Non-perturbative Collins-Soper kernel from a Coulomb-gauge-fixed quasi-TMD

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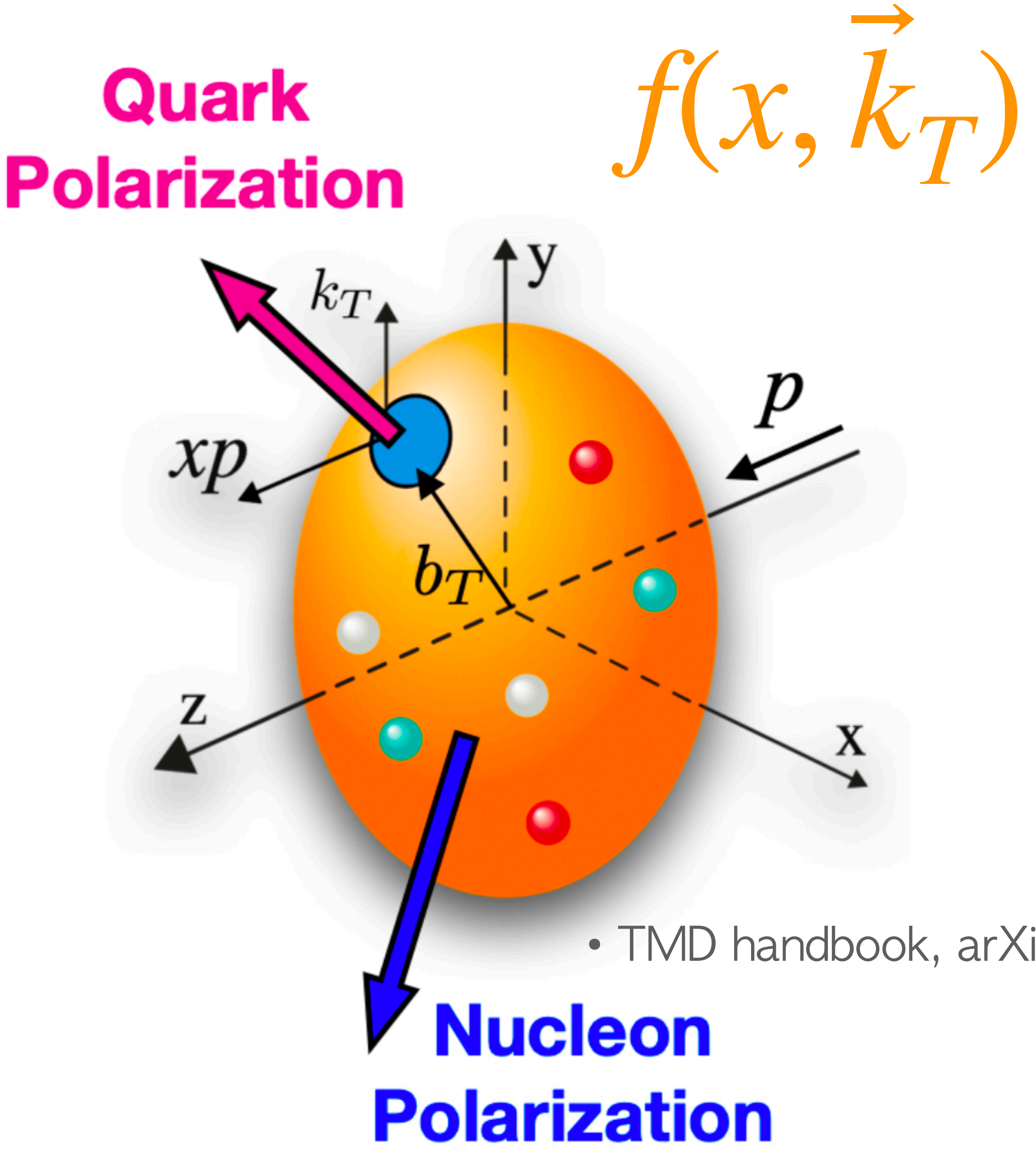
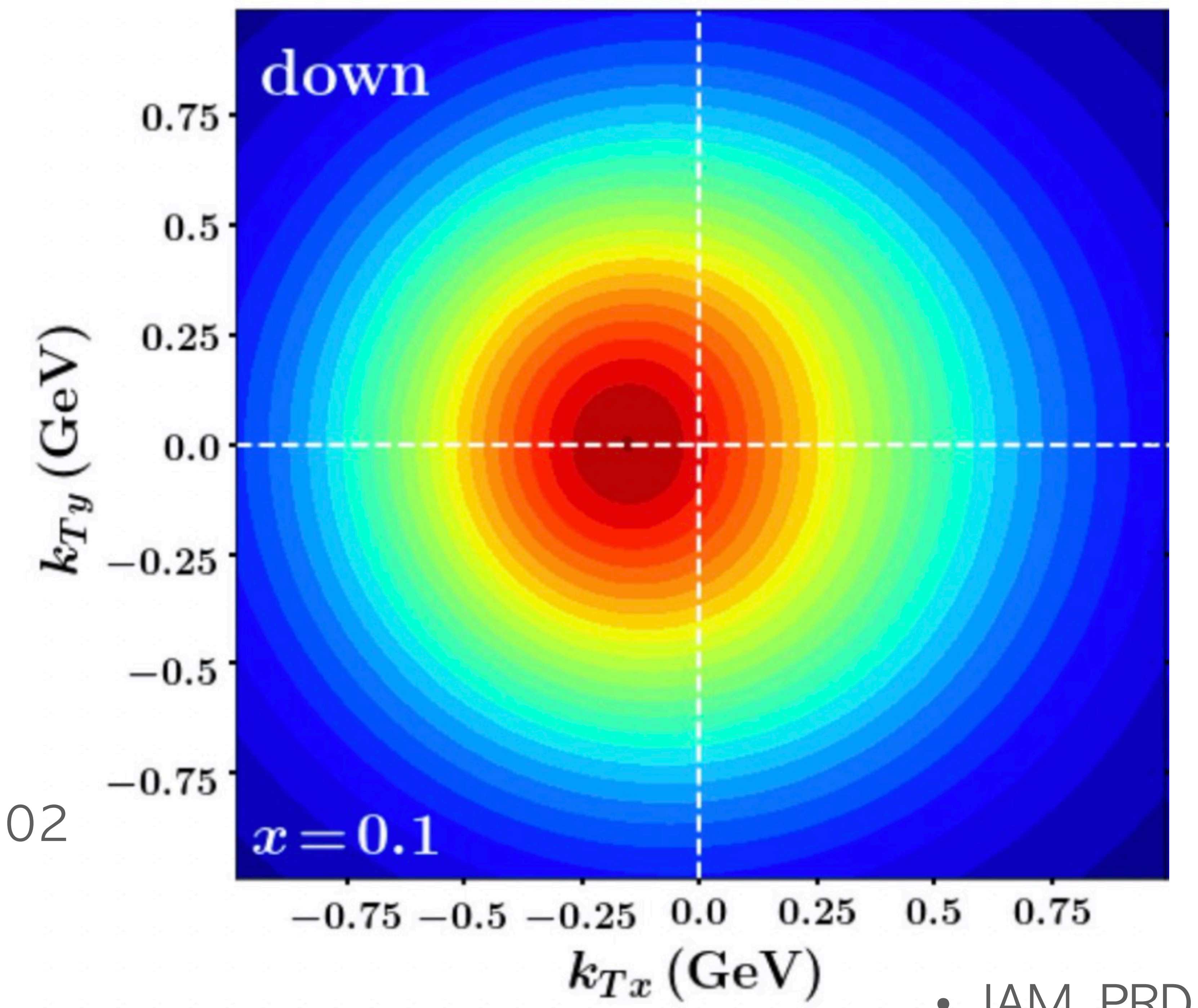
Argonne NATIONAL LABORATORY

❷ Transverse-momentum-dependent distributions



• TMD handbook, arXiv:2304.03302

Quark Sivers function



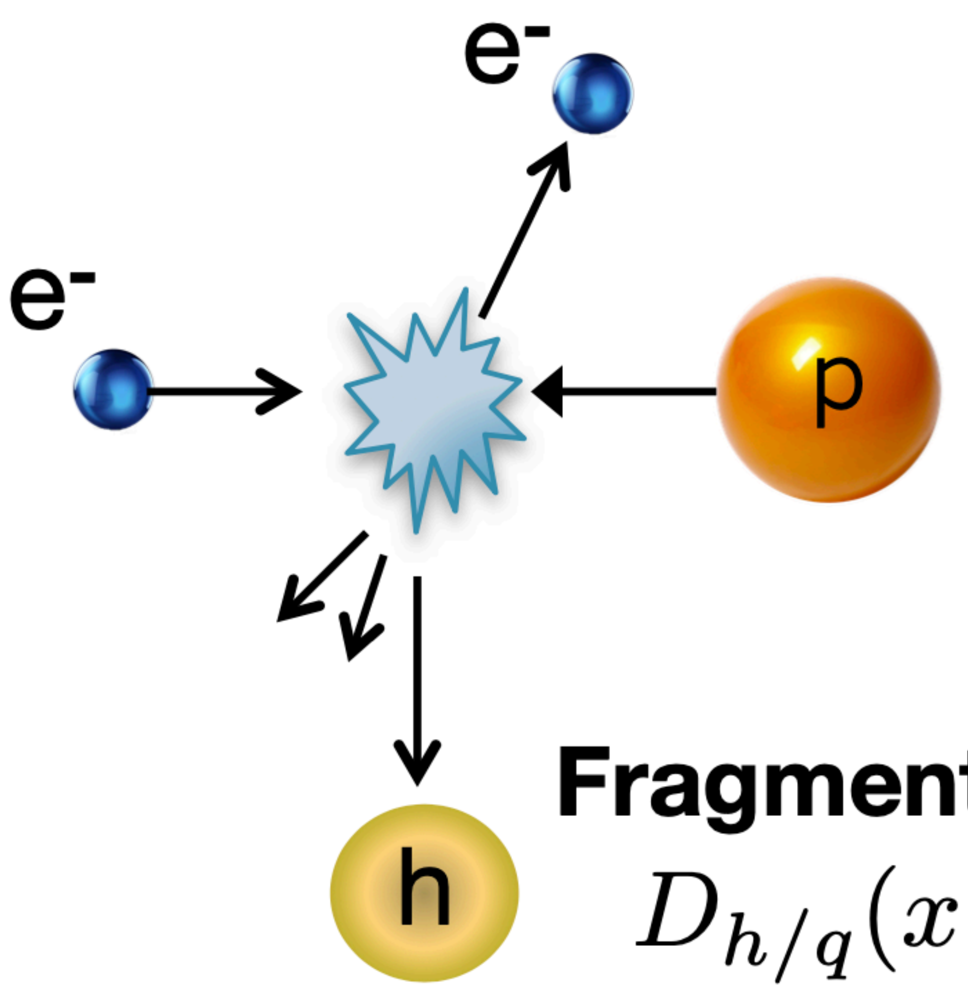
• JAM, PRD 102 (2020) 5, 054002

- 3D image: longitudinal momentum fraction x and confined motion $\vec{k}_T$.
- Nucleon spin structure: Spin-orbit correlations.
- QCD input for particle physics (e.g., m_W).

3 TMDs from global analyses of experimental data

Semi-Inclusive DIS

$$\sigma \sim f_{q/P}(x,k_T) D_{h/q}(x,k_T)$$

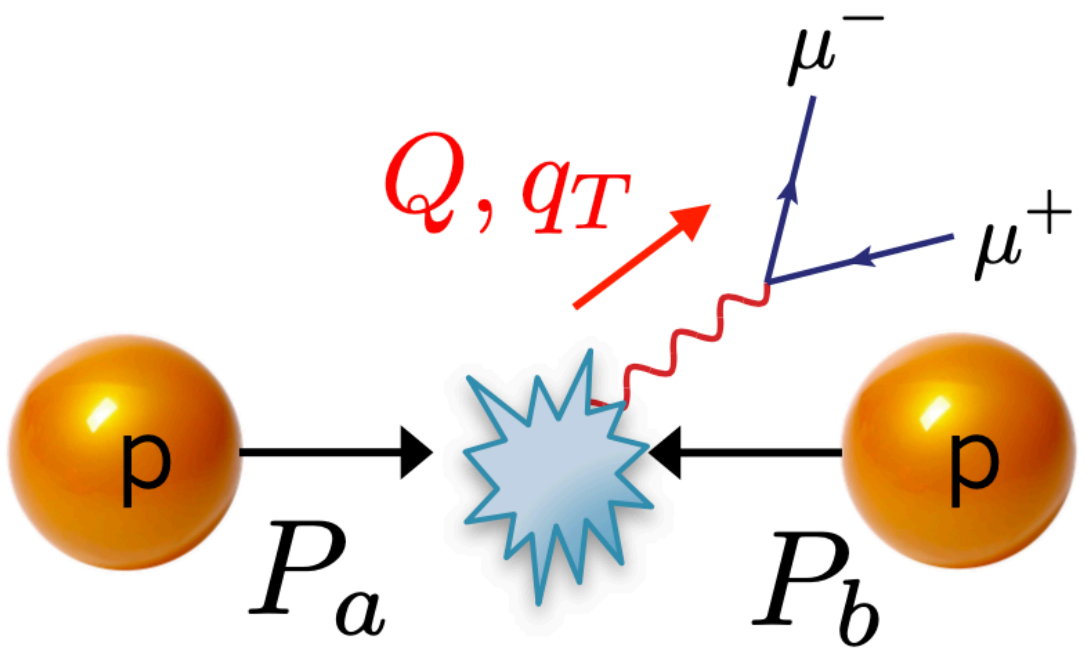


Fragmentation

$D_{h/q}(x,k_T)$

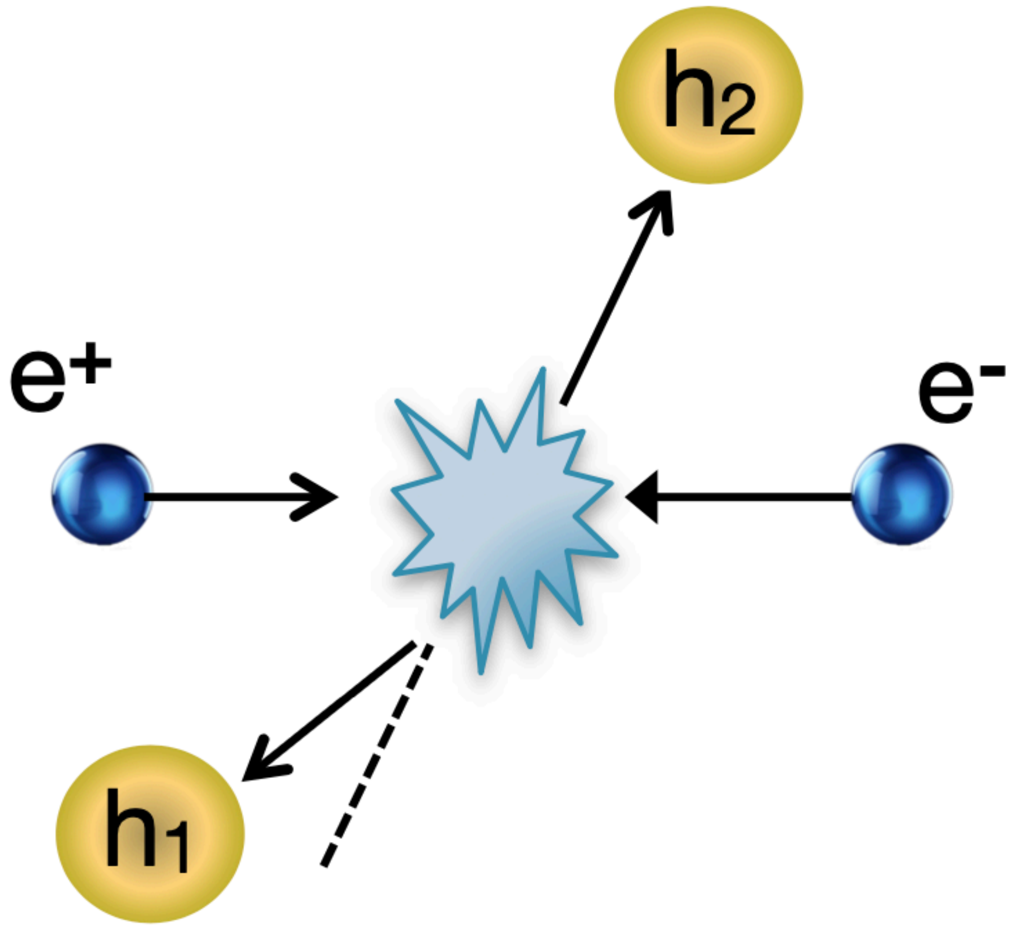
Drell-Yan

$$\sigma \sim f_{q/P}(x,k_T) f_{q/P}(x,k_T)$$



Dihadron in e+e-

$$\sigma \sim D_{h_1/q}(x,k_T) D_{h_2/q}(x,k_T)$$



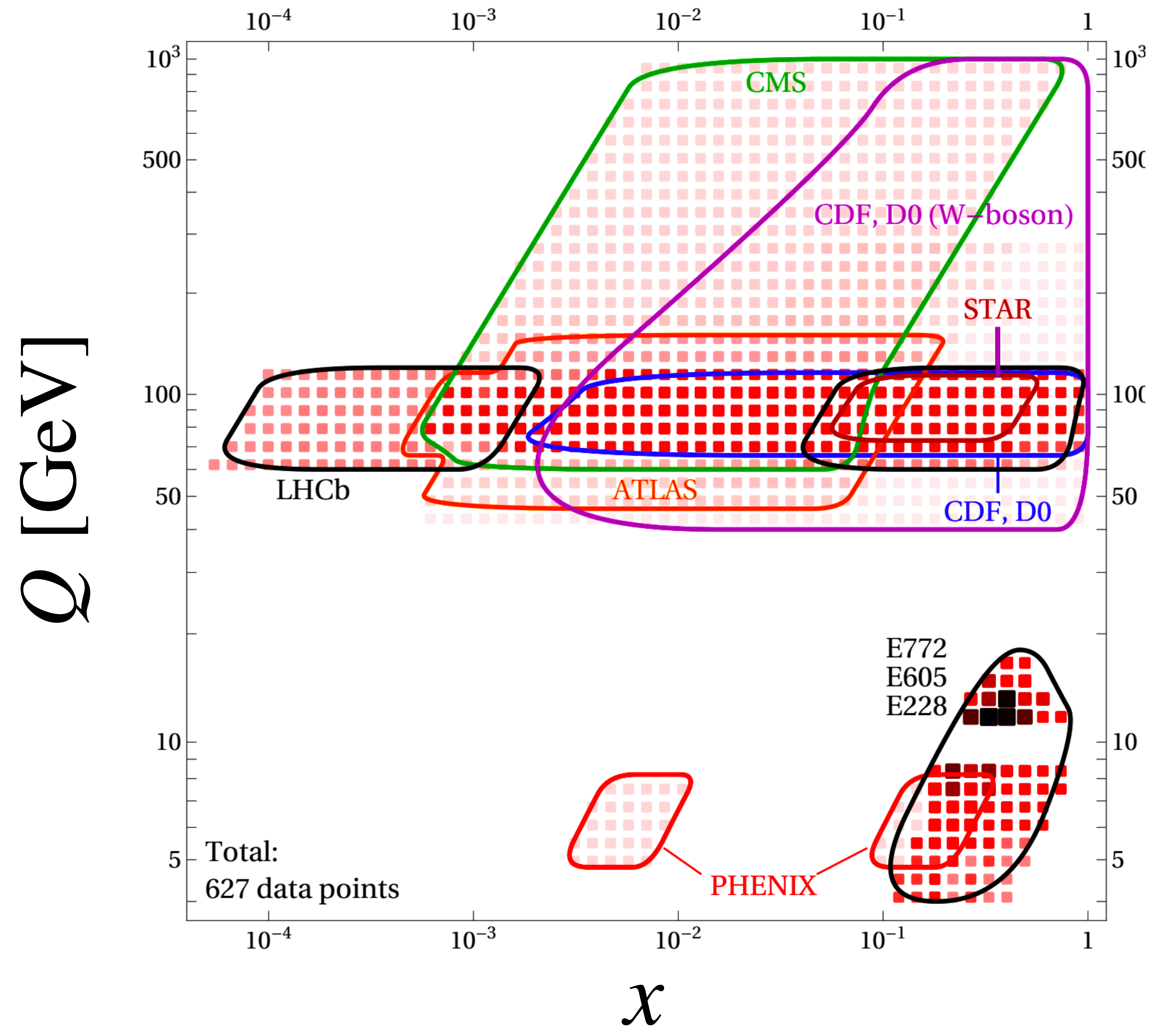
$$\frac{d\sigma_{DY}}{dQ\,dY\,dq_T^2} = H(Q,\mu) \int d^2\vec{b}_T e^{i\vec{q}_T\cdot\vec{b}_T} f_q(x_a,\vec{b}_T,\mu,\zeta_a)\, f_q(x_b,\vec{b}_T,\mu,\zeta_b)\left[1+\mathcal{O}\left(\frac{q_T^2}{Q^2}\right)\right]$$

Perturbative hard kernels

Nonperturbative TMDs

$$q_T^2 \ll Q^2$$

4 TMDs from global analyses of experimental data



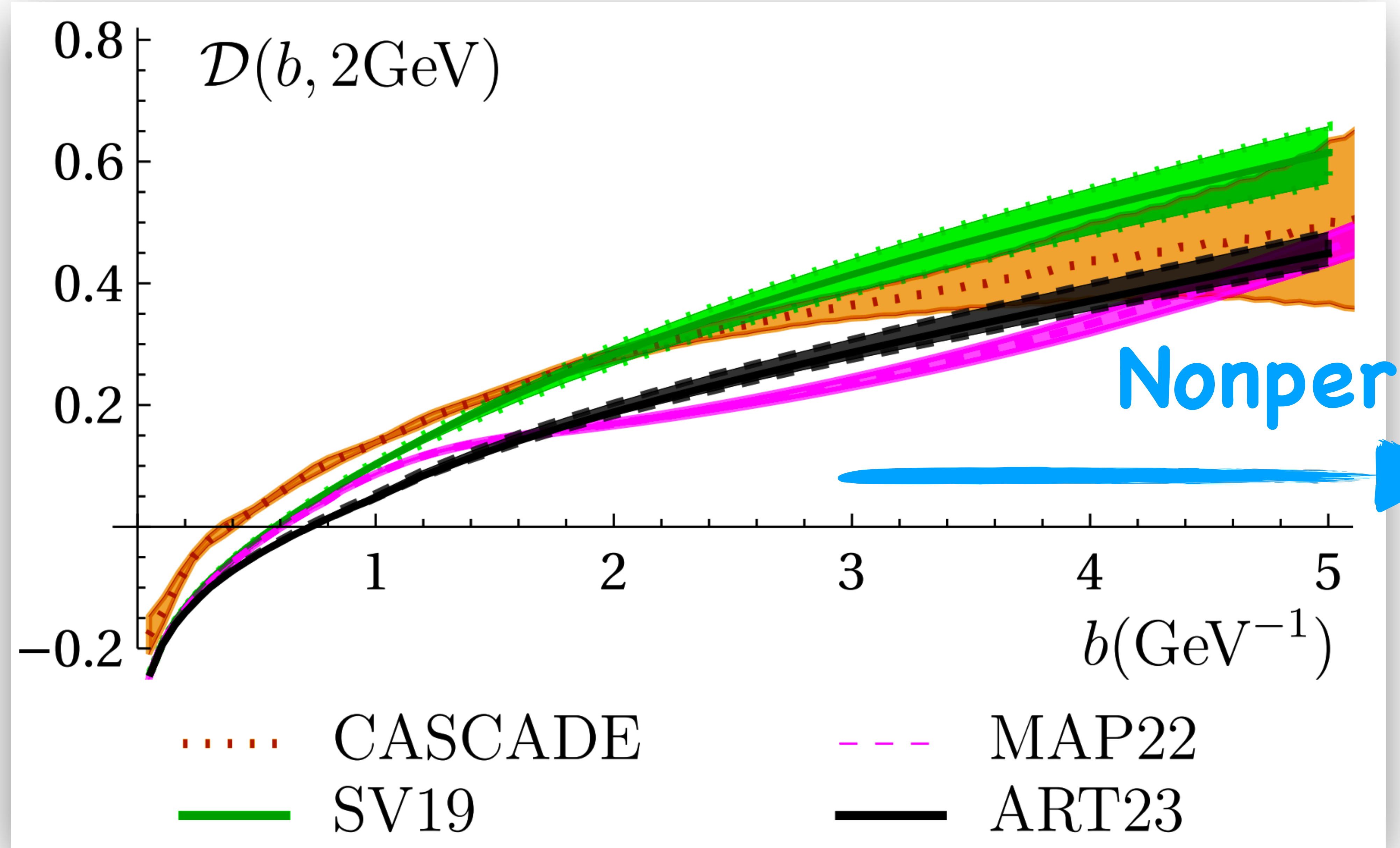
• V. Moos, et. al. (ART23), JHEP 05 (2024) 036

- **Relate TMDs at different energy scales**

$$\mu \frac{d}{d\mu} \ln f_q(x, \vec{b}_T, \mu, \zeta) = \gamma_\mu^q(\mu, \zeta)$$

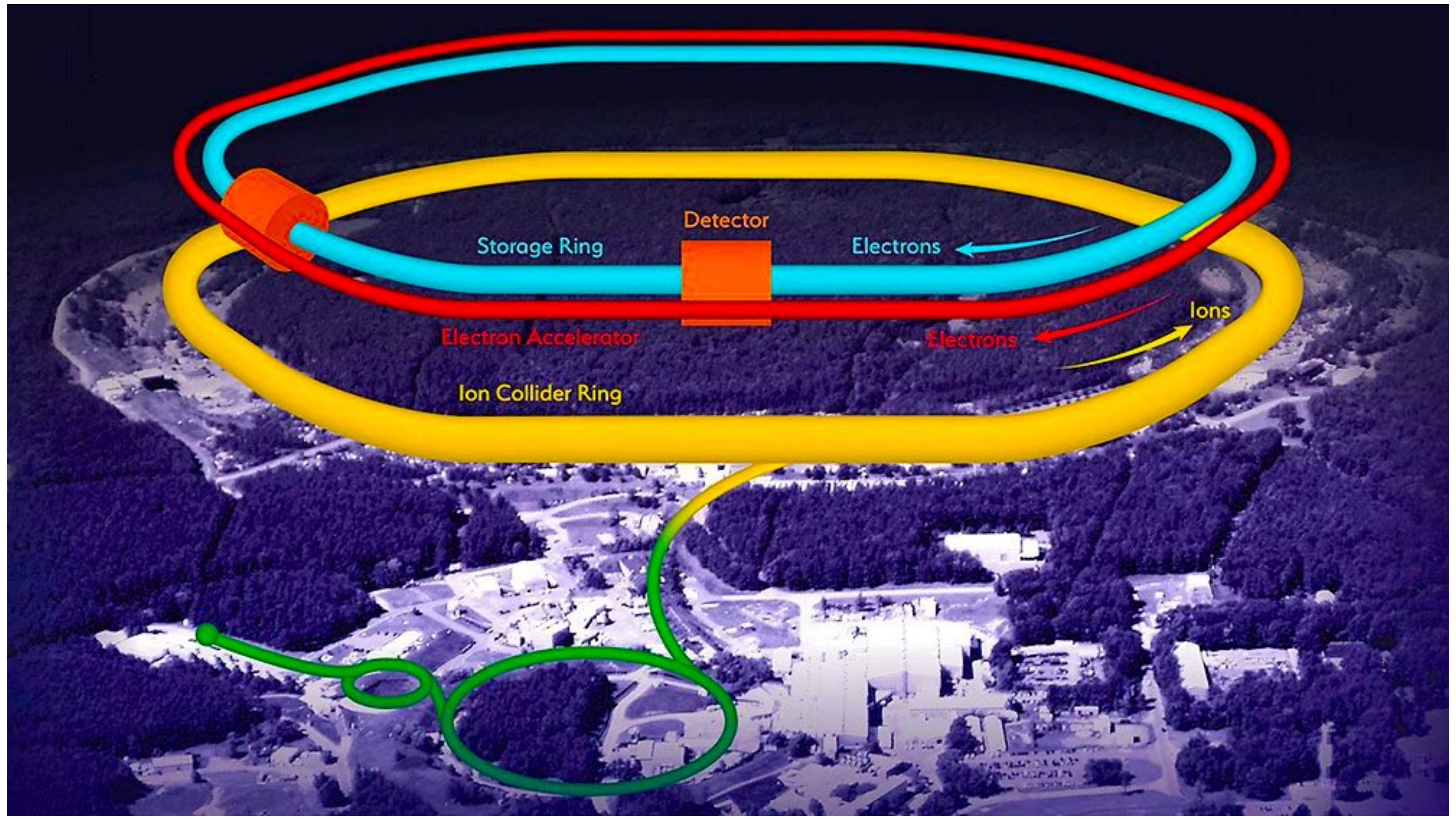
$$\zeta \frac{d}{d\zeta} \ln f_q(x, \vec{b}_T, \mu, \zeta) = \gamma_\zeta^q(\mu, b_T)$$

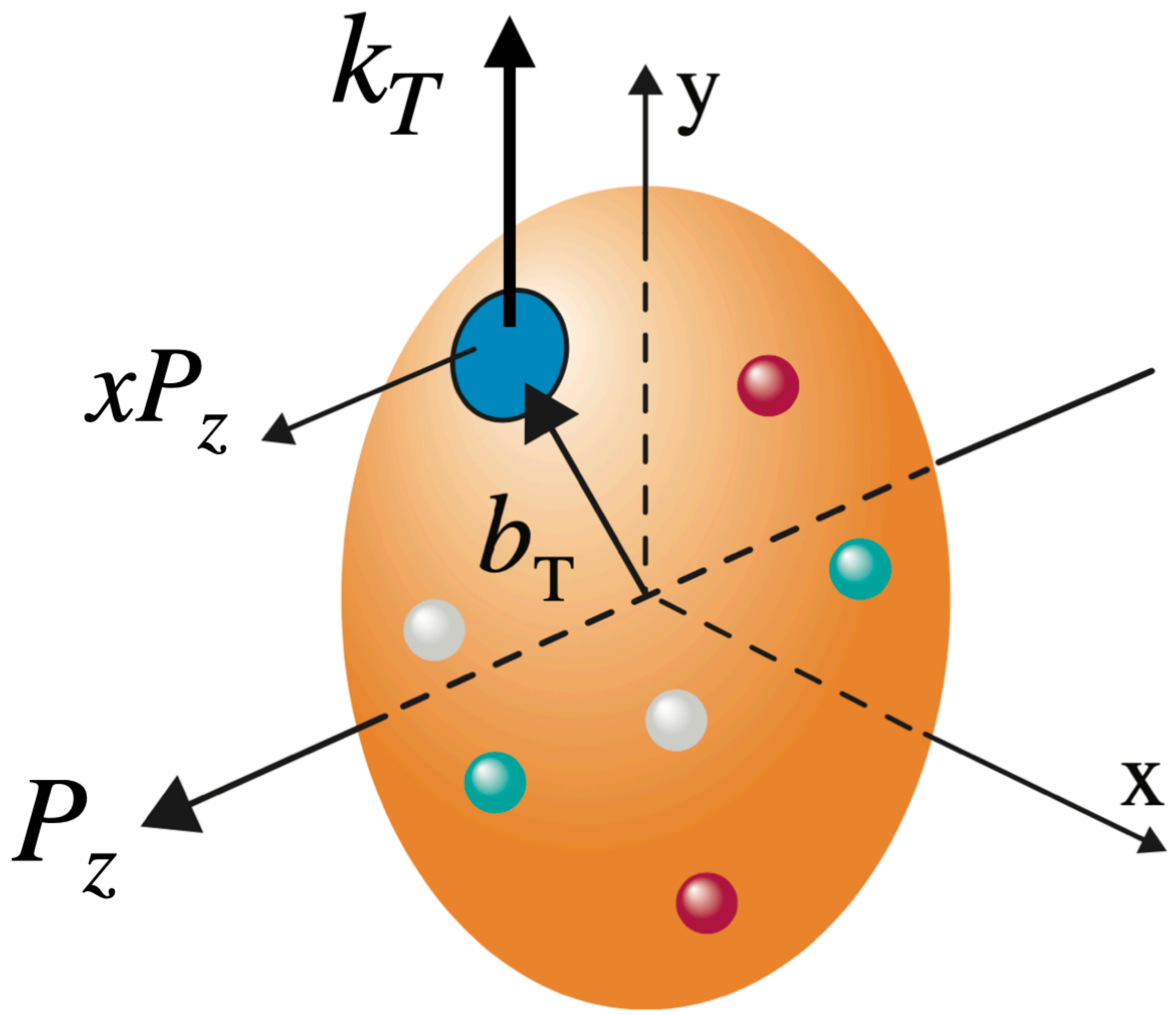
Collins-Soper kernel



Nonperturbative

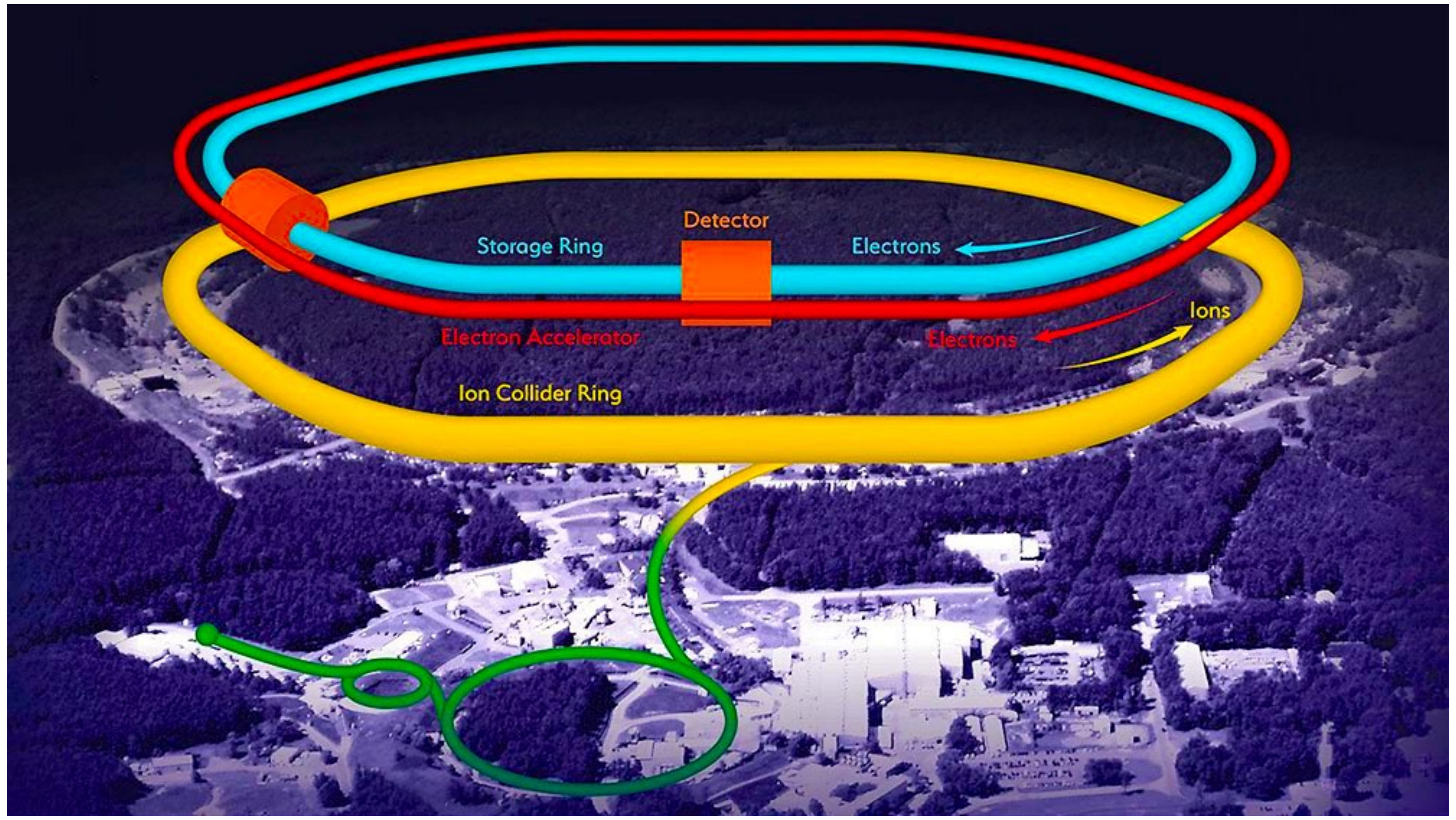
5 Determination of TMDs

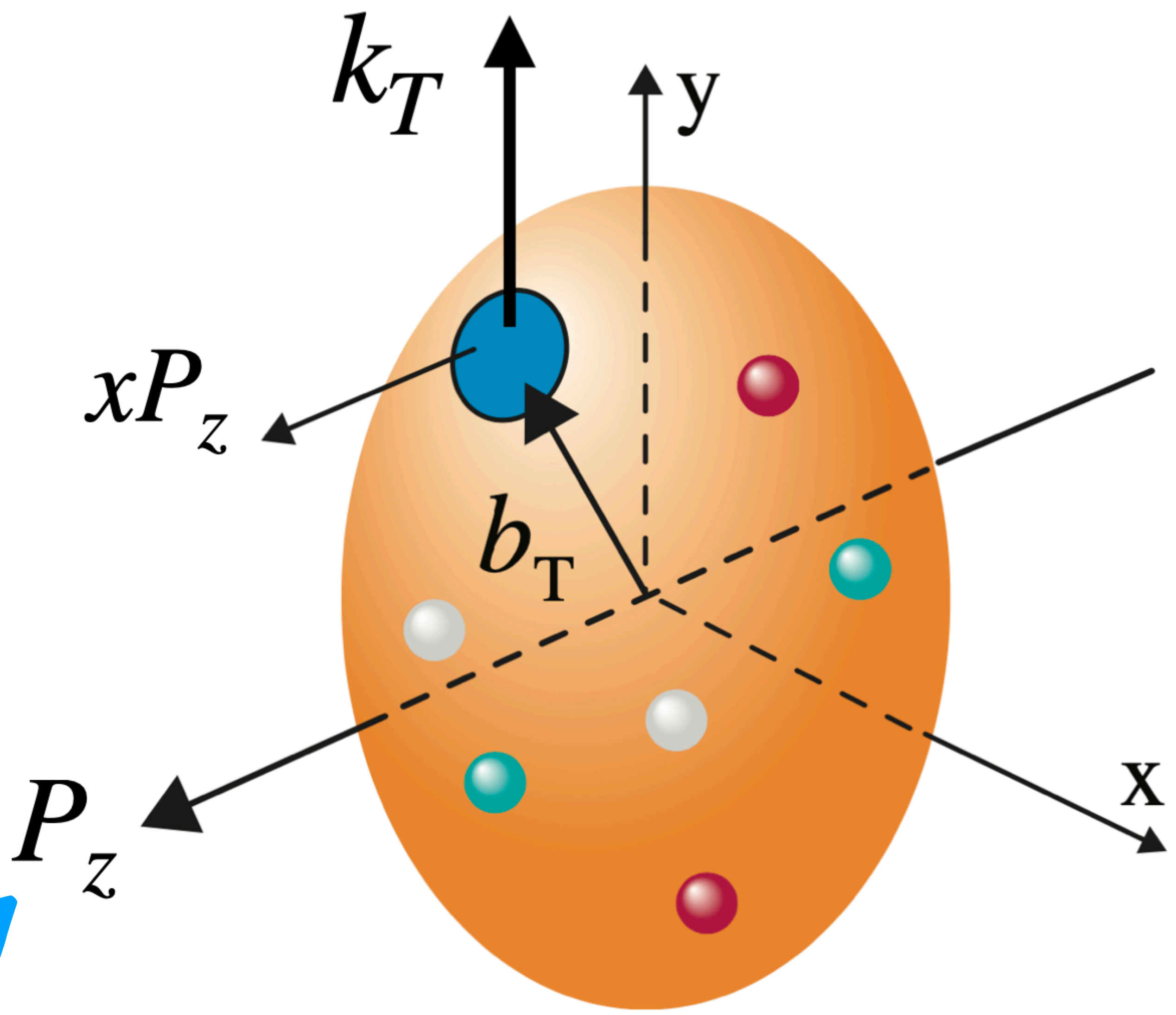


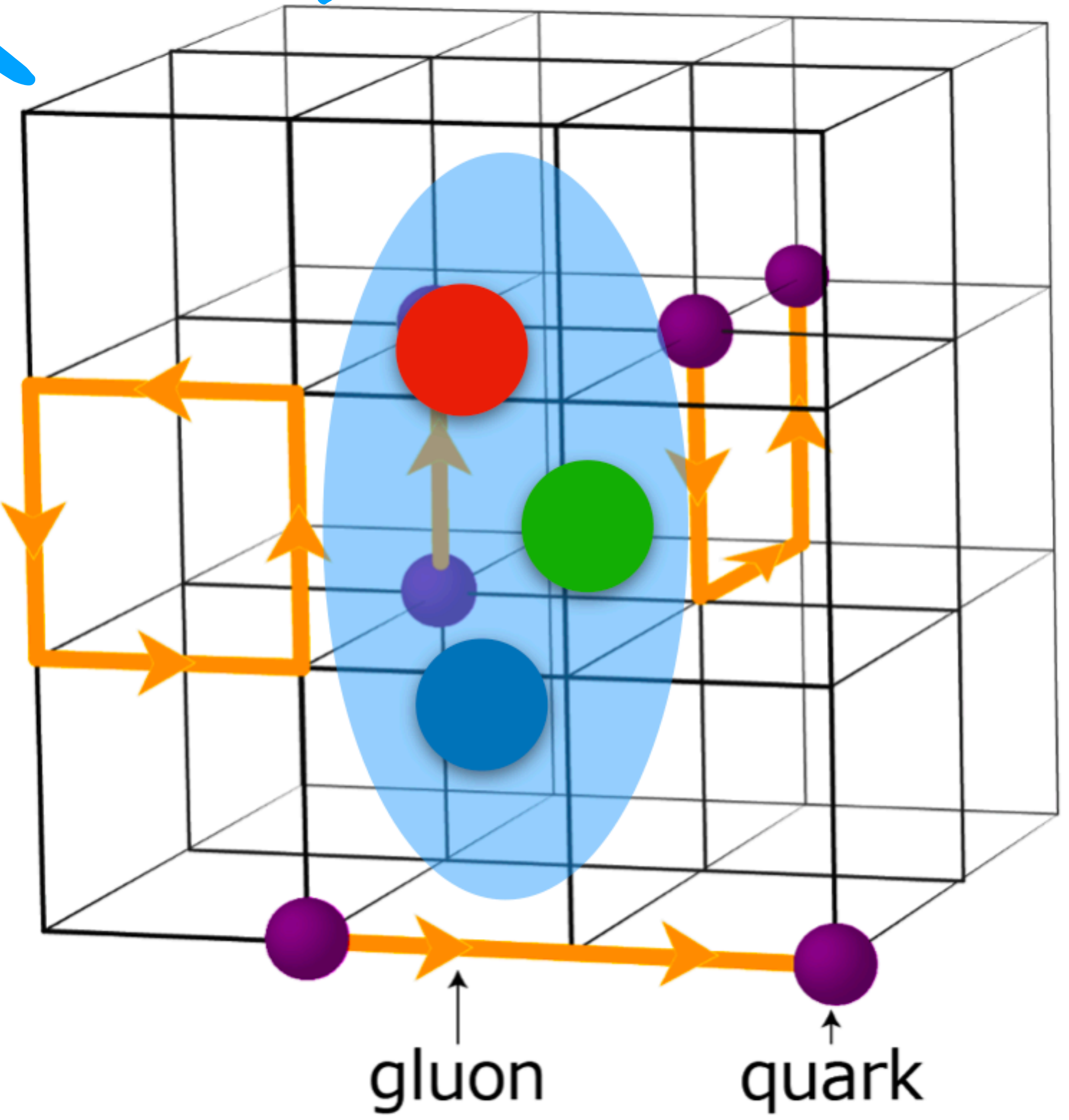


- Global analysis of experimental data.

Determination of TMDs







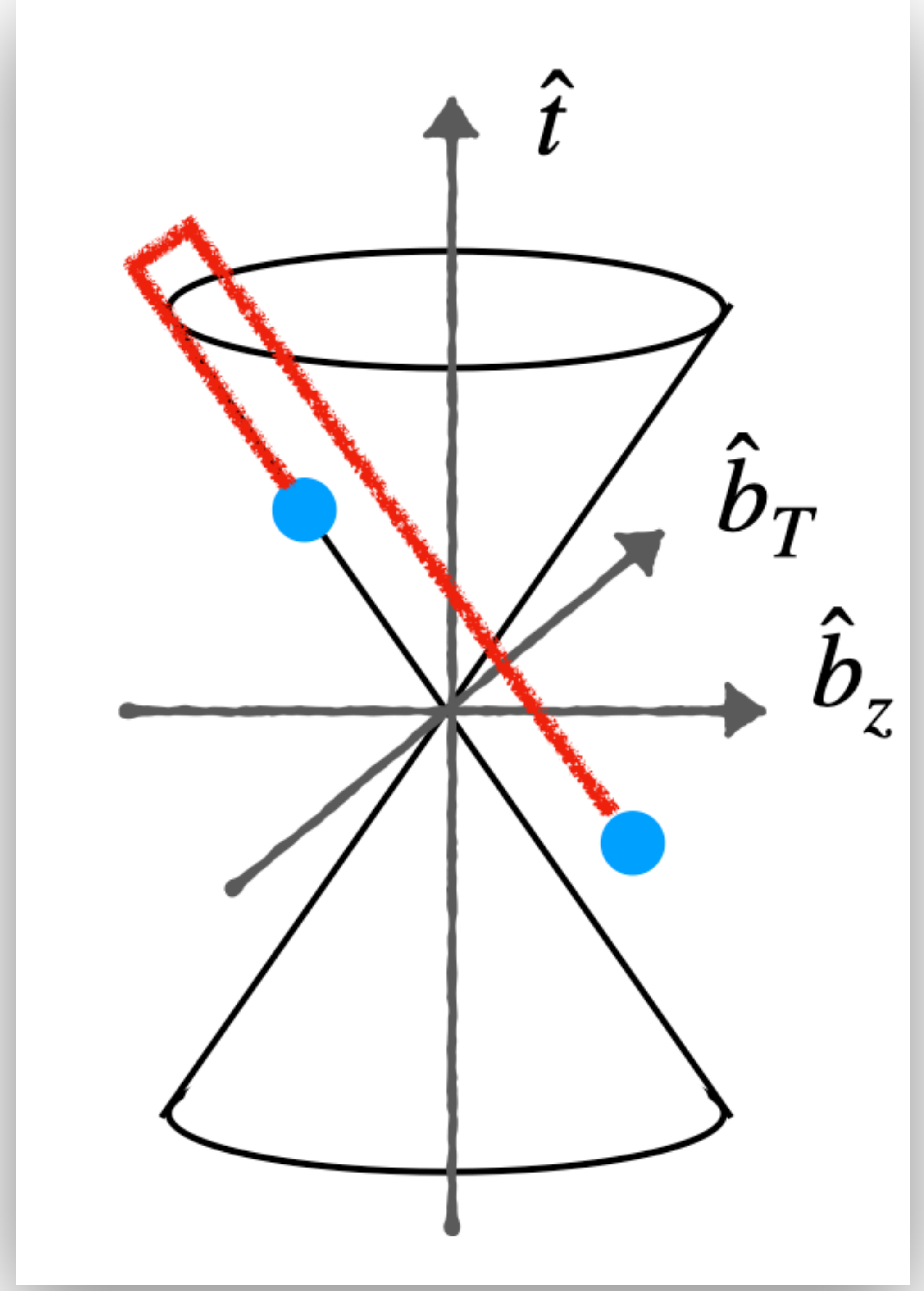
- Global analysis of experimental data.
- Complementary knowledge from lattice QCD is essential.

7 The definition of TMDs

Beam function

$$f_q(x, \vec{b}_T, \mu, \zeta) = \lim_{\epsilon \to 0} Z_{\mathrm{UV}}(\epsilon, \mu, \zeta) \lim_{\tau \to 0} \frac{B_q(x, \vec{b}_T, \epsilon, \tau, \zeta)}{\sqrt{S_q(\vec{b}_T, \epsilon, \tau)}}$$

UV regulator　　Rapidity regulator　　Soft function



$$\langle P | \overline{\psi}(\frac{b^+}{2}, b_\perp)\Gamma W_{\sqsupset^+}\psi(-\frac{b^+}{2}, 0) | P \rangle$$

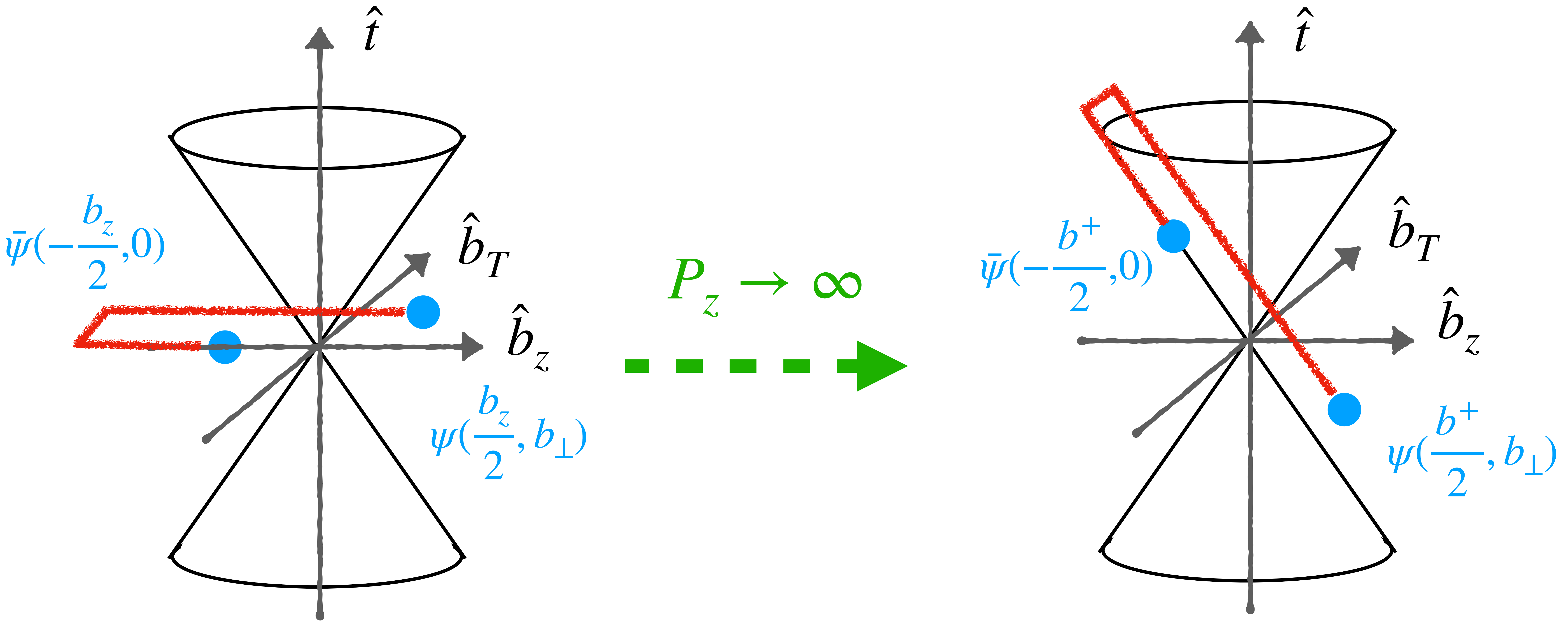
✗ Light-cone correlations: forbidden on Euclidean lattice

TMDs from lattice: quasi TMDs

- Ji, Liu and Liu, NPB 955 (2020), PLB 811 (2020);
- A. Vladimirov, A. Schäfer Phys.Rev.D 101 (2020), 074517
- I. Stewart, Y. Zhao et al., JHEP 09 (2020) 099
- X. Ji et al., Phys.Rev.D 103 (2021) 7, 074005
- I. Stewart, Y. Zhao et al., JHEP 08 (2022) 084

Quasi-TMDs from equal-time correlators:

- Computable from Lattice QCD.
- Have same IR physics as light-cone TMDs.



Quasi TMD

$$\langle P|\bar{\psi}(\frac{b_z}{2},b_\perp)\Gamma W_{\sqsupset z}\psi(-\frac{b_z}{2},0)|P\rangle$$

Light-cone TMD

$$\langle P|\bar{\psi}(\frac{b^+}{2},b_\perp)\Gamma W_{\sqsupset +}\psi(-\frac{b^+}{2},0)|P\rangle$$

Large P_z expansion and perturbative matching

Quasi beam function

Collins-Soper kernel

$$\frac{\tilde{\phi}(x, \vec{b}_T, \mu, P_z)}{\sqrt{S_r(\vec{b}_T, \mu)}} = C(\mu, xP_z) e^{\frac{1}{2}\gamma_\zeta(\mu, b_T) \ln \frac{(2xP_z)^2}{\zeta}} f(x, \vec{b}_T, \mu, \zeta) \{1 + \mathcal{O}[\frac{1}{(xP_z b_T)^2}, \frac{\Lambda_{\mathrm{QCD}}^2}{(xP_z)^2}]\}$$

Physical TMD

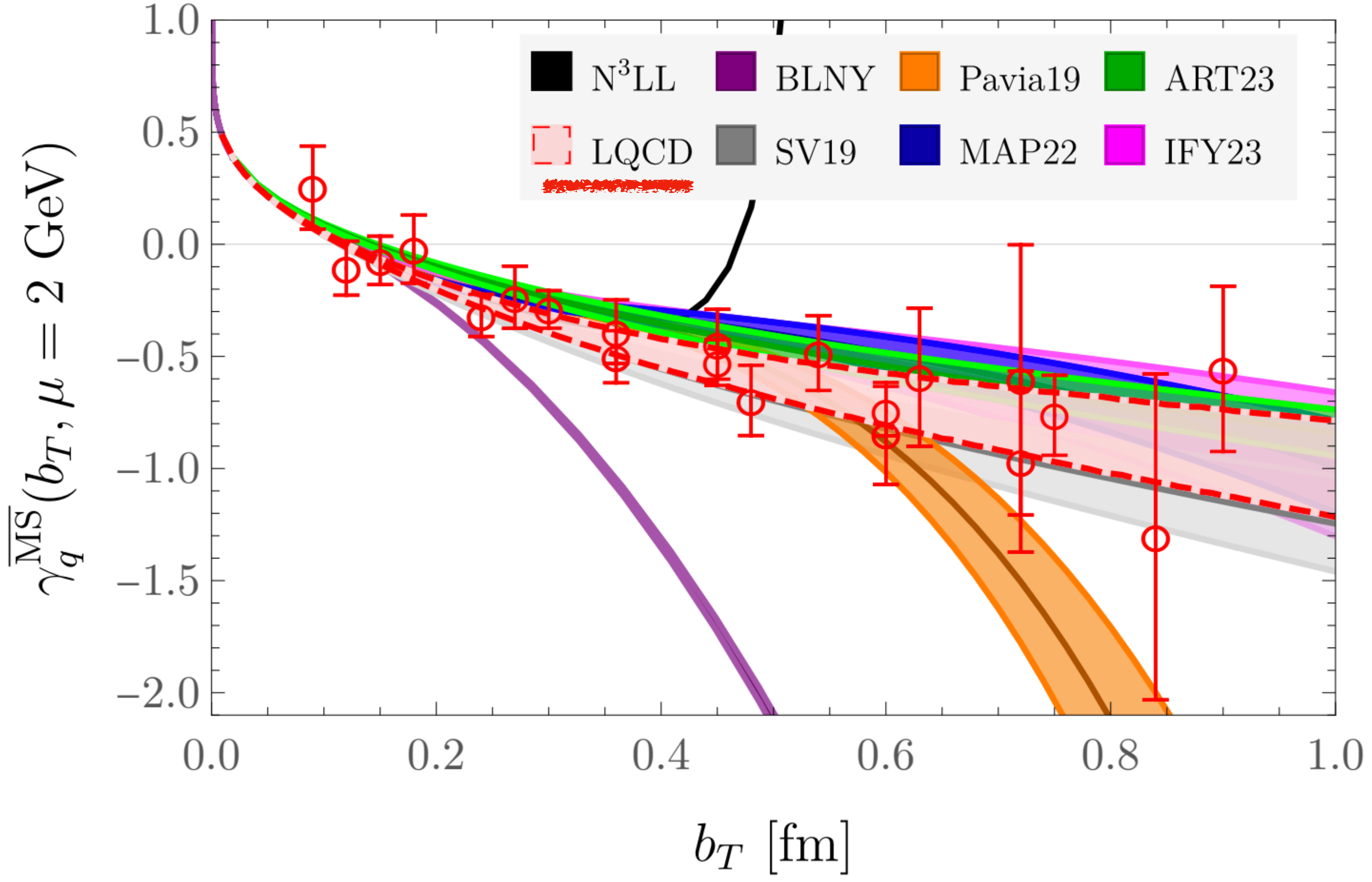
Reduced soft factor

- Quasi TMDs: first regularize QCD on a lattice (a or $\epsilon \to 0$), then take the $P_z \to \infty$ limit.
- Differ from the Collins scheme by order of $y_B \to -\infty$ (rapidity) and $\epsilon \to 0$ limit, inducing a perturbative matching $C(\mu, xP_z)$.

The Collins-Soper kernel from quasi-TMDs

Quasi-TMDWF

Collins-Soper kernel



Wilson clover fermion, physical quark masses,
a = 0.09, 0.12, 0.15 fm

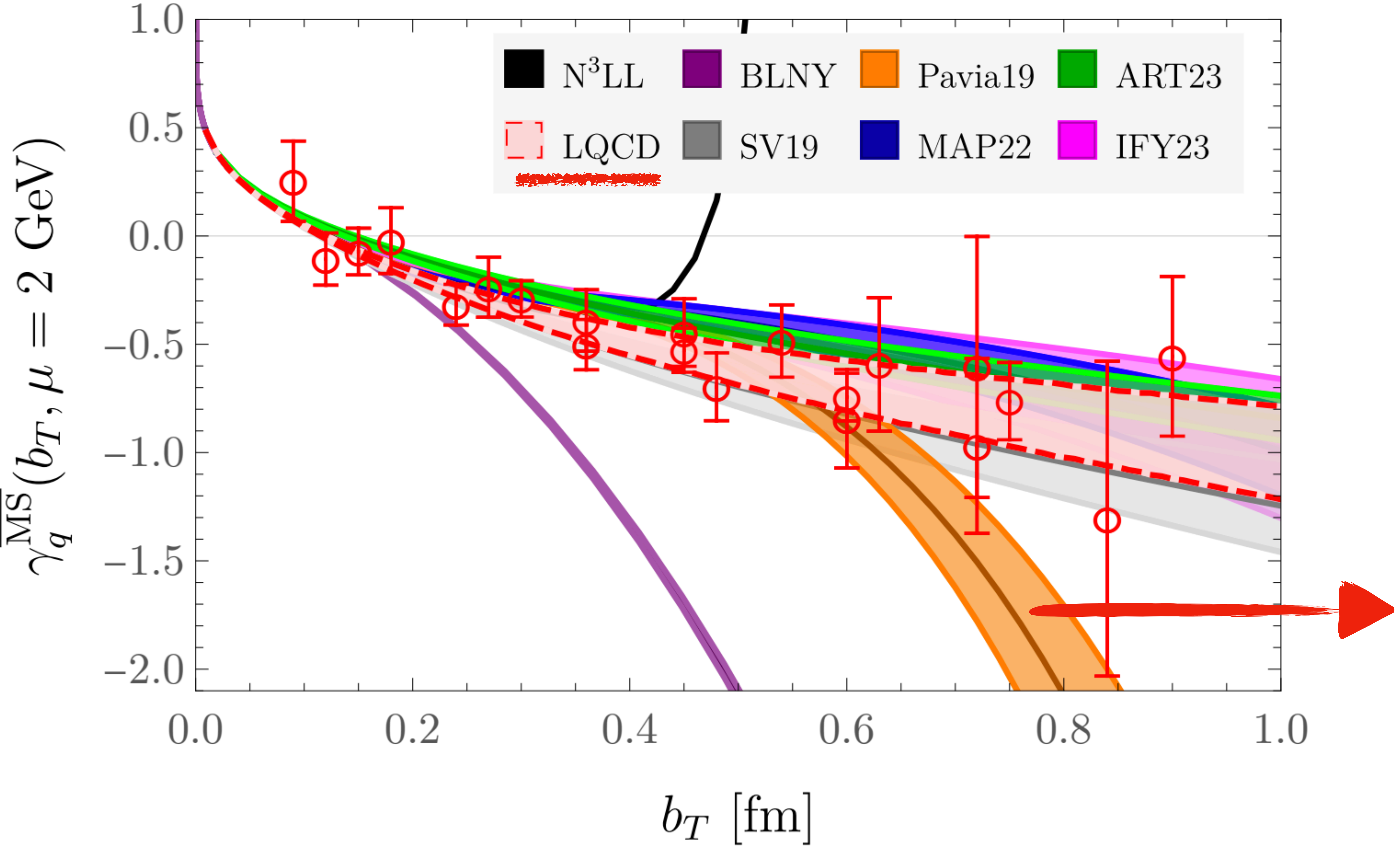
$$\gamma_\zeta(\mu, b_T) = \frac{d}{d \ln P_z} \ln \frac{\tilde{f}(x, \vec{b}_T, \mu, P_z)}{C(\mu, xP_z)}$$

- Three different lattice spacing, physical pion mass.
- Controlled renormalization and Fourier transform.
- Next-to-next-to-leading logarithmic (NNLL) order.

• A. Avkhadiev, P. Shanahan, M. Wagman, Y. Zhao, PRL 132 (2024) 23, 231901

The Collins-Soper kernel from quasi-TMDs

Collins-Soper kernel

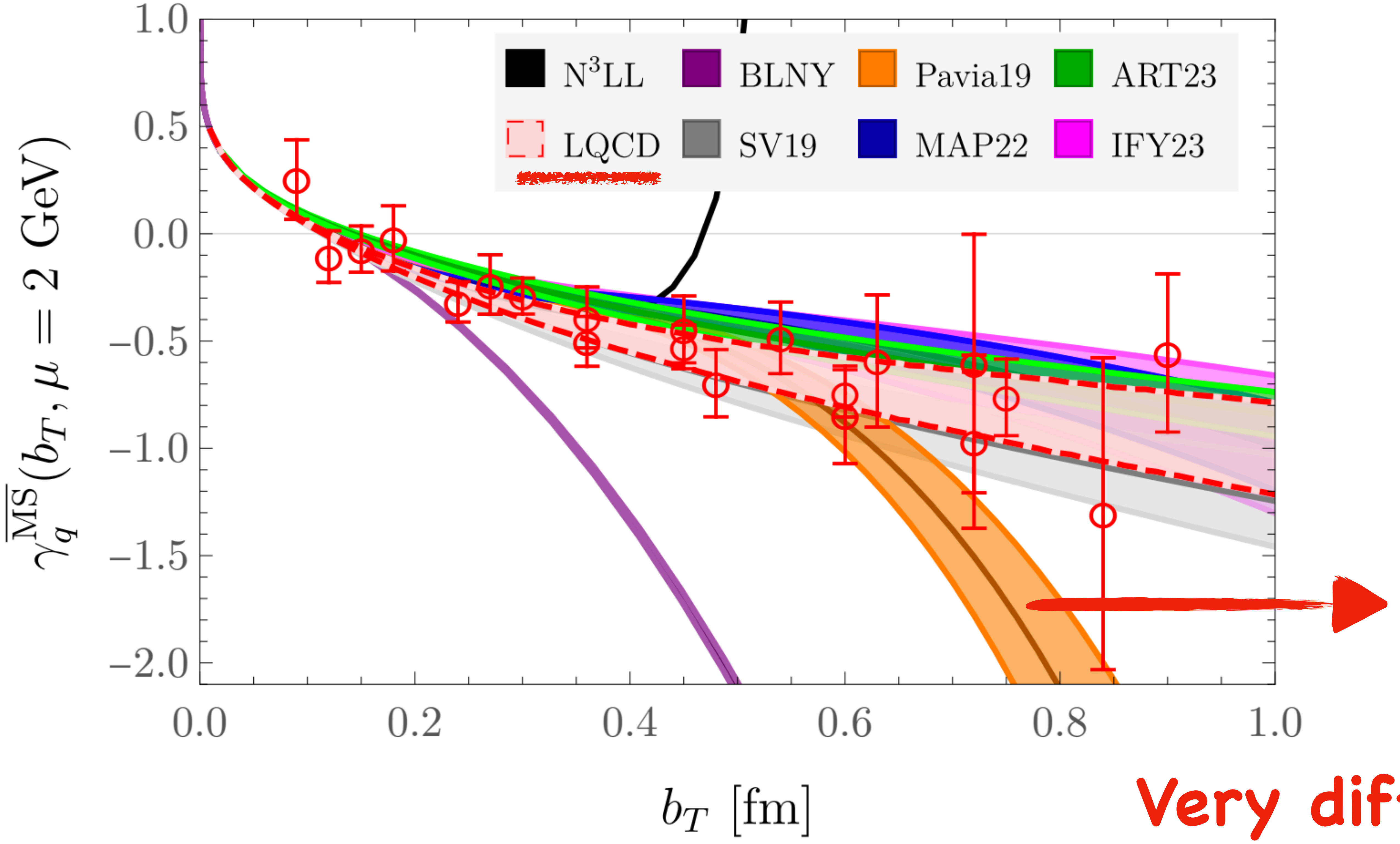


- **Experimental constrain** at deep non-perturbative region is **very limited**: lack of data, model dependence …
- **Can lattice QCD push further?**

• A. Avkhadiev, P. Shanahan, M. Wagman, Y. Zhao, PRL 132 (2024) 23, 231901

The Collins-Soper kernel from quasi-TMDs

Collins-Soper kernel

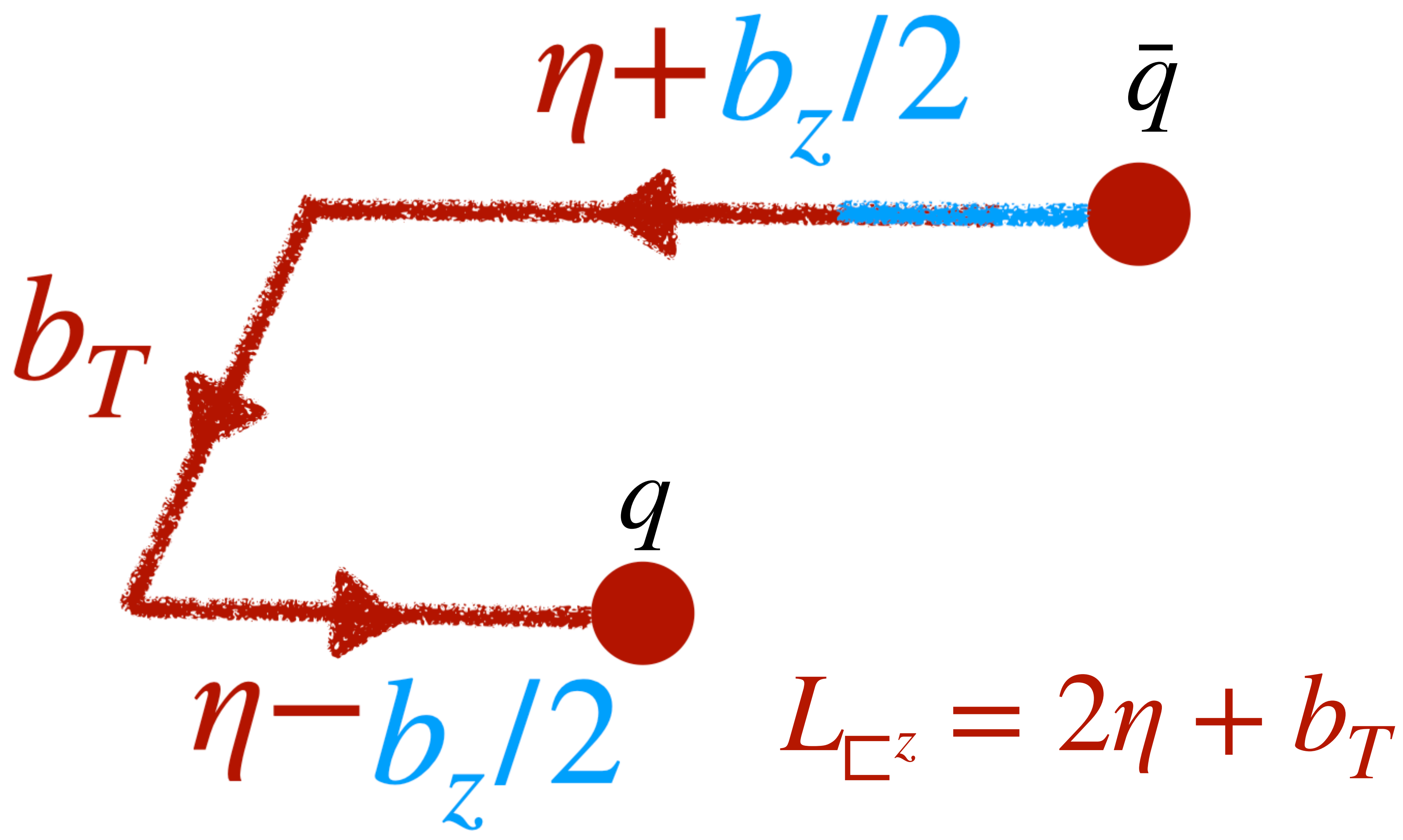


- **Experimental constrain** at deep non-perturbative region is **very limited**: lack of data, model dependence …
- **Can lattice QCD push further?**

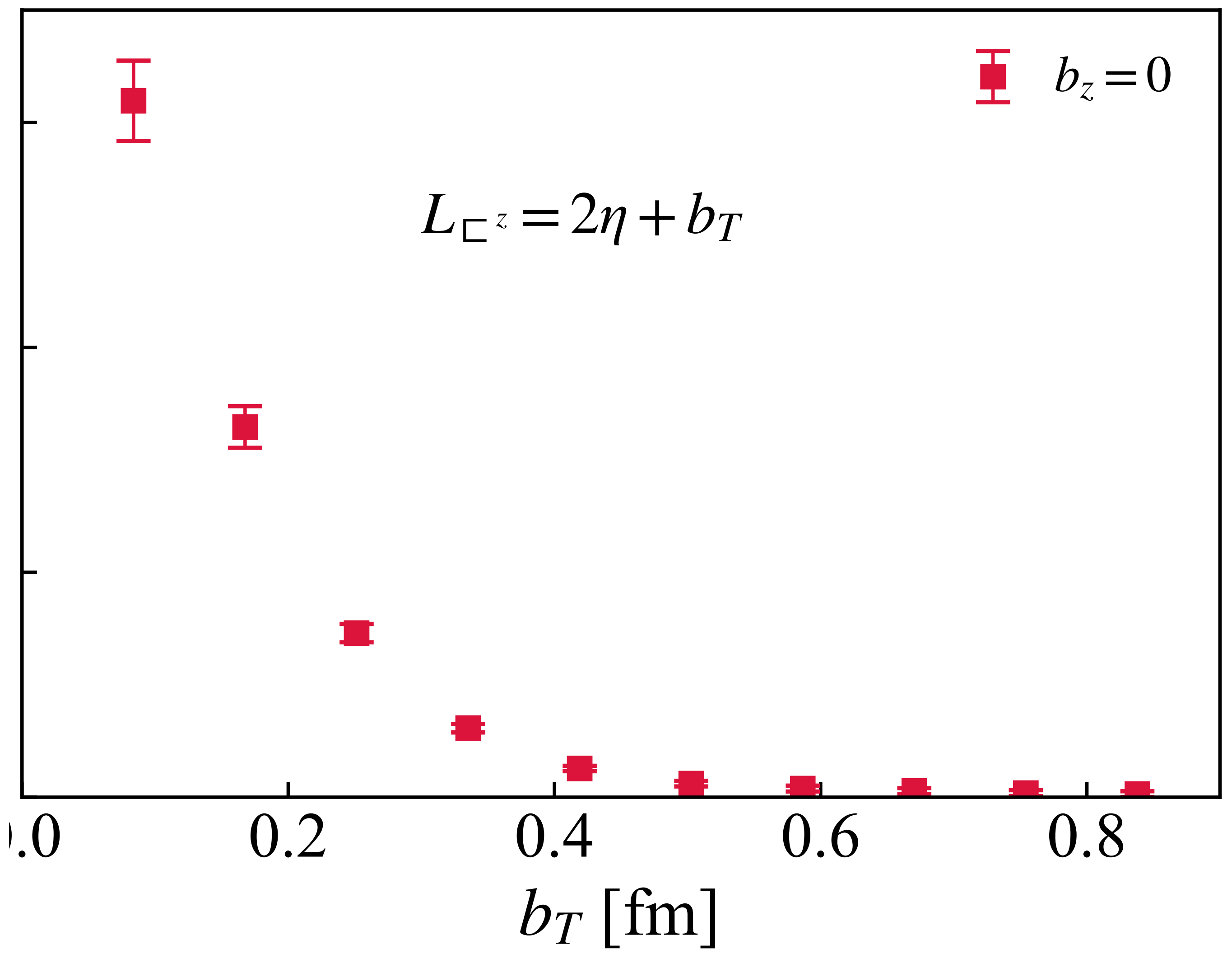
Very difficult: errors grow rapidly!

• A. Avkhadiev, P. Shanahan, M. Wagman, Y. Zhao, PRL 132 (2024) 23, 231901

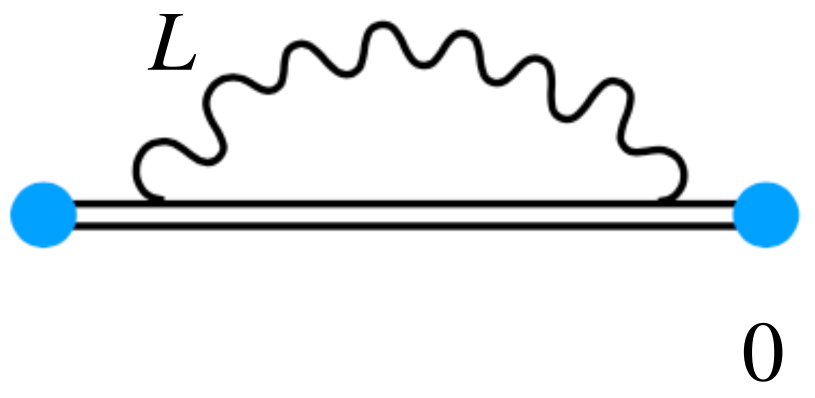
Difficulties in the conventional quasi-TMDs



Bare matrix elements



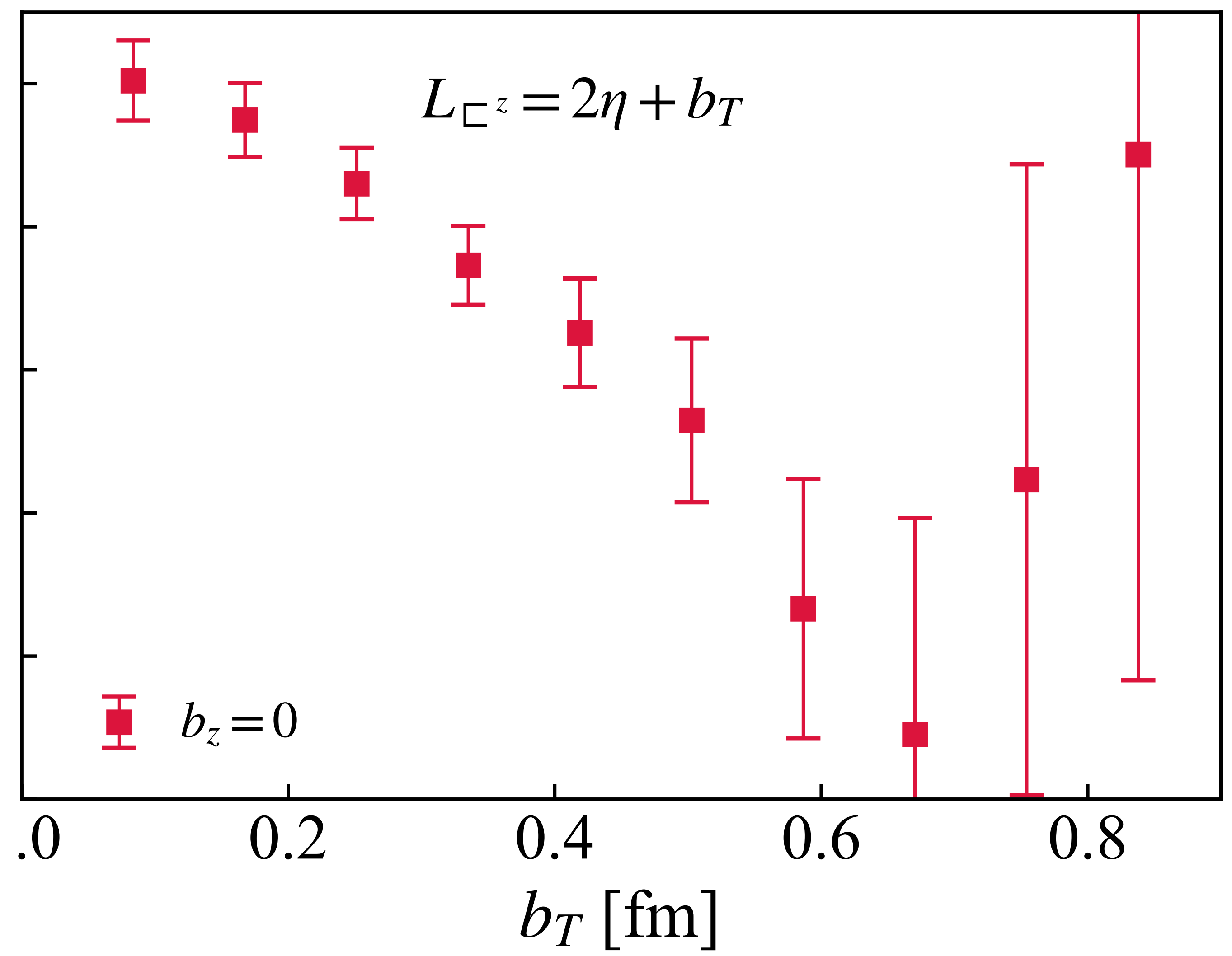
- Exponential decaying signal and complicated renormalization due to the Wilson line artifacts.



$$\sim e^{-\delta m(a)\cdot L_{\sqsubset^z}}$$

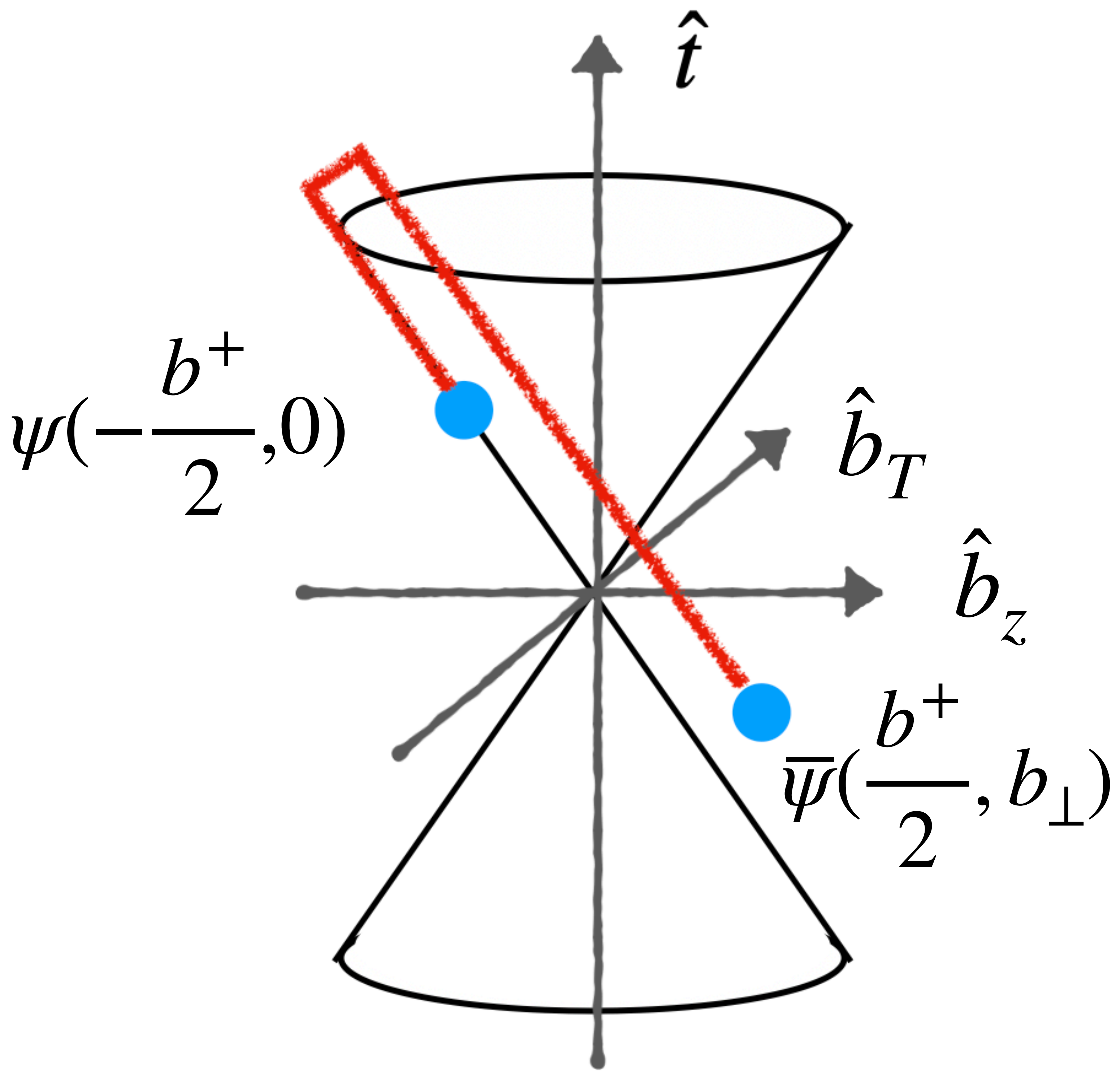
Linear divergence from Wilson line self energy

Renormalized matrix elements



Overcoming difficulties

Light-cone TMD



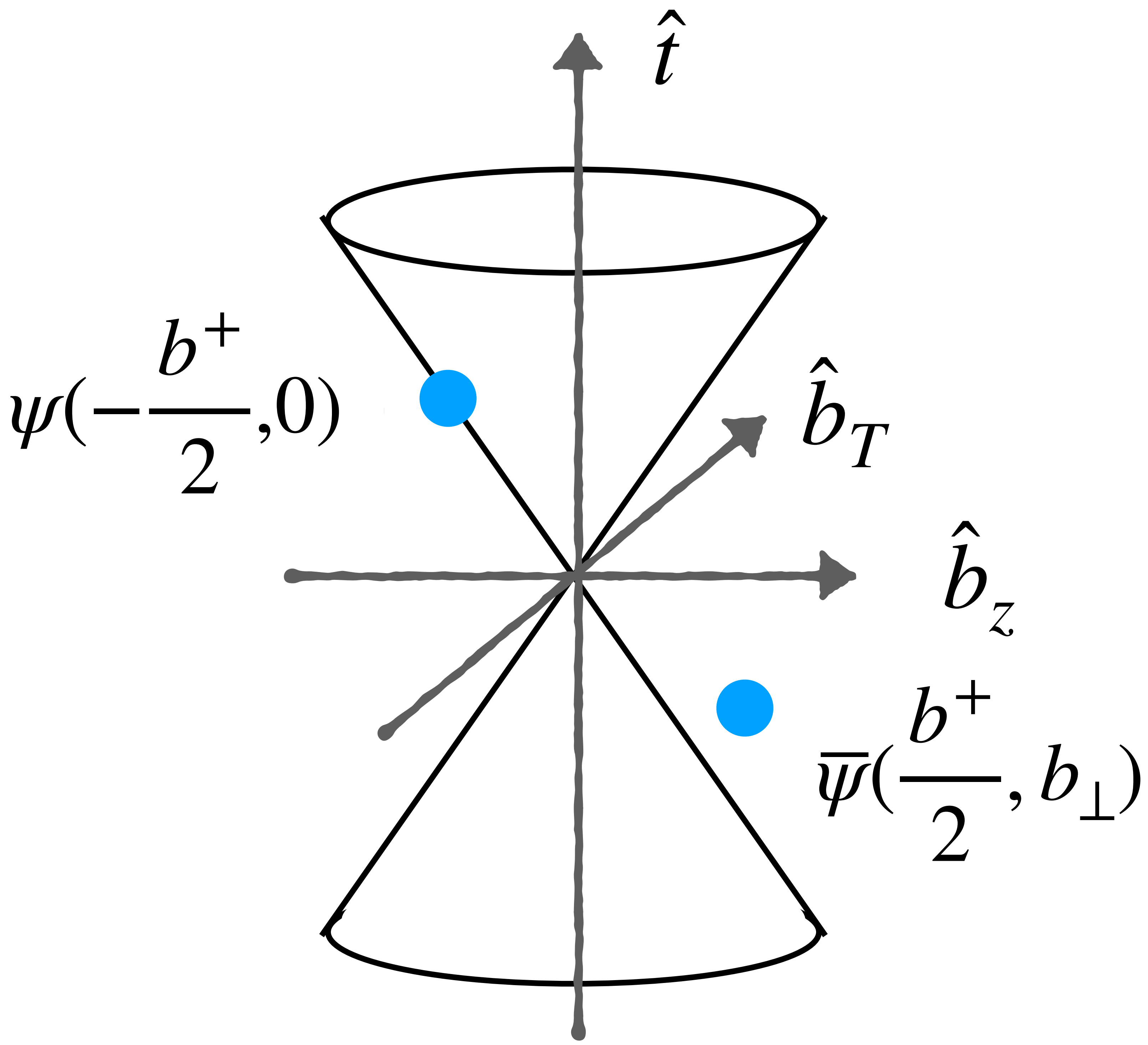
$$\overline{\psi}(\frac{b^+}{2},b_\perp)\Gamma W_{\sqsupset^+}\psi(-\frac{b^+}{2},0)$$

Equivalent

=

TMD in light gauge

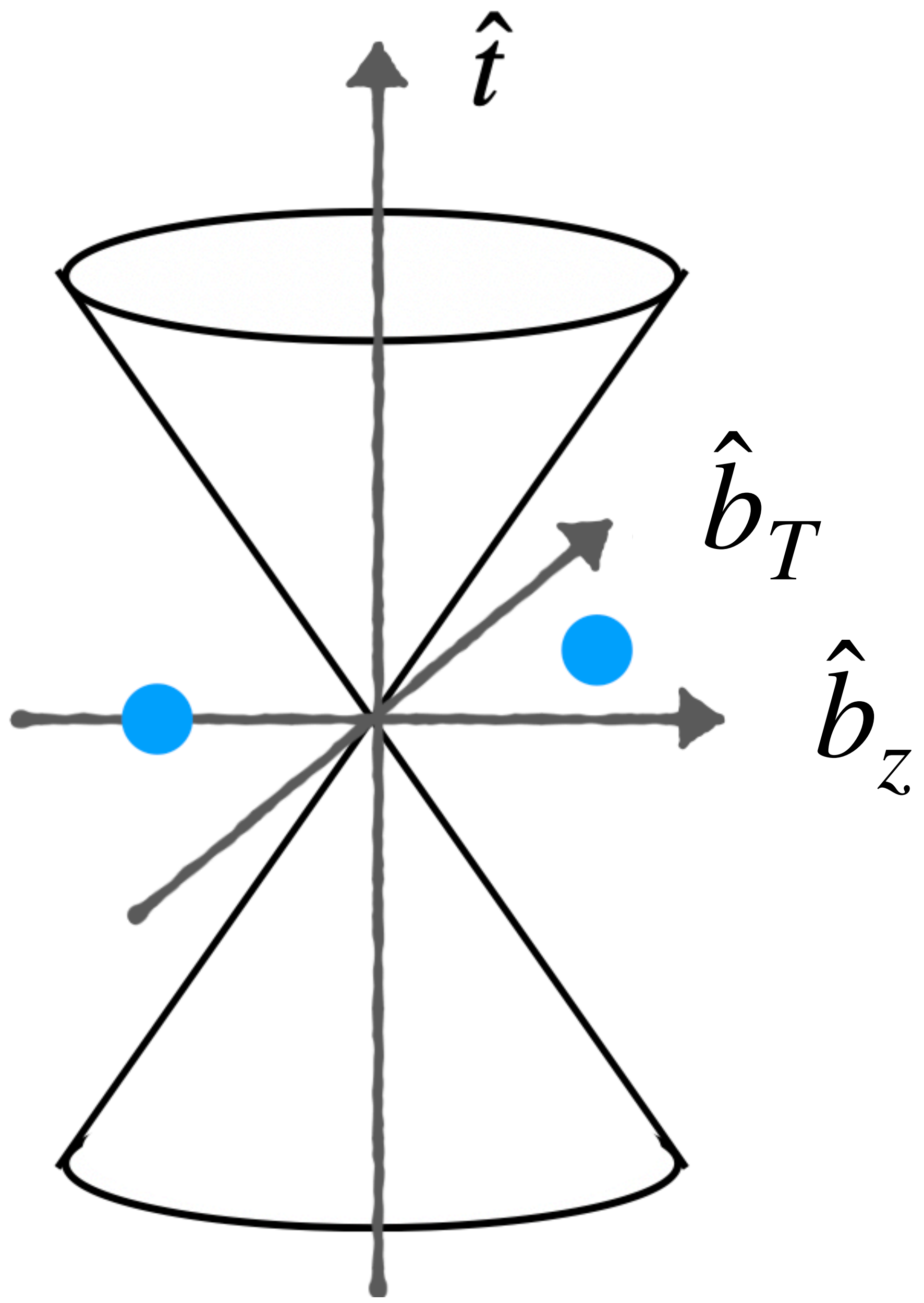
$A^+=0$



$$\overline{\psi}(\frac{b^+}{2},b_\perp)\Gamma\psi(-\frac{b^+}{2},0)\,|_{A^+=0}$$

Overcoming difficulties: Coulomb-gauge qTMDs

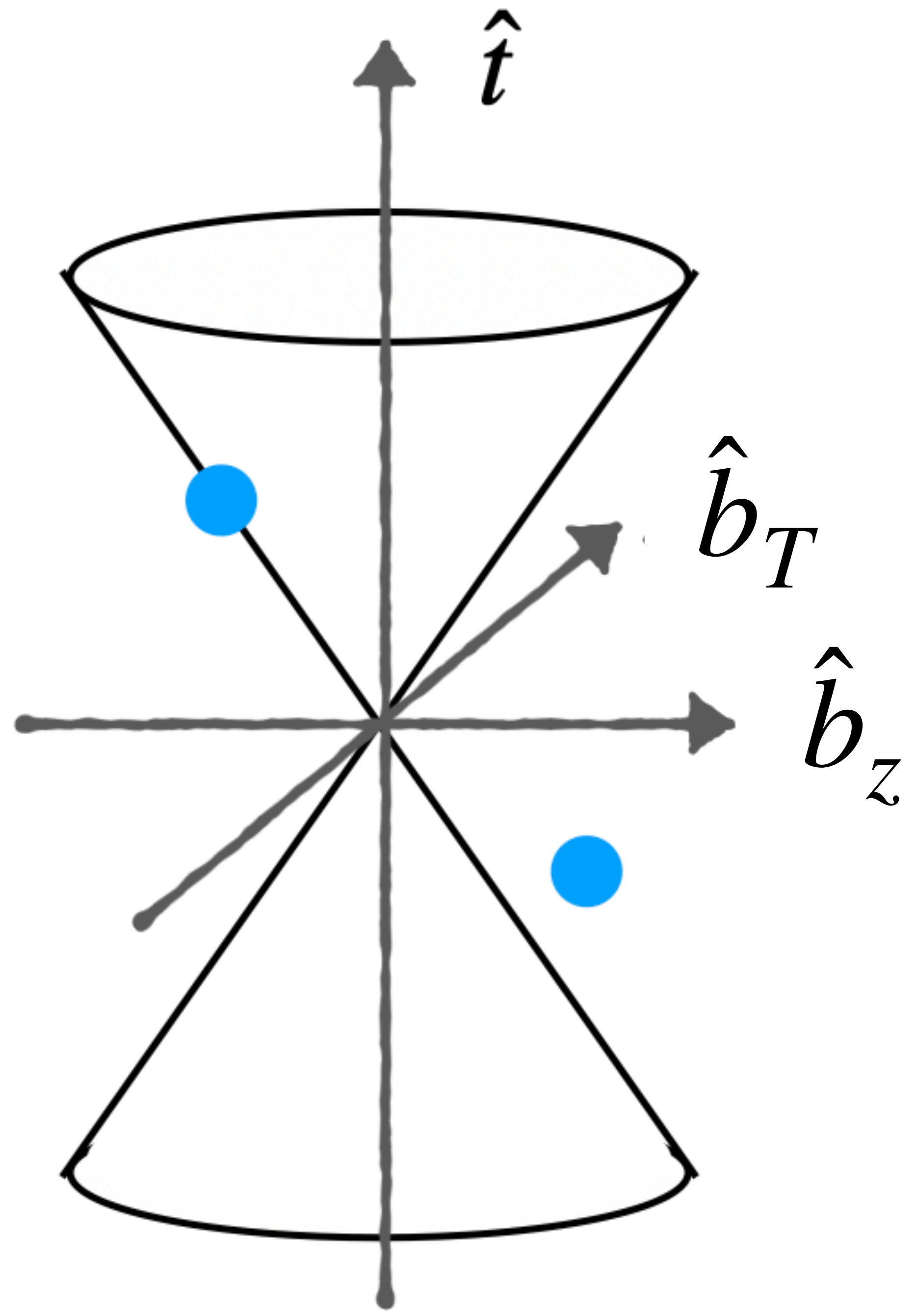
Quasi-TMD in physical gauge



$$\overline{\psi}(\frac{b^+}{2}, b_\perp)\Gamma\psi(-\frac{b^+}{2},0)\,|_{\vec{\nabla}\cdot\vec{A}=0}$$

$P_z \to \infty$

TMD in light gauge $A^+ = 0$

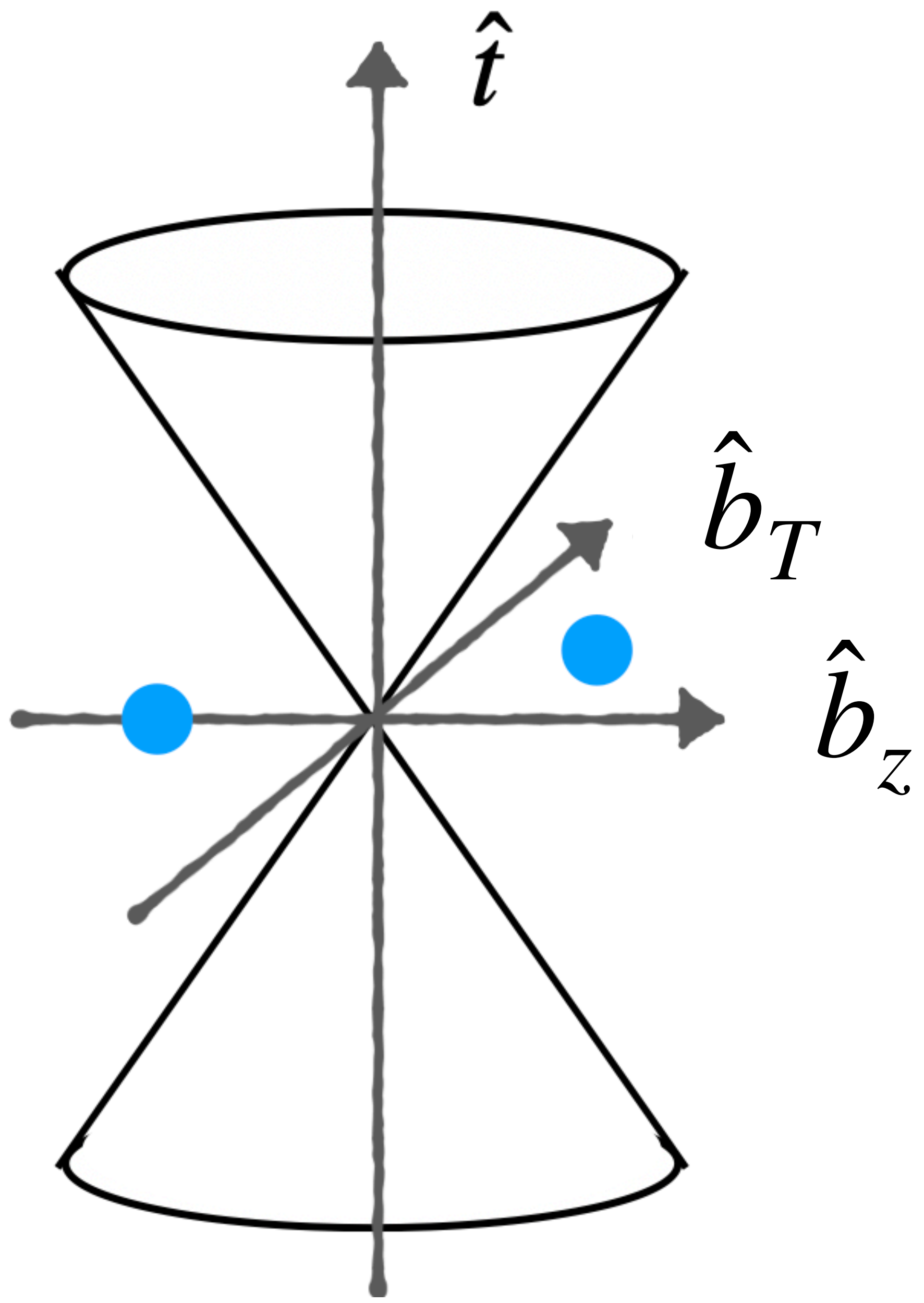


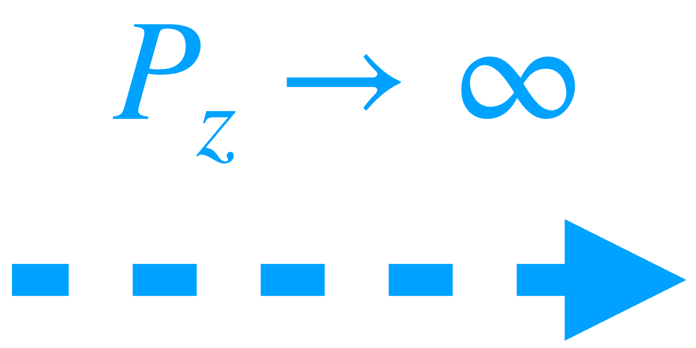
$$\overline{\psi}(\frac{b^+}{2}, b_\perp)\Gamma\psi(-\frac{b^+}{2},0)\,|_{A^+=0}$$

- **XG**, W.-Y. Liu, Y. Zhao, PRD 109 (2024) 9, 094506
- Y. Zhao, arXiv: 2311.01391

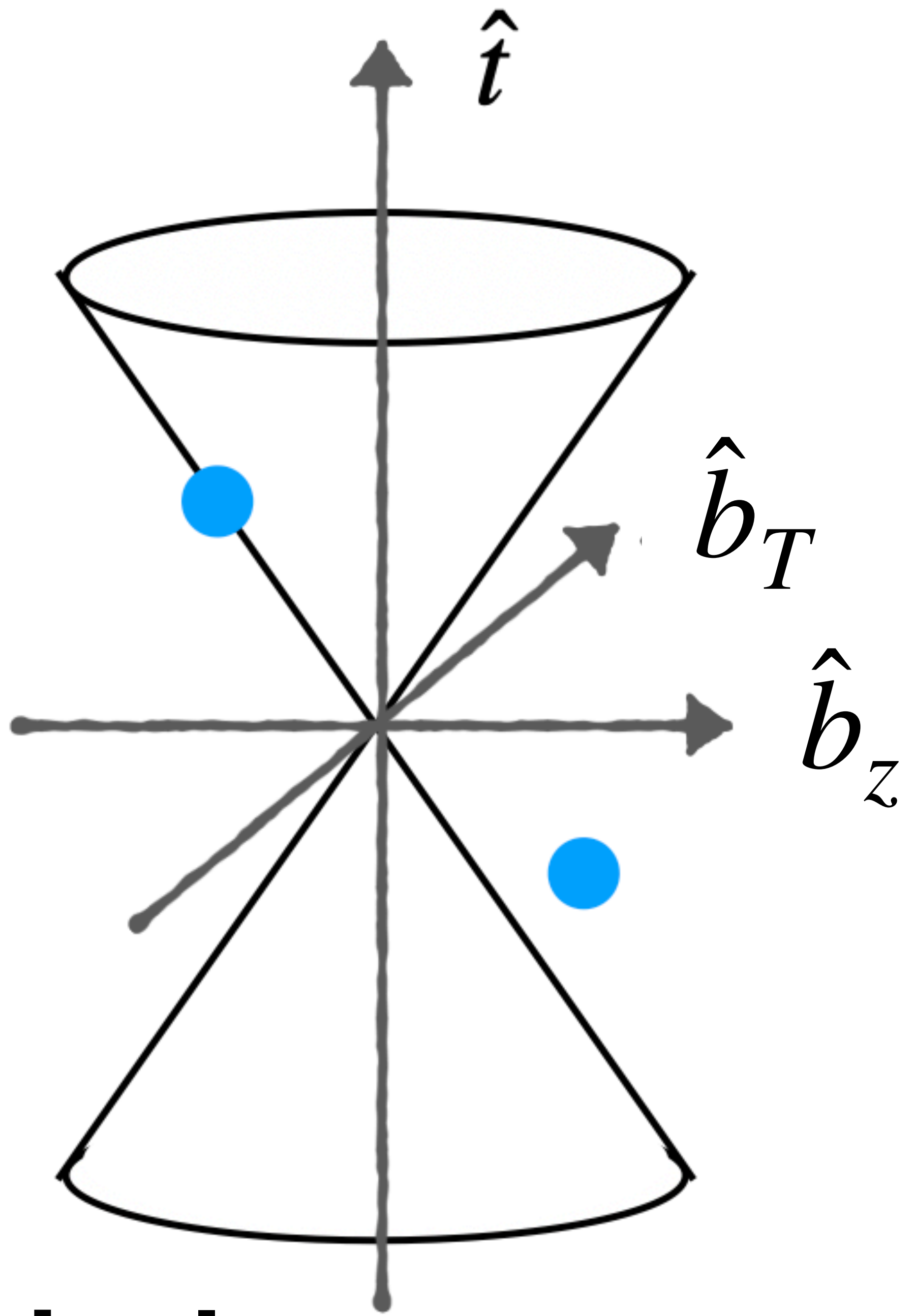
16 Overcoming difficulties: Coulomb-gauge qTMDs

Quasi-TMD in physical gauge





TMD in light gauge $A^+ = 0$



Boost the operator to light cone and also the physical gauges, such as $A_z = 0$, Coulomb gauge $\vec{\nabla} \cdot \vec{A} = 0$, to the light-cone gauge $A^+ = 0$.

- **XG**, W.-Y. Liu, Y. Zhao, PRD 109 (2024) 9, 094506
- Y. Zhao, arXiv: 2311.01391

CG quasi-TMDs without Wilson lines

$$\frac{\tilde{f}_C(x,\vec{b}_T,\mu,P_z)}{\sqrt{S_C(\vec{b}_T,\mu)}} = C(\mu,xP_z)e^{\frac{1}{2}\gamma_\zeta(\mu,b_T)\ln\frac{(2xP_z)^2}{\zeta}} f(x,\vec{b}_T,\mu,\zeta)\{1+\mathcal{O}[\frac{1}{(xP_z b_T)^2},\frac{\Lambda_{\rm QCD}^2}{(xP_z)^2}]\}$$

- Y. Zhao, arXiv: 2311.01391
- Y.-Z. Liu, Y.-S. Su., JHEP 02 (2024) 204

- The **same form of factorization formula** as the conventional gauge invariant (GI) case: verified through SCET.
- **IR pole cancels** in the one-loop calculation, differ only by UV:

$$\tilde{f}_C^{(1)}(x,\vec{b}_T,\mu,P_z,\epsilon_{\rm IR}) - \tilde{f}^{(1)}(x,\vec{b}_T,\mu,\epsilon_{\rm IR}) = -\frac{\alpha_s(\mu)C_F}{2\pi}\left[\frac{1}{2}\ln^2\frac{\mu^2}{4P_z^2} + 3\ln\frac{\mu^2}{4p_z^2} + 12 - \frac{7\pi^2}{12}\right]$$

- Both CG and GI quasi-TMDs fall into **the same universality class of LaMET** in large P_z limit but with differently: power correction and $C(\mu,xP_z)$.

CG quasi-TMDs without Wilson lines

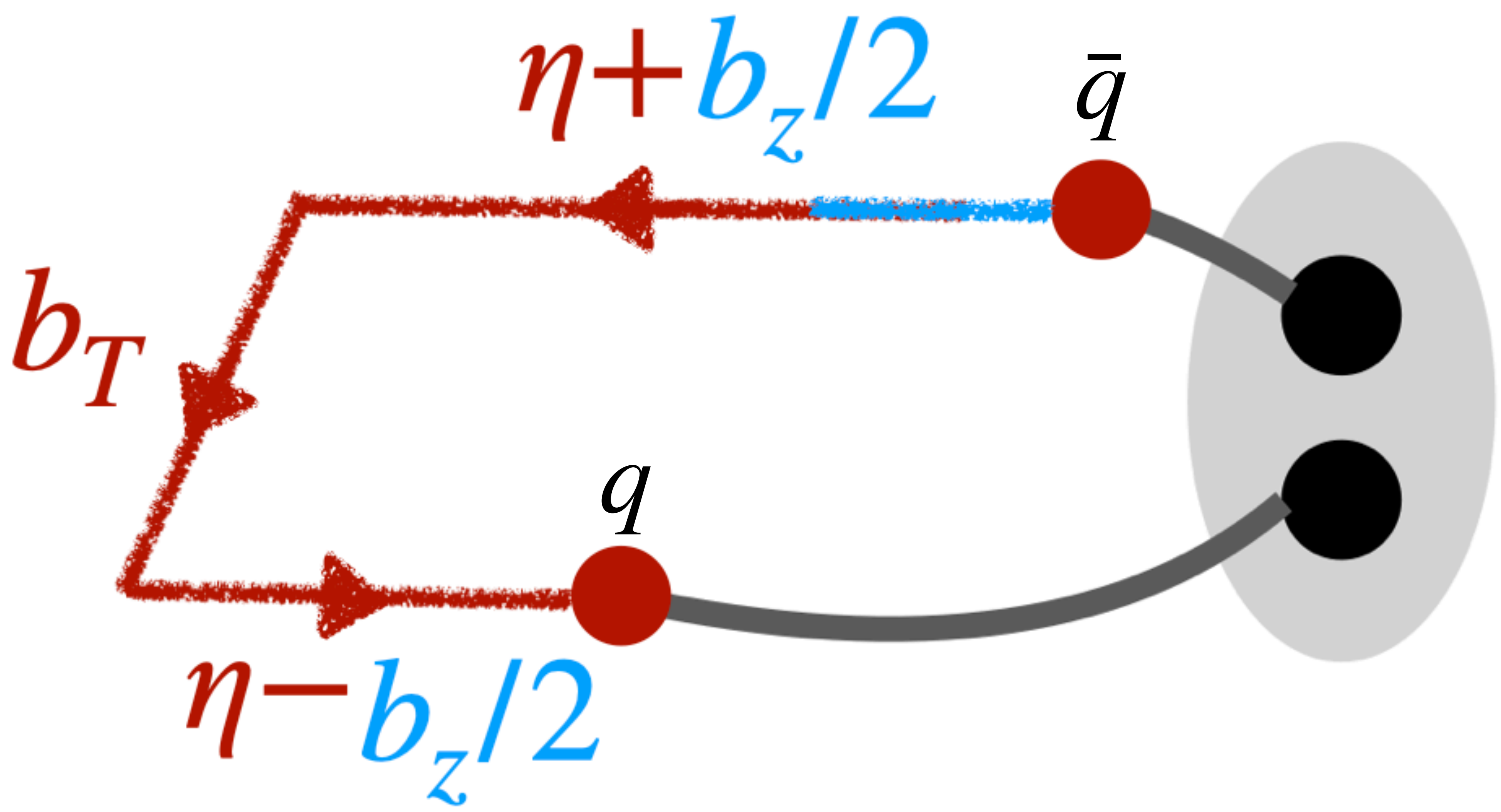
$$\frac{\tilde{f}_C(x, \vec{b}_T, \mu, P_z)}{\sqrt{S_C(\vec{b}_T, \mu)}} = C(\mu, xP_z) e^{\frac{1}{2}\gamma_\zeta(\mu, b_T)\ln\frac{(2xP_z)^2}{\zeta}} f(x, \vec{b}_T, \mu, \zeta)\{1 + \mathcal{O}[\frac{1}{(xP_z b_T)^2}, \frac{\Lambda_{\rm QCD}^2}{(xP_z)^2}]\}$$

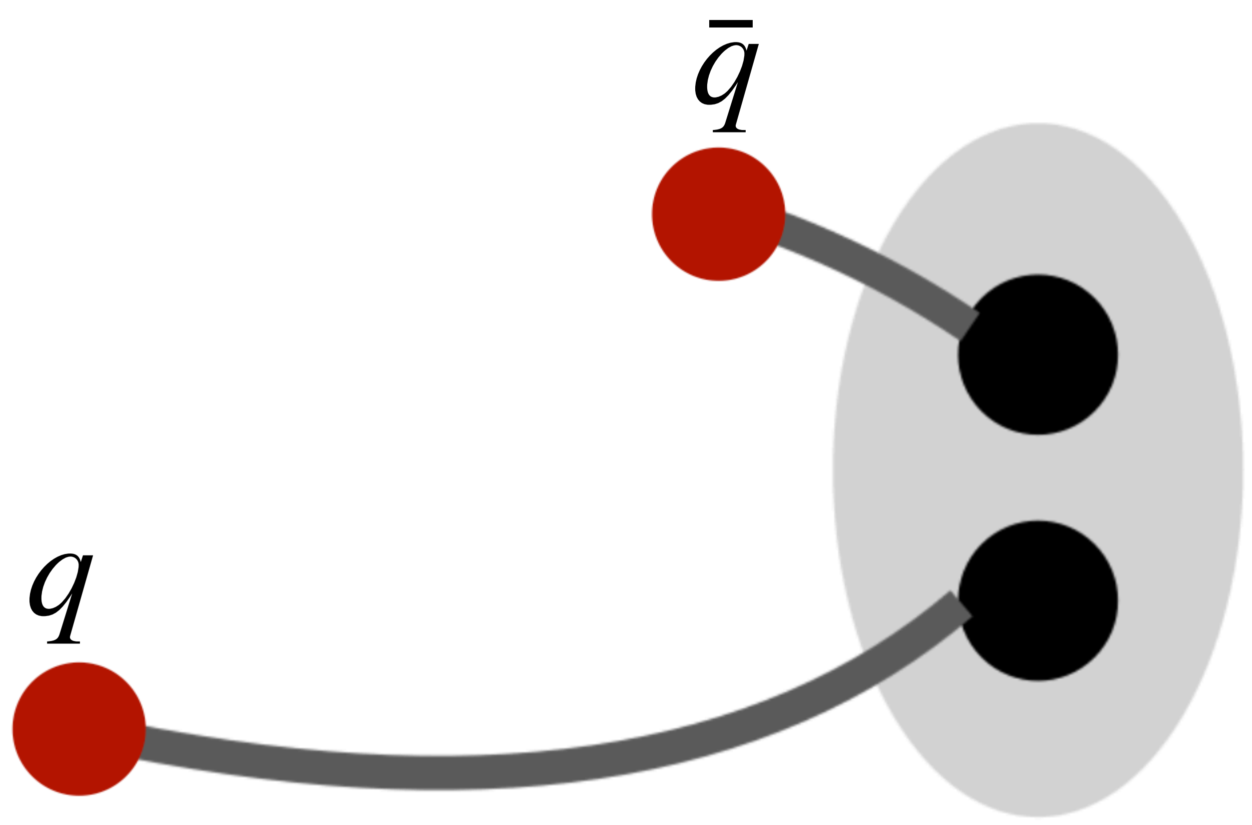
- Y. Zhao, arXiv: 2311.01391
- Y.-Z. Liu, Y.-S. Su., JHEP 02 (2024) 204

- Gribov copies in the non-perturbative Coulomb gauge fixing?
- Complexity from Wilson line disappear?
- Power corrections under control?

see Jinchen He's talk

Quasi-TMDs in the Coulomb gauge





$$\langle \Omega | \overline{\psi}(\frac{b_z}{2}, b_\perp)\Gamma W_{\sqsupset^z}\psi(-\frac{b_z}{2},0) | \pi^+, P_z\rangle$$

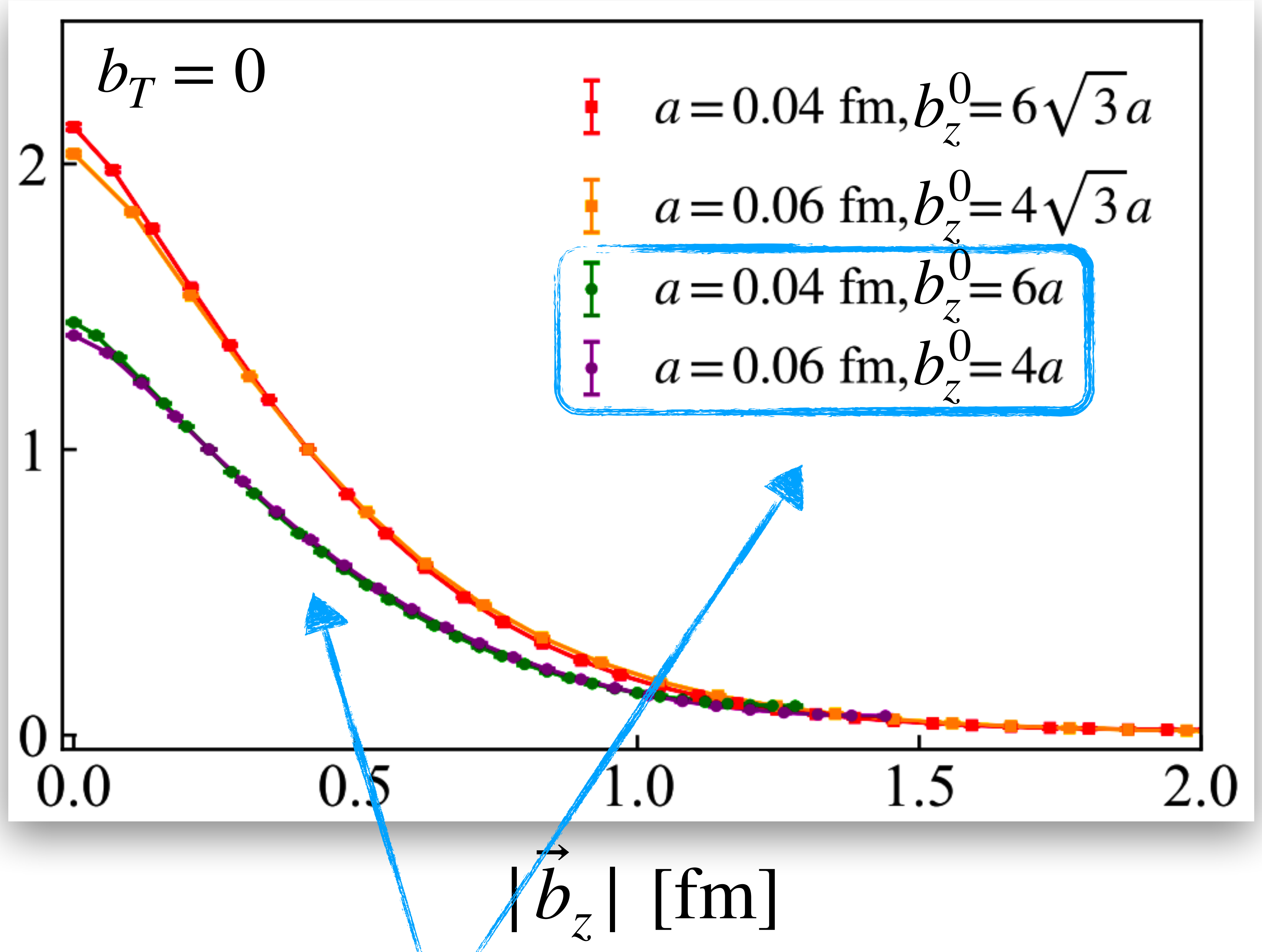
Gauge-invariant (GI)
quasi-TMDWF

$$\langle \Omega | \overline{\psi}(\frac{b_z}{2}, b_\perp)\Gamma \psi(-\frac{b_z}{2},0) |_{\vec{\nabla}\cdot\vec{A}=0} | \pi^+, P_z\rangle$$

Coulomb gauge (CG)
quasi-TMDWF

CG quasi-TMDs: simplified renormalization

Renormalized matrix elements



Two lattice spacings: excellent continuum limit!

- No linear divergence: the renormalization is an overall constant.

$$[\bar{\psi}(-\frac{\vec{b}}{2})\Gamma\psi(\frac{\vec{b}}{2})]_B = Z_\psi(a)[\bar{\psi}(-\frac{\vec{b}}{2})\Gamma\psi(\frac{\vec{b}}{2})]_R$$

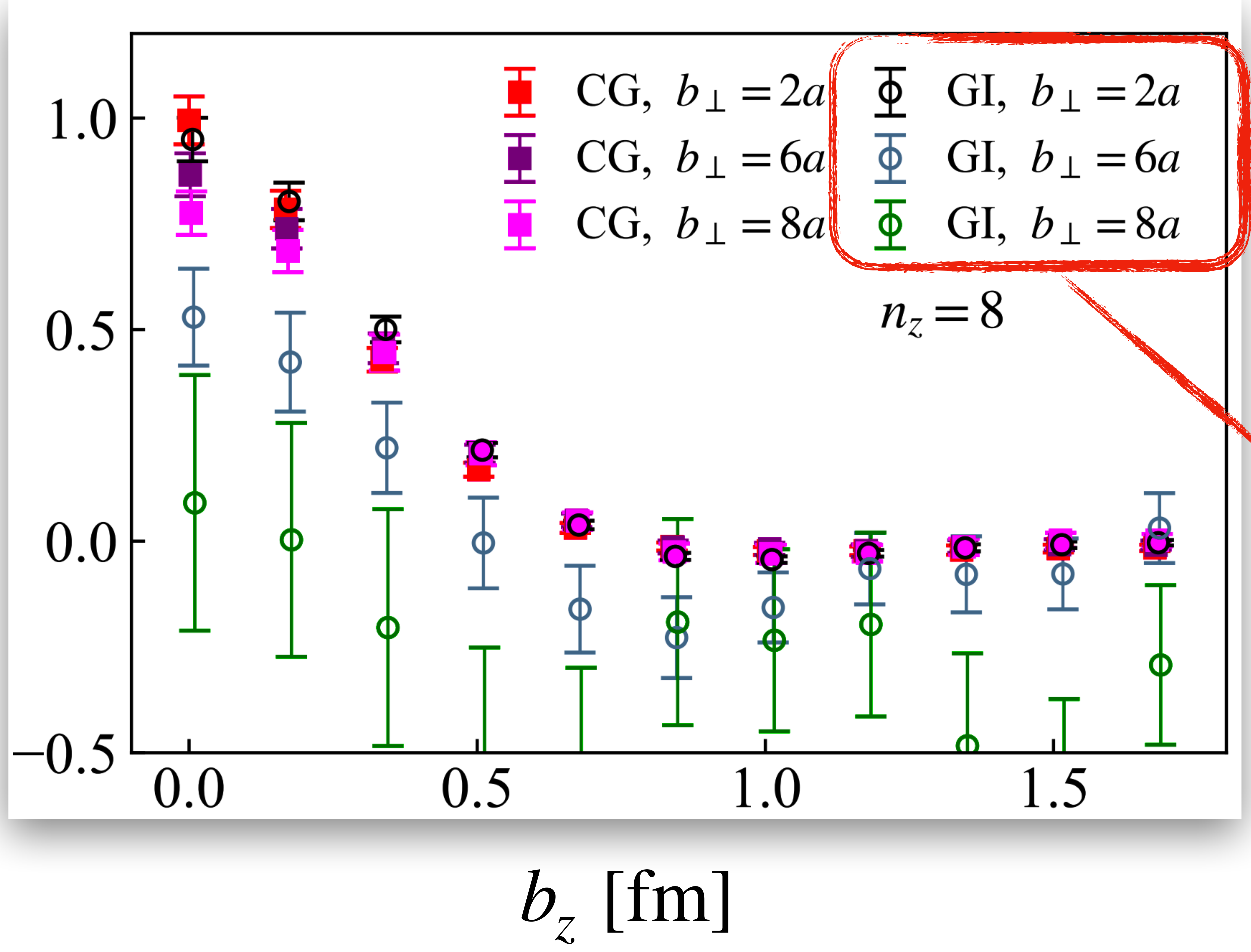
- Matrix elements with any $\vec{b}$ can be used to remove the UV divergence.

$$\frac{\tilde{h}^B(b_T, b_z, a)}{\tilde{h}^B(b_T^0, b_z^0, a)} = \frac{\tilde{h}^R(b_T, b_z, \mu)}{\tilde{h}^R(b_T^0, b_z^0, \mu)}$$

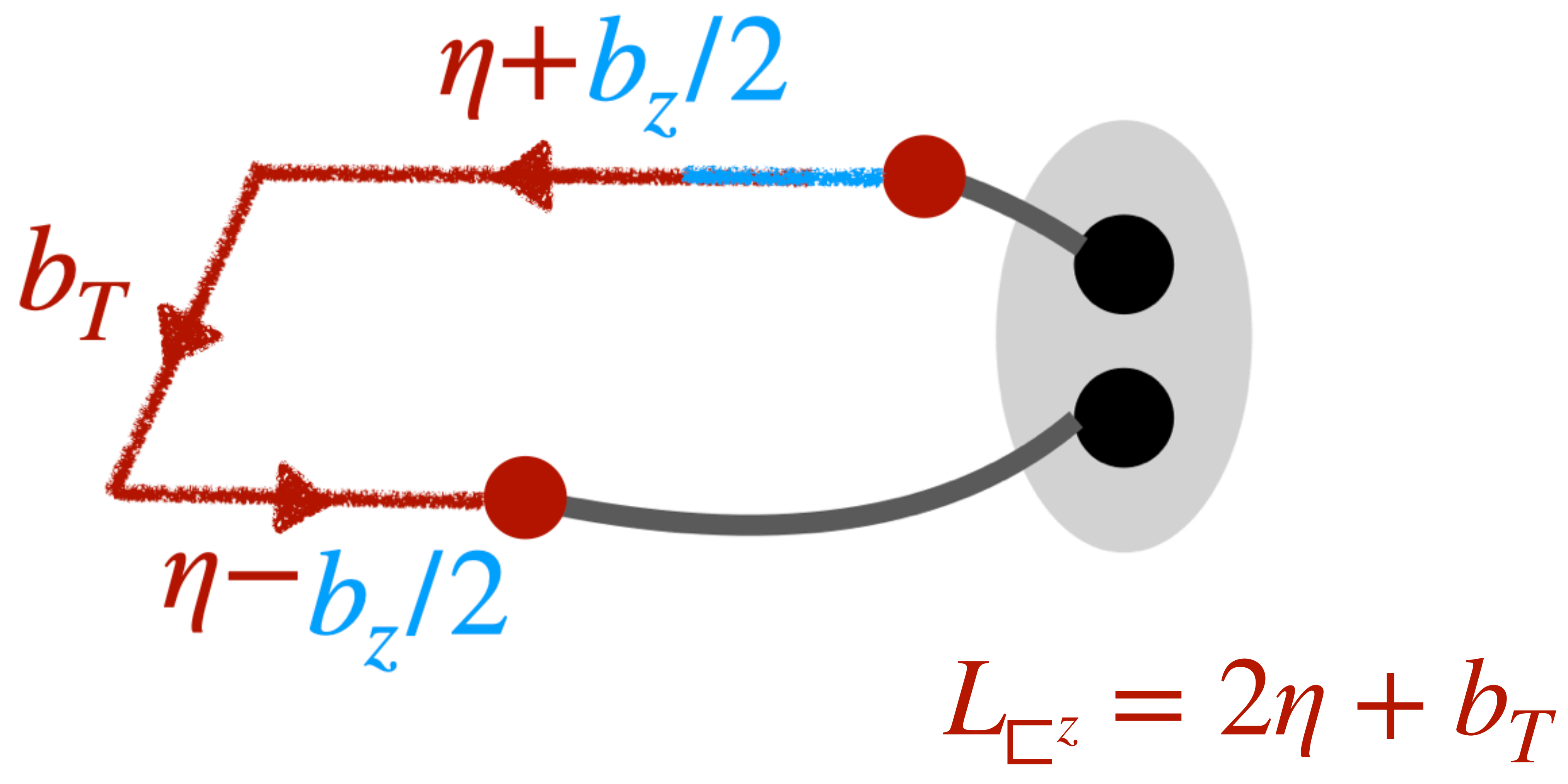
- **XG**, W.-Y. Liu, Y. Zhao, PRD 109 (2024) 9, 094506

CG quasi-TMDs: enhanced long-range precision

Renormalized matrix elements



Domain wall fermion, physical quark masses
$64^3 \times 128$, a = 0.084 fm



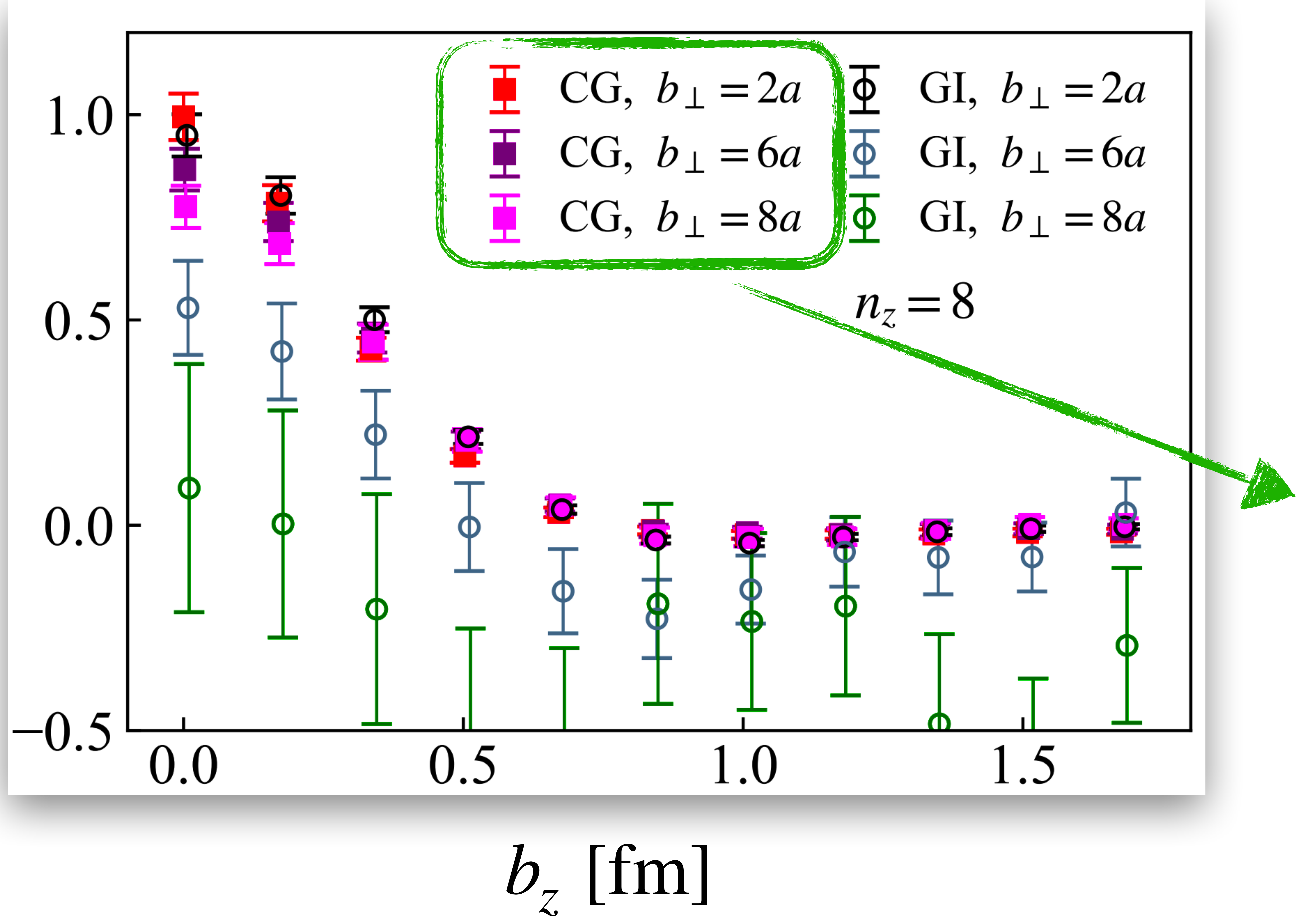
b_T: $2a \to 6a \to 8a$

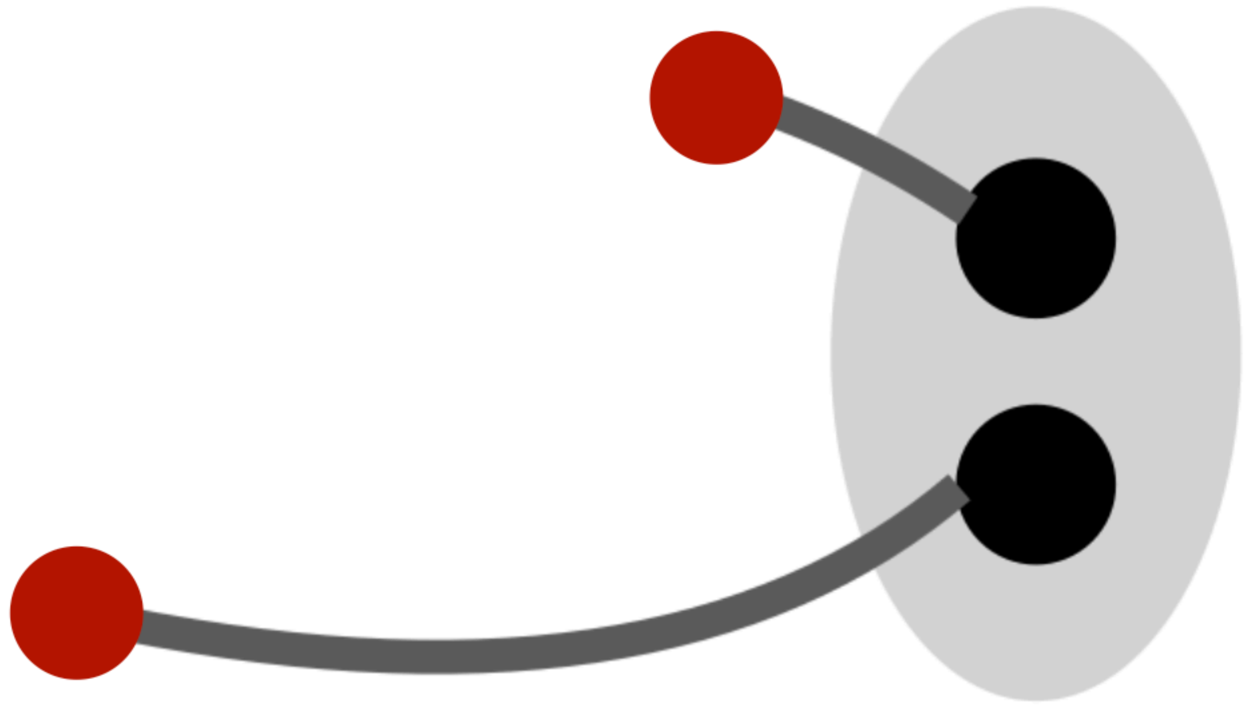
- GI shows rapid signal decay.

• D. Bollweg, **XG**, S. Mukherjee, Y. Zhao, PLB 852 (2024) 138617

CG quasi-TMDs: enhanced long-range precision

Renormalized matrix elements





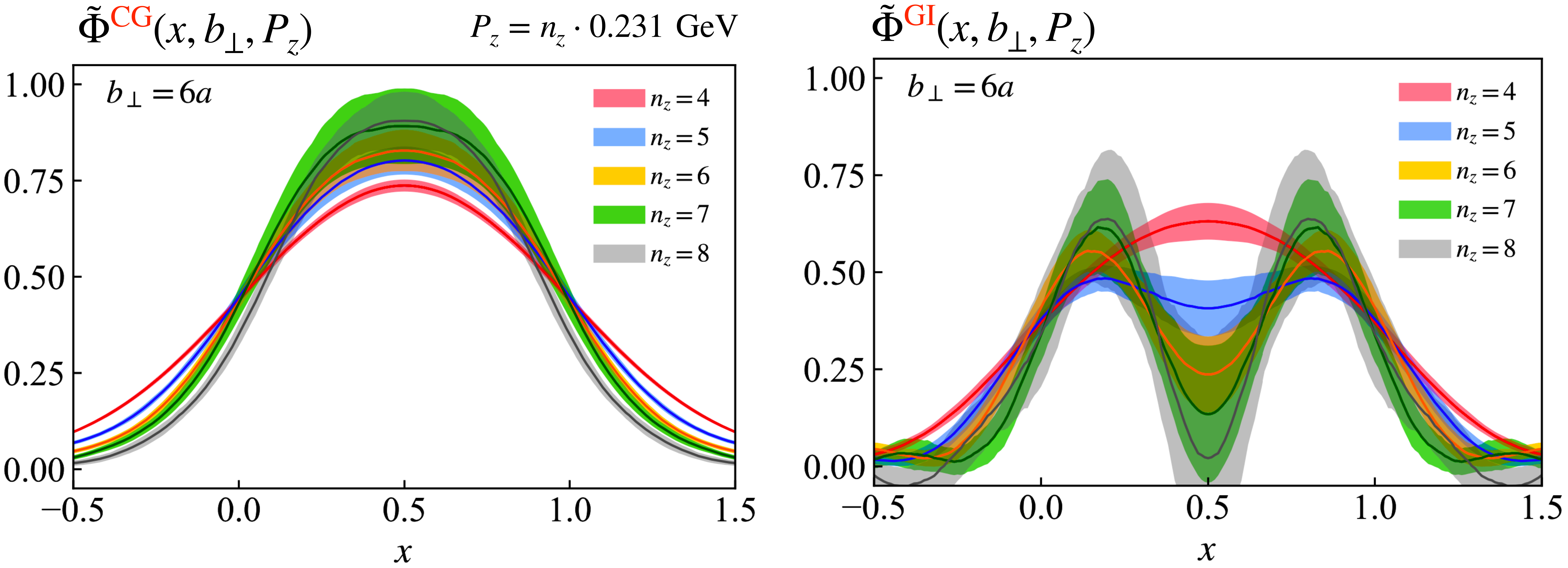
b_T: $2a \rightarrow 6a \rightarrow 8a$

- CG shows much slower signal decay compared to the GI cases.

Domain wall fermion, physical quark masses
$64^3 \times 128$, a = 0.084 fm

• D. Bollweg, **XG**, S. Mukherjee, Y. Zhao, PLB 852 (2024) 138617

Quasi-TMD wave functions after F.T.



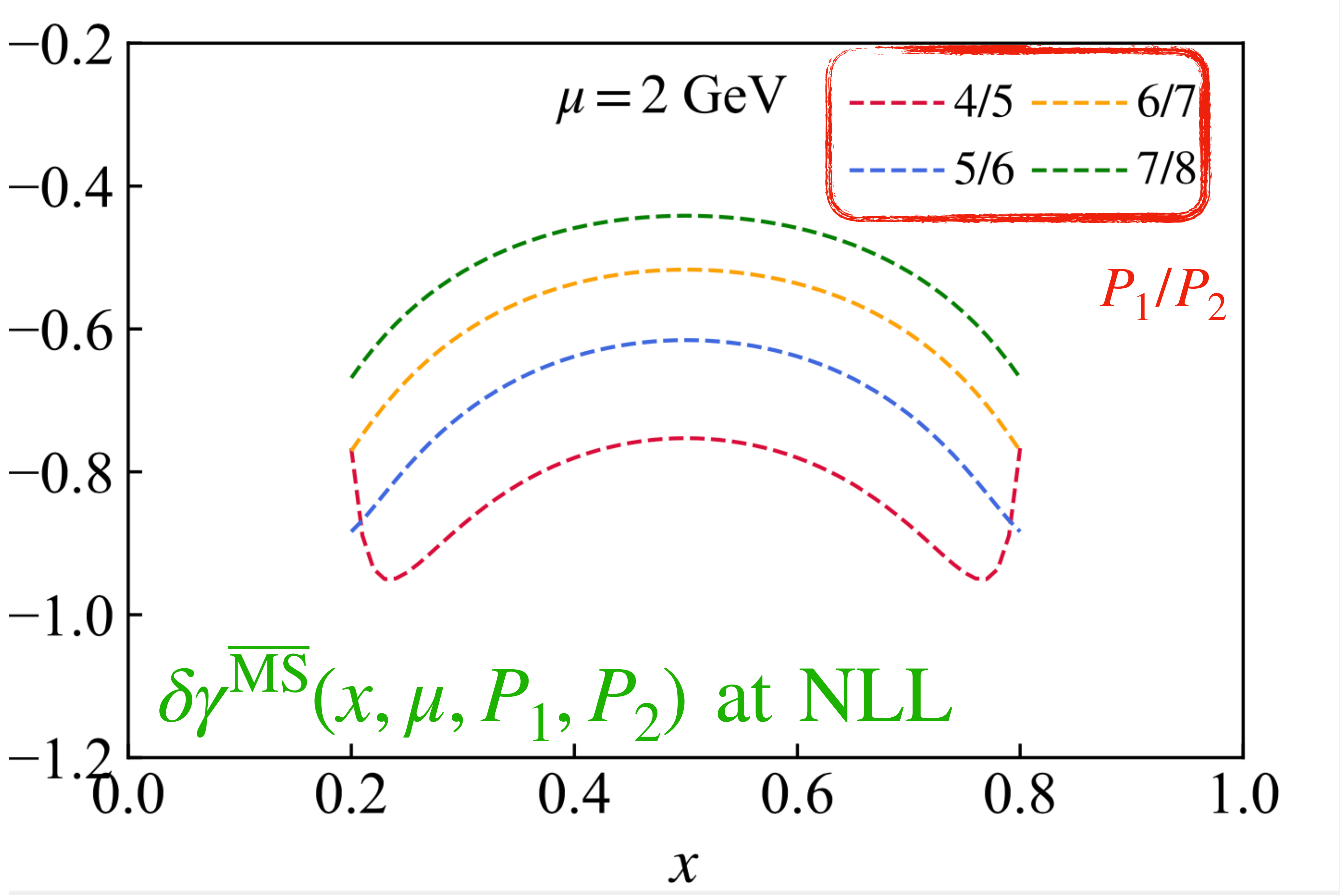
- The CG quasi-TMD wave functions are more stable and show better signal.

The Collins-Soper kernel from CG quasi-TMDWF

Perturbative correction

$$\gamma^{\overline{\rm MS}}(b_\perp,\mu) = \frac{1}{\ln(P_2/P_1)} \ln\left[\frac{\tilde\phi(x,b_\perp,P_2,\mu)}{\tilde\phi(x,b_\perp,P_1,\mu)}\right] + \delta\gamma^{\overline{\rm MS}}(x,\mu,P_1,P_2) + \mathcal{O}\left(\frac{\Lambda^2_{\rm QCD}}{(xP_z)^2}, \frac{1}{(b_\perp(xP_z))^2}\right)$$

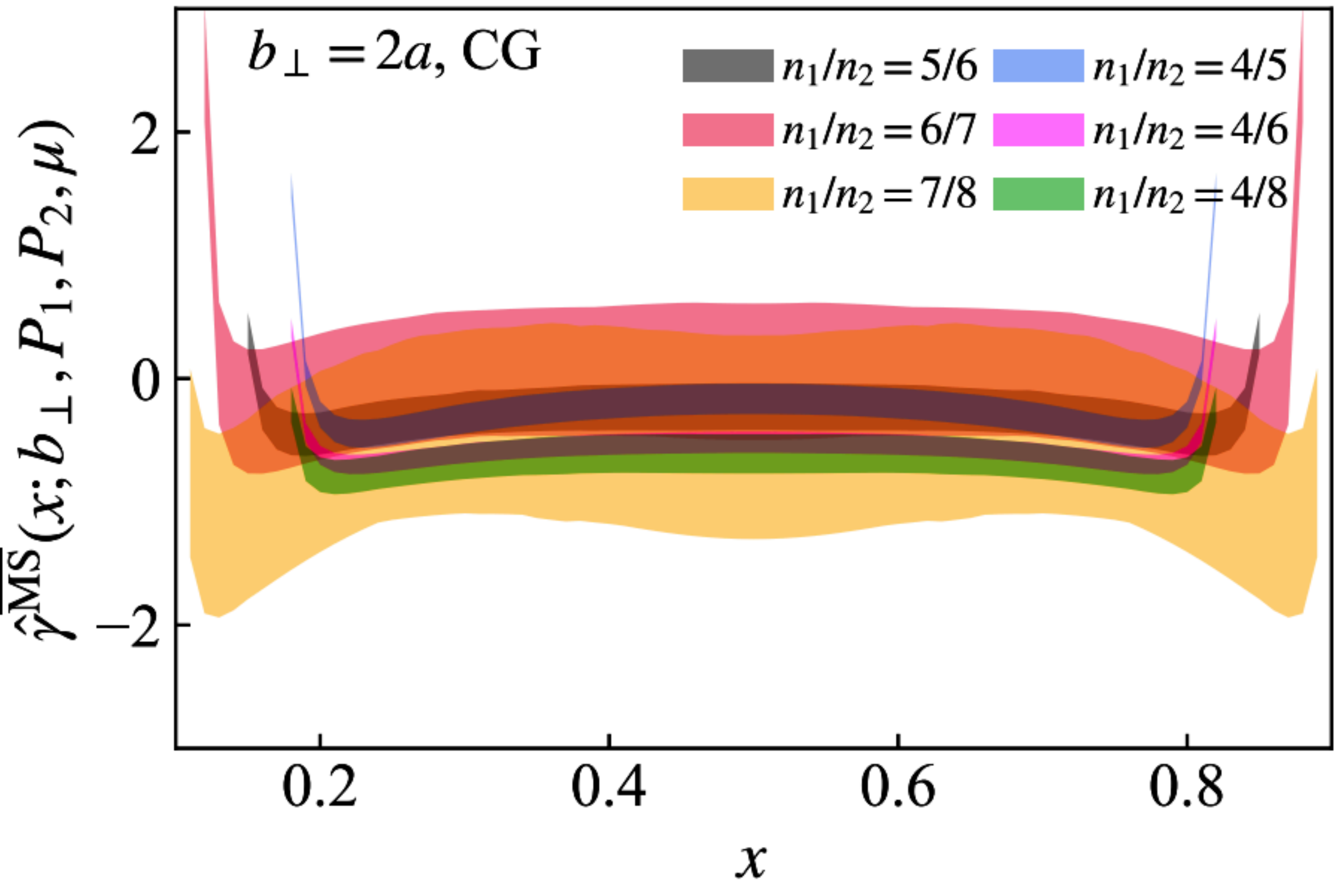
Ratio of quasi-TMDWFs

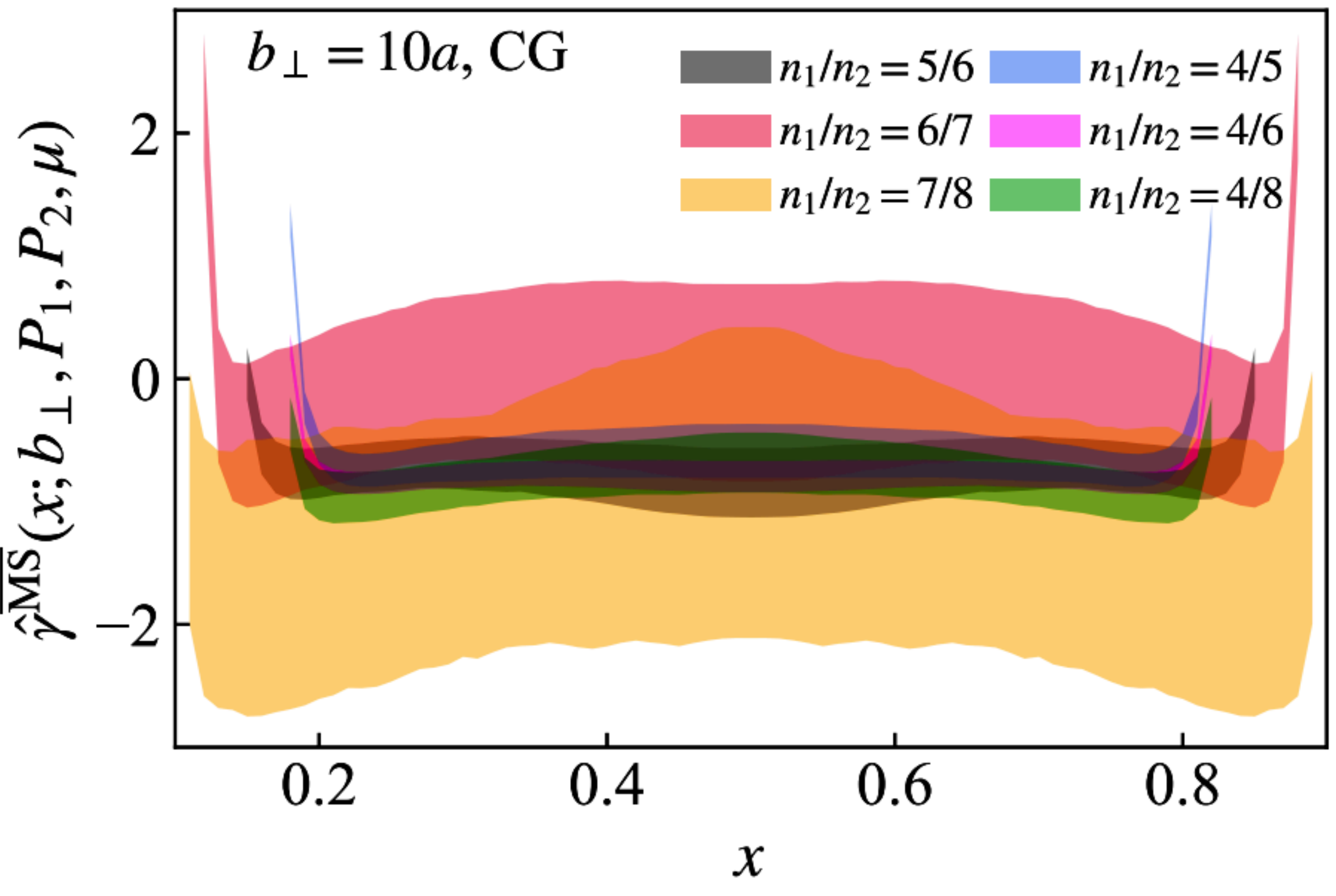


- The CS kernel $\gamma^{\overline{\rm MS}}(b_\perp,\mu)$ is **independent (universal) of P_z and x**, up to higher-order and power corrections.

The CS kernel from NLL matching

$a = 0.084$ fm, $\quad P_z = n_z \cdot 0.23$ GeV

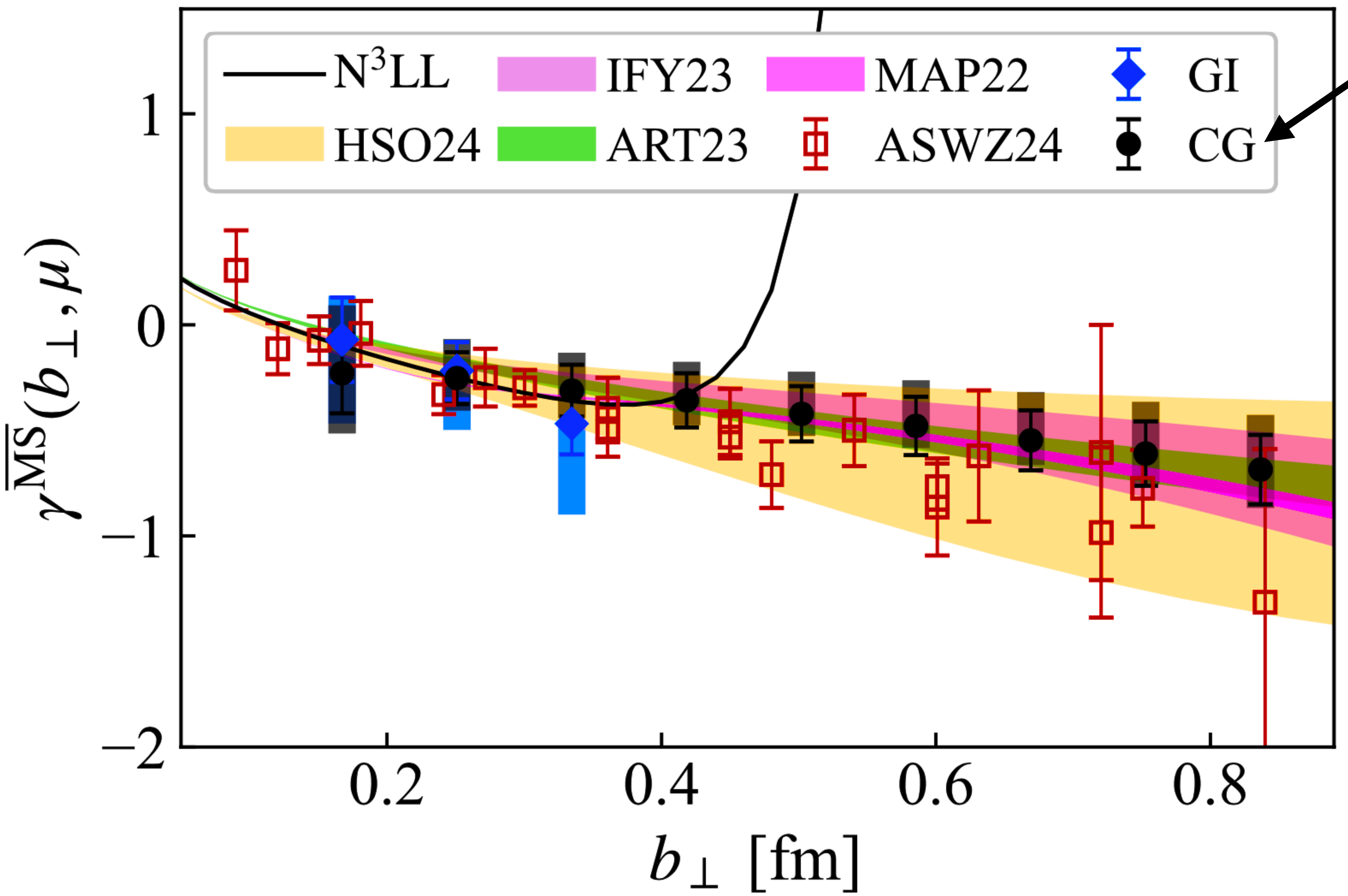




- Small $b_T \sim 0.1$ fm: visible P_z dependence.
- Sizable power corrections.

- Large b_T: no x and P_z dependence.
- Perturbative factorization work well!

Nonperturbative Collins-Soper kernel

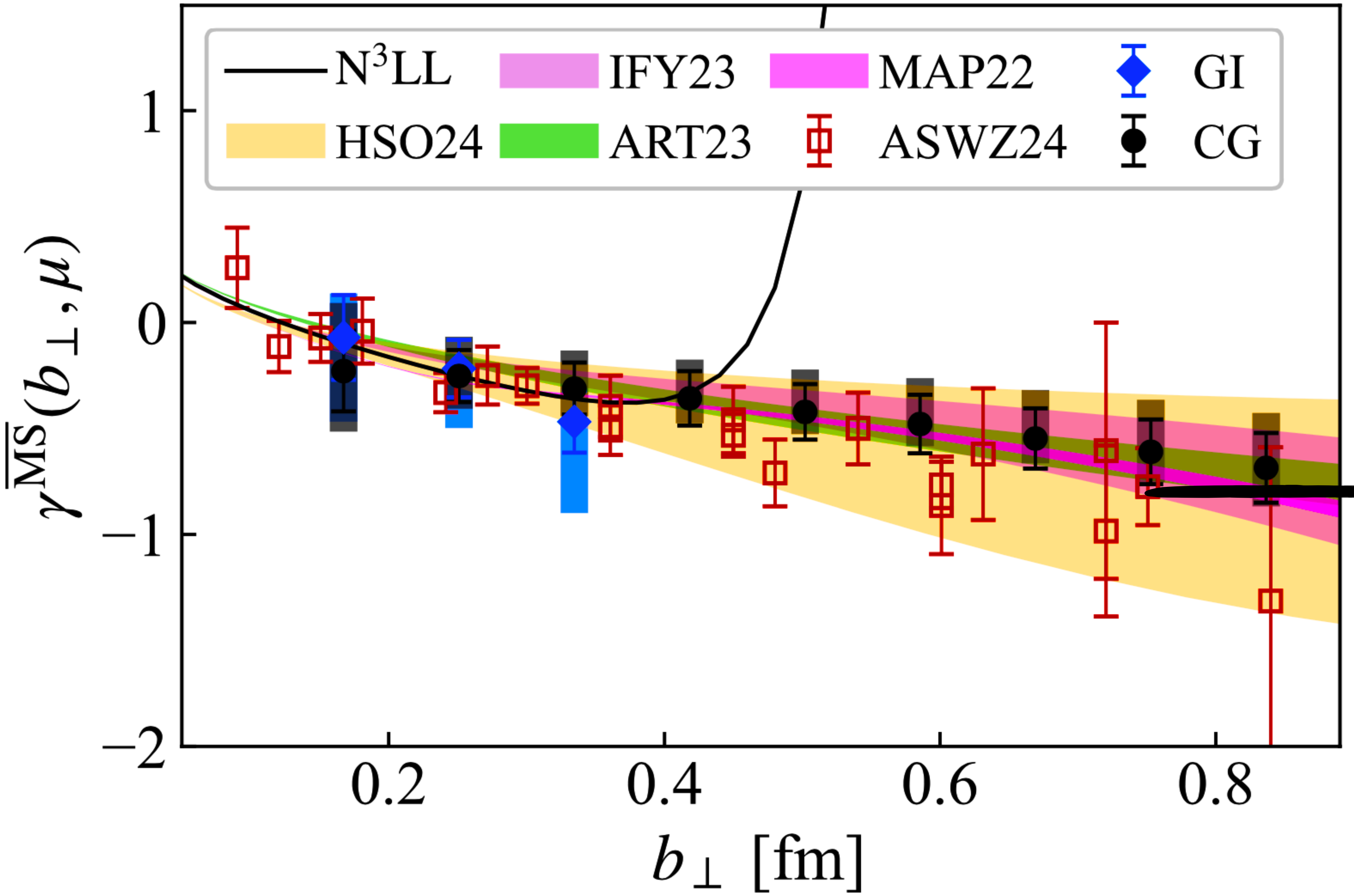


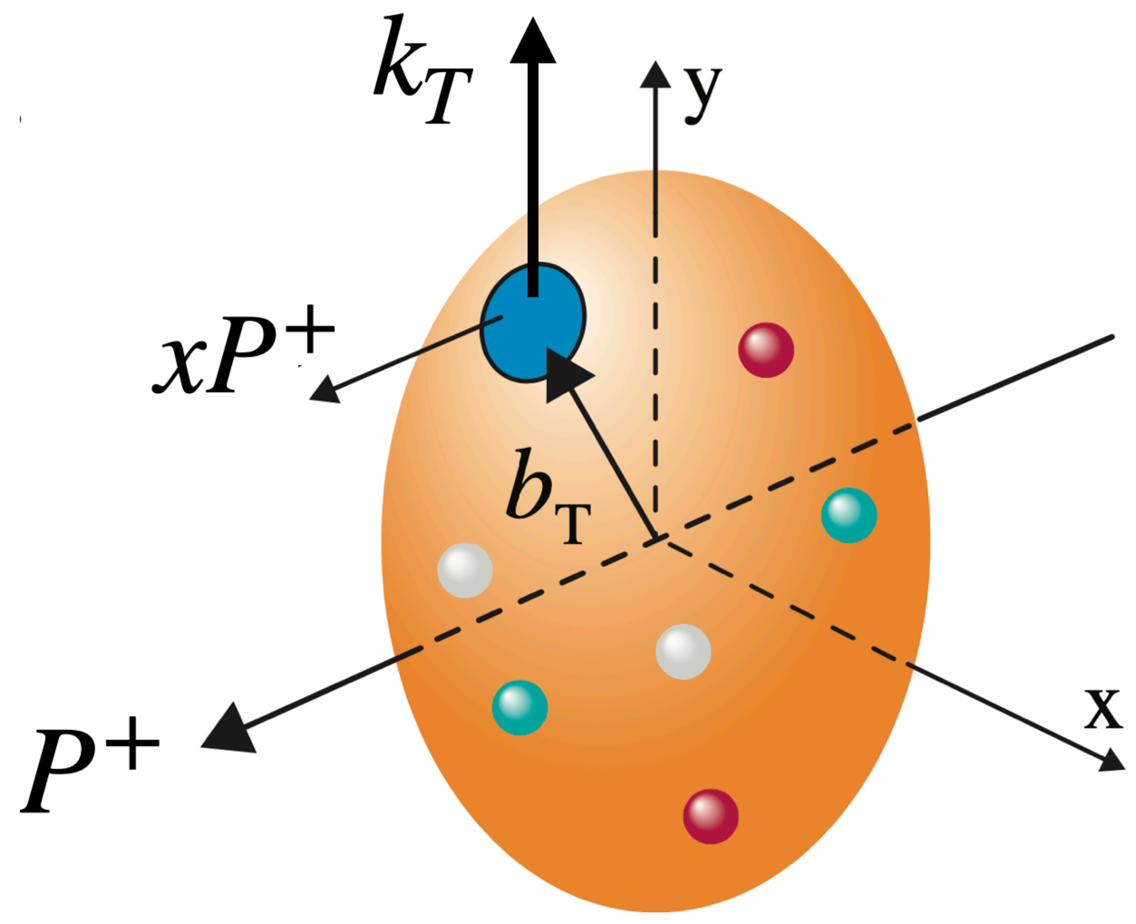
- Our QCD prediction: consistent with recent global fits and lattice results from GI operators.

Domain wall fermion, physical quark masses
$64^3 \times 128$, a = 0.084 fm

- D. Bollweg, **XG**, S. Mukherjee, Y. Zhao, PLB 852 (2024) 138617

Nonperturbative Collins-Soper kernel





- CG approach greatly improve the efficiency: broader use in the nonperturbative regime of TMDs!

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Summary

- The TMDs can be extracted from quasi-TMD correlators. The novel CG quasi-TMDs have the advantages of the simplified renormalization and enhanced long-range precision.
- We extracted the non-perturbative CS kernel from the quasi-TMD wave functions in the CG which appears to be consistent with recent parametrization of experimental data.
- The CG methods could have broader use in the future particularly in the non-perturbative regime of TMD physics, including the gluons and the Wigner distributions.

Thanks for your attention!

Back up

CG quasi distribution without Wilson lines

- **The quark field in the Coulomb gauge**

$$\psi_C(z) = U_C(z)\psi(z)$$

satisfying,

$$\vec{\nabla}\cdot\left[U_C\vec{A}U_C^{-1} + \frac{i}{g}U_C\vec{\nabla}U_C^{-1}\right] = 0$$

order by order in g, the solution:

$$U_C = \sum_{n=0}^{\infty}\frac{(ig)^n}{n!}\omega_n$$

$$\omega_1 = -\frac{1}{\nabla^2}\vec{\nabla}\cdot\vec{A},$$

$$\omega_2 = \frac{1}{\nabla^2}\left(\vec{\nabla}\cdot(\omega_1^\dagger\vec{\nabla}\omega_1) - [\vec{\nabla}\omega_1, \vec{A}]\right)$$

$\ldots$

▶ $P \to \infty$ **limit boost**

$$-\frac{1}{\nabla^2}\vec{\nabla}\cdot\vec{A} = i\int\frac{d^4k}{(2\pi)^4}e^{-ik\cdot z}\frac{1}{k_z^2+k_\perp^2}[k_zA_z(k) + k_\perp A_\perp(k)]$$

$$\approx i\int\frac{d^4k}{(2\pi)^4}e^{-ik\cdot z}\frac{k^+}{(k^+)^2+\epsilon^2}A^+(k)$$

$$= \frac{1}{2}\left[\int_{-\infty^-}^{z^-} + \int_{+\infty^-}^{z^-}\right]d\eta^- A^+ \equiv \frac{1}{\partial^+_{\mathrm{P.V.}}}A^+(z)$$

Principle value prescription (P.V.) averaging over past and future.

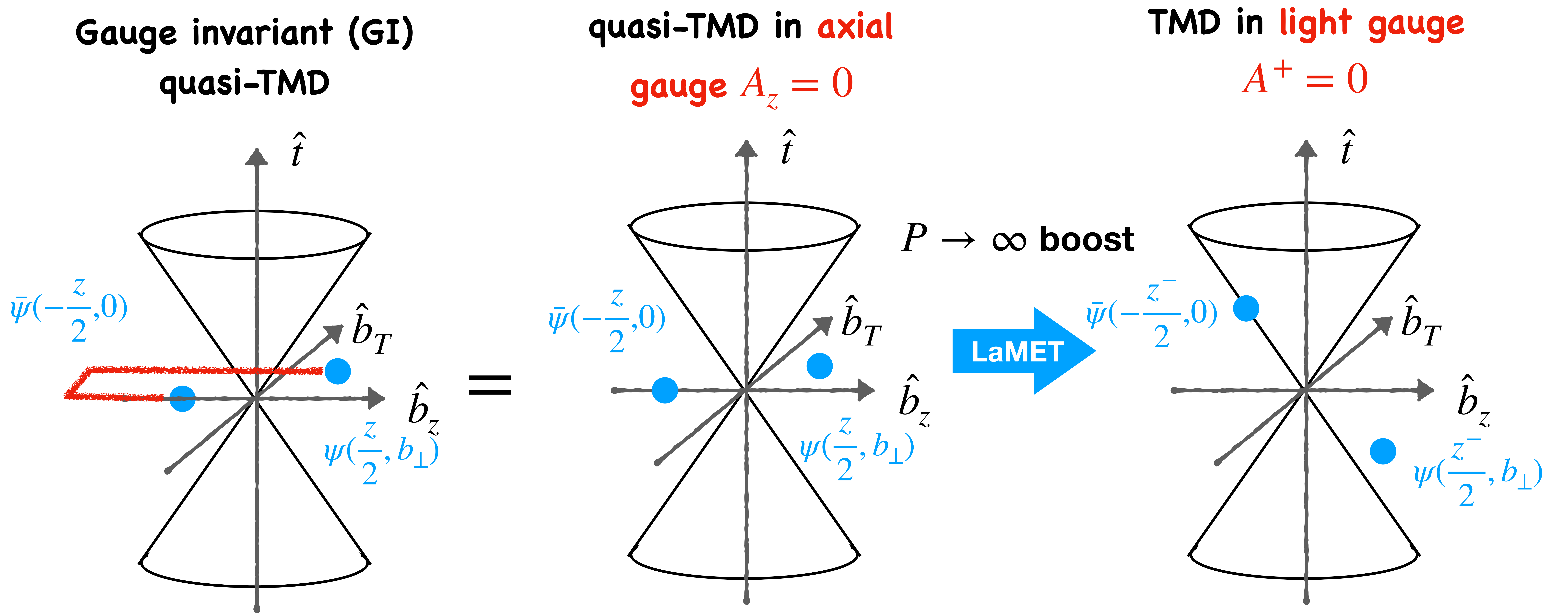
Path-ordered integral

$$\frac{\omega_n}{n!} \to \left(\ldots\left(\frac{1}{\partial^+_{\mathrm{P.V.}}}\left(\left(\frac{1}{\partial^+_{\mathrm{P.V.}}}A^+\right)A^+\right)A^+\right)\ldots A^+\right)$$

$$U_C \to \mathscr{P}\exp\left[-ig\int_{z^-}^{\mp\infty^-}dzA^+(z)\right] \equiv W(z^-, \mp\infty^-)$$

Infinite light-cone Wilson link

Conventional quasi-TMDs



$$\overline{\psi}(\frac{b_z}{2}, b_\perp)\Gamma W_\sqsupset(\frac{\mathbf{b}}{2}, -\frac{\mathbf{b}}{2}, \eta)\psi(-\frac{b_z}{2},0) \quad = \quad \overline{\psi}(\frac{b_z}{2}, b_\perp)\Gamma\psi(-\frac{b_z}{2},0)|_{A_z=0} \qquad \overline{\psi}(\frac{b^+}{2}, b_\perp)\Gamma\psi(-\frac{b^+}{2},0)|_{A^+=0}$$