Nucleon Tomography with 0-jettiness

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XXIII Annual Workshop on Soft-Collinear Effective Theory

Seoul, Republic of Korea Mar 4, 2026

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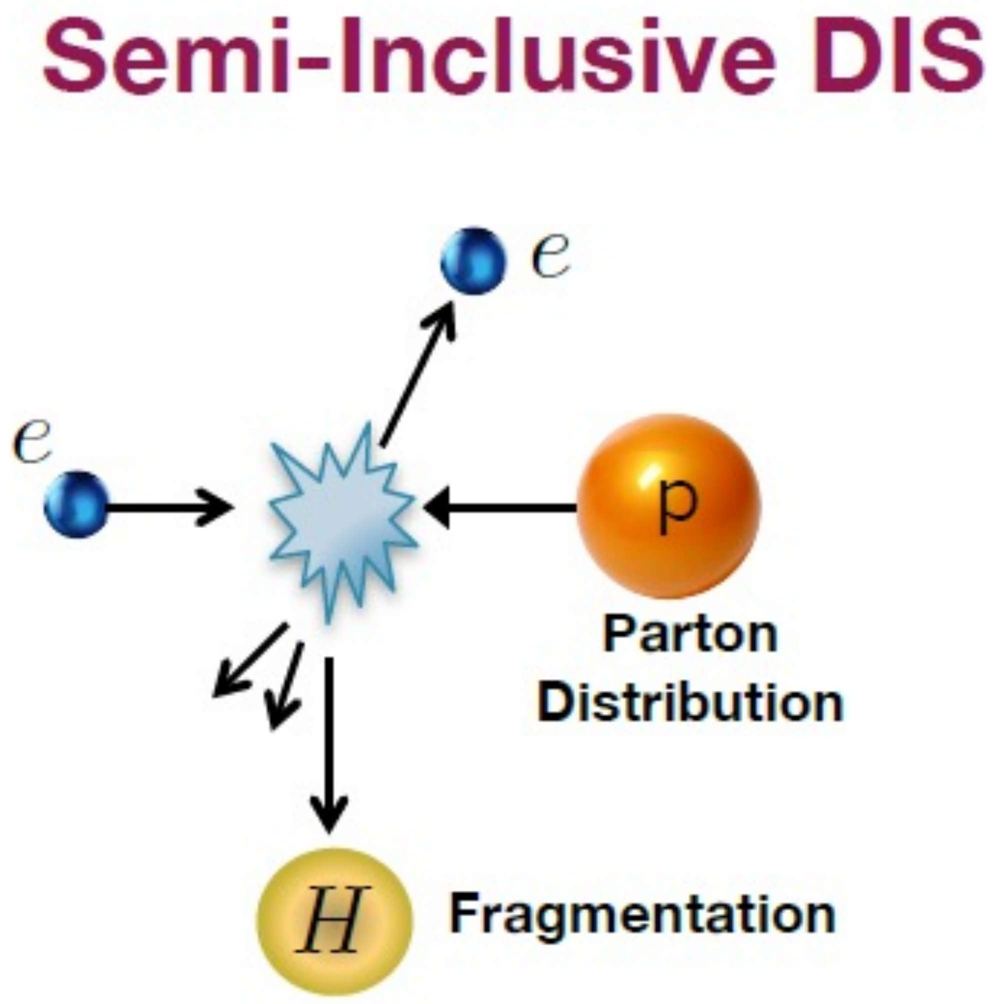
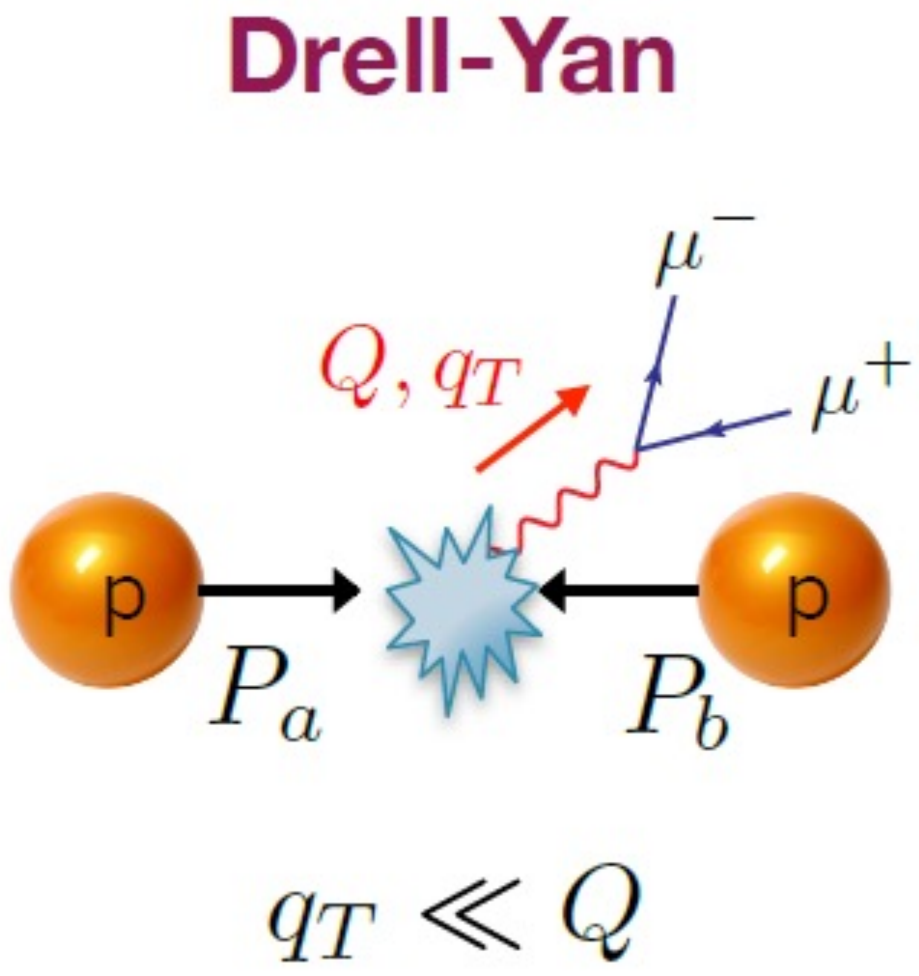
Reference: Phys.Rev.Lett. 136 (2026) 2, 021901

Nucleon tomography: a fundamental quest





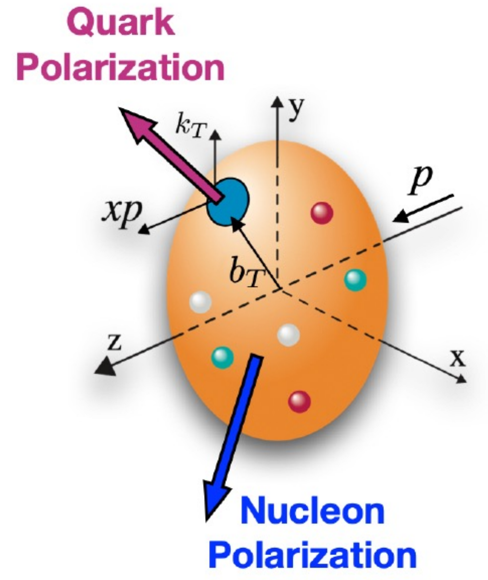
Proton structure: encoded in PDFs

$$\sigma = \sum_{a,b} \int_0^1 dx_1 dx_2\, \hat{\sigma}_{ab}(Q, x_1, x_2, \mu_f)\, f_a(x_1, \mu_f)\, f_b(x_2, \mu_f) + \mathcal{O}(\Lambda_{\rm QCD}/Q)$$

TMDs: 3D tomography of nucleon structure

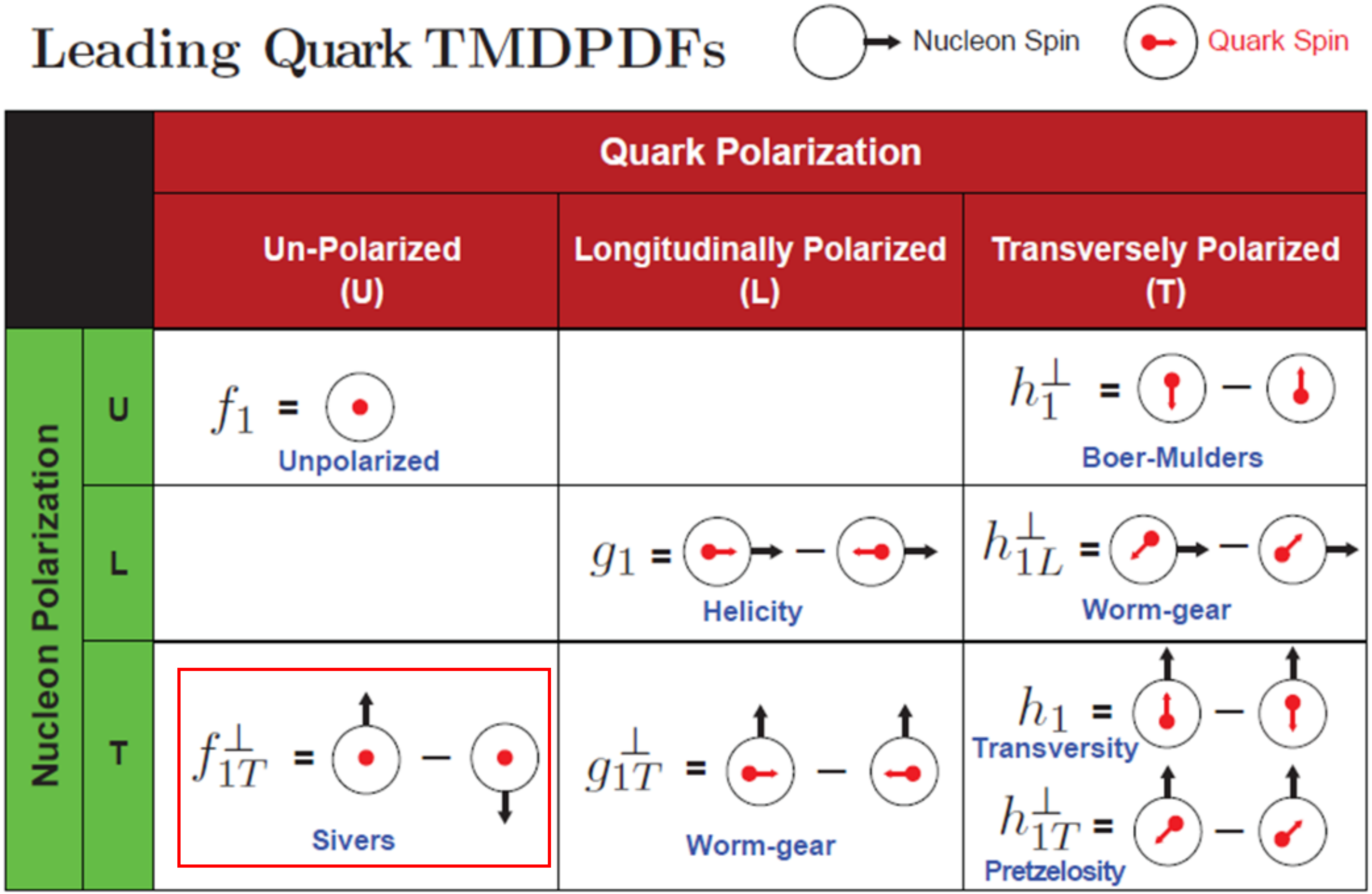
- **TMD PDF:** $$\tilde{f}_{i/ps}^{[\Gamma]0(u)}(x, \mathbf{b}_T, \epsilon, \tau, xP^+) = \int \frac{db^-}{2\pi} e^{-ib^-(xP^+)} \left\langle p(P,S) \middle| \left[\bar{\psi}^i(b^\mu) W_{\sqsubset}(b^\mu, 0) \frac{\Gamma}{2} \psi^i(0) \right]_\tau \middle| p(P,S) \right\rangle$$

- **Dirac structures:** $\Gamma \in \{ \gamma^+ , \gamma^+\gamma_5 , i\sigma^{\alpha+}\gamma_5 \}$



- **Drell-Yan:**
  - **small p_T: N^{4}LL** Camarda, Cieri, Ferrera ’23; Moos, Scimemi, Vladimirov, Zurita ’23; Billis, Michel, Tackmann 24’
  - **large p_T: N^{2}LO V+jet** Gehrmann-De Ridder et al. ’16, 18; Boughezal et al. ’15, 16; Campbell, Ellis, Williams ’17
- **SIDIS:**
  - **small p_T: N^{4}LL** Moos, Scimemi, Vladimirov, Zurita ’25
  - **large p_T: N^{2}LO h+jet** Dong, SF, Gao, Li, Shao, Zhu ’26: see Rong-Jun’s talk

TMDs: 3D tomography of nucleon structure

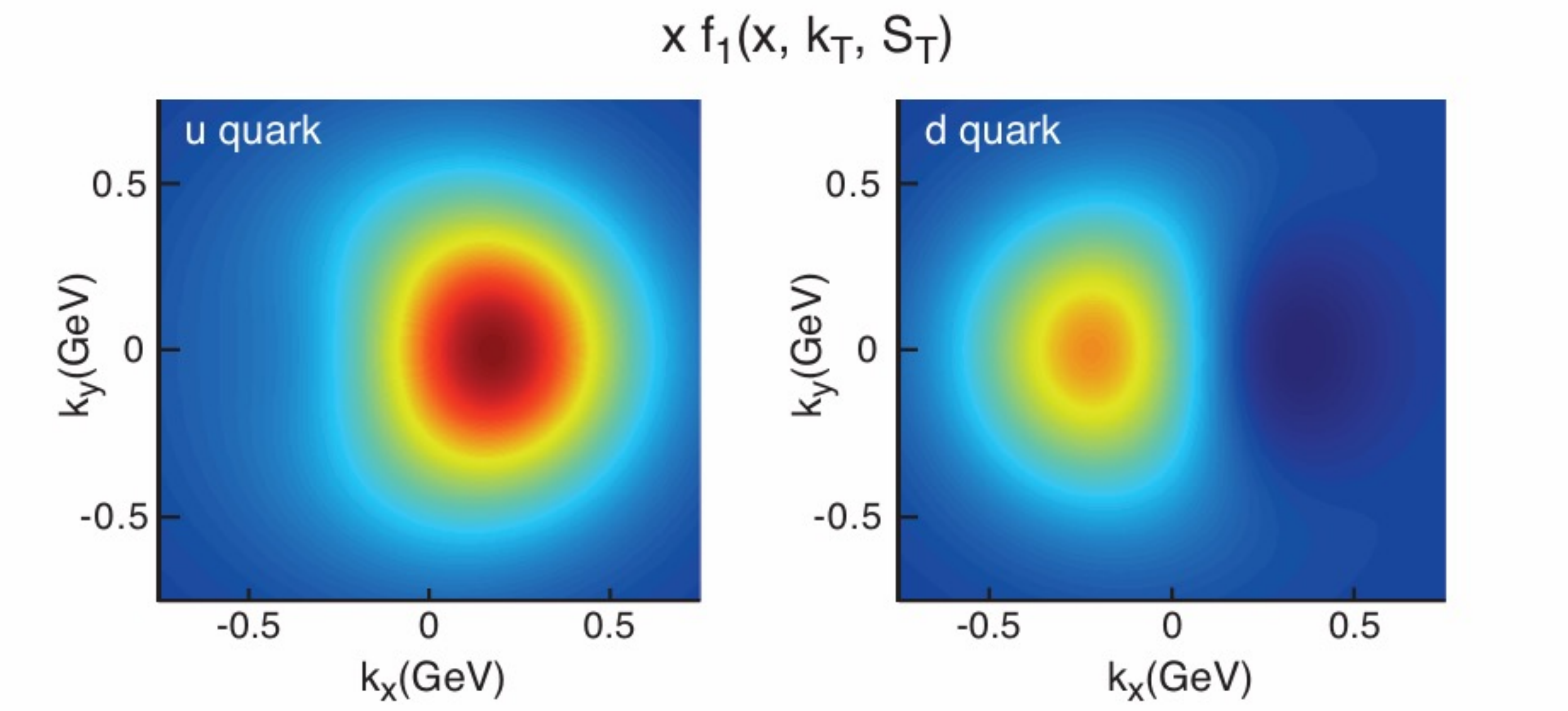


Sivers function

- **Sivers function describes the transverse momentum distribution correlated with the transverse polarization vector of the nucleon.**

$$f_{q/h^\uparrow}(x,\mathbf{k}_\perp,\vec{S}) \equiv f_{q/h}(x,k_\perp) - \frac{1}{M} f_{1T}^{\perp q}(x,k_\perp)\,\vec{S}\cdot(\hat{p}\times\mathbf{k}_\perp)$$

Spin-independent — Spin-dependent



Accardi et al. ’16

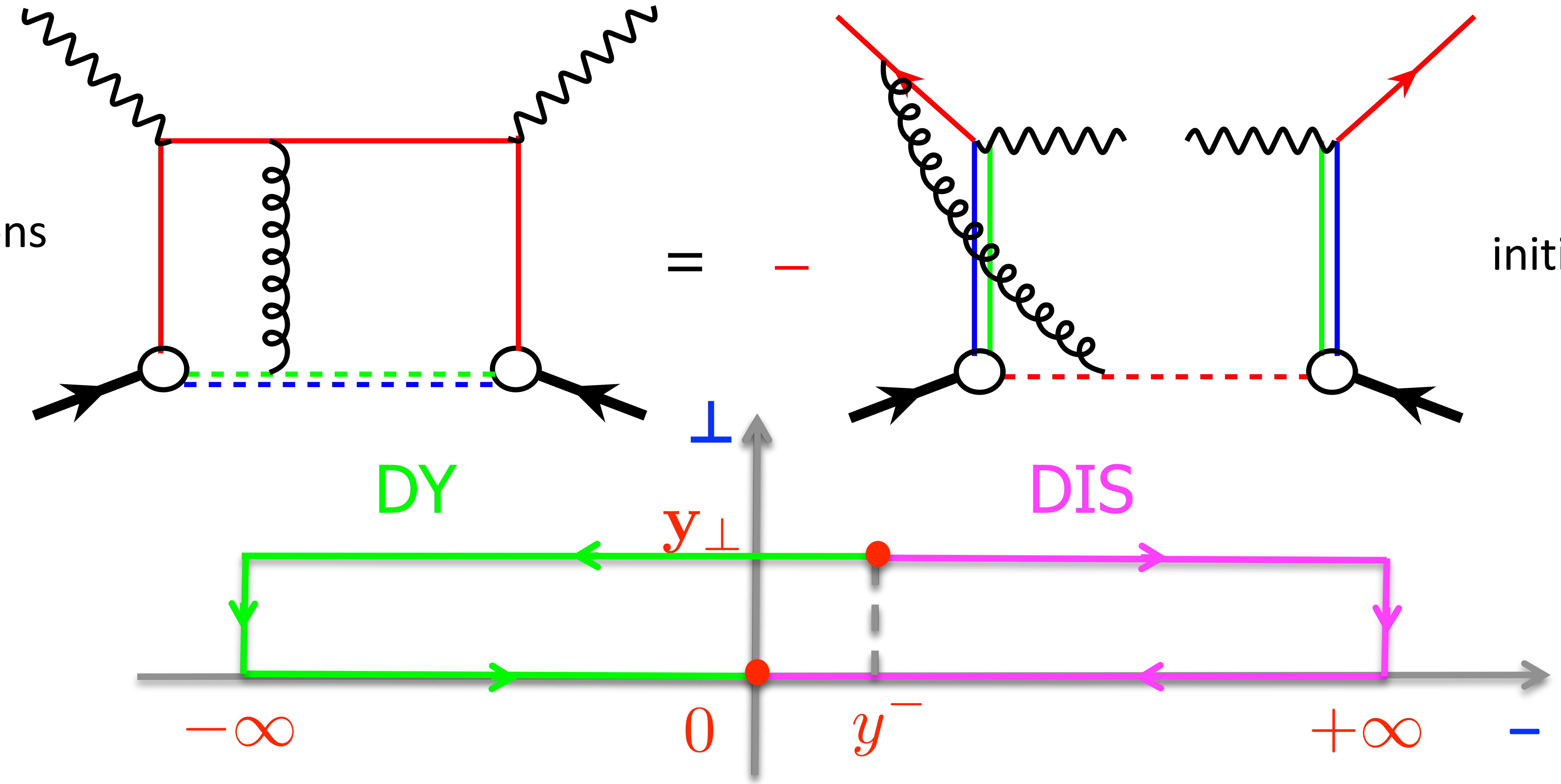
- **The quark distribution will be azimuthally asymmetric in the transverse momentum space in a transversely polarized nucleon.**

Sivers function

- **Naïve time-reversal-odd, and its existence requires a phase (generate through interactions)**

Brodsky, Hwang, Schmidt, '02
Collins , '02

final state interactions



initial state interactions

$$f_{1T}^{\perp,\mathrm{DIS}}(x,k_\perp) = -f_{1T}^{\perp,\mathrm{DY}}(x,k_\perp)$$

Sivers function and Qiu-Sterman function

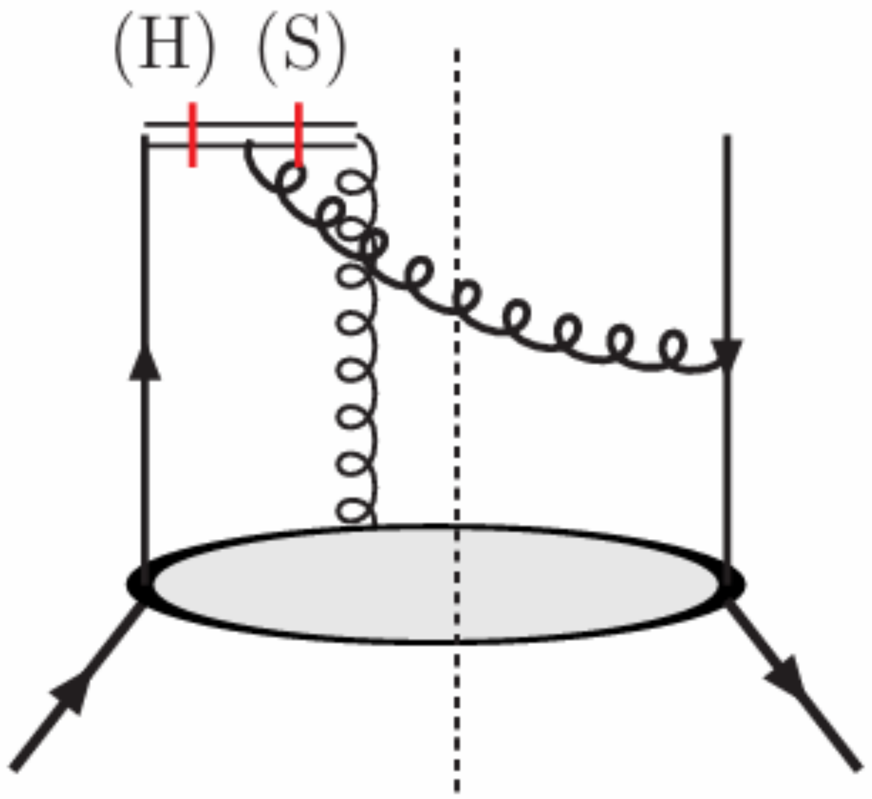
- **Qiu-Sterman Function**

$$T_F(x_2, x_2') \equiv \int \frac{d\zeta^- d\eta^-}{4\pi} e^{i(x_2 P^+ \eta^- + (x_2' - x_2) P_B^+ \zeta^-)} \epsilon_\perp^{\beta\alpha} S_{\perp\beta}$$
$$\times \langle PS | \overline{\psi}(0) \mathcal{L}(0, \zeta^-) \gamma^+ g F_\alpha{}^+(\zeta^-) \mathcal{L}(\zeta^-, \eta^-) \psi(\eta^-) | PS \rangle$$

Qiu, Sterman, 1991, 1992 & 1999

- **Sivers function at NLO in small b limit**

$$\begin{aligned}\tilde{f}_{1T}^{\alpha}(z,b) = \frac{\alpha_s}{2\pi}\left(\frac{-ib_\perp^\alpha}{2}\right)\Bigg\{&\left(-\frac{1}{\epsilon} + \ln\frac{c_0^2}{b^2\mu^2}\right)\mathcal{P}_{qg\to qg}^T \otimes T_F(z)\\ &-\delta(1-\xi)T_F(x,x)C_F\ln\frac{c_0^2}{b^2\mu^2} - \frac{1}{2N_c}T_F(x,x)(1-\xi)\\ &+\delta(1-\xi)T_F(x,x)C_F\left[\frac{3}{2}\ln\frac{b^2\mu^2}{c_0^2} + \ln\frac{z^2\zeta^2}{\mu^2} - \frac{1}{2}\left(\ln\frac{z^2\zeta^2 b_\perp^2}{c_0^2}\right)^2 - 2 - \frac{\pi^2}{2}\right]\Bigg\}\end{aligned}$$

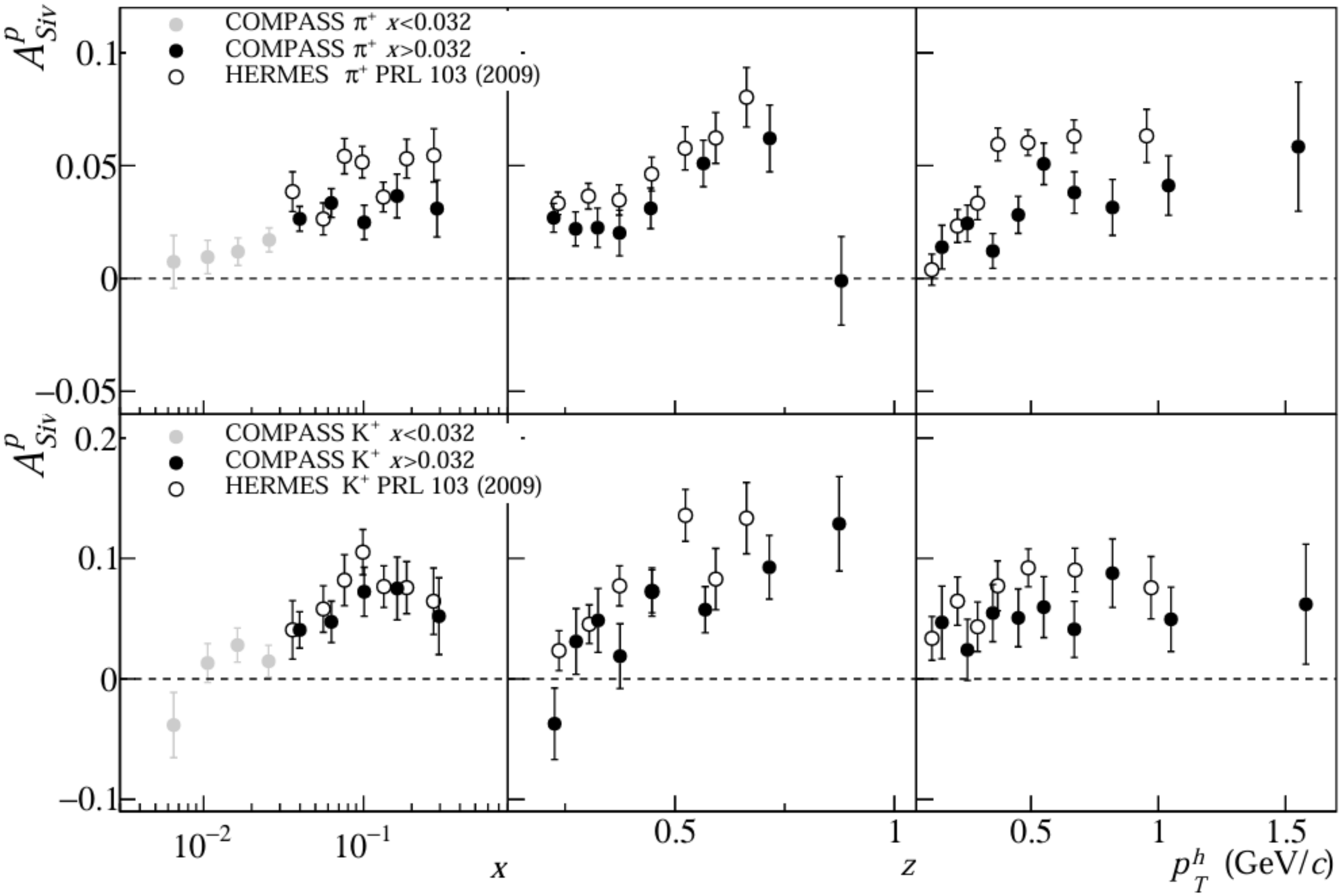


$$\begin{aligned}\mathcal{P}_{qg\to qg}^T \otimes T_F(z) = \int \frac{dx}{x}\Bigg\{&T_F(x,x)\left[C_F\left(\frac{1+\xi^2}{1-\xi}\right)_+ - C_A\delta(1-\xi)\right]\\ &+\frac{C_A}{2}\left(T_F(x,z)\frac{1+\xi}{1-\xi} - T_F(x,x)\frac{1+\xi^2}{1-\xi}\right)\Bigg\},\end{aligned}$$

$$\xi = z/x$$

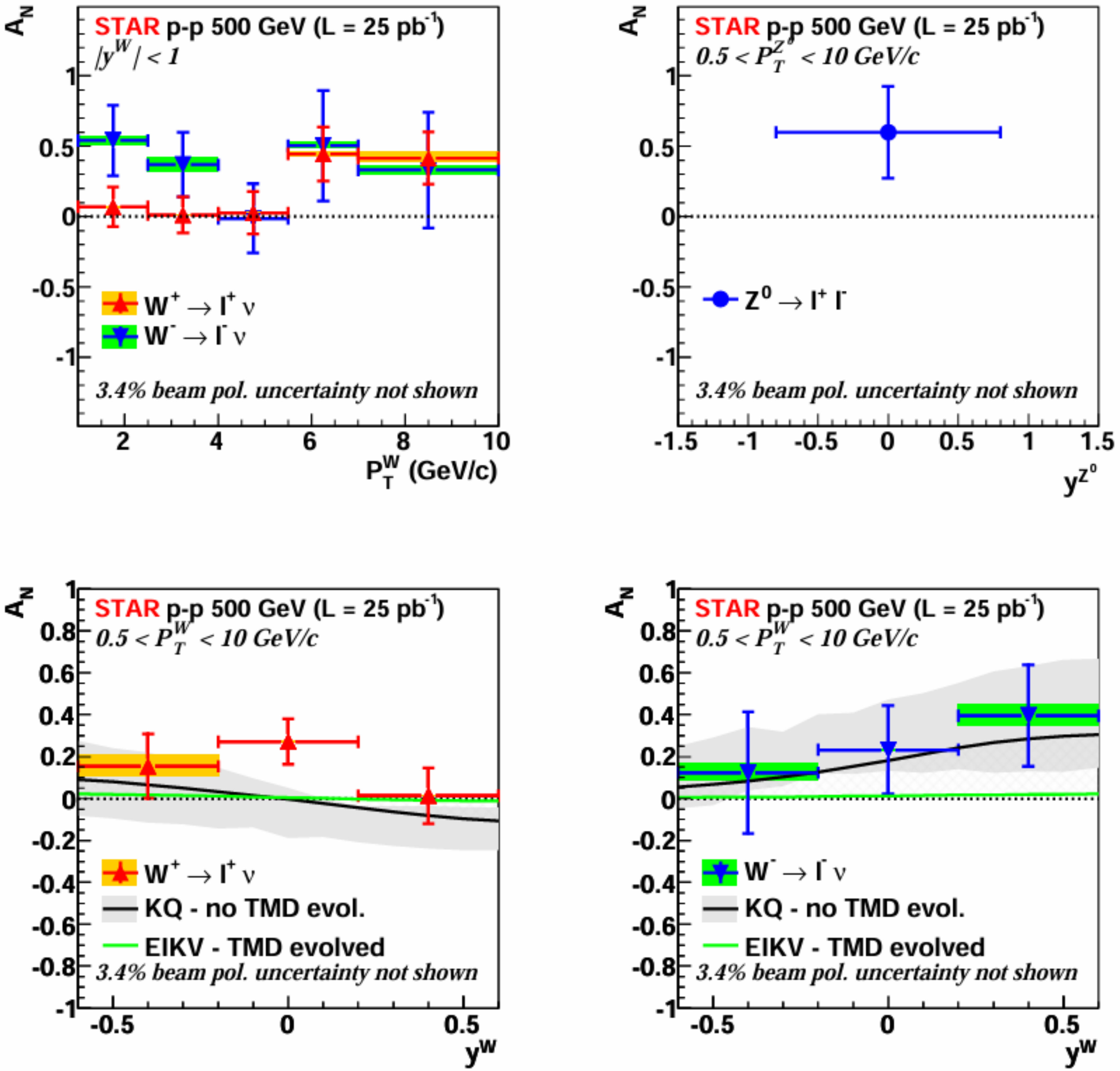
Ji, Qiu, Vogelsang, Yuan '06
Zhou, Yuan, Liang '08
Sun, Yuan '13

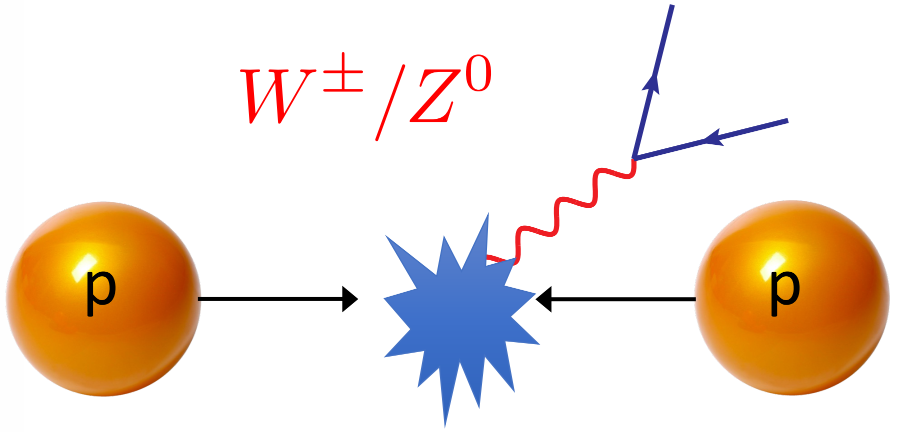
Transverse single spin asymmetries (SSAs) in SIDIS



COMPASS ’15
HERMES ’09

Transverse SSAs in weak boson production

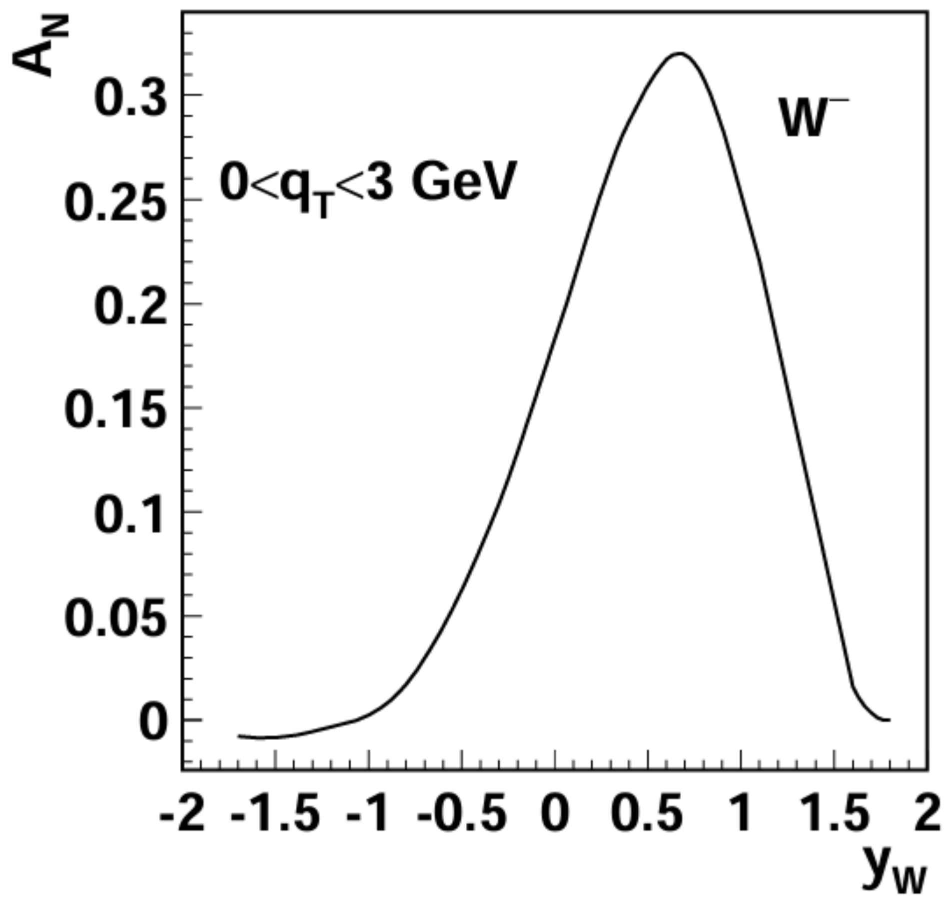




STAR Collaboration, ’16

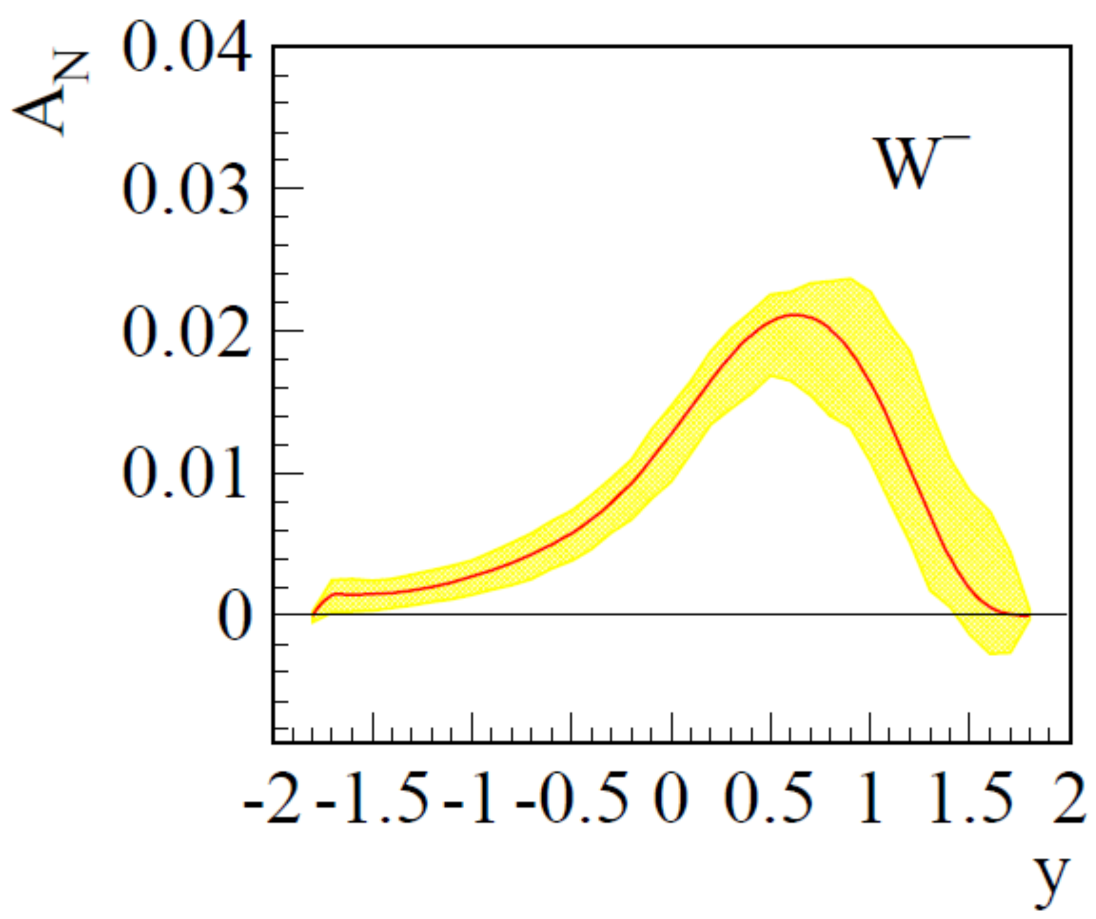
TMD evolution effect

Without TMD evolution



Kang, Qiu '09

With TMD evolution



Echevarria, Idilbi, Kang, Vitev '14

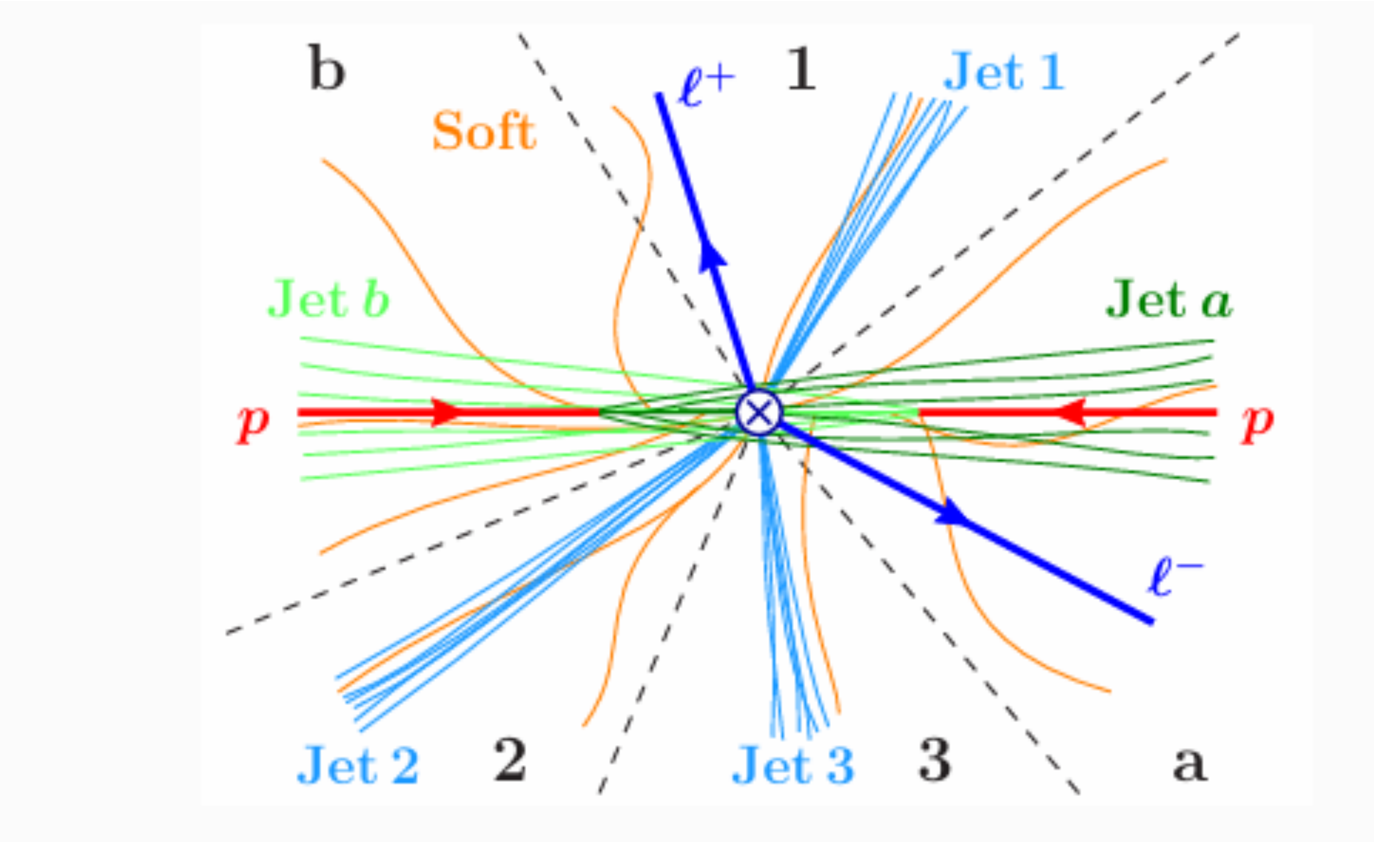
TMD evolution reduces the asymmetry.

How to enhance the asymmetry? SF, Lin, Shao, Zhou '25

Our solution: imposing a 0-jettiness veto

N-jettiness

N-jettiness is a global event shape defined in terms of the beam directions $q_{a,b}$ and N jet directions q_j



$$\tau_N = \frac{2}{Q^2} \sum_k \min\{q_a \cdot p_k,\ q_b \cdot p_k,\ q_1 \cdot p_k,\ \ldots,\ q_N \cdot p_k\}$$

Stewart, Tackmann, Waalewijn '10

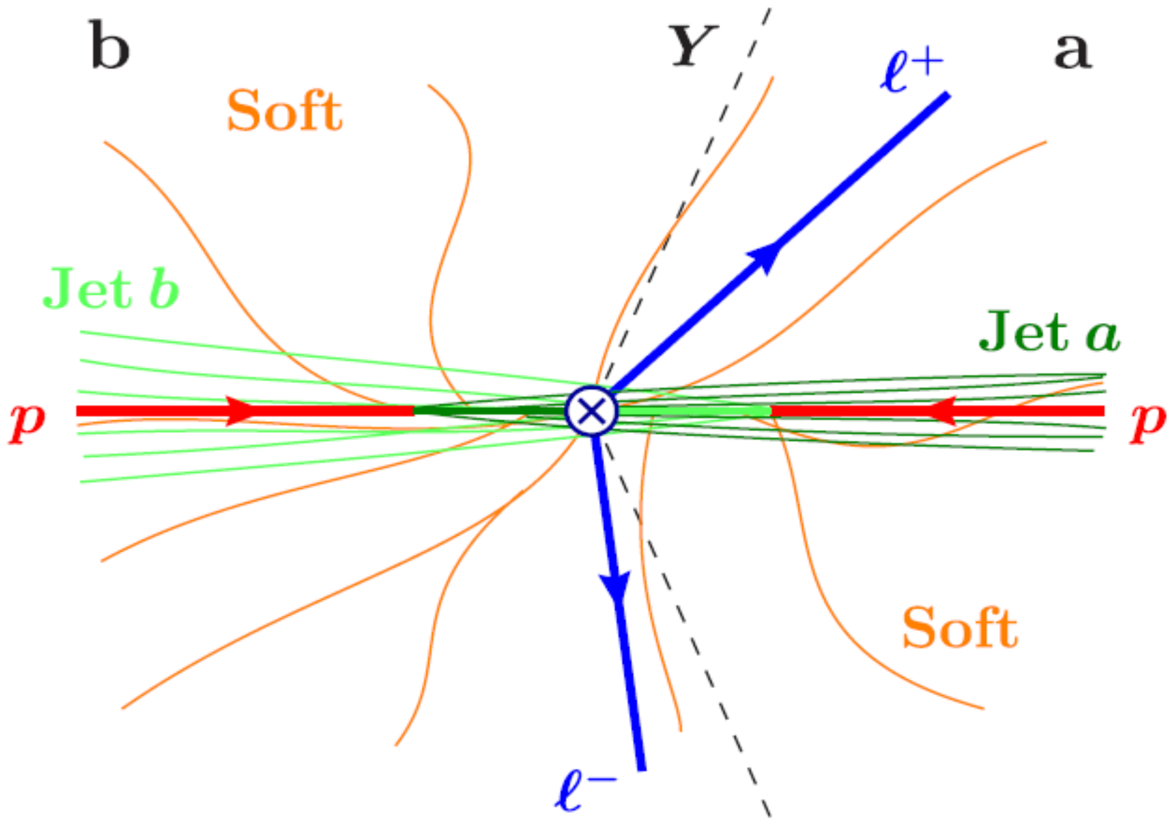
TMD with 0-jettiness

- For electroweak Drell-Yan processes, the 0-jettiness variable is defined as

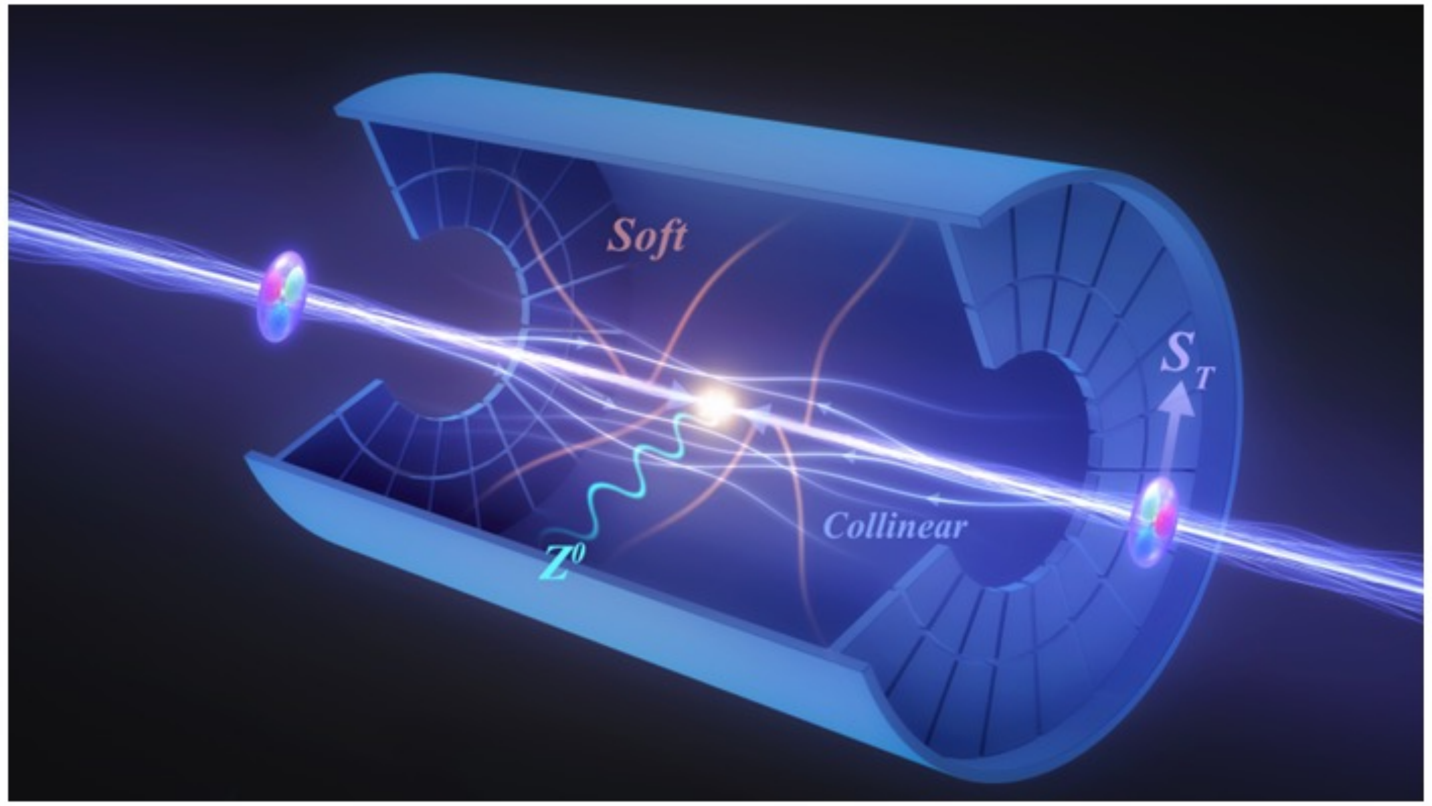
$$\tau \equiv \frac{2}{Q^2}\sum_i \min\{p_a \cdot l_i, p_b \cdot l_i\} = \sum_i \frac{|\vec{l}_{\perp,i}|}{Q} e^{-|y_i - y|}$$

The sum runs over all particles i (excluding the gauge boson) with momentum l_i

- 0-jettiness veto: $\tau < \tau_0$
- strongly suppresses central gluon radiation and effectively constrains initial state radiation (ISR).
- enhance the sensitivity to the intrinsic non-perturbative structure of TMDs
- Two types of large logs: $\ln \frac{Q^2}{q_\perp^2}$ $\ln \frac{1}{\tau_0}$

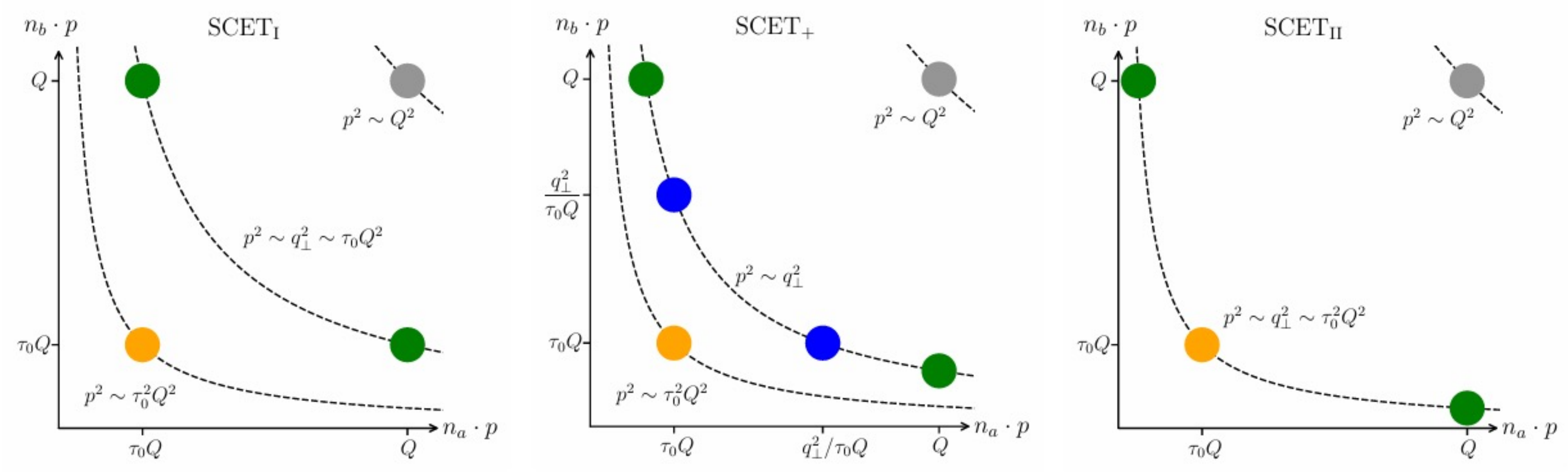


(b) Isolated Drell-Yan.



Formulation in SCET

- **Three distinct scale hierarchies:**



$\tau_0^2 Q^2 \ll q_\perp^2 \sim \tau_0 Q^2 \ll Q^2$ $\qquad$ $\tau_0^2 Q^2 \ll q_\perp^2 \ll \tau_0 Q^2 \ll Q^2$ $\qquad$ $\tau_0^2 Q^2 \sim q_\perp^2 \ll \tau_0 Q^2 \ll Q^2;$

Procura, Waalewijn, Zeune ’15
Lustermans, Michel, Tackmann, Waalewijn ’19

SCET$_\mathrm{I}$ regime $\quad \tau_0^2 Q^2 \ll q_\perp^2 \sim \tau_0 Q^2 \ll Q^2$

- **Factorization formula:**

Stewart, Tackmann, Waalewijn ’09
Jain, Procura, Waalewijn, Zeune ’11

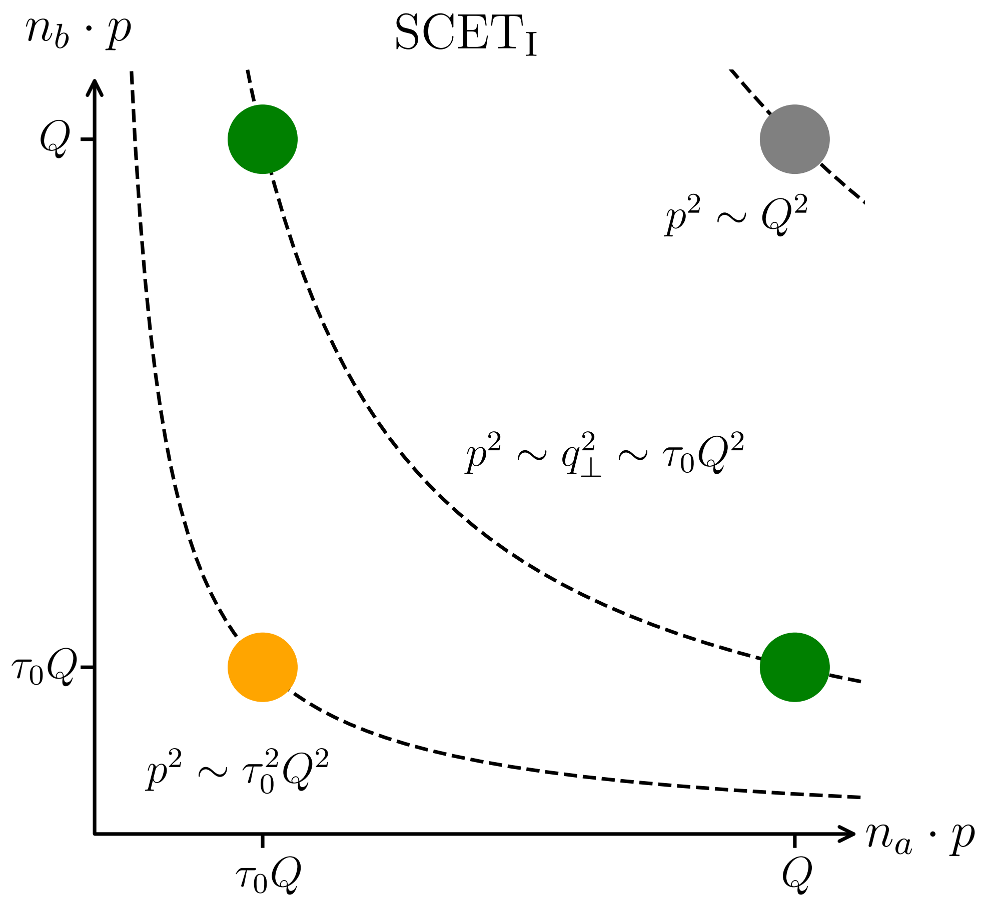
$$\frac{\mathrm{d}\sigma_\mathrm{I}(\tau_0)}{\mathrm{d}y\,\mathrm{d}^2\vec{q}_\perp} = \sigma_0 H(Q,\mu) \sum_{q,q'} C_{qq'} \int_0^{\tau_0 Q} \mathrm{d}\mathcal{T} \int \frac{e^{s\mathcal{T}}\mathrm{d}s}{2\pi i} \int_0^\infty \frac{b\,\mathrm{d}b}{2\pi} J_0(b\,q_\perp) \mathcal{B}_{q/p}(s/Q, x_q, b, \mu) \mathcal{B}_{q'/p}(s/Q, x_{q'}, b, \mu) \mathcal{S}(s,\mu),$$

- **RGEs:**

$$\gamma^q_\mathcal{B}(s/Q,\mu) = -2\Gamma^q_\mathrm{cusp}(\alpha_s)\ln\frac{Q}{\mu^2 s e^{\gamma_E}} + \gamma^q_\mathcal{B}(\alpha_s)\,,$$

$$\gamma^q_\mathcal{S}(s,\mu) = 2\Gamma^q_\mathrm{cusp}(\alpha_s)\ln\frac{1}{\mu^2 s^2 e^{2\gamma_E}} + \gamma^q_\mathcal{S}(\alpha_s)\,,$$

$$\gamma^q_H(Q,\mu) = 2\Gamma^q_\mathrm{cusp}(\alpha_s)\ln\frac{Q^2}{\mu^2} + 2\gamma^q_V(\alpha_s)\,.$$



- **Scale choice:** $\mu_H^\mathrm{I} \sim Q\,, \qquad \mu_\mathcal{B}^\mathrm{I} \sim \sqrt{\tau_0}Q\,, \qquad \mu_\mathcal{S}^\mathrm{I} \sim \tau_0 Q\,.$

SCET$_+$ regime

$$\tau_0^2 Q^2 \ll q_\perp^2 \ll \tau_0 Q^2 \ll Q^2$$

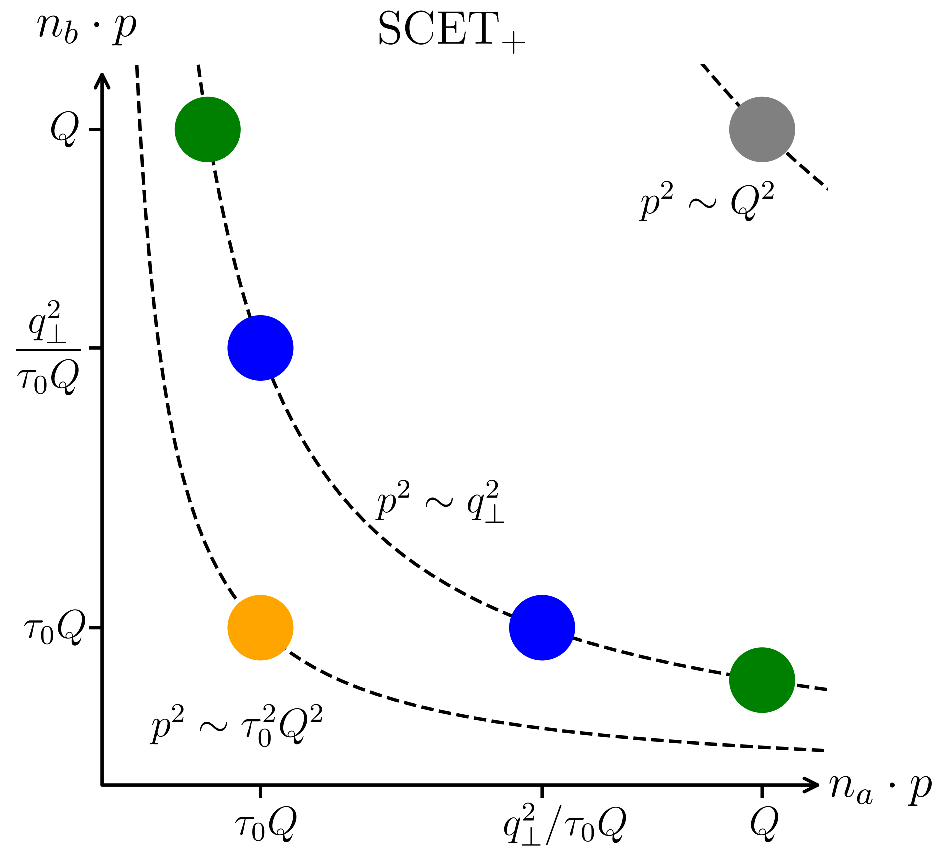
- **Factorization formula:**

Procura, Waalewijn, Zeune '14

$$\frac{d\sigma_+(\tau_0)}{dy\, d^2\vec{q}_\perp} = \sigma_0 H(Q,\mu) \sum_{q,q'} C_{qq'} \int_0^{\tau_0 Q} d\mathcal{T} \int \frac{e^{s\mathcal{T}} ds}{2\pi i} \int_0^\infty \frac{b\, db}{2\pi} J_0(b\, q_\perp) B_{q/p}(x_q, b, \mu, \nu/\omega_q) B_{q'/p}(x_{q'}, b, \mu, \nu/\omega_{q'})$$
$$\times \tilde{S}_q(s,b,\mu,\nu) \tilde{S}_{q'}(s,b,\mu,\nu) \mathcal{S}(s,\mu).$$

- **RGEs:**

$$\gamma_B^q(\mu, \nu/\omega_q) = \Gamma_{\rm cusp}^q(\alpha_s) \ln\frac{\nu^2}{\omega_q^2} + \gamma_B^q(\alpha_s),$$
$$\gamma_\nu^q(b,\mu) = 2\left[\int_{\mu^2}^{\mu_b^2} \frac{d\mu'^2}{\mu'^2} \Gamma_{\rm cusp}^q(\alpha_s) + \gamma_r^q(\alpha_s)\right],$$
$$\tilde{\gamma}_{\mathcal{S}}^q(s,\mu,\nu) = -2\Gamma_{\rm cusp}^q(\alpha_s) \ln\frac{\nu}{\mu^2 s e^{\gamma_E}} + \tilde{\gamma}_{\mathcal{S}}^q(\alpha_s),$$
$$\gamma_{\mathcal{S}}^q(s,\mu) = 2\Gamma_{\rm cusp}^q(\alpha_s) \ln\frac{1}{\mu^2 s^2 e^{2\gamma_E}} + \gamma_{\mathcal{S}}^q(\alpha_s),$$
$$\gamma_H^q(Q,\mu) = 2\Gamma_{\rm cusp}^q(\alpha_s) \ln\frac{Q^2}{\mu^2} + 2\gamma_V^q(\alpha_s).$$



- **Scale choice:** $\mu_H^+ \sim Q,\quad \mu_B^+ \sim \mu_b,\quad \mu_{\tilde{S}}^+ \sim \mu_b,\quad \mu_{\mathcal{S}}^+ \sim \tau_0 Q,$

$$\nu_B^+ \sim Q,\quad \nu_{\tilde{S}}^+ \sim \frac{\mu_b^2}{\tau_0 Q}.$$

SCET$_{\text{II}}$ regime

$$\tau_0^2 Q^2 \sim q_\perp^2 \ll \tau_0 Q^2 \ll Q^2;$$

- **Factorization formula:**

Procura, Waalewijn, Zeune '14

$$\frac{\mathrm{d}\sigma_{\text{II}}(\tau_0)}{\mathrm{d}y\,\mathrm{d}^2\vec{q}_\perp} = \sigma_0 H(Q,\mu) \sum_{q,q'} C_{qq'} \int_0^{\tau_0 Q} \mathrm{d}\mathcal{T} \int \frac{e^{s\mathcal{T}}\mathrm{d}s}{2\pi i} \int_0^\infty \frac{b\,\mathrm{d}b}{2\pi} J_0(b\,q_\perp)\, B_{q/p}(x_q, b, \mu, \nu/\omega_q)\, B_{q'/p}(x_{q'}, b, \mu, \nu/\omega_{q'})\, S(s, b, \mu, \nu),$$

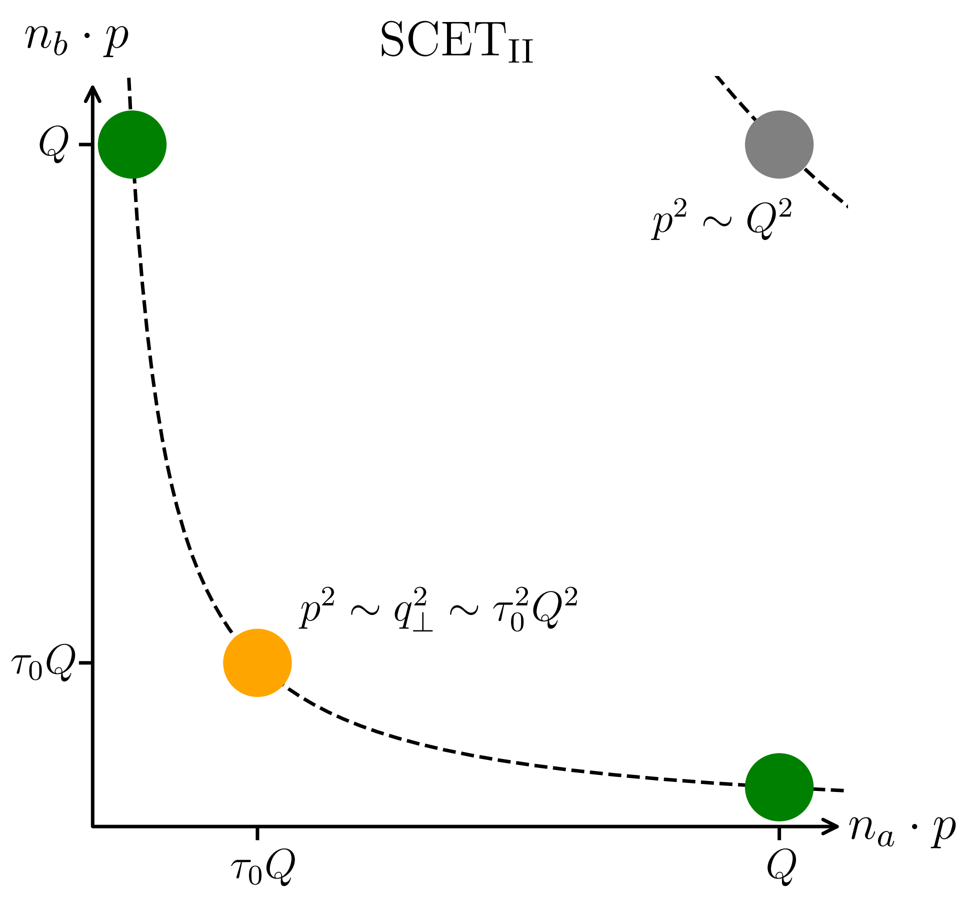
- **RGEs:**

$$\gamma_B^q(\mu, \nu/\omega_q) = \Gamma_{\text{cusp}}^q(\alpha_s) \ln\frac{\nu^2}{\omega_q^2} + \gamma_B^q(\alpha_s)\,,$$

$$\gamma_\nu^q(b,\mu) = 2\left[\int_{\mu^2}^{\mu_b^2} \frac{\mathrm{d}\mu'^2}{\mu'^2} \Gamma_{\text{cusp}}^q(\alpha_s) + \gamma_r^q(\alpha_s)\right]\,,$$

$$\gamma_S^q(\mu,\nu) = 2\Gamma_{\text{cusp}}^q(\alpha_s) \ln\frac{\mu^2}{\nu^2} + \gamma_S^q(\alpha_s)\,,$$

$$\gamma_H^q(Q,\mu) = 2\Gamma_{\text{cusp}}^q(\alpha_s) \ln\frac{Q^2}{\mu^2} + 2\gamma_V^q(\alpha_s)\,.$$



- **Scale choice:**

$$\mu_H^{\text{II}} \sim Q\,, \qquad \mu_B^{\text{II}} \sim \mu_b\,, \qquad \mu_S^{\text{II}} \sim \mu_b\,,$$

$$\nu_B^{\text{II}} \sim Q\,, \qquad \nu_S^{\text{II}} \sim \mu_b\,.$$

Combined Perturbative Sudakov Factor

- **Combination choice:**
  - $\mu_b^2 > \tau_0 Q^2$, **SCET$_{\text{I}}$: the DGLAP evolution is frozen and instead replaced by scale evolution of beam functions** Stewart, Tackmann, Waalewijn '09
  - $\tau_0^2 Q^2 < \mu_b^2 < \tau_0 Q^2$, **SCET$_+$**
  - $\mu_b^2 < \tau_0^2 Q^2$, **SCET$_{\text{II}}$: corresponds to standard TMD evolution**

- **Combined Sudakov factor at NLL:**

$$S_{\mathrm{P}}(b) = \frac{C_F}{\pi}\left[\int_{\tau_0 Q^2}^{\mu_b^2} \frac{\mathrm{d}\mu^2}{\mu^2}\left(2\ln\frac{\tau_0 Q^2}{\mu^2} - \frac{3}{2}\right)\theta(\mu_b^2 - \tau_0 Q^2) - \int_{\tau_0^2 Q^2}^{\mu_b^2} \frac{\mathrm{d}\mu^2}{\mu^2}\ln\frac{\tau_0^2 Q^2}{\mu^2}\,\theta(\mu_b^2 - \tau_0^2 Q^2)\right.$$
$$\left. + \int_{\mu_b^2}^{Q^2} \frac{\mathrm{d}\mu^2}{\mu^2}\left(\ln\frac{Q^2}{\mu^2} - \frac{3}{2}\right)\right]\alpha_s(\mu)\,,$$

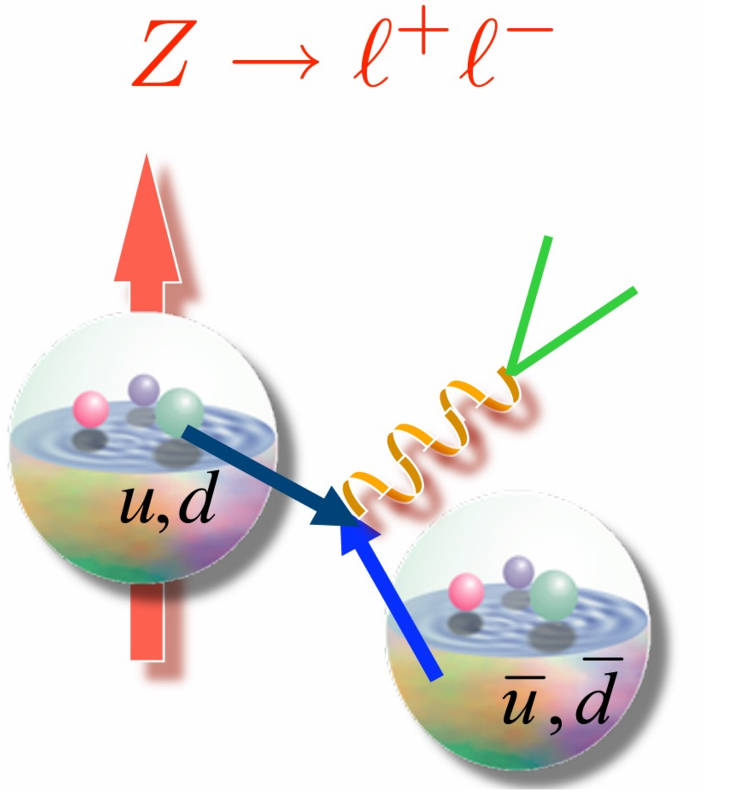
Impact of 0-jettiness veto on SSAs

- **Unpolarized:**

$$\frac{\mathrm{d}\sigma_{UU}}{\mathrm{d}y\,\mathrm{d}^2\vec{q}_\perp} = \sigma_0 \sum_{q,q'} |V_{qq'}|^2 \int_0^\infty \frac{b\,\mathrm{d}b}{2\pi} J_0(b\,q_\perp) \times f_q(x_q,\mu_b) f_{q'}(x_{q'},\mu_b) e^{-S_{\mathrm{P}}(b)} \,,$$

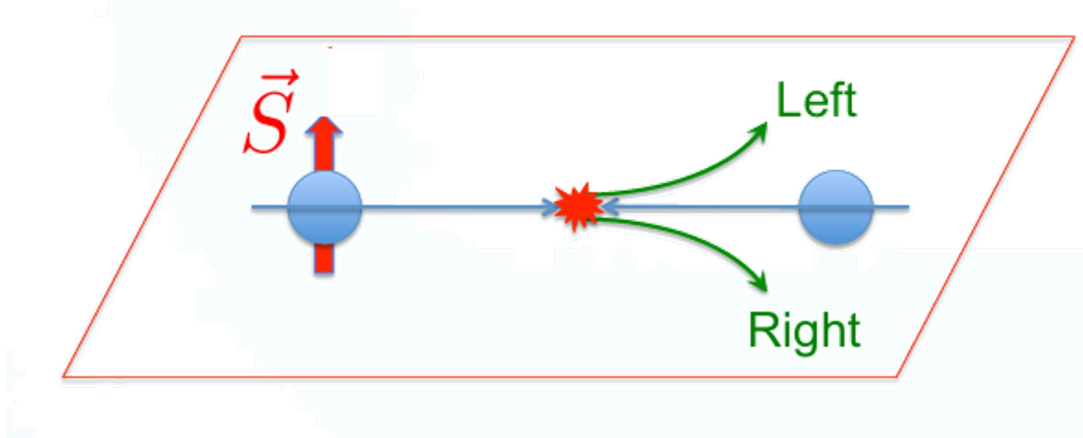
- **Transversely-polarized:**

$$\frac{\mathrm{d}\sigma_{UT}(S_\perp)}{\mathrm{d}y\,\mathrm{d}^2\vec{q}_\perp} = -\sin(\phi_q - \phi_S)\,\sigma_0 \int_0^\infty \frac{b^2\,\mathrm{d}b}{4\pi} J_1(b\,q_\perp) \times \sum_{q,q'} |V_{qq'}|^2 T_{F,q}(x_a,x_a,\mu_b) f_{q'}(x_b,\mu_b) e^{-S_{\mathrm{P}}(b)} \,.$$



- **SSA:**

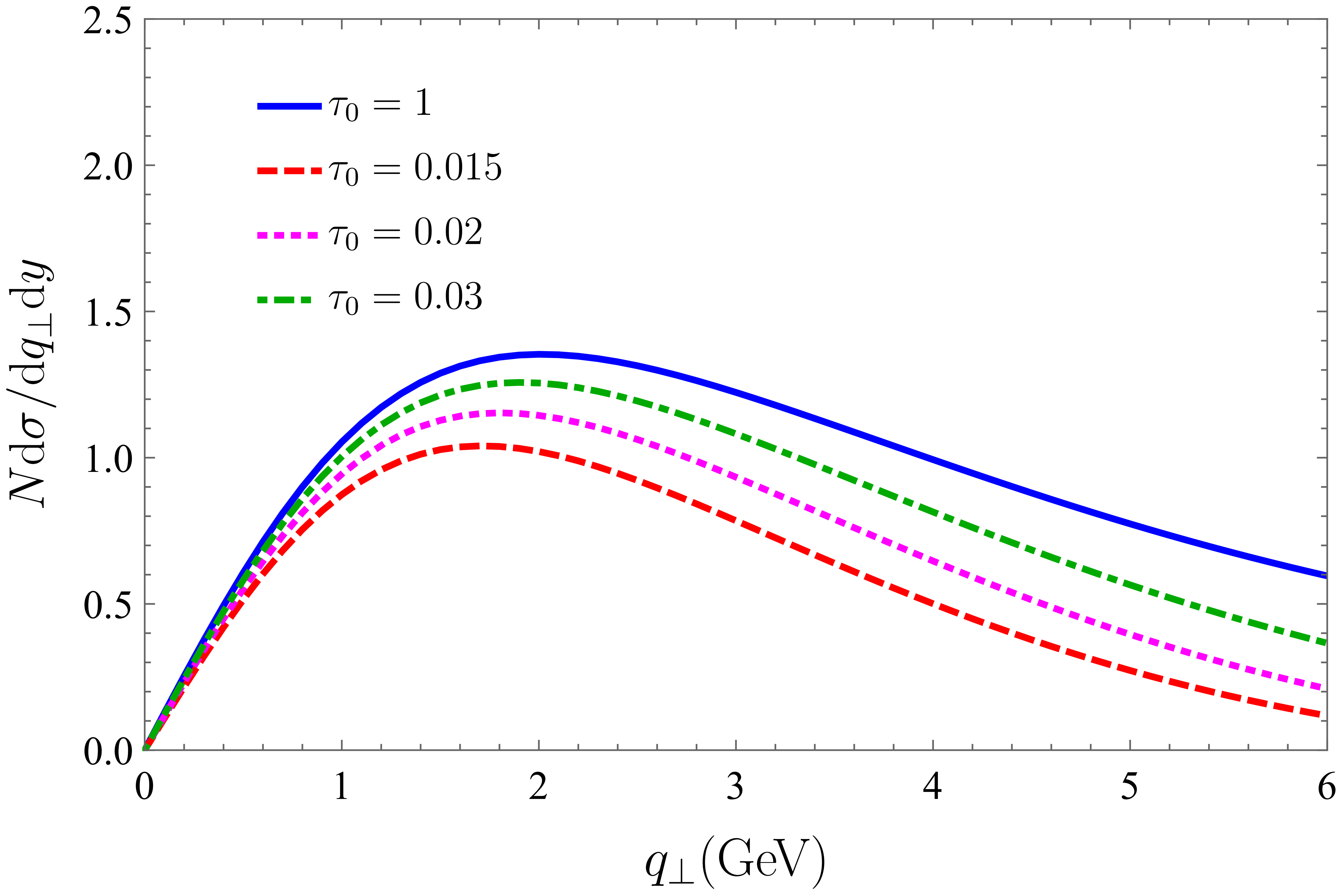
$$A_N = \frac{\int_0^{2\pi} \mathrm{d}\phi_q\, 2\sin(\phi_q - \phi_S)\,\mathrm{d}\sigma_{UT}}{\int_0^{2\pi} \mathrm{d}\phi_q\,\mathrm{d}\sigma_{UU}} \,.$$



Numerical results

SF, Lin, Shao, Zhou '25

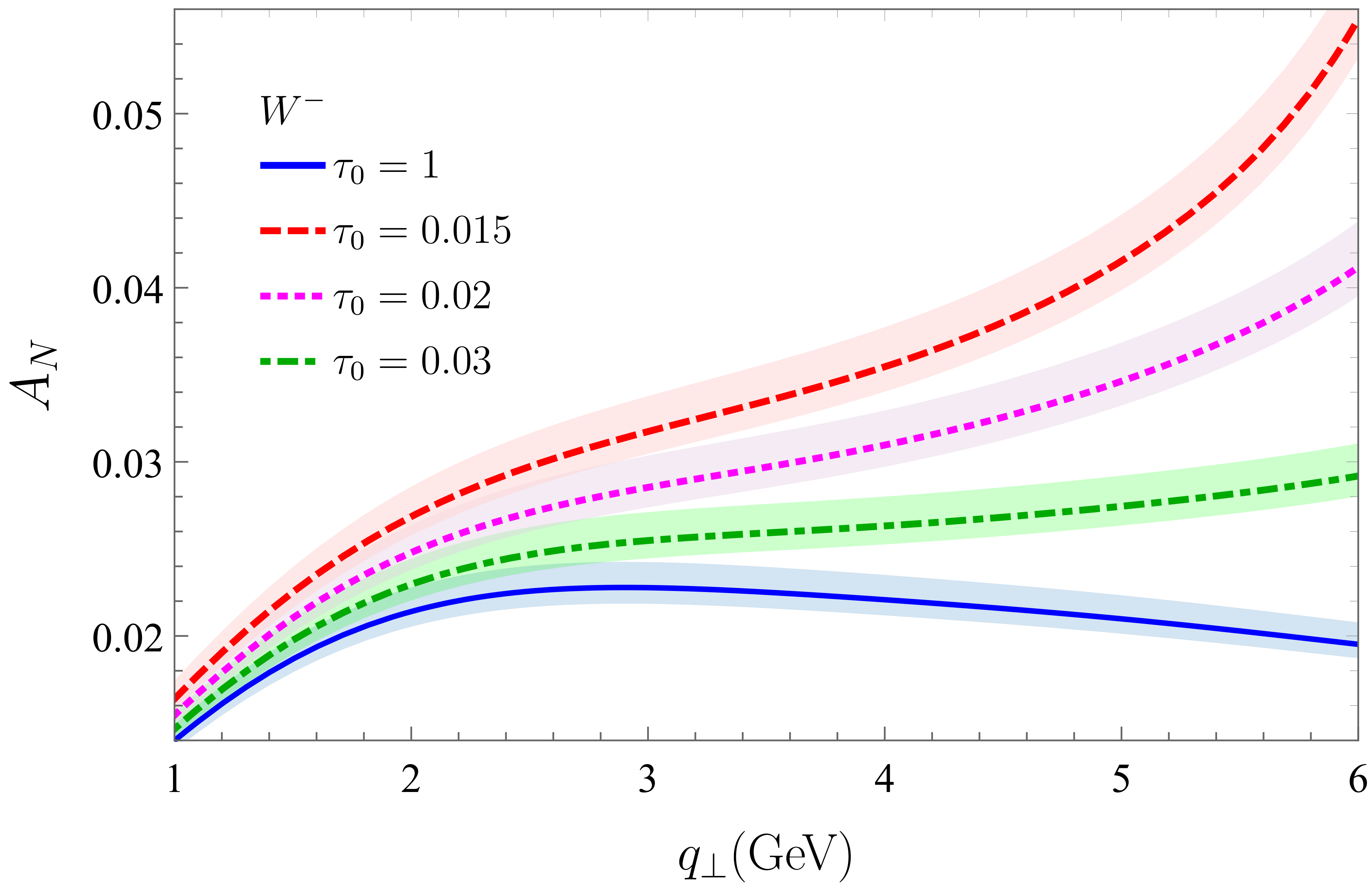
The normalized unpolarized cross section for W^- production at RHIC energy



The enhanced SSAs

0-jettiness $\tau \equiv \frac{2}{Q^2}\sum_i \min\{p_a \cdot l_i, p_b \cdot l_i\} = \sum_i \frac{|\vec{l}_{\perp,i}|}{Q} e^{-|y_i - y|}$ **with veto** $\tau < \tau_0$

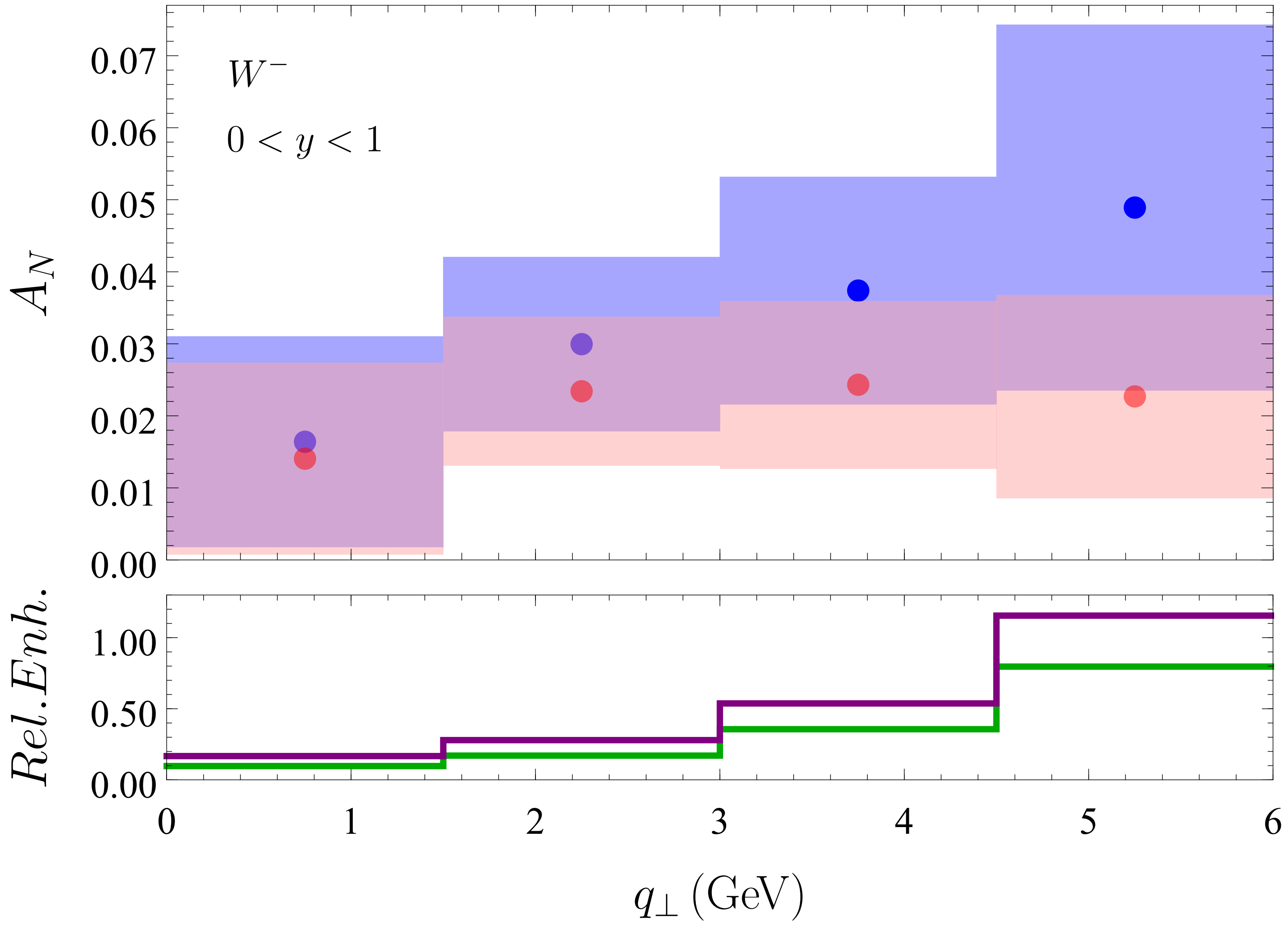
The SSAs for W⁻ production at RHIC energy

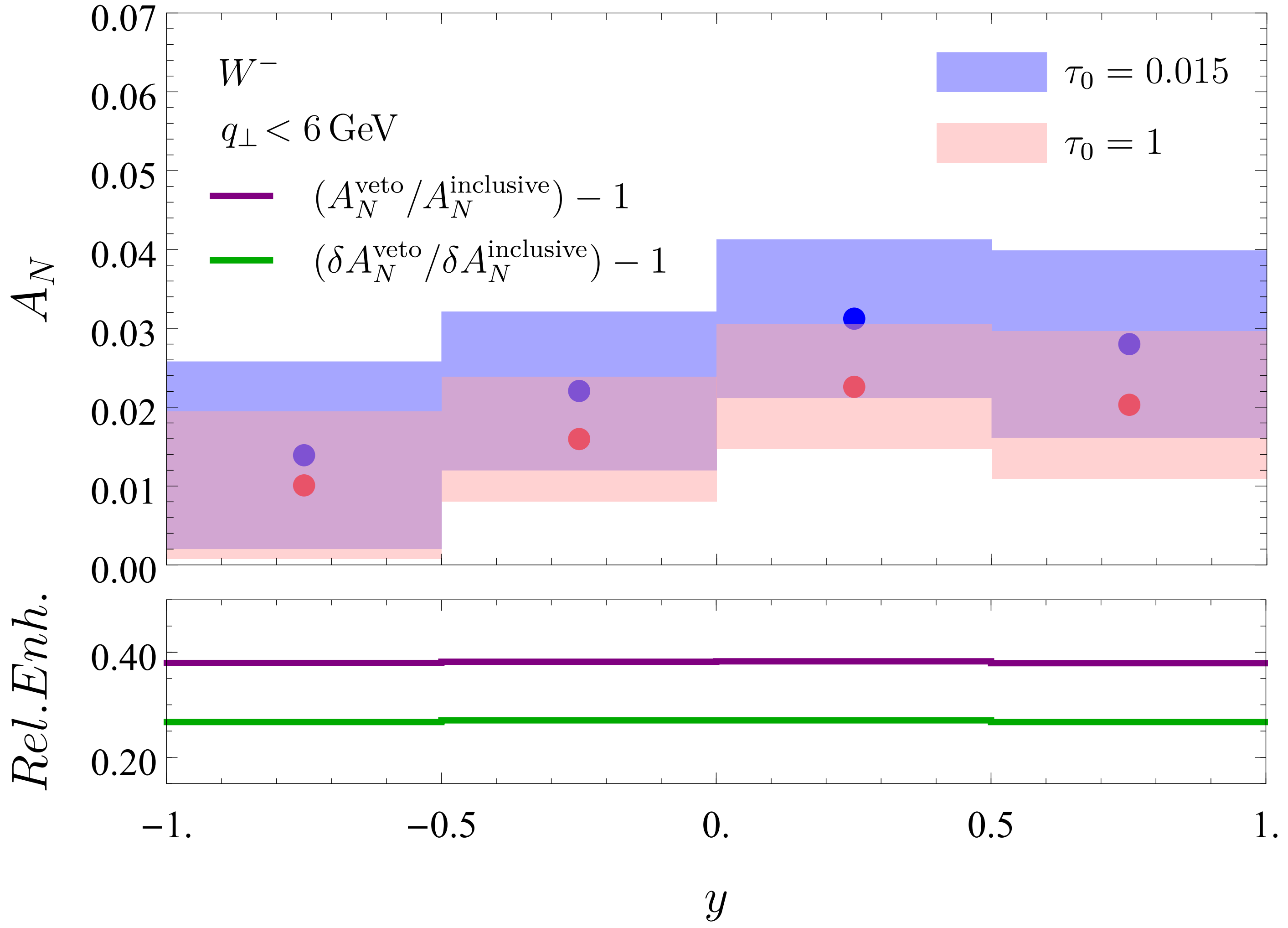


Statistical uncertainties

- **Statistical uncertainty:** $\delta A_N = \frac{1}{P}\sqrt{\frac{1-(A_N)^2}{\sigma\cdot\mathcal{L}}} \simeq \frac{1}{P}\frac{1}{\sqrt{\sigma\cdot\mathcal{L}}}$

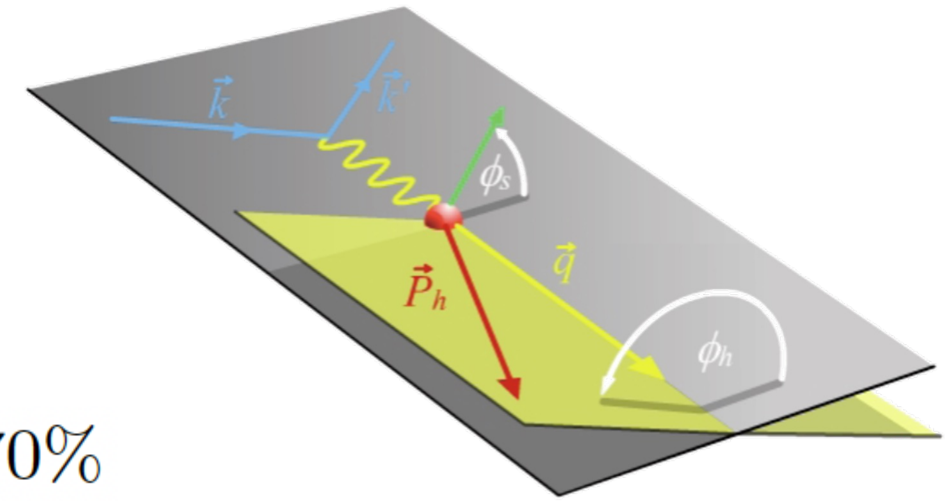
$$\mathcal{L} = 780\,\mathrm{pb}^{-1}$$
$$P = 53\%$$





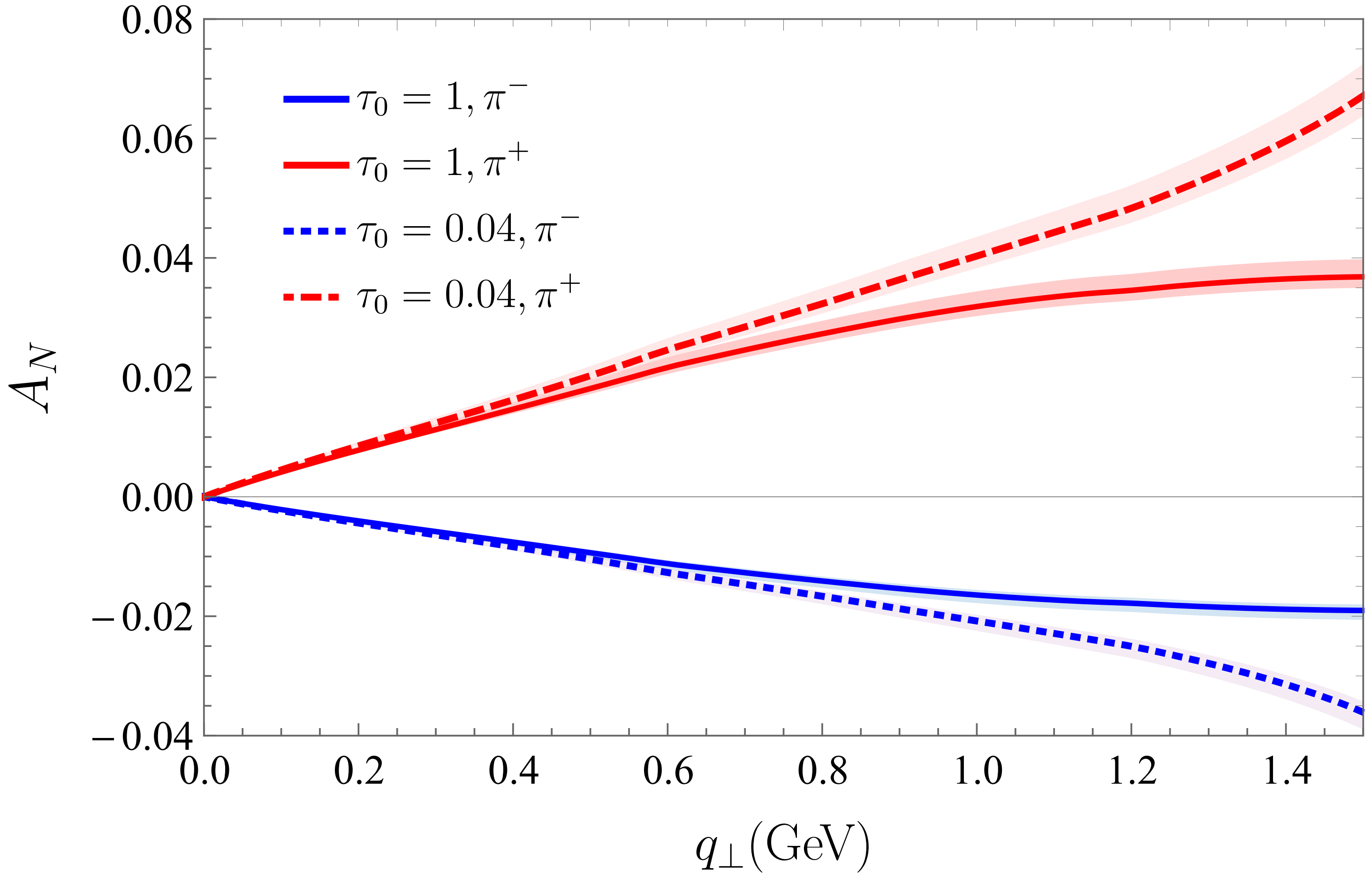
Implementing a 0-jettiness veto can significantly enhance the sensitivity of SSA measurements to the predicted sign flip of the Sivers function, thereby offering a more robust avenue for testing fundamental TMD dynamics in polarized collisions.

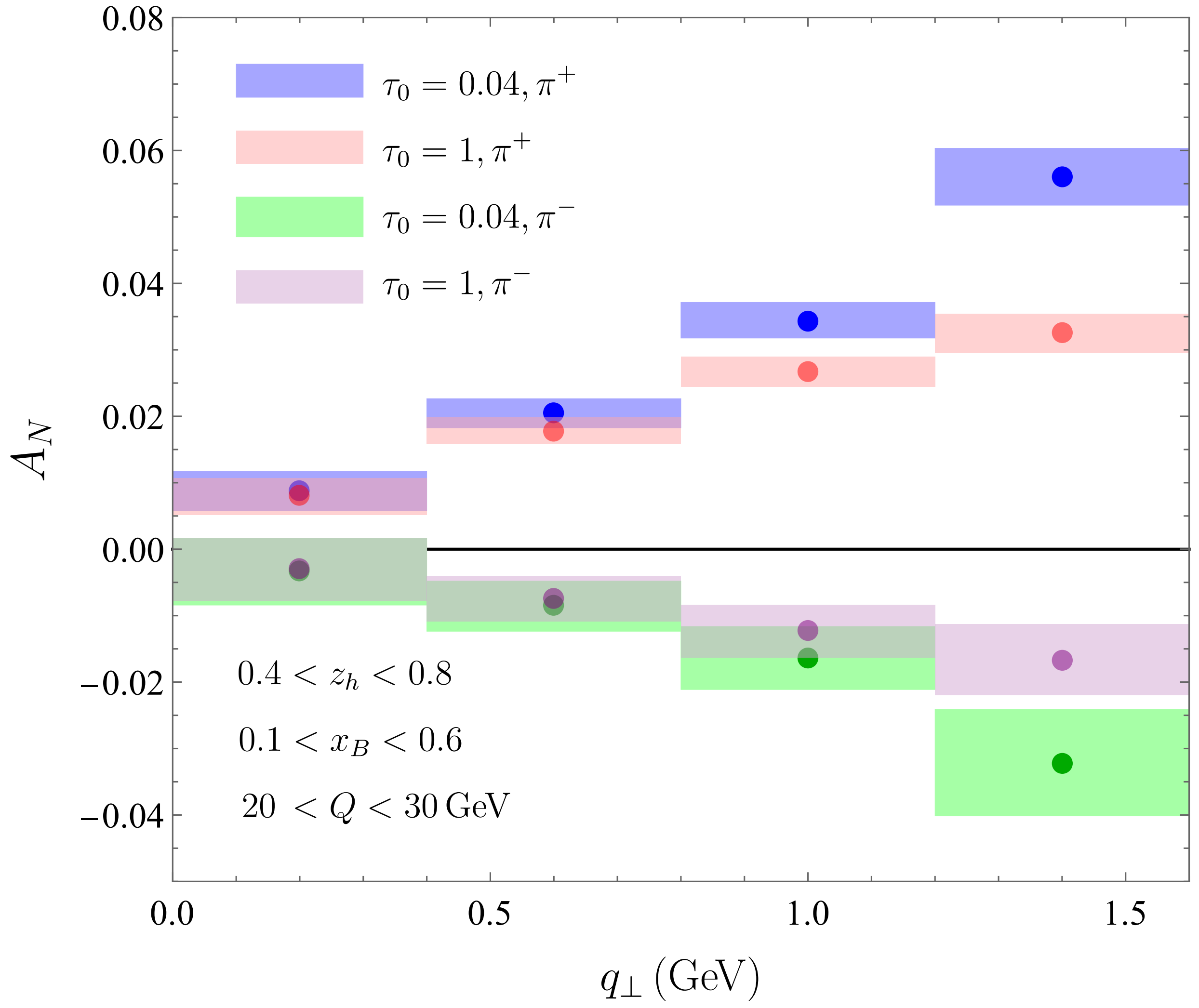
SSAs in DIS



- **1-jettiness** $\ell + p^{\uparrow} \to \ell' + \pi(p_T) + X$

$\mathcal{L} = 100\,\text{fb}^{-1} \quad P = 70\%$





The results show that the SSAs are enhanced at moderately large pion transverse momentum when the veto is applied.

Summary

- **We introduced a 0-jettiness veto method to suppress TMD evolution effects and probe the nucleon spin structure.**

- **Single-spin asymmetries (SSAs) in both W^- production at RHIC and $\pi^\pm$ production at EIC are significantly enhanced with the veto.**

- **The 0-jettiness veto provides a promising new tool to study the spin dynamics of the nucleon in polarized collisions.**

Thank you!