Confinement, chiral symmetry breaking and holography: the 3D image of the pion

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2022 年 9 月 30 日

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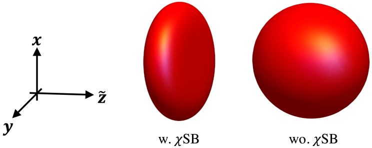
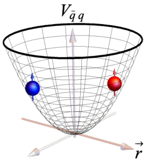
- Confinement & chiral symmetry breaking
- Light front and holography
- PCAC and chiral sum rule
- 3D image of the pion, form factor & parton distribution
- Summary

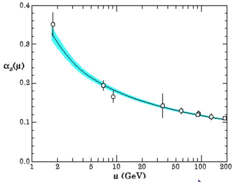
Based on:
YL, Maris, Vary, arXiv:2203.14447 [hep-th];
YL, Vary, PLB (2022), arXiv:2103.09993 [hep-ph];
YL, Vary, PRD (2022), arXiv: 2202.05581 [hep-ph]

Pion light-front amplitude in 3D

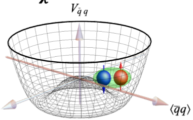


Non-perturbative QCD: last frontier within Standard Model



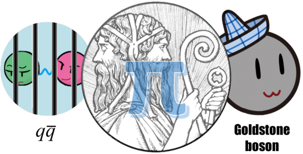


$\Lambda_{QCD}\sim 0.3$ GeV $\Lambda_\chi \sim 1$ GeV $\mu \gg 1$ GeV



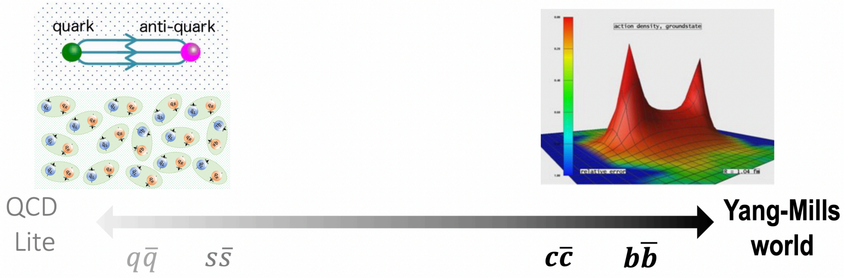
- Confinement
- Chiral symmetry breaking
- Pion: dichotomy 「矛盾的对立统一」

$r_{q\bar{q}} \lesssim \Lambda_{QCD}^{-1}$



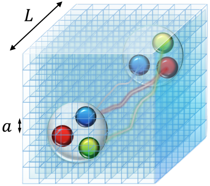
$r_\pi \to \infty$

QCD vacuum



Tremendous progress in the past 20 years; yet many open questions remain:

- Confinement in QCD: various possibilities [Greensite:2016pfc]
  - *flux tube, dual superconductor, central vortices, Gribov horizon, ...*
- Chiral symmetry breaking: [Faber:2017alm]

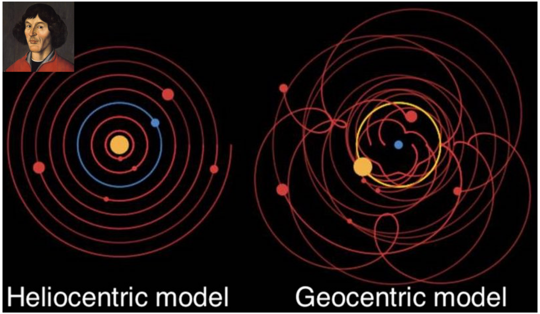


``Berlin wall'': $$\text{Cost} = K\left(\frac{M_\rho}{M_\pi}\right)^{2\sim6} a^{-(6\sim7)} L^5,$$

[Ukawa:2002pc; cf. Schaefer:2012tq]

Is there a simplified description of the pion?

[Brodsky et. al., Nature Rev. Phys. (2022)]



nature reviews physics

Artificial dynamical effects in quantum field theory

Stanley J. Brodsky, Alexandre Deur and Craig D. Roberts

Abstract | In Newtonian mechanics, studying a system in a non-Galilean reference frame can lead to inertial pseudoforces appearing, such as the centrifugal force that seems to arise in dynamics analysed in a rotating frame. Likewise, artificial

Today, no approach to QFT is perfect, but LF quantization possesses many merits. It often provides the simplest known description of nature. As always in physics, one can formulate a problem using any framework one desires. But if the wrong approach is chosen, the costs are high[65].

Light-front QCD

- Intrinsic structure of hadrons: [Miller:2018ybm; cf. Li:2022ldb]
- In-hadron condensate [Brodsky:2010xf; Casher:1974xd]

$$Q_5|0\rangle_{\text{LF}} = 0$$

  - *Axial-vector Ward-Takahashi identity in DSE/BSE* [Maris:1997hd]

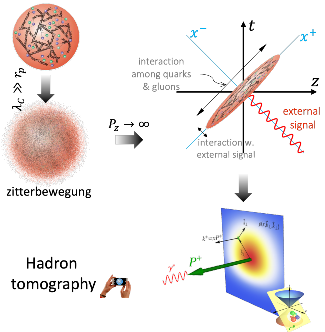
$$f_\pi E_\pi(k, 0) = B_q(k^2), \cdots$$

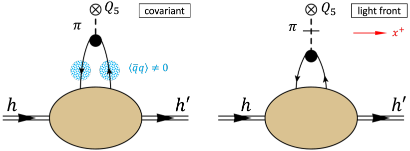
- LF vacuum

[Wu:2003vn; Beane:2013oia, Beane:2015ufo, Burkardt:1996pa]

$$\frac{m_q}{2}\langle 0|\bar{q}\frac{\gamma^+}{i\overleftrightarrow{\partial}^+}q|0\rangle_{\text{LF}} = \langle 0|\bar{q}q|0\rangle_{\text{IF}}$$

Chiral symmetry breaking is encoded in the hadronic light-front wave functions

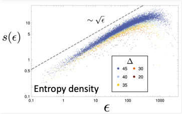


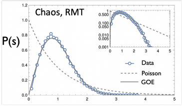


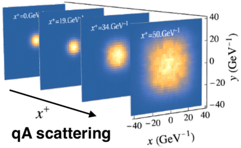
Light-front wave functions

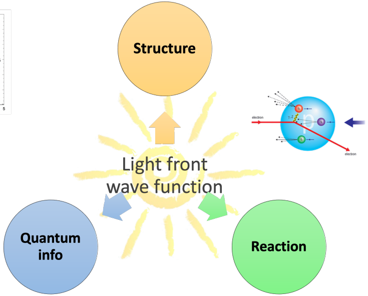
[Reviews: Brodsky:1997de; Anand:2020gnn]

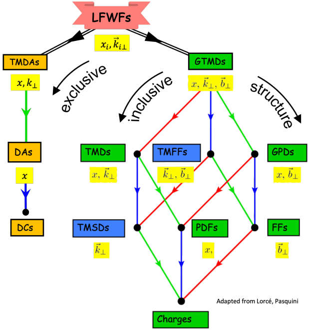
- Light-front physics underlines hadron structures measured in high-energy scattering experiments
- Light-front wave functions provide the full quantum information of hadrons











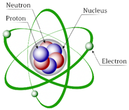
「道生一，一生二，二生三，三生万物」

Access to light front amplitudes

- Experimental measurements [E791:2000xcx]
- Global fits
- OPE (moments) [e.g. Chang:2013pq, Yang:2018nqn]
- Nakanishi representation & LF projection of BSA [dePaula:2022pcb]
- un-Wick rotation [Eichmann:2021vnj, Frederico:2019noo]
- Large momentum effective theory [Ji:2013dva]
- Quasi-PDFs [Radyushkin:2017cyf]
- Interpolation between instant form and front form [Ma:2021yqx]
- Hamiltonian formalism: [review: Hiller:2016itl]

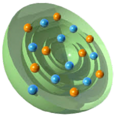
$$\underline{H}_{\text{LFQCD}}|\psi_h\rangle = M_h^2|\psi_h\rangle \qquad \underline{H}_{\text{LFQCD}} = P^+\underline{P}^-_{\text{LFQCD}} - \vec{P}_\perp^2$$

Light-front Hamiltonian formalism



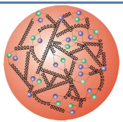
Non-relativistic, weakly coupling

Bohr Model



Non-relativistic, strongly coupling

Shell Model

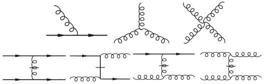


Relativistic, strongly coupling

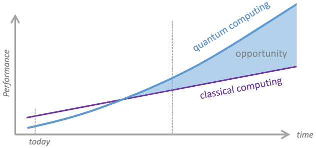
?

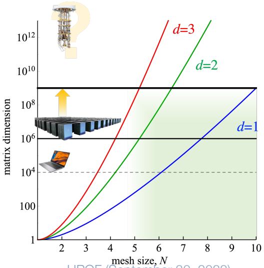
LFQCD as a strong-coupling relativistic quantum many-body problem

$$H_{\text{LFQCD}} = \sum_i \frac{\vec{p}_{i\perp}^{\,2} + m_i^2}{x_i} + U_i + \sum_{ij} V_{ij}^{(\text{QCD})} - \delta_{ij} U_i$$



- Exponential wall: $\dim \mathscr{H} = N^{dN}$ [Hornbostel:1988fb, Anand:2020gnn]
- Quantum advantage? [Kreshchuk:2020dla]
- Need a semi-classical first approximation





Semiclassical first approximation to QCD

[Review: Brodsky:2014yha]

Light-front Schrödinger wave equation with a factorization ansatz:

[Chabysheva:2012fe, Li:2021jqb, deTeramond:2021yyi]

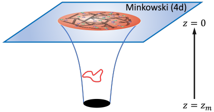
$$\Big(\frac{\vec{k}_\perp^2 + m_q^2}{x} + \frac{\vec{k}_\perp^2 + m_{\bar{q}}^2}{1-x} + U\Big)\psi(x, \vec{k}_\perp) = M^2 \psi(x, \vec{k}_\perp)$$

factorization ansatz $\Downarrow\ \psi = \varphi(\vec{\zeta}_\perp)\chi(x)$

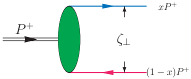
$$\Big[-\nabla^2_{\zeta_\perp} + U_\perp(\vec{\zeta}_\perp)\Big]\varphi(\vec{\zeta}_\perp) = M_\perp^2 \varphi(\vec{\zeta}_\perp), \quad \Big[\frac{\cancel{m_q^2}}{x} + \frac{\cancel{m_{\bar{q}}^2}}{1-x} + U_\parallel(\tilde{z})\Big]\chi(x) = M_\parallel^2 \chi(x)$$

Light-front holography provides a unique correspondence between semiclassical LFQCD and semiclassical fields in 5D anti-de Sitter space

[Brodsky:2003px, Erlich:2005qh, Karch:2006pv]

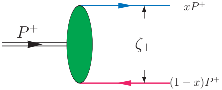


Weak coupling		Strong coupling
?	AdS/QCD	QCD
↑		↑
Semiclassical fields in AdS_5	LF holography	Semiclassical LFQCD
↑		
Type IIB string theory in $AdS_5 \times S^5$	AdS/CFT	N=4 SUSY Yang-Mills theory (CFT)

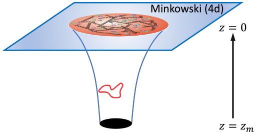


Light-front holography

[Review: Brodsky:2014yha]



semiclassical LFQCD	$\leftrightarrow$	semiclassical field theory in AdS
$\zeta_\perp = \sqrt{x(1-x)}r_\perp$	$\leftrightarrow$	fifth coordinate z,
LF amplitude	$\leftrightarrow$	string amplitude
confining potential	$\leftrightarrow$	dilation field Φ
$L^2 - (J-2)^2$	$\leftrightarrow$	$(\mu R)^2$



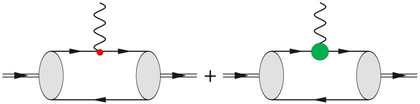
- Correspondence within equation of motions (hadron spectra)

$$U(z) = \frac{1}{4}\Phi'^2 + \frac{1}{2}\Phi'' + \frac{2J-3}{2z}\Phi'$$

- Correspondence within form factors [Drell:1969km, West:1970av; Hong:2004sa, Grigoryan:2007wn, Kwee:2007dd]

$$F_{\text{LF}}(Q^2) = \int \zeta_\perp \mathrm{d}\zeta_\perp \varphi_\pi^2(\zeta_\perp) \zeta_\perp Q K_1(\zeta_\perp Q) + \text{high Fock sectors}$$

$$F_{\text{AdS}}(Q^2) = \int \frac{\mathrm{d}z}{z^3}\left[zQK_1(zQ) + zQI_1(zQ)\frac{K_0(Qz_m)}{I_0(Qz_m)}\right]\phi_\pi^2(z)$$

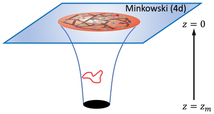


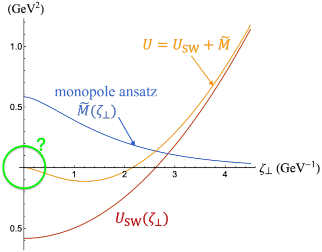
Confinement in AdS/QCD

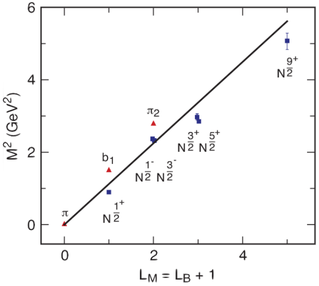
[Review: Brodsky:2014yha]

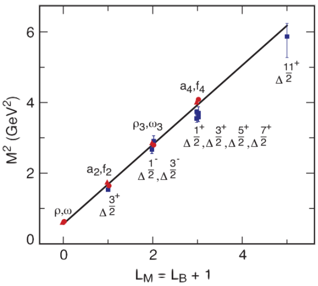
Breaking of the conformal symmetry by the dilaton field $\Phi(z)$ at IR $z \to \infty$ [Erlich:2005qh]

- CFT at UV (asymptotic freedom): $\Phi(z \to 0) \to 0$
- Regge trajectory at IR: $\Phi(z \to \infty) \sim z^2$ [Karch:2006pv]
- Soft-wall AdS/QCD: $\Phi(z) = \lambda z^2$ [Karch:2006pv]
  - *Effective LF confining potential:* $U_{SW}(z) = \lambda^2 z^2 + 2(J-1)\lambda$
  - *Emergent superconformal symmetry: pion as a massless susy singlet* [Brodsky:2013ar, deAlfaro:1976vlx]





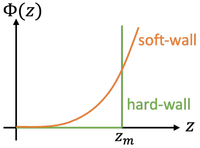




What about chiral symmetry breaking? (cf. dynamical mass generation)

Chiral symmetry breaking in soft-wall AdS/QCD

[Erlich:2005qh, Karch:2006pv]



PRL **95,** 261602 (2005)

QCD and a Holographic Model of Hadrons

Joshua Erlich,[1] Emanuel Katz,[2] Dam T. Son,[3] and Mikhail A. Stephanov[4]

Hard-wall model: with chiral symmetry breaking, but no Regge trajectory

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PHYSICAL REVIEW D **74,** 015005 (2006)

Linear confinement and AdS/QCD

Andreas Karch,[1,*] Emanuel Katz,[2,†] Dam T. Son,[3,‡] and Mikhail A. Stephanov[4,§]

Soft-wall model: with Regge trajectory, but no chiral symmetry breaking

tion between bulk and boundary theories [12,19]. The action at quadratic order in the fields and derivatives reads

$$I = \int d^5x e^{-\Phi(z)} \sqrt{g}\Big\{-|DX|^2 + 3|X|^2 - \frac{1}{4g_5^2}(F_L^2 + F_R^2)\Big\}$$

asymptotics $e^{z^2} \to \infty$ and $\exp\{-(3/4)z^{-2}\} \to 1$. Since the equation is linear, selecting one of the solutions in the IR (the $X < \infty$ one, of course) gives Σ simply proportional to M. This is not what one wants in a theory with spontaneous symmetry breaking such as QCD. It is clear that one has to consider higher order terms in the potential $U(X, \ldots)$ for X and all other scalar condensates. Such a potential would

Various implementations of χSB in soft-wall AdS/QCD:

[Gherghetta:2009ac, Zuo:2009dz, Sui:2009xe, Sui:2010ay, Iatrakis:2010zf, Iatrakis:2010jb, Vega:2010ne, Jarvinen '12; Afonin:2012jn, Li:2012ay, Li:2013oda, Cui:2013xva, Chelabi:2015cwn, Fang:2016nfj, Ballon-Bayona:2021ibm, Rinaldi:2022dyh, ...]

Chiral symmetry breaking in soft-wall AdS/QCD

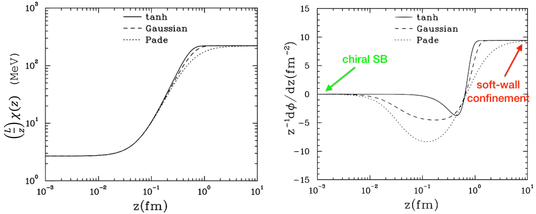
[Gherghetta:2009ac, Kapusta:2010mf]

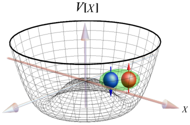
Scalar field X dual to $\bar{q}q$, with a non-vanishing VEV: $\langle X \rangle = \frac{1}{2}\chi(z)$

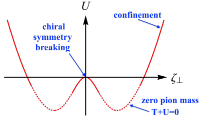
$$S = -\int d^5x \sqrt{-g} e^{-\Phi(z)} \mathrm{Tr}\Big\{ |DX|^2 - V[X] + \frac{1}{4g_5^2} F^2 \Big\},$$

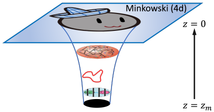
Higgs potential: $V[X] = -m_X^2 |X|^2 + \kappa |X|^4$, $m_X^2 = -3$

- At the CFT boundary ($z \to 0$): $\chi(z) \sim m_q z + \Sigma z^3$ [Klebanov:1999tb]
- (Non-linear) Eq. of Motion $\Rightarrow$ $\Phi(z) \sim z^6 \Rightarrow U(z) \sim -z^4$ at $z \to 0$
- χSB & confinement dictate the UV & IR behaviors of $U(\zeta_\perp)$, respectively





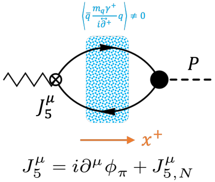




Model independent constraints from light-front dynamics?

Partially conserved axial-vector current (PCAC)

$$\partial_\mu J_5^\mu = 2im_q\bar{q}\gamma_5 q \quad \Rightarrow \quad \langle 0|\partial_\mu J_5^\mu - 2im_q\bar{q}\gamma_5 q|P(p)\rangle = 0.$$



- $J_5^\mu = \bar{q}\gamma^\mu\gamma_5 q$ is the full axial-vector current, not the LF axial-vector current $\hat{J}_5^\mu$

  $J_5^+ = \hat{J}_5^+$, but $\hat{J}_5^\mu$ does not create the pion from the vacuum

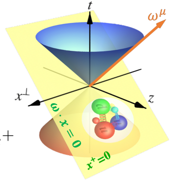
- Fock space expansion: only valence LFWFs contribute
- The *most general covariant structure* of the pion valence LFWFs: covariant LFD [Carbonell:1998rj]

$$\psi_{s\bar{s}/P}(x,\vec{k}_\perp) = \bar{u}_s(p_1)\Big[\gamma_5\,\phi_1(x,k_\perp) + \hat{f}_\chi\frac{\gamma_5\not{\omega}}{\omega\cdot p}\phi_2(x,k_\perp)\Big]v_{\bar{s}}(p_2),$$

  - ω-term: direction of the light front - conformal structure $\omega^\mu \to \lambda\omega^\mu$
  - ω-term: allowed by kinematical symmetries, required by rotational invariance
  - ω-term does not satisfy the ``covariant LF condition" and is often neglected
  - Chiral broken phase: $f_\pi \neq 0 \;\Rightarrow\; \hat{f}_\chi \neq 0$

$$\frac{f_P}{2\sqrt{2N_C}} = \int\frac{\mathrm{d}x}{2\sqrt{x(1-x)}}\int\frac{\mathrm{d}^2k_\perp}{(2\pi)^3}\psi_{\uparrow\downarrow-\downarrow\uparrow/P}(x,\vec{k}_\perp).$$

$x\cdot\omega = x^+$



Chiral sum rule

[Li:2022ytx]

In the chiral limit $m_q \to 0$,

$$\int \frac{\mathrm{d}x}{2\sqrt{x(1-x)}} \int \frac{\mathrm{d}^2 k_\perp}{(2\pi)^3} \frac{k_\perp^2}{x(1-x)} \psi^{(0)}_{\uparrow\downarrow-\downarrow\uparrow/P}(x, \vec{k}_\perp) = 0$$

- Exact relation: no Fock sector truncations, no approximations
- If $\hat{f}_\chi = 0$, this sum rule is automatically satisfied. However, $f_\pi = 0 \;\to\;$ chiral symmetric phase (not QCD)
- Gell-Mann-Oakes-Renner relation: $f_P^{(0)2} M_P^2 = 2m_q g_P^{(0)} + O(m_q^2)$, where $g_P = \langle 0|j_5|P(p)\rangle$
- Additional sum rules from further light-front current algebra [Beane:2013oia, Beane:2015ufo]

Chiral sum rule

[Li:2022ytx]

Application to semiclassical light-front QCD:

$$f_P \nabla_\perp^2 \varphi_P(\zeta_\perp = 0) = 0$$

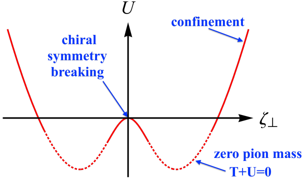
for any pseudo-scalar P. Recall,

$$\Big[-\nabla_\perp^2 + U(\zeta_\perp)\Big]\varphi_P(\zeta_\perp) = M_P^2 \varphi_P(\zeta_\perp)$$

The pion: $M_\pi = 0$,

$$\Rightarrow \quad U(\zeta_\perp = 0) = 0 \qquad (\text{cf. } U_{\text{Higgs}} \sim -\zeta_\perp^4 \to 0)$$

For excited pions, the decay constants $f_{\pi^n} = 0$. [Maris:1997hd, Ballon-Bayona:2014oma]



Analytic model

Let's build a chiral pion:

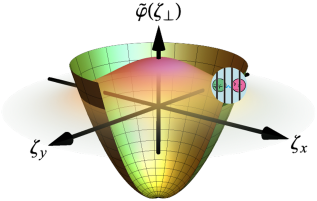
$$\Big[-\nabla_\perp^2 + U(\zeta_\perp)\Big]\varphi_P(\zeta_\perp) = M_P^2\varphi_P(\zeta_\perp), \qquad \nabla_\perp^2\varphi_\pi(\zeta_\perp = 0) = 0, \quad U(\zeta_\perp) \to \begin{cases} \zeta_\perp^2 & \zeta_\perp \to \infty \\ -\zeta_\perp^4 & \zeta_\perp \to 0 \end{cases}$$

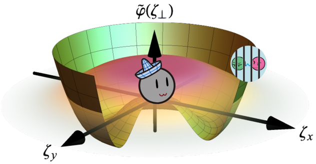
We propose the following pion wave function based on light-front holography:

$$\varphi_\pi(\zeta_\perp) = \underbrace{\left(1 + \frac{1}{2}\zeta_\perp^2 + \frac{c}{8}\zeta_\perp^4\right)}_{\text{chiral symmetry breaking}} \overbrace{e^{-\frac{\zeta_\perp^2}{2}}}^{\text{confinement}}$$

Given the pion wave function, the potential is ($c = 1$),

$$U(\zeta_\perp) = \frac{\nabla_\perp^2\varphi_\pi(\zeta_\perp)}{\varphi_\pi(\zeta_\perp)} = \frac{\zeta_\perp^4(\zeta_\perp^2 - 6)}{\zeta_\perp^4 + 4\zeta_\perp^2 + 8}$$

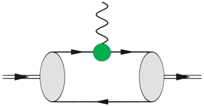




Pion electromagnetic form factor & PDF

[deTeramond:2018ecg, Liu:2019vsn]

$$F_\pi(q^2) = \int \zeta_\perp \mathrm{d}\zeta_\perp \rho_\pi(\zeta_\perp) V_{\mathrm{SW}}(q^2, \zeta_\perp) = \int \mathrm{d}x\, H_\pi(x, t = q^2)$$



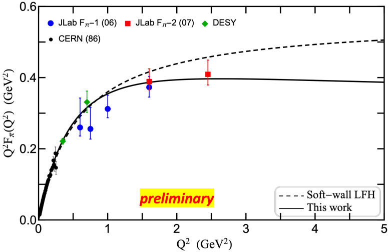
Veneziano amplitudes

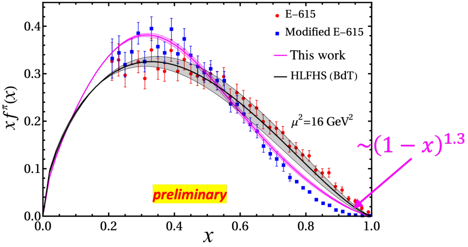
- Soft-wall AdS/QCD: only leading-twist contribution $\sim Q^{-2}$

$$\rho_\pi(\zeta_\perp) = N \exp(-\zeta_\perp^2) \ \Rightarrow\ F_\pi(q^2) = F_{\tau=2}(q^2)$$

- χSB modifies the large-Q^2 behavior: incorporating high-twist ($\tau = N$) contributions [Brodsky:1973kr]

$$\rho_\pi(\zeta_\perp) = [1 + \frac{1}{2}\zeta_\perp^2 + \frac{c}{8}\zeta_\perp^4]^2 \exp(-\zeta_\perp^2) \ \Rightarrow\ F_\pi(q^2) = N\Big\{\underbrace{F_{\tau=2}(q^2)}_{[q\bar{q}]} + \underbrace{F_{\tau=3}(q^2)}_{[q\bar{q}g]} + c_1 \underbrace{F_{\tau=4}(q^2)}_{[q\bar{q}q\bar{q}]} + \cdots\Big\}$$





[See also, Chang:2020kjj, Dosch:2022mop, Gurjar:2022jkx]

Global analysis: $\sim (1-x)^{1.0\sim1.3}$ [Barry:2021osv]

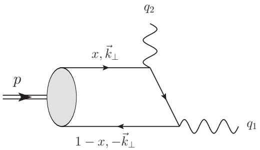
Pion transition form factor

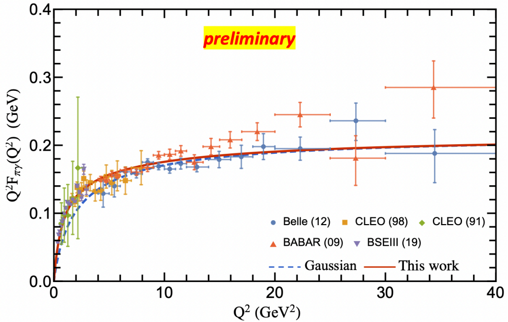
[In preparation]

Singly-virtual two-photon transition form factor:

$$F_{\pi\gamma}(Q^2) = e_f^2 2\sqrt{2N_C} \int \frac{\mathrm{d}x}{2\sqrt{x(1-x)}} \int \frac{\mathrm{d}^2 k_\perp}{(2\pi)^3} \frac{\psi_\pi(x, \vec{k}_\perp)}{k_\perp^2 + x(1-x)Q^2}$$

- VMD: $Q^2 \to Q^2 + M_\rho^2$
- pQCD normalization: $Q^2 F_{\pi\gamma}(Q^2) \to 2f_\pi$, $Q^2 \to \infty$





3D image of the pion

[Li:2022ytx]

$$\widetilde{\psi}_\pi(\vec{z}_\perp, \tilde{z}) = \int_0^1 \frac{\mathrm{d}x}{2\sqrt{x(1-x)}} \int \frac{\mathrm{d}^2 k_\perp}{(2\pi)^3} e^{ix\tilde{z} - i\vec{k}_\perp\cdot\vec{z}_\perp} \psi_\pi(x, \vec{k}_\perp) = \langle 0|\bar{q}(-\tfrac{1}{2}z)\frac{\gamma^+\gamma_5}{p^+}q(+\tfrac{1}{2}z)|P(p)\rangle_{z^+=0}$$

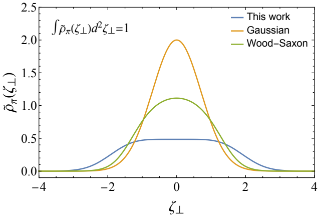
where $\tilde{z} = p\cdot z$ is the Ioffe time of Miller and Brodsky. [Miller:2019ysh]

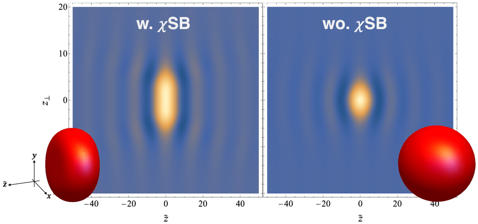
- Infinitely long in the longitudinal direction, $r_\pi \propto -\ln M_\pi^2 \to \infty$ [Li:2022izo, Weller:2021wog]

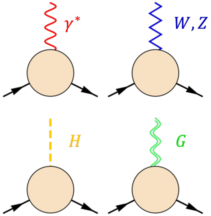
$$r^2_{\text{em}} = -6F'_{\text{ch}}(0) = \frac{3}{2}\langle \vec{b}^2_\perp\rangle, \quad r^2_{\text{grav}} = -6A'(0) = \frac{3}{2}\langle\vec{\zeta}^2_\perp\rangle \qquad \vec{b}_\perp = (1-x)\vec{r}_\perp$$

- Plateau in the transverse direction: the pion is uniform within up to $r_\perp \sim \kappa^{-1}_{\text{confin}}$

$$\nabla^2_\perp \varphi_\pi(\zeta_\perp = 0) = 0$$





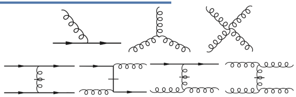


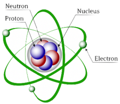
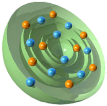
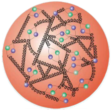
Implication to *ab initio* LFQCD

[Review: Brodsky:1997de, cf. Wilson:1994fk]

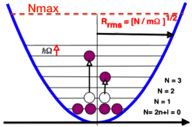
Light-front QCD in
light cone gauge $A^+ = 0$

$$H_{\text{LFQCD}} = \sum_i \frac{\vec{p}_{i\perp}^{\,2} + m_i^2}{x_i} + U_i + \sum_{ij} V_{ij}^{(\text{QCD})} - \delta_{ij} U_i$$



Atoms	Nuclei	Hadrons
		
Coulomb interaction	NN, NNN interactions	QCD interactions
↓	↓	↓
Bohr Model 	Shell Model 	Light Front Holography
$\left(\frac{\vec{p}^2}{2m} - \frac{Z\alpha}{r}\right)\psi = E\psi$	$\left(\frac{\vec{p}^2}{2m} + \frac{m\omega^2}{2} r^2\right)\psi = E\psi$	$\left(\frac{k_\perp^2 + m_q^2}{x(1-x)} + \kappa^4\zeta_\perp^2 + U_{\parallel}\right)\psi = M^2\psi$

- It is important to preserve all kinematical symmetries under the truncation
- Covariant LFD gets too complicated for many-body ($A \le 3$) system [Carbonell:1998rj]
- Discretized momentum basis (DLCQ): choose between rotational symmetry and boost symmetry
- Basis light-front quantization (BLFQ) [Vary:2009gt]

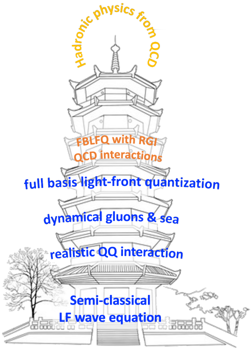


[Review: Barrett:2013nh (NCSM)]

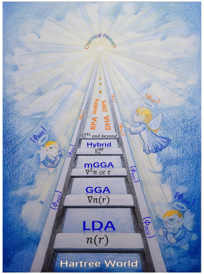
Implication to *ab initio* LFQCD

[Review: Brodsky:1997de, cf. Wilson:1994fk]

- Semi-classical LF wave equations: [Reviews: Brodsky:2014yha] [Li:2021jqb, Li:2022izo, deTeramond:2021yyi, Ahmady:2021lsh, Ahmady:2021yzh, Li:2022izo, Lyubovitskij:2022rod, Ahmady:2022dfv]
- Realistic QQ interaction:
  - QED: [Wiecki:2014ola, Hu:2020arv, Nair:2022evk]
  - heavy flavor [Li:2015zda, Li:2017mlw, Leitao:2017esb, Li:2018uif, Adhikari:2018umb, Tang:2018myz, Lan:2019img, Tang:2019gvn, Tang:2020org, Li:2021ejv, Li:2021cwv, Shuryak:2021fsu, Shuryak:2021hng, Shuryak:2021mlh, Shuryak:2022thi, Shuryak:2022wtk]
  - light mesons [Jia:2018ary, Lan:2019vui, Lan:2019rba, Qian:2020utg, Mondal:2021czk, Adhikari:2021jrh, Peng:2022lte]
  - nucleons [Mondal:2019jdg, Xu:2021wwj, Liu:2022fvl, Hu:2022ctr]
  - tetraquarks [Kuang:2022vdy]
- Dynamical gluons & sea: [Lan:2021wok, Xu:2022abw]
- Full basis light-front quantization [Vary:2009gt]



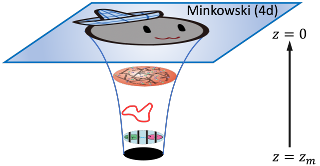
Jacob's ladder in quantum chemistry

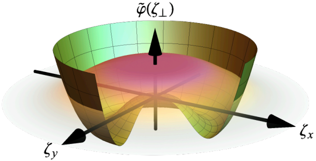


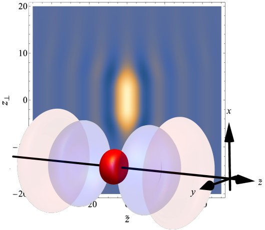
Summary

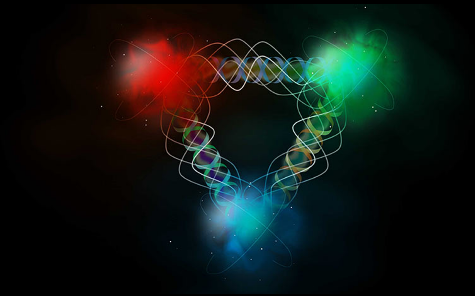
[YL, Maris, Vary, arXiv:2203.14447 [hep-th]]

- The pion is the key to understand confinement and chiral symmetry breaking in QCD
- Light-front wave functions provide the direct access to the parton structure of the pion
- Obtained an exact sum rule for the valence sector wave function based on the most general covariant structure and PCAC
- This chiral sum rule is consistent with chiral symmetry breaking in soft-wall AdS/QCD and leads to a remarkable feature of the pion structure









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