PAC 53

d(e,e'p) FSI Studies

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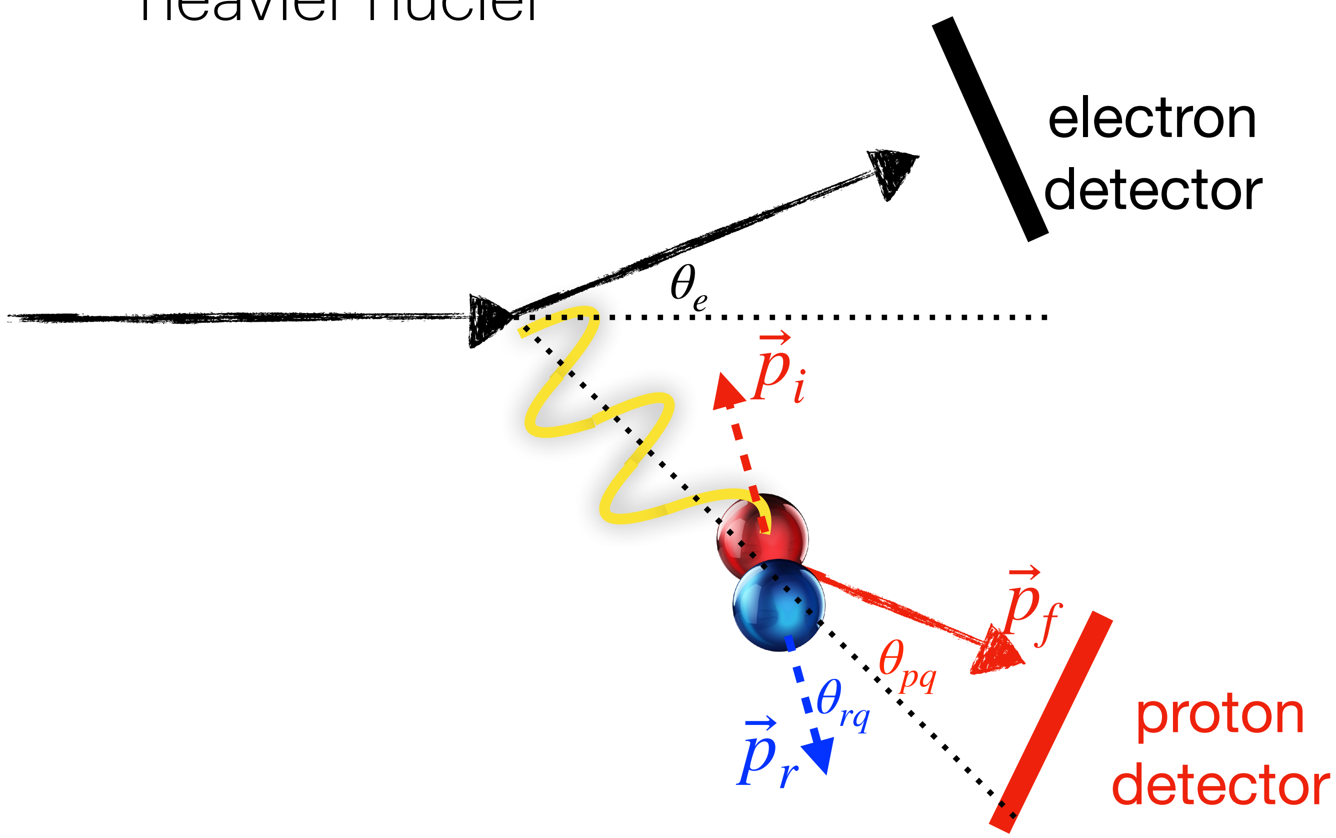
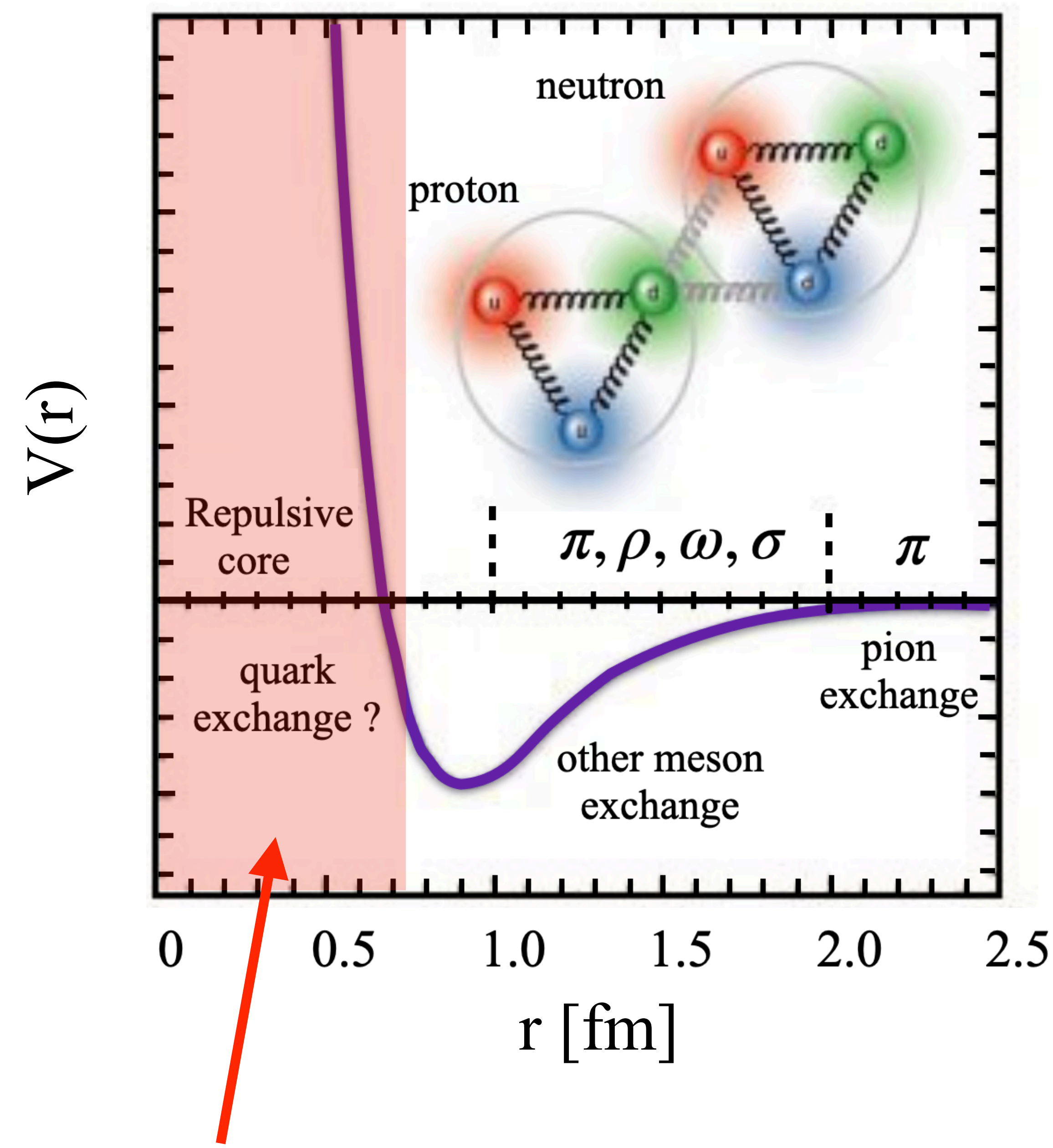
Hall C 2025 Summer Collaboration Meeting

* contact

Why study the deuteron ?

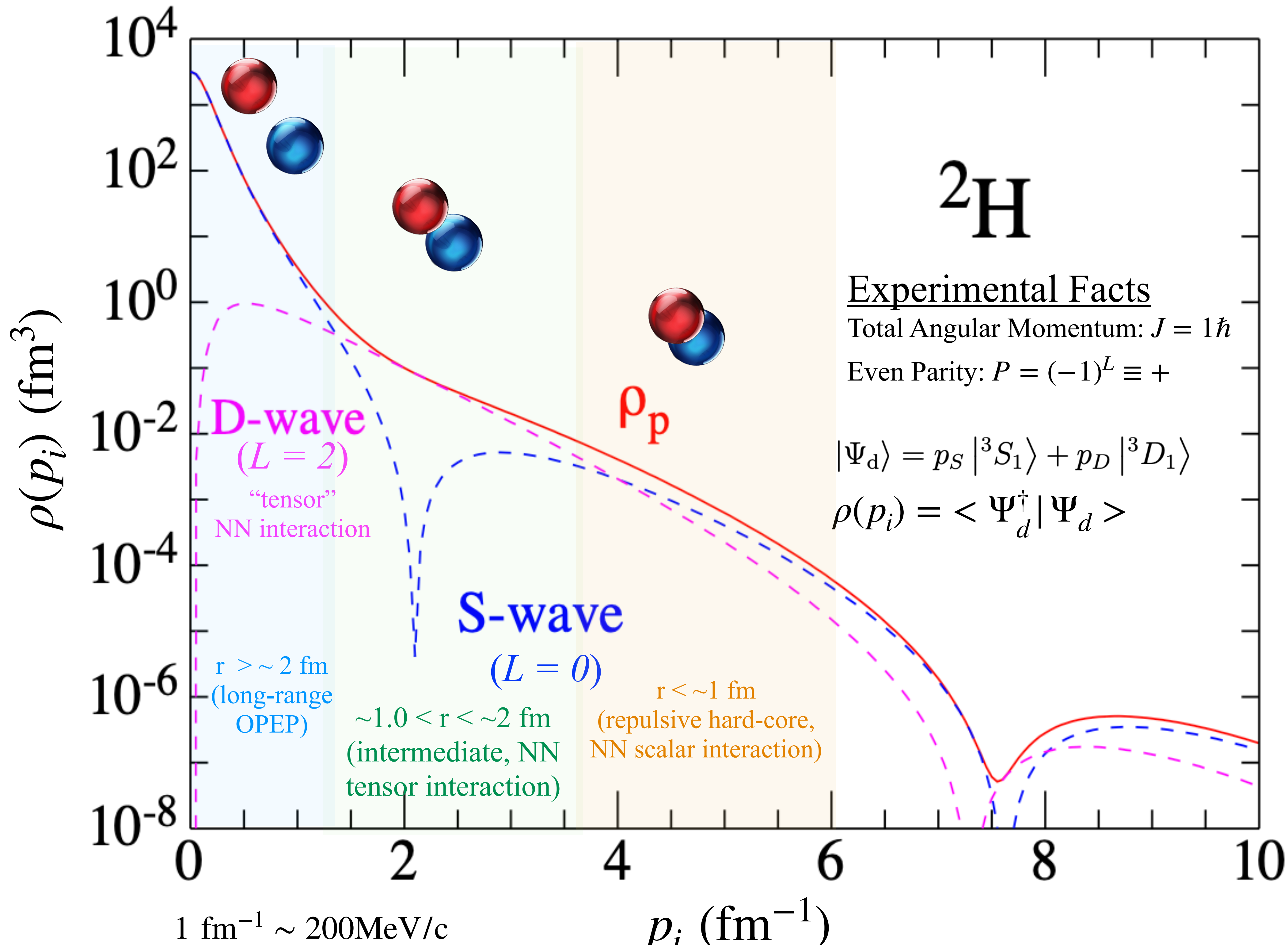
- d(e, e′p) ideal for nuclear core studies
  - most simple *np* bound system (no 3N forces or additional complications)
  - provides basis for short-range correlations in heavier nuclei (SRCs are deuteron-like)
  - reliable FSI calculations compared to heavier nuclei





Short-range part
NOT well understood ! ! !

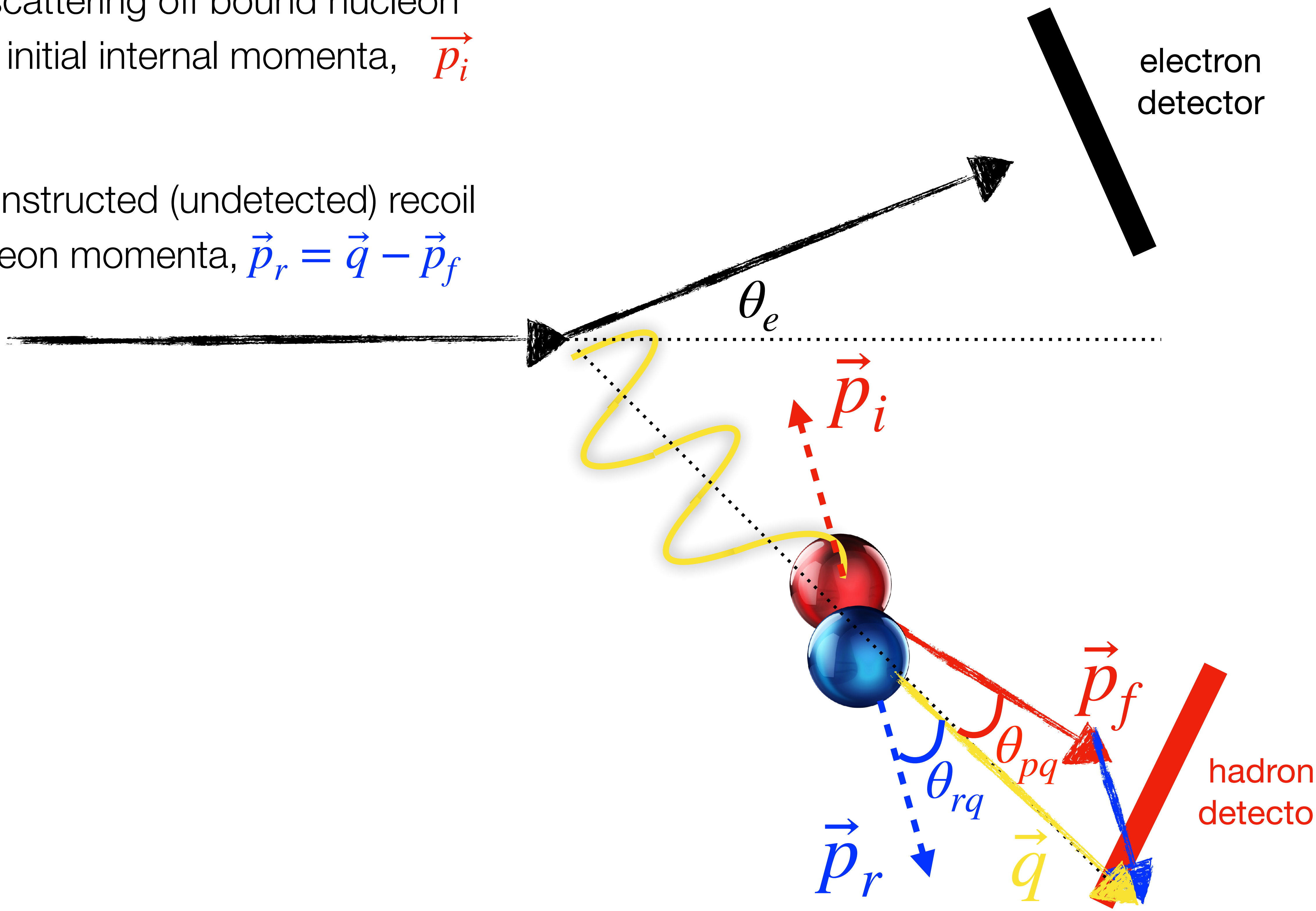
Momentum Distribution



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

Probing High-Momentum Structure

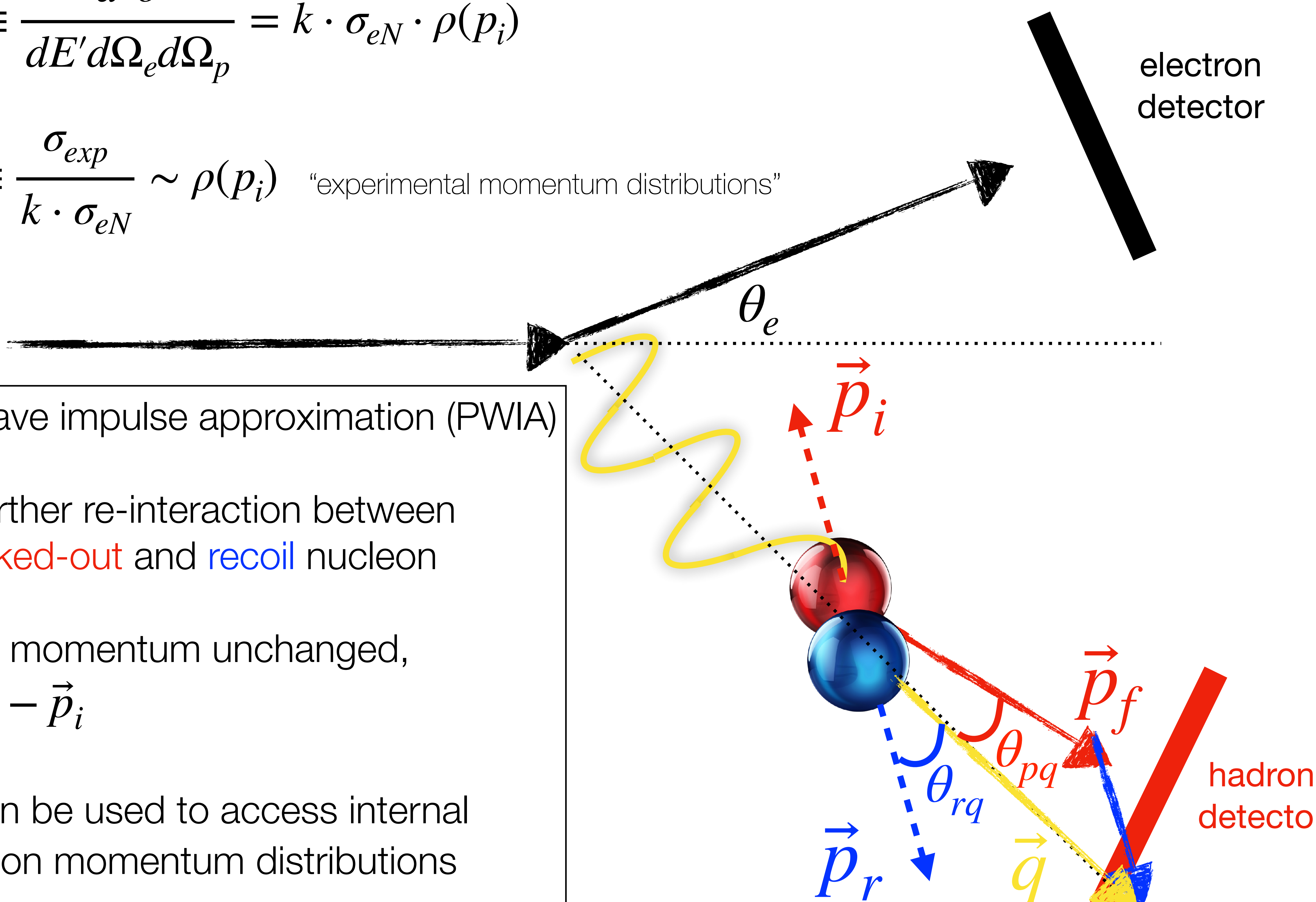
- e- scattering off bound nucleon with initial internal momenta, $\overrightarrow{p_i}$
- reconstructed (undetected) recoil nucleon momenta, $\vec{p}_r = \vec{q} - \vec{p}_f$



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"



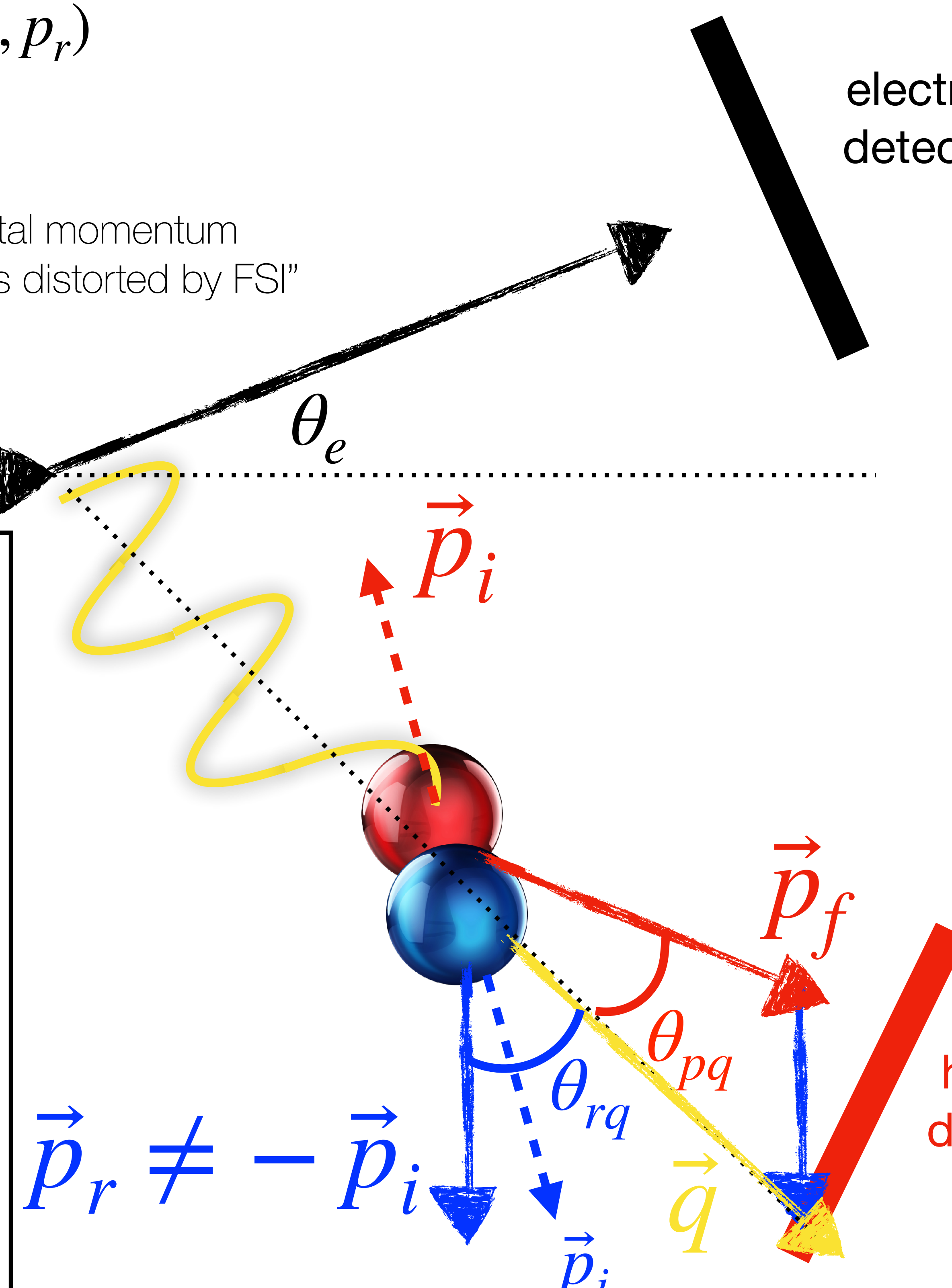
- plane-wave impulse approximation (PWIA)
  - no further re-interaction between knocked-out and recoil nucleon
  - recoil momentum unchanged, $\vec{p}_r \sim -\vec{p}_i$
  - $\vec{p}_r$ can be used to access internal nucleon momentum distributions

Probing High-Momentum Structure

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

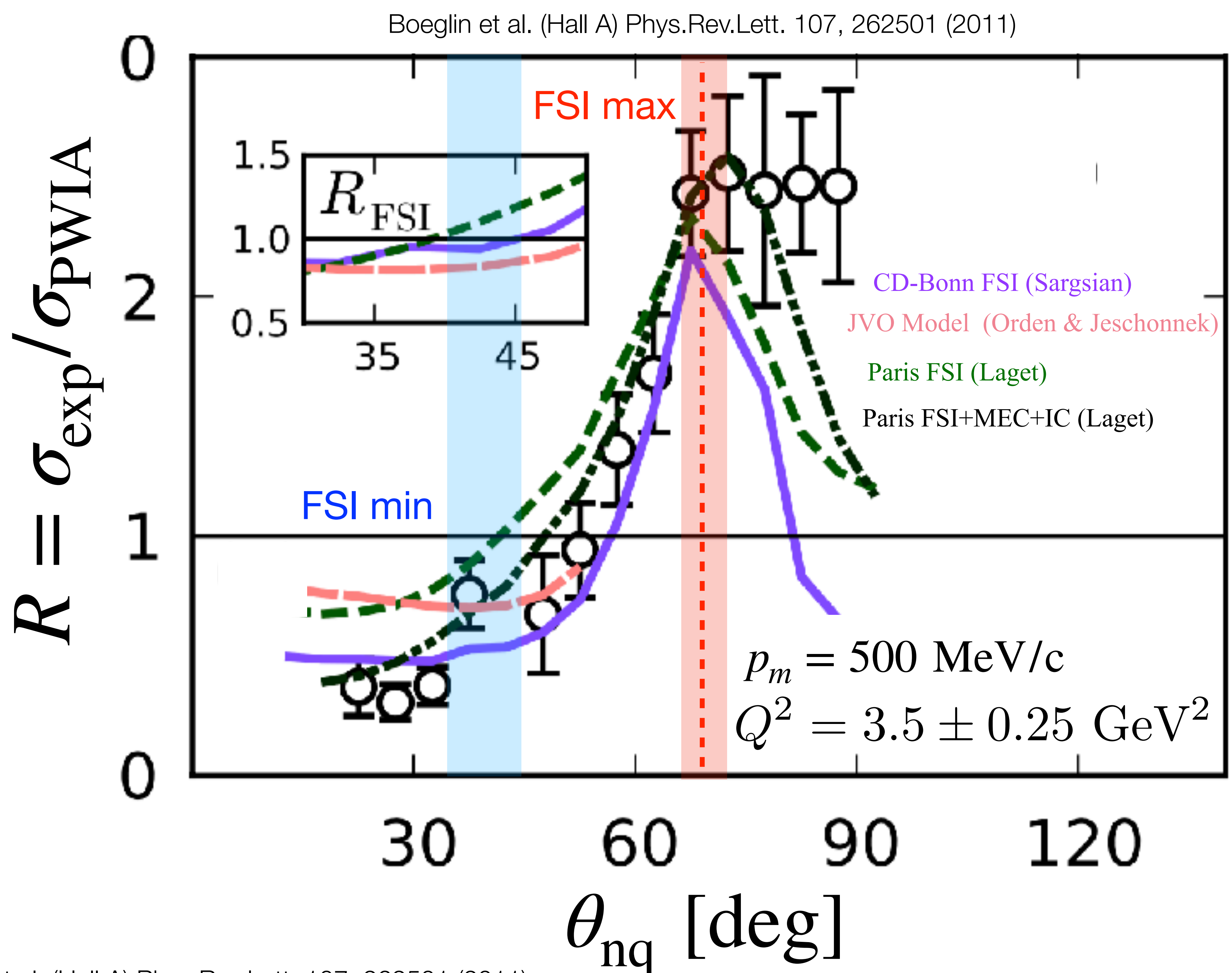
$$\sigma_{red} \equiv \frac{\sigma_{exp}}{k \cdot \sigma_{eN}} \sim \rho_D(p_i, p_r)$$

"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



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

K. S. Egiyan et al. (CLAS) Phys. Rev. Lett. 98, 262502 (2007)

Controlling Final-State Interactions

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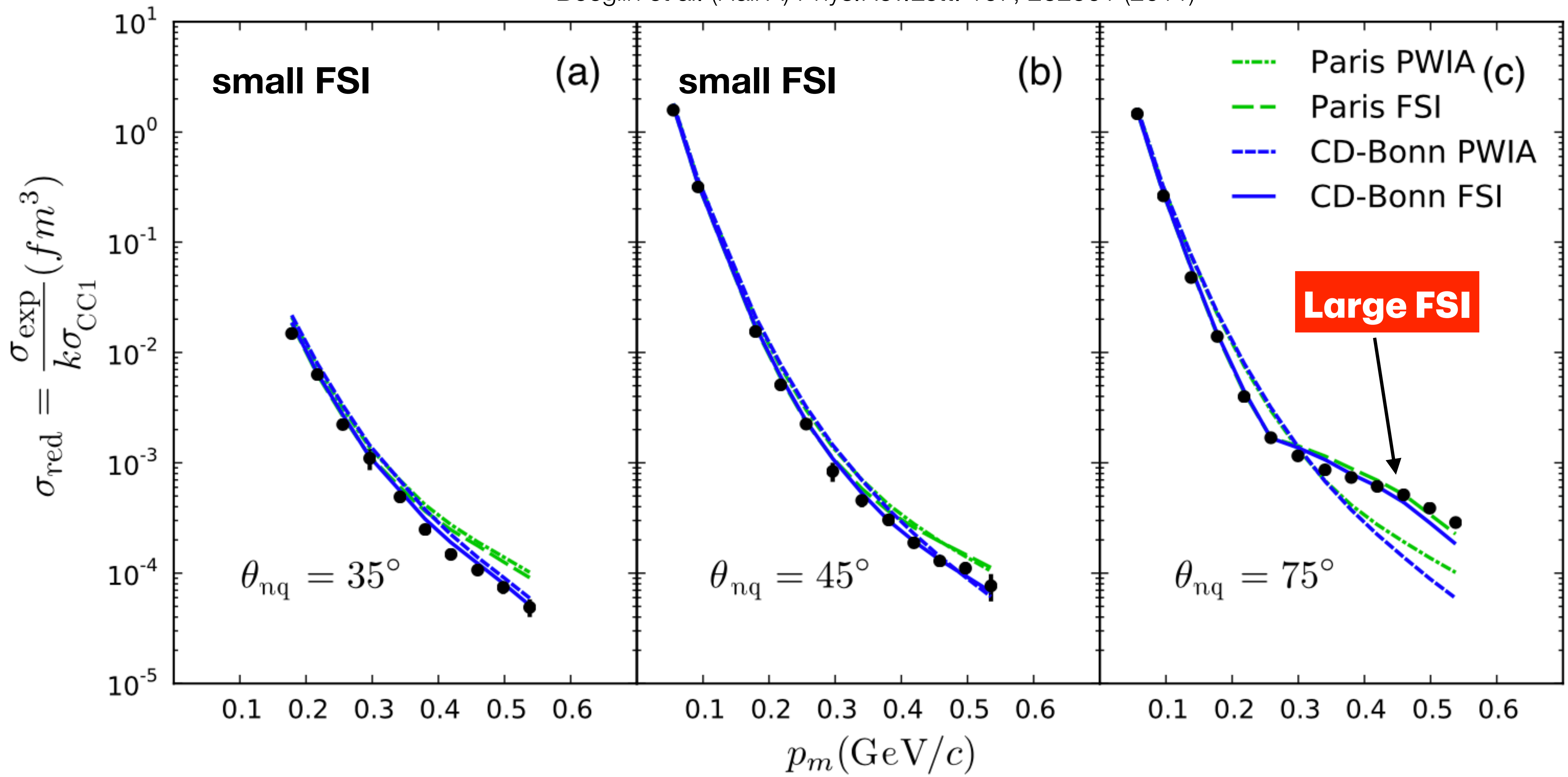
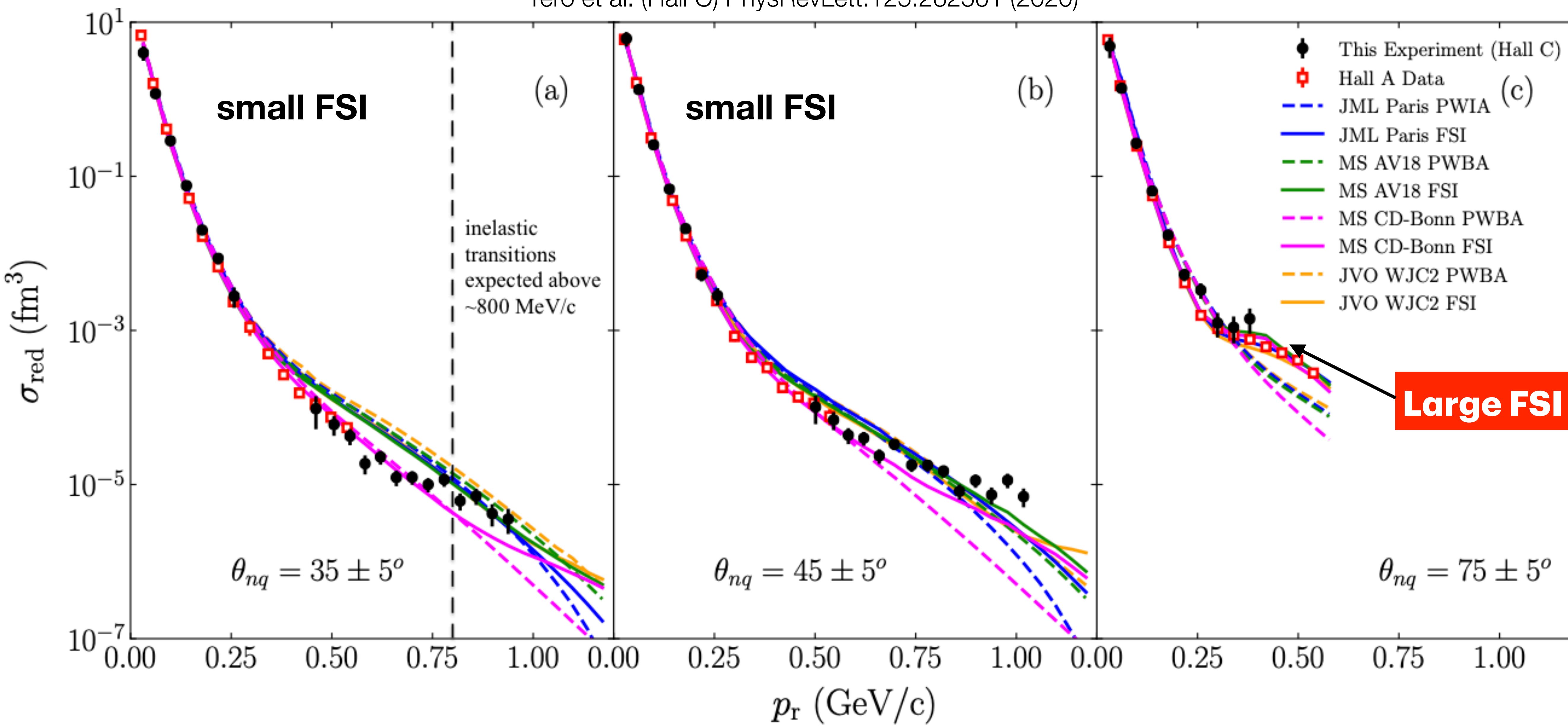


[Phys.Rev.C82014612]

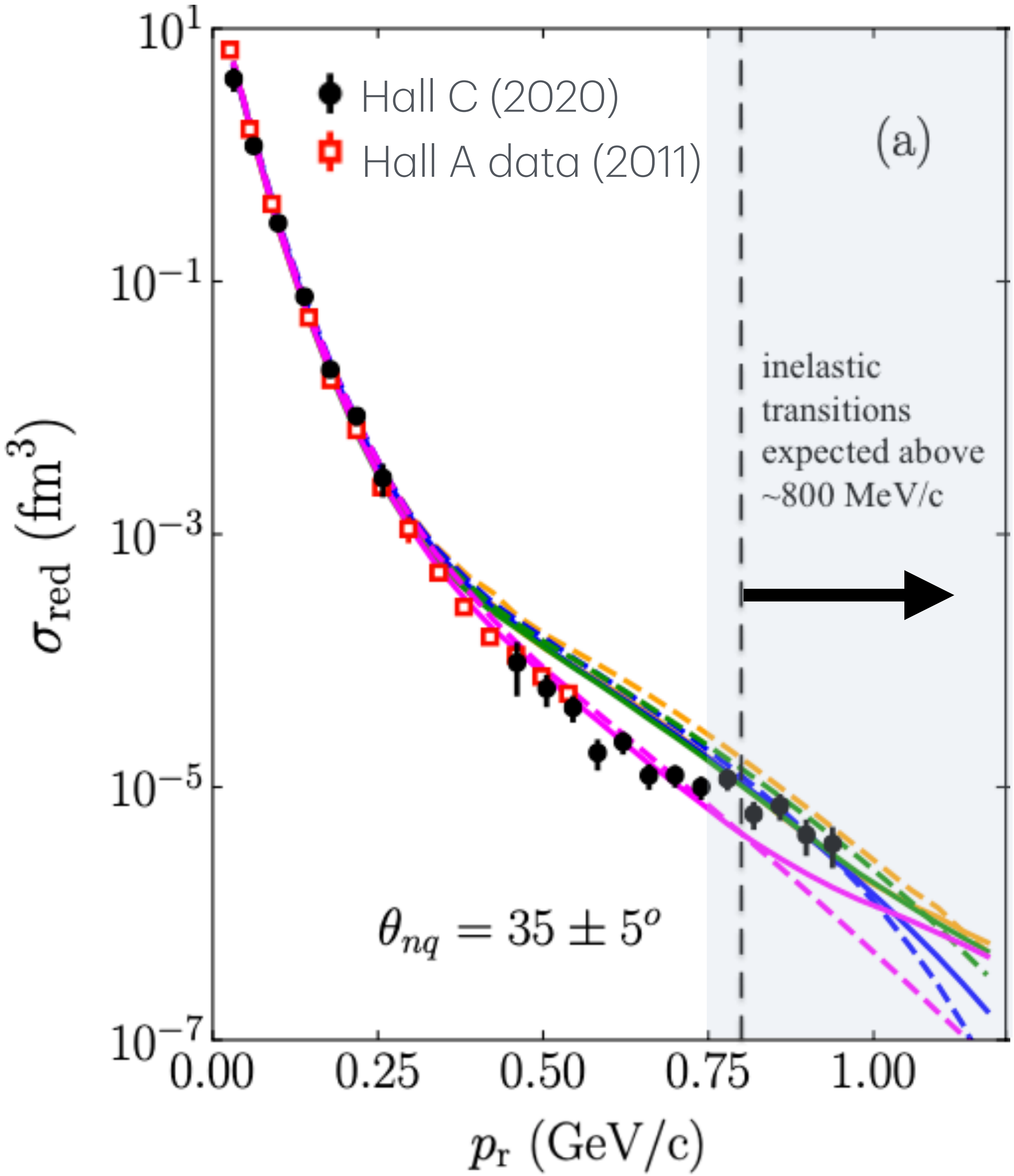
[Phys.Lett.B60949]

Probing the NN Repulsive Core

Yero et al. (Hall C) PhysRevLett.125.262501 (2020)



Probing the NN Repulsive Core

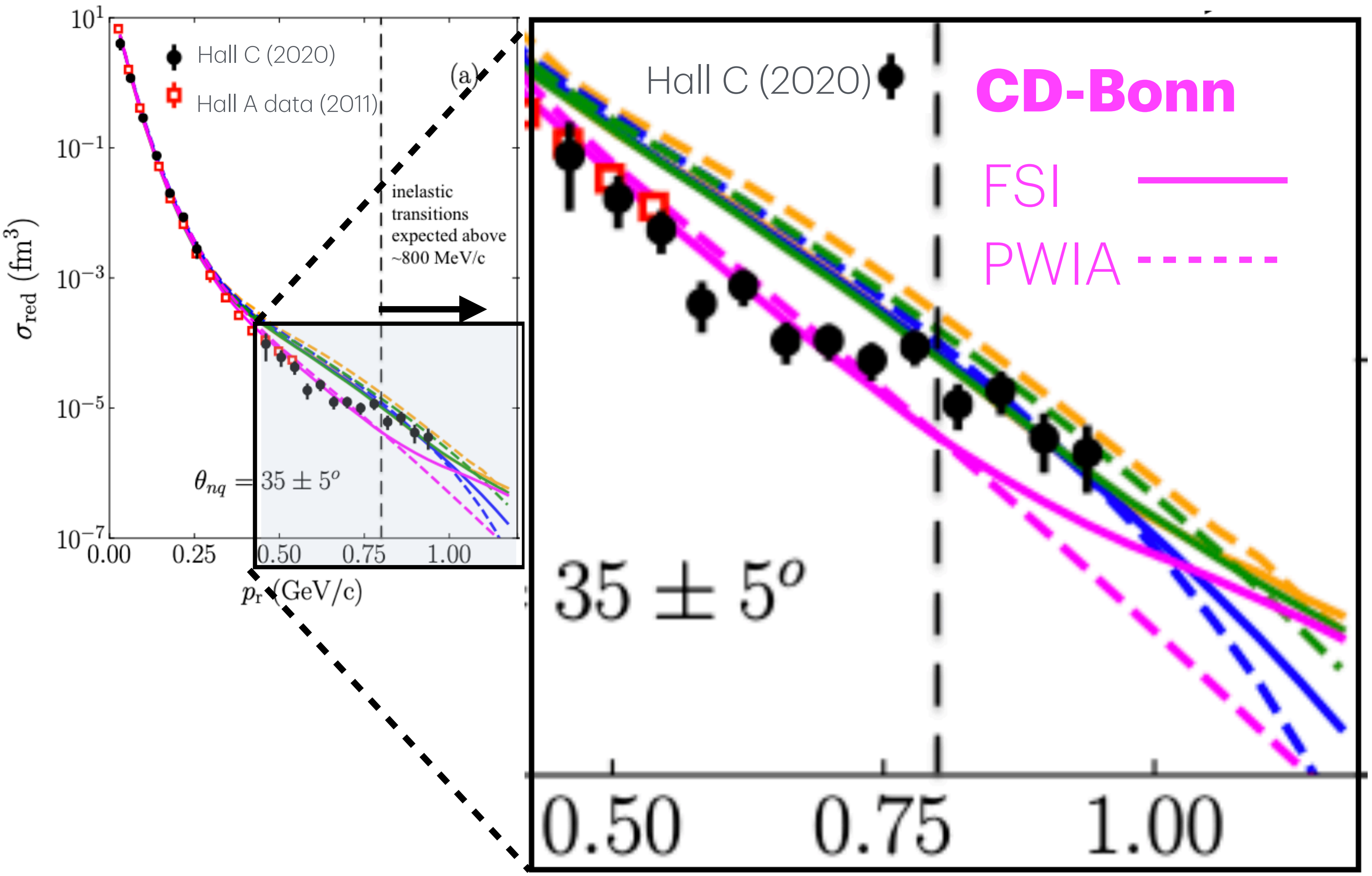


VNA Theoretical Framework

- only $pn \rightarrow pn$ transitions (non-nucleonic transitions explicitly excluded)
- accounts for relativistic dynamics of γ^*N and FSI (GEA)
- initial-state deuteron w.f. is *non-relativistic*

Virtual Nucleon Approximation (VNA) treats the bound nucleon as off-energy shell and uses deuteron w.f. which accounts for baryonic number conservation

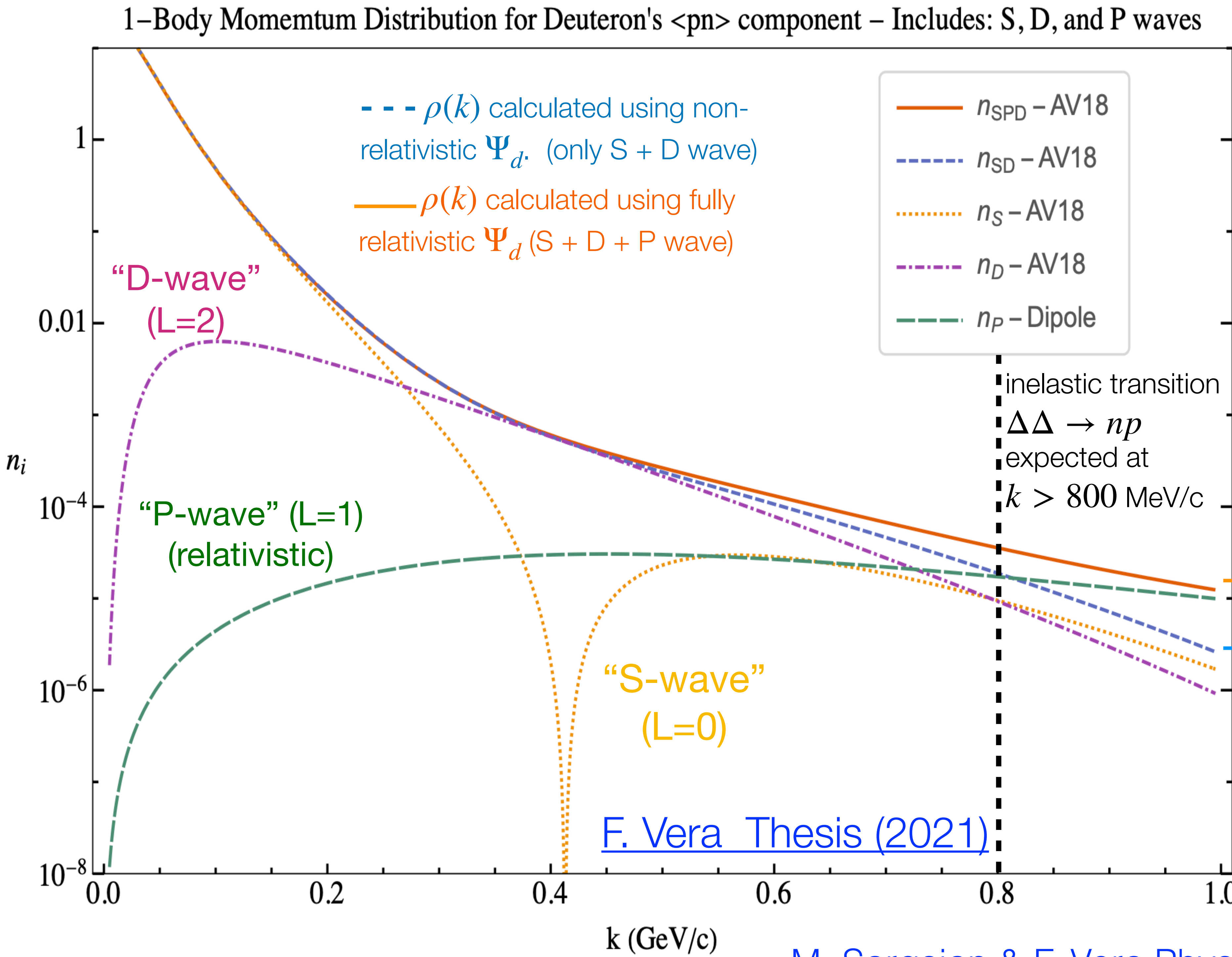
Probing the NN Repulsive Core



NO theoretical calculation is able to reproduce the data above $p_r \sim 750$ MeV$/c$

Inelastic $\Delta\Delta \rightarrow np$ transitions inside deuteron expected to become dominant above $p_i \sim 800$ MeV$/c$

Probing the NN Repulsive Core



- using a fully relativistic initial- *pn* state Ψ_d with the inclusion of non-nucleonic components, gives rise to the presence of a P-wave (L=1) -like structure (in violation of the "angular condition")
- 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

fully-relativistic Ψ_d

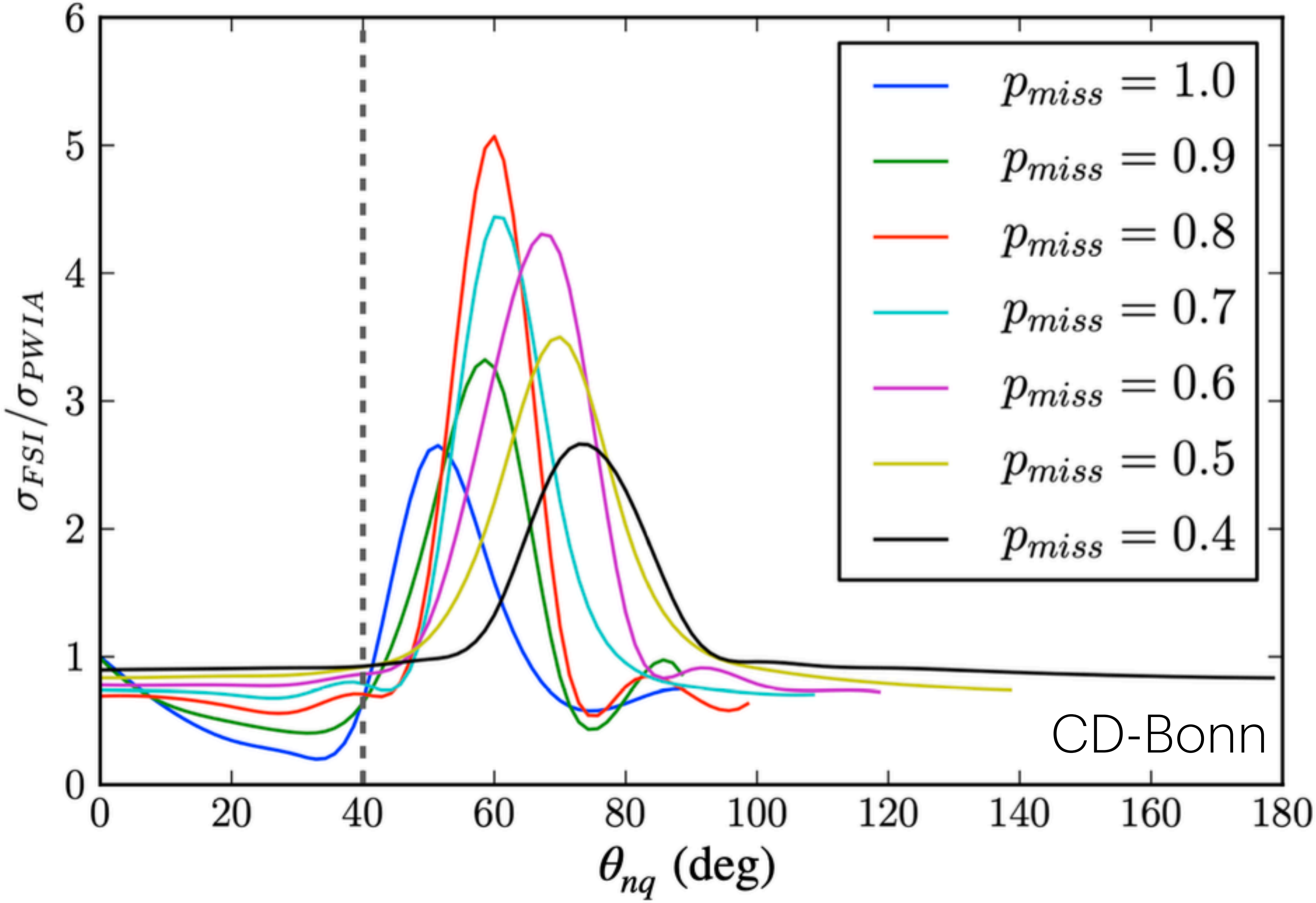
VNA (non-relativistic Ψ_d)

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

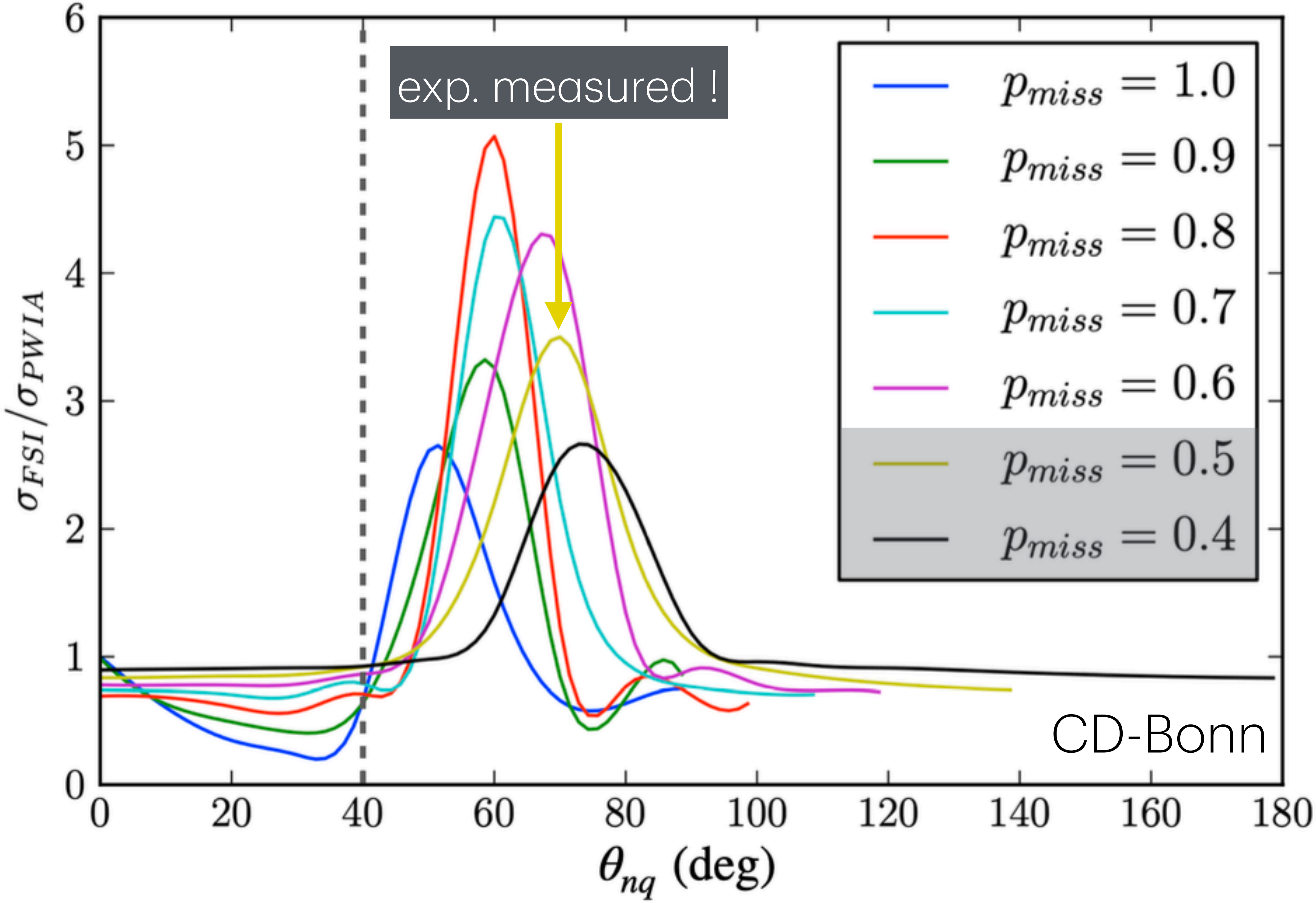
non-relativistic relativistic (nucleonic + non-nucleonic)

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

NN Repulsive Core Sensitivity to FSI



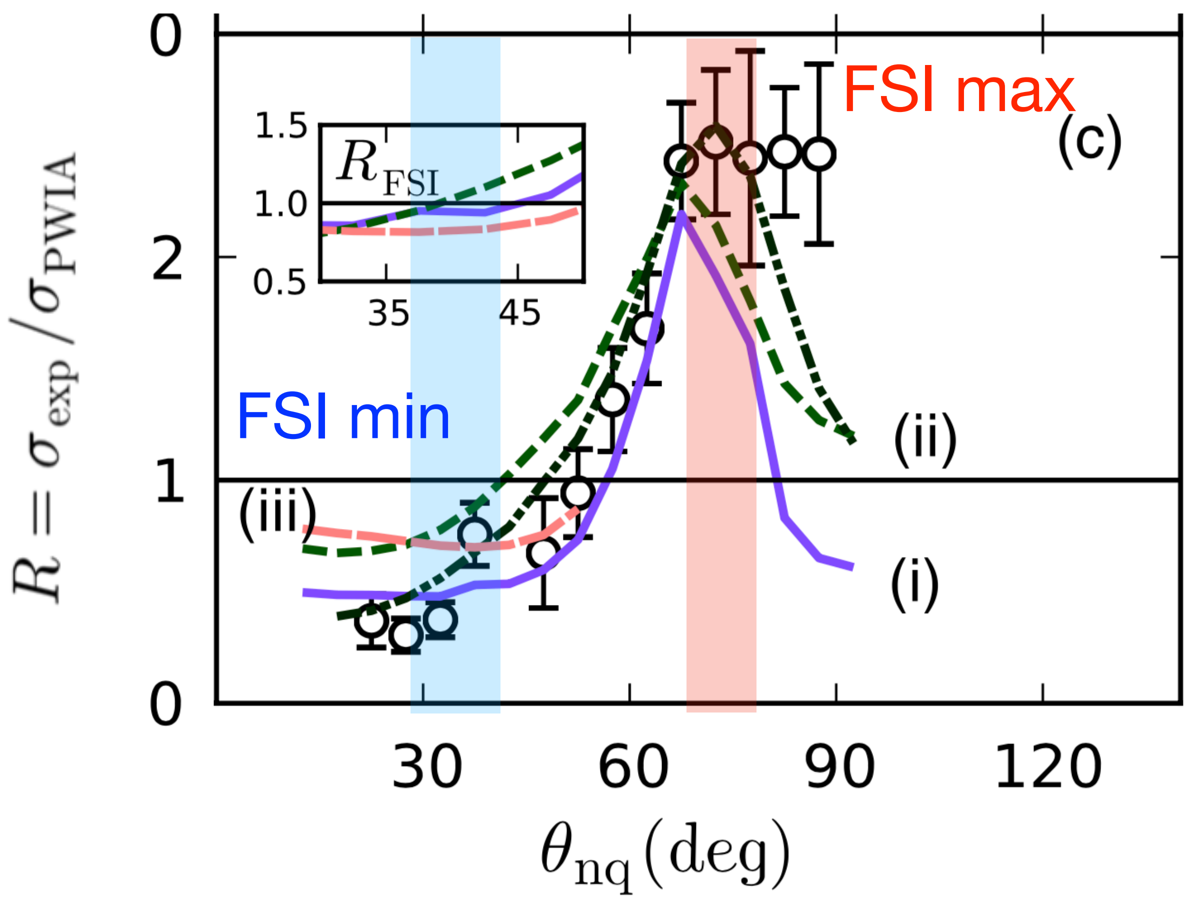
NN Repulsive Core Sensitivity to FSI



NN Repulsive Core Sensitivity to FSI

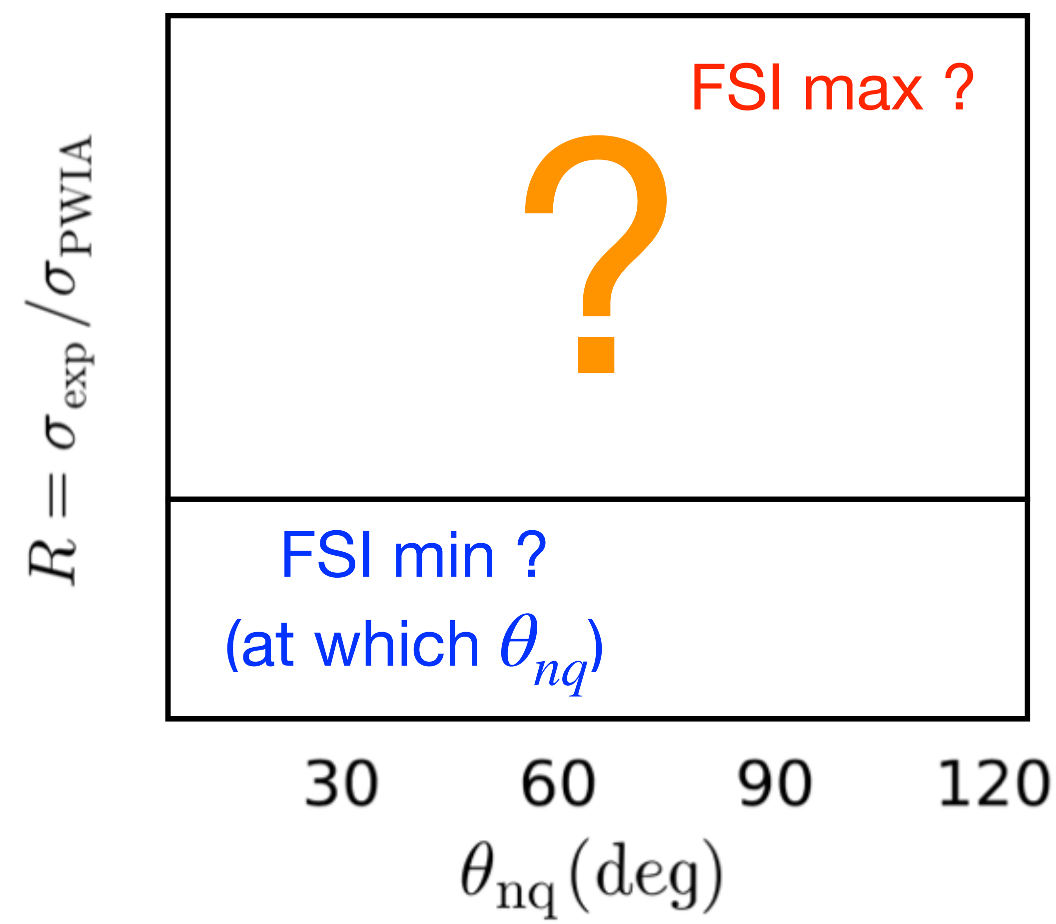
exp. measured !

$P_m = 500$ MeV/c, $Q^2 = 3.5$ GeV^2



NO data !

$P_m > 500$ MeV/c, $Q^2 = 4.5$ GeV^2



- determine angular dependence of FSI + quantify FSI contributions
- test relativistic limit of the various FSI theoretical models

looking for a possible signature of non-nucleonic components in the deuteron

1. measure angular distribution ($R = \sigma_{exp}/\sigma_{PWIA}$ vs. θ_{nq}) at $p_r \sim 800$ MeV/c where non-nucleonic components are expected to become important (already observed an anomaly in this region, see Yero 2020 *et al.*)

2. determine at which recoil angle $\theta_{nq'}$ the ratio $R \sim 1$ (small FSI) and extract the corresponding reduced cross-sections as a function of missing momenta corresponding to that particular θ_{nq}

3. Compare the reduced cross-section measurements to full relativistic calculations with FSI including **only** the np component; exclude non-nucleonic components $\Delta\Delta \rightarrow np$, ... etc (use relativistic initial-state deuteron w.f.)

   (i) if the calculations describe the data, as it does for < 650 MeV/c, then we conclude that the discrepancy was only due to relativistic effects

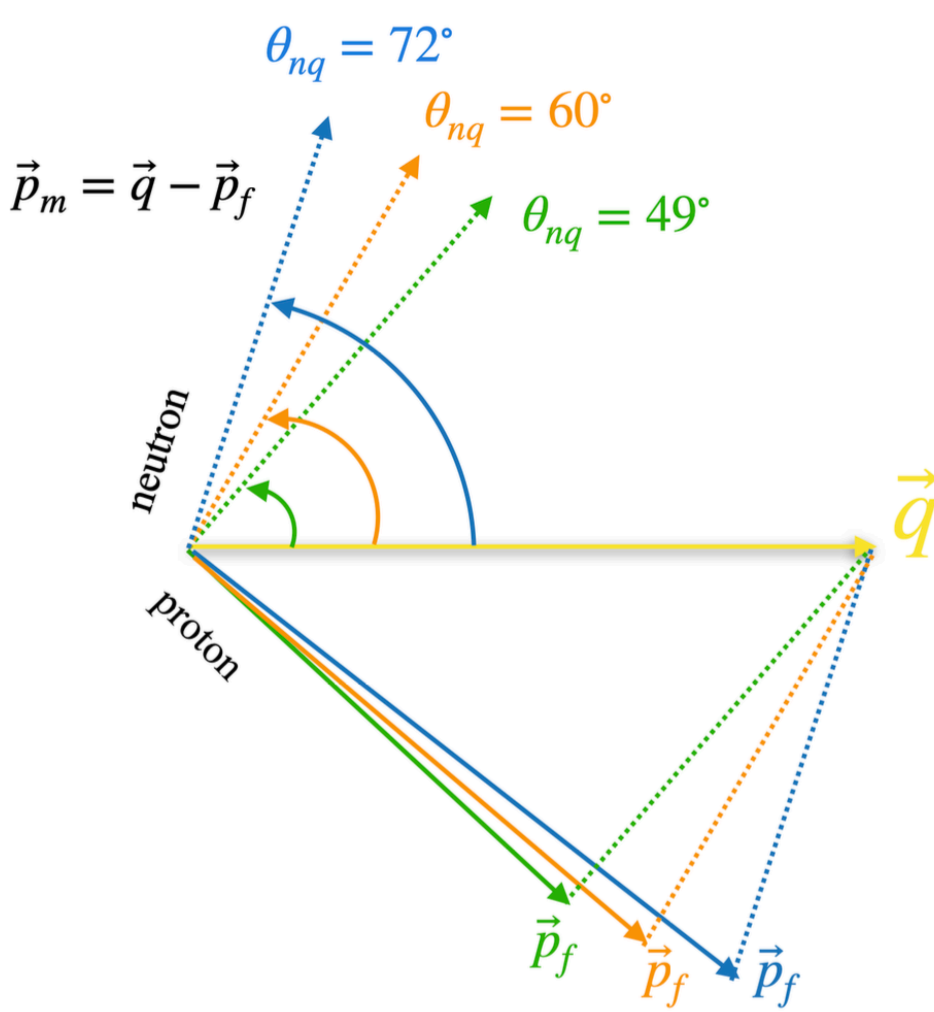
   (ii) if calculations do not describe data, then this could indicate the emergence of possible non-nucleonic components inside the deuteron;

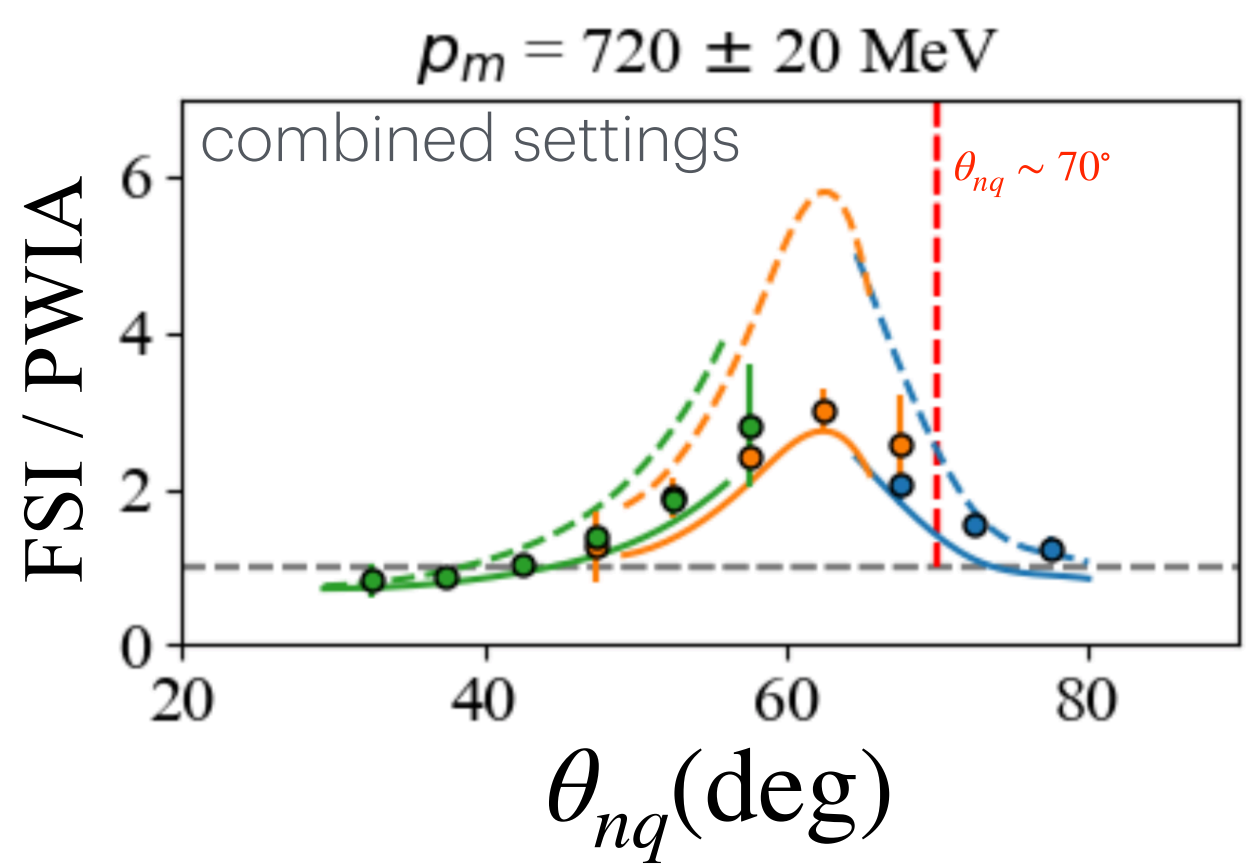
   the existence of non-nucleonic components will result in a violation of so-called "angular condition", in which case the extracted light-cone momentum distribution of the deuteron will depend on light cone momentum k and its transverse component $k_\perp$ independently

This Proposal: Kinematics

$E_b = 10.55$ GeV
10 cm LD2

p_{m} (MeV/c)	θ_{nq} (deg)	k_{f} (GeV/c)	θ_e (deg)	p_{f} (GeV/c)	θ_p (deg)	
500	70	8.151	13.14	3.069	44.17	calibration setting
800	49	8.551	12.82	2.468	54.85	3 main kinematics
	60	8.151	13.14	2.891	49.27	
	72	7.552	13.65	3.516	41.57	



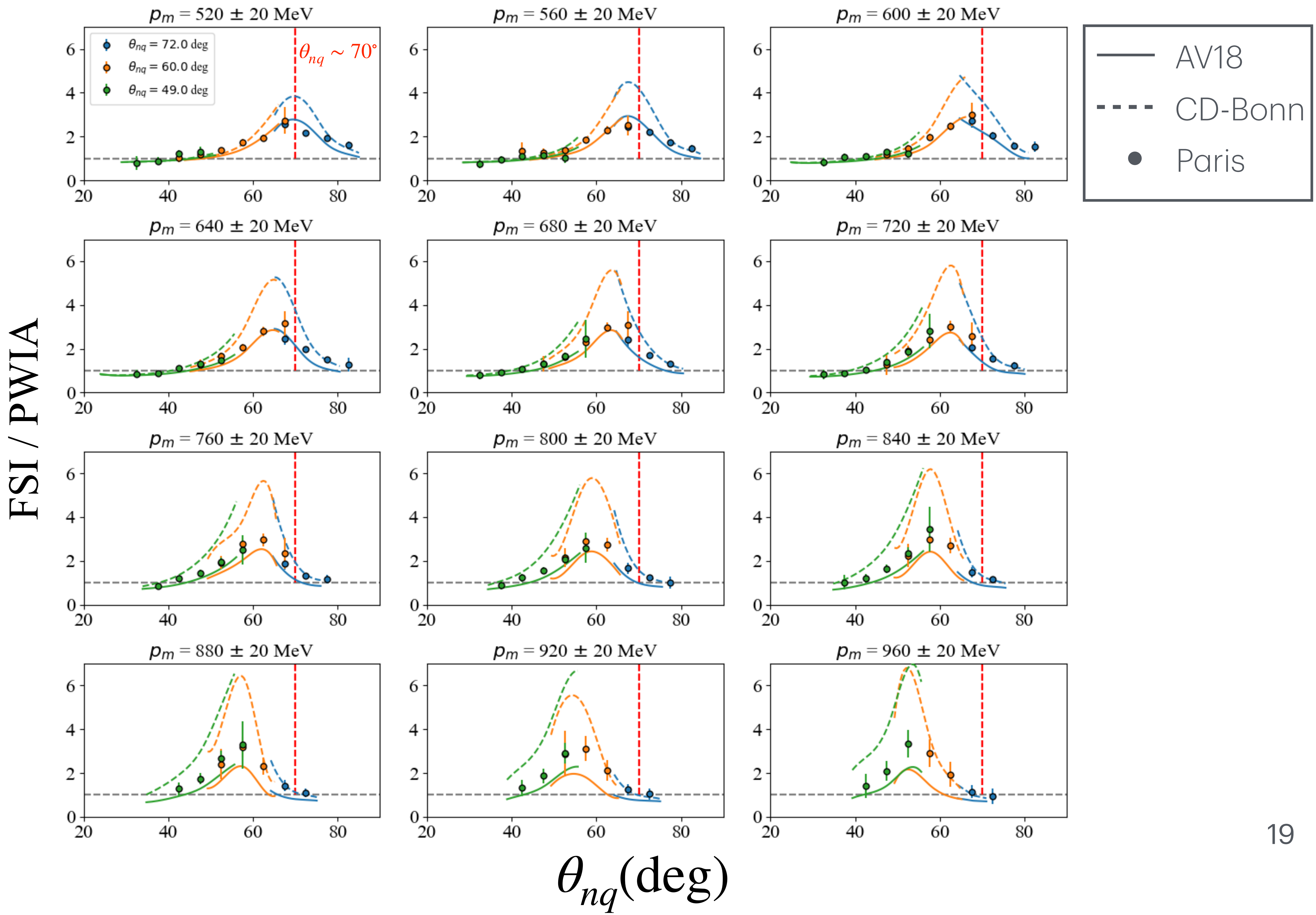


This Proposal: Beam Time Request

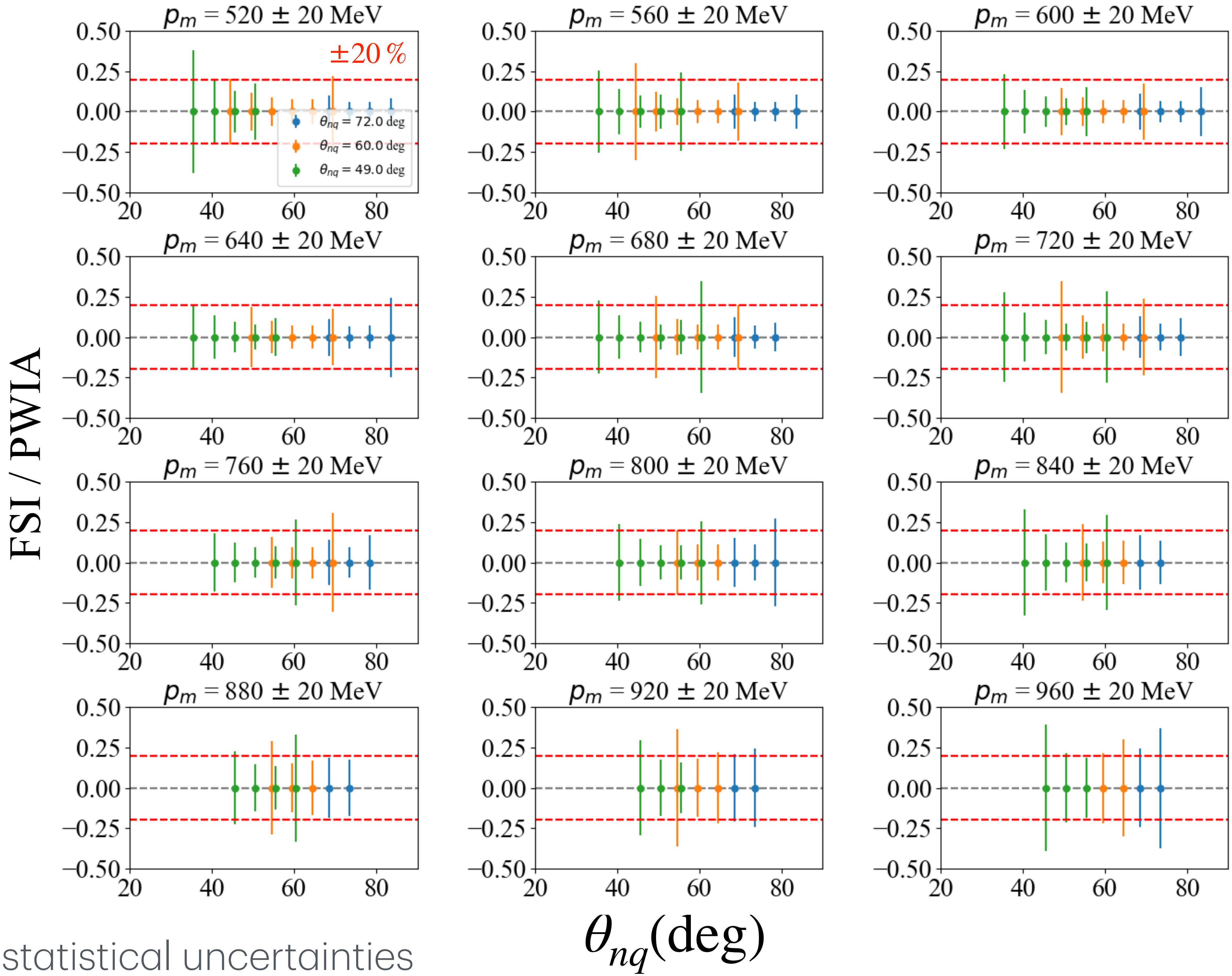
target	current (μA)	p_m (MeV/c)	θ_{nq} (deg)	data-taking (hrs)	overhead (hrs)	
LD2	80	500	70	24	2	
LD2	80	800	49	200	2	
			60	144	2	
			72	160	2	
LH2	80	^{1}H$(e, e'p)$ elastic		8		
C12/LD2/LH2	10-80	target boiling		2		
no target	0-80	BCM calibration		2		
		total		540 (23 PAC days)	8	**548 hrs**

We request a total of **548 hrs (23 PAC days)**

Projections: FSI / PWIA Angular Distributions



Projections: FSI / PWIA Angular Distributions



only statistical uncertainties

Estimated Uncertainties

Statistical: $\leq 10\,\%$

Systematics:

Normalization: $\sim 3 - 4\,\%$ (BCM calibration, DAQ 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 that 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)

Conclusion

This experimental proposal main objectives are:

1. determine and quantify the angular dependence of FSI at recoil momenta ~800 MeV/c, where non-nucleonic effects are expected to emerge in the ground state of deuteron wave function

2. test the relativistic limit of various FSI theoretical models

Novelty of this Proposal:

The novel results of this proposed experiment will be a determinant factor to obtain a signature of non-nucleonic components of the deuteron, as isolating the momentum distribution of the deuteron without effects of final-state interactions at different neutron recoil angles is a pre-requirement

Thank You