PAC 51: Color Transparency in Maximal Rescattering Kinematics

Proposal PR12-23-010

Spokespersons:

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Overview of this talk:

1. Importance of CT
    - Fundamental prediction of pQCD

2. Deuterium
    - Rescattering kinematics

3. Proposed experiment
    - Exceptional sensitivity for observing the onset of CT in protons

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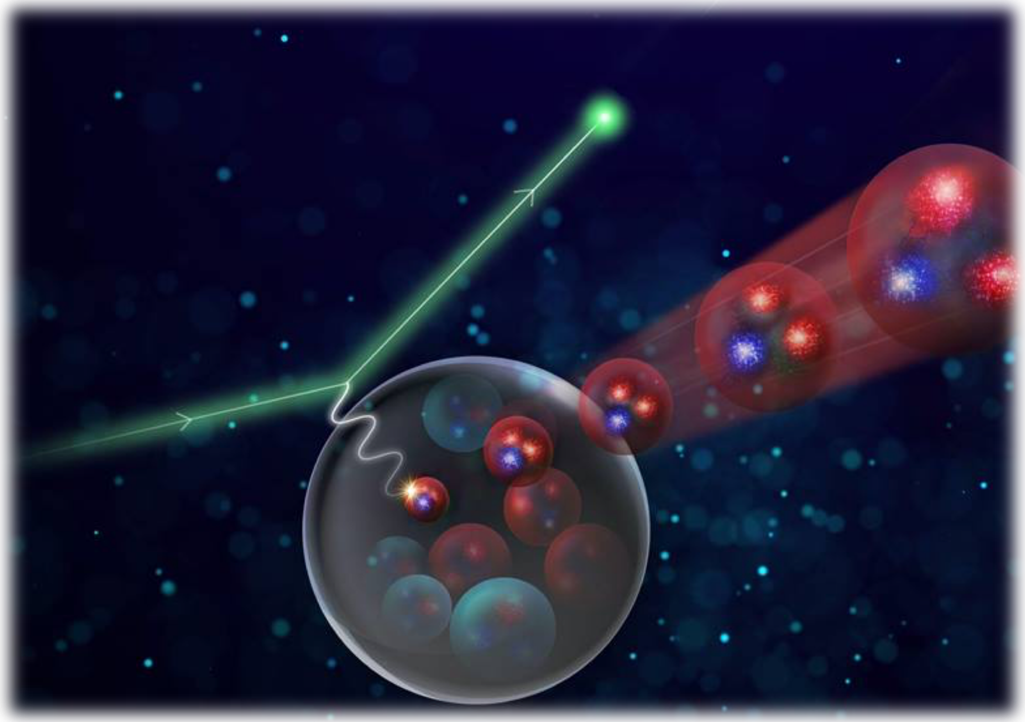
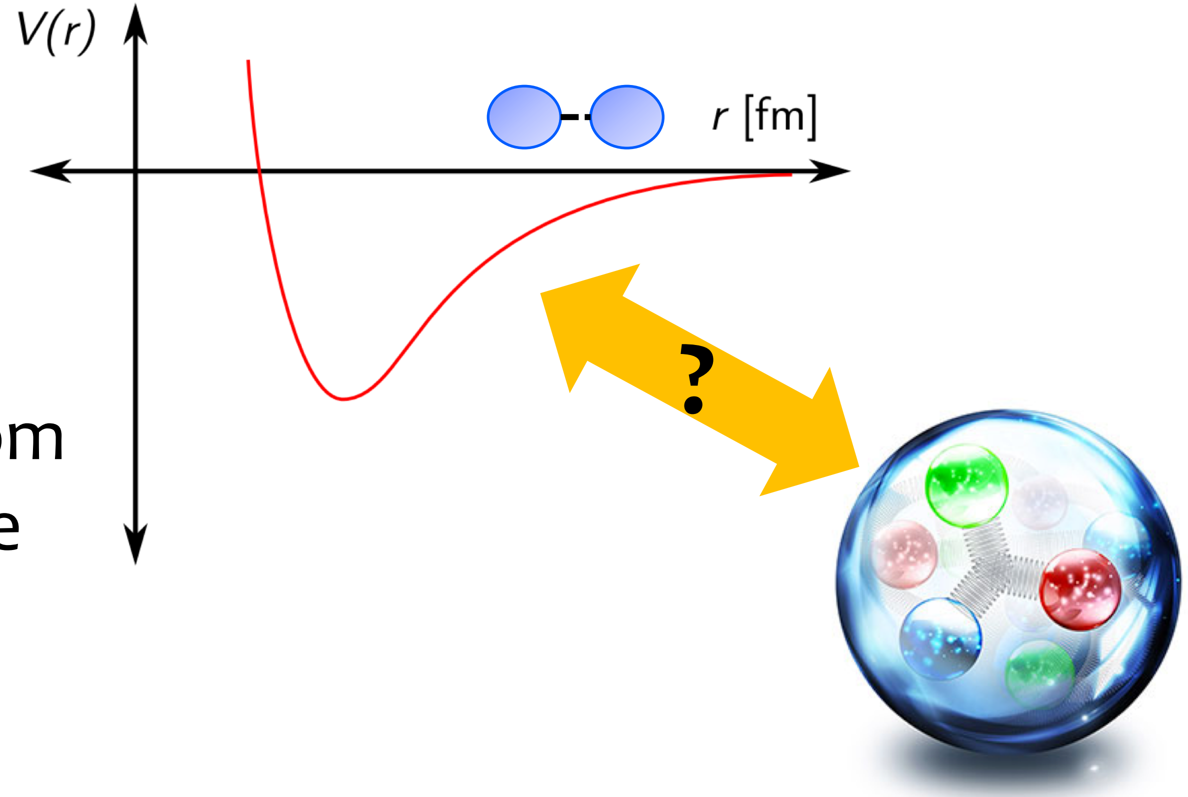


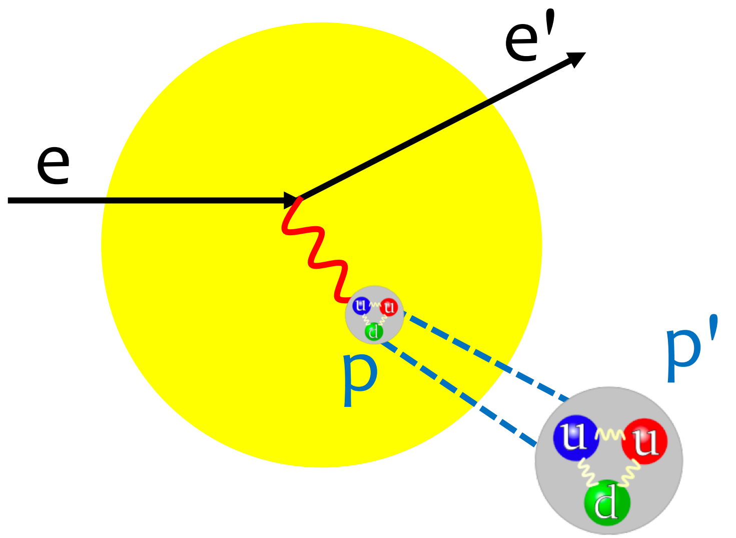
The quark-level description of nuclei is fundamental to our understanding of the strong force interaction



Exclusive processes probe transition from the strongly interacting hadronic picture to quark-gluon degrees of freedom

Color transparency is a fundamental prediction of pQCD

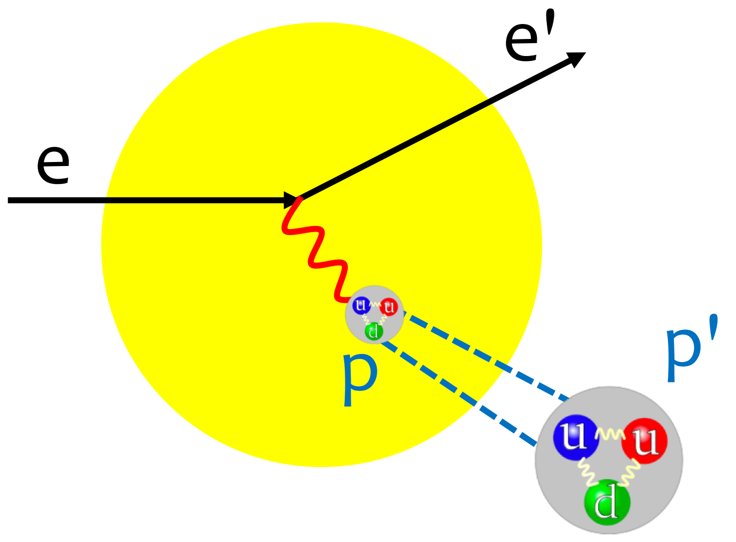
Introduced by
Mueller and Brodsky, 1982



Vanishing of final state interaction of hadrons with nuclear medium in exclusive processes at high momentum transfer

Color transparency is a fundamental prediction of pQCD

Quantum mechanics:
Hadrons fluctuate to small transverse size (*squeezing*, transferred momentum)



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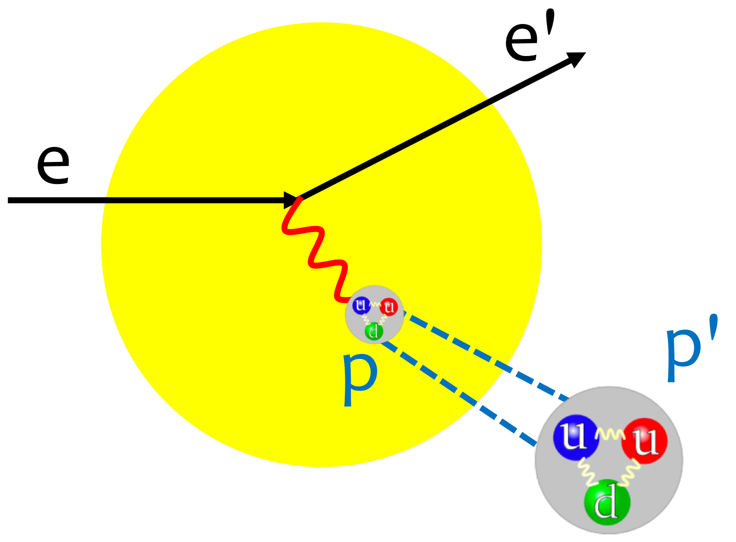

Relativity:
Maintains this small size as it propagates out of the nucleus (*freezing*, transferred energy)

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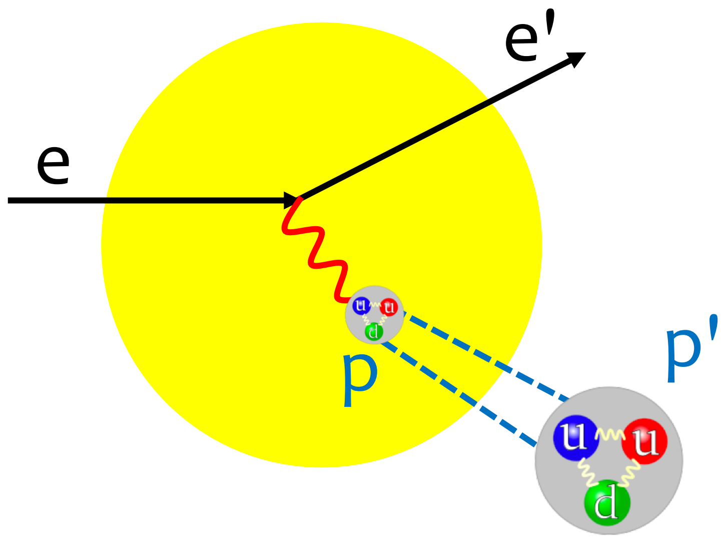
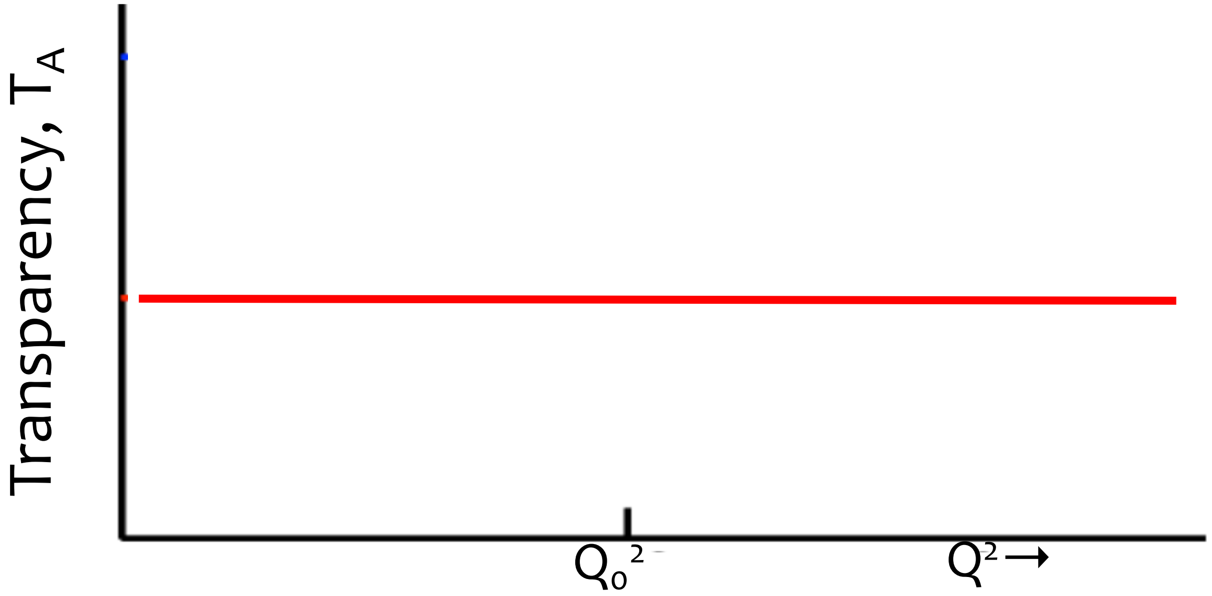


Relativity:
Maintains this small size as it propagates out of the nucleus (*freezing*, transferred energy)

Strong force:
Experience reduced attenuation in the nucleus, color screened

CT is unexpected in the strongly interacting hadronic picture

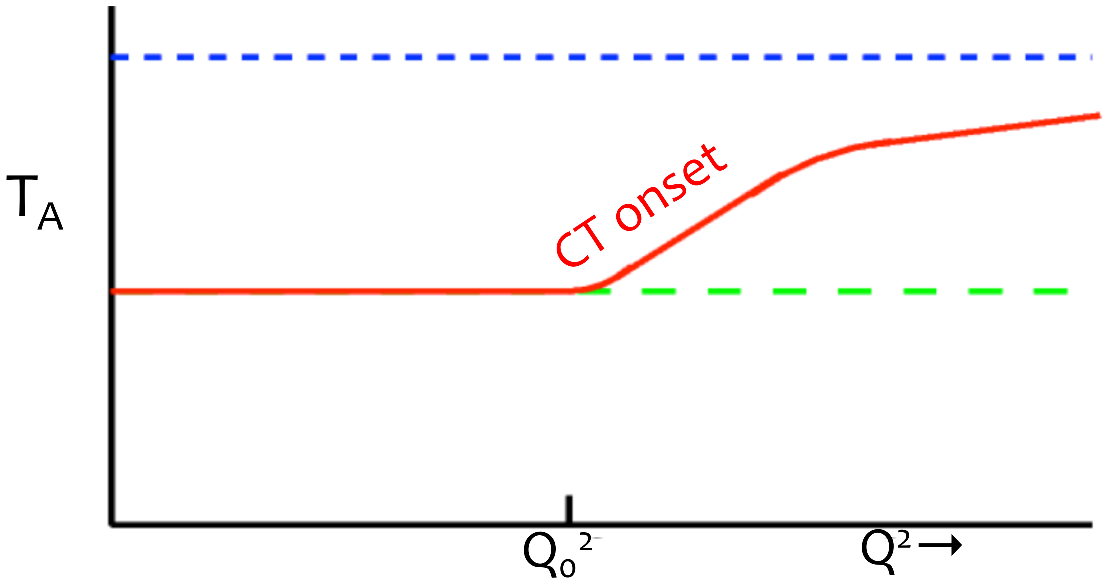
$$T_A = \frac{\sigma_A}{A\ \sigma_N}$$

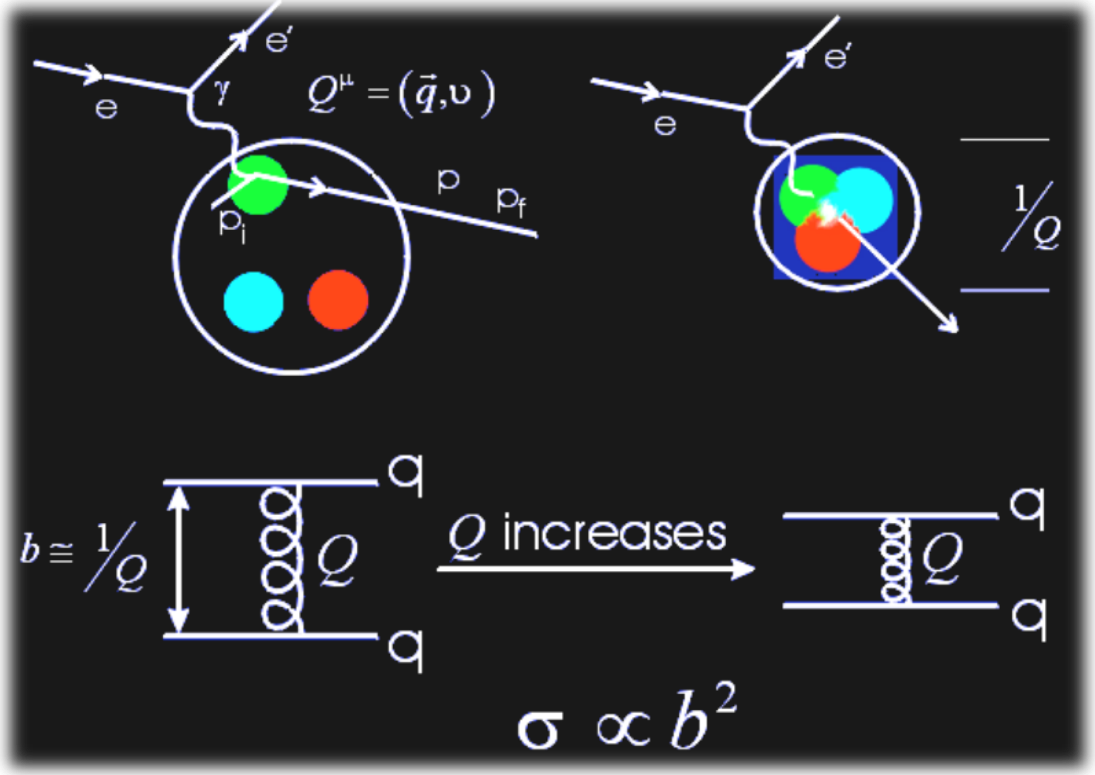


$$\sigma_A = \sigma_N\ A^{\alpha}$$

- scattering cross section
- Glauber multiple scattering
- Correlations and Final State Interaction (FSI) effects

Onset of CT indicates the transition to quark-gluon degrees of freedom





Quantum diffusion model describes the PLC lifetime:

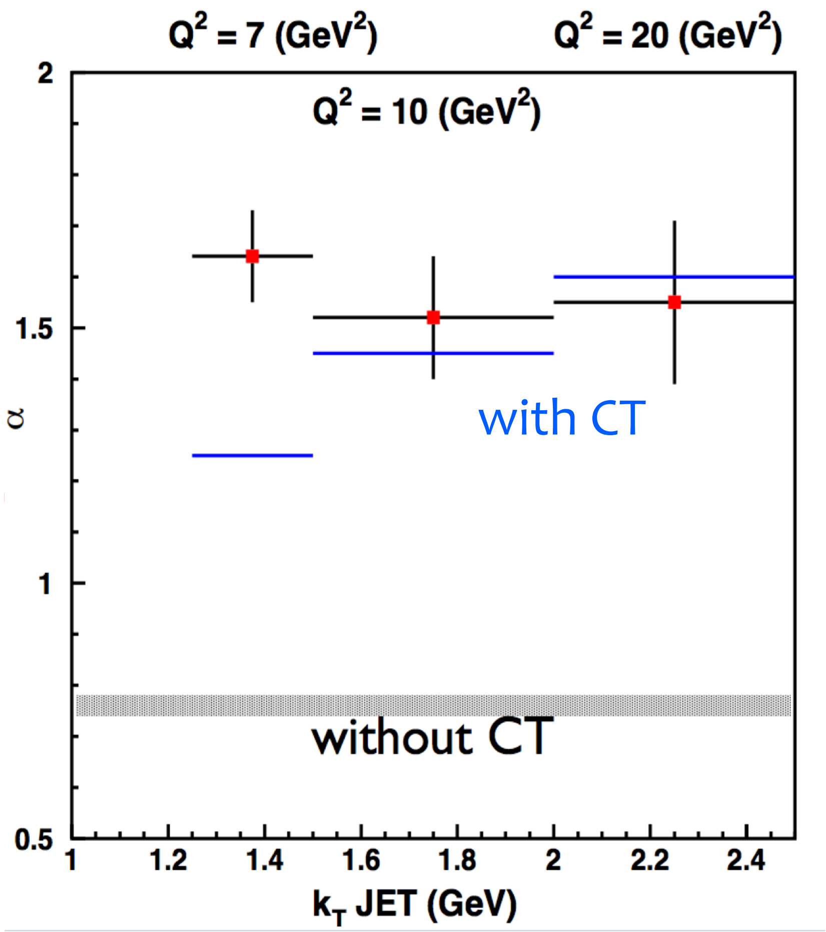
$$l_h = 2p_h/\Delta M^2$$

Farrar et al., PRL (1988)

CT established at high energies

Coherent diffractive dissociation of 500 GeV/c pions on C and Pt

π + A → 2 jets + A'



Fit to $\sigma = \sigma_0 A^{\alpha}$

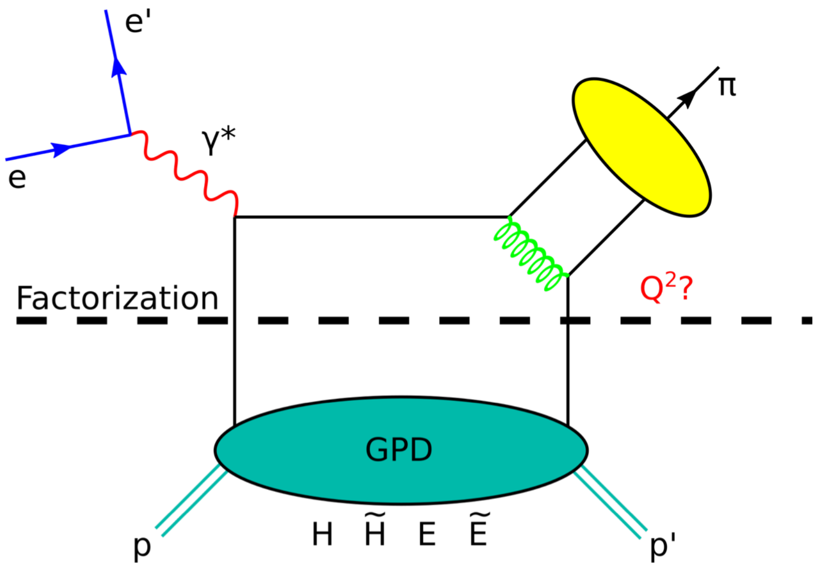
Pion-nucleus total cross section, α=1.6

CT predictions by L. L. Frankfurt, G. A. Miller, and M. Strikman, Phys. Lett. B304, 1 (1993)

Aitala et al., PRL 86, 4773 (2001)

CT is connected to JLab 12 GeV physics interpretations

GPD framework requires factorization into a hard interaction with single quark and soft part (GPDs).



Color cancellation required for factorization:

-> small size configurations

-> at high Q^2, small size object moves through nucleus with no further interactions

L. Frankfurt and M. Strikman, Phys Rep. 160, 235 (1988).

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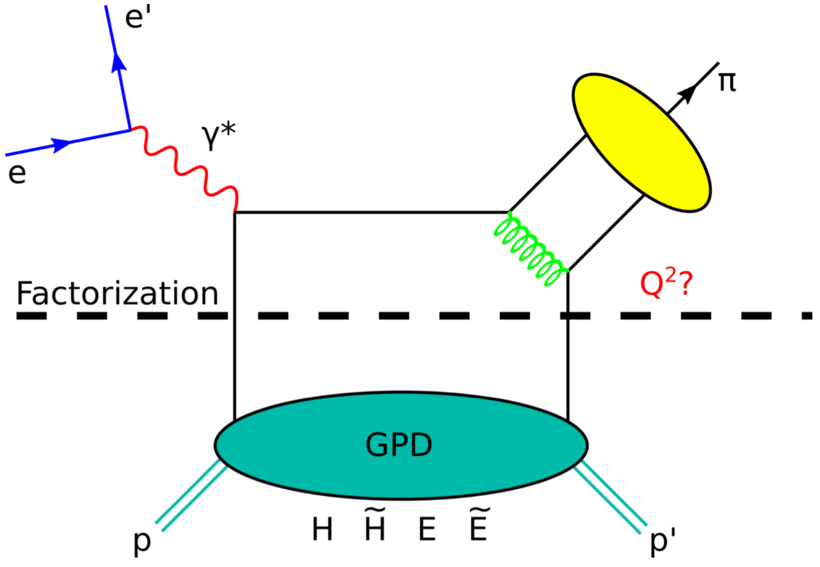

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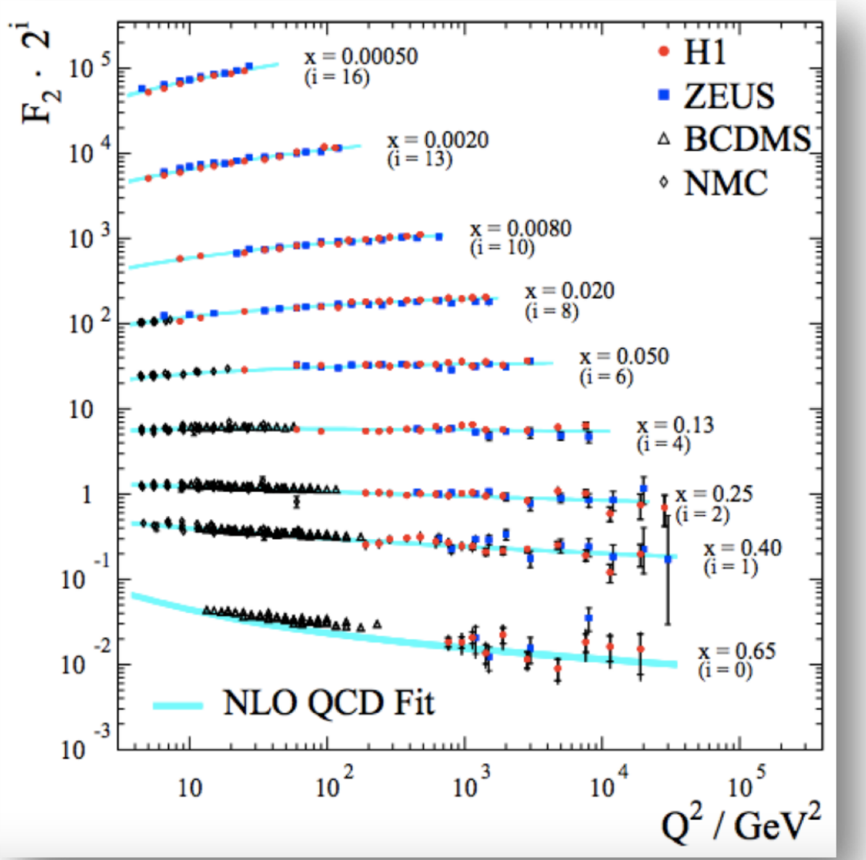
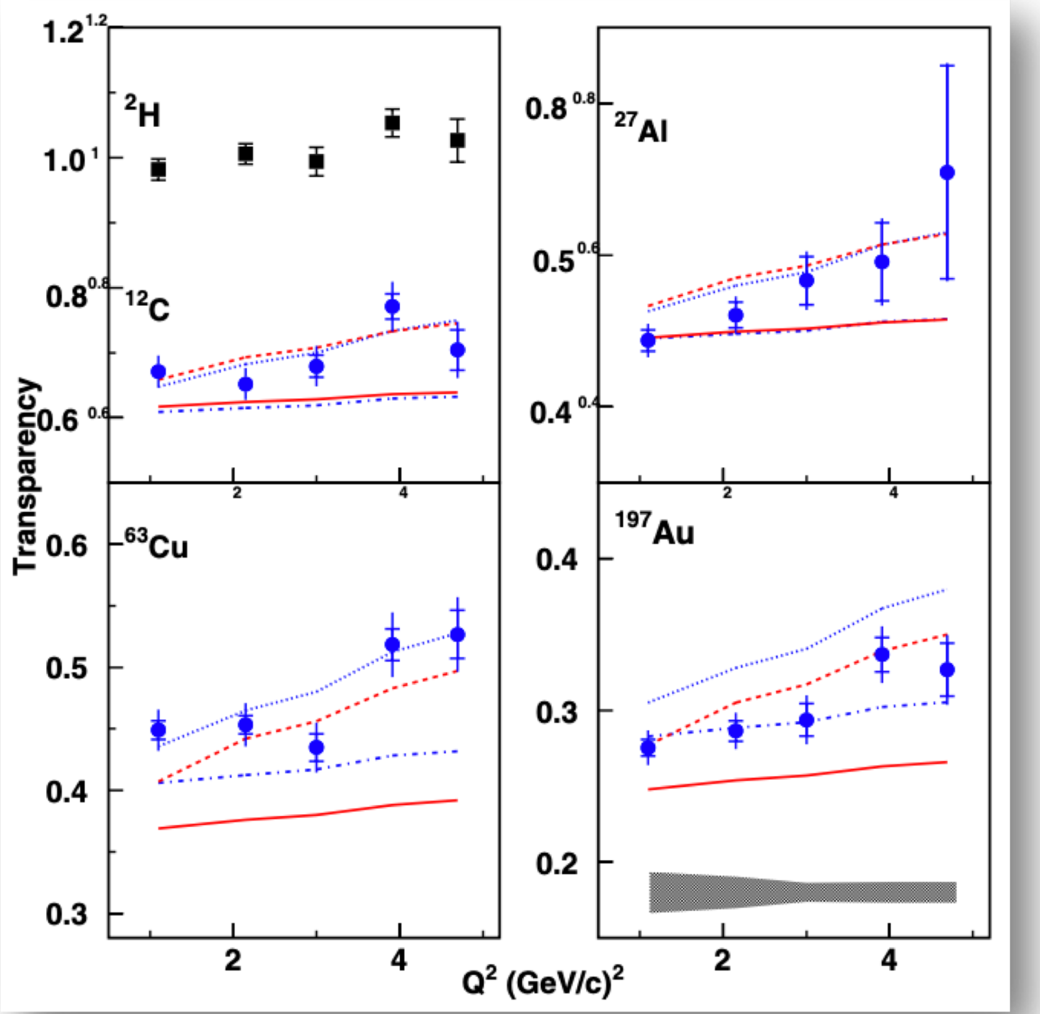
CT is implied by successful description of DIS.

Reduced interaction at high energies due to CT is assumed in calculations of structure functions.

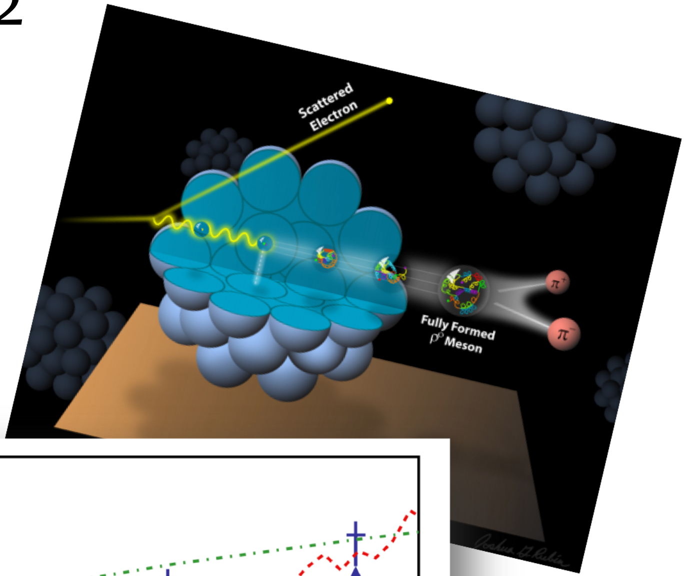


Onset for mesons observed at few GeV²

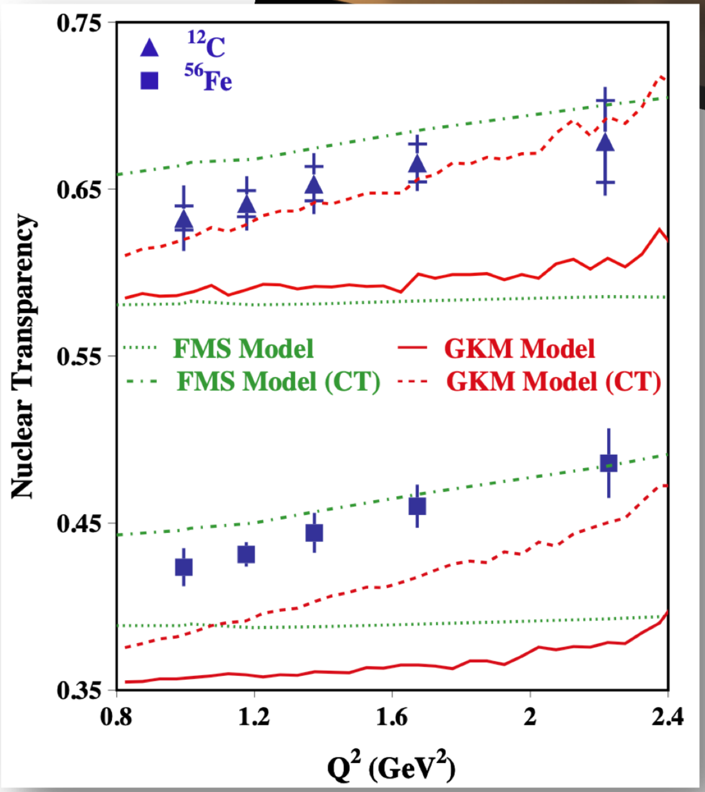
A(e,e'π^+)



B. Clasie et al, PRL99:242502 (2007)
X. Qian et al, PRC81:055209 (2010)



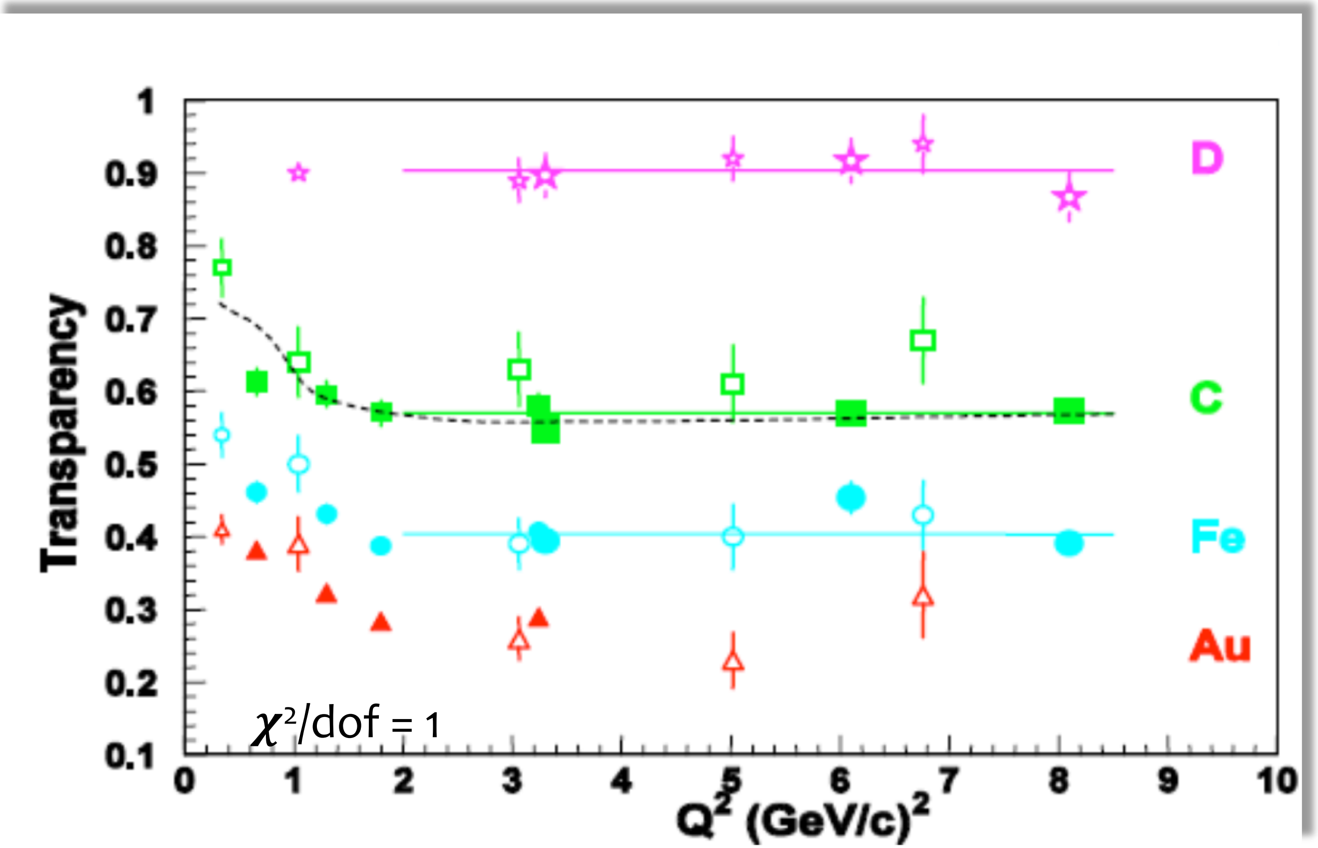
A(e,e'ρ^o)



L. El Fassi et al, PLB 712,326 (2012)
L. El Fassi, Physics 4, no. 3 (2022)

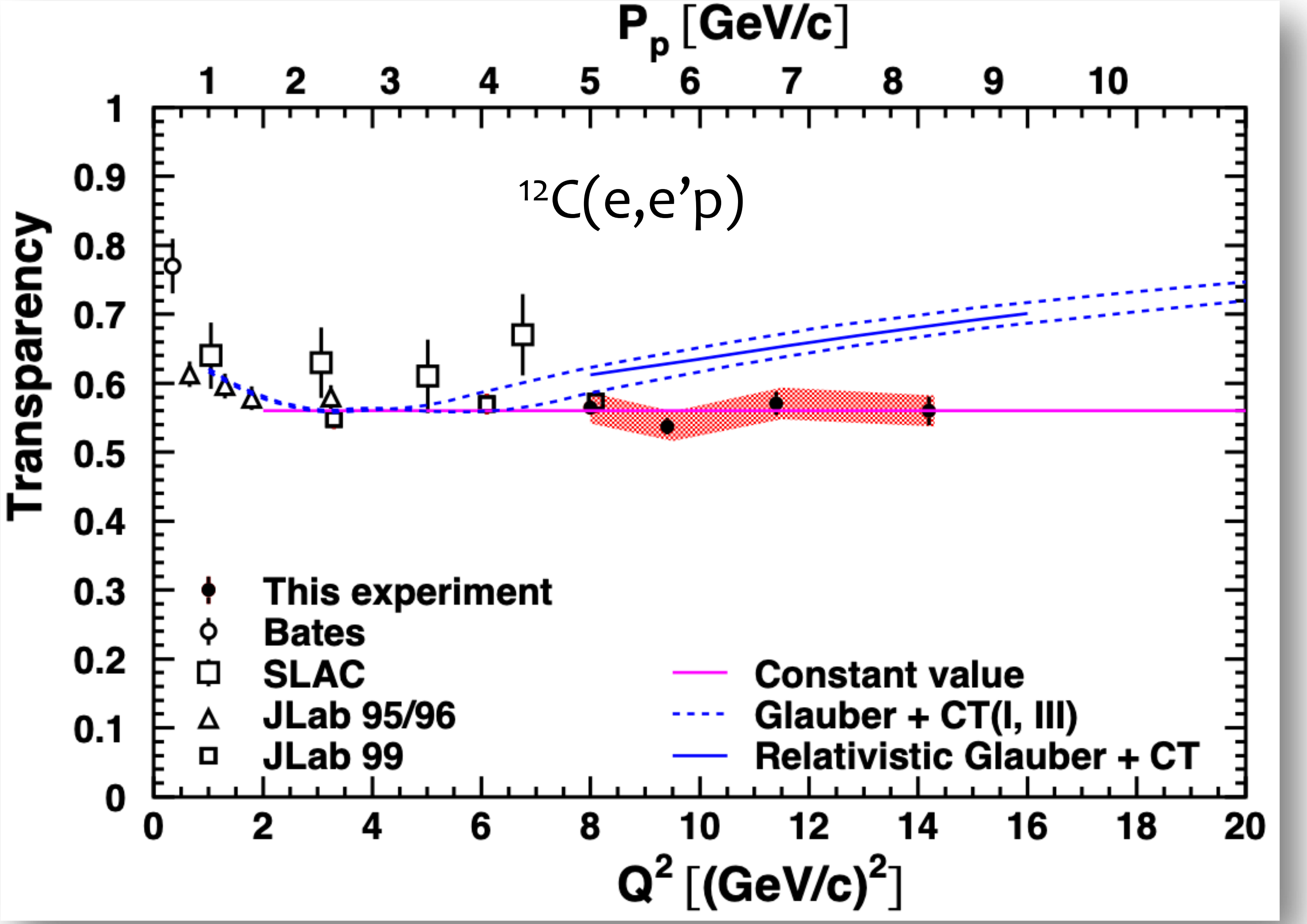
Protons are historically challenging

No evidence for CT in A(e,e'p) up to Q^2<8 GeV^2



N. C. R. Makins et al. PRL 72, 1986 (1994)
G. Garino et al. PRC 45, 780 (1992)
D. Abbott et al. PRL 80, 5072 (1998)
K. Garrow et al. PRC 66, 044613 (2002)

And continue to show a lack of CT onset up to $Q^2<14$ GeV^2…

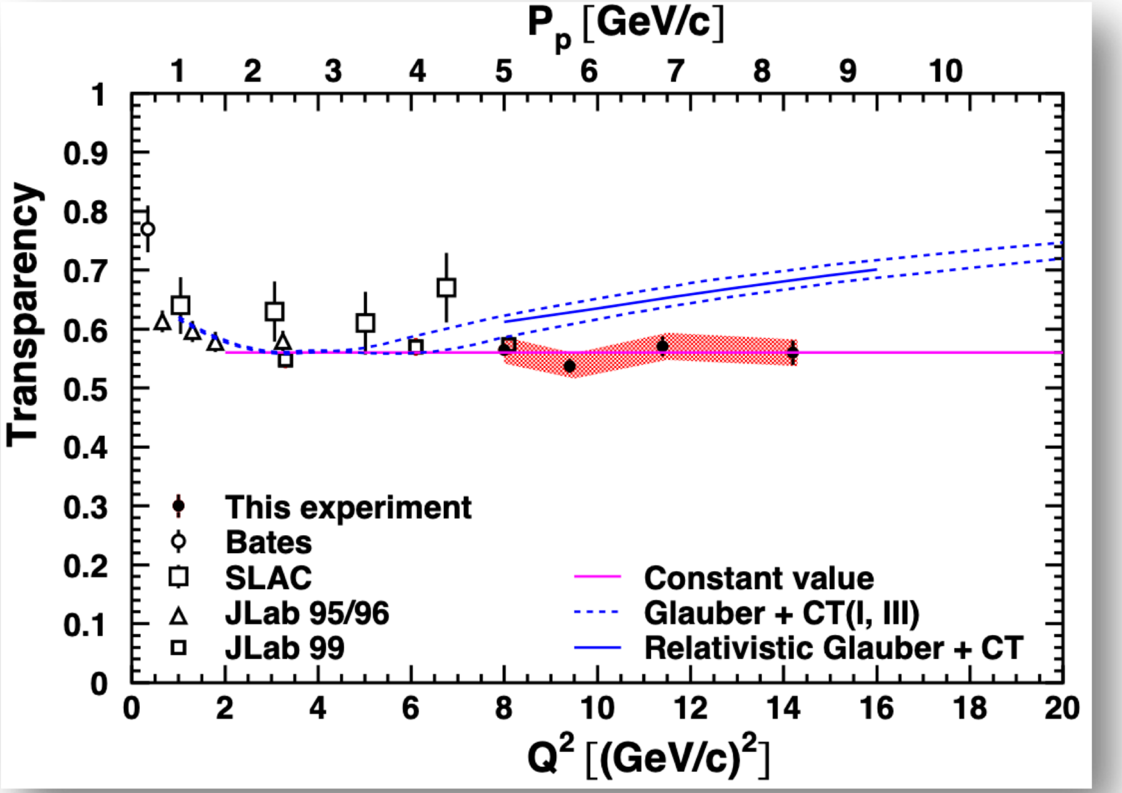


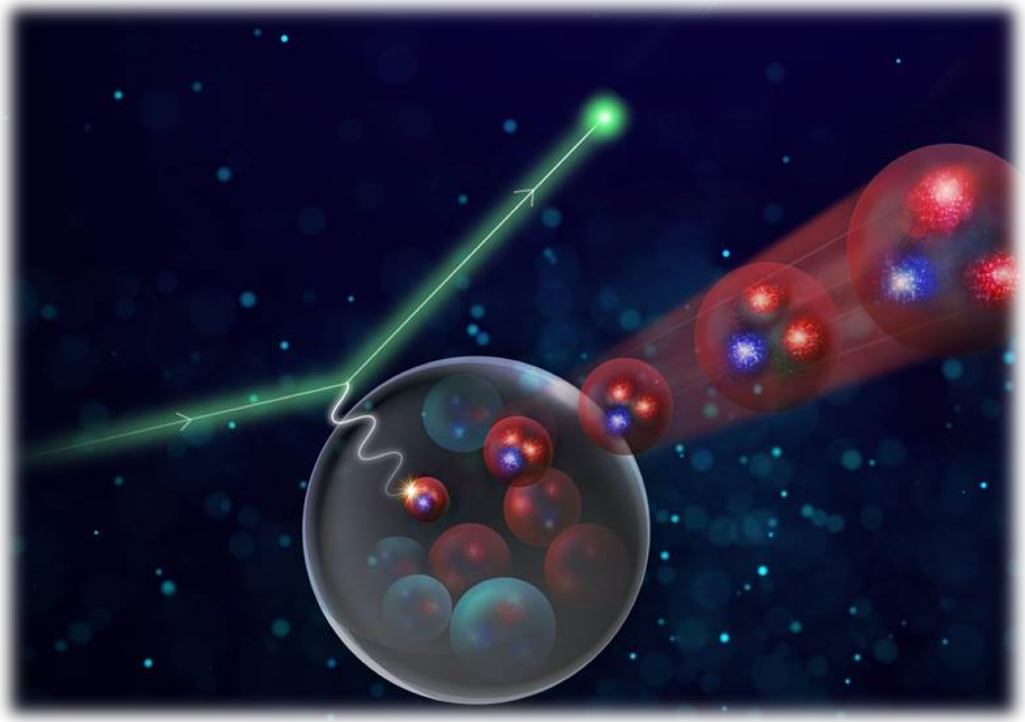
D. Bhetuwal et al, PRL126:082301 (2021)

Time for a new strategy!

Previous (e,e'p) experiments chose kinematics with relatively low sensitivity to FSIs

Also PLC had to remain "frozen" while exiting the nucleus





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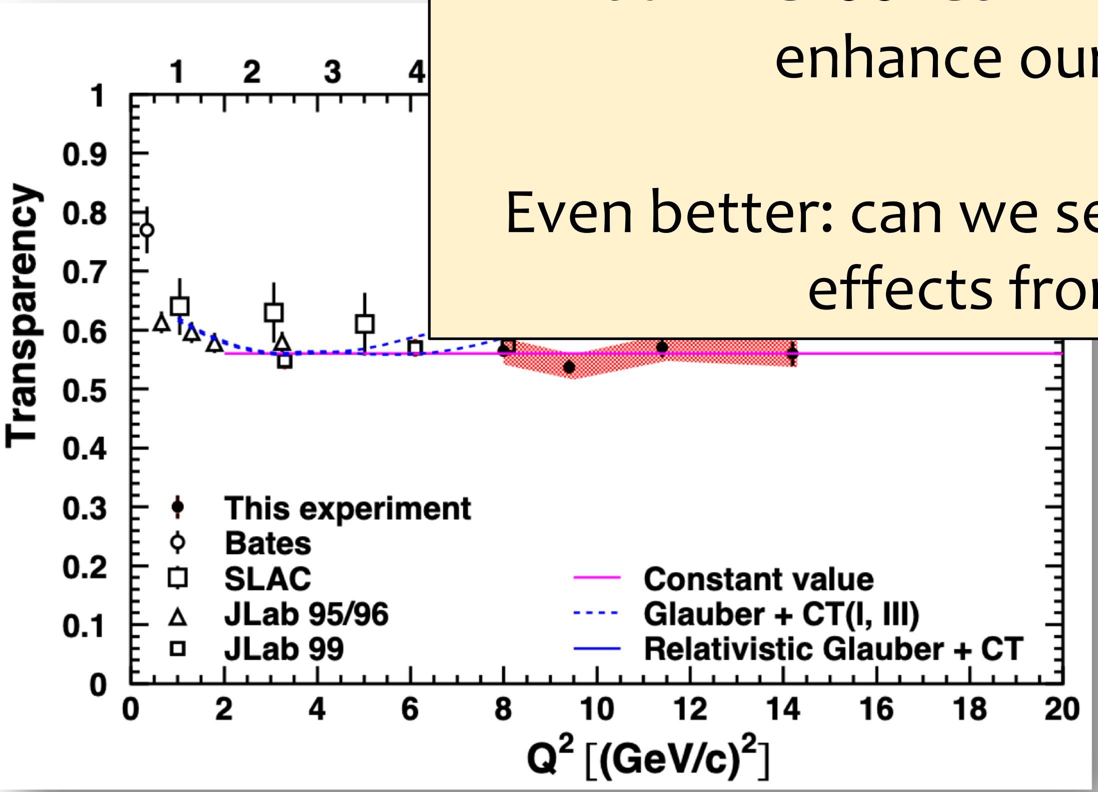
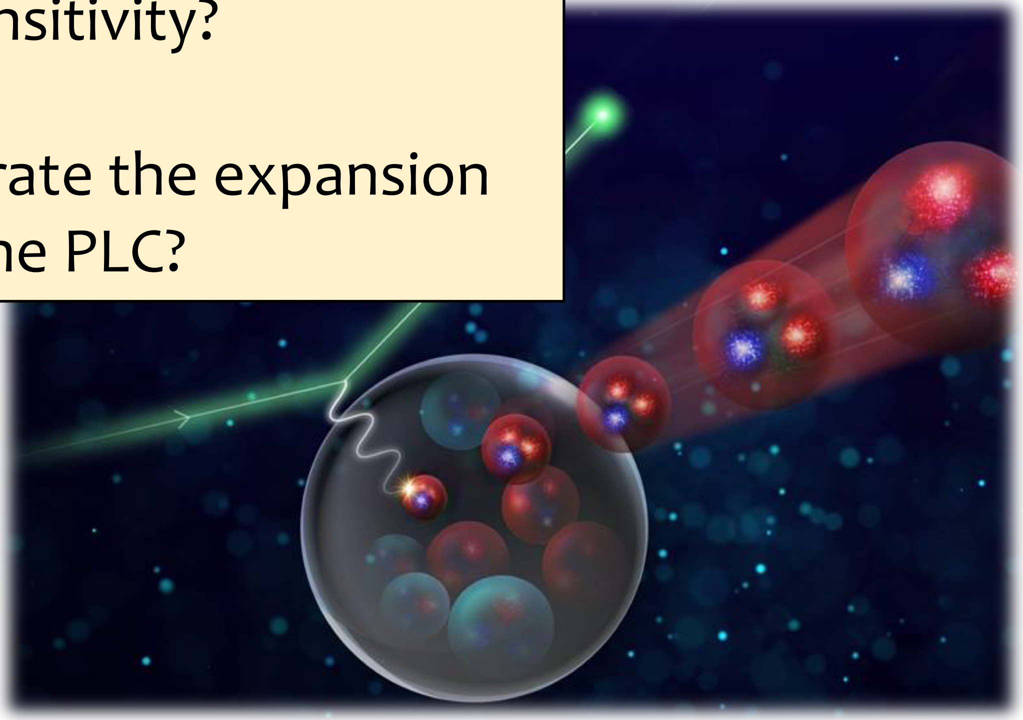


What if we looked in regions of high FSIs to enhance our sensitivity?

Even better: can we separate the expansion effects from the PLC?



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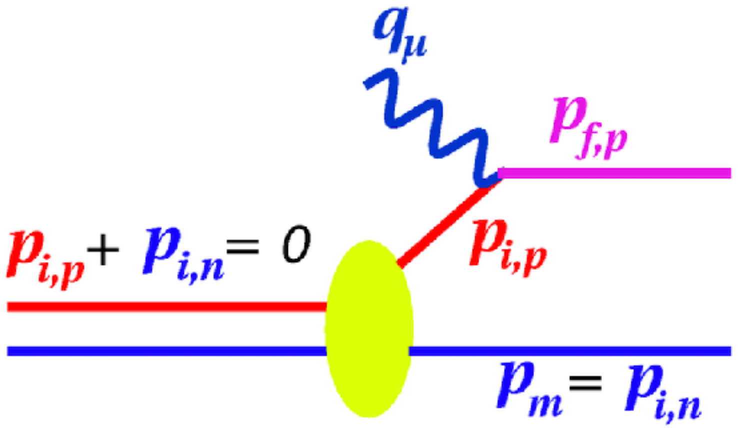
Deuteron breakup reaction

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



Plane Wave Impulse Approximation (PWIA)

Detect the scattered electron and the knocked out proton.

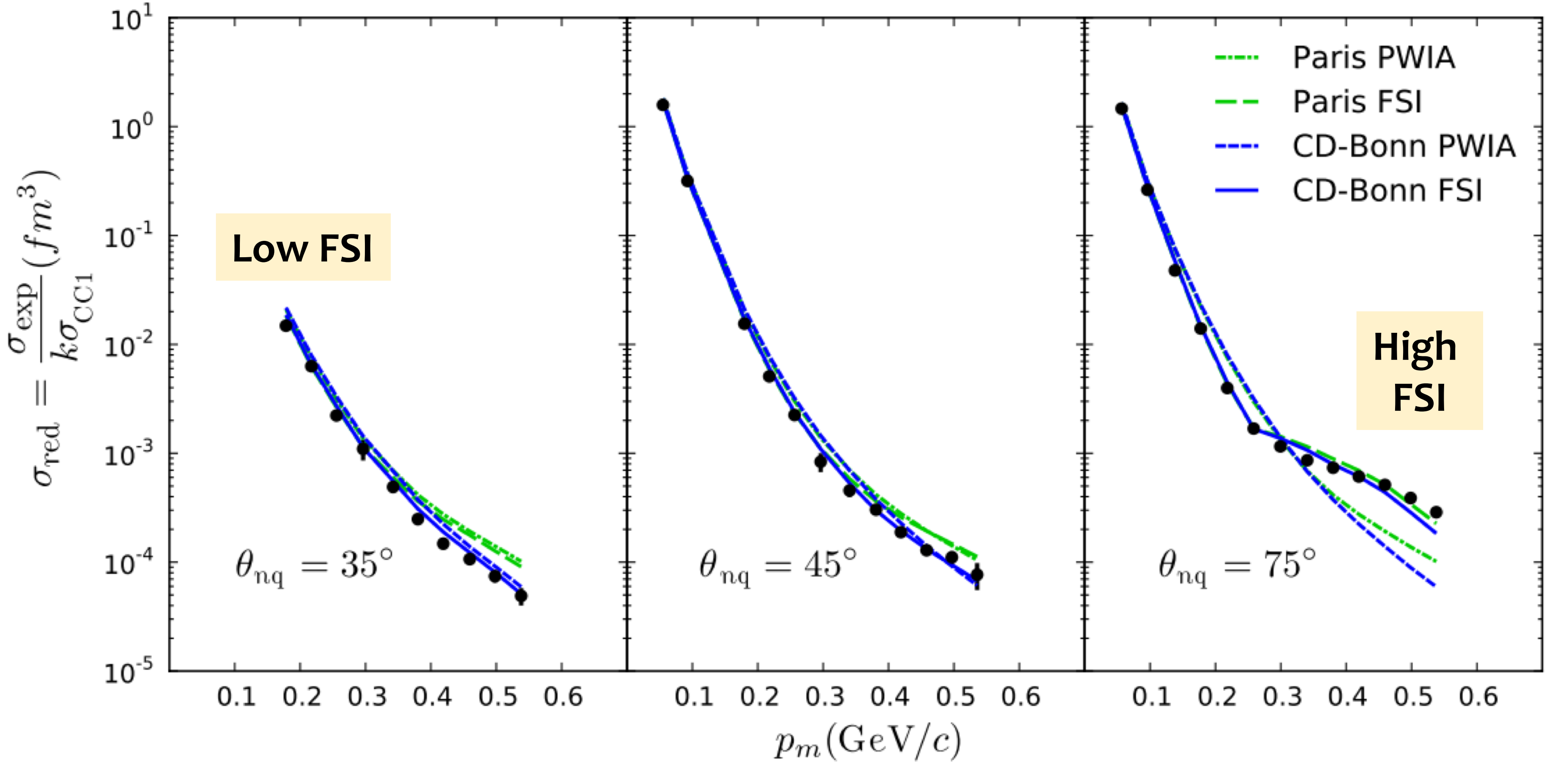
Observables - reconstruct the undetected **neutron:**

$\vec{p}_m = \vec{q} - \vec{p}_{f,p}$ “recoil” momentum

θ_{nq} “recoil” angle

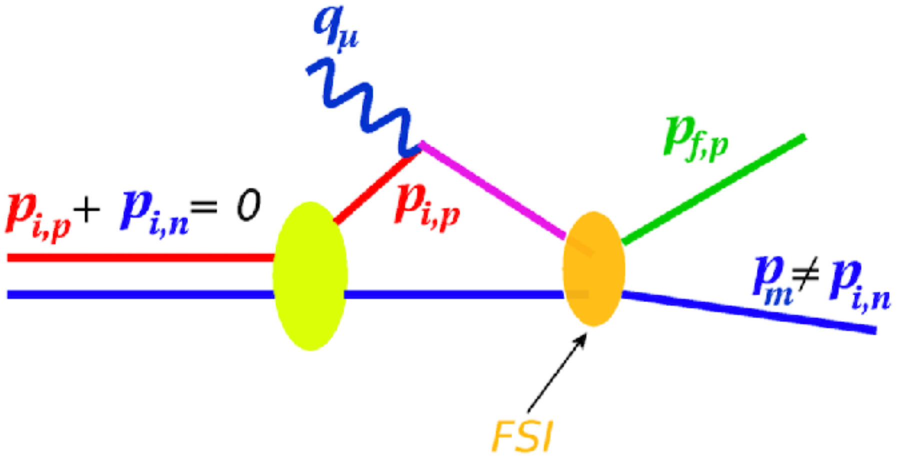
Kinematics with enhanced FSI are well-known

$Q^2 = 3.5$ (GeV/c)²

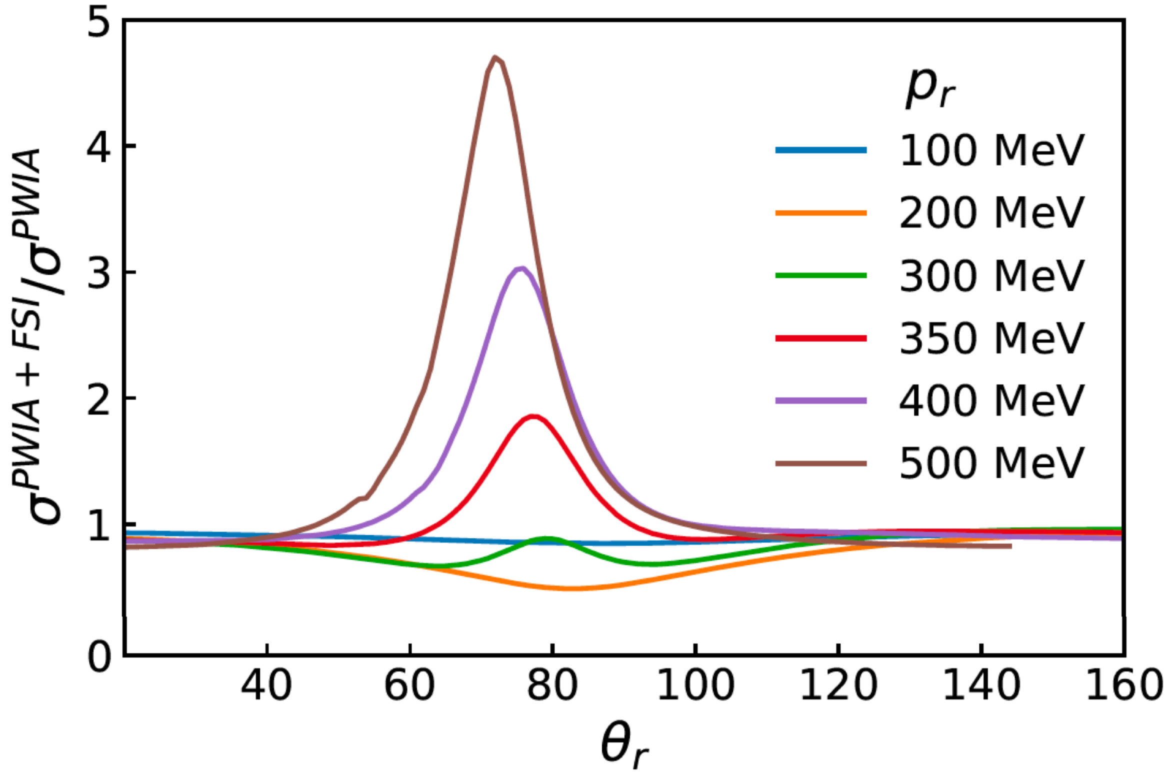


W. Boeglin et al., PRL (2011)

Double scattering FSIs



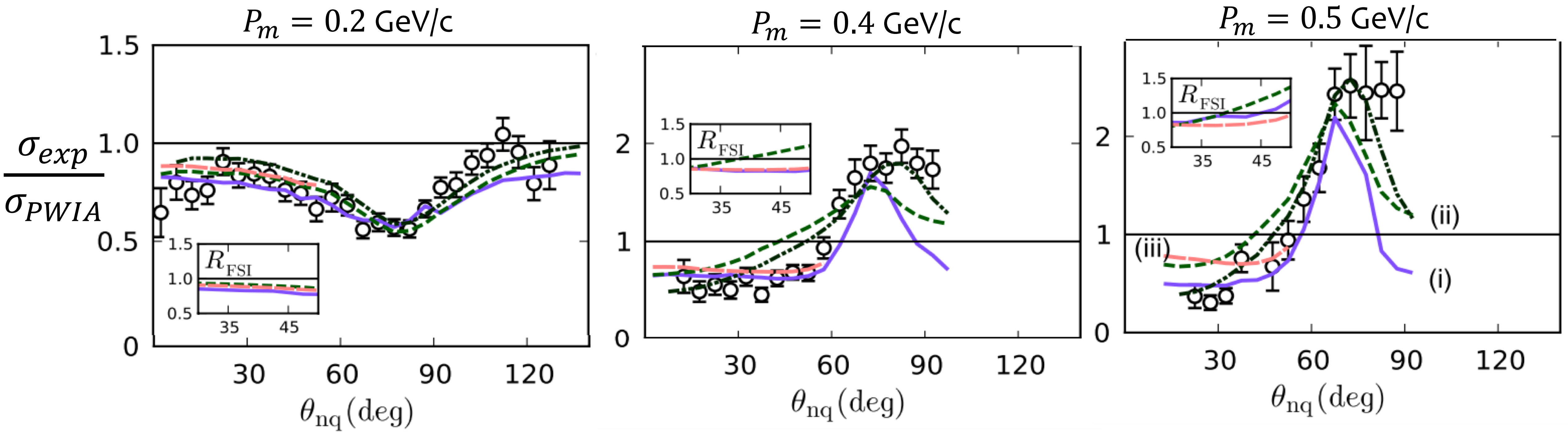
Final State Interactions (FSI)



Double-scattering is the square of re-scattering amplitude of knocked out nucleon

Larger missing momentum increases the sensitivity to FSIs

$Q^2 = 3.5\ (\text{GeV/c})^2$



W. Boeglin et al., PRL (2011)

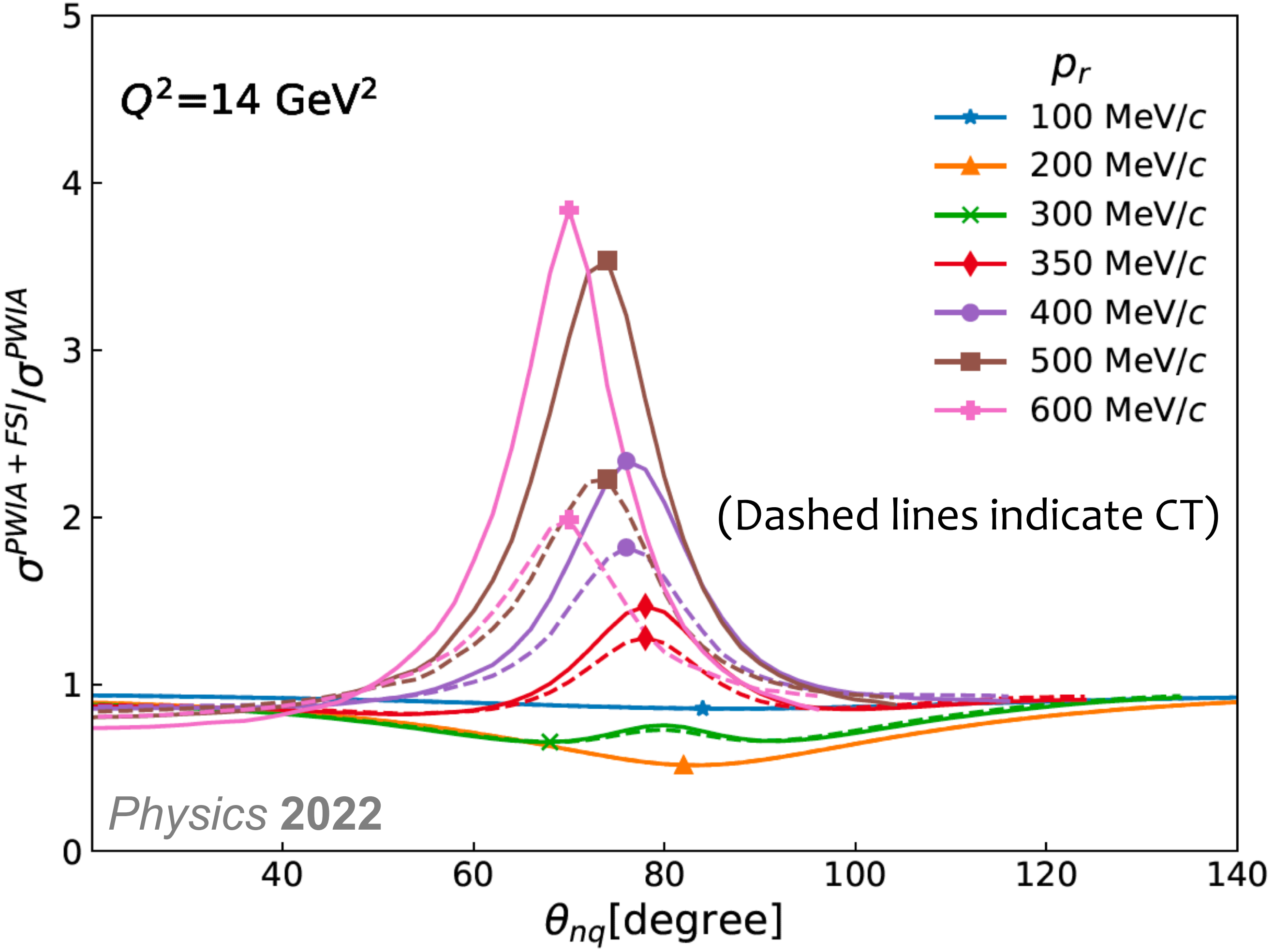
CT signal in deuterium

$$R = \frac{\sigma(p_r = 400\ MeV)}{\sigma(p_r = 200\ MeV)}$$

- Measured cross section ratio
- Double cross section ratio / PWIA
- Reduced cross section ratio

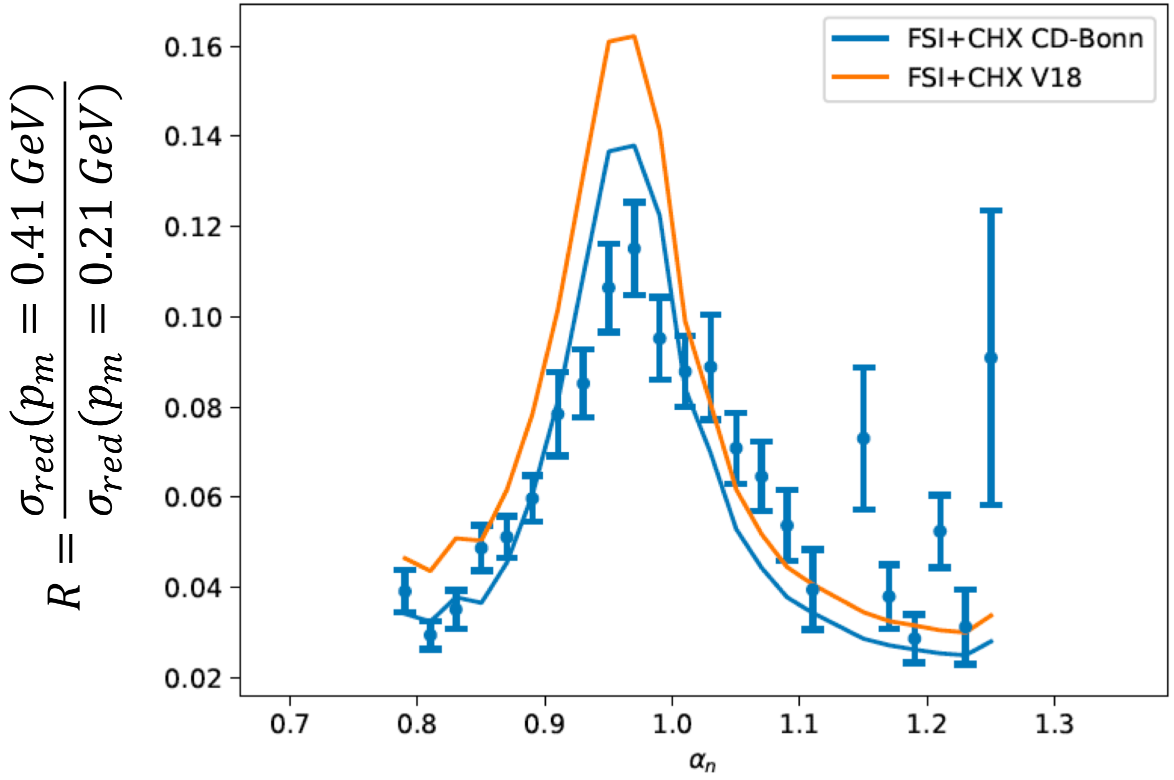
In the case of CT, reduced FSIs:

$$\downarrow R = \frac{\sigma(p_r = 400\ MeV) \downarrow}{\sigma(p_r = 200\ MeV) \uparrow}$$

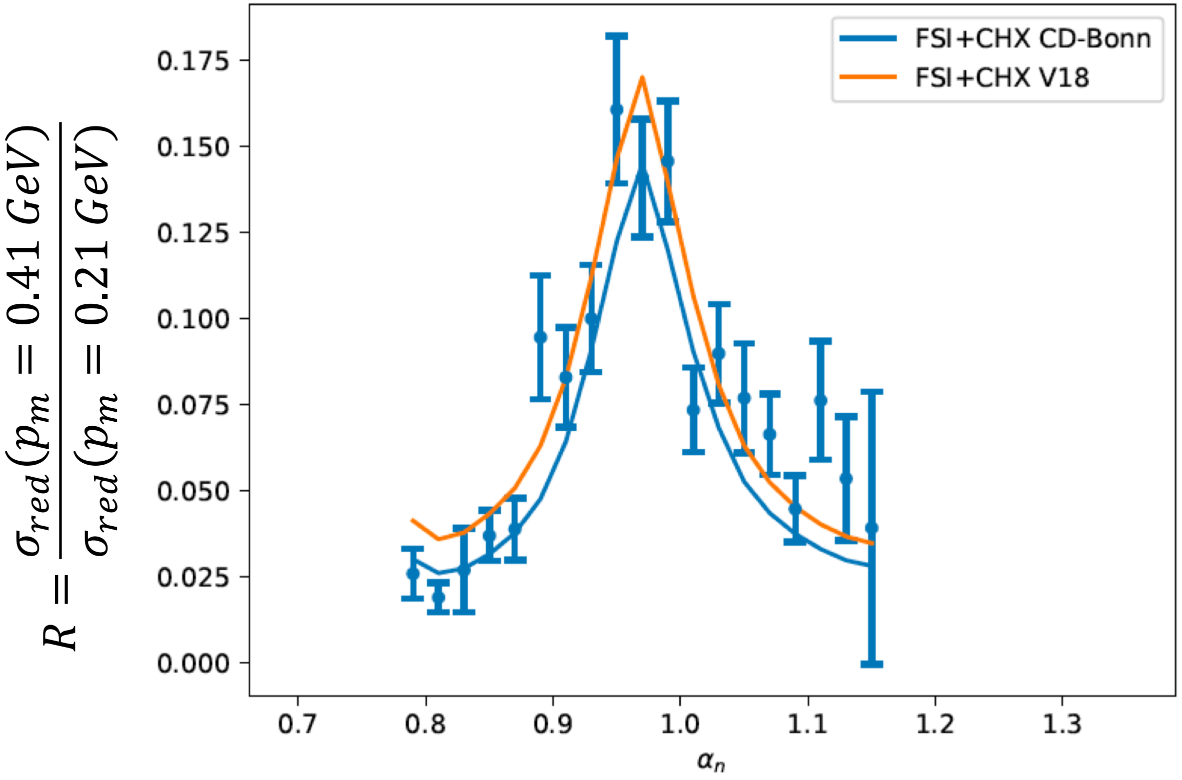


Ratio is well-calculable using GEA framework

$Q^2 = 2.1\ (\mathrm{GeV/c})^2$



$Q^2 = 3.5\ (\mathrm{GeV/c})^2$



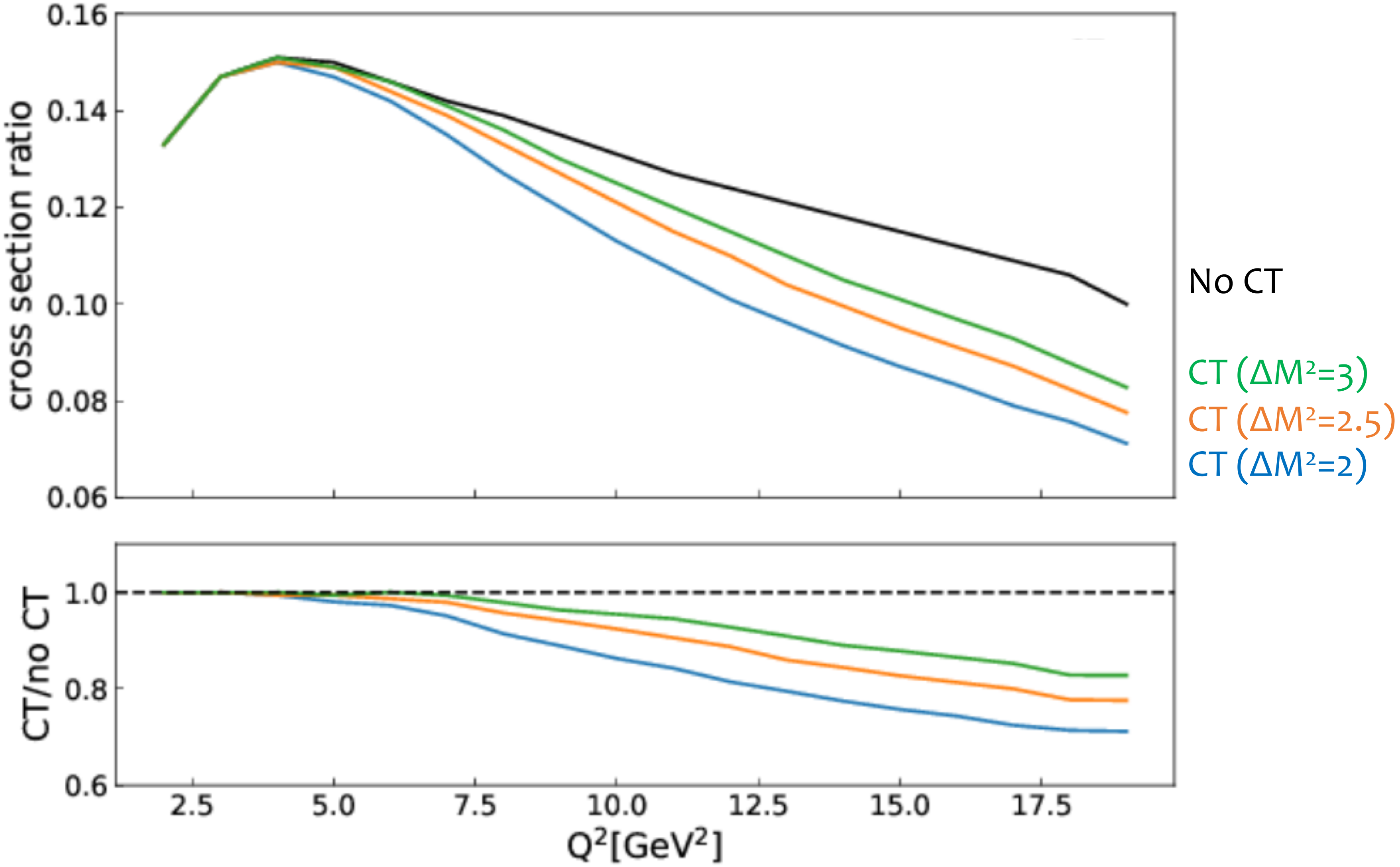
Light cone momentum fraction optimal near 1: $\alpha = (E_n - p_n cos\theta_{\gamma n})/m_n$

Courtesy of W. Boeglin

Using the ratio to enhance the CT signal observation

$$\downarrow R = \frac{\sigma(p_r = 400\ MeV)\downarrow}{\sigma(p_r = 200\ MeV)\uparrow}$$

Compare the ratio with the "no CT" prediction with increasing Q^2



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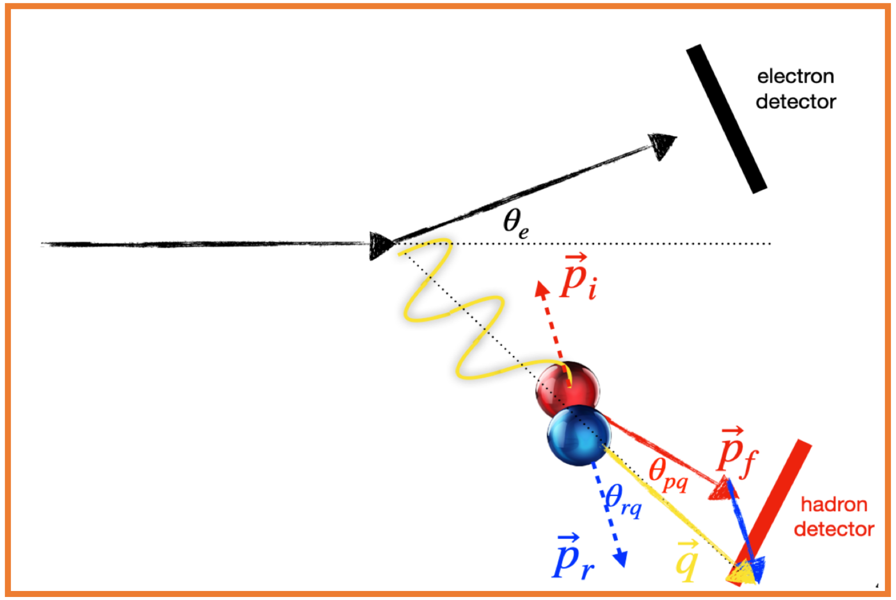
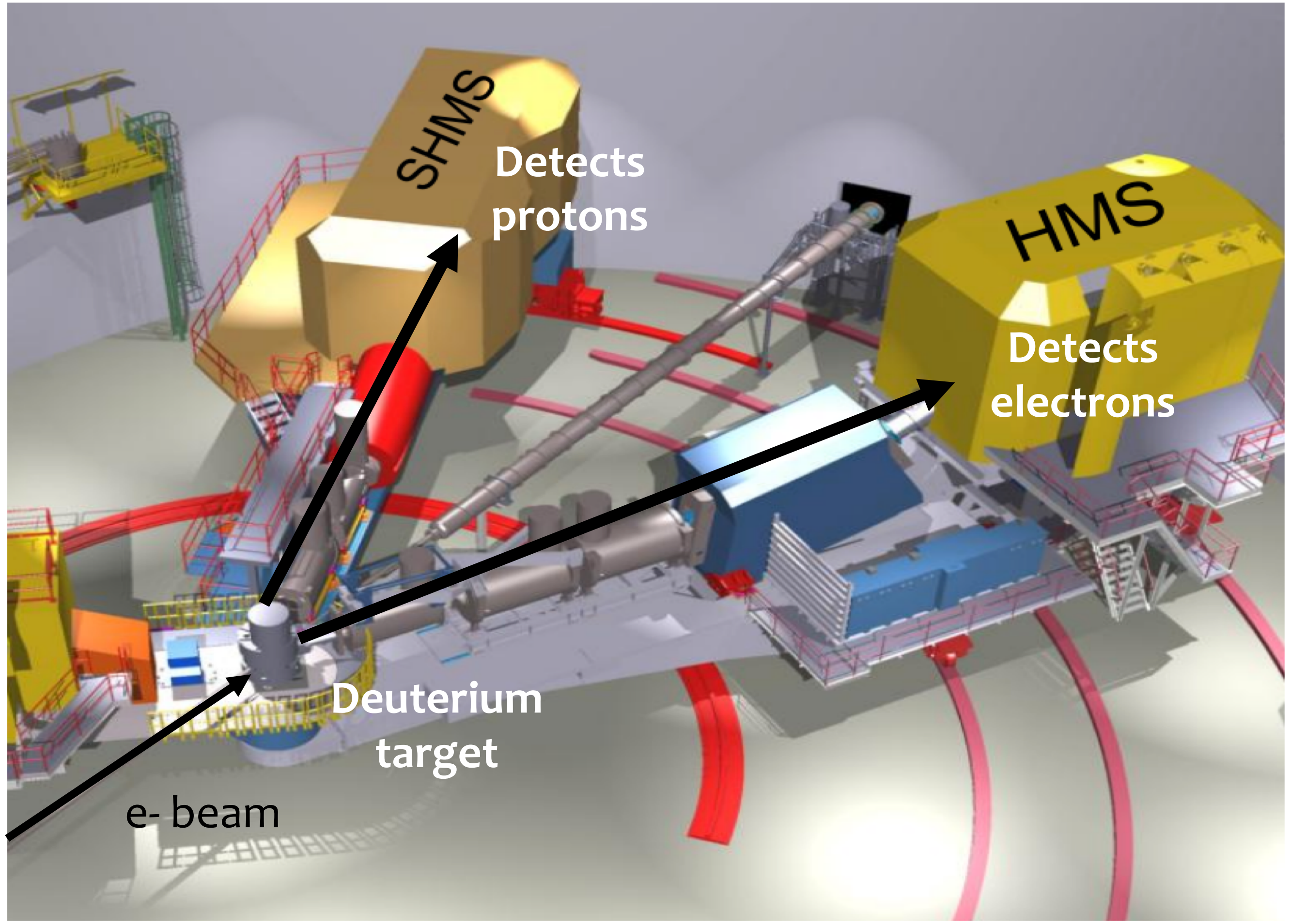
Experimental setup in Hall C



SHMS:
- 5 x 10^{-4} δ_p/P resolution
- 4 mSr Acceptance

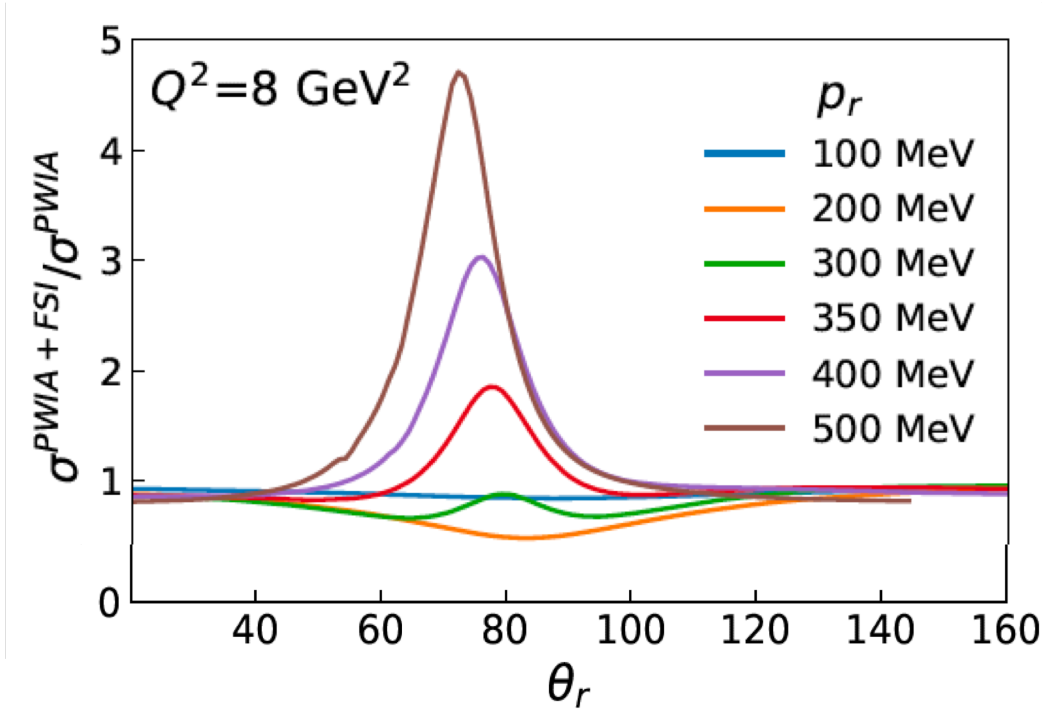
HMS:
- <0.1% δ_p/P resolution
- >6 mSr Acceptance

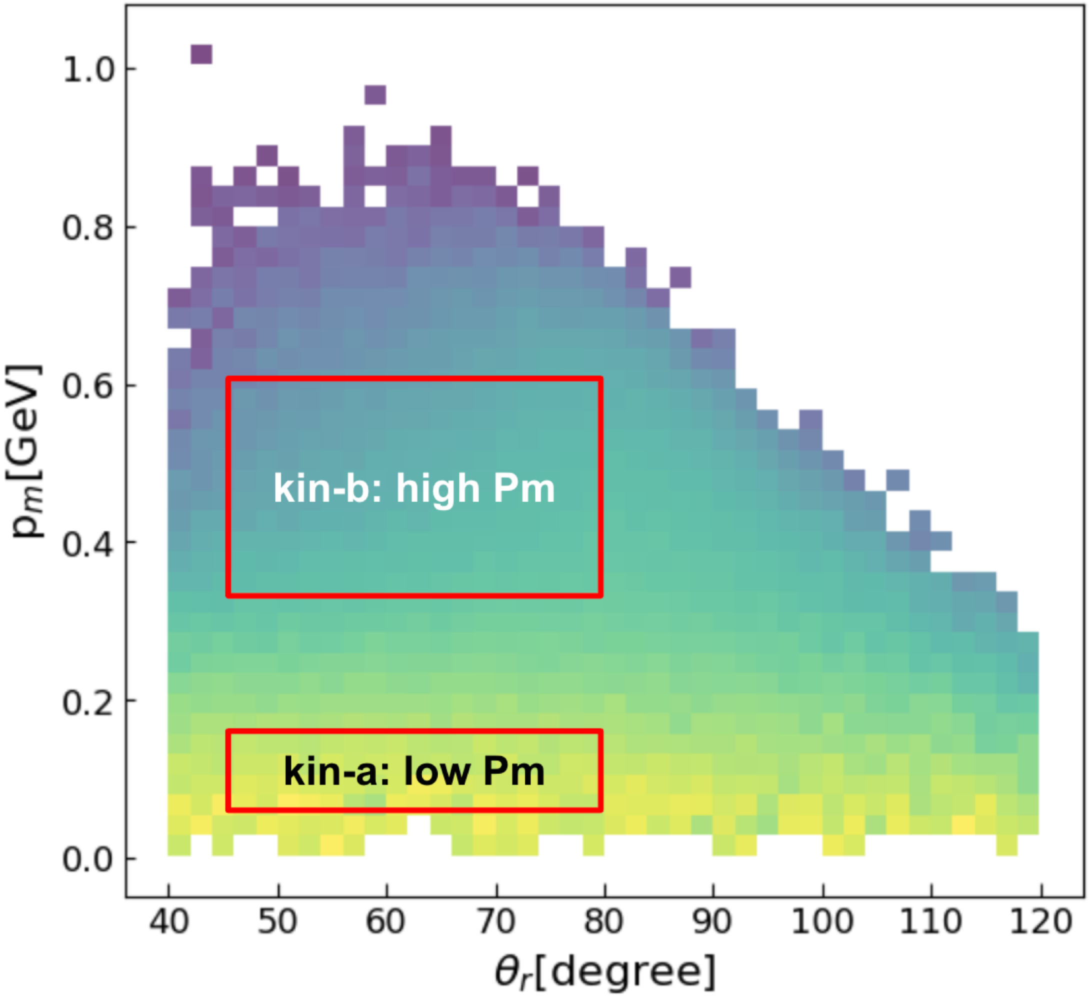


What we can measure

Measure d(e,e'p)n in high and low P_m

$$R = \frac{\sigma(high\ Pm)}{\sigma(low\ Pm)}$$

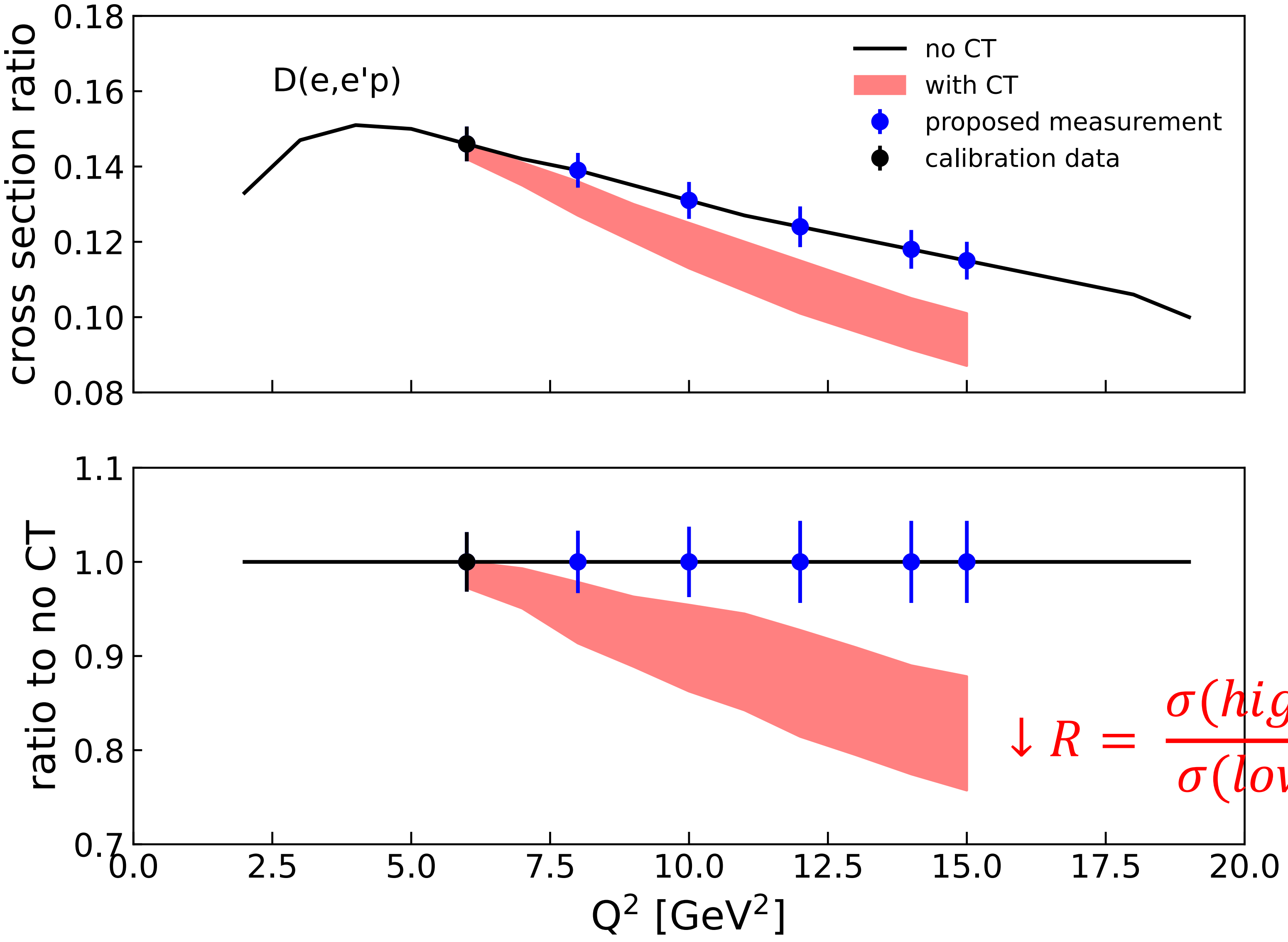




$x_B \approx 1, \alpha \approx 1$

Increased sensitivity for detecting the onset of CT!

$$R = \frac{\sigma(high\ Pm)}{\sigma(low\ Pm)}$$



$$\downarrow R = \frac{\sigma(high\ Pm)\downarrow}{\sigma(low\ Pm)\uparrow}$$

Beam time requirement

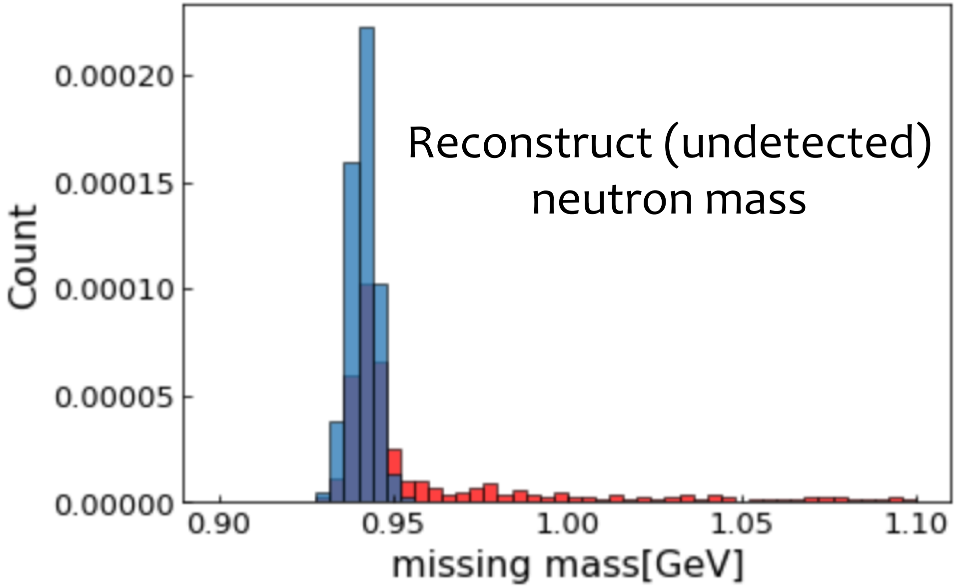
Q^2 [GeV^2]	High Pm, rate/hr	Beam Days	Statistical uncertainty
8	150	2	1.5%
10	36	3	2%
12	9	6	3%
14	2	25	3%
15	1	56	3%

+3 days at Q^2=6 GeV^2 for calibrations

Total time requested: 95 days

11 GeV electron beam

80 μA on 25-cm LD_2 cell



Systematics

Q^2-dependent

Systematic source	
Spectrometer acceptance	1.4%
Live time & detector efficiency	0.5%
Event selection	1.4%
Radiative corrections	1%
Tracking efficiency	1%

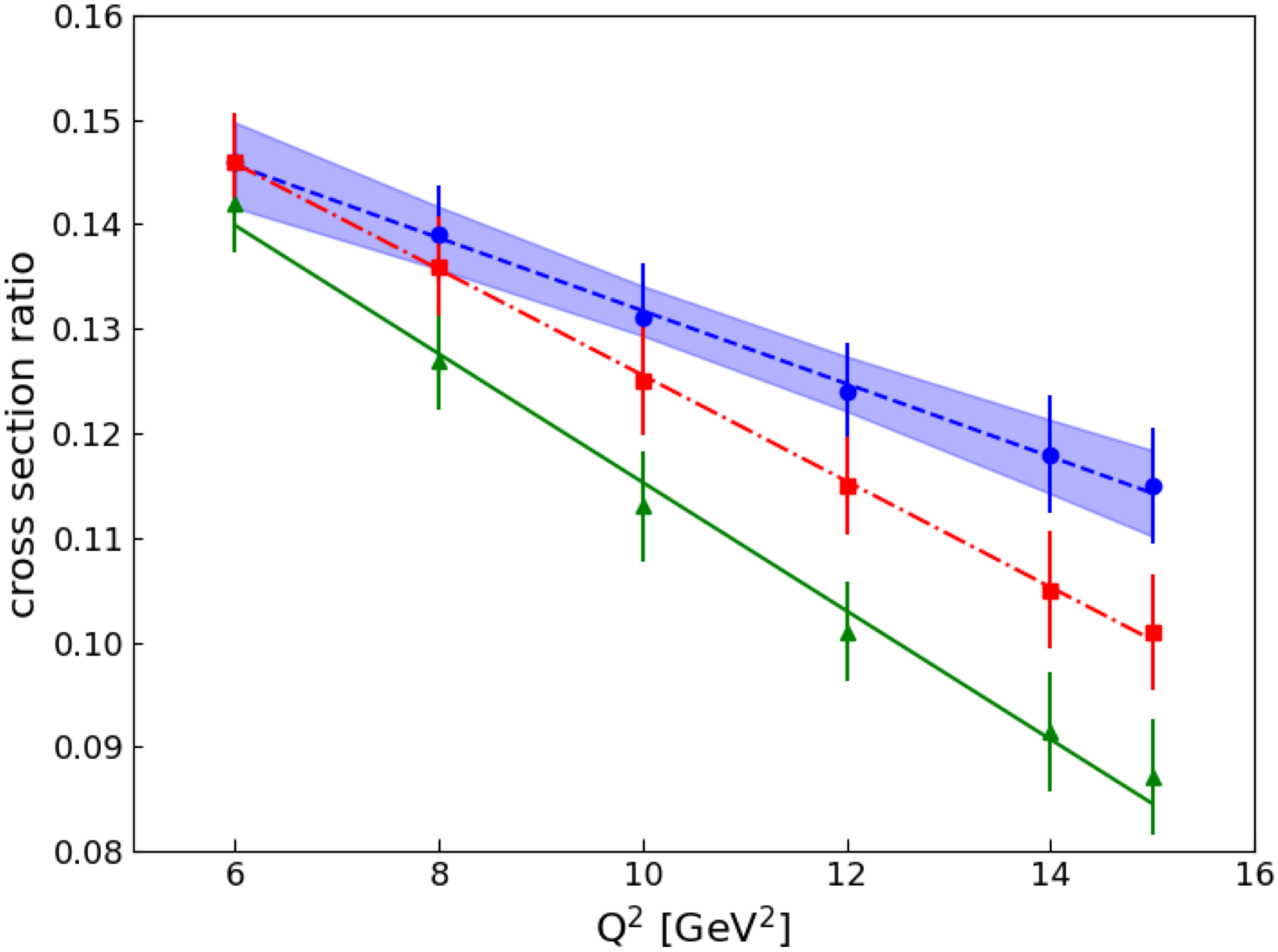
Total systematic on the ratio <3%

Q^2-independent (normalization) Cancelled by the ratio

Systematic source	
Target boiling/density	0.5%
Proton absorption	1%
Beam charge	1%
Target wall contributions	2.5%

Experience from the previous Hall C experiments

Sensitivity to the CT onset

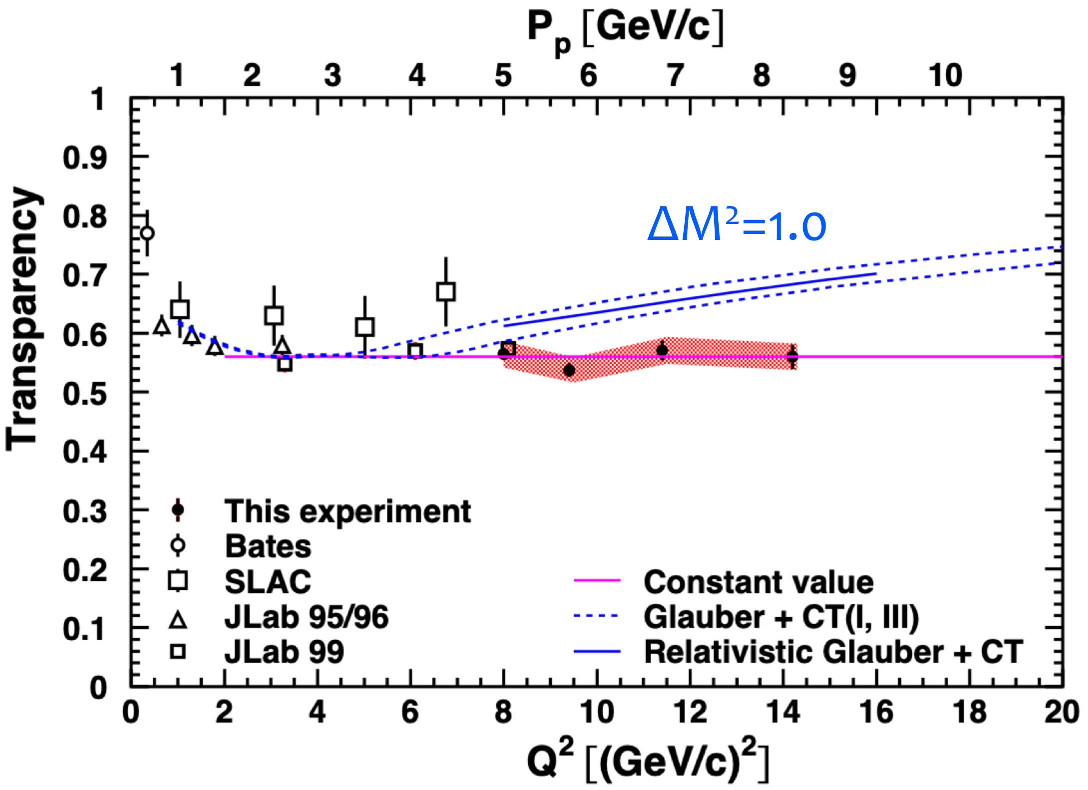


no CT (1σ band)

CT model (ΔM^2=3)

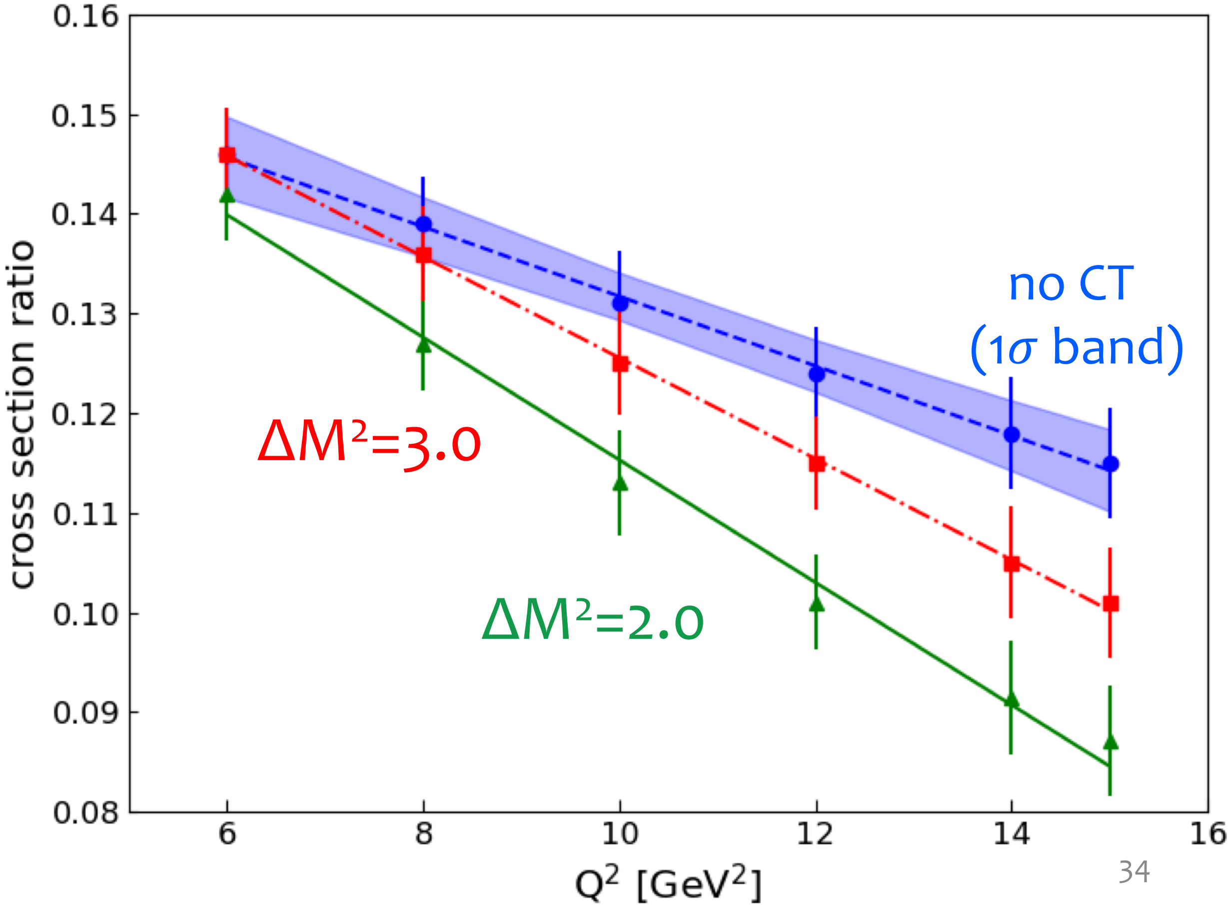
CT model (ΔM^2=2)

CT Model Sensitivity

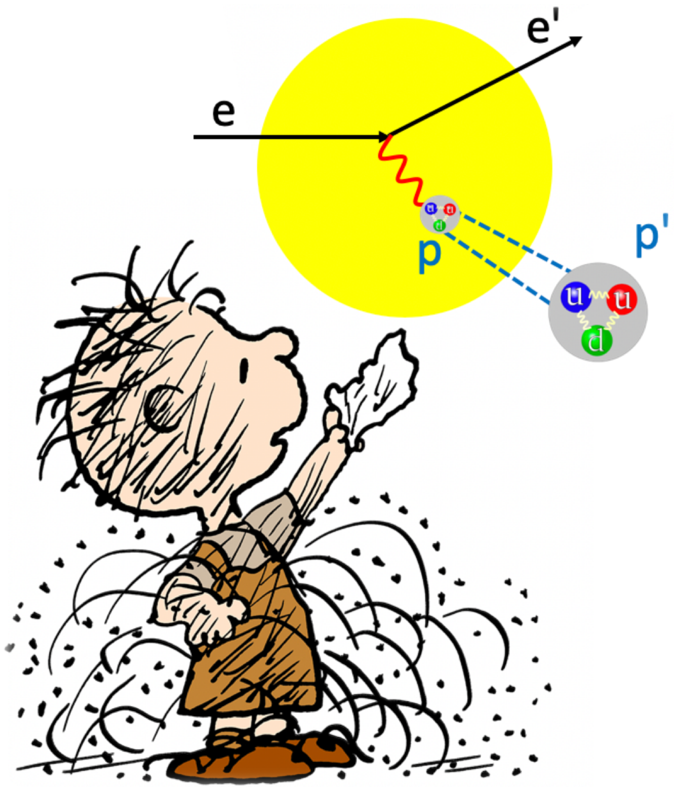


Sensitive to MUCH larger ΔM^2

Larger ΔM^2 → shorter PLC lifetime → delays CT onset



Summary



- Onset of CT in protons is a fundamental prediction of pQCD and is important for understanding hadron propagation in the nuclear medium

- Deuterium is the ideal target to search for the onset of CT
  - Known kinematic dependencies with FSIs
  - Double scattering is well-understood, enables observation of the PLC apart from the expansion
  - New test of CT!

- Unique kinematics and enhanced sensitivity for CT compared to all previous attempts