Intrinsic gluons and their impact on hadron parton structure

-perspectives from Dyson-Schwinger equations

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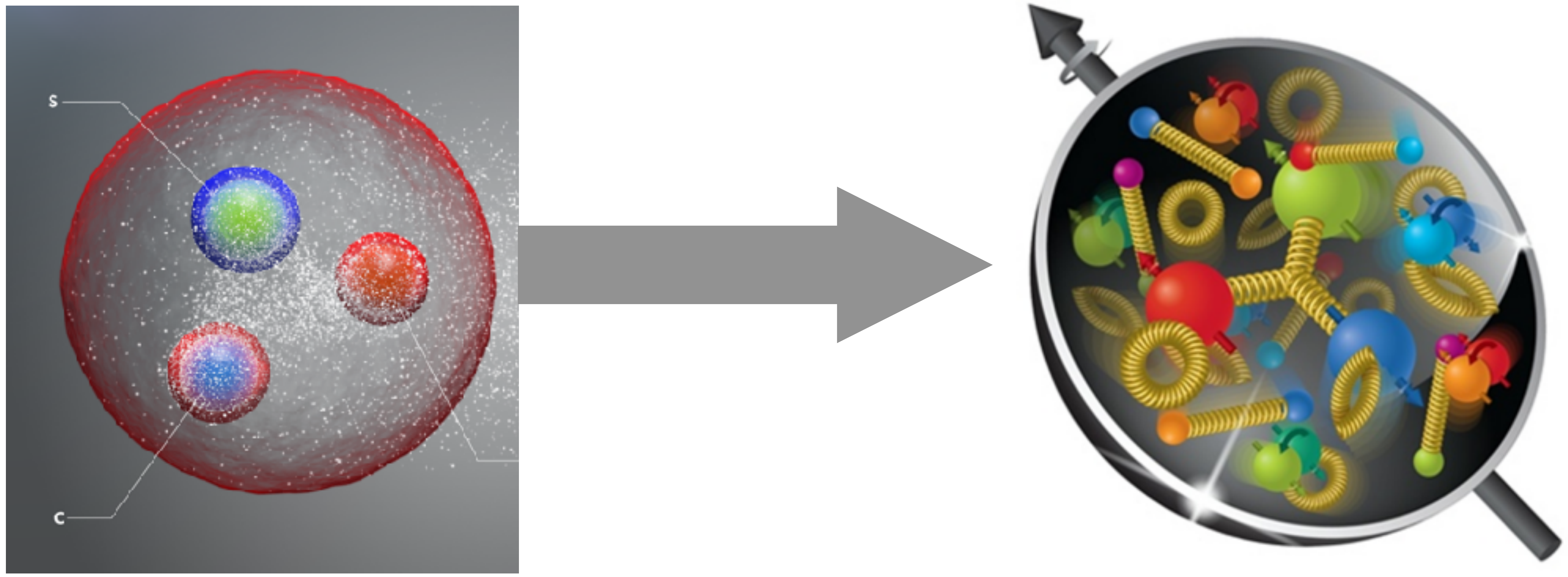
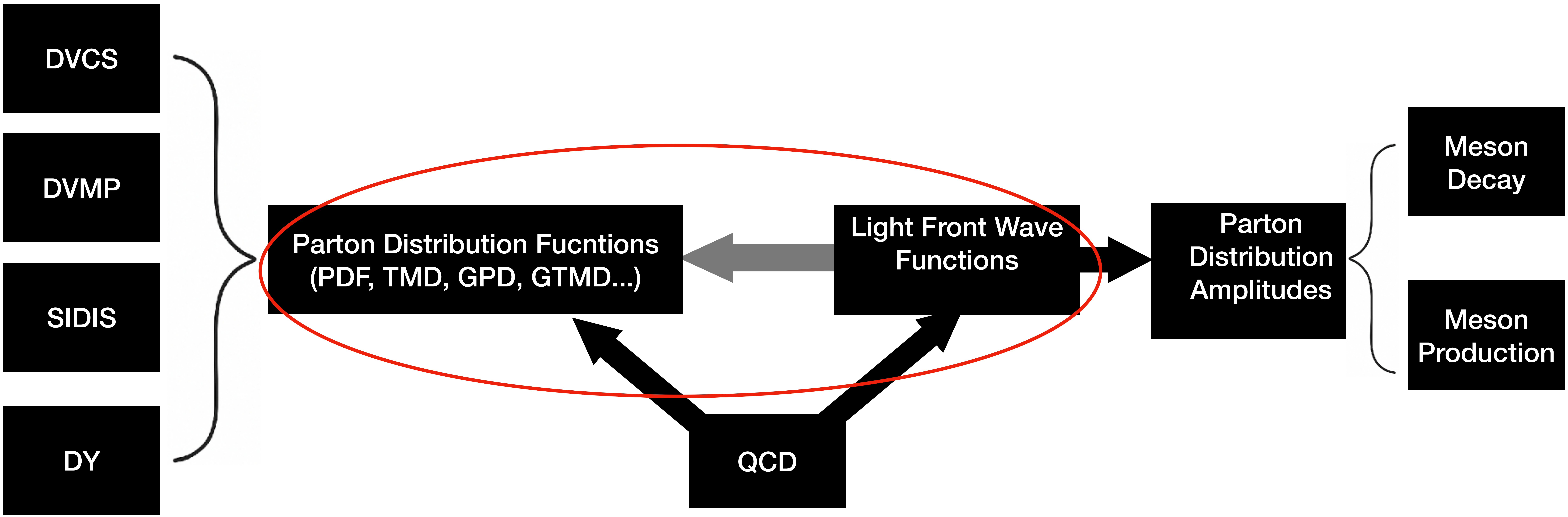
Intrinsic gluons

- **Intrinsic gluons** refer to gluons that are part of the **nonperturbative bound-state structure of a hadron**, rather than gluons generated dynamically through short-time perturbative radiation.
- Theoretically, they indicate gluonic Fock components are indispensable in nonperturbative Fock-state expansion $|proton\rangle = |qqq\rangle + |qqqg\rangle + |qqqgg\rangle + \ldots$.



Parton physics



Outline

- Light front wave functions in presence of intrinsic gluons.
- Parton distribution functions in presence of intrinsic gluons.
- Summary.

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Light-Front Wave Functions

$$|M\rangle = |q\bar{q}\rangle + |q\bar{q}g\rangle + |q\bar{q}gg\rangle + \ldots$$

$$|M\rangle = \sum_{\lambda_1,\lambda_2} \int \frac{d^2\boldsymbol{k}_T}{(2\pi)^3} \frac{dx}{2\sqrt{x\bar{x}}} \frac{\delta_{ij}}{\sqrt{3}} \underline{\Phi_{\lambda_1,\lambda_2}(x,\boldsymbol{k}_T)}\, b^\dagger_{f,\lambda_1,i}(x,\boldsymbol{k}_T)\, d^\dagger_{h,\lambda_2,j}(\bar{x},\bar{\boldsymbol{k}}_T)|0\rangle. + |q\bar{q}g\rangle + \ldots$$

$q\bar{q}$-Light-Front Wave Function

- LFWFs can be obtained by diagonalizing light front Hamiltonian, which gets complicated by higher Fock-states.

$$\hat{H}|\psi\rangle = E|\psi\rangle$$

- LFWFs can also be obtained by projection Bethe-Salpter wave functions onto light front, without the need to impose Fock-state truncation.

$$\langle b^+_\alpha d^+_\beta | h\rangle$$

('thooft, NPB1978)

(H. Liu and D. Soper, PRD1993)

(M. Burkardt, X. Ji, F. Yuan, PLB 2002)

Light mesons $q\bar{q}$−LFWFs

$$\Phi^{\{\Lambda\}}_{\lambda,\lambda'}(x,\boldsymbol{k}_T) = -\frac{1}{2\sqrt{3}}\int \frac{dk^- dk^+}{2\pi}\delta(xP^+ - k^+)\ \mathrm{Tr}\left[\Gamma_{\lambda,\lambda'}\gamma^+ S_f(k_\eta)\Gamma^\chi(k;P)\{\cdot\epsilon_\Lambda(P)\}S_g(k_{\bar{\eta}})\right]$$

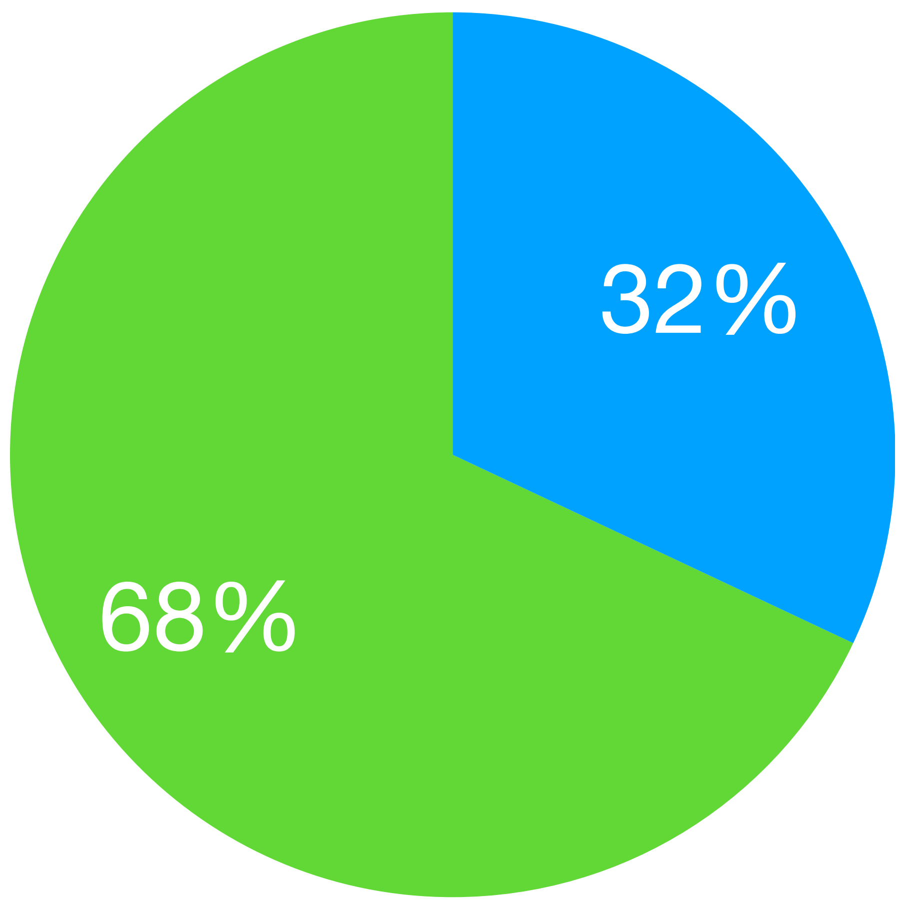
C.S., Y. Xie, M Li, X. Chen, et al,
Phys.Rev.D 104 (2021) 9, L091902

$$|M\rangle = |q\bar{q}\rangle + |q\bar{q}g\rangle + |q\bar{q}gg\rangle + \ldots$$

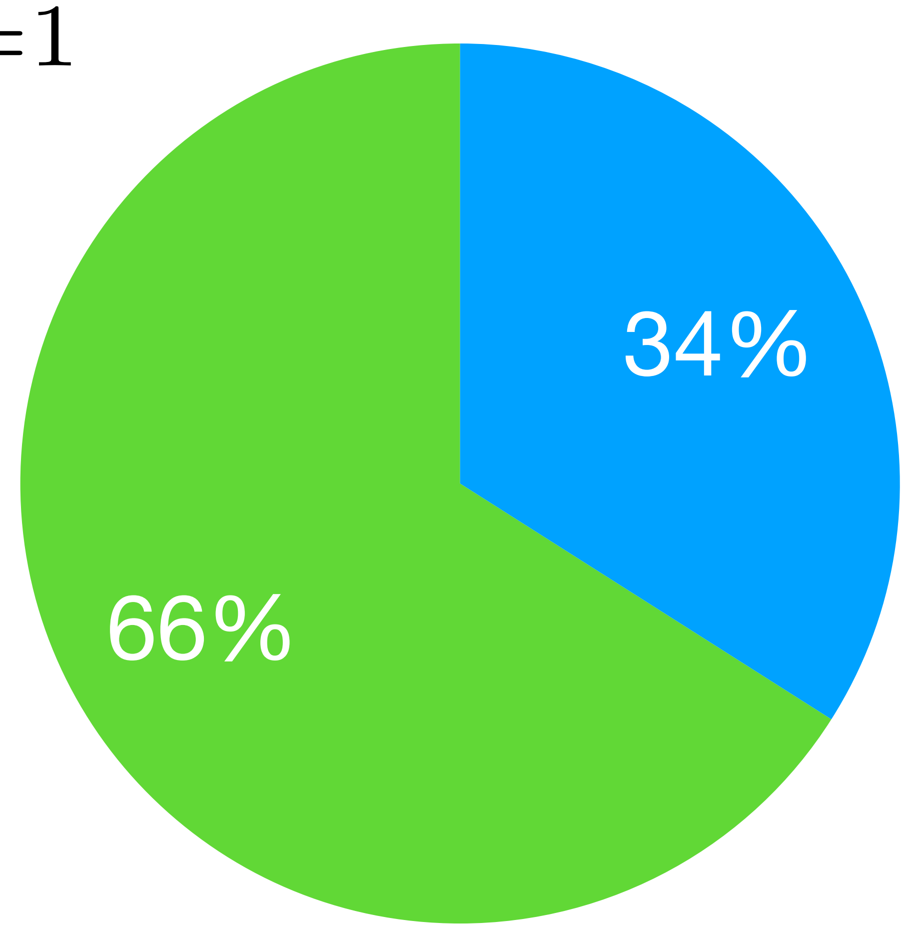
$$HF = \langle q\bar{q}g|q\bar{q}g\rangle + \langle q\bar{q}gg|q\bar{q}gg\rangle + \ldots = 1 - \langle q\bar{q}|q\bar{q}\rangle$$

Phys.Rev.Lett. 122 (2019) 8, 082301
Phys.Rev.D 101 (2020) 7, 074014
Phys.Rev.D 104 (2021) 9, 094016
Phys.Rev.D 106 (2022) 1, 014026
Phys.Rev.D 107 (2023) 7, 074009

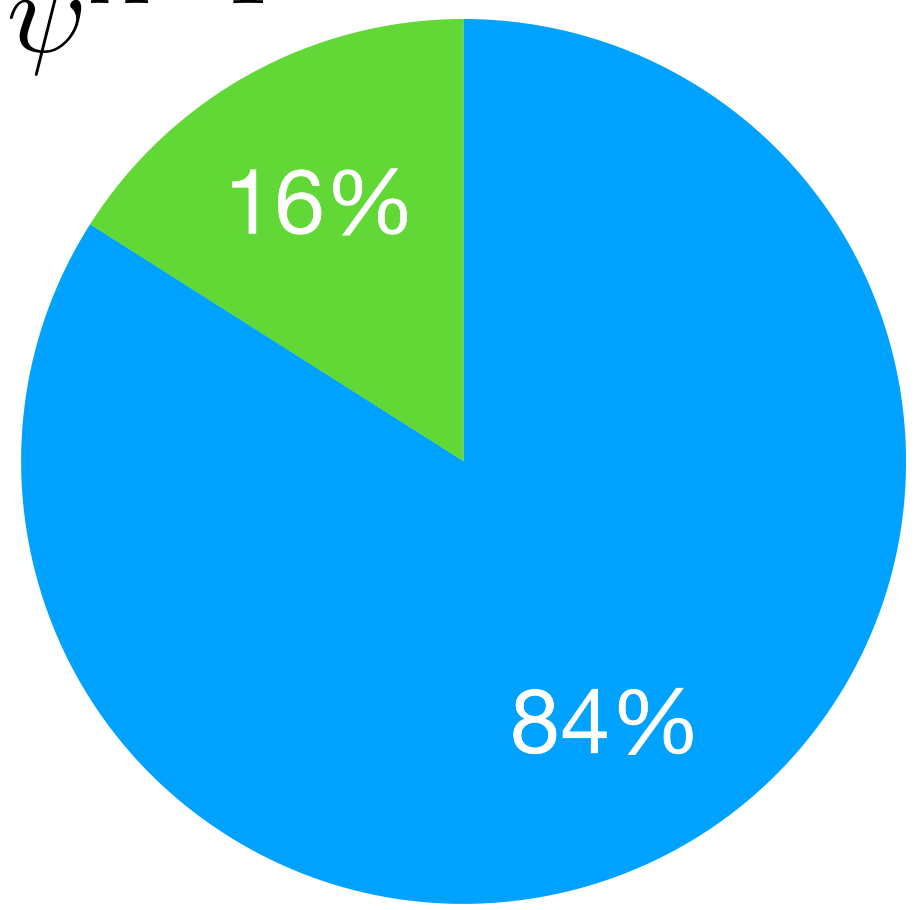
π



$\rho^{\Lambda=1}$

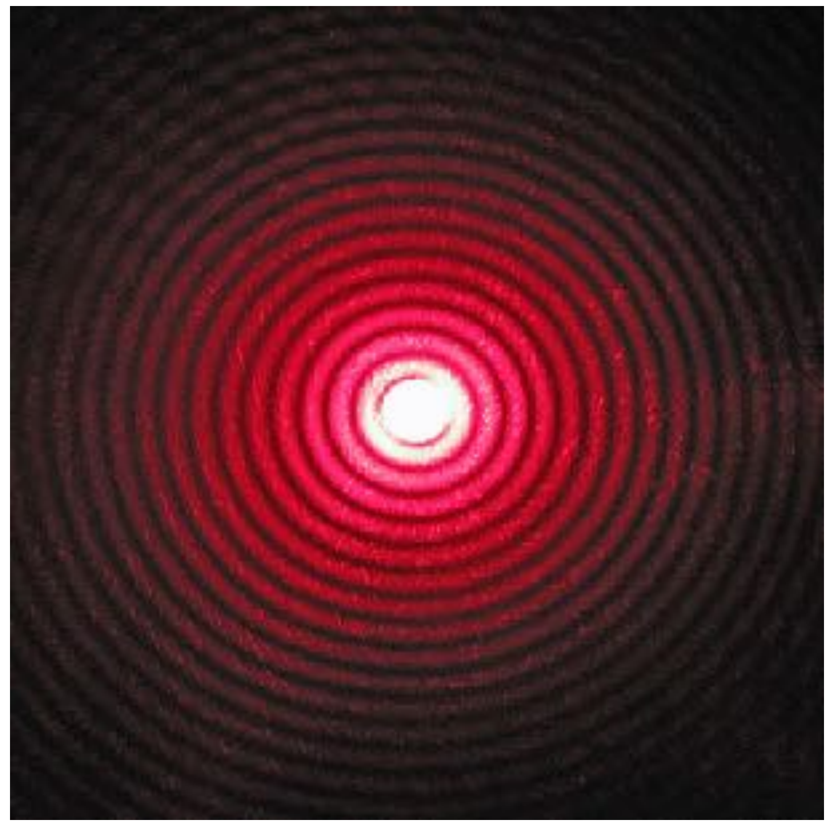


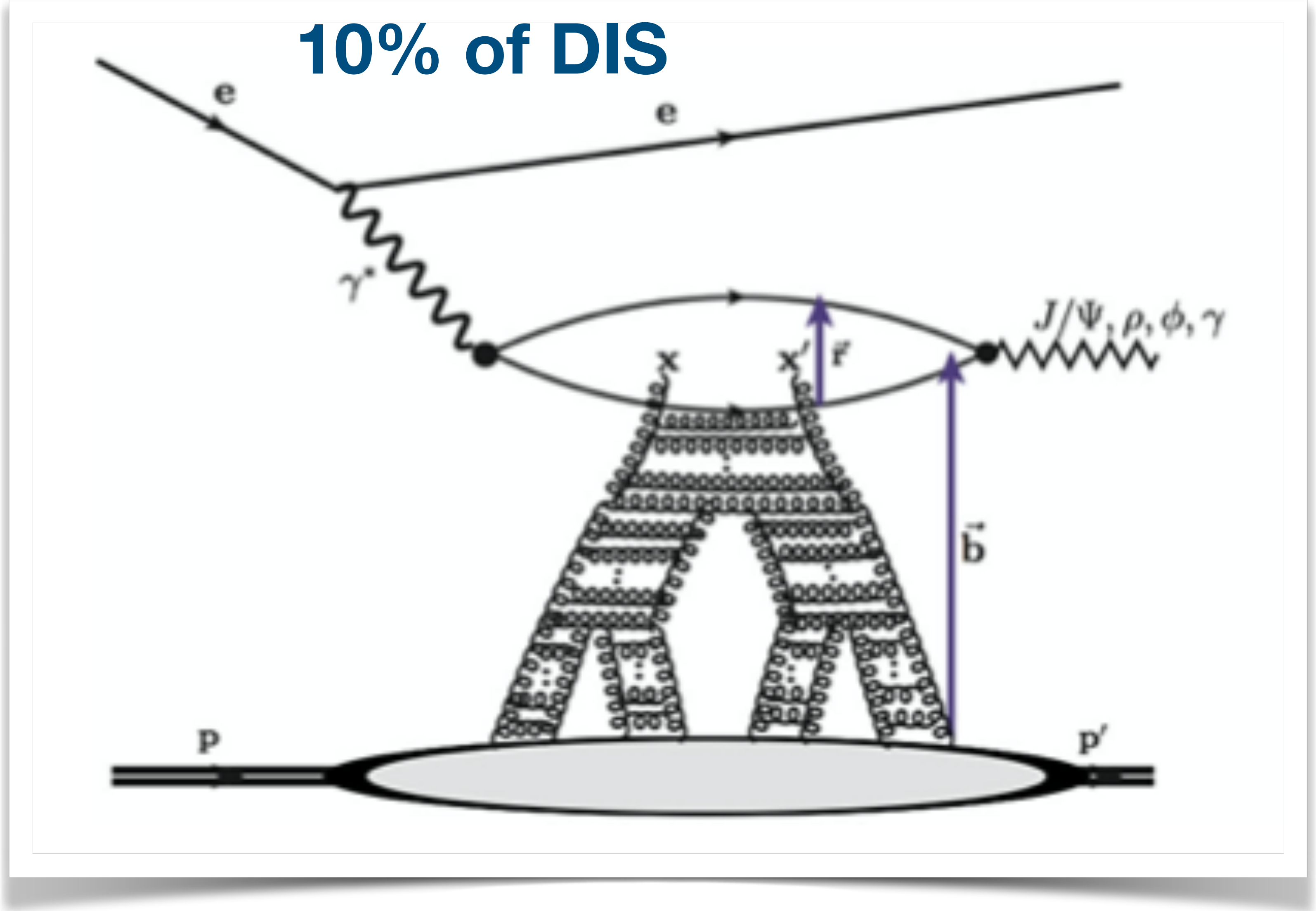
$J/\psi^{\Lambda=1}$



- Gluonic components contribute significantly.

Diffractive Vector Meson Production





- Color Dipole Picture of diffractive VM production

$$\sigma \sim \phi_{\gamma^*}^{q\bar{q}} \otimes \sigma_{q\bar{q},N} \otimes \phi_V^{q\bar{q}}$$

$$\sigma_{q\bar{q},N} \sim g^2(x)$$

Sensitive to small x gluons!

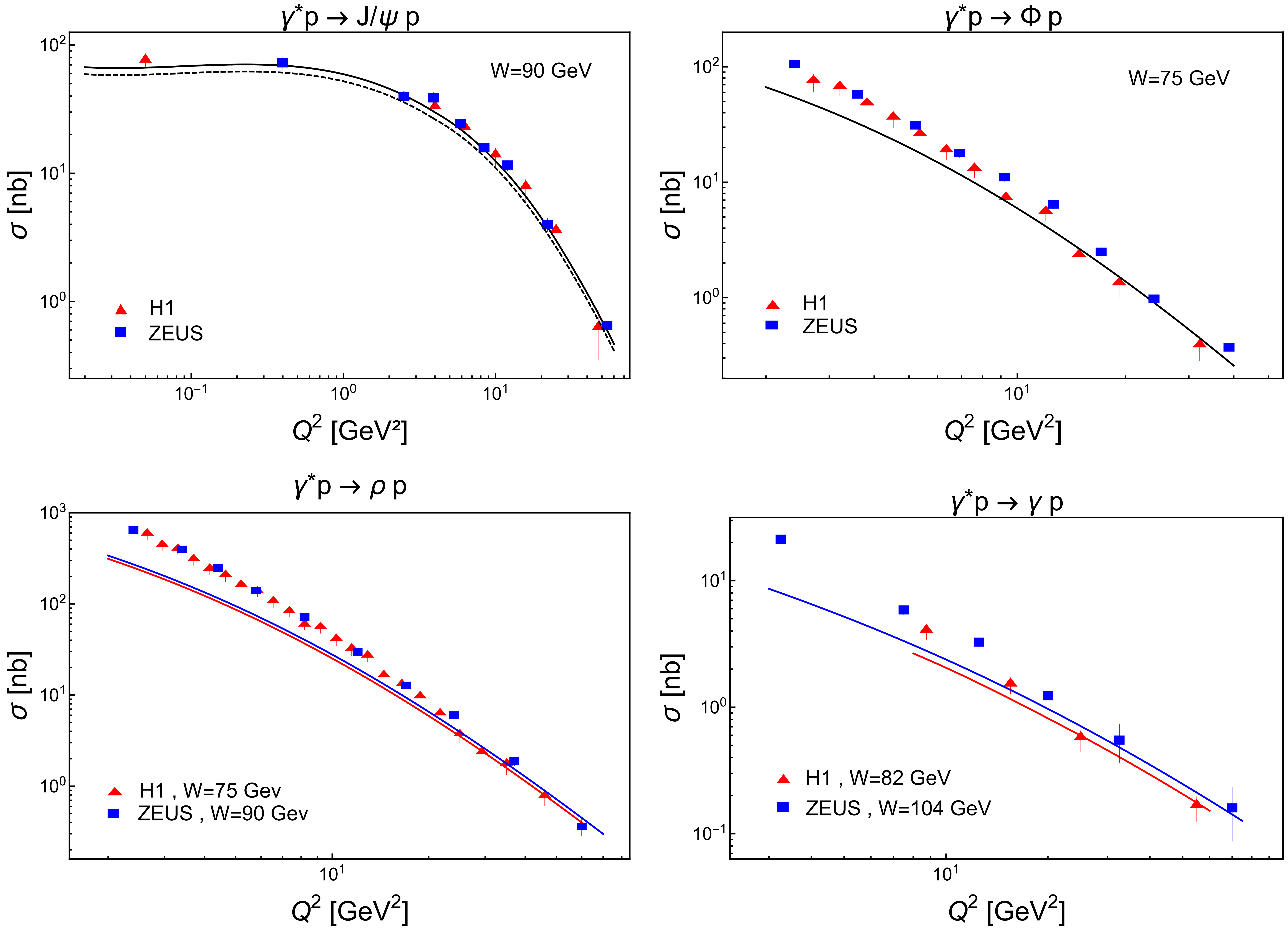
$\phi_{\gamma*}^{q\bar{q}}$ QED+light-cone perturbation

$\sigma_{q\bar{q},N}$ Color-dipole and nucleon scattering amplitude

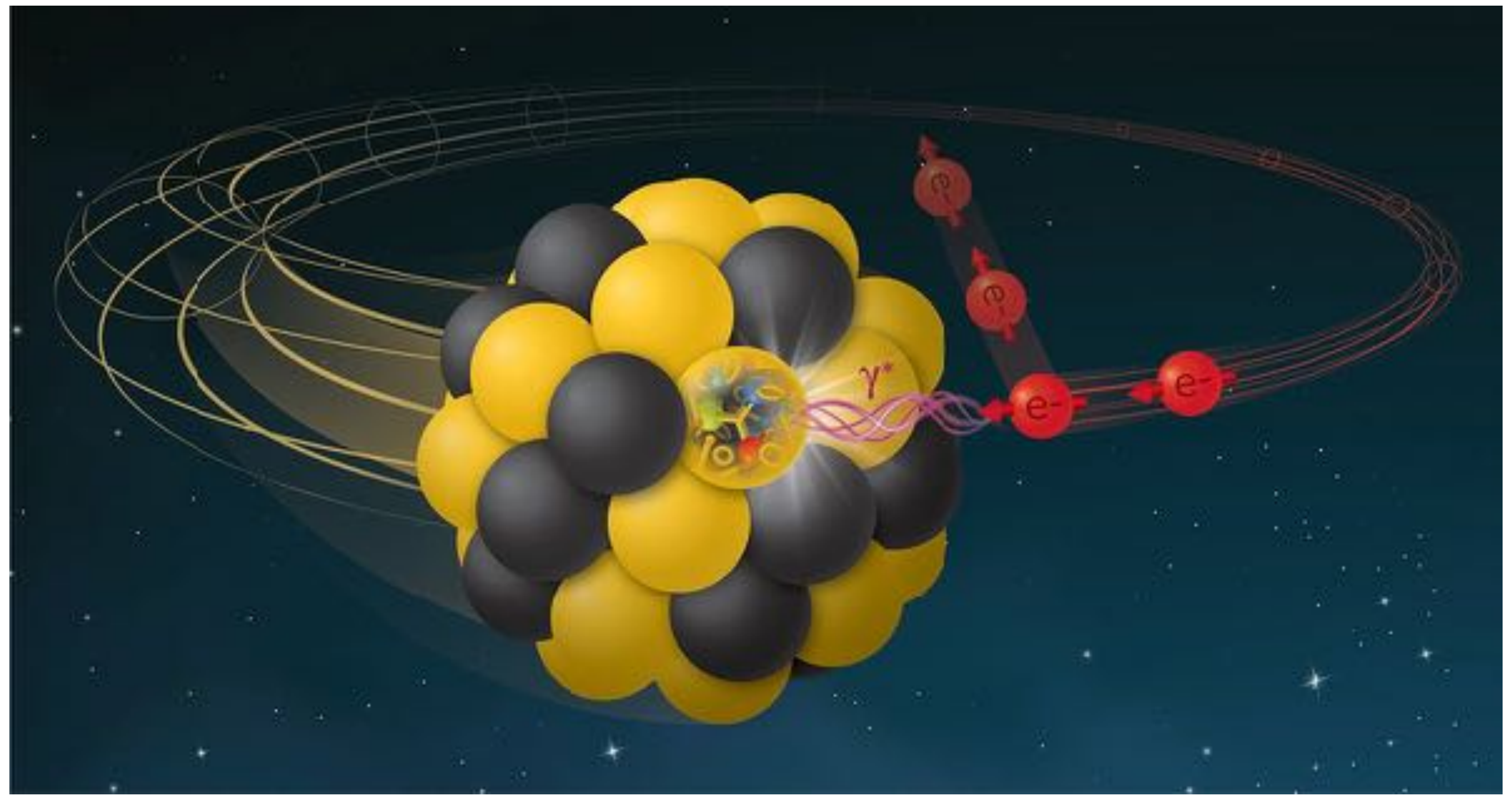
EIC: color glass condensate

$\phi_V^{q\bar{q}}$ Vector particle LF-LFWFs

Color Dipole ($q\bar{q}/Q\bar{Q}$) as Probes for Saturation



- "underscores the special role of ϕ electroproduction in the color-dipole picture: it strikes a balance between the large dipole size typical of light mesons and the smaller size associated with high-Q2 photons, making it potentially well suited for probing gluon saturation effects."



CS, et al, Phys.Rev.D 112 (2025) 7, 074027

Outline

- Light front wave functions in presence of intrinsic gluons.
  - Considerable intrinsic gluons reside in light mesons.
  - Intrinsic gluons affect the search for gluon saturation effects in exclusive vector particle production.
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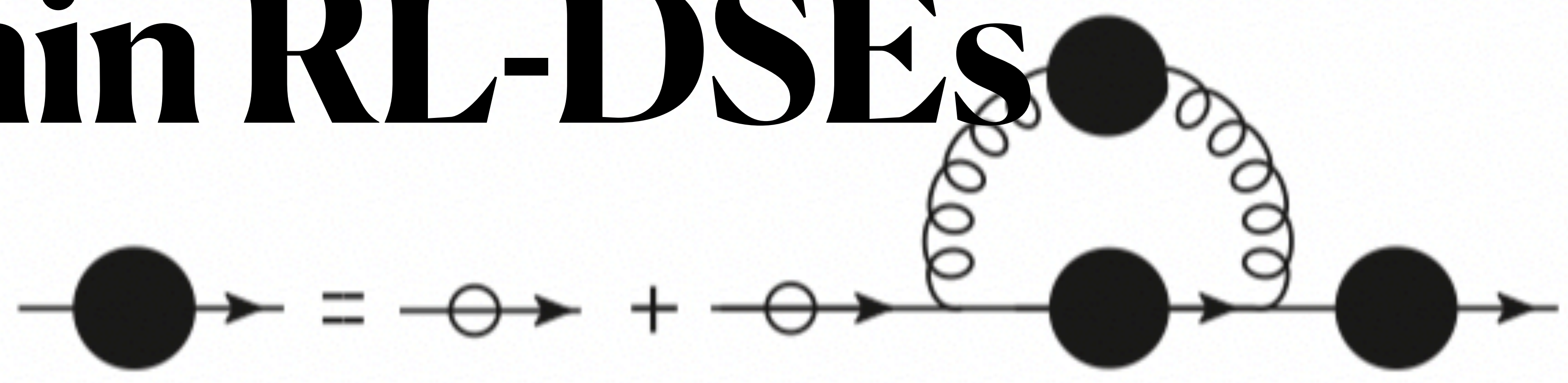
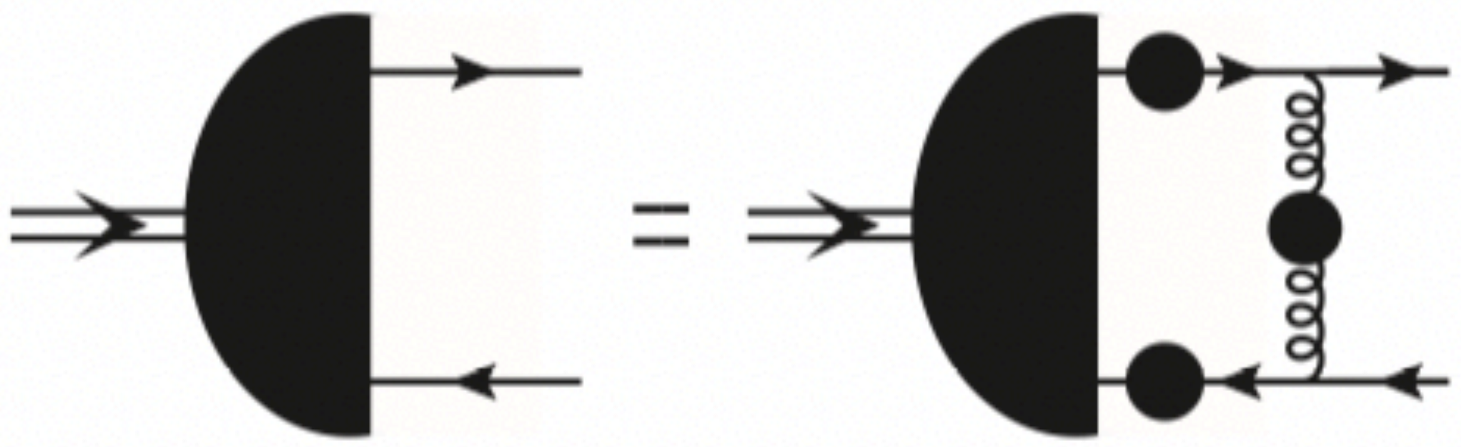
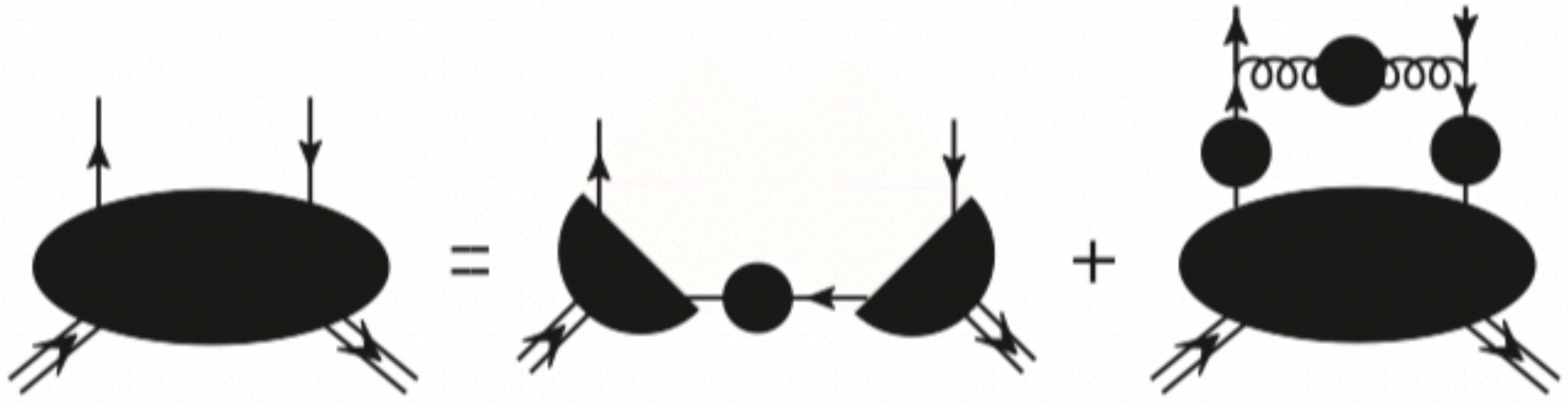
PDFs with ALL Fock-states within RL-DSEs



- Quark DSE.
- Meson BSE.
- We introduce a new DSE aimed for quark-quark correlation matrix, which is the generating function of almost all leading and subleading-twist PDFs concerned.

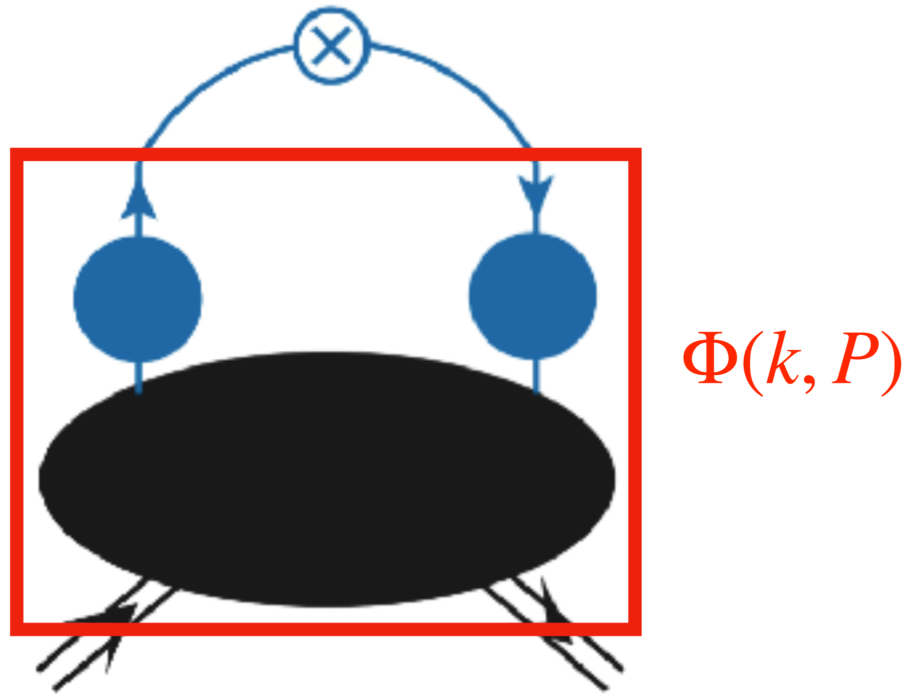


$$\Phi_{ij}(k,P) = \int \mathrm{d}^4\xi \; \mathrm{e}^{\mathrm{i}k\cdot\xi} \langle \mathrm{P}|\bar{\psi}_\mathrm{j}(0)\psi_\mathrm{i}(\xi)|\mathrm{P}\rangle.$$

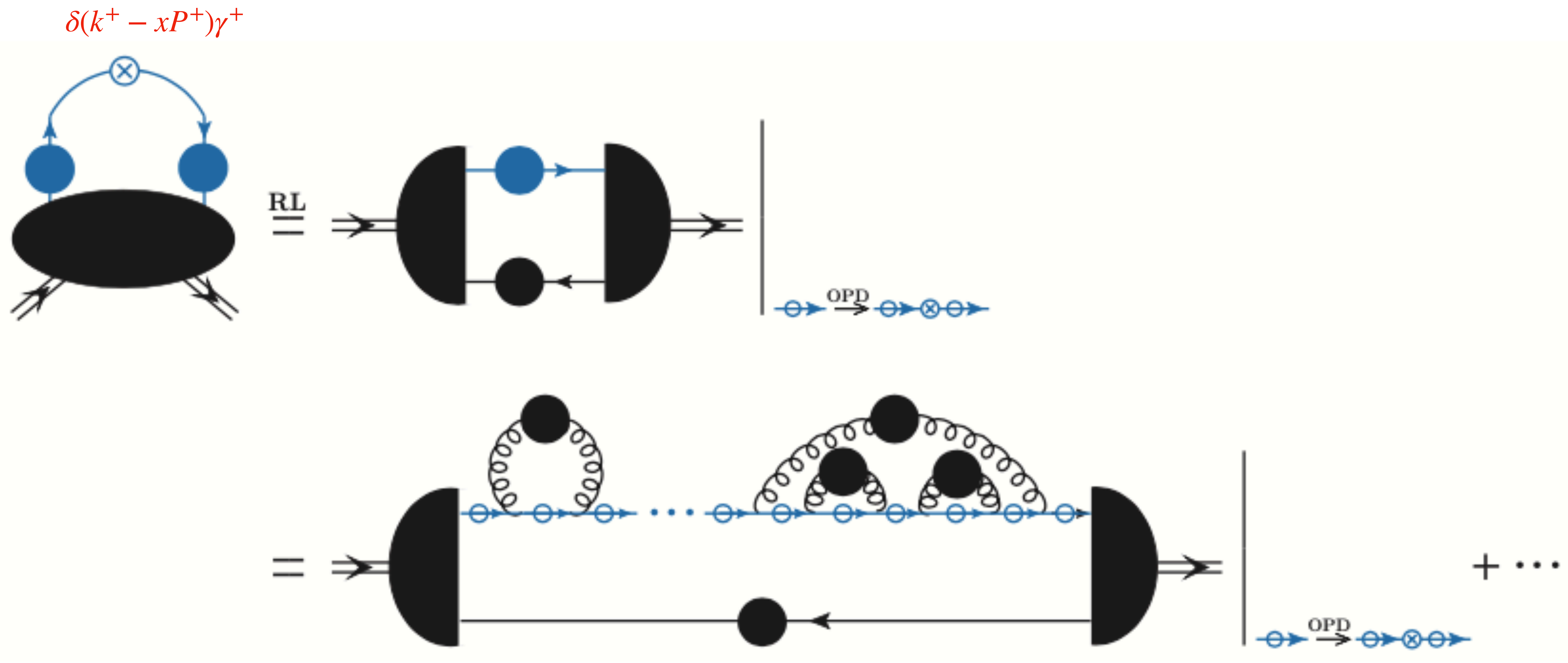


- PDFs can be extracted from Φ by

$$f(x) = \frac{1}{2}\int \frac{\mathrm{d}^4k}{(2\pi)^4}\delta(k_\eta^+ - xP^+)\mathrm{Tr}\left[\Phi(k,P)\Gamma_f\right]$$

$f(x) =$ 

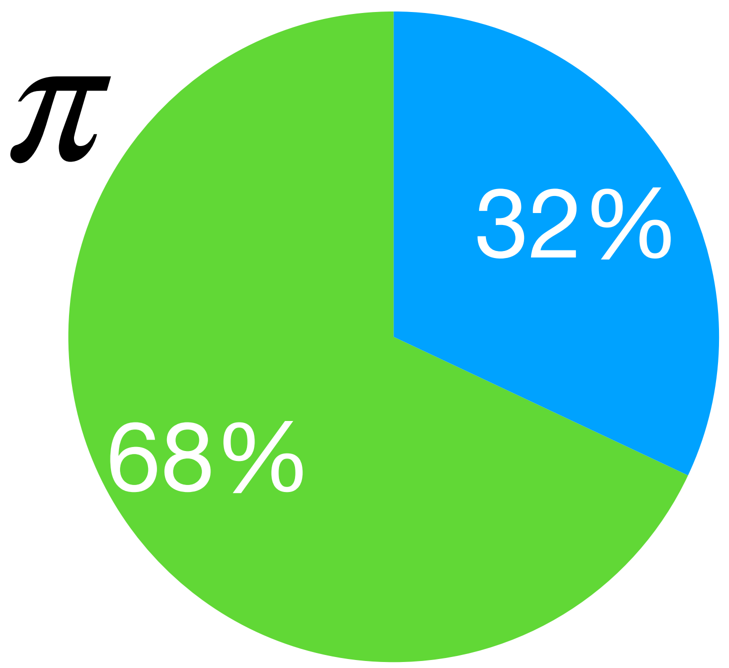
Probing every current quark within dressed quark



- EVERY bare quark propagator (parton) in the dressed quark propagator is probed by the light-cone vertex concerned.

Pion unpolarized PDF

$$\Phi_{ij}(k,P) = \int d^4\xi\, e^{ik\cdot\xi} \langle P|\bar{\psi}_j(0)\psi_i(\xi)|P\rangle.$$

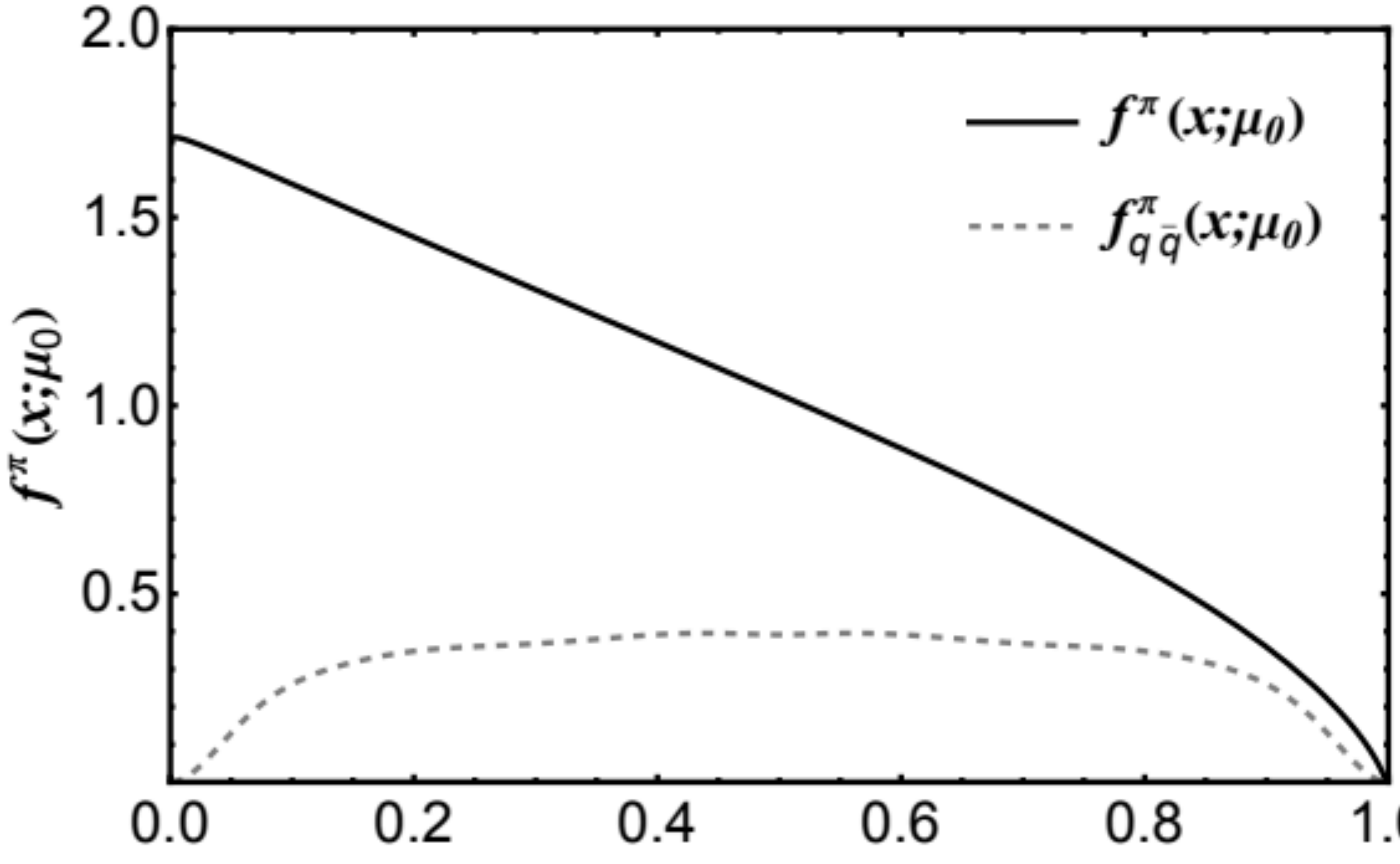


$$f_\pi(x) = \frac{1}{2}\int \frac{d^4k}{(2\pi)^4}\delta(k_\eta\cdot n - xP\cdot n)\mathrm{Tr}\,[\Phi(k,P)\not{n}]$$

$$|M\rangle = \phi_2|q\bar{q}\rangle + \phi_3|q\bar{q}g\rangle + \phi_4|q\bar{q}gg\rangle + \dots$$

m	0	1	2	3	4	5	6	7
$\langle(2x-1)^m\rangle_\pi$	1.00	-0.257	0.321	-0.159	0.189	-0.114	0.134	-0.0899

- $2\langle x\rangle_q = 0.74 \rightarrow \langle x\rangle_g = 0.26$, a fraction of momentum is carried away by intrinsic gluons.
- Intrinsic gluons substantially changes the profile of pion PDF at hadronic scale.

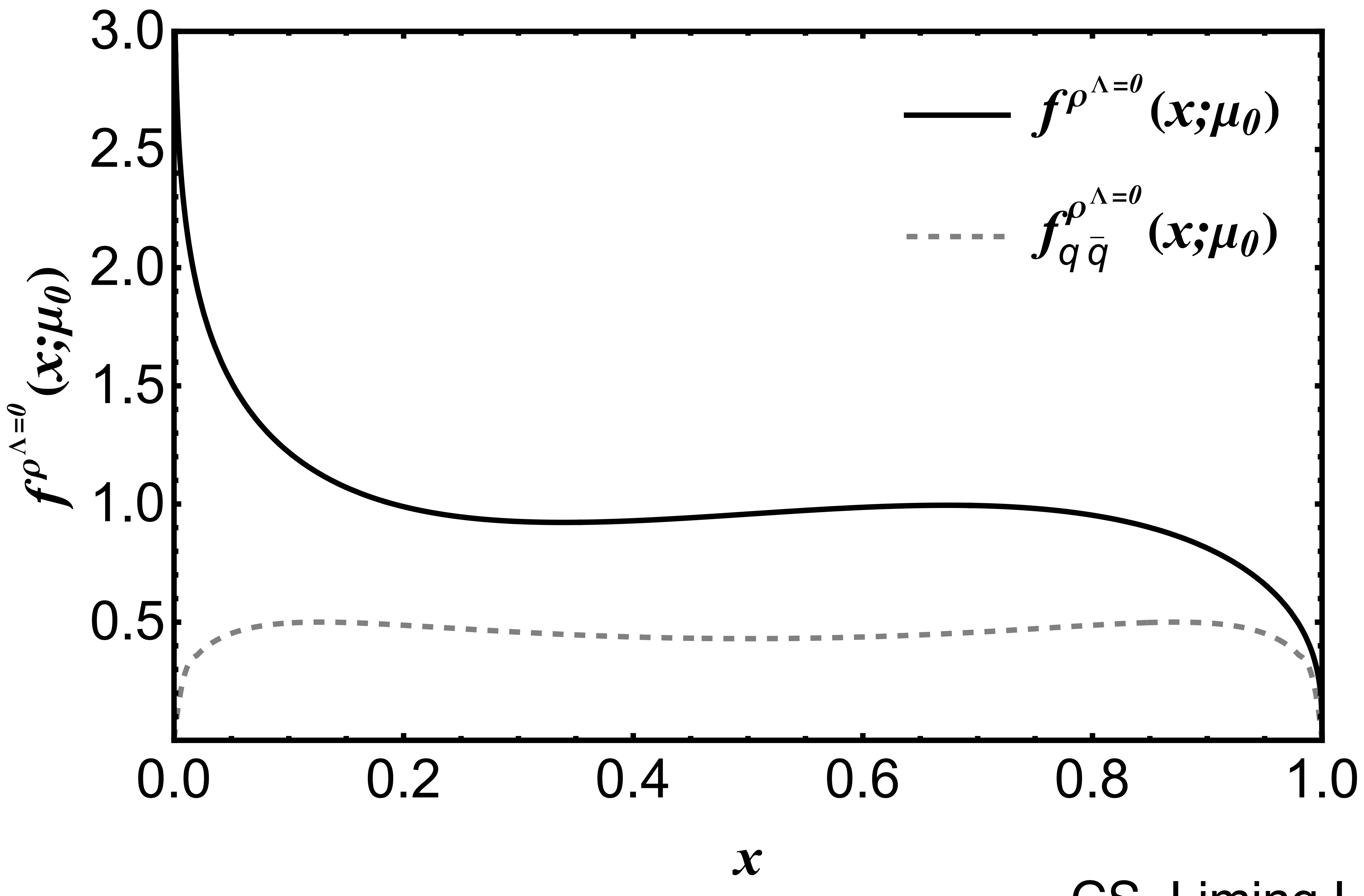


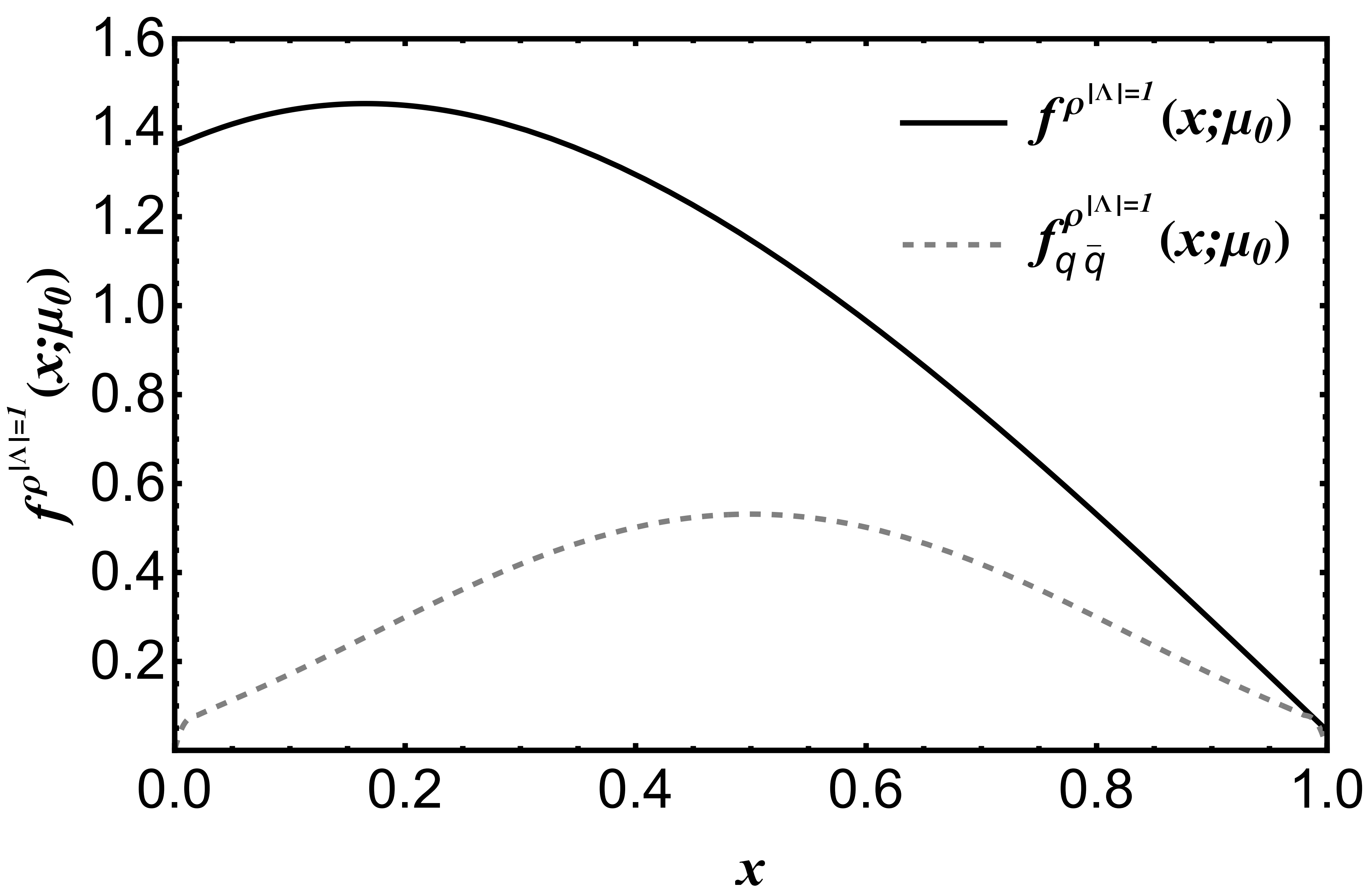
CS, Liming Lu, Wenbao Jia, arXiv:2602.24187

Rho unpolarized PDF

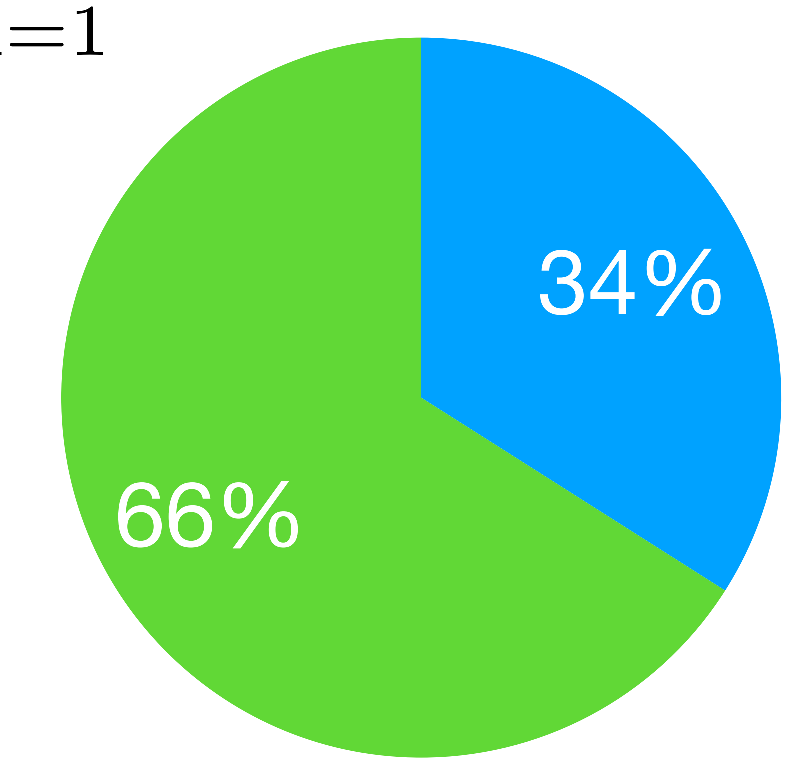
$$\epsilon_{\mu,(\Lambda)}(P)\Phi^{\mu\nu}_{ij}(k,P)\epsilon^*_{\nu,(\Lambda)}(P) = \int d^4\xi\, e^{ik_\eta\cdot\xi}\ {}_{\boldsymbol{n}}\langle P,\Lambda|\bar{\psi}_j(0)\psi_i(\xi)|P,\Lambda\rangle_{\boldsymbol{n}}$$

$$f_\rho^\Lambda(x) = \frac{1}{2}\int \frac{d^4k}{(2\pi)^4}\delta(k_\eta\cdot n - xP\cdot n)\ \mathrm{Tr}\left[\Phi_{\mu\nu}(k,P)\not{n}\right]\epsilon_{\mu,(\Lambda)}(P)\epsilon^*_{\nu,(\Lambda)}(P)$$

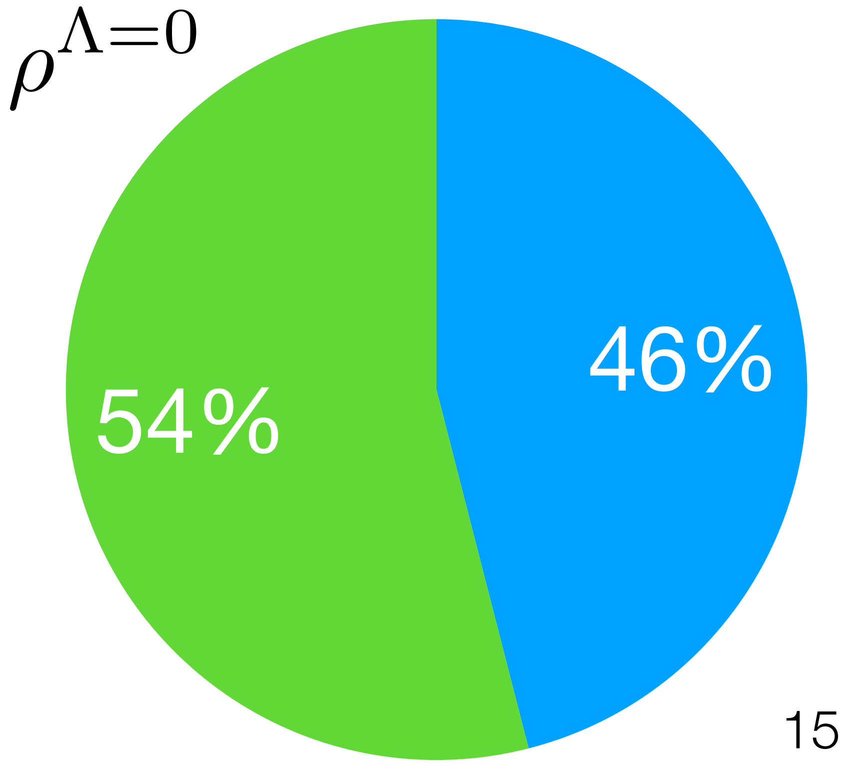




$\rho^{\Lambda=1}$



$\rho^{\Lambda=0}$



CS, Liming Lu, Wenbao Jia, arXiv:2602.24187

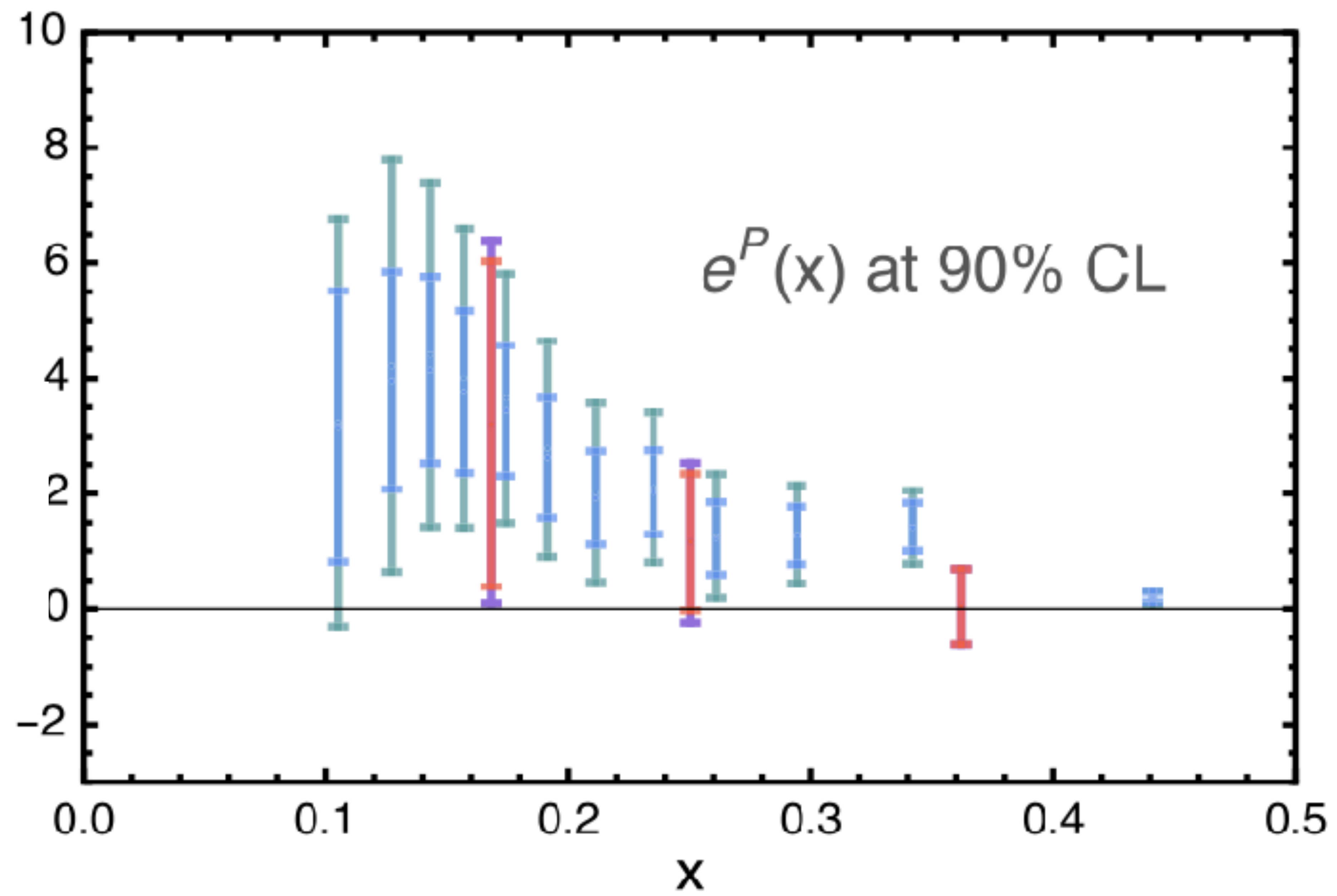
e(x) in experiment

- Dihadron SIDIS — beam single-spin asymmetry

$$e(\ell) + p(P) \to e'(\ell') + \pi^+(P_1) + \pi^-(P_2) + X,$$

$$A_{LU}^{\sin\phi_R} = \frac{\sum_q e_q^2 [x e^q(x,Q^2) H_{1,sp}^{\sphericalangle,q}(z,M_h,Q^2) + \frac{M_h}{zM} f_1^q(x,Q^2) \tilde{G}_{sp}^{\sphericalangle,q}(z,M_h,Q^2)]}{\sum_q e_q^2 f_1^q(x,Q^2) D_{1,ss+pp}^q(z,M_h,Q^2)}$$

Aurore Courtoy et al, PRD 106, 014027 (2022)
CLAS, PRL 126, 152501 (2021)
CLAS, PRC, 112, 055202 (2025)

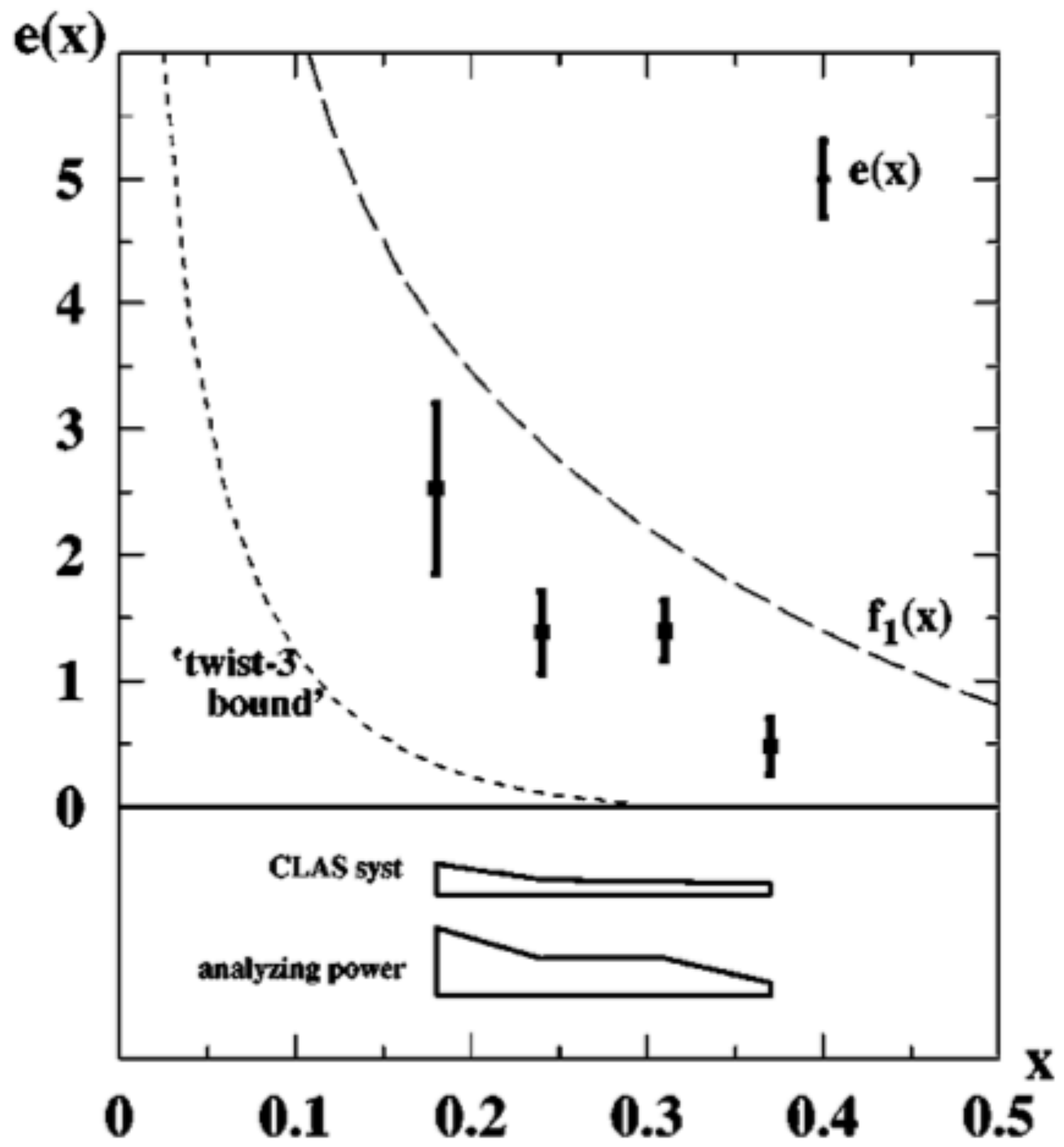


- Single-hadron SIDIS — beam single-spin asymmetry

$$ep \to e'hX$$

$$A_{LU}^{\sin\phi}(x) = \frac{1}{\langle z\rangle \sqrt{1+\langle \mathbf{P}_{N\perp}^2\rangle/\langle \mathbf{k}_\perp^2\rangle}} \frac{\int dy 4y\sqrt{1-y} M_N/Q^5 \sum_a e_a^2 x^2 e^a(x) \langle H_1^{\perp a}\rangle}{\int dy (1+(1-y)^2)/Q^4 \sum_b e_b^2 x f_1^b(x) \langle D_1^b\rangle}$$

A. Efremov, et al, PRD 67, 114014 (2003)
CLAS,arXiv:2602.1471



e(x) in theory

$$e_q(x) = \frac{P\cdot n}{M_h}\int \frac{d\lambda}{4\pi} e^{ixP\cdot n\lambda}\langle P|\bar{\psi}_q(0)[0,\lambda n]\psi_q(\lambda n)|P\rangle$$

$$\bar{\psi}(0)[0,z]\psi(z) = \bar{\psi}(0)\psi(0) +$$

zero mode

$$+\frac{1}{2}\int_0^1 du \int_0^u dv \bar{\psi}(0)\sigma^{\alpha\beta} z_\beta [0,vz] g G_{\alpha\nu}(vz) z^\nu [vz,uz]\,\psi(uz) -$$

$qg\bar{q}$-correlation

$$-im_q \int_0^1 du \bar{\psi}(0)\ \not{z}[0,uz]\,\psi(uz) -$$

current quark mass

$$-\frac{i}{2}\int_0^1 du\Big(\bar{\psi}(0)(i\not{D} - m_q)\ \not{z}[0,uz]\psi(uz) + \bar{\psi}(0)\ \not{z}[0,uz](i\not{D} - m_q)\psi(uz)\Big).$$

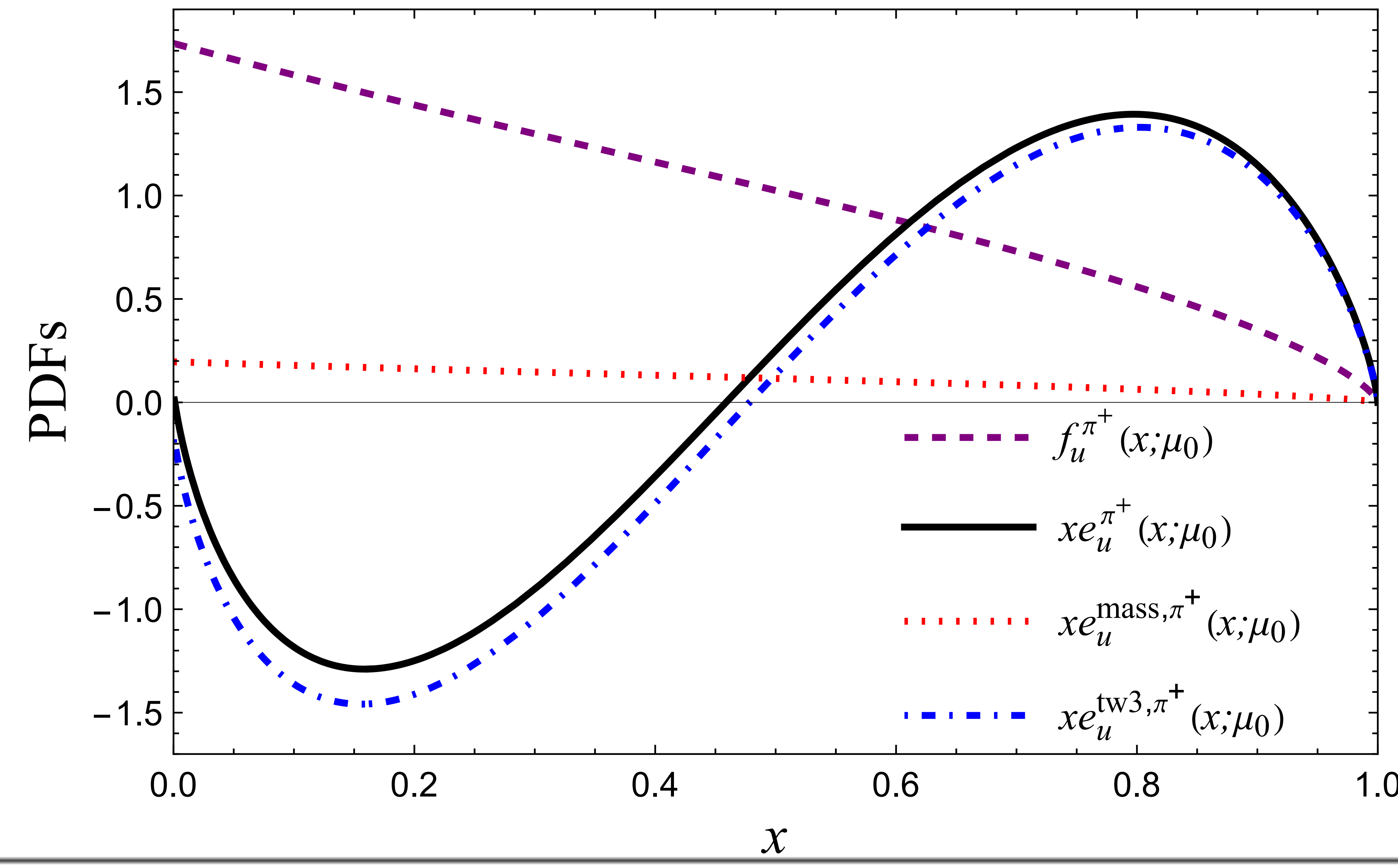
$$e_q(x) = \frac{\langle h|\bar{\psi}_q(0)\psi_q(0)|h\rangle}{2M_h}\delta(x) + \frac{m_q}{xm_h} f_q(x) + e_q^{tw3}(x)$$

Wandzura-Wilczek (WW)-type approximation is invalid

Pion e(x)

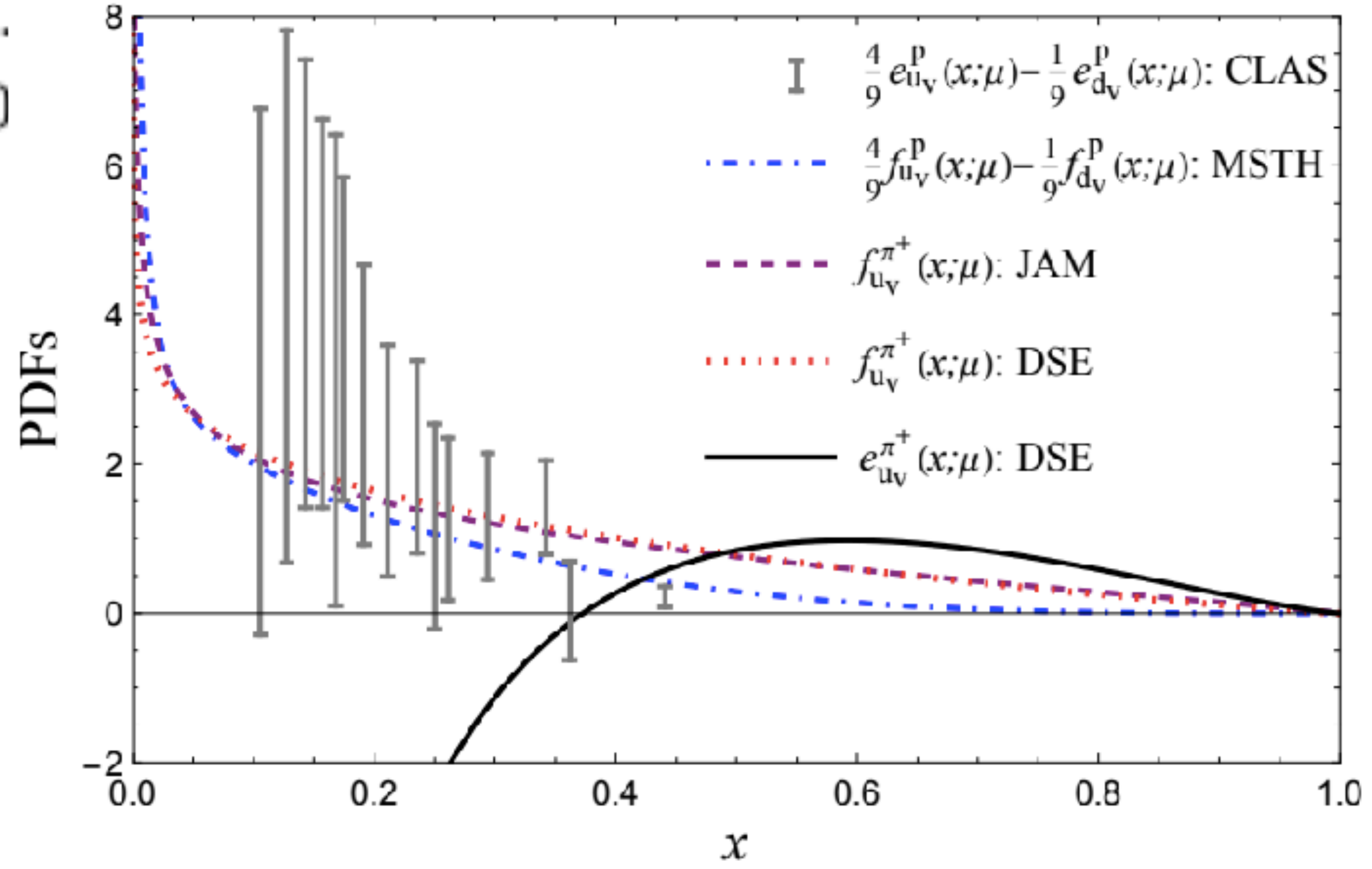
$$e_q(x) = \frac{\langle h|\bar{\psi}_q(0)\psi_q(0)|h\rangle}{2M_h}\delta(x) + \frac{m_q}{x m_h} f_q(x) + e_q^{tw3}(x)$$

$$e_\pi(x) = \frac{1}{2}\int \frac{d^4k}{(2\pi)^4}\delta(k_\eta\cdot n - xP\cdot n)\mathrm{Tr}\left[\Phi(k,P)\right]$$



n	0	1	2	3	4	5	6	7	8
$\langle x^n\rangle_{f(x)}$	1.00	0.372	0.202	0.129	0.0910	0.			
$\langle x^n\rangle_{e(x)}$	6.45	0.113	0.303	0.278	0.231	0			

- Strong indication of $\delta(x)$ is found.
- Twist-2 contribution is suppressed. $GMOR: m_q \propto m_\pi^2, \frac{m_q}{m_\pi} \to 0$
- Pure twist-3 contribution is dominant.
- We argue the nonmonotonic feature in e(x) is an imprint of intrinsic $qg\bar{q}$ correlation.
- EIC: smaller x and higher statistics.



CS, Liming Lu, Ian Cloet, Wenbao Jia, Peter Tandy, arXiv:2602.14164

Outline

- Light front wave functions in presence of intrinsic gluons.
- Parton distribution functions in presence of intrinsic gluons.
  - Intrinsic gluons substantially reshape the profile of PDFs.
  - Intrinsic gluons can generate significant $qg\bar{q}$ correlation in twist-3 PDFs.
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Summary

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  - Intrinsic gluons reside in light mesons.
  - Intrinsic gluons affect the search for gluon saturation effects in exclusive vector particle production.
- Parton distribution functions in presence of intrinsic gluons.
  - Intrinsic gluons substantially shape the profile of DFs.
  - Intrinsic gluons can generate significant $qg\bar{q}$ correlation in twist-3 PDFs.

Thank you!