

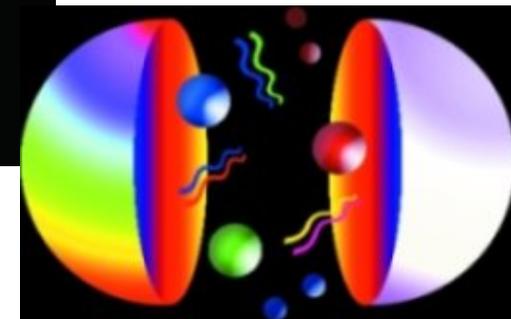
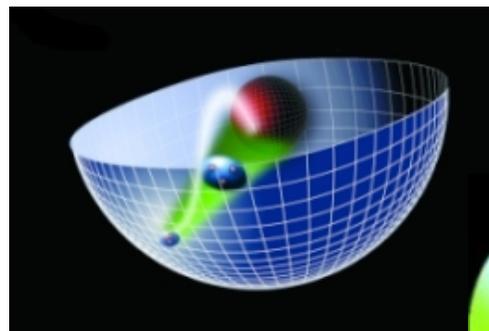
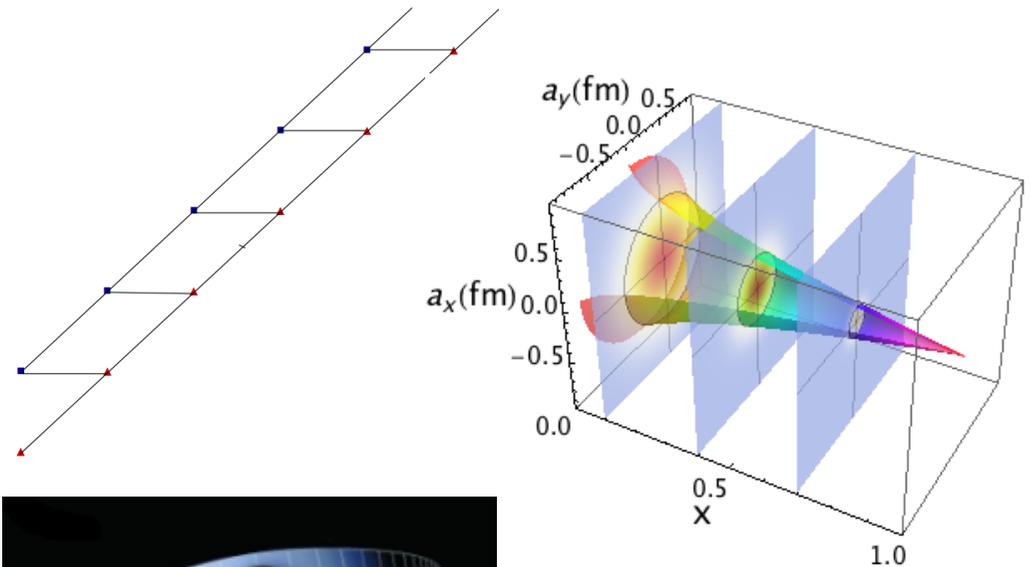
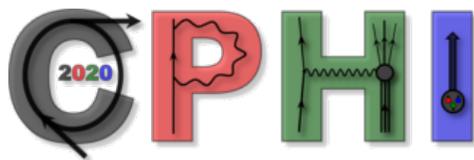
Light-Front Holographic QCD: From counting rules to a unified description of parton distributions

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Stan Brodsky 80th's Fest at
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Review: S. J. Brodsky, GdT, H.G. Dosch, J. Erlich, Light-front holographic QCD and emerging confinement, Phys. Rept. **584**, 1 (2015) [[hep-ph/9705477](https://arxiv.org/abs/hep-ph/9705477)]

1 Hard scattering power counting rules and holography

- Confinement in QCD is a vastly complex problem: Increase of the strong coupling in the infrared implies an infinite number of quark and gluons dynamically intertwined
- Recent analytical insights into the nonperturbative structure of QCD based on the gauge/gravity correspondence and light-front quantization have lead to effective semiclassical bound state equations where the confinement potential is determined by an underlying superconformal algebraic structure
- Our work in this area can be traced to the pivotal article [J. Polchinski and M. Strassler (2002)] where the hard scattering counting rules [S. J. Brodsky and G. Farrar (1973)] are derived using the gauge/string duality
- B-F power counting rules ($s, t \gg \Lambda$)

$$\frac{d\sigma}{dt}(A + B \rightarrow C + D) \sim \frac{1}{s^2} |M|^2 \sim \frac{1}{s^{n-2}}$$

where $n = n_A + n_B + n_C + n_D$

- “...is quite remarkable for so simply explaining such a large number of observations ... Even when the parton which receives a large momentum transfer remains bound within a hadron, the system behaves like a collection of free quarks ... (B-F)

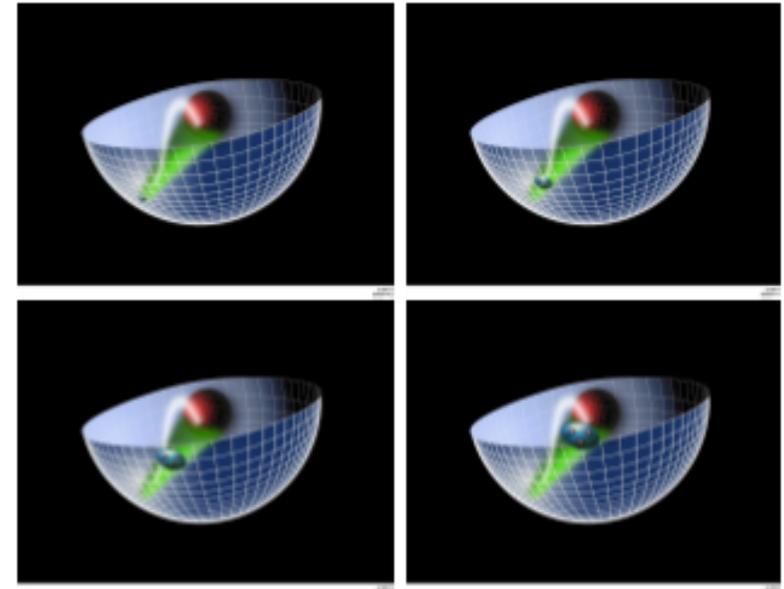
- Is it possible to obtain hard behavior for a hadron bound state from the gauge/gravity correspondence?
- P-S used AdS₅ from AdS/CFT: a space with negative curvature and 4-dim boundary: Minkowski space
- AdS₅ metric:

$$\underbrace{ds^2}_{L_{\text{AdS}}} = \frac{R^2}{z^2} \left(\underbrace{\eta_{\mu\nu} dx^\mu dx^\nu}_{L_{\text{Minkowski}}} - dz^2 \right)$$

AdS metric is invariant under a dilatation of all coordinates $x^\mu \rightarrow \lambda x^\mu$, $z \rightarrow \lambda z$

- A distance L_{AdS} shrinks by a warp factor z/R as observed in Minkowski space ($dz = 0$):

$$L_{\text{Minkowski}} \sim \left(\frac{z}{R} \right) L_{\text{AdS}}$$



- Short distances $x_\mu x^\mu \rightarrow 0$ map to the UV conformal AdS₅ boundary $z \rightarrow 0$
- Large dimensions $x_\mu x^\mu \sim 1/\Lambda_{\text{QCD}}^2$ map to the IR region of AdS₅: need a cut-off for large z
- Power law behavior follows from the warped geometry: The entire hadron in elastic scattering at high momentum transfer shrinks to a small size near $z = 0$ where the dual space is conformal

2 Light front holographic mapping

- Following exploratory work with Stan on the relevance of Dirac's light-front form for a gravity dual [S. J. Brodsky and GdT (2004, 2005)], we carried out a specific mapping of string modes in AdS_5 to LFWFs of hadrons in physical space-time [S. J. Brodsky and GdT (2006, 2008)]

$$\int d^4x dz \sqrt{g} A^M(x, z) \Phi_{P'}^*(x, z) \overleftrightarrow{\partial}_M \Phi_P(x, z) \sim (2\pi)^4 \delta^{(4)}(P' - P - q) \epsilon_\mu(P + P') F(q^2)$$

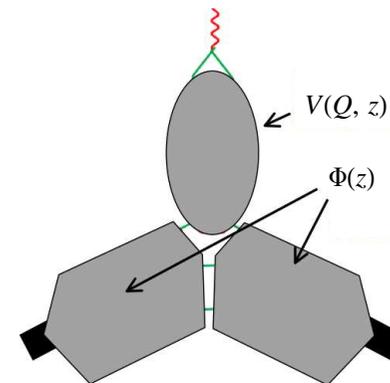
where $A^M(x, t)$ is an external EM field propagating in AdS ($M = 0, \dots, 4$) coupled to an extended field $\Phi(x, z)$ describing a hadron in the gravity side

- On the right side $F(q^2)$ is the EM FF in physical space-time

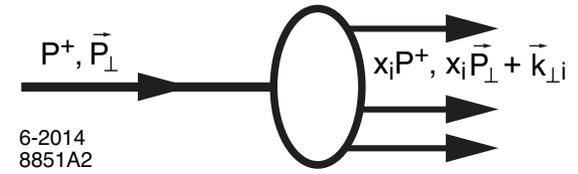
$$\langle P' | J^\mu | P \rangle = (P + P') F(q^2)$$

with $J^\mu = e_q \bar{q} \gamma^\mu q$ the quark current which couples locally to point-like constituents

- The expressions for the EM FF look very different, however a precise mapping can be carried out for an arbitrary number of partons
- We found identical results from the mapping of the matrix elements of the energy-momentum tensor [S. J. Brodsky and GdT (2008)]



Schematic derivation for the hard wall model



- FF expressed in terms of effective single particle density [D. Soper (1977)]

$$F(q^2) = \int_0^1 dx \rho(x, q) = \int_0^1 dx \int d^2 \mathbf{a}_\perp e^{i \mathbf{a}_\perp \cdot \vec{q}_\perp} \rho(x, \mathbf{a}_\perp)$$

where

$$\rho(x, \mathbf{a}_\perp) = \sum_n \prod_{j=1}^{n-1} \int dx_j d^2 \mathbf{b}_{\perp j} \delta(1 - x - \sum_{j=1}^{n-1} x_j) \delta^{(2)}(\sum_{j=1}^{n-1} x_j \mathbf{b}_{\perp j} - \mathbf{a}_\perp) |\psi_n(x_j, \mathbf{b}_{\perp j})|^2$$

is the sum of impact parameter parton distributions [M. Burkardt (2000)] and $\mathbf{a}_\perp = \sum_{j=1}^{n-1} x_j \mathbf{b}_{\perp j}$

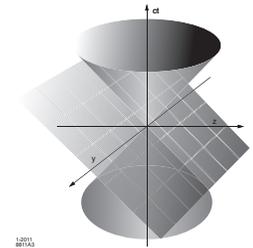
- For AdS EM current $A_\mu = \epsilon_\mu e^{-iq \cdot x} z q K_1(zq)$, $A_z = 0$, and hadron mode $\Phi(x, z) = e^{-iP \cdot x} \Phi(z)$

$$\rho_n(x, \zeta) = \frac{1}{2\pi} \frac{x}{1-x} \frac{|\Phi_{\tau=n}(\zeta)|^2}{\zeta^4}, \quad \zeta^2 = z^2 = \left(\frac{x}{1-x} \right)^2 \mathbf{a}_\perp^2$$

- For two partons $\rho_{n=2}(x, \zeta) = |\psi(x, \zeta)|^2 / (1-x)^2$ we find

$$|\psi(x, \zeta)|^2 = \frac{1}{2\pi} x(1-x) \frac{|\Phi(\zeta)|^2}{\zeta^4}, \quad \zeta^2 = z^2 = x(1-x) \mathbf{b}_\perp^2$$

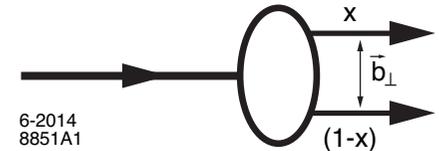
3 Semiclassical approximation to light front QCD



- Strings describe spin- J extended objects (no quarks), but QCD degrees of freedom are pointlike particles and hadrons have internal orbital angular momentum: how can they be related?
- We compute the hadron matrix element $\langle \psi(P') | P_\mu P^\mu | \psi(P) \rangle$ with $P = (P^-, P^+, \mathbf{P}_\perp)$ and factor out the longitudinal $X(x)$ and orbital $e^{iL\varphi}$ kinematical dependence from the LFWF ψ

$$\psi(x, \zeta, \varphi) = e^{iL\varphi} X(x) \frac{\phi(\zeta)}{\sqrt{2\pi\zeta}}$$

with transverse invariant impact variable LF $\zeta^2 = x(1-x)\mathbf{b}_\perp^2$



- Ultra relativistic limit $m_q \rightarrow 0$ longitudinal modes $X(x)$ decouple ($L = L^z$)
- LF Hamiltonian equation $P_\mu P^\mu |\psi\rangle = M^2 |\psi\rangle$ is a relativistic and frame-independent LF wave equation for ϕ [GdT and S. J. Brodsky (2009)]

$$\left(-\frac{d^2}{d\zeta^2} - \frac{1 - 4L^2}{4\zeta^2} + U(\zeta) \right) \phi(\zeta) = M^2 \phi(\zeta)$$

where the effective potential U includes all interactions, including those from higher Fock states

- Critical value of orbital angular momentum $L = 0$ corresponds to lowest possible stable solution
- Semiclassical approximation to LF QCD has similar structure of AdS WE with $z = \zeta$

4 Higher-spin wave equations in AdS and LF holographic embedding

- In 2009 Hans Guenter Dosch joined us and a new collaborative phase allowed the exploration of new and unsuspected connections in holographic QCD. One of the problems we examined was the holographic embedding of arbitrary spin hadrons [GdT, H. G. Dosch and S. J. Brodsky (2013)]
- We started from the AdS action for a rank- J tensor field $\Phi_{N_1 \dots N_J}$ with AdS mass μ and a dilaton profile φ which breaks the maximal symmetry of AdS

$$S = \int d^d x dz \sqrt{g} e^{\varphi(z)} g^{N_1 N'_1} \dots g^{N_J N'_J} \left(g^{MM'} D_M \Phi_{N_1 \dots N_J}^* D_{M'} \Phi_{N'_1 \dots N'_J} - \mu^2 \Phi_{N_1 \dots N_J}^* \Phi_{N'_1 \dots N'_J} + \dots \right)$$

where $\sqrt{g} = (R/z)^{d+1}$ and D_M is the covariant derivative with affine connection

$$D_M \Phi_{M_1 \dots M_J} = \partial_M \Phi_{M_1 \dots M_J} - \Gamma_{MM_1}^K \Phi_{K \dots M_J} - \dots - \Gamma_{MM_J}^K \Phi_{M_1 \dots K}$$

- In holographic QCD a hadron state is described by a z -dependent wave function $\Phi_J(z)$ and a plane wave in physical space with polarization indices ν along Minkowski coordinates

$$\Phi_{\nu_1 \dots \nu_J}(x, z) = e^{iP \cdot x} \Phi_J(z) \epsilon_{\nu_1 \dots \nu_J}(P)$$

with invariant mass $P_\mu P^\mu = M^2$

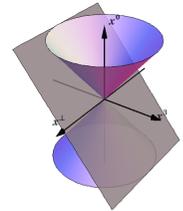
- From $\delta S/\delta\Phi = 0$ follows the eigenvalue equation ($m = m(\mu, \varphi)$)

$$\left[-\frac{z^{d-1-2J}}{e^{\varphi(z)}} \partial_z \left(\frac{e^{\varphi(z)}}{z^{d-1-2J}} \partial_z \right) + \frac{(mR)^2}{z^2} \right] \Phi_J(z) = M^2 \Phi_J(z)$$

plus kinematical constraints to eliminate lower spin from the symmetric tensor field $\Phi_{N_1 \dots N_J}$

- Upon the substitution $\Phi_J(z) = z^{(d-1)/2-J} e^{-\varphi(z)/2} \phi_J(z)$ we find for $d = 4$ the semiclassical QCD light-front wave equation

$$\left(-\frac{d^2}{d\zeta^2} - \frac{1 - 4L^2}{4\zeta^2} + U(\zeta) \right) \phi(\zeta) = M^2 \phi(\zeta)$$



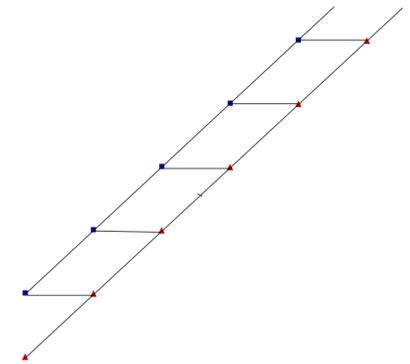
with $\zeta^2 = z^2 = x(1-x)b_\perp^2$ the LF invariant separation between two quarks and

$$U(\zeta, J) = \frac{1}{2} \varphi''(\zeta) + \frac{1}{4} \varphi'(\zeta)^2 + \frac{2J-3}{2\zeta} \varphi'(\zeta)$$

the effective LF confinement potential with $(mR)^2 = -(2-J)^2 + L^2$

- QM condition $L^2 \geq 0$ equivalent to the Breitenlohner-Freedman AdS bound $(mR)^2 \geq 4$ for $J = 0$
- Similar derivation for higher half-integral spin from Dirac equation in AdS for Rarita-Schwinger spinors
- Question: how shall we determine the effective confinement interaction ?

5 Superconformal algebraic structure in LFHQCD



- Superconformal algebra underlies in LFHQCD the scale invariance of the QCD Lagrangian. It leads to the introduction of a scale in the Hamiltonian maintaining the action invariant. It also leads to a specific connection between mesons, baryons and tetraquarks underlying the $SU(3)_C$ representation properties, namely $\bar{3} \rightarrow 3 \times 3$ (Hadronic SUSY was introduced by Miyazawa in 1967)
- Our work in this area [S. J. Brodsky, H. G. Dosch and GdT (2014, 2015)] is rooted in the articles by De Alfaro, Fubini and Furlan (1976) and Fubini and Rabinovici (1984)
- SUSY QM [E. Witten (1981)] contains two fermionic generators Q and Q^\dagger with anticommutation relations $\{Q, Q\} = \{Q^\dagger, Q^\dagger\} = 0$ and the Hamiltonian $H = \frac{1}{2}\{Q, Q^\dagger\}$ which commutes with the fermionic generators $[Q, H] = [Q^\dagger, H] = 0$ closing the graded-Lie $sl(1/1)$ algebra
- Since $[Q^\dagger, H] = 0$ the states $|E\rangle$ and $Q^\dagger|E\rangle$ have identical eigenvalues E , but for a zero eigenvalue we can have the trivial solution $|E = 0\rangle = 0$ (the pion ?)

Schematic derivation of bound state equations

- For a conformal theory (f is dimensionless)

$$q = -\frac{d}{dx} + \frac{f}{x}, \quad q^\dagger = \frac{d}{dx} + \frac{f}{x}$$

- In matrix notation

$$Q = \begin{pmatrix} 0 & q \\ 0 & 0 \end{pmatrix}, \quad Q^\dagger = \begin{pmatrix} 0 & 0 \\ q^\dagger & 0 \end{pmatrix}, \quad H = \frac{1}{2} \begin{pmatrix} q q^\dagger & 0 \\ 0 & q^\dagger q \end{pmatrix}$$

- Superconformal QM: Conformal graded-Lie algebra has in addition to the Hamiltonian H and supercharges Q and Q^\dagger , a new operator S related to the generator of conformal transformations K

$$S = \begin{pmatrix} 0 & x \\ 0 & 0 \end{pmatrix}, \quad S^\dagger = \begin{pmatrix} 0 & 0 \\ x & 0 \end{pmatrix}$$

- It leads to the conformal enlarged algebra [Haag, Lopuszanski and Sohnius (1974)]

$$\begin{aligned} \frac{1}{2}\{Q, Q^\dagger\} &= H, & \frac{1}{2}\{S, S^\dagger\} &= K, \\ \{Q, S^\dagger\} &= f - B + 2iD, & \{Q^\dagger, S\} &= f - B - 2iD \end{aligned}$$

where $B = \frac{1}{2}\sigma_3$ is a baryon number operator and H , D and K are the generators of translation, dilatation and the special conformal transformation

- H, D and K

$$H = \frac{1}{2} \left(-\frac{d^2}{dx^2} + \frac{f^2 + 2Bf}{x^2} \right), \quad D = \frac{i}{4} \left(\frac{d}{dx}x + x\frac{d}{dx} \right), \quad K = \frac{1}{2}x^2$$

satisfy the conformal algebra $[H, D] = iH, \quad [H, K] = 2iD, \quad [K, D] = -iK$

- Following F&R we define the fermionic generator $R = Q + \lambda S$ with anticommutation relations $\{R_\lambda, R_\lambda\} = \{R_\lambda^\dagger, R_\lambda^\dagger\} = 0$. It generates the new Hamiltonian $G_\lambda = \{R_\lambda, R_\lambda^\dagger\}$ which also closes under the graded algebra $sl(1/1)$: $[R_\lambda, G_\lambda] = [R_\lambda^\dagger, G_\lambda] = 0$

- The Hamiltonian G_λ is given by

$$G_\lambda = 2H + 2\lambda^2 K + 2\lambda (f - \sigma_3)$$

and leads to the eigenvalue equations

$$\left(-\frac{d^2}{dx^2} + \lambda^2 x^2 + 2\lambda f - \lambda + \frac{4(f + \frac{1}{2})^2 - 1}{4x^2} \right) \phi_1 = E \phi_1$$

$$\left(-\frac{d^2}{dx^2} + \lambda^2 x^2 + 2\lambda f + \lambda + \frac{4(f - \frac{1}{2})^2 - 1}{4x^2} \right) \phi_2 = E \phi_2$$

6 Superconformal meson-baryon symmetry

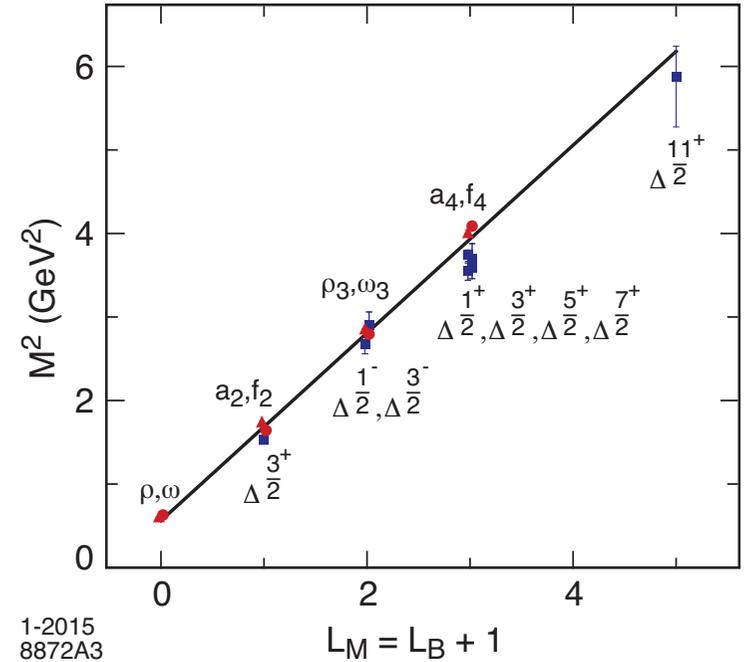
- Upon the substitutions in (slide 12)

$$x \mapsto \zeta$$

$$E \mapsto M^2$$

$$\lambda \mapsto \lambda_B = \lambda_M$$

$$f \mapsto L_M - \frac{1}{2} = L_B + \frac{1}{2}$$



we find the LF bound-state equations [H.G. Dosch, GdT, and S. J. Brodsky (2015)]

$$\left(-\frac{d^2}{d\zeta^2} + \frac{4L_M^2 - 1}{4\zeta^2} + \lambda_M^2 \zeta^2 + 2\lambda_M(L_M - 1) \right) \phi_{Meson} = M^2 \phi_{Meson}$$

$$\left(-\frac{d^2}{d\zeta^2} + \frac{4L_B^2 - 1}{4\zeta^2} + \lambda_B^2 \zeta^2 + 2\lambda_B(L_B + 1) \right) \phi_{Baryon} = M^2 \phi_{Baryon}$$

- Superconformal QM imposes the condition $\lambda = \lambda_M = \lambda_B$ (equality of Regge slopes) and the remarkable relation $L_M = L_B + 1$ [Symmetry for VM first noticed by E. Klempt]
- L_M is the LF angular momentum between the quark and antiquark in the meson and L_B is the relative angular momentum between the active quark and spectator cluster in the baryon

- Special role of the pion as a unique state of zero energy

$$R^\dagger |M, L\rangle = |B, L - 1\rangle, \quad R^\dagger |M, L = 0\rangle = 0$$

- Hadron quantum numbers determined from the pion quantum number assignment

- Spin-dependent Hamiltonian to describe mesons and baryons with internal spin (chiral limit)

[S. J. Brodsky, GdT, H. G. Dosch, C. Lorcé (2016)]

$$G = \{R_\lambda^\dagger, R_\lambda\} + 2\lambda S \quad S = 0, 1$$

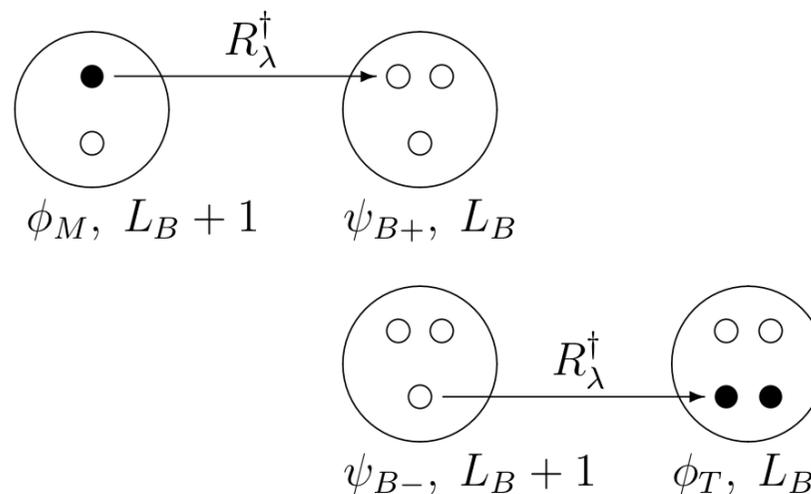
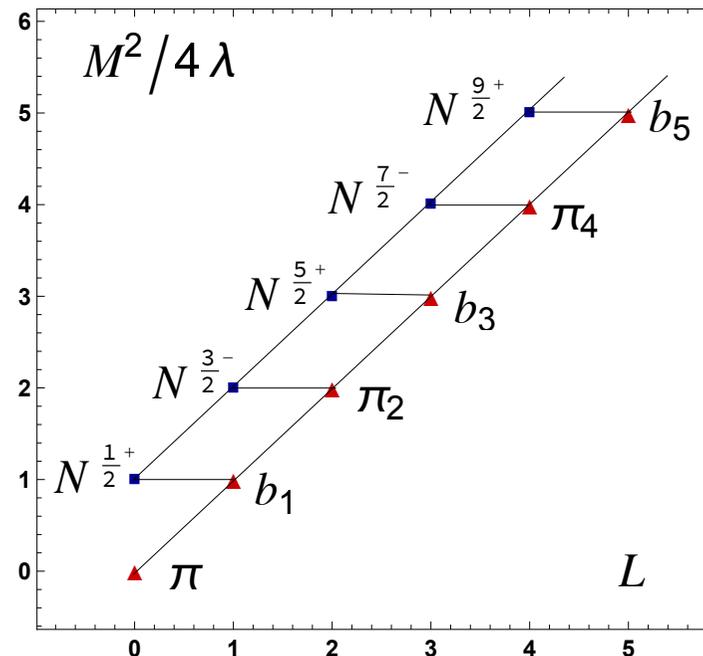
- Supersymmetric 4-plet: quark-antiquark (M), quark-diquark (B), diquark-antidiquark (T)

$$M_M^2 = 4\lambda (n + L_M) + 2\lambda S$$

$$M_B^2 = 4\lambda (n + L_B + 1) + 2\lambda S$$

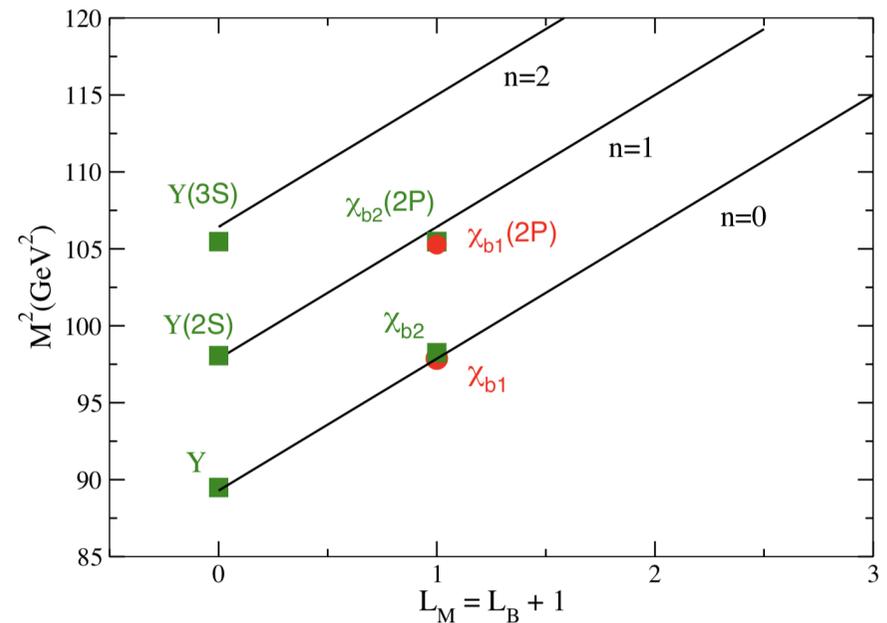
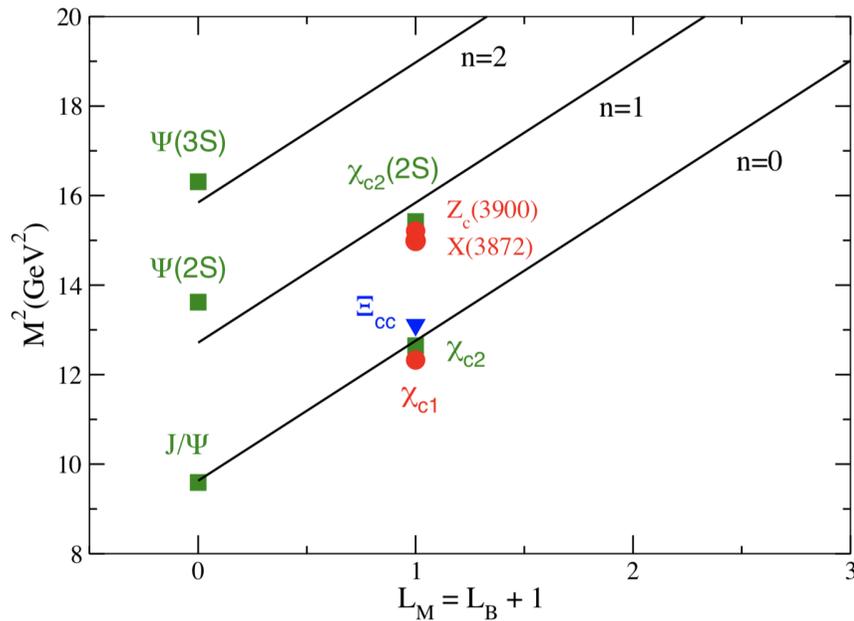
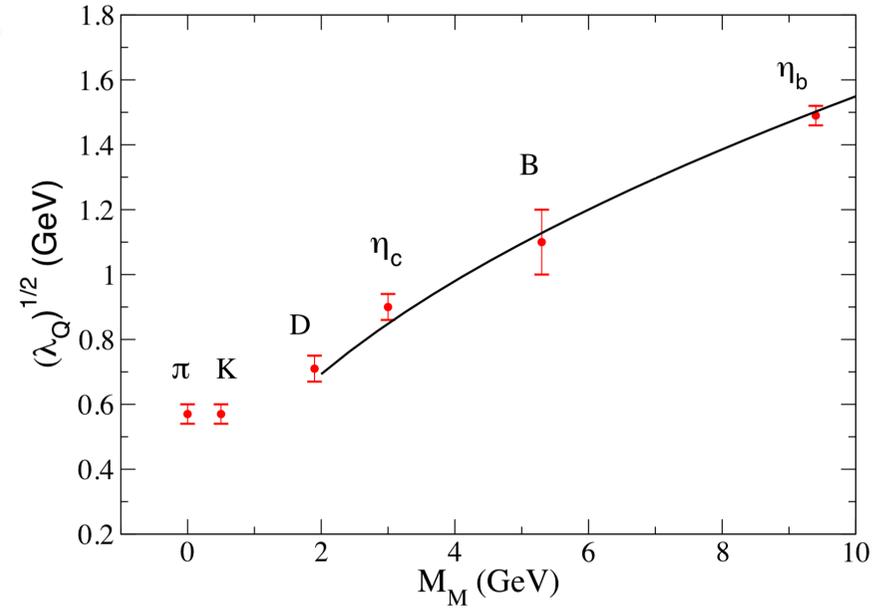
$$M_T^2 = 4\lambda (n + L_T + 1) + 2\lambda S$$

- $\sqrt{\lambda} = 0.523 \pm 0.024$ GeV from the light hadron spectrum including radial and orbital excitations



7 Heavy-light and heavy-heavy sectors

- Scale dependence of hadronic scale λ from HQET
- Extension to the heavy-light hadronic sector:
[H. G. Dosch, GdT, S. J. Brodsky, (2015, 2017)]
- Extension to the double-heavy hadronic sector:
[M. Nielsen, S. J. Brodsky *et al.* (2018)]
- Extension to the isoscalar hadronic sector:
[L. Zou, H. G. Dosch, GdT, S. J. Brodsky (2018)]



8 Infrared behavior of the strong coupling in LFHQCD

- In 2010 we started a collaboration with Alexandre Deur to establish a connection between the short-distance behavior of the QCD coupling α_s with JLab long-distance measurements of α_s from the Bjorken sum rule [A. Deur, S. J. Brodsky and GdT (2010, 2015, 2016, 2017)]
- Infrared (IR) behavior of strong coupling in LFHQCD

$$\alpha_s^{IR}(Q^2) = \alpha_s^{IR}(0)e^{-Q^2/4\lambda}$$

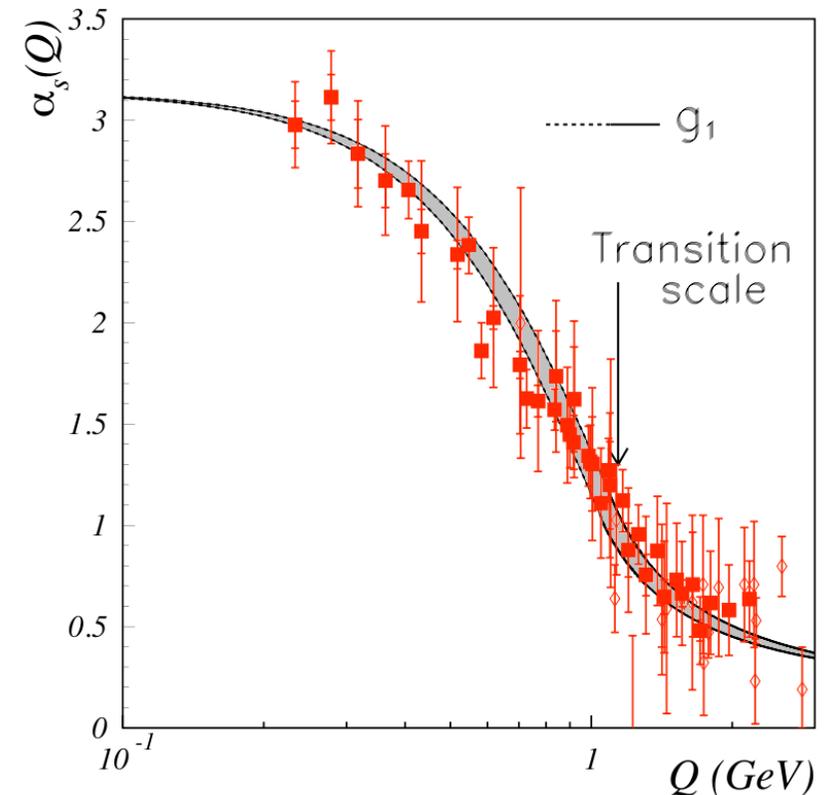
- Λ_{QCD} and transition scale Q_0 from matching perturbative (5-loop) and nonperturbative regimes:
for $\sqrt{\lambda} = 0.523 \pm 0.024$ GeV

$$\Lambda_{\overline{MS}} = 0.339 \pm 0.019 \text{ GeV}$$

World Average: $\Lambda_{\overline{MS}} = 0.332 \pm 0.017$ GeV

Transition scale: $Q_0^2 \simeq 1$ GeV²

- Connection between the proton mass $M_p^2 = 4\lambda$ and the perturbative QCD scale Λ_{QCD} in any RS !
- Similar behavior of the IR strong coupling from DSE [Binosi *et al.*, (2017)]



9 Form factors, parton distributions and intrinsic quark sea

- Recently Raza Sabbir Sufian (2016) and Tianbo Liu (2017) from JLab joined our growing team (now dubbed the HLFHS Collaboration) for an extensive study of form factors, parton distributions and the sea content of the proton
- Nucleon Form Factors
[R. S. Sufian, GdT, S. J. Brodsky, A. Deur, H. G. Dosch (2017)]
- Generalized parton distributions
[GdT, T. Liu, R. S. Sufian, H. G. Dosch, S. J. Brodsky, A. Deur (2018)]
- Strange-quark sea in the nucleon
[R. S. Sufian, T. Liu, GdT, H. G. Dosch, S. J. Brodsky, A. Deur, M. T. Islam, B-Q. Ma (2018)]
- Unified description of polarized and unpolarized quark distributions
[T. Liu, R. S. Sufian, GdT, H. G. Dosch, S. J. Brodsky, A. Deur (2019)]

- Form factor expressed as a sum from the Fock expansion of states

$$F(t) = \sum_{\tau} c_{\tau} F_{\tau}(t)$$

where the c_{λ} are spin-flavor expansion coefficients

- $F_{\tau}(t)$ in LFHQCD has the Euler's Beta form structure

$$F_{\tau}(t) = \frac{1}{N_{\tau}} B(\tau - 1, 1 - \alpha(t))$$

found by Ademollo and Del Giudice and Landshoff and Polkinghorne in the pre-QCD era, extending the Veneziano duality model (1968)

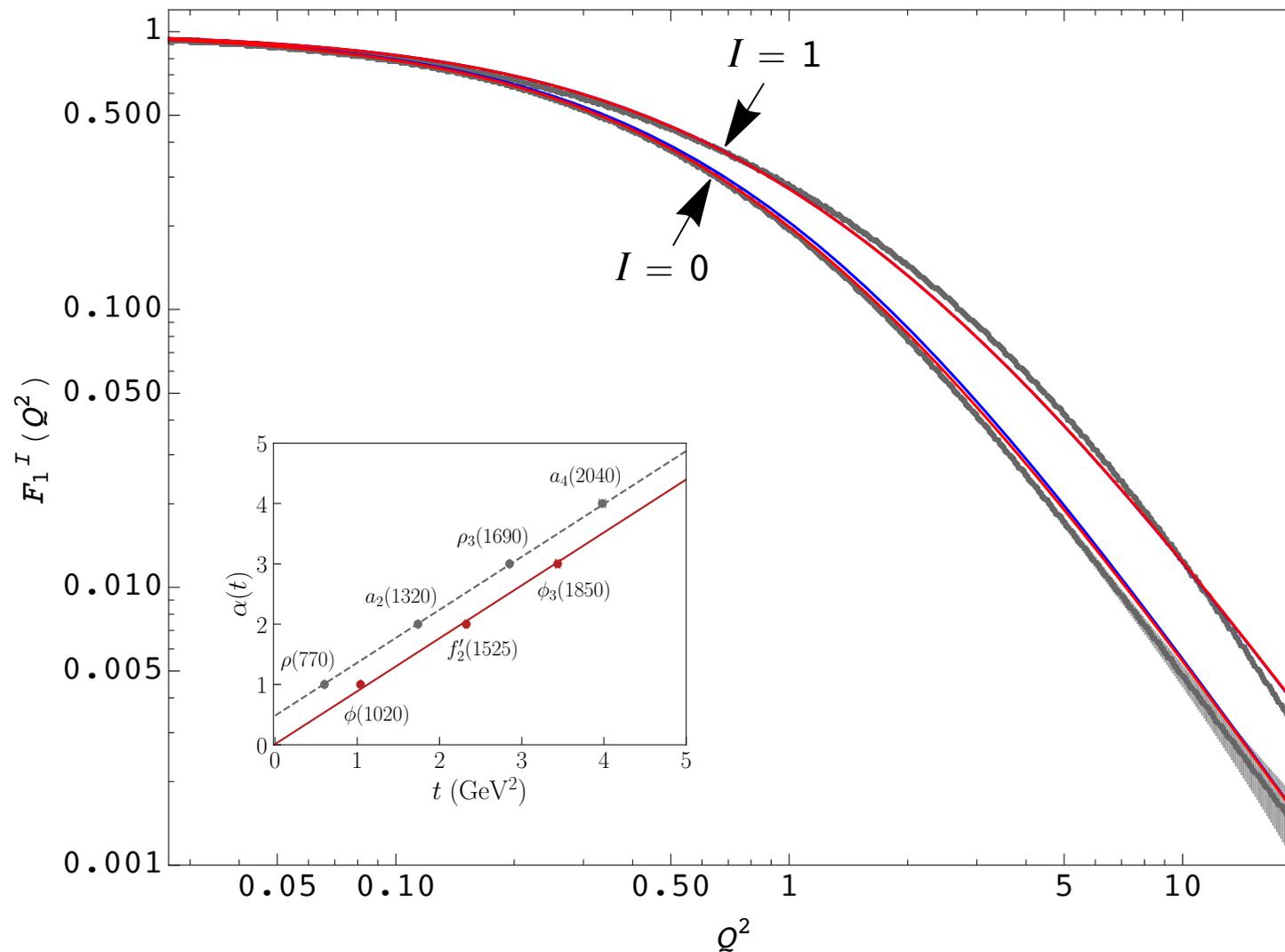
- $\alpha(t)$ is the Regge trajectory of the VM which couples to the quark EM current in the hadron
- For $\tau = N$, the number of constituents in a Fock component, the FF is an $N - 1$ product of poles

$$F_{\tau}(Q^2) = \frac{1}{\left(1 + \frac{Q^2}{M_{n=0}^2}\right) \left(1 + \frac{Q^2}{M_{n=1}^2}\right) \cdots \left(1 + \frac{Q^2}{M_{n=\tau-2}^2}\right)}$$

located at

$$-Q^2 = M_n^2 = \frac{1}{\alpha'} (n + 1 - \alpha(0))$$

which generates the radial excitation spectrum of the exchanged VM particles in the t -channel



Nucleon isospin form factors $F^{I=0,1}(t) = F_p(t) \pm F_n(t)$

Liu et al. (2020): — Valence contribution only (This work I)

Liu et al. (2020): — Including $u\bar{u}$ and $d\bar{d}$ (This work II)

Ye et al. (2018): — z -expansion data analysis

- Using integral representation of Beta function FF is expressed in a reparametrization invariant form

$$F(t)_\tau = \frac{1}{N_\tau} \int_0^1 dx w'(x) w(x)^{-\alpha(t)} [1 - w(x)]^{\tau-2}$$

with $w(0) = 0$, $w(1) = 1$, $w'(x) \geq 0$

- Flavor FF is given in terms of the valence GPD $H_\tau^q(x, \xi = 0, t)$ at zero skewness

$$F_\tau^q(t) = \int_0^1 dx H_\tau^q(x, t) = \int_0^1 dx q_\tau(x) \exp[tf(x)]$$

with the profile function $f(x)$ and PDF $q(x)$ determined by $w(x)$

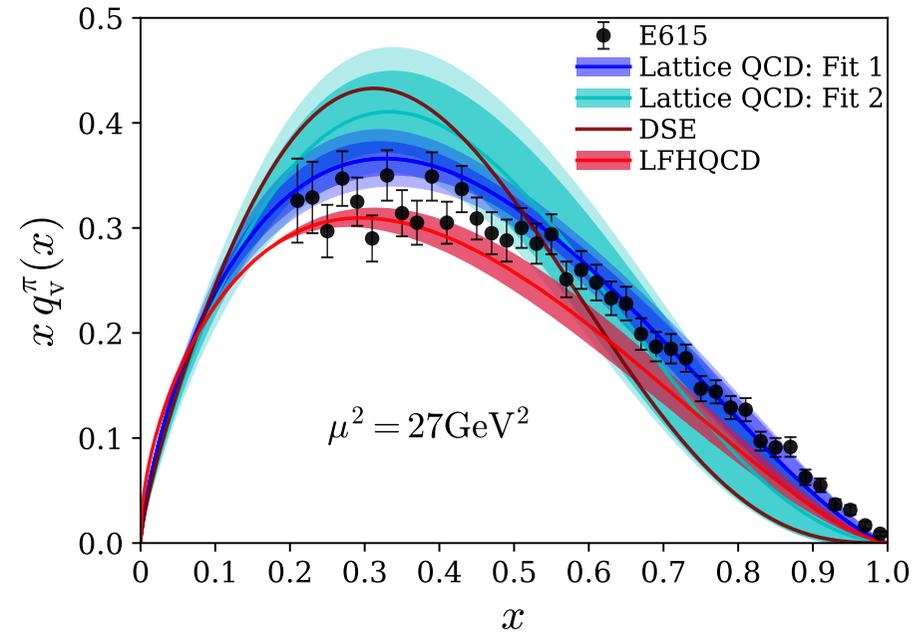
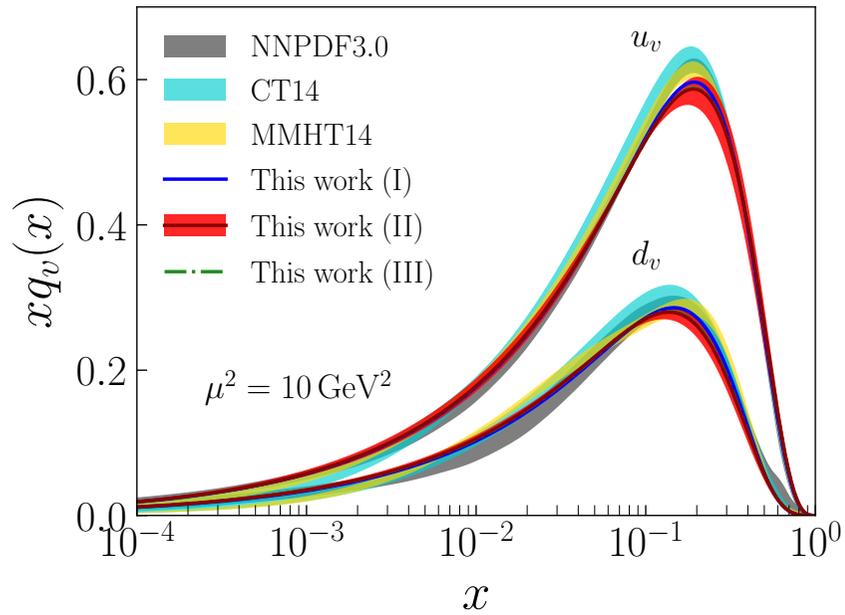
$$f(x) = \frac{1}{4\lambda} \log\left(\frac{1}{w(x)}\right)$$

$$q_\tau(x) = \frac{1}{N_\tau} [1 - w(x)]^{\tau-2} w(x)^{-\alpha(0)} w'(x)$$

- Boundary conditions: At $x \rightarrow 0$, $w(x) \sim x$ from Regge behavior, $q(x) \sim x^{-\alpha(0)}$, and $w'(1) = 0$ to recover Drell-Yan counting rules at $x \rightarrow 1$, $q_\tau(x) \sim (1-x)^{2\tau-3}$ (inclusive-exclusive connection)
- If $w(x)$ is fixed by the nucleon PDFs then the pion PDF is a prediction. Example:

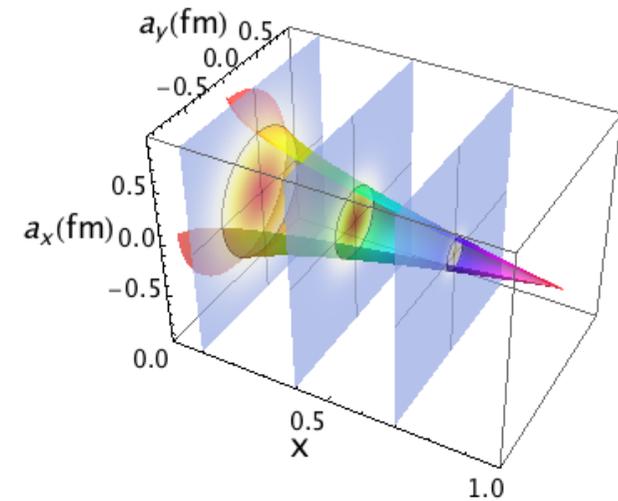
$$w(x) = x^{1-x} e^{-a(1-x)^2}$$

Unpolarized GPDs and PDFs



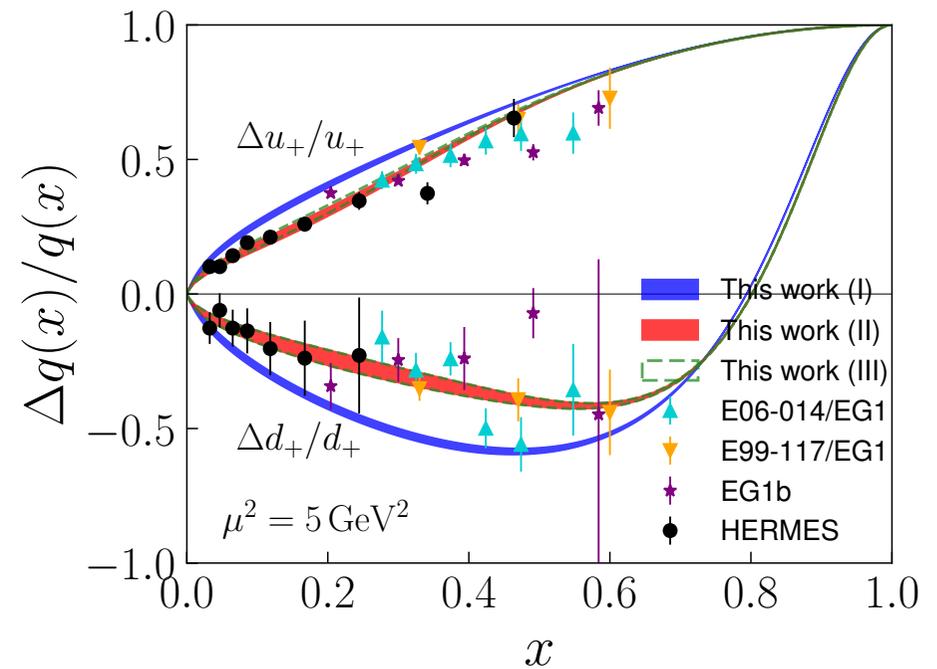
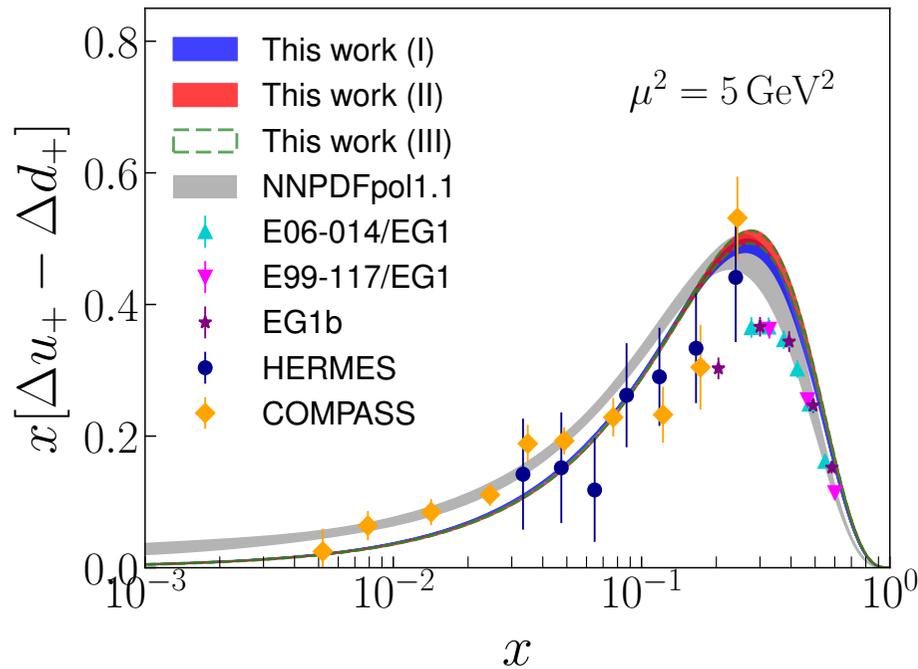
- Transverse impact parameter quark distribution

$$u(x, \mathbf{a}_\perp) = \int \frac{d^2 \mathbf{q}_\perp}{(2\pi)^2} e^{-i\mathbf{a}_\perp \cdot \mathbf{q}_\perp} H^u(x, \mathbf{q}_\perp^2)$$



Polarized GPDs and PDFs

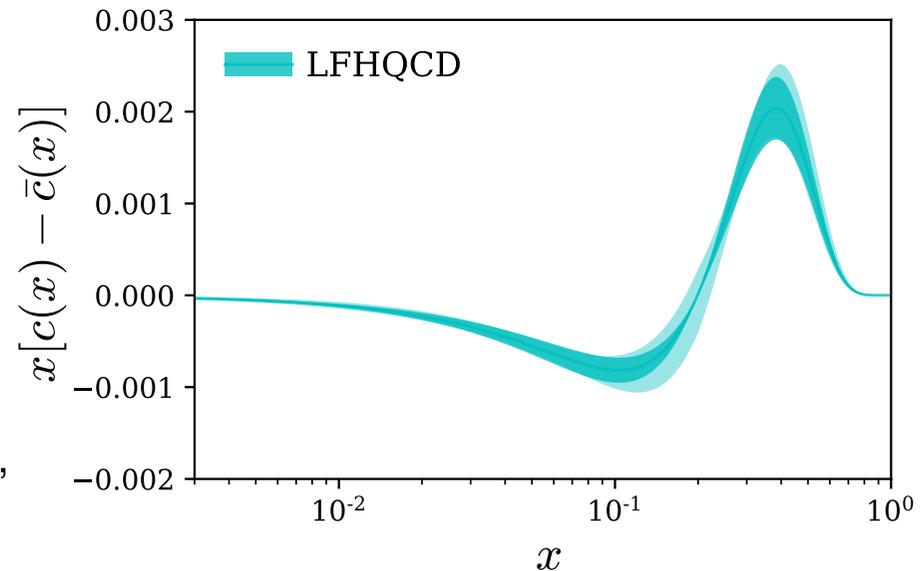
- Separation of chiralities in the AdS action allows computation of the matrix elements of the axial current –including the correct normalization, once the coefficients c_λ are fixed for the vector current
- Helicity retention between quark and parent hadron (pQCD prediction): $\lim_{x \rightarrow 1} \frac{\Delta q(x)}{q(x)} = 1$
- No spin correlation with parent hadron: $\lim_{x \rightarrow 0} \frac{\Delta q(x)}{q(x)} = 0$

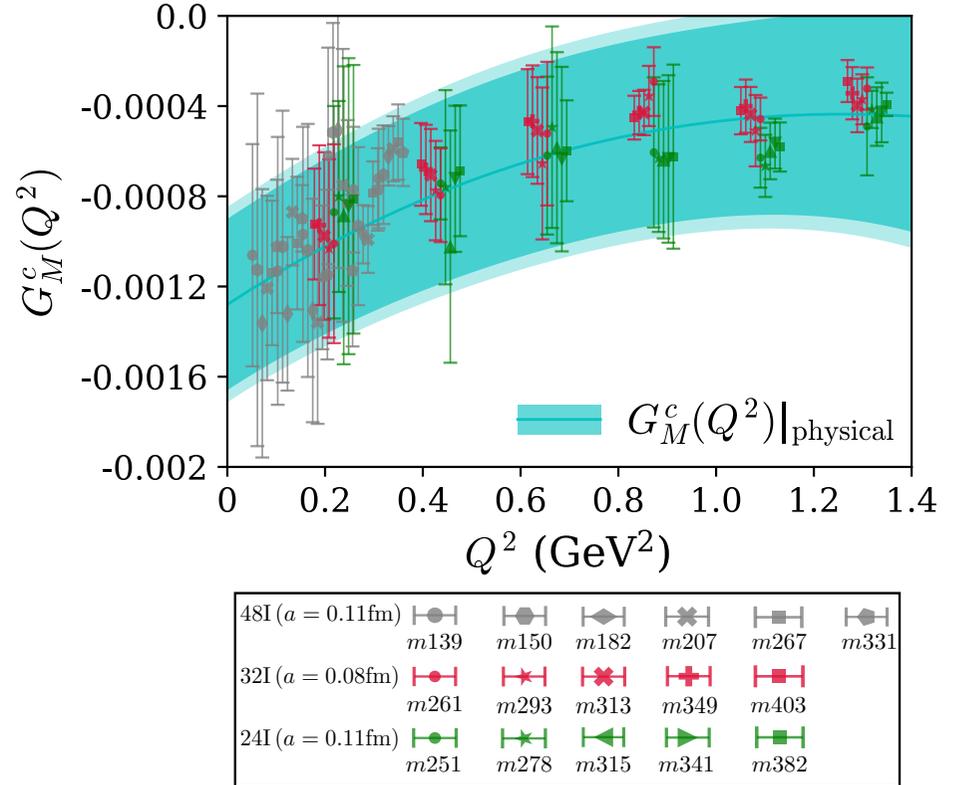
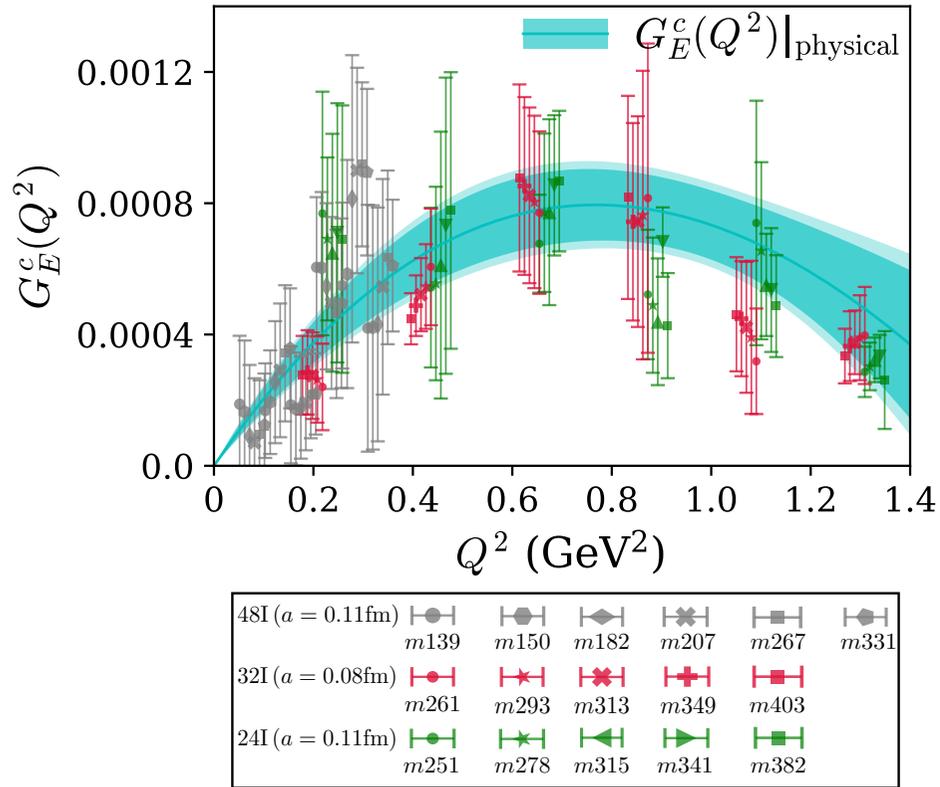


Intrinsic charm in the proton

R. S. Sufian, T. Liu *et al.*

- S. J. Brodsky, P. Hoyer, C. Peterson, N. Sakai,
The intrinsic charm of the proton (1980)
- First lattice QCD computation of the the charm quark EM form factors with three gauge ensembles
(one at the physical pion mass)
- Nonperturbative intrinsic charm asymmetry $c(x) - \bar{c}(x)$ computed from LFHQCD analysis

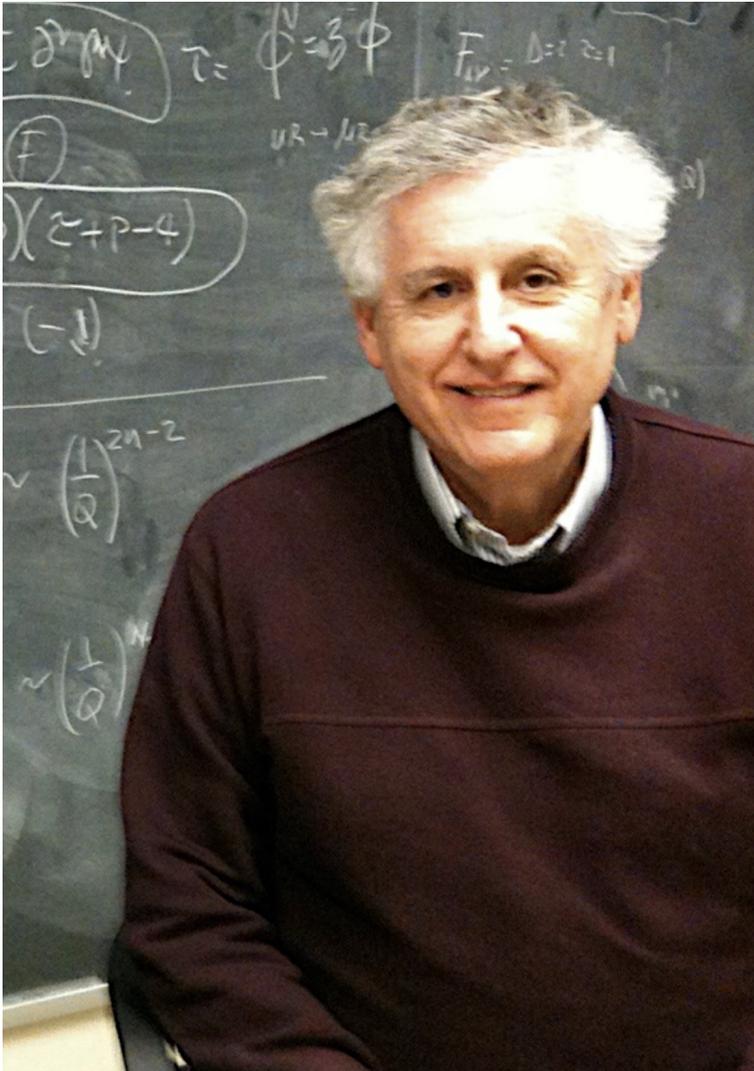




PRELIMINARY

10 Outlook

- Classical equations of motion derived from the 5-dim theory have identical form of the semiclassical bound-state equations for massless constituents in LF quantization
- Implementation of superconformal algebra determines uniquely the form of the confining interaction and thus the modification of the AdS action, both for mesons and nucleons
- Approach incorporates basic nonperturbative properties which are not apparent from the chiral QCD Lagrangian, such as the emergence of a mass scale and the connection between mesons and baryons
- Prediction of massless pion in chiral limit is a consequence of the superconformal algebraic structure and not of the Goldstone mechanism
- Structural framework of LFHQCD also provides nontrivial connection between the structure of form factors and polarized and unpolarized quark distributions with pre-QCD nonperturbative results such as Regge theory and the Veneziano model



Thank you Stan for your inspiration
and always sharing your astounding
knowledge and insight