Perspectives on short-distance phenomena in nuclei

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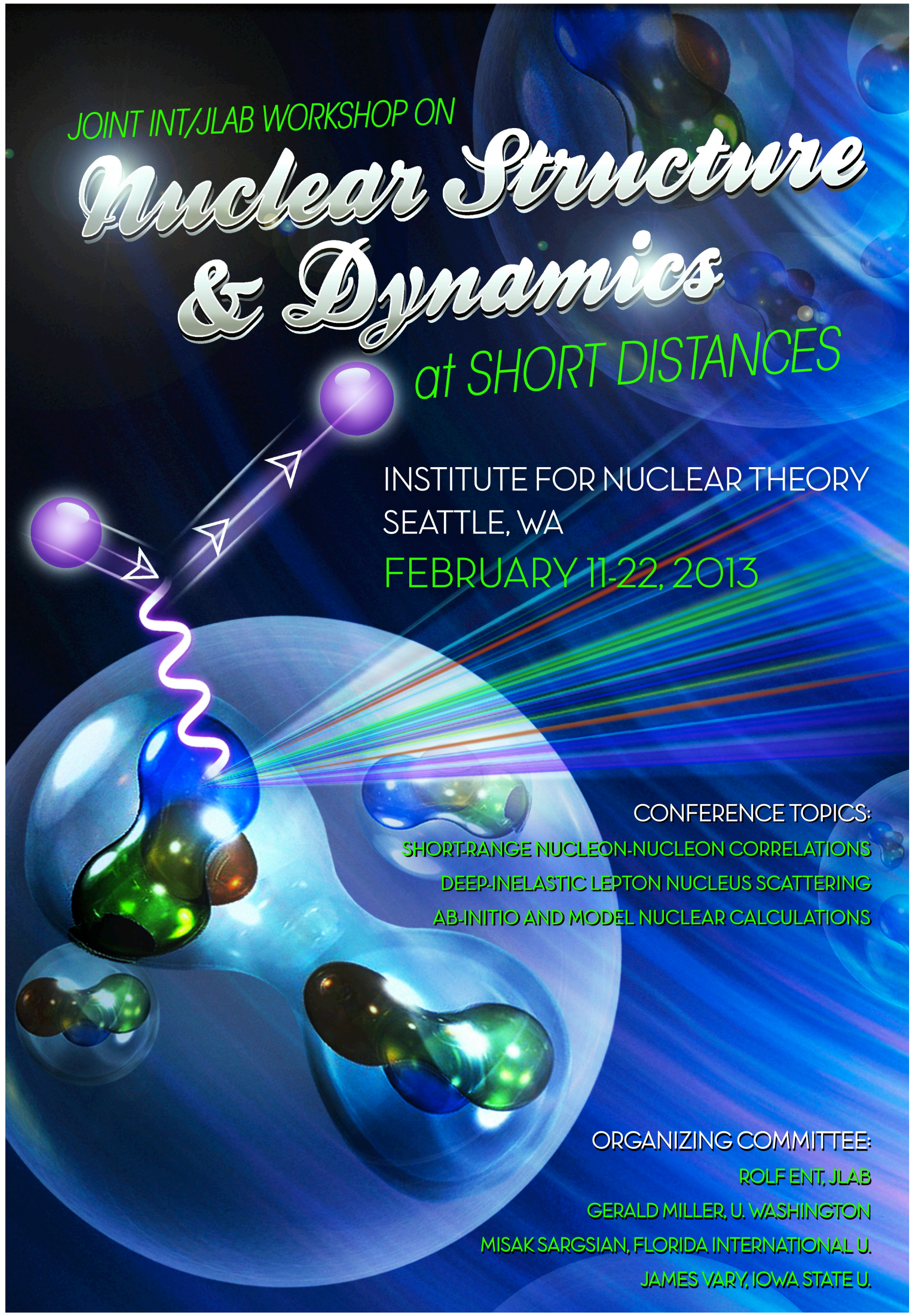
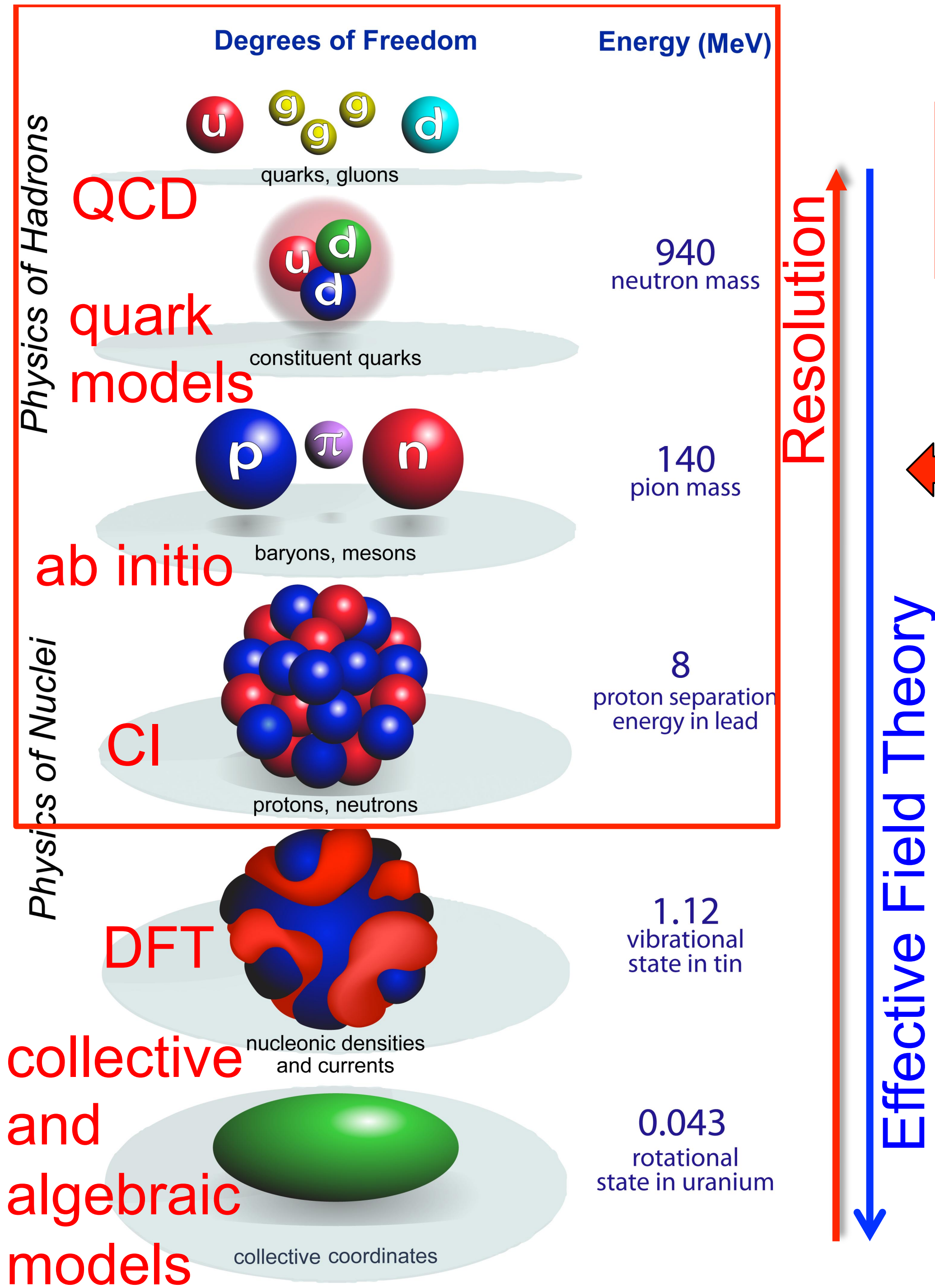
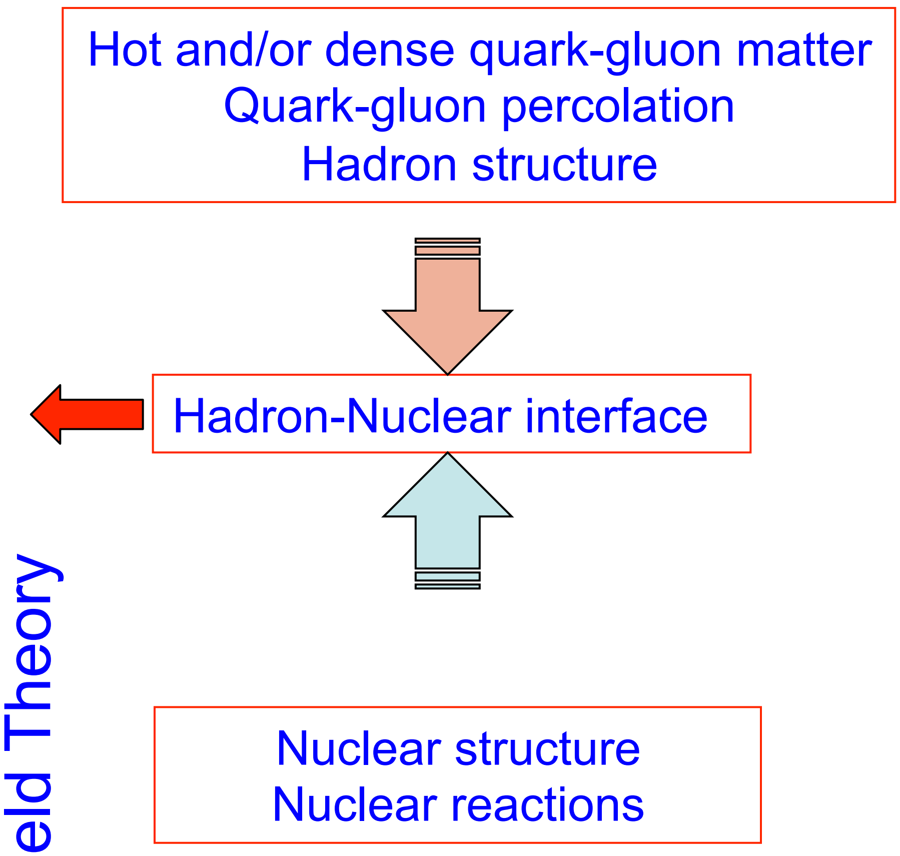
Short-Range Nuclear Correlations at an Electron-Ion Collider

CFNS Workshop, BNL
September 5 – 7, 2018







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

All interactions are "effective" until the ultimate theory unifying all forces in nature is attained.

Thus, even the Standard Model, incorporating QCD,
is an effective theory valid below the Planck scale
$\lambda < 10^{19}$ GeV/c

The "bare" NN interaction, usually with derived quantities,
is thus an effective interaction valid up to some scale, typically
the scale of the known NN phase shifts and Deuteron gs properties
$\lambda \sim 600$ MeV/c ($3.0\ \mathrm{fm}^{-1}$)

Effective NN interactions can be further renormalized to lower scales
and this can enhance convergence of the many-body applications
$\lambda \sim 300$ MeV/c ($1.5\ \mathrm{fm}^{-1}$)

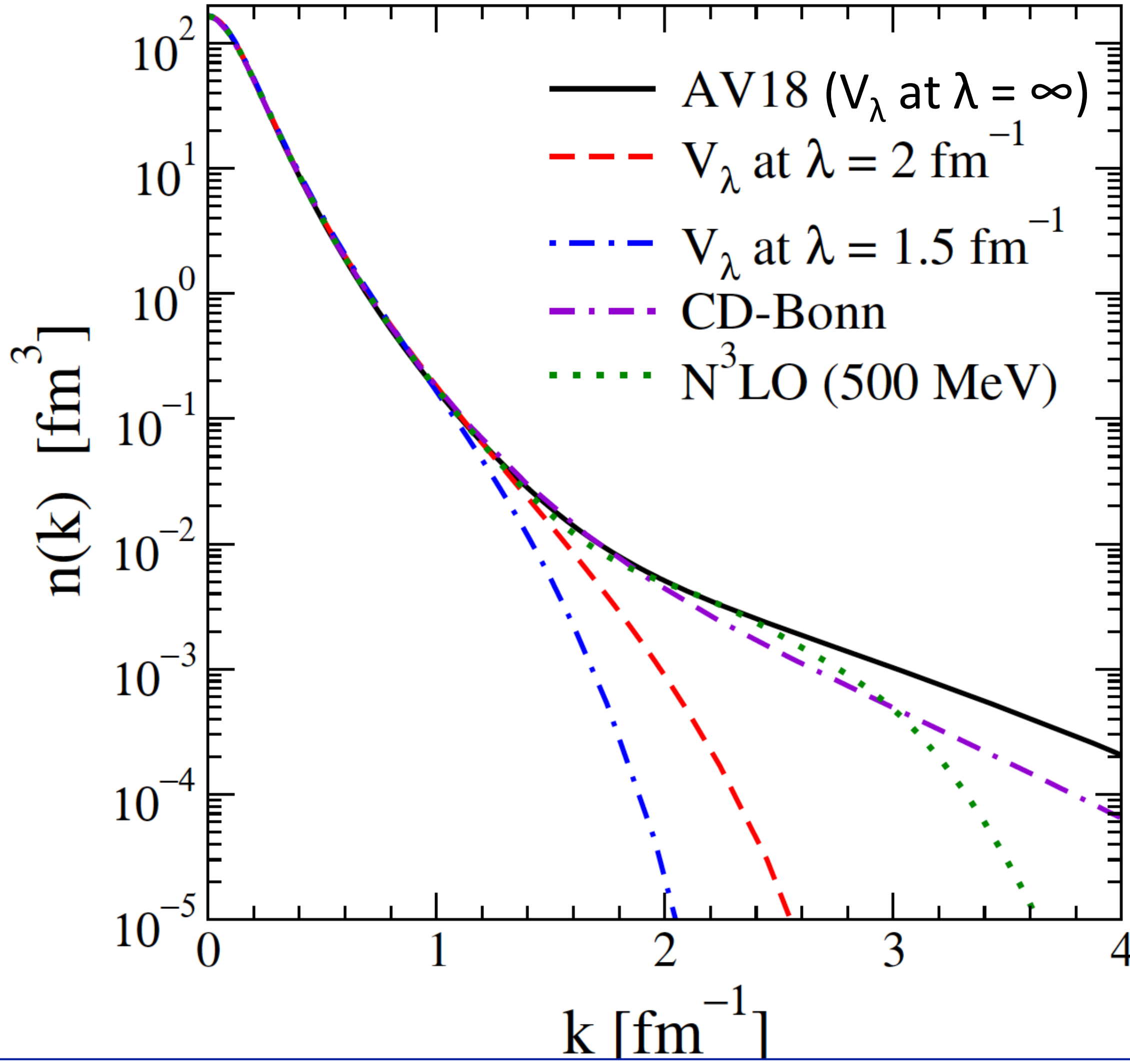
"Consistent" NNN and higher-body forces, as well as electroweak
currents, are those valid to the same scale as their corresponding
NN partner, and obtained in the same renormalization scheme.

ab initio renormalization schemes

SRG: Similarity Renormalization Group
OLS: Okubo-Lee-Suzuki
Vlowk: V with low k scale limit
UCOM: Unitary Correlation Operator Method
and there are more!

Similarity Renormalization Group (SRG) effects on the relative momentum distribution of nucleons in the deuteron

S. N. More, et. al., Phys Rev C .92, 064002 (2015)



However, a consistent SRG transformation of the relevant operators would lead to no change in any observable from the result obtained with AV18.

Low-energy observables are quasi-independent of short-range correlations including the elastic form factor through five decades of falloff. Note the "extra" radial nodes imparted to the deuteron radial wavefunction.

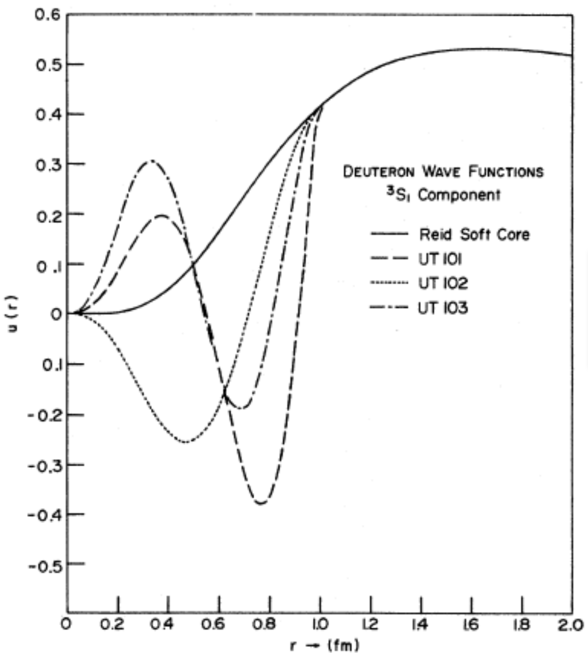


FIG. 4. $^3S_1$ component of the deuteron wave functions. The case (b) or fixed-range transformation wave functions are compared with the Reid soft-core wave function.

Same transformation on d-wave

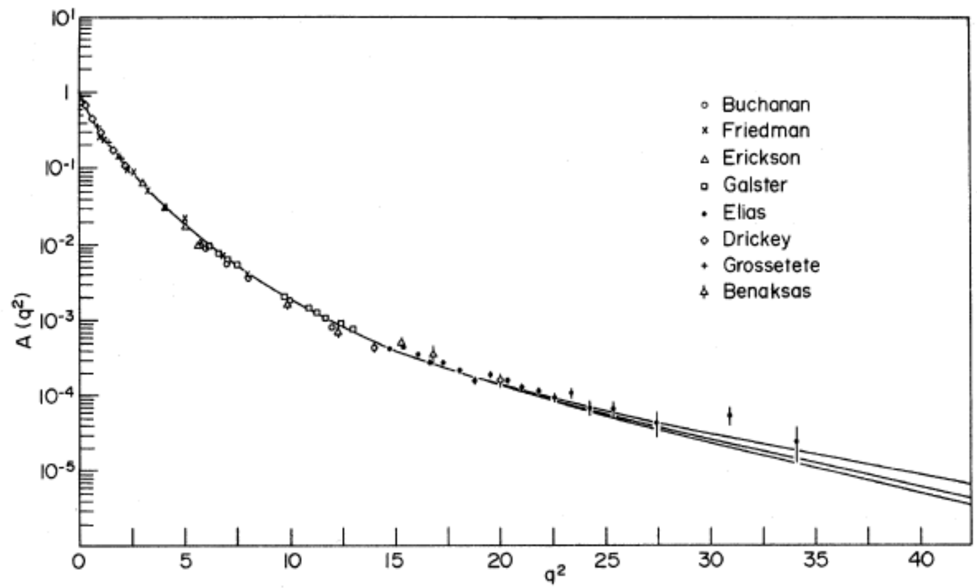


FIG. 6. Elastic scattering form factor $A(q^2)$ for the Reid soft-core and case (b) wave functions versus q^2 in fm^{-2}. All agree with the data. Reference 7 is the key to the experimental points.

Phase equivalent short range (< 1 fm) transformations introduced that leave Measured deuteron properties (static, form factors) nearly unchanged within experimental constraints. **No transform of EM ops.**

J.P. Vary, Phys. Rev. C7, 521(1973)

Larger impacts of uncertainty in SRCs are seen in “smearing corrections” used to extract neutron inelastic structure function from deuteron DIS data. **No transform of EM ops.**

Role of “Fermi motion” in the “EMC-region” and the uncertainty in that role arising from undetermined SRCs - exhibits an EMC effect.

J.P. Vary, Phys. Rev. C7, 521(1973)

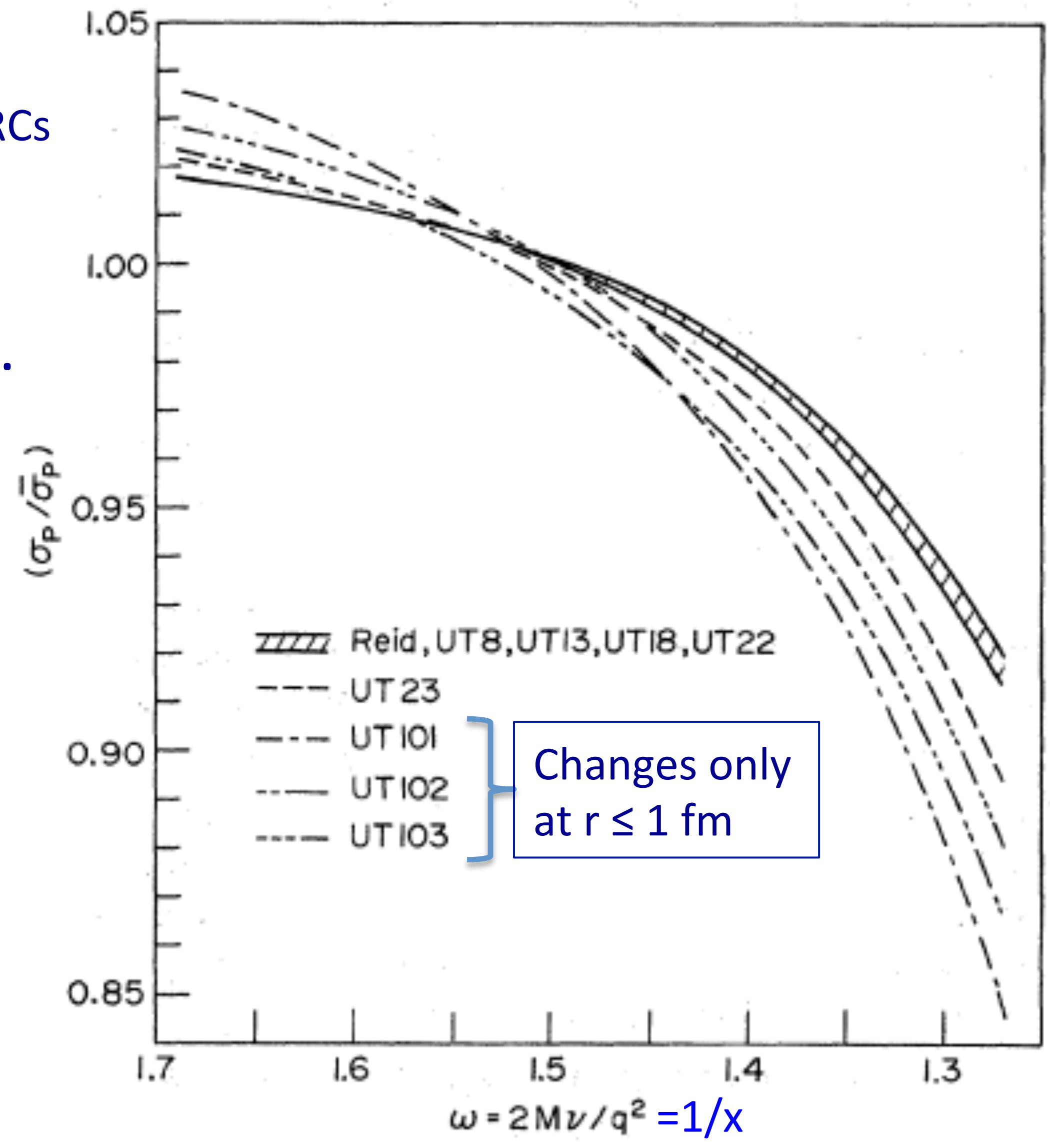
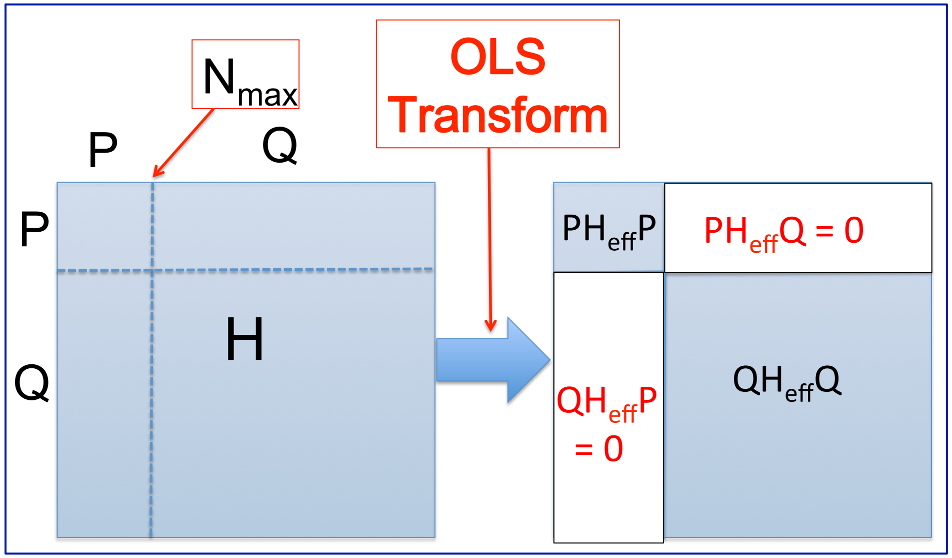


FIG. 7. Ratio of unsmeared to smeared proton cross section for different deuteron wave functions. These results are obtained using a beam energy of 17.0 GeV and a lab scattering angle of 18°.

OLS Transform:

Unitary transformation that block-diagonalizes the Hamiltonian – i.e. it integrates out Q-space degrees of freedom.



$$UHU^\dagger = U[T+V]U^\dagger = H_d, \text{ the diagonalized } H$$

$$H_{\text{eff}} \equiv U_{OLS} H U_{OLS}^\dagger = PH_{\text{eff}}P = P[T+V_{\text{eff}}]P$$

$$W^P \equiv PUP$$

$$\tilde{U}^P \equiv P\tilde{U}^P P \equiv \frac{W^P}{\sqrt{W^{P\dagger}W^P}}$$

$$H_{\text{eff}} = \tilde{U}^{P\dagger} H_d \tilde{U}^P = \tilde{U}^{P\dagger} UHU^\dagger \tilde{U}^P = P[T+V_{\text{eff}}]P$$

We conclude that:

$$U_{OLS} = \tilde{U}^{P\dagger} U$$

Similarly, we have effective operators for observables:

$$O_{\text{eff}} \equiv \tilde{U}^{P\dagger} UOU^\dagger \tilde{U}^P = P[O_{\text{eff}}]P$$

Consistent observables

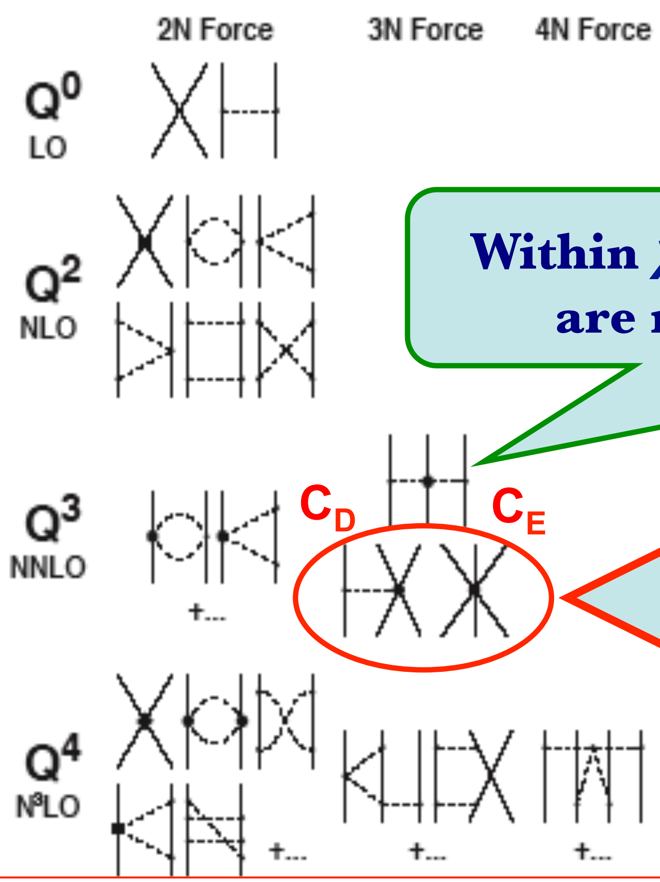
See: J.P. Vary, et al., arXiv: 1809.00276 for applications

Effective Nucleon Interaction
(Chiral Perturbation Theory)

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

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

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



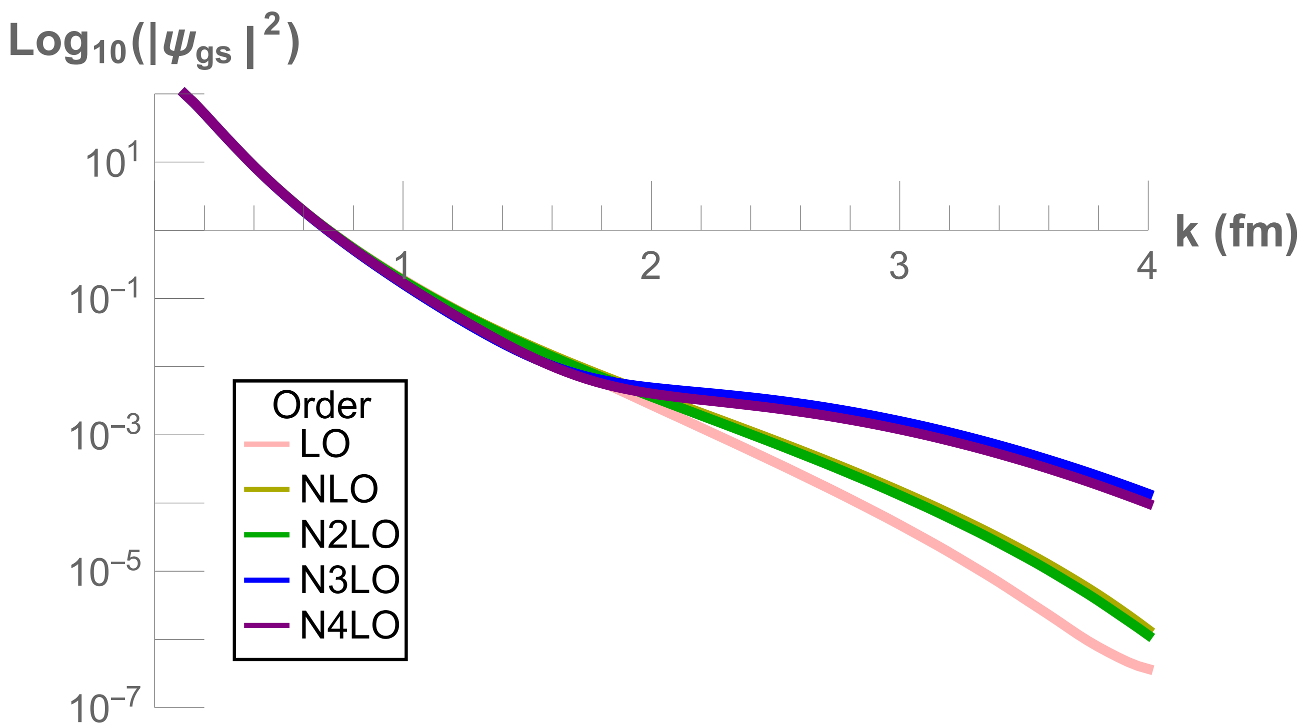
Within χPT 2π-NNN Low Energy Constants (LEC) are related to the NN-interaction LECs $\{c_i\}$.

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

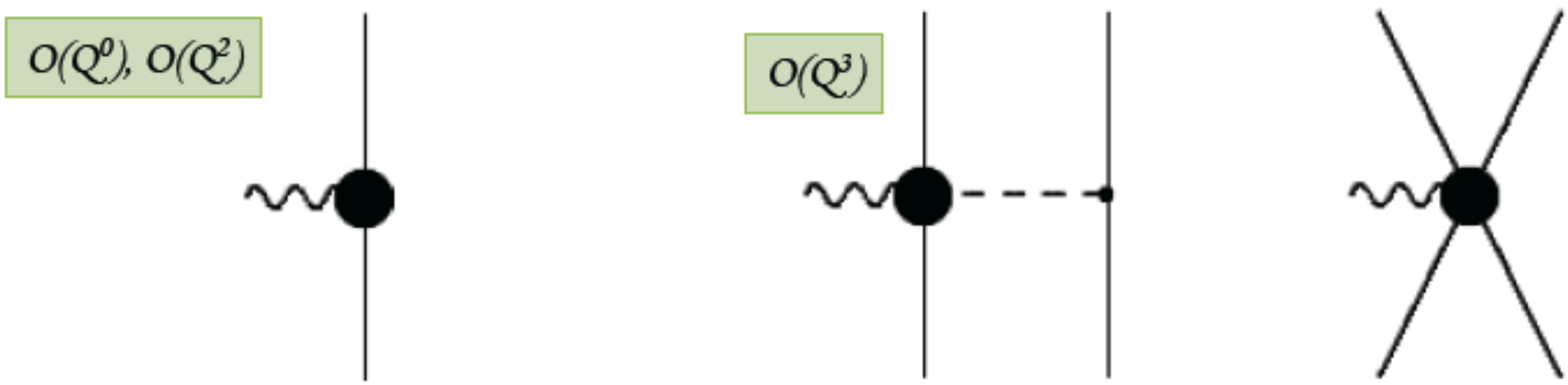


R. Basili, W. Du, et al., in preparation

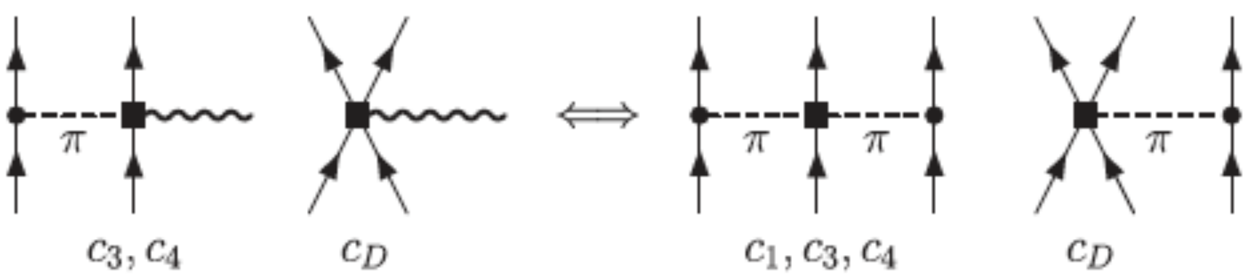
Coupling to External Probes in Chiral EFT

- Nuclear Current Operators

Single nucleon current | 1 pion exchange | Contact term



Two-Body Currents (N^2LO)



No-Core Configuration Interaction calculations

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

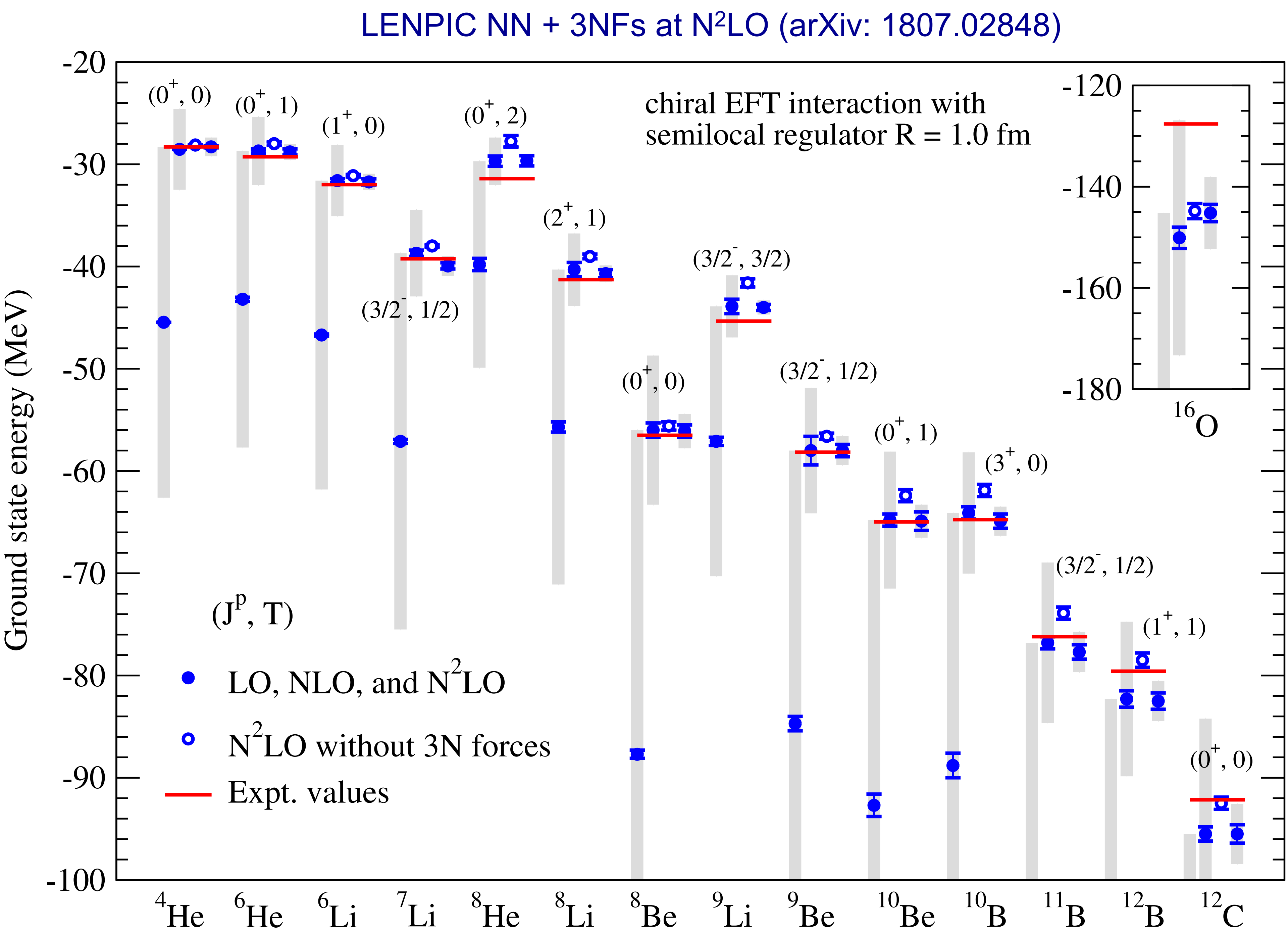
Given a Hamiltonian operator

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

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)
-20
-30
-40
-50
-60
-70
-80
-90
-100
(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)
(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
-120
-140
-160
-180
16O

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):

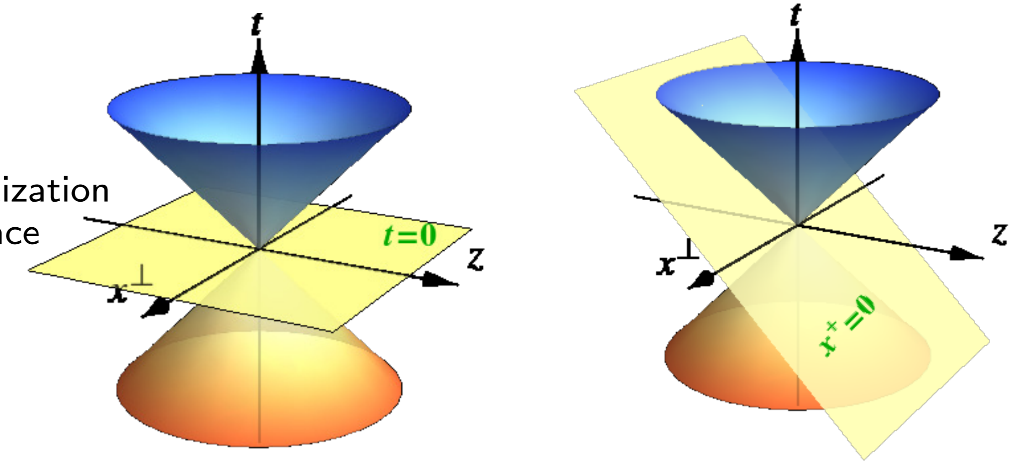
1. possess boost invariance
2. Provide access to experimental observables

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^{μ}
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

$\Downarrow$

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

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

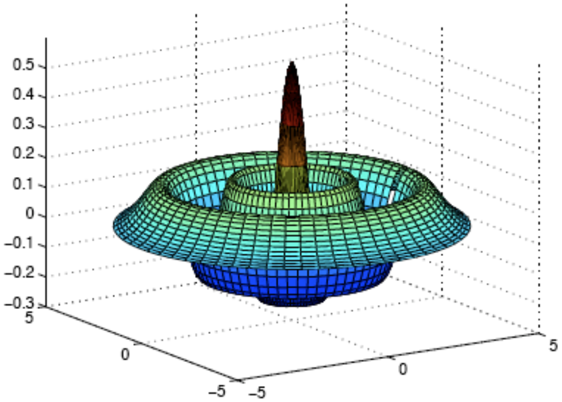
=> Wide range of choices for $f_a(\vec{x})$ and our initial choice is

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

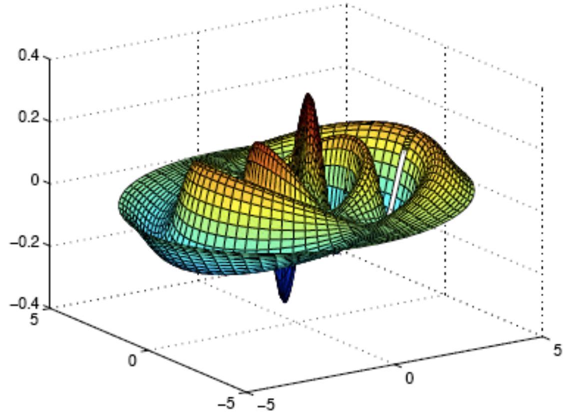
*J.P. Vary, H. Honkanen, J. Li, P. Maris, S.J. Brodsky, A. Harindranath, G.F. de Teramond, P. Sternberg, E.G. Ng and C. Yang, PRC 81, 035205 (2010). ArXiv:0905:1411

Set of transverse 2D HO modes for n=4

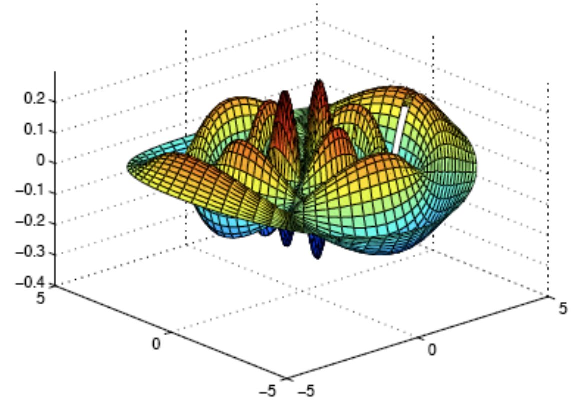
m=0



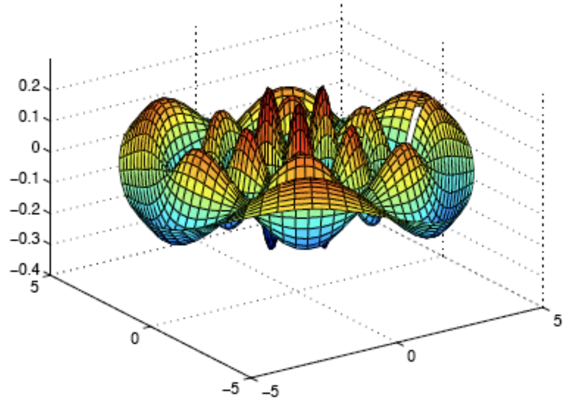
m=1



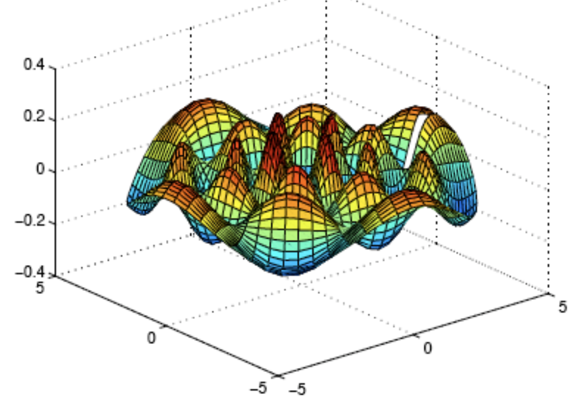
m=2



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) $\sum_i (2n_i + |m_i| + 1) \leq N_{\max}$

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

Global Color Singlets (QCD)

Light Front Gauge

Optional Fock-Space Truncation

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

All $J \geq J_z$ states in one calculation

Finite basis regulators

Preserve transverse boost invariance

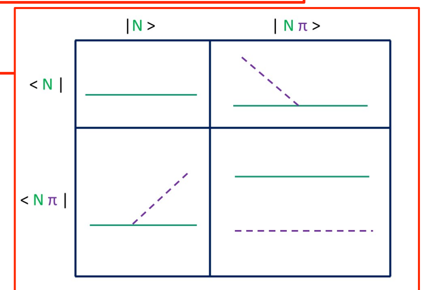
Can we develop a fully relativitistic Chiral EFT?

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

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

By Legendre transformation,
with the constraint equation

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



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

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

Model Problem

Parameters

K_{max}=3/2	M_N=1054 MeV
N_{max}<=2	M_π=139 MeV
M_J=1/2	f=94.3 MeV
N_{baryon}=1	b_{HO}=250 MeV
T_z=1/2	

BLFQ basis set

	k^N	n^N	m^N	λ^N	t_z^N	k^π	n^π	m^π	λ^π	t_z^π
$\vert N\rangle$	$\frac{3}{2}$	0	0	$\frac{1}{2}$	$\frac{1}{2}$					
$\vert N\pi\rangle$	$\frac{1}{2}$	0	0	$\frac{1}{2}$	$\frac{1}{2}$	1	0	0	0	0
$\vert N\pi\rangle$	$\frac{1}{2}$	0	0	$\frac{1}{2}$	$-\frac{1}{2}$	1	0	0	0	1

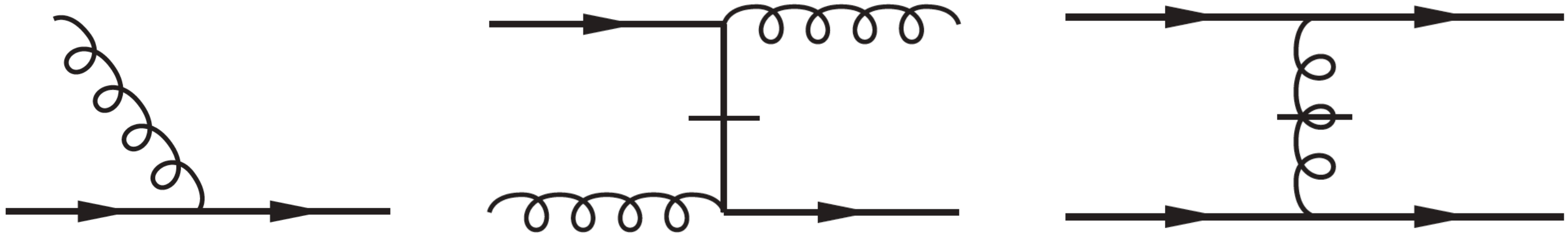
Preliminary Results

Light front Hamiltonian/Mass operator

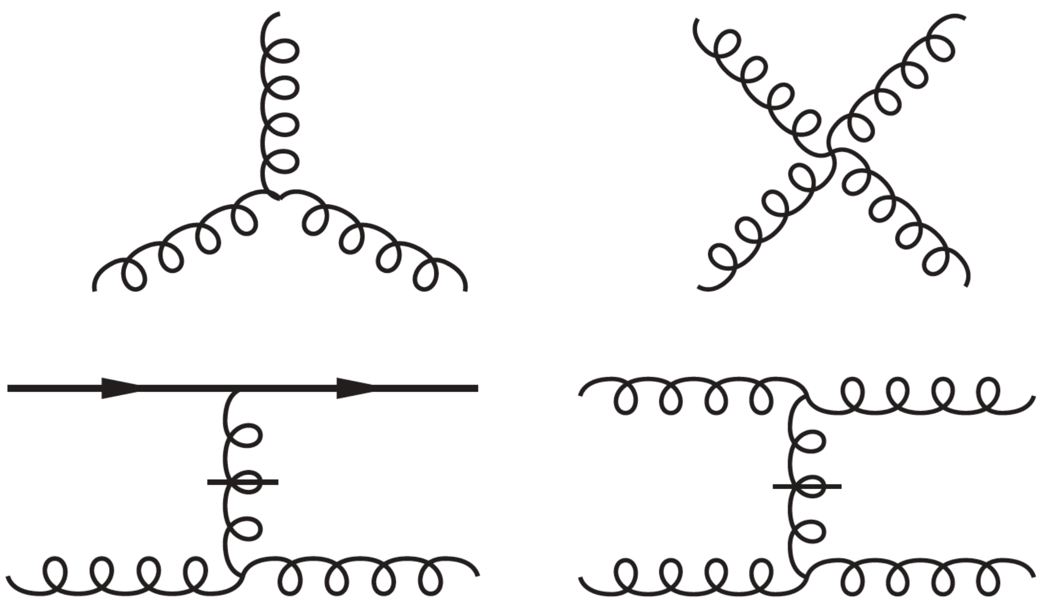
$$M^2 = P^+_{\text{total}} P^- = \begin{pmatrix} 1110916 & 0. - 441930.\,i & 0. - 624983.\,i \\ 0. + 441930.\,i & \frac{6848459}{2} & 0 \\ 0. + 624983.\,i & 0 & \frac{6848459}{2} \end{pmatrix}$$

Eigenvalue	Amplitude of basis		
M_p (MeV)	|p>	$\vert p\pi^0\rangle$	$\vert n\pi^+\rangle$
938.39	0.957583 i	0.166369	0.235281
1850.47	0	0.816497	-0.57735
1911.69	-0.288159 i	0.552861	0.781863

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

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

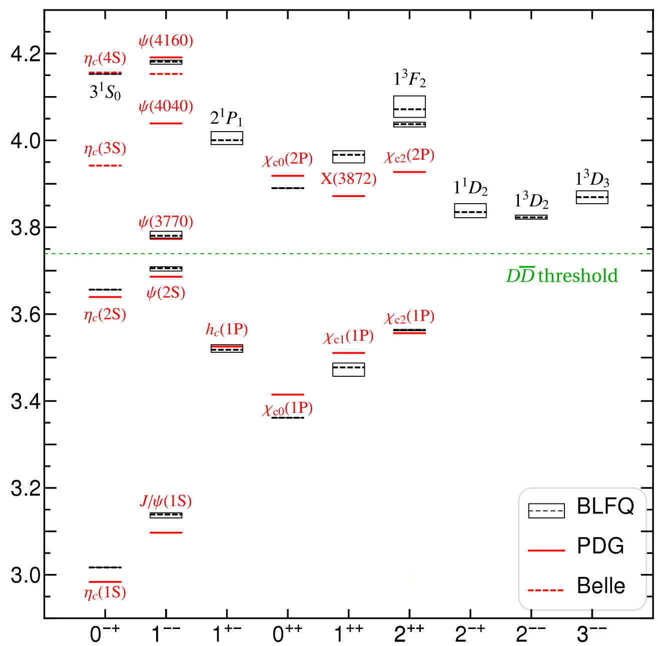
where $x = p_q^+/P^+$, $\vec{k}_\perp = \vec{p}_{q\perp} - x\vec{P}_\perp$, $\vec{r}_\perp = \vec{r}_{q\perp} - \vec{r}_{\bar{q}\perp}$.

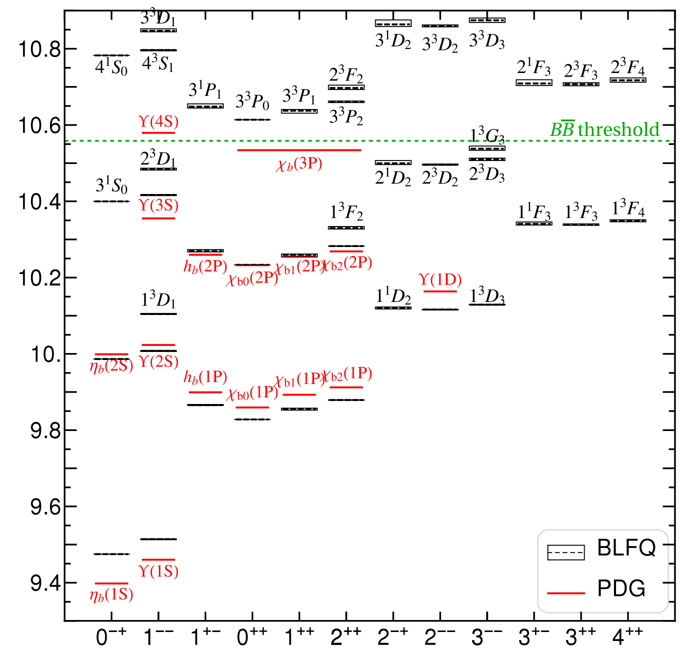
  - Confinement
    transverse holographic confinement [S.J.Brodsky,PR584,2015]
    longitudinal confinement [Y.Li,PLB758,2016]
  - One-gluon exchange with running coupling
    $V_g = -\frac{4}{3}\frac{4\pi\alpha_s(Q^2)}{Q^2}\bar{u}_{\sigma'}\gamma^\mu u_\sigma \bar{v}_s \gamma_\mu v_{s'}$

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

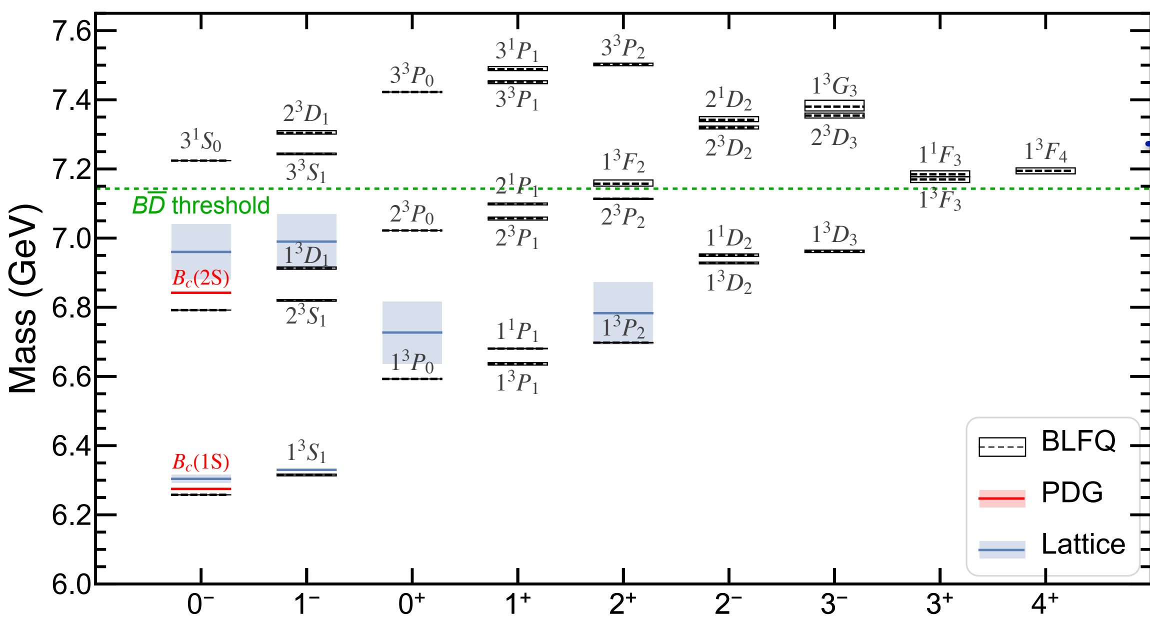
Spectroscopy

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

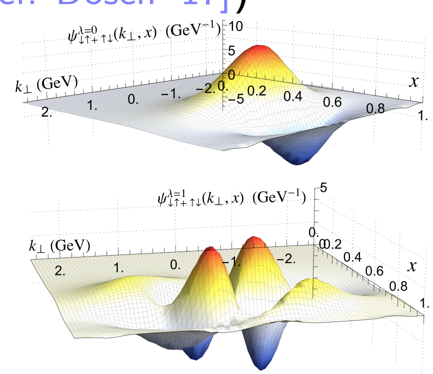




Heavy mesons: rms deviations 31 – 38 MeV



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

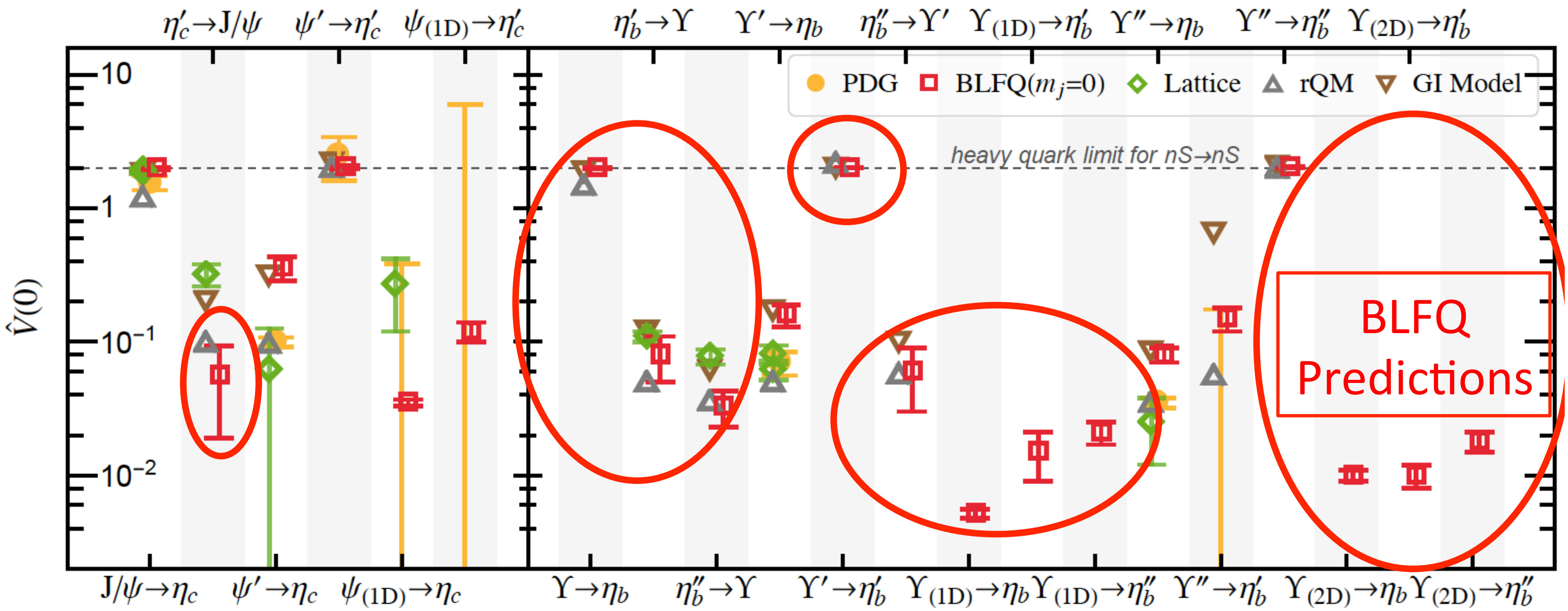


Radiative transitions between 0^{-+} and 1^{--} heavy quarkonia

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

Decay width:

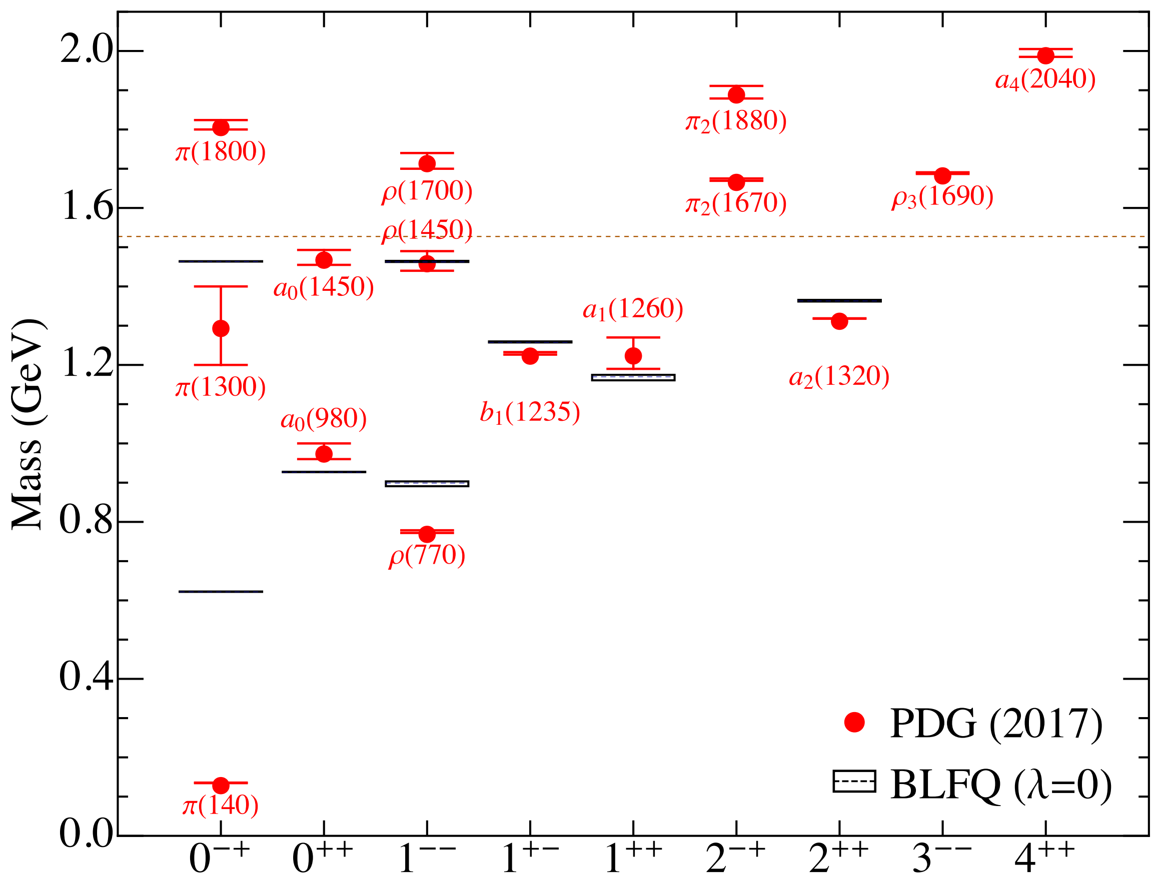
$$\Gamma(\mathcal{V}\to\mathcal{P}+\gamma)=\int \mathrm{d}\Omega_q \frac{1}{32\pi^2}\frac{|\vec{q}|}{m_{\mathcal{V}}^2}\frac{1}{2J_{\mathcal{V}}+1}\sum_{m_j,\lambda}|\mathcal{M}_{m_j,\lambda}|^2=\frac{(m_{\mathcal{V}}^2-m_{\mathcal{P}}^2)^3}{(2m_{\mathcal{V}})^3(m_{\mathcal{P}}+m_{\mathcal{V}})^2}\frac{|V(0)|^2}{(2J_{\mathcal{V}}+1)\pi}$$



[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:

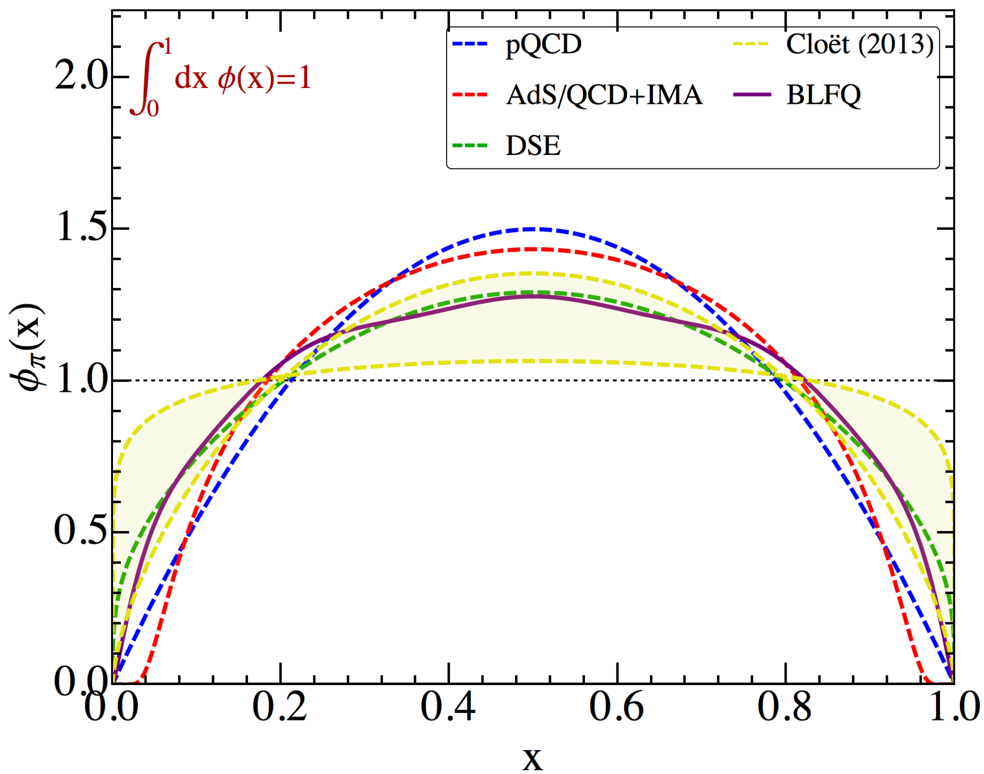
$\kappa =$ 0.57 GeV

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

Wenyang Qian, et al., In preparation

Wenyang Qian, et al., In preparation

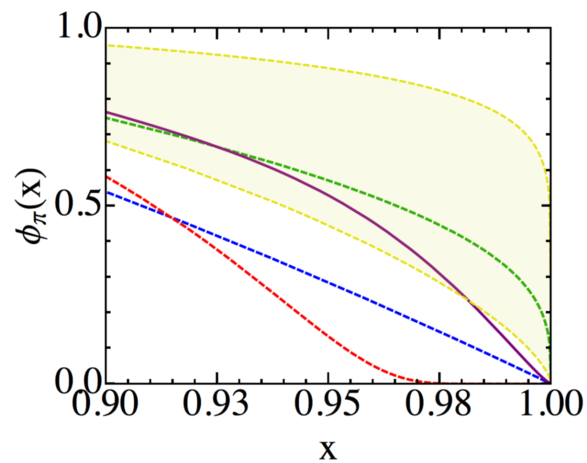
Parton distribution amplitudes for the pion



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)

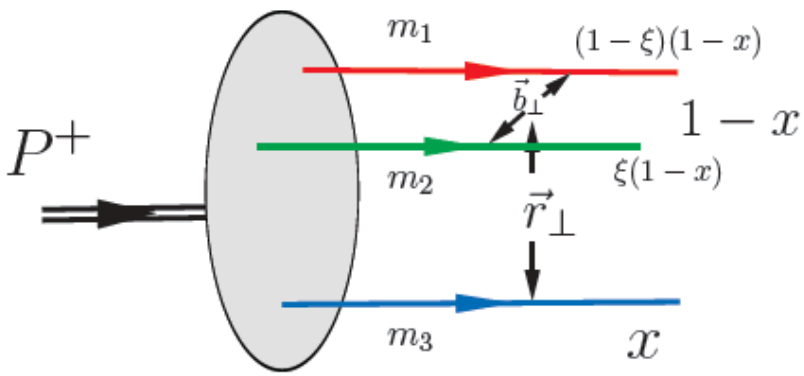
Exclusive processes at large momentum transfer

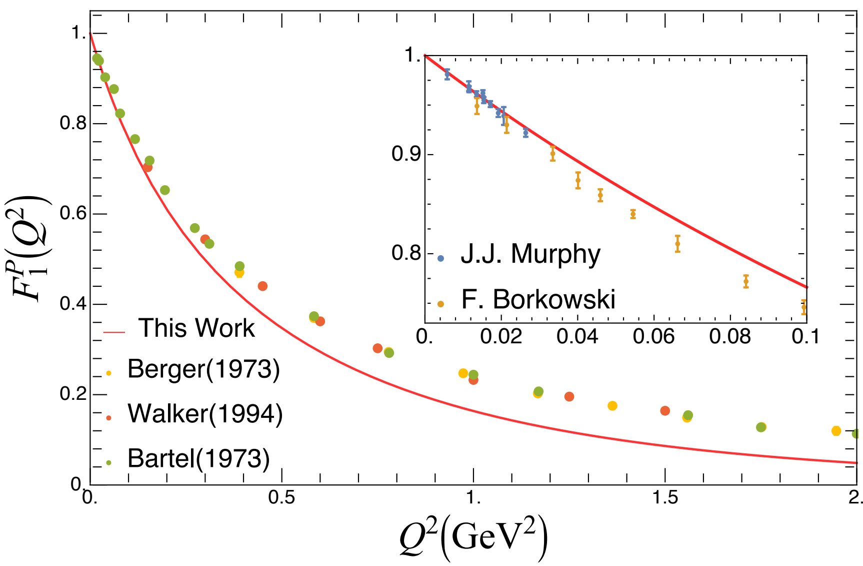
$$\phi_{\mathcal{P},\mathcal{V}}(x,\mu) \sim \frac{1}{f_{\mathcal{P},\mathcal{V}}\sqrt{x(1-x)}} \times \int \frac{d^2\boldsymbol{k}_\perp}{(2\pi)^3}\psi^{(m_j=0)}_{\uparrow\downarrow\pm\downarrow\uparrow}(x,\boldsymbol{k}_\perp)$$

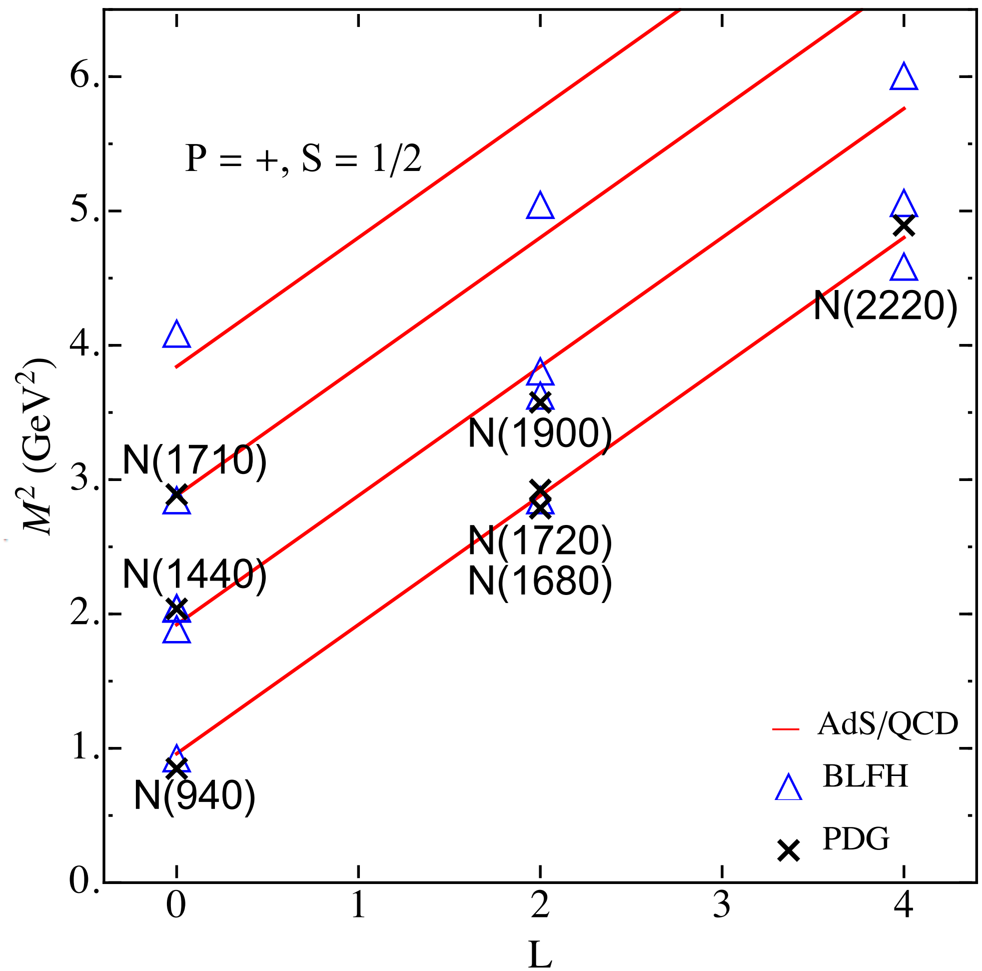


Baryons

Anji Yu, et al., in preparation







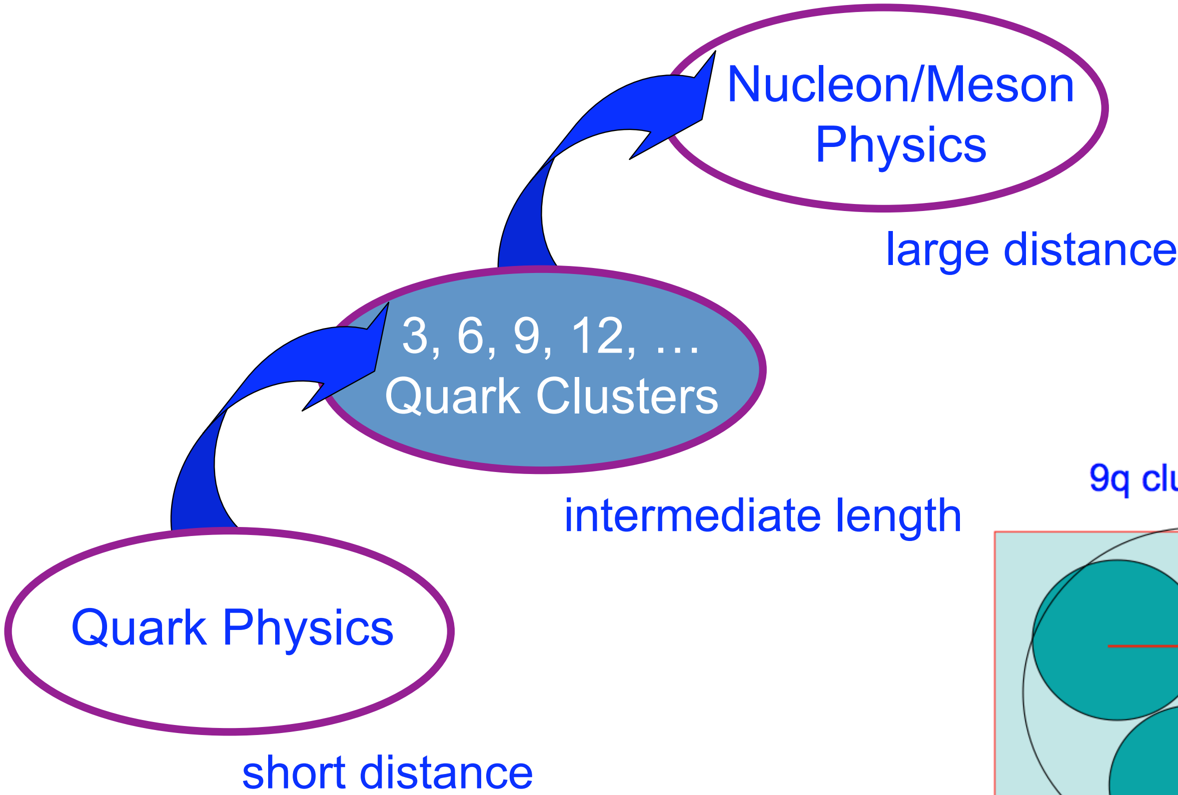
$$M^2_{\mathbf{n_1},\mathbf{m_1},\mathbf{n_2},\mathbf{m_2},L,l} = (\mathrm{m}_3 + \mathrm{M}_L)^2 + 2\kappa^2(2\mathbf{n}_1 + |\mathbf{m}_1| + 2\mathbf{n}_2 + |\mathbf{m}_2| + 2)$$

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

$$\mathrm{M}_L^2 = (\mathrm{m}_1 + \mathrm{m}_2)^2 + \frac{\mathrm{m}_1 + \mathrm{m}_2}{\mathrm{m}_1 + \mathrm{m}_2 + \mathrm{m}_3}\kappa^2(2L+1) + \frac{\kappa^4}{(\mathrm{m}_1 + \mathrm{m}_2 + \mathrm{m}_3)^2} L(L+1)$$

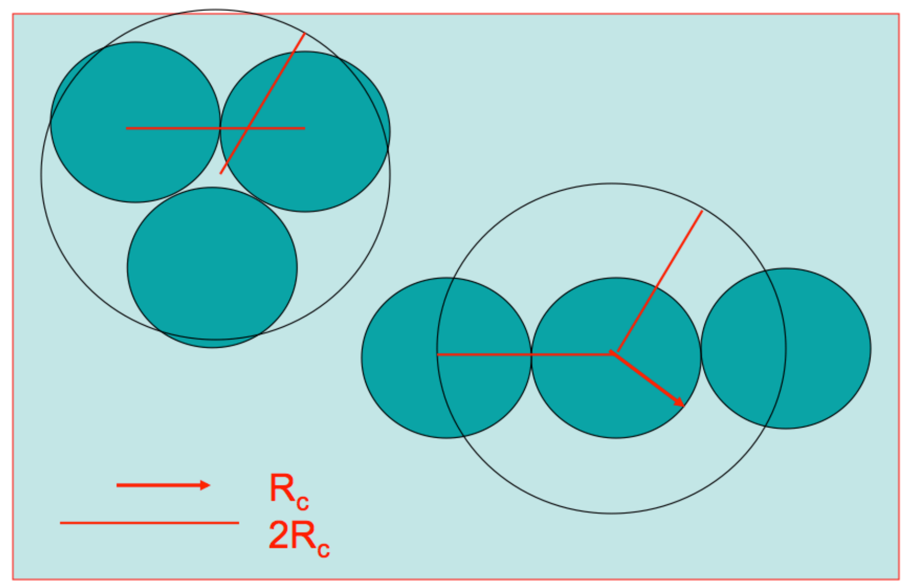
Looking ahead: under what conditions do we require a quark-based description of nuclear structure?

"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
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

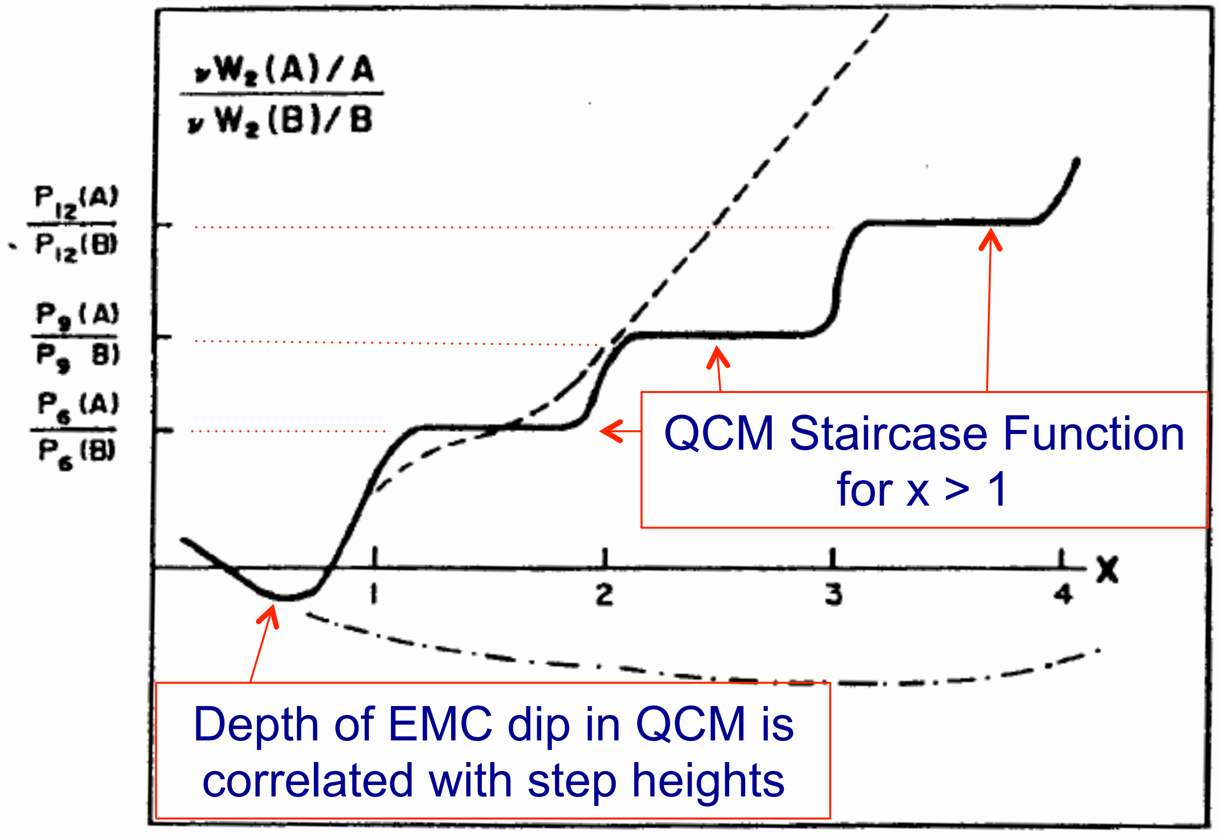
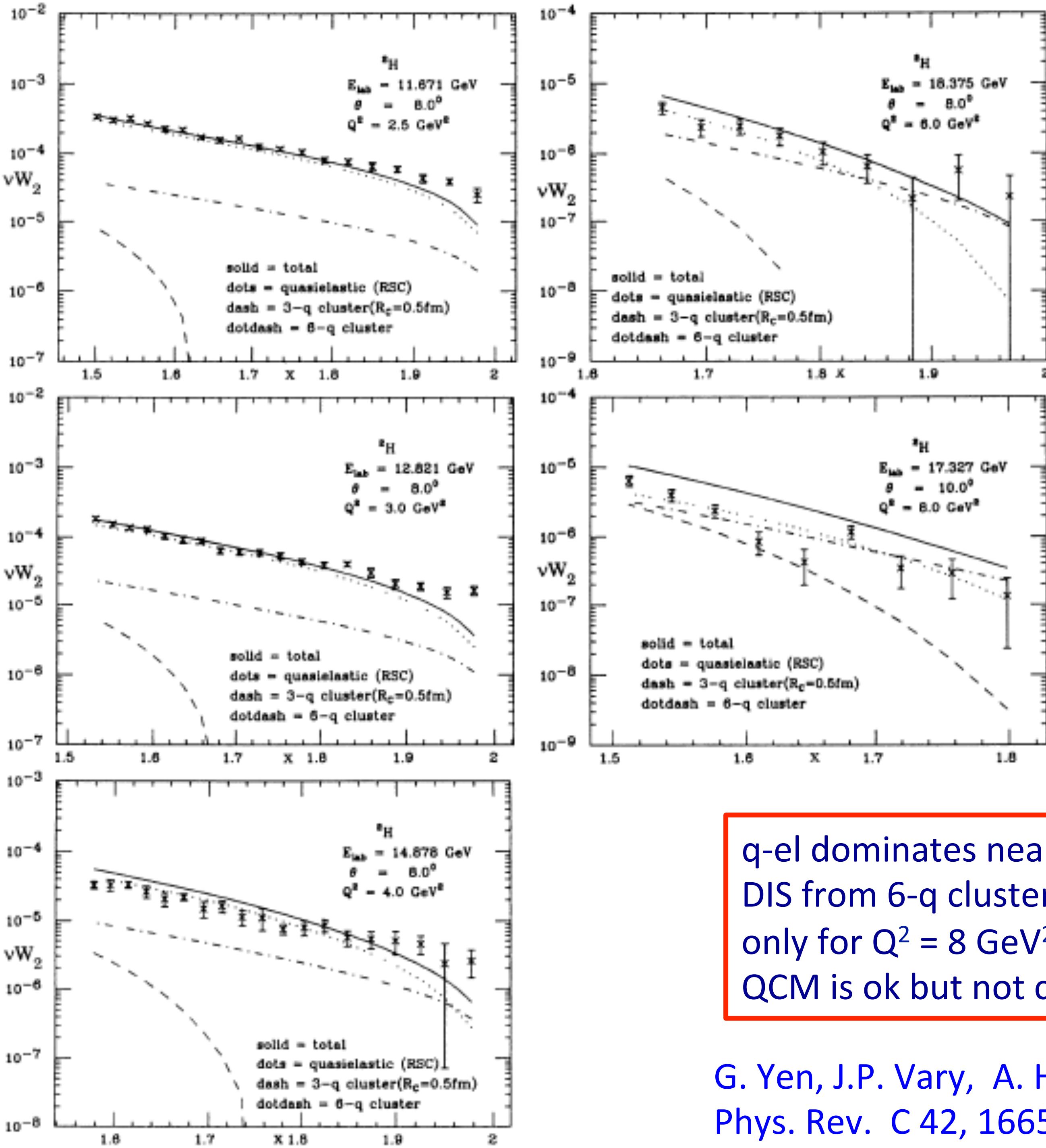


Fig. 2. Characteristic behaviour of the ratio of nuclear structure functions per nucleon for different models over a wide kinematic range of x. The QCM gives the solid curve. The dashed curve is due to the model of reference 22. The dashed-dot curve approximates the predictions of references 23 and 24.

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

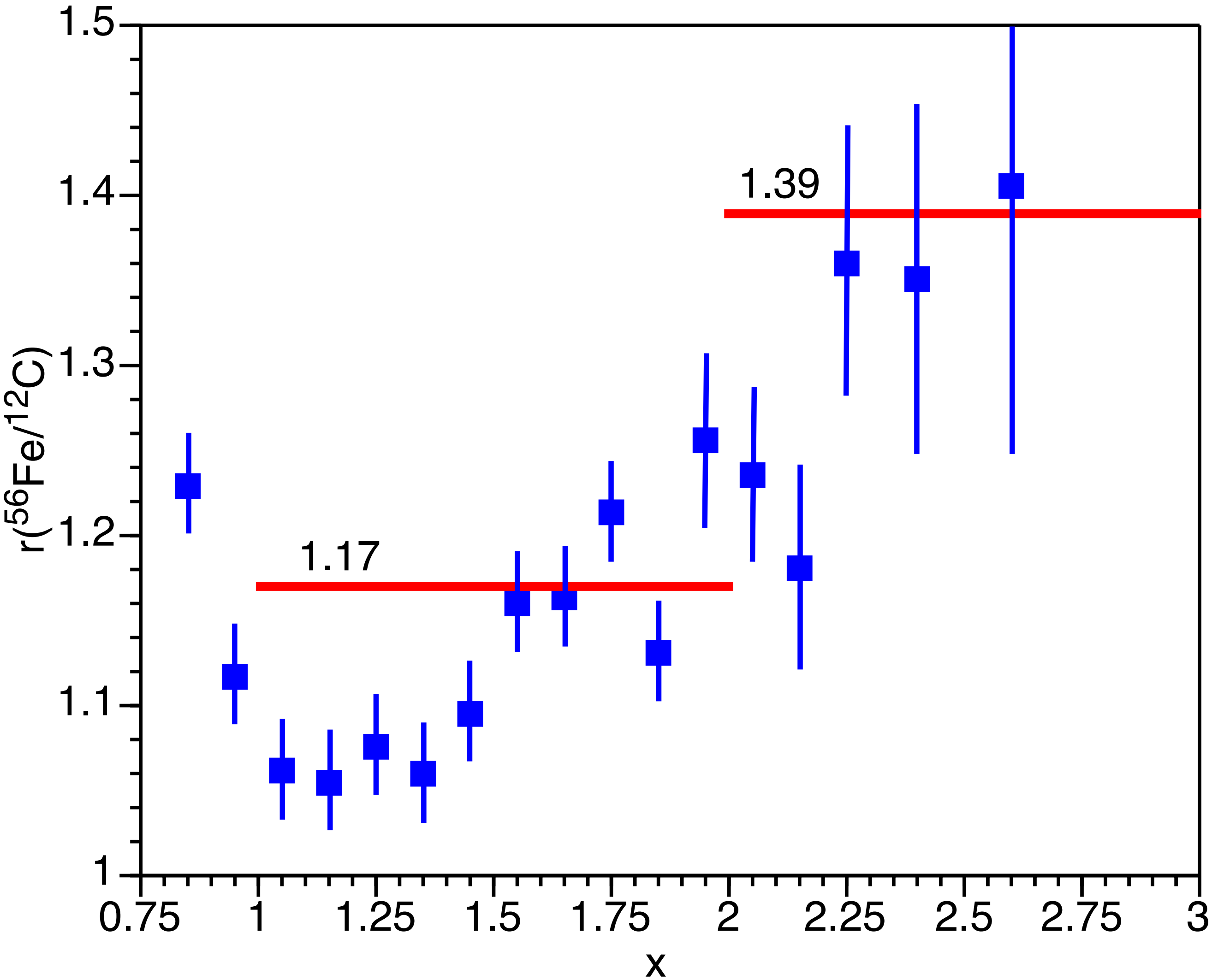


SLAC DIS data from deuterium compared with model inelastic structure function including Quasi-elastic knockout, nucleon excitations, 6-quark clusters (4.4%) and realistic momentum distributions (Reid Soft Core)

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 $\quad$ ^{4}He/^{3}He = 1.55

0.08/0.04 = 2.0

0.13/0.04 = 3.3

0.14/0.04 = 3.5 $\quad$ Fe/C = 1.17

0.15/0.04 = 3.8

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)

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

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
- Outlook: two-baryon systems with effective LF Hamiltonians from chiral EFT to quark-gluon systems
- Next goal: mesons and baryons in BLFQ with one dynamical gluon
- 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
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