Insights into hadron structure from superconformal light-front holographic QCD

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UCR

3rd Proton Mass Workshop:

Origin and Perspective

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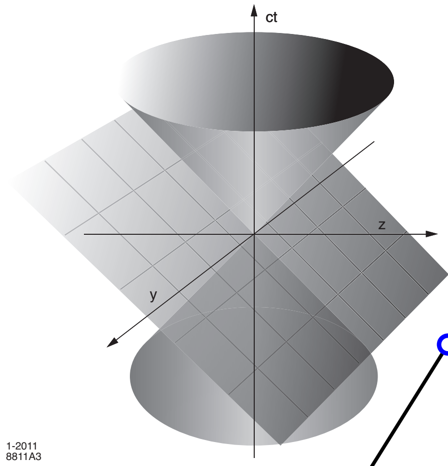

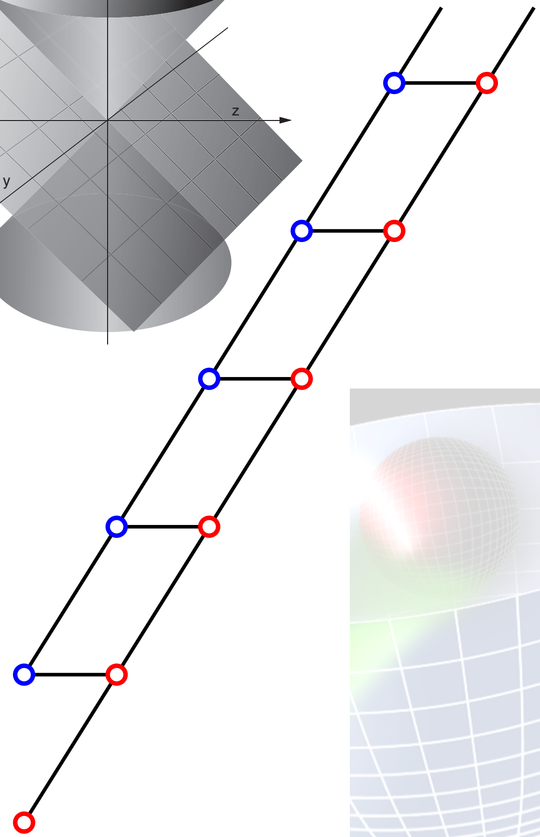

Stan Brodsky, Hans G. Dosch, Alexandre Deur, Tianbo Liu, Raza Sabbir Sufian, Marina Nielsen and Liping Zou

Motivation: *“While there has been great progress in Lattice Gauge Theory, there is no quantitative analytic understanding yet of the mass gap and confinement”* From Igor Klebanov’s talk

- The light-front (LF) frame independent Hamiltonian based on Dirac’s front form of relativistic dynamics is a rigorous formalism for computing bound states in QCD: Is is the natural formalism for describing partonic physics and also maps directly to AdS and superconformal eigenvalue equations
- Recent insights into the nonperturbative structure of QCD based on LF quantization and its holographic embedding have lead to effective semiclassical bound-state equations for arbitrary spin: LFHQCD
- Confinement potential for baryons, mesons and tetraquarks are uniquely determined by an underlying superconformal algebraic structure leading to unsuspected connections across the entire mass spectrum of hadrons
- Breaking of scale invariance in the LF Hamiltonian which emerges from the superconformal structure leads simultaneously to a massless pion and a massive proton
- Phenomenological extension incorporates the structure of pre-QCD Generalized Veneziano models useful to describe form factors and parton distributions including the sea component of the proton

Review in:

S. J. Brodsky, GdT, H.G. Dosch, J. Erlich, Phys. Rept. **584**, 1 (2015) [hep-ph/9705477]

S. J. Brodsky, GdT, H. G. Dosch, arXiv:2004.07756 [hep-ph]

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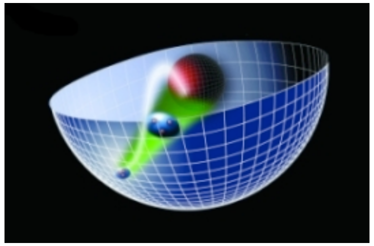
1 Half-integer-spin wave equations in AdS and LF holographic embedding

[J. Polchinski and M. J. Strassler, JHEP **0305**, 012 (2003)]

[GdT and S. J. Brodsky, PRL **94**, 201601 (2005)]

[Z. Abidin and C. E. Carlson, PRD **79**, 115003 (2009)]

[GdT, H.G. Dosch and S. J. Brodsky, PRD **87**, 075004 (2013)]



- AdS$_5$ is a 5-dim space of maximal symmetry, negative curvature and a four-dim boundary: Minkowski space

$$ds^2 = \frac{R^2}{z^2}\left(dx_\mu dx^\mu - dz^2\right)$$

- Isomorphism of $SO(4,2)$ conformal group with the group of isometries of AdS$_5$
- Physical interpretation: holographic variable z inverse of energy scale of a probe
- To describe the proton and its excited states we start from the effective AdS action for a half-integer spin $J = T + \frac{1}{2}$ RS spinor $\Psi_{N_1 \cdots N_T}$ with AdS mass μ and effective potential $\rho(z)$

$$S_{\mathit{eff}} = \frac{1}{2} \int d^d x \, dz \, \sqrt{g} \, g^{N_1 \, N_1'} \cdots g^{N_T \, N_T'} \left[\overline{\Psi}_{N_1 \cdots N_T}\Big(i \, \Gamma^A \, e_A^M \, D_M - \mu - \rho(z)\Big)\Psi_{N_1' \cdots N_T'} + h.c.\right] \tag{1}$$

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

- e_A^M is the vielbein, $e_A^M = (z/R)\delta_A^M$, and Γ^A tangent space Dirac matrices $\quad \left\{\Gamma^A, \Gamma^B\right\} = 2\eta^{AB}$

- In holographic QCD a nucleon is described by a z-dependent wave function $\psi(z)$ and a plane wave and spinors along Minkowski coordinates

$$\Psi^T(x,z) = e^{iP\cdot x} u_{\nu_1\cdots\nu_T}(P) \left(\frac{R}{z}\right)^{T-d/2} \psi(z)$$

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

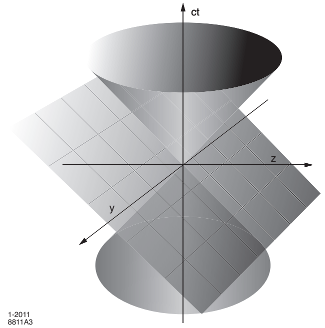
- From the RS action in AdS (1) follows the coupled equations for the chiral components $\psi_\pm(z)$

$$\boxed{\begin{aligned} -\frac{d}{dz}\psi_- - \frac{\nu+\frac{1}{2}}{z}\psi_- - V(z)\psi_- &= M\psi_+ \\ \frac{d}{dz}\psi_+ - \frac{\nu+\frac{1}{2}}{z}\psi_+ - V(z)\psi_+ &= M\psi_- \end{aligned}} \tag{2}$$

with $|\mu R| = \nu + \frac{1}{2}$ and $V(z) = \frac{R}{z}\rho(z)$

- Non-trivial geometry of AdS encodes the higher-spin kinematics, including the constraints required to eliminate lower-spin from the symmetric RS spinor $\Psi_{N_1\cdots N_T}$ with $J = T + \frac{1}{2}$

Light-front mapping



[GdT and S. J. Brodsky, PRL **102**, 081601 (2009)]

- LF Hamiltonian from Poincaré group invariant $P^2 = P_\mu P^\mu = P^- P^+ - \mathbf{P}_\perp^2$

$$P^2|\psi(P)\rangle = M^2|\psi(P)\rangle, \qquad |\psi\rangle = \sum_n \psi_n|n\rangle$$

becomes in QCD a relativistic semiclassical LF wave equation in the limit $m_q \to 0$

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

where ζ is the impact invariant transverse variable $\zeta^2 = x(1-x)\mathbf{b}_\perp^2$

- Mapping to the light front $z \to \zeta$, system of linear Eqs in AdS (2) is equivalent to second order Eqs:

$$\boxed{\begin{aligned} \left(-\frac{d^2}{d\zeta^2} - \frac{1-4L^2}{4\zeta^2} + U^+(\zeta)\right)\psi_+ &= M^2\psi_+ \\ \left(-\frac{d^2}{d\zeta^2} - \frac{1-4(L+1)^2}{4\zeta^2} + U^-(\zeta)\right)\psi_- &= M^2\psi_- \end{aligned}} \tag{3}$$

the semiclassical QCD LF WE with ψ_+ and ψ_- corresponding to LF orbital L and $L+1$ with

$$U^\pm(\zeta) = V^2(\zeta) \pm V'(\zeta) + \frac{1+2L}{\zeta}V(\zeta), \qquad L = \nu,$$

- $V(\zeta)$ plays the role of a superpotential and its form is completely fixed by superconformal QM

2 Superconformal algebraic structure and emergence of a mass scale

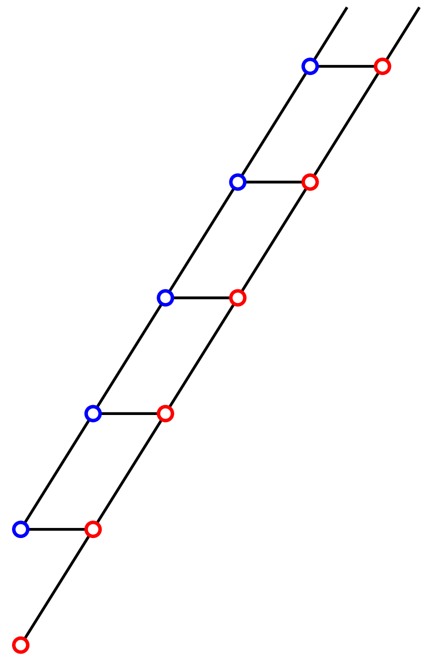
[V. de Alfaro, S. Fubini and G. Furlan, Nuovo Cim. A **34**, 569 (1976)]

[S. Fubini and E. Rabinovici, NPB **245**, 17 (1984)]

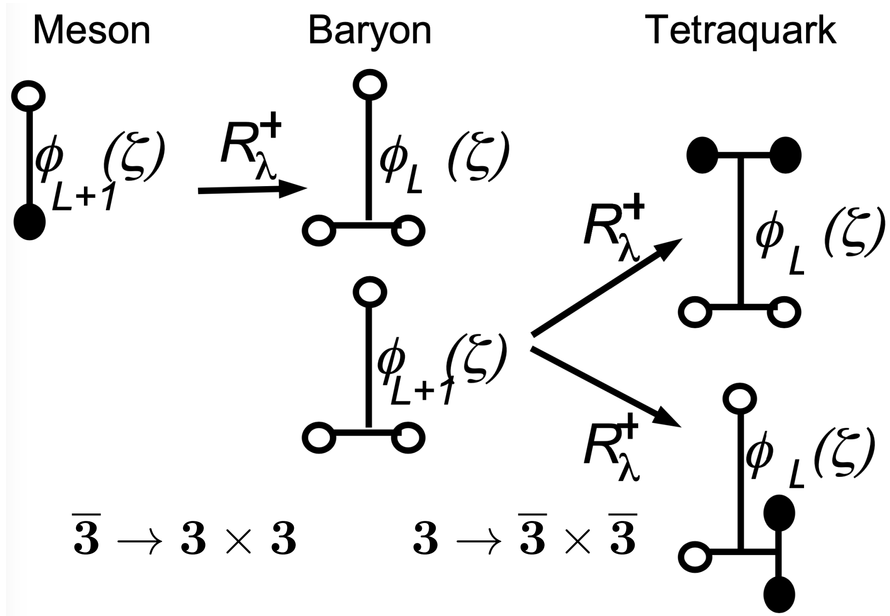
[S. J. Brodsky, GdT and H. G. Dosch, Phys. Lett. B **729**, 3 (2014)]

[GdT, H. G. Dosch and S. J. Brodsky, PRD **91**, 045040 (2015)]

[H. G. Dosch, GdT, and S. J. Brodsky, PRD **91**, 085016 (2015)]



- Superconformal algebra underlies in LFHQCD the scale invariance of the QCD Lagrangian: Its breaking leads to the emergence of a scale in the Hamiltonian keeping the action conformal invariant



Supersymmetric Quantum Mechanics

[E. Witten, NPB **188**, 513 (1981)]

- SUSY QM contains two fermionic generators Q and $Q^\dagger$ and a bosonic generator, the Hamiltonian H

$$\tfrac{1}{2}\{Q, Q^\dagger\} = H$$
$$\{Q, Q\} = \{Q^\dagger, Q^\dagger\} = 0, \quad [Q, H] = [Q^\dagger, H] = 0$$

which closes under the graded algebra $sl(1/1)$

- Since $[Q^\dagger, H] = 0$, the states $|E\rangle$ and $Q^\dagger|E\rangle$ for $E \neq 0$ are degenerate, but for $E = 0$ we can have the trivial solution $Q^\dagger|E = 0\rangle = 0$ (the pion)

- Matrix representation of SUSY generators $Q, Q^\dagger$ and H

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

- For a conformal theory (f dimensionless)

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

- 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 $\frac{1}{2}\{S, S^\dagger\} = K$

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

  and leads to a conformal enlarged algebra [Haag, Lopuszanski and Sohnius (1974)]

- Following Fubini and Rabinovici we define the fermionic generator $R = Q + \lambda\, S$, $[\lambda]$ = GeV^2,

$$\{R_\lambda, R_\lambda^\dagger\} = G_\lambda$$

$$\{R_\lambda, R_\lambda\} = \{R_\lambda^\dagger, R_\lambda^\dagger\} = 0, \quad [R_\lambda, G_\lambda] = [R_\lambda^\dagger, G_\lambda] = 0$$

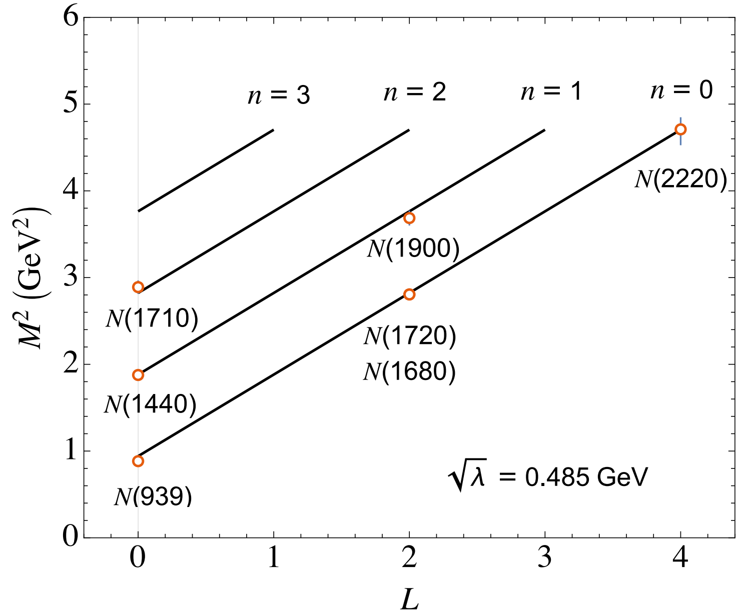
  which also closes under the graded algebra $sl(1/1)$:

- In a 2×2 matrix representation the Hamiltonian equation $G|\phi\rangle = E|\phi\rangle$ leads to the equations

$$\boxed{\begin{aligned} &\left(-\frac{d^2}{dx^2} + \lambda^2 x^2 + 2\lambda f - \lambda + \frac{4(f+\frac{1}{2})^2 - 1}{4x^2}\right)\phi_1 = E\,\phi_1 \\ &\left(-\frac{d^2}{dx^2} + \lambda^2 x^2 + 2\lambda f + \lambda + \frac{4(f-\frac{1}{2})^2 - 1}{4x^2}\right)\phi_2 = E\,\phi_2 \end{aligned}} \tag{4}$$

3 Light-front mapping and baryons

[GdT, H.G. Dosch and S. J. Brodsky, PRD **91**, 045040 (2015)]



- Upon LF mapping to the superconformal eigenvalue equations (4)

$$x \mapsto \zeta, \quad E \mapsto M^2, \quad f \mapsto L + \tfrac{1}{2}$$
$$\phi_1 \mapsto \psi_-, \quad \phi_2 \mapsto \psi_+$$

  we recover the nucleon bound-state equations (3)

$$\boxed{\begin{aligned} \left(-\frac{d^2}{d\zeta^2} - \frac{1-4L^2}{4\zeta^2} + \lambda^2\zeta^2 + 2\lambda(L+1)\right)\psi_+ &= M^2\psi_+ \\ \left(-\frac{d^2}{d\zeta^2} - \frac{1-4(L+1)^2}{4\zeta^2} + \lambda^2\zeta^2 + 2\lambda L\right)\psi_- &= M^2\psi_- \end{aligned}} \tag{5}$$

with $U^+ = \lambda^2\zeta^2 + 2\lambda(L+1)$ and $U^- = \lambda^2\zeta^2 + 2\lambda L$

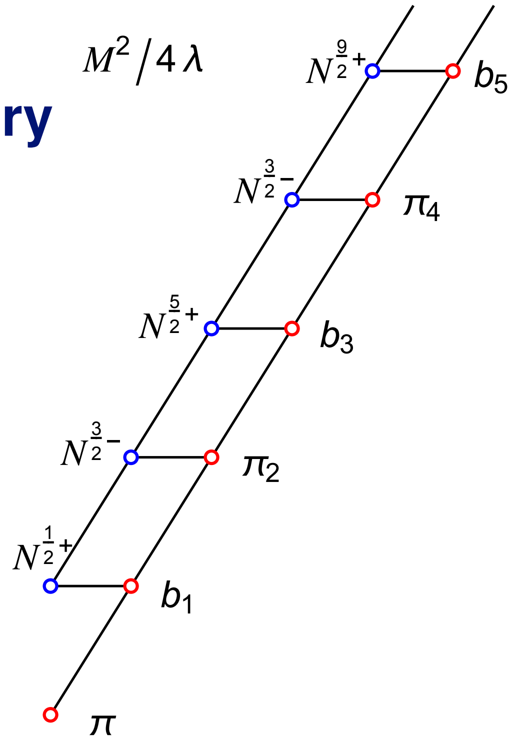
- Eigenvalues

$$M^2 = 4\lambda(n + L + 1)$$

- Eigenfunctions

$$\psi_+(\zeta) \sim \zeta^{\frac{1}{2}+L} e^{-\lambda\zeta^2/2} L_n^L(\lambda\zeta^2), \quad \psi_-(\zeta) \sim \zeta^{\frac{3}{2}+L} e^{-\lambda\zeta^2/2} L_n^{L+1}(\lambda\zeta^2)$$

4 Superconformal meson-baryon-tetraquark symmetry



[H.G. Dosch, GdT, and S. J. Brodsky, PRD **91**, 085016 (2015)]

- Upon substitution in the superconformal equations (4)

$$\begin{aligned} x &\mapsto \zeta, \quad E \mapsto M^2, \\ \lambda &\mapsto \lambda_B = \lambda_M, \quad f \mapsto L_M - \tfrac{1}{2} = L_B + \tfrac{1}{2} \\ \phi_1 &\mapsto \phi_M, \quad \phi_2 \mapsto \phi_B \end{aligned}$$

we find the LF bound-state equations

$$\boxed{\begin{aligned} \left(-\frac{d^2}{d\zeta^2} + \frac{4L_M^2 - 1}{4\zeta^2} + \lambda_M^2\,\zeta^2 + 2\lambda_M(L_M - 1)\right)\phi_M = M^2\,\phi_M \\ \left(-\frac{d^2}{d\zeta^2} + \frac{4L_B^2 - 1}{4\zeta^2} + \lambda_B^2\,\zeta^2 + 2\lambda_B(L_N + 1)\right)\phi_B = M^2\,\phi_B \end{aligned}} \tag{6}$$

- Superconformal QM imposes the condition $\lambda = \lambda_M = \lambda_B$ (equality of Regge slopes) and the remarkable relation $\boxed{L_M = L_B + 1}$
- L_M is the LF angular momentum between the quark and antiquark in the meson and L_B between the active quark and spectator cluster in the baryon: effective quark-diquark approximation

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

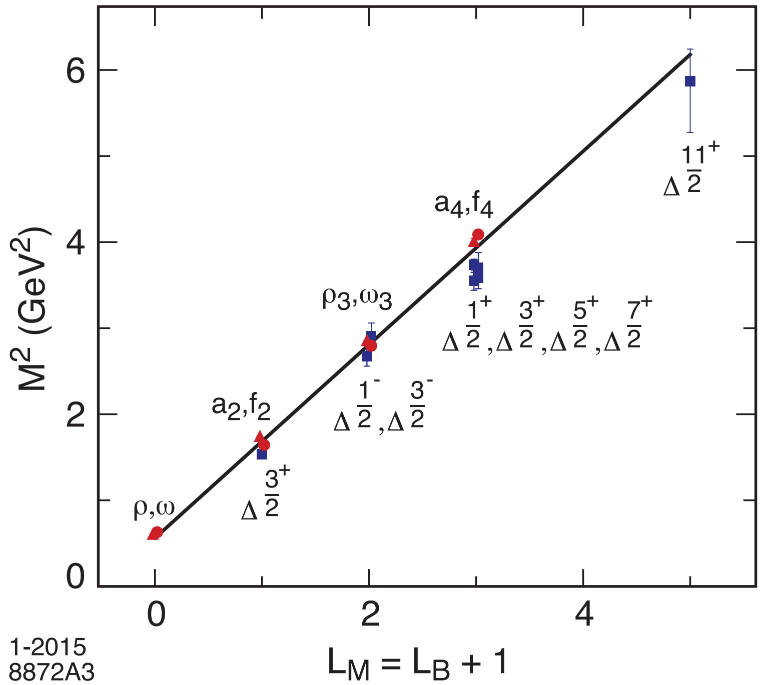
$$R^\dagger |M, L\rangle = |B, L-1\rangle, \quad R^\dagger |M, L=0\rangle = 0$$

- Hadron quantum numbers determined from the pion

- Spin-dependent Hamiltonian for mesons and baryons with internal spin S

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

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



- Supersymmetric 4-plet

$$\begin{aligned} M_M^2 &= 4\lambda\,(n + L_M) + 2\lambda S \\ M_B^2 &= 4\lambda\,(n + L_B + 1) + 2\lambda S \\ M_T^2 &= 4\lambda\,(n + L_T + 1) + 2\lambda S \end{aligned}$$

- Expected accuracy $1/N_C^2 \sim 10\%$

5 Longitudinal dynamics in LFHQCD

- BdT LFWF ansatz [S. J. Brodsky, GdT (2009)]

$$\psi_{\overline{q}q/\pi}(x, \mathbf{k}_\perp) \sim \frac{1}{\sqrt{x(1-x)}} e^{-\frac{1}{2\lambda}\frac{\mathbf{k}_\perp^2}{x(1-x)}} \to \frac{1}{\sqrt{x(1-x)}}\, e^{-\frac{1}{2\lambda}\left(\frac{\mathbf{k}_\perp^2}{x(1-x)} + \frac{m_1^2}{x} + \frac{m_2^2}{1-x}\right)}$$

- Quark masses treated as effective masses in LF Hamiltonian ($m_{u,d} = 46\,\mathrm{MeV}, m_s = 357\,\mathrm{MeV}$)

  [S. J. Brodsky, GdT, H. G. Dosch, J. Erlich (2015)]

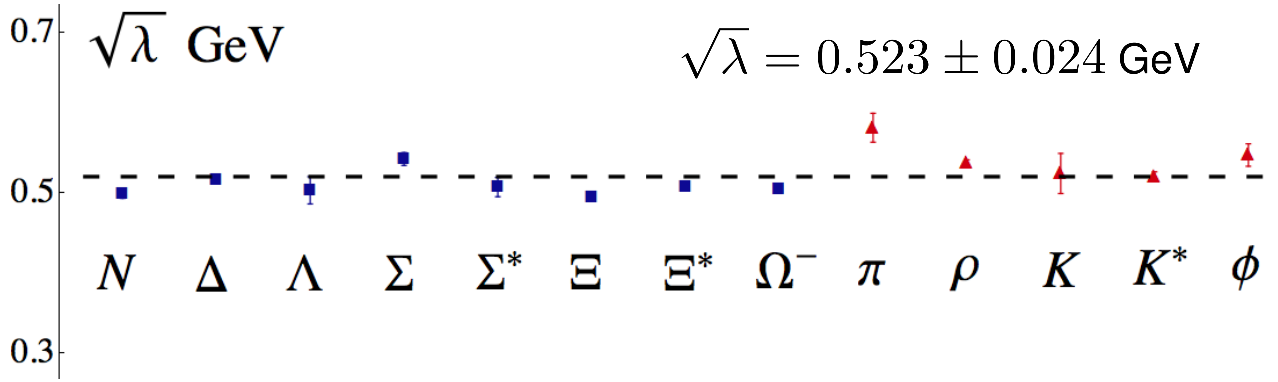
$$\Delta M^2[m_1, \cdots, m_n] = \frac{\lambda^2}{F}\frac{\mathrm{d}F}{\mathrm{d}\lambda}$$

  with

$$F[\lambda] = \int_0^1 \cdots \int_0^1 \mathrm{d}x_1 \cdots \mathrm{d}x_n\, e^{-\frac{1}{\lambda}\left(\sum_{i=1}^n \frac{m_i^2}{x_i}\right)} \delta\Big(\sum_{i=1}^n x_i - 1\Big)$$

- Hadron scale determined from different light hadron channels including all radial and orbital excitations

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



Longitudinal dynamics

[G. 't Hooft, NPB **B 75**, 461 (1974)]

[S. S. Chabysheva and J. R. Hiller, Annals Phys **337**, 143 (2013)]

[A. P. Trawiński, S. D. Głazek, S. J. Brodsky, GdT and H. G. Dosch, PRD **90**, 074017 (2014)]

[Y. Li, P. Maris, X. Zhao and J. P. Vary, PLB **758**, 118 (2016)]

[A. B. Sheckler and G. A. Miller, [arXiv:2101.00100 [hep-ph]]

- LMZV longitudinal potential constrained to recover spherical symmetry of LF transverse oscillator in the non-relativistic limit of heavy quark masses

$$\left[-\partial_x\left(x(1-x)\partial_x\right) - \boxed{\gamma} + \frac{1}{4}\left(\frac{\alpha^2}{x} + \frac{\beta^2}{1-x}\right)\right]\chi = \nu^2\,\chi$$

where $\alpha = \frac{2m_1(m_1+m_2)}{\lambda}$, $\beta = \frac{2m_2(m_1+m_2)}{\lambda}$, $\gamma = \frac{(m_1+m_2)^2}{\lambda}$, $\nu = \frac{M_L(m_1+m_2)}{\lambda}$

- Eigenvalues

$$\nu^2_{\alpha,\beta,\ell} = -\gamma + \left(\tfrac{1}{2}(\alpha+\beta)+\ell\right)\left(\tfrac{1}{2}(\alpha+\beta)+\ell+1\right)$$

and eigenfunctions

$$\chi_\ell^{\alpha,\beta}(x) = N_{\alpha,\beta}\,x^{\beta/2}(1-x)^{\alpha/2}P_\ell^{\alpha,\beta}(2x-1)$$

with normalization $\int_0^1 dx\,\chi_\ell^{\alpha,\beta}(x)\chi_m^{\alpha,\beta}(x) = \delta_{\ell m}$

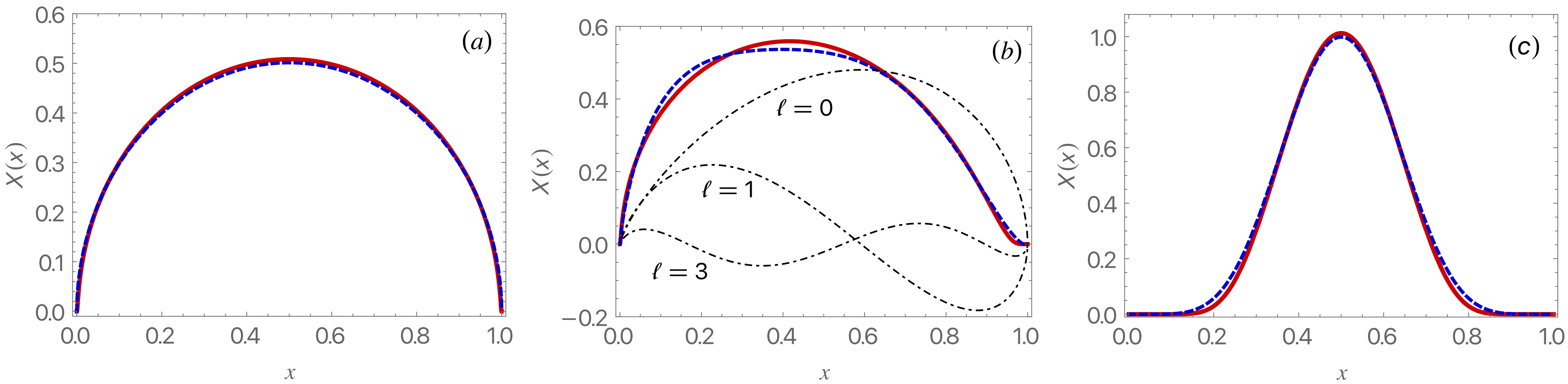
- We introduce the constant γ-term to enforce the chiral symmetry limit: $\nu \to 0$ for $m_q \to 0$

- Following C&H we expand the BdT exponential ansatz in terms of Jacobi polynomials

$$\mathcal{N} e^{-\frac{1}{2\lambda}\left(\frac{m_1^2}{x}+\frac{m_2^2}{1-x}\right)} = \sum_\ell C_\ell\, \chi_\ell(x), \quad \sum_\ell |C_\ell|^2 = 1$$

- Only first few modes in the expansion are relevant

	$\ell = 0$	$\ell = 1$	$\ell = 2$	$\ell = 3$	$\ell = 4$
$C(u\bar{d})$	0.998	0	-0.027	0	-0.029
$C(u\bar{s})$	0.895	-0.431	-0.029	-0.108	0.012
$C(c\bar{c})$	0.999	0	-0.029	0	0.020



Distribution amplitude $X(x) = \sqrt{x(1-x)}\,\chi(x)$ for a) pions, b) kaons, c) J/Ψ : —— BdT, - - - - LMZV

Extension to heavy-light, heavy-heavy, isoscalar and exotic sectors

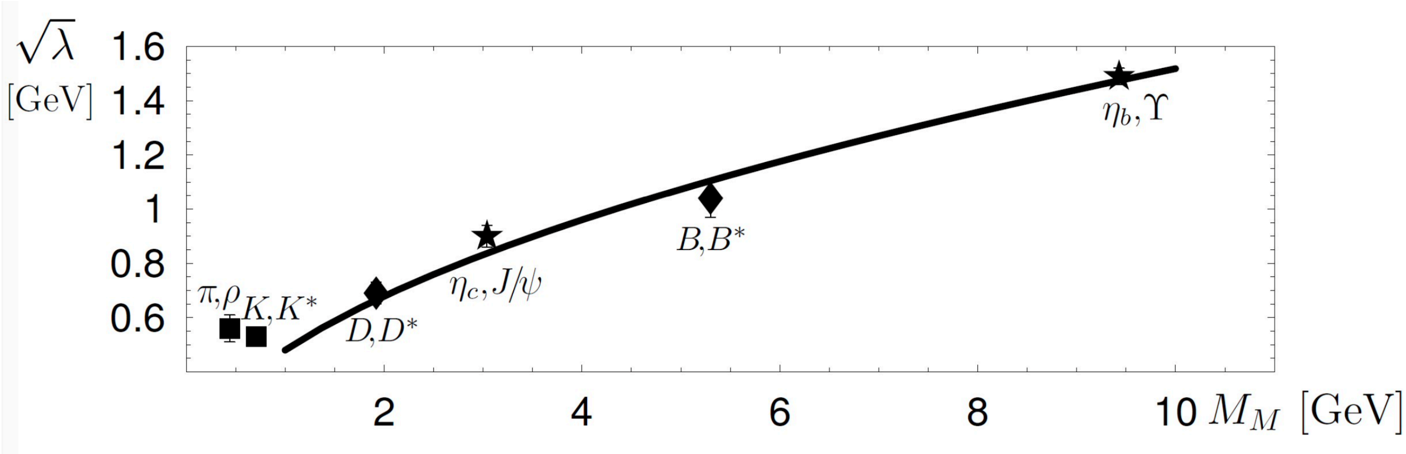
- Scale dependence of hadronic scale λ from HQET
- Extension to the heavy-light hadronic sector:

  [H. G. Dosch, GdT, S. J. Brodsky (2015, 2017)]
- Extension to the double-heavy hadronic sector:

  [M. Nielsen, S. J. Brodsky, GdT, H. G. Dosch, F. S. Navarra (2018)]
- Extension to the isoscalar hadronic sector:

  [L. Zou, H. G. Dosch, GdT, S. J. Brodsky (2018)]
- Tetraquarks and Exotic States:

  [H. G. Dosch, S. J. Brodsky, GdT, M. Nielsen, L. Zou (2020)]



6 Form factors, parton distributions and intrinsic quark sea

- Form factors and parton distributions from phenomenological extension of LF holographic framework to arbitrary Regge trajectories incorporating the analytic structure of Veneziano amplitudes
- Study of strange and charm quark-sea in the proton from combined LQCD and holographic methods
- Nucleon Form Factors:

  [R. S. Sufian, GdT, S. J. Brodsky, A . Deur, H. G. Dosch (2017)]
- Generalized quark distributions:

  [GdT, T. Liu, R. S. Sufian, H. G. Dosch, S. J. Brodsky, A. Deur (HLFHS Collaboration (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 (HLFHS Collaboration (2019)]
- Intrinsic-charm content of the proton:

  [R. S. Sufian, T. Liu, A. Alexandru, S. J. Brodsky, GdT, H. G. Dosch, T. Draper, K. F. Liu and Y. B. Yang (2020)]

Form factors

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

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

where the c_τ are spin-flavor expansion coefficients for different twist

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

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

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

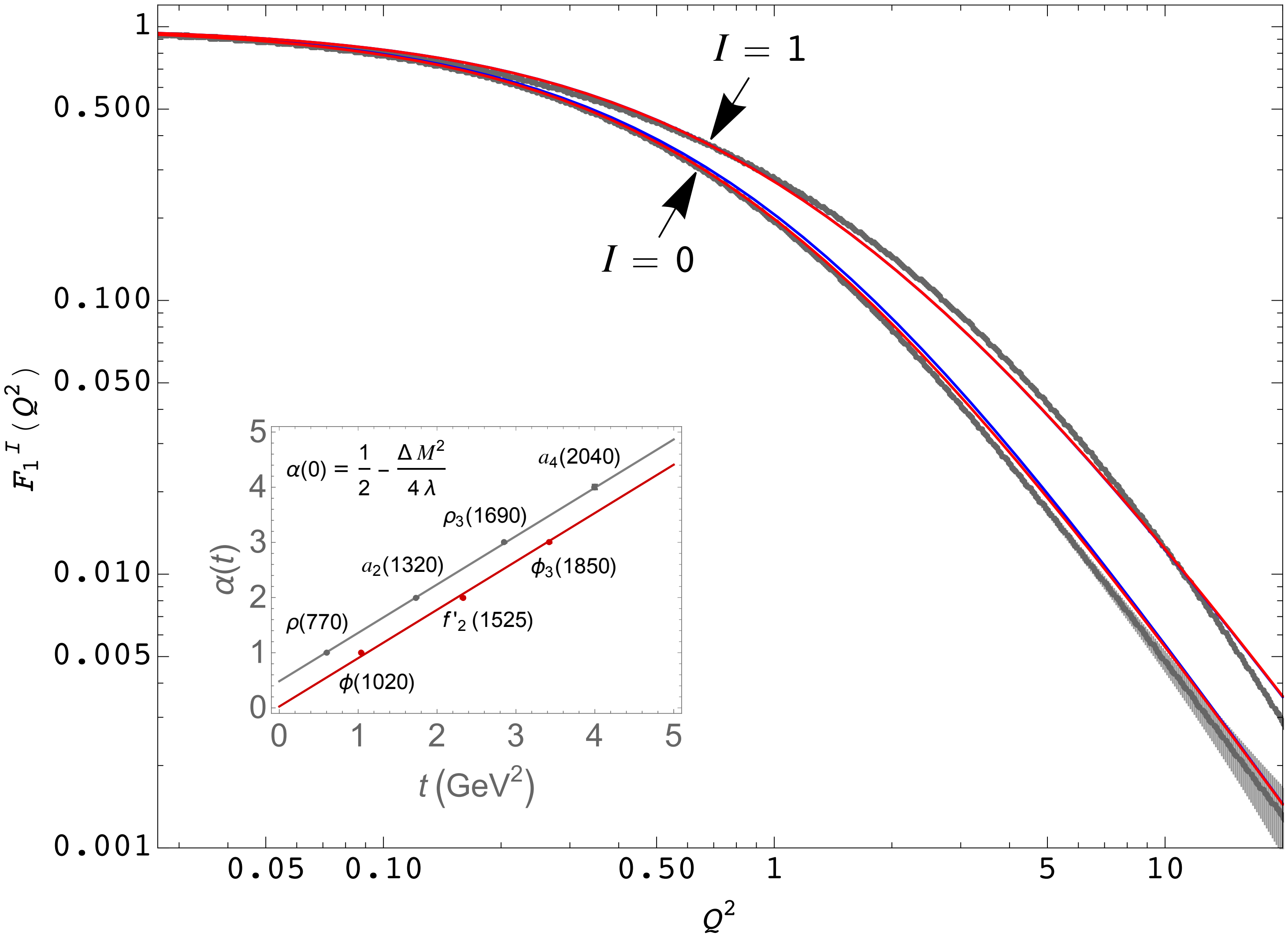
- For $\tau = N$, the number of constituents in a Fock component, the FF is an $N - 1$ product of poles

$$F_\tau(Q^2) = \frac{1}{\Big(1 + \frac{Q^2}{M^2_{n=0}}\Big)\Big(1 + \frac{Q^2}{M^2_{n=1}}\Big) \cdots \Big(1 + \frac{Q^2}{M^2_{n=\tau-2}}\Big)}$$

located at

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

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



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

HLFHS (2019): Valence contribution only

HLFHS (2019): Including $u\overline{u}$ and $d\overline{d}$

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

Quark distributions

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

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

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

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

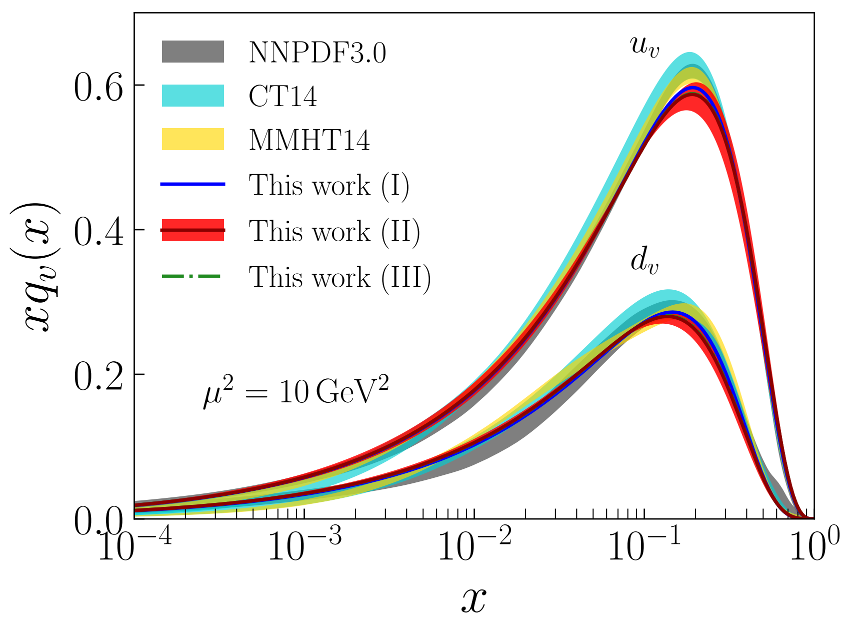
$$F_\tau^q(t) = \int_0^1 dx H_\tau^q(x, t) = \int_0^1 dx\, q_\tau(x) \exp[t f(x)]$$

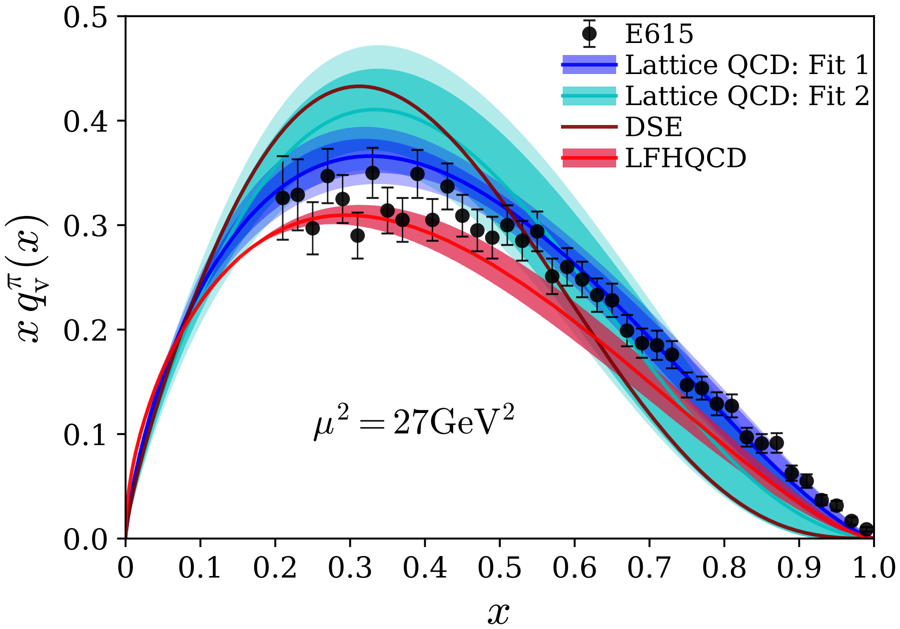
with the profile function $f(x)$ and PDF $q(x)$ determined by $w(x)$

$$\begin{aligned} f(x) &= \frac{1}{4\lambda} \log\left(\frac{1}{w(x)}\right) \\ q_\tau(x) &= \frac{1}{N_\tau} [1 - w(x)]^{\tau - 2} w(x)^{-\alpha(0)} w'(x) \end{aligned}$$

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

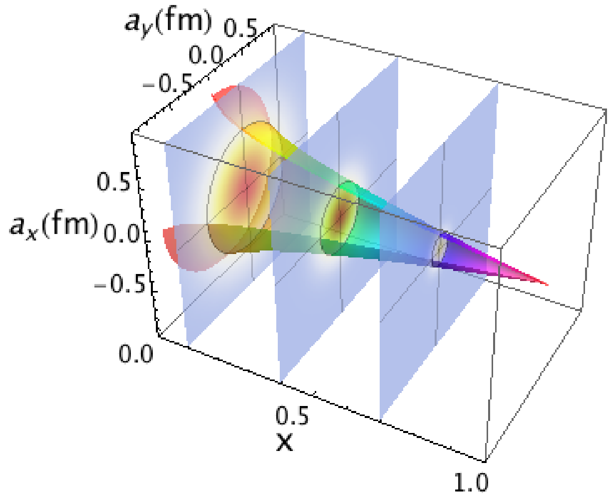
Unpolarized GPDs and PDFs (HLFHS Collaboration, 2018)





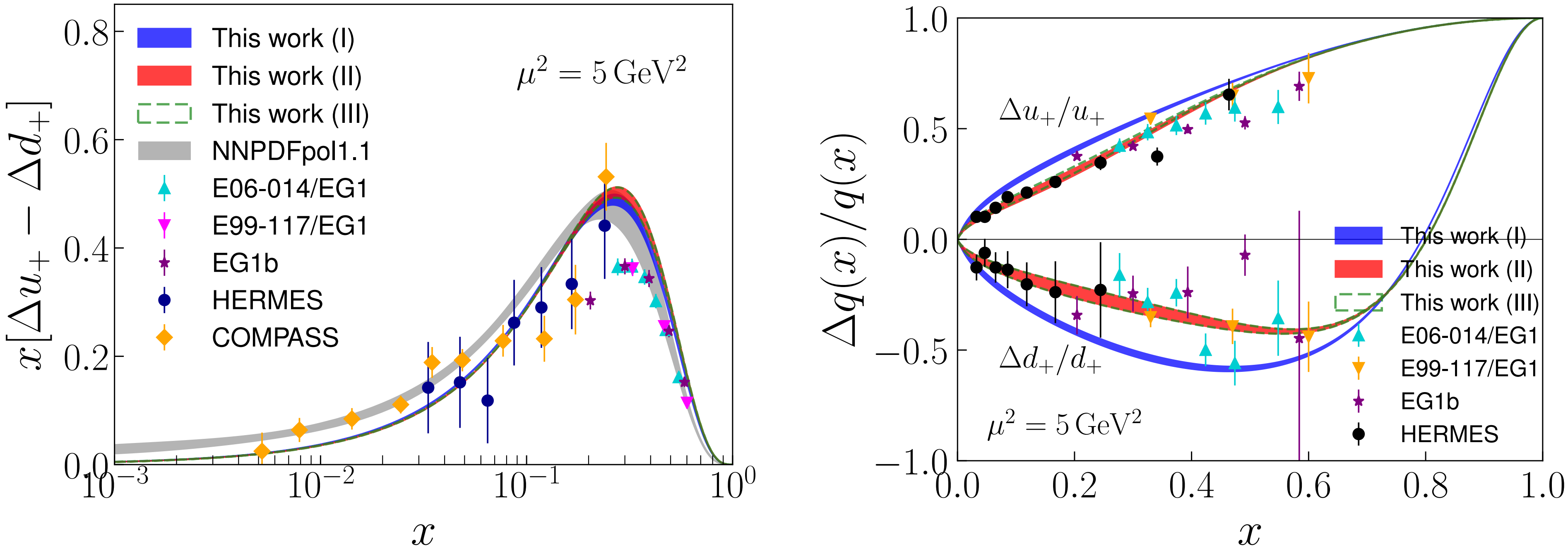
- Transverse impact parameter quark distribution

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



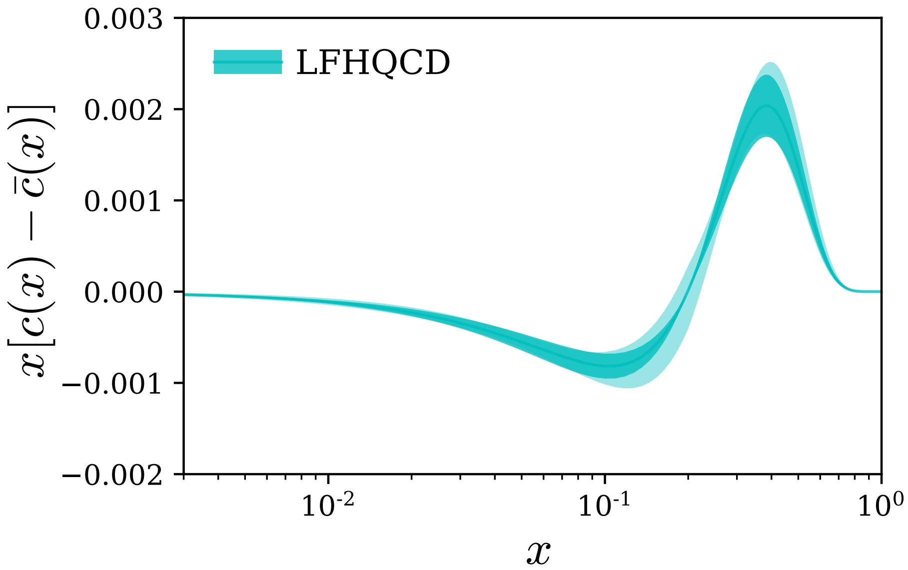
Polarized GPDs and PDFs (HLFHS Collaboration, 2019)

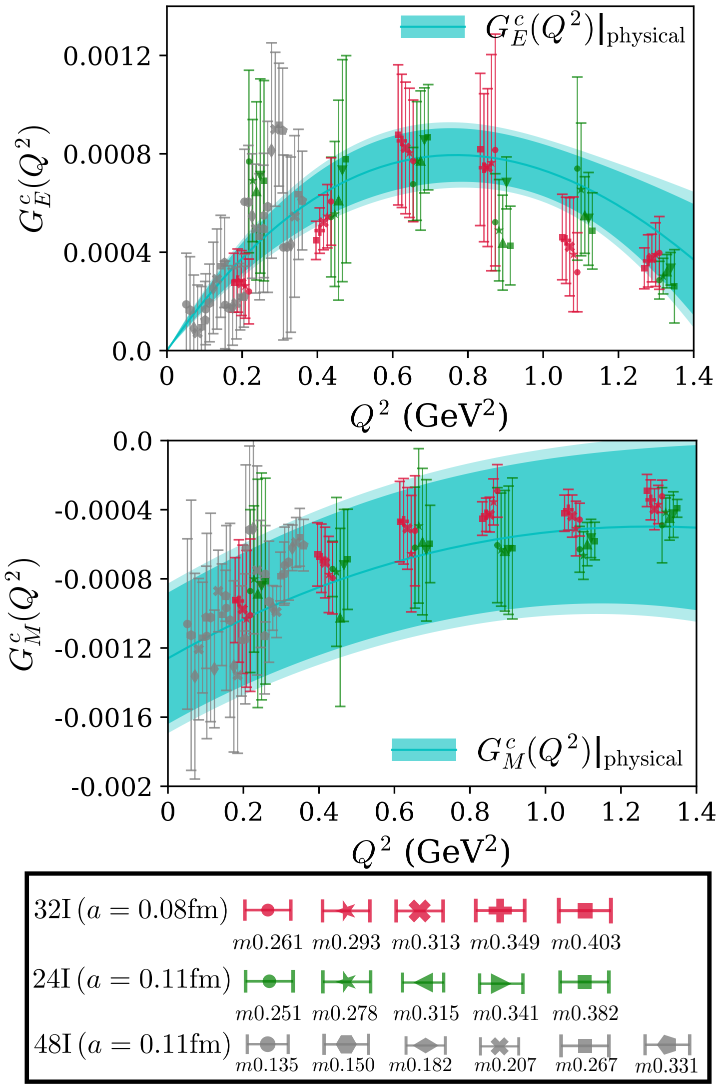
- Separation of chiralities in the AdS action allows computation of the matrix elements of the axial current including the correct normalization, once the coefficients c_τ are fixed for the vector current
- Helicity retention between quark and parent hadron at $x \to 1$: $\lim_{x\to 1} \frac{\Delta q(x)}{q(x)}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



Intrinsic charm in the proton (2020)

- S. J. Brodsky, P. Hoyer, C. Peterson, N. Sakai (1980)
- Nonperturbative intrinsic heavy-quark content of hadron structure is now verified by LGTH
- EM form factors compjuted with three gauge ensembles (one at the physical pion mass)
- Nonperturbative intrinsic charm asymmetry $c(x) - \bar{c}(x)$ determined from LQCD and LFHQCD analysis





Unpolarized gluon distribution (HLFHS Collaboration)

- Confinement in LFHQCD emerges from intrinsic gluon contribution: the graviton couples to the T^{++} component of the energy-momentum tensor which leads to the gluon distribution function $g(x)$

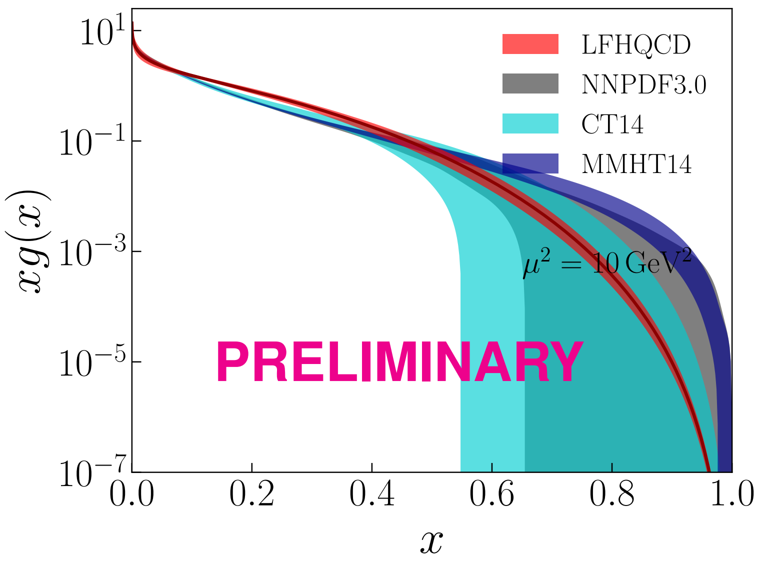
- Gravitational FF expressed in terms of Euler Beta function

$$A_\tau(t) \sim B\left(\tau - 1, 2 - \alpha(t)\right)$$

- Pomeron-proton vertex described by Regge trajectory for a soft Donnachie-Landshoff Pomeron

$$\alpha(t) = \alpha_P(0) + \alpha'_P t$$

  interpreted in QCD as a bound state of two gluons with $\alpha'_P(0) \simeq 1.08$ and $\alpha' \simeq 0.25\,\mathrm{GeV}^{-2}$



- Gluon PDF normalization determined from the sum rule: $\sum_q \langle x \rangle_q + \sum_{\overline{q}} \langle x \rangle_{\overline{q}} + \langle x \rangle_g = 1$

- Basic parameters fixed in quark sector: No adjustable parameters for prediction of $g(x)$

- Red error band from initial evolution scale, uncertainty from sum rule not included

7 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 for mesons, nucleons and tetraquarks: tetraquarks are as fundamental as mesons and baryons
- Approach incorporates basic properties which are not apparent from the 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 algebra and not of the Goldstone mechanism: vacuum chosen *ab initio*
- 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