Probing the Nuclear Repulsive Core via Electro-Disintegration of Tensor-Polarized Deuterium

October 14, 2025

C. Yero

Jefferson Lab

Exclusive electro-disintegration of tensor polarized deuterium (PAC53)

Letter of Intent (submitted)

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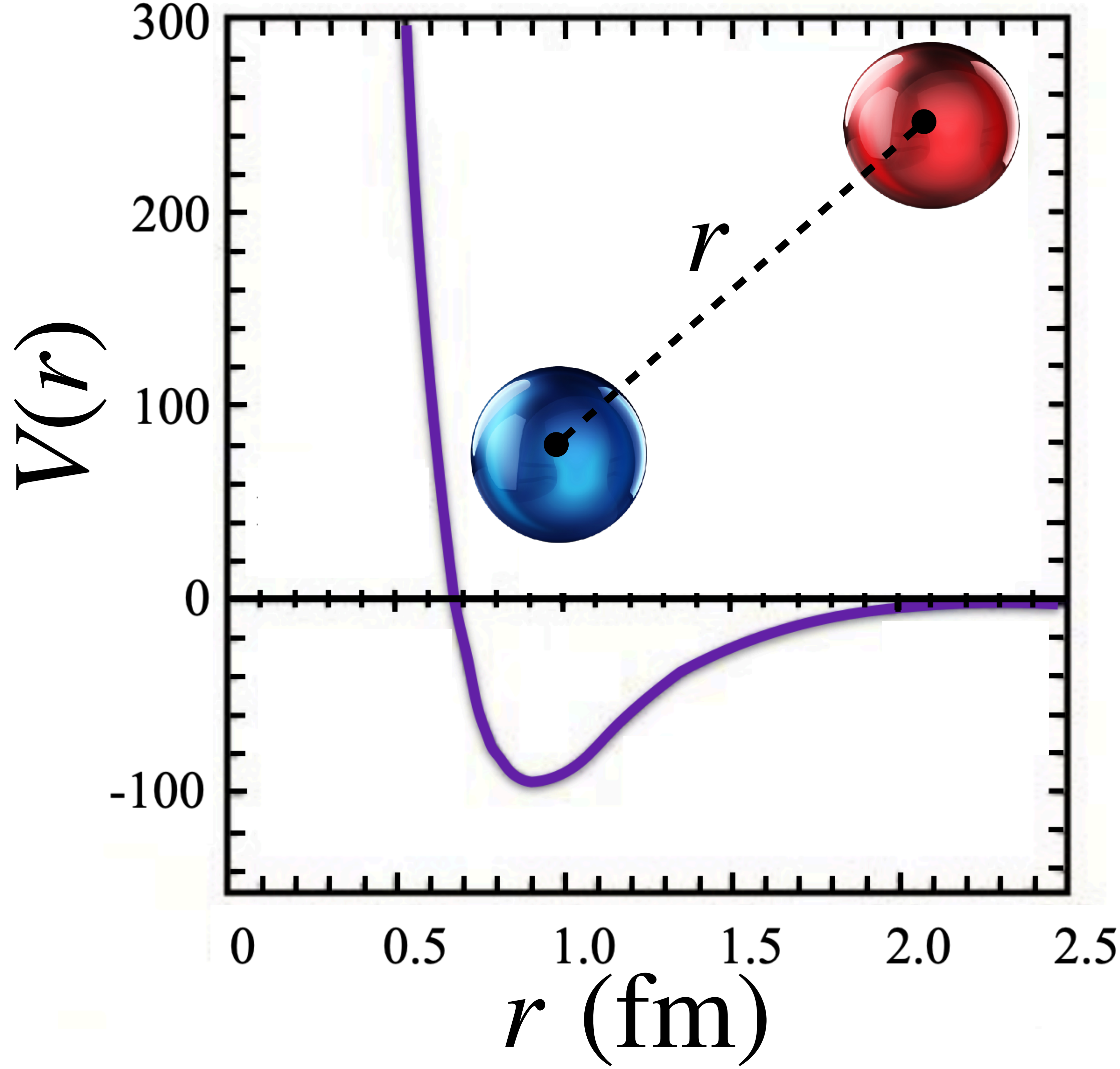
what is the dynamical origin of repulsive core ?



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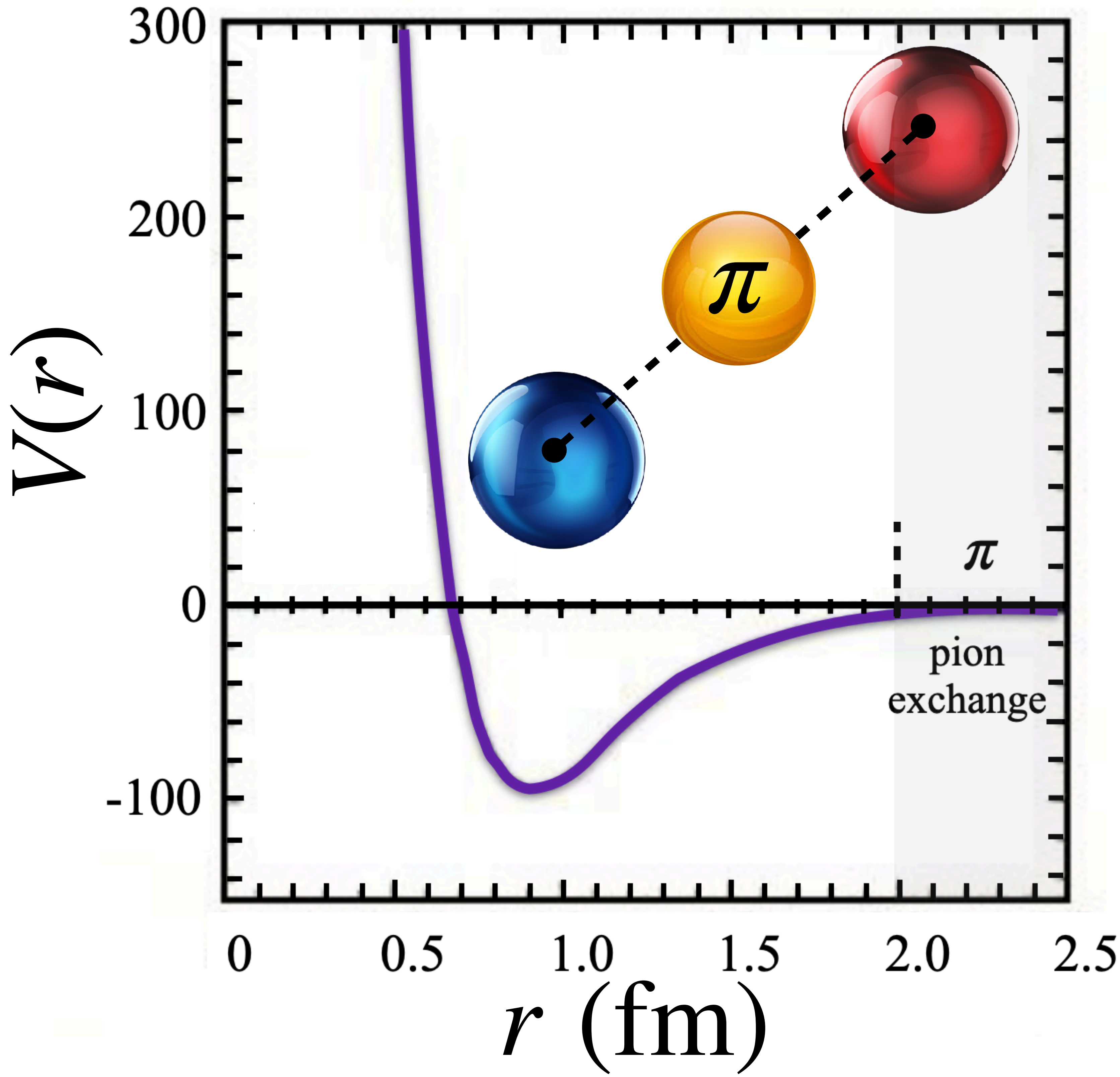

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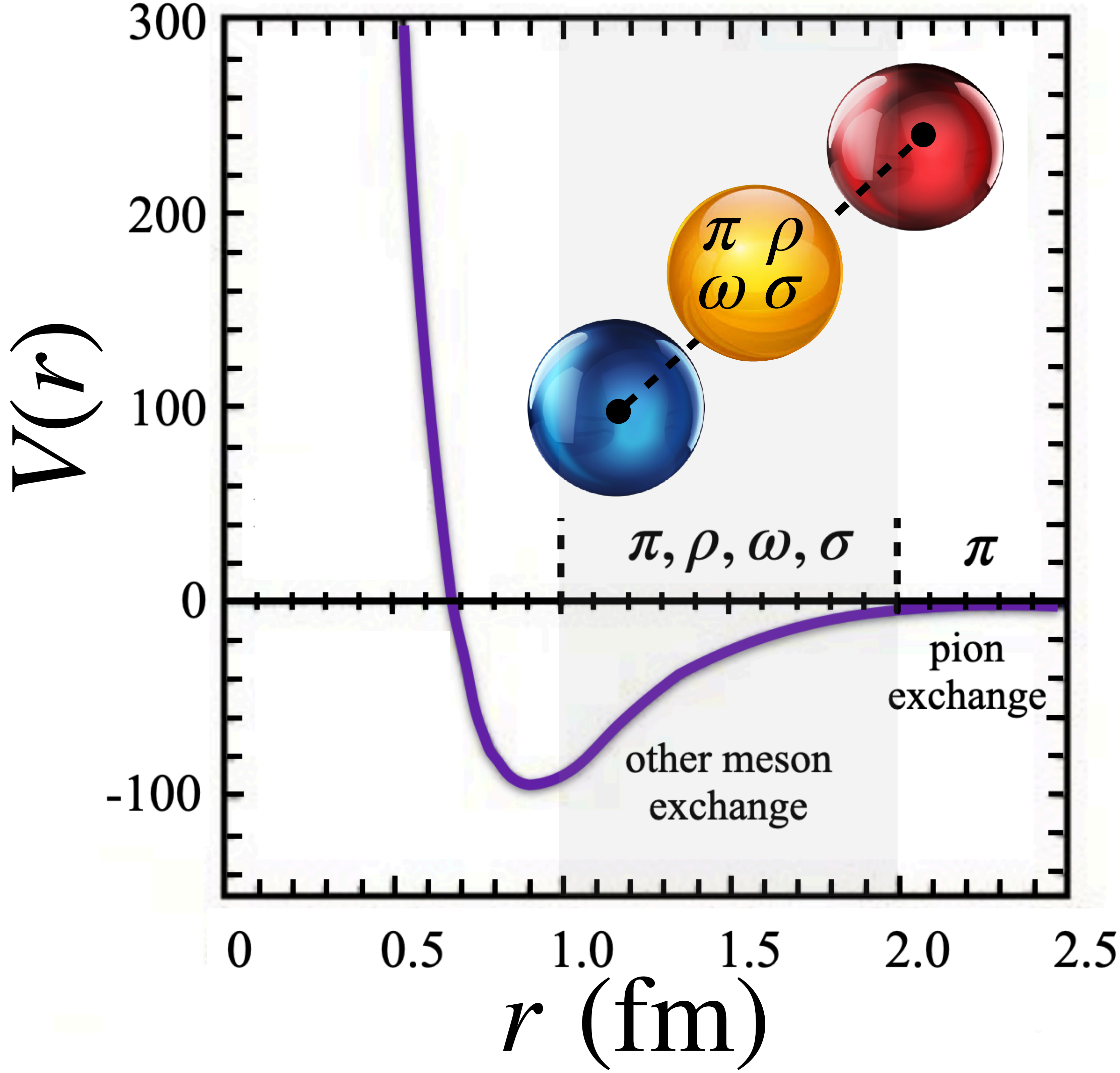

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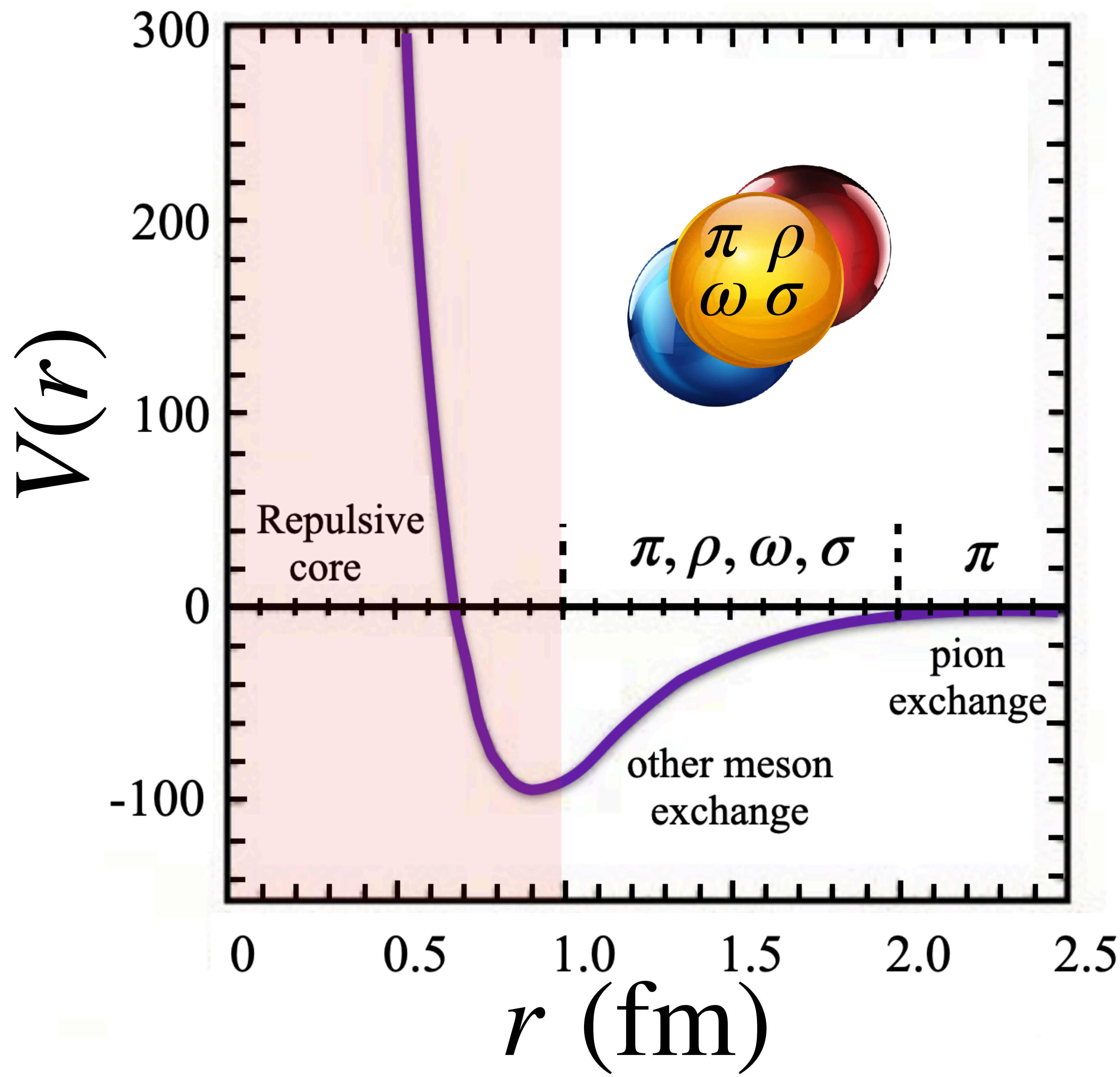
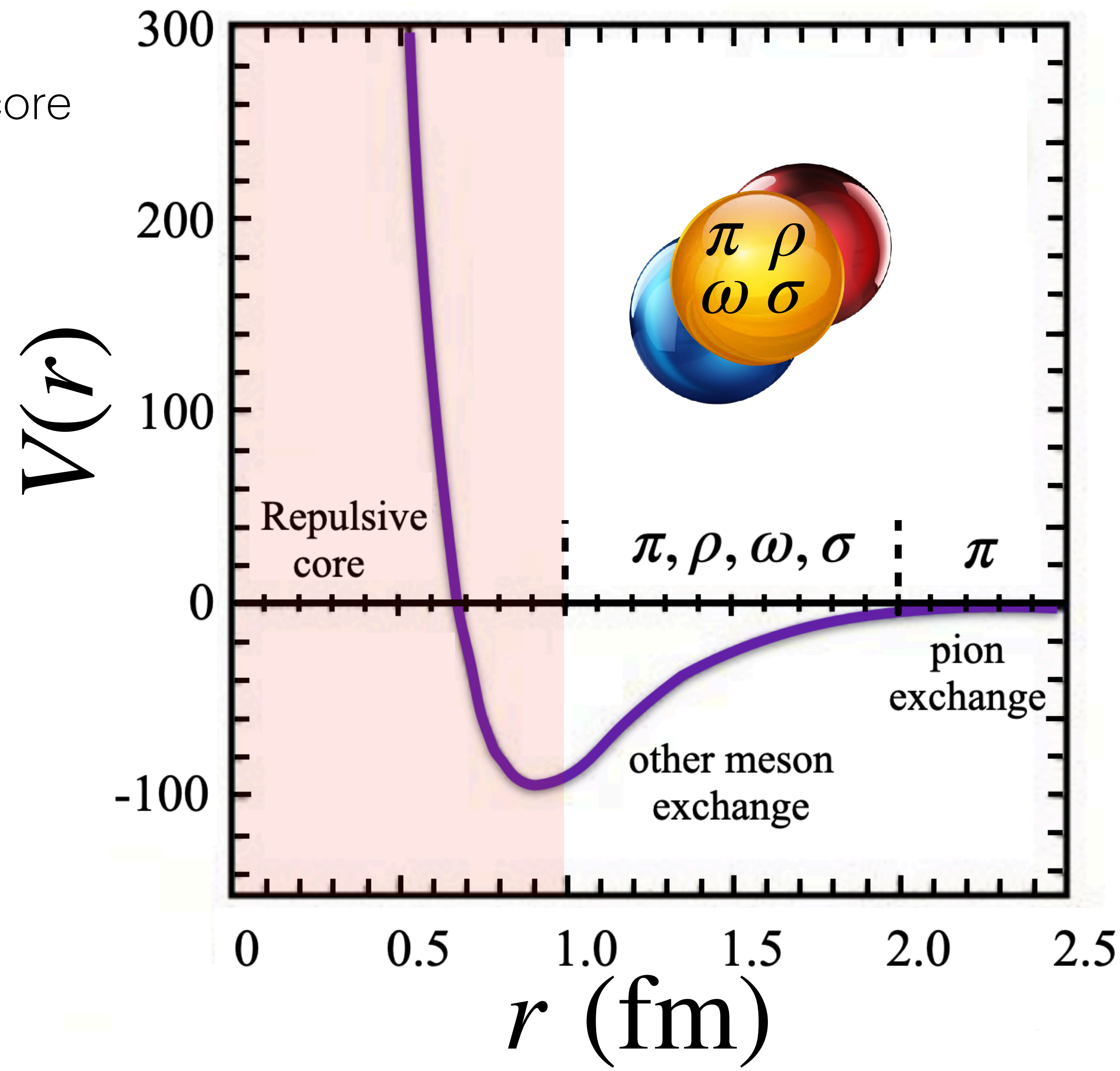


what is the dynamical origin of repulsive core ?

- theoretical challenges
  - 1950s: meson theory **FAILS** to describe repulsive core (meson radius at least size of NN overlap)



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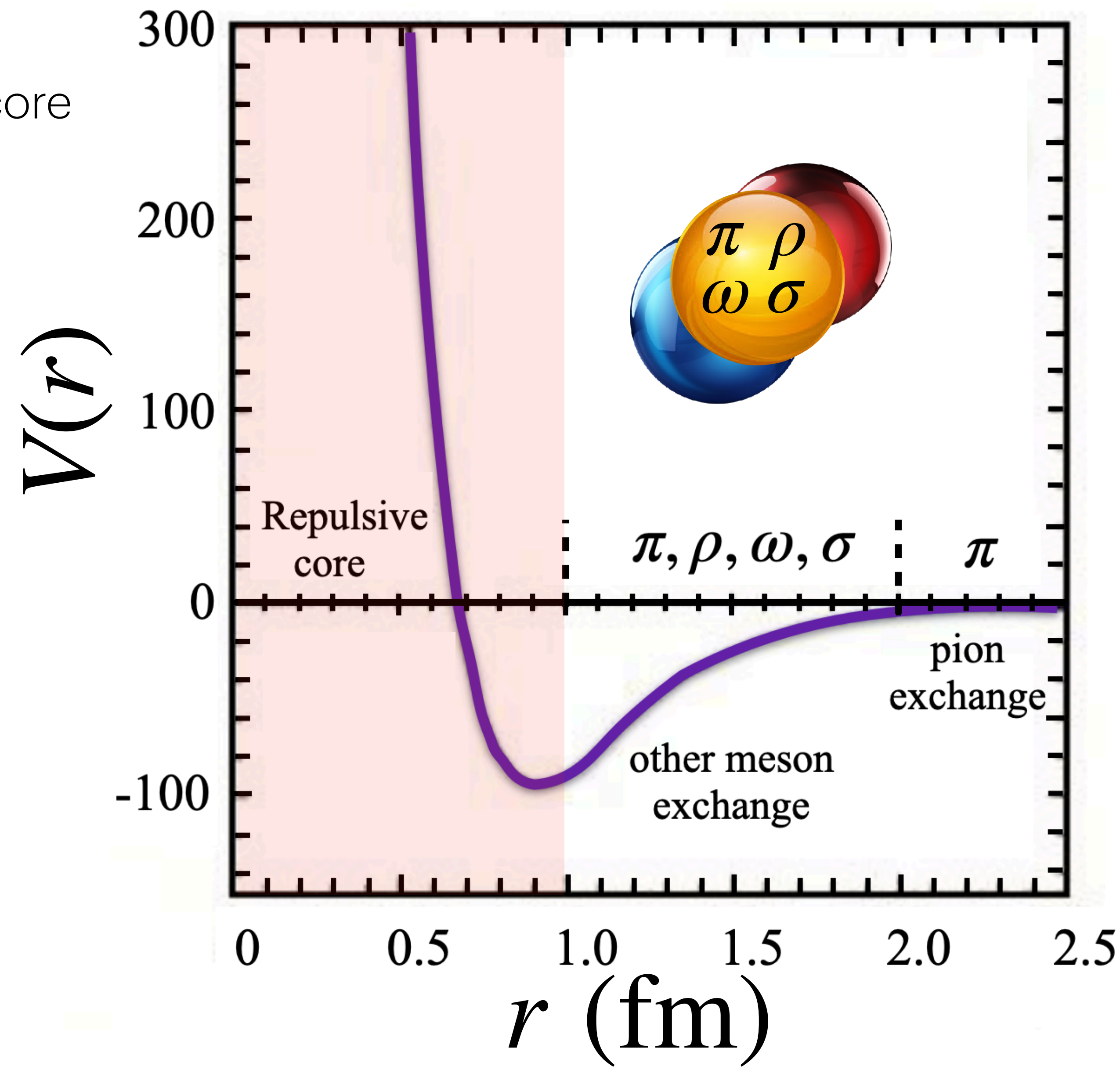
  - 1960s: development of phenomenological models (still use *ansatz* to describe the repulsive core)



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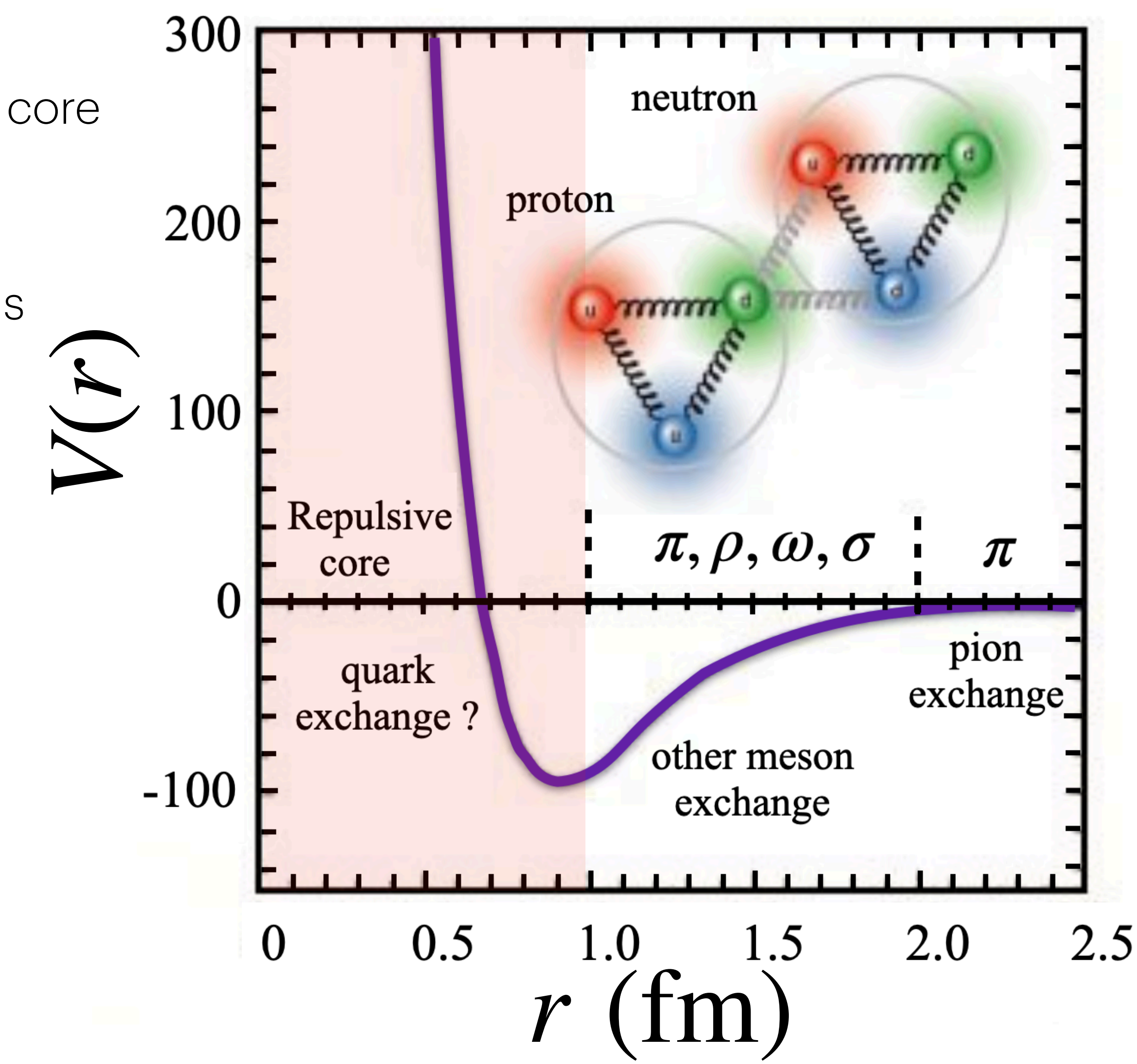
  - 1970s: discovery of quarks/gluons; repulsion expected due to Pauli Exclusion on overlapping quarks, but exact mechanism unclear (quark/gluon exchange ?, inelastic transitions ?, . . . etc.)



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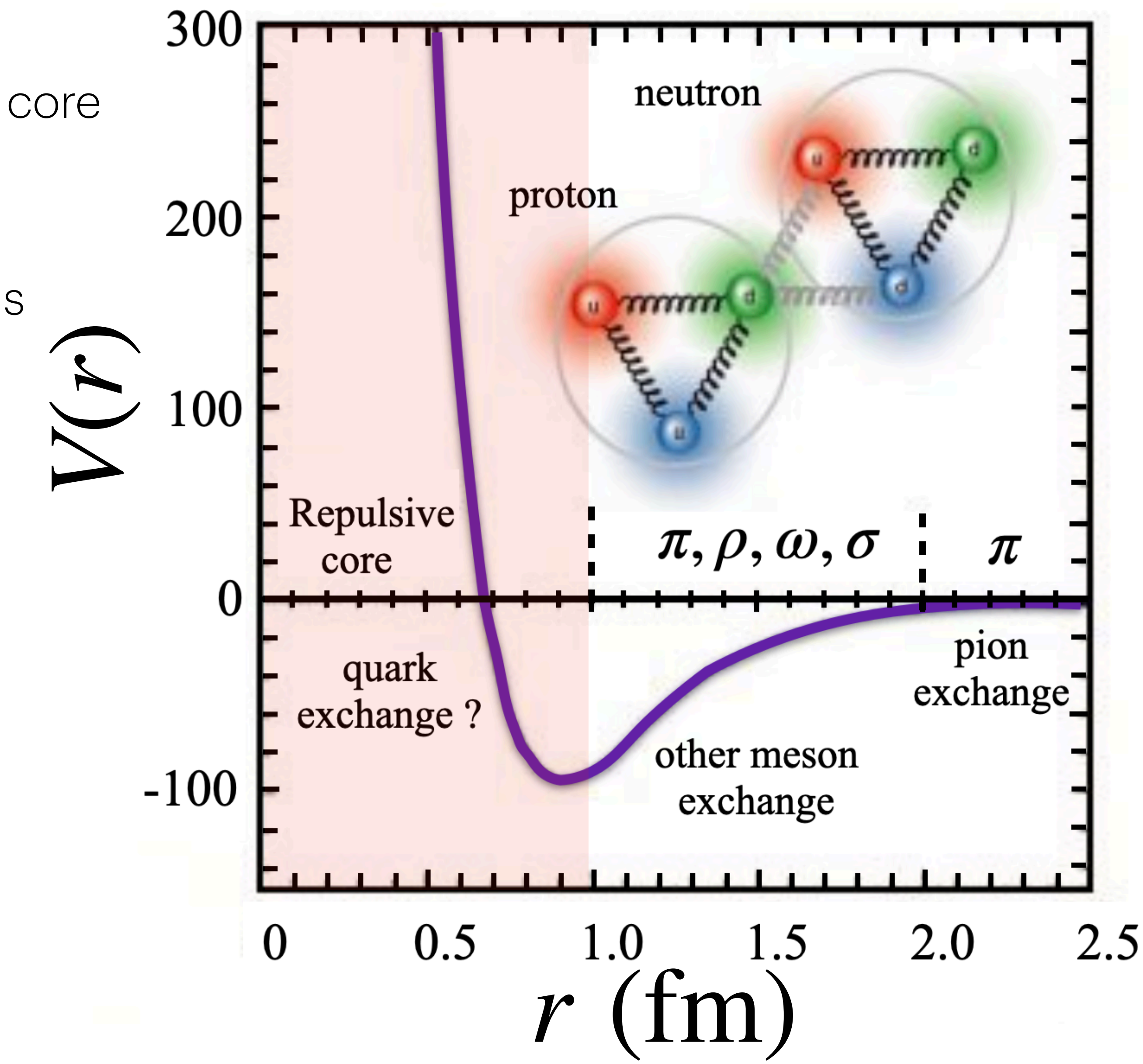
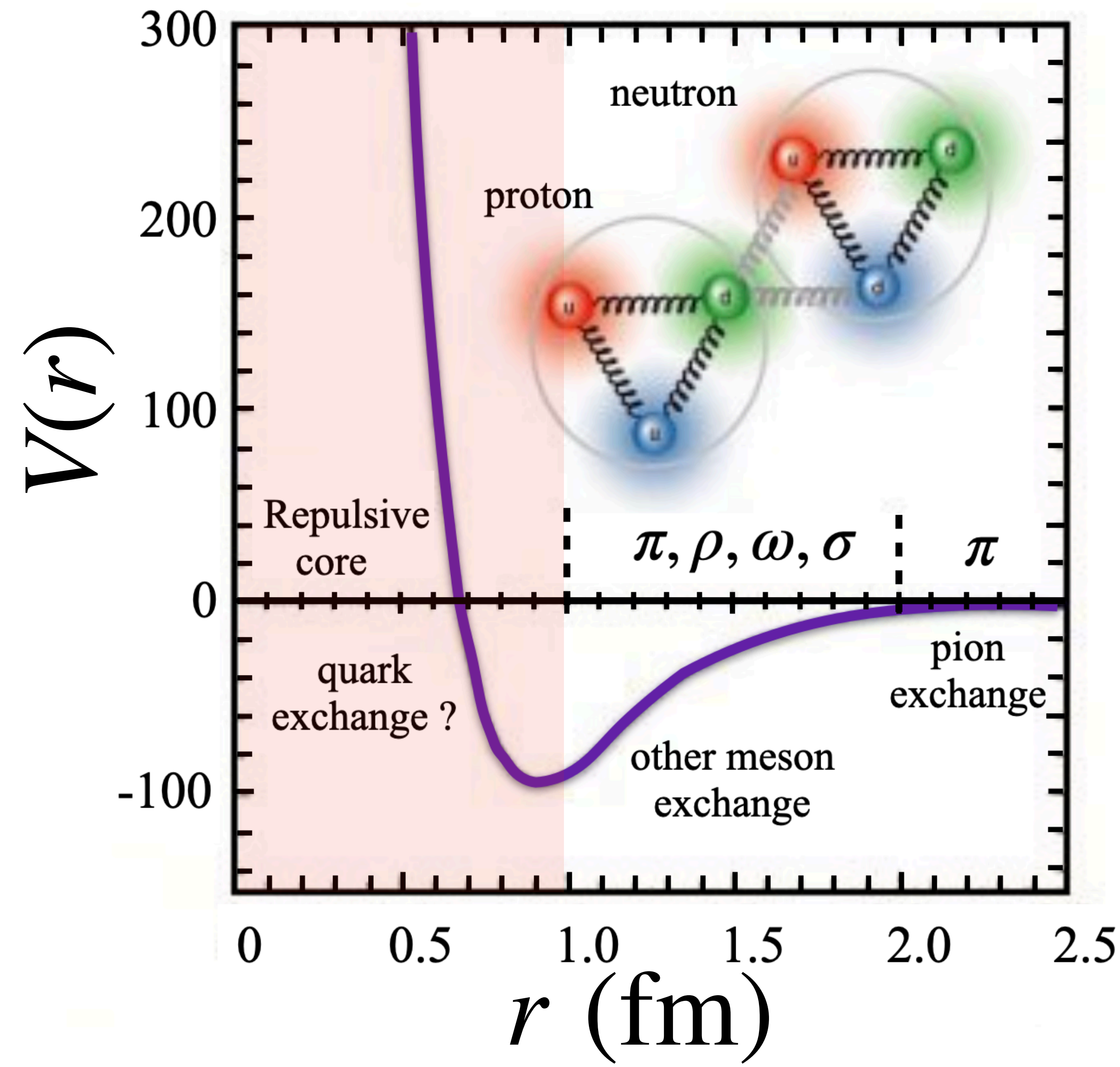
  - relativistic effects become important with increasing internal relative momenta, p_r
  - heavier nuclei calculations become increasingly difficult



what is the dynamical origin of repulsive core ?

- experimental challenges
  - energy limitations in nuclear probe (low Q^2)
  - measuring increasingly small cross sections
  - Identifying observables directly related to the core (i.e. isolating PWIA)
  - for a polarized target (e.g. ND3):
    - achieving/maintaining polarization
    - extremely low beam current limitations



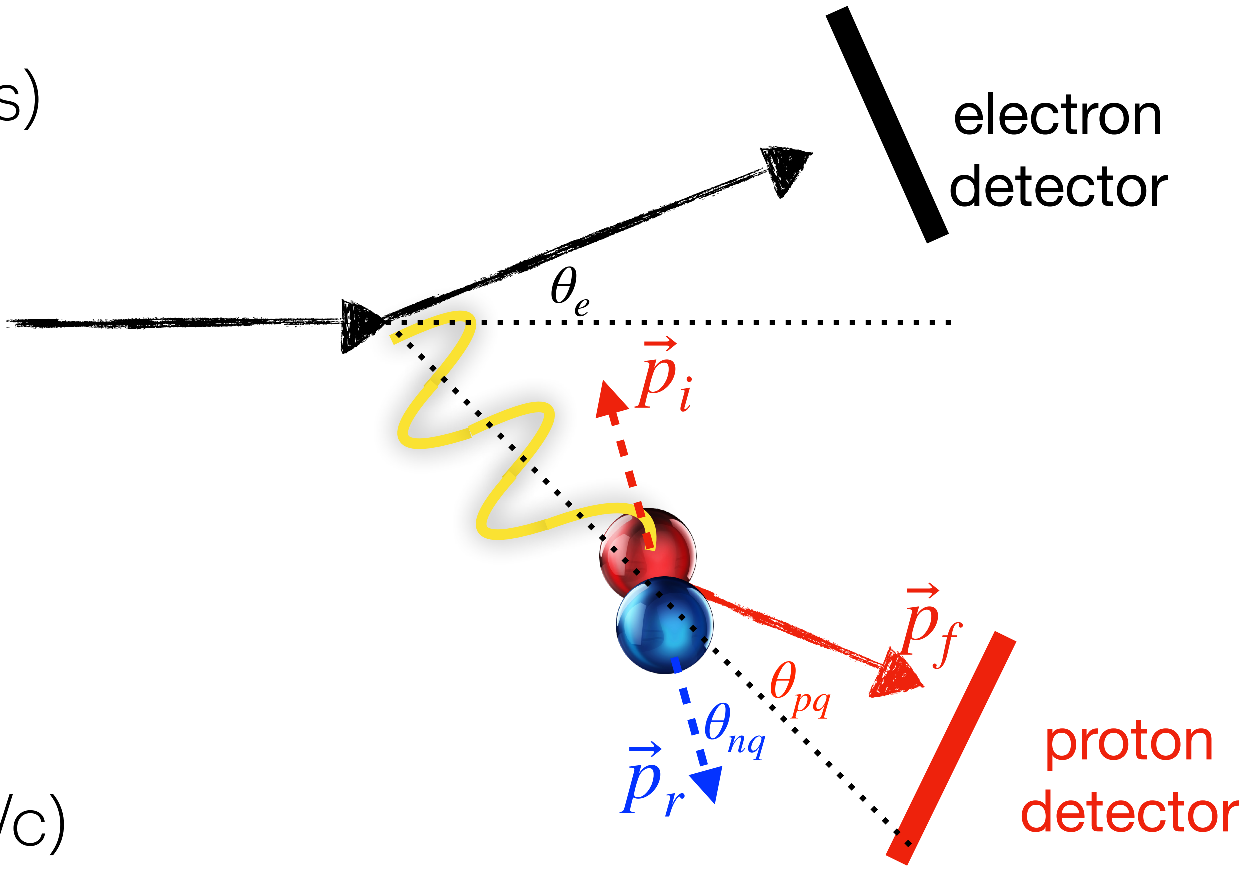
why study the deuteron ?

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

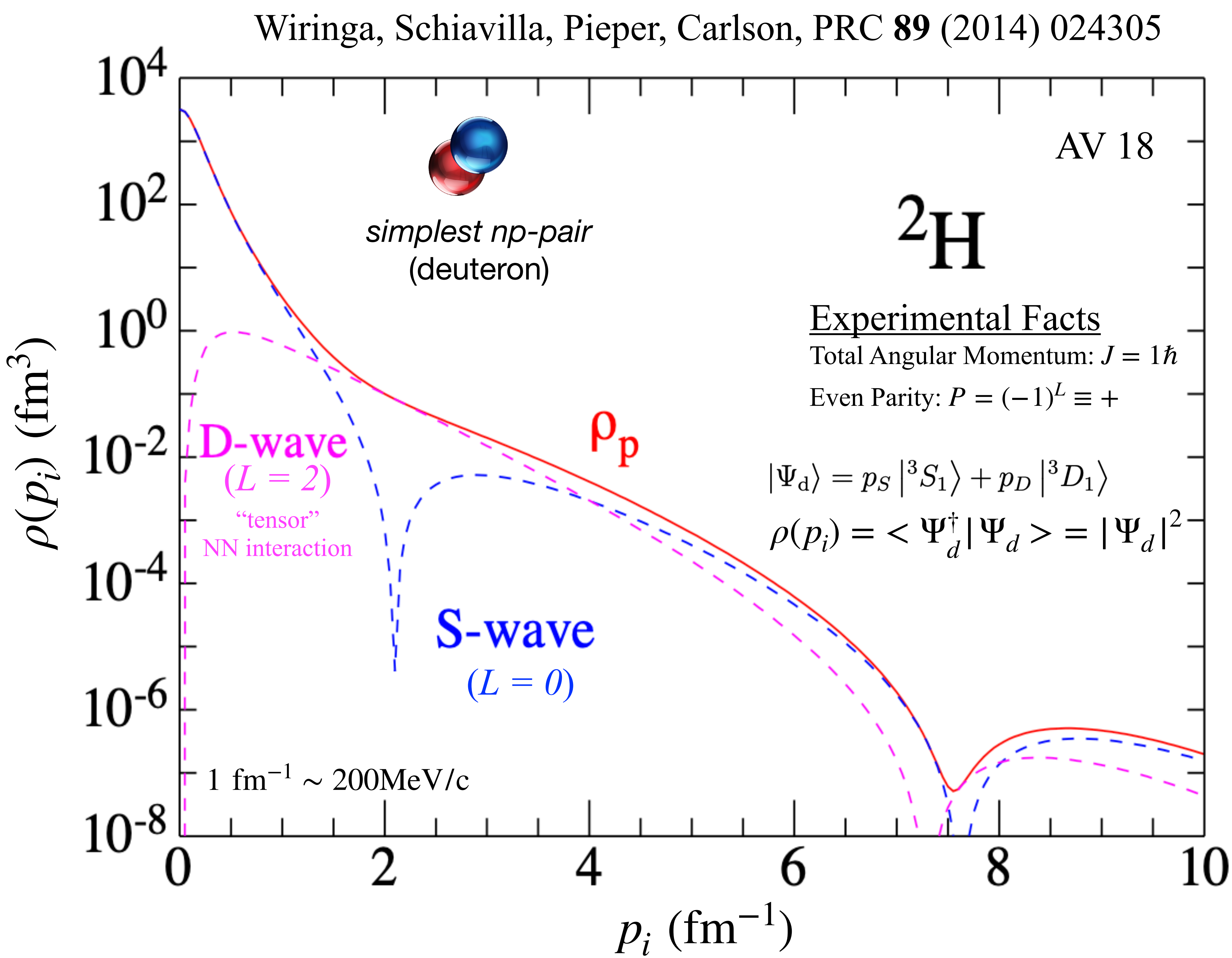
- most simple *np* bound system
  (no 3*N* forces or additional complications)

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

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

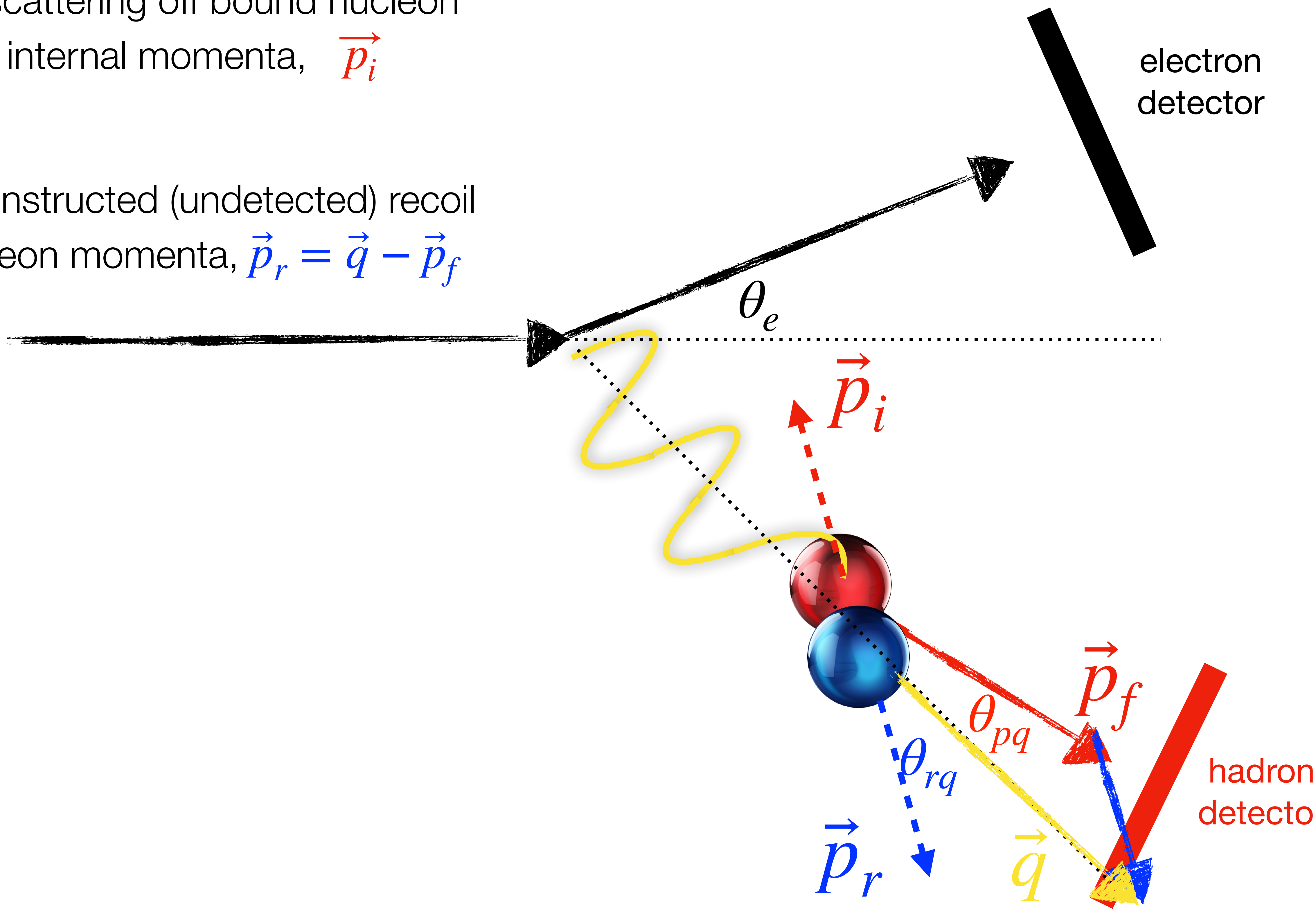


momentum distribution



probing high-momentum structure

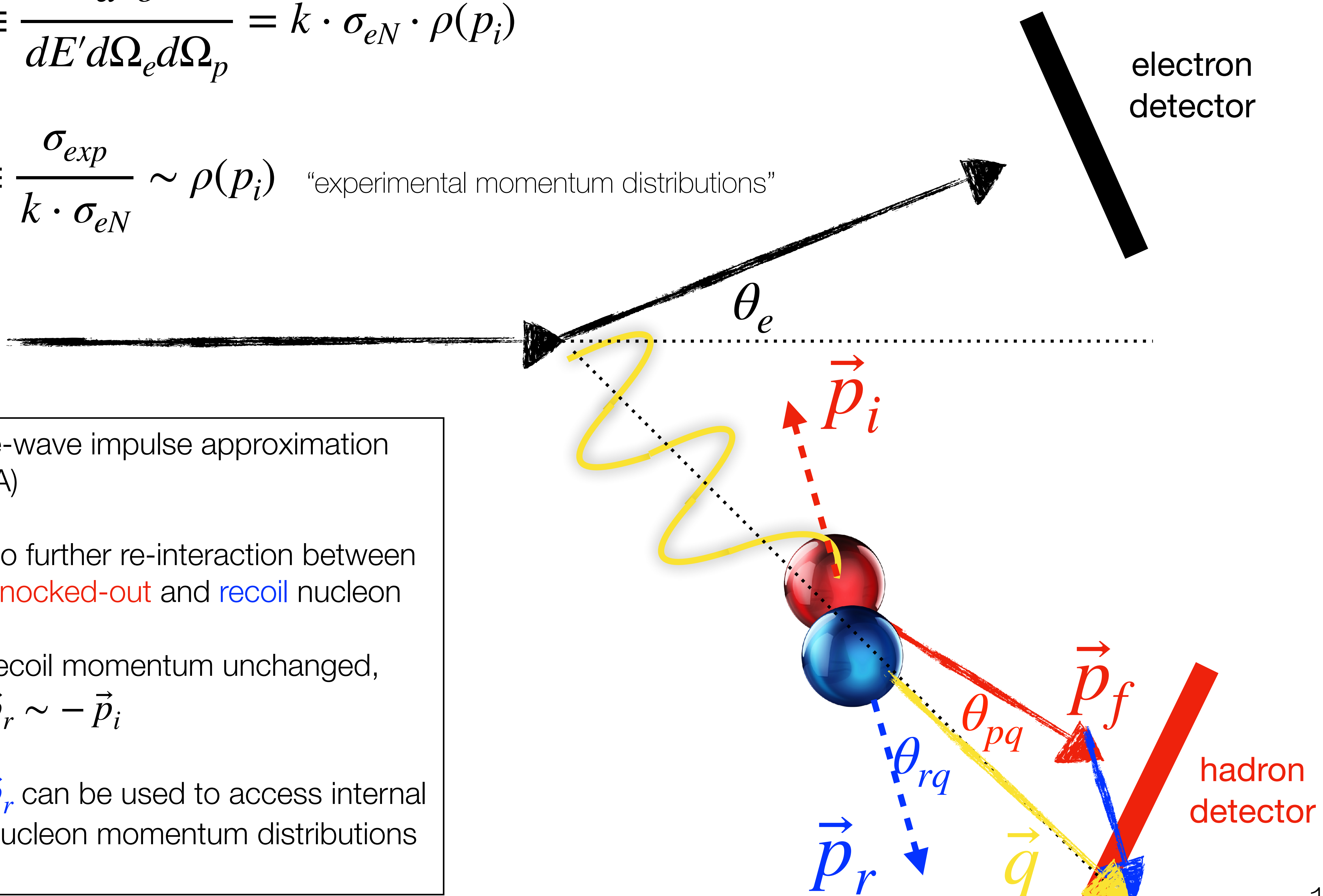
- e- scattering off bound nucleon with internal momenta, $\overrightarrow{p_i}$
- reconstructed (undetected) recoil nucleon momenta, $\vec{p}_r = \vec{q} - \vec{p}_f$



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"



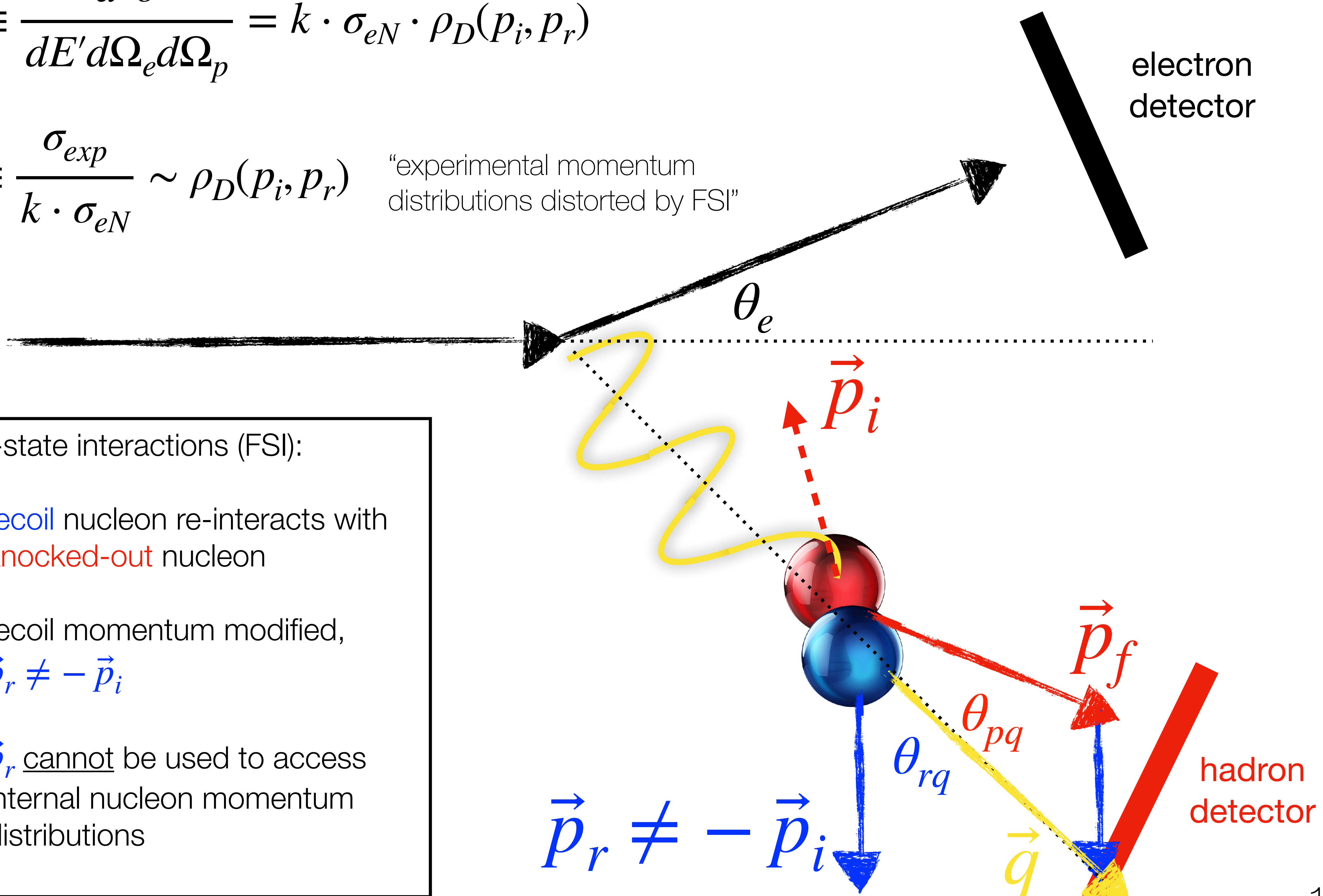
- plane-wave impulse approximation (PWIA)
  - no further re-interaction between knocked-out and recoil nucleon
  - recoil momentum unchanged, $\vec{p}_r \sim -\vec{p}_i$
  - $\vec{p}_r$ can be used to access internal nucleon momentum distributions

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"

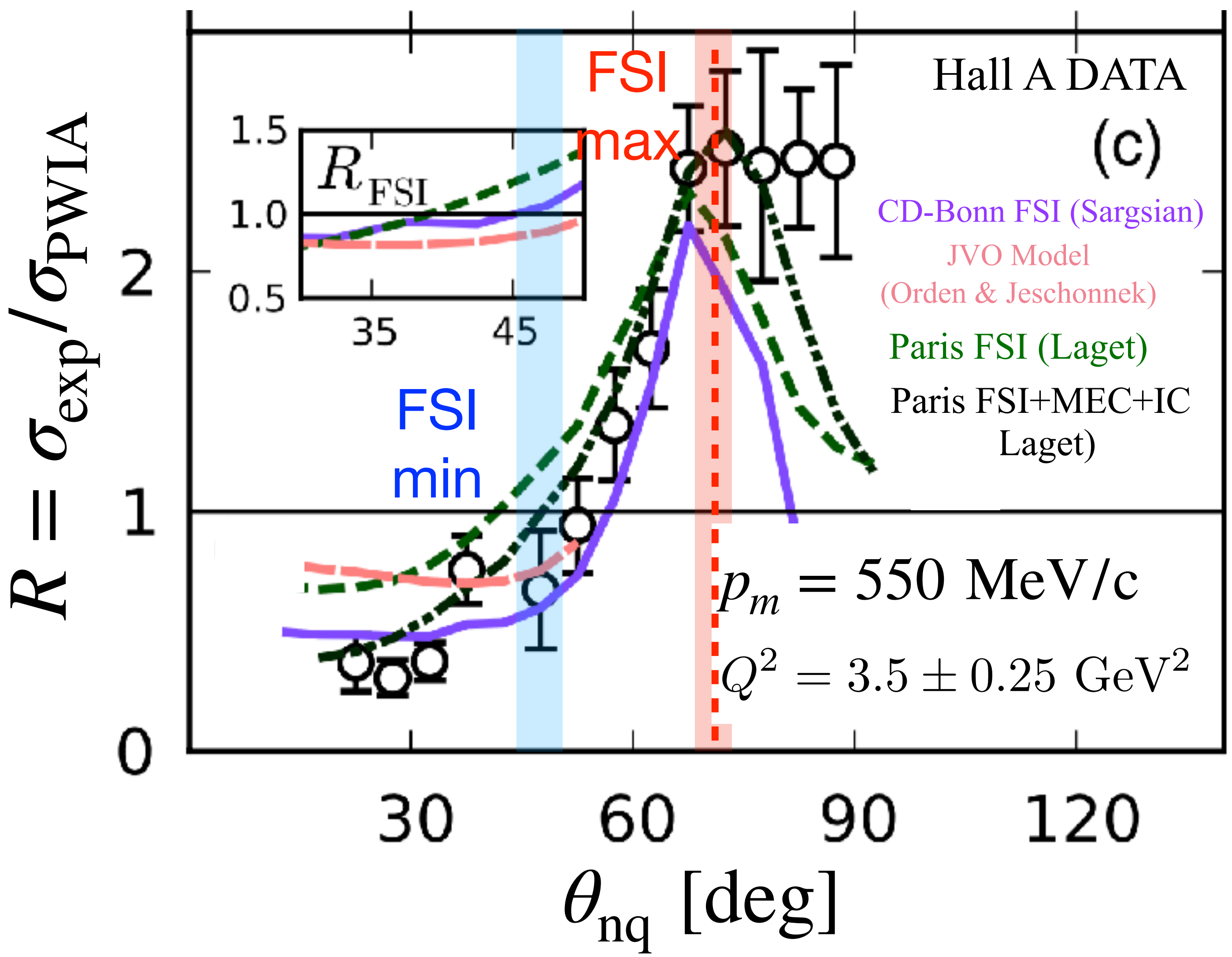


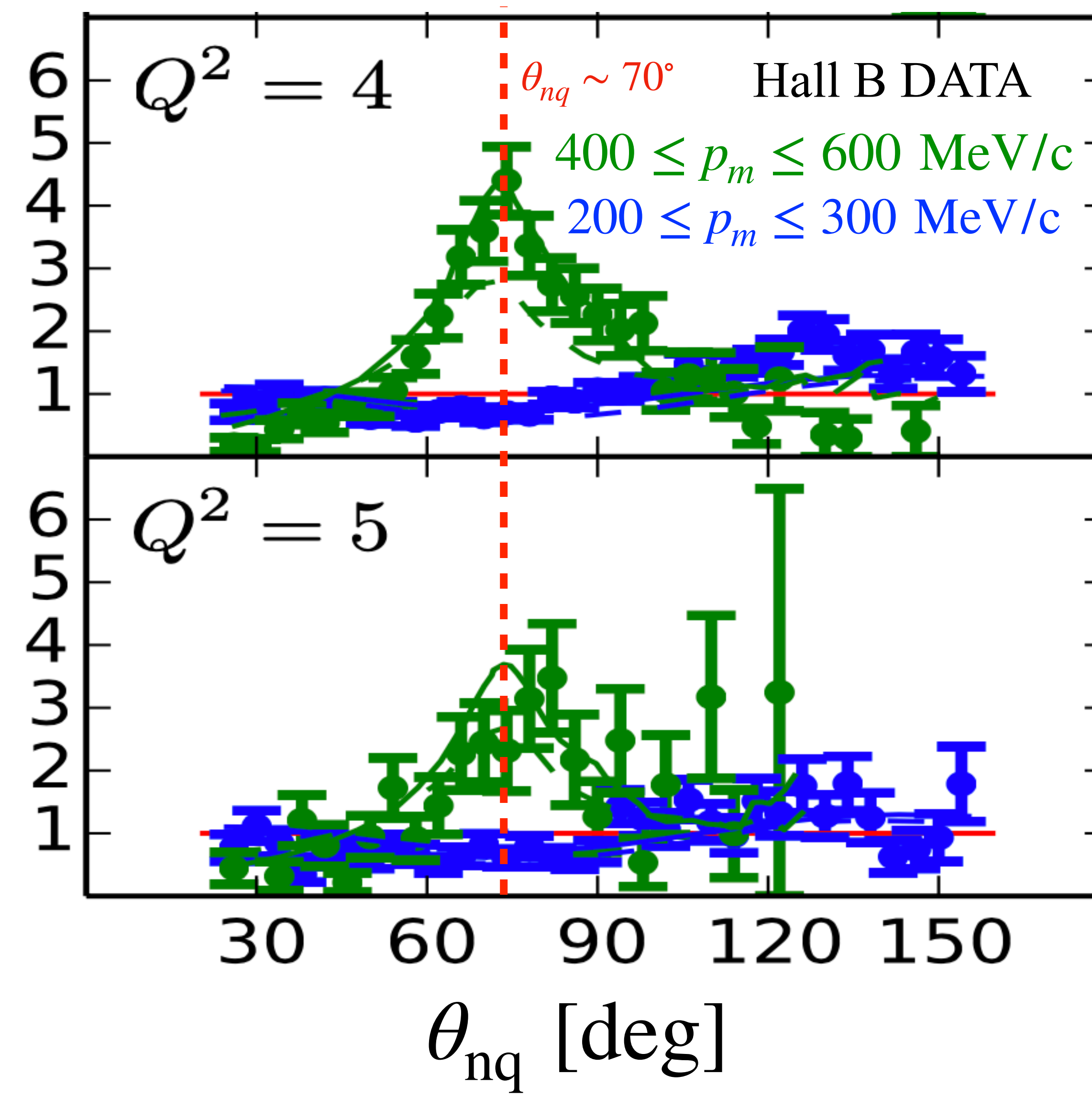
- Final-state interactions (FSI):
  - recoil nucleon re-interacts with knocked-out nucleon
  - recoil momentum modified, $\vec{p}_r \neq -\vec{p}_i$
  - $\vec{p}_r$ <u>cannot</u> be used to access internal nucleon momentum distributions

controlling final-state interactions

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

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



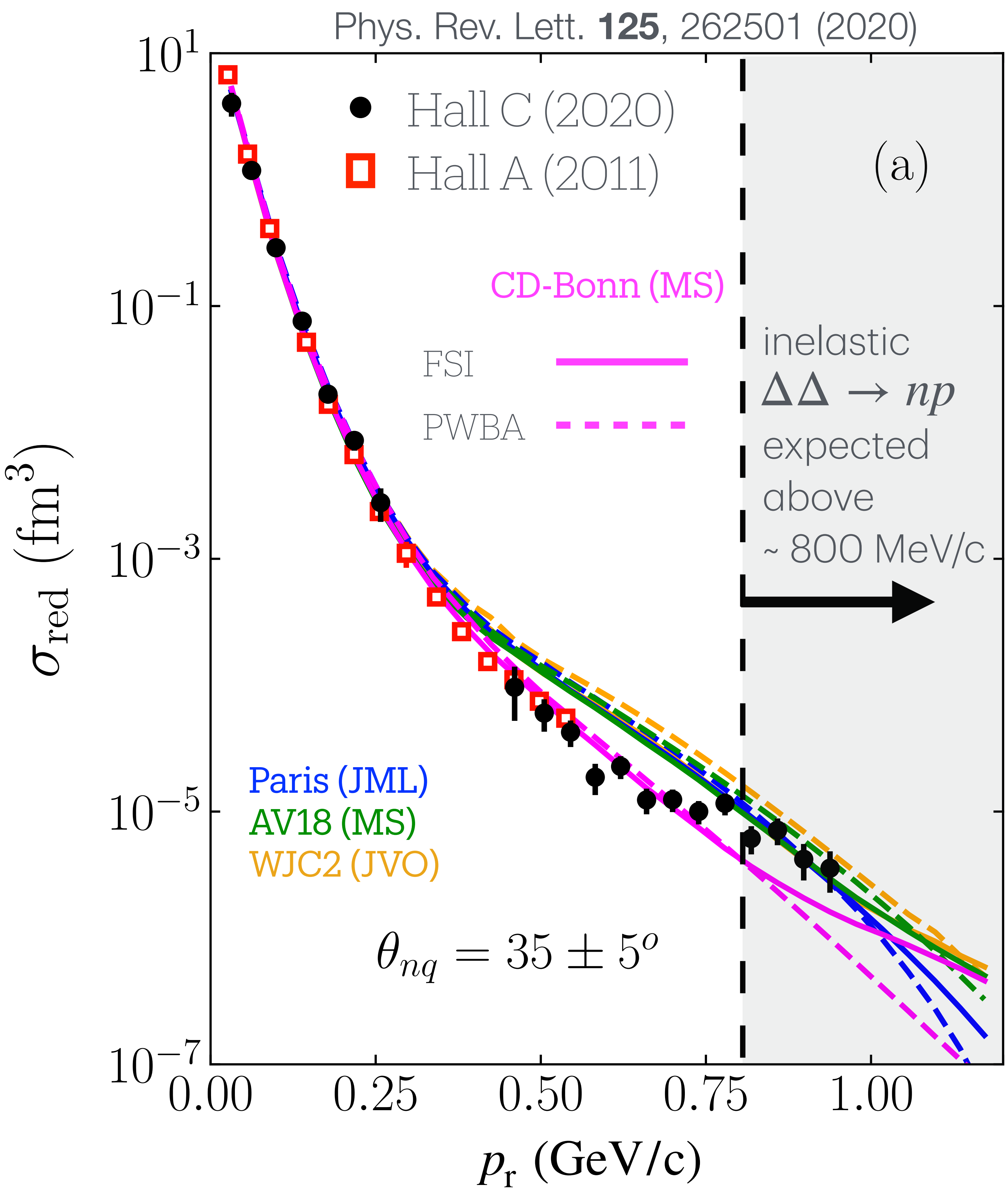


Phys. Rev. B **609**, 49 (Laget 2005)

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

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

probing the NN repulsive core

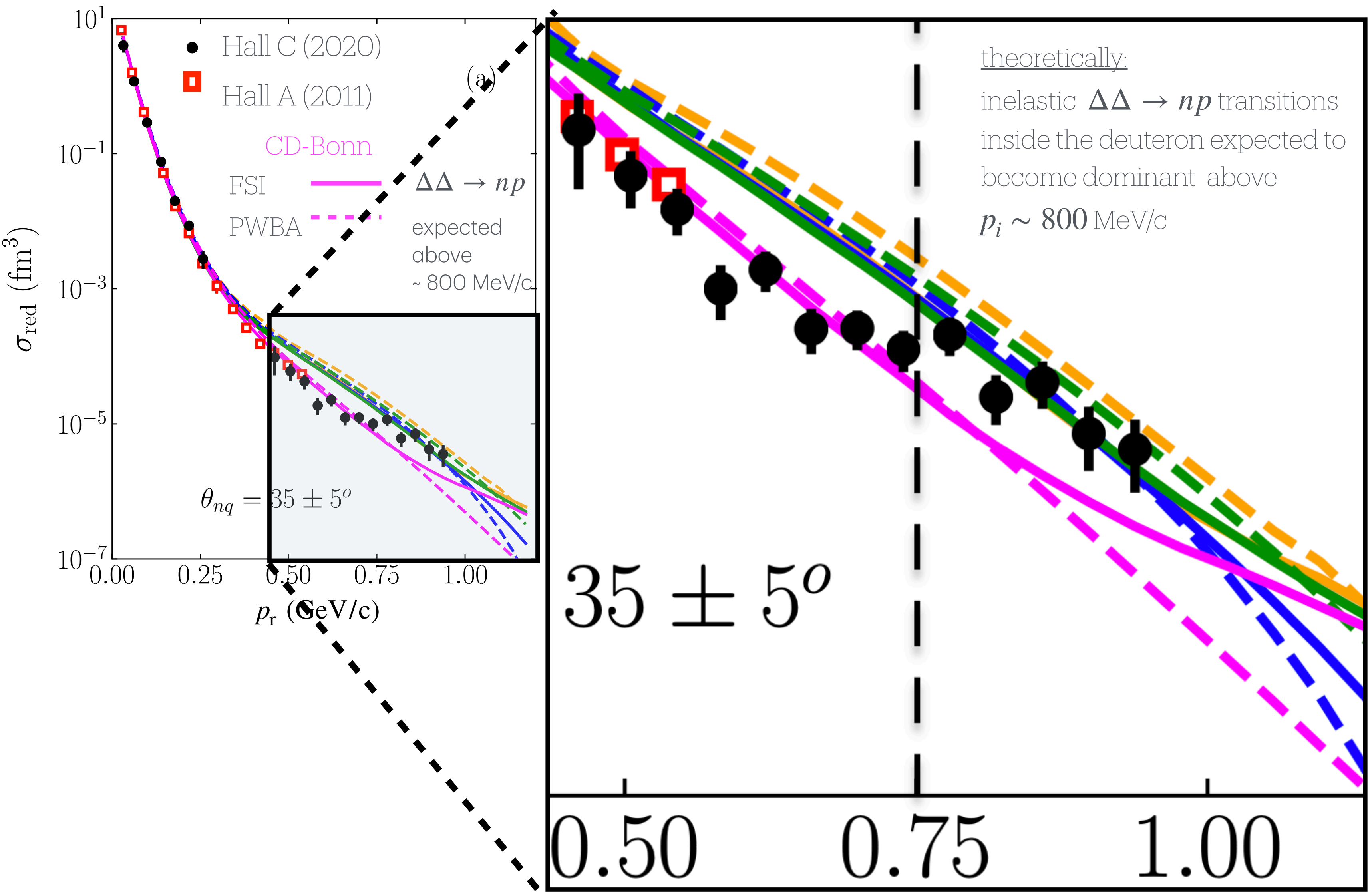


Virtual Nucleon Approximation (VNA) Theoretical Framework (Sargsian 2010)

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

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

probing the NN repulsive core



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

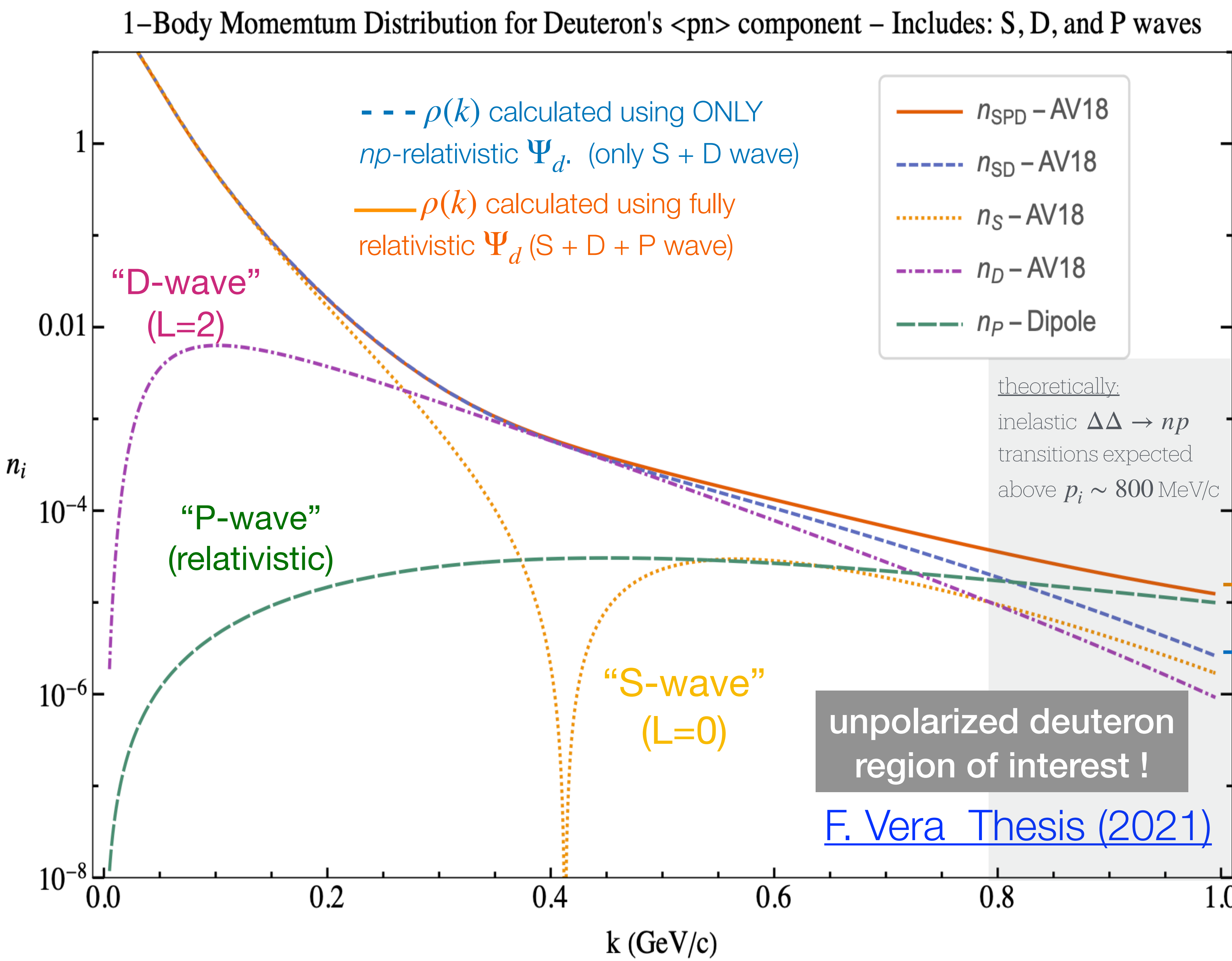
"anomaly" in data starts very close to the threshold of non-nucleonic transitions (~800 MeV/c) of the *NN* system

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

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

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

probing the NN repulsive core: recent theoretical advances



unpolarized deuteron studies

- 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 angular cond.)
- 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
- Challenge: disentangle FSI + non-nucleonic + relativistic effects at very high relative momenta

Is there a complementary approach to study the repulsive core ? YES tensor-polarized deuteron

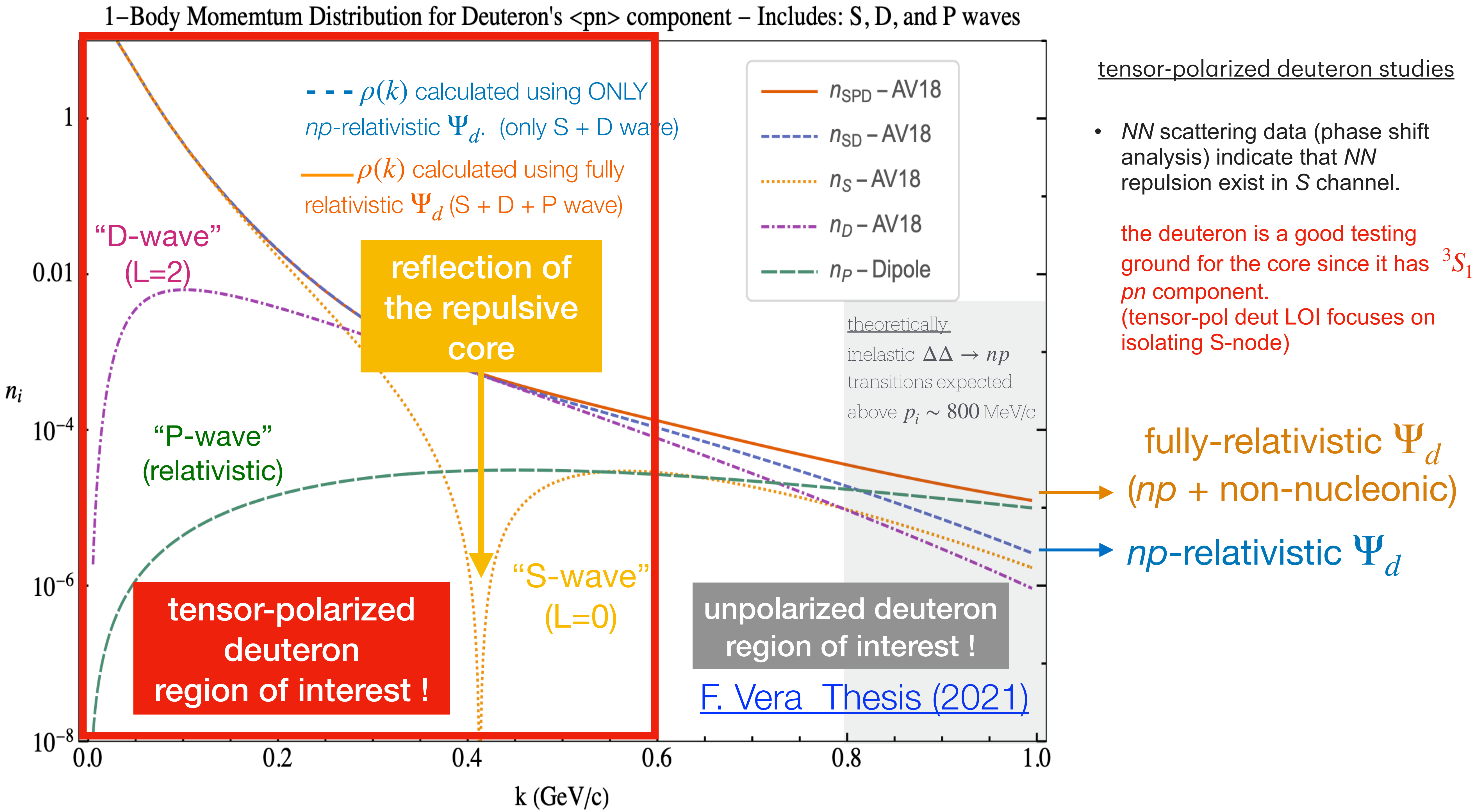
M. Sargsian & F. Vera Phys. Rev. Lett. 130, 112502 (2023)

non-relativistic (or) relativistic

relativistic (non-nucleonic)

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

probing the NN repulsive core: recent theoretical advances



tensor-polarized deuteron studies

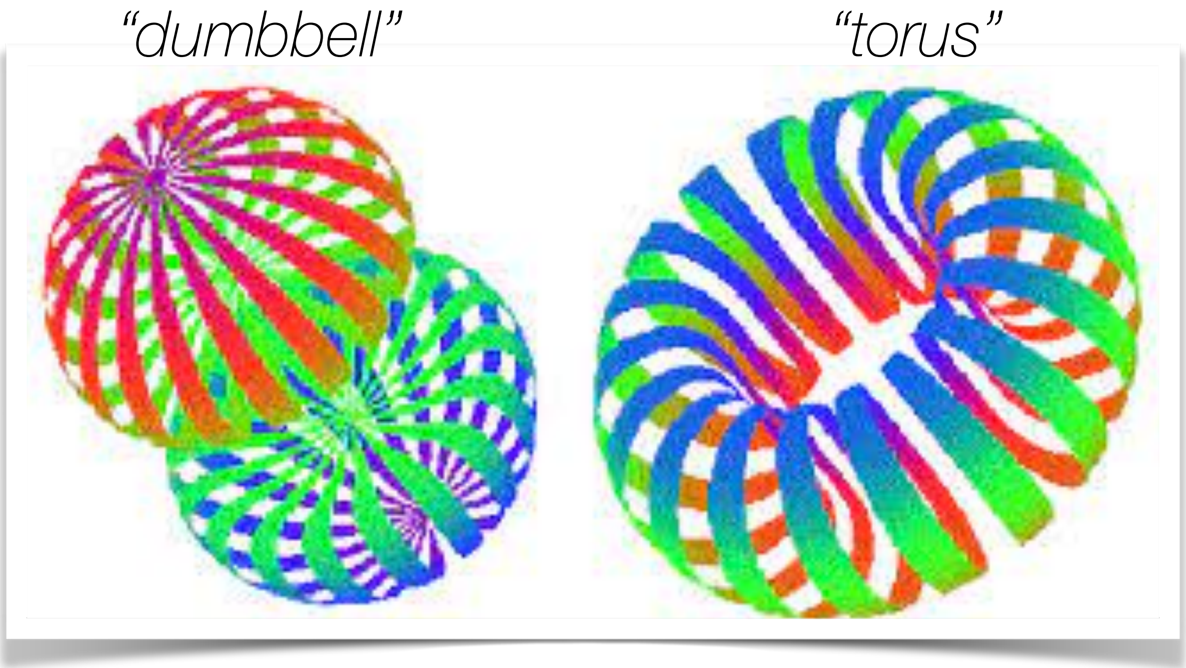
- *NN* scattering data (phase shift analysis) indicate that *NN* repulsion exist in *S* channel.

  the deuteron is a good testing ground for the core since it has $^3S_1$ *pn* component.
  (tensor-pol deut LOI focuses on isolating S-node)

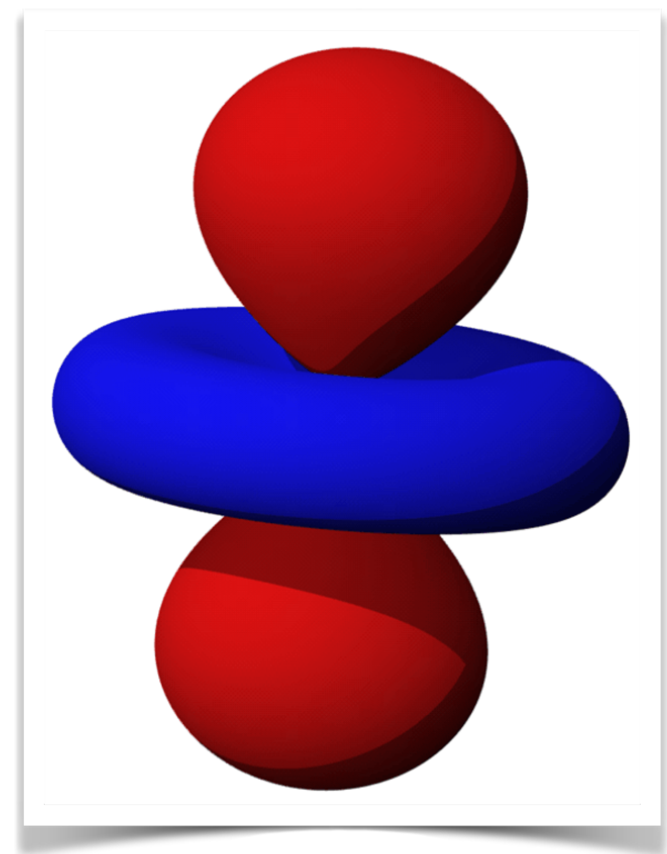
M. Sargsian & F. Vera Phys. Rev. Lett. 130, 112502 (2023)

non-relativistic (or) relativistic — relativistic (non-nucleonic)

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



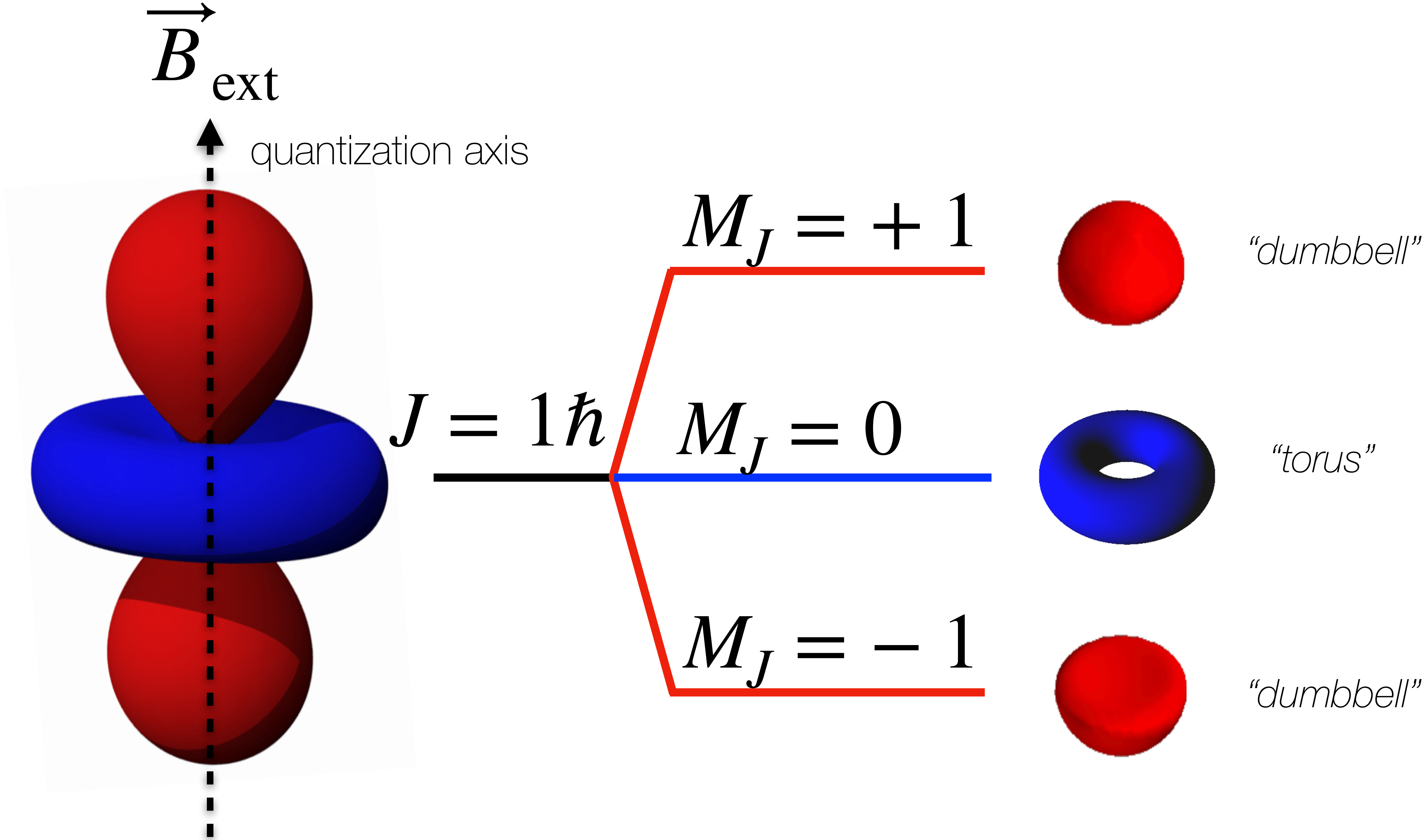
Polarizing the Deuteron



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.

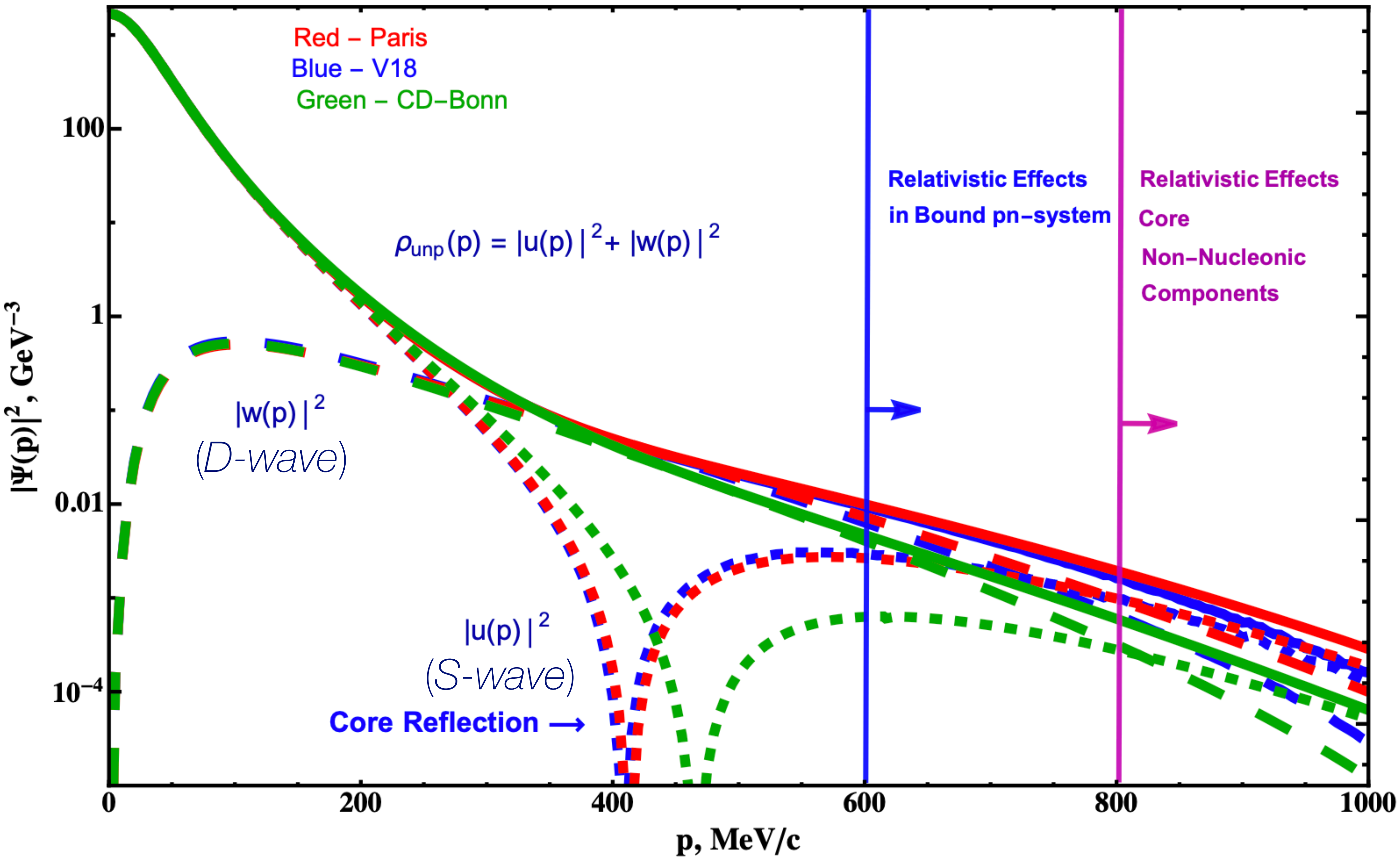
spin-1 (deuteron) system under magnetic field
splits into 3 spin-substates via Zeeman Interaction



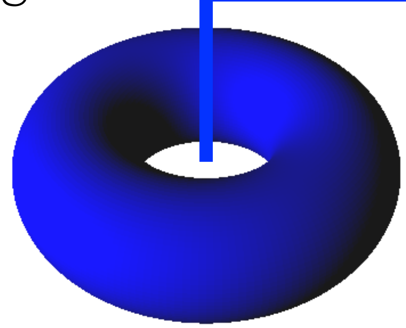
[Forest J et al. 1996 Phys. Rev. C 54 646]

Isolating the S-wave

M. Sargsian 2410.08384 (2024).



"torus"



node in the S-wave is a reflection of the repulsive core

Isolating the S-wave

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

"unpolarized momentum distribution"

$$\rho_{20}(p,\theta_N) \equiv \frac{|\psi_d^1|^2 + |\psi_d^{-1}|^2 - 2|\psi_d^0|^2}{3}$$

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

"tensor-polarized momentum distribution"

Isolating the S-wave

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"tensor-polarized momentum distribution"

$$\boxed{\rho_{node}(p) \equiv \rho_{unp}(p) + \frac{2\rho_{20}}{3\cos^2(\theta_N) - 1} = u^2(p) + 2\sqrt{2}u(p)w(p)}$$

Isolating the S-wave

New Asymmetry (A_{node}) can be extracted from an experimental observable (A_{zz})

"experimental"

$$A_{node}(p) \equiv \frac{\rho_{node}(p)}{\rho_{unp}(p)} = 1 + \frac{2A_{zz}(p,\theta_N)}{3\cos^2(\theta_N) - 1}$$

$$= \frac{u^2(p) + 2\sqrt{2}u(p)w(p)}{|u(p)|^2 + |w(p)|^2}$$

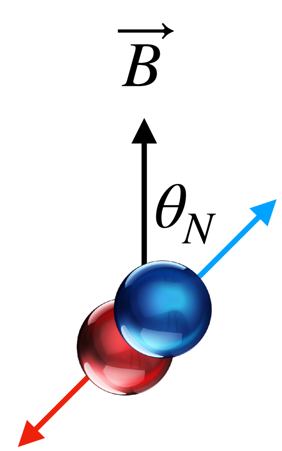
"theoretical"

<u>Tensor-asymmetry</u>

"theoretical" "experimental"

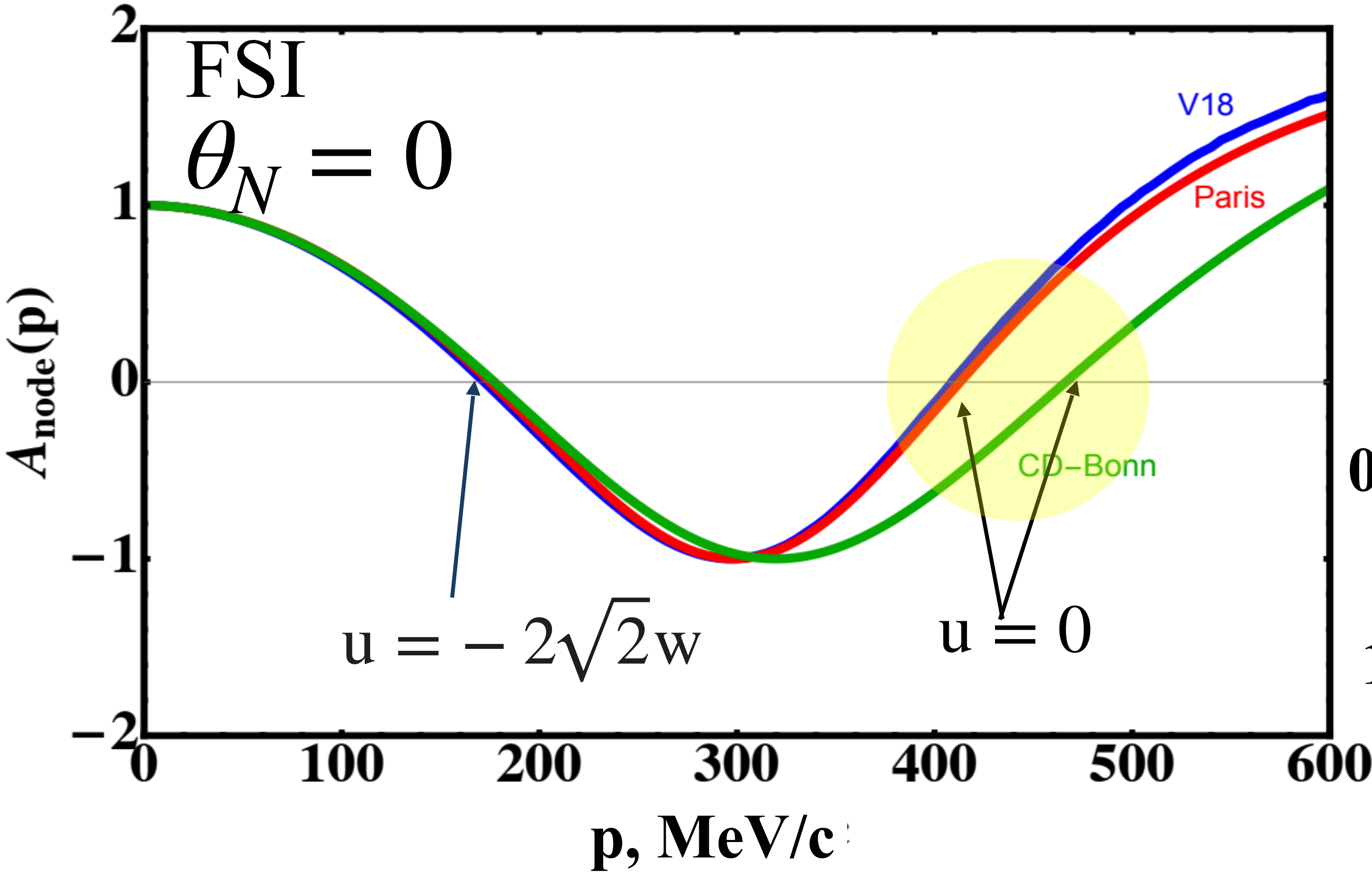
$$A_{zz} = \frac{\rho_{20}}{\rho_{unp}} \sim \frac{\sigma_{tensor}}{\sigma_{unp}}$$

ONLY within ~PWIA

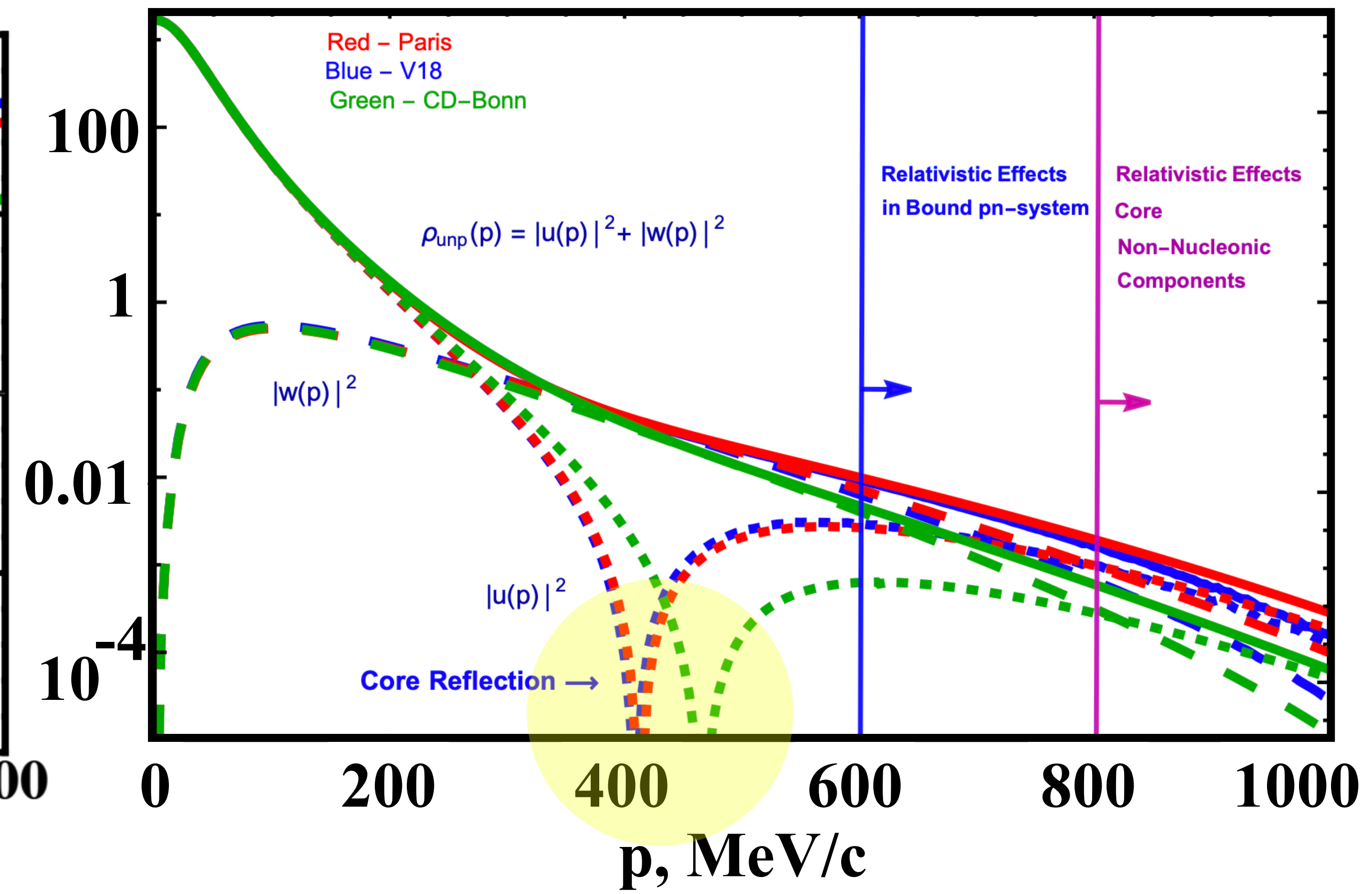


Isolating the S-wave

$A_{node}(p)$



$\rho_{unp} = |\Psi_d(p)|^2$

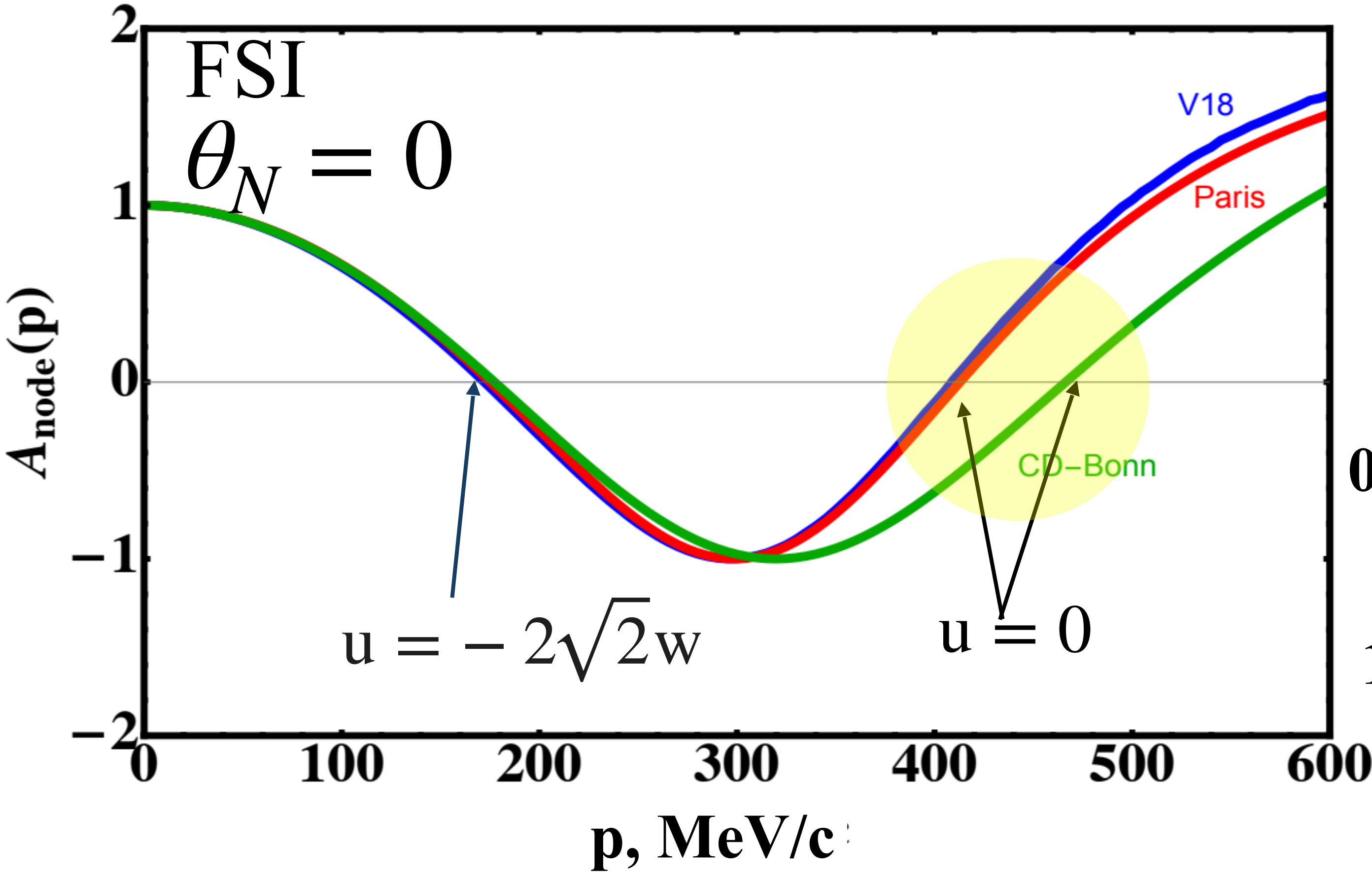


$$A_{node} = 0 \quad \begin{cases} u(p) = -2\sqrt{2}w(p), \; p \sim 180 \text{ MeV/c} \\ u(p) = 0, \; p \geq 400 \text{ MeV/c} \end{cases}$$

M. Sargsian [2410.08384 (2024)](2410.08384 (2024)).

Isolating the S-wave

$A_{node}(p)$



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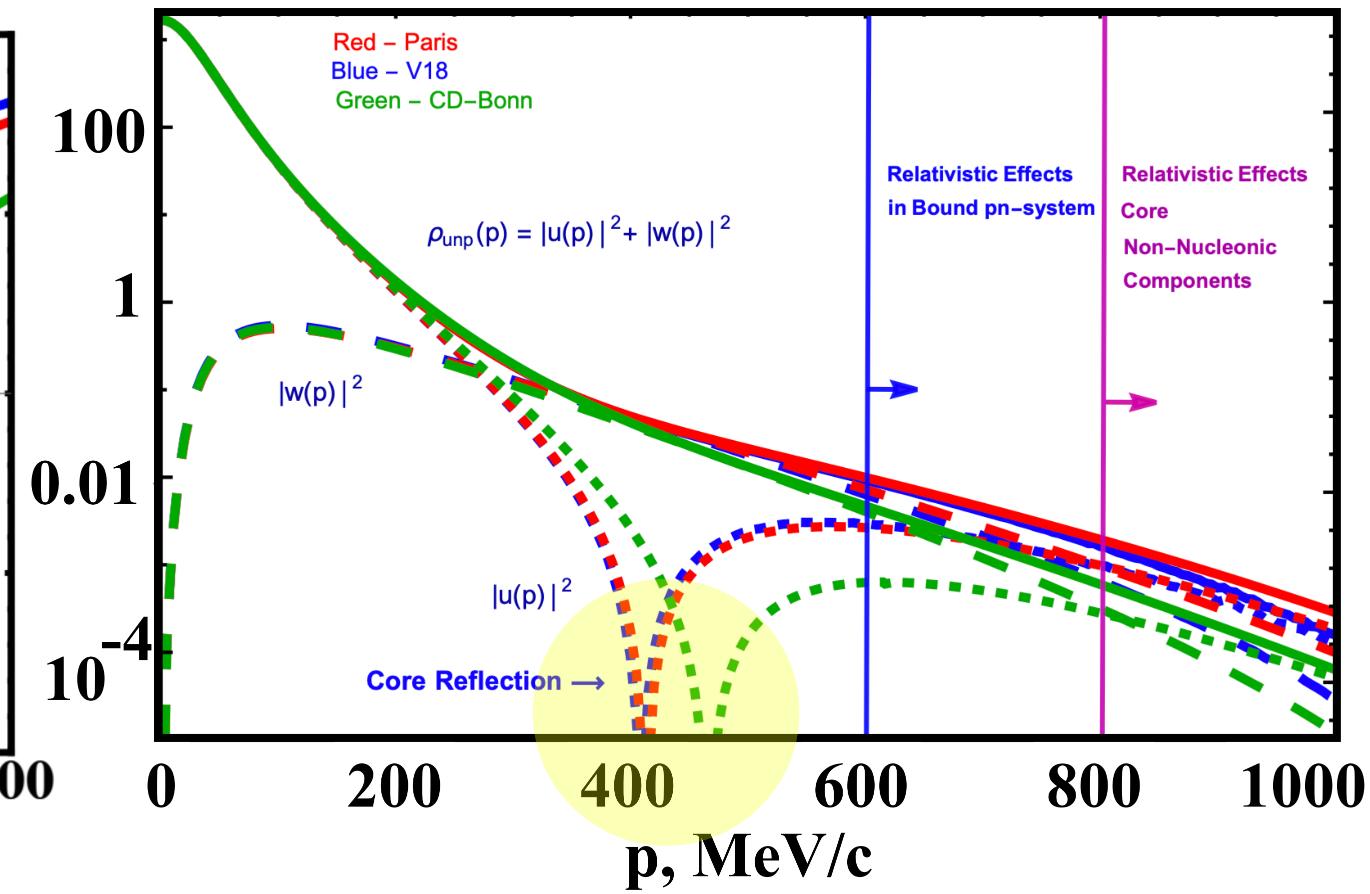
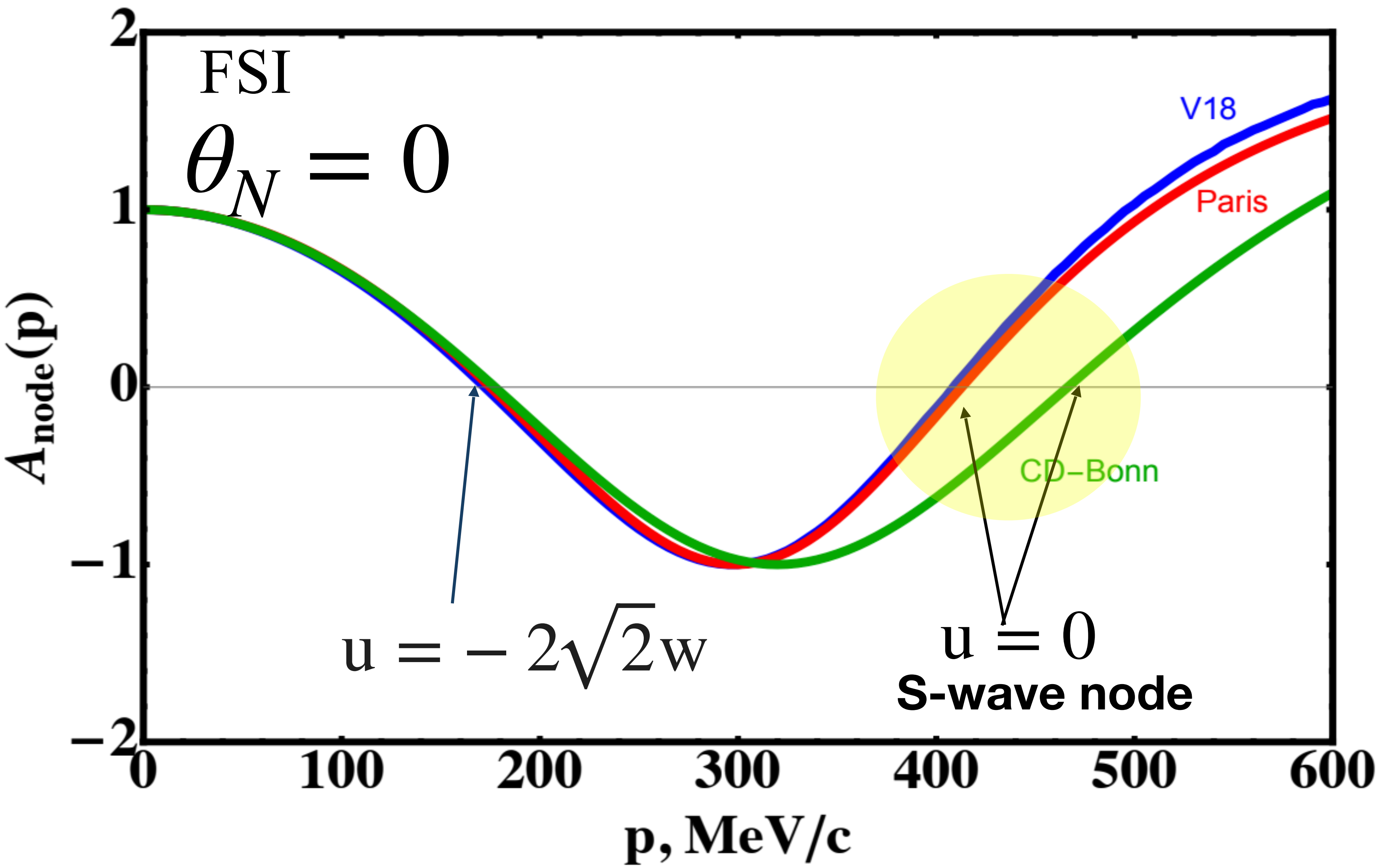


The node is a signature of nuclear repulsive core: In the PWIA approximation, if deuteron consisted of only the S-state, then in this case the node is like a hole in the momentum space through which the probe-electron will pass without interaction.

M. Sargsian [2410.08384 (2024)](2410.08384).

Experimental Objective: Extraction of the deuteron S-wave



first direct measurement of the repulsive strength via S-wave node extraction

- large sensitivity of NN potentials to the location of the node (~400 - 450 MeV/c)
- zero-crossing at ~180 MeV/c corresponds to well-known (experimentally measured) region of $\Psi_d(p)$ and will be used as a calibration point

M. Sargsian 2410.08384 (2024).

Experimental Setup: Tensor-polarized target (deuterated ammonia)

target/beam parameters

ND_3^*

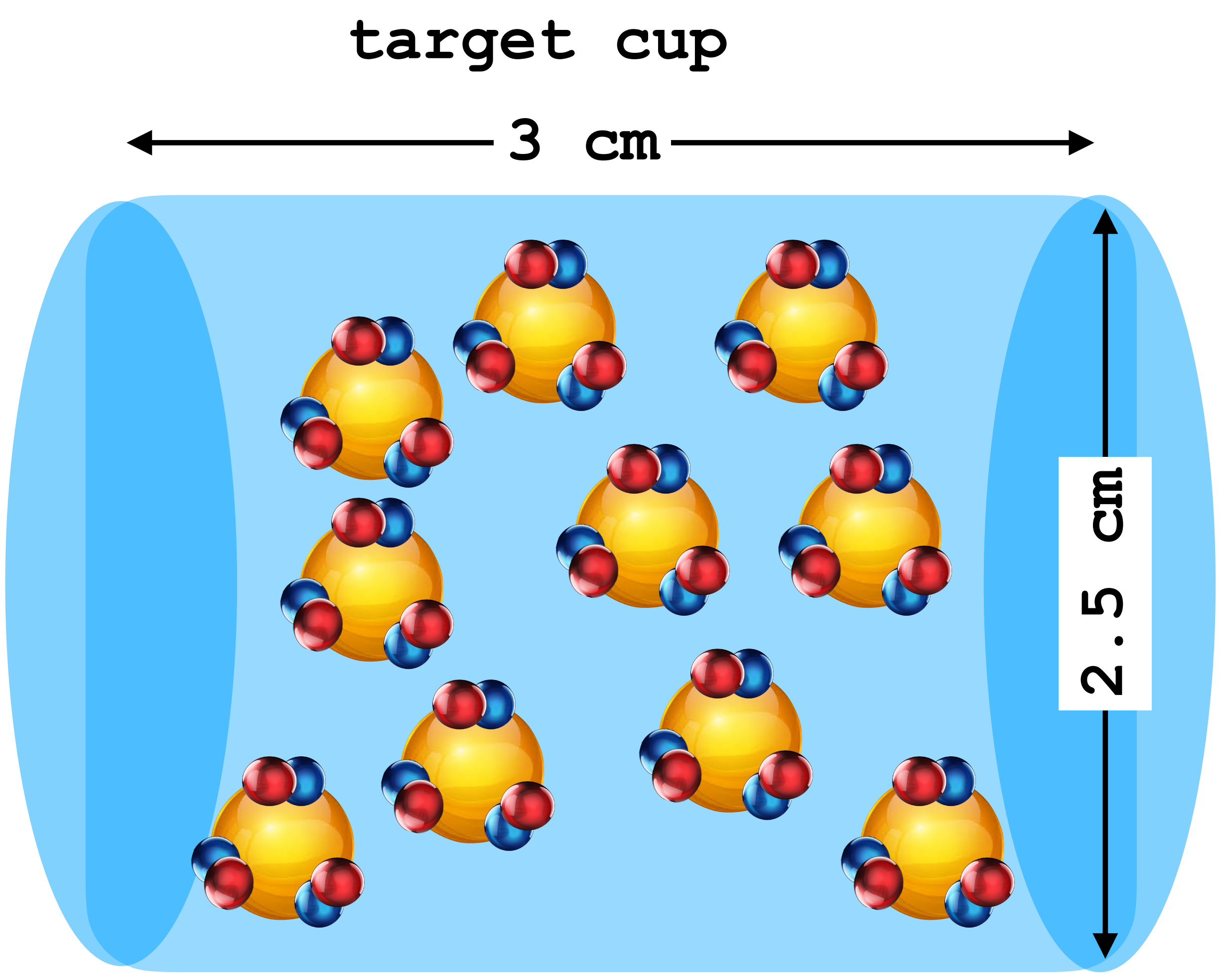
^{4}He bath (blue)*

$T = 1$ K

$B_{\text{field}} = 5$ T

target pol : $\sim 26 - 30\,\%$

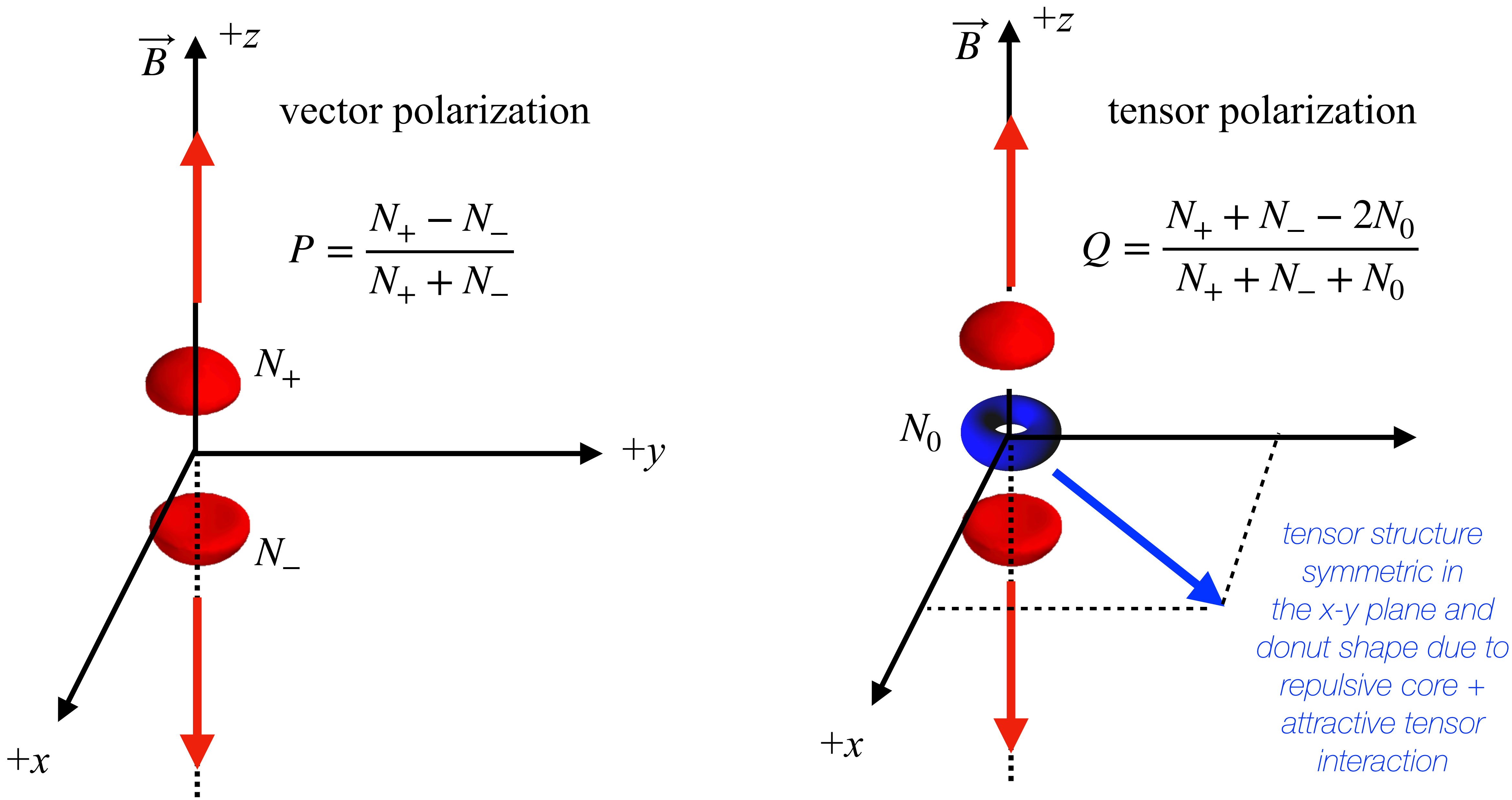
$50 - 100$ nA



(2 target cups required to complete exp. in 4 weeks)

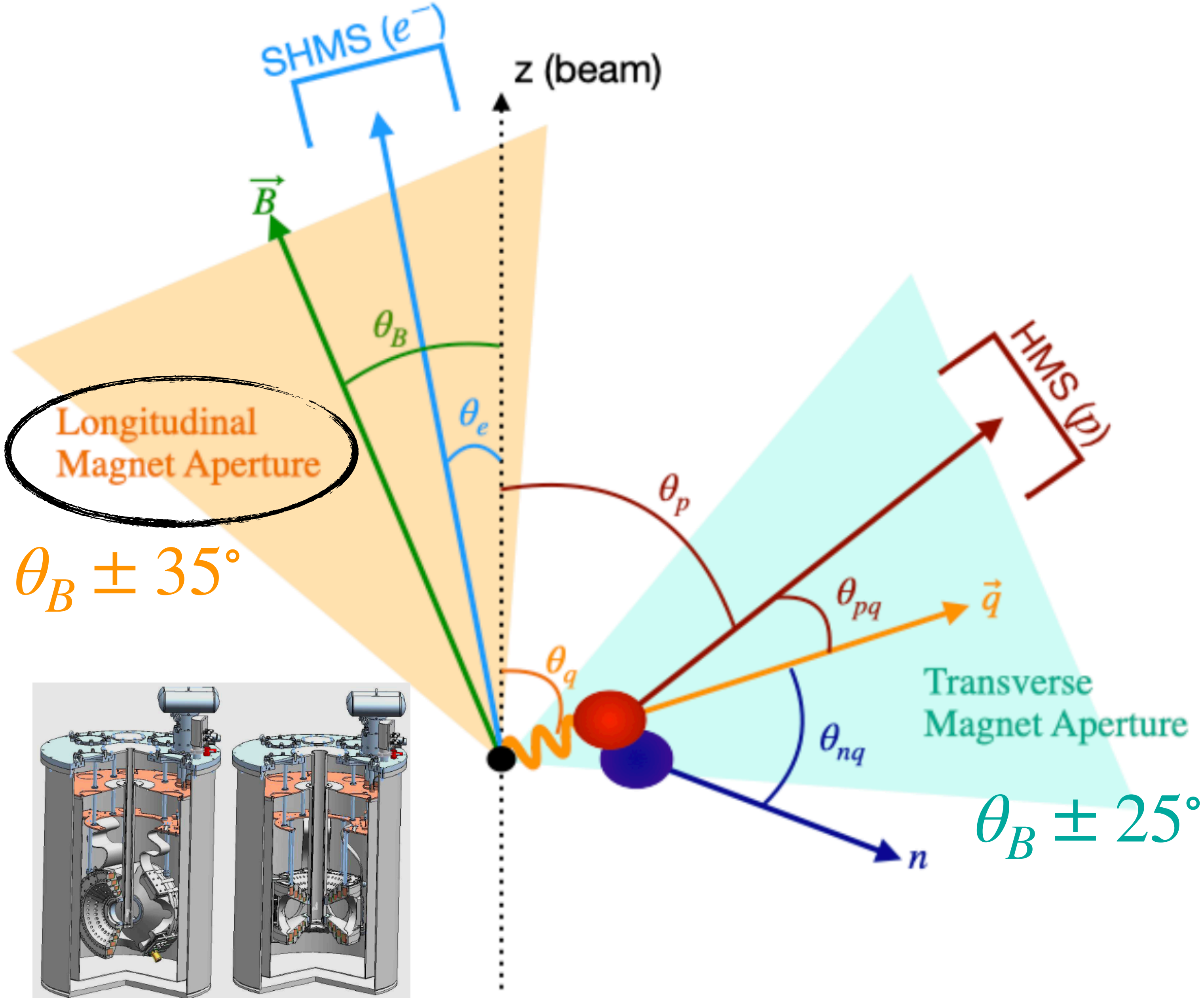
*background contributions from N and He will need to be subtracted (dilution)

Experimental Setup: Tensor-polarized deuteron states



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

Experimental Setup: Spectrometer Configuration



kinematical challenges

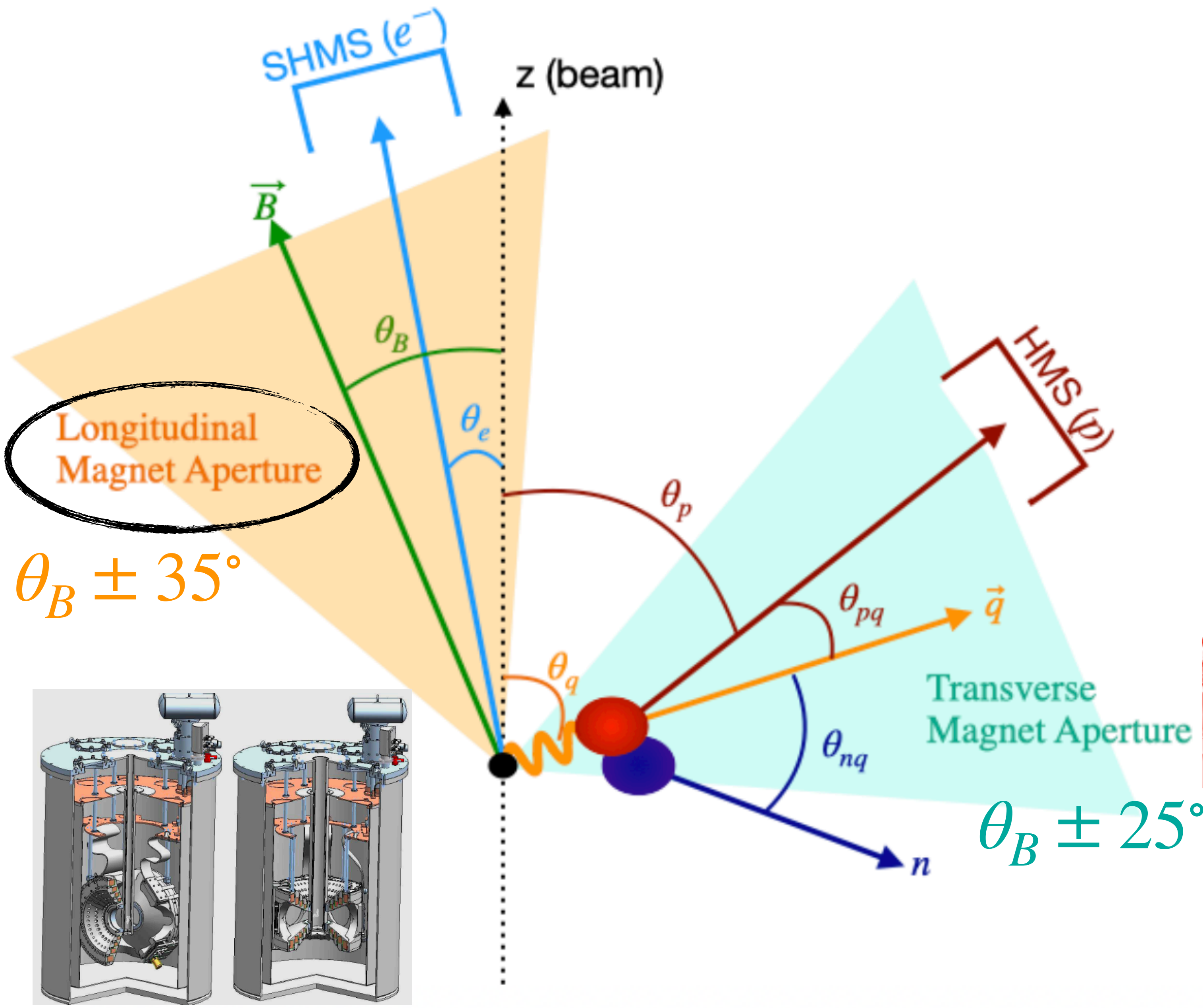
Setting $\theta_{nq} < 35^\circ$ (required to minimize FSI) restricts $\theta_p \sim 60-70^\circ$

at $\theta_B = 0$ (field aligned along +z), neither aperture allows for proton detection, leaving two possible solutions:

(i) use existing magnet, rotate it $\theta_B = 20^\circ$ towards SHMS, and use longitudinal aperture (for e-) and transverse aperture (for p)

(ii) design/acquire a completely new magnet

Experimental Setup: Spectrometer Configuration



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(ii) design/acquire a completely new magnet

	k_f (GeV/c)	θ_e (deg)	p_f (GeV/c)	θ_p (deg)	P_{miss} (MeV/c)	Q^2 (GeV/c)^2
central setting	10.46	6.54°	1.06	69.83°	–	–
kinematic coverage	10.1–10.8	5–8	0.95–1.2	65–75	100-500	1–2

experimental measurement of the tensor asymmetry

Full cross-section:

unpolarized — tensor — vector

$$\frac{d^6\sigma_p}{dE_{e'}d\Omega_{e'}dE_p d\Omega_p} = \sigma_u\left[1 + PA_d^V + \frac{1}{2}QA_d^T\right]$$

Tensor asymmetry:

$$A_d^T = \frac{2}{Q}\left(\frac{\sigma(P,Q)+\sigma(-P,Q)}{\sigma(P,0)+\sigma(-P,0)} - 1\right)$$

4 target configurations (polarization states) vector pol. (P, -P) will cancel out

Assuming most factors cancel in the cross-section ratios

$$A_d^T = \frac{2}{fQ}\frac{N_p - N_u}{N_u}$$

A_{node} can be extracted from A_d^T (see earlier slides)

$N_p \sim N(P,Q) + N(-P,Q)$ *number of polarized counts*

$N_u \sim N(P,0) + N(-P,0)$ *number of unpolarized counts*

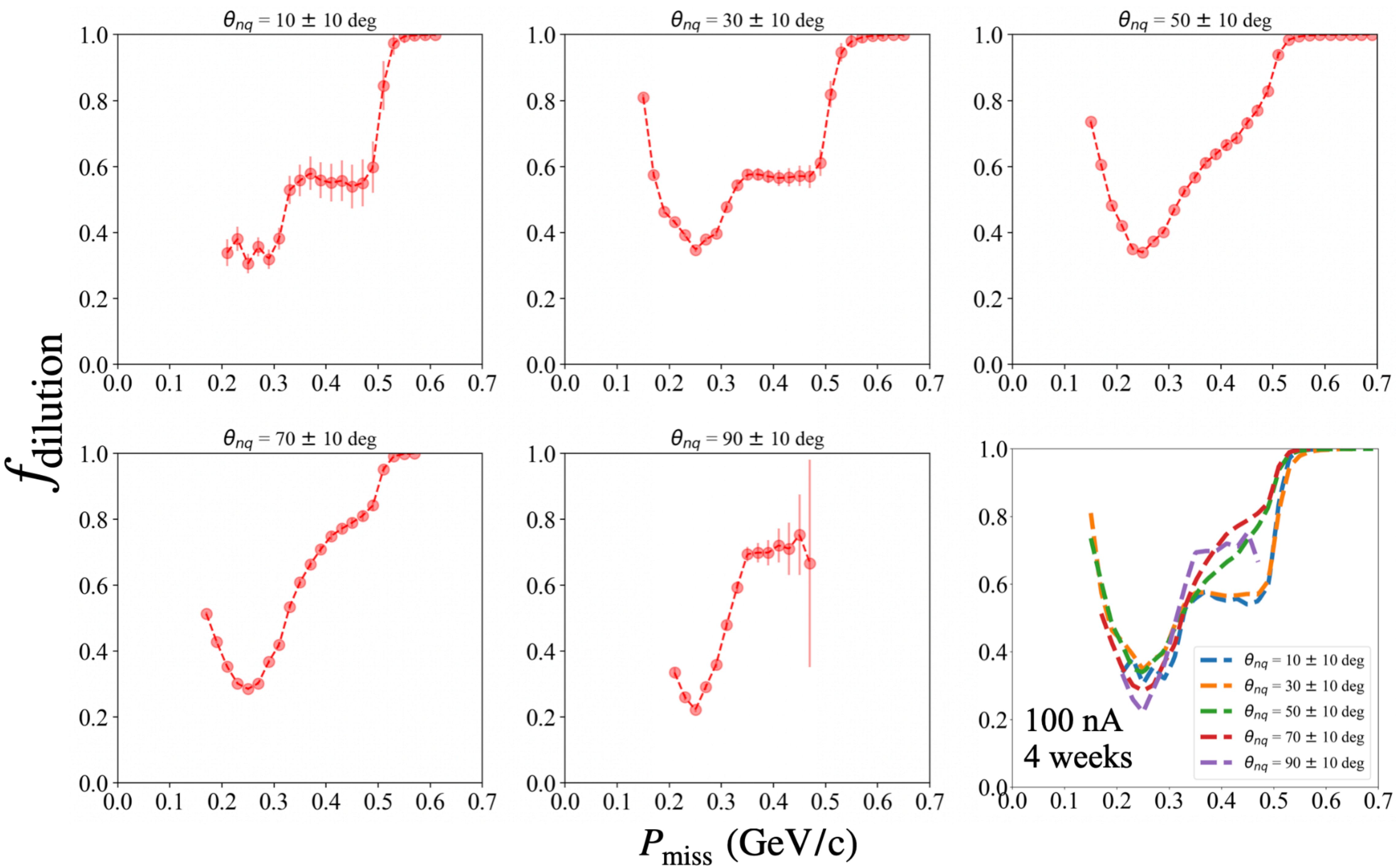
$f \rightarrow$ *dilution factor* $Q \rightarrow$ *tensor polarization*

$A_{zz} \equiv A_d^T$

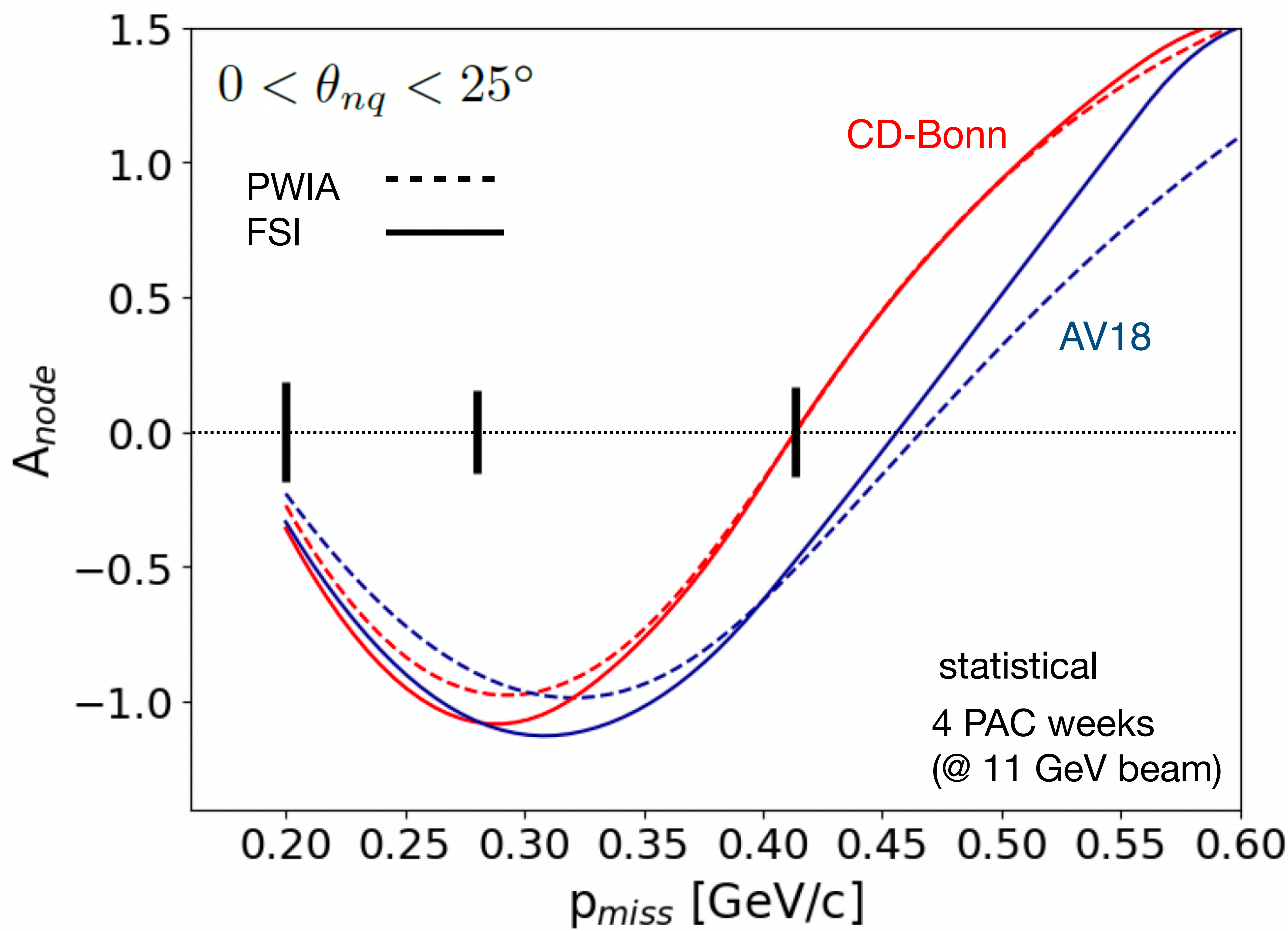
dilution factor

- dilution factor adjusts for the presence of different nuclei in the target, since e- will scatter from deuteron (D), Nitrogen (N) and helium-4 ($\mathbf{ND_3}$ is immersed in a $^4\mathbf{He}$ bath)

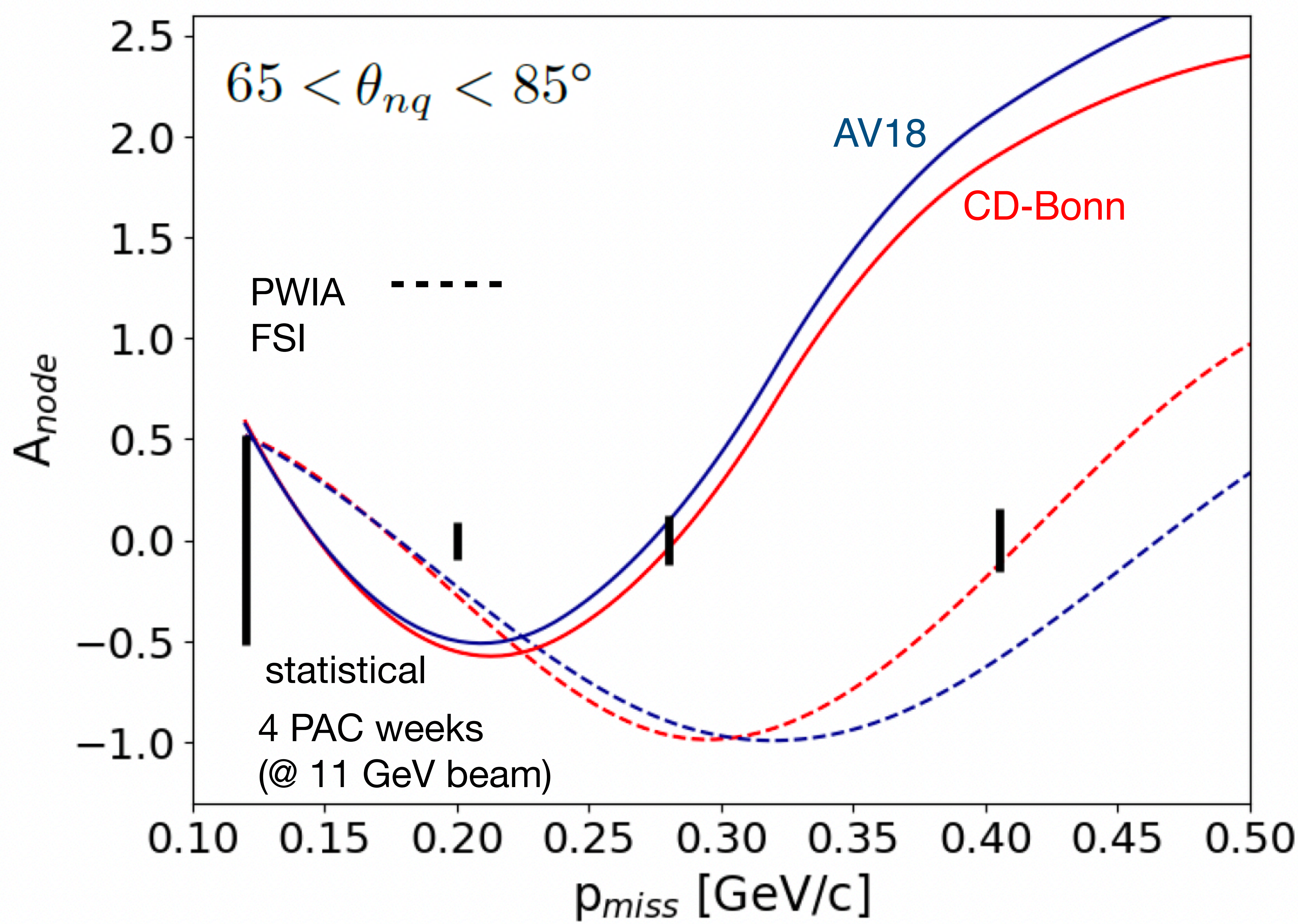
$$f = \frac{N_D \sigma_D}{N_D \sigma_D + N_N \sigma_N + \sum_A N_A \sigma_A}$$



expected measurement



expected measurement



systematic uncertainty

Source	(%)
Polarization	7
Dilution and Packing fraction	6
Radiative corrections	3
Charge determination	1
Trigger/tracking Efficiency	1
Acceptance	0.5

Based on previous experiments.

$\sim 9.8\,\%$

Theory Support

Professor Misak Sargsian has been collaborating with our team for over a year. His recent publications reflect the impact of this experiment to his work. M. Sargsian 2410.08384 (2024).

Professor Sabine Jeschonnek will help us to motivate studies to measure vector-polarized asymmetries of deuterons at the same kinematics to disentangle the effects of final state interactions and ground state properties. This observable is non-zero only with FSI, and when measured out-of-plane. Thus, it is more sensitive to details of the FSI.

Thank You