Nuclei
at
Short Distance Scales

Patricia Solvignon
UNH/JLab

NSAC 2014 Long Range Plan
Temple University, Philadelphia
September 13-15, 2014

What were 2007 LRP questions ?

From R. Ransonne's Talk at the 2007 LRP meeting

How is the nucleon affected by the nuclear medium ?

- Change in quark distribution
- Change in nucleon size and shape

How do we get from quarks and gluons to nucleons and mesons ?

- At what distance scale does this occur ?
- What are the signatures ?

How does the nuclear force arise from QCD ?

JLab highlights from the last 7 years

The EMC effect

Super-fast quarks

Neutron structure function at high x

Hadronization

Color transparency

JLab 12 GeV program

The EMC effect

Super-fast quarks

Neutron structure function at high x

Hadronization

Color transparency

access to higher x & Q^2 →

The EMC effect

Super-fast quarks

Neutron structure function at high x

Tensor structure functions

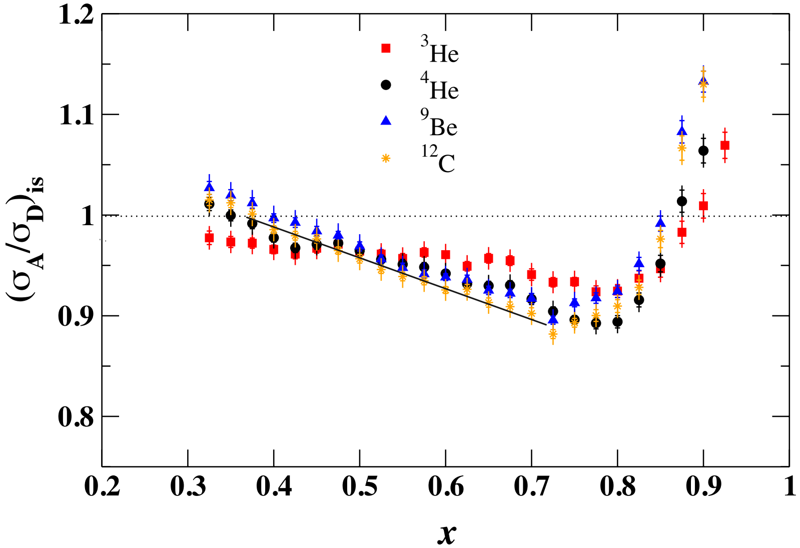
Hadronization

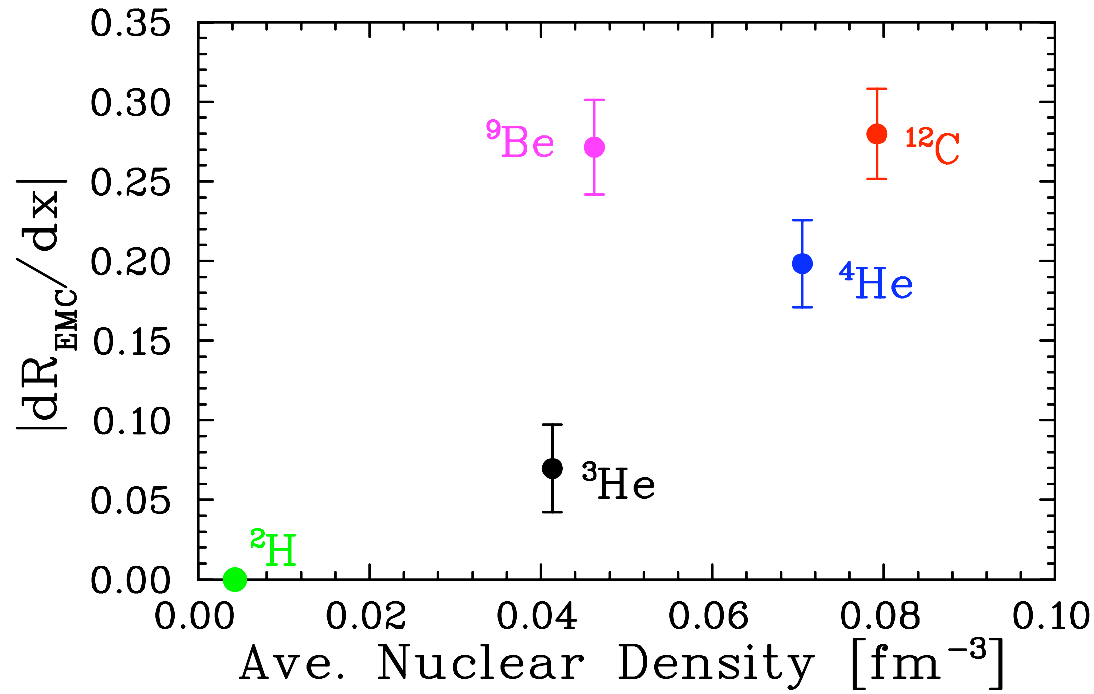
Color transparency

Quark distributions in nuclei

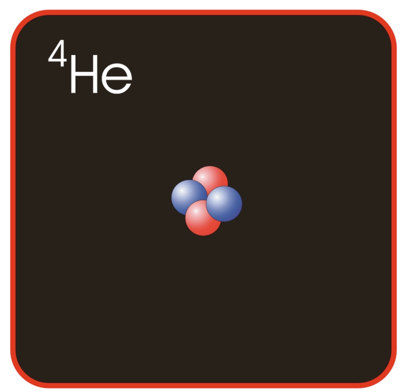
The EMC effect on light nuclei

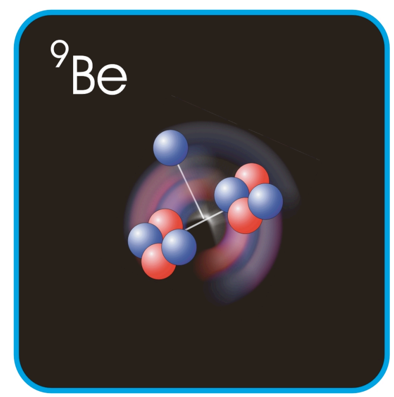
J. Seely et al, PRL103, 202301(2009)





^{9}Be has low average density, but large component of structure is 2α+n most nucleons in tight, α-like configurations





E12-10-008: EMC effect

A. Daniel, J. Arrington, D. Gaskell

Stable light nuclei: ^{3}He, ^{4}He, ^{6,7}Li, ^{9}Be, ^{10,11}B and ^{12}C

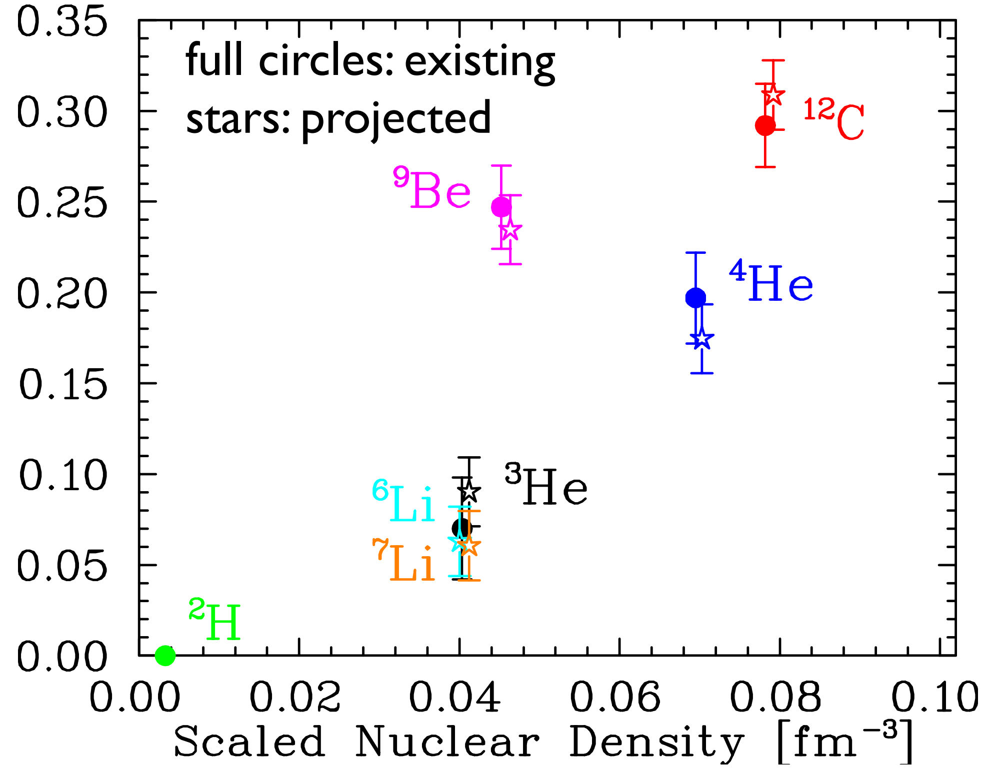
- Nuclei with significant **clustering** contributions: will provide further information on the detailed behavior in these well-understood nuclei.
- For ^{6,7}Li, the **local density picture** predicts an EMC effect well below the other models.
- From nuclei which differ by just one proton or one neutron: measurement of the **nuclear effects on a single proton or neutron**.

Data for 0.1 < x < 1 (DIS till x=0.8):

- EMC effect with **high precision at large x**
- precise measurements of the **x dependence in the low x region.**

Data on ^{40,48}Ca:

- **Isospin-dependence** for the EMC effect
- Significant variation of the n/p ratio in the nucleus but similar mass and density.



E12-14-002: Nuclear dependence of R

S. Malace, E. Christy, D. Gaskell, C. Keppel, P. Solvignon

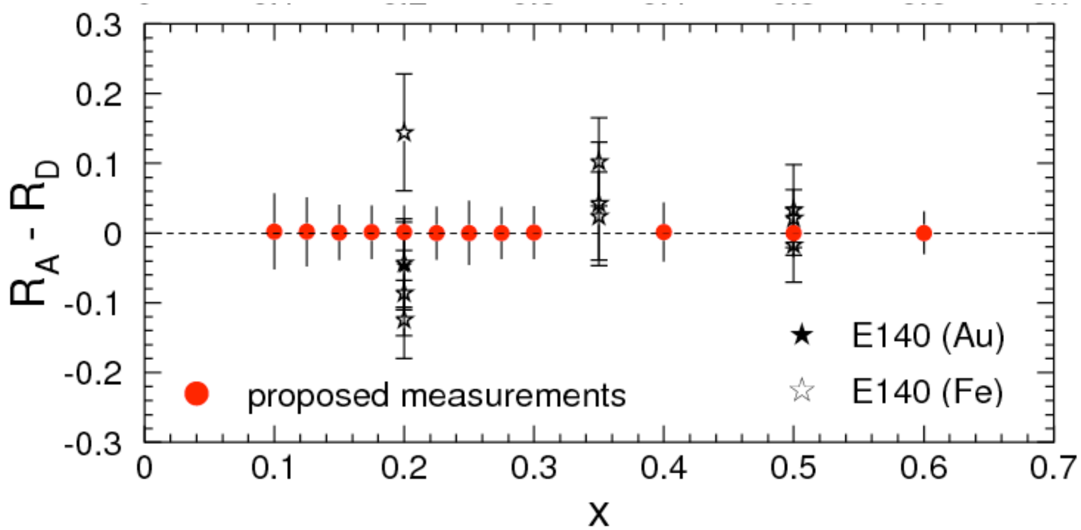
$$\frac{\sigma_A}{\sigma_D} \simeq \frac{F_2^A}{F_2^D}\left[1 - \frac{\Delta R(1-\epsilon)}{(1+R_D)(1+\epsilon R_D)}\right]$$

really only true for ε=1

$$\frac{\sigma_A}{\sigma_D} \simeq \frac{F_1^A}{F_1^D}\left[1 + \frac{\epsilon \Delta R}{(1+\epsilon R_D)}\right]$$

really only true for ε=0

Recent analyses showed R_A-$R_D \neq 0$ --> implications to medium modifications in the anti-shadowing and in the EMC effect regions

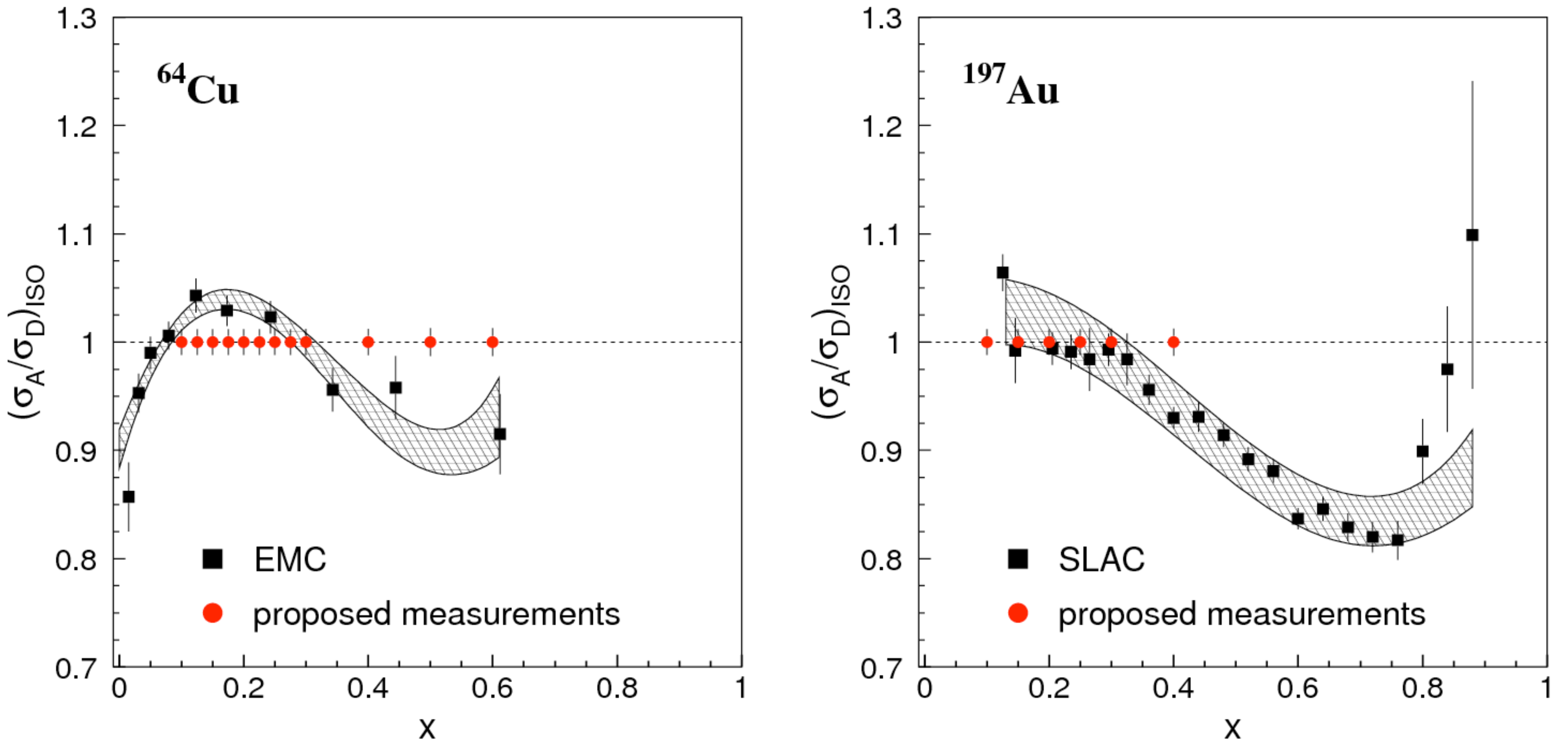


E12-14-002 will measure via **true, model-independent Rosenbluth L/Ts R_A-R_D** in one dedicated experiment

E12-14-002: Impact for σ_A/σ_D

S. Malace, E. Christy, D. Gaskell, C. Keppel, P. Solvignon

- Constrain/verify the universality of nuclear modification in σ_A/σ_D
- Provide experimental constraints for nuclear PDF fits from separated structure functions



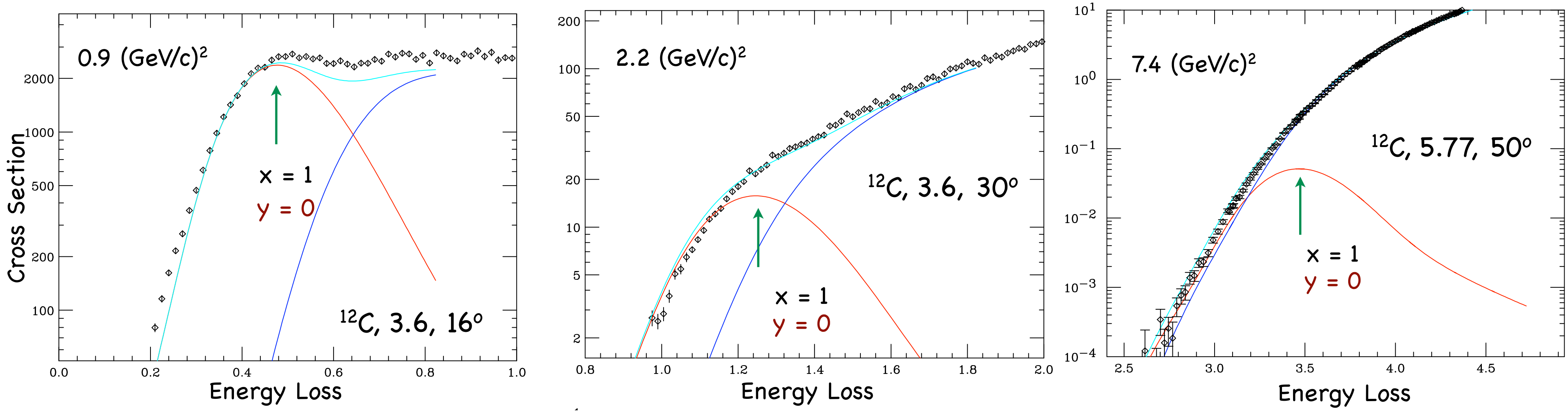
JLab E02-019: quarks in SRC

Inelastic contribution increases with Q^2

DIS begins to contribute at x>1

SRC dominates at x≳1.3 and $Q^2 \gtrsim 1.5$ GeV^2

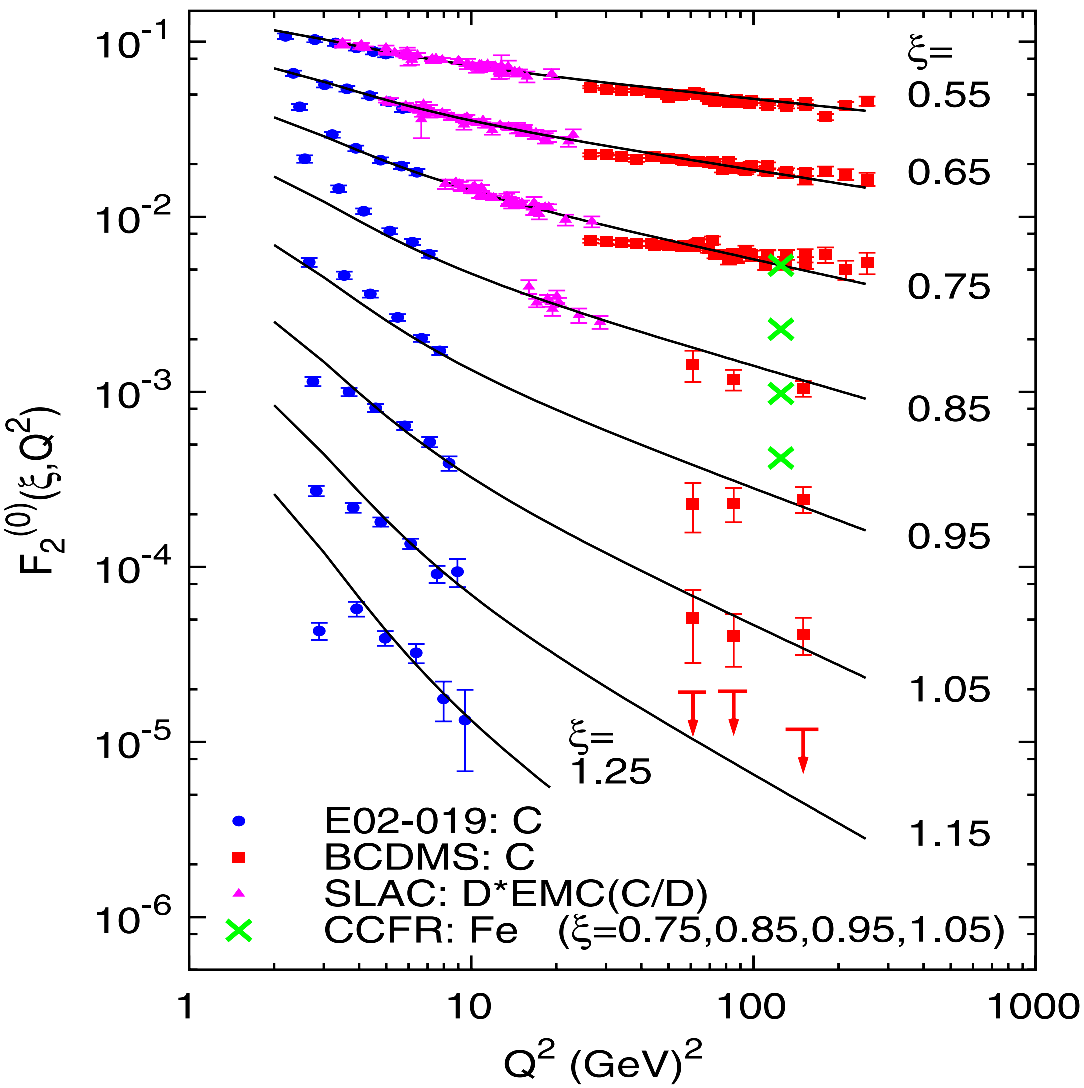
→ "super-fast" quarks



As Q^2 increases, we expect to see evidence that we are scattering from a quark at x>1, i.e. x-scaling.

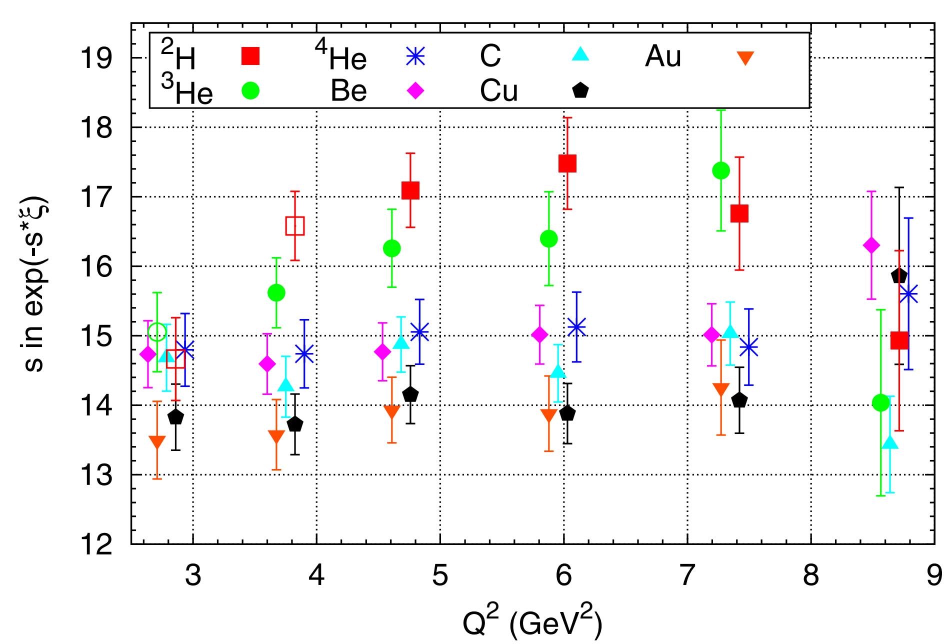
JLab E02-019: quarks in SRC

N. Fomin et al, PRL105, 212502 (2010)



After applying QCD evolution and TMC, we should be left with quark distributions

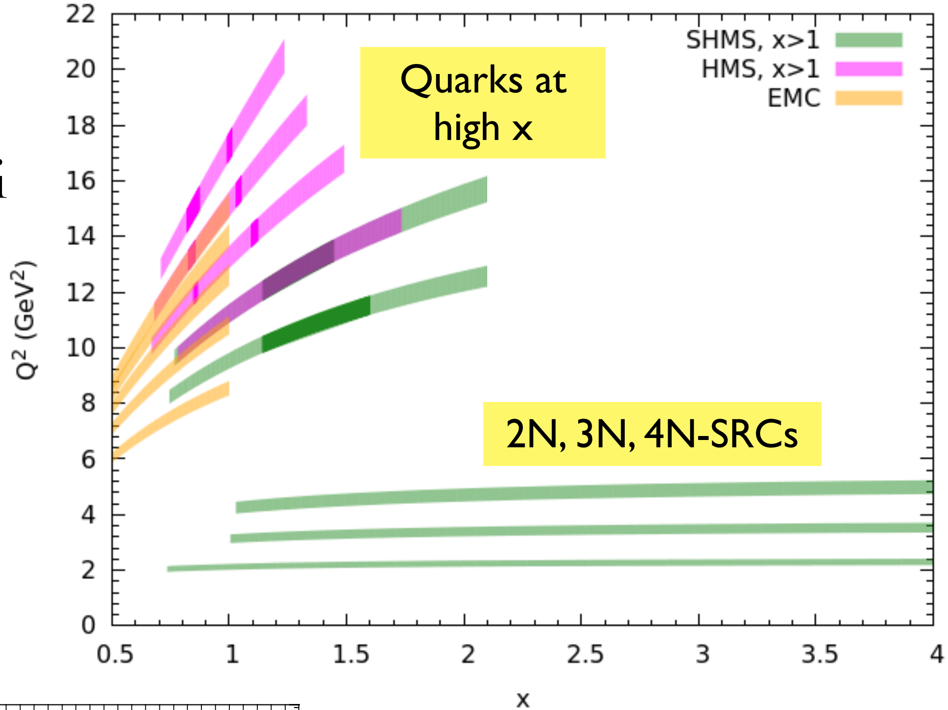
Slope s in exp(-sξ)

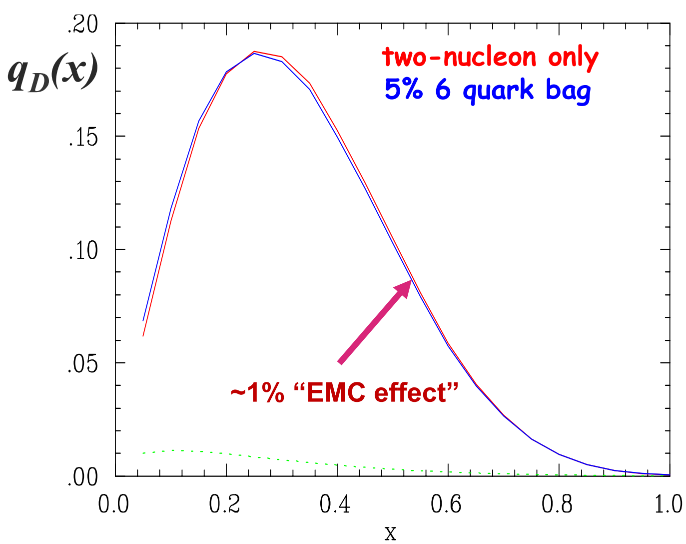


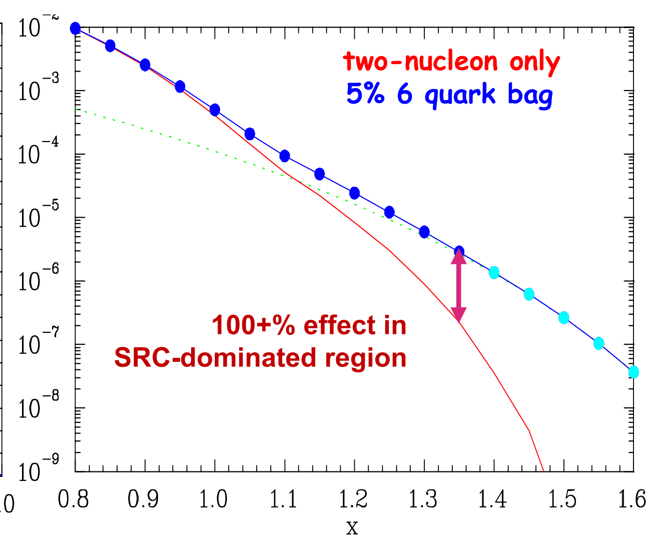
JLab E12-06-105: x>1

J. Arrington, D. Day, N. Fomin, P. Solvignon

- Higher Q^2 to directly access parton distributions of super-fast quarks in nuclei
- Great sensitivity to multi-quarks configurations
- Access 2N, 3N and 4N-SRC



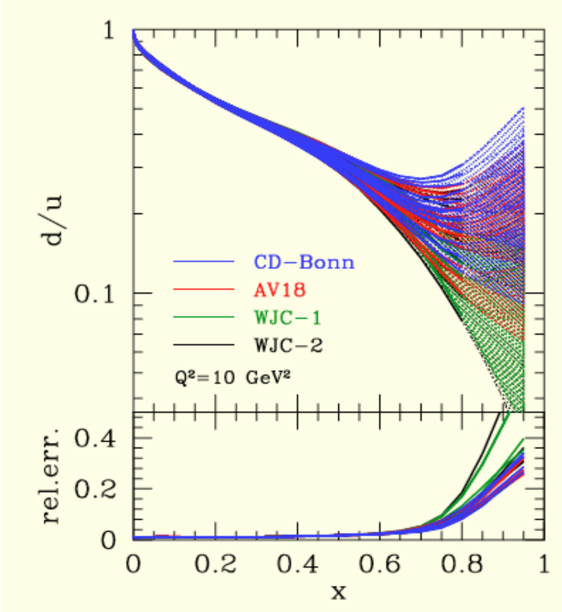




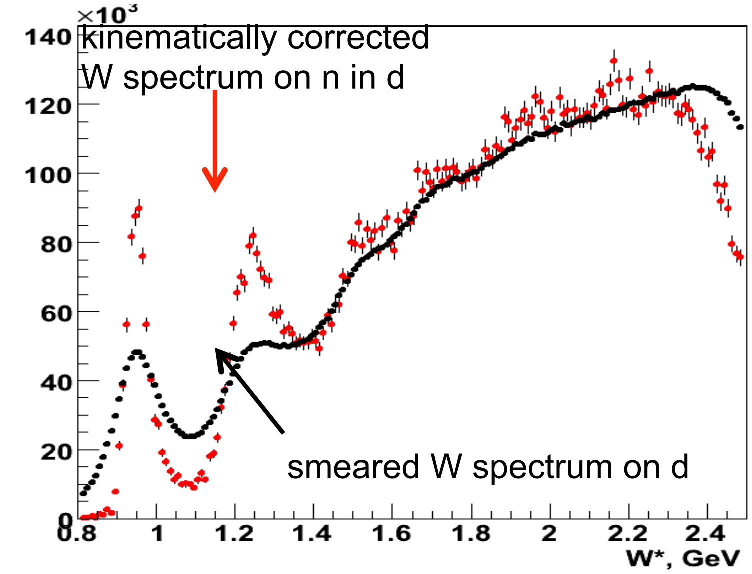
Extracting the neutron structure function from lightest nuclei

BoNuS

(Experiment e8 w/ CLAS)

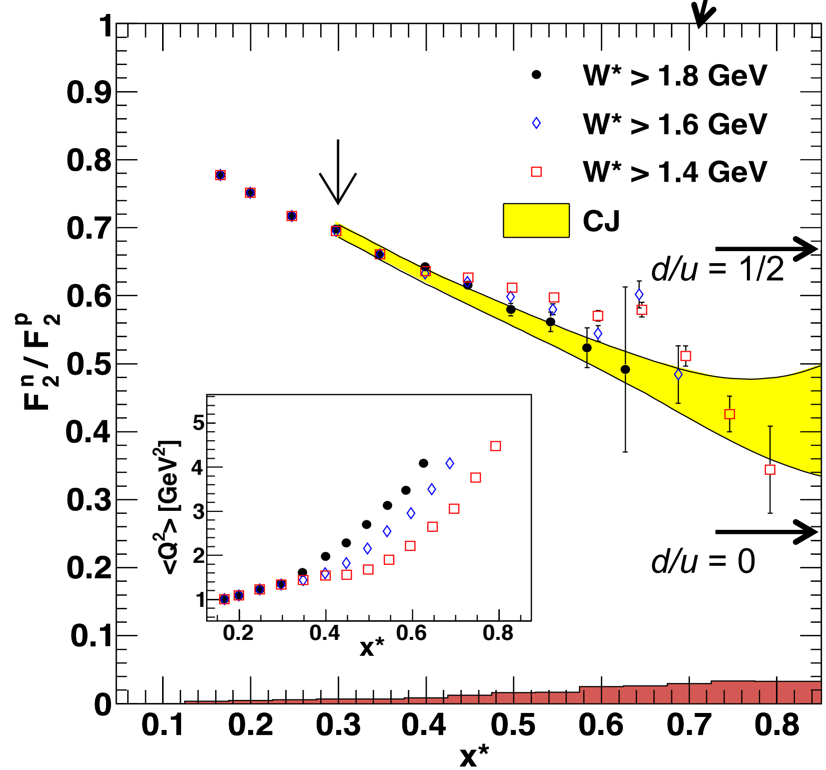


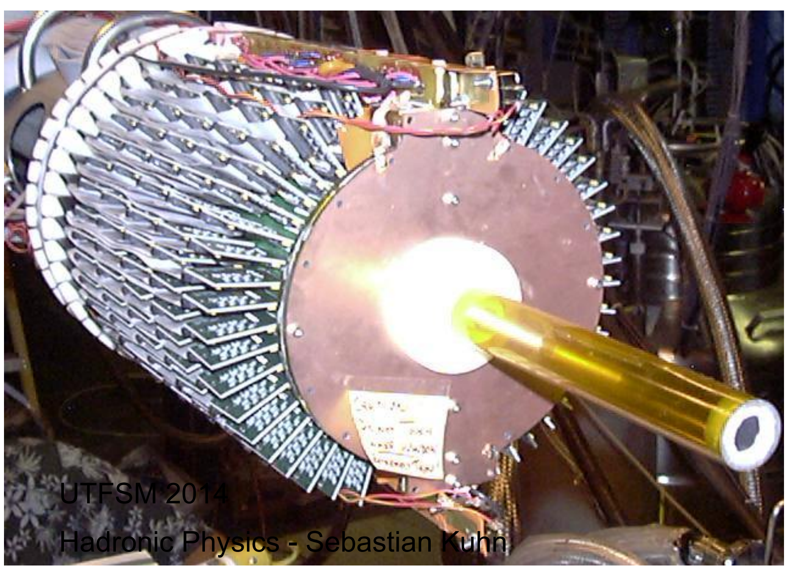
CTEQ-JLab (CJ) fit of world data with various deuteron models



The Problem: nuclear binding uncertainties prevent us from knowing F_{2n} in the resonance region and *d*/*u* ($x \to 1$)
The Solution: tag slow spectator protons in d(e,e'p_s)X with a "radial TPC" (below) to select events on "nearly free" neutrons and to correct for their initial motion.

Results: Unsmeared resonance spectrum
Large *x* F_{2n}/F_{2p} ratio (to access *d*/*u*).



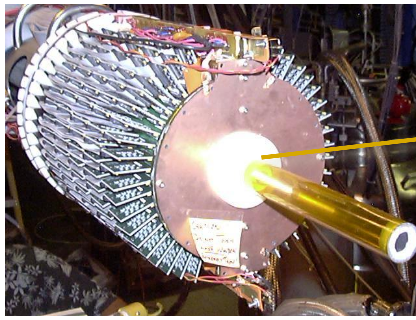


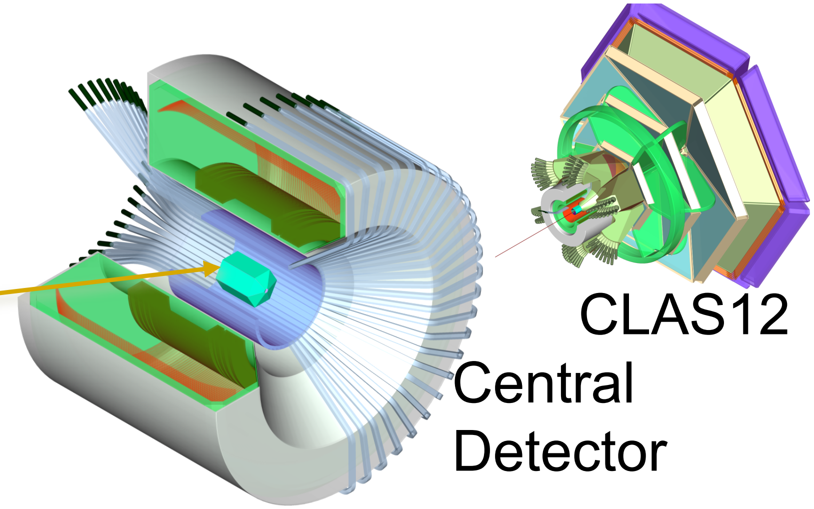
slides for S. Kuhn

S. Bultmann, S. Kuhn, E. Christy, C. Keppel, H. Fenker, W. Melnitchouk, K. Griffioen

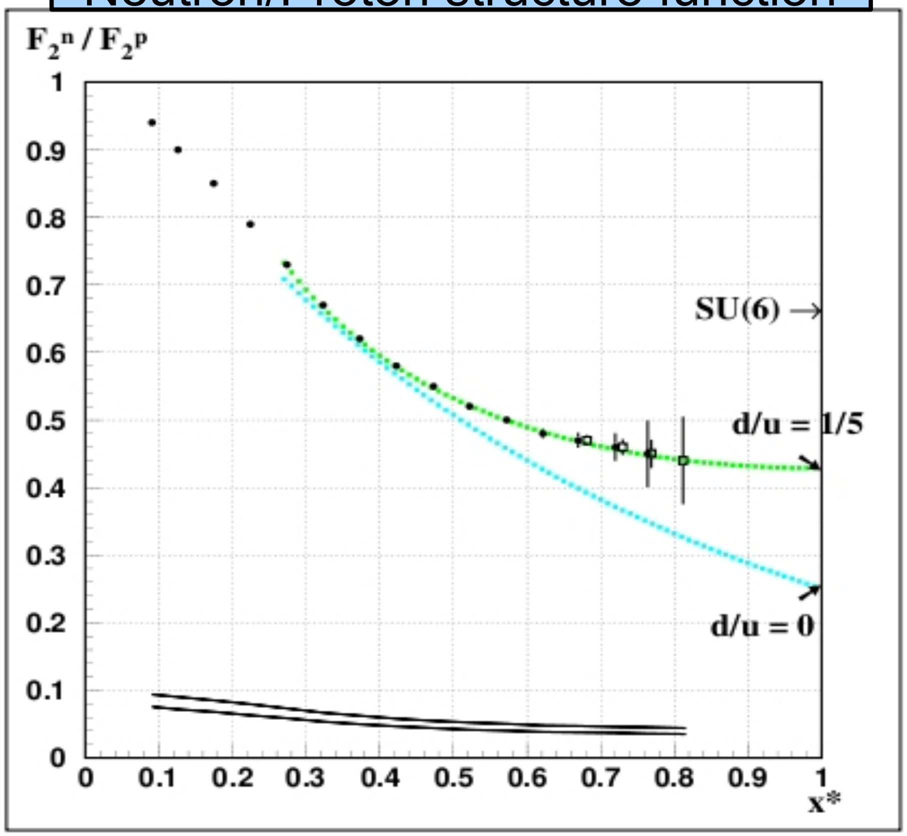
BONuS at 12 GeV

E12-06-113

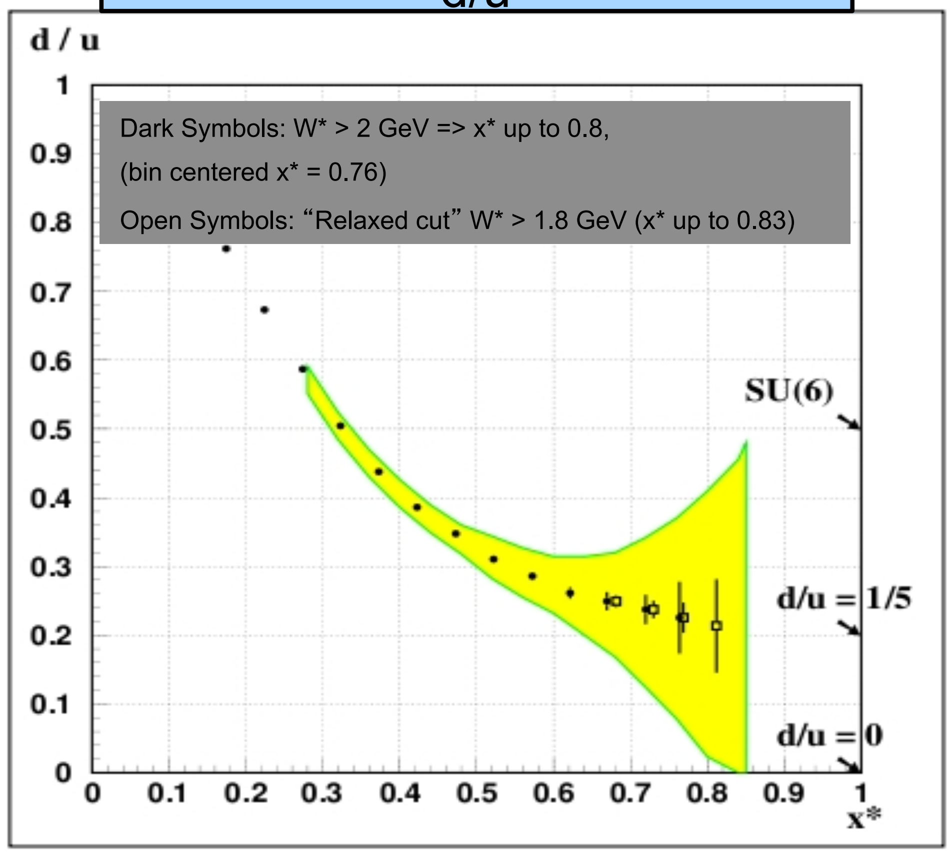




Neutron/Proton structure function



d/u



Data taking of 35 days on D_2 and 5 days on H_2 with $\mathcal{L} = 2 \cdot 10^{34}$ cm^{-2} sec^{-1}

slides for S. Kuhn

F_2^n from the ratio of A=3 mirror nuclei

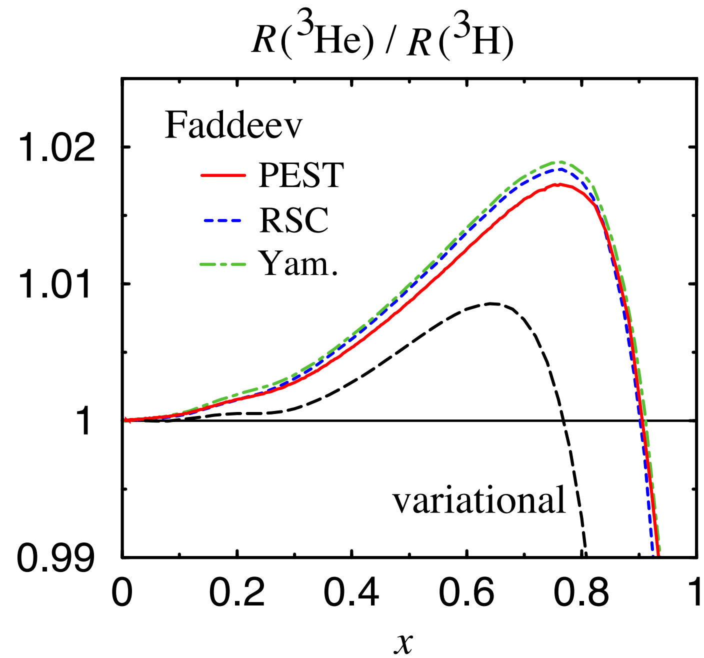
Measure F_2's and form ratios:

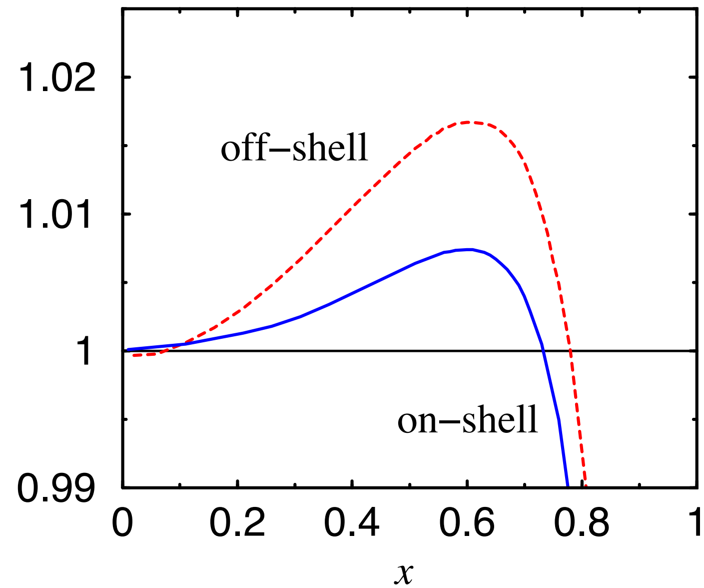
$$R(^3He) = \frac{F_2^{^3He}}{2F_2^p + F_2^n}, \quad R(^3H) = \frac{F_2^{^3H}}{F_2^p + 2F_2^n}$$

Form "super-ratio": $r \equiv \frac{R(^3He)}{R(^3H)}$

then

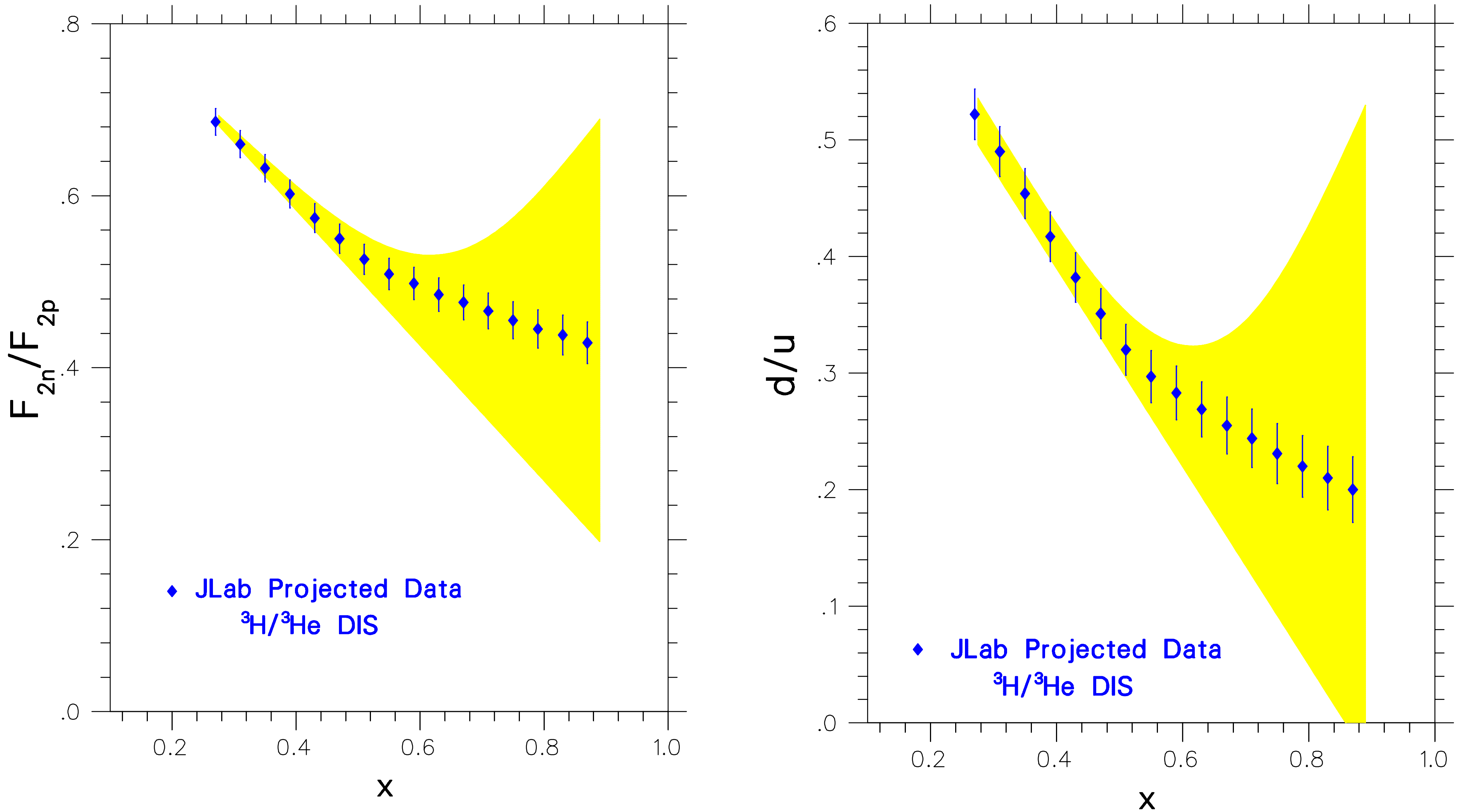
$$\frac{F_2^n}{F_2^p} = \frac{2r - F_2^{^3He}/F_2^{^3H}}{2F_2^{^3He}/F_2^{^3H} - r}$$





E12-10-008: MARATHON

G. Petratos, J. Gomez, R. Holt, R. Ransome



Tensor polarized deuteron program

Tensor Structure Functions

Frankfurt & Strikman (1983)

Hoodbhoy, Jaffe, Manohar (1989)

$$\begin{aligned} W_{\mu\nu} &= -F_1 g_{\mu\nu} + F_2 \frac{P_\mu P\nu}{\nu} \\ &+ i\frac{g_1}{\nu}\epsilon_{\mu\nu\lambda\sigma} q^\lambda s^\sigma + i\frac{g_2}{\nu^2}\epsilon_{\mu\nu\lambda\sigma} q^\lambda (p\cdot q s^\sigma - s\cdot q p^\sigma) \\ &- b_1 r_{\mu\nu} + \frac{1}{6} b_2 (s_{\mu\nu} + t_{\mu\nu} + u_{\mu\nu}) \\ &+ \frac{1}{2} b_3 (s_{\mu\nu} - u_{\mu\nu}) + \frac{1}{2} b_4 (s_{\mu\nu} - t_{\mu\nu}) \end{aligned}$$

Tensor Polarized Spin-1 Target

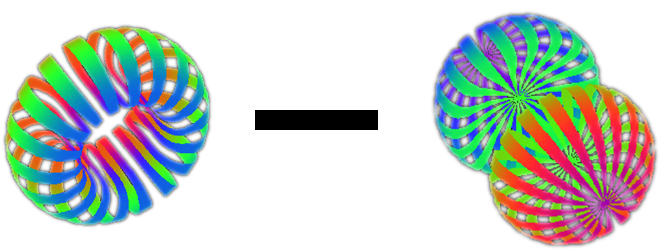
Tensor Structure Functions

Frankfurt & Strikman (1983)

Hoodbhoy, Jaffe, Manohar (1989)

$$
\begin{aligned}
W_{\mu\nu} \;=\; & -F_1 g_{\mu\nu} + F_2 \frac{P_\mu P\nu}{\nu} \\
& + i\frac{g_1}{\nu}\epsilon_{\mu\nu\lambda\sigma} q^\lambda s^\sigma + i\frac{g_2}{\nu^2}\epsilon_{\mu\nu\lambda\sigma} q^\lambda (p\cdot q s^\sigma - s\cdot q p^\sigma) \\
& - b_1 r_{\mu\nu} + \frac{1}{6} b_2 (s_{\mu\nu} + t_{\mu\nu} + u_{\mu\nu}) \\
& + \frac{1}{2} b_3 (s_{\mu\nu} - u_{\mu\nu}) + \frac{1}{2} b_4 (s_{\mu\nu} - t_{\mu\nu})
\end{aligned}
$$

Tensor Polarized Spin-1 Target



$$b_1(x) = \frac{q^0(x) - q^1(x)}{2}$$

b1 : Nice mix of nuclear and quark physics

measured in DIS (so probing quarks), but depends solely on the deuteron spin state

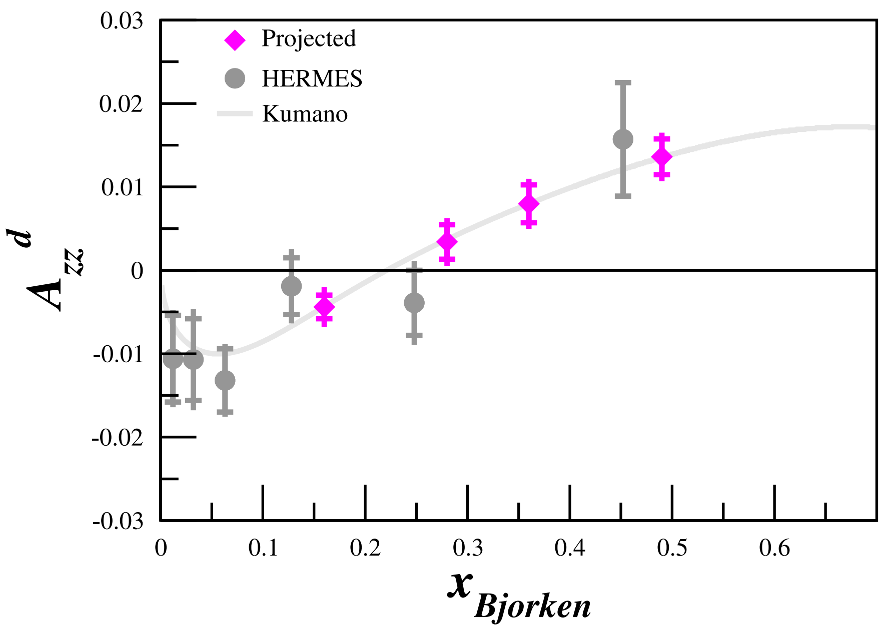
We can investigate nuclear effects at the level of partons!

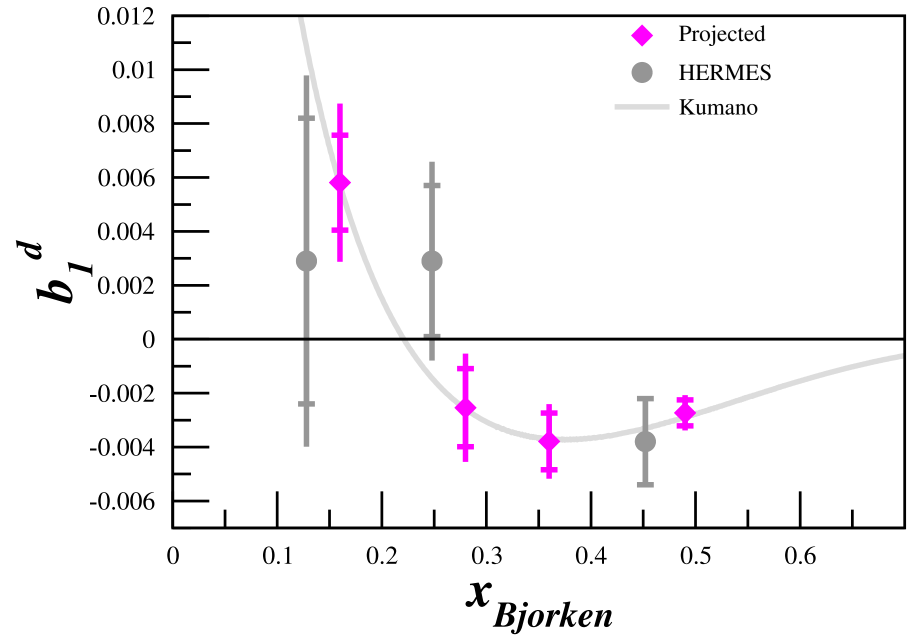
slides for K. Slifer

E12-13-011 : b_1

A⁻ Rating, C_1 Approval

Slifer(contact), Chen, Long, Kalantarians, Keller, Rondon, Solvignon





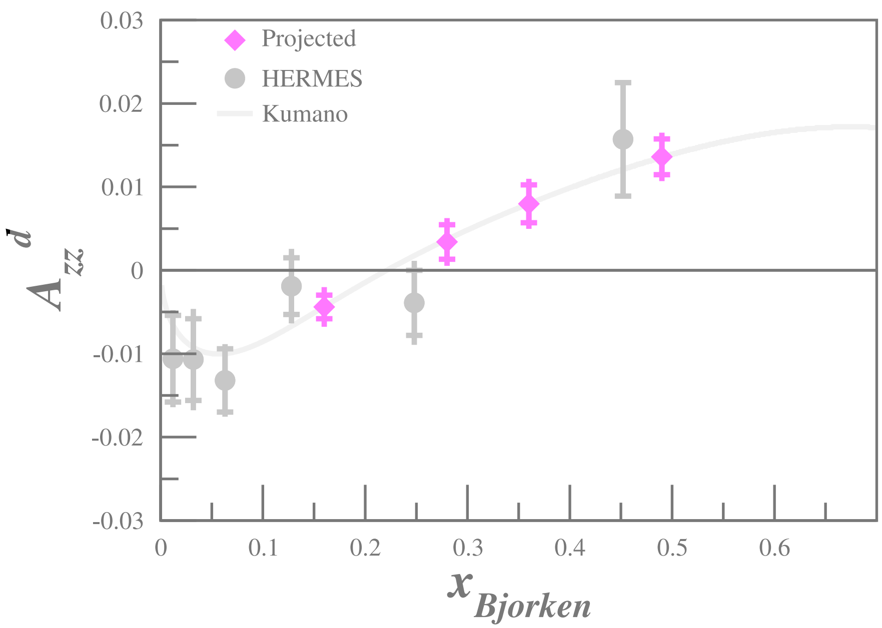
JLab Hall C Inclusive Scattering

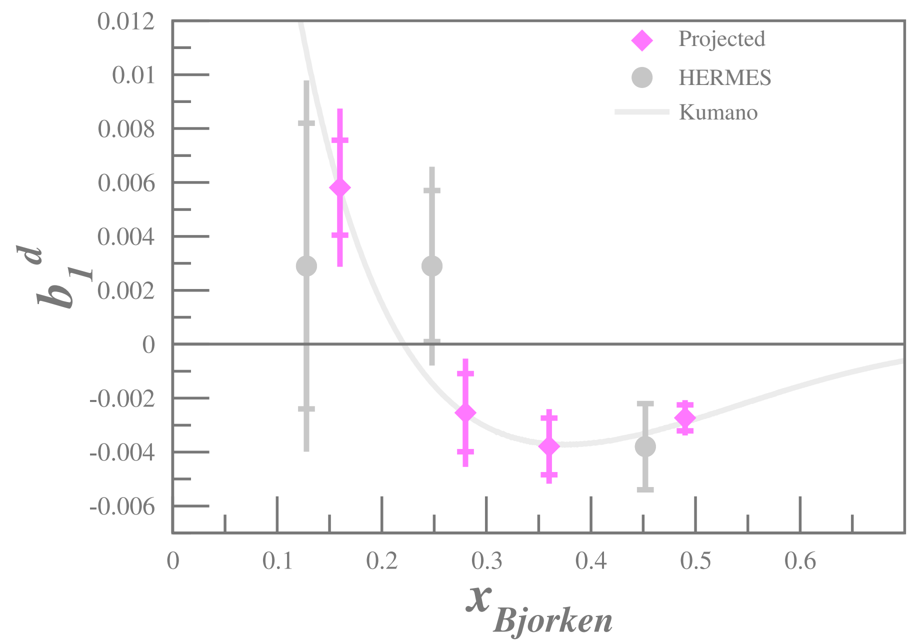
P_{zz} = 35% Tensor Polarized ND_3

E12-13-011 : b_1

A^- Rating, C_1 Approval

Slifer(contact), Chen, Long, Kalantarians, Keller, Rondon, Solvignon





JLab Hall C Inclusive Scattering

P_{zz} = 35% Tensor Polarized ND_3

Sensitive to tensor pol of quark sea

Allows test of CK Sum Rule

$$\int_0^1 dx\ b_1(x) \quad = \quad 0$$

Clean Probe of Hidden Color

G. Miller, Phys.Rev. C89 (2014) 045203

no conventional nuclear mechanism can reproduce the Hermes data, but that the 6-quark probability needed to do so (P_{6Q} = 0.0015) is small enough that it does not violate conventional nuclear physics.

Verification of b1 Zero-Crossing

critical for satisfaction of CK sum rule
clear signature of exotic effects

Sum rule for the 2nd moment of deuteron's b_1

slide for O.Teryaev

- Must give zero if summed over quarks, antiquarks and gluons
- Deuteron as isoscalar target provides sum of light quarks contributions
- Deviation from zero signals on the collective tensor polarized glue, like the quarks momentum ~1/2 indicated the gluons existence
- Also probes the quarks coupling to gravity and equivalence principle

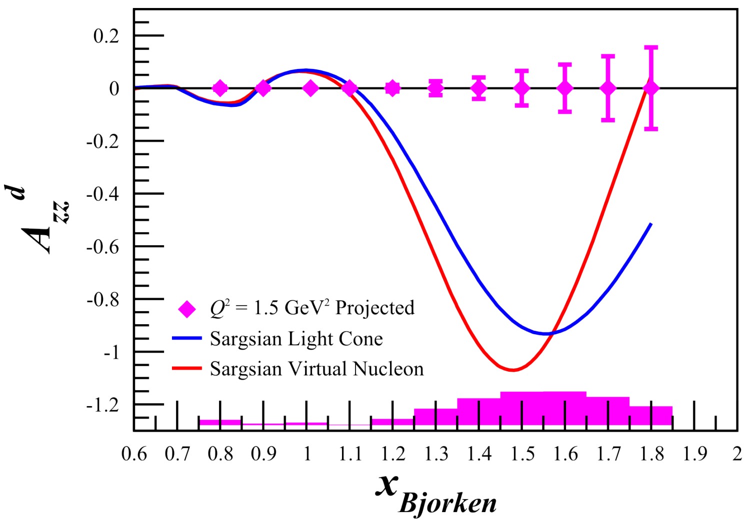
Mod.Phys.Lett. A24 (2009) 2831-2837

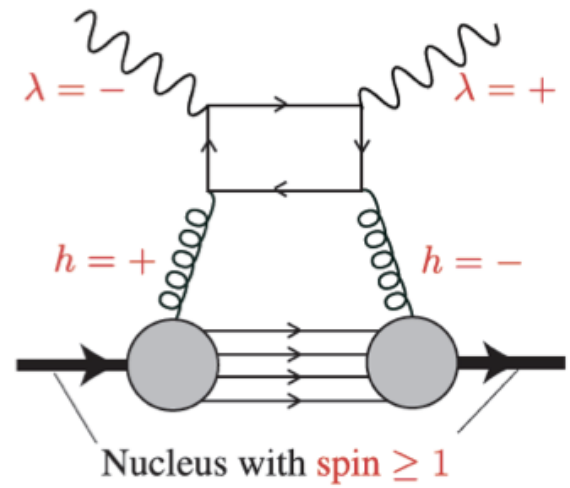
LOI12-14-002

Long(contact), Day, Higinbothan, Keller, Slifer, Solvignon

LOI12-14-001

Maxwell (contact), Milner, Jaffe





Azz for x>1

P_{zz} = 35% Tensor Polarized ND_3
A_{zz} ≈ 1 in this region

Direct probe of Tensor force
SRCs and pn dominance
Sensitive to S-wave/D-wave ratio

Encouraged for full submission by PAC42

b4 structure function (aka Δ)

Polarized $^{14}NH_3$ Target

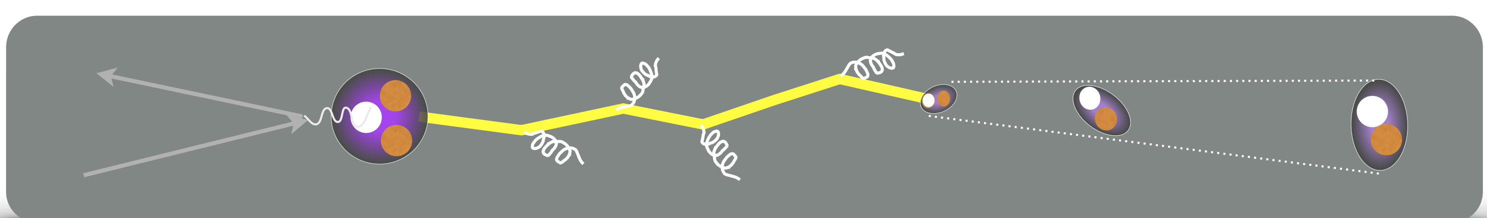
Non-zero value would be a clear signature of exotic gluon states in the nucleus

Encouraged for full submission by PAC42

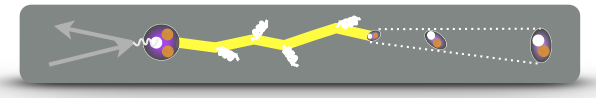
How do we get from quarks and gluons to nucleons and mesons ?

Hadronization Physics: E-02-104 and E12-06-117

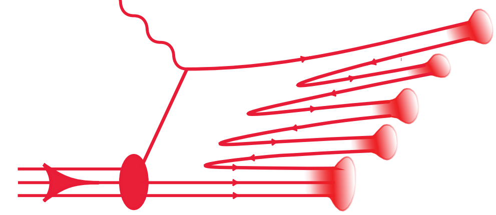
- Hadronization: a QCD puzzle for more than four decades
- Fundamental process, but nonperturbative:
  - ➡ time-based, so not historically accessible with lattice QCD
  - ➡ constrained by hadron multiplicities, but these are not sensitive to dynamics at the femtometer scale
- Now there is a *new opportunity:*
  - ➡ Identified hadrons + nuclear targets + high luminosity
  - ➡ Access to color propagation, neutralization, and fluctuations



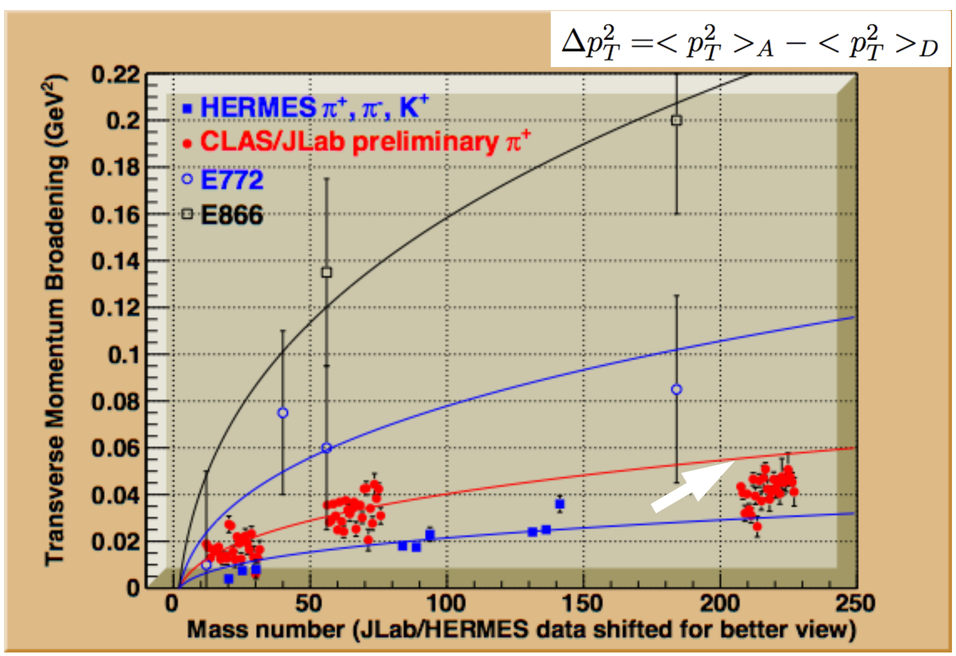
slides for W. Brooks

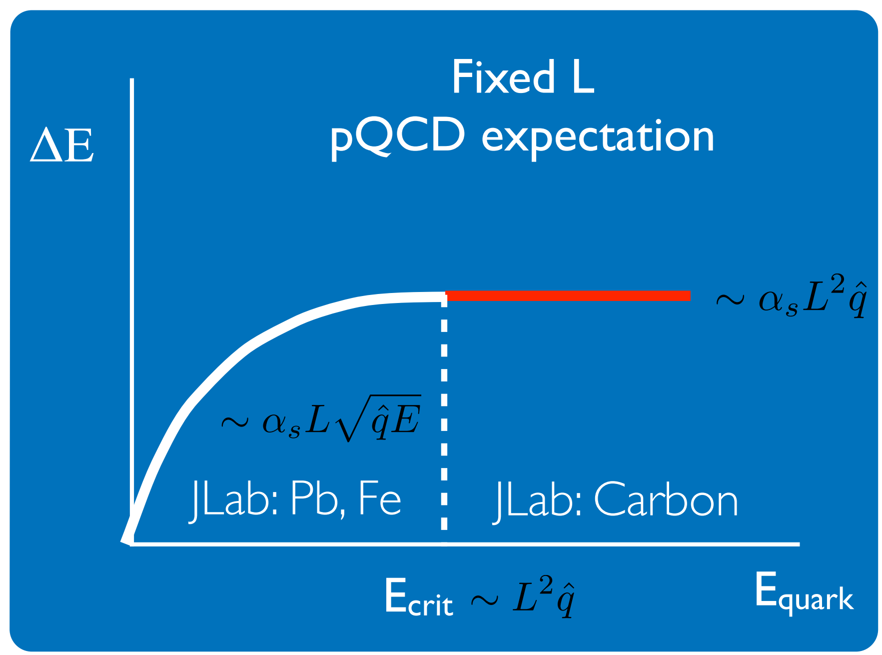


What we are learning



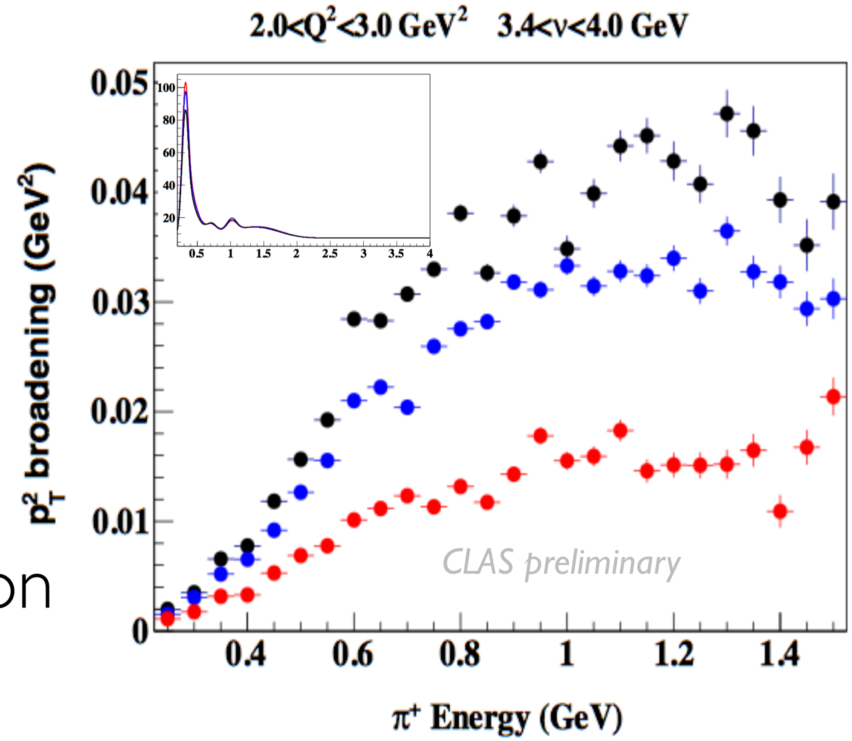
- Can constrain the *virtual quark lifetime* via p_T broadening
  - ➡ @12 GeV: should clearly see time dilation with increasing $\boldsymbol{\nu}$
- Quark energy loss is significantly less than $-\frac{dE}{dx} = \frac{\alpha_s N_c}{4}\Delta p_T^2$
  - ➡ @12 GeV: probing the critical energy region
- New@12 GeV: polarization degrees of freedom - SSA and more



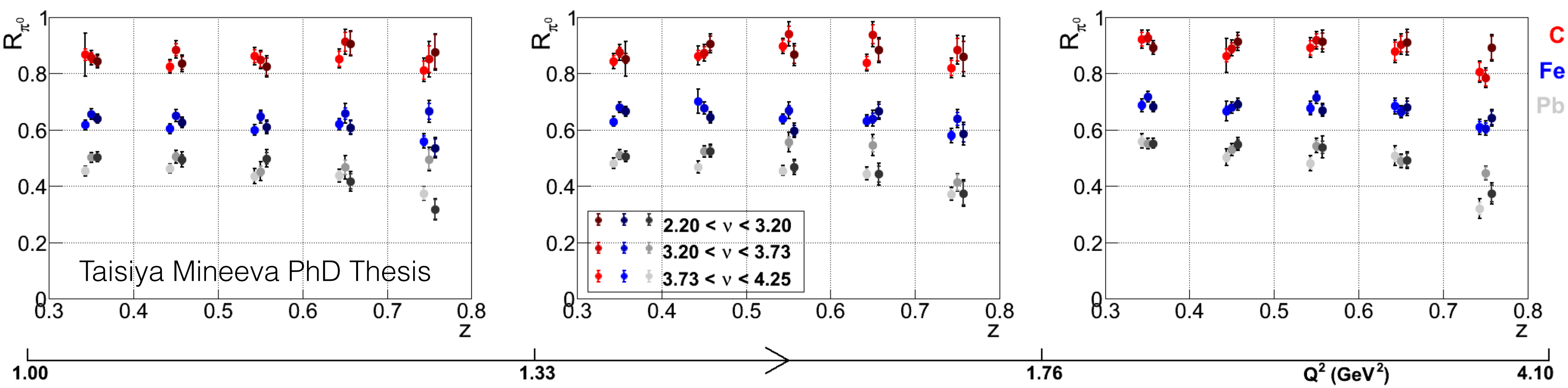


What we are learning

- Can constrain hadron formation time via p_T broadening
  - ➡ @12 GeV: rare hadrons (ϕ meson); baryon hadronization; hadron mass dependence and flavor content



- Multiplicity ratios, and thus hadronization mechanisms, have at least 3-fold differential kinematic dependences

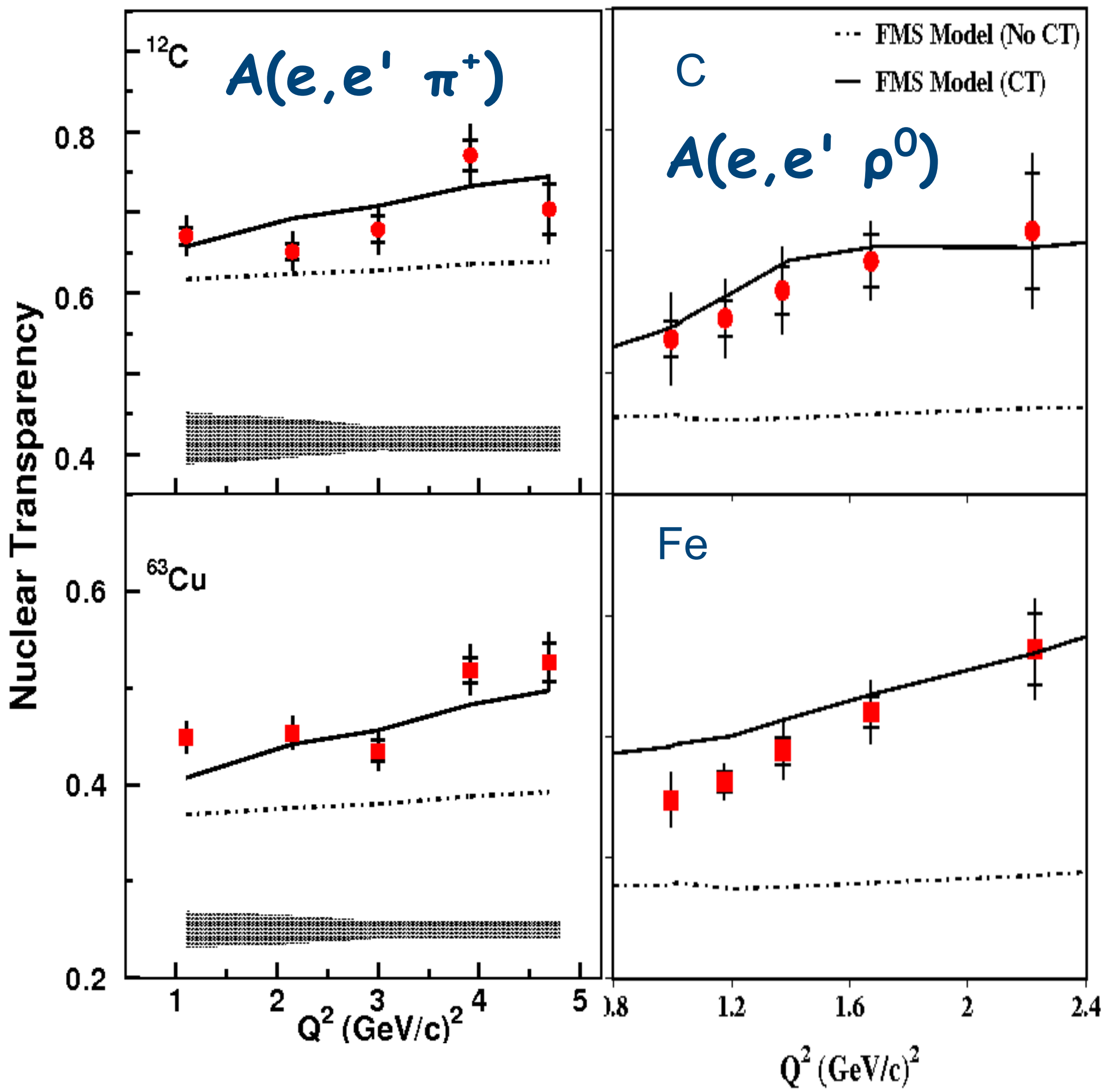


Neutral pion, 3-fold differential multiplicity ratio, z dependence vs. ν and Q^2

The Onset of Color Transparency

slides for D. Dutta

JLab Experiments conclusively find the onset of CT



· Hall-C Experiment E01-107 pion electroproduction from nuclei found an enhancement in transparency with increasing Q^2 & A, consistent with the prediction of CT.
(X. Qian et al., PRC81:055209 (2010), B. Clasie et al, PRL99:242502 (2007))

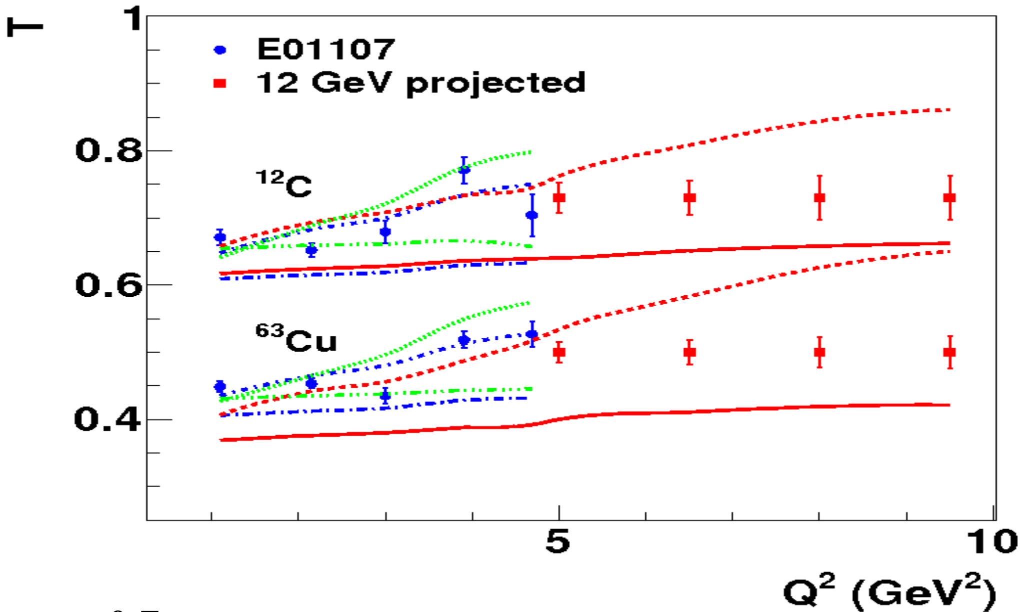
· CLAS Experiment E02-110 rho electroproduction from nuclei found a similar enhancement, consistent with the same predictions

(L. El-Fassi, et al., PLB 712, 326 (2012))

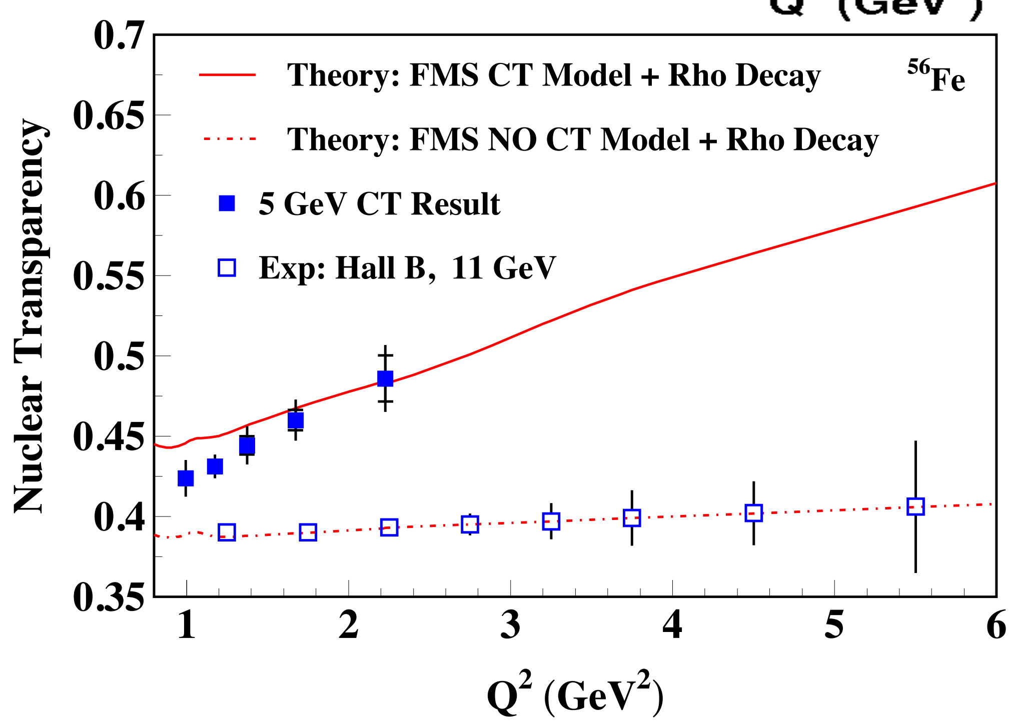
FMS: Frankfurt, Miller and Strikman, Phys. Rev., C78: 015208, 2008

Meson Transparency @ 11 GeV

slides for D. Dutta



Both pion and rho transparency measurements will be extended at 11 GeV to the highest Q^2 accessible



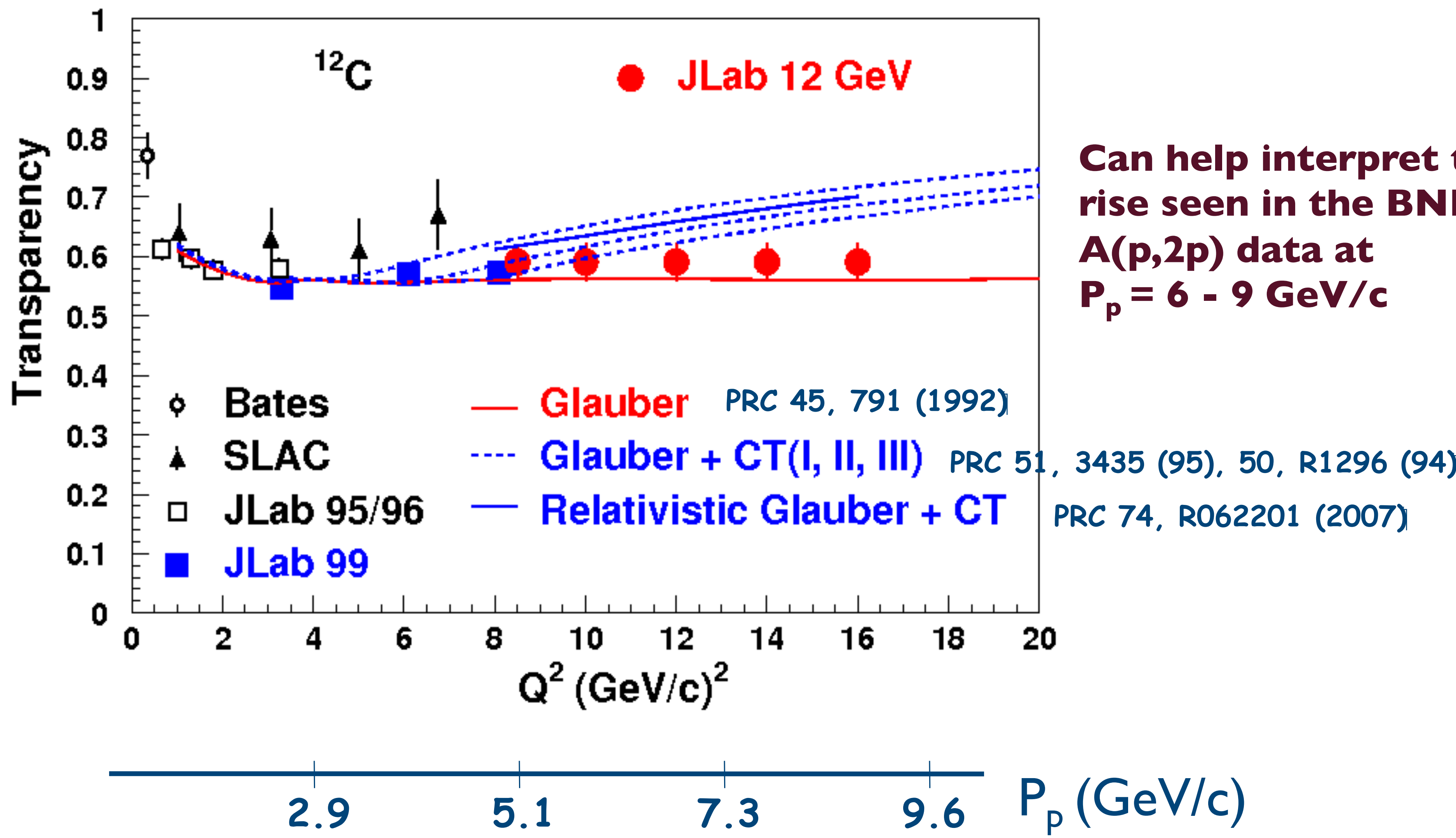
will help confirm the onset of CT observed at 6 GeV

will verify the strict applicability of factorization theorems for meson electroproduction

Proton Transparency @ 11 GeV

slides for D. Dutta

A(e,e'p) @ 11 GeV JLab
E12-06-107



Can help interpret the rise seen in the BNL A(p,2p) data at P_p = 6 - 9 GeV/c

Quarks in Nuclei at JLab 12 GeV

The EMC effect:

- Extended study on the local density effect and first study of the isospin dependence
- Is the SRC-EMC relationship real and what is the origin ?
- Also related: Nuclear dependence of R, super-fast quarks and extraction of the neutron structure function

Tensor Structure functions:

- Another way to look at nuclear effect at the parton level
- High sensitivity to hidden color
- Access to possible novel partonic components in nuclei

Hadronization at 12 GeV:

- High sensitivity to time dilation and quark energy loss
- Constraint on hadron formation time

Color transparency at 12 GeV:

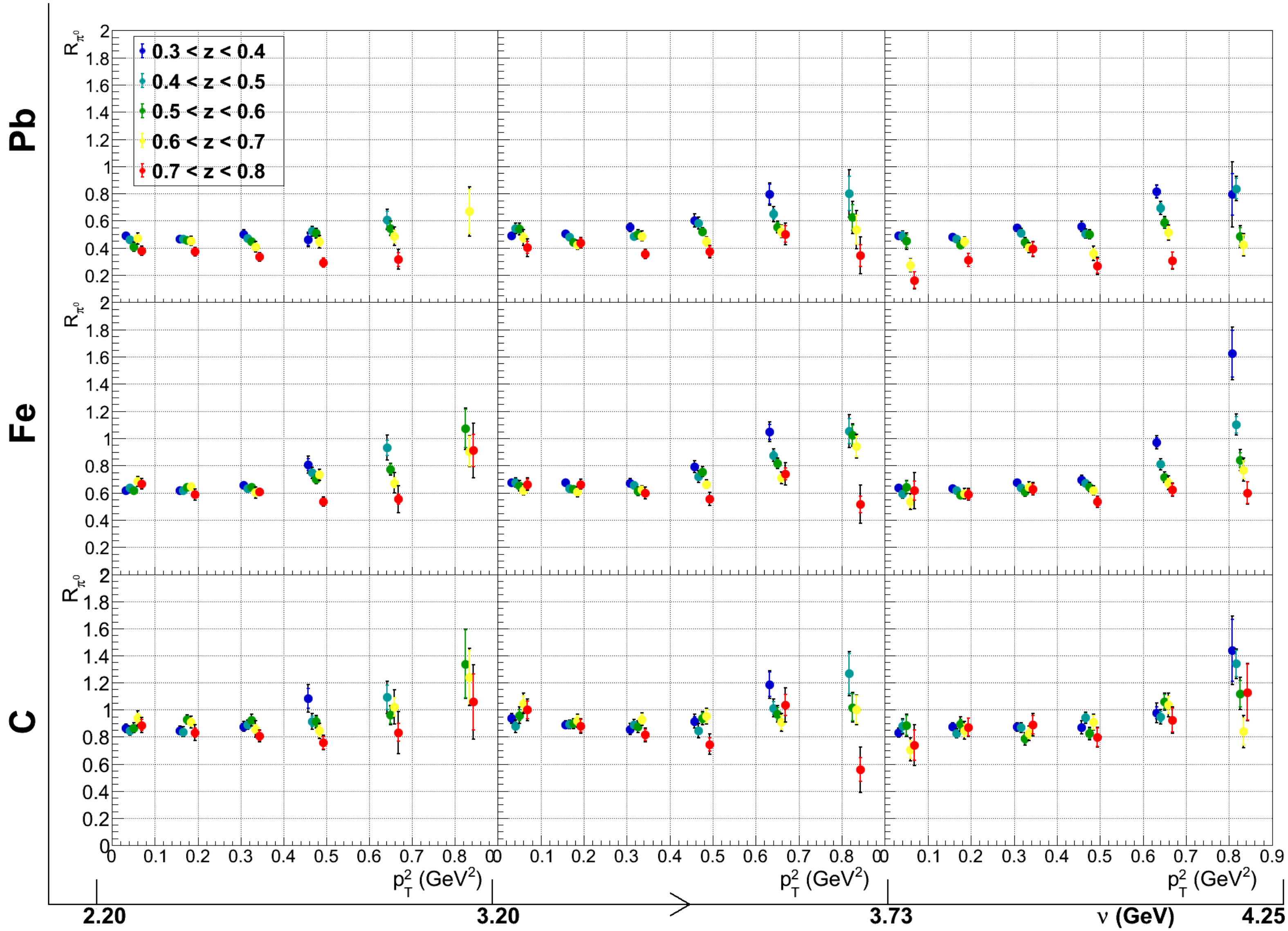
- Unique probe of the space−time evolution of special configurations of the hadron WF
- Disentangle different effects: small-size-configuration (SSC) creation, its formation and interaction with the nuclear medium

Ackownledgements

Thanks to
John Arrington, Will Brooks, Donal Day, Dipangkar Dutta, Nadia Fomin, Kawtar Hafidi, Sebastian Kuhn, James Maxwell, Karl Slifer, Oleg Terayev
for providing slides and comments.

EXTRA SLIDES

Hadronization



T. Mineeva Ph.D thesis

Issues

1) Structure of two nucleon SRC - S vs D wave
(polarized deuteron or measurement of the polarization in the final state)

2) Discovery of the nonnucleonic degrees of freedom in nuclei - we know that they present (EMC effect) etc - but this is indirect.

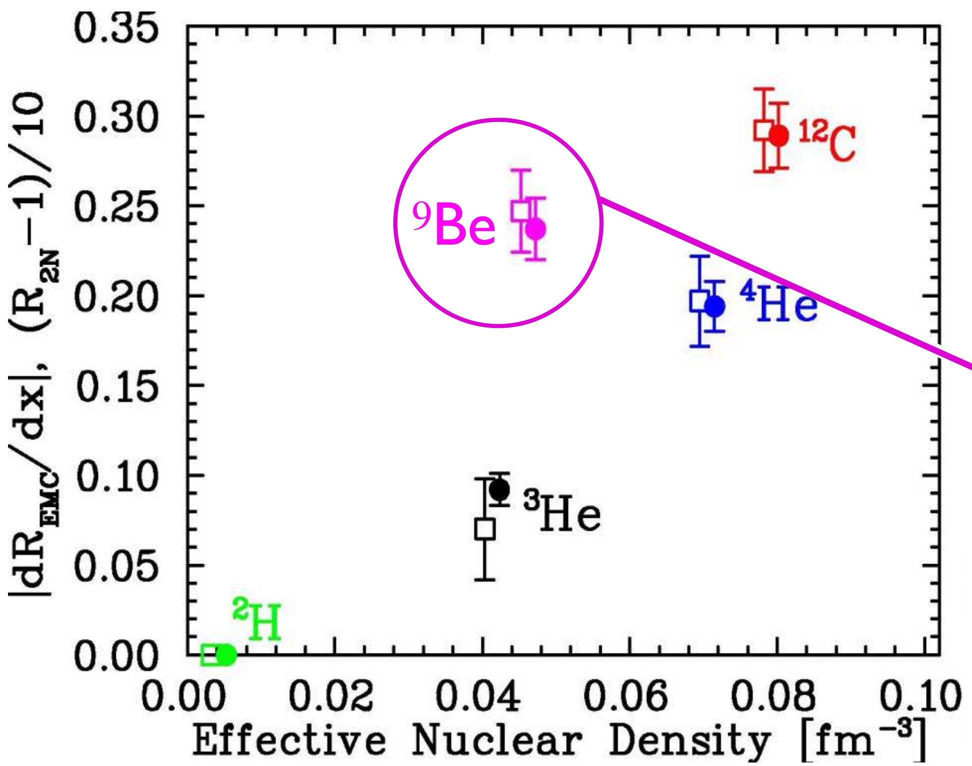
this includes tagged EMC effect in the deuteron, looking for Delta isobars,...

3) Direct observation of the three nucleon correlations

4) Testing different treatments of the relativistic descriptions of nuclei.

5) Observing superfast ($x > 1$) quarks in nuclei in DIS at Jlab 12.

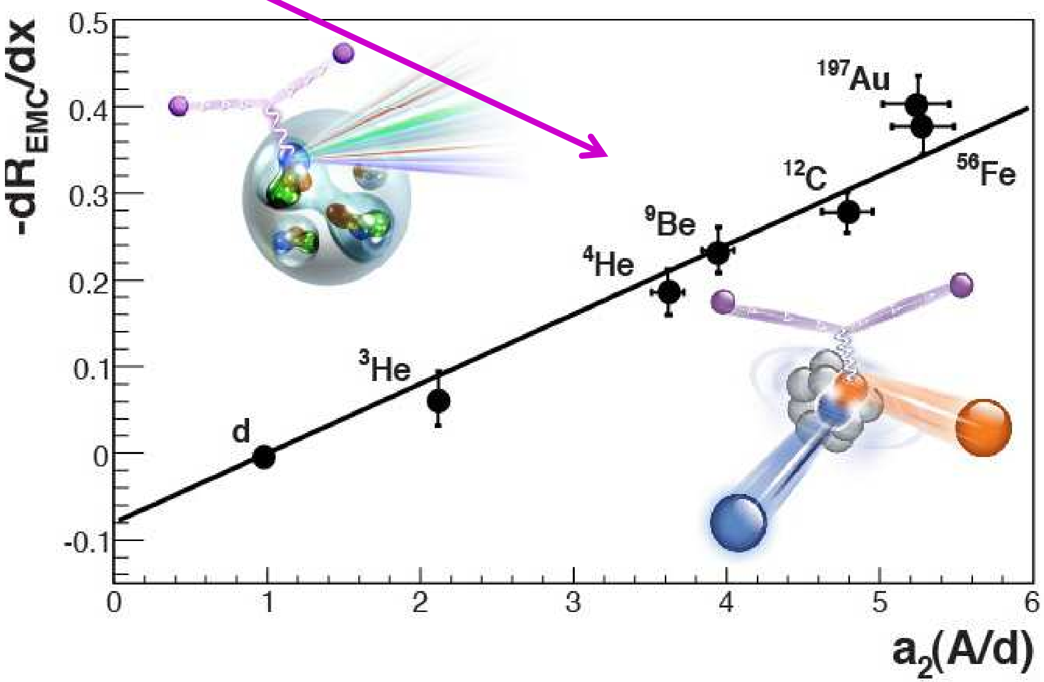
EMC vs. SRC



J. Seely et al, PRL103, 20231 (2009)
N. Fomin et al, PRL108, 092502 (2012)
J. Arrington, A. Daniel, D. Day, N. Fomin, D. Gaskell and P. Solvignon, PRC 86, 065204 (2012)

Same odd behavior for SRC and EMC effect in ^{9}Be

Both observables show similar behavior, suggesting a common origin



O. Hen, E. Piasetzky and L. Weinstein, PRC85, 047301 (2012)
L. Weinstein, E. Piasetzky, D. Higinbotham, J. Gomez, O. Hen and R. Shneor, PRL106, 052301 (2011)

MARATHON: Physics motivations

SU(6)-symmetric wave function of the proton in the quark model (spin up):

$$|p\uparrow\rangle = \frac{1}{\sqrt{18}}\left(3u\uparrow[ud]_{S=0} + u\uparrow[ud]_{S=1} - \sqrt{2}u\downarrow[ud]_{S=1} - \sqrt{2}d\uparrow[uu]_{S=1} - 2d\downarrow[uu]_{S=1}\right)$$

u and d quarks identical, N and Δ would be degenerate in mass.
In this model: d/u = 1/2, $F_2^n/F_2^p = 2/3$.

pQCD: helicity conservation (q↑↑p)
=> d/u =2/(9+1) = 1/5, F_2^n/F_2^p = 3/7 for x ->1

SU(6) symmetry is broken: N-Δ Mass Splitting

- Mass splitting between S=1 and S=0 diquark spectator.
- symmetric states are raised, antisymmetric states are lowered (~300 MeV).
- S=1 suppressed

=> d/u = 0, F_2^n/F_2^p = 1/4, for x -> 1