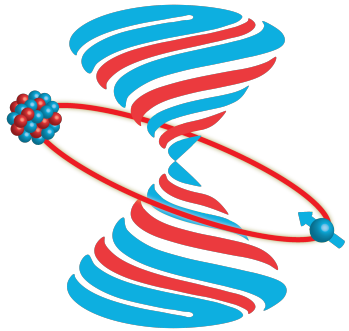
06/30-07/04
中国科学技术大学东区
物质科研楼C楼三层会议室
第二届强子物理新发展研讨会
暨强子物理在线论坛100期特别活动

Light meson structure from a light-front Hamiltonian approach



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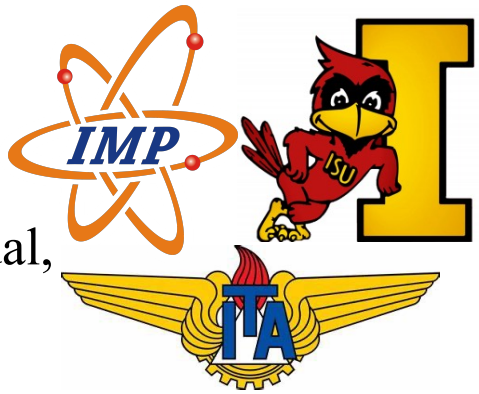
Iowa State University, Ames, US



合肥 • 2024年7月2日

Outline

- Basis Light-front Quantization
- Application to Light Mesons
  - Light mesons with $q\bar{q} + q\bar{q}\mathrm{g}$
  - Light mesons with $q\bar{q} + q\bar{q}\mathrm{g} + q\bar{q}q\bar{q}$
- Conclusion & Outlook

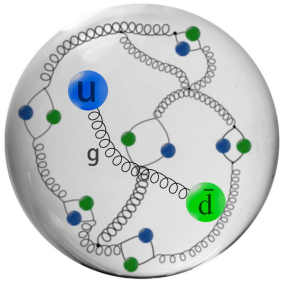
Basis Light-front Quantization

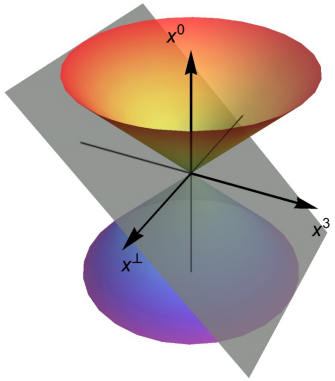
- Nonperturbative eigenvalue problem

[Vary et al, PRC 2010]

$$P^-|\beta\rangle = P^-_\beta|\beta\rangle$$

  - P^-: light-front Hamiltonian
  - $|\beta\rangle$: mass eigenstate
  - P^-_β: eigenvalue for $|\beta\rangle$





- Evaluate observables for eigenstate

$$O \equiv \langle\beta|\hat{O}|\beta\rangle$$

- Fock sector expansion

$$|\text{meson}\rangle = a|q\bar{q}\rangle + b|q\bar{q}g\rangle + c|q\bar{q}q\bar{q}\rangle + d|q\bar{q}gg\rangle + \cdots$$

- Discretized basis
  - Transverse: 2D harmonic oscillator basis: $\Phi^b_{n,m}(\vec{p}_\perp)$.
  - Longitudinal: plane-wave basis, labeled by k.
  - Basis truncation:

$$\sum_i (2n_i + |m_i| + 1) \le N_{max},$$
$$\sum_i k_i = K.$$

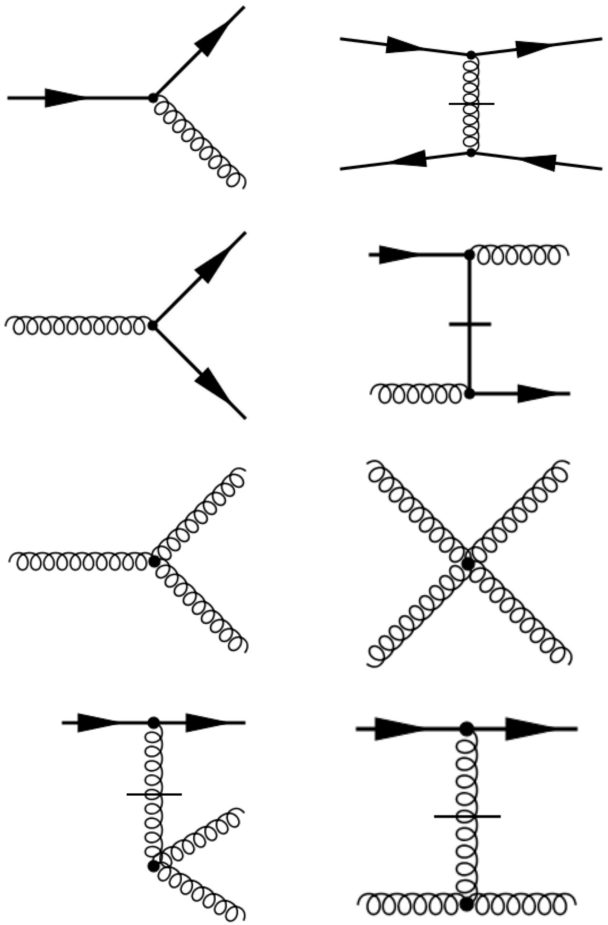
N_{max}, K are basis truncation parameters.

Large N_{max} and K : High UV cutoff & low IR cutoff

Light-front Hamiltonian

QCD light-front Hamiltonian can be derived from QCD Lagrangian:

$$\mathcal{L}_{QCD} = \bar{\psi}(i\not{\partial} - m)\psi - \frac{1}{4} G^{\alpha}_{\mu\nu} G^{\mu\nu}_{\alpha} \quad \Rightarrow \quad P^{-}_{QCD} = H_K + H_I \qquad A^{+} = 0$$



$$H_K = \frac{1}{2}\int d^3x\, \bar{\psi}\gamma^{+}\frac{(i\partial^{\perp})^2 + m^2}{i\partial^{+}}\psi + \frac{1}{2}\int d^3x\, A^{i}_{a}(i\partial^{\perp})^2 A^{i}_{a}$$

$$H_I = g\int d^3x\, \bar{\psi}\gamma_{\mu}A^{\mu}\psi$$

$$+\frac{1}{2}g^2\int d^3x\, \bar{\psi}\gamma_{\mu}A^{\mu}\frac{\gamma^{+}}{i\partial^{+}}\gamma_{\nu}A^{\nu}\psi$$

$$-ig^2\int d^3x\, f^{abc}\bar{\psi}\gamma^{+}T^{c}\psi\frac{1}{(i\partial^{+})^2}\left(i\partial^{+}A^{\mu}_{a}A_{\mu b}\right)$$

$$+\frac{1}{2}g^2\int d^3x\, \bar{\psi}\gamma^{+}T^{a}\psi\frac{1}{(i\partial^{+})^2}\bar{\psi}\gamma^{+}T^{a}\psi$$

$$+ig\int d^3x\, f^{abc}i\partial^{\mu}A^{\nu a}A^{b}_{\mu}A^{c}_{\nu}$$

$$-\frac{1}{2}g^2\int d^3x\, f^{abc}\, f^{ade}\, i\partial^{+}A^{\mu}_{b}A_{\mu c}\frac{1}{(i\partial^{+})^2}(i\partial^{+}A^{+}_{d}A_{\nu e})$$

$$+\frac{1}{4}g^2\int d^3x\, f^{abc}\, f^{ade}\, A^{\mu}_{b}A^{\nu}_{c}A_{\mu d}A_{\nu e}.$$

ψ: quark field operator

A^{a}_{μ}: gluon field operator

Take a review

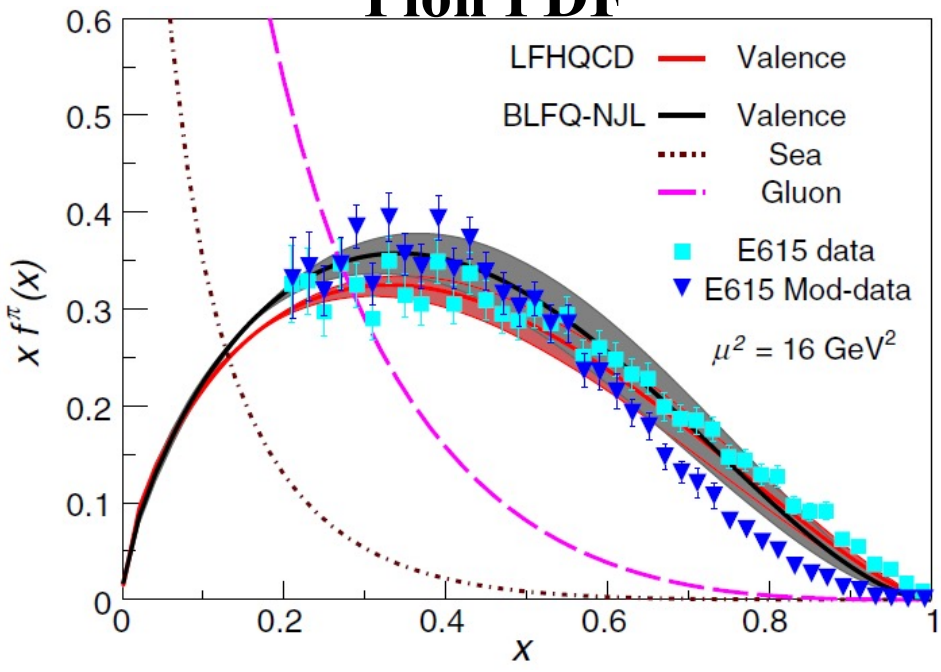
PDFs for light mesons

$|\text{meson}\rangle = |q\bar{q}\rangle + \cdots$

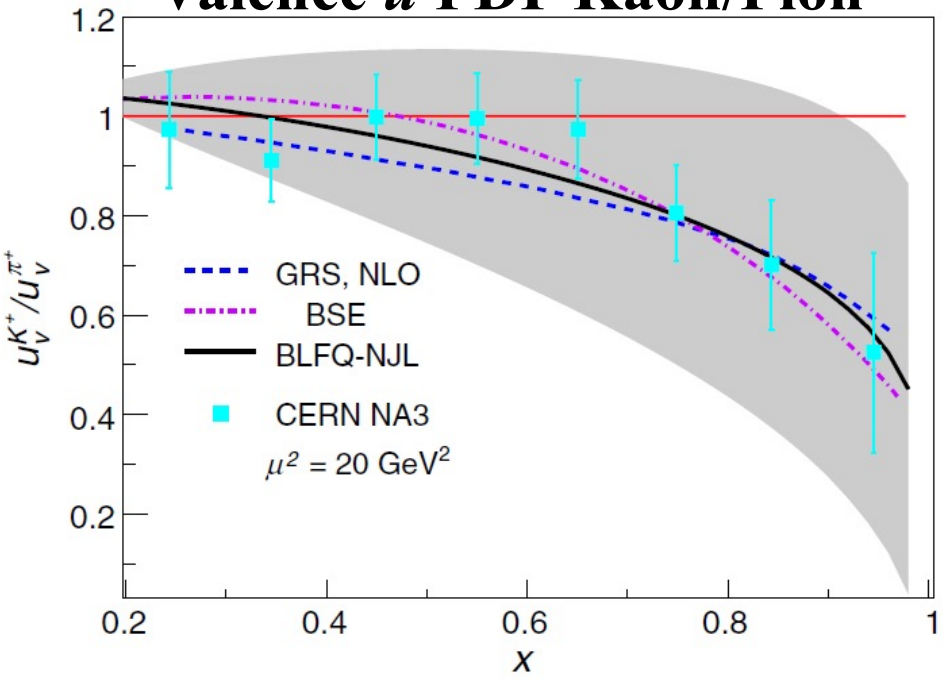
$$H_{\text{eff}} = \frac{\vec{k}_\perp^2 + m_q^2}{x} + \frac{\vec{k}_\perp^2 + m_{\bar{q}}^2}{1-x} + \kappa^4 x(1-x)\vec{r}_\perp^2 - \frac{\kappa^4}{(m_q + m_{\bar{q}})^2}\partial_x(x(1-x)\partial_x) + H_{\text{eff}}^{\text{NJL}}$$

Diagonalizing H_{eff} → LF wave function → Initial PDFs → Scale evolution

Pion PDF



Valence *u* PDF Kaon/Pion



[J. Lan et al, PRL122, 172001(2019), PRD 101 (2020) 034024]

Agree with experimental results

Light mesons up to $|q\bar{q}g\rangle$

$$|\text{meson}\rangle = |q\bar{q}\rangle + \cdots$$

[J. Lan et al, PRL122, 172001(2019)]
[J. Lan et al, PRD 101 (2020) 034024]

$$|\text{meson}\rangle = a|q\bar{q}\rangle + b|q\bar{q}g\rangle + \cdots$$

[J. Lan et al, PLB 825 (2022) 136890]
[Z. Zhu et al, PLB 839(2023) 137808]
[S. Kaur et al, PLB 851 (2024) 138563]

Light mesons up to $|q\bar{q}g\rangle$

$$|\text{meson}\rangle = a|q\bar{q}\rangle + b|q\bar{q}g\rangle$$

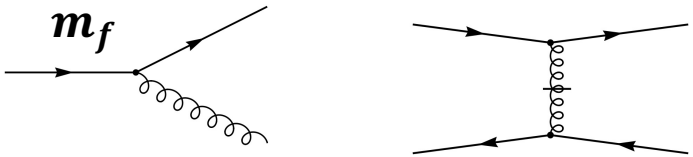
$$P^- = H_{K.E.} + H_{trans} + H_{longi} + H_{Interact}$$

$$H_{K.E.} = \sum_i \frac{p_i^2 + m_q^2}{p_i^+}$$

$$H_{trans} \sim \kappa_T^4 r^2$$ ---Brodsky, Teramond arXiv: 1203.4025

$$H_{longi} \sim -\sum_{ij} \kappa_L^4 \partial_{x_i}\left(x_i x_j \partial_{x_j}\right)$$ ---Y Li, X Zhao , P Maris , J Vary, PLB 758(2016)

$$H_{Interact} = H_{Vertex} + H_{inst} = g\bar{\psi}\,\gamma^\mu T^a\,\psi\,A_\mu^a + \frac{g^2 C_F}{2}\,j^+\,\frac{1}{(i\partial^+)^2}\,j^+$$



We allow an independent quark mass m_f in the vertex interaction.

[PRD 45 (1992) 3740–3754]

[J. Lan et al, PLB 825 (2022) 136890]

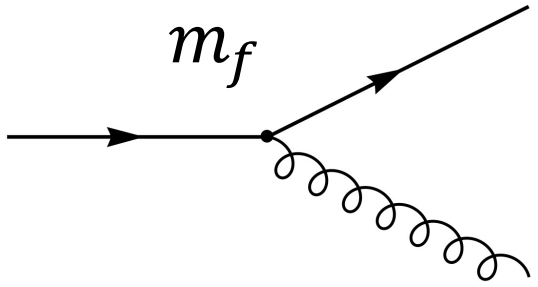
Mass splitting between $\pi - \rho$?

"…how one can obtain a massless π meson in such a picture without having at the same time a massless ρ:

…

The key observation to resolve this problem is that one needs to find a mechanism which dynamically generates a large helicity flip amplitude."

[M. Burkardt, PRD 58 (1998) 096015]

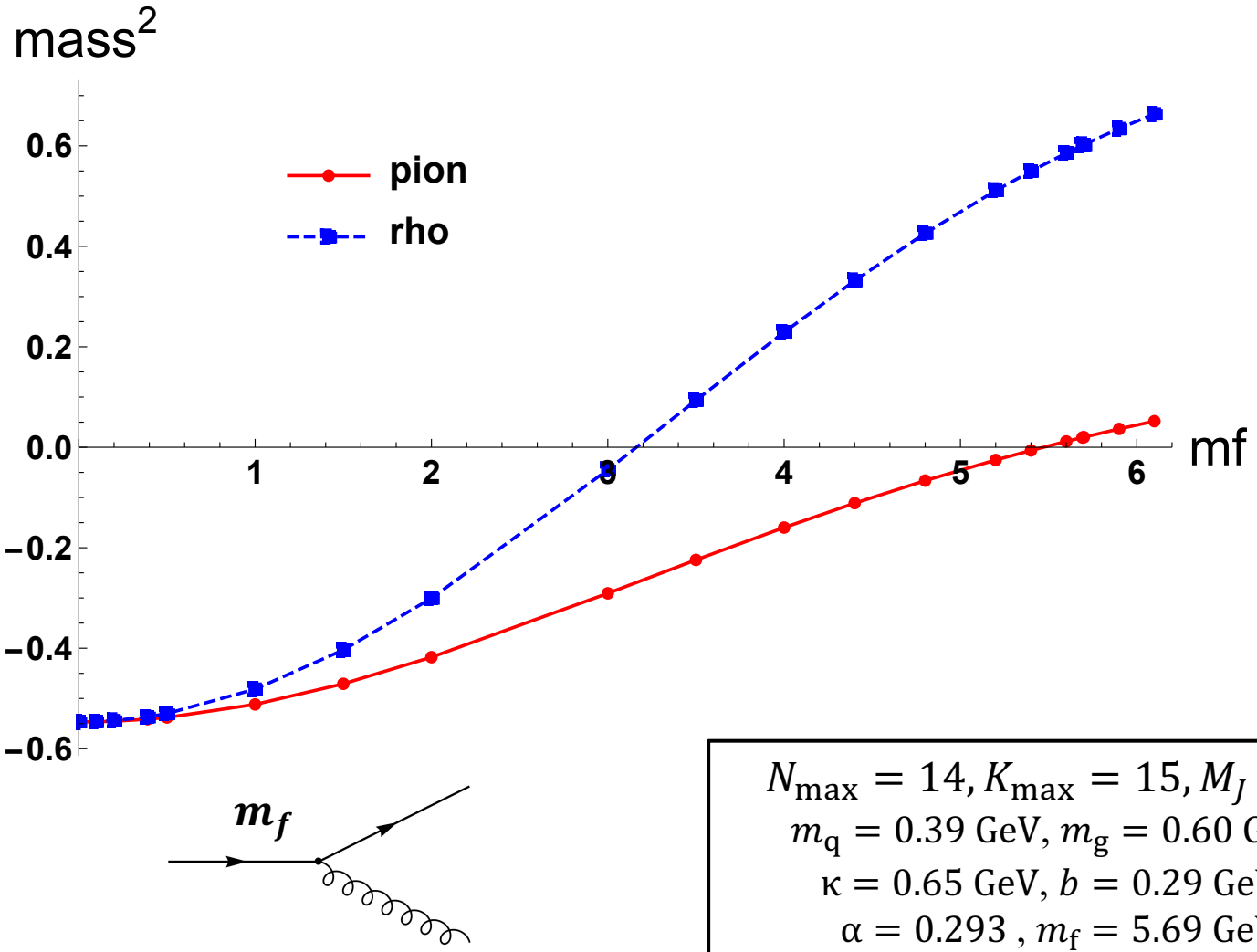


spin-flip

$$u(p,\lambda) = \begin{cases} \begin{pmatrix} 1 \\ 0 \\ \frac{im_f}{p^+} \\ \frac{(ip^1 - p^2)}{p^+} \end{pmatrix}, & \text{if } \lambda = +1/2; \\ \begin{pmatrix} 0 \\ 1 \\ \frac{(-ip^1 - p^2)}{p^+} \\ \frac{im_f}{p^+} \end{pmatrix}, & \text{if } \lambda = -1/2. \end{cases}$$

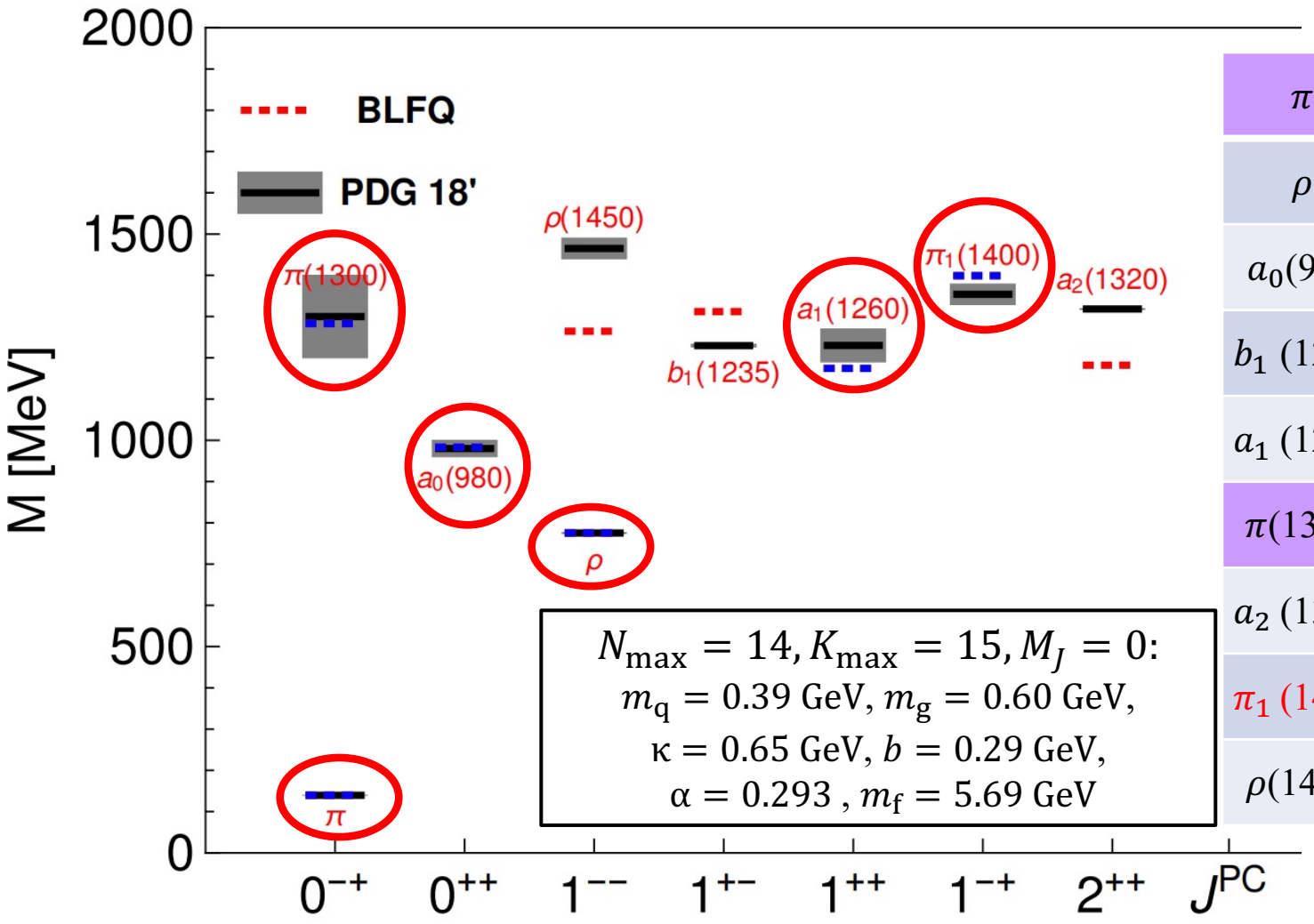
[J. Lan et al, arXiv: 2406. 18878]

$\pi - \rho$ mass splitting .VS. m_f



$N_{\max} = 14, K_{\max} = 15, M_J = 0$:
$m_{\mathrm{q}} = 0.39$ GeV, $m_{\mathrm{g}} = 0.60$ GeV,
$\kappa = 0.65$ GeV, $b = 0.29$ GeV,
$\alpha = 0.293$, $m_{\mathrm{f}} = 5.69$ GeV

Light meson mass spectrum



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$\alpha = 0.293$, $m_f = 5.69$ GeV

	Norm$q\bar{q}$	DC [MeV]
π	0.492	151
ρ	0.486	141
$a_0(980)$	0.370	0
b_1 (1235)	0.30	0
a_1 (1260)	0.324	13
$\pi(1300)$	0.284	59
a_2 (1320)	0.320	0
π_1 (1400)	0.002	0
$\rho(1450)$	0.312	50

$$|\text{meson}\rangle = a|q\bar{q}\rangle + b|q\bar{q}g\rangle + \cdots$$

[J. Lan et al, PLB 825 (2022) 136890]

Fix the parameters by fitting six blue states

- $\pi_1(1400)$: $|q\bar{q}g\rangle$ dominates
- $\pi(1300)$: the DC is smaller than the DC of pion

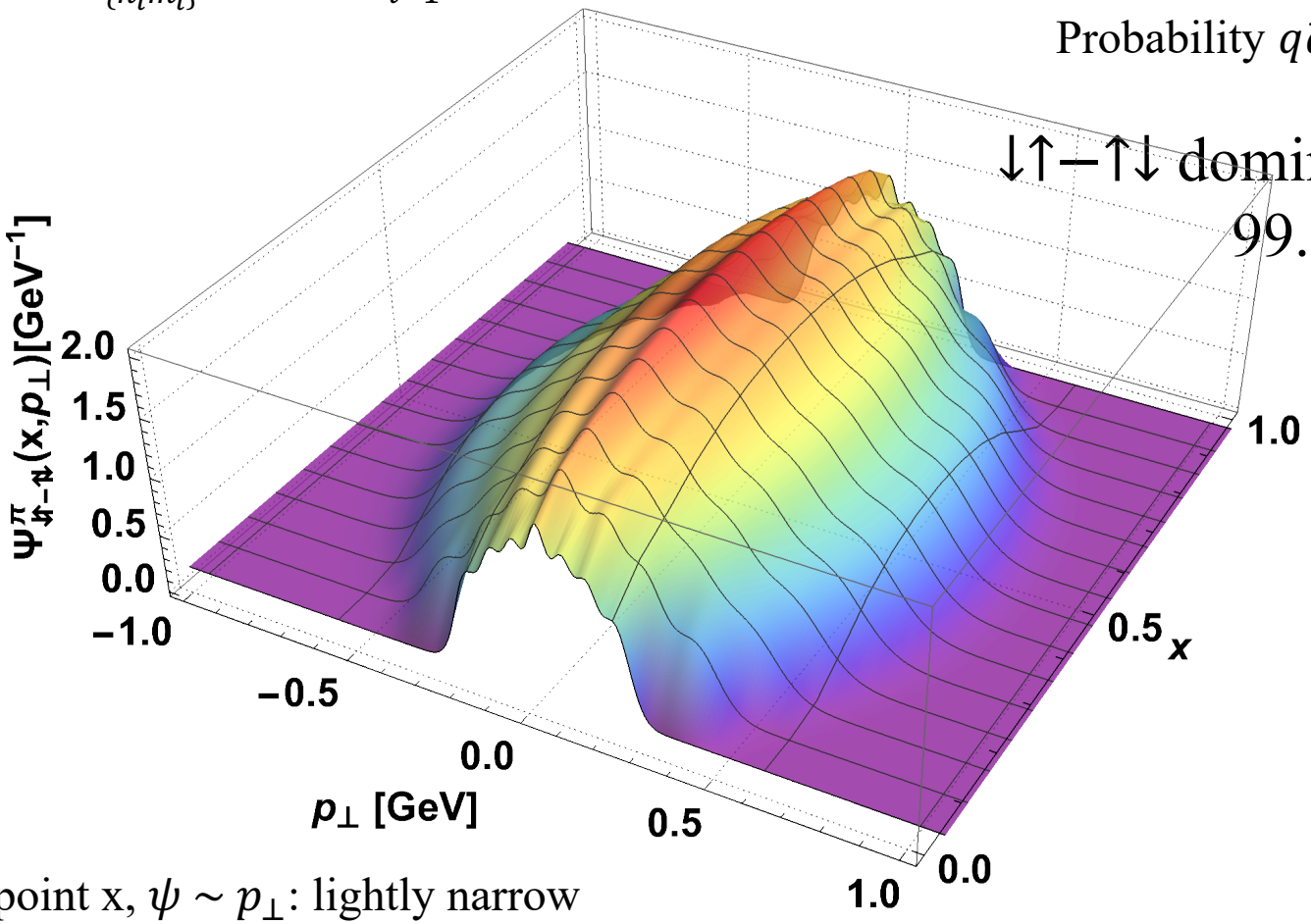
The LFWF in $q\bar{q}$ Fock sector

$$\Psi^{\mathcal{N},M_J}_{\{x_i,\vec{p}^{\,2}_{\perp i},\lambda_i\}} = \sum_{\{n_i m_i\}} \psi^{\mathcal{N}}(\{\bar{\alpha}_i\}) \prod_{i=1}^{\mathcal{N}} \phi_{n_i m_i}(\vec{p}_{\perp i}, b)$$

$$|\pi\rangle = a|q\bar{q}\rangle + b|q\bar{q}g\rangle + \cdots$$

Probability $q\bar{q}$ =0.486

$\downarrow\uparrow - \uparrow\downarrow$ dominant in $|q\bar{q}\rangle$ 99.7%



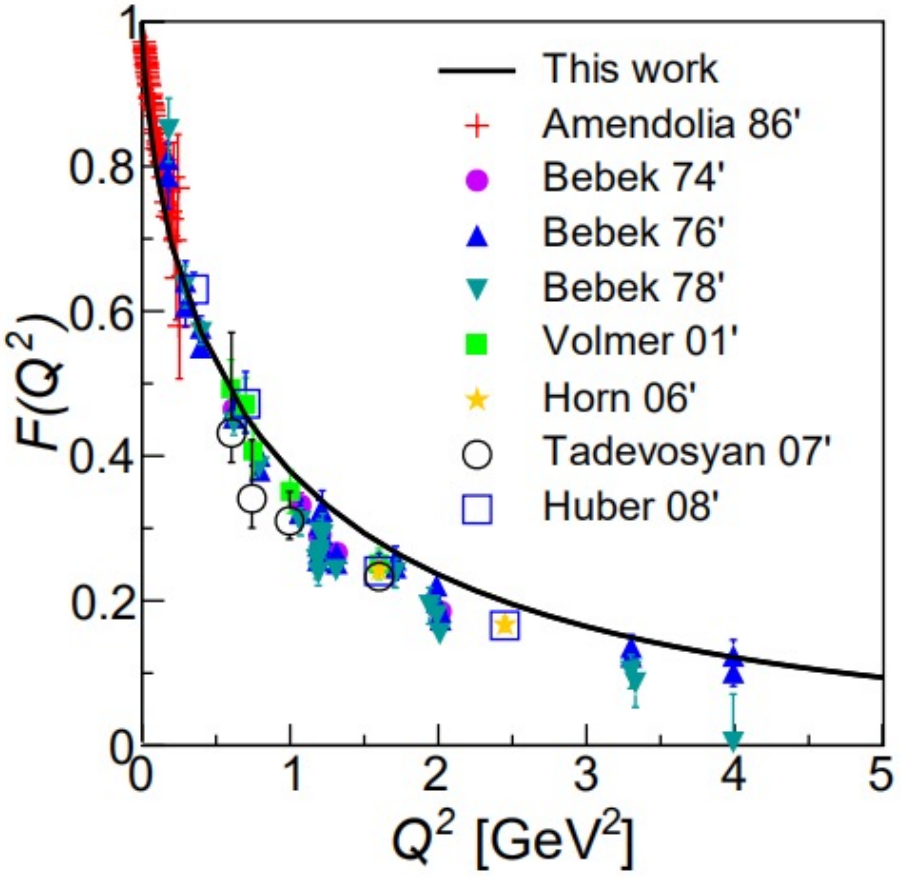
- At endpoint x, $\psi \sim p_\perp$: lightly narrow
- At middle x, $\psi \sim p_\perp$: a little bit wide

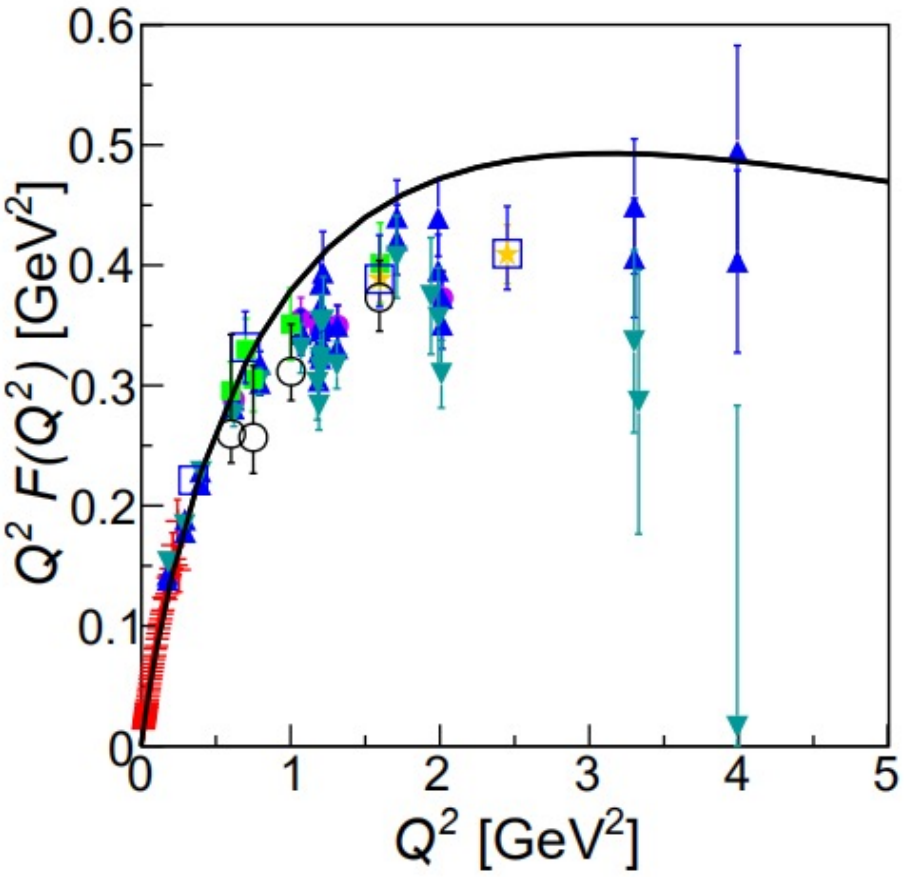
Pion form factor

[Brodsky & de Teramond, PRD 77(2008)056007]

$$|\pi\rangle = a|q\bar{q}\rangle + b|q\bar{q}g\rangle + \cdots$$

$$\langle\Psi(p')|J^{+}_{EM}(0)|\Psi(p)\rangle = (\mathrm{p}+\mathrm{p}')^{+}\,\mathrm{F}(\mathrm{Q}^2)$$





- FF is in reasonable agreement with experimental data
- $F(Q^2) \propto 1/Q^2$ for large Q^2

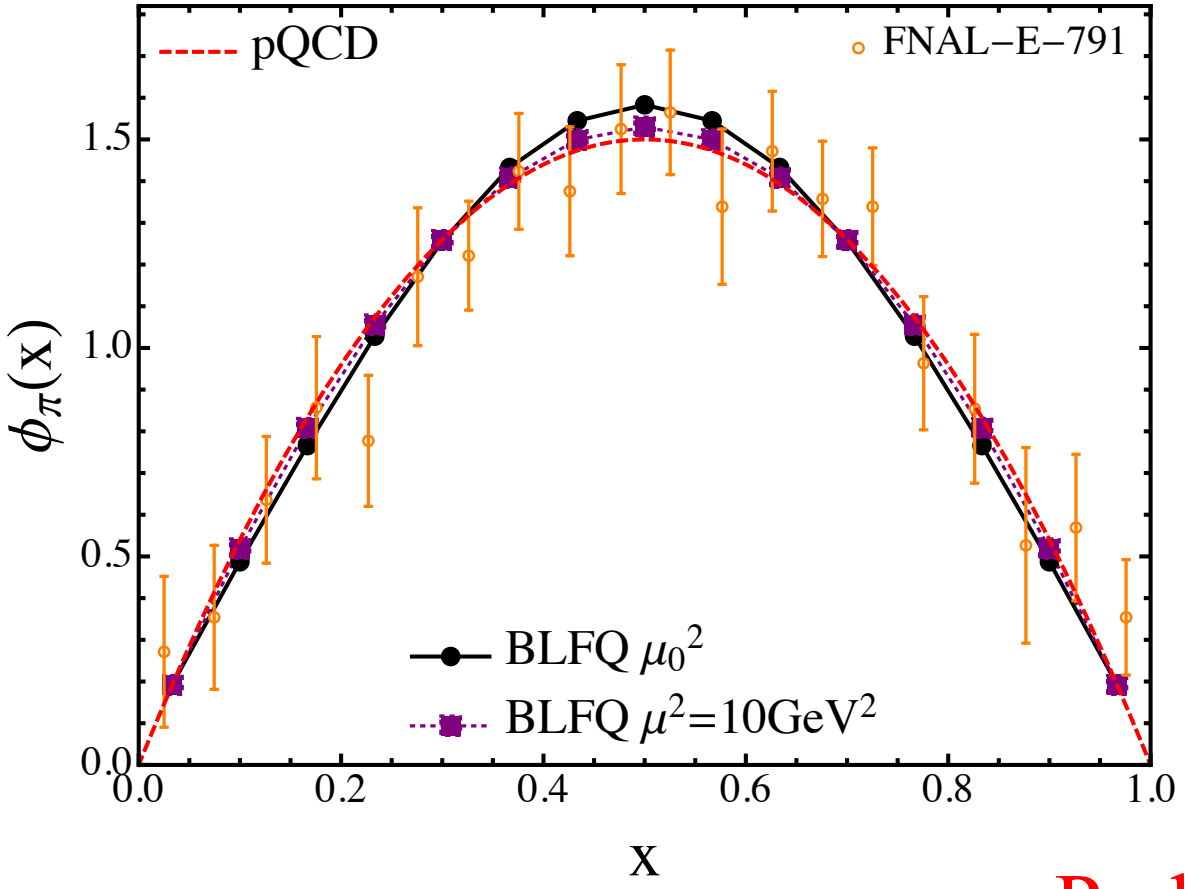
[J. Lan et al, PLB 825 (2022) 136890]

Pion PDA

$$|\pi\rangle = a|q\bar{q}\rangle + b|q\bar{q}g\rangle + \cdots$$

[Ruiz Arriola & Broniowski, PRD 66(2002)094016]

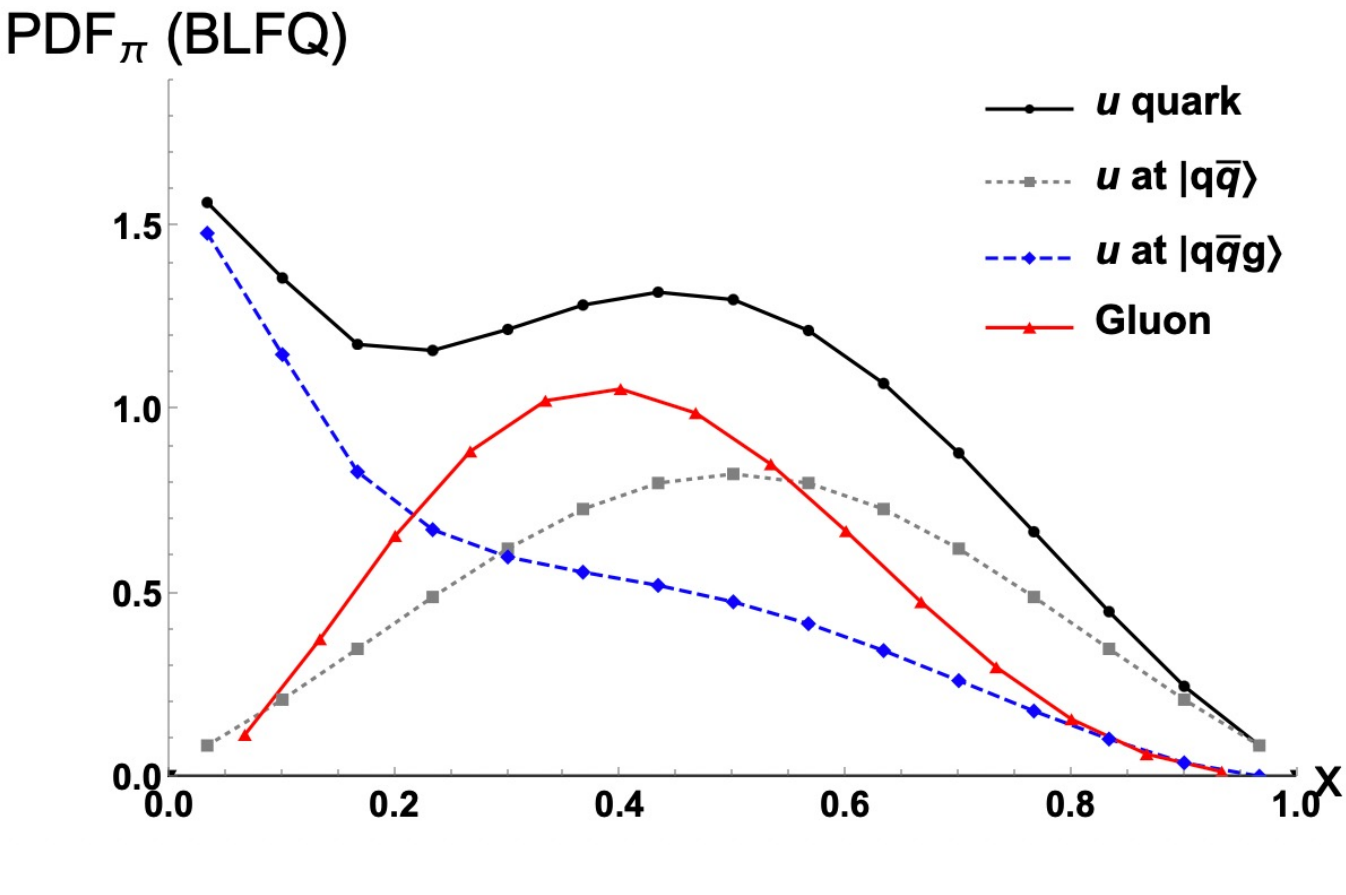
[PRL86. 4768]



Preliminary

- Endpoint behavior almost agrees with pQCD
- Consistent with FNAL-E-791 experiment on Drell-Yan (pion-platinum) process

Pion PDF at model scale

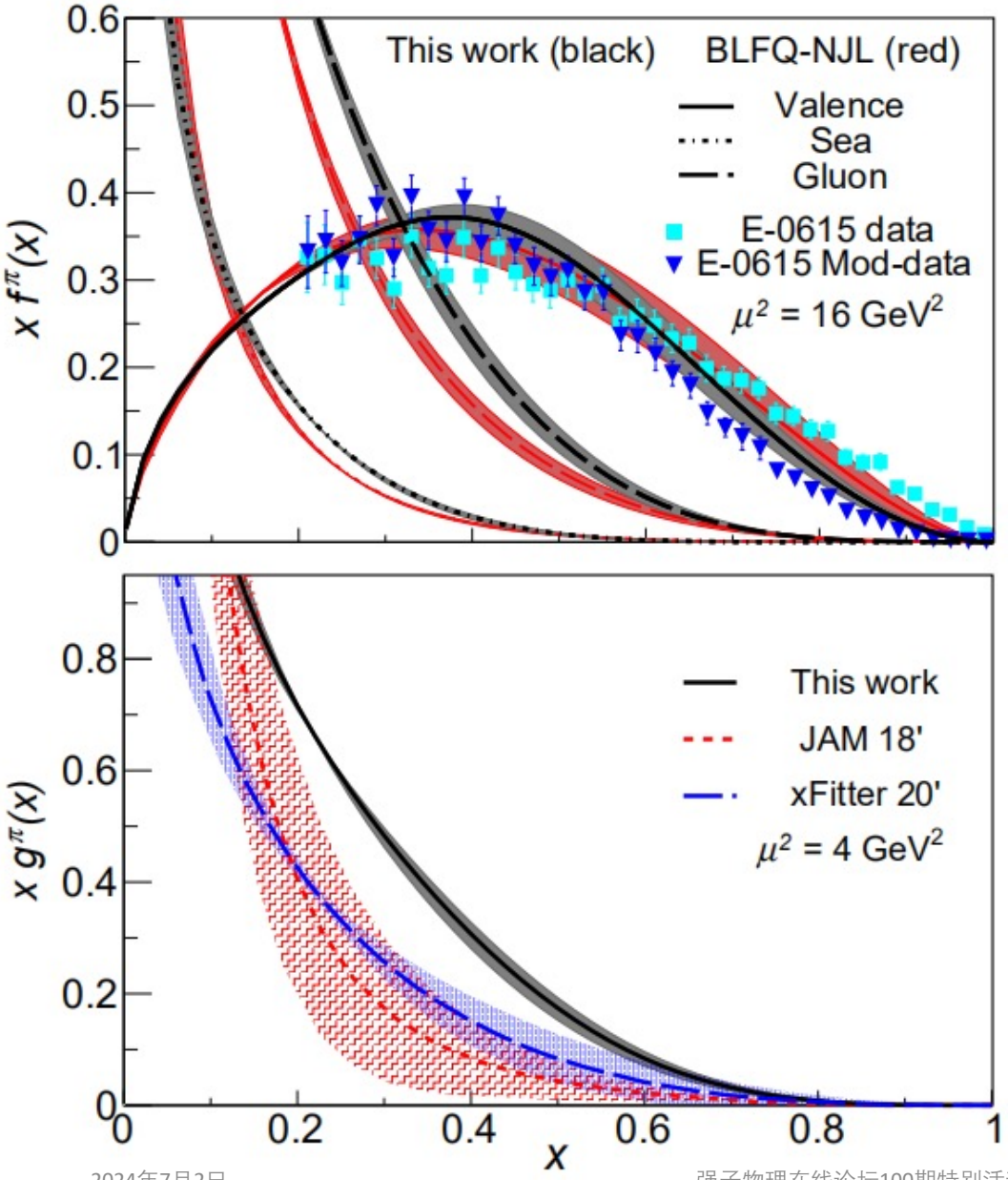


large x

$\mu^2_{0\mathrm{BLFQ}} = 0.34\ \mathrm{GeV}^2$ $\quad \langle x\rangle_{\mathbf{gluon}} = \mathbf{0.216};\ \langle x\rangle_{\mathbf{valence}\ u} = \mathbf{0.392}$ $\quad (1-x)^{1.4}$

[J. Lan et al, PLB 825 (2022) 136890]

Pion PDF with QCD evolution



$$|\pi\rangle = a|q\bar{q}\rangle + b|q\bar{q}g\rangle + \cdots$$

- Large-x behavior $(1-x)^{1.77}$ closer to pQCD
- The gluon distribution significantly increases

$\langle x \rangle$ @ 4 GeV^2	Valence	Gluon	Sea
BLFQ	**0.483**	**0.421**	**0.096**
BLFQ-NJL	0.489	0.398	0.113
[BSE 2019']	0.48(3)	0.41(2)	0.11(2)

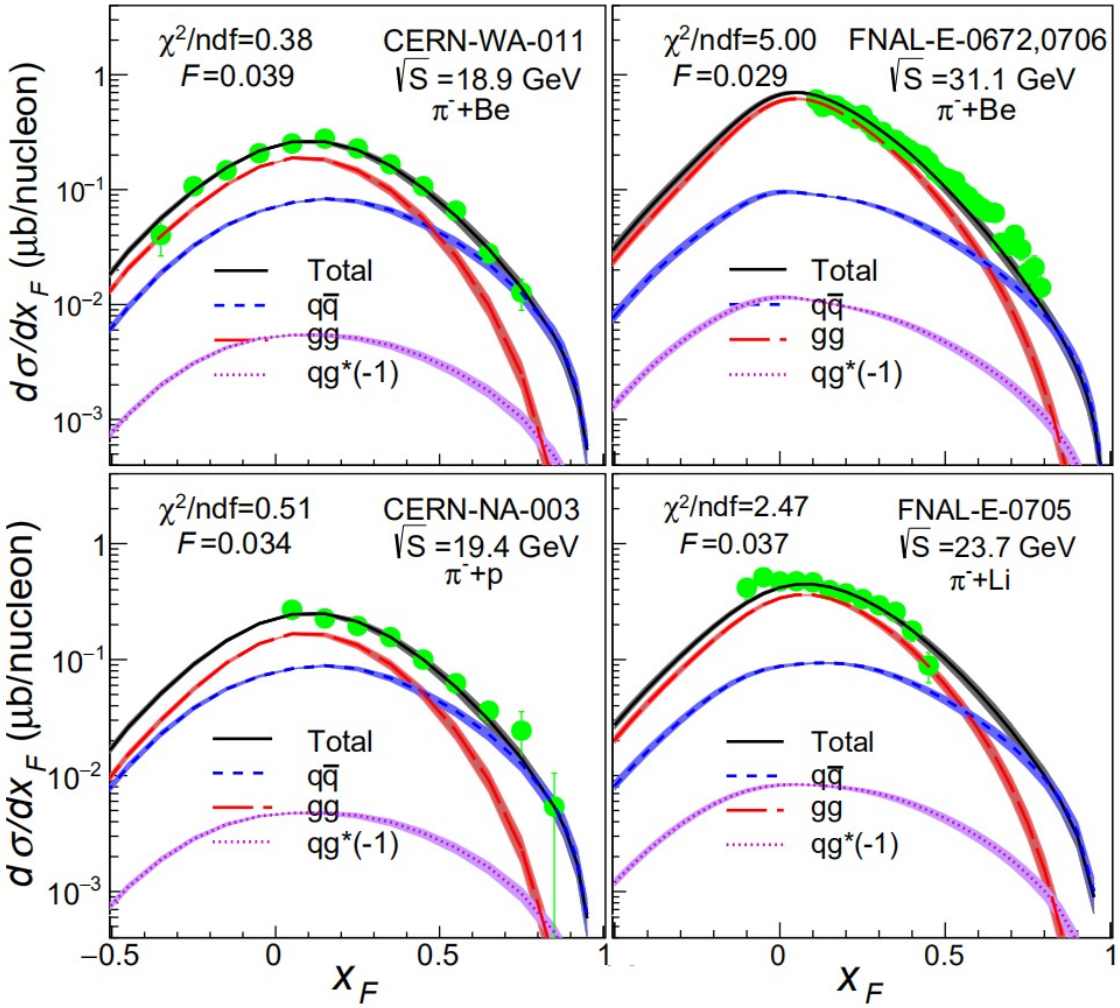
[J. Lan et al, PLB 825 (2022) 136890]

J/ψ production cross section

$\pi^{\pm} N \rightarrow J/\psi\ X$

$$\frac{d\sigma}{dx_F}|J/\psi = F \sum_{i,j=q,\bar{q},g} \int_{2m_c}^{2m_D} dM_{c\bar{c}} \frac{2M_{c\bar{c}}}{S\sqrt{x_F^2 + \frac{4M_{c\bar{c}}^2}{S}}} \hat{\sigma}_{ij}(s, m_c^2, \mu_R^2, \mu_F^2) f_i^{\pi^{\pm}}(x_1, \mu_F^2) f_j^N(x_2, \mu_F^2)$$

[nCTEQ 2015]



- Significant gg contribution
- Various energies of pions
- Various targets (Be, p, Li)

Agree with experimental data (FNAL E672, E706, E705, CERN NA3,WA11).

[J. Lan et al, PLB 825 (2022) 136890]

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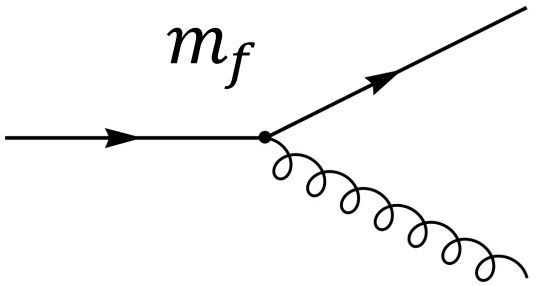
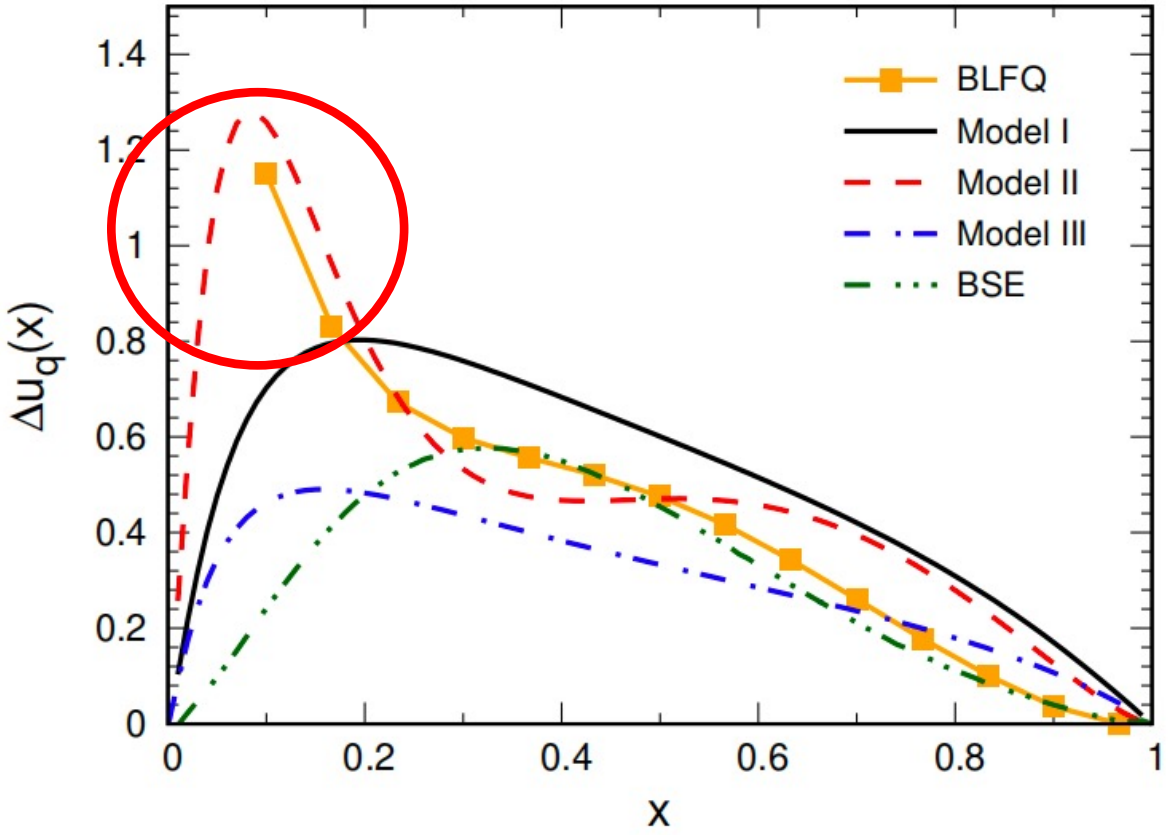


spin-flip

$$u(p,\lambda) = \begin{cases} \begin{pmatrix} 1 \\ 0 \\ \frac{im_f}{p^+} \\ \frac{(ip^1 - p^2)}{p^+} \end{pmatrix}, & \text{if } \lambda = +1/2; \\ \begin{pmatrix} 0 \\ 1 \\ \frac{(-ip^1 - p^2)}{p^+} \\ \frac{im_f}{p^+} \end{pmatrix}, & \text{if } \lambda = -1/2. \end{cases}$$

[J. Lan et al, arXiv: 2406. 18878]

Observable effect with m_f?



a low-x peak ?

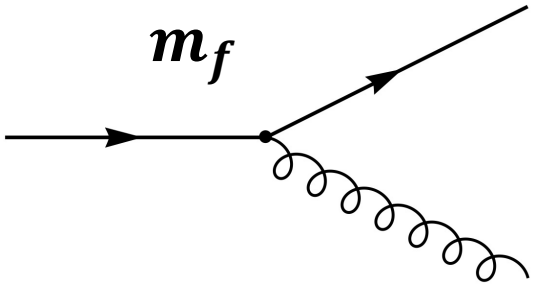
Model	m_q[GeV]	m_f[GeV]	m_g[GeV]	1-P_{val}
I	0.390	0.390	0.600	0.508
II	0.390	5.69	0.600	0.508
III	0.255	0.255	0.638	0.300

[J. Lan et al, arXiv: 2406. 18878]

Pion $q\bar{q}g$ BLFQ .vs. BSE

We introduce a LF model:

$$|\text{Meson}\rangle = |q\bar{q}\rangle + |q\bar{q}g\rangle$$



$$\psi^{(s_q,s_{\bar{q}},\lambda)}_{q\bar{q}g;(i_q,i_{\bar{q}},a)} = \frac{1}{M_\pi^2 - M^2_{0,q\bar{q}g}}\left[V\psi^{(s_q,s_{\bar{q}})}_{q\bar{q};(i_q,i_{\bar{q}})}\right],$$

V: interaction connecting $q\bar{q}$ and $q\bar{q}g$ sector

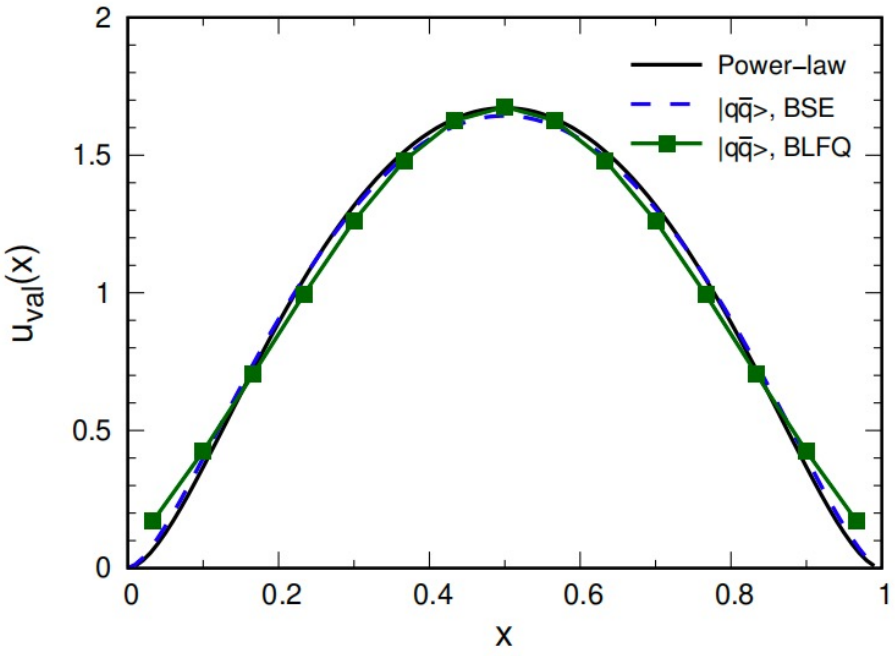
$$\left[V\psi^{(s_q,s_{\bar{q}})}_{q\bar{q};(i_q,i_{\bar{q}})}\right] = \frac{g_s\sqrt{2}}{x_q + x_g}\sum_{i_1 s_1} T^a_{i_q i_1} W^{(s_q,s_1)}_\lambda(p_q, p_g)$$
$$\times \psi^{(s_1,s_{\bar{q}})}_{q\bar{q};(i_1,i_{\bar{q}})}(x_{\bar{q}}, \vec{p}_{\bar{q}\perp}) - \frac{g_s\sqrt{2}}{x_{\bar{q}} + x_g}$$
$$\times \sum_{i_1 s_1} T^a_{i_1 i_{\bar{q}}} \bar{W}^{(s_1,s_{\bar{q}})}_\lambda(p_{\bar{q}}, p_g)\psi^{(s_q,s_1)}_{q\bar{q};(i_q,i_1)}(x_q, \vec{p}_{q\perp}).$$

- To get the LFWF for $|q\bar{q}g\rangle$ based on the LFWF for $|q\bar{q}\rangle$ with the interaction V.

[J. Lan et al, arXiv: 2406. 18878]

Pion $q\bar{q}g$ BLFQ .vs. BSE

To get LFWF for $|q\bar{q}g\rangle$



BLFQ: [PLB 825 (2022) 136890]
BSE: [PRD 103 (2021) 014002]

[Phys. Rev. D 50 (1994) 6895]

Take a power-law form for simplicity:

$$\psi_{pl}(x_q, \boldsymbol{p}_{q\perp}) = N\left[1 + \frac{A_{0,eff}(x_q, \boldsymbol{p}_{q\perp})/4 - m_q^2}{\beta^2}\right]^{-s}$$

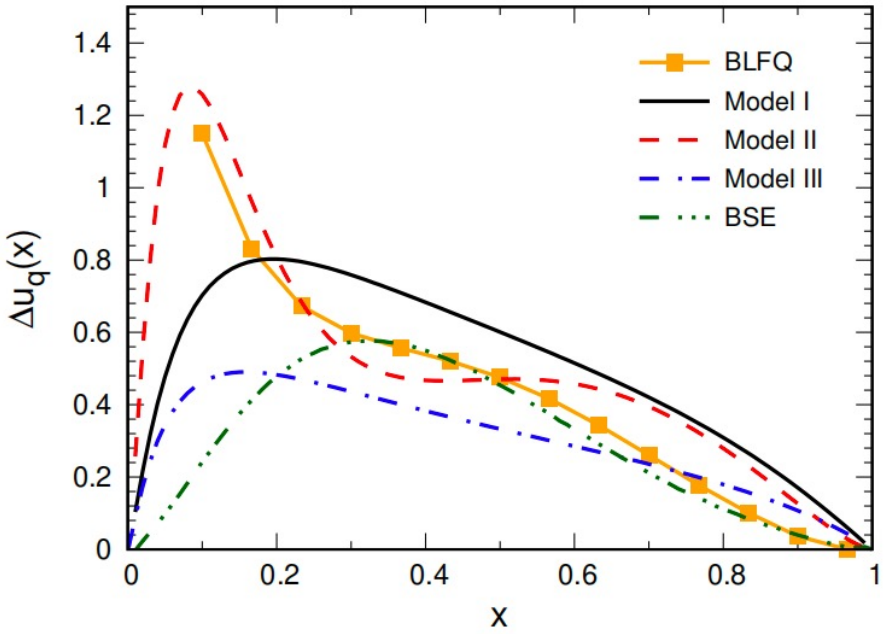
$$A_{0,eff}(x_q, \boldsymbol{p}_{q\perp}) = \frac{\boldsymbol{p}_{q\perp}^2 + m_q^2}{x_q} + \frac{\boldsymbol{p}_{\bar{q}\perp}^2 + m_{\bar{q}}^2}{x_{\bar{q}}}$$

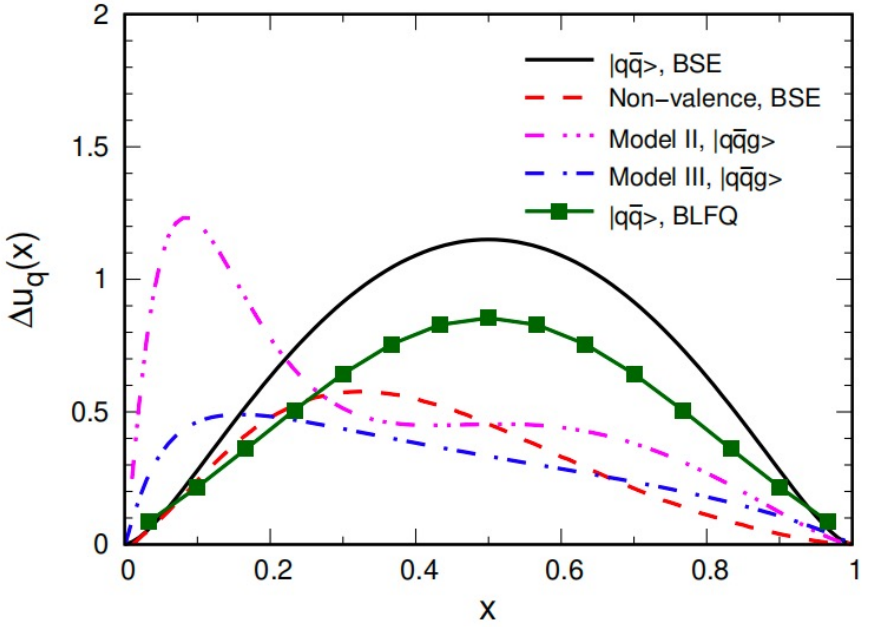
Fitting the valence PDF of both the BLFQ and the BSE:

$$s = 1.4$$
$$\beta/m_q = 1.16$$

[J. Lan et al, arXiv: 2406. 18878]

Pion $q\bar{q}g$ BLFQ .vs. BSE





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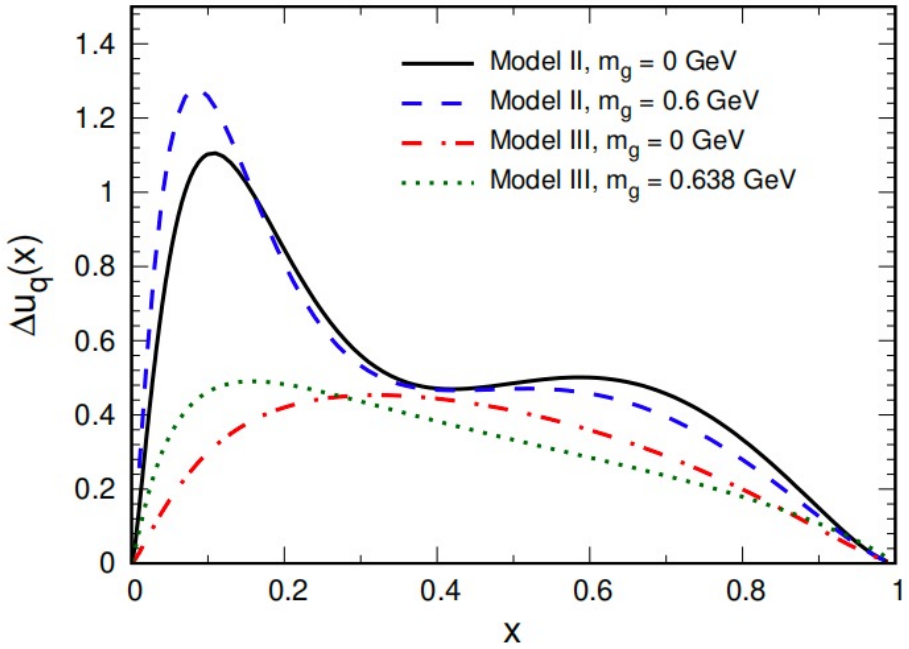
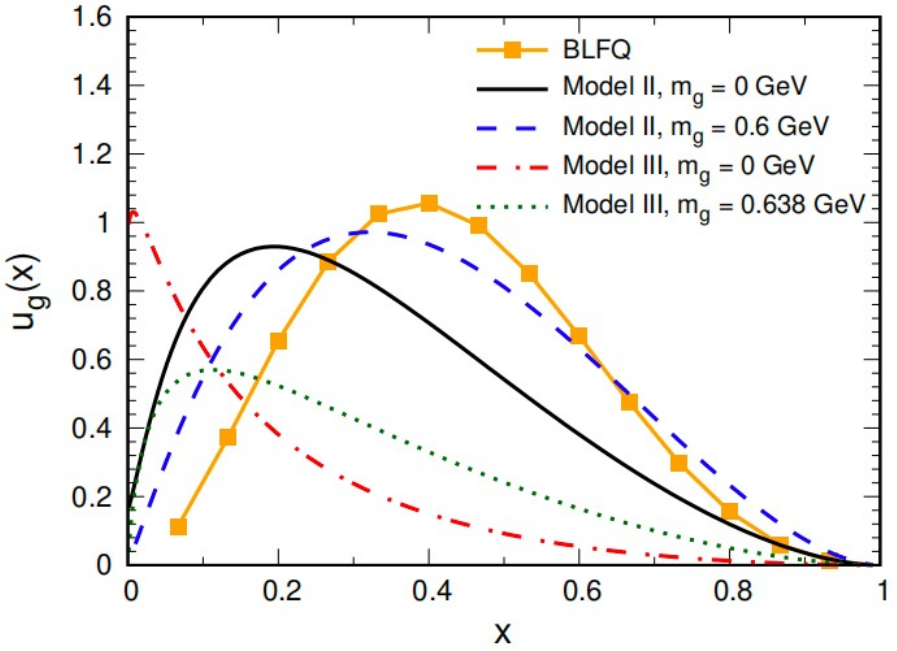
- Model II: input from BLFQ PLB 22'
- Model III: input from BSE PRD 21'
- Model I .vs. II: bump is related to large value of m_f
- Model II agrees with BLFQ: a large bump at low-x is reproduced
- BSE result differs from Model III: BSE result contains contributions from $q\bar{q}ng$, where $n = 1,2,\ldots,\infty$
- $q\bar{q}g$ Fock sector is mostly important at small- x

[J. Lan et al, arXiv: 2406. 18878]

Pion $q\bar{q}g$ BLFQ .vs. BSE





Model	m_q[GeV]	m_f[GeV]	m_g[GeV]	1-P_{val}
I	0.390	0.390	0.600	0.508
II	0.390	5.69	0.600	0.508
III	0.255	0.255	0.638	0.300

Impact of m_g on pion PDFs:

- Model II: input from BLFQ PLB 22'
- Model III: input from BSE PRD 21'
- An increase of m_g leads to a shift of quark PDF to lower values of x
- A larger m_g gives a gluon PDF shifted towards larger- x
- Perturbative results agree qualitatively with the BLFQ

[J. Lan et al, arXiv: 2406. 18878]

Pion GPD

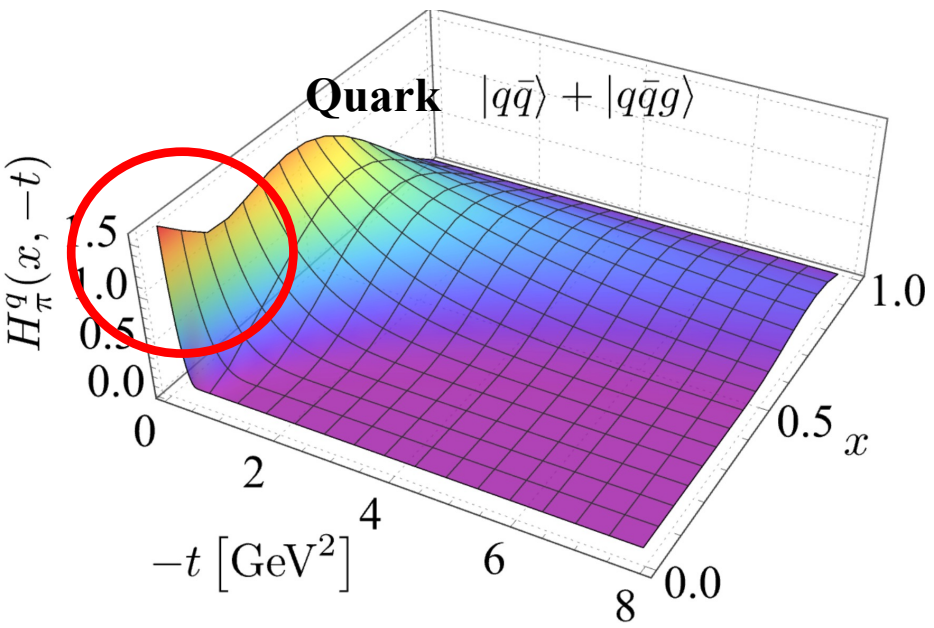
[M. Diehl, Phys. Rep. 388 (2003) 41-277]

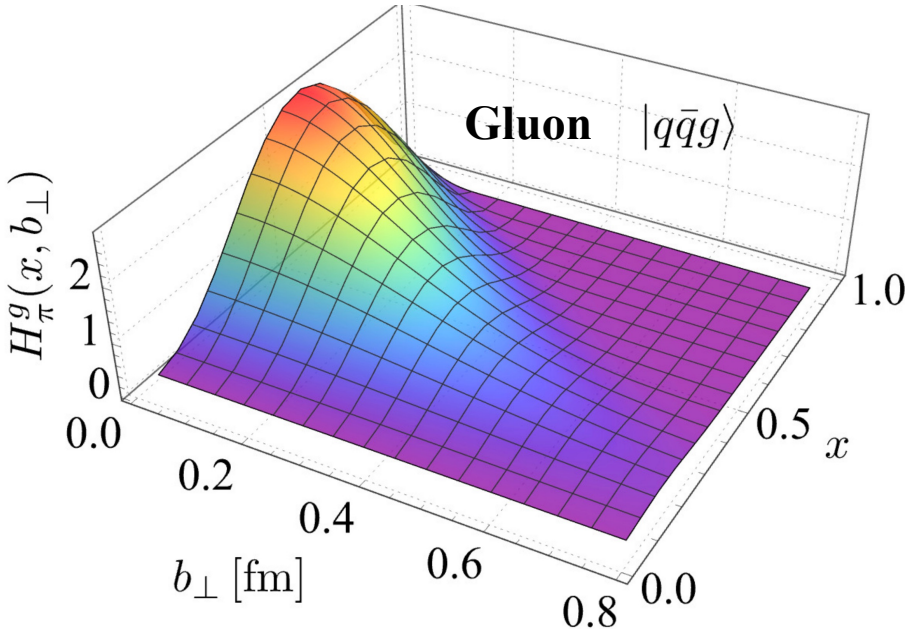
$$|\pi\rangle = a|q\bar{q}\rangle + b|q\bar{q}g\rangle + \cdots$$

$$H_\pi^q(x,\xi=0,t) = \frac{1}{2}\int \frac{dz^-}{2\pi} e^{ixP^+z^-} \left\langle \pi, P+\frac{\Delta}{2}\middle|\bar{q}\left(-\frac{z}{2}\right)\gamma^+ q\left(\frac{z}{2}\right)\middle|\pi, P-\frac{\Delta}{2}\right\rangle_{\substack{z^+=0\\ z_\perp=0}}$$

$$H_\pi^g(x,\xi=0,t) = \frac{1}{P^+}\int \frac{dz^-}{2\pi} e^{ixP^+z^-} \left\langle \pi, P+\frac{\Delta}{2}\middle|G^{+\mu}\left(-\frac{z}{2}\right)G_\mu^+\left(\frac{z}{2}\right)\middle|\pi, P-\frac{\Delta}{2}\right\rangle_{\substack{z^+=0\\ z_\perp=0}}$$

$A^+ = 0$





- Falls slowly at larger x
- Emerge at larger x range for larger $-t$
- Increase in low-x region (because of m_f)

Preliminary

[K. Fu, et al, in preparation]

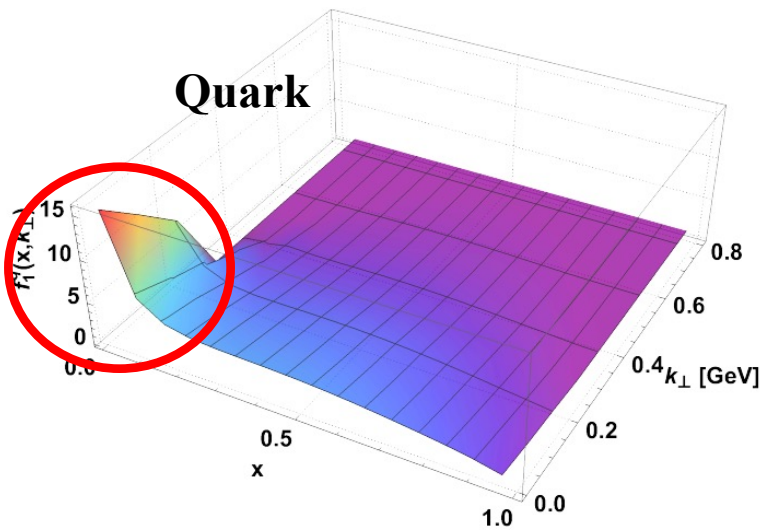
Pion TMD

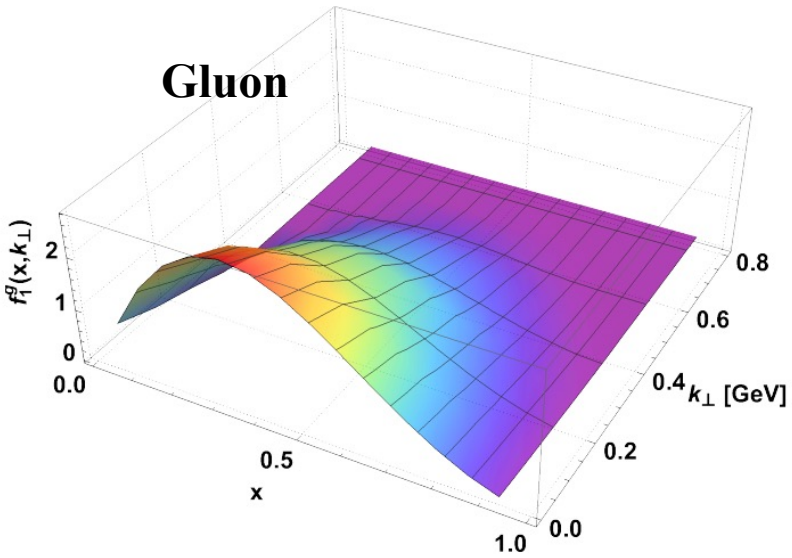
[Boer & Mulders PRD 57 (1998) 5780]
[Pasquini et al, PRD 90 (2014) 014050]

$$|\pi\rangle = a|q\bar{q}\rangle + b|q\bar{q}g\rangle + \cdots$$

$$f_1^q(x,k_\perp) = \frac{1}{2}\int \frac{dz^- d^2 z_\perp}{(2\pi)^3} e^{i(z^- k^+ - z_\perp k_\perp)} \left\langle \pi, P \middle| \bar{q}\left(-\frac{z}{2}\right)\gamma^+ q\left(\frac{z}{2}\right) \middle| \pi, P \right\rangle_{z^+=0}$$

$$f_1^g(x,k_\perp) = \frac{1}{xP^+}\int \frac{dz^- d^2 z_\perp}{(2\pi)^3} e^{i(z^- k^+ - z_\perp k_\perp)} \left\langle \pi, P \middle| G^{+\mu}\left(-\frac{z}{2}\right) G_\mu^+\left(\frac{z}{2}\right) \middle| \pi, P \right\rangle_{z^+=0}$$





- The TMD decreases with $k_\perp$
- Vanishes after $k_\perp \sim 0.6$ GeV
- Increase in low-x region (because of m_f)

Preliminary

[K. Fu, et al, in preparation]

Light mesons up to $|q\bar{q}q\bar{q}\rangle$

$$|\text{meson}\rangle = a|q\bar{q}\rangle + b|q\bar{q}g\rangle + \cdots$$

[J. Lan et al, PLB 825 (2022) 136890]
[Z. Zhu et al, PLB 839(2023) 137808]
[S. Kaur et al, PLB 851 (2024) 138563]

$$|\text{meson}\rangle = a|q\bar{q}\rangle + b|q\bar{q}g\rangle + c|q\bar{q}q\bar{q}\rangle + \cdots$$

[J. Chen et al, in preparation]

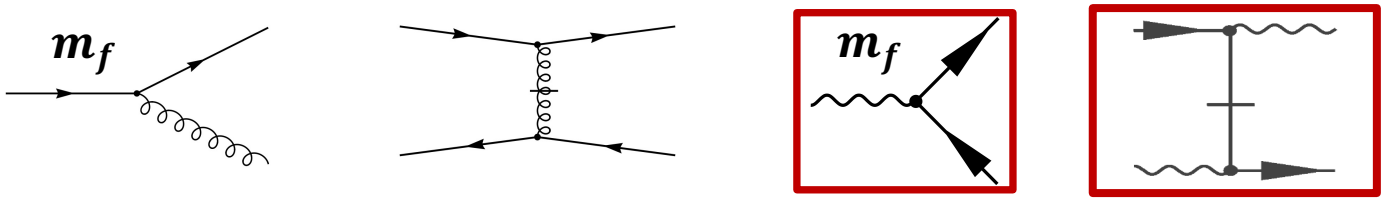
Light mesons up to $|q\bar{q}q\bar{q}\rangle$

$$|\text{meson}\rangle = a|q\bar{q}\rangle + b|q\bar{q}g\rangle + c|q\bar{q}q\bar{q}\rangle$$

$$P^- = H_{K.E.} + \cancel{H_{trans} + H_{longi}} + H_{Interact}$$

$$H_{K.E.} = \sum_i \frac{p_i^2 + m_q^2}{p_i^+}$$

$$H_{Interact} = g\bar{\psi}\,\gamma^\mu T^a\,\psi\,A_\mu^a + \frac{g^2 C_F}{2}\,j^+\frac{1}{(i\partial^+)^2}j^+ + \frac{g^2 C_F}{2}\,\bar{\psi}\gamma^\mu A_\mu \frac{\gamma^+}{i\partial^+} A_\nu \gamma^\nu \psi$$

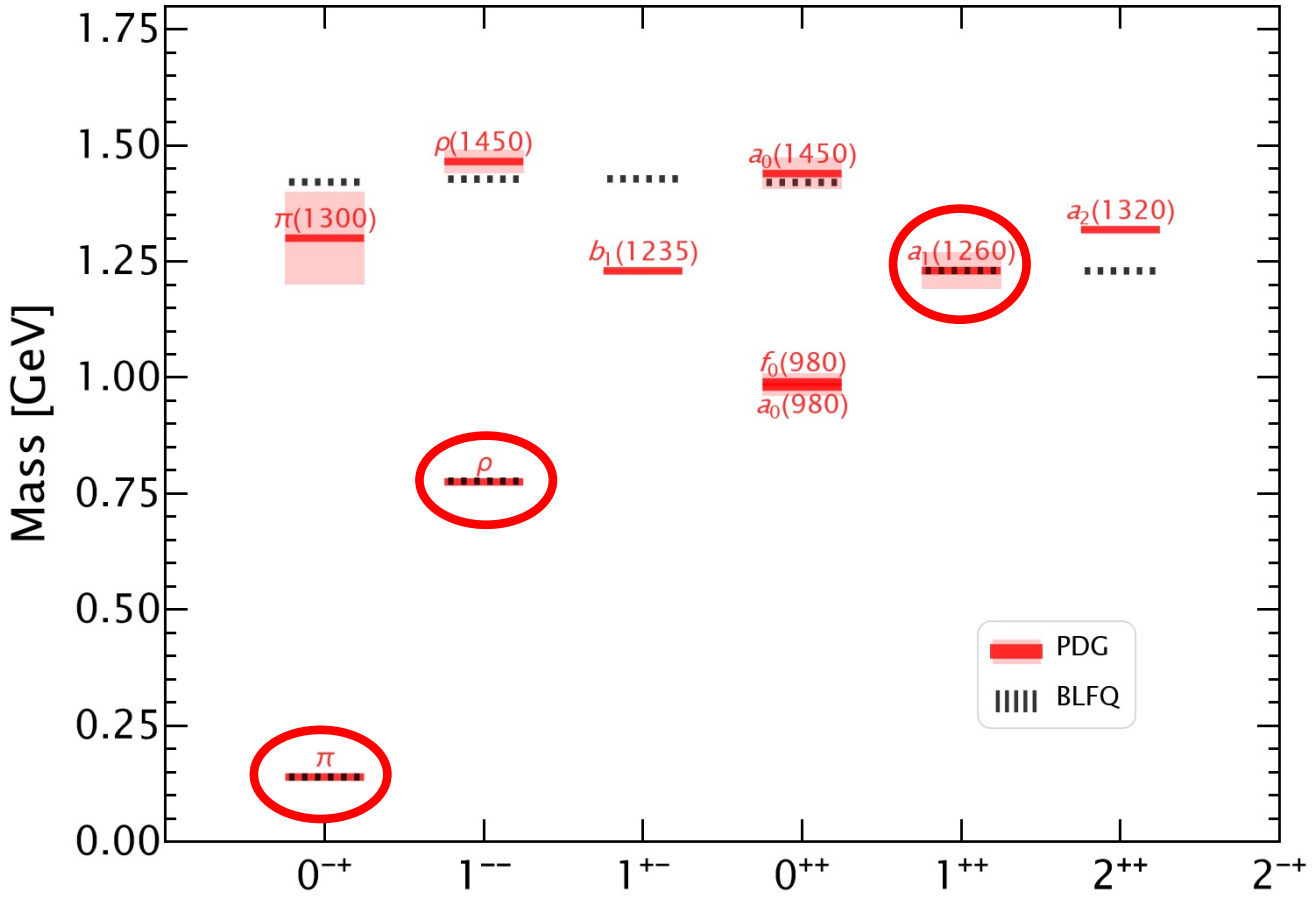


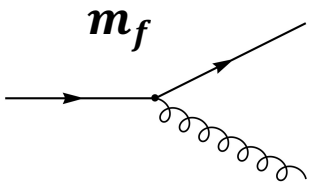
We allow an independent quark mass m_f in the vertex interaction.

[PRD 45 (1992) 3740–3754]

[J. Chen et al, in preparation]

Light meson mass spectrum





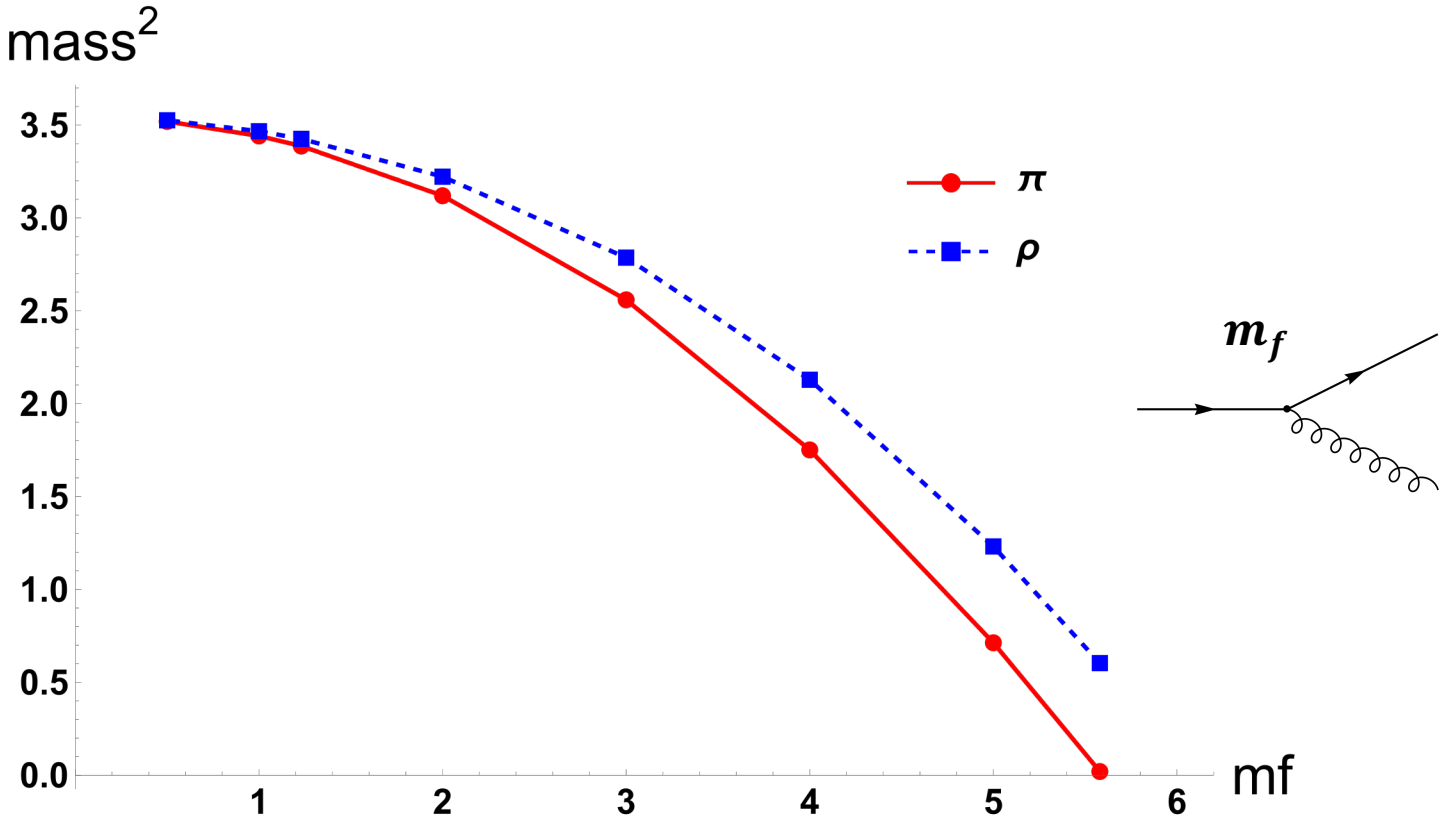
N_{max}	K	b(GeV)	m_q(GeV)	m_f(GeV)	g
8	7	0.271	1.23	5.58	5.785

$DC^{0^-+}_{BLFQ}$	$DC^{0^-+}_{EXP}$
130.25 MeV	**130.2MeV**

Fix parameters by fitting states (π, ρ, $a_1(1260)$) and DC of pion

[J. Chen et al, in preparation]

$\pi - \rho$ mass splitting .VS. m_f



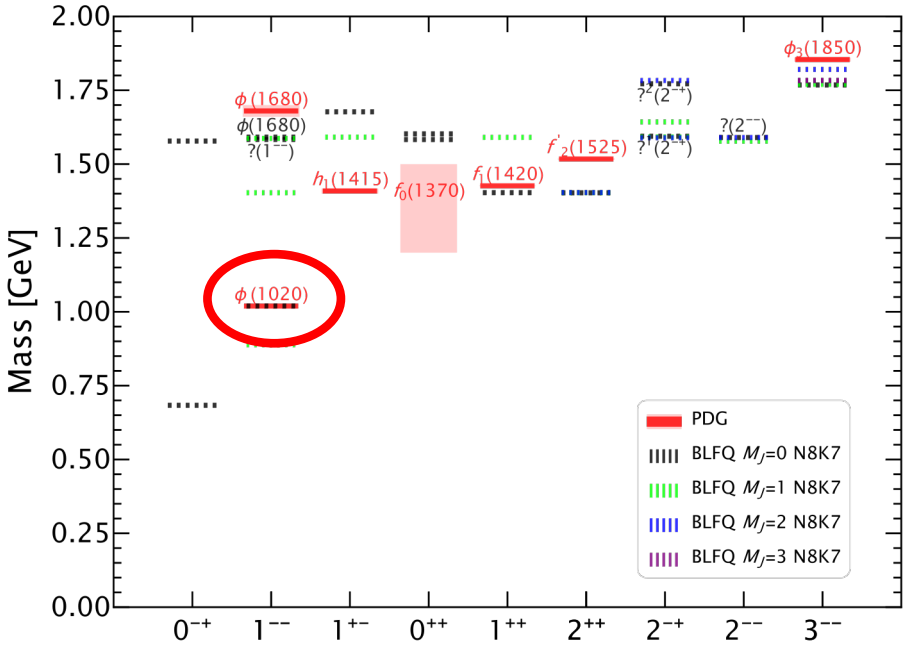
N_{max}	K	b(GeV)	m_q(GeV)	m_f(GeV)	g
8	7	0.271	1. 23	5.58	5.785

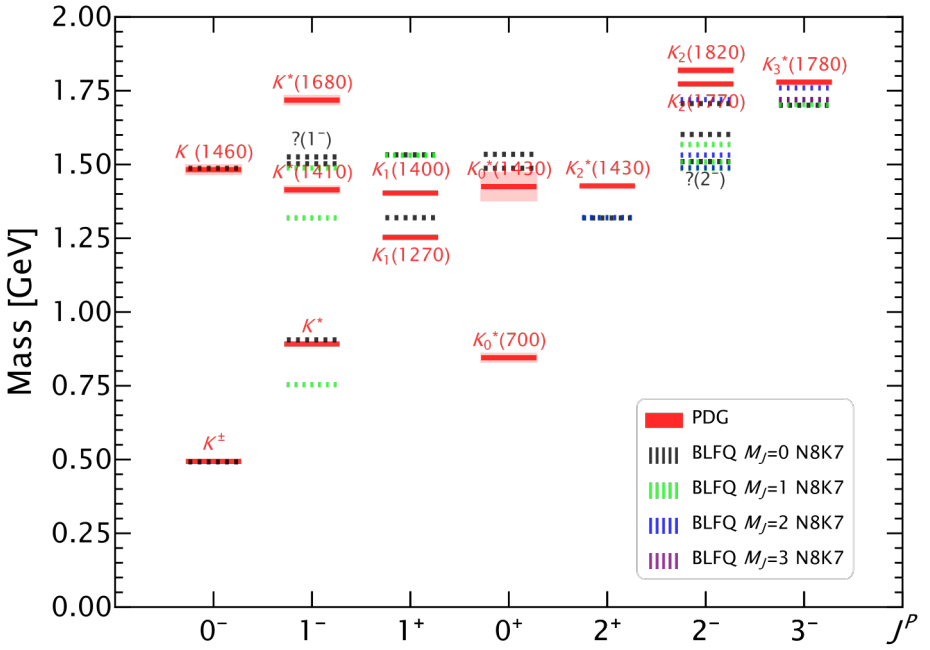
- A larger m_f provides $\pi - \rho$ mass splitting

[J. Chen et al, in preparation]

Strange meson mass spectrum

$$|\text{meson}\rangle = a|q\bar{q}\rangle + b|q\bar{q}g\rangle + c|q\bar{q}q\bar{q}\rangle$$





	N_{max}	K	b(GeV)	m_q(GeV)	m_s(GeV)	m_f(GeV)	g
$q\bar{q}$	8	7	0.271	1. 2306	-	5.58	5.785
$s\bar{s}$	8	7	0.271	-	1.2659	5.58	5.785
$q\bar{s}$	8	7	0.271	1.2306	1.2659	5.58	5.785

- Agree with experimental data: K, $K^*(892)$, $K(1460)$

[J. Chen et al, in preparation]

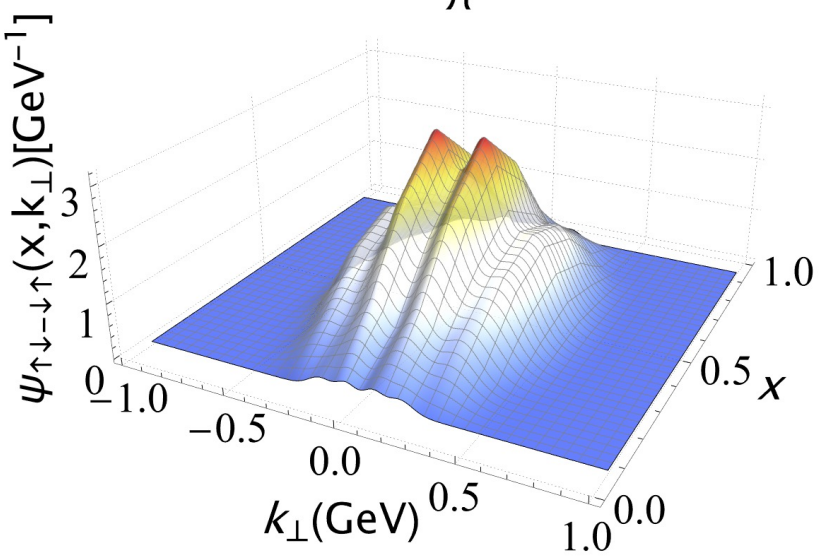
LFWF in $q\bar{q}$ Fock sector

Probability $q\bar{q}$ =0.786

$\downarrow\uparrow - \uparrow\downarrow$ dominant in $|q\bar{q}\rangle$

99.89%

π

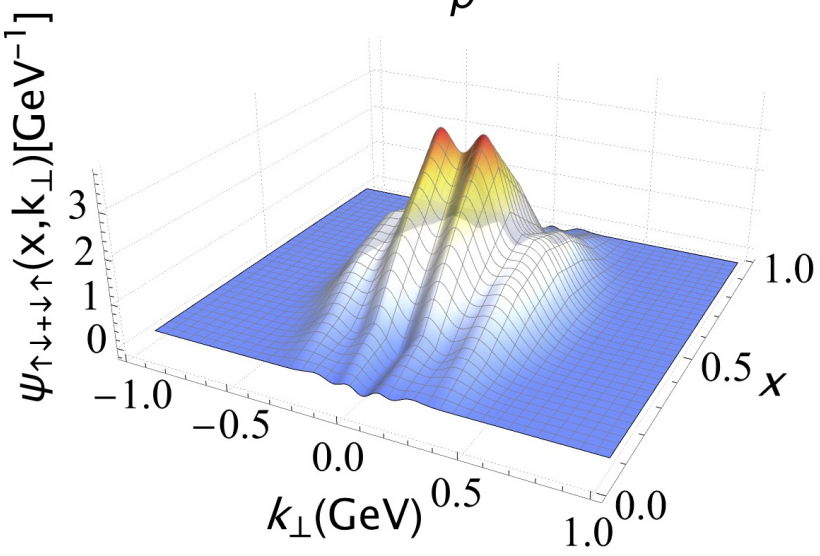


Probability $q\bar{q}$ =0.813

$\downarrow\uparrow + \uparrow\downarrow$ dominant in $|q\bar{q}\rangle$

99.98%

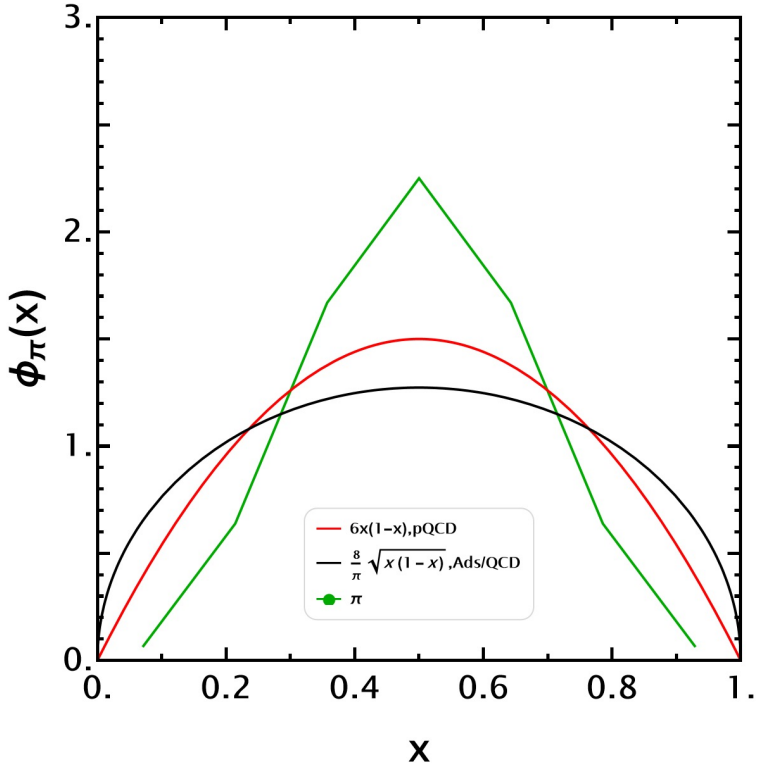
ρ

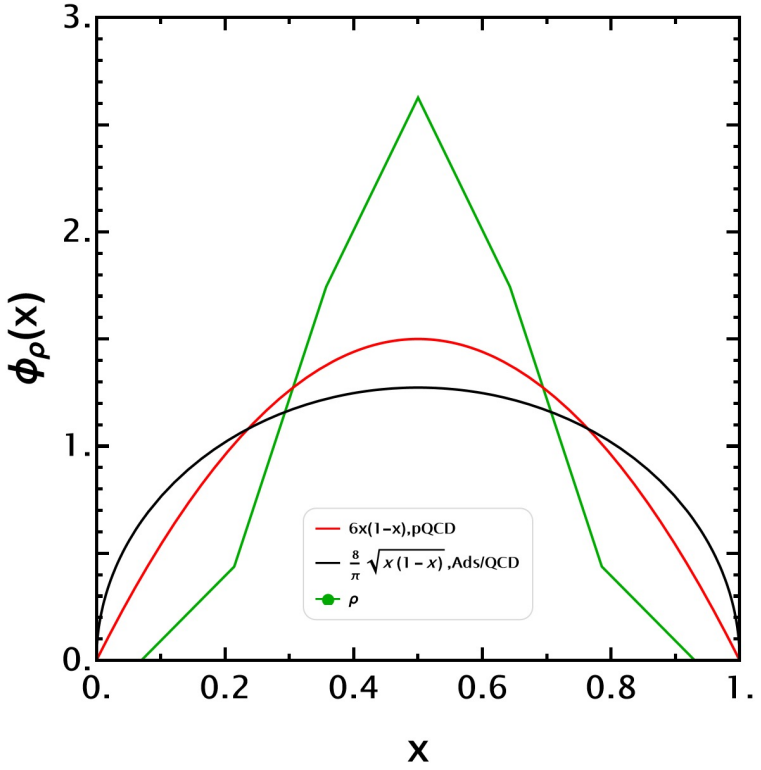


- At endpoint x, $\psi \sim p_\perp$: lightly narrow
- At middle x, $\psi \sim p_\perp$: a little bit wide
- Oscillations: HO basis artifact in transverse direction

[J. Chen et al, in preparation]

Pion and rho PDAs



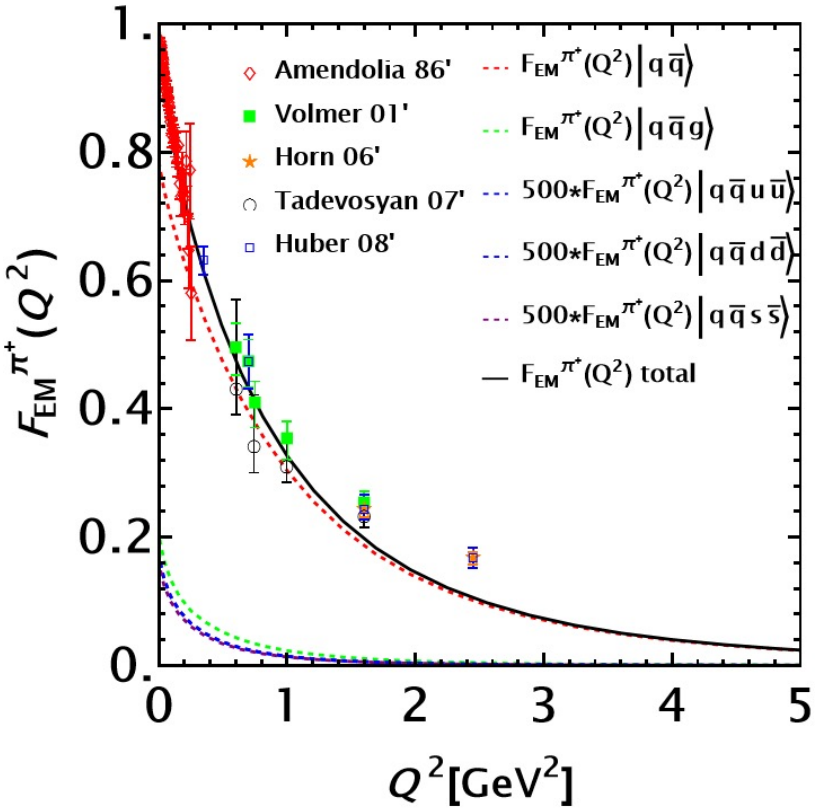


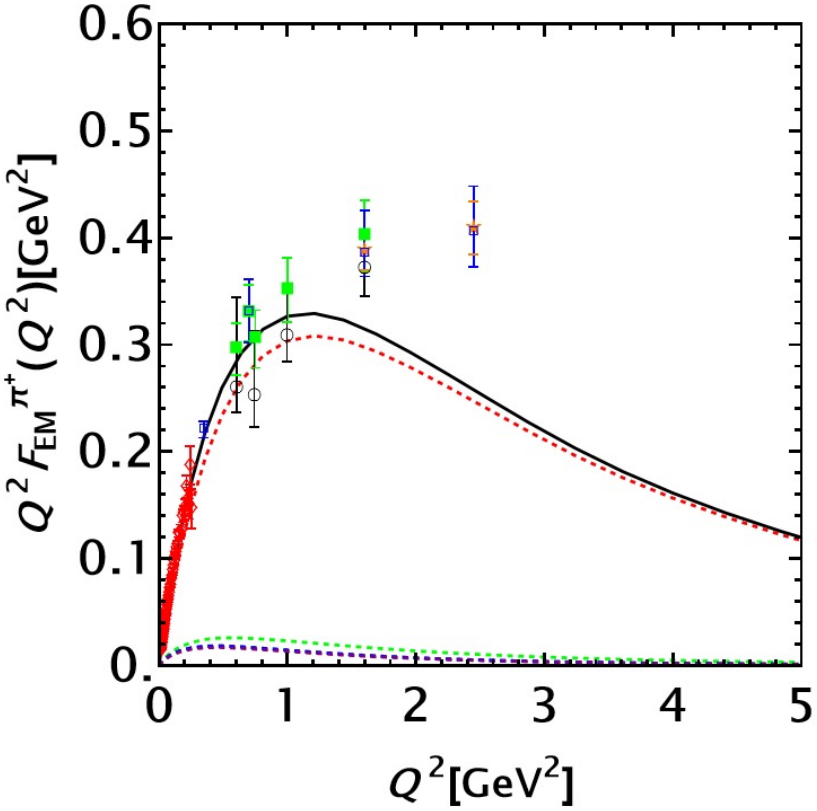
- Narrower compare to pQCD

[J. Chen et al, in preparation]

Pion form factor

$\langle \Psi(p')|J^{+}_{EM}(0)|\Psi(p)\rangle = (\mathrm{p}+\mathrm{p}')^{+}\,\mathrm{F}(\mathrm{Q}^2)$



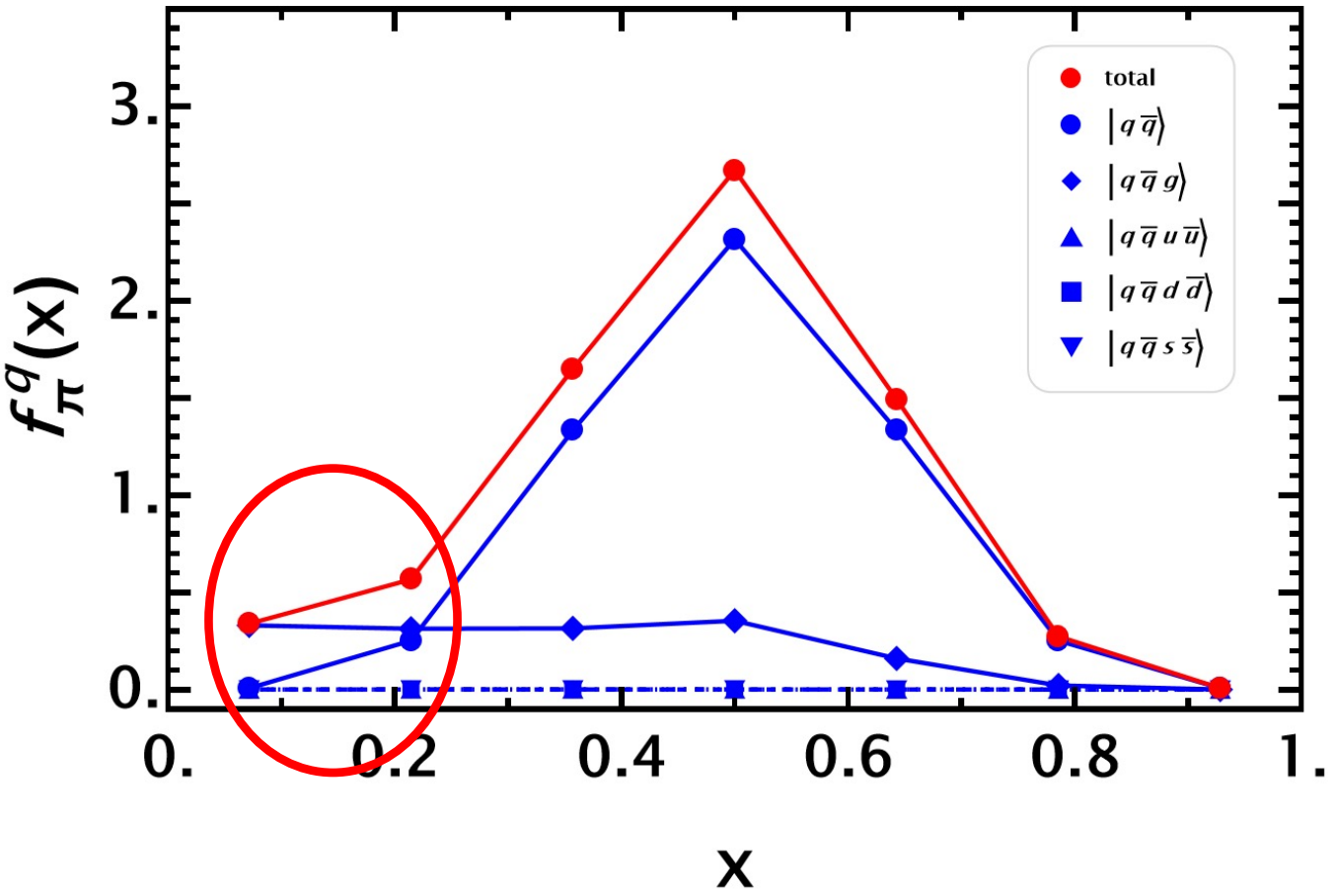


$\sqrt{\langle r^2 \rangle} = 0.973$ fm

- FF is in good agreement with experimental data at lower Q^2

[J. Chen et al, in preparation]

Pion PDFs



- a low-x bump (because of m_f)
- Larhe-x behavior $(1-x)^{3.3}$ closer to pQCD

[J. Chen et al, in preparation]

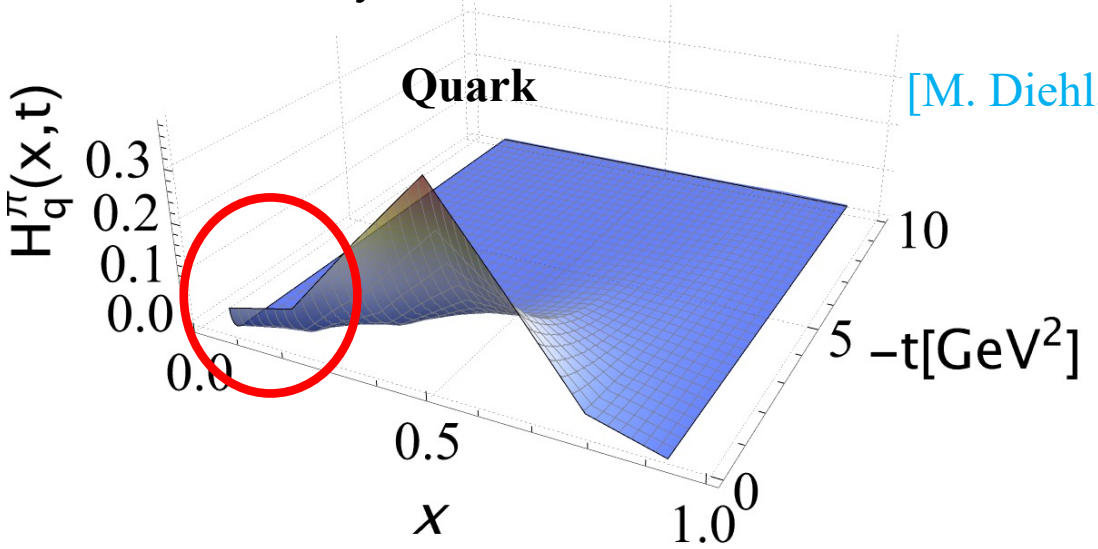
Pion GPD

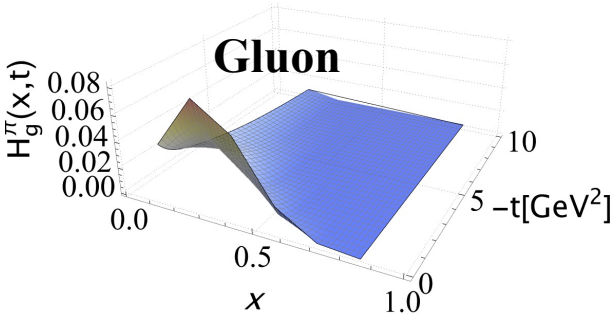
$$H_\pi^q(x,\xi=0,t)=\frac{1}{2}\int\frac{dz^-}{2\pi}e^{ixP^+z^-}\left\langle\pi,P+\frac{\Delta}{2}\left|\bar{q}\left(-\frac{z}{2}\right)\gamma^+q\left(\frac{z}{2}\right)\right|\pi,P-\frac{\Delta}{2}\right\rangle_{\substack{z^+=0\\ z_\perp=0}}$$

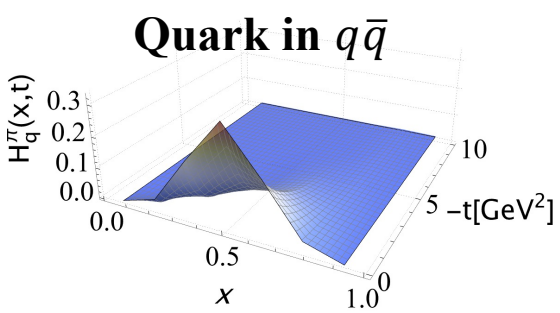
$$H_\pi^g(x,\xi=0,t)=\frac{1}{P^+}\int\frac{dz^-}{2\pi}e^{ixP^+z^-}\left\langle\pi,P+\frac{\Delta}{2}\left|G^{+\mu}\left(-\frac{z}{2}\right)G_\mu^+\left(\frac{z}{2}\right)\right|\pi,P-\frac{\Delta}{2}\right\rangle_{\substack{z^+=0\\ z_\perp=0}}$$

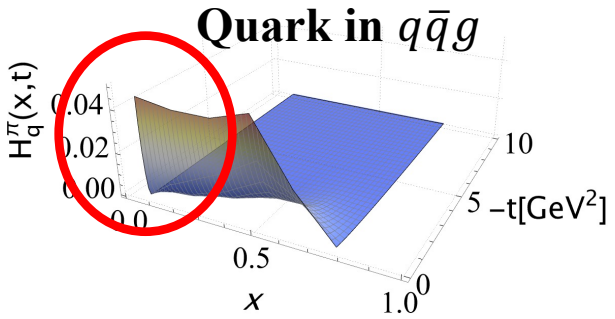
$A^+=0$

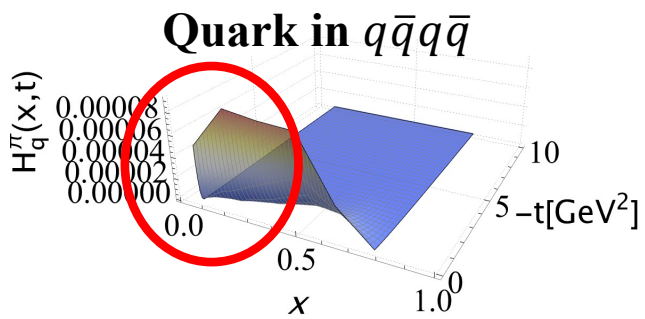
[M. Diehl, Phys. Rep. 388 (2003) 41-277]











[J. Chen et al, in preparation]

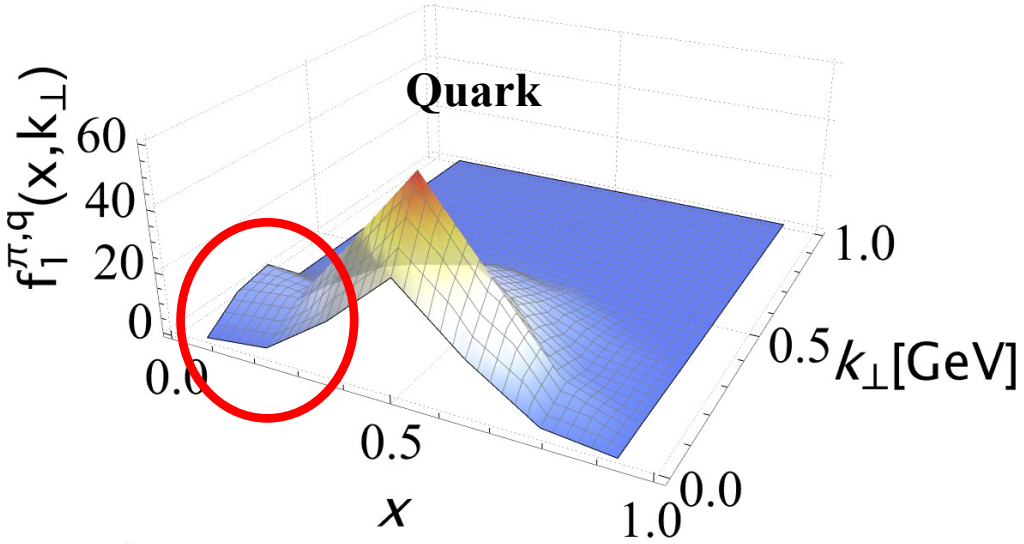
- Increase in low-x region (because of m_f)

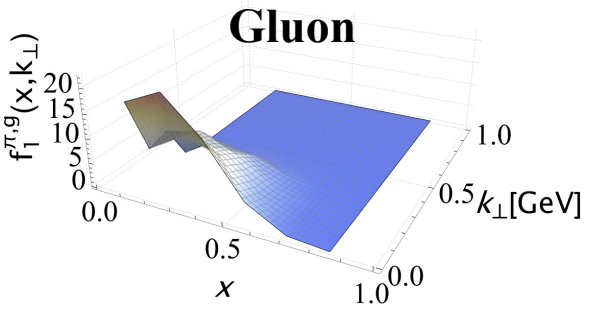
Pion TMD

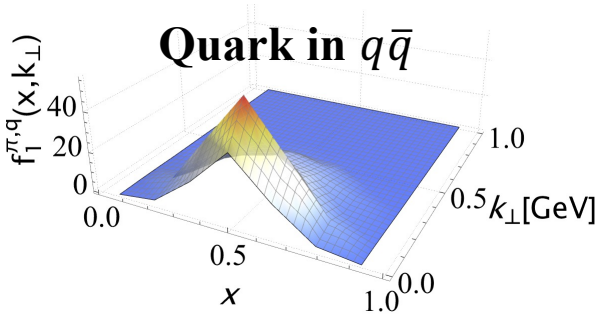
$$f_1^q(x,k_\perp) = \frac{1}{2}\int \frac{dz^- d^2 z_\perp}{(2\pi)^3} e^{i(z^- k^+ - z_\perp k_\perp)} \left\langle \pi, P \left| \bar{q}\left(-\frac{z}{2}\right)\gamma^+ q\left(\frac{z}{2}\right)\right| \pi, P \right\rangle_{z^+=0}$$

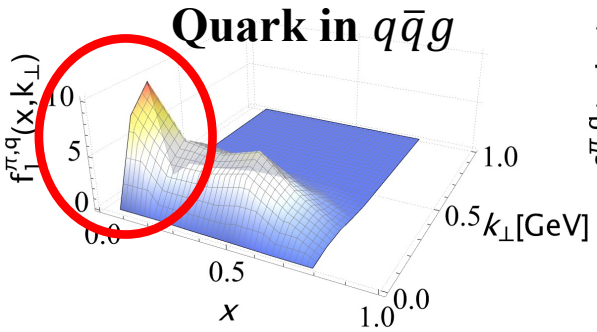
$$f_1^g(x,k_\perp) = \frac{1}{xP^+}\int \frac{dz^- d^2 z_\perp}{(2\pi)^3} e^{i(z^- k^+ - z_\perp k_\perp)} \left\langle \pi, P \left| G^{+\mu}\left(-\frac{z}{2}\right) G_\mu^+\left(\frac{z}{2}\right)\right| \pi, P \right\rangle_{z^+=0}$$

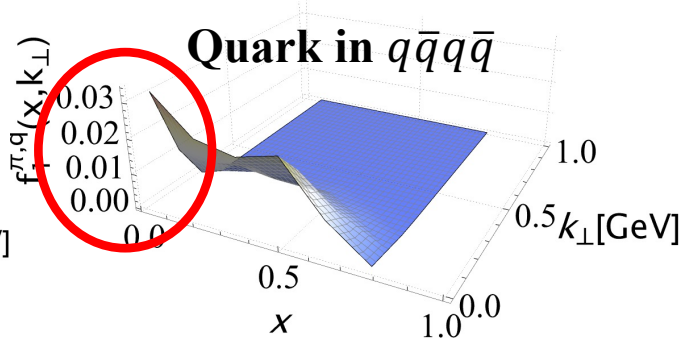
[Boer & Mulders PRD 57 (1998) 5780]
[Pasquini et al, PRD 90 (2014) 014050]









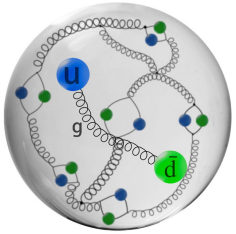


[J. Chen et al, in preparation]

- Increase in low-x region (because of m_f)

Conclusion & Outlook

- BLFQ : A non-perturbative approach based on light-front QCD Hamiltonian
- LF QCD Hamiltonian ⇒ Wave functions ⇒ Observables
- Solved for light mesons structure based on $q\bar{q} + q\bar{q}\mathrm{g} + q\bar{q}q\bar{q}$ Fock components
- An independent quark mass in vertex interaction (m_f) provide a large $\pi-\rho$ mass splitting
- A larger m_f reflects a bump at low-x quark PDF and gluon PDF shifted towards larger-x
- BLFQ results qualitatively agree with BSE results



$$|\mathrm{Meson}\rangle = |q\bar{q}\rangle + |q\bar{q}\ g\rangle + |q\bar{q}\ q\bar{q}\rangle + |q\bar{q}\ gg\rangle + |q\bar{q}\ q\bar{q}\ g\rangle + |q\bar{q}\ ggg\rangle + |gg\rangle + \cdots$$

LIGHT CONE 2024

Hadron Physics in the EIC era

The Institute of Modern Physics,
Chinese Academy of Sciences,
Huizhou Campus, China.

November 25-29, 2024

Thank you !

Physics Topics and Tools

- Physics of EIC and EicC
- Hadron spectroscopy and reactions
- Hadron/nuclear structure
- Spin physics
- Relativistic many-body physics
- QCD phase structure
- Light-front field theory
- AdS/CFT and holography
- Nonperturbative QFT methods
- Effective field theories
- Lattice field theories
- Quantum computing
- Present and future facilities

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Abstract submission deadline : 31st August, 2024
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