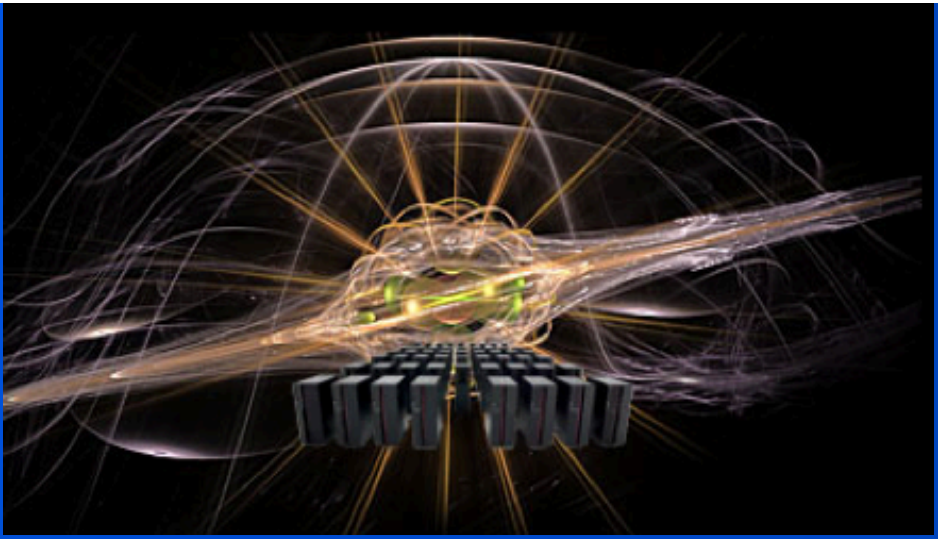


Deep Inelastic Scattering from Nuclear Targets at x>1

James P. Vary
Iowa State University

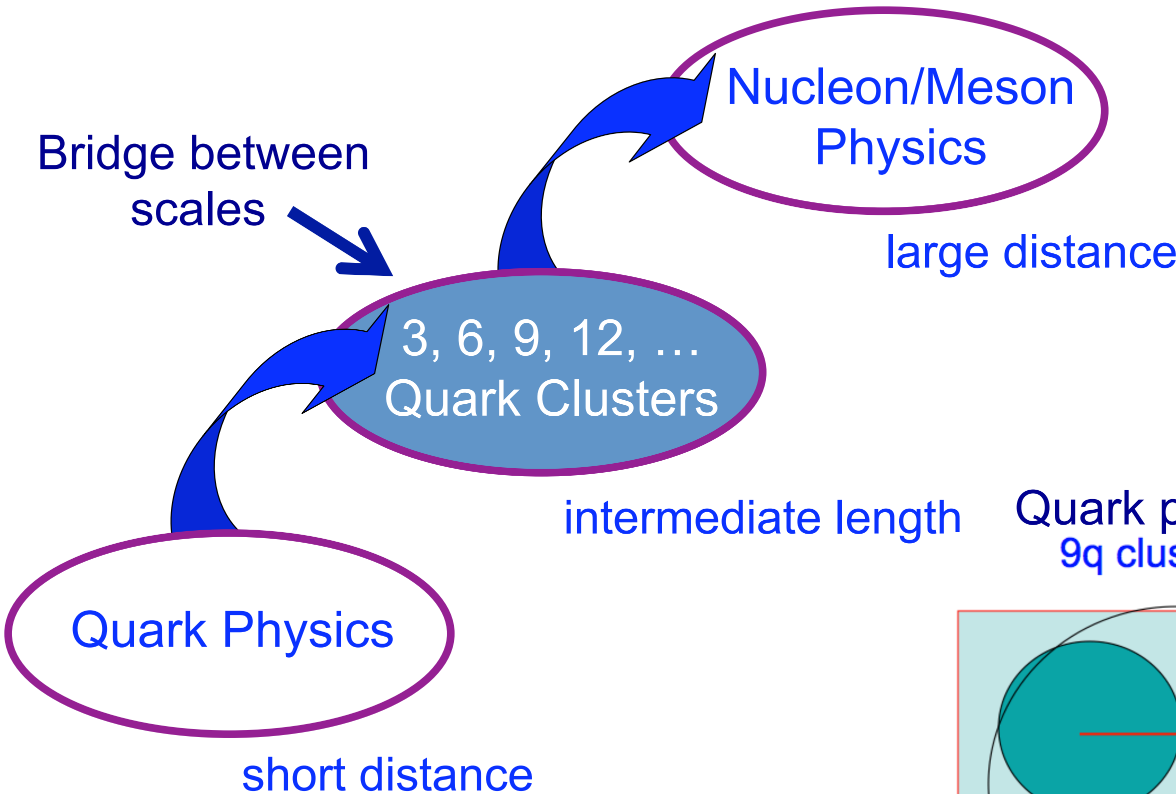
Nuclear Structure and Dynamics
February 13-22, 2013

NUCLEI
Nuclear Computational Low-Energy Initiative
U.S. DEPARTMENT OF ENERGY
INCITE
LEADERSHIP COMPUTING
National Science Foundation
WHERE DISCOVERIES BEGIN

Can we build a covariant model of the nucleus at the level of quarks and gluons that utilizes advances in ab initio nuclear structure and successful phenomenology of QCD?

At what scale(s) do we transition, for efficient description of data, from non-relativistic hadrons to quarks and gluons?

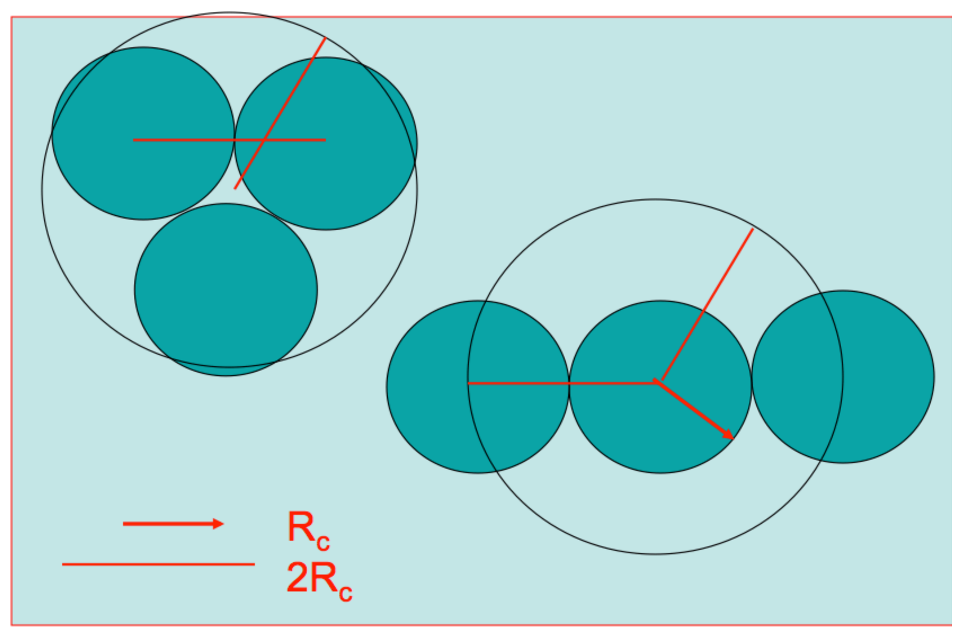
Under what conditions do we require a quark-based description on nuclear structure?



Probes with Q > 1 GeV/c
Spin content of the proton
Nuclear form factors at high Q
DIS on nuclei: EMC, Bjorken x > 1
Nuclear EOS at high T and/or ρ

Quark percolation in cold and hot nuclei

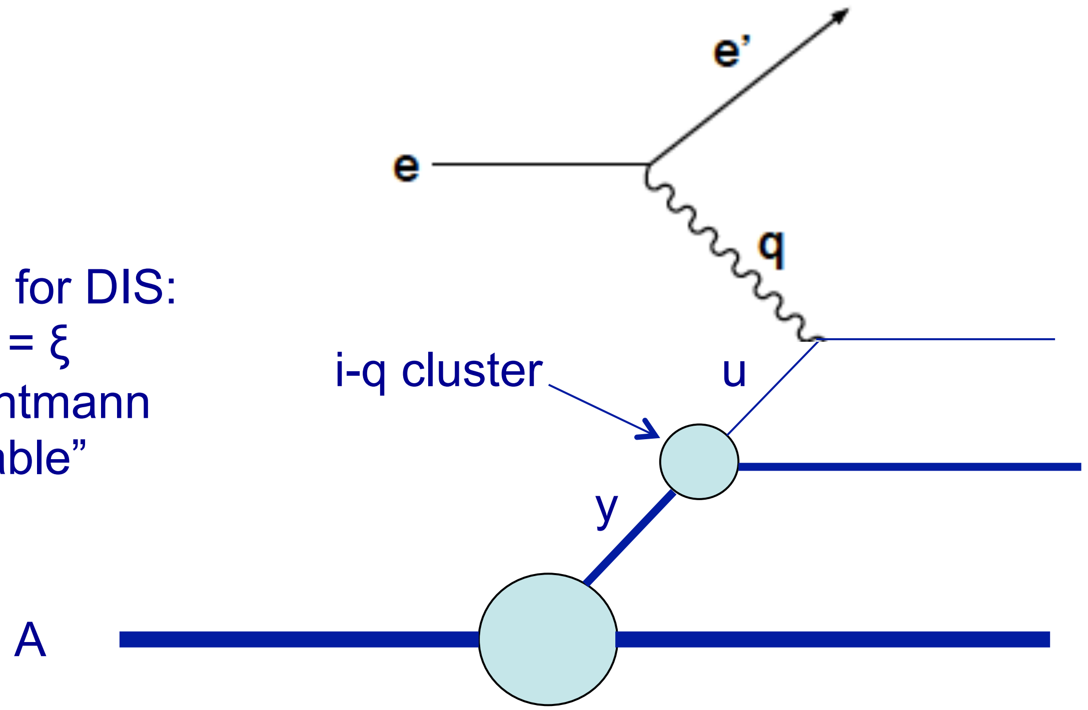
9q cluster at geometrical limits of formation



H.J. Pirner and J.P. Vary,
Phys. Rev. Lett. **46**, 1376 (1981);
Phys. Rev. C. **84**, 015201(2011);
arXiv: nucl-th/1008.4962;

DIS from nuclei at high Q in the Quark Cluster Model (QCM)

QCM for DIS:
$uy = \xi$
“Nachtmann variable”

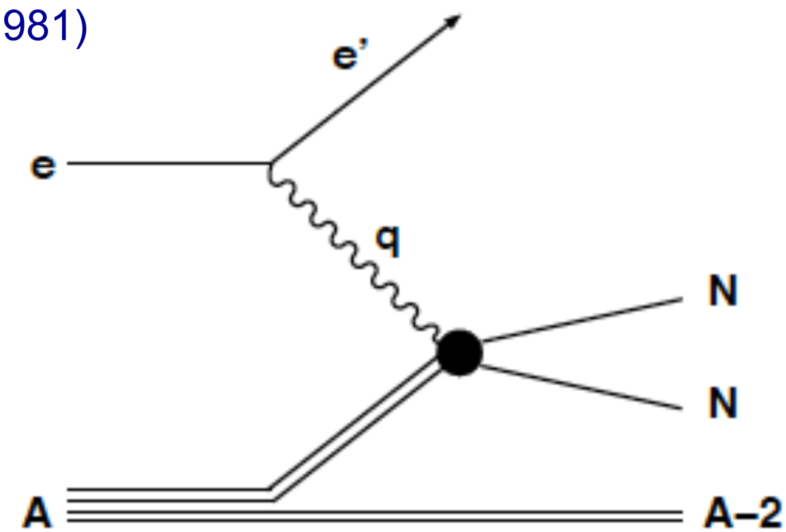


X

All kinematically accessible final states

H.J. Pirner and J.P. Vary,
Phys. Rev. Lett. **46**, 1376 (1981)

NN SRC approaches:



Requires NN to share q

At what scale should we separate the low-energy ab initio nuclear structure region from the high-energy quark structure?

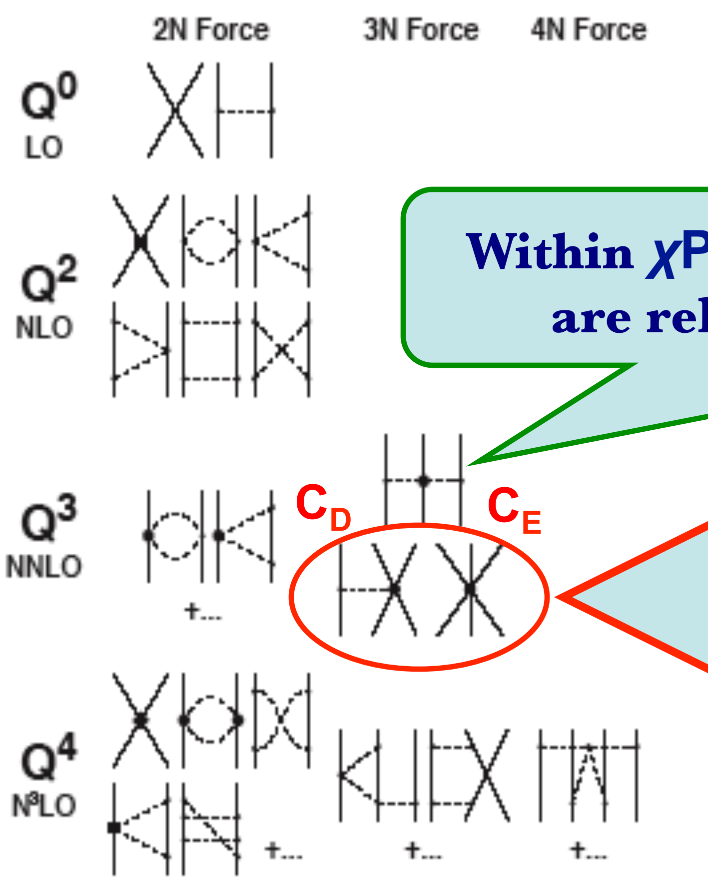
Given the advances in chiral effective field theory, it appears natural to adopt the chiral symmetry-breaking scale.

Effective Intra-Nucleon Interactions
(Chiral Perturbation Theory)

Chiral perturbation theory (χPT) allows for controlled power series expansion

Expansion parameter : $\left(\frac{Q}{\Lambda_\chi}\right)^\nu$, Q – momentum transfer,

χ-symmetry breaking scale: $\Lambda_\chi \approx 1$ GeV/c $\approx \frac{2\pi}{r} \Rightarrow r \approx 1$ fm



R. Machleidt, D. R. Entem, nucl-th/0503025

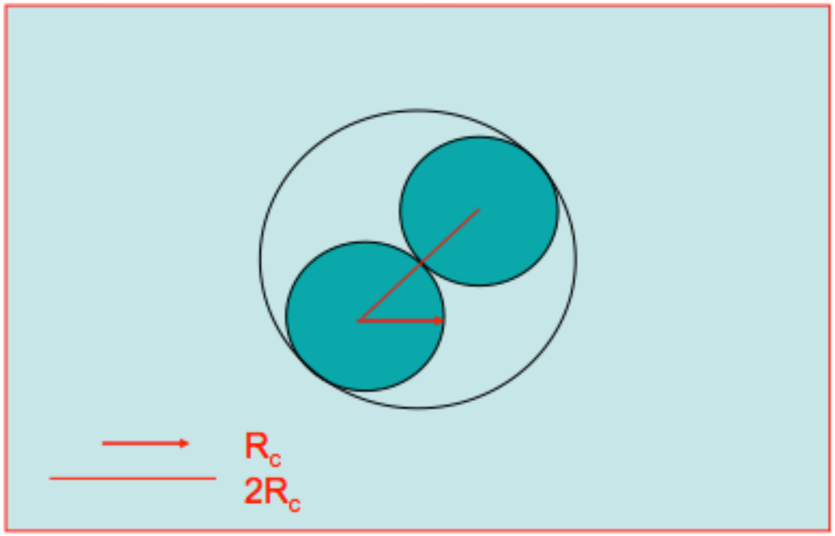
Within χPT 2π-NNN Low Energy Constants (LEC) are related to the NN-interaction LECs $\{c_i\}$.

Terms suggested within the Chiral Perturbation Theory

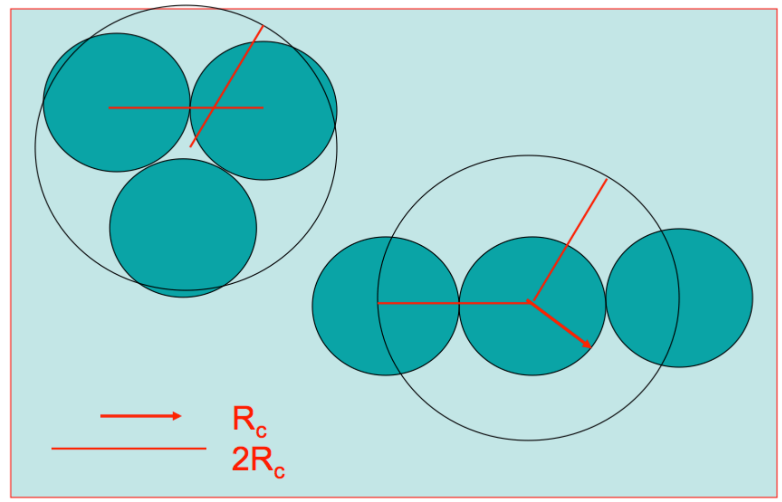
Regularization is essential, which is obvious within the Harmonic Oscillator wave function basis.

Geometric definitions of quark clusters ~ quark percolation

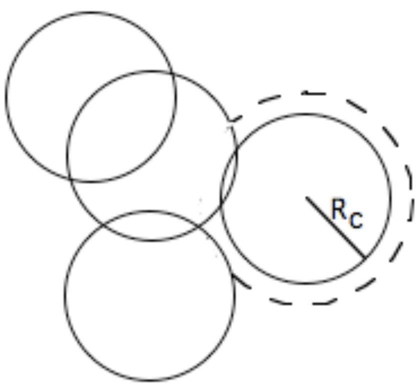
6q cluster at geometrical limits of formation



9q cluster at geometrical limits of formation



Example - 12q cluster configuration.



Coincidence?

1981 fits to ^{3}He DIS data gave $2R_c$ ~ 1 fm for optimal 6q and 9q probabilities from ab initio Faddeev equation solutions:
H.J. Pirner and J.P. Vary,
Phys. Rev. Lett. 46, 1376 (1981)

PHYSICAL REVIEW C VOLUME 33, NUMBER 3 MARCH 1986

Quark cluster probabilities in nuclei

A = 2, 3 & 4 in detail: p_i as function of 2Rc

M. Sato* and S. A. Coon
Department of Physics, University of Arizona, Tucson, Arizona 85721

H. J. Pirner
CERN, Geneva, Switzerland

J. P. Vary
Iowa State University, Ames, Iowa 50011

(Received 28 October 1985)

Computational challenge to use ab initio nuclear structure to evaluate QCM probabilities – consider 9-quark cluster probability in 4He & develop geometrical constraints using:

$$\theta_c(z) \equiv \theta(z - 2R_c) = 1 \text{ for } z \geq 2R_c$$
$$\bar{\theta}_c(z) \equiv 1 - \theta_c(z)$$

+ full A-body density matrix

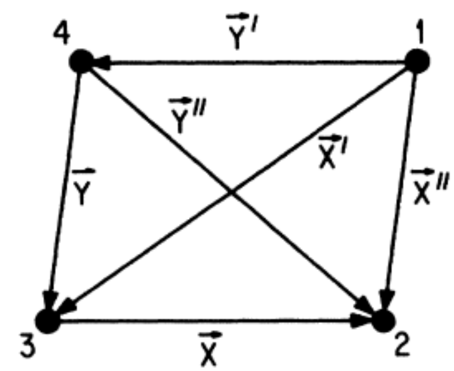


FIG. 5. Coordinate vectors of three-quark subsystems used in Eqs. (5) to define quark cluster probabilities in the $A=4$ nucleus.

$$\begin{aligned}\tilde{p}_9^{(4)} = \int d^3\mathbf{x}' d^3\mathbf{x}'' d^3\mathbf{y}' \rho_4(\mathbf{x}',\mathbf{x}'',\mathbf{y}') \\ \times\{\theta_c(x')\theta_c(x)\theta_c(y)[\bar{\theta}_c(x'')\bar{\theta}_c(y')+\bar{\theta}_c(y')\bar{\theta}_c(y'')+\bar{\theta}_c(x'')\bar{\theta}_c(y'')-2\bar{\theta}_c(x'')\bar{\theta}_c(y')\bar{\theta}_c(y'')] \\ +\theta_c(y')\theta_c(y'')\theta_c(y)[\bar{\theta}_c(x'')\bar{\theta}_c(x')+\bar{\theta}_c(x'')\bar{\theta}_c(x)+\bar{\theta}_c(x')\bar{\theta}_c(x)-2\bar{\theta}_c(x'')\bar{\theta}_c(x')\bar{\theta}_c(x)] \\ +\theta_c(x'')\theta_c(x)\theta_c(y'')[\bar{\theta}_c(x')\bar{\theta}_c(y')+\bar{\theta}_c(x')\bar{\theta}_c(y)+\bar{\theta}_c(y')\bar{\theta}_c(y)-2\bar{\theta}_c(x')\bar{\theta}_c(y')\bar{\theta}_c(y)]\}\ .\end{aligned}$$

DIS in the quark cluster model (unites low and high resolution physics): Convolution model based on ab initio structure (assumes scale separation)

$$\frac{\nu}{\sigma_M}\frac{d^2\sigma}{d\Omega dE'} = \nu W_2\left(\nu,Q^2\right) + \nu W_1\left(\nu,Q^2\right)\tan^2(\theta/2)$$

$$\nu W_2\left(\nu,Q^2\right) = \nu W_2^{in}\left(\nu,Q^2\right) + \nu W_2^{q-el}\left(\nu,Q^2\right)$$

$$\nu W_2^{in}\left(\nu,Q^2\right) = \sum_{quarks-j} e_j^2 \xi \mathrm{P}(\xi)$$

$$\mathrm{P}(\xi) = \sum_{clusters-i} p_i \bar{P}_i(\xi)$$

$$\bar{P}_i(\xi) = \int_0^{\xi_{i/A}^{th}} dy \int_0^{\xi_{q/i}^{th}} du\ \bar{n}_{q/i}(u) N_{i/A}(y)\delta(uy-\xi)$$

Nachtmann variable:

$$\xi_{i/A}^{th} = \left\{\left(1+\frac{m_i^2}{M^2}\frac{Q^2}{\nu^2}\right)^{1/2}+1\right\}\Big/\left\{\left(1+\frac{Q^2}{\nu^2}\right)^{1/2}+1\right\} \underset{Q^2\to\infty}{\longrightarrow} \frac{m_i}{M}$$

$$\xi_{q/i}^{th} = 2\Big/\left\{\left(1+\frac{4m_i^2}{Q^2}\right)^{1/2}+1\right\} \underset{Q^2\to\infty}{\longrightarrow} 1$$

$\bar{n}_{q/i}$ from Regge behavior and counting rules (phase space)

$N_{i/A}$ from non-relativistic wave functions (NRWFs)

p_i quark cluster probabilities evaluated from NRWFs based on critical separation of $2R_c \sim 1\,fm$

Ab initio NRWF inputs

H.J. Pirner and J.P. Vary, Phys. Rev. Lett. 46, 1376 (1981)

Distribution function for quarks in 6-quark clusters
weighted by probability that the quark originates from 6-quark cluster (p_6).

$$\nu W_2^{6\text{-q}} = \frac{\xi}{2}\left[\sum_{i=1}^{6} e_i^2\right]\bar{P}_6(\xi)\, p_6$$

where

$$\bar{P}_6(\xi) = \frac{1.850\,069}{\sqrt{\xi/2}}\left[1-\frac{\xi}{2}\right]^{10},$$

Norm dictated by momentum sum rule

Regge behavior

Counting rule: $2(n_q - 1)$

with Nachtmann variable (kinematic Q^2 correction)

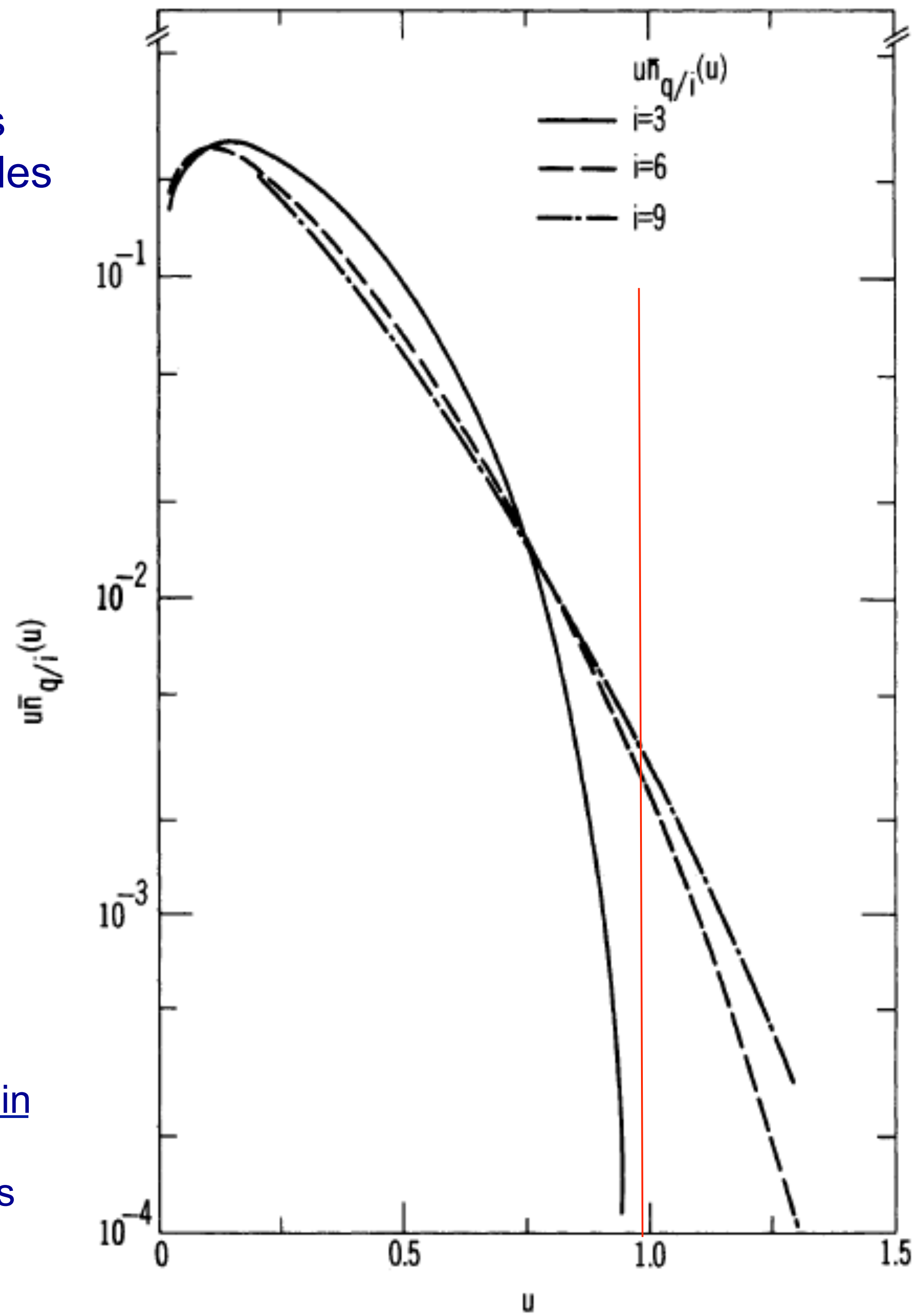
$$\xi = \frac{2x}{1+(1+Q^2/\nu^2)^{1/2}} \xrightarrow[\text{fixed } Q^2/\nu]{Q^2,\nu\to\infty} x$$

Detailed model for q-el contribution – see G. Yen, J.P. Vary, A. Harindranath and H.J. Pirner, Phys. Rev. C 42, 1665 (1990)

Normalized inelastic structure functions Of quark clusters based on counting rules and Regge behavior as a function of Bjorken x = u in the figure.

Actual calculations employ measured nucleon inelastic structure functions to include resonances and other scaling violations.

Note the hierarchy even without the A-dependent cluster probabilities (p_i)



J. P. Vary, "Quark Distributions in Nuclei from Lepton Experiments," in Hadron Substructure in Nuclear Physics, W.-Y. P. Hwang and M. H. Macfarlane, eds., American Institute of Physics Conference Proceedings No. 110 (New York) 1984, p. 171.

Characteristic predictions of the Quark Cluster Model (QCM) for DIS

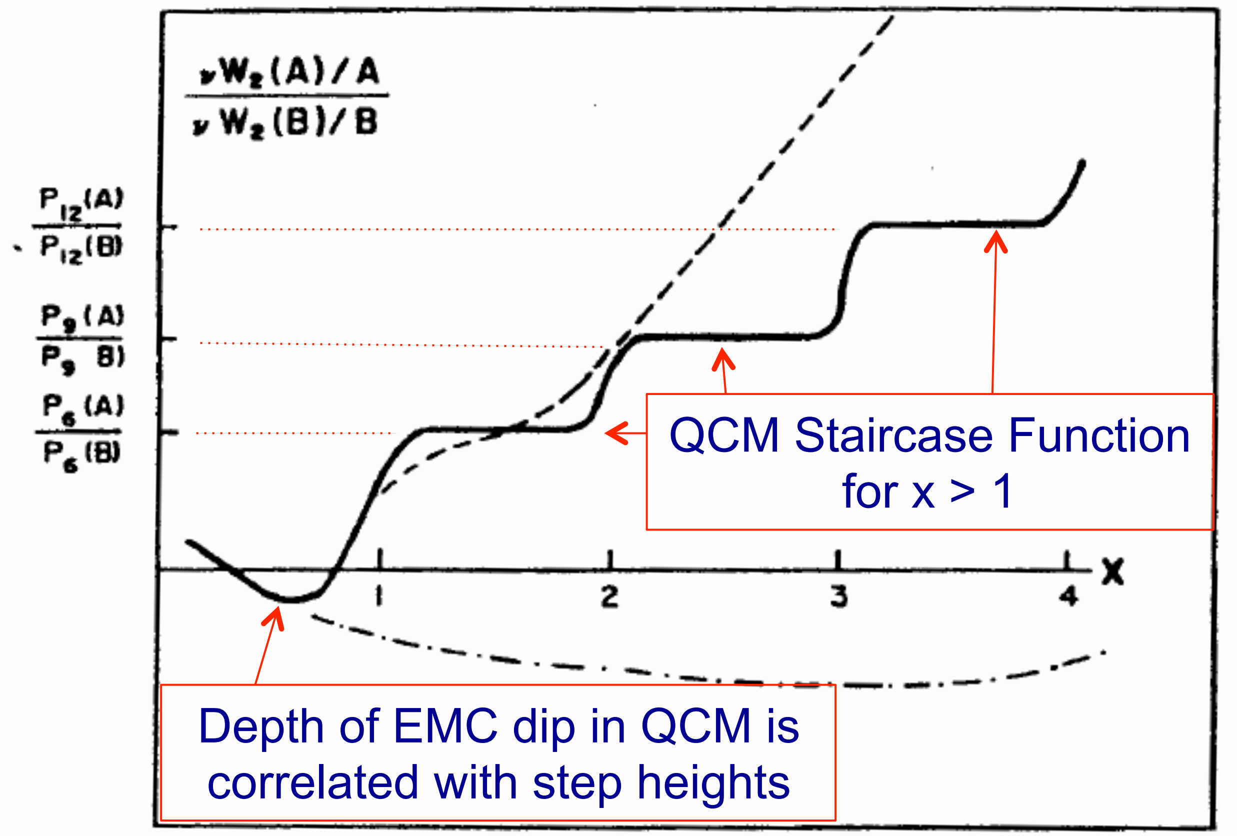
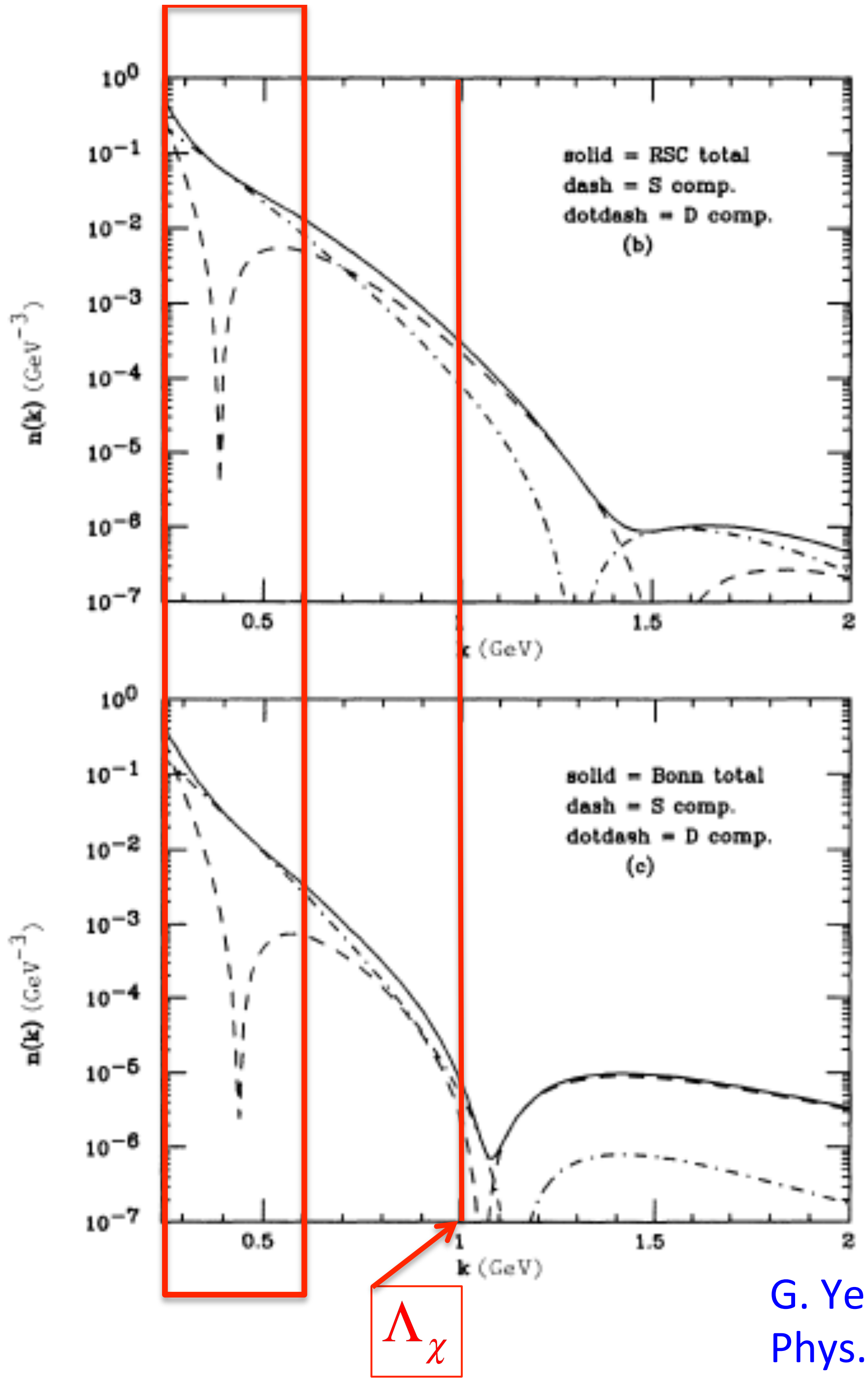


Fig. 2. Characteristic behaviour of the ratio of nuclear structure functions per nucleon for different models over a wide kinematic range of x. The QCM gives the solid curve. The dashed curve is due to the model of reference 22. The dashed-dot curve approximates the predictions of references 23 and 24.

J.P. Vary, Proc. VII Int'l Seminar on High Energy Physics Problems, "Quark Cluster Model of Nuclei and Lepton Scattering Results," Multiquark Interactions and Quantum Chromodynamics, V.V. Burov, Ed., Dubna #D-1, 2-84-599 (1984) 186 [staircase function for x > 1]

See also: numerous other conference proceedings



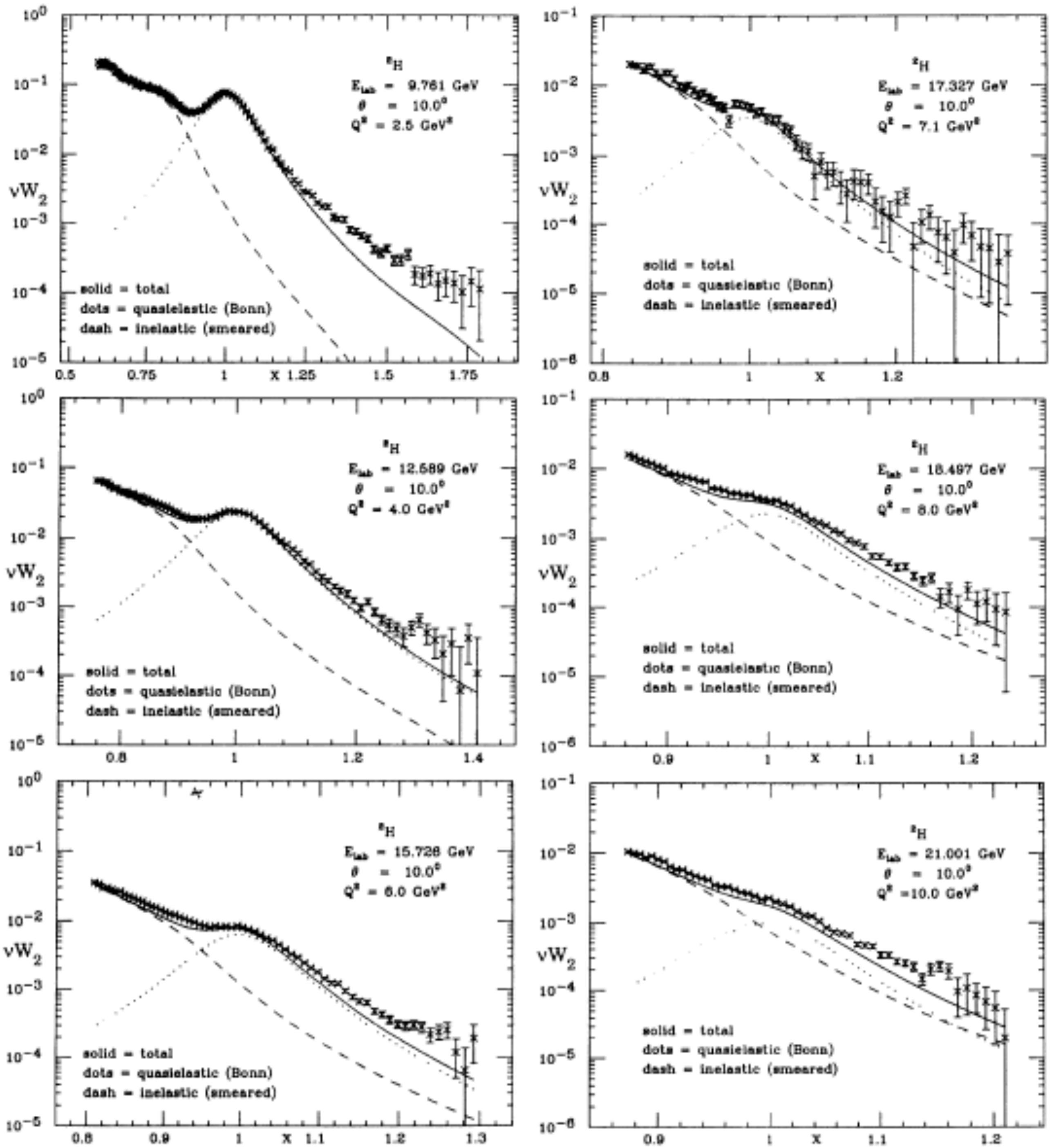
Nucleon momentum distributions in the Deuteron with Reid Soft Core (RSC) and Bonn

Note strong tensor dominance in the region of 250 < k < 600 MeV/c

Note large differences between RSC and Bonn above the chiral symmetry scale Λ_χ where:

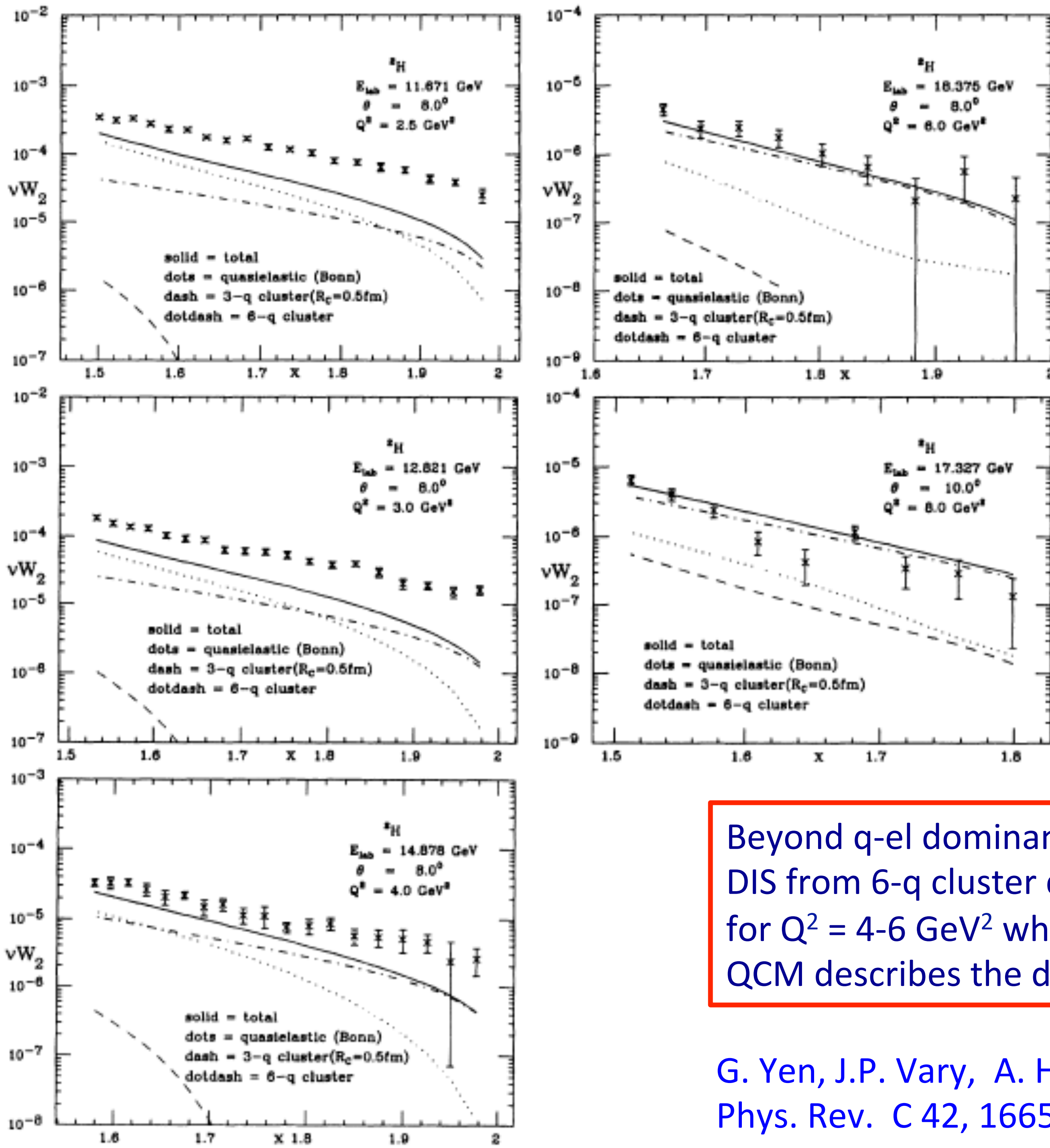
$$\Lambda_\chi \approx 1\ \text{GeV/c} \approx \frac{2\pi}{r} \Rightarrow r \approx 1\ \text{fm}$$

G. Yen, J.P. Vary, A. Harindranath and H.J. Pirner, Phys. Rev. C 42, 1665 (1990)



SLAC DIS data from Deuterium compared with model inelastic structure function including Quasi-elastic knockout, nucleon excitations and realistic momentum distributions (Bonn)

G. Yen, J.P. Vary, A. Harindranath and H.J. Pirner, Phys. Rev. C 42, 1665 (1990)



SLAC DIS data from Deuterium compared with model inelastic structure function including Quasi-elastic knockout, nucleon excitations, 6-quark clusters (5.4%) and realistic momentum distributions (Bonn)

Beyond q-el dominance:
DIS from 6-q cluster dominates for Q^2 = 4-6 GeV^2 where the QCM describes the data well

G. Yen, J.P. Vary, A. Harindranath and H.J. Pirner, Phys. Rev. C 42, 1665 (1990)

Use scaling with density to estimate p_i based on ab initio correlated basis function solutions for ^{4}He

Ref: M. Sato, S.A. Coon, H.J. Pirner and J.P. Vary, Phys. Rev. C33, 1062(1986)

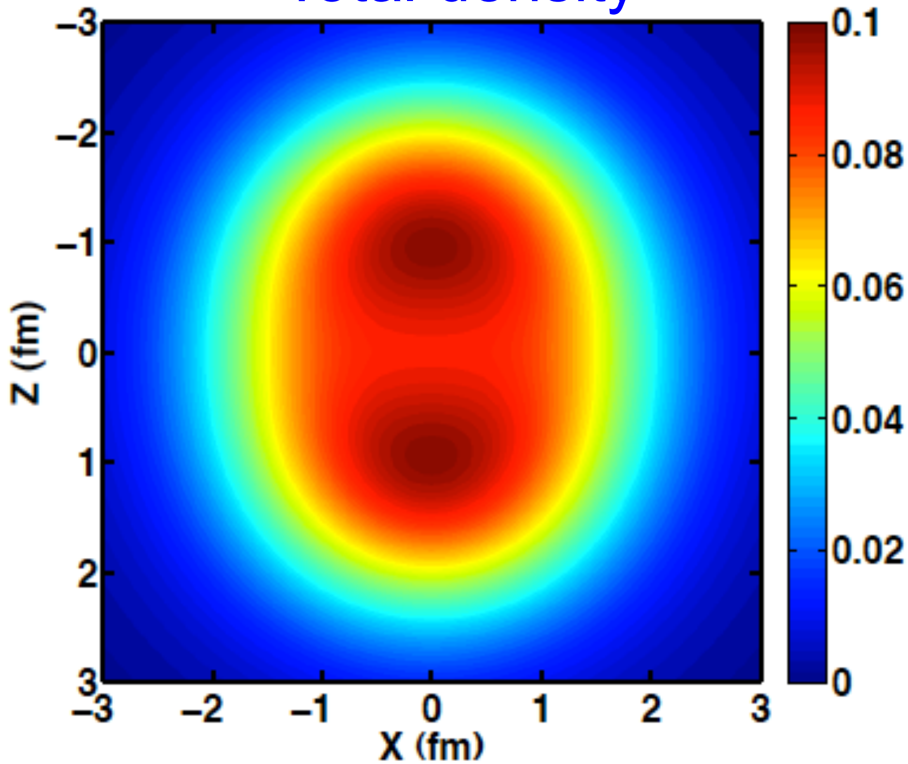
Nucleus	Expt. r_m (fm)	η	$\tilde{p}_3$	$\tilde{p}_6$	$\tilde{p}_9$	$\tilde{p}_{12}$
^{4}He	1.45	0.547	0.780	0.166	0.047	0.007
* ^{9}Be	2.38	0.437	0.905	0.083	0.011	0.001
^{12}C	2.32	0.493	0.847	0.125	0.026	0.003
^{16}O	2.59	0.486	0.854	0.120	0.024	0.003
^{20}Ne	2.91	0.466	0.876	0.104	0.018	0.002
^{24}Mg	2.97	0.486	0.854	0.120	0.024	0.003
^{27}Al	2.95	0.508	0.829	0.137	0.031	0.004
^{40}Ca	3.37	0.507	0.830	0.136	0.031	0.004
^{56}Fe	3.68	0.520	0.814	0.146	0.036	0.005
^{58}Ni	3.70	0.523	0.810	0.148	0.037	0.005
^{90}Zr	4.19	0.535	0.795	0.157	0.042	0.006
^{107}Ag	4.47	0.531	0.800	0.154	0.040	0.006
^{184}W	5.36	0.531	0.800	0.154	0.040	0.006
^{197}Au	5.24	0.555	0.770	0.171	0.051	0.008
^{208}Pb	5.44	0.545	0.783	0.165	0.046	0.007
^{238}U	5.79	0.535	0.795	0.157	0.042	0.006

$$\text{Heavy nucleus avg } \eta = 0.548 \Rightarrow \tilde{p}_3 = 0.779$$

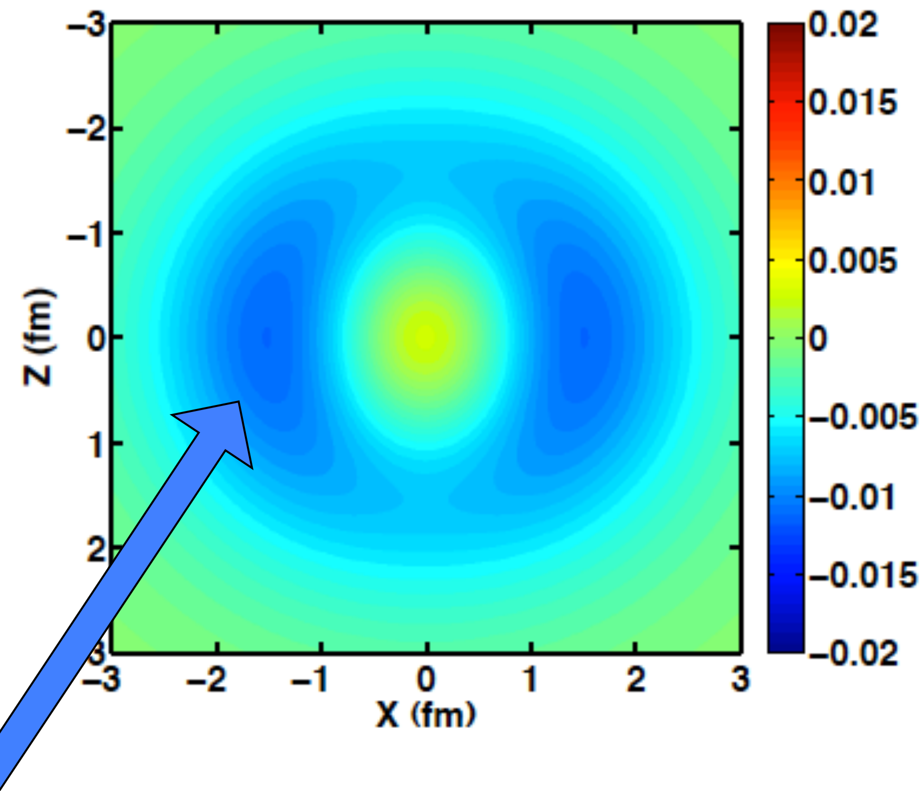
* See my workshop talk last week => ab initio alpha clustering in ^{9}Be
i.e. ^{9}Be ~ two alphas bound by a neutron torus

9Be Translationally invariant gs density
Full 3D densities = rotate around the vertical axis

Total density



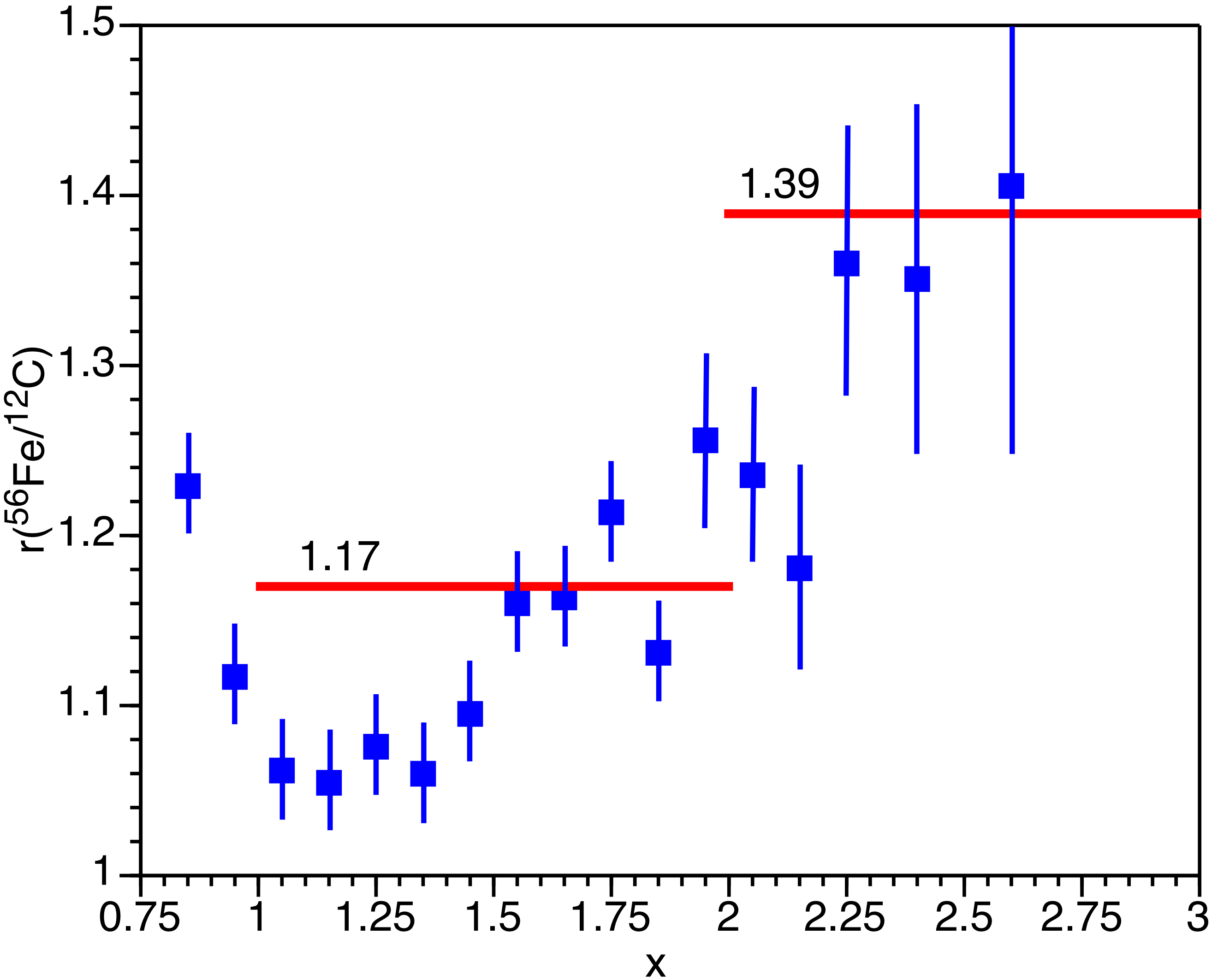
Neutron – Proton density



Shows that one neutron provides a “ring” cloud around two alpha clusters binding them together

C. Cockrell, J.P. Vary, P. Maris, Phys. Rev. C 86, 034325 (2012); arXiv:1201.0724
C. Cockrell, PhD, Iowa State University

Comparison between Quark-Cluster Model and JLAB data



Data: K.S. Egiyan, et al., Phys. Rev. Lett. **96**, 082501 (2006)
Theory: H.J. Pirner and J.P. Vary, Phys. Rev. Lett. **46**, 1376 (1981)
and Phys. Rev. C **84**, 015201 (2011); nucl-th/1008.4962;
M. Sato, S.A. Coon, H.J. Pirner and J.P. Vary, Phys. Rev. C **33**, 1062 (1986)

New Measurements of High-Momentum Nucleons and Short-Range Structures in Nuclei

N. Fomin,[1,2,3] J. Arrington,[4] R. Asaturyan,[5,*] F. Benmokhtar,[6] W. Boeglin,[7] P. Bosted,[8] A. Bruell,[8] M. H. S. Bukhari,[9] M. E. Christy,[8] E. Chudakov,[8] B. Clasie,[10] S. H. Connell,[11] M. M. Dalton,[3] A. Daniel,[9] D. B. Day,[3] D. Dutta,[12,13] R. Ent,[8] L. El Fassi,[4] H. Fenker,[8] B. W. Filippone,[14] K. Garrow,[15] D. Gaskell,[8] C. Hill,[3] R. J. Holt,[4] T. Horn,[6,8,16] M. K. Jones,[8] J. Jourdan,[17] N. Kalantarians,[9] C. E. Keppel,[8,18] D. Kiselev,[17] M. Kotulla,[17] R. Lindgren,[3] A. F. Lung,[8] S. Malace,[18] P. Markowitz,[7] P. McKee,[3] D. G. Meekins,[8] H. Mkrtchyan,[5] T. Navasardyan,[5] G. Niculescu,[19] A. K. Opper,[20] C. Perdrisat,[21] D. H. Potterveld,[4] V. Punjabi,[22] X. Qian,[13] P. E. Reimer,[4] J. Roche,[20,8] V. M. Rodriguez,[9] O. Rondon,[3] E. Schulte,[4] J. Seely,[10] E. Segbefia,[18] K. Slifer,[3] G. R. Smith,[8] P. Solvignon,[8] V. Tadevosyan,[5] S. Tajima,[3] L. Tang,[8,18] G. Testa,[17] R. Trojer,[17] V. Tvaskis,[18] W. F. Vulcan,[8] C. Wasko,[3] F. R. Wesselmann,[22] S. A. Wood,[8] J. Wright,[3] and X. Zheng[3,4]

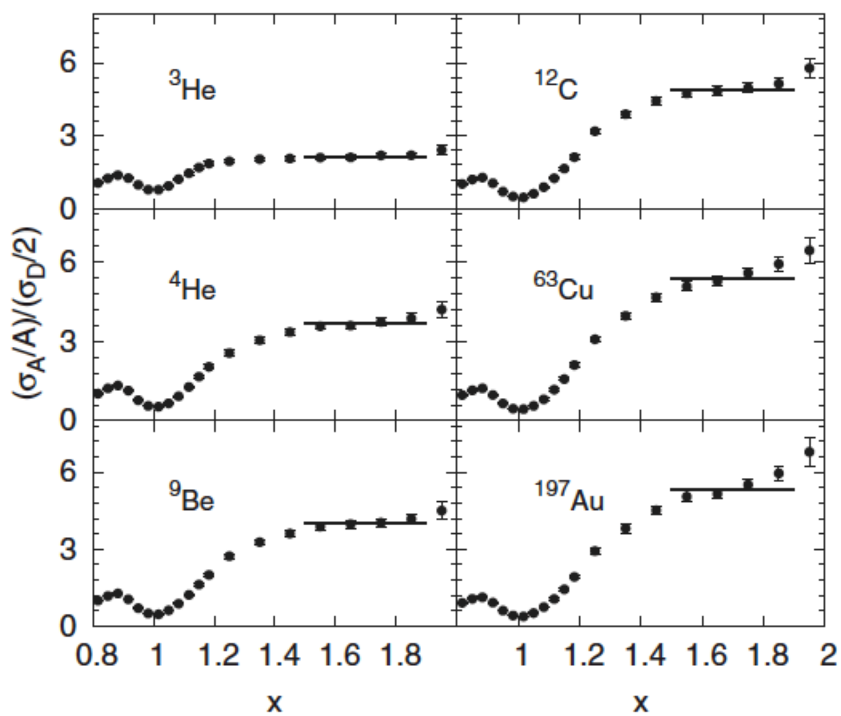


FIG. 2. Pernucleon cross section ratios vs x at $\theta_e = 18°$.

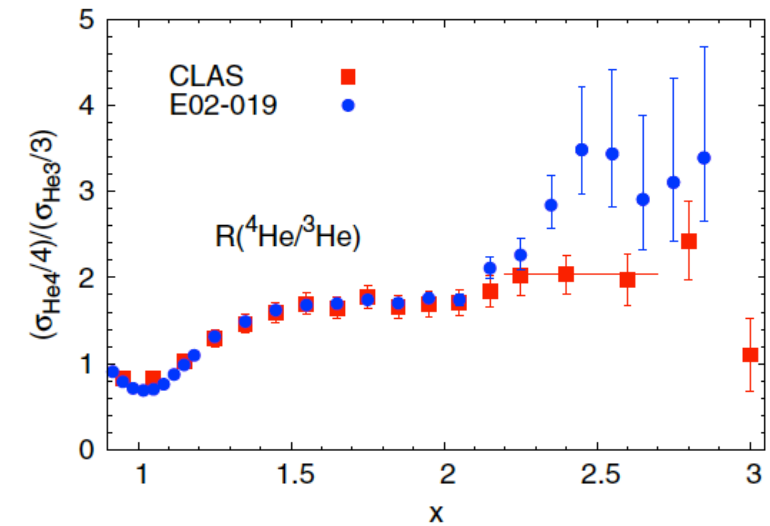


FIG. 3 (color online). The ^{4}He/^{3}He ratios from E02-019 ($Q^2 \approx 2.9$ GeV^2) and CLAS ($\langle Q^2 \rangle \approx 1.6$ GeV^2); errors are combined statistical and systematic uncertainties. For $x > 2.2$, the uncertainties in the ^{3}He cross section are large enough that a one-sigma variation of these results yields an asymmetric error band in the ratio. The error bars shown for this region represent the central 68% confidence level region.

A detailed study of the nuclear dependence of the EMC effect and short-range correlations

J. Arrington,[1] A. Daniel,[2,3] D. B. Day,[3] N. Fomin,[4] D. Gaskell,[5] and P. Solvignon[5]

TABLE II: Existing measurements of SRC ratios, R_{2N} all corrected for c.m. motion of the pair. The second-to-last column combines all the measurements, and the last column shows the ratio a_2, obtained without applying the c.m. motion correction. No isoscalar corrections are applied. SLAC and CLAS results do not have Coulomb corrections applied, estimated to be up to ∼5% for the CLAS data on Fe and up to ∼10% for the SLAC data on Au.

	E02-019	SLAC	CLAS	R_{2N}-ALL	a_2-ALL
^{3}He	1.93±0.10	1.8±0.3	–	1.92±0.09	2.13±0.04
^{4}He	3.02±0.17	2.8±0.4	2.80±0.28	2.94±0.14	3.57±0.09
Be	3.37±0.17	–	–	3.37±0.17	3.91±0.12
C	4.00±0.24	4.2±0.5	3.50±0.35	3.89±0.18	4.65±0.14
Al	–	4.4±0.6	–	4.40±0.60	5.30±0.60
Fe	–	4.3±0.8	3.90±0.37	3.97±0.34	4.75±0.29
Cu	4.33±0.28	–	–	4.33±0.28	5.21±0.20
Au	4.26±0.29	4.0±0.6	–	4.21±0.26	5.13±0.21

QCM ab initio wavefunctions + simple scaling*

$p_6(A)/p_6(D)$

0.11/0.04 = 2.8

0.17/0.04 = 4.3

^{4}He/^{3}He = 1.55

0.08/0.04 = 2.0

0.13/0.04 = 3.3

0.14/0.04 = 3.5

0.15/0.04 = 3.8

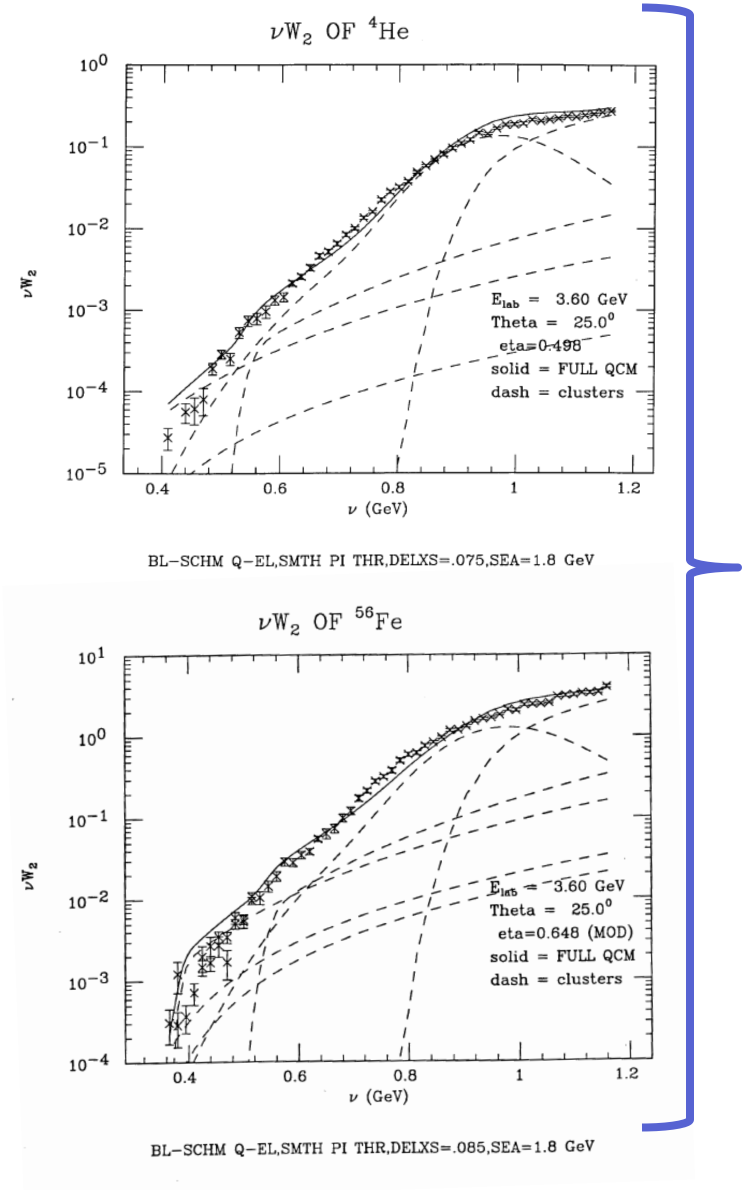
Fe/C = 1.17

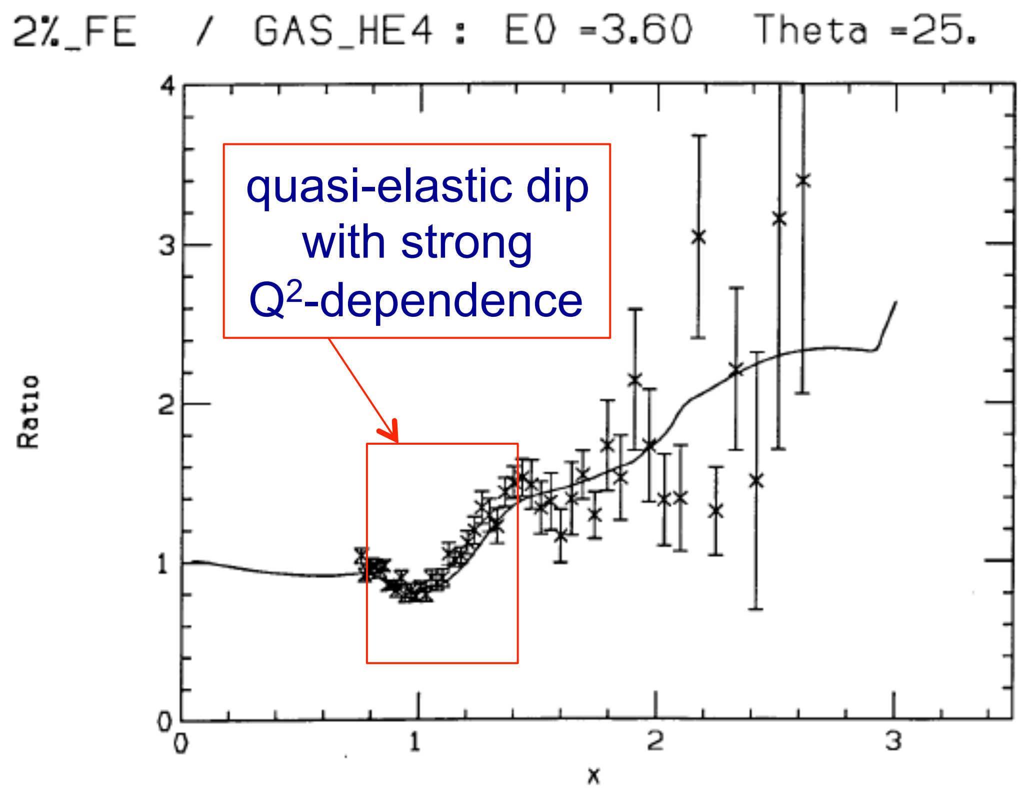
0.15/0.04 = 3.8

0.17/0.04 = 4.3

*M. Sato, S.A. Coon, H.J. Pirner and J.P. Vary, Phys. Rev. C33, 1062(1986)

DIS in the quark cluster model: Low Q^2 – quasi-elastic "dip"





Data: SLAC

Calculations: QCM

Note: steps less defined due to Nachtmann scaling violations

Quark Cluster Model selected references

H.J. Pirner and J.P. Vary,
"Deep-Inelastic Electron Scattering and the Quark Structure of ^{3}He,"
Phys. Rev. Lett. **46**, 1376 (1981)

J.P. Vary, Proc. VII Int'l Seminar on High Energy Physics Problems,
"Quark Cluster Model of Nuclei and Lepton Scattering Results,"
Multiquark Interactions and Quantum Chromodynamics, V.V. Burov, Ed.,
Dubna #D-1, 2-84-599 (1984) 186 **[EMC region + staircase function]**

J. P. Vary, S. A. Coon, and H. J. Pirner,
"Charge Form Factor of 3He in a Quark Cluster Model,"
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American Institute of Physics Conference Proceedings No. 110 (New York) 1984, p. 171.

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"Quark Cluster Probabilities in Nuclei,"
Phys. Rev. C **33**, 1062 (1986)

A. Harindranath and J. P. Vary,
"Quark Cluster Model Predictions for the Nuclear Drell-Yan Process,"
Phys. Rev. D **34**, 3378 (1986) **[staircase function for x > 1 in Drell-Yan]**

G. Yen, J. P. Vary, A. Harindranath, and H. J. Pirner,
"Quark Cluster Model for Deep-Inelastic Lepton-Deuteron Scattering,"
Phys. Rev. C **42**, 1665 (1990)

H.J. Pirner and J.P. Vary,
"Boundary between hadron and quark/gluon structure of nuclei,"
Phys. Rev. C **84**, 015201 (2011); nucl-th/1008.4962

Quark-cluster-model predictions for the nuclear Drell-Yan process

A. Harindranath and J. P. Vary
Physics Department, Iowa State University, Ames, Iowa 50011
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We evaluate the quark-cluster-model predictions for lepton pair production in proton-nucleus, pion-nucleus, and nucleus-nucleus interactions. We examine the issue of a possible ambiguity between the K factor and the probability of six-quark clusters in nuclei. We present predictions for cross sections and cross-section ratios which show substantial sensitivity to different features of the model. The model compares well with the existing data.

I. DY CROSS SECTION

In the hadron-hadron center-of-momentum frame we denote the total energy by $\sqrt{s}$. For hadrons A and B the four-momenta are $P_A=(\sqrt{s}/2,0,0,\sqrt{s}/2)$ and $P_B=(\sqrt{s}/2,0,0,-\sqrt{s}/2)$. Let x_1 (x_2) denote the fraction of longitudinal momentum carried by quark 1 (2) in hadron A (B). Then the longitudinal momentum of the lepton pair with invariant mass M is given by

$$P_L=p_1+p_2=(x_1-x_2)\frac{\sqrt{s}}{2} .$$

$$\frac{d^2\sigma}{dx_1dx_2}=\frac{4\pi\alpha^2}{9sx_1x_2}\sum e_a{}^2F_a(x_1,x_2)$$

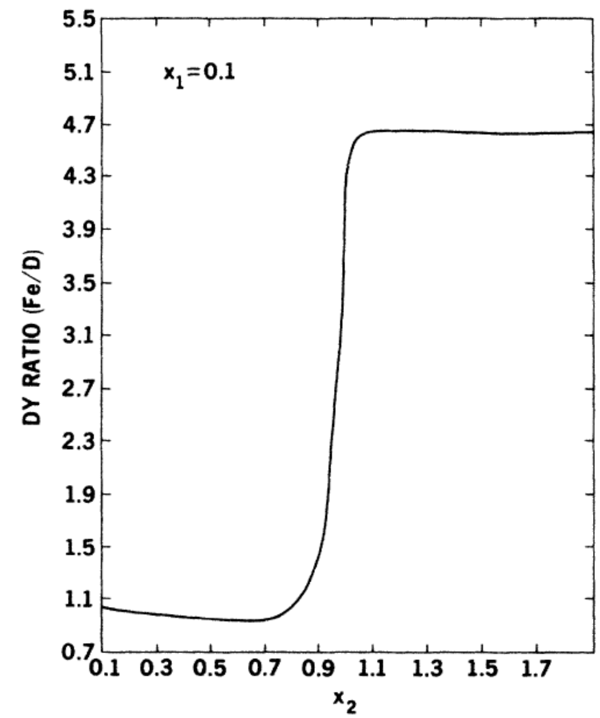
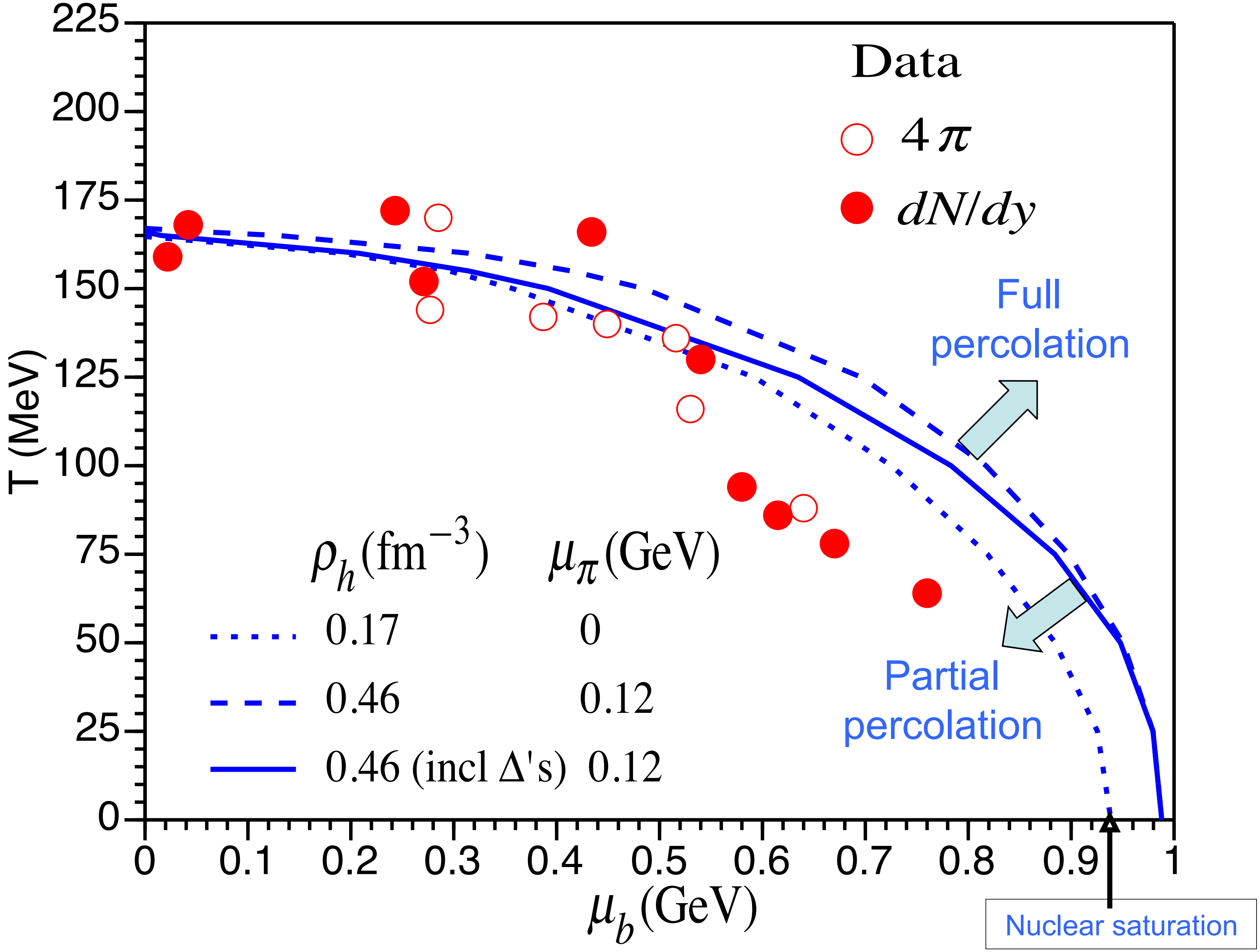


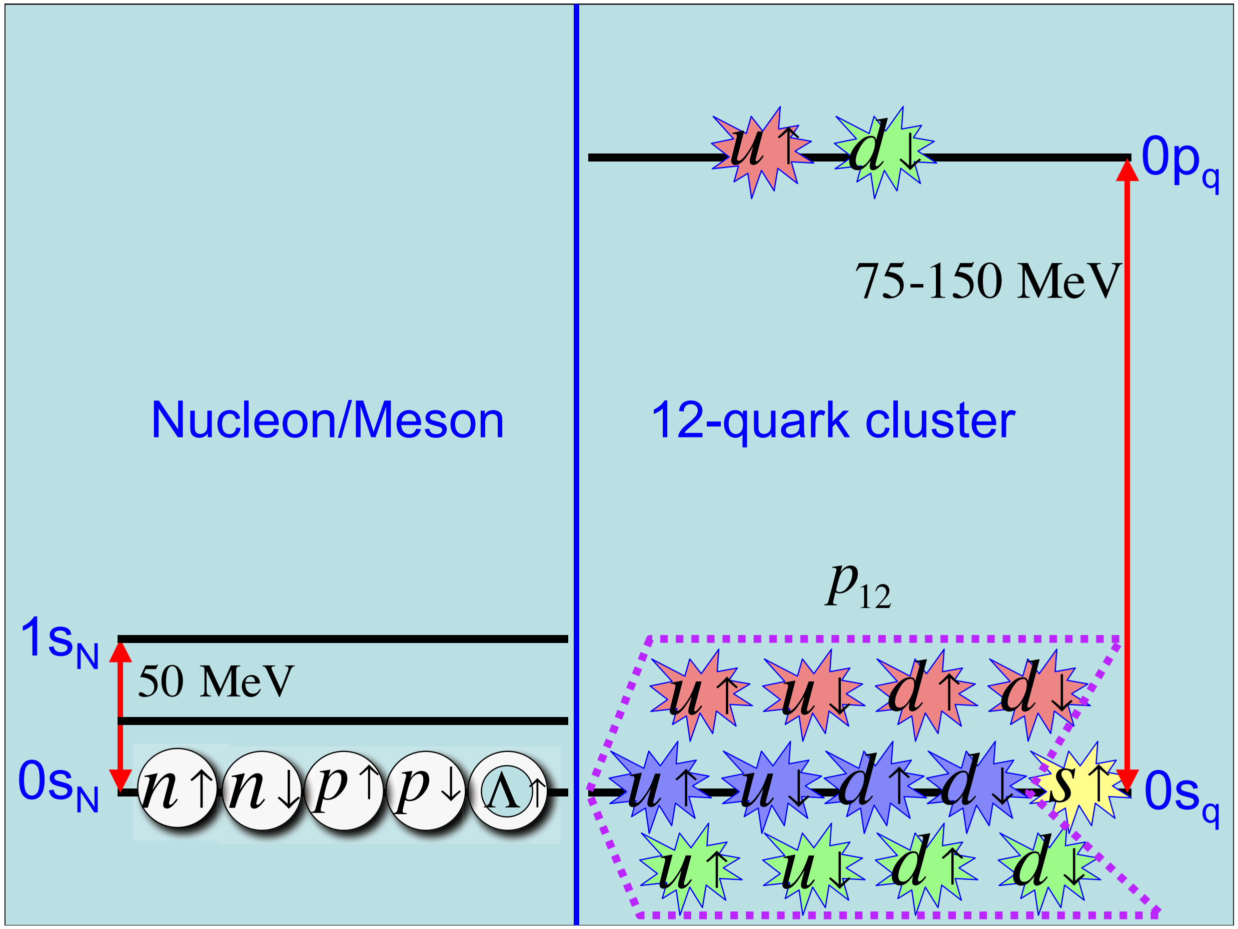
FIG. 7. QCM prediction for the ratio of DY cross sections for Fe and D as a function of x_2 (for $x_1=0.1$) in the region $0.1\le x_2\le 1.9$.

Comparison of quark percolation with RHIC data



Data: A. Andronic, P. Braun-Munzinger and J. Stachel, Nucl. Phys. A **772**, 167 (2006)
Theory: H.J. Pirner and J.P. Vary, Phys. Rev. C **84**, 015201 (2011); nucl-th/1008.4962

Comparison of quark percolation with Hypernuclear binding data



Energy shift: $\Delta E \sim p_{12} * 2 *$ (Quark Shell spacing)
$\sim 0.007 * 2 *$ (75 – 150 MeV)
~ 1 – 2 MeV

Data: E. Hungerford and L.C. Biedenharn, Phys. Lett. B **142**, 232 (1984)
Theory: H.J. Pirner and J.P. Vary, Phys. Rev. C **84**, 015201 (2011); nucl-th/1008.4962

Overview of selected predictions of QCM

1. DIS at X > 1 staircase
   - EMC effect is a feature of the QCM & correlated with staircase
2. Drell-Yan staircase at $x_2 > 1$
3. "Subthreshold" particle production
4. Contributions to nuclear form factors at high Q^2
5. Percolation in Relativistic HI collisions & EOS at high density and temperature
6. Shifts in hypernuclear states

Beyond Model Building

- Central problems in hadron physics:
  - Structure of hadron -> Parton distribution?
  - Spin structure of hadron -> Where does proton spin come from?

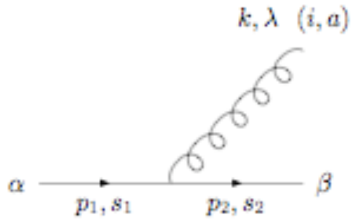
- These problems involve the non-perturbative aspects of QCD

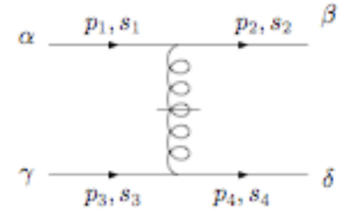
  not well understood so far

- Lattice QCD set up in imaginary time
  - limited ability in extracting hadron structure

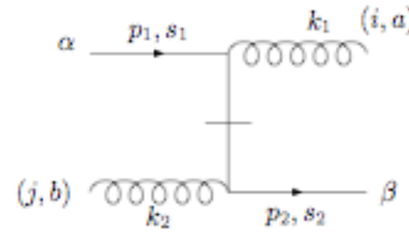
- A reliable non-perturbative approach in real time needed.
- Basis Light-Front Quantization (BLFQ) approach!
  - Solve quantum field theory in the Hamiltonian framework
  - See talk by Xingbo Zhao at this workshop on Basis Light Front Quantization (BLFQ) [See Refs: J. P. Vary, H. Honkanen, Jun Li, P. Maris, S. J. Brodsky, A. Harindranath, G. F. de Teramond, P. Sternberg, E. G. Ng, C. Yang, "Hamiltonian light-front field theory in a basis function approach", Phys. Rev. C 81, 035205 (2010); H. Honkanen, P. Maris, J. P. Vary and S. J. Brodsky, "Electron in a transverse harmonic cavity", Phys. Rev. Lett. 106, 061603 (2011)]

Light Front (LF) Hamiltonian defined by its elementary vertices in LF gauge

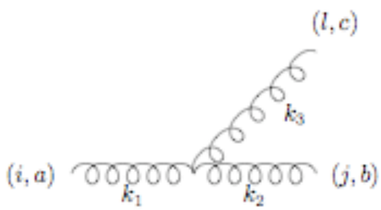


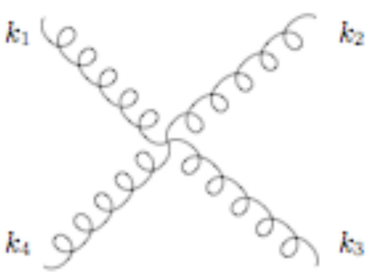


H_{qqgg1}

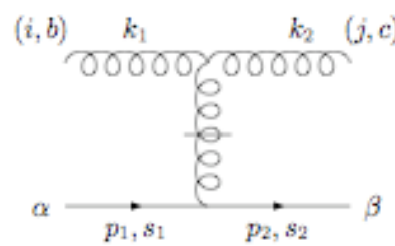


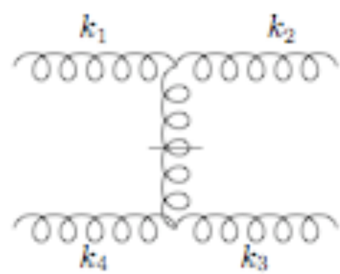
QED & QCD





H_{qqgg2}





QCD

Dream project

Covariant QCM consistent with ab initio structure theory and QCD

Every ingredient is computationally challenging!

- Chiral NN + NNN Hamiltonian (complete through N3LO)
- Many-body solutions for A up to ~ 20 (GFMC, NCSM, CC, . . .)
- Cluster probabilities from these solutions (Monte Carlo integrations)
- Derivation of free-space and in-medium cluster structure functions from QCD (LGT, BLFQ, . . .)

Outlook for a unified low and high resolution nuclear physics

Many challenges remain and are being addressed:

Improved accuracy in the ab initio Hamiltonians and the Many-Body methods
Proper accounting for cluster, other collective phenomena, continuum effects, . . .
Advances in non-perturbative solutions of QCD (Lattice, BLFQ)
Improve efficiency in use of supercomputer facilities (GPUs, . . .)

Promising new developments:

Forefront experimental facilities – FRIB, TJLAB 12 GeV upgrade, JPARC, FAIR, . . .
Leadership class computational faciltiies – discoveries enabled by simulations
Next generation Chiral interactions (pionful, deltaful,…)
Improving many-body theory (GFMC, NCSM, CC, lattice EFT, . . .)
Teams: physics + applied math + computer science have proven invaluable

=> Joint theory and experimental efforts for additional dividends

Exciting era of predictive and testable science is just beginning – portends using nuclei as laboratories for tests of non-perturbative strong interaction physics and physics beyond the standard model (neutrinoless double beta decay, dark matter detection, . . .)