Nucleon Tomography with 0-jettiness

26th International Symposium on Spin Physics
A Century of Spin

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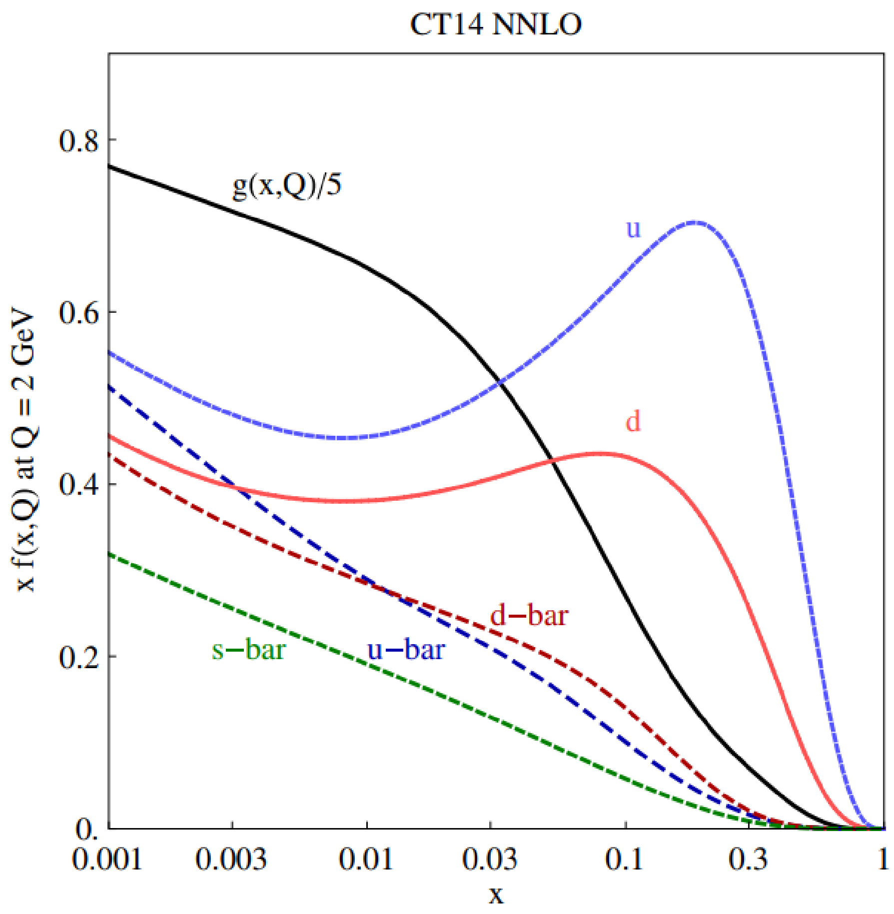
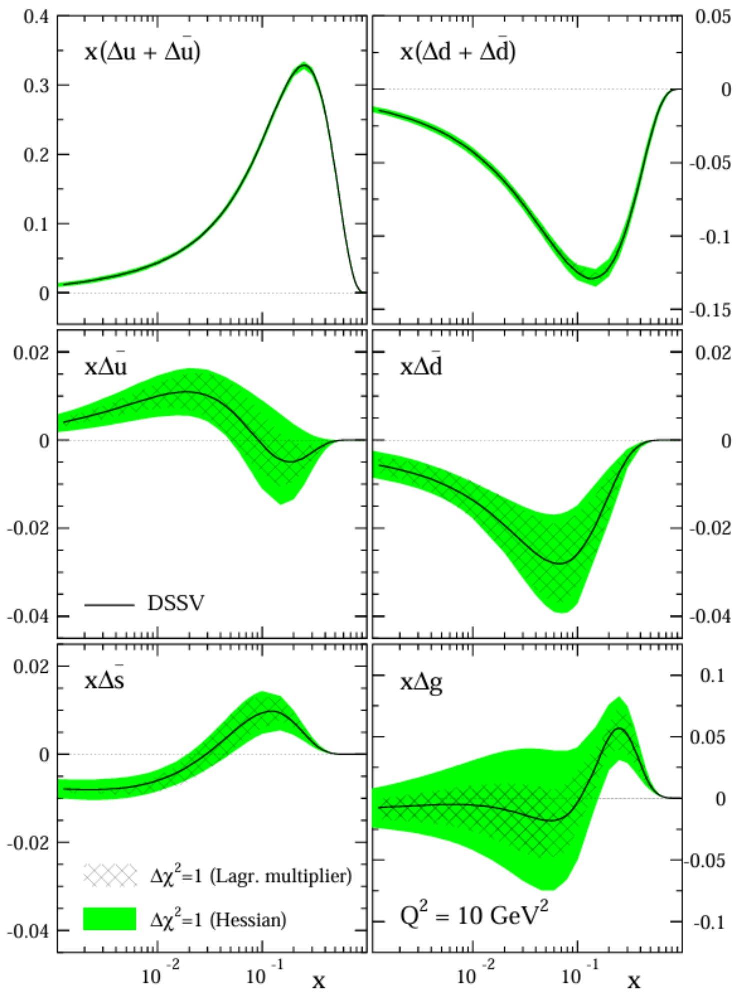
arXiv:2506.15962
In collaboration with Shen Fang,Ding Yu Shao,and Jian Zhou

Nucleon Tomography : a fundamental quest

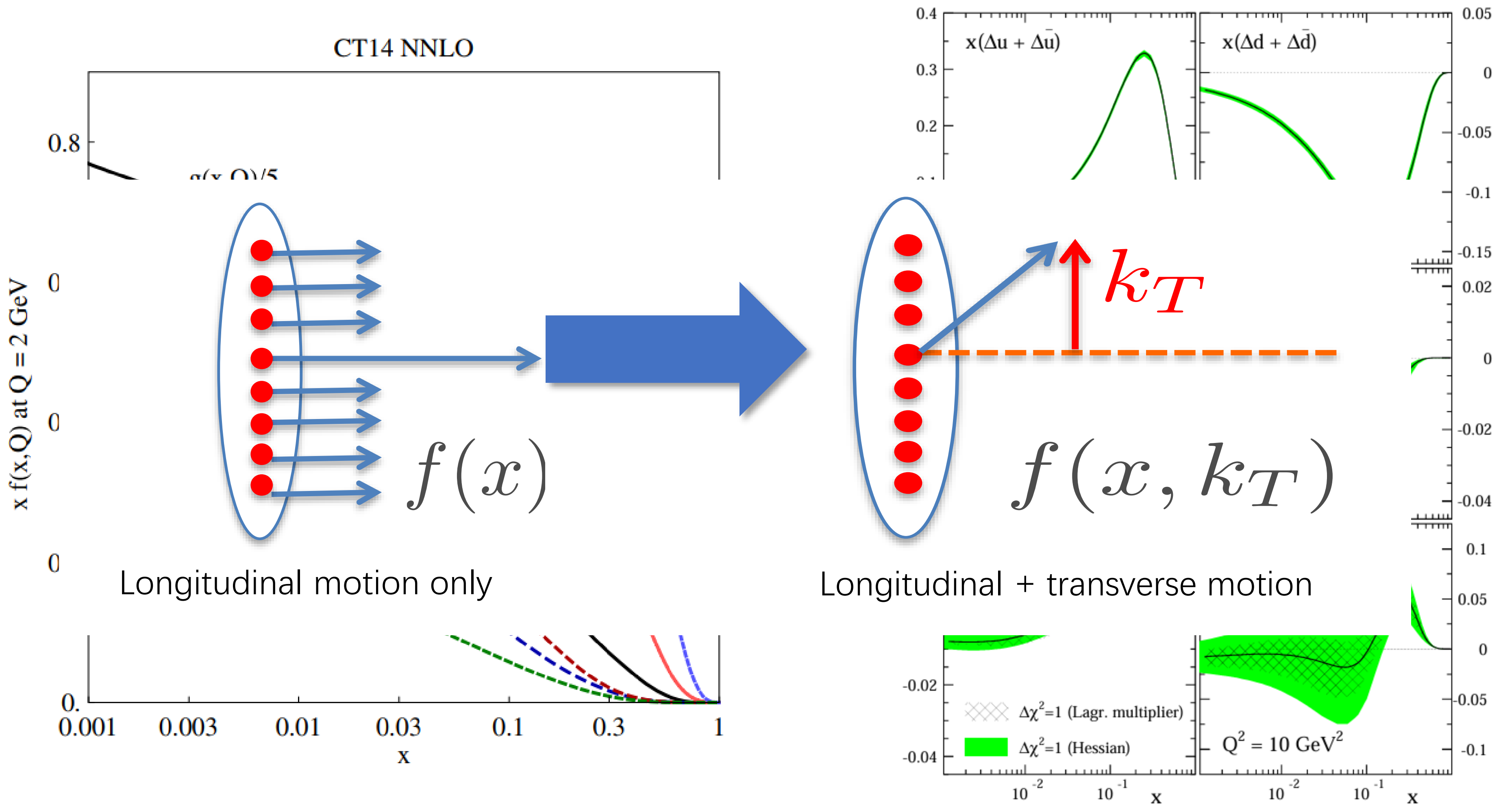




S. Dulat et al,Phys.Rev.D 93 (2016) 3, 033006

D.de Florian, R.Sasso, M.Stratmann, W.Vogelsang，Phys.Rev.D 80 (2009) 034030

Nucleon Tomography : a fundamental quest

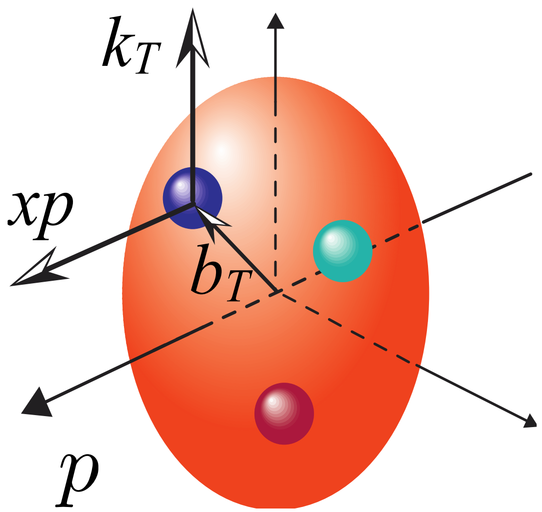


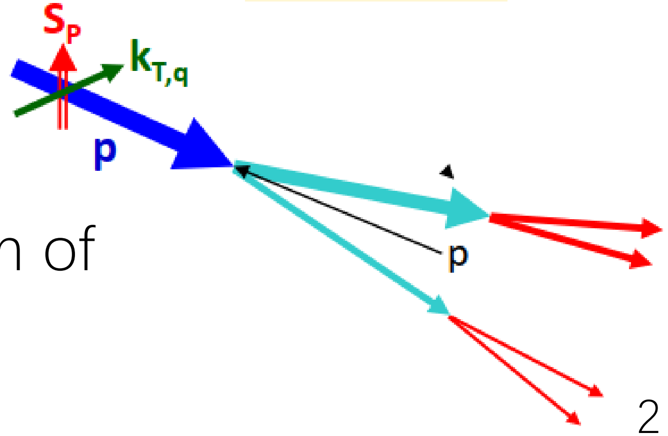
S. Dulat et al,Phys.Rev.D 93 (2016) 3, 033006

D.de Florian, R.Sasso, M.Stratmann, W.Vogelsang，Phys.Rev.D 80 (2009) 034030

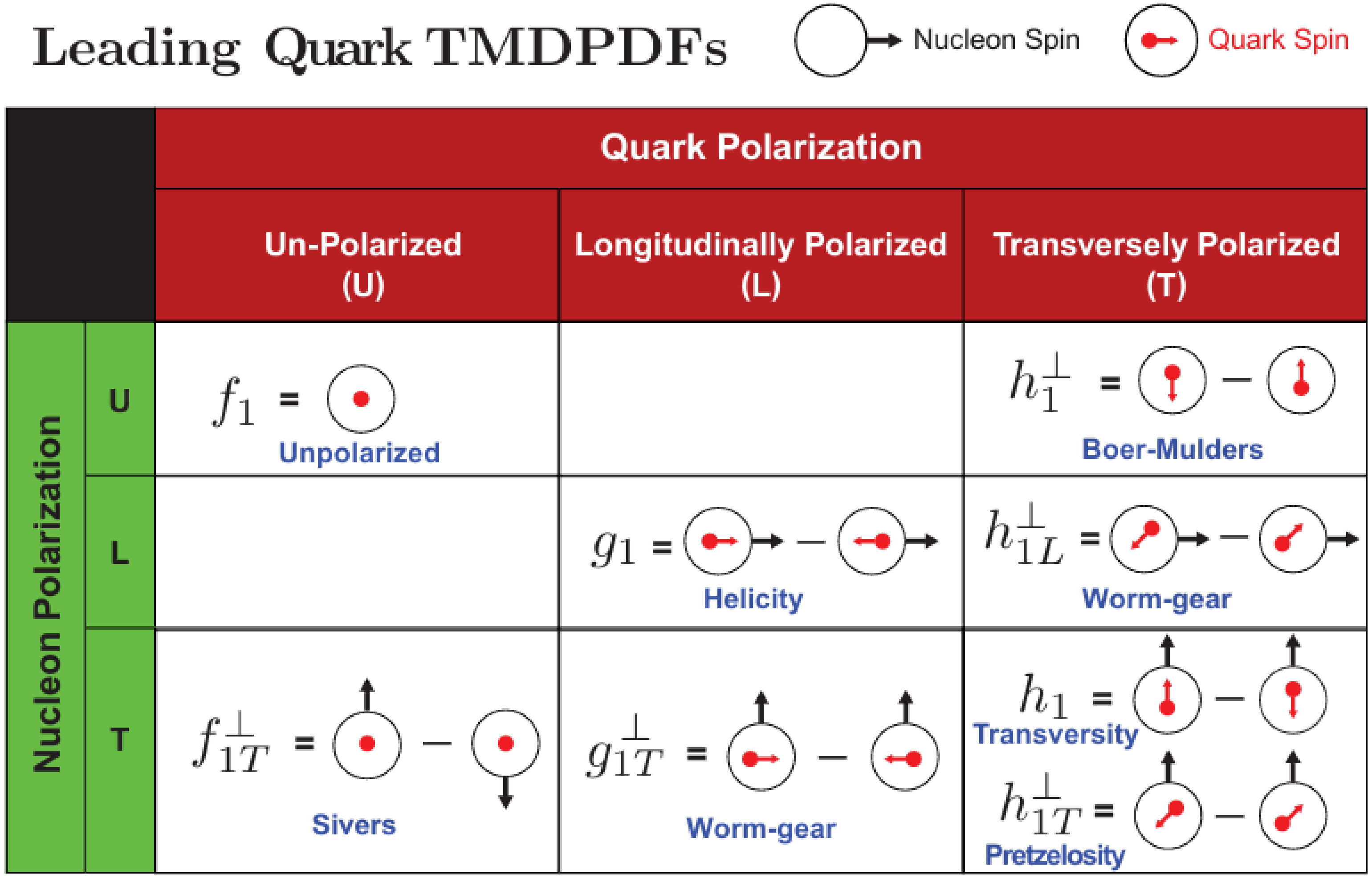
TMDs: center piece of nucleon structure

- Phenomenological needs
- Both longitudinal and transverse motion of partons inside proton
- Quantum correlation: spin-spin, spin-momentum (orbit) correlations
- Orbital motion
  - Most TMDs would vanish in the absence of parton orbital angular momentum
- Universality issue, QCD factorization
- Information on the color glass condensate —a unique form of nuclear matter at small x

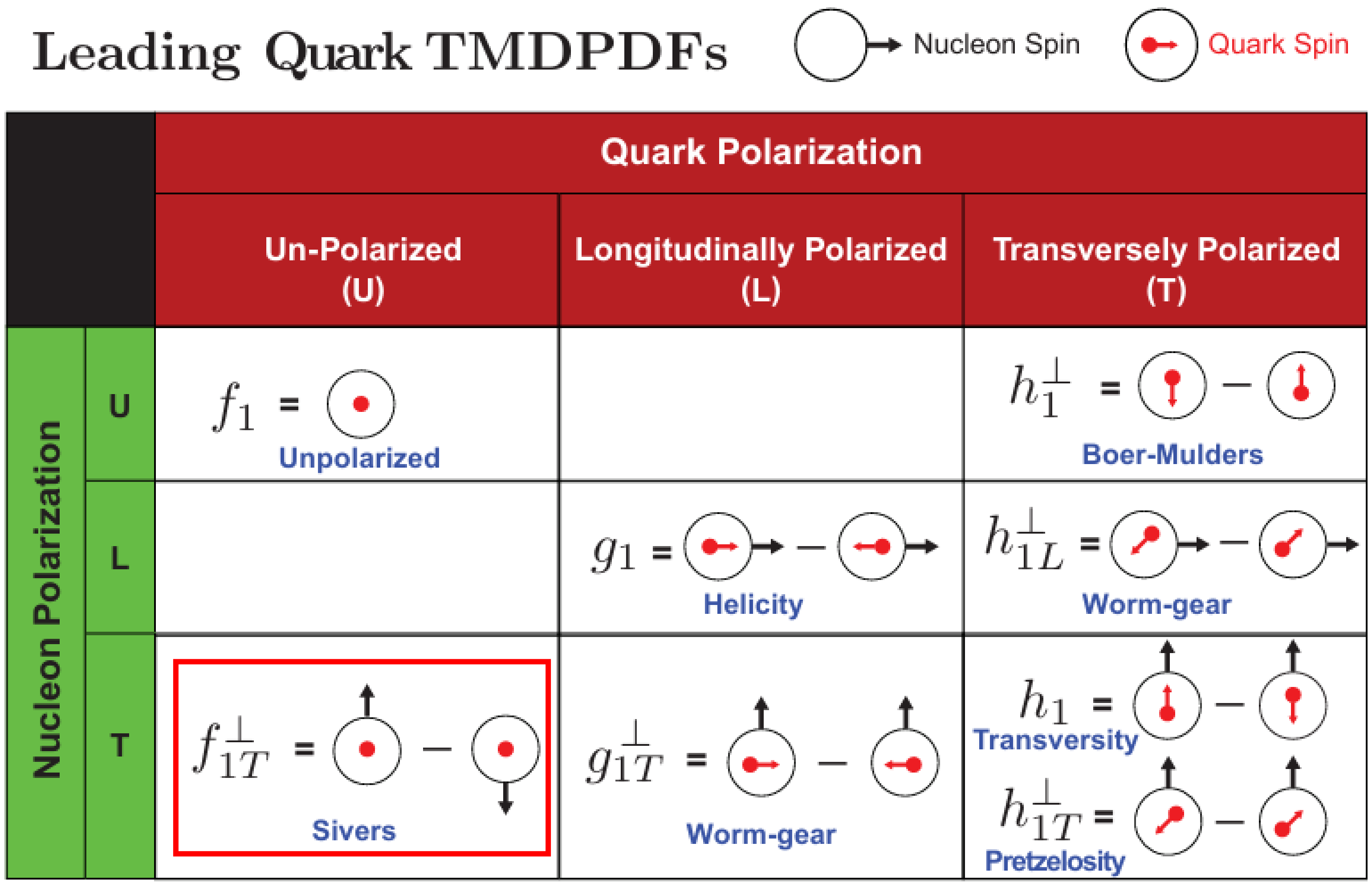




TMDs: center piece of nucleon structure



TMDs: center piece of nucleon structure



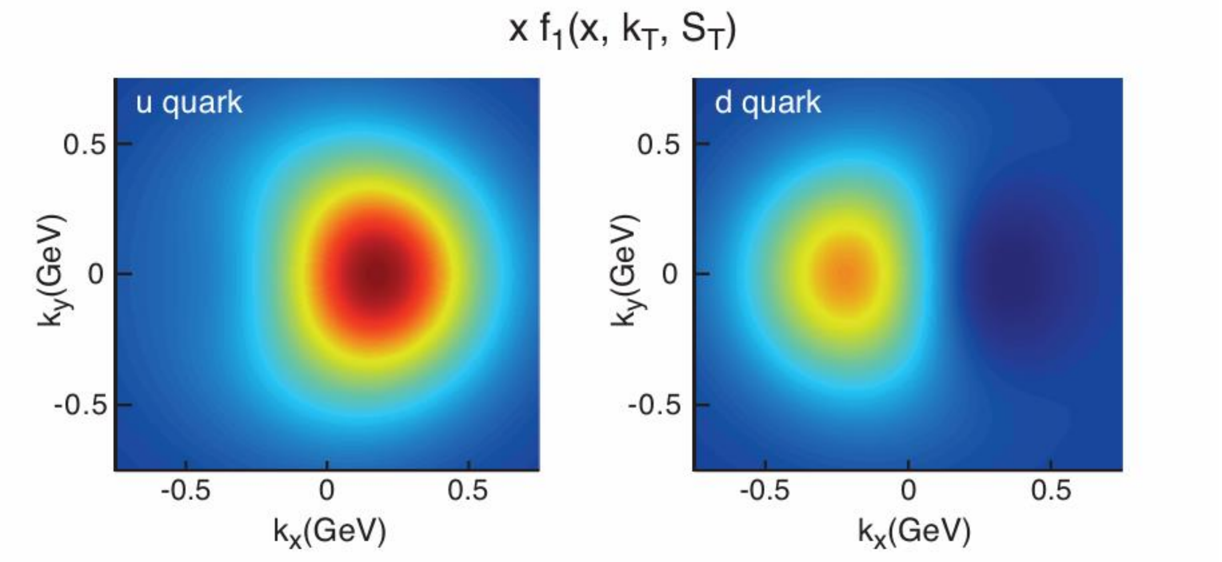
One example: Sivers function

- 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



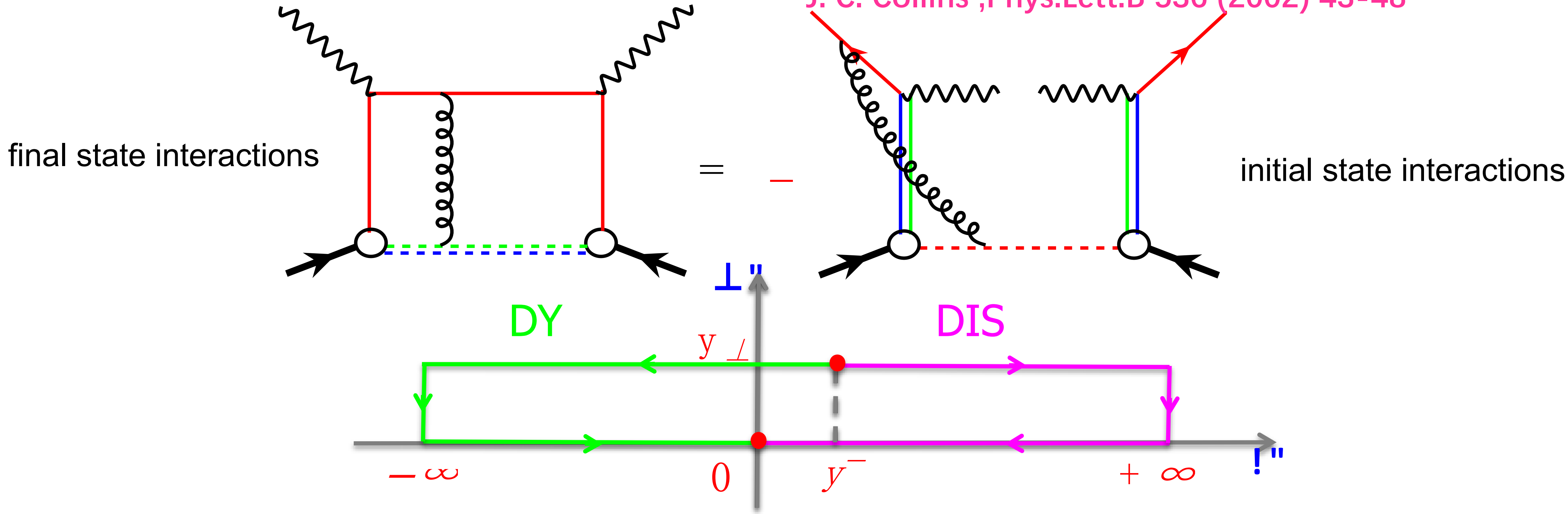
A.Accardi et al.Eur.Phys.J.A 52 (2016) 9, 268

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

One example: Sivers function

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

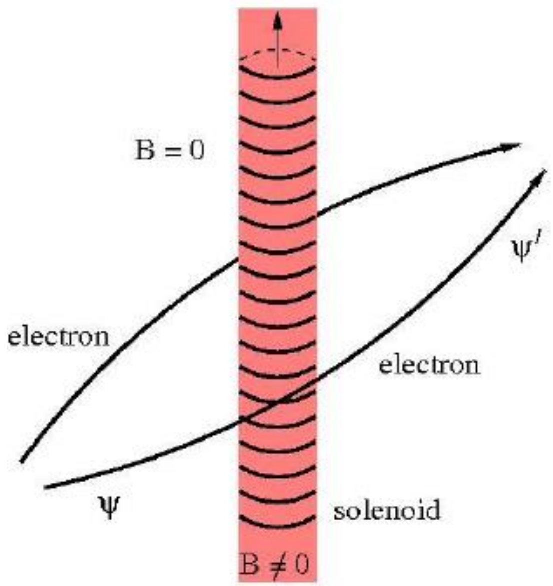
S. J. Brodsky, D. S. Hwang, and I. Schmidt, Phys.Lett.B 530 (2002) 99-107
J. C. Collins ,Phys.Lett.B 536 (2002) 43-48

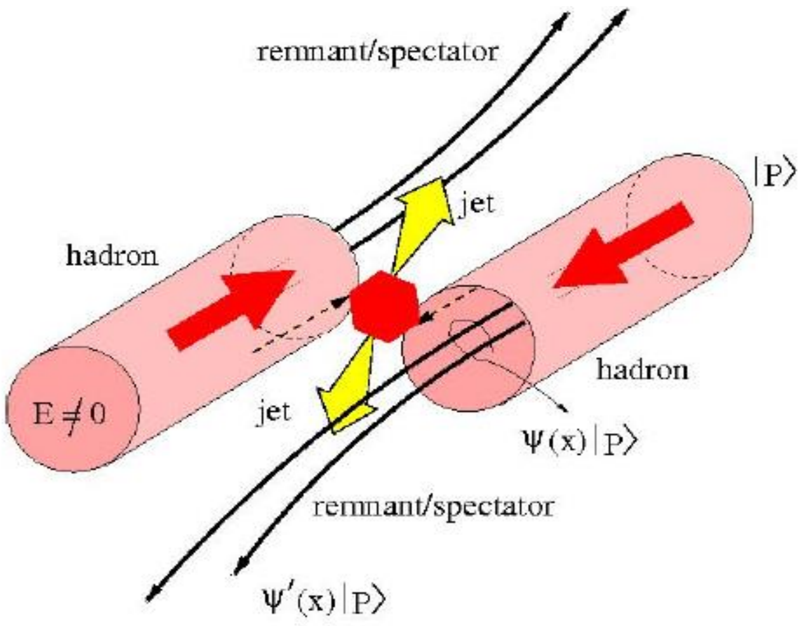


$$f_{1T}^{\perp,\mathrm{DIS}}(x,k_\perp) = -f_{1T}^{\perp,\mathrm{DY}}(x,k_\perp)$$

One example: Sivers function

- ➢Akin to Aharonov-Bohm Effect





$$\psi' = e^{ie\int ds.A}\psi$$

$$\psi_i(x)|P\rangle = e^{-ig\int_x^{x'} ds_\mu A^\mu}\psi_i(x')|P\rangle$$

Sivers Function and Qiu-Sterman Function

- Qiu-Sterman Function

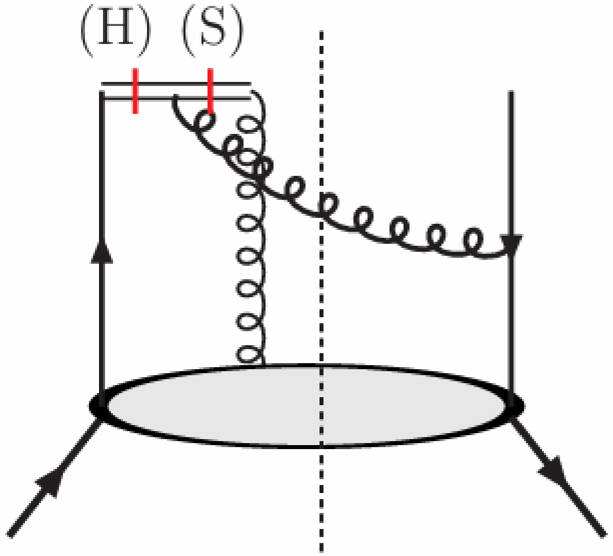
$$T_F(x_2, x_2') \equiv \int \frac{d\zeta^- d\eta^-}{4\pi} e^{i(x_2 P^+ \eta^- + (x_2' - x_2) P_B^+ \zeta^-)} \epsilon_\perp^{\beta\alpha} S_{\perp\beta}$$
$$\times \langle PS|\overline{\psi}(0)\mathcal{L}(0,\zeta^-)\gamma^+ g F_\alpha{}^+(\zeta^-)\mathcal{L}(\zeta^-,\eta^-)\psi(\eta^-)|PS\rangle$$

- $T_F(x,x) = \int \frac{d^2\vec{k}_\perp}{2\pi} \frac{\vec{k}_\perp^2}{M^2} f_{1T}^\perp|_{\rm DY}(x,k_\perp)$

D. Boer, P. J. Mulders and F. Pijlman, Nucl. Phys. B 667, 201 (2003

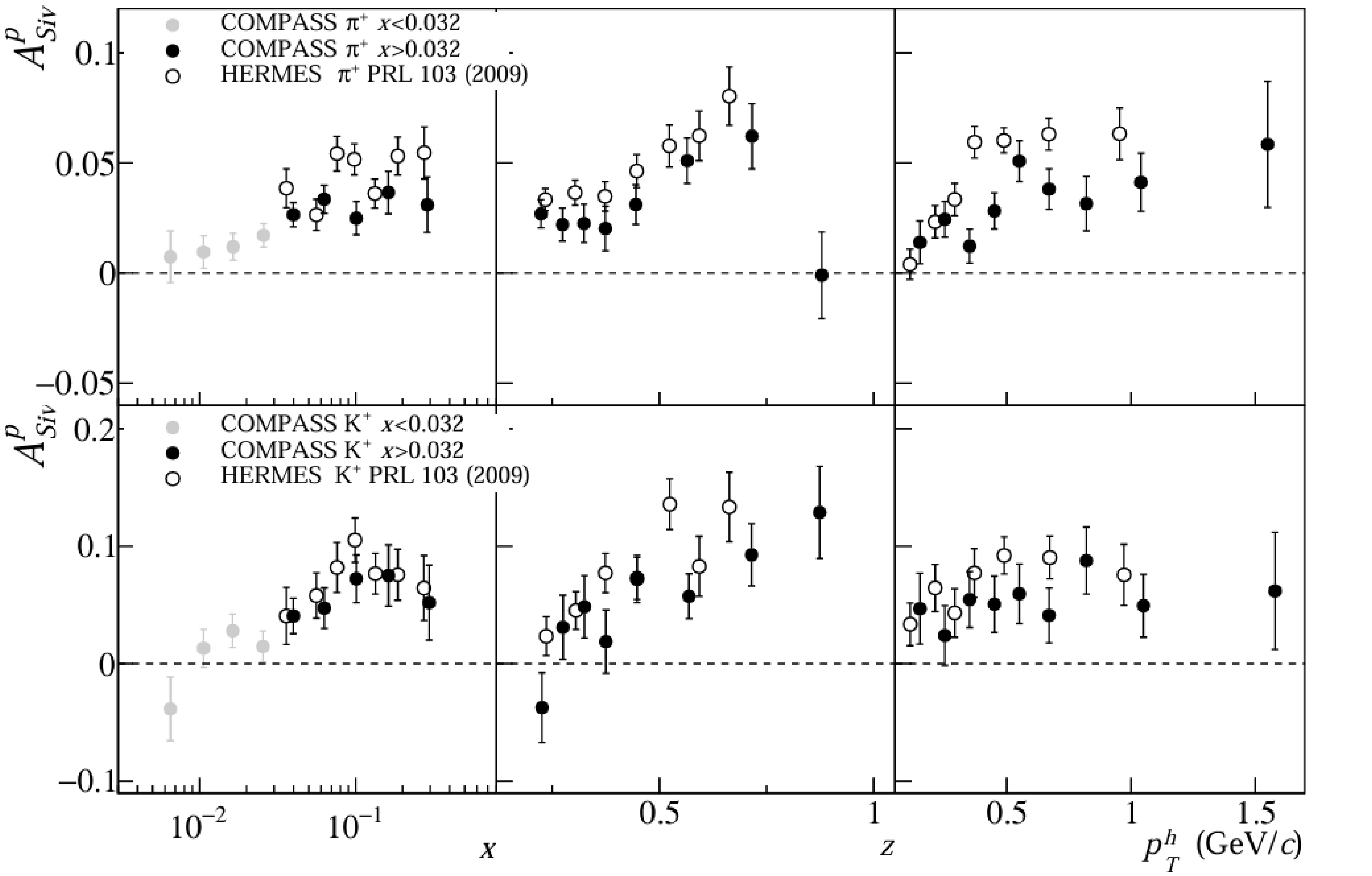
- Sivers function at large kt

$$f_{1T}^\perp(z,k_\perp) = \frac{\alpha_s}{2\pi^2}\frac{M}{(k_\perp^2)^2}\int\frac{dx}{x}\left\{\frac{C_A}{2}T_F(x,z)\frac{1+\xi}{(1-\xi)_+} + T_F(x,x)\frac{-1}{2N_c}\frac{D-2}{2}(1-\xi)\right.$$
$$+\frac{1}{2N_C}\left[\left(x\frac{\partial}{\partial x}T_F(x,x)\right)(1+\xi^2) + T_F(x,x)\frac{(1-\xi)^2(2\xi+1)-2}{(1-\xi)_+}\right]$$
$$\left.+T_F(x,x)\delta(1-\xi)C_F\left(\ln\frac{x^2\zeta^2}{k_\perp^2}-2\right)\right\} .$$



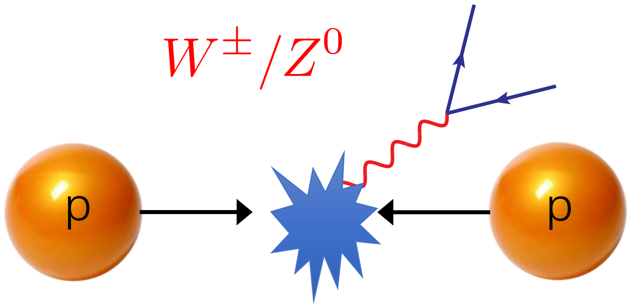
X. Ji, J.W. Qiu, W. Vogelsang, F. Yuan, Phys.Rev.Lett. 97 (2006) 082002 , Phys.Rev.D 73 (2006) 094017
J. Zhou F. Yuan Z. T. Liang,Phys.Rev.D78:114008,2008
Peng Sun, Feng Yuan ,Phys.Rev.D 88 (2013) 11, 114012

Transverse single spin asymmetries in SIDIS

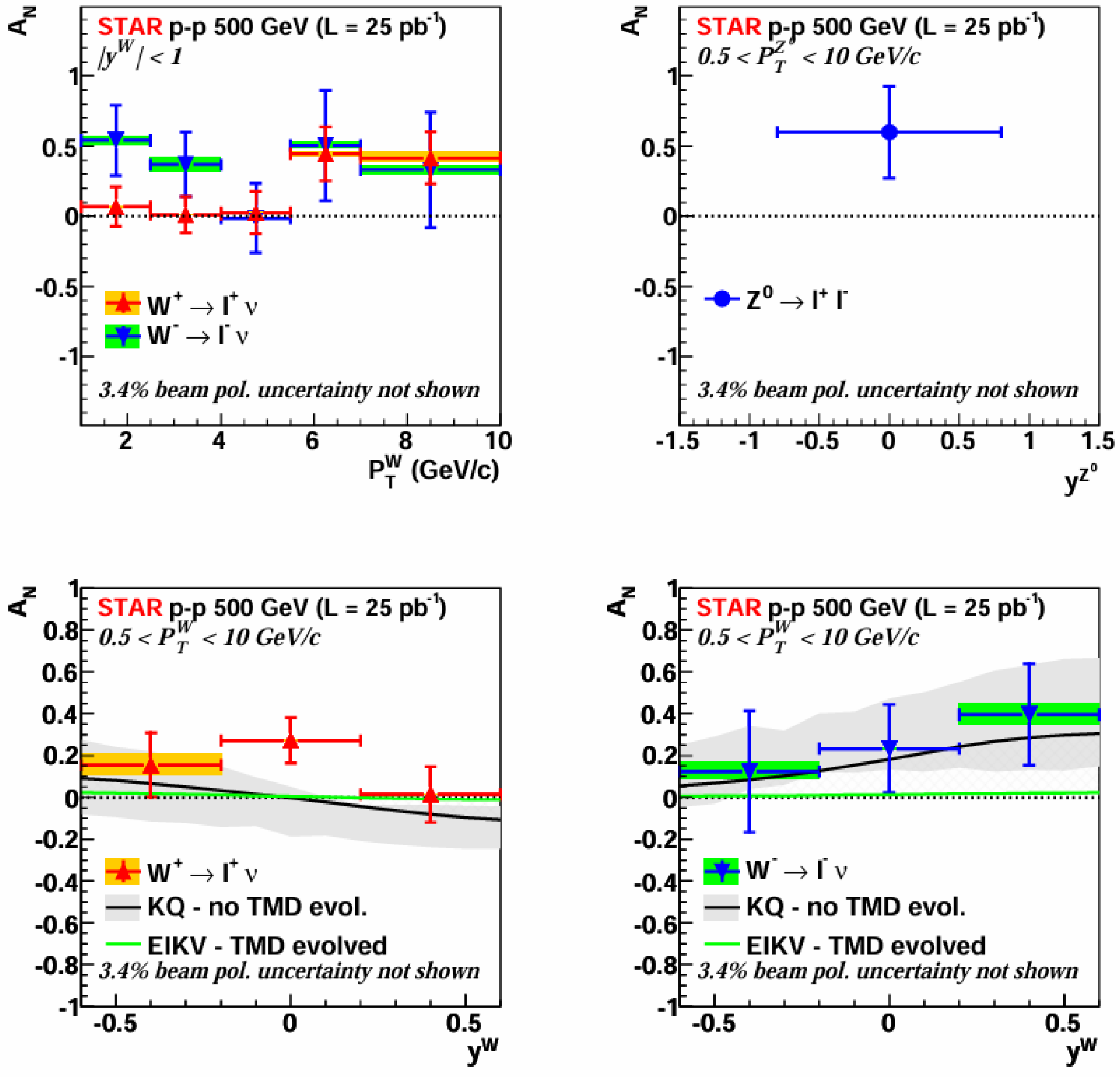


COMPASS
Phys. Lett. B744 (2015) 250
HERMES
Phys. Rev. Lett. 103 (2009) 152002

Transverse single spin asymmetries in weak boson production



STAR Collaboration,
Phys. Rev. Lett. 116, 132301 (2016)



Resummation

Soft gluon radiation leads to Sudakov Logarithms

$$\ln\left(Q^2 b_\perp^2\right) \sim \ln \frac{Q^2}{q_\perp^2}$$

The large logs will be resummed into the exponential form factor

$$W(Q,b) = e^{-\int_{1/b}^{Q} \frac{d\mu}{\mu}\left(\ln \frac{Q}{\mu} A + B\right)} C \otimes f_1 C \otimes f_2$$

Phenomenogical applications of the QCD resummation to the transverse momentum spectrum have been very successful

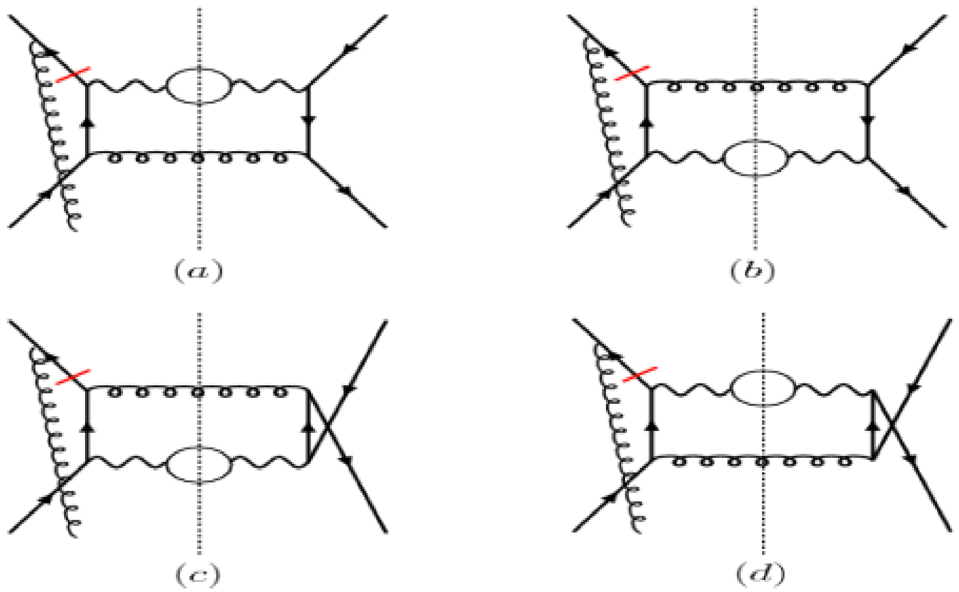
Resummation

Z.-B. Kang, B.-W. Xiao, and F. Yuan, Phys.Rev.Lett. 107 (2011) 152002

$$\frac{d\Delta\sigma(S_\perp)}{dy\,dQ^2 d^2q_\perp} = \sigma_0 \epsilon^{\alpha\beta} S_\perp^\alpha W_{UT}^\beta(Q;q_\perp)$$

$$\begin{aligned}\widetilde{W}_{UT}^\alpha(Q;b) &= e^{-\mathcal{S}_{UT}(Q^2,b)}\widetilde{W}_{UT}^\alpha(C_1/b,b)\\ &= (-ib_\perp^\alpha/2)\,e^{-\mathcal{S}_{UT}(Q^2,b)}\Sigma_{i,j}\\ &\quad \times \Delta C_{qi}^T \otimes f_{i/A}^{(3)}(z_1) C_{\bar{q}j} \otimes f_{j/B}(z_2)\end{aligned}$$

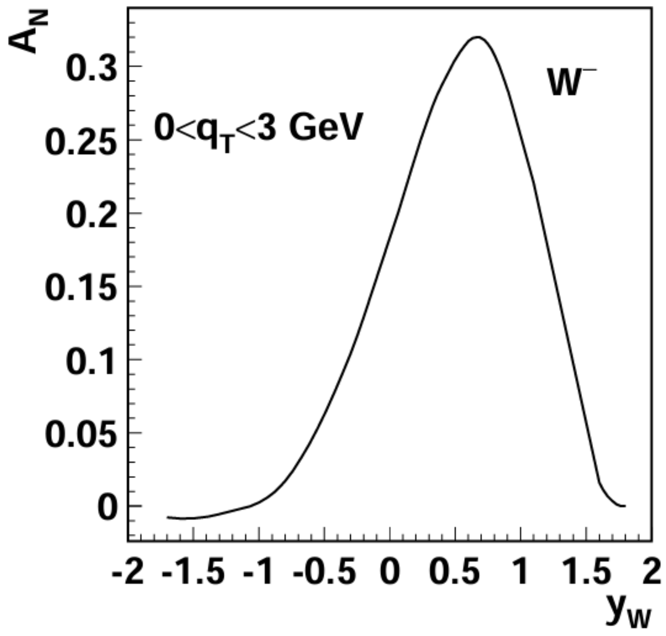
$$\mathcal{S}_{UT}(Q^2,b) = \int_{C_1^2/b^2}^{C_2^2Q^2} \frac{d\mu^2}{\mu^2}\left[\ln\left(\frac{C_2^2Q^2}{\mu^2}\right) A_{UT}(C_1;g(\mu)) + B_{UT}(C_1,C_2;g(\mu))\right] ,$$



Sudakov factor S_{UT} have the same form as that for the spin-average case

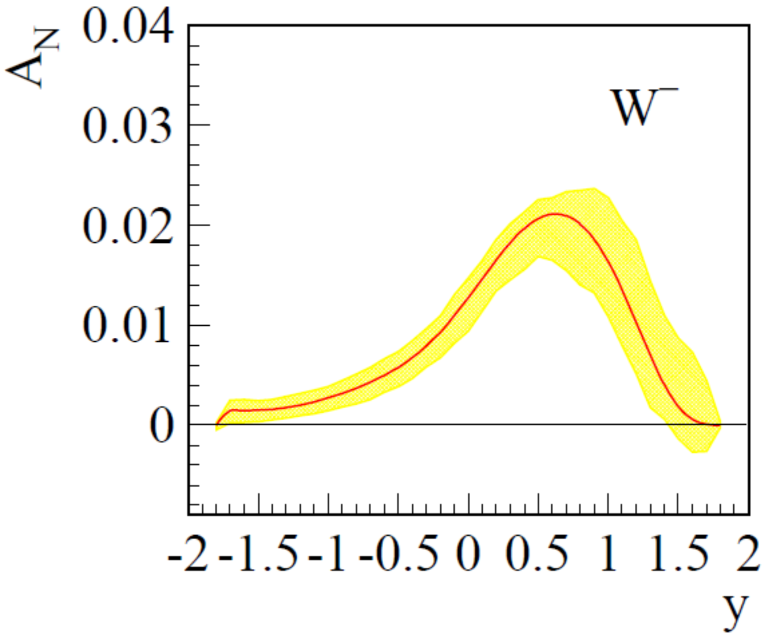
TMD evolution effect

Without TMD evolution



Z.B Kang, J.W Qiu,
Phys.Rev.Lett. 103 (2009) 172001

With TMD evolution



M.G. Echevarria,A. Idilbi,, Z.B Kang, I. Vitev, Phys.Rev.D 89 (2014) 074013

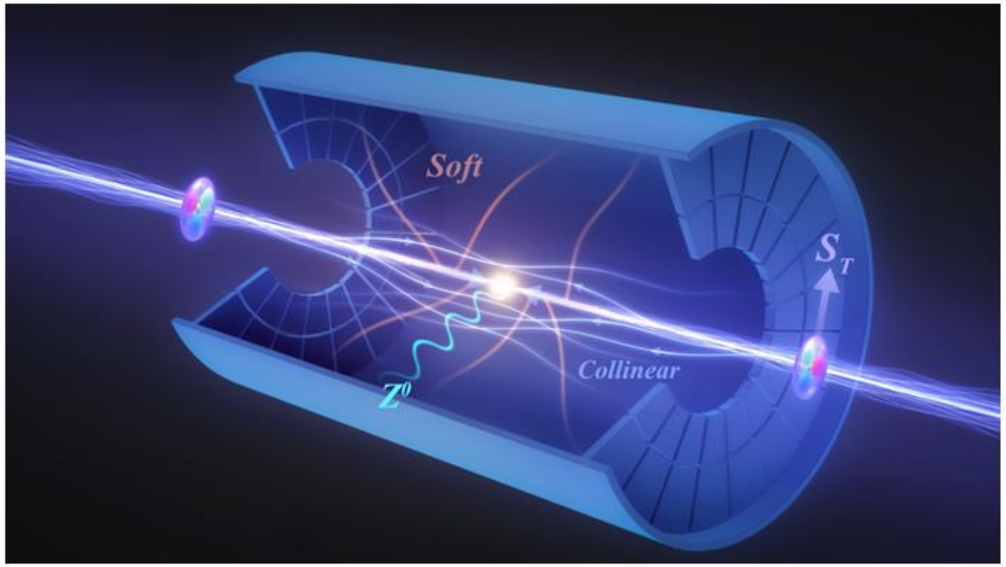
TMD evolution reduces the asymmetry.

How to enhance the asymmetry?

Our solution: 0-jettiness veto method

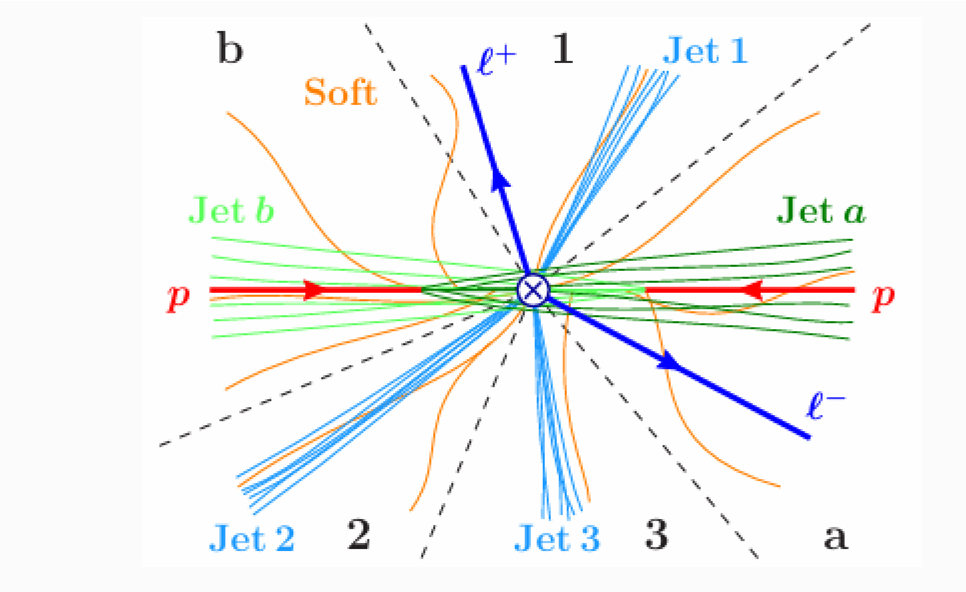
$$\tau \equiv \frac{2}{Q^2}\sum_i \min\{p_a \cdot l_i, p_b \cdot l_i\} = \sum_i \frac{|\vec{l}_{\perp,i}|}{Q} e^{|y_i - y|},$$

$$\tau < \tau_0$$



N-Jettiness

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



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

I.W. Stewart, F.J. Tackmann, W.J. Waalewijn,Phys.Rev.Lett.105:092002,2010

TMDs with 0-jettiness

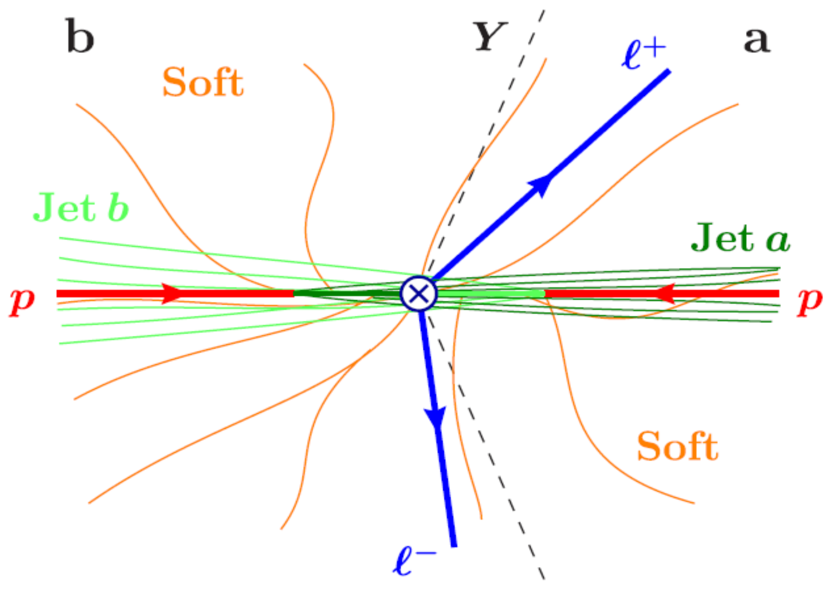
- For electroweak Drell-Yan processes, the 0-jettiness variable is defined as

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

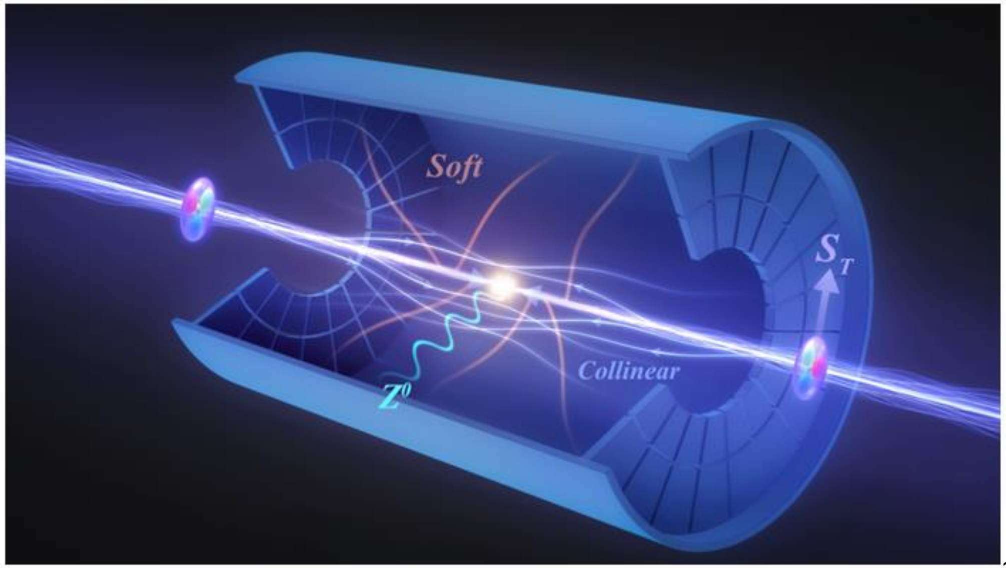
The sum runs over all particles i (excluding the gauge boson) with momentum l_i

$$\tau < \tau_0$$

- strongly suppresses central gluon radiation and effectively constrains initial state radiation.
- enhance the sensitivity to the intrinsic non-perturbative structure of TMDs



(b) Isolated Drell-Yan.



TMDs with 0-jettiness

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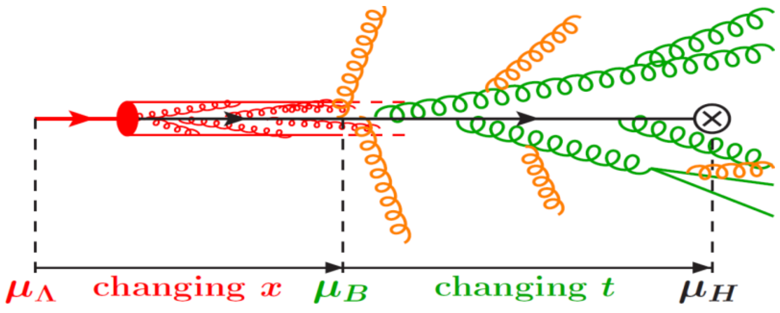
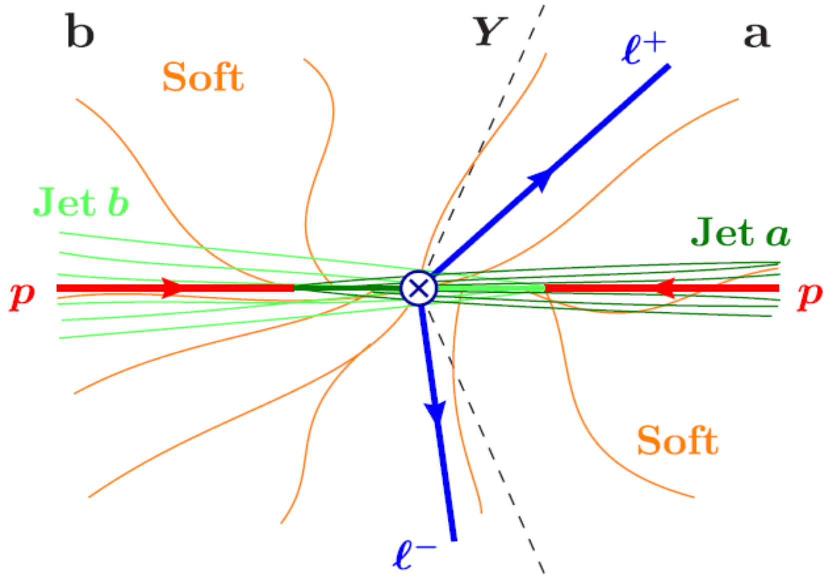
The sum runs over all particles i (excluding the gauge boson) with momentum l_i

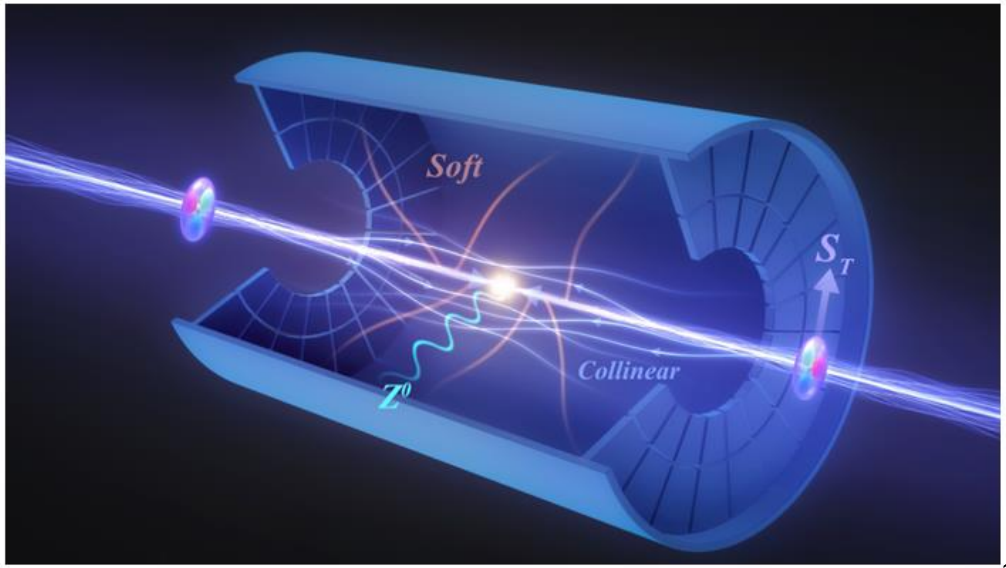
$$\tau < \tau_0$$

- The restricted phase space has a significant impact on the resummation procedure





(b) Isolated Drell-Yan.



Joint resummation of TMDs with 0-jettiness

Two types of large logs: $\ln \frac{Q^2}{q_\perp^2} \qquad \ln \frac{1}{\tau_0}$

- The modified Sudakov factor with vetoes:

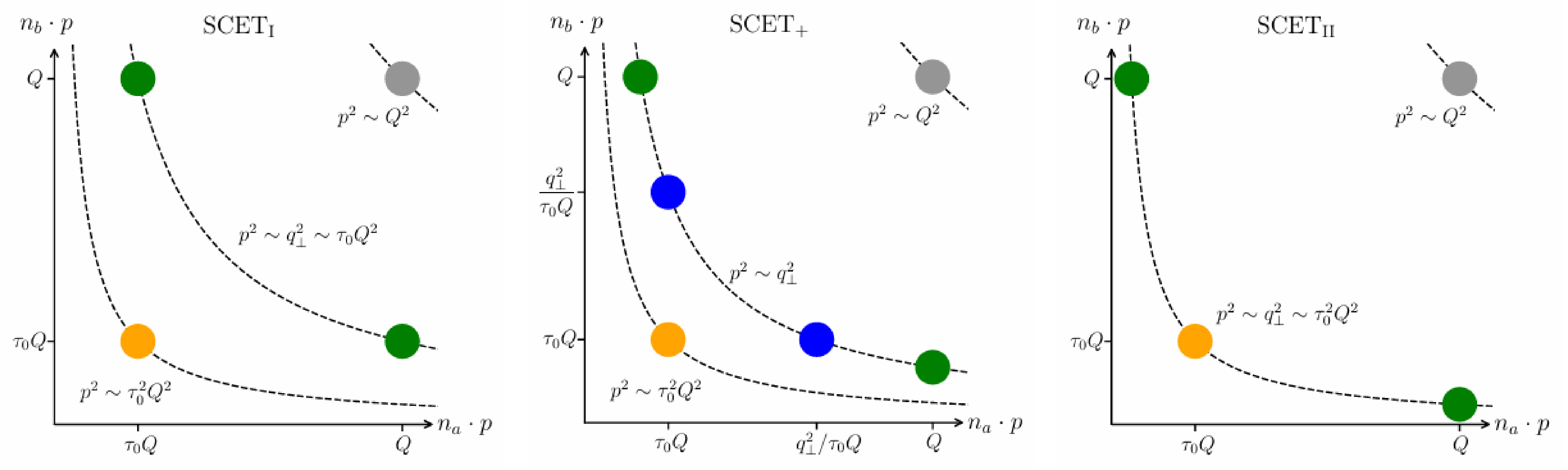
$$\frac{C_F}{\pi}\left[\int_{\mu_b^2}^{t}\frac{d\mu^2}{\mu^2}\left(2\ln\frac{t}{\mu^2}-\frac{3}{2}\right)-\int_{\mu_b^2}^{\tau_0 t}\frac{d\mu^2}{\mu^2}\ln\frac{\tau_0 t}{\mu^2}+\int_{t}^{Q^2}\frac{d\mu^2}{\mu^2}\left(\ln\frac{Q^2}{\mu^2}-\frac{3}{2}\right)+\int_{\tau_0 t}^{t}\frac{d\mu^2}{\mu^2}\ln\frac{\mu^2}{\tau_0 t}\right]\alpha_s(\mu)$$

- The standard Sudakov factor:

$$\frac{C_F}{\pi}\int_{\mu_b^2}^{Q}\frac{d\mu^2}{\mu^2}\left(\ln\frac{Q}{\mu^2}-\frac{3}{2}\right)\alpha_s(\mu)$$

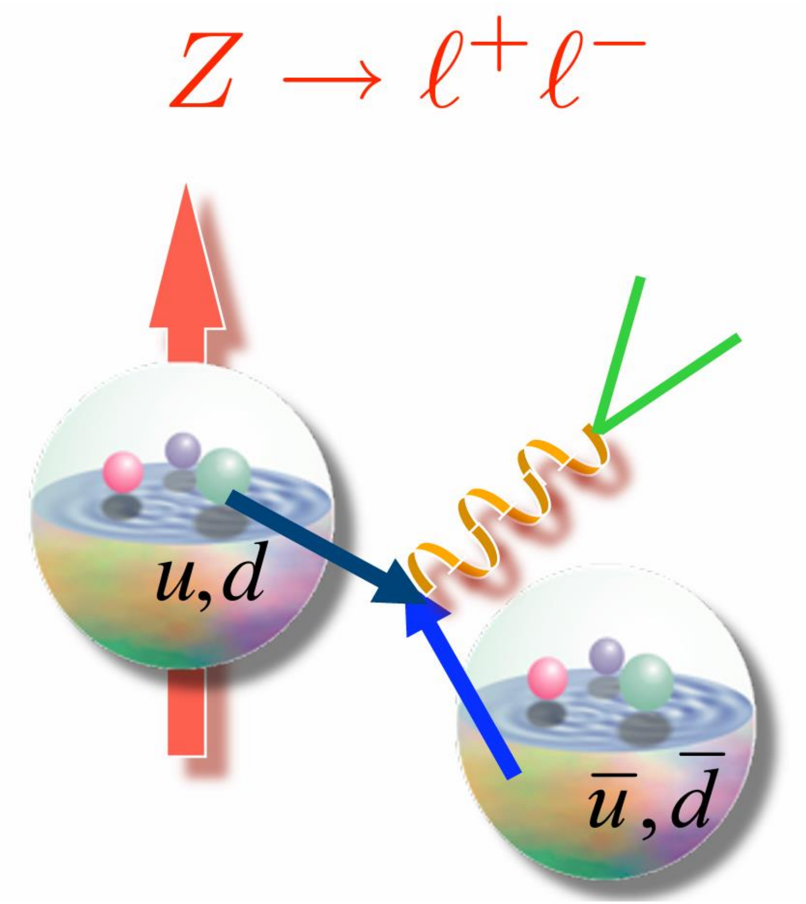
Formulation in SCET

G. Lustermans, J. K. L. Michel, F. J. Tackmann, and W. J. Waalewijn, JHEP 03, 124 (2019), 1901.03331.
M. Procura, W. J. Waalewijn, and L. Zeune, JHEP 02, 117 (2015), 1410.6483.

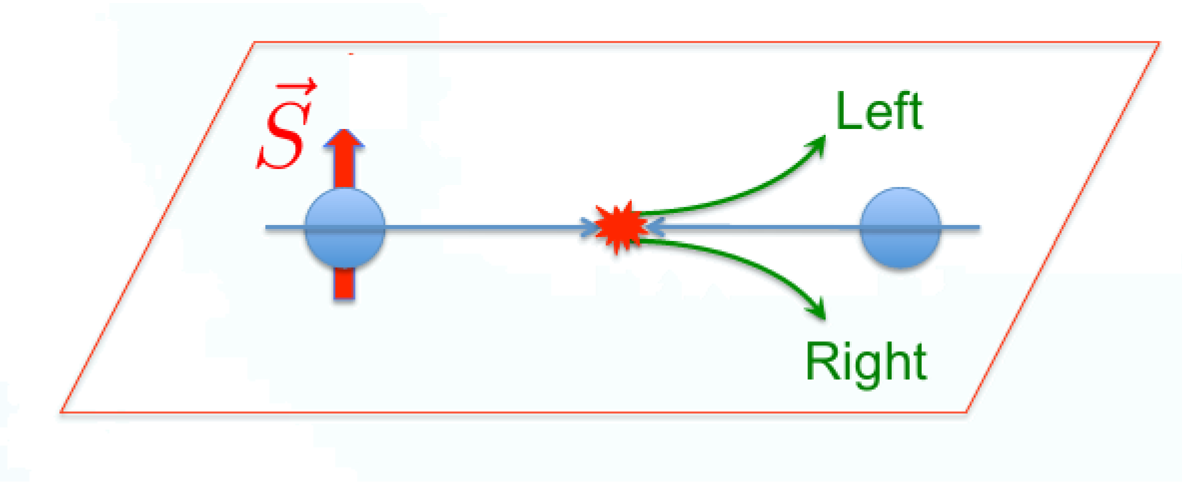


$\tau_0^2 Q^2 \ll q_\perp^2 \sim \tau_0 Q^2 \ll Q^2$ $\tau_0^2 Q^2 \ll q_\perp^2 \ll \tau_0 Q^2 \ll Q^2$ $\tau_0^2 Q^2 \sim q_\perp^2 \ll \tau_0 Q^2 \ll Q^2;$

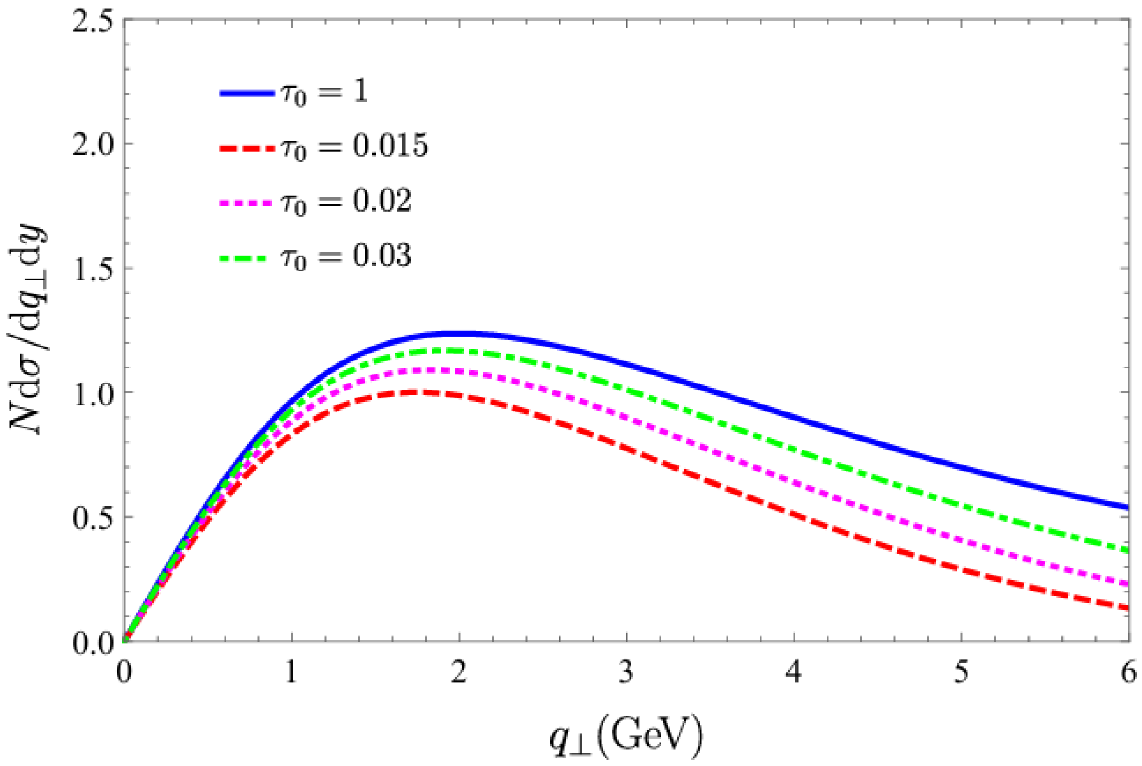
Impact of 0-jettiness on spin asymmetries



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



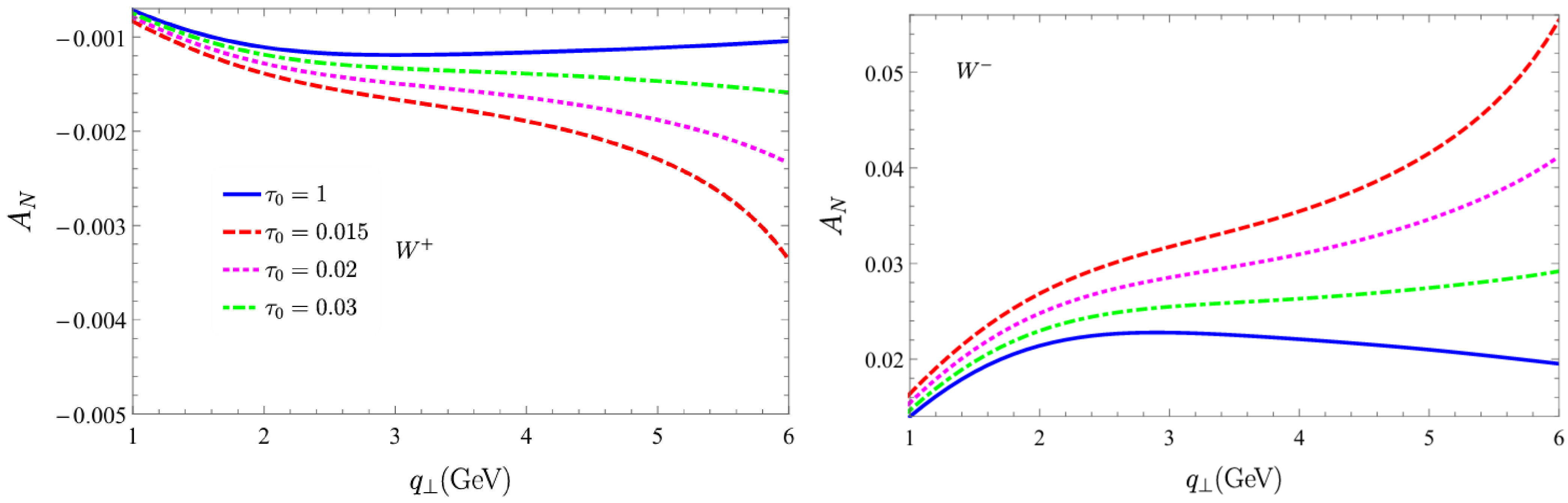
Numerical results



The normalized unpolarized cross section for Z^0 production at RHIC energy

The enhanced asymmetries

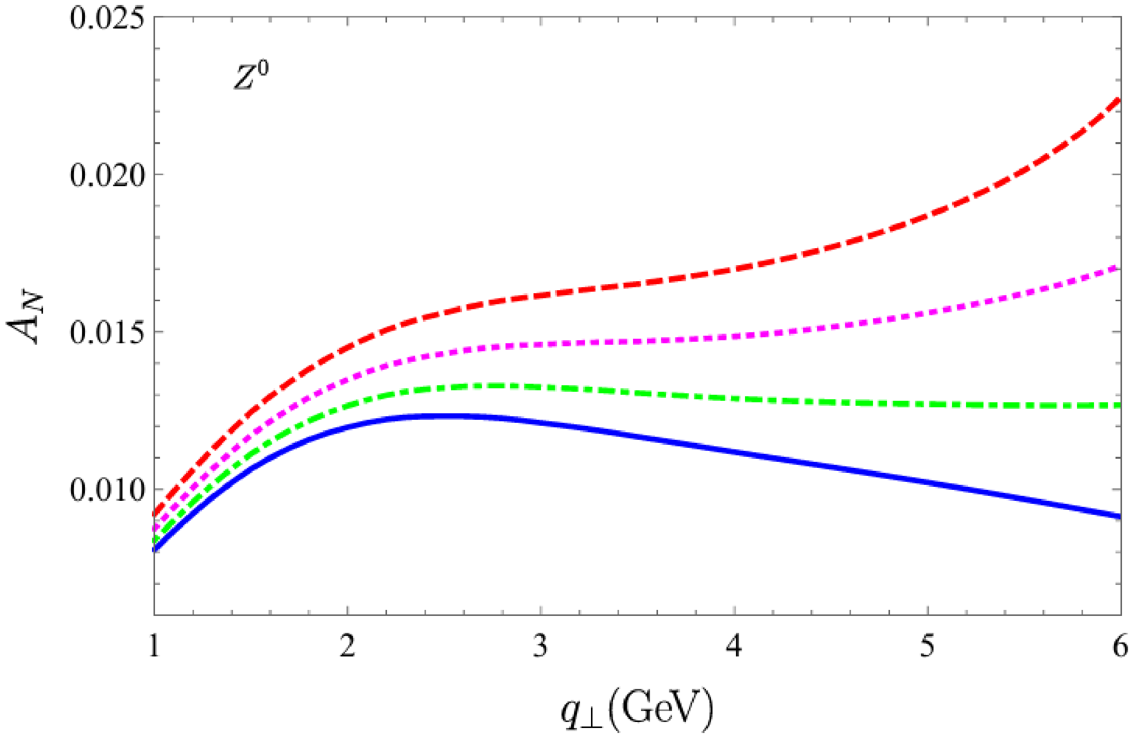
- Transverse single spin asymmetries in $W^{\pm}$ production



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

The enhanced asymmetries

- Transverse single spin asymmetries in Z^0 production

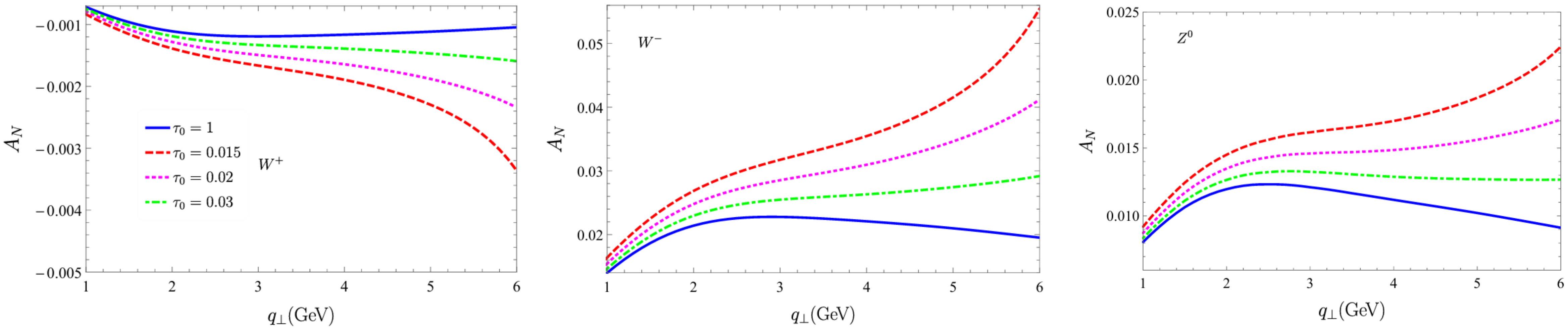


For Z^0 at $\tau_0 = 0.015$,the single-spin asymmetry is enhanced by approximately 83% at $q_\perp = 5$GeV

The enhanced asymmetries

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

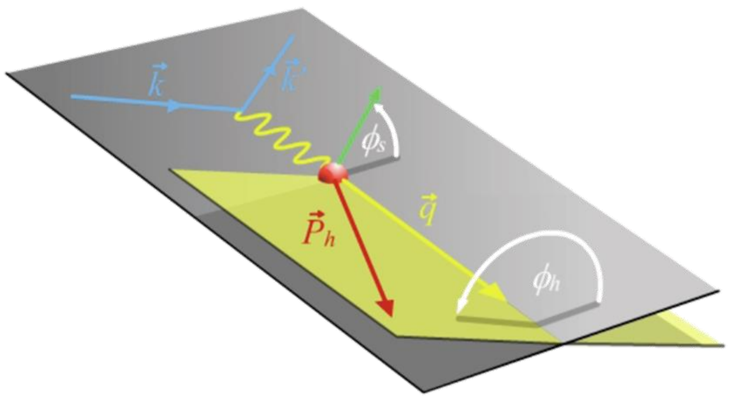
$$\tau < \tau_0$$



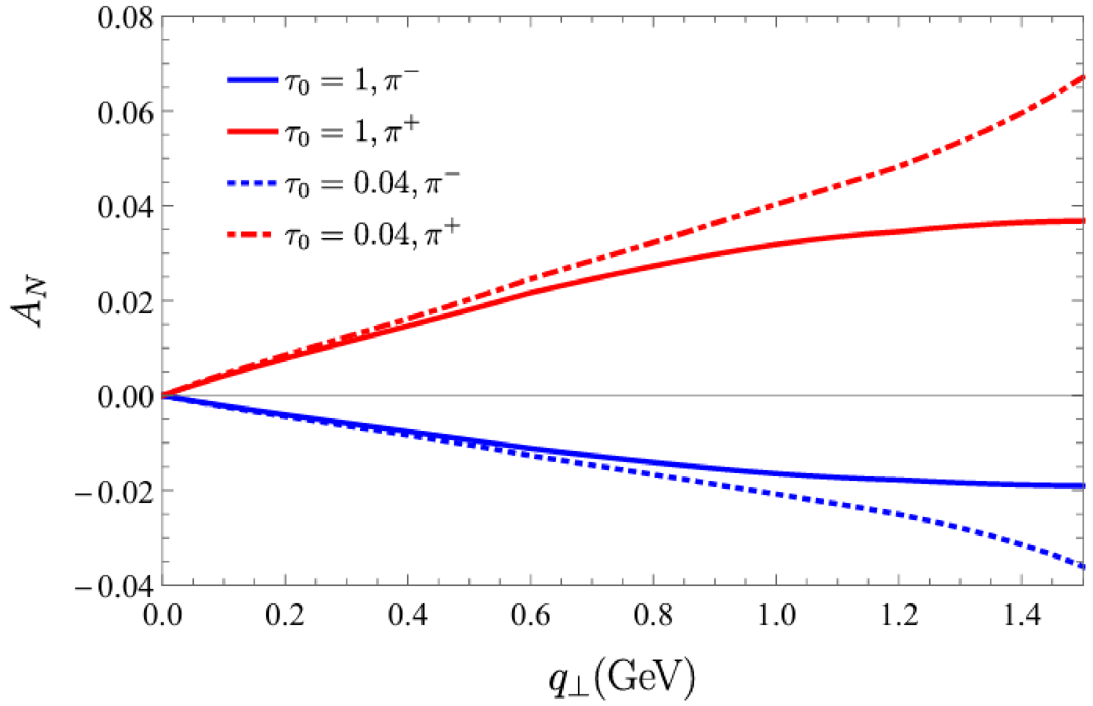
Implementing a 0-jettiness veto can significantly enhance the sensitivity of SSA measurements to the predicted sign flip of the Sivers function, thereby offering a more robust avenue for testing fundamental TMD dynamics in polarized collisions.

Single spin asymmetry in SIDIS

- 1-jettiness



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



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

Summary

- Introduced a 0-jettiness veto method to suppress TMD evolution effects and probe nucleon spin structure.
- Single-spin asymmetries (SSAs) in $W^{\pm}/Z^{0}$ production at RHIC are significantly enhanced with the veto.
- Other kinematic variable to constraint events

Thanks for your attention!

Back up

Resummation

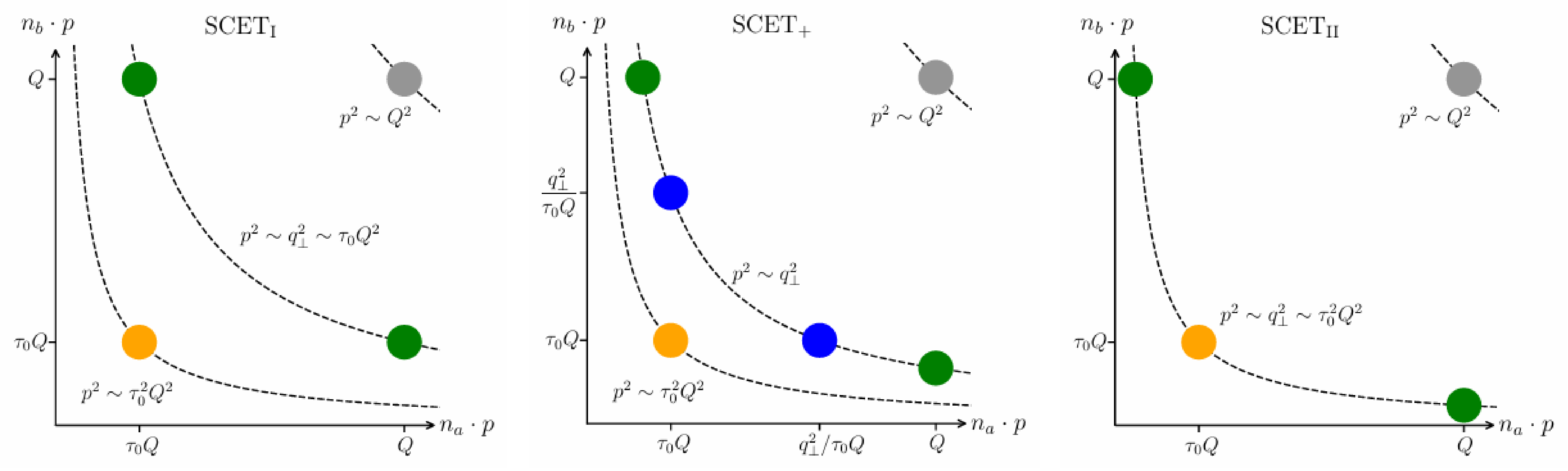
A. Idilbi, X. Ji, J.-P. Ma, F. Yuan, Phys.Rev.D 70 (2004) 074021

The scale evolution of the Sivers function at one-loop order,

$$\zeta\frac{\partial}{\partial\zeta}\partial_b^i q_T(x,b,\mu,x\zeta,\rho) = \left(K(b,\mu,\rho)+G(x\zeta,\mu,\rho)\right)\partial_b^i q_T(x,b,\mu,x\zeta,\rho)$$

K and G are the same as those for the unpolarized distribution.

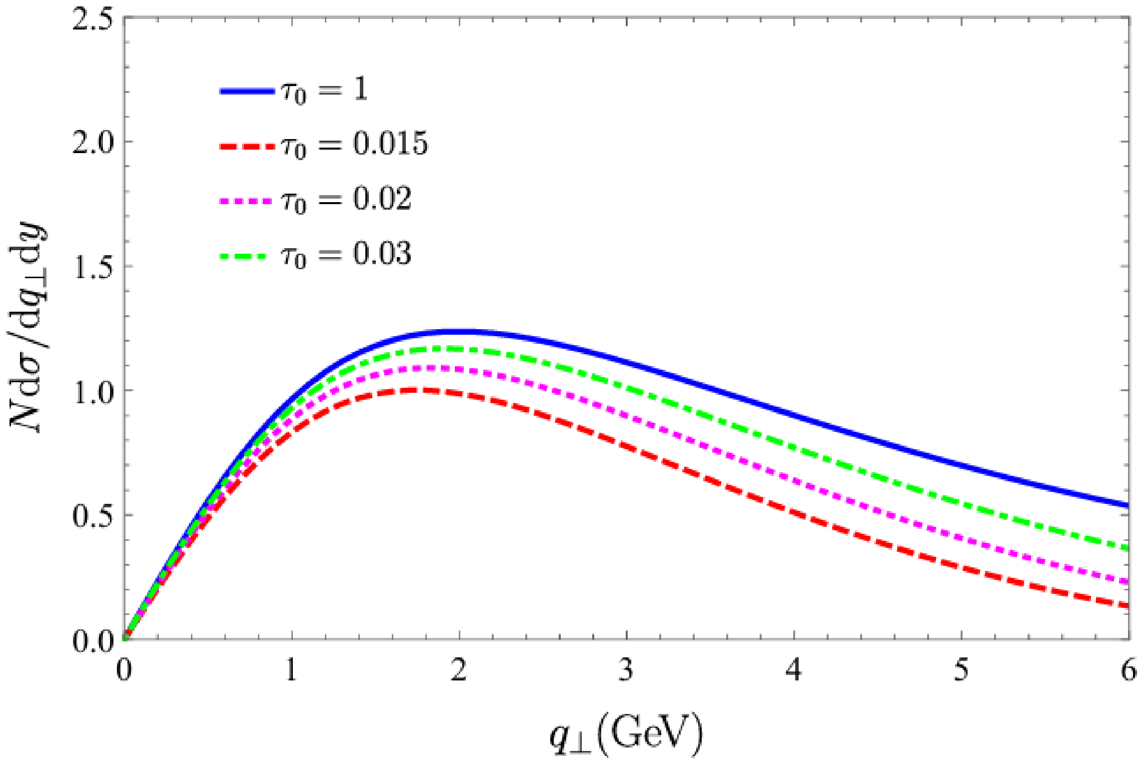
The scale evolution of polarization dependent TMDs is governed by the standard Collins–Soper equation, since the light-cone divergence have the same structure in polarized and unpolarized cases.

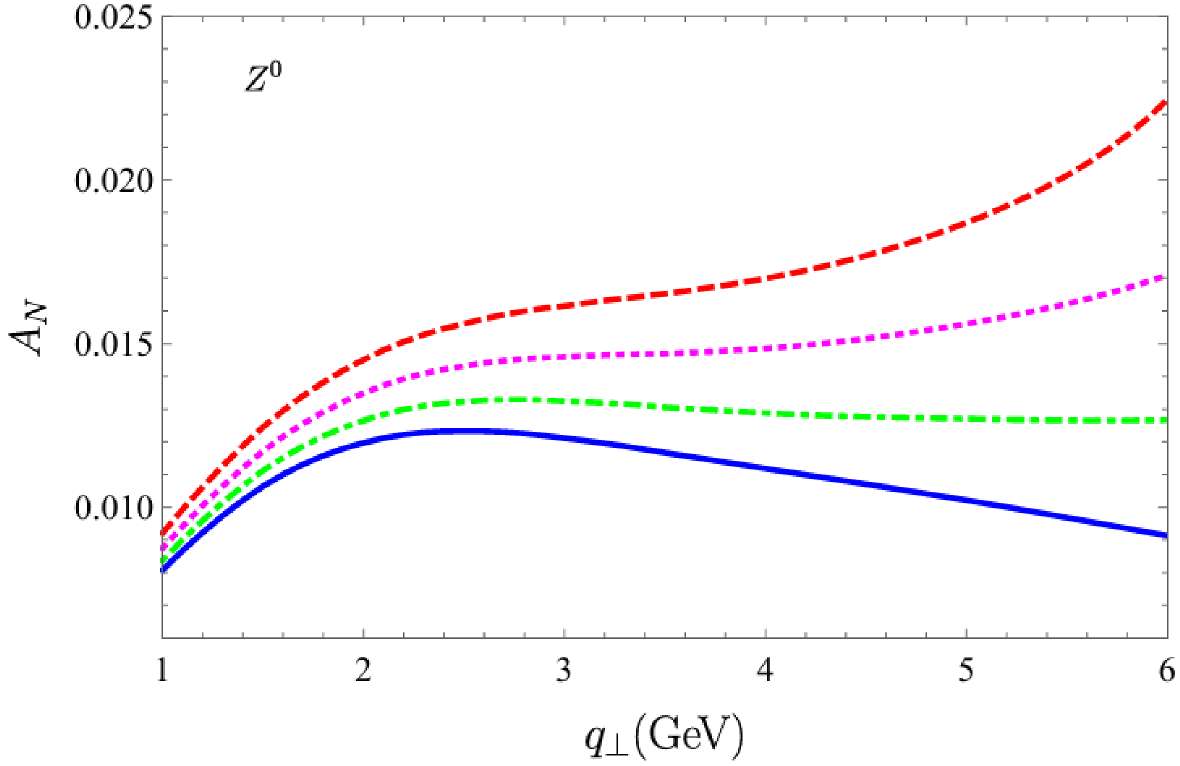


$$\tau_0^2 Q^2 \ll q_\perp^2 \sim \tau_0 Q^2 \ll Q^2 \qquad \tau_0^2 Q^2 \ll q_\perp^2 \ll \tau_0 Q^2 \ll Q^2 \qquad \tau_0^2 Q^2 \sim q_\perp^2 \ll \tau_0 Q^2 \ll Q^2;$$

We implement the transitions between these regimes using Heaviside θ functions, resulting in the final combined perturbative Sudakov factor:

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





Statistical error for τ_0=0.015 increased by 27% compared to the unrestricted measurement of the SSA in Z^0 production.

The SSA is enhanced by approximately 42% in the same kinematic region.

Despite the statistical cost, the overall sensitivity of the analysis improves.