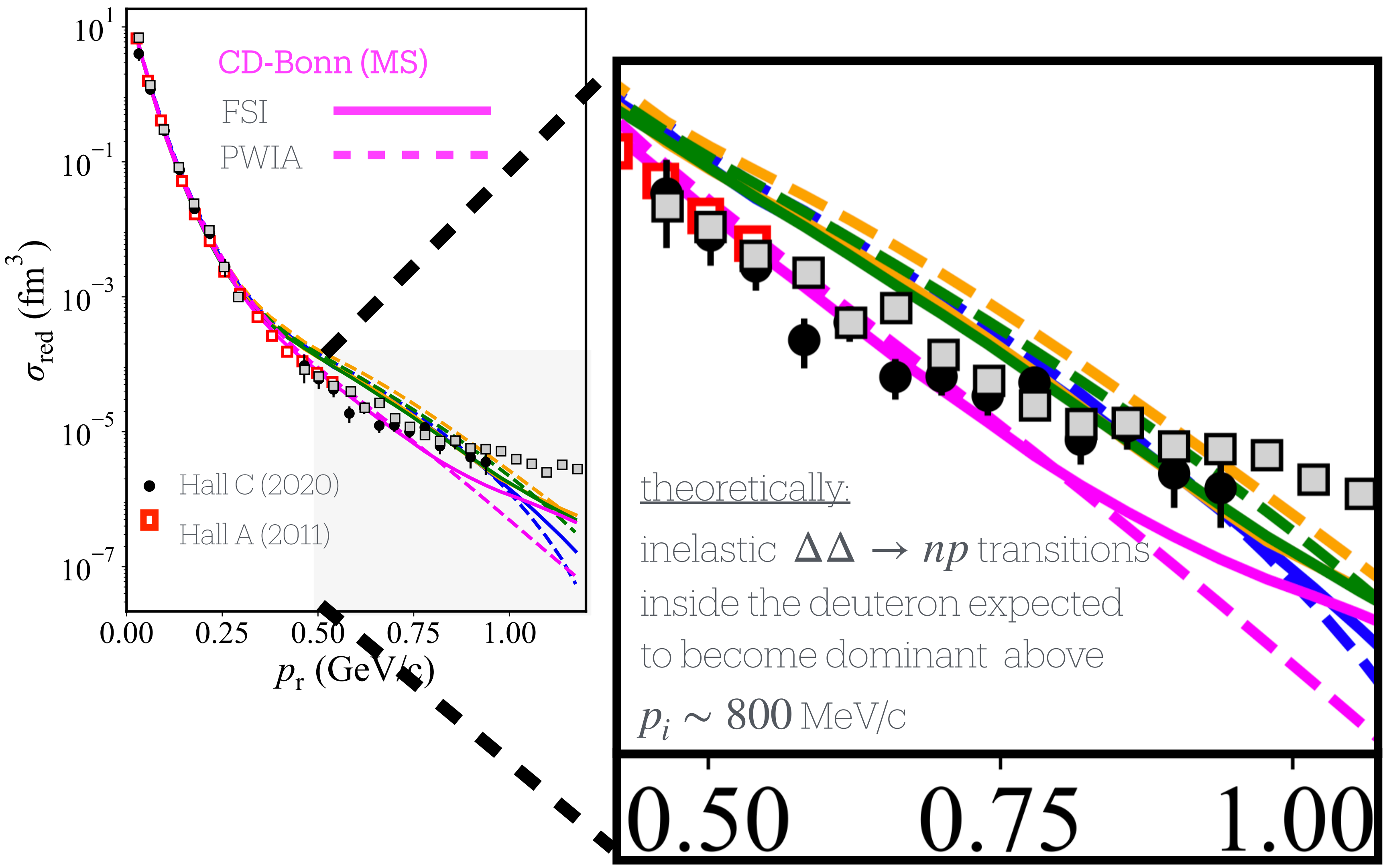
(below p_r ~ 700 MeV/c VF. are expected to be small)

vacuum fluctuations diagram:



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

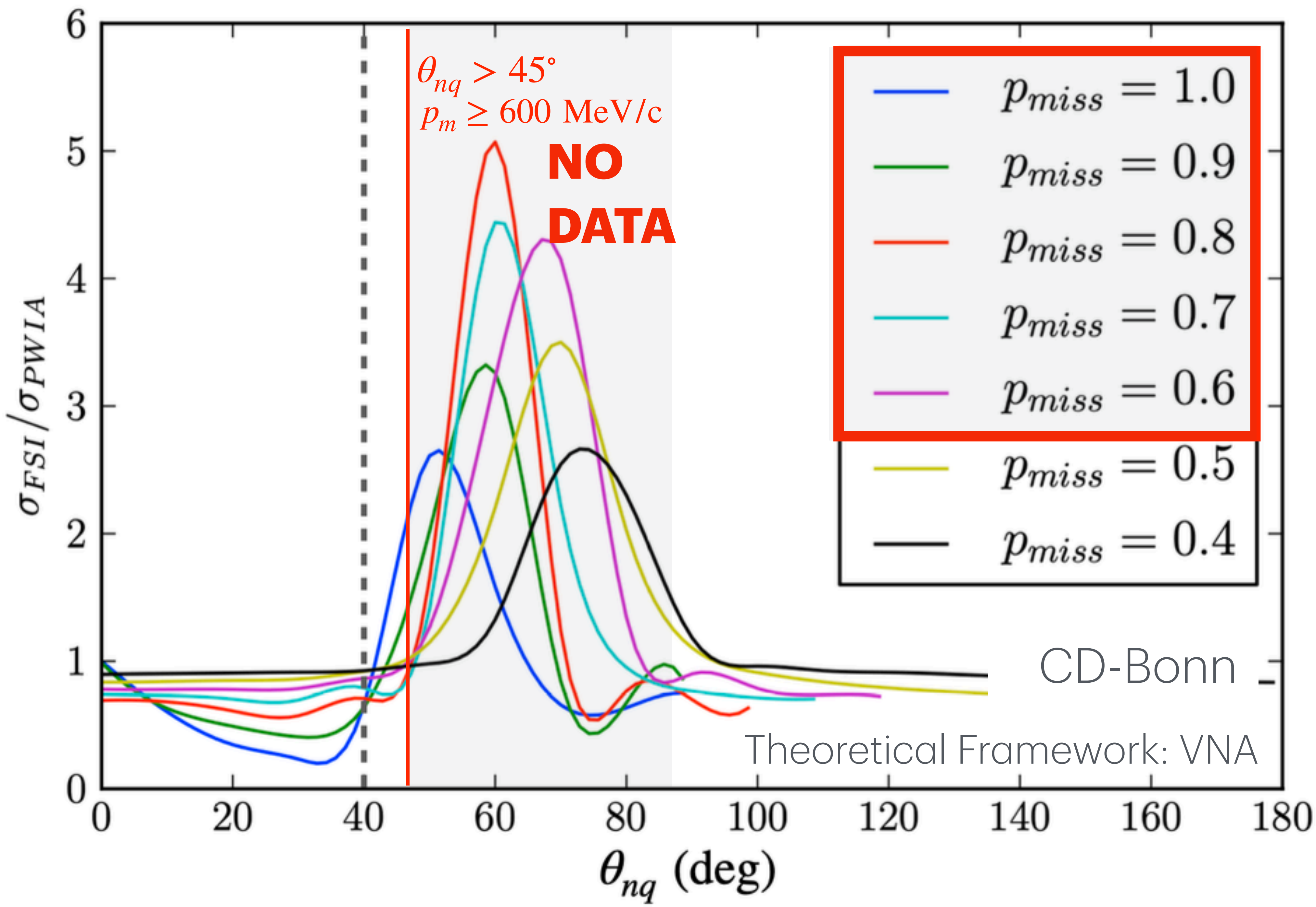
How to dis-entangle **FSI** + **relativistic** + **non-nucleonic(?)** effects at high missing momenta ?

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

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

NN Repulsive Core Sensitivity to FSI

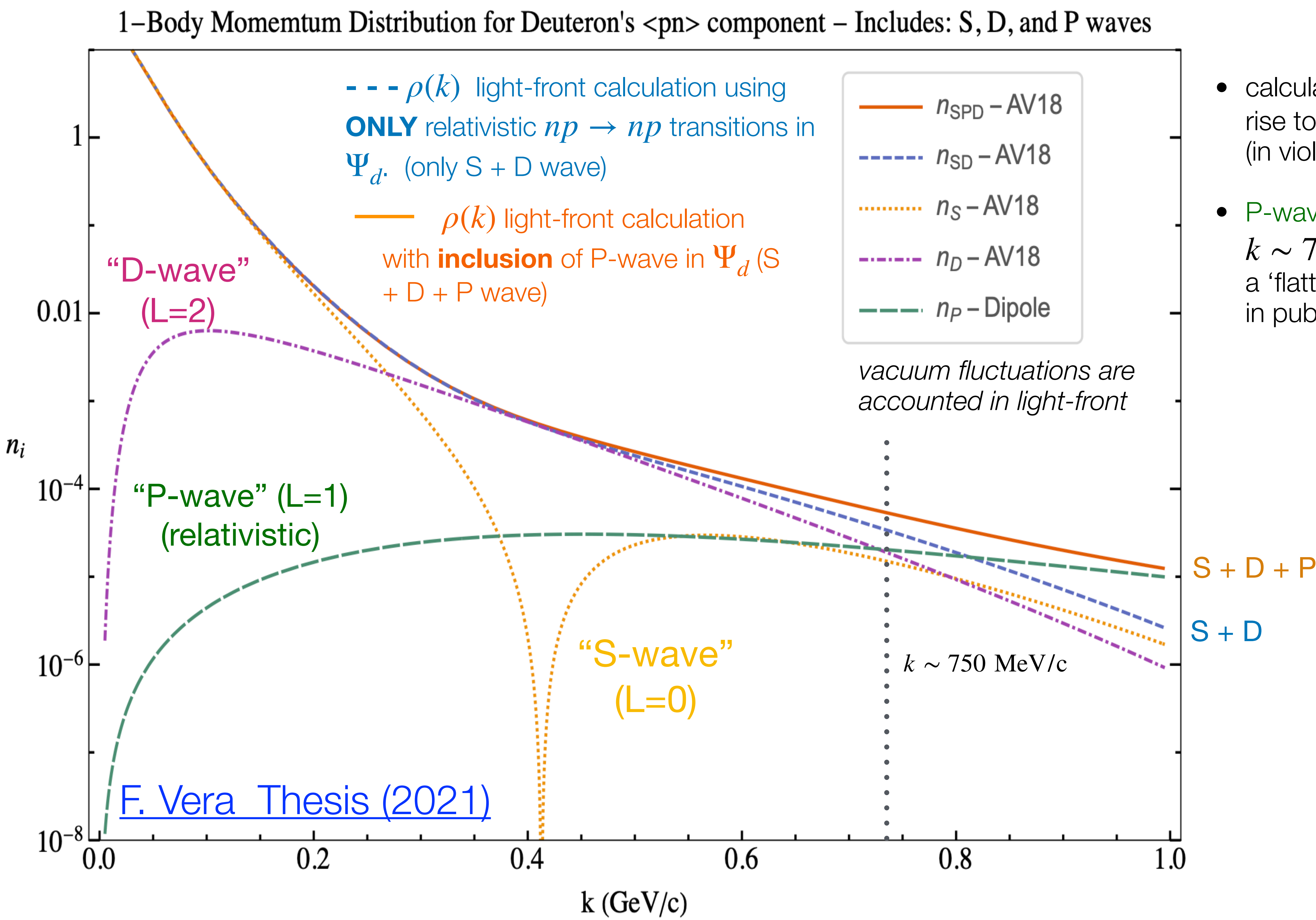
IJMP E Vol. **24**, No. 03, 1530003 (Boeglin & Sargsian, 2015)



*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' also observed in published data Yero et al. 2020

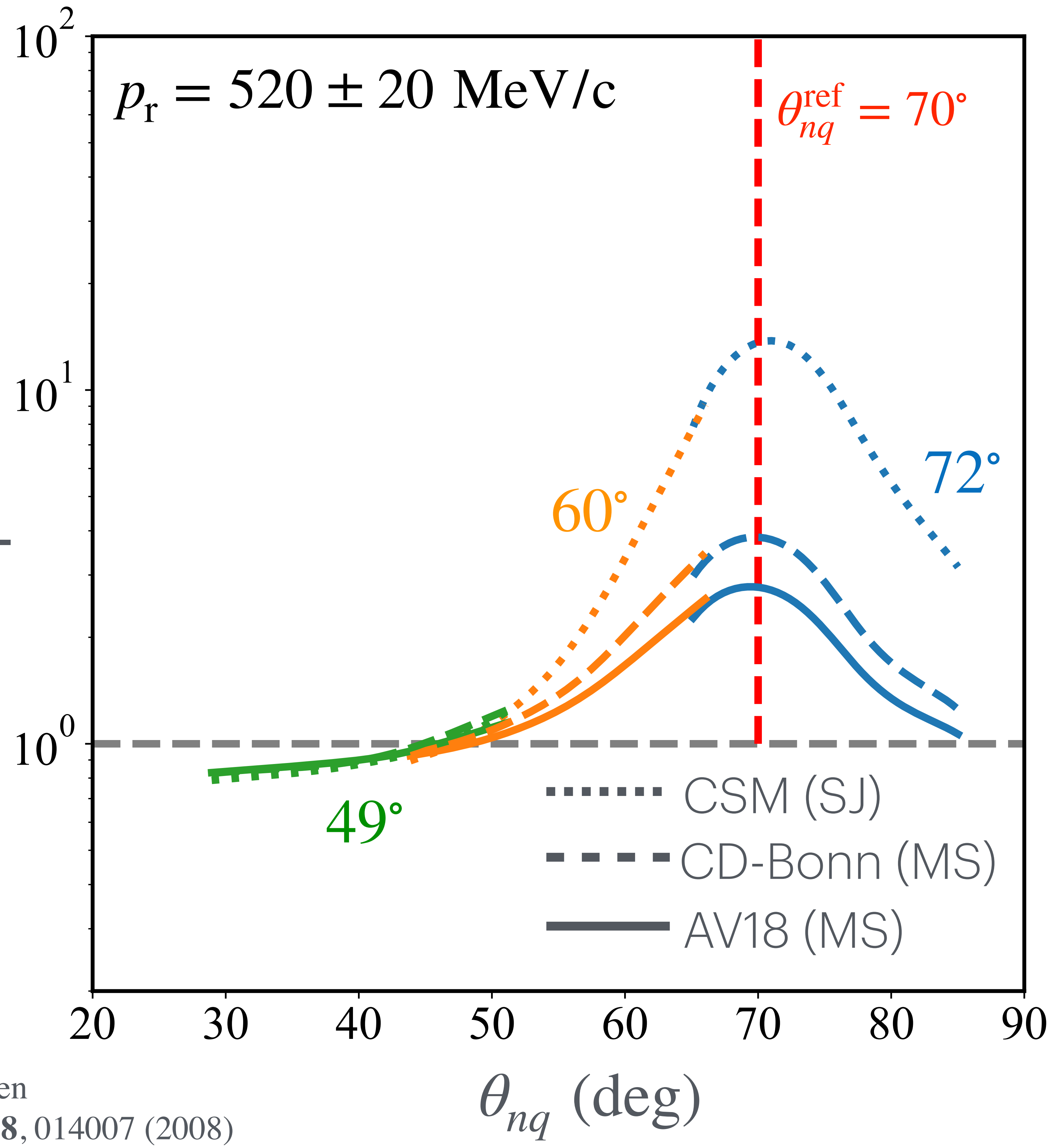
M. Sargsian & F. Vera Phys. Rev. Lett. 130, 112502 (2023)

relativistic (np) relativistic (non-nucleonic)

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

Proposed Measurement

$$R = \frac{\sigma^{FSI}}{\sigma^{PWIA}}$$

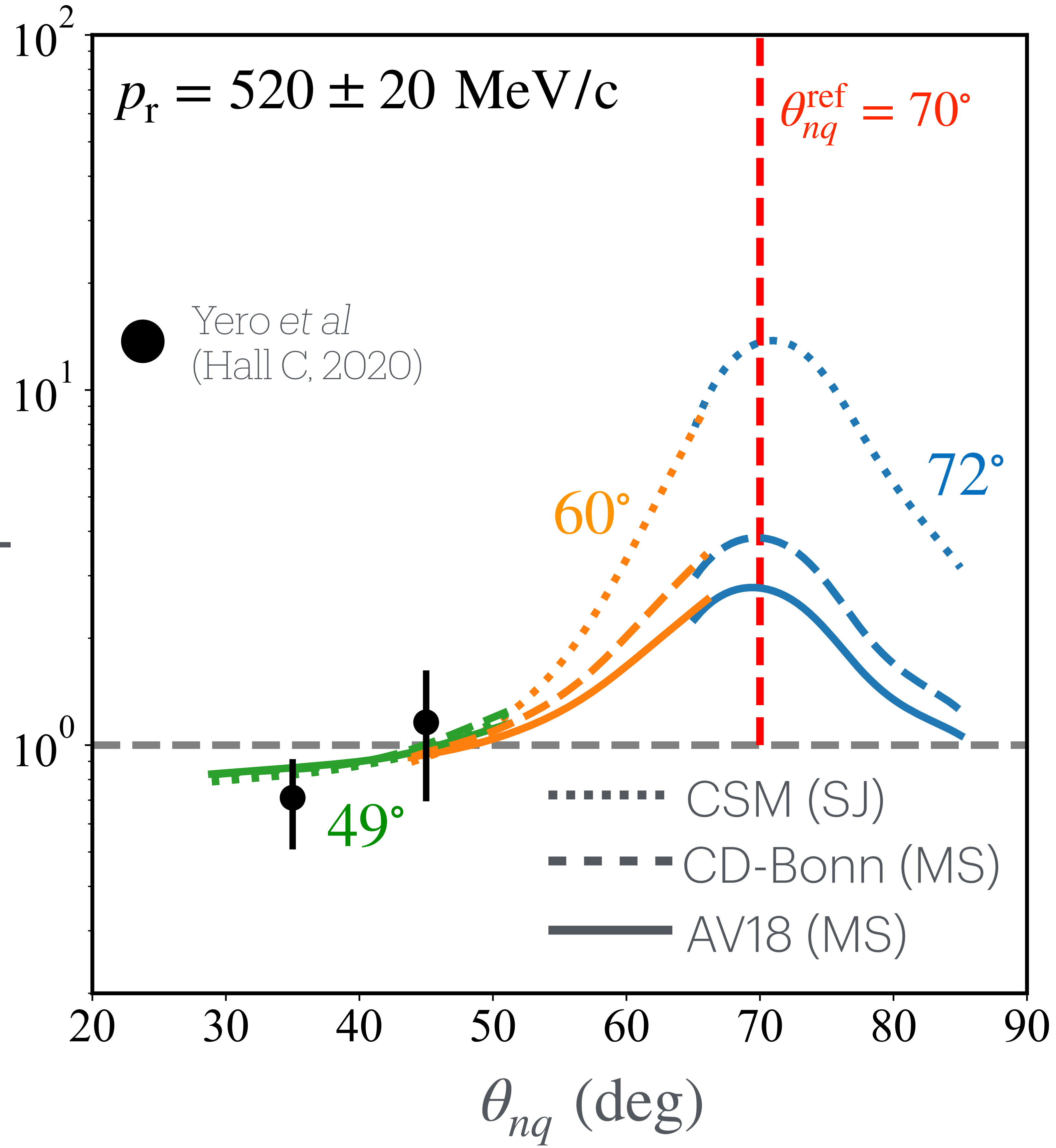


CSM*: covariant spectator model (Gross Eq.)

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

Proposed Measurement

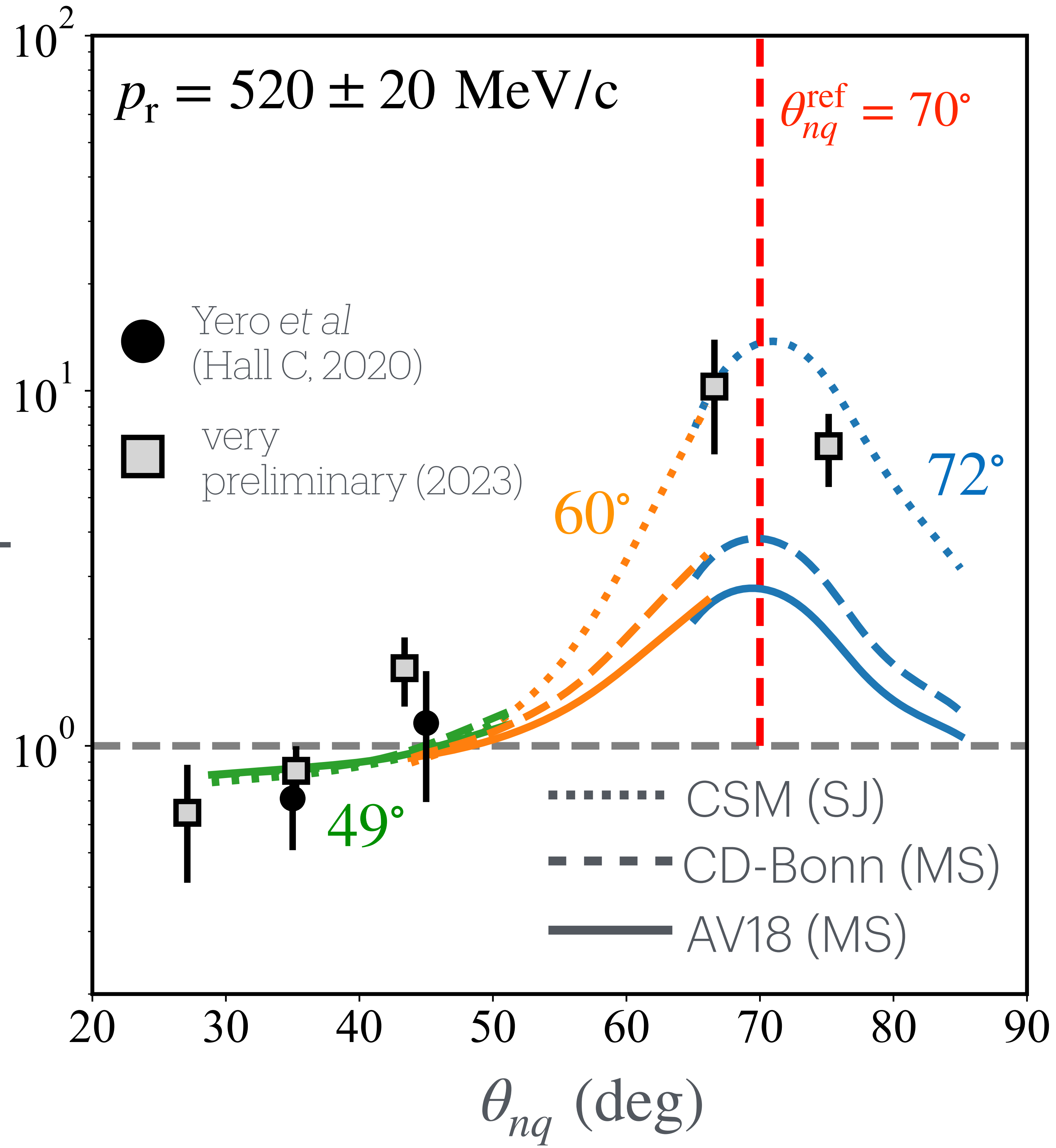
$$R = \frac{\sigma^{FSI}}{\sigma^{PWIA}}$$



Proposed Measurement

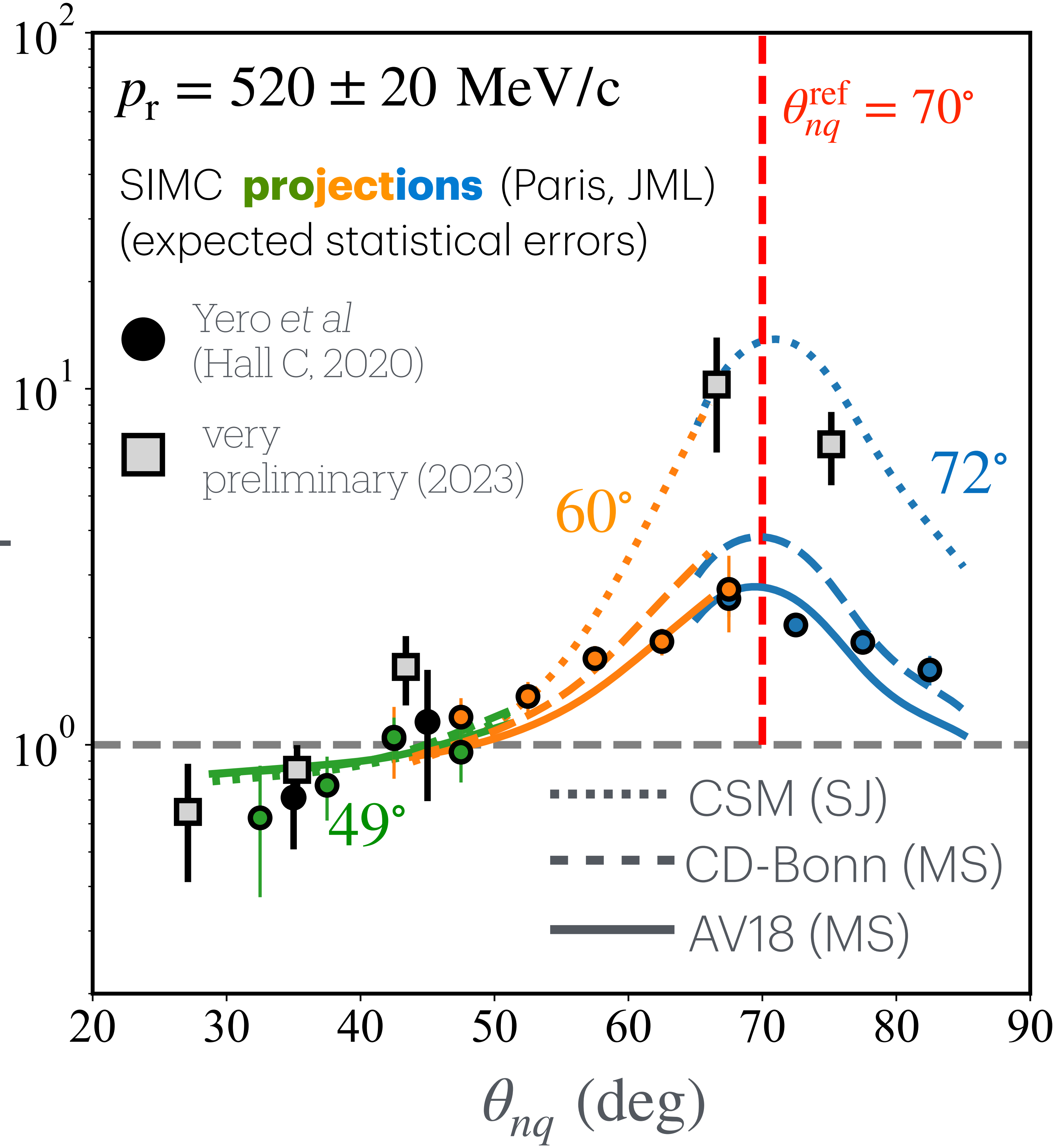
*

$$R = \frac{\sigma^{FSI}}{\sigma^{PWIA}}$$



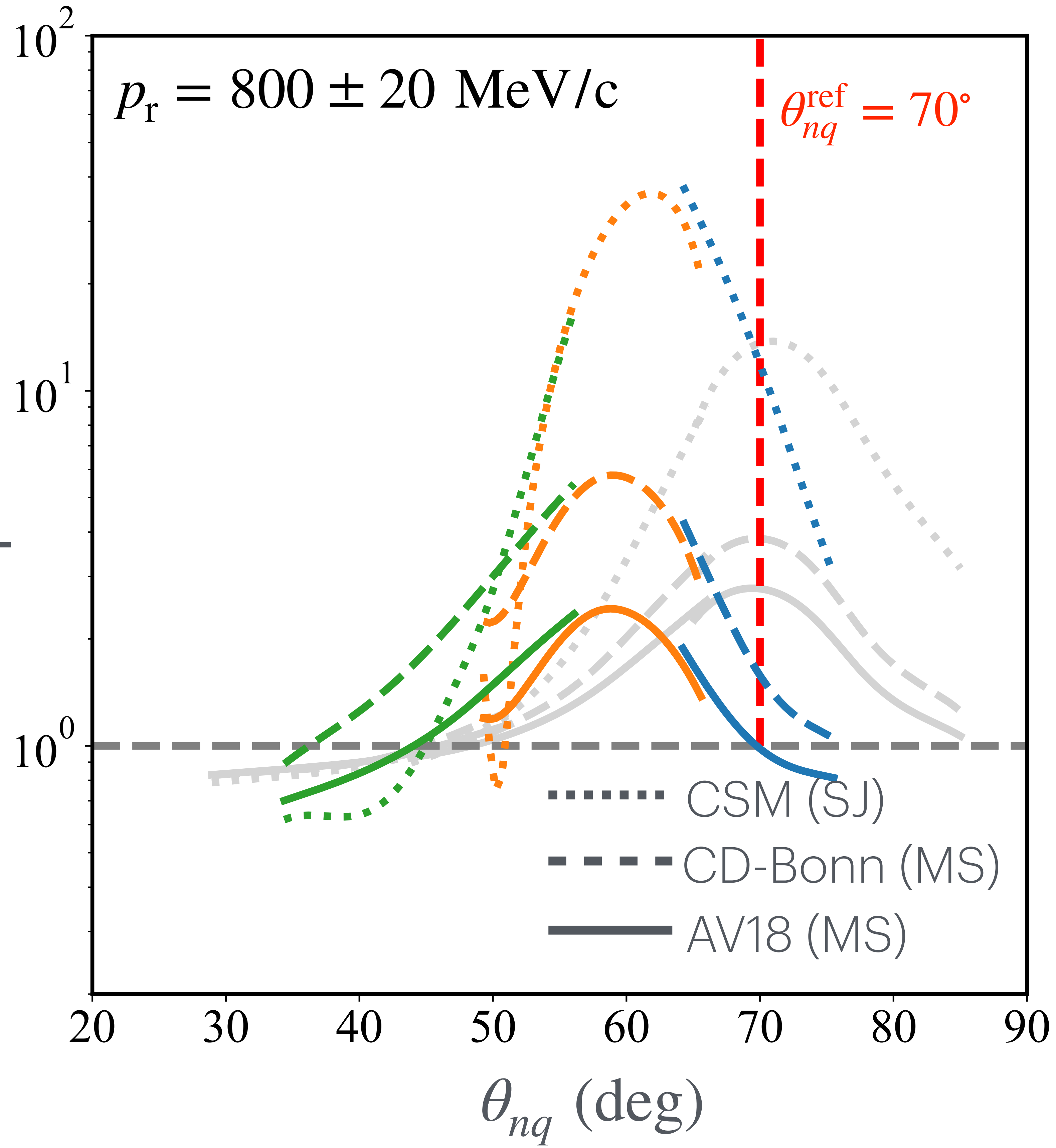
Proposed Measurement

$$R = \frac{\sigma^{FSI}}{\sigma^{PWIA}}$$



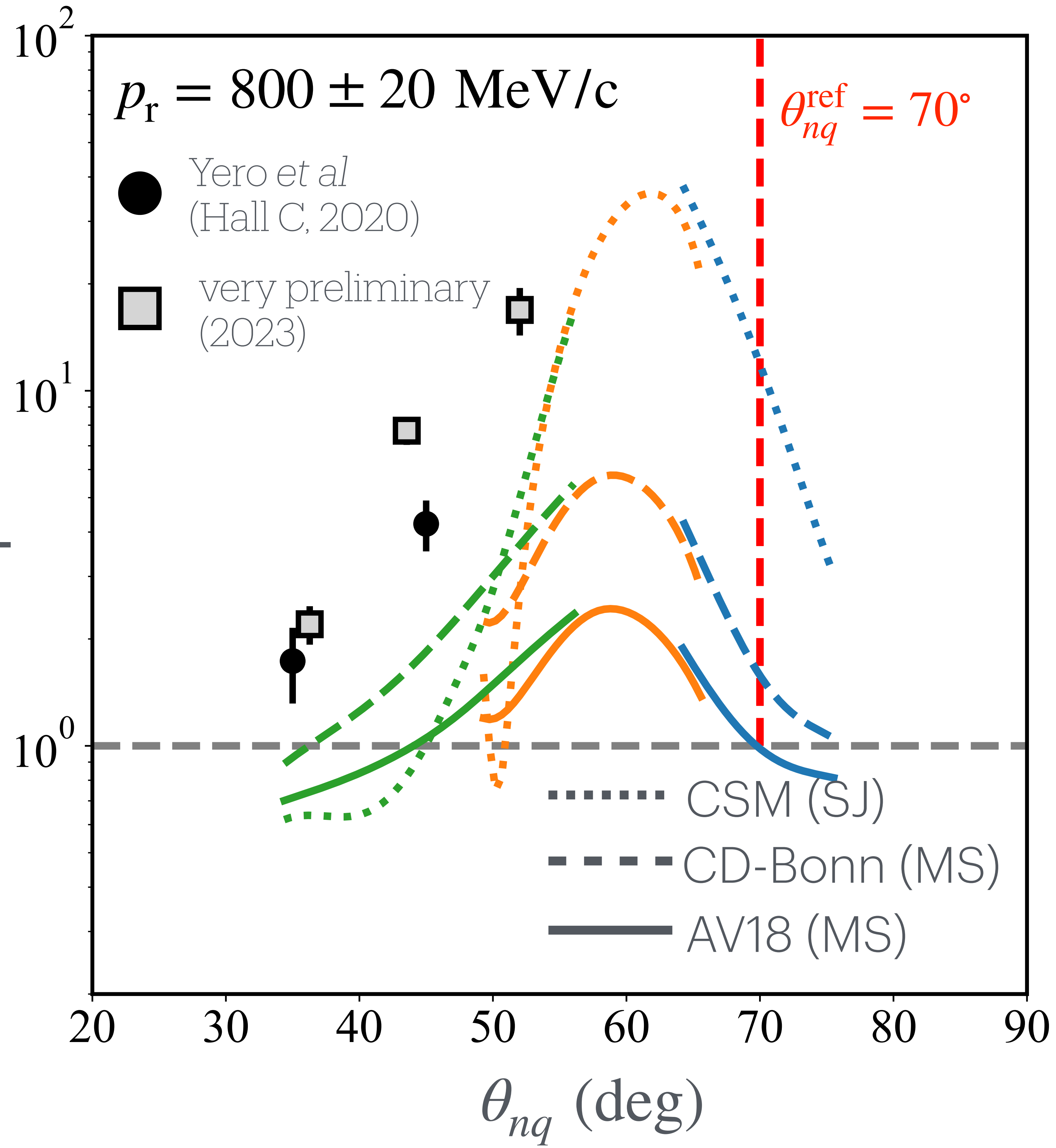
Proposed Measurement

$$R = \frac{\sigma^{FSI}}{\sigma^{PWIA}}$$



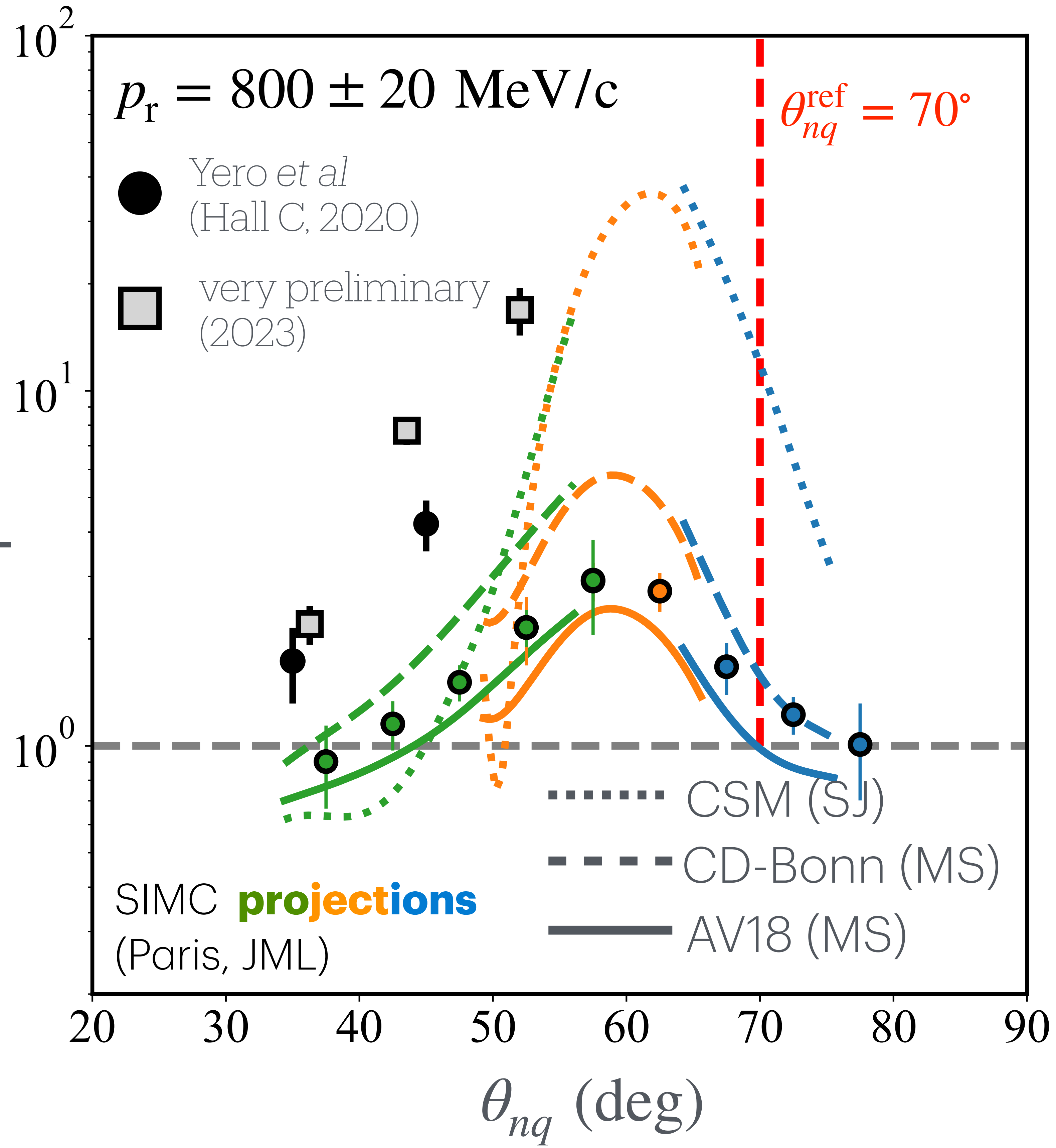
Proposed Measurement

$$R = \frac{\sigma^{FSI}}{\sigma^{PWIA}}$$



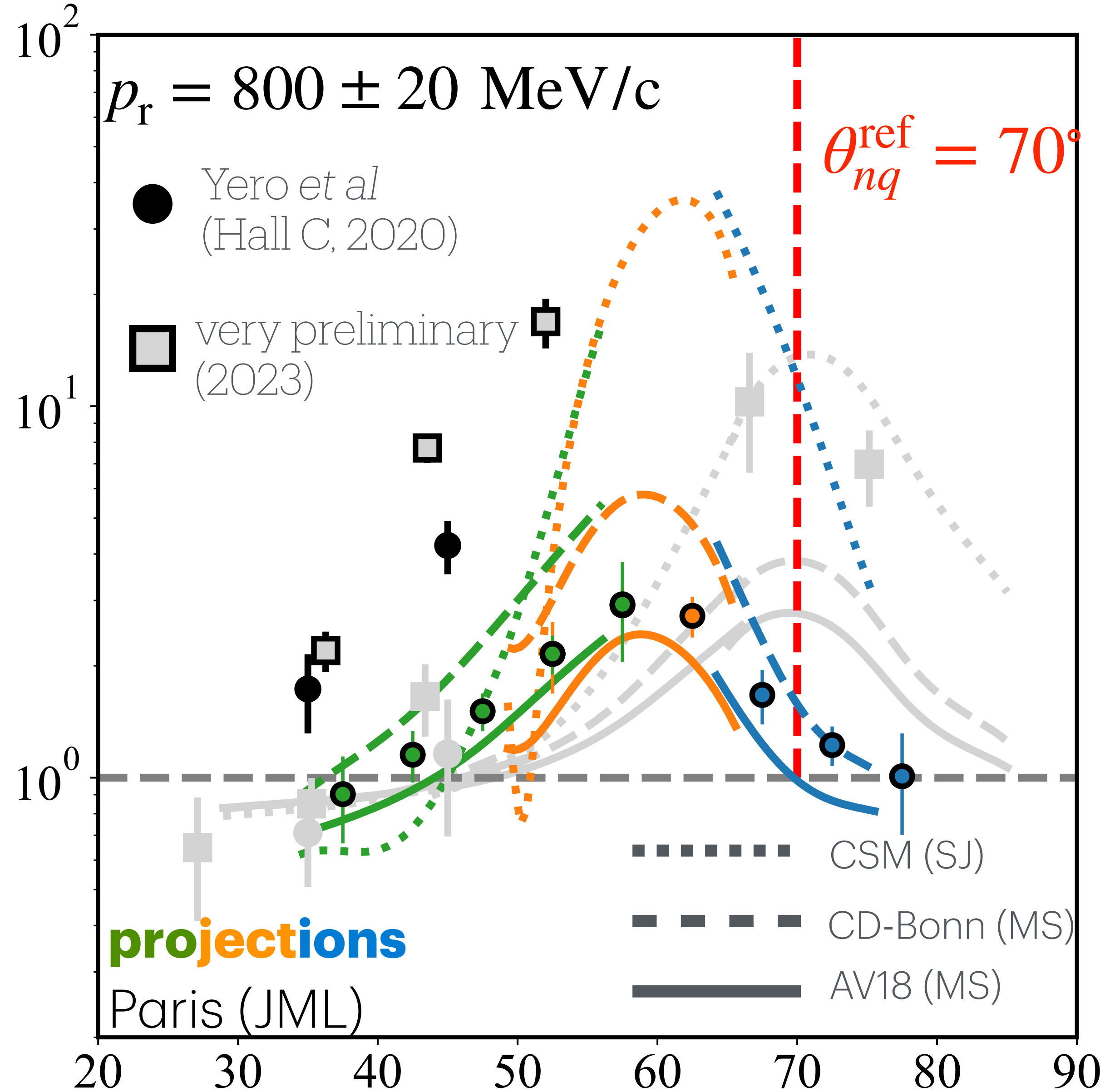
Proposed Measurement

$$R = \frac{\sigma^{FSI}}{\sigma^{PWIA}}$$



Proposed Measurement

$$\frac{\sigma_{FSI}}{\sigma_{PWIA}}$$

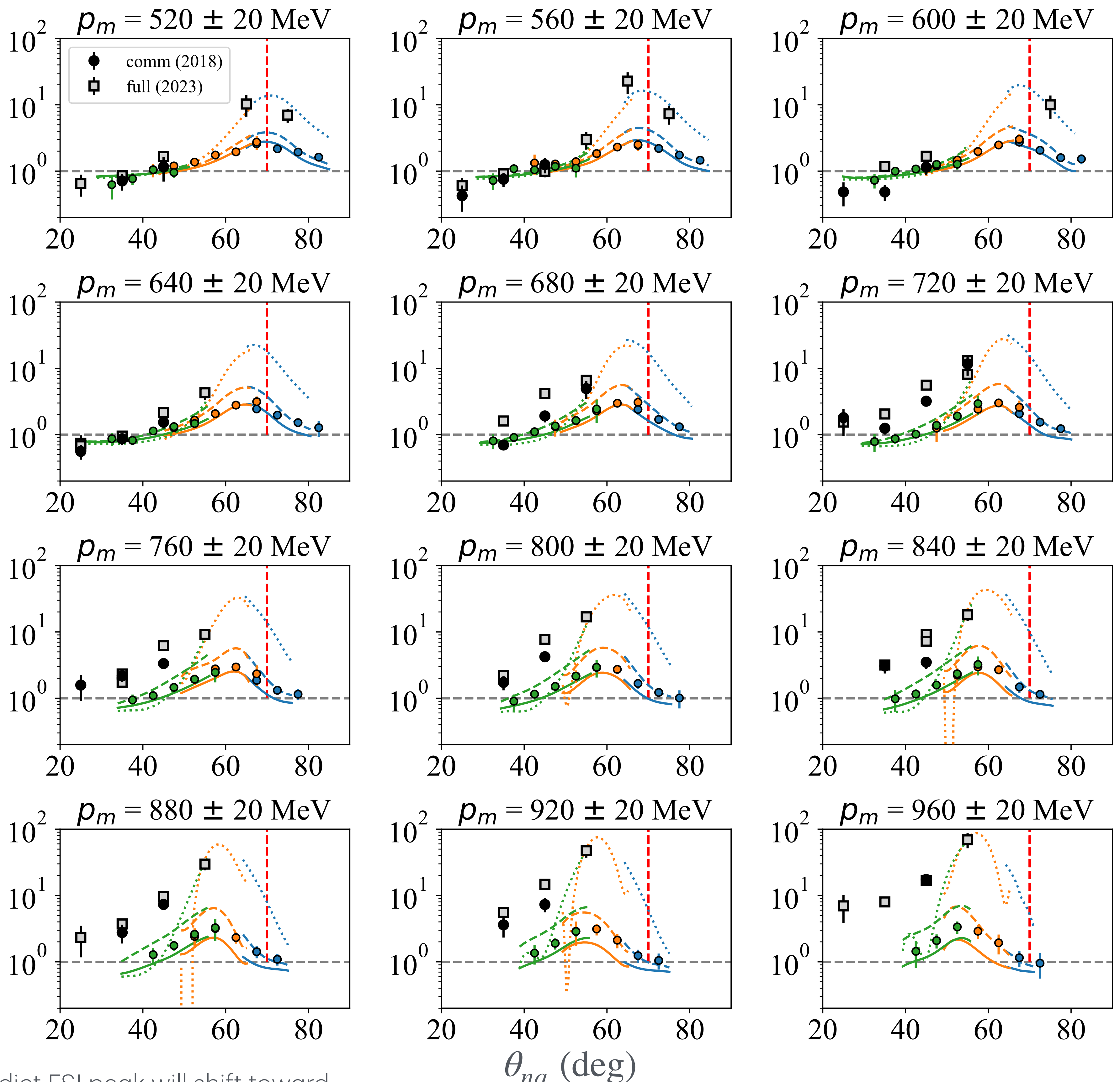


NEW proposed measurement will address the following:

- **check reliability** of FSI calculations above $p_r \sim 500$ MeV/c; (required for *NN* core studies) over the full angular range
- determine more precisely θ_{nq} region where FSI are negligible, e.g., FSI / PWIA ~ 1 and compare data vs relativistic momentum distributions at θ_{nq} where FSI / PWIA ~ 1

This Proposal: Projected Angular Distributions

$$R = \frac{\sigma^{FSI}}{\sigma^{PWIA}}$$



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: 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	
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		548 (23 PAC days)	8	**556 hrs**

We request a total of **556 hrs (23 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 **NOT** yet understood ; how to disentangle FSI + relativistic + non-nucleonic ? (measure θ_{nq} angular distributions at centered at ~800 MeV/c)
- light-front deuteron calculations (including FSI) are in progress (Sargsian)

test validity of FSI models:

(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.

Novelty of the proposed measurement:

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: Theory Part

Back-up: Difficulty of Probing the NN Core

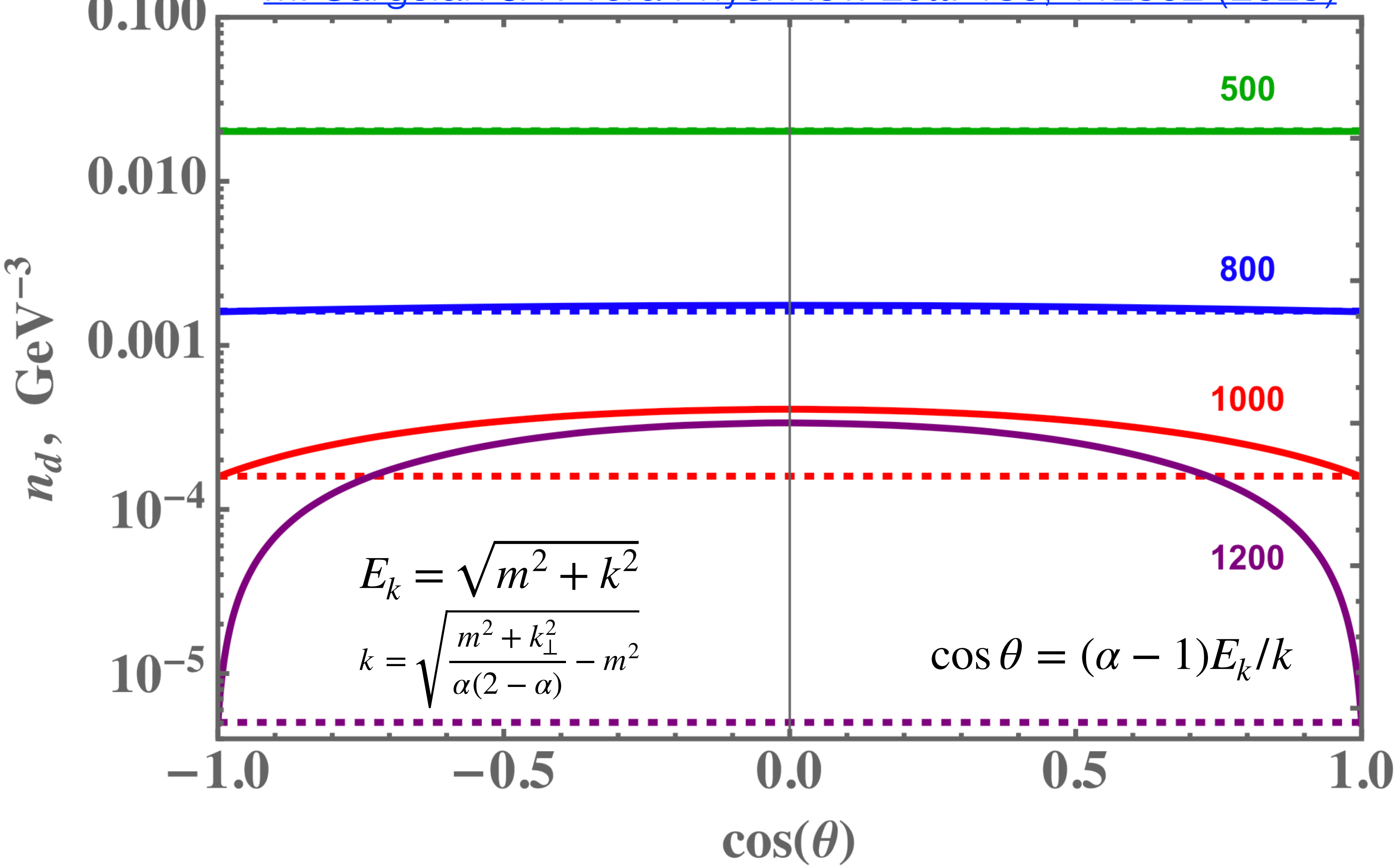
the nuclear core is responsible for the stability for atomic nuclei, without which the matter would collapse, however, since its introduction in the 1960's not much progress has been made

- 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)

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

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

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

where α is the proton light-cone momentum fraction

- In the light-front, if only Ψ_{pn}^{LC} 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. $\Psi_{np+\Delta\Delta'}^{LC}$ 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 $d \rightarrow N\bar{N}$ transition, then this approximation similar to the Gross approach in the relativistic description of the deuteron. However if one neglects $d \rightarrow N\bar{N}$ (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>

$$M_N = 0.938272$$

$$M_\pi = 0.139$$

$$M_\Delta = 1.232$$

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

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

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

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

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

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

($NN\pi$ 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.

Back-up: Experimental

Expected Systematic Uncertainties

Normalization

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

total normalization: $\lesssim$ 4 %

Kinematic

point-to-point uncertainty on:

- beam energy
- spectrometer angles/momentum

total kinematic: $\lesssim$ 6.5 %

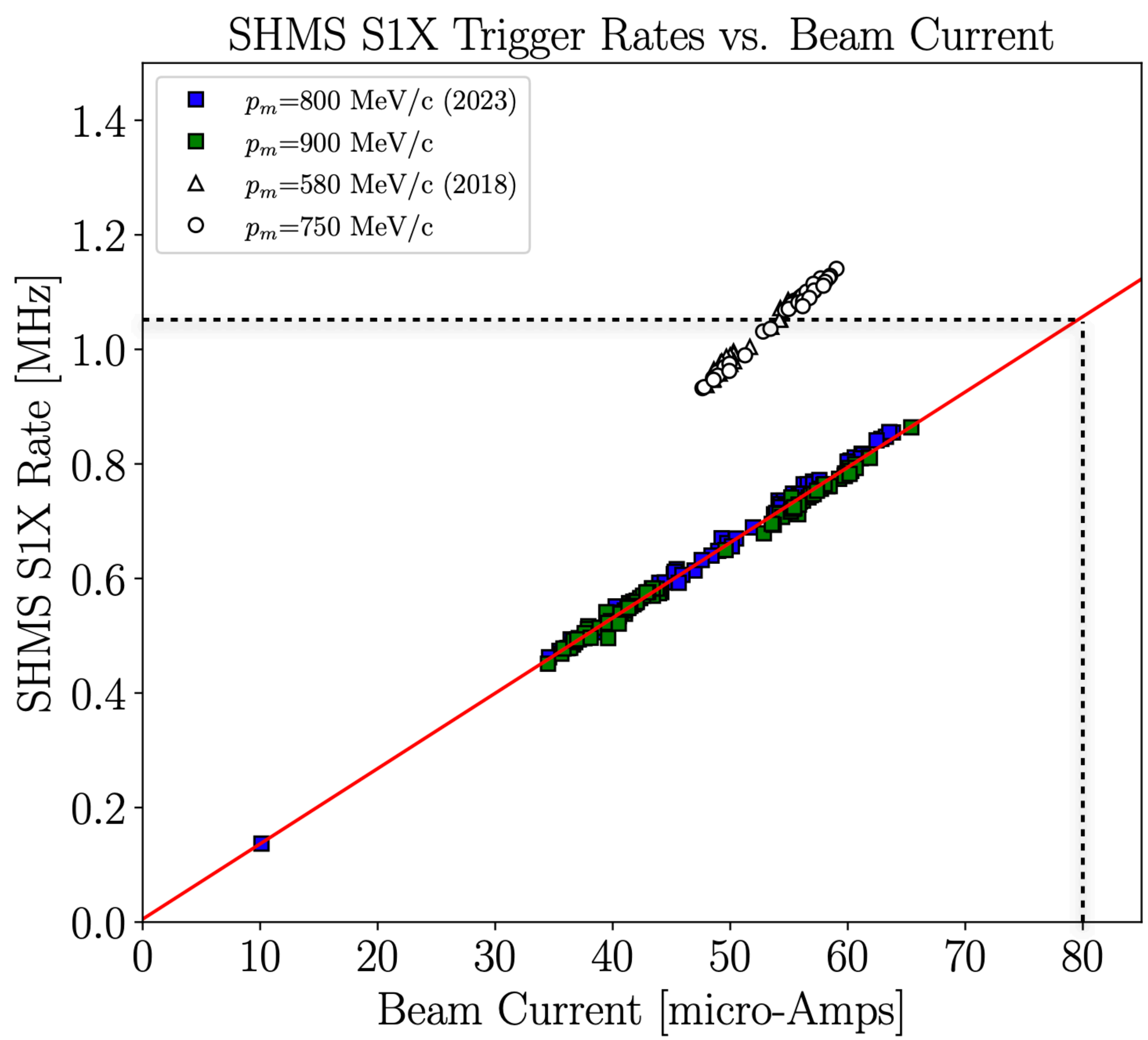
Total Systematic Uncertainty : ~ 7.6 %
(added in quadrature)

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

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

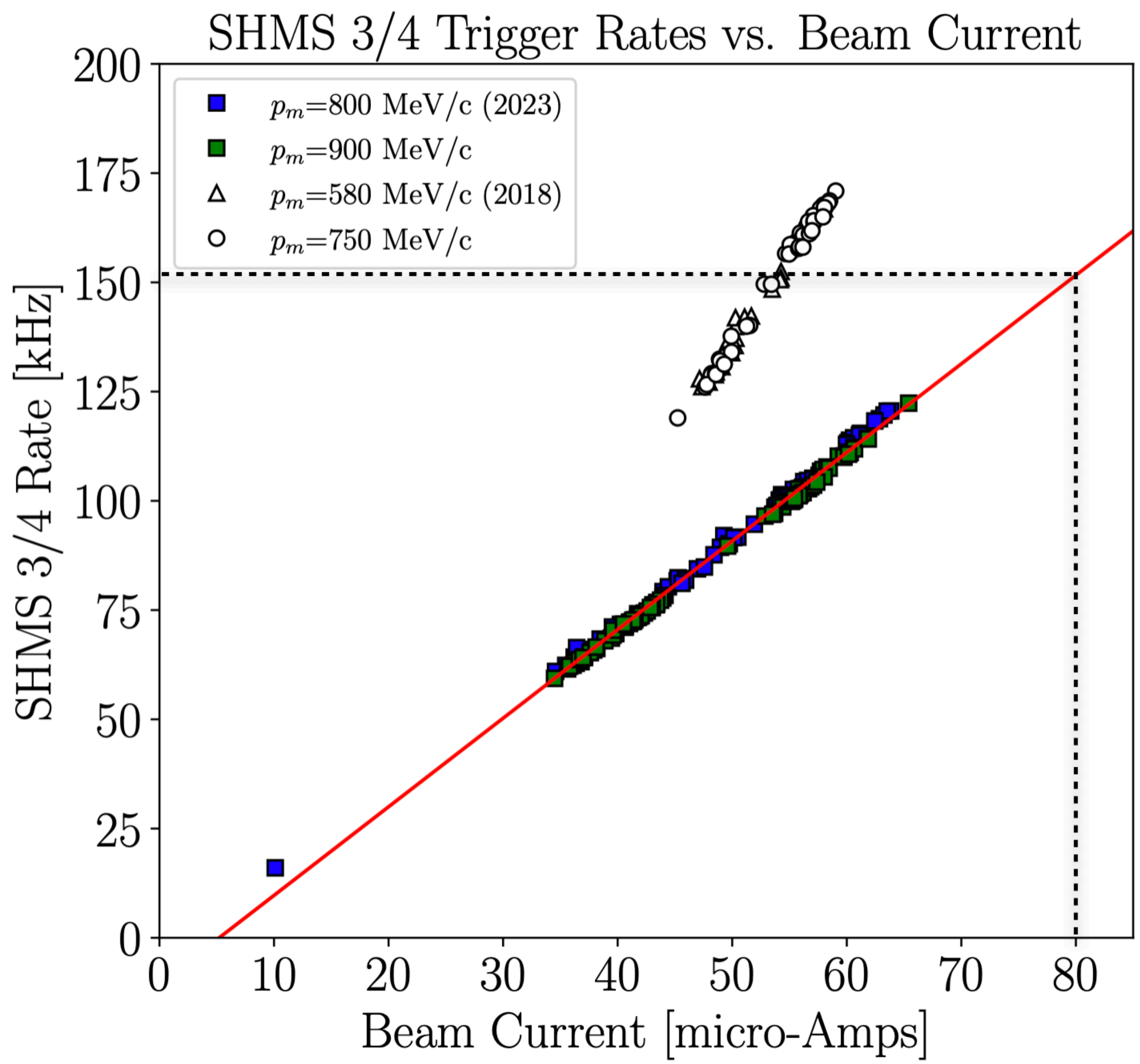
Phys. Rev. Lett. **125**, 262501 (2020)

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).

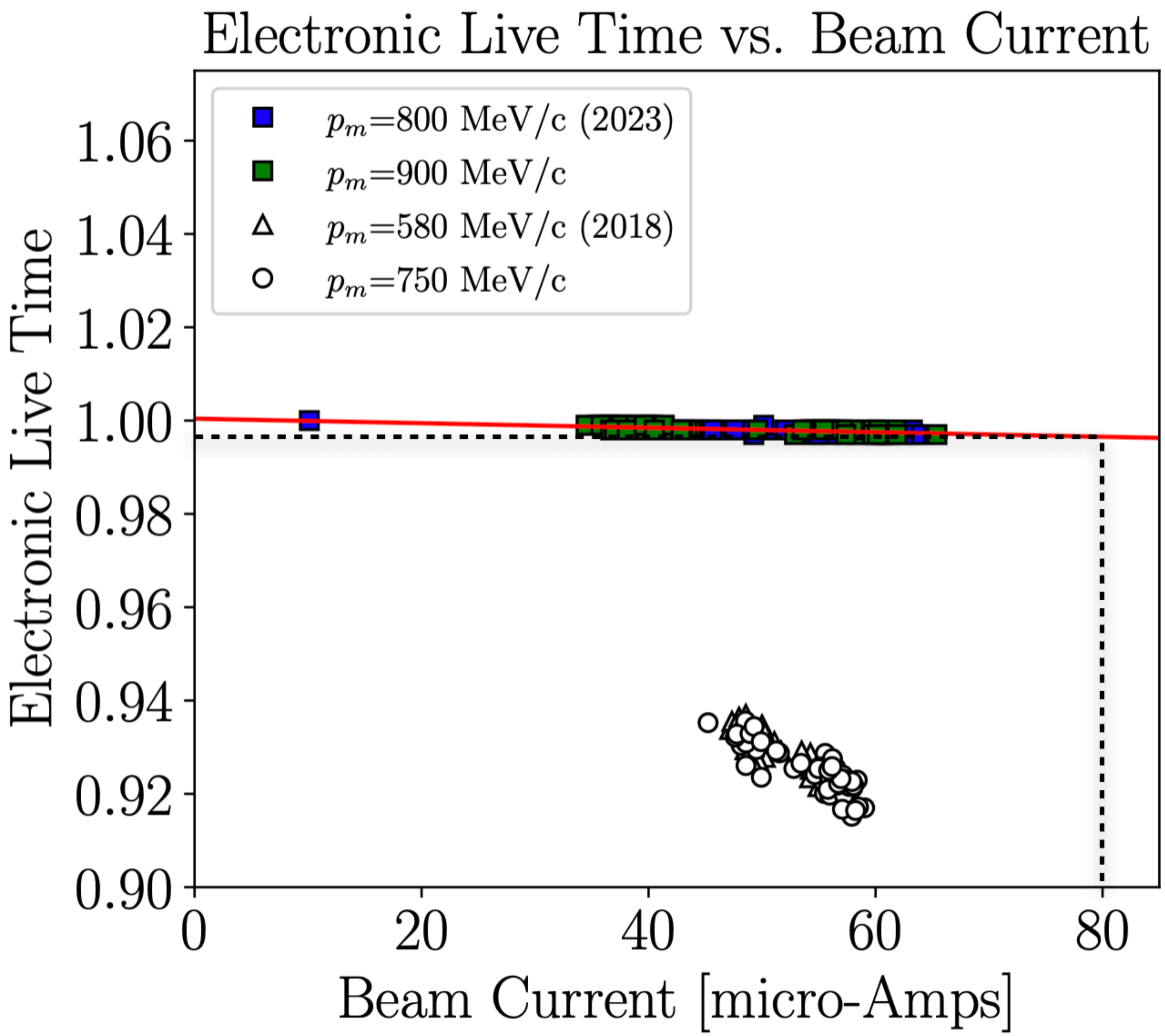
Experimental Expectations



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.

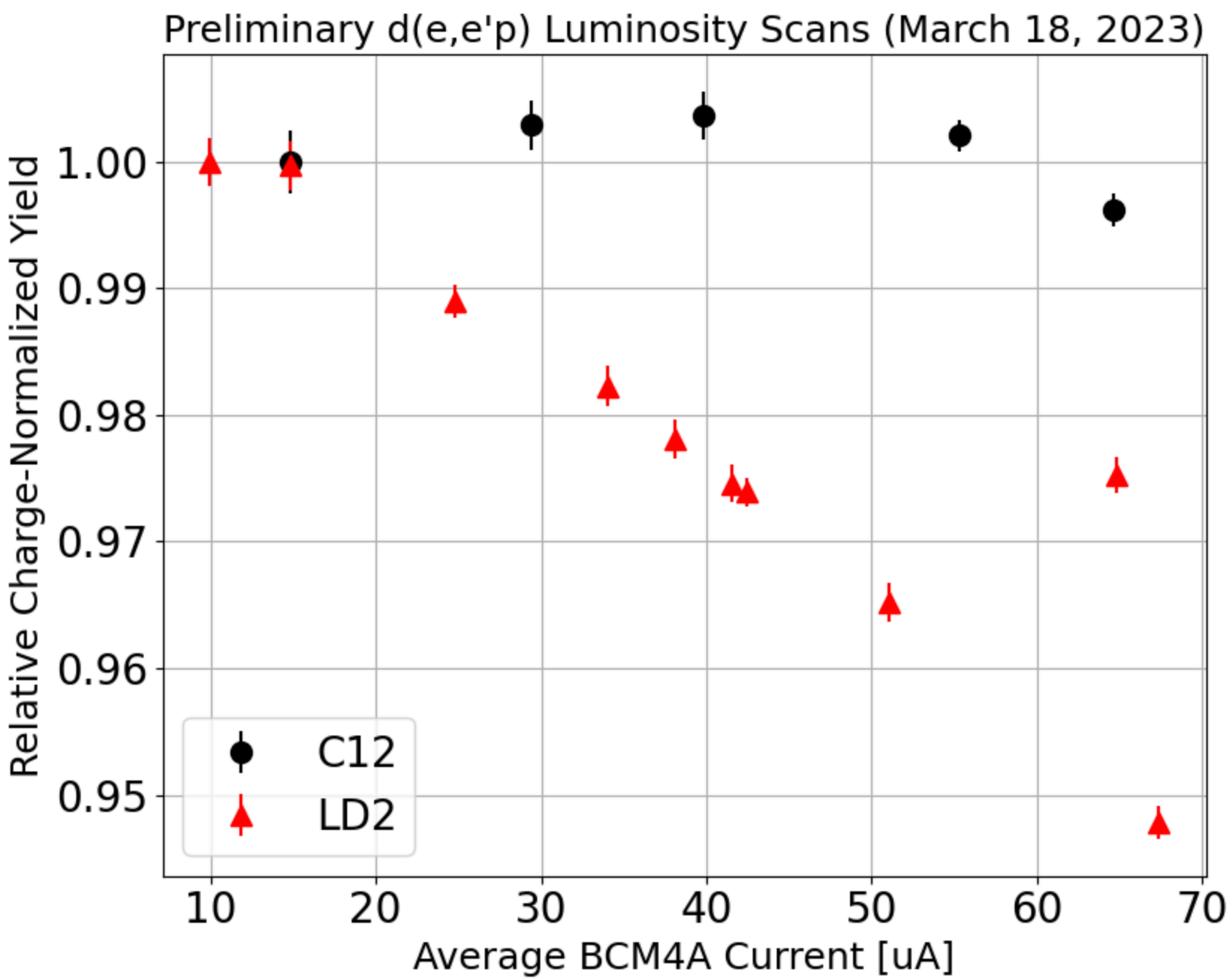
Experimental Expectations



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

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

Experimental Expectations



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

This Proposal: Projected Uncertainties (Statistical)