Lattice QCD in the Frontier of Electron-Ion Colliders

August 2024,
Liverpool, UK

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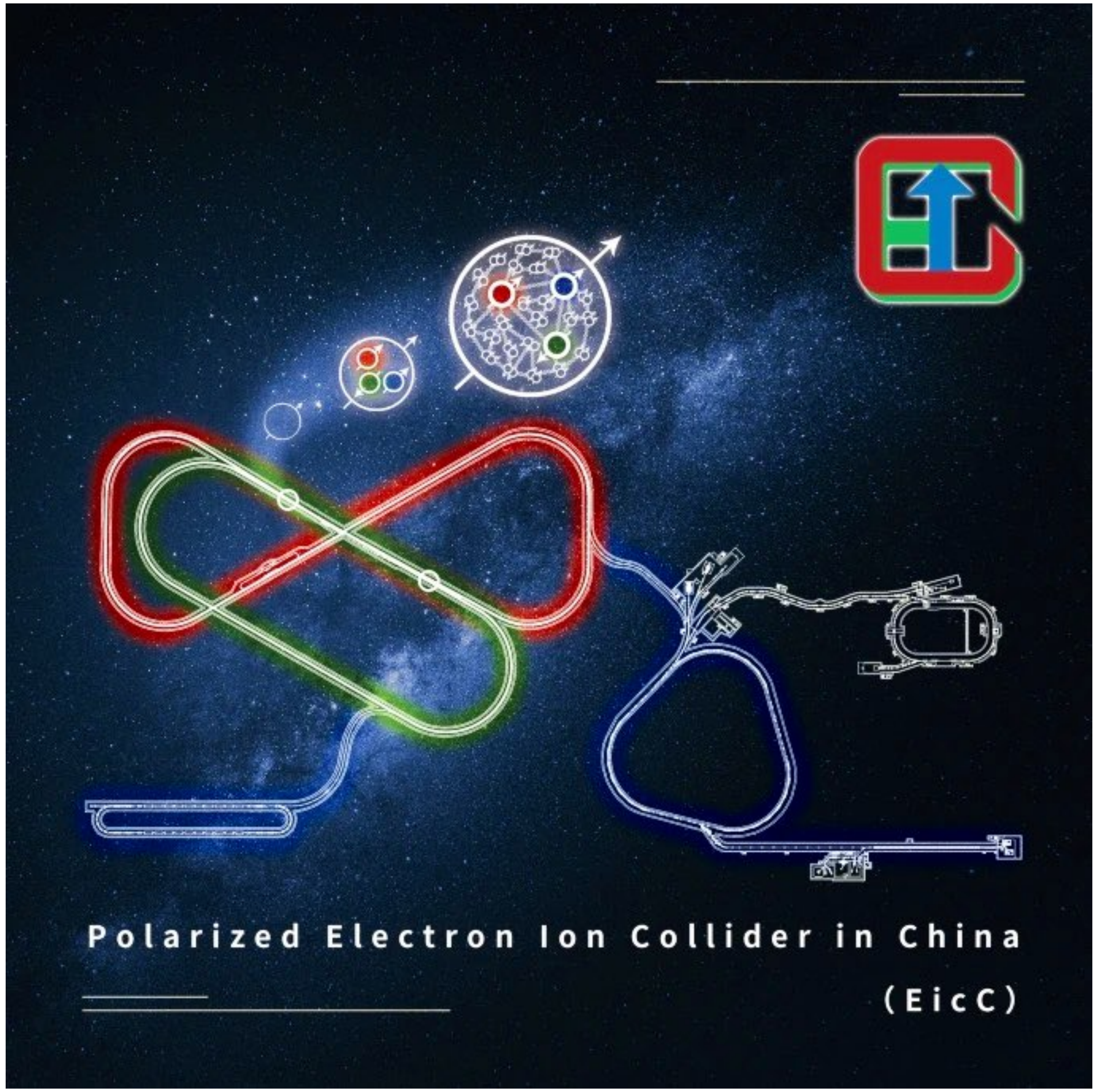
Brookhaven National Laboratory

electron-ion colliders

shine light on atoms & proton

future electron-ion colliders

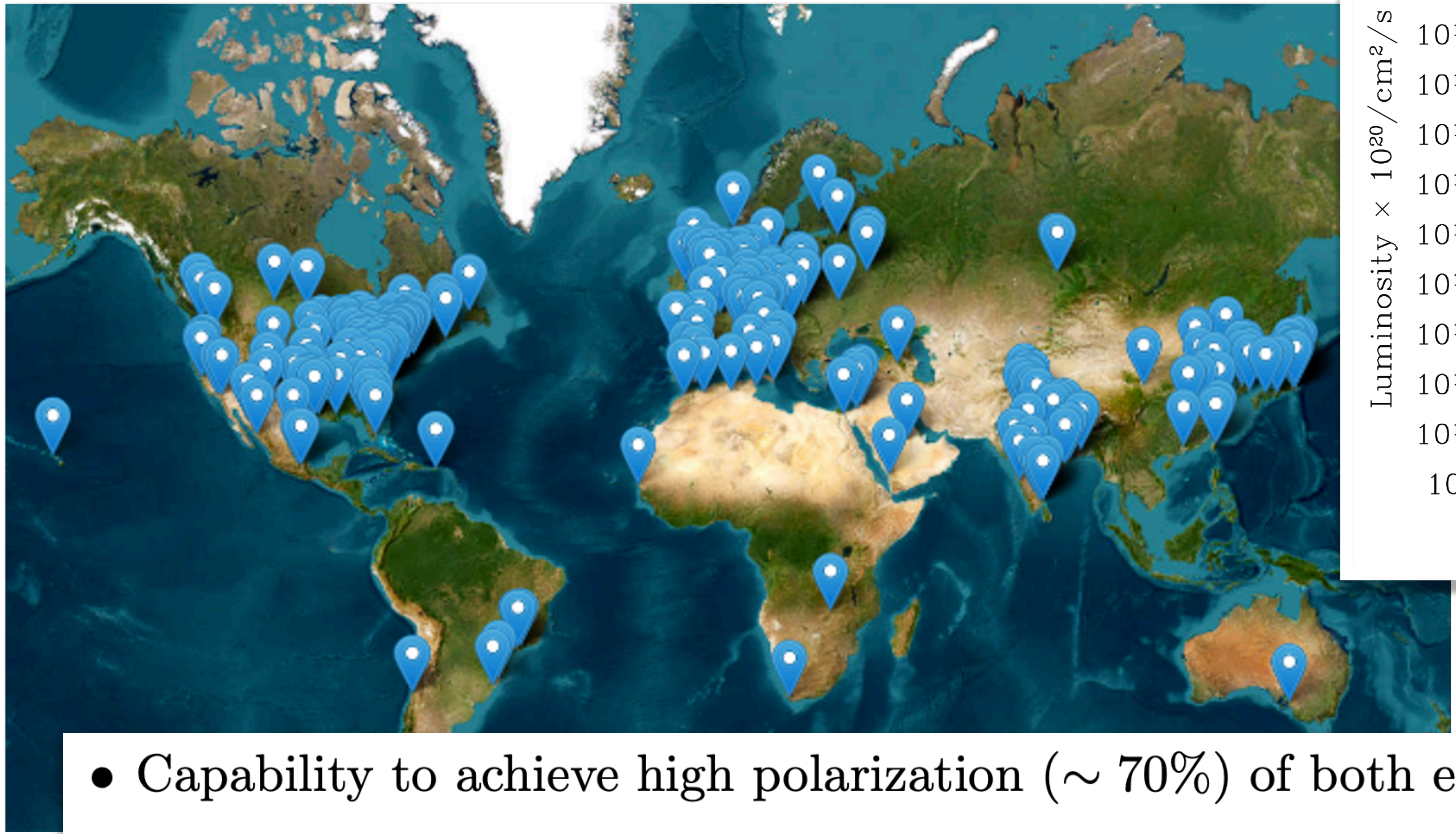
electron-ion collider in China

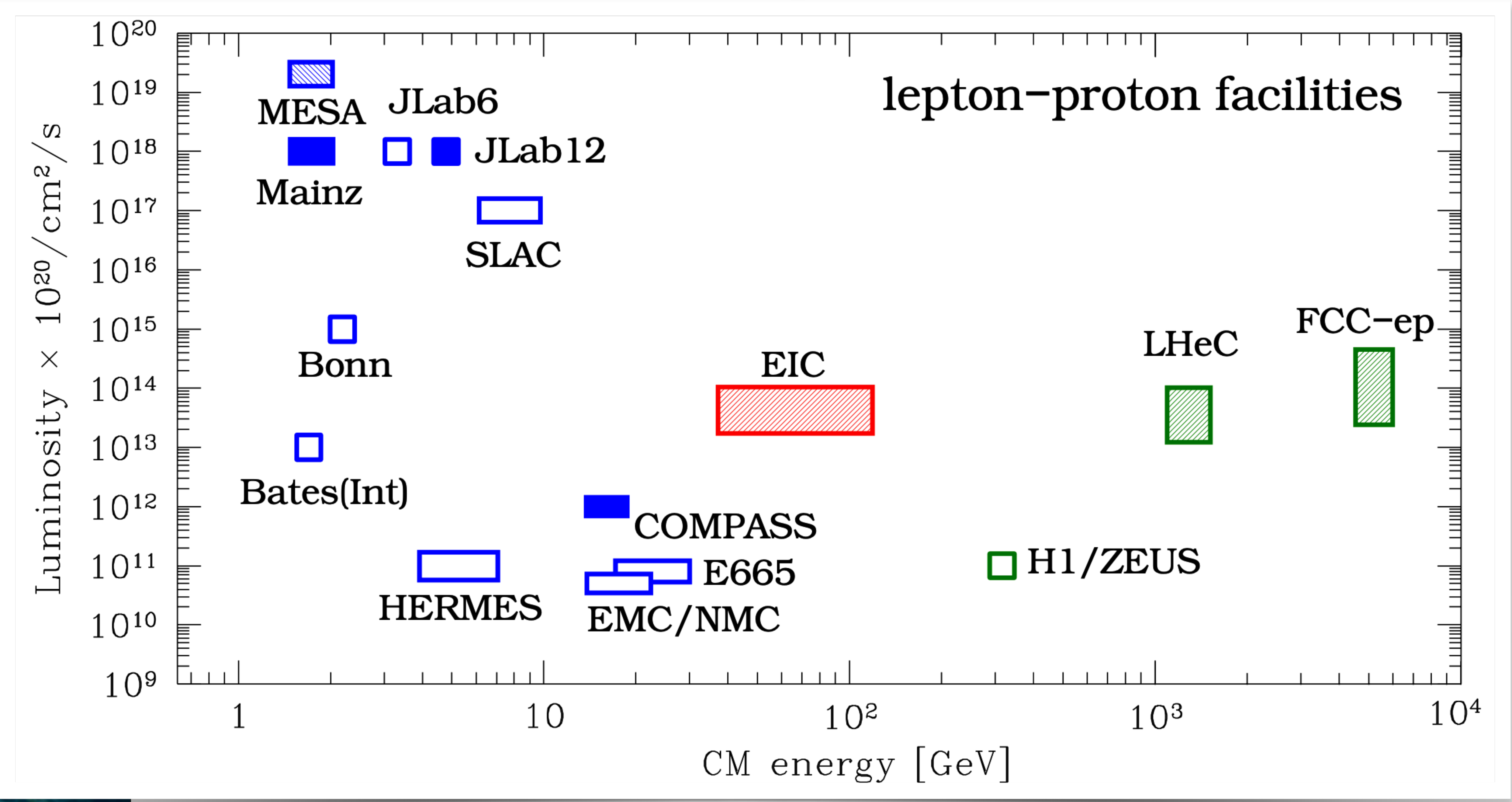


future circular collider @ CERN

Electron-Ion Collider @ Brookhaven National Laboratory

science phase: 2033 —





- Capability to achieve high polarization ($\sim 70\%$) of both electron and proton beams.
- Variable center-of-mass energies $\sqrt{s} = 20 - 100$ GeV, upgradable up to $\sqrt{s} = 140$ GeV, for $e + p$ collisions.
- Luminosity up to $10^{33} - 10^{34}$ cm^{-2}s^{-1} for $e + p$ collisions.
- Capability for colliding ion beams from deuterons to heavy nuclei, such as gold, lead or uranium.
- Flexibility to accommodate more than one interaction regions.

Major research and innovation infrastructure investment announced

UK Research and Innovation

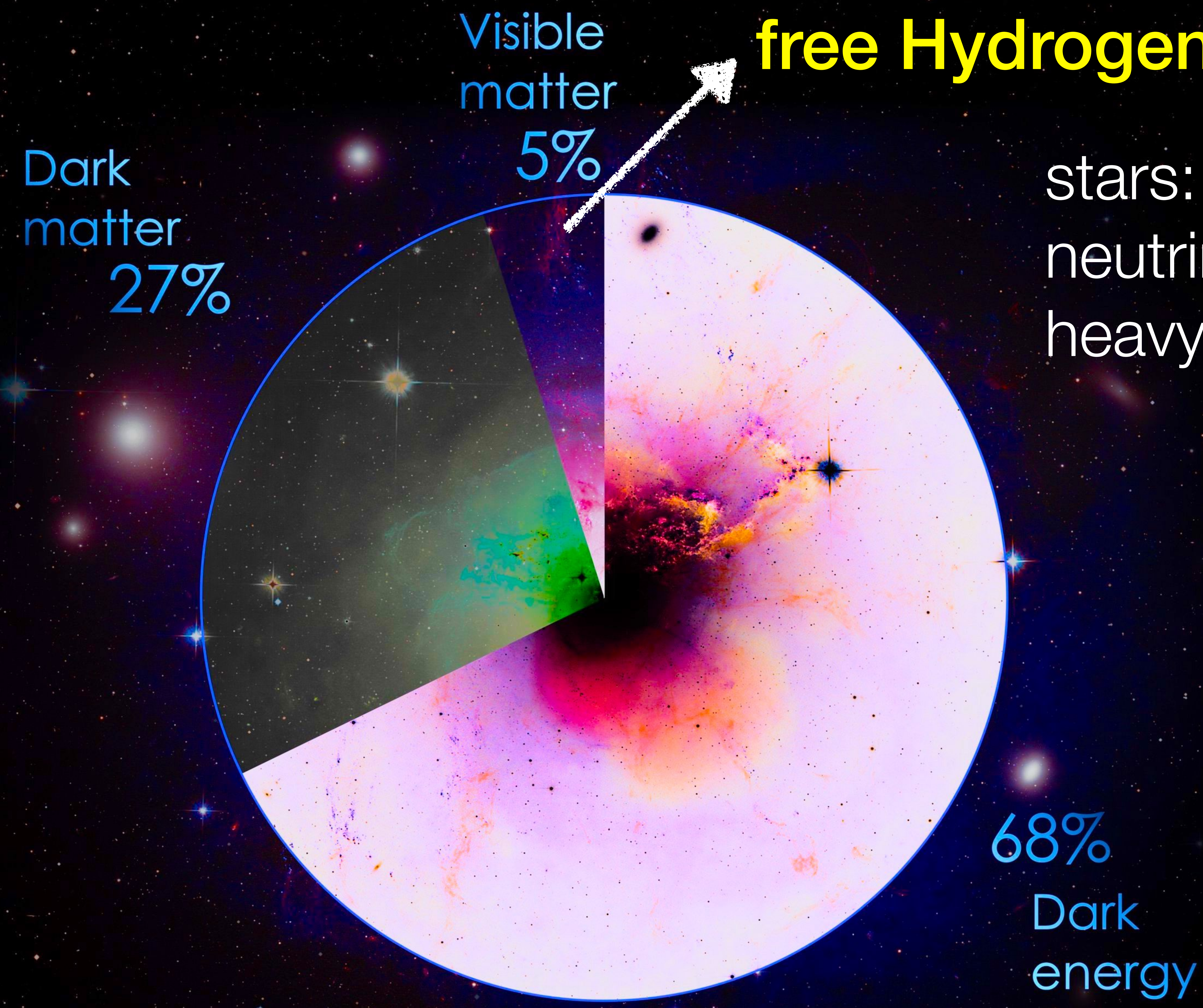
UK-US collaboration

Another project will receive £58.8 million from UKRI in a partnership with the US Department of Energy (DOE), to develop new detector and accelerator infrastructure to address fundamental questions on the nature of matter.

The technology will be built by:

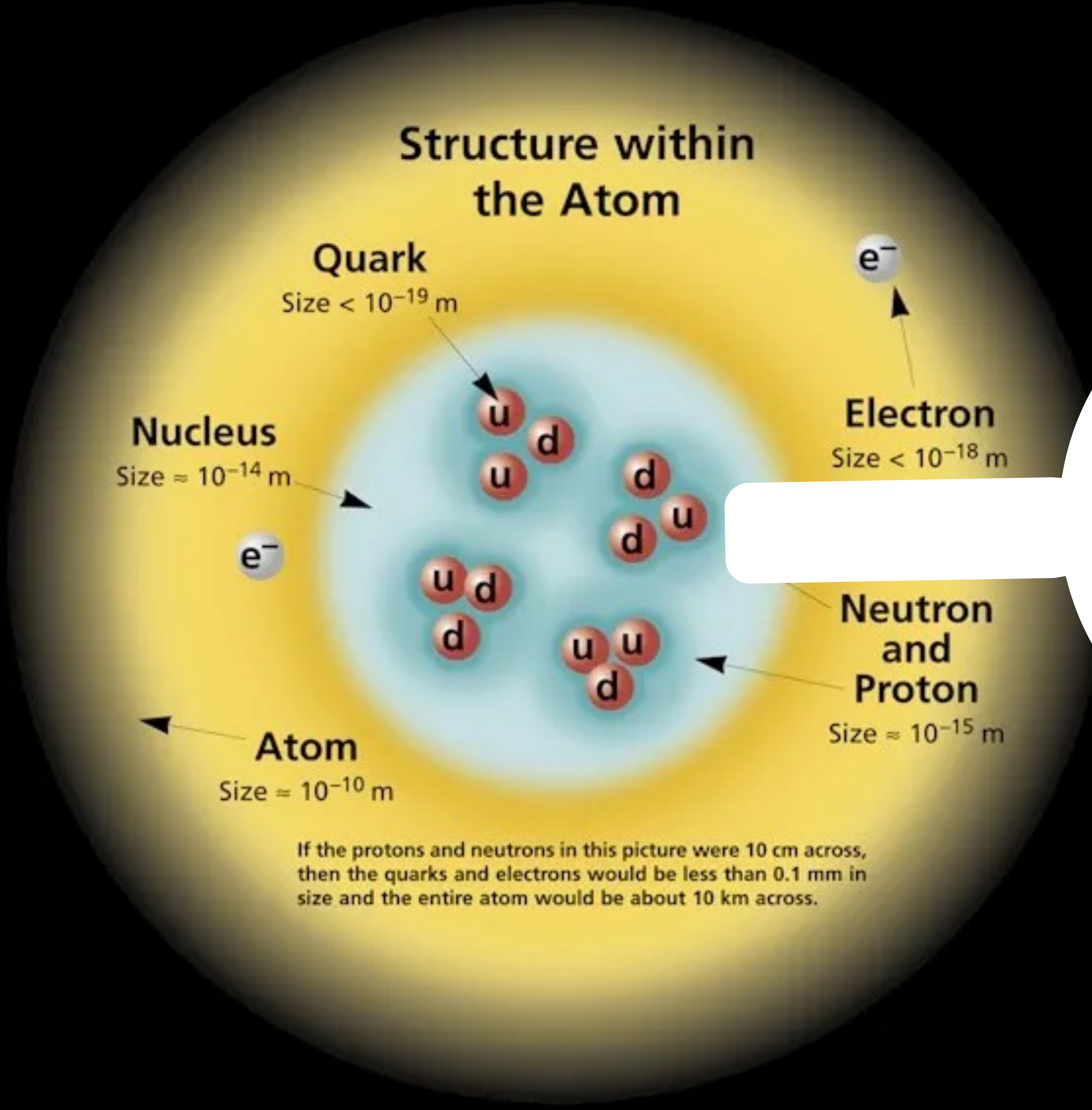
- two STFC national laboratories, Daresbury Laboratory in Cheshire and the Rutherford Appleton Laboratory in Oxfordshire
- the universities of Birmingham, Brunel, Glasgow, Lancaster, Liverpool, Oxford and York
- the Cockcroft Institute for Accelerator Science and Technology in Cheshire

It will be installed at the Electron-Ion Collider (EIC), a major new particle accelerator facility at the Brookhaven National Laboratory in New York in the US.

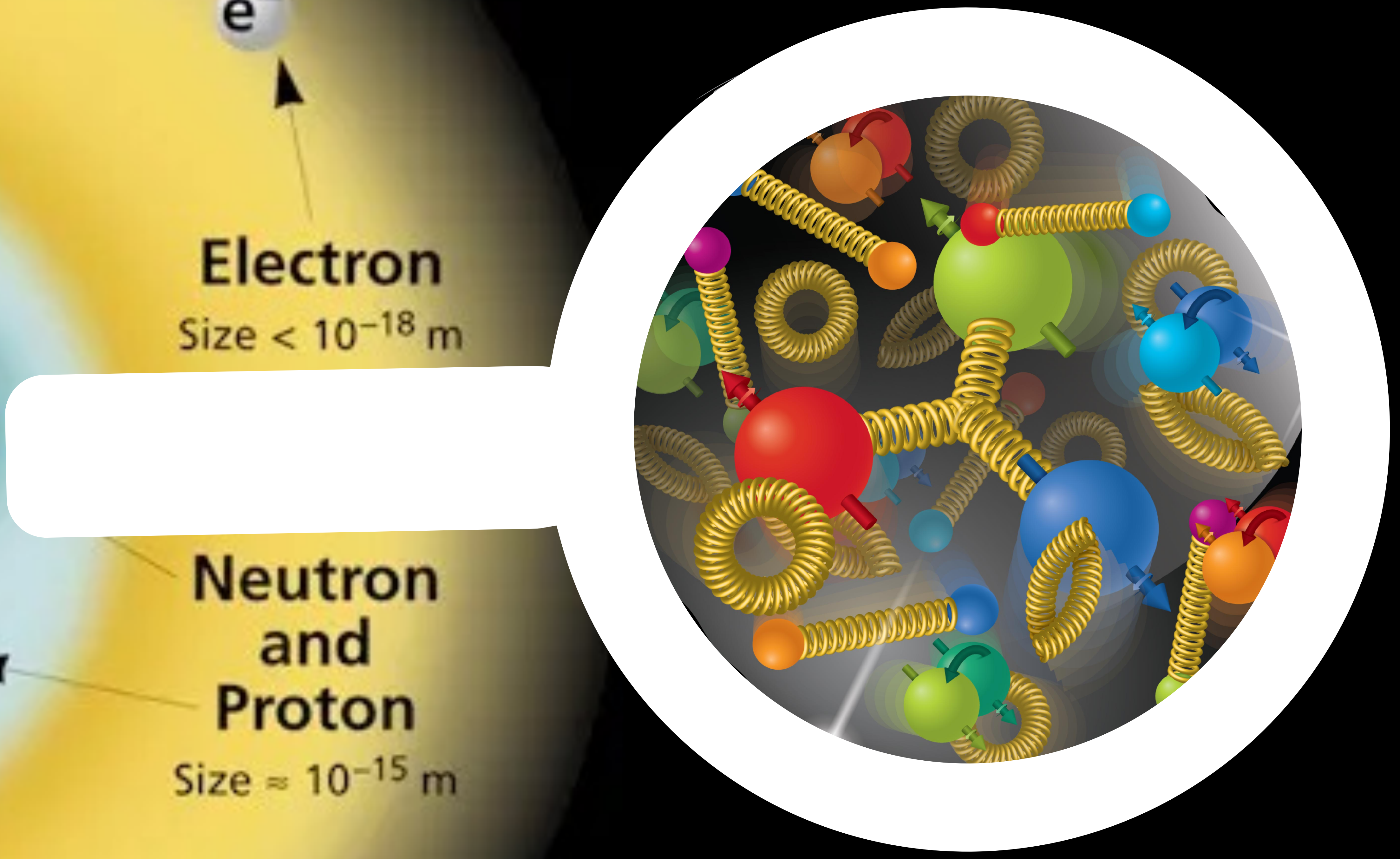


free Hydrogen & Helium: 4%

stars: 0.5%
neutrinos: 0.3%
heavy elements: 0.03%



Structure within the Atom
Quark
Size < 10−19 m
e−
Electron
Size < 10−18 m
Nucleus
Size ≈ 10−14 m
u
d
e−
Neutron and Proton
Size ≈ 10−15 m
Atom
Size ≈ 10−10 m
If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

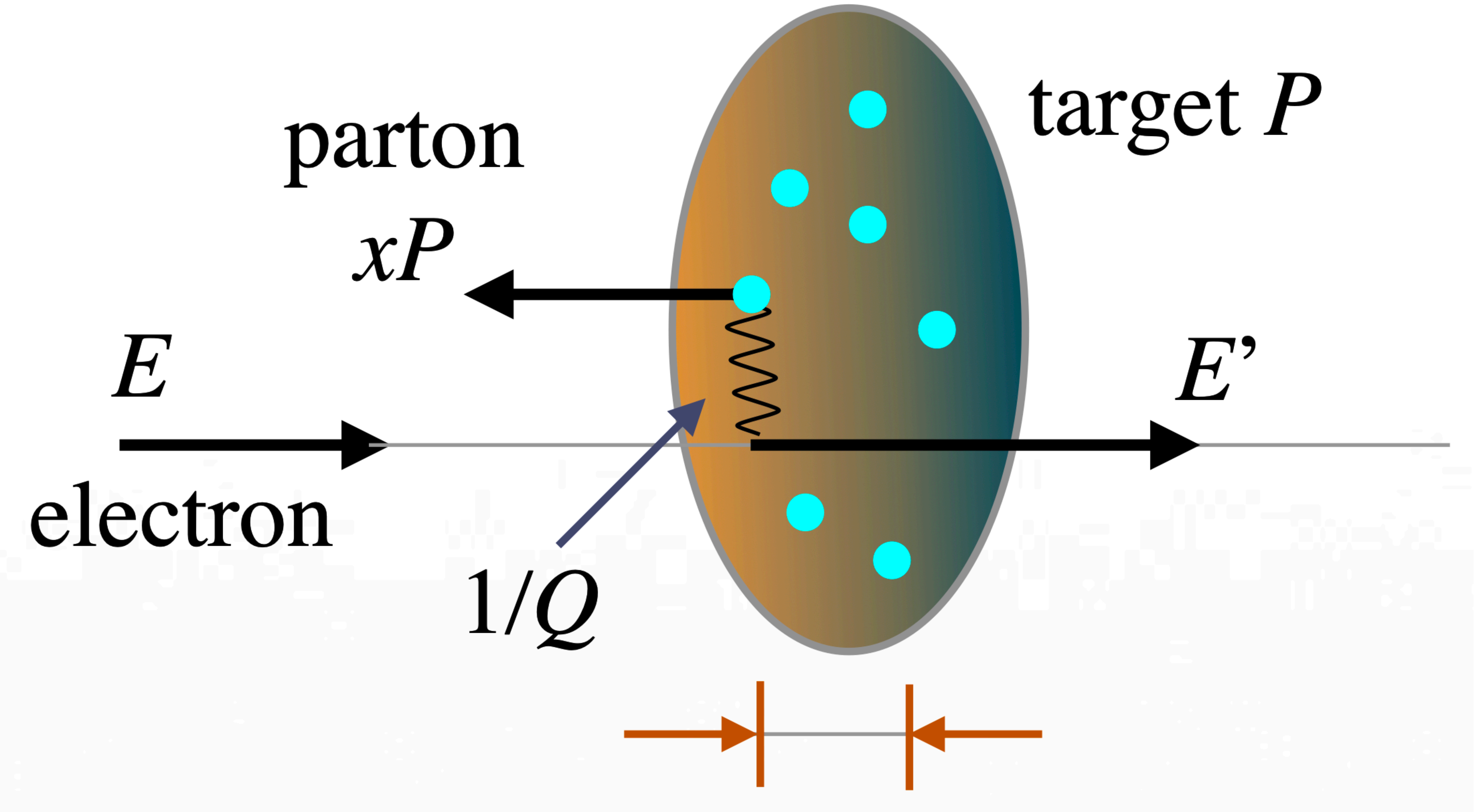


partonic origin of proton mass

proton in the eyes of the light: partonic image

an effective description observed from an infinite-momentum frame

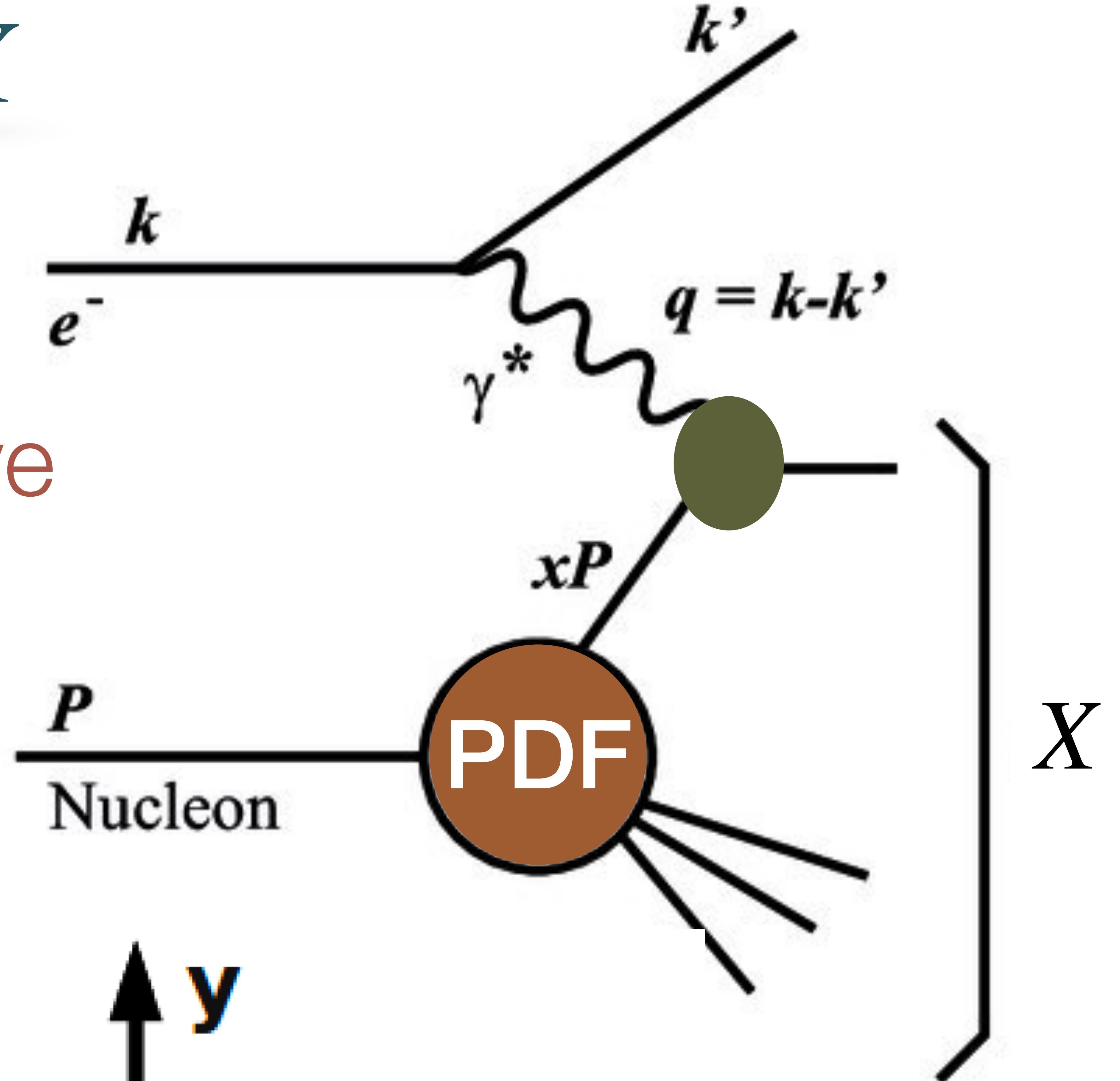
x_i : fraction of the momentum of proton carried by a parton



- in c.m. frame electron sees a Lorentz-contracted proton; parton's virtual life Lortentz-dialted

- $Q^2 \to \infty$, electron crosses proton in $t \to 0$: sees partons 'frozen' on approx. mass-shell

deep inelastic scattering: $e + P \longrightarrow e + X$

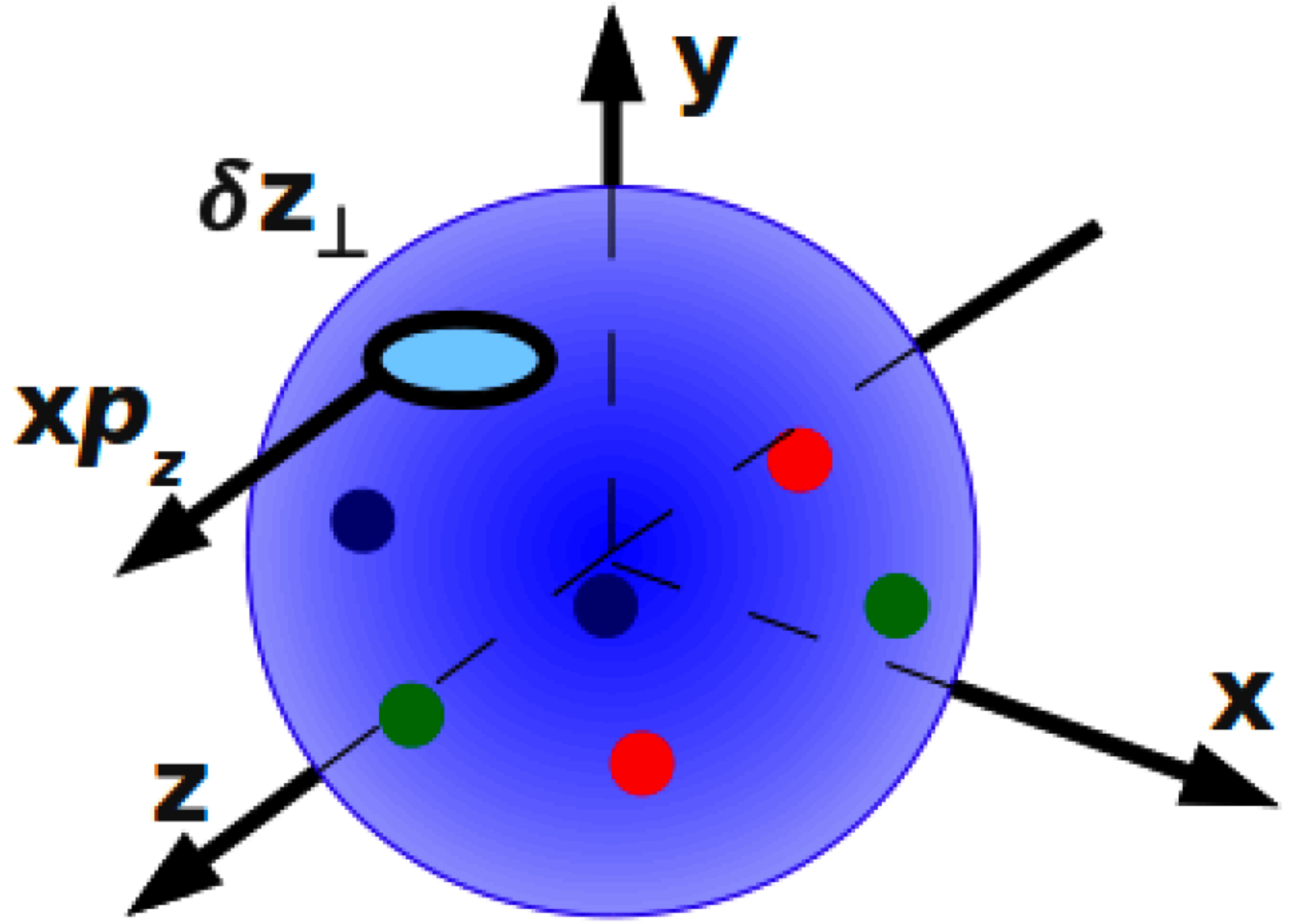


factorization ~ perturbative ⊗ non-perturbative

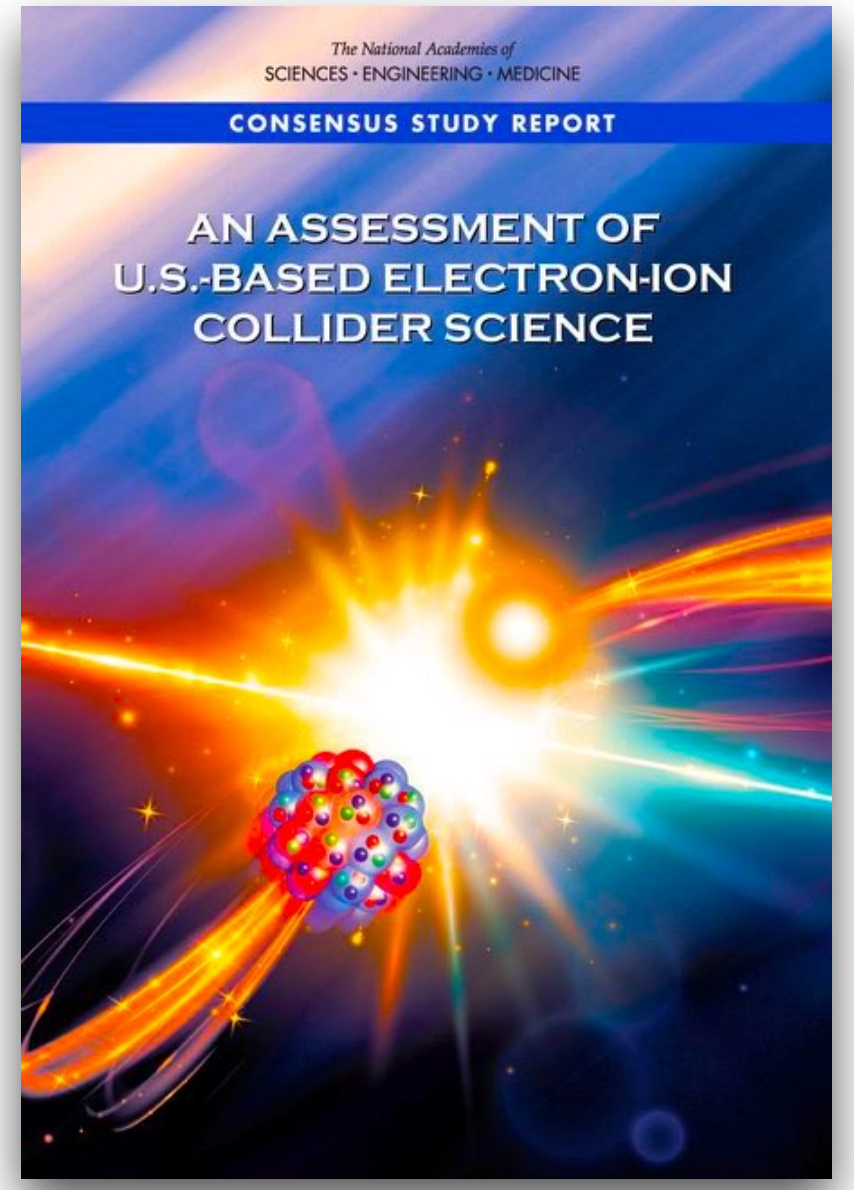
$$\sigma(y) \sim c(y, x, \mu) \otimes f_{LC}(x, \mu)$$

parton distribution function (PDF)

distribution, at scale μ, of longitudinal momentum fractions of a parton inside hadron moving with infinite momentum



science at EIC needs help from lattice QCD

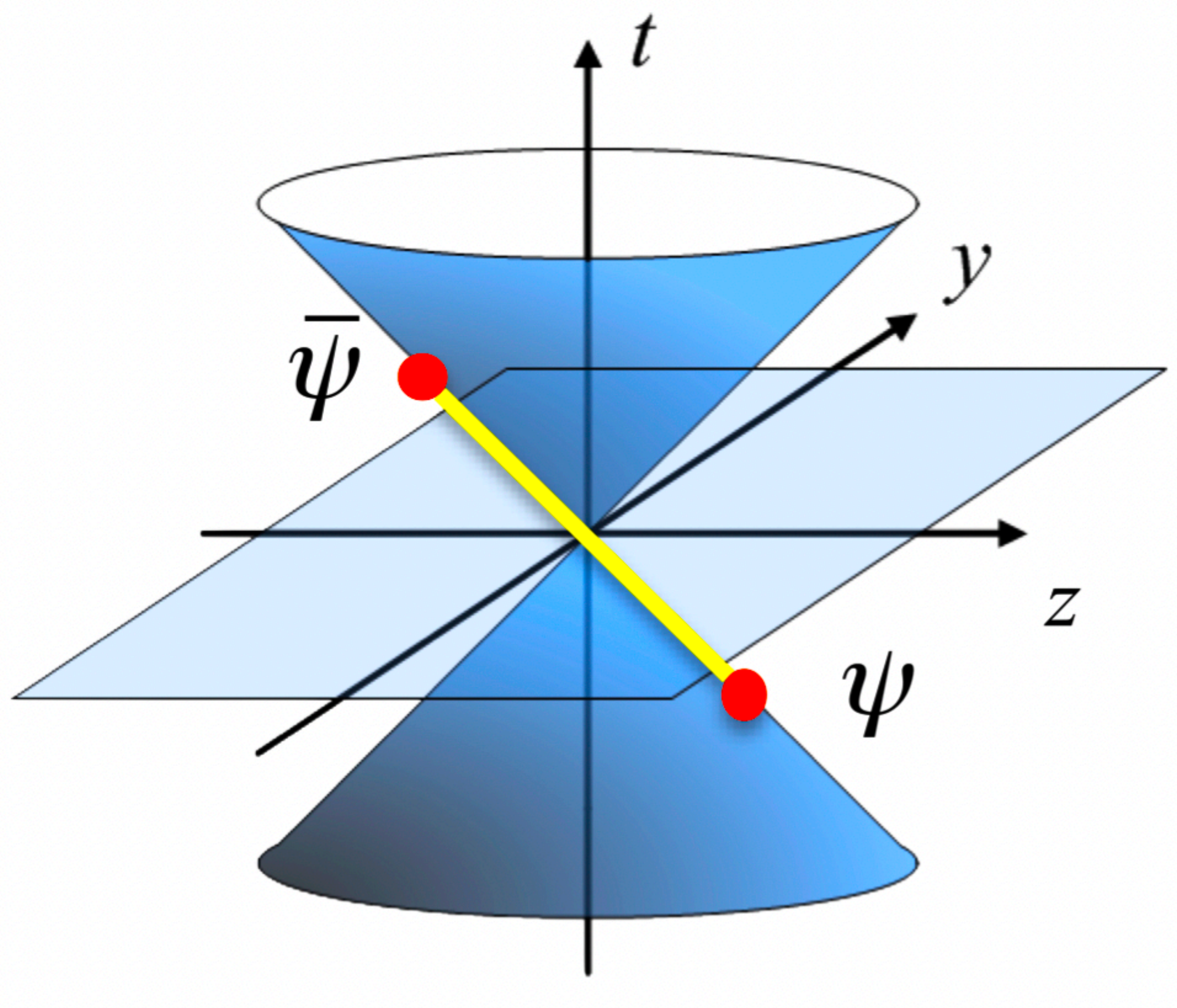


Summary of the National Academy of Science report

"The scientific challenges that would unfold with EIC require a robust theory program, not simply to design and interpret experiments, but also to develop the broad implications in an understanding of the quantum world, both through analytic theory as well as through lattice QCD simulations on large-scale computers."

nonperturbative partonic image of hadron

regularize QCD after taking the lightcone, $P_z \to \infty$ / $z^2 \to 0$, limit

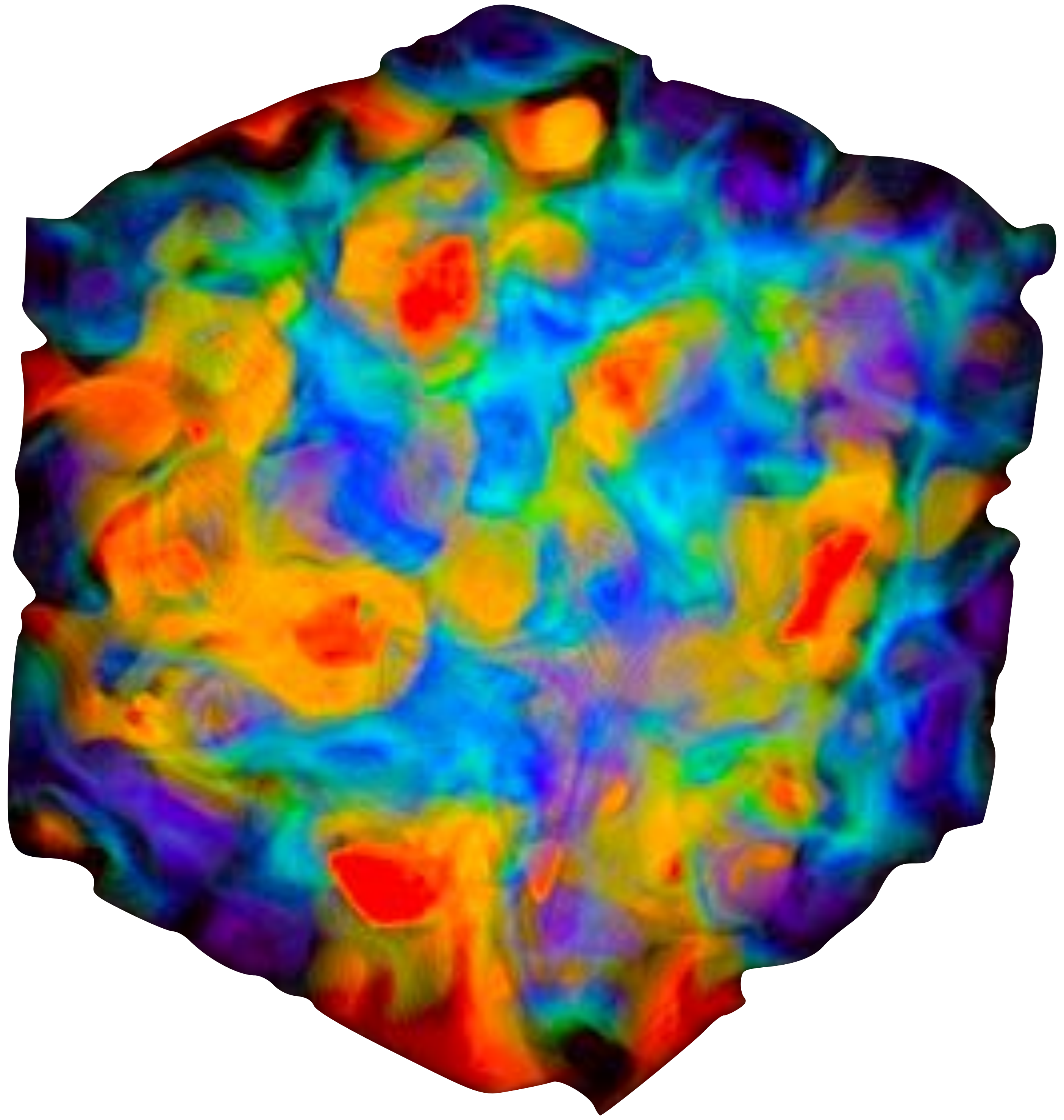


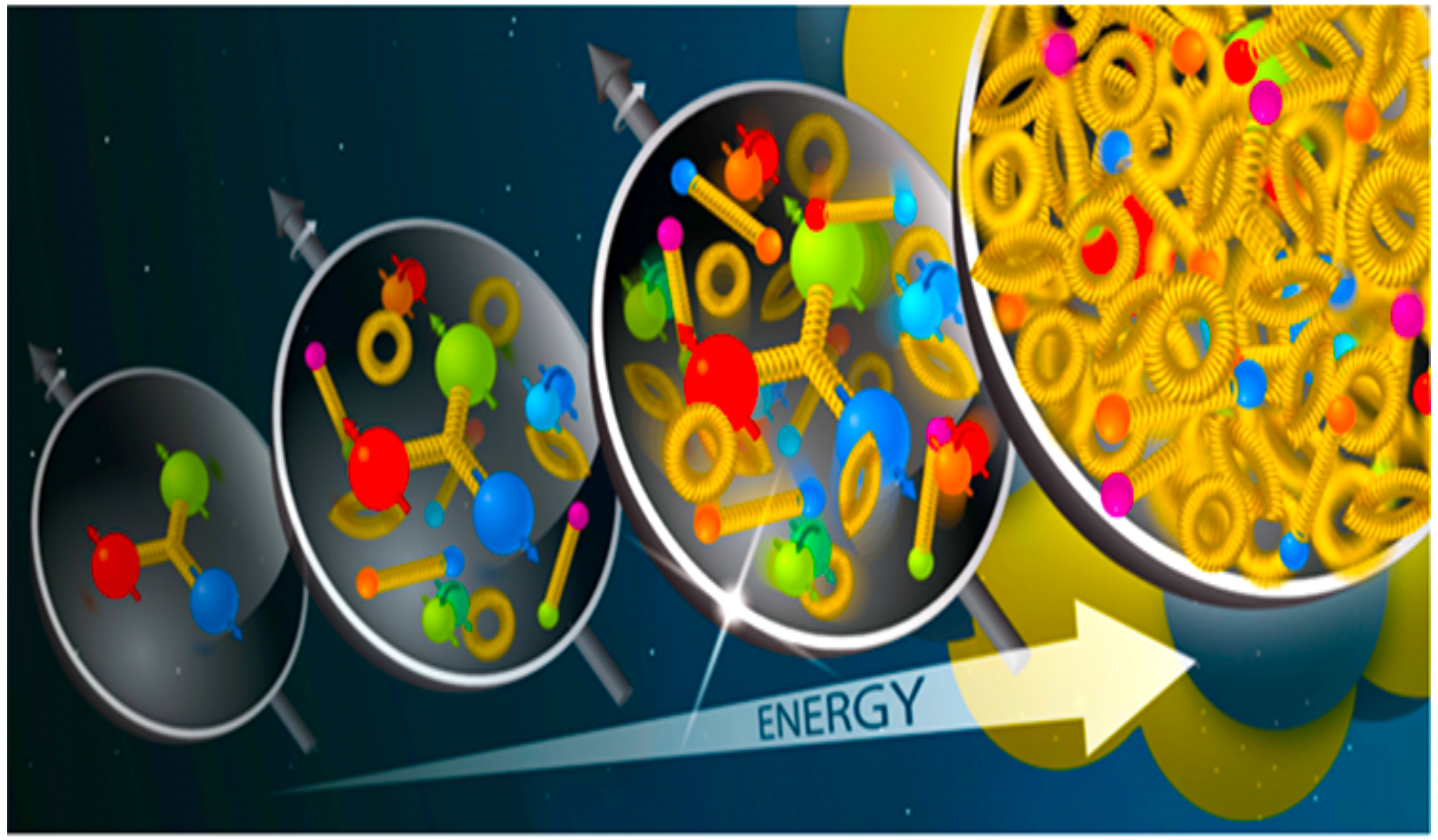
$$f(x,\mu) \sim \left\langle H(P_z) \,|\, \hat{O}(z^-,\mu) \,|\, H(P_z) \right\rangle$$

timelike separated bilocal operator

lattice QCD in EIC era —

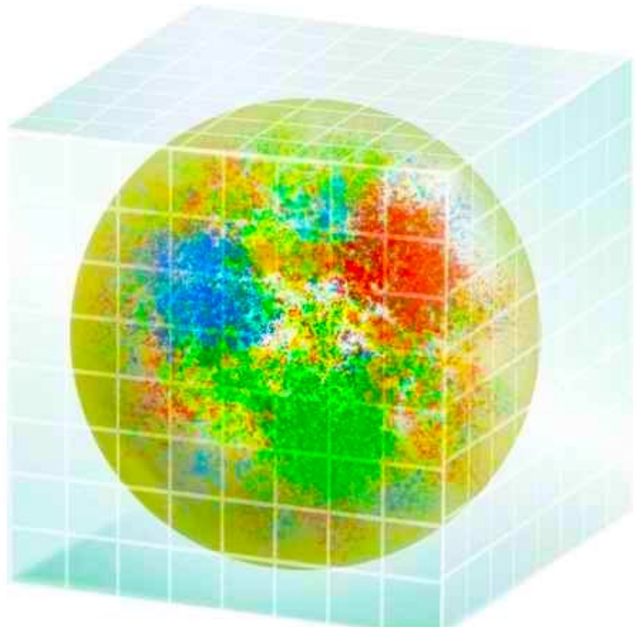
how to ‘see’ a parton on the lattice?

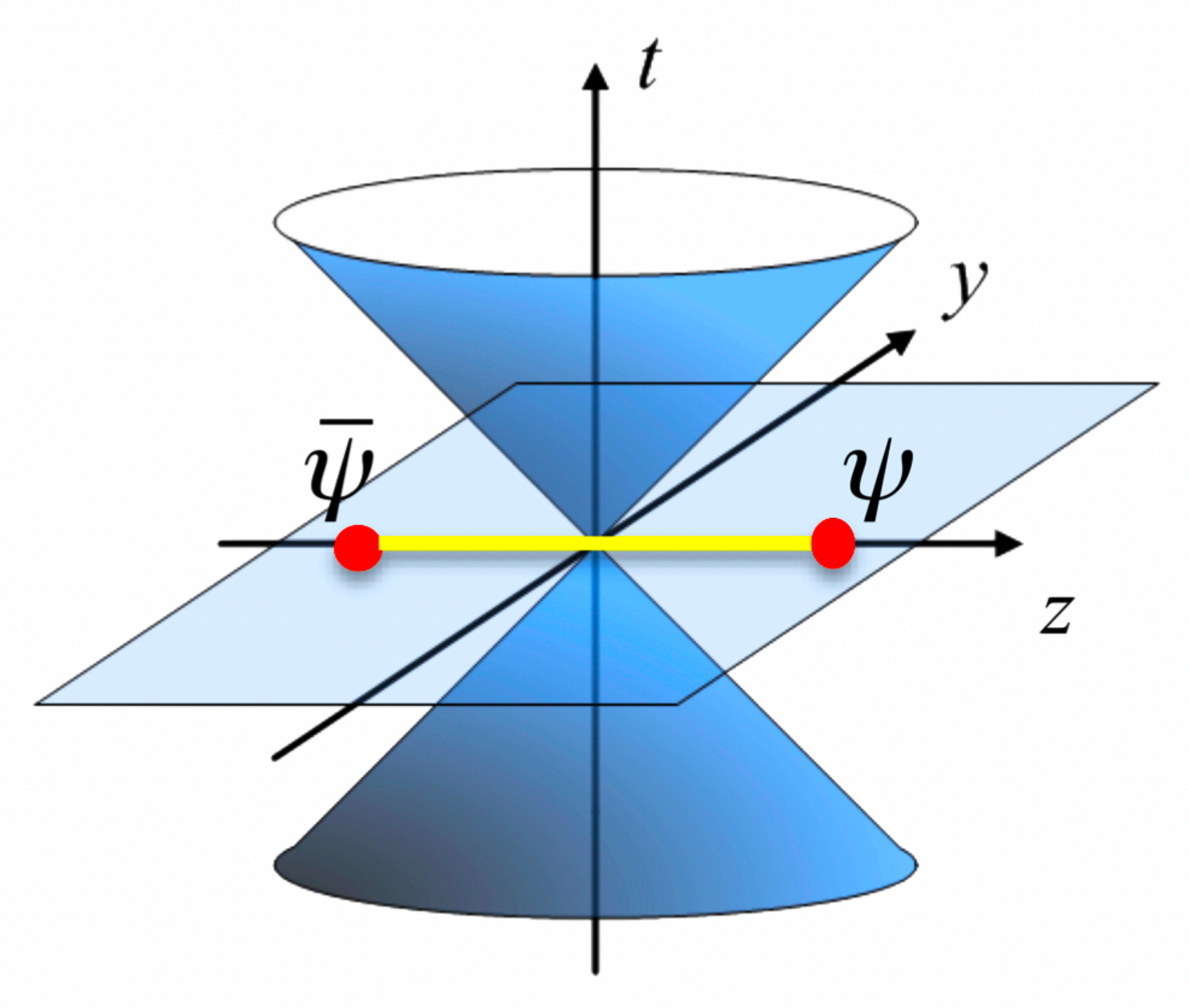




partonic structures from lattice QCD

hadron at rest



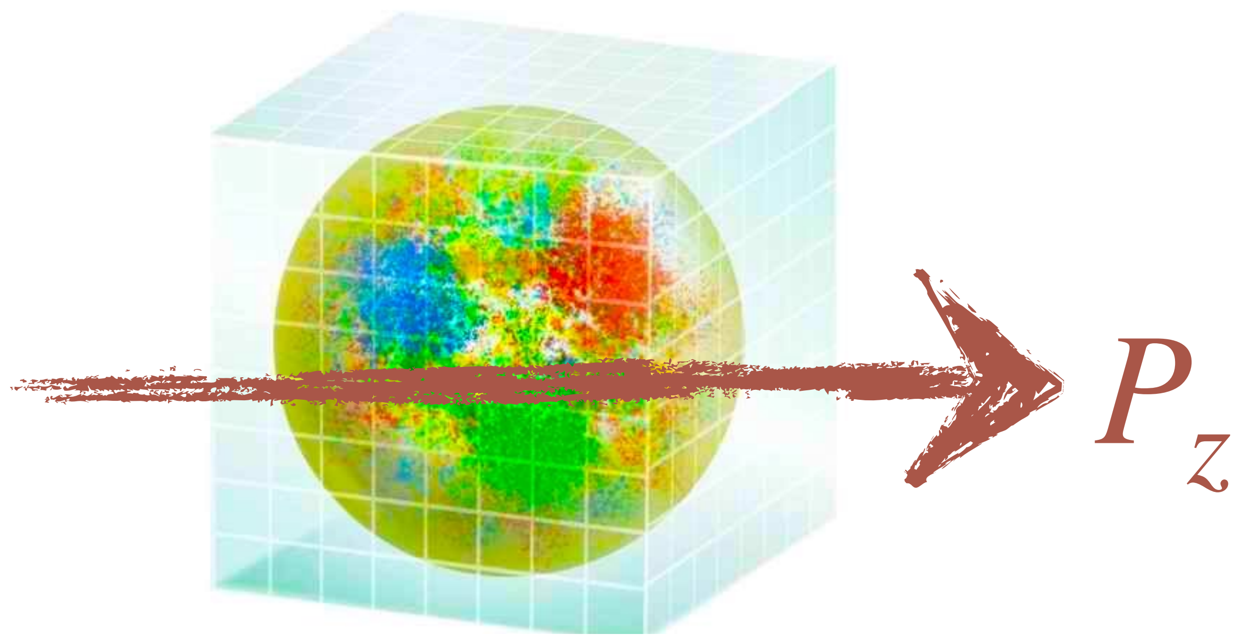


$$M(z^2, \mu) \sim \left\langle H(0) \,|\, \hat{O}(z, \mu) \,|\, H(0) \right\rangle$$

spacelike separated bilocal operator

renormalize: scale μ

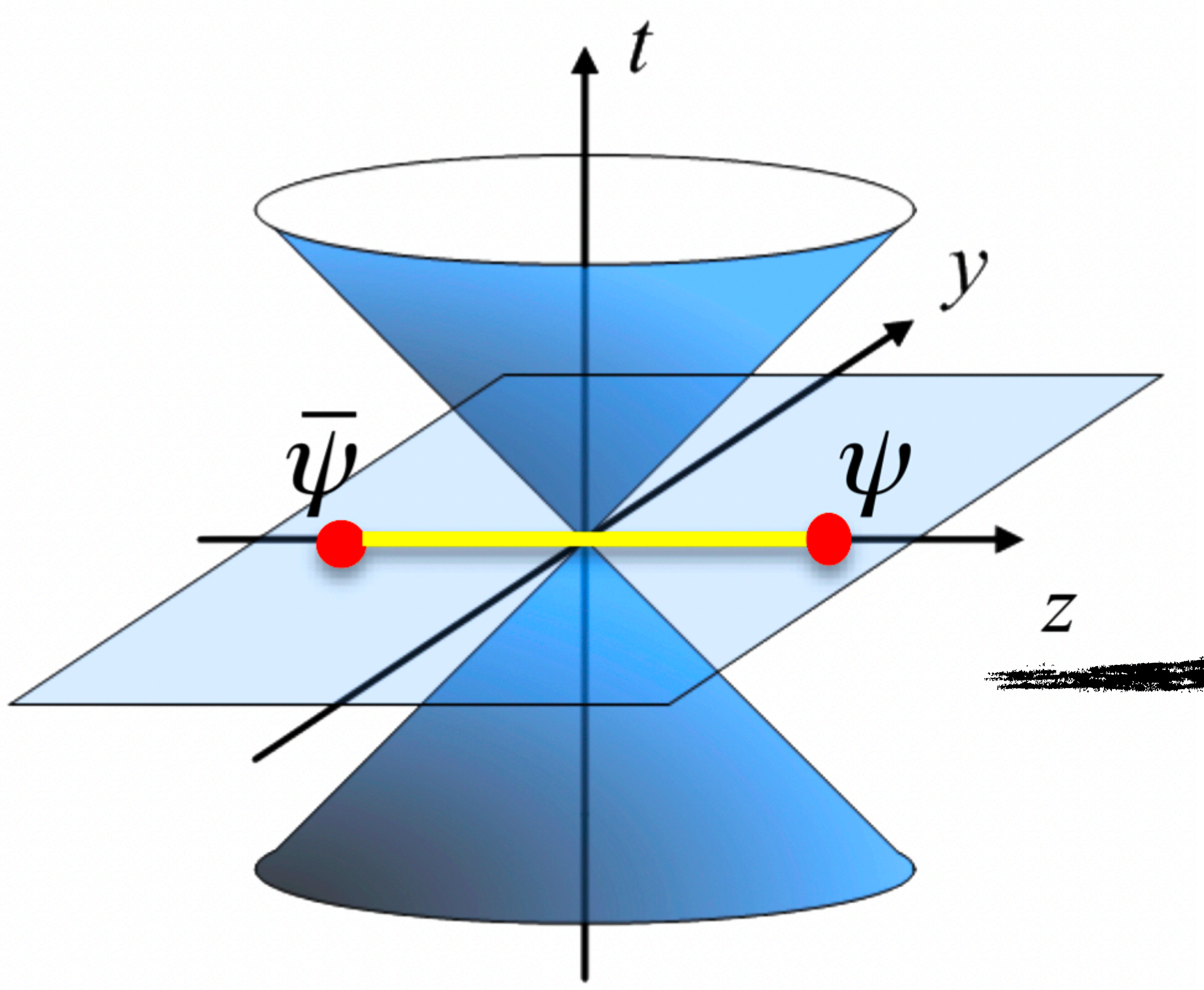
fast-moving hadron

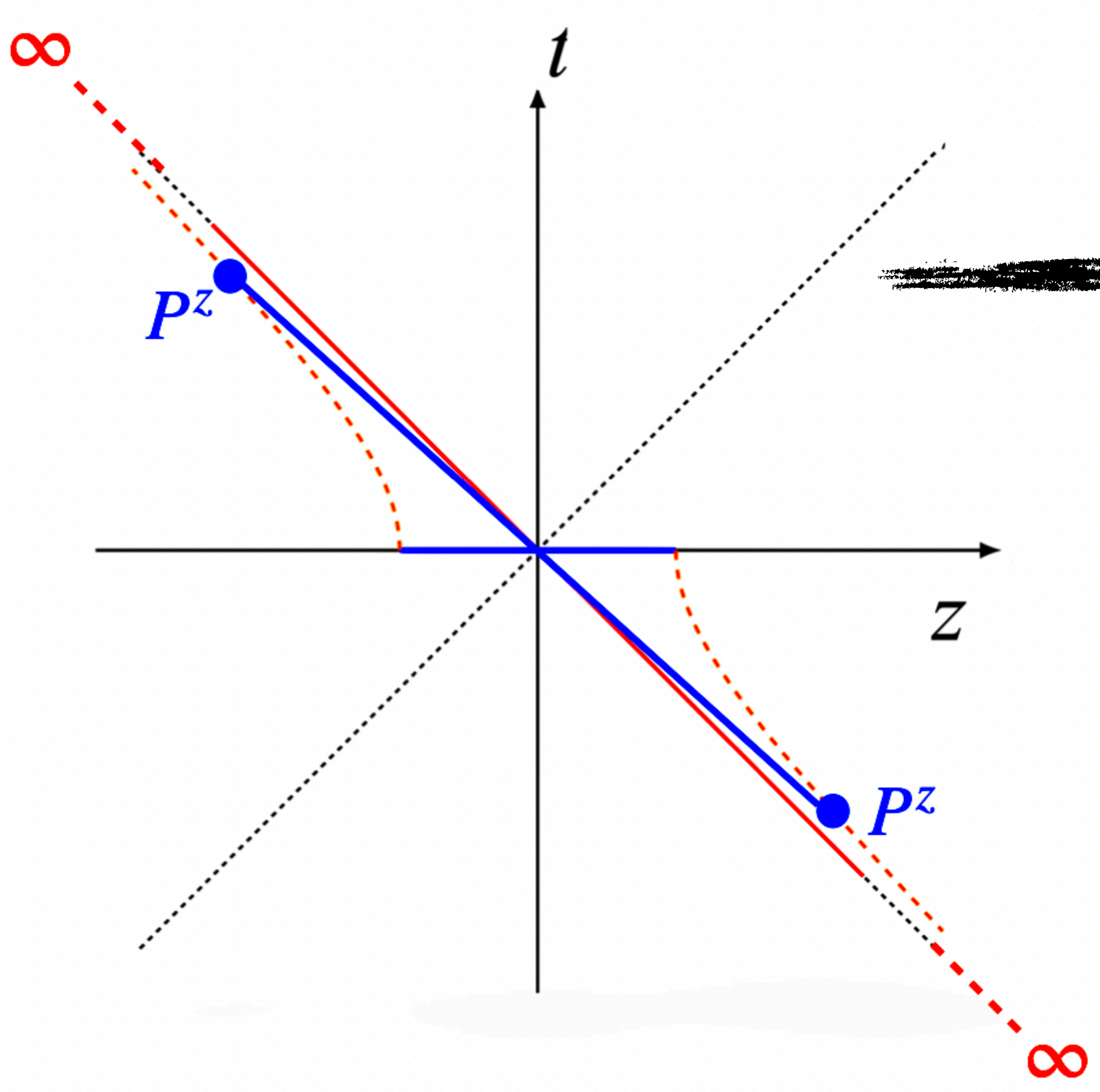


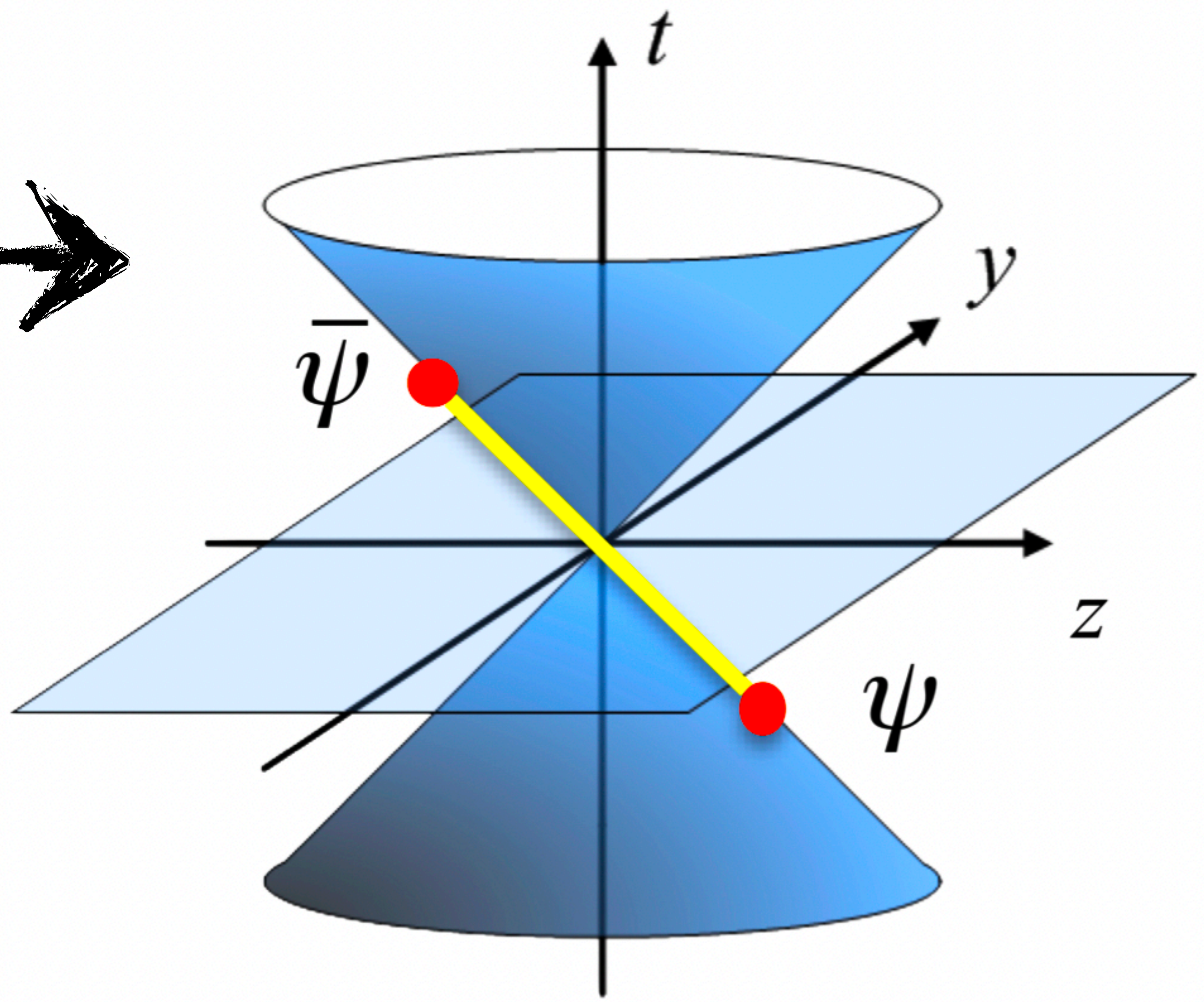
$P_z \approx E$

$$\left\langle H(0)\,|\,\hat{O}(z,\mu)\,|\,H(0)\right\rangle$$

$$\left\langle H(P_z)\,|\,\hat{O}(z^-,\mu)\,|\,H(P_z)\right\rangle$$







factorization of $M(y, \mu, P_z) \sim$ perturbative $\otimes$ non-perturbative

$\tilde{c}(y, x, \mu, P_z) \otimes f_{LQCD}(x, \mu)$

momentum space

$\tilde{c}(y, x, \mu, z^2) \otimes f_{LQCD}(x, \mu)$

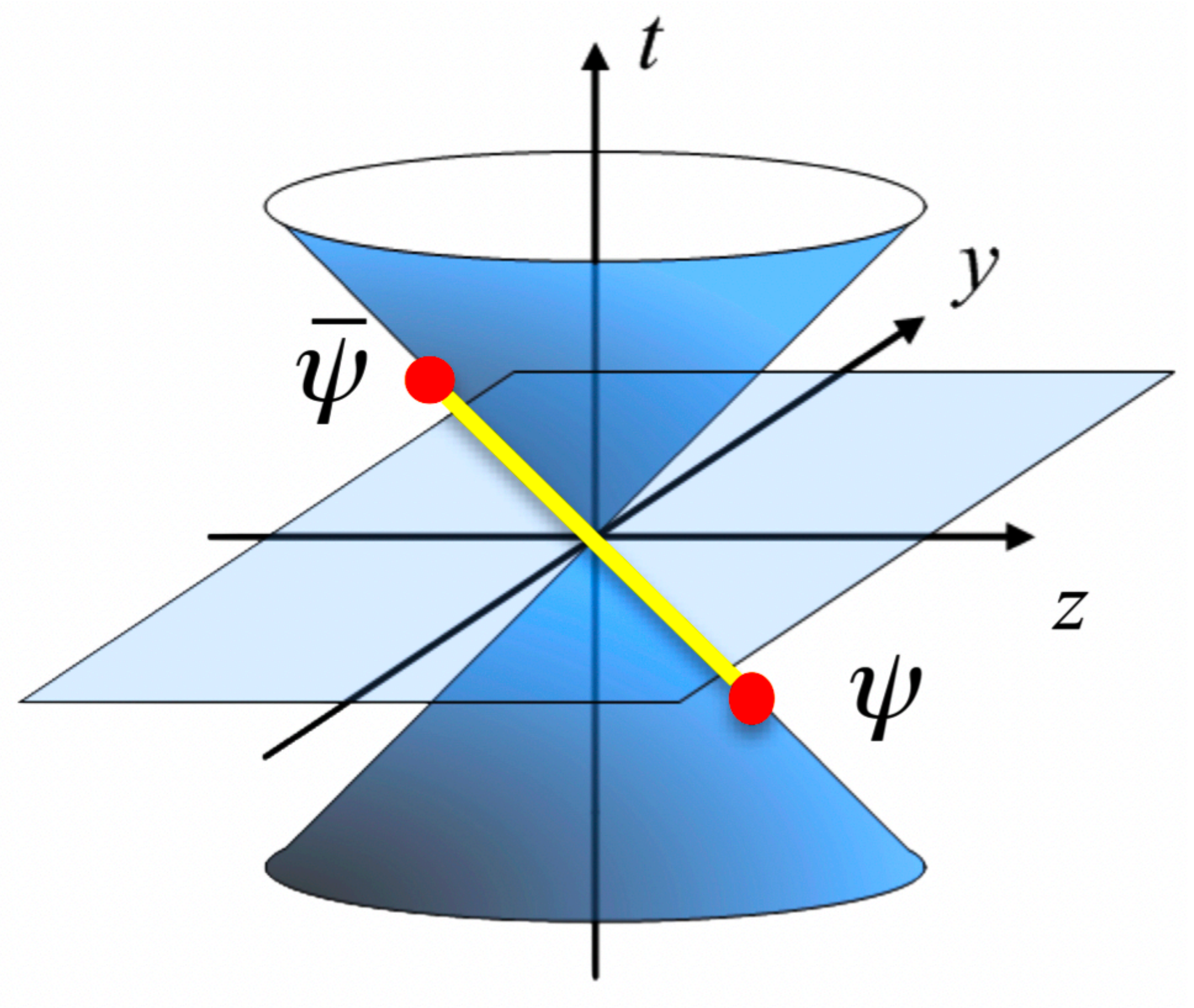
position space

nonperturbative objects on the lightcone, $f_{LC}(x, \mu)$, and from lattice QCD, $f_{LQCD}(x, \mu)$, shares same infrared singularities, i.e. governed by same evolution equations factorization: perturbative $\otimes$ non-perturbative

$$M(y,\mu,P_z) \sim \tilde{\sigma}(y,x,\mu,P_z) \otimes \tilde{f}(x,\mu) \qquad M(y,\mu,z^2) \sim \tilde{\sigma}(y,x,\mu,z^2) \otimes \tilde{f}(x,\mu)$$

- regularize QCD on a lattice, then $P_z \to \infty \,/\, z^2 \to 0$
- opposite order of limits from light-cone quantization
- two limits don't commute
- difference is UV physics, can be taken care of through perturbative matching

parton physics

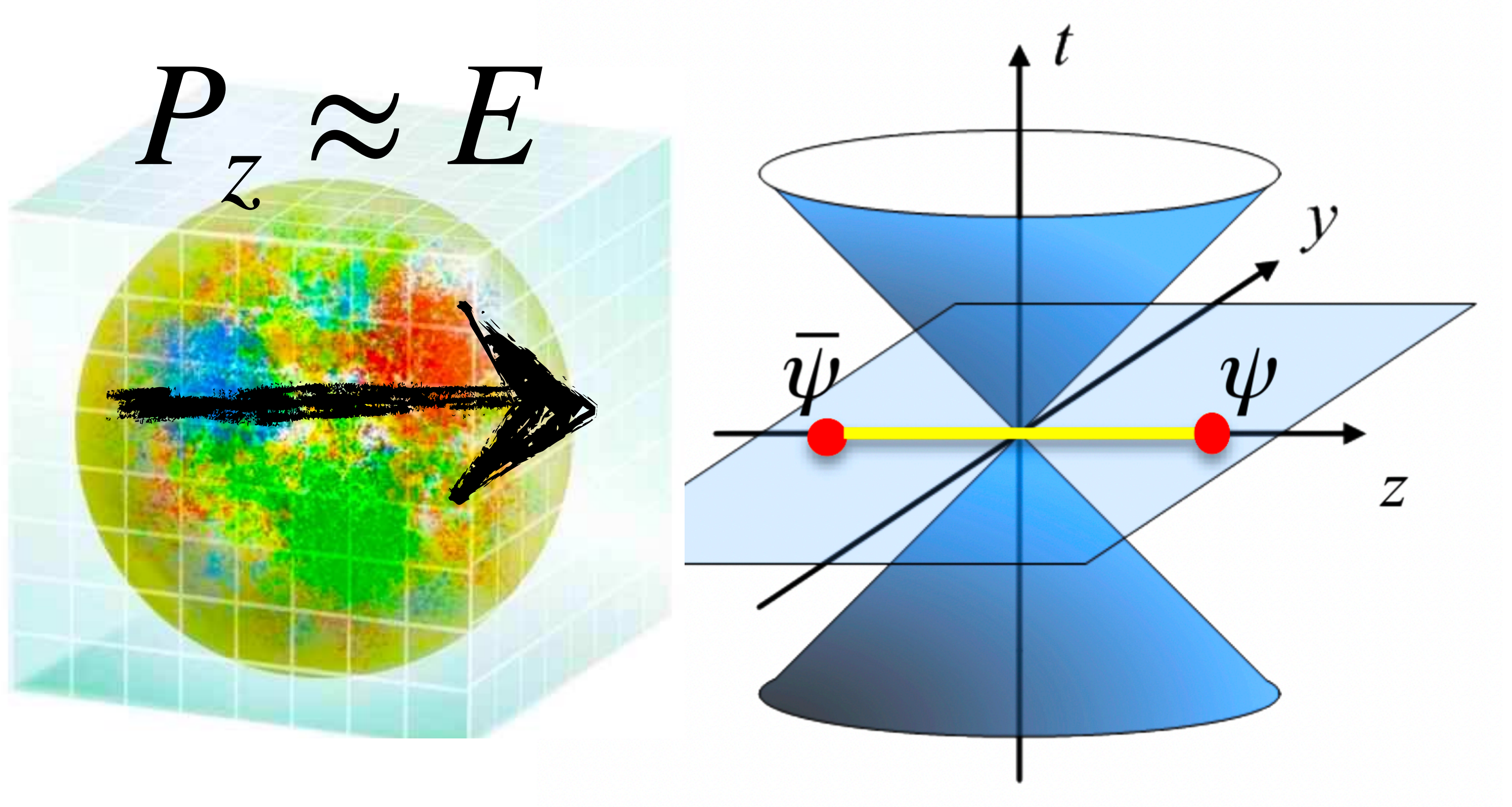


perturbative matching

$$C(x, P_z, \mu) \otimes$$

$$C(\alpha, z^2, \mu) \otimes$$

lattice QCD

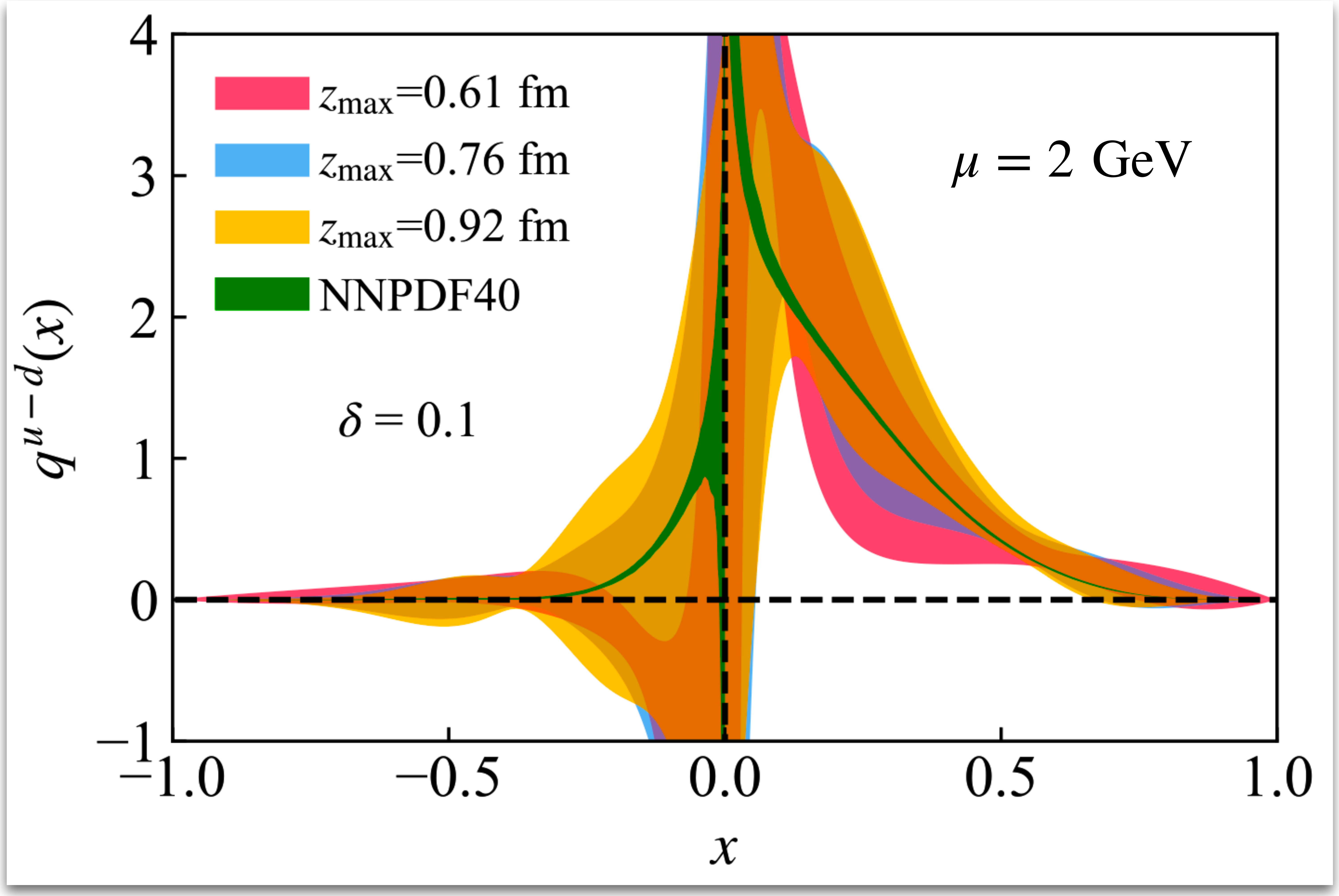


LO NLO NNLO

$$C(\mathcal{S}, \mu) \;\sim\; \alpha_s^0(\mu) \;+\; \alpha_s(\mu) f\left(\ln[\mathcal{S}\mu]\right) \;+\; \alpha_s^2(\mu) f\left(\ln[\mathcal{S}\mu]\right) \;+\; \cdots$$

$$\mathcal{S} \;=\; 2xP_z \;,\; z^2$$

isovector quark PDF of unpolarized proton at NNLO

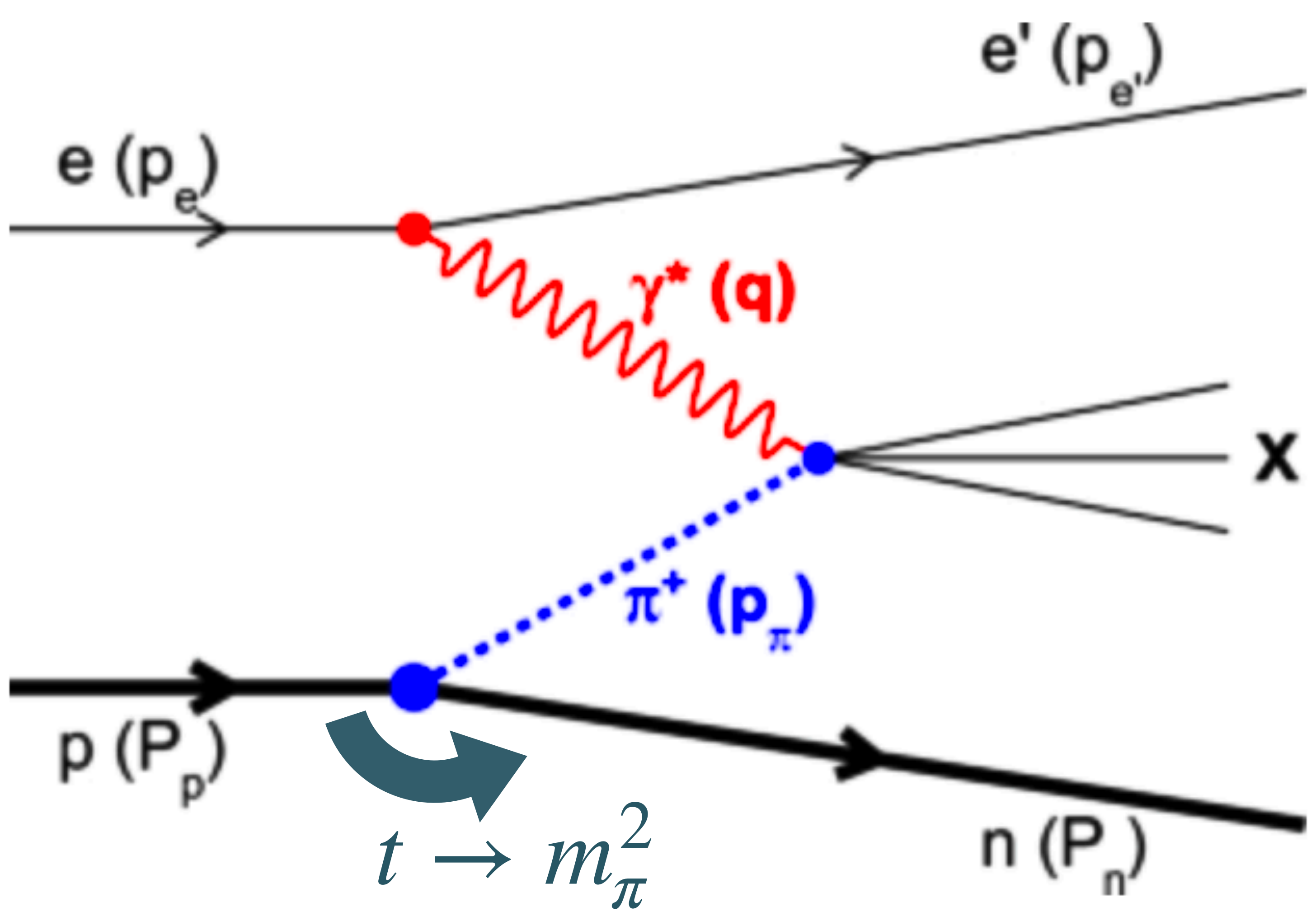


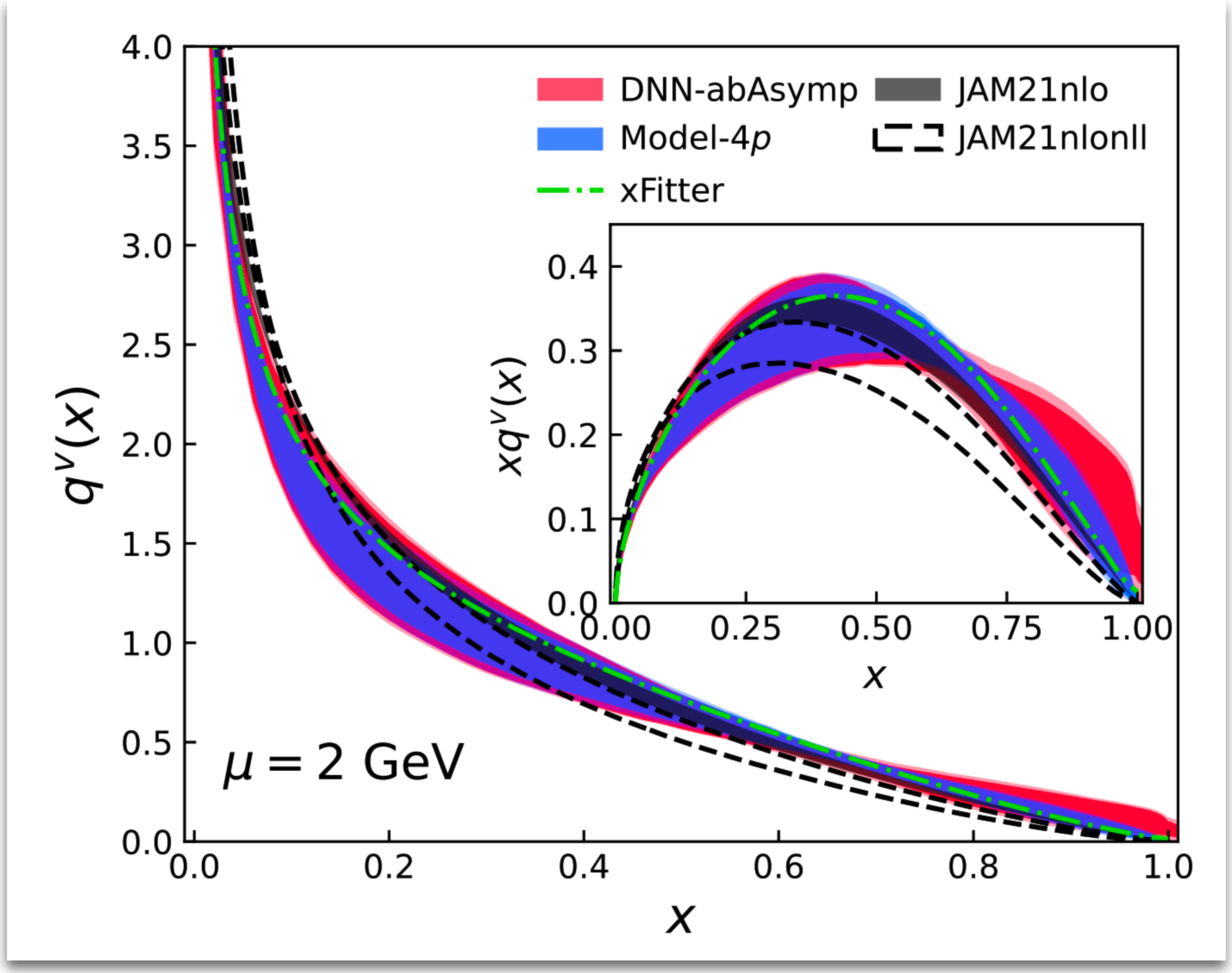
physical quark masses

A. Hanlon et al., Phys. Rev. D107, 7, 074509 (2023)

valance quark PDF of pion at NNLO

Sullivan process @ EIC





physical quark masses,
continuum-extrapolated

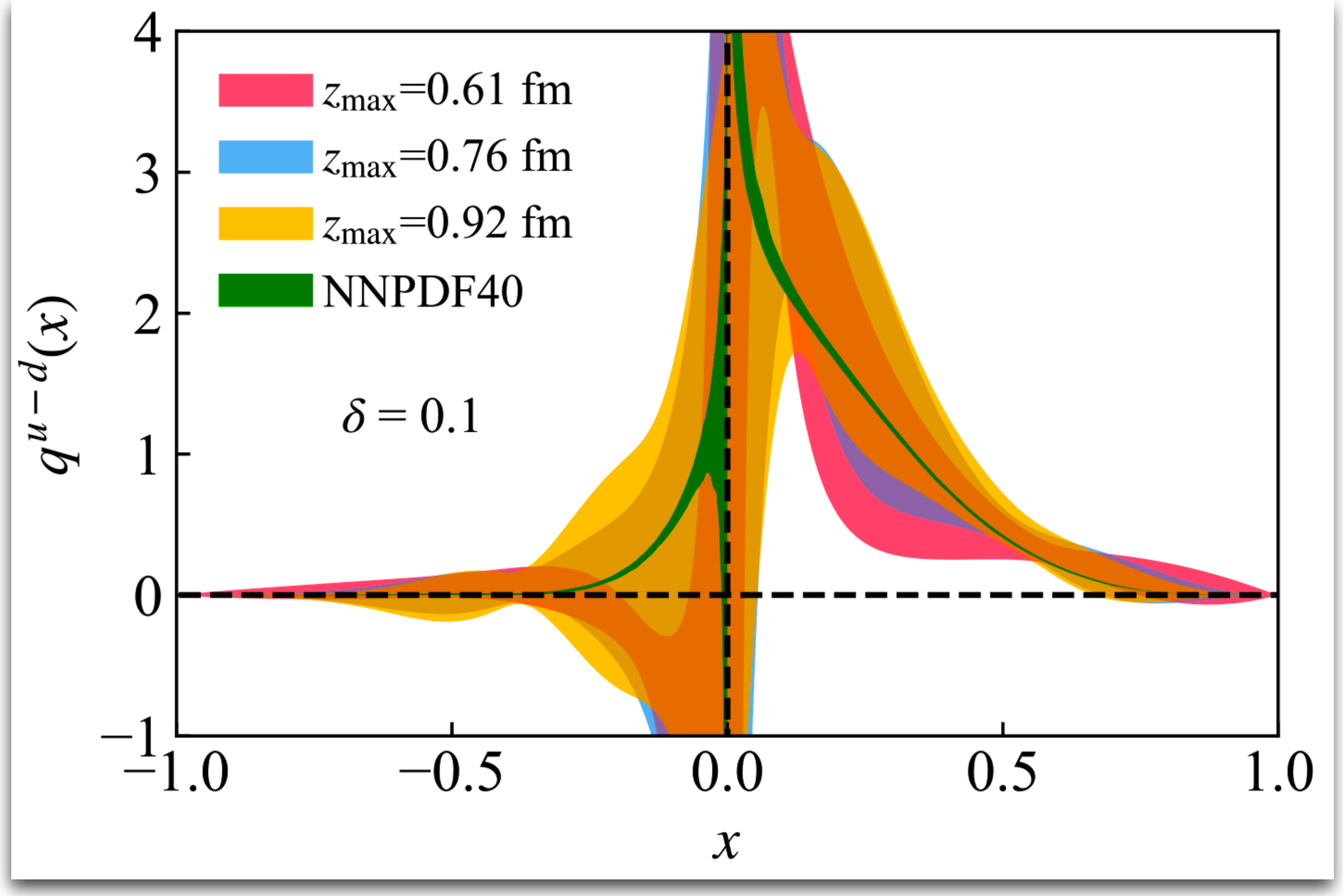
Y. Zhao et al., Phys. Rev. Lett. 128, 14, 142003 (2022)

X. Gao et al., Phys. Rev. D06, 11, 114510 (2022)

quark energy contributions to hadron masses

$$E_q(\mu) = \frac{3}{4} m_H \int_0^1 x f(x,\mu)\, dx$$

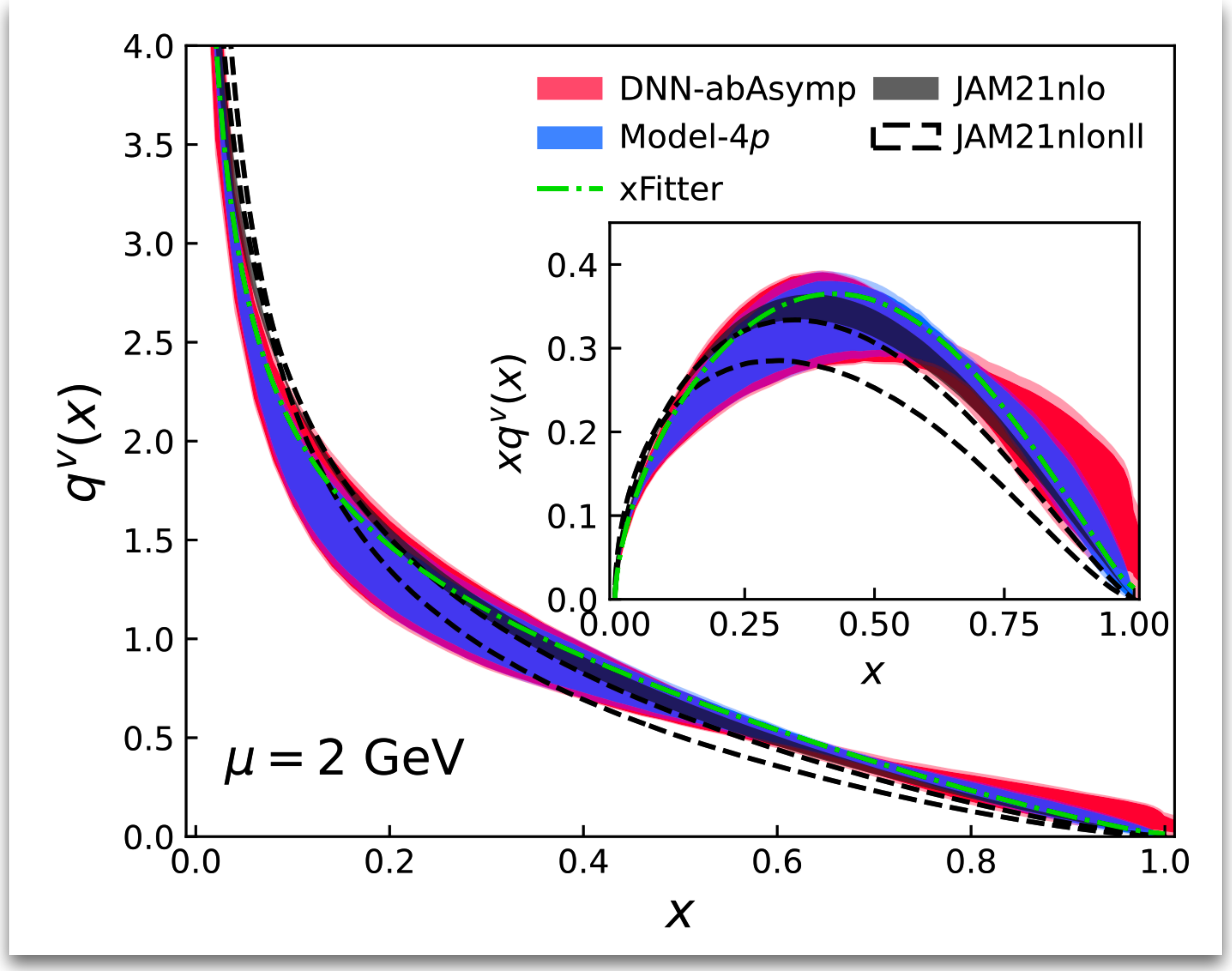
proton



$E_q(2\ \text{GeV})/m_p \approx 40\,\%$

vs.

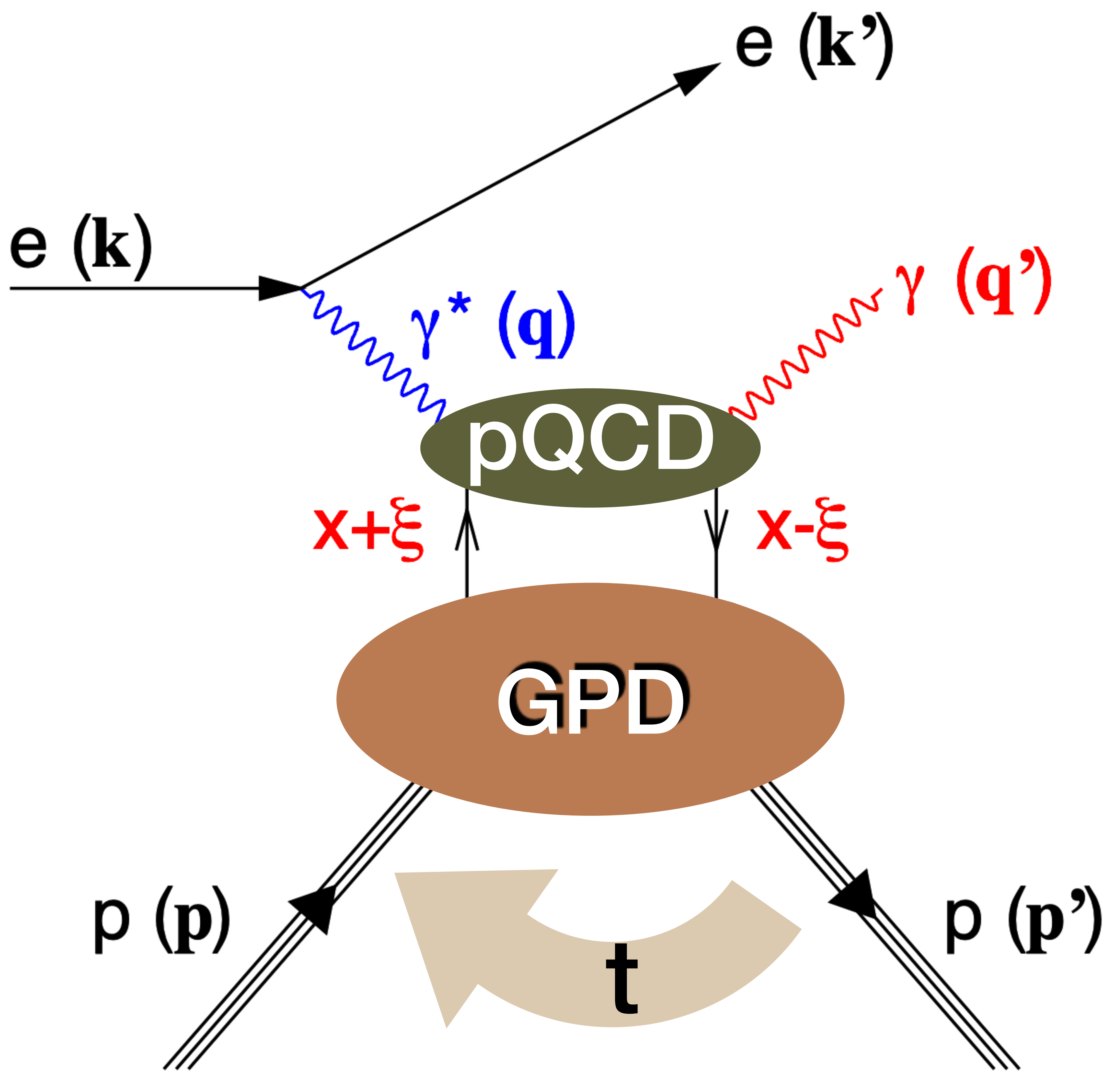
pion



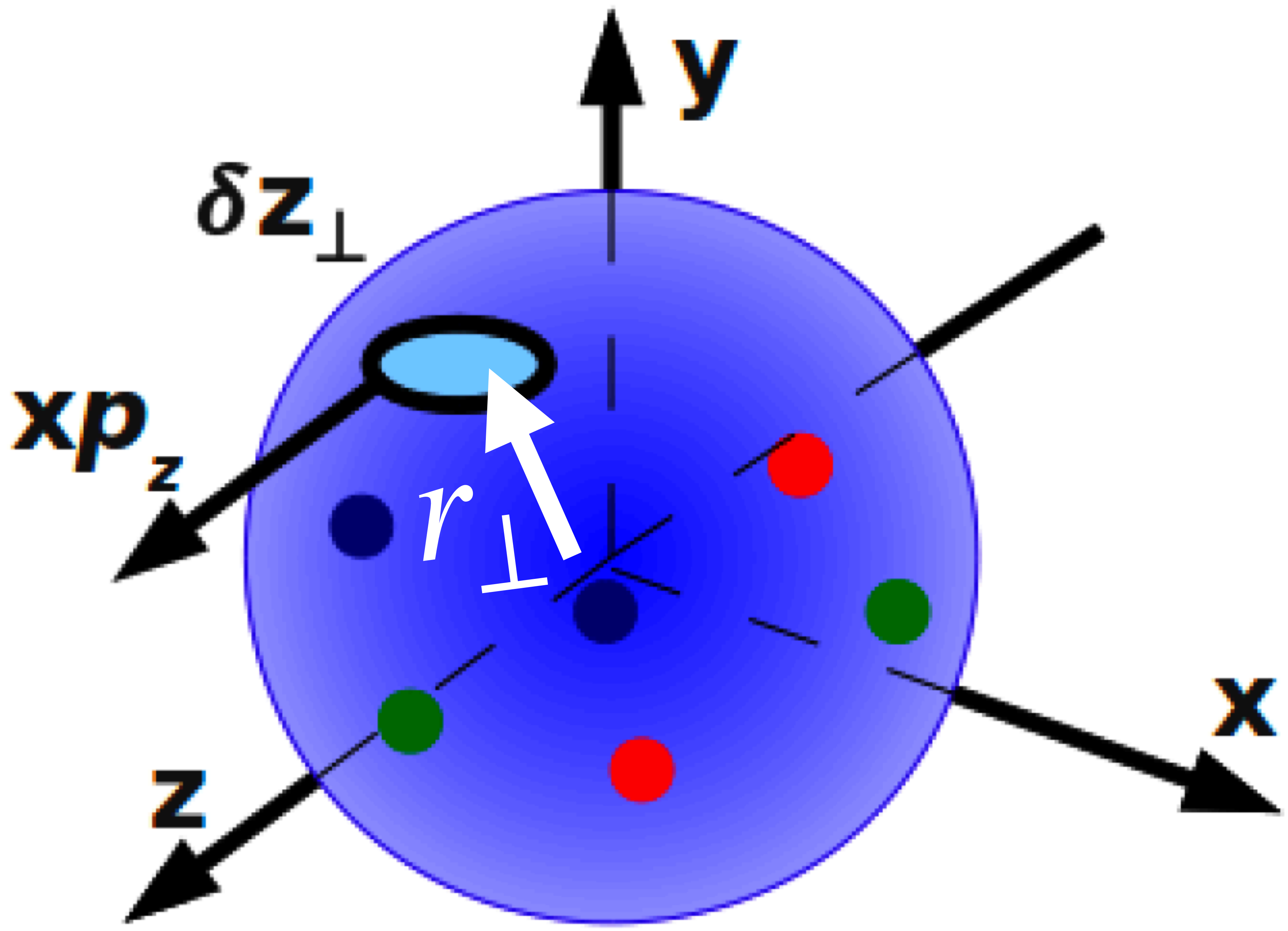
$E_q(2\ \text{GeV})/m_\pi \approx 30\,\%$

partonic origin of proton spin

deeply virtual compton scattering: $e + P \to e + P' + \gamma$



$r_\perp$ is Fourier conjugate of t

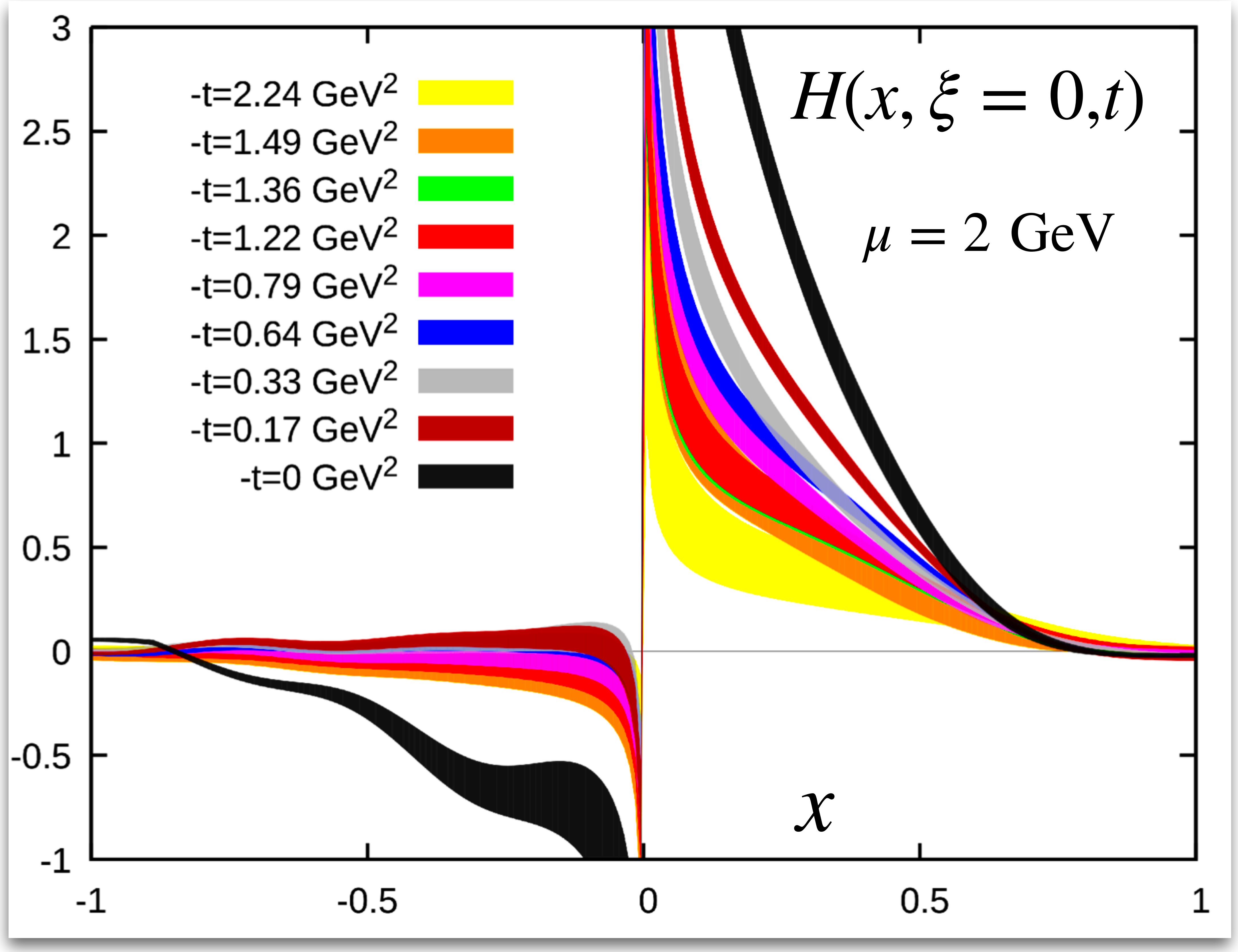


generalized parton distributions (GPD)

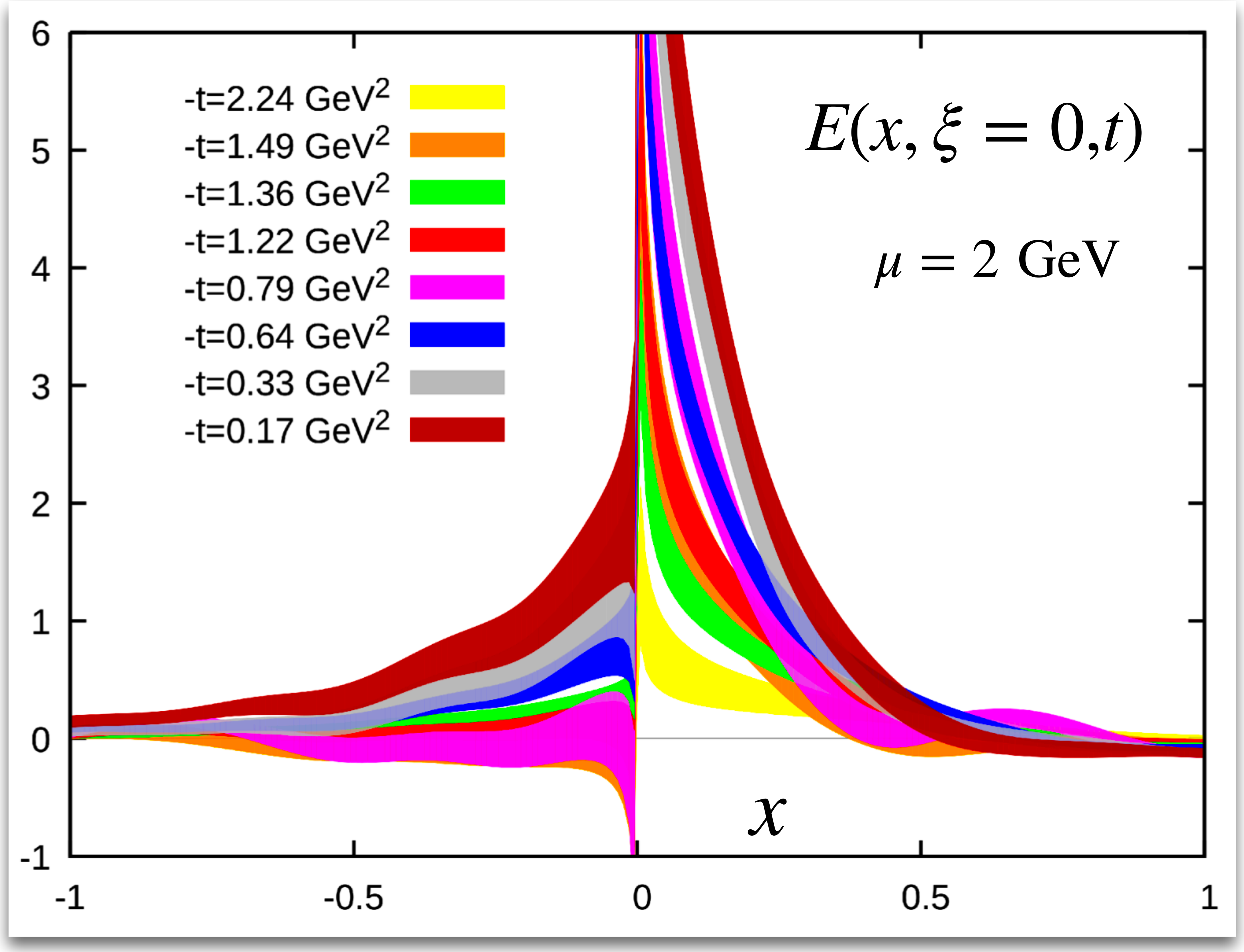
distribution of the longitudinal momentum fractions of partons in the transverse plane the hadron

proton GPD: unpolarized quarks inside …

unpolarized proton



longitudinally polarized proton



J. Miller et. al., Acta Phys. Polon. Supp. 167, 7-A6 (2023); Phys. Rev. D 106, 1, 114512 (2022)

from proton GPD to proton spin

contributions of quarks' total angular momentum to proton spin:

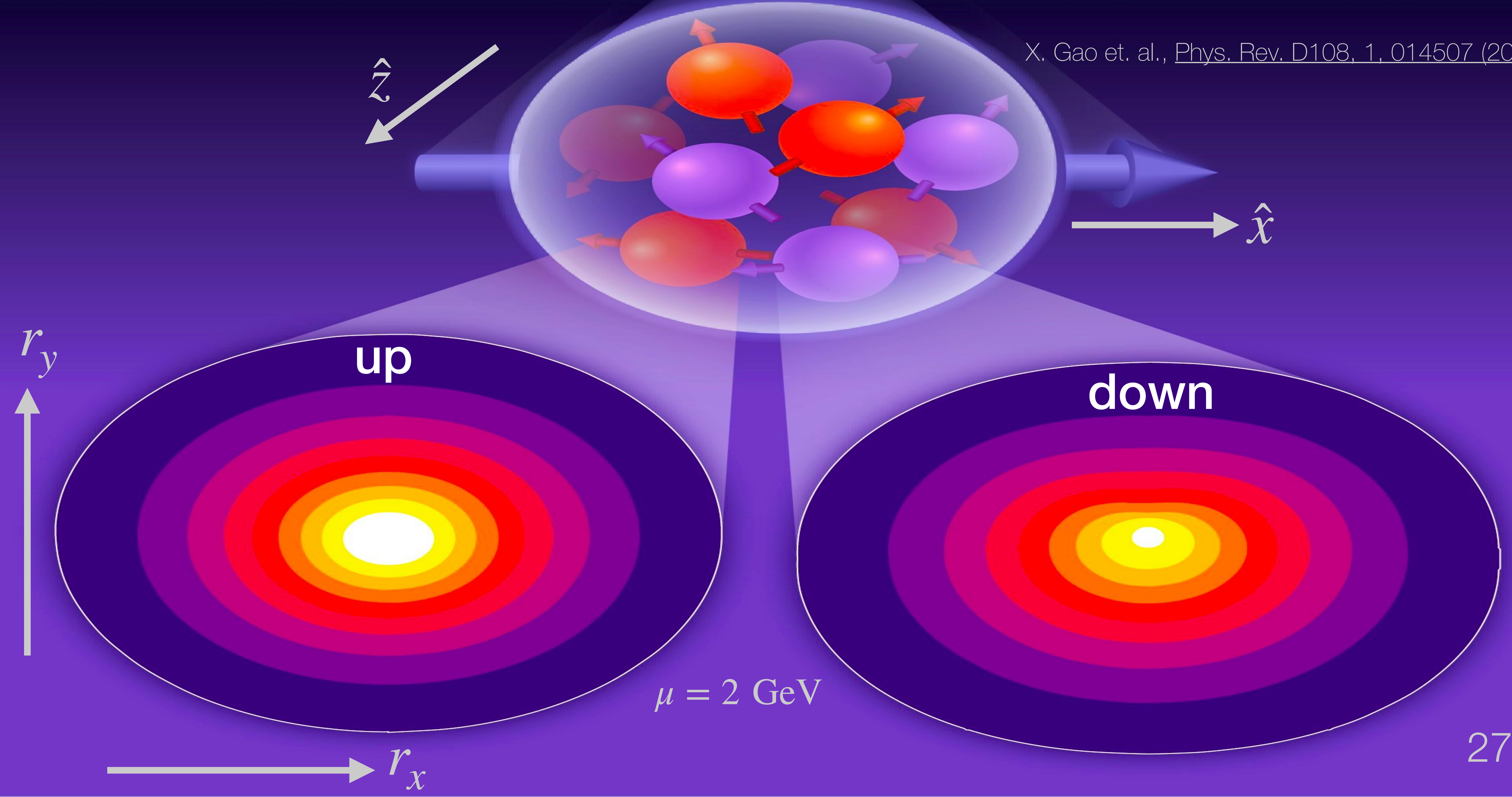
$$J^q = \frac{1}{2}\left[A_{20}(0) + B_{20}(0)\right]$$

$$A_{2,0}(t) = \int_{-1}^{1} xH^q(x,\xi=0,t)dx \qquad B_{2,0}(t) = \int_{-1}^{1} xE^q(x,\xi=0,t)dx$$

and it's distribution in the transverse plane $J^q(r_\perp)$

distributions of quarks' angular momenta

X. Gao et. al., Phys. Rev. D108, 1, 014507 (2023)



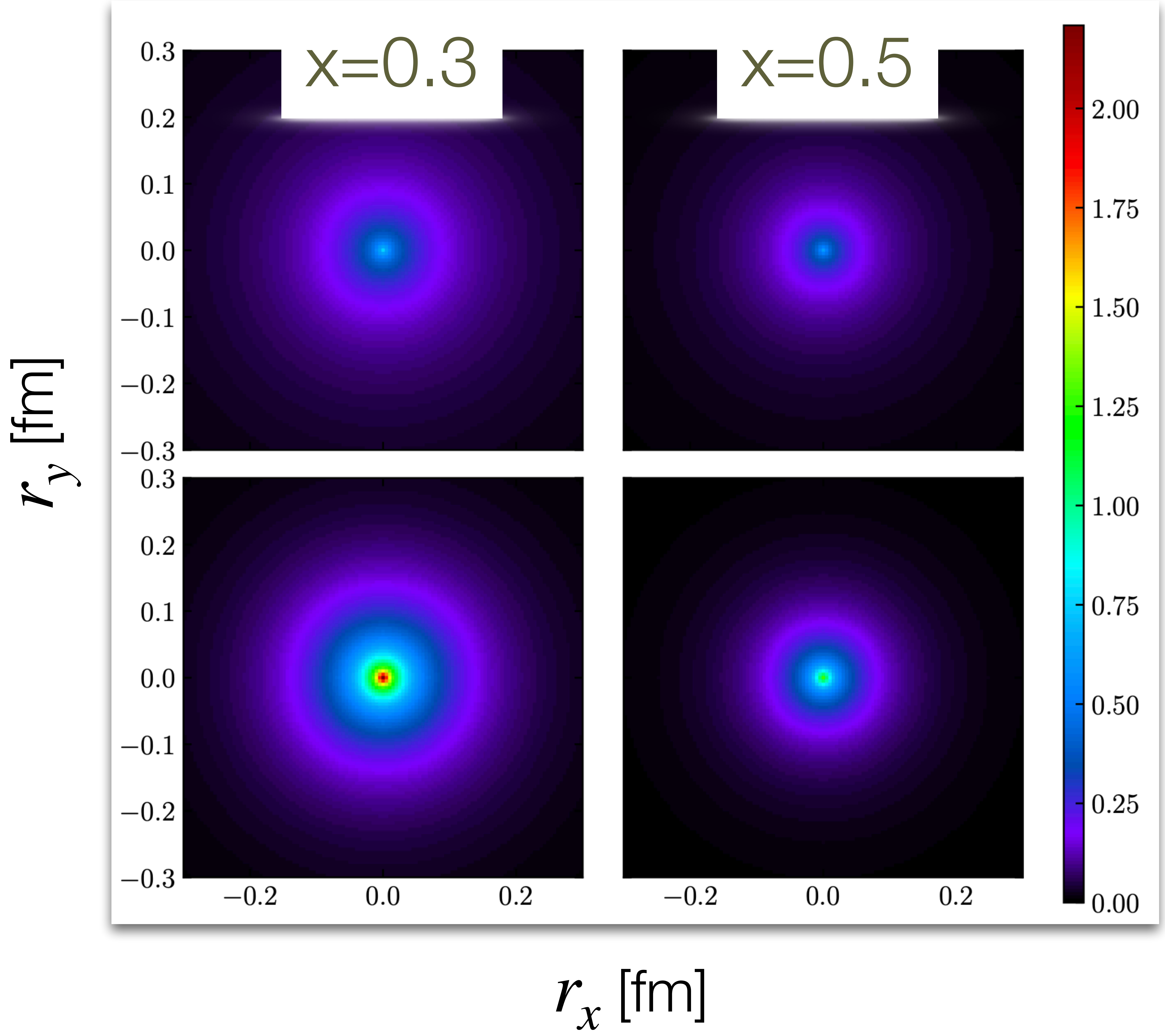
2+1 dimensional image …

pion

vs.

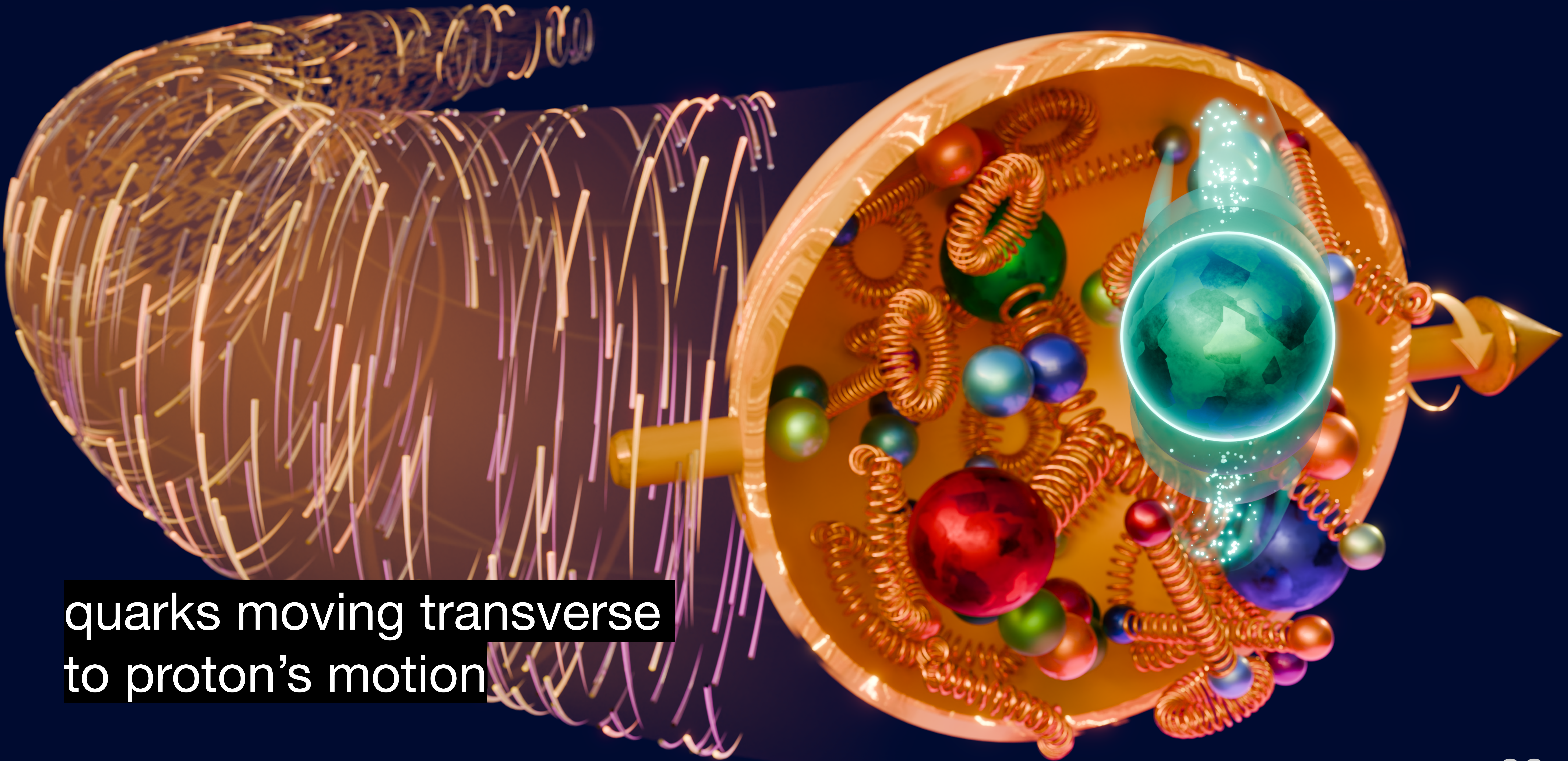
proton

quark's longitudinal momentum fraction

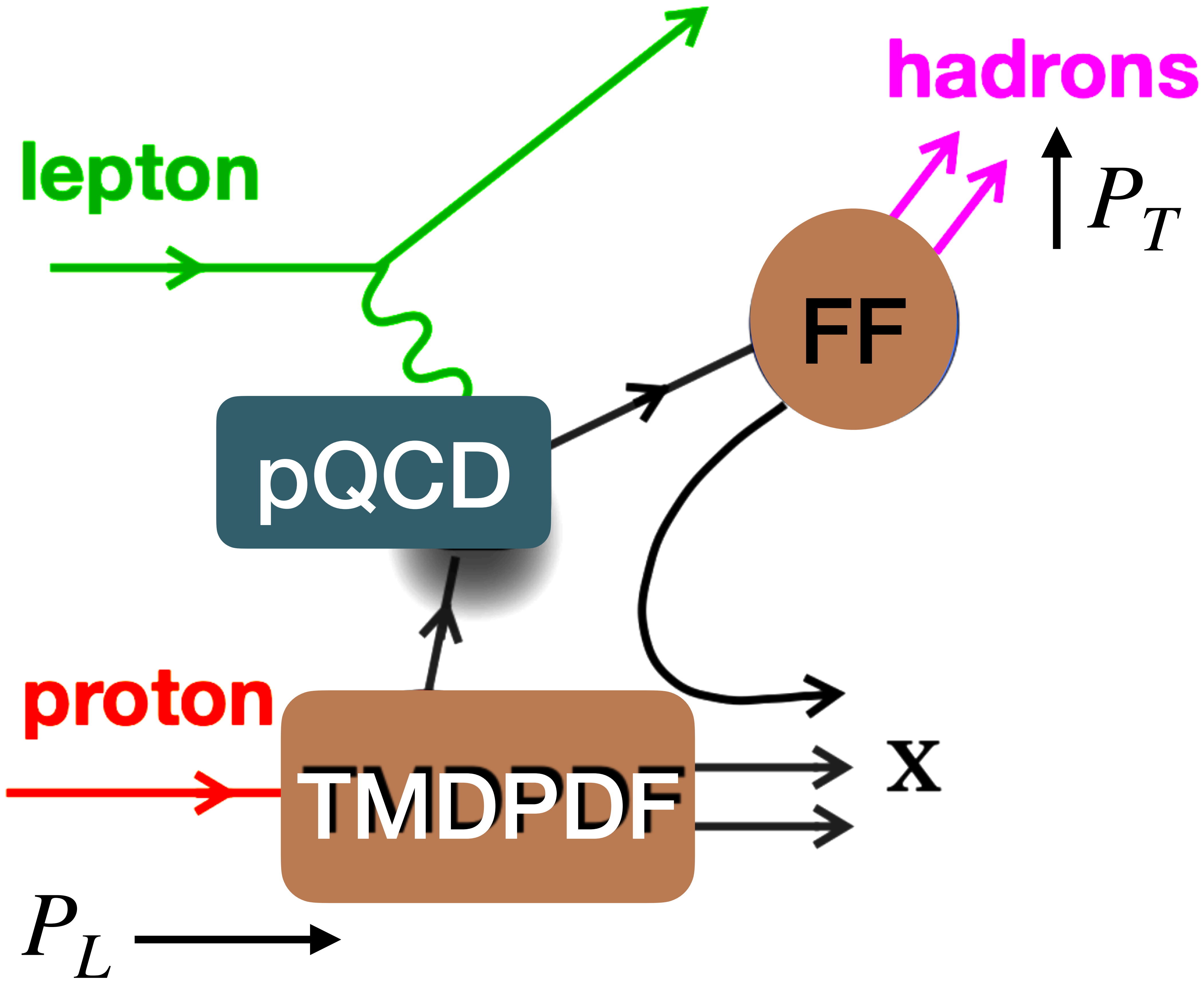


Q. Shi et. al., arXiv:2407.03516

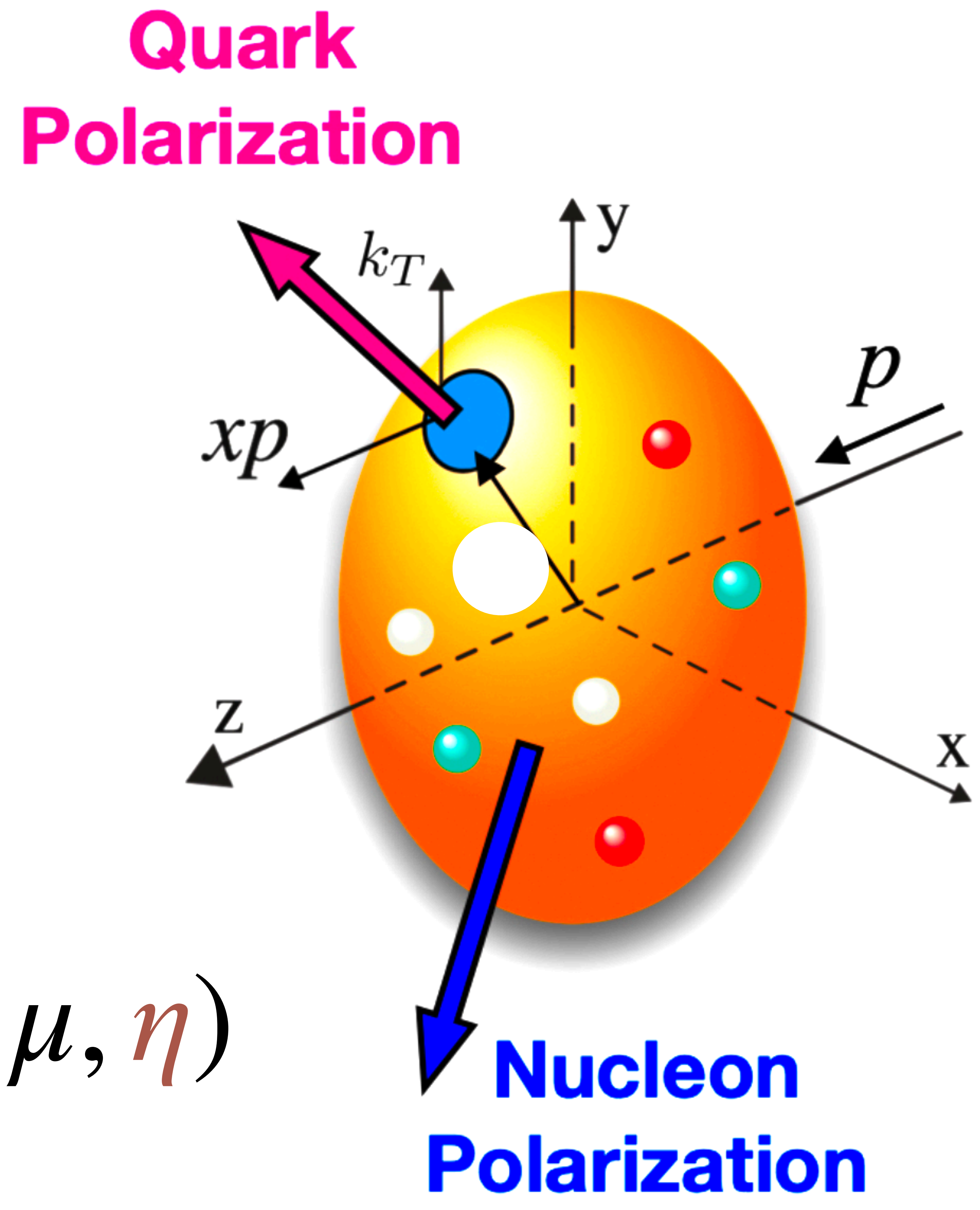
partonic image of proton: 3-dimensional momentum space



semi-inclusive deep inelastic scattering



$$f(x, k_T, \mu, \eta)$$



transverse momentum-dependent PDF (TMDPDF)

b_T is Fourier conjugate of k_T

evolution of TMD functions across collision energies ...

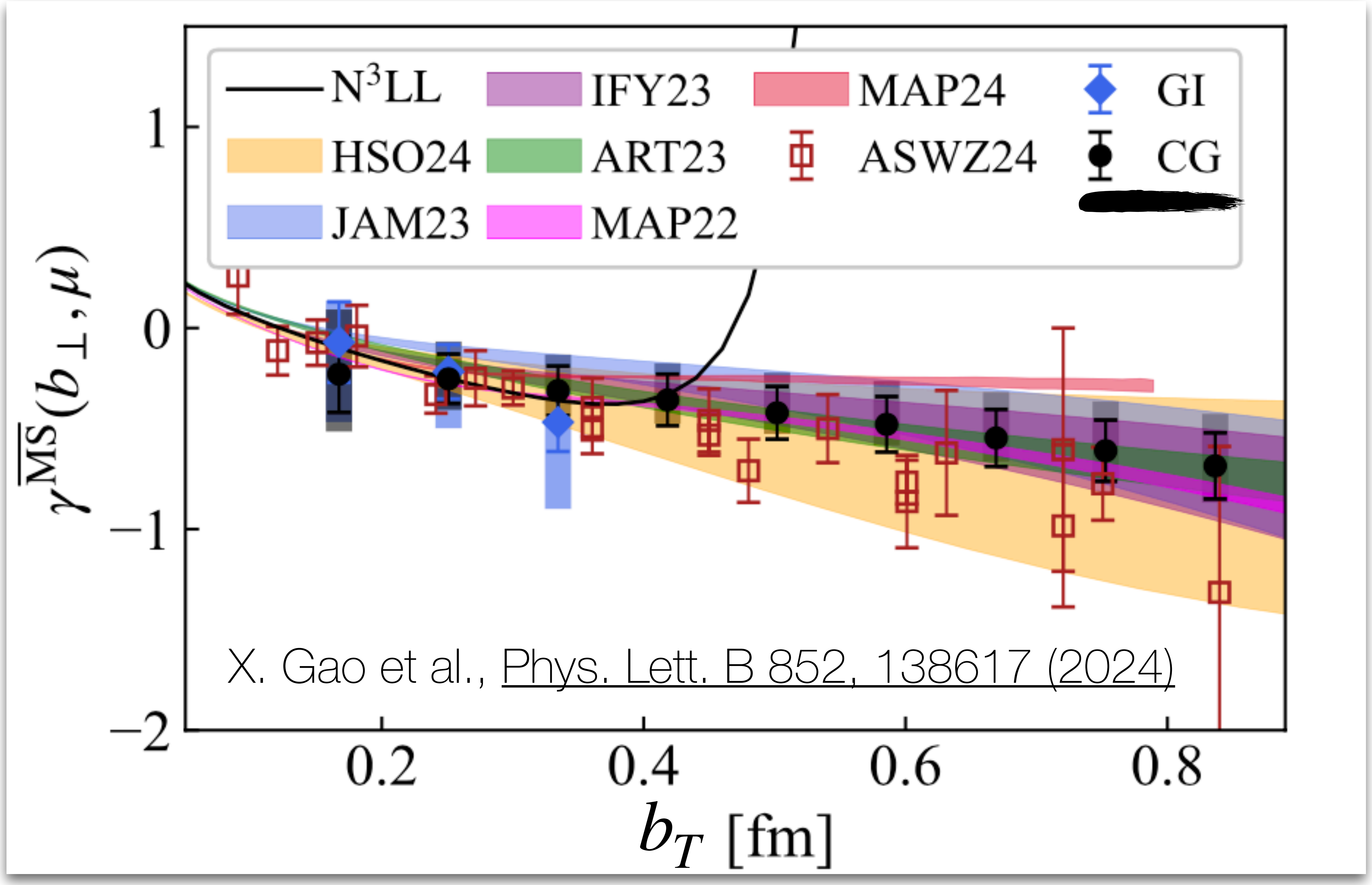
Collins-Soper kernel

$$\gamma^{\overline{\mathrm{MS}}}(b_T, \mu) = \frac{\partial \phi(x, b_T, \eta, \mu)}{\partial \ln \sqrt{\eta}}$$

property of QCD vacuum — independent of hadronic state

nonperturbative Collins-Soper kernel

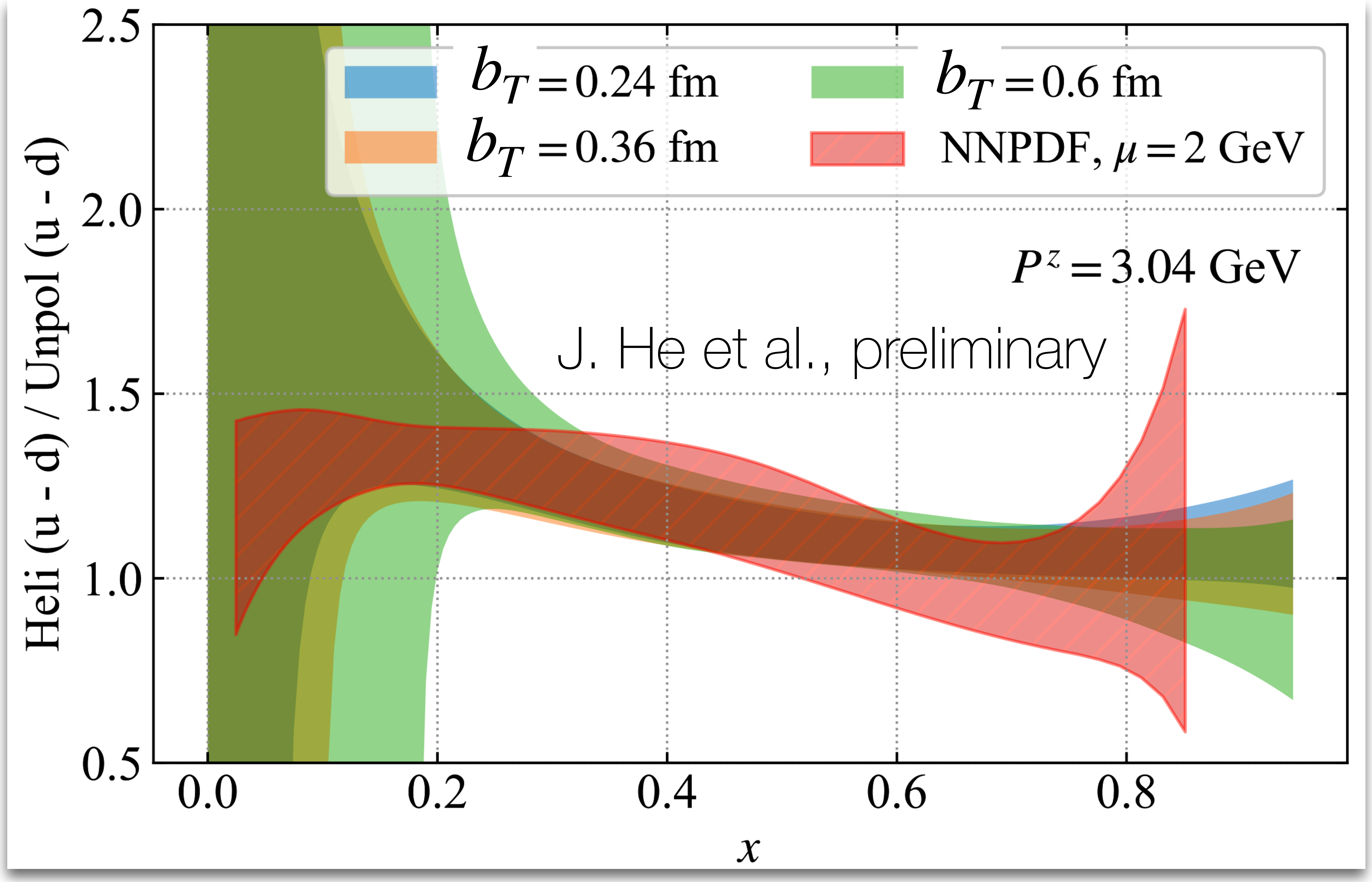
nonperturbative Collins-Soper kernel from LQCD



unitary chiral quarks, physical mass

TMDPDF: polarized vs. unpolarized proton

$$\frac{\text{helicity TMDPDF}}{\text{unplol. TMDPDF}}$$

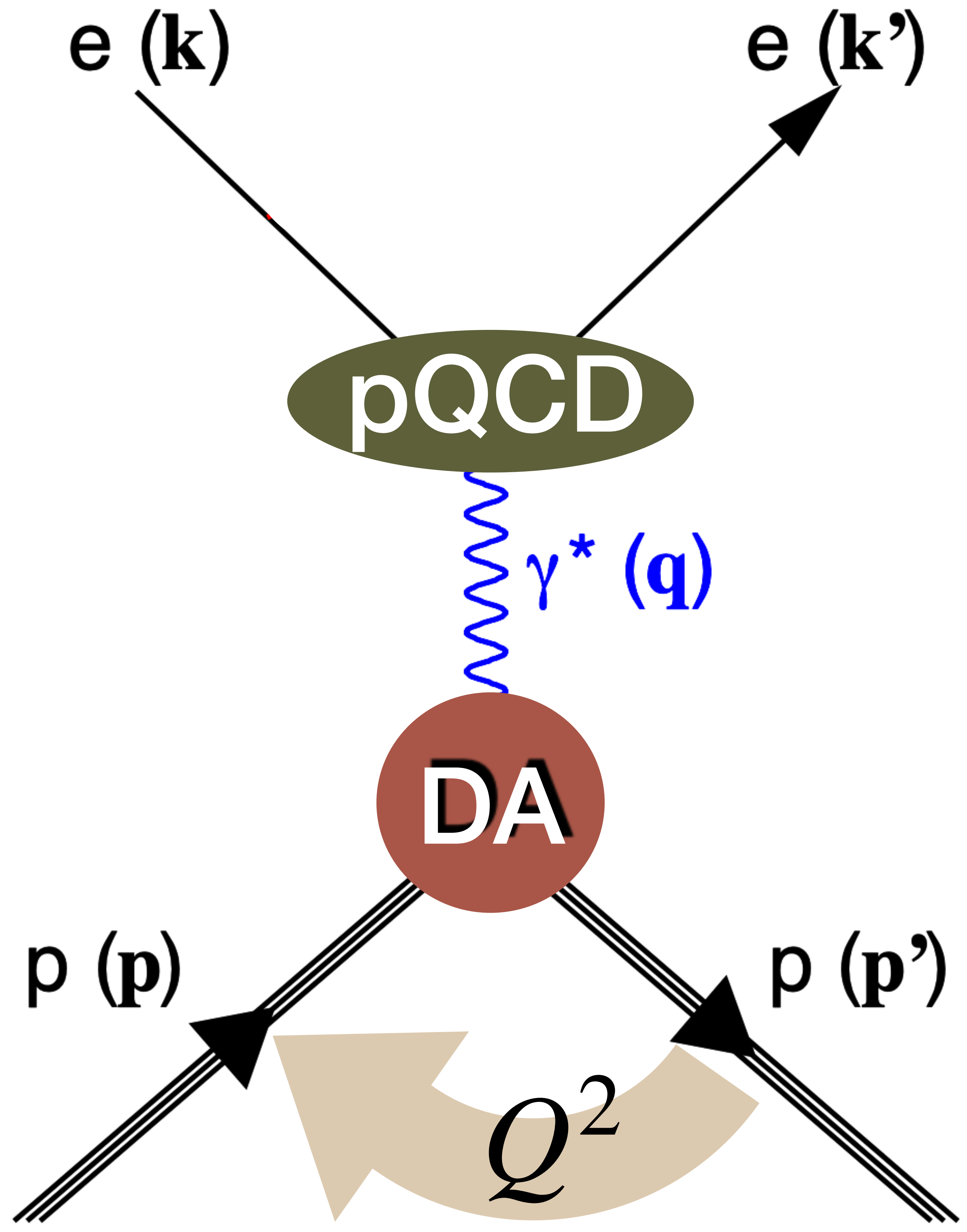


unitary chiral quarks, physical mass

electromagnetic form factor at large momenta

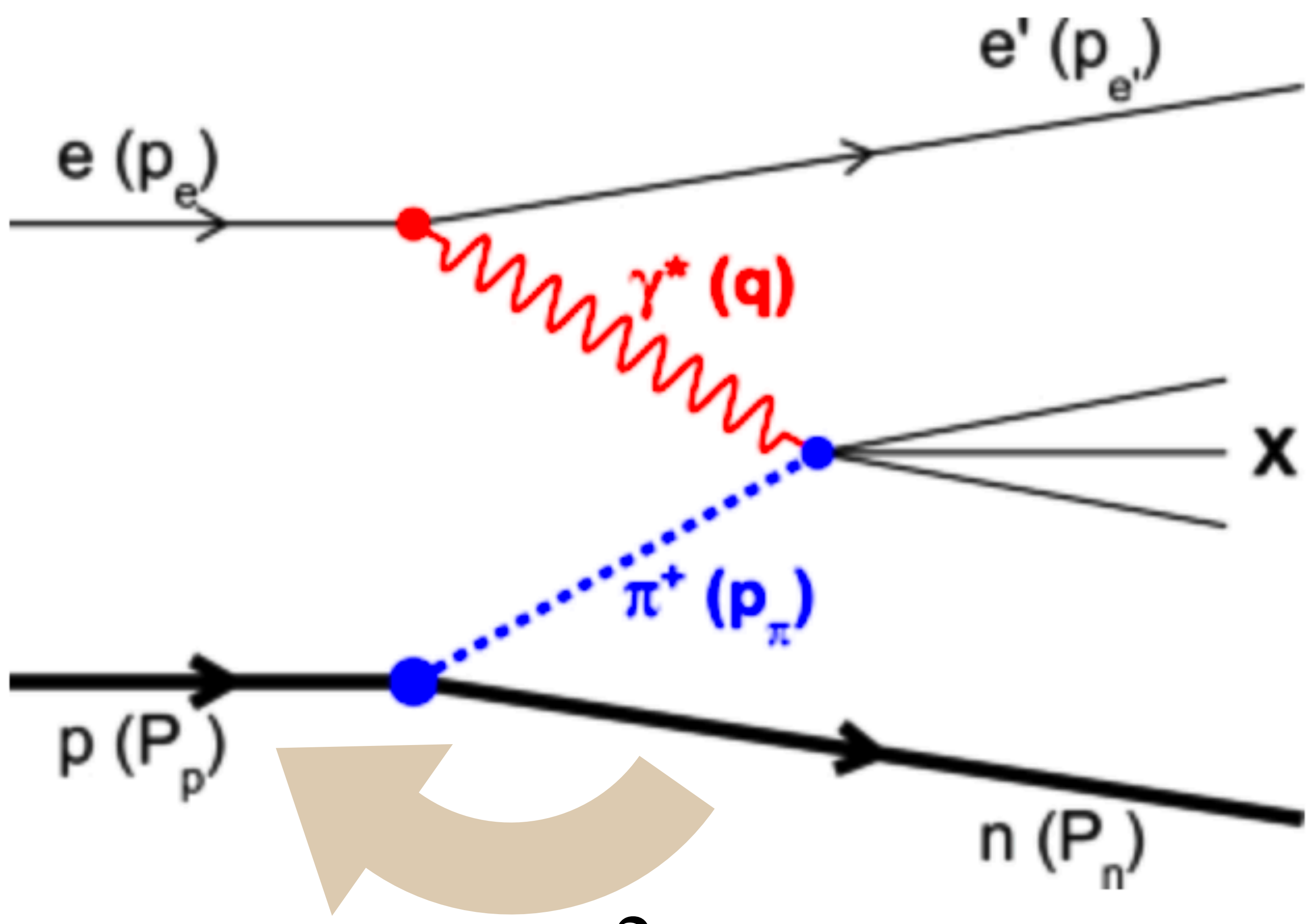
$F(Q^2 \gg \Lambda_{QCD}) \sim$ pQCD $\otimes$ DA

distribution amplitude (DA)

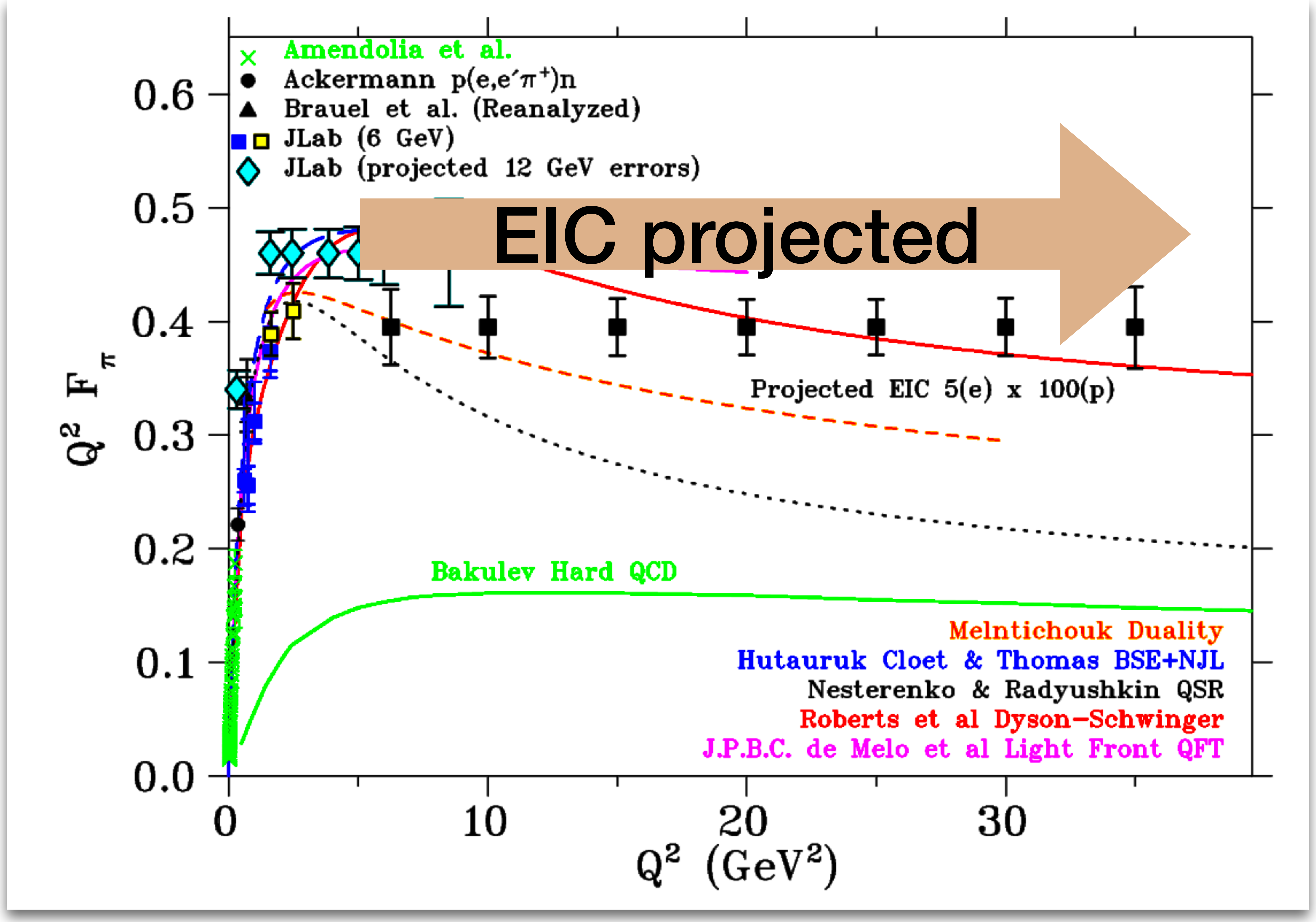


large momenta π^+ from factor at EIC ...

Sullivan process @ EIC



$t \to m_\pi^2$

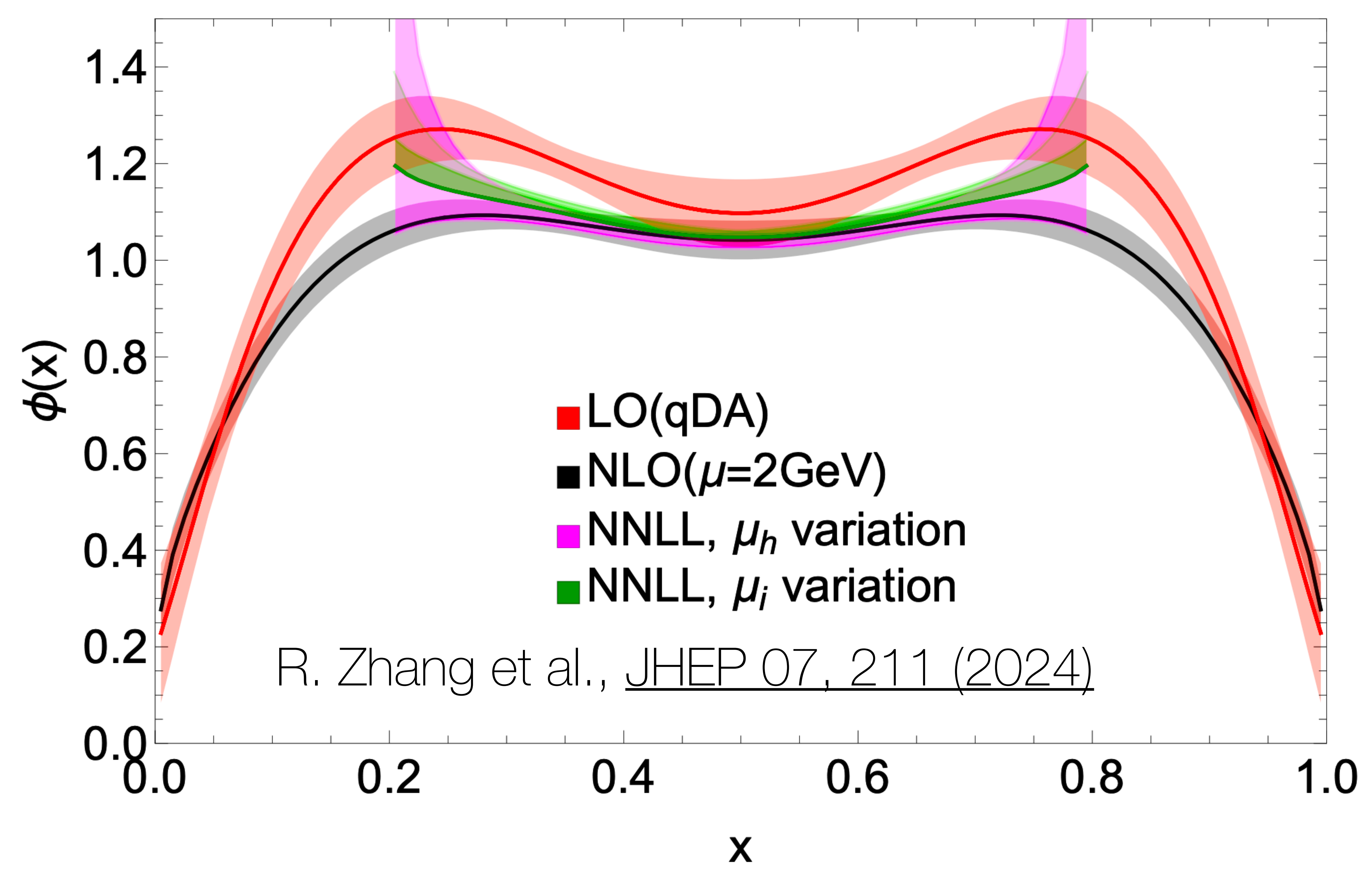


2102.11788

$F_\pi(Q^2 \gg \Lambda_{QCD}) \sim$ pQCD $\otimes$ pion DA

NNLO pQCD

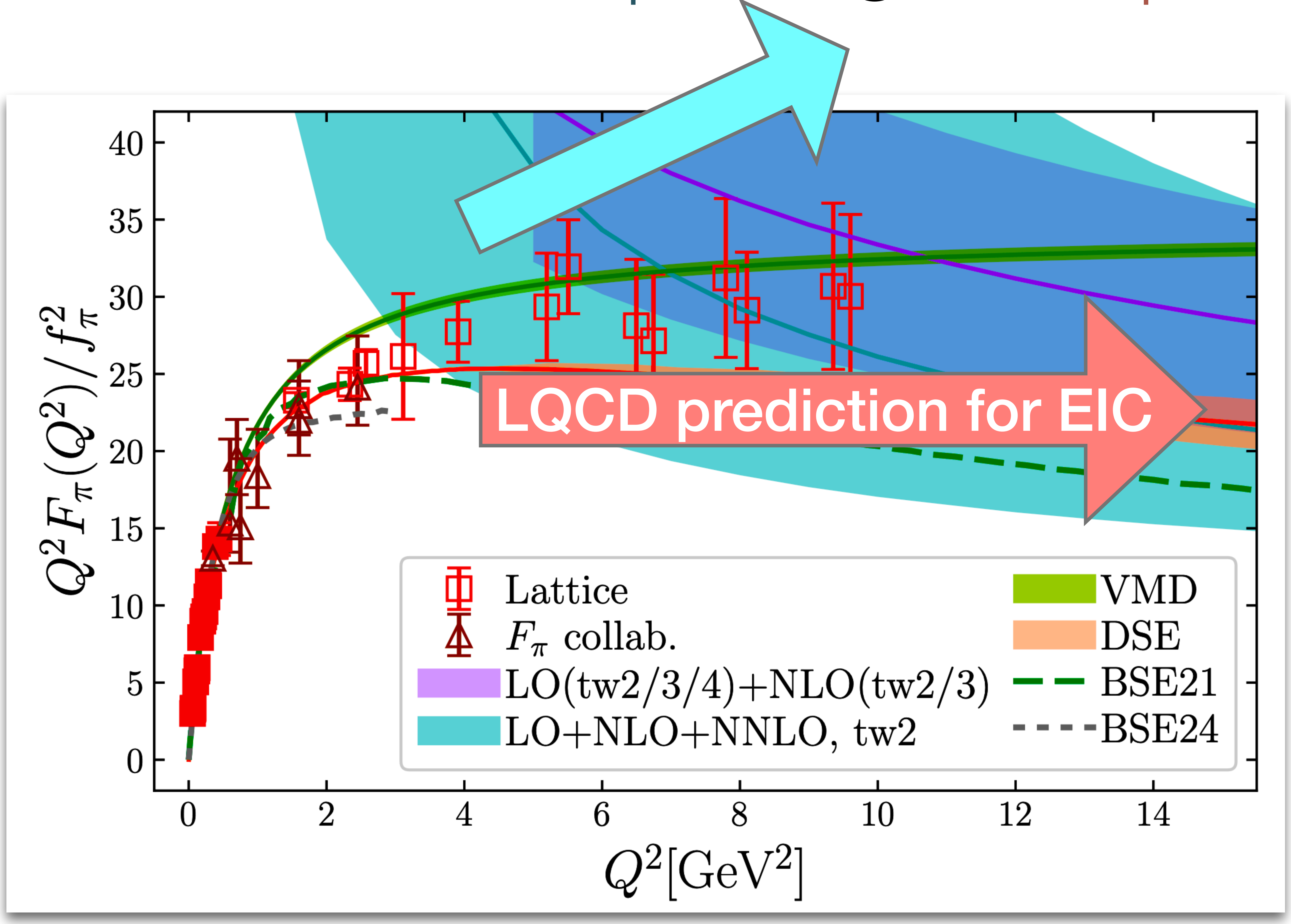
Phys. Rev. Lett. 132, 20190 (2024)



unitary chiral quarks, physical mass

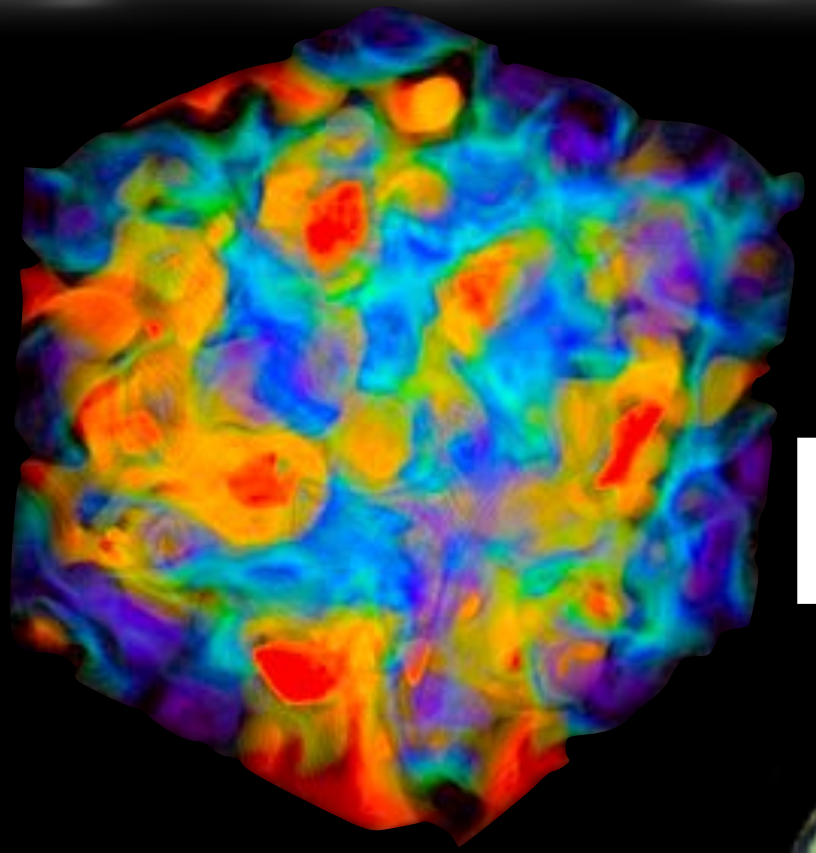
from QCD to EIC …

QCD factorization ~ NNLO pQCD ⊗ LQCD pion DA

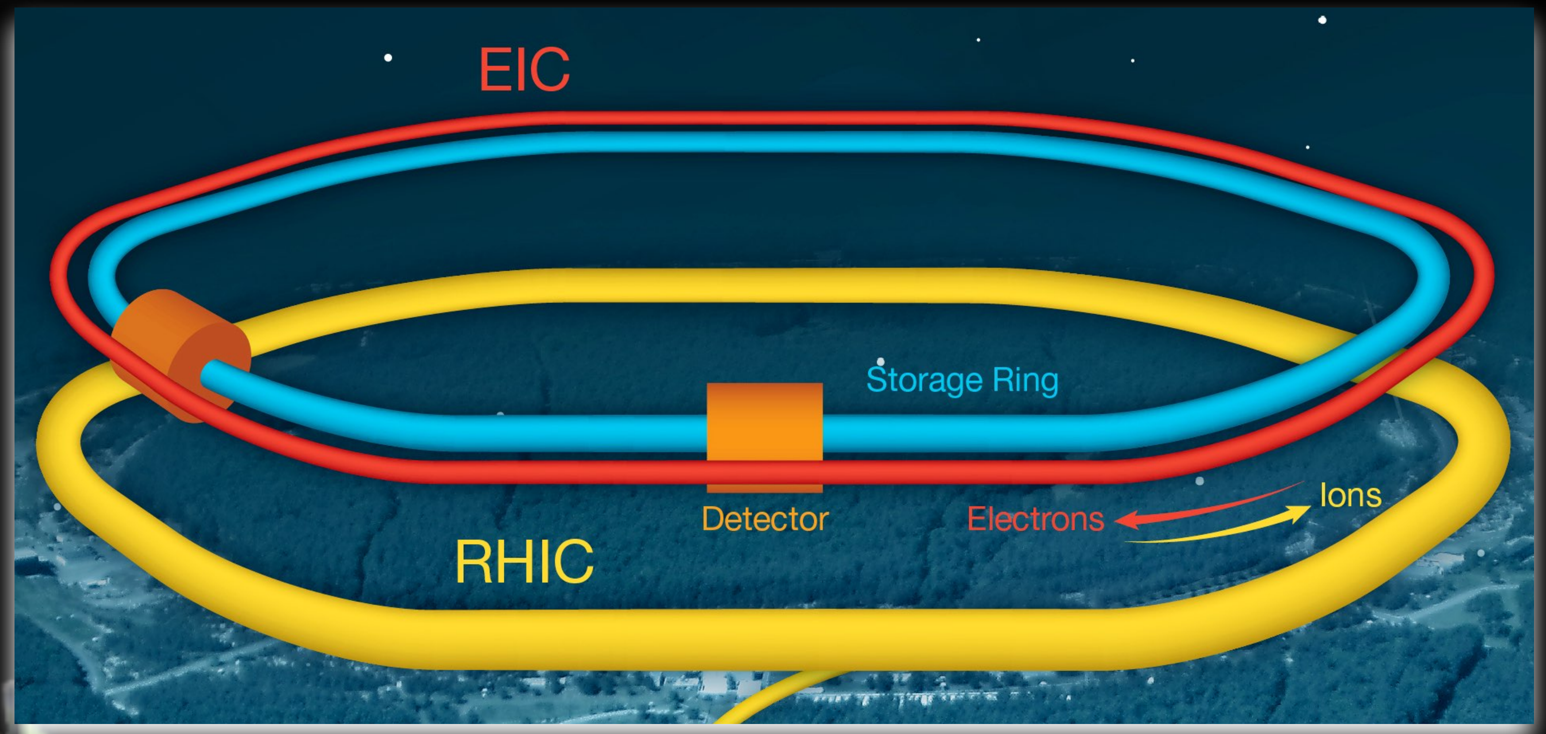


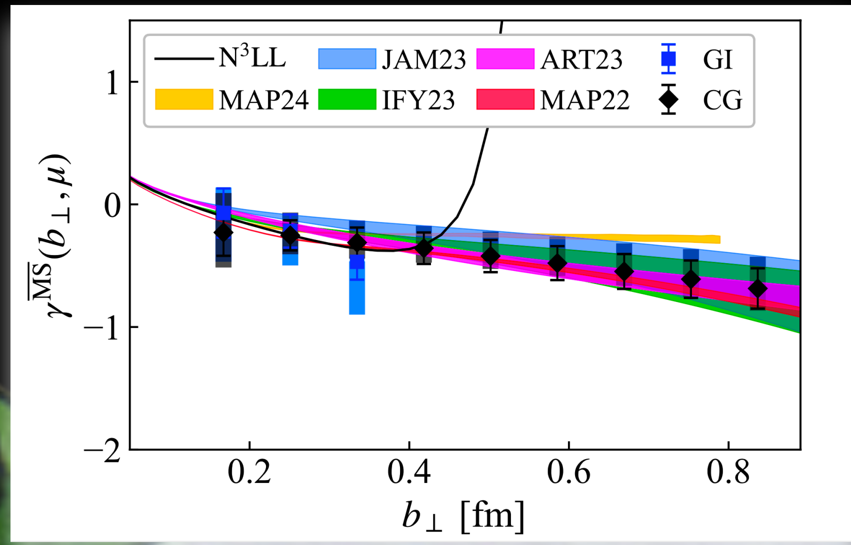
Q. Shi et. al., 2404.04412

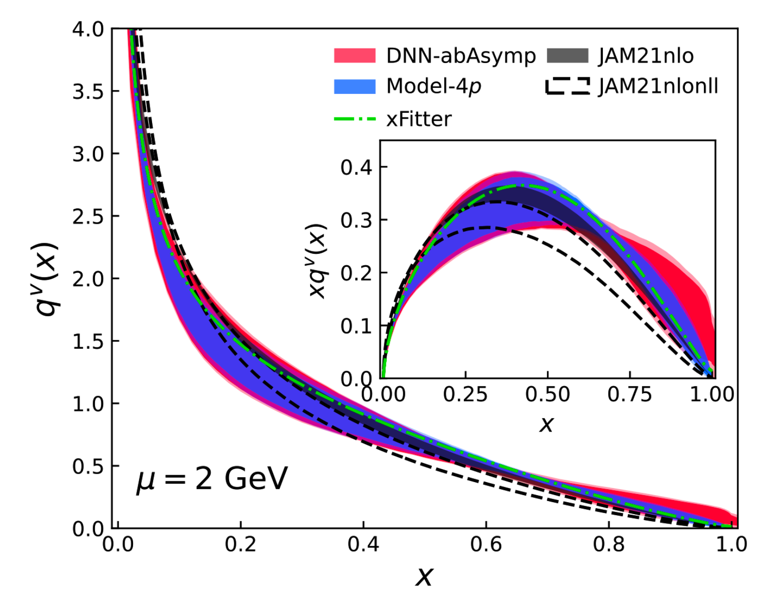
beginning of a new journey…from QCD to EIC

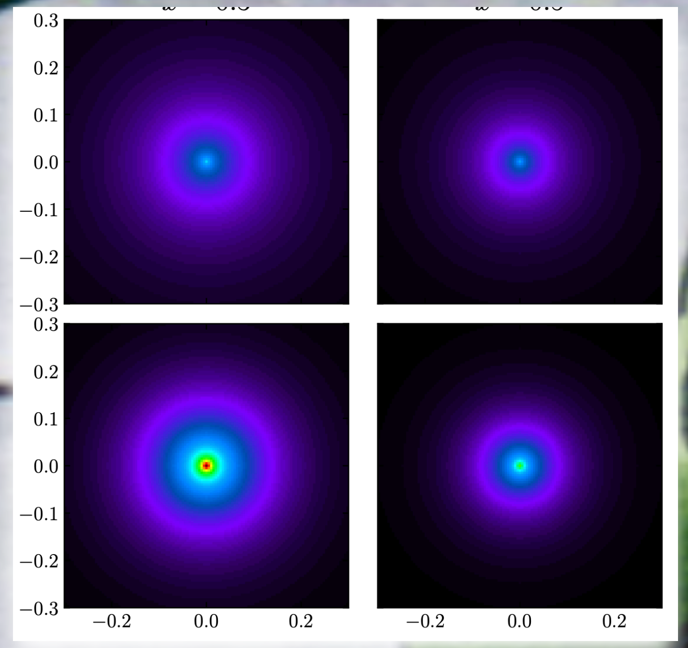


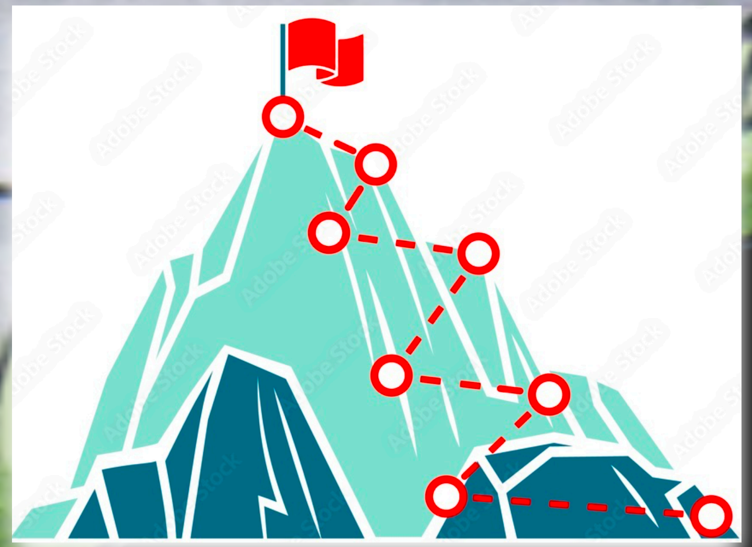
$\otimes$ pQCD

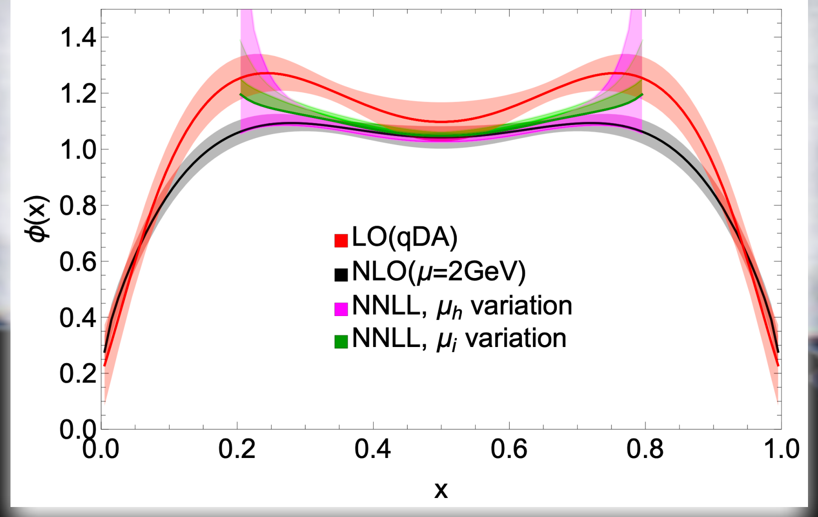












small x & saturation physics