Ab-initio methods for light nuclei from low to high resolution

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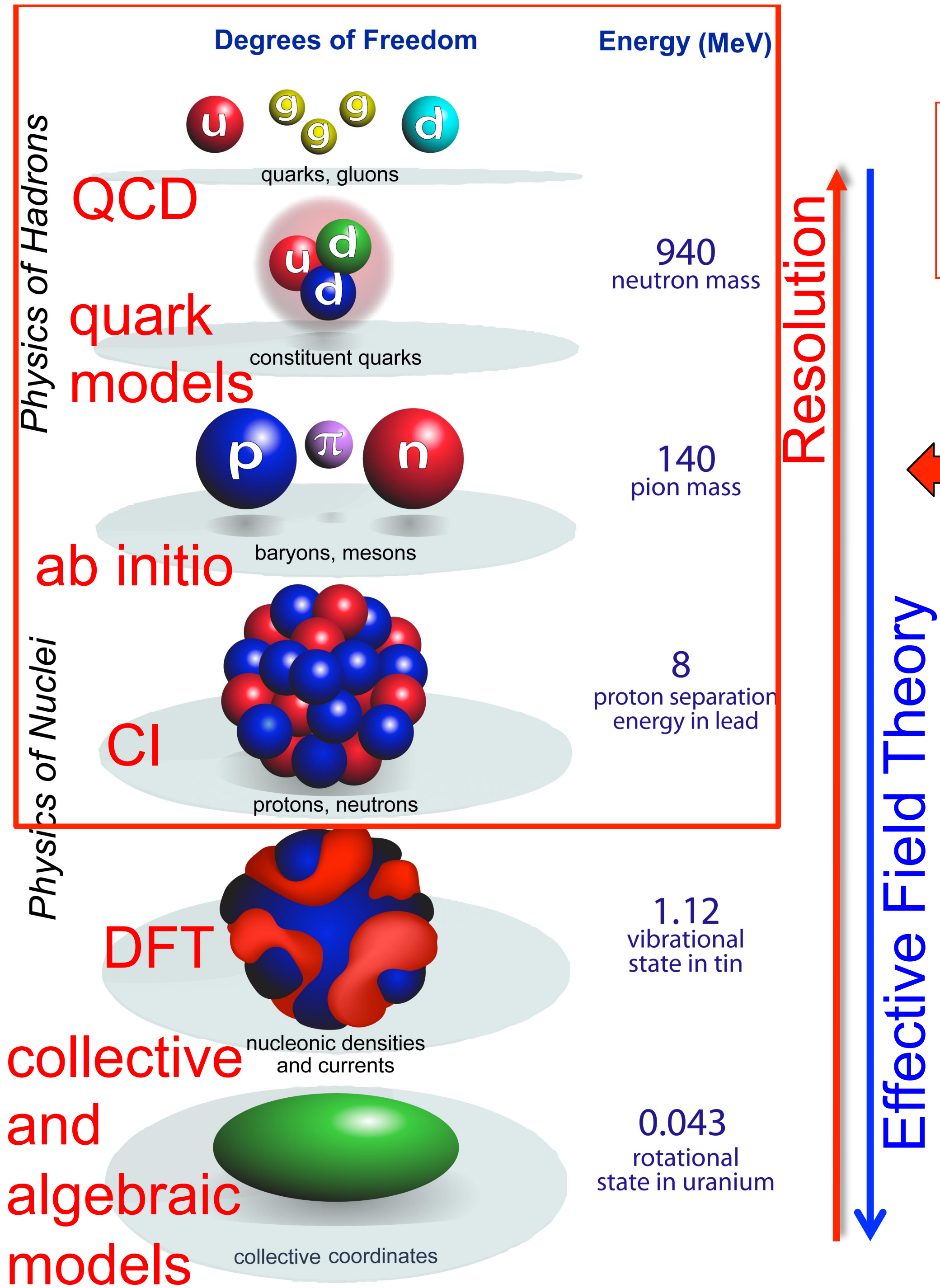
Polarized light ion physics with EIC
Ghent, Belgium
Feb. 5 – 9, 2018

Meeting Topics include:
* Neutron spin structure from polarized deep-inelastic scattering on light nuclei (d, 3He)
* Nuclear fragmentation and final-state interactions in high-energy processes
* Spin-orbit effects and azimuthal asymmetries in scattering on proton and light nuclei
* Tensor-polarized deuteron in low- and high-energy processes
* Theoretical methods for light nuclear structure: Few-body, Lattice, Light-front
* Nuclear structure at variable scales: Effective degrees of freedom, EFT methods
* Quarks and gluons in light nuclei: EMC effect, non-nucleonic degrees of freedom
* Diffraction and nuclear shadowing in DIS on light nuclei
* Polarized light ion beams: Sources, acceleration, polarimetry
* Forward detection of spectators and nuclear fragments at EIC

issues in this talk



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:

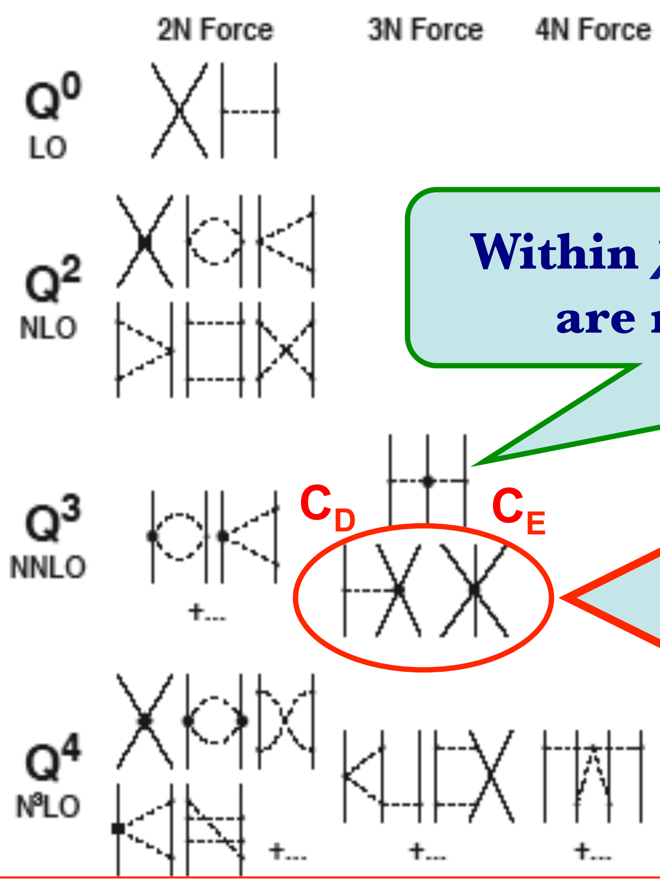
"You may use any degrees of freedom you like to describe a physical system, but if you use the wrong ones, you'll be sorry!"

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)

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

Basis expansion $\Psi(r_1,\ldots,r_A) = \sum a_i \Phi_i(r_1,\ldots,r_A)$

- Many-Body basis states $\Phi_i(r_1,\ldots,r_A)$ Slater Determinants
- Single-Particle basis states $\phi_\alpha(r_k)$ with $\alpha = (n,l,s,j,m_j)$
- Radial wavefunctions: Harmonic Oscillator (HO), natural orbitals, Woods-Saxon, Coulomb-Sturmian, Complex Scaled HO, Berggren,. . .
- M-scheme: Many-Body basis states eigenstates of $\hat{\mathbf{J}}_\mathbf{z}$

$$\hat{\mathbf{J}}_\mathbf{z}|\Phi_i\rangle = M|\Phi_i\rangle = \sum_{k=1}^{A} m_{ik}|\Phi_i\rangle$$

- N_{max} truncation: Many-Body basis states satisfy

$$\sum_{\alpha\ \text{occ.}}^{A} (2n+l)_\alpha \le N_0 + N_{\text{max}}$$

N_{max} runs from zero to computational limit.
(N_{max} , $\hbar\Omega$) fix HO basis

- Alternatives:
  - Full Configuration Interaction (single-particle basis truncation)
  - Importance Truncation — Roth, PRC79, 064324 (2009)
  - No-Core Monte-Carlo Shell Model — Abe *et al*, PRC86, 054301 (2012)
  - SU(3) Truncation — Dytrych *et al*, PRL111, 252501 (2013)

Calculation of three-body forces at N^3LO

Low
Energy
Nuclear
Physics
International
Collaboration

LENPIC

J. Golak, R. Skibinski,
K. Tolponicki, H. Witala

RUB — E. Epelbaum, H. Krebs

JÜLICH — A. Nogga

THE OHIO STATE UNIVERSITY — R. Furnstahl

TECHNISCHE UNIVERSITÄT DARMSTADT — S. Binder, A. Calci, K. Hebeler,
J. Langhammer, R. Roth

STATE — P. Maris, J. Vary

Kyutech — H. Kamada

Goal

Calculate matrix elements of 3NF in a partial-wave decomposed form which is suitable for different few- and many-body frameworks

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Challenge

Due to the large number of matrix elements, the calculation is extremely expensive.

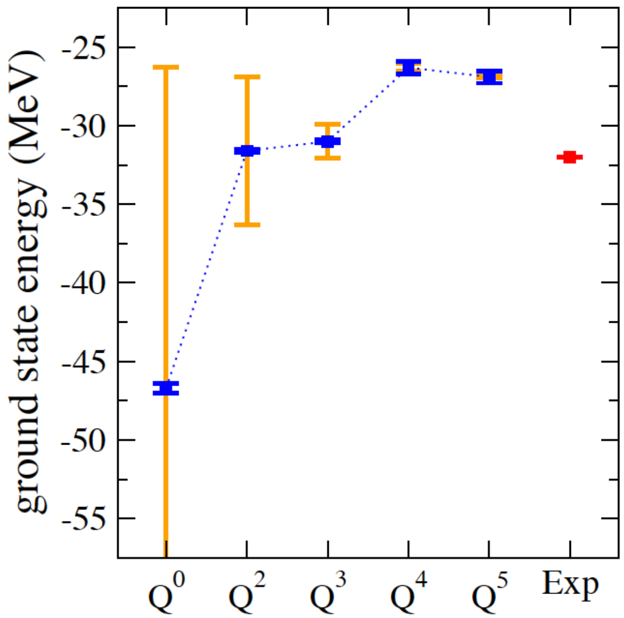
Strategy

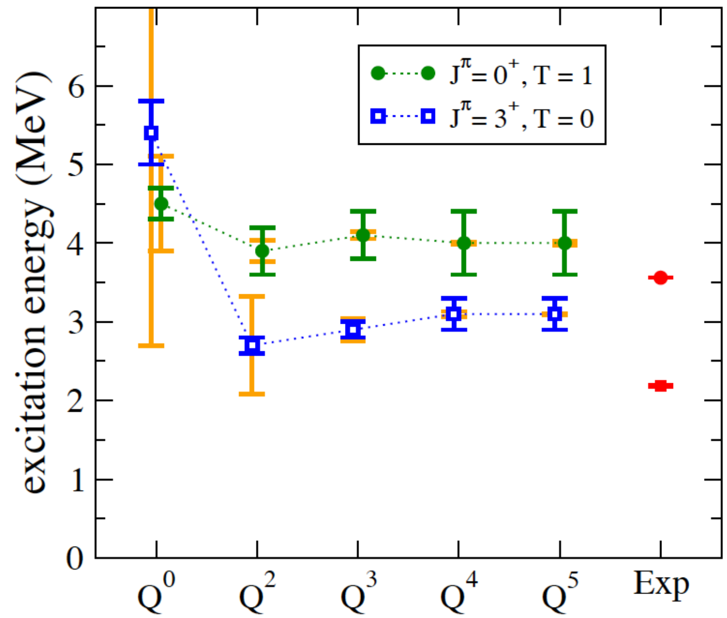
Develop an efficient code which allows to treat arbitrary local 3N interactions.
(Krebs and Hebeler)

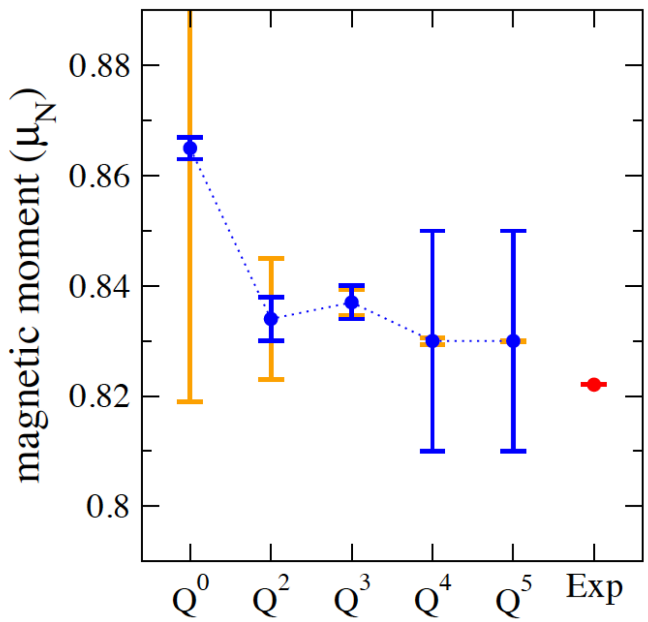
Initial LENPIC Collaboration results: Chiral NN results for ^{6}Li by Chiral order

Orange: Chiral order uncertainties; Blue/Green: Many-body method uncertainties

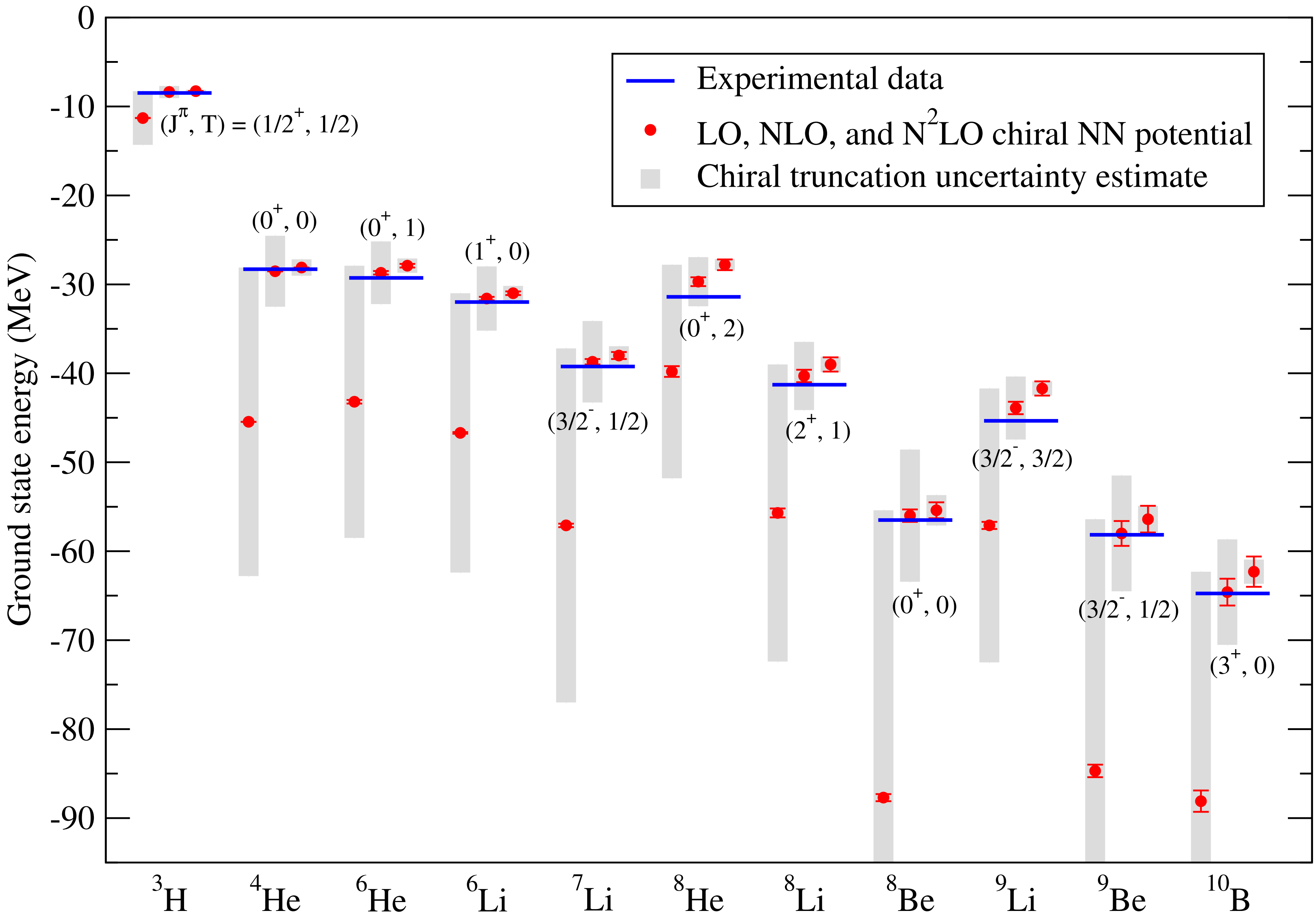
S. Binder, et al, Phys. Rev. C **93,** 044002 (2016); arXiv:1505.07218





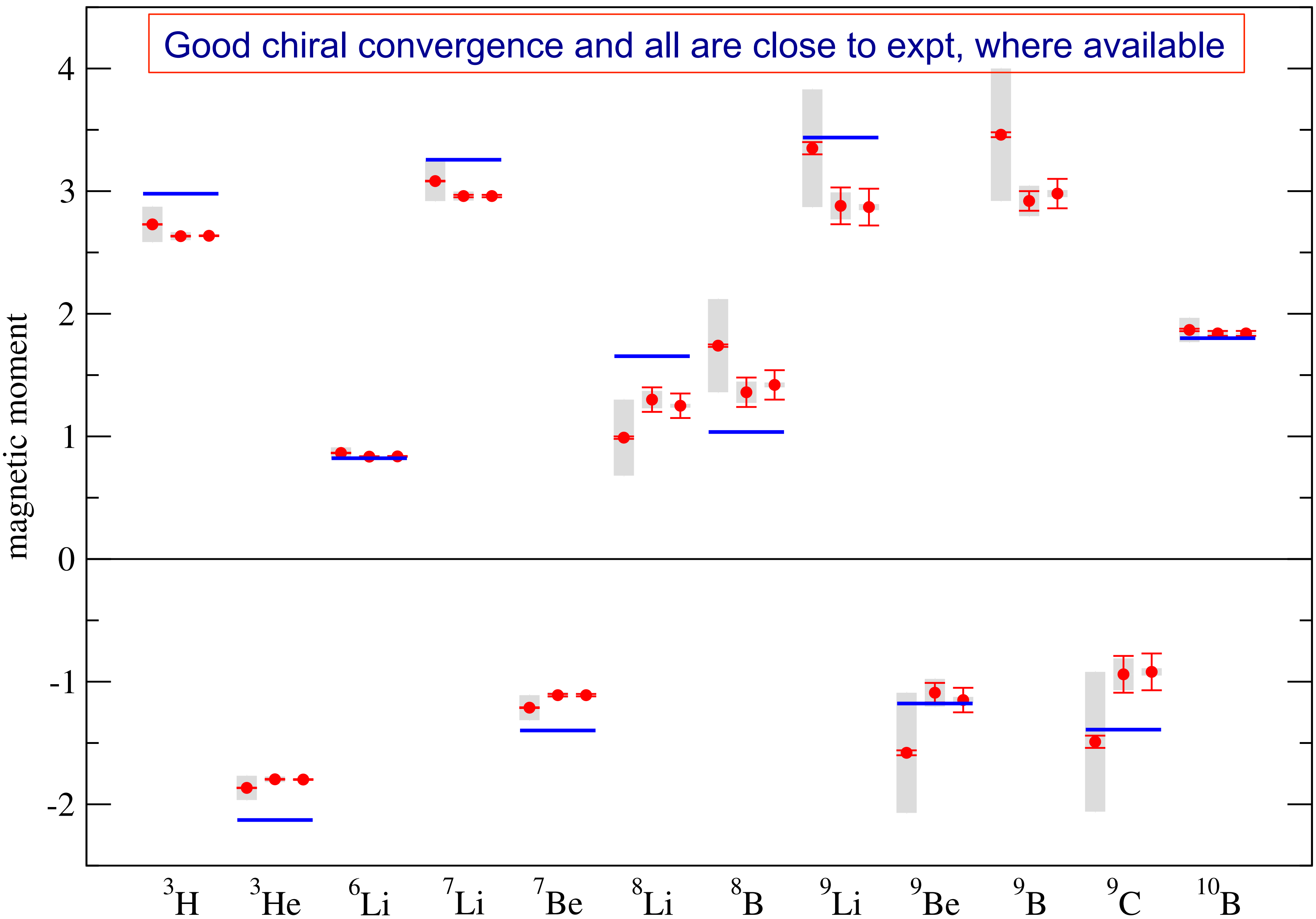


- Ground state energy similar behavior as ^{3}H and ^{4}He
- Open question:
  - Are chiral uncertainty estimates applicable to excitation energies?
- Need compatible chiral 3NFs
- Need chiral expansion conserved current operator



S. Binder, et al., LENPIC Collaboration, in preparation

Preliminary LENPIC results with Chiral NN only and R = 1.0 fm, IA for operator
S. Binder, et al., LENPIC Collaboration, in preparation



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

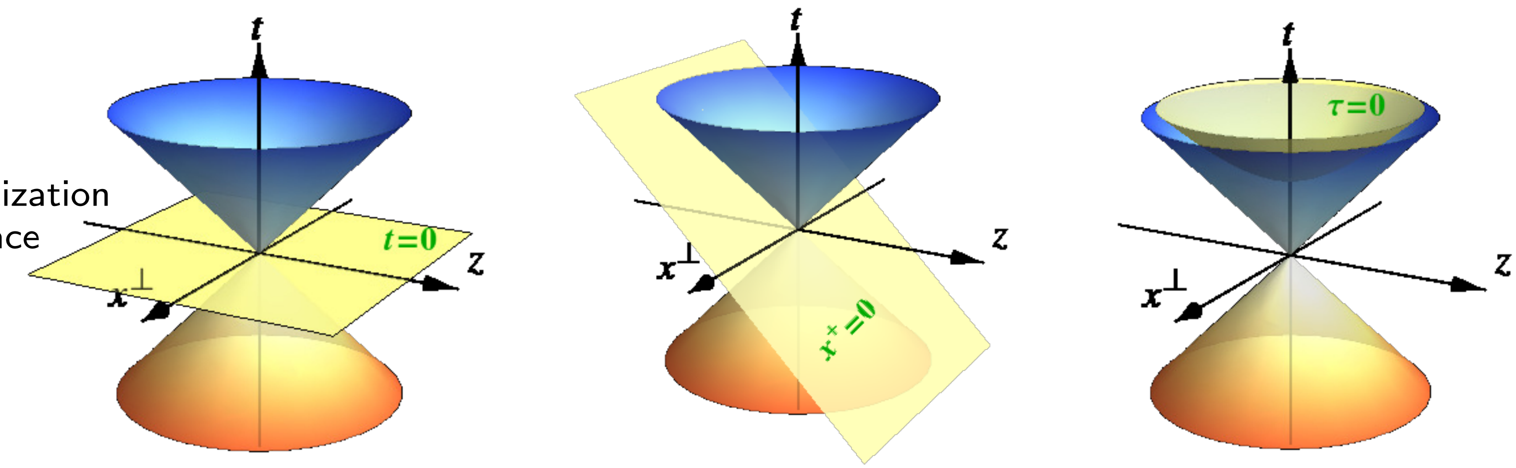
Instant form is the well-known form of dynamics starting with $x^0 = t = 0$

$K^i = M^{0i}$, $J^i = \frac{1}{2}\varepsilon^{ijk}M^{jk}$, ε^{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			
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

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

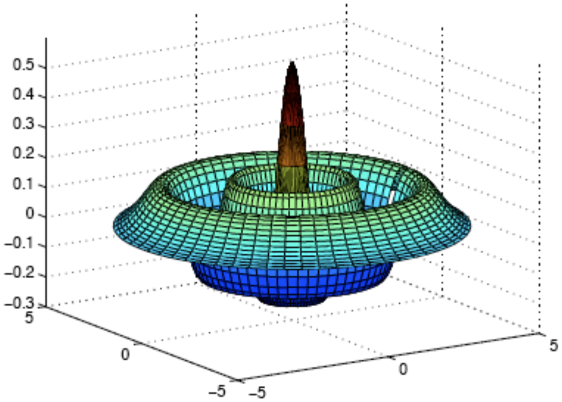
=> Wide range of choices for $f_{a}(\vec{x})$ and our initial choice is

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

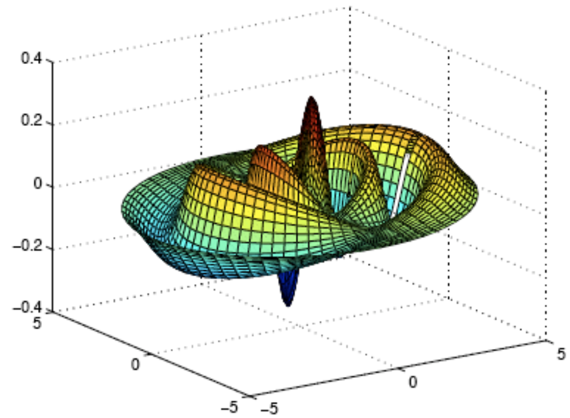
*J.P. Vary, H. Honkanen, J. Li, P. Maris, S.J. Brodsky, A. Harindranath, G.F. de Teramond, P. Sternberg, E.G. Ng and C. Yang, PRC 81, 035205 (2010). ArXiv:0905:1411

Set of transverse 2D HO modes for n=4

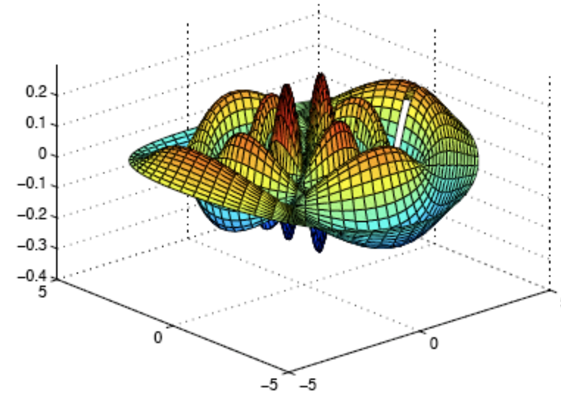
m=0



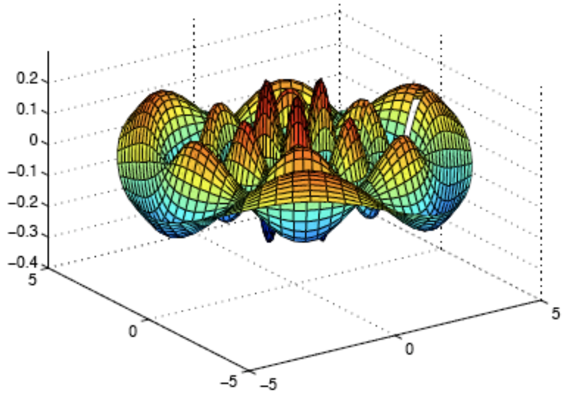
m=1



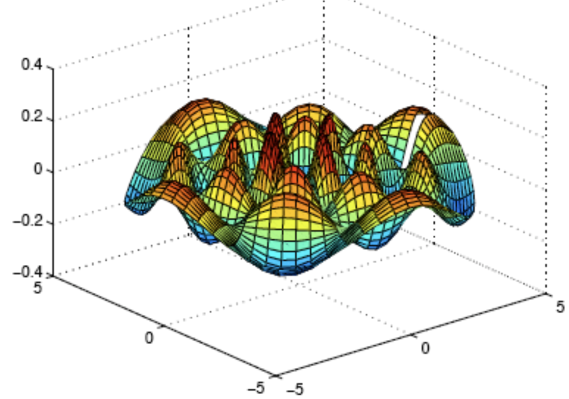
m=2



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

Symmetries & Constraints

$$\sum_i b_i = B$$

$$\sum_i e_i = Q$$

$$\sum_i (m_i + s_i) = J_z$$

$$\sum_i k_i = K$$

$$\sum_i \left[2n_i + |m_i| + 1\right] \leq N_{\max}$$

Global Color Singlets (QCD)

Light Front Gauge

Optional - Fock space cutoffs

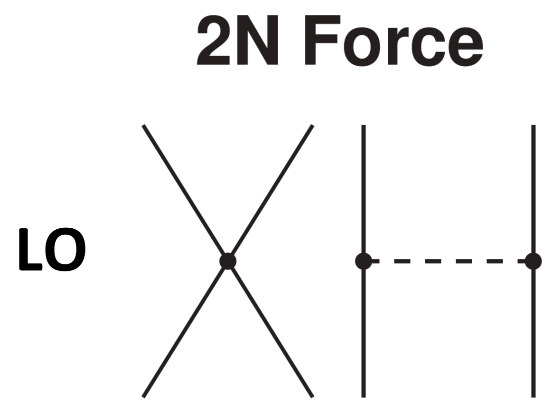
$$\mathrm{H} \rightarrow \mathrm{H} + \lambda \mathrm{H}_{CM}$$

Finite basis regulators

Effective Yukawa Model in BLFQ
Wenyang Qian, et al. in preparation

Inspiration: Chiral Perturbation Theory *

Four-nucleon-leg contact term + one pion exchange



LF treatment:

Approximate the contact term by heavy scalar boson exchange + effective one pion exchange

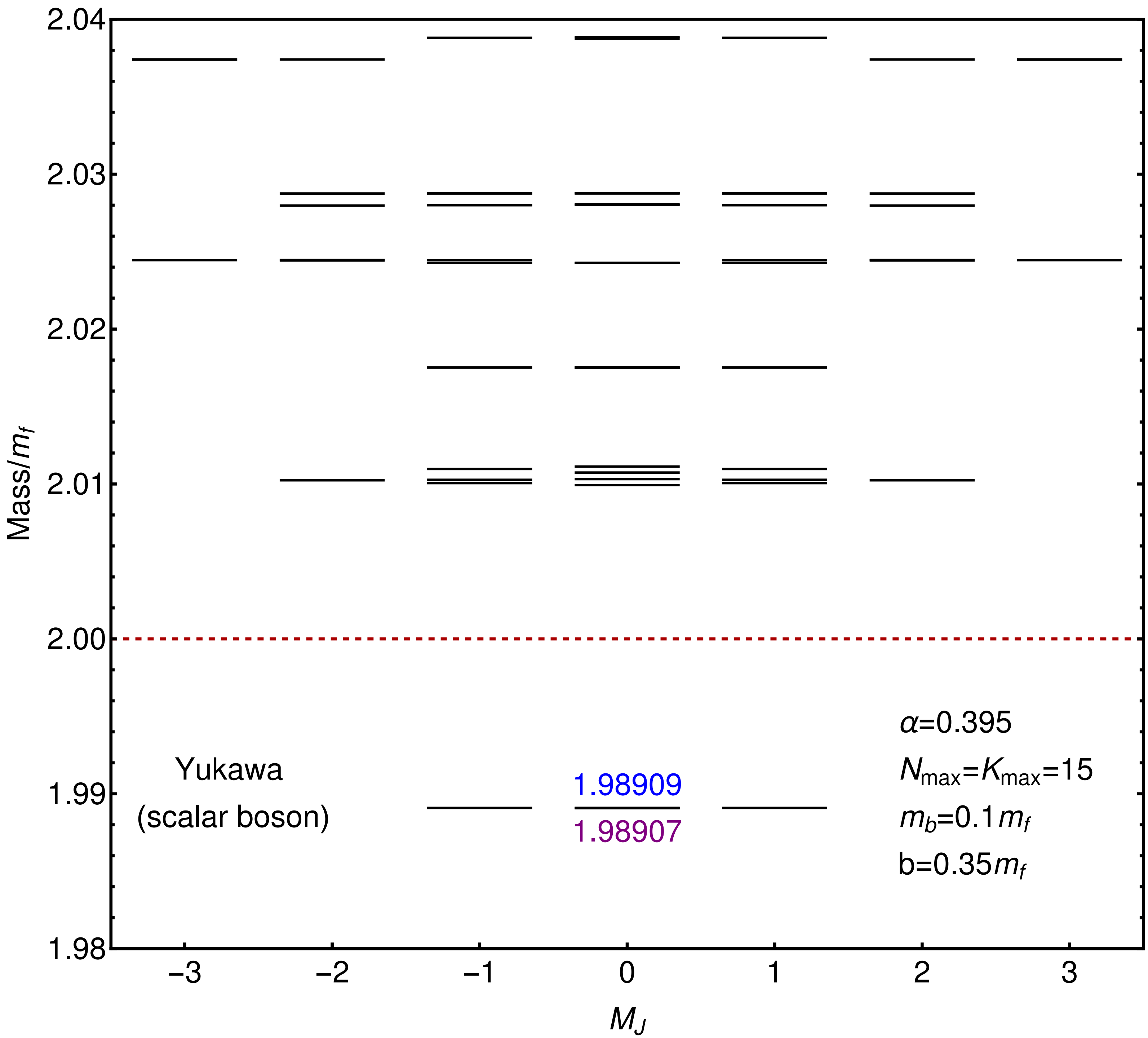
Basis Light-Front Quantization(BLFQ) Approach:

Hamiltonian formalism

Relativistic theory

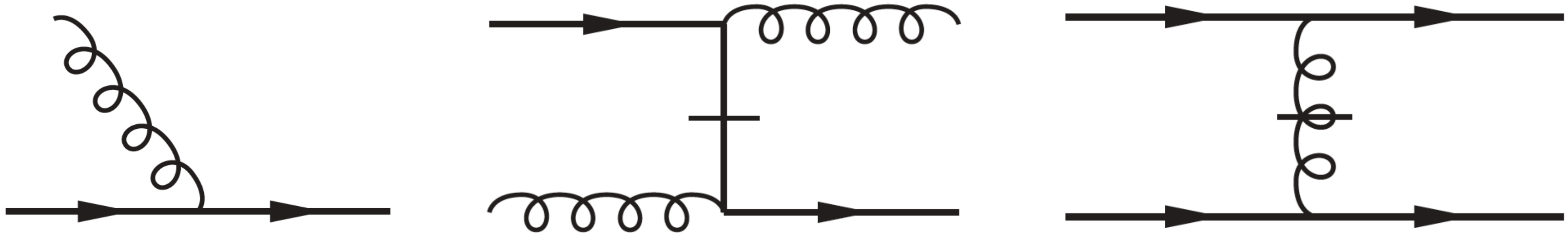
Light-front wave functions provides direct access to all physical observables

* R. Machleidt, D.R. Entem, Phys.Rept.503:1-75 (2011)

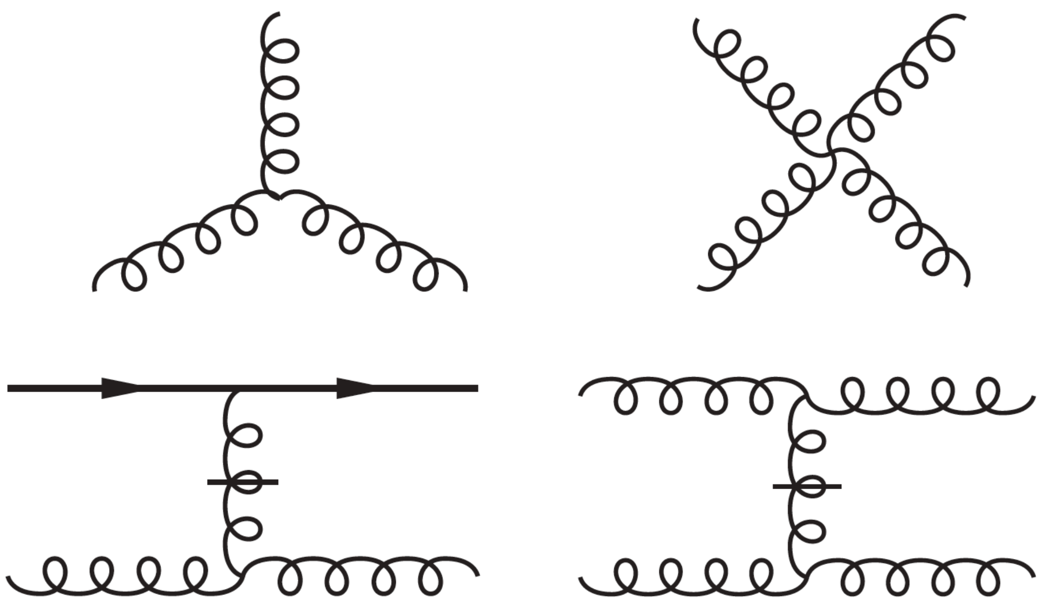


2.04
2.03
2.02
2.01
2.00
1.99
1.98
Mass/m_f
−3
−2
−1
0
1
2
3
M_J
Yukawa
(scalar boson)
1.98909
1.98907
α=0.395
N_{max}=K_{max}=15
m_b=0.1m_f
b=0.35m_f

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



QED & QCD



QCD

Light-Front Regularization and Renormalization Schemes

1. Regulators in BLFQ (Ω, N_{max}, K)
2. Additional Fock space truncations (if any)
3. Counterterms identified/tested*
4. Sector-dependent renormalization**
5. SRG & OLS in NCSM*** - adapted to BLFQ (future)

*D. Chakrabarti, A. Harindranath and J.P. Vary,
Phys. Rev. D **69**, 034502 (2004)
*P. Wiecki, Y. Li, X. Zhao, P. Maris and J.P. Vary,
Phys. Rev. D **91**, 105009 (2015)

**V. A. Karmanov, J.-F. Mathiot, and A. V. Smirnov,
Phys. Rev. D **77**, 085028 (2008); Phys. Rev. D **86**, 085006 (2012)
**Y. Li, V.A. Karmanov, P. Maris and J.P. Vary,
Phys. Letts. B. 748, **278** (2015); arXiv: 1504.05233

***B.R. Barrett, P. Navratil and J.P. Vary,
Prog. Part. Nucl. Phys. **69**, 131 (2013)

Light-Front Schrödinger equation for quark – antiquark systems

$$M_h^2\,\psi^{\lambda}_{s\bar{s}/h}(x,\vec{k}_\perp) = \Big[\underbrace{\frac{\vec{k}_\perp^2 + m_q^2(x,k_\perp)}{x} + \frac{\vec{k}_\perp^2 + m_{\bar{q}}^2(x,k_\perp)}{1-x}}_{\text{kinetic energy w. running masses}}\Big]\psi^{\lambda}_{s\bar{s}/h}(x,\vec{k}_\perp)$$

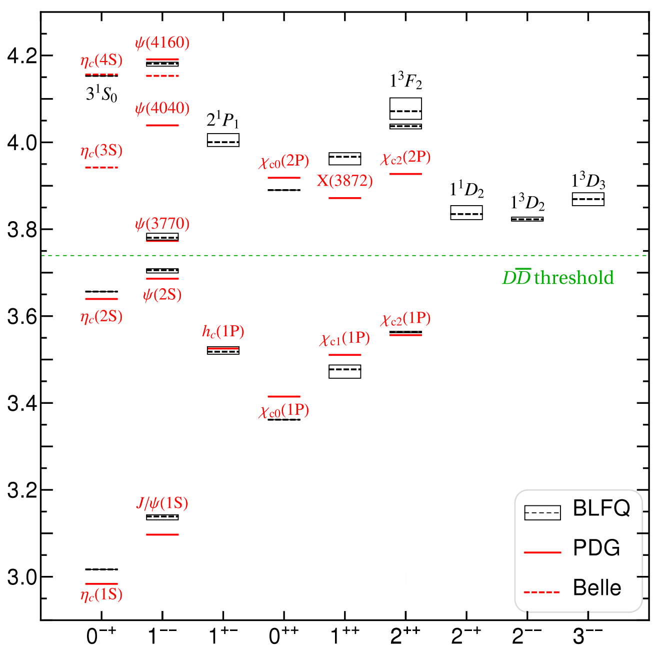
$$+\sum_{s',\bar{s}'}\int_0^1 \frac{\mathrm{d}x'}{2x'(1-x')}\int\frac{\mathrm{d}^2k'_\perp}{(2\pi)^3}\underbrace{V_{s'\bar{s}',s\bar{s}}(x,\vec{k}_\perp,x',\vec{k}'_\perp)}_{\text{effective relativistic interaction}}\psi^{\lambda}_{s'\bar{s}'/h}(x',\vec{k}'_\perp)$$

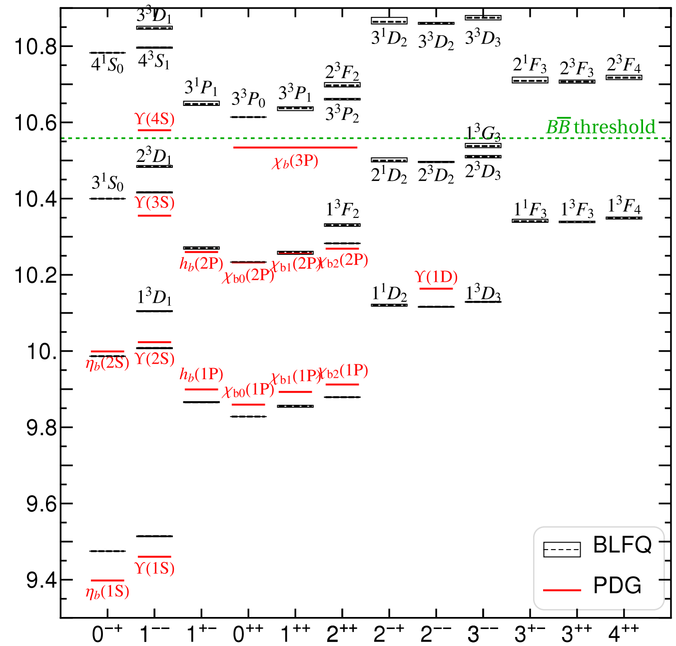
$$V = \underbrace{\kappa^2\varsigma_\perp^2}_{\text{LFH}} - \underbrace{\frac{\kappa^4}{4m_q^2}\partial_x\big(x(1-x)\partial_x\big)}_{\text{Longitudinal confinement}} - \underbrace{\frac{C_F 4\pi\alpha_s(Q^2)}{Q^2}\bar{u}_s(k)\gamma^\mu u_{s'}(k')\bar{v}_{\bar{s}'}(\bar{k}')\gamma^\nu v_{\bar{s}}(\bar{k})d_{\mu\nu}}_{\text{Krautgartner-Pauli-Wolz one-gluon exchange with running coupling}}$$

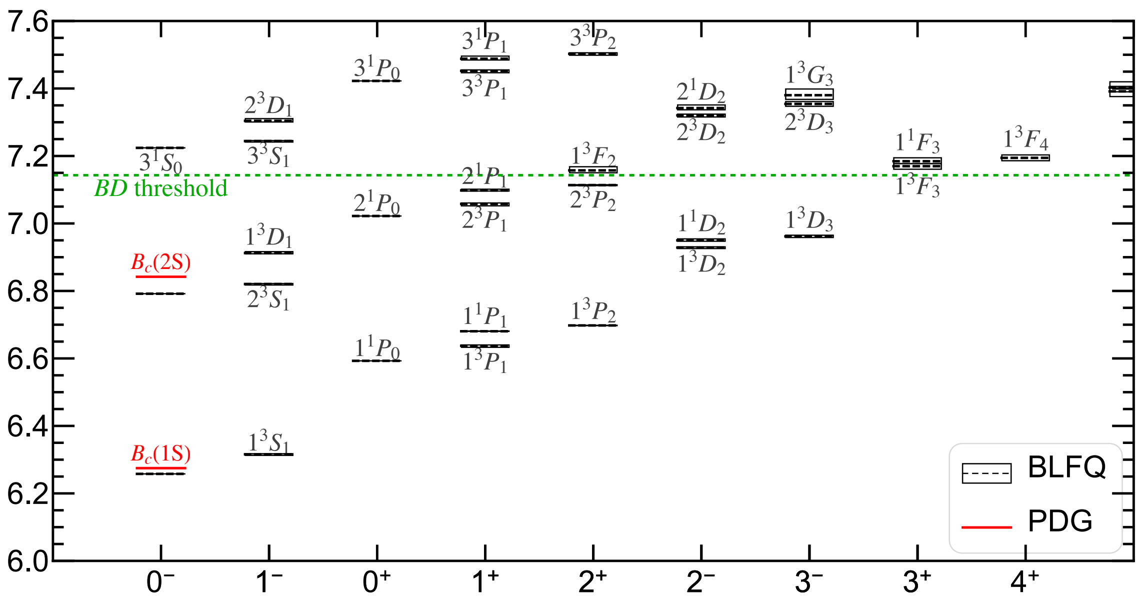
- Implement quark masses with longitudinal degree of freedom: identical to LFH in both chiral limit and NR limit; $X(x) \sim x^a(1-x)^b$
- Introduce short-distance physics with spinor structure [cf. Głazek '17]
- Self-energy and dynamical chiral symmetry breaking to be implemented
- Basis light-front quantization [Vary et al, PRC 2010]

Spectroscopy

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







fitting parameters:

$m_c, m_b, \kappa_{qQ} = c\sqrt{M_{qQ}}$

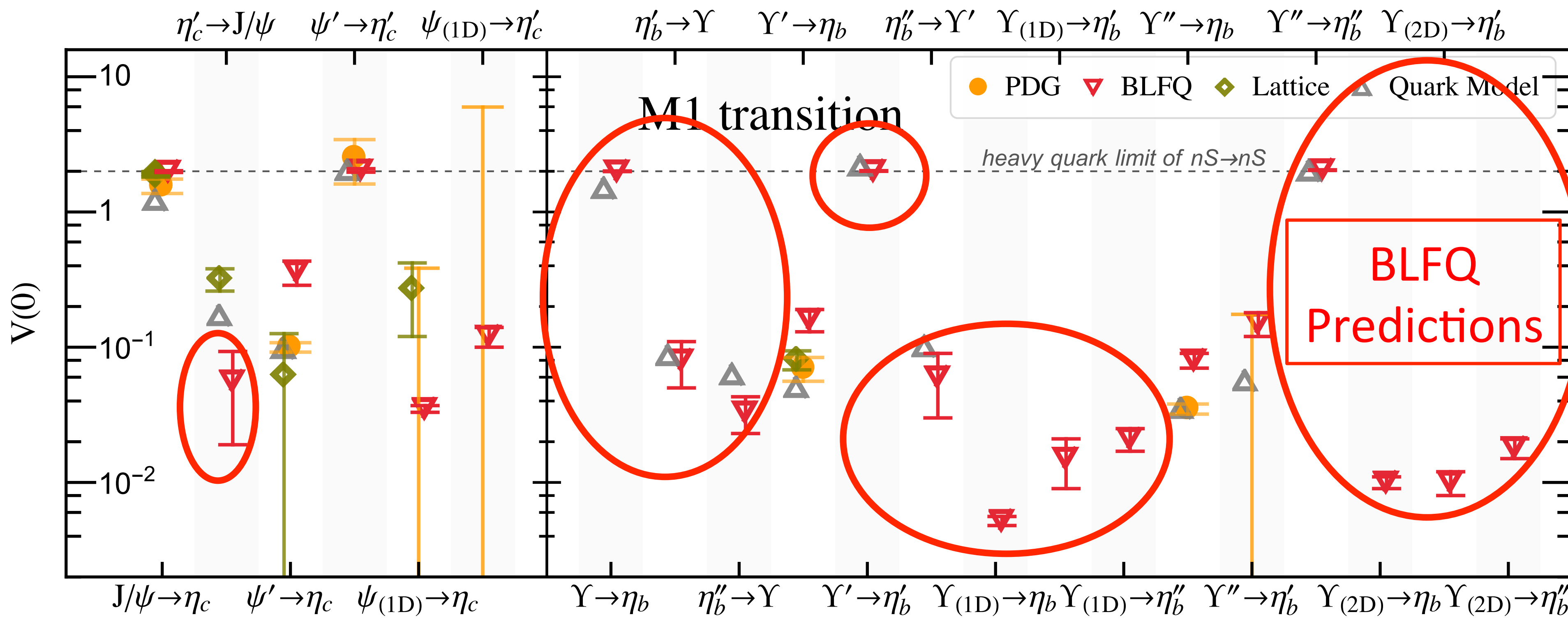
(HQET, [cf. Dosch ’17])

rms deviation: 31–38 MeV

Radiative transitions of heavy quarkonia

$$V^{+}(0) = -\frac{\sqrt{2}(m_P + m_V)}{4\pi}\sum_{\sigma_1,\sigma_2}\int \mathrm{d}r_\perp \int_0^1 \mathrm{d}x \int \mathrm{d}\theta\, \tilde{\psi}^{\sigma_1,\sigma_2}_{\mathcal{V},m_j=1}(r_\perp,\theta,x)\tilde{\psi}^{\sigma_1,\sigma_2 *}_{\mathcal{P}}(r_\perp,\theta,x)(1-x)r_\perp^2\cos\theta$$

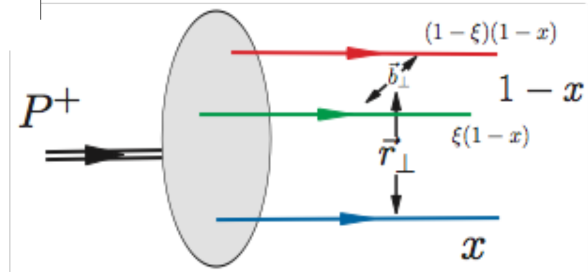
$$V^{\perp}(0) = \frac{m_P + m_V}{4\pi m_V}\sum_{\sigma_2}\int \mathrm{d}r_\perp \int_0^1 \mathrm{d}x \int \mathrm{d}\theta\, \tilde{\psi}^{\uparrow,\sigma_2}_{\mathcal{V},m_j=0}(r_\perp,\theta,x)\tilde{\psi}^{\uparrow,\sigma_2 *}_{\mathcal{P}}(r_\perp,\theta,x)\frac{r_\perp}{x}$$



[PDG] Chin. Phys. C40, 100001 (2016).
[Lattice] J. J. Dudek, et al., Phys. Rev. D 73, 074507 (2006), Phys. Rev. D 79, 094504 (2009); D. Bečirević, et al., Journal of High Energy Physics 2015, 14 (2015). C. Hughes et al., Phys. Rev. D 92, 094501 (2015).
[Quark Model] D. Ebert, et al. Phys. Rev. D67, 014027 (2013).

Baryons

Anji Yu, et al., in preparation



$$\vec{k}_\perp \equiv \vec{k}_{1\perp} = \frac{x_1\vec{p}_{2\perp} - x_2\vec{p}_{1\perp}}{x_1+x_2} \qquad \vec{b}_\perp \equiv \vec{b}_{1\perp} = \vec{r}_{2\perp} - \vec{r}_{1.}$$

$$\vec{p}_\perp \equiv \vec{k}_{2\perp} = \vec{p}_{3\perp} - x_3\vec{P}_\perp \qquad \vec{r}_\perp \equiv \vec{b}_{2\perp} = \frac{\vec{r}_{3\perp} - \vec{R}_\perp}{1-x_3}$$

$$\vec{P}_\perp = \sum_{a=1}^{3} \vec{p}_{a\perp} \qquad \vec{R}_\perp = \sum_{a=1}^{3} x_a \vec{r}_{a\perp}$$

Effective Hamiltonian

Kinetic energy — Harmonic oscillator confining potential

$$H_{\text{eff}} = \frac{\vec{p}_\perp^2 + m_3^2}{x} + \frac{1}{1-x}\left[\vec{p}_\perp^2 + \frac{\vec{k}_\perp^2 + m_2^2}{\xi} + \frac{\vec{k}_\perp^2 + m_1^2}{1-\xi}\right] + \kappa^4 x(1-x)\vec{r}_\perp^2 + \kappa^4(1-x)\xi(1-\xi)\vec{b}_\perp^2$$
$$- \frac{\kappa^4}{(m_1+m_2+m_3)^2}\left[\partial_x\big(x(1-x)\partial_x\big) + \frac{1}{1-x}\partial_\xi\big(\xi(1-\xi)\partial_\xi\big)\right] + \text{const.}$$

Longitudinal confining potential

Mass eigenvalue

$$\left[M_{\mathrm{L}}^2 = (m_1+m_2)^2 + \frac{m_1+m_2}{m_1+m_2+m_3}\kappa^2(2\mathrm{L}+1) + \frac{\kappa^4}{(m_1+m_2+m_3)^2}\mathrm{L}(\mathrm{L}+1)\right]$$

$$E_{\mathtt{n}_1,\mathtt{m}_1,\mathtt{n}_2,\mathtt{m}_2,\mathtt{L},\mathtt{l}} = (m_3 + M_{\mathrm{L}})^2 + 2\kappa^2(2\mathtt{n}_1 + |\mathtt{m}_1| + 2\mathtt{n}_2 + |\mathtt{m}_2| + 2)$$
$$+ \frac{M_{\mathrm{L}} + m_3}{m_1+m_2+m_3}\kappa^2(2\mathtt{l}+1) + \frac{\kappa^4}{(m_1+m_2+m_3)^2}\mathtt{l}(\mathtt{l}+1) + \text{const.}$$

Eigenfunction

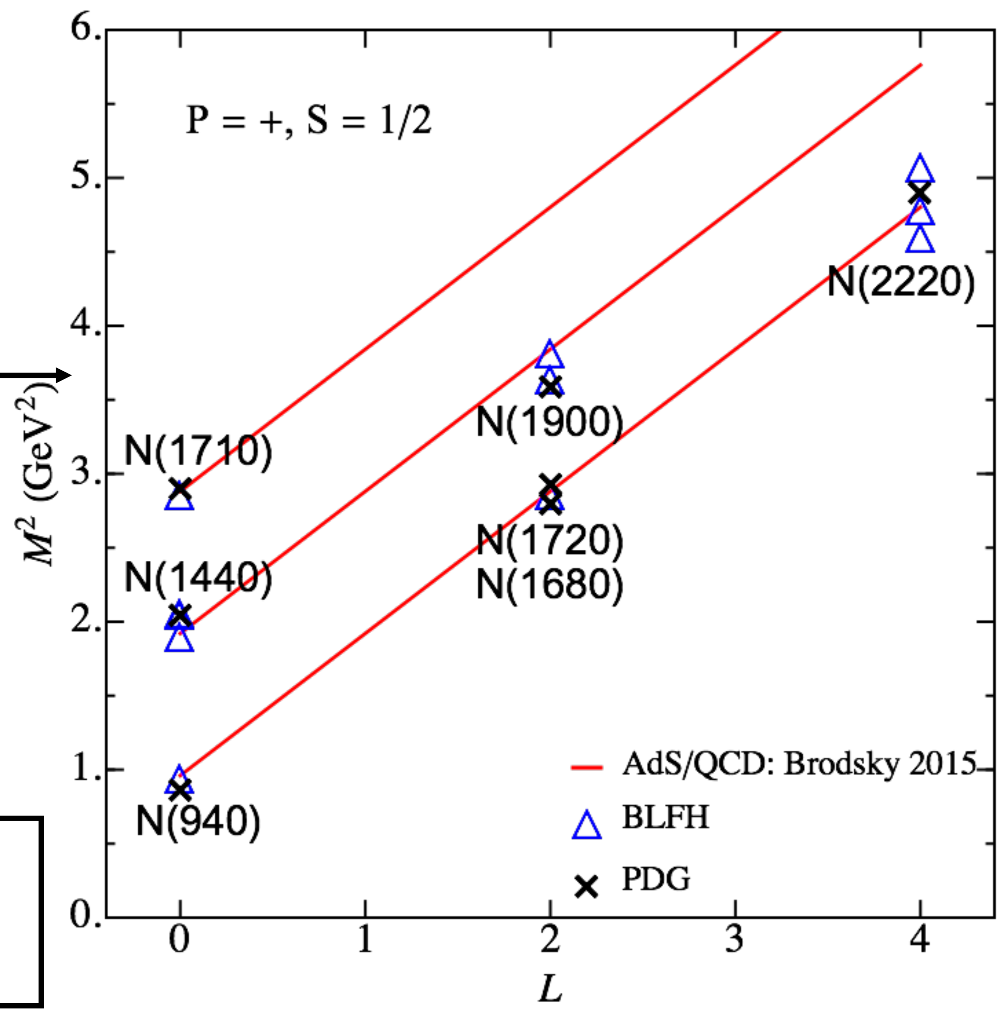
$$\Phi_{\mathtt{n}_1\mathtt{m}_1\mathtt{n}_2\mathtt{m}_2\mathtt{L}\mathtt{l}}(\vec{p}_\perp, x, \vec{k}_\perp, \xi) = \phi_{\mathtt{n}_1\mathtt{m}_1}(\vec{q}_{1\perp})\chi_{\mathrm{L}}^{(A,B)}(\xi)\phi_{\mathtt{n}_2\mathtt{m}_2}(\vec{q}_{2\perp})\chi_{\mathtt{l}}^{(\alpha_{\mathrm{L}},\beta)}(x).$$

$$A = 2m_1(m_1+m_2+m_3)/\kappa^2, B = 2m_2(m_1+m_2+m_3)/\kappa^2,$$
$$\alpha_{\mathrm{L}} = 2M_L(m_1+m_2+m_3)/\kappa^2, \beta = 2m_3(m_1+m_2+m_3)/\kappa^2$$

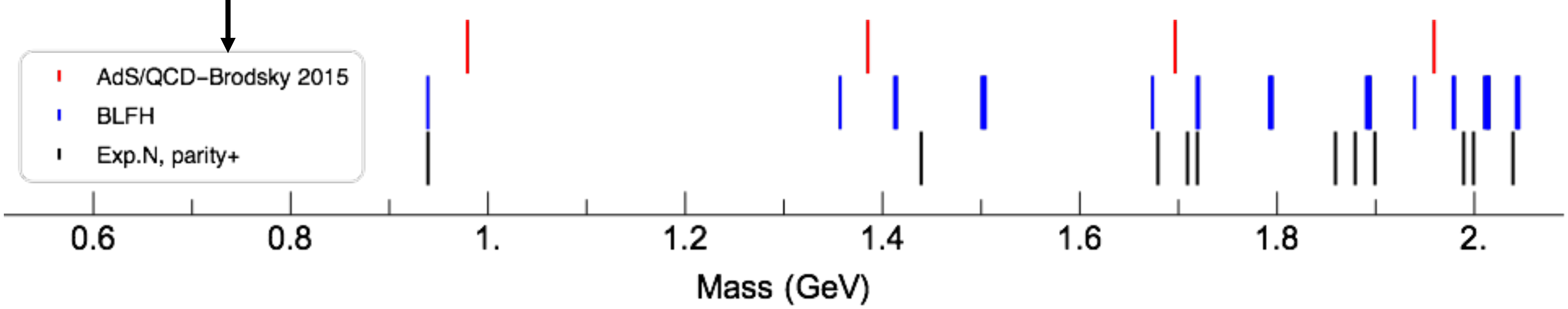
$$\vec{q}_{1\perp} \equiv \frac{\vec{k}_\perp}{\sqrt{(1-x)\xi(1-\xi)}} \qquad \vec{q}_{2\perp} \equiv \frac{\vec{p}_\perp}{\sqrt{x(1-x)}}$$

Baryons

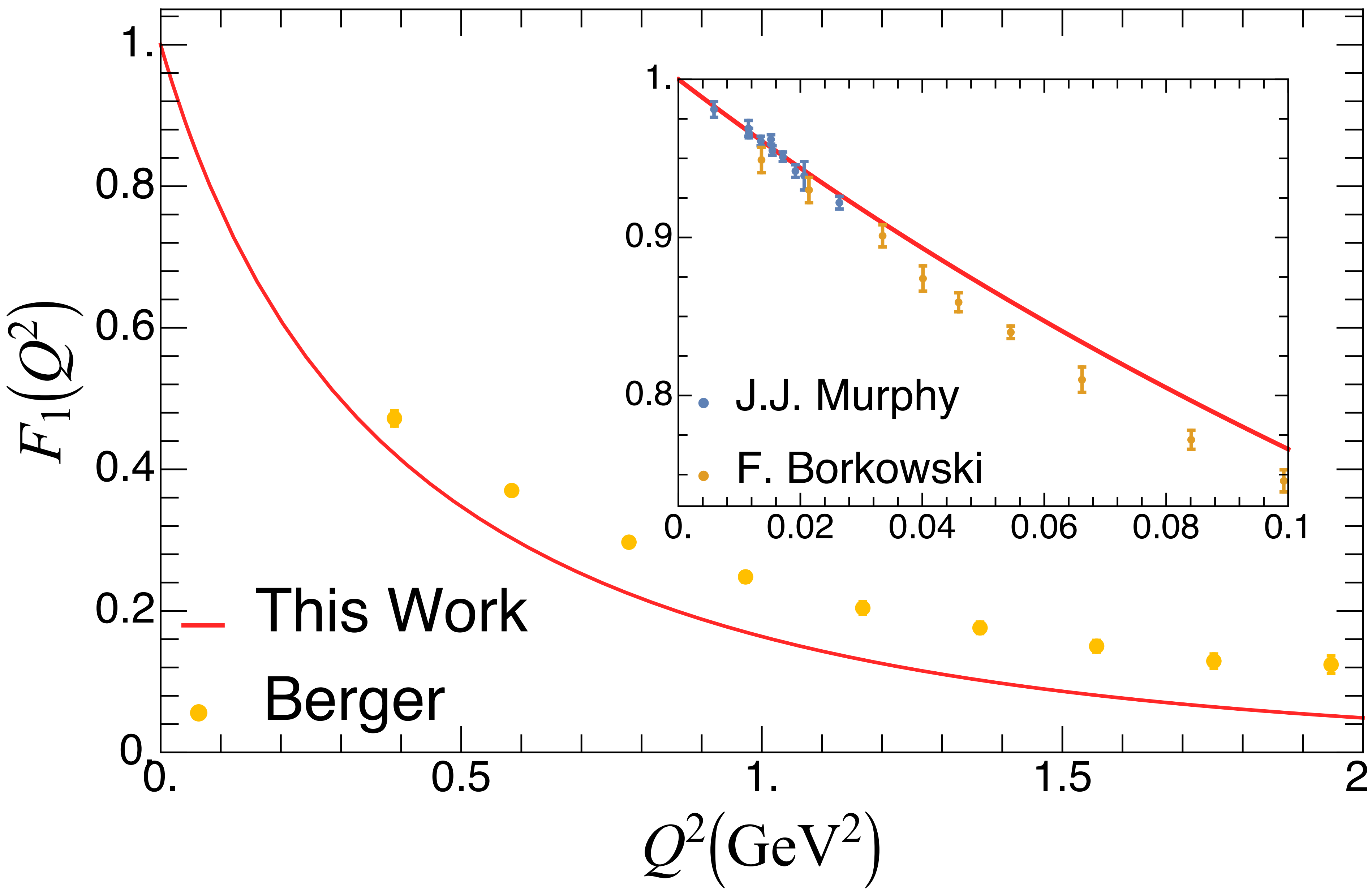
1. All mass eigenvalues in AdS/QCD can be covered by BLFH under appropriate mass shift
2. Spin has not been assigned yet, we choose the nearest mass states to present. Great chances that we are able to find desired spin configuration since exited states are highly degenerate.



Baryon excitation spectrum of positive parity nucleons: PDG vs BLFH with even ($L+l+m_1+m_2$), κ = 0.49 GeV, m = 0.35 GeV, matching the ground state value to mass of proton by mass shift.



Brodsky, S. J., de Téramond, G. F., Dosch, H. G., & Erlich, J., "Light-front holographic QCD and emerging confinement", *Physics Reports*, *584*, 1 (2015)



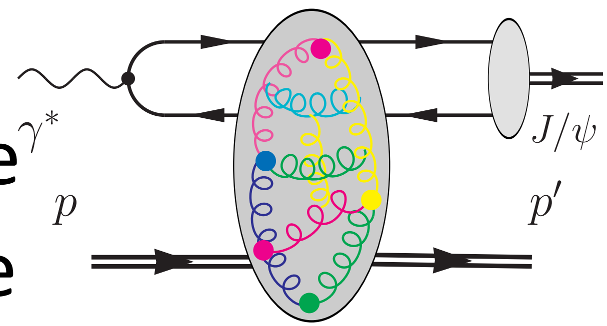
1.
0.8
0.6
0.4
0.2
0
0.
0.5
1.
1.5
2.
$F_1(Q^2)$
$Q^2(\mathrm{GeV}^2)$
This Work
Berger
1.
0.9
0.8
0.
0.02
0.04
0.06
0.08
0.1
J.J. Murphy
F. Borkowski

Measuring VM LFWF

- Diffractive VM production

$$\sigma_{\text{tot}} \sim \Psi_{photon} \circledast \sigma_{\text{dipole}} \circledast \Psi_{VM}$$

- Photon LFWF can be calculated from first principles.
- Dipole cross section can be obtained by measuring the inclusive DIS cross section.

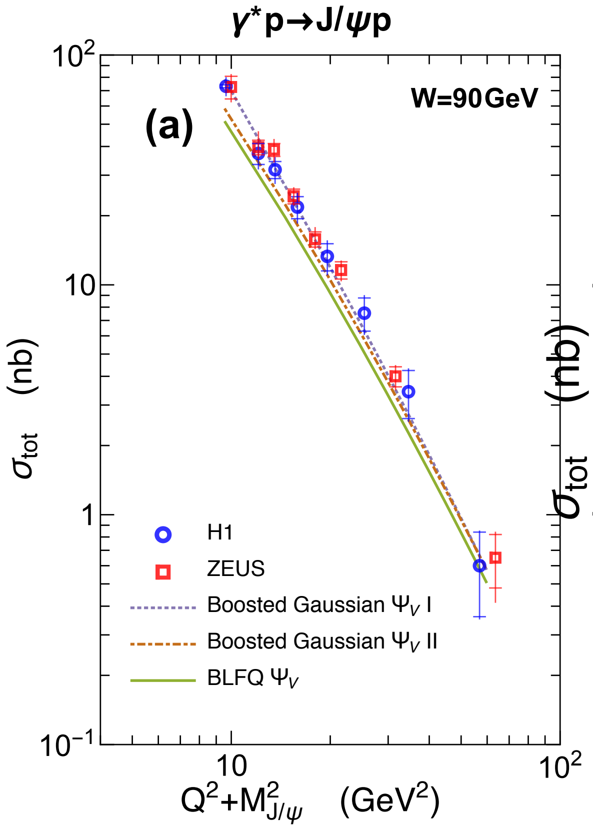


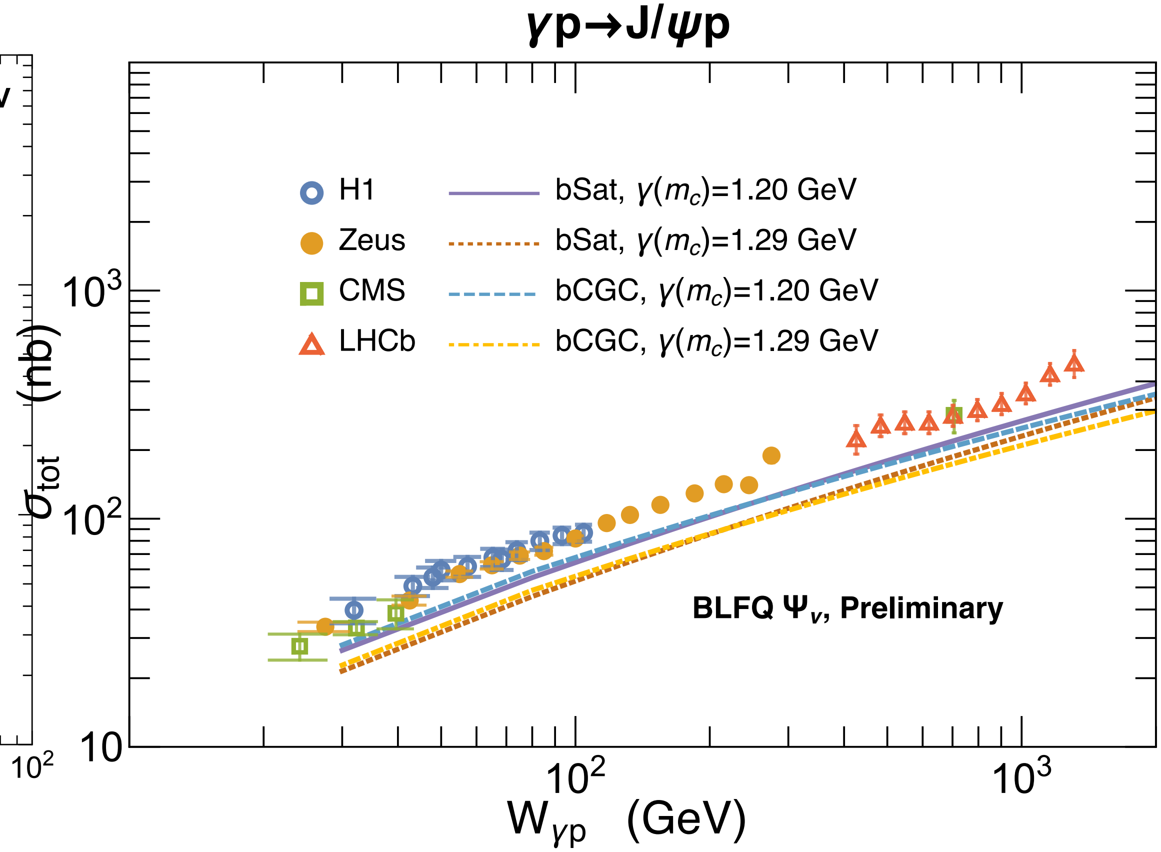
- Provide measurements of VM LFWF and gluon distribution.

A. Mueller, '90
N. Nikolaev, '91
K. Golec-Biernat et al., '99

Confront existing data

- In agreement with HERA, RHIC and LHC data.



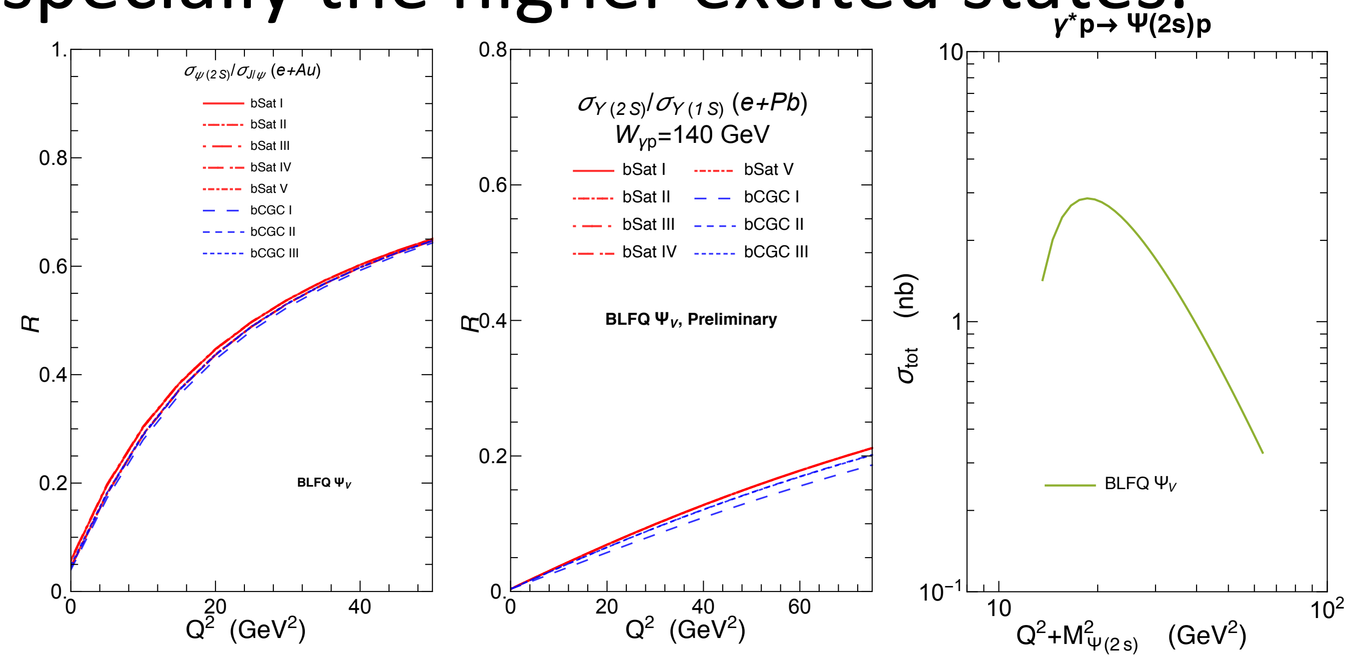


Chen, Li, Maris, Tuchin and Vary, PLB 769, 477, 2017

Prediction for future experiment

Guangyao Chen, et al., in preparation

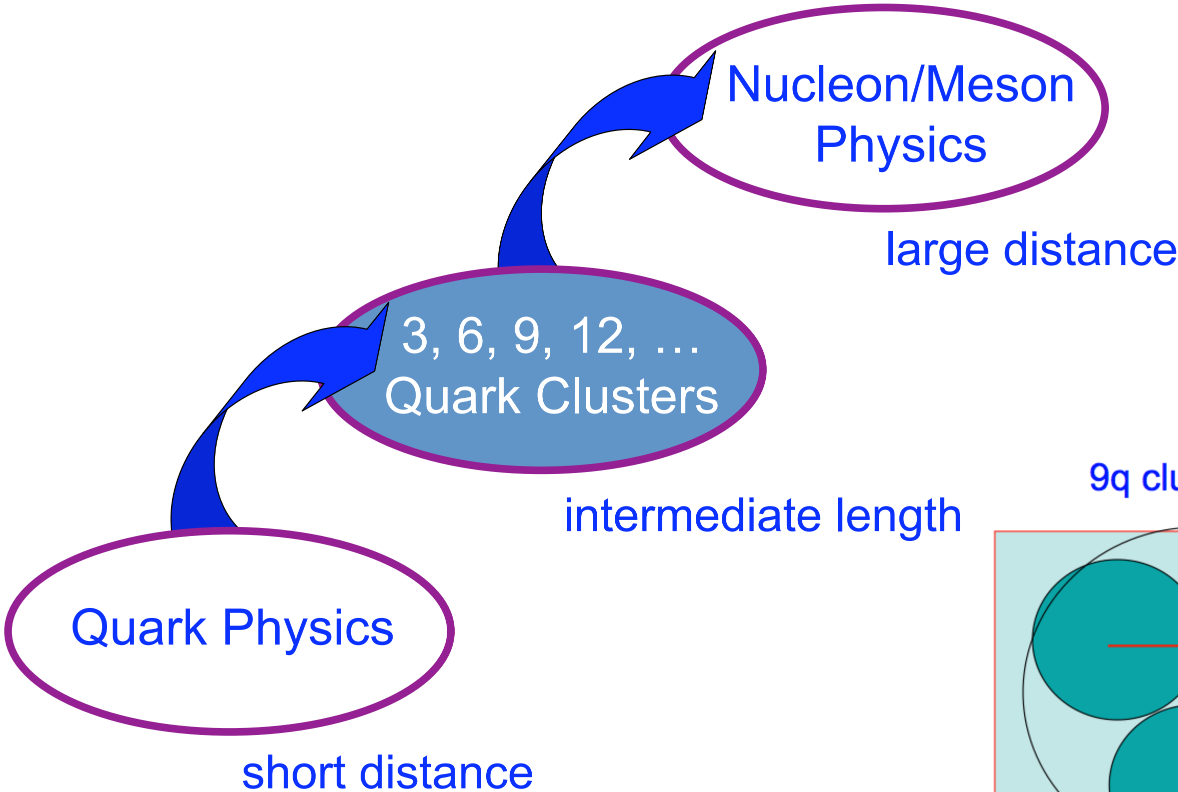
- Electron Ion Collider--high luminosity, wide kinematic range.
- Enable precision measurement of VM LFWF, especially the higher excited states.



Chen, Li, Maris, Tuchin and Vary, PLB 769, 477, 2017

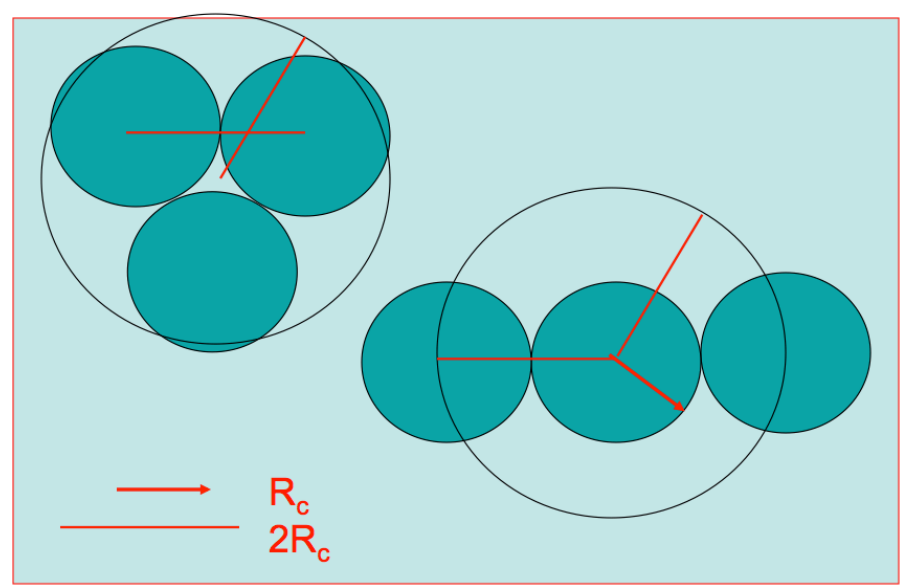
Looking ahead: under what conditions do we require a quark-based description of nuclear structure?

"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)

Sketch: hierarchy of strong interaction scales

Effective Field Theory	Scale	Range of Q	Phenomena
Pionless	Chiral symmetry breaking $\sim \Lambda_{QCD} \sim m_N$	$Q < m_\pi \sim k_F$ $Q \sim 0.2\, k_F$	Scattering lengths Stellar burning Halo nuclei Clustering, . . .
Pionfull, Deltafull	Chiral symmetry breaking $\sim \Lambda_{QCD} \sim m_N$	$Q < m_N$ $Q \sim m_\pi$	Low Energy Nuclear Structure & Reactions ^{14}C anomalous lifetime Tetraneutron, . . .
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, . .
QCD	Chiral symmetry restoration	$Q < m_{Planck}$	Asymptotic freedom pQCD domain sQCD-Quark-Gluon Plasma Color glass condensate Hadron tomography, . . .

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 high resolution
- Next goal: two-baryon systems with effective LF Hamiltonians from chiral EFT to quark-gluon systems
- Next goal: mesons and baryons with one dynamical gluon
- Future: EFT at the quark-percolation scale