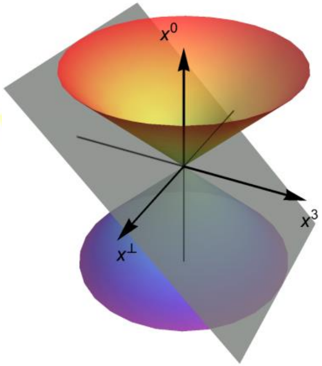
Perceiving the Emergence
of Hadron Mass through
AMBER@CERN

10 – 13 May 2022
CERN, Geneve - Switzerland

GPDs and TMDs of Light Mesons from a Basis Light-front Approach

Xingbo Zhao*

With: Jiangshan Lan*, Chandan Mondal* and James P. Vary†



*Institute of Modern Physics, CAS, Lanzhou, China
† Iowa State University, Ames, US

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Outline

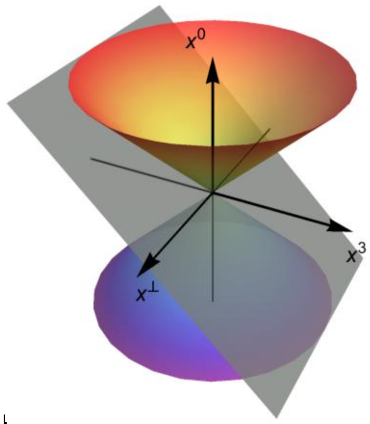
- Basis Light-front Quantization approach
- Application to light mesons
  - A review of BLFQ-NJL
  - **Light mesons with one dynamical gluon**
- Application to strangeonia and strange mesons
- Conclusion & outlook

Basis Light-front Quantization

- Nonperturbative eigenvalue problem [Vary et al, 2008]

$$P^{-}|\beta\rangle = P_{\beta}^{-}|\beta\rangle$$

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

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

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

N_{max}, K are basis truncation parameters.

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

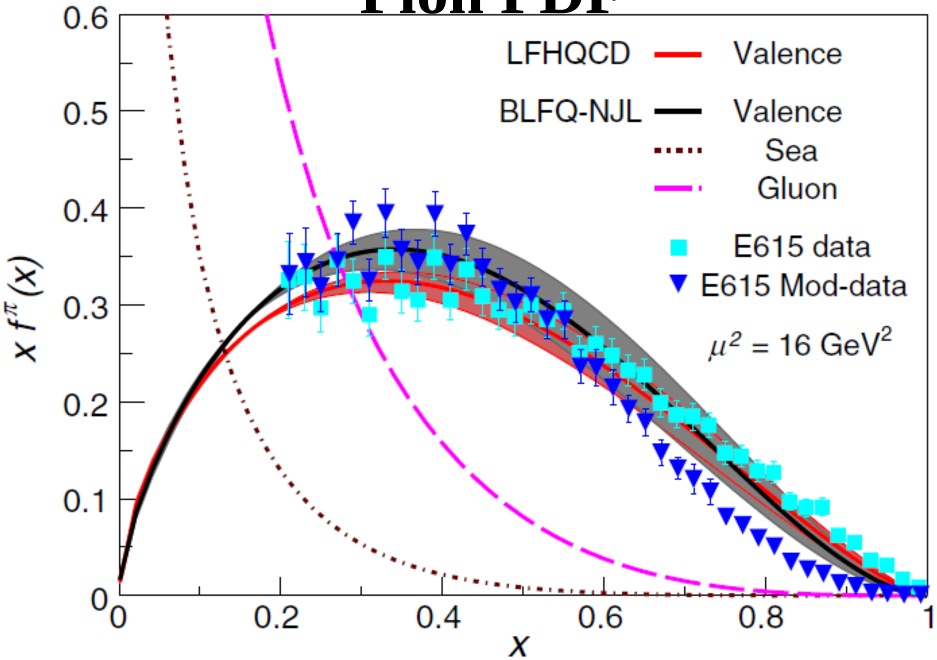
Light Meson Structure from NJL Interaction

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

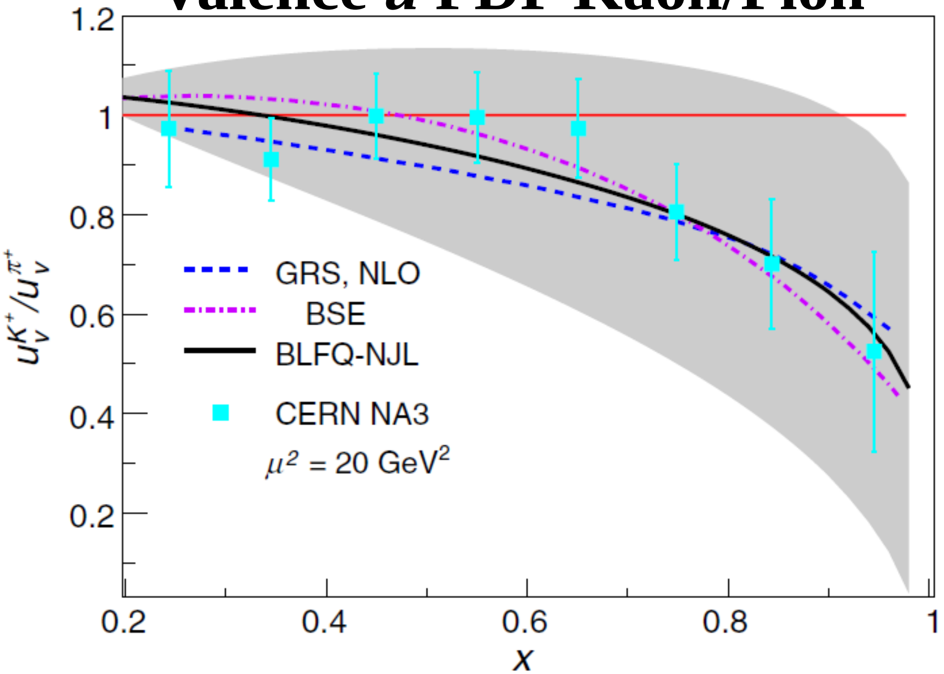
$$|\text{meson}\rangle = |q\bar{q}\rangle + \cdots$$

Diagonalize H_{eff} → LF wave function → PDF@initial scale → Scale evolution

Pion PDF



Valence *u* PDF Kaon/Pion



[Lan, Mondal, Jia, Zhao, Vary, PRL122, 172001(2019)]

Agree with experimental results

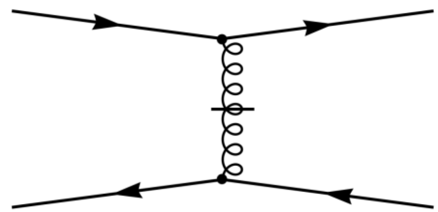
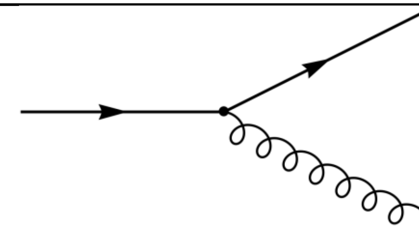
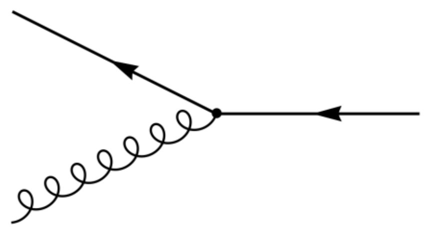
Dynamical Gluon in Light Mesons

[Lan, et al, PRL 19']

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

[Lan, Fu, Mondal, Zhao, Vary, Phys. Lett. B 825 (2022) 136890]

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

$\boldsymbol{H}_{\textbf{int}}$	$\lvert q\bar{q}\rangle$	$\lvert q\bar{q}g\rangle$
$\langle q\bar{q}\rvert$		
$\langle q\bar{q}g\rvert$		0

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

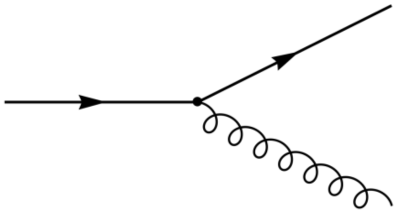
$$P^- = \frac{\vec{k}_\perp^2 + m_q^2}{x} + \frac{\vec{k}_\perp^2 + m_{\bar{q}}^2}{1-x} + \kappa^4 x(1-x)\vec{r}_\perp^2 - \frac{\kappa^4}{(m_q + m_{\bar{q}})^2}\partial_x(x(1-x)\partial_x) + \boldsymbol{H}_{\textbf{int}}$$

Light-front QCD Hamiltonian

[Brodsky et al, 1998]

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

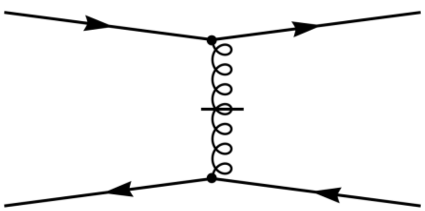
$$+g\int d^3x\, \bar{\psi}\gamma_\mu A^\mu\,\psi$$



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

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

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

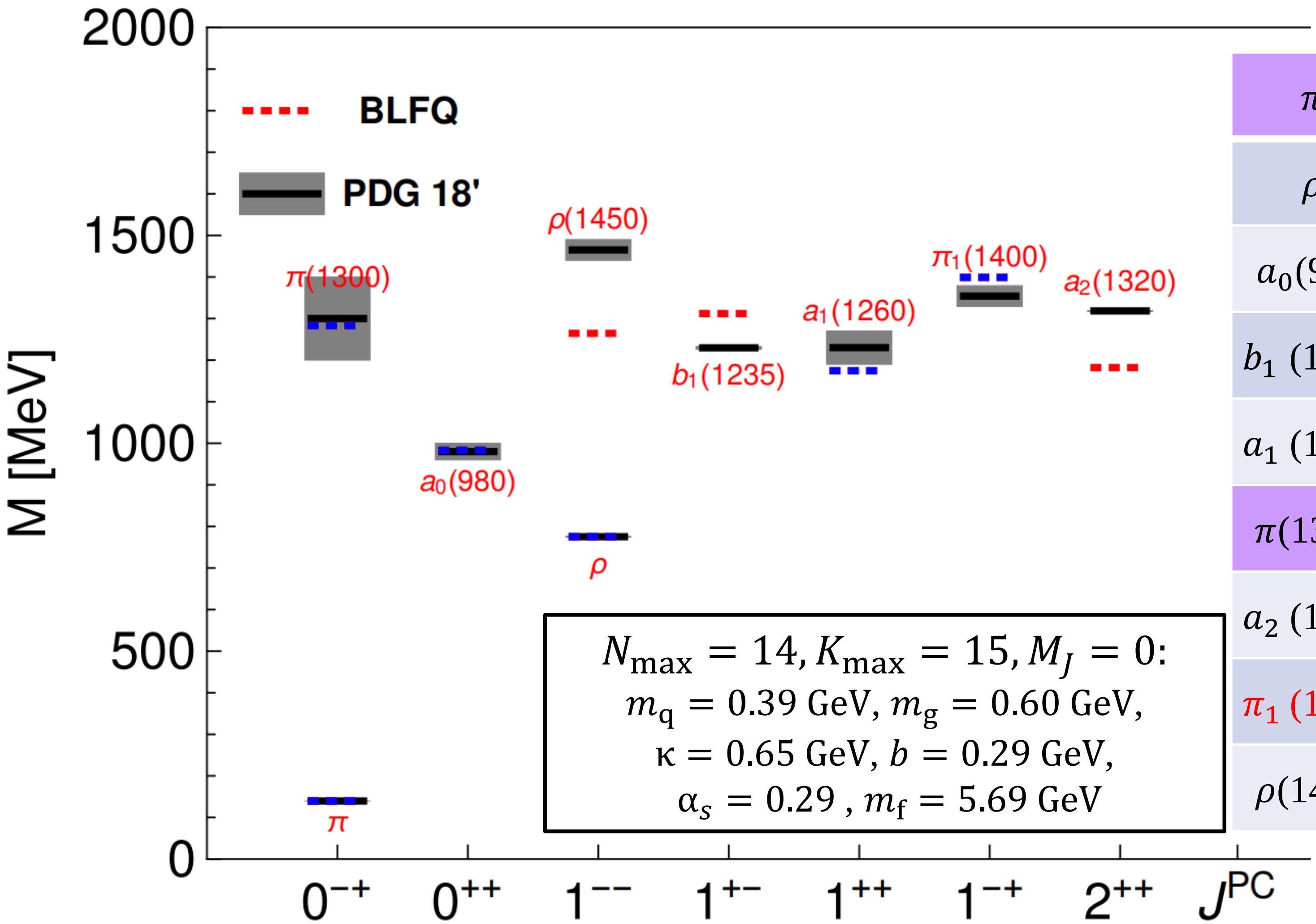


$$+ig\int d^3x\, f^{abc} i\partial^\mu A^{\nu a} A^b_\mu A^c_\nu$$

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

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

Light Meson Mass Spectrum



	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

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

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

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

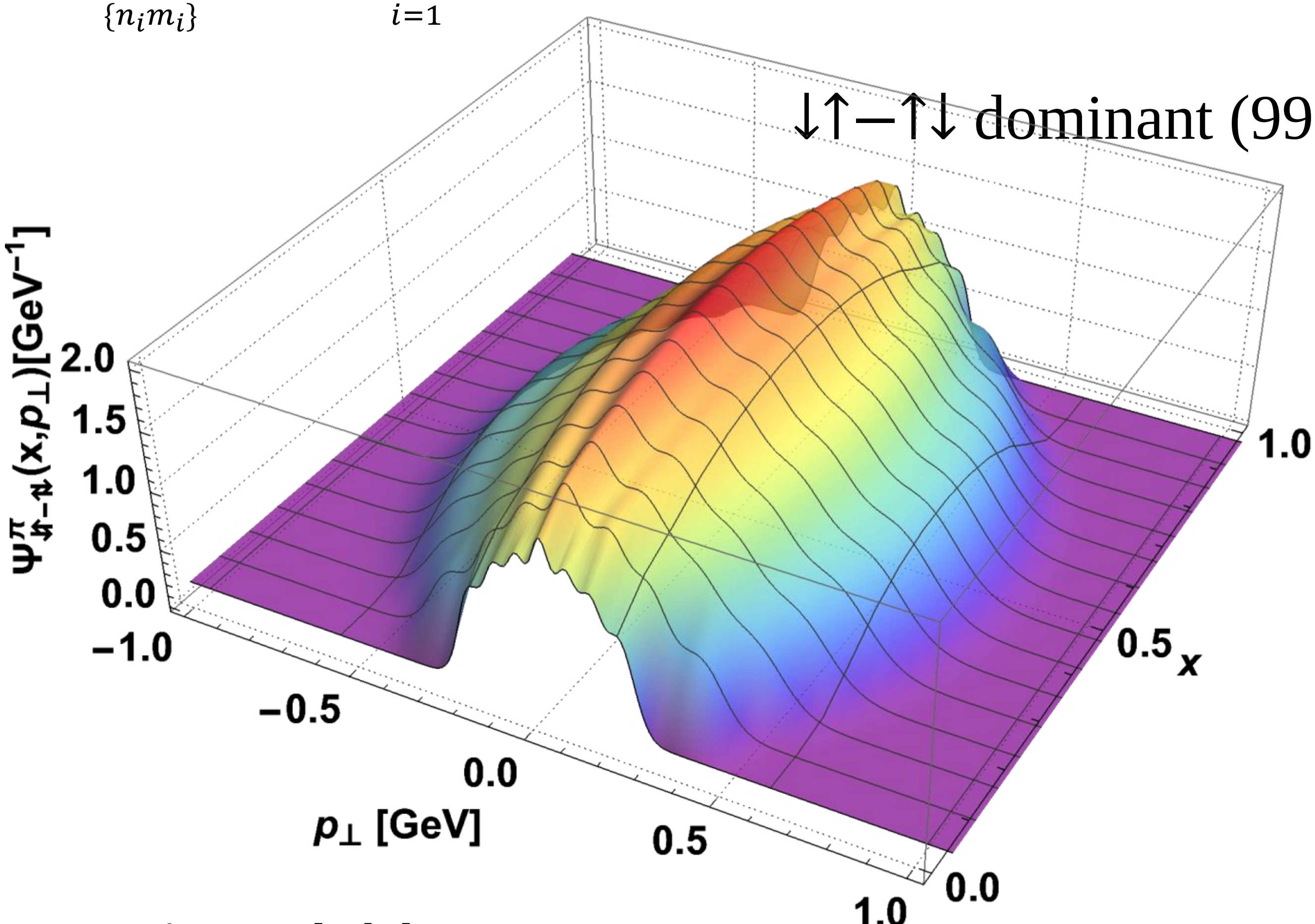
[Lan, Fu, Mondal, Zhao, Vary, Phys. Lett. B 825 (2022) 136890]

The Wave Function in Leading Fock Sector

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

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

↓↑−↑↓ dominant (99.7%) in $|q\bar{q}\rangle$



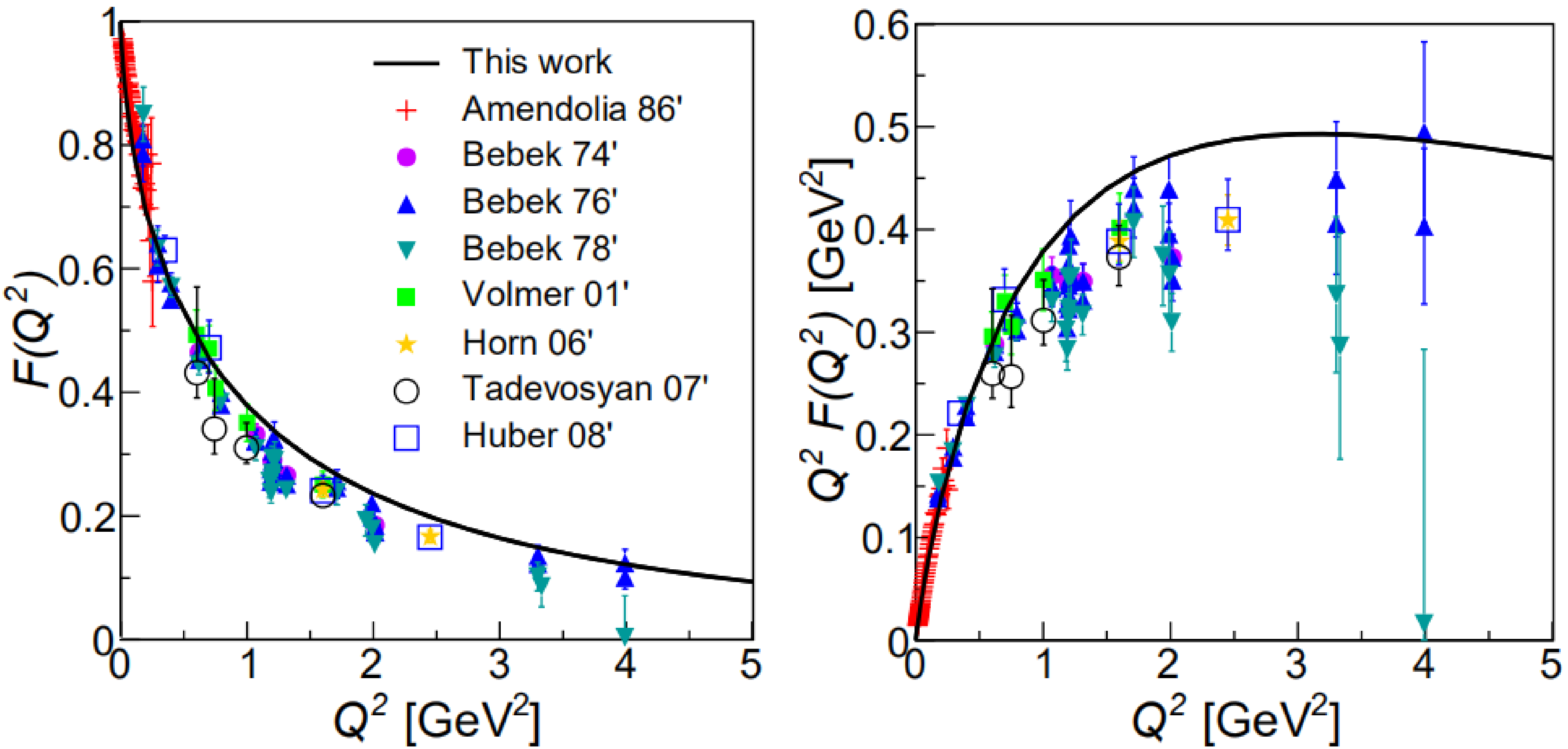
- At endpoint x, $\psi \sim p_\perp$: lightly narrow
- At middle x, $\psi \sim p_\perp$: a little bit wide

Pion Electromagnetic Form Factor

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

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

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



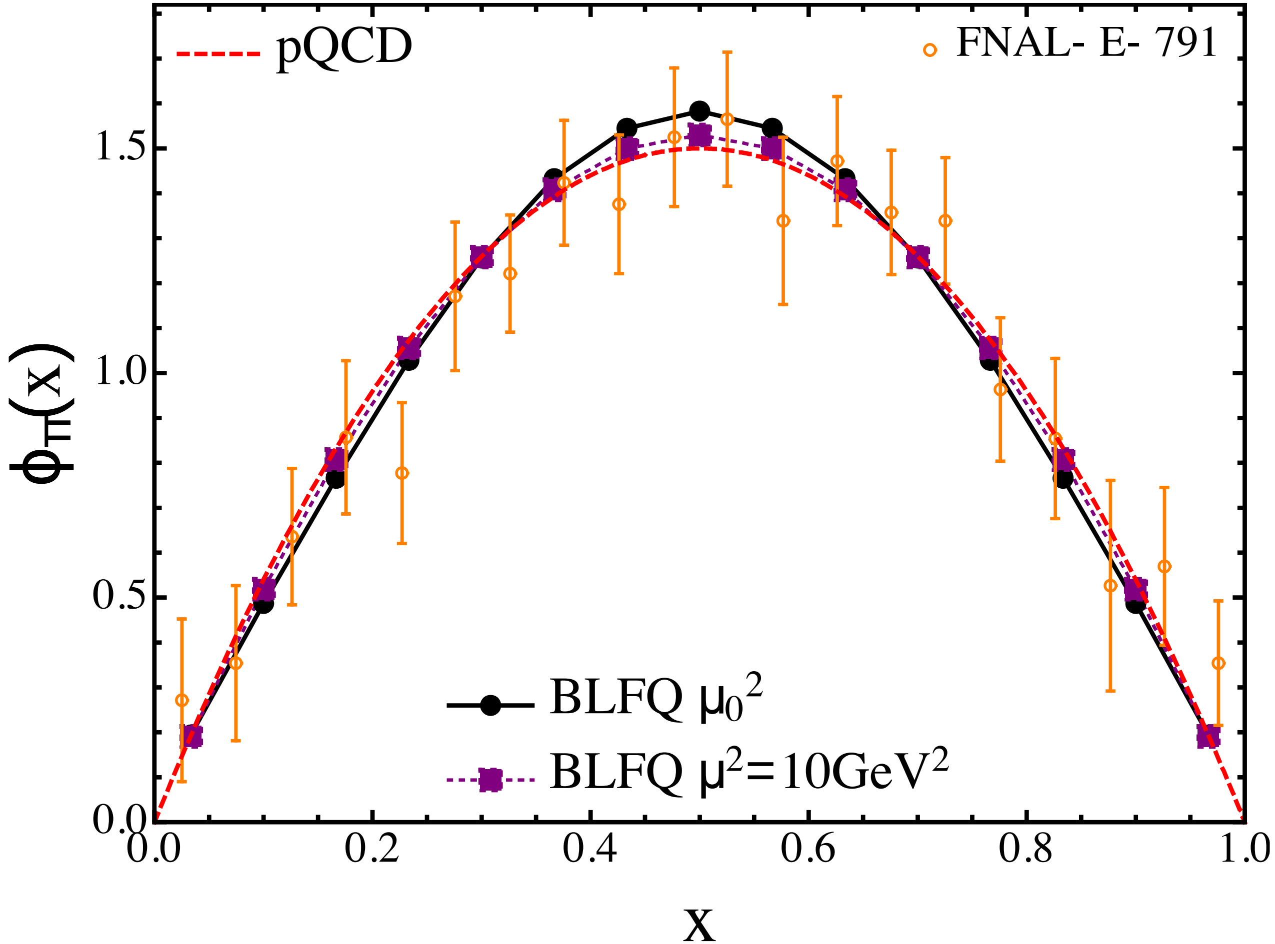
- FF is in reasonable agreement with experimental data
- $F(Q^2) \propto 1/\,Q^2$ for large Q^2

[Lan, Fu, Mondal, Zhao, Vary, Phys. Lett. B 825 (2022) 136890]

Pion PDA

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

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



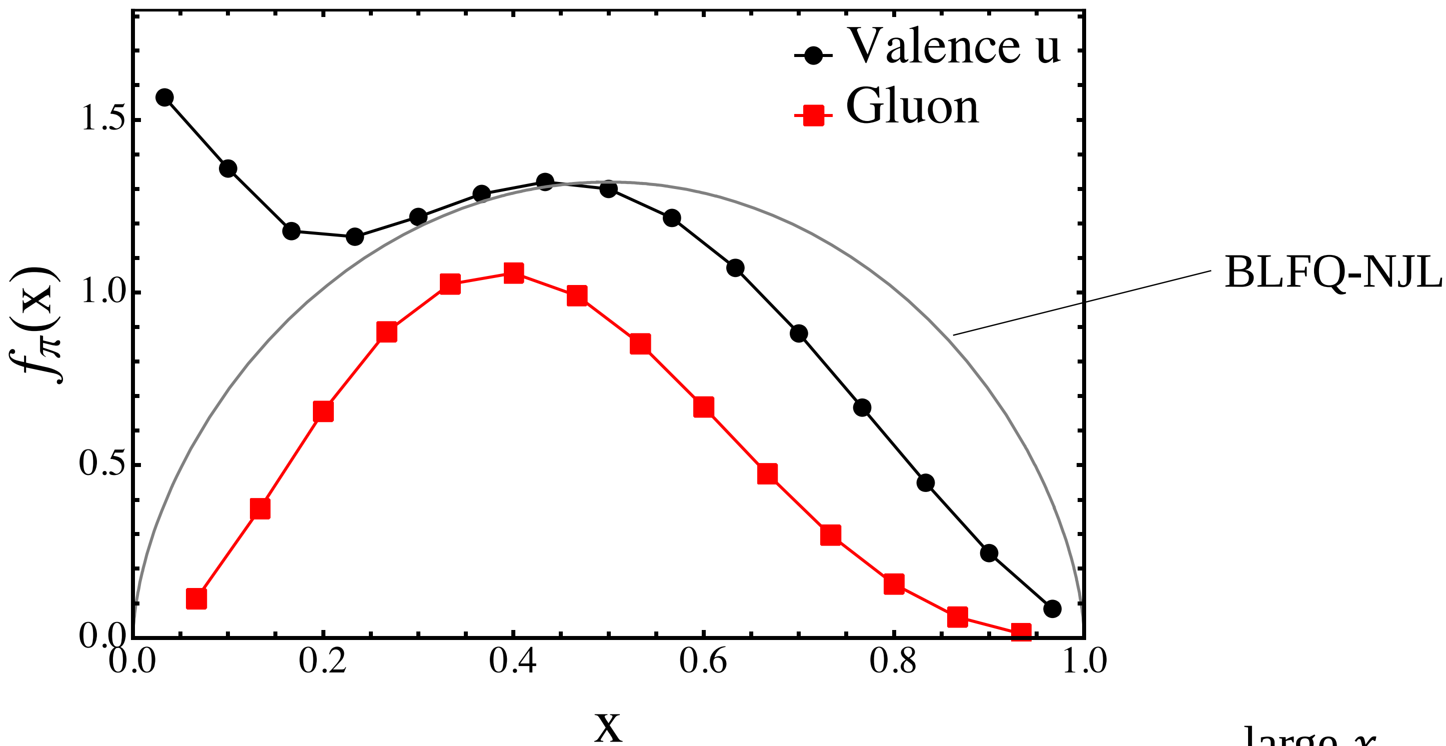
- Endpoint behavior almost agrees with pQCD
- Consistent with FNAL-E-791 experiment

Preliminary

Pion PDF at Model Scale

$$f_i(x) = \sum_{\mathcal{N},\lambda_i} \int [d\mathcal{X} d\mathcal{P}^\perp]_{\mathcal{N}} \left| \psi^{\mathcal{N},M_j=0}_{\{x_i,\vec{p}^2_{\perp i},\lambda_i\}} \right|^2 \delta(x - x_i)$$

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

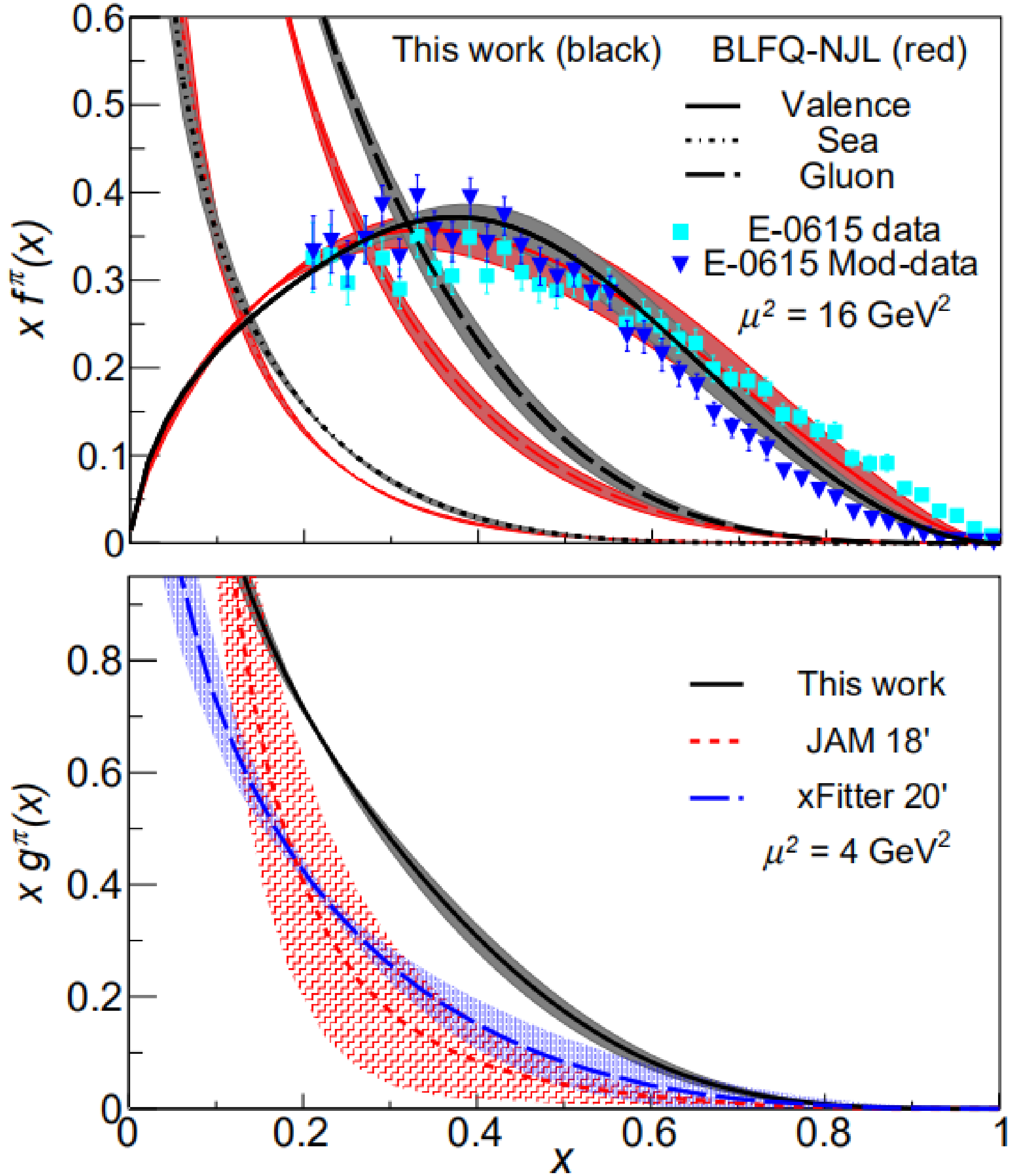


large x

$\mu^2_{0\text{BLFQ-NJL}} = 0.240\ \text{GeV}^2$	$\langle x\rangle_{\text{gluon}} = \mathbf{0}$;	$\langle x\rangle_{\text{valence } u} = \mathbf{0.5}$	$(1-x)^{0.596}$
$\mu^2_{0\text{BLFQ}} = 0.34\ \text{GeV}^2$	$\langle x\rangle_{\text{gluon}} = \mathbf{0.216}$;	$\langle x\rangle_{\text{valence } u} = \mathbf{0.392}$	$(1-x)^{1.4}$

[Lan, Fu, Mondal, Zhao, Vary, Phys. Lett. B 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)

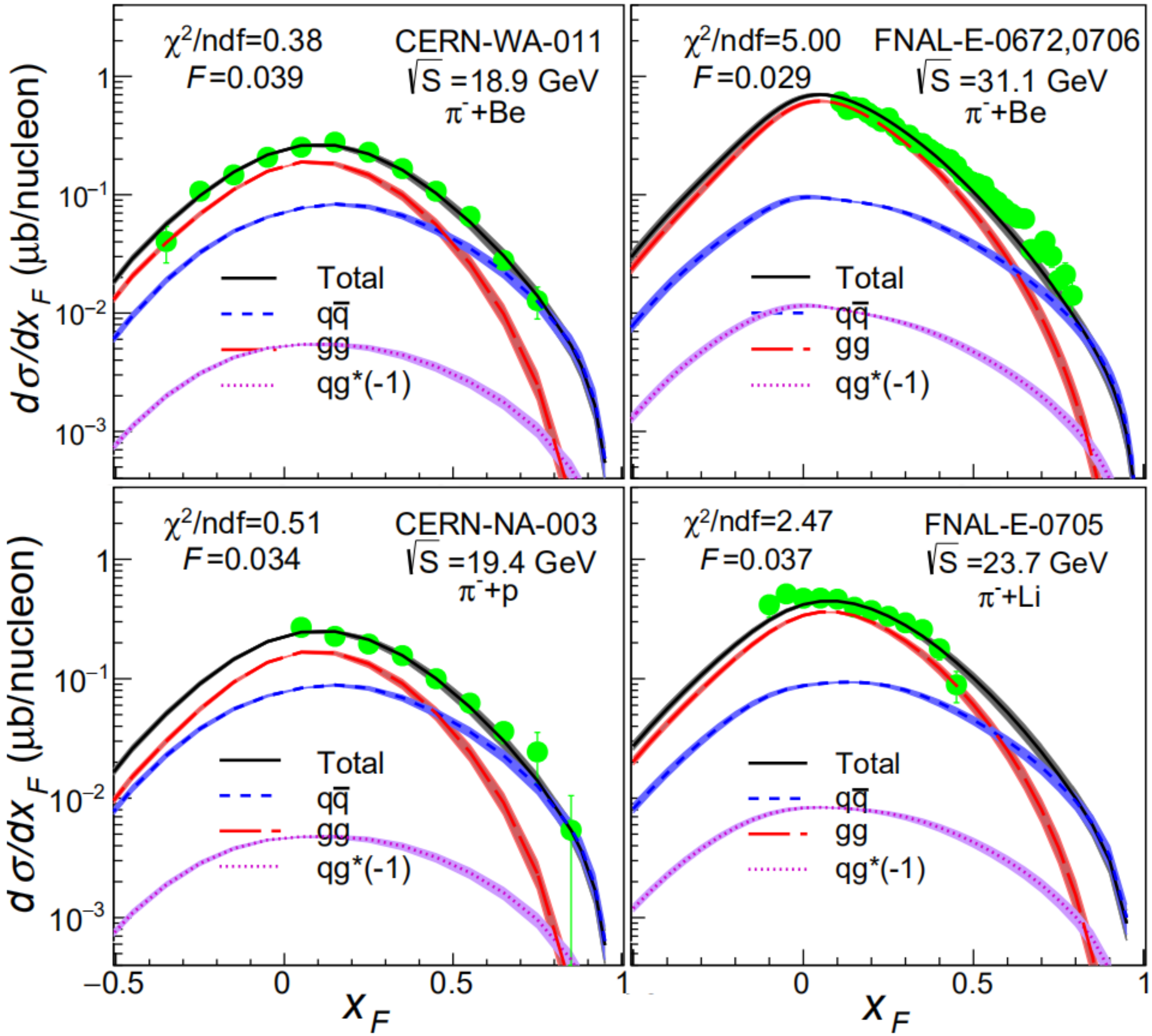
[Lan, Fu, Mondal, Zhao, Vary, Phys. Lett. B 825 (2022) 136890]

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]



CEM

[Chang, et al, PRD 102 (2020) 054024];
[Nason, et al, NPB 303 (1988) 607];
[Mangano, et al, NPB 405 (1993) 507]

- significantly gg contribution
- various energies of pions
- different target

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

[Lan, Fu, Mondal, Zhao, Vary, Phys. Lett. B 825 (2022) 136890]

Pion GPD

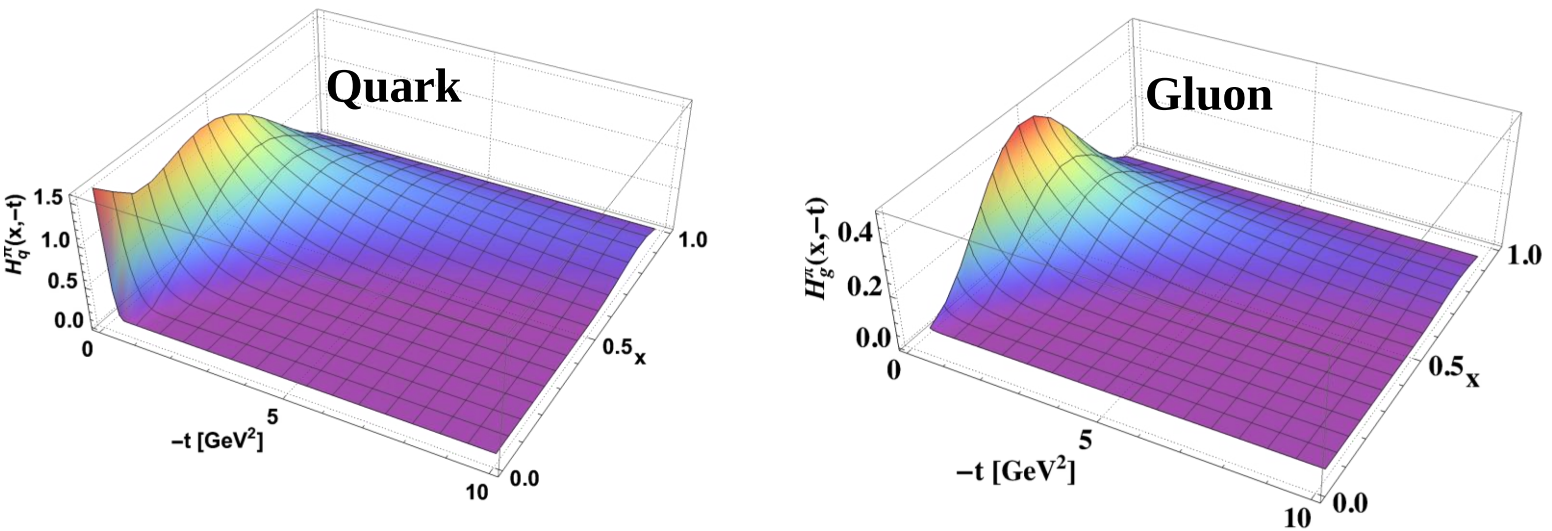
Preliminary

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

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

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

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



- Quark content enhanced at small x with $|q\bar{q}g\rangle$
- Falls slowly at larger x
- Emerge at larger x range for larger $-t$

[Jiangshan Lan, et al, in preparation]

Pion GPD

Preliminary

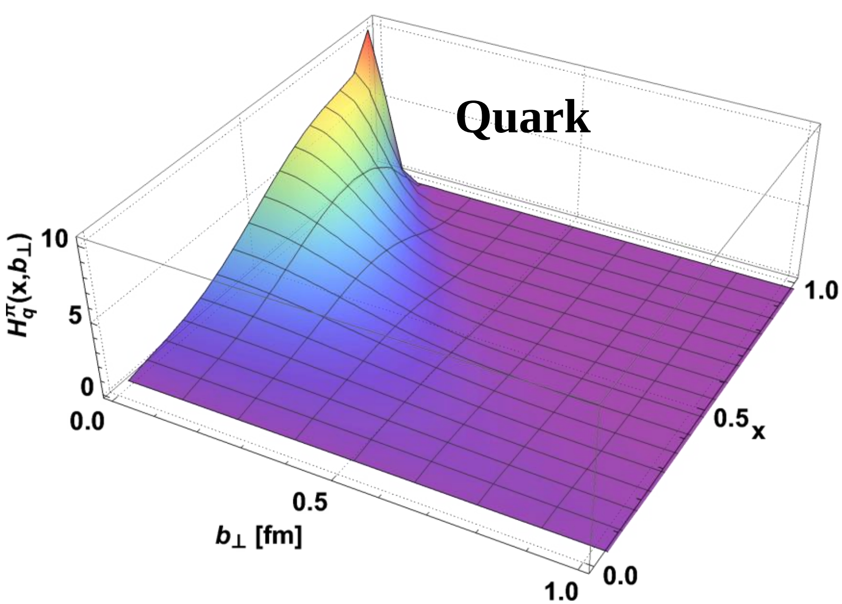
[M. Diehl, Phys. Rep. 388 (2003) 41-277]

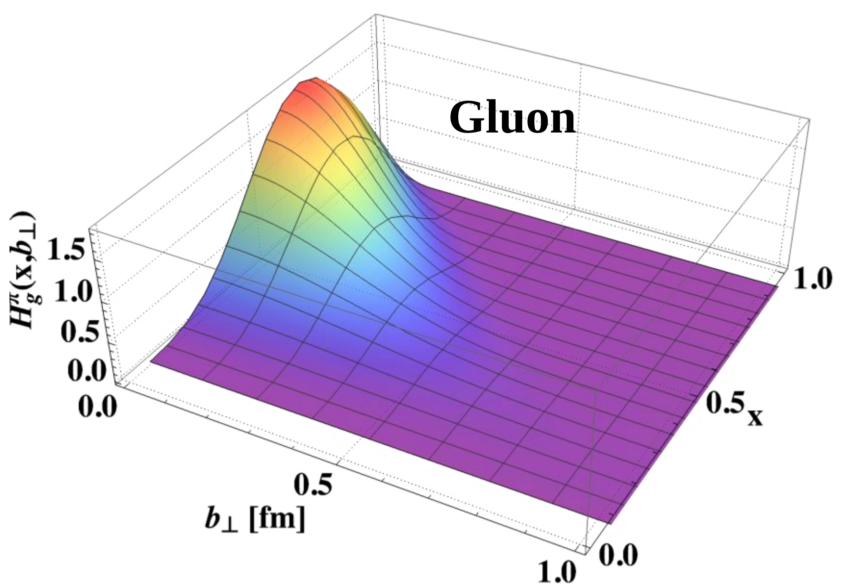
$$|\pi\rangle = a|q\bar{q}\rangle + b|q\bar{q}g\rangle + \cdots$$

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

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

FT → The impact parameter distributions (IPDs)





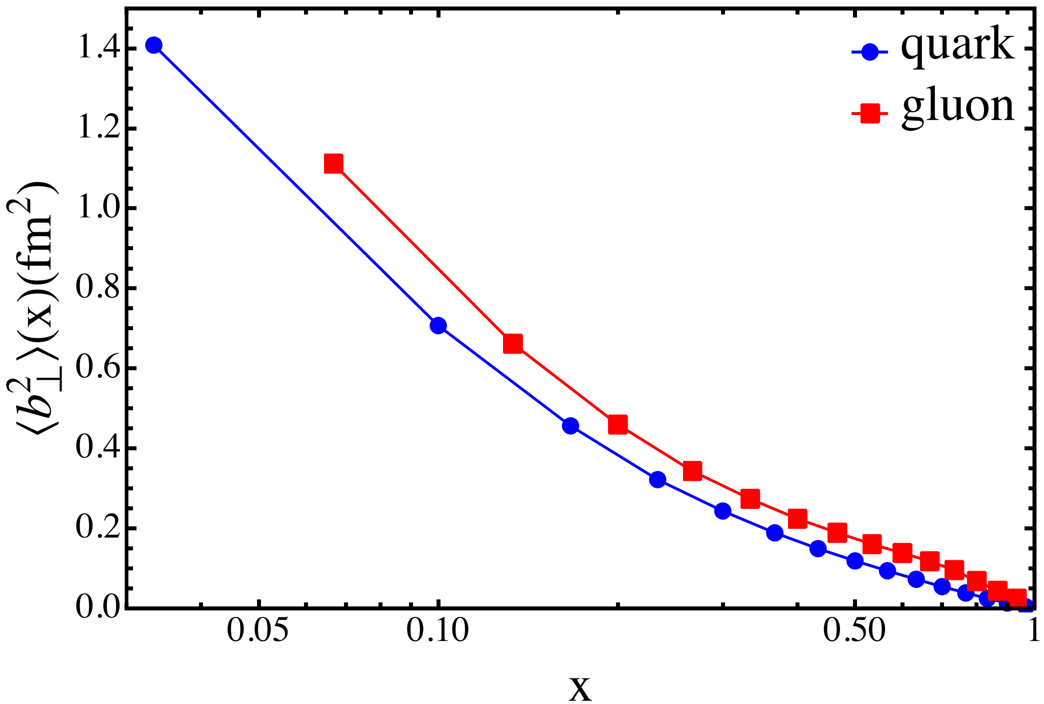
[Jiangshan Lan, et al, in preparation]

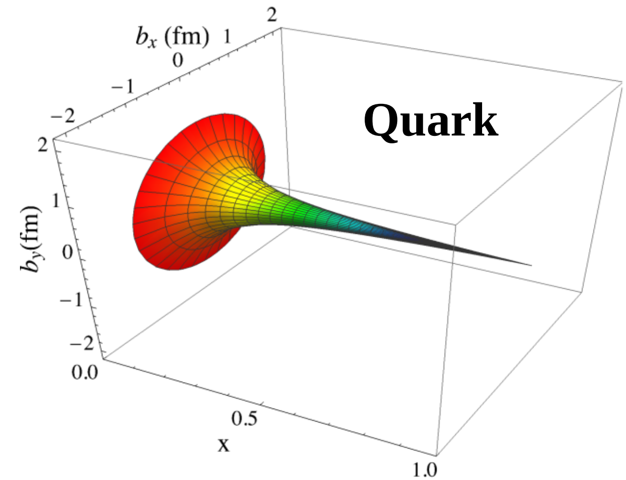
Pion Impact Parameter Distribution

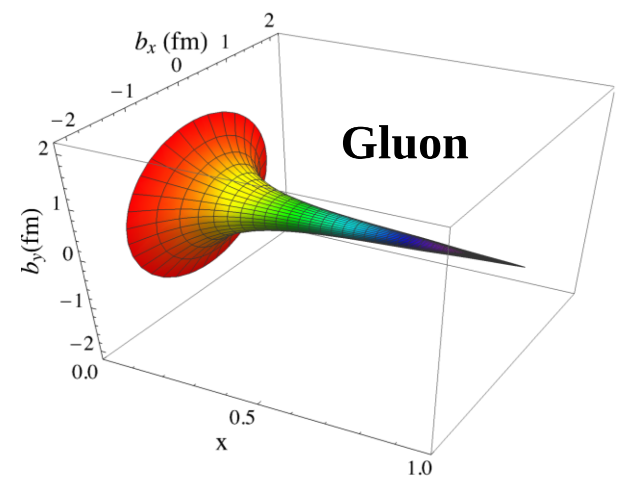
One can define the x-dependent squared radius of the quark and the gluon density in the transverse plane as

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

$$\langle b_\perp^2 \rangle^{q,g}(x) = \frac{\int d^2\boldsymbol{b}_\perp \boldsymbol{b}_\perp^2 H_\pi^{q.g}(x, \boldsymbol{b}_\perp)}{\int d^2\boldsymbol{b}_\perp H_\pi^{q.g}(x, \boldsymbol{b}_\perp)}$$







➢ Gluon distribution is slightly broader than the quark

Preliminary

[Jiangshan Lan, et al, in preparation]

Pion TMD

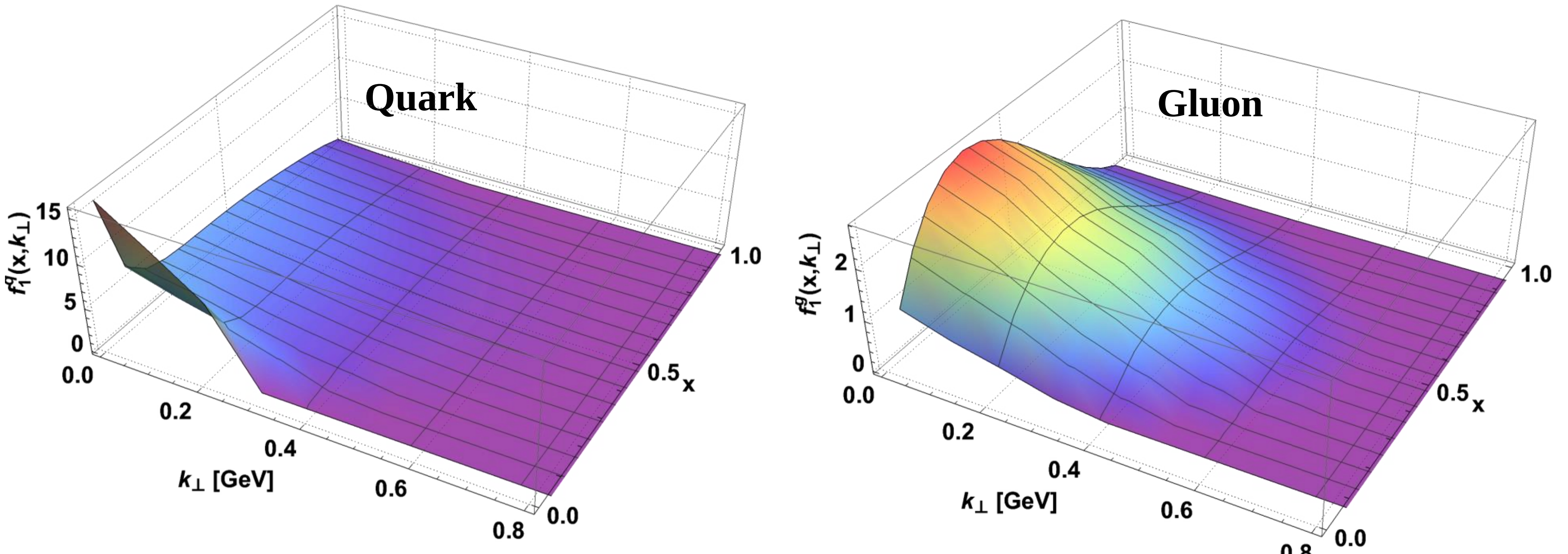
Preliminary

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

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

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

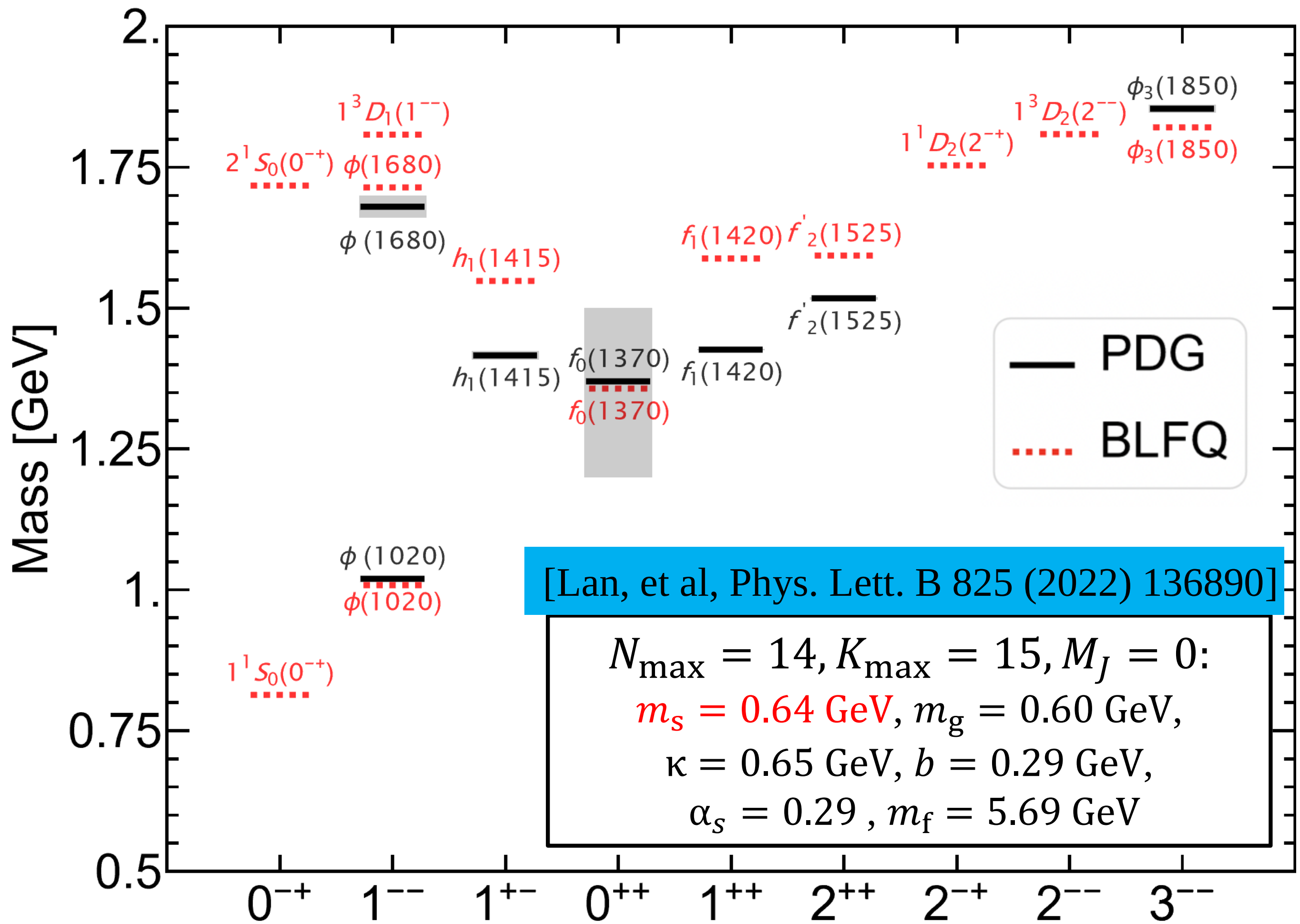
$$f_1^g(x,k_\perp) = \frac{1}{xP^+}\int \frac{dz^- d^2 z_\perp}{(2\pi)^3} e^{i(z^- k^+ - z_\perp k_\perp)} \left\langle \pi, P \middle| G^{+\mu}\left(-\frac{z}{2}\right) G_\mu^+\left(\frac{z}{2}\right) \middle| \pi, P \right\rangle_{z^+=0}$$



- The TMD decreases with $k_\perp$
- Vanishes after $k_\perp$ ~ 0.7 GeV

[Jiangshan Lan, et al, in preparation]

Strangeonium Mass Spectrum



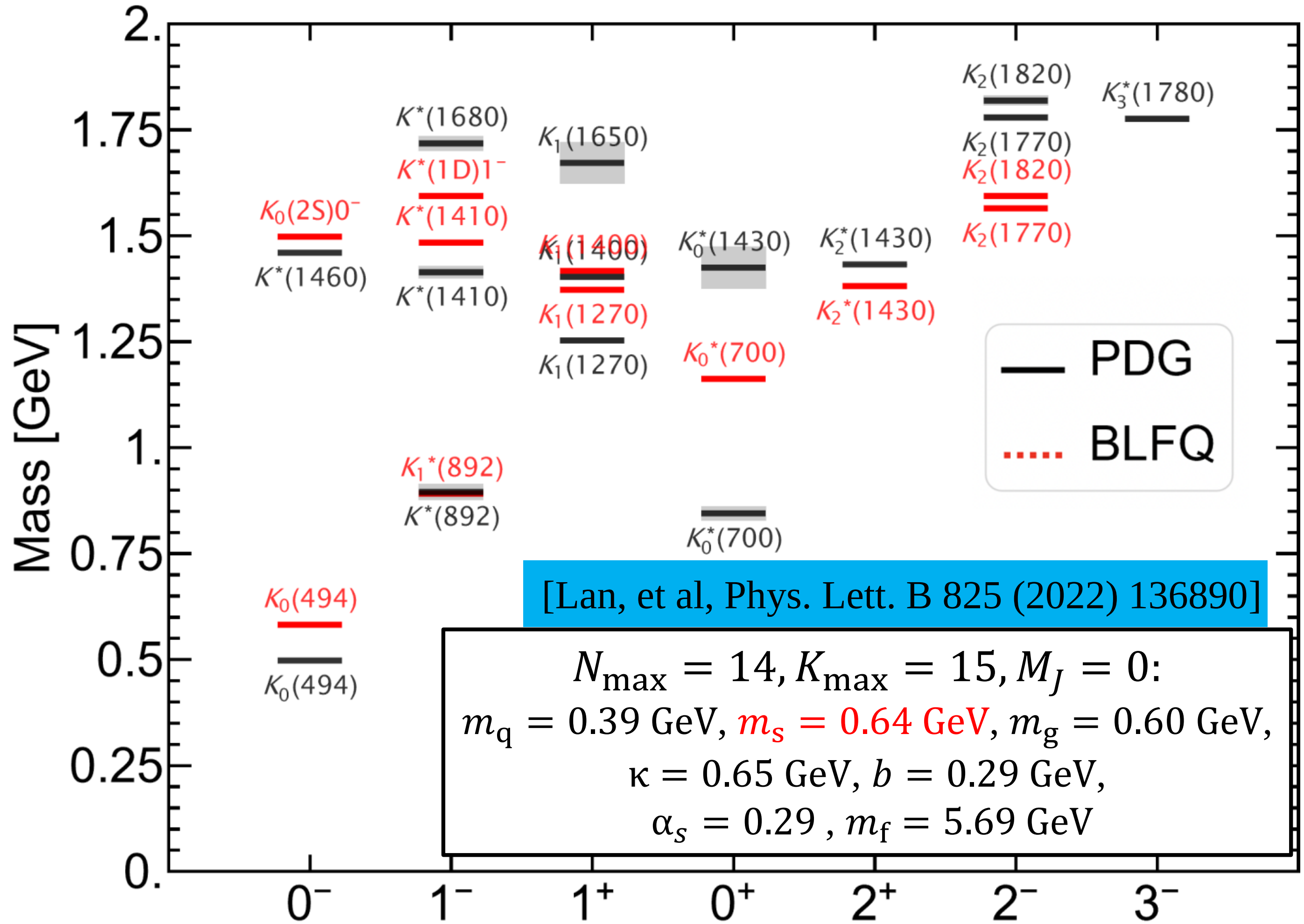
$$|\text{meson}\rangle = a|s\bar{s}\rangle + b|s\bar{s}g\rangle + \cdots$$

Fix the only additional parameter m_s by fitting vector states

$$\phi(1020), \phi(1680), \phi_3(1850)$$

[Jialin Chen, Jiangshan Lan, et al, in preparation]

Strange Meson Mass Spectrum



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

- Zero parameter

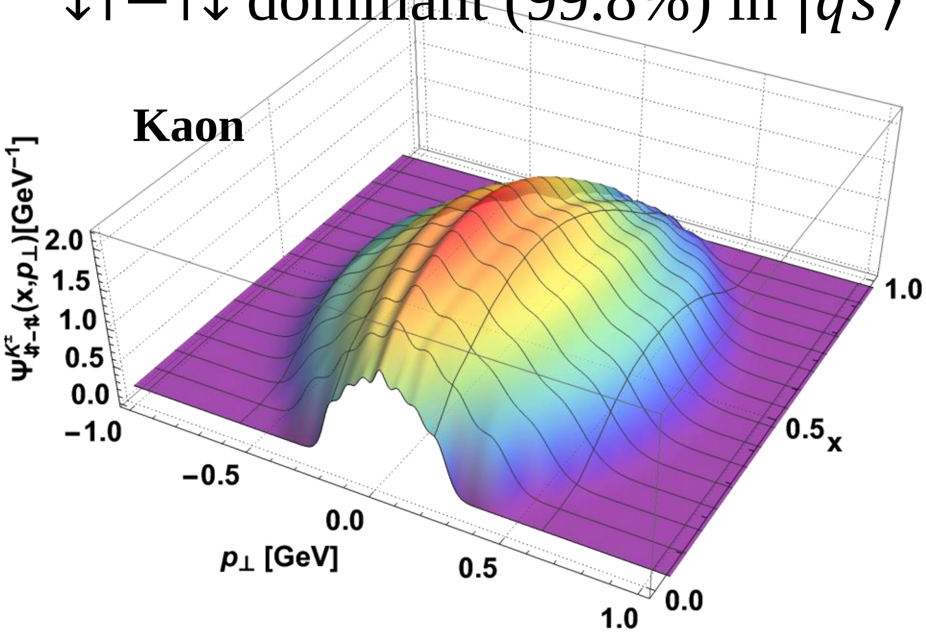
[Jialin Chen, Jiangshan Lan, et al, in preparation]

The Wave Function in Leading Fock Sector

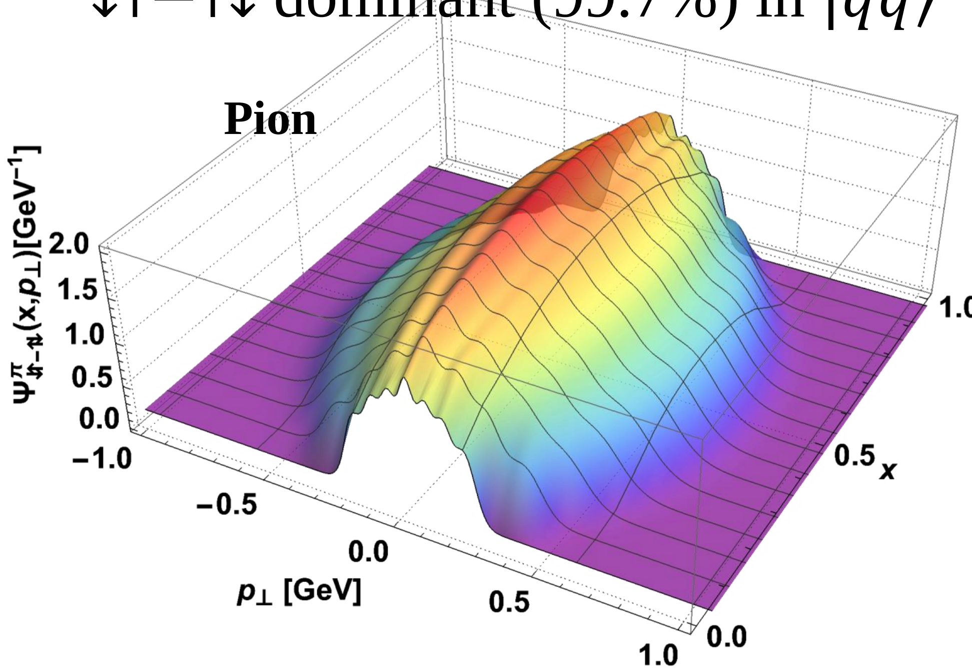
$$\Psi^{\mathcal{N},M_J}_{\{x_i,\vec{p}^2_{\perp i},\lambda_i\}} = \sum_{\{n_i m_i\}} \psi^{\mathcal{N}}(\{\bar{\alpha}_i\}) \prod_{i=1}^{\mathcal{N}} \phi_{n_i m_i}(\vec{p}_{\perp i}, b)$$

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

$\downarrow\uparrow - \uparrow\downarrow$ dominant (99.8%) in $|q\bar{s}\rangle$

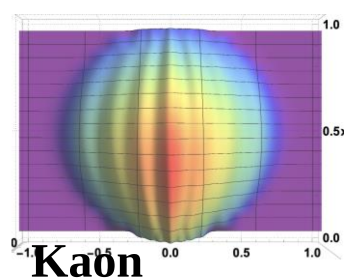


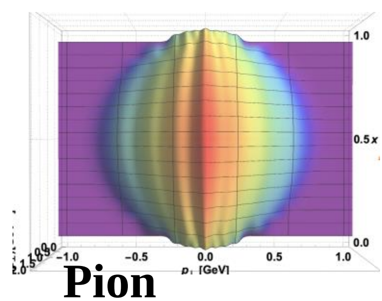
$\downarrow\uparrow - \uparrow\downarrow$ dominant (99.7%) in $|q\bar{q}\rangle$



Compared with pion

- Narrower in longitudinal direction
- Asymmetric in longitudinal direction
- Comparable in transverse direction



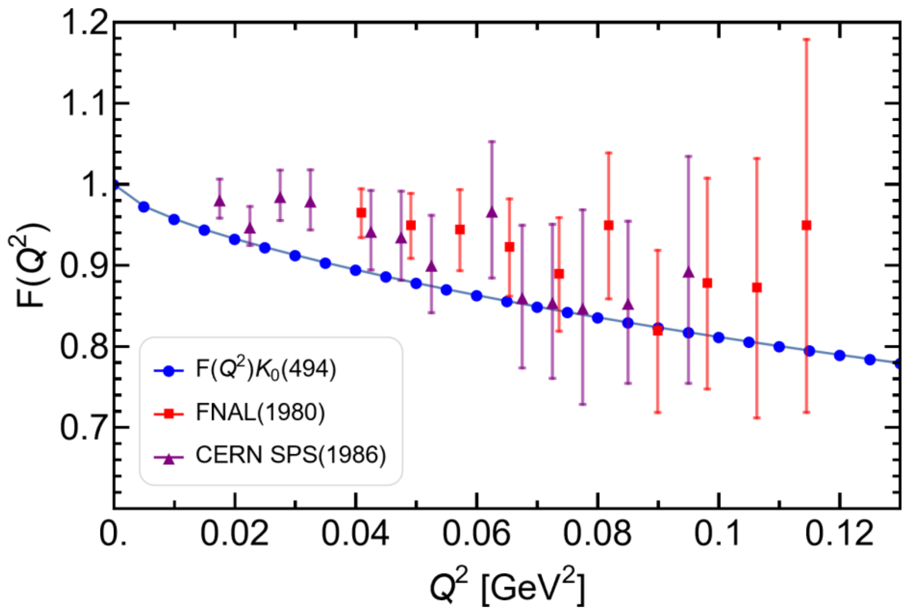


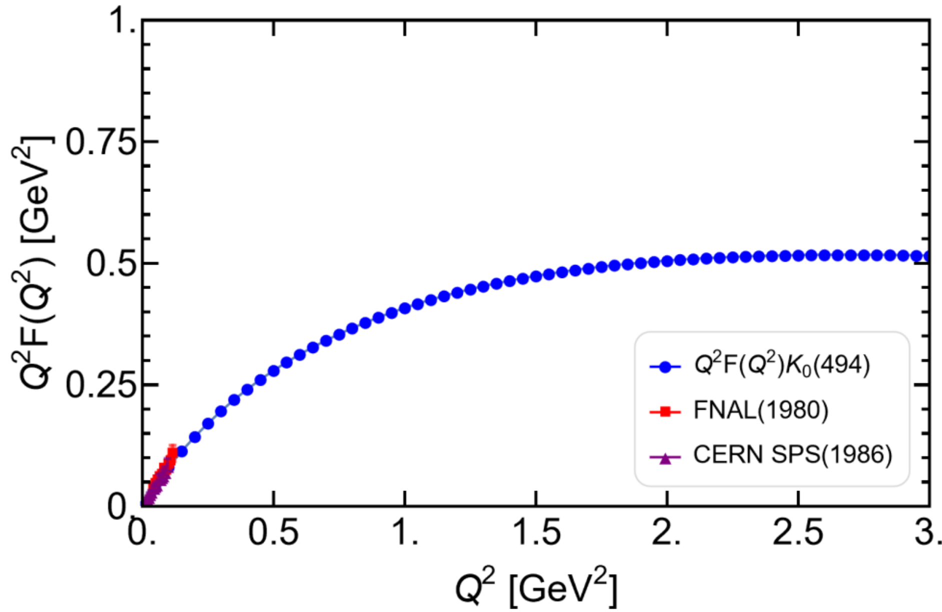
Kaon Electromagnetic Form Factor

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

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

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



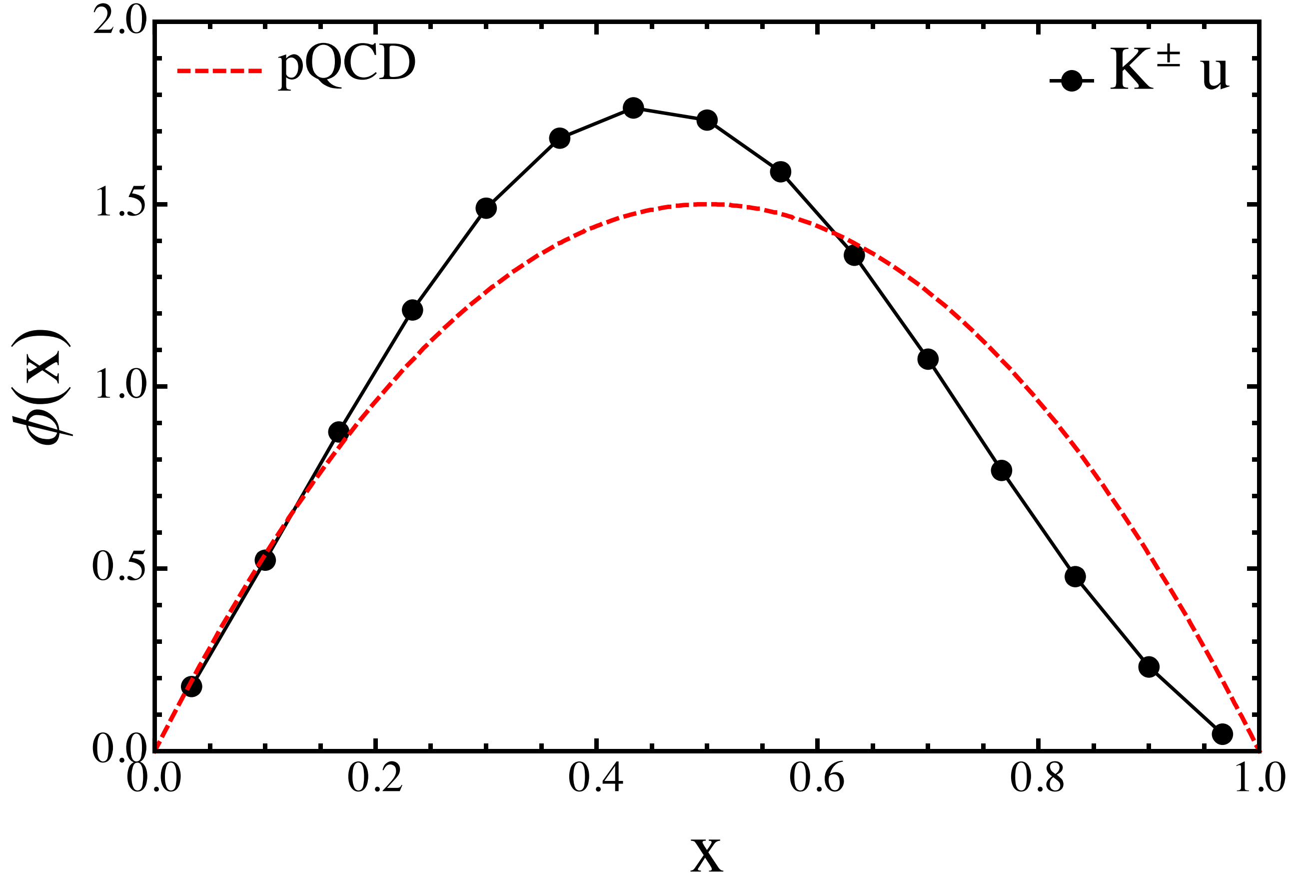


- FF is in reasonable agreement with experimental data
- $F(Q^2) \propto 1/Q^2$ for large Q^2

[Jialin Chen, Jiangshan Lan, et al, in preparation]

Kaon PDA

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



- Endpoint behavior at small x almost agrees with pQCD

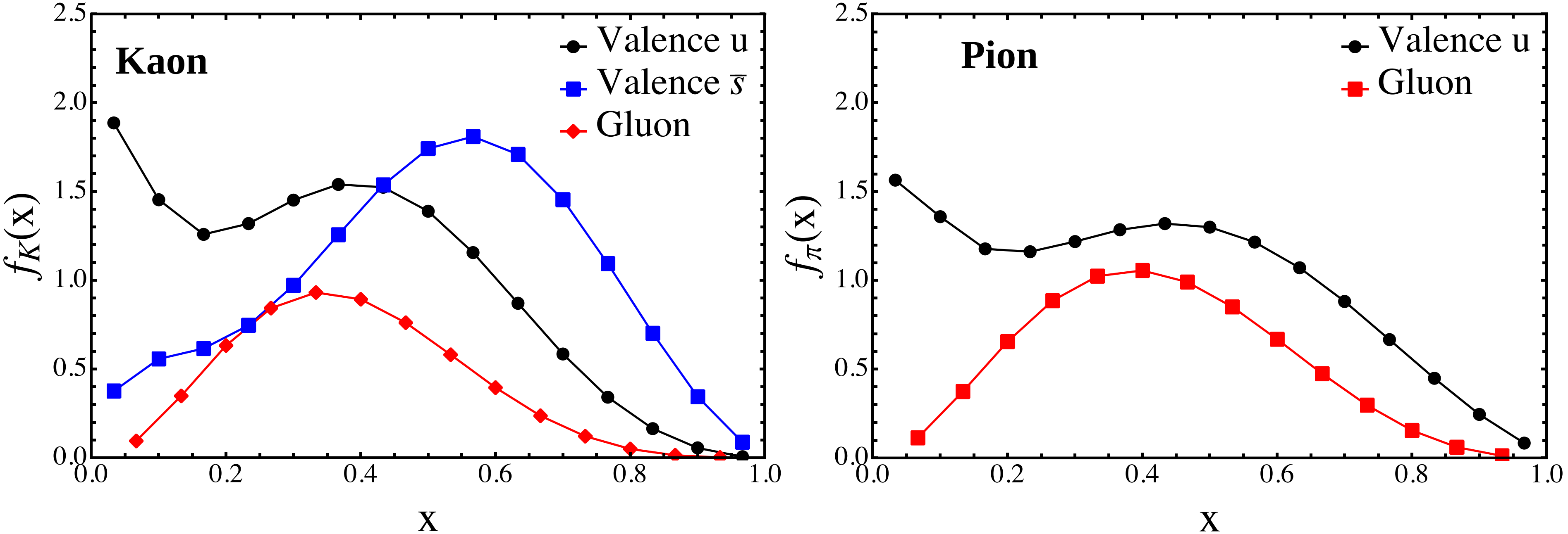
Preliminary

[Jialin Chen, Jiangshan Lan, et al, in preparation]

Kaon PDF at Model Scale

$$f_i(x) = \sum_{\mathcal{N},\lambda_i} \int [d\mathcal{X} d\mathcal{P}^\perp]_\mathcal{N} \left| \psi^{\mathcal{N},M_j=0}_{\{x_i,\vec{p}^2_{\perp i},\lambda_i\}} \right|^2 \delta(x - x_i)$$

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



$\mu^2_{0\text{BLFQ}\,kaon} = 0.50\ \text{GeV}^2$

$\mu^2_{0\text{BLFQ}\,pion} = 0.34\ \text{GeV}^2$

$\langle x \rangle_{\text{gluon}} = 0.152$; $\langle x \rangle_{\text{valence}\ u} = 0.343$; $\langle x \rangle_{\text{valence}\ \bar{s}} = 0.505$

- Smaller gluon content in kaon
- At small x, u dominates over $\bar{s}$

[Jialin Chen, Jiangshan Lan, et al, in preparation]

Kaon PDF with QCD Evolution

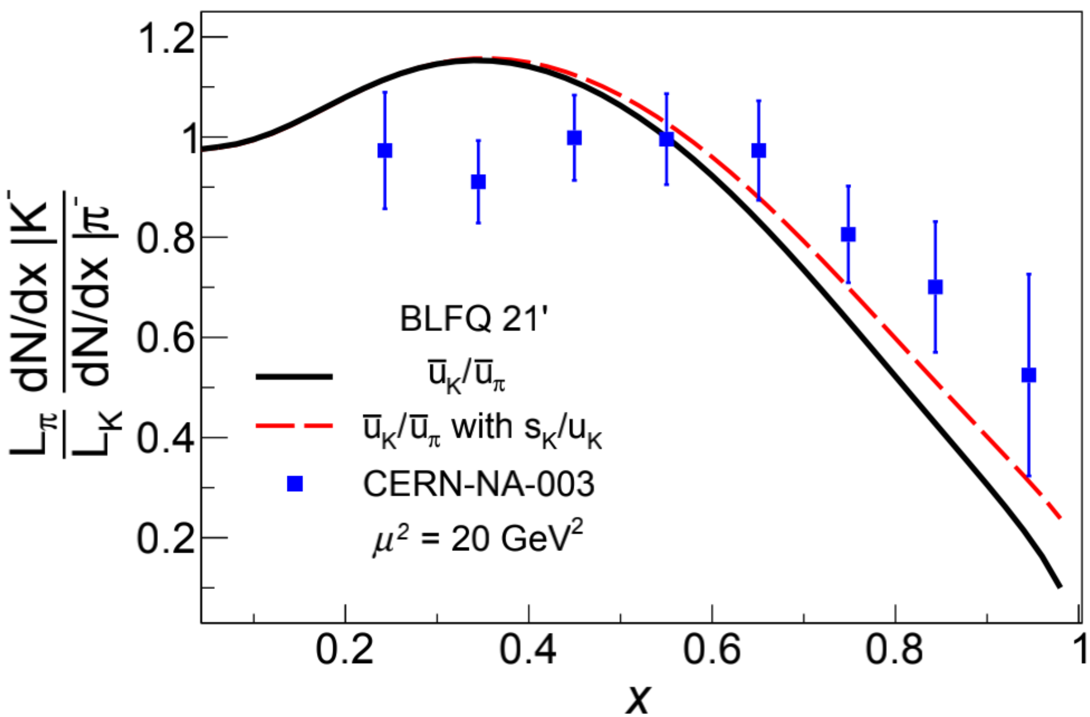
[Badier et al. PLB 1980 (NA3)];

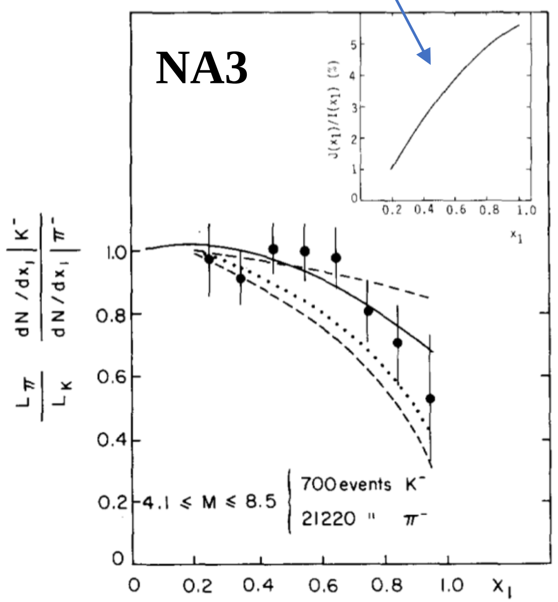
$$|K\rangle = a|q\bar{s}\rangle + b|q\bar{s}g\rangle + \cdots$$

$$\frac{L_\pi}{L_K}\frac{dN/dx|K^-}{dN/dx|\pi^-} = \frac{\bar{u}_K(x)I(x) + s_K(x)J(x)}{\bar{u}_\pi(x)I(x) + d_\pi(x)J(x)} = \frac{\bar{u}_K(x)I(x)(1+0.055x\frac{s_K(x)}{\bar{u}_K(x)})}{\bar{u}_\pi(x)I(x)(1+0.055x)}$$

$$= \frac{\bar{u}_K(x)}{\bar{u}_\pi(x)} \times \frac{(1+0.055x\frac{s_K(x)}{\bar{u}_K(x)})}{(1+0.055x)} = R(x)C(x),$$

$J(x)/I(x) \sim 0.055x$



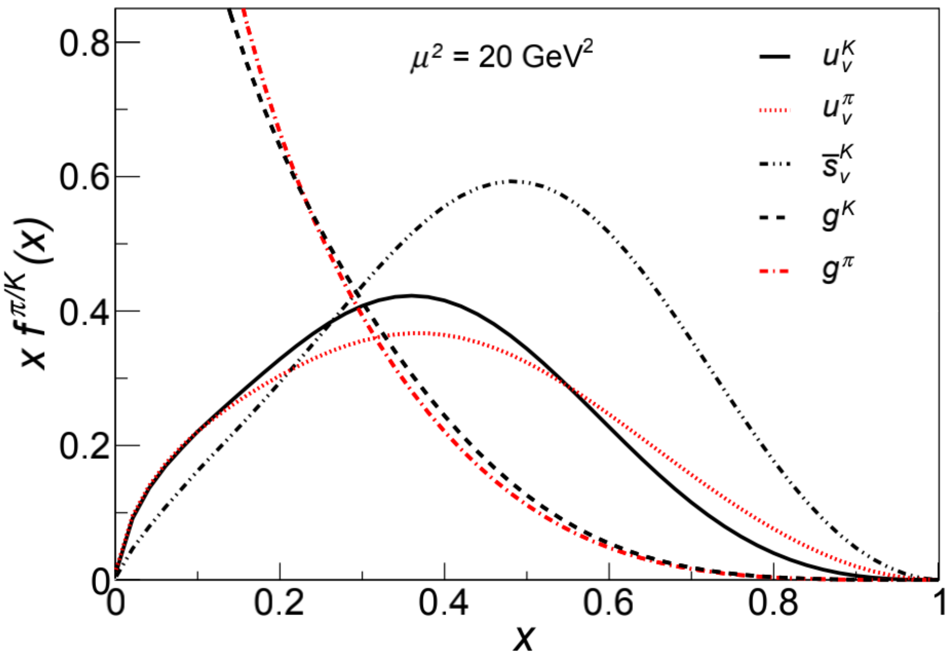


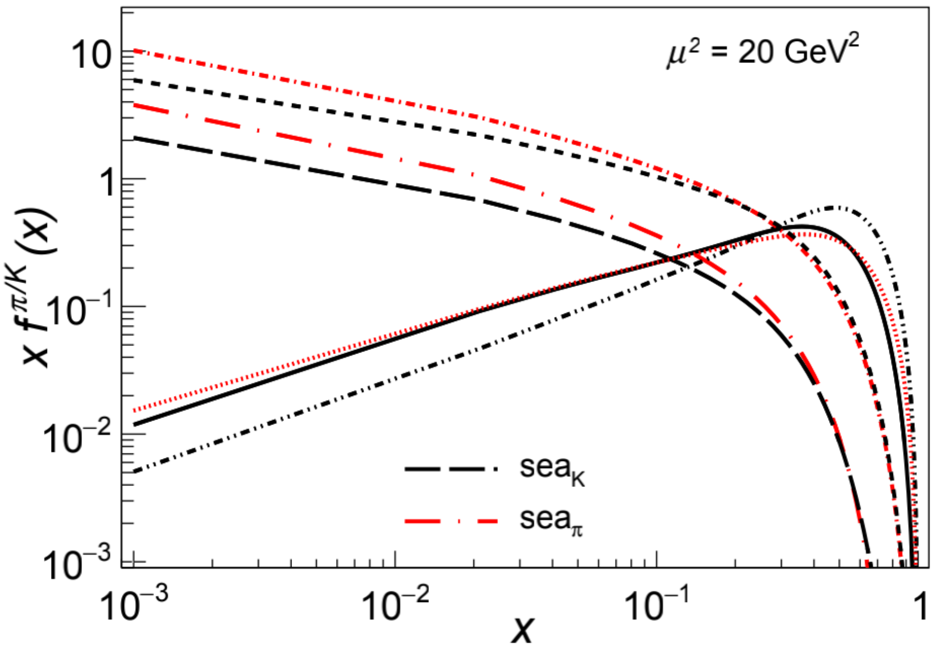
- Roughly touch the result from NA3

[Jiangshan Lan, et al, in preparation]

Kaon PDFs VS Pion PDFs

At $\mu^2 = 20\ \mathrm{GeV}^2$





Kaon

$\langle x\rangle_{\mathrm{gluon}} = 0.381$; $\langle x\rangle_{\mathrm{valence}\ u} = 0.214$; $\langle x\rangle_{\mathrm{valence}\ \bar{s}} = 0.316$; $\langle x\rangle_{\mathrm{sea}} = 0.089$

Pion

$\langle x\rangle_{\mathrm{gluon}} = 0.449$; $\langle x\rangle_{\mathrm{valence}\ u} = 0.211$; $\langle x\rangle_{\mathrm{sea}} = 0.129$

- The gluon in the kaon carries less longitudinal moment is slightly less than the gluon in the pion

[Jiangshan Lan, et al, in preparation]

J/ψ production cross section

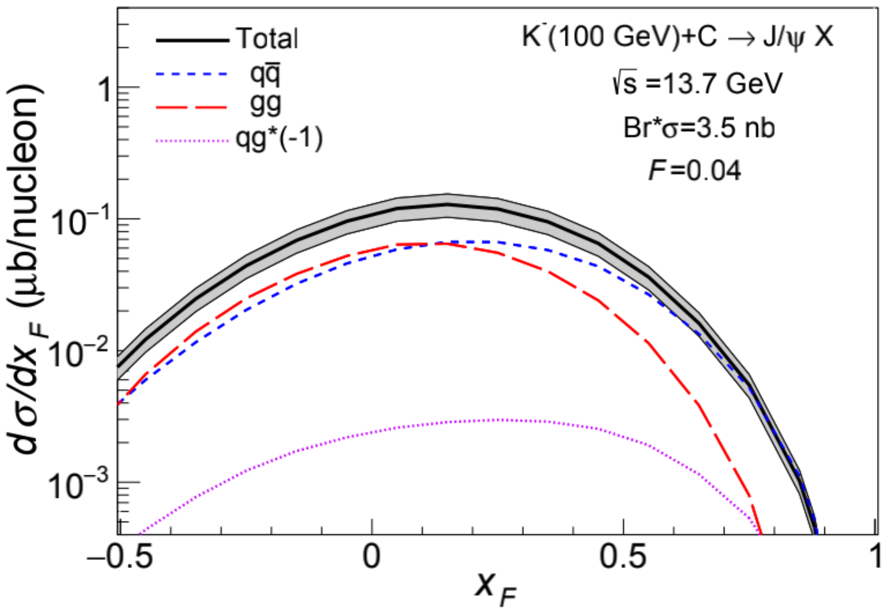
$K^{\pm} N \to J/\psi \ X$

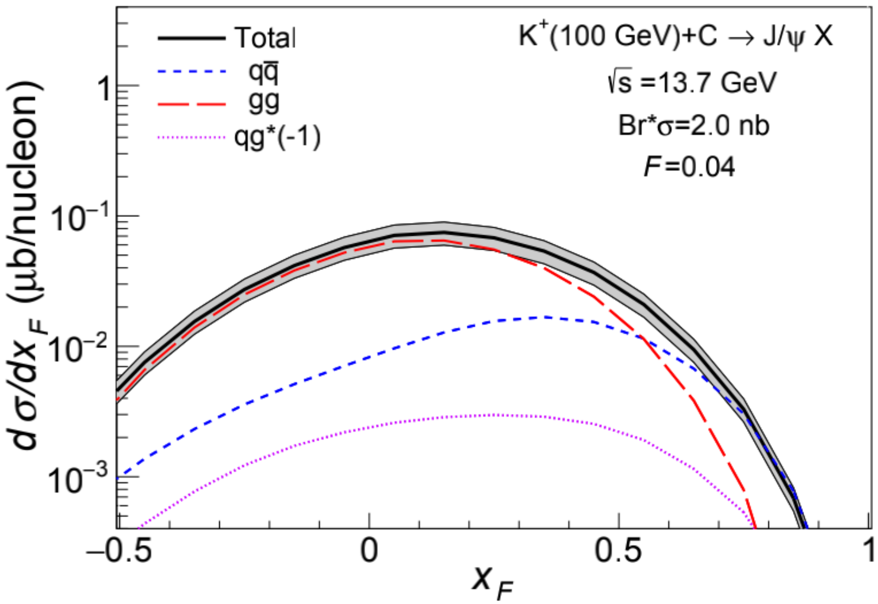
[Chang, et al, PRD 102 (2020) 054024]; [Nason, et al, NPB 303 (1988) 607]; [Mangano, et al, NPB 405 (1993) 507]

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

CEM

[nCTEQ 2015]





assuming the cross section of $K^- + C$ is 3.7 nb, then the cross section of 2.0 nb

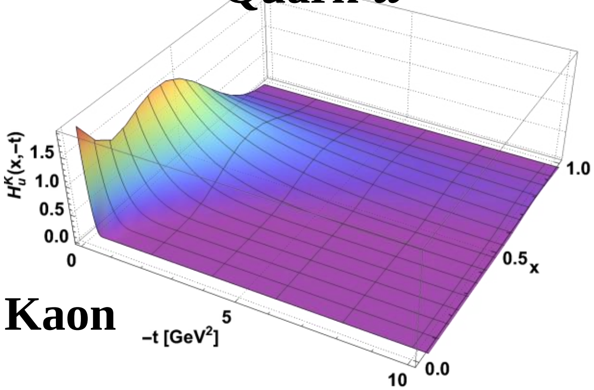
- $q\bar{q}$ contribution different between $K^- + C$ and $K^+ + C$

[Jiangshan Lan, et al, in preparation]

Kaon GPD

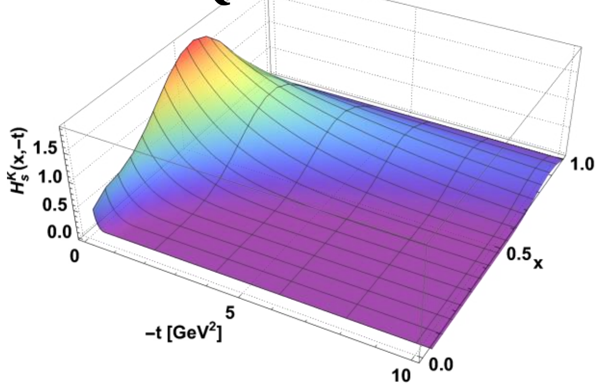
$$|K\rangle = a|q\bar{s}\rangle + b|q\bar{s}g\rangle + \cdots$$

Quark u

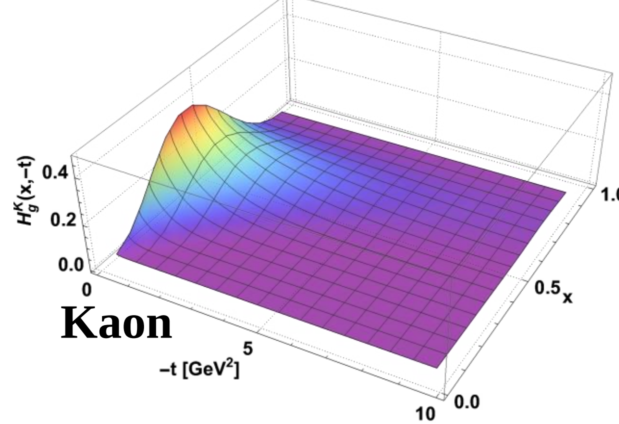


Kaon

Quark $\bar{s}$

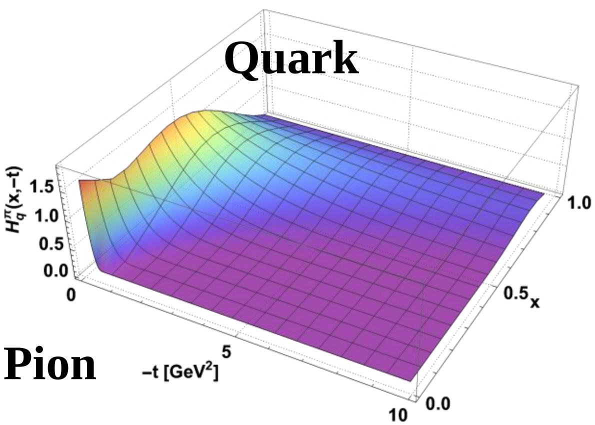


Gluon



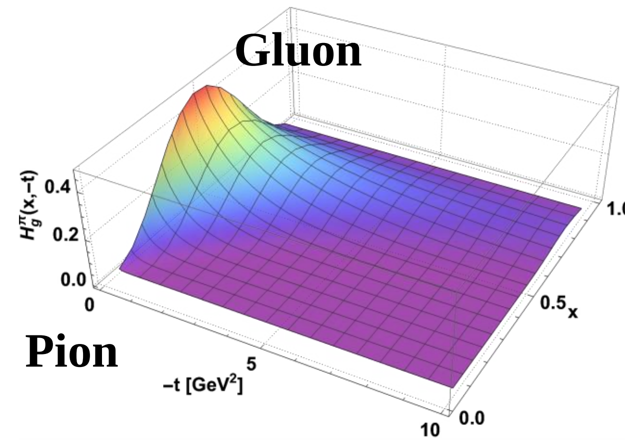
Kaon

Quark



Pion

Gluon



Pion

- Quark u content enhanced at small x with $|q\bar{s}g\rangle$
- Falls slowly at larger x
- Emerge at larger x range for larger $-t$

[Jialin Chen, Jiangshan Lan, et al, in preparation]

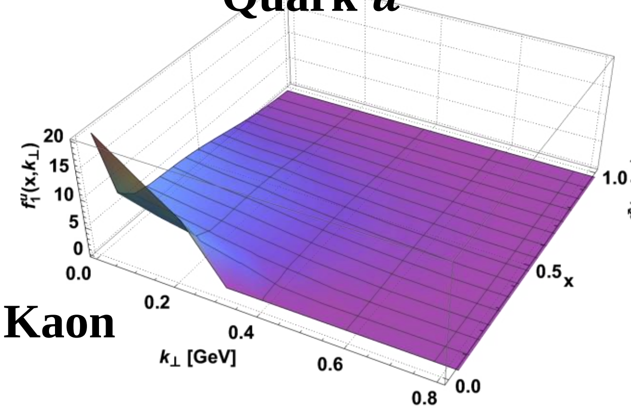
Kaon TMD

Preliminary

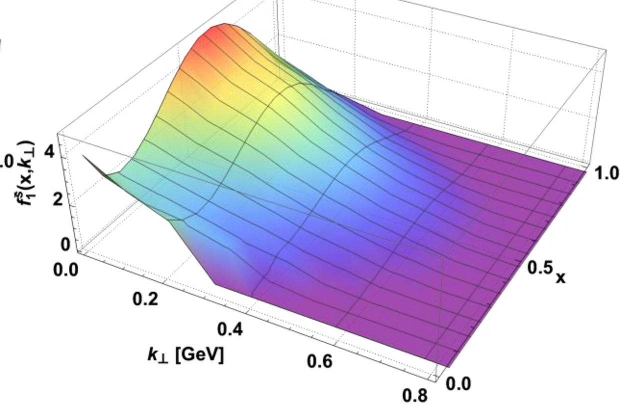
$$|K\rangle = a|q\bar{s}\rangle + b|q\bar{s}g\rangle + \cdots$$

Quark u

Kaon

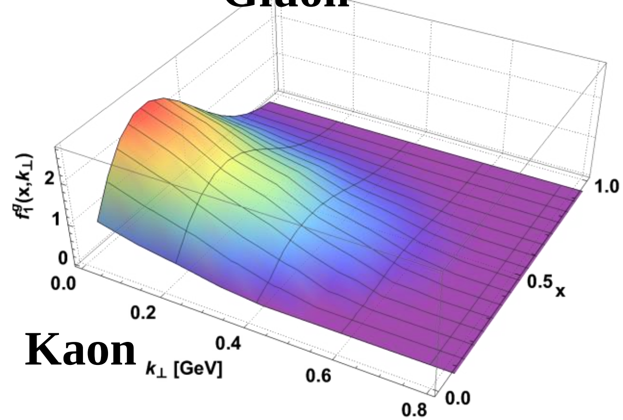


Quark $\bar{s}$



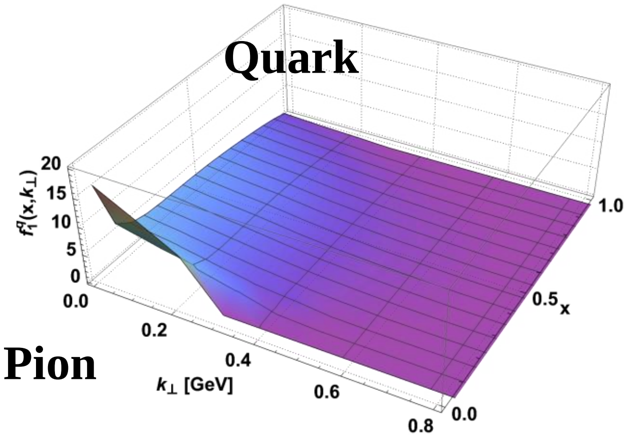
Gluon

Kaon



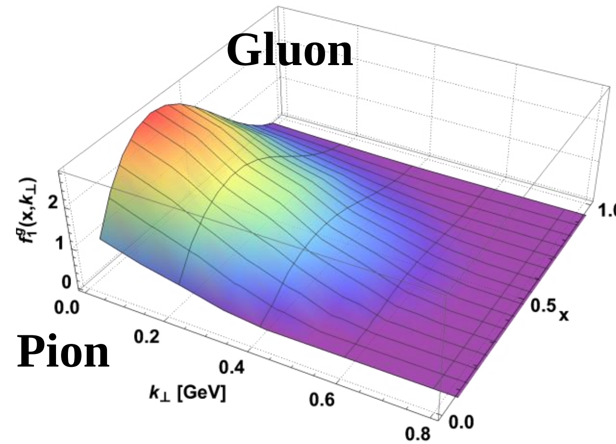
Quark

Pion



Gluon

Pion



- The TMD decreases with $k_\perp$
- Quark u and $\bar{s}$ contents enhanced at small x with $|q\bar{s}g\rangle$
- A peak for $\bar{s}$ quark

[Jiangshan Lan, et al, in preparation]

Conclusion & Outlook

- Light-front Hamiltonian approach: **Mass Spectrum** ⟺ **Structure**

- Compared to NJL interaction, dynamical gluon in light meson:
  - ✓ Explains the properties of excited/exotic states such as $\pi(1300)$, $\pi_1(1400)$
  - ✓ Describes EMFF, $F(Q^2) \propto 1/Q^2$ for large Q^2
  - ✓ Improves endpoint behavior in PDF/PDA
  - ✓ Generates more gluon at moderate x/less gluon at small x
  - ✓ Improves agreement on J/ψ production cross section with experimental data

- Preliminary results on **gluon** **GPDs** and **TMDs** of light mesons

- It works on strangeonia and strange mesons

- Systematically expandable by including higher Fock sectors

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

Thank you for your attention!