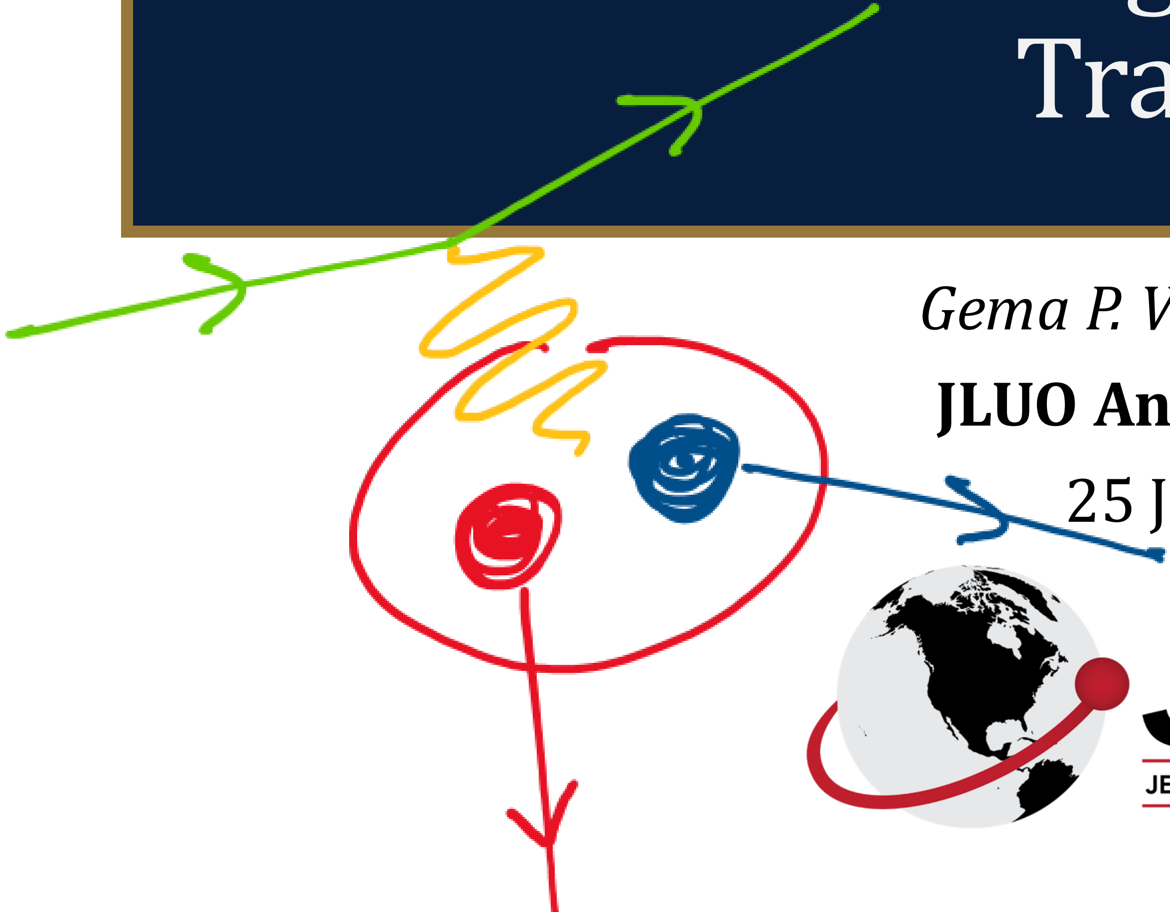
Study of the Short-Range Nucleon-Nucleon Potentials via Electro-disintegration of the Deuteron at High Four Momentum Transfers Q^2



Gema P. Villegas Minyety

JLUO Annual Meeting

25 June 2026

JLUO
JEFFERSON LAB USERS ORGANIZATION

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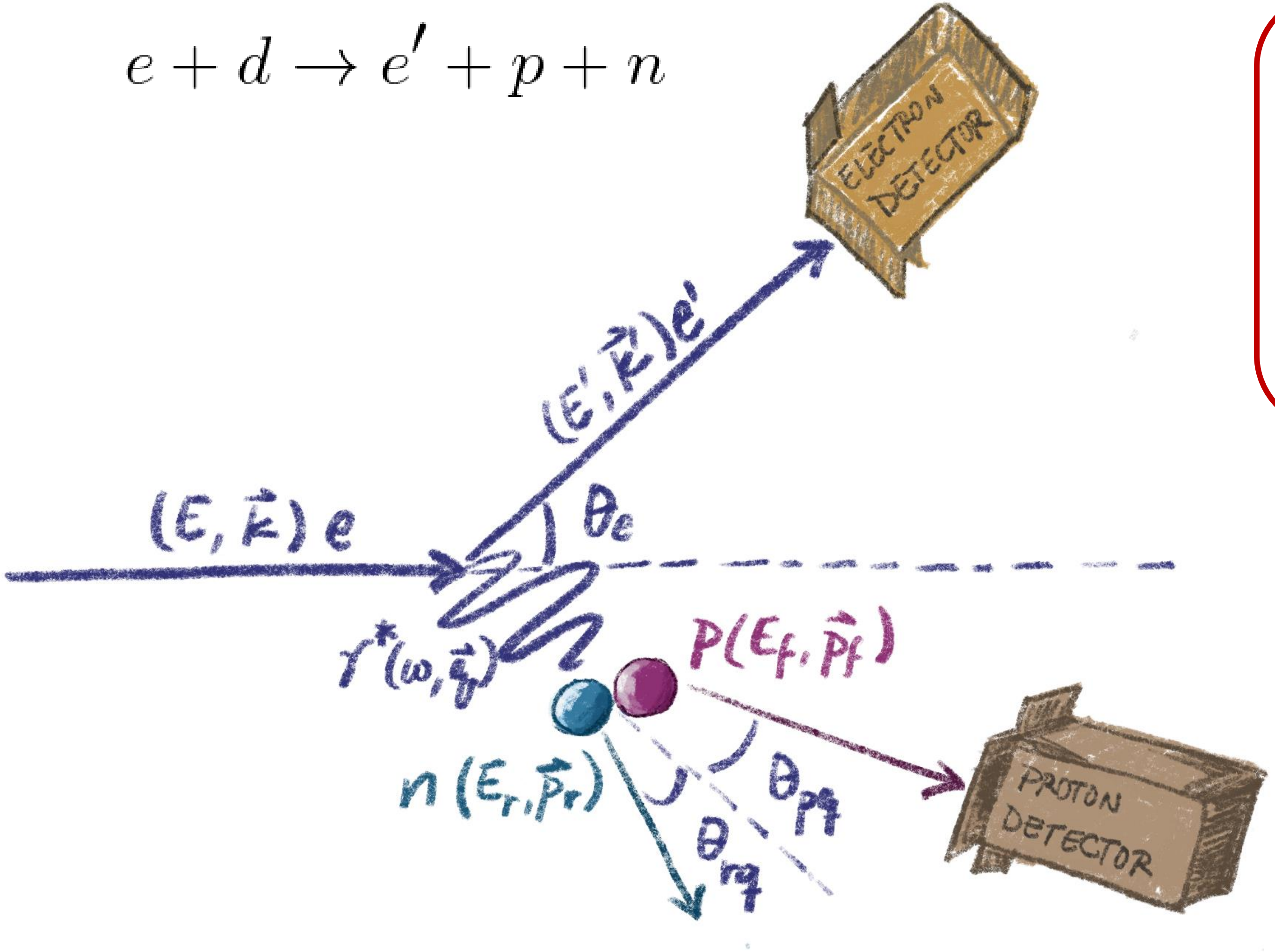
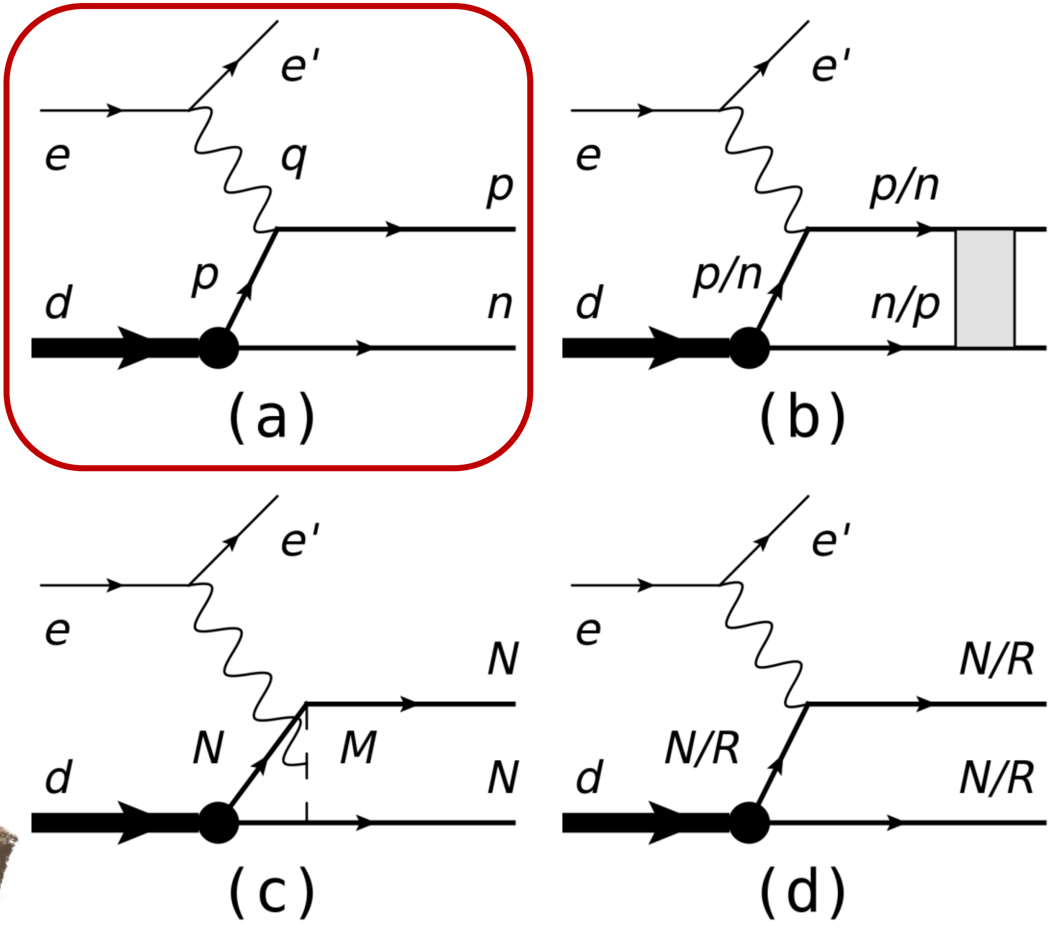
Brief Overview of Deuteron Breakup

$$e + d \to e' + p + n$$



Plane Wave Impulse Approx.

Final State Interactions



Meson Exchange Currents

Isobar Configurations

(b), (c), and (d) are suppressed in the kinematic window used

Brief Overview of Deuteron Breakup

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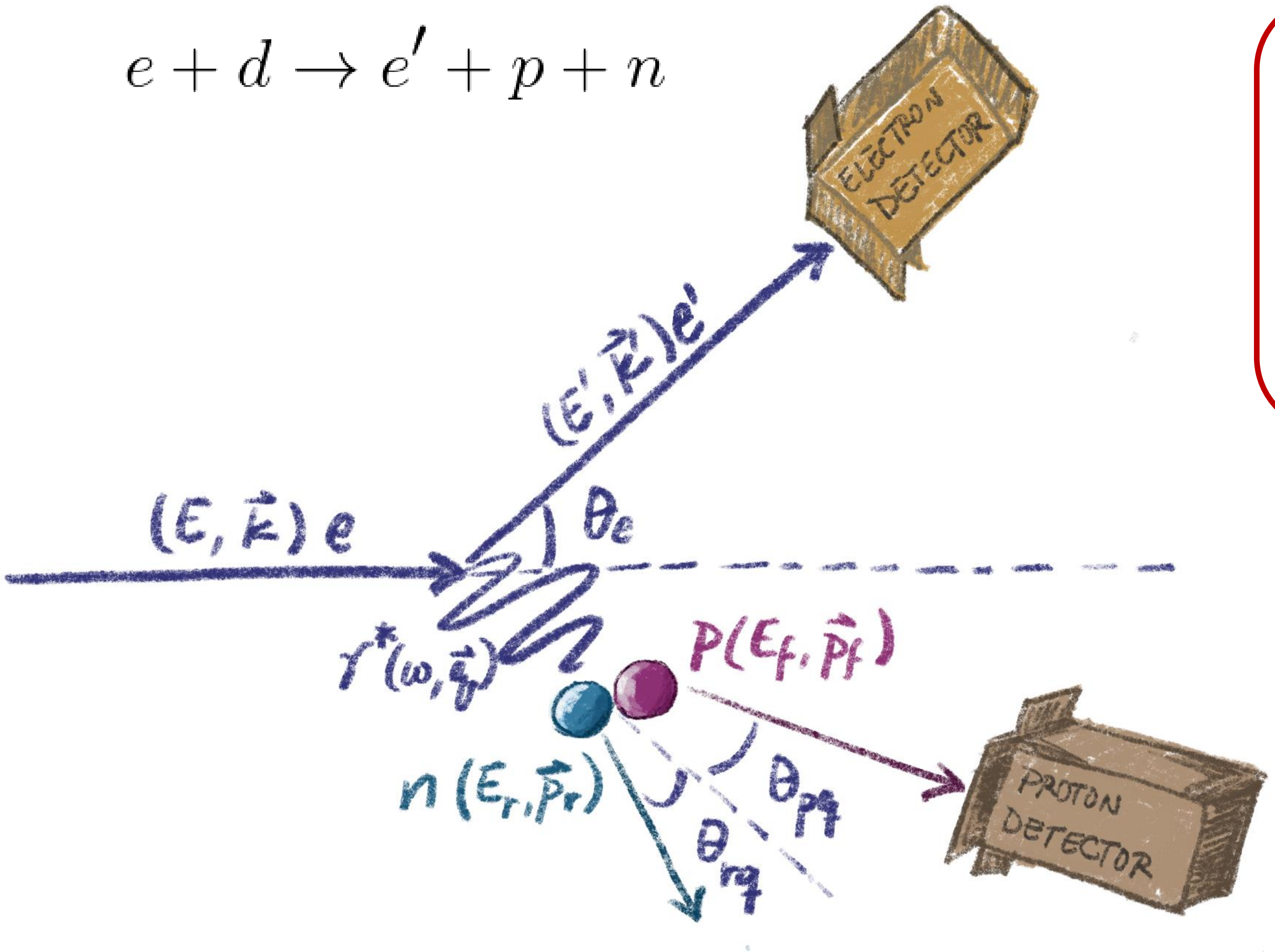

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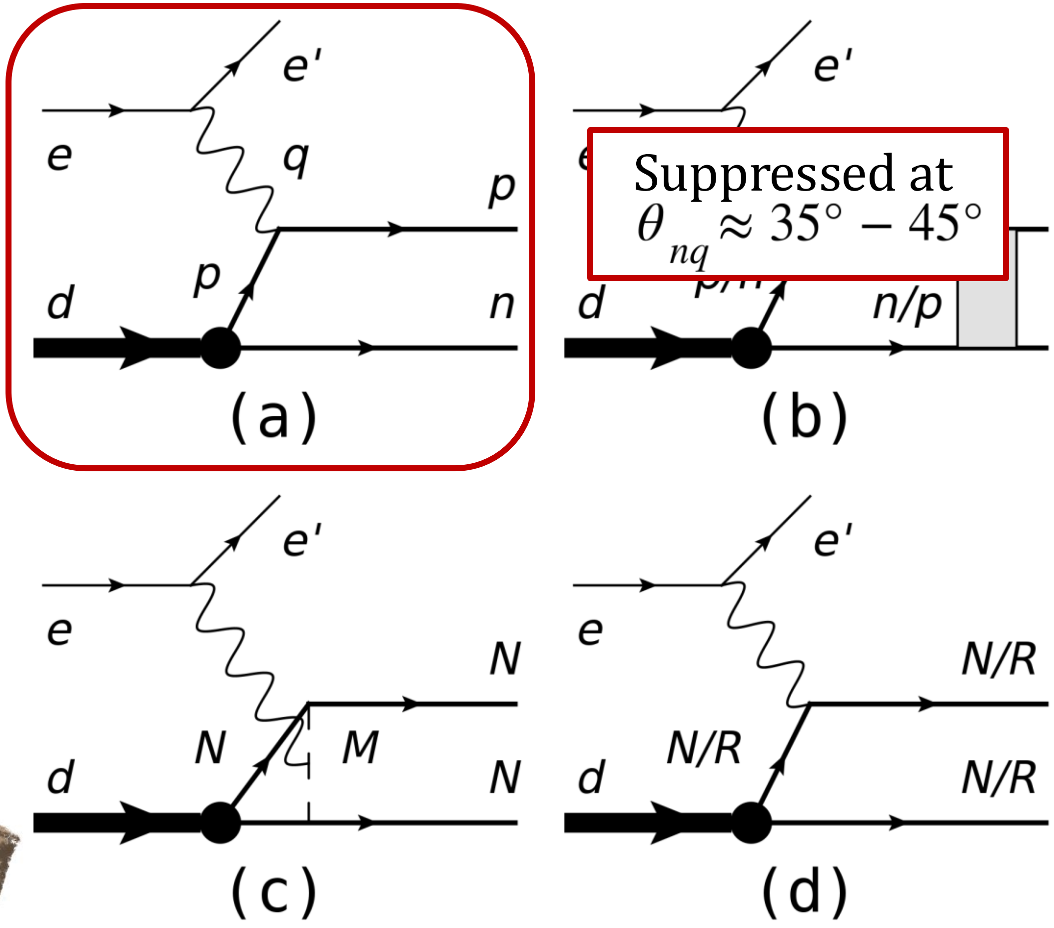

Suppressed at $\theta_{nq} \approx 35° - 45°$

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Brief Overview of Deuteron Breakup

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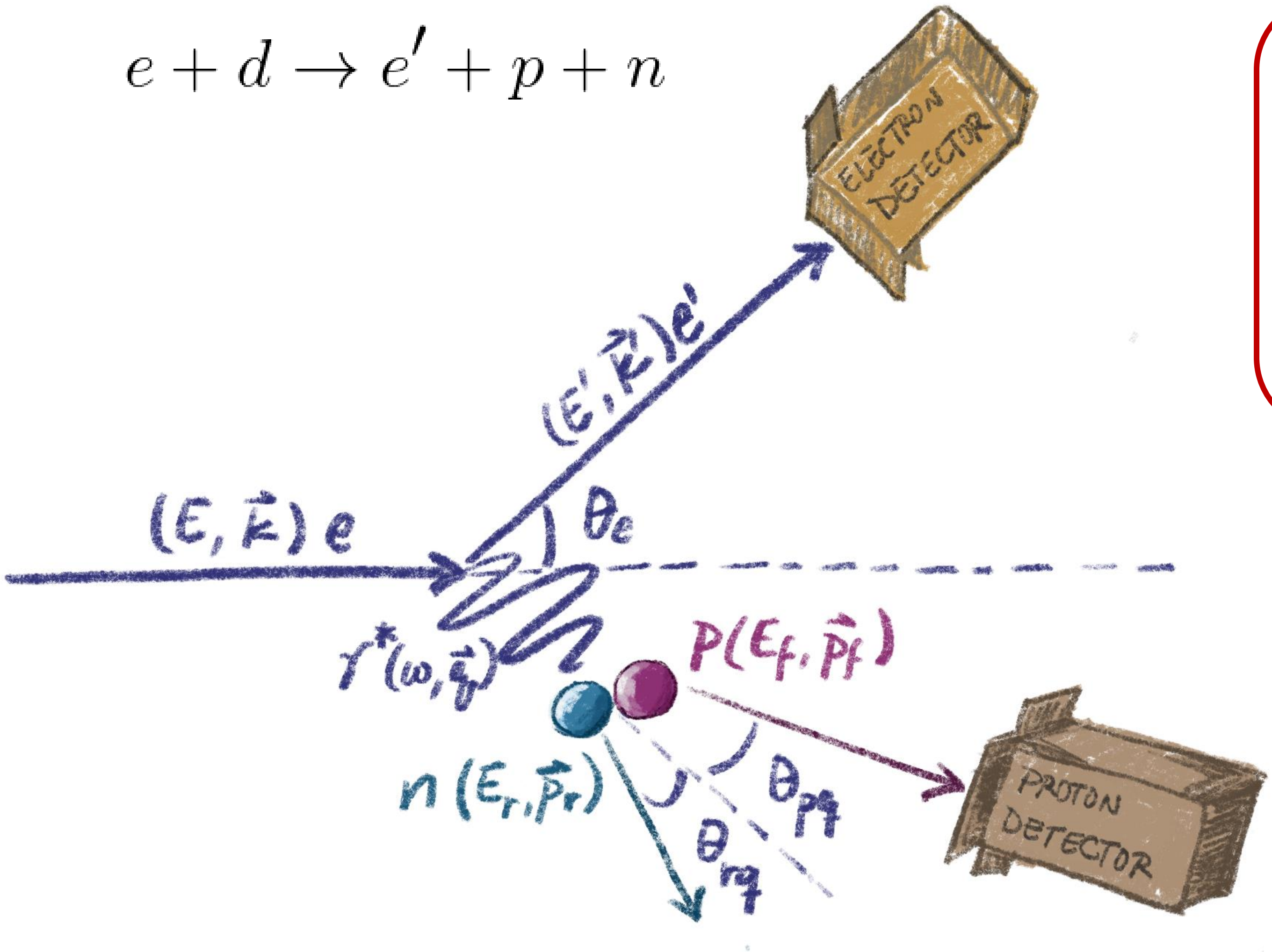

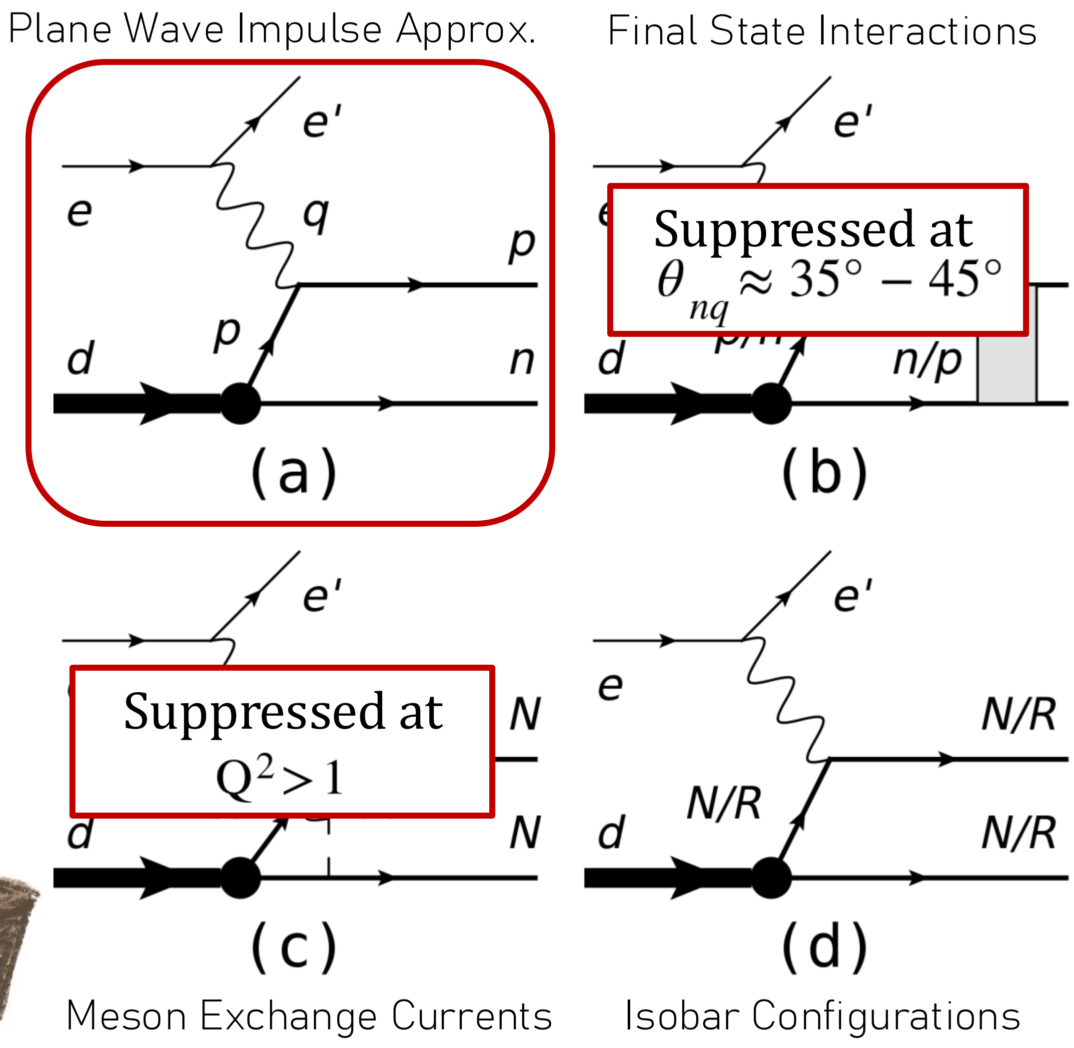

Plane Wave Impulse Approx.

Final State Interactions

Suppressed at $\theta_{nq} \approx 35° - 45°$

Suppressed at $Q^2 > 1$

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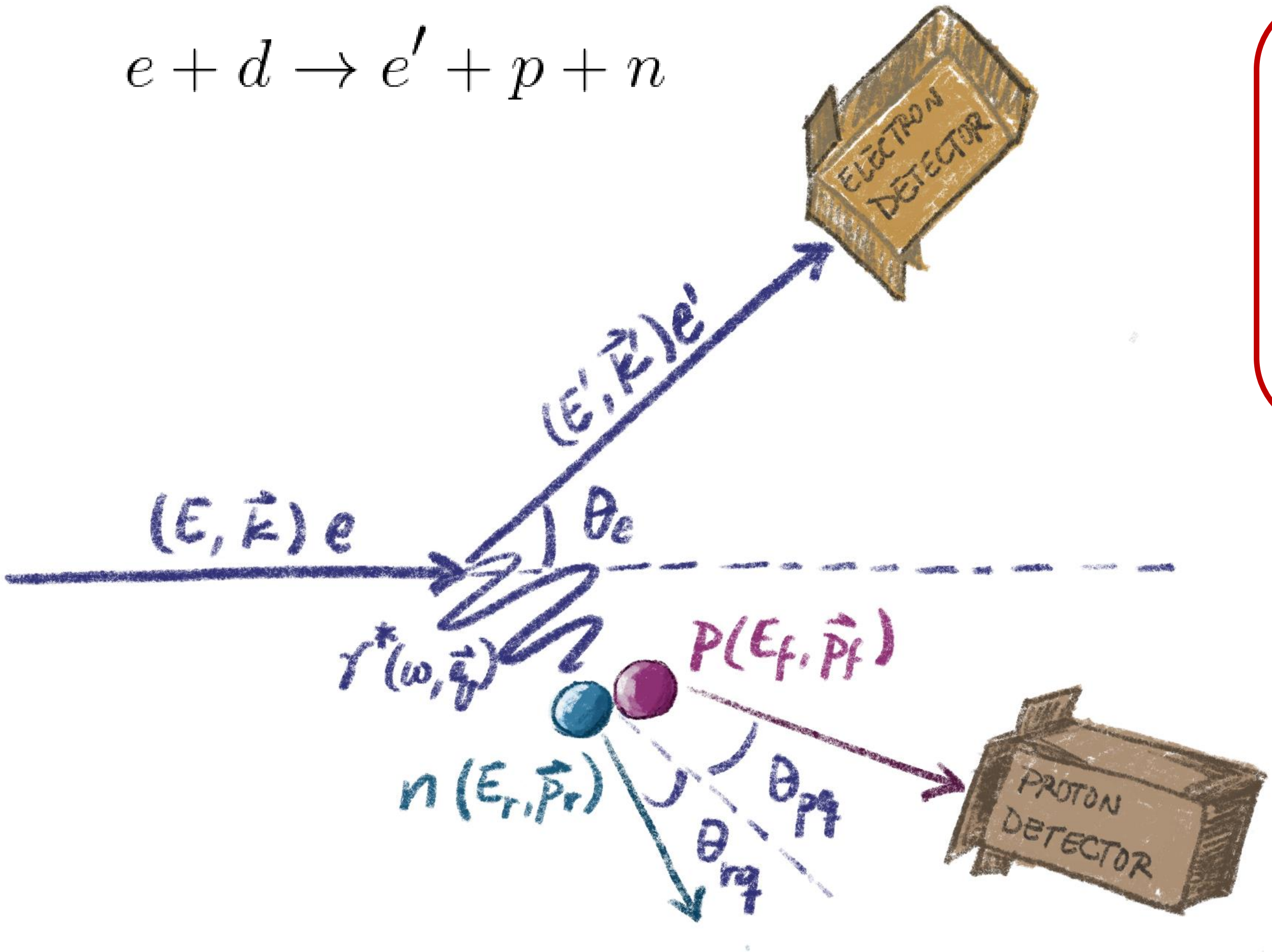
Brief Overview of Deuteron Breakup

$$e + d \rightarrow e' + p + n$$



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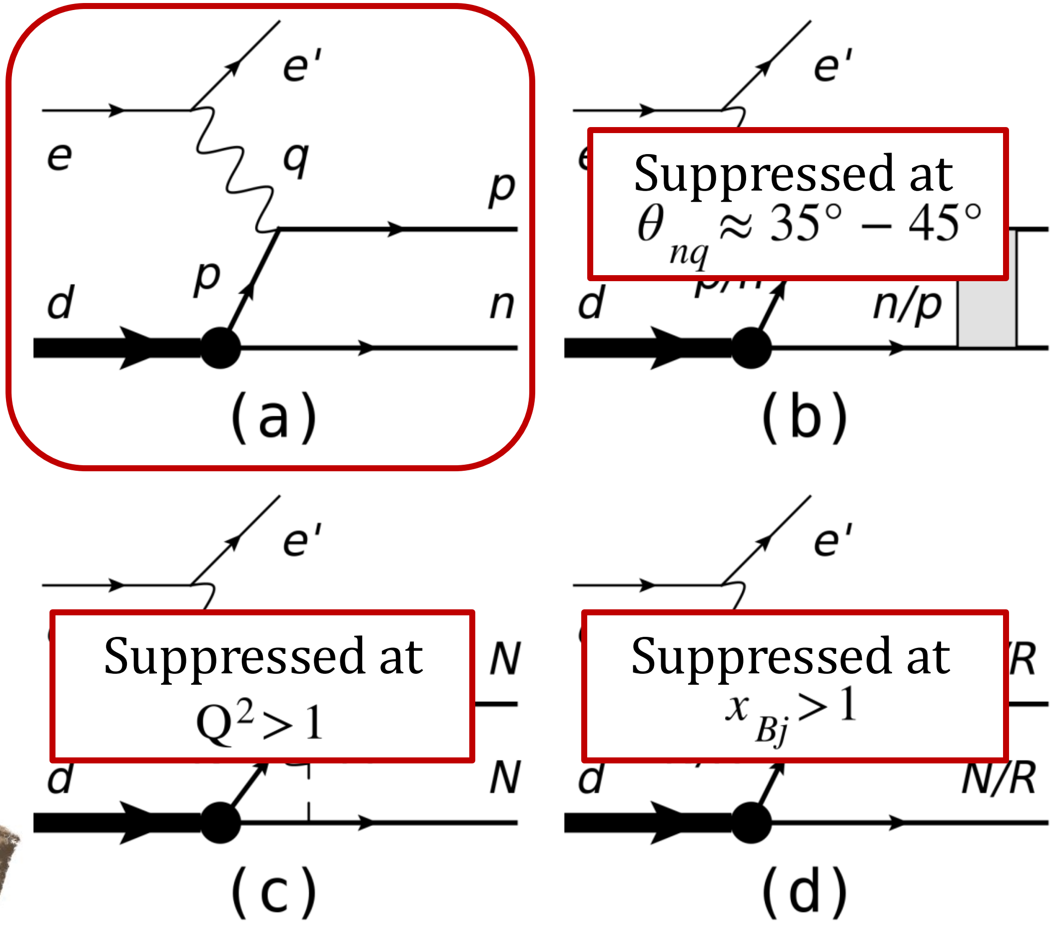


Suppressed at $\theta_{nq} \approx 35° - 45°$

Suppressed at $Q^2 > 1$

Suppressed at $x_{Bj} > 1$

Meson Exchange Currents

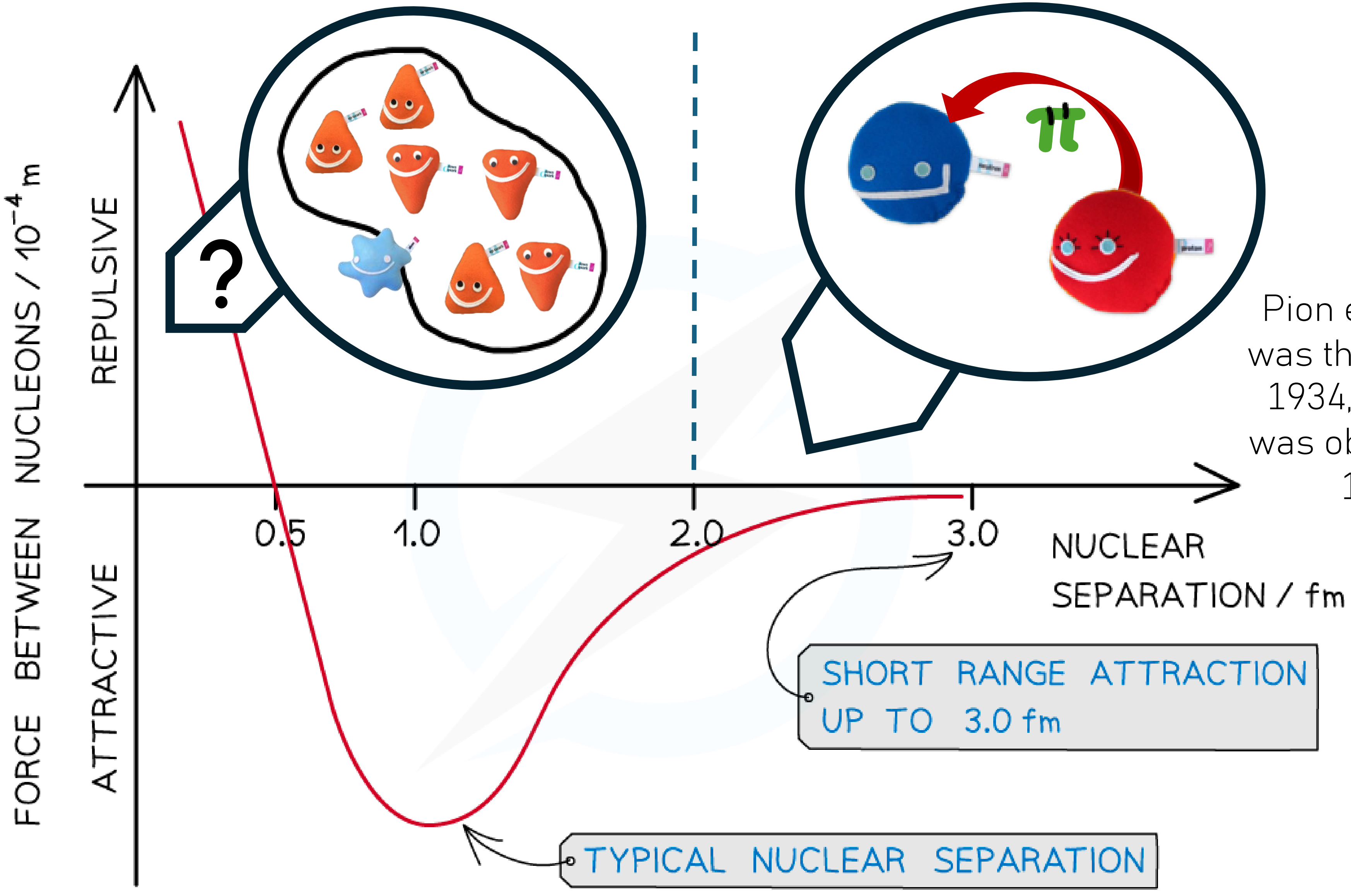
Isobar Configurations

(b), (c), and (d) are suppressed in the kinematic window used

Motivation : Refining our Picture of the Deuteron

Higher recoil momenta allow us to see shorter nucleon distances, possibly to quark degrees of freedom

The short-range part of the nucleon-nucleon interaction is the **least understood** and hardest to access experimentally



Pion exchange was theorized in 1934, the pion was observed in 1947

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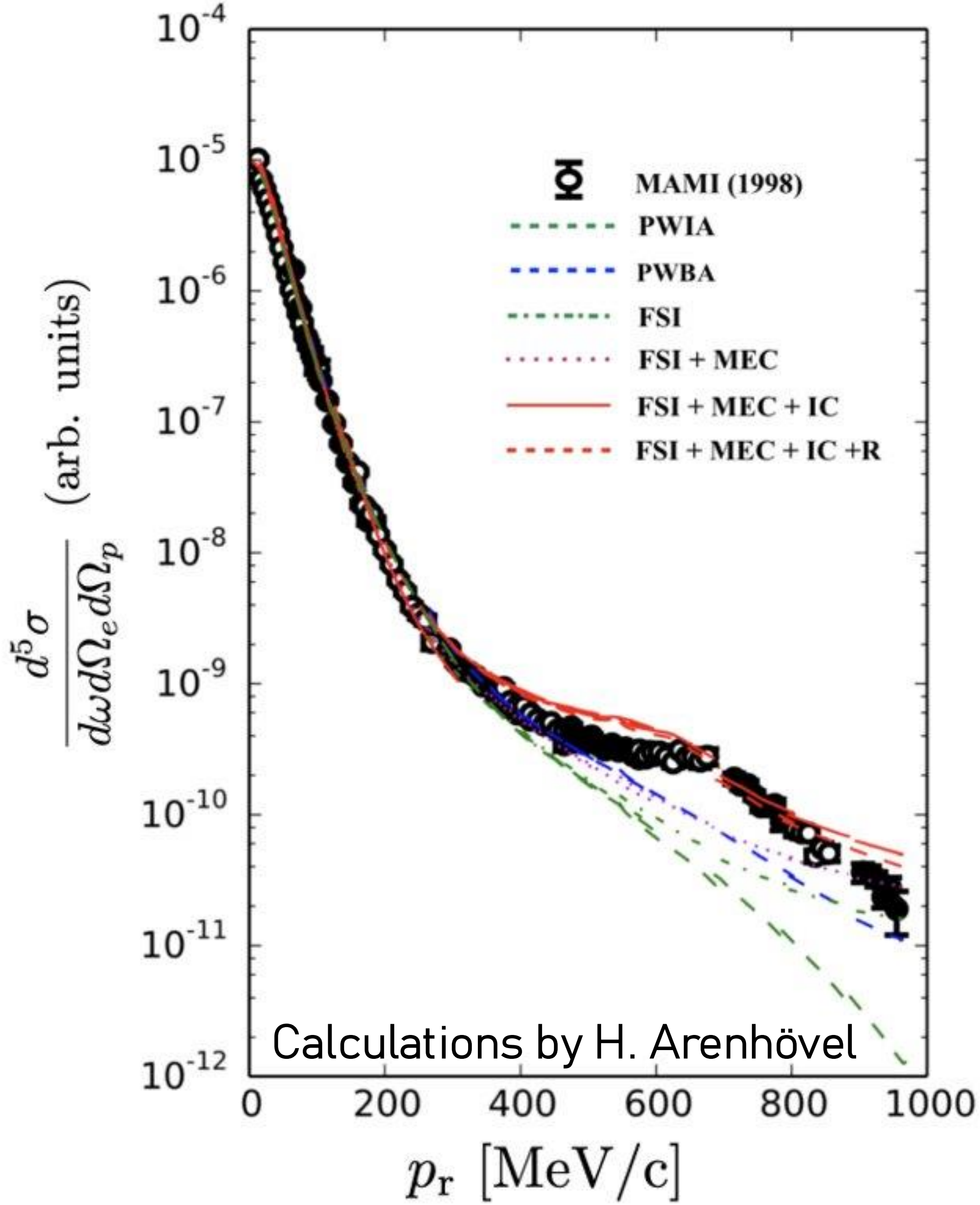
Previous Experiments

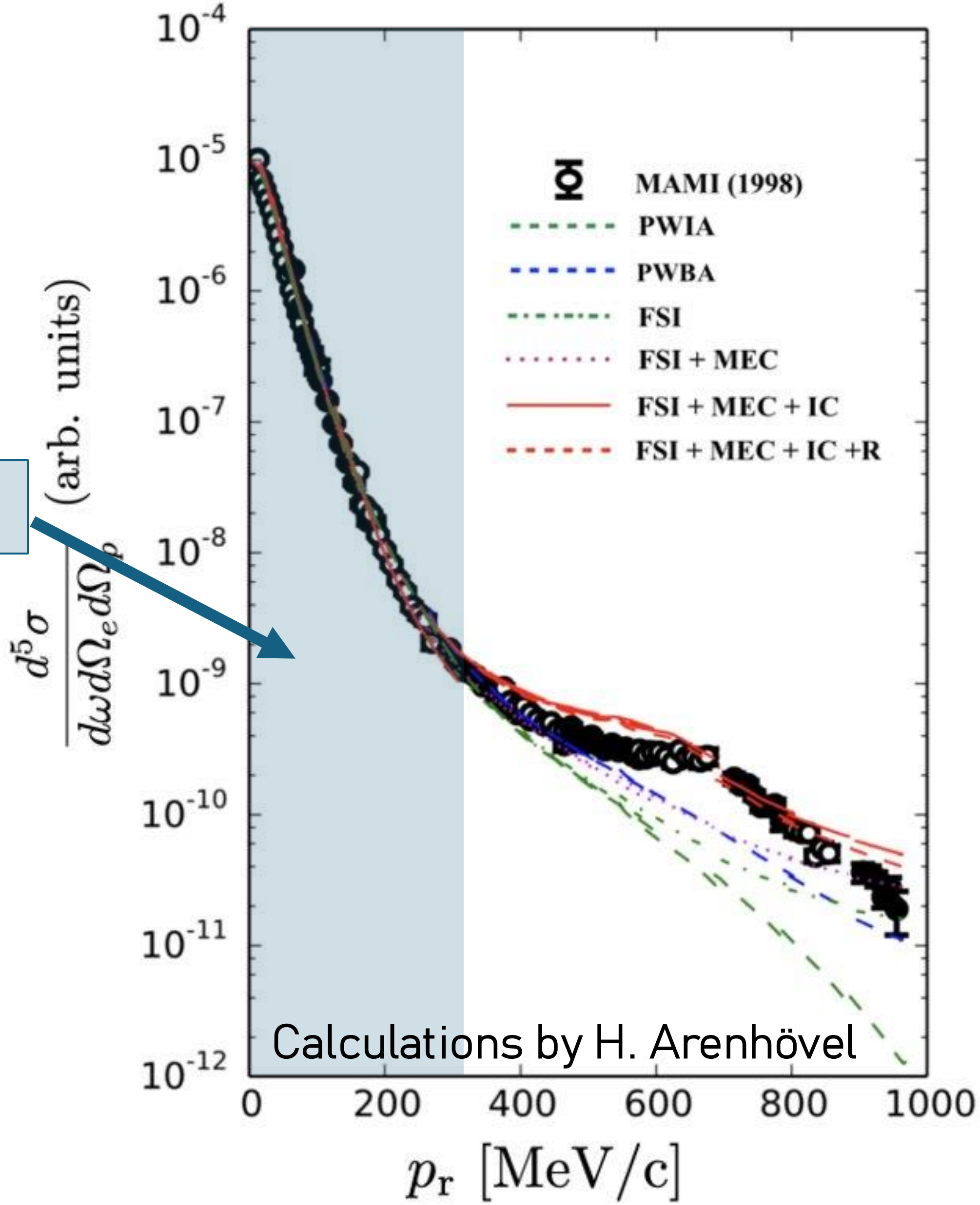


Calculations by H. Arenhövel

MAMI (1998). [Physics Letters B, 424(1–2), 33–38.]()

Previous Experiments

r > ~ 2 fm (long-range)



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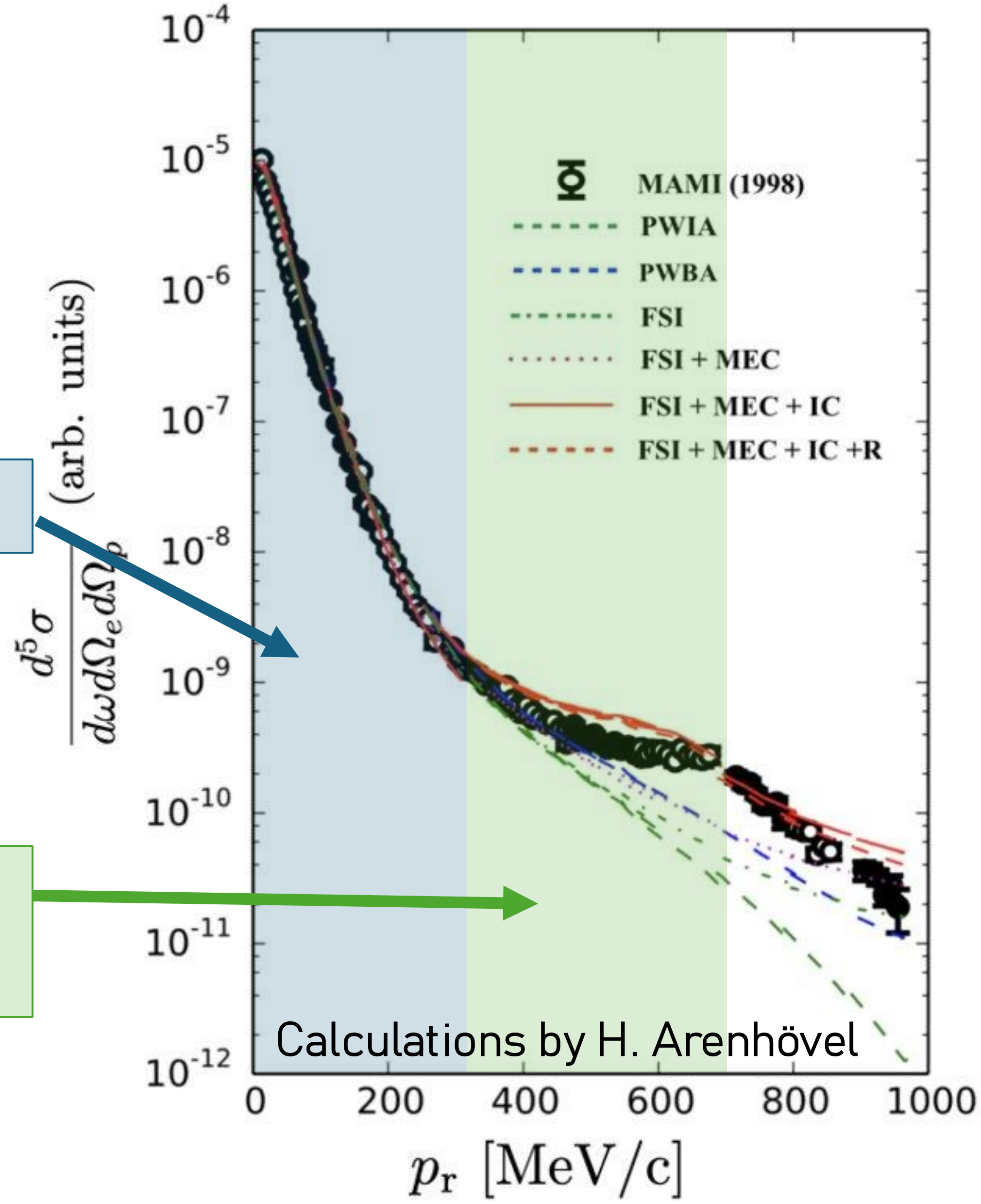

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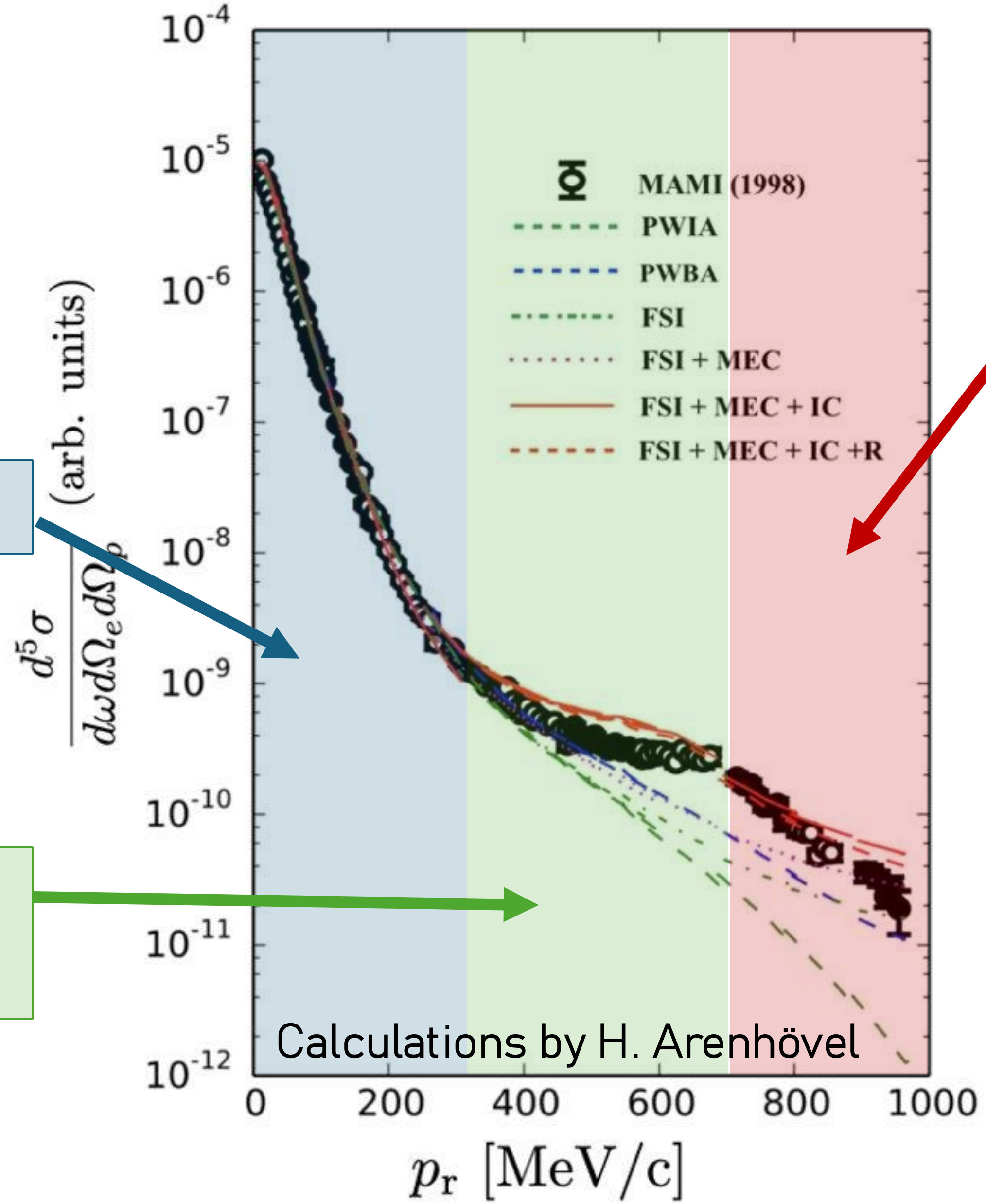

Calculations by H. Arenhövel

r < ~ 1 fm (short-range)

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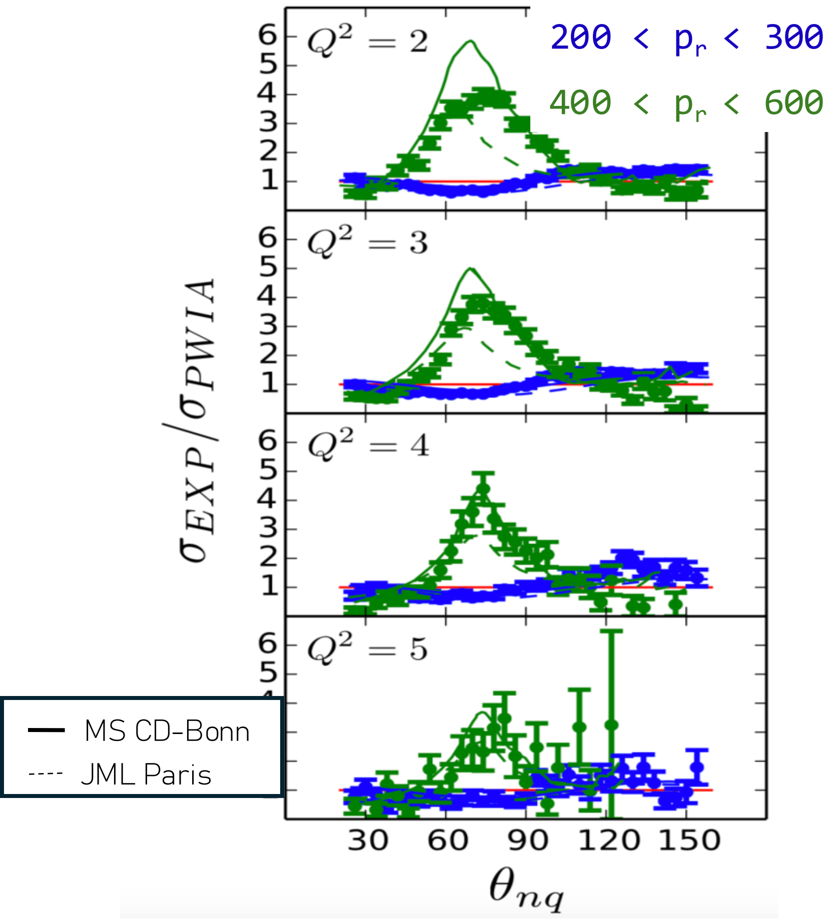
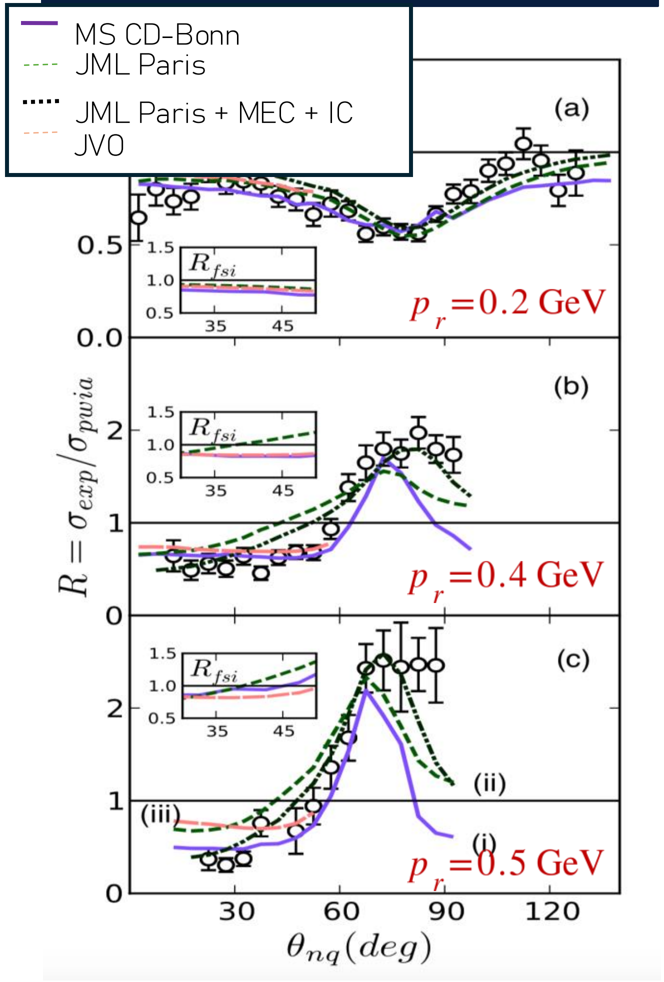
Previous Experiments

Hall B Experiment (CLAS)



K. S. Egiyan et al. (2007)
10.1103/PhysRevLett.98.262502

Hall A Experiment (E01-020)



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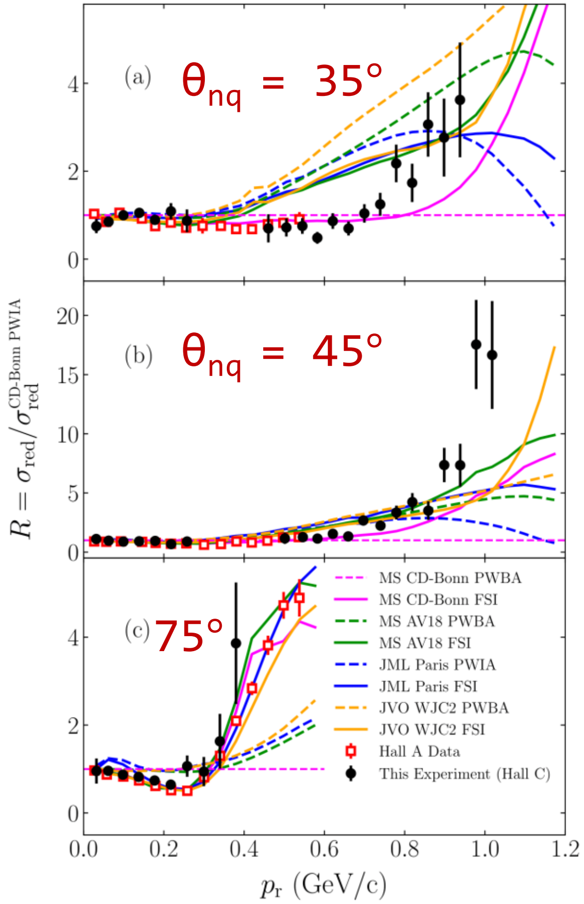
Hall C Experiment (E12-10-003)



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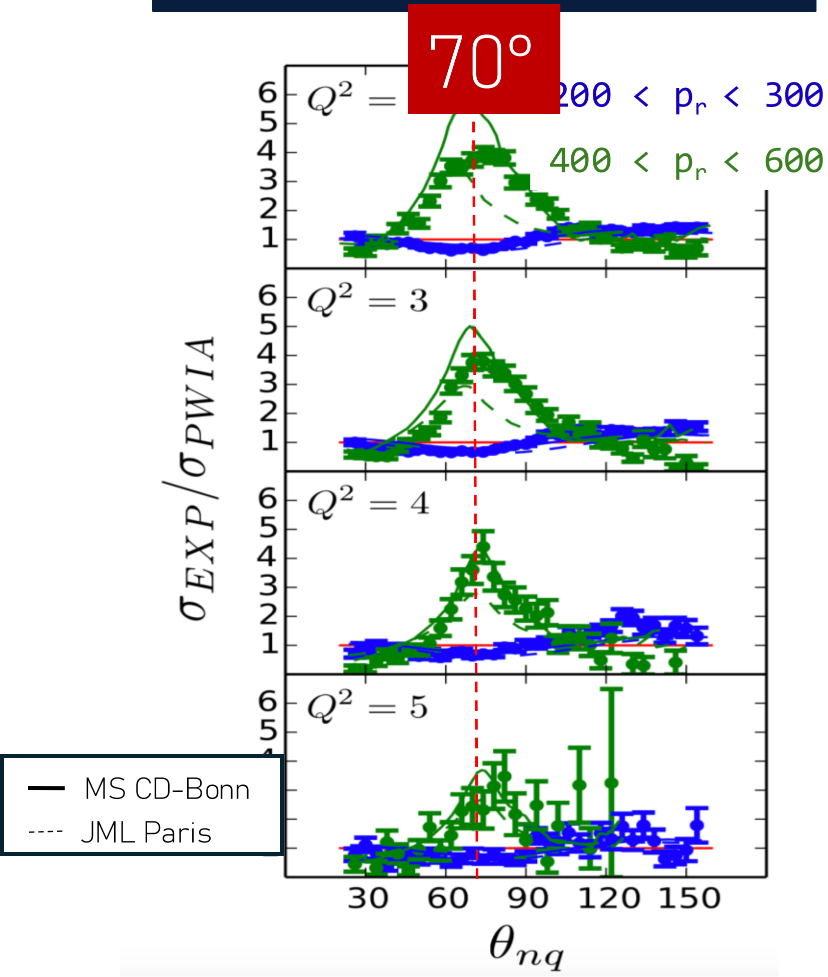

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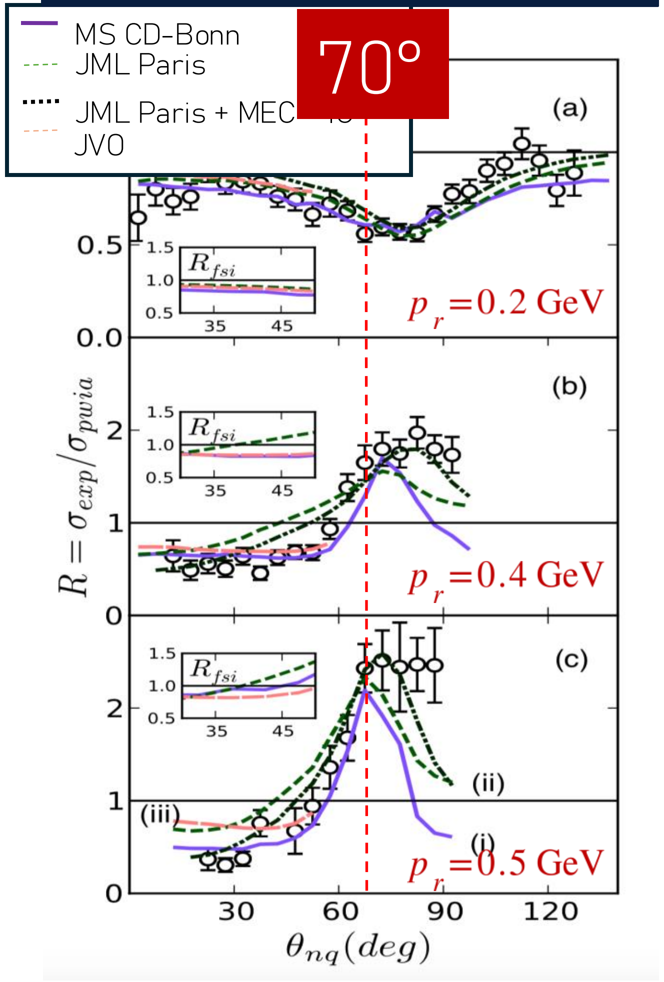

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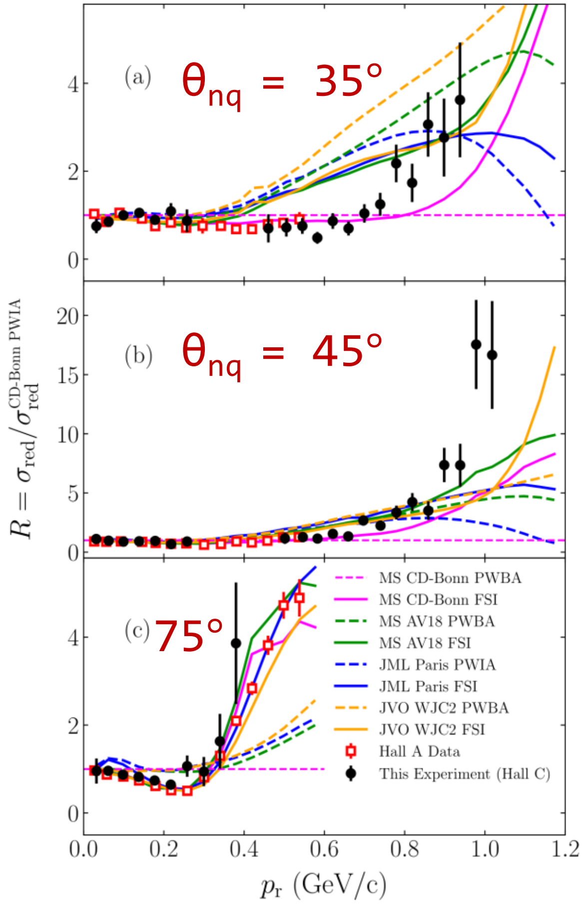

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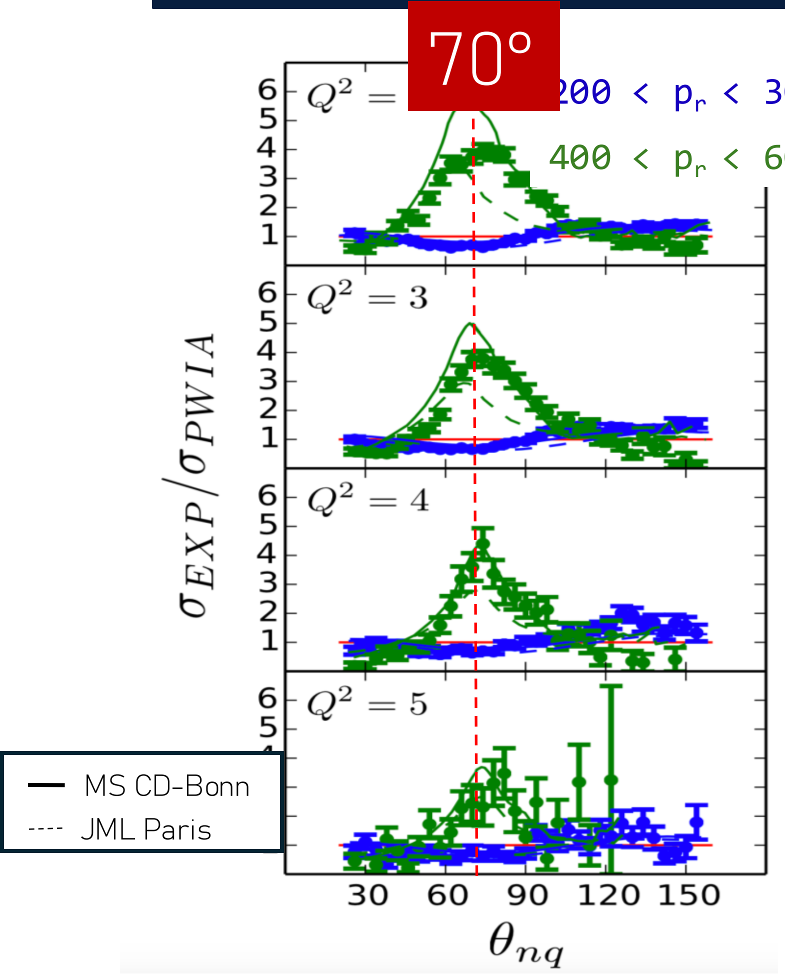

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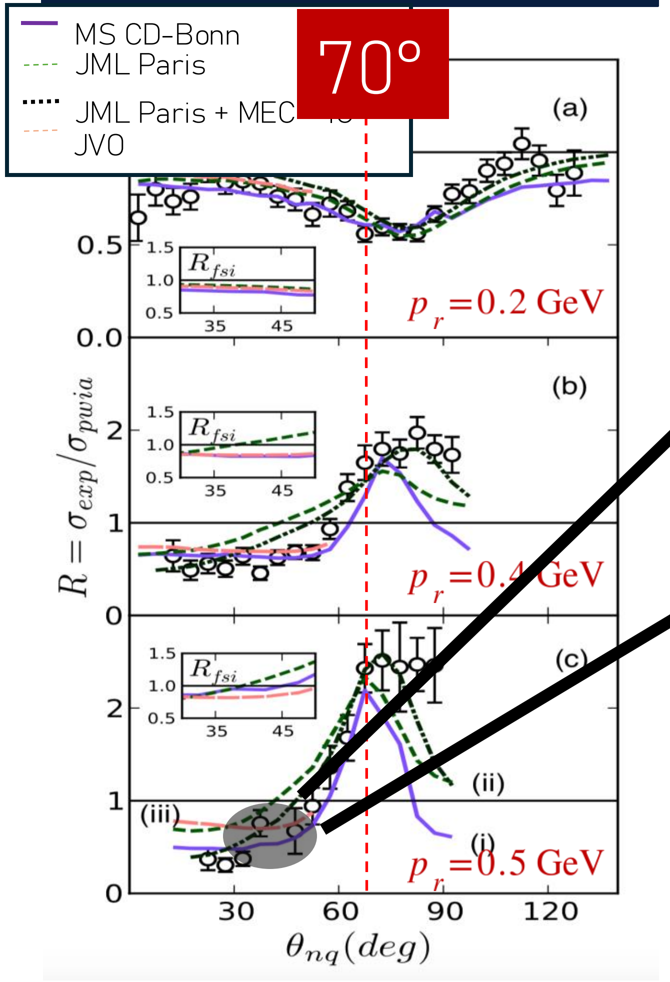

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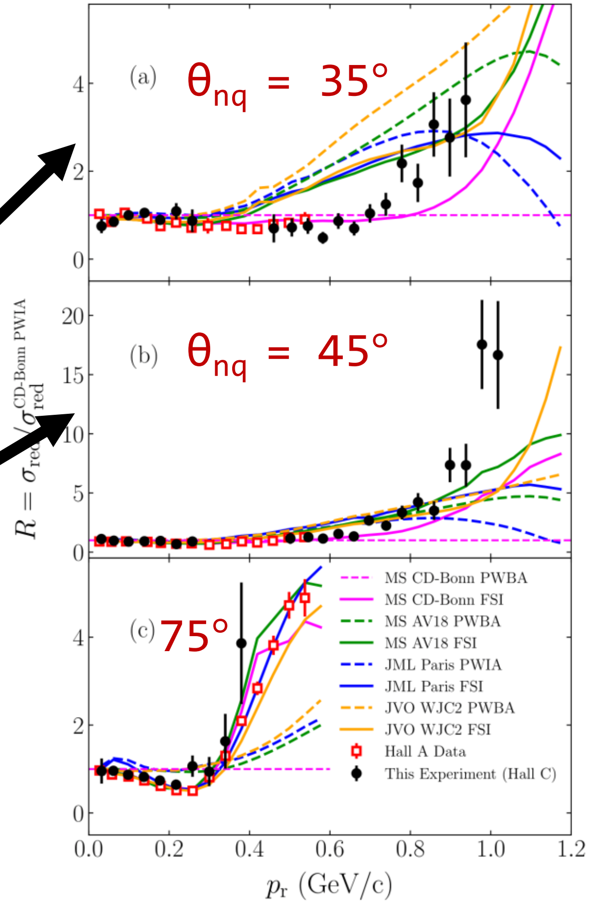

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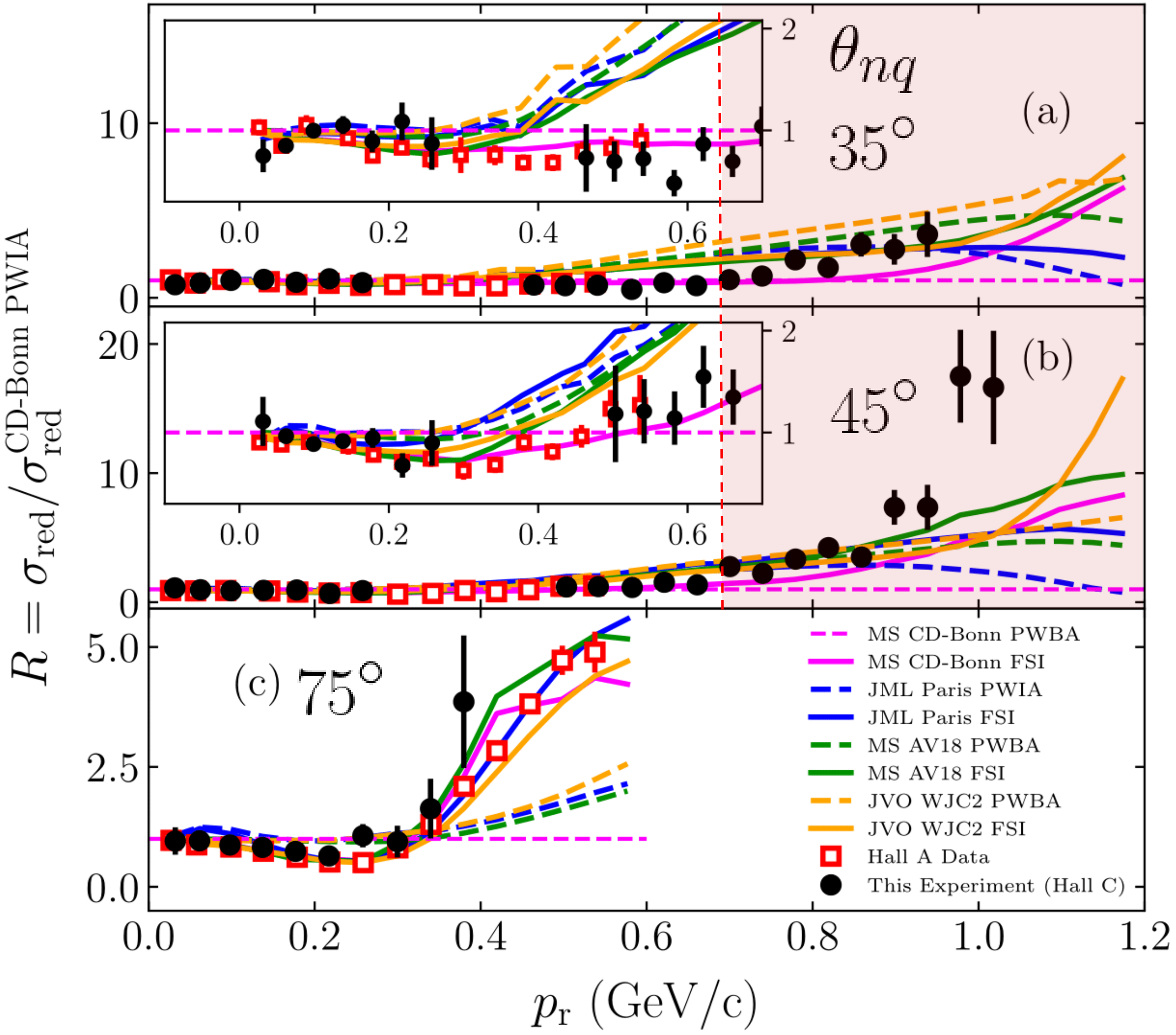


$$\sigma_{exp} = K \cdot \sigma_{eN} \cdot S(p_i)$$

$$\sigma_{red} \equiv \frac{\sigma_{exp}}{K \cdot \sigma_{eN}} \sim S(p_i)$$

Theoretical Models:

(1) Charge-Dependent (CD) Bonn

(2) Paris

(3) AV18

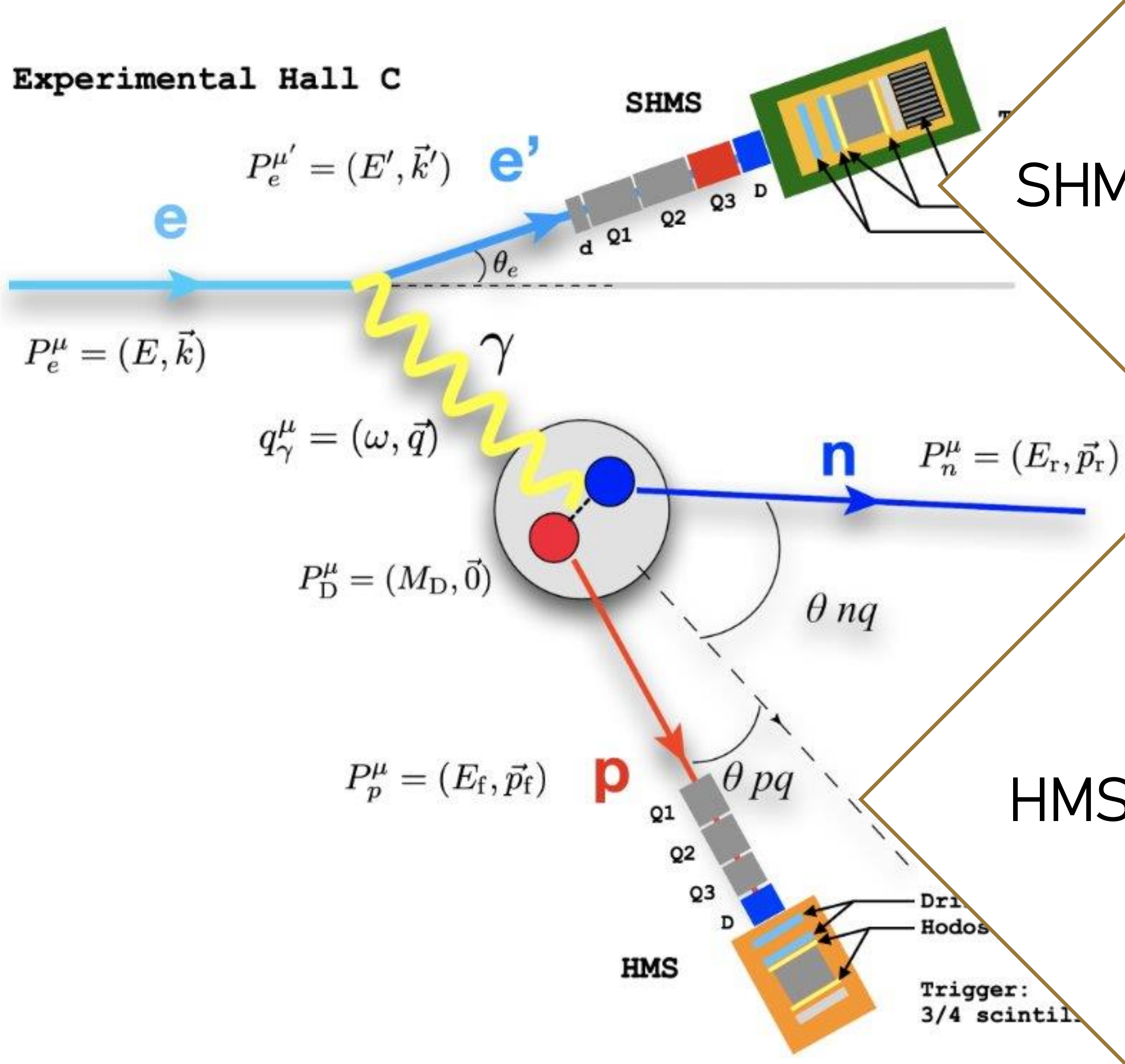
(4) WJC2

The models differ in the way they use empirical NN scattering data.

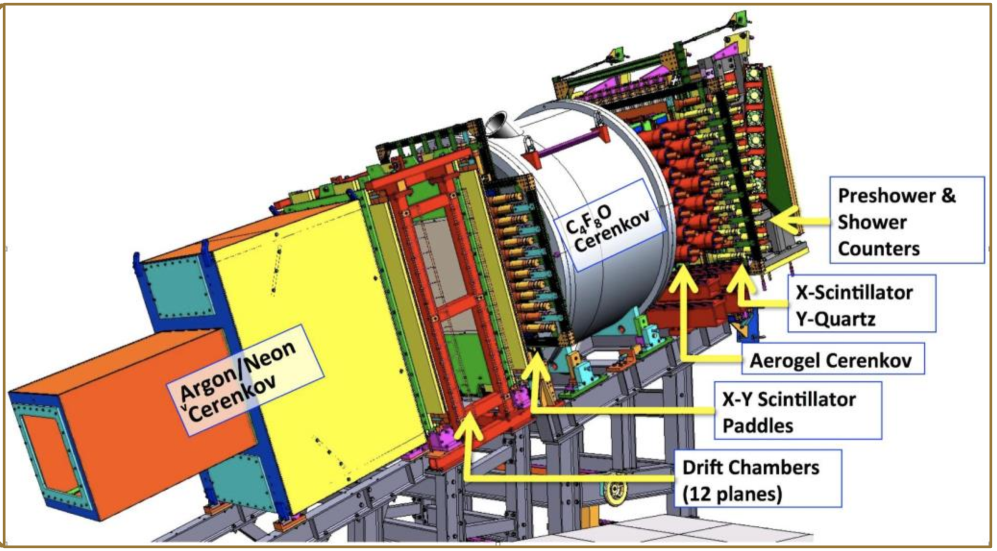
CD-Bonn and WJC2 models use an OBE potential approach, while AV18 and Paris are purely phenomenological.

The data agrees well with the CD-Bonn model up to ~ 700 MeV/c

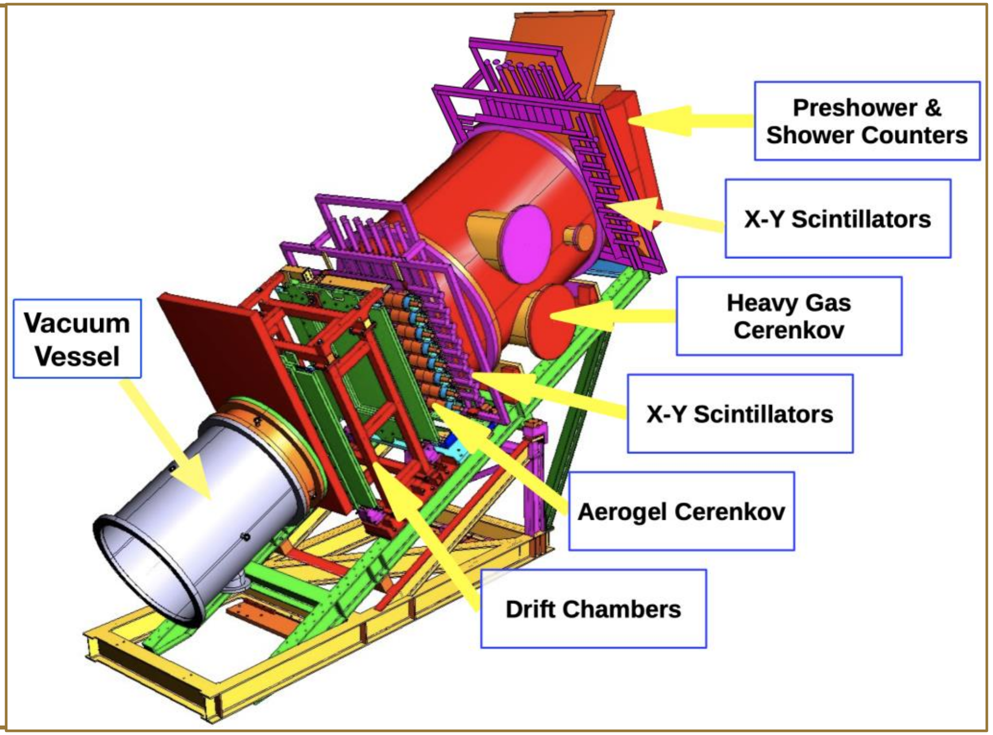
Deuteron Experiment Details



SHMS



HMS



Deuteron Experiment Details

- Ran from Feb 24th, 2023 until March 20th, 2023
- Took hydrogen elastic H(e,e'p) data, in a wide range of delta settings.
- D(e,e'p)n production had 4 missing momentum settings chosen to cover much of the area of interest.
- Also took luminosity data for target boiling studies.

H(e,e'p) δ scan				
δ [%]	SHMS momentum [GeV]	SHMS angle [°]	HMS momentum [GeV]	HMS angle [°]
-8	-8.55	14.15	3.499	33.34
-4		12.94	3.145	35.76
0		11.71	2.703	38.55
+4		10.44	2.417	41.82
+8		9.13	2.048	45.67
+12		7.70	1.664	50.50

D(e,e'p)n Production				
Missing momentum [MeV]	SHMS momentum [GeV]	SHMS angle [°]	HMS momentum [GeV]	HMS angle [°]
120	-8.55	12.2	3.052	38.63
580			2.262	54.96
800			2.121	59.39
900			2.047	61.34

D(e,e'p)n Data Cross Section

How do we extract the data cross section?

$$Y_{corr} = \frac{Y_{uncorr} \cdot \boxed{f_{rad}}}{\boxed{\epsilon_{htrk}} \cdot \boxed{\epsilon_{ptrk}} \cdot \boxed{\epsilon_{tLT}} \cdot \boxed{\epsilon_{tgtBoil}} \cdot \boxed{\epsilon_{pTr}}}$$

The **yield** is corrected by:

☐ Radiative correction factor (from SIMC)
☐ HMS tracking efficiency
☐ SHMS tracking efficiency
☐ Total EDTM Live Time
☐ Target Boiling factor
☐ Proton Transmission factor

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$$\boxed{\frac{d^5\sigma}{dE' d\Omega_e d\Omega_p} = \frac{Y_{corr}}{\boxed{\mathfrak{L}} \cdot \boxed{V_{PS}}}}$$

The **yield** is corrected by:
- ☐ Radiative correction factor (from SIMC)
- ☐ HMS tracking efficiency
- ☐ SHMS tracking efficiency
- ☐ Total EDTM Live Time
- ☐ Target Boiling factor
- ☐ Proton Transmission factor

The corrected yield is then divided by:
- ☐ Luminosity
- ☐ Phase Space Volume

The phase space is simulated by SIMC

From Cross Sections to Momentum Distributions

$$\sigma_{exp} \equiv \frac{d^5\sigma}{dE' d\Omega_e d\Omega_p} = \boxed{K} \cdot \boxed{f_{rec}} \cdot \boxed{\sigma_{eN}} \cdot \boxed{S(p_i)}$$

$$\sigma_{red} \equiv \frac{\sigma_{exp}}{K \cdot f_{rec} \cdot \sigma_{eN}} \sim S(p_i)$$

⚠

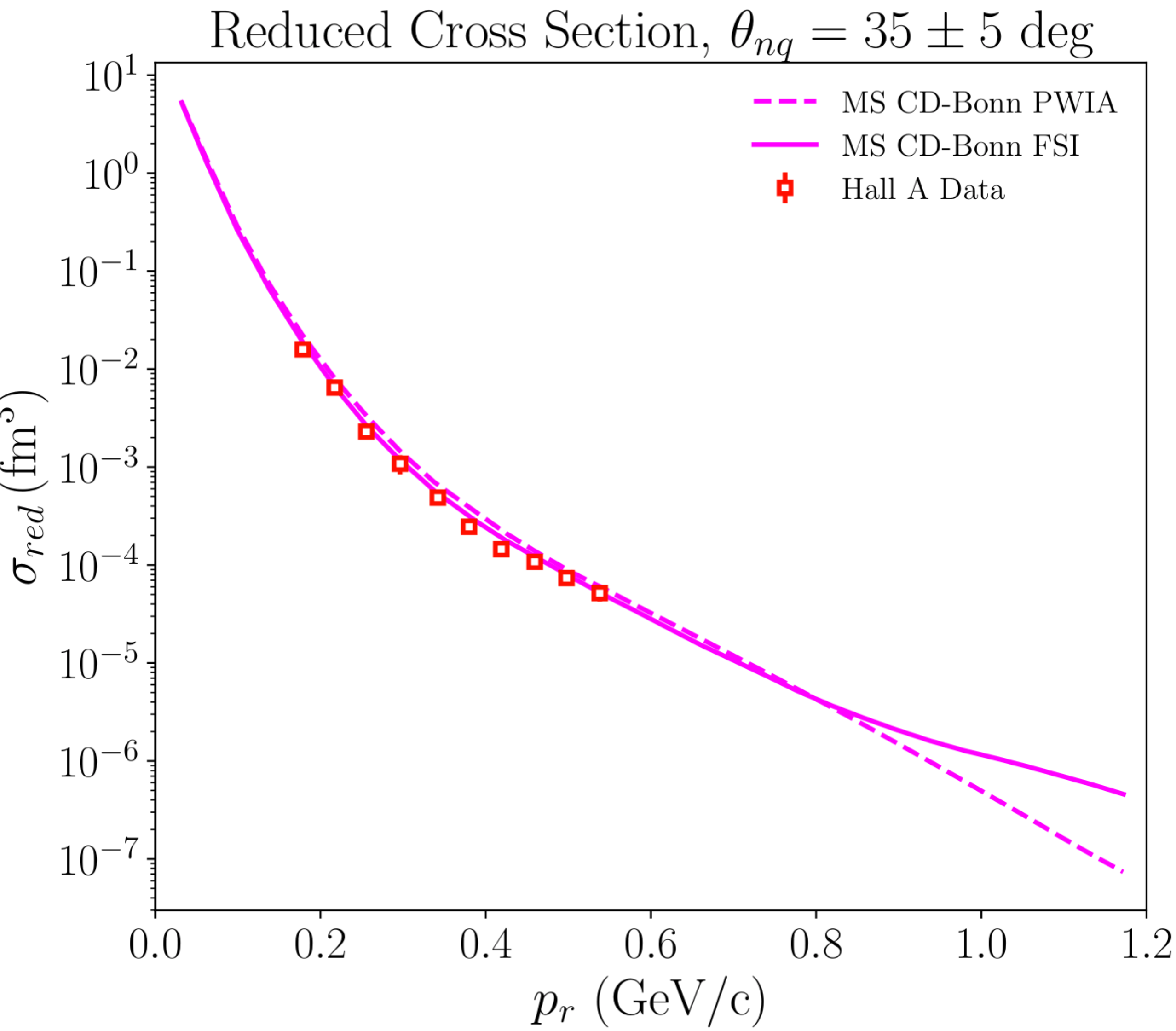
Only in the PWIA
This is equivalent to our experimental momentum distributions

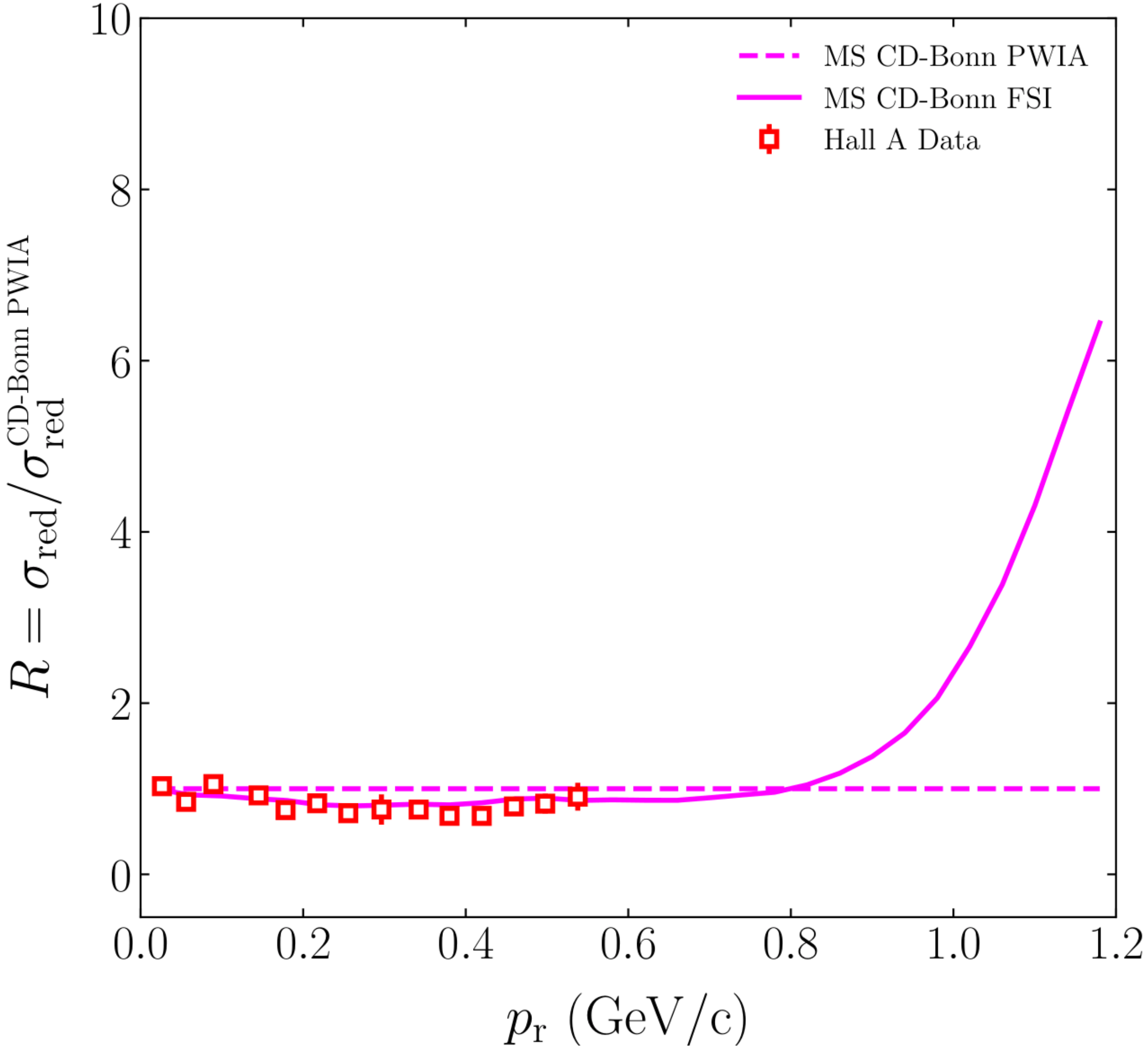
In the PWIA the cross section can be factorized into:

- ☐ Kinematic factor $K = E_f p_f$
- ☐ Binding energy factor
- ☐ Electron-nucleon cross section for which we use the de Forest off-shell cross section
- ☐ Spectral Function

Preliminary Results

Preliminary D(e,e'p)n Momentum Distributions





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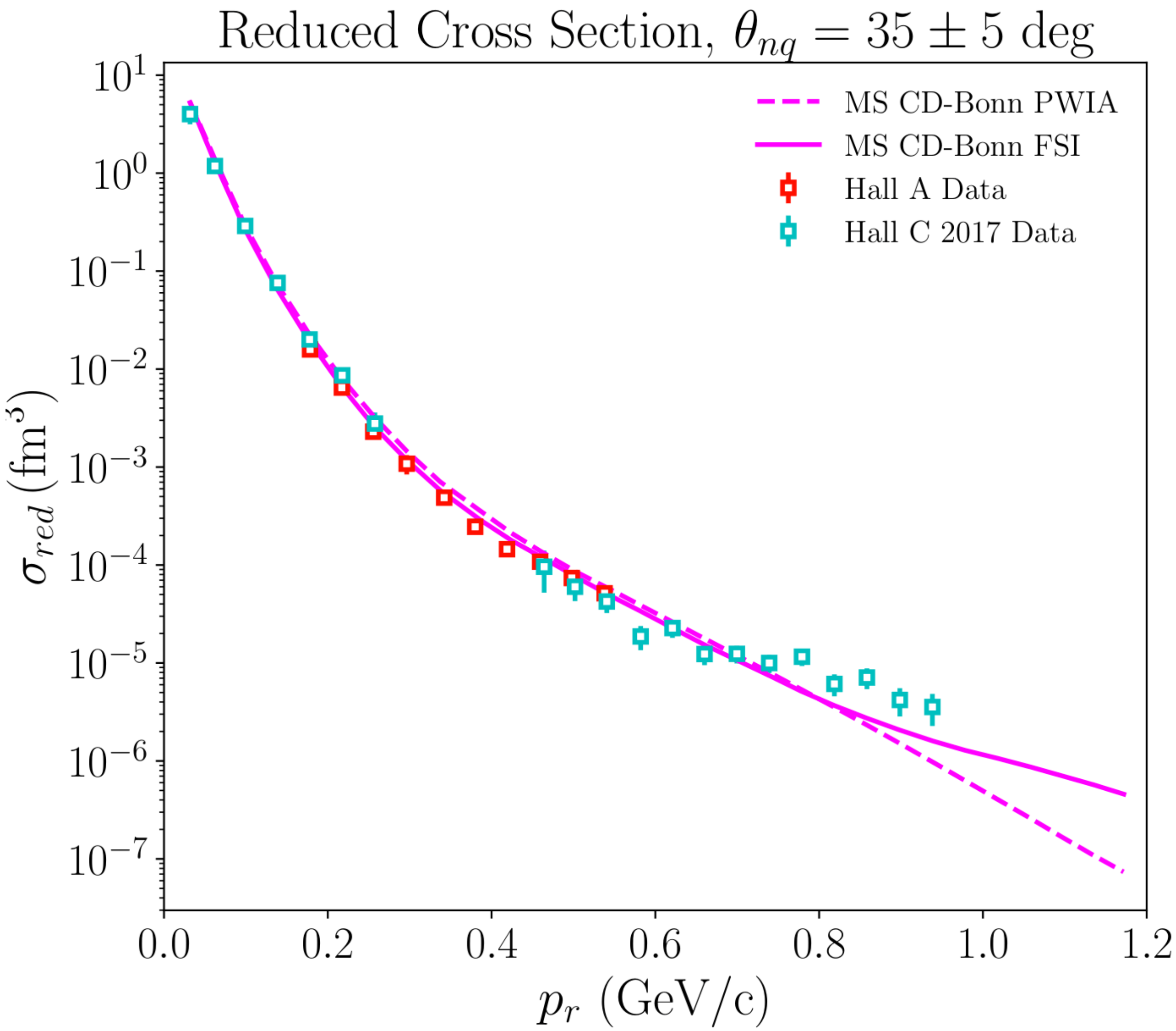

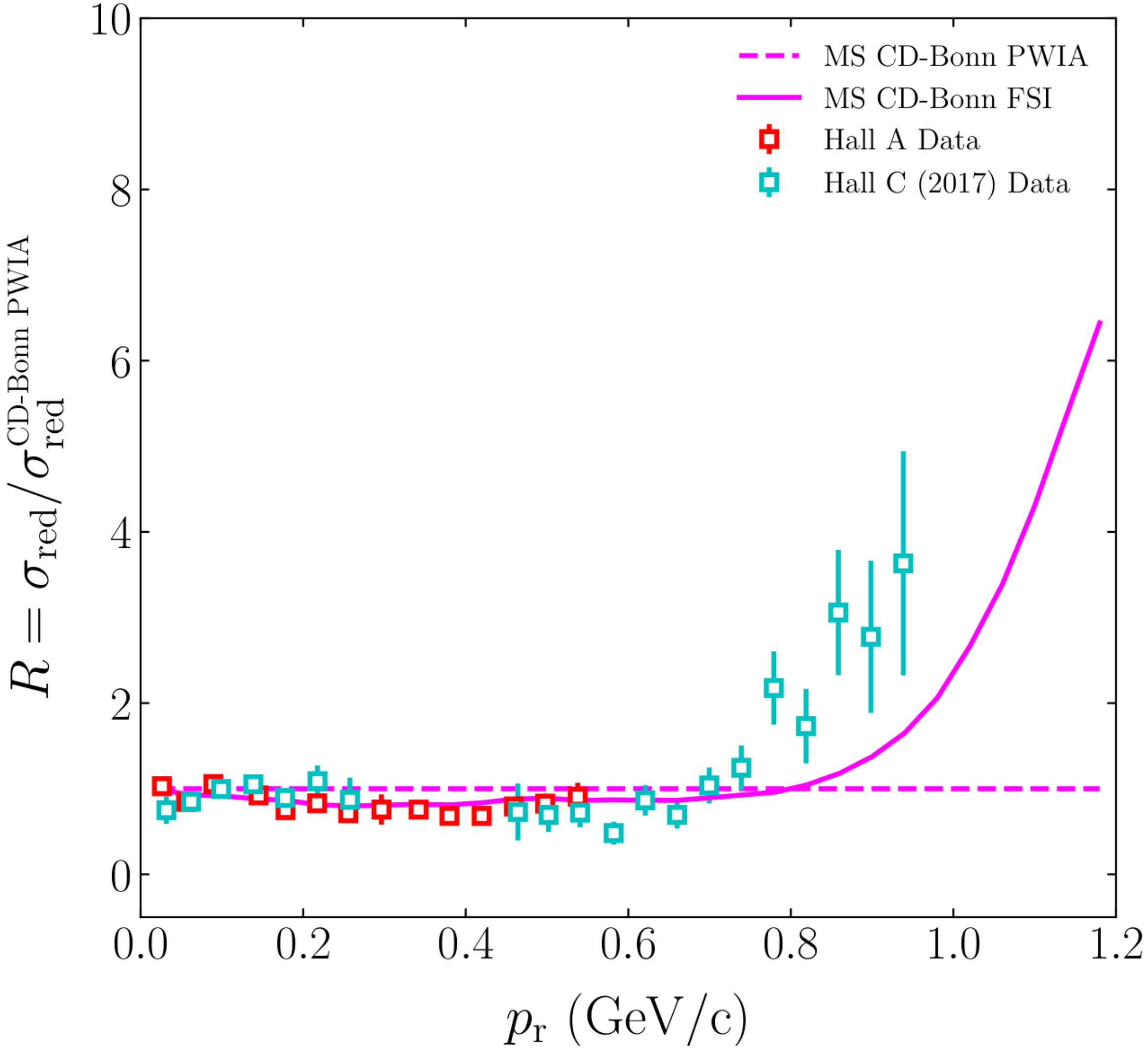

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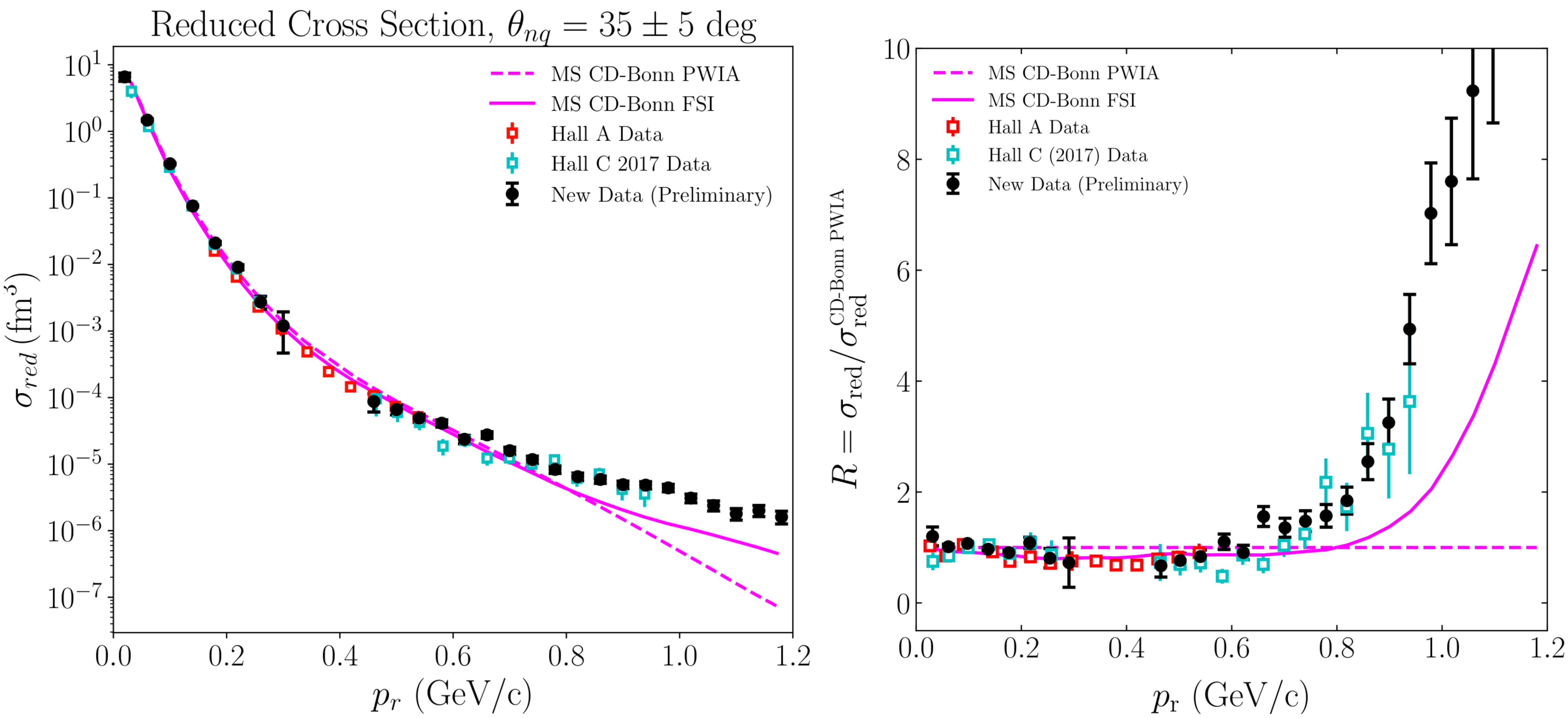

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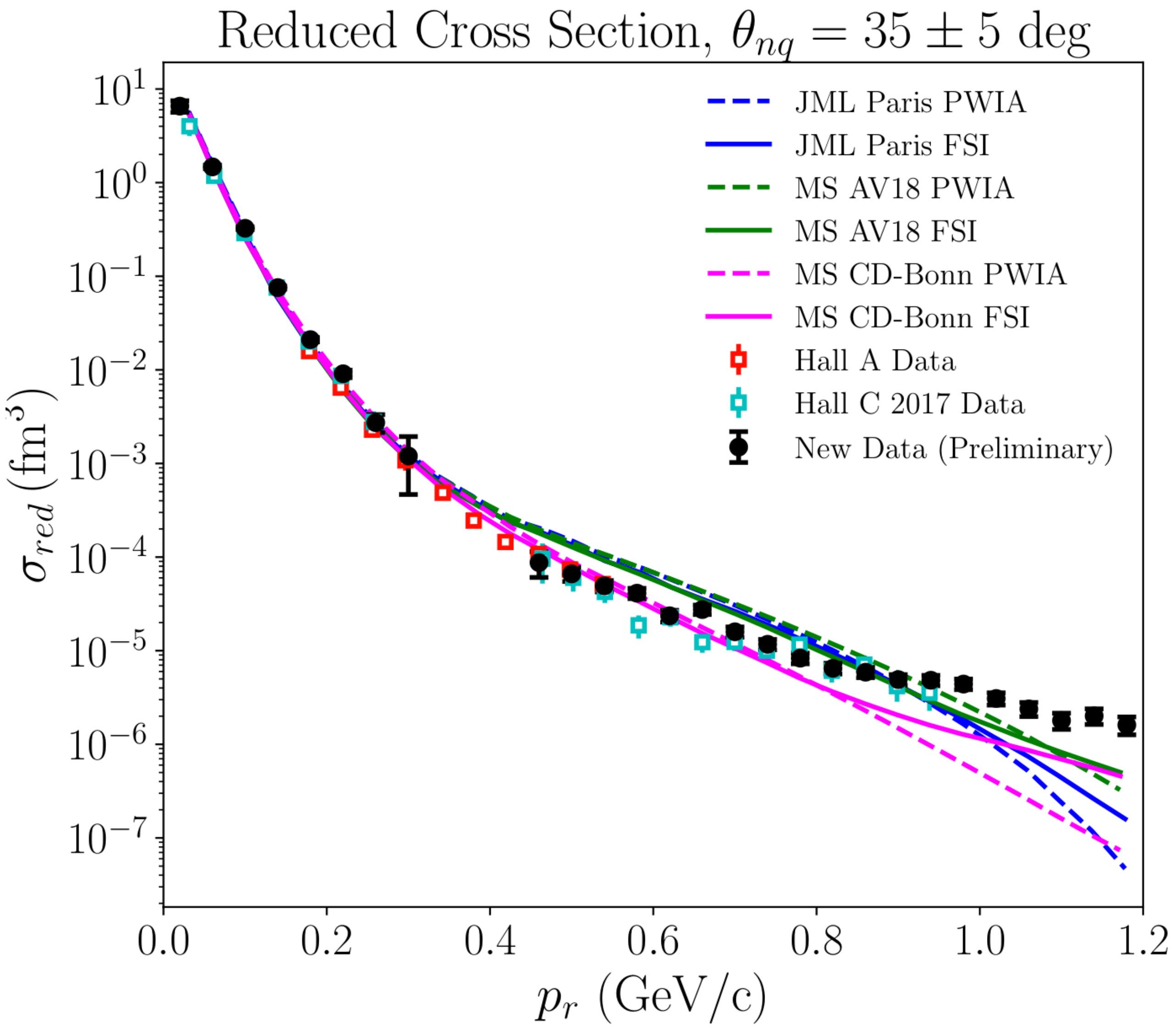

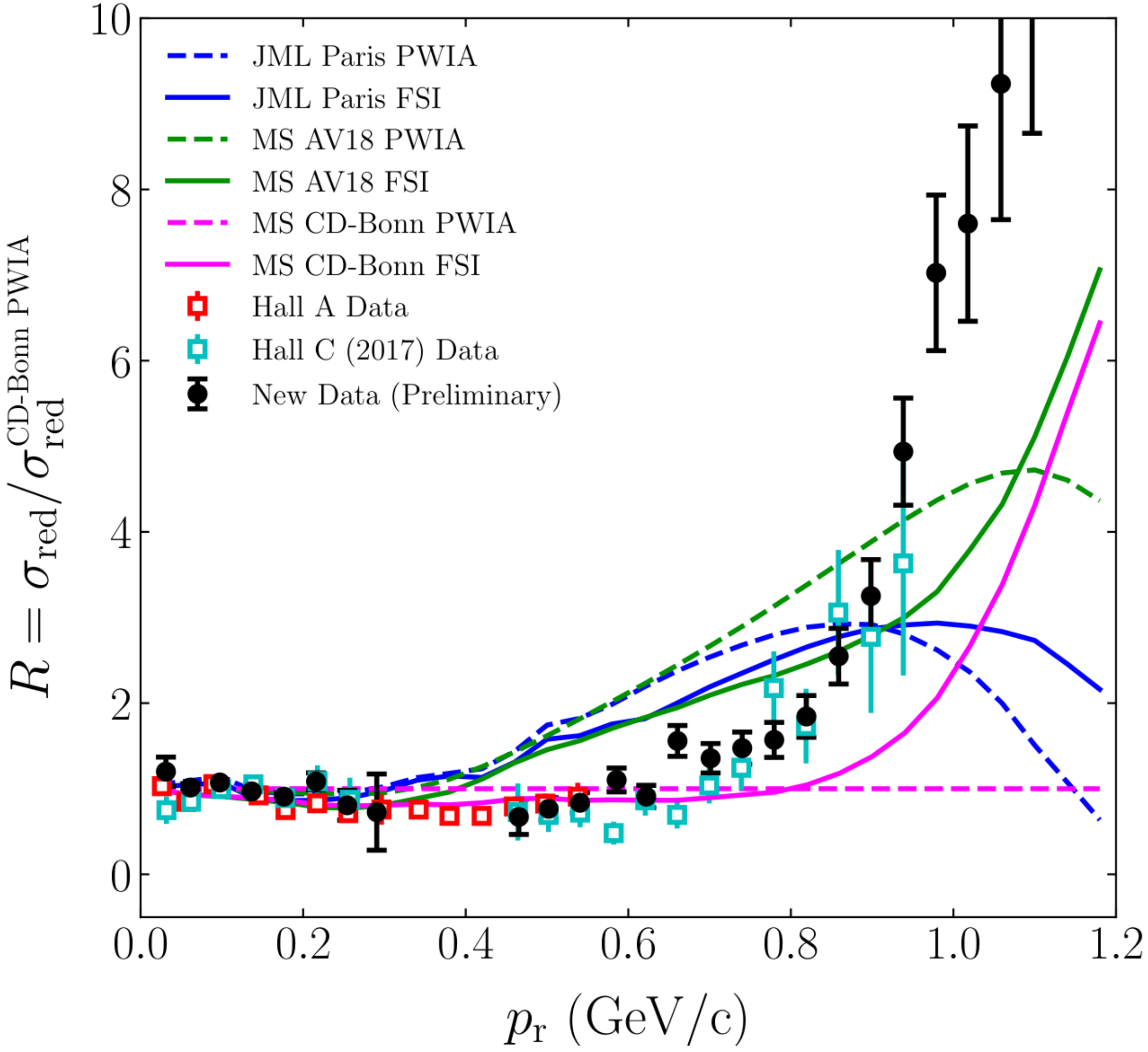

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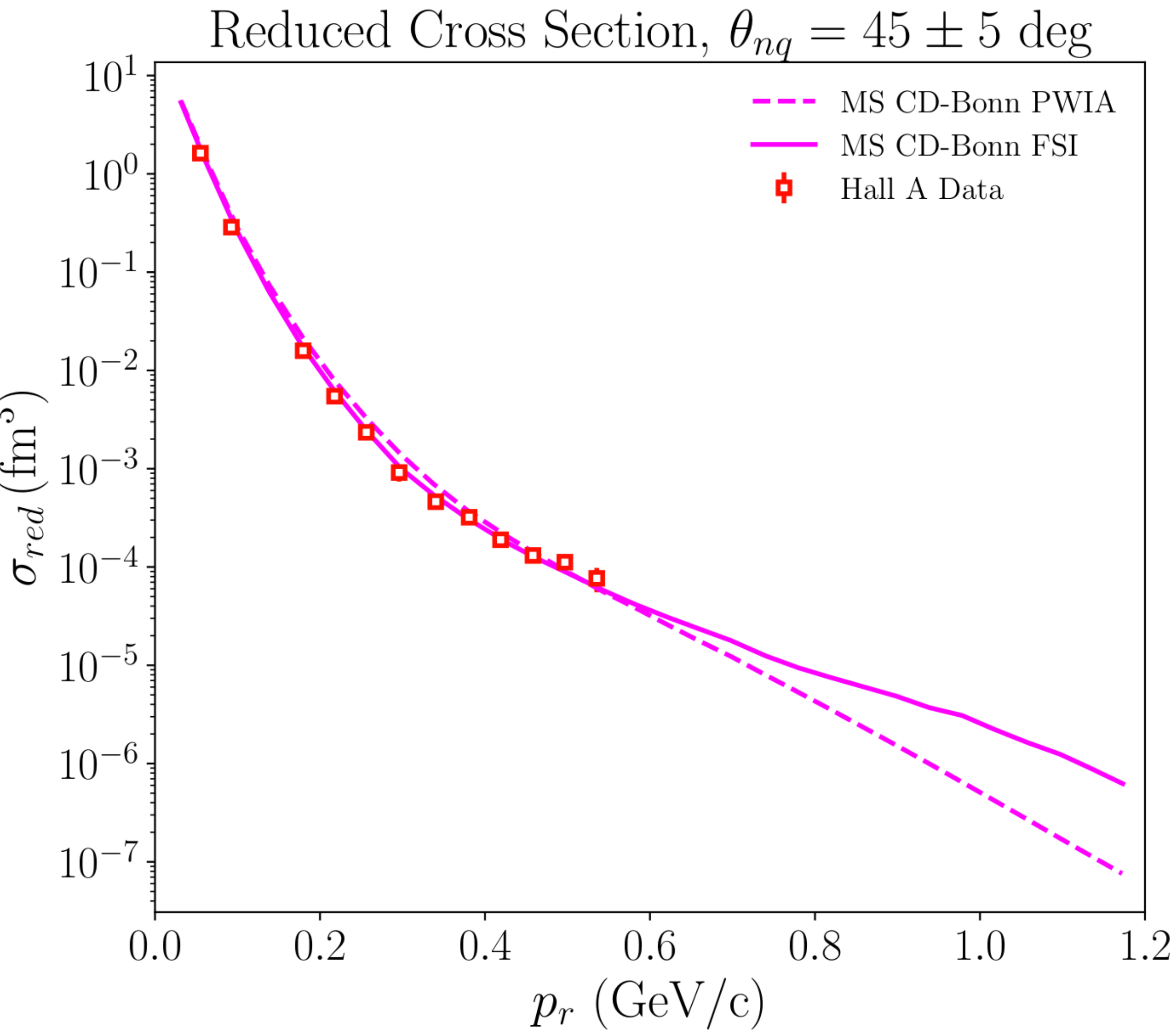

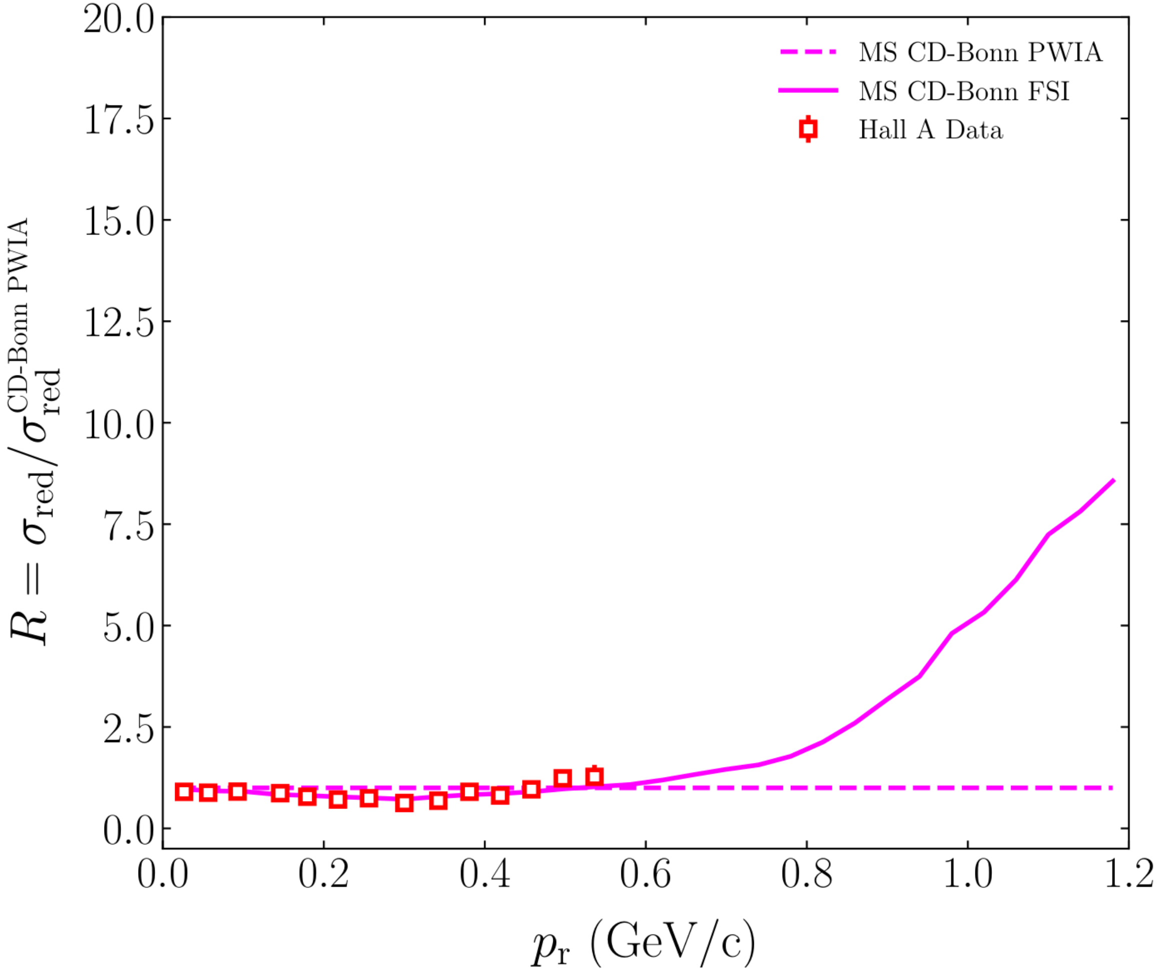

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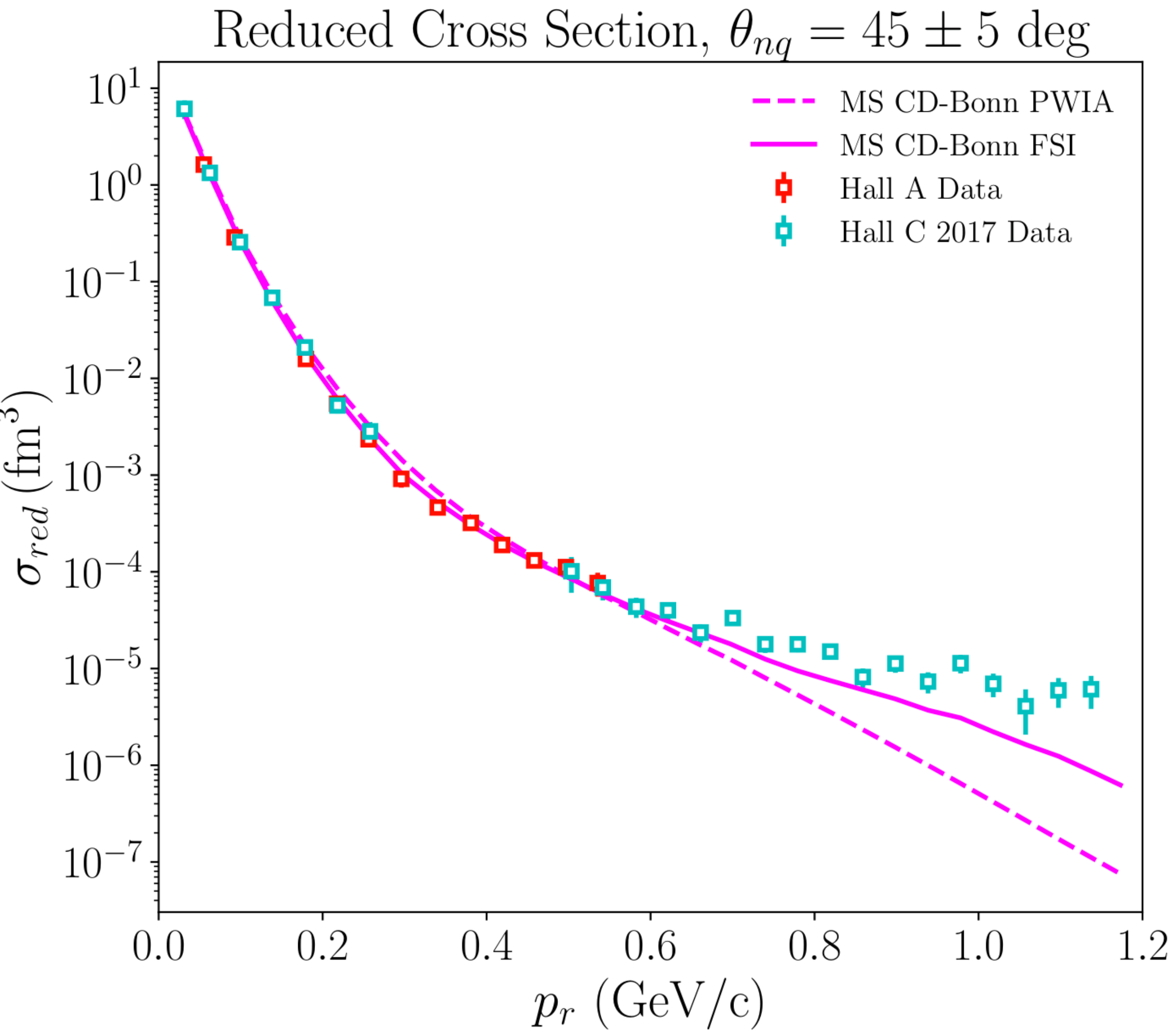

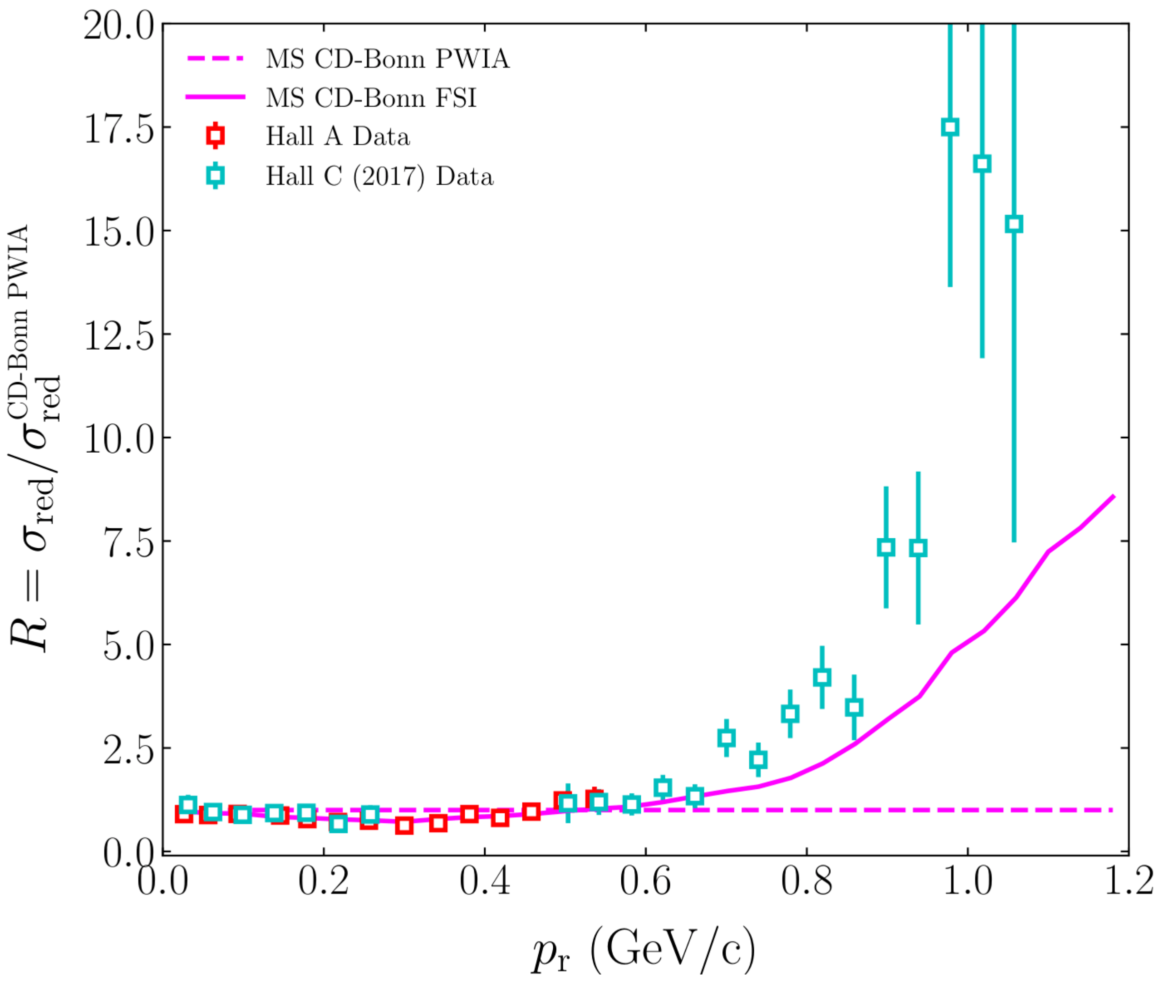

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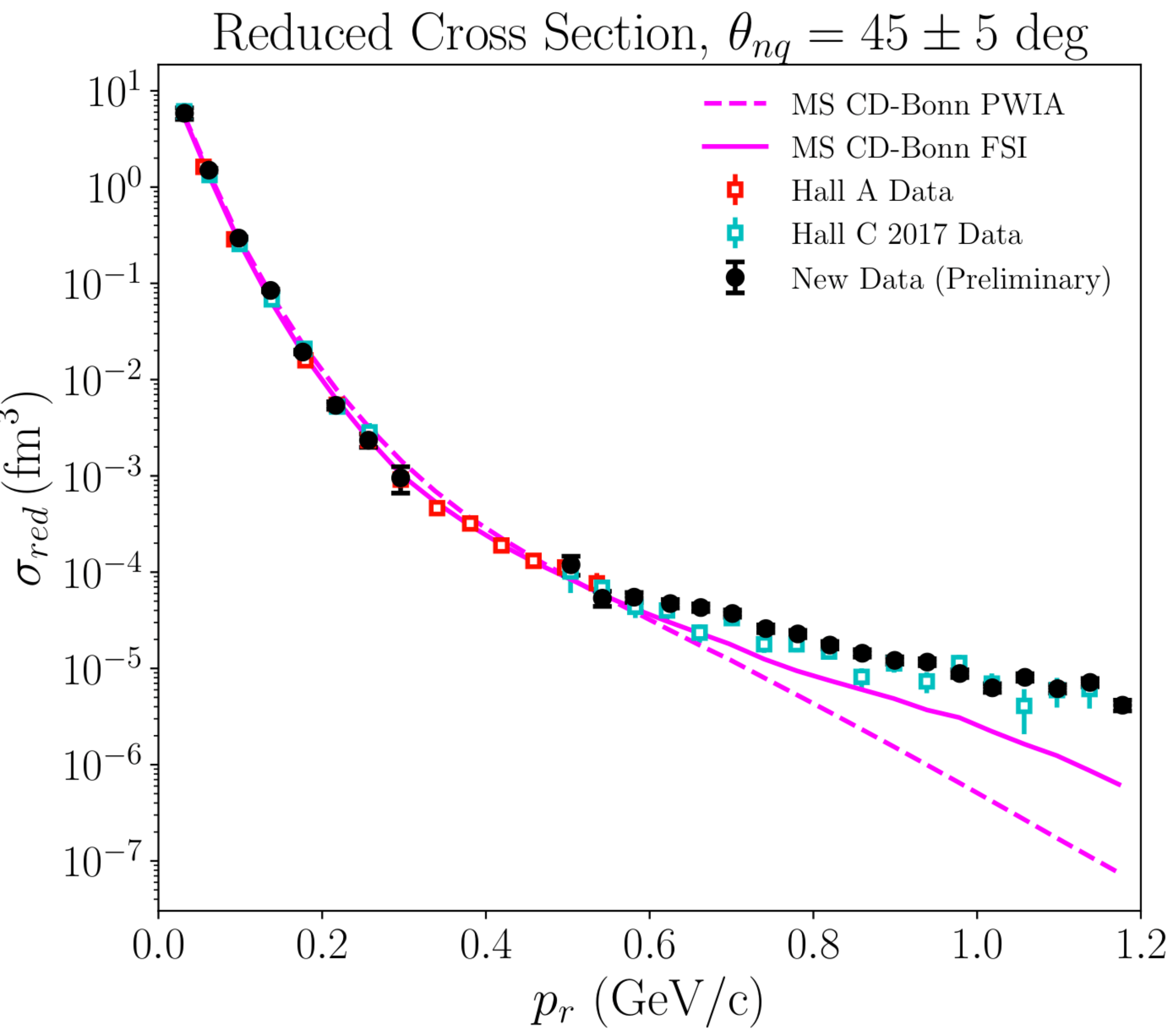

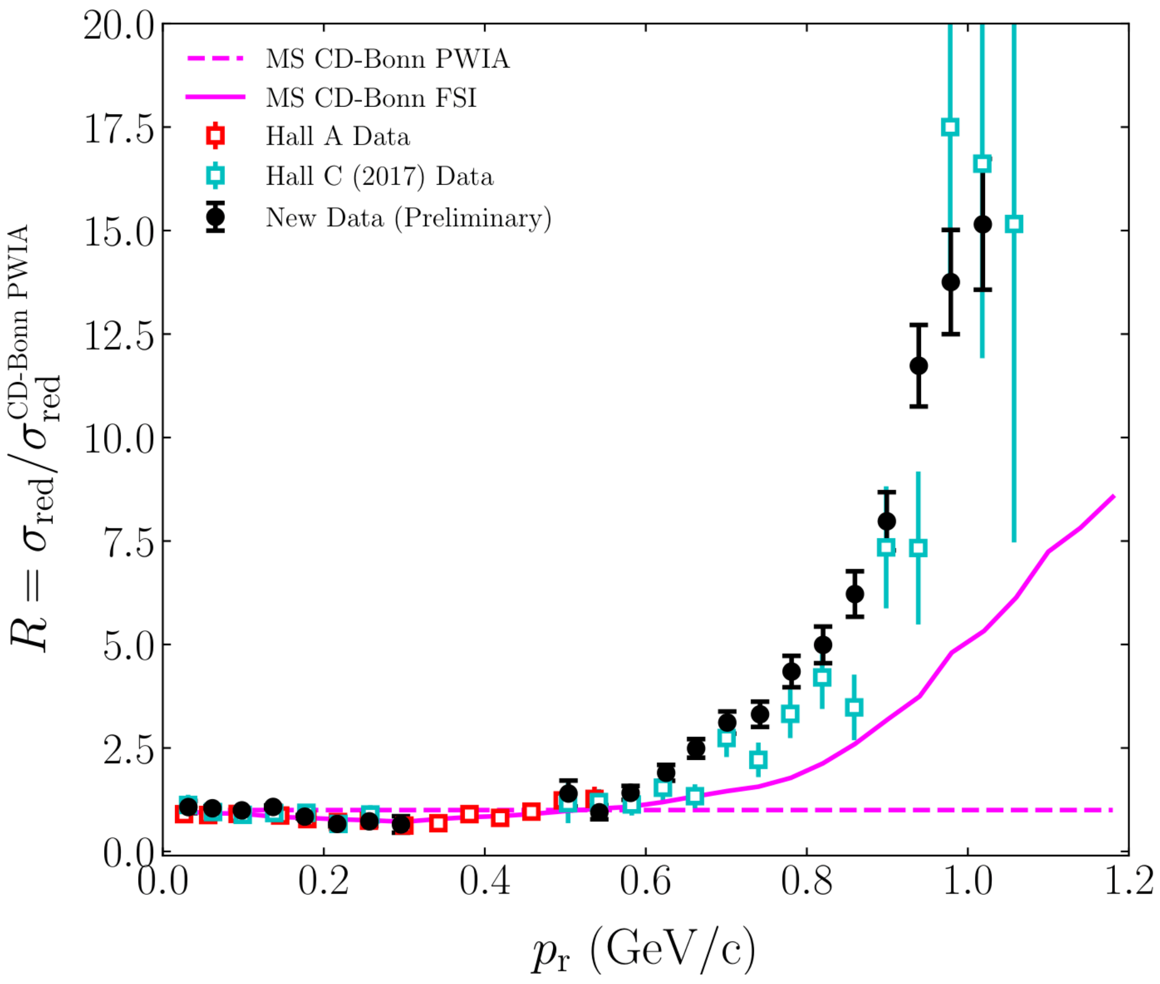

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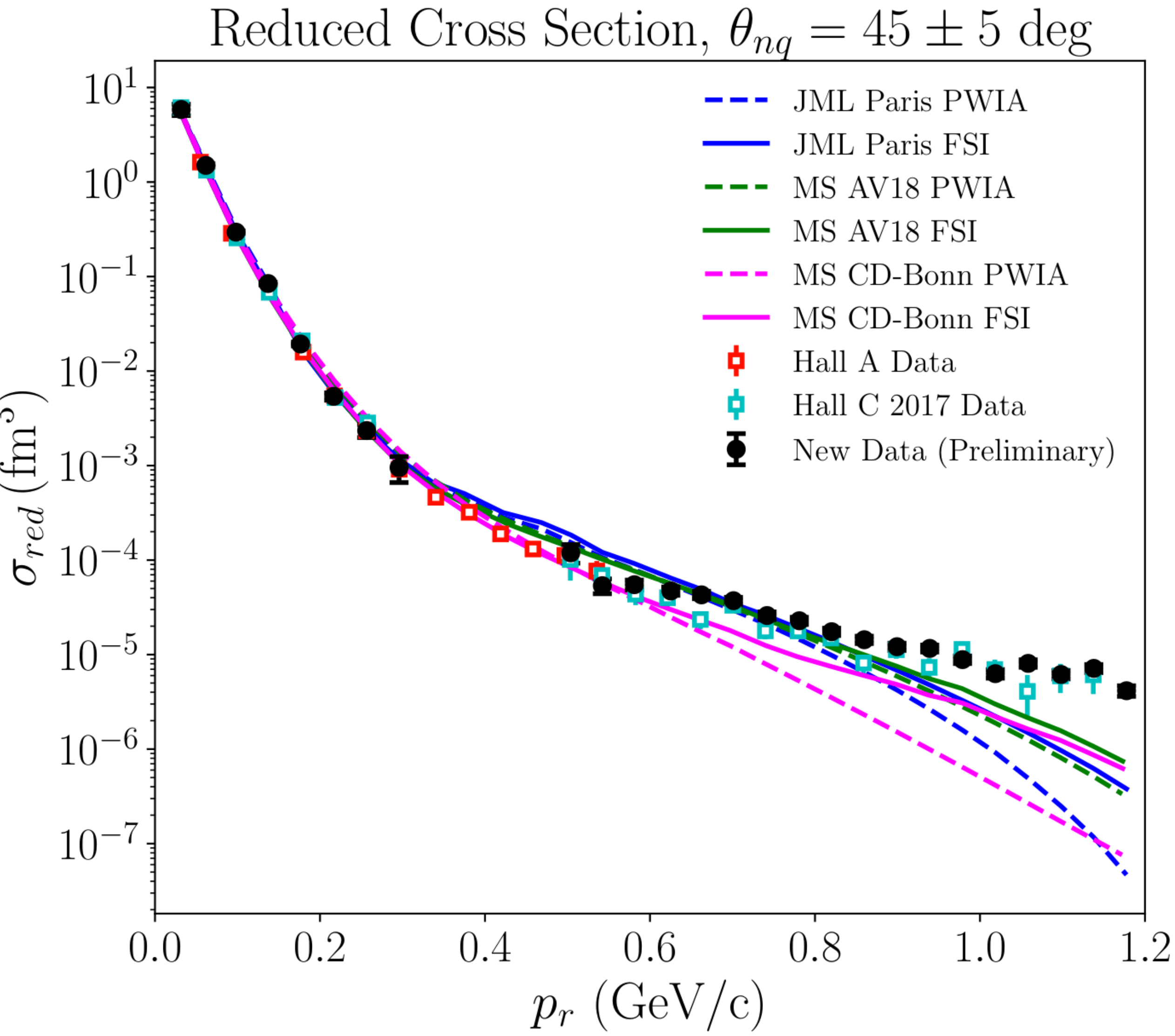

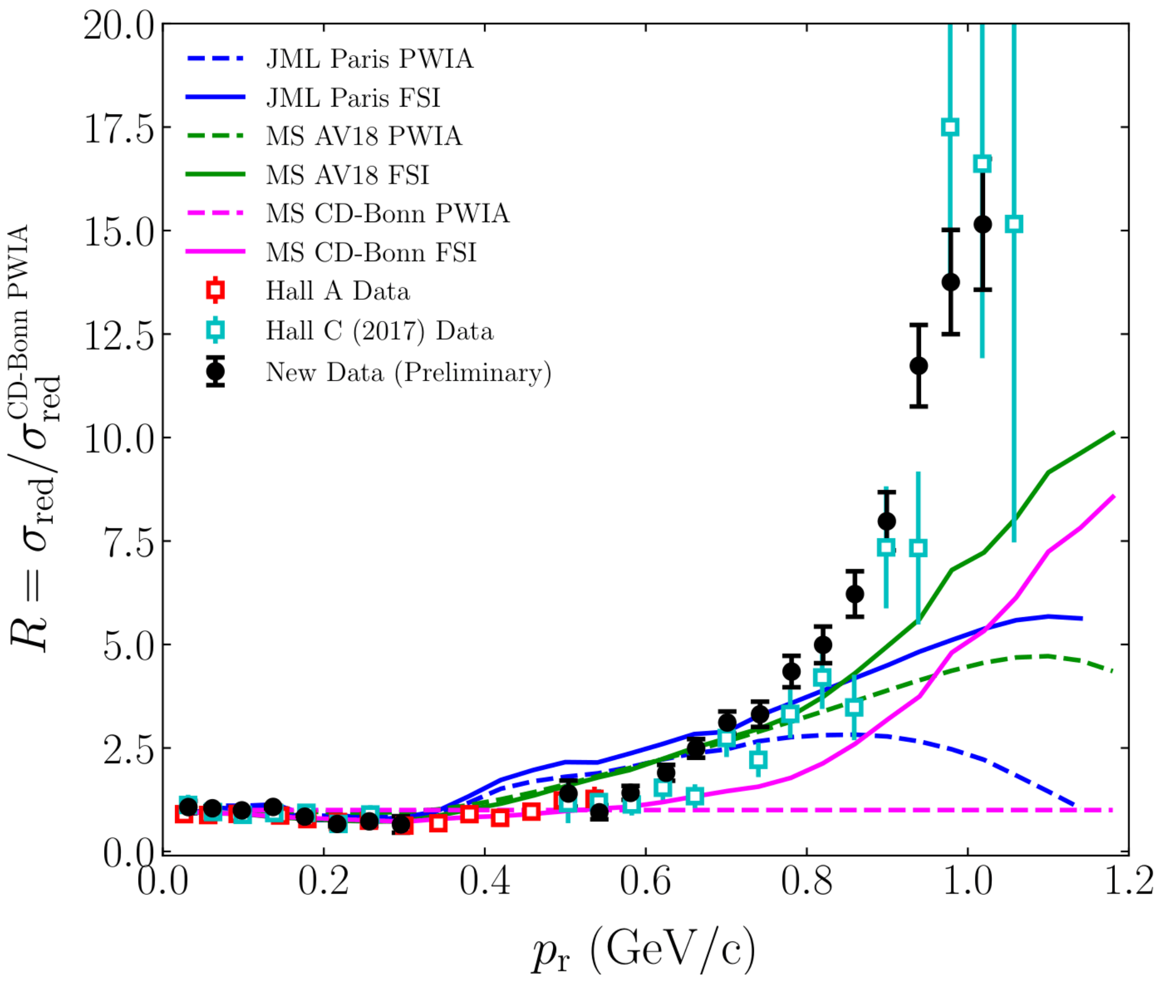

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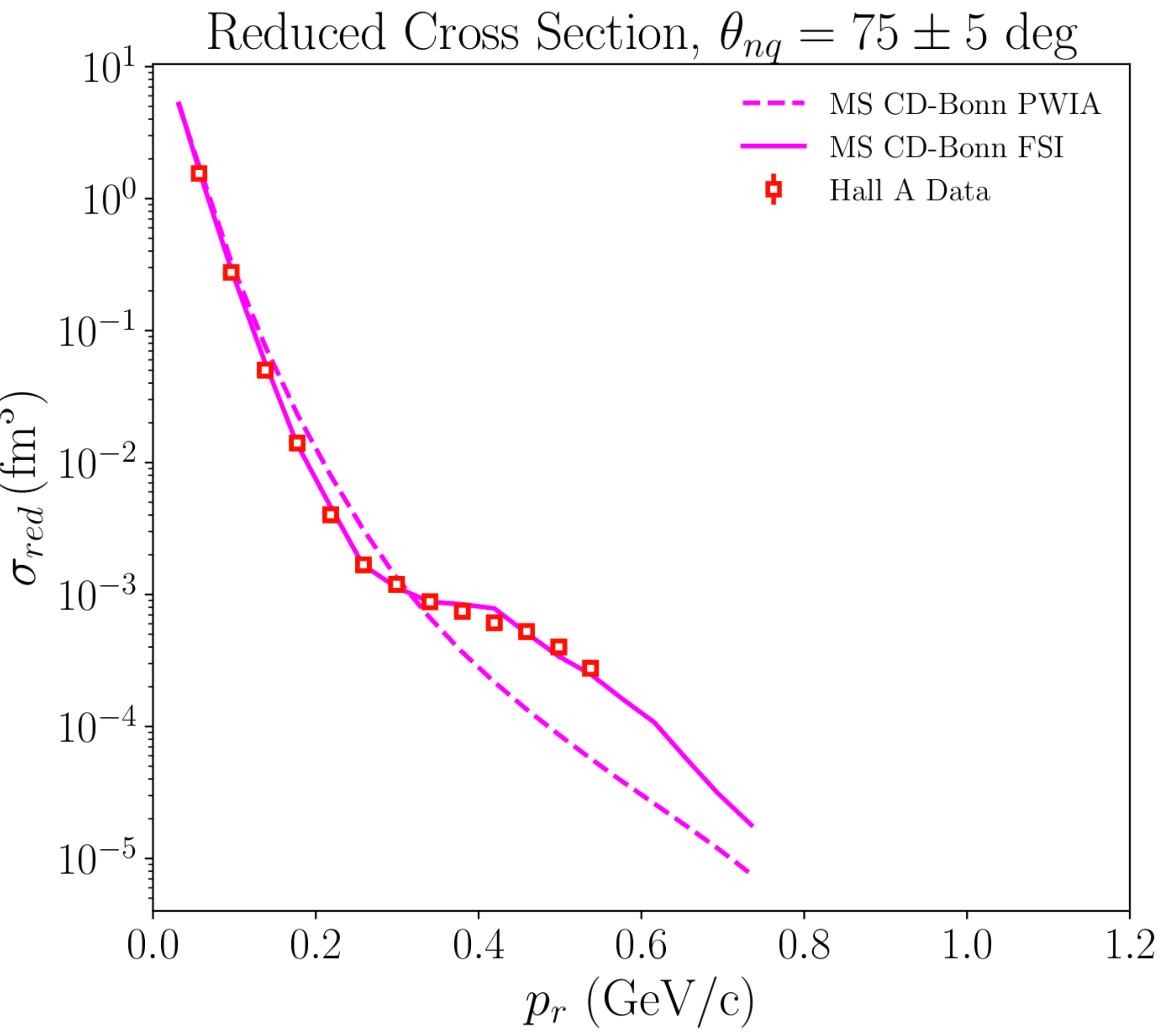

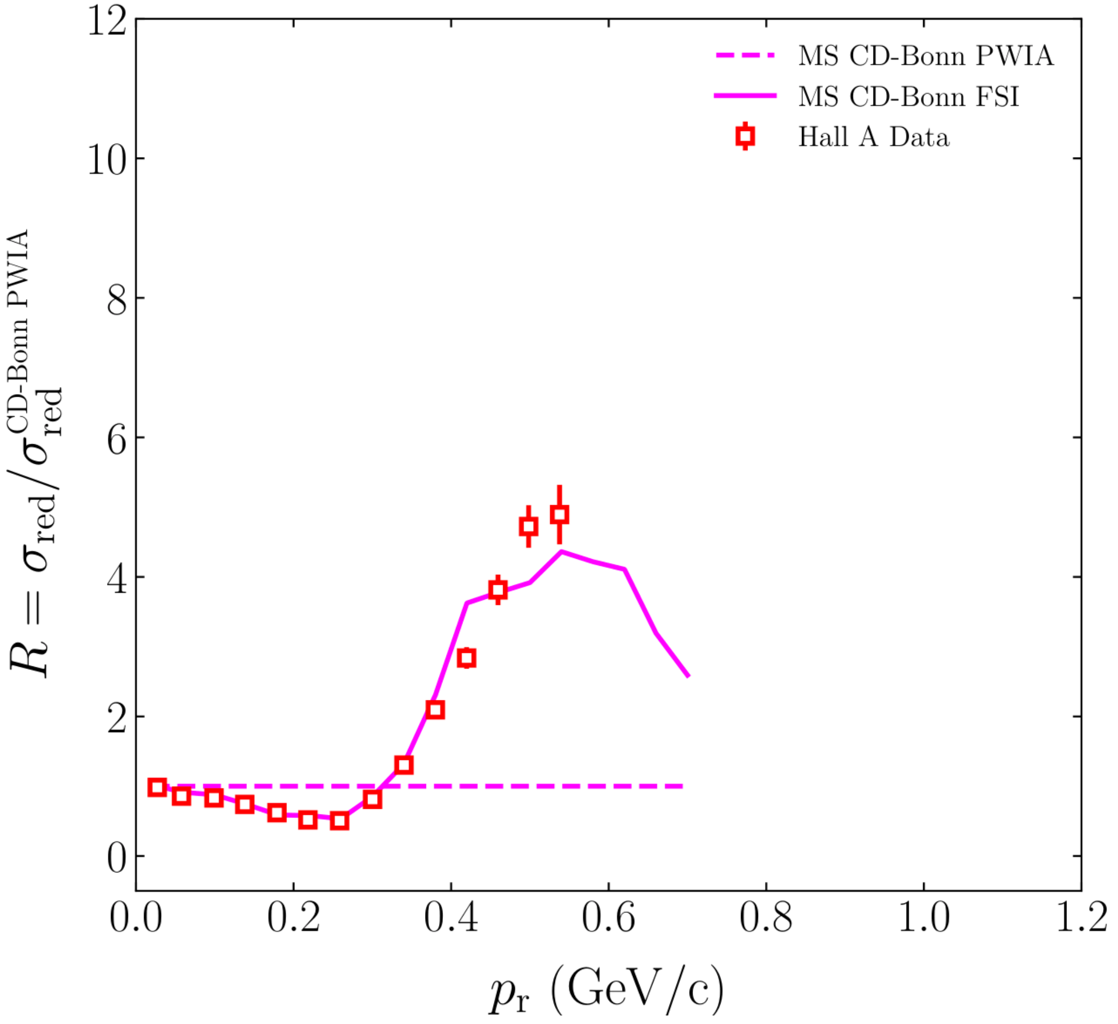

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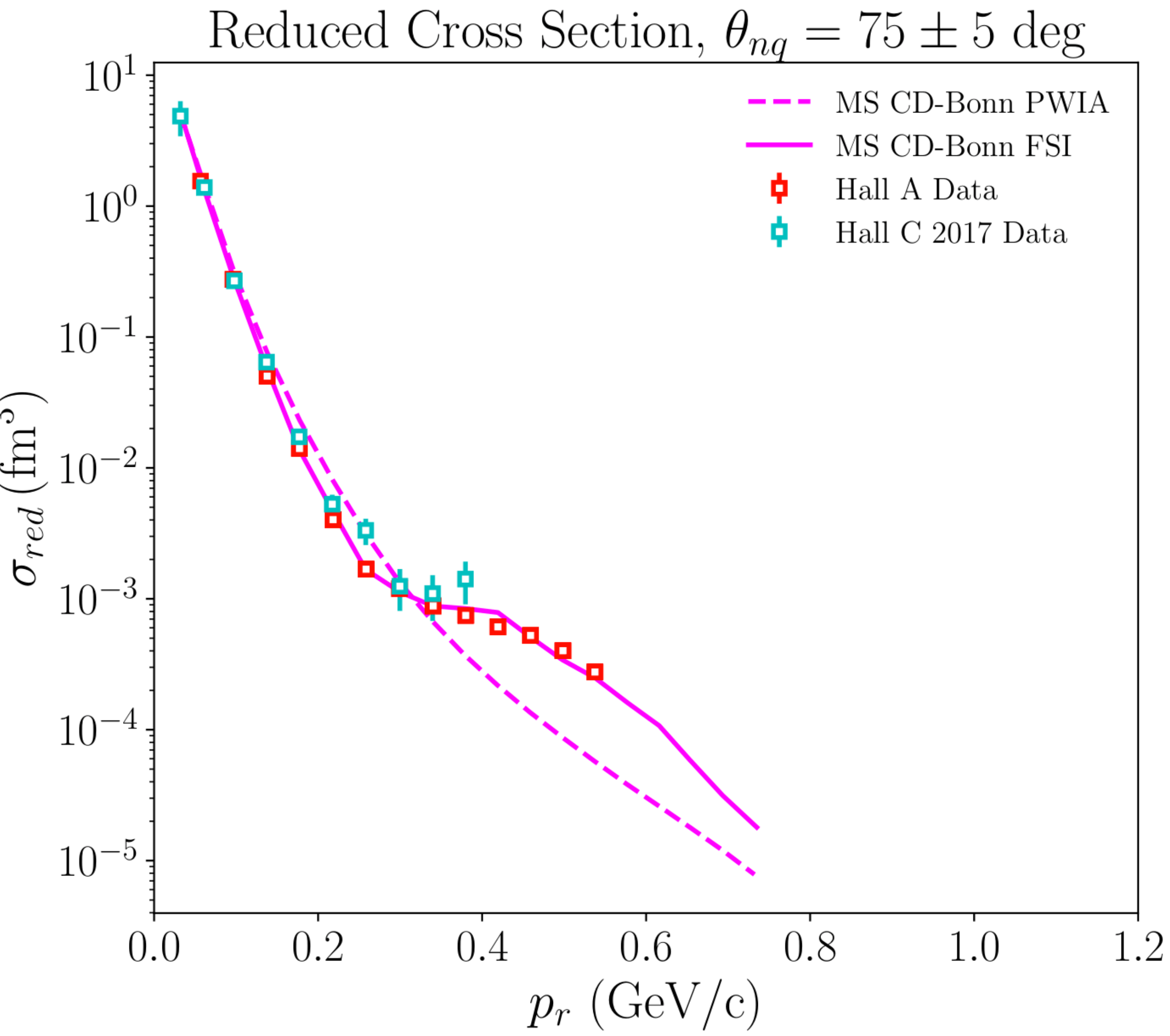

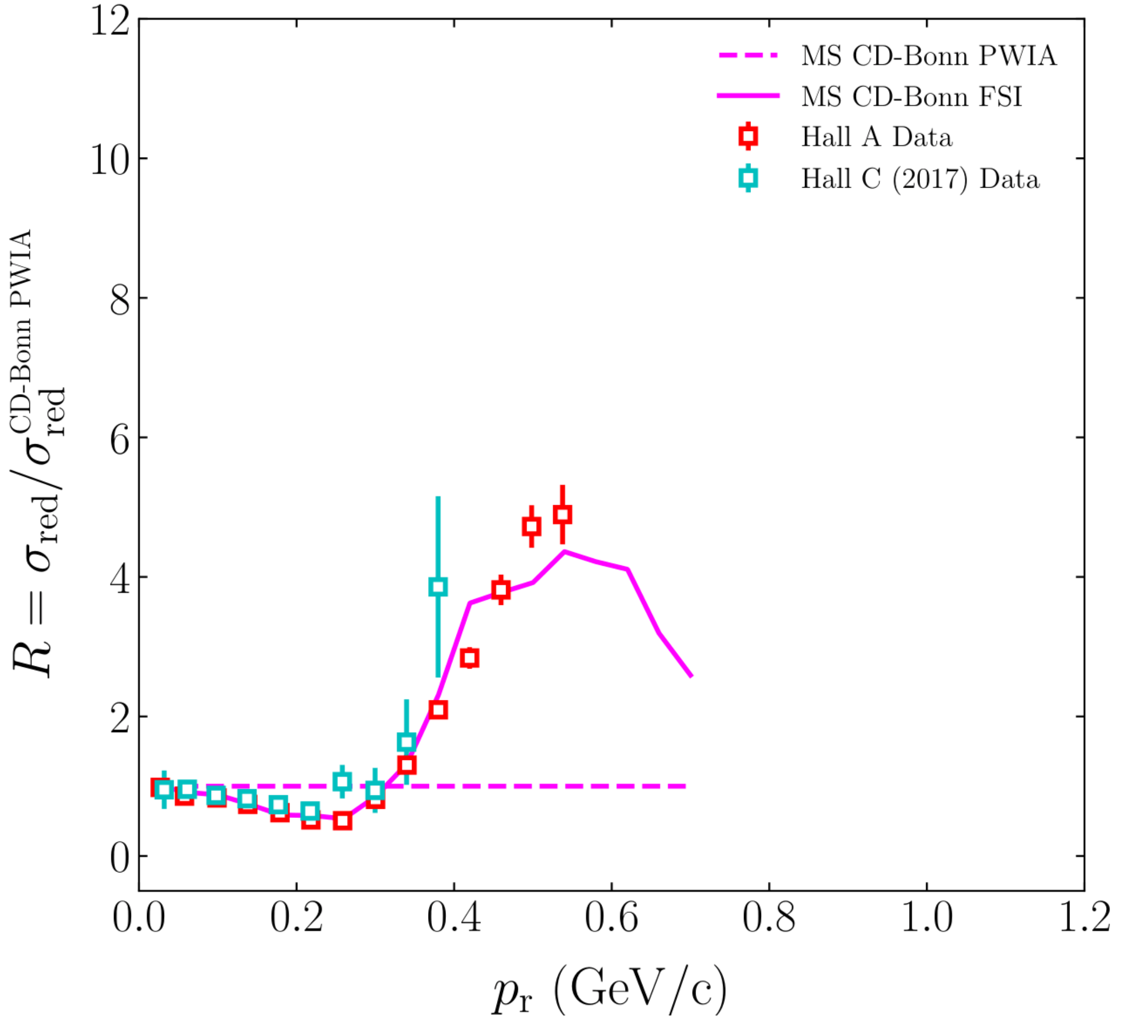

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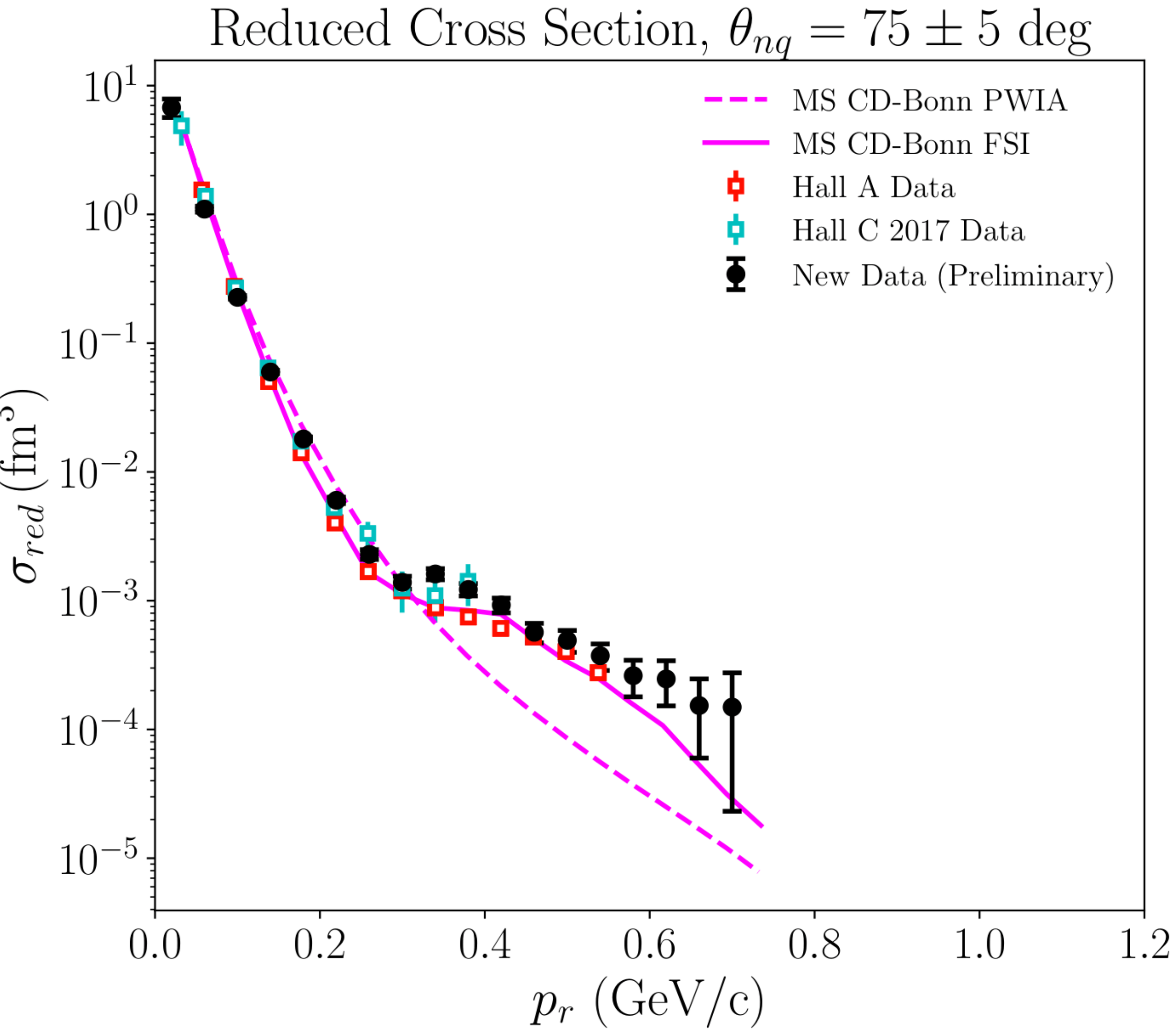

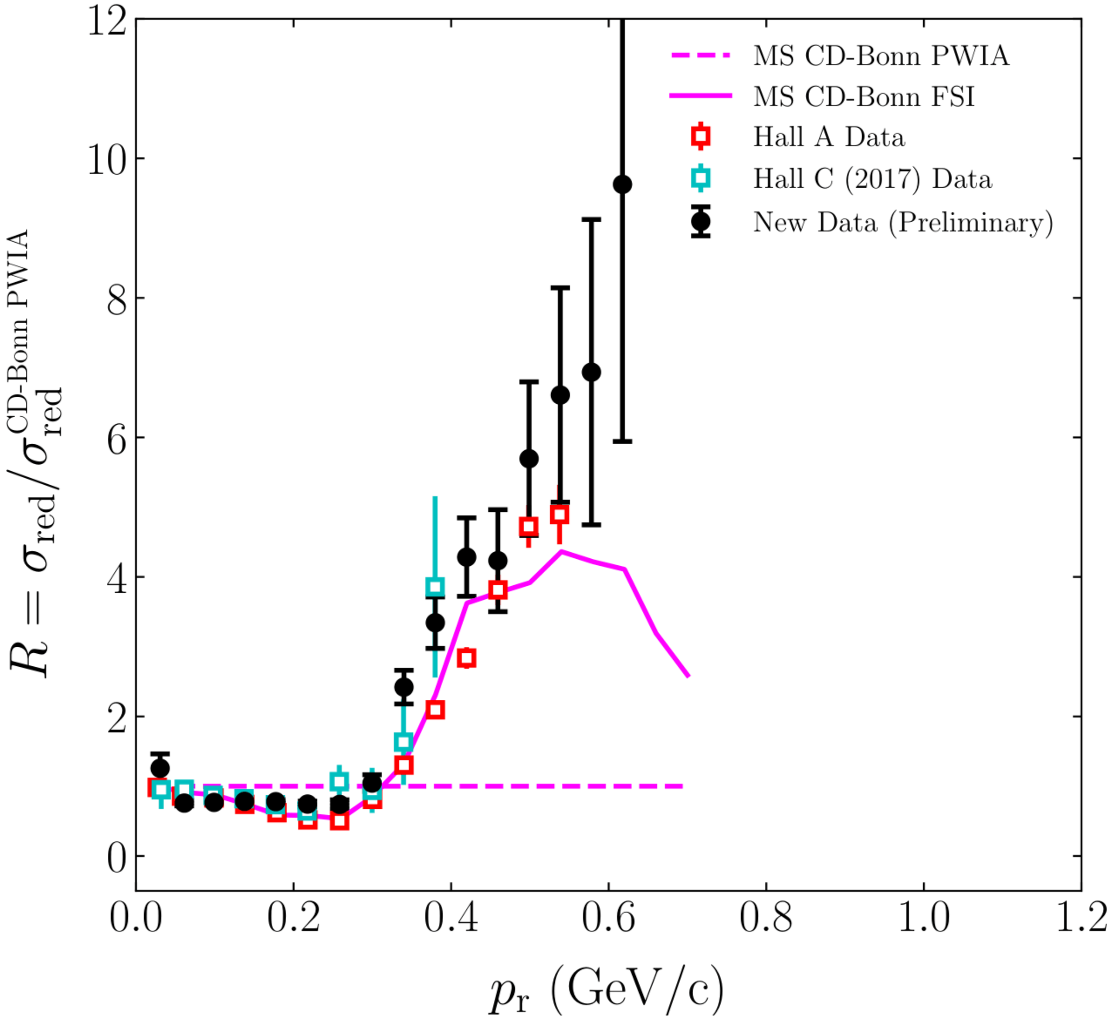

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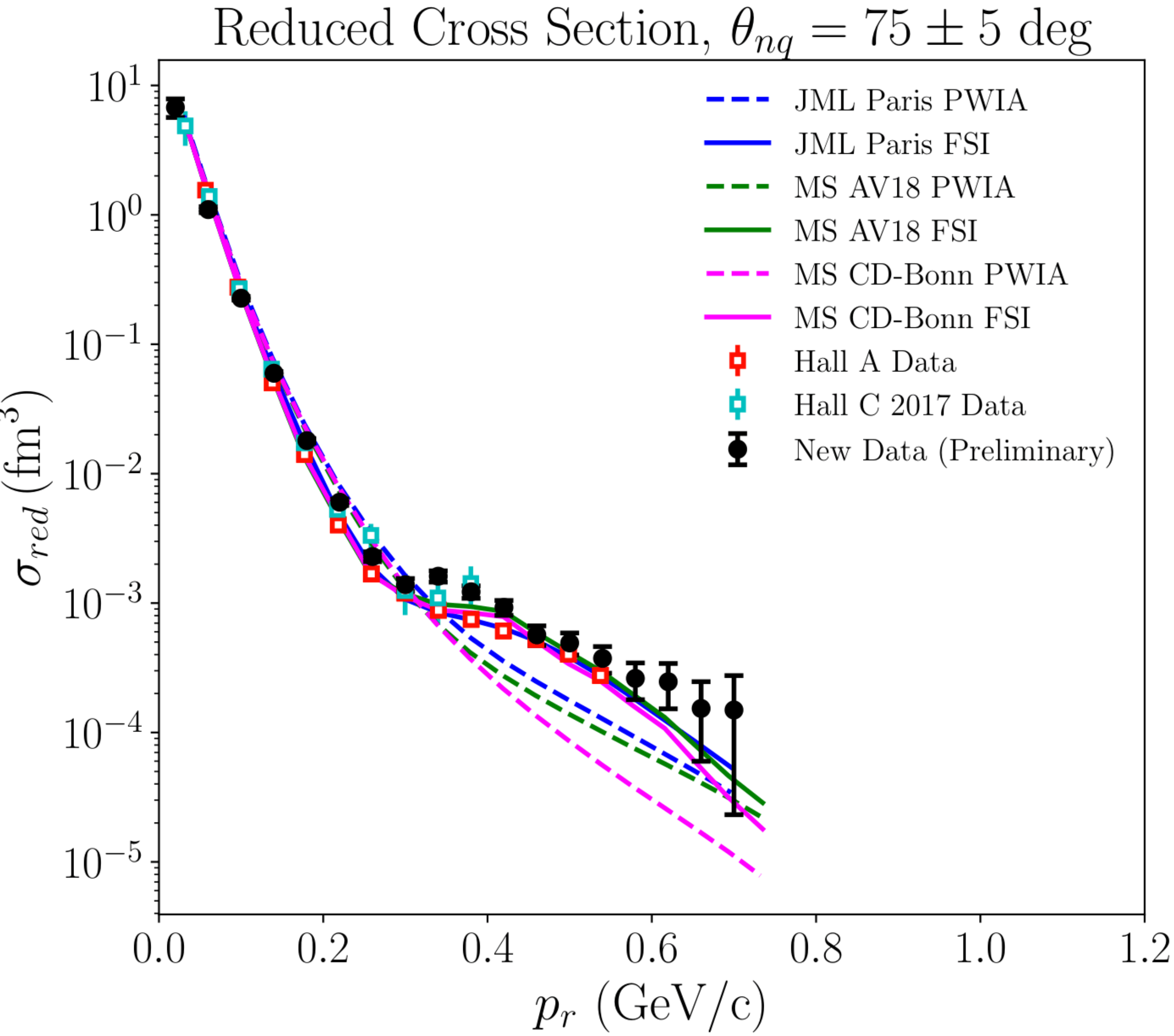
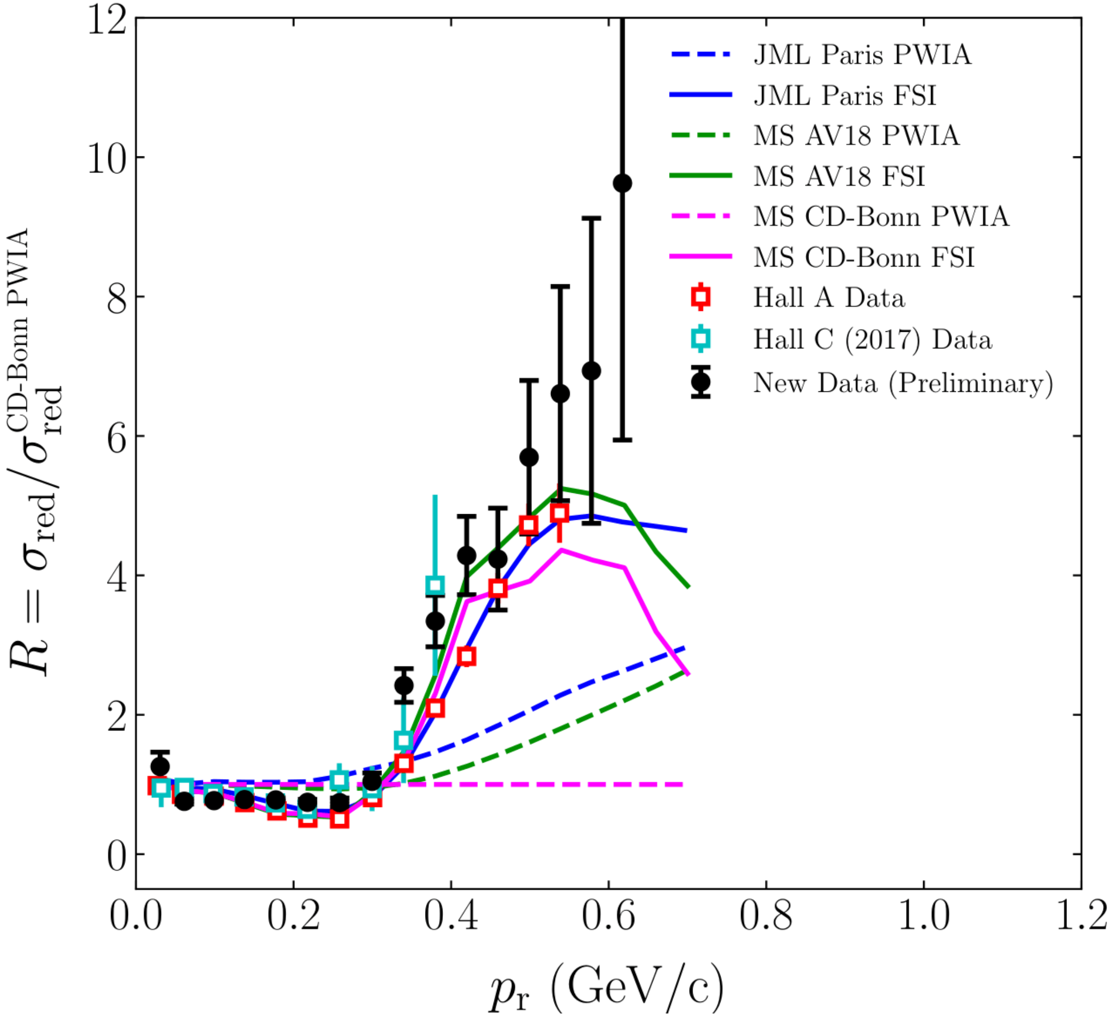
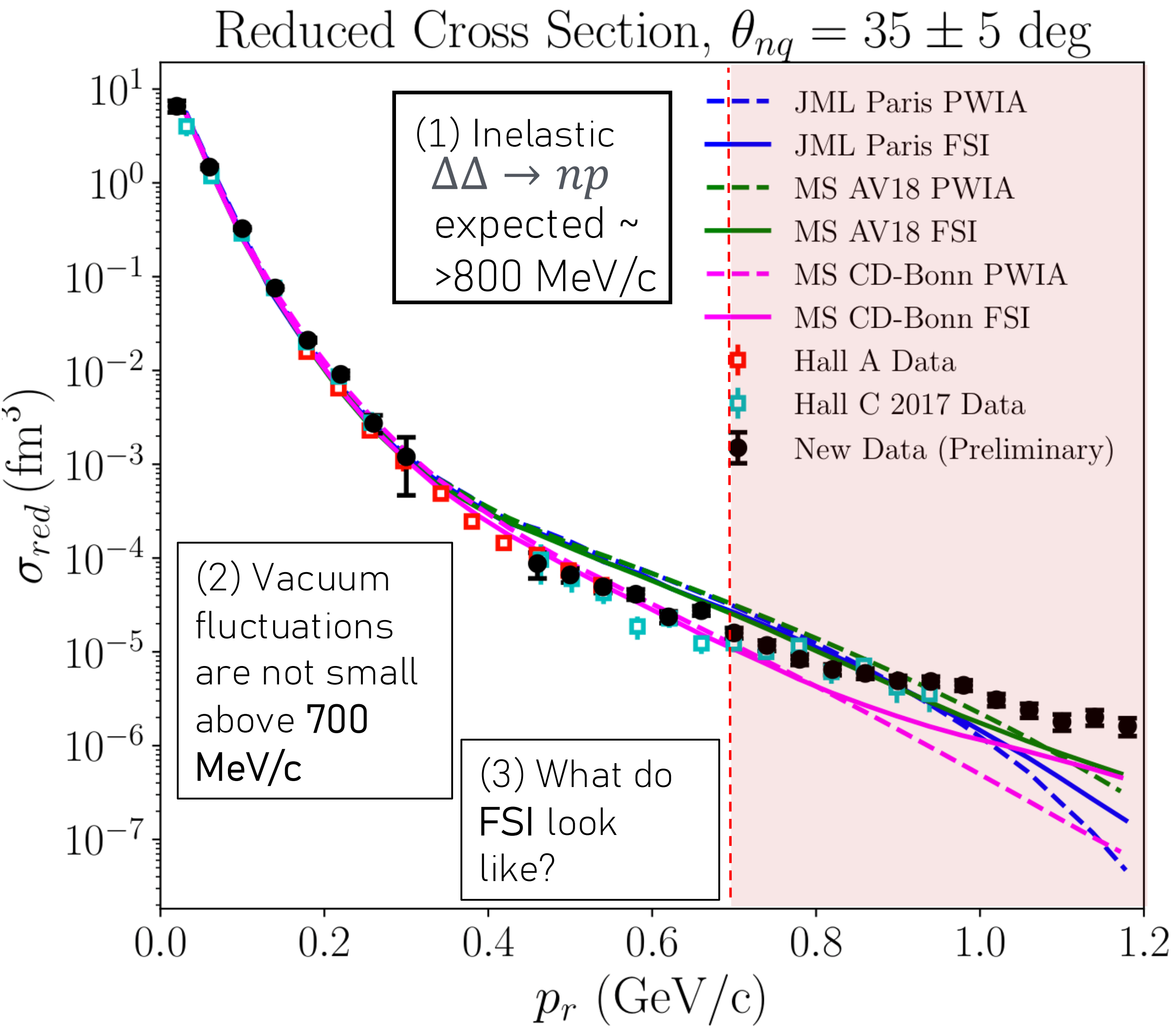




Why the discrepancy? Probing the NN Repulsive Core



(1) Inelastic $\Delta\Delta \rightarrow np$ expected ~ >800 MeV/c

(2) Vacuum fluctuations are not small above 700 MeV/c

(3) What do FSI look like?

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
- $d \rightarrow N\overline{N}$ (vacuum fluctuations) neglected; $\Psi_d = \Psi_d^{\mathrm{NR}} \times f_{corr}^{rel.}$ (at p_{r} < 700 MeV/c vac. fluct. are expected to be small)

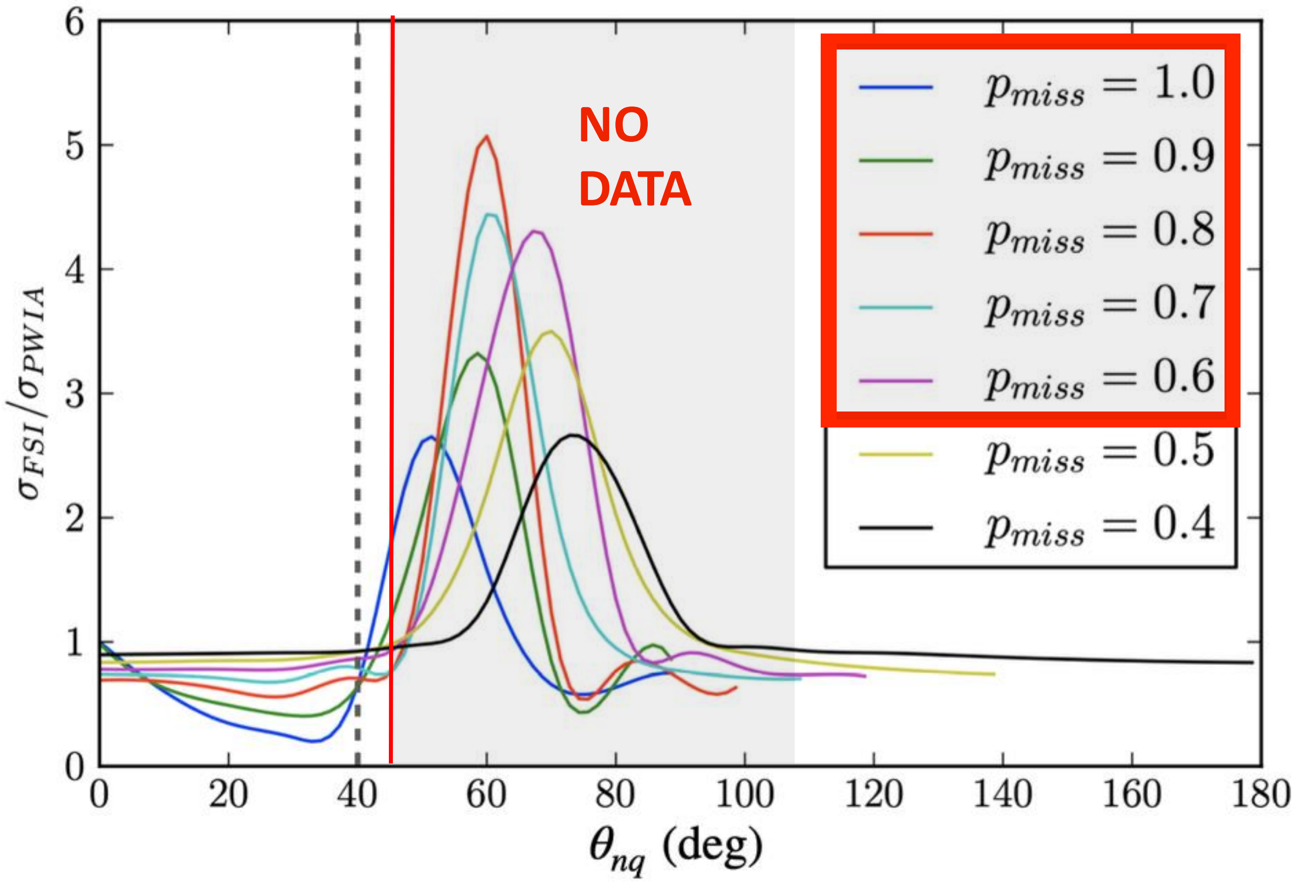
M. Sargsian (2009). 10.1103/PhysRevC.82.014612

Deuteron FSI Studies (PR12-25-003)

New proposed measurement will address the following:

- ➢ Check **reliability of FSI calculations** above neutron recoil momentum of 500 MeV/c
- ➢ Disentangle **FSI + Relativistic + Non Nucleonic** effects

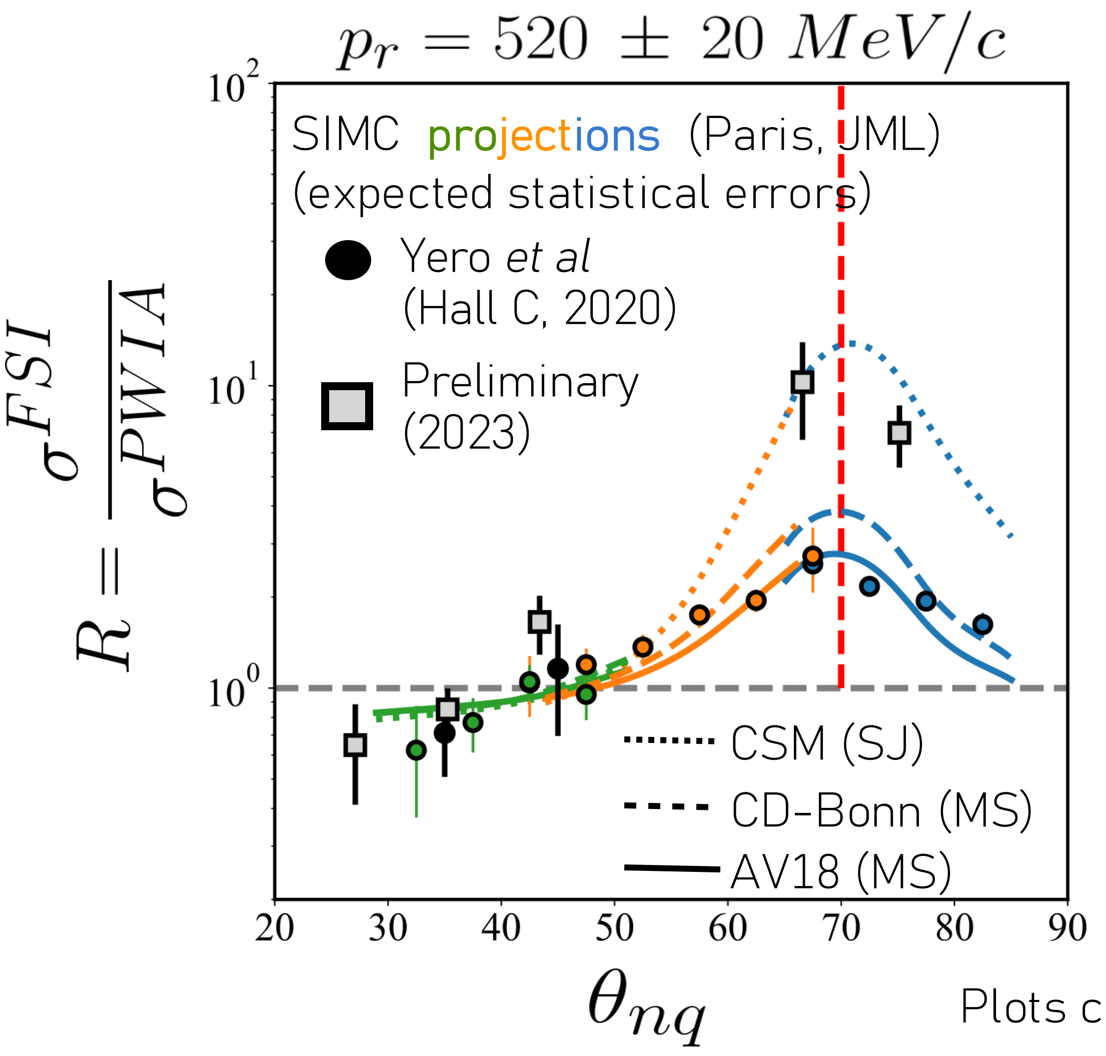
W. Boeglin & M. Sargsian (2015). 10.1142/S0218301315300039

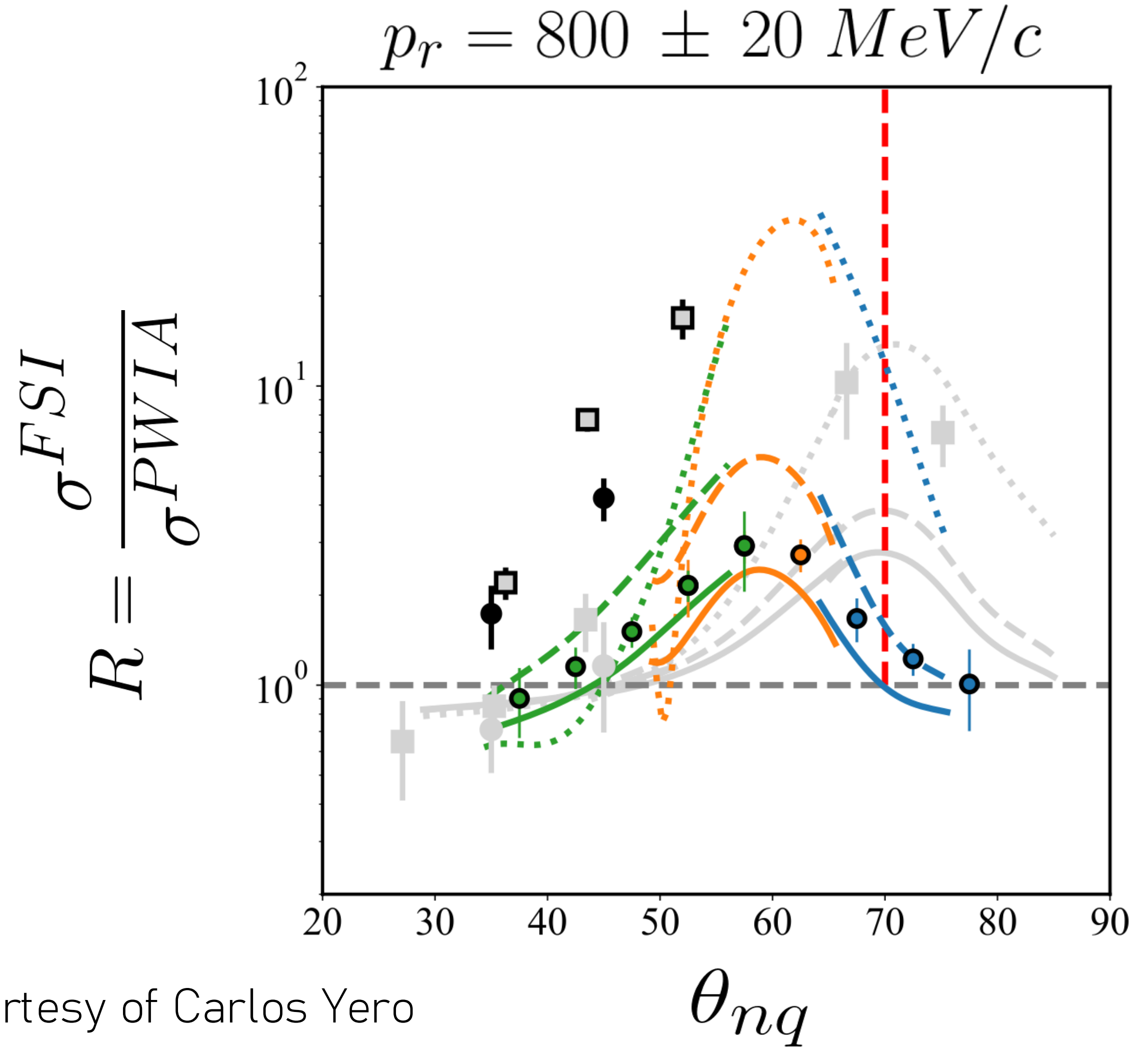


Deuteron FSI Studies (PR12-25-003)

Proposed Measurement

Calculations:
S. Jeschonnek (2008). 10.1103/PhysRevC.78.014007
M. Sargsian (2010). 10.1103/PhysRevC.82.014612





Plots courtesy of Carlos Yero

Summary

- The latest instance of the deuteron break-up experiment ran successfully in 2023
- Analysis shows so far that the data agrees well with previous data, still showing the discrepancy between theoretical models around 700 MeV/c
- Possible reasons for the discrepancy are:
    - Non-nucleonic components not negligible
    - Vacuum fluctuations
    - FSI not well understood
- To address the FSI question a new experiment was proposed (PR12-25-003)

Backup Slides

D(e,e'p)n Data Cross Section

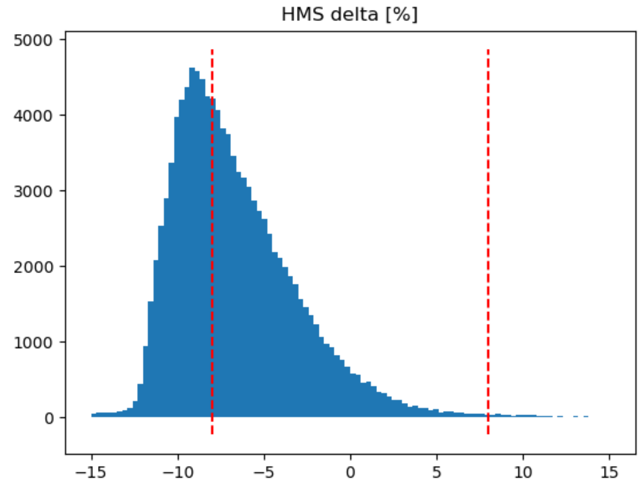
How do we extract the data cross section?

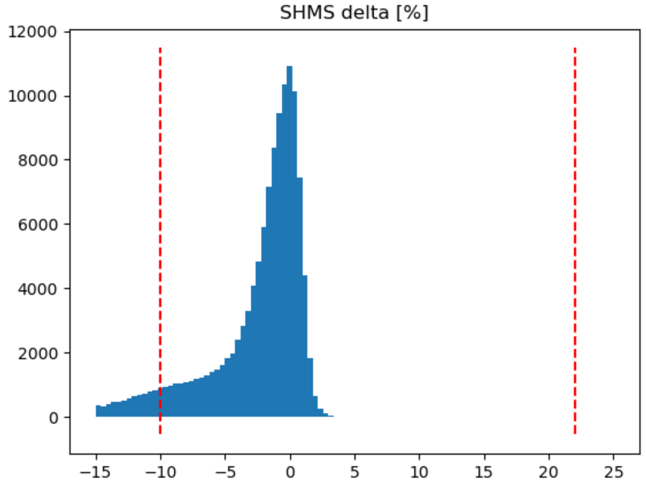
Work in 2026:

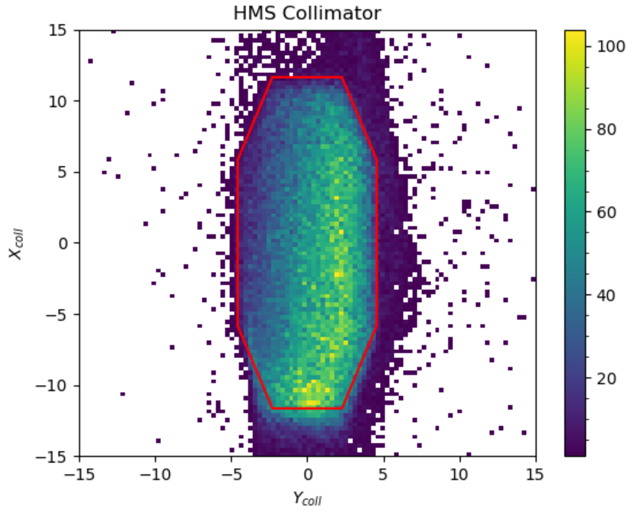
- The HMS and SHMS tracking efficiencies were on average 0.983
- The average live time was 0.970
- Target Boiling and Proton Transmission/Absorption Studies were done at the beginning 2026
- The target boiling for LD2 was 4.85% per 100 muA
- The proton absorption studies were done 3 ways: via spreadsheet (**6.19%**), **Geant4 simulation** (available on github) (**6.029 ± 0.01 %**), and data (**4.7 ± 1.1 %**)

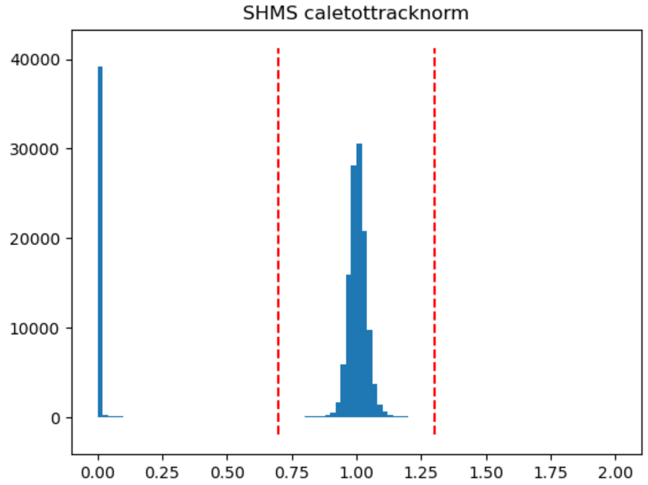
Event Selection Cuts

- Acceptance cuts:
  - HMS momentum acceptance: (-8,8)
  - SHMS momentum acceptance (-7,22)
  - HMS collimator cut
- SHMS Calorimeter PID
- Coincidence time cut
- Current Cut
- No EDTM Cut
- Z-tar difference Cut
- Kinematic cuts:
  - Missing energy: (-0.05,0.05)
  - Q^2 : (4,5)









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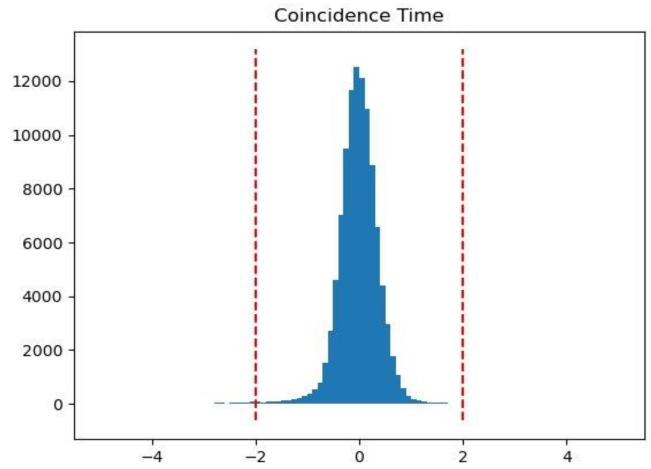

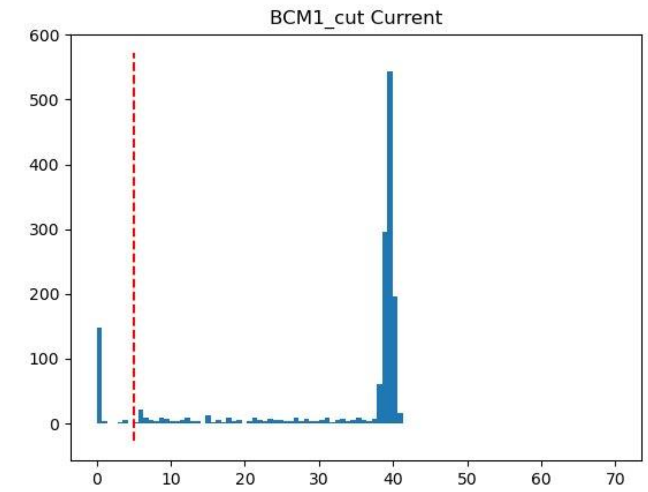

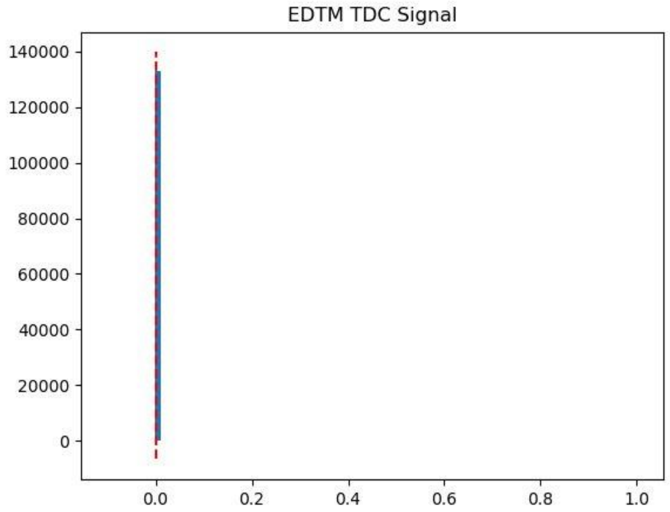

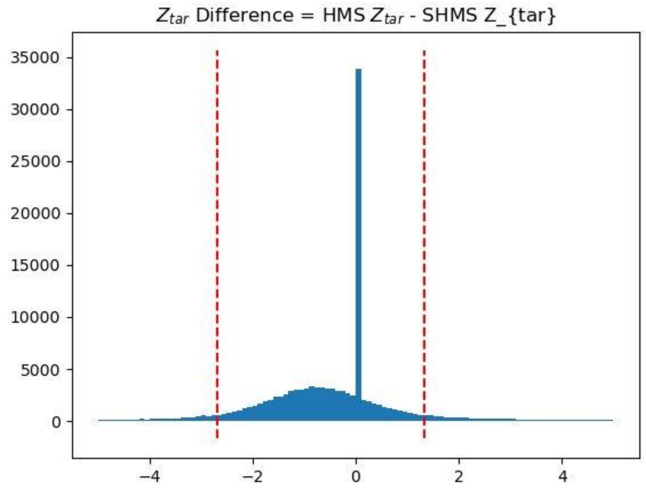

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