Future deuteron studies at Hall C

Hall C 2025 Winter Collaboration Meeting

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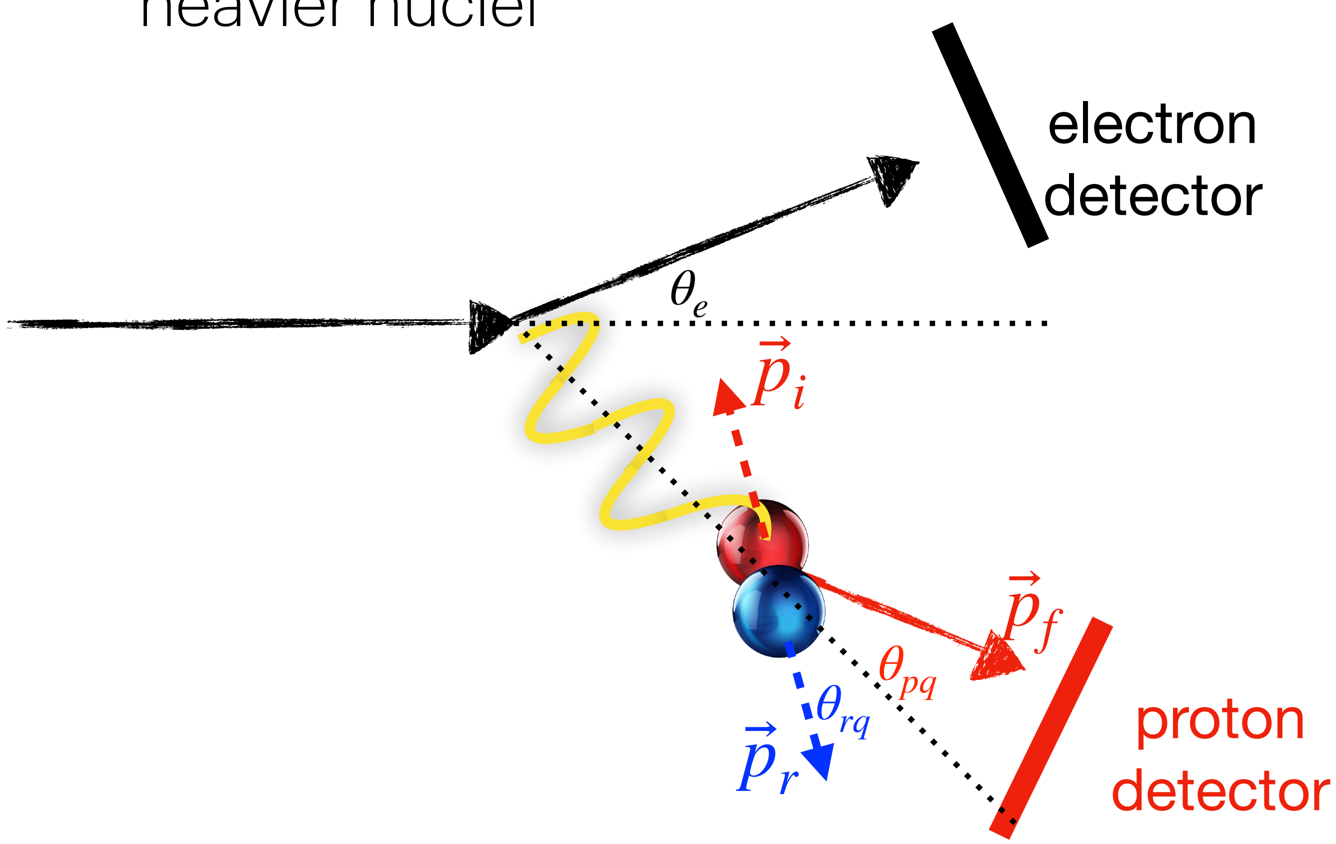
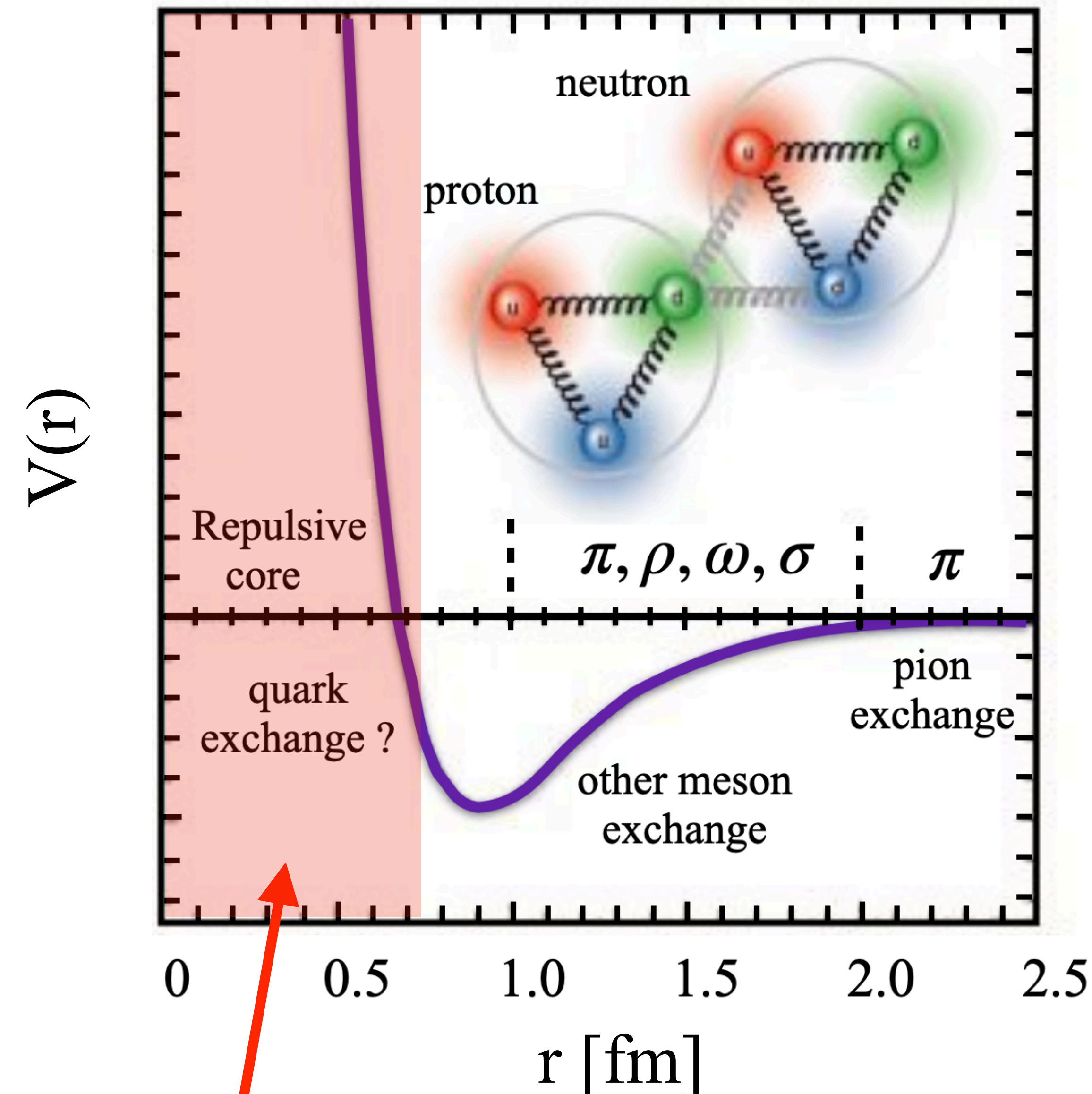
Jan 14, 2025

Why study the deuteron ?

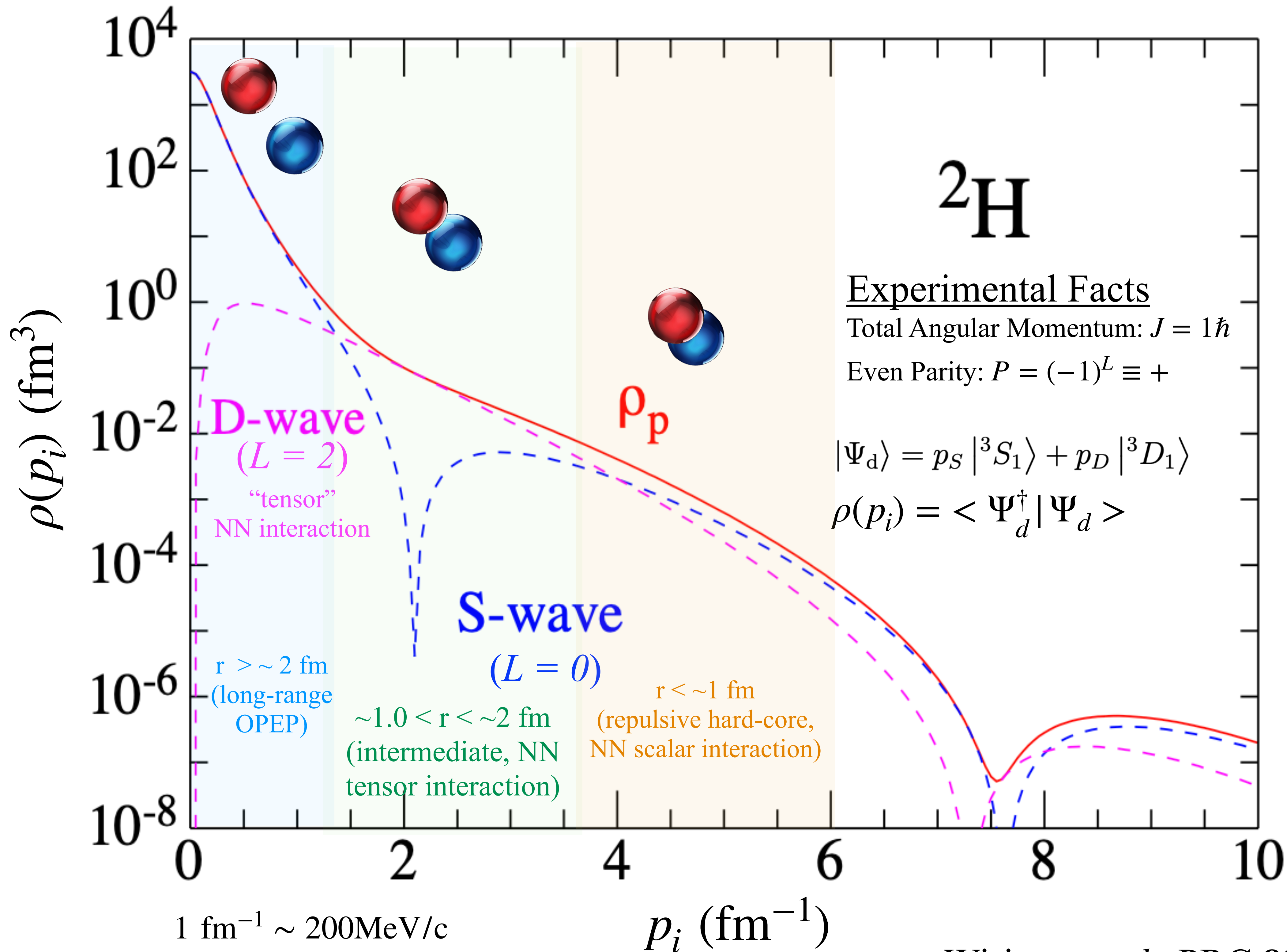
- d(e, e′p) ideal for nuclear core studies
  - most simple *np* bound system
    (no 3N forces or additional complications)
  - provides basis for short-range correlations in heavier nuclei (SRCs are deuteron-like)
  - reliable FSI calculations compared to heavier nuclei





Short-range part
NOT well understood ! ! !

Momentum Distribution

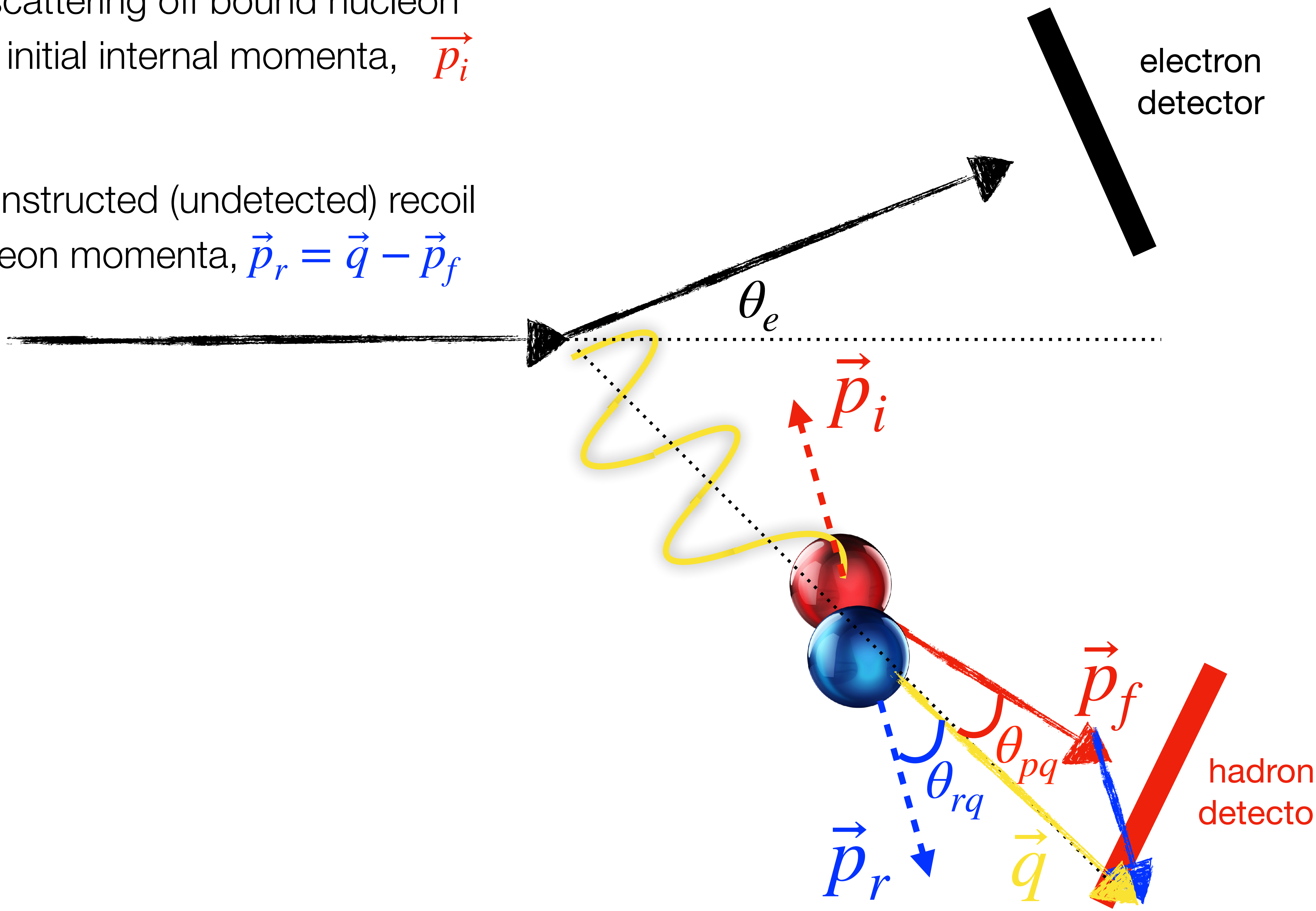


1 fm^{-1} ~ 200MeV/c

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

Probing High-Momentum Structure

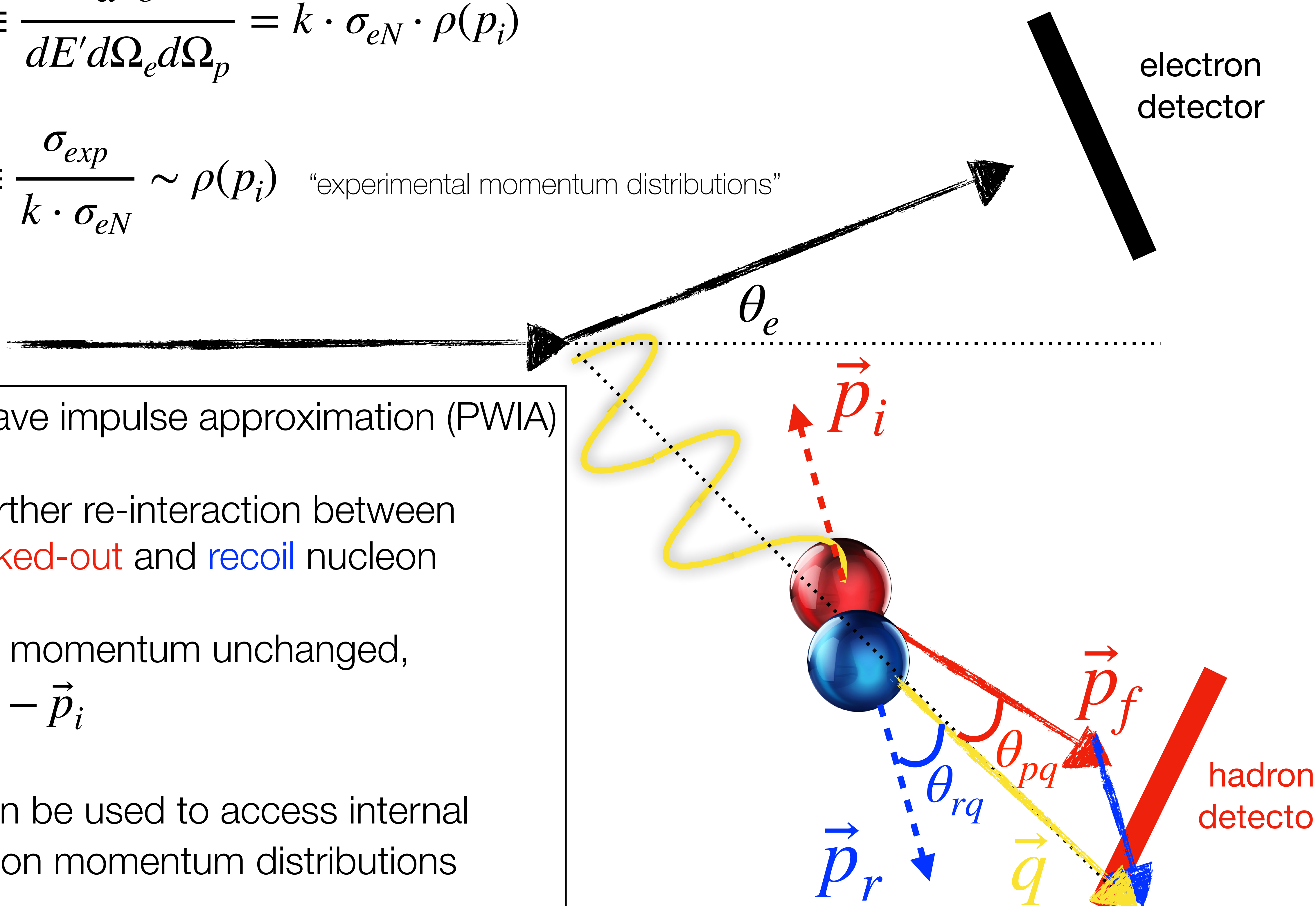
- e- scattering off bound nucleon with initial internal momenta, $\overrightarrow{p_i}$
- reconstructed (undetected) recoil nucleon momenta, $\vec{p}_r = \vec{q} - \vec{p}_f$



Probing High-Momentum Structure

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

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



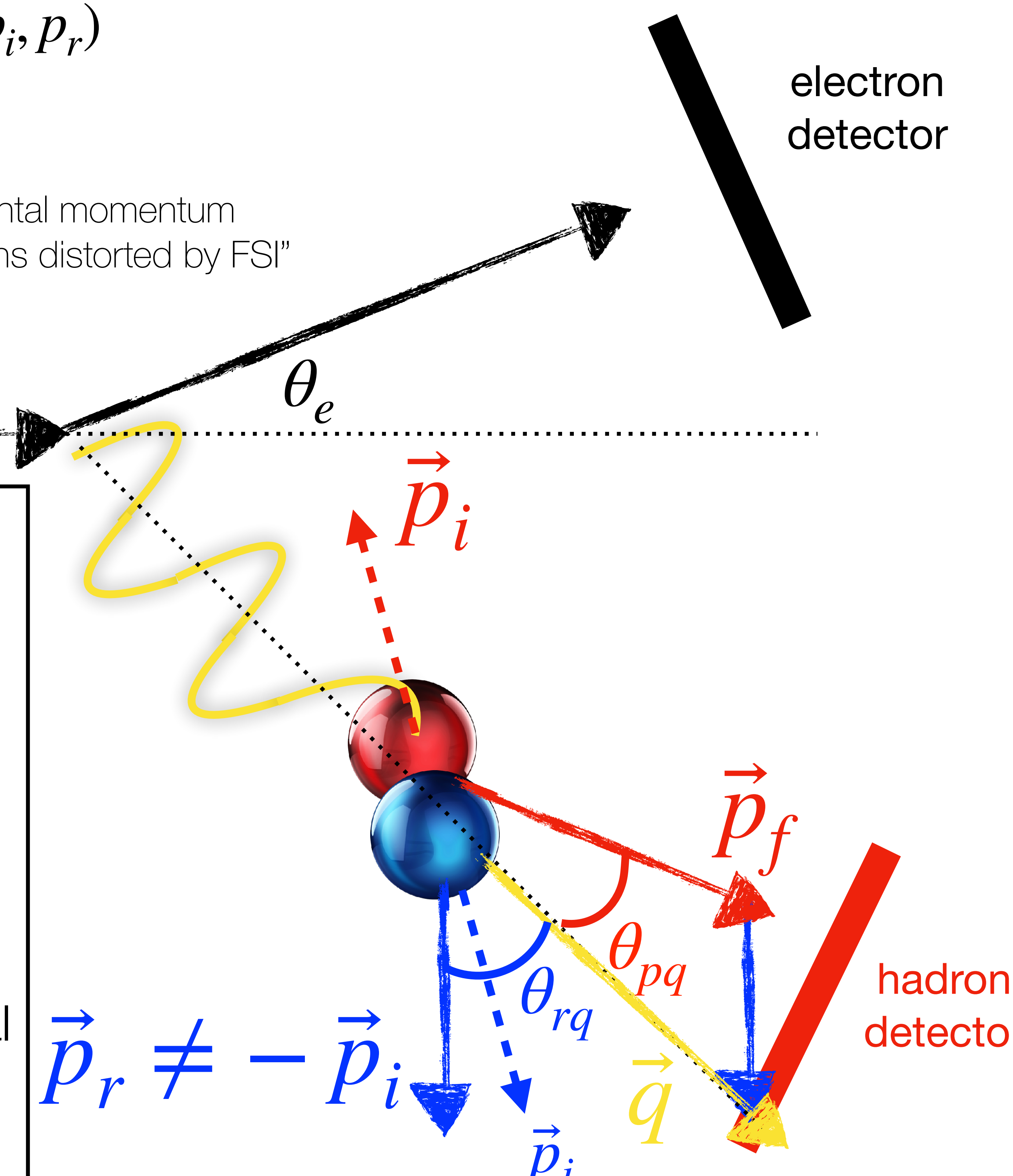
- plane-wave impulse approximation (PWIA)
  - no further re-interaction between knocked-out and recoil nucleon
  - recoil momentum unchanged, $\vec{p}_r \sim -\vec{p}_i$
  - $\vec{p}_r$ can be used to access internal nucleon momentum distributions

Probing High-Momentum Structure

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

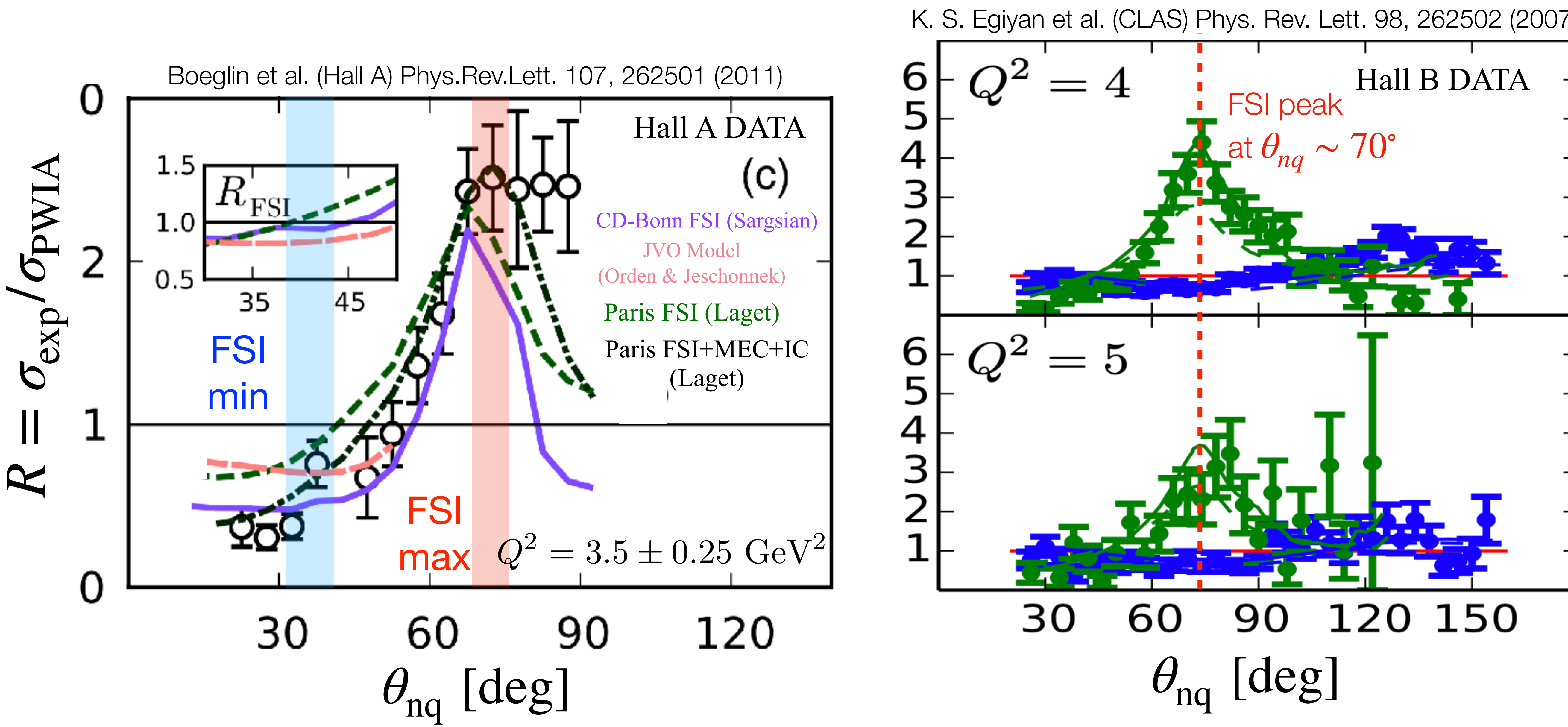
$$\sigma_{red} \equiv \frac{\sigma_{exp}}{k \cdot \sigma_{eN}} \sim \rho_D(p_i, p_r)$$

"experimental momentum distributions distorted by FSI"



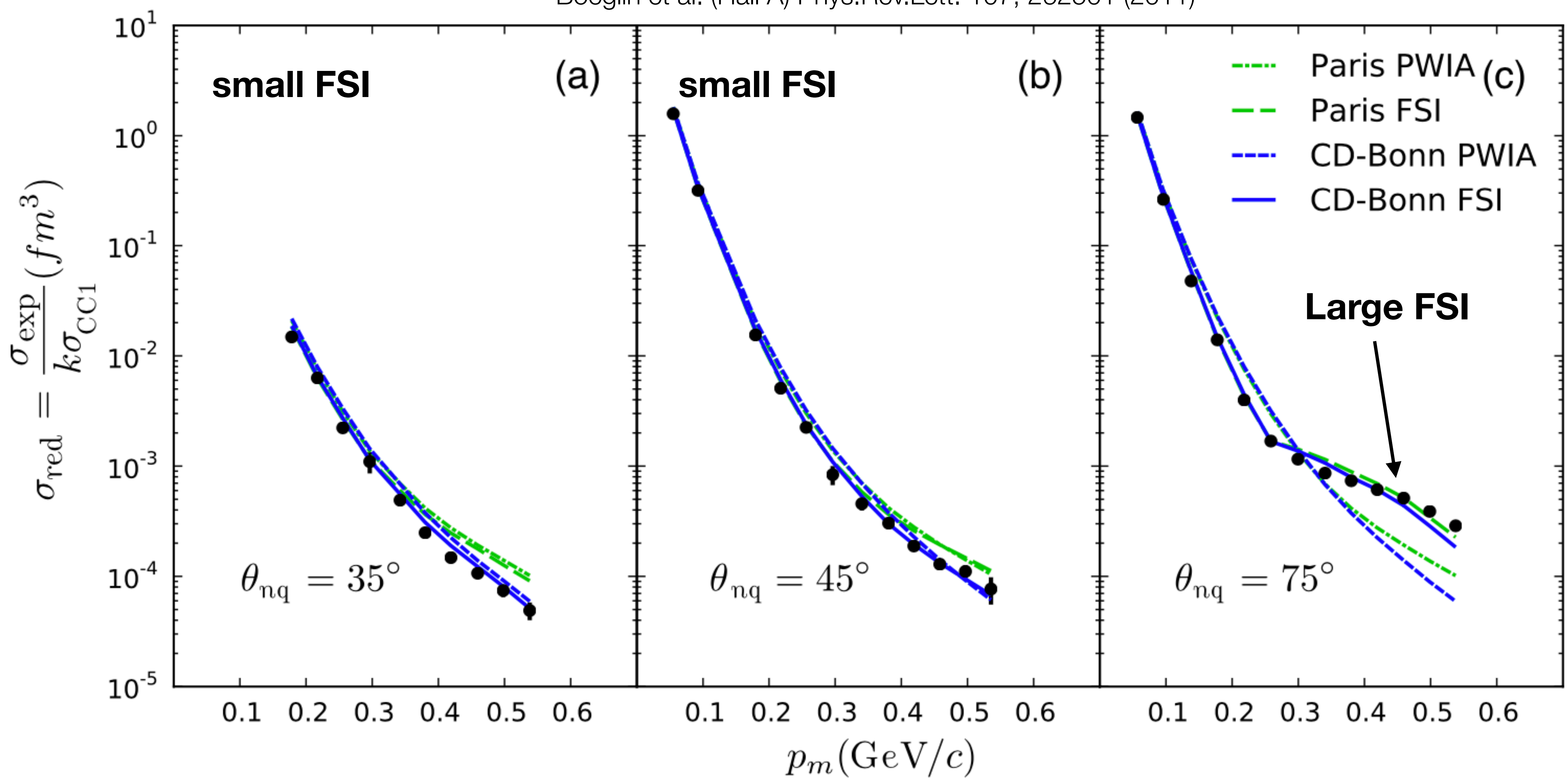
- Final-state interactions (FSI):
  - recoil nucleon re-interacts with knocked-out nucleon
  - recoil momentum modified, $\vec{p}_r \neq -\vec{p}_i$
  - $\vec{p}_r$ cannot be used to access internal nucleon momentum distributions

Controlling Final-State Interactions



Controlling Final-State Interactions

Boeglin et al. (Hall A) Phys.Rev.Lett. 107, 262501 (2011)

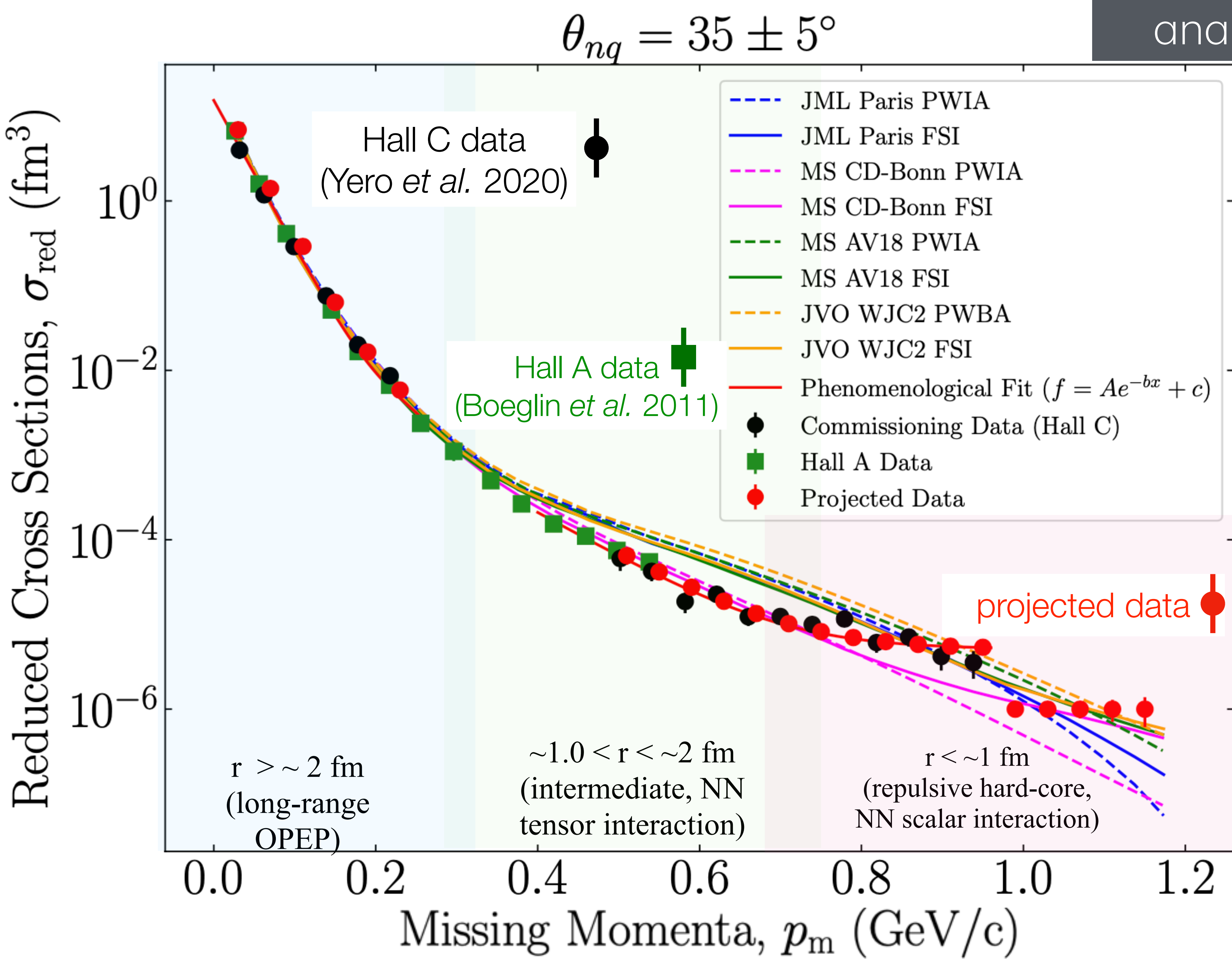


CD-Bonn (Calculations: Misak Sargsian)
Misak M. Sargsian Phys.Rev.C82014612 (2010)

Paris (Calculations: J.M. Laget)
J. Laget Phys.Lett.B60949 (2005)

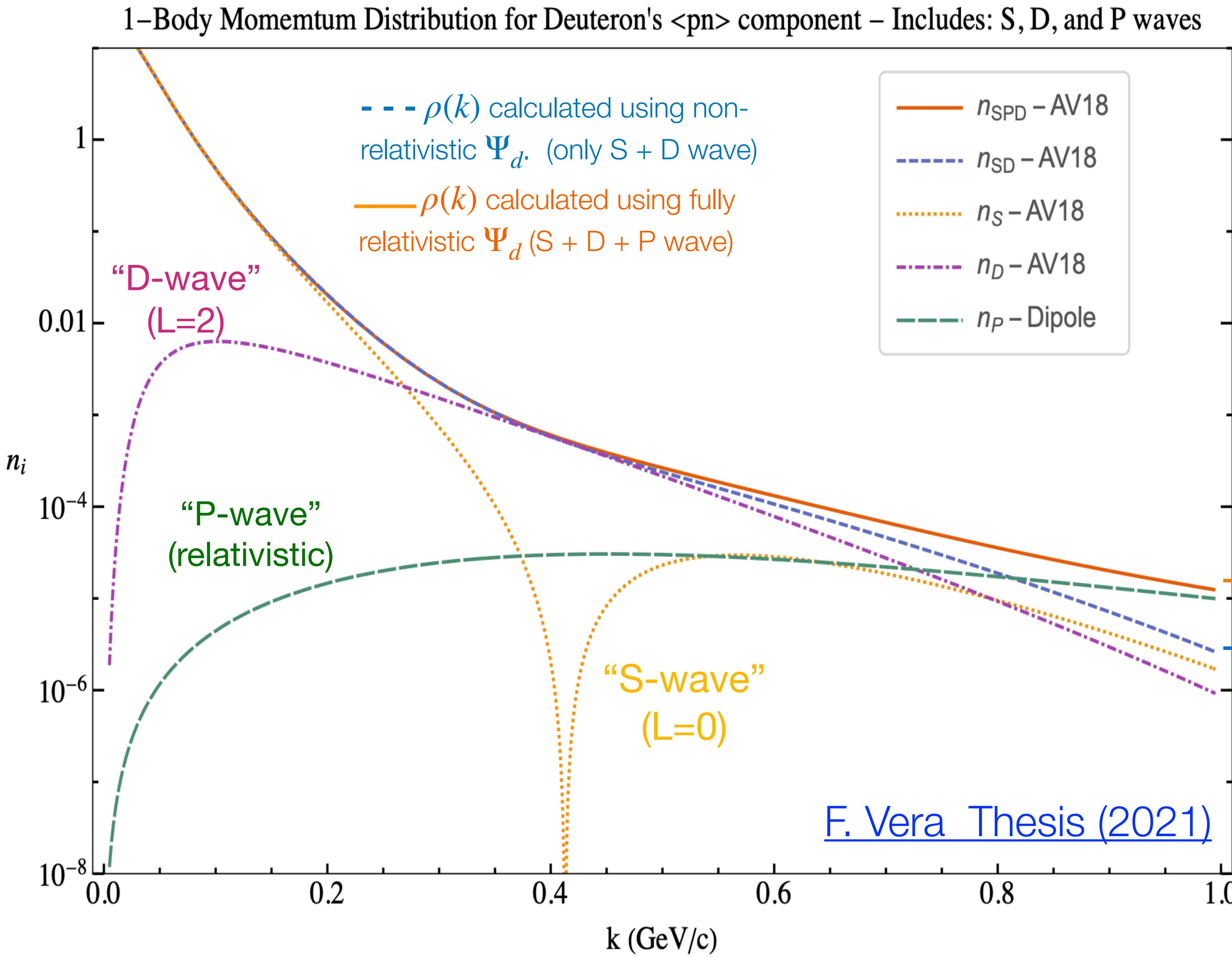
Probing the NN Repulsive Core

See afternoon talk by Pramila & Gema on analysis update !



- non-relativistic theory calc. using CD-Bonn (M. Sargsian) reproduce data up to $p_{\rm m} \sim 0.7$ GeV/c
- no model reproduces data $p_{\rm m} > 0.7$ GeV/c (non-nucleonic degrees of freedom?, quarks?)

Probing the NN Repulsive Core: Recent Theoretical Advances



fully-relativistic

non-relativistic

- fully relativistic calculation of Ψ_d in the light-front give rise to a 'P-wave' -like component
- P-wave starts to dominate at $k \sim 800$ MeV/c, characterized by a 'flattening trend' also observed in published data Yero et al. 2020
- could this 'flattening' be indication of transition from nucleonic to non-nucleonic degrees of freedom?
- recent Hall C d(e, e'p) experiment with higher statistics / improved quality currently being analyzed to verify theory prediction

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

non-relativistic relativistic (non-nucleonic)

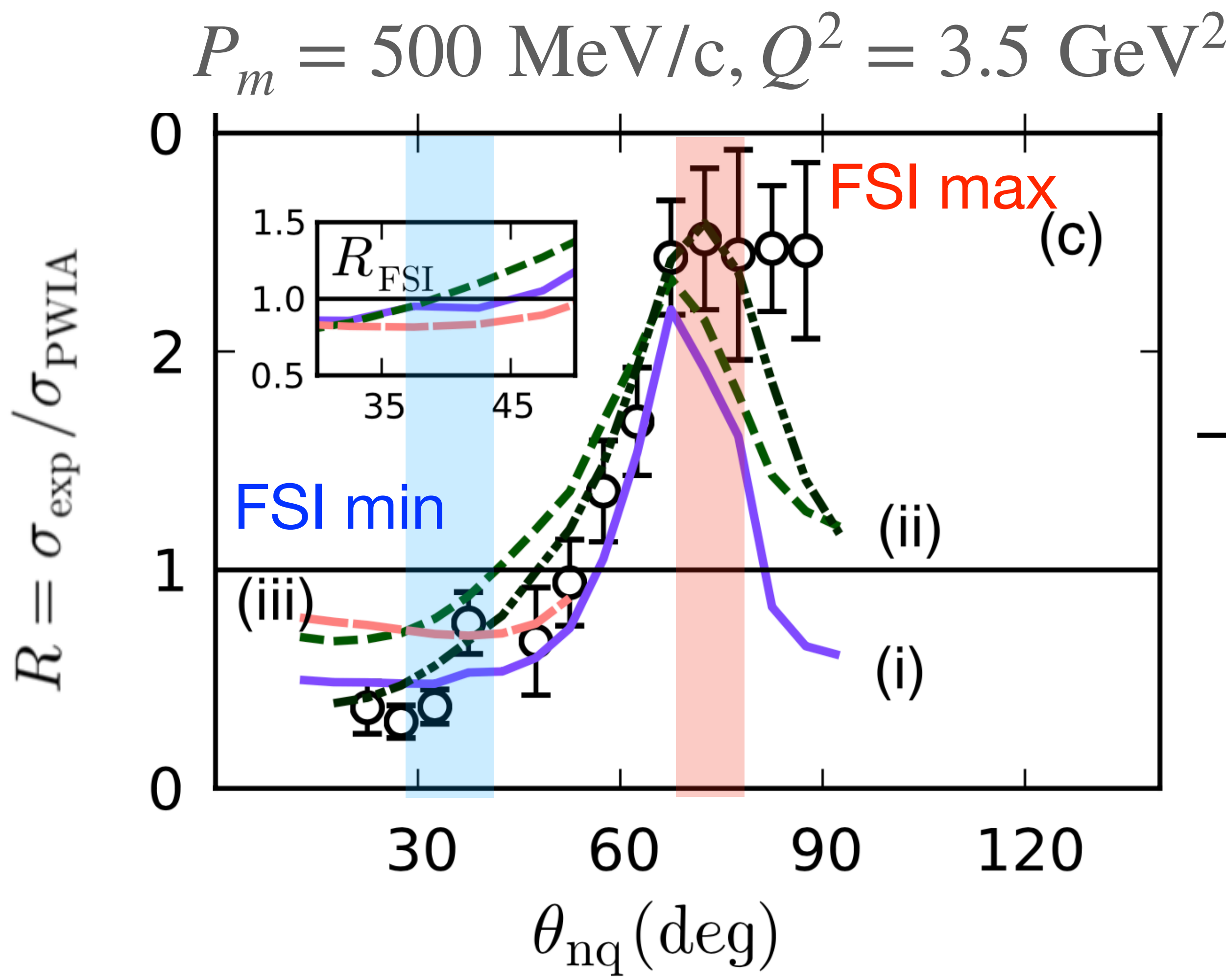
$$\Psi_d = \boxed{\Psi_{pn}} + \boxed{\Psi_{\Delta\Delta} + \Psi_{NN^*} + \Psi_{hc} + \Psi_{NN\pi} \cdots}$$

Future d(e, e'p) Deuteron Studies:

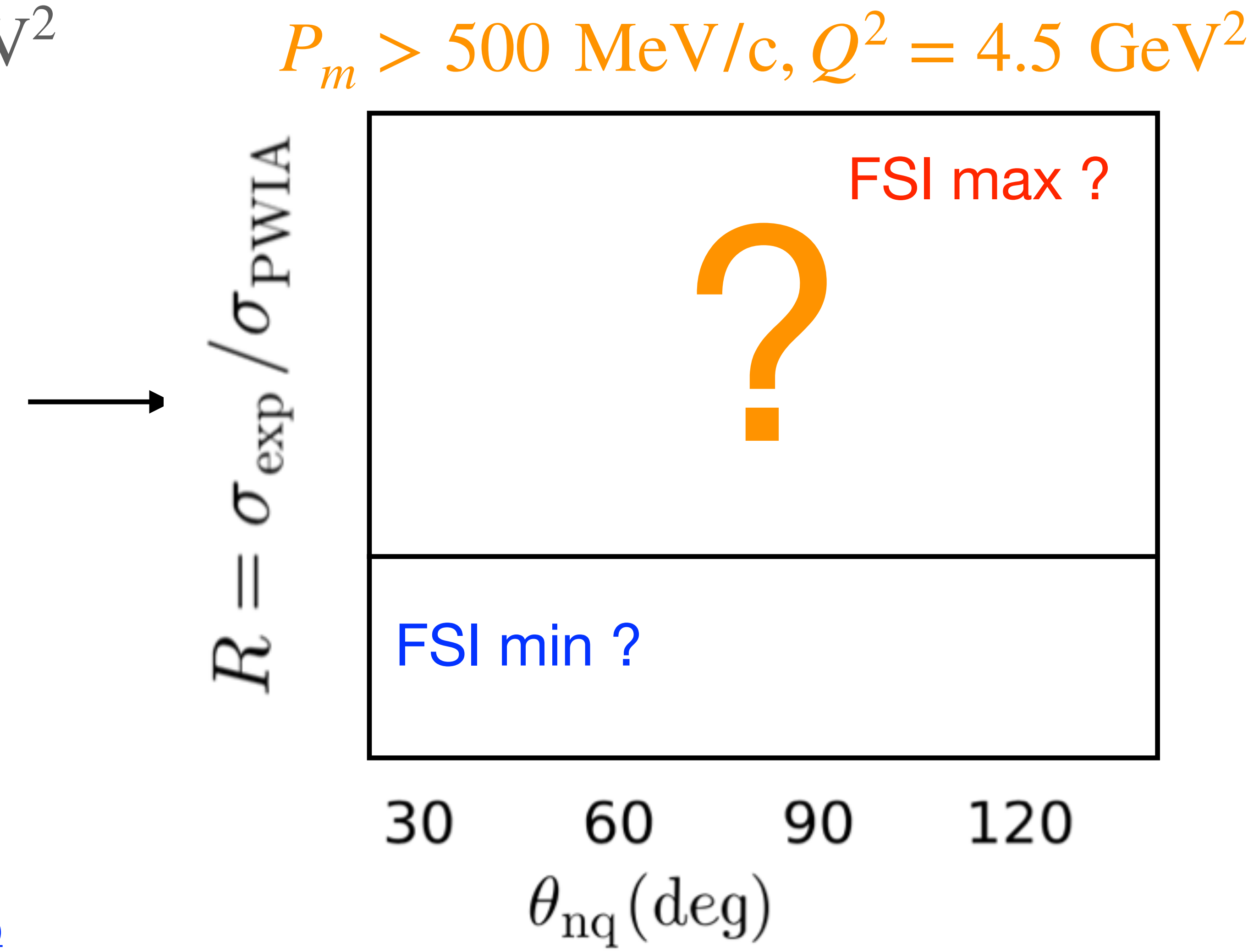
- Final-State Interaction Studies
  Submitted LOI 12-24-005 (2024)
  C. Yero, W. Boeglin, M. Jones, M. Sargsian

- Tensor-Polarized Studies
  C. Yero, N. Santiesteban, H. Szumila-Vance, I.P. Fernando, E. Long
  W. Boeglin, M. Jones, M. Sargsian

Final-State Interaction Studies

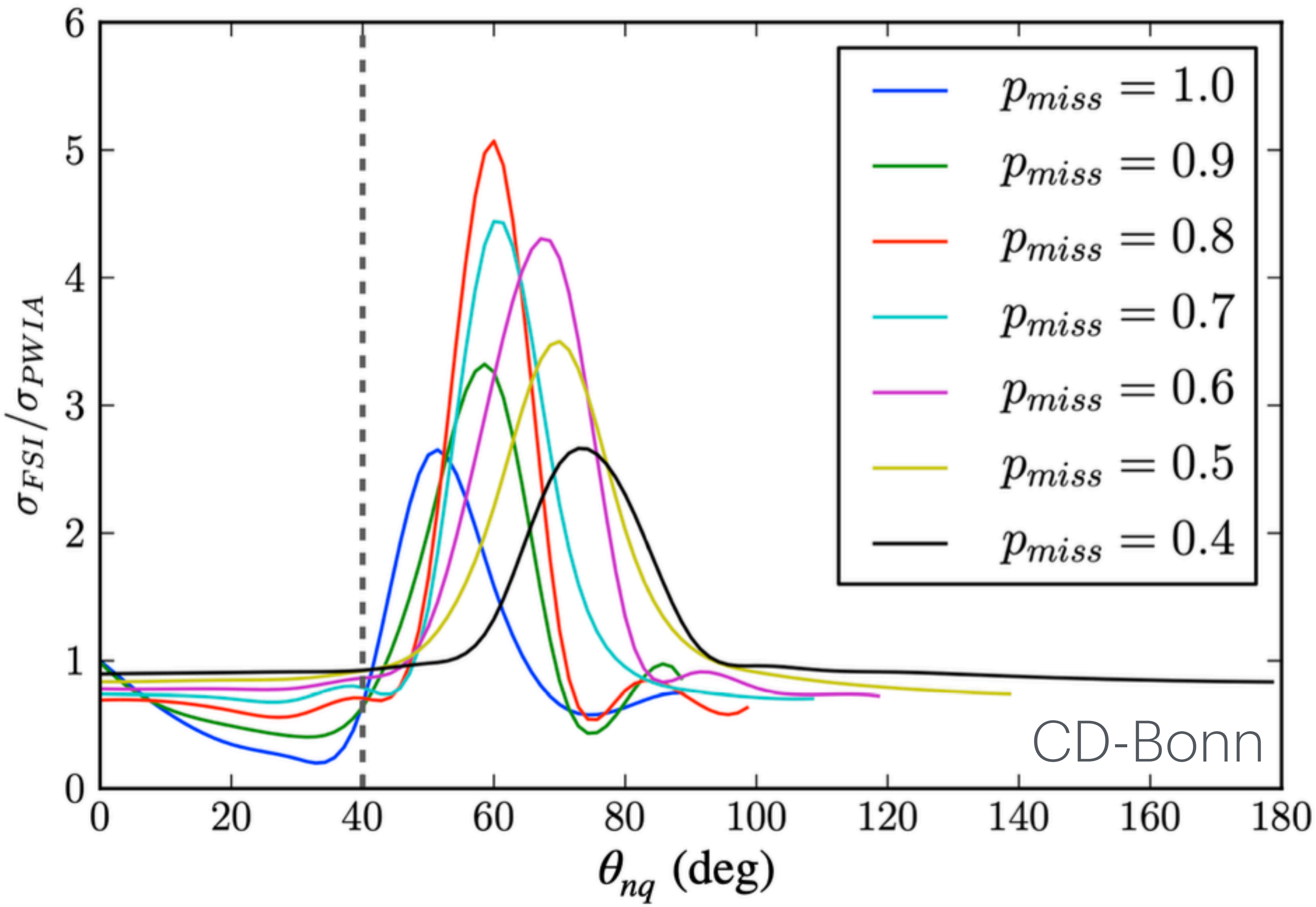


Boeglin et al. (Hall A) Phys.Rev.Lett. 107, 262501 (2011)



- Repulsive Core studies assume small FSI >~ 500 MeV/c (but FSI at this range has not been measured)

Final-State Interaction Studies



- FSI peak shifts with missing (recoil) momenta
- Need experimental data to verify FSI are still small at $\theta_{rq} \lesssim 40°$

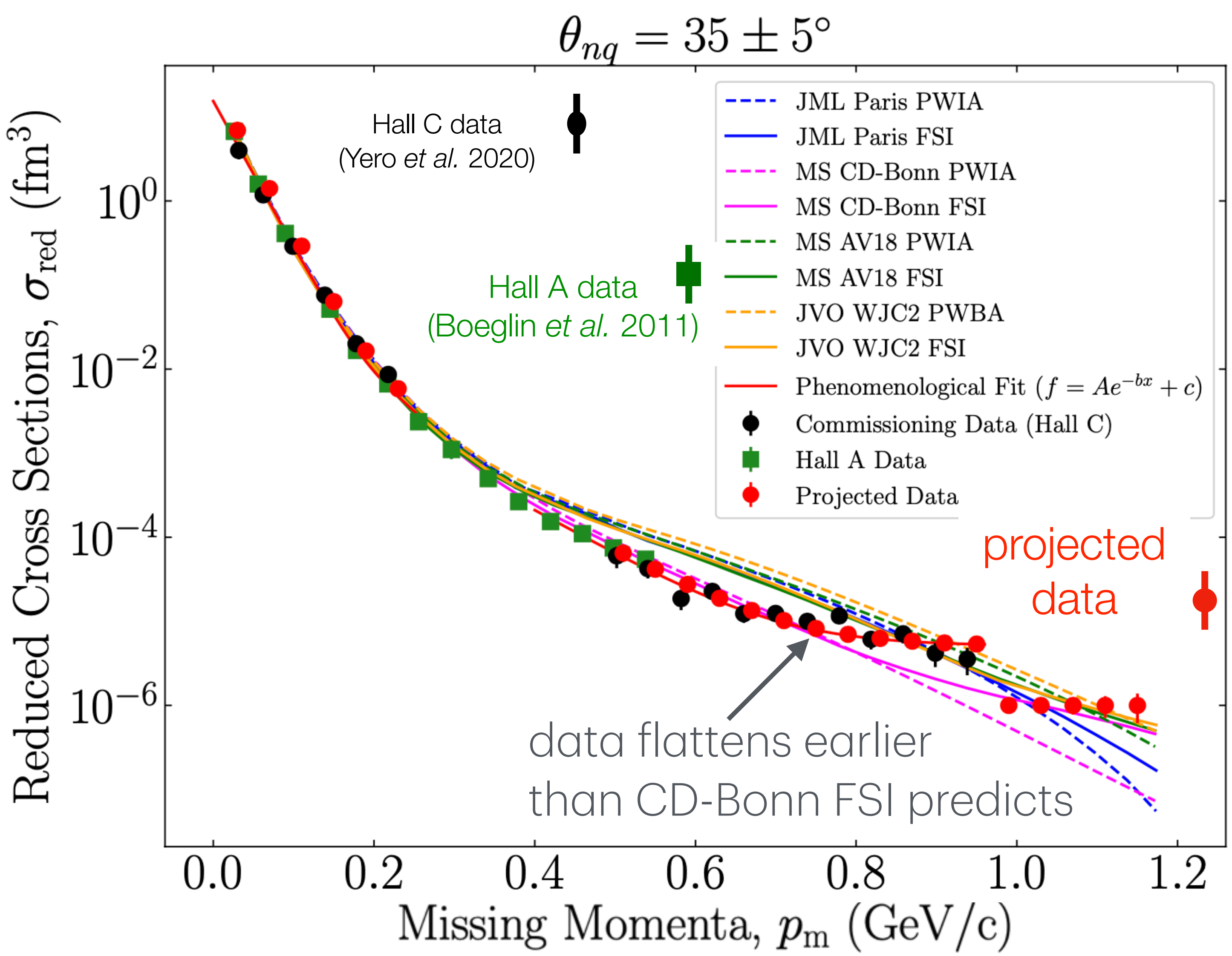
Final-State Interaction Studies

Why data flattens earlier than predicted by CD-Bonn FSI calculations ?

1. Could FSI start earlier than predicted by calculations ?

2. Are we probing non-nucleonic part of there deuteron ?

3. Or a combination of both effects (or something else ?)

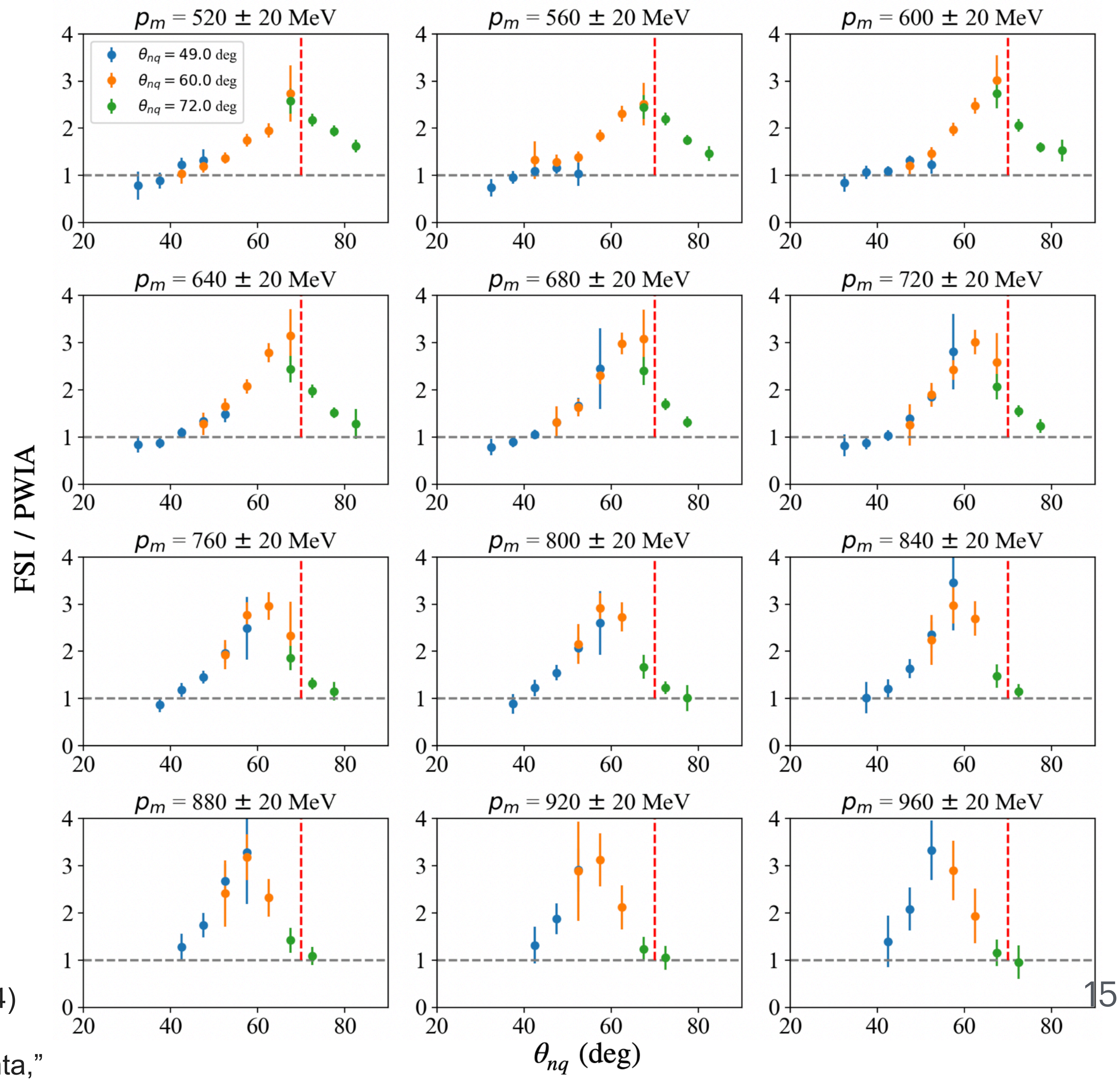


Final-State Interaction Studies

- Simulation Ratio FSI/PWIA versus neutron recoil angle (angular distributions)
- Calculations used the J.M. Laget d(e,e′p) FSI (using Paris Potential)
- FSI peak shifts toward lower recoil angles with increasing momenta

$\theta_{nq} \sim 70^{\circ}$

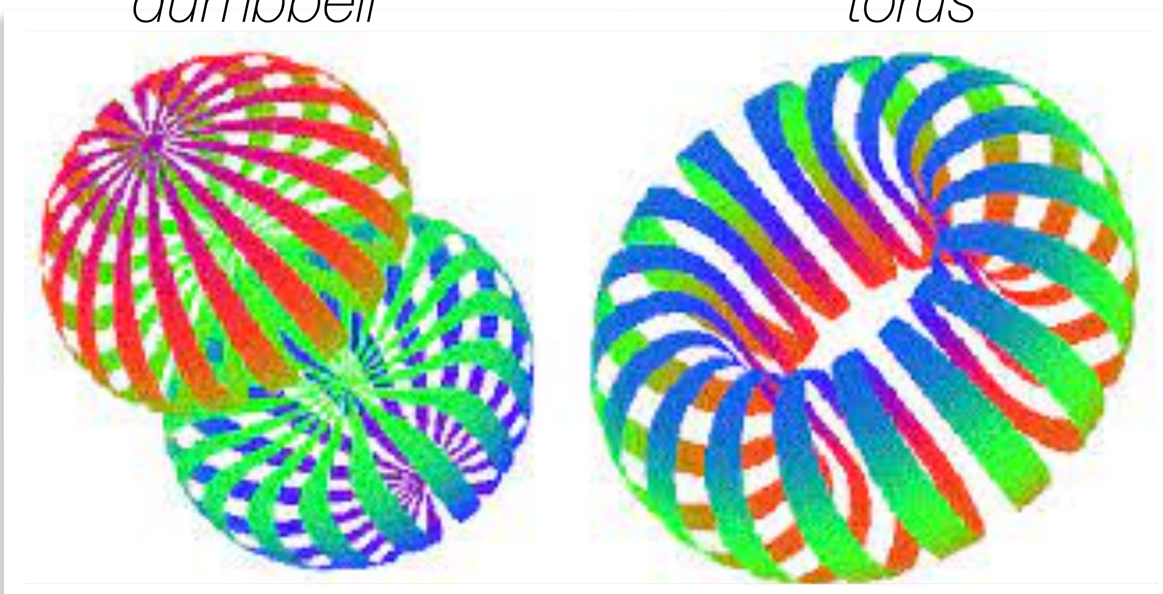
(Reference line)

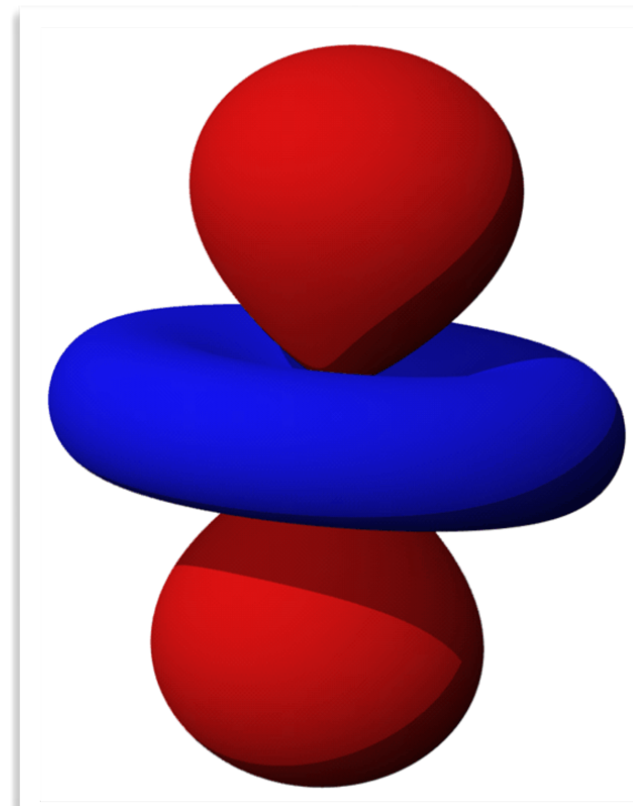


LOI12-24-005 (Submitted to PAC 52, 2024)
Titled: "Final-State Interactions Studies in Deuterium at Very High Missing Momenta,"

Exclusive electro-disintegration of tensor-polarized deuterium

“dumbbell” “torus”



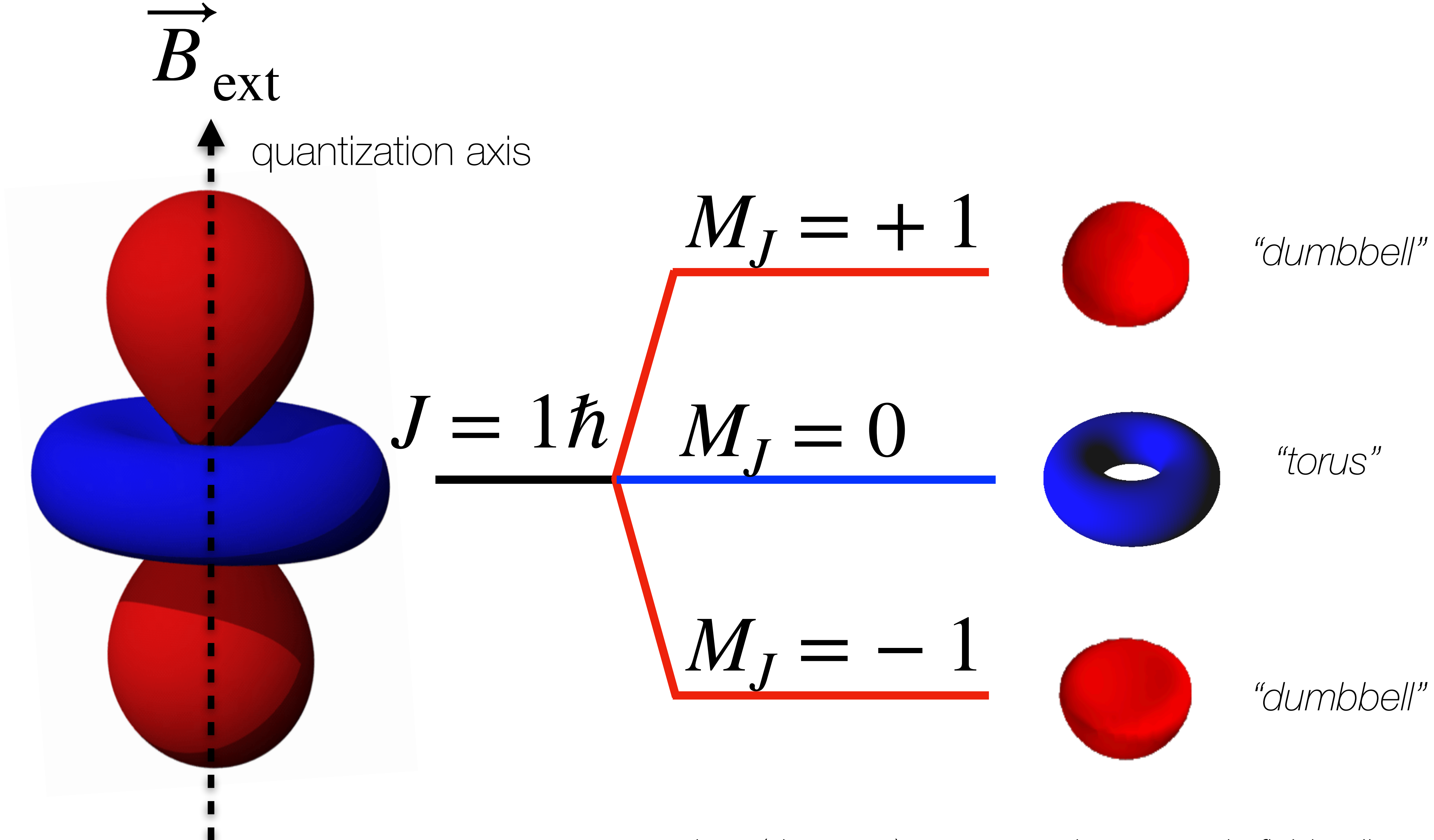


See next talk by David Ruth
on other tensor-polarized deuteron
experiment proposal !

D Keller 2014 J. Phys.: Conf. Ser. 543 012015 (2014)

D. Keller, D. Crabb, D. Day Enhanced tensor polarization in solid-state targets *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment,* vol. 981, pp. 164503, 2020, issn: 0168-9002.

Spin-1 Tensor Polarization



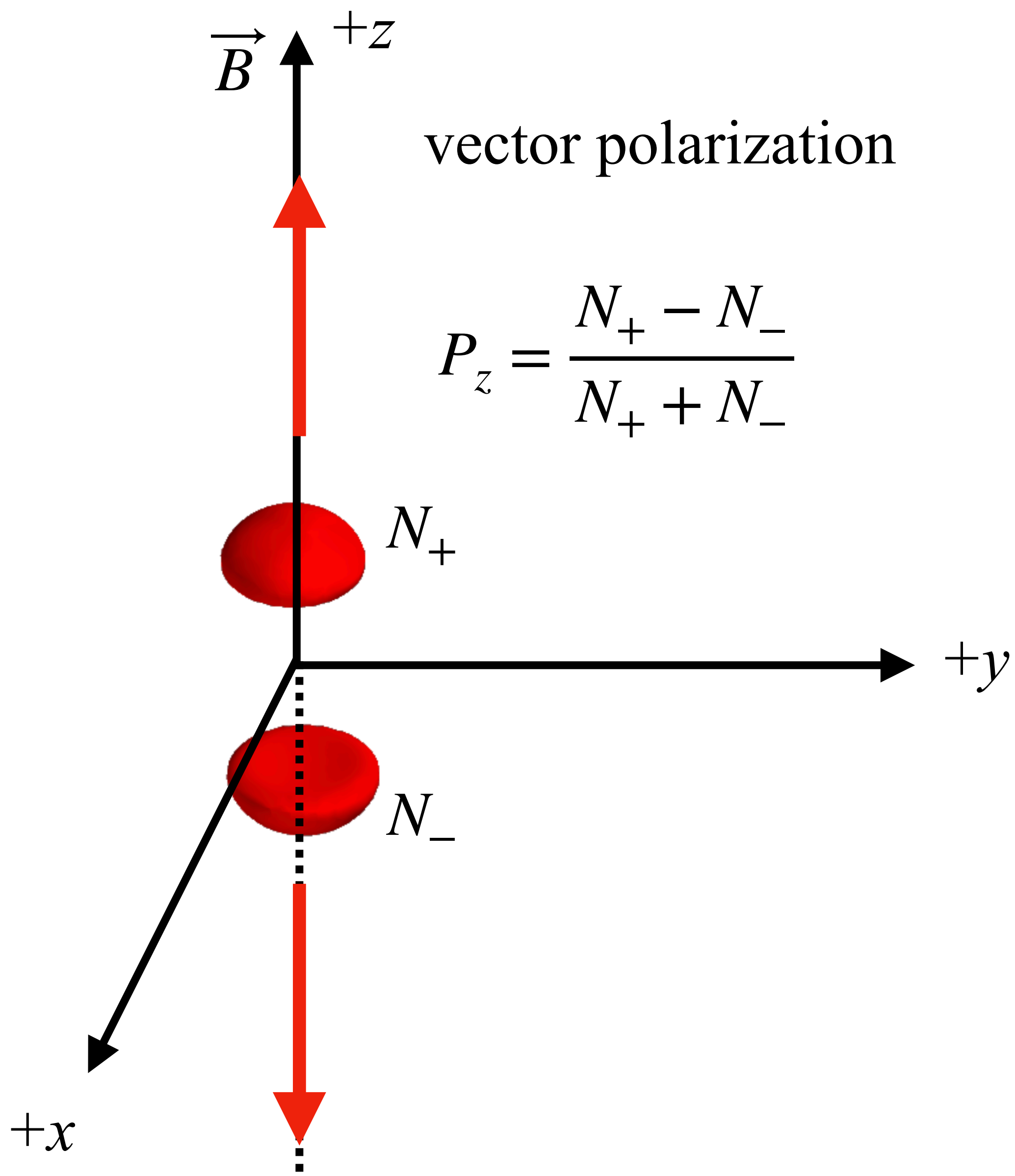
spin-1 (deuteron) system under magnetic field splits into 3 spin-substates via Zeeman Interaction

[Forest J et al. 1996 Phys. Rev. C 54 646]

Spin-1 Polarization

vector polarization

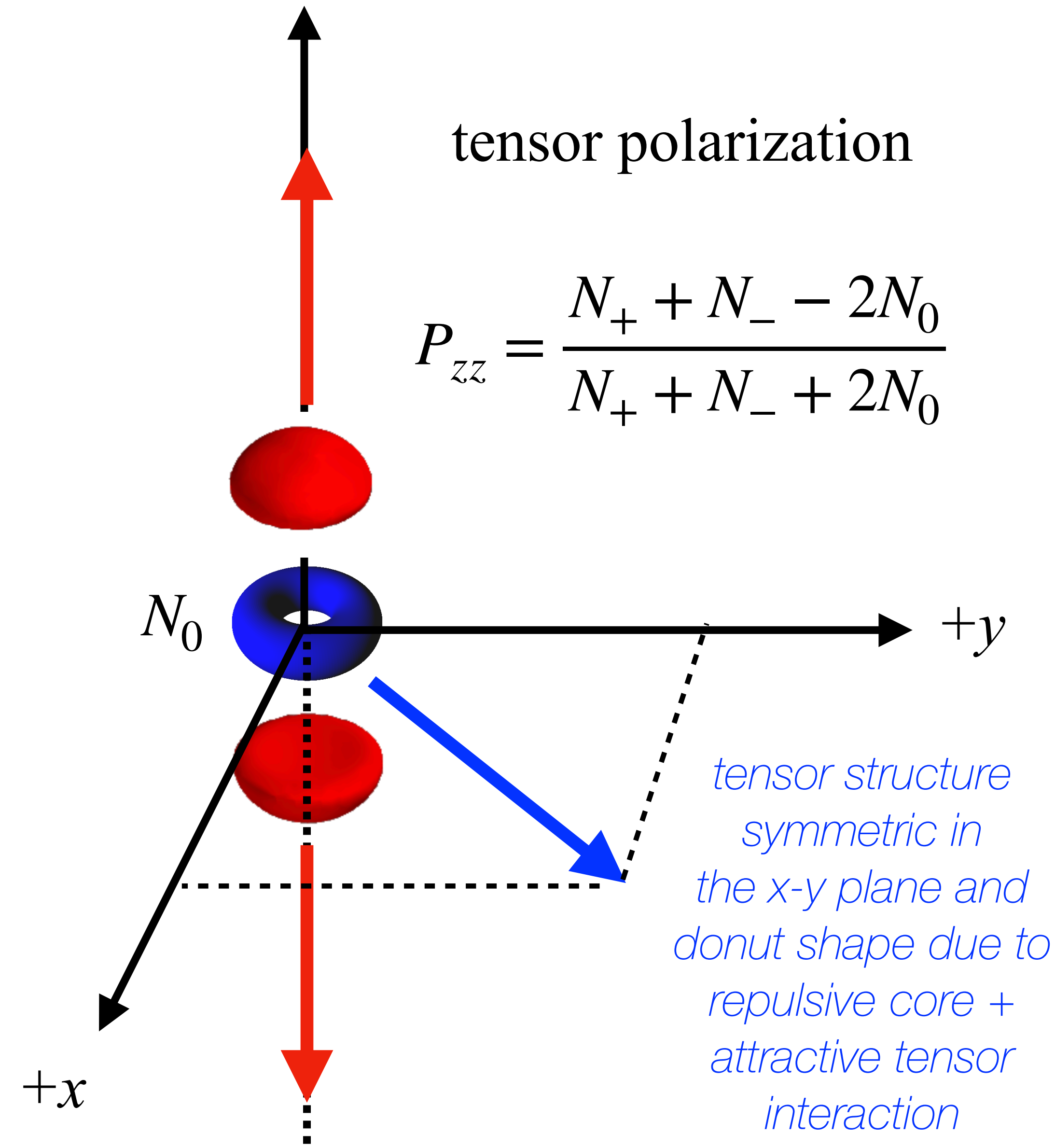
$$P_z = \frac{N_+ - N_-}{N_+ + N_-}$$



vector asymmetry $A_z = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$

tensor polarization

$$P_{zz} = \frac{N_+ + N_- - 2N_0}{N_+ + N_- + 2N_0}$$

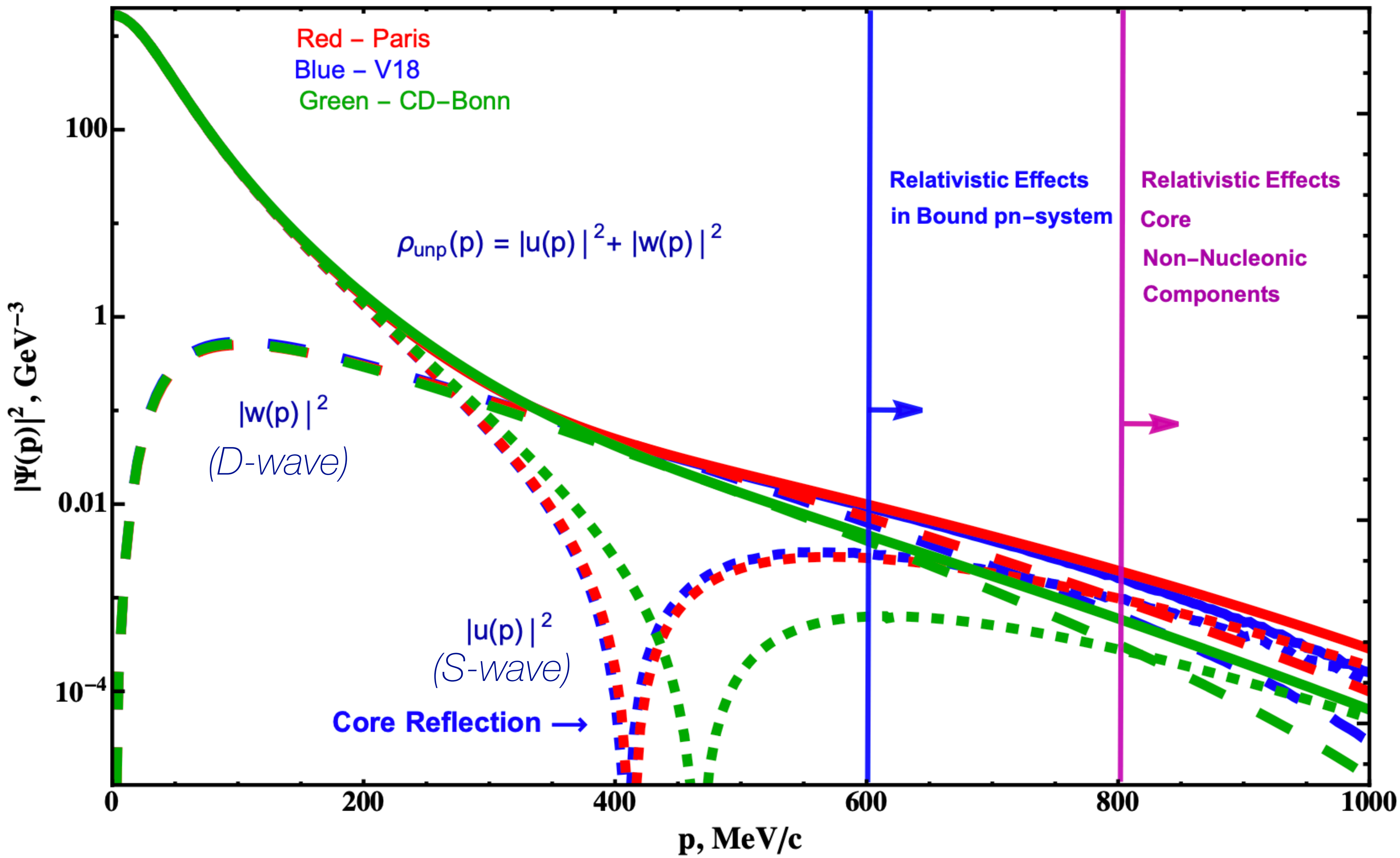


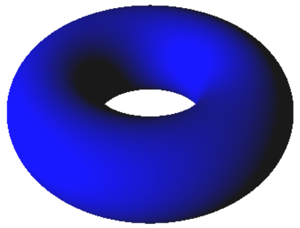
tensor asymmetry $A_{zz} = \frac{\sigma_+ + \sigma_- - 2\sigma_0}{\sigma_+ + \sigma_- + 2\sigma_0}$

N_+, N_-, N_0 : relative population of target nuclei in a particular spin configuration

See D. Keller [Eur. Phys. J. A53 (2017)]
for recent studies on enhanced DNP tensor-polarization experimental techniques

Unpolarized Deuteron Momentum Distribution





"torus"

- **S-wave node**: directly related to the NN hard core (***how to isolate S-wave experimentally?***)

M. Sargsian [2410.08384 (2024)]

Probing the NN core

unpolarized momentum distribution

$$\rho_{unp}(p_m) = |u(p_m)|^2 + |w(p_m)|^2$$

$u(p_m)|$: S-partial wave of the deuteron
w$(p_m)|$: D-partial wave of the deuteron

tensor-polarized momentum distribution

$$\rho_{20}(p_m) = \frac{3cos^2(\theta_N)\ -1}{2}\left[2\sqrt{2}u(p_m)w(p_m){-}w(p_m)^2|\right]$$

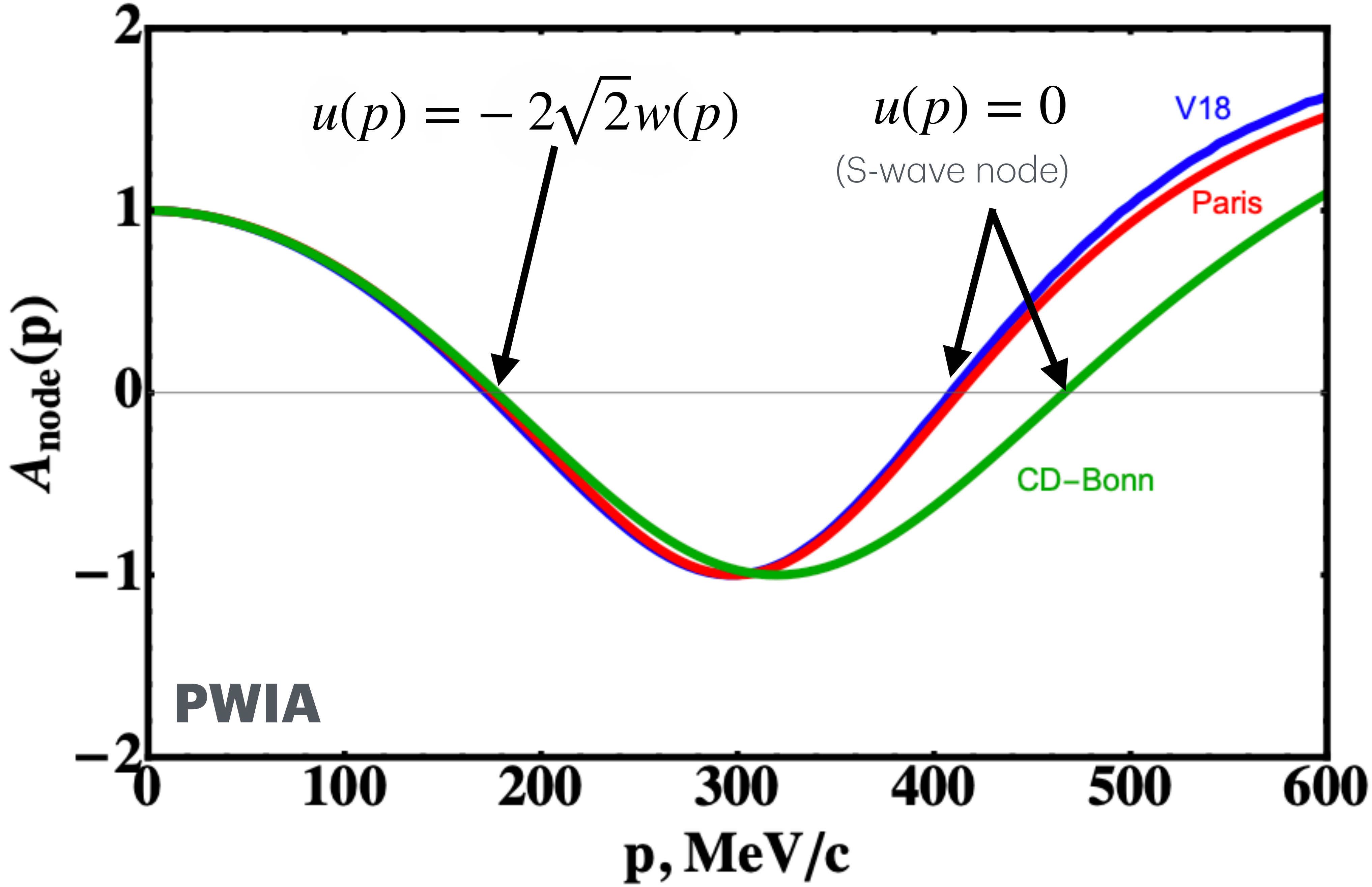
θ_N : direction of internal momenta with respect to the polarization axis of the deuteron

$$A_{node} = \frac{u(p_m)^2 + 2\sqrt{2}u(p_m)w(p_m)}{|u(p_m)|^2 + |w(p_m)|^2}$$

$$A_{node}(p) = 0 \begin{cases} u(p) = -2\sqrt{2}w(p) \longrightarrow p \sim 180MeV \\ u(p) = 0 \longrightarrow p \geq 400MeV \end{cases}$$

M. Sargsian [2410.08384 (2024)]

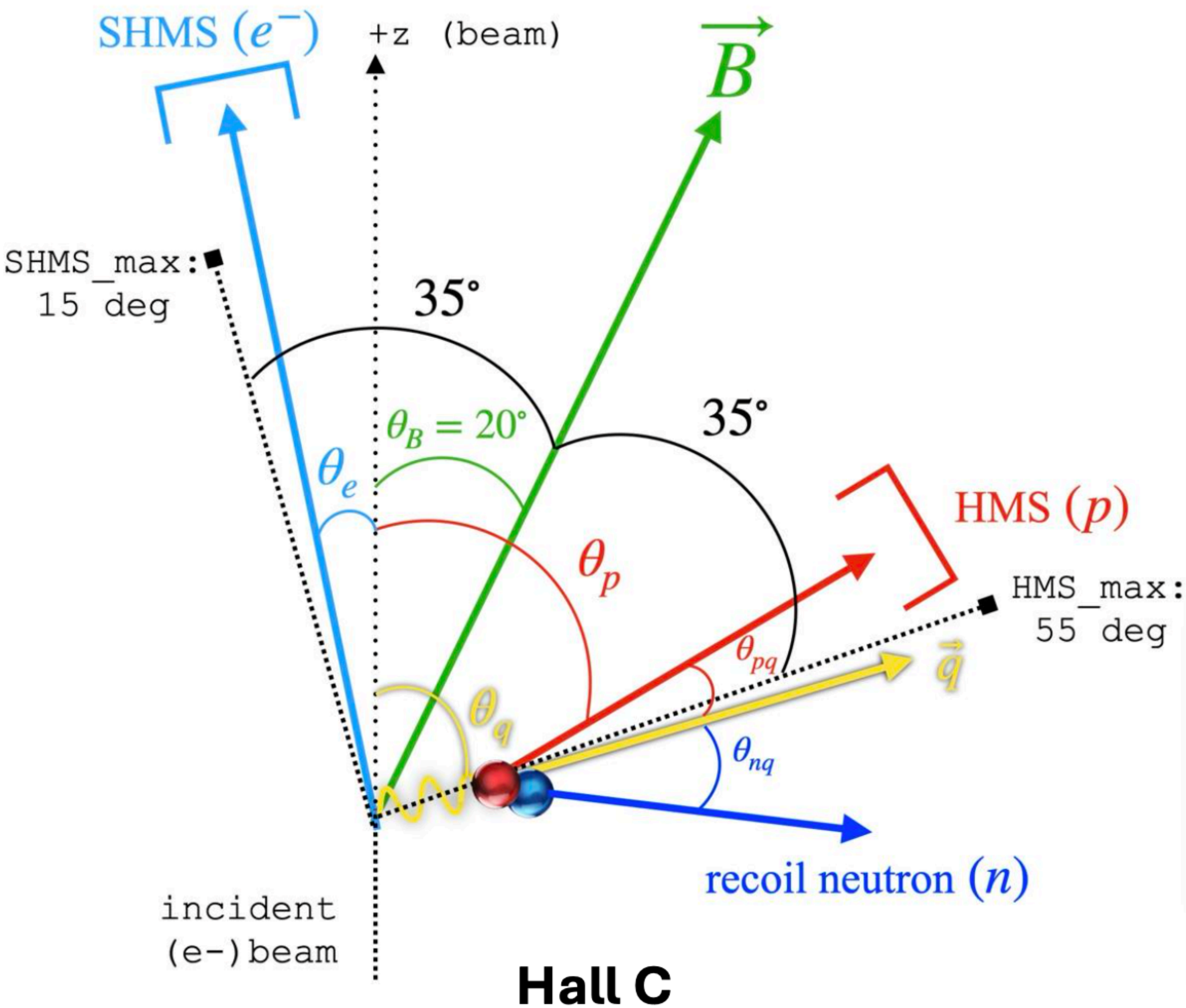
Node Asymmetry



The node is a signature of nuclear repulsive core: In the PWIA approximation, if deuteron consisted of only the S-state, then in this case the node is like a hole in the momentum space through which the probe-electron will pass without interaction.

M. Sargsian [2410.08384 (2024)]

Kinematics

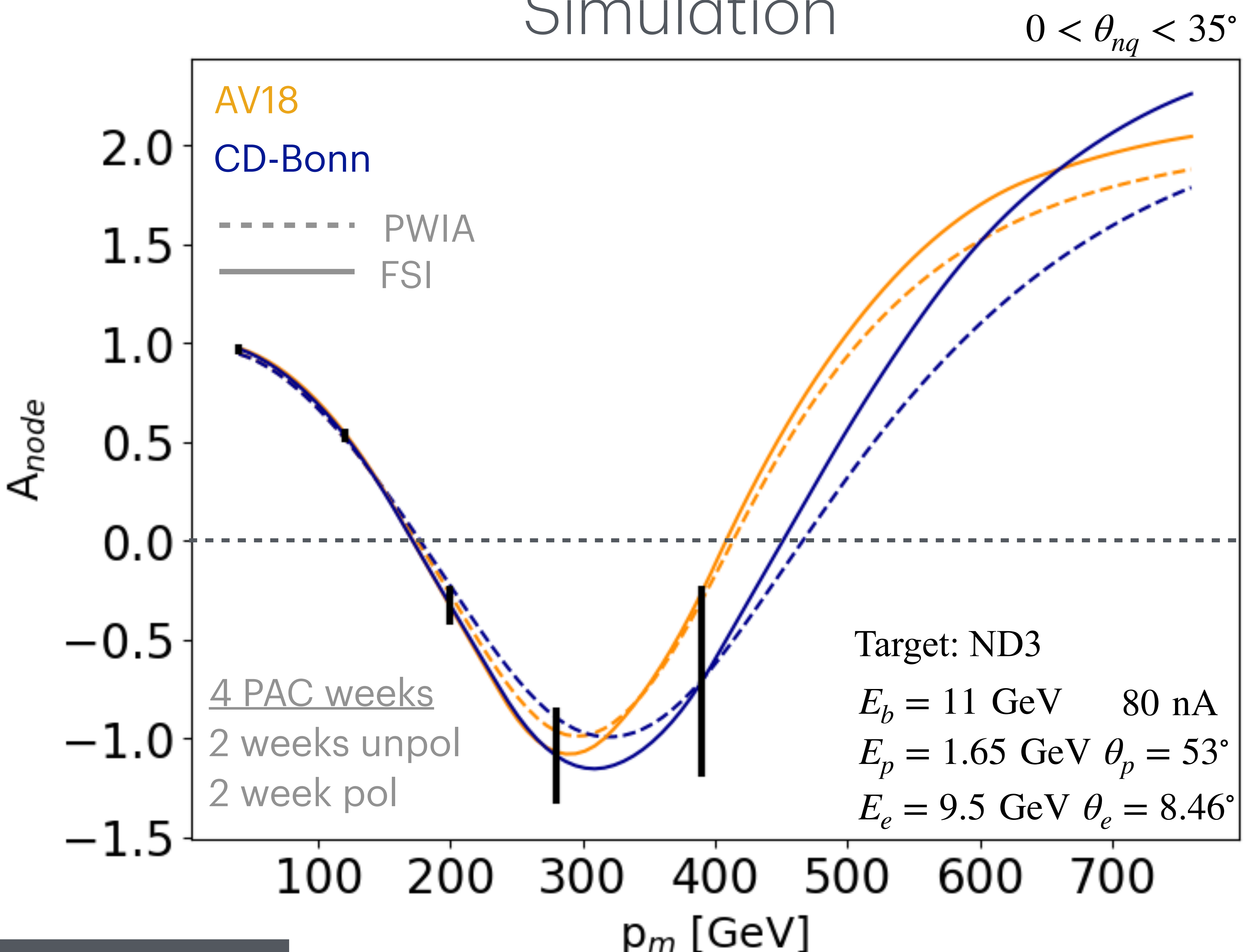


Looking at forward kinematics to minimize FSI $(0 < \theta_{nq} < 35)$ which implies $\theta_p > 50$ deg

We currently are limited by the acceptance of the target magnet (± 35 deg)

Target magnet can rotate to a maximum angle of 20 deg, which limited the proton angle to < 55 deg

Simulation



NEVER MEASURED !

Conclusion

- deuteron FSI studies at high-Pm
  - necessary to validate kinematics used in probing repulsive NN core
  - LOI submitted last year, full proposal this year

- exclusive d(e, e’p) polarized deuteron studies
  - isolation of the S-wave (novel, no exp. measurement) can provide insight into the nuclear repulsive core
  - complementary to high-Pm unpolarized d(e, e’p) studies
  - full proposal to be submitted this year

future deuteron studies have great discovery potential (*repulsive NN core is practically unexplored!*)

Thank You