

# Probing the Nuclear Repulsive Core Using Deuterium

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June 10, 2026

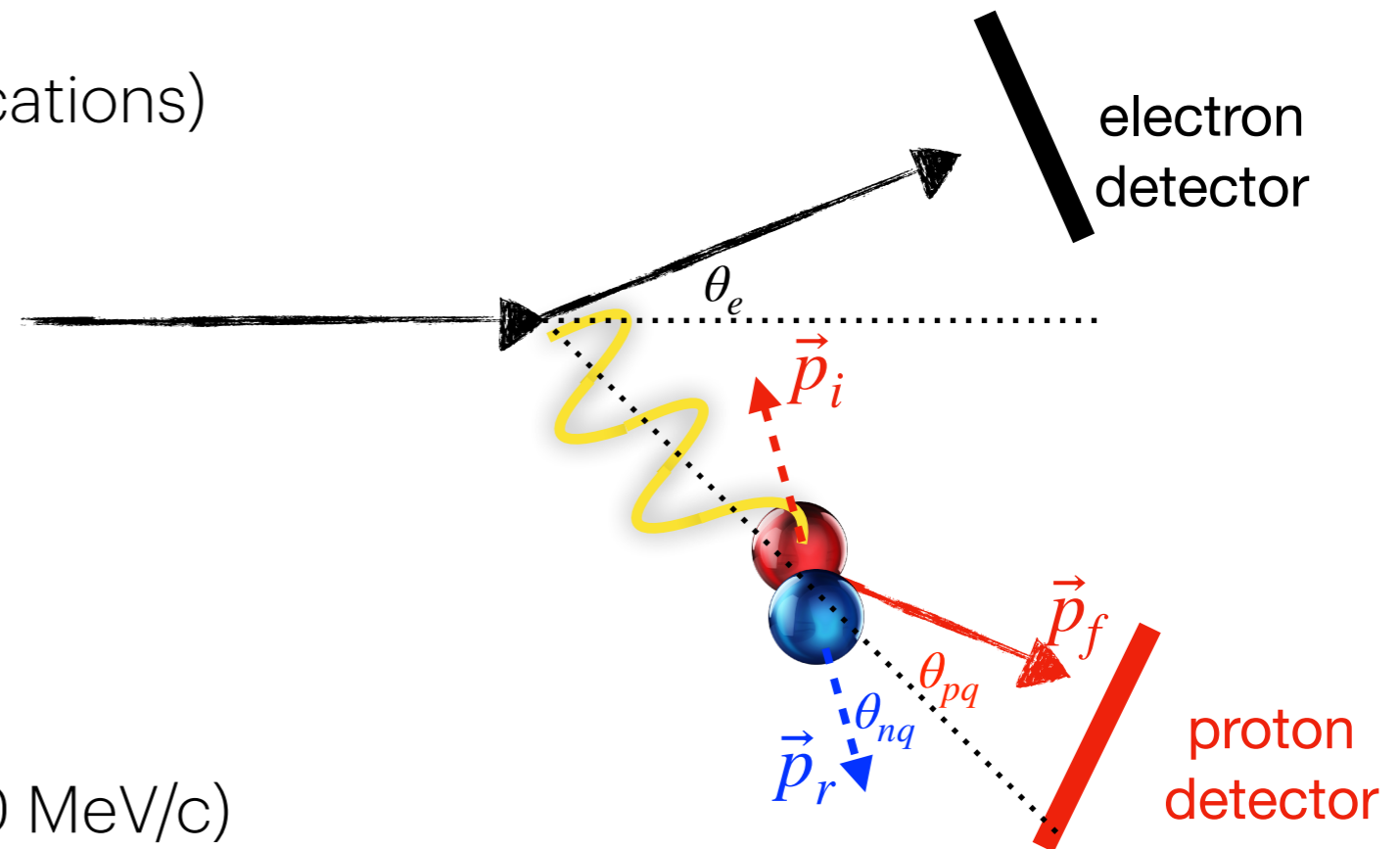
**5th International Workshop on Quantitative Challenges in  
SRC & EMC-Effect Research**

**Lawrence Berkeley National Laboratory, California  
8 - 12 June 2026**

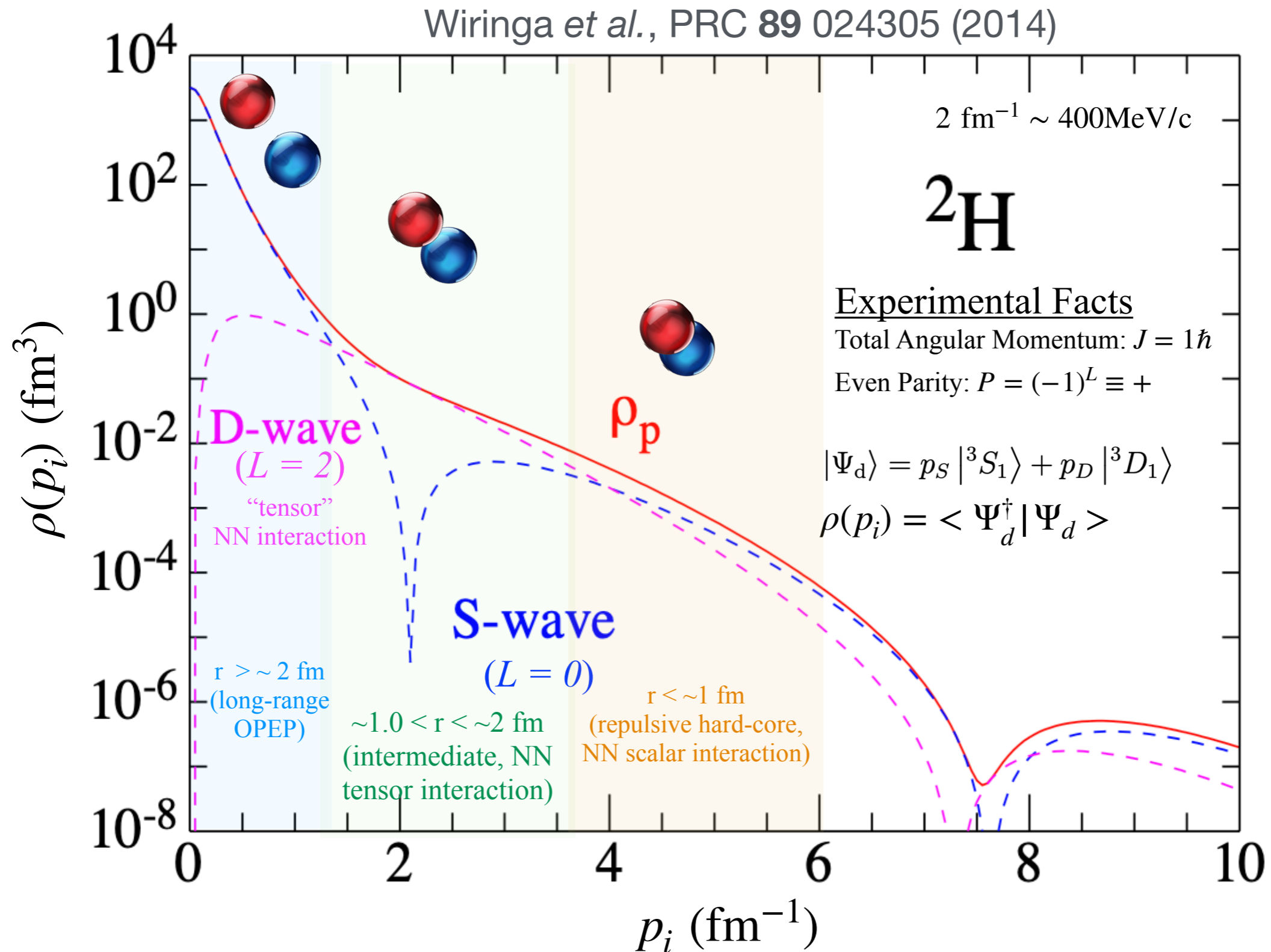
# Why Study the Deuteron ?

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

- most simple  $np$  bound system  
(no  $3N$  forces or additional complications)
- foundation for short-range correlations in heavier nuclei  
( $np$ -dominance, scaling in  $A > 2$ )
- reliable FSI calculations (up to  $\sim 550$  MeV/c)  
compared to heavier nuclei

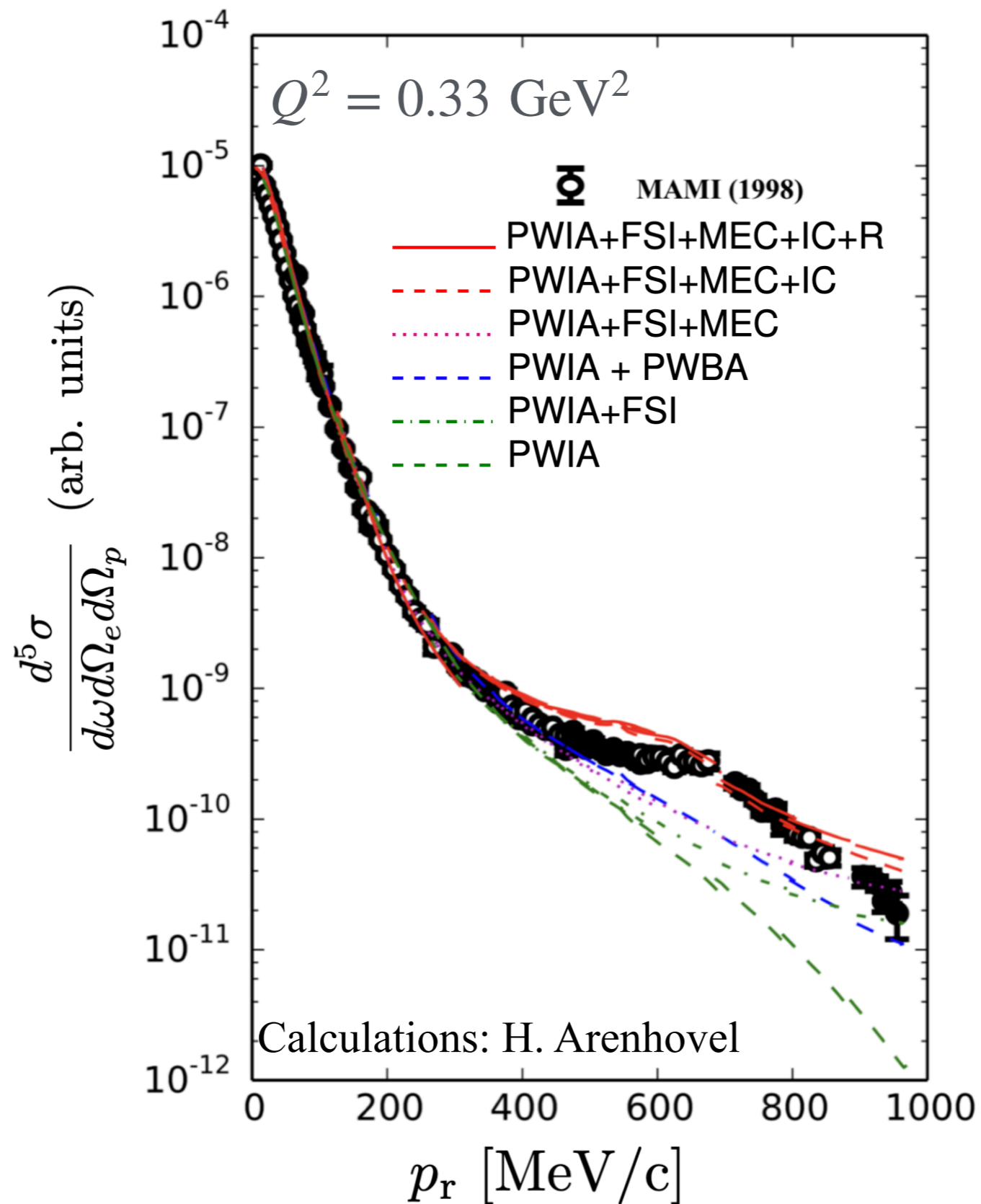


# Momentum Distribution



# Experimental Cross Sections

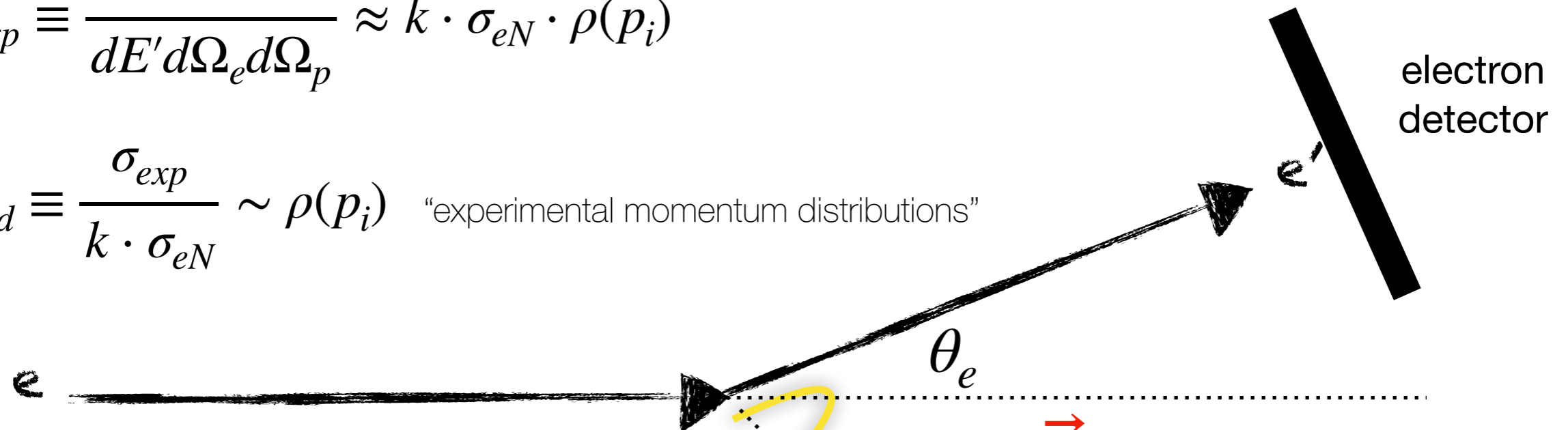
Blomqvist, Boeglin *et al.*, PLB **424** 33 (1998)



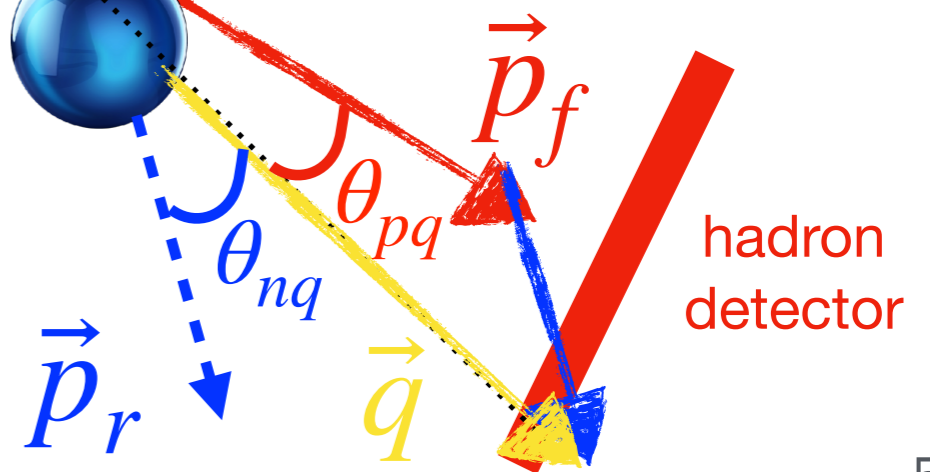
# Probing High-Momentum Structure

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

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



- 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

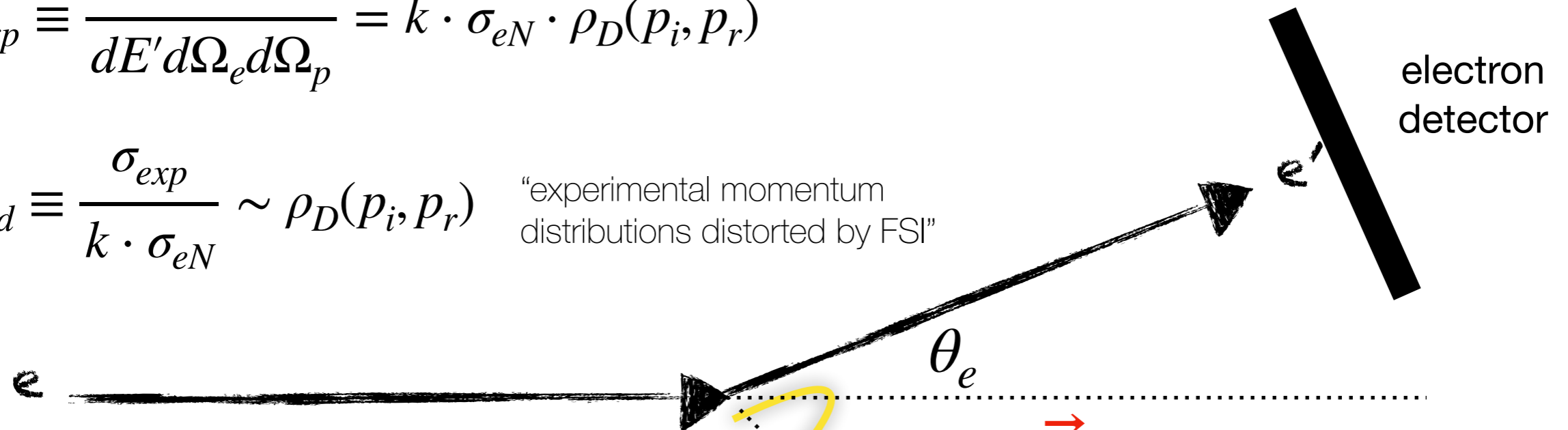


# Probing High-Momentum Structure

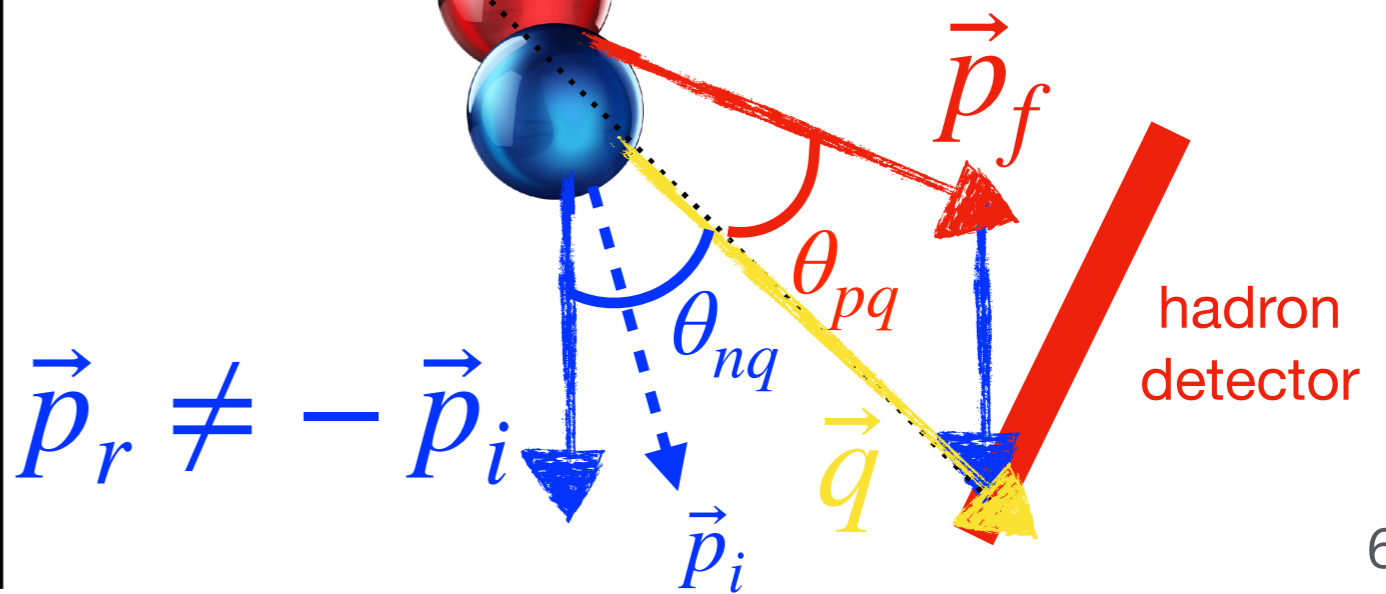
$$\sigma_{exp} \equiv \frac{d^5\sigma}{dE' d\Omega_e d\Omega_p} = k \cdot \sigma_{eN} \cdot \rho_D(p_i, p_r)$$

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

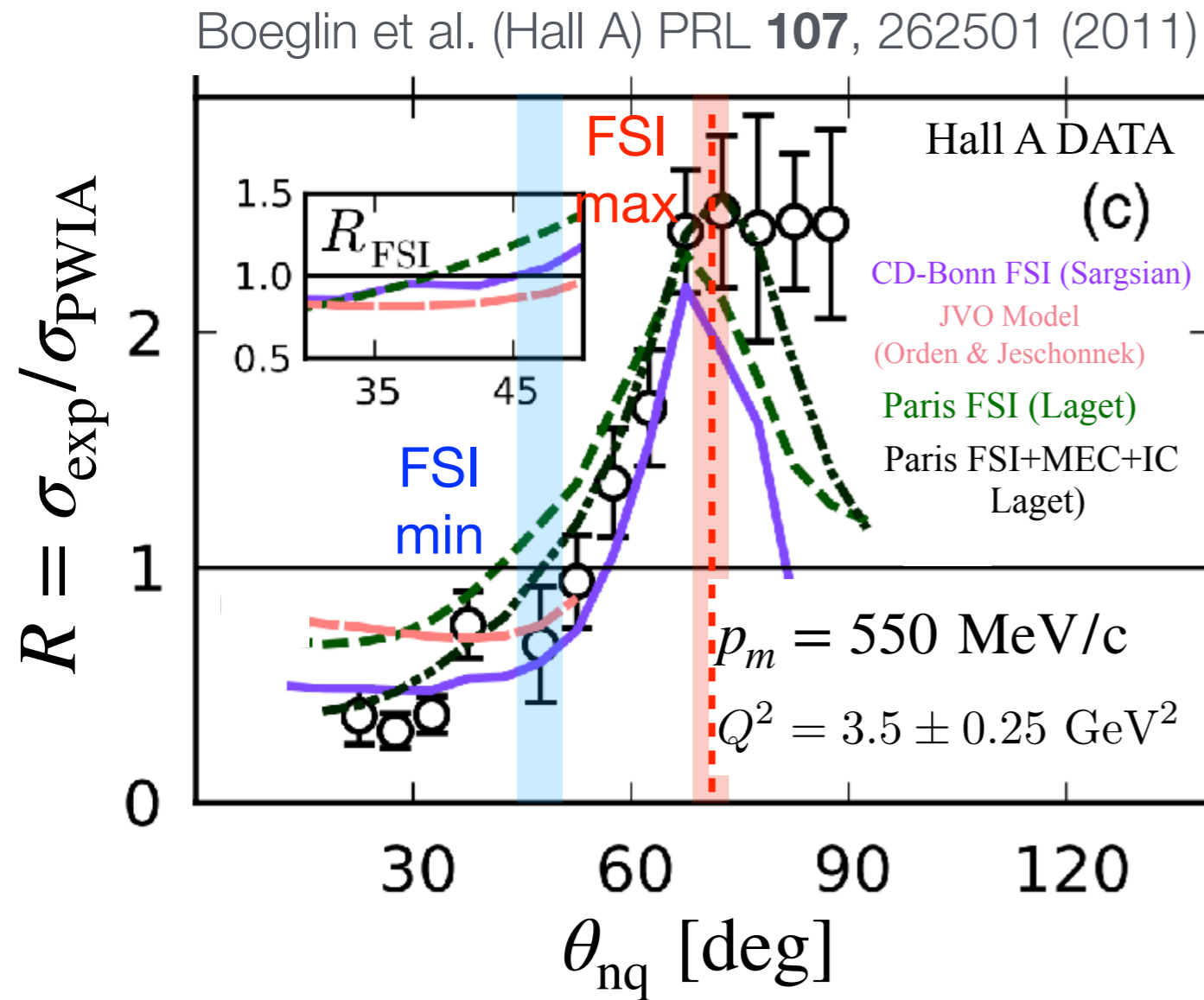
"experimental momentum distributions distorted by FSI"



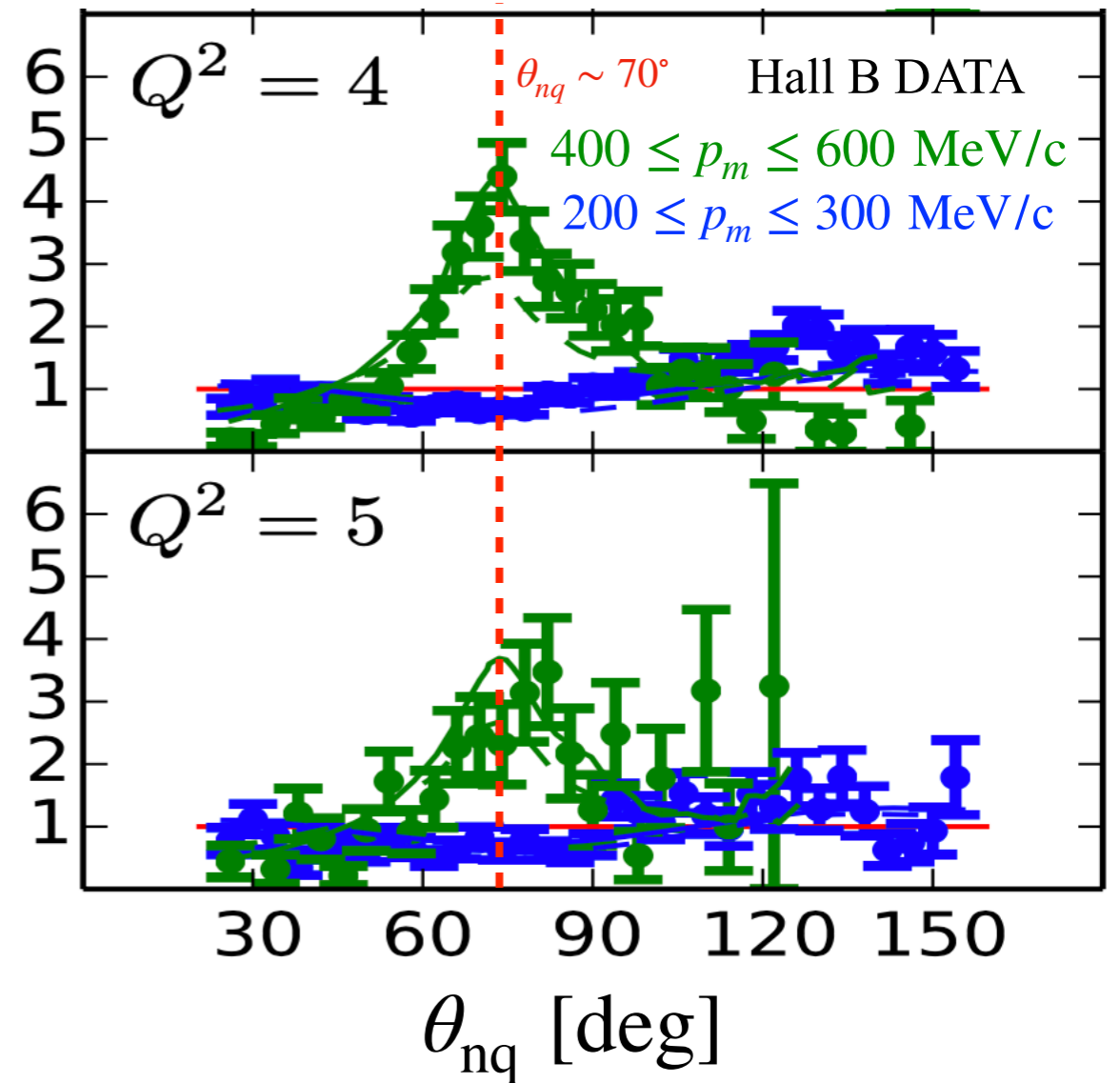
- Final-state interactions (FSI):
  - ▶ recoil nucleon re-interacts with knocked-out nucleon
  - ▶ recoil momentum modified,  $\vec{p}_r \neq -\vec{p}_i$
  - ▶  $\vec{p}_r$  cannot be used to access internal nucleon momentum distributions



# Controlling Final-State Interactions



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



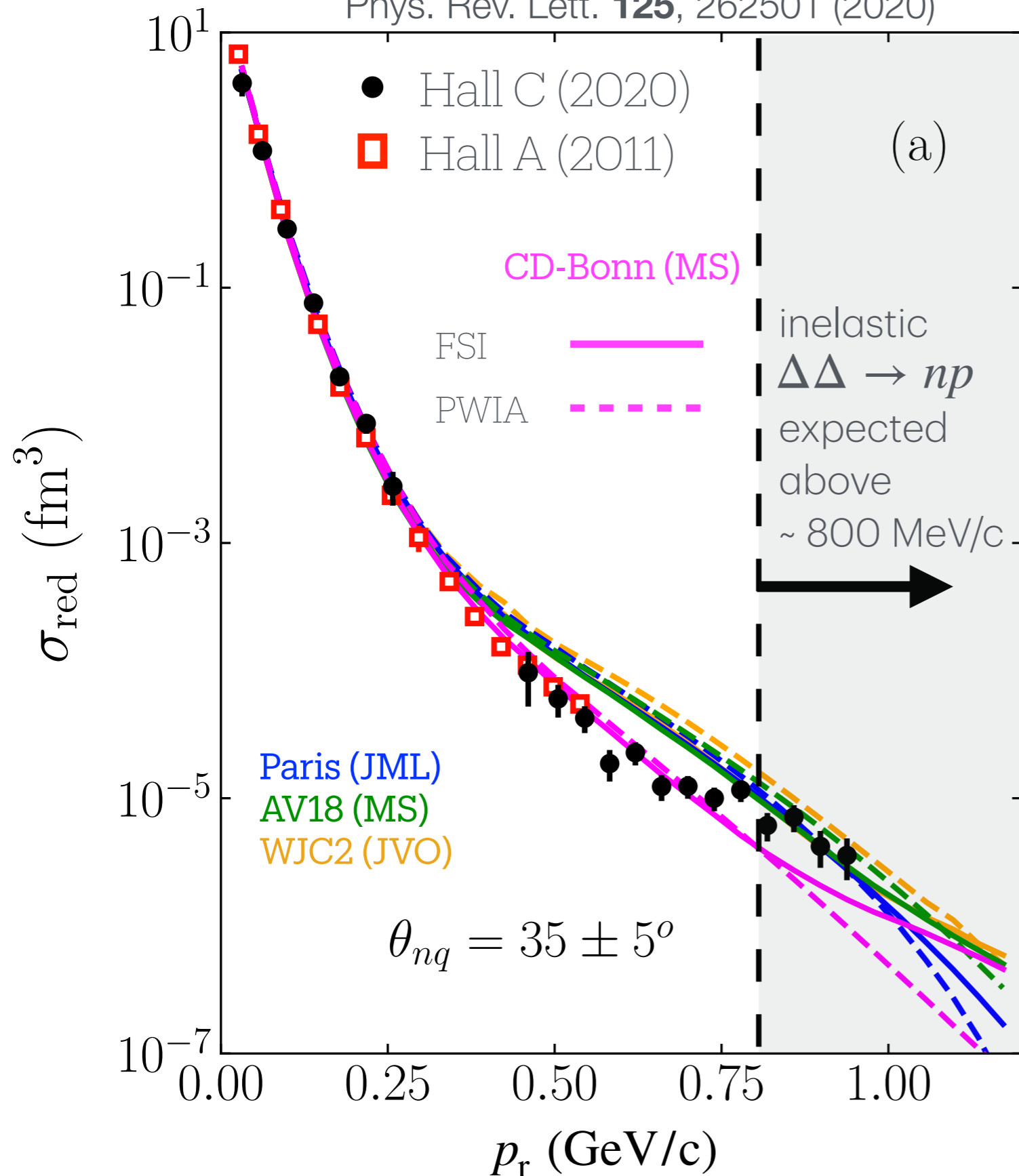
Phys. Rev. B **609**, 49 (Laget 2005)

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)

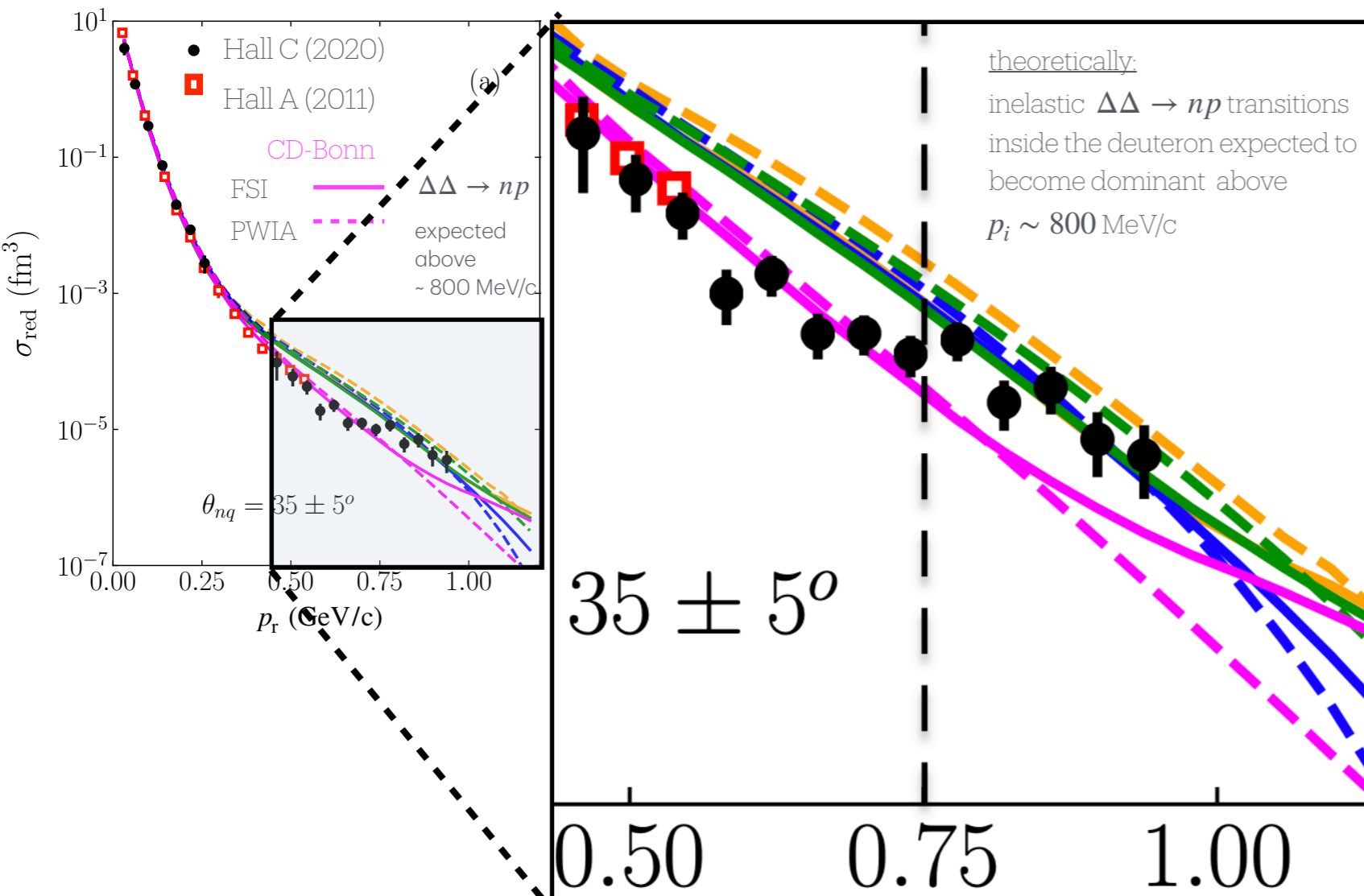


Virtual Nucleon Approximation (VNA)  
 Theoretical Framework (Sargsian 2010)

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

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

# Probing the NN Repulsive Core



**NO** theory calculation reproduces data trend above  $\sim 750 \text{ MeV/c}$

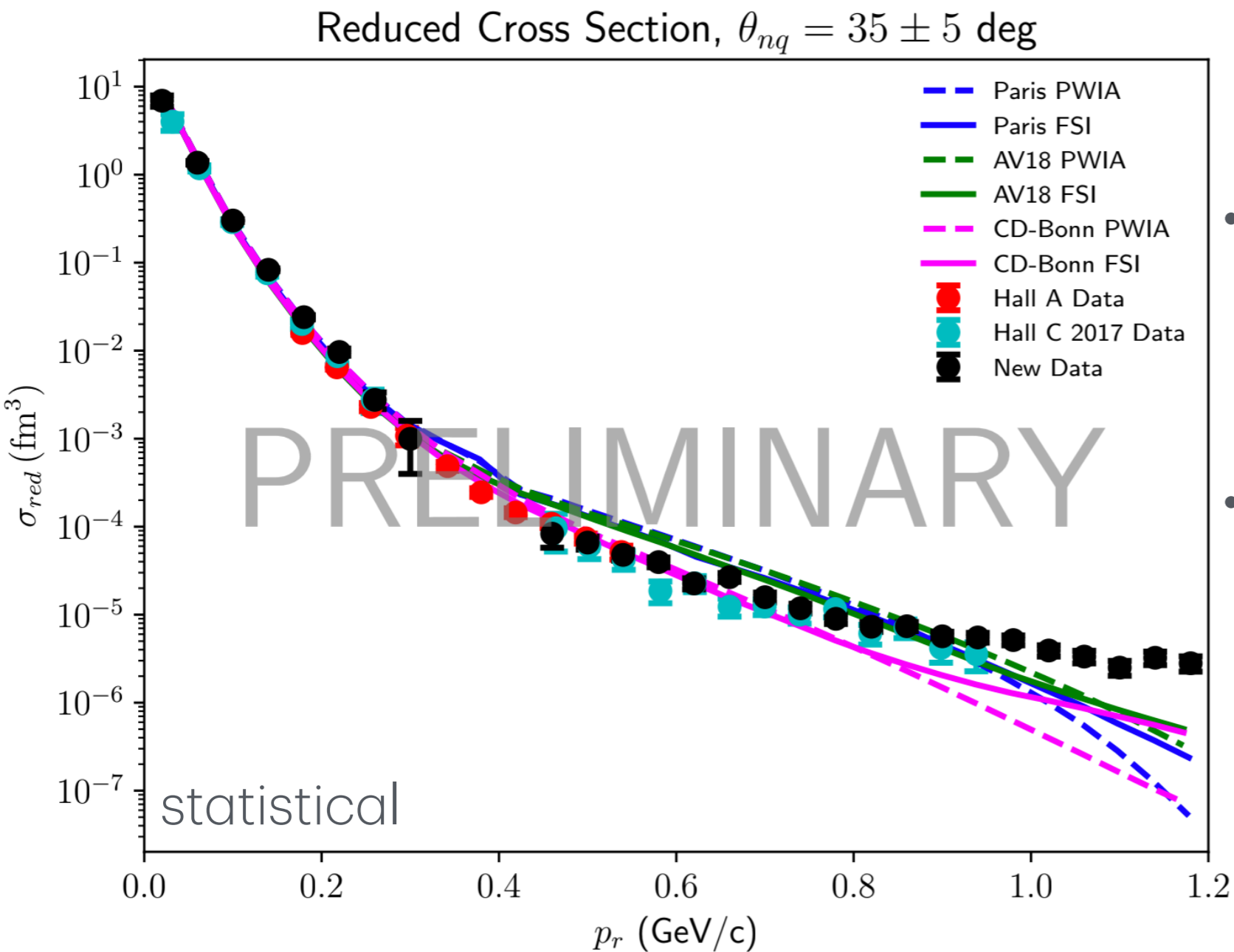
“anomaly” in data starts very close to the threshold of non-nucleonic transitions ( $\sim 800 \text{ MeV/c}$ ) of the NN system

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

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

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

# Very Preliminary Results of $d(e, e'p)n$ (completed in 2023)



- full experiment completed in 2023, extends up to missing momenta  $\sim 1.2$  GeV

- on-going analysis by graduate students:

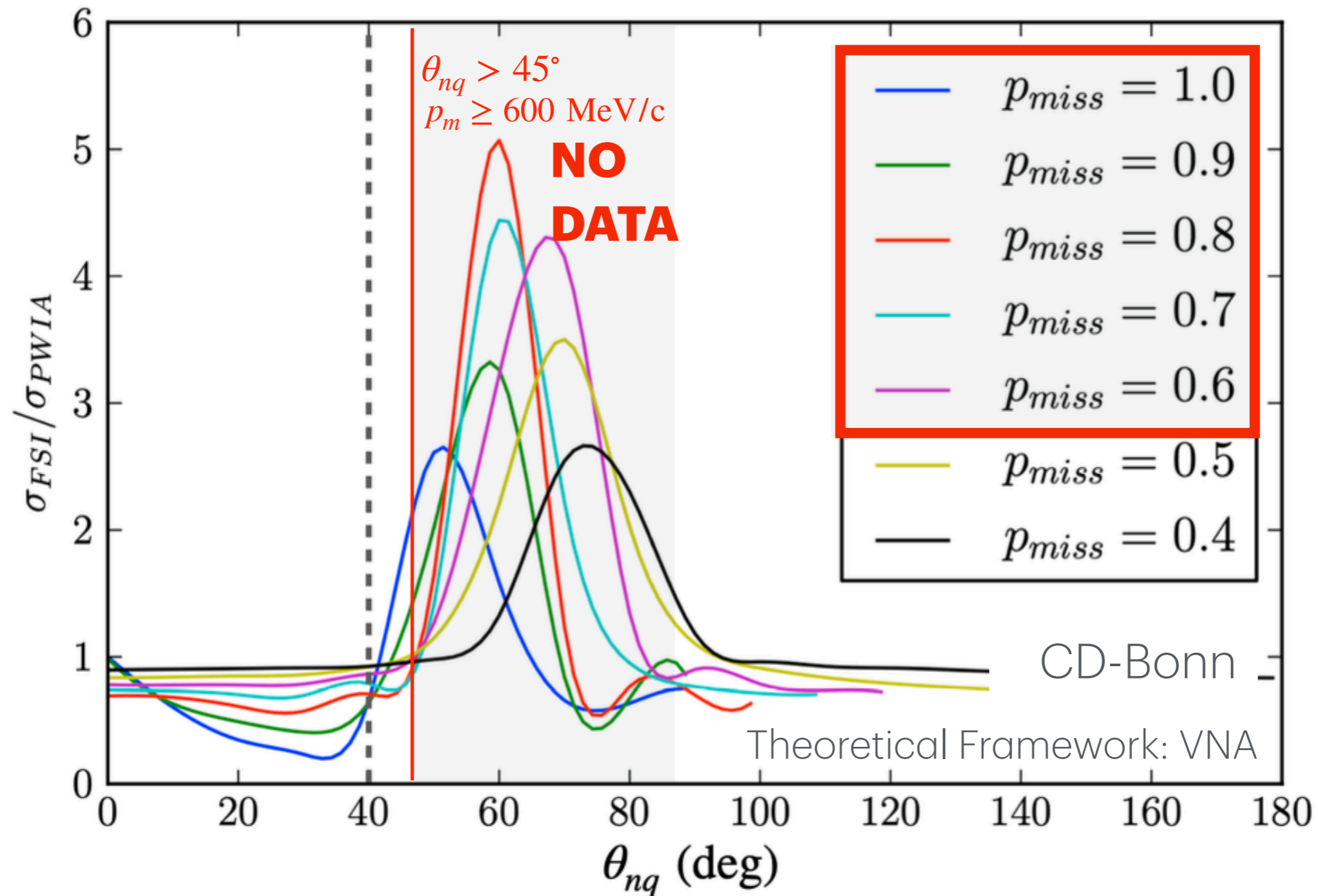
- ▶ Pramila Pokhrel (CUA)

- ▶ Gema Villegas (FIU)

Plot Courtesy of Gema Villegas

# NN Repulsive Core Sensitivity to FSI

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

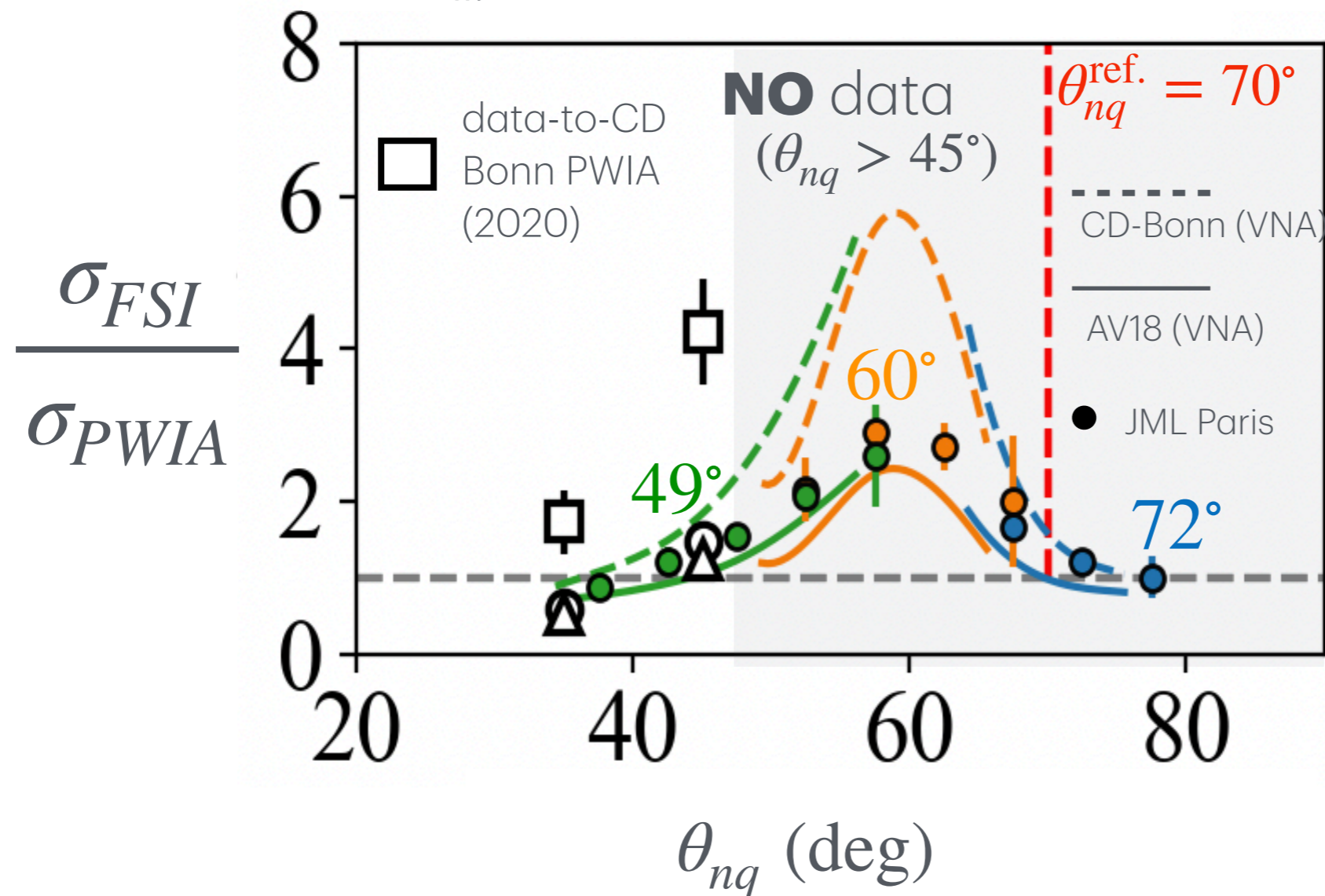


\*GEA predict FSI peak shifts towards lower  $\theta_{nq}$  with increasing  $p_m$

\*generalized eikonal approximation: relativistic theoretical framework for FSI calculations

# Proposed Measurement

$$P_m = 800 \text{ MeV}/c, Q^2 = 4.5 \text{ GeV}^2$$

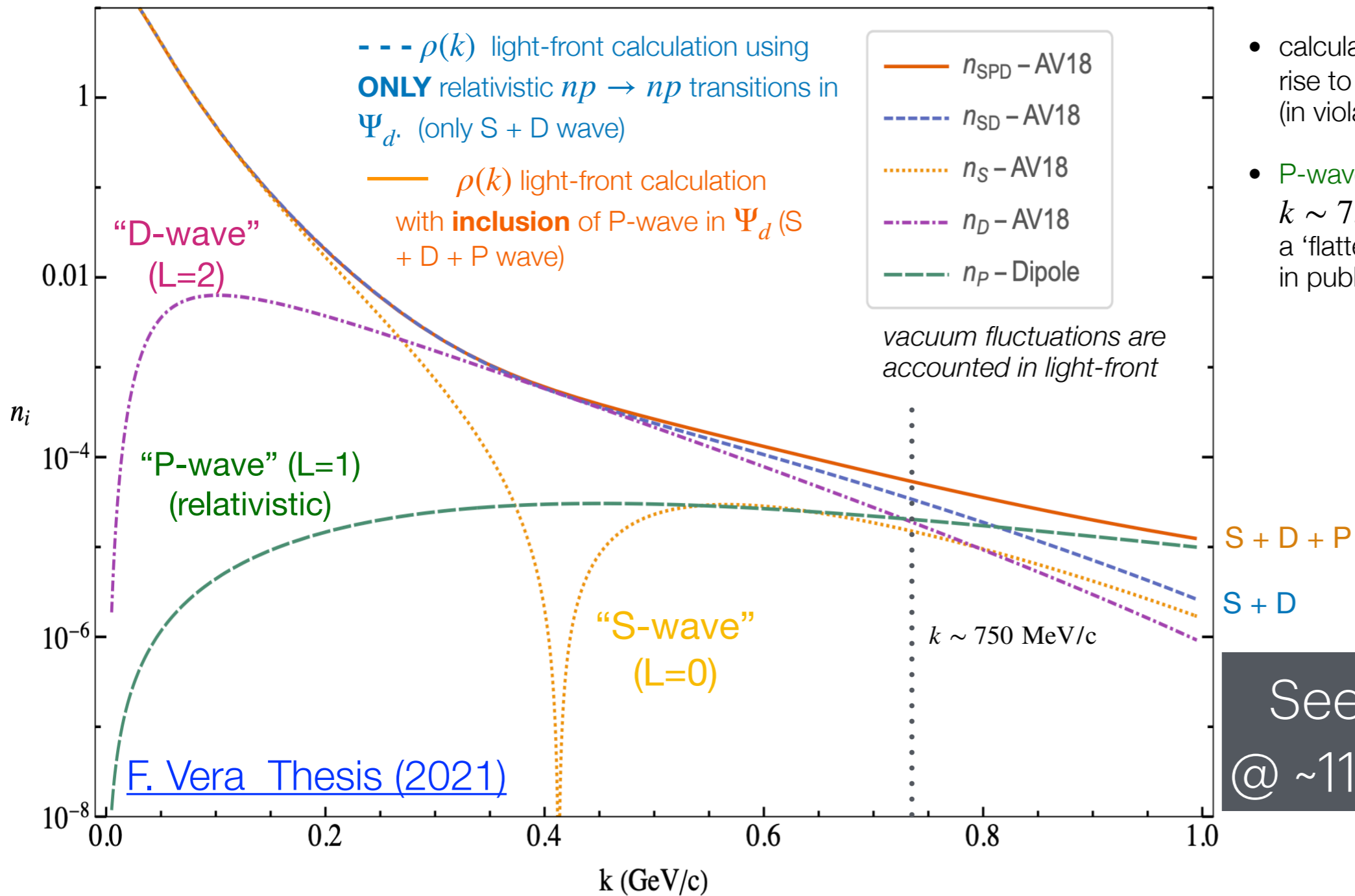


## NEW proposed measurement will address the following:

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

# Deuteron on the Light-Front

1-Body Momentum Distribution for Deuteron's  $\langle pn \rangle$  component – Includes: S, D, and P waves



- calculation of  $\Psi_d$  in the light-front give rise to a 'P-wave' -like component (in violation of angular condition)
- P-wave starts to dominate at  $k \sim 750 \text{ MeV}/c$ , characterized by a 'flattening trend' also observed in published data [Yero et al. 2020](#)

See Misak's Talk @ ~11:15 am today !

[M. Sargsian & F. Vera Phys. Rev. Lett. 130, 112502 \(2023\)](#)

relativistic (np)      relativistic (non-nucleonic)

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

# Conclusion and Outlook

- deuteron w.f. ( $\Psi_d$ ) well-understood up to  $\sim 550$  MeV / c (Boeglin 2011)
- anomaly observed in high-momentum component ( $\geq \sim 750$  MeV/c ) is **NOT** yet understood ; how to disentangle FSI + relativistic + non-nucleonic ? (measure  $\theta_{nq}$  angular distributions at centered at  $\sim 800$  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 ( $\theta_{nq}$ ) with increasing  $p_m$  as predicted by theory ?

(ii) will the deuteron  $\Psi_{np}^{LC}$  (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

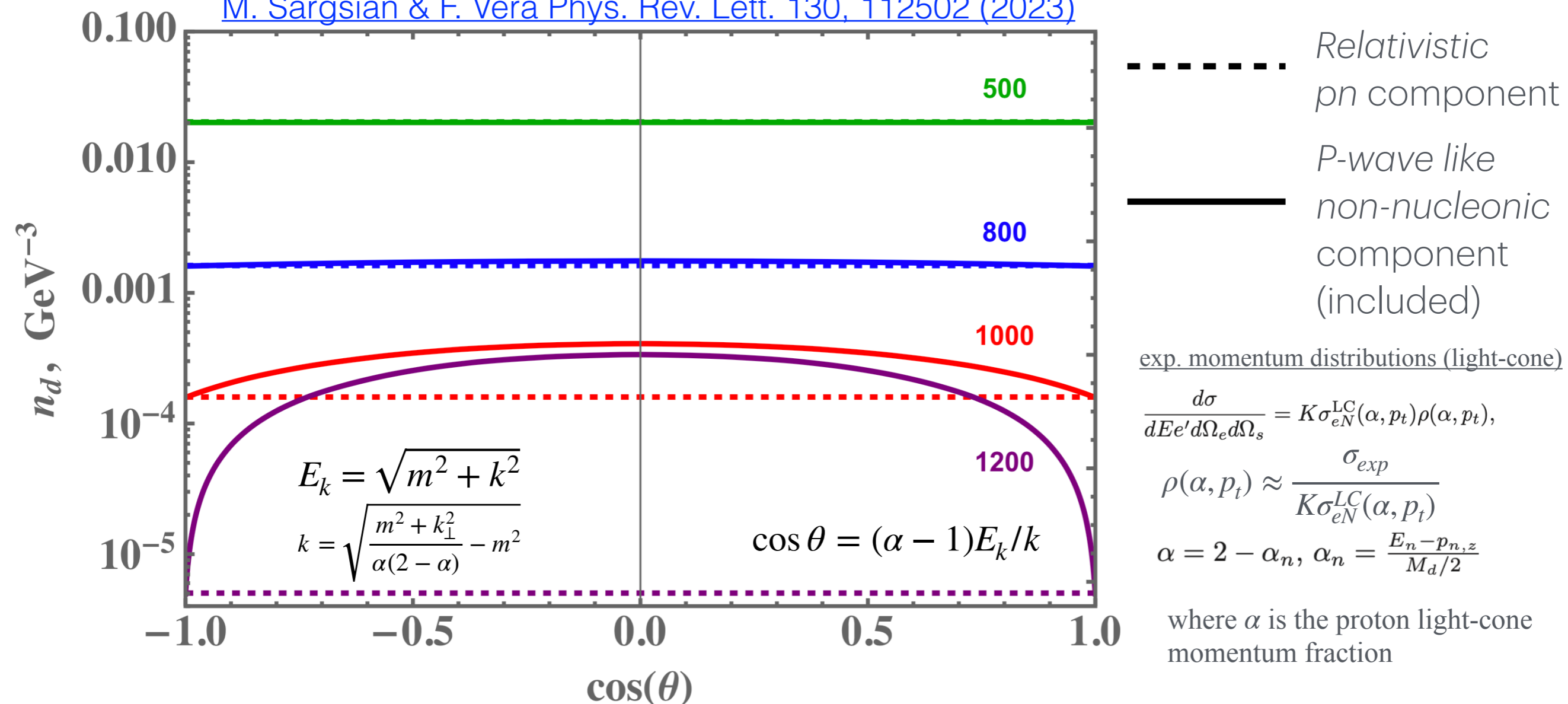
# Back-up: Difficulty of Probing the NN Core

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

# Probing the NN Repulsive Core: Recent Theoretical Advances

[M. Sargsian & F. Vera Phys. Rev. Lett. 130, 112502 \(2023\)](#)



- In the light-front, if only  $\Psi_{pn}^{LC}$  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 is 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 an 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

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

particle mass (GeV)

$$M_N = 0.938272$$

$$M_\pi = 0.139$$

$$M_\Delta = 1.232$$

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

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

Inelastic threshold momenta (GeV/c)

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

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

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

*( $NN\pi$  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.