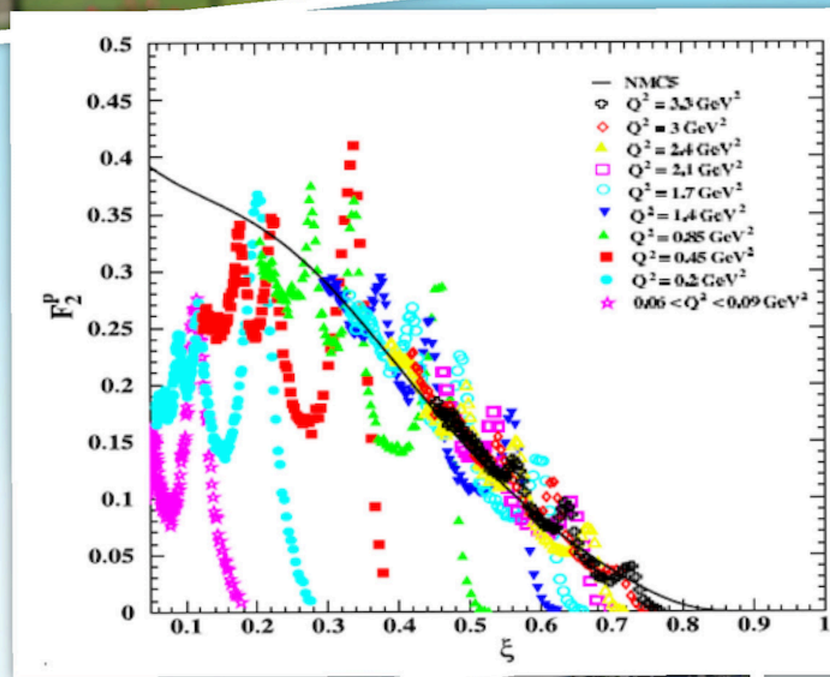
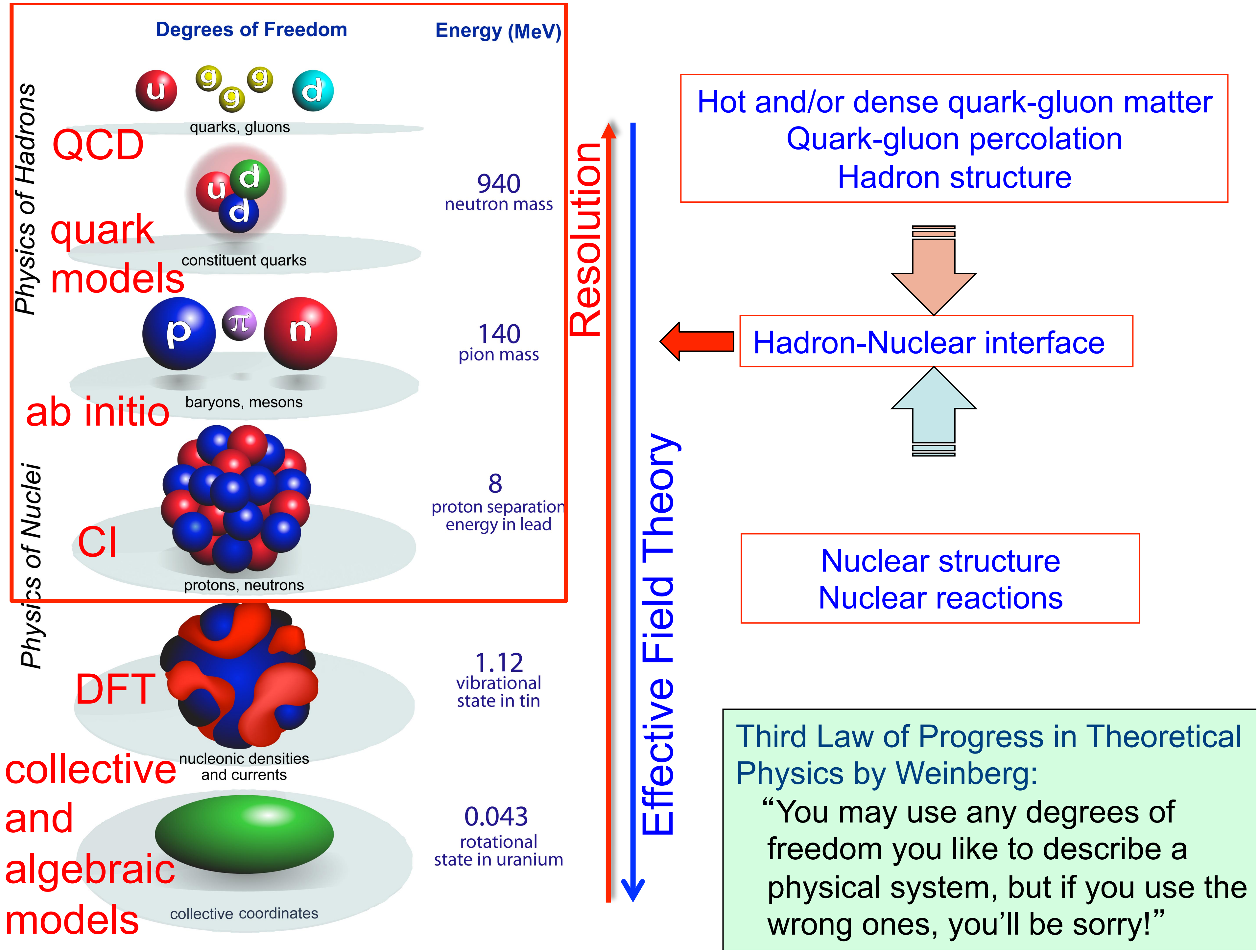
# Duality as Seen in Basis Light Front Quantization

James P. Vary
Iowa State University
Ames, Iowa, USA

Quark Hadron Duality Workshop:
Probing the Transition
from Free to Confined Quarks
James Madison University
September 23 – 25, 2018




Degrees of Freedom
Energy (MeV)
Physics of Hadrons
Physics of Nuclei
QCD
quark models
ab initio
CI
DFT
collective and algebraic models
u g g g d
quarks, gluons
u d d
constituent quarks
940
neutron mass
p π n
baryons, mesons
140
pion mass
protons, neutrons
8
proton separation energy in lead
nucleonic densities and currents
1.12
vibrational state in tin
collective coordinates
0.043
rotational state in uranium
Resolution
Effective Field Theory
Hot and/or dense quark-gluon matter
Quark-gluon percolation
Hadron structure
Hadron-Nuclear interface
Nuclear structure
Nuclear reactions
Third Law of Progress in Theoretical Physics by Weinberg:
"You may use any degrees of freedom you like to describe a physical system, but if you use the wrong ones, you'll be sorry!"

# Sketch: hierarchy of strong interaction theories/scales/phenomena

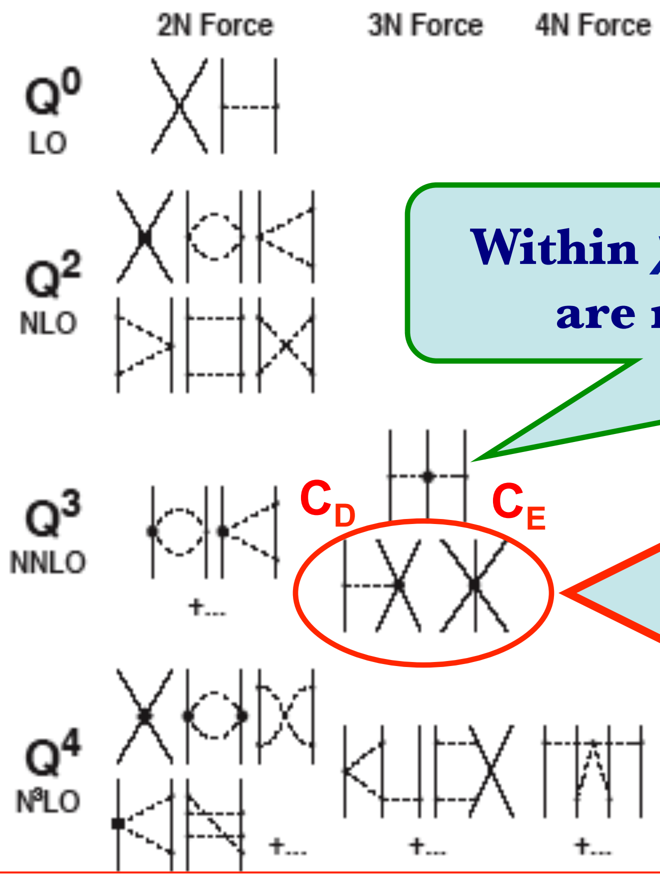
| Effective Field Theory | Scale | Range of Q | Phenomena |
|---|---|---|---|
| QCD | Chiral symmetry restoration | $Q < m_{Planck}$ | Asymptotic freedom, pQCD<br>sQCD-Quark-Gluon Plasma<br>Color glass condensate<br>Hadron tomography, . . . |
| Quark Clusters | Chiral symmetry crossover transition<br>$\sim (1 - 4)\,\Lambda_{QCD}$<br>$\sim (1 - 4)\,m_N$ | $Q < (1 - 4)\,m_N$<br><br>$Q \sim m_N$ | $X > 1$ staircase<br>EMC effect<br>Quark percolation<br>Color conducting drops<br>Deconfining fluctuations, . . |
| Pionfull, Deltafull | Chiral symmetry breaking<br>$\sim \Lambda_{QCD} \sim m_N$ | $Q < m_N$<br><br>$Q \sim m_\pi$ | Low-E  Nucl. Struc/Reac'ns<br>$^{14}C$ anomalous lifetime<br>$g_A$ quenching<br>Tetraneutron, . . . |
| Pionless | Chiral symmetry breaking<br>$\sim \Lambda_{QCD} \sim m_N$ | $Q < m_\pi \sim k_F$<br><br>$Q \sim 0.2\,k_F$ | NN Scattering lengths<br>Stellar burning<br>Halo nuclei<br>Nuclear clusters, . . . |

# Effective Nucleon Interaction
## (Chiral Perturbation Theory)

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

$$\text{Expansion parameter}: \left(\frac{Q}{\Lambda_\chi}\right)^{\upsilon}, \; Q - \text{momentum transfer},$$

$$\Lambda_\chi \approx 1\ GeV, \; \chi \text{ - symmetry breaking scale}$$



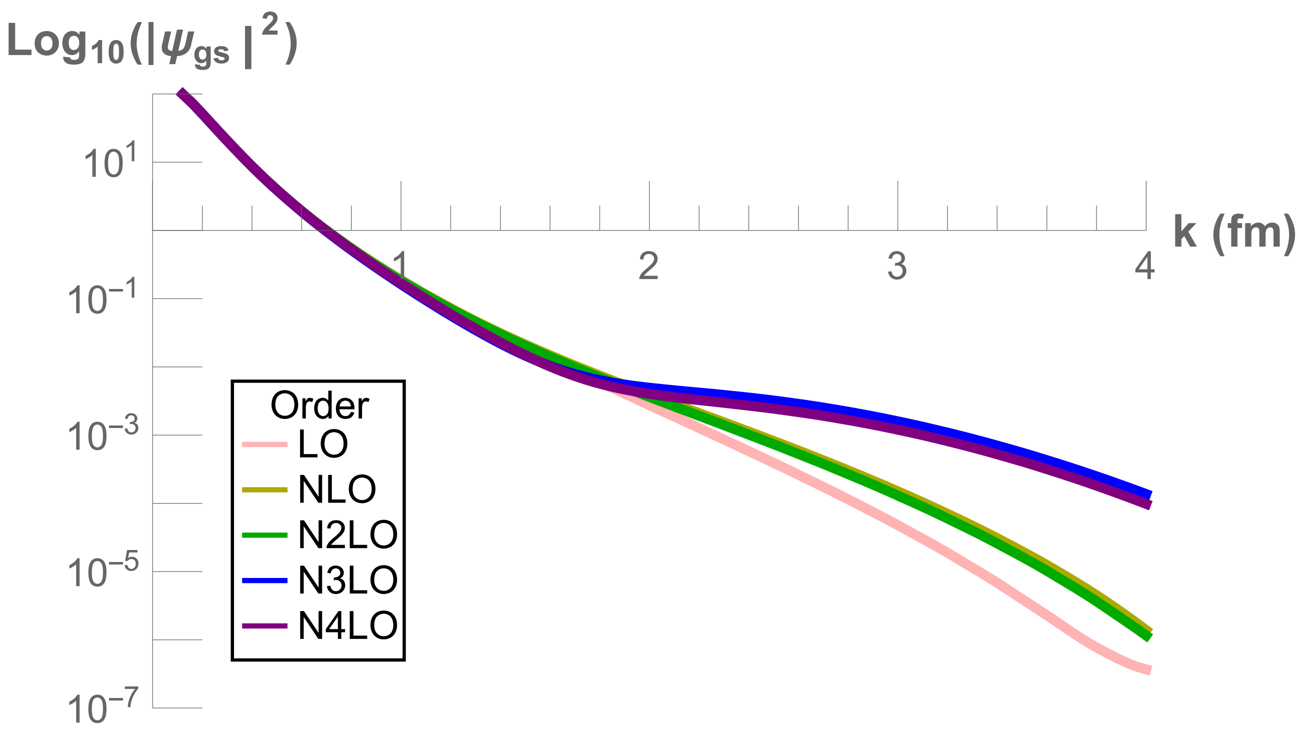

**Within χPT 2π-NNN Low Energy Constants (LEC) are related to the NN-interaction LECs $\{c_i\}$.**

**Terms suggested within the Chiral Perturbation Theory**

**Regularization is essential, which is also implicit within the Harmonic Oscillator (HO) wave function basis (see below)**


R. Machleidt and D.R. Entem, Phys. Rep. 503, 1 (2011);
E. Epelbaum, H. Krebs, U.-G Meissner, Eur. Phys. J. A51, 53 (2015); Phys. Rev. Lett. 115, 122301 (2015)

Progressing to higher chiral order builds higher momentum components into the deuteron ground state wave function




**Lesson**: Physics at higher momentum scales (short distances) begins to have impact at higher order in the chiral EFT expansion

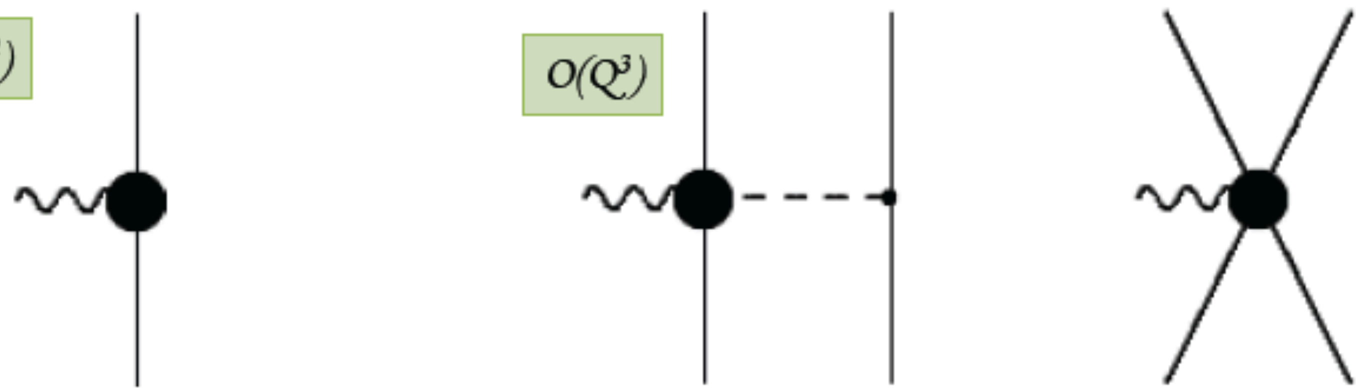
R. Basili, W. Du, et al., in preparation

# Coupling to External Probes in Chiral EFT

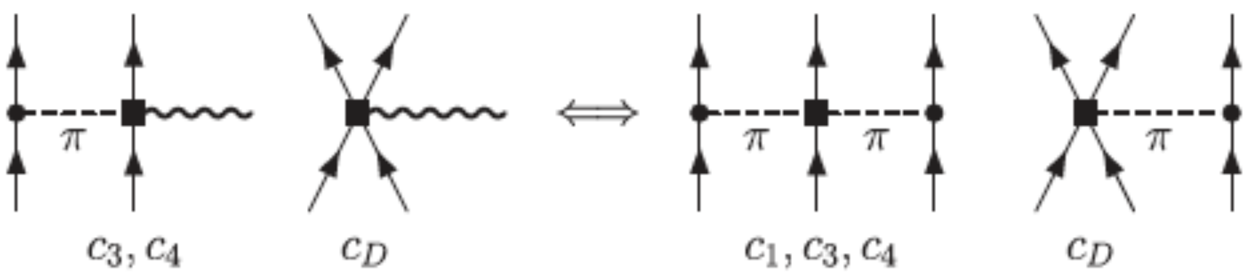
- Nuclear Current Operators

Single nucleon current | 1 pion exchange | Contact term

$O(Q^0)$, $O(Q^2)$ | $O(Q^3)$



## Two-Body Currents ($N^2LO$)



## *No-Core Configuration Interaction calculations*

Barrett, Navrátil, Vary, *Ab initio no-core shell model*, PPNP69, 131 (2013)

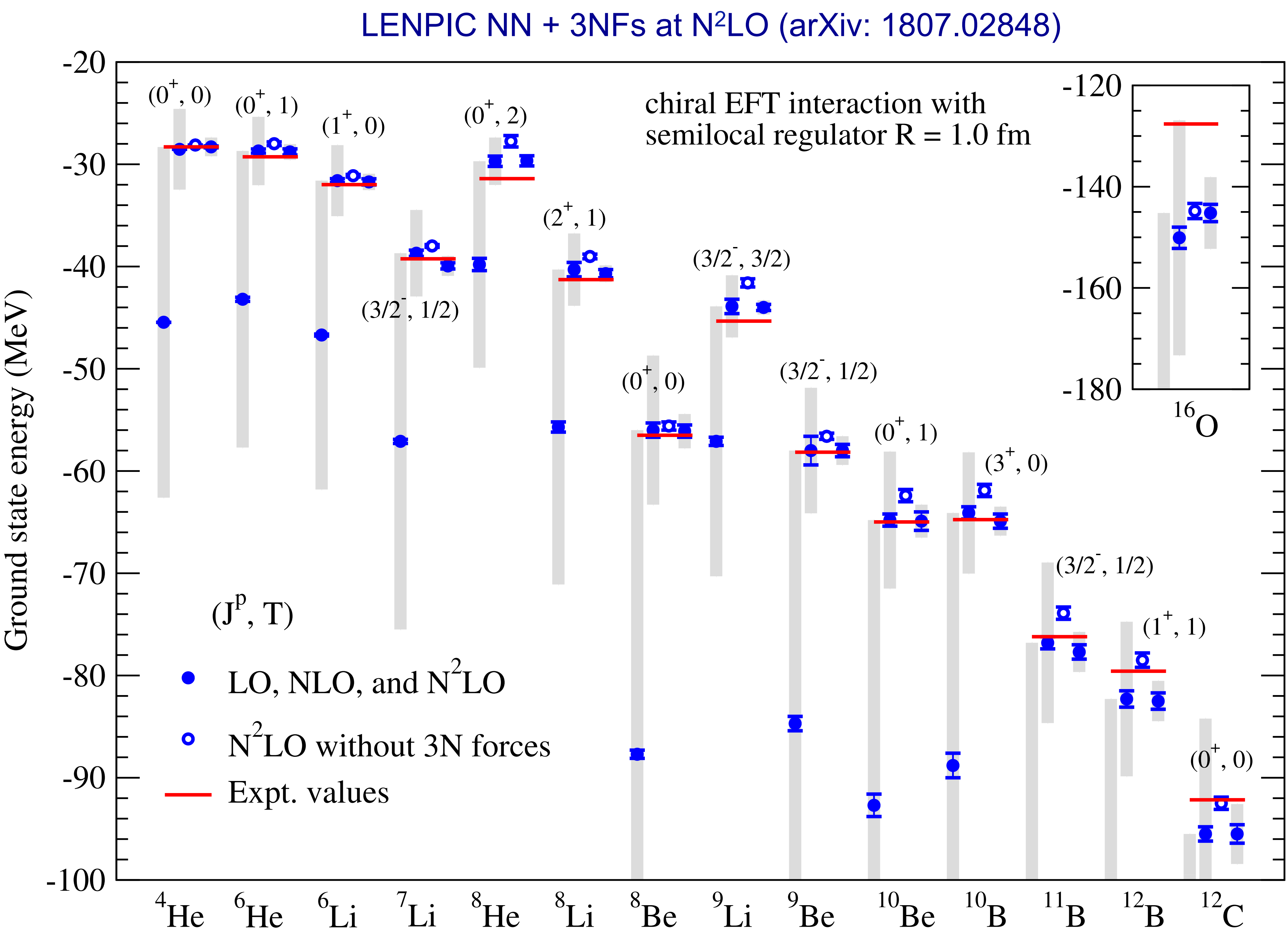
Given a Hamiltonian operator

$$\hat{\mathbf{H}} = \sum_{i<j} \frac{(\vec{p}_i - \vec{p}_j)^2}{2\,m\,A} + \sum_{i<j} V_{ij} + \sum_{i<j<k} V_{ijk} + \ldots$$

solve the eigenvalue problem for wavefunction of $A$ nucleons

$$\hat{\mathbf{H}}\,\Psi(r_1, \ldots, r_A) = \lambda\,\Psi(r_1, \ldots, r_A)$$

- Expand eigenstates in basis states $|\Psi\rangle = \sum a_i |\Phi_i\rangle$
- Diagonalize Hamiltonian matrix $H_{ij} = \langle\Phi_j|\hat{\mathbf{H}}|\Phi_i\rangle$
- No Core Full Configuration (NCFC) – All A nucleons treated equally
- Complete basis $\longrightarrow$ exact result
- In practice
  - truncate basis
  - study behavior of observables as function of truncation



LENPIC NN + 3NFs at N2LO (arXiv: 1807.02848)
chiral EFT interaction with
semilocal regulator R = 1.0 fm
Ground state energy (MeV)
(Jp, T)
LO, NLO, and N2LO
N2LO without 3N forces
Expt. values
4He
6He
6Li
7Li
8He
8Li
8Be
9Li
9Be
10Be
10B
11B
12B
12C
16O
(0+, 0)
(0+, 1)
(1+, 0)
(3/2-, 1/2)
(0+, 2)
(2+, 1)
(0+, 0)
(3/2-, 3/2)
(3/2-, 1/2)
(0+, 1)
(3+, 0)
(3/2-, 1/2)
(1+, 1)
(0+, 0)

## Is there a bridge between present-day chiral EFT and full QCD?

Consider Light-front Hamiltonian approach to chiral Effective Field Theory that is relativistic and incorporates nucleon finite size effects.

➔Light-Front Wave Functions (LFWFs):

1. possess boost invariance
2. Provide access to experimental observables

Dirac's forms of relativistic dynamics [Dirac, Rev. Mod. Phys. **21**, 392 1949]

Instant form is the well-known form of dynamics starting with $x^0 = t = 0$

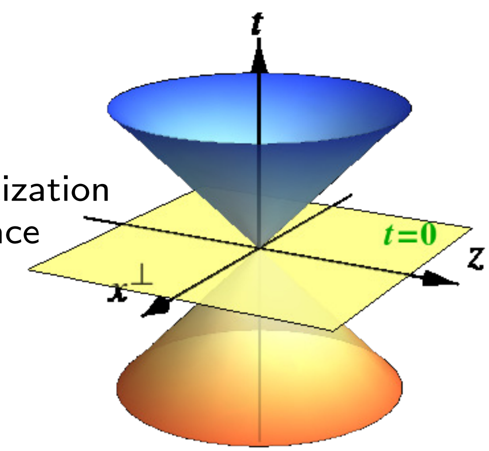
$K^i = M^{0i}$, $J^i = \frac{1}{2}\varepsilon^{ijk}M^{jk}$, $\varepsilon^{ijk}$ = (+1,-1,0) for (cyclic, anti-cyclic, repeated) indeces

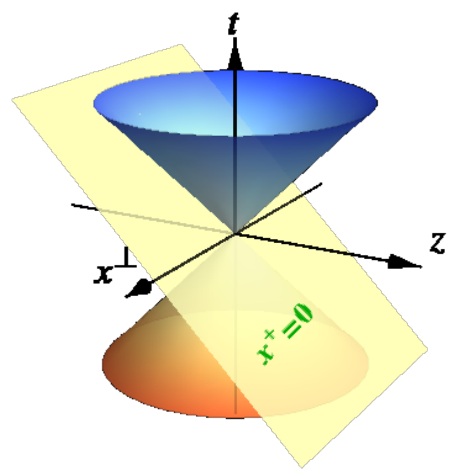
Front form defines relativistic dynamics on the light front (LF): $x^+ = x^0 + x^3 = t + z = 0$

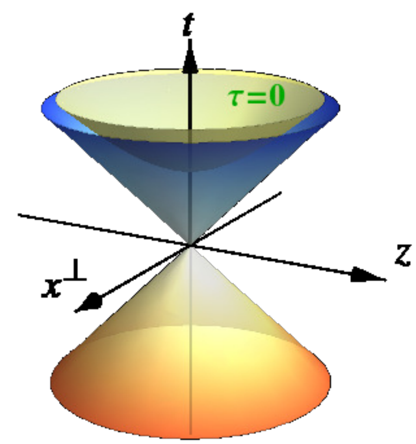
$$P^{\pm} \triangleq P^0 \pm P^3,\ \vec{P}^{\perp} \triangleq (P^1, P^2),\ x^{\pm} \triangleq x^0 \pm x^3,\ \vec{x}^{\perp} \triangleq (x^1, x^2),\ E^i = M^{+i},$$
$$E^+ = M^{+-},\ F^i = M^{-i}$$

| | instant form | front form | point form |
|---|---|---|---|
| time variable | $t = x^0$ | $x^+ \triangleq x^0 + x^3$ | $\tau \triangleq \sqrt{t^2 - \vec{x}^2 - a^2}$ |

quantization surface




| | instant form | front form | point form |
|---|---|---|---|
| Hamiltonian | $H = P^0$ | $P^- \triangleq P^0 - P^3$ | $P^\mu$ |
| kinematical | $\vec{P}, \vec{J}$ | $\vec{P}^\perp, P^+, \vec{E}^\perp, E^+, J^-$ | $\vec{J}, \vec{K}$ |
| dynamical | $\vec{K}, P^0$ | $\vec{F}^\perp, P^-$ | $\vec{P}, P^0$ |
| dispersion relation | $p^0 = \sqrt{\vec{p}^2 + m^2}$ | $p^- = (\vec{p}_\perp^2 + m^2)/p^+$ | $p^\mu = mv^\mu \ (v^2 = 1)$ |

Adapted from talk by Yang Li

# Discretized Light Cone Quantization

Pauli & Brodsky c1985

# Basis Light Front Quantization*

$$\phi(\vec{x}) = \sum_{\alpha} \left[ f_{\alpha}(\vec{x}) a_{\alpha}^{+} + f_{\alpha}^{*}(\vec{x}) a_{\alpha} \right]$$

Operator-valued distribution function

where $\{a_{\alpha}\}$ satisfy usual (anti-) commutation rules.

Furthermore, $f_{\alpha}(\vec{x})$ are arbitrary except for conditions:

Orthonormal: $$\int f_{\alpha}(\vec{x}) f_{\alpha'}^{*}(\vec{x}) d^{3}x = \delta_{\alpha\alpha'}$$

Complete: $$\sum_{\alpha} f_{\alpha}(\vec{x}) f_{\alpha}^{*}(\vec{x}') = \delta^{3}(\vec{x} - \vec{x}')$$

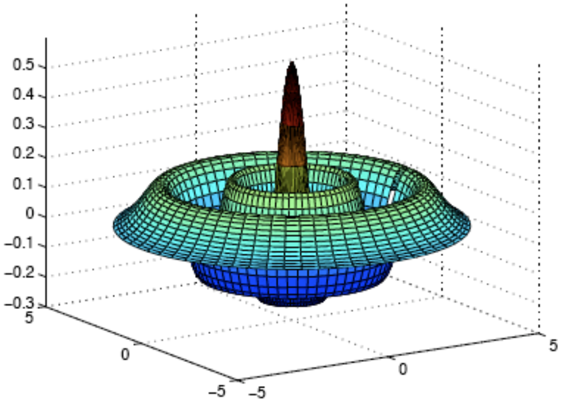
=> Wide range of choices for $f_{a}(\vec{x})$ and our initial choice is

$$f_{\alpha}(\vec{x}) = N e^{ik^{+}x^{-}} \Psi_{n,m}(\rho,\varphi) = N e^{ik^{+}x^{-}} f_{n,m}(\rho) \chi_{m}(\varphi)$$

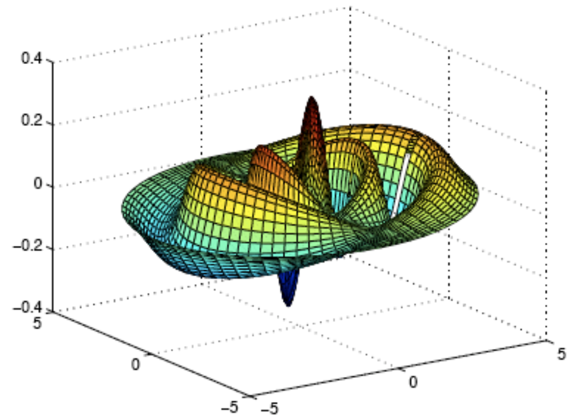
*J.P. Vary, H. Honkanen, J. Li, P. Maris, S.J. Brodsky, A. Harindranath, G.F. de Teramond, P. Sternberg, E.G. Ng and C. Yang, PRC 81, 035205 (2010). ArXiv:0905:1411

# Set of transverse 2D HO modes for n=4

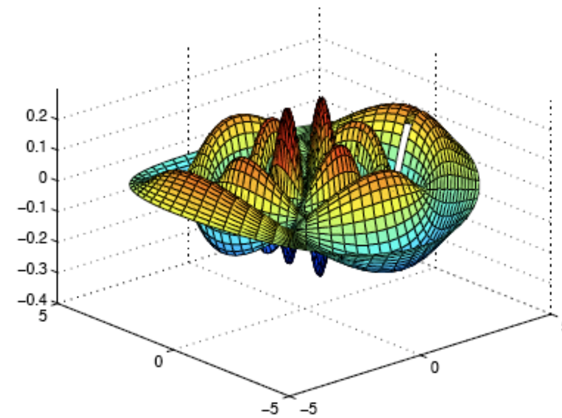
m=0



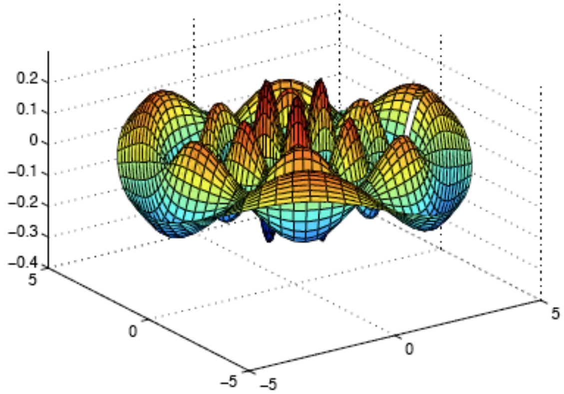

m=1



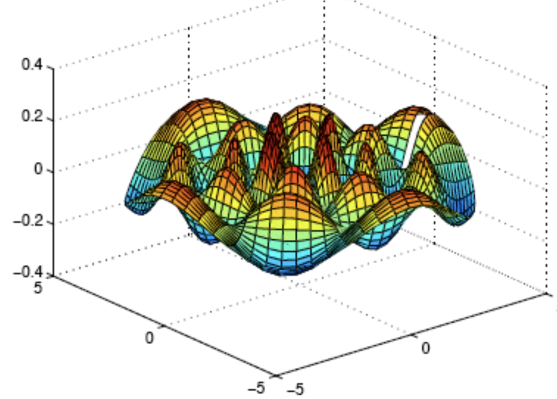

m=2




m=3




m=4




J.P. Vary, H. Honkanen, J. Li, P. Maris, S.J. Brodsky, A. Harindranath,
G.F. de Teramond, P. Sternberg, E.G. Ng and C. Yang, PRC 81, 035205 (2010).
ArXiv:0905:1411

# BLFQ
# Symmetries & Constraints

Baryon number $\sum_i b_i = B$

Charge $\sum_i q_i = Q$

Angular momentum projection (M-scheme) $\sum_i (m_i + s_i) = J_z$

Longitudinal momentum (Bjorken sum rule) $\sum_i x_i = \sum_i \frac{k_i}{K} = 1$

Transverse mode regulator (2D HO) $\sum_i (2n_i + |m_i| + 1) \le N_{\max}$

Longitudinal mode regulator (Jacobi) $\sum_i l_i \le L$

Global Color Singlets (QCD)

Light Front Gauge

Optional Fock-Space Truncation

$H \to H + \lambda H_{CM}$

All $J \geq J_z$ states in one calculation

Finite basis regulators

Preserve transverse boost invariance

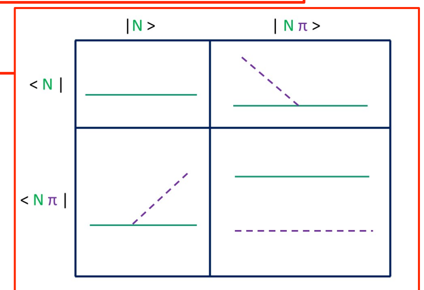
Can we develop a fully relativitistic Chiral EFT?

G. A. Miller, Phys. Rev. C 56, 2789 (1997);
Weijie Du, et al., in preparation

$$\mathcal{L} = \underbrace{\frac{1}{2}\partial_\mu \vec{\pi}\cdot\partial^\mu\vec{\pi} - \frac{1}{2}m_\pi^2\ \vec{\pi}\cdot\vec{\pi}}_{\text{free pion field}} + \underbrace{\bar{\chi}\Big\{\gamma_\mu i\partial^\mu - M - M\Big(i\gamma_5\frac{\vec{\tau}\cdot\vec{\pi}}{f} - \frac{1}{2f^2}\pi^2\Big)\Big\}\chi}_{\text{free nucleon field and nucleon-pion interaction}}$$

By Legendre transformation,
with the constraint equation

$$\chi_- = \frac{1}{i\partial^+}\Big[\gamma^0\gamma^\perp\cdot i\partial^\perp + M\gamma^0\Big(1 + i\gamma_5\frac{\vec{\tau}\cdot\vec{\pi}}{f} - \frac{1}{2f^2}\pi^2\Big)\Big]\chi_+$$




$$\mathcal{P}^- = \underbrace{\frac{1}{2}\partial^\perp\pi_a\cdot\partial^\perp\pi_a + \frac{1}{2}m_\pi^2\pi_a\pi_a + \chi_+^\dagger\frac{(p^\perp)^2+M^2}{p^+}\chi_+}_{\text{Kinetic energy for free pion and nucleon}}$$

$$+\chi_+^\dagger\Big[-\gamma^\perp\cdot i\partial^\perp + M\Big]\frac{1}{p^+}M\Big[i\gamma_5\frac{\vec{\tau}\cdot\vec{\pi}}{f}\Big]\chi_+ + \chi_+^\dagger M\Big[-i\gamma_5\frac{\vec{\tau}\cdot\vec{\pi}}{f}\Big]\frac{1}{p^+}\Big[\gamma^\perp\cdot i\partial^\perp + M\Big]\chi_+ + \mathcal{O}(1/f^2)$$

Now solve for the mass spectra and LFWFs in the proton sector

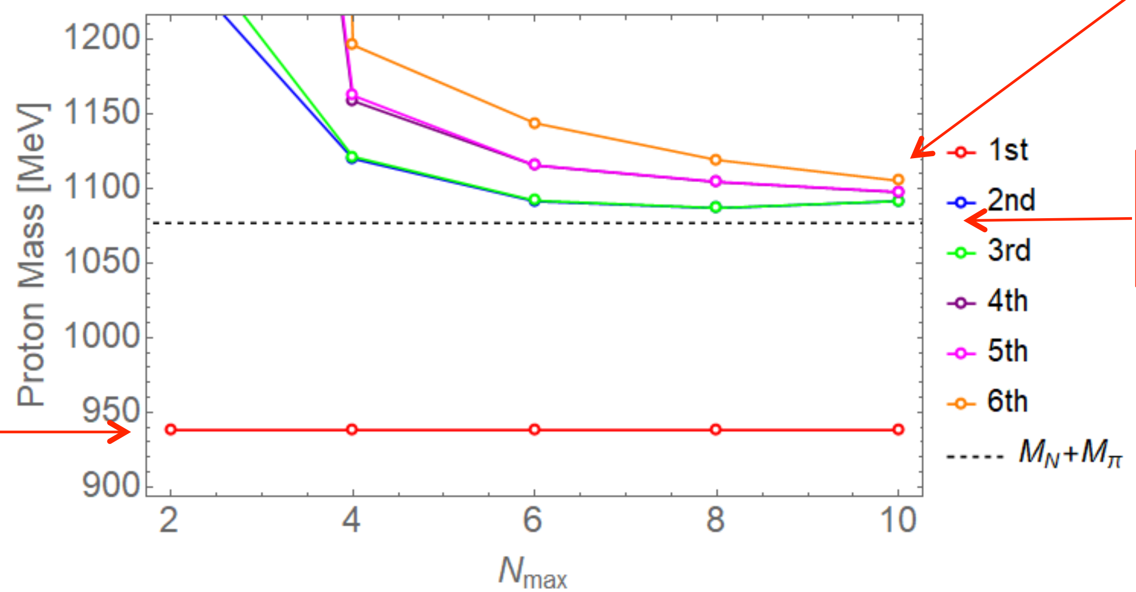
Weijie Du, et al.,
in preparation

# Preliminary results for the proton

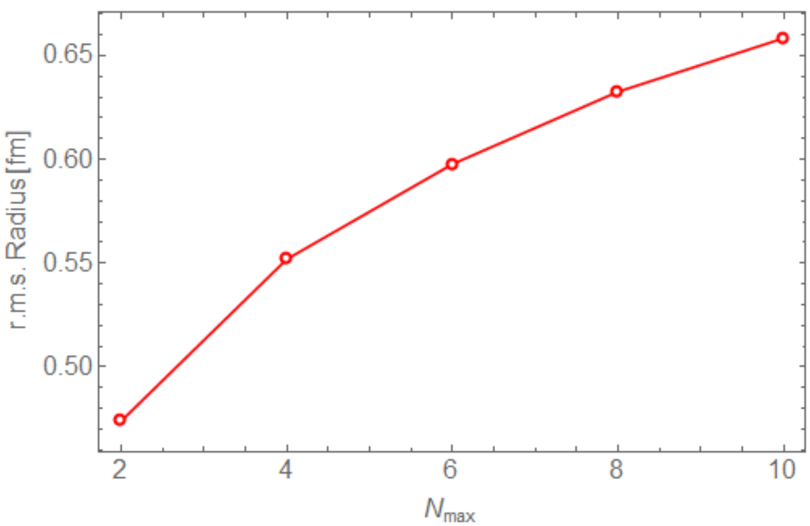
pion-nucleon scattering states emerge

pion-nucleon threshold

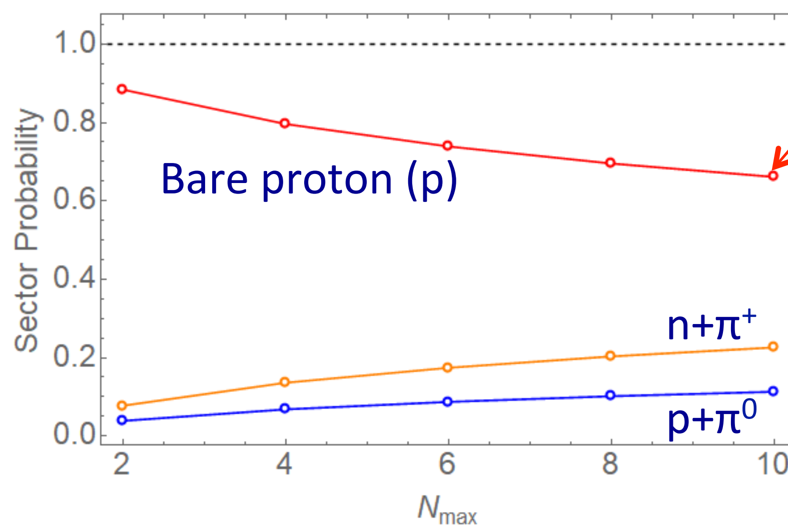
lowest mass eigenstate renormalized to experiment




proton charge radius increases with $N_{max}$



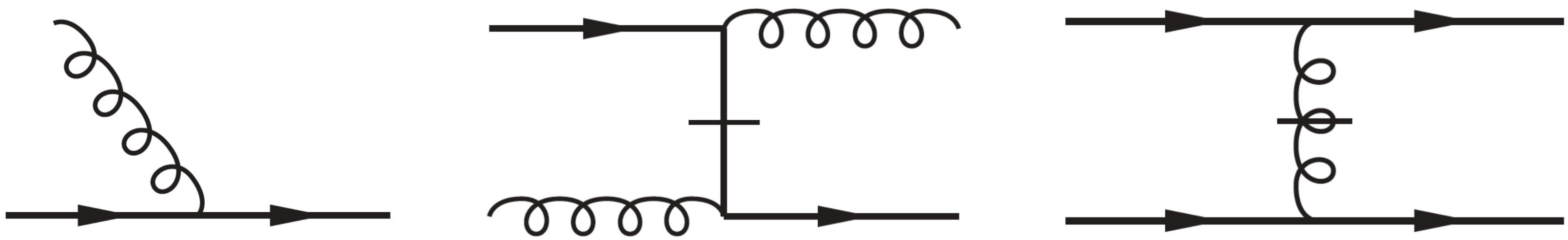

Fock sector probabilities vs Nmax



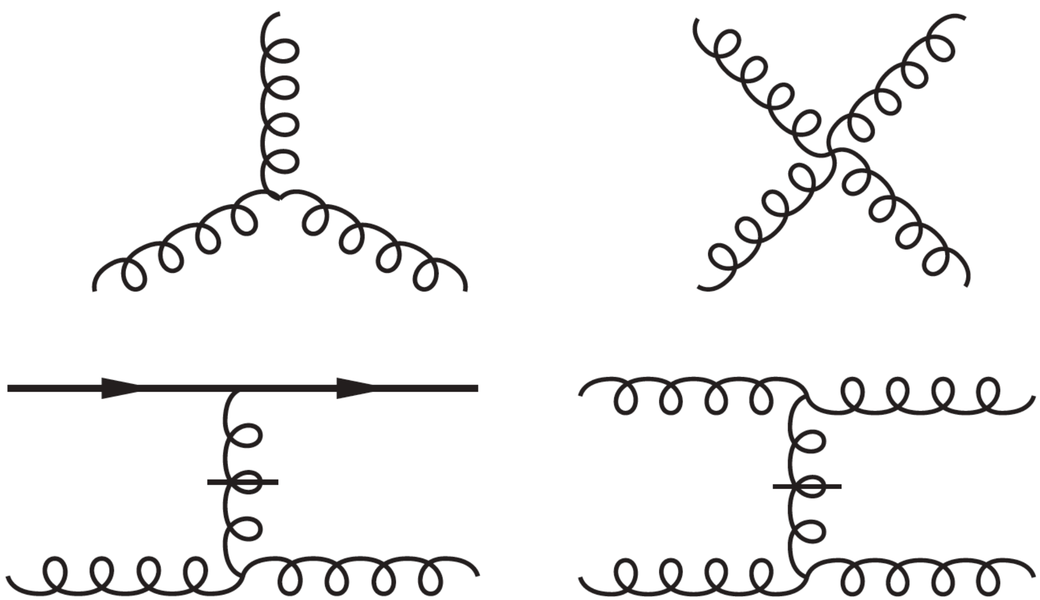

0.66

Now move to higher momentum scales, shorter distances, where the substructure of the mesons and baryons plays an essential role

## Light Front (LF) Hamiltonian Defined by its Elementary Vertices in LF Gauge



QED & QCD



QCD

# Heavy Quarkonia [Y.Li,PLB758,2016; PRD96,2017]

- Effective Hamiltonian in the $q\bar{q}$ sector

$$H_{\text{eff}} = \overbrace{\underbrace{\frac{\vec{k}_\perp^2 + m_q^2}{x} + \frac{\vec{k}_\perp^2 + m_{\bar{q}}^2}{1-x}}_{\text{LF kinetic energy}} + \underbrace{\kappa^4 x(1-x)\vec{r}_\perp^2 - \frac{\kappa^4}{(m_q + m_{\bar{q}})^2}\frac{\partial}{\partial x}\Big(x(1-x)\frac{\partial}{\partial x}\Big)}_{\text{confinement}}}^{H_0} + \underbrace{V_g}_{\text{one-gluon exchange}}$$

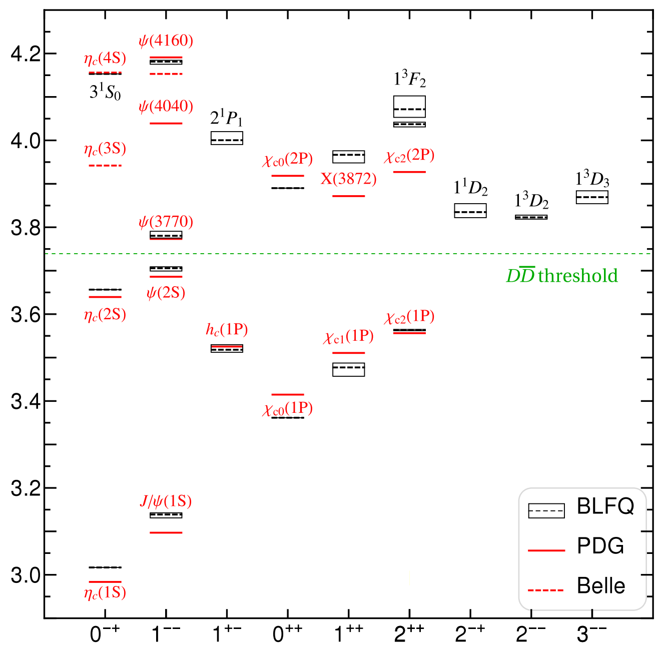
where $x = p_q^+/P^+$, $\vec{k}_\perp = \vec{p}_{q\perp} - x\vec{P}_\perp$, $\vec{r}_\perp = \vec{r}_{q\perp} - \vec{r}_{\bar{q}\perp}$.

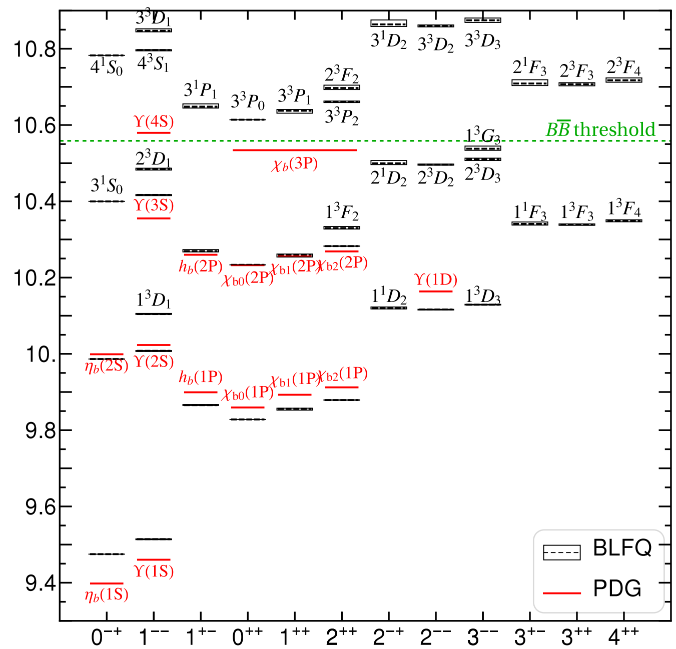
  - Confinement
    transverse holographic confinement [S.J.Brodsky,PR584,2015]
    longitudinal confinement [Y.Li,PLB758,2016]
  - One-gluon exchange with running coupling
    $V_g = -\frac{4}{3}\frac{4\pi\alpha_s(Q^2)}{Q^2}\bar{u}_{\sigma'}\gamma^\mu u_\sigma \bar{v}_s \gamma_\mu v_{s'}$

- Basis representation
  - valence Fock sector: $|q\bar{q}\rangle$
  - basis functions: eigenfunctions of $H_0$ (LF kinetic energy+ confinement)

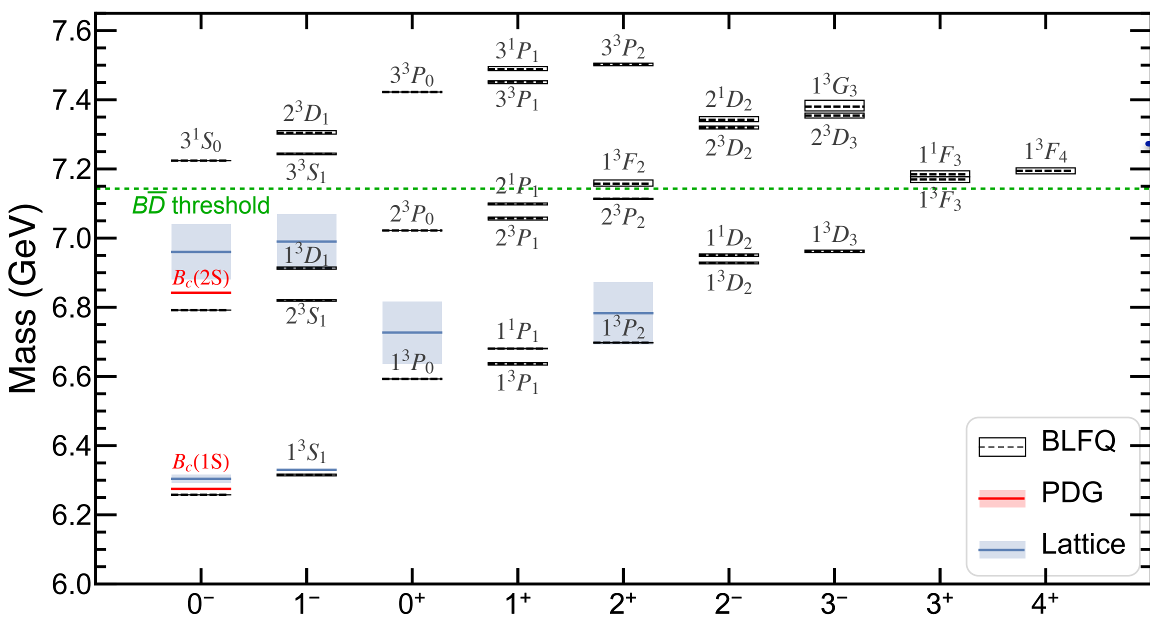
# Spectroscopy

[Li, Maris & Vary, PRD '17; Tang, Li, Maris & Vary, in preparation]

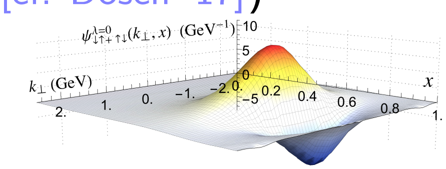


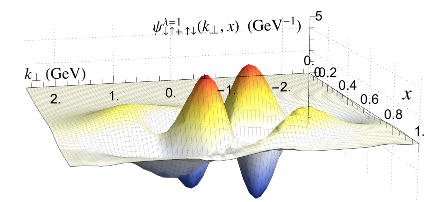




Heavy mesons: rms deviations 31 – 38 MeV




No new parameters for $B_c$ with HQET fixing confining strength (HQET, [cf. Dosch '17])



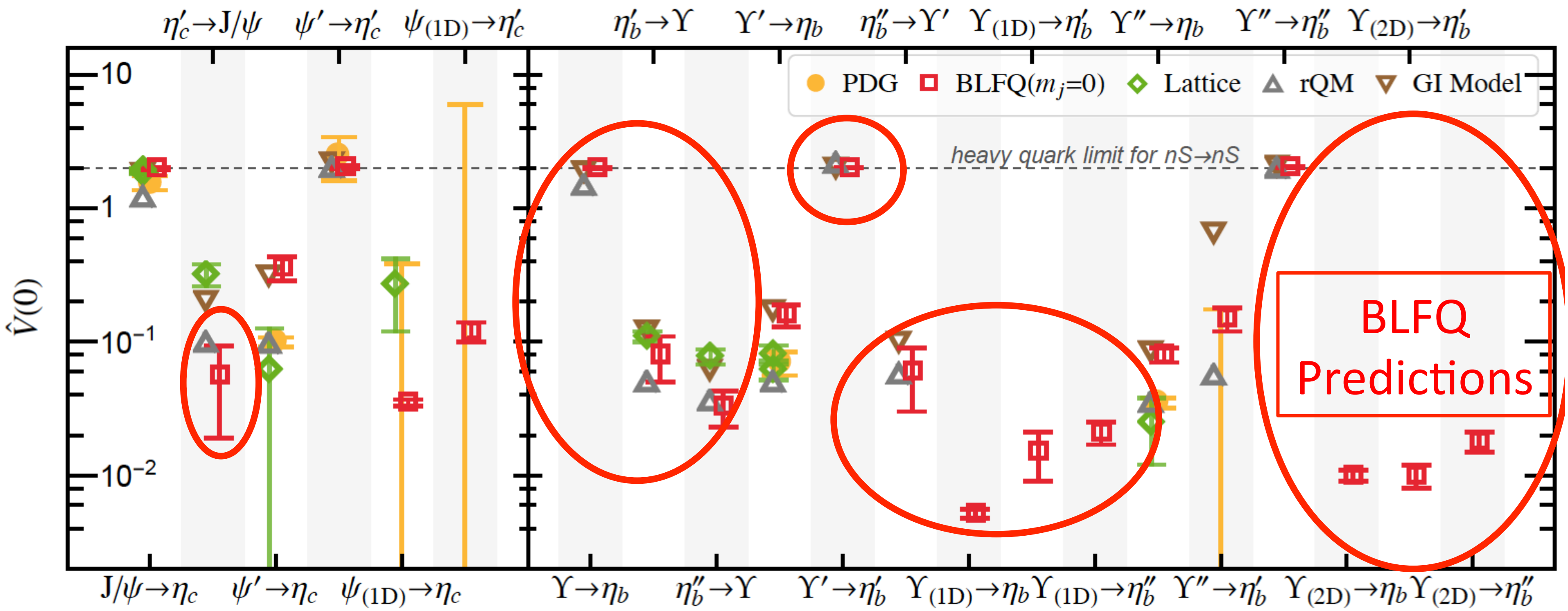



# Radiative transitions between $0^{-+}$ and $1^{--}$ heavy quarkonia

Meijian Li, et al.; PRD **98,** 034024 (2018)

Decay width:

$$\Gamma(\mathcal{V} \to \mathcal{P} + \gamma) = \int d\Omega_q \frac{1}{32\pi^2} \frac{|\vec{q}|}{m_{\mathcal{V}}^2} \frac{1}{2J_{\mathcal{V}}+1} \sum_{m_j,\lambda} |\mathcal{M}_{m_j,\lambda}|^2 = \frac{(m_{\mathcal{V}}^2 - m_{\mathcal{P}}^2)^3}{(2m_{\mathcal{V}})^3 (m_{\mathcal{P}} + m_{\mathcal{V}})^2} \frac{|V(0)|^2}{(2J_{\mathcal{V}}+1)\pi}$$





*[PDG] C.Patrignani, et al., CPC40,2016.*

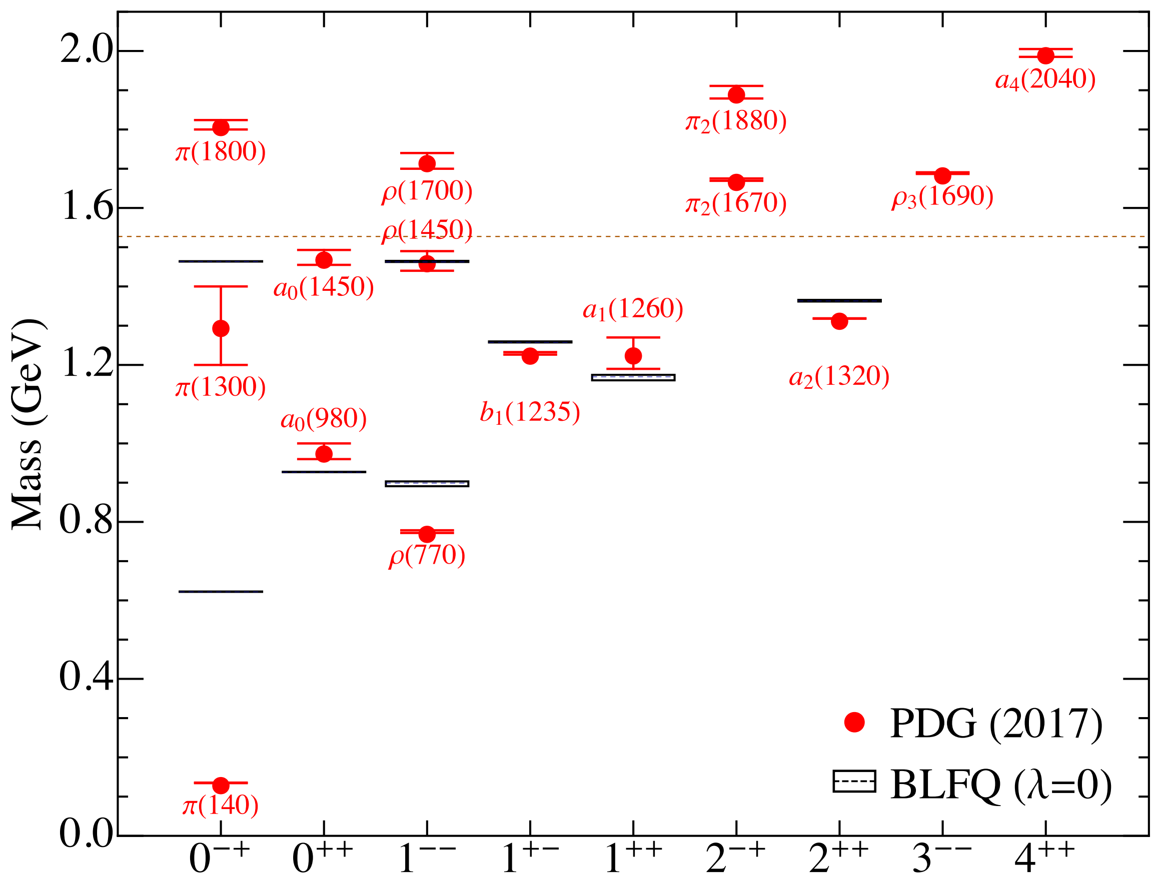
*[Lattice] J. J. Dudek, et al., PRD73,2006; PRD79, 2009. D. Bečirević, et al., JHEP01,2013; JHEP05,2015. C. Hughes, et al., PRD92,2015. R.Lewis, et al.,PRD86,2012.*

*[relativistic Quark Model (rQM)] D.Ebert, et al., PRD67, 2013.*

*[Godfrey-Isgur Model (GI Model)] T.Barnes, et al., PRD72,2005; S.Godfrey, et al., PRD92, 2015.*

Moving to light mesons – role of chiral symmetry

# Spectroscopy: BLFQ with one-gluon dynamics




Confining strength and quark mass obtained by fitting the lowest PDG masses excluding pion

BLFQ mass uncertainty due to very small violation of rotational symmetry

**r.m.s. deviation (8 states): 189 MeV**

Model parameters:

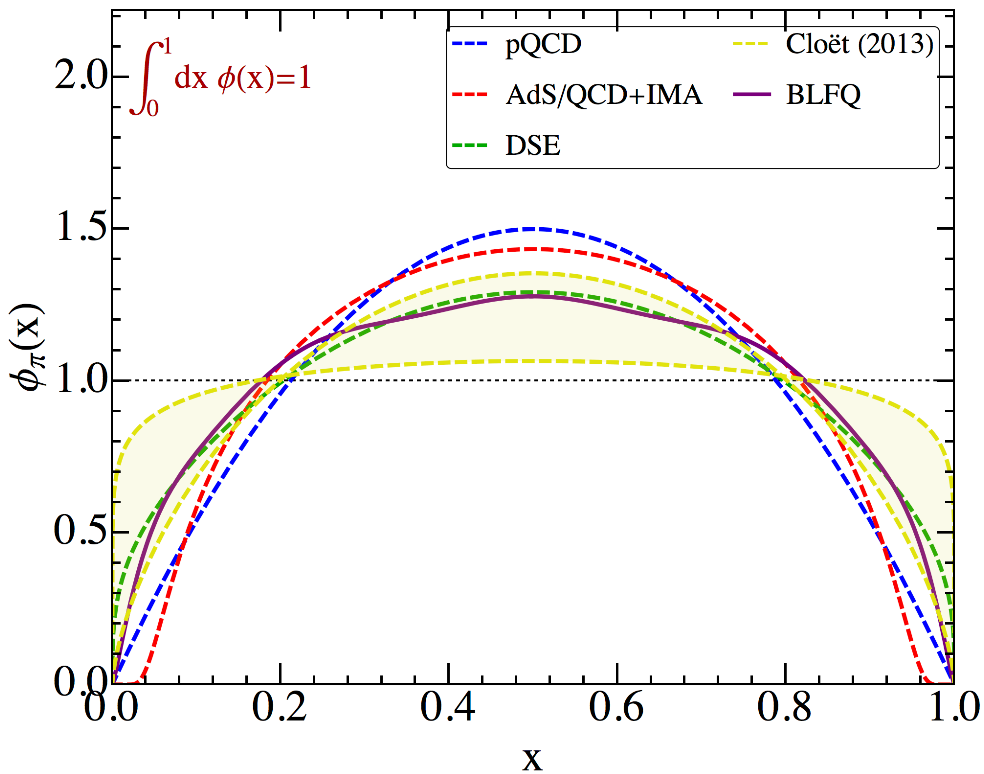
$\kappa =$ 0.57 GeV

$m_q = m_{\bar{q}} =$ 540 MeV

Wenyang Qian, et al., In preparation

Wenyang Qian, et al., In preparation

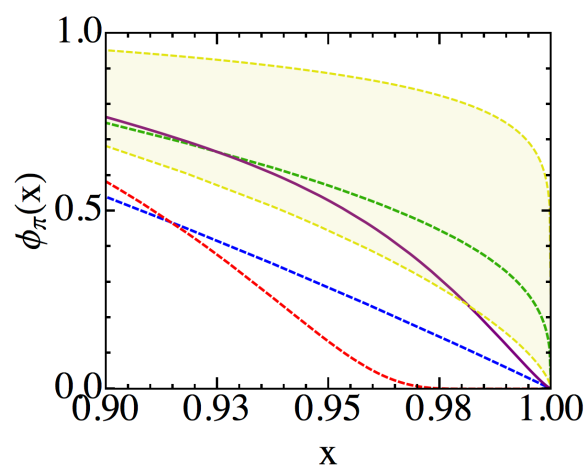
# Parton distribution amplitudes for the pion




DSE: Lei Chang et al, PRL110, 132001(2013)
Cloët(2013): Cloët et al, PRL111, 092001(2013)
AdS/QCD + IMA: Brodsky et al, PhysRep548, 1(2015)

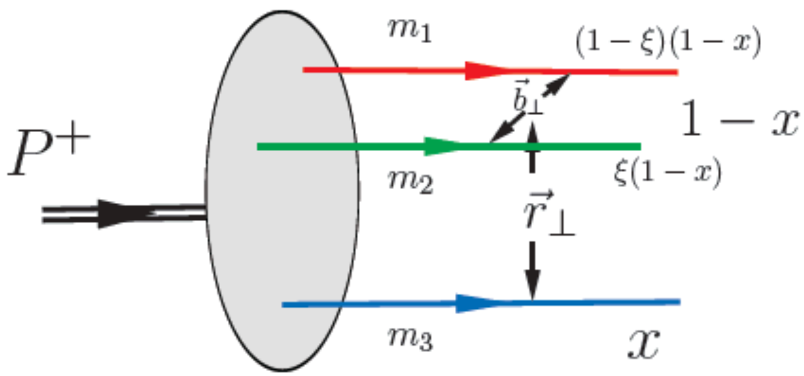
Exclusive processes at large momentum transfer

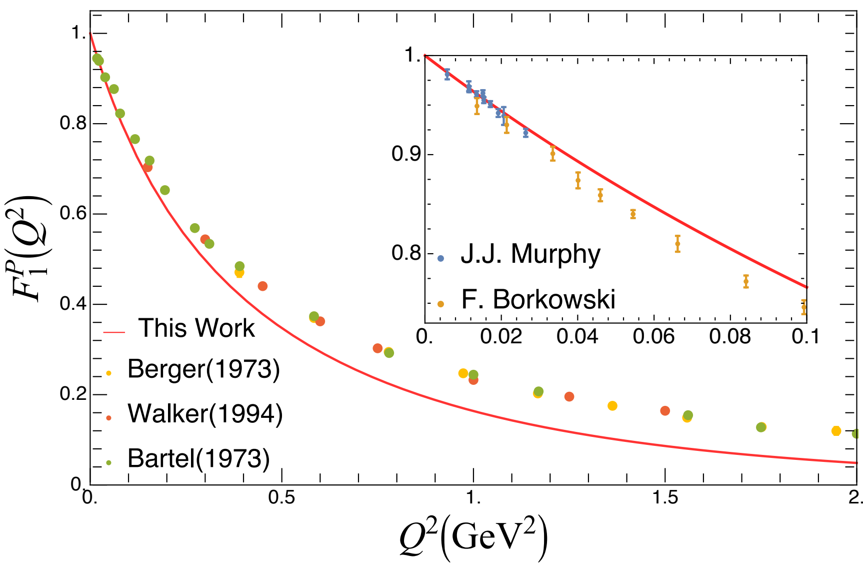
$$\phi_{\mathcal{P},\mathcal{V}}(x,\mu) \sim \frac{1}{f_{\mathcal{P},\mathcal{V}}\sqrt{x(1-x)}} \times \int \frac{d^2\boldsymbol{k}_\perp}{(2\pi)^3}\psi^{(m_j=0)}_{\uparrow\downarrow\pm\downarrow\uparrow}(x,\boldsymbol{k}_\perp)$$

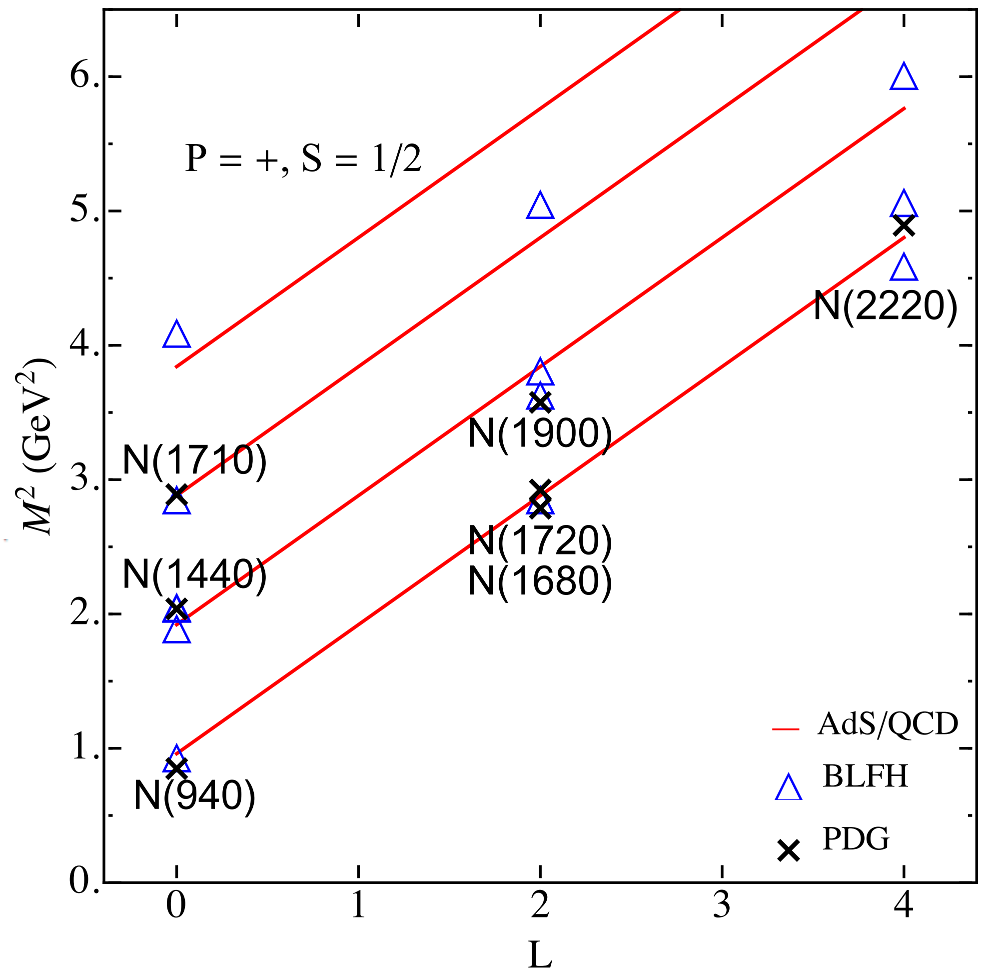


## Baryons

Anji Yu, et al., in preparation



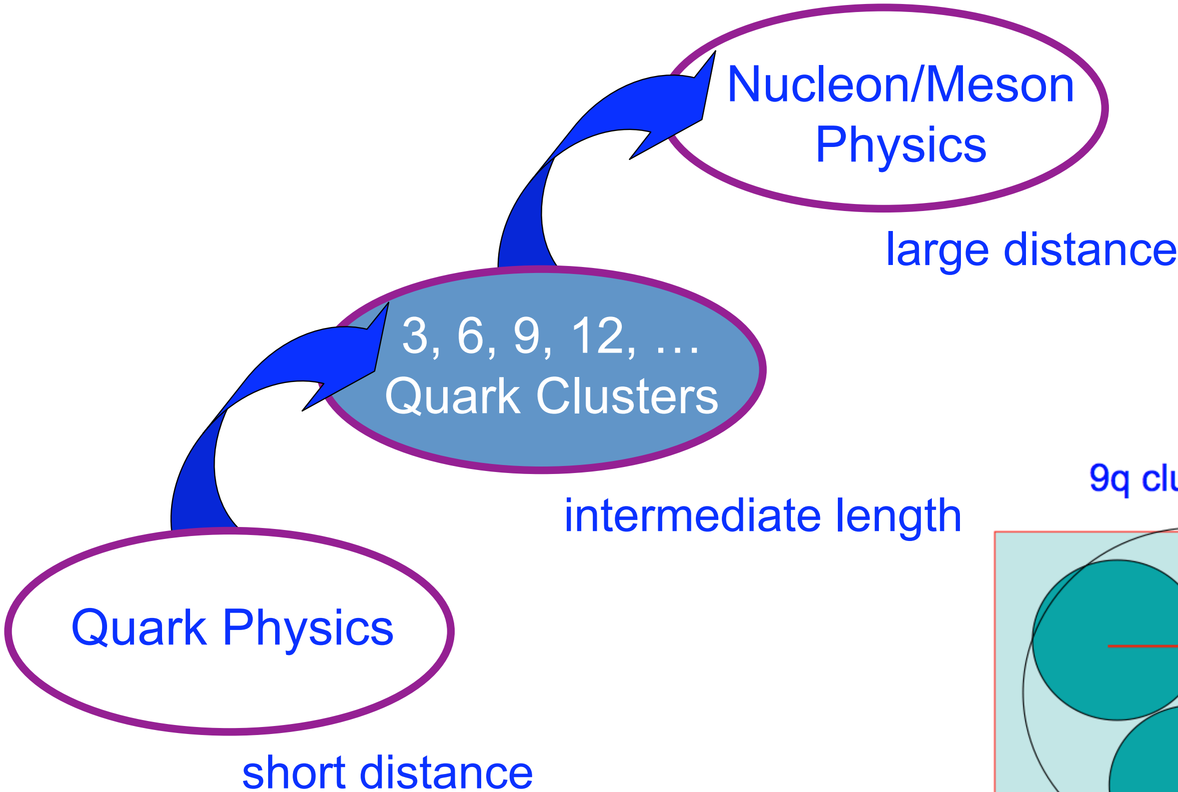




$$M^2_{\mathbf{n}_1,\mathbf{m}_1,\mathbf{n}_2,\mathbf{m}_2,L,l} = (\mathrm{m}_3 + \mathrm{M}_L)^2 + 2\kappa^2(2\mathbf{n}_1 + |\mathbf{m}_1| + 2\mathbf{n}_2 + |\mathbf{m}_2| + 2)$$
$$+ \frac{\mathrm{M}_L + \mathrm{m}_3}{\mathrm{m}_1 + \mathrm{m}_2 + \mathrm{m}_3}\kappa^2(2l+1) + \frac{\kappa^4}{(\mathrm{m}_1 + \mathrm{m}_2 + \mathrm{m}_3)^2} l(l+1) + \mathrm{const.},$$
$$\mathrm{M}_L^2 = (\mathrm{m}_1 + \mathrm{m}_2)^2 + \frac{\mathrm{m}_1 + \mathrm{m}_2}{\mathrm{m}_1 + \mathrm{m}_2 + \mathrm{m}_3}\kappa^2(2L+1) + \frac{\kappa^4}{(\mathrm{m}_1 + \mathrm{m}_2 + \mathrm{m}_3)^2} L(L+1)$$

Duality, in this view, is also the issue of crossing over between scales as one changes the resolution

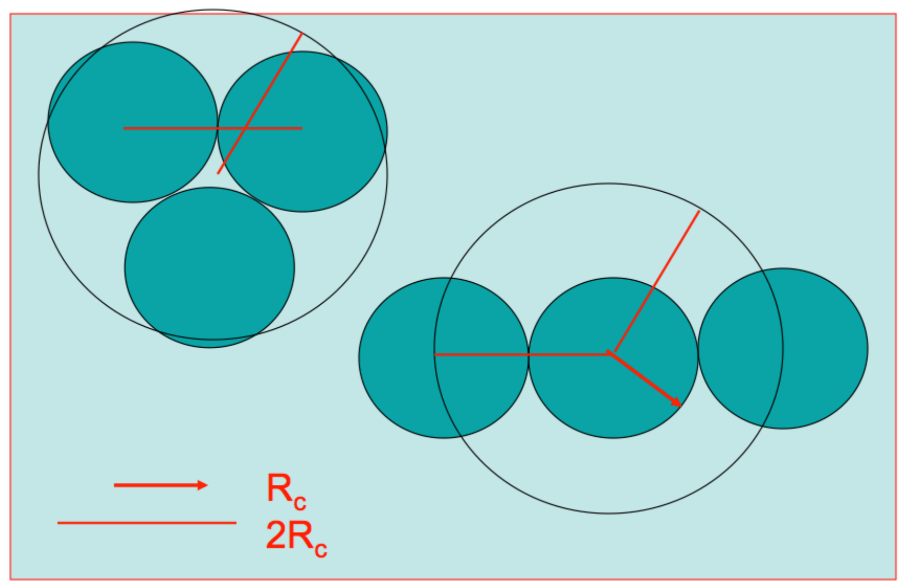
# Looking ahead: under what conditions do we require a quark-based description of nuclear structure?

## "Quark Percolation in Cold and Hot Nuclei"




Probes with Q > 1 GeV/c
Spin content of the proton
Nuclear form factors
DIS on nuclei – Bjorken x > 1
DIS in Duality region
Nuclear Equation of State

9q cluster at geometrical limits of formation




Also looking ahead: can such a sequence of EFTs be constructed in light-front field theory?

H.J. Pirner and J.P. Vary, Phys. Rev. C. **84**, 015201(2011)

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

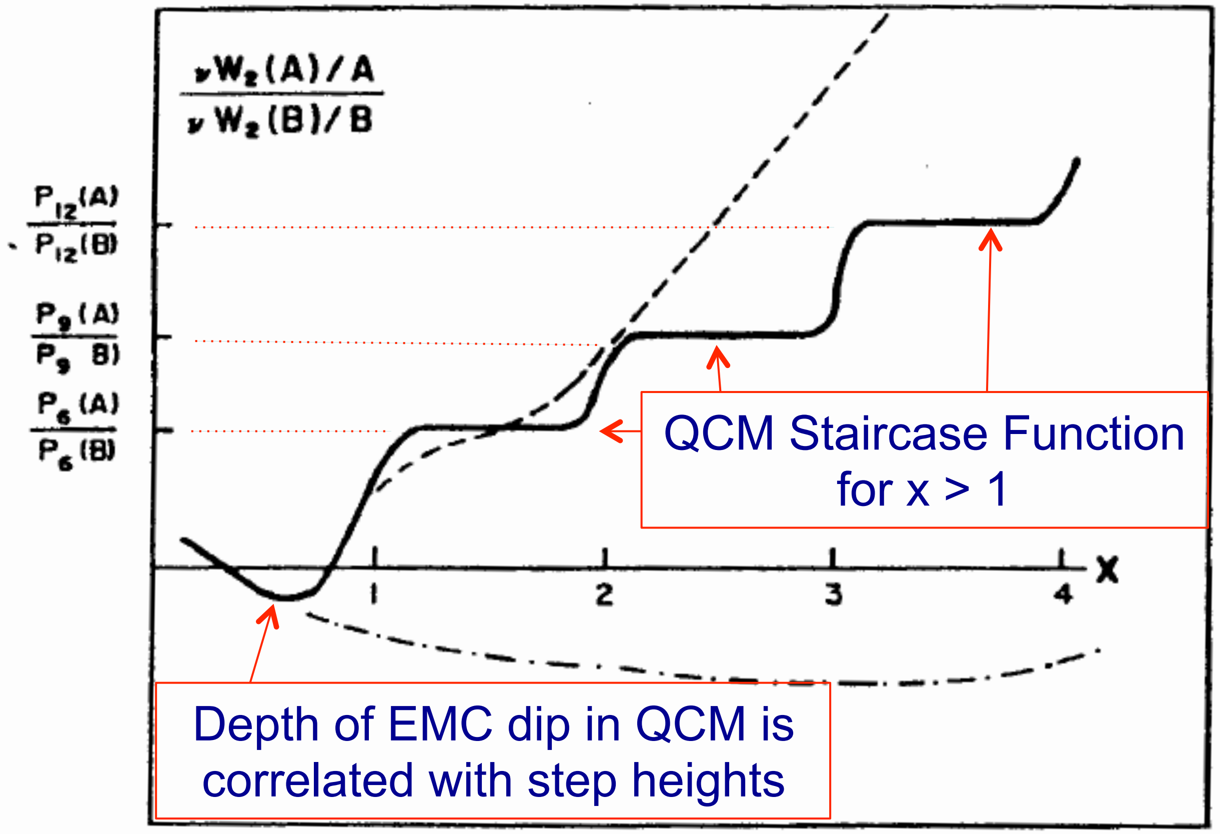



Fig. 2. Characteristic behaviour of the ratio of nuclear structure functions per nucleon for different models over a wide kinematic range of x. The QCM gives the solid curve. The dashed curve is due to the model of reference 22. The dashed-dot curve approximates the predictions of references 23 and 24.

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

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

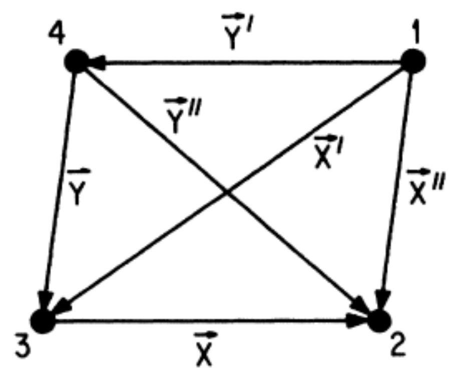



FIG. 5. Coordinate vectors of three-quark subsystems used in Eqs. (5) to define quark cluster probabilities in the $A=4$ nucleus.

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

## 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:

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

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

$\bar{n}_{q/i}$ 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 $2R_c \sim 1\, fm$

For i=3, we use the measured nucleon inelastic structure function. **Note: $p_3$ < 1**

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

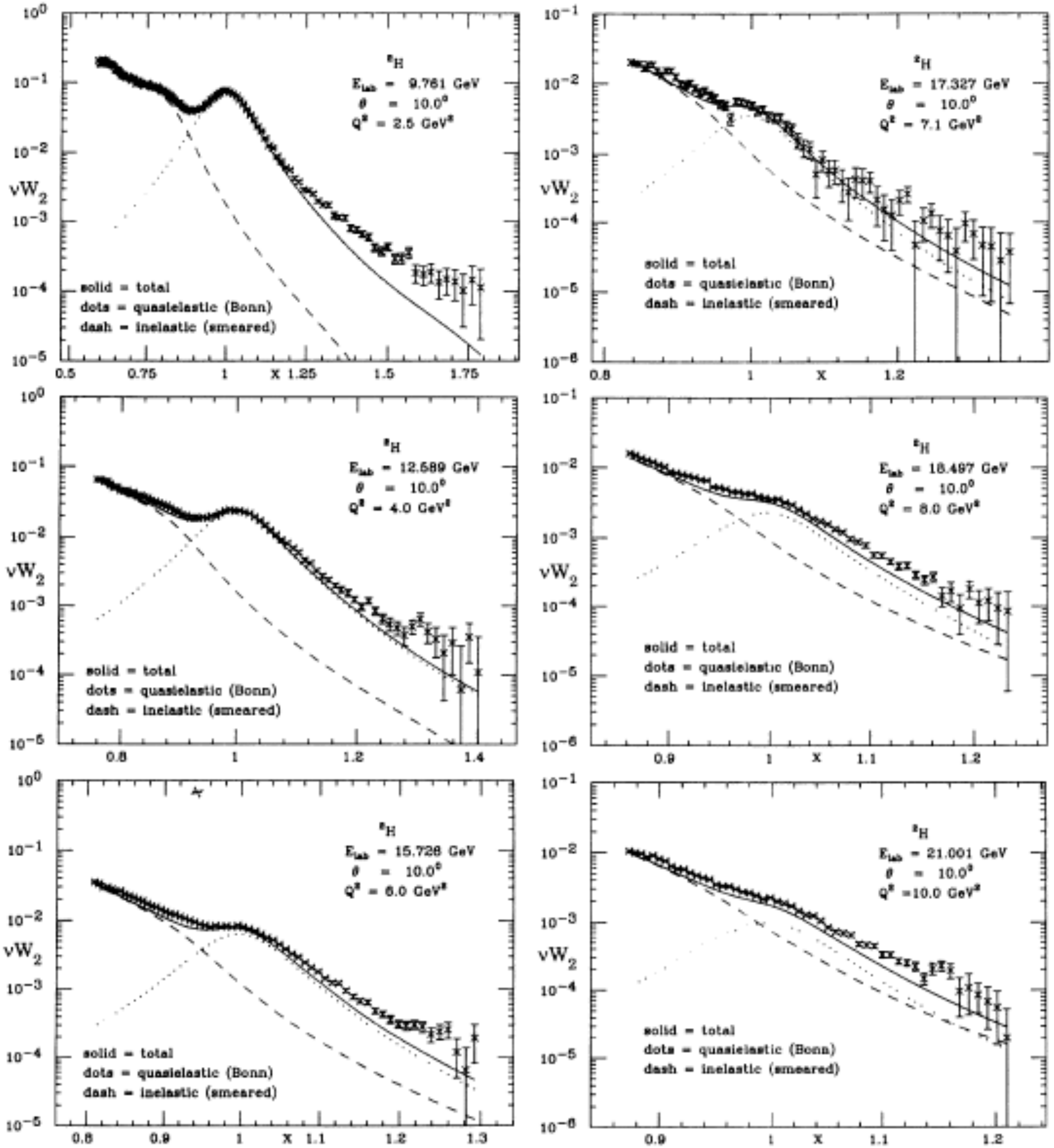
Regge behavior

Counting rule: $2(n_q - 1)$

with Nachtmann variable (kinematic $Q^2$ correction)

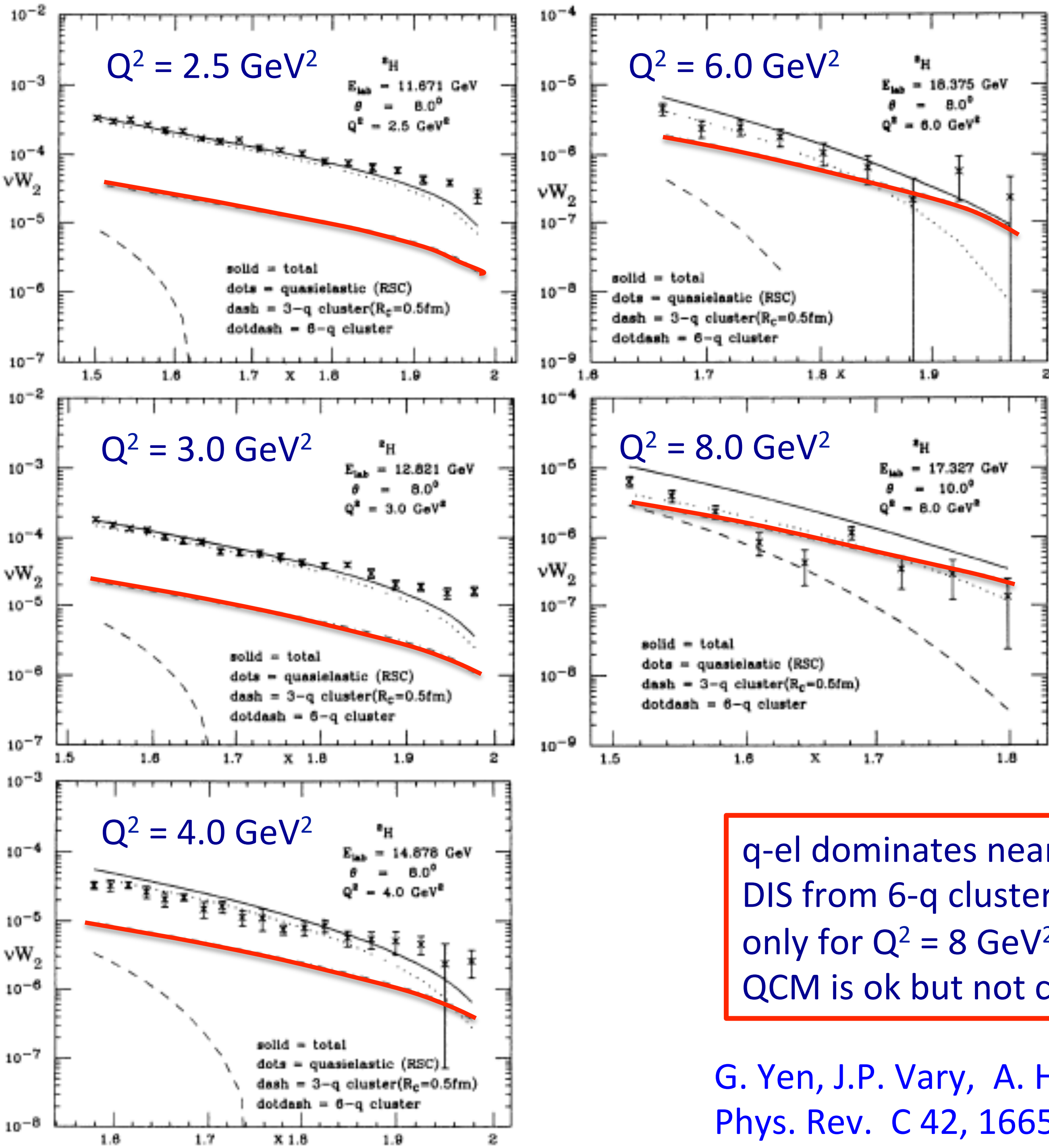
$$\xi = \frac{2x}{1 + (1 + Q^2/\nu^2)^{1/2}} \xrightarrow[\text{fixed } Q^2/\nu]{Q^2,\nu \to \infty} x$$

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




SLAC DIS data from Deuterium compared with model inelastic structure function including Quasi-elastic knockout, nucleon excitations and realistic momentum distributions (Bonn).
**No** 6-q clusters ($p_3$ = 1).

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

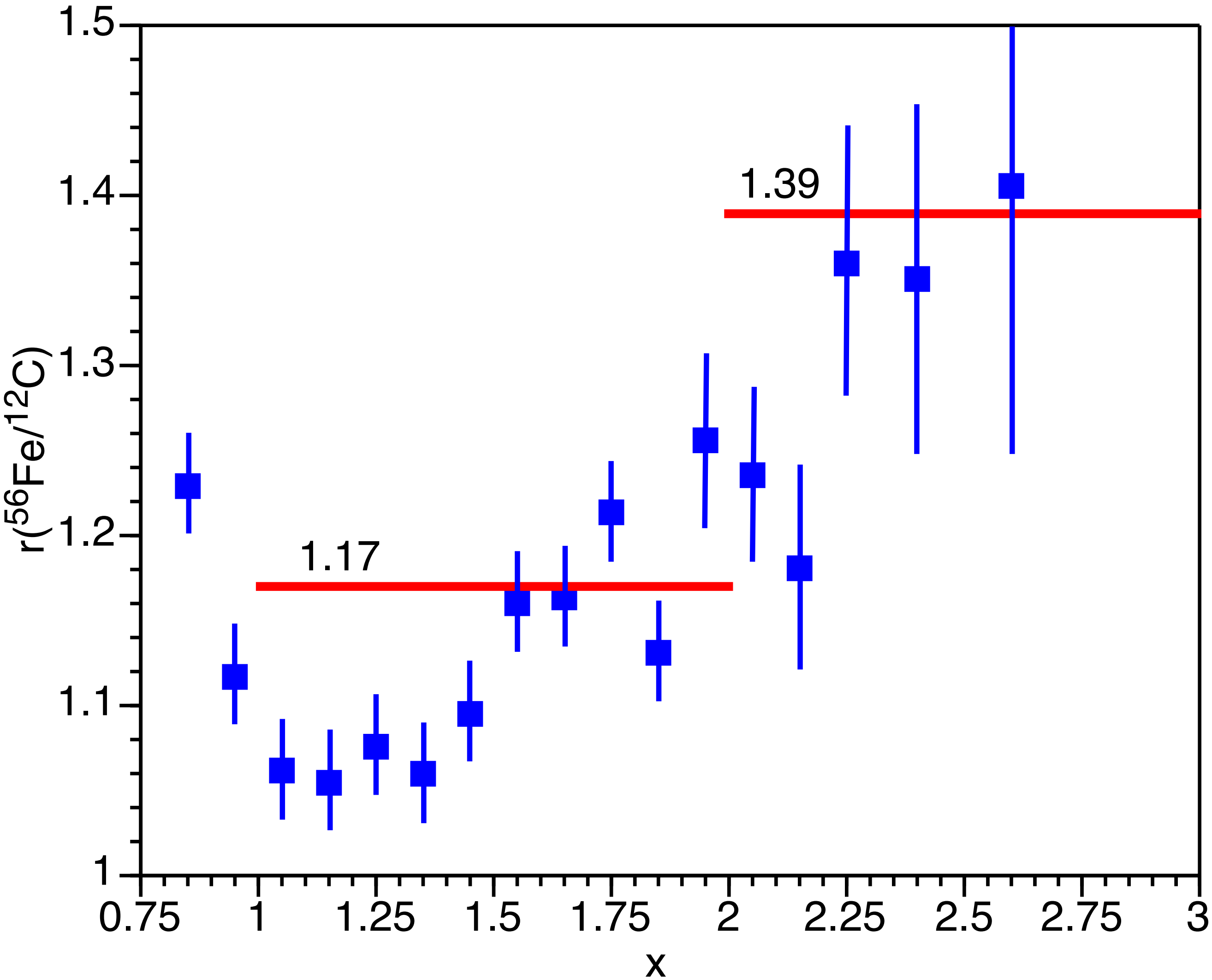



SLAC DIS data from deuterium compared with model inelastic structure function including Quasi-elastic knockout, nucleon excitations, 6-quark clusters (4.4%) and realistic momentum distributions (Reid Soft Core)

q-el dominates nearly all data: DIS from 6-q cluster dominates only for $Q^2$ = 8 $GeV^2$ where the QCM is ok but not conclusive

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

## 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)

# 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

0.08/0.04 = 2.0

0.13/0.04 = 3.3

0.14/0.04 = 3.5

0.15/0.04 = 3.8

0.15/0.04 = 3.8

0.17/0.04 = 4.3

$^4$He/$^3$He = 1.55

Fe/C = 1.17

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

## Overview

Preserving predictive power in order to test theory with experiment requires effective field theories with controlled approximations and solutions that span the changes of scale from low to high resolution within the range of their validity

## Conclusions and Outlook

- Chiral EFT is making rapid progress for nuclear structure at low Q
- BLFQ/tBLFQ are practical approaches to light-front QFT
- Provide a pathway to understand nuclei at increasing resolution
- Next goal: mesons and baryons in BLFQ with one dynamical gluon
- Outlook: two-baryon systems with effective LF Hamiltonians from chiral EFT to quark-gluon systems
- Future: EFT at the quark-percolation scale

## Announcement

New faculty position at Iowa State in Nuclear Theory
Supported, in part, by the Fundamental Interactions
Topical Collaboration

**Watch for the advertisement appearing soon**